



Aix Marseille Université, CNRS, Laboratoire d'Astrophysique de Marseille

École Doctorale Physique et Sciences de la Matière

Astrophysique et Cosmologie

Morphology as a tracer of evolution in the early phases of galaxy assembly

RIBEIRO, Bruno

Thèse dirigée par: LE FÈVRE, Olivier,

Soutenue le 5 Décembre 2016

Jury

AMRAM, Philippe
MAIOLINO, Roberto
FONTANA, Adriano
BERTIN, Emmanuel
TASCA, Lidia
LE FÈVRE, Olivier

October 18, 2016



Aix Marseille Université, CNRS, Laboratoire d'Astrophysique de Marseille

École Doctorale Physique et Sciences de la Matière

Astrophysique et Cosmologie

Morphology as a tracer of evolution in the early phases of galaxy assembly



RIBEIRO, Bruno

Thèse dirigée par: LE FÈVRE, Olivier,

Soutenue le 5 Décembre 2016

October 18, 2016

"[S]ince every piece of matter in the Universe is in some way affected by every other piece of matter in the Universe, it is in theory possible to extrapolate the whole of creation - every sun, every planet, their orbits, their composition and their economic and social history from, say, one small piece of fairy cake."

in The Restaurant at the End of the Universe, Douglas Adams

Preface

This thesis is partially based on the following publications, written in collaboration with the VIMOS Ultra Deep Survey team.

REFEREED PUBLICATIONS ACCEPTED OR SUBMITTED

- **Ribeiro, B.;** Le Fèvre, O.; Tasca, L. et al., **Size evolution of star-forming galaxies at $2 < z < 4.5$ from the VIMOS Ultra-Deep Survey**, 2016, *A&A*, 593, 22
- Tasca, L.; Le Fèvre, O.; **Ribeiro, B.** et al., **The VIMOS Ultra Deep Survey First Data Release: spectra and spectroscopic redshifts of 698 objects up to $z_{\text{spec}} \sim 6$ in CANDELS**, [arXiv:1602.01842](#), *A&A*, in press
- **Ribeiro, B.;** Le Fèvre, O.; Cassata, P. et al., **A major merger origin for the high fraction of galaxies at $2 < z < 6$ with 2 bright clumps**, (submitted to *A&A*)

Copies of these three publications may be found in the appendix.

REFEREED PUBLICATIONS IN PREPARATION

- **Ribeiro, B.;** Le Fèvre, O.; Tasca, L. et al., **Lyman-alpha line morphology and galaxy shapes at $2 < z < 6$ with VUDS**, (in prep.)
- **Ribeiro, B.;** Le Fèvre, O.; Tasca, L. et al., **The connection between spectro-photometric properties and the morphology of galaxies with $2 < z < 6$** , (in prep.)

This thesis incorporates text from the aforementioned articles. Unless stated explicitly, all figures and calculations presented in this thesis were performed by the author.

Sections of this thesis describing the overview on galaxy formation and evolution in general, and morphology in particular, are based on reviews by [Kormendy & Kennicutt \(2004\)](#), [Conselice \(2014\)](#) and [Somerville & Davé \(2015\)](#), and the books by [Mo et al. \(2010\)](#) and [Sparke & Gallagher \(2007\)](#).

Acknowledgments

I would like to start by thanking Ana. She is the reason you are reading this thesis. Without her support, resilience, ideas and hours and hours of discussions this manuscript would not see the light of day in its current form.

I am deeply grateful to my supervisor, Olivier, for all the support, the knowledge and encouragement to experiment with new ideas. I could also not have made it through without the collaboration of several members of the VUDS team, in particular Lidia, Brian, Paolo, Janine and Nimish that have accompanied me for all or most part of the period on which I was working on this project. A special thanks is also required for all those who have contributed directly to this project by helping me classify the objects in my samples: Brian, Dario, Janine, Laurence, Lidia, Lucia, Marco, Margherita, Nimish, Olivier, Paolo, Ricardo, Sotiria, Stephane, Vincent.

This work is supported by funding from the European Research Council Advanced Grant ERC-2010-AdG-268107-EARLY. This work is based on data products made available at the CESAM data center, Laboratoire d’Astrophysique de Marseille.

This research made use of Astropy, a community-developed core Python package for Astronomy ([Astropy Collaboration et al., 2013](#)); Numpy & Scipy ([Walt et al., 2011](#)); Matplotlib ([Hunter, 2007](#)).

• This page is intentionally left blank •

Résumé

Les propriétés globales des galaxies montrent une forte évolution du taux de formation stellaire et de la densité de masse stellaire à l'époque de l'assemblage des galaxies précédent le pic de formation stellaire dans l'univers, produite par plusieurs processus physiques concurrents (fusion, accrétion, rétroaction, environnement, ...). Les propriétés morphologiques des galaxies ont aussi fortement évolué à la même époque. Dans cette thèse, j'étudie comment l'évolution des propriétés morphologique est reliée aux propriétés spectrophotométriques des galaxies depuis $z \sim 6$. Les données spectroscopiques obtenues au sein du VIMOS Ultra Deep Survey (VUDS), un nouveau sondage spectroscopique unique de ~ 10000 galaxies entre redshift $z \sim 2$ et $z \sim 6$ menée à l'ESO-VLT, combinée avec l'imagerie du télescope spatial Hubble des sondages COSMOS et CANDELS, fournissent un excellent moyen de sonder l'évolution galactique à travers cette époque cosmique. Ce manuscrit est globalement divisé en 4 sujets abordant l'évolution des galaxies et sa morphologie.

Un premier sujet est lié à l'évolution de la taille des galaxies à haut redshift. J'ai développé un nouvel algorithme qui mesure la taille des galaxies d'une manière non-paramétrique en calculant la superficie totale couverte par la galaxie à une brillance de surface fixée. Je compare mes nouvelles mesures avec celles utilisées en standard dans la littérature et trouve une évolution différente. Je trouve que les galaxies ont une même taille typique constante dans l'intervalle $2 < z < 4.5$ contrairement à l'évolution modérée vers des petites tailles trouvée pour la même population pendant la même période lors de l'utilisation d'une mesure de taille standard. J'attribue cette différence à la morphologie irrégulière pré dominante à ces époques. Je trouve une grande dispersion dans la taille des galaxies avec, au même redshift, des galaxies compactes et non résolues avec HST, et de très grandes galaxies avec des tailles totales au delà de 10 kpc. Je discute l'implication de ces résultats et conclu que cette dispersion doit être le résultat de plusieurs chemins d'évolution distincts pour assembler les galaxies.

Le deuxième sujet concerne l'analyse des super-amas d'étoiles et de gaz (*clumps*) et leur importance dans l'assemblage des galaxies. Sur la base de l'algorithme utilisé pour calculer la surface totale des galaxies, j'ai développé un nouveau module pour détecter ces super-amas dans un isophote de luminosité fixée. Je trouve que la fraction des galaxies avec des super-amas est élevée à $2 < z < 6$ ($\sim 35 - 55\%$) et augmente à plus grands redshifts. Une observation intéressante est que la classe dominante est celle des galaxies avec deux super-amas, et ceux-ci se trouvent souvent être plus brillants et plus grands que les autres. Ces résultats indiquent un scénario où nous assistons à la fusion de galaxies dans sa phase finale, en accord avec la fraction de fusions mesurée à partir d'études de paires de galaxies. Les super-amas petits et les moins lumineux sont quand à eux similaires à ceux observés dans les simulations numériques de disques galactiques, avec des instabilités dynamiques produisant des super-amas qui migrent au centre de la galaxie et fusionnent pour former un proto-bulbe.

Ensuite, après un bref résumé de notre compréhension de l'évolution de la séquence de Hubble au cours du temps cosmique je décris l'application d'un système de classification morphologique visuelle à un échantillon de galaxies à formation d'étoiles à grands redshifts. Je constate une

prévalence de galaxies irrégulières sur tout l'intervalle $2 < z < 6$ avec une fraction d'environ $\sim 40 - 50\%$ de l'échantillon. En ce qui concerne leurs propriétés physiques globales, je trouve un scénario diversifié où les différents types morphologiques couvrent une large gamme de masses stellaires, de taux de formation d'étoiles, de contenu en poussière, et d'âges. Je conclus qu'il n'y a pas de correspondance univoque entre un type morphologique et un chemin unique de formation.

Enfin, j'examine les mécanismes physiques qui sont proposés pour expliquer l'émission de photons Ly- α dans les galaxies à grands redshifts et je présente une étude sur les conditions typiques qui permettent aux photons Ly- α de s'échapper dans ces galaxies. Avec l'aide de plusieurs membres de la collaboration de VUDS j'ai produit un catalogue de galaxies émetteurs de la raie Ly- α classés visuellement en fonction de la forme de la raie dans les spectres 2D. Nous identifions une classe d'émetteurs avec la raie spatialement étendue (par rapport à l'émission du continuum UV) qui correspond aux émetteurs Ly- α (LAEs) identifiés classiquement dans la littérature en raison de leur grande largeur équivalente. Ces objets se trouvent être plus petits, moins poussiéreux, moins massifs et avec une formation d'étoiles plus faible que d'autres catégories d'émetteurs ou de galaxies sans émission Ly- α . Je conclus que cette classe d'objets explique en partie les différences constatées dans la littérature entre les LAEs et les galaxies à formation d'étoiles normales.

A partir des résultats présentés ci-dessus, je conclus que les différentes propriétés morphologiques de galaxies à formation stellaire aux redshifts $2 < z < 6$ montrent qu'il existe plusieurs façons pour les galaxies de se former. La grande diversité de tailles, la fraction importante de superamas d'étoiles et de gaz très lumineux indiquant des fusions et ceux moins lumineux résultant probablement d'instabilités dans la formation des disques galactiques, avec la prévalence de galaxies irrégulières couvrant un grand domaine de masse stellaire et formation stellaire, pointent ensemble un scénario où l'assemblage des galaxies procède de différents mécanismes physiques. La formation des galaxies apparaît ainsi plus complexe qu'un scénario simple impliquant la formation d'un disque avec de l'accrétion de gaz froid pourrait le faire croire. Je présente des arguments observationnels qui identifient plusieurs chemins de formation et d'assemblage des galaxies dans lesquels les principaux mécanismes physiques, principalement les fusions, l'accrétion et les instabilités dans les disques, ainsi que les effets de rétroaction dus aux vents stellaires ou des noyaux actifs, contribuent de façon radicalement différente.

Mots clés: Galaxies: morphologie; Galaxies: évolution; Galaxies: haut redshift; Galaxies: Ly- α

Abstract

The global properties of galaxies show a strong evolution of the star formation rate and stellar mass density at the epoch of galaxy assembly, driven by several competing physical processes (merging, accretion, feedback, environment,...). The morphological properties of galaxies are also strongly evolving over the same timescales. I investigate how the evolution of the morphological properties is connected to the spectrophotometric properties of galaxies since $z \sim 6$. The spectroscopic data obtained within the VIMOS Ultra Deep Survey (VUDS), a new unique spectroscopic survey of ~ 10000 galaxies between redshifts $z \sim 2$ and $z \sim 6$ conducted at the ESO-VLT, combined with the available Hubble Space Telescope imaging surveys such as COSMOS or CANDELS provide a great opportunity of probing galactic evolution across this cosmic epoch. This thesis is broadly divided in 4 topics tackling galaxy morphology evolution.

A first topic is related to the evolution in galaxy sizes at high redshift. I have developed a new algorithm that measures galaxy sizes in a non-parametric way by computing the total area covered by the galaxy above a fixed luminosity isophote. I compare my new measurements with those standardly used in the literature and find that in terms of typical evolution they differ substantially. I find that galaxies have the same typical size across $2 < z < 4.5$ contrary to a moderate evolution found for the same population in the same period when using a standard size measurement. I attribute this difference to the often irregular shape of galaxies at these epochs. Importantly, I find that the dispersion of sizes is very large, with, at the same redshift, compact galaxies that are basically unresolved with HST, and very large galaxies with total sizes over 5 kpc. I discuss the implications of these findings and conclude that the wide range of galaxy sizes must be the result of several different paths for galaxy assembly.

The second topic provides context for the search of galactic clumps at high redshift and the importance it has for galaxy assembly studies. Based on the algorithm used to compute the total extent of galaxies, I developed a new code to detect clumps within a given isophote. I find that the fraction of clumpy galaxies is high at $2 < z < 6$ ($\sim 35 - 55\%$) and increases at higher redshifts. An interesting finding is that the predominant class of clumpy galaxies has two clumps, and these are often found to be the brightest and largest of all clumps. I argue that these results point to a scenario where we are witnessing merging of galaxies in its final stages, and that it complements the merger fraction derived from pair finding studies. The faint and small clumps are more akin to the clumps produced in the simulation of discs, where violent disc instabilities produce several clumps migrating to form a central proto-bulge.

Then I move to a brief summary on our understanding of the evolution of the Hubble sequence across cosmic time and an extension of a visual classification scheme to a high-redshift sample of star-forming galaxies. I find a prevalence of irregular galaxies at all redshifts $2 < z < 6$ that amount to around $\sim 40 - 50\%$ of the star-forming sample. With respect to their global physical properties I find a diverse scenario where different morphological types span a wide range in stellar masses, star formation rates, dust content and ages. I argue that star-forming galaxies at these redshifts show diverse paths of galaxy formation and that no single morphological type corresponds univocally to a single path for formation.

Finally I provide some context about the physical mechanisms that are thought to power the emission of Ly- α photons in high redshift galaxies to introduce a study on the typical conditions for Ly- α emission in high redshift galaxies. With the help of several members of the VUDS collaboration I have produced a catalog of visually classified Ly- α emitters based on the shape of the line on the 2D spectra. I identify a class of spatially extended line emitters (with respect to the UV continuum emission) that is the typical object corresponding to Ly- α emitters (LAEs) due to its large equivalent width. These objects are found to be smaller, less dusty, less massive and less star-forming than other classes of line emitters and also objects with no emission at all. I argue that this class of objects is partially the explanation for the differences found between LAEs and normal star-forming galaxies that are found in the literature.

From the results that I have obtained, I conclude that the different morphological properties of star-forming galaxies at $2 < z < 6$ show that there are several mechanisms that take part in galaxy formation. The great diversity in galaxy sizes, the high number of bright two clump systems as well as faint multi-clump systems indicating merging and disk instabilities processes, respectively, and the wide range in physical properties that are populated by irregular galaxies all point to a diverse history for galaxy formation. This suggests that forming galaxies is far more complex than a scenario involving cold gas accretion alone. I present observational evidence in favor of several different path for galaxy formation and assembly, for which the contribution of key physical processes like merging, accretion and disc instabilities, as well as stellar and AGN feedback, are very different.

Keywords: Galaxies: morphology; Galaxies: evolution; Galaxies: high redshift; Galaxies: Ly- α

Contents

	Page
Preface	iii
Résumé	vii
Abstract	ix
Contents	xi
List of Figures	xiii
List of Tables	xvii
1. Introduction: morphology as a tracer of galaxy evolution	1
1.1 Overview on galaxy morphology	3
1.2 Outline	6
2. Galaxy morphological evolution: current knowledge	9
2.1 Physical drivers of morphology evolution	9
2.2 Methods for the quantification of galaxy morphology	15
2.3 Tracing morphological evolution across cosmic time	16
2.4 Topics in this thesis	18
3. Data and sample selection	23
3.1 The VIMOS Ultra Deep Survey	23
3.2 Imaging surveys in the optical and NIR	27
3.3 Methods for data analysis	29
3.4 Selection function	35
4. A quantitative approach to galaxy morphology at $2 < z \lesssim 5$	39
4.1 Parametric Fitting	40
4.2 Non-Parametric Fitting	45
	xi

4.3	Beyond symmetric models for size estimates	55
4.4	A search for high-redshift clumps	63
4.5	Visual Classification	70
4.6	Classifying the Ly- α emission in 2D spectrograms	76
5.	Morphological properties of $2 < z \lesssim 6$ star-forming galaxies	83
5.1	A different look on galaxy sizes	84
5.2	The prevalence of clumps in assembling galaxies	98
5.3	Morphology visual classification	105
5.4	Extending morphology to Ly- α studies	121
6.	The perspective on galaxy evolution from quantified morphological analysis	135
6.1	Size measurements in the context of galaxy evolution	135
6.2	A merger origin for the bright and large clumps in two-clump galaxies	137
6.3	Tracing evolution with visual morphology	140
6.4	The physical nature of Ly- α emitters	141
6.5	Overview on galaxy evolution as traced by morphology at $2 < z \lesssim 6$	142
7.	Conclusions and perspectives	145
7.1	Conclusions from this thesis work	145
7.2	Future perspectives	146
A.	Refereed and submitted publications	157

List of Figures

	Page
1.1 Modern depiction of the Hubble sequence of morphology classification.	2
1.2 Morphology and size evolution	6
2.1 Morphology box of galaxy transformation	10
3.1 VUDS and HST surveys footprint in COSMOS and ECDFS fields	24
3.2 VUDS survey footprint in VVDS	25
3.3 VUDS examples of massive galaxies.	26
3.4 VUDS DR1 sky coverage	28
3.5 Outlook of the SPVT interface	31
3.6 SPVT - image orientation changes	33
3.7 SPVT - quick 2D inspection	34
3.8 SPVT - quick 2D extraction	35
3.9 Redshift distribution of the VUDS sample	36
3.10 The SFR-stellar mass relation in VUDS	38
3.11 The VUDS sample in a NUVrJ diagram	38
4.1 Example Sérsic profiles	40
4.2 Numerical approximation of κ	42
4.3 Pre-selection of candidate stars for PSF	43
4.4 Success recovery of r_e from simulations	44
4.5 Concentration parameter on simulated galaxies	47
4.6 Simulated values for A	48
4.7 The n dependence of the Gini coefficient.	49
4.8 The n dependence of M_{20}	51
4.9 Angular diameter distance in cosmology	52
4.10 Illustration of the size measurement process	57
4.11 Examples of measured sizes in F814W for 12 galaxies	58

4.12	Value of k as a function of redshift for different choices of k_p	60
4.13	Color dependence of $r_{T,PSF-corr}^{100}$	62
4.14	F814W and F160W images of 6 example galaxies in VUDS	62
4.15	Results of the computation of T_{100} for a set of 15 000 galaxies	64
4.16	Methodology for detecting clumps	64
4.17	Twelve examples of galaxies for which only one clump was detected	67
4.18	Twelve examples of galaxies with two clumps detected	68
4.19	Twelve examples of galaxies with more than two clumps detected	69
4.20	Magnitude and area distribution for negative clumps detected within 20 kpc of the VUDS target	71
4.21	Different morphological classes	73
4.22	Outlook of the GUI interface.	74
4.23	GUI pop up window after selecting the pair subclass	76
4.24	Examples of each of the main classes of Ly- α	78
4.25	Schematic view of four of the main classes and its relation to the spectral ob- servations	79
4.26	GUI interface for Ly- α classification	81
5.1	Effective radius distribution for different redshift bin	85
5.2	Effective radius evolution with redshift	86
5.3	Rest-frame wavelength dependence of the effective radius	87
5.4	Measured effective radius as a function of wavelength	87
5.5	Total size distribution for different redshift bins	89
5.6	Comparison of the two size estimates computed in this thesis	90
5.7	Total size evolution with redshift	91
5.8	Total size measurements defined at different values of k_p	91
5.9	Normalized surface luminosity profiles of the median stacked images	92
5.10	Evolution of light concentration in galaxies as defined in this thesis	93
5.11	Slope of the evolution of PSF corrected galaxy sizes as a function of the flux level considered	95
5.12	Correlation of the measured galaxy sizes with parameters derived from SED fitting	97
5.13	Stellar mass surface density as a function of stellar mass	98
5.14	Number of galaxies as a function of the number of clumps detected within the selected isophote	99
5.15	Fraction of clumpy galaxies within the VUDS sample as a function of redshift .	101
5.16	Fraction of clumpy galaxies within the VUDS sample as a function of redshift - alternative method	101

5.17 Absolute magnitude in the rest-frame FUV and area distribution for clumps found in galaxies with $N_c \geq 2$ at $2 < z < 4.5$	103
5.18 Absolute magnitude in the rest-frame FUV and area distribution for clumps found in galaxies with $N_c \geq 2$ at $4.5 < z < 6.0$	104
5.19 The distribution of stellar masses in clumps for three different samples.	106
5.20 Typical agreement between different classifiers on the primary class	106
5.21 Frequency of each morphological class	108
5.22 Morphological k -correction from visual classification	109
5.23 Frequency of each morphological class using median classification	109
5.24 Class agreement statistics for the extended sample	110
5.25 Frequency of each morphological class for the extended sample	111
5.26 Redshift evolution of each morphological class	112
5.27 Redshift evolution of each morphological class	112
5.28 Non-parametric class discrimination in the I band	113
5.29 Non-parametric class discrimination in the H band	114
5.30 Stellar mass-SFR relation in morphological classes	115
5.31 Age and dust content in morphological classes	115
5.32 Median size and concentration for each morphological class - extended sample .	116
5.33 UVJ color diagram morphological segregation - extended sample	117
5.34 Main sequence of star formation morphological segregation - extended sample .	118
5.35 Physical properties in morphological classes - extended sample	120
5.36 Summary of the agreement between different observers performing the classification	121
5.37 Summary of the main class distribution for the 1022 LAGs with secure classifications	122
5.38 The redshift dependence of each Ly- α line morphology class	123
5.39 The impact of redshift on each of the main classes of Ly- α line morphology, in stellar mass bins	124
5.40 The impact of redshift on each of the main classes of Ly- α line morphology, in line equivalent width bins	124
5.41 The impact of redshift on each of the main classes of Ly- α line morphology, in line flux bins	125
5.42 The impact of redshift on each of the main classes of Ly- α line morphology, in absolute FUV magnitude bins	125
5.43 Summary of the main Ly- α class physical properties	126
5.44 Stacks of spectra grouped by its Ly- α class - Coincident, Extended and Offset .	128
5.45 Stacks of spectra grouped by its Ly- α class - None, Faint and Single Line	129
5.46 Example of the fitting routine on each of the lines marked on the plot	130
5.47 Median size of galaxies measured in the rest-frame UV as a function of Ly- α class	133

5.48	Fraction of LAEs as a function of total extent	133
6.1	A compilation of size measurements at different redshifts for a number of different studies	136
6.2	Evolution of compact galaxies in the Illustris simulations	143

List of Tables

	Page
3.1 Redshift reliability flags used in VUDS	27
3.2 Summary of characteristics of the surveys from which the images were taken . .	29
4.1 Interval of simulated values of artificial galaxies	44
4.2 Morphological classes for visual classification	72
5.1 Median size values per redshift bin	94
5.2 Best fit slope and normalization factor for size evolution parametrization	94
5.3 Fraction of 2 clump systems in 4 redshift intervals	104
5.4 Number of LAGs in each redshift bin and for each selection that I use in this study	122
5.5 Equivalent width found in the stacked spectra of Ly- α classes	131
5.6 Velocity offsets found in the stacked spectra of Ly- α classes	132

• This page is intentionally left blank •

1 | Introduction: morphology as a tracer of galaxy evolution

Contents

1.1	Overview on galaxy morphology	3
1.2	Outline	6

Galaxies are ubiquitous in the Universe and current scientific research, both in observations and theoretical models, span most of the cosmic time since the formation of the first galaxies. The farthest object spectroscopically confirmed as of yet is at $z \sim 11$ (observed as it was 13.3 billion years ago [Oesch et al., 2016](#)). Although we are far from understanding the intricacies of the complex Universe we live in, we have made substantial advances on our understanding of how galaxies evolve throughout cosmic time and on which physical mechanisms govern such evolution (e.g. books and reviews by [Sparke & Gallagher, 2007](#); [Mo et al., 2010](#); [Maiolino, 2013](#); [Madau & Dickinson, 2014](#); [Conselice, 2014](#); [Somerville & Davé, 2015](#)).

The standard cosmological model is now globally constrained by the latest observations, including the cosmic microwave background (CMB, e.g. [Planck Collaboration et al., 2015](#)). It states that we live in a Universe in accelerated expansion composed mostly of non-baryonic components: dark energy and dark matter. This model predicts that the Universe began in a very hot and dense state approximately ~ 13.8 billion years ago and, from these initial conditions, the expansion led the material to cool down until electrons eventually combined with protons and the photons were permitted to roam free, allowing us to witness the first picture of the early Universe (the CMB, see [Mather et al., 1990](#); [Bennett et al., 2013](#); [Planck Collaboration et al., 2015](#)). The small scale perturbations that we observe in the CMB are the structural seeds of all that we observe today.

As time moved forward, perturbations grew to a point where the self-gravity surpassed the strength of the expansion and the first astrophysical objects formed - first stars and black holes, primitive galaxies (see [Bromm & Yoshida, 2011](#), for a review). Objects form once gas clouds inside dark matter halos collapse under their own gravity. As it collapses, a cloud fragments into smaller cores which through effective cooling become dense and hot enough to start nuclear reactions known to power all stars in the Universe. Large groups of stars bound by gravity and embedded in large gas reservoirs assemble to form the first galaxies in the Universe. There is currently no confirmed observations of such entities (some candidates have been proposed e.g. [Sobral et al., 2015b](#)) and it is still unclear how these first stars and galaxies actually formed, but it is generally accepted that this is the way first galaxies come to be.

Fast-forwarding to the beginning of the 20th century, the first photographs of galaxies led to the first classification of galaxies into groups according to their properties - their shape at that time ([Hubble, 1926, 1936](#), see also [Sandage 1961](#)). Galaxies with spiral, elliptical or irregular morphology were identified and specific attributes were found in each, which allowed a classification in sub-classes, identifying bars or the relative contribution of a bulge and a

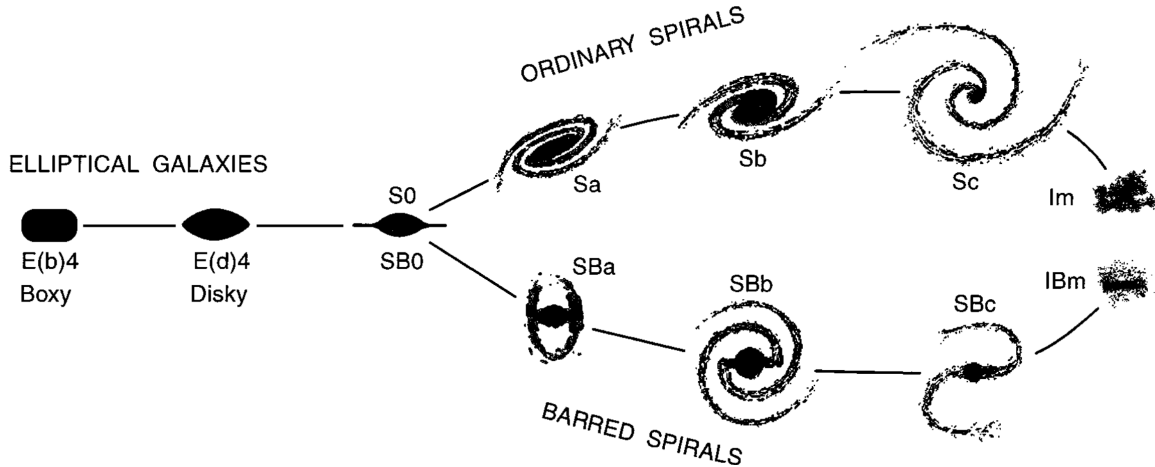


Figure 1.1. Modern depiction of the Hubble sequence of morphology classification. Elliptical galaxies are classified according to their ellipticity, then we have intermediate type galaxies, S0. The sequence also shows spirals grouped into barred and ordinary and classified from a to c according to the tightness of the spiral arms. In the right end we have the irregular galaxies (from [Kormendy & Bender, 1996](#)).

disc component. It was proposed to organize these classes into what is called now the *Hubble sequence of galaxies* (figure 1.1). Since then many attempts have been made to find a physical motivation for this sequence, linking galaxies of each class to some peculiar evolution history. To explain the existence of different galaxy types, an early explanation owed the difference in structure to the difference in the cooling time ([Eggen et al., 1962](#)). In the case of short cooling times, the gas would collapse very rapidly and monolithically and form an elliptical galaxy. Whereas a long cooling time would allow some gravitational energy to be radiated away through radiative cooling and shocks until the original cloud became rotationally supported and formed a galactic disk. There is an additional important process that was identified early on to help shape galaxies, galaxy interactions, from tidal forces to merger events (e.g. [Toomre & Toomre, 1972](#); [Toomre, 1977](#)). The merger process between two disk galaxies is thought to be a way to form elliptical galaxies (although there was some controversy, see [Ostriker, 1980](#), and [Hopkins et al. 2008, 2009](#)). More recently, there are new models that call for the presence of cold gas inflow into dark matter halos which may also produce elliptical/bulges and galactic disks depending in the properties of the stream (e.g., smoothness or clumpiness, [Dekel et al., 2009](#)).

Once a galaxy forms there are a number of processes that help shape its structure (e.g. see review [Kormendy & Kennicutt, 2004](#)). These processes can be broadly grouped into external and internal processes, and also in short and long timescales mechanisms. These processes include *in-situ* star formation that drives secular structural evolution through instabilities in the gaseous disk and *ex-situ* star formation that refers to stellar components that were formed elsewhere and later aggregated by the galaxy via galaxy harassment and merger events. During a galaxy lifetime, we expect that gas in the intergalactic medium will infall onto the disk due to their gravitational potential and eventually form new stars. If gas was able to cool efficiently, then all gas would be converted into stars. However, we observe that only $\sim 10\%$ of the baryonic matter is in the form of stars ([Somerville & Davé, 2015](#)). Thus, one or more mechanisms that prevents gas from cooling and renders star formation inefficient is necessary to explain observations. It is now recognized that stellar and active galactic nuclei feedback, in the form of winds or supernovae explosions or an active central super massive black hole (e.g. [Kormendy & Ho, 2013](#)), is likely the explanation for the suppression of star formation in galaxies (e.g. [Hopkins et al., 2012a](#)).

To identify the processes and timescales forging the morphology of galaxies, one important development since the mid 80s is the ability to measure the properties of galaxies at different epochs, using the redshift time machine, directly following evolution by looking at galaxies at increasingly large look-back times. Our knowledge on how galaxies have evolved has then increased significantly (see reviews by [Maiolino, 2013](#); [Madau & Dickinson, 2014](#)). One key observable is the number of stars formed per unit volume and per unit time as a function of cosmic history (star formation rate density, SFRD, ρ_{SFR}). This quantity has been thoroughly explored in different galaxy surveys starting with the Canada-France Redshift Survey (CFRS [Lilly et al., 1996](#)) and deep HST imaging building the now classical ‘Lilly-Madau diagram’ ([Madau et al., 1996](#)), and constantly improved since then (e.g. [Madau & Dickinson, 2014](#)) and it is now established that the SFRD has increased since the early Universe and peaked at around $z \sim 1.5 - 2$, to then decrease by a factor ~ 10 to the present time. Another tracer of galaxy evolution is the rate at which galaxy assembled their stellar masses, the stellar mass density (SMD, ρ_*), that has seen a strong rise from $z \sim 4$ to $z \sim 1$ (e.g. [Ilbert et al., 2013](#)). Theoretical models and simulations have been attempting to reproduce and explain the evolution of the SFRD and SMD, with only partial success, despite the continuously refined numerical models (e.g. [Genel et al., 2014](#); [Furlong et al., 2015](#); [Henriques et al., 2015](#)). Linked with the stellar mass growth is the rate at which galaxy merge. This quantity is also rising or peaking during the same epoch (e.g. [Le Fèvre et al., 2000](#); [de Ravel et al., 2009](#); [López-Sanjuan et al., 2013](#); [Tasca et al., 2014b](#); [Rodríguez-Gomez et al., 2015](#)). When combined, these observations imply that at $z \gtrsim 2$ galaxies are undergoing a rapid assembly of stellar mass and a likely morphological change.

1.1 OVERVIEW ON GALAXY MORPHOLOGY

In the beginning of the 20th century the existence of objects outside our own galaxy was the subject of intense debate (see [Shapley & Curtis, 1921](#)). In 1925 [Hubble \(1925\)](#), using the 100m inch Hooker Telescope at Mount Wilson, measured the distance to Andromeda using variable Cepheid and confirmed the existence of *extragalactic nebulae* due to its distance. Soon after, the first classification scheme was born. From a collection of 400 images of nearby galaxies, [Hubble \(1926\)](#) divided the objects into three main categories: ellipticals, spirals and irregulars. This scheme became later known as the Hubble Sequence and it was updated regularly to include more and more details on the exact shape seen in galaxies. One of the extensions was proposed by [de Vaucouleurs \(1959\)](#) that aim to include galactic rings and bars in the classification. Later, [van den Bergh \(1960\)](#) also added a classification system based on the spiral pattern regularity.

This classification scheme was purely based on the observed shape of galaxies. However, the regularity with which galaxies could be classified raised the idea that different physical mechanisms were likely associated with the different galaxy types. In fact, we do observe that galaxy morphology correlates with several physical parameters ([Conselice, 2014](#), for a review, see also [Buta et al. 2015](#)) and with the galaxy density around them (e.g. [Dressler, 1980](#)). I summarize the main characteristics of each galaxy type in the following paragraphs.

Elliptical galaxies are characterized by a smooth stellar distribution, usually ellipsoidal forms and rarely display any morphological features like dust lanes or spiral arms. The dominant old stellar population and the lack of gas and dust are the reasons behind its shape and color. They span several orders of magnitude in stellar mass being found at the massive end in the center of galaxy clusters supported by random stellar motions. In the low mass end ellipticals usually have some rotation support.

Spiral galaxies have prominent spiral arms in the galactic disk that are populated by blue

young stars. It is also in the arms regions that large amounts of dust and gas are found to fuel the formation of new stars. Often, the central regions of spirals have a spheroidal component (the bulge) or a central bar. There is a relation between age and bulge prominence, with the younger galaxies having little or no bulge component.

Between ellipticals and spirals, there is an intermediate morphological type - the lenticular galaxies. These objects are usually prominent bulgy systems with a large rotating disk with no special features. They have a fast rotating disk as found in spiral galaxies but usually have little gas and dust and are red as elliptical galaxies. The last major class of galaxies are those which show no obvious symmetry from which they got their name of irregular. Commonly young and low mass systems in the local Universe, these are thought to be analogs to the galaxies that we may find in the early phases of galaxy assembly.

Apart from these main classes, there are a number of strange shapes that are found in galaxy surveys. These include the presence of large tails of stars and dust, asymmetric rings, stellar shells. Due to their peculiar nature, these systems are found to be dynamically perturbed systems due to merger events or tidal interactions and are in the process of morphological transformation.

Despite its usefulness, the visual classification method remains subjective to individual interpretations. On top of that, galaxies in the younger Universe resemble less and less those that observed in the local Universe and the morphological discrimination of galaxies is harder (e.g. Driver et al., 1995; Glazebrook et al., 1995; Abraham et al., 1996; Lilly et al., 1998; Conselice et al., 2005; Delgado-Serrano et al., 2010; Mortlock et al., 2013; Buitrago et al., 2013; Huertas-Company et al., 2015b). Throughout the years several attempts at quantifying the structure of galaxies have been put forward. These methods help improve our views on galaxy morphology across cosmic time. One of the most common methods relies on the modeling of the surface brightness distribution of galaxies (e.g. de Vaucouleurs, 1948; Sérsic, 1968; King, 1978; Simard, 1998; Peng et al., 2002, 2010). Another approach assumes no empirical model and tries to directly quantify the light distribution in galaxies from the images (e.g. Abraham et al., 1994; Conselice, 2003; Lotz et al., 2004; Law et al., 2007; Freeman et al., 2013). These morphological quantifiers have been subject to numerous studies and found to correlate with the stellar mass, star formation, and stellar populations of galaxies (e.g. Roberts & Haynes, 1994; Kauffmann et al., 2003; Conselice, 2003; Blanton et al., 2003; Blanton & Moustakas, 2009; Tasca & White, 2011; Wuyts et al., 2011; Whitaker et al., 2016).

For instance, star-forming galaxies are known to be more asymmetric, often composed of several knots of star formation, clumpy spiral arms, and correlate with galaxy structural parameters (e.g. Conselice, 2003). They are also likely to have smaller morphological k -corrections (differences in structure between optical and UV rest-frame observations) than passive elliptical galaxies (e.g. Windhorst et al., 2002; Taylor-Mager et al., 2007). Highly disturbed systems as probed with non-parametric measurements have also been used to probe the merger activity of galaxies across cosmic time (e.g. Conselice, 2003; Conselice & Arnold, 2009; Lotz et al., 2004, 2008; Freeman et al., 2013). Another underlying correlation exists between the galaxy size and its stellar mass which is seen both in the local Universe (e.g. Shen et al., 2003; Guo et al., 2009) and at high-redshift (e.g. Trujillo et al., 2006b; Franx et al., 2008; Mosleh et al., 2011, 2012; Ichikawa et al., 2012; van der Wel et al., 2014; Morishita et al., 2014).

First studies on the evolution of galaxy morphology focused on the relative abundance of Hubble types across time. All results on this topic agree that the fraction of irregular (or peculiar) galaxies increases rapidly with cosmic time up to $z \sim 3$ (e.g. Driver et al., 1995; Glazebrook et al., 1995; Abraham et al., 1996; Lilly et al., 1998; Conselice et al., 2005; Delgado-Serrano et al., 2010; Mortlock et al., 2013; Buitrago et al., 2013; Huertas-Company et al., 2015b, see also figure 1.2). At higher redshifts there have been studies about the fraction of

irregular systems up to $z \sim 7$ that confirm that these types of galaxies remain the dominant population of UV bright galaxies, but the fraction is reported to remain constant at 30 – 60% (e.g. Conselice & Arnold, 2009; Jiang et al., 2013; Curtis-Lake et al., 2016; Bowler et al., 2016).

A particular population of irregular galaxies that has been subject of scientific scrutiny have been galaxies with star-forming clumps (e.g. Elmegreen et al., 2004; Elmegreen & Elmegreen, 2006; Elmegreen et al., 2007, 2013; Genzel et al., 2008; Bournaud et al., 2008; Wuyts et al., 2012; Guo et al., 2012). In particular there have been reports on the fraction of these clumpy systems among the star-forming population that suggest a rapid rise up to $z \sim 2$ and then a possible decline at higher redshifts (e.g. Guo et al., 2015; Shibuya et al., 2016). However there are still a lot of uncertainties on this fraction at $z \gtrsim 3$ and there is an active discussion on the physical origin of these clumpy systems with arguments supporting merger events (e.g. Di Matteo et al., 2008) or disk instabilities (e.g. Genzel et al., 2008; Elmegreen et al., 2008, 2009; Dekel & Krumholz, 2013; Perez et al., 2013; Bournaud et al., 2014; Bournaud, 2016), with the latter currently being favored in the literature (see e.g. Shibuya et al., 2016).

One of the most studied aspects of galaxy morphology evolution is linked to the evolution in galaxy sizes. It is generally accepted that galaxies were smaller at higher redshift (up to $z \sim 10$, e.g. Bouwens et al., 2003; Ferguson et al., 2004; Bouwens et al., 2004; Daddi et al., 2005; Ravindranath et al., 2006; Trujillo et al., 2006c; Akiyama et al., 2008; Franx et al., 2008; van der Wel et al., 2014; Morishita et al., 2014; Hathi et al., 2008; Jiang et al., 2013; Ono et al., 2013; Kawamata et al., 2015; Holwerda et al., 2015; Shibuya et al., 2015) and that the size evolution depends on the population we are probing with star-forming galaxies experiencing smaller growth when compared to passive galaxies, which are always smaller (e.g. Trujillo et al., 2006b; van der Wel et al., 2014; Straatman et al., 2015, see also figure 1.2). But when using different methodologies or statistics behind the measurements of galaxy sizes can still provide different evolution scenarios with results showing little to no evolution from $z \sim 2 - 3$ to $z \sim 4 - 6$ in UV rest-frame sizes of typical star-forming galaxies (e.g. Law et al., 2007; Curtis-Lake et al., 2016, see also Stott et al. 2013 for rest-frame optical sizes in H α -selected galaxies). There are also results pointing to the prevalence of small galaxies with no size evolution (when compared to normal star-forming galaxies) among Ly- α emitters (LAEs) at $2 \lesssim z \lesssim 7$ (e.g. Malhotra et al., 2012, for a compilation), although there are reasons to believe that these differences are caused by the different mass-regimes that are probed by the two populations (e.g. Hagen et al., 2016b). In what concerns the evolution of the surface brightness profile of galaxies, star-forming galaxies are found to have disk-like profiles at all times (e.g. Ravindranath et al., 2006; Buitrago et al., 2013; Morishita et al., 2014) up to $z \sim 3$ in the optical rest-frame, and this trend seems to be found up to higher redshifts ($z \sim 3 - 10$ e.g. Shibuya et al., 2015) although this picture is made more complex by the existence of compact star-forming galaxies (e.g. Barro et al., 2014; Nelson et al., 2014; Williams et al., 2014; van Dokkum et al., 2015).

To summarize, the preferred scenario for the evolution of galaxies consists of a Universe with cold dark matter on which galaxies form and live within dark matter halos (see summary by Efsthathiou & Silk, 1983; Blumenthal et al., 1984). We have access to large and diverse surveys (e.g. Giavalisco et al., 2004; Rix et al., 2004; Scoville et al., 2007; Lilly et al., 2007; Grogin et al., 2011; van Dokkum et al., 2011; Ahn et al., 2012; McCracken et al., 2012; Le Fèvre et al., 2013, 2015; Sobral et al., 2015a) that help narrow the number of accepted explanations and also to large numerical simulations (e.g. Vogelsberger et al., 2014; Schaye et al., 2015) which are able to globally reproduce the observed properties of the galaxy population at $z \approx 0$. However we still debate the rate of growth of star-forming galaxies, and what is the impact of the assumption of symmetry on the measurement of galaxy sizes at high redshift. It is still unclear how many galaxies are found to be clumpy at $z \gtrsim 2$ and whether the observed clumps are formed via merger or disk instabilities. The relative abundance of irregular galaxies at

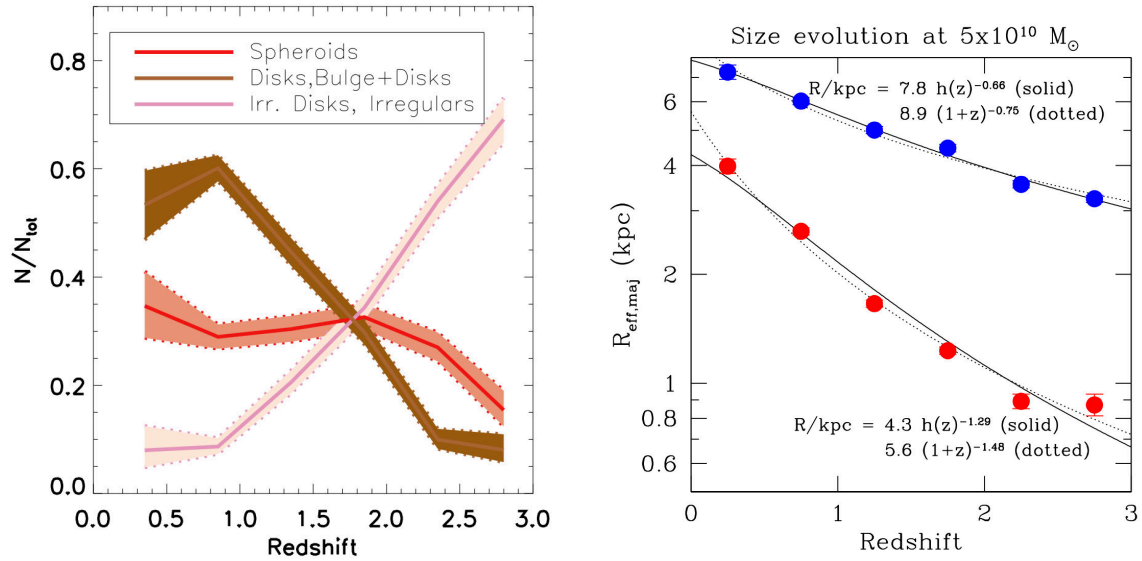


Figure 1.2. Left: Evolution of the main morphological types of the Hubble sequence up to $z \sim 3$ (from Huertas-Company et al., 2015b). Right: Size evolution of star-forming galaxies (in blue) and passive galaxies (in red) since $z \sim 3$ (from van der Wel et al., 2014).

high redshift is known to be high but several studies report fractions ranging from 30 – 70% and the evolution of this fraction at $z \gtrsim 3$ is still largely unknown.

1.2 OUTLINE

The goal of this thesis is to explore the morphological properties and quantify their evolution from a large sample of star forming galaxies during the phase of major galaxy assembly ($2 \lesssim z \lesssim 6$). During my PhD I have developed new algorithms to quantify the evolution of galaxy sizes and for the identification of clumps in high-redshift galaxies and attempted at establishing a visual classification scheme on galaxy morphology and also on the extent of the Ly- α line (with respect to the UV continuum) to answer some on the current open questions of galaxy evolution.

In chapter 2 I detail the current knowledge on galaxy morphology evolution by reviewing recent results that contextualize the analysis that will be done in the following chapters. In chapter 3 I present the VIMOS Ultra Deep survey (VUDS, Le Fèvre et al., 2015) from which the sample of high-redshift star-forming galaxies that is subject of analysis is selected. I detail more specifically the VUDS public data release and a new tool that I developed to tackle data reduction issues. I end this chapter by giving an overview of the VUDS sample and the particular sample selections that were put in place.

In chapter 4 I give an overview on all the methodology that I developed during the course of my PhD. This chapter is divided in several topics that include parametric and non-parametric morphology methods that have been adapted from the literature, the description of the new algorithms for computing galaxy sizes and for the detection of clumps in high-redshift galaxies, and the tools and classification schemes used for the visual characterization of galaxies and the Ly- α line.

In chapter 5 I present the main results of my PhD, done in collaboration with the VUDS team, in the 4 different topics that I studied in detail. In chapter 6 I discuss the implications of my results to the current paradigm of galaxy formation and then summarize my findings in chapter 7. Papers accepted or submitted to refereed journals are presented in Appendix A.

All results on this thesis assume a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{0,\Lambda} = 0.7$ and $\Omega_{0,m} = 0.3$. All magnitudes are given in the AB system. I assume a [Chabrier \(2003\)](#) Initial Mass Function (IMF) in my results.

• This page is intentionally left blank •

2 | Galaxy morphological evolution: current knowledge

Contents

2.1	Physical drivers of morphology evolution	9
2.1.1	Overview of physical mechanisms driving galaxy evolution	9
2.1.2	Physical processes affecting galaxy morphology	11
2.1.3	Theoretical expectations on size estimates	13
2.1.4	Summary	14
2.2	Methods for the quantification of galaxy morphology	15
2.2.1	Parametrization of galaxy light profiles	15
2.2.2	Non-parametric galaxy morphology	16
2.3	Tracing morphological evolution across cosmic time	16
2.4	Topics in this thesis	18
2.4.1	Size measurements at high redshift for star-forming galaxies	18
2.4.2	The origin of galactic clumps during the assembly phase of galaxies	19
2.4.3	Ly- α emission and galaxy morphology	21

2.1 PHYSICAL DRIVERS OF MORPHOLOGY EVOLUTION

In this section I will give a general overview on the physical mechanisms that are thought to play an important role in the current paradigm of galaxy formation and evolution and their expected morphological signatures. A summary of all these processes is found in figure 2.1.

2.1.1 OVERVIEW OF PHYSICAL MECHANISMS DRIVING GALAXY EVOLUTION

Galaxy formation, and early stage evolution, is believed to be a turbulent process where gas inflows, strong winds, and galaxy-galaxy interactions give rise to the intricate shapes we have found since the first deep high- z HST observations (e.g. [Driver et al., 1995](#); [Glazebrook et al., 1995](#); [Abraham et al., 1996](#); [Lilly et al., 1998](#)).

The main driver for structure formation in the Universe is the force of gravity. It plays a crucial role in the determination of the the number of collapsed regions (dark matter halos) in the Universe. In the standard paradigm, all galaxies form within such regions. Gravity also governs the rate at which different halos merge and how they cluster in space. When different halos merge the galaxies residing within will lose angular momentum through dynamical friction causing them to eventually coalesce in a single larger galaxy.

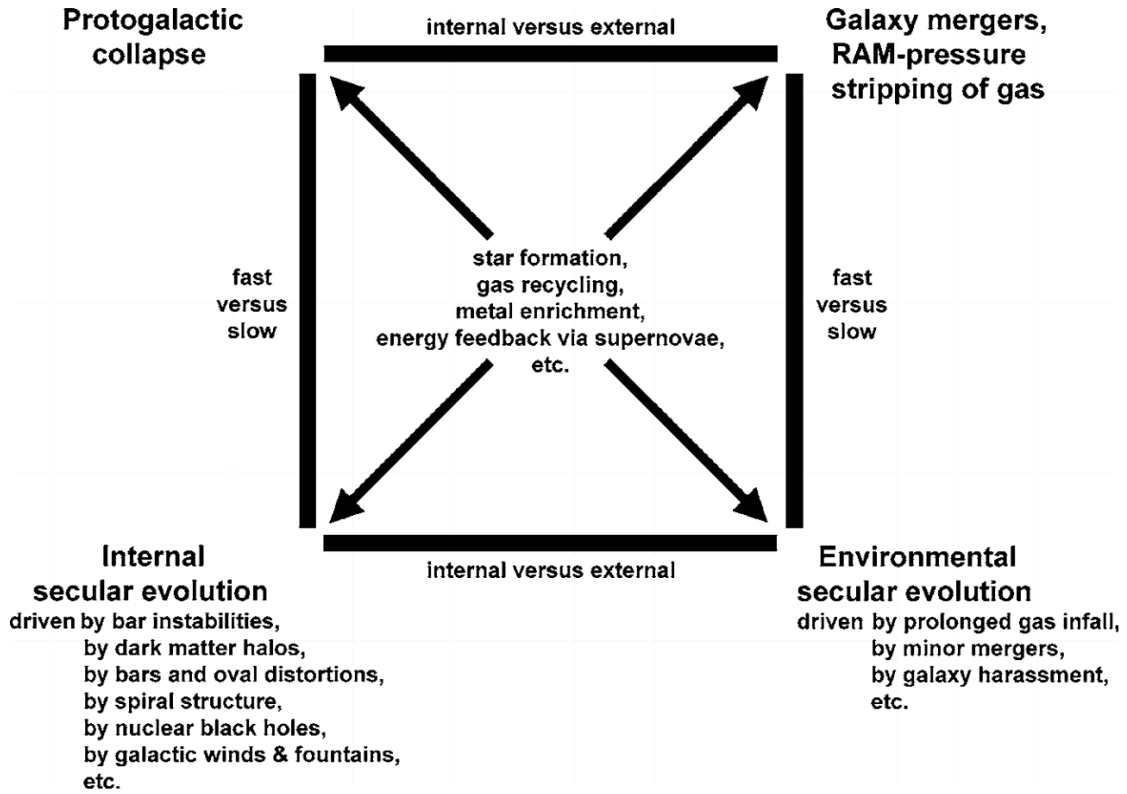


Figure 2.1. Morphology box of transformation processes grouped into external and internal processes, and rapid and secular mechanisms (from [Kormendy & Kennicutt, 2004](#)).

Galaxies are formed through the collapse of gas clouds within the dark matter halos first set by gravity. During the collapsing process, we may witness the formation of large shocks and the rising of gas temperature. In order to form stars we require the condensation of gas into small regions which is only possible through effective cooling processes. At different gas temperatures, there are different efficient methods for gas cooling. At the highest temperatures the gas cools mostly via the *bremssstrahlung* effect. When the gas is cool enough for the hydrogen atoms to form and survive, gas cools by the recombination process where electrons and protons bound to form hydrogen atoms. At lower temperatures the cooling is either done by molecular or metal cooling where particles loose energy in electron level transitions caused mainly by collisions. During the cooling process we may either form a pressure-supported hot halo, if the cooling is inefficient, or cold gas flows, if the cooling time is shorter than the dynamical timescale (e.g. [Birnboim & Dekel, 2003](#); [Kereš et al., 2005](#)). An alternative scenario for the formation of galaxies, that is considered to be important as the origin of massive ellipticals is a monolithic collapse of gas clouds (e.g. [Eggen et al., 1962](#); [Collins et al., 2009](#)).

Once the gas effectively cools into small dense cores they potentially become self-gravitating entities. At this point, the gas density rises and cooling is carried out more effectively until the extreme densities required to ignite nuclear fusion are reached. At this point, stars are forming within the initially collapsed dark matter halos. This process is still poorly constrained as both observations and simulations lack the required resolution to pinpoint the exact physics happening at these scales in the distant Universe. However we can assume some empirical star formation laws derived from observations in the local Universe (e.g. [Kennicutt & Evans, 2012](#)). At the same time, the first seeds of super massive black holes are forming either by direct collapse of large gas clouds or of massive stars (e.g. [Volonteri, 2010](#)).

As soon the first stars and black holes form there is an additional process that impacts and

drives galaxy evolution which is related to feedback processes. For example, massive stars and supernovae can produce strong large-scale winds and heat the surrounding gas (e.g. [Hopkins et al., 2012b](#)). On the other hand AGN feedback can induce large scale winds and hot bubbles that have impact on the evolution of its host galaxy (e.g. [Heckman & Best, 2014](#)). These processes render star formation inefficient and are the accepted explanation for the low fraction of baryons that is found in the form of stars.

The combination of all these processes set the stage for a turbulent gas medium in and around galaxies where gas infall through cold streams, merge events and stellar, and AGN feedback all contribute to define the evolution of every single galaxy. In the early phases of galaxy assembly, when the gas fraction in galaxies is high and can fuel star formation steadily through large infall rates. If a steady flow of gas is fueled to the galactic disk through cold streams simulations show that large instabilities are produced in the disk leading to the formation of large star-forming clumps (e.g. [Dekel et al., 2009](#); [Bournaud, 2016](#)). This disk instabilities scenario is also thought to be important to the formation of compact star-forming galaxies observed at $z \gtrsim 2$, by merging of giant clumps into a compact spheroidal object (e.g. [Dekel & Burkert, 2014](#); [Barro et al., 2014](#)).

On top of all physical mechanisms that act on a galactic scale, galaxies do not live in isolated bubbles and we can find several regions that are overdense in galaxies, galaxy groups and clusters, that enhances the rate of interactions between galaxies. On these environments galaxies experience a number of physical processes that act on the morphology, stellar mass, star formation activity, and gas fractions. These include ram pressure stripping (e.g. [Gunn & Gott, 1972](#)), gas removal (e.g. [Larson et al., 1980](#)), galaxy harassment (e.g. [Moore et al., 1996](#)), and eventual galaxy mergers (e.g. [Burke & Collins, 2013](#)).

This picture is based on standard theory and enriched by the results of numerical simulations. It is essential for this picture to be confronted to the best observations to help validate or revise a coherent scenario for galaxy formation and evolution.

2.1.2 PHYSICAL PROCESSES AFFECTING GALAXY MORPHOLOGY

Morphological- k correction is the term used to define the different appearances of the same galaxy when observed at different observed wavelength. This effect is particularly important when comparing galaxies at $z > 1.5$ with the local Universe because of the scarcity of rest-frame optical images with high spatial resolution. At $z > 3$, due to the lack of high resolution coverage in the mid-infrared bands, direct rest-frame comparisons are impossible. These differences are mainly caused by two effects. On one hand, different stellar populations shine in different wavelength intervals and old stellar populations characteristic of elliptical galaxies can be significantly fainter at wavelengths lower than the Balmer break (e.g. [Bruzual & Charlot, 2003](#)). On the other hand, dust absorption is stronger in the UV than it is in the optical rest-frame (e.g. [Calzetti et al., 2000](#)) and it can make galaxy morphology significantly different if prominent dust lanes are found in galaxies. However, this effects do not necessarily changes the classification of galaxies (e.g. [Windhorst et al., 2002](#)). In fact, for star-forming galaxies both in the local Universe and at high-redshift it is found that morphological- k correction affects only a small percentage of the population (e.g. [Windhorst et al., 2002](#); [Taylor-Mager et al., 2007](#); [Law et al., 2012a](#); [Lee et al., 2013](#)). This is also found to be true in terms of the structural parameters of galaxies with little star formation at $z \sim 1 - 2$ (e.g. [Trujillo et al., 2007](#); [Cassata et al., 2010, 2011](#)). In terms of galaxy sizes at $z \sim 2$, [van der Wel et al. \(2014\)](#) find that late-type galaxies are typically smaller at longer wavelengths and that this effect is stronger for the most massive galaxies. For $z \gtrsim 2 - 3$ sizes measured in the rest-frame in star-forming galaxies using I and H bands ($\sim 2000 - 2700\text{\AA}$ and $\sim 4000 - 5300\text{\AA}$ rest-frame) are statistically the same (e.g. [Ribeiro et al., 2016](#)). Nonetheless, the observations of smaller

sizes at larger wavelengths has been argued as evidence of an inside-out growth of galaxies (e.g. [van den Bosch, 1998](#)) where galaxy centers are dominated by old and red stellar populations and the outskirts by young blue stars (e.g. [Nelson et al., 2013](#); [Patel et al., 2013](#); [Lang et al., 2014](#); [van der Wel et al., 2014](#); [Tacchella et al., 2015](#); [Hagen et al., 2016a](#); [Paulino-Afonso et al., 2016](#)). This effect gets more pronounced along cosmic time when galaxy populations have had enough time to differentiate between an old bulge and a disc dominated by recent star formation.

On the topic of size growth of galaxies there has been a recent focus on a particular set of massive compact and quiescent galaxies that have been found at $z \sim 1 - 2$ (e.g. [Daddi et al., 2005](#); [Trujillo et al., 2006a](#); [van Dokkum et al., 2008](#); [Cimatti et al., 2008](#); [Cassata et al., 2011](#); [Szomoru et al., 2012](#); [Patel et al., 2013](#); [Ikarashi et al., 2014](#); [Ma et al., 2014](#); [Marsan et al., 2014](#)). The population of massive quiescent galaxies is found to grow much faster than the star-forming population (e.g. [Trujillo et al., 2007](#); [Franx et al., 2008](#); [van der Wel et al., 2014](#)). While the growth of disks is thought to be linked to the growth of dark matter halos (see section 2.1.3), the mechanism through which these compact objects grow with time is yet subject of discussion. Proposed scenarios include dry mergers (e.g. [Naab et al., 2007, 2009](#); [Hopkins et al., 2009, 2010](#)), adiabatic expansion (e.g. [Fan et al., 2008, 2010](#)) or simply an observational effect (progenitor bias, e.g. [Cassata et al., 2011](#); [Newman et al., 2012](#); [Carollo et al., 2013](#)). Also intriguing is the formation mechanism of these objects with proposed mechanisms being either merger remnants of gas-rich galaxies ([Mihos & Hernquist, 1996](#); [Hopkins et al., 2008](#); [Wuyts et al., 2010](#)) or the end result of rapid and dissipative accretion of giant star-forming clumps migrating to the galaxy center (e.g. [Dekel et al., 2009](#); [Dekel & Krumholz, 2013](#)). In a recent study using cosmological simulations, [Wellons et al. \(2015\)](#) followed the evolution of a sample of massive compact and quiescent galaxies at $z \sim 2$ and found two main paths of evolution. One is consistent with gas-rich galaxy merges and the other invokes the higher density of the Universe at early times to explain the formation of compact objects that stayed compact until $z \sim 2$ (see also e.g. [Barro et al., 2014](#)). They show that most of these galaxies grow in size and stellar mass by accretion of ex-situ stars through mergers ([Wellons et al., 2016](#)).

Galaxy mergers are the physical mechanisms that lead to the largest disruptions of galaxy morphology (e.g. [Conselice, 2014](#), and references therein). And in early studies on the assembly of galaxies morphological transformations were associated with major merger events, namely the transformation of disk galaxies into ellipticals (e.g. [Toomre, 1977](#); [González-García & Balcells, 2005](#); [Naab et al., 2007](#); [Bournaud et al., 2007a](#)). However, the exact effect on morphology (and other physical parameters) depends on a number of factors such as impact parameters, gas fractions and stellar masses (e.g. [Hopkins et al., 2009, 2010](#)). For instance, gas-rich merges are expected to maintain a galactic disk while dry mergers are more likely to build a bulge or lead to the formation of elliptical galaxies (e.g. [Springel & Hernquist, 2005](#); [Robertson et al., 2006](#); [Hopkins et al., 2010](#)). As for minor merging events (normally associated with satellite accretion) they have small impact in the morphology of the central galaxy but may contribute to the build-up of central bulge-like components (e.g. [Eliche-Moral et al., 2006](#)). In terms of observations it is also not clear how to define a complete sample of merging galaxies based on structure alone. Considering extreme asymmetric objects has been used as a method to select merging events (e.g. [Lotz et al., 2004, 2008](#); [Conselice, 2003](#); [Conselice et al., 2014](#); [Freeman et al., 2013](#)) which complements pair finding techniques which aim to find pre-merger events (e.g. [Le Fèvre et al., 2000](#); [López-Sanjuan et al., 2011, 2013](#); [Tasca et al., 2014b](#)). However such irregular structures may be mimicked by clumpy morphologies induced by disk instabilities in the galaxy (e.g. [Bournaud et al., 2008](#); [Genzel et al., 2011](#)) which may explain why galaxies selected through irregular shapes may be similar to non-merging systems in terms of their physical properties (e.g. [Law et al., 2012a](#)).

One common mechanism to produce irregular shapes in galaxies, namely clumpy structures is the formation of violent disk instabilities (VDI). This occurs when massive gas disks in high redshift galaxies reach high surface densities and fragment under their own self-gravity (e.g. Genzel et al., 2006, 2008; Elmegreen et al., 2007; Bournaud & Elmegreen, 2009; Bournaud, 2016). To maintain the clumpy morphology of these systems a continuous stream of infall gas is required so that the gas fraction remains high for a large period of time (e.g. Bournaud & Elmegreen, 2009). Such mechanism can be provided by a coherent stream of cold gas inflowing into the galaxy disk (e.g. Birnboim & Dekel, 2003; Dekel et al., 2009). However not all simulations agree that such cold streams are able to feed directly into the galaxy (e.g. Nelson et al., 2015b). Nevertheless it is expected that a large fraction of galaxies have gone through VDI at some point in their lifetimes and this process can be the precursor to the appearance of spiral galaxies and even contribute to the formation of galactic bulges (e.g. Genzel et al., 2008; Elmegreen et al., 2008, 2009; Dekel & Krumholz, 2013; Perez et al., 2013; Bournaud et al., 2014; Bournaud, 2016).

2.1.3 THEORETICAL EXPECTATIONS ON SIZE ESTIMATES

In the past years there have been some proposed models for the size evolution of dark matter (DM) halos and the formation of disks from collapsing gas within. Fall & Efstathiou (1980) laid the foundations for models on the formation of galactic disks from collapsing gas inside a DM halo. Such considerations imply that correlations between the galaxy and the DM halo exist, and can be used to test the hierarchical picture of galaxy evolution within such halos. One simple idea is that the radius of galaxies should scale with the virial radius of the host halo. This, in turn, depends on the expansion of the Universe as (Ferguson et al., 2004)

$$r_{\text{vir}} = \left(G \frac{M_{\text{vir}}}{100H^2(z)} \right)^{1/3} = \frac{v_{\text{vir}}}{10H(z)} \quad (2.1)$$

where, r, M and v are the radius, mass, and velocity of the virialized system and $H(z)$ describes the evolution of the Hubble parameter with cosmic time. More recently, Mo et al. (1998) derived the scaling relation of effective radius of the galaxy with the virial radius of its host for a self-gravitating disk inside a Navarro-Frenk-White halo (NFW profile, Navarro et al., 1996) which is described in (Kawamata et al., 2014)

$$\frac{r_e}{r_{\text{vir}}} = 1.678 \left(\frac{j_d}{m_d} \lambda \right) \frac{f_R}{\sqrt{2}f_c} \quad (2.2)$$

where $r_e/r_d = 1.678$ (r_d is the disc scale length of a exponential profile which is a Sérsic profile with $n = 1$ and $\kappa(1) \approx 1.678$ that can be derived from equation 4.8), m_d and j_d are the fractions of mass and angular momentum ascribed to the galactic disk, λ is the spin parameter of the DM halo, and f_c, f_R are functions described as (Mo et al., 1998)

$$f_c \approx \frac{2}{3} + \left(\frac{c}{21.5} \right)^{0.7}, \quad (2.3)$$

and

$$f_R = 2 \left[\int_0^{+\infty} u^2 e^{-u} \frac{V_c(r_e u / 1.678)}{V_{200}} du \right]^{-1} \quad (2.4)$$

where V_c is the sum in quadrature of the rotation velocity of the disk and DM components (see Mo et al., 1998, for more details). From an observational point of view I can rewrite equation 2.2 as

$$\frac{r_e}{r_{\text{vir}}} = \frac{1.678}{\sqrt{2}} \lambda' \quad (2.5)$$

and constrain the value of λ' . Since λ and c are well constrained from N-body simulations (Davis & Natarajan, 2009; Prada et al., 2012, and references therein) one can constrain the ratio j_d/m_d for given values of m_d which enter in the computation of f_R as seen in figure 6 of Kawamata et al. (2014). Even more recently, Stringer et al. (2014) proposes that the evolution of collapsed cosmic structures should follow a well determined mass-size relation as an instantaneous virialization trend at any given epoch

$$R_v \approx \left(\frac{2M_v G}{\Delta_z H_z^2} \right)^{1/3} \quad (2.6)$$

using the same reasoning of equation 2.1. Here, Δ_z represents the ratio of a given region density with respect to the critical density of the Universe. To account for the non-instantaneous virialization of entire populations at the same instant, it is interesting to explore for a given redshift the relation between size and mass parameterized by

$$R(M, z) \approx \frac{R_0}{(1+z)^\gamma} \left(\frac{M}{M_0} \right)^\beta \quad (2.7)$$

where R_0 represents the offset with respect to the idealized scenario of equation 2.6 at a given mass M_0 . For a fixed redshift the mass-size relation scales with the expected slope $\beta \sim 1/3$ and this relation evolves with time through the slope γ . The evolving offset $R_0 \propto \Delta_z^{-1/3} H_z^{-2/3}$ shall correspond to a value of $\gamma = 1$ at early epochs evolving into slightly smaller lower values of γ as we reach the current time. Observations of the effective radius (which can be scaled with the virial radius of the DM halo) can be used then as a first approximation to verify such trends in real galaxies (even comparing different populations) as shown by Stringer et al. (2014) and try to contextualize their evolution with respect to the expected average background evolution.

The size distribution of galaxies should have a lognormal distribution (Ferguson et al., 2004) that is proportional to the dimensionless spin parameter of the halo

$$p(\lambda)d\lambda = \frac{1}{\sigma\sqrt{2\pi}} \exp \left[-\frac{\ln^2(\lambda/\bar{\lambda})}{2\sigma^2} \right] \frac{d\lambda}{\lambda} \quad (2.8)$$

where λ is a parameter dependent on the total angular momentum of the galaxy, their total energy and mass. This functional form is observed on present-day disk galaxies, but for elliptical ones that is not so clear (see, e.g. de Jong & Lacey, 2000; Shen et al., 2003; Courteau et al., 2007; Huang et al., 2013; Curtis-Lake et al., 2016).

2.1.4 SUMMARY

In summary there are several mechanisms that contribute to the evolution in galaxy morphology through cosmic time.

- **Monolithic collapse** where galaxies form from the collapse of a single cloud and either form a compact spheroidal object or a disk supported by angular momentum.
- **Mergers** where violent interactions shape the end-result of galaxy encounters leading to the formation of massive ellipticals and large bulges in spiral galaxies. The effect of merging is more or less dramatic if the merger is major (mass ratio between the components < 4) or minor (> 4).
- **Disk instabilities** where high gas densities lead to the formation of giant galactic clumps that induce irregular and clumpy morphologies. Migration of clumps can contribute to the formation of compact galaxies or central bulges in extended disks.

- **Galaxy interactions** are the softer version of galaxy mergers where morphological disturbances are seen in the form of large tails, rings, lopsided stellar distributions, to name a few. These shapes may indicate an on-going merger event or a galactic collision.
- **Dust and age gradients** can affect galaxy morphology depending on the wavelength of the observations by providing different classifications for the same galaxy based on the distribution of stellar populations and dust lanes.
- **Stellar and AGN feedback** can effectively quench star-formation activity and change the morphological appearance of a galaxy.

2.2 METHODS FOR THE QUANTIFICATION OF GALAXY MORPHOLOGY

2.2.1 PARAMETRIZATION OF GALAXY LIGHT PROFILES

The spatial distribution of the stellar light in galaxies can tell us about their history. With the first recorded images of galaxies, models that describe the radial dependence of the luminosity were created. At first, the Reynolds-Hubble model (Reynolds, 1913; Hubble, 1930) was a common method to describe that. However, that model failed to properly adjust the outer regions of elliptical galaxies. de Vaucouleurs (1948) showed that the light profile of elliptical galaxies was well fit by $I(r) \propto \exp(-r^{1/4})$ at all radii. Galaxy disks in spiral galaxies were typically fit with an exponential profile ($I(r) \propto \exp(-r)$). This model was generalized by Sérsic (1968) when he proposed that all light profiles of galaxies could be described by the functional form $I(r) \propto \exp(-r^{1/n})$. By adding a new parameter, the Sérsic index n , it could adjust to both ellipticals with $n = 4$ and disks with $n = 1$. But some spiral galaxies have a spheroidal component in their center and a single profile fails to reproduce the full radial range. For those sources, a combination of an exponential disk with a de Vaucouleurs elliptical profile for the central region is found to reproduce better the light distribution (Freeman, 1970). Nowadays, the Sérsic model is the preferred for using in both local and high redshift galaxies (e.g. Kormendy et al., 2009; Graham, 2013; van der Wel et al., 2014) since it can generally reproduce the shape of most galaxies. For special classes of galaxies there are other profiles that can be used like the King profile (e.g. King, 1978) for globular clusters, the Nuker profile (Lauer et al., 1995) and the core-Sérsic profile (Graham et al., 2003) for the nucleus of nearby galaxies.

To simplify the process of fitting a radial model to the light distribution often the images are azimuthally averaged in elliptical apertures to produce one-dimensional surface brightness profiles. This method is very simple but fails to use the total amount of information that we have at our disposal. It is also shown that multiple solutions can be fit on the same galaxy depending on the type of apertures used to collapse the information (Peng et al., 2010). Furthermore, the asymmetric sub-structures are often diluted in the extracted profile. An alternative method consists in producing two dimensional analytical models that can be directly compared to the galaxy image (Simard, 1998; Simard et al., 2011; Peng et al., 2002, 2010; de Souza et al., 2004). These have the advantage of exploiting all the information encoded in the images and have been shown to more faithfully recover the structural parameters of model galaxies in a general scenario (e.g. Guo et al., 2009). They also allow for the accurate representation of the intrinsic values due to a better PSF-modeling technique. It also automatically produces a residual image on which we may find hidden substructures that are often created by past interactions that the galaxy experienced. They are however limited to azimuthal symmetry and assume constant ellipticity at all radii.

2.2.2 NON-PARAMETRIC GALAXY MORPHOLOGY

The parametrization of the light profile requires that galaxies are on average symmetric and that one empirical model is to be used. In order to directly measure structural properties with a minimum of assumptions, a new approach has gained momentum in recent years. The idea is to directly quantify a specific aspect of galaxy shape (concentration, asymmetry, smoothness) from the image without parameterizing the light distribution of galaxies. These non-parametric measurements were commonly used since the first deep HST images were available (e.g. [Abraham et al., 1994, 1996](#)).

Although being first designed for high-redshift systems, they have also been applied to local samples and found to be correlated with galaxy color and its peculiar features, often indicating galaxy interactions or mergers ([Conselice, 1997](#); [Bershady et al., 2000](#); [Conselice et al., 2000](#)). In the following years several new non-parametric schemes have been defined and used to automatically classify galaxies in a completely model independent way ([Takamiya, 1999](#); [Conselice et al., 2000](#); [Bershady et al., 2000](#); [Abraham et al., 2003](#); [Conselice, 2003](#); [Lotz et al., 2004](#); [Papovich et al., 2003, 2005](#); [Law et al., 2007](#); [Matsuda et al., 2011](#); [Freeman et al., 2013](#)).

One of the widespread non-parametric methods is the CAS system ([Conselice, 2003](#)) that can be used to select highly disturbed systems in comparison to the more common Hubble types. It also provides a way to distinguish between spirals and ellipticals and typical values for several galaxy populations may be found in the review by [Conselice \(2014\)](#). Another very popular method, the Gini- M_{20} system, was developed by [Lotz et al. \(2004\)](#) and attempts to automatically select merging and starburst galaxies, distinguishing them from normal Hubble type galaxies in a similar way as the CAS system ([Lotz et al., 2004, 2008](#)).

With the increase of irregular galaxies at high redshift, a number of other non-parametric measurements was developed. They include the $T^1 \Psi$ parameters defined by [Law et al. \(2007\)](#) which aim at computing the total observed area and a proxy for the potential energy associated with the galaxy light distribution, respectively. These have the objective of defining a new size measurement for highly irregular galaxies and a way to distinguish between compact objects from irregular and peculiar ones. The MID system proposed by [Freeman et al. \(2013\)](#) was designed to maximize the potential to distinguish merging systems from smoother regular galaxies at high redshift. It computes the relative importance of the clumps found (if any) compared to the total light distribution of the galaxy. Another non-parametric measurement, the filamentarity, F , was proposed by [Matsuda et al. \(2011\)](#) to measure the deviation from a round shape for a sample of extended Ly- α halos but that can be used to distinguish compact round objects from more disturbed and elongated ones.

2.3 TRACING MORPHOLOGICAL EVOLUTION ACROSS COSMIC TIME

Early studies at low redshifts started to show some correlations between the shape of a galaxy and some of its physical properties. For instance, and based on the Hubble sequence classification, ellipticals tend to have redder colors and thus older stellar populations and low current star formation activity, and lower percentage of gas content. In opposition, spiral galaxies show bluer colors, younger stellar populations, higher star formation activity and higher fraction of neutral hydrogen. In what concerns dynamics, ellipticals are mostly supported by random motion whereas spirals present coherent rotational velocities. Irregular galaxies are thought to be galaxies in formation which are in general smaller, have high fraction of gas, and young stellar populations accompanied by high star formation rates (e.g. [Roberts & Haynes, 1994](#);

¹in this thesis I use the symbol T instead of the original I to distinguish from the intensity parameter of the MID system ([Freeman et al., 2013](#))

Kauffmann et al., 2003; Conselice, 2003; Blanton et al., 2003; Blanton & Moustakas, 2009; Tasca & White, 2011; Wuyts et al., 2011; Whitaker et al., 2015).

As we move towards higher redshifts, the Hubble sequence tends to lose its values as distant galaxies have more and more peculiar shapes and thus do not fall in the classical scheme of morphological classification. Several studies indicate that the fraction of elliptical galaxies and disc galaxies has increased from out to $z = 3$ till today mainly at the expense of high redshift irregular galaxies which show a dramatic decrease in their population from high redshifts to $z \sim 0$ (Driver et al., 1995; Glazebrook et al., 1995; Abraham et al., 1996; Lilly et al., 1998; Conselice et al., 2005; Delgado-Serrano et al., 2010; Buitrago et al., 2013; Mortlock et al., 2013; Talia et al., 2014; Huertas-Company et al., 2015a,c, 2016).

Delgado-Serrano et al. (2010) have proposed a scenario for the Hubble sequence at $z \sim 1$. By selecting galaxies above the same absolute magnitude threshold, they present a link between local and distant galaxies. Their results include no evolution in the number of ellipticals and lenticulars. More than 50% of the distant galaxies have peculiar morphologies. There were ~ 2 times less spirals at that time. Thus, almost all evolution must be from irregular galaxies evolving into regular spiral galaxies. This result is supported by Huertas-Company et al. (2016, see also Lilly et al. 1998) where they find that the majority of stellar mass density of star-forming galaxies at $z \sim 3$ is in irregular galaxies and that they gradually transform into normal spirals without any abrupt interruption of the star formation activity. The irregular galaxy population is dominant at $z \gtrsim 2$ whereas disk galaxies are rare. However there is still a significant fraction of compact spheroids (Buitrago et al., 2013; Mortlock et al., 2013; Huertas-Company et al., 2015c). In terms of their properties, peculiar and disk galaxies are bluer and have higher star formation rates than spheroidal galaxies (Mortlock et al., 2013; Talia et al., 2013; Lee et al., 2013). Spheroidal galaxies are typically compact and also show very little evidence for AGN activity (Weinzirl et al., 2011).

The evolution in galaxy structure is also evident for galaxies of the same type. For instance, Buitrago et al. (2013) finds that the Sérsic index increases at lower redshifts, and that change is stronger for disks than it is for spheroidals. By comparing galaxies at the same rest-frame, and in the size- n plane, Weinzirl et al. (2011) finds a real evolution when comparing real with artificially redshifted galaxies from $z \sim 2 - 3$ to $z \approx 0$. The evolution in galaxy sizes is discussed in more detail in section 2.4.1. As it happens at lower redshift, spheroidal galaxies which have typically higher Sérsic indexes show little star formation activity and are found mainly at the higher stellar masses ($\log M_*/M_\odot \gtrsim 10$ Wuyts et al., 2011; Whitaker et al., 2015).

At $z \gtrsim 3$ we are limited to observations of UV rest-frame morphologies and large samples are based on color selections or narrow-band imaging to pick Ly- α emitters at a particular redshift. There are studies reporting on the fraction of irregular galaxies that show that UV bright sources have typical irregular morphologies for 30 – 60% (Conselice & Arnold, 2009; Oesch et al., 2010; Jiang et al., 2013; Curtis-Lake et al., 2016; Bowler et al., 2016) suggesting a constant fraction from $z \sim 3$ up to $z \sim 7$. There are also several studies attempting to measure galaxy sizes up to $z \sim 10$ where they find that galaxies become increasingly compact reaching effective radius smaller than 1 kpc at $z \gtrsim 3 - 5$ (e.g. Hathi et al., 2008; Jiang et al., 2013; Ono et al., 2013; Kawamata et al., 2015; Holwerda et al., 2015; Shibuya et al., 2015). At these redshifts, there is a proxy for the stellar mass-size relation by studying the size-luminosity relation in the UV. Results point to an underlying correlation but there are large discrepancies in the observed slope of the correlation for $z \gtrsim 3$ (e.g. Grazian et al., 2012; Huang et al., 2013; Jiang et al., 2013; Shibuya et al., 2015; Curtis-Lake et al., 2016). On the nature of clumpy galaxies there is a study extending to $z \sim 8$ reporting a peak in the clumpy fraction at 60% $z \sim 2 - 3$ (compatible with the findings of Guo et al., 2015, at $z \lesssim 3$) and then a rapid decline down to $\sim 20\%$ at $z \sim 4$ that remains constant up to $z \sim 8$ (Shibuya et al., 2016).

In terms of the environmental impact on galaxy morphology, Dressler (1980) reported on the first observations of the morphology density relation in 55 local galaxy clusters by finding an excess of elliptical and red galaxies in the center of clusters, and a dominance of blue spiral disks in the less dense regions in the outskirts (see also, e.g. Goto et al., 2003; Kauffmann et al., 2004; Skibba et al., 2009). This relation has been found to persist out to intermediate redshifts ($z < 1$, e.g. Dressler et al., 1997; van der Wel et al., 2007; Tasca et al., 2009) and hints from size evolution studies try to establish this dichotomy at $z \gtrsim 1$ (e.g. Bassett et al., 2013; Strazzullo et al., 2013). By comparing the different structures of galaxies observed in both field and cluster we can pinpoint the epoch of morphological diversification within denser environments with respect to that of the field population that seems to fade at $z \sim 2$ (e.g. Peter et al., 2007; Mortlock et al., 2015; Mei et al., 2015; Allen et al., 2015).

2.4 TOPICS IN THIS THESIS

2.4.1 SIZE MEASUREMENTS AT HIGH REDSHIFT FOR STAR-FORMING GALAXIES

A simple, yet fundamental, shape parameter is the galaxy size. This quantity, together with other physical parameters like stellar mass and star formation rate, is one of the basic ingredients that can help to elaborate a galaxy evolution scenario.

Although it is a simple concept, obtaining galaxy sizes is not an easy task and is subject to a number of assumptions. The most common way to derive galaxy sizes is by performing light profile fitting assuming a given shape for the surface brightness profile using a χ^2 minimization (e.g. Simard et al., 1999; Peng et al., 2002; Ravindranath et al., 2004; Daddi et al., 2005; Ravindranath et al., 2006; Trujillo et al., 2006c; Akiyama et al., 2008; Franx et al., 2008; Tasca et al., 2009; Cassata et al., 2010; Williams et al., 2010; Mosleh et al., 2011; Cassata et al., 2013; Huang et al., 2013; Ono et al., 2013; Stott et al., 2013; Morishita et al., 2014; van der Wel et al., 2014; Straatman et al., 2015; Shibuya et al., 2015). Another method assumes circular or elliptical apertures around a pre-defined galactic center and computes the size enclosing a given percentage of the total galaxy flux (e.g. Ferguson et al., 2004; Bouwens et al., 2004; Hathi et al., 2008; Oesch et al., 2010; Ichikawa et al., 2012; Curtis-Lake et al., 2016). A third approach, involving counting the number of pixels belonging to the galaxy to derive its size, was also explored in Law et al. (2007).

Studies of galaxy sizes at $z > 2$ became possible with the deep imaging obtained with HST. The first reports on size evolution found that galaxy sizes as observed in the UV rest-frame were becoming smaller at the highest redshifts (Bouwens et al., 2003; Ferguson et al., 2004; Bouwens et al., 2004). We have now access to the size evolution up to $z \sim 10$ from the deepest HST imaging data (e.g. Hathi et al., 2008; Jiang et al., 2013; Ono et al., 2013; Kawamata et al., 2015; Holwerda et al., 2015; Shibuya et al., 2015). With the multi-wavelength and near-infrared coverage of CANDELS (Grogin et al., 2011; Koekemoer et al., 2011) optical rest-frame measurements are reported up to $z \sim 3$ for a large collection of galaxies in diverse populations (e.g. Bruce et al., 2012; van der Wel et al., 2014; Morishita et al., 2014). At $z \sim 2$ the size of SFGs is, to first order, independent of the observed rest-frame bands (Shibuya et al., 2015). It is generally accepted that galaxy sizes tend to decrease with increasing redshift (e.g. Bouwens et al., 2003, 2004; Ferguson et al., 2004; Mosleh et al., 2012) and that galaxy sizes depend on stellar mass (e.g. Franx et al., 2008; van der Wel et al., 2014; Morishita et al., 2014) and luminosity (e.g. Grazian et al., 2012; Huang et al., 2013). However some results point to a scenario consistent with no size evolution as seen in UV rest-frame from HST data (Law et al., 2007; Curtis-Lake et al., 2016) and, at a fixed stellar mass, from optical rest-frame ground-based data (Ichikawa et al., 2012; Stott et al., 2013).

Most samples in the literature that are used to measure sizes at high redshift are composed of galaxies selected through the dropout technique (Steidel et al., 1999) or photometric redshifts. Typical 1σ errors in photometric redshift measurements of $dz \sim 0.2-0.3$ add an error of $\sim 5\%$ (increasing from $z = 2$ to $z = 4.5$) to angular diameter measurements. This is a small but sizable error that can be reduced when measuring sizes for galaxy samples with known spectroscopic redshifts. Moreover, having a precise knowledge of the redshift of the galaxy minimizes the ambiguity on which rest-frame bands are observed and allows an accurate estimate of surface brightness dimming effects which are important to reduce measurement scatter for a consistent analysis in a large redshift range. The knowledge of the spectroscopic redshift and the availability of spectra also allow to better characterize the physical properties of the galaxies for which sizes are measured. Uncertainties on stellar masses, star formation rates, and ages, are reduced (Thomas et al., 2016) and spectral features like Lyman- α emission can be correlated with galaxy sizes.

In this thesis I present in sections 4.1, 4.3 and 5.1 the evolution of the size and size distribution of a sample of ~ 1200 star-forming galaxies with spectroscopic redshifts $2 < z_{\text{spec}} < 4.5$ selected from the VIMOS Ultra-Deep Survey (VUDS, Le Fèvre et al., 2015). In addition to using standard profile fitting to derive effective radii, I develop and apply a non-parametric method (adapted from Law et al., 2007) to compute galaxy sizes which takes into account the surface brightness dimming effect and does not require any assumption on the symmetry of the studied sources. I test the impact of using different rest-frame bands (for a subset of my galaxies) and different methods when deriving size evolution. I then probe the evolution of light profiles of galaxies using image stacks and comparing the concentration of light across the redshift range studied.

2.4.2 THE ORIGIN OF GALACTIC CLUMPS DURING THE ASSEMBLY PHASE OF GALAXIES

The morphology of galaxies is a visible outcome of all processes at work when galaxies are assembling along cosmic time (e.g. Conselice, 2014). While at lower redshifts galaxies are predominantly regular and symmetric in the form of elliptical or spiral galaxies, the situation at redshifts higher than the peak in star formation $z \sim 1.5-2$ is very different with galaxies mostly having irregular shapes (e.g. Buitrago et al., 2013; Mortlock et al., 2013; Huertas-Company et al., 2015b).

Quantitative morphology allows to follow the evolution of the two main components of galaxies, disks and bulges, and studies have focused on understanding the evolutionary paths of these fundamental components (e.g. Bruce et al., 2012, 2014b,a; Lang et al., 2014; Tasca et al., 2014a; Margalef-Bentabol et al., 2016). Observational studies and numerical simulations seem to support a picture where disk galaxies build from the original collapse of baryonic matter in a dark matter halo. Several studies point to a scenario where gas gains angular momentum leading to rotation support system, with violent disk instabilities (VDI) forming large star-forming clumps. These large clumps may then migrate to the disk center to form the bulges of spiral galaxies (e.g. Genzel et al., 2008; Elmegreen et al., 2008, 2009; Dekel & Krumholz, 2013; Perez et al., 2013; Bournaud et al., 2014; Bournaud, 2016). Alternatively, considerable effort has been invested in studying the development of elliptical galaxies along cosmic time. On this scenario, bulges would form from violent dissipative events, going through a stage of compact quiescent objects at $z \sim 2$. Such objects would then grow into massive ellipticals after star formation quenching and a succession of merging events (e.g. Hopkins et al., 2008; Oser et al., 2012; López-Sanjuan et al., 2012; Porter et al., 2014). Two major physical processes are thought to play a key role in the evolution of different types of galaxy galaxies: gas accretion mostly in cold form and flowing along the cosmic web and/or smoothly distributed (e.g. Dekel

et al., 2009; Rodriguez-Gomez et al., 2016), and major or minor merging (e.g. Hopkins et al., 2008; Di Matteo et al., 2008), each leading to different morphological signatures.

An important morphological property related to these processes is the number of large clumps of gas and stars present within a galaxy. Clumps may have either an *in-situ* or an *ex-situ* formation history depending on which physical processes are at play (e.g. Shibuya et al., 2016). Clumps forming from disk instabilities are mostly the result of in-situ dynamical processes, while major and minor merging events are driving clumps of ex-situ material into a galaxy in assembly phase. The properties and fate of these clumps has been extensively studied in the literature both from observations (e.g. Elmegreen et al., 2004; Elmegreen & Elmegreen, 2006; Elmegreen et al., 2007, 2013; Genzel et al., 2008; Bournaud et al., 2008; Wuyts et al., 2012; Guo et al., 2012) and in hydrodynamical simulations (e.g. Bournaud et al., 2007b; Dekel et al., 2009; Genel et al., 2012; Bournaud et al., 2014; Mandelker et al., 2014; Oklopčić et al., 2016). They report clumps with typical stellar masses of $10^7 - 10^9 M_\odot$ and with lifetimes spanning short to long periods with timescales of $\lesssim 1$ Gyr. Some studies suggest that short-lived clump are destroyed by internal feedback before migrating to the center of the galaxy (e.g. Genel et al., 2012).

The measurement of clumps at redshifts beyond the peak of cosmic star formation are notoriously difficult. The identification of clumpy galaxies in the dominant population of irregular galaxies at high redshift dates back to the first deep *Hubble Space Telescope* (HST) images (e.g. Williams et al., 1996), superseded with each deeper survey following new instrumentation, with the Advanced Camera for Surveys (ACS) then Wide Field Camera 3 (WFC3) bringing larger areas and samples. Detailed studies at $z \sim 1 - 3$ have revealed that clumpy galaxies are more numerous than in the local Universe (e.g. Cowie et al., 1995; Abraham et al., 1996; van den Bergh et al., 1996; Giavalisco et al., 1996; Elmegreen et al., 2004; Elmegreen & Elmegreen, 2006; Elmegreen et al., 2007, 2008, 2009, 2013; Kubo et al., 2013, 2016; Glazebrook, 2013; Tadaki et al., 2014; Murata et al., 2014; Guo et al., 2015; Garland et al., 2015; Bournaud, 2016). The fraction of clumpy galaxies has been studied from $z=0$ up to the most distant galaxies identified today at $z \sim 10$ (Ravindranath et al., 2006; Guo et al., 2012, 2015; Shibuya et al., 2016). In the sample of galaxies with $0.5 < z < 3$ in the CANDELS survey, Guo et al. (2015) find that galaxies with low mass $\log(M_{\text{star}}/M_\star) < 9.8$ have a high fraction of off-center clumps $f_{\text{clumpy}} \sim 60\%$ constant over the observed redshift range, while for intermediate and massive galaxies f_{clumpy} decreases from $\sim 40\%$ at $z \sim 3$ to $\sim 15\%$ at $z \sim 0.5$. Combining deep HST imaging from the 3D-HST, CANDELS, HUDF and HFF surveys Shibuya et al. (2016) claim that $f_{\text{clumpy}}^{\text{UV}}$ follows a similar evolution to the star formation rate density (e.g. Madau & Dickinson, 2014), increasing from $z \sim 8$ to $z \sim 1 - 3$ and decreasing from $z \sim 1$ to $z \sim 0$. In comparing these observed trends with the predictions of simulations, Guo et al. (2015) conclude that VDI are likely responsible for f_{clumpy} at high mass and that minor mergers are a viable explanation for f_{clumpy} at intermediate mass for $z < 1.5$, while Shibuya et al. (2016) conclude that VDI is the main origin of the clumps. Both these studies exclude major mergers as a possible contribution to the evolution of the fraction of clumps. This is somewhat surprising as the major merger fraction for star-forming galaxies is observed to increase up to $\sim 20\%$ at $z \sim 1 - 2$ (e.g. Lotz et al., 2011; López-Sanjuan et al., 2011, 2013), staying high at least to $z \sim 3 - 4$ (e.g. Conselice et al., 2008; Tasca et al., 2014b), and one would therefore expect that a fraction of the clumps is related to *ex-situ* mergers.

When deriving volume average quantities like f_{clumpy} it is critical to observe samples representative of the general star-forming population, with well defined physical parameters including luminosity, stellar masses and sizes. The size of irregular high redshift galaxies is very different when using the effective radius or a total size (Ribeiro et al., 2016), and searching for clumps using one or the other of these sizes to define a search area may lead to significantly different results on f_{clumpy} . Moreover, the issue of the clump definition is quite tricky and one must

be aware of the impact of specific definitions and sample selection, for subsequent analysis to have a statistically robust meaning in a representative volume of the Universe at a given redshift.

In this thesis (sections 4.4 and 5.2) I use a sample of 1242 galaxies with secure spectroscopic redshifts from VUDS and HST imaging in the COSMOS and ECDFS fields to measure f_{clumpy} . I use a clump definition expanded from Guo et al. (2015), counting all clumps within the isophote defining the total size $r_{T,100}$ and in a 20 kpc physical radius.

2.4.3 LY- α EMISSION AND GALAXY MORPHOLOGY

The Ly- α emission line is the intrinsically brightest feature in a hot source spectrum (e.g. Schaerer, 2003). Combined with the fact that it redshifts into the optical and near-infrared rest-frame for a broad redshift range ($2 < z \lesssim 12$), it is one of the most used tracers of galaxies at high redshift. However, due to its resonant nature it is easily scattered by gas clouds (HI) and its emission can be suppressed by the presence of dust.

The radiative transfer process that eventually lead the Ly- α photons to escape its emitting region give rise to a number of line profiles that have been already reported in observations: asymmetric line profiles (e.g. Kunth et al., 1998; Rhoads et al., 2003; Shapley et al., 2003; Shimasaku et al., 2006; Tapken et al., 2007; Vanzella et al., 2010; Lidman et al., 2012; Wofford et al., 2013), double peak profiles (e.g. Shapley et al., 2006; Quider et al., 2009; Kulas et al., 2012; Yamada et al., 2012) as well as spatially extended emission surrounding galaxies (e.g. Fynbo et al., 2001; Steidel et al., 2003, 2011; Rhoads et al., 2005; Hayes et al., 2005, 2007; Rauch et al., 2008; Östlin et al., 2009; Matsuda et al., 2012; Wisotzki et al., 2016). In an attempt to explain such diversity of profiles theoretical and numerical models have been proposed (e.g. Harrington, 1973; Neufeld, 1990, 1991; Loeb & Rybicki, 1999; Ahn et al., 2000; Zheng & Miralda-Escudé, 2002; Dijkstra et al., 2006; Hansen & Oh, 2006; Tasitsiomi, 2006; Verhamme et al., 2006, 2012; Laursen et al., 2009; Duval et al., 2014; Gronke et al., 2015).

Being a very successful method to identify high-redshift galaxies using large narrow band surveys in the optical (e.g. Ouchi et al., 2008, 2010; Sobral et al., 2016) and to spectroscopically detect or confirm high-redshift candidates (e.g. Martin & Sawicki, 2004; Ono et al., 2012; Bacon et al., 2015; Le Fèvre et al., 2015), large samples of such galaxies have been collected to date. From these samples, the study of their rest-frame UV morphologies at $z > 2$ is also widely covered (Pirzkal et al., 2007; Taniguchi et al., 2009; Bond et al., 2009, 2011, 2012; Gronwall et al., 2011; Kobayashi et al., 2016). When considering the local Universe and due to the impossibility of obtaining rest-frame UV observations from ground observatories, the Ly- α Reference Sample (LARS Östlin et al., 2014) is the only statistical study that focus on the morphology of these sources (Guaita et al., 2015).

Ly- α emission is often found to be more extended (in a diffuse halo) than the stellar UV continuum emission (e.g. Rauch et al., 2008; Matsuda et al., 2012; Momose et al., 2014; Matthee et al., 2016; Wisotzki et al., 2016). The process responsible for such observations is thought to be the scattering of photons by neutral HI gas around galaxies at high redshift (e.g. Zheng et al., 2011). Galaxies with observed Ly- α emission are found to be small compact objects at all observed redshifts (e.g. Venemans et al., 2005; Malhotra et al., 2012). Such findings are contrary to the stronger evolution in galaxy sizes seen for other populations (Lyman-break galaxies and star-forming galaxies, e.g. Ferguson et al., 2004; Bouwens et al., 2004; van der Wel et al., 2014; Shibuya et al., 2016). Additionally, there are evidences for a correlation between line luminosity and galaxy UV continuum size (e.g. Hagen et al., 2014) as well as a correlation between the extent of Ly- α with the extent of the UV emission (e.g. Wisotzki et al., 2016). However, one must be cautious of how representative of the general star forming population

these studies are before drawing strong conclusions.

The mechanisms through which Ly- α photons escape into inter-galactic space are complex and photons can travel for several kpc in random walks before free-roaming towards our line of sight (e.g. Zheng et al., 2011; Dijkstra & Kramer, 2012; Lake et al., 2015). Such large excursions increase the chance of dust absorption corresponding to photon destruction (e.g. Neufeld, 1991; Laursen et al., 2013). And there are simulations that show that the escape fraction is linked to the galaxy inclination with respect to the line of sight (Verhamme et al., 2012; Behrens & Braun, 2014). Observationally, the escape fraction of Ly- α photons is correlated to dust attenuation and SFR but large scatter is observed (e.g. Hayes et al., 2010, 2011; Atek et al., 2014; Matthee et al., 2016). Other studies show that a key quantity in determining Ly- α emissivity is the column density of neutral hydrogen (e.g. Shibuya et al., 2014a,b).

The comparison of Ly- α emitters (LAEs) with galaxies with weak or no Ly- α emission is ubiquitous in the literature (e.g. Shapley et al., 2001; Erb et al., 2006; Gawiser et al., 2006, 2007; Pentericci et al., 2007; Lai et al., 2008; Reddy et al., 2008; Finkelstein et al., 2009; Kornei et al., 2010; Nilsson et al., 2011; Acquaviva et al., 2012; Hathi et al., 2016). While some studies indicate that LAEs are low mass dusty galaxies and likely the early stage of galactic evolution others point to a scenario where LAEs are older and more massive and dusty galaxies. Some find even marginal differences between LAEs and the normal star-forming population. Emission line galaxies detected at $z \sim 2$ are also found to be similar to LAEs but less massive and star-forming than color-selected galaxies at the same redshifts and stellar mass range (e.g. Hagen et al., 2016b).

In this thesis (sections 4.6 and 5.4) I report a taxonomy study on the shape of the 2D Ly- α emission line analyzed in > 4000 galaxies of the VUDS survey. I divide our sample into different classes according to the Ly- α 2D shape with respect to the UV continuum and then report on the abundance of each class as a function of redshift and several key physical parameters derived from SED fitting. I also attempt at corresponding each class to an underlying 3D model of line emission and compare the typical properties of each class. I use the acronym LAGs for Ly- α emitting Galaxies instead of LAEs for Ly- α emitters to avoid confusion with the standard definition of LAEs in the literature.

3 | Data and sample selection

Contents

3.1	The VIMOS Ultra Deep Survey	23
3.1.1	Redshift flag system	25
3.1.2	VUDS data release 1	27
3.2	Imaging surveys in the optical and NIR	27
3.2.1	Space Observations	27
3.2.2	Ground observations	28
3.3	Methods for data analysis	29
3.3.1	Preparing the data for the interface	30
3.3.2	SPVT graphical interface features	32
3.3.2.1	Adapting the color and size scales	32
3.3.2.2	Manipulating 1D spectra and Stamp orientation	32
3.3.2.3	Top Level Menu	33
3.3.2.4	Navigation and Other Tools	34
3.3.2.5	Display related options	34
3.4	Selection function	35
3.4.1	A sample with reliable redshifts to study Ly- α	36
3.4.2	High image resolution sample to study galaxy morphology at high redshift	36
3.4.3	A stellar mass-selected sub-sample	37

3.1 THE VIMOS ULTRA DEEP SURVEY

One key aspect of a successful census of galaxies in Astronomy is having a well controlled and defined sample from which conclusions on the general properties of the galaxy population at a given epoch may be derived. Largely successful in obtaining large samples of high redshift galaxies, broad band color selection (e.g. [Steidel et al., 2003](#); [Daddi et al., 2004](#); [Beckwith et al., 2006](#); [Bouwens et al., 2007](#); [Ellis et al., 2013](#)) or narrow-band techniques (e.g. [Taniguchi et al., 2005](#); [Ouchi et al., 2008, 2010](#)) have provided much of our current knowledge for galaxy formation and evolution in the early Universe. However, these techniques are quite crude and prone to degeneracy in redshift space with contamination and completeness issues hard to quantify over a broad redshift range. Spectroscopic redshifts are required to properly define a clean sample at any given period (e.g. [Le Fèvre et al., 2013, 2015](#)).

VUDS is a large spectroscopic survey with the VISIBLE Multi-Object Spectrograph on the ESO-VLT, that targeted ~ 10000 objects covering an area of 1deg^2 on three separate fields: COSMOS, ECDFS and VVDS-02h (see figure [3.1](#) and [3.2](#)). With the objective to observe galaxies in the redshift range $2 < z < 6+$, targets were mostly ($\sim 85\%$) selected based on the

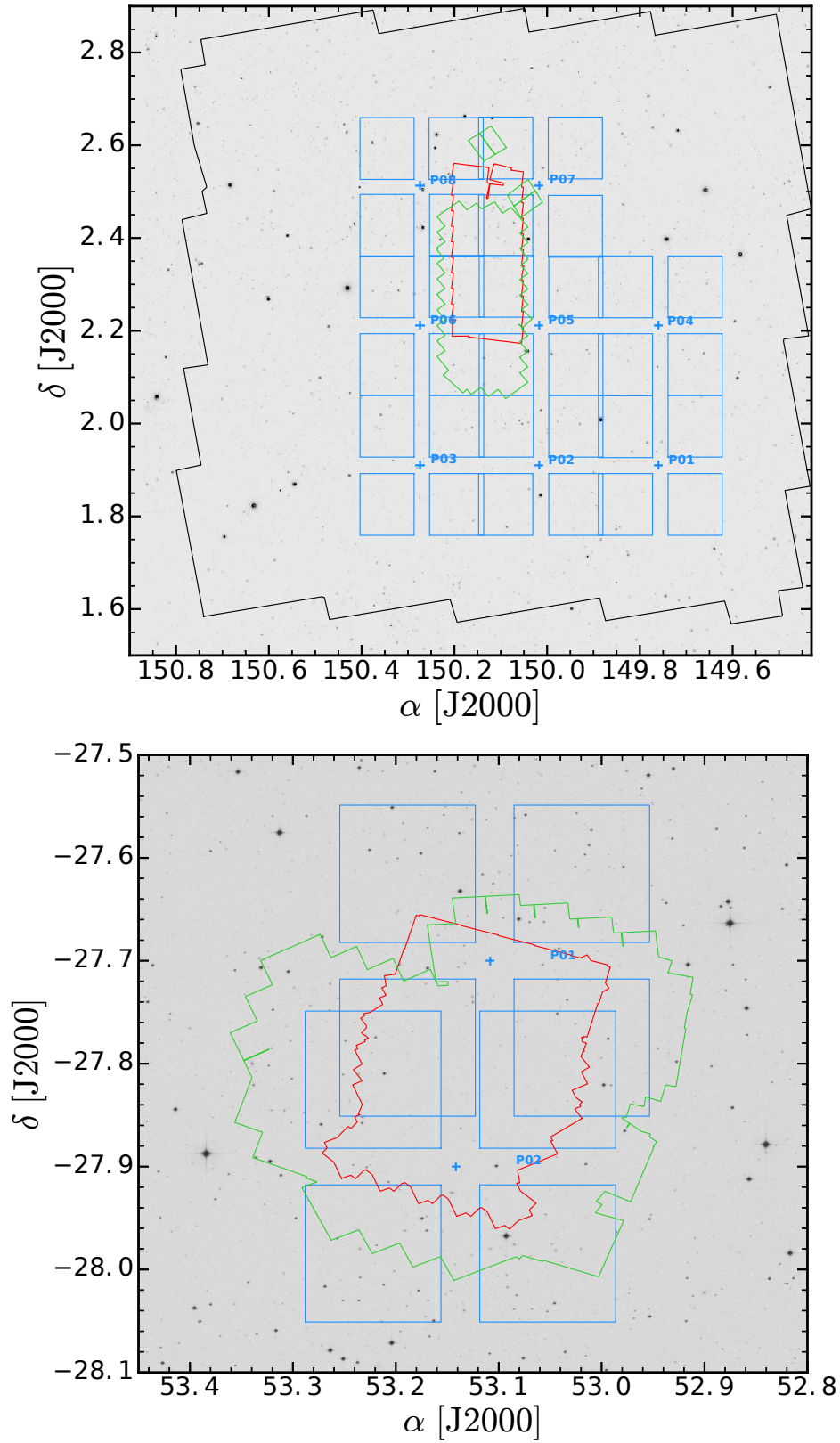


Figure 3.1. Overlay of the 64 quadrants of the VUDS survey (in blue) on top of an I band imaging from DSS in the COSMOS (top) and ECDFS (bottom) fields. The HST ACS survey footprint is shown in black on the COSMOS field. The CANDELS coverage is shown in red (for the H band) and green (for the I band) in both fields.

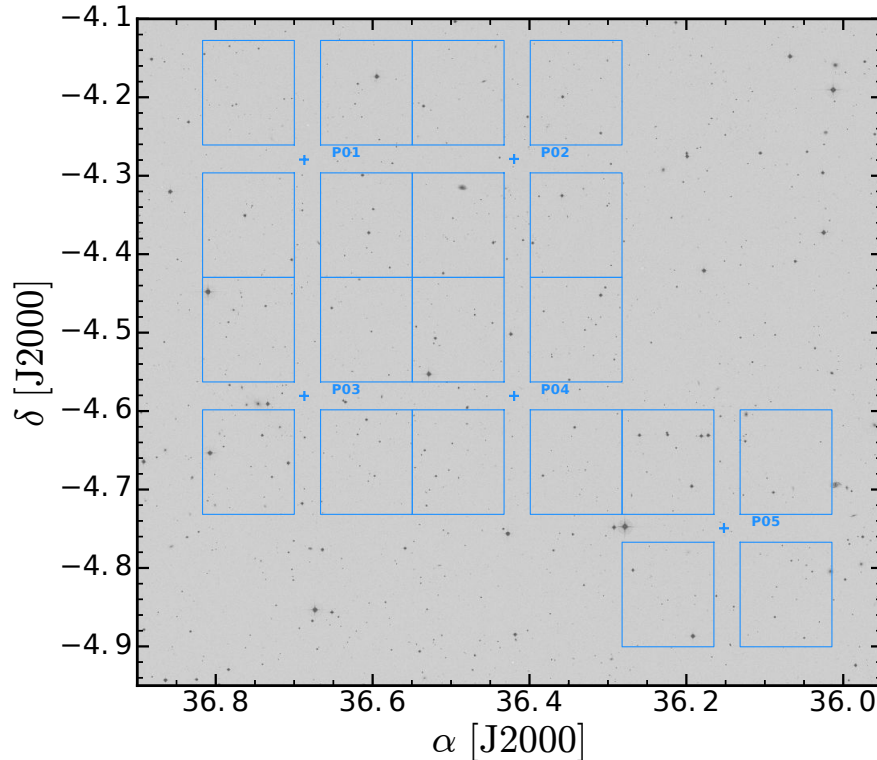


Figure 3.2. Overlay of the 64 quadrants of the VUDS survey (in blue) on top of an I band imaging from DSS in the VVDS field.

first or second photometric redshift peaks being at $z_{\text{phot}} + 1\sigma > 2.4$, adding objects selected in the same redshift range from their color based on the spectral energy distribution (SED) when not selected by photometric redshifts, and with a color selection criteria based on the SED and with flux limits $22.5 \leq i_{AB} \leq 25$. To fill in the remaining available space on the VIMOS slit-masks, a randomly flux selected sample with $23 < i_{AB} < 25$ is added to the target list. The spectra were obtained combining observations in two low resolution grisms ($R=230$), a wavelength range of $3650 < \lambda < 9350$. The total integration is of $\sim 14\text{h}$ for all galaxies in a given VIMOS pointing, and for each grism.

Data processing is performed within the VIPGI environment (Scodeggio et al., 2005), and is followed by extensive redshift measurements campaigns using the EZ redshift measurement engine (Garilli et al., 2010). At the end of this process each galaxy has flux and wavelength calibrated 2D and 1D spectra, a spectroscopic redshift measurement and associated redshift reliability flag. For more information on this process I refer to Le Fèvre et al. (2015). The redshift reliability flag system is described in section 3.1.1.

3.1.1 REDSHIFT FLAG SYSTEM

The difficulty of obtaining reliable redshift estimates from automated algorithms required manual intervention for roughly half of the sample in VUDS. Each galaxy was measured independently by two observers and then a single measurement was produced upon discussion and agreement on an object per object basis. In this process, the reliability of the redshift estimate is then provided by the perceived quality of the spectra. This led to the implementation of a redshift flag system that was first developed for the Canada France Redshift Survey (CFRS Le Fèvre et al., 1995) and later refined in successive redshift surveys (VVDS - Le Fèvre et al. 2005, 2013, zCOSMOS - Lilly et al. 2007, and VIPERS Guzzo et al. 2014). The reliability flag

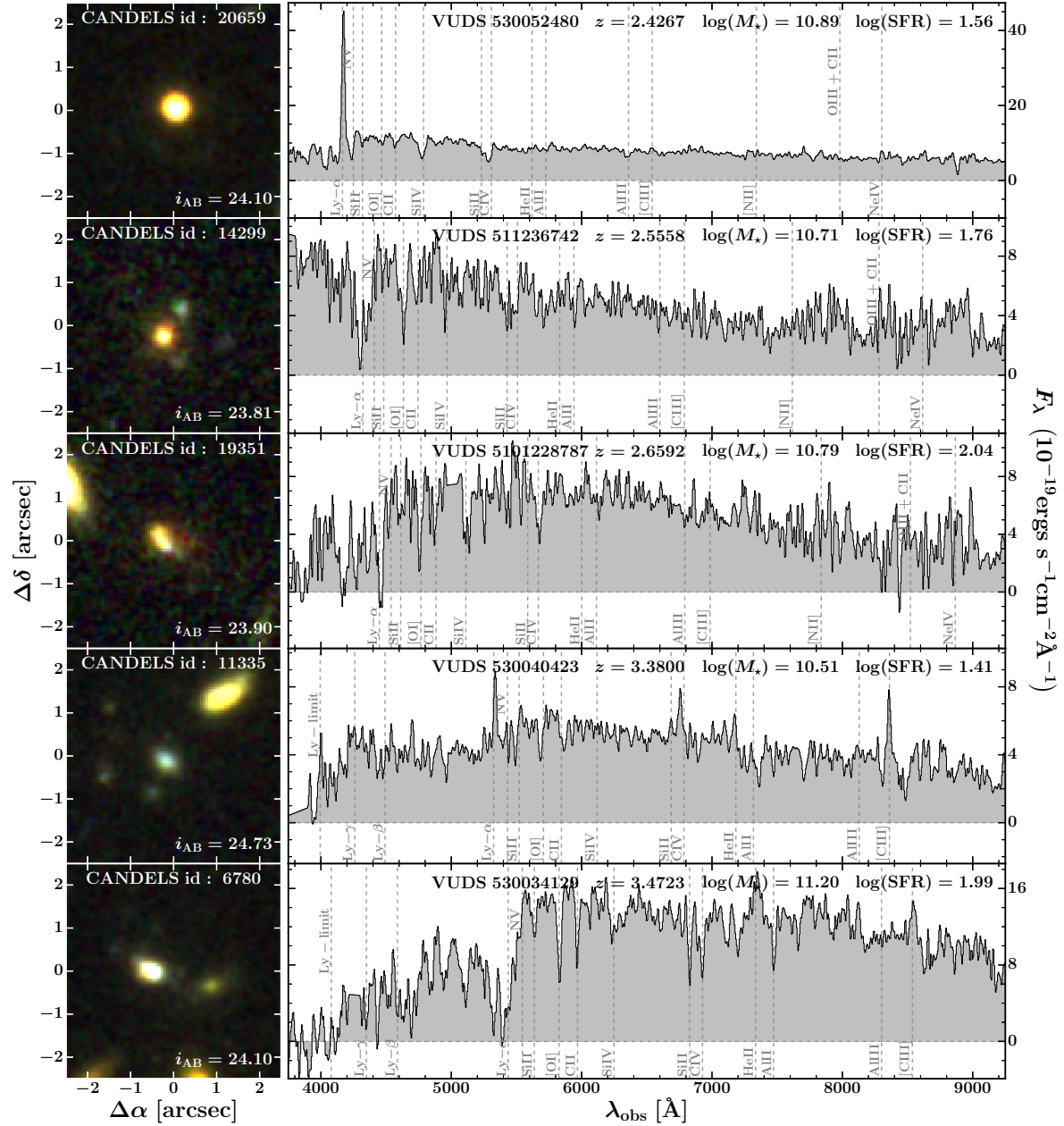


Figure 3.3. Five of the most massive objects included in the VUDS DR1. For each object I show the color image made from IJH CANDELS stamps, the extracted 1D spectra, some corresponding spectral lines and information on the redshift, stellar mass, star formation rate and CANDELS ID.

