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The role of mass and environment in the quenching and structural transformation of galaxies up to $z \sim 3$

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Abstract

It is not very well understood how galaxies quench their star formation and undergo morphological transformation. It is hard to separate how both the internal structure of galaxies and their environment affect their star formation properties. Furthermore, the observed morphological and size evolution of galaxies is still a topic of much research.

In this thesis, we investigate the role of mass and environment in the quenching of star formation and size evolution of galaxies in the redshift range $0.5 < z < 3$, using data from the 11th data release (DR11) of the UKIDSS Ultra-Deep Survey (UDS). We do this by studying the fraction of quiescent galaxies and the mass-size relation as a function of environment. We define environment as the normalized galaxy counts in a fixed aperture of 250 or 400 kpc and use a Principal Component Analysis (PCA) to identify star-forming (SF), passive and post-starburst (PSB) galaxies. The environmental measurements and the PCA technique are explained in Chapter 2, where the structural parameters are also explained.

We find that the fraction of quiescent galaxies increases with both mass and local galaxy density at all redshifts, extending the trends observed at lower redshifts. From the mass-size relation, in agreement with previous studies, we confirm that massive passive galaxies at $2 < z < 3$ are approximately a factor of two smaller on average than their counterparts at $0.5 < z < 1$. When comparing the mass-size relation in different environments, however, at a given epoch we find that passive galaxies are on average larger in dense environments than their counterparts of comparable mass in less dense regions. In the redshift range $1 < z < 2$, high mass ($\log M^*/M_\odot > 11$) quiescent galaxies are ~ 50 per cent larger in the highest density environments compared to the least dense environments. These trends may be explained by an increased rate of minor dry mergers in dense environments. In addition, we also confirm previous findings that the most recently quenched “post-starburst” galaxies are the most compact of all galaxy types, extending these findings to $z = 3$. Combining these results, we propose a scenario in which massive galaxies initially become exceptionally compact immediately prior to being rapidly quenched at high redshift. Thereafter, these galaxies accrete satellites at a rate dependent on their environment, and gradually grow into the larger passive galaxies we observe in the local Universe.

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List of Publications

The work in this thesis will be presented in a forthcoming paper:

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‘The role of mass and environment in the quenching and structural transformation of galaxies up to $z \sim 3$ ’.

Contents

Abstract	i
Acknowledgements	ii
List of Publications	iii
1 Introduction	1
1.1 Structure formation in the Universe	2
1.2 Galaxies in the Universe	5
1.2.1 Galaxy Bimodality	6
1.2.2 Structural evolution of galaxies	8
1.3 Galaxy environments	11
1.3.1 Morphology-density relation	12
1.3.2 Environmental processes	13
1.4 Quenching of star formation	15
1.4.1 Mass quenching	16
1.4.2 Environment quenching	16
1.5 Mass-size relation	17
1.5.1 The size growth of passive galaxies	18

1.6	The aim of this work	20
2	Description of the data	21
2.1	The UDS DR11 catalogue	21
2.2	Photometric redshifts	22
2.3	Galaxy classification and stellar masses	22
2.4	Size and Sérsic index	24
2.5	Galaxy environments	25
3	Results	29
3.1	Environment and mass	29
3.2	Average density of galaxies	32
3.3	Size-mass relation	32
3.4	Galaxy size and environment	36
4	Discussion	39
4.1	Mass and environment	39
4.2	Size evolution of galaxies	39
4.3	Environment and size of quiescent galaxies	41
5	Conclusions and future work	43
5.1	Limitations of this work	44
	Bibliography	46
	Appendices	53
A	Environment distribution	53

B	Fraction of quiescent galaxies	55
B.1	Evolution of the mass-size relation with redshift	55
C	Mass-size relation with environment	58

List of Tables

2.1	Mass completeness values	23
2.2	Number of galaxies in each population	24
3.1	Size growth of quiescent galaxies in denser environments	36

List of Figures

1.1	Hubble tuning fork	2
1.2	Velocity dispersion curve	3
1.3	Merger Tree	4
1.4	Star formation rate through cosmic time	6
1.5	Colour-mass diagram for the u-r bands	7
1.6	Galaxy bimodality with cosmic time	9
1.7	Sérsic light profile	10
1.8	Galaxy morphology with cosmic time	11
1.9	Morphology-density relation	13
1.10	Mass-size relation from Buitrago et al. (2008)	18
2.1	Mass completeness limits	24
2.2	Galaxy size measurements from the UDS compared to CANDELS	26
2.3	Angular Scale	27
2.4	Environment Histogram	28
3.1	Quiescent fraction as a function of mass and environment	31

3.2	Average density of galaxies	33
3.3	Mass-size relation for star-forming, passive and PSB galaxies. . .	34
3.4	Average size of star-forming, passive and PSB galaxies	35
3.5	Size of quiescent galaxies with environment	37
A.1	Environment Histogram	54
B.1	Quiescent fraction as a function of mass and environment for passive galaxies	55
B.2	Mass-size relation with redshift	57
C.1	Size of quiescent galaxies in different overdensity bins in a 250 kpc aperture	59
C.2	Size of star-forming galaxies in different environments, using an aperture of 250 kpc.	60

Chapter 1

Introduction

For many years, our galaxy, the Milky Way, was thought to be the only galaxy in the Universe. It was not until the works carried out by Hubble in the 1920s that the existence of other galaxies external to our own was established. This discovery meant that the Universe is significantly larger than previously thought, and with this revelation, new scientific interests were born. These mainly focus on the formation, properties, and evolution of these galaxies, and together comprise the field of extra-galactic astronomy.

The first attempt to classify galaxies based on their morphology was made in 1926 by Edwin Hubble ([Hubble, 1926](#)), who developed a way to classify and group similar looking galaxies. One of the most important features of this arrangement was the implication that galaxies might evolve with time, that is, they start with one morphology and, as the Universe gets older, evolve towards a different shape. We now know that galaxies are likely to evolve from right to left of the Hubble tuning fork diagram (disc-like to spheroid-like morphology) however, Hubble originally thought that the opposite was true, that galaxies evolved from the left to the right (early to late-type). This classification is based on the Tuning Fork diagram and is illustrated in Fig. 1.1.

Fig. 1.1 shows three clearly distinct galaxy types: Ellipticals (E0 to E7), Lenticular (S0) and Spirals (S and SB). Elliptical galaxies have a roughly oval shape, they lack any major internal structural features and have almost featureless stellar distributions. The numbers 0 to 7 represent how elliptical the galaxy is, with 0 being a perfectly round object and 7 the maximum observed ellipticity for an elliptical galaxy. Spiral galaxies have a disc shape, well-defined spiral arms and have clear internal structure, due to a well arranged stellar distribution. Furthermore, these galaxies can be further divided into normal (S) and barred (SB) spirals with both exhibiting clear spiral arms, but the latter having a central bar present. Finally, the letters “a” to “c” correspond to the prominence of the central bulge and the pitch angle of the spiral arms. Lenticular galaxies (S0) are featureless discs and are considered to be galaxies in transition between the two classes (see e.g. [Spitzer & Baade 1951](#), [Dressler et al. 1997](#)). When using their morphology, galaxies can also be divided into early-type galaxies (ETGs) and late-type galaxies (LTGs), where LTGs have a clear internal structure and ETGs have a simple and smooth structure (see

Cappellari 2016 for a review on the structure of ETGs). Therefore, with the above, elliptical and lenticular galaxies are ETGs, while spirals are LTGs.

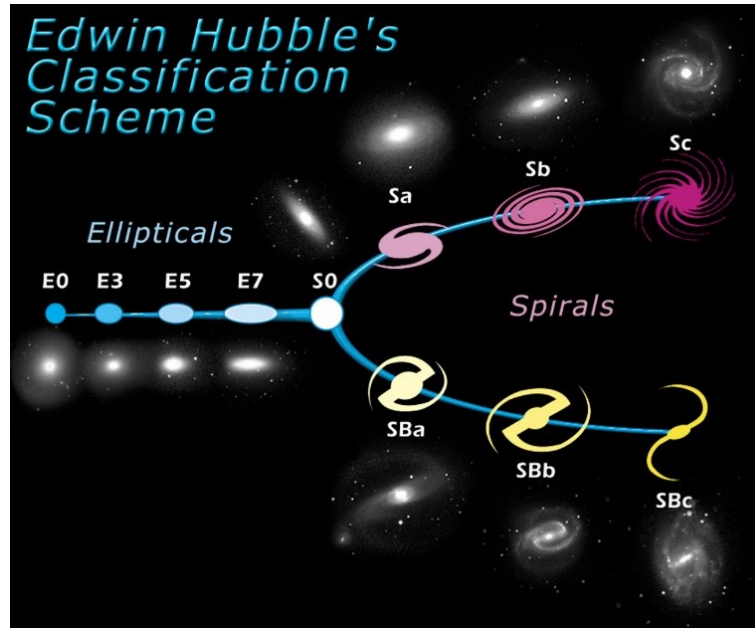


Figure 1.1: Illustration of the Hubble tuning fork diagram. This classification can lead to the misconception that galaxies evolve from left to right, however, it is now known that this evolution happens from the right to the left. Image credit: NASA & ESA

As stated previously, the tuning fork classification suggests that during their lifetime, galaxies undergo morphological transformations, which has lead astronomers to investigate how these objects form and evolve. To understand the formation and evolution of these galaxies, it is also important to consider how the overall large-scale structure of the Universe, within which they reside, might have formed and evolved. In the following sections, we give a broad overview of the current state of this field.