Value	Meaning
0	No redshift assigned to the object
1	50-75% probability of being correct
2	75-85% probability of being correct
3	95-100% probability of being correct
4	100% probability of being correct
9	single line emission spectra. $\sim 80\%$ probability of being correct

Table 3.1. Redshift reliability flags used in VUDS.

may take the values shown in table 3.1.

3.1.2 VUDS DATA RELEASE 1

In summer 2015, the VUDS collaboration provided the community with its first data release (see [Tasca et al., 2016](#)). This release contains all measured redshifts for galaxies that have coverage in the CANDELS survey in the COSMOS and ECDFS fields (see figure 3.4). This combines a total of 698 objects of which ~ 500 galaxies with $z_{\text{spec}} > 2.48$ spanning a area of 276.9 arcmin².

All these objects were checked for mis-identification and wrong or bad extractions using the tool described in section 3.3. I actively participated in the preparation of this data release by providing the aforementioned tool as well as processing the results to provide ready to use lists where all required changes were compiled for batch use. I have also worked on the material used in the implementation of the public website and user interface that is available there. The current database interface includes a global overview of the observations by displaying each object as an interactive button on top of the field images that were produced by me. When clicking on any object, a new panel with specific information on the object pops-up in a new window. These include color images combining IJH images from CANDELS and the spectra, both elements for which I contributed. An example of massive objects in this data release with reliable spectroscopic redshifts and corresponding color images may be seen in figure 3.3 (see also [Tasca et al., 2016](#)).

Future public releases are planned where redshifts, spectra and physical parameters will be made available to the research community for further exploration of the large dataset produced from this large observation program.

3.2 IMAGING SURVEYS IN THE OPTICAL AND NIR

3.2.1 SPACE OBSERVATIONS

To conduct a morphological study of high-redshift galaxies, one should use the deepest, best resolution images coming from Hubble Space Telescope imaging surveys. Covering the largest contiguous sky region, the COSMOS ([Scoville et al., 2007](#); [Koekemoer et al., 2007](#)) survey has $\approx 2\text{deg}^2$ of ACS F814W coverage down to a limiting magnitude of 27.2 (5σ point-source detection limit). As it covers the entirety of the VUDS COSMOS pointings it is the most complete image set to undertake morphological studies with my sample albeit only covering the UV rest-frame.

The more recent CANDELS survey ([Grogin et al., 2011](#); [Koekemoer et al., 2011](#)) covers five different sky regions, including the COSMOS and ECDFS fields with a large overlap with VUDS fields (see [Le Fèvre et al., 2015](#), and figure 3.1). The area covered is smaller than

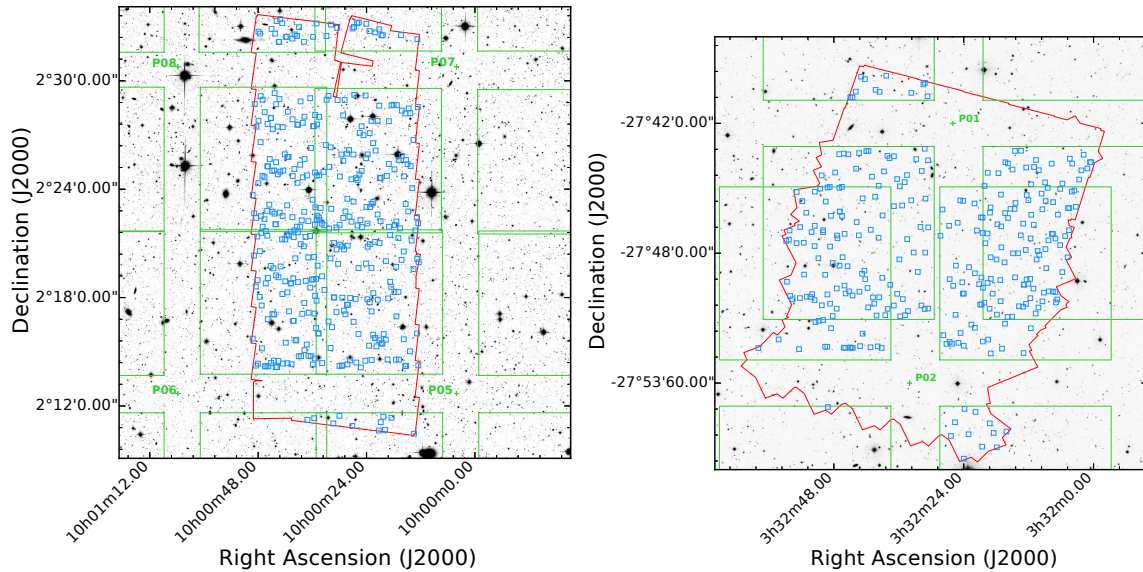


Figure 3.4. Subset of VUDS sources that matches the COSMOS (left) and ECDFS(right) CANDELS coverage. In green I show the position of VUDS quadrants, in red the overlay of the CANDELS survey and in blue squares the position of each source that is now public.

VUDS but near-infrared coverage (namely F125W and F160W) is important because it allows us to probe optical rest-frame morphologies for the majority of my sample in this field. It reaches depths at 5σ of 28.4, 27.0 and 26.9 at F814W, F125W and F160W respectively, deeper in the F814W band than the aforementioned COSMOS observations. The typical spatial resolution of these images ranges from $0.09''$ (0.6, 0.8 kpc, at $z = 4.5, 2.0$) for the F814W band up to $0.18''$ (1.2, 1.5 kpc, at $z = 4.5, 2.0$) in the F160W band. The pixel scale of the mosaics used in this paper are of $0.03''/\text{pixel}$ for F814W images and $0.06''/\text{pixel}$ for F125W/F160W images.

In addition to the CANDELS observation in ECDFS, there are also publicly available F850LP observations from GEMS (Rix et al., 2004). However, the VUDS pointings were designed to maximize the overlap with the CANDELS area in ECDFS, thus, adding GEMS observations leads only to a small increase in the number of sources in the sample (68 additional sources to the stellar mass selected sample defined in section 3.4.3). For that reason I exclude data from these surveys from the size analysis presented in this thesis. The GOODS survey (Giavalisco et al., 2004) covers a similar area as the CANDELS observations and thus I have opted to not include those images in my analysis since they reach shallower depths and are limited to optical observations providing little added value to my study (see table 3.2).

3.2.2 GROUND OBSERVATIONS

As the multi-wavelength coverage with HST of the large area covered by VUDS is scarce, I also use deep ground based imaging covering the entire VUDS area on the COSMOS field for a control check on the wavelength dependence of my measurements. From the CFHT Legacy Survey (CFHTLS) data release 7¹ I use the deep i' and z' band imaging which reach an 80% completeness limit in AB of 25.4 and 25.0 for point sources, respectively. I use the WIRCam Deep Survey (WIRDS, Bielby et al., 2012) data release 2 covering 1 square degree in COSMOS. The J , H and K_s WIRDS images reach a 50% completeness limit for point sources of 23.4, 24.1 and 24.0 AB magnitudes in COSMOS/VUDS suitable only for the brightest objects in VUDS. Extensive near infrared ground-based imaging is also available on the COSMOS field. The

¹<http://www.cfht.hawaii.edu/Science/CFHTLS/>

Survey	Band	Pixel Scale ["/pix]	PSF FWHM ["]	Sensitivity
COSMOS	I	0.030	~0.09	27.0
CANDELS	I	0.030	0.09	28.4
	J	0.060	0.12	27.0
	H	0.060	0.18	26.9
GEMS	Z	0.030	0.09	27.27
CFHTLS	I	0.186	0.719	26.13
	Y ^a	0.186	0.693	26.20
	Z	0.186	0.657	25.86
MUSYC	BVR	0.267	0.93	26.82
WIRDS	J	0.186	1.09	24.25
	H	0.186	0.86	24.54
	Ks	0.186	0.80	24.32
ULTRA VISTA	Y	0.150	0.82	24.6
	J	0.150	0.79	24.7
	H	0.150	0.76	23.9
	Ks	0.150	0.75	23.7

^aThe Y in this case is not representative of the Y band redwards of the SDSS z band but instead it is the nomenclature of the new I band filter that was installed at MEGAPRIME

Table 3.2. Summary of characteristics of the surveys from which the images were taken. For CFHTLS and WIRDS the sensitivity value represents the 50% completeness limit for point-sources and for the others it represents the 5σ limit detection of point-sources.

UltraVISTA survey covers 1.5 square degree of the field and provides the deepest observations in the near-infrared bands. The Y, J, H and K_s UltraVISTA DR2 images reach 5σ limiting magnitudes of 24.8 (25.4), 24.6 (25.1), 24.7 (24.7) and 23.98 (24.8) AB in the deep (ultra-deep) regions (McCracken et al., 2012) (see also table 3.2).

3.3 METHODS FOR DATA ANALYSIS

Processing a large dataset of spectroscopic observations with automated algorithms is prone to errors in the object identification and attribution of redshifts to a significant number of sources. For the case of the VUDS survey all objects were inspected by at least two people and a double check on the redshift measurements was performed by a team of selected experts to ensure that proper redshifts were provided (see Le Fèvre et al., 2015, section 3.3, for details).

This visual inspection of the data allowed for the identification of bad redshift cases and prompted people to identify new extractions and bad extractions from the automated reduction pipeline and manually adding new spectral traces whenever necessary. One important step of the data reduction of slit spectroscopic observations is to match any given spectral trace to its corresponding photometric counterpart. The tool used to inspect and measure redshifts provided only with the spectroscopic information from the reduced VIMOS data and any image correspondence was done separately using an image search tool centered on the primary target. After the first stage of measurements a small percentage of cases ($\lesssim 10\%$) still had problematic identifications and some cases of spectral pairs, faint or single line emission spectra had yet to be properly handled.

This prompted me to develop a new user interactive tool, the SpectroPhotometric Visualization Tool (SPVT), that simultaneously provided the user with photometric and spectroscopic information and allowed for the real-time correspondence between any position in the VIMOS slit data to a sky position in the imaging data. This tool is fully implemented in PYTHON

using the *tkinter* environment. The main objective of this tool is to look for cases on which the automated pipeline and the manual extraction failed. The main classes of situations to be identified by the user of the tool include:

- **Not Extracted:** when an object is in the slit in addition to what as already been extracted. In this category there are still two subclass of such objects. Faint/Single Line for standard non-extracted objects. Double Spectra for cases where the extraction window encompasses two traces and one wants to re-extract the traces separately.
- **Wrongly Extracted** when the same object is extracted on the wrong place or has a small/large extraction window with respect to what it should be.
- **Wrong Flag/ID** when an object as a wrong redshift reliability flag or ID. This is mainly to address the issue of fake detections/problematic extractions (flags -99,-10,0) but can be used for other cases. If there is a problem with the ID given to the selected extraction a new ID is to be indicated to that particular object without changing the flag.
- **ΔY mismatch:** whenever a re-extraction is to be done, If the 2D joining of the blue and red spectrograms failed to match to a reasonable extent the traces in the red and blue grism, it is noted here the approximate number of pixels between the center of the two traces (always with respect to the blue grism) with positive meaning upward of the trace, and negative meaning downward of the trace.
- **Additional Comments** since, as it is normal for any large dataset, I cannot predict all the possible failures induced by machine or human error, if there is anything strange or interesting that cannot be accounted for with the available options it is possible to type it in the provided box.

3.3.1 PREPARING THE DATA FOR THE INTERFACE

To increase the processing speed of all VUDS observations, several key aspects related to the observations had to be carried out prior setting up a user interface. This includes compiling a list of slit positions, preparing image cutouts from different bands/surveys along with photometric and spectroscopic information that I had in hands.

All VUDS low-resolution observations were taken with a North-East orientation where the spatial coordinate of the imaged slit goes from west to east (from down up) in a corresponding photometric image. To ensure that all slits were positioned correctly I did not use the absolute values for the slit position as reported in the observation files. Instead I used the relative difference in right ascension and declination between the slit center and the primary target position and then applied that offset to the position of the primary target in the photometric parent catalog to obtain a correct slit overlay.

Since the primary selection on the VUDS sample was done with a magnitude limit in the *i* band I have created image stamps for each primary target using both space and ground surveys. Due to memory performance, each ground based image had a total 15'' by 15'' size while HST images had only 10'' by 10''. In case of multiple HST observations (CANDELS vs. COSMOS) it was always the deepest image from CANDELS that was used.

The tool is also accompanied by the photometric magnitude measurements and the VUDS full spectroscopic catalog to provide some general information such as the magnitudes for all identified sources in the image and the spectroscopic measurements for the VUDS targets that have been processed.

This tool then works on a quadrant by quadrant basis, following the data structure of VIMOS observations, to go through all ~ 11000 identified traces, manually or automatically, in the



Figure 3.5. Outlook of the SPVT interface. In the left panel I show general information on the object, user input fields, tools for data handling and navigation. On the right I show the images in photometry, the zoom in of the 2D spectra, sky emission spectra on top of the full 2D spectra and the extracted spectra on the bottom.

2D spectra. Despite being specifically designed to work with VUDS data, the tool is ready to be ported to different surveys once the required information stated above is provided in the requested format.

3.3.2 SPVT GRAPHICAL INTERFACE FEATURES

As with any tool that requires user interaction, there are a number of features that have to be available to make most of the information useful. Below I list some of the most important aspects of the Graphical User Interface (GUI) that I have developed to help tackle the issues with data mis-handling stated in the previous section.

- Slit position overlaid in the image to locate each object in the sky with respect to the actual observed 2D spectra;
- A way of mapping the position in the slit into the position in the photometric image by moving the mouse up and down the 2D spectra;
- A zoom in on the 2D spectrum that follows the movement of the mouse while moving on top of the 2D spectra;
- Entries of the parent photometric catalog overlaid in the images;
- Extraction windows overlaid on the 2D spectra for each spectra that was extracted;
- Direct Visualization of 1D spectra and known lines (with matched wavelength through the source redshift) and possibility for smoothing the 1D spectra;
- Contrast manipulation in the images and 2D spectra;
- Check for entries in the window table and of some columns of the photometric parent catalog;
- Adapt the color schemes to your preferences;
- Quick re-extraction of the 2D spectra for visualization only;
- Quick inspection of the extraction profile for visualization only;

I provide a more detailed description on how to use this capabilities is explained in the following subsections (these are also included in a user manual that was provided for optimum use of the tool) .

3.3.2.1 ADAPTING THE COLOR AND SIZE SCALES

The first tab *Scale Spectra* is meant to let the user have a better control over the contrast on the visualization of the 2D spectra. Setting the minimum and maximum values allows to stretch the color map across the pixels which have number counts in between. The scaling regime can be switched by choosing the appropriate option: linear, logarithmic, squared or root squared. The second tab *Stamp Size* allows the user to adjust the default stamp size to be shown on the interface (default is 4 arcseconds). The changes in the stamp radius and spectral minimum will persist after changing the object displayed.

3.3.2.2 MANIPULATING 1D SPECTRA AND STAMP ORIENTATION

On the bottom left part of the main window you can find some buttons/sliders to adapt the visualization of the 1D spectra. There is also a check button there that allows you to switch the orientation of the image stamps (see bottom left options in figure 4.22). The effect of

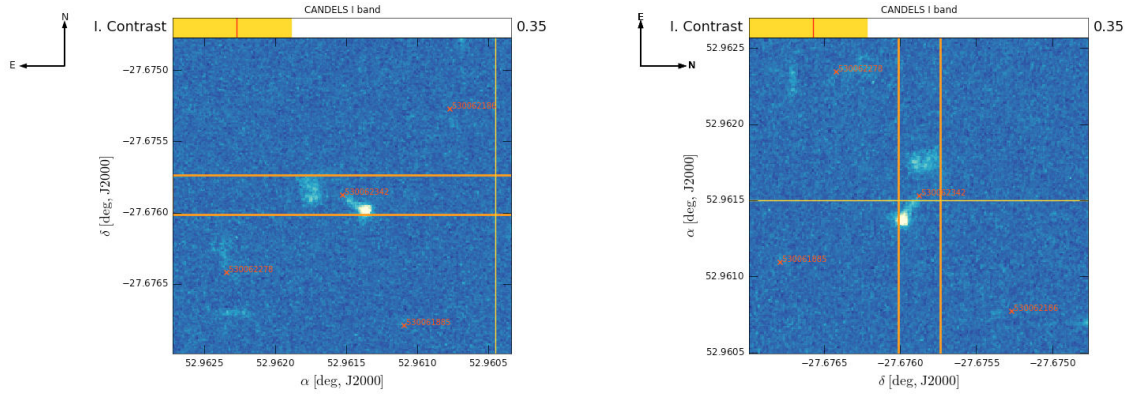


Figure 3.6. Examples of the two possible orientations of the image stamps. Left: the original orientation of standard astronomical image mosaics. Right: Orientation to match the spatial direction of the slit.

rotating the stamps will result on a slit orientation change that matches the one displayed on the 2D spectra (see figure 3.6)

3.3.2.3 TOP LEVEL MENU

File: In here you only have two options. Either open a new seq file from the system dialog or quit the tool saving the results you have checked so far.

Color Management: This menu relates to every color that can be customized inside the GUI. It also has an option to toggle on/off the full-screen. The colors that one can customize include

1. GUI background - This will affect all the backgrounds of the interface (note that for Mac OS X the background of the buttons remains unchanged due to a theme incompatibility).
2. Extraction Line Colors - To change the color of a given extraction line (those overlaid on the 2D spectra) just choose the object number that you prefer. There are up to 5 extraction colors, one per object in the slit. (If there are more than 5 objects in the slit, the extra lines' colors cannot be changed).
3. Slit Rectangle Color - Change the color of the slit
4. Slit Mapper Color - Change the color of the vertical line that connects the 2D spectra to the imaging.
5. Annotations Color - Change the color of the crosses and IDs overlaid in the image (this change affects immediately the color of the IDs but not the color of the crosses, they will change to the chosen color after clicking on any of the navigation buttons)
6. Spectrum Colormap - change the colormap of the 2D spectra. Note that names appended with *_r* correspond to the reversed colormap.
7. Image Colormap - same as the item above but applied to the stamp images.

Scale Management: The two options here correspond to setting a new minimum value for each of the displayed images. A minimum value is that for which all pixels in the image that have lower values than that will be displayed with the first color of the colormap. On each option, a small window will pop up. To update the value, click on the *Update* button, to reset to the original click on the *Reset* button.

Help: Here you can find a link to a manual and some information regarding the version of the tool you are using (by choosing the sub-option *Help* -> *About...*).

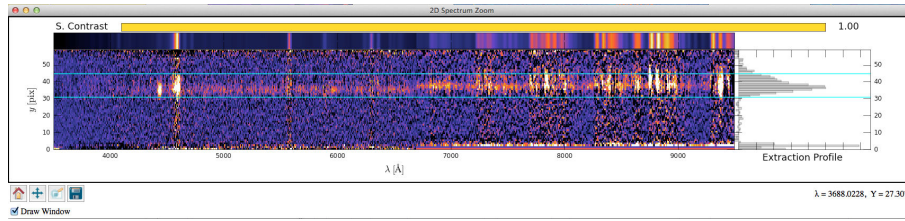


Figure 3.7. Window for close inspection of the 2D spectra. The extraction window is shown on top of the imaged spectrum and the histogram of the collapsed information along the spectral direction is displayed on the right panel.

3.3.2.4 NAVIGATION AND OTHER TOOLS

The displayed graphics can be manipulated in several ways. There are four buttons (right of the *quit* button in figure 4.22). By order of appearance, the function of each button is

1. Home - Restore the original view
2. Pan - move the images/plots around with your mouse when activated
3. Zoom - rectangular zoom defined with the mouse when activated
4. Save - Save current figure to a file

To navigate between objects there are multiple choices available for the user (see bottom left of figure 4.22). The previous and next buttons allow the user to go through each object sequentially. The number of the object currently being displayed on the interface is displayed in between those two buttons alongside the total number of objects of the loaded seq file. To skip to a given object/slit, write the desired number and then click Enter or the associated button. Finally there are additional options that may help the user throughout the process.

The *inspect 2D* button will trigger a new window where one can inspect more closely the 2D spectra (accompanied by the 2D sky spectra) and the extraction profile (see figure 3.7). You can turn on/off the extraction window for the selected object. Note that the extraction profile that is displayed is the sum of each line of the 2D spectra directly. It is to be used with caution if there is not a good enough alignment between the red and blue grism spectra. The *quick extraction* will trigger a new window where one can re-extract (in a very quick manner) the 2D spectra. For that, one as simply to drag the mouse between the desired locations of the beginning and end of the extraction window (see figure 3.8). The extraction window size will be displayed via the cyan lines on top of the 2D spectrum. The re-extracted spectra will be displayed on the bottom panel. You can then adjust the zoom to have a better look at the extracted spectrum.

Then you have the option to open the magnitudes table which is simply a subset of columns of the parent catalog associated with the sources displayed on the stamp file. The columns that are displayed cannot be changed (for now). The last extra option is to open the window table associated with the loaded seq file.

3.3.2.5 DISPLAY RELATED OPTIONS

As for the graphics themselves, besides being able to navigate through them by using the navigation tool bar (see above) it is also possible to change a few other things. There are individual contrast sliders to adjust the level of contrast in each of the displayed images. There is a chance to toggle on/off all the layers (parent catalog, slit, slit mapper, extraction windows, spectral lines) by clicking on the desired check button. There is also an additional

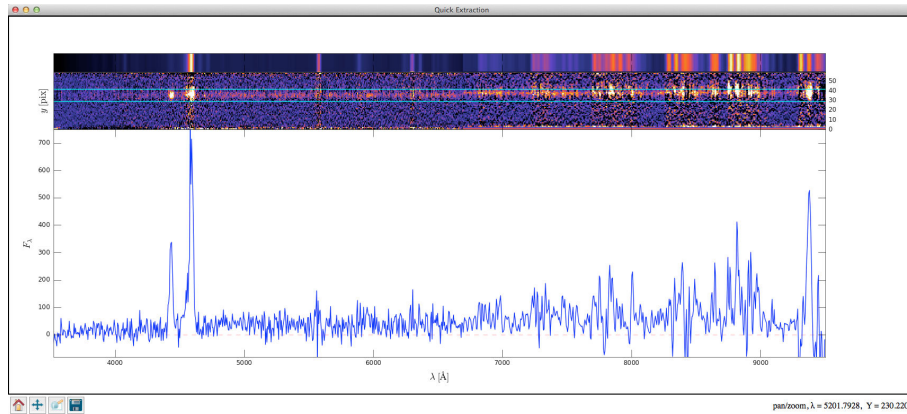


Figure 3.8. Window for interactive extraction of a 1D spectra (bottom panel) from user defined limits in the 2D display (on the top panel)

option to smooth (with a Gaussian filter) the extracted 1D spectra. This can be done by moving along the slider on the bottom left of the graphics window.

3.4 SELECTION FUNCTION

With the knowledge of the spectroscopic redshift, SED fitting was performed on the VUDS sample using Le Phare (Arnouts et al., 1999; Ilbert et al., 2006) applied to the extensive photometric data available in the COSMOS, VVDS2h and ECDFS fields. The SED fitting procedure closely follows the method described in Ilbert et al. (2013), and the specifics for VUDS are detailed in Tasca et al. (2015). To fit the photometric data we use templates derived from Bruzual & Charlot (2003) models and assuming a Chabrier (2003) IMF. To model the star formation histories we use an exponentially declining parameterization $SFR \propto \exp(-t/\tau)$ (τ in the range 0.1 Gyr to 30 Gyr), and an additional two models with delayed SFH peaking at 1 and 3 Gyr. The templates are created for a grid of 51 ages (in the range 0.1 Gyr to 14.5 Gyr). We apply a Calzetti et al. (2000) dust extinction law to the templates, using $E(B - V)$ in the range 0 to 0.5. Models with two different metallicities are used. The two main parameters of interest in this paper are the stellar mass, M_* , and the star formation rate (SFR) for which the median values of the probability density function are used. I refer to Ilbert et al. (2013); Thomas et al. (2016) for typical uncertainties on these quantities (see also Tasca et al., 2015). In summary, I expect a statistical uncertainty of ~ 0.1 dex in stellar masses and of ~ 0.15 dex in SFR. These are relative uncertainties given a set of reference models allowing a quite accurate relative comparison between different populations, but systematic uncertainties coming from a change in the parameter space of reference models (e.g. SFH or IMF) are larger, up to the 0.2-0.3 dex level (e.g. Pforr et al., 2012).

I also use the physical parameters derived from the simultaneous SED fitting of the VUDS spectra and all multi-wavelength photometry available for each galaxy, using the code GOSSIP+ as described by Thomas et al. (2016). This method expands the now classical SED fitting technique to the use of UV rest-frame spectra in addition to photometry, further improving the accuracy of key physical parameter measurements (see Thomas et al., 2016, for details). It also provides measurements of physical quantities such as galaxy ages as well as the IGM transmission along the line of sight of each galaxy, an improvement compared to using a fixed transmission at a given redshift (Thomas et al., 2014).

The sample selection and color correction detailed in section 4.3.5 rely on the parameters derived from LePhare. All the comparisons with physical parameters described throughout this thesis use the results from GOSSIP+. I stress that the results presented in this thesis are

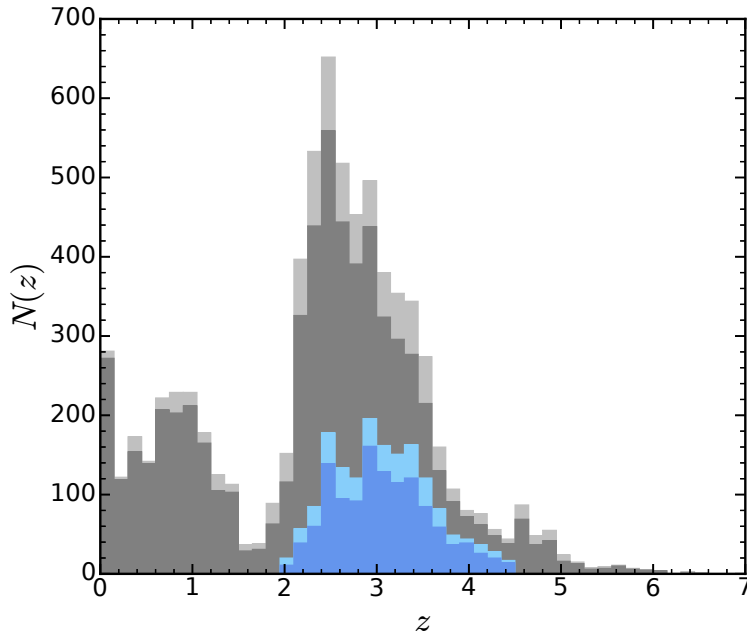


Figure 3.9. The number of galaxies per redshift bin for the entire VUDS sample considering all galaxies with a redshift measurement in light gray and those with a redshift reliability flag corresponding to a $> 75\%$ certainty in dark gray. In blue colors I present the distribution for the COSMOS+ECDFS, stellar mass selected and $2 < z < 4.5$ sample (all flags in light blue and reliable flags in darker blue). The results shown in sections 5.1 and 5.2 are based on the darker blue histogram which contains 1242 galaxies.

robust against the method used to derive the stellar mass selection of my sample.

3.4.1 A SAMPLE WITH RELIABLE REDSHIFTS TO STUDY $\text{Ly-}\alpha$

To conduct a classification on the shape of $\text{Ly-}\alpha$ emission in 2D spectra (see sections 4.6 and 5.4) I selected all galaxies in the VUDS survey for which we have the most reliable redshift measurements, i.e. galaxies with redshift flags 2 and 9 ($\sim 80\%$ probability to be correct), and flags 3 and 4 (95 to 100% probability to be correct). I refer to [Le Fèvre et al. \(2015\)](#) for more details. This constraint led to a total of 4360 galaxies (2100 in COSMOS, 1743 in VVDS and 517 in ECDFS) to be visually inspected for the presence and morphology of the $\text{Ly-}\alpha$ line.

Despite having classifications for the entire sample, I restrict the interpretation of my results to a stellar-mass selected sub-sample with $\log_{10}(M_{\star}/M_{\odot}) > 9.5$.

3.4.2 HIGH IMAGE RESOLUTION SAMPLE TO STUDY GALAXY MORPHOLOGY AT HIGH REDSHIFT

To conduct a morphological classification of high-redshift sources (see sections 4.5 and 5.3) I restrict the classifications to galaxies in the COSMOS and ECDFS fields where images from HST are available (see e.g. section 3.2). This corresponds to a total of 2506 galaxies with reliable spectroscopic redshifts of which 2100 are in COSMOS and 406 are in ECDFS.

Despite having classifications for a larger sample, I restrict the interpretation of my results to a stellar-mass selected sub-sample with $\log_{10}(M_{\star}/M_{\odot}) > 9.5$.

3.4.3 A STELLAR MASS-SELECTED SUB-SAMPLE

To follow the evolution of galaxy sizes in a similar population as a function of redshift, I define the sample by imposing an evolving lower stellar mass limit. This choice implies that stellar masses of galaxy populations at different redshifts follow the general stellar mass growth of star-forming galaxies, broadly representing the same coeval population. With this simple evolving stellar mass cut one could possibly miss galaxies if their properties make them fall out from the VUDS selection function, i.e. if galaxies selected at the high redshift end of my sample become quiescent by the time they reach $z \sim 2$. The average size I report would then be biased against these galaxies at the lower redshift end of the survey. The other possible choice that could be made is to opt for a constant stellar mass limit at all redshifts. In this condition, the sample would contain more lower stellar mass star-forming galaxies at lower redshifts. If the stellar mass-size relation is not evolving with redshift (see e.g. [van der Wel et al., 2014](#); [Morishita et al., 2014](#)) then this would add galaxies with lower sizes in the lower redshift bins of my study, complicating the comparisons of size distributions. I define a lower stellar mass limit in my sample anchored at $z = 4.5$ as $\log_{10}(M_{\star}/M_{\odot}) > 9.35$ (below which the VUDS sampling drops). I then use the stellar mass function evolution from [Ilbert et al. \(2013\)](#) together with the typical sSFR of VUDS galaxies ([Tasca et al., 2015](#)) to follow the typical stellar mass growth of VUDS galaxies, and define the stellar mass selection threshold at different redshifts using

$$\log_{10}(M_{\star}/M_{\odot}) > -0.204(z - 4.5) + 9.35. \quad (3.1)$$

In figure 3.9 one can see the redshift distribution of the entire VUDS sample and that of the stellar mass-selected sample in the redshift range considered defined for the purpose of this study. Such selection translates into 1645 galaxies in the COSMOS and ECDFS fields with a spectroscopic redshift measurements and with stellar masses obeying equation 3.1 of which 1242 have spectroscopic redshift flags that have a reliability of $> 75\%$ (flags X2,X3,X4 and X9 with X=0,1,2 see [Le Fèvre et al., 2015](#), for more details).

I show the stellar mass-SFR relation of my sample divided in four redshift bins in figure 3.10. It shows that my sample probes galaxies with typical median stellar masses of $10^{10}M_{\odot}$ and ranging from $\log_{10}(M_{\star}/M_{\odot}) \gtrsim 9.35$ and up to $10^{11}M_{\odot}$. In terms of SFR, galaxies are in the range $0.5 \lesssim \log_{10}(SFR) \lesssim 3.0$ at all redshifts with median values of $\log_{10}(SFR) \sim 1.4$.

To further characterize my galaxy population I plot in figure 3.11 the position of each galaxy with respect to the quiescent region as defined in [Ilbert et al. \(2013\)](#). The lack of galaxies in the upper right part of the panels in the NUVrJ diagram indicates that I am missing dusty star-forming galaxies. I also lack the quiescent population (only 4 galaxies fall in the quiescent region of the diagram). This confirms that my sample is probing the bulk of the massive, low dust star-forming population at the redshifts considered.

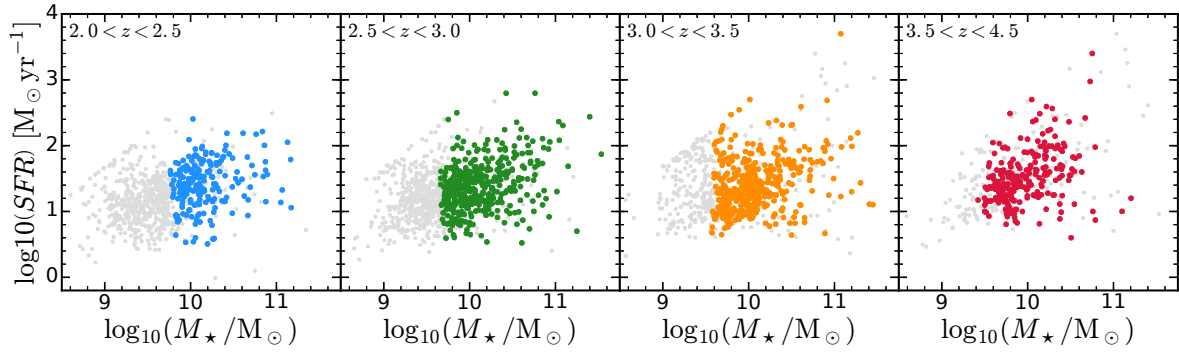


Figure 3.10. Range in stellar masses and SFRs for the sample studied in sections 4.5 and 5.3. In each panel, the light gray points refer to the entire VUDS sample in each redshift bin. The colored points represent each of the 1242 galaxies in the selected stellar mass range and with reliable spectroscopic flags (correct redshift probability of $> 75\%$, see text for more details).

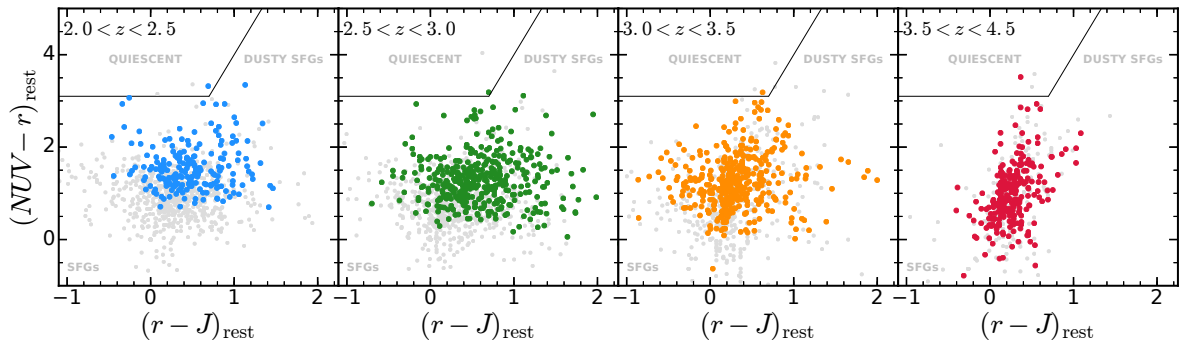


Figure 3.11. NUVrJ diagram (Ilbert et al., 2010, 2013) for the sample studied in sections 4.5 and 5.3 in different redshift bins. In each panel the colors have the same meaning as in figure 3.10.

4 | A quantitative approach to galaxy morphology at $2 < z \lesssim 5$

Contents

4.1	Parametric Fitting	40
4.1.1	The Sérsic profile	40
4.1.2	Generation of 2D images from models	41
4.1.3	GALFIT	42
4.1.4	PSF construction	43
4.1.5	Masking bad pixels	43
4.1.6	Image Simulations	43
4.2	Non-Parametric Fitting	45
4.2.1	The Petrosian Radius.	45
4.2.2	CAS	46
4.2.3	Gini- M_{20}	48
4.2.4	$T\Psi$	51
4.2.5	MID	53
4.2.6	Others	54
4.3	Beyond symmetric models for size estimates	55
4.3.1	Total extent of galaxies	56
4.3.2	Cosmological dimming and Luminosity Evolution	57
4.3.3	Detection threshold	59
4.3.4	Correcting for PSF broadening	61
4.3.5	Dependency with color	61
4.3.6	Correcting for sky pixels detection	61
4.3.7	T_{100} in simulated galaxies	63
4.4	A search for high-redshift clumps	63
4.4.1	Isophotal threshold	65
4.4.2	Resulting clumps counts	66
4.4.3	Luminosity and Sizes	66
4.4.4	False clump detections	70
4.4.5	Morphological k-correction	70
4.5	Visual Classification	70
4.5.1	Morphological classes	72
4.5.2	Classification procedure	76
4.6	Classifying the Ly- α emission in 2D spectrograms	76
4.6.1	Classification procedure	77
4.6.2	Dependency of the classification on the flux limit and geometry of the spectrograms	78

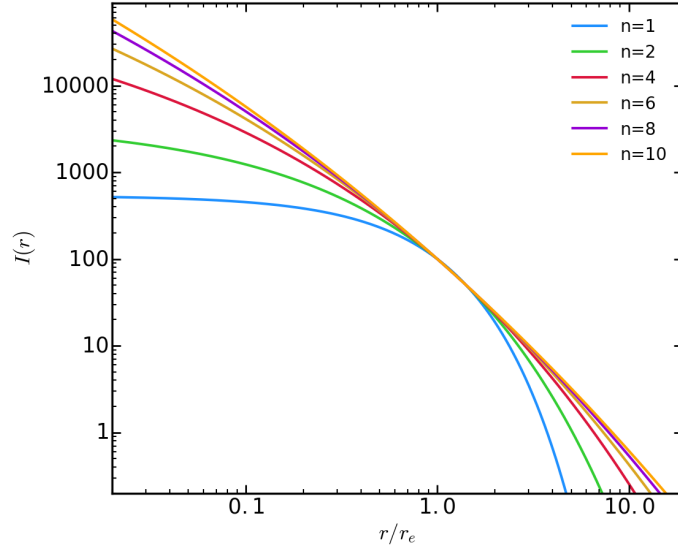


Figure 4.1. Sérsic profiles for several values of n with fixed central intensity and effective radius.

4.1 PARAMETRIC FITTING

One of the most widespread ways of measuring galaxy sizes at all redshifts is by parameterizing their surface brightness profiles with a given functional form (e.g. [Simard et al., 1999](#); [Peng et al., 2002](#); [Ravindranath et al., 2004](#); [Daddi et al., 2005](#); [Ravindranath et al., 2006](#); [Trujillo et al., 2006c](#); [Akiyama et al., 2008](#); [Franx et al., 2008](#); [Cassata et al., 2010](#); [Williams et al., 2010](#); [Mosleh et al., 2011](#); [Cassata et al., 2013](#); [Huang et al., 2013](#); [Morishita et al., 2014](#); [van der Wel et al., 2014](#); [Straatman et al., 2015](#); [Shibuya et al., 2015](#)). One common parametrization used for studying galaxy morphology both at low and high redshift is the [Sérsic \(1968\)](#) profile which is generally described in the next section.

4.1.1 THE SÉRSIC PROFILE

This profile is characterized by the functional form

$$I(r) = I_e \exp[-\kappa(r/r_e)^{1/n} + \kappa] \quad (4.1)$$

where the Sérsic index n describes the shape of the light profile, r_e is the effective radius of the profile, I_e is the surface brightness at radius $r = r_e$ and κ is a parameter coupled to n (see for example [Ciotti & Bertin 1999](#)) such that half of the total flux is enclosed within r_e . An index of $n = 1$ corresponds to a typical pure disk galaxy, whereas $n = 4$ corresponds to the de Vaucouleurs profile associated to elliptical galaxies. On 2D images, each Sérsic model has potentially seven free parameters: the position of the center, given by x_c and y_c , the total magnitude of the model, m_{tot} , the effective radius, r_e , the Sérsic index, n , the axis ratio of the ellipse, b/a and the position angle, θ_{PA} , which refers to the angle between the major axis of the ellipse and the vertical axis and has the sole purpose of rotating the model to match the galaxy's image.

The projected intensity within a region S is defined as the surface integral:

$$F(S) = \int_S I(\vec{r}) dS \quad (4.2)$$

Since the light profile has only a dependence in the distance to the center it is convenient to express this integral in terms of polar coordinates where $dS = r dr d\theta$. Thus, for a given

circular aperture, the flux of the object is

$$F(< r) = \int_0^{2\pi} d\theta \int_0^r I(r') r' dr' = 2\pi I_0 \int_0^r \exp[-\kappa(r'/r_e)^{1/n} + \kappa] r' dr', \quad (4.3)$$

which can be written in terms of the incomplete left gamma function (see [Ciotti & Bertin 1999](#)):

$$F(< r) = \frac{2\pi n}{\kappa^{2n}} I_e e^{\kappa} r_e^2 \gamma \left(2n, \kappa \left[\frac{r}{r_e} \right]^{1/n} \right), \quad (4.4)$$

where

$$\gamma \left(2n, \kappa \left[\frac{r}{r_e} \right]^{1/n} \right) = \int_0^{\kappa \left[\frac{r}{r_e} \right]^{1/n}} e^{-t} t^{2n-1} dt. \quad (4.5)$$

That becomes, for $r = \infty$, the total flux of the galaxy

$$F_{tot} = \frac{2\pi n}{\kappa^{2n}} I_e e^{\kappa} r_e^2 \Gamma(2n), \quad \Gamma(2n) = \gamma(2n, \infty). \quad (4.6)$$

Imposing the condition that the effective radius is that for which the flux within is equal to half of the total flux I get

$$F(< r_e) = \frac{F_{tot}}{2} \Leftrightarrow \gamma(2n, \kappa) = \frac{\Gamma(2n)}{2} / \quad (4.7)$$

Therefore, I can now get the value of κ for a given n by inverting the equation

$$\kappa = \gamma^{-1} \left(2n, \frac{\Gamma(2n)}{2} \right). \quad (4.8)$$

[Ciotti & Bertin \(1999\)](#) derived an approximation for this last expression that performs very well for values of n from 1 up to 10

$$\kappa \approx 2n - \frac{1}{3} + \frac{4}{405n} + \frac{46}{25515n^2}, \quad (4.9)$$

which can be compared to the solution of equation (4.8) computed numerically in this work using the implementation of Γ -related functions from the package *scipy.special*. The comparison of the obtained values may be seen in figure 4.2. It is noticeable the rapid rise on the absolute relative error for values of $n < 1$. As for the performance, the evaluation of the analytical expression takes ≈ 0.03 milliseconds in an 3.5GHz Intel Core i7 processor with 16GB of RAM, which amounts to 15% of the time to compute the numerical solution (≈ 0.2 milliseconds).

4.1.2 GENERATION OF 2D IMAGES FROM MODELS

For testing purposes I devised an algorithm to generate 2D images from one-dimensional surface brightness profiles. The first step to perform this method consists on creating a model galaxy based on the set of morphological parameters necessary: $xc, yc, I_0, r_e, q, \theta$. To do so, first one has to compute the distance to the galaxy center based on the ellipse equation (normalized to the major axis).

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = \frac{r^2}{a^2} \quad (4.10)$$

where a and b are the major and minor axis respectively. However, in order to reproduce a ellipse not centered at the origin and with the axis of the ellipse rotated with respect to the

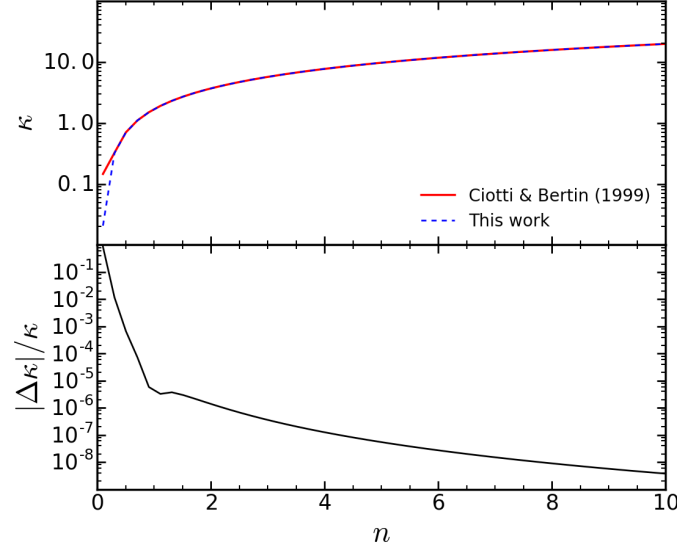


Figure 4.2. Comparison of the exact (numerical) solution of equation (4.8) to the expression by Ciotti & Bertin (1999).

coordinate system I have to perform two transformations: a translation between the coordinate system origin and the galaxy center and a rotation around the center of the galaxy of the given angle θ . That is performed by the set of equations:

$$x_{rt} = (x - x_c) \cos(\theta) - (y - y_c) \sin(\theta) \quad (4.11)$$

$$y_{rt} = (x - x_c) \sin(\theta) + (y - y_c) \cos(\theta) \quad (4.12)$$

Now, the distance to the center of the galaxy in this new coordinate system (in elliptical form) is simply

$$r = \sqrt{x_{rt}^2 + \frac{y_{rt}^2}{q^2}} \quad (4.13)$$

where $q = b/a$. Using this definition of r in equation (4.1) I can generate a 2D model of the galaxy from the set of parameters given. With the created image now one can convolve with an instrumental PSF and add a noise image to create a realistic observation of the profile.

4.1.3 GALFIT

To measure the effective radius of my objects I use the 2D surface brightness fitting tool GALFIT (Peng et al., 2002, 2010). For each galaxy I choose to fit a single Sérsic profile with no constraint in the parameters. To remove the effect of the ellipticity of each source, the final size value as measured from GALFIT is computed as the circularized radius via

$$r_{e,circ} = r_e \sqrt{q}, \quad (4.14)$$

where q is the axis ratio (b/a) of the elliptical isophotes that best fit the galaxy. In this sense, a comparison with r_T defined in section 4.3.1 is also more immediate, as both are circularized forms of size measurements. The initial parameters were retrieved from running SExtractor (Bertin & Arnouts, 1996).

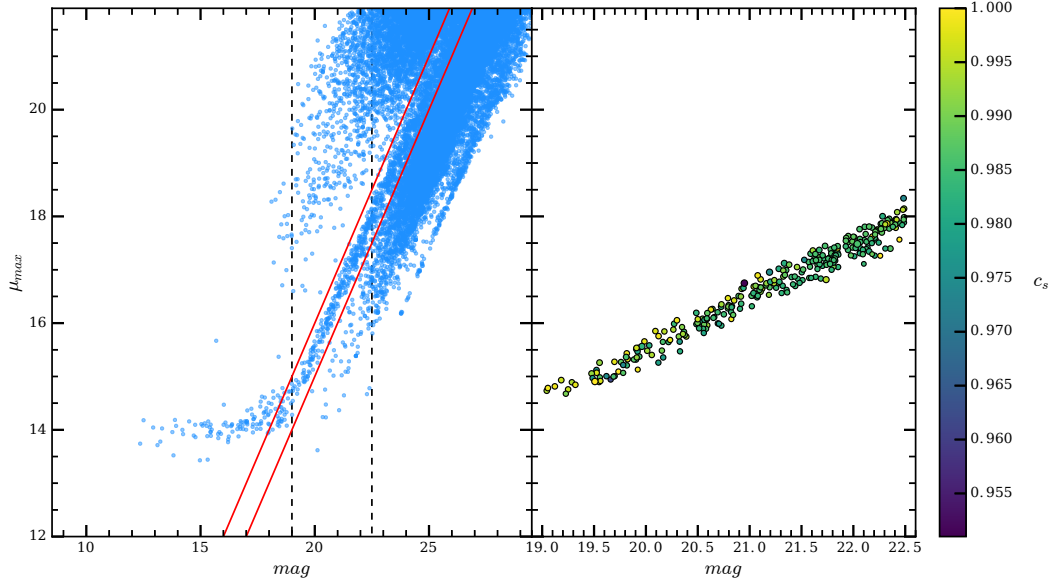


Figure 4.3. A pre-selection on the sources to be considered as stars for PSF construction. On the left panel I show the full distribution (in blue points) of all sources detected in the image with SExtractor. The red and black lines delimit the region from which the candidates are selected. On the right I show the selected candidates color coded with the class star parameter from SExtractor which is to be 1 for point sources and 0 for extended sources.

4.1.4 PSF CONSTRUCTION

In order to provide accurate size measurements it is crucial to have a good image representing the point spread function (PSF) of the data. For that purpose a list of individual, bright, non-saturated, field stars were pre-selected based on their position in the stellar locus of the $\mu_{\max} - \text{mag}$ diagram (see figure 4.3). This procedure was applied to all the CANDELS, UltraVISTA and CFHTLS mosaic images. Then, I selected by visual inspection the stars to be used for the stack. Thus, I built a high S/N image of the PSF for each image by stacking ~ 40 stars in each CANDELS field. For COSMOS I have used the models built with *TinyTim*¹ described in Rhodes et al. (2007).

4.1.5 MASKING BAD PIXELS

For space based imaging, I fed GALFIT with $6'' \times 6''$ image cutouts around the galaxy. As for the masking procedure, I used the segmentation map produced by SExtractor and flagged all companion objects for which all pixels associated with it are at a distance greater than $1''$ of the VUDS target. The flagged pixels are not taken into account when doing the χ^2 fitting by GALFIT. Based on deep galaxy counts (Capak et al., 2007) I estimate the fraction of companions at a distance smaller than $1''$ and brighter than $i_{\text{AB}} = 25.5$ is 6%. This reassures us that I am getting size measurements for sources that fall within the slits, i.e. it is unlikely that GALFIT will lock on a companion object.

4.1.6 IMAGE SIMULATIONS

Simulations of 15 000 galaxies using GALFIT Sérsic profiles convolved with the observed PSF are performed to test the reliability of the obtained values for the effective radius of the galaxies in the sample. To do so, I use the computed SExtractor source catalog to select

¹<http://www.stsci.edu/hst/observatory/focus/TinyTim>

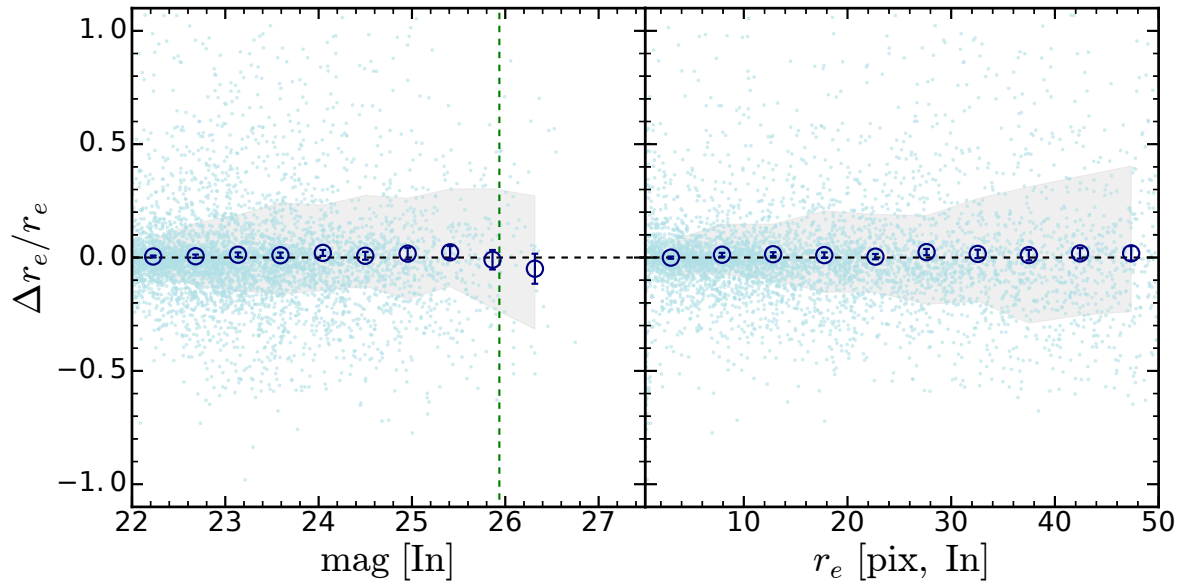


Figure 4.4. Variance of the value of r_e for a set of 15 000 galaxies as a function of input magnitude (left) and effective radii (right). Only galaxies where GALFIT convergence was attained are included in this figure. The large dark blue points represent the median sizes per bin, the error bar in the y-axis is $\sigma/\sqrt{N}$. The shaded region delimits the 16th and 84th percentiles and includes 68% of the sample of each bin.

Table 4.1. Interval of simulated values of artificial galaxies. All parameters were randomly selected from a uniform distribution within the reported range.

mag	r_e [pixel]	n	q	θ_{PA} [degrees]
22 - 27	0.5 - 30	0.5 - 10	0.1 - 1.0	-90 - 90

200×200 pixel sky regions on which the simulated galaxies are dropped. The sky regions are randomly selected so that I do not introduce artificial bias by using hand picked regions. However, since the selection of pure sky regions in a random way is very time consuming a method is devised to select the required size regions in a faster way while still taking cautions not to overlap simulated and real sources and to avoid bright sources within the region. This method selects random regions where: there are no pixel detections within a 50 pixel radius from the center of the sky region; the neighboring sources allowed in the stamp image must not be brighter than 20 mag; the number of SExtractor detected sources within the stamp is limited to 10; all pixels have a non-zero value. Then the simulated galaxies have Sérsic profiles that are randomly generated from a set of values drawn from uniform distributions in the intervals defined in table 4.1. The profiles are subsequently convolved with the PSF and dropped on extracted regions. Finally all the simulated objects are fed onto the same pipeline as the real images to get their output parameters from GALFIT. The results of these simulations (see figure 4.4) show that one can retrieve the input effective radius value within 10-20% for 68% of the simulated galaxies that have a total magnitude $\lesssim 25$. There is also a slight trend with the input effective radii in the sense that galaxies with higher input r_e tend to have slightly higher dispersion (up to $\sim 20 - 30\%$) of the difference one gets. I note however that 93% of the galaxies in my sample have measured radii smaller than 20 pixels for which I obtain a radius within $\sim 15\%$ of the input value. I have tested this simulation by using different background images from which to extract the sky regions (COSMOS F814W tiles and CANDELS F814W, F125W, F160W mosaics) and found no significant differences in the simulation results. Similar conclusions were found by, e.g. Mosleh et al. (2011); Morishita et al. (2014).

An additional test is carried out to test the robustness of GALFIT results against the choice of

first guess parameters. In this case, for each galaxy, I run GALFIT fifty times, each of which with a set of Gaussian randomly deviated values centered on the SExtractor input guesses and with widths that include at least a 50% deviation from the input value within 1σ . I then compare the median value of the fifty runs with the results from the single run with SExtractor first guesses and find that no more than $\sim 9\%$ of the galaxies for which GALFIT converge have median values offset by more than 3σ and that most of the galaxies ($\sim 90\%$) are within 1σ . The outliers tend to happen for cases where GALFIT does not converge for one or more of the fifty tries. Nonetheless, the majority of the galaxies for which I have GALFIT results (around $\sim 74\%$) allow the convergence more than 40 (out of 50) times.

4.2 NON-PARAMETRIC FITTING

In this section I will detail the implementation of non-parametric measurements that have been defined in the literature in the past years and for which I have developed a comprehensive algorithm that computes all the described quantities for a faint galaxy population.

4.2.1 THE PETROSIAN RADIUS.

This radius, (Petrosian, 1976), is defined as the distance for which the ratio between the surface brightness at that radius and the average surface brightness within that aperture is equal to a fixed value η (usually taken as $\eta = 0.2$)

$$\eta = \frac{I(r)}{\langle I(< r) \rangle}. \quad (4.15)$$

It is straightforward to note that the average surface brightness within a certain circular aperture can be derived from the total flux on that aperture divided by its area:

$$\langle I(< r) \rangle = \frac{F(< r)}{\pi r^2}. \quad (4.16)$$

For the sake of clarity I will define a new variable

$$u = \kappa \left(\frac{r}{r_e} \right)^{1/n}. \quad (4.17)$$

Now, with the help of equations (4.4) and (4.17) I can write equation (4.16) as

$$\langle I(< r) \rangle = \frac{1}{\pi r^2} \frac{2\pi n}{\kappa^{2n}} I_e e^{\kappa} r_e^2 \gamma(2n, u) = I_e e^{\kappa} \frac{2n}{\kappa^{2n}} \left(\frac{r_e}{r} \right)^2 \gamma(2n, u). \quad (4.18)$$

Using now the surface brightness equation for a Sérsic profile - equation (4.1) - η is described by

$$\eta(r) = \frac{\kappa^{2n}}{2n} \left(\frac{r}{r_e} \right)^2 \frac{e^{-u}}{\gamma(2n, u)}. \quad (4.19)$$

For the computation of the petrosian radius on a 2D image, G , of a given object I take advantage of the distance definition in elliptical form to construct a distance matrix R where each entry $[i, j]$ is computed from equation (4.13). Then I determine η using the methods

$$I(r_k) = \frac{1}{N} \sum_{i,j} G_{i,j}, \text{ if } 0.9r_k \leq R_{i,j} \leq 1.1r_k, \quad (4.20)$$

where N is the number of pixels that enter the computation of $I(r)$, and

$$\langle I(< r_k) \rangle = \frac{1}{N} \sum_{i,j} G_{i,j}, \text{ if } R_{i,j} \leq r_k, \quad (4.21)$$

and then, by iterating over increasing values of r_k until the value of $\eta = 0.2$ is reached, I get the numerical value of r_p .

4.2.2 CAS

THE CONCENTRATION PARAMETER

This parameter, designed to measure the light concentration of a galaxy and studied by several authors (e.g. [Abraham et al. 1994](#), [Bershady et al. 2000](#), [Conselice 2003](#)) is defined in terms of the ratio of the radii at which the flux within reaches specific values in terms of the total flux. The case adopted here follows the definition of [Conselice \(2003\)](#)

$$C = 5 \log_{10} \left(\frac{r_{20}}{r_{80}} \right), \quad (4.22)$$

where r_α is the radius which encloses a flux $F(< r_\alpha) = (\alpha/100)F(< 1.5r_p)$. The amount of flux above the defined threshold at $1.5r_p$ is dependent on the Sérsic index, and is higher in the case of the exponential disk than that of the classical bulge profile.

To compute C from a given 2D image one defines the flux within a given radius r_k as:

$$F(< r_k) = \sum_{i,j} G_{i,j}, \text{ if } R_{i,j} \leq r_k, \quad (4.23)$$

where R as the same meaning as before (in the determination of the petrosian radius). With that algorithm I then iterate over increasing values of r_k until I reach the predefined values of 20% and 80% of the total flux within $1.5r_p$.

To test the recovery of the value of the concentration parameter I generated 200 galaxies with linearly spaced values of n ranging from 1 to 8 for three distinct values of $r_e = 10, 20$ and 30 pixel giving a total of 600 test galaxies. Then I computed the concentration parameter using a step of $\Delta r_k = 0.05$ pixel for both the petrosian radius and the Concentration determination. The results are displayed on figure 4.5. One can see that the retrieved value of C depends not only on n , as expected from the analytical solution, but also on the value of r_e . Models with lower values of r_e tend to depart from the true value at lower values of n (left panel, figure 4.5). That figure also presents two kinds of plateaus: one of constant values of C which corresponds to the case where r_{20} and r_{80} are constant with n (thus their relative error increases as seen in the right panel of figure 4.5) and another where C is decreasing with n that happens when only r_{20} is constant with n but r_{80} decreases with n . In addition to these plateaus, there is also a systematic increase in the relative error of both r_{20} and r_{80} with n . The case of r_{20} is worse since it becomes very small for increasing values of n (for example, in the case of $r_e = 10$, r_{20} becomes smaller than two pixels at $n \approx 4$ and smaller than one pixel at $n \approx 7$).

THE ASYMMETRY PARAMETER

The asymmetry index is based on the subtraction of a given galaxy image by its rotation of 180 degrees and then sum all the intensities of the subtraction map as compared to the total intensity of the original image. This parameter measures the amount of non-asymmetric

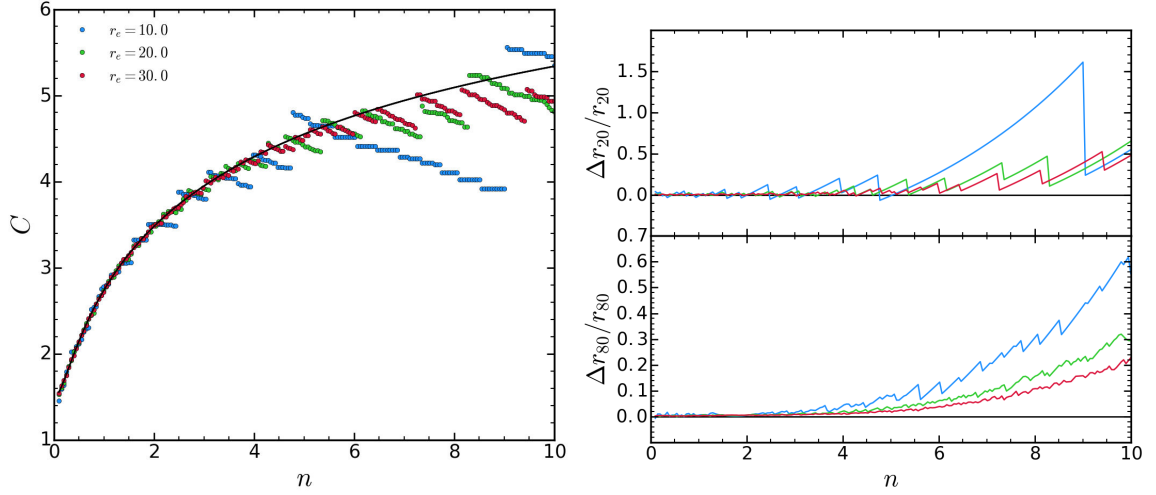


Figure 4.5. The values of the concentration parameter (left) as a function of Sérsic index for the simulated galaxies (filled circles). The analytical values are plotted as the solid curves. The relative errors on the radii that are used to compute C are shown in the right panel.

features an object has and so it is a proxy for the star formation and merger activities. In practice it is computed via (Conselice et al., 2000; Conselice, 2003; Lotz et al., 2004)

$$A = \frac{\sum_{i,j} |I_{i,j} - I_{i,j}^{180}|}{\sum_{i,j} I_{i,j}} - B_{180}, \quad (4.24)$$

where $I_{i,j}$ is the intensity at the pixel (i,j), the 180 index denotes the rotated image intensities, and B_{180} is the total intensity of the background asymmetries. The center definition around which the image is rotated is a very important set to define as the final value of A strongly depends on the definition of the galaxy center. Due to this factor, Conselice et al. (2000) devised a way to disregard a fixed center definition that might influence the posterior analysis. This method consists in computing the asymmetry index using the center for which A is of minimum value. The minimization consists in computing the value of A in a sub-region of pixels and select the pixel for which the value of A is minimal. Then I define a new region centered on that pixel and compute the values of A on the new adjacent pixels. The procedure is repeated until the center of the sub-region has the minimum value of A . This method may be trapped in a local minimum or in a constant valued region. To prevent that from happening one defines the size of the sub-region to be big enough to allow jumps between two different local minimum if they exist. Of course that it is a compromise between computation time (as to compute the value of A for every pixel is very time-consuming) and the recovery of the true value A . Nevertheless, if the starting pixel position is close to the center of the object, these effects are largely minimized and one can choose a fast small region to compute the minimum value of A .

To test the recuperation of the true value of A one image with two non-intersecting shapes with the same constant intensity value is generated. From that image is possible to define the analytical value of the asymmetry as:

$$A = \frac{2|A_1 - A_2|}{A_1 + A_2} \quad (4.25)$$

where A_1 and A_2 are the area values of each of the intervening shapes. From a set of 1000 combinations of two shapes chosen from circles, ellipses, squares and rectangles with randomly selected integer sizes (between 40 and 50) I recovered the true value of A for most of the cases (see figure 4.6). The interval of sizes chosen is to prevent that a combination between a big

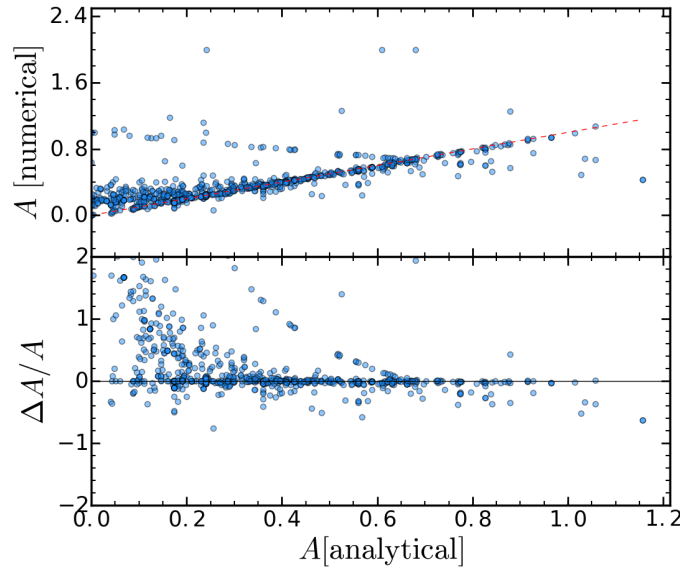


Figure 4.6. Comparison between input and output values of A from shape simulations.

and a small shape would result in a mis-computation of A in its analytical form since it would be favored the case of a rotation of the biggest shape over itself. The discretization of the values of A observed are a direct result of the constraints on the shape generation (from a limited set of integer sizes).

THE CLUMPINESS PARAMETER

This parameter measures the amount of clumps a given object possesses by analyzing high frequency variations within an image. To do so, it firsts performs a convolution of the original image with a smooth kernel (usually a Gaussian with parameter σ) and then subtract it to the original Image. The aftermath of this operation is a residual map with high frequency components of the object in study. The index S is then computed via (Conselice, 2003)

$$S = 10 \times \frac{\sum_{i,j} (I_{i,j} - I_{i,j}^{\sigma}) - B_{i,j}}{\sum_{i,j} I_{i,j}}, \quad (4.26)$$

where the indices have the same meaning as before.

4.2.3 GINI- M_{20}

THE GINI PARAMETER

This morphological coefficient based on an economic curve devised by Lorenz (1905) used to describe the wealth distribution among a certain population was first applied to astronomy by (Abraham et al., 2003). In its astronomical use, it is a measure of the flux is distributed among the pixels that belong to a galaxy. In its mathematical form it is written as

$$L(p) = \frac{1}{\bar{X}} \int_0^p F^{-1}(u) du, \quad (4.27)$$

where $L(p)$ is the integral of the cumulative distribution function $F(x)$ up to the percentage p of the fainter pixels normalized to the mean pixel flux, $\bar{X}$. The Gini coefficient is the ratio of the curve defined by $L(p)$ and the equality curve $L(p) = p$. For an analytical Sérsic profile the

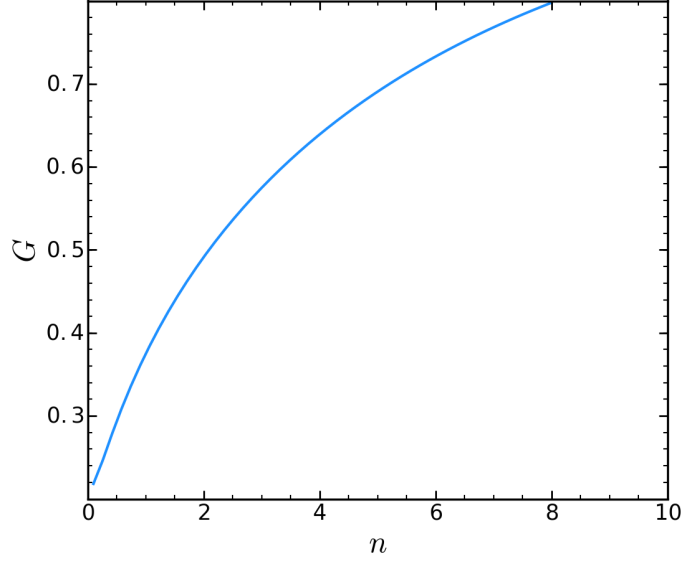


Figure 4.7. The n dependence of the Gini coefficient.

cumulative distribution function as also an analytical form given by equation (4.4). However, there is no simple way to define the inverse ($r(F)$) of that function in terms of an analytical form. Nonetheless it is easy to construct such a function using root finding techniques applied to

$$F(< r) - F_i = 0, \quad (4.28)$$

which, for any given value of F_i , returns the value of r corresponding to that flux thus providing a simple way of knowing $r(F)$. With this in hands one can perform the computation of the Lorenz curve for the given profile and then compute the Gini coefficient as

$$G = \frac{\int_0^p p' dp' - \int_0^p L(p') dp'}{\int_0^p p' dp'}, \quad (4.29)$$

but, since $\int_0^p p' dp' = 1/2$ this simplifies to

$$G = 1 - 2 \int_0^p L(p') dp'. \quad (4.30)$$

Performing this evaluation for different Sérsic profiles it is possible to establish a direct relation between G and n that can be seen in figure 4.7 and which, as expected, relates high values of n to high values of G since profiles with greater values of Sérsic index are steeper and thus concentrate their light in a smaller area thus increasing the computed value of G .

In a discrete population (such as a discrete sampling of a galaxy profile in a pixel grid) it can be computed as

$$G = \frac{1}{2\bar{X}n(n-1)} \sum_{i,j}^n |X_i - X_j|, \quad (4.31)$$

where n is the number of pixels of the galaxy. $G = 0$ if all the pixels have the same nonzero flux and $G = 1$ if all the flux is contained in one pixel. An efficient way to compute this coefficient is to first sort the pixels of the galaxy in increasing order of flux and then compute simply

$$G = \frac{1}{\bar{X}n(n-1)} \sum_i^n (2i - n - 1)X_i. \quad (4.32)$$

Due to the scattering of low surface brightness pixels below the sky level (negative values of flux) it is applied a first order correction by computing the Gini coefficient based on the absolute values of the flux at each pixel.

THE M_{20} PARAMETER

The light moments of t -th order of any surface brightness profile distribution are given by

$$M_t(r) = \int_S r^t I(r) dS = 2\pi \int_0^r (r')^{t+1} I(r') dr'. \quad (4.33)$$

Each moment has its own simple definition. For instance, for $t = 0$ we have the cumulative flux distribution given in equation (4.4). This integral is a generalization of that one and can be seen as

$$M_t(r) = 2\pi I_e e^\kappa \left(\frac{r_e}{\kappa^n} \right)^{t+2} \gamma \left((t+2)n, \kappa \left[\frac{r}{r_e} \right]^{1/n} \right). \quad (4.34)$$

The second-order light moment of the profile, hereafter named simply M , is that for which $t = 2$. Then, the total second order moment of light is simply the integral up to $r = \infty$ and is given by

$$M_{tot} = 2\pi I_e e^\kappa \left(\frac{r_e}{\kappa^n} \right)^4 \Gamma(4n). \quad (4.35)$$

It is also easy to see that, using r_{20} as the radius for which one has enclosed 20% of the total galaxy flux, that $M(r_{20})$ is given by

$$M(r_{20}) = 2\pi I_e e^\kappa \left(\frac{r_e}{\kappa^n} \right)^4 \gamma \left(4n, \kappa \left[\frac{r_{20}}{r_e} \right]^{1/n} \right), \quad (4.36)$$

leading to the wanted M_{20} statistic being computed in terms of γ -related functions:

$$M_{20} = \log_{10} \left(\frac{M(r_{20})}{M_{tot}} \right) = \log_{10} \left(\frac{\gamma \left(4n, \kappa \left[\frac{r_{20}}{r_e} \right]^{1/n} \right)}{\Gamma(4n)} \right), \quad (4.37)$$

which is a decreasing function of n (see figure 4.8).

In its discrete form, the total second order moment M_{tot} is the flux in each pixel I_i multiplied by the squared distance to the center of the galaxy, summed over all the galaxy pixels assigned by the segmentation map. The center of the galaxy is that which minimizes M_{tot}

$$M_{tot} = \sum_i^n I_i [(x_i - x_c)^2 + (y_i - y_c)^2]. \quad (4.38)$$

Then, M_{20} can be defined as when computed for a intensity sorted values in a descending order:

$$M_{20} = \log_{10} \left(\frac{\sum_i^n I_i [(x_i - x_c)^2 + (y_i - y_c)^2]}{M_{tot}} \right), \quad \text{while } I_i < 0.2 I_{tot}, \quad (4.39)$$

where I_{tot} is the total flux of the galaxy within the segmentation map. The normalization by M_{tot} is done so that there is no dependence of this parameter either on galaxy size or total flux and so galaxies from different types can be compared with one another. The main

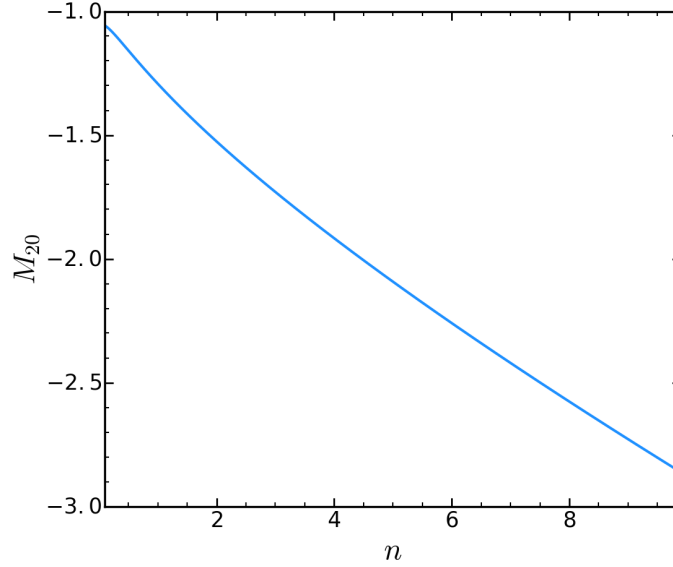


Figure 4.8. The n dependence of M_{20} .

difference between C and M_{20} is that the latter does not depend on a specific definition of center nor depends on elliptical/circular apertures and so it is independent of other morphological information. This translates into a better sensitivity of M_{20} to the presence of multiple bright spots in a galaxy.

4.2.4 $T\Psi$

SIZE (T) PARAMETER ²

This parameter takes advantage of the spectroscopic information of redshift to estimate the projected galaxy area in square physical kpc. It is computed by [Law et al. \(2007\)](#)

$$T = NL^2 \left(2 \times 10^{-11} \frac{\text{ster}}{\text{arcsec}^2} \right) D_A^2, \quad (4.40)$$

where N is the number of pixels of size L (in arcsec/pixel) in the segmentation map of the galaxy and D_A is the angular diameter distance as given by cosmology. The first test to make sure that this is working as expected is to check the behavior of D_A . From the standard model of cosmology, the angular diameter distance is given by:

$$D_A = \frac{D_c}{1+z} \quad (4.41)$$

where D_c is the comoving distance from the observer to the object and is given, in its general form, by:

$$D_c = c \int_0^z \frac{dz'}{H(z')} \quad (4.42)$$

and $H(z)$ is the function that defines the dependence of the Hubble parameter with redshift. In a general case for an isotropic and homogeneous Universe with matter, radiation and a dark energy components (this last one with equation of state $p/\rho = w$) plus non-zero curvature it

²to avoid confusion with intensity parameter or clumpiness parameter I will use the letter T

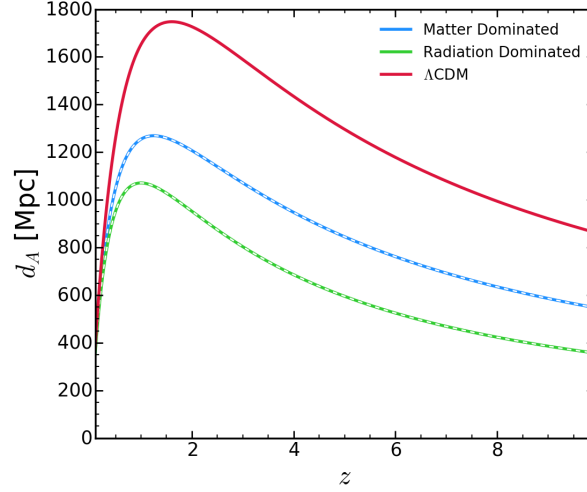


Figure 4.9. Testing the algorithm that computes the value of D_A as a function of z . Three cases are plotted as solid curves. The dashed lines represent the analytical expressions for the radiation and matter dominated scenarios respectively.

becomes:

$$\frac{H(z)}{H(z=0)} = \sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_w(1+z)^{3(1+w)}} \quad (4.43)$$

For the simple cases where only one component exists, the equation for the angular diameter distance has an analytical solution. For instance, in a flat radiation dominated scenario ($\Omega_r = 1$ and $\Omega_m = \Omega_w = \Omega_k = 0$),

$$D_A = \frac{c}{H_0(1+z)} \left(1 - \frac{1}{1+z} \right) \quad (4.44)$$

and in a flat matter dominated scenario ($\Omega_m = 1$ and $\Omega_r = \Omega_w = \Omega_k = 0$)

$$D_A = \frac{2c}{H_0(1+z)} \left(1 - \frac{1}{\sqrt{1+z}} \right) \quad (4.45)$$

So, the solution of equation (4.41) can be tested against these simple cases (see figure 4.9). As an additional curve it was plotted the variation of the angular diameter distance for a standard Λ CDM scenario ($\Omega_m = 0.3, \Omega_\Lambda = 0.7, w = -1$ and $\Omega_r = \Omega_k = 0$) as the green solid curve.

MULTIPLICITY (Ψ) PARAMETER

This parameter is used to discern how many apparent components there are in the light distribution of an object. Similar in practice to A and M_{20} due to their sensitivity on the presence of multiple clumps, it performs better than those two because it does not need the definition of the object center nor a conventional normalization. By using the light distribution as a proxy for mass, it is possible to compute the *potential energy* associated with a given object as projected onto the line of sight as (Law et al., 2007)

$$\psi_a = \sum_{i,j=1}^N \sum_{k,l \neq i,j}^N \frac{I_{i,j} I_{k,l}}{r_{ij}}. \quad (4.46)$$

Then, the intensity map is rearranged in the most compact possible configuration (a circular form with decreasing intensity with radius) and then I can calculate

$$\psi_c = \sum_{i,j=1}^N \sum_{k,l \neq i,j}^N \frac{I_{i,j} I_{k,l}}{r'_{ij}}. \quad (4.47)$$

Then I can compute the multiplicity parameter as the ratio of those two quantities

$$\Psi = 100 \times \log_{10} \left(\frac{\psi_c}{\psi_a} \right). \quad (4.48)$$

The values of Ψ vary from 0 up to ~ 30 where $\Psi \sim 0 - 2$ means a strong single nucleated object, $\Psi \sim 5$ for a weak second nucleated source and $\Psi \sim 10$ for a strong double nucleated source. For values $\Psi > 10$ it increases as the number of separated nucleus or distance between two nucleus increase and only at $\Psi \gtrsim 25$ the sources become low surface brightness nebulous objects.

4.2.5 MID

MULTI-MODE (M)

To compute this statistic I first have to define intensity quantiles denoted by q_l where l is the percentage of pixels I want below a given intensity q_l . Then, for a fixed value of l I can define a group map listing all contiguous pixels above that intensity threshold defined as:

$$g_{i,j} = \begin{cases} 1, & \text{if } I_{i,j} > q_l \\ 0, & \text{otherwise} \end{cases} \quad (4.49)$$

After selecting all the pixels obeying the rule I proceed to quantify the number of groups that I have and for each group the number of contiguous pixels it has. Defining $A_{l,m}$ as the number of pixels for the quantile q_l and group m , where m represents the rank of the group in terms of its area (i.e. $m = 1$ represents the largest group, $m = 2$ the second largest group...) I can compute the ratio:

$$R_l = \frac{A_{l,2}^2}{A_{l,1}} \quad (4.50)$$

Performing this calculation for a sufficiently large number of intensity quantiles I can now define the multi-mode statistic as the maximum value of all the computed ratios:

$$M = \max_l R_l \quad (4.51)$$

INTENSITY (I)

To take into account pixel intensities (which do not enter in the computation of M) there is a different statistic. To define groups of pixels for which to compute the total intensity the method used consists on two simple steps. First, the image is smoothed via a Gaussian kernel with a given σ (usually $\sigma = 1\text{pixel}$). Then, for each pixel in the segmentation map, I compute the corresponding local maximum via maximum gradient paths (i.e., for each pixel I compute the intensities of the 8 adjoint pixels and then move to the pixel with maximum intensity; the process stops when a local maximum is reached and none of the neighbor pixels have higher intensities than the one I am considering). So, a group is defined as the collection of pixels linked to a particular local maximum. Once I have all the intensity groups I sum all the intensities for all the groups and then compute I as the ratio between the total intensities of the brightest and the second brightest group:

$$I = \frac{I_2}{I_1} \quad (4.52)$$

DEVIATION (D)

Since I have defined the intensity groups in the previous calculation it is straightforward to obtain the local maximum coordinates associated with the brightest group of pixels (x_{I_1}, y_{I_1}) . Then I can define the intensity centroid as the mean pixel position as averaged by the flux within the segmentation map.

$$x_{cen} = \frac{1}{I_{tot}} \sum_{i,j} i \times I_{i,j} \quad (4.53)$$

$$y_{cen} = \frac{1}{I_{tot}} \sum_{i,j} j \times I_{i,j} \quad (4.54)$$

With that information I can compute the D statistic (normalized to an approximated galactic radius N_{seg}/π) as:

$$D = \sqrt{\frac{\pi}{N_{seg}}} \sqrt{(x_{cen} - x_{I_1})^2 + (y_{cen} - y_{I_1})^2} \quad (4.55)$$

4.2.6 OTHERS

FILAMENTARITY (F) PARAMETER

Inspired by the idea of [Matsuda et al. \(2011\)](#) I devised a new parameter that quantifies the covering fraction of a given object with respect to a circular aperture.

$$F = N_{pix} / \pi r_{min}^2 \quad (4.56)$$

where r_{min} is the minimum radius of the circle which encloses all the pixels of the segmentation map which has a total area $A = N_{pix}$. In practice, r_{min} is half the maximum of the distances between every set of two pixels from the segmentation map.

AXIS RATIO Q AND POSITION ANGLE θ

To measure this two quantities it is useful to first define the barycenter of a given object within the segmentation map (which is defined on a sky threshold basis). Then, one has $\bar{x}$ and $\bar{y}$ as defined in equations (4.53) and (4.54). Then, one may define the second order moments of the profile as:

$$\overline{x^2} = \frac{1}{I_{tot}} \sum_{i,j} i^2 \times I_{i,j} - \bar{x}^2 \quad (4.57)$$

$$\overline{y^2} = \frac{1}{I_{tot}} \sum_{i,j} j^2 \times I_{i,j} - \bar{y}^2 \quad (4.58)$$

$$\overline{xy} = \frac{1}{I_{tot}} \sum_{i,j} i \times j \times I_{i,j} - \bar{x}\bar{y} \quad (4.59)$$

Then, it is possible to show that (see [Bertin & Arnouts 1996](#)):

$$\tan 2\theta = 2 \frac{\overline{xy}}{\overline{x^2} - \overline{y^2}} \Leftarrow \theta = \frac{\text{sign}(\overline{xy})}{2} \arctan \left(2 \frac{\overline{xy}}{\overline{x^2} - \overline{y^2}} \right) \quad (4.60)$$

Which is then corrected according to the quadrant it is referring in order to span the entire range from -90 to 90 degrees. It is also possible to define directly the semi-major and semi-minor axis of the corresponding ellipse as:

$$a^2 = \frac{\overline{x^2} + \overline{y^2}}{2} + \sqrt{\left(\frac{\overline{x^2} + \overline{y^2}}{2} \right)^2 + \overline{xy}^2} \quad (4.61)$$

$$b^2 = \frac{\overline{x^2} + \overline{y^2}}{2} - \sqrt{\left(\frac{\overline{x^2} + \overline{y^2}}{2} \right)^2 + \overline{xy}^2} \quad (4.62)$$

$$(4.63)$$

which in turns makes it easier to compute $q = b/a$.

4.3 BEYOND SYMMETRIC MODELS FOR SIZE ESTIMATES

While the local Universe is dominated by galaxies with symmetric shape in the form of discs and bulges, the distribution of galaxy shapes becomes more complex as redshift increases. By redshift $z \sim 1-2$ irregular galaxies make up to 52% of the population of galaxies ([Delgado-Serrano et al., 2010](#); [Huertas-Company et al., 2015b](#)). By redshift $z \sim 3$ galaxies with irregular shapes dominate as they represent $\sim 65(40)\%$ of the population of massive, $\log_{10}(M_{\star}) > 10(11)$, galaxies ([Mortlock et al., 2013](#); [Buitrago et al., 2013](#)). These irregular shapes often come in the form of clumpy galaxies representing $\sim 60\%$ of the star-forming galaxies at $2 < z < 3$ (e.g. [Elmegreen et al., 2007, 2009](#); [Wuyts et al., 2012](#); [Guo et al., 2015](#); [Huertas-Company et al., 2015b](#)). This fraction might be higher when going to higher redshifts ([Conselice & Arnold, 2009](#)). Irregular shapes can take very diverse forms, including objects with one single asymmetric component, with multiple components, with a tadpole shape, extended with low surface brightness, and can be confused in the presence of close projected or physical companions. Some examples of galaxies in my sample are shown in figure 4.11. The fit with GALFIT gives an effective radius which highly depends on the relative brightness of each clump of the galaxy, but the residuals after fitting show how difficult it is to fit such an object with a symmetric profile.

These considerations prompted us to use other ways to derive sizes of galaxies than parametric fitting. A non-parametric definition removes the need for assuming a surface brightness profile. Measuring the half-light radius based on SExtractor and/or Curve of Growth methods is also widely used (e.g. [Ferguson et al., 2004](#); [Bouwens et al., 2004](#); [Hathi et al., 2008](#); [Oesch et al., 2010](#); [Curtis-Lake et al., 2016](#)). However, these non-parametric methods require a center and an aperture definition to be computed. Such quantities can, again, be misleading in cases of highly disturbed morphology.

With this in mind I developed a simple size estimator based on the total area covered by a galaxy above a given surface brightness threshold. In the following sections I define a non-parametric size measurement independent of any assumption related to a symmetric light distribution. This method is more affected by PSF broadening and noise when going towards low surface brightness in contrast to parametric fitting. Nonetheless it has the advantage

of being independent of the shape of the galaxy, and nicely complements the standard r_e measurements. The other advantage of this method is that it does not depend on initial guesses and does not require a fit to converge

4.3.1 TOTAL EXTENT OF GALAXIES

I define the area of a galaxy by counting the number of pixels above a given surface brightness threshold that belong to it. This approach has the advantage of being completely independent of any asymmetries that the galaxy may have and does not require any centroid/aperture definition. As most of the objects in my sample show irregular morphology I define physical sizes using the total area T_x as (adapted from [Law et al., 2007](#))

$$T_x = N_x L^2 \left(2 \times 10^{-11} \frac{\text{ster}}{\text{arcsec}^2} \right) D_A^2, \quad (4.64)$$

where N_x is the number of pixels of size L (in arcsec/pixel) that sum up to $x\%$ of the galaxy measured flux and D_A is the angular diameter distance derived using cosmological parameters. From this one can define the area equivalent radius, r_T^x ,

$$r_T^x = \sqrt{\frac{T_x}{\pi}}. \quad (4.65)$$

In the following I use T_{100} and r_T^{100} , the area and the equivalent circularized radius that enclose 100% of the measured flux above a given surface brightness threshold. The quantity r_T^{50} , the radius equivalent to the area that sums up to 50% of the total galaxy light, is similar to the effective radius derived from the GALFIT profile fitting, but taking into account irregular and asymmetric morphology. I also use the values of r_T^{80} and r_T^{20} enclosing 80% and 20% of the flux, respectively.

In practice, the method works as follows.

1. I smooth an image stamp of $6'' \times 6''$ centered on the VUDS galaxy with a Gaussian kernel with 1 pixel sigma width, truncated at 4 pixels;
2. I compute the segmentation map of the smoothed image based on a given surface brightness threshold;
3. From the segmentation map I select the area of connected pixels which contains the brightest pixel within a 0.5 arc-second radius from the target coordinates;
4. Using the pixels selected, I compute the total flux of the galaxy by summing up the flux in each pixel;
5. Finally, I iterate (using 1000 steps) f_i from the maximum to the minimum flux detected within the segmentation map. At each step I compute the summed flux from the pixels for which $f_{\text{pixel}} > f_i$. When the summed flux corresponds to $x\%$ of the galaxy total flux, I store the number of pixels that have fluxes greater than f_i at that step and then compute T_x using equation 4.64.

I smooth the original image so that one improves the sensibility to faint surface brightness features of galaxies. I choose a Gaussian kernel smoothing of 1 pixel sigma width since it provides a compromise between a boost in the S/N of the faint features and prevents a large degradation of the image resolution necessary to properly trace the asymmetries in the shape of the object.

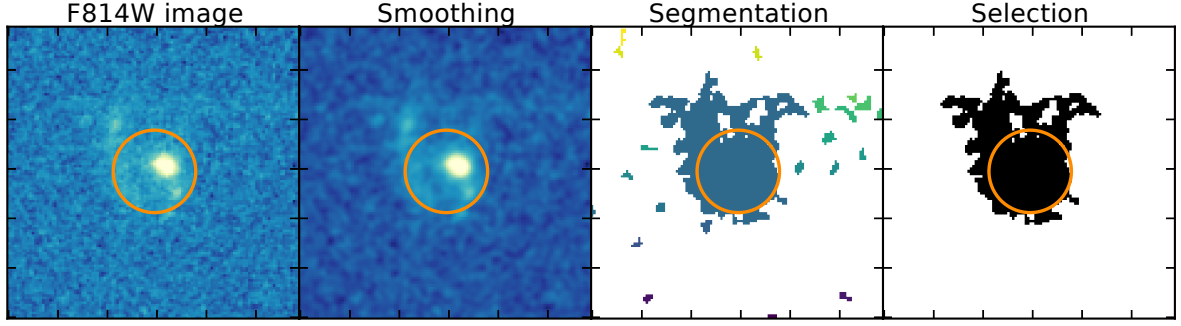


Figure 4.10. Illustration of the size measurement process for VUDS 510799304 at $z = 2.4281$. From left to right: 1) The original F814W image from COSMOS (Koekemoer et al., 2007). 2) The same image after smoothing by a Gaussian kernel of 1 pixel width and extending over 4 times the width. This kernel ensures an improvement of the signal to noise for low surface brightness levels while preventing a significant boost of noisy pixels which would incidentally increase the measured radius if the kernel was too large. 3) The segmentation map obtained after running the detection algorithm including all pixels greater than $k\sigma$. 4) The selection of the target galaxy. All panels have $1.77''$ by $1.77''$ and the orange circle has a radius of $0.5''$. The total size is computed from the number of pixels in the last panel.

The selection method chosen for the purpose of this project has the main goal of minimizing the effect of neighbor contamination and of not imposing any size constraints on the derived measurements. I have tested two other different methods: selecting the largest area or the brightest area (by summing the fluxes of all its pixels) for which a subset of its pixels is inside the $0.5''$ radius. Both methods yield similar results.

I have tested the contamination by neighbors dropping simulated galaxies in random regions of the images with and without a constraint on the presence of sources within 2.0 arcsec of the simulated galaxy. When no constraints are imposed sizes are sometimes artificially increased by the area occupied by a neighboring source. Still, the rate of contamination does not dominate the measurements. I find that the percentage of simulated galaxies with recovered sizes twice as big as the input is of 8% for the random clean regions and 17% for the purely random regions. I expect that the contamination rate of my galaxies will be closer to the first reported value since, due to the data processing for a spectroscopic survey, galaxies with large bright companions are excluded from the sample due to problematic redshift estimation.

4.3.2 COSMOLOGICAL DIMMING AND LUMINOSITY EVOLUTION

Tolman (1930) demonstrated that in an expanding Universe the relation between the flux and angular size of a nebula should follow the relation (adapted from his equation 30)

$$\frac{F}{\delta\theta^2} \propto (1+z)^{-4}. \quad (4.66)$$

At the time (see Lubin & Sandage, 2001) it was the only observational test that was proposed to confirm the reality of the expansion of the Universe, which is now well established. This dimming effect, independent of the cosmological model, has to be taken into account if one wants to measure galaxy sizes (by means of counting pixels) at the same surface brightness level at different redshifts.

However, when one is analyzing the image recorded with the detector, one is looking at the number of detected photons arriving from the observed source, and not at an integrated flux. Let us consider a square region of the emitting source corresponding to the pixel size at the location of the object. The monochromatic energy emitted is given by

$$L_p = \int_A I(x, y) dx dy \quad (4.67)$$

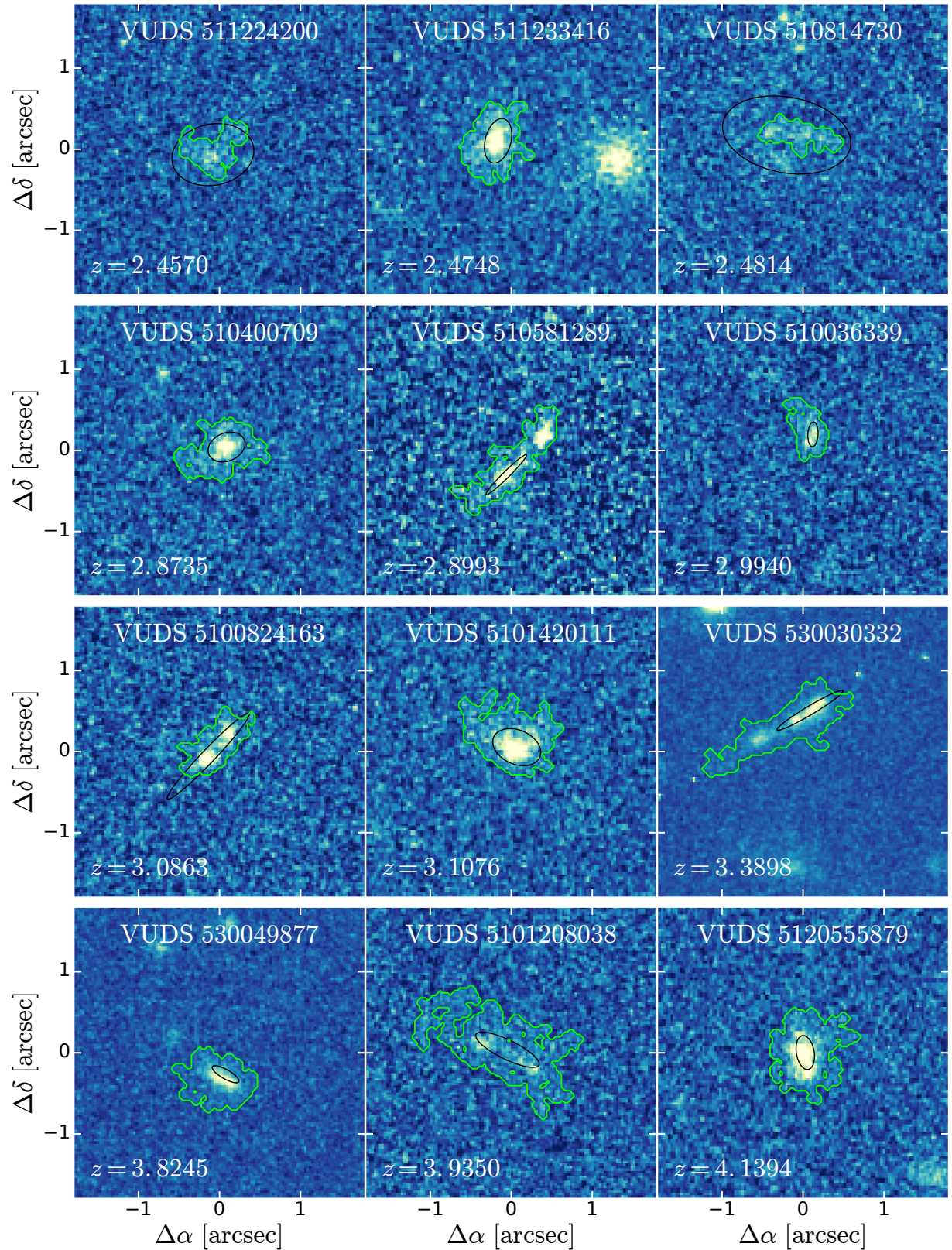


Figure 4.11. F814W imaging in COSMOS (Koekemoer et al., 2007) and CANDELS (when available, Koekemoer et al., 2011) of the measured sizes for three galaxies in each of four increasing redshift bins from $z \sim 2.4$ to $z \sim 4.1$ (top to bottom) in my sample. The green contours show a smoothed version of the segmentation map of the galaxy at the defined threshold which translates to T_{100} from equation 4.64 measured at $k_p = 1.0$. The black ellipses are constructed from the values of r_e , b/a and θ_{PA} derived from GALFIT for those galaxies. The parametric and symmetric 2D profile fitting with GALFIT fails to properly account for the complex irregular morphology when deriving the size of galaxies at these redshifts, while the non-parametric method presented in this paper is able to derive more realistic sizes.

which, for a source emitting at constant brightness inside that pixel simplifies as

$$L_p = T \times I, \quad (4.68)$$

where T is the physical size of that pixel. Considering a pixel size p , the physical size, in kiloparsec, is proportional to

$$T \propto (p \times D_A)^2. \quad (4.69)$$

At a distance D_L the observed light is

$$F_p = \frac{L_p}{4\pi D_L^2}. \quad (4.70)$$

The number of observed photons is³

$$N_{\text{photons},o} = \frac{F}{E_{\text{photon},o}}, \quad E_{\text{photon},o} = h\nu_o = \frac{h\nu_e}{1+z}. \quad (4.71)$$

Combining the equations above I get

$$N_{\text{photons},o} \propto \frac{I \times (p \times D_A)^2 (1+z)}{4\pi D_L^2 h\nu_e}. \quad (4.72)$$

With $D_L = D_A(1+z)^2$, the number of observed photons per unit area is

$$N_{\text{photons},o} \propto \frac{p^2}{4\pi} \frac{I}{h\nu_e} \frac{1+z}{(1+z)^4} \propto (1+z)^{-3}. \quad (4.73)$$

The factor $I/(h\nu_e)$ represents the number of emitted photons per unit area. The same redshift dependence was found by [Giavalisco et al. \(1996\)](#) and used in [Law et al. \(2007\)](#).

On top of the dimming effect, the average evolution in luminosity of a population of galaxies has an impact on the typical threshold defined at any given redshift. This means that a galaxy with a fixed size but with an increased luminosity because of luminosity evolution will appear larger above a fixed luminosity threshold. The average luminosity evolution from $z \sim 4.5$ to $z \sim 2$ as reported in the literature is 0.4 magnitudes in the UV rest-frame [Reddy & Steidel \(2009\)](#); [Bouwens et al. \(2015\)](#).

I take this effect into account by parameterizing the evolution of the characteristic luminosity L_* within the redshift range I am considering. Taking the L_* values in [Reddy & Steidel \(2009\)](#) at $z < 3$ and those from [Bouwens et al. \(2015\)](#) at $z > 4$ I define a broken luminosity evolution which is steeper below $z < 3$ and flattens at $z > 4$:

$$L(z) = \begin{cases} 10^{-0.4(-0.36z)} & z \leq 3 \\ 2.25 \times 10^{-0.4(-0.07z)} & z > 3 \end{cases} \quad (4.74)$$

4.3.3 DETECTION THRESHOLD

The dimming effect described in the previous subsection relates to an important tuning parameter for this non-parametric size measurement which is the detection threshold above which a pixel is classified as a detection and may be assigned to the galaxy. This detection threshold is defined as a multiple k of the standard deviation of the sky emission, σ , computed globally. To be sure that I am fairly comparing galaxies imaged at different depths, the value of σ is taken as the median standard deviation of the image noise computed from 100 different regions in

³a special thanks to James Dunlop for help in the clarification of this issue

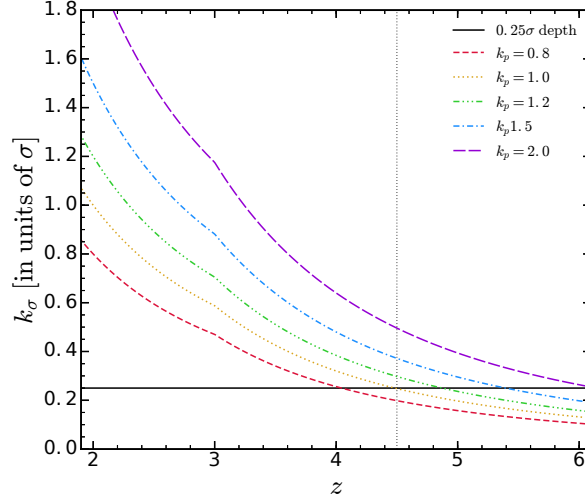


Figure 4.12. Value of k as a function of redshift for different choices of k_p . The vertical dotted line shows the upper redshift limit I assume in this paper. The black solid line shows the depth limit above which the noise correction is larger than 100 pixels.

the shallowest survey. In my case, $\sigma = 1.1 \times 10^{-14} \text{ ergss}^{-1}\text{cm}^{-2}\text{arcsec}^{-2}$ is computed from the COSMOS images.

The choice of k plays an important role on the size estimates that one gets. The simplest assumption is to define a constant value k_0 across all redshifts. Another approach consists in taking into account the effect of cosmological dimming and typical luminosity evolution (described above) and choose k as a function of the galaxy redshift following

$$k = k_p \left(\frac{1+z}{1+z_p} \right)^{-3} \times \frac{L(z)}{L(z_p)}, \quad (4.75)$$

where k_p is the value of k at the pivot redshift z_p and $L(z)$ is defined in equation 4.80. To use this method, the availability of spectroscopic redshifts is even more important as errors in the redshift would affect the threshold used and consequently impact the final size measurements of the galaxies.

Such drastic evolution of the detection threshold (see figure 4.12) led us to restrict the redshift interval of my study to $2 < z < 4.5$. In this range I probe the total extent of galaxies down to a lower surface brightness level at lower redshift while avoiding to overestimate galaxy sizes at the high redshift end due to random sky background noise detection. To obtain a size measurement corresponding as closely as possible to the total physical area covered by a galaxy, the choice of the threshold is based on the average number of connected sky pixels as a function of the threshold. I find that it is at the level of 1.0σ that I start to detect connected pixels (4-6 pixels) only due to random sky noise fluctuations. Based on that, and on the average galaxy color which I discuss in section 4.3.5, I define k such that at $z = 2$ it has a value of 1.0 to probe galaxies down to their fainter regions. This corresponds to a detection limit of $\approx 0.25\sigma$ per pixel at $z = 4.5$. I discuss the contamination from random fluctuations and the correction made to the size measurements measured down to these thresholds in section 4.3.6.

the galaxy sizes that I measure are tied to the choice of k_p and/or the depth of the image which determines the value of σ . By setting the value of $k \times \sigma$ at higher/lower values, the absolute value for the galaxy size will decrease/increase. I therefore report total size measurements indexed to a specific choice of k_p , i.e. to a specific limiting isophote defined at $z = z_p$. For the sake of simplicity I shall refer hereafter to my non-parametric size as the total size.

4.3.4 CORRECTING FOR PSF BROADENING

Since I am measuring sizes directly on images we are affected by the broadening of the profile by the instrumental PSF. To correct for this effect I simulate with GALFIT a PSF image re-scaled to match the magnitude of the galaxy. I then run the simulated PSF through the same detection algorithm and obtain the size of the PSF at the object magnitude and same surface brightness level. I then compute the galaxy size by correcting from the PSF broadening using the following formula

$$r_{T,\text{PSF-corr}}^x = \sqrt{(r_T^x)^2 - (r_{T,\text{PSF}}^x)^2} = \sqrt{\frac{T_x - T_{x,\text{PSF}}}{\pi}} \quad (4.76)$$

4.3.5 DEPENDENCY WITH COLOR

The method of measuring galaxy sizes presented above is dependent of individual pixel detection, and it is therefore more sensitive to the galaxy spectral energy distribution than other methods relying on a given surface brightness profile. Even in the absence of color gradients, the simple fact that one object could have a wavelength-dependent brightness leads the number of selected pixels to vary due to relative brightness change of the galaxy within a given filter with respect to the detection threshold.

To correct for this I apply a simple color correction to the detection threshold taking into account the different brightness at different rest-frame wavelengths:

$$k_c = k \times 10^{-0.4(B_{\text{obs}} - NUV_{\text{rest}})}, \quad (4.77)$$

where k is that of equation 4.79 and $(B_{\text{obs}} - NUV_{\text{rest}})$ is the color term. The color is defined to be the observed band, B , minus the rest-frame NUV band derived from SED fitting with Le Phare. The choice of the NUV band was done such that, for the majority of my galaxies, the color term is minimal since it overlaps with the observed band.

I compare the PSF-corrected values of r_T^{100} derived in the F814W, F125W and F160W bands in figure 4.13 (see also figure 4.14). I report a small offset in the median values of $r_I - r_H \approx -0.08$ kpc and $r_I - r_J \approx 0.51$ kpc. The dispersion on the size measurements across different bands is 0.27 dex and 0.22 dex for F814W-F160W and F814W-F125W comparisons respectively. I stress that part of the scatter observed in this figure is due to the color correction described above which is sensitive to the objects' magnitude in each of the bands. This in turns impacts the final isophote threshold and therefore the final measurements. Nonetheless, I highlight that I observe no large systematic offsets in the comparison between the I and H bands.

4.3.6 CORRECTING FOR SKY PIXELS DETECTION

In the presence of uncorrelated Gaussian noise, the probability of a *sky* pixel being above the detection threshold defined above is not negligible. To estimate the level of contamination produced by random sky noise, I compute the N_{100} area (equation 4.64, size of the segmentation map) on a search radius of 0.5 arc second (the same as when computing T_{100} for the real galaxies) randomly selected on $500 \times 300'' \times 300''$ regions.

For each search radius, I compute the area defined for surface brightness thresholds ranging from 0.05σ to 2.05σ using steps of 0.025. This provides the median area of sky connected pixels for a given threshold value. I use this to correct the value of r_T^{100} following

$$r_{T,\text{corr}}^{100} = \sqrt{(r_{T,\text{PSF-corr}}^{100})^2 - T_{\text{sky}}(k)/\pi} \quad (4.78)$$

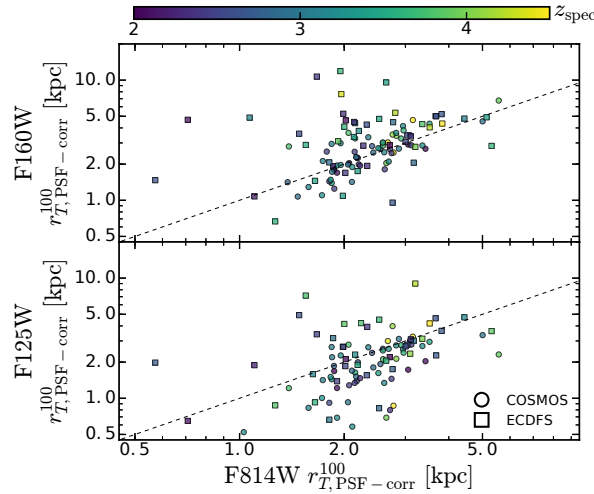


Figure 4.13. Comparison of $r_{T,PSF-corr}^{100}$ size measurements for a subset of VUDS galaxies at $2 < z < 4.5$ with available F814W and F160W/F125W images from CANDELS. Results are split in two bands: F160W on the top panel and F125W on the bottom panel. Circles and squares refer to COSMOS and ECDFS respectively. The dashed black line is showing where both radii are equal. The symbols are color coded according to their spectroscopic redshift and the mapping is shown in the colorbar on top of the plots.

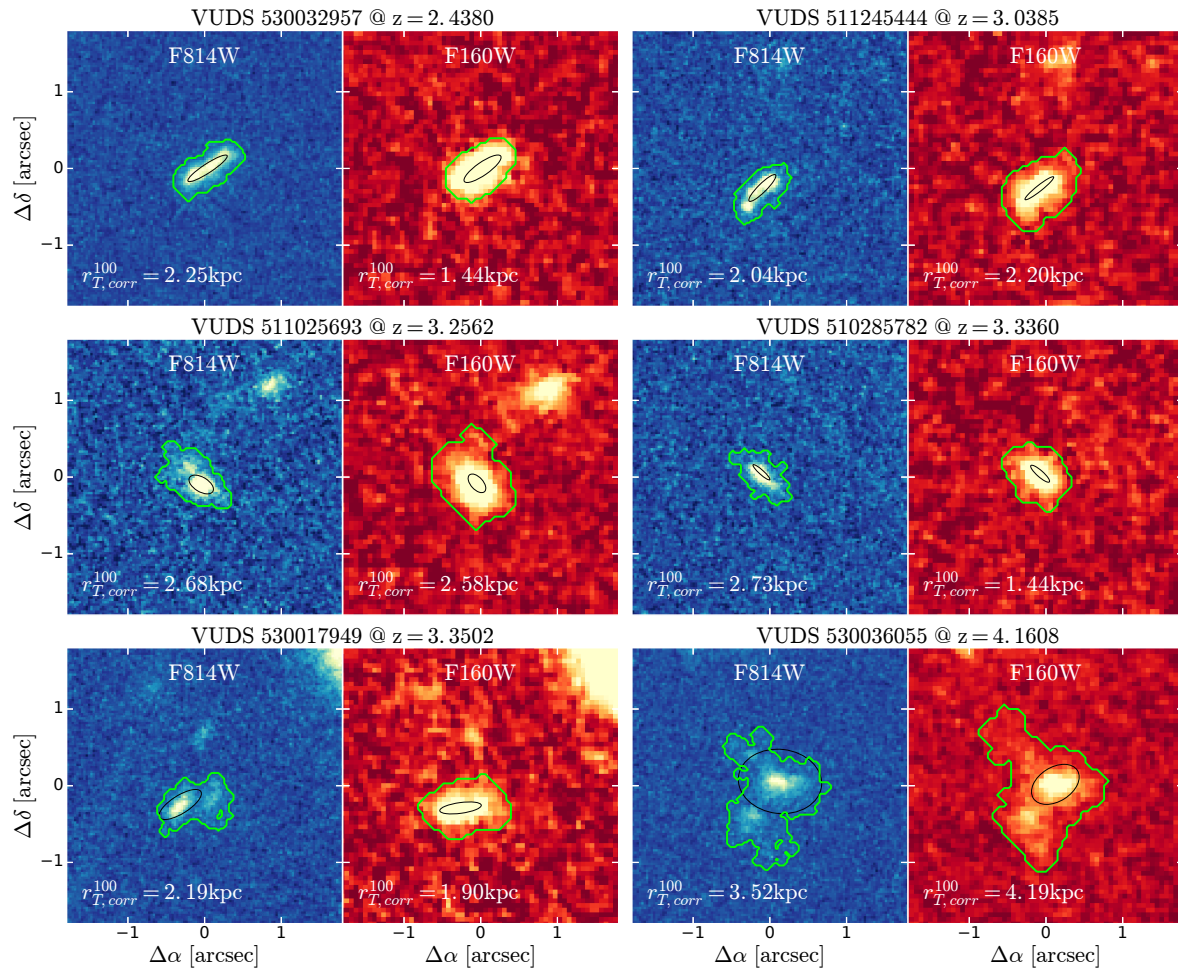


Figure 4.14. F814W (in blue) and F160W (in red) imaging in CANDELS (Koekemoer et al., 2011) of 6 example galaxies in VUDS. The green contours show the isophote used to derive r_T^{100} prior to the PSF and sky correction. The black ellipses are constructed from the values of r_e , b/a and θ_{PA} derived from GALFIT for those galaxies in each band. I refer to figures 5.3 and 4.13 where comparison of derived sizes is shown for the full set covered by CANDELS.

where $T_{\text{sky}}(k)$ is the median number of connected *sky* pixels at a threshold k . In figure 4.15 I show the impact of this correction on a set of simulated galaxies. I stress that this correction is only applied to the value of r_T^{100} . I note however that the impact of the noise is greater when increasing the fraction of the flux used to derive sizes. Sky noise effects are negligible for sizes computed using 10% of the total flux.

4.3.7 T_{100} IN SIMULATED GALAXIES

I have used the same set of simulated galaxy images described in section 4.1.6 to compute the value of T_{100} and assess the impact of the noise on the retrieved values. To compute the value of the expected total area, I have used the noise free simulated models, convolved with a PSF, and applied the same thresholding method as explained in section 4.3.2. To ensure that I would probe different thresholds, for each galaxy, a random redshift was attributed taken from a uniform distribution between the limits I have defined for this paper. This, in practice, translates to mapping the thresholds used in the computation of sizes in real data.

In figure 4.15 one can see the output results from the simulation. As it should be straightforward to understand, brighter galaxies have larger sizes simply because more pixels are found above the threshold that I defined. The scatter that I find increasing for smaller galaxies (fainter magnitudes) is explained by the increasing contamination of the sky connected pixels that are detected close to the galaxy and gain importance as I lower the flux of simulated galaxies which produces an overestimation of the galaxy size. Additionally, since I am dropping galaxy models on top of a real background, with potentially other sources in image area, some large scatter is expected at all magnitudes where sizes are consistently overestimated. It is somehow unexpected the underestimation of galaxy sizes at the largest simulated sources. However, since $\sim 90\%$ of the galaxies in my sample have $100 < T_{100} < 2000$ pixels I find it a negligible correction with no impact in my findings.

I have also applied the same correction method for the contamination of sky connected pixels and the results are found in the right panel of figure 4.15. I find that it increases somehow the scatter at the lower input sizes and overall approximates the retrieved value from the input one. Being far from perfect, I believe that my sky corrections estimates are good enough for an approximation on the derived galaxy sizes of my sample.

4.4 A SEARCH FOR HIGH-REDSHIFT CLUMPS

There are various methods described in the literature with the goal of detecting and characterizing galactic clumps at high redshift ranging from visual classification to automated algorithms (e.g. Elmegreen et al., 2007; Puech, 2010; Guo et al., 2012; Wuyts et al., 2012; Tadaki et al., 2014; Guo et al., 2015; Shibuya et al., 2016). Usually, the algorithms involve the subtraction of a smoothed version of an image from the original and then search for positive detections in the residual image that can be considered as galactic clumps. I follow a slightly different approach. My clump search is based on the assumption that clumps are locally the brightest region within a larger isophote which defines the total extent of the galaxy it resides in. I summarize my method in the steps below.

1. I smooth the image of $6'' \times 6''$ centered on the VUDS galaxy with a Gaussian kernel with 1 pixel ($0.03''$) width;
2. I compute the segmentation map of the smoothed image based on a given surface brightness threshold;

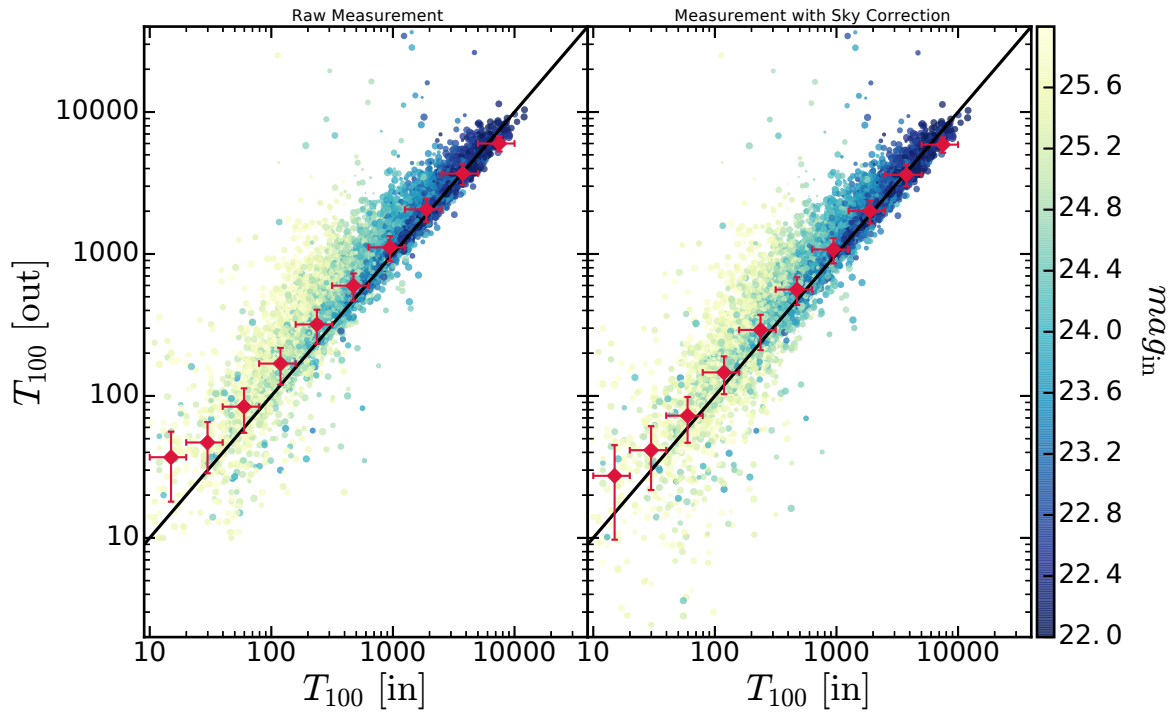


Figure 4.15. Results of the computation of T_{100} for a set of 15 000 galaxies. The points are color coded by their input magnitude and the size of each point is determined by the input r_e of the GALFIT model. The solid red line denotes the one-to-one relation. The left panel refers to the size measurement without any correction and the right panel presents the same results but after applying the same sky correction as described in section 4.3.6. The large red points represent the median sizes per bin, the error bar in the x-axis represents the bin width, and in the y-axis represents the median absolute dispersion of the bin.

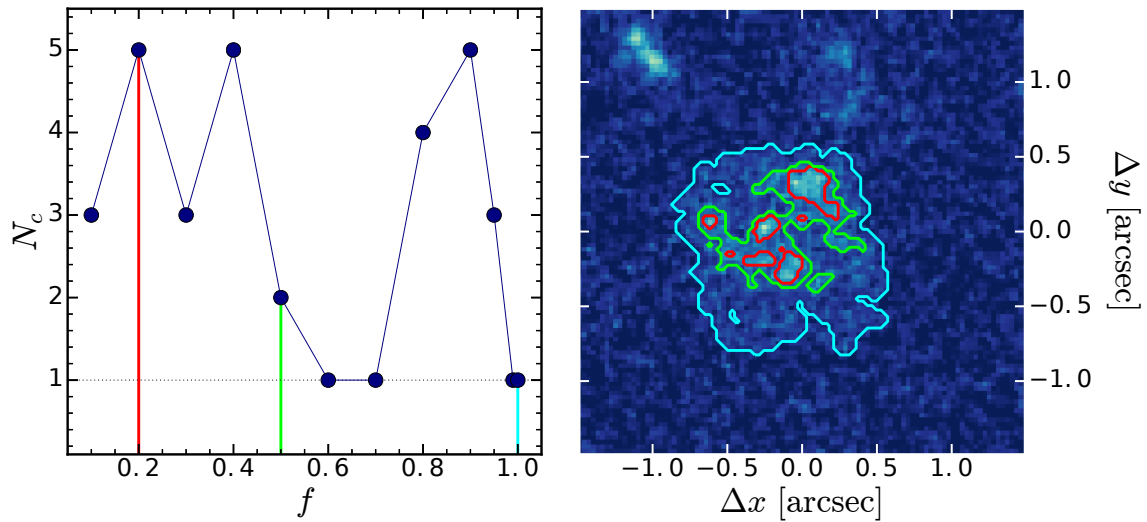


Figure 4.16. Exemplification of the method for detecting galaxy clumps. On the left I show the number of disconnected regions with more than 10 pixels as a function of flux level cut. When $f = 1$ the isophote limit represents the limiting area of the galaxy. On the right I show the contours corresponding to three different flux level cuts at 20%, 50% and 100% of total flux that are identified in the same color as the vertical lines in the left panel.

3. From the segmentation map I select the area of connected pixels above the adopted surface brightness threshold which contains the brightest pixel within a 0.5 arc-second radius from the target coordinates;
4. Using the selected pixels, I compute the total flux of the galaxy by summing up the flux in each pixel;
5. I iterate (using 1000 steps) a flux level f_i from the maximum to the minimum flux detected. At each step I compute the number of disconnected regions (defined from all pixels with fluxes greater than f_i) within the segmentation map and store the position of local maximum associated with each disconnected region (see Fig. 4.16).
6. I define the number of clumps as the number of disconnected regions detected above the isophote level corresponding to 80% of the total galaxy flux, which are associated with the different local maximums.

I repeat this process for all galaxies found in the image stamp. I note that I only consider clumps with a detection area greater than 10 pixels. This minimum area for clump detection ensures that I am excluding the contribution from random fluctuations of photon counts and also imposes a lower limit of ~ 3 pixels (roughly the FWHM of the PSF) on the separation of any given two clumps that I can detect.

4.4.1 ISOPHOTAL THRESHOLD

One of the key elements of this algorithm is the limiting isophote at which I define the total extent of a single galaxy. For my method, it is defined as

$$k = k_p \left(\frac{1+z}{1+z_p} \right)^{-3} \times 10^{-0.4(I_{\text{obs}} - B_{\text{rest}})} \times \frac{L(z)}{L(z_p)}, \quad (4.79)$$

which is composed by three different terms.

The dimming correction which accounts for the fact that due to the expansion of the Universe the observed number of photons of a source with constant intrinsic luminosity scales with $(1+z)^{-3}$.

The color correction which accounts for the fact that I am not exactly observing at the same rest-frame wavelengths and corrects for the relative brightness based on the slope of the SED close to the band I am observing. To be consistent in the large redshift range I choose to use rest-frame FUV magnitudes to compute the color correction term since it is the central wavelength where I have the peak of the redshift distribution.

The luminosity correction which accounts for the average luminosity evolution in galaxies. $L(z)$ is derived from the L_* values in Reddy & Steidel (2009) at $z < 3$ and those from Bouwens et al. (2015) at $z > 4$. I define a luminosity evolution which is steeper below $z < 3$ and flattens at $z > 3$:

$$L(z) = \begin{cases} 10^{-0.4(-0.36z)} & z \leq 3 \\ 2.25 \times 10^{-0.4(-0.07z)} & z > 3 \end{cases}. \quad (4.80)$$

In equation 4.79 there are two parameters that are correlated. The value k_p represents the detection threshold, in units of σ , at $z = z_p$. In this study I set $z_p = 2$ and I use several values of k_p throughout the paper. In particular I use $k_p = 1.5, 2.0$ for $2 < z < 4.5$ and $k_p = 5.0$ for $4.5 < z < 6$. Since the value of k can vary by a factor of $(1+2)/(1+6)^{-3} \sim 0.009$ from $z = 2$ to $z = 6$ based only on surface brightness dimming I choose different values of k_p to allow for an estimate of the total extent of galaxies at the lower limit while preventing noise contaminated detections at the high redshift end. All these factors are explained in detail in sections 4.3.2, 4.3.3 and 4.3.5.

4.4.2 RESULTING CLUMPS COUNTS

At the end of this process a list of galaxies is identified within a 20 kpc radius (search radius defined to be equal to López-Sanjuan et al., 2013; Tasca et al., 2014b). This value is defined from dynamical considerations, as two clumps of mass at a distance of 20 kpc are expected to merge within a timescale of 1-2 Gyr (e.g. Kitzbichler & White, 2008). Then, a list of clumps is identified in each galaxy. My algorithm may identify several *galaxies* within the search radius of 20 kpc, as pixels groupings isolated from other pixel groupings, i.e. these groups of pixels are not connected to each other at the isophote considered. It is well possible that if deeper images were available, allowing to lower the search isophote, some of these pixel groupings could be connected and possibly associated to a single galaxy.

To provide a cleaner interpretation, all my results on galactic clumps take only into account clumps that are associated with the VUDS target. I choose to do this because it is only for these sources that I have spectroscopic information (important to compute k in equation 4.79) as well as physical parameters from SED fitting. However I keep information about other galaxy detections within 20 kpc to compute the pair fraction at the same redshifts. Several examples of detected clumps in VUDS galaxies are shown in Figs. 4.17, 4.18 and 4.19.

I attempt to correct for line of sight contamination, to transform the pair fraction into a merger fraction, by using a simple statistical argument. Starting with the expected number of galaxies within a square degree, as derived by Capak et al. (2007), I compute the probability of a galaxy of magnitude m to be found at a distance r of the VUDS target. The total number of galaxies brighter than magnitude m in one square degree is computed integrating the number counts, $N(< m)$ computed by Capak et al. (2007). Then I estimate how many galaxies I expect to find within $\pi \times r^2$. This is summarized by

$$p = \frac{\pi r^2}{3600 \times 3600} \times \int_{15}^m N(< m') dm'. \quad (4.81)$$

In the end, each galaxy of magnitude m counts as $0 < p < 1$, and this quantity gives the contaminating counts when later considering galaxy pairs.

4.4.3 LUMINOSITY AND SIZES

In order to obtain further information on the physical characteristics of clumps I adapted the method defined by Freeman et al. (2013) to compute the intensity parameter I giving the luminosity of each clump.

This algorithm defines groups of pixels associated with a local maximum inside a segmentation map. First, the image is smoothed via a Gaussian kernel with a given σ (I use $\sigma = 1$ pixel). Then, for each pixel in the segmentation map, I compute the corresponding local maximum via maximum gradient paths. This means that for each pixel I compute the intensities of the 8 surrounding pixels and then move to the pixel with maximum intensity. I continue this process until a local maximum is reached and none of the neighbor pixels have higher intensities than the one I am considering. So, a pixel group is defined as the collection of pixels linked to a particular local maximum.

Once I have all the pixel groups defined, I match the local maximum of each group to the local maximum of the detected clumps in the previous algorithm. Then I compute the luminosity and area associated with each clump by counting all the light and pixels in each group, respectively. It is important to stress that since I am stopping at the border of two contiguous groups of pixels, the derived areas and luminosities are lower limits to the real values. This happens since I am not considering flux from pixels with a contribution coming mostly from a neighbor clump rather than the clump being considered.

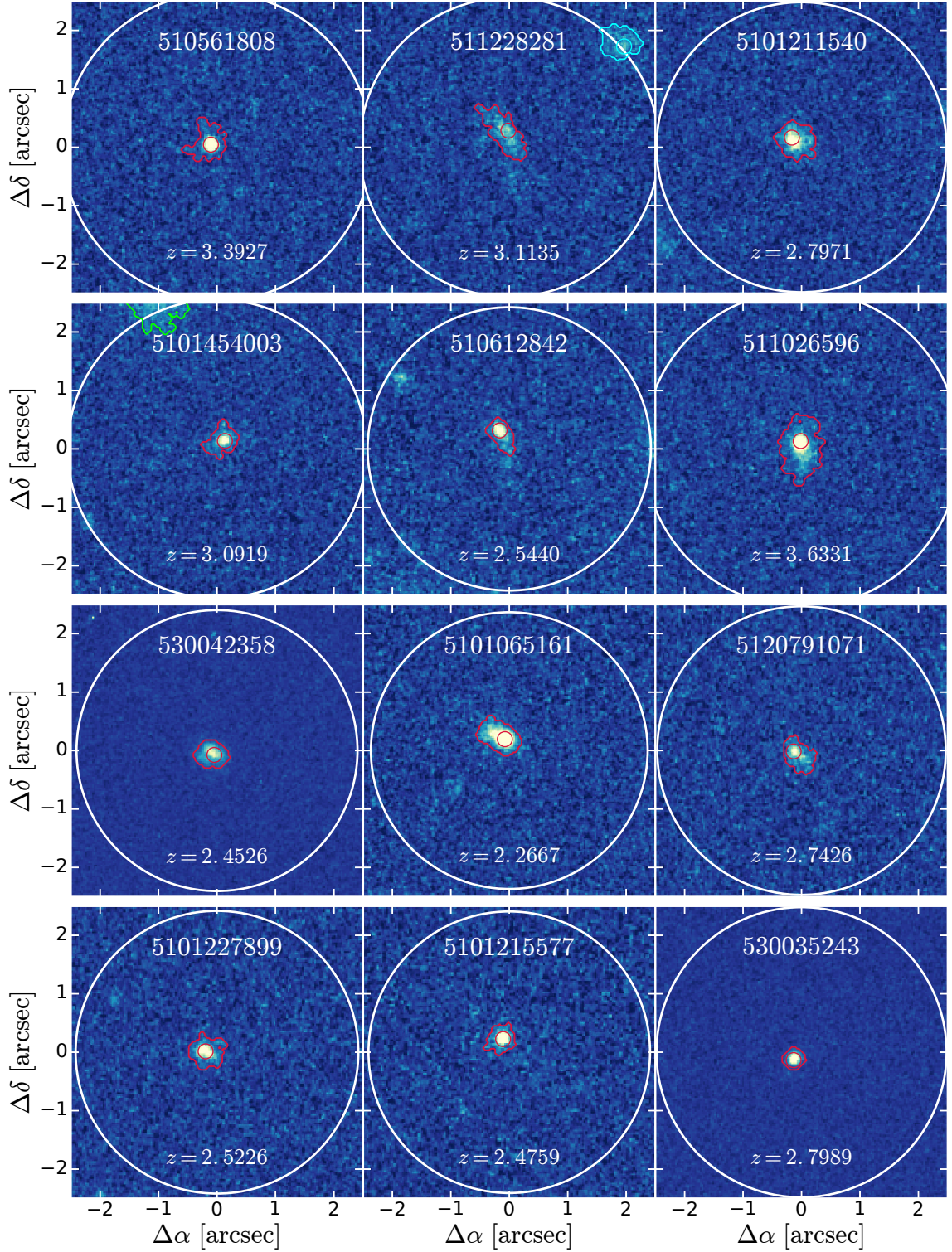


Figure 4.17. Twelve examples of galaxies for which only one clump was detected. The white circle shows the 20 kpc projected search radius. The contours represent the detection isophote of each galaxy identified within this search radius. Each circle shows the position of a detected clump within the isophote of the same color. VUDS targets are identified with red contours and circles.

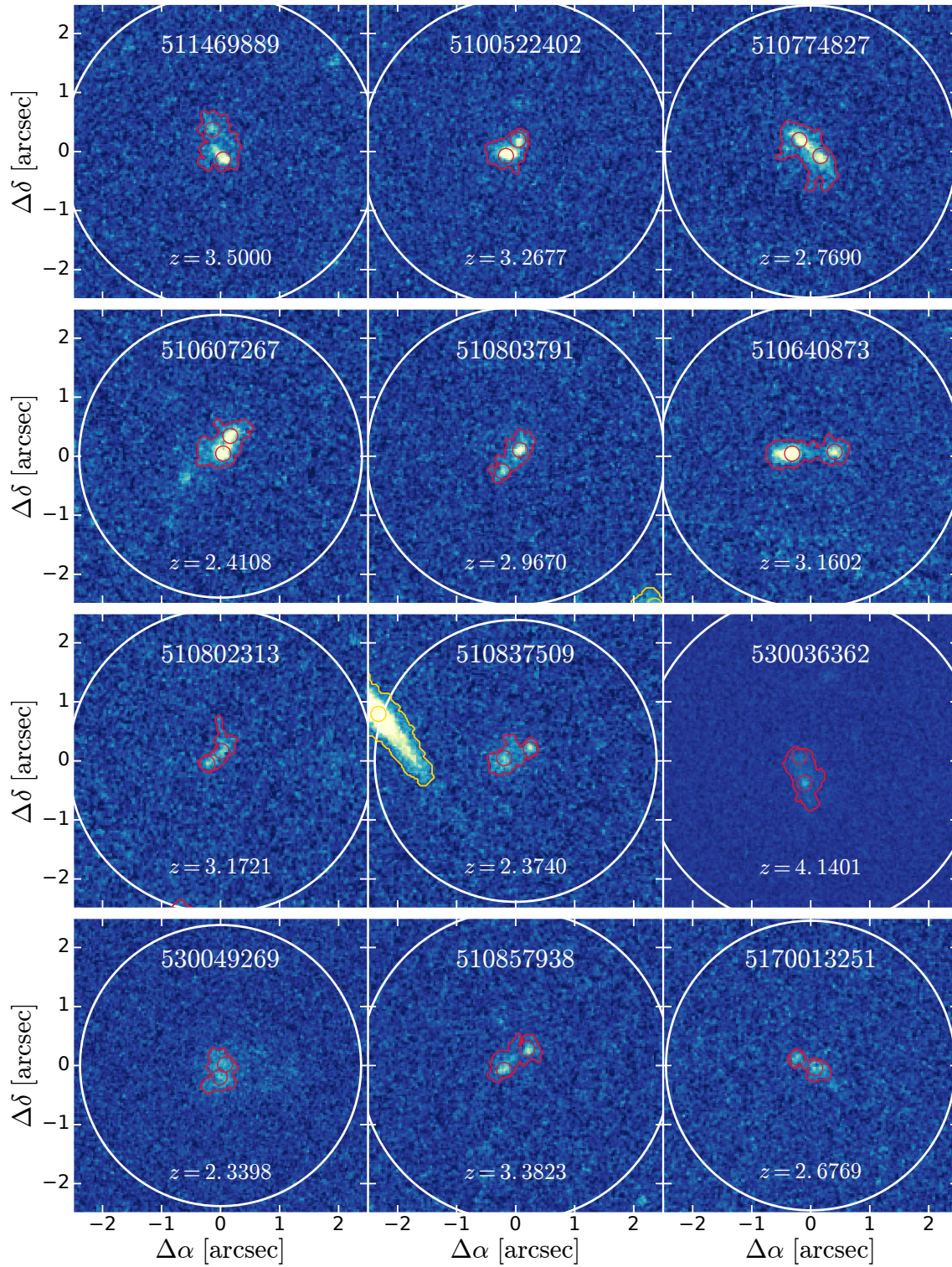


Figure 4.18. Twelve examples of galaxies with two clumps detected. The top six examples show cases for which at least one bright clump was detected whereas the bottom six examples show pairs of faint clumps. The white circle shows the 20 kpc projected search radius. The contours represent the detection isophote of each galaxy identified within this search radius. Each circle shows the position of a detected clump within the isophote of the same color. VUDS targets are identified with red contours and circles.

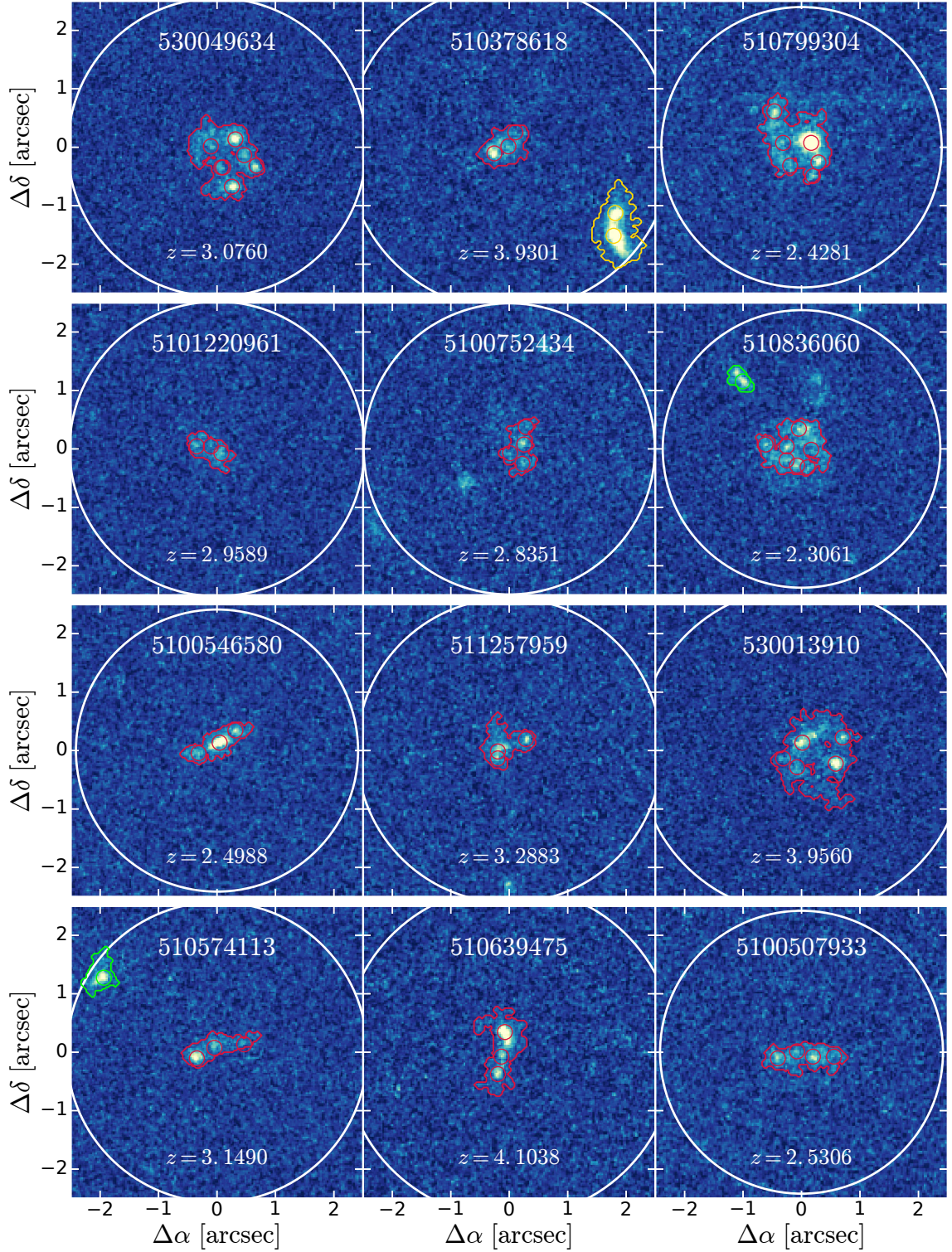


Figure 4.19. Twelve examples of galaxies with more than two clumps detected. The white circle shows the 20 kpc projected search radius. The contours represent the detection isophote of each galaxy identified within this search radius. Each circle shows the position of a detected clump within the isophote of the same color. VUDS targets are identified with red contours and circles.

With the knowledge of the spectroscopic redshift from VUDS, I can then compute physical areas in kpc^2 . Absolute magnitudes are computed using the flux measured from the F814W images. I correct the magnitudes to FUV rest-frame using the k-correction derived for the galaxy from SED fitting. This means that the clump magnitude is derived as

$$M_{\text{clump,FUV}} = M_{\text{clump,F814W}} + k_{\text{corr,FUV}}. \quad (4.82)$$

4.4.4 FALSE CLUMP DETECTIONS

To estimate the impact of false detections on the inferred distributions of areas and luminosities I perform a simple test. I run my clump detection algorithm using the same threshold as before on the negative image of each galaxy and compute the area and magnitude of each negative clump which is, by its nature, a false peak detection. I can see in Fig. 4.20 that the inferred distribution of false clumps is found at small areas (peaking at $\sim 1 \text{ kpc}^2$) and faint luminosities (peaking at $M_{\text{F814W}} \sim -17.4 \text{ mag}$) as expected.

Most of the negative detections are found at $M_{\text{clump}} > -18$ which is fainter than the peak for the fainter clumps that is observed in the magnitude distribution (see figure 5.17). This indicates that the smaller clumps with $M_{\text{clump}} < -18$ are mostly real physical clumps.

4.4.5 MORPHOLOGICAL K-CORRECTION

I test my assumption that clumps are evenly detected across the rest-frame wavelength range that I probe at different redshifts by computing the same quantities on a degraded version of the F814W images and on a subsample of galaxies for which I have H-band imaging from CANDELS. In terms of the clumpy fraction I detect a lower fraction of clumpy galaxies in the degraded version of the I band by a factor of 2 and a little lower when using the measurements in the H band. I argue that my measurements might be more affected by the spatial resolution of the images since the fraction of clumpy galaxies in the degraded version of the I band images is closer to that reported in the H band than what I report for the normal resolution I band images. I note that the spatial resolution of the H band is even poorer than the degraded I band image due to the larger PSF (which is 3 times that of the I band) and I expect a lower fraction on the H band simply due to that effect.

I have also attempted to compute the area-luminosity distribution of clumps detected in the H band and I am only able to detect clumps in the large and bright regime (see Fig. 4.20). Again I believe that the resolution in the H band images is the main reason for the differences that I find. However I cannot exclude the existence of morphological k-correction.

4.5 VISUAL CLASSIFICATION

Due to the peculiar nature of galaxy morphologies at high redshift it is not always simple to establish automated methods for classification of galaxies. Usually such methods involve only the identification of galaxy mergers (e.g. Conselice, 2003; Lotz et al., 2004; Conselice & Arnold, 2009; Law et al., 2012a) and fail to account for the diversity of galaxy shapes that may be found at high redshift. Additionally, these methods need to be calibrated through visual inspection to establish the basis on which the morphological discrimination is done. Studies based on visual classification applied out to $z \sim 3$ usually define classes close to what is found in the local Universe to establish the evolution of the Hubble sequence across time (e.g. Lilly et al., 1998; Delgado-Serrano et al., 2010; Buitrago et al., 2013; Mortlock et al., 2013; Kartaltepe et al., 2015). These visual classifications are also crucial for the establishment of

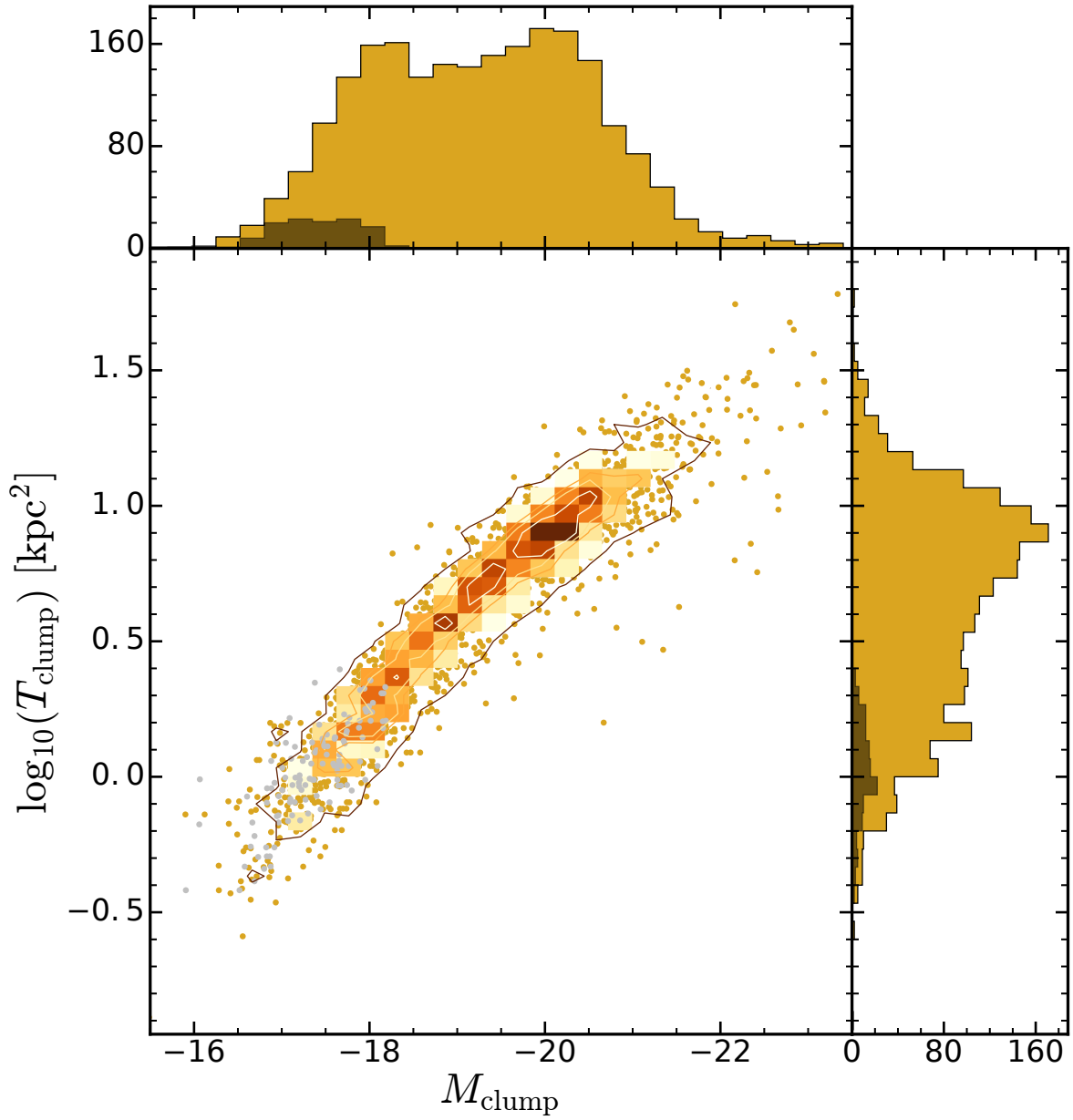


Figure 4.20. The black points and histograms show the distribution in areas and magnitudes for the negative clumps detected applying the same method on the inverted galaxy image. Most of the negative detections are found at $M_{\text{clump}} > -18$ which is fainter than the peak for the fainter clumps that is observed in the magnitude distribution (see figure 5.17). This indicates that the smaller clumps with $M_{\text{clump}} < -18$ are mostly real physical clumps.

Primary Class	Secondary Class	Identifier
Compact	Point-like	0
	Compact	1
Extended/Symm.	Round Shape	2
	2 centered components	3
	Elliptical Shape	5
	Cometary/Tadpole	7
Irregular/ Pair	Elongated	8
	Multicore/Clumpy	10
	Pair	-
Diffuse	Symmetric	13
	Asymmetric	14
Too Faint	-	16
No Image	-	-

Table 4.2. The grouping of primary and secondary morphological classes defined for the purpose of this study. The third column shows the scalar identifier associated with each sub-class that will be used for the establishment of a linear classification scheme. The adopted linear scheme is missing integers on the separation between primary classes. The exception is the distinction between extended round galaxies and compact galaxies which is subtler than other transitions (e.g. from extended elliptical to irregular).

unsupervised classification that will be required when future surveys produce datasets too large to be humanly processed (e.g. [Huertas-Company et al., 2015a](#)). I attempted to establish an adapted classification scheme better suited to the typical shapes I found at these redshifts which I will detail in the next section.

To perform this visual classification I developed a convenient graphical user interface (GUI) so that users could go quickly and classify large numbers of galaxies. This GUI is fully implemented in PYTHON using the *tkinter* (see figure 4.22). The code has been tested in both Linux and Mac OS X operative systems and since it is written in pure PYTHON should work under Windows as well.

4.5.1 MORPHOLOGICAL CLASSES

The main goal of this interface is to provide a simple, fast and reliable way to visual classify galaxies and systematize the information in a consistent manner. To do so, one will have available a set of images, in different photometric bands whenever possible, on which to decide which category best fits what one is seeing. The current objective is to do visual classification separately in the I and H bands using the information on other available bands to help assess the structure of the objects. The classification scheme that shall be used is a two step process based on primary general classes and secondary (see table 4.2).

Examples and description of what one means by each class/subclass are stated below. The primary classes are mutually exclusive, meaning that you can only choose one of the available options. As for the secondary classes you may, in principle chose more than one item. However, this should not be the general case as most of these classes are opposite of one another. The most common case where you may find useful to choose two secondary classifiers is related to the elongated+multicore/clumpy combination that resembles the *chain* morphological class defined in other studies. For two cases, pair and multicore/clumpy, there will be an additional parameter that you should input to better classify the galaxy. Whenever you choose one of them, a window pops up for you to enter the value you deem appropriate. Further details may be found on the subsection of each classifier.

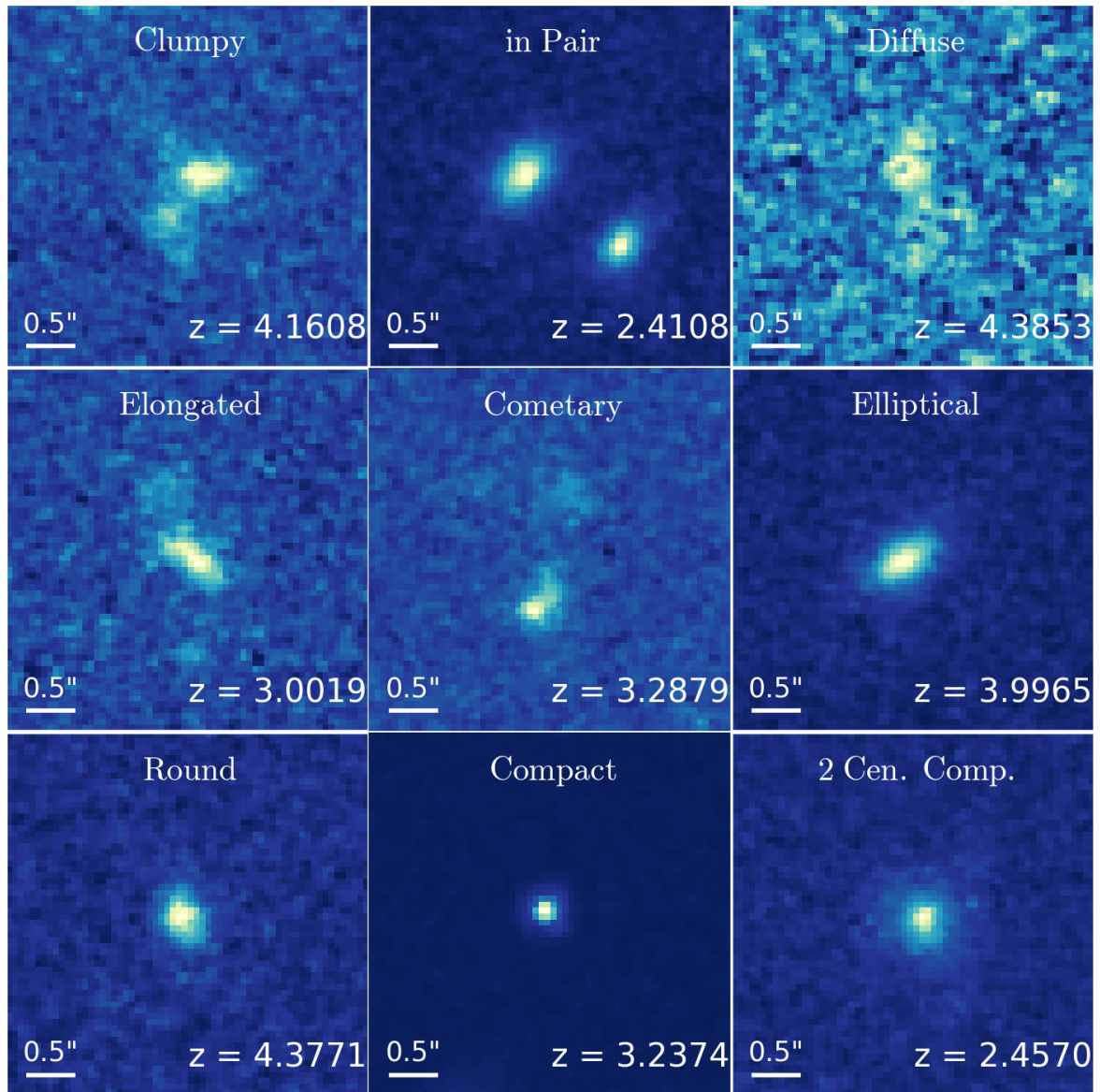


Figure 4.21. Different examples of morphological classes defined for visual classification.

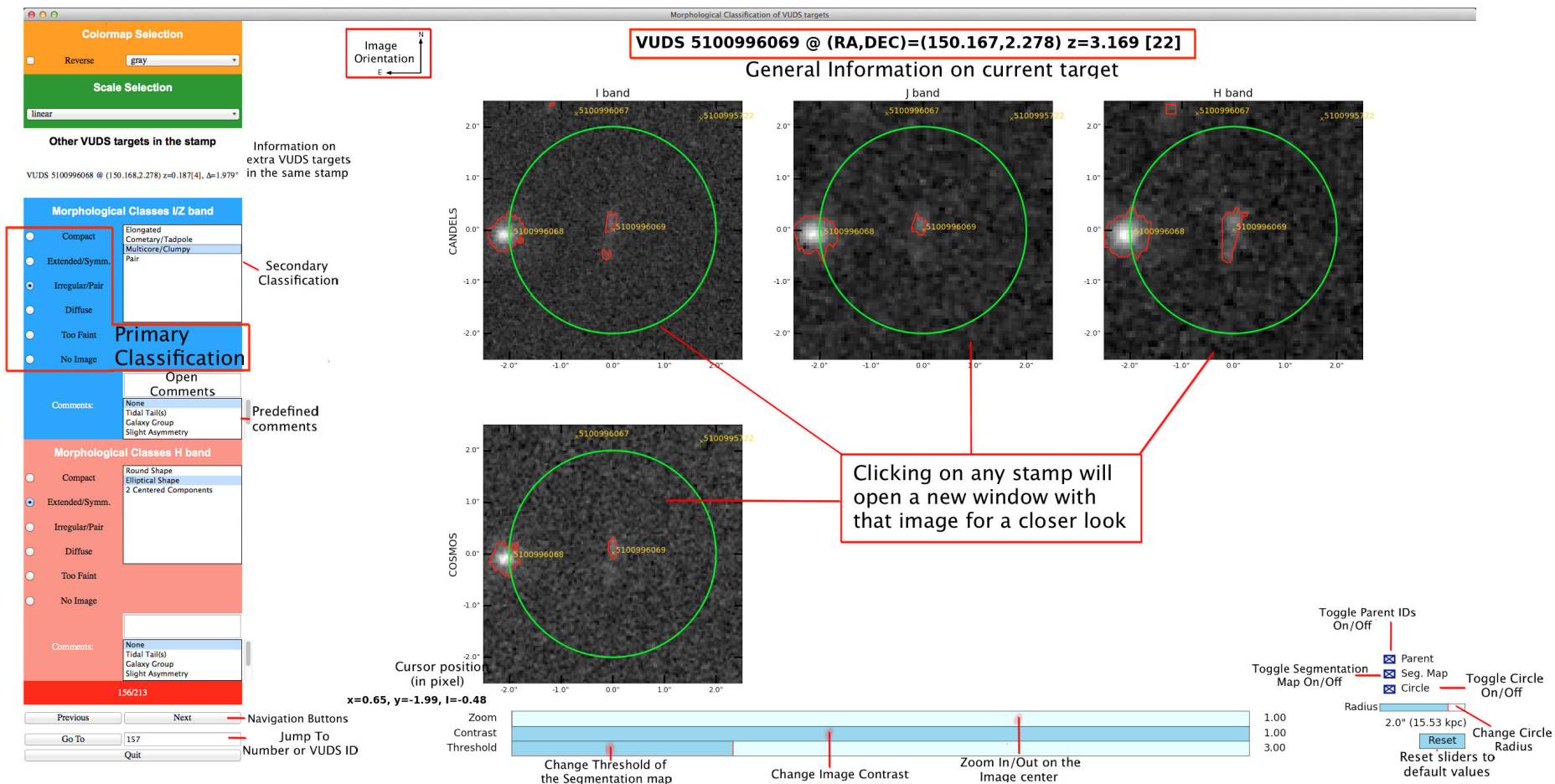


Figure 4.22. Outlook of the GUI interface.

- **Compact** - essentially small objects that are usually round in shape and have no hints of substructure. Point-like objects are a special subclass of compact objects due to their higher brightness and almost perfectly round shape resembling the image one would expect from a faint star in these surveys.
- **Extended/Symm** - Slightly more extended than compact objects, these galaxies should indicate the presence of a larger diffuse emission around the center resembling a local face-on disk. This class shall also be used for objects with extended emission that are symmetrical and can be approximated by an ellipse. They should resemble mildly inclined disks up to full edge on disks with no evident bulge. A rare but interesting class comprises the objects that appear to be a combination of a central light clump surrounded by large, diffuse and symmetrical emission. These are the objects that look like face-on disks with a central bulge component.
- **Irregular** - General class for irregular galaxies. A first subclass includes irregular elongated emission with no clear presence of more than one clump or even with no visible clumps at all. Cometary/Tadpole objects are elongated but lopsided leading to a shape resembling that of a comet or a tadpole. There should be a bright clump of light with one faint tail with no other clumps in it. Another class is objects clumpy in nature of with visible clumps embedded in a diffuse light. The clumps should be included in the same region of the segmentation map to be considered multicore. If the clumps seem to follow a single line you should choose the elongated+multicore/clumpy subclasses.
- **Diffuse** - This class subtends any diffuse objects with some degree of symmetry or not in their shape that do not fit any other of the previous classes.

If something remarkable about the object to be classified that does not fit well with any of the classifications above, or if anything of relevance to be added for posterior analysis the user is free to comment in the input box provided for the effect. There is also an additional set of predefined comments that one may want to choose whenever appropriate. It is possible to select more than one of the following options.

- *Tidal Tail(s)* - to select if you think that some of the faint features that you observe may be of tidal nature.
- *Galaxy Group* - To select if you see more than two large interacting members on the stamp file.
- *Slight Asymmetry* - To select if even though it may fit the Extended/Symmetrical class it presents a small asymmetry that is worth of notice.
- *Irregular Disk* - To select if it appears to be an extended disk with a patchy appearance.
- *Non-interacting companion* - In the case you see more than one source in the stamp of which one is clearly centered and no signs of interactions are present you should classify only the centered galaxy and select this option on the comments.

THE SPECIAL CASE OF PAIRS

Pairs are identified essentially as two (or more) distinct blobs of light separated in the segmentation map and at a distance of $< 2''$ from each other. However if the object seems composed of two merging galaxies, even if they are close enough to be extracted in the same region of the segmentation map, this subclass is to be chosen. After choosing this subclass a new window opens for further information on the particular object and on the morphology of the two main members of the system (see figure 4.23). The separation between those members and a simple classification for each of them should be provided. The meaning of each class is the same as

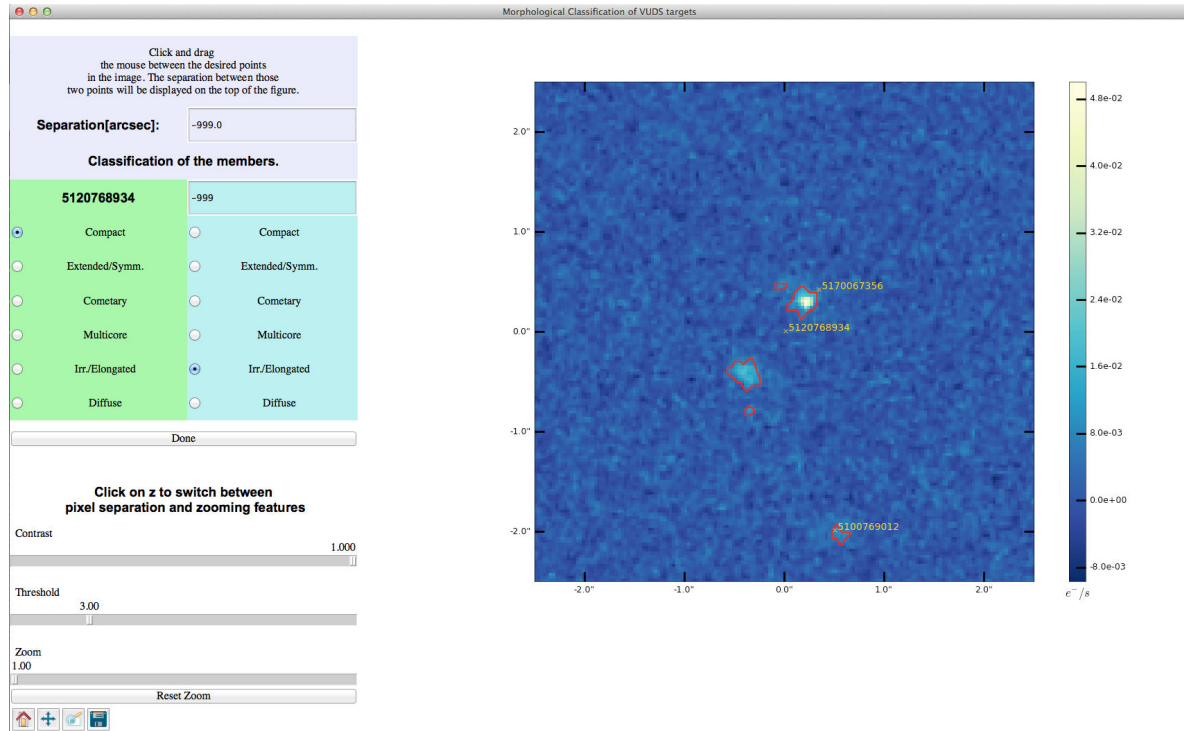


Figure 4.23. GUI pop up window after selecting the pair subclass. This window includes contrast sliders form the manipulation of images and a simplified version of the classification system presented in section 4.5.1 and table 4.2.

the main classification scheme. This allows one to trace the morphological type of the VUDS target while keeping the information on the existence of a neighbor source.

4.5.2 CLASSIFICATION PROCEDURE

The visual classification of galaxies was a two stage process. In the first stage, 9 volunteers from the VUDS collaboration contributed to classify 297 galaxies taken from the VUDS-CANDELS area where deep and multi-band imaging was available for all sources. In the second stage, 2507 galaxies with HST imaging (most from the COSMOS ACS survey) were individually classified by 12 volunteers. This classification was done using an interactive tool developed for that purpose (see figure 4.22) and in a way that each object was independently classified by two people.

4.6 CLASSIFYING THE $\text{Ly-}\alpha$ EMISSION IN 2D SPECTROGRAMS

The physical processes involved in the escape of $\text{Ly-}\alpha$ photons from their emitting region is not simple (e.g. Neufeld, 1991; Zheng et al., 2011; Dijkstra & Kramer, 2012; Verhamme et al., 2012; Laursen et al., 2013; Behrens & Braun, 2014; Lake et al., 2015). From observations there are evidences that the escape fraction of $\text{Ly-}\alpha$ photons is correlated to dust attenuation and SFR (e.g. Hayes et al., 2010, 2011; Atek et al., 2014; Matthee et al., 2016), and also correlated with the column density of neutral hydrogen (e.g. Shibuya et al., 2014a,b). To pinpoint the mechanisms which favor the observation of $\text{Ly-}\alpha$ in distant galaxies I take advantage of the VUDS large spectroscopic sample and aim to classify different type of emitters according to the spatial profile of the $\text{Ly-}\alpha$ line in 2D spectrograms with respect to the UV continuum emission. These classes will then be matched to the wealth of spectrophotometric data to

shed some light on the topic of Ly- α escape mechanisms.

I have devised a classification scheme that aims to divide galaxies with Ly- α in emission with respect to the spatial properties observed on the 2D spectra obtained with the VIMOS spectrograph. After data processing sky subtracted, wavelength and flux calibrated, 2D spectrograms are available for each galaxy in the form of an image, with one axis being the dispersion direction, with wavelengths in Angstroms, and the other axis being the spatial direction of the slit on the sky, crossing each galaxy in an East-West direction centered on the galaxy position as measured on ground based multi-band imaging catalogs (see [Le Fèvre et al., 2015](#)). The property of a spectrum can therefore be explored along the slit in the spatial direction to give indications on the distribution of line or continuum emission along the slit. For most objects a continuum emission trace is readily visible and its position along the slit easy to identify. At the position in wavelength corresponding to Ly- α the distribution of emission can be followed along the slit. Single emission line galaxies, and in the case of interest here Ly- α , is the only category of galaxies for which no continuum emission is visible and only the line can be observed. From these considerations I have defined the following Ly- α classes:

- **Class 1: No emission**, where there is no line emission found in the 2D spectra.
- **Class 2: Coincident**, where the total extent of the emission line coincides with the extent of the galaxy continuum
- **Class 3: Extended**, where the total extent of the emission line is more extended than that of the galaxy continuum
- **Class 4: Offset**, where there is an offset between the center of the emission line and the center of the continuum emission.

There are two more classes that are defined in the classification. **Single Line** emitters (Class 5), where there is only an emission line and no flux continuum is seen. **Faint** emitters (Class 6), where there is an hint of an emission line and continuum emission, but the line is too faint to be properly classified in one of the above classes. Examples of each of the classes with line emission are shown in figure 4.24.

Each class can be schematically represented by different modes of Ly- α escape from the galaxy. Coincident emission occurs when there is little to no scattering of the radiation and one is observing the emission from its original regions. Extended emission is when there is significant scatter on the surrounding gas and we observe the halo around the galaxy. Offset emission can happen for one of two reasons, either there are two clumps/galaxies spatially offset and one is emitting and the second is not or there is a single galaxy with an asymmetric gas/dust distribution (potentially cause from stellar winds and/or supernovae explosions) from where the Ly- α photons preferentially escape from one side of the galaxy. If no emission is observed there is likely high dust contents or high density of neutral hydrogen preventing Ly- α from being observed in emission. Faint and Single line emitters are low S/N in the line and continuum, respectively, and thus are purely observational classes. These are summarized in figure 4.25.

4.6.1 CLASSIFICATION PROCEDURE

To perform this visual classification I developed a new graphical user interface (GUI) inspired by what I described in section 3.3. This GUI is also fully implemented in PYTHON using the *tkinter* (see figure 4.26). The code has been tested in both Linux and Mac OS X operative systems and since it is written in pure PYTHON should work under Windows as well.

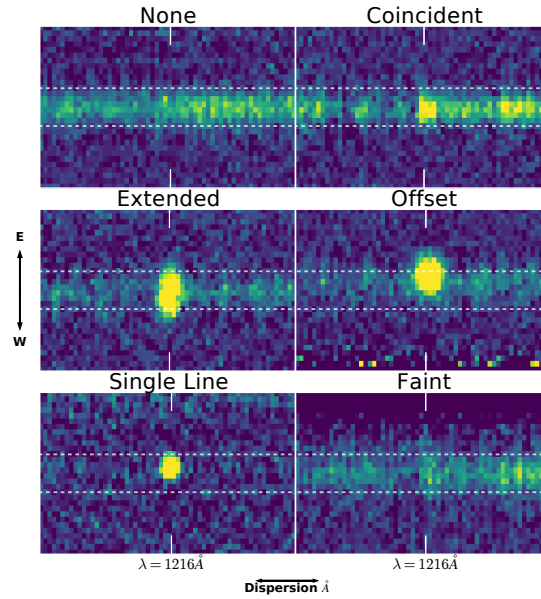


Figure 4.24. Examples of each of the main classes that are defined for the purpose of this study. The dispersion direction is along the horizontal axis while the spatial direction goes from West to East (from bottom to top) in the vertical axis. Each panel is identified with the typical class and I show the typical window on the continuum as dashed white lines. Each frame is centered at the rest-frame of the Ly- α line.

In order to carry on with the individual visual classification of the 4360 galaxies I had a total of 10 volunteers. The sample was divided in 20 data packages of 218 galaxies each and then each volunteer was assigned 4 different data packages. The package distribution was done so that no pair of volunteers is repeated and for each set of 218 spectra I have results from a different pair of classifiers. This was done in order to minimize personal bias in the final classification.

Each person used the interactive tool that I developed within the VUDS collaboration (see figure 4.26) that allows the user to see and interact with both 1D and 2D spectra, imaging centered on the VIMOS slit and allow for a instantaneous visual mapping between the photometry and the spectroscopy by moving the mouse along the spatial direction of the slit. Then, each classifier had to choose one of the main classes defined above whenever an emission line was seen on the 2D and 1D spectra.

4.6.2 DEPENDENCY OF THE CLASSIFICATION ON THE FLUX LIMIT AND GEOMETRY OF THE SPECTROGRAMS

The classification described in section 4.6 relies uniquely on the visual appearance of the continuum and Ly- α emission on the 2D spectrograms. The person performing the classification has access to the wavelength and flux values along the spectrogram, and color stretch manipulation, and can forge a judgment based on this. This qualitative assessment works well for a classification along the broad classes identified above. It is however dependent on the depth of the spectra. The average surface brightness reached by the VUDS observations is $\sim 10^{-18}$ erg cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$, and my classification scheme is directly linked to this depth. Deeper observations may uncover emission regions with a different spatial distribution which may then lead to change the classification of a given object. This would affect mainly classes two and three only if the spatial distribution of line emission versus continuum emission would be significantly different than at the levels probed here.

Another important element is that I sample an object spatially along one random direction (in the objects' frame), and this spatial slice may not be representative of the whole galaxy.

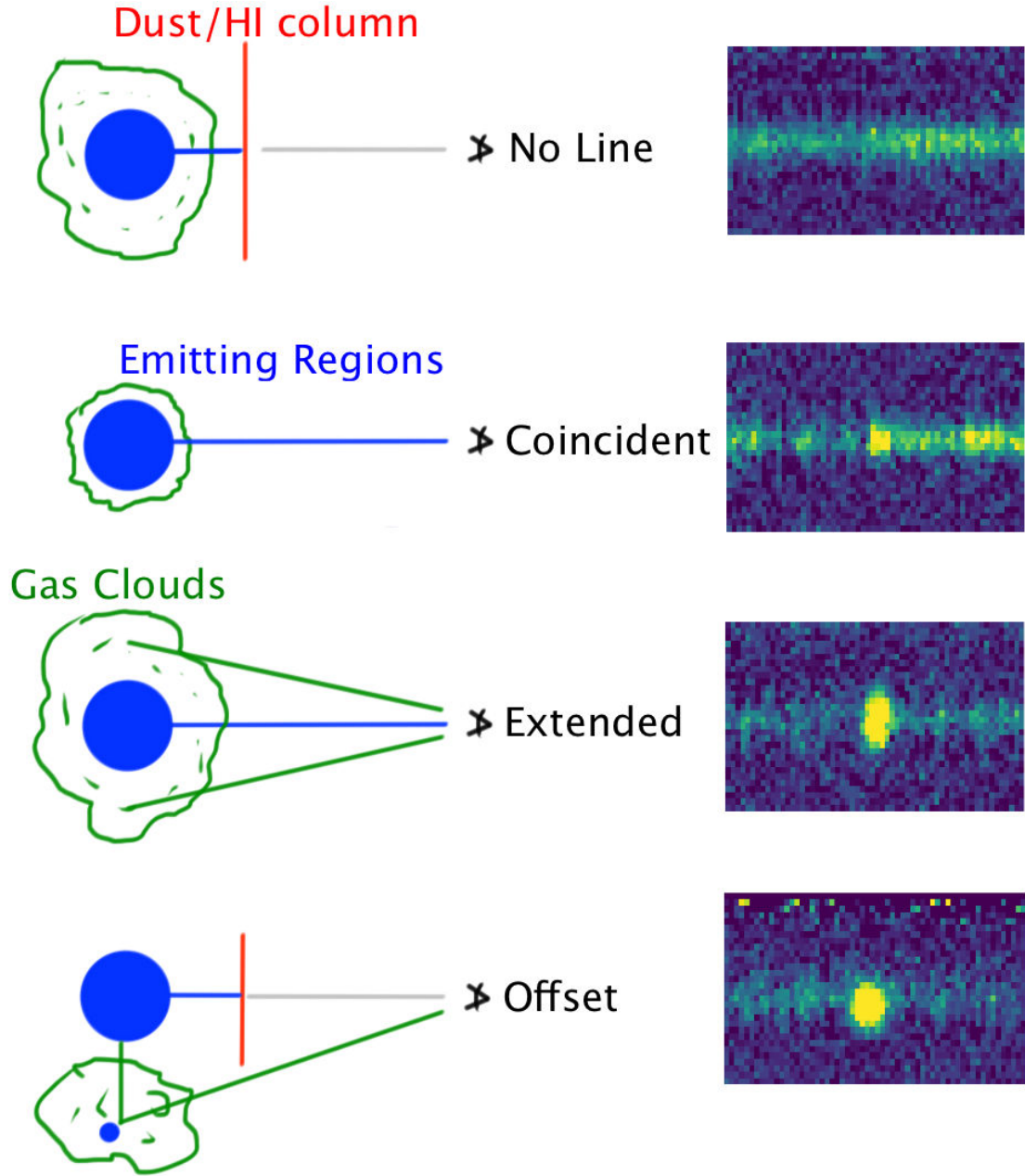


Figure 4.25. Schematic view of four of the main classes and its relation to the spectral observations. From top I show no line emission, coincident line emission, extended line emission and offset line emission. The blue circles represent Ly- α emitting regions. The red vertical lines represent the dust and/or HI gas columns that absorb or destroy Ly- α photons. In green amorphous regions I show gas clouds surrounding the emitting regions.

However, this study analyses for the first time a large sample of galaxies and these number statistics are giving a robust estimate of the fraction of galaxies in different classes. It is evident that more detailed observations of the geometry of the Ly- α emission with respect to the continuum can be obtained using integral field spectroscopy, but is currently available only for a limited number of objects (e.g. [Wisotzki et al., 2016](#)). My study offers the possibility to pursue more detailed studies by selecting specific classes of galaxies from a large sample representative of the star-forming galaxy population at the high redshifts $2 < z < 6$.

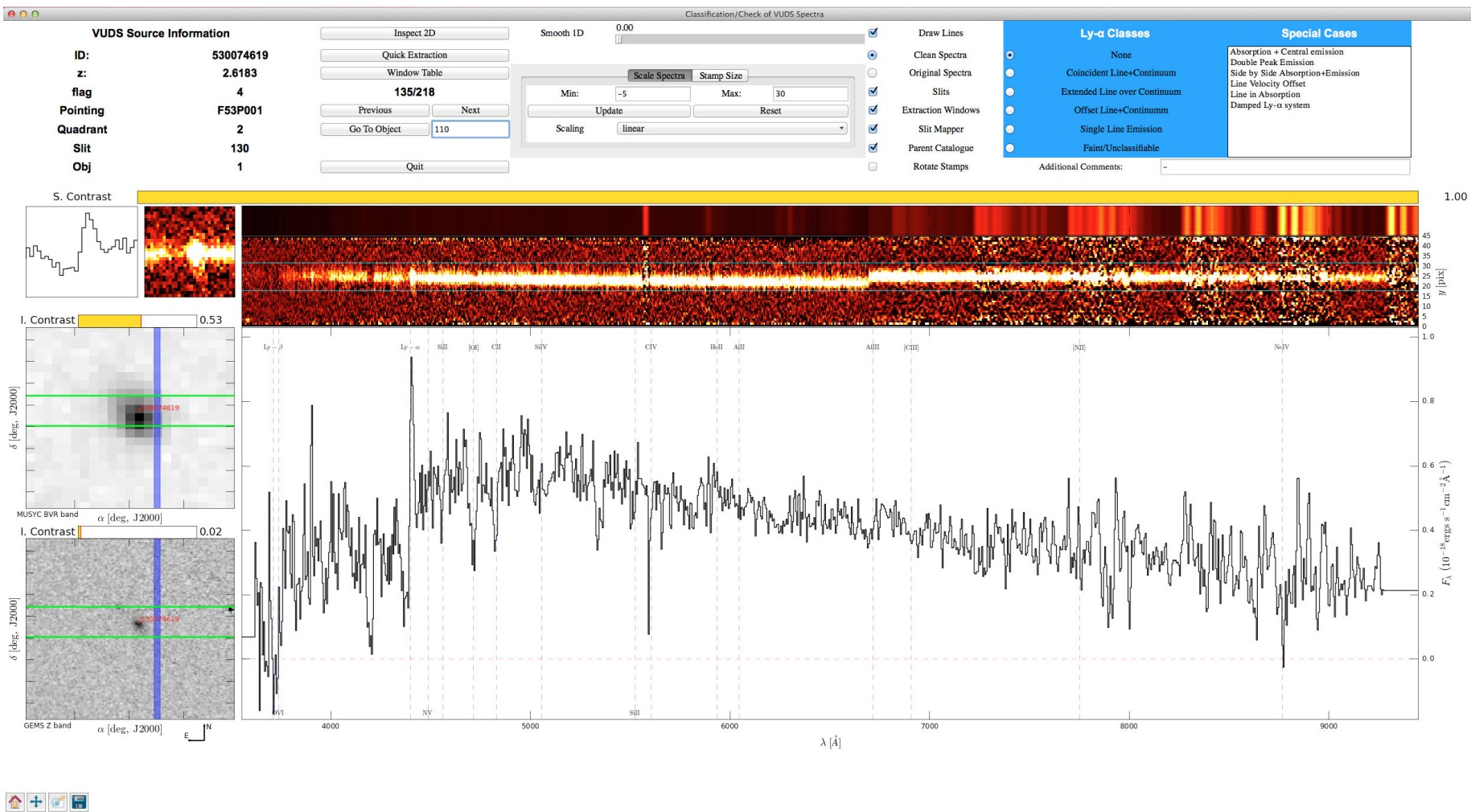


Figure 4.26. Outlook of the GUI interface for Ly- α classification.

• This page is intentionally left blank •

5 | Morphological properties of $2 < z \lesssim 6$ star-forming galaxies

Contents

5.1	A different look on galaxy sizes	84
5.1.1	Results: r_e measurements	84
5.1.1.1	Dependency with color	84
5.1.1.2	The impact of cosmological dimming on r_e	88
5.1.2	Results: r_T measurements	88
5.1.3	Average galaxy profiles and light concentration	90
5.1.3.1	Image stacks	90
5.1.3.2	Luminosity profiles	92
5.1.3.3	Light concentration of individual galaxies	92
5.1.4	Size evolution with redshift	93
5.1.4.1	Effective radius r_e evolution	95
5.1.4.2	Total size r_T evolution	95
5.1.5	Size relations with physical parameters	95
5.2	The prevalence of clumps in assembling galaxies	98
5.2.1	The distribution of the number of clumps per galaxy	98
5.2.2	The fraction of clumpy galaxies	98
5.2.2.1	Computing the clumpy fraction using a different methodology	100
5.2.3	Physical properties of clumps	102
5.2.3.1	Bright and large clumps are in two-clump galaxies	102
5.2.3.2	Luminosity ratios	105
5.2.3.3	Clump stellar masses	105
5.3	Morphology visual classification	105
5.3.1	Agreeing on a classification	105
5.3.2	Class distribution in CANDELS	107
5.3.3	Extending the classification to COSMOS	108
5.3.4	Evolution with redshift	110
5.3.5	Automated Morphological Discrimination	111
5.3.6	Physical description of morphological classes	113
5.4	Extending morphology to Ly- α studies	121
5.4.1	Classifier agreement	121
5.4.2	Ly- α shapes	122
5.4.3	Physical properties of the different Ly- α line morphology classes	123
5.4.3.1	Stacked spectra	127
5.4.3.2	The UV size of Ly- α emitting galaxies.	131

5.1 A DIFFERENT LOOK ON GALAXY SIZES

In this section I present my results on the measurement of galaxy sizes through standard parametric fitting which is fully described in section 4.1 and through the new non-parametric method that was defined in section 4.3.

5.1.1 RESULTS: r_e MEASUREMENTS

I fit all galaxies in the stellar mass selected sample defined in section 3.4.3 using the automated GALFIT procedure described in section 4.1 to obtain effective size measurements r_e . After fitting all galaxies, a subset of 19.5% of those GALFIT failed to converge. These galaxies are analyzed on an object-per-object basis and a manual re-fitting is attempted by tuning the initial set of parameters. After this manual try, of the 1242 galaxies in the stellar mass selected sample, 263 (15.7%) objects have no structural parameters because GALFIT failed to converge. These objects are usually very low surface brightness or highly concentrated galaxies.

The distribution of effective radii presented in figure 5.1 show similar shapes at all redshifts showing a slow monotonic decrease in their median sizes as redshift increases. Each distribution is fitted with a normal function (in log space) and the derived sigma values from the fit are similar at all redshifts (0.23, 0.26, 0.29 and 0.24 with growing redshift).

The overall evolution of sizes across the redshifts considered here is shown in figure 5.2. I find that the effective radius of galaxies continuously decreases over the redshift range of my sample. Galaxies with $2 < z < 2.5$ have $\langle r_{e,circ} \rangle = 1.67 \pm 0.09$ kpc, while in $4 < z < 4.5$ the median effective radius is a factor of 1.6 smaller, $\langle r_{e,circ} \rangle = 1.05 \pm 0.05$ kpc. In every redshift bin a large dispersion in the effective radii is measured amongst the galaxy population and for all redshift bins $\sim 9\%$ of the population has measured radii which are large ($r_{e,circ} > 3$ kpc) and some extremely so (7 – 10 kpc) in all redshift bins save the last. These features of the distribution are discussed together with other measurements in sections 5.1.4 and 6.1.

5.1.1.1 DEPENDENCY WITH COLOR

To study size evolution across a large redshift range one should use common rest-frame measurements whenever possible. When not possible some approximations must be made. The simplest one consists on using the observed band closest to the rest-frame one wants to consider (e.g. Morishita et al., 2014; Shibuya et al., 2015). A more evolved approach is presented by van der Wel et al. (2014) where a wavelength dependence of the measured radii is observed and fitted. A correction is then applied to each galaxy to obtain the value of the radius at exactly the wavelength one chooses. However, such approaches require a multi-wavelength coverage of the targets which is not available for the majority of my sample.

For those galaxies which are in the CANDELS area (roughly 10% of my sample), I did compute their effective radii in three different bands: F814W, F125W and F160W. Doing a simple inter-wavelength comparison one finds that the derived sizes are similar in all three bands (see figure 5.3). I report a small offset in the median values of $r_I - r_H \approx -0.04$ kpc and $r_I - r_J \approx -0.01$ kpc. The dispersion on the size measurements across different bands is 0.21 dex and 0.20 dex for F814W-F160W and F814W-F125W comparisons respectively. For further inspection, I used the wealth of multi-wavelength observations on the COSMOS field (space and ground based imaging) with a variety of instruments from three different surveys (CFHTLS in the optical, and WIRDS and UltraVISTA in the near-infrared) to obtain size measurements up to the Ks band which, at the highest redshifts considered here, still probes the regions above the Balmer/ D_n 4000 break. Then, for each galaxy in my sample, I plot its size value as a function

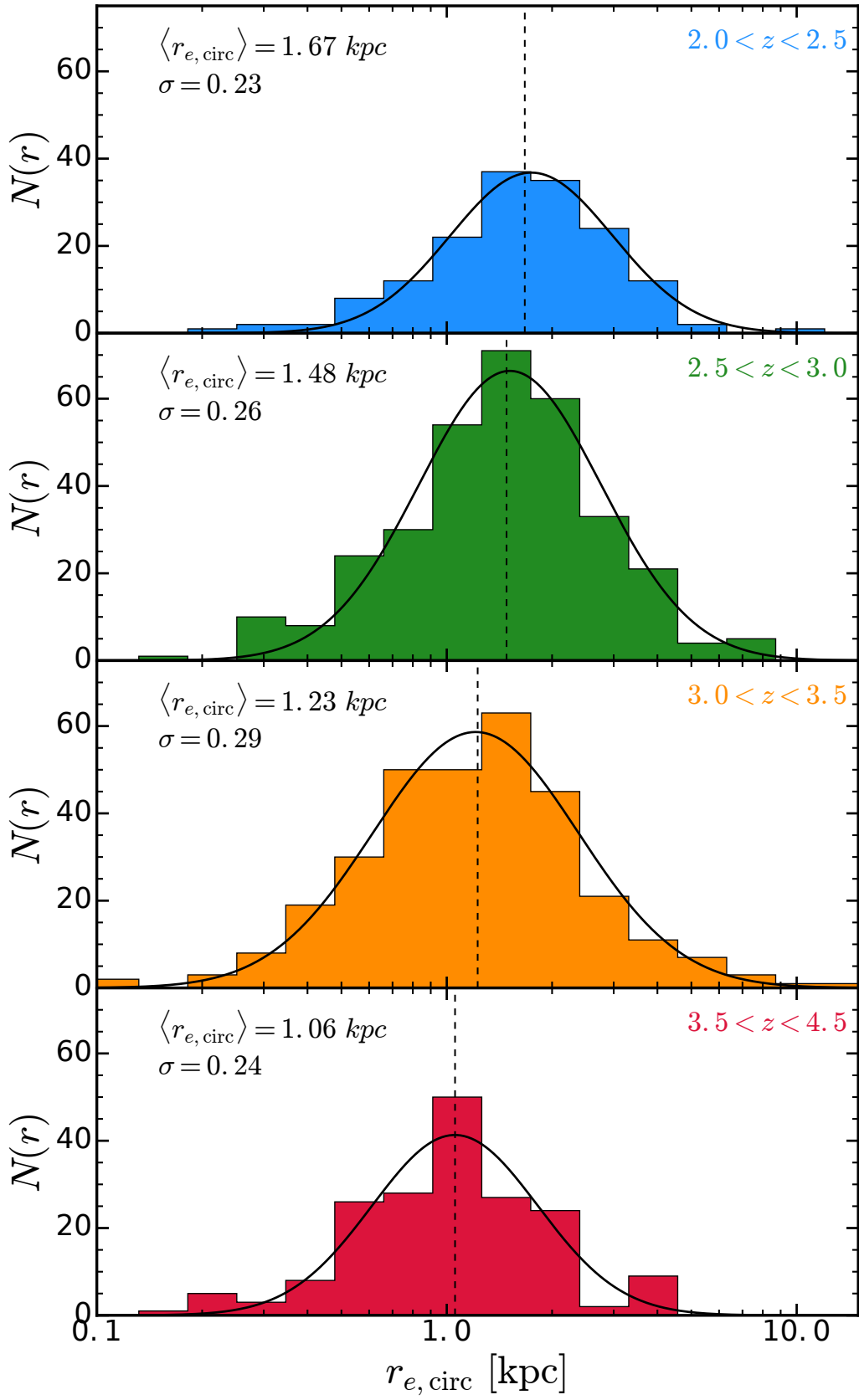


Figure 5.1. Effective radius distribution for different redshift bins. The vertical dashed line indicates the median value for each bin. The black line is the fit of the distribution using a normal function in log space.

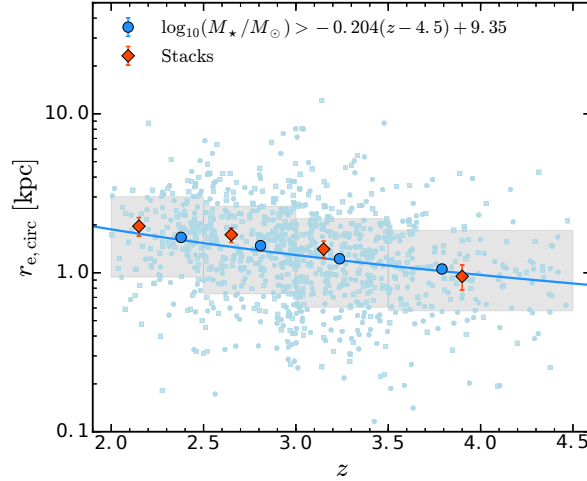


Figure 5.2. Effective radius evolution with redshift. Each galaxy with a good size measurement is plotted with a small blue point (squares for redshift confidence 2 and 9, circles for 3 and 4). The median values (in redshift and size for each bin) and respective error ($\sigma/\sqrt{N}$) per redshift bin are shown by the large blue points with the error bars. The shaded region delimits the 16th and 84th percentiles including 68% of the sample in each redshift bin. The red diamonds are the effective radii of stacked images computed from the method described in section 5.1.3 and are plotted at the center of the redshift bin.

of the observed wavelength computed using the knowledge of the spectroscopic redshift and the filter wavelength, λ_F .

$$\lambda_0 = \frac{\lambda_F}{1+z} \quad (5.1)$$

Size measurement results at different wavelengths obtained from my galaxies are presented in figure 5.4. The overall trend is that, at the redshifts considered here, measurements of circularized effective radii are independent on wavelength to first order. This result tells us that circularized effective radii computed from F814W observations are not much affected by the rest-frame wavelength at which the galaxies are observed. To quantify the wavelength dependence I have opted to fit the relation

$$\log(r) = \beta_\lambda + \alpha_\lambda \log(\lambda_0) \quad (5.2)$$

to all the data points considering space based imaging and ground based imaging separately. I find that for ground based data (covering from I to Ks bands) the slopes measured are all consistent with no wavelength dependence ($\alpha_\lambda = 0$ is within 1σ at all redshift intervals). For space based data (covering from I to H bands) I find slightly positive slopes indicating slightly larger sizes in the redder bands, but only marginally significant 1.9σ away from a flat slope $\alpha_\lambda = 0$. Using my fit values in equation 5.2 I estimate that the ratio ranges within $r_{1700}/r_{2500} = 0.89 - 1.01$.

In a complementary test, I fit the size-wavelength relation for all individual galaxies which have measurements in three or more bands. The median slope is $\alpha_\lambda = 0.03 \pm 0.27$ and $\alpha_\lambda = -0.12 \pm 0.34$ for space and ground based observations, respectively. This translates into a ratio $r_{1700}/r_{2500} = 0.99(1.05)$ for space (ground) based data. This supports the fact that the wavelength dependence of galaxies in my sample is very shallow and consistent with no dependence at all for the ensemble of the galaxies in my sample. I note however that there is a large dispersion amongst my galaxies, which means that the wavelength dependence requires a different treatment when considering a case by case basis.

I show in figure 5.4 that I can measure sizes from ground-based data for the galaxies in my sample. This would allow for the use of the entire VUDS sample, including galaxies in the VVDS-2h field. However, since the convergence success of GALFIT is much less ($\sim 30\%$)

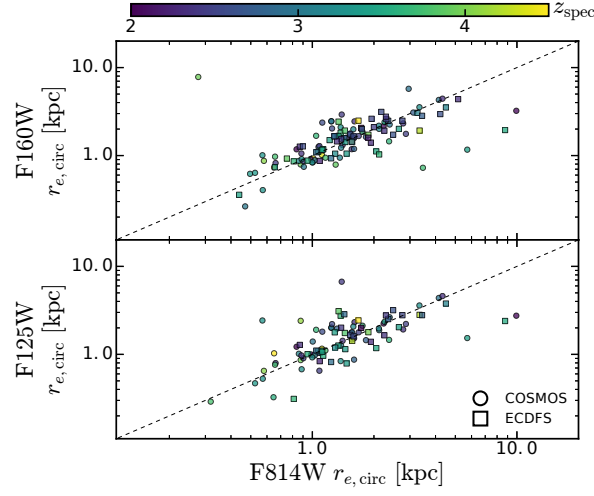


Figure 5.3. Comparison of size measurements derived with GALFIT for a subset of 153 (118) VUDS galaxies at $2 < z < 4.5$ with available F814W and F160W (F125W) images from CANDELS. Results are split in two bands: F160W on the top panel and F125W on the bottom panel. Circles and squares refer to COSMOS and ECDFS respectively. The dashed black line is showing where both radii are equal. The symbols are color coded according to their spectroscopic redshift and the mapping is shown in the colorbar on top of the plots. Less galaxies are available in the J-band comparison because there is no such data available in ECDFS.

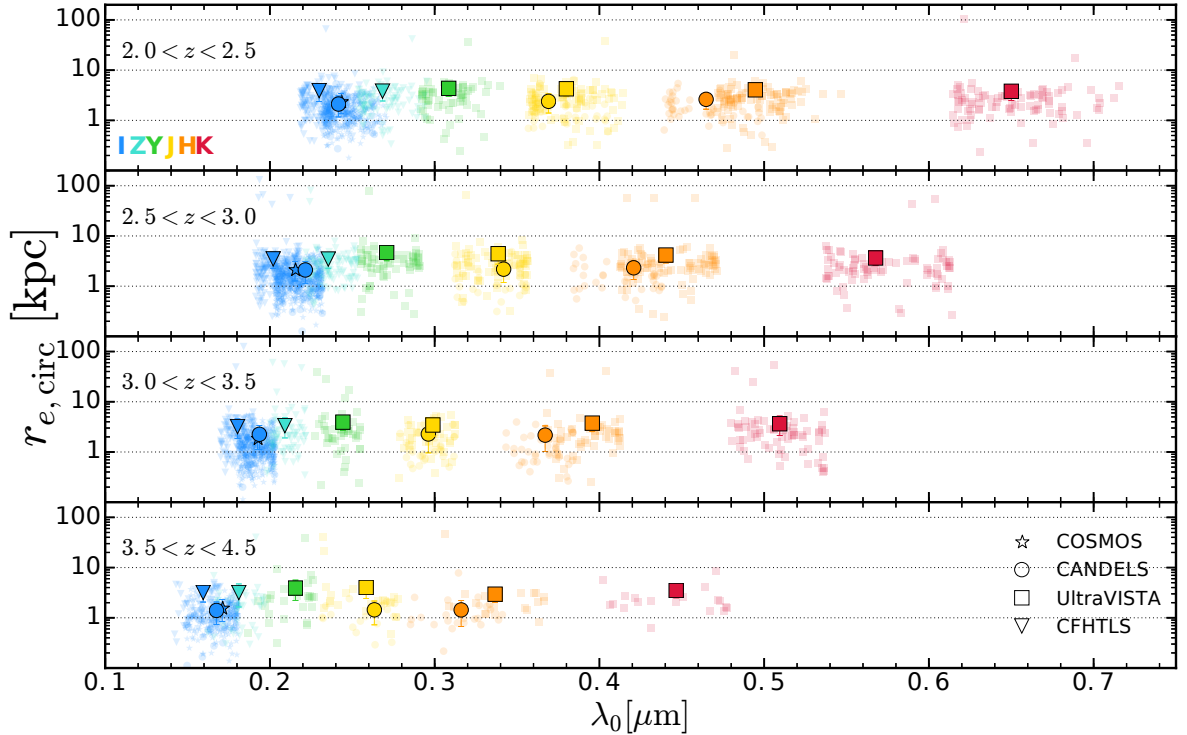


Figure 5.4. Measured Sizes as a function of wavelength for galaxies with $\log_{10}(M_{\star}) > 9.5$ at $2 < z < 4.5$ in the COSMOS field. Different symbols correspond to different surveys (symbol coding on the bottom panel) and different colors to different observed bands (color coding in the top panel). Each point represents the size of a given galaxy at the rest-frame wavelength of the pivot of the filter.

and the fact that the method described in section 4.3.1 is PSF dominated preventing us from getting galaxy sizes (sizes are systematically overestimated when compared to those obtained with HST images) I opt to conduct my analysis on space-based data only.

5.1.1.2 THE IMPACT OF COSMOLOGICAL DIMMING ON r_e

A key point to take into account in this analysis is that GALFIT-based measurements do not take into account the surface brightness (SB) dimming effect which is a strong function of redshift. Parametric modeling works well even under low S/N conditions¹, recovering the right parameter values, although with larger uncertainties. This should, in principle, deal with the increased SB dimming of galaxies at higher redshift. The dimming effect, if significant, would act in the sense of getting smaller sizes at higher redshifts that would in turn impact the derived evolution into having a steeper slope. Thus, a correction for the cosmological dimming could lead to a weaker size evolution.

I have tested this scenario by masking the pixels that are below the surface brightness threshold that I use (see section 4.3.3) and then run GALFIT to obtain the size measurements from this pixel set reduced to the brightest regions of galaxies. I find that GALFIT finds similar sizes for both cases with and without masking those low surface brightness pixels and that the trend in evolution is not affected.

5.1.2 RESULTS: r_T MEASUREMENTS

I now turn to the results obtained on using the total size measurements that I described in section 4.3. This is designed to avoid the limitation of computing effective radii based on the assumption that galaxies have symmetric shapes. Of the 1242 galaxies in my stellar mass selected sample, 67 objects have no measured value of r_T . These failures are due to the lack of pixel fluxes above the selection threshold defined in equation 4.77 for 17 objects and due to the lack of color information for 5 objects. The other 45 objects are on the edge of the image mosaic and thus no sufficient information is available to derive a size.

The distribution of total sizes is presented in figure 5.5 for the four redshift bins previously defined. The shape of the distribution remains roughly the same with redshift. The Gaussian fit on each sub-sample yields sigma values of (0.154, 0.141, 0.168, 0.154 kpc) with increasing redshift.

I compare the total size measurements to the circularized effective radius obtained in section 5.1.1 in figure 5.6. Galaxies with the larger $r_{e,circ}$ are also larger in total size. However, this trend deviates from the linear relation and there is a large scatter in the relation. The scatter is somewhat expected as I am dealing with highly irregular morphology. While GALFIT gives a heavier weight to the brightest pixels (which can be locked into a single bright clump in a large galaxy), r_T measures the whole galaxy extent. GALFIT can pick up fainter *buried* flux of a galaxy by extrapolation of the profile measured on the bright pixels, which is not picked up when computing the total size using my method which explains why some galaxies have $r_{e,circ}$ larger than r_T . It is interesting to note that the $r_{T,PSF-corr}^{50}$ is nicely correlated with $r_{e,circ}$, as shown in figure 5.6, with a dispersion of 0.23 dex which is a consequence of the frequent asymmetric shapes in my sample.

The evolution of total sizes across the redshifts considered here is shown in figure 5.7. I find that total sizes are staying roughly constant over the redshift range $2 < z < 4.5$, with $r_{T,corr}^{100} \simeq 2.2$ kpc. The dispersion around the mean is $\sigma \simeq 0.9$ kpc (0.21 dex), and I find galaxies that are as large as ~ 5.5 kpc and as small as ~ 0.5 kpc at all redshifts in this range. Size

¹See http://users.obs.carnegiescience.edu/peng/work/galfit/TFAQ.html#size_and_noise

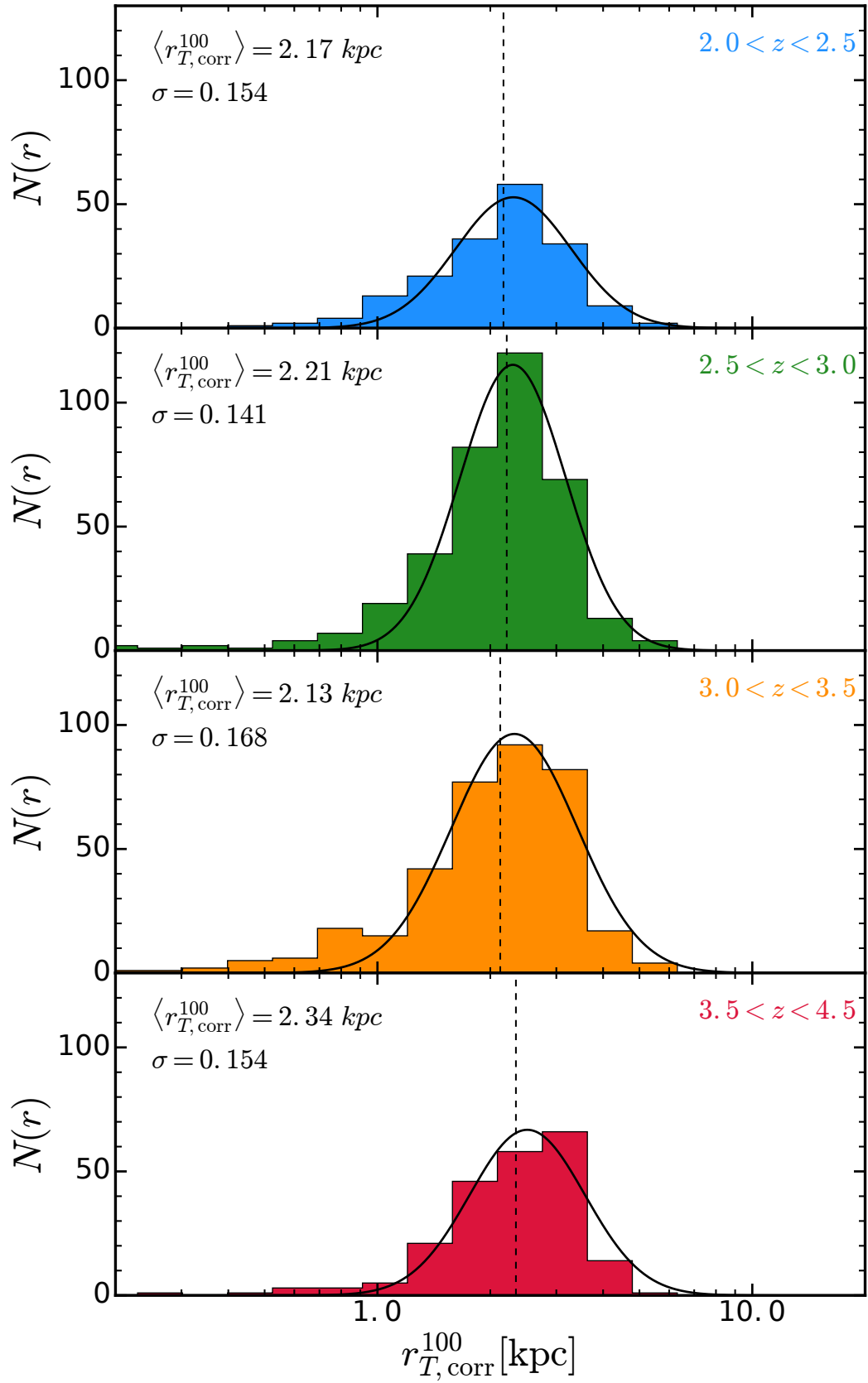


Figure 5.5. Total size distribution for different redshift bins. The vertical dotted line indicates the median value for each bin. The black line is the fit of the distribution using a normal function in log space.

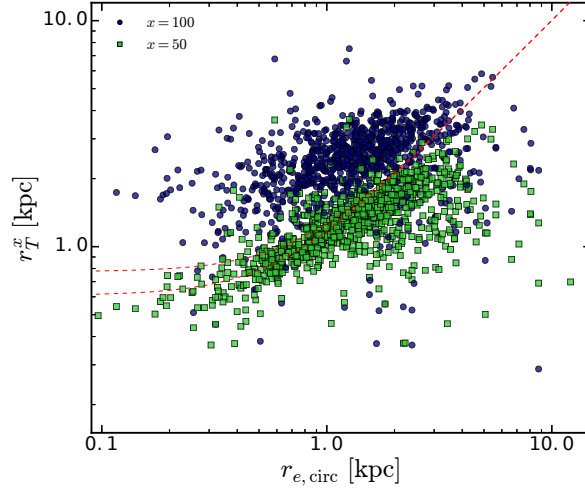


Figure 5.6. Comparison of the two size estimates computed in this thesis. In dark blue points I show the comparison to $r_{T, \text{corr}}^{100}$ and in green points to $r_{T, \text{PSF-corr}}^{50}$. The red dashed lines corresponds to the equation $r_T = \sqrt{r_{e, \text{circ}}^2 + \text{FWHM}^2}$ for the limit redshifts 2 and 4.5 (top and bottom lines respectively).

measurements using this definition are consistently larger than sizes provided by the effective radius r_e . This is discussed in sections 5.1.4 and 6.1.

I show the dependence of the absolute value of the measured sizes as a function of the chosen value of k_p in figure 5.8. As expected when using different limiting isophotes over a range of 2.5 in luminosity changes the size values. It is therefore essential to quote the absolute luminosity of the isophote used to compute galaxy sizes. I note that at all times, the observed trends as a function of redshift are consistently different from those observed with GALFIT, with approximately constant sizes as a function of redshift while the effective radius is observed to strongly decrease.

5.1.3 AVERAGE GALAXY PROFILES AND LIGHT CONCENTRATION

Since the total sizes of galaxies, measured at the same surface brightness level, seem to not evolve much with redshift, I investigate if the same pattern applies to the light profiles. I do this by looking at the stacked profiles and at the individual measurements of light concentration in galaxies.

5.1.3.1 IMAGE STACKS

In order to investigate the evolution of the light profiles I stack images of the large number of sources in my sample to follow the profile at larger radii than from individual images. The stacking procedure starts by collecting a $10'' \times 10''$ stamp image for each galaxy in the sample. Then, one runs SExtractor to find the light-weighted center of each source. I shift the image by the difference between the light-weighted center and the physical image center, using a cubic spline interpolation to re-scale the image onto a common grid. After processing the entire sample for a given redshift bin, I take, at each position, the median pixel value as the *flux* of the stacked image. I also produced a stack based on the straightforward sum to the images normalized by the total galaxy flux. The results of both methods give the same qualitative answers.

Stacking within a redshift bin, smears the rest-frame light over the interval. Also, when comparing different redshift bins I am effectively looking at different rest-frame light. This

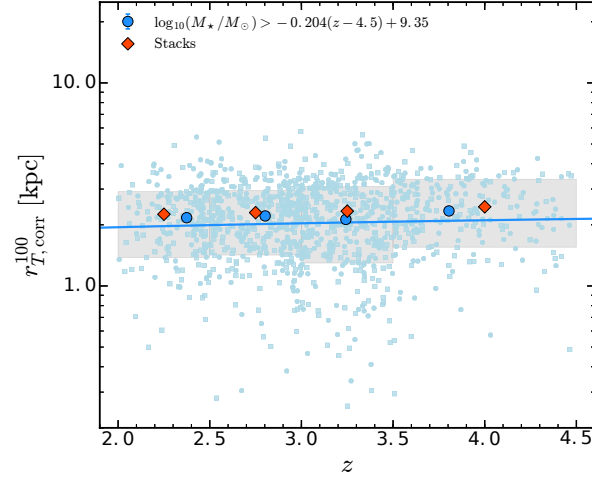


Figure 5.7. Total size evolution with redshift. Each galaxy is plotted with a small blue point (squares for redshift confidence 2 and 9, circles for 3 and 4). The median values and respective error ($\sigma/\sqrt{N}$) per redshift bin are shown by the large blue points with the error bars. The shaded region delimits the 16th and 84th percentiles including 68% of the sample in each redshift bin. The red diamonds are from the stacked images computed from the method described in section 5.1.3.

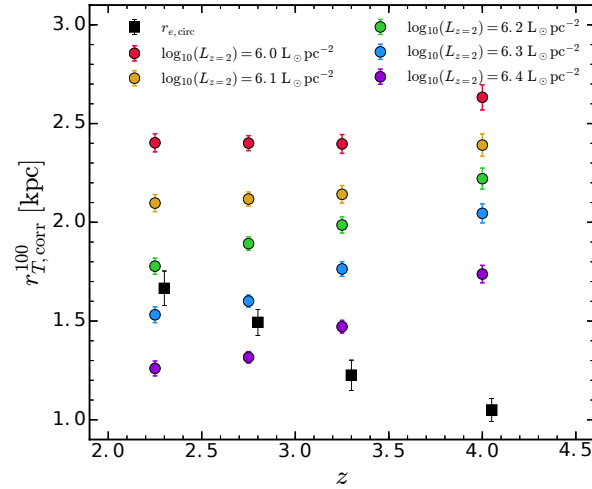


Figure 5.8. Total size measurements defined at different values of k_p that correspond to different luminosity thresholds at $z = 2$. From top to bottom, the colored circles correspond to $k_p = 0.8, 1.0, 1.2, 1.5, 2.0$. The color coding is the same as figure 4.12.

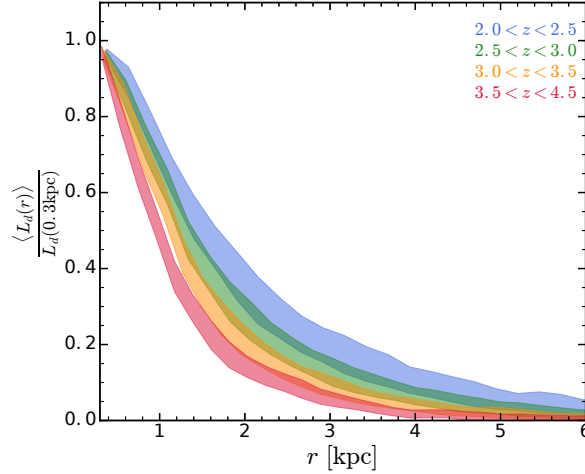


Figure 5.9. Normalized surface luminosity profiles of the median stacked F814W band images of galaxies in my sample at four different redshift bins (normalized at $r=0.3$ kpc). The width of each profile encodes the surface luminosity error. This profile comparison shows the increased light concentration at higher redshifts.

ranges from ~ 2500 in the lowest redshift bin down to ~ 1600 in the highest redshift bin. As shown in section 5.1.1.1, sizes derived are roughly the same across this wavelength range. This difference in rest-frame wavelengths has no effect on the comparison of the profiles discussed in the next section.

5.1.3.2 LUMINOSITY PROFILES

The redshift dependency of the light profile derived from the stacked images is presented in figure 5.9. I convert the median stacked profiles into surface luminosity profiles and show these profiles normalized at $r = 0.3$ kpc. The light profiles change smoothly across redshift starting from a highly peaked, concentrated profile at the higher redshifts $z \sim 4$ and becoming less concentrated as one moves towards the lower redshifts $z \sim 2.25$.

5.1.3.3 LIGHT CONCENTRATION OF INDIVIDUAL GALAXIES

To further investigate the change in light profiles with redshift I use a different but quite commonly used way to quantify the light concentration. The concentration parameter was originally defined by [Bershady et al. \(2000\)](#) as the ratio of the 80% and 20% light radius derived from elliptical apertures centered on the galaxy. This measurement assumes symmetrical isophotes to derive the galaxy concentration, which makes it difficult to apply to irregular and asymmetric galaxies at high redshifts as it is the case of my sample. To overcome this limitation I derive the concentration parameter C_T , using r_T^{20} and r_T^{80} as defined in section 4.3.1, generalizing the computation of C to the case of irregular and asymmetric galaxies

$$C_T = 5 \times \log_{10} \left(\frac{r_T^{80}}{r_T^{20}} \right). \quad (5.3)$$

I plot the evolution of C_T in figure 5.10. In that figure I show the fit of the equation

$$C_T = \alpha_C z + \beta_C \quad (5.4)$$

and find a value of $\alpha_C = 0.23 \pm 0.02$ and $\beta_C = 1.64 \pm 0.06$. Thus, C_T strongly evolves with redshift, light being more concentrated going to higher redshifts. The concentration C_T increases by $\sim 25\%$ from $z \sim 2$ to $z \sim 4.5$.

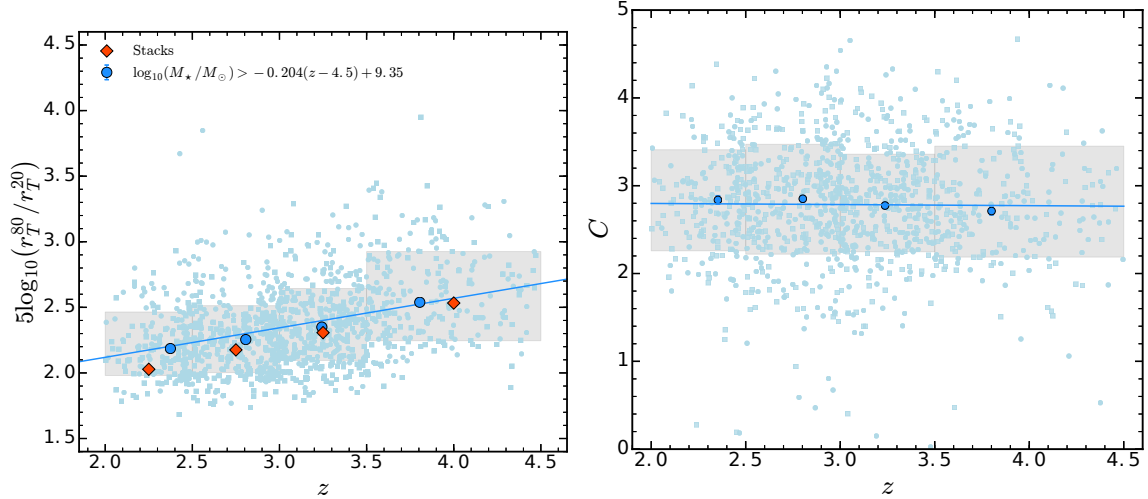


Figure 5.10. Evolution of light concentration in galaxies computed from the ratio of the non-parametric radii enclosing 80% and 20% of the total flux, as defined in section 4.3.1. The solid line is a linear fit to all the small blue points. Each galaxy is plotted with a small blue point (squares for redshift confidence 2 and 9, circles for 3 and 4). The median values and respective error ($\sigma/\sqrt{N}$) per redshift bin are shown as large blue points with error bars. The shaded region delimits the 16th and 84th percentiles including 68% of the sample in each redshift bin. The orange diamonds are the values obtained from the stacked images computed from the method described in section 5.1.3. On the right panel I show the same measurements using a standard definition of light concentration measured in symmetric apertures.

Using the standard definition of concentration with symmetric apertures (see section 4.2.2 for details on the computation) leads to a different trend ($\alpha_C = 0.01 \pm 0.04$ and $\beta = 2.82 \pm 0.13$) with light concentration being rather constant within my redshift interval. This difference is easily explained because of the impact of defining a galaxy center for irregular morphology. For instance, on a galaxy composed by several same-brightness level clumps, the center of light would be defined somewhere in between the clumps leading to a lower concentration as the radius containing 20% of the total light would be larger to include the clumps.

The concentration values derived for the median stack images report the same trend as those derived from the full sample (figure 5.10). While the concentration value for the stacked images is sensitive to the threshold definition (average color and k_p from equation 4.79) the evolution trend remains unaffected and the slope is rather stable.

5.1.4 SIZE EVOLUTION WITH REDSHIFT

On sections 5.1.1 and 5.1.2 I have mentioned that I could not obtain galaxy sizes for the entirety of my sample for each of the measurements presented and for different reasons in each case. I have tested a scenario where I remove from the sample all galaxies without both size measurements which comprise 238 (19%) of the stellar mass selected sample. I find that the results do not change due to the removal of those objects and thus I kept them in the final sample for the individual analysis of r_T and r_e to reduce the statistical errors in my measurements.

To quantify the redshift evolution of sizes I fit the data points with a commonly used parameterization (e.g. Shibuya et al., 2015; Straatman et al., 2015; van der Wel et al., 2014; Morishita et al., 2014):

$$\log_{10}(r) = \beta_r + \alpha_r \log_{10}(1 + z) \quad (5.5)$$

I fit this relation to all galaxies with a size measurement weighted equally due to the lack of individual errors on r_T^x . The sample variance of the parameters β_r and α_r is obtained from

	$2.0 < z < 2.5$	$2.5 < z < 3.0$	$3.0 < z < 3.5$	$3.5 < z < 4.5$
r_e	1.67 ± 0.09	1.49 ± 0.07	1.23 ± 0.08	1.05 ± 0.06
r_T^{50}	1.28 ± 0.03	1.26 ± 0.02	1.16 ± 0.03	1.27 ± 0.03
$r_{T,\text{corr}}^{100}$	2.17 ± 0.06	2.21 ± 0.04	2.13 ± 0.05	2.34 ± 0.06

Table 5.1. Median size values (for F814W, in kiloparsecs) per redshift bin considered here. The value of r_e is the circularized effective radius from GALFIT, r_T^{50} corresponds to the PSF corrected values and $r_{T,\text{corr}}^{100}$ to the PSF+sky corrected values.

Size estimate	F814W		F160W	
	α_r	β_r	α_r	β_r
r_e	-1.29 ± 0.18	0.89 ± 0.11	-1.40 ± 0.34	1.01 ± 0.20
r_T^{10}	-0.36 ± 0.10	-0.16 ± 0.06	-0.22 ± 0.19	-0.16 ± 0.12
r_T^{20}	-0.31 ± 0.10	-0.03 ± 0.06	-0.18 ± 0.22	-0.04 ± 0.13
r_T^{30}	-0.26 ± 0.10	0.06 ± 0.06	-0.09 ± 0.24	-0.01 ± 0.15
r_T^{40}	-0.19 ± 0.10	0.11 ± 0.06	0.03 ± 0.26	-0.01 ± 0.16
r_T^{50}	-0.12 ± 0.10	0.14 ± 0.06	0.13 ± 0.20	0.01 ± 0.12
r_T^{60}	-0.02 ± 0.10	0.15 ± 0.06	0.24 ± 0.22	-0.02 ± 0.14
r_T^{70}	0.08 ± 0.10	0.15 ± 0.06	0.41 ± 0.25	-0.08 ± 0.16
r_T^{80}	0.21 ± 0.10	0.13 ± 0.06	0.56 ± 0.27	-0.14 ± 0.17
r_T^{90}	0.32 ± 0.10	0.12 ± 0.06	0.67 ± 0.28	-0.19 ± 0.17
r_T^{100}	0.48 ± 0.11	0.06 ± 0.07	0.34 ± 0.28	0.07 ± 0.17
$r_{T,\text{corr}}^{100}$	0.15 ± 0.12	0.22 ± 0.07	0.02 ± 0.24	0.24 ± 0.14

Table 5.2. Best fit slope and normalization factor for equation $\log(r) = \alpha_r \log(1+z) + \beta_r$ for the different size estimates used throughout the paper. Values for both F814W and F160W, valid for $2 < z < 4.5$, are given here. The size measurements used to derive the slope for each r_T^x correspond to PSF corrected sizes.

bootstrapping the data 5000 times using 80% of the full sample each time. The resulting fit through the data are plotted in figures 5.2 and 5.7. I also compute the same evolutionary trend for different values of x of equation 4.64 ranging from 10% up to 100% with a 10% step value. All the fit results are given in Tables 5.1 and 5.2 and summarized in figure 5.11.

The figure 5.11 encodes the information on the slope of the size evolution as a function of the flux level and compares to the effective radius evolution derived from GALFIT. There are three main points to be taken from this figure. First, there is a clear trend of the slope as a function of the flux cut level: the brightest regions (10% brightest pixels) evolve faster than the total size with a smooth trend towards slower evolution when going from the brightest regions to the total area of the objects. This differential trend is again a hint on the evolution of light concentration as a function of redshift where the brightest regions of the galaxy tend to become larger with time while the total size remains constant effectively suggesting that light becomes less concentrated with time. Second, the evolution in sizes is far from that reported from the effective radii $r_{e,\text{circ}}$. For the size measurements including the brightest pixels that amount to 50% of the total flux (comparable to r_e) the derived evolution slopes are separated by more than 3σ (figure 5.11) indicating that the choice of method to compute sizes can have a very significant impact on the observed evolution. I note that the points in figure 5.11 indicate the lower limits on the slope. At the highest redshifts a galaxy size will be more often overestimated as lower flux thresholds increase noise contamination. I attempt to correct for that using the prescription described in section 4.3.6, but it applies only to r_T^{100} . However, this effect can not explain the observed difference between r_e and r_T as the size evolution slope after the said correction still differs by more than 3σ from that derived from $r_{e,\text{circ}}$ and it is where the impact of the noise affects the slope the most.