1.1 Structure formation in the Universe

The current model proposed to explain how all structure in the Universe formed is called the Lambda Cold Dark Matter model (Λ CDM). Here, the general theory of relativity is applied to the scale of the Universe, and describes a Universe dominated by a cosmological constant (Λ) thought to be the reason for its observed accelerated expansion (Perlmutter et al., 1999). This parameter is often referred to as dark energy (DE), an unknown form of energy invoked to explain the accelerated expansion of the Universe. DE accounts for 69 per cent of the total mass/energy budget in the Universe, while DM is responsible for 26 per cent and the remaining 5 per cent corresponds to baryonic matter (i.e. stars and galaxies, see Planck Collaboration et al. 2014). This means that 95 per cent of the Universe's composition is unknown in nature. This model enhances the Big Bang model and is able to explain many observations, which include: the relative amounts of each element, the cosmic microwave

background (CMB), and the spatial distribution of galaxies.

As astronomers, we rely upon electromagnetic (EM) radiation to observe the Universe. This only allows us to directly observe the baryonic component of the Universe from which it originates. DM and DE do not emit EM radiation and therefore cannot be observed directly. Their existence can only be inferred via their gravitational effects on the observable baryons. Significant efforts have been made during the second half of the 20th century to find evidence for the existence of dark matter. [Roberts \(1976\)](#) was the first to report that galaxy rotation curves do not have the expected shape. Fig 1.2 shows the observed (solid lines) and expected (dashed lines) rotation curves for the M33 galaxy, studied by [Zasov et al. \(2017\)](#). With increasing distance from the centre of the galaxy, the velocity of the stars remains constant rather than decreasing as would be expected from Keplerian laws. This suggests that there has to be more mass in the galaxy than inferred from the visible component (stars). [Rubin et al. \(1978\)](#) have suggested that dark matter is able to explain this discrepancy. Another piece of evidence for the existence of dark matter comes from the velocity dispersion of cluster galaxies and Virial Theorem. [Zwicky \(1933\)](#) used this Virial Theorem to determine the mass of the Coma cluster of galaxies and found that the mass of that cluster was significantly different (larger) than the expected from the estimated stellar mass (via the galaxies luminosities). This suggests that the inferred mass from the visible component (i.e. stars) is not the only contributor to the total mass of the cluster, and that a considerable fraction is not directly observable and hence ‘dark’.

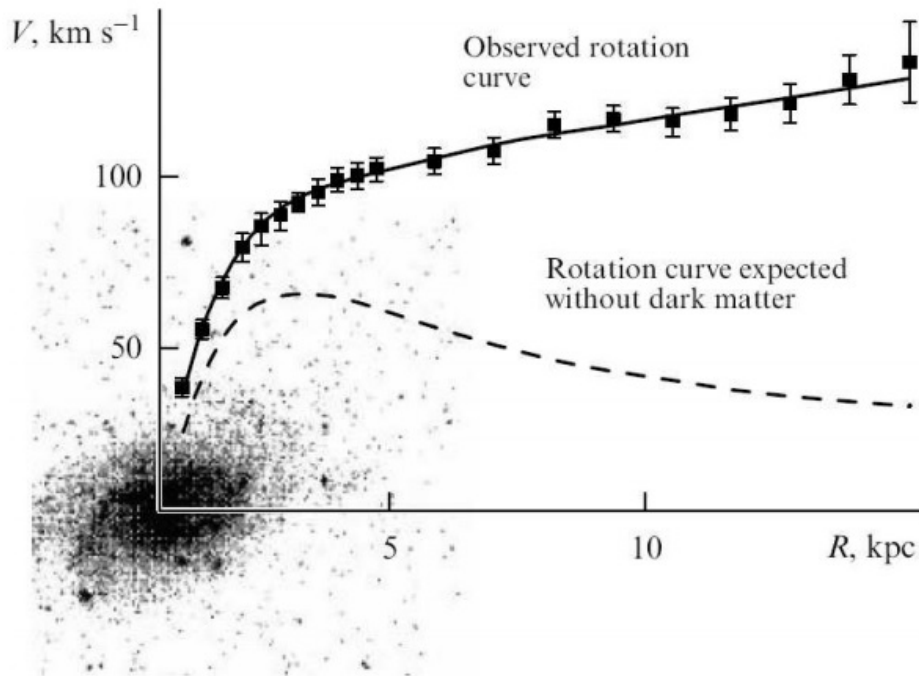


Figure 1.2: Rotation velocity dispersion curve of the M33 galaxy produced by [Zasov et al. \(2017\)](#). The solid black line shows the observed curve and the dashed line shows the rotation curve that would be expected without the presence of dark matter. This shows that the velocity of the stars is approximately constant with increasing distance.

In its very early stages, the Universe was a hot and dense plasma of photons and matter. During the epoch of inflation, this plasma experienced density fluctuations which propagated (Davis et al., 1985), leading to regions which were over-dense and others that were under-dense. Consequently, the density distribution in the early Universe was not uniform. In the epoch of recombination, the over-dense regions collapsed to form dark matter haloes (DMH). In the Λ CDM model the dark matter is non-relativistic, therefore, the collapse of the DMH happened on small scales first, and these small objects subsequently merged in a continuous manner to form progressively larger structures. This is called the hierarchical growth of structure (e.g. Lacey & Cole 1993) and is illustrated in Fig. 1.3.

In this model, galaxies are thought to form as a result of gas cooling onto the centers of dark matter halos (White & Rees, 1978), forming gas clouds which will later collapse to form stars. Here, conservation of angular momentum is able to explain the flat rotation curves of stars in galactic discs (Fall & Efstathiou, 1980). Additionally, in this theory of structure formation, galaxies found in large-scale structures (large DM halos, i.e. clusters) are expected to be older than those in smaller structures (smaller DM halos, i.e. in the field), as can be seen in Fig. 1.3.

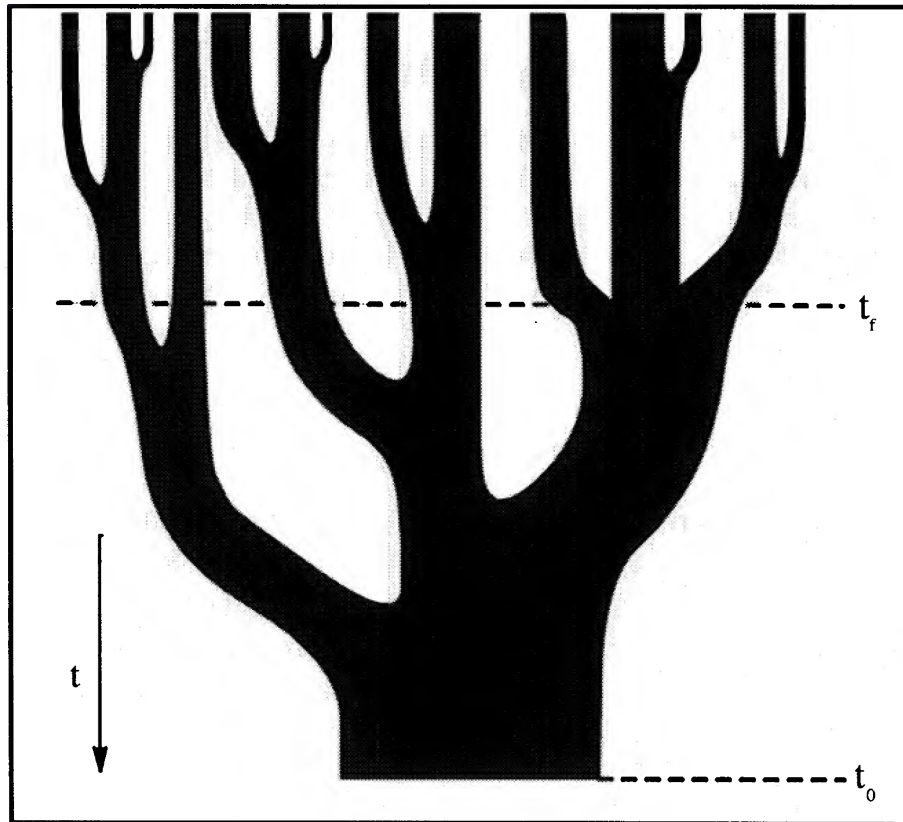


Figure 1.3: Illustration of the hierarchical growth of DM halos by Lacey & Cole (1993), called the “merger tree”. In this figure the time is greater at the bottom than at the top. This means that the bottom represents the Universe at the current time, while the top is a representation of the early Universe. It is evident that the smaller structures present at higher redshift and increase their mass and size (via DM halo merging) as the redshift decreases.