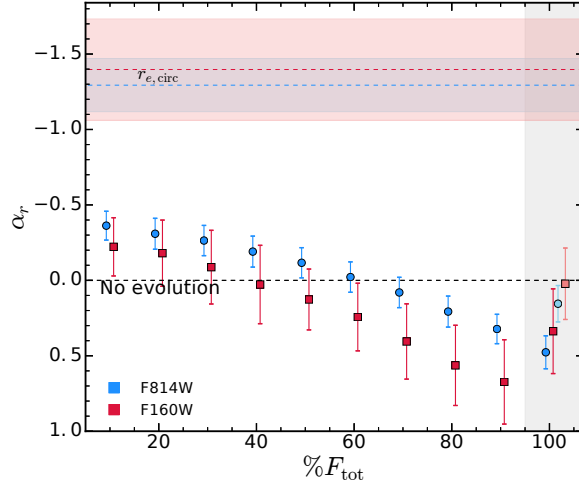


Figure 5.11. Slope of the evolution of PSF corrected galaxy sizes as a function of the flux level considered. The light colored symbols corresponds to the slope computed from sky-corrected r_T^{100} sizes. The dashed lines and shaded regions are the value and error derived in α for the GALFIT size measurements. Blue and red colored symbols/regions correspond to F814W and F160W measurements respectively.

5.1.4.1 EFFECTIVE RADIUS r_e EVOLUTION

the galaxy size evolution derived from the circularized effective half-light radius shows strong size evolution across the redshift range probed. Assuming that galaxy sizes evolve according to the parametrization of equation 5.5 I derive a slope of $\alpha_r = -1.29 \pm 0.18$.

Values reported in the literature range from $\alpha_r = -0.56 \pm 0.09$ for a sample of star-forming spectroscopically confirmed galaxies at $0.5 < z < 3.0$ with $\log_{10}(M_*/M_\odot) > 10$ (Morishita et al., 2014) up to $\alpha_r = -1.32 \pm 0.52$ for a sample of LBGs with $(0.12 - 0.3)L_*$ at $z \sim 4 - 6$ (Oesch et al., 2010). The differences between these results (see also Ferguson et al., 2004; Bouwens et al., 2004; Trujillo et al., 2006c; Franx et al., 2008; Williams et al., 2010; Mosleh et al., 2011, 2012; Ono et al., 2013; van der Wel et al., 2014; Morishita et al., 2014; Curtis-Lake et al., 2016; Shibuya et al., 2015; Straatman et al., 2015) can be traced to different likely sources: 1) the samples are selected in different ways; 2) there are two different methods for measuring sizes, both relying on a certain degree of symmetry; and perhaps most importantly 3) samples with different stellar masses yield different sizes (Franx et al., 2008; van der Wel et al., 2014).

5.1.4.2 TOTAL SIZE r_T EVOLUTION

The typical total size of a SFG, corrected for sky noise contamination as computed in section 4.3.1, is $r_T^{100} \simeq 2.2\text{kpc}$ and shows negligible evolution of galaxy sizes across the redshifts probed here (see the light color points of figure 5.11). This is markedly different from what is observed using the standard effective radii measurement. The r_T^{100} measurements are consistent with the results of Law et al. (2007) who report only a small increase in the the total area from $z \sim 2$ to $z \sim 3$ ($T = 15.0 \pm 0.7$ and $17.4 \pm 0.9 \text{ kpc}^2$, respectively). This corresponds to an equivalent radius of $r_T = 2.19 \pm 0.47\text{kpc}$ at $z \sim 2$ and $r_T = 2.35 \pm 0.54\text{kpc}$ at $z \sim 3$.

5.1.5 SIZE RELATIONS WITH PHYSICAL PARAMETERS

To further explore the properties of galaxies with different sizes I compare galaxy sizes to several key physical parameters characterizing galaxies including stellar mass, SFR, age, metallic-

ity and dust extinction. I also investigate any possible relation between sizes and inter-galactic medium (IGM) transmission towards the galaxies. These parameters are derived from the simultaneous SED fitting of the VUDS spectra and all multi-wavelength photometry available for each galaxy, using the code GOSSIP+ as described by [Thomas et al. \(2016\)](#). This method expands the now classical SED fitting technique to the use of UV rest-frame spectra in addition to photometry, further improving the accuracy of key physical parameter measurements (see [Thomas et al., 2016](#), for details).

The distributions of $r_{e,\text{circ}}$ and $r_{T,\text{corr}}^{100}$ sizes versus M_* , SFR, age, A_V , and IGM transmission are presented in figure 5.12. Several interesting trends can be observed. To quantify the degree of correlation of each parameter with size, I use the [Pearson \(1896\)](#) correlation coefficient. In my sample, the null hypothesis (i.e. no correlation) is excluded at the 3σ level if $|r(\text{Pearson})| > 0.12$.

My data shows a correlation between galaxy size and M_* with larger galaxies having on average higher stellar masses. This supports the correlation reported from other samples (e.g. [Franx et al., 2008](#); [Ichikawa et al., 2012](#); [van der Wel et al., 2014](#); [Morishita et al., 2014](#)) at redshifts $z > 2$ and extending it up to $z \simeq 4.5$. This correlation is of similar strength for $r_{T,\text{corr}}^{100}$ as is for r_e . I obtain $r(\text{Pearson}) = 0.08$ for $r_{T,\text{corr}}^{100}$ against $r(\text{Pearson}) = 0.13$ for r_e . Interestingly, the most massive galaxies in my sample show a break at stellar masses higher than $\log_{10}(M_*/M_\odot) > 10.5$ in this correlation. While, when considering $r_{e,\text{circ}}$, sizes are getting smaller, sizes computed from $r_{T,\text{corr}}^{100}$ increase as one moves towards higher stellar masses. This supports in part my analysis that low surface brightness regions in massive galaxies with complex morphology are not taken into account by parametric fitting like done in GALFIT resulting in artificially smaller effective radius (by a factor of ~ 2).

I find that the SFR is strongly related to galaxy sizes. For sizes measured with $r_{T,\text{corr}}^{100}$ I find that larger galaxies have higher star formation rates, with a positive correlation ($r(\text{Pearson}) = 0.29$). The correlation is not significant with $r(\text{Pearson}) = 0.03$ for $r_{e,\text{circ}}$. Considering the M_* -SFR main-sequence of star-forming galaxies in VUDS ([Tasca et al., 2015](#)), this correlation may be partly reflecting the underlying stellar mass-size relation described above.

Galaxies appear to be older when they are smaller when looking at the relation between age (as defined by the start of star formation, see [Thomas et al., 2016](#)) and $r_{T,\text{corr}}^{100}$ ($r(\text{Pearson}) = -0.21$). From the hierarchical assembly scenario one would expect that larger galaxies have older stellar populations. On the other hand the less significant relation between $r_{e,\text{circ}}$ and age ($r(\text{Pearson}) = -0.10$) may also mean that the derived age is dominated by the age of the last major burst of star formation washing out underlying older stellar populations that may exist in the central brightest clumps from previous starburst episodes.

Galaxies with lower extinction values have smaller median sizes than galaxies with higher dust extinction. This trend is more significant for $r_{T,\text{corr}}^{100}$ ($r(\text{Pearson}) = 0.13$) than it is for $r_{e,\text{circ}}$ ($r(\text{Pearson}) = 0.03$). This hints that extended regions of galaxies have a higher dust content than smaller ones.

The projected stellar density computed as the ratio of the stellar mass to the projected area of a galaxy is shown in figure 5.13. I observe a strong correlation for both $r_{T,\text{corr}}^{100}$ ($r(\text{Pearson}) = 0.59$) and $r_{e,\text{circ}}$ ($r(\text{Pearson}) = 0.36$). Galaxies with higher stellar masses having higher stellar mass densities.

I do not observe any significant correlation between galaxy sizes and metallicity or IGM transmission for any of my measurements.

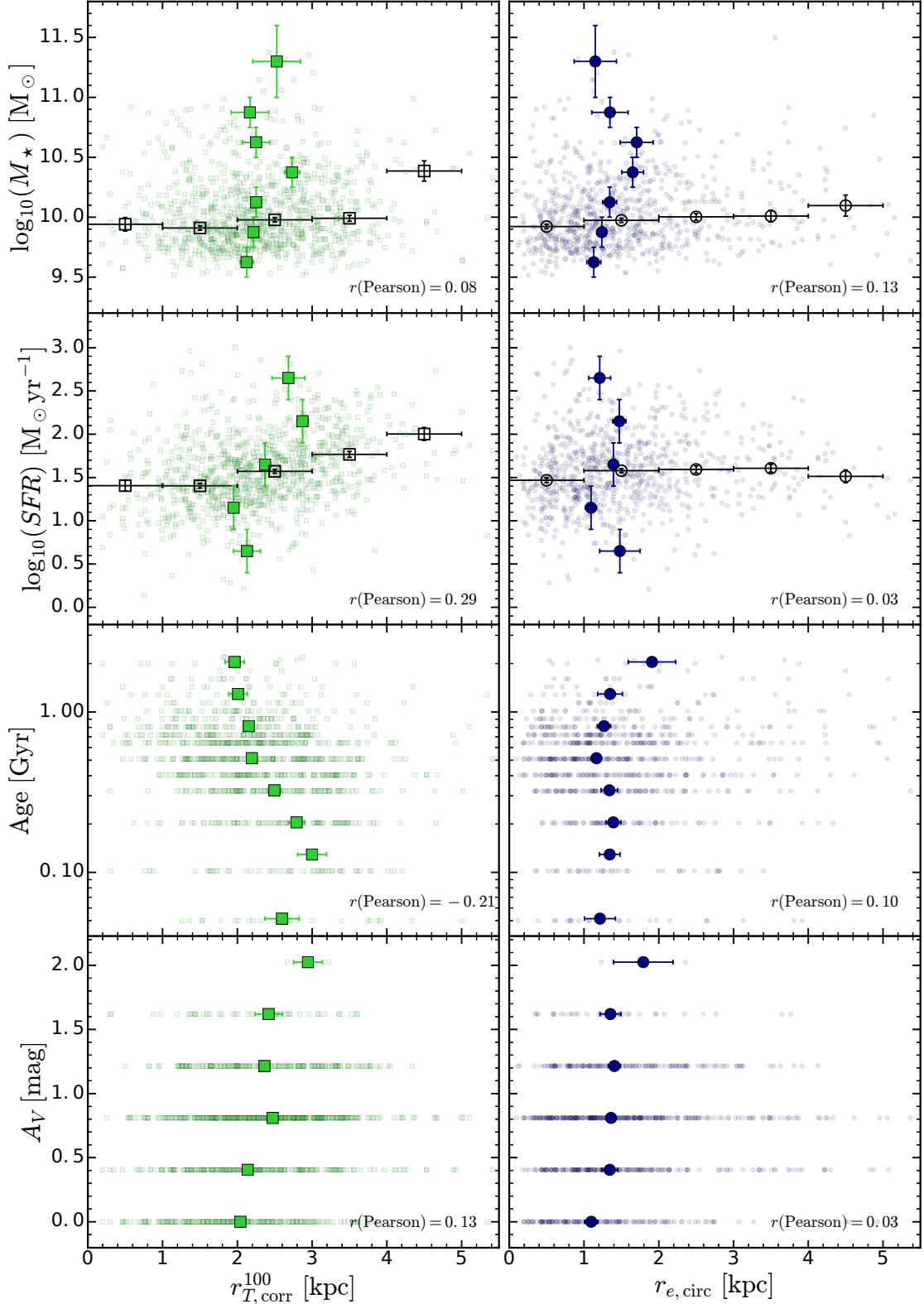


Figure 5.12. Correlation of the measured galaxy sizes with parameters derived from GOSSIP+ SED fitting for my stellar mass selected sample (using the stellar masses derived with GOSSIP+ and equation 3.1). Only galaxies with good and excellent spectrophotometric fits are included. From top to bottom I show the stellar mass, SFR, age and dust extinction. On the right panels I show the results for GALFIT derived $r_{e,circ}$ and in the left panels I show the results for the value of $r_{T,corr}^{100}$. The solid colored symbols represent the median values in bins of the physical parameter in question. The error bar in the y-direction shows the bin size and in the x-direction shows the error on the median ($\sigma/\sqrt{N}$). The open black symbols represent the median values in bins of radii. In this case, error bars have the same meaning as before, in the inverted directions. Small points represent individual measurements.

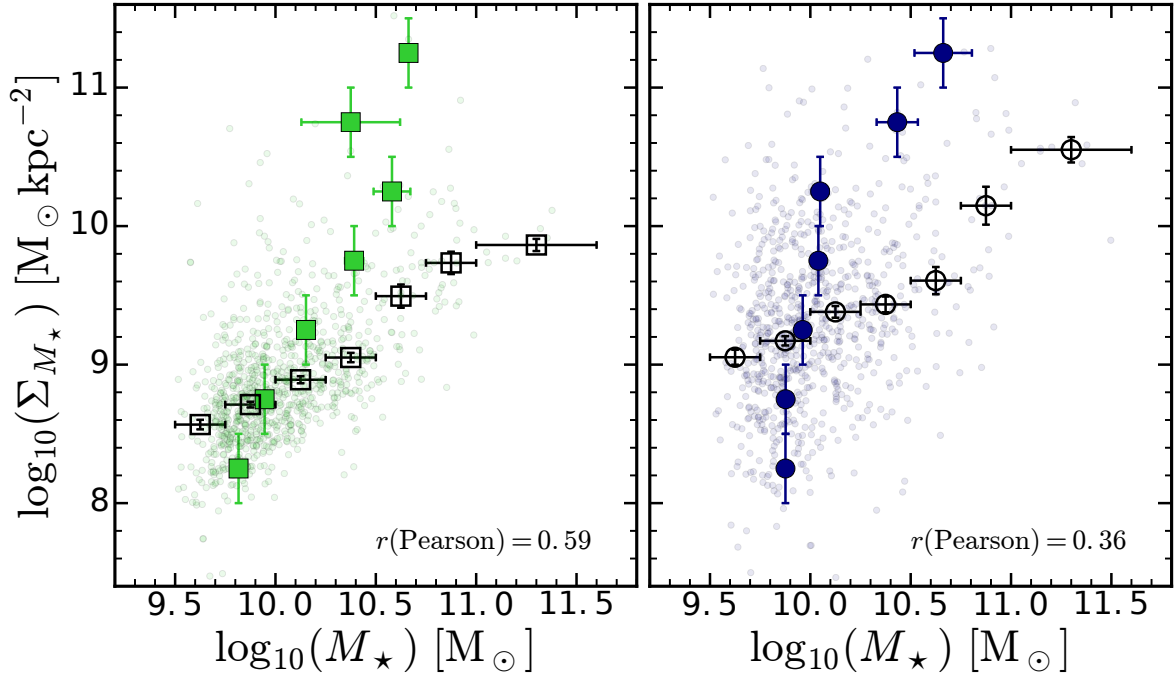


Figure 5.13. Stellar mass surface density as a function of stellar mass. On the right panels I show the results for GALFIT derived $r_{e,\text{circ}}$ and in the left panels I show the results for the value of $r_{T,\text{corr}}^{100}$. The color and symbols have the same meaning as in figure 5.12.

5.2 THE PREVALENCE OF CLUMPS IN ASSEMBLING GALAXIES

In this section I present the results I obtained after applying a new algorithm to detect galactic clumps at high redshift using an isophote evolving with redshift (described in section 4.3.3) and which I fully describe in section 4.4. This method was designed to account for surface brightness dimming effects on the distribution of detected clumps in a wide redshift interval.

5.2.1 THE DISTRIBUTION OF THE NUMBER OF CLUMPS PER GALAXY

I compare in Fig. 5.14 the number of galaxies as a function of the number of detected clumps per galaxy in two different redshift ranges. I consider only clumps that reside inside the isophote belonging to the VUDS target when showing this histogram. I find that the fraction of multi-clump systems decreases as the number of clumps increases. Systems with only one clump (i.e. a single clump in a smooth galaxy at the observed resolution) are the dominant population ($\sim 55\%$ at $2 < z < 4.5$ and $\sim 61\%$ at $4.5 < z < 6.0$). I find that the fraction of galaxies with only two clumps dominates the distribution of clumpy galaxies with $\sim 25 \pm 2.7\%$ double clumps galaxies at $2 < z < 4.5$ and $\sim 21 \pm 7.7\%$ at $4.5 < z < 6.0$. Galaxies with 3 clumps are about $\sim 11 \pm 1.6\%$ at $2 < z < 4.5$ and $\sim 8 \pm 4.1\%$ at $4.5 < z < 6.0$. Galaxies with four or more clumps amount to only $\sim 7 \pm 1.2\%$ at $2 < z < 4.5$ and $\sim 9 \pm 4.5\%$ at $4.5 < z < 6.0$. Several examples of galaxies with one, two, or more clumps may be found in Figs. 4.17, 4.18 and 4.19, respectively.

5.2.2 THE FRACTION OF CLUMPY GALAXIES

I define as a clumpy galaxy any source that has more than one clump detected within its isophote. To compute this fraction as a function of redshift, I consider only clumpy (and non-clumpy galaxies) within the VUDS galaxies for which I have reliable information on the

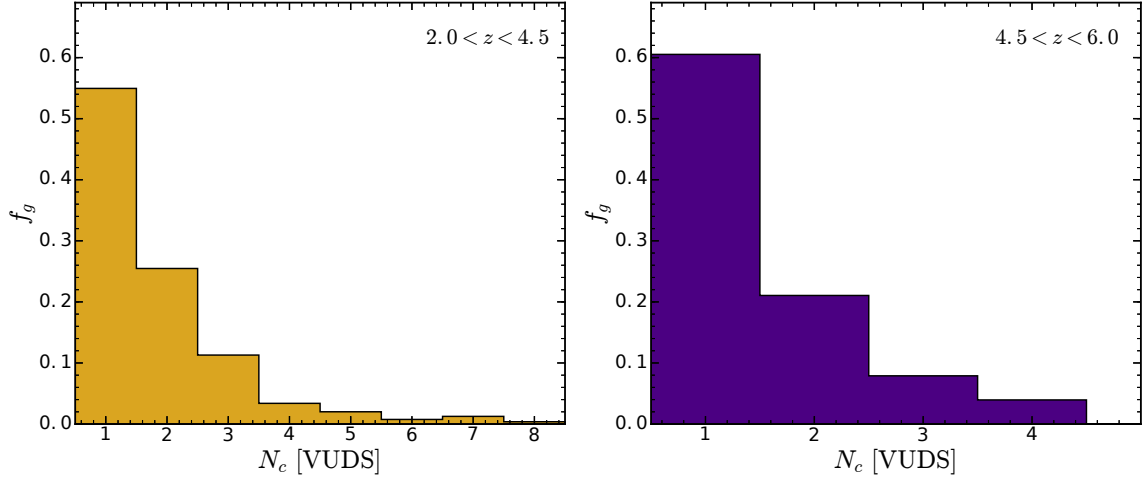


Figure 5.14. Number of galaxies as a function of the number of clumps detected within the selected isophote. Note that I include in this plot single clump galaxies which correspond to galaxies with no substructure or a single central clump. I plot this quantity for two redshift intervals each with its respective value of $k_p = 1.5$ for $2 < z < 4.5$ in gold (left panel) and $k_p = 5$ for $4.5 < z < 6.0$ in purple (right panel). On each panel I show the number of clumps for the VUDS targets.

spectroscopic redshift. This ensures that I am not smearing my results between redshift bins by including galaxies with uncertain or incorrect redshifts. I have compared the stellar mass distribution of clumpy and non-clumpy galaxies and find that they are indistinguishable from one another. The clumpy fraction evolution with redshift is shown in figure 5.15.

I stress that the clumpy fraction with my method depend on the selected isophote (value of k_p) which in turns depends on the color correction I choose to use, as allowed by the depth of available images. Nonetheless, I find a rising trend with redshift of the clumpy fraction at all values of k_p that I have tested as well as when using NUV as the base rest-frame band. Due to the asymmetric nature of most galaxies at high redshift (e.g. Huertas-Company et al., 2015b; Curtis-Lake et al., 2016) and since deriving a center and a size can lead to different results when using different assumptions (e.g. Ribeiro et al., 2016). I am not including in my sample of clumpy galaxies any source with an off-center clump as defined by, e.g. Guo et al. (2015); Shibuya et al. (2016). The clumpy fraction evolution with redshift is shown in figure 5.15.

At $2 < z < 4.5$ I observe that the clumpy fraction remains in the range 35 to 55% at all redshifts. This fraction is observed to be rising from low to high redshift. I also report the clumpy fraction for two different values of k_p for $2 < z < 4.5$ showing that the absolute value does indeed depend on the isophote used. I note that increasing the value of k_p lowers the probability of detecting faint clumps and it is no surprise that the fraction of clumpy systems decreases as the value of k_p increases. However changing k_p does not change the observed evolution of the clumpy fraction with redshift. The rising evolution with redshift of the clumpy fraction observed using my method is different from results obtained in other studies (e.g. Guo et al., 2015; Shibuya et al., 2016). A possible explanation for the lower fraction of clumpy galaxies that I observe at $z \sim 2 - 3$ could be connected with the evolving threshold defined in section 4.4, including luminosity evolution. By imposing a higher threshold at lower redshifts, I am effectively reducing the are within I search clumps which is likely to prevent us from detecting faint clumps if they are located in the outskirts of the galaxy.

At $z > 4.5$ the depth of the data only allows the use of a higher value of k_p , as shown in figure 5.15. In this redshift range I observe a slightly lower clumpy fraction of 20 – 40%. At these redshifts it is necessary to use a brighter isophote limit for the clumps detection to avoid excessive contamination from noise. It is clear from my results at lower redshifts that if the

depth of the data was enabling to use a fainter isophote I would likely observe a higher clumpy fraction also in this redshift bin.

Since I have computed the clumpy fraction at all redshifts for all values of k_p shown in figure 5.15 I attempted to compute a correction to estimate the clumpy fraction at high redshift as if it was measured with $k_p = 1.5$. To do that I fitted a linear curve to the quantity $\frac{f_{c,K}}{f_{c,5}}(z)$ which quantifies the underestimation of the clumpy fraction measured at $k_p = 5$ with respect to that measured at $k_p = K$. I then apply this correction factor measured at $z = 5.25$ to correct the measured clumpy fraction $k_p = 5.0$. In doing so, I estimate that the clumpy fraction at $4.5 < z < 6.0$ is $\sim 64 \pm 19\%$ when corrected for $k_p = 1.5$.

5.2.2.1 COMPUTING THE CLUMPY FRACTION USING A DIFFERENT METHODOLOGY

I have attempted to mimic the method used by Guo et al. (2015) and Shibuya et al. (2016) to test the impact of the method and selection on the derived values for the clumpy fraction. A short description of the method and results can be found in appendix 5.2.2.1. I show that I get clumpy fractions within the error bars of the measurements made with my proposed algorithm when I use this alternative method. At $z < 3$ my results obtained using this method are closer in their trends to those reported Guo et al. (2015) and Shibuya et al. (2016). However, I still observe a rising trend on the clumpy fraction with redshift contrary to the decreasing trend reported by Shibuya et al. (2016) at $z > 3$, although my error bars are large because the number of galaxies satisfying the criteria of this method is reduced. The alternative method that I use summarizes as follows

1. I run SExtractor on a $7''$ by $7''$ image to obtain the segmentation map.
2. I dilate the segmentation map using a binary operation that effectively smooths and enlarges by a maximum of 3 pixels the outer edge of the segmentation map.
3. I select a small cutout of the original image that adapts to the size of the created segmentation map.
4. I apply a boxcar filter (10 pixels width) to the new cutout.
5. I create a residual image by subtracting the filtered image to the original one.
6. I measure the residual background flux using a 3σ -clipping method.
7. I mask all pixels that have fluxes smaller than 2σ of the calculated background.
8. Run a new detection algorithm on the masked residual image to detect clumps.

All regions in the masked residual image that have more than 5 connected pixels are counted as single clumps. I also compute the magnitude of each clump using a 3 pixel aperture.

To compute then the final clump fraction, I select only galaxies for which I have GALFIT results (see Ribeiro et al., 2016) and that have effective radius $r_e > 0.2''$, and axis ratio $q > 0.5$. I apply the same intermediate mass selection ($9.8 < \log_{10}(M_*/M_\odot) < 10.6$). Finally, I only consider clumps which contain more than 8% of the galaxy light. The result is found as the red squares of Fig. 5.16. I compare to my clumpy fraction computed at $k_p = 2.0$ to be comparable with the 2σ detection limit that is imposed when finding clumps using this alternative method. In this exercise I have also included off-center clumps as defined above when computing the clumpy fraction using the method presented in this thesis. It is possible that the differences in the clumpy fraction are caused by sample selection and not the methodology, although my errors cannot confirm this hypothesis.

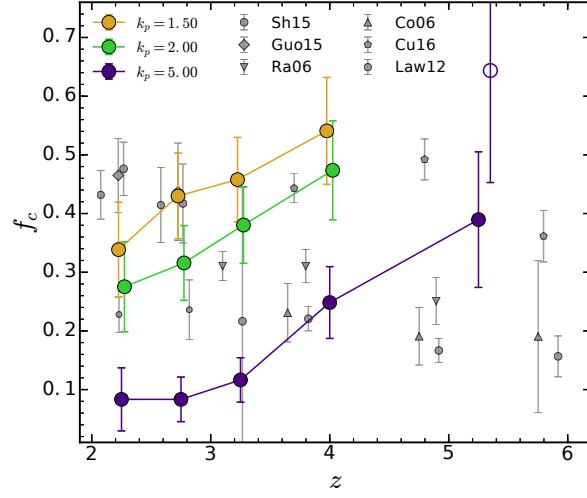


Figure 5.15. Fraction of clumpy galaxies within the VUDS sample as a function of spectroscopic redshift. Different large colored circles (gold, green and purple) represent different values of the normalization k_p . The smaller gray symbols represent values from the literature for clumpy galaxies: circles (Shibuya et al., 2015); squares (Guo et al., 2015); and for asymmetric galaxies: inverted triangles (Ravindranath et al., 2006); triangles (Conselice & Arnold, 2009); octagons (Law et al., 2012a); pentagons (Curtis-Lake et al., 2016).

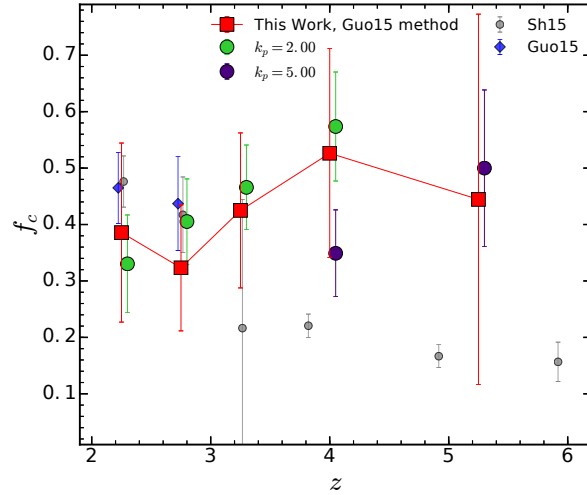


Figure 5.16. Clumpy fraction in the VUDS sample as computed using the method described by Guo et al. (2015) (red squares) when compared to that defined in this paper with the inclusion of off-center clumps (see text) as green/purple circles, and the studies by Guo et al. (2015) as blue diamonds and Shibuya et al. (2016) as gray circles which use the same methodology.

5.2.3 PHYSICAL PROPERTIES OF CLUMPS

As stated in Sect. 4.4.3, I derive areas and absolute magnitudes for each clump by computing the flux and area within each group of pixels associated with the local maximum that defines the clump. I show in Figs. 5.17 and 5.18 the tight correlation that I observe between clump magnitude and clump area. This is expected by construction since the larger the area (i.e. the number of pixels of the clump) the more likely it is for it to be brighter. In this figure I am excluding galaxies with a single clump detection.

In the same figure I can observe that there appears to be a bimodal distribution in the clump area distribution, also hinted by the asymmetric shape in the magnitude distribution. I fitted each distribution with a two Gaussian model with six free parameters: two amplitudes, two centers and two widths, one for each Gaussian curve. The fit was done using the Levenberg-Marquardt minimization algorithm implemented in *scipy*. For clumps at $2 < z < 4.5$ I observe two peaks in the magnitude distribution at $M_{NUV} = -18.1 \pm 0.1$ and $M_{NUV} = -19.7 \pm 0.1$. In the area distribution the two peaks are found at $\log(T) = 0.25 \pm 0.05$ and $\log(T) = 0.78 \pm 0.03$, which correspond to ~ 1.8 and $\sim 6.0 \text{ kpc}^2$, respectively. At $4.5 < z < 6.0$ the bimodality is not so evident and due to the low number of detected clumps I opt not to fit any model to the two distributions at this redshift. (see Fig. 5.18)

This bimodal hypothesis is likely linked to the different processes of clump formation where large and bright clumps are likely associated with merger events and the small and faint clump population is associated with disk instabilities. I further discuss this in section 6.2. I test the statistical significance of this bimodality using the Hartigan's dip test (Hartigan & Hartigan, 1985). While a bimodal distribution is favored I find that the unimodal distribution hypothesis cannot be rejected for either of the distributions. Larger samples are required to confirm or reject this bimodal hypothesis.

5.2.3.1 BRIGHT AND LARGE CLUMPS ARE IN TWO-CLUMP GALAXIES

A key information shown in Fig. 5.17 is the number of clumps in the galaxy that each clump belongs to. The larger and brightest clumps are most likely to be found in two-clump galaxies and as I move towards fainter and smaller clumps I observe that they are more commonly found in galaxies with a larger number of clumps. This information is summarized in the contour lines of Fig. 5.17 showing the distribution of the fraction of clumps in two-clump systems as a function of clump area and absolute magnitude. More than 50% of the brightest and largest clumps are found in two-clump systems and the probability of finding two clumps in a galaxy decreases for fainter clump magnitudes and smaller areas (down to $\sim 10\%$, respectively).

The information on how the fraction of clumps in two-clump systems evolves with redshift is found in Tab. 5.3. I see that this fraction evolves with redshift in the sense that it is more likely to find two-clump systems at lower redshift ($\sim 40 \pm 6.1\%$ at $2 < z < 2.75$) than at higher redshift ($\sim 12 \pm 2.5\%$ at $4.5 < z < 6.0$). Imposing a magnitude cut ($M_{\text{clump}} < -19.1$) the fraction of clumps in two-clump systems is larger at all redshifts, confirming that the largest and brightest clumps are more likely to reside in two-clump systems than their fainter smaller counterparts.

I have computed the average luminosity that is locked in the UV clumps by comparing the total luminosity in clumps to that of its host galaxy. I find that for clumpy galaxies (with two or more clumps) $46 \pm 1.5\%$ of all light is found to be in clumps. If I further divide the sample into two-clump systems and multi-clump systems I find that the light fraction locked in clumps is virtually the same with $46 \pm 2\%$ for both cases.

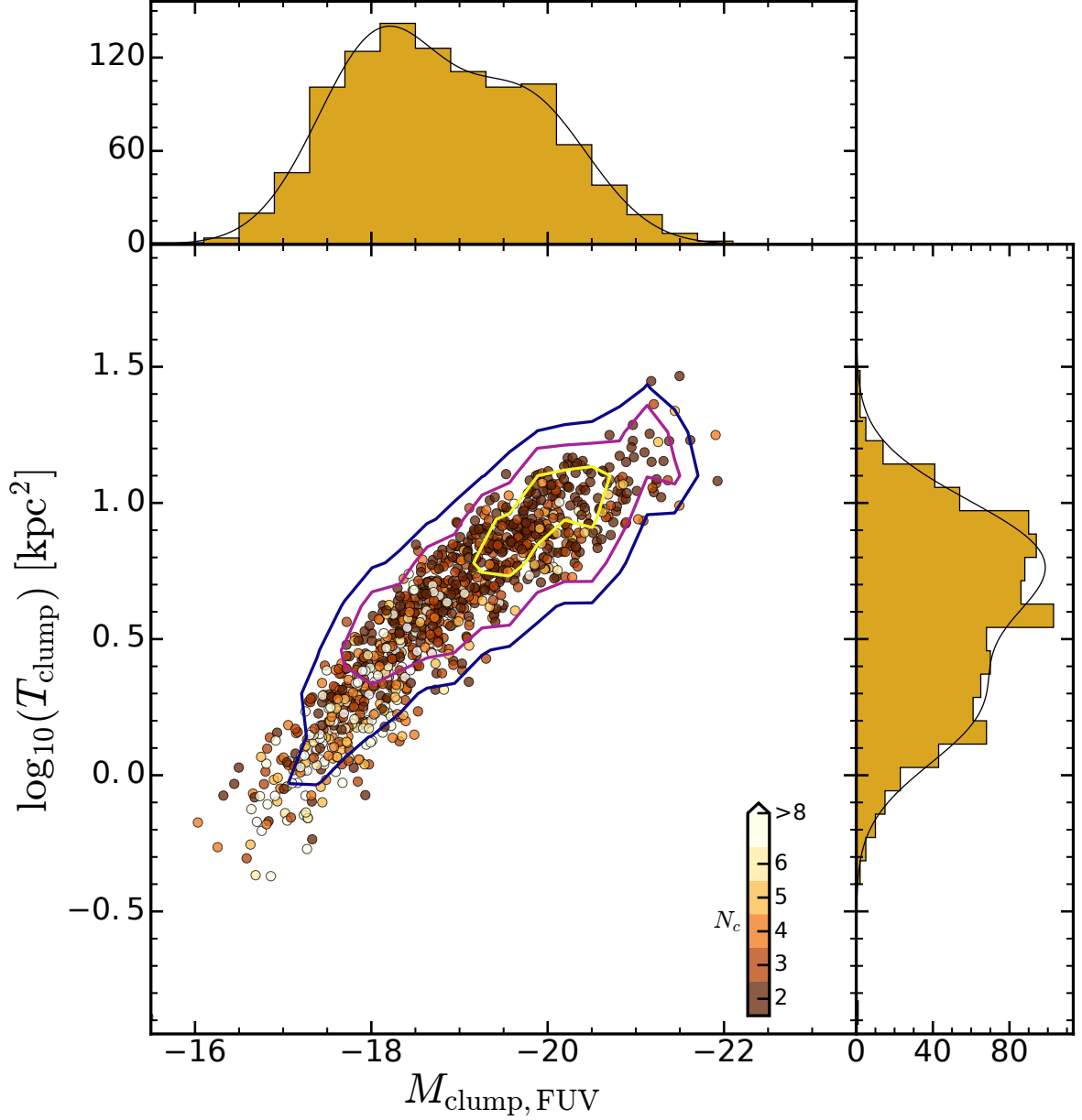


Figure 5.17. Absolute magnitude in the rest-frame FUV and area distribution for clumps found in galaxies with $N_c \geq 2$ detected at $2 < z < 4.5$ with $k_p = 1.5$. Each clump is color coded by the number of clumps found in its parent galaxy. The color scheme is found at the bottom right of the main panel. The black solid line in each of the auxiliary panels shows a fit of a two Gaussian model to the observed distribution of areas and magnitudes of the clumps. There is a bimodality present in both distributions and I observe that it is more probable to find the brightest and largest clumps in two clump systems. The contours show the smoothed distribution of the fraction of 2 clump-systems at levels of 10, 25 and 50%. It is clear that the majority of two-clump systems (with respect to all clumpy systems) is found in brighter and larger clumps.

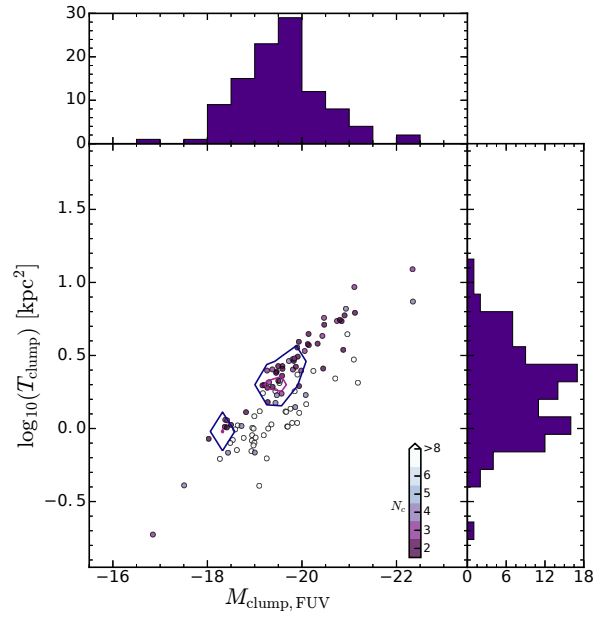


Figure 5.18. Absolute magnitude in rest-frame FUV and area distribution for clumps found in galaxies with $N_c \geq 2$ detected at $4.5 < z < 6.0$ with $k_p = 5$. Each clump is color coded by the number of clumps found in its parent galaxy. The color scheme is found at the bottom right of the main panel. The contours shows the distribution of fraction of 2 clump-systems at levels of 10 and 25%.

redshift	f_{2c} [%]	$f_{2c,bright}$ [%]	$f_{major,bright}$ [%]	$f_{minor,bright}$ [%]	$f_{gal,pair}$ [%]
$2.0 < z < 2.75$	40 ± 6.1	60 ± 15.4	77 ± 22.8	23 ± 9.9	15 ± 4.5
$2.75 < z < 3.5$	38 ± 3.9	60 ± 9.0	64 ± 14.0	36 ± 9.4	21 ± 5.1
$3.5 < z < 4.5$	19 ± 2.4	37 ± 6.3	43 ± 13.8	57 ± 17.0	39 ± 11.6
$4.5 < z < 6.0$	12 ± 2.5	15 ± 3.4	53 ± 32.6	47 ± 29.7	38 ± 24.0

Table 5.3. Fraction of 2 clump systems in 4 redshift intervals. The second column represents the total fraction of two-clump systems. The third column represents the fraction of clumps in two-clump-systems with at least one of them being brighter than $M_{clump} < -19.1$. The fourth and fifth columns represent the fraction of bright two-clump systems that are in major ($1/4 < L_f/L_b < 1$) and minor ($L_f/L_b < 1/4$) systems. The luminosities are measured in FUV rest-frame. The last column shows the pair fraction corrected for projection effects (see Sect. 4.4.2) considering pairs of $i_{AB} < 24.5$ VUDS targets with fainter galaxies.

5.2.3.2 LUMINOSITY RATIOS

To classify each two-clump group I have computed the luminosity ratio between the two clumps, L_f/L_b , with L_f being the luminosity of the fainter clump and L_b that of the brighter of the two. The resulting fractions as a function of redshift may be found in Tab 5.3. The fraction of two-clump galaxies is classified in major ($1/4 < L_f/L_b < 1$) and minor ($L_f/L_b < 1/4$) systems, for galaxies which have at least one clump with $M_{\text{clump}} < -19.1$, although statistical uncertainties get large because of the reduced number of galaxies for which I am able to compute this quantity.

5.2.3.3 CLUMP STELLAR MASSES

I aim to describe the clumps in term of their stellar-mass by assuming that the mass to light ratio of clumps is the same as its host galaxy. This hypothesis allows us to estimate the stellar mass of each clump by computing the clump to galaxy luminosity ratio and applying that factor to the total stellar mass of the galaxy. However my estimate is just an approximation and I might overestimate the stellar masses of clumps since they should be on average more star-forming than the galaxy as a whole and I am measuring the luminosities in UV rest-frame.

In Fig. 5.19 I show the distribution of stellar masses in clumps for three samples. A first sample considering clumps that are in clump systems with at least 3 clumps (hereafter multi-clump-systems). I also show the sample of clumps in two-clump-systems. I compare that sample to the distribution of the stellar masses in single clumps. I note that for single clump systems, a clump can correspond the entire galaxy. This explains why I find clumps with stellar masses up to $\log_{10}(M_*/M_\odot) \sim 11$.

It is interesting to see that the clumps that are found in two-clump-systems have stellar-masses that peak at higher values (around $\log_{10}(M_*/M_\odot) \sim 9.4$) when compared to clumps in multi-clump-systems. It is also interesting to note that their stellar masses are higher than what is expected for giant molecular clumps from simulations/observations (see e.g. Elmegreen et al., 2009; Genzel et al., 2011; Guo et al., 2012; Bournaud, 2016). They show that clumps have stellar masses in the $8 \lesssim \log_{10}(M_*/M_\odot) \lesssim 9$ range which is consistent with the bulk ($\sim 55\%$) of the stellar mass distribution I see in multi-clump-systems. I have tested the similarity between the two distributions using a Kolmogorov-Smirnov test and the null hypothesis (that both distributions are the same) is discarded at a 95% confidence level. This difference persists when considering higher values of k_p .

5.3 MORPHOLOGY VISUAL CLASSIFICATION

I show in this section the results of morphological classification based on the scheme and the GUI described in section 4.5. My results on the morphological classification of VUDS galaxies are excluding explicitly the contribution of galaxy pairs. For galaxies with multiple secondary selections that include the pair sub-classification I simply ignored the pair identification. For galaxies exclusively classified as pairs I attempt to get the classification of the brighter and/or central component as identified with the VUDS identification number. These objects amount to 7% of the sample with the same classification from different people.

5.3.1 AGREEING ON A CLASSIFICATION

I show in figure 5.20 the frequency on which a given number of classifiers agreed on the primary class. I find that on only $\sim 10\%$ of all galaxies all people agreed on the primary class. However,

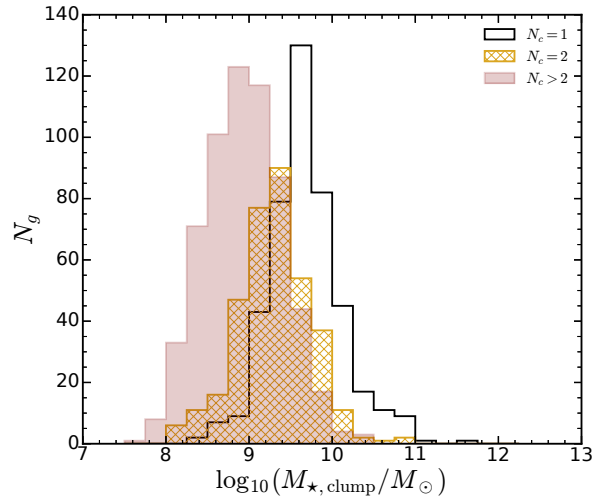


Figure 5.19. The distribution of stellar masses in clumps for three different samples. In the black solid line histogram I show the distribution considering single clump galaxies. In the filled brown histogram I show the distribution of stellar masses of clumps in galaxies with 3 or more clumps. The golden hatched histogram shows the stellar mass of clumps in galaxies with 2 clumps.

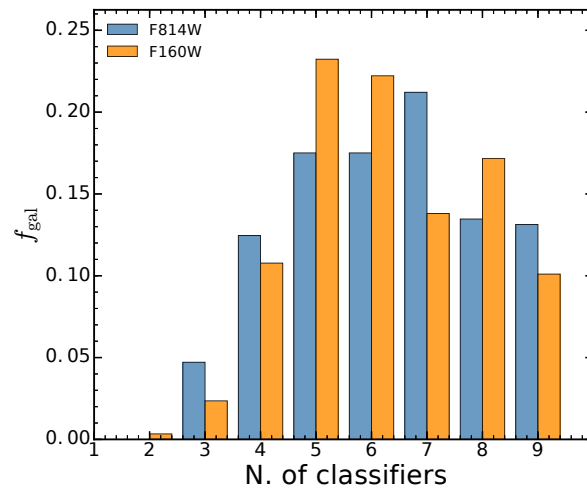


Figure 5.20. Typical agreement between different classifiers on the primary class. In blue I show the results from classifications based on the I and in orange for the H band.

for the majority of galaxies I do find that I get a majority (≥ 5) of classifiers agreeing on the same primary class ($\gtrsim 80\%$ in both bands). These results portray the difficulty of defining a successful classification scheme in the characterization of the morphology of high redshift sources. Nonetheless, I can get a majority of agreement on 4/5 of my sample.

Since the agreement among different people seems hard to attain for a majority of sources, I aimed to design an algorithm to account for the dispersion in the classification. To do so, for each galaxy I computed the fraction of people that classified in each class and noting that for any galaxy

$$\sum_n^{N_{\text{class}}} f_n = 1, \quad (5.6)$$

where f_n is the fraction of people that classify a single galaxy as the n -th class. Then, I

compute the total fraction of galaxies per class by doing

$$F_n = \frac{1}{N_{\text{gal}}} \sum_i^{N_{\text{gal}}} f_{n,i}, \quad (5.7)$$

where F_n now represents the weighted fraction of objects in my sample that were classified in the n -th class. This method will account for all the dispersion in each classification while still providing statistical information on the distribution of morphologies within my sample. However, it fails to produce a single classification for every galaxy which is required to study any distinction in physical parameter space between different morphological classes.

To circumvent this problem there are different approaches to define single classification to every galaxy. A straightforward way to do it is by assigning to each galaxy the class on which most people agree upon (the modal class). A different approach is to map each classification into a scalar scheme (see table 4.2) and then compute the mean or median class based on the individual classifications by different people. While the first method is robust against individual biases, by picking the majority vote, it loses any information about the intrinsic dispersion in the classification of each object. The second method allows for the use of the full information on each object but if not done right might produce classifications that fail to be representative of the object's nature. I have tested three different methods and I find that using the median class provides the best compromise between accounting for class dispersion while not losing information and maximizing the sampling of the population by including all objects that would otherwise be missed due to disagreements at the secondary classification level preventing it to reach a minimum number of agreements for a modal classification.

5.3.2 CLASS DISTRIBUTION IN CANDELS

One of the first results that I can derive from my classification on multi-band imaging is to know which classes are more common in my sample. Since the agreement is not perfect each galaxy is classified according to the weight it has in each class. This means that the final distribution encodes the information on the dispersion of the classification by weighting each galaxy in each class according to the fraction of people that classified it as such. I show in figure 5.21 that for the I band there is a clear dominance of irregular galaxies (with more than 40% of the sample being classified as such). In the I band $\sim 20\%$ of the objects are classified as compact and $\sim 17\%$ as extended/symmetrical. In the H band I find that the irregular and extended/symmetrical classes have roughly the same fraction of objects ($\sim 35\%$) while compact objects represent $\sim 14\%$ of the sample.

To investigate the differences of classifications between different bands I took an alternative approach. I computed the fraction of objects (selected from those who at least 5 different people agree on the primary class) for which the primary classes were different from one band to the other. Then, I also computed the fraction of objects for which only the secondary classification was different. I compare those values to the fraction of objects for which both primary and secondary classes are exactly the same. I find (see figure 5.22) that for $\sim 60\%$ of the sample, no morphological k-correction was found as both primary and secondary classes were the same in I and H band. Nevertheless, there is a non-negligible fraction of $\sim 25\%$ objects for which there is a disagreement on the primary class.

I argue that the main cause for the differences found in classifying the different bands is linked to the spatial resolution of each image. I note that the spatial scale in the I band is half of the H band and that the PSF is three times wider in the H band. This effect is particularly important when thinking of clumpy or elongated galaxies as defined in the I band since due to the poorer spatial resolution are more likely to be found as extended and symmetrical sources

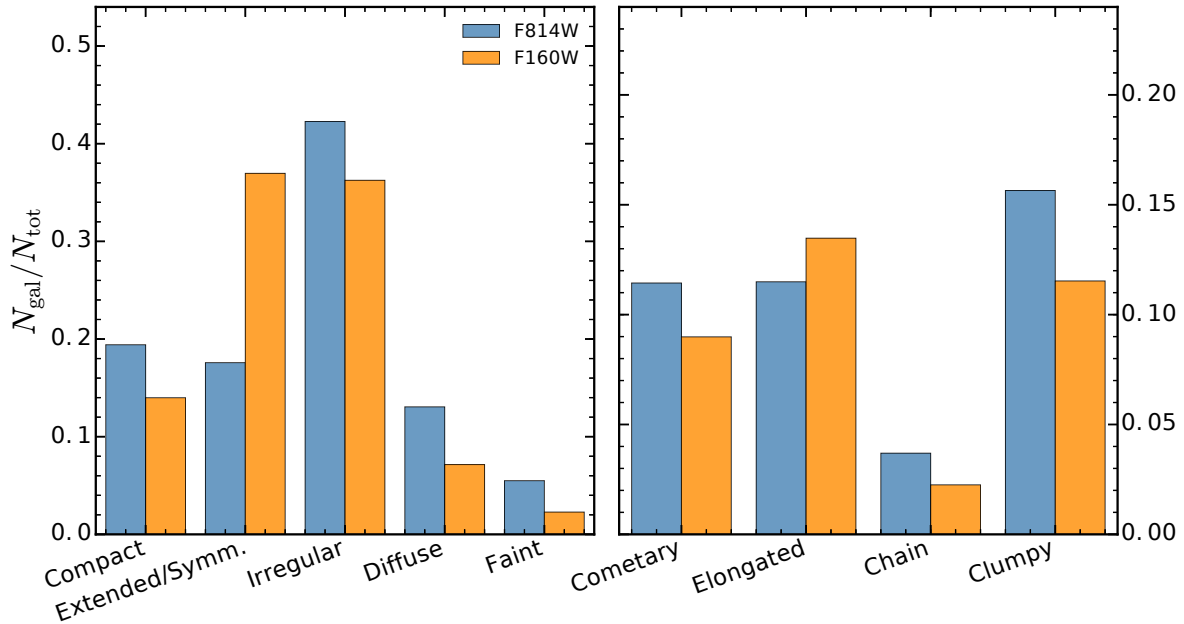


Figure 5.21. Weighted frequency of each morphological primary class (left panel) and each secondary irregular class (right panel) 1 for the VUDS-CANDELS sample. Blue bars correspond to I band classifications whereas orange bars correspond to H band classifications.

in the H band. This is supported by the fact that the largest different in the final classification that I find is that the number of these extended and symmetrical sources is much higher in the H band when compared to the I band (38% to 12%, respectively).

Regarding the use of a scalar classification scheme (see table 4.2), I show in figure 5.23 the distribution of morphological classes after attributing a single class per object based on its median value classification. As with the weighted classification I find the same relative fractions where the irregular class dominates the I band classification whereas in the H band I have the irregular and extended/symm. classes to have the same fraction of objects. This provides evidence that in the statistical description of the morphological types of galaxies that are found in VUDS is well represented by this method for selecting an individual classification for each galaxy.

I computed the probability that for any pair of 2 classifiers they would agree on the primary classification by randomly taking and comparing 2 primary classifications for all galaxies classified in CANDELS. I find that, in the I band of CANDELS, that happens for only 55% of the cases. In the H band the fraction is practically the same at 54% of agreement between any pair of 2 classifiers.

5.3.3 EXTENDING THE CLASSIFICATION TO COSMOS

I show in figure 5.24 a summary of the rate of agreement on the primary classification for a total of 1861 galaxies for which the classification by two different people was completed. Overall I get an agreement rate of $\sim 50\%$ which is lower to what I find from random realizations of classification pairs from my control sample in CANDELS. This lower agreement rate is likely explained due to the lower image depth of the COSMOS ACS survey which induces more confusion between different morphological classes. I also show that the rate of agreement on the secondary class is valid for $\sim 60\%$ (563 objects) of the sample for which the primary class was the same. In the same figure I explore in more detail which is the major cause for class disagreement among different people. I find that there is confusion between the compact and

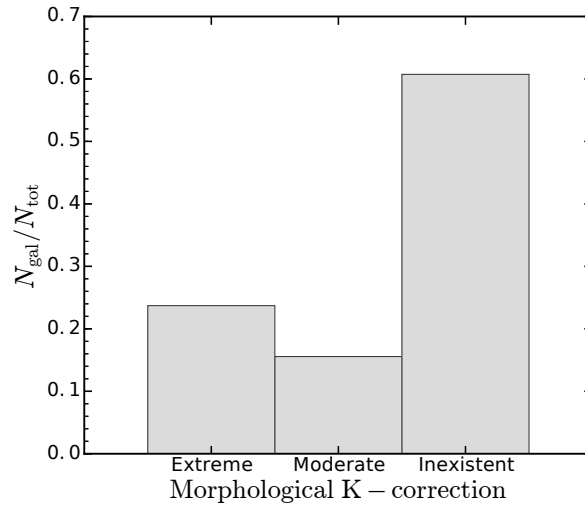


Figure 5.22. Morphological k-correction from visual classification for galaxies where at least 5 people agree on the primary classification. *Extreme* corresponds to cases where primary classes are different in I and H. *Moderate* corresponds to cases where the primary class is the same but the secondary class is different. Finally *Inexistent* is for cases where both primary and secondary classes are exactly the same.

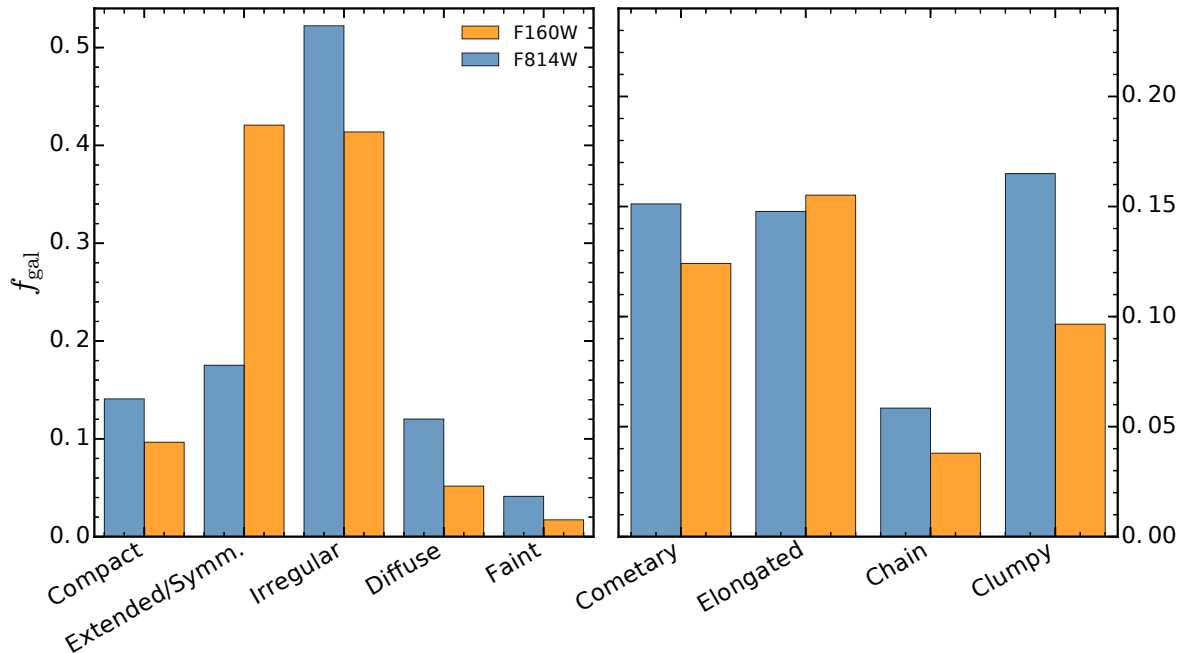


Figure 5.23. Median classification distribution for the VUDS-CANDELS sample by primary class (left panel) and by secondary irregular class (right panel). Blue bars correspond to I band classifications whereas orange bars correspond to H band classifications.

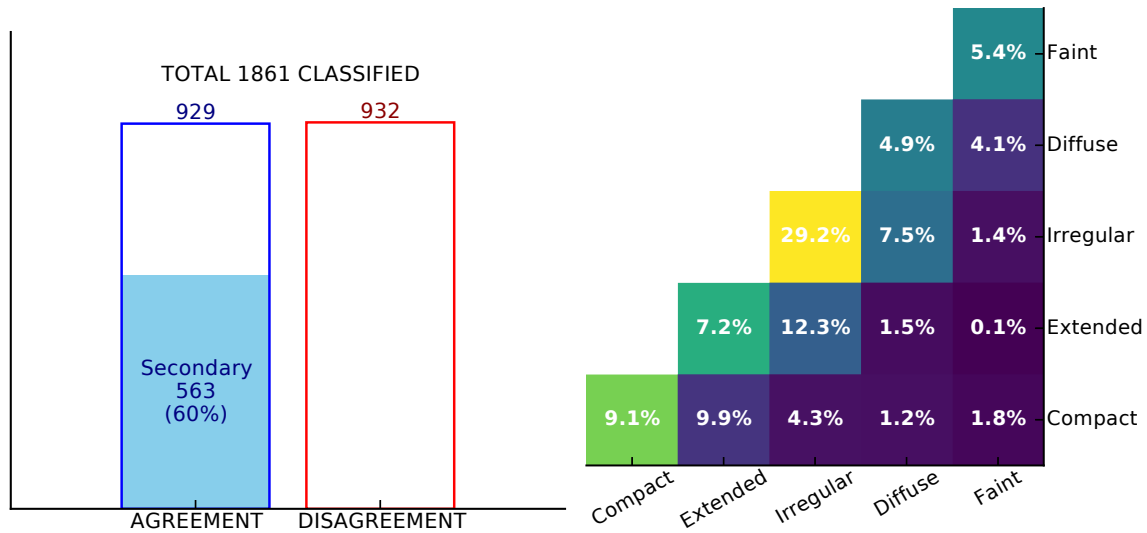


Figure 5.24. Class agreement statistics for the extended sample. On the left panel I show the overall number of objects with primary and secondary class agreement. On the right panel I show in detail which class discrepancies are found to be more common.

extended/symm. class where $\sim 10\%$ of objects were classified as both. The most common case for disagreement is found for $\sim 12\%$ of the objects were classified differently as either extended/symm. or irregular.

I have conducted the same exercise to quantify the distribution in morphological class for this extended sample and show my findings in figure 5.25. Consistent with the results from the CANDELS subsample in the I band, I find that most galaxies are classified as irregular ($\sim 48\%$). When contrasted to the results from the CANDELS subsample, I find a larger fraction of faint galaxies (consistent with the lower survey depth of COSMOS) and a larger fraction of compact galaxies ($\sim 15\%$) with respect to extended/symm. galaxies ($\sim 12\%$). In terms of the secondary classification within irregular galaxies, I find that only 210 galaxies have agreement between the two different classifiers. I show in the right panel of figure 5.25 the distribution of these subset with respect to each secondary class. I find that half of the irregular sample is classified as being clumpy, followed by $\sim 32\%$ of that subset being classified as cometary/tadpole galaxies. Elongated and chain galaxies make up $\sim 12\%$ and $\sim 6\%$ of this subset, respectively. I stress however that I only get agreement for the secondary classification for less than half (210 out of 448 galaxies) of the irregular sample.

5.3.4 EVOLUTION WITH REDSHIFT

Using a weighted classification I computed the fraction I find for each primary class (also including a discrimination among secondary classes) in three redshift bins spanning the entire redshift range in VUDS $2 < z < 6$. In the I band I find that irregular galaxies are dominant at all redshifts with fractions around $35 - 45\%$ of all sources. I do find that there is a rising trend on identified compact sources from redshift $z \sim 2.5$ ($\sim 17\%$) to redshift $z \sim 5$ ($\sim 30\%$). All the other classes have almost constant fractions across this period. In the H band I find a clearly decreasing trend on extending/symm. galaxies from $\sim 40\%$ at $z \sim 2.5$ to $\sim 22\%$ at $z \sim 5$. At the same time I see an almost constant fraction of irregular galaxies and a rising trend in the fraction of compact galaxies as seen in the I band. among the irregular sub-classes there is no strong evolution observed in the H band.

I would like to point out that irregular galaxies seem to have a lower fraction at $z \sim 3.5$ than in the lower and higher redshift bins. This trend is mainly driven by the dip observed in the

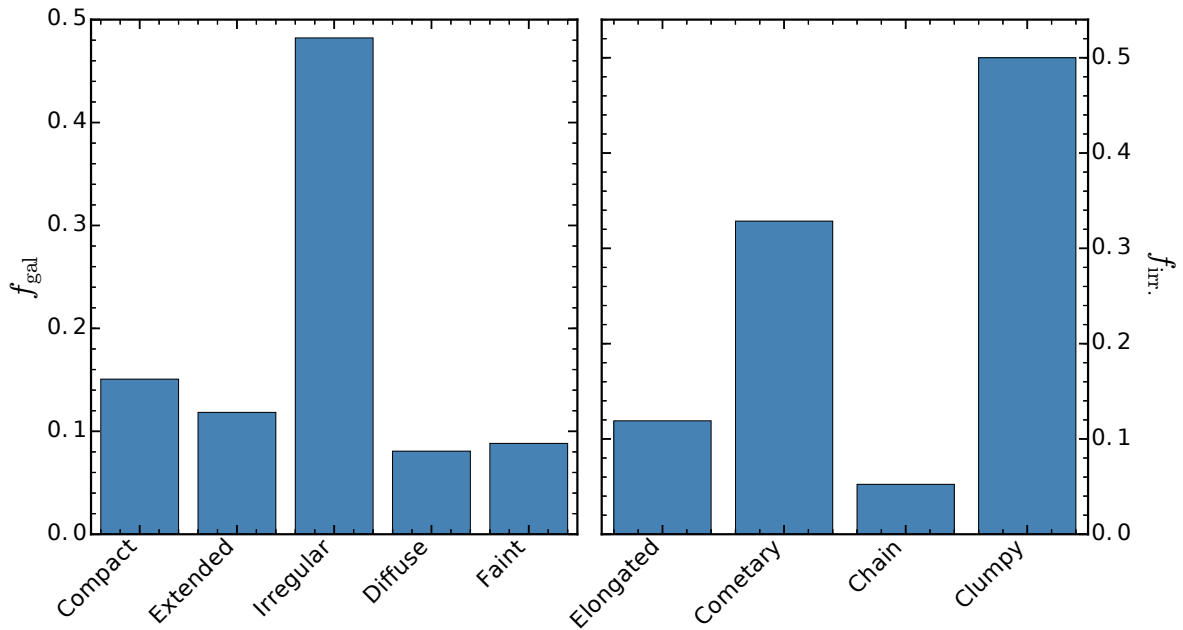


Figure 5.25. Left: frequency of each morphological class for the extended sample. Right: secondary class distribution among 210 irregular galaxies with agreement on the secondary identifier. All classifications are based on I band images.

fraction of clumpy galaxies in the same redshift bin. Despite not being significantly strong (error bars within 1σ) this is observed both in the H and I bands.

I show in figure 5.27 the evolution of the main morphological classes for the 929 galaxies that have primary agreement on the extended sample. I first show the redshift evolution for the entire sample, where I observe that irregular galaxies are dominant at $2 < z < 4.5$ with roughly constant fraction of $\sim 50\%$ and it drops to $\sim 30\%$ in the higher redshift bin, $4.5 < z < 6.0$. I find a rise on the fraction of compact galaxies that is more evident for $z > 3.5$ reaching almost 30% of the sample at the highest redshift bin. A similar trend is found for the extended/symm. galaxies but they remain at lower fractions than compact galaxies at all redshifts. I find little evolution in the fraction of diffuse galaxies with redshift. I explore the evolution in different bins of stellar mass in the right panel of the same figure where no significant differences are found in the low ($9.5 < \log_{10}(M_{\star}/M_{\odot}) < 10.0$) and high ($10 < \log_{10}(M_{\star}/M_{\odot}) < 12$) stellar mass subsamples.

5.3.5 AUTOMATED MORPHOLOGICAL DISCRIMINATION

One useful tool to pave the way towards an automated morphological classification is to establish morphological descriptors that will allow for establishing boundaries between different classes. This has been done locally and at high redshift to distinguish between different types of galaxy morphologies based on some non-parametric diagrams (e.g. Conselice et al., 2000; Conselice, 2003; Conselice & Arnold, 2009; Lotz et al., 2004, 2008; Freeman et al., 2013). Extending on top of this simple definitions several studies attempted at establishing automated classification machines that make use of several morphological descriptors to successfully recover morphologies for large samples at $0 < z \lesssim 3$ (e.g. Ball et al., 2004; Huertas-Company et al., 2009, 2011, 2015a; Shamir & Wallin, 2014).

I have computed a number of morphological non-parametric quantities that I show in figures 5.28 and 5.29. I color code each galaxy according to their primary class as defined from the median classification. There are some regions where I can obtain clean (but not complete)

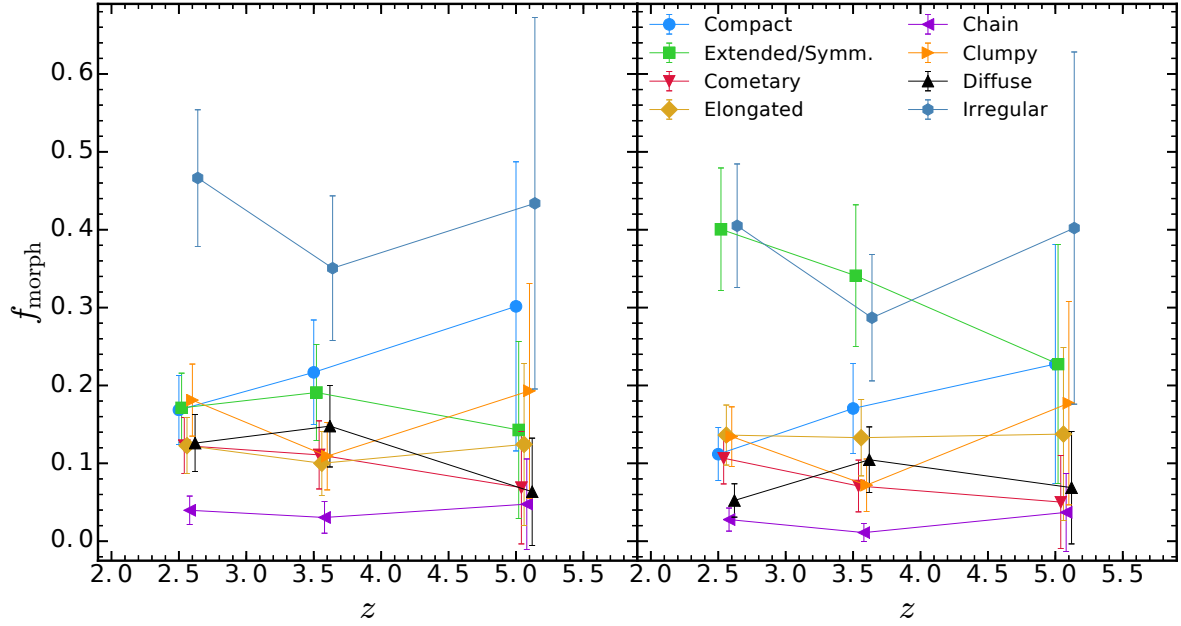


Figure 5.26. Redshift evolution of each weighted morphological class. Each color and symbol represents a different class: compact as light blue circles, extended as light green squares, cometary as red inverted triangles, elongated as gold diamonds, chain as purple left triangles, clumpy as orange right triangles, diffuse as black triangles and irregular as dark blue hexagons.

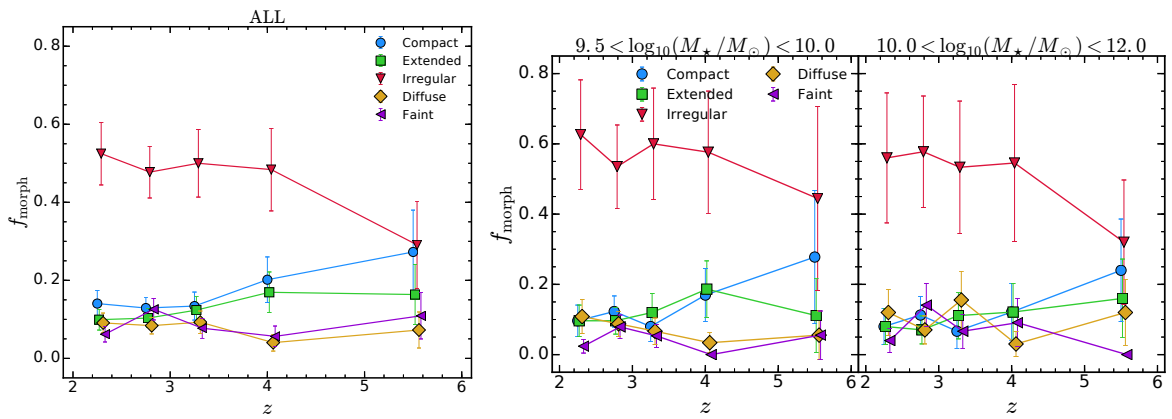


Figure 5.27. Redshift evolution of each primary morphological class in the extended sample. On the left I show the full sample of 929 galaxies and on the right two panels divided in different stellar mass bins. Each color and symbol represents a different class: compact as light blue circles, extended as light green squares, irregulars as red inverted triangles, diffuse as gold diamonds and faint as purple left triangles.

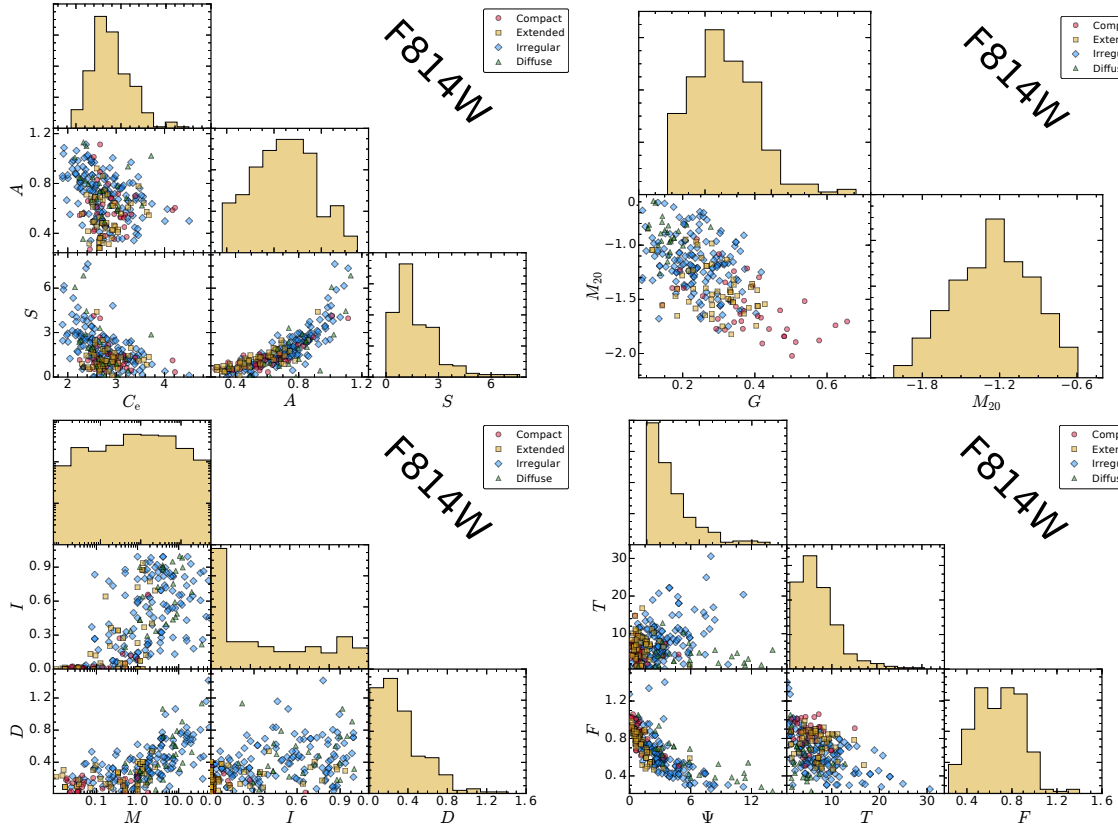


Figure 5.28. Non-parametric class discrimination in the I band using the morphological descriptors defined in section 4.2. Each panel corresponds to a specific set of parameters as defined in the literature: CAS (Conselice, 2003), GM_{20} (Lotz et al., 2004), ΨT (Law et al., 2007), and MID (Freeman et al., 2013). Each morphological class is plotted with a different color and symbol: compact as red circles, extended as golden squares, irregulars as blue diamonds, and diffuse as green triangles.

samples of a given morphological type as defined in this study. I would like to highlight the $G - M_{20}$ diagram (especially that defined in the I band) where compact galaxies clearly stand-out as having high values of G and low values of M_{20} which is also common for spheroidal galaxies in the lower redshift Universe (e.g. Lotz et al., 2004). In this diagram there also seems to be a sequential segregation (although with large overlap) of the 4 major classes defined with diffuse and irregular galaxies occupying the high M_{20} , low G region, extended/symm. galaxies are found in the intermediate region and then the compact galaxies are found at the low M_{20} , high G , region.

In other several diagrams there are regions where one can extract clean samples of irregular+diffuse galaxies using for instance $M > 10$, $\Psi \gtrsim 5$, $C_e \lesssim 2.2$, or $F \lesssim 0.4$. However, in all these diagrams I often see that there is an overlap between several classes and that clean separations are hard to define. This work will be complemented in the future with an automated classification system based on a combination of all parameters and several machine learning techniques that are now available in public python packages like *scikit-learn*. However, I need to build larger samples in order to obtain a reliable estimator that will work at these redshifts.

5.3.6 PHYSICAL DESCRIPTION OF MORPHOLOGICAL CLASSES

I show the typical morphology of galaxies in the star-forming main sequence (e.g. Tasca et al., 2015) in figure 5.34. There is no obvious locus for a particular morphological class as they all span several orders of magnitude both in stellar mass and in SFR. When looking at pop-

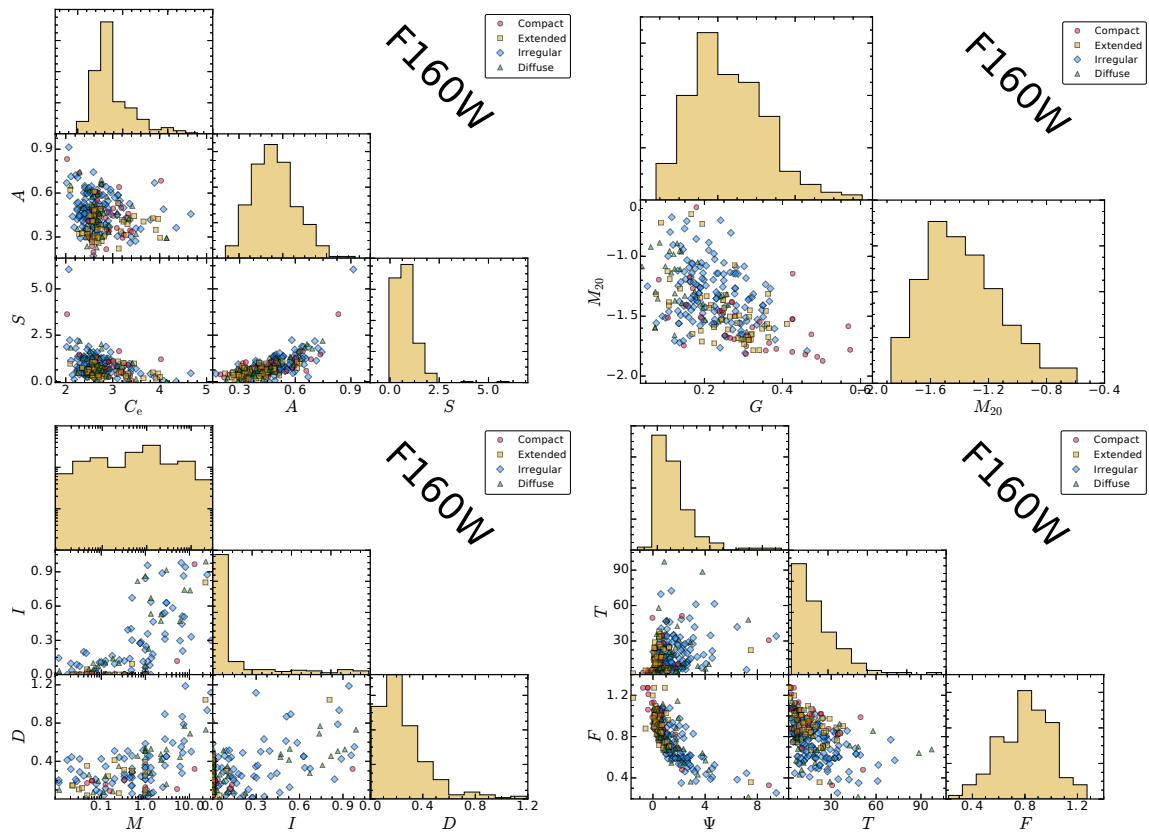


Figure 5.29. Non-parametric class discrimination in the H band using the morphological descriptors defined in section 4.2. Each panel corresponds to a specific set of parameters as defined in the literature: CAS (Conselice, 2003), GM₂₀ (Lotz et al., 2004), ΨT (Law et al., 2007), and MID (Freeman et al., 2013). Each morphological class is plotted with a different color and symbol: compact as red circles, extended as golden squares, irregulars as blue diamonds, and diffuse as green triangles.

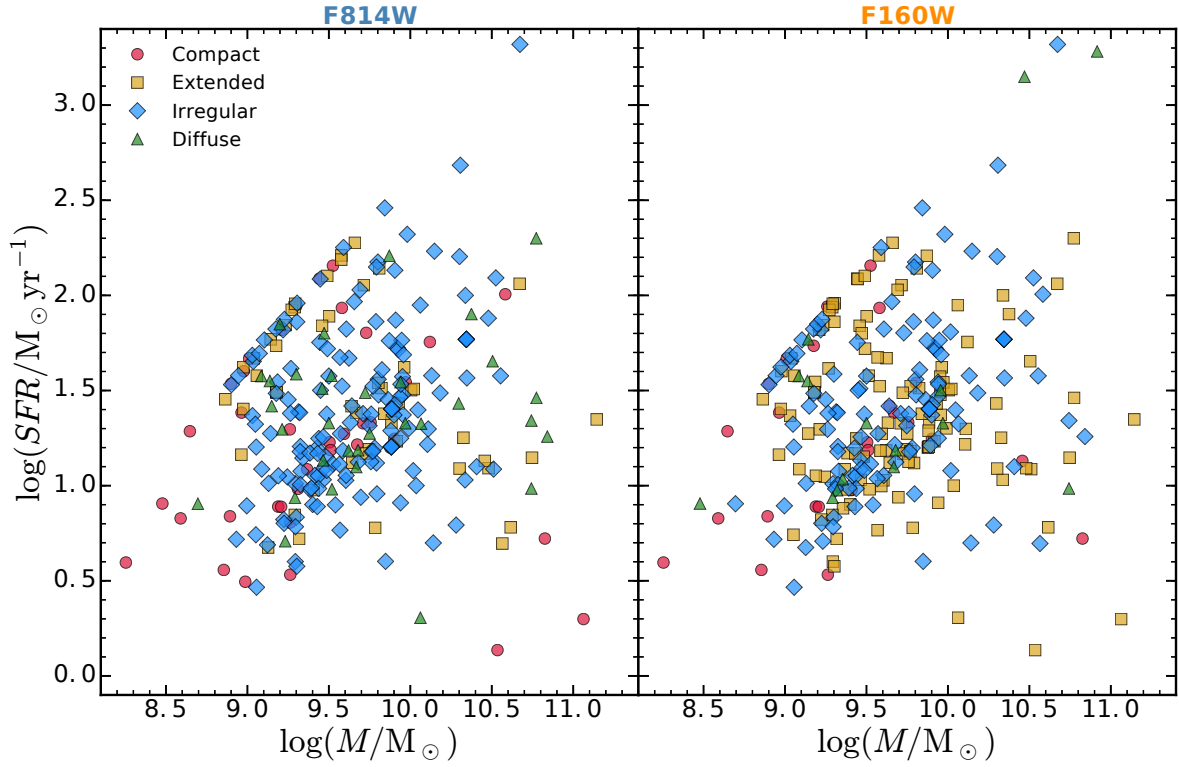


Figure 5.30. Morphological discrimination in the stellar mass-SFR main sequence. Each morphological class is plotted with a different color and symbol: compact as red circles, extended as golden squares, irregulars as blue diamonds, and diffuse as green triangles.

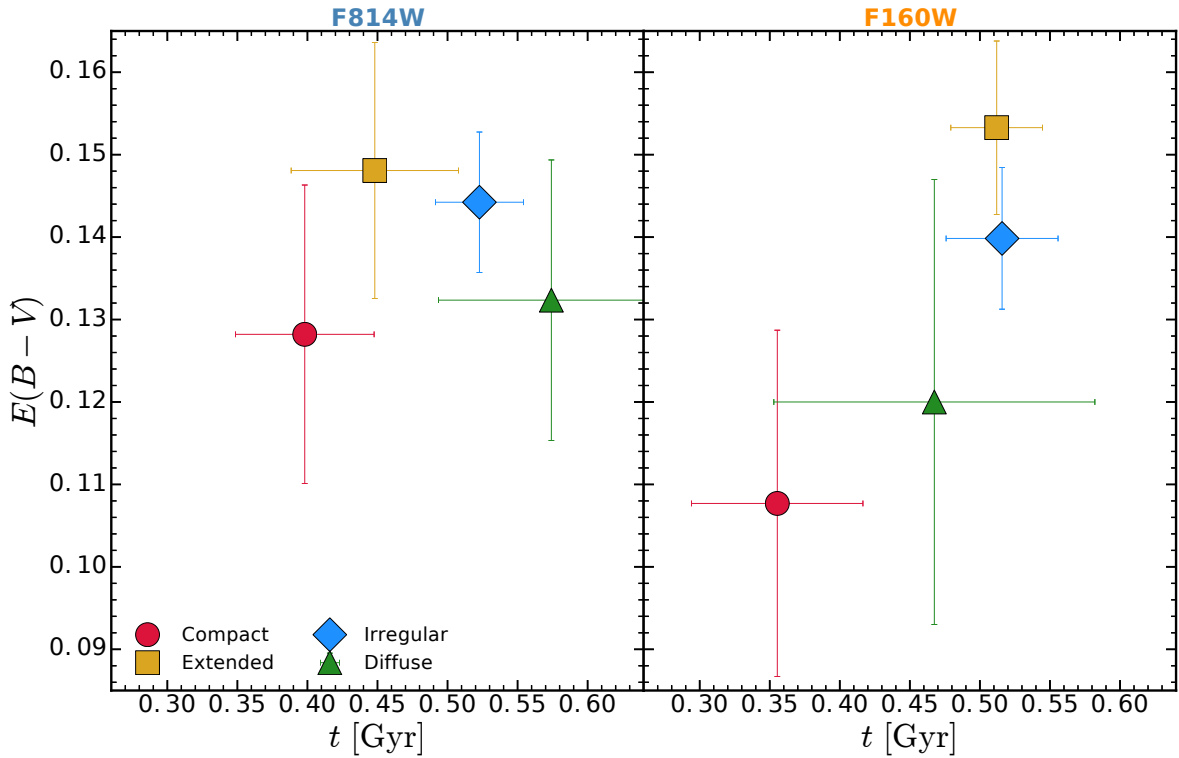


Figure 5.31. Median age and dust extinction for different morphological classes. Each morphological class is plotted with a different color and symbol: compact as red circles, extended as golden squares, irregulars as blue diamonds, and diffuse as green triangles.

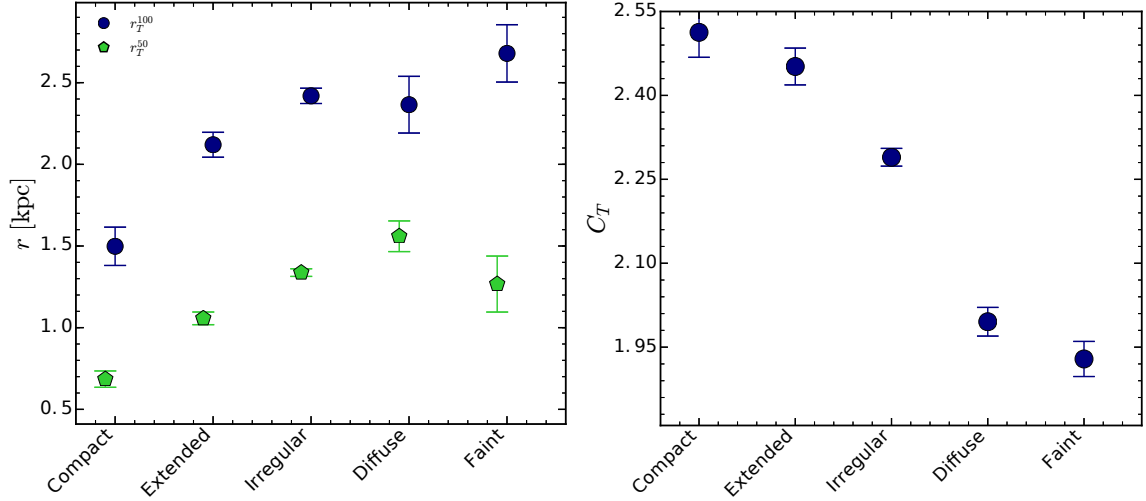


Figure 5.32. The median size as measured from r_T^{50} and r_T^{100} (left, section 4.3.1) and light concentration (right, section 5.1.3.3) for each defined morphological class. This sample is limited to $2 < z < 4.5$ and $\log_{10}(M_*/M_\odot) > 9.35$.

ulation extremes I find that the most star-forming galaxies are typically irregular or diffuse, representing large disks with a clumpy structure. On the lower mass end, I do find an excess of compact sources. However this is likely due to survey limitations rather than motivated by any physical mechanism actuating at lower masses since at the faint end VUDS is more likely to pick high surface brightness galaxies, hence their compactness.

I study as well the mean values for age and dust content as measured from SED fitting (Thomas et al., 2016). I show the median values since for these two parameters there was only available a grid of models and the mean is a statistic that weights on the number of galaxies in each grid value. I tend to find extended/symm. galaxies to be more dusty and compact galaxies to be the youngest of the morphological classes. However there is a large spread in both directions meaning that no single morphological class has a typical physical interpretation able to explain the entire population.

I extend my analysis to the sample that has been classified in the COSMOS field where 929 galaxies were visually classified independently by two different people. In figure 5.47 I show the typical median sizes for each morphological class computed as explained in section 4.3.1, for a sample limited to $2 < z < 4.5$ and $\log_{10}(M_*/M_\odot) > 9.35$. As expected, the compact class has the smallest sizes in both $r_T^{50} \sim 0.7$ kpc and $r_T^{100} \sim 1.5$ kpc. I find that the largest galaxies are classified in the irregular, diffuse and faint classes with total extent $r_T^{100} \sim 2.4 - 2.7$ kpc. The class of extended/symm. galaxies shows intermediate sizes of $r_T^{50} \sim 1.1$ kpc and $r_T^{100} \sim 2.1$ kpc. In the same figure I show in the left panel the median concentration as computed using the method defined in section 5.1.3.3. It is evident that this parameters strongly correlates with morphological class. I find that compact galaxies are the ones where light is more concentrated ($C_T \sim 2.48$) closely followed by the extended/symm. objects ($C_T \sim 2.42$). Then I find that irregular galaxies have typical light concentration values around $C_T \sim 2.27$. Finally, diffuse and faint galaxies are found to be low concentration galaxies with $C_T \sim 2.0 - 1.9$, respectively.

I show in figure 5.33 the distribution of galaxies in the UVJ color diagram (e.g. Williams et al., 2009; Whitaker et al., 2012) as a function of morphological class. As somehow hinted by the $z > 2$ panels produced by Kartaltepe et al. (2015) and Huertas-Company et al. (2015a) there are no substantial differences in color among different morphological types. This is further exaggerated in VUDS since the sample is UV-selected and is picking preferentially star forming galaxies among which the morphological distinction is less pronounced.

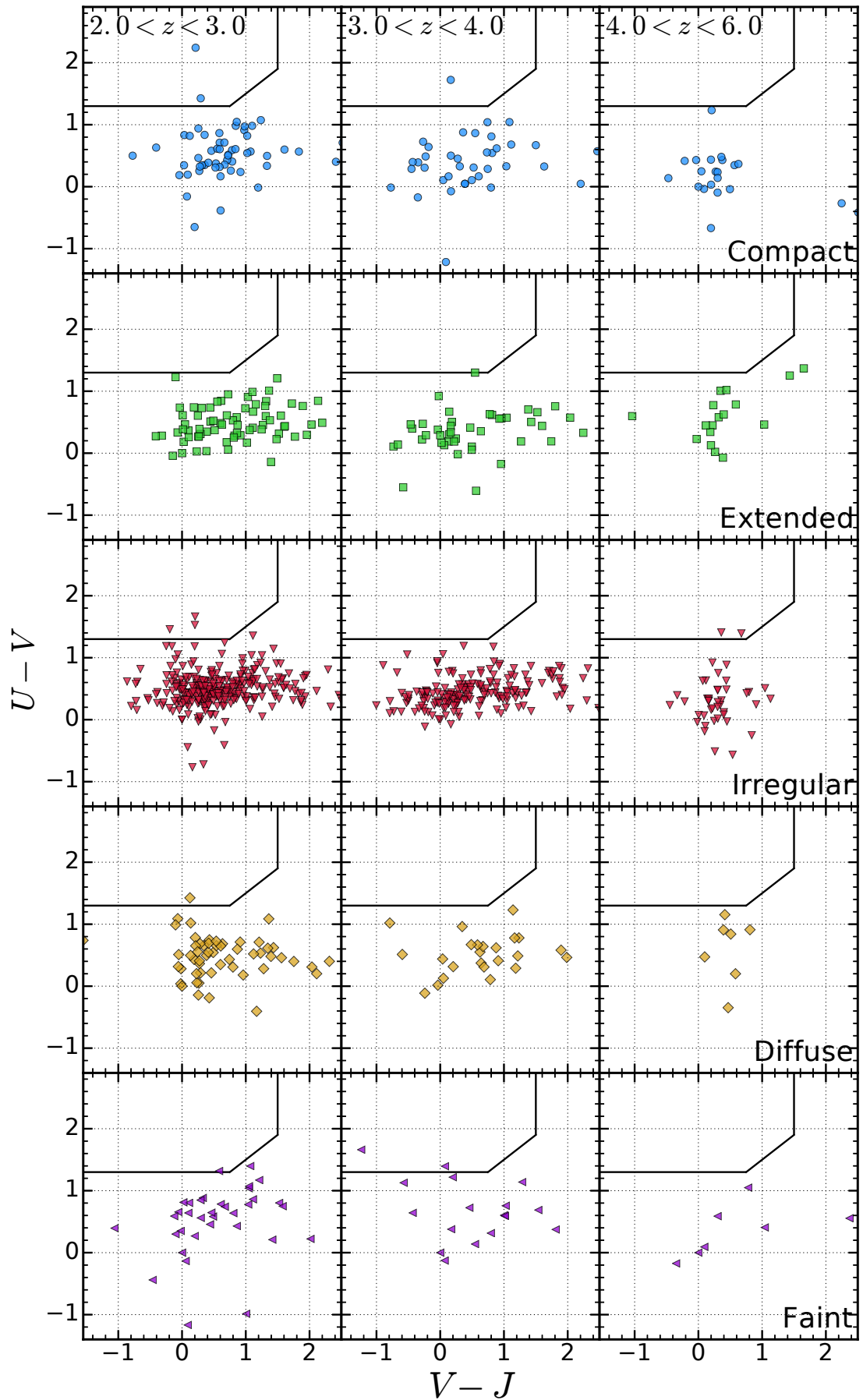


Figure 5.33. UVJ color diagram for the extended sample divided in three redshift bins (from left to right) and in different morphological classes (from top to bottom). The selection box of quiescent galaxies is the same as defined in [Whitaker et al. \(2012\)](#). There is no real distinction in the population of this diagram among different classes and as expected most galaxies are located in the star forming region of the plot.

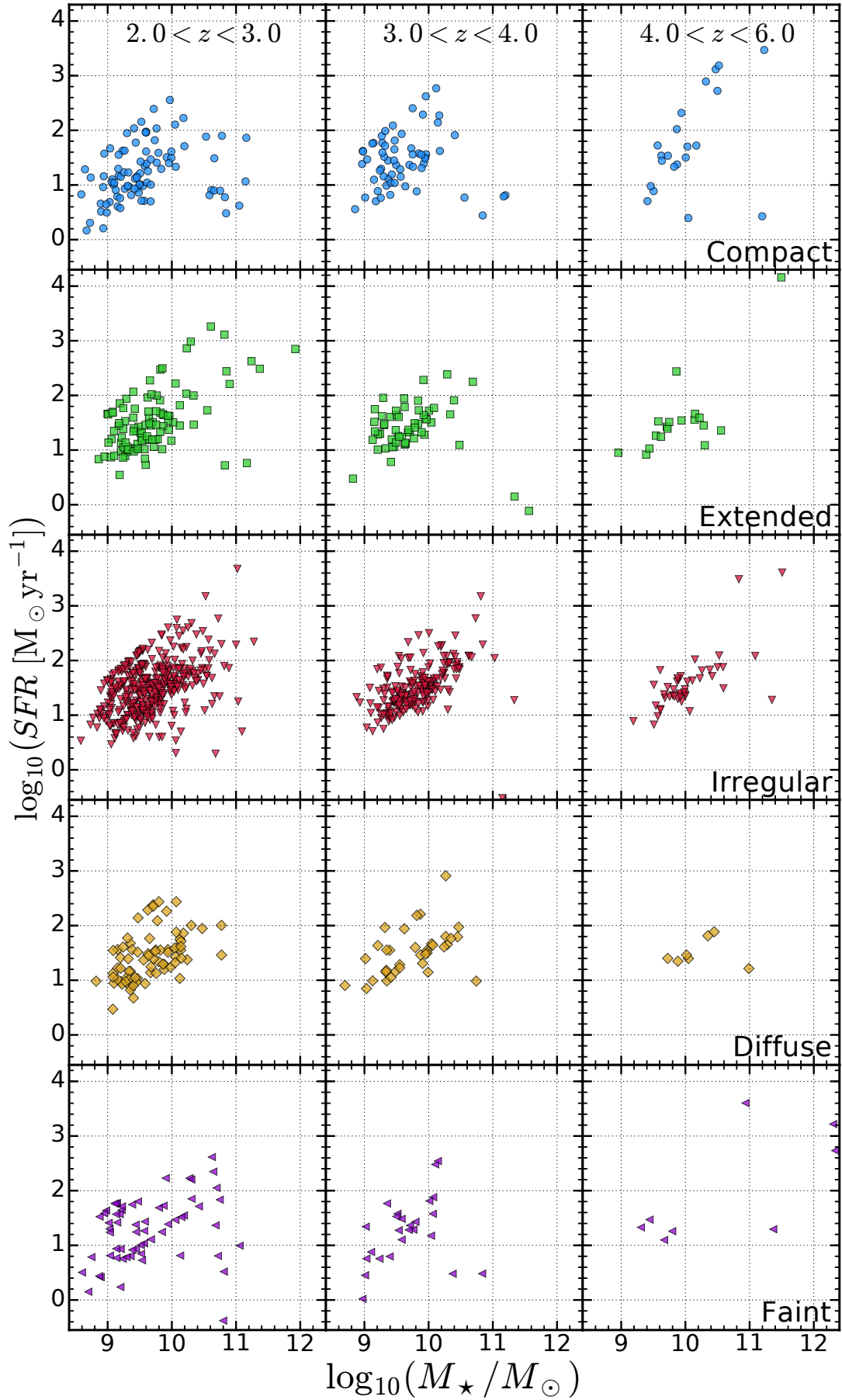


Figure 5.34. The main sequence of star formation divided in three redshift bins (from left to right) for the different morphological classes (from top to bottom). Each class occupies essentially the same star-forming region of the plot, but there are hints that some populations (namely compact and faint galaxies) are dominant in the high mass and low SFR regime.

In terms of stellar mass and star formation rates, I can see in figure 5.34 the distribution of each morphological class in the main sequence of star formation for three different redshift slices from $2 < z < 6$. At first glance, there is no real disparity between different galaxy types as they all span various orders of magnitude in both stellar mass and star formation rate, at all redshifts. This picture is similar as to what I found for the subset in the VUDS-CANDELS sample (see figure 5.34). Nonetheless, there seems to be more frequent faint or compact galaxies in the high stellar mass and low star formation region of the plot ($\log_{10}(M_*/M_\odot) > 10.5$ and $\log_{10}(SFR) < 1$).

I inspect differences more closely in the stellar mass and SFR by looking in the top panels of figure 5.35, where restrict the sample to $\log_{10}(M_*/M_\odot) > 9.35$. On this subset I find that galaxies that have typically symmetric shapes (compact and extended+symmetric) are less massive ($\log_{10}(M_*/M_\odot) \sim 9.76 \pm 0.05$) than the irregular galaxies ($\log_{10}(M_*/M_\odot) \sim 9.82 \pm 0.02$). Interestingly, the galaxies with the highest median mass are the ones classified as diffuse and faint with $\log_{10}(M_*/M_\odot) \sim 9.88 \pm 0.04$, 9.9 ± 0.1 , respectively. In what concerns the SFR of galaxies, they have roughly the same typical median values with $\log_{10}(SFR) \sim 1.4 - 1.5$ (within the errors). Nonetheless, the least star-forming galaxies are found to be the ones classified as faint with $\log_{10}(SFR) \sim 1.4 \pm 0.1$ despite not being statistically significant and a large dispersion is observed. On the other hand, irregular and diffuse galaxies are the ones with the highest values of SFR with $\log_{10}(SFR) \sim 1.52 \pm 0.02$, 1.51 ± 0.05 , respectively.

When looking at these trends in three different redshift slices (left panel of figure 5.35), I see that faint or diffuse galaxies are the most massive at any redshift. At the highest redshift bin, there are three (out of six) very massive galaxies, with $\log_{10}(M_*/M_\odot) > 11$, classified as faint (see also left panel of figure 5.34). These galaxies have the lowest redshift confidence flag (2, 9 and 29) that is included in my sample and for the two most massive, only when using GOSSIP+ I am able to get a stellar mass estimates. The other galaxy has a consistent stellar mass value both from LePhare and GOSSIP+ with $\log_{10}(M_*/M_\odot) \sim 11.1$, 11.4 , respectively. However, I also find that in the lower redshift bin, $2 < z < 3$, faint galaxies are the ones with the highest median stellar mass. In term of their SFR, there is no obvious differences between different redshift bins as the median values are always within the error bars for all classes. The exception is the lowest redshift bin where the trend is similar to what is found for the entire sample in the right panel, which may be expected since it contains more than half of the entire sample (508 out of 929 galaxies).

I further explore the mean dust extinction and mean galaxy age (defined as the onset of star formation in the galaxy Thomas et al., 2016) in figure 5.35. When looking at the full sample (left panel) I see that compact galaxies have lower dust extinction values ($E(B - V) \sim 0.16 \pm 0.01$) while all other morphological classes show higher values of $0.17 \gtrsim E(B - V) \lesssim 0.19$. However this is only true for $z < 4$, since for the highest redshift bin compact galaxies are the ones found to have the higher dust extinction values ($E(B - V) \sim 0.13 \pm 0.01$), whereas all other classes show average values of $0.01 \gtrsim E(B - V) \lesssim 0.12$. In the highest redshift bin I see a strong trend of morphological class with dust extinction with extended/symm. galaxies and irregular galaxies having $E(B - V) \sim 0.07$ and diffuse galaxies having the lower dust extinction with $E(B - V) \sim 0.01 \pm 0.01$.

In terms of age, I find that faint galaxies are the ones that show the oldest population of stars ($t \sim 0.64 \pm 0.06$ Gyr) while all other morphological populations show ages $0.50 \text{ Gyr} \gtrsim t \lesssim 0.55$ Gyr. This picture becomes more intricate as I look to the different redshift bins shown in the left bottom panel of figure 5.35. In the lower redshift bin, compact and faint galaxy populations show the oldest age and in the intermediate redshift bin this trend is reversed and they are among the youngest populations, albeit within 1σ of the other classes. In the highest redshift bin I see a strong trend of morphological class with age where compact galaxies have $t \sim 0.47 \pm 0.08$ Gyr, followed by extended symm. galaxies with $t \sim 0.52 \pm 0.06$ Gyr, then

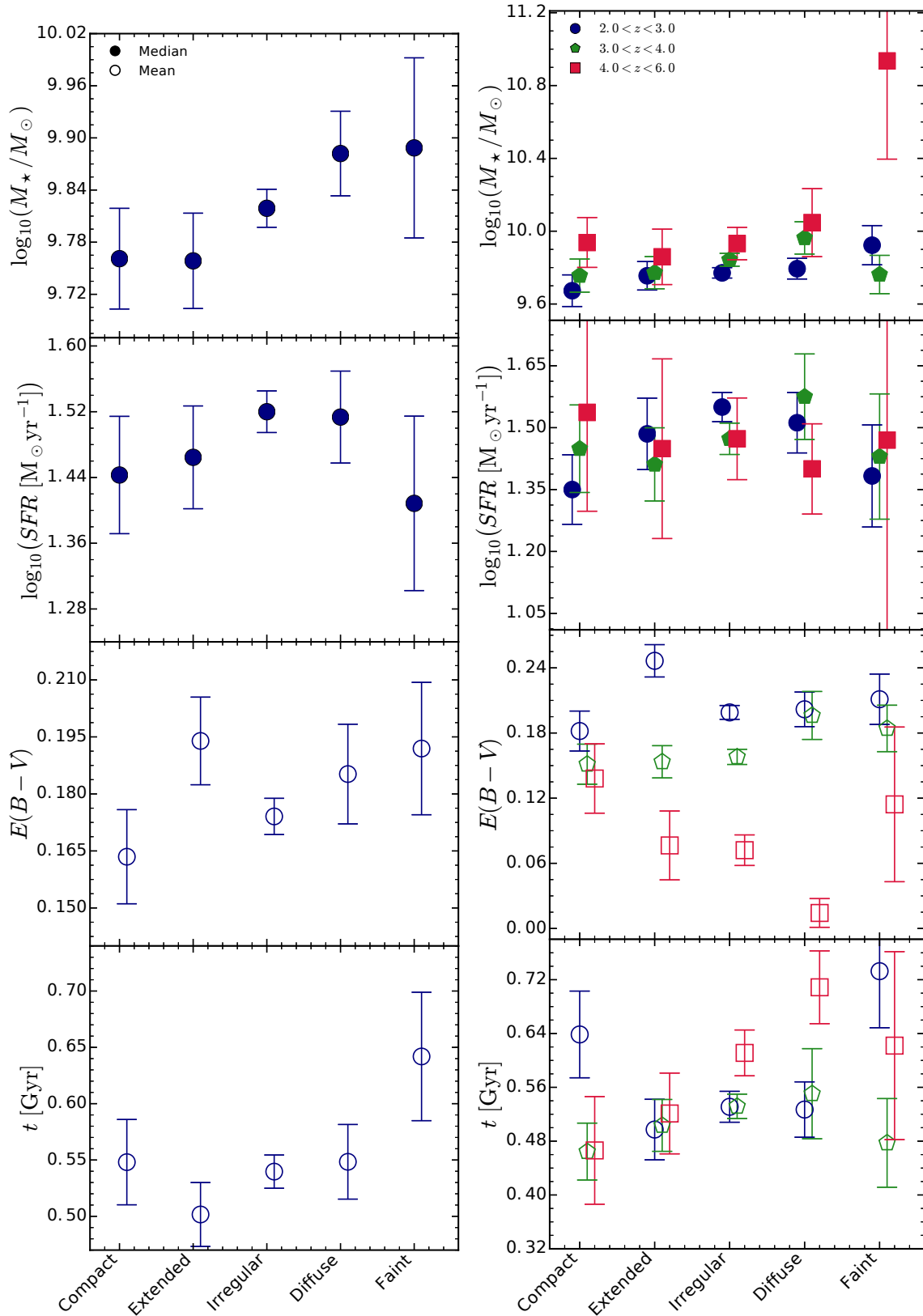


Figure 5.35. Summary of the main class physical properties for the galaxies with $\log_{10}(M_{\star}/M_{\odot}) > 9.5$ secure classifications for the full sample in the range $2 < z < 6$ on the left panels, and in three redshift bins in the right panel. Filled circles represent median values whereas empty circles represent mean values. Blue circles, red squares, and green pentagons correspond to redshifts $2 < z < 3$, $3 < z < 4$, and $4 < z < 6$, respectively. From top to bottom I show the class depended on stellar mass, star formation rate, dust extinction, and age.

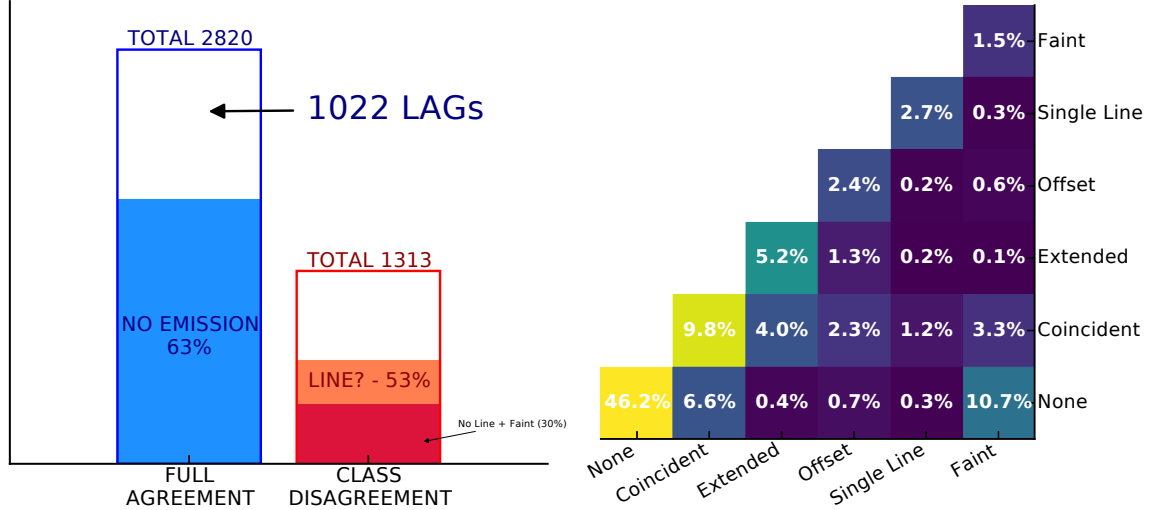


Figure 5.36. Summary of the agreement between different observers performing the classification. The number of galaxies on which both classifiers agreed (divided in emitting and non-emitting galaxies) is shown as the blue bar. In the red bar I have the number of galaxies on which the classifiers disagree. The dark red portion of this bar indicates the fraction of galaxies which was classified with faint or no emission and the orange portion indicates the fraction of cases for which one classifier chose an emission line (classes 2, 3, 4 or faint) and the other chose the no emission line class 1. The white fraction of the bar indicates the cases where both classifiers agree on the existence of a line, but disagree on the line classification. Out of this exercise I have a total of 1022 Ly- α emitting galaxies with secure classification. On the right panel I show the full classification analysis where the reasons for non-agreement among two different people are identified. Each square is color coded according to the number of objects and the corresponding object fraction is shown in white text.

irregular galaxies with $t \sim 0.61 \pm 0.03$ Gyr and finally diffuse galaxies with $t \sim 0.70 \pm 0.05$ Gyr. This trend seems to be anti-correlated with what I find for the dust-extinction values where the oldest population is also the one with the lowest dust extinction.

5.4 EXTENDING MORPHOLOGY TO LY- α STUDIES

I show in this section the results from the Ly- α classification in the 2D spectrograms which uses the scheme and was carried out using the GUI described in section 4.6.

5.4.1 CLASSIFIER AGREEMENT

After the classification was done, I checked for the overall agreement between each pair of classifiers for my entire sample. I have classifications for a total of 4133 objects since out of the 4360 objects some of them were double observations of the same target and thus I have 4 classifications for those objects (2 per each observation). The summary of these results is shown in figure 5.36. I note that I have agreement in the classification for 2820 ($\sim 68\%$) galaxies of which 1022 have Ly- α in emission and 1798 have no line in emission. For 1313 galaxies I have no agreement for more than 50% of the classifiers (for the case of double observations, three out of the 4 people had to agree on the main class). Of those 1313 galaxies, 729 ($\sim 54\%$) have their classifiers disagree on the existence of line emission and in most of the cases that happens when one chooses the *Faint* class and the other chooses no class, an indication of the low signal to noise of these spectra. There are also a total of 607 galaxies for which the classifiers disagree of the primary class. On this subset of galaxies I can see in the left panel of figure 5.36 that the majority of disagreements report to the confusion between coincident and extended classes (165 galaxies), between coincident and faint classes (136 galaxies) and

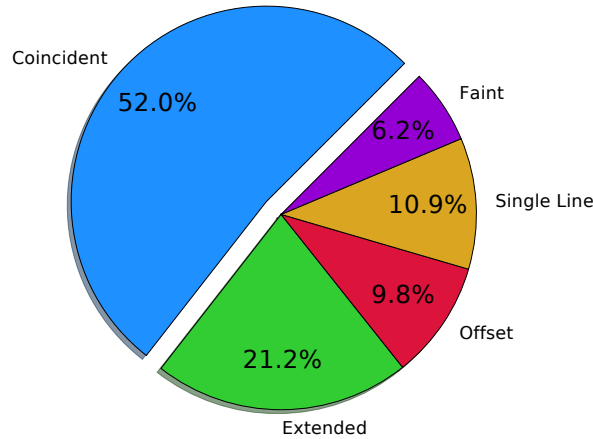


Figure 5.37. Summary of the main class distribution for the 1022 LAGs with secure classifications.

Selection	$2.0 < z < 2.5$	$2.5 < z < 3.0$	$3.0 < z < 3.5$	$3.5 < z < 4.5$	$4.5 < z < 6.0$	Total
All	209	378	219	143	73	1022
$-23.0 < M_{\text{FUV}} < -21.0$	27	86	74	97	46	330
$-21.0 < M_{\text{FUV}} < -20.5$	50	121	94	32	8	305
$-20.5 < M_{\text{FUV}} < -19.5$	110	142	38	5	2	297
$9.3 < \log_{10}(M_{\star}/M_{\odot}) < 9.7$	64	113	52	50	10	289
$9.7 < \log_{10}(M_{\star}/M_{\odot}) < 10.1$	57	95	69	42	15	278
$10.1 < \log_{10}(M_{\star}/M_{\odot}) < 12.0$	41	76	53	34	25	229
$-800.0 < W_{\text{Ly-}\alpha} < -50.0$	29	57	49	28	24	187
$-50.0 < W_{\text{Ly-}\alpha} < -25.0$	33	57	31	33	10	164
$-25.0 < W_{\text{Ly-}\alpha} < -10.0$	44	96	50	47	19	256
$-19.0 < \log_{10}(F_{\text{Ly-}\alpha}) < -18.0$	31	78	72	45	41	267
$-18.0 < \log_{10}(F_{\text{Ly-}\alpha}) < -17.5$	67	117	52	37	11	284
$-17.5 < \log_{10}(F_{\text{Ly-}\alpha}) < -16.0$	61	114	53	40	7	275

Table 5.4. Number of LAGs in each redshift bin and for each selection used in this study.

between coincident and offset classes (95 galaxies).