1.2 Galaxies in the Universe

In the local Universe, galaxies have been observed to display a bimodal distribution in several key characteristics. This means that when classifying galaxies based on these properties, they can be placed into one of two main categories. These categories depend on which characteristics are being looked at. For example:

1. Classification based on galaxy colours: In this case, galaxies can either belong to the blue cloud or the red sequence. Galaxies in the blue cloud have optical light dominated by young blue stars while galaxies in the red sequence have optical light dominated by older red stars (e.g. [Strateva et al. 2001](#)).
2. Classification based on the specific star formation rate (SSFR): When classifying galaxies based on their SSFR, they can either be star-forming (SF) if they show a high SSFR or passive, if they exhibit significantly low SSFRs (e.g. [Balogh et al. 2004](#), [Moustakas et al. 2013](#)). The rate at which galaxies form stars is also usually associated with their colour, where without the presence of dust, objects that have high SSFRs display a blue colour while galaxies with low SSFRs show a red colour. However, this relationship is somewhat complicated by the presence of dust, which if present in sufficient quantities, has a reddening effect on the galaxy's optical colour (e.g. dusty star-forming galaxies; red spirals; see e.g. [Whitaker et al. 2014](#)).
3. Classification based on morphology: When galaxies are classified depending on their morphology, they can either be ETGs or LTGs. In this case, there is some evidence for a relationship between the star formation properties of galaxies and their morphology (e.g. [Larson et al. 1980](#), [Lee et al. 2013](#)), where ETGs are generally associated with passive galaxies and LTGs with star-forming.

These observations are still not very well understood, but it is generally agreed that galaxies start their lives in the star-forming blue cloud and evolve into the passive red sequence, through the quenching of their star formation. Interestingly, this bimodality is not just observed in the local Universe, some authors have observed it out to $z \sim 2.5$ (e.g. [Brammer et al. 2009](#), [Williams et al. 2009](#)).

The star formation rate of a galaxy is of great importance to study their evolution over cosmic time. Understanding how the SFR properties of galaxies change with cosmic time can shed a light on the processes involved in the quenching of star formation in galaxies. [Madau & Dickinson \(2014\)](#) have studied the history of the combined star formation rate density in the Universe for $0 < z < 8$. Their results are presented in Fig. 1.4. It is clear that at $z \sim 2$, the SFR density in the Universe was at its peak, and then decreased until the present day. Therefore, studying the properties of galaxies before, after and during this peak of activity is essential to gain further insights into the evolution of galaxies from the blue cloud to the red sequence.

In this thesis, the redshift range we use is $0.5 < z < 3$ and the results in Fig. 1.4 provide a justification for this: it is when the star formation rate density of the Universe shows a significant change, thus it is an optimum epoch to investigate the global quenching of star formation in the Universe and the establishment of the galaxy bimodality.

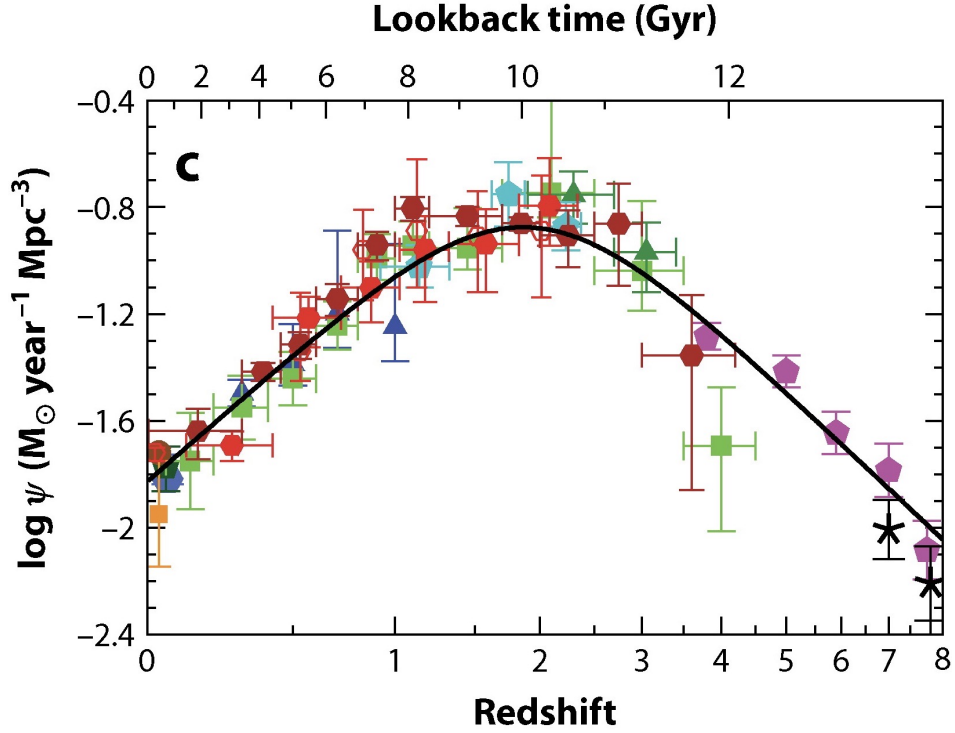


Figure 1.4: History of the cosmic star formation from FUV-IR rest-frame measurements shown in [Madau & Dickinson \(2014\)](#). The different colours represent results from different studies. This plot shows that the star formation rate density of the Universe peaked at $z \sim 2$.

1.2.1 Galaxy Bimodality

In Section 1.2, we mention that the colour, morphology and star formation rate properties of galaxies show a bimodal distribution. In this section we further investigate the galaxy bimodality, in particular its evolution over cosmic time.

Fig. 1.5 shows the local colour($u - r$)-mass relation for the sample of galaxies in the SDSS studied by [Schawinski et al. 2014](#). The top left panel shows the diagram for all galaxies, and it is clear there is a colour-mass relation. The most massive galaxies seem to be predominantly red and form a tight relation known as the “red sequence”. The low mass end seems to be dominated by a distribution of blue objects which form the “blue cloud”. It is important to note that galaxies in the red sequence show a much tighter relationship than those in the blue sequence, which are much more spread in the diagram. The region between the green lines represents a group of galaxies called the green valley galaxies, which are a population in transition between the blue cloud and red sequence. The colour-mass relations for different morphologies

(separated into ETGs/LTGs) are also shown. The three figures combined form a clear picture where most ETGs are red and most LTGs are blue. This is called the colour–morphology relation (e.g. [Roberts & Haynes 1994](#), [Strateva et al. 2001](#), [Blanton et al. 2003](#), [Baldry et al. 2004](#), [Gallazzi et al. 2007](#), [Bell 2008](#), [Cassata et al. 2008](#)).

Fig. 1.5 also shows a relationship between the morphology and the galaxy stellar mass, where ETGs occupy the high-mass end, while LTGs dominate at low mass. This is a relation that has also been found in other studies: for example, [Kauffmann et al. \(2003\)](#) report that above $10^{10.5} M^*/M_\odot$ galaxies are mainly passive.

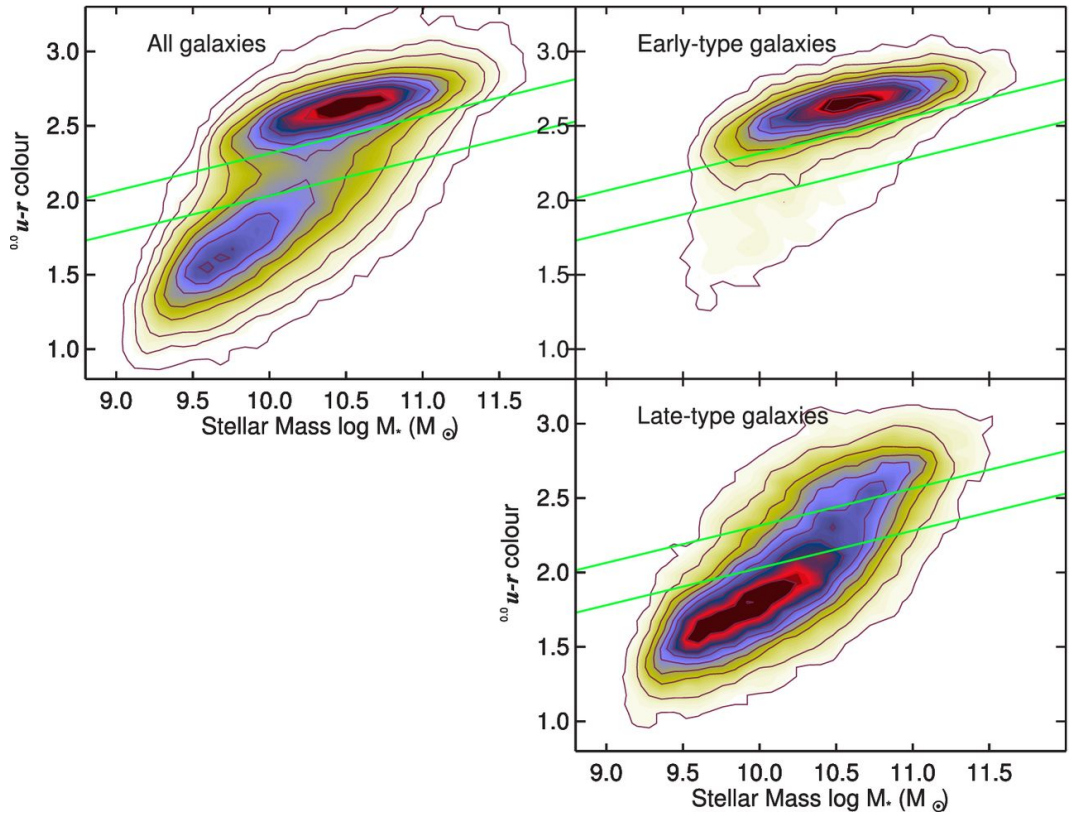


Figure 1.5: Colour–mass diagram for the $u-r$ bands from [Schawinski et al. \(2014\)](#). The three panels show the diagrams for all galaxies (top left), early-type galaxies (top-right) and late-type galaxies (bottom right). The green lines enclose a region between the peaks in the bimodal distribution, which is thought to contain transitional galaxies (i.e. the green valley). For more details see [Schawinski et al. \(2014\)](#).