In the end, I have a sample of 1022 galaxies at $2 < z < 6$ with Ly- α in emission and for which I have a high degree of certitude in the visual classification since the majority of the observers agreed on the same class. I use the acronym LAGs for these Ly- α emitting Galaxies, presenting Ly- α emission down to equivalent width of a few angstroms, to avoid confusion with strong Ly- α emitters (e.g. with $W_{\text{Ly-}\alpha} < -25\text{\AA}$) for which the acronym LAE (Ly- α Emitters) is usually used for in the literature. I discuss the properties of this sample of 1022 LAGs in the following.

5.4.2 LY- α SHAPES

I show in figure 5.37 the distribution of classes for the 1022 objects with secure classifications. I find that half of my sample ($\approx 52\%$) shows Ly- α in emission that is consistent with the extent of the UV continuum. I find that one fifth ($\approx 21.2\%$) of my sample has extended Ly- α emission, $\approx 10.9\%$ have only an emission line and the continuum is not seen, $\approx 9.8\%$ show an emission offset with respect to the UV continuum, and finally $\approx 6.2\%$ are too faint to be classified. The number statistics of each sub-sample that I discuss in the following paragraphs as a function of redshift, stellar mass and line properties is summarized in Tab. 5.4.

I show how these class fractions vary with redshift in figure 5.38. I find that the class with coincident continuum and Ly- α emission dominates at $z < 4.5$, with fractions always above 50%. At $z > 4.5$ the most common cases are single line emitters. These show a strong increase

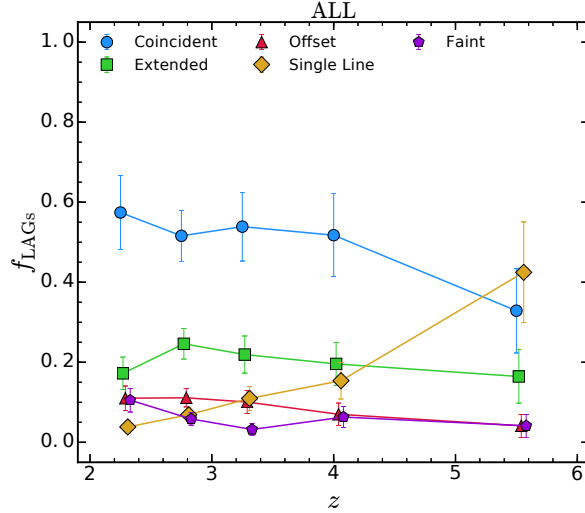


Figure 5.38. The redshift dependence of each Ly- α line morphology class, considering all 1022 LAGs identified during the classification at $2 < z < 6$. Coincident class is shown as blue circles, extended is shown as green squares, offset is shown as red triangles, single line emitters are shown as gold diamonds, and faint line emitters are shown as dark violet pentagons.

in their fraction at high redshift, rising from $\sim 4\%$ at $z \sim 2.25$ to 46% at $z \sim 5 - 6$. The fraction of extended emission is the second most frequent case at $z < 4.5$ and it shows an almost constant fraction around $\sim 15 - 25$ at all redshifts. Faint and offset line emitters observe a decrease in their fractions as a function of redshift and are never above $\sim 10\%$.

I divide further the sample in sub-sets based on their stellar-mass, line equivalent width and line flux in figure 5.39, 5.40 and 5.41. When considering stellar masses I observe the same general trends as in the entire sample where the coincident Ly- α emission dominates at all stellar masses and at all redshifts (with the exception of the highest bin in the intermediate stellar mass bin where extended Ly- α emission is more common). Other interesting trend is that at the higher stellar masses the fraction of extended Ly- α emitters is smaller than the two lower stellar mass bins.

When dividing my sample based on the absolute FUV magnitude I see in figure 5.42 that single line emitters dominate the faintest galaxies at the highest redshifts. This results imply that the rising fraction of single line emitters as a function of redshift seen in almost all panels is dominated by UV continuum faint galaxies that are in my sample.

I observe a strong dependency of the derived class fractions on the equivalent width of Ly- α . The larger equivalent width galaxies are dominated by extended emission at lower redshifts and single line emitters at the highest redshifts. As I move progressively to lower equivalent widths the population of coincident line emission starts to be the most common. A similar trend is observed for line fluxes where the extended emission lines dominate at higher luminosity and coincident emission is the most common at lower luminosity.

5.4.3 PHYSICAL PROPERTIES OF THE DIFFERENT LY- α LINE MORPHOLOGY CLASSES

I show in the left panel of figure 5.43 the median values for stellar masses, star formation rates, dust extinction and stellar age for the four main classes defined in section 4.6. When looking at the stellar masses of each class it is clear that galaxies with no emission and coincident emission are slightly more massive ($\log_{10}(M_*/M_\odot) \sim 9.90$) than galaxies with offset or extended emission ($\log_{10}(M_*/M_\odot) \sim 9.75$). In terms of SFR, there is an interesting

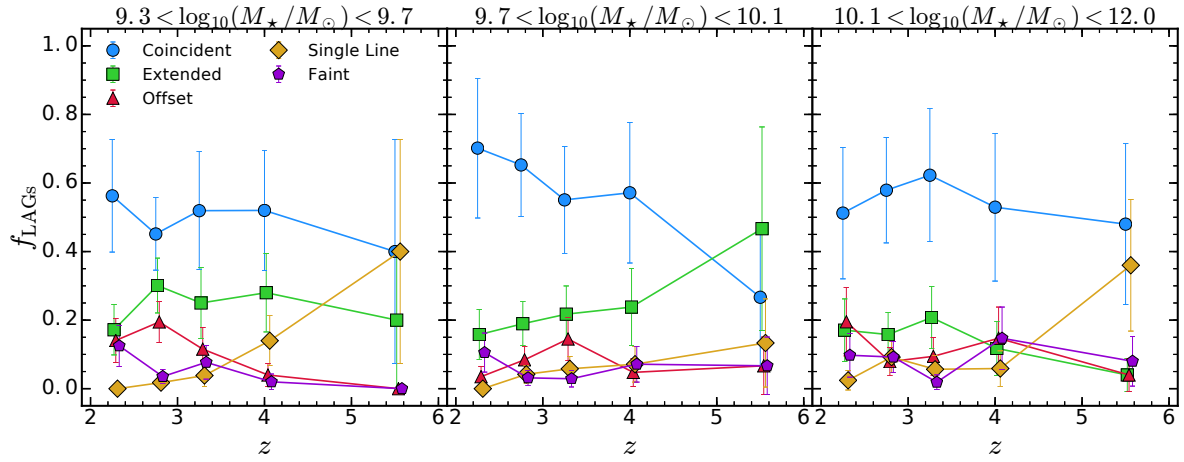


Figure 5.39. The impact of redshift on each of the main classes of Ly- α line morphology, in three stellar mass bins. Coincident class is shown as blue circles, extended is shown as green squares, offset is shown as red triangles, single line emitters are shown as gold diamonds, and faint line emitters are shown as dark violet pentagons.

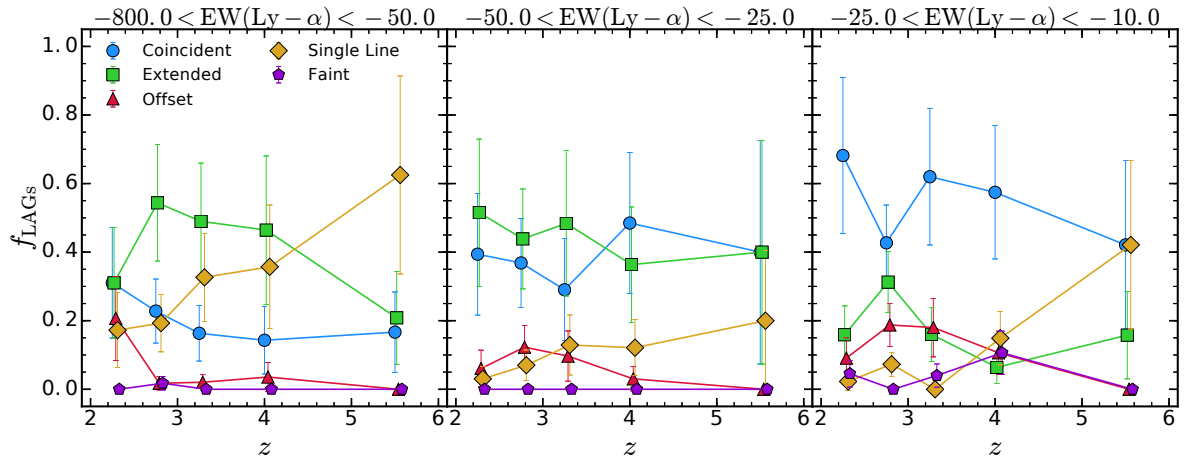


Figure 5.40. The impact of redshift on each of the main classes of Ly- α line morphology, in three line equivalent width bins. Coincident class is shown as blue circles, extended is shown as green squares, offset is shown as red triangles, single line emitters are shown as gold diamonds, and faint line emitters are shown as dark violet pentagons.

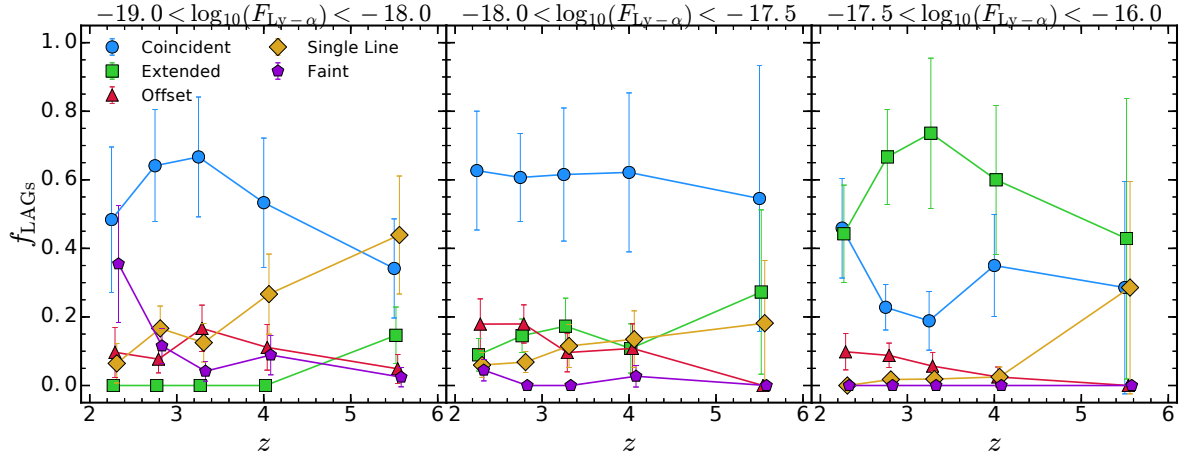


Figure 5.41. The impact of redshift on each of the main classes of Ly- α line morphology, in three line flux bins. Coincident class is shown as blue circles, extended is shown as green squares, offset is shown as red triangles, single line emitters are shown as gold diamonds, and faint line emitters are shown as dark violet pentagons.

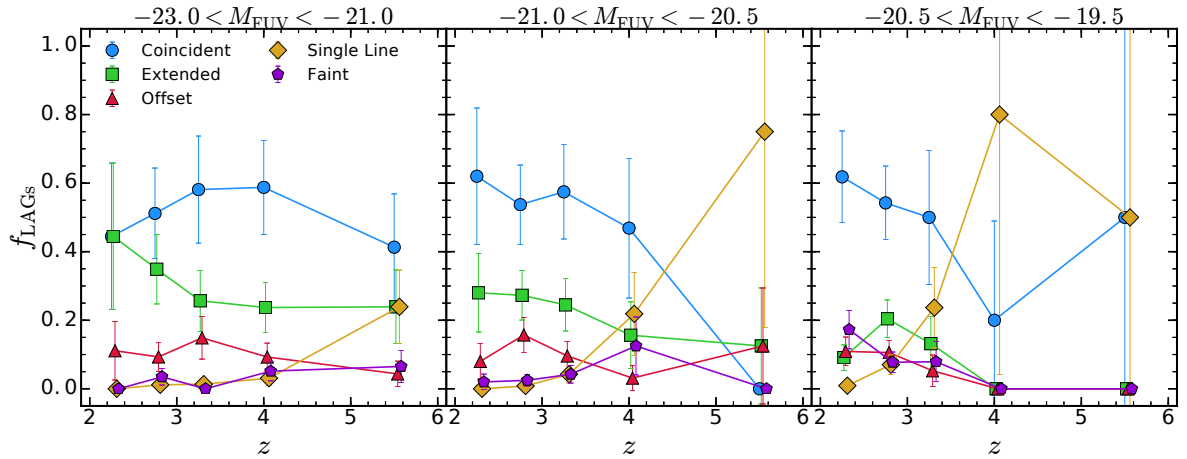


Figure 5.42. The impact of redshift on each of the main classes of Ly- α line morphology, in three absolute FUV magnitude bins. Coincident class is shown as blue circles, extended is shown as green squares, offset is shown as red triangles, single line emitters are shown as gold diamonds, and faint line emitters are shown as dark violet pentagons.

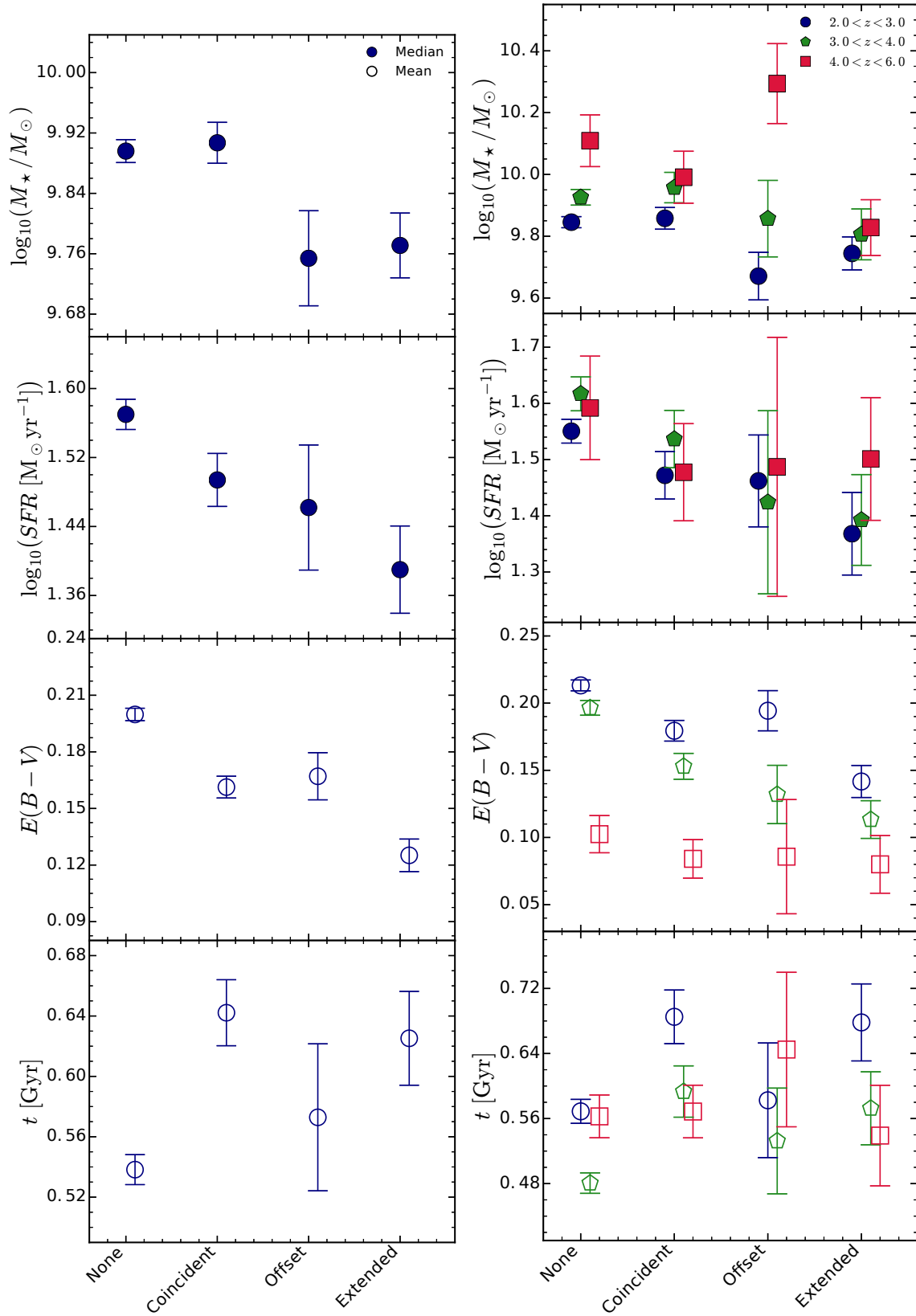


Figure 5.43. Summary of the main class physical properties for the 1022 LAGs with secure classifications for the full sample in the range $2 < z < 6$ on the left panels, and in three redshift bins in the right panel. Filled circles represent median values whereas empty circles represent mean values. Blue circles, red squares, and green pentagons correspond to redshifts $2 < z < 3$, $3 < z < 4$, and $4 < z < 6$, respectively. From top to bottom I show the class depended on stellar mass, star formation rate, dust extinction, and age.

trend where the most star-forming galaxies, with $\log_{10}(SFR) \sim 1.57 \pm 0.02$, have no Ly- α emission. Coincident emission line galaxies are the second most star-forming population ($\log_{10}(SFR) \sim 1.49 \pm 0.03$) followed by offset ($\log_{10}(SFR) \sim 1.46 \pm 0.07$) and extended emission lines ($\log_{10}(SFR) \sim 1.39 \pm 0.05$). The latter is the population with the lowest star formation rate.

Since the values for dust extinction and stellar age are derived from a grid of models, the median value is fixed at one of this grid values. Thus, I opt to use the mean value for these two quantities in my interpretation. Dust extinction is observed to be significantly lower with $E(B - V) = 0.1$ for extended emission line galaxies than the other classes for which the dust extinction is similar at $E(B - V) \sim 0.2$. In terms of stellar age I find that coincident line galaxies are the oldest population with $t \sim 0.64 \pm 0.01$ Gyrs and galaxies with no emission are on average the younger population with $t \sim 0.40 \pm 0.06$ Gyrs. Extended line emitters are as old as the coincident line emitters with $t \sim 0.51$ Gyrs.

On the right panel of figure 5.43 I do the same exercise but diving my sample in three different redshift bins to identify evolutionary trends. The trend in stellar mass for the 4 populations remains the same at all redshifts: stellar masses are found to be higher on average for the non emitters than for the offset or extended classes. The relative mass ratios between coincident and extended line emitters remain roughly constant with the latter being the least massive population. When looking at the median SFRs, the trends are broadly the same as found for the full redshift range with extended line emitters being the least star-forming population whereas galaxies with no line emission are the most star-forming.

I find again that at $z < 4$ the extended line emitters have the least dust content and that dust content increases gradually to the offset, coincident and no line populations. I find a similar trend at $z > 4$, although the dust attenuation is limited to $E(B - V) < 0.15$ and errors are larger, with the extended line emitters having the lower amount of dust. Coincident line emitters remain the oldest population over the redshift range $2 < z < 4$.

5.4.3.1 STACKED SPECTRA

I have stacked the spectra for all the classes using a flux-weighted average (each spectra is normalized to the continuum flux measured at 1250-1500Å rest-frame) onto a common wavelength baseline with 2Å resolution. I restricted the wavelength range to 900-2000Å to probe the region around the Ly- α emission line and up to [CIII]. I only keep wavelength bins for which more than 90% of all spectra contributed. Spectrum that were identified as AGN during the VUDS data processing are excluded from the stacks. I show my results in figures 5.44 and 5.45.

I fit the absorption lines with a single Gaussian model with three free parameters (amplitude, width, line center). The exception is the fit to the Ly- α line which is done using a half Gaussian model (with the same three free parameters) to the emission line. I do this on spectra normalized on the continuum as derived from the spectra by extreme smoothing (Gaussian filter with 8Å kernel) of a spectrum masking 16Å around each marked line (see figure 5.46). From each fit I compute the line equivalent width (see Tab. 5.5) and line velocity offsets (see Tab. 5.6). Line equivalent widths are equal to the negative integral of the Gaussian model, and velocity offsets are computed through the difference between the line center as measured in the Gaussian model and the average redshift of the sample. I report my measurements in 4 absorption lines (2 SiII, [OI], and CII marked in blue in figure 5.46) that trace low ionization regions in the interstellar medium (e.g. Shapley et al., 2003).

One of my findings is that for Ly- α , as expected from what I show in figure 5.40, the extended line emitters show the largest equivalent width (in emission) of all the classes ($W_{\text{Ly}\alpha} = -37 \pm$

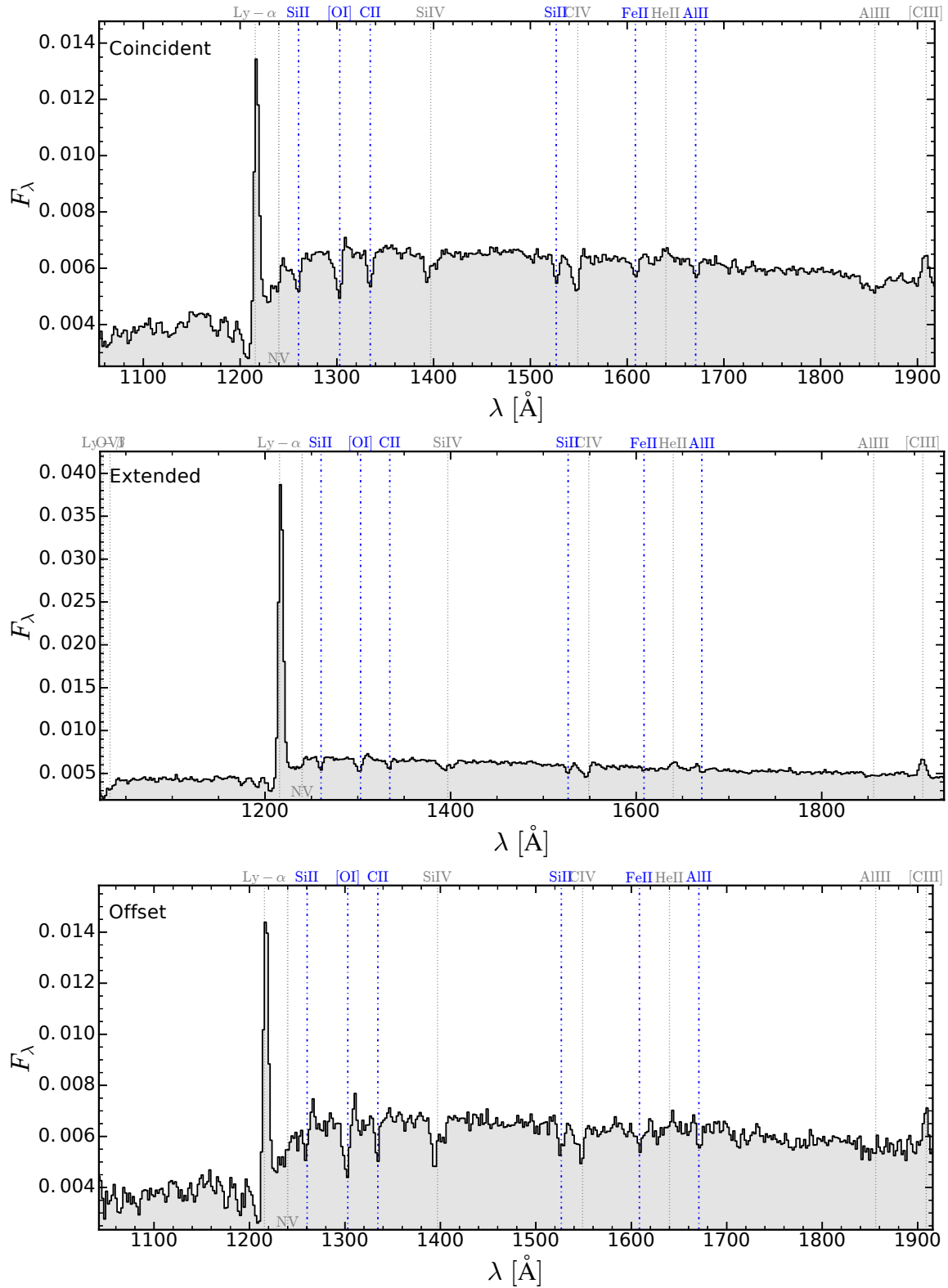


Figure 5.44. Stacks of spectra grouped by its Ly- α class. Each spectra is normalized to the continuum flux measured at 1250-1500 $\text{\AA}$ rest-frame and added to a common wavelength baseline with 2 $\text{\AA}$ resolution. In each panel I show the more prominent spectral lines that are observed. In blue dash-dotted lines I show the location of the low ionization interstellar medium lines.

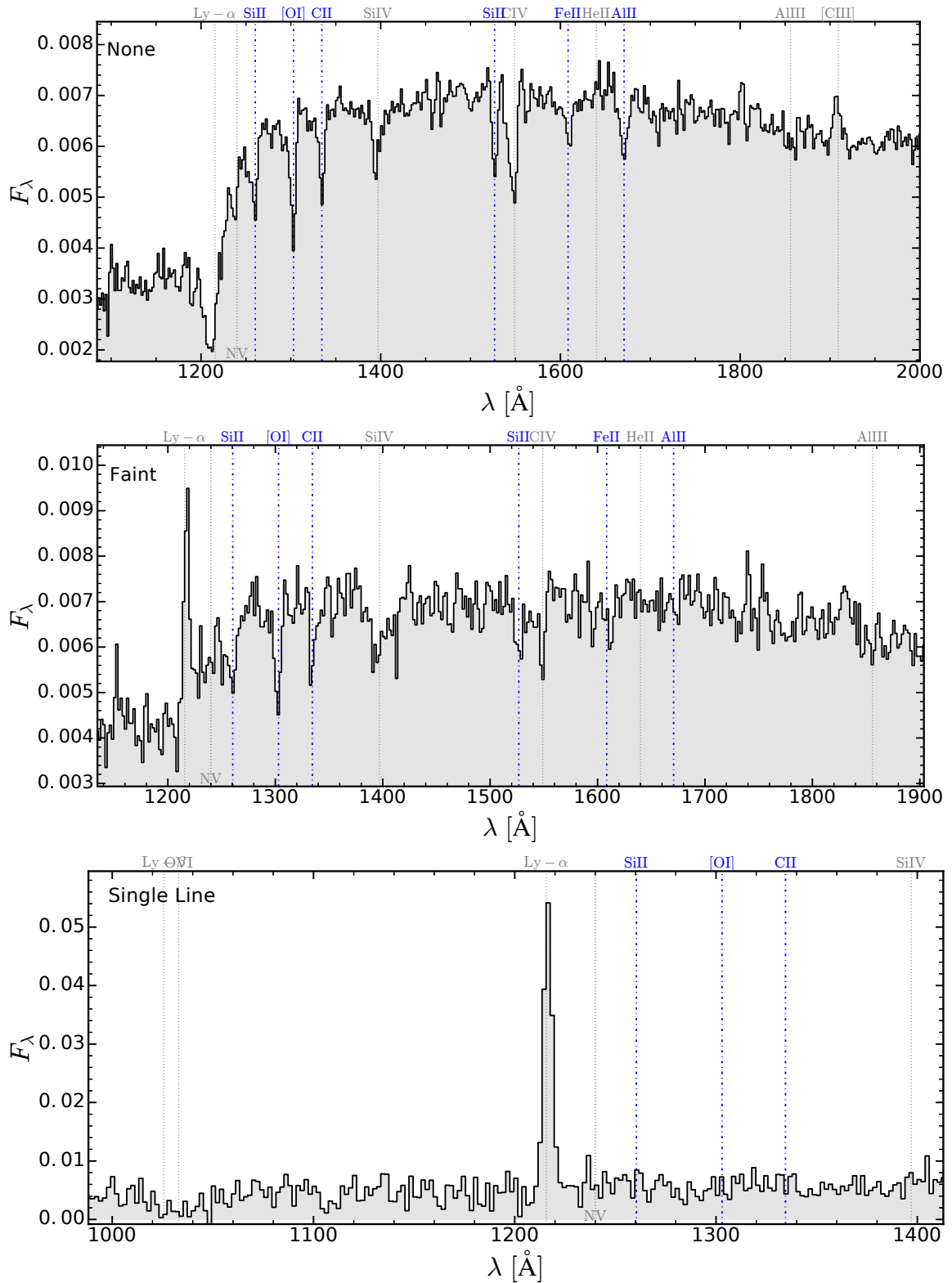


Figure 5.45. Stacks of spectra grouped by its Ly- α class. Each spectra is normalized to the continuum flux measured at 1250-1500 $\text{\AA}$ rest-frame and added to a common wavelength baseline with 2 $\text{\AA}$ resolution. In each panel I show the more prominent spectral lines that are observed. In blue dash-dotted lines I show the location of the low ionization interstellar medium lines.

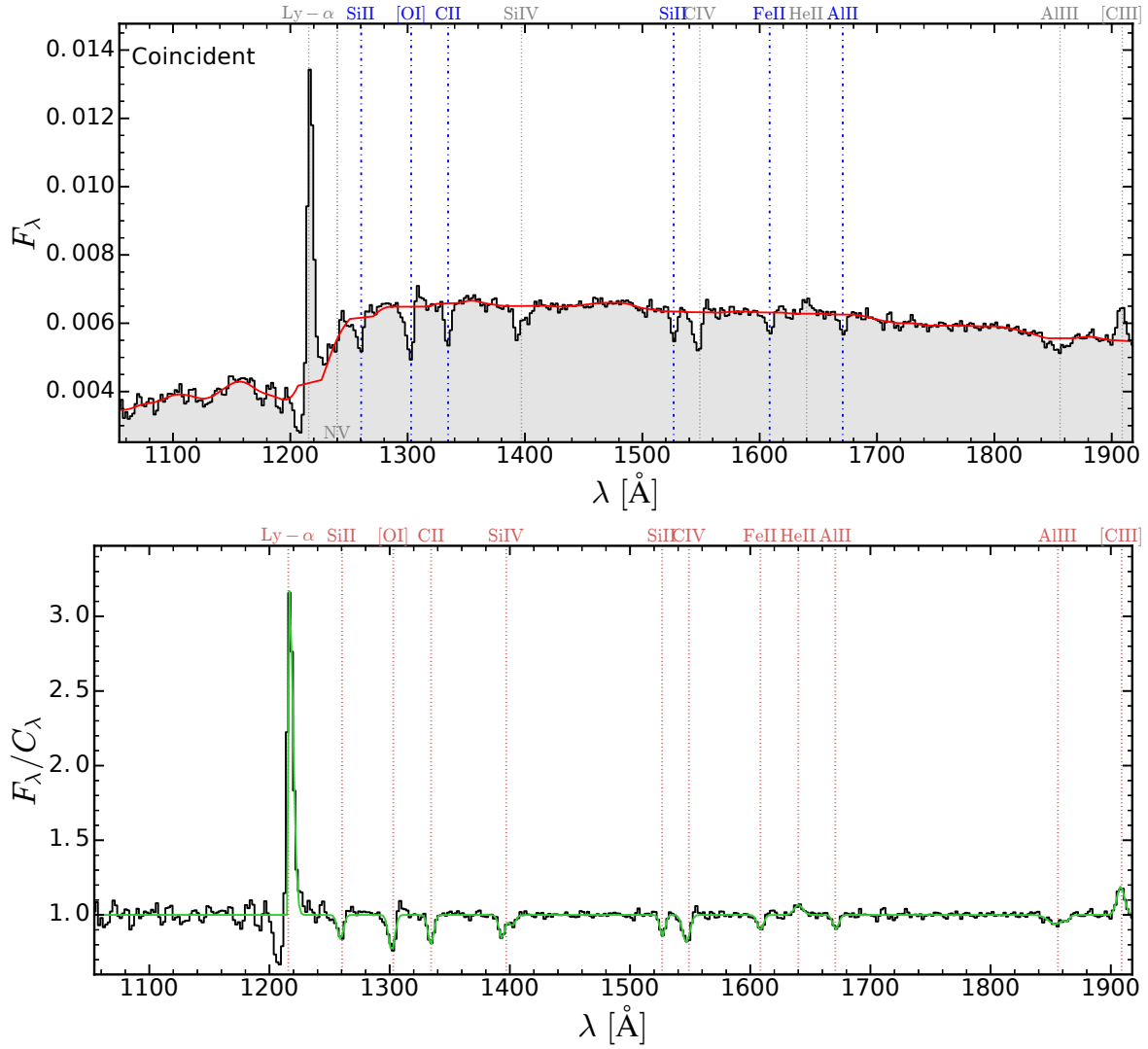


Figure 5.46. Example of the fitting routine on each of the lines marked on the plot. On the top panel I show my derived continuum level (red solid line) from smoothing a masked version of the original spectrum (black solid line). On the bottom panel I show the normalized spectra (black solid line) and the combination of all Gaussian models used to adjust each line (green solid line).

Line	None	Coincident	Offset	Extended
Ly $-\alpha_{1215}$	6.6 ± 1.4	-10.3 ± 2.8	-13.3 ± 3.3	-37.2 ± 8.4
[CIII] $_{1909}$	-1.5 ± 0.3	-1.5 ± 0.2	-1.6 ± 0.5	-3.5 ± 0.3
HeII $_{1640}$	N/A	-0.6 ± 0.4	-0.6 ± 0.5	-1.3 ± 0.5
SiII $_{1260}$	1.4 ± 0.8	1.0 ± 0.4	0.5 ± 0.5	0.8 ± 0.4
SiII $_{1526}$	1.2 ± 1.1	0.8 ± 0.6	0.9 ± 0.8	0.7 ± 0.7
CII $_{1334}$	1.6 ± 0.7	1.2 ± 0.4	1.0 ± 0.6	0.8 ± 0.3
[OI] $_{1303}$	2.3 ± 0.8	1.6 ± 0.7	2.1 ± 0.9	1.4 ± 0.6
AlII $_{1670}$	1.8 ± 0.5	0.6 ± 0.2	0.6 ± 0.4	0.4 ± 0.5

Table 5.5. Equivalent width, in Å, for 3 emission lines and 5 low ionization interstellar absorption lines found in the stacked spectra. For each line I show the values obtained for the four main classes in each of the four columns.

8). The offset emitters have slightly stronger equivalent widths than the coincident emitters ($W_{\text{Ly}\alpha} = -13 \pm 3$, -10 ± 3 , respectively) but none of them are above the -20 to -25Å limit which is often used to define LAEs (e.g. [Cassata et al., 2015](#); [Hathi et al., 2016](#)). The extended emitters are also the ones with stronger HeII and [CIII] emission lines. Regarding the equivalent width of low ionization interstellar lines (W_{LIS}), I always find that the stack of non-emitting galaxies has stronger absorption features than all emitters classes. I also observe that the equivalent width of this low ionization absorption lines is anti-correlated with $W_{\text{Ly}-\alpha}$. This has already been found (e.g. [Shapley et al., 2003](#)) and is thought to be linked to the covering gas fraction of galaxies. Alternatively, it may be linked to the amount of dusty gas clouds that permeate the interstellar medium as if I compare with the results of the correlation between $E(B - V)$ with class, they follow a similar trend as W_{LIS} (e.g. [Shapley et al., 2003](#)).

For Ly- α , the line center in the emission cases corresponds to the red peak in emission while for the no line sample it corresponds to the dip in the absorption feature. In order to compare velocity offsets in the different classes I compute the offset relative to the measured rest Ly- α line center.

Since the only difference that is consistent to all low ionization lines is that the non-emitters have the positive offsets on the absorption lines, and that is dependent on the definition of reference redshift, I need to refine these numbers in order for a coherent interpretation extending to the non-emitting class. Considering only the cases for which the velocity offset is computed with respect to the red emission peak of Ly- α I see that the average velocity offset are within the computed errors. However, for the extended line emitters I am able to pinpoint a velocity offset that is 3.4σ away from Ly- α_{rest} . For the offset and coincident line emitters the null hypothesis (that low ionization ISM lines are at rest with respect to Ly- α emission) is at 1.02σ from the measured velocity offsets for both cases. I speculate that the presence of outflows is certainly more likely to be observed in the extended line emitters but I cannot exclude the possibility that there are similar outflow velocities for the other line emitter classes.

5.4.3.2 THE UV SIZE OF LY- α EMITTING GALAXIES.

I use the size measurements described in sections 4.1 and 4.3. In summary I use GALFIT on F814W images from COSMOS ([Koekemoer et al., 2007](#)) and CANDELS ([Koekemoer et al., 2011](#)) to derive effective radii and use the total extent measurement r_T^{100} which defines the radius of a circle with the same area as the total extent of the galaxy above a limiting isophote. I also use r_T^{50} which is derived from the area containing 50% of the galaxy light above the same isophote.

Line	None	Coincident	Offset	Extended
Ly $-\alpha_{1215}$	-1320 ± 147	201 ± 263	223 ± 252	223 ± 223
[CIII] $_{1909}$	-245 ± 63	-120 ± 38	-84 ± 62	-41 ± 23
HeII $_{1640}$	N/A	41 ± 232	599 ± 155	190 ± 127
SiII $_{1260}$	1012 ± 250	-513 ± 293	-624 ± 321	-323 ± 240
SiII $_{1526}$	1371 ± 248	-137 ± 323	-293 ± 327	-250 ± 297
CII $_{1334}$	1322 ± 192	-247 ± 283	-354 ± 268	-421 ± 242
[OI] $_{1303}$	1188 ± 183	-501 ± 296	-612 ± 289	-631 ± 256
AlII $_{1670}$	1302 ± 182	-121 ± 279	-92 ± 279	-11 ± 326
Average LIS	1239 ± 211	-304 ± 295	-395 ± 297	-327 ± 272

Table 5.6. Velocity offsets, in km s^{-1} , for 5 low ionization interstellar lines found in the stacked spectra. For each line I show the values obtained for the four main classes in each of the four columns. For Ly- α , the measurement correspond to the red emission peak for the offset, coincident and extended classes and to the absorption dip for the none class. For the other lines the velocity offset is computed with respect to the Ly- α peak (or dip) rest frame. In the last line I show the average velocity offset of the low ionization lines for each class.

I restrict my sample of Ly- α emitters to have stellar masses $\log(M_{\star}/M_{\odot}) > 9.5$ and to be in the redshift range $2 < z < 4.5$ where my measurements of total extent are the most robust (see Ribeiro et al., 2016, for more details). The median size, both effective radius r_e and total radius r_T , for each class is shown in figure 5.47. Interestingly I do find that the extended line emitters have smaller UV extent than the other classes with typical sizes of $r_e = 0.7 \pm 0.1$ kpc, $r_T^{50} = 0.90 \pm 0.07$ kpc and $r_T^{100} = 1.9 \pm 0.1$ kpc. The non-emitters are the largest in terms of the 50% light radius (both $r_e = 1.36 \pm 0.06$ and $r_T^{50} = 1.29 \pm 0.02$ kpc) but are within the same size as the coincident and offset line emitters ($r_T^{100} = 2.28 \pm 0.4$ kpc).

I further explore the dependence of Ly- α emission on the UV rest-frame size in figure 5.48 with the fraction of LAEs, defined through their line equivalent width, as a function of the total extent of the UV rest-frame emission. I find that there is a rising trend in this fraction where the smaller galaxies show the highest fraction of LAEs. This fraction is $\lesssim 5\%$ for galaxies with $r_T^{100} \gtrsim 3.5$ kpc and rises to $\gtrsim 15\%$ for galaxies with $r_T^{100} \lesssim 1.0$ kpc. This results explains why galaxies in the extended line emitters class have the smaller UV-continuum sizes since they are also the ones with the stronger Ly- α equivalent widths.

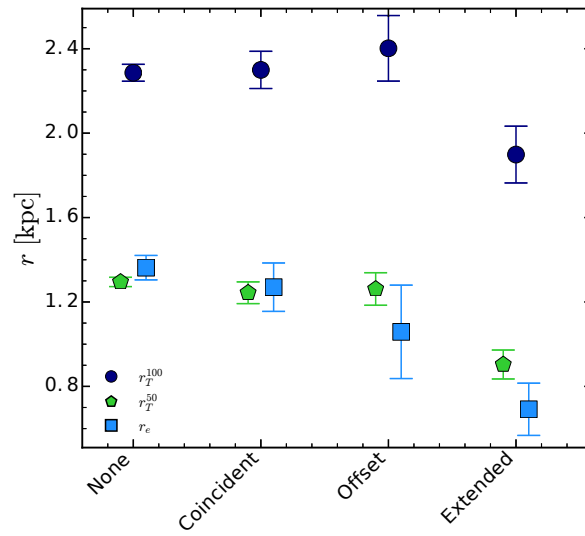


Figure 5.47. Median size of galaxies measured in the rest-frame UV as a function of classification. I show values for the effective radius (light blue square), total extent (dark blue circle) and 50% light radius (light green pentagon) for galaxies with stellar mass $\log(M_*/M_\odot) > 9.5$. In all cases the extended line emitters have smaller UV sizes.

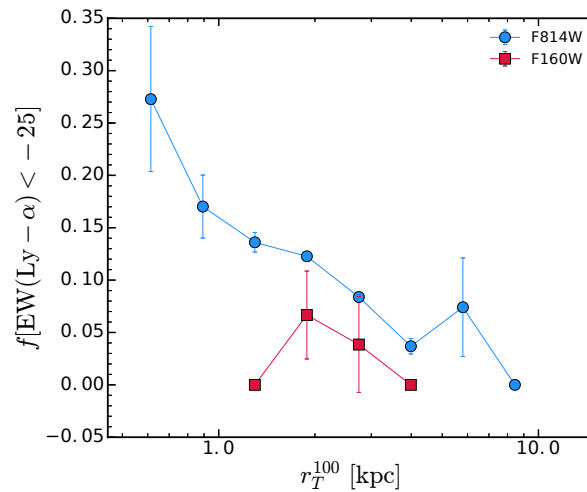


Figure 5.48. Fraction of LAEs as a function of total extent for galaxies with stellar mass $\log(M_*/M_\odot) > 9.5$. The blue circles line is the result considering size measurements from F814W images, and the red squares shows the results from considering size measurements from F160W images. I see on both cases that the occurrence of Ly- α in emission is more common in smaller galaxies. All size bins have at least 5 galaxies.

• This page is intentionally left blank •

6 | The perspective on galaxy evolution from quantified morphological analysis

Contents

6.1	Size measurements in the context of galaxy evolution	135
6.2	A merger origin for the bright and large clumps in two-clump galaxies . . .	137
6.3	Tracing evolution with visual morphology	140
6.4	The physical nature of Ly- α emitters	141
6.5	Overview on galaxy evolution as traced by morphology at $2 < z \lesssim 6$	142

6.1 SIZE MEASUREMENTS IN THE CONTEXT OF GALAXY EVOLUTION

As stated in chapter 2, galaxy size is a fundamental parameter linked to the way galaxies form and evolve. It is a relatively straightforward parameter to measure when one takes care of several possible caveats (see sections 4.1 and 4.3). I summarize my measurements of the size evolution of star-forming galaxies with $2 < z < 4.5$ in the VUDS survey, and compare them with the literature in figure 6.1.

In the context of the hierarchical assembly of dark matter halos one can consider that the size of a disk galaxy scales with the virial radius of its host halo. In this scenario, the redshift evolution of galaxy sizes has a slope $\alpha_r = -1$ for halos with fixed mass and a slope of $\alpha_r = -1.5$ for halos with fixed circular velocity (see Ferguson et al., 2004; Stringer et al., 2014, and references therein). When considering the effective radius I obtain a slope $\alpha_r = -1.29 \pm 0.18$ which lies between the values expected for those two scenarios. However, my computation of the evolution of the total size of each galaxy (measured at the same surface brightness level), leads to a slope $\alpha_r = 0.13 \pm 0.12$ inconsistent with either of these two hypotheses. This likely happens because the VUDS sample, representative of the population of star-forming galaxies, contains a majority of galaxies that do not resemble disks (i.e they are highly irregular) and, without any constraint on the profile shapes, the size measurements cannot be compared to any of those scenarios. This suggests that to correlate the size growth of galaxies with that of its host dark matter halo, more complex analytical models or more realistic numerical simulations are required to understand the evolution of galaxy sizes in dark matter halos.

I find that the effective radius $r_{e,\text{circ}}$ decreases with increasing redshift, indicating effective radii $r_{e,\text{circ}} \sim 2\text{kpc}$ at $z \sim 2$, and a value twice smaller at $z \sim 4$ at $r_{e,\text{circ}} \simeq 1\text{ kpc}$. The effective radius measured on my galaxies is comparable to other $r_{e,\text{circ}}$ measurements in the literature for galaxies at close or similar redshifts, particularly when comparing to samples with similar stellar masses (figure 6.1). In such samples, as in my own, this leads to the conclusion that

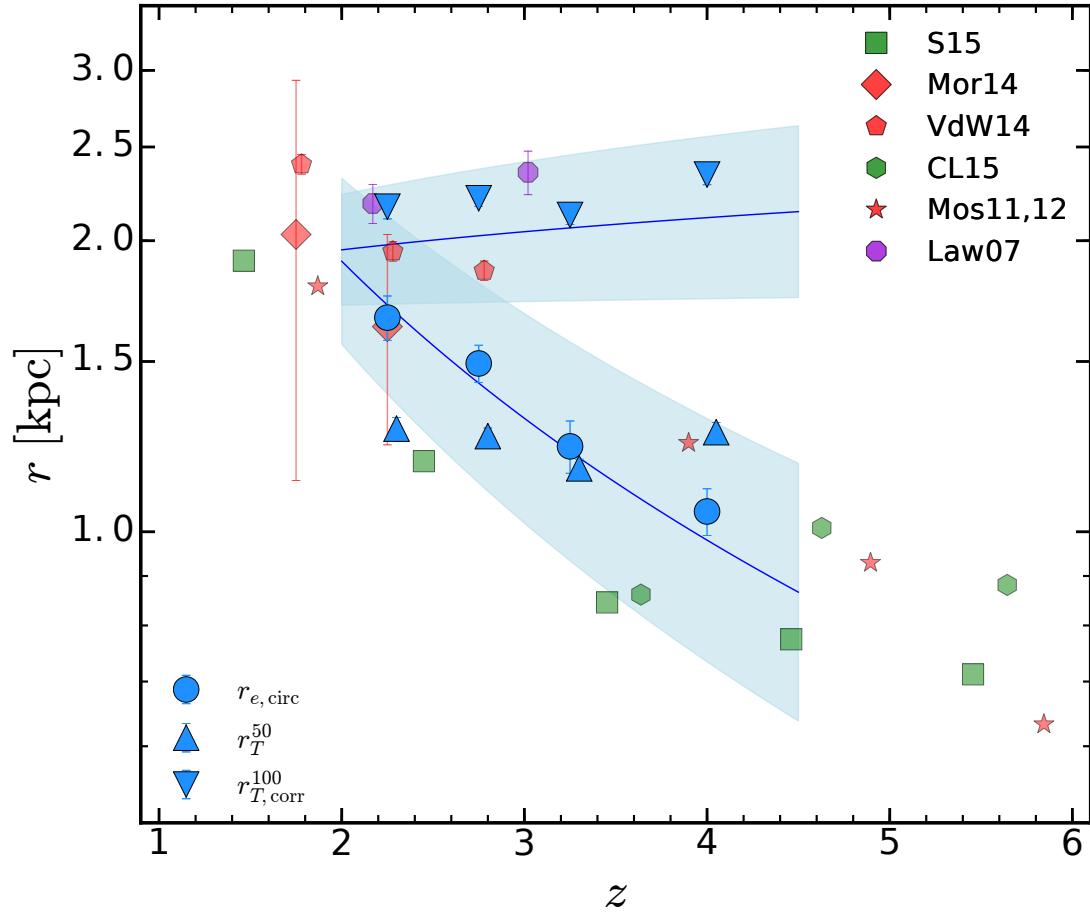


Figure 6.1. A compilation of size measurements at different redshifts for a number of different studies. First, in blue I show the measurements of this thesis. Circles are taken from the GALFIT effective radius, and the triangles and inverted triangles are from r_T^{50} and r_T^{100} respectively. The blue solid lines and respective shaded regions show the derived evolution for $r_{e, \text{circ}}$ and r_T^{100} . Each other color represents a different sample selection (green for luminosity selected samples, red for stellar mass selected samples and purple for a different selection) and each symbol represents a different study. They are: squares (Shibuya et al., 2015), $0.3L_* < L < 1L_*$; diamonds (Morishita et al., 2014), $10.0 < \log_{10}(M_*/M_\odot) < 10.5$; pentagons (van der Wel et al., 2014), $10.0 < \log_{10}(M_*/M_\odot) < 10.5$; hexagons (Curtis-Lake et al., 2016), $0.3L_* < L < 1L_*$; stars (Mosleh et al., 2011, 2012), $9.5 < \log_{10}(M_*/M_\odot) < 10.4$; octagons (Law et al., 2007), spectroscopic sample, no mass or luminosity selection.

galaxies are getting smaller at higher redshifts (e.g. Mosleh et al., 2011, 2012; van der Wel et al., 2014; Morishita et al., 2014; Shibuya et al., 2015). However, I argue that the use of this metric making an a priori assumption of symmetry is not appropriate to constrain the redshift evolution of galaxy sizes when asymmetric and multi-component shapes are common occurrences.

When measuring sizes based on the total area covered by a galaxy I find that the evolution of size with redshift is strikingly different. This size measured at an isophote with an absolute luminosity $\log_{10}(L_{z=2}) = 6.1L_{\odot}\text{pc}^2$, after correction for the effects of surface brightness dimming with redshift and luminosity evolution, remains approximately constant with redshift with $r_{T,\text{corr}}^{100} \sim 2.2\text{kpc}$ (figure 6.1). In addition, galaxies selected using an evolving stellar mass cut-off $\log(M_{\star}) > -0.204(z - 4.5) + 9.35$, have a higher concentration index C_T indicating a more peaked light distribution when going to the highest redshifts, with a significant change of C_T by $\sim 20\%$ over only ~ 2 Gyr of evolution.

While it is expected that the effective radius should be smaller than a radius defined from the total size of a galaxy at a much fainter isophote level, the strong observed differential evolution between the two is likely to be resulting from important physical processes working at a cosmic time when galaxies are still early in their assembly process. The fact that the size $r_{T,\text{corr}}^{100}$ remains large at all redshifts indicates that galaxies in their early assembly phase are quite extended with a constant characteristic size, and that the initial collapse that led to star formation seems to have been spread-out in quite a large volume of $\sim 10\text{kpc}^3$.

The large dispersion observed around the mean size value may indicate quite a diversity of initial assembly conditions. Indeed I find a large spread of sizes in my sample with galaxies as small as $r_{T,\text{corr}}^{100} = 0.3\text{kpc}$, and galaxies as large as $r_{T,\text{corr}}^{100} = 5.5\text{kpc}$. The smallest galaxies could be the signature of the first collapse of a small to medium mass cloud when the universe was very dense or a more evolved dynamical state later in the life of a galaxy as indicated by larger ages for smaller galaxies, while the most extended ones could indicate on-going early merging of a few small size objects following the hierarchical assembly picture or the result of the multi-component collapse of a massive gas cloud. As the timescale of these processes is currently unknown, we may be witnessing the combined effects of different key physical processes each at different evolution stages.

The evolution in light concentration with redshift that I find may be understood in a scenario of compact bright clumps merging together to create a more smooth light distribution by $z = 2$ (e.g. Guo et al., 2015). This could be extended to merger events of compact galaxies redistributing angular momentum and leading to a less concentrated luminosity profile. Inside-out growth with stellar mass building-up in the outskirts of galaxies (e.g. Wuyts et al., 2011; Nelson et al., 2013, 2015a; Tacchella et al., 2016) is also compatible with the evolution of the light concentration and the absence of evolution of total sizes.

6.2 A MERGER ORIGIN FOR THE BRIGHT AND LARGE CLUMPS IN TWO-CLUMP GALAXIES

The physical mechanisms through which galaxies assemble their stellar mass and change their morphology is still subject of debate with galaxy mergers and disk instabilities fed by cold gas accretion being the proposed scenarios (see chapter 2). My study brings to light two important morphological properties of high redshift galaxies and their evolution from $z \sim 6$ to $z \sim 2$: the fraction of clumpy galaxies as well as the distribution of the number of clumps per galaxy (see sections 5.2). Both of these properties are a direct consequence of the evolutionary path followed by galaxies, and the physical processes driving this evolution at these early cosmic times.

Defining clumps is a delicate process. At these high redshifts, and with the spatial resolution and depth of HST ACS or WFC3 imaging, only the brightest clumps separated by $\gtrsim 1\text{ kpc}$ can be identified. I opted to apply an evolving cut in the isophotal threshold used to define the area of a galaxy where to look for clumps, following the luminosity evolution observed in the star-forming galaxy population at these redshifts. I find the different local maxima, apply a minimum area of 10 connected pixels, and retain groups of pixels which are disconnected down to a level of 80% of the total galaxy flux, to identify clumps within this isophote. The isophote definition has an impact on the number of clumps identified: as the area covered by a brighter isophote gets smaller, the number of clumps within the isophote also gets smaller. I measure the area and absolute luminosity of the clumps and estimate that I am able to reliably identify clumps larger than $\sim 1.5\text{ kpc}^2$ and with a luminosity brighter than $M_{\text{clump}} < -18$. This process differs from previous attempts at clump identification algorithms (Guo et al., 2015; Shibuya et al., 2016) mainly by the definition of the evolving isophotal cut and the procedure of identifying clumps as local maximum groups detected within such an isophote.

I find that the fraction of clumpy galaxies rises from $\sim 34 \pm 8\%$ at $z \sim 2.25$ to $54 \pm 9\%$ at $z \sim 4$. I observe a trend for a higher clumpy fraction going to higher redshifts, more pronounced when I use a fainter isophote to define the clump search area. I find a slightly lower ($39 \pm 11\%$) clumpy fraction in the higher redshift bin $4.5 < z < 6$, but with an increasing trend with redshift when compared to the bin immediately below at the same isophote level. The depth of the data does not allow to use a comparable isophote when taking into account luminosity evolution between the low redshift and high redshift samples. Nevertheless, the trend suggests that when measured at the same isophote level the clumpy fraction would be the highest at $4.5 < z < 6$.

These results are at odds with the decreasing fraction of clumpy galaxies reported by Guo et al. (2015) and Shibuya et al. (2016). Differences in the definition of what a clumpy galaxy is and in the sample used to compute the clumpy fraction may be the main reasons for this discrepancy. I define a clumpy galaxy as a galaxy with 2 or more detected clumps within its isophote, whereas Guo et al. (2015) and Shibuya et al. (2016) define it when at least one off-center clump is identified. Another important difference resides in my sample selection which does not a priori exclude galaxies because of their morphology (Guo et al., 2015; Shibuya et al., 2016, impose an effective radius $r_e > 0.2''$ and axis ratio $q > 0.5$ cut). As I include in my sample small compact sources, this might further increase the number of non-clumpy galaxies and decrease the clumpy fraction, while including galaxies with low values of q like elongated clump chain galaxies (see e.g. Elmegreen et al., 2004, 2008) would rather increase it.

In summary, I find that the fraction of clumpy galaxies in the star-forming population as selected in the UV rest-frame with stellar masses $\log_{M_*/M_\odot} > -0.204 \times (z - 4.5) + 9.35$, and identifying clumps brighter than $M_{\text{clump,NUV}} < -18$ and larger than $\sim 2\text{ kpc}^2$ remains at 35-55% over the redshift range $2 < z < 6$, with a trend for an increasing clumpy fraction with redshift. As expected, this fraction does depend on the luminosity threshold and minimum clump area that I impose (see Fig. 5.15), and hence on the depth and spatial resolution of the images used. It is therefore likely that the clumpy fraction reported here is a lower value to the real clumpy fraction.

Now turning to the analysis of the distribution of the number of clumps per galaxies, there is a large fraction $\sim 21 - 25\%$ of galaxies with only two clumps *and* the clumps in these galaxies are the brightest and largest as shown in figures 4.18, 5.14, 5.17 and 5.18. I can identify a few possibilities to form the clumps in these two-clumps galaxies: they could be either (1) the result of disc fragmentation and VDI, (2) two individual galaxies in the final merging process of a galaxy pair, or (3) the chance projection of a galaxy on the line of sight, physically unrelated.

Galaxies with VDI induced clumps have been studied in detailed hydrodynamical simulations

which show how fragmentation in a proto-galactic disc produces several clumps, visible over timescales $\lesssim 1$ Gyr, before migrating and merging in a galaxy central core (e.g. Bournaud et al., 2007b; Dekel et al., 2009; Genel et al., 2012; Bournaud et al., 2014; Oklopčić et al., 2016). I note that I am able to detect clumps that are 1 to 2 magnitudes fainter than what I find for bright clumps in two clump systems. This implies that if additional clumps were to be found with deeper imaging they would be much fainter than what I find and thus I would still observe a large fraction of two clump systems detected above a given luminosity limit. It seems unlikely that a physical scenario following disc fragmentation and VDI would preferentially produce only two bright clumps (F. Bournaud, private communication). Cloud fragmentation due to disk instabilities are more likely to give rise to a higher number of clumps, with the number of clumps reducing over the dynamical timescale of clump merging, as shown in simulations (Mandelker et al., 2014). If VDI is the only process capable of producing clumps one would rather expect to observe more galaxies with 3 or more clumps than two-clumps systems, opposite to what I find (Fig. 4.20). It is possible that some two-clump systems are the end result of clumps formed through VDI after migration and merging of smaller clumps. The typical timescale for clump migration to the galaxy center is of 500 Myr (e.g. Förster Schreiber et al., 2011b; Guo et al., 2012; Bournaud, 2016) which is typically one fourth of the redshift interval I probe from $2 < z < 4.5$. However, the period on which I would observe two clumps at the same time should be shorter than that. Additionally, I would need to take into account the survival rate of large clumps for which some simulations suggest even shorter lifetimes (e.g. Genel et al., 2012). I would need spatially resolved information from multi-band high resolution observations or IFU data to compute velocity offsets and stellar ages of the different clumps to confirm or not this scenario against the possibility of it being the final stages of a merging pair of galaxies (e.g. Förster Schreiber et al., 2011a,b; Guo et al., 2012).

Another interpretation is that these two-clumps systems are indicative of on-going merger events. Major or minor mergers do indeed produce a bi-modal light distribution with each of the merging galaxy counted as a clump. merging is observed to be a significant process with a high fraction of $\sim 15 - 20\%$ of galaxies involved in major mergers at redshifts $z \sim 1$ and up to $z \sim 4$ (e.g. Le Fèvre et al., 2000; de Ravel et al., 2009; López-Sanjuan et al., 2013; Tasca et al., 2014b). The bright clumps in two-clumps systems and $L_f/L_b > 1/4$ have absolute magnitudes $-19 > M_{NUV} > -22$, producing together a total luminosity equivalent to that of the median of the star-forming population I am probing. Two-clumps systems with one bright clump and $L_f/L_b < 1/4$ may include minor merger events participating to the build-up of stellar mass with time. If I assume that clumps which have $L_f/L_b > 1/4$ are representative of major galaxy mergers I find that 24 – 40% of two-clump systems are then classified as major merger events, remaining roughly constant at $z \gtrsim 3$. This fraction is the same whether I consider VUDS targets only or if I include neighboring two-clump systems found within the 20 kpc search radius. As two-clump systems represent $\sim 25\%$ of the total population, using the fraction of bright two-clump systems (Tab. 5.3) I find a total merger fraction slightly decreasing with redshift from $\sim 18\%$ at $z \sim 3$ to $\sim 10\%$ at $z \sim 5$.

The derived fraction of merging systems is considering merging of clumps alone. To expand it to a total merger fraction one would also need to account for the fraction of galaxy pairs within a 20 kpc search radius. I find a rising pair fraction corrected for line of sight contamination (see Sect. 4.4.2), of $\sim 15\%$ at $z \sim 2.3$ which rises to $\sim 38\%$ at $z \sim 5$. One interesting trend is that while the pair fraction is increasing at higher redshifts, the contrary trend is observed for the merger fraction derived from clumps statistics. One may naively expect that I am observing an evolving merger rate measured in two stages, the first, which is more common at the higher redshifts, where galaxies have yet to merge and the second, as observed from bright clumps counts, representing the final phases of merging before coalescence, which is more common at lower redshifts.

There is a low probability that the observations of two-clumps systems might be consequence of line of sight contamination from lower redshift galaxies which might then be confused with high redshift clumps. I observe that these two-clump systems with at least one bright $M_{\text{clump,NUV}} < -19.1$ element have a median clump separations of ~ 3 kpc ($\sim 0.4''$). At such small separations, even when dealing with faint objects with $i_{\text{AB}} \sim 27 - 28$, the probability of random line of sight contamination is very small, at less than 3% (see Sect. 4.4.2 for details). Thus, I conclude that most of these two-clump systems are real physical systems at the same redshift.

As a conclusion, a straightforward interpretation of galaxies with two bright clumps is that this population predominantly includes galaxies caught in the act of a merging event. This interpretation is further reinforced when looking at the typical stellar masses of clumps. I find that for these two clumps systems with at least one bright component, the majority of them ($\sim 77\%$) has stellar masses greater than $\log(M_{\star}/M_{\odot}) > 9$ which is the typical upper limit on the stellar mass of clumps induced by VDI (see e.g. Elmegreen et al., 2009; Guo et al., 2012; Bournaud, 2016) and therefore are unlikely to be the result of this process. On the other hand, $\sim 55\%$ of clumps in multi-clump systems have stellar masses lower than $\log(M_{\star}/M_{\odot}) < 9$, which might likely result from VDI as well as minor mergers. The typical masses of the two clumps are more alike the masses of galaxies observed in merging pairs with larger separations (e.g. López-Sanjuan et al., 2013; Tasca et al., 2014b).

6.3 TRACING EVOLUTION WITH VISUAL MORPHOLOGY

Galaxy morphology has the imprints of the physical mechanisms that governed the evolution history of galaxies (see chapter 2). I have defined a new visual classification system for galaxies at high redshift in section 4.5. With the help of collaborators, I carried out the visual classification for a sample of ~ 1800 objects with $2 < z \lesssim 6$ on the VUDS survey and present the results in section 5.3. I find that the majority of galaxies are classified as irregular in the I band (40 – 50%). When compared to the classification in the H band I find that there is a comparable fraction of irregular and extended+symmetrical galaxies at $\sim 40\%$ of the population in VUDS-CANDELS that I believe is mainly due to the poorer spatial resolution of the H band. I stress that the classification at these redshifts is highly subject to individual bias and I can only get agreement between two different individuals on 50-55% of the objects. When compared to the results presented by Kartaltepe et al. (2015) I find a lower fraction of agreement of any set of two people. They get a majority agreement ($>3/5$ people) that depends on the magnitude of the objects and reaches 75-85% for galaxies fainter than $H < 23$. This is consistent with the fraction of majority classifications (more than half the classifiers agree on the primary class) that I obtain for the VUDS-CANDELS sample which is around $\sim 80\%$.

In what concerns the fraction of irregular galaxies at high redshift my results show that at $2 < z < 4.5$ and $\log(M_{\star}/M_{\odot}) > 10$, I find a constant fraction of $\sim 55 \pm 15\%$. This fraction is consistent to that reported by Huertas-Company et al. (2015b) of $\sim 70 \pm 10\%$ at $z \sim 2.75$ for a slightly higher stellar mass selection $\log(M_{\star}/M_{\odot}) > 10.5$. Other studies on the peculiar fraction up to $z \sim 3$ report $\sim 42 \pm 8\%$ (Mortlock et al., 2013, for $\log(M_{\star}/M_{\odot}) \geq 10$) and $\sim 37 \pm 10\%$ (Buitrago et al., 2013, for $\log(M_{\star}/M_{\odot}) \geq 11$). The fraction of disturbed systems remains high up to $z \sim 4 - 7$ with results ranging from $\sim 40 - 60\%$ for UV bright galaxies ($M_{\text{FUV}} < -20$, e.g. Jiang et al., 2013; Curtis-Lake et al., 2016; Bowler et al., 2016).

In light of my findings in the global properties of different galaxy morphological populations, I tend to conclude that morphology as a global evolution tracer is not cleanly working at these redshifts. I do believe that the higher percentage of irregular galaxies and the different

mechanisms for galaxy formation are eluding my proposed classification system in terms of isolating clear paths of galaxy formation based solely on a morphological type. For instance, compact galaxies can be either low mass and low star-forming dwarfs that are in their initial stages of formation (Amorín et al, submitted) or being massive and evolved objects, likely on their way to become the massive quiescent compact galaxies found at $z \sim 2$ (e.g. Daddi et al., 2005; Trujillo et al., 2006a; van Dokkum et al., 2008; Cimatti et al., 2008; Szomoru et al., 2012; Patel et al., 2013; Ikarashi et al., 2014; Ma et al., 2014; Marsan et al., 2014). As for irregular galaxies they can also be composed of large irregular and clumpy disks (e.g. Elmegreen et al., 2009; Guo et al., 2012), merging systems (see section 6.2) or even lower mass systems that are in a dynamically active state and are high-redshift analogs to the irregular galaxies found in the local Universe.

I believe that the class of diffuse, low surface brightness objects is mainly composed by fainter extended or clumpy disks that can also be the result of several different physical processes, in the same way as for irregular galaxies. On the other hand, faint and diffuse galaxies as seen in UV rest-frame can be massive galaxies with an old stellar population for which the morphological k -correction is strong (e.g. Law et al., 2012a). This result is partially supported when I look at the median stellar masses, ages and SFRs of the faint class which is the most massive, oldest and least star-forming of all classes. Another hint to a morphological k -correction on this class of objects is that when considering the most massive galaxies ($\log(M_*/M_\odot) > 10$) classified as diffuse objects in the I band of VUDS-CANDELS subsample, 6 out of 10 were classified as extended and symmetrical sources and 3 out of 10 as irregular sources in the H-band.)

6.4 THE PHYSICAL NATURE OF LY- α EMITTERS

I have defined a new classification system based on the extent of the Ly- α emission as compared to that of the UV continuum in section 4.6 to study the mechanisms through which Ly- α photons escape galaxies. With the help of VUDS collaborators, I carried out the visual classification for a sample of ~ 4360 objects with $2 < z \lesssim 6$ on the VUDS survey (see section 5.4) and compiled a sample of 1022 galaxies with Ly- α in emission and 1798 with no emission line that have been identified in the same class by two different people. I find that the most common case for line emitters is having coincident line and UV continuum emission ($\sim 52\%$) followed by extended line emitters ($\sim 21\%$) and then offset line emitters ($\sim 10\%$). Other emitters have either too faint continuum or line to be classified.

I find that extended line emitters are the least massive, least star-forming and have the lowest amount of dust extinction from all the main classes. At the same time, it is the class for which the line equivalent width is the largest and the only one for which the stacked spectrum has an equivalent width high enough to be classified as LAE. They also amount to 43.4% of all line emitting galaxies with Ly- α equivalent width $W_{\text{Ly}-\alpha} < -25\text{\AA}$ making them the likely population (along with single line emitters which amount to $\sim 21\%$) to be detected with narrow band surveys.

In what concerns the derived trend that larger galaxies have lower fraction of Ly- α emitters, there is a possibility of biased measurements due to slit losses. This happens since Wisotzki et al. (2016) found that the Ly- α extension scales with UV continuum size and therefore, larger galaxies are more likely to have extended Ly- α emission beyond the $1''$ aperture of the slits. However I do not believe that our measurements are biased since the effect of slit loss would impact both continuum and line fluxes and therefore does not substantially affect the equivalent width measurements.

Another problem that may affect my results is the surface brightness limit of the observations

($\sim 10^{-18}$ erg cm $^{-2}$ s $^{-1}$ arcsec $^{-2}$) that can prevent lower surface brightness emission halos to be seen in the 2D spectra and thus bias the classifications towards a higher fraction of coincident line emitters. However, the qualitative separation into the different four classes effectively works at the limiting surface brightness limit. This implies that bright and extended Ly- α emitters in VUDS, the class of line emitters closer to typical LAEs in the literature, being a sub-class of the global extended emitters, have underlying physical conditions that differ from lower surface brightness emitters which are included in the coincident class in this study. Wisotzki et al. (2016) found that when restricted to emission matching the spatial extent of the continuum, lower equivalent width galaxies have most of their flux in the surrounding halos. If that is the case (and combined with the UV-Ly- α size correlation) then one may expect that the coincident line emitters are in fact the galaxies with the more extended Ly- α halos but at surface brightness lower than the VUDS detection limit. One caveat to consider when comparing my sample to that presented by Wisotzki et al. (2016) is that they are probing galaxies with stellar masses $\sim 10 - 100$ times lower ($\sim 10^8 - 10^9 M_{\odot}$) than the typical stellar mass of VUDS galaxies ($\gtrsim 10^9$). It is possible that by simply probing different stellar mass regimes, I am finding different properties (e.g. Hagen et al., 2016b).

In terms of the physical properties of LAEs, one may expect that part of the difference with my sample is explained due to the physical conditions that render their detection possible. Selecting stronger equivalent width galaxies (as done in all narrow band surveys) is biased to galaxies with bright extended Ly- α emission which I showed are the class of galaxies that have the largest differences compared to the population of no line emitters (similar to those already reported by Hathi et al., 2016). Nonetheless, my sample is primarily comprised of UV-selected objects and thus the observed differences are not as large as pure emission line surveys which can probe down to lower masses (e.g. Gawiser et al., 2007; Finkelstein et al., 2007; Guaita et al., 2011; Vargas et al., 2014; Hagen et al., 2016b). Nonetheless, Hagen et al. (2016b) have shown that when selected in the same typical mass range, galaxies with Ly- α emission have similar properties as star-forming galaxies selected through their emission lines.

My findings that galaxies with Ly- α emission are smaller than their non-emitting counterparts are consistent with most studies in the literature (e.g. Malhotra et al., 2012). However, I am able to show that there is a smooth trend with the fraction of strong line emitters increasing from large to small galaxies. This is similar to the trend found by e.g. Law et al. (2012b), even though they are using the effective radius from GALFIT rather than the total size that I use. Again, this trend includes mostly bright extended line emitters in VUDS due to the imposed equivalent width cut and therefore samples only the subset of the stronger line emitters which are indeed biased towards smaller UV continuum sizes.

Linking to models, there is an association with smaller and less massive galaxies where stellar winds, supernovae and AGN feedback are more likely to produce windows/holes in the HI, with little dust content, allowing for an easier path towards photon escape and back scattering from large-scale HI clouds surrounding these objects. However, since the VUDS sample is typically an UV continuum selected sample, we are probing similar ranges in stellar masses for galaxies with and without Ly- α in emission and I can only hint at a small effect of stellar mass on the emission of Ly- α photons.

6.5 OVERVIEW ON GALAXY EVOLUTION AS TRACED BY MORPHOLOGY AT $2 < z \lesssim 6$

The results that were discussed in the previous sections highlight some key properties that define the morphology of the star forming population at $2 < z < 6$ that one observes with VUDS. I argue that the ubiquitous diversity in the relationships between galaxy morphology

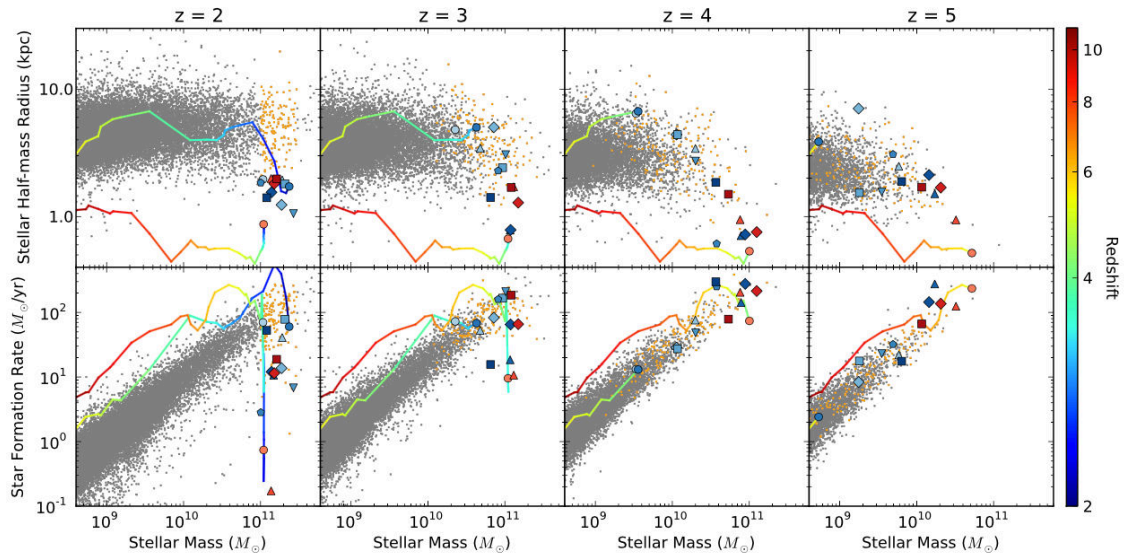


Figure 6.2. Evolution of compact galaxies in the Illustris simulations in size, stellar mass and star formation rates observed in 4 different redshifts (from Wellons et al., 2015).

and physical properties are hinting to different tracks in the formation and evolution of galaxies.

One population that can be compared to current cosmological simulations is the evolution of compact galaxies. By looking at the top panel of figure 5.34 one can see that compact galaxies tend to follow the stellar mass-SFR main sequence at lower masses and then fall off the main sequence at $\log_{10}(M_{\star}/M_{\odot}) \gtrsim 10$ (especially at $2 < z < 3$). This is in agreement with the picture portrayed by Wellons et al. (2015, see figure 6.2) where the progenitors of massive compact galaxies selected at $z \sim 2$ follow the stellar mass-SFR relation at earlier times and then drop off the relation. Additionally, the dominance of compact galaxies in the high stellar mass and low-star formation regime points to a scenario where this class of objects are the first to start quenching among the star-forming population. This might explain the existence of compact and massive quiescent galaxies that are observed at $z \sim 2$ (e.g. Daddi et al., 2005; Trujillo et al., 2006a; van Dokkum et al., 2008; Cimatti et al., 2008; Szomoru et al., 2012; Patel et al., 2013; Ikarashi et al., 2014; Ma et al., 2014; Marsan et al., 2014). But I would require sampling of the quiescent population at these redshifts to concluded that in fact most of the quiescent population is compact in morphology which is hinted by size evolution studies (e.g. van der Wel et al., 2014). However I cannot still discriminate among different scenarios (compacting star bursts or monolithic collapse formation Wellons et al., 2015) of the formation of these galaxies but is likely possible that my sample of compact SFGs is the progenitor of such a population (see also e.g. Barro et al., 2014).

On the other hand I observe populations with large sizes (up to a factor of ~ 100 larger than my smallest sources). This population shows a diversity of irregular morphologies. I find a significant fraction of $\sim 25\%$ of galaxies with two bright clumps that are likely galaxies in the final stages of merging. A number of large galaxies also exhibit multi-clump systems akin to the clump formation observed in the simulation of large forming disks. The large galaxies therefore require different paths of formation and evolution, strongly linked to key physical processes like galaxy merging or to the formation of a disk subject to violent instabilities and fed by cold gas accretion.

In terms of the typical size evolution I find a scenario of no-evolution in terms of the total extent. This is in contrast with theoretical expectations of disk scale length evolution that is linked to the growth of dark matter halos with cosmic time (e.g. Mo et al., 1998). I argue that this observation is linked to the irregular nature of galaxies at these redshifts and the high

merger activity (e.g. high fraction of two bright clump systems) that prevents the gas from achieving a state of dynamical equilibrium supported by its angular momentum that would then scale with the typical growth of dark matter halos. On the other hand, the evolution of the brightest regions, as traced by the effective radius through GALFIT, is probably connected to the halo growth since one expects that the brightest clumps are more dynamically evolved than the entire galaxy.

The irregular nature of galaxies is dominated by clumpy systems and I find that there are numerous clumpy systems in the VUDS sample and that these are dominated by bright two-clump systems. The existence of a large population of bright clumps in two clump systems points to a direct evidence of the final stages of galaxy mergers whereas the existence of a population of multi-clump systems points to the existence of violent disk instabilities. Again these observations point to different paths for galaxy evolution where I am observing two distinct physical processes at play in the redshift range $2 < z < 6$. I am also presenting evidence of the existence of monolithic collapse to form compact galaxies at very high-redshift. And when I link the galaxy morphology to the properties derived by the Ly- α line emission I also show that I have a large diversity of objects which further emphasizes the underlying diversity in the distribution of gas, stars and dust in galaxies.

Starting from simple, yet fundamental, quantitative measurement of morphological properties of galaxies at $2 < z < 6$, my results point to a striking diversity of galaxy properties at a time of galaxy assembly. As we are observing galaxies only 1 to 3 Gyr after the Big Bang it means that this diversity is taking place quite early in the life of the universe. To be able to witness the existence of galaxy populations as diverse as the very compact galaxies and the very large galaxies that I observe, each with a range of properties, likely requires that several different paths of galaxy formation and evolution co-exist. Key physical processes likely to play a major role include merging and violent disc instabilities in proto-discs possibly fed by accretion. My observational constraints offer a wealth of properties that will have to be reproduced by next generation numerical simulations. This picture will need to be further clarified by observations with future facilities like JWST and the ELTs.

7 | Conclusions and perspectives

Contents

7.1	Conclusions from this thesis work	145
7.2	Future perspectives	146

7.1 CONCLUSIONS FROM THIS THESIS WORK

The results presented in this thesis on a sample of star-forming galaxies observed 10.5 to 12.9 Gyr ago and shortly after the end of the reionization at $z \sim 6$ emphasize the diversity of galaxy morphological properties at a time of intense galaxy assembly.

I use two different methods to compute sizes: a parametric profile fitting using the GALFIT tool to derive the effective radius $r_{e,circ}$, and I define and use a non-parametric size measurement based on the area defined as enclosing 100% of the measured flux of a galaxy above a given surface brightness threshold, r_T^{100} . While the former makes a strong hypothesis on the symmetry of a galaxy shape, the latter can be applied on galaxies with irregular and asymmetric morphology. I find that the total size of a galaxy is observed to remain approximately constant with a radius $r_{T,corr}^{100} \simeq 2.2$ kpc over the redshift range $2 < z < 4.5$, while the effective radius $r_{e,circ}$ decreases from ~ 2 kpc at $z \sim 2$ to ~ 1 kpc at $z \sim 4.5$. The evolution of galaxy sizes is therefore drastically different when using parametric methods with a symmetry prior or a non-parametric method with no *a priori* assumption of symmetry. This difference between the total radius and the effective radius is more important at the highest redshifts, with a factor ~ 2 difference at $z \sim 4$, likely due to the increasing fraction of irregularly shaped galaxies. The observation of galaxies with total sizes ranging from less than 1 kpc to ~ 10 kpc seems to require several different processes driving mass assembly, and may represent different snapshots in the early life history of the dominant population of galaxies at these redshifts.

In quantifying the properties of clumps in star-forming galaxies with $2 < z < 6$, I conclude that I am witnessing the effects of two different galaxy assembly processes working in parallel. First I report that the majority of clumpy galaxies are found to have only two clumps. I also observe a bimodality in the clump size-luminosity distribution where bright and large clumps are predominantly found to be in two-clump systems. I conclude that the large and bright clumps in two-clumps systems are likely evidence for pairs of galaxies in the late stages of a merging process. This population of large and bright merging clumps formed *ex-situ* is important because even if they are less numerous they contribute the most to the stellar mass of a galaxy (López-Sanjuan et al., 2013; Tasca et al., 2014b; Mandelker et al., 2014). The fainter and smaller clumps are likely the result of gas accretion which is expected to feed the buildup of discs which then become unstable and produce clumps that will build galaxy bulges (e.g. Dekel et al., 2009; Bournaud et al., 2009; Dekel & Krumholz, 2013; Bournaud, 2016). These two processes are therefore important in building a galaxy formation and evolution scenario both from the point of view of the evolution of the cosmic star formation rate and the build-

up of stellar mass of galaxies throughout cosmic time, and explaining key observables like the evolution of the specific star formation rate, and its possible flattening at redshifts $z > 2$ (e.g. Dekel & Mandelker, 2014; Tasca et al., 2015; Faisst et al., 2016; Mármol-Queraltó et al., 2016).

In terms of the visual classification of high- z star-forming galaxies I have defined 4 different main classes of star-forming galaxies based on the spatial distribution of the rest-frame UV light and find that 40-50% of all star-forming galaxies in my sample with $\log_{10}(M_*/M_\odot) > 9.5$ are classified as irregular systems. I find that the second most common morphological type corresponds to compact galaxies (with a rising fraction from $\sim 10\%$ to $\sim 25\%$ from $z \sim 2$ to $z \sim 5$). Galaxies with extended and symmetric morphologies are found to be around $\sim 10-15\%$ of all galaxies. The remainder are either diffuse objects or too faint to be classified. I explore the physical properties of each sub-sample linked to a single morphological class and find that they all span wide ranges in stellar mass, star formation rates, ages and dust extinction values. I argue that there are several physical mechanisms at play that provide a variety of formation scenarios (or formation stages) for the same morphological class and that no single morphological population is univocally linked to a single formation scenario (see e.g. Wellons et al., 2015).

On a last topic I have shown how different observed spatial line emission profiles of Ly- α correlate with the physical properties of the host galaxy. I have defined 4 different main classes of star-forming galaxies based on the spatial properties of the Ly- α emission as compared to the UV continuum emission. I find a total of 1022 galaxies with line emission of which 51%, 21% and 10% have coincident, extended and offset line emission, respectively. I also identified a sample of 1798 galaxies with no Ly- α emission line at all. I find that extended line emitters show the strongest equivalent widths. In fact, when considering all galaxies with $W_{\text{Ly-}\alpha} < -25$ 43.4% of them are extended and $\sim 21\%$ are single line emitters. In terms of physical properties, extended line emitters distinguish themselves from the other classes by being the least massive, least star-forming, lower dust content and smaller UV continuum sizes. I conclude that this class of Ly- α emission is likely the population analog to LAEs found in narrow-band imaging surveys or deep integral field spectroscopy observations.

The overall result that I obtained during the course of this work is that the large diversity in morphological properties I observe in star-forming galaxies at $2 < z < 6$ are indicative of the variety of physical mechanisms that drive evolution in the early phase of galaxy assembly. The large range in galaxy sizes, from a few hundred to ten thousand parsecs, the high number of clumpy systems, with a significant population of systems with two bright clumps, and the non distinctive physical properties associated with several morphological classes all point to a complex picture of galaxy formation which goes beyond a simple scenario of cold gas accretion driving the evolution of all galaxies.

7.2 FUTURE PERSPECTIVES

The future of galaxy morphology studies will be fruitful in terms of new data, especially in the optical rest-frame regime, with the launch of JWST in 2018 which will extend quantitative morphology studies such as presented in this thesis up to the onset of the first objects in the universe at $z \gg 10$. This will be complemented by large samples of bright and massive galaxies out to the reionisation assembled with the Euclid and WFIRST space missions. New morphological classes well suited to the irregular shapes found at high redshift need to be further established and pushed towards automated and unsupervised methods that rely on well defined training sets (e.g. Huertas-Company et al., 2015a). At the same time, similar morphological analysis will be possible at higher redshifts from cosmological scale simulations as is now possible for the local Universe (e.g. Snyder et al., 2015). Combining efforts on

new observations and models we will be able to detail the different stages of evolution in the multiple paths of galaxy formation and morphological transformation and link them to the main physical mechanisms (be it merging, accretion, feedback or environment) that shape the evolution of different galaxy types into the observed Hubble sequence that is found locally.

More detailed investigations connecting size and morphology analyses to different properties from multi-wavelength observations complementary to the UV that is available in VUDS (e.g. by computing gas fractions, kinematics, $H\alpha$ emission) are needed to further understand the diversity of galaxy shapes in the early phases of galaxy assembly. And certainly the upcoming EELT (the European one) or ELTs (the future generation of ELTs worldwide) with adaptive optics will provide improved resolution in both imaging and spectroscopy to target typical examples of morphological populations, and large surveys like Euclid, WFIRST and LSST will be needed to provide robust statistical studies.

Another interesting prospect is to focus onto particular subsets of galaxies, like large diffuse objects, small and low mass compact objects, or the massive compact galaxies that are found below the star-forming main sequence, and through a dedicated analysis pinpoint the exact mechanisms and properties that define their evolution.

With respect to the nature of $Ly-\alpha$ emission, it is likely that forthcoming observations either from large and deep spectroscopic surveys like VANDELS and Integral Field Unit observations from MUSE/KMOS/JWST will shed more light on the underlying physical motivation for the differences that I find. Additionally, doing a similar analysis on a large sample of galaxies with spectroscopically resolved maps would provide improved constraints on the spatial distribution of the $Ly-\alpha$ emission.

From the work presented in this thesis, I can predict that the quantitative study of the morphology of galaxies up to the highest possible redshifts will remain a fundamental tool to understand the intricacies of the formation and evolution of galaxies.

• This page is intentionally left blank •

Bibliography

- Abraham R. G., Valdes F., Yee H. K. C., van den Bergh S., 1994, *ApJ*, **432**, 75
- Abraham R. G., van den Bergh S., Glazebrook K., Ellis R. S., Santiago B. X., Surma P., Griffiths R. E., 1996, *ApJS*, **107**, 1
- Abraham R. G., van den Bergh S., Nair P., 2003, *ApJ*, **588**, 218
- Acquaviva V., Vargas C., Gawiser E., Guaita L., 2012, *ApJ*, **751**, L26
- Ahn S.-H., Lee H.-W., Lee H. M., 2000, *Journal of Korean Astronomical Society*, **33**, 29
- Ahn C. P., et al., 2012, *ApJS*, **203**, 21
- Akiyama M., Minowa Y., Kobayashi N., Ohta K., Ando M., Iwata I., 2008, *ApJS*, **175**, 1
- Allen R. J., et al., 2015, *ApJ*, **806**, 3
- Arnouts S., Cristiani S., Moscardini L., Matarrese S., Lucchin F., Fontana A., Giallongo E., 1999, *MNRAS*, **310**, 540
- Astropy Collaboration et al., 2013, *A&A*, **558**, A33
- Atek H., Kunth D., Schaerer D., Mas-Hesse J. M., Hayes M., Östlin G., Kneib J.-P., 2014, *A&A*, **561**, A89
- Bacon R., et al., 2015, *A&A*, **575**, A75
- Ball N. M., Loveday J., Fukugita M., Nakamura O., Okamura S., Brinkmann J., Brunner R. J., 2004, *MNRAS*, **348**, 1038
- Barro G., et al., 2014, *ApJ*, **791**, 52
- Bassett R., et al., 2013, *ApJ*, **770**, 58
- Beckwith S. V. W., et al., 2006, *AJ*, **132**, 1729
- Behrens C., Braun H., 2014, *A&A*, **572**, A74
- Bennett C. L., et al., 2013, *ApJS*, **208**, 20
- Bershady M. A., Jangren A., Conselice C. J., 2000, *AJ*, **119**, 2645
- Bertin E., Arnouts S., 1996, *A&AS*, **117**, 393
- Bielby R., et al., 2012, *A&A*, **545**, A23
- Birnboim Y., Dekel A., 2003, *MNRAS*, **345**, 349
- Blanton M. R., Moustakas J., 2009, *ARA&A*, **47**, 159
- Blanton M. R., et al., 2003, *ApJ*, **594**, 186
- Blumenthal G. R., Faber S. M., Primack J. R., Rees M. J., 1984, *Nature*, **311**, 517
- Bond N. A., Gawiser E., Gronwall C., Ciardullo R., Altmann M., Schawinski K., 2009, *ApJ*, **705**, 639
- Bond N. A., Gawiser E., Koekemoer A. M., 2011, *ApJ*, **729**, 48
- Bond N. A., Gawiser E., Guaita L., Padilla N., Gronwall C., Ciardullo R., Lai K., 2012, *ApJ*, **753**, 95
- Bournaud F., 2016, *Galactic Bulges*, **418**, 355
- Bournaud F., Elmegreen B. G., 2009, *ApJ*, **694**, L158
- Bournaud F., Jog C. J., Combes F., 2007a, *A&A*, **476**, 1179
- Bournaud F., Elmegreen B. G., Elmegreen D. M., 2007b, *ApJ*, **670**, 237
- Bournaud F., et al., 2008, *A&A*, **486**, 741
- Bournaud F., Elmegreen B. G., Martig M., 2009, *ApJ*, **707**, L1
- Bournaud F., et al., 2014, *ApJ*, **780**, 57
- Bouwens R., Broadhurst T., Illingworth G., 2003, *ApJ*, **593**, 640
- Bouwens R. J., Illingworth G. D., Blakeslee J. P., Broadhurst T. J., Franx M., 2004, *ApJ*, **611**, L1
- Bouwens R. J., Illingworth G. D., Franx M., Ford H., 2007, *ApJ*, **670**, 928
- Bouwens R. J., et al., 2015, *ApJ*, **803**, 34
- Bowler R. A. A., Dunlop J. S., McLure R. J., McLeod D. J., 2016, preprint, ([arXiv:1605.05325](https://arxiv.org/abs/1605.05325))
- Bromm V., Yoshida N., 2011, *ARA&A*, **49**, 373
- Bruce V. A., et al., 2012, *MNRAS*, **427**, 1666
- Bruce V. A., et al., 2014a, *MNRAS*, **444**, 1001
- Bruce V. A., et al., 2014b, *MNRAS*, **444**, 1660
- Bruzual G., Charlot S., 2003, *MNRAS*, **344**, 1000
- Buitrago F., Trujillo I., Conselice C. J., Häußler B., 2013, *MNRAS*, **428**, 1460
- Burke C., Collins C. A., 2013, *MNRAS*, **434**, 2856
- Buta R. J., et al., 2015, *ApJS*, **217**, 32
- Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, *ApJ*, **533**, 682
- Capak P., et al., 2007, *ApJS*, **172**, 99
- Carollo C. M., et al., 2013, *ApJ*, **773**, 112
- Cassata P., et al., 2010, *ApJ*, **714**, L79
- Cassata P., et al., 2011, *ApJ*, **743**, 96
- Cassata P., et al., 2013, *ApJ*, **775**, 106
- Cassata P., et al., 2015, *A&A*, **573**, A24

- Chabrier G., 2003, *ApJ*, **586**, L133
- Cimatti A., et al., 2008, *A&A*, **482**, 21
- Ciotti L., Bertin G., 1999, *A&A*, **352**, 447
- Collins C. A., et al., 2009, *Nature*, **458**, 603
- Conselice C. J., 1997, *PASP*, **109**, 1251
- Conselice C. J., 2003, *ApJS*, **147**, 1
- Conselice C. J., 2014, *ARA&A*, **52**, 291
- Conselice C. J., Arnold J., 2009, *MNRAS*, **397**, 208
- Conselice C. J., Bershadsky M. A., Jangren A., 2000, *ApJ*, **529**, 886
- Conselice C. J., Blackburne J. A., Papovich C., 2005, *ApJ*, **620**, 564
- Conselice C. J., Rajgor S., Myers R., 2008, *MNRAS*, **386**, 909
- Conselice C. J., Bluck A. F. L., Mortlock A., Palamara D., Benson A. J., 2014, *MNRAS*, **444**, 1125
- Courteau S., Dutton A. A., van den Bosch F. C., MacArthur L. A., Dekel A., McIntosh D. H., Dale D. A., 2007, *ApJ*, **671**, 203
- Cowie L. L., Hu E. M., Songaila A., 1995, *AJ*, **110**, 1576
- Curtis-Lake E., et al., 2016, *MNRAS*, **457**, 440
- Daddi E., Cimatti A., Renzini A., Fontana A., Mignoli M., Pozzetti L., Tozzi P., Zamorani G., 2004, *ApJ*, **617**, 746
- Daddi E., et al., 2005, *ApJ*, **626**, 680
- Davis A. J., Natarajan P., 2009, *MNRAS*, **393**, 1498
- Dekel A., Burkert A., 2014, *MNRAS*, **438**, 1870
- Dekel A., Krumholz M. R., 2013, *MNRAS*, **432**, 455
- Dekel A., Mandelker N., 2014, *MNRAS*, **444**, 2071
- Dekel A., Sari R., Ceverino D., 2009, *ApJ*, **703**, 785
- Delgado-Serrano R., Hammer F., Yang Y. B., Puech M., Flores H., Rodrigues M., 2010, *A&A*, **509**, A78
- Di Matteo P., Bournaud F., Martig M., Combes F., Melchior A.-L., Semelin B., 2008, *A&A*, **492**, 31
- Dijkstra M., Kramer R., 2012, *MNRAS*, **424**, 1672
- Dijkstra M., Haiman Z., Spaans M., 2006, *ApJ*, **649**, 14
- Dressler A., 1980, *ApJ*, **236**, 351
- Dressler A., et al., 1997, *ApJ*, **490**, 577
- Driver S. P., Windhorst R. A., Griffiths R. E., 1995, *ApJ*, **453**, 48
- Duval F., Schaerer D., Östlin G., Laursen P., 2014, *A&A*, **562**, A52
- Efstathiou G., Silk J., 1983, *Fund. Cosmic Phys.*, **9**, 1
- Eggen O. J., Lynden-Bell D., Sandage A. R., 1962, *ApJ*, **136**, 748
- Eliche-Moral M. C., Balcells M., Aguerri J. A. L., González-García A. C., 2006, *A&A*, **457**, 91
- Ellis R. S., et al., 2013, *ApJ*, **763**, L7
- Elmegreen D. M., Elmegreen B. G., 2006, *ApJ*, **651**, 676
- Elmegreen D. M., Elmegreen B. G., Sheets C. M., 2004, *ApJ*, **603**, 74
- Elmegreen D. M., Elmegreen B. G., Ravindranath S., Coe D. A., 2007, *ApJ*, **658**, 763
- Elmegreen B. G., Bournaud F., Elmegreen D. M., 2008, *ApJ*, **688**, 67
- Elmegreen B. G., Elmegreen D. M., Fernandez M. X., Lemnias J. J., 2009, *ApJ*, **692**, 12
- Elmegreen B. G., Elmegreen D. M., Sánchez Almeida J., Muñoz-Tuñón C., Dewberry J., Putko J., Teich Y., Popinchalk M., 2013, *ApJ*, **774**, 86
- Erb D. K., Shapley A. E., Pettini M., Steidel C. C., Reddy N. A., Adelberger K. L., 2006, *ApJ*, **644**, 813
- Faisst A. L., et al., 2016, *ApJ*, **821**, 122
- Fall S. M., Efstathiou G., 1980, *MNRAS*, **193**, 189
- Fan L., Lapi A., De Zotti G., Danese L., 2008, *ApJ*, **689**, L101
- Fan L., Lapi A., Bressan A., Bernardi M., De Zotti G., Danese L., 2010, *ApJ*, **718**, 1460
- Ferguson H. C., et al., 2004, *ApJL*, **600**, L107
- Finkelstein S. L., Rhoads J. E., Malhotra S., Pirzkal N., Wang J., 2007, *ApJ*, **660**, 1023
- Finkelstein S. L., Rhoads J. E., Malhotra S., Grogin N., 2009, *ApJ*, **691**, 465
- Förster Schreiber N. M., Shapley A. E., Erb D. K., Genzel R., Steidel C. C., Bouché N., Cresci G., Davies R., 2011a, *ApJ*, **731**, 65
- Förster Schreiber N. M., et al., 2011b, *ApJ*, **739**, 45
- Franx M., van Dokkum P. G., Schreiber N. M. F., Wuyts S., Labbé I., Toft S., 2008, *ApJ*, **688**, 770
- Freeman K. C., 1970, *ApJ*, **160**, 811
- Freeman P. E., Izbicki R., Lee A. B., Newman J. A., Conselice C. J., Koekemoer A. M., Lotz J. M., Mozena M., 2013, *MNRAS*, **430**, 1
- Furlong M., et al., 2015, *MNRAS*, **450**, 4486
- Fynbo J. U., Möller P., Thomsen B., 2001, *A&A*, **374**, 443
- Garilli B., Fumana M., Franzetti P., Paioro L., Scodreggio M., Le Fèvre O., Paltani S., Scaramella R., 2010, *PASP*, **122**, 827
- Garland C. A., Pisano D. J., Mac Low M.-M., Kreckel K., Rabidoux K., Guzmán R., 2015, *ApJ*, **807**, 134
- Gawiser E., et al., 2006, *ApJ*, **642**, L13
- Gawiser E., et al., 2007, *ApJ*, **671**, 278
- Genel S., et al., 2012, *ApJ*, **745**, 11
- Genel S., et al., 2014, *MNRAS*, **445**, 175
- Genzel R., et al., 2006, *Nature*, **442**, 786
- Genzel R., et al., 2008, *ApJ*, **687**, 59
- Genzel R., et al., 2011, *ApJ*, **733**, 101
- Giallisco M., Livio M., Bohlin R. C., Macchetto F. D., Stecher T. P., 1996, *AJ*, **112**, 369
- Giallisco M., et al., 2004, *ApJ*, **600**, L93

- Glazebrook K., 2013, *PASA*, **30**, e056
- Glazebrook K., Ellis R., Santiago B., Griffiths R., 1995, *MNRAS*, **275**, L19
- González-García A. C., Balcells M., 2005, *MNRAS*, **357**, 753
- Goto T., Yamauchi C., Fujita Y., Okamura S., Sekiguchi M., Smail I., Bernardi M., Gomez P. L., 2003, *MNRAS*, **346**, 601
- Graham A. W., 2013, Elliptical and Disk Galaxy Structure and Modern Scaling Laws. p. 91, doi:10.1007/978-94-007-5609-0_2
- Graham A. W., Erwin P., Trujillo I., Asensio Ramos A., 2003, *AJ*, **125**, 2951
- Grazian A., et al., 2012, *A&A*, **547**, A51
- Grogin N. A., et al., 2011, *ApJS*, **197**, 35
- Gronke M., Bull P., Dijkstra M., 2015, *ApJ*, **812**, 123
- Gronwall C., Bond N. A., Ciardullo R., Gawiser E., Altmann M., Blanc G. A., Feldmeier J. J., 2011, *ApJ*, **743**, 9
- Guaita L., et al., 2011, *ApJ*, **733**, 114
- Guaita L., et al., 2015, *A&A*, **576**, A51
- Gunn J. E., Gott III J. R., 1972, *ApJ*, **176**, 1
- Guo Y., et al., 2009, *MNRAS*, **398**, 1129
- Guo Y., Giallisco M., Ferguson H. C., Cassata P., Koekemoer A. M., 2012, *ApJ*, **757**, 120
- Guo Y., et al., 2015, *ApJ*, **800**, 39
- Guzzo L., et al., 2014, *A&A*, **566**, A108
- Hagen A., et al., 2014, *ApJ*, **786**, 59
- Hagen A., et al., 2016a, preprint, ([arXiv:1610.01163](https://arxiv.org/abs/1610.01163))
- Hagen A., et al., 2016b, *ApJ*, **817**, 79
- Hansen M., Oh S. P., 2006, *MNRAS*, **367**, 979
- Harrington J. P., 1973, *MNRAS*, **162**, 43
- Hartigan J. A., Hartigan P. M., 1985, *Ann. Statist.*, **13**, 70
- Hathi N. P., Malhotra S., Rhoads J. E., 2008, *ApJ*, **673**, 686
- Hathi N. P., et al., 2016, *A&A*, **588**, A26
- Hayes M., Östlin G., Mas-Hesse J. M., Kunth D., Leitherer C., Petrosian A., 2005, *A&A*, **438**, 71
- Hayes M., Östlin G., Atek H., Kunth D., Mas-Hesse J. M., Leitherer C., Jiménez-Bailón E., Adamo A., 2007, *MNRAS*, **382**, 1465
- Hayes M., et al., 2010, *Nature*, **464**, 562
- Hayes M., Schaerer D., Östlin G., Mas-Hesse J. M., Atek H., Kunth D., 2011, *ApJ*, **730**, 8
- Heckman T. M., Best P. N., 2014, *ARA&A*, **52**, 589
- Henriques B. M. B., White S. D. M., Thomas P. A., Angulo R., Guo Q., Lemson G., Springel V., Overzier R., 2015, *MNRAS*, **451**, 2663
- Holwerda B. W., Bouwens R., Oesch P., Smit R., Illingworth G., Labbe I., 2015, *ApJ*, **808**, 6
- Hopkins P. F., Hernquist L., Cox T. J., Dutta S. N., Rothberg B., 2008, *ApJ*, **679**, 156
- Hopkins P. F., et al., 2009, *MNRAS*, **397**, 802
- Hopkins P. F., et al., 2010, *ApJ*, **724**, 915
- Hopkins P. F., Kereš D., Murray N., Quataert E., Hernquist L., 2012a, *MNRAS*, **427**, 968
- Hopkins P. F., Kereš D., Murray N., Quataert E., Hernquist L., 2012b, *MNRAS*, **427**, 968
- Huang K.-H., Ferguson H. C., Ravindranath S., Su J., 2013, *ApJ*, **765**, 68
- Hubble E. P., 1925, *Popular Astronomy*, **33**
- Hubble E. P., 1926, *ApJ*, **64**, 321
- Hubble E. P., 1930, *ApJ*, **71**
- Hubble E. P., 1936, *Realm of the Nebulae*
- Huertas-Company M., et al., 2009, *A&A*, **497**, 743
- Huertas-Company M., Aguerri J. A. L., Bernardi M., Mei S., Sánchez Almeida J., 2011, *A&A*, **525**, A157
- Huertas-Company M., et al., 2015a, *ApJS*, **221**, 8
- Huertas-Company M., et al., 2015b, *ApJ*, **809**, 95
- Huertas-Company M., et al., 2015c, *ApJ*, **809**, 95
- Huertas-Company M., et al., 2016, *MNRAS*, **462**, 4495
- Hunter J. D., 2007, *Computing In Science & Engineering*, **9**, 90
- Ichikawa T., Kajisawa M., Akhlaghi M., 2012, *MNRAS*, **422**, 1014
- Ikarashi S., et al., 2014, preprint, ([arXiv:1411.5038](https://arxiv.org/abs/1411.5038))
- Ilbert O., et al., 2006, *A&A*, **457**, 841
- Ilbert O., et al., 2010, *ApJ*, **709**, 644
- Ilbert O., et al., 2013, *A&A*, **556**, A55
- Jiang L., et al., 2013, *ApJ*, **773**, 153
- Kartaltepe J. S., et al., 2015, *ApJS*, **221**, 11
- Kauffmann G., et al., 2003, *MNRAS*, **341**, 54
- Kauffmann G., White S. D. M., Heckman T. M., Ménard B., Brinchmann J., Charlot S., Tremonti C., Brinkmann J., 2004, *MNRAS*, **353**, 713
- Kawamata R., Ishigaki M., Shimasaku K., Oguri M., Ouchi M., 2014, preprint, ([arXiv:1410.1535](https://arxiv.org/abs/1410.1535))
- Kawamata R., Ishigaki M., Shimasaku K., Oguri M., Ouchi M., 2015, *ApJ*, **804**, 103
- Kennicutt R. C., Evans N. J., 2012, *ARA&A*, **50**, 531
- Kereš D., Katz N., Weinberg D. H., Davé R., 2005, *MNRAS*, **363**, 2
- King I. R., 1978, *ApJ*, **222**, 1
- Kitzbichler M. G., White S. D. M., 2008, *MNRAS*, **391**, 1489
- Kobayashi M. A. R., et al., 2016, *ApJ*, **819**, 25
- Koekemoer A. M., et al., 2007, *ApJS*, **172**, 196

- Koekemoer A. M., et al., 2011, *ApJS*, **197**, 36
- Kormendy J., Bender R., 1996, *ApJ*, **464**, L119
- Kormendy J., Ho L. C., 2013, *ARA&A*, **51**, 511
- Kormendy J., Kennicutt Jr. R. C., 2004, *ARA&A*, **42**, 603
- Kormendy J., Fisher D. B., Cornell M. E., Bender R., 2009, *ApJS*, **182**, 216
- Kornei K. A., Shapley A. E., Erb D. K., Steidel C. C., Reddy N. A., Pettini M., Bogosavljević M., 2010, *ApJ*, **711**, 693
- Kubo M., et al., 2013, *ApJ*, **778**, 170
- Kubo M., Yamada T., Ichikawa T., Kajisawa M., Matsuda Y., Tanaka I., Umehata H., 2016, *MNRAS*, **455**, 3333
- Kulas K. R., Shapley A. E., Kollmeier J. A., Zheng Z., Steidel C. C., Hainline K. N., 2012, *ApJ*, **745**, 33
- Kunth D., Mas-Hesse J. M., Terlevich E., Terlevich R., Lequeux J., Fall S. M., 1998, *A&A*, **334**, 11
- Lai K., et al., 2008, *ApJ*, **674**, 70
- Lake E., Zheng Z., Cen R., Sadoun R., Momose R., Ouchi M., 2015, *ApJ*, **806**, 46
- Lang P., et al., 2014, *ApJ*, **788**, 11
- Larson R. B., Tinsley B. M., Caldwell C. N., 1980, *ApJ*, **237**, 692
- Lauer T. R., et al., 1995, *AJ*, **110**, 2622
- Laursen P., Sommer-Larsen J., Andersen A. C., 2009, *ApJ*, **704**, 1640
- Laursen P., Duval F., Östlin G., 2013, *ApJ*, **766**, 124
- Law D. R., Steidel C. C., Erb D. K., Pettini M., Reddy N. A., Shapley A. E., Adelberger K. L., Simenc D. J., 2007, *ApJ*, **656**, 1
- Law D. R., Steidel C. C., Shapley A. E., Nagy S. R., Reddy N. A., Erb D. K., 2012a, *ApJ*, **745**, 85
- Law D. R., Steidel C. C., Shapley A. E., Nagy S. R., Reddy N. A., Erb D. K., 2012b, *ApJ*, **759**, 29
- Le Fèvre O., Crampton D., Lilly S. J., Hammer F., Tresse L., 1995, *ApJ*, **455**, 60
- Le Fèvre O., et al., 2000, *MNRAS*, **311**, 565
- Le Fèvre O., et al., 2005, *A&A*, **439**, 877
- Le Fèvre O., et al., 2013, *A&A*, **559**, A14
- Le Fèvre O., et al., 2015, *A&A*, **576**, A79
- Lee B., et al., 2013, preprint, ([arXiv:1306.4980](https://arxiv.org/abs/1306.4980))
- Lidman C., Hayes M., Jones D. H., Schaerer D., Westra E., Tapken C., Meisenheimer K., Verhamme A., 2012, *MNRAS*, **420**, 1946
- Lilly S. J., Le Fèvre O., Hammer F., Crampton D., 1996, *ApJ*, **460**, L1
- Lilly S., et al., 1998, *ApJ*, **500**, 75
- Lilly S. J., et al., 2007, *ApJS*, **172**, 70
- Loeb A., Rybicki G. B., 1999, *ApJ*, **524**, 527
- López-Sanjuan C., et al., 2011, *A&A*, **530**, A20
- López-Sanjuan C., et al., 2012, *A&A*, **548**, A7
- López-Sanjuan C., et al., 2013, *A&A*, **553**, A78
- Lorenz M. O., 1905, *Publications of the American Statistical Association*, **9**, 209
- Lotz J. M., Primack J., Madau P., 2004, *AJ*, **128**, 163
- Lotz J. M., et al., 2008, *ApJ*, **672**, 177
- Lotz J. M., Jonsson P., Cox T. J., Croton D., Primack J. R., Somerville R. S., Stewart K., 2011, *ApJ*, **742**, 103
- Lubin L. M., Sandage A., 2001, *AJ*, **122**, 1084
- Ma Z., Fang G., Kong X., Fan L., 2014, preprint, ([arXiv:1411.6212](https://arxiv.org/abs/1411.6212))
- Madau P., Dickinson M., 2014, *ARA&A*, **52**, 415
- Madau P., Ferguson H. C., Dickinson M. E., Giavalisco M., Steidel C. C., Fruchter A., 1996, *MNRAS*, **283**, 1388
- Maiolino R., 2013, *Asociacion Argentina de Astronomia La Plata Argentina Book Series*, **4**, 23
- Malhotra S., Rhoads J. E., Finkelstein S. L., Hathi N., Nilsson K., McLinden E., Pirzkal N., 2012, *ApJ*, **750**, L36
- Mandelker N., Dekel A., Ceverino D., Tweed D., Moody C. E., Primack J., 2014, *MNRAS*, **443**, 3675
- Margalef-Bentabol B., Conselice C. J., Mortlock A., Hartley W., Duncan K., Ferguson H. C., Dekel A., Primack J. R., 2016, *MNRAS*, **461**, 2728
- Mármol-Queraltó E., McLure R. J., Cullen F., Dunlop J. S., Fontana A., McLeod D. J., 2016, *MNRAS*, **460**, 3587
- Marsan Z. C., et al., 2014, preprint, ([arXiv:1406.0002](https://arxiv.org/abs/1406.0002))
- Martin C. L., Sawicki M., 2004, *ApJ*, **603**, 414
- Mather J. C., et al., 1990, *ApJ*, **354**, L37
- Matsuda Y., et al., 2011, *MNRAS*, **410**, L13
- Matsuda Y., et al., 2012, *MNRAS*, **425**, 878
- Matthee J., Sobral D., Oteo I., Best P., Smail I., Röttgering H., Paulino-Afonso A., 2016, *MNRAS*, **458**, 449
- McCracken H. J., et al., 2012, *A&A*, **544**, A156
- Mei S., et al., 2015, *ApJ*, **804**, 117
- Mihos J. C., Hernquist L., 1996, *ApJ*, **464**, 641
- Mo H. J., Mao S., White S. D. M., 1998, *MNRAS*, **295**, 319
- Mo H., van den Bosch F., White S., 2010, *Galaxy Formation and Evolution*. Cambridge University Press, <https://books.google.fr/books?id=Eb6tAQAAQBAJ>
- Momose R., et al., 2014, *MNRAS*, **442**, 110
- Moore B., Katz N., Lake G., Dressler A., Oemler A., 1996, *Nature*, **379**, 613
- Morishita T., Ichikawa T., Kajisawa M., 2014, *ApJ*, **785**, 18
- Mortlock A., et al., 2013, *MNRAS*, **433**, 1185
- Mortlock A., et al., 2015, *MNRAS*, **447**, 2
- Mosleh M., Williams R. J., Franx M., Kriek M., 2011, *ApJ*, **727**, 5

- Mosleh M., et al., 2012, [ApJL](#), **756**, L12
- Murata K. L., et al., 2014, [ApJ](#), **786**, 15
- Naab T., Johansson P. H., Ostriker J. P., Efstathiou G., 2007, [ApJ](#), **658**, 710
- Naab T., Johansson P. H., Ostriker J. P., 2009, [ApJ](#), **699**, L178
- Navarro J. F., Frenk C. S., White S. D. M., 1996, [ApJ](#), **462**, 563
- Nelson E. J., et al., 2013, [ApJ](#), **763**, L16
- Nelson E., et al., 2014, [Nature](#), **513**, 394
- Nelson E. J., et al., 2015a, preprint, ([arXiv:1507.03999](#))
- Nelson D., Genel S., Vogelsberger M., Springel V., Sijacki D., Torrey P., Hernquist L., 2015b, [MNRAS](#), **448**, 59
- Neufeld D. A., 1990, [ApJ](#), **350**, 216
- Neufeld D. A., 1991, [ApJ](#), **370**, L85
- Newman A. B., Ellis R. S., Bundy K., Treu T., 2012, [ApJ](#), **746**, 162
- Nilsson K. K., Östlin G., Möller P., Möller-Nilsson O., Tapken C., Freudling W., Fynbo J. P. U., 2011, [A&A](#), **529**, A9
- Oesch P. A., et al., 2010, [ApJL](#), **709**, L21
- Oesch P. A., et al., 2016, [ApJ](#), **819**, 129
- Oklopčić A., Hopkins P. F., Feldmann R., Keres D., Faucher-Giguere C.-A., Murray N., 2016, preprint, ([arXiv:1603.03778](#))
- Ono Y., et al., 2012, [ApJ](#), **744**, 83
- Ono Y., et al., 2013, [ApJ](#), **777**, 155
- Oser L., Naab T., Ostriker J. P., Johansson P. H., 2012, [ApJ](#), **744**, 63
- Östlin G., Hayes M., Kunth D., Mas-Hesse J. M., Leitherer C., Petrosian A., Atek H., 2009, [AJ](#), **138**, 923
- Östlin G., et al., 2014, [ApJ](#), **797**, 11
- Ostriker J. P., 1980, *Comments on Astrophysics*, **8**, 177
- Ouchi M., et al., 2008, [ApJS](#), **176**, 301
- Ouchi M., et al., 2010, [ApJ](#), **723**, 869
- Papovich C., Giallisco M., Dickinson M., Conselice C. J., Ferguson H. C., 2003, [ApJ](#), **598**, 827
- Papovich C., Dickinson M., Giallisco M., Conselice C. J., Ferguson H. C., 2005, [ApJ](#), **631**, 101
- Patel S. G., et al., 2013, [ApJ](#), **766**, 15
- Paulino-Afonso A., Sobral D., Afonso J., Buitrago F., 2016, [MNRAS](#)
- Pearson K., 1896, *Philosophical Transactions of the Royal Society of London Series A*, **187**, 253
- Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2002, [AJ](#), **124**, 266
- Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2010, [AJ](#), **139**, 2097
- Pentericci L., Grazian A., Fontana A., Salimbeni S., Santini P., de Santis C., Gallozzi S., Giallongo E., 2007, [A&A](#), **471**, 433
- Perez J., Valenzuela O., Tissera P. B., Michel-Dansac L., 2013, [MNRAS](#), **436**, 259
- Peter A. H. G., Shapley A. E., Law D. R., Steidel C. C., Erb D. K., Reddy N. A., Pettini M., 2007, [ApJ](#), **668**, 23
- Petrosian V., 1976, [ApJL](#), **209**, L1
- Pforr J., Maraston C., Tonini C., 2012, [MNRAS](#), **422**, 3285
- Pirzkal N., Malhotra S., Rhoads J. E., Xu C., 2007, [ApJ](#), **667**, 49
- Planck Collaboration et al., 2015, preprint, ([arXiv:1502.01589](#))
- Porter L. A., Somerville R. S., Primack J. R., Croton D. J., Covington M. D., Graves G. J., Faber S. M., 2014, [MNRAS](#), **445**, 3092
- Prada F., Klypin A. A., Cuesta A. J., Betancort-Rijo J. E., Primack J., 2012, [MNRAS](#), **423**, 3018
- Puech M., 2010, [MNRAS](#), **406**, 535
- Quider A. M., Pettini M., Shapley A. E., Steidel C. C., 2009, [MNRAS](#), **398**, 1263
- Rauch M., et al., 2008, [ApJ](#), **681**, 856
- Ravindranath S., et al., 2004, [ApJL](#), **604**, L9
- Ravindranath S., et al., 2006, [ApJ](#), **652**, 963
- Reddy N. A., Steidel C. C., 2009, [ApJ](#), **692**, 778
- Reddy N. A., Steidel C. C., Pettini M., Adelberger K. L., Shapley A. E., Erb D. K., Dickinson M., 2008, [ApJS](#), **175**, 48
- Reynolds J. H., 1913, [MNRAS](#), **74**, 132
- Rhoads J. E., et al., 2003, [AJ](#), **125**, 1006
- Rhoads J. E., et al., 2005, [ApJ](#), **621**, 582
- Rhodes J. D., et al., 2007, [ApJS](#), **172**, 203
- Ribeiro B., et al., 2016, preprint, ([arXiv:1602.01840](#))
- Rix H.-W., et al., 2004, [ApJS](#), **152**, 163
- Roberts M. S., Haynes M. P., 1994, [ARA&A](#), **32**, 115
- Robertson B., Bullock J. S., Cox T. J., Di Matteo T., Hernquist L., Springel V., Yoshida N., 2006, [ApJ](#), **645**, 986
- Rodriguez-Gomez V., et al., 2015, [MNRAS](#), **449**, 49
- Rodriguez-Gomez V., et al., 2016, [MNRAS](#), **458**, 2371
- Sandage A., 1961, *The Hubble atlas of galaxies*
- Schaerer D., 2003, [A&A](#), **397**, 527
- Schaye J., et al., 2015, [MNRAS](#), **446**, 521
- Scodreggio M., et al., 2005, [PASP](#), **117**, 1284
- Scoville N., et al., 2007, [ApJS](#), **172**, 38
- Sérsic J. L., 1968, *Atlas de galaxies australes*
- Shamir L., Wallin J., 2014, [MNRAS](#), **443**, 3528

- Shapley H., Curtis H. D., 1921, *Bulletin of the National Research Council*, Vol. 2, Part 3, No. 11, p. 171-217, [2](#), [171](#)
- Shapley A. E., Steidel C. C., Adelberger K. L., Dickinson M., Giavalisco M., Pettini M., 2001, [ApJ](#), **562**, [95](#)
- Shapley A. E., Steidel C. C., Pettini M., Adelberger K. L., 2003, [ApJ](#), **588**, [65](#)
- Shapley A. E., Steidel C. C., Pettini M., Adelberger K. L., Erb D. K., 2006, [ApJ](#), **651**, [688](#)
- Shen S., Mo H. J., White S. D. M., Blanton M. R., Kauffmann G., Voges W., Brinkmann J., Csabai I., 2003, [MNRAS](#), **343**, [978](#)
- Shibuya T., Ouchi M., Nakajima K., Yuma S., Hashimoto T., Shimasaku K., Mori M., Umemura M., 2014a, [ApJ](#), **785**, [64](#)
- Shibuya T., et al., 2014b, [ApJ](#), **788**, [74](#)
- Shibuya T., Ouchi M., Harikane Y., 2015, [ApJS](#), **219**, [15](#)
- Shibuya T., Ouchi M., Kubo M., Harikane Y., 2016, [ApJ](#), **821**, [72](#)
- Shimasaku K., et al., 2006, [PASJ](#), **58**, [313](#)
- Simard L., 1998, in Albrecht R., Hook R. N., Bushouse H. A., eds, *Astronomical Society of the Pacific Conference Series* Vol. 145, *Astronomical Data Analysis Software and Systems VII*. p. 108
- Simard L., et al., 1999, [ApJ](#), **519**, [563](#)
- Simard L., Mendel J. T., Patton D. R., Ellison S. L., McConnachie A. W., 2011, [ApJS](#), **196**, [11](#)
- Skibba R. A., et al., 2009, [MNRAS](#), **399**, [966](#)
- Snyder G. F., et al., 2015, [MNRAS](#), **454**, [1886](#)
- Sobral D., et al., 2015a, [MNRAS](#), **451**, [2303](#)
- Sobral D., Matthee J., Darvish B., Schaerer D., Mobasher B., Röttgering H. J. A., Santos S., Hemmati S., 2015b, [ApJ](#), **808**, [139](#)
- Sobral D., et al., 2016, preprint, ([arXiv:1609.05897](#))
- Somerville R. S., Davé R., 2015, [ARA&A](#), **53**, [51](#)
- Sparke L., Gallagher J., 2007, *Galaxies in the Universe: An Introduction*. Cambridge University Press, [http://books.google.fr/books?id=N8Hngab5liQC](#)
- Springel V., Hernquist L., 2005, [ApJ](#), **622**, [L9](#)
- Steidel C. C., Adelberger K. L., Giavalisco M., Dickinson M., Pettini M., 1999, [ApJ](#), **519**, [1](#)
- Steidel C. C., Adelberger K. L., Shapley A. E., Pettini M., Dickinson M., Giavalisco M., 2003, [ApJ](#), **592**, [728](#)
- Steidel C. C., Bogosavljević M., Shapley A. E., Kollmeier J. A., Reddy N. A., Erb D. K., Pettini M., 2011, [ApJ](#), **736**, [160](#)
- Stott J. P., Sobral D., Smail I., Bower R., Best P. N., Geach J. E., 2013, [MNRAS](#), **430**, [1158](#)
- Straatman C. M. S., et al., 2015, [ApJ](#), **808**, [L29](#)
- Strazzullo V., et al., 2013, [ApJ](#), **772**, [118](#)
- Stringer M. J., Shankar F., Novak G. S., Huertas-Company M., Combes F., Moster B. P., 2014, [MNRAS](#), **441**, [1570](#)
- Szomoru D., Franx M., van Dokkum P. G., 2012, [ApJ](#), **749**, [121](#)
- Tacchella S., et al., 2015, [ApJ](#), **802**, [101](#)
- Tacchella S., Dekel A., Carollo C. M., Ceverino D., DeGraf C., Lapiner S., Mandelker N., Primack J. R., 2016, [MNRAS](#), **458**, [242](#)
- Tadaki K.-i., Kodama T., Tanaka I., Hayashi M., Koyama Y., Shimakawa R., 2014, [ApJ](#), **780**, [77](#)
- Takamiya M., 1999, [PASP](#), **111**, [772](#)
- Talia M., Cimatti A., Mignoli M., Pozzetti L., Renzini A., Kurk J., Halliday C., 2013, preprint, ([arXiv:1307.1366](#))
- Talia M., Cimatti A., Mignoli M., Pozzetti L., Renzini A., Kurk J., Halliday C., 2014, [A&A](#), **562**, [A113](#)
- Taniguchi Y., et al., 2005, [PASJ](#), **57**, [165](#)
- Taniguchi Y., et al., 2009, [ApJ](#), **701**, [915](#)
- Tapken C., Appenzeller I., Noll S., Richling S., Heidt J., Meinköhn E., Mehlert D., 2007, [A&A](#), **467**, [63](#)
- Tasca L. A. M., White S. D. M., 2011, [A&A](#), **530**, [A106](#)
- Tasca L. A. M., et al., 2009, [A&A](#), **503**, [379](#)
- Tasca L. A. M., et al., 2014a, [A&A](#), **564**, [L12](#)
- Tasca L. A. M., et al., 2014b, [A&A](#), **565**, [A10](#)
- Tasca L. A. M., et al., 2015, [A&A](#), **581**, [A54](#)
- Tasca L. A. M., et al., 2016, preprint, ([arXiv:1602.01842](#))
- Tasitsiomi A., 2006, [ApJ](#), **645**, [792](#)
- Taylor-Mager V. A., Conselice C. J., Windhorst R. A., Jansen R. A., 2007, [ApJ](#), **659**, [162](#)
- Thomas R., et al., 2014, preprint, ([arXiv:1411.5692](#))
- Thomas R., et al., 2016, preprint, ([arXiv:1602.01841](#))
- Tolman R. C., 1930, *Proceedings of the National Academy of Science*, **16**, [511](#)
- Toomre A., 1977, in Tinsley B. M., Larson D. Campbell R. B. G., eds, *Evolution of Galaxies and Stellar Populations*. p. 401
- Toomre A., Toomre J., 1972, [ApJ](#), **178**, [623](#)
- Trujillo I., et al., 2006a, [MNRAS](#), **373**, [L36](#)
- Trujillo I., et al., 2006b, [ApJ](#), **650**, [18](#)
- Trujillo I., et al., 2006c, [ApJ](#), **650**, [18](#)
- Trujillo I., Conselice C. J., Bundy K., Cooper M. C., Eisenhardt P., Ellis R. S., 2007, [MNRAS](#), **382**, [109](#)
- Vanzella E., et al., 2010, [A&A](#), **513**, [A20](#)
- Vargas C. J., et al., 2014, [ApJ](#), **783**, [26](#)
- Venemans B. P., et al., 2005, [A&A](#), **431**, [793](#)
- Verhamme A., Schaerer D., Maselli A., 2006, [A&A](#), **460**, [397](#)
- Verhamme A., Dubois Y., Blaizot J., Garel T., Bacon R., Devriendt J., Guiderdoni B., Slyz A., 2012, [A&A](#), **546**, [A111](#)

- Vogelsberger M., et al., 2014, *Nature*, **509**, 177
- Volonteri M., 2010, *Nature*, **466**, 1049
- Walt S. v. d., Colbert S. C., Varoquaux G., 2011, *Computing in Science & Engineering*, **13**, 22
- Weinzirl T., et al., 2011, *ApJ*, **743**, 87
- Wellons S., et al., 2015, *MNRAS*, **449**, 361
- Wellons S., et al., 2016, *MNRAS*, **456**, 1030
- Whitaker K. E., Kriek M., van Dokkum P. G., Bezanson R., Brammer G., Franx M., Labbé I., 2012, *ApJ*, **745**, 179
- Whitaker K. E., et al., 2015, *ApJ*, **811**, L12
- Whitaker K. E., et al., 2016, preprint, ([arXiv:1607.03107](https://arxiv.org/abs/1607.03107))
- Williams R. E., et al., 1996, *AJ*, **112**, 1335
- Williams R. J., Quadri R. F., Franx M., van Dokkum P., Labbé I., 2009, *ApJ*, **691**, 1879
- Williams R. J., Quadri R. F., Franx M., van Dokkum P., Toft S., Kriek M., Labbé I., 2010, *ApJ*, **713**, 738
- Williams C. C., et al., 2014, *ApJ*, **780**, 1
- Windhorst R. A., et al., 2002, *ApJS*, **143**, 113
- Wisotzki L., et al., 2016, *A&A*, **587**, A98
- Wofford A., Leitherer C., Salzer J., 2013, *ApJ*, **765**, 118
- Wuyts S., Cox T. J., Hayward C. C., Franx M., Hernquist L., Hopkins P. F., Jonsson P., van Dokkum P. G., 2010, *ApJ*, **722**, 1666
- Wuyts S., et al., 2011, *ApJ*, **742**, 96
- Wuyts S., et al., 2012, *ApJ*, **753**, 114
- Yamada T., Matsuda Y., Kousai K., Hayashino T., Morimoto N., Umemura M., 2012, *ApJ*, **751**, 29
- Zheng Z., Miralda-Escudé J., 2002, *ApJ*, **578**, 33
- Zheng Z., Cen R., Weinberg D., Trac H., Miralda-Escudé J., 2011, *ApJ*, **739**, 62
- de Jong R. S., Lacey C., 2000, *ApJ*, **545**, 781
- de Ravel L., et al., 2009, *A&A*, **498**, 379
- de Souza R. E., Gadotti D. A., dos Anjos S., 2004, *ApJS*, **153**, 411
- de Vaucouleurs G., 1948, *Annales d'Astrophysique*, **11**, 247
- de Vaucouleurs G., 1959, *Handbuch der Physik*, **53**, 275
- van Dokkum P. G., et al., 2008, *ApJL*, **677**, L5
- van Dokkum P. G., et al., 2011, *ApJ*, **743**, L15
- van Dokkum P. G., et al., 2015, *ApJ*, **813**, 23
- van den Bergh S., 1960, *ApJ*, **131**, 215
- van den Bergh S., Abraham R. G., Ellis R. S., Tanvir N. R., Santiago B. X., Glazebrook K. G., 1996, *AJ*, **112**, 359
- van den Bosch F. C., 1998, *ApJ*, **507**, 601
- van der Wel A., et al., 2007, *ApJ*, **670**, 206
- van der Wel A., et al., 2014, *ApJ*, **788**, 28

Note: All of my graphical outputs were produced using Matplotlib ([Hunter, 2007](https://matplotlib.org/))

• This page is intentionally left blank •

A | Refereed and submitted publications

Size evolution of star-forming galaxies with $2 < z < 4.5$ in the VIMOS Ultra-Deep Survey [★]

B. Ribeiro¹, O. Le Fèvre¹, L. A. M. Tasca¹, B. C. Lemaux¹, P. Cassata², B. Garilli³, D. Maccagni³, G. Zamorani⁴, E. Zucca⁴, R. Amorín⁵, S. Bardelli⁴, A. Fontana⁵, M. Giavalisco⁶, N.P. Hathi¹, A. Koekemoer⁷, J. Pforr¹, L. Tresse¹, and J. Dunlop⁸

¹ Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388, Marseille, France

² Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Gran Bretaña 1111, Playa Ancha, Valparaíso Chile

³ INAF–IASF Milano, via Bassini 15, I–20133, Milano, Italy

⁴ INAF–Osservatorio Astronomico di Bologna, via Ranzani, 1 - 40127, Bologna

⁵ INAF–Osservatorio Astronomico di Roma, via di Frascati 33, I-00040, Monte Porzio Catone, Italy

⁶ Astronomy Department, University of Massachusetts, Amherst, MA 01003, USA

⁷ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

⁸ SUPA, Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, EH9 3HJ, United Kingdom

e-mail: bruno.ribeiro@lam.fr

ABSTRACT

Context. The size of a galaxy encapsulates the signature of the different physical processes driving its evolution. The distribution of galaxy sizes in the universe as a function of cosmic time is therefore a key to understand galaxy evolution.

Aims. We aim to measure the average sizes and size distributions of galaxies as they are assembling before the peak in the comoving star formation rate density of the universe to better understand the evolution of galaxies across cosmic time.

Methods. We use a sample of ~ 1200 galaxies in the COSMOS and ECDFS fields with confirmed spectroscopic redshifts $2 \leq z_{\text{spec}} \leq 4.5$ in the VIMOS Ultra Deep Survey (VUDS), representative of star-forming galaxies with $i_{\text{AB}} \leq 25$. We first derive galaxy sizes applying a classical parametric profile fitting method using GALFIT. We then measure the total pixel area covered by a galaxy above a given surface brightness threshold, which overcomes the difficulty of measuring sizes of galaxies with irregular shapes. We then compare the results obtained for the equivalent circularized radius enclosing 100% of the measured galaxy light r_T^{100} to those obtained with the effective radius $r_{e,\text{circ}}$ measured with GALFIT.

Results. We find that the sizes of galaxies computed with our non-parametric approach span a large range but remain roughly constant on average with a median value $r_T^{100} \sim 2.2$ kpc for galaxies with $2 < z < 4.5$. This is in stark contrast with the strong downward evolution of r_e with increasing redshift, down to sizes of < 1 kpc at $z \sim 4.5$. We analyze the difference and find that parametric fitting of complex, asymmetric, multi-component galaxies is severely underestimating their sizes. By comparing r_T^{100} with physical parameters obtained through SED fitting we find that the star-forming galaxies that are the largest at any redshift are, on average, more massive and more star-forming. We discover that galaxies present more concentrated light profiles as we move towards higher redshifts. We interpret these results as the signature of several, possibly different, evolutionary paths of galaxies in their early stages of assembly, including major and minor merging or star-formation in multiple bright regions.

Key words. high redshift universe – galaxy morphology – galaxy evolution – galaxy formation

1. Introduction

Galaxy formation, and early stage evolution, is believed to be a turbulent process where gas inflows, strong winds and galaxy-galaxy interactions give rise to the intricate shapes we encounter in deep, high- z , HST observations (e.g. Law et al. 2007; Delgado-Serrano et al. 2010; Buitrago et al. 2013; Mortlock et al. 2013; Talia et al. 2014; Guo et al. 2015). A simple, yet fundamental, shape parameter is the galaxy size. This quantity, together with other physical parameters like stellar mass and star-formation rate, is one of the basic ingredients that can help to elaborate a galaxy evolution scenario.

Although it is a simple concept, obtaining galaxy sizes is not an easy task and is subject to a number of assumptions. The most common way to derive galaxy sizes is by performing light profile fitting assuming a given shape for the surface brightness profile using a χ^2 minimization (e.g. Simard et al. 1999; Peng et al. 2002; Ravindranath et al. 2004; Daddi et al. 2005; Ravindranath et al. 2006; Trujillo et al. 2006; Akiyama et al. 2008; Franx et al. 2008; Tasca et al. 2009; Cassata et al. 2010; Williams et al. 2010; Mosleh et al. 2011; Cassata et al. 2013; Huang et al. 2013; Ono et al. 2013; Stott et al. 2013; Morishita et al. 2014; van der Wel et al. 2014; Straatman et al. 2015; Shibuya et al. 2015). Another method assumes circular or elliptical apertures around a pre-defined galactic center and computes the size enclosing a given percentage of the total galaxy flux (e.g. Ferguson et al. 2004; Bouwens et al. 2004; Hathi et al. 2008; Oesch et al. 2010; Ichikawa et al. 2012; Curtis-Lake et al. 2016). A third approach,

[★] Based on data obtained with the European Southern Observatory Very Large Telescope, Paranal, Chile, under Large Program 185.A–0791.

involving counting the number of pixels belonging to the galaxy to derive its size, was also explored in Law et al. (2007). Studies of galaxy sizes at $z > 2$ became possible with the deep imaging obtained with the *Hubble Space Telescope*. The first reports on size evolution found that galaxy sizes as observed in the UV rest-frame were becoming smaller at the highest redshifts (Bouwens et al. 2003; Ferguson et al. 2004; Bouwens et al. 2004). We have now access to the size evolution up to $z \sim 10$ from the deepest HST imaging data (e.g. Hathi et al. 2008; Jiang et al. 2013; Ono et al. 2013; Kawamata et al. 2015; Holwerda et al. 2015; Shibuya et al. 2015). With the multi-wavelength and near-infrared coverage of CANDELS (Grogin et al. 2011; Koekemoer et al. 2011) optical rest-frame measurements are reported up to $z \sim 3$ for a large collection of galaxies in diverse populations (e.g. Bruce et al. 2012; van der Wel et al. 2014; Morishita et al. 2014). At $z \sim 2$ the size of SFGs is, to first order, independent of the observed rest-frame bands (Shibuya et al. 2015). It is generally accepted that galaxy sizes tend to decrease with increasing redshift (e.g. Bouwens et al. 2003, 2004; Ferguson et al. 2004; Mosleh et al. 2012) and that galaxy sizes depend on stellar mass (e.g. Franx et al. 2008; van der Wel et al. 2014; Morishita et al. 2014) and luminosity (e.g. Grazian et al. 2012; Huang et al. 2013). However some results point to a scenario consistent with no size evolution as seen in UV rest-frame from HST data (Law et al. 2007; Curtis-Lake et al. 2016) and, at a fixed stellar mass, from optical rest-frame ground-based data (Ichikawa et al. 2012; Stott et al. 2013).

Most samples in the literature that are used to measure sizes at high redshift are composed of galaxies selected through the dropout technique (Steidel et al. 1999) or photometric redshifts. Typical 1σ errors in photometric redshift measurements of $dz \sim 0.2$ – 0.3 add an error of $\sim 5\%$ (increasing from $z = 2$ to $z = 4.5$) to angular diameter measurements. This is a small but sizable error that can be reduced when measuring sizes for galaxy samples with known spectroscopic redshifts. Moreover, having a precise knowledge of the redshift of the galaxy minimizes the ambiguity on which rest-frame bands are observed and allows an accurate estimate of surface brightness dimming effects which are important to reduce measurement scatter for a consistent analysis in a large redshift range. The knowledge of the spectroscopic redshift and the availability of spectra also allow to better characterize the physical properties of the galaxies for which sizes are measured. Uncertainties on stellar masses, star formation rates, and ages, are reduced (Thomas et al. 2016) and spectral features like Lyman- α emission can be correlated with galaxy sizes.

In this paper we present the evolution of the size and size distribution of a sample of ~ 1200 star-forming galaxies with spectroscopic redshifts $2 < z_{spec} < 4.5$ selected from the VIMOS Ultra-Deep Survey (VUDS, Le Fèvre et al. 2015). In addition to using standard profile fitting to derive effective radii, we develop and apply a non-parametric method (adapted from Law et al. 2007) to compute galaxy sizes which takes into account the surface brightness dimming effect and does not require any assumption on the symmetry of the studied sources. We test the impact of using different rest-frame bands (for a subset of our galaxies) and different methods when deriving size evolution. We then probe the evolution of light profiles of galaxies using image stacks and comparing the concentration of light across the redshift range studied here.

This paper is organized as follows. In section 2 we give an overview of the sample we are working with, how galaxies are selected and describe the imaging data. In sections 3 and 4 we describe the methods used to obtain size measurements and their

inherent assumptions, and present results on effective radii and non-parametric sizes, respectively. In section 5 we present results based on stacked images/profiles. We discuss the redshift evolution of galaxy sizes in section 6. Section 7 is dedicated to the relation between some physical parameters derived from SED fitting and the sizes of our galaxies. We discuss and summarize our results in sections 8 and 9.

We use a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{0,\Lambda} = 0.7$ and $\Omega_{0,m} = 0.3$. All magnitudes are given in the AB system. For this paper we assume a Chabrier (2003) initial mass function (IMF).

2. Data and Sample Selection

VUDS is a large spectroscopic survey that targeted ~ 10000 objects covering an area of 1 deg^2 on three separate fields: COSMOS, ECFDS and VVDS-02h. With the objective to observe galaxies in the redshift range $2 < z < 6+$, targets were selected based on the first or second photometric redshift peaks being at $z_{phot} + 1\sigma > 2.4$, combined with a color selection criteria based on the spectral energy distribution (SED) and with flux limits $22.5 \leq i_{AB} \leq 25$. To fill in the remaining available space on the masks, a randomly flux selected sample with $23 < i_{AB} < 25$ is added to the target list. The spectra were obtained using the VIMOS spectrograph on the ESO-VLT covering, with two low resolution grisms ($R=230$), a wavelength range of $3650\text{\AA} < \lambda < 9350\text{\AA}$. The total integration is of $\sim 14 \text{ h}$ per pointing and grism.

Data processing is performed within the VIPGI environment (Scodreggio et al. 2005), and is followed by extensive redshift measurements campaigns using the EZ redshift measurement engine (Garilli et al. 2010). At the end of this process each galaxy has flux and wavelength calibrated 2D and 1D spectra, a spectroscopic redshift measurement and associated redshift reliability flag. For more information on this process we refer the reader to Le Fèvre et al. (2015).

2.1. Imaging data in the COSMOS and ECFDS fields

To conduct a morphological study of high-redshift galaxies, one should use the deepest, best resolution images coming from Hubble Space Telescope imaging surveys. Covering the largest contiguous sky region, the COSMOS (Scoville et al. 2007; Koekemoer et al. 2007) survey has $\approx 2 \text{ deg}^2$ of ACS F814W coverage down to a limiting magnitude of 27.2 (5σ point-source detection limit). As it covers the entirety of the VUDS COSMOS pointings it is the most complete image set to undertake morphological studies with our sample albeit only covering the UV rest-frame.

The more recent CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011) covers five different sky regions, including the COSMOS and ECFDS fields with a large overlap with VUDS fields (see Le Fèvre et al. 2015). The area covered is smaller than VUDS but near-infrared coverage (namely F125W and F160W) is important because it allows us to probe optical rest-frame morphologies for the majority of our sample in this field. It reaches depths at 5σ of 28.4, 27.0 and 26.9 at F814W, F125W and F160W respectively, deeper in the F814W band than the aforementioned COSMOS observations. The typical spatial resolution of these images ranges from $0.09''$ (0.6, 0.8 kpc, at $z = 4.5, 2.0$) for the F814W band up to $0.18''$ (1.2, 1.5 kpc, at $z = 4.5, 2.0$) in the F160W band. The pixel scale of the mo-

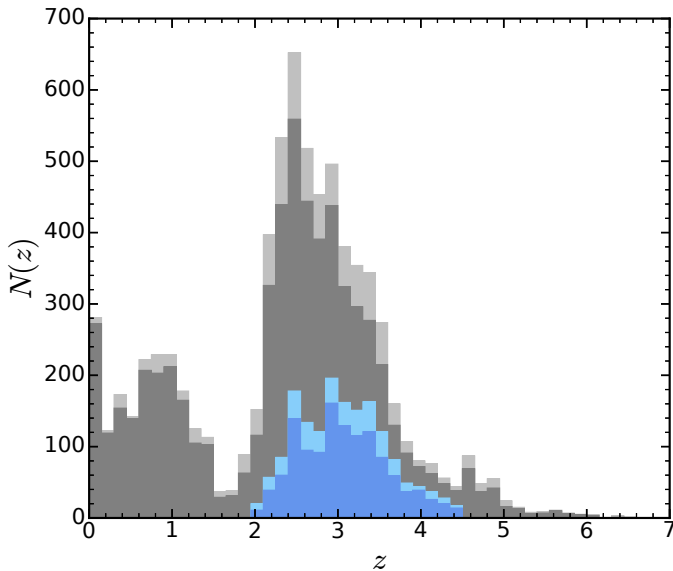


Fig. 1. The number of galaxies per redshift bin for the entire VUDS sample considering all galaxies with a redshift measurement in light gray and those with a redshift reliability flag corresponding to a $> 75\%$ certainty in dark gray. In blue colors we present the distribution for the COSMOS+ECDFS, stellar mass selected and $2 < z < 4.5$ sample (all flags in light blue and reliable flags in darker blue). Our results are based on the darker blue histogram which contains 1242 galaxies.

saics used in this paper are of $0.03''/\text{pixel}$ for F814W images and $0.06''/\text{pixel}$ for F125W/F160W images.

As the multi-wavelength coverage with HST of the large area covered by VUDS is scarce, we also use deep ground based imaging covering the entire VUDS area on the COSMOS field for a control check on the wavelength dependence of our radii measurements. From the CFHT Legacy Survey (CFHTLS) data release ⁷¹ we use the deep i' and z' band imaging which reach an 80% completeness limit in AB of 25.4 and 25.0 for point sources, respectively. Extensive near infrared ground-based imaging is also available on the COSMOS field. The UltraVISTA survey covers 1.5 square degree of the field and provides the deepest observations in the near-infrared bands. The Y, J, H and K_s UltraVISTA DR2 images reach 5σ limiting magnitudes of 24.8 (25.4), 24.6 (25.1), 24.7 (24.7) and 23.98 (24.8) AB in the deep (ultra-deep) regions (McCracken et al. 2012).

In addition to the CANDELS observation in ECDFS, there are also publicly available F850LP observations from GEMS (Rix et al. 2004). However, the VUDS pointings were designed to maximize the overlap with the CANDELS area in ECDFS, thus, adding GEMS observations cause only a small increase in the number of sources in the sample (68 additional sources to the stellar mass selected sample defined in the next section). For that reason we exclude data from these surveys from the size analysis presented in this paper. The GOODS survey (Giavalisco et al. 2004) covers a similar area as the CANDELS observations and thus we have opted to not include images in our analysis.

2.2. A stellar mass-selected sub-sample from the VUDS spectroscopic survey

With the knowledge of the spectroscopic redshift, SED fitting was performed on the VUDS sample using Le Phare (Arnouts

et al. 1999; Ilbert et al. 2006) applied to the extensive photometric data available in the COSMOS and ECDFS fields as described in Sect. 2.1.

The SED fitting procedure closely follows the method described in Ilbert et al. (2013), and the specifics for VUDS are detailed in Tasca et al. (2015). To fit the photometric data we use templates derived from Bruzual & Charlot (2003) models and assuming a Chabrier (2003) IMF. To model the star formation histories we use an exponentially declining parameterization $\text{SFR} \propto \exp(-t/\tau)$ (τ in the range 0.1 Gyr to 30 Gyr), and an additional two models with delayed SFH peaking at 1 and 3 Gyr. The templates are created for a grid of 51 ages (in the range 0.1 Gyr to 14.5 Gyr). We apply a Calzetti et al. (2000) dust extinction law to the templates, using $E(B - V)$ in the range 0 to 0.5. Models with two different metallicities are used. The two main parameters of interest in this paper are the stellar mass, M_* , and the star formation rate (SFR) for which the median values of the probability density function are used. We refer the reader to Ilbert et al. (2013); Thomas et al. (2016) for typical uncertainties on these quantities (see also Tasca et al. 2015). In summary, we expect an uncertainty of ~ 0.1 dex in stellar masses, ~ 0.15 dex in SFR. We also use the physical parameters derived from the simultaneous SED fitting of the VUDS spectra and all multi-wavelength photometry available for each galaxy, using the code GOSSIP+ as described by Thomas et al. (2016). This method expands the now classical SED fitting technique to the use of UV rest-frame spectra in addition to photometry, further improving the accuracy of key physical parameter measurements (see Thomas et al. 2016, for details). It also provides measurements of physical quantities such as galaxy ages as well as the IGM transmission along the line of sight of each galaxy, an improvement compared to using a fixed transmission at a given redshift (Thomas et al. 2014). The sample selection (discussed below) and color correction detailed in section 4.5 rely on the parameters derived from LePhare. The comparison of sizes with physical parameters described in section 7 uses the results from GOSSIP+. We stress that the results presented in this paper are robust against the method used to derive the stellar mass selection of our sample.

To follow the evolution of galaxy sizes in a similar population as a function of redshift, we define our sample imposing an evolving lower stellar mass limit. This choice implies that stellar masses of galaxy populations at different redshifts follow the general stellar mass growth of star-forming galaxies, broadly representing the same coeval population. With this simple evolving stellar mass cut we could possibly miss galaxies if their properties make them fall out from the VUDS selection function, i.e. if galaxies selected at the high redshift end of our sample become quiescent by the time they reach $z \sim 2$. The average size we report would then be biased against these galaxies at the lower redshift end of our survey. The other possible choice that could be made is to opt for a constant stellar mass limit at all redshifts. In this condition, the sample would contain more lower stellar mass star-forming galaxies at lower redshifts. If the stellar mass-size relation is not evolving with redshift (see e.g. van der Wel et al. 2014; Morishita et al. 2014) then this would add galaxies with lower sizes in the lower redshift bins of our study, complicating the comparisons of size distributions. We define a lower stellar mass limit in our sample anchored at $z = 4.5$ as $\log_{10}(M_*/M_\odot) > 9.35$ (below which the VUDS sampling drops). We then use the stellar mass function evolution from Ilbert et al. (2013) together with the typical sSFR of VUDS galaxies (Tasca et al. 2015) to follow the typical stellar mass growth of VUDS galaxies, and define the stellar mass selection threshold

¹ <http://www.cfht.hawaii.edu/Science/CFHTLS/>

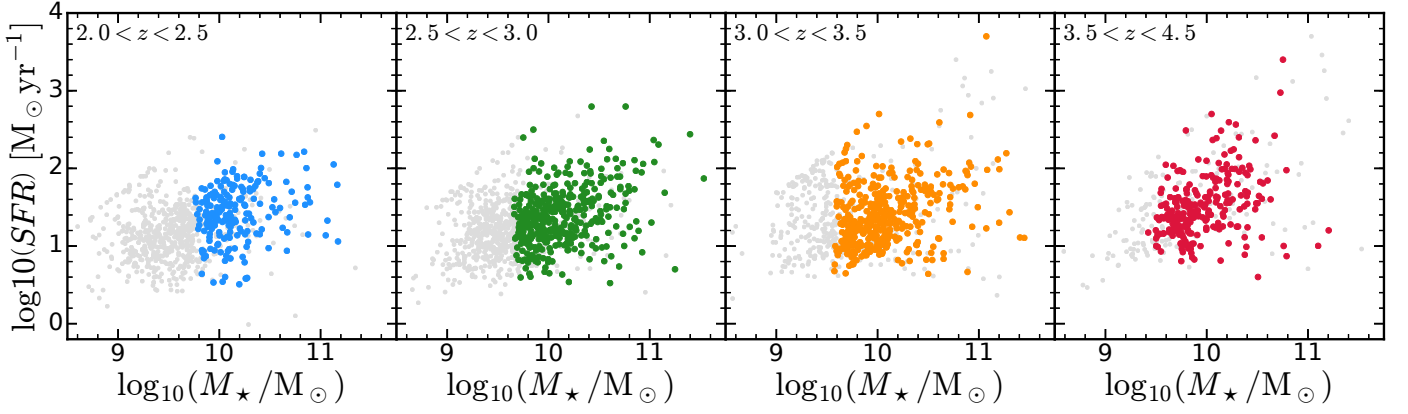


Fig. 2. Range in stellar masses and SFRs for the sample studied here. In each panel, the light gray points refer to the entire VUDS sample in each redshift bin. The colored points represent each of the 1242 galaxies in the selected stellar mass range and with reliable spectroscopic flags (correct redshift probability of $> 75\%$, see text for more details).

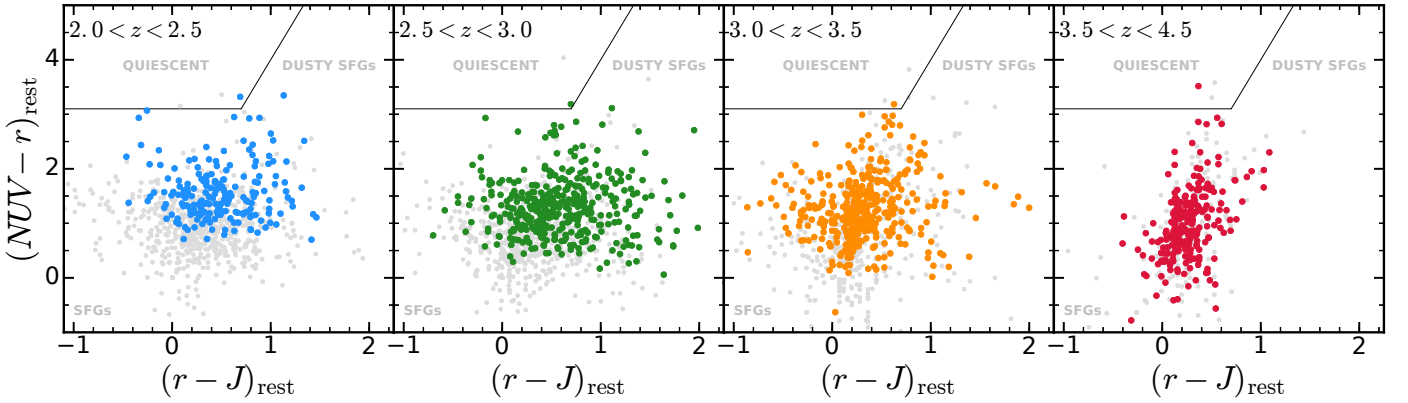


Fig. 3. NUVrJ diagram (Ilbert et al. 2010, 2013) for the sample studied here in different redshift bins. In each panel the colors have the same meaning as in figure 2.

at different redshifts using

$$\log_{10}(M_{\star}/M_{\odot}) > -0.204(z - 4.5) + 9.35. \quad (1)$$

In figure 1 one can see the redshift distribution of the entire VUDS sample and that of the stellar mass-selected sample in the redshift range considered defined for the purpose of this study. Such selection translates into 1645 galaxies in the COSMOS and ECDFS fields with a spectroscopic redshift measurements and with stellar masses obeying equation 1 of which 1242 have spectroscopic redshift flags that have a reliability of $> 75\%$ (flags X2,X3,X4 and X9 with X=0,1,2 see Le Fèvre et al. 2015, for more details).

We show the stellar mass-SFR relation of our sample divided in four redshift bins in figure 2. It shows that our sample probes galaxies with typical median stellar masses of $10^{10}M_{\odot}$ and ranging from $\log_{10}(M_{\star}/M_{\odot}) \gtrsim 9.35$ and up to $10^{11}M_{\odot}$. In terms of SFR, our galaxies are in the range $0.5 \lesssim \log_{10}(SFR) \lesssim 3.0$ at all redshifts with median values of $\log_{10}(SFR) \sim 1.4$.

To further characterize our galaxy population we plot in figure 3 the position of each galaxy with respect to the quiescent region as defined in Ilbert et al. (2013). The lack of galaxies in the upper right part of the panels in the NUVrJ diagram indicates that we are missing dusty star-forming galaxies. We also lack the quiescent population (only 4 galaxies fall in the quiescent region of the diagram). This confirms that our sample is probing the bulk of the massive, low dust star-forming population at the redshifts considered.

3. Parametric size measurements: Effective radius

r_e

One of the most widespread ways of measuring galaxy sizes at all redshifts is by parameterizing their surface brightness profiles with a given functional form (e.g. Simard et al. 1999; Peng et al. 2002; Ravindranath et al. 2004; Daddi et al. 2005; Ravindranath et al. 2006; Trujillo et al. 2006; Akiyama et al. 2008; Franx et al. 2008; Cassata et al. 2010; Williams et al. 2010; Mosleh et al. 2011; Cassata et al. 2013; Huang et al. 2013; Morishita et al. 2014; van der Wel et al. 2014; Straatman et al. 2015; Shibuya et al. 2015). The Sérsic (1968) profile is the preferred choice for fitting galaxy photometry and it is given by

$$I(r) = I_e \exp[-\kappa(r/r_e)^{1/n} + \kappa] \quad (2)$$

where the Sérsic index n describes the shape of the light profile, r_e is the radius enclosing 50% of the total flux, I_e is the surface brightness at radius $r = r_e$ and κ is a parameter coupled to n (see for example Ciotti & Bertin 1999) such that half of the total flux is enclosed within r_e . An index of $n = 1$ corresponds to a typical pure disk galaxy, whereas $n = 4$ corresponds to the de Vaucouleurs profile which is associated to elliptical galaxies and spiral bulges (although indices $n > 4$ are very common, especially at low redshift). On 2D images, each Sérsic model has potentially seven free parameters: the position of the center, given by x_c and y_c , the total magnitude of the model, m_{tot} , the effective radius, r_e , the Sérsic index, n , the axis ratio of the ellipse, b/a

and the position angle, θ_{PA} , which refers to the angle between the major axis of the ellipse and the vertical axis and has the sole purpose of rotating the model to match the galaxy's image.

3.1. Method

To measure the effective radius of our objects we use the 2D surface brightness fitting tool GALFIT (Peng et al. 2002, 2010). For each galaxy we choose to fit a single Sérsic profile with no constraint in the parameters. To remove the effect of the ellipticity of each source, the final size value as measured from GALFIT is computed as the circularized radius via

$$r_{e,circ} = r_e \sqrt{q}, \quad (3)$$

where q is the axis ratio (b/a) of the elliptical isophotes that best fit the galaxy. In this sense, a comparison with r_T defined in section 4 is also more immediate, as both are circularized forms of size measurements. The initial parameters were retrieved from running SExtractor (Bertin & Arnouts 1996).

3.2. PSF and masks

In order to provide accurate size measurements it is crucial to have a good image representing the point spread function (PSF) of the data. For that purpose a list of individual, bright, non-saturated, field stars were pre-selected based on their position in the stellar locus of the $\mu_{\max} - mag$ diagram. This procedure was applied to all the CANDELS, UltraVISTA and CFHTLS mosaic images. Then, we selected by visual inspection the stars to be used for the stack. Thus, we built a high S/N image of the PSF for each image by stacking ~ 40 stars in each CANDELS field. For COSMOS we have used the models built with *TinyTim*² described in Rhodes et al. (2007).

For space based imaging, we fed GALFIT with $6'' \times 6''$ image cutouts around the galaxy. As for the masking procedure, we used the segmentation map produced by SExtractor and flagged all companion objects for which all pixels associated with it are at a distance greater than $1''$ of the VUDS target. The flagged pixels are not taken into account when doing the χ^2 fitting by GALFIT. Based on deep galaxy counts (Capak et al. 2007) we estimate the number of companions at a distance smaller than $1''$ and brighter than $i_{AB} = 25.5$ is 6%. This reassures us that we are getting size measurements for sources that fall within the slits, i.e. it is unlikely that GALFIT will lock on a companion object.

3.3. Image simulations

Simulations of 15 000 galaxies using GALFIT Sérsic profiles convolved with the observed PSF are performed to test the reliability of the obtained values for the effective radius of the galaxies in the sample. To do so, we use the computed SExtractor source catalog to select 200×200 pixel sky regions on which the simulated galaxies are dropped. The sky regions are randomly selected so that we do not introduce artificial bias by using hand picked regions. However, since the selection of pure sky regions in a random way is very time consuming a method is devised to select the required size regions in a faster way while still taking cautions not to overlap simulated and real sources and to avoid bright sources within the region. This method selects random regions where: there are no pixel detections within a 50

Table 1. Interval of simulated values of artificial galaxies. All parameters were randomly selected from a uniform distribution within the reported range.

mag	r_e [pixel]	n	q	θ_{PA} [degrees]
22 - 27	0.5 - 30	0.5 - 10	0.1 - 1.0	-90 - 90

pixel radius from the center of the sky region; the neighboring sources allowed in the stamp image must not be brighter than 20 mag; the number of SExtractor detected sources within the stamp is limited to 10; all pixels have a non-zero value. Then the simulated galaxies have Sérsic profiles that are randomly generated from a set of values drawn from uniform distributions in the intervals defined in table 1. The profiles are subsequently convolved with the PSF and dropped on extracted regions. Finally all the simulated objects are fed onto the same pipeline as the real images to get their output parameters from GALFIT. The results of these simulations (see figure A.2) show that one can retrieve the input effective radius value within 10-20% for 68% of the simulated galaxies that have a total magnitude ≤ 25 . There is also a slight trend with the input effective radii in the sense that galaxies with higher input r_e tend to have slightly higher dispersion (up to $\sim 20 - 30\%$) of the difference one gets. We note however that 93% of the galaxies in our sample have measured radii smaller than 20 pixels for which we obtain a radius within $\sim 15\%$ of the input value. We have tested this simulation by using different background images from which to extract the sky regions (COSMOS F814W tiles and CANDELS F814W, F125W, F160W mosaics) and found no significant differences in the simulation results. Similar conclusions were found by, e.g., Mosleh et al. (2011); Morishita et al. (2014).

An additional test is carried out to test the robustness of GALFIT results against the choice of first guess parameters. In this case, for each galaxy, we run GALFIT fifty times, each of which with a set of Gaussian randomly deviated values centered on the SExtractor input guesses and with widths that include at least a 50% deviation from the input value within 1σ . We then compare the median value of the fifty runs with the results from the single run with SExtractor first guesses and find that no more than $\sim 9\%$ of the galaxies for which GALFIT converged have median values offset by more than 3σ and that most of the galaxies ($\sim 90\%$) are within 1σ . The outliers tend to happen for cases where GALFIT does not converge for one or more of the fifty tries. Nonetheless, the majority of the galaxies for which we have GALFIT results (around $\sim 74\%$) allow the convergence more than 40 (out of 50) times.

3.4. Dependency with color

To study size evolution across a large redshift range one should use common rest-frame measurements whenever possible. When not possible some approximations must be made. The simplest one consists on using the observed band closest to the rest-frame one wants to consider (e.g. Morishita et al. 2014; Shibuya et al. 2015). A more evolved approach is presented by van der Wel et al. (2014) where a wavelength dependence of the measured radii is observed and fitted. A correction is then applied to each galaxy to obtain the value of the radius at exactly the wavelength one chooses. However, such approaches require a multi-wavelength coverage of the targets which is not available for the majority of our sample.

For those galaxies which are in the CANDELS area (roughly 10% of our sample), we did compute their effective radii in three

² <http://www.stsci.edu/hst/observatory/focus/TinyTim>

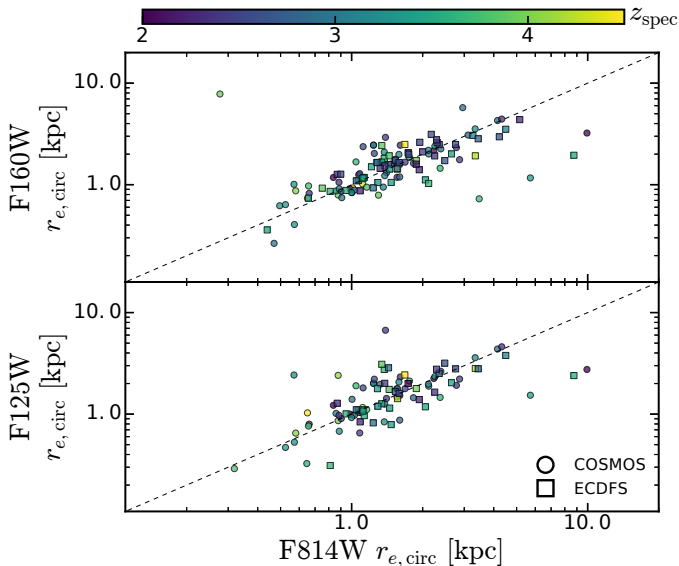


Fig. 4. Comparison of size measurements derived with GALFIT for a subset of 153 (118) VUDS galaxies at $2 < z < 4.5$ with available F814W and F160W (F125W) images from CANDELS. Results are split in two bands: F160W on the top panel and F125W on the bottom panel. Circles and squares refer to COSMOS and ECDFS respectively. The dashed black line is showing where both radii are equal. The symbols are color coded according to their spectroscopic redshift and the mapping is shown in the colorbar on top of the plots. Less galaxies are available in the J-band comparison because there is no such data available in ECDFS.

different bands: F814W, F125W and F160W. Doing a simple inter-wavelength comparison one finds that the derived sizes are similar in all three bands (see Figure 4). We report a small offset in the median values of $r_I - r_H \approx -0.04$ kpc and $r_I - r_J \approx -0.01$ kpc. The dispersion on the size measurements across different bands is 0.21 dex and 0.20 dex for F814W-F160W and F814W-F125W comparisons respectively. For further inspection, we used the wealth of multi-wavelength observations on the COSMOS field (space and ground based imaging) with a variety of instruments from three different surveys (CFHTLS in the optical, and WIRDS and UltraVISTA in the near-infrared) to obtain size measurements up to the Ks band which, at the highest redshifts considered here, still probes the regions above the Balmer/ D_n 4000 break. Then, for each galaxy in our sample, we plot its size value as a function of the observed wavelength computed using the knowledge of the spectroscopic redshift and the filter wavelength, λ_F .

$$\lambda_0 = \frac{\lambda_F}{1+z} \quad (4)$$

Size measurement results at different wavelengths obtained from our galaxies are presented in figure 5. The overall trend is that, at the redshifts considered here, measurements of circularized effective radii are independent on wavelength to first order. This result tells us that circularized effective radii computed from F814W observations are not much affected by the rest-frame wavelength at which the galaxies are observed. To quantify the wavelength dependence we have opted to fit the relation

$$\log(r) = \beta_\lambda + \alpha_\lambda \log(\lambda_0) \quad (5)$$

to all the data points considering space based imaging and ground based imaging separately. We find that for ground based

data (covering from I to Ks bands) the slopes measured are all consistent with no wavelength dependence ($\alpha_\lambda = 0$ is within 1σ at all redshift intervals). For space based data (covering from I to H bands) we find slightly positive slopes indicating slightly larger sizes in the redder bands, but only marginally significant 1.9σ away from a flat slope $\alpha_\lambda = 0$. Using our fit values in equation 5 we estimate that the ratio ranges within $r_{1700\text{\AA}}/r_{2500\text{\AA}} = 0.89 - 1.01$.

In a complementary test, we fit the size-wavelength relation for all individual galaxies which have measurements in three or more bands. The median slope is $\alpha_\lambda = 0.03 \pm 0.27$ and $\alpha_\lambda = -0.12 \pm 0.34$ for space and ground based observations, respectively. This translates into a ratio $r_{1700\text{\AA}}/r_{2500\text{\AA}} = 0.99(1.05)$ for space (ground) based data. This supports the fact that the wavelength dependence of galaxies in our sample is very shallow and consistent with no dependence at all for the ensemble of the galaxies in our sample. We note however that there is a large dispersion amongst our galaxies, which means that the wavelength dependence requires a different treatment when considering a case by case basis.

We have shown in figure 5 that we can measure sizes from ground-based data for the galaxies in our sample. This would allow for the use of the entire VUDS sample, including galaxies in the VUDS-2h field. However, since the convergence success of GALFIT is much less ($\sim 30\%$) and the fact that the method described in section 4 is PSF dominated preventing us from getting galaxy sizes (sizes are systematically overestimated when compared to those obtained with HST images) we opt to conduct our analysis on space-based data only.

3.5. Results: r_e measurements

We fit all galaxies in the stellar mass selected sample using the automated GALFIT procedure described in the previous sections to obtain effective size measurements r_e . After fitting all galaxies, a subset of 19.5% of those GALFIT failed to converge. These galaxies are analyzed on an object-per-object basis and a manual re-fitting is attempted by tuning the initial set of parameters. After this manual try, of the 1242 galaxies in our stellar mass selected sample, 263 (15.7%) objects have no structural parameters because GALFIT failed to converge. These objects are usually very low surface brightness or highly concentrated galaxies.

The size distributions presented in Figure 6 show similar shapes at all redshifts showing a slow monotonic decrease in their median sizes as redshift increases. Each distribution is fitted with a normal function (in log space) and the derived sigma values from the fit are similar at all redshifts (0.23, 0.26, 0.29 and 0.24 with growing redshift).

The overall evolution of sizes across the redshifts considered here is shown in figure 7. We find that the effective radius of galaxies continuously decreases over the redshift range of our sample. Galaxies with $2 < z < 2.5$ have $\langle r_{e,\text{circ}} \rangle = 1.67 \pm 0.09$ kpc, while in $4 < z < 4.5$ the median effective radius is a factor of 1.6 smaller, $\langle r_{e,\text{circ}} \rangle = 1.05 \pm 0.05$ kpc. In every redshift bin a large dispersion in the effective radii is measured amongst the galaxy population and for all redshift bins $\sim 9\%$ of the population has measured radii which are large ($r_{e,\text{circ}} > 3$ kpc) and some extremely so (7–10 kpc) in all redshift bins save the last. These features of the distribution are discussed together with other measurements in Sections 6 and 9.

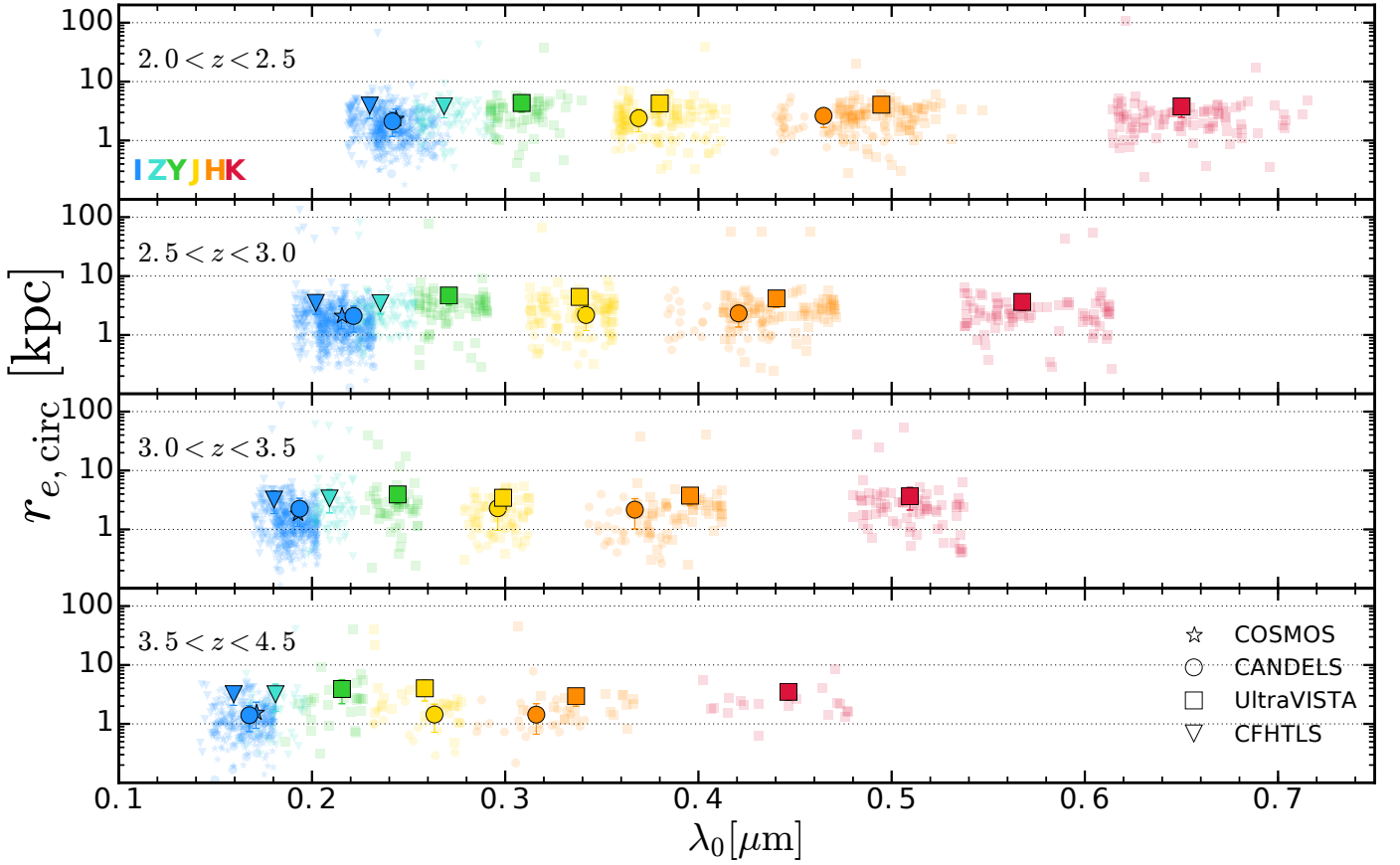


Fig. 5. Measured Sizes as a function of wavelength for galaxies with $\log_{10}(M_*) > 9.5$ at $2 < z < 4.5$ in the COSMOS field. Different symbols correspond to different surveys (symbol coding on the bottom panel) and different colors to different observed bands (color coding in the top panel). Each point represents the size of a given galaxy at the rest-frame wavelength of the pivot of the filter.

3.6. The impact of cosmological dimming on r_e

A key point to take into account in this analysis is that GALFIT-based measurements do not take into account the surface brightness (SB) dimming effect which is a strong function of redshift. Parametric modeling works well even under low S/N conditions³, recovering the right parameter values, although with larger uncertainties. This should, in principle, deal with the increased SB dimming of galaxies at higher redshift. The dimming effect, if significant, would act in the sense of getting smaller sizes at higher redshifts that would in turn impact the derived evolution into having a steeper slope. Thus, a correction for the cosmological dimming could lead to a weaker size evolution.

We have tested this scenario by masking the pixels that are below the surface brightness threshold that we use (see section 4.3) and then run GALFIT to obtain the size measurements from this pixel set reduced to the brightest regions of galaxies. We find that GALFIT finds similar sizes for both cases with and without masking those low surface brightness pixels and that the trend in evolution is not affected.

4. Galaxy area and equivalent radius r_T

While the local universe is dominated by galaxies with symmetric shape in the form of discs and bulges, the distribution of galaxy shapes becomes more complex as redshift increases.

By redshift $z \sim 1 - 2$ irregular galaxies make up to 52% of the population of galaxies (Delgado-Serrano et al. 2010; Huertas-Company et al. 2015). By redshift $z \sim 3$ galaxies with irregular shapes dominate as they represent $\sim 65(40)\%$ of the population of massive, $\log_{10}(M_*) > 10(11)$, galaxies (Mortlock et al. 2013; Buitrago et al. 2013). These irregular shapes often come in the form of clumpy galaxies representing $\sim 60\%$ of the star-forming galaxies at $2 < z < 3$ (e.g. Elmegreen et al. 2007, 2009; Wuyts et al. 2012; Guo et al. 2015; Huertas-Company et al. 2015). This fraction might be higher when going to higher redshifts (Conselice & Arnold 2009). Irregular shapes can take very diverse forms, including objects with one single asymmetric component, with multiple components, with a tadpole shape, extended with low surface brightness, and can be confused in the presence of close projected or physical companions. Some examples of galaxies in our sample are shown in Figure 9. The fit with GALFIT gives an effective radius which highly depends on the relative brightness of each clump of the galaxy, but the residuals after fitting show how difficult it is to fit such an object with a symmetric profile.

These considerations prompted us to use other ways to derive sizes of galaxies than parametric fitting. A non-parametric definition removes the need for assuming a surface brightness profile. Measuring the half-light radius based on SExtractor and/or Curve of Growth methods is also widely used (e.g. Ferguson et al. 2004; Bouwens et al. 2004; Hathi et al. 2008; Oesch et al. 2010; Curtis-Lake et al. 2016). However, these non-parametric methods require a center and an aperture definition to be com-

³ See http://users.obs.carnegiescience.edu/peng/work/galfit/TFAQ.html#size_and_noise

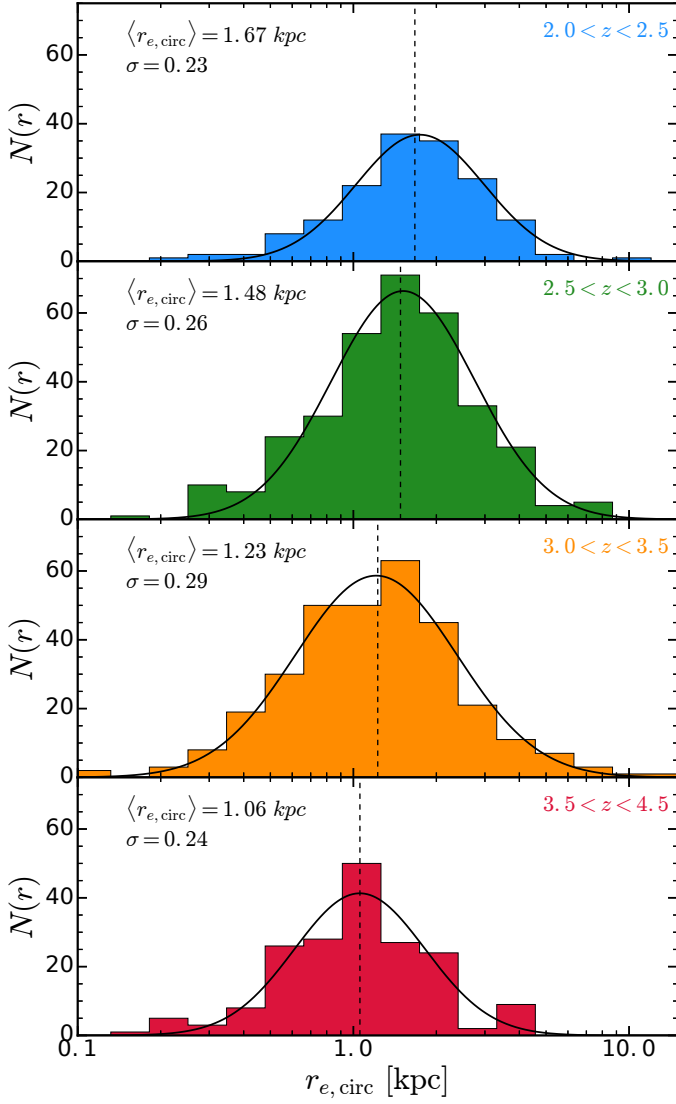


Fig. 6. Size distribution for different redshift bins. The vertical dashed line indicates the median value for each bin. The black line is the fit of the distribution using a normal function in log space.

puted. Such quantities can, again, be misleading in cases of highly disturbed morphology.

With this in mind we developed a simple size estimator based on the total area covered by a galaxy above a given surface brightness threshold. In the following sections we define a non-parametric size measurement independent of any assumption related to a symmetric light distribution. This method is more affected by PSF broadening and noise when going towards low surface brightness in contrast to parametric fitting. Nonetheless it has the advantage of being independent of the shape of the galaxy, and nicely complements the standard r_e measurements. The other advantage of this method is that it does not depend on initial guesses and does not require a fit to converge.

4.1. Method

We define the area of a galaxy by counting the number of pixels above a given surface brightness threshold that belong to it. This approach has the advantage of being completely independent of any asymmetries that the galaxy may have and does not require any centroid/aperture definition. As most of the objects in our

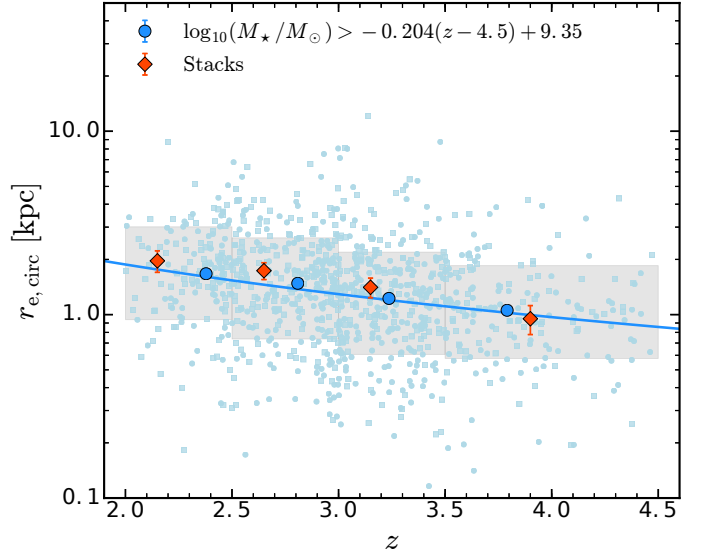


Fig. 7. Size evolution with redshift. Each galaxy with a good size measurement is plotted with a small blue point (squares for redshift confidence 2 and 9, circles for 3 and 4). The median values (in redshift and size for each bin) and respective error ($\sigma / \sqrt{N}$) per redshift bin are shown by the large blue points with the error bars. The shaded region delimits the 16th and 84th percentiles including 68% of the sample in each redshift bin. The red diamonds are the effective radii of stacked images computed from the method described in section 5 and are plotted at the center of the redshift bin.

sample show irregular morphology we define physical sizes using the total area T_x as (adapted from Law et al. 2007)

$$T_x = N_x L^2 \left(2 \times 10^{-11} \frac{\text{ster}}{\text{arcsec}^2} \right) D_A^2, \quad (6)$$

where N_x is the number of pixels of size L (in arcsec/pixel) that sum up to $x\%$ of the galaxy measured flux and D_A is the angular diameter distance derived using cosmological parameters. From this one can define the area equivalent radius, r_T^x ,

$$r_T^x = \sqrt{\frac{T_x}{\pi}}. \quad (7)$$

In the following we use T_{100} and r_T^{100} , the area and the equivalent circularized radius that enclose 100% of the measured flux above a given surface brightness threshold. The quantity r_T^{50} , the radius equivalent to the area that sums up to 50% of the total galaxy light, is similar to the effective radius derived from the GALFIT profile fitting, but taking into account irregular and asymmetric morphology. We also use the values of r_T^{80} and r_T^{20} enclosing 80% and 20% of the flux, respectively.

In practice, the method works as follows.

1. We smooth an image stamp of $6'' \times 6''$ centered on the VUDS galaxy with a Gaussian kernel with 1 pixel sigma width, truncated at 4 pixels;
2. We compute the segmentation map of the smoothed image based on a given surface brightness threshold;
3. From the segmentation map we select the area of connected pixels which contains the brightest pixel within a 0.5 arc-second radius from the target coordinates;
4. Using the pixels selected, we compute the total flux of the galaxy by summing up the flux in each pixel;

5. Finally, we iterate (using 1000 steps) f_i from the maximum to the minimum flux detected within the segmentation map. At each step we compute the summed flux from the pixels for which $f_{\text{pixel}} > f_i$. When the summed flux corresponds to $x\%$ of the galaxy total flux, we store the number of pixels that have fluxes greater than f_i at that step and then compute T_x using equation 6.

We smooth the original image so that we improve our sensibility to faint surface brightness features of galaxies. We choose a gaussian kernel smothing of 1 pixel sigma width since it provides a compromise between a boost in the S/N of the faint features and prevents a large degradation of the image resolution necessary to properly trace the asymmetries in the shape of the object.

The selection method chosen for the purpose of this project has the main goal of minimizing the effect of neighbor contamination and of not imposing any size constraints on the derived measurements. We have tested two other different methods: selecting the largest area or the brightest area (by summing the fluxes of all its pixels) for which a subset of its pixels is inside the $0.5''$ radius. Both methods yield similar results.

We have tested the contamination by neighbors dropping simulated galaxies in random regions of the images with and without a constraint on the presence of sources within 2.0 arcsec of the simulated galaxy. When no constraints are imposed sizes are sometimes artificially increased by the area occupied by a neighboring source. Still, the rate of contamination does not dominate the measurements. We find that the percentage of simulated galaxies with recovered sizes twice as big as the input is of 8% for the random clean regions and 17% for the purely random regions. We expect that the contamination rate of our galaxies will be closer to the first reported value since, due to the data processing for a spectroscopic survey, galaxies with large bright companions are excluded from the sample due to problematic redshift estimation.

4.2. Cosmological dimming and Luminosity Evolution

Tolman (1930) demonstrated that in an expanding universe the relation between the flux and angular size of a nebula should follow the relation (adapted from his equation 30)

$$\frac{F}{\delta\theta^2} \propto (1+z)^{-4}. \quad (8)$$

At the time (see Lubin & Sandage 2001) it was the only observational test that was proposed to confirm the reality of the expansion of the universe, which is now well established. This dimming effect, independent of the cosmological model, has to be taken into account if one wants to measure galaxy sizes (by means of counting pixels) at the same surface brightness level at different redshifts.

However, when one is analyzing the image recorded with the detector, one is looking at the number of detected photons arriving from the observed source, and not at an integrated flux. Let us consider a square region of the emitting source corresponding to the pixel size at the location of the object. The monochromatic energy emitted is given by

$$L_p = \int_A I(x, y) dx dy \quad (9)$$

which, for a source emitting at constant brightness inside that pixel simplifies as

$$L_p = T \times I, \quad (10)$$

where T is the physical size of that pixel. Considering a pixel size p , the physical size, in kiloparsec, is proportional to:

$$T \propto (p \times D_A)^2. \quad (11)$$

At a distance D_L the observed light is

$$F_p = \frac{L_p}{4\pi D_L^2}. \quad (12)$$

The number of observed photons is

$$N_{\text{photons},o} = \frac{F}{E_{\text{photon},o}}, \quad E_{\text{photon},o} = h\nu_o = \frac{h\nu_e}{1+z}. \quad (13)$$

Combining the equations above we get

$$N_{\text{photons},o} \propto \frac{I \times (p \times D_A)^2 (1+z)}{4\pi D_L^2 h\nu_e}. \quad (14)$$

With $D_L = D_A(1+z)^2$, the number of observed photons per unit area is

$$N_{\text{photons},o} \propto \frac{p^2}{4\pi} \frac{I}{h\nu_e} \frac{1+z}{(1+z)^4} \propto (1+z)^{-3}. \quad (15)$$

The factor $I/(h\nu_e)$ represents the number of emitted photons per unit area. The same redshift dependence was found by Giavalisco et al. (1996) and used in Law et al. (2007).

On top of the dimming effect, the average evolution in luminosity of a population of galaxies has an impact on the typical threshold defined at any given redshift. This means that a galaxy with a fixed size but with an increased luminosity because of luminosity evolution will appear larger above a fixed luminosity threshold. The average luminosity evolution from $z \sim 4.5$ to $z \sim 2$ as reported in the literature is 0.4 magnitudes in the UV rest-frame Reddy & Steidel (2009); Bouwens et al. (2015). We take this effect into account by parameterizing the evolution of the characteristic luminosity L_* within the redshift range we are considering. Taking the L_* values in Reddy & Steidel (2009) at $z < 3$ and those from Bouwens et al. (2015) at $z > 4$ we define a broken luminosity evolution which is steeper below $z < 3$ and flattens at $z > 4$:

$$L(z) = \begin{cases} 10^{-0.4(-0.36z)} & z \leq 3 \\ 2.25 \times 10^{-0.4(-0.07z)} & z > 3 \end{cases} \quad (16)$$

4.3. Detection threshold

The dimming effect described in the previous subsection relates to an important tuning parameter for this non-parametric size measurement which is the detection threshold above which a pixel is classified as a detection and may be assigned to the galaxy. This detection threshold is defined as a multiple k of the standard deviation of the sky emission, σ , computed globally. To be sure that we are fairly comparing galaxies imaged at different depths, the value of σ is taken as the median standard deviation of the image noise computed from 100 different regions in the shallowest survey. In our case, $\sigma = 1.1 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$ is computed from the COSMOS images.

The choice of k plays an important role on the size estimates that one gets. The simplest assumption is to define a constant value k_0 across all redshifts. Another approach consists in taking

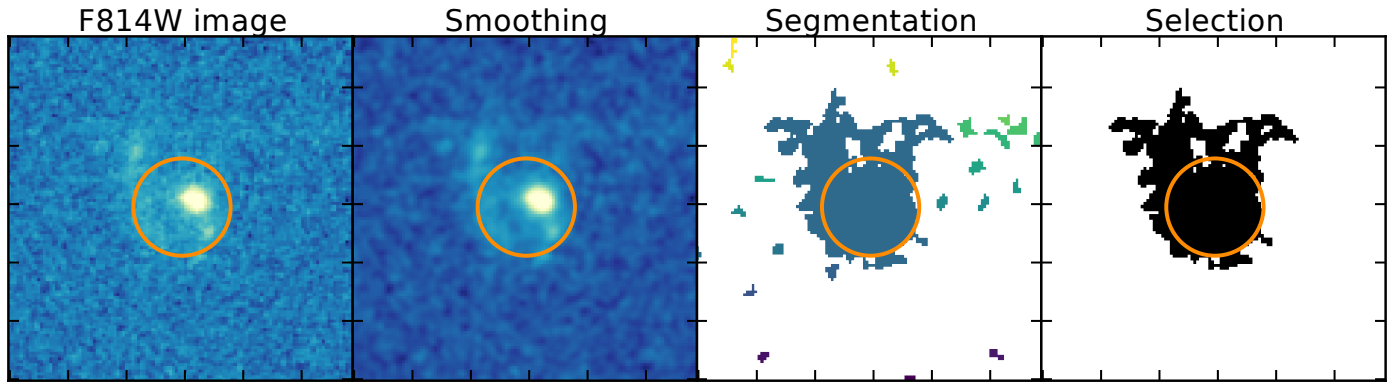


Fig. 8. Illustration of the size measurement process for VUDS 510799304 at $z = 2.4281$. From left to right: 1) The original F814W image from COSMOS (Koekemoer et al. 2007). 2) The same image after smoothing by a Gaussian kernel of 1 pixel width and extending over 4 times the width. This kernel ensures an improvement of the signal to noise for low surface brightness levels while preventing a significant boost of noisy pixels which would incidentally increase the measured radius if the kernel was too large. 3) The segmentation map obtained after running the detection algorithm including all pixels greater than $k\sigma$. 4) The selection of the target galaxy. All panels have $1.77''$ by $1.77''$ and the orange circle has a radius of $0.5''$. The total size is computed from the number of pixels in the last panel.

into account the effect of cosmological dimming and typical luminosity evolution (described above) and choose k as a function of the galaxy redshift following

$$k = k_p \left(\frac{1+z}{1+z_p} \right)^{-3} \times \frac{L(z)}{L(z_p)}, \quad (17)$$

where k_p is the value of k at the pivot redshift z_p and $L(z)$ is defined in equation 16. To use this method, the availability of spectroscopic redshifts is even more important as errors in the redshift would affect the threshold used and consequently impact the final size measurements of the galaxies.

Such drastic evolution of the detection threshold (see figure 10) led us to restrict the redshift interval of our study to $2 < z < 4.5$. In this range we probe the total extent of galaxies down to a lower surface brightness level at lower redshift while avoiding to overestimate galaxy sizes at the high redshift end due to random sky background noise detection. To obtain a size measurement corresponding as closely as possible to the total physical area covered by a galaxy, the choice of the threshold is based on the average number of connected sky pixels as a function of the threshold. We find that it is at the level of 1.0σ that we start to detect connected pixels (4-6 pixels) only due to random sky noise fluctuations. Based on that, and on the average galaxy color which we discuss in section 4.5, we define k such that at $z = 2$ it has a value of 1.0 to probe galaxies down to their fainter regions. This corresponds to a detection limit of $\approx 0.25\sigma$ per pixel at $z = 4.5$. We discuss the contamination from random fluctuations and the correction made to the size measurements measured down to these thresholds in section 4.6.

The galaxy sizes that we measure are tied to the choice of k_p and/or the depth of the image which determines the value of σ . By setting the value of $k \times \sigma$ at higher/lower values, the absolute value for the galaxy size will decrease/increase. We therefore report total size measurements indexed to a specific choice of k_p , i.e. to a specific limiting isophote defined at $z = z_p$. For the sake of simplicity we shall refer hereafter to our non-parametric size as the total size.

4.4. Correcting for PSF broadening

Since we are measuring sizes directly on images we are affected by the broadening of the profile by the instrumental PSF. To cor-

rect for this effect we simulate with GALFIT a PSF image re-scaled to match the magnitude of the galaxy. We then run the simulated PSF through the same detection algorithm and obtain the size of the PSF at the object magnitude and same surface brightness level. We then compute the galaxy size by correcting from the PSF broadening using the following formula

$$r_{T, \text{PSF-corr}}^x = \sqrt{(r_T^x)^2 - (r_{T, \text{PSF}}^x)^2} = \sqrt{\frac{T_x - T_{x, \text{PSF}}}{\pi}} \quad (18)$$

4.5. Dependency with color

The method of measuring galaxy sizes presented above is dependent of individual pixel detection, and it is therefore more sensitive to the galaxy spectral energy distribution than other methods relying on a given surface brightness profile. Even in the absence of color gradients, the simple fact that one object could have a wavelength-dependent brightness leads the number of selected pixels to vary due to relative brightness change of the galaxy within a given filter with respect to the detection threshold.

To correct for this we apply a simple color correction to the detection threshold taking into account the different brightness at different rest-frame wavelengths:

$$k_c = k \times 10^{-0.4(B_{\text{obs}} - NUV_{\text{rest}})}, \quad (19)$$

where k is that of equation 17 and $(B_{\text{obs}} - NUV_{\text{rest}})$ is the color term. The color is defined to be the observed band, B , minus the rest-frame NUV band derived from SED fitting with Le Phare. The choice of the NUV band was done such that, for the majority of our galaxies, the color term is minimal since it overlaps with the observed band.

We compare the PSF-corrected values of r_T^{100} derived in the F814W, F125W and F160W bands in figure 11 (see also figure 12). We report a small offset in the median values of $r_I - r_H \approx -0.08$ kpc and $r_I - r_J \approx 0.51$ kpc. The dispersion on the size measurements across different bands is 0.27 dex and 0.22 dex for F814W-F160W and F814W-F125W comparisons respectively. We stress that part of the scatter observed in this figure is due to the color correction described above which is sensitive to the objects' magnitude in each of the bands. This in turns impacts the final isophote threshold and therefore the final measurements. Nonetheless, we highlight that we observe no

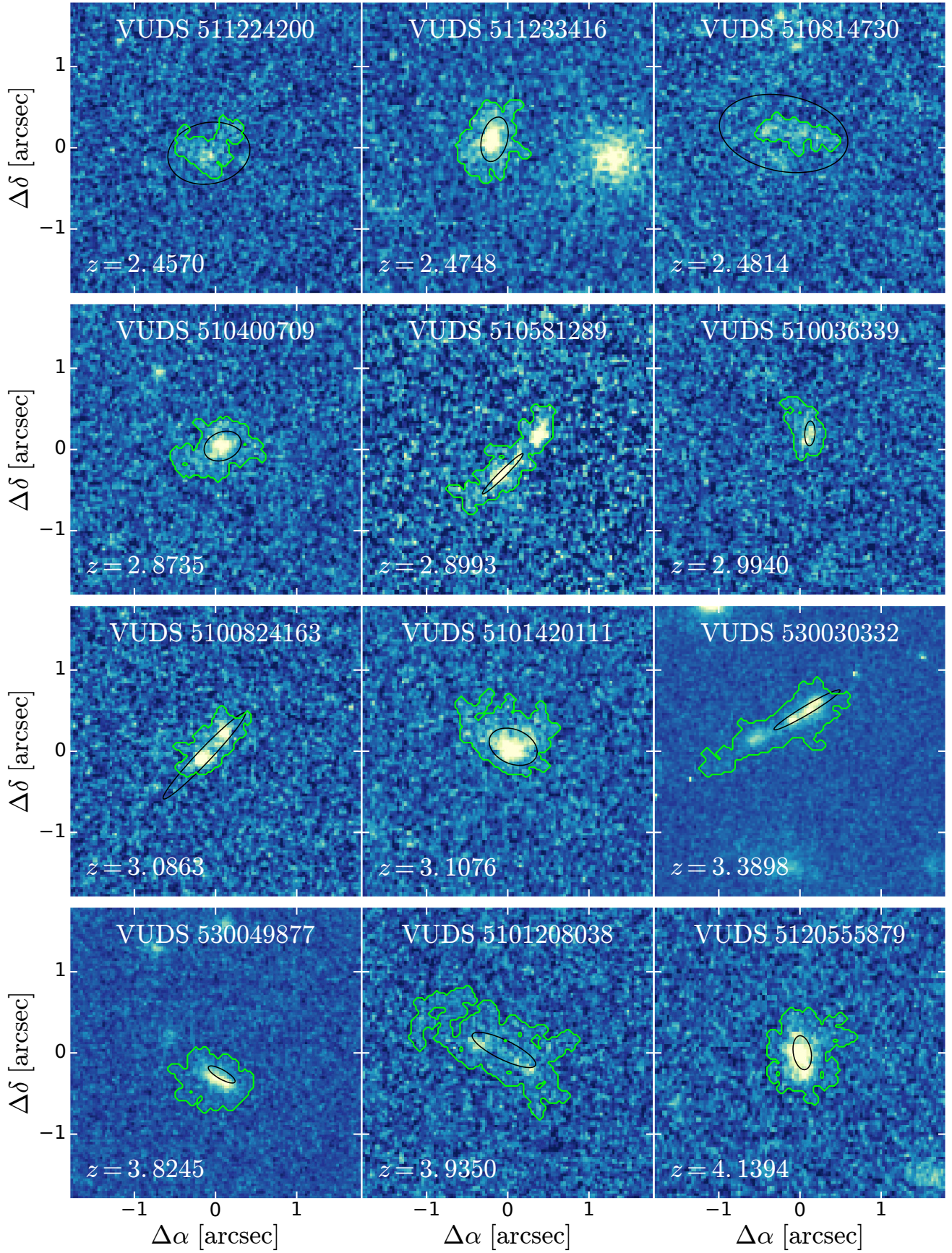


Fig. 9. F814W imaging in COSMOS (Koekemoer et al. 2007) and CANDELS (when available, Koekemoer et al. 2011) of the measured sizes for three galaxies in each of four increasing redshift bins from $z \sim 2.4$ to $z \sim 4.1$ (top to bottom) in our sample. The green contours show a smoothed version of the segmentation map of the galaxy at the defined threshold which translates to T_{100} from equation 6 measured at $k_p = 1.0$. The black ellipses are constructed from the values of r_e , b/a and θ_{PA} derived from GALFIT for those galaxies. The parametric and symmetric 2D profile fitting with GALFIT fails to properly account for the complex irregular morphology when deriving the size of galaxies at these redshifts, while the non-parametric method presented in this paper is able to derive more realistic sizes.

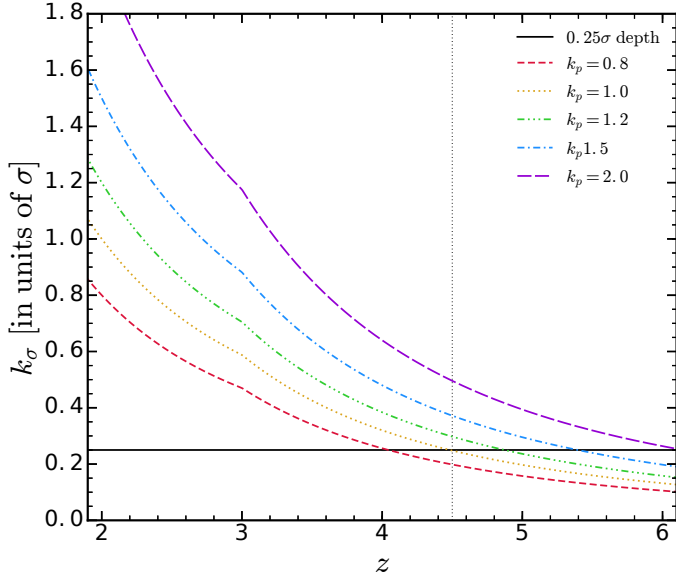


Fig. 10. Value of k as a function of redshift for different choices of k_p . The vertical dotted line shows the upper redshift limit we assume in this paper. The black solid line shows the depth limit above which the noise correction is larger than 100 pixels.

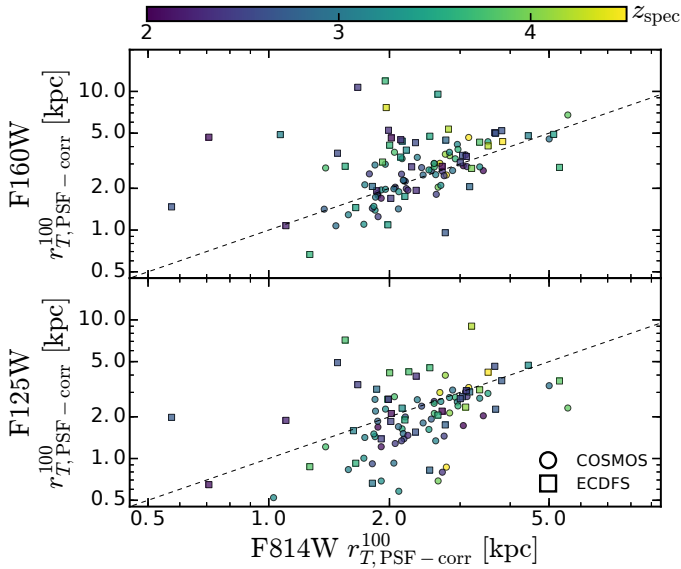


Fig. 11. Comparison of $r_{T,PSF-corr}^{100}$ size measurements for a subset of VUDS galaxies at $2 < z < 4.5$ with available F814W and F160W/F125W images from CANDELS. Results are split in two bands: F160W on the top panel and F125W on the bottom panel. Circles and squares refer to COSMOS and ECDFS respectively. The dashed black line is showing where both radii are equal. The symbols are color coded according to their spectroscopic redshift and the mapping is shown in the colorbar at top of the plots.

large systematic offsets in the comparison between the I and H bands.

4.6. Correcting for sky pixels detection

In the presence of uncorrelated Gaussian noise, the probability of a sky pixel being above the detection threshold defined above is not negligible. To estimate the level of contamination produced by random sky noise, we compute the N_{100} area (equation 6, size

of the segmentation map) on a search radius of 0.5 arc second (the same as when computing T_{100} for the real galaxies) randomly selected on $500 300'' \times 300''$ regions.

For each search radius, we compute the area defined for surface brightness thresholds ranging from 0.05σ to 2.05σ using steps of 0.025. This provides the median area of sky connected pixels for a given threshold value. We use this to correct the value of r_T^{100} following

$$r_{T,corr}^{100} = \sqrt{\left(r_{T,PSF-corr}^{100}\right)^2 - T_{sky}(k)/\pi} \quad (20)$$

where $T_{sky}(k)$ is the median number of connected sky pixels at a threshold k . In figure A.1 we show the impact of this correction on a set of simulated galaxies. We stress that this correction is only applied to the value of r_T^{100} . We note however that the impact of the noise is greater when increasing the fraction of the flux used to derive sizes. Sky noise effects are negligible for sizes computed using 10% of the total flux.

4.7. Results

Of the 1242 galaxies in our stellar mass selected sample, 67 objects have no measured value of r_T . These failures are due to the lack of pixel fluxes above the selection threshold defined in equation 19 for 17 objects and due to the lack of color information for 5 objects. The other 45 objects are on the edge of the image mosaic and thus no sufficient information is available to derive a size.

The distribution of total sizes is presented in Figure 13 for the four redshift bins previously defined. The shape of the distribution remains roughly the same with redshift. The Gaussian fit on each sub-sample yields sigma values of (0.154, 0.141, 0.168, 0.154) with increasing redshift.

We compare the total size measurements to the circularized effective radius obtained in Section 3.5 in Figure 14. Galaxies with the larger $r_{e,circ}$ are also larger in total size. However, this trend deviates from the linear relation and there is a large scatter in the relation. The scatter is somewhat expected as we are dealing with highly irregular morphology. While GALFIT gives a heavier weight to the brightest pixels (which can be locked into a single bright clump in a large galaxy), r_T measures the whole galaxy extent. GALFIT can pick up fainter *buried* flux of a galaxy by extrapolation of the profile measured on the bright pixels, which is not picked up when computing the total size using our method which explains why some galaxies have $r_{e,circ}$ larger than r_T . It is interesting to note that the $r_{T,PSF-corr}^{50}$ is nicely correlated with $r_{e,circ}$, as shown in Figure 14, with a dispersion of 0.23 dex which is a consequence of the frequent asymmetric shapes in our sample.

The evolution of total sizes across the redshifts considered here is shown in figure 15. We find that total sizes are staying roughly constant over the redshift range $2 < z < 4.5$, with $r_{T,corr}^{100} \approx 2.2$ kpc. The dispersion around the mean of $\sigma \approx 0.9$ kpc (0.21 dex), and we find galaxies that are as large as ~ 5.5 kpc and as small as ~ 0.5 kpc at all redshifts in this range. Size measurements using this definition are consistently larger than sizes provided by the effective radius r_e . This is discussed in Sections 6 and 8.

We show the dependence of the absolute value of the measured sizes as a function of the chosen value of k_p in figure 16. As expected when using different limiting isophotes over a range of 2.5 in luminosity changes the size values. It is therefore essential to quote the absolute luminosity of the isophote used to

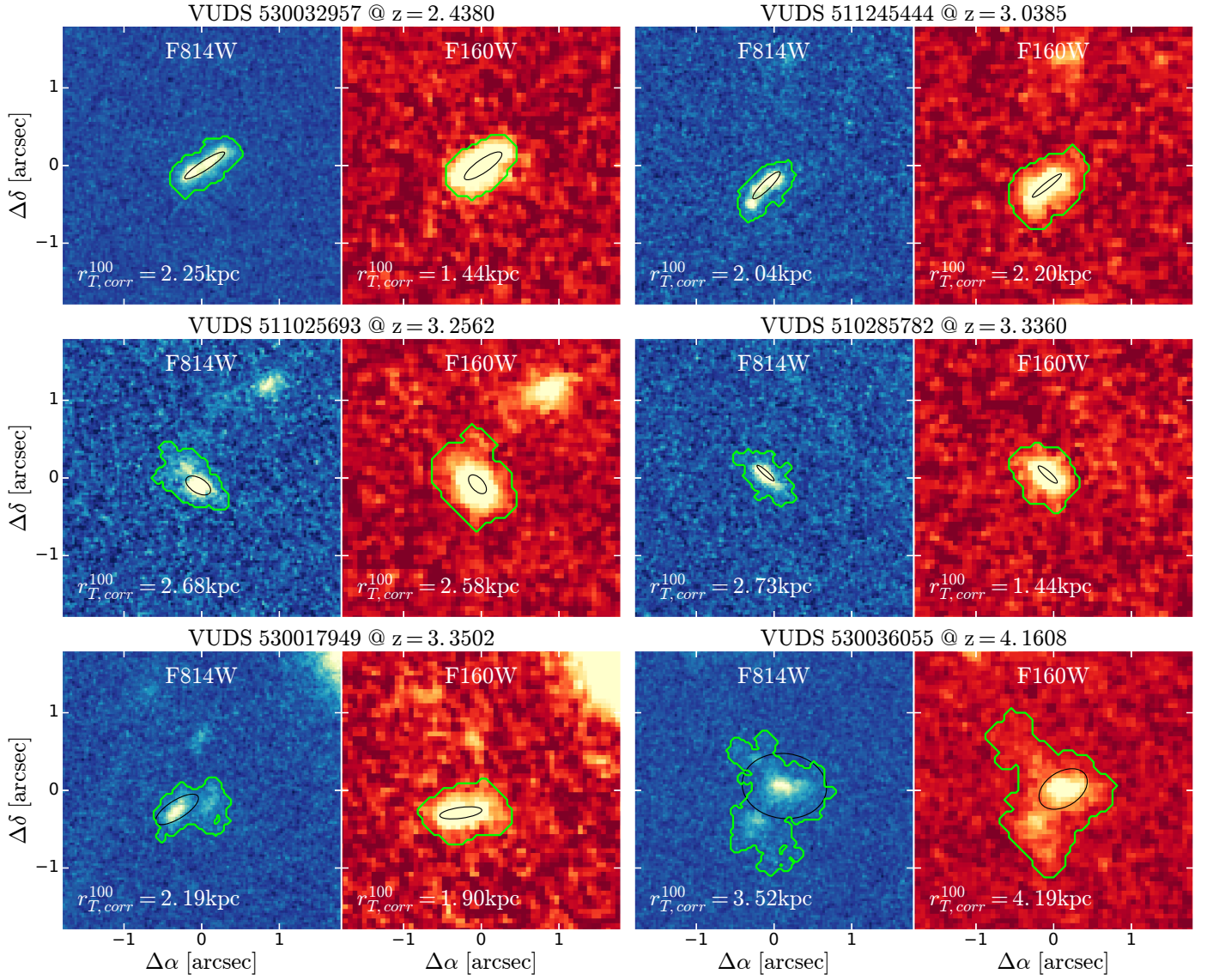


Fig. 12. F814W (in blue) and F160W (in red) imaging in CANDELS (Koekemoer et al. 2011) of 6 example galaxies in VUDS. The green contours show the isophote used to derive r_T^{100} prior to the PSF and sky correction. The black ellipses are constructed from the values of r_e , b/a and θ_{PA} derived from GALFIT for those galaxies in each band. We refer the reader to figures 4 and 11 where comparison of derived sizes is shown for the full set covered by CANDELS.

compute galaxy sizes. We note that at all times, the observed trends as a function of redshift are consistently different from those observed with GALFIT, with approximately constant sizes as a function of redshift while the effective radius is observed to strongly decrease.

5. Average galaxy profiles and light concentration

Since the total sizes of galaxies, measured at the same surface brightness level, seem to not evolve much with redshift, we investigate if the same pattern applies to the light profiles. We do this by looking at the stacked profiles and at the individual measurements of light concentration in galaxies.

5.1. Image stacks

In order to investigate the evolution of the light profiles we stack images of the large number of sources in our sample to follow

the profile at larger radii than from individual images. The stacking procedure starts by collecting a $10'' \times 10''$ stamp image for each galaxy in the sample. Then, one runs SExtractor to find the light-weighted center of each source. We shift the image by the difference between the light-weighted center and the physical image center, using a cubic spline interpolation to re-scale the image onto a common grid. After processing the entire sample for a given redshift bin, we take, at each position, the median pixel value as the *flux* of the stacked image. We also produce a straightforward sum to the images normalized by the total galaxy flux. The results of both methods give the same qualitative answers.

Stacking within a redshift bin, smears the rest-frame light over the interval. Also, when comparing different redshift bins we are effectively looking at different rest-frame light. This ranges from $\sim 2500\text{\AA}$ in the lowest redshift bin down to $\sim 1600\text{\AA}$ in the highest redshift bin. As shown in section 3.4, sizes derived are roughly the same across this wavelength range. This

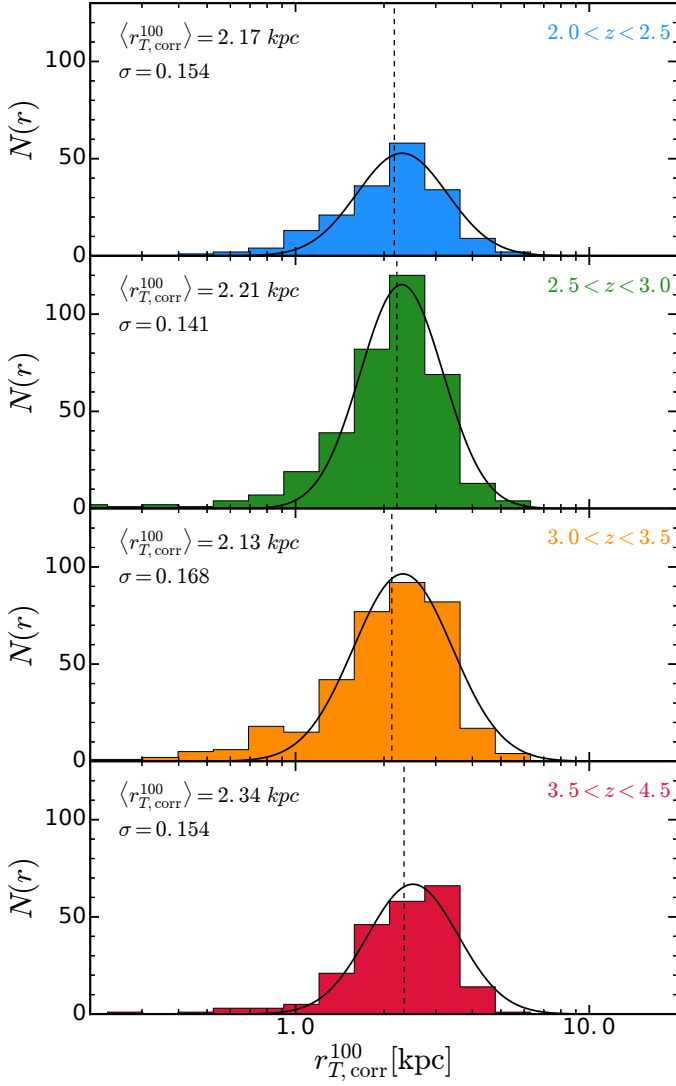


Fig. 13. Total size distribution for different redshift bins. The vertical dotted line indicates the median value for each bin. The black line is the fit of the distribution using a normal function in log space.

difference in rest-frame wavelengths has no effect on the comparison of the profiles discussed in the next section.

5.2. Luminosity profiles

The redshift dependency of the light profile derived from the stacked images is presented in Figure 17. We convert the median stacked profiles into surface luminosity profiles and show these profiles normalized at $r = 0.3$ kpc. The light profiles change smoothly across redshift starting from a highly peaked, concentrated profile at the higher redshifts $z \sim 4$ and becoming less concentrated as we move towards the lower redshifts $z \sim 2.25$.

5.3. Light concentration of individual galaxies

To further investigate the change in light profiles with redshift we use a different but quite commonly used way to quantify the light concentration. The concentration parameter was originally defined by Bershady et al. (2000) as the ratio of the 80% and 20% light radius derived from elliptical apertures centered on the galaxy. This measurement assumes symmetrical isophotes to

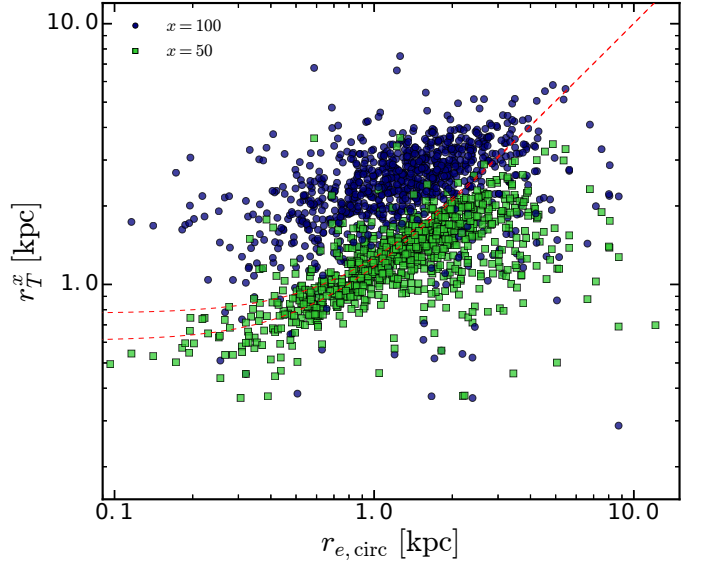


Fig. 14. Comparison of the two size estimates computed in this paper. In dark blue points we have the comparison to $r_{T,corr}^{100}$ and in green points to $r_{T,PSF-corr}^{50}$. The red dashed lines corresponds to the equation $r_T = \sqrt{r_{e,circ}^2 + FWHM^2}$ for the limit redshifts 2 and 4.5 (top and bottom lines respectively).

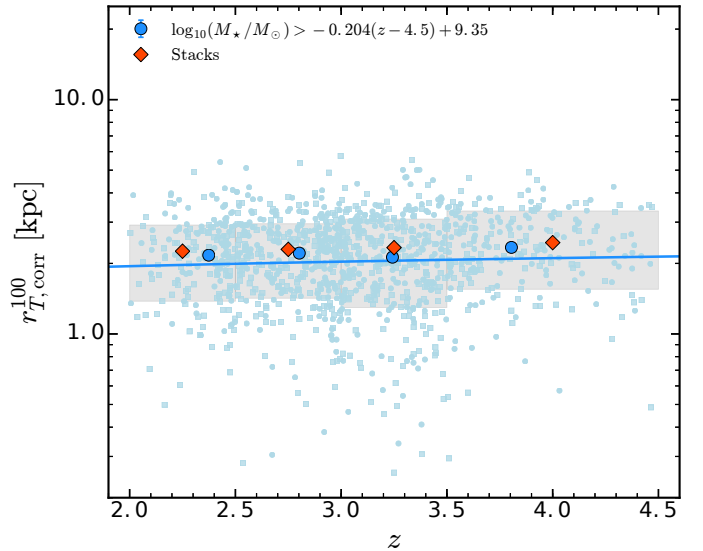


Fig. 15. Total size evolution with redshift. Each galaxy is plotted with a small blue point (squares for redshift confidence 2 and 9, circles for 3 and 4). The median values and respective error ($\sigma/\sqrt{N}$) per redshift bin are shown by the large blue points with the error bars. The shaded region delimits the 16th and 84th percentiles including 68% of the sample in each redshift bin. The red diamonds are from the stacked images computed from the method described in section 5.

derive the galaxy concentration, which makes it difficult to apply to irregular and asymmetric galaxies at high redshifts as it is the case of our sample. To overcome this limitation we derive the concentration parameter C_T , using r_T^{20} and r_T^{80} as defined in Section 4, generalizing the computation of C to the case of irregular and asymmetric galaxies

$$C_T = 5 \times \log_{10} \left(\frac{r_T^{80}}{r_T^{20}} \right). \quad (21)$$

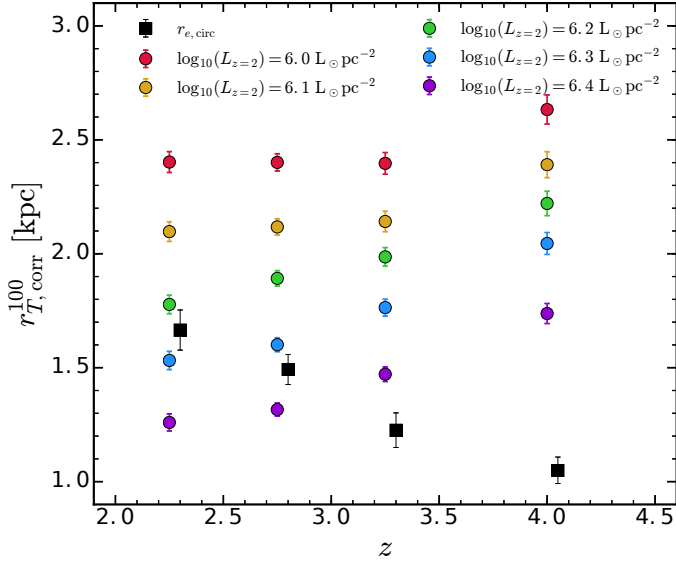


Fig. 16. Total size measurements defined at different values of k_p that correspond to different luminosity thresholds at $z = 2$. From top to bottom, the colored circles correspond to $k_p = 0.8, 1.0, 1.2, 1.5, 2.0$. The color coding is the same as figure 10.

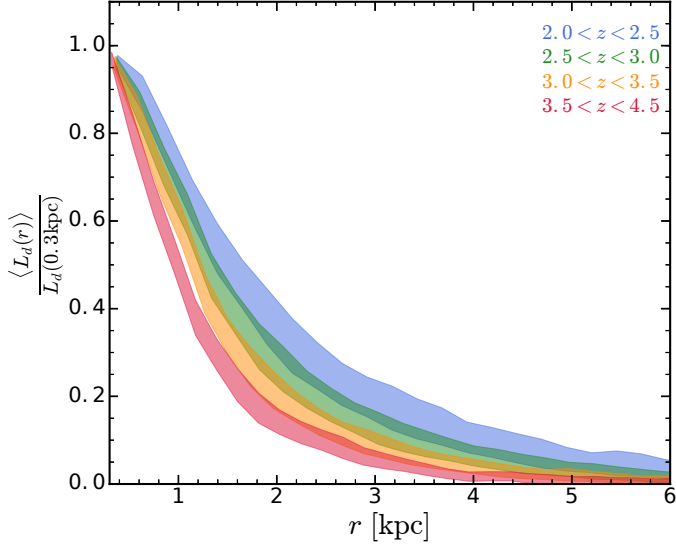


Fig. 17. Normalized surface luminosity profiles of the median stacked F814W band images of galaxies in our sample at four different redshift bins (normalized at $r=0.3$ kpc). The width of each profile encodes the surface luminosity error. This profile comparison shows the increased light concentration at higher redshifts.

We plot the evolution of C_T in figure 18. In that figure we show the fit of the equation

$$C_T = \alpha_C z + \beta_C \quad (22)$$

and find a value of $\alpha_C = 0.23 \pm 0.02$ and $\beta_C = 1.64 \pm 0.06$. Thus, C_T strongly evolves with redshift, light being more concentrated going to higher redshifts. The concentration C_T increases by $\sim 25\%$ from $z \sim 2$ to $z \sim 4.5$.

Using the standard definition of concentration with symmetric apertures (see appendix B for details on the computation) leads to a different trend ($\alpha_C = 0.01 \pm 0.04$ and $\beta = 2.82 \pm 0.13$) with light concentration being rather constant within our redshift interval. This difference is easily explained because of the

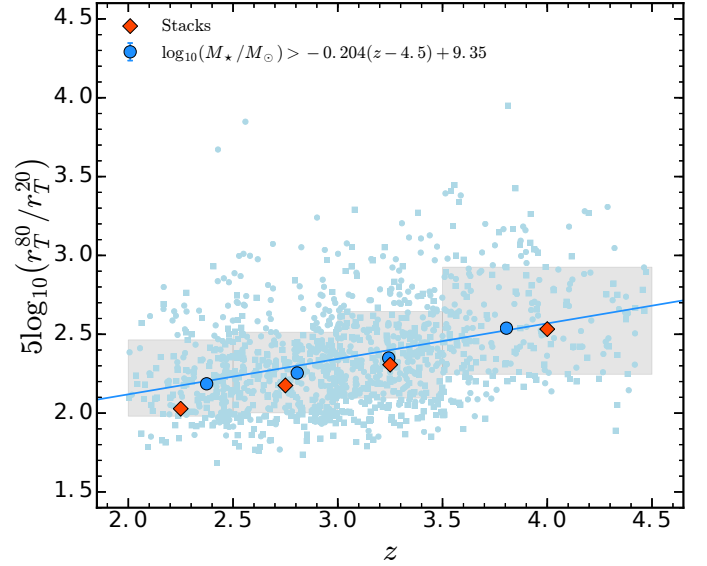


Fig. 18. Evolution of light concentration in galaxies computed from the ratio of the non-parametric radii enclosing 80% and 20% of the total flux, as defined in Section 4. The solid line is a linear fit to all the small blue points. Each galaxy is plotted with a small blue point (squares for redshift confidence 2 and 9, circles for 3 and 4). The median values and respective error ($\sigma/\sqrt{N}$) per redshift bin are shown as large blue points with error bars. The shaded region delimits the 16th and 84th percentiles including 68% of the sample in each redshift bin. The orange diamonds are the values obtained from the stacked images computed from the method described in section 5.

impact of defining a galaxy center for irregular morphology. For instance, on a galaxy composed by several same-brightness level clumps, the center of light would be defined somewhere in between the clumps leading to a lower concentration as the radius containing 20% of the total light would be larger to include the clumps.