The Hubble Tuning Fork classification presented in Fig. 1.1, suggests that galaxy evolution involves morphological transformations. However, in Fig. 1.5, it is clear that galaxy evolution includes both morphological transformation and changes in colour (i.e. through a shutdown of star formation; e.g. see [Bamford et al. 2009](#)). When galaxies halt their star formation, through a process called quenching, they also appear to undergo morphological transformation. However, it is not well understood if these two events are connected to the same process.

In Fig. 1.5 there is a class of galaxies called the green valley galaxies (represented between the green lines in that figure), which are considered transitional

galaxies between the blue cloud and red sequence. These transitional galaxies occur in the trough of the bimodality, and are thought to be in the process of quenching their star formation. As a consequence, they are of particular interest since their properties might shed light on the quenching process involved. Another interesting class of transitional galaxy are called post-starburst (PSB) galaxies. Firstly discovered in clusters by [Dressler & Gunn \(1983\)](#) PSBs show strong Balmer lines, which implies that the stellar population in these galaxies has both A and F stars in its composition. In the spectra of PSB galaxies, the presence of F stars indicates that these objects have an old stellar population (resembling passive galaxies) furthermore, the presence of A stars clearly shows that there has been a recent and major burst of star formation which was recently and rapidly quenched, within the last 1 Gyr. It is also important to note that these objects show very weak emission lines, indicating that they are not experiencing any significant star formation activity. It has been shown that large samples of these galaxies can be detected via photometric methods (see [Wild et al. 2014, 2016](#), [Maltby et al. 2016](#) for details). Like green valley galaxies, these rare class of recently-quenched post-starbursts are of particular interest since their properties could provide clues to the processes that quenched their star formation. The processes by which PSB galaxies quench their star formation are still not very well understood, however, there is some evidence suggesting that different quenching mechanisms are present at different redshifts (see [Wild et al. 2016](#), [Maltby et al. 2018](#)).

The bimodality present in [Fig. 1.5](#) corresponds to what is observed in the local Universe. However, as galaxies evolve with time, so does the bimodal distribution. [Fig. 1.6](#) shows the evolution of the stellar mass density with redshift, for both the star-forming and quiescent galaxy populations. The bulk of the mass density in passive galaxies is established by $z \sim 1$, but at higher redshift the mass density is dominated by the star-forming population. This figure also shows the rapid formation of the quiescent population (i.e. red sequence), due to the quenching of star-forming galaxies, between $z \sim 4$ and $z \sim 1$. This figure also further supports our choice of redshift range explored in this thesis ($0.5 < z < 3$), which is where most of the evolution of bimodality occurs and becomes established.

1.2.2 Structural evolution of galaxies

When distinguishing galaxies based on their morphological properties, visual classifications do not always work. The concentration of light in a galaxy correlates strongly with morphology ([Takamiya, 1999](#)), and can be used to distinguish between the two morphological types. The Sérsic index, n ([Sérsic, 1968](#)) is a parameter that describes the light profile of a galaxy and is shown in [Fig. 1.7](#). There are two values of Sérsic index that are of particular significance: $n=1$, which corresponds to the light profile of a pure exponential disc and $n=4$, corresponding to a $R^{1/4}$ or De Vaucouleurs profile typical of spheroidal systems (e.g. elliptical galaxies, galactic bulges). As a consequence, the Sérsic index can be used to separate galaxy populations into disc- and spheroidally-dominated systems, with the former typically having $n < 2.5$, and the latter $n > 2.5$ (e.g.

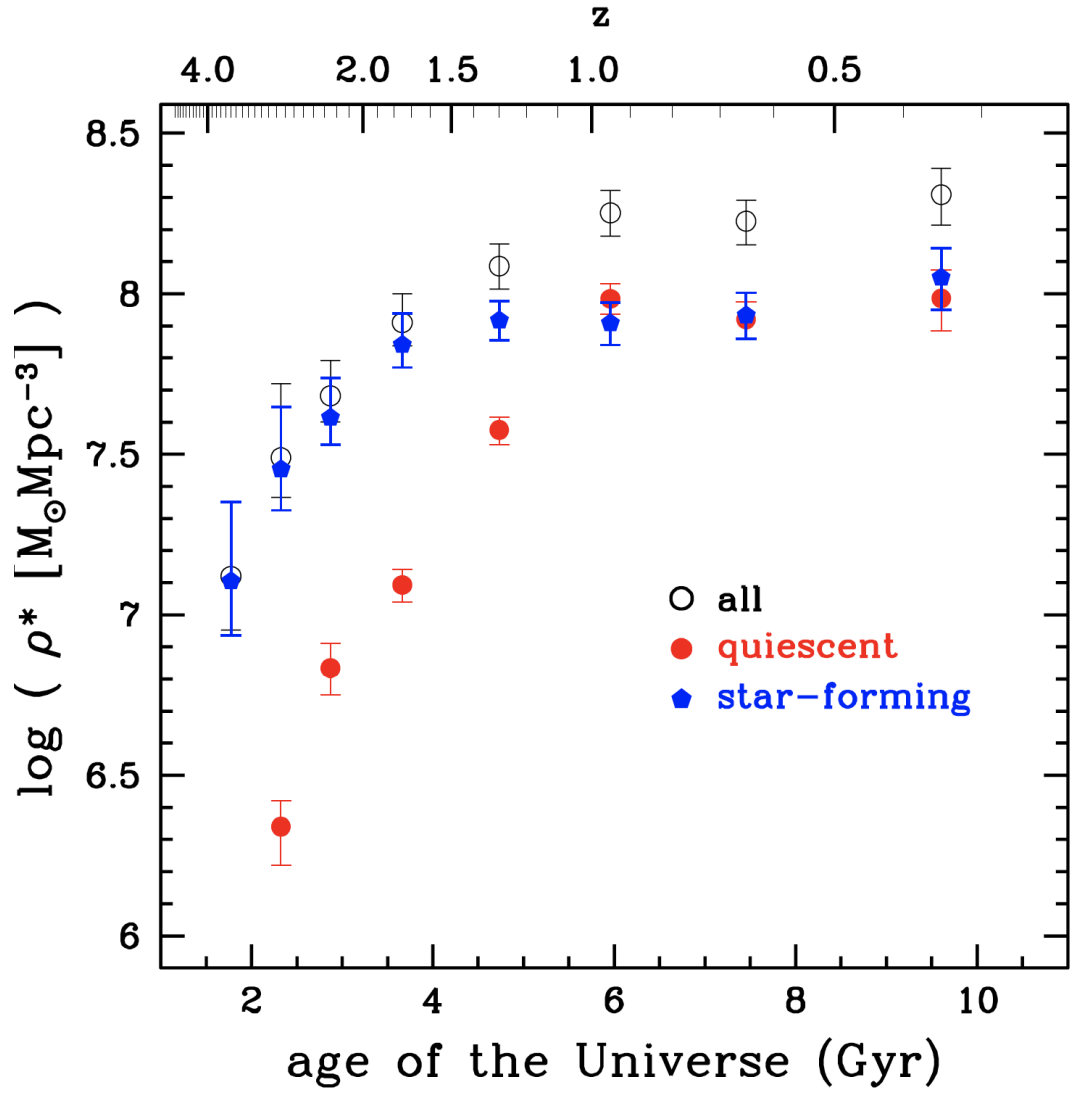


Figure 1.6: This figure shows the stellar mass density for different galaxy populations as a function of redshift from [Ilbert et al. \(2013\)](#). The quiescent galaxies are represented by the solid red circles, the star-forming sample corresponds to the blue pentagons and all the galaxies are represented by the open black circles.

[Ravindranath et al. 2004](#)). The Sérsic light profile is given by:

$$\Sigma(R) = \Sigma_{\text{eff}} \times \exp \left(-\kappa \left[\left(\frac{R}{R_{\text{eff}}} \right)^{1/n} - 1 \right] \right) \quad (1.1)$$

Where $\Sigma(R)$ is the surface brightness as a function of the radius R ; Σ_e is the surface brightness at the effective radius R_e ; n is the Sersic index and κ is a function of n .

This method of distinguishing between disc and spheroidally-dominated galaxies can be used to investigate the morphological evolution of galaxies over cosmic time. For example, [Buitrago et al. \(2013\)](#) have studied the structure of massive ($M^*/M_\odot > 10^{11}$) galaxies and found that the galaxy population changes with cosmic time. The fraction of massive spheroids ($n > 2.5$) increases

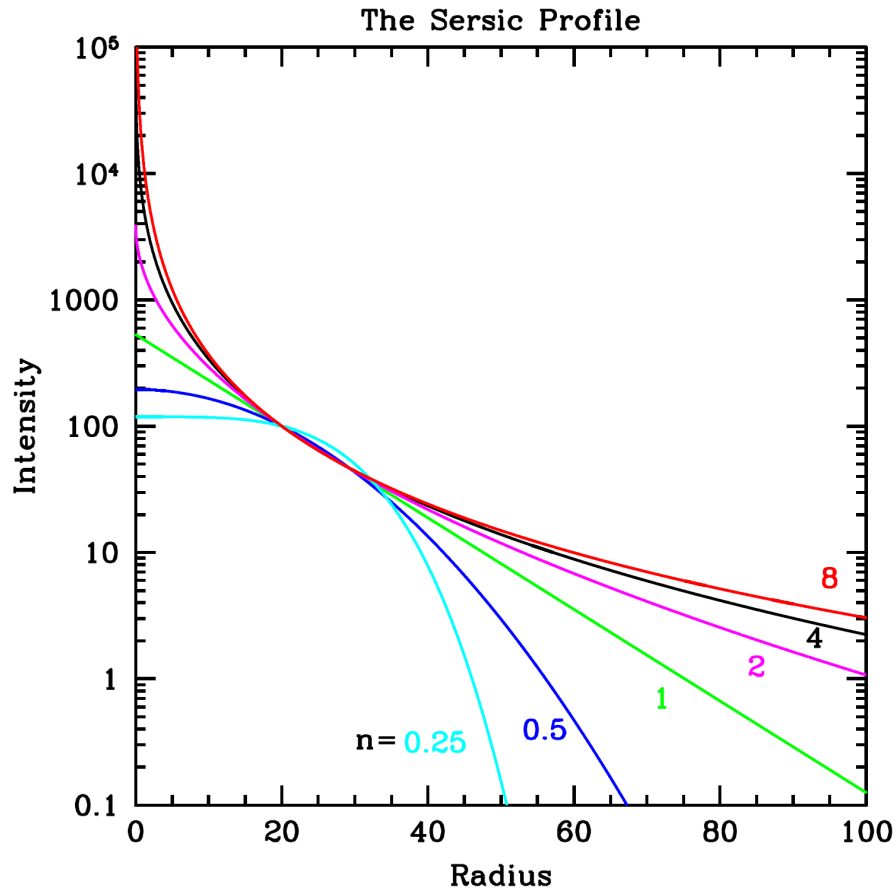


Figure 1.7: Sérsic profile at fixed R_e and Σ_e from [Peng et al. \(2010a\)](#), where Σ_e is the pixel surface brightness at the effective radius R_e . The two key values are $n=1$ and $n=4$, corresponding to the profile of a stellar disc and bulge, respectively.

from ~ 30 percent at $z \sim 3$ to ~ 80 percent in the local Universe. Their results are shown in Fig. 1.8, where the fraction of massive spheroid-like and disc-like galaxies is shown. Discs dominate at high redshift, however, this changes from $z \sim 1$, where the fraction of spheroids is greater than that of discs. This suggests that massive galaxies start as discs and evolve to become spheroids.

Another interesting aspect of galaxy evolution is that not all spheroids are red and not all discs are star-forming. Several authors (e.g. [McGrath et al. 2008](#), [Lee et al. 2008](#), [Masters et al. 2010](#), [McLure et al. 2013](#), [Bruce et al. 2014](#)) have observed quenched galaxies with light profiles resembling those corresponding to a disc-like morphology, and such objects are called passive discs. Studying these galaxies can help improve our understanding of their evolution. For example, [McLure et al. \(2013\)](#) found that 44 ± 12 per cent of the passive galaxies in their sample have disc-like morphologies and suggested that the quenching of star formation and morphological transformation in galaxies are not a product of the same process.

The evolution of galaxies from star-forming to passive, disc to spheroid, and from late-type to early type is a complex process that is not very well understood. In the next sections we explore how studying both environment and mass can provide further insights into this topic.

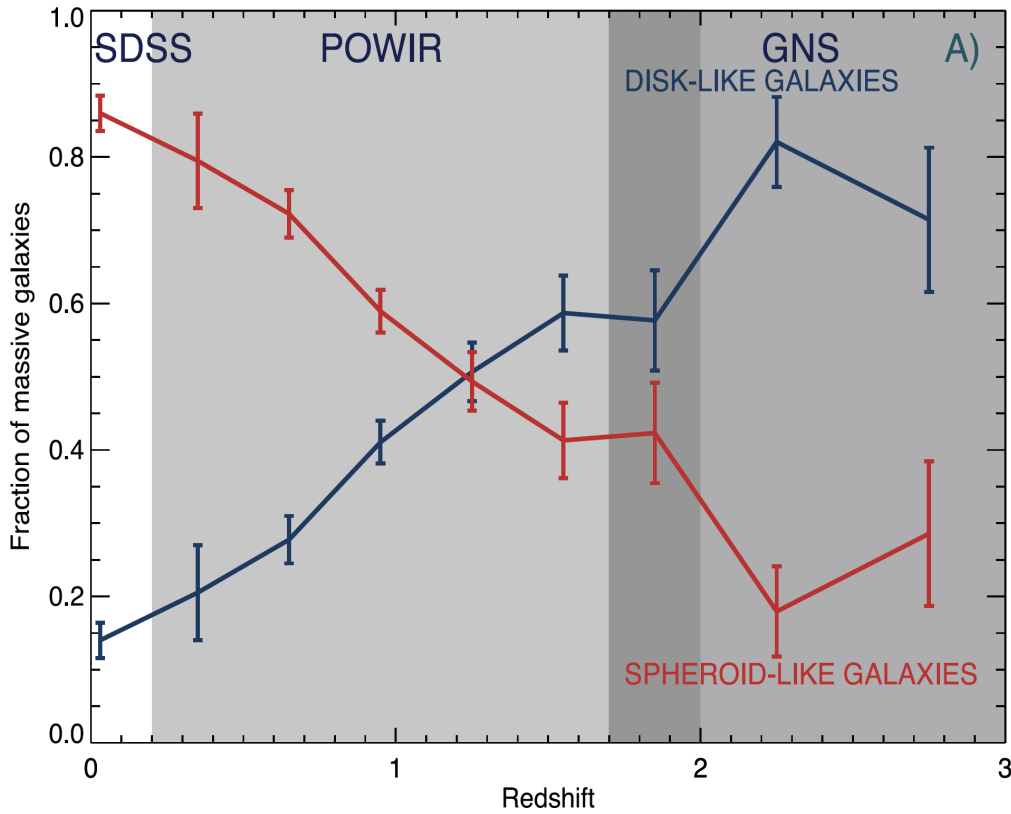


Figure 1.8: *Fraction of massive ($M^*/M_\odot > 10^{11}$) spheroid ($n > 2.5$) and disc ($n < 2.5$) galaxies from $z \sim 3$ to the local Universe. The different shaded areas correspond to the different surveys used in [Buitrago et al. \(2013\)](#)*

1.3 Galaxy environments

The environment of a galaxy is defined by its surroundings. Galaxies can either be isolated (with no galaxies nearby to interact), in small groups (up to around 50) or in clusters, which can have up to thousands of those objects. Interactions between galaxies are more common in denser environments than in less dense ones (see e.g. [Hashimoto & Augustus Oemler 2000](#)). Furthermore, the evolution of galaxies seems to be accelerated in denser environments (e.g. [Andreon 2013, 2018, Pintos-Castro et al. 2019](#)).

The most important aspect in studying the effects of environment in galaxy evolution is the definition used for environment. This is because there is not a single definition to determine the environmental density, and each author chooses to use a certain method. The most common methods are: the number density of galaxies to a n^{th} nearest neighbour (e.g. [Yoon et al. 2017](#)); projected distance from the cluster centre (e.g. [Bassett et al. 2013](#)); stellar mass density inside a fixed aperture (e.g. [Cebrián & Trujillo 2014](#)); galaxy counts in a fixed aperture (e.g. [Chuter et al. 2011](#), and this study). These differences in the definition of environment make it difficult to compare between studies and lead to discrepancies between them. See, for example, [Wolf et al. \(2009\)](#), [Wilman et al. \(2010\)](#), [Haas et al. \(2012\)](#) and [Muldrew et al. \(2012\)](#) for a comparison between different measurements of environment.