The concentration values derived for the median stack images report the same trend as those derived from the full sample (figure 18). While the concentration value for the stacked images is sensitive to the threshold definition (average color and k_p from equation 17) the evolution trend remains unaffected and the slope is rather stable.

6. Size evolution with redshift

On sections 3.5 and 4.7 we have mentioned that we could not obtain galaxy sizes for the entirety of our sample for each of the measurements presented and for different reasons in each case. We have tested a scenario where we remove from the sample all galaxies without both size measurements which comprise 238 (19%) of the stellar mass selected sample. We find that the results do not change due to the removal of those objects and thus we kept them in the final sample for the individual analysis of r_T and r_e to reduce the statistical errors in our measurements.

To quantify the redshift evolution of sizes we fit the data points with a commonly used parameterization (e.g. Shibuya et al. 2015; Straatman et al. 2015; van der Wel et al. 2014; Morishita et al. 2014):

$$\log_{10}(r) = \beta_r + \alpha_r \log_{10}(1+z) \quad (23)$$

We fit this relation to all galaxies with a size measurement weighted equally due to the lack of individual errors on r_T^x . The

	$2.0 < z < 2.5$	$2.5 < z < 3.0$	$3.0 < z < 3.5$	$3.5 < z < 4.5$
r_e	1.67 ± 0.09	1.49 ± 0.07	1.23 ± 0.08	1.05 ± 0.06
r_T^{50}	1.28 ± 0.03	1.26 ± 0.02	1.16 ± 0.03	1.27 ± 0.03
$r_{T,\text{corr}}^{100}$	2.17 ± 0.06	2.21 ± 0.04	2.13 ± 0.05	2.34 ± 0.06

Table 2. Median size values (for F814W, in kiloparsecs) per redshift bin considered here. The value of r_e is the circularized effective radius from GALFIT, r_T^{50} corresponds to the PSF corrected values and $r_{T,\text{corr}}^{100}$ to the PSF+sky corrected values.

Size estimate	F814W		F160W	
	α_r	β_r	α_r	β_r
r_e	-1.29 ± 0.18	0.89 ± 0.11	-1.40 ± 0.34	1.01 ± 0.20
r_T^{10}	-0.36 ± 0.10	-0.16 ± 0.06	-0.22 ± 0.19	-0.16 ± 0.12
r_T^{20}	-0.31 ± 0.10	-0.03 ± 0.06	-0.18 ± 0.22	-0.04 ± 0.13
r_T^{30}	-0.26 ± 0.10	0.06 ± 0.06	-0.09 ± 0.24	-0.01 ± 0.15
r_T^{40}	-0.19 ± 0.10	0.11 ± 0.06	0.03 ± 0.26	-0.01 ± 0.16
r_T^{50}	-0.12 ± 0.10	0.14 ± 0.06	0.13 ± 0.20	0.01 ± 0.12
r_T^{60}	-0.02 ± 0.10	0.15 ± 0.06	0.24 ± 0.22	-0.02 ± 0.14
r_T^{70}	0.08 ± 0.10	0.15 ± 0.06	0.41 ± 0.25	-0.08 ± 0.16
r_T^{80}	0.21 ± 0.10	0.13 ± 0.06	0.56 ± 0.27	-0.14 ± 0.17
r_T^{90}	0.32 ± 0.10	0.12 ± 0.06	0.67 ± 0.28	-0.19 ± 0.17
r_T^{100}	0.48 ± 0.11	0.06 ± 0.07	0.34 ± 0.28	0.07 ± 0.17
$r_{T,\text{corr}}^{100}$	0.15 ± 0.12	0.22 ± 0.07	0.02 ± 0.24	0.24 ± 0.14

Table 3. Best fit slope and normalization factor for equation $\log(r) = \alpha_r \log(1+z) + \beta_r$ for the different size estimates used throughout the paper. Values for both F814W and F160W, valid for $2 < z < 4.5$, are given here. The size measurements used to derive the slope for each r_T^x correspond to PSF corrected sizes.

sample variance of the parameters β_r and α_r is obtained from bootstrapping the data 5000 times using 80% of the full sample each time. The resulting fit through the data are plotted in figures 7 and 15. We also compute the same evolutionary trend for different values of x of equation 6 ranging from 10% up to 100% with a 10% step value. All the fit results are given in Tables 2 and 3 and summarized in Figure 19.

The Figure 19 encodes the information on the slope of the size evolution as a function of the flux level and compares to the effective radius evolution derived from GALFIT. There are three main points to be taken from this figure. First, there is a clear trend of the slope as a function of the flux cut level: the brightest regions (10% brightest pixels) evolve faster than the total size with a smooth trend towards slower evolution when going from the brightest regions to the total area of the objects. This differential trend is again a hint on the evolution of light concentration as a function of redshift where the brightest regions of the galaxy tend to become larger with time while the total size remains constant effectively suggesting that light becomes less concentrated with time. Second, the evolution in sizes is far from that reported from the effective radii $r_{e,\text{circ}}$. For the size measurements including the brightest pixels that amount to 50% of the total flux (comparable to r_e) the derived evolution slopes are separated by more than 3σ (Figure 19) indicating that the choice of method to compute sizes can have a very significant impact on the observed evolution. We note that the points in figure 19 indicate the lower limits on the slope. At the highest redshifts a galaxy size will be more often overestimated as lower flux thresholds increase noise contamination. We attempt to correct for that using the prescription described in Section 4.6, but it applies only to r_T^{100} . However, this effect can not explain the observed difference between r_e and r_T as the size evolution slope after the said correction still differs by more than 3σ from that derived from $r_{e,\text{circ}}$ and it is where the impact of the noise affects the slope the most.

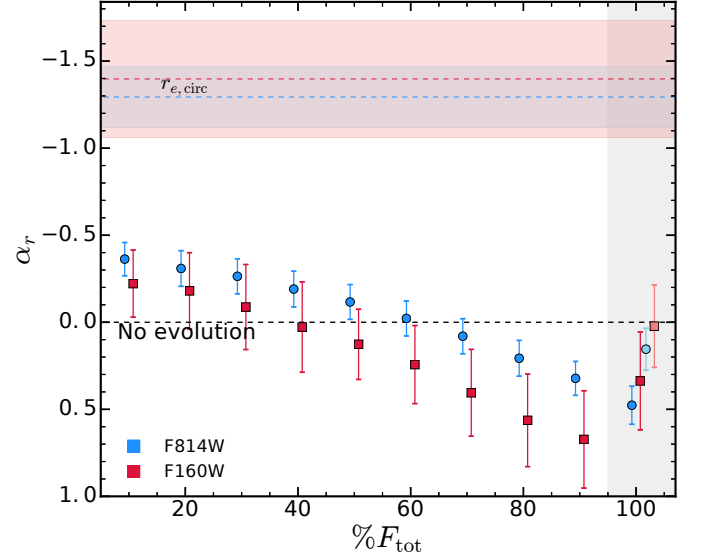


Fig. 19. Slope of the evolution of PSF corrected galaxy sizes as a function of the flux level considered. The light colored symbols corresponds to the slope computed from sky-corrected r_T^{100} sizes. The dashed lines and shaded regions are the value and error derived in α for the GALFIT size measurements. Blue and red colored symbols/regions correspond to F814W and F160W measurements respectively.

6.1. Effective radius r_e evolution

The galaxy size evolution derived from the circularized effective half-light radius shows strong size evolution across the redshift range probed. Assuming that galaxy sizes evolve according to the parametrization of equation 23 we derive a slope of $\alpha_r = -1.29 \pm 0.18$.

Values reported in the literature range from $\alpha_r = -0.56 \pm 0.09$ for a sample of star-forming spectroscopically confirmed galax-

ies at $0.5 < z < 3.0$ with $\log_{10}(M_{\star}/M_{\odot}) > 10$ (Morishita et al. 2014) up to $\alpha_r = -1.32 \pm 0.52$ for a sample of LBGs with $(0.12-0.3)L_{\star}$ at $z \sim 4-6$ (Oesch et al. 2010). The differences between these results (see also Ferguson et al. 2004; Bouwens et al. 2004; Trujillo et al. 2006; Franx et al. 2008; Williams et al. 2010; Mosleh et al. 2011, 2012; Ono et al. 2013; van der Wel et al. 2014; Morishita et al. 2014; Curtis-Lake et al. 2016; Shibuya et al. 2015; Straatman et al. 2015) can be traced to different likely sources: 1) the samples are selected in different ways; 2) there are two different methods for measuring sizes, both relying on a certain degree of symmetry; and perhaps most importantly 3) samples with different stellar masses yield different sizes (Franx et al. 2008; van der Wel et al. 2014).

6.2. Total size r_{tot} evolution

The typical total size of a SFG, corrected for sky noise contamination as computed in Section 4, is $r_T^{100} \simeq 2.2\text{kpc}$ and shows negligible evolution of galaxy sizes across the redshifts probed here (see the light color points of figure 19). This is markedly different from what is observed using the standard effective radii measurement. The r_T^{100} measurements are consistent with the results of Law et al. (2007) who report only a small increase in the the total area from $z \sim 2$ to $z \sim 3$ ($T = 15.0 \pm 0.7$ and 17.4 ± 0.9 kpc^2 , respectively). This corresponds to an equivalent radius of $r_T = 2.19 \pm 0.47\text{kpc}$ at $z \sim 2$ and $r_T = 2.35 \pm 0.54\text{kpc}$ at $z \sim 3$.

7. Size relations with physical parameters

To further explore the properties of galaxies with different sizes we compare galaxy sizes to several key physical parameters characterizing galaxies including stellar mass, SFR, age, metallicity and dust extinction. We also investigate any possible relation between sizes and inter-galactic medium (IGM) transmission towards the galaxies. These parameters are derived from the simultaneous SED fitting of the VUDS spectra and all multi-wavelength photometry available for each galaxy, using the code GOSSIP+ as described by Thomas et al. (2016). This method expands the now classical SED fitting technique to the use of UV rest-frame spectra in addition to photometry, further improving the accuracy of key physical parameter measurements (see Thomas et al. 2016, for details).

The distributions of $r_{e,\text{circ}}$ and $r_{T,\text{corr}}^{100}$ sizes versus $M_{\star}$, SFR, age, A_V , and IGM transmission are presented in Figure 20. Several interesting trends can be observed. To quantify the degree of correlation of each parameter with size, we use the Pearson (1896) correlation coefficient. In our sample, the null hypothesis (i.e. no correlation) is excluded at the 3σ level if $|r(\text{Pearson})| > 0.12$.

Our data show a correlation between galaxy size and $M_{\star}$ with larger galaxies having on average higher stellar masses. This supports the correlation reported from other samples (e.g. Franx et al. 2008; Ichikawa et al. 2012; van der Wel et al. 2014; Morishita et al. 2014) at redshifts $z > 2$ and extending it up to $z \simeq 4.5$. This correlation is of similar strength for $r_{T,\text{corr}}^{100}$ as is for r_e . We obtain $r(\text{Pearson}) = 0.08$ for $r_{T,\text{corr}}^{100}$ against $r(\text{Pearson}) = 0.13$ for r_e . Interestingly, the most massive galaxies in our sample show a break at stellar masses higher than $\log_{10}(M_{\star}/M_{\odot}) > 10.5$ in this correlation. While, when considering $r_{e,\text{circ}}$, sizes are getting smaller, sizes computed from $r_{T,\text{corr}}^{100}$ increase as we move towards higher stellar masses. This supports in part our analysis that low surface brightness regions in massive galaxies with complex morphology are not taken into

account by parametric fitting like done in GALFIT resulting in artificially smaller effective radius (by a factor of ~ 2).

We find that the SFR is strongly related to galaxy sizes. For sizes measured with $r_{T,\text{corr}}^{100}$ we find that larger galaxies have higher star-formation rates, with a positive correlation ($r(\text{Pearson}) = 0.29$). The correlation is not significant with $r_{e,\text{circ}}$ ($r(\text{Pearson}) = 0.03$ for $r_{e,\text{circ}}$). Considering the $M_{\star}$ -SFR main-sequence of star-forming galaxies in VUDS (Tasca et al. 2015), this correlation may be partly reflecting the underlying stellar mass-size relation described above.

Galaxies appear to be older when they are smaller when looking at the relation between age (as defined by the start of star formation, see Thomas et al. 2016) and $r_{T,\text{corr}}^{100}$ ($r(\text{Pearson}) = -0.21$). From the hierarchical assembly scenario one would expect that larger galaxies have older stellar populations. On the other hand the less significant relation between $r_{e,\text{circ}}$ and age ($r(\text{Pearson}) = -0.10$) may also mean that the derived age is dominated by the age of the last major burst of star formation washing out underlying older stellar populations that may exist in the central brightest clumps from previous starburst episodes.

Galaxies with lower extinction values have smaller median sizes than galaxies with higher dust extinction. This trend is more significant for $r_{T,\text{corr}}^{100}$ ($r(\text{Pearson}) = 0.13$) than it is for $r_{e,\text{circ}}$ ($r(\text{Pearson}) = 0.03$). This hints that extended regions of galaxies have a higher dust content than smaller ones.

The projected stellar density computed as the ratio of the stellar mass to the projected area of a galaxy is shown in Figure 21. We observe a strong correlation for both $r_{T,\text{corr}}^{100}$ ($r(\text{Pearson}) = 0.59$) and $r_{e,\text{circ}}$ ($r(\text{Pearson}) = 0.36$). Galaxies with higher stellar masses having higher stellar mass densities.

We do not observe any significant correlation between galaxy sizes and metallicity or IGM transmission for any of our measurements.

The analysis of spectral properties like the strength of the Lyman- α line as a function of size will be the subject of a forthcoming paper (Ribeiro et al., in preparation).

8. Discussion

We summarize our measurements of the size evolution of star-forming galaxies with $2 < z < 4.5$ in the VUDS survey, and compare them with the literature in Figure 22.

In the context of the hierarchical assembly of dark matter halos one can consider that the size of a disk galaxy scales with the virial radius of its host halo. In this scenario, the redshift evolution of galaxy sizes has a slope $\alpha_r = -1$ for halos with fixed mass and a slope of $\alpha_r = -1.5$ for halos with fixed circular velocity (see Ferguson et al. 2004; Stringer et al. 2014, and references therein). We find that when considering the effective radius we obtain a slope $\alpha_r = -1.29 \pm 0.18$ which lies between the values expected for those two scenarios. However, our computation of the evolution of the total size of each galaxy (measured at the same surface brightness level), leads to a slope $\alpha_r = 0.13 \pm 0.12$ inconsistent with either of these two hypotheses. This likely happens because we are looking at a majority of galaxies that do not resemble disks (i.e. they are highly irregular) and, without any constraint on the profile shapes, the size measurements cannot be compared to any of those scenarios. This suggests that to correlate the size growth of galaxies with that of its host dark matter halo, more complex analytical models or more realistic numerical simulations are required to estimate galaxy and halo sizes.

We find that the effective radius $r_{e,\text{circ}}$ decreases with increasing redshift, indicating effective radii $r_{e,\text{circ}} \sim 2\text{kpc}$ at $z \sim 2$, and

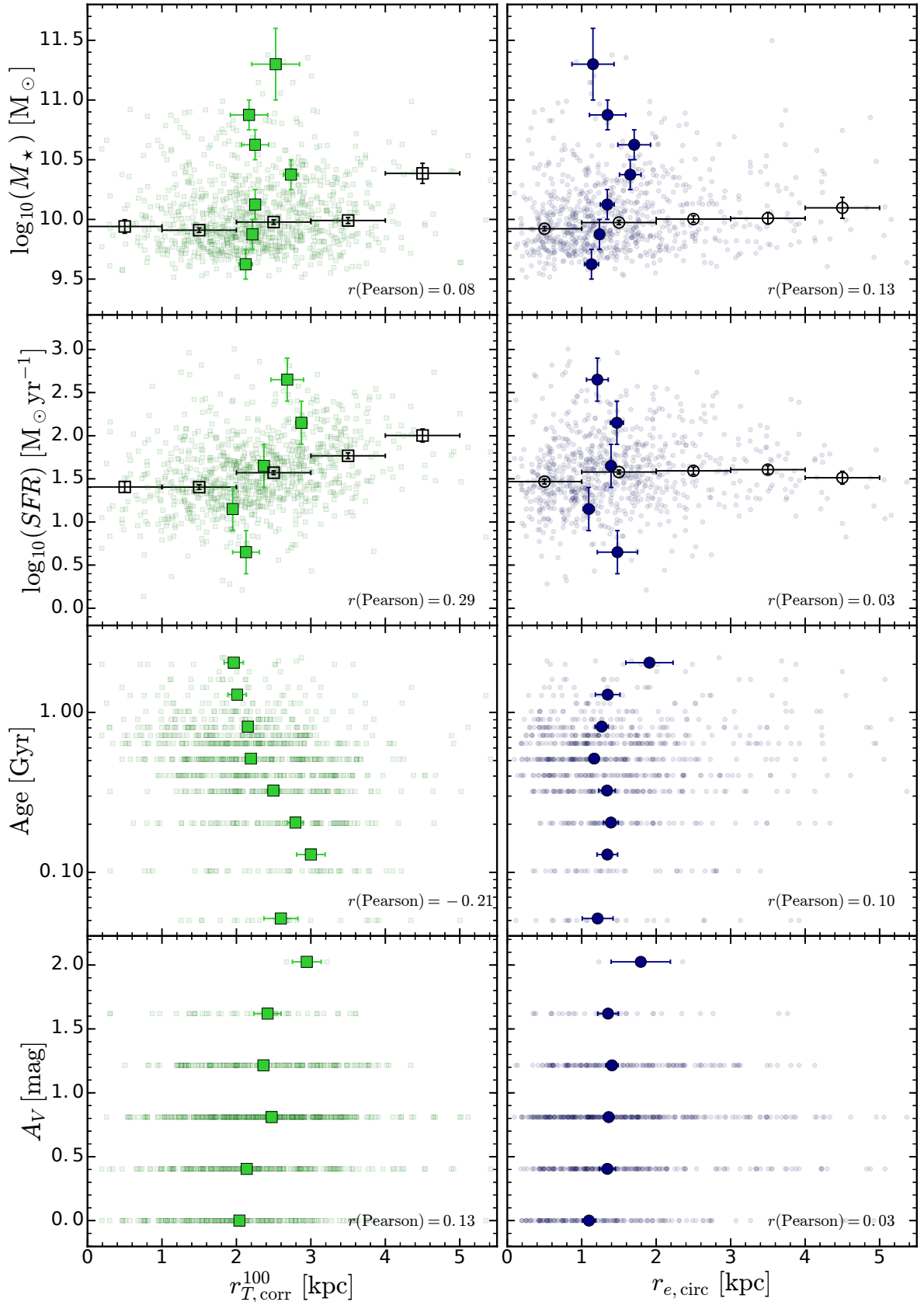


Fig. 20. Correlation of the measured galaxy sizes with parameters derived from GOSSIP+ SED fitting for our stellar mass selected sample (using the stellar masses derived with GOSSIP+ and equation 1). Only galaxies with good and excellent spectrophotometric fits are included. From top to bottom we have the stellar mass, SFR, age and dust extinction. On the right panels we show the results for GALFIT derived $r_{e,circ}$ and in the left panels we show the results for our value of $r_{T,corr}^{100}$. The solid colored symbols represent the median values in bins of the physical parameter in question. The error bar in the y-direction shows the bin size and in the x-direction shows the error on the median ($\sigma/\sqrt{N}$). The open black symbols represent the median values in bins of radii. In this case, error bars have the same meaning as before, in the inverted directions. Small points represent individual measurements.

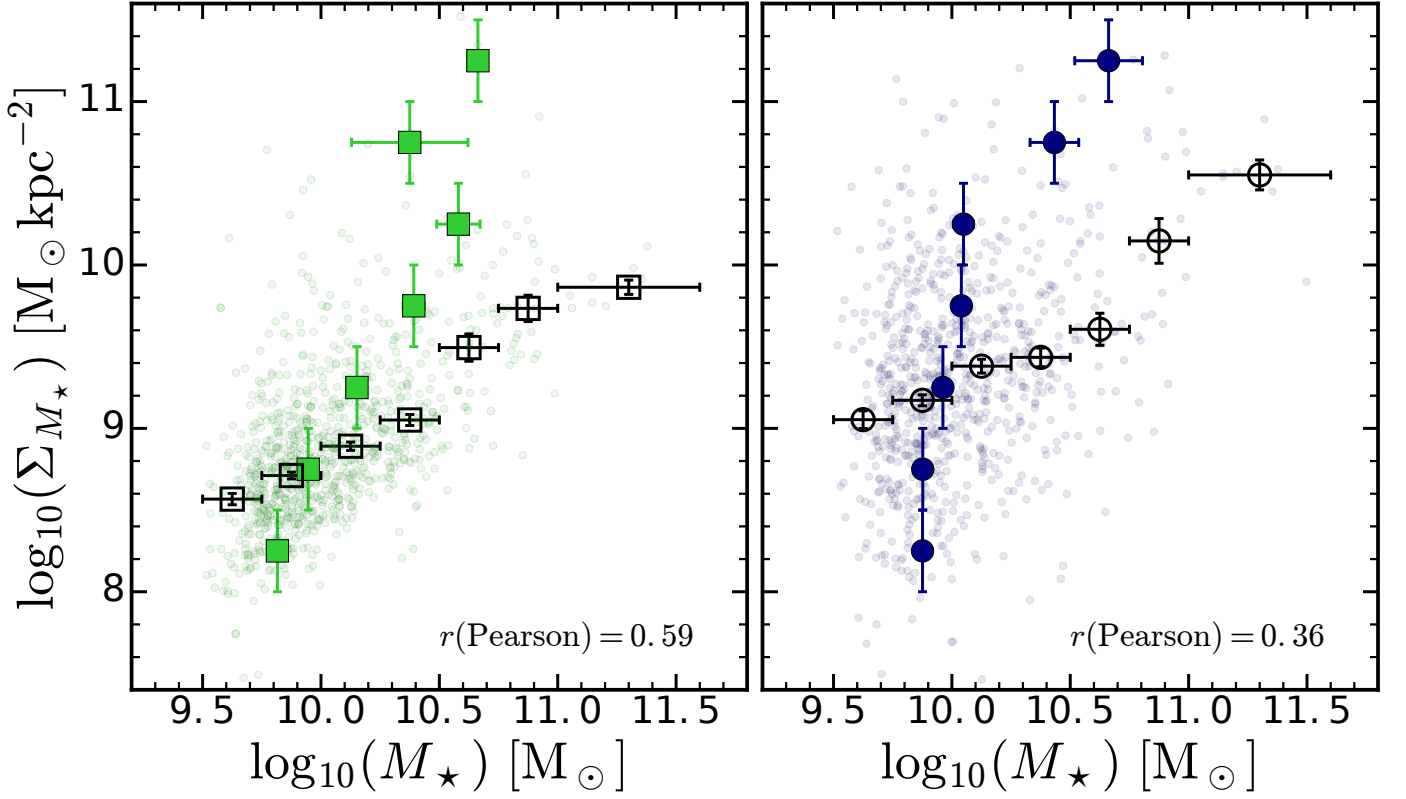


Fig. 21. Stellar mass surface density as a function of stellar mass. On the right panels we show the results for GALFIT derived $r_{e,circ}$ and in the left panels we show the results for our value of $r_{T,corr}^{100}$. The color and symbols have the same meaning as in figure 20.

a value twice smaller at $z \sim 4$ at $r_{e,circ} \approx 1$ kpc. The effective radius measured on our galaxies is comparable to other $r_{e,circ}$ measurements in the literature for galaxies at close or similar redshifts, particularly when comparing to samples with similar stellar masses (Figure 22). In such samples, as in our own, this leads to the conclusion that galaxies are getting smaller at higher redshifts (e.g. Mosleh et al. 2011, 2012; van der Wel et al. 2014; Morishita et al. 2014; Shibuya et al. 2015). However, we argue that the use of this metric making an a priori assumption of symmetry is not appropriate to constrain the redshift evolution of galaxy sizes when asymmetric and multi-component shapes are common occurrences.

However when measuring a size based on the total area covered by a galaxy we find that the evolution of size with redshift is strikingly different. This size measured at an isophote with an absolute luminosity $\log_{10}(L_{z=2}) = 6.1 L_{\odot} \text{pc}^2$, after correction for the effects of surface brightness dimming and luminosity evolution, remains approximately constant with redshift with $r_{T,corr}^{100} \sim 2.2$ kpc (Figure 22). In addition, galaxies selected using an evolving stellar mass cut-off $\log(M_{\star}) > -0.204(z-4.5)+9.35$, have a higher concentration index C_T indicating a more peaked light distribution when going to the highest redshifts, with a significant change of C_T by $\sim 20\%$ over only ~ 2 Gyr of evolution.

While it is expected that the effective radius should be smaller than a radius defined from the total size of a galaxy at a much fainter isophote level, the strong observed differential evolution between the two is likely to be resulting from important physical processes working at a cosmic time when galaxies are still early in their assembly process. The fact that the size $r_{T,corr}^{100}$ remains large at all redshifts indicates that galaxies in their early assembly phase are quite extended with a constant characteristic

size, and that the initial collapse that led to star formation seems to have been spread-out in quite a large volume of $\sim 10 \text{kpc}^3$.

The large dispersion observed around the mean size value may indicate quite a diversity of initial assembly conditions. Indeed we find a large spread of sizes in our sample with galaxies as small as $r_{T,corr}^{100} = 0.3 \text{kpc}$, and galaxies as large as $r_{T,corr}^{100} = 5.5 \text{kpc}$. The smallest galaxies could be the signature of the first collapse of a small to medium mass cloud or a more evolved dynamical state later in the life of a galaxy as indicated by larger ages for smaller galaxies, while the most extended ones could indicate on-going early merging of a few small size objects following the hierarchical assembly picture or the result of the multi-component collapse of a massive gas cloud. As the timescale of these processes is currently unknown, we may be witnessing the combined effects of different key physical processes each with different evolution stages.

The evolution in light concentration with redshift that we observe may be understood in a scenario of compact bright clumps merging together to create a more smooth light distribution by $z = 2$ (e.g. Guo et al. 2015). This could be extended to merger events of compact galaxies redistributing angular momentum and leading to a less concentrated luminosity profile. Inside-out growth with stellar mass building-up in the outskirts of galaxies (Wuyts et al. 2011; Nelson et al. 2013, 2015; Tacchella et al. 2016) is also compatible with the evolution of the light concentration and the absence of evolution of total sizes.

9. Summary

In this paper we study the evolution of the sizes of star-forming galaxies obtained from a detailed analysis of ~ 1200 galaxies with $2 < z < 4.5$ and stellar masses $9.5 < \log(M_{\star}) < 11.5$ in

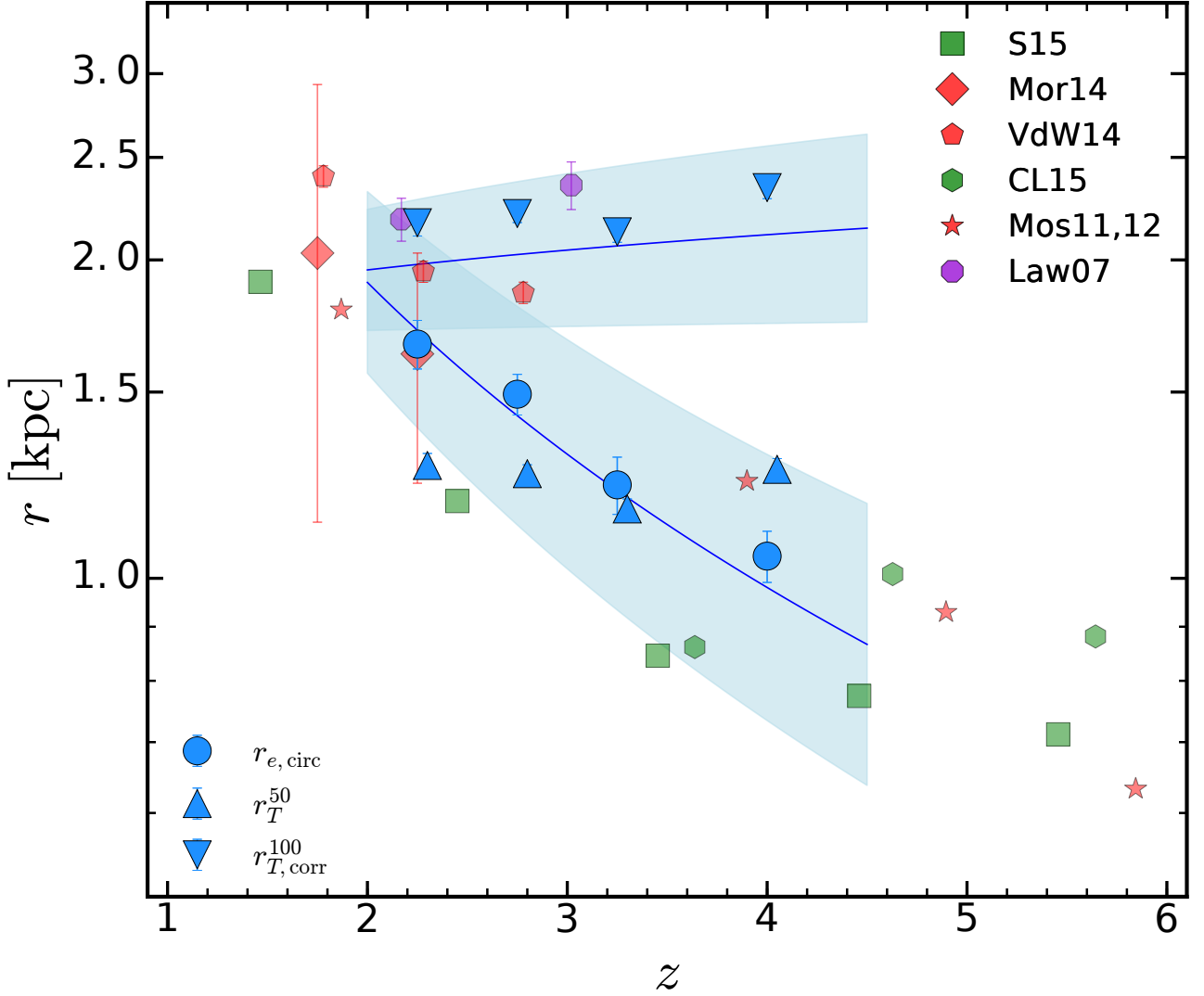


Fig. 22. A compilation of size measurements at different redshifts for a number of different studies. First, in blue we have the measurements of this paper. Circles are taken from the GALFIT effective radius, and the triangles and inverted triangles are from r_T^{50} and $r_{T,\text{corr}}^{100}$ respectively. The blue solid lines and respective shaded regions show the derived evolution for $r_{e,\text{circ}}$ and $r_{T,\text{corr}}^{100}$. Each other color represents a different sample selection (green for luminosity selected samples, red for stellar mass selected samples and purple for a different selection) and each symbol represents a different study. They are: squares (Shibuya et al. 2015), $0.3L_* < L < 1L_*$; diamonds (Morishita et al. 2014), $10.0 < \log_{10}(M_*/M_\odot) < 10.5$; pentagons (van der Wel et al. 2014), $10.0 < \log_{10}(M_*/M_\odot) < 10.5$; hexagons (Curtis-Lake et al. 2016), $0.3L_* < L < 1L_*$; stars (Mosleh et al. 2011, 2012), $9.5 < \log_{10}(M_*/M_\odot) < 10.4$; octagons (Law et al. 2007), spectroscopic sample, no mass or luminosity selection.

the VIMOS Ultra Deep Survey. We use two different methods to compute sizes: a parametric profile fitting using the GALFIT tool to derive the effective radius $r_{e,\text{circ}}$, and we define and use a non-parametric size measurements based on the area defined as enclosing 100% of the measured flux of a galaxy above a given surface brightness threshold, r_T^{100} . While the former makes a strong hypothesis on the symmetry of a galaxy shape, the latter can be applied on galaxies with irregular and asymmetric morphology.

Our results on size measurements can be summarized as follows:

- The total size of a galaxy is observed to remain approximately constant with a radius $r_{T,\text{corr}}^{100} \approx 2.2$ kpc over the redshift range $2 < z < 4.5$, while the effective radius $r_{e,\text{circ}}$ de-

creases from ~ 2 kpc at $z \sim 2$ to ~ 1 kpc at $z \sim 4.5$. The evolution of galaxy sizes is therefore drastically different when using parametric methods with a symmetry prior or a non-parametric method with no *a priori* assumption of symmetry. This difference between the total radius and the effective radius is more important at the highest redshifts, with a factor ~ 2 difference at $z \sim 4$, likely due to the increasing fraction of irregularly shaped galaxies.

- There is a large scatter in galaxy sizes observed at all redshifts. We observe galaxies as large as ~ 11 kpc (total extent) out to $z = 4.5$.
- The projected luminosity density of galaxies is higher at the highest redshifts. Using stacking analysis as well as indi-

vidual measurements we find that the light concentration of galaxies is $\sim 20\%$ higher at $z \sim 4$ than at $z \sim 2$.

- On average, larger SFGs have higher stellar masses, SFRs and stellar mass densities.
- These correlations between size and physical properties depend on the size measurement method. We find a stronger correlation between sizes and star-formation rates for $r_{T, \text{corr}}^{100}$ than for $r_{e, \text{circ}}$ whilst it is of similar strength when considering the stellar mass-size relations.

The results presented in this paper on a sample of star-forming galaxies observed 10.5 to 12.5 Gyr ago and 0.5 Gyr after the end of re-ionization at $z \sim 6$ emphasize the diversity of galaxy size properties at a time of intense galaxy assembly. The observation of galaxies with total sizes ranging from less than 1 kpc to ~ 10 kpc seems to require several different processes driving mass assembly, and may represent different snapshots in the early life history of the dominant population of galaxies at these redshifts.

More detailed investigations connecting size and morphology analyses to different spectral properties from the UV (e.g. Ly- α emission, β -slope) to the optical domain are needed to further understand the diversity of sizes in the early phases of galaxy assembly (Ribeiro et al., in preparation).

Future observations with next generation facilities like the *James Webb Space Telescope* and extremely large telescopes will be necessary to further investigate the nature of large and irregular galaxies at these high redshifts and well into the re-ionization epoch.

Acknowledgements. This work is supported by funding from the European Research Council Advanced Grant ERC-2010-AdG-268107-EARLY and by INAF Grants PRIN 2010, PRIN 2012 and PICS 2013. This work is based on data products made available at the CESAM data center, Laboratoire d'Astrophysique de Marseille. This work partly uses observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This work is based in part on data products produced at TERAPIX and the Canadian Astronomy Data Centre as part of the Canada-France-Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS.

References

Akiyama, M., Minowa, Y., Kobayashi, N., et al. 2008, *ApJS*, 175, 1
 Arnouts, S., Cristiani, S., Moscardini, L., et al. 1999, *MNRAS*, 310, 540
 Bershad, M. A., Jangren, A., & Conselice, C. J. 2000, *AJ*, 119, 2645
 Bertin, E. & Arnouts, S. 1996, *A&AS*, 117, 393
 Bouwens, R., Broadhurst, T., & Illingworth, G. 2003, *ApJ*, 593, 640
 Bouwens, R. J., Illingworth, G. D., Blakeslee, J. P., Broadhurst, T. J., & Franx, M. 2004, *ApJL*, 611, L1
 Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015, *ApJ*, 803, 34
 Bruce, V. A., Dunlop, J. S., Cirasuolo, M., et al. 2012, *MNRAS*, 427, 1666
 Bruzual, G. & Charlot, S. 2003, *MNRAS*, 344, 1000
 Buitrago, F., Trujillo, I., Conselice, C. J., & Häußler, B. 2013, *MNRAS*, 428, 1460
 Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682
 Capak, P., Aussel, H., Ajiki, M., et al. 2007, *ApJS*, 172, 99
 Cassata, P., Giavalisco, M., Guo, Y., et al. 2010, *ApJ*, 714, L79
 Cassata, P., Giavalisco, M., Williams, C. C., et al. 2013, *ApJ*, 775, 106
 Chabrier, G. 2003, *ApJ*, 586, L133
 Ciotti, L. & Bertin, G. 1999, *A&A*, 352, 447
 Conselice, C. J. & Arnold, J. 2009, *MNRAS*, 397, 208
 Curtis-Lake, E., McLure, R. J., Dunlop, J. S., et al. 2016, *MNRAS*, 457, 440
 Daddi, E., Renzini, A., Pirzkal, N., et al. 2005, *ApJ*, 626, 680
 Delgado-Serrano, R., Hammer, F., Yang, Y. B., et al. 2010, *A&A*, 509, A78
 Elmegreen, B. G., Elmegreen, D. M., Fernandez, M. X., & Lemonias, J. J. 2009, *ApJ*, 692, 12

Elmegreen, D. M., Elmegreen, B. G., Ravindranath, S., & Coe, D. A. 2007, *ApJ*, 658, 763
 Ferguson, H. C., Dickinson, M., Giavalisco, M., et al. 2004, *ApJL*, 600, L107
 Franx, M., van Dokkum, P. G., Schreiber, N. M. F., et al. 2008, *ApJ*, 688, 770
 Garilli, B., Fumana, M., Franzetti, P., et al. 2010, *PASP*, 122, 827
 Giavalisco, M., Ferguson, H. C., Koekemoer, A. M., et al. 2004, *ApJ*, 600, L93
 Giavalisco, M., Livio, M., Bohlin, R. C., Macchetto, F. D., & Stecher, T. P. 1996, *AJ*, 112, 369
 Grazian, A., Castellano, M., Fontana, A., et al. 2012, *A&A*, 547, A51
 Grogin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, *ApJS*, 197, 35
 Guo, Y., Ferguson, H. C., Bell, E. F., et al. 2015, *ApJ*, 800, 39
 Hathi, N. P., Malhotra, S., & Rhoads, J. E. 2008, *ApJ*, 673, 686
 Holwerda, B. W., Bouwens, R., Oesch, P., et al. 2015, *ApJ*, 808, 6
 Huang, K.-H., Ferguson, H. C., Ravindranath, S., & Su, J. 2013, *ApJ*, 765, 68
 Huertas-Company, M., Pérez-González, P. G., Mei, S., et al. 2015, *ApJ*, 809, 95
 Ichikawa, T., Kajisawa, M., & Akhlaghi, M. 2012, *MNRAS*, 422, 1014
 Ilbert, O., Arnouts, S., McCracken, H. J., et al. 2006, *A&A*, 457, 841
 Ilbert, O., McCracken, H. J., Le Fèvre, O., et al. 2013, *A&A*, 556, A55
 Ilbert, O., Salvato, M., Le Floc'h, E., et al. 2010, *ApJ*, 709, 644
 Jiang, L., Egami, E., Fan, X., et al. 2013, *ApJ*, 773, 153
 Kawamata, R., Ishigaki, M., Shimasaku, K., Oguri, M., & Ouchi, M. 2015, *ApJ*, 804, 103
 Koekemoer, A. M., Aussel, H., Calzetti, D., et al. 2007, *ApJS*, 172, 196
 Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011, *ApJS*, 197, 36
 Law, D. R., Steidel, C. C., Erb, D. K., et al. 2007, *ApJ*, 656, 1
 Le Fèvre, O., Tasca, L. A. M., Cassata, P., et al. 2015, *A&A*, 576, A79
 Lubin, L. M. & Sandage, A. 2001, *AJ*, 122, 1084
 McCracken, H. J., Milvang-Jensen, B., Dunlop, J., et al. 2012, *A&A*, 544, A156
 Morishita, T., Ichikawa, T., & Kajisawa, M. 2014, *ApJ*, 785, 18
 Mortlock, A., Conselice, C. J., Hartley, W. G., et al. 2013, *MNRAS*, 433, 1185
 Mosleh, M., Williams, R. J., Franx, M., et al. 2012, *ApJL*, 756, L12
 Mosleh, M., Williams, R. J., Franx, M., & Kriek, M. 2011, *ApJ*, 727, 5
 Nelson, E. J., van Dokkum, P. G., Förster Schreiber, N. M., et al. 2015, *ArXiv e-prints [arXiv:1507.03999]*
 Nelson, E. J., van Dokkum, P. G., Momcheva, I., et al. 2013, *ApJ*, 763, L16
 Oesch, P. A., Bouwens, R. J., Carollo, C. M., et al. 2010, *ApJL*, 709, L21
 Ono, Y., Ouchi, M., Curtis-Lake, E., et al. 2013, *ApJ*, 777, 155
 Pearson, K. 1896, *Philosophical Transactions of the Royal Society of London Series A*, 187, 253
 Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2002, *AJ*, 124, 266
 Peng, C. Y., Ho, L. C., Impey, C. D., & Rix, H.-W. 2010, *AJ*, 139, 2097
 Petrosian, V. 1976, *ApJL*, 209, L1
 Ravindranath, S., Ferguson, H. C., Conselice, C., et al. 2004, *ApJL*, 604, L9
 Ravindranath, S., Giavalisco, M., Ferguson, H. C., et al. 2006, *ApJ*, 652, 963
 Reddy, N. A. & Steidel, C. C. 2009, *ApJ*, 692, 778
 Rhodes, J. D., Massey, R. J., Albert, J., et al. 2007, *ApJS*, 172, 203
 Rix, H.-W., Barden, M., Beckwith, S. V. W., et al. 2004, *ApJS*, 152, 163
 Scodreggio, M., Franzetti, P., Garilli, B., et al. 2005, *PASP*, 117, 1284
 Scoville, N., Abraham, R. G., Aussel, P., et al. 2007, *ApJS*, 172, 38
 Sersic, J. L. 1968, *Atlas de galaxies australes*
 Shibuya, T., Ouchi, M., & Harikane, Y. 2015, *ApJS*, 219, 15
 Simard, L., Koo, D. C., Faber, S. M., et al. 1999, *ApJ*, 519, 563
 Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, *ApJ*, 519, 1
 Stott, J. P., Sobral, D., Smail, I., et al. 2013, *MNRAS*, 430, 1158
 Straatman, C. M. S., Labbé, I., Spitler, L. R., et al. 2015, *ApJ*, 808, L29
 Stringer, M. J., Shankar, F., Novak, G. S., et al. 2014, *MNRAS*, 441, 1570
 Tacchella, S., Dekel, A., Carollo, C. M., et al. 2016, *MNRAS*, 458, 242
 Talia, M., Cimatti, A., Mignoli, M., et al. 2014, *A&A*, 562, A113
 Tasca, L. A. M., Kneib, J.-P., Iovino, A., et al. 2009, *A&A*, 503, 379
 Tasca, L. A. M., Le Fèvre, O., Hathi, N. P., et al. 2015, *A&A*, 581, A54
 Thomas, R., Le Fèvre, O., Cassata, P., et al. 2014, *ArXiv e-prints [arXiv:1411.5692]*
 Thomas, R., Le Fèvre, O., Scodreggio, M., et al. 2016, *ArXiv e-prints [arXiv:1602.01841]*
 Tolman, R. C. 1930, *Proceedings of the National Academy of Science*, 16, 511
 Trujillo, I., Förster Schreiber, N. M., Rudnick, G., et al. 2006, *ApJ*, 650, 18
 van der Wel, A., Franx, M., van Dokkum, P. G., et al. 2014, *ApJ*, 788, 28
 Williams, R. J., Quadri, R. F., Franx, M., et al. 2010, *ApJ*, 713, 738
 Wuyts, S., Förster Schreiber, N. M., Genzel, R., et al. 2012, *ApJ*, 753, 114
 Wuyts, S., Förster Schreiber, N. M., van der Wel, A., et al. 2011, *ApJ*, 742, 96

Appendix A: T_{100} in simulated galaxies

We have used the same set of simulated galaxy images described in section 3.3 to compute the value of T_{100} and assess the impact of the noise on the retrieved values. To compute the value of the expected total area, we have used the noise free simulated models, convolved with a PSF, and applied the same thresholding method as explained in section 4. To ensure that we would probe different thresholds, for each galaxy, a random redshift was attributed taken from a uniform distribution between the limits we have defined for this paper. This, in practice, translates to mapping the thresholds used in the computation of sizes in real data.

In figure A.1 we can see the output results from the simulation. As it should be straightforward to understand, brighter galaxies have larger sizes simply because more pixels are found above the threshold that we defined. The scatter that we find increasing for smaller galaxies (fainter magnitudes) is explained by the increasing contamination of the sky connected pixels that are detected close to the galaxy and gain importance as we lower the flux of simulated galaxies which produces an overestimation of the galaxy size. Additionally, since we are dropping galaxy models on top of a real background, with potentially other sources in image area, some large scatter is expected at all magnitudes where sizes are consistently overestimated. It is somehow unexpected the underestimation of galaxy sizes at the largest simulated sources. However, since $\sim 90\%$ of the galaxies in our sample have $100 < T_{100} < 2000$ pixels we find it a negligible correction with no impact in our findings.

We have also applied the same correction method for the contamination of sky connected pixels and the results are found in the right panel of figure A.1. We can see that it increases somehow the scatter at the lower input sizes and overall approximates the retrieved value from the input one. Being far from perfect, we believe that our sky corrections estimates are good enough for an approximation on the derived galaxy sizes of our sample.

Appendix B: The Concentration parameter

This concentration index is defined as the ratio of the 80% to the 20% curve of growth radii within 1.5 times the Petrosian (1976) radius for a parameter $\eta = 0.2$:

$$\eta = \frac{\mu(r_p)}{\bar{\mu}(r < r_p)} \quad (\text{B.1})$$

where r_p is the computed petrosian radius for a given value of η . With that radius we can compute the flux within circular apertures (or elliptical ones) up to which 20% and 80% of the light is contained. But first, it is necessary to define a light center and the axis ratio and position angle so that we can define the elliptical apertures.

To measure this quantities we shall first define the barycenter of the galaxy. The intensity centroid is computed as the mean pixel position, averaged by the flux, within the segmentation map:

$$x_{cen} = \frac{1}{I_{tot}} \sum_{i,j} i \times I_{i,j} \quad (\text{B.2})$$

$$y_{cen} = \frac{1}{I_{tot}} \sum_{i,j} j \times I_{i,j} \quad (\text{B.3})$$

Once one has $\bar{x}$ and $\bar{y}$ it is possible to compute the second order moments of the profile as:

$$\overline{x^2} = \frac{1}{I_{tot}} \sum_{i,j} i^2 \times I_{i,j} - \bar{x}^2 \quad (\text{B.4})$$

$$\overline{y^2} = \frac{1}{I_{tot}} \sum_{i,j} j^2 \times I_{i,j} - \bar{y}^2 \quad (\text{B.5})$$

$$\overline{xy} = \frac{1}{I_{tot}} \sum_{i,j} i \times j \times I_{i,j} - \bar{x}\bar{y} \quad (\text{B.6})$$

From there, it is possible to show that (see Bertin & Arnouts 1996):

$$\tan 2\theta = 2 \frac{\overline{xy}}{\overline{x^2} - \overline{y^2}} \Leftrightarrow \theta = \frac{\text{sign}(\overline{xy})}{2} \arctan \left(2 \frac{\overline{xy}}{\overline{x^2} - \overline{y^2}} \right) \quad (\text{B.7})$$

Which is then corrected according to the quadrant it is referring in order to span the entire range from -90 to 90 degrees. It is also possible to define directly the semi-major and semi-minor axis of the corresponding ellipse as:

$$a^2 = \frac{\overline{x^2} + \overline{y^2}}{2} + \sqrt{\left(\frac{\overline{x^2} + \overline{y^2}}{2} \right)^2 + \overline{xy}^2} \quad (\text{B.8})$$

$$b^2 = \frac{\overline{x^2} + \overline{y^2}}{2} - \sqrt{\left(\frac{\overline{x^2} + \overline{y^2}}{2} \right)^2 + \overline{xy}^2} \quad (\text{B.9})$$

which in turns makes it easier to compute $q = b/a$.

Finally, we can compute the total flux within an elliptical aperture defined by the shape parameters above and a semi-major axis of $1.5r_p$. From there, we iterate over different apertures with an increasing major-axis to define the radius enclosing 20% and 80% of the total flux defined before. Once we have those values it is straightforward to use equation 21 to compute the light concentration of the object.

In figure B.1 it is possible to confirm that for the same sample defined in this paper, the standard light concentration measurement yields different results and trends. This is most likely due to the fact that using the elliptical apertures fails to give a actual insight onto how concentrated is the light inside a galaxy that is highly irregular.

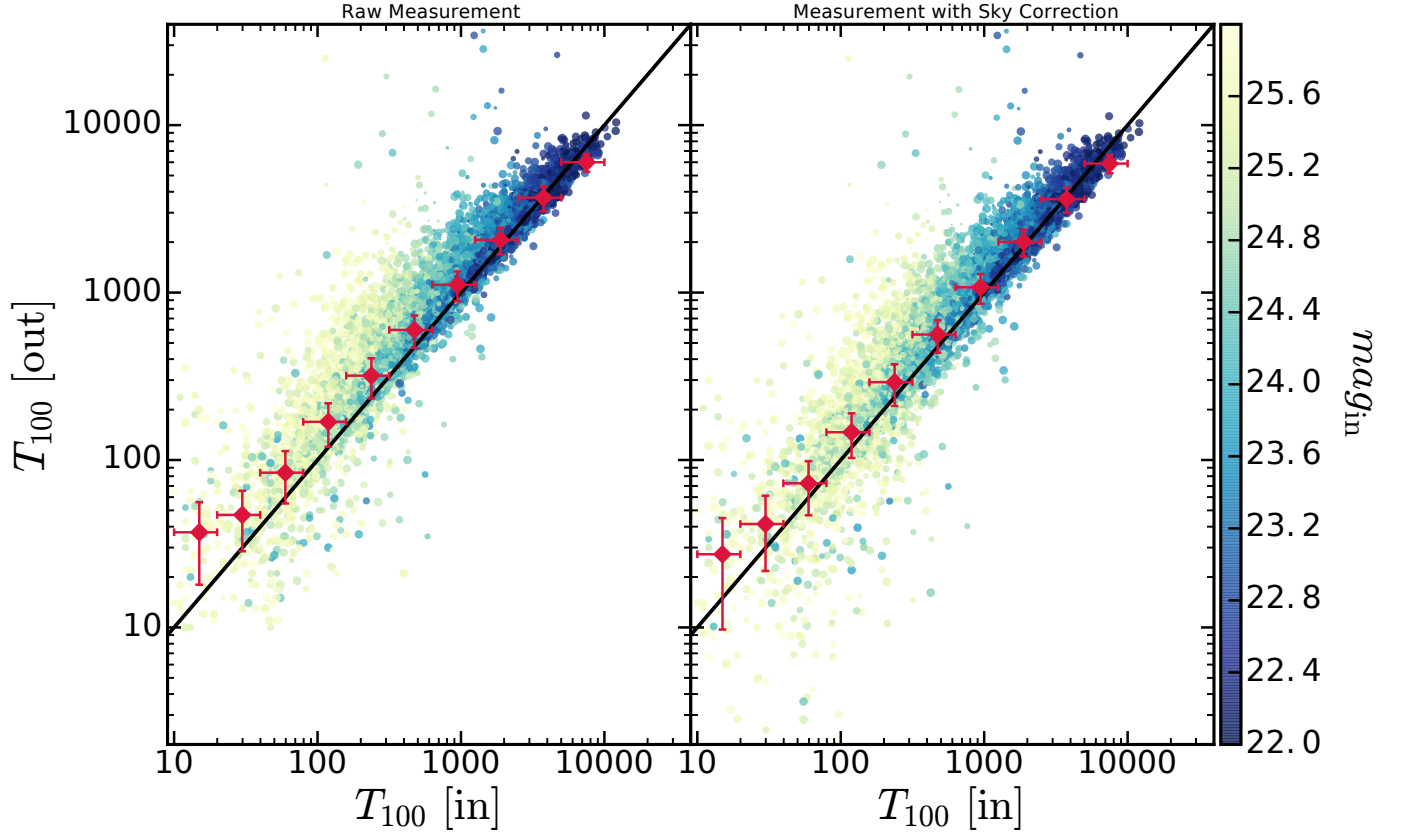


Fig. A.1. Results of the computation of T_{100} for a set of 15 000 galaxies. The points are color coded by their input magnitude and the size of each point is determined by the input r_e of the GALFIT model. The solid red line denotes the one-to-one relation. The left panel refers to the size measurement without any correction and the right panel presents the same results but after applying the same sky correction as described in section 4.6. The large red points represent the median sizes per bin, the error bar in the x-axis represents the bin width, and in the y-axis represents the median absolute dispersion of the bin.

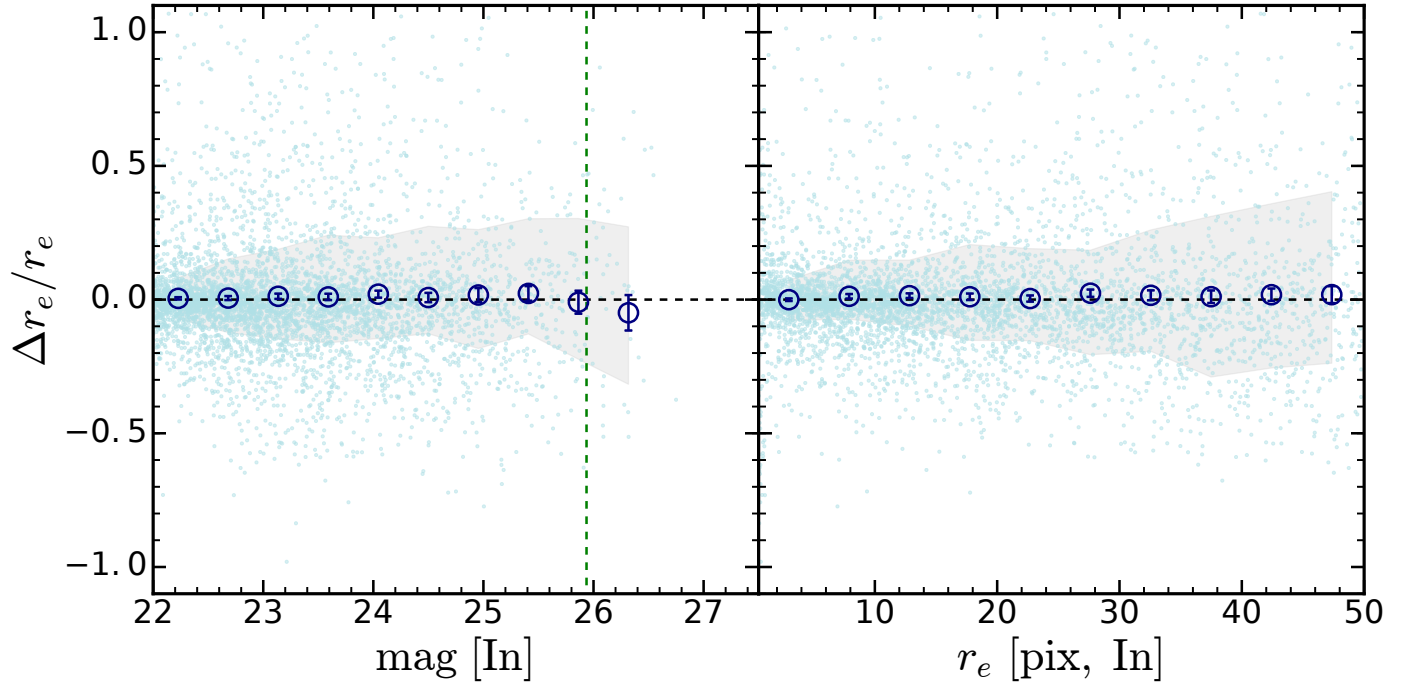


Fig. A.2. Variance of the value of r_e for a set of 15 000 galaxies as a function of input magnitude (left) and effective radii (right). Only galaxies where GALFIT convergence was attained are included in this figure. The large dark blue points represent the median sizes per bin, the error bar in the y-axis is $\sigma / \sqrt{N}$. The shaded region delimits the 16th and 84th percentiles and includes 68% of the sample of each bin.

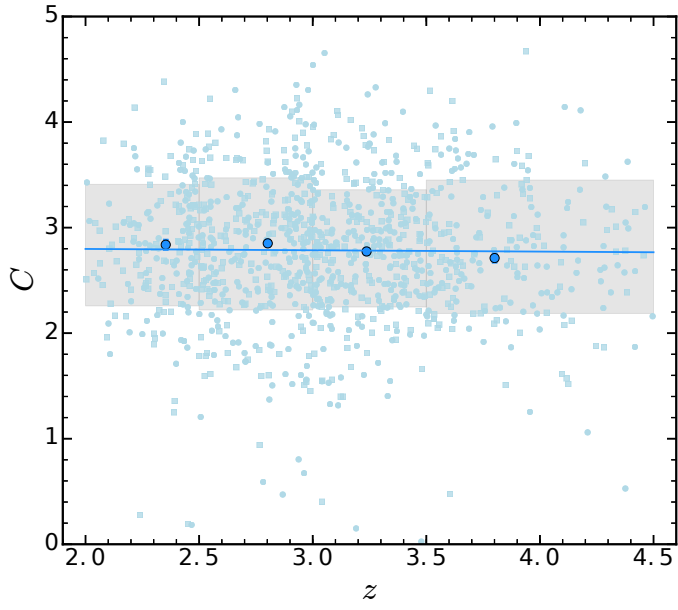


Fig. B.1. The redshift dependence of the standard concentration measurement describe in this section. The symbols and regions have the same meaning as in figure 18.

• This page is intentionally left blank •

A major merger origin for the high fraction of galaxies at $2 < z < 6$ with 2 bright clumps [★]

B. Ribeiro¹, O. Le Fèvre¹ and P. Cassata², D. Maccagni³, G. Zamorani⁴, E. Zucca⁴, R. Amorín⁵, S. Bardelli⁴,
N.P. Hathi¹, D. Schaerer^{6,7}, and J. Pforr¹

¹ Aix Marseille Univ, CNRS, LAM, Laboratoire d'Astrophysique de Marseille, Marseille, France

² Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Gran Bretaña 1111, Playa Ancha, Valparaíso Chile

³ INAF–IASF Milano, via Bassini 15, I–20133, Milano, Italy

⁴ INAF–Osservatorio Astronomico di Bologna, via Ranzani, 1 - 40127, Bologna

⁵ INAF–Osservatorio Astronomico di Roma, via di Frascati 33, I-00040, Monte Porzio Catone, Italy

⁶ Geneva Observatory, University of Geneva, ch. des Maillettes 51, CH-1290 Versoix, Switzerland

⁷ Institut de Recherche en Astrophysique et Planétologie - IRAP, CNRS, Université de Toulouse, UPS-OMP, 14, avenue E. Belin, F31400

e-mail: bruno.ribeiro@lam.fr

ABSTRACT

The properties of stellar clumps in star forming galaxies and their evolution over the redshift range $2 \lesssim z \lesssim 6$ is presented. We use HST/ACS images of galaxies with spectroscopic redshifts from the VIMOS Ultra Deep Survey (VUDS) to identify clumps within a 20 kpc radius. We find that the population of galaxies with more than one clump is dominated by galaxies with two clumps, representing $\sim 21 - 25\%$ of the population, while the fraction of galaxies with 3, or 4 and more, clumps is 8-11 and 7-9%, respectively. The fraction of clumpy galaxies is in the range $\sim 35 - 55\%$ over $2 < z < 6$, increasing at higher redshifts, indicating that the fraction of irregular galaxies is high up to the highest redshifts. The large and bright clumps ($M_{\text{star}} \sim 10^9$ up to $\sim 10^{10} M_{\odot}$) are found to reside predominantly in galaxies with two clumps. Smaller and lower luminosity clumps ($\log(M_{\text{star}}/M_{\odot}) < 9$) are found in galaxies with three clumps or more. We interpret these results as evidence for two different modes of clump formation working in parallel. The small low luminosity clumps are likely the result of disc fragmentation, with violent disc instabilities (VDI) forming several long-lived clumps *in-situ*, as suggested from simulations. A fraction of these clumps is also likely coming from minor mergers. The clumps in the dominating population of galaxies with two clumps are significantly more massive than those observed in VDI numerical simulations, and rather have properties akin to those in merging pairs observed at similar redshifts. We therefore infer that the bright and large clumps are most likely the result of major mergers bringing-in *ex-situ* matter, and we derive a high major merger fraction of $\sim 20\%$. These results suggest that the assembly of star-forming galaxies at $z \sim 2 - 6$ is more complex than a simple cold accretion picture would suggest and rather proceeds from several different dissipative processes including an important contribution from major and minor mergers.

Key words. high redshift Universe – galaxy morphology – galaxy evolution – galaxy formation

1. Introduction

The morphology of galaxies is a visible outcome of all processes at work when galaxies are assembling along cosmic time (e.g. Conselice 2014). While at lower redshifts galaxies are predominantly regular and symmetric in the form of elliptical or spiral galaxies, the situation at redshifts higher than the peak in star formation $z \approx 1.5-2$ is very different with galaxies mostly having irregular shapes (e.g. Buitrago et al. 2013; Mortlock et al. 2013; Huertas-Company et al. 2015).

Quantitative morphology allows to follow the evolution of the two main components of galaxies, disks and bulges, and studies have focused on understanding the evolutionary paths of these fundamental components (e.g. Bruce et al. 2012, 2014a,b; Lang et al. 2014; Tasca et al. 2014b; Margalef-Bentabol et al. 2016). Observational studies and numerical simulations seem

to support a picture where disk galaxies build from the original collapse of baryonic matter in a dark matter halo. Several studies point to a scenario where gas gains angular momentum leading to rotation support system, with violent disk instabilities (VDI) forming large star-forming clumps. This large clumps may then migrate to the disk center to form the bulges of spiral galaxies (e.g. Genzel et al. 2008; Elmegreen et al. 2008, 2009; Dekel & Krumholz 2013; Perez et al. 2013; Bournaud et al. 2014; Bournaud 2016). Alternatively, considerable effort has been invested in studying the development of elliptical galaxies along cosmic time. On this scenarios, bulges would form from violent dissipative events, going through a stage of compact quiescent objects at $z \sim 2$. Such objects would then grow into massive ellipticals after star formation quenching and a succession of merging events (e.g. Hopkins et al. 2008; Oser et al. 2012; López-Sanjuan et al. 2012; Porter et al. 2014). Two major physical processes are thought to play a key role in the evolution of different types of galaxy galaxies: gas accretion mostly in cold form and flowing along the cosmic web and/or smoothly distributed (e.g. Dekel

[★] Based on data obtained with the European Southern Observatory Very Large Telescope, Paranal, Chile, under Large Program 185.A–0791.

et al. 2009; Rodriguez-Gomez et al. 2016), and major or minor merging (e.g. Hopkins et al. 2008; Di Matteo et al. 2008), each leading to different morphological signatures.

An important morphological property related to these processes is the number of large clumps of gas and stars present within a galaxy. Clumps may have either an *in-situ* or an *ex-situ* formation history depending on which physical processes are at play (e.g. Shibuya et al. 2016). Clumps forming from disk instabilities are mostly the result of in-situ dynamical processes, while major and minor merging events are driving clumps of ex-situ material into a galaxy in assembly phase. The properties and fate of these clumps has been extensively studied in the literature both from observations (e.g. Elmegreen et al. 2004; Elmegreen & Elmegreen 2006; Elmegreen et al. 2007, 2013; Genzel et al. 2008; Bournaud et al. 2008; Wuyts et al. 2012; Guo et al. 2012) and in hydrodynamical simulations (e.g. Bournaud et al. 2007; Dekel et al. 2009; Genel et al. 2012; Bournaud et al. 2014; Mandelker et al. 2014; Oklopčic et al. 2016). They report clumps with typical stellar masses of $10^7 - 10^9 M_\odot$ and with lifetimes spanning short to long periods with timescales of $\lesssim 1$ Gyr. Some studies suggest that short-lived clump are destroyed by internal feedback before migrating to the center of the galaxy (e.g. Genel et al. 2012).

The measurement of clumps at redshifts beyond the peak of cosmic star formation are notoriously difficult. The identification of clumpy galaxies in the dominant population of irregular galaxies at high redshift dates back to the first deep *Hubble Space Telescope* (HST) images (e.g. Williams et al. 1996), superseded with each deeper survey following new instrumentation, with the Advanced Camera for Surveys (ACS) then Wide Field Camera 3 (WFC3) bringing larger areas and samples. Detailed studies at $z \sim 1 - 3$ have revealed that clumpy galaxies are more numerous than in the local Universe (e.g. Cowie et al. 1995; Abraham et al. 1996; van den Bergh et al. 1996; Giavalisco et al. 1996; Elmegreen et al. 2004; Elmegreen & Elmegreen 2006; Elmegreen et al. 2007, 2008, 2009, 2013; Kubo et al. 2013, 2016; Glazebrook 2013; Tadaki et al. 2014; Murata et al. 2014; Guo et al. 2015; Garland et al. 2015; Bournaud 2016). The fraction of clumpy galaxies has been studied from $z=0$ up to the most distant galaxies identified today at $z \sim 10$ (Ravindranath et al. 2006; Guo et al. 2012, 2015; Shibuya et al. 2016). In the sample of galaxies with $0.5 < z < 3$ in the CANDELS survey, Guo et al. (2015) find that galaxies with low mass $\log(M_{\text{star}}/M_\odot) < 9.8$ have a high fraction of off-center clumps $f_{\text{clumpy}} \sim 60\%$ constant over the observed redshift range, while for intermediate and massive galaxies f_{clumpy} decreases from $\sim 40\%$ at $z \sim 3$ to $\sim 15\%$ at $z \sim 0.5$. Combining deep HST imaging from the 3D-HST, CANDELS, HUDF and HFF surveys Shibuya et al. (2016) claim that $f_{\text{clumpy}}^{\text{UV}}$ follows a similar evolution to the star formation rate density (e.g. Madau & Dickinson 2014), increasing from $z \sim 8$ to $z \sim 1 - 3$ and decreasing from $z \sim 1$ to $z \sim 0$. In comparing these observed trends with the predictions of simulations, Guo et al. (2015) conclude that VDI are likely responsible for f_{clumpy} at high mass and that minor mergers are a viable explanation for f_{clumpy} at intermediate mass for $z < 1.5$, while Shibuya et al. (2016) conclude that VDI is the main origin of the clumps. Both these studies exclude major mergers as a possible contribution to the evolution of the fraction of clumps. This is somewhat surprising as the major merger fraction for star-forming galaxies is observed to increase up to $\sim 20\%$ at $z \sim 1 - 2$ (e.g. Lotz et al. 2011; López-Sanjuan et al. 2011, 2013), staying high at least to $z \sim 3 - 4$ (e.g. Conselice et al. 2008; Tasca et al. 2014a), and one would therefore expect that a fraction of the clumps is related to *ex-situ* merging.

When deriving volume average quantities like f_{clumpy} it is critical to observe samples representative of the general star-forming population, with well defined physical parameters including luminosity, stellar masses and sizes. The size of irregular high redshift galaxies is very different when using the effective radius or a total size (Ribeiro et al. 2016), and searching for clumps using one or the other of these sizes to define a search area may lead to significantly different results on f_{clumpy} . We show that total extent sizes are larger by a factor of $\sim 1.5 - 2$ than what previous findings report and that this difference is larger at higher redshifts (comparing $z \sim 2$ to $z \sim 4$, Ribeiro et al. 2016). Moreover, the issue of the clump definition is quite tricky and one must be aware of the impact of specific definitions and sample selection, for subsequent analysis to have a statistically robust meaning in a representative volume of the Universe at a given redshift.

In this paper we use a sample of 1242 galaxies with secure spectroscopic redshifts from the VIMOS Ultra-Deep Survey (VUDS) and HST imaging in the COSMOS and ECDFS fields to measure f_{clumpy} . We use a clump definition expanded from Guo et al. (2015), counting all clumps within the isophote defining the total size $r_{T,100}$ and in a 20 kpc physical radius. The sample and the data used are described in Sect. 2. We present our method for identifying and characterizing clumps in Sect. 3. The evolution of the fraction of clumps is presented in Sect. 4. We analyze the statistical properties of clumps in star-forming galaxies in Sect. 5 where we explore the distribution of clumps in galaxies, their areas and luminosities and their spatial distribution. The results are discussed in Sect. 6 and summarized in Sect. 7.

We use a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{0,\Lambda} = 0.7$ and $\Omega_{0,m} = 0.3$. All magnitudes are given in the AB system.

2. Data and Sample Selection

2.1. The VIMOS Ultra Deep Survey sample

VUDS is a large spectroscopic survey that targeted $\sim 10\,000$ objects covering an area of 1 deg^2 on three separate fields: COSMOS, ECDFS and VVDS-02h (Le Fèvre et al. 2015). With the objective to observe galaxies in the redshift range $2 < z < 6+$, targets were predominantly selected based on the first or second photometric redshift peaks being at $z_{\text{phot}} + 1\sigma > 2.4$, adding objects satisfying Lyman break galaxies (LBG) criteria in color-color diagrams and not in the z_{phot} selection, with flux limits $22.5 \leq i_{AB} \leq 25$. To fill in the remaining available space on the masks, a randomly flux selected sample with $23 < i_{AB} < 25$ is added to the target list. The spectra were obtained using the VIMOS spectrograph on the ESO-VLT (Le Fèvre et al. 2003) covering, with two low resolution grisms ($R=230$), a wavelength range of $3650\text{\AA} < \lambda < 9350\text{\AA}$. The total integration is $T_{\text{exp}} \sim 14\text{h}$ per pointing and grism.

Data processing is performed within the VIPGI environment (Scodreggio et al. 2005), and is followed by extensive redshift measurements campaigns using the EZ redshift measurement engine (Garilli et al. 2010). At the end of this process each galaxy has flux and wavelength calibrated 2D and 1D spectra, a spectroscopic redshift measurement, and associated redshift reliability flag. For more information on this process we refer the reader to Le Fèvre et al. (2015).

In the following we analyze exclusively VUDS galaxies with the most reliable redshift measurements, i.e. galaxies with redshift flags 2 and 9 ($\sim 80\%$ probability to be correct), and flags 3

and 4 (95 to 100% probability to be correct), see Le Fèvre et al. (2015) for more details.

2.2. Imaging data in the VUDS-COSMOS and VUDS-ECDFS fields

For this study, we use deep high resolution images from HST surveys. Covering the largest contiguous sky region, the COSMOS (Scoville et al. 2007; Koekemoer et al. 2007) survey has $\approx 2\text{deg}^2$ of HST ACS F814W coverage down to a limiting magnitude of 27.2 (5σ point-source detection limit). As it covers the entirety of the VUDS COSMOS area (Le Fèvre et al. 2015) it is the most complete image set to undertake morphological studies with our sample. These images cover the UV rest-frame from $\sim 2700\text{\AA}$ at $z \sim 2$ to $\sim 1500\text{\AA}$ at $z \sim 4.5$.

The more recent CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011) covers five different sky regions, including the COSMOS and ECDFS fields with a large overlap with VUDS fields (see Le Fèvre et al. 2015; Tasca et al. 2016). The area covered is smaller than VUDS but near-infrared coverage (with the F125W and F160W bands) is important because it allows us to probe the rest-frame optical morphology for the majority of our sample in this field. It reaches depths at 5σ of 28.4, 27.0 and 26.9 at F814W, F125W and F160W, respectively. These observations are deeper in the F814W band than the aforementioned COSMOS observations. The typical spatial resolution of these images ranges from $0.09''$ (0.8, 0.6 kpc, at $z = 2.0, 4.5$) for the F814W band up to $0.18''$ (1.5, 1.2 kpc, at $z = 2.0, 4.5$) in the F160W band.

2.3. Spectral Energy Distribution

The SED fitting procedure closely follows the method described in Ilbert et al. (2013), and the specifics for VUDS are detailed in Tasca et al. (2015). To fit the photometric data we use templates derived from Bruzual & Charlot (2003) models and assuming a Chabrier (2003) IMF. To model the star formation histories we use an exponentially declining parameterization $\text{SFR} \propto \exp(-t/\tau)$ (τ in the range 0.1 Gyr to 30 Gyr), and an additional two models with delayed SFH peaking at 1 and 3 Gyr. The templates are created for a grid of 51 ages (in the range 0.1 Gyr to 14.5 Gyr). We apply a Calzetti et al. (2000) dust extinction law to the templates, using $E(B - V)$ in the range 0 to 0.5. Models with two different metallicities are used ($Z = \odot$). The main parameter of interest in this paper is the stellar mass, M_* for which the median values of the probability density function are used. We refer the reader to Ilbert et al. (2013) and Thomas et al. (2016) for typical uncertainties on these quantities (see also Tasca et al. 2015). We expect a statistical uncertainty of ~ 0.1 dex in stellar masses. Systematic uncertainties due to choice of IMF can be as high as a factor of ~ 1.7 , if we use the Salpeter (1955) instead of the Chabrier (2003) IMF. The sample selection (discussed below), color correction detailed in Sect. 3.1 and the k-correction used in Sect. 3.3 rely on the parameters derived from LePhare. Using the stellar masses from GOSSIP+ to perform our sample selection has no impact on the results we present in this paper.

2.4. Sample selection

To follow the evolution of galaxy sizes in a similar population as a function of redshift, we define our sample imposing an evolving lower stellar mass limit. This choice implies that stellar masses of galaxy populations at different redshifts fol-

low the general stellar mass growth of star-forming galaxies, broadly representing the same coeval population. We define a lower stellar mass limit in our sample anchored at $z = 4.5$ as $\log_{10}(M_*/M_\odot) > 9.35$ (below which the VUDS sampling drops). We then use the stellar mass function evolution from Ilbert et al. (2013) together with the typical sSFR of VUDS galaxies (Tasca et al. 2015) to follow the typical stellar mass growth of VUDS galaxies, and define the stellar mass selection threshold at different redshifts using

$$\log_{M_*/M_\odot} > -0.204 \times (z - 4.5) + 9.35. \quad (1)$$

We refer to Ribeiro et al. (2016) for more details on the choice of this mass selection in the context of the VUDS survey. In the higher redshift interval we select all galaxies with spectroscopic redshift and stellar masses $\log_{M_*/M_\odot} > 9$ to have a statistical sample to compute the quantities on the clumpy fraction and clump properties.

We identify a total of 1242 galaxies with $2 < z < 4.5$ that satisfy the mass-selection and the redshift quality criteria in the VUDS survey with ACS F814W images, of which 1087 are in the COSMOS field and 155 are in the CANDELS-ECDFS field. We also examine a higher redshift sample of 96 galaxies with $4.5 < z < 6$, however the available imaging data is not as deep as needed to search for clumpy galaxies at the same luminosity limit.

3. Defining clumps in galaxies

There are various methods described in the literature with the goal of detecting and characterizing galactic clumps at high redshift ranging from visual classification to automated algorithms (e.g. Elmegreen et al. 2007; Puech 2010; Guo et al. 2012; Wuyts et al. 2012; Tadaki et al. 2014; Guo et al. 2015; Shibuya et al. 2016). Usually, the algorithms involve the subtraction of a smoothed version of an image from the original and then search for positive detections in the residual image that can be considered as galactic clumps. We follow a slightly different approach. Our clump search is based on the assumption that clumps are locally the brightest region within a larger isophote which defines the total extent of the galaxy it resides in. We summarize our method in the steps below.

1. We smooth the image of $6'' \times 6''$ centered on the VUDS galaxy with a Gaussian kernel with 1 pixel ($0.03''$) width;
2. We compute the segmentation map of the smoothed image based on a given surface brightness threshold;
3. From the segmentation map we select the area of connected pixels above the adopted surface brightness threshold which contains the brightest pixel within a 0.5 arc-second radius from the target coordinates;
4. Using the selected pixels, we compute the total flux of the galaxy by summing up the flux in each pixel;
5. We iterate (using 1000 steps) a flux level f_i from the maximum to the minimum flux detected. At each step we compute the number of disconnected regions (defined from all pixels with fluxes greater than f_i) within the segmentation map and store the position of local maximum associated with each disconnected region (see Fig. 1).
6. We define the number of clumps as the number of disconnected regions detected above the isophote level corresponding to 80% of the total galaxy flux, which are associated with the different local maximums.

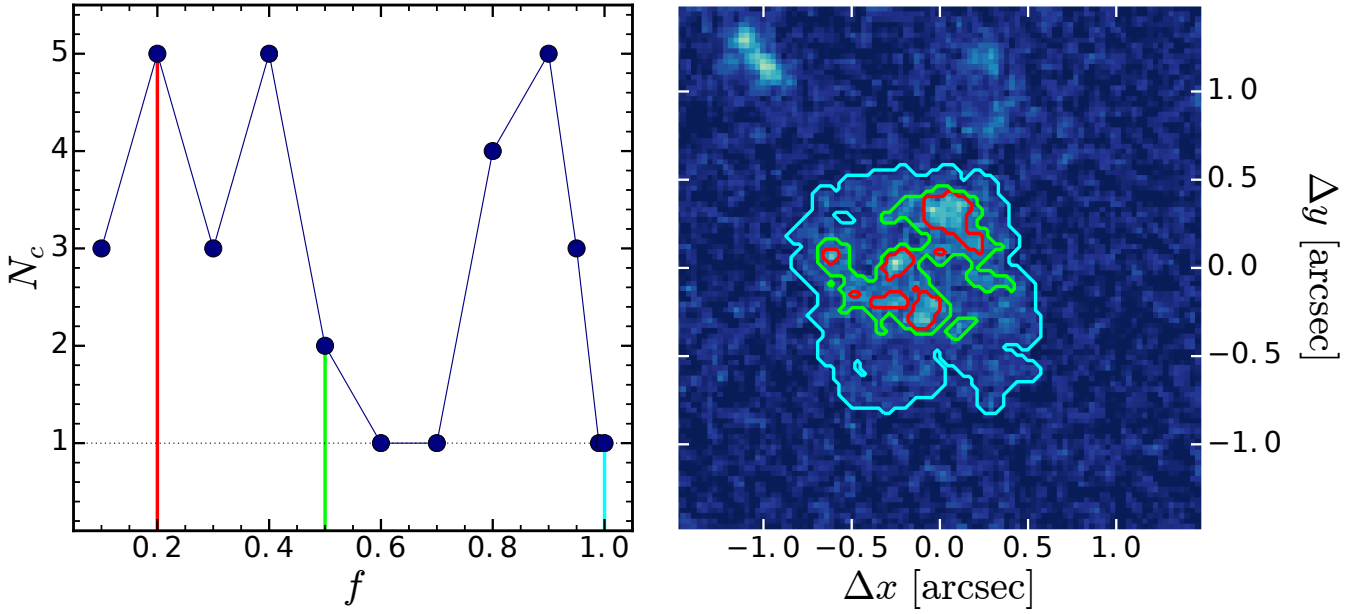


Fig. 1. Exemplification of the method for detecting galaxy clumps. On the left we show the number of disconnected regions with more than 10 pixels as a function of flux level cut. When $f = 1$ the isophote limit represents the limiting area of the galaxy. On the right we show the contours corresponding to three different flux level cuts at 20%, 50% and 100% of total flux that are identified in the same color as the vertical lines in the left panel.

We repeat this process for all galaxies found in the image stamp. We note that we only consider clumps with a detection area greater than 10 pixels. This minimum area for clump detection ensures that we are excluding the contribution from random fluctuations of photon counts and also imposes a lower limit of ~ 3 pixels (roughly the FWHM of the PSF) on the separation of any given two clumps that we can detect.

3.1. Isophotal threshold

One of the key elements of this algorithm is the limiting isophote at which we define the total extent of a single galaxy. For our method, it is defined as

$$k = k_p \left(\frac{1+z}{1+z_p} \right)^{-3} \times 10^{-0.4(I_{\text{obs}} - B_{\text{rest}})} \times \frac{L(z)}{L(z_p)}, \quad (2)$$

which is composed by three different terms.

The dimming correction which accounts for the fact that due to the expansion of the Universe the observed number of photons of a source with constant intrinsic luminosity scales with $(1+z)^{-3}$.

The color correction which accounts for the fact that we are not exactly observing at the same rest-frame wavelengths and corrects for the relative brightness based on the slope of the SED close to the band we are observing. To be consistent in our large redshift range we choose to use rest-frame FUV magnitudes to compute the color correction term since it is the central wavelength where we have the peak of our redshift distribution.

The luminosity correction which accounts for the average luminosity evolution in galaxies. $L(z)$ is derived from the L_* values in Reddy & Steidel (2009) at $z < 3$ and those from Bouwens et al. (2015) at $z > 4$. We define a luminosity evolution which is steeper below $z < 3$ and flattens at $z > 3$:

$$L(z) = \begin{cases} 10^{-0.4(-0.36z)} & z \leq 3 \\ 2.25 \times 10^{-0.4(-0.07z)} & z > 3 \end{cases}. \quad (3)$$

In equation 2 there are two parameters that are correlated. The value k_p represents the detection threshold, in units of σ , at $z = z_p$. In this study we set $z_p = 2$ and we use several values of k_p throughout the paper. In particular we use $k_p = 1.5, 2.0$ for $2 < z < 4.5$ and $k_p = 5.0$ for $4.5 < z < 6$. Since the value of k can vary by a factor of $(1+2)/(1+6)^{-3} \sim 0.009$ from $z = 2$ to $z = 6$ based only on surface brightness dimming we choose different values of k_p to allow for an estimate of the total extent of galaxies at the lower limit while preventing noise contaminated detections at the high redshift end. All these factors are explained in detail in Ribeiro et al. (2016).

3.2. Resulting clumps and pair counts

At the end of this process a list of galaxies is identified within a 20 kpc radius (search radius defined to be equal to López-Sanjuan et al. 2013; Tasca et al. 2014a), and a list of clumps is identified in each galaxy. Our algorithm may identify several *galaxies* within the search radius of 20 kpc, as pixels groupings isolated from other pixel groupings, i.e. these groups of pixels are not connected to each other at the isophote considered. It is well possible that if deeper images were available, allowing to lower the search isophote, some of these pixel groupings could be connected and possibly associated to a single galaxy.

To provide a cleaner interpretation, all our results on galactic clumps take only into account clumps that are associated with the VUDS target. We choose to do this because it is only for these sources that we have spectroscopic information (important to compute k in equation 2) as well as physical parameters from SED fitting. However we keep information about other galaxy detections within 20 kpc to compute the pair fraction at the same redshifts. Several examples of detected clumps in VUDS galaxies are shown in Figs. 2, 3 and 4.

We attempt to correct for line of sight contamination, to transform our pair fraction into a merger fraction, by using a simple statistical argument. Starting with the expected number

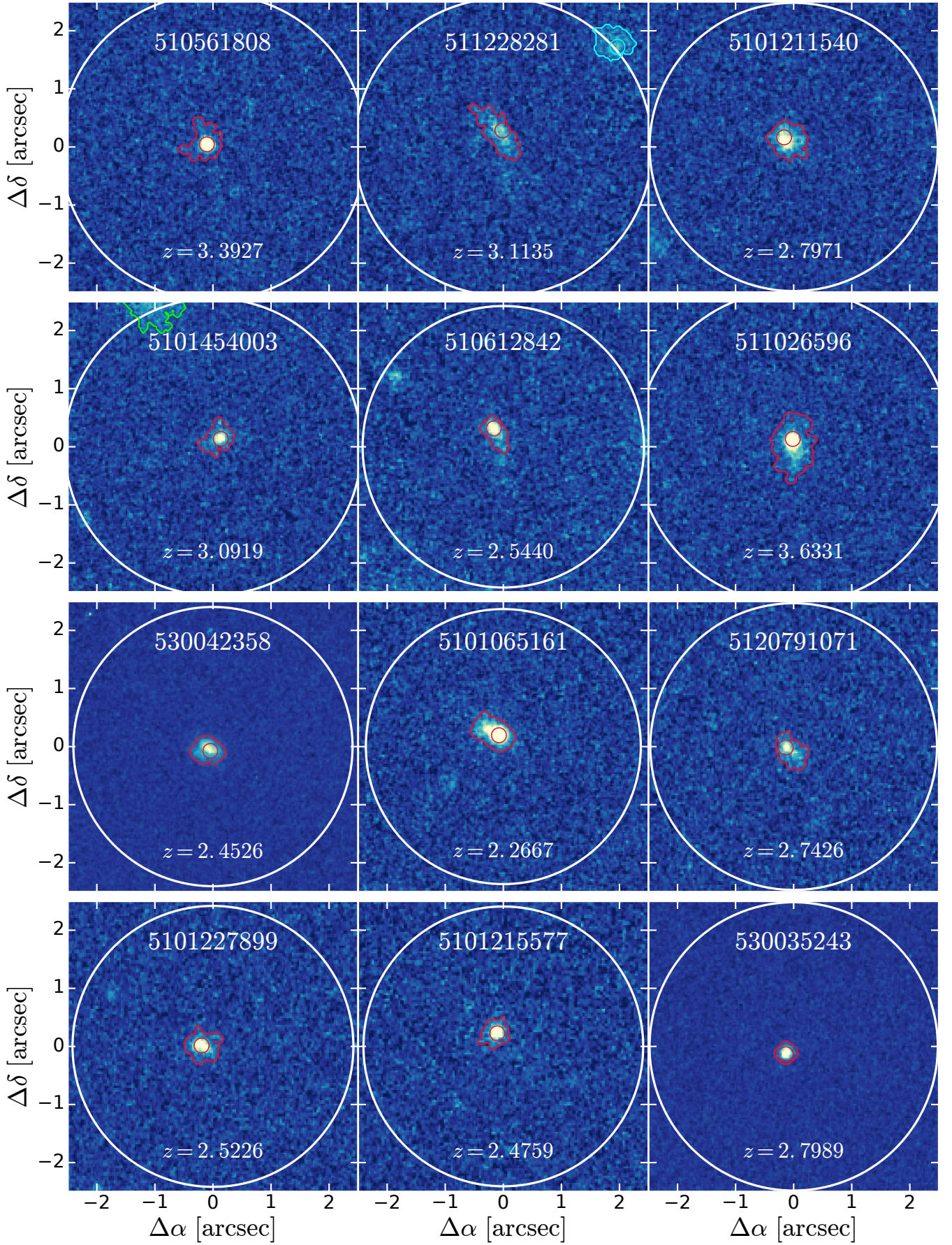


Fig. 2. Twelve examples of galaxies for which only one clump was detected. The white circle shows the 20 kpc projected search radius. The contours represent the detection isophote of each galaxy identified within this search radius. Each circle shows the position of a detected clump within the isophote of the same color. VUDS targets are identified with red contours and circles.

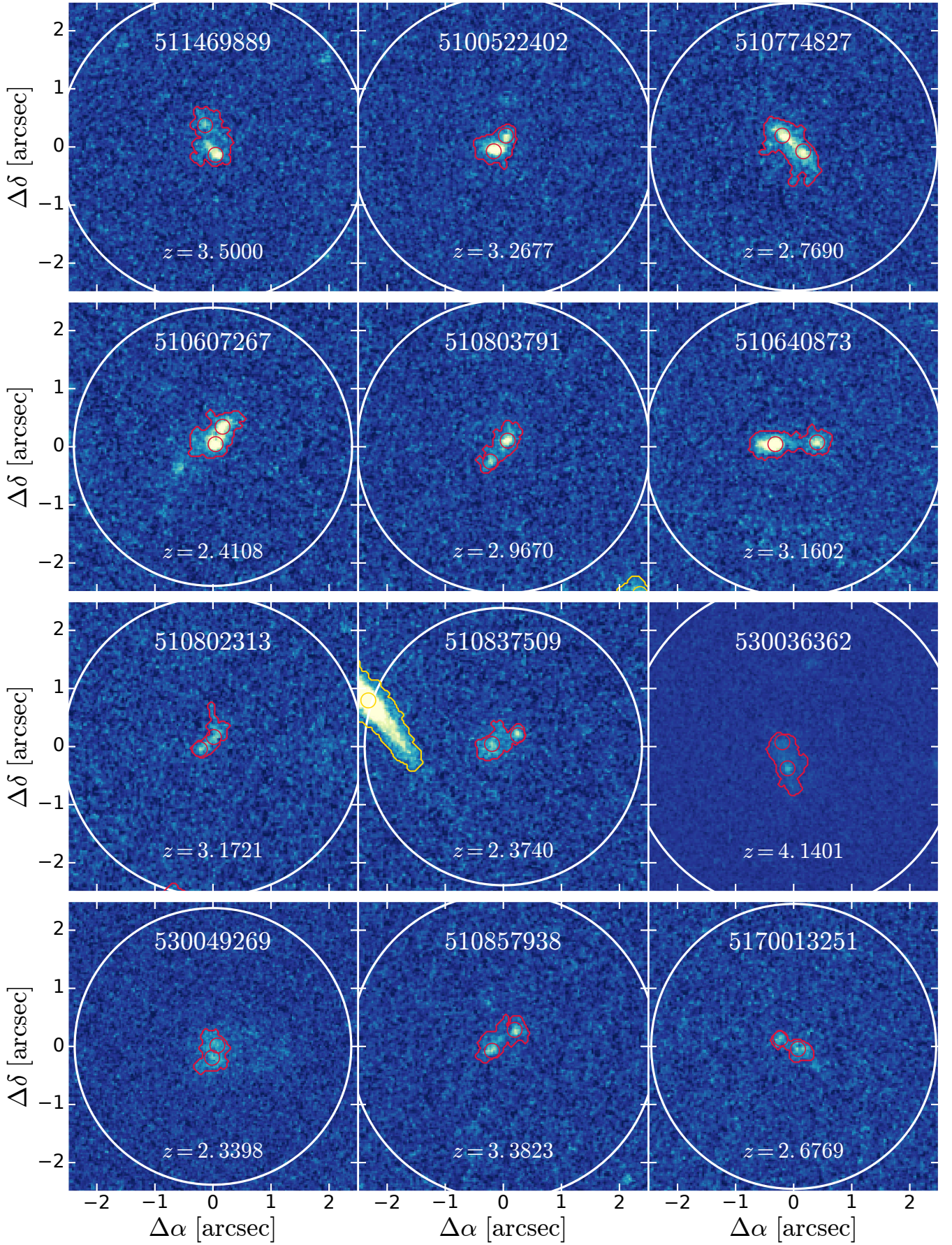


Fig. 3. Twelve examples of galaxies with two clumps detected. The top six examples show cases for which at least one bright clump was detected whereas the bottom six examples show pairs of faint clumps. The white circle shows the 20 kpc projected search radius. The contours represent the detection isophote of each galaxy identified within this search radius. Each circle shows the position of a detected clump within the isophote of the same color. VUDS targets are identified with red contours and circles.

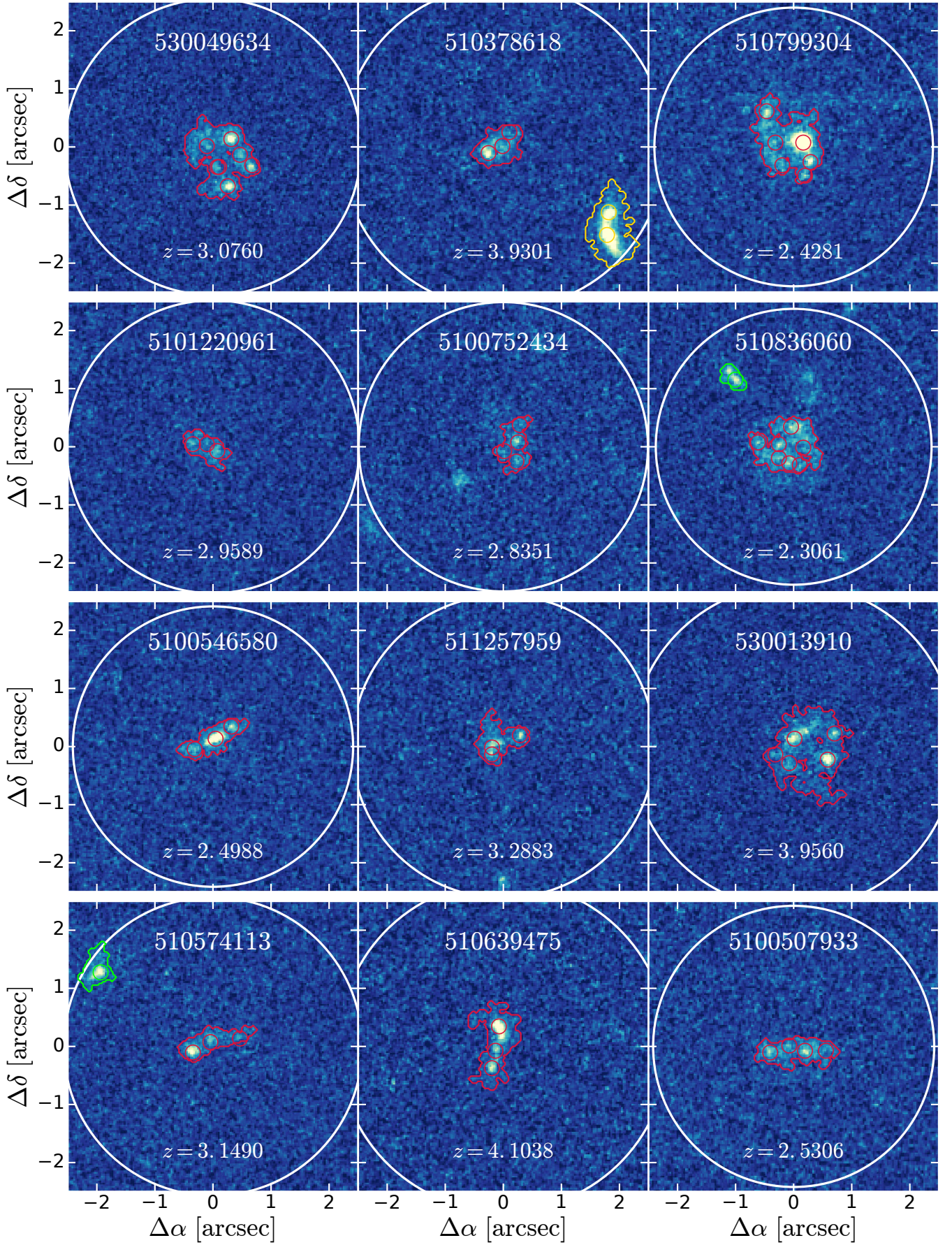


Fig. 4. Twelve examples of galaxies with more than two clumps detected. The white circle shows the 20 kpc projected search radius. The contours represent the detection isophote of each galaxy identified within this search radius. Each circle shows the position of a detected clump within the isophote of the same color. VUDS targets are identified with red contours and circles.

of galaxies within a square degree, as derived by Capak et al. (2007), we compute the probability of a galaxy of magnitude m to be found at a distance r of the VUDS target. The total number of galaxies brighter than magnitude m in one square degree is computed integrating the number counts, $N(< m)$ computed by Capak et al. (2007). Then we estimate how many galaxies we expect to find within $\pi \times r^2$. This is summarized by

$$p = \frac{\pi r^2}{3600 \times 3600} \times \int_{15}^m N(< m') dm'. \quad (4)$$

In the end, each galaxy of magnitude m counts as $0 < p < 1$, and this quantity gives the contaminating counts when later considering galaxy pairs.

3.3. Luminosity and Sizes

In order to obtain further information on the physical characteristics of clumps we adapted the method defined by Freeman et al. (2013) to compute the intensity parameter I giving the luminosity of each clump.

This algorithm defines groups of pixels associated with a local maximum inside a segmentation map. First, the image is smoothed via a Gaussian kernel with a given σ (we use $\sigma = 1$ pixel). Then, for each pixel in the segmentation map, we compute the corresponding local maximum via maximum gradient paths. This means that for each pixel we compute the intensities of the 8 surrounding pixels and then move to the pixel with maximum intensity. We continue this process until a local maximum is reached and none of the eight neighbor pixels have higher intensities than the one we are considering. So, a pixel group is defined as the collection of pixels linked to a particular local maximum.

Once we have all the pixel groups defined, we match the local maximum of each group to the local maximum of the detected clumps in the previous algorithm. Then we compute the luminosity and area associated with each clump by counting all the light and pixels in each group, respectively. It is important to stress that since we are stopping at the border of two contiguous groups of pixels, the derived areas and luminosities are lower limits to the real values. This happens since we are not considering flux from pixels with a contribution coming mostly from a neighbor clump rather than the clump being considered.

With the knowledge of the spectroscopic redshift from VUDS, we can then compute physical areas in kpc^2 . Absolute magnitudes are computed using the flux measured from the F814W images. We correct the magnitudes to FUV rest-frame using the k -correction derived for the galaxy from SED fitting. This means that the clump magnitude is derived as

$$M_{\text{clump},\text{FUV}} = M_{\text{clump},\text{F814W}} + k_{\text{corr},\text{FUV}}. \quad (5)$$

3.4. False clump detections

To estimate the impact of false detections on the inferred distributions of areas and luminosities we perform a simple test. We run our clump detection algorithm using the same threshold as before on the negative image of each galaxy and compute the area and magnitude of each negative clump which is, by its nature, a false peak detection. We can see in Fig. 5 that the inferred distribution of false clumps is found at small areas (peaking at $\sim 1 \text{ kpc}^2$) and faint luminosities (peaking at $M_{\text{F814W}} \sim -17.4 \text{ mag}$) as expected.

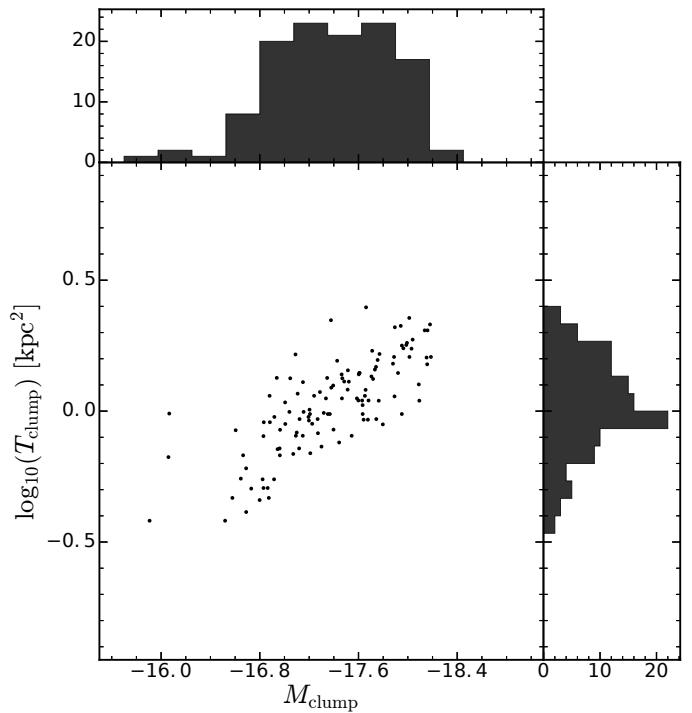


Fig. 5. The black points and histograms show the distribution in areas and magnitudes for the negative clumps detected applying the same method on the inverted galaxy image. Most of the negative detections are found at $M_{\text{clump}} > -18$ which is fainter than the peak for the fainter clumps that is observed in the magnitude distribution (see figure 8). This indicates that the smaller clumps with $M_{\text{clump}} < -18$ are mostly real physical clumps.

Most of the negative detections are found at $M_{\text{clump}} > -18$ which is fainter than the peak for the fainter clumps that is observed in the magnitude distribution (see figure 8). This indicates that the smaller clumps with $M_{\text{clump}} < -18$ are mostly real physical clumps.

3.5. Morphological k -correction

We test our assumption that clumps are evenly detected across the rest-frame wavelength range that we probe at different redshifts by computing the same quantities on a degraded version of the F814W images and on a subsample of galaxies for which we have H-band imaging from CANDELS. In terms of the clumpy fraction we detect a lower fraction of clumpy galaxies in the degraded version of the I band by a factor of 2 and a little lower when using the measurements in the H band. We argue that our measurements might be more affected by the spatial resolution of the images since the fraction of clumpy galaxies in the degraded version of the I band images is closer to that reported in the H band than what we report for the normal resolution I band images. We note that the spatial resolution of the H band is even poorer than the degraded I band image due to the larger PSF (which is 3 times that of the I band) and we expect a lower fraction on the H band simply due to that effect.

We have also attempted to compute the area-luminosity distribution of clumps detected in the H band and we are only able to detect clumps in the large and bright regime (see Fig. 5). Again we believe that the resolution in the H band images is the main reason for the differences that we find. However we cannot exclude the existence of morphological k -correction.

4. The evolution of the clumpy fraction with redshift

4.1. The distribution of the number of clumps per galaxy

We compare in Fig. 6 the number of galaxies as a function of the number of detected clumps per galaxy in two different redshift ranges. We consider only clumps that reside inside the isophote belonging to the VUDS target when showing this histogram. We find that the fraction of multi-clump systems decreases as the number of clumps increases. Systems with only one clump (i.e. a single clump in a smooth galaxy at the observed resolution) are the dominant population ($\sim 55\%$ at $2 < z < 4.5$ and $\sim 61\%$ at $4.5 < z < 6.0$). We find that the fraction of galaxies with only two clumps dominates the distribution of clumpy galaxies with $\sim 25 \pm 2.7\%$ double clumps galaxies at $2 < z < 4.5$ and $\sim 21 \pm 7.7\%$ at $4.5 < z < 6.0$. Galaxies with 3 clumps are about $\sim 11 \pm 1.6\%$ at $2 < z < 4.5$ and $\sim 8 \pm 4.1\%$ at $4.5 < z < 6.0$. Galaxies with four or more clumps amount to only $\sim 7 \pm 1.2\%$ at $2 < z < 4.5$ and $\sim 9 \pm 4.5\%$ at $4.5 < z < 6.0$. Several examples of galaxies with one, two, or more clumps may be found in Figs. 2, 3 and 4, respectively.

4.2. The fraction of clumpy galaxies

We define as a clumpy galaxy any source that has more than one clump detected within its isophote. To compute this fraction as a function of redshift, we consider only clumpy (and non-clumpy galaxies) within the VUDS galaxies for which we have reliable information on the spectroscopic redshift. This ensures that we are not smearing our results between redshift bins by including galaxies with uncertain or incorrect redshifts. We have compared the stellar mass distribution of clumpy and non-clumpy galaxies and find that they are indistinguishable from one another. The clumpy fraction evolution with redshift is shown in figure 7.

We stress that the clumpy fraction with our method depend on the selected isophote (value of k_p) which in turns depends on the color correction we choose to use, as allowed by the depth of available images. Nonetheless, we find a rising trend with redshift of the clumpy fraction at all values of k_p that we have tested as well as when using NUV as the base rest-frame band. Due to the asymmetric nature of most galaxies at high redshift (e.g. Huertas-Company et al. 2015; Curtis-Lake et al. 2016) and since deriving a center and a size can lead to different results when using different assumptions (e.g. Ribeiro et al. 2016) we are not including in our sample of clumpy galaxies any source with an off-center clump as defined by, e.g., Guo et al. (2015); Shibuya et al. (2016). The clumpy fraction evolution with redshift is shown in figure 7.

4.2.1. Clumpy fraction in $2 < z < 4.5$

At $2 < z < 4.5$ we observe that the clumpy fraction remains in the range 35 to 55% at all redshifts. This fraction is observed to be rising from low to high redshift. We also report the clumpy fraction for two different values of k_p for $2 < z < 4.5$ showing that the absolute value does indeed depend on the isophote used. We note that increasing the value of k_p lowers the probability of detecting faint clumps and it is no surprise that the fraction of clumpy systems decreases as the value of k_p increases. However changing k_p does not change the observed evolution of the clumpy fraction with redshift. The rising evolution with redshift of the clumpy fraction observed using our method is different from results obtained in other studies (e.g. Guo et al. 2015;

Shibuya et al. 2016). A possible explanation for the lower fraction of clumpy galaxies that we observe at $z \sim 2 - 3$ could be connected with the evolving threshold defined in section 3, including luminosity evolution. By imposing a higher threshold at lower redshifts, we are effectively reducing the are within we search clumps which is likely to prevent us from detecting faint clumps if they are located in the outskirts of the galaxy.

We have attempted to mimic the method used by Guo et al. (2015) and Shibuya et al. (2016) to test the impact of the method and selection on the derived values for the clumpy fraction. A short description of the method and results can be found in appendix A. We show that we get clumpy fractions within the error bars of the measurements made with our proposed algorithm when we use this alternative method. At $z < 3$ our results obtained using this method are closer in their trends to those reported Guo et al. (2015) and Shibuya et al. (2016). However, we still observe a rising trend on the clumpy fraction with redshift contrary to the decreasing trend reported by Shibuya et al. (2016) at $z > 3$, although our error bars are large because the number of galaxies satisfying the criteria of this method is reduced.

4.2.2. Clumpy fraction $4.5 < z < 6$

At $z > 4.5$ the depth of the data only allows the use of a higher value of k_p , as shown in figure 7. In this redshift range we observe a slightly lower clumpy fraction of 20 – 40%. At these redshifts it is necessary to use a brighter isophote limit for the clumps detection to avoid excessive contamination from noise. It is clear from our results at lower redshifts that if the depth of the data was enabling to use a fainter isophote we would likely observe a higher clumpy fraction also in this redshift bin.

Since we have computed the clumpy fraction at all redshifts for all values of k_p shown in figure 7 we attempted to compute a correction to estimate the clumpy fraction at high redshift as if it was measured with $k_p = 1.5$. To do that we fitted a linear curve to the quantity $\frac{f_{c,K}}{f_{c,5}}(z)$ which quantifies the underestimation of the clumpy fraction measured at $k_p = 5$ with respect to that measured at $k_p = K$. We then apply this correction factor measured at $z = 5.25$ to correct the measured clumpy fraction $k_p = 5.0$. In doing so, we estimate that the clumpy fraction at $4.5 < z < 6.0$ is $\sim 64 \pm 19\%$ when corrected for $k_p = 1.5$.

5. Physical properties of clumps

5.1. The relation between clump luminosity and area

As stated in Sect. 3.3, we derive areas and absolute magnitudes for each clump by computing the flux and area within each group of pixels associated with the local maximum that defines the clump. We show in Figs. 8 and 9 the tight correlation that we observe between clump magnitude and clump area. This is expected by construction since the larger the area (i.e. the number of pixels of the clump) the more likely it is for it to be brighter. In this figure we are excluding galaxies with a single clump detection.

In the same figure we can observe that there appears to be a bimodal distribution in the clump area distribution, also hinted by the asymmetric shape in the magnitude distribution. We fitted each distribution with a two Gaussian model with six free parameters: two amplitudes, two centers and two widths, one for each Gaussian curve. The fit was done using the Levenberg-Marquardt minimization algorithm implemented in *scipy*. For clumps at $2 < z < 4.5$ we observe two peaks in the magnitude

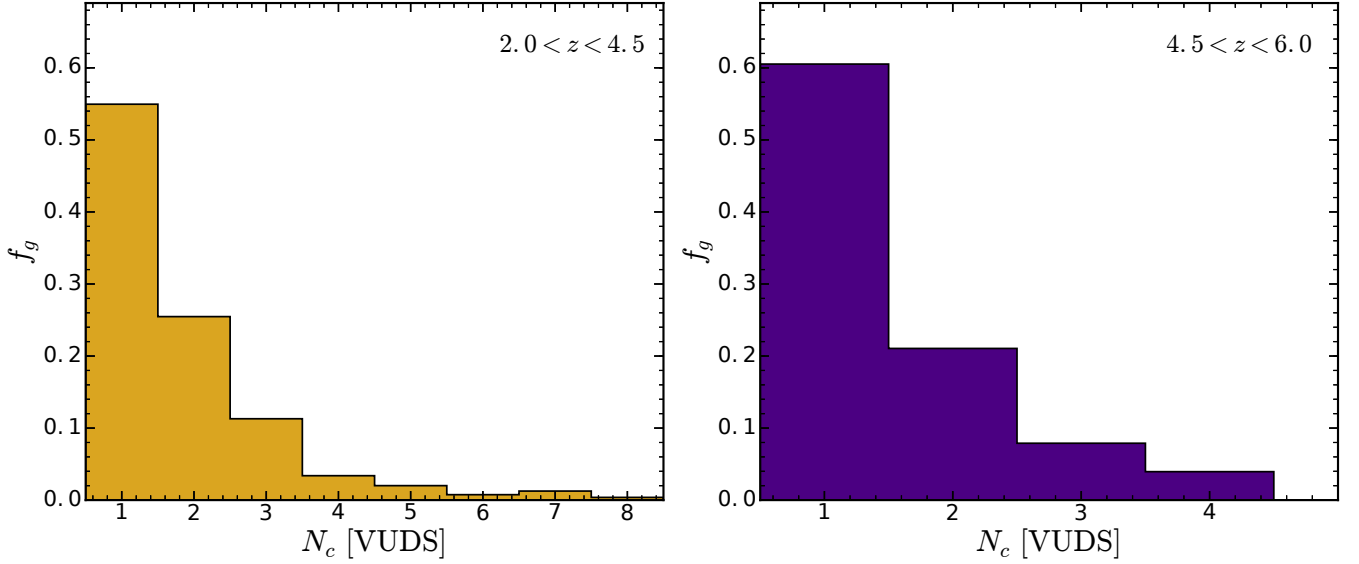


Fig. 6. Number of galaxies as a function of the number of clumps detected within the selected isophote. Note that we include in this plot single clump galaxies which correspond to galaxies with no substructure or a single central clump. We plot this quantity for two redshift intervals each with its respective value of $k_p = 1.5$ for $2 < z < 4.5$ in gold (left panel) and $k_p = 5$ for $4.5 < z < 6.0$ in purple (right panel). On each panel we show the number of clumps for the VUDS targets.