Several authors have observed that the properties of galaxies depend in their environment (e.g. [Balogh et al. 1998](#), [Hashimoto et al. 1998](#)). There are three main relationships between galaxy properties and their environment:

1. Star formation rate–density relation: The star formation rate of a galaxy depends on its environment in the way that galaxies inhabiting cluster environments have a lower SFR than those in the field (e.g. [Gómez et al. 2003](#), [Vulcani et al. 2010](#)). This means that passive galaxies are generally found in denser environments than their star-forming counterparts.
2. Morphology–density relation: Early-type galaxies are generally found in denser environments than their late-type counterparts (e.g. [Oemler 1974](#), [Dressler 1980](#)).
3. Colour–density relation: Galaxies that show optically red colours are generally found in denser environments when compared to those showing optically blue colours (see e.g. [Bamford et al. 2009](#)).

Furthermore, several studies have found that passive early-type galaxies are found mainly in denser environments than their star-forming late-type counterparts (e.g. [Oemler 1974](#), [Dressler 1980](#), [Whitmore et al. 1993](#), [Poggianti et al. 1999](#), [Kauffmann et al. 2004](#), [von der Linden et al. 2010](#)), which combines both the SFR–density and the morphology–density relations. Additionally, following the same trends as the SFR, the AGN activity in galaxies has also been observed to be lower in galaxies which live in denser environments when compared to those in the field (e.g. [Kauffmann et al. 2004](#), [Montero-Dorta et al. 2009](#)). These environmental correlations are only valid in the local Universe and can be extremely different when looking at the high-redshift Universe.

The relationships found between colour, SFR and galaxy morphology with environment are important to understand galaxy evolution, in particular the effects of environment in the quenching of star formation and in the morphological transformation of galaxies.

1.3.1 Morphology-density relation

Many early studies in galaxy evolution have reported that there is a relationship between the environmental density of a galaxy and its morphology (e.g. [Hubble & Humason 1931](#), [Abell 1965](#), [Oemler 1974](#)). In the local Universe, galaxies with an early-type morphology are more common in high-density regions while late-types are more likely found in the field. To understand the morphological evolution of galaxies, it is important to investigate how the internal structure of galaxies changes in different environments. [Dressler \(1980\)](#) quantified the relationship between galaxy morphology and their environment in the local Universe, which is shown in Fig. 1.9. Here, the number of spiral+irregular (S+Irr) galaxies decreases with increasing density. This is known as the morphology-density relation.

It is important to note that the morphology-density relation presented in Fig. 1.9 corresponds to the one observed in the local Universe. As mentioned pre-

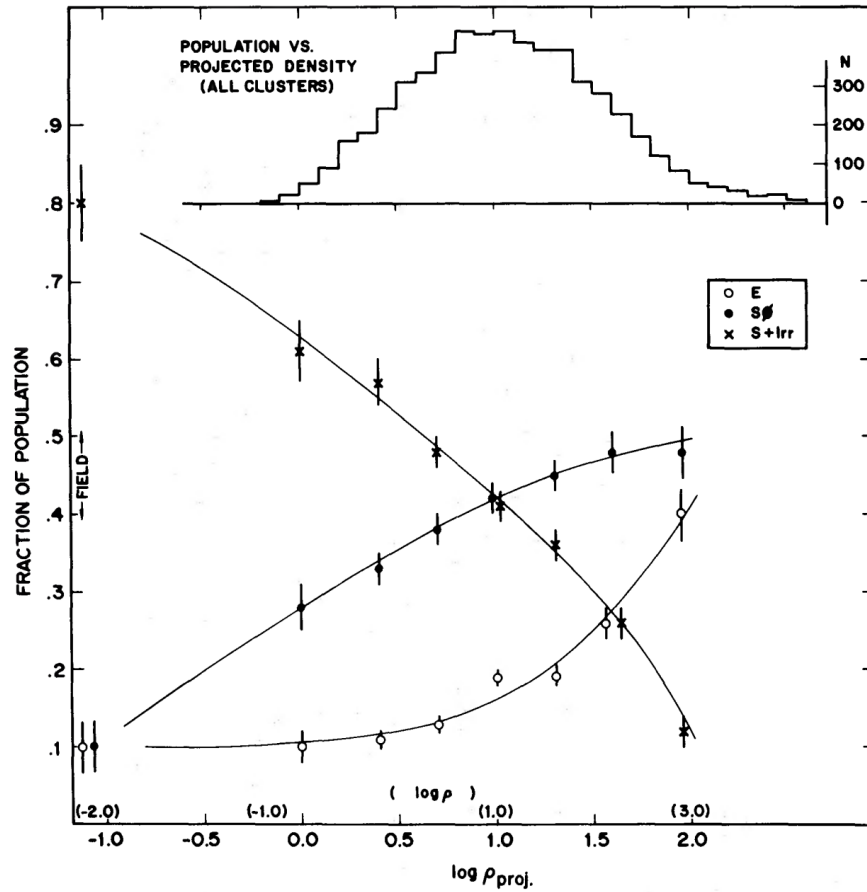


Figure 1.9: Morphology-density relation from [Dressler \(1980\)](#). The fraction of Elliptical galaxies (E), Lenticular (S0) and Spiral+Irregular (S+Irr) galaxies is shown as a function of projected density, using a sample of 55 galaxy clusters in the local Universe ($z=0$).

viously, galaxy structure evolves with cosmic time, so at higher redshift, this relation will look different. [Dressler et al. \(1997\)](#) have studied clusters at intermediate ($z \sim 0.5$) clusters and find that the fraction of elliptical galaxies does not show a significant change between low and intermediate redshift. On the other hand, the fraction S0 galaxies in clusters have been found to show a significant (a factor of 2-3) decrease from the local Universe to $z \sim 0.5$. The authors have proposed that cluster virialization is needed before enough S0s can transform from spirals to be found in significant numbers. However, whether these correlations are due to an environmental related process acting directly on the galaxies, or just the natural consequence of galaxies in denser environments being older (since they are members of a more massive DM halo that formed earlier), is not certain.

1.3.2 Environmental processes

A galaxy can be affected by its surroundings in different ways. The star formation can be both enhanced or suppressed, depending on how the environment process in question affects the gas supply. Furthermore, the internal structure of the galaxy can also be affected by environment. These different environ-

mental processes can be split into two main categories: interactions between galaxies, and interactions between the galaxies and the intracluster medium (ICM). Some of these mechanisms are listed below.

1. Interactions between galaxies

- (a) *Mergers*: When galaxies interact at low speeds their stellar distributions can merge (e.g. [Icke 1985](#)). The mass ratio between the two merging objects determines the type of merger.
 - i. *Major mergers*: The merging galaxies have similar masses. In this case, the remnant galaxy suffers significant structural transformation. These events disturb the stellar orbits inside the galaxy and can transform spiral objects into featureless (elliptical) ones (e.g. [González-García & Balcells 2005](#)).
 - ii. *Minor mergers*: The galaxies involved in these interactions are of significantly different masses. In this case, the smaller galaxy is accreted by the larger object, also known as satellite accretion (e.g. [Naab et al. 2007, 2009](#)).

In addition to the ratio between the stellar mass of the two merging galaxies, mergers can also be classified depending on their gas content.

- i. “Wet” mergers: The gas content of the galaxies merging is high (for example, two star-forming galaxies merging together), which can trigger bursts of star formation as the gaseous components are driven into the central regions of the remnant galaxy (e.g. [Mihos & Hernquist 1996](#)).
 - ii. “Dry” mergers: This term applies when the interaction occurs between galaxies containing significantly small amounts of gas (e.g. [van Dokkum 2005](#)). This leads to little triggered star formation, and may lead to an expansion of the stellar distribution.
- (b) *Tidal stripping*: When galaxy encounters take place at low speed, it does not always result in a merger. These interactions can result in the stripping of both stars and gas from the interacting galaxies, see [Smith et al. \(2016\)](#) for a review.
- (c) *Harassment*: Unlike mergers and tidal stripping, harassment is multiple high-speed interactions between galaxies (high-speed tidal interactions). During this interaction, galaxies come close to each other at very high velocities without colliding. The gas available for star formation can be disturbed or even removed. This process can also cause morphological transformation, distorting spiral galaxies, leading to the evolution from discs to spheroids ([Moore et al., 1996](#)).

2. ICM and galaxy interactions

- (a) *Ram-pressure stripping*: When a galaxy enters the cluster environment, it can lead to the removal of the cold gas (interstellar medium,

ISM) due to interactions between the gas in the galaxy and the hot gas in the ICM (Gunn & Gott, 1972). Since the cold gas in the ISM is the raw material for star formation, this can lead to a suppression and eventual quenching of the star formation in the galaxy.

- (b) *Strangulation*: When entering a cluster, the effect of ram pressure can also cause the removal of a galaxy’s outer hot gas reservoir or halo. This halts the gas inflow which usually replenishes the ISM, leading to a slow decline in star formation as the galaxy depletes its remaining cold gas supply. This is called strangulation (Larson et al., 1980).

1.4 Quenching of star formation

The existence of both the blue cloud and red sequence combined with observations where the fraction of red galaxies increases with cosmic time (see Fig. 1.8) suggests that galaxies evolve from the blue cloud to the red sequence through the quenching of their star formation.

One of the main differences between star-forming and passive galaxies is the amount of gas in the centre of the galaxy. The gas content will be greater in a galaxy with a higher star formation rate than in a galaxy with a low SFR (e.g. Santini et al. 2014). Which implies that SF galaxies have a significantly greater quantity of gas available than their passive counterparts. This means that for galaxies to quench their star formation, either their gas supply or reservoir has to be disturbed or removed. Both observations and simulations show that it is extremely unlikely that galaxies simply run out of gas for further star formation. The cluster core has hot and dense gas, which is efficiently cooled and falls into the galaxy through cooling flows (Fabian 1994). Using hydrodynamical cosmological simulations, the works carried out by Brooks et al. (2009) and Kereš et al. (2009) show that galaxies can be fed gas from the intergalactic medium via the flow of cold gas through filaments, continuously replenishing the fuel for star formation.

The morphological transformation and quenching of star formation in galaxies seem to be related to the environment. However it is possible that these two events are related to a common third factor (age), which leads to the “Nature” versus “Nurture” debate, first started by Dressler 1980. In the previous sections, we have shown that smaller structures form first and merge to form the large-scale structures we see today (see Fig. 1.3). Thus, galaxies in clusters are older than those in the field, meaning they exhibit more evolved properties than objects that have formed later (i.e. field galaxies). In this scenario, environment does not play a role in quenching star formation, since galaxies in denser environments are simply older than those in less dense regions. In the *Nature* scenario, a galaxy is not affected by its environment, and internal processes are responsible for its evolution. *Nurture* means that environment is the main driver in the evolution of galaxies.

In reality, both the nature and nurture scenarios are expected to play a role in galaxy evolution. Peng et al. (2010b) showed that both internal (nature; mass

related processes) and external (nurture; environment related processes) can play a role in the evolution of galaxies and the quenching of star formation. This has given rise to a framework with two main routes for quenching: “mass-quenching” (nature) and “environment quenching” (nurture).

1.4.1 Mass quenching

The star formation in galaxies can be quenched due to their stellar mass. Some studies report that the probability that a galaxy will become quenched increases with its stellar mass (e.g. [Peng et al. 2010b](#)). Some of the processes responsible for this internal quenching are presented below. We split these mechanisms into two categories: processes which are related to the internal structure of the galaxy and morphological quenching.

1. Internal processes

- (a) *AGN feedback*: This originates from the central black hole (BH) of the galaxy. When the BH accretes matter, significant amounts of heat and energy are injected into the host galaxy. It has been proposed that this can be responsible for heating and ejecting the interstellar medium (ISM) (e.g. [Silk & Rees 1998](#)). While AGN feedback has enough energy to tear the galaxy apart, it is still uncertain whether it can couple to the gas in the galaxy to such degree to cause the removal of the gaseous component.
 - (b) *Supernova feedback*: Supernova (SN) can generate stellar winds which could be strong enough to generate strong outflows of gas from the galaxy (e.g. [Chevalier & Clegg 1985](#), [Diamond-Stanic et al. 2012](#)). These outflows have the ability to quench star formation in a similar way to AGN feedback. Since massive galaxies may require powerful AGN to quench their star formation, SN feedback is expected to be more dominant in low-mass galaxies.
 - (c) *Disc instability*: In this scenario, the galaxy’s disc grows until it has become unstable, causing it to collapse (e.g. [Dekel et al. 2009](#)). The gas in the galaxy is exhausted due to a starburst caused by this collapse.
2. Morphological quenching: [Martig et al. \(2009\)](#) have suggested that the evolution from a disc-dominated to a spheroidal morphology is able to quench the star formation in galaxies, turning spheroids into red galaxies without the need for other mechanisms.

1.4.2 Environment quenching

In Section [1.3.2](#), we have explored some of the effects that environment might have on the evolution of galaxies. However, not all of those mechanisms lead to the quenching of star formation. In this section we explore which of those mechanisms have the ability to cause galaxies to halt their star formation.

It is clear that both galaxy-galaxy interactions and galaxy-ICM interactions can disturb the gas content in the galaxy. Galaxy mergers are unlikely to cause the galaxy to quench its star formation. Even though the fraction of mergers increases with galaxy stellar mass, galaxies that have been quenched via a merger event only represent 1-5 per cent of the observed quiescent population (Weigel et al., 2017). However, both tidal stripping and harassment have the capability to disrupt the gas orbit as well as removing it completely, leading to the ceasing of star formation. Ram-pressure stripping and strangulation are examples of galaxy-ICM interactions that can also lead to the quenching of star formation. The former is the main mechanism that affects galaxies in clusters.

From what we have mentioned in previous sections, it is clear that galaxy environments can alter the gas content in galaxies, making them become quenched. Even if environment is not directly responsible for that event, it appears to play a role in increasing the probability that a galaxy will become quenched.

1.5 Mass-size relation

Several authors have studied the size of galaxies at high and low redshifts (e.g. Daddi et al. 2005, Trujillo et al. 2006, 2007, Longhetti et al. 2007, Buitrago et al. 2008, van Dokkum et al. 2008a, Morishita et al. 2014, van der Wel et al. 2014) and found that for the same stellar mass, galaxies at high redshift are significantly smaller than those in the local Universe. For example, Trujillo et al. (2007) found that massive ($M^* \geq 10^{11} h_{70}^{-2} M_{\odot}$) spheroids at $z \approx 1.5$ are 4 times smaller than their counterparts of the same stellar mass in the local Universe, while from $z \approx 1.5$ discs have only doubled their size. Other studies at $z \sim 2$ have found that, for similar mass ranges, galaxies at this epoch can be up to a factor of 5 smaller when compared to those found in the local Universe (e.g. van Dokkum et al. 2008b, Damjanov et al. 2011).

The size evolution of passive galaxies is still a topic where a considerable amount of research is being carried out. The mechanisms through which early-type galaxies grow in size are not very well understood and there is no consensus on what process might be dominant in driving this evolution. Massive early-type galaxies show a strong size evolution, as shown in Fig. 1.10, which is also consistent with the findings from other works (e.g. Daddi et al. 2005).

The properties of galaxies are observed to have several scaling relations. Two of the most important are the Faber-Jackson (Faber & Jackson 1976) and Tully-Fisher (Tully & Fisher, 1977) relations, which are observed correlations between a galaxy's luminosity and the velocity of its component stars. The Faber-Jackson relation uses the velocity dispersion of elliptical galaxies while the Tully-Fisher relation uses the rotational velocity of the stellar distribution of disc/S0 galaxies. Both relations make it clear that the luminosity of a galaxy is related to its mass, in the way that the brighter the galaxy, the greater its stellar mass. Furthermore, the Kormendy relation (Kormendy, 1977) states that there is a relationship between the luminosity and the size of the galaxy. Combining these three relationships, we find that both elliptical and spiral/S0

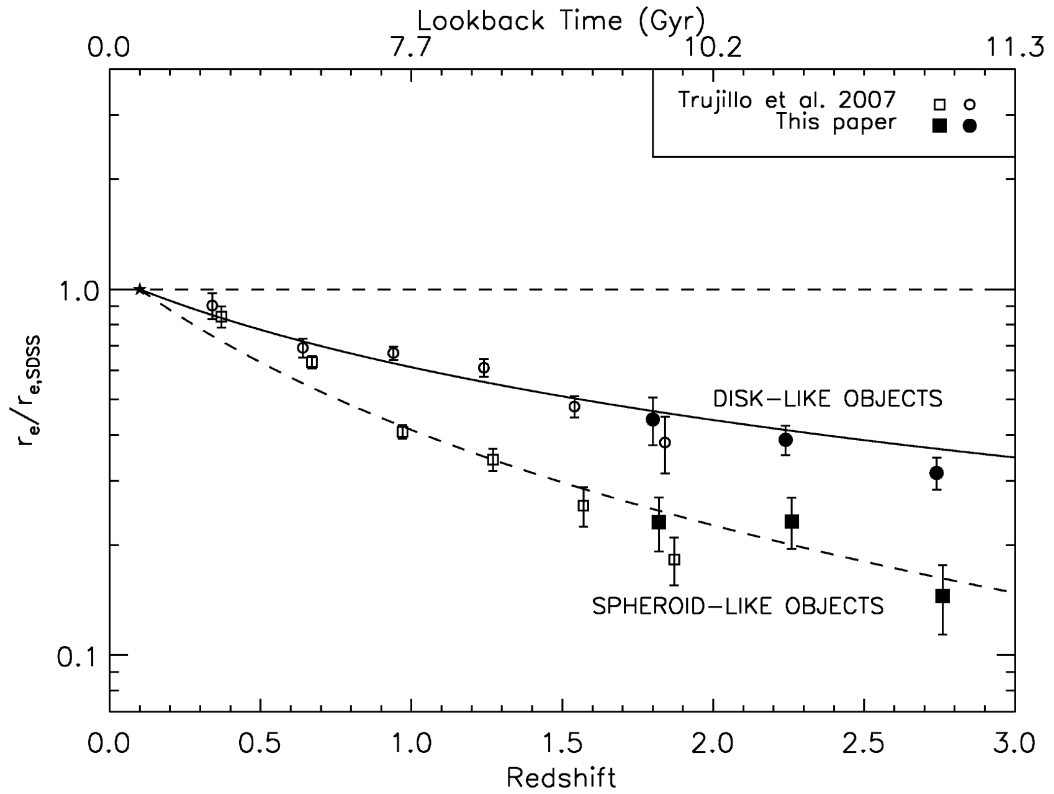


Figure 1.10: Size evolution with redshift ($0 < z < 3$) for massive ($M > 10^{11} M_{\odot}$) galaxies from [Buitrago et al. \(2008\)](#). In this figure, the authors compare their results (open symbols) to those obtained by [Trujillo et al. \(2007\)](#) (solid points).

galaxies show a relationship between their mass and the size of the galaxy, since mass is proportional to luminosity. This relationship is known as the mass-size relation.