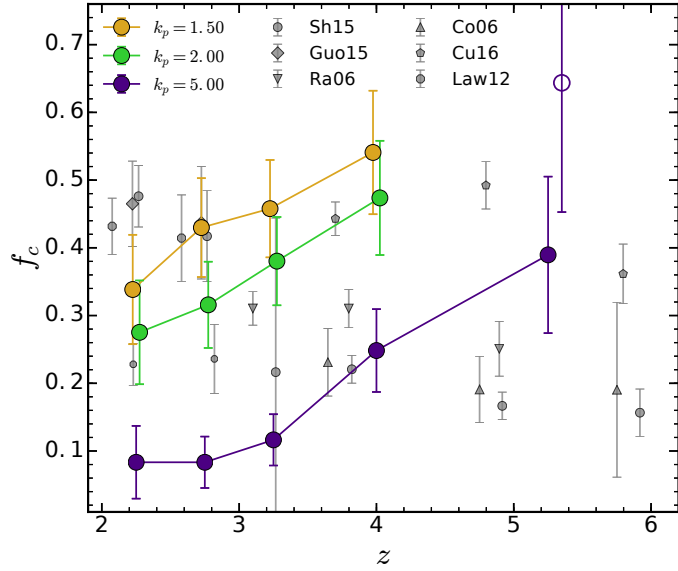


Fig. 7. Fraction of clumpy galaxies within the VUDS sample as a function of spectroscopic redshift. Different large colored circles (gold, green and purple) represent different values of the normalization k_p . The smaller gray symbols represent values from the literature for clumpy galaxies: circles (Shibuya et al. 2015); squares (Guo et al. 2015); and for asymmetric galaxies: inverted triangles (Ravindranath et al. 2006); triangles (Conselice & Arnold 2009); octagons (Law et al. 2012); pentagons (Curtis-Lake et al. 2016). We note that for $k_p = 5$, the isophote at $z < 4$ is very high and we are only probing the brightest regions of galaxies and thus miss a large fraction of clumpy galaxies. The empty purple circle at $z \sim 5$ is the extrapolation of the clumpy fraction as if it was measured at $k_p = 1.5$ (see Sect. 4.2.2 for details).

distribution at $M_{NUV} = -18.1 \pm 0.1$ and $M_{NUV} = -19.7 \pm 0.1$. In the area distribution the two peaks are found at $\log(T) = 0.25 \pm 0.05$ and $\log(T) = 0.78 \pm 0.03$, which correspond to ~ 1.8 and ~ 6.0 kpc^2 , respectively. At $4.5 < z < 6.0$ the bimodality is not so evident and due to the low number of detected clumps we

opt not to fit any model to the two distributions at this redshift. (see Fig. 9)

This bimodal hypothesis is likely linked to the different processes of clump formation where large and bright clumps are likely associated with merger events and the small and faint clump population is associated with disk instabilities. We further discuss this in section 6. We test the statistical significance of this bimodality using the Hartigan's dip test (Hartigan & Hartigan 1985). While a bimodal distribution is favored we find that the unimodal distribution hypothesis cannot be rejected for either of the distributions. Larger samples are required to confirm or reject this bimodal hypothesis.

5.2. Bright and large clumps are in two-clump galaxies

A key information shown in Fig. 8 is the number of clumps in the galaxy that each clump belongs to. The larger and brightest clumps are most likely to be found in two-clump galaxies and as we move towards fainter and smaller clumps we observe that they are more commonly found in galaxies with a larger number of clumps. This information is summarized in the contour lines of Fig. 8 showing the distribution of the fraction of clumps in two-clump systems as a function of clump area and absolute magnitude. More than 50% of the brightest and largest clumps are found in two-clump systems and the probability of finding two clumps in a galaxy decreases for fainter clump magnitudes and smaller areas (down to $\sim 10\%$, respectively).

The information on how the fraction of clumps in two-clump systems evolves with redshift is found in Tab. 1. We see that this fraction evolves with redshift in the sense that it is more likely to find two-clump systems at lower redshift ($\sim 40 \pm 6.1\%$ at $2 < z < 2.75$) than at higher redshift ($\sim 12 \pm 2.5\%$ at $4.5 < z < 6.0$). Imposing a magnitude cut ($M_{\text{clump}} < -19.1$) the fraction of clumps in two-clump systems is larger at all redshifts, confirming that the largest and brightest clumps are more likely to reside in two-clump systems than their fainter smaller counterparts.

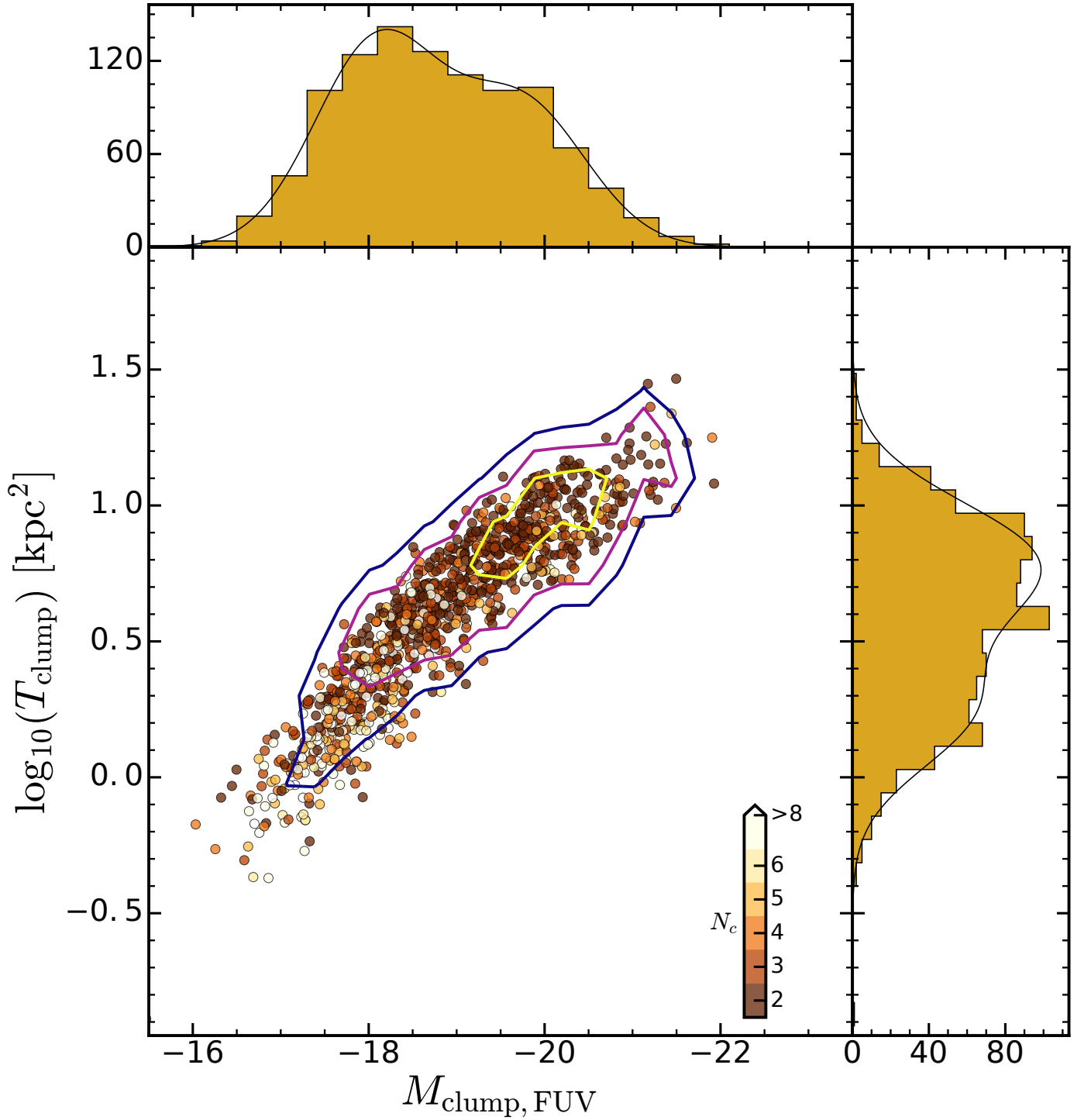


Fig. 8. Absolute magnitude in the rest-frame FUV and area distribution for clumps found in galaxies with $N_c \geq 2$ detected at $2 < z < 4.5$ with $k_p = 1.5$. Each clump is color coded by the number of clumps found in its parent galaxy. The color scheme is found at the bottom right of the main panel. The black solid line in each of the auxiliary panels shows a fit of a two gaussian model to the observed distribution of areas and magnitudes of the clumps. There is a bimodality present in both distributions and we observe that it is more probable to find the brightest and largest clumps in two clump systems. The contours show the smoothed distribution of the fraction of 2 clump-systems at levels of 10, 25 and 50%. It is clear that the majority of two-clump systems (with respect to all clumpy systems) is found in brighter and larger clumps.

We have computed the average luminosity that is locked in the UV clumps by comparing the total luminosity in clumps to that of its host galaxy. We find that for clumpy galaxies (with two or more clumps) $46 \pm 1.5\%$ of all light is found to be in clumps. If we further divide the sample into two-clump systems

and multi-clump systems we find that the light fraction locked in clumps is virtually the same with $46 \pm 2\%$ for both cases.

redshift	f_{2c} [%]	$f_{2c,bright}$ [%]	$f_{major,bright}$ [%]	$f_{minor,bright}$ [%]	$f_{gal,pair}$ [%]
$2.0 < z < 2.75$	40 ± 6.1	60 ± 15.4	77 ± 22.8	23 ± 9.9	15 ± 4.5
$2.75 < z < 3.5$	38 ± 3.9	60 ± 9.0	64 ± 14.0	36 ± 9.4	21 ± 5.1
$3.5 < z < 4.5$	19 ± 2.4	37 ± 6.3	43 ± 13.8	57 ± 17.0	39 ± 11.6
$4.5 < z < 6.0$	12 ± 2.5	15 ± 3.4	53 ± 32.6	47 ± 29.7	38 ± 24.0

Table 1. Fraction of 2 clump systems in 4 redshift intervals. The second column represents the total fraction of two-clump systems. The third column represents the fraction of clumps in two-clump-systems with at least one of them being brighter than $M_{clump} < -19.1$. The fourth and fifth columns represent the fraction of bright two-clump systems that are in major ($1/4 < L_f/L_b < 1$) and minor ($L_f/L_b < 1/4$) systems. The luminosities are measured in FUV rest-frame. The last column shows the pair fraction corrected for projection effects (see Sect. 3.2) considering pairs of $i_{AB} < 24.5$ VUDS targets with fainter galaxies.

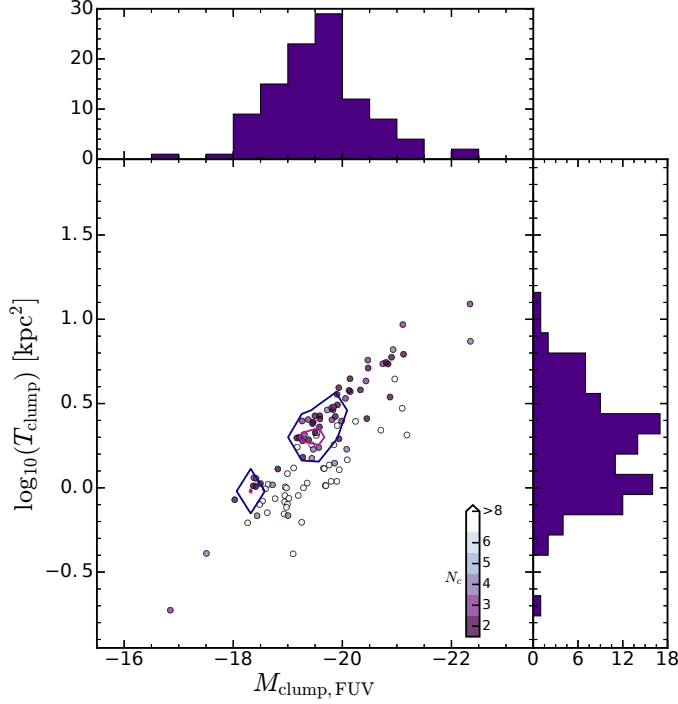


Fig. 9. Absolute magnitude in rest-frame FUV and area distribution for clumps found in galaxies with $N_c \geq 2$ detected at $4.5 < z < 6.0$ with $k_p = 5$. Each clump is color coded by the number of clumps found in its parent galaxy. The color scheme is found at the bottom right of the main panel. The contours show the distribution of fraction of 2 clump-systems at levels of 10 and 25%.

5.3. Luminosity ratios

To classify each two-clump group we have computed the luminosity ratio between the two clumps, L_f/L_b , with L_f being the luminosity of the fainter clump and L_b that of the brighter of the two. The resulting fractions as a function of redshift may be found in Tab 1. The fraction of two-clump galaxies is classified in major ($1/4 < L_f/L_b < 1$) and minor ($L_f/L_b < 1/4$) systems, for galaxies which have at least one clump with $M_{clump} < -19.1$, although statistical uncertainties get large because of the reduced number of galaxies for which we are able to compute this quantity.

5.4. Clump stellar masses

We aim to describe our clumps in term of their stellar-mass by assuming that the mass to light ratio of clumps is the same as its host galaxy. This hypothesis allows us to estimate the stellar mass of each clump by computing the clump to galaxy luminosity ratio and applying that factor to the total stellar mass of the galaxy.

However our estimate is just an approximation and we might overestimate the stellar masses of clumps since they should be on average more star-forming than the galaxy as a whole and we are measuring our luminosities in UV rest-frame.

In Fig. 10 we show the distribution of stellar masses in clumps for three samples. A first sample considering clumps that are in clump systems with at least 3 clumps (hereafter multi-clump-systems). We also show the sample of clumps in two-clump-systems. We compare that sample to the distribution of the stellar masses in single clumps. We note that for single clump systems, a clump can correspond to the entire galaxy. This explains why we find clumps with stellar masses up to $\log_{10}(M_*/M_\odot) \sim 11$.

It is interesting to see that the clumps that are found in two-clump-systems have stellar-masses that peak at higher values (around $\log_{10}(M_*/M_\odot) \sim 9.4$) when compared to clumps in multi-clump-systems. It is also interesting to note that their stellar masses are higher than what is expected for giant molecular clumps from simulations/observations (see e.g. Elmegreen et al. 2009; Genzel et al. 2011; Guo et al. 2012; Bournaud 2016). They show that clumps have stellar masses in the $8 \leq \log_{10}(M_*/M_\odot) \leq 9$ range which is consistent with the bulk ($\sim 55\%$) of the stellar mass distribution we see in multi-clump-systems. We have tested the similarity between the two distributions using a Kolmogorov-Smirnov test and the null hypothesis (that both distributions are the same) is discarded at a 95% confidence level. This difference persists when considering higher values of k_p .

6. Discussion: a merger origin for the bright and large clumps in two-clump galaxies

Our study brings to light two important morphological properties of high redshift galaxies and their evolution from $z \sim 6$ to $z \sim 2$: the fraction of clumpy galaxies as well as the distribution of the number of clumps per galaxy. Both of these properties are a direct consequence of the evolutionary path followed by galaxies, and the physical processes driving this evolution at these early cosmic times.

Defining clumps is a delicate process. At these high redshifts, and with the spatial resolution and depth of HST ACS or WFC3 imaging, only the brightest clumps separated by $\geq 1 kpc$ can be identified. We opted to apply an evolving cut in the isophotal threshold used to define the area of a galaxy where to look for clumps, following the luminosity evolution observed in the star-forming galaxy population at these redshifts. We find the different local maximums, apply a minimum area of 10 connected pixels, and retain groups of pixels which are disconnected down to a level of 80% of the total galaxy flux, to identify clumps within this isophote. The isophote definition has an impact on the number of clumps identified: as the area covered by a brighter isophote gets smaller, the number of clumps within the isophote

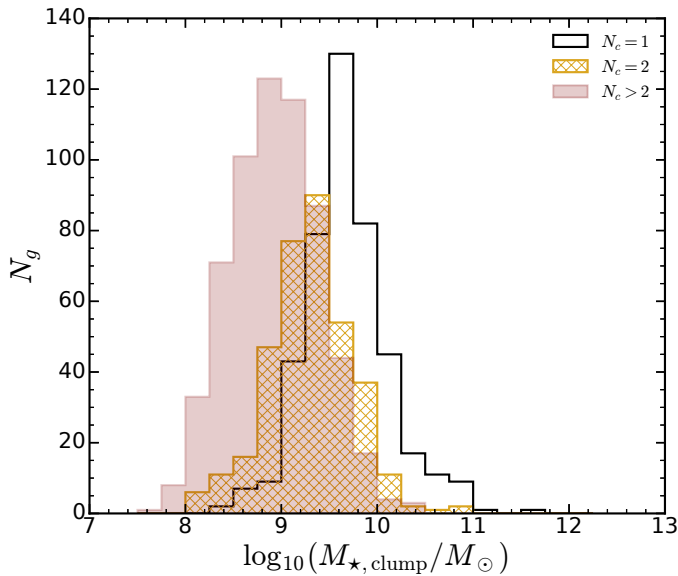


Fig. 10. The distribution of stellar masses in clumps for three different samples. In the black solid line histogram we show the distribution considering single clump galaxies. In the filled brown histogram we show the distribution of stellar masses of clumps in galaxies with 3 or more clumps. The golden hatched histogram shows the stellar mass of clumps in galaxies with 2 clumps.

also gets smaller. We measure the area and absolute luminosity of the clumps and estimate that we are able to reliably identify clumps larger than $\sim 1.5 \text{ kpc}^2$ and with a luminosity brighter than $M_{\text{clump}} < -18$. This process differs from previous attempts at clump identification algorithms (Guo et al. 2015; Shibuya et al. 2016) mainly by the definition of the evolving isophotal cut and the procedure of identifying clumps as local maximum groups detected within such an isophote.

We find that the fraction of clumpy galaxies rises from $\sim 34 \pm 8\%$ at $z \sim 2.25$ to $54 \pm 9\%$ at $z \sim 4$. We observe a trend for a higher clumpy fraction going to higher redshifts, more pronounced when we use a fainter isophote to define the clump search area. We find a slightly lower ($39 \pm 11\%$) clumpy fraction in the higher redshift bin $4.5 < z < 6$, but with an increasing trend with redshift when compared to the bin immediately below at the same isophote level. The depth of the data does not allow to use a comparable isophote when taking into account luminosity evolution between the low redshift and high redshift samples. Nevertheless, the trend suggests that when measured at the same isophote level the clumpy fraction would be the highest at $4.5 < z < 6$.

These results are at odds with the decreasing fraction of clumpy galaxies reported by Guo et al. (2015) and Shibuya et al. (2016). Differences in the definition of what a clumpy galaxy is and in the sample used to compute the clumpy fraction may be the main reasons for this discrepancy. We define a clumpy galaxy as a galaxy with 2 or more detected clumps within its isophote, whereas Guo et al. (2015) and Shibuya et al. (2016) define it when at least one off-center clump is identified. Another important difference resides in our sample selection which does not a priori exclude galaxies because of their morphology (Guo et al. 2015; Shibuya et al. 2016, impose an effective radius $r_e > 0.2''$ and axis ratio $q > 0.5$ cut). As we include in our sample small compact sources, this might further increase the number of non-clumpy galaxies and decrease the clumpy fraction, while including galaxies with low values of q like elongated clump chain

galaxies (see e.g. Elmegreen et al. 2004, 2008) would rather increase it.

In summary, we find that the fraction of clumpy galaxies in the star-forming population as selected in the UV rest-frame with stellar masses $\log_{10}(M_{\star}/M_{\odot}) > -0.204 \times (z - 4.5) + 9.35$, and identifying clumps brighter than $M_{\text{clump,NUV}} < -18$ and larger than $\sim 2 \text{ kpc}^2$ remains at 35-55% over the redshift range $2 < z < 6$, with a trend for an increasing clumpy fraction with redshift. As expected, this fraction does depend on the luminosity threshold and minimum clump area that we impose (see Fig. 7), and hence on the depth and spatial resolution of the images used. It is therefore likely that the clumpy fraction reported here is a lower value to the real clumpy fraction.

Now turning to the analysis of the distribution of the number of clumps per galaxies, there is a large fraction $\sim 21 - 25\%$ of galaxies with only two clumps and the clumps in these galaxies are the brightest and largest as shown in figures 3, 6, 8 and 9. We can identify a few possibilities to form the clumps in these two-clumps galaxies: they could be either (1) the result of disc fragmentation and VDI, (2) two individual galaxies in the final merging process of a galaxy pair, or (3) the chance projection of a galaxy on the line of sight, physically unrelated.

Galaxies with VDI induced clumps have been studied in detailed hydrodynamical simulations which show how fragmentation in a proto-galactic disc produces several clumps, visible over timescales $\lesssim 1 \text{ Gyr}$, before migrating and merging in a galaxy central core (e.g. Bournaud et al. 2007; Dekel et al. 2009; Genel et al. 2012; Bournaud et al. 2014; Oklopčić et al. 2016). We note that we are able to detect clumps that are 1 to 2 magnitudes fainter than what we find for bright clumps in two clump systems. This implies that if additional clumps were to be found with deeper imaging they would be much fainter than what we find and thus we would still observe a large fraction of two clump systems detected above a given luminosity limit. It seems unlikely that a physical scenario following disc fragmentation and VDI would preferentially produce only two bright clumps (F. Bournaud, private communication). Cloud fragmentation due to disk instabilities are more likely to give rise to a higher number of clumps, with the number of clumps reducing over the dynamical timescale of clump merging, as shown in simulations (Mandelker et al. 2014). If VDI is the only process capable of producing clumps one would rather expect to observe more galaxies with 3 or more clumps than two-clumps systems, opposite to what we find (Fig. 5). It is possible that two-clump systems are the end result of clumps formed through VDI after migration and merging of smaller clumps. The typical timescale for clump migration to the galaxy center is of 500 Myr (e.g. Förster Schreiber et al. 2011; Guo et al. 2012; Bournaud 2016) which is typically one fourth of the redshift interval we probe from $2 < z < 4.5$. However, the period on which we would observe two clumps at the same time should be shorter than that. Additionally, we would need to take into account the survival rate of large clumps for which some simulations suggest even shorter lifetimes for clumps (e.g. Genel et al. 2012). We would need spatially resolved information from multi-band high resolution observations or IFU data to compute velocity offsets and stellar ages of the different clumps to confirm or not this scenario against the possibility of it being the final stages of a merging pair of galaxies (e.g. Förster Schreiber et al. 2011; Guo et al. 2012).

Another interpretation is that these two-clumps systems are indicative of on-going merger events. Major or minor mergers do indeed produce a bi-modal light distribution with each of the merging galaxy counted as a clump. Merging is observed

to be a significant process with a high fraction of $\sim 15 - 20\%$ of galaxies involved in major mergers at redshifts $z \sim 1$ and up to $z \sim 4$ (e.g. Le Fèvre et al. 2000; de Ravel et al. 2009; López-Sanjuan et al. 2013; Tasca et al. 2014a). The bright clumps in two-clumps systems and $L_f/L_b > 1/4$ have absolute magnitudes $-19 > M_{NUV} > -22$, producing together a total luminosity equivalent to that of the median of the star-forming population we are probing. Two-clumps systems with one bright clump and $L_f/L_b < 1/4$ may include minor merger events participating to the build-up of stellar mass with time. If we assume that clumps which have $L_f/L_b > 1/4$ are representative of major galaxy mergers we find that 24 – 40% of two-clump systems are then classified as major merger events, remaining roughly constant at $z \gtrsim 3$. This fraction is the same whether we consider VUDS targets only or if we include neighboring two-clump systems found within our 20 kpc search radius. As two-clump systems represent $\sim 25\%$ of the total population, using the fraction of bright two-clump systems (Tab. 1) we find a total merger fraction slightly decreasing with redshift from $\sim 18\%$ at $z \sim 3$ to $\sim 10\%$ at $z \sim 5$. Using those systems with $L_f/L_b > 1/4$ we find a major merger fraction in the range 6.5 to 11%. Similarly, using the fraction of two-clump systems with $L_f/L_b < 1/4$ we find a minor merger fraction of 2.7 to 10.5%.

The derived fraction of merging systems is considering merging of clumps alone. To expand it to a total merger fraction one would also need to account for the fraction of galaxy pairs within a 20 kpc search radius. We find a rising pair fraction corrected for line of sight contamination (see Sect. 3.2), of $\sim 15\%$ at $z \sim 2.3$ which rises to $\sim 38\%$ at $z \sim 5$. One interesting trend is that while the pair fraction is increasing at higher redshifts, the contrary trend is observed for the merger fraction derived from clumps statistics. One may naively expect that we are observing an evolving merger rate measured in two stages, the first, which is more common at the higher redshifts, where galaxies have yet to merge, and the second, as observed from bright clumps counts, representing the final phases of merging before coalescence, which is more common at lower redshifts.

There is a low probability that our observations of two-clumps systems might be consequence of line of sight contamination from lower redshift galaxies which might then be confused with high redshift clumps. We observe that these two-clump systems with at least one bright $M_{clump,NUV} < -19.1$ element have a median clump separations of ~ 3 kpc ($\sim 0.4''$). At such small separations, even when dealing with faint objects with $i_{AB} \sim 27 - 28$, the probability of random line of sight contamination is very small, at less than 3% (see Sect. 3.2 for details). Thus, we conclude that most of these two-clump systems are real physical systems at the same redshift.

As a conclusion, a straightforward interpretation of galaxies with two bright clumps is that this population predominantly includes galaxies caught in the act of a merging event. This interpretation is further reinforced when looking at the typical stellar masses of clumps. We find that for these two clumps systems with at least one bright component, the majority of them ($\sim 77\%$) has stellar masses greater than $\log(M_*/M_\odot) > 9$ which is the typical upper limit on the stellar mass of clumps induced by VDI (see e.g. Elmegreen et al. 2009; Guo et al. 2012; Bournaud 2016). On the other hand, $\sim 55\%$ of clumps in multi-clump systems have stellar masses lower than $\log(M_*/M_\odot) < 9$, which might likely result from VDI as well as minor mergers. The typical masses of the two clumps are more alike the masses of galaxies observed in merging pairs with larger separations (López-Sanjuan et al. 2013; Tasca et al. 2014a).

We are therefore likely witnessing two different modes of clump formation happening in parallel. The overall fraction of clumps is dominated by small and faint clumps, likely the result of both VDI clumps production and minor mergers. However, we do observe an important fraction (in $\sim 10 - 25\%$ of all galaxies) of large bright clumps in two-clump systems that are most likely major mergers.

7. Summary

The results presented in this paper can be summarized as follows:

- The search for clumps in distant galaxies with images at a given depth critically depends on how clumps are defined, on the search area, whether clumps must be embedded within a common isophote limit, and on a priori selection of the galaxy population tested for clumps. We use a new algorithm for detecting clumps, where clumps are defined as groups of connected pixels associated with the same local maximum within the galaxy isophote.
- We compute the number of clumps per galaxy in a sample of 1242 galaxies with $2 < z < 4.5$ and 96 galaxies with $4.5 < z < 6$ with confirmed spectroscopic redshifts from the VIMOS Ultra Deep Survey and in the COSMOS and ECDFS areas where deep HST imaging in the F814W filter is available from the COSMOS and CANDELS surveys. We find that, at $2 < z < 4.5$, the dominant population of clumpy galaxies has two clumps ($\sim 25\%$) followed by galaxies with 3, and more than 3 clumps ($\sim 11, \sim 7\%$ respectively). The same trend is found at higher redshifts ($4.5 < z < 6$) which is dominated by two clump galaxies ($\sim 21\%$) followed by galaxies with 3, and more than 3 clumps ($\sim 8, \sim 9\%$ respectively).
- The fraction of clumpy galaxies, with ≥ 2 clumps and corrected for line of sight chance projections, is found to remain in the range 35 to 55% over $2 < z < 6$, with a trend of an increasing fraction with redshift.
- We find a continuous, possibly bi-modal, distribution of the luminosity and area of clumps with a population of large and bright clumps separated in luminosity and area from a population of small and less luminous clumps. The population of large and bright clumps has typical absolute magnitudes $M_{FUV} \sim -19.7$ and areas $T \sim 6.0$ kpc². In contrast, the population of small and less luminous clumps has typical absolute magnitudes $M_{FUV} \sim -18.1$ and areas $T \sim 1.8$ kpc². We associate the bimodality to the existence of two physical processes, mergers and disk instabilities, that explain the observed properties of clumps.
- The faint and small clumps are preferentially found in multiple clump galaxies. They are comparable in luminosity and stellar mass ($10^8 - 10^9 M_\odot$) to the large star clusters forming in large numerical simulations from violent disc instabilities, consistent with findings from other studies (e.g. Elmegreen et al. 2009; Guo et al. 2012; Bournaud 2016). It is also possible that a fraction of these clumps is related to minor merging events.
- The bright and large clumps are preferentially found in two-clumps systems. These bright clumps have luminosities and stellar masses $\sim 10^9 - 10^{10} M_\odot$, larger than expected from VDI processes. It appears as unlikely that, if clumps were solely produced by VDI, two-clumps systems would strongly dominate the population of clumpy galaxies. We rather conclude that the bright and large clumps in two clump

systems have properties similar to those of galaxies in merging pairs (López-Sanjuan et al. 2013; Tasca et al. 2014a). Using the fraction of galaxies with bright clumps we infer a major merger fraction going from 18% at $z \sim 3$ to 10% at $z \sim 5$. When combined with the pair fraction of galaxies that are not embedded in the same isophote, we find a major merger rate at $\sim 20\%$ comparable to other estimates at similar redshifts (López-Sanjuan et al. 2013; Tasca et al. 2014a).

In quantifying the properties of clumps in star-forming galaxies with $2 < z < 6$ we therefore conclude that we are witnessing the effects of two different galaxy assembly processes working in parallel. Clumps are likely the result of both violent disc instabilities with an in-situ clump formation mode, as well as from major and minor merging of galaxies with an ex-situ assembly of matter. On the one hand gas accretion is expected to feed the buildup of discs which then become unstable and produce clumps that will build galaxy bulges (e.g. Dekel et al. 2009; Bournaud et al. 2009; Dekel & Krumholz 2013; Bournaud 2016). The population of large and bright merging clumps formed *ex-situ* is important because even if they are less numerous they contribute the most to the stellar mass of a galaxy (López-Sanjuan et al. 2013; Tasca et al. 2014a; Mandelker et al. 2014). Both processes are therefore important in building a galaxy formation and evolution scenario both from the point of view of the evolution of the cosmic star formation rate and the build-up of stellar mass of galaxies throughout cosmic time, and explaining key observables like the evolution of the specific star formation rate, and its possible flattening at redshifts $z > 2$ (e.g. Dekel & Mandelker 2014; Tasca et al. 2015; Faisst et al. 2016; Mármol-Queraltó et al. 2016).

Testing the evolution of the number of clumps from larger simulations of galaxies in complete cosmologically representative volumes would bring further insight into these processes. As the clumpy fraction and the number of clumps identified strongly depend on the spatial resolution and depth of images, and as galaxies with large sizes are observed up to large redshifts (Ribeiro et al. 2016), it is likely that future facilities like JWST and extremely large telescopes with adaptive optics may well identify more clumps. Taken together with the high fraction of bright two-clumps galaxies, the wide range of clump properties reported here must be taken into account when planning for future surveys aimed at a complete census of the properties of clumps in the high redshift population.

Acknowledgements. This work is supported by funding from the European Research Council Advanced Grant ERC-2010-AdG-268107-EARLY and by INAF Grants PRIN 2010, PRIN 2012 and PICS 2013. This work is based on data products made available at the CESAM data center, Laboratoire d'Astrophysique de Marseille. This work partly uses observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada-France-Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Sciences de l'Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This work is based in part on data products produced at TERAPIX and the Canadian Astronomy Data Centre as part of the Canada-France-Hawaii Telescope Legacy Survey, a collaborative project of NRC and CNRS. BR gratefully thanks Ana Afonso for late-night and helpful discussions, style tips and English typo corrections. This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013); Numpy & Scipy (Walt et al. 2011); Matplotlib (Hunter 2007).

References

Abraham, R. G., van den Bergh, S., Glazebrook, K., et al. 1996, *ApJS*, 107, 1
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, 558, A33

Bournaud, F. 2016, *Galactic Bulges*, 418, 355
Bournaud, F., Daddi, E., Elmegreen, B. G., et al. 2008, *A&A*, 486, 741
Bournaud, F., Elmegreen, B. G., & Elmegreen, D. M. 2007, *ApJ*, 670, 237
Bournaud, F., Elmegreen, B. G., & Martig, M. 2009, *ApJ*, 707, L1
Bournaud, F., Perret, V., Renaud, F., et al. 2014, *ApJ*, 780, 57
Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015, *ApJ*, 803, 34
Bruce, V. A., Dunlop, J. S., Cirasuolo, M., et al. 2012, *MNRAS*, 427, 1666
Bruce, V. A., Dunlop, J. S., McLure, R. J., et al. 2014a, *MNRAS*, 444, 1660
Bruce, V. A., Dunlop, J. S., McLure, R. J., et al. 2014b, *MNRAS*, 444, 1001
Bruzual, G. & Charlot, S. 2003, *MNRAS*, 344, 1000
Buitrago, F., Trujillo, I., Conselice, C. J., & Häußler, B. 2013, *MNRAS*, 428, 1460
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682
Capak, P., Aussel, H., Ajiki, M., et al. 2007, *ApJS*, 172, 99
Chabrier, G. 2003, *ApJ*, 586, L133
Conselice, C. J. 2014, *ARA&A*, 52, 291
Conselice, C. J. & Arnold, J. 2009, *MNRAS*, 397, 208
Conselice, C. J., Rajgor, S., & Myers, R. 2008, *MNRAS*, 386, 909
Cowie, L. L., Hu, E. M., & Songaila, A. 1995, *AJ*, 110, 1576
Curtis-Lake, E., McLure, R. J., Dunlop, J. S., et al. 2016, *MNRAS*, 457, 440
de Ravel, L., Le Fèvre, O., Tresse, L., et al. 2009, *A&A*, 498, 379
Dekel, A. & Krumholz, M. R. 2013, *MNRAS*, 432, 455
Dekel, A. & Mandelker, N. 2014, *MNRAS*, 444, 2071
Dekel, A., Sari, R., & Ceverino, D. 2009, *ApJ*, 703, 785
Di Matteo, P., Bournaud, F., Martig, M., et al. 2008, *A&A*, 492, 31
Elmegreen, B. G., Bournaud, F., & Elmegreen, D. M. 2008, *ApJ*, 688, 67
Elmegreen, B. G., Elmegreen, D. M., Fernandez, M. X., & Lemonias, J. J. 2009, *ApJ*, 692, 12
Elmegreen, B. G., Elmegreen, D. M., Sánchez Almeida, J., et al. 2013, *ApJ*, 774, 86
Elmegreen, D. M. & Elmegreen, B. G. 2006, *ApJ*, 651, 676
Elmegreen, D. M., Elmegreen, B. G., Ravindranath, S., & Coe, D. A. 2007, *ApJ*, 658, 763
Elmegreen, D. M., Elmegreen, B. G., & Sheets, C. M. 2004, *ApJ*, 603, 74
Faisst, A. L., Capak, P., Hsieh, B. C., et al. 2016, *ApJ*, 821, 122
Fürster Schreiber, N. M., Shapley, A. E., Genzel, R., et al. 2011, *ApJ*, 739, 45
Freeman, P. E., Izbicki, R., Lee, A. B., et al. 2013, *MNRAS* [arXiv:1306.1238]
Garilli, B., Fumana, M., Franzetti, P., et al. 2010, *PASP*, 122, 827
Garland, C. A., Pisano, D. J., Mac Low, M.-M., et al. 2015, *ApJ*, 807, 134
Genel, S., Naab, T., Genzel, R., et al. 2012, *ApJ*, 745, 11
Genzel, R., Burkert, A., Bouché, N., et al. 2008, *ApJ*, 687, 59
Genzel, R., Newman, S., Jones, T., et al. 2011, *ApJ*, 733, 101
Giavalisco, M., Livio, M., Bohlin, R. C., Macchetto, F. D., & Stecher, T. P. 1996, *AJ*, 112, 369
Glazebrook, K. 2013, *PASA*, 30, e056
Grogan, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, *ApJS*, 197, 35
Guo, Y., Ferguson, H. C., Bell, E. F., et al. 2015, *ApJ*, 800, 39
Guo, Y., Giavalisco, M., Ferguson, H. C., Cassata, P., & Koekemoer, A. M. 2012, *ApJ*, 757, 120
Hartigan, J. A. & Hartigan, P. M. 1985, *Ann. Statist.*, 13, 70
Hopkins, P. F., Hernquist, L., Cox, T. J., Dutta, S. N., & Rothberg, B. 2008, *ApJ*, 679, 156
Huertas-Company, M., Pérez-González, P. G., Mei, S., et al. 2015, *ApJ*, 809, 95
Hunter, J. D. 2007, *Computing In Science & Engineering*, 9, 90
Ilbert, O., McCracken, H. J., Le Fèvre, O., et al. 2013, *A&A*, 556, A55
Koekemoer, A. M., Aussel, H., Calzetti, D., et al. 2007, *ApJS*, 172, 196
Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011, *ApJS*, 197, 36
Kubo, M., Uchimoto, Y. K., Yamada, T., et al. 2013, *ApJ*, 778, 170
Kubo, M., Yamada, T., Ichikawa, T., et al. 2016, *MNRAS*, 455, 3333
Lang, P., Wuyts, S., Somerville, R. S., et al. 2014, *ApJ*, 788, 11
Law, D. R., Steidel, C. C., Shapley, A. E., et al. 2010, *ApJ*, 745, 85
Le Fèvre, O., Abraham, R., Lilly, S. J., et al. 2002, *MNRAS*, 311, 565
Le Fèvre, O., Saisse, M., & Mancini, D. 2003, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 4841, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, ed. M. Iye & A. F. M. Moorwood, 1670–1681
Le Fèvre, O., Tasca, L. A. M., Cassata, P., et al. 2015, *A&A*, 576, A79
López-Sanjuan, C., Le Fèvre, O., de Ravel, L., et al. 2011, *A&A*, 530, A20
López-Sanjuan, C., Le Fèvre, O., Ilbert, O., et al. 2012, *A&A*, 548, A7
López-Sanjuan, C., Le Fèvre, O., Tasca, L. A. M., et al. 2013, *A&A*, 553, A78
Lotz, J. M., Jonsson, P., Cox, T. J., et al. 2011, *ApJ*, 742, 103
Madau, P. & Dickinson, M. 2014, *ARA&A*, 52, 415
Mandelker, N., Dekel, A., Ceverino, D., et al. 2014, *MNRAS*, 443, 3675
Margalef-Bentabol, B., Conselice, C. J., Mortlock, A., et al. 2016, *MNRAS*, 461, 2728
Mármol-Queraltó, E., McLure, R. J., Cullen, F., et al. 2016, *MNRAS*, 460, 3587
Mortlock, A., Conselice, C. J., Hartley, W. G., et al. 2013, *MNRAS*, 433, 1185
Murata, K. L., Kajisawa, M., Taniguchi, Y., et al. 2014, *ApJ*, 786, 15
Oklopčić, A., Hopkins, P. F., Feldmann, R., et al. 2016, *ArXiv e-prints* [arXiv:1603.03778]

- Oser, L., Naab, T., Ostriker, J. P., & Johansson, P. H. 2012, *ApJ*, 744, 63
- Perez, J., Valenzuela, O., Tissera, P. B., & Michel-Dansac, L. 2013, *MNRAS*, 436, 259
- Porter, L. A., Somerville, R. S., Primack, J. R., et al. 2014, *MNRAS*, 445, 3092
- Puech, M. 2010, *MNRAS*, 406, 535
- Ravindranath, S., Giallisco, M., Ferguson, H. C., et al. 2006, *ApJ*, 652, 963
- Reddy, N. A. & Steidel, C. C. 2009, *ApJ*, 692, 778
- Ribeiro, B., Le Fèvre, O., Tasca, L. A. M., et al. 2016, *ArXiv e-prints* [arXiv:1602.01840]
- Rodríguez-Gómez, V., Pillepich, A., Sales, L. V., et al. 2016, *MNRAS*, 458, 2371
- Salpeter, E. E. 1955, *ApJ*, 121, 161
- Scodeggio, M., Franzetti, P., Garilli, B., et al. 2005, *PASP*, 117, 1284
- Scoville, N., Abraham, R. G., Aussel, H., et al. 2007, *ApJS*, 172, 38
- Shibuya, T., Ouchi, M., & Harikane, Y. 2015, *ApJS*, 219, 15
- Shibuya, T., Ouchi, M., Kubo, M., & Harikane, Y. 2016, *ApJ*, 821, 72
- Tadaki, K.-i., Kodama, T., Tanaka, I., et al. 2014, *ApJ*, 780, 77
- Tasca, L. A. M., Le Fèvre, O., Hathi, N. P., et al. 2015, *A&A*, 581, A54
- Tasca, L. A. M., Le Fèvre, O., López-Sanjuan, C., et al. 2014a, *A&A*, 565, A10
- Tasca, L. A. M., Le Fèvre, O., Ribeiro, B., et al. 2016, *ArXiv e-prints* [arXiv:1602.01842]
- Tasca, L. A. M., Tresse, L., Le Fèvre, O., et al. 2014b, *A&A*, 564, L12
- Thomas, R., Le Fèvre, O., Scodeggio, M., et al. 2016, *ArXiv e-prints* [arXiv:1602.01841]
- van den Bergh, S., Abraham, R. G., Ellis, R. S., et al. 1996, *AJ*, 112, 359
- Walt, S. v. d., Colbert, S. C., & Varoquaux, G. 2011, *Computing in Science & Engineering*, 13, 22
- Williams, R. E., Blacker, B., Dickinson, M., et al. 1996, *AJ*, 112, 1335
- Wuyts, S., Förster Schreiber, N. M., Genzel, R., et al. 2012, *ApJ*, 753, 114

Appendix A: Computing the clumpy fraction using a different methodology

To contextualize our results with those that are available through recent studies (e.g. Guo et al. 2015; Shibuya et al. 2016) we have attempted to implement the same methodology and compare what we obtain against the results we get from the algorithm described in Sect. 3. The alternative method that we use summarizes as follows

1. We run SExtractor on a $7''$ by $7''$ image to obtain the segmentation map.
2. We dilate the segmentation map using a binary operation that effectively smooths and enlarges by a maximum of 3 pixels the outer edges of the segmentation map.
3. We select a small cutout of the original image that adapts to the size of the created segmentation map.
4. We apply a boxcar filter (10 pixels width) to the new cutout.
5. We create a residual image by subtracting the filtered image to the original one.
6. We measure the residual background flux using a 3σ -clipping method.
7. We mask all pixels that have fluxes smaller than 2σ of the calculated background.
8. Run a new detection algorithm on the masked residual image to detect clumps.

All regions in the masked residual image that have more than 5 connected pixels are counted as single clumps. We also compute the magnitude of each clump using a 3 pixel aperture.

To compute then the final clumpy fraction, we select only galaxies for which we have GALFIT results (see Ribeiro et al. 2016) and that have effective radius $r_e > 0.2''$, and axis ratio $q > 0.5$. We apply the same intermediate mass selection ($9.8 < \log_{10}(M_*/M_\odot) < 10.6$). Finally, we only consider clumps which contain more than 8% of the galaxy light. The result is found as the red squares of Fig. A.1. We compare to our clumpy fraction computed at $k_p = 2.0$ to be comparable with the 2σ detection limit that is imposed when finding clumps using this alternative method. In this exercise we have also included off-center clumps as defined above when computing the clumpy fraction using the method presented in this paper. It is possible that the differences in the clumpy fraction are caused by sample selection and not the methodology, although our errors cannot confirm this hypothesis.

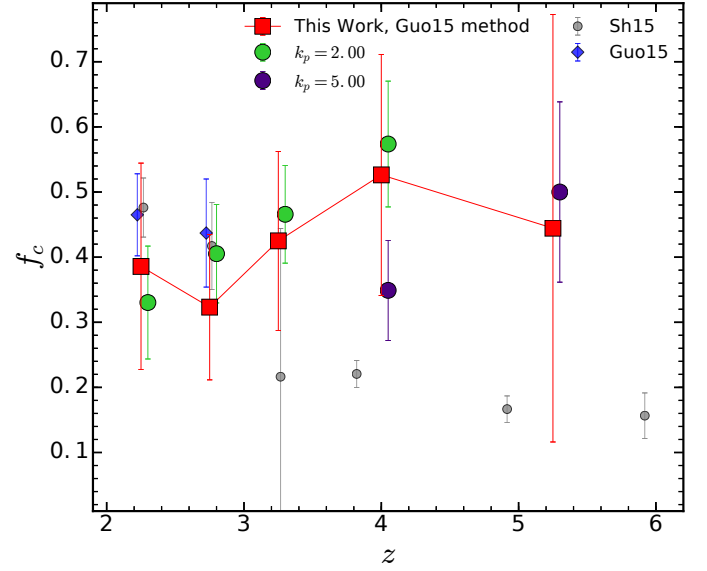


Fig. A.1. Clumpy fraction in the VUDS sample as computed using the method described by Guo et al. (2015) (red squares) when compared to that defined in this paper with the inclusion of off-center clumps (see text) as green/purple circles, and the studies by Guo et al. (2015) as blue diamonds and Shibuya et al. (2016) as gray circles which use the same methodology.

The VIMOS Ultra Deep Survey First Data Release: spectra and spectroscopic redshifts of 698 objects up to $z_{spec} \sim 6$ in CANDELS [★]

L. A. M. Tasca¹, O. Le Fèvre¹, B. Ribeiro¹, R. Thomas¹, C. Moreau¹, P. Cassata⁵, B. Garilli⁶, V. Le Brun¹, B. C. Lemaux¹, D. Maccagni⁶, L. Pentericci⁷, D. Schaerer^{2,3}, E. Vanzella⁴, G. Zamorani⁴, E. Zucca⁴, R. Amorin⁷, S. Bardelli⁴, L. P. Cassarà⁶, M. Castellano⁷, A. Cimatti⁸, O. Cucciati^{8,4}, A. Durkalec^{1,21}, A. Fontana⁷, M. Giavalisco⁹, A. Grazian⁷, N.P. Hathi¹, O. Ilbert¹, S. Paltani¹⁰, J. Pforr¹, M. Scodeggio⁶, V. Sommariva^{8,7}, M. Talia⁸, L. Tresse¹, D. Vergani^{11,4}, P. Capak¹², S. Charlot¹³, T. Contini¹⁴, S. de la Torre¹, J. Dunlop¹⁵, S. Fotopoulou¹⁰, L. Guaita⁷, A. Koekemoer¹⁶, C. López-Sanjuan¹⁷, Y. Mellier¹³, M. Salvato¹⁸, N. Scoville¹⁹, Y. Taniguchi²⁰, and P.W. Wang¹

¹ Aix Marseille Université, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 13388, Marseille, France

² Geneva Observatory, University of Geneva, ch. des Maillettes 51, CH-1290 Versoix, Switzerland

³ Institut de Recherche en Astrophysique et Planétologie - IRAP, CNRS, Université de Toulouse, UPS-OMP, 14, avenue E. Belin, F31400 Toulouse, France

⁴ INAF-Osservatorio Astronomico di Bologna, via Ranzani, 1 - 40127, Bologna

⁵ Instituto de Física y Astronomía, Facultad de Ciencias, Universidad de Valparaíso, Gran Bretaña 1111, Playa Ancha, Valparaíso Chile

⁶ INAF-IASF Milano, via Bassini 15, I-20133, Milano, Italy

⁷ INAF-Osservatorio Astronomico di Roma, via di Frascati 33, I-00040, Monte Porzio Catone, Italy

⁸ University of Bologna, Department of Physics and Astronomy (DIFA), V.le Berti Pichat, 6/2 - 40127, Bologna

⁹ Astronomy Department, University of Massachusetts, Amherst, MA 01003, USA

¹⁰ Department of Astronomy, University of Geneva ch. d'Écogia 16, CH-1290 Versoix, Switzerland

¹¹ INAF-IASF Bologna, via Gobetti 101, I-40129, Bologna, Italy

¹² Department of Astronomy, California Institute of Technology, 1200 E. California Blvd., MC 249-17, Pasadena, CA 91125, USA

¹³ Institut d'Astrophysique de Paris, UMR7095 CNRS, Université Pierre et Marie Curie, 98 bis Boulevard Arago, 75014 Paris, France

¹⁴ Institut de Recherche en Astrophysique et Planétologie - IRAP, CNRS, Université de Toulouse, UPS-OMP, 14, avenue E. Belin, F31400 Toulouse, France

¹⁵ SUPA, Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, EH9 3HJ, United Kingdom

¹⁶ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

¹⁷ Centro de Estudios de Física del Cosmos de Aragón, Teruel, Spain

¹⁸ Max-Planck-Institut für Extraterrestrische Physik, Postfach 1312, D-85741, Garching bei München, Germany

¹⁹ Department of Astronomy, California Institute of Technology, 1200 E. California Blvd., MC 249-17, Pasadena, CA 91125, USA

²⁰ Research Center for Space and Cosmic Evolution, Ehime University, Bunkyo-cho 2-5, Matsuyama 790-8577, Japan

²¹ National Centre for Nuclear Research, Astrophysics Division, Hoza 69, 00-681, Warszawa, Poland

e-mail: lidia.tasca@lam.fr

Received ...; accepted ...

ABSTRACT

This paper describes the first data release (DR1) of the VIMOS Ultra Deep Survey (VUDS). The DR1 includes all low-resolution spectroscopic data obtained in 276.9 arcmin² of the CANDELS-COSMOS and CANDELS-ECFDS survey areas, including accurate spectroscopic redshifts z_{spec} and individual spectra obtained with VIMOS on the ESO-VLT. A total of 698 objects have a measured redshift, with 677 galaxies, two type-I AGN and a small number of 19 contaminating stars. The targets of the spectroscopic survey are selected primarily on the basis of their photometric redshifts to ensure a broad population coverage. About 500 galaxies have $z_{spec} > 2$, 48 with $z_{spec} > 4$, and the highest reliable redshifts reach beyond $z_{spec} = 6$. This dataset approximately doubles the number of galaxies with spectroscopic redshifts at $z > 3$ in these fields. We discuss the general properties of the sample in terms of the spectroscopic redshift distribution, the distribution of Lyman- α equivalent widths, and physical properties including stellar masses M_* and star formation rates (SFR) derived from spectral energy distribution fitting with the knowledge of the knowledge of z_{spec} . We highlight the properties of the most massive star-forming galaxies, noting the large range in spectral properties, with Lyman- α in emission or in absorption, and in imaging properties with compact, multi-component or pair morphologies. We present the catalogue database and data products. All data are publicly available and can be retrieved from a dedicated query-based database available at <http://cesam.lam.fr/vuds>.

Key words. Galaxies: distances and redshifts – Galaxies: high redshift – Cosmology: observations – Astronomical data bases: surveys – Astronomical data bases: catalogs

1. Introduction

Deep uniformly targeted galaxy surveys are reliably uncovering the average properties of distant galaxy populations, a primary source of information to consolidate a galaxy formation and evolution scenario. Spectroscopic surveys play a key role as they provide accurate redshifts together with a wealth of spectral properties including continuum, emission or absorption line features and indexes, which allow to fully characterize the physical properties of galaxies. An important goal of these surveys is to provide robust properties of galaxy populations and their distributions around mean values from volume-complete samples, and also enable serendipitous discoveries and studies of rare populations.

A number of spectroscopic galaxy surveys were performed in the past years, reaching increasingly higher redshifts and larger volumes. The local universe is well surveyed by the staged Sloan Digital Sky Survey (SDSS) with more than a million galaxies observed at redshifts $z \sim 0.1 - 0.7$, as presented in the latest DR12 data release (Alam et al. 2015; Reid et al. 2016). At redshifts ~ 1 several spectroscopic surveys have sampled large volumes of the universe with $\sim 10\,000$ to $\sim 100\,000$ galaxies, VVDS-Wide (Le Fèvre et al. 2005, 2013), DEEP2 (Davis et al. 2003), zCOSMOS (Lilly et al. 2007), VIPERS (Guzzo et al. 2014), providing a reliable description of the galaxy properties in relation to their local environment. At redshifts $z > 2$ spectroscopic surveys have been more limited in scope with several thousand galaxies identified at $z \sim 2 - 4$ (Steidel et al. 2003; Bielby et al. 2011; Le Fèvre et al. 2013; Kriek et al. 2015; Momcheva et al. 2015), and only a few hundred at $z > 4$ (Vanzella et al. 2009; Stark et al. 2009; Le Fèvre et al. 2013; Pentericci et al. 2014). At these high redshifts the main reference samples discussed in the literature are mostly based on photometric redshift estimates obtained from SED fitting of a set of broad and medium band filters (e.g. Ilbert et al. 2006, 2009, 2010, 2013), are selected using the Lyman-break technique (e.g. Bouwens et al. 2015), or result from the identification of excess flux in narrow band filters selecting high- z Lyman- α emitters (e.g. Rhoads et al. 2003; Ouchi et al. 2008).

Data releases from spectroscopic surveys are a fundamental step to provide access to a documented data set for a wide community. They enable a wide range of science investigations and provide a basis to establish a galaxy evolution scenario that needs to be accurately reproduced by theoretical predictions and numerical simulations. The availability of a documented reference for such data releases greatly aids this process. The galaxy samples accessed from data releases provide an observational reference upon which our view of the universe is built. SDSS has produced 12 data releases (DR12; Alam et al. 2015; Reid et al. 2016), and data release papers can be found for most major spectroscopic surveys including VVDS (Le Fèvre et al. 2013), DEEP2 (Newman et al. 2013), zCOSMOS-bright (Lilly et al. 2009a), and VIPERS (Garilli et al. 2014). The interactions of users with large datasets are easily facilitated by the availability of databases, where query-based interfaces allow advanced data mining.

In this paper we present the first data release (DR1) of the VIMOS Ultra Deep Survey (VUDS). VUDS is conceived to alleviate some of the limitations related to photometric samples by assembling a large sample of galaxies with *spectroscopic redshifts* up to some of the highest redshifts that can be reached with

an 8m-class telescope (Le Fèvre et al. 2015). The primary goal of VUDS is to provide an accurate view of star-forming galaxies in the distant universe at redshifts $z > 2$ and up to $z \sim 6$, as seen from a UV rest-frame perspective. With a large sample assembled over a large volume and star-forming galaxies dominating galaxy counts it becomes possible to build a robust statistical description of the galaxy population at a key time in galaxy evolution, leading to an improved understanding of galaxy assembly at early cosmic times. Targets in VUDS are selected based on their photometric redshifts supplemented with colour selection and then observed with long integrations with the VIMOS multi-slit spectrograph on the VLT. With $\sim 10\,000$ objects targeted in one square degree built from three separate fields to minimize cosmic variance, VUDS is today the largest spectroscopic survey of the universe at these high redshifts (Le Fèvre et al. 2015).

The availability to a broad community of spectra of high redshift galaxies in well studied extragalactic fields is essential for an improved knowledge of galaxy evolution. The VUDS-DR1 presented in this paper consists of 698 spectroscopic redshift measurements and calibrated one-dimensional spectra in 276.9 arcmin² of the COSMOS and ECDFS areas of the CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011a), as well as associated physical quantities including stellar masses and star-formation rates. The VUDS data in the COSMOS and ECDFS regions of the HST-CANDELS survey offers the opportunity to couple the exquisite HST imaging data with the largest deep spectroscopy sample available to date.

We present the VUDS survey in CANDELS in Section 2, and the observations in Sect.3. The general properties of the sample are discussed in Sect.4, and some remarkable galaxies in this sample are presented in Sect.5. The content of the VUDS data release number 1 is described in Sect.6. A summary is provided in Sect.7.

When quoting absolute quantities we use a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{0,\Lambda} = 0.7$ and $\Omega_{0,m} = 0.3$. All magnitudes are given in the AB system.

2. The VUDS survey in the CANDELS fields

VUDS is a spectroscopic survey targeting $\approx 10\,000$ galaxies to study galaxy evolution in the redshift range $2 < z < 6+$. We provide a summary of the survey below and the reader is referred to Le Fèvre et al. (2015) for a detailed description.

Prior to spectroscopy, targets are primarily selected from their photometric redshifts. Photometric redshifts z_{phot} are computed using available broad-band visible and infrared photometry, as well as medium-band photometry in the COSMOS field, and fitting the spectral energy distribution (SED) using the Le Phare software (Ilbert et al. 2006). We retain as primary targets all objects at $i_{AB} \leq 25$ which satisfy $z_{phot} + 1\sigma \geq 2.4$, representing more than 90% of the sample. Objects which verify Lyman-break galaxy colour selection criteria in the ugr, gri and riz colour-colour diagrams (see criteria in Bouwens et al. 2007), and which are not already selected by their photometric redshift, are added to the target list; this concerns about 10% of the final targets.

The VIMOS field of view is 224 arcmin^2 covered by four spectrograph channels with external dimensions $14 \times 16 \text{ arcmin}^2$ and a typical footprint as identified in Le Fèvre et al. (2005), with the four channels separated by sky areas without VIMOS field coverage. We define the area of this data release as the area in common between the area covered by the CANDELS H-band observations with the WFC3 camera on-board the Hubble Space

* Based on data obtained with the European Southern Observatory Very Large Telescope, Paranal, Chile, under Large Program 185.A-0791.

Telescope (Koekemoer et al. 2011b), and the different VUDS pointings.

The VUDS–CANDELS data release concerns two of the most observed extragalactic fields: COSMOS at $\alpha_{2000} = 10^{\text{h}}00^{\text{m}}28.2^{\text{s}}$, $\delta_{2000} = 02^{\circ}21'36''$ and ECDFS at $\alpha_{2000} = 03^{\text{h}}32^{\text{m}}30^{\text{s}}$, $\delta_{2000} = -27^{\circ}48'00''$.

The COSMOS field is rooted on the original HST–COSMOS survey covering about 2 square degrees (Scoville et al. 2007; Koekemoer et al. 2007) with a wealth of multi-wavelength optical and infrared photometry (e.g. Taniguchi et al. 2007; Ilbert et al. 2009; McCracken et al. 2012). The COSMOS field has been the focus of extensive redshift survey campaigns with the VLT (e.g. zCOSMOS survey, Lilly et al. 2007, 2009b, & Lilly et al. in prep.), Keck (P. Capak, P.I.) and Subaru (Silverman et al. 2015). In the 163.4 arcmin^2 CANDELS area of the COSMOS field, about 1000 galaxies have spectroscopic redshifts from the literature prior to VUDS, mainly at low redshifts but including about 300 galaxies with $2 < z < 3$.

The ECDFS covers $30 \times 30 \text{ arcmin}^2$ and has been the target of a number of spectroscopic observations at the VLT (e.g. Le Fèvre et al. 2004; Vanzella et al. 2008; Balestra et al. 2010) as well as Magellan (Cooper et al. 2012), totalling over 7000 spectroscopic redshifts at various depths and in various redshift ranges. In the CANDELS 113.5 arcmin^2 area of the ECDFS about 2400 spectroscopic redshifts are available from the literature prior to VUDS, including about 500 with $z > 2$.

The VUDS–CANDELS release presented here significantly increases the number of available spectroscopic redshifts at $z > 2$ in two of the most observed extragalactic fields as described below.

3. Observations

Multi-slit spectroscopy is conducted with the Visible Multi-Object Spectrograph (VIMOS) on the ESO–VLT unit number 3 “Melipal” (Le Fèvre et al. 2003). Each VIMOS pointing is observed for about 14 hours in the LRBLUE grism with a wavelength coverage from 3600 to 6700 Å, and another 14 hours with the LRRED grism covering 5500 to 9350 Å. Each of the LRBLUE and LRRED observations cumulate about 40 individual exposures of $\sim 20 \text{ min}$ integrations each. To remove most of the small scale detector pattern, the telescope is offset between each exposure to move objects along the slits with a repeated offset pattern -1.0, -0.5, 0, +0.5, +1.0 arcsecond from the nominal pointing position.

The VIMOS pointings relevant for this release and associated observing conditions are listed in Table 1. In the COSMOS field eight VIMOS quadrants in four separate VIMOS pointings fall in the CANDELS area (Figure 1 and Table 1). The total area in common between VUDS–COSMOS and CANDELS–COSMOS is 163.43 arcmin^2 , excluding the regions where VIMOS did not observe (i.e. in the sky area which is blocked from view between the four channels of the VIMOS focal plane Le Fèvre et al. 2005). The CANDELS area in ECDFS was observed with seven quadrants coming from two VIMOS pointings and include 113.49 arcmin^2 of the CANDELS–ECDFS area (Figure 2 and Table 1). All observations were executed in the ESO–VLT service mode, requesting excellent observing conditions with seeing less than 1 arcsec FWHM, photometric quality, and dark time with moon distance larger than 60 degrees if present. The process of quality control associated to the service mode observations resulted in an excellent and homogeneous set of observations with seeing in the range FWHM=0.5–1 arcsec.

Data reduction follows well established protocols for multi-slit observations (e.g. Le Fèvre et al. 1995; Le Fèvre et al. 2005, 2015). Each observed slit of the multi-slit masks and each of the individual ~ 40 exposures is processed in the following way using the VIPGI environment (Scodreggio et al. 2005). First, 2D spectrograms are extracted, wavelength calibrated using He+Ar spectra, and sky subtraction is performed at each wavelength using a low-order polynomial fit along the slit profile. The spectra are registered to the same relative position in the slit to take into account the offsets applied during the observations, and then stacked using a sigma-clipped average which removes most of the instrumental signatures. Spectra are then placed in the FK5 celestial coordinates grid. The spectrum associated to the primary target on which the slit has been positioned is identified, and other spectra traces or single emission lines objects (e.g. faint Ly α emitters) are associated to photometric catalogue entries (secondary target, spectroscopic flag 2X, see Sect. 6.1), or categorized as spectroscopic emitters without photometric counterpart (flag -2X).

One-dimensional spectra are then extracted using optimal weighting based on a Gaussian fit of the 1D profile of each object projected along the dispersion axis, and are sky-corrected as well as flux calibrated using calibrations performed at regular intervals on spectrophotometric standards. The flux calibration assumes that each observing sequence (observing block) is obtained under photometric conditions, which is generally the case for observations in service mode forced to comply to strict observations requirements. This sequence is applied to both the LRBLUE and LRRED grating observations. The LRBLUE and LRRED spectra are then joined to build the final 1D spectrum for each object covering the wavelength range 3600 to 9350 Å after scaling based on the average flux in the overlap wavelength range $5500 < \lambda < 6700 \text{ Å}$ in common between the LRBLUE and LRRED. Each 1D spectrum is associated with the nearest object in $(\alpha_{2000}, \delta_{2000})$ coordinates in the parent target catalogue. A further joint visual examination of photometric images and 2D-spectra is performed to sort out any ambiguity in associating a photometric image to a trace in a 2D-spectrum.

All 1D and 2D spectra are visually examined to assign a redshift, following a method extensively used for high redshift galaxy surveys as described in Le Fèvre et al. (2005), Lilly et al. (2007), Le Fèvre et al. (2013), and Le Fèvre et al. (2015). The method makes use of the EZ redshift measuring package (Garilli et al. 2010) which cross-correlates observed spectra with empirical galaxy, AGN, and stellar templates.

At the end of this process each object observed has flux and wavelength calibrated 2D and 1D spectra associated to it and gets assigned a spectroscopic redshift z_{spec} and a reliability flag z_{flag} (see Section 6.1 and Table 3 for a description of the spectroscopic flag system).

4. General properties of galaxies in VUDS–CANDELS

4.1. Redshift distribution

The redshift distribution in each of the VUDS–CANDELS COSMOS and VUDS–CANDELS ECDFS fields is shown in Figure 3. The redshift distributions show a number of significant peaks as the lines of sight in each of the fields crosses over the large-scale structure distribution.

Several peaks in the $N(z)$ distribution are associated with documented structures in the literature and support the existence of these over-densities. In the COSMOS field the two most

Table 1. List of VUDS pointings covering the CANDELS–ECDFS and CANDELS–COSMOS

Field	α_{2000}	δ_{2000}
COSMOS–P05	10h00m04.08s	+02 deg 12'41.4"
COSMOS–P06	10h01m05.76s	+02 deg 12'41.4"
COSMOS–P07	10h00m04.08s	+02 deg 30'46.7"
COSMOS–P08	10h01m05.76s	+02 deg 30'46.7"
ECDFS–P01	03h32m25.99s	−27 deg 41'59.9"
ECDFS–P02	03h32m34.00s	−27 deg 53'59.9"

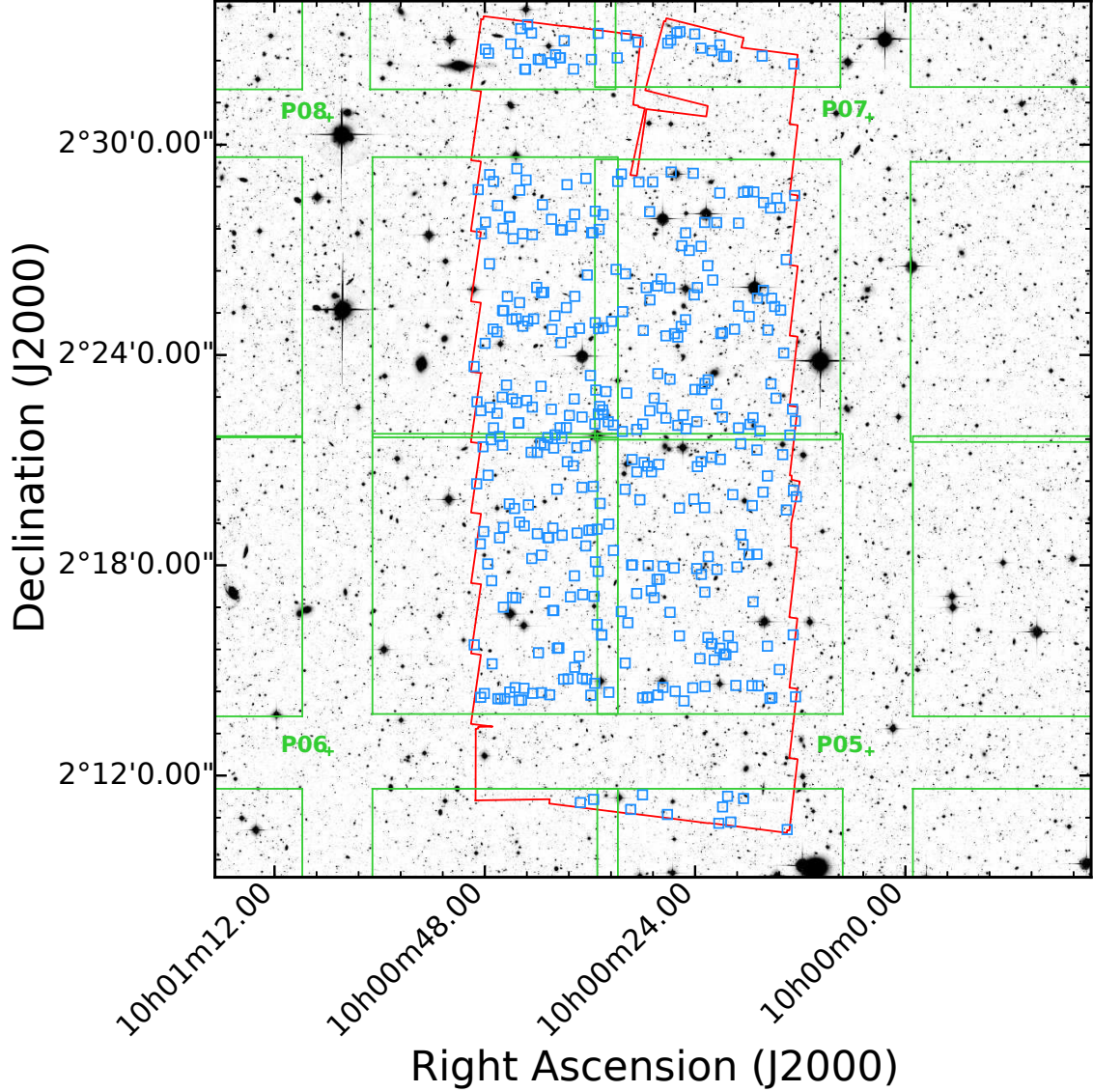


Fig. 1. The VUDS coverage of the CANDELS H-band F160W area in the COSMOS field. The CANDELS area is indicated by the red polygon, and the 4-quadrant footprint of the 4 overlapping VIMOS pointings is overlaid as the green rectangles with the pointing number identified. Because of the geometry of the VUDS footprint on the sky, regions corresponding to the ~ 2 arcmin gap between VIMOS channels did not receive spectroscopic observations as it is apparent in the lower and upper parts of the CANDELS area. The 384 galaxies with VUDS redshifts falling in the area in common between CANDELS and VUDS are plotted as the blue squares.

prominent peaks in the VUDS $N(z)$ are at $z \sim 2.45$ and $z \sim 2.9$. The strong over-density at $z \sim 2.45$ was recently pointed out by Chiang et al. (2015) and identified by Casey et al. (2015) as a proto-cluster including seven star-bursting submillimeter-luminous galaxies and five AGN. In the COSMOS–CANDELS

area alone we find 22 galaxies with $2.45 \leq z_{\text{spec}} \leq 2.5$. This appears to be a massive and complex structure comprised of two or three main components which will be further investigated in Lemaux & al. (2016). The peak at $z \sim 2.9$ corresponds to a surrounding structure associated to the proto-cluster identified

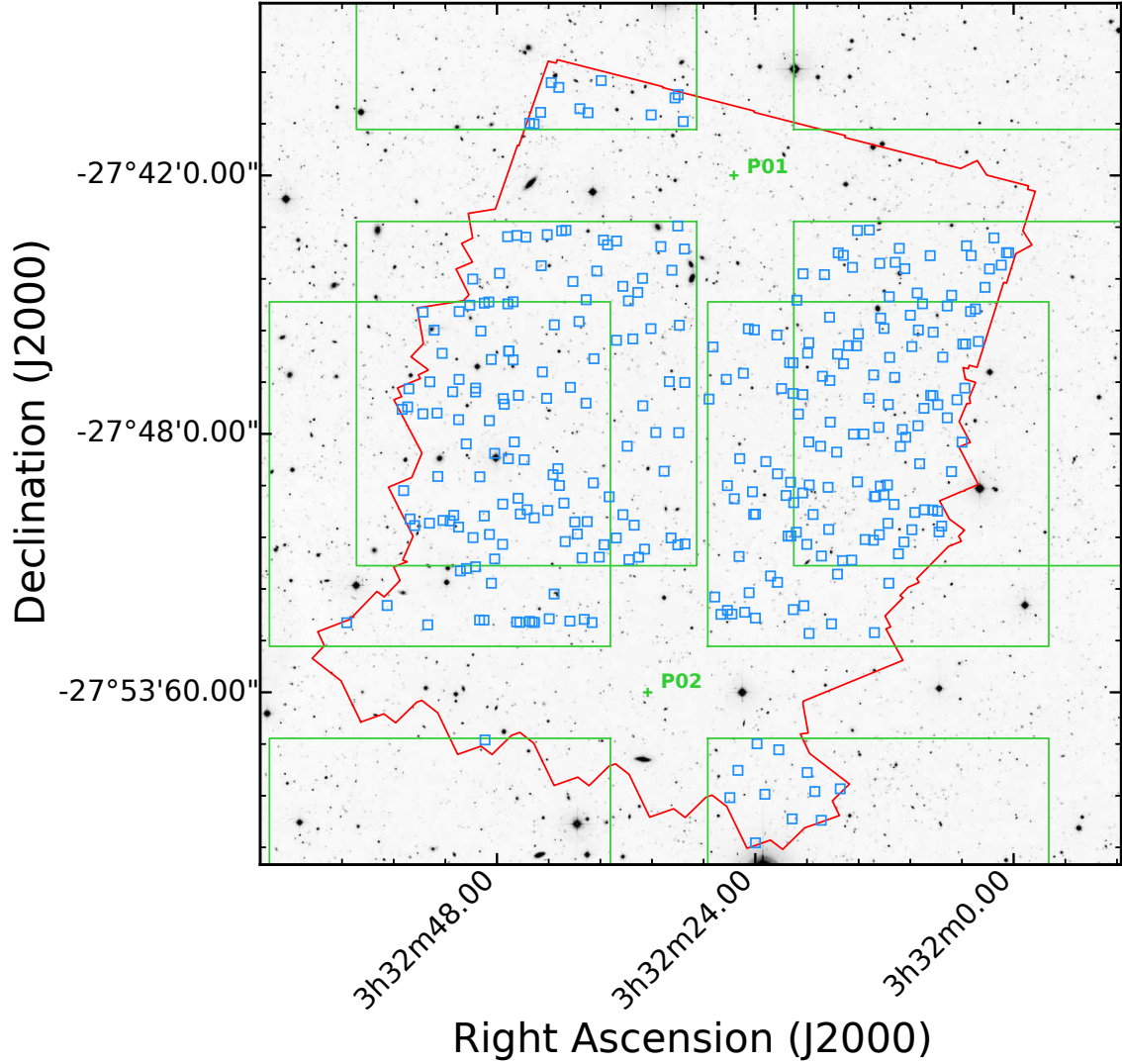


Fig. 2. The VUDS coverage of the CANDELS H-band F160W area in the ECDFS field. The CANDELS area is indicated by the red polygon, and the 4-quadrant footprint of the 2 overlapping VIMOS pointings is overlaid as the green rectangles with the pointing number identified. Because of the geometry of the VUDS footprint on the sky, regions corresponding to the ~ 2 arcmin gap between VIMOS channels did not receive spectroscopic observations as it is apparent in the lower and upper parts of the CANDELS area. The 314 galaxies with VUDS redshifts falling in the area in common between CANDELS and VUDS are plotted as the blue squares.

from the full VUDS data in COSMOS by Cucciati et al. (2014) who claim a possible signature of the intra-cluster medium ($\text{Ly}\alpha$ absorption at the redshift of the proto-cluster in the spectra of background galaxies). In the ECDFS two peaks are identified beyond $z = 2$ at $z \sim 2.9$ and $z \sim 3.5$, this latter peak possibly connected to the overdensity reported in Kang & Im (2009). From the redshift distributions in the CANDELS areas and the full VUDS survey area it appears that VUDS does sample a large number of over-dense regions as a result of the large volume sampled and target selection strategy.

A complete search and 3D characterization of large-scale structures in the full VUDS sample will be presented elsewhere.

4.2. Synthetic model fitting

To derive associated physical parameters for all spectroscopic objects encompassed in VUDS-DR1, e.g., stellar masses, mean luminosity-weighted stellar ages, SFRs, and rest-frame absolute

magnitudes, we utilized the package Le Phare¹ (Arnouts et al. 1999; Ilbert et al. 2006, 2009).

The $FUV, NUV, u^*, B, V, g+, r+, i', i+, z+, J, K_s, [3.6], [4.5]$ photometry in the COSMOS field was drawn from a variety of surveys covering the field (Capak et al. 2007; Sanders et al. 2007; Taniguchi et al. 2007; Zamojski et al. 2007; McCracken et al. 2012). The process of PSF-homogenizing all UV/optical/ground-based NIR images, source detection, the inclusion of the *Spitzer*/IRAC data, and the conversion of all magnitudes to 'pseudo-total' magnitudes is described in detail in Ilbert et al. (2013). The [5.8] and [8.0] cryogenic *Spitzer*/IRAC channels were not included in this fitting because offsets of 1–2.5 mags were noticed relative to the best-fit templates excluding these bands for $\sim 40\%$ of the objects in VUDS-DR1 irrespective of redshift or model. As the original targeting for VUDS used an official COSMOS photometric catalogue (v1.7), the cross-matching of this catalogue with the photometric catalogue used for the fitting process is straightforward.

¹ <http://cfht.hawaii.edu/~arnouts/LEPHARE/lephare.html>

For ECDFS, in VUDS-DR1 we provide two different SED-fitting results based on two different photometric catalogues. The first fitting was performed on the ground-based $U, B, V, R, I, z, J, H, K$ MUSYC photometry and *Spitzer*/IRAC [3.6], [4.5], [5.8], [8.0] photometry presented in Cardamone et al. (2010), which was, in turn drawn from a variety of different surveys (see Table 3 of Cardamone et al. 2010). Details of detection, PSF-homogenization, and correction of aperture magnitudes to close-to-total magnitudes is described in detail in Cardamone et al. (2010). The Cardamone et al. (2010) photometric source catalogue was used to select targets for VUDS and thus no additional astrometry mapping was needed. The second set of fitting on ECDFS was performed on the $U, F435W, F606W, F775W, F814W, F850LP, F098M, F105W, F125W, F160W, K_s$, [3.6], [4.5], [5.8], [8.0] mostly space-based photometry presented in Guo et al. (2013). For further details on the properties and creation of this catalogue as well as how the CANDELS sources were matched and consistently photometered with the ancillary data see Guo et al. (2013). VUDS-DR1 objects were mapped to the CANDELS catalogue through nearest-neighbour matching. We did not notice any systematic offset of the derived physical parameters between the results of the SED fitting on the CANDELS photometry and the MUSYC photometry, and the scatter of estimated physical parameters between the two sets of fits was consistent with Gaussian statistics. While both photometric catalogues resulted in a large percentage of converging SED fits using Le Phare ($> 97\%$ for objects with measured magnitudes), we adopt for the presentation of VUDS-DR1 here the fitting based on the MUSYC photometry as it more closely matches the depth and filter set currently used in the COSMOS fitting.

For all sources in VUDS-DR1 with a measured spectroscopic redshift, these redshifts were used as a prior for the SED-fitting process. In the fitting we employed seven different Bruzual & Charlot (2003; hereafter BC03) models, five with star formation histories (SFHs) characterized by an exponentially decaying tau model of the form $\psi(t) \propto \tau^{-1}e^{-t/\tau}$ and two delayed exponentially decaying tau models of the form $\psi(t) \propto \tau^{-2}te^{-t/\tau}$. All templates are considered at 43 possible ages between 50 Myr and 13.5 Gyr with the constraint that the age of the model fit to a given galaxy cannot be older than the age of the universe t_H at the redshift of that galaxy. The delayed tau models are included as it has been suggested that high-redshift galaxies have SFHs which may deviate considerably from the simple exponentially decaying tau models (e.g. Maraston et al. 2010; Schaerer et al. 2013). Values of τ range from 0.1 to 30 Gyr in roughly logarithmically equal time steps and delay times are set to 1 and 3 Gyr. Each BC03 model employs a Chabrier (2003) initial mass function and two values of stellar-phase metallicity, $0.4Z_\odot$ and $Z_\odot$. Stellar extinction is allowed to vary between $E_s(B - V) = 0$ and 0.5 in steps of 0.05, with the prescription also allowed to vary between the Calzetti et al. (2000) starburst law and a Small Magellanic Cloud-like law (Prevot et al. 1984; Arnouts et al. 2013). Several prominent nebular emission lines are also added to the templates following the methodology of Ilbert et al. (2009).

4.3. UV luminosity, stellar masses and star formation rates

Galaxies in the VUDS DR1 show a range of physical properties (e.g. stellar mass, SFR, dust extinction) comparable to that of the complete VUDS sample (Le Fèvre et al. 2015). This indicates that the VUDS DR1 forms a representative sample of the UV-selected star-forming galaxy population.

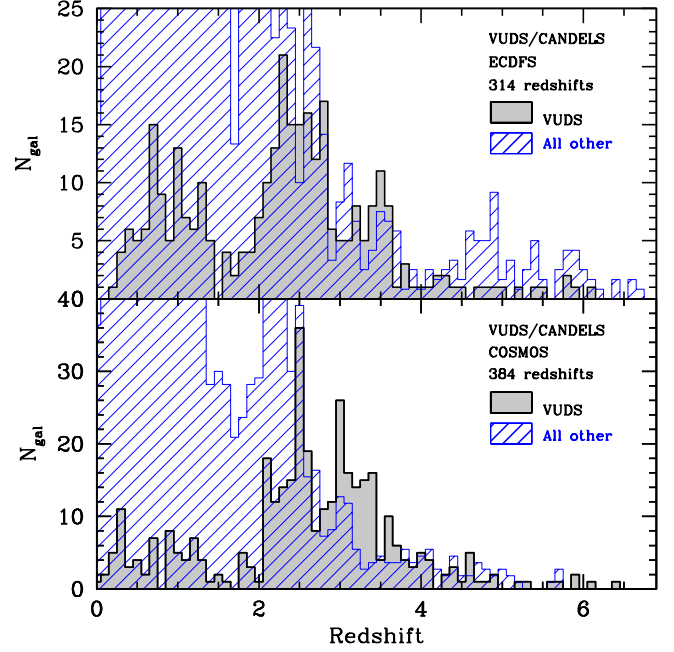


Fig. 3. Redshift distribution in the VUDS-CANDELS COSMOS (bottom) and in the VUDS-CANDELS ECDFS (top) fields. All galaxies with a spectroscopic redshift measurement available in these two fields are presented. The light grey histograms are for VUDS sources while the blue diagonal shaded histograms are for measurements obtained by other surveys.

4.4. Lyman- α EW

The equivalent width (EW) of the Ly α line was measured manually using the *splot* tool in the *noao.onedspec* package in IRAF, similarly to Tresse et al. (1999). We first put each galaxy spectrum in its rest-frame according to the spectroscopic redshift. Then, two continuum points bracketing the Ly α are manually marked and the rest-frame equivalent width is measured. The line is not fitted with a Gaussian, but the flux in the line is obtained integrating the area encompassed by the line and the continuum. This method allows the measurement of lines with asymmetric shapes (i.e., with deviations from Gaussian profiles), which is expected to be the case for most Ly α lines. The interactive method also allows us to control by eye the level of the continuum, taking into account defects that may be present around the line measured. It does not have the objectivity of automatic measurements, but, given the sometimes complex blend between Ly α emission and Ly α absorption, it does produce reliable and accurate measurements.

The distribution of rest-frame Lyman- α EW₀ as a function of redshift is presented in Figure 4. The VUDS-DR1 sample, like the full VUDS sample, is dominated by galaxies with Ly α in absorption for $z < 3.5$ and Ly α in emission for $z > 3.5$.

5. Individual objects of interest

The VUDS sample in the CANDELS areas is rich of a number of interesting objects. We mentioned several over-dense regions in Sect. 4.1. Following Tasca et al. (2014) a number of galaxy pairs are identified from the secure spectroscopic redshift measurements of each component in a pair and will be used to calculate the pair fraction at these redshifts (Le Fèvre & al. 2016).

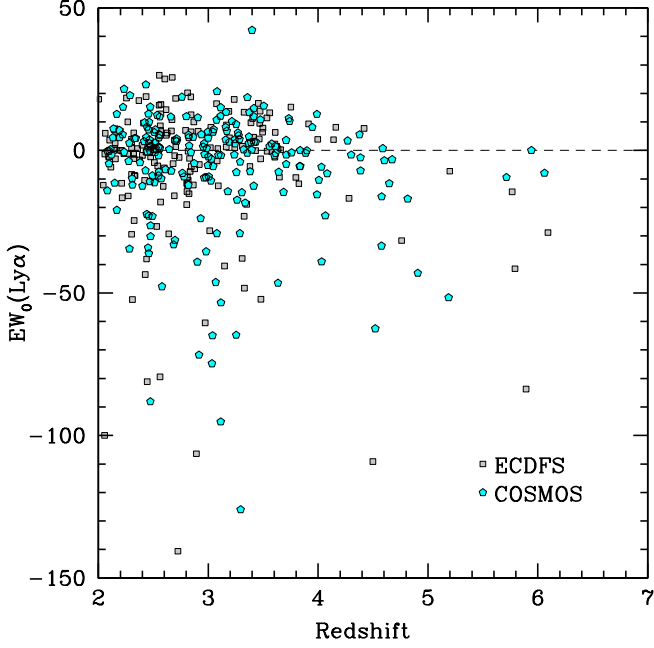


Fig. 4. Lyman- α rest-frame equivalent widths as a function of spectroscopic redshift. Negative EW values indicate Ly α in emission. Galaxies in the VUDS-DR1 sample show predominantly Ly α in absorption up to $z \sim 3.5$, and Ly α in emission at $z > 3.5$ (see Cassata et al. 2015, for the full VUDS sample).

To illustrate the content of the VUDS-DR1, we choose to present the 10 most massive galaxies verifying a redshift dependent stellar mass $\log(M_*) > -0.204 \times (z - 5) + 10.15$. The evolution of this mass selection is based on the evolution of the characteristic mass as measured from the stellar mass function of Ilbert et al. (2013), and our selection uses only the most reliable spectroscopic flags 3 and 4 (see Section 6.1 and Table 3 for a description of the spectroscopic flag system).

The properties of these ten most massive galaxies are listed in Table 2. The VUDS spectra of these galaxies are presented together with the CANDELS images in Figure 5 and 6. We find massive galaxies at all redshifts from $z \sim 2.5$ to $z \sim 5$. The diversity of galaxy types at these masses is well illustrated in these examples with a large range of morphologies and spectral properties. Images show both very compact objects, and extended or multiple component objects, as well as pairs possibly indicative of mergers. The spectra of these objects include galaxies with only absorption lines as well as galaxies with strong Lyman- α emission. Their SFRs are generally large, ranging from ~ 7 to more than $100 M_\odot/\text{yr}$.

6. Description of the VUDS-DR1 content

6.1. VUDS-DR1 data

The VUDS-DR1 includes the VUDS spectroscopic data in the CANDELS-COSMOS and CANDELS-ECDFS, as well as matched photometric data and derived quantities, as described below.

The primary catalogue information concerns the VIMOS spectroscopic data. The fundamental advance provided by this release is the spectroscopic redshift z_{spec} . These measurements result from the data reduction described in Sect.3 (see

Le Fèvre et al. 2005, 2013, 2015, for more details). From repeated observations of VUDS galaxies, as well as duplicate observations using the same configuration as in the VVDS (Le Fèvre et al. 2013), the velocity accuracy of redshift measurements is about $\sigma_v = 200 \text{ km/s}$. A flagging scheme is associated to each redshift measurements. Originated with the Canada-France Redshift Survey (CFRS, Le Fèvre et al. 1995), this flag system indicates the *reliability* of the redshift being accurate based on repeatability of the measurements on re-observed targets and does not speak to metrics of “quality” of the spectrum from which the redshift is measured, a term which may manifest itself in a variety of definitions across different surveys (see, e.g., discussion in Le Fèvre et al. 2013). Besides VUDS, this flag system, or slight variants of it, have been used by the VVDS, zCOSMOS and VIPERS surveys (Le Fèvre et al. 2013; Lilly et al. 2007; Guzzo et al. 2014). The VUDS flag system inspired from this is described in Le Fèvre et al. (2015) and a complete list with the meaning of the spectroscopic flags in the VUDS-DR1 is given in Table 3.

Associated to the spectroscopic redshift and reliability flag, the 2D and 1D object spectra and corresponding noise are made available (in FITS format). The 2D spectra are the result of the data processing described in Sect.3, after sky subtraction, stacking of the individual exposures, wavelength and flux calibration. Given a 2D spectrum, we can compute sky subtraction residuals as

$$\langle \text{skyResidual} \rangle_i = \frac{\sum_{j \in \text{NRegion}} (\langle C \rangle - C_j)^2}{\text{NRegion} - 1}, \quad (1)$$

where NRegion is the number of pixels in the sky region on one side of the object, $\langle C \rangle$ is the mean of the counts in the sky region and C_j are the counts in pixel j , at wavelength i . This computation is done on both sides of the object (resL and resR), taking into account slit borders and possible second objects in the slit. From such residuals, a mean noise spectrum is computed, the noise in the i -th pixel being given by

$$\text{noise}_i^2 = \frac{\text{resL}_i + \text{resR}_i}{2} + S_i = \langle \text{skyResidual} \rangle_i + S_i, \quad (2)$$

where S_i are the source counts at wavelength i .

The 1D spectra are produced from joining the 1D spectra extracted from the LRBLUE and LRRED 2D spectrograms, and are calibrated in wavelength and flux. To join the VIMOS blue and red grism spectra which have a slightly different spectra dispersion (5.3 and $7.5 \text{ \AA/pixel}$), the red spectrum is re-sampled to the same dispersion as the blue one. The overlapping region between 5600 and $6700 \text{ \AA}$ is used to compute the flux normalization factor between the two spectra. The S/N ratio of the final joined spectrum is the S/N weighted mean of the two spectra in the overlapping region. The 1D spectra are corrected for atmospheric effects (refraction and extinction) comparing with broad band photometry from the u-band to the i-band. The pseudo-spectrum produced by atmospheric refraction at the elevation of the observations, made available in the VIMOS spectra headers, is computed in combination with an elliptical geometrical model of each galaxy image to estimate the fraction of the light lost through the one-arcsecond wide slit (Thomas et al. 2014). This correction concerns mostly the bluer spectral data with $\lambda \leq 4500 \text{ \AA}$. After this process we find that the agreement between the spectra flux and the broad band photometry is accurate to better than 10% r.m.s for $\lambda \leq 4500 \text{ \AA}$ and 5% r.m.s. for $\lambda > 4500 \text{ \AA}$.

Table 2. The 10 most massive galaxies with $\log(M_\star) > -0.204 \times (z - 5) + 10.15$ in the VUDS-DR1

VUDS-ID	CANDELS-ID	α_{2000}	δ_{2000}	i_{AB}	z_{spec}^1	z_{flag}^2	Age (Gyr) ³	$\log(M_\star)^4$	$\log(SFR)^5$
5100998496	6868	150.20502	2.26216	24.48	3.8979	4	0.44	10.39	1.92
5101228787	19351	150.15880	2.41091	23.89	2.6592	3	0.95	10.79	2.04
5101232355	17264	150.18970	2.38569	24.17	4.2685	4	0.37	10.33	1.95
5101233539	16657	150.18010	2.37834	24.66	4.9077	4	0.71	10.53	1.81
511236742	14299	150.08801	2.35036	23.80	2.5558	4	1.42	10.71	1.76
5131463678	24389	150.19586	2.48250	25.18	4.032	3	1.17	10.79	0.87
530019471	273 ⁶	53.12201	-27.9387	24.26	4.7591	4	0.35	10.29	1.93
530034129	6780	53.07440	-27.8473	24.09	3.4723	4	1.28	11.20	1.99
530040423	11335	53.06850	-27.8071	24.73	3.38	3	1.31	10.51	1.41
530052480	20659	53.18285	-27.7349	24.10	2.4267	4	1.27	10.89	1.56

¹ z_{spec} : spectroscopic redshift² z_{flag} : spectroscopic redshift reliability flag³ Age, in Gyr: obtained from SED fitting at z_{spec} ⁴ $\log(M_\star)$: stellar mass (in log) obtained from SED fitting at z_{spec} ⁵ $\log(SFR)$: star formation rate (in log) obtained from SED fitting at z_{spec} ⁶ Identified as an AGN with an X-ray counterpart by Giallongo et al. (2015)

6.2. Cross-match with the HST-CANDELS catalogue

Each of the VUDS catalogue entries were cross-matched to the CANDELS source list in each of the COSMOS and ECDFS fields as kindly provided by the CANDELS collaboration. For each VUDS target the coordinates based on the original VIMOS targeting scheme were cross-matched to the CANDELS catalogue using a matching radius of $0.5''$. As a result of this process, all of the VUDS entries are associated to a CANDELS identification number. This facilitates data searches across different catalogues. When a source is resolved in the HST images with multiple components identified in the CANDELS catalogue, only the closest match to the VUDS catalogue is chosen. Therefore while a single VUDS source can have several counterparts in CANDELS, the reverse should not happen, and we estimate that this concerns 1.4% of objects for a 0.5 arcsecond search radius (this would rise to 12.3% for a 1 arcsecond search radius). Such a resolution effect may have important implications e.g. in counting faint galaxies, and we mention it here to alert the reader.

All spectroscopic data and parameters derived from SED fitting are available in the VUDS-DR1. We list the main parameters of interest in Table 4.

7. Summary

The VIMOS Ultra Deep Survey first Data Release (VUDS-DR1) gives full access to low-resolution spectroscopic data of 698 sources in the CANDELS-COSMOS and CANDELS-ECDFS fields, covering a total area of 276.9 arcmin². The key new information provided by this release is the spectroscopic redshifts z_{spec} , and associated reliability flag, as well as the full 1D flux, the wavelength calibrated VIMOS spectra, and the Liman- α rest-frame equivalent widths. We release also SED-derived quantities at the spectroscopic redshift value, including stellar mass $M_\star$ and star formation rate. Out of the 677 galaxies identified about 500 are at a redshift $z_{spec} > 2$ and up to $z_{spec} \sim 6$, with ~ 50 with $z_{spec} > 4$. The VUDS-DR1 therefore approximately doubles the number of high redshift galaxies with spectroscopic redshifts measured at $z > 3$ in the COSMOS and ECDFS fields.

All the 698 objects in the CANDELS-COSMOS and CANDELS-ECDFS are publicly released from the CESAM data center at <http://cesam.lam.fr/vuds/DR1>.

Future VUDS data releases will follow this VUDS-DR1 to give complete access to the spectra and associated measurements of ~ 8000 objects in the full ~ 1 square degree of the VUDS survey.

Acknowledgements. This work is supported by funding from the European Research Council Advanced Grant ERC-2010-AdG-268107-EARLY and by INAF Grants PRIN 2010, PRIN 2012 and PICS 2013. AC, OC, MT and VS acknowledge the grant MIUR PRIN 2010-2011. This work is based on data products made available at the CESAM data center, Laboratoire d'Astrophysique de Marseille, France.

References

- Alam, S., Albareti, F. D., Allende Prieto, C., et al. 2015, *ApJS*, 219, 12
 Arnouts, S., Cristiani, S., Moscardini, L., et al. 1999, *MNRAS*, 310, 540
 Arnouts, S., Le Floc'h, E., Chevillard, J., et al. 2013, *A&A*, 558, A67
 Balestra, I., Mainieri, V., Popesso, P., et al. 2010, *A&A*, 512, A12
 Bielby, R. M., Shanks, T., Weilbacher, P. M., et al. 2011, *MNRAS*, 414, 2
 Bouwens, R. J., Illingworth, G. D., Franx, M., & Ford, H. 2007, *ApJ*, 670, 928
 Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2015, *ApJ*, 803, 34
 Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, *ApJ*, 533, 682
 Capak, P., Aussel, H., Ajiki, M., et al. 2007, *ApJS*, 172, 99
 Cardamone, C. N., van Dokkum, P. G., Urry, C. M., et al. 2010, *ApJS*, 189, 270
 Casey, C. M., Cooray, A., Capak, P., et al. 2015, *ApJ*, 808, L33
 Cassata, P., Tasca, L. A. M., Le Fèvre, O., et al. 2015, *A&A*, 573, A24
 Chabrier, G. 2003, *PASP*, 115, 763
 Chiang, Y.-K., Overzier, R. A., Gebhardt, K., et al. 2015, *ApJ*, 808, 37
 Cooper, M. C., Yan, R., Dickinson, M., et al. 2012, *MNRAS*, 425, 2116
 Cucciati, O., Zamorani, G., Lemaux, B. C., et al. 2014, *A&A*, 570, A16
 Davis, M., Faber, S. M., Newman, J., et al. 2003, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 4834, Discoveries and Research Prospects from 6- to 10-Meter-Class Telescopes II, ed. P. Guhathakurta, 161–172
 Garilli, B., Fumana, M., Franzetti, P., et al. 2010, *PASP*, 122, 827
 Garilli, B., Guzzo, L., Scodreggio, M., et al. 2014, *A&A*, 562, A23
 Giallongo, E., Grazian, A., Fiore, F., et al. 2015, *A&A*, 578, A83
 Grogin, N. A., Kocevski, D. D., Faber, S. M., et al. 2011, *ApJS*, 197, 35
 Guo, Y., Ferguson, H. C., Giavalisco, M., et al. 2013, *ApJS*, 207, 24
 Guzzo, L., Scodreggio, M., Garilli, B., et al. 2014, *A&A*, 566, A108
 Ilbert, O., Arnouts, S., McCracken, H. J., et al. 2006, *A&A*, 457, 841
 Ilbert, O., Capak, P., Salvato, M., et al. 2009, *ApJ*, 690, 1236
 Ilbert, O., McCracken, H. J., Le Fèvre, O., et al. 2013, *A&A*, 556, A55
 Ilbert, O., Salvato, M., Le Floc'h, E., et al. 2010, *ApJ*, 709, 644
 Kang, E. & Im, M. 2009, *ApJ*, 691, L33
 Koekemoer, A. M., Aussel, H., Calzetti, D., et al. 2007, *ApJS*, 172, 196
 Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011a, *ApJS*, 197, 36
 Koekemoer, A. M., Faber, S. M., Ferguson, H. C., et al. 2011b, *ApJS*, 197, 36
 Kriek, M., Shapley, A. E., Reddy, N. A., et al. 2015, *ApJS*, 218, 15
 Le Fèvre, O. & al. 2016, *A&A*, in preparation
 Le Fèvre, O., Cassata, P., Cucciati, O., et al. 2013, *A&A*, 559, A14

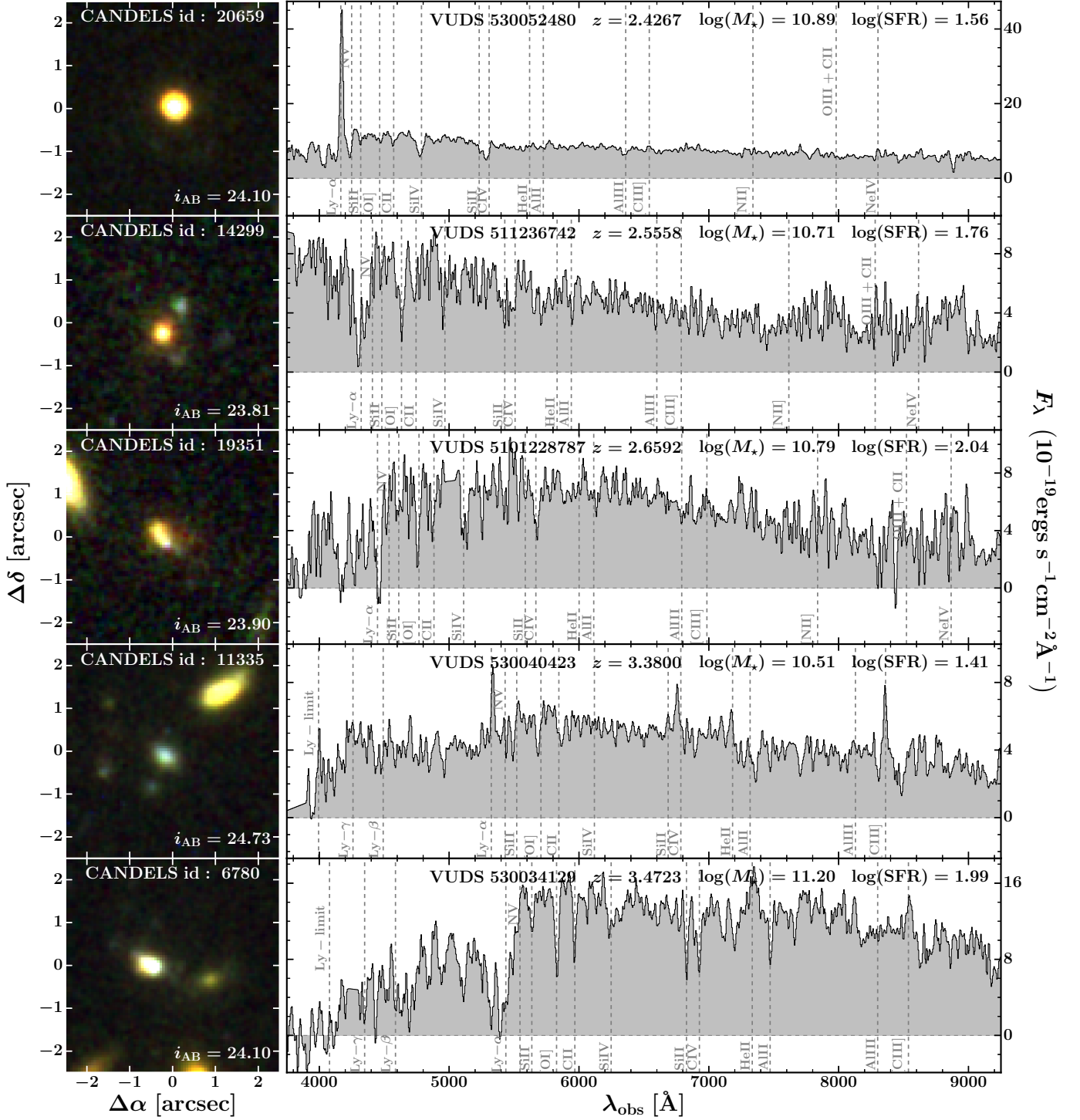


Fig. 5. HST images, composite of F814W (blue), F125W (green), and F160W (red) from the CANDELS survey (left panels), and observed spectra from VUDS (right panels) for the ten most massive and stronger star-forming galaxies (see text) in the VUDS-DR1. The CANDELS ID number is indicated on each of the left panels, while the ID, the spectroscopic redshift from VUDS and the stellar mass M_* and SFR are indicated for each galaxy on the right panels.

Le Fèvre, O., Crampton, D., Lilly, S. J., Hammer, F., & Tresse, L. 1995, *ApJ*, 455, 60
 Le Fèvre, O., Saisse, M., & Mancini, D. 2003, in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, Vol. 4841, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, ed. M. Iye & A. F. M. Moorwood, 1670–1681
 Le Fèvre, O., Tasca, L. A. M., Cassata, P., et al. 2015, *A&A*, 576, A79
 Le Fèvre, O., Vettolani, G., & Garilli, B. 2005, *A&A*, 439, 845
 Le Fèvre, O., Vettolani, G., Paltani, S., et al. 2004, *A&A*, 428, 1043

Lemaux, B. & al. 2016, *A&A*, in preparation
 Lilly, S. J., Le Brun, V., Maier, C., et al. 2009a, *ApJS*, 184, 218
 Lilly, S. J., Le Brun, V., Maier, C., et al. 2009b, *ApJS*, 184, 218
 Lilly, S. J., Le Fèvre, O., Renzini, A., et al. 2007, *ApJS*, 172, 70
 Maraston, C., Pforr, J., Renzini, A., et al. 2010, *MNRAS*, 407, 830
 McCracken, H. J., Milvang-Jensen, B., Dunlop, J., et al. 2012, *A&A*, 544, A156
 Momcheva, I. G., Brammer, G. B., van Dokkum, P. G., et al. 2015, *ArXiv e-prints*
 Newman, J. A., Cooper, M. C., Davis, M., et al. 2013, *ApJS*, 208, 5

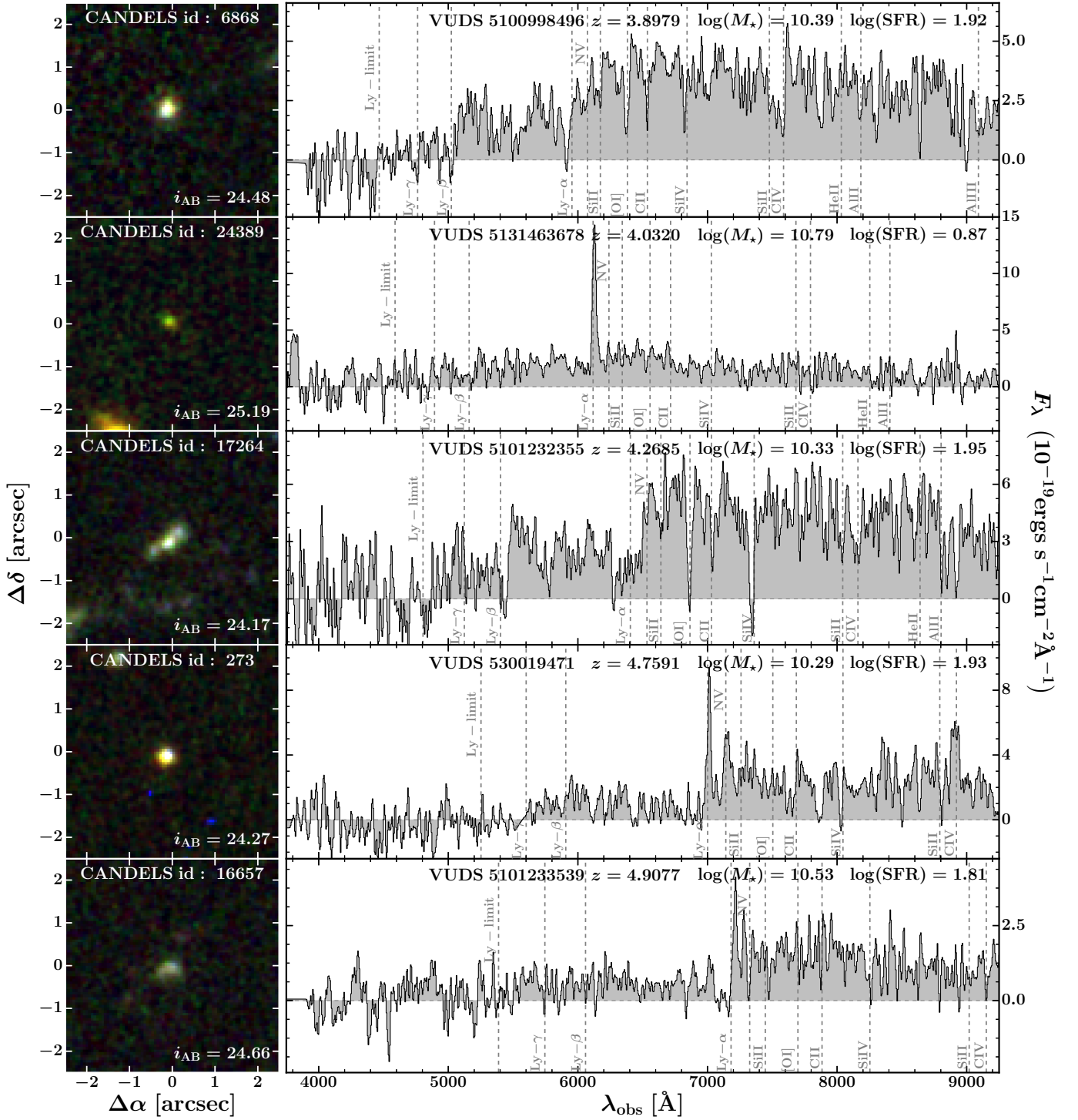


Fig. 6. HST images, composite of F814W (blue), F125W (green), and F160W (red) from the CANDELS survey (left panels), and observed spectra from VUDS (right panels) for the ten most massive and stronger star-forming galaxies (see text) in the VUDS-DR1. The CANDELS ID number is indicated on each of the left panels, while the ID, the spectroscopic redshift from VUDS and the stellar mass M_* and SFR are indicated for each galaxy on the right panels.

Ouchi, M., Shimasaku, K., Akiyama, M., et al. 2008, *ApJS*, 176, 301
 Pentericci, L., Vanzella, E., Fontana, A., et al. 2014, *ApJ*, 793, 113
 Prevot, M. L., Lequeux, J., Prevot, L., Maurice, E., & Rocca-Volmerange, B. 1984, *A&A*, 132, 389
 Reid, B., Ho, S., Padmanabhan, N., et al. 2016, *MNRAS*, 455, 1553
 Rhoads, J. E., Dey, A., Malhotra, S., et al. 2003, *AJ*, 125, 1006
 Sanders, D. B., Salvato, M., Aussel, H., et al. 2007, *ApJS*, 172, 86
 Schaerer, D., de Barros, S., & Sklias, P. 2013, *A&A*, 549, A4
 Scodreggio, M., Franzetti, P., Garilli, B., et al. 2005, *PASP*, 117, 1284

Scoville, N., Abraham, R. G., Aussel, H., et al. 2007, *ApJS*, 172, 38
 Silverman, J. D., Kashino, D., Sanders, D., et al. 2015, *ApJS*, 220, 12
 Stark, D. P., Ellis, R. S., Bunker, A., et al. 2009, *ApJ*, 697, 1493
 Steidel, C. C., Adelberger, K. L., Shapley, A. E., et al. 2003, *ApJ*, 592, 728
 Taniguchi, Y., Scoville, N., Murayama, T., et al. 2007, *ApJS*, 172, 9
 Tasca, L. A. M., Le Fèvre, O., López-Sanjuan, C., et al. 2014, *A&A*, 565, A10
 Thomas, R., Le Fèvre, O., Cassata, P., et al. 2014, *ArXiv e-prints*
 Tresse, L., Dennefeld, M., Petitjean, P., Cristiani, S., & White, S. 1999, *A&A*, 346, L21

Table 3. VUDS redshift reliability flags summary

z_{flag}	Reliability	Comments
4	100%	High S/N with many absorption and/or emission lines; strong cross-correlation signal with excellent continuum match to templates
3	95-100%	Moderate to high S/N with several absorption and/or emission lines; strong cross-correlation signal with good to excellent continuum match to templates
2	70-80%	Moderate S/N with matching absorption and/or emission lines; good cross-correlation signal
1	40-50%	Low S/N lines or continuum; weak to moderate cross-correlation signal
9	80 %	Single emission line spectrum; the line has moderate to high S/N. Redshift is assigned based on the exclusion of alternative solutions in the absence of other expected key features
1X	–	Like flag X but spectral features indicate the presence of an AGN
2X	–	Like flag X but for a secondary target falling in the slit of a primary
3X	–	Like flag X but the spectrum shows two line systems at different redshifts, the highest of the two redshifts is given as z_{spec}
4X	–	Like flag X but the two spectra are close in velocity indicative of a physical pair

Table 4. VUDS–DR1 database parameters

Parameter	Description	Comments
VUDS-ID	VIMOS Ultra-Deep Survey Identification number	
CANDELS-ID	CANDELS Identification number	
z_{spec}	Spectroscopic redshift measured with VIMOS	Typical accuracy: $\Delta z = 0.0007$, $\lesssim 200$ km/s
z_{flag}	Spectroscopic redshift reliability	
EW(Ly α)	Rest-frame Ly α –1215Å equivalent width	
$M_{\star}$	Stellar mass	From SED fitting at z_{spec}
SFR	Star formation rate	From SED fitting at z_{spec}
Age	Mean age of the stellar population corresponding to the best fit	From SED fitting at z_{spec}
E(B-V)	Galactic extinction	From SED fitting at z_{spec}
L_{NUV}	Absolute luminosity at 1500Å rest-frame	From SED fitting at z_{spec}
M_{band}	Absolute magnitudes in <i>band</i>	From SED fitting at z_{spec}

Vanzella, E., Cristiani, S., Dickinson, M., et al. 2008, A&A, 478, 83

Vanzella, E., Giavalisco, M., Dickinson, M., et al. 2009, ApJ, 695, 1163

Zamojski, M. A., Schiminovich, D., Rich, R. M., et al. 2007, ApJS, 172, 468