1.5.1 The size growth of passive galaxies

There are three main scenarios that could explain the size evolution of passive galaxies: major dry mergers (not favoured), minor mergers (favoured), and AGN feedback.

A key aspect of size evolution is that, at a fixed stellar mass, passive galaxies are smaller at higher redshift. This implies that these passive galaxies evolve by increasing their physical size but without a significant increase in their stellar mass. Therefore, the mechanisms that lead to the growth of these objects have to be efficient at increasing the size of a galaxy but without causing it to grow in stellar mass. In [Section 1.3.2](#), we have explored the many different ways by which galaxies can interact with each other. Both major and minor mergers have the ability to increase the size of a galaxy. Minor mergers are able to shred the accreted galaxy and form an outer thick envelope and thus cause an increase in size. Additionally, major mergers have been observed to significantly increase the mass of galaxies, leading also to a size increase, but there is no clear change to the mass-size relation as the growth happens parallel to that relation (e.g. [Bezanson et al. 2009](#)). On the other

hand, several authors have proposed that minor mergers provide an efficient way to increase the size of a galaxy, without its mass increasing significantly as well (e.g. [Miller & Smith 1980](#), [Naab et al. 2009](#), [Trujillo et al. 2011](#)). Furthermore, passive galaxies have extremely low gas content, thus to grow in size and stay in the red sequence, the event that promotes this expansion cannot produce bursts of star formation, making dry mergers ideal candidates, since they are gas-free and, therefore, do not lead to newly available gas in the centre of the galaxy. With this, it seems that dry minor mergers meet the two constraints in the size increase of passive galaxies, they are able to grow passive galaxies without producing a growth in mass or a star-formation burst. Making use of simulations, [Oogi et al. \(2016\)](#) investigated how dry mergers affect the size growth of ETGs in high-density environments. They found that the contribution of dry minor mergers to the growth of massive central ETGs could be considerable.

Dry minor mergers and AGN feedback are not the only mechanisms that can explain the size evolution of passive galaxies. Some authors propose that this observed growth can be explained by a change in the passive population, where recently quenched galaxies are added to the population at lower redshifts (e.g. [Belli et al. 2015](#), [Carollo et al. 2013](#), [Franx et al. 2008](#), [Poggianti et al. 2013](#)). This is called “progenitor bias”. The gas content in the Universe decreases with cosmic time, and consequently galaxies that formed in the early Universe were a product of gas rich, and therefore, dissipative mergers. This leads to galaxies in the local Universe (lower gas content) being larger than those former in earlier epochs. In the “progenitor bias” theory, the galaxies that have been added to the population were formed at a later epoch, making them larger than those formed earlier on (see e.g. [van Dokkum et al. 2008b](#)). When developing models of galaxy evolution, galaxies at high redshift are thought to have the same properties as those at low redshift, and “progenitor bias” has to be considered if this is not the case. Several authors have studied this effect as the possible main driver of the observed size evolution, however it is generally thought that there is only a remote possibility that “progenitor bias” is the leading effect in this observation (e.g. [Bruce et al. 2012](#), [López-Sanjuan et al. 2012](#), [Szomoru et al. 2011](#), [van Dokkum et al. 2008b](#)).

Several works have proposed that active galactic nuclei (AGN) feedback may also lead to the size growth observed via adiabatic expansion, caused by the removal of the gas to the outer regions (e.g. [Fan et al. 2008](#); see also [Silk & Rees 1998](#), [Granato et al. 2001](#)), although the mass loss does not appear to be sufficient to explain the required growth in size ([Damjanov et al., 2009](#)).

As mentioned previously, galaxy environments affect the properties of galaxies, therefore, it is natural to investigate whether the size of a galaxy is also affected by its environment. Extensive work has been done on the effect of environment on the size of quiescent galaxies. However, there are contradictions in the results: some authors at low redshift (e.g. [Delaye et al. 2014](#), [Yoon et al. 2017](#), [Kuchner et al. 2017](#)) and intermediate to high redshift (e.g. [Papovich et al. 2012](#), [Cooper et al. 2012](#), [Strazzullo et al. 2013](#), [Lani et al. 2013](#)) have found that the size of quiescent galaxies increases with galaxy environment, where at fixed mass, quiescent galaxies are typically larger in the denser environments.

Other authors, at low redshift, (e.g. [Maltby et al. 2010](#), [Huertas-Company et al. 2012](#), [Kelkar et al. 2015](#)) found no evidence of a relationship between galaxy size and its environment. This discrepancy in the results might arise from the fact that there is not a single definition of environment, making it difficult to directly compare the results from different studies, or it may also be due to the different redshift ranges probed by different authors.

1.6 The aim of this work

The quenching of star formation is one of the main current research topics in the field of extra-galactic astronomy. As discussed in the previous sections, both mass (internal processes) and environment (external processes) are able to explain the halting of star formation in galaxies. However, differentiating between the effects of both mass and environment is a complicated task. In this thesis we investigate this topic, aiming to understand how the internal and external properties of galaxies affect their properties at different epochs in the Universe. We achieve this by investigating the role of mass and environment in the evolution of galaxies up to $z \approx 3$, where we study the fraction of quiescent galaxies as a function of both mass and environment aiming to determine if the relationship found by [Peng et al. \(2010b\)](#) at low redshift also holds at earlier epochs in the Universe. We also investigate the mass-size relation for star-forming, passive and PSB galaxies, with the main focus in understanding if the compact size of PSB galaxies found by [Almaini et al. \(2017\)](#) is also present out to $z \approx 3$. Finally, to study the effects of environment in the internal structure of galaxies, we combine both the effect of galaxy environments and the mass-size relation and explore the difference between size of quiescent (passive+PSB) galaxies in high and low density environments, following from [Lani et al. \(2013\)](#). In summary, the main goal of this work is to combine the results from these two areas to contribute to a better understanding on the evolution of galaxies from the blue cloud to the red sequence.

This thesis is sectioned as follows. In Section 2 we describe the data used, and explain how the galaxy environment was measured. We present our key results in Section 3, a detailed discussion in Section 4, and our conclusions in Section 5. Complementary results can be found in the Appendix, which are referred to where appropriate in the main body of the thesis.

The cosmology assumed is: $\kappa = 0$, $\Omega_{m=0.3}$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70 \text{ Kms}^{-1}\text{Mpc}^{-1}$. All magnitudes have been calculated using the AB magnitude system.

Chapter 2

Description of the data

In this chapter, we present a description of the catalogue used in this work. We also explain how we measured the structural parameters as well as how we distinguish between the different galaxy populations.

This thesis is based on joint work from the UDS collaboration. The photometric and spectroscopic redshifts, supercolours, environments, stellar masses and structural properties described in this chapter were not measured by me. However, I calculated the 95 per cent mass completeness limits (Section 2.3) and converted the angular size of the galaxies into kpc. I used the resulting catalogues to carry out all of the analysis presented from Chapter 3 onwards.

2.1 The UDS DR11 catalogue

In this study we use the K -band selected catalogues from the 11th data release (DR11) of the Ultra Deep Survey (UDS; Almaini et al., in preparation). This is the deepest of five surveys that comprise the UKIRT (United Kingdom Infra-Red Telescope) Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007). The UDS comprises photometry in JHK which covers an area of 0.77 degrees^2 and with the limiting depths being $J=25.4$, $H=24.8$ and $K=25.3$ (5σ depths in 2 arcsecond apertures). This survey is complemented by additional coverage in several wavelength bands: B, V, R, i' and z' from the Subaru/*XMM-Newton* Deep Survey (SXDS; Furusawa et al. 2008); Y from the VISTA VIDEO survey (Jarvis et al., 2013); and mid-infrared data from the *Spitzer* UDS Legacy Program (SpUDS; PI: Dunlop), using the IRAC camera at 3.6 and $4.5 \mu\text{m}$ with AB depths of 24.2 and 24.0 respectively. Further u -band photometry is also available from the Canada-France-Hawaii Telescope (CFHT) with $u = 26.75$ to a 5σ depth. The area with complete multi-wavelength coverage, after masking, is $0.62 \text{ square degrees}$.

2.2 Photometric redshifts

The photometric redshifts (z_{phot}) used in this work were calculated following [Simpson et al. \(2013\)](#), using the EAZY package ([Brammer et al. 2008](#)) to fit templates built from [Bruzual & Charlot \(2003\)](#) models to the 12-band photometry from the UDS (U , B , V , $R_{i'}$, z' , Y , J , H , K , 3.6 and 4.5 μm). These photometric redshifts will be described in Hartley et al. (in preparation). To test their robustness, 7000 secure spectroscopic redshifts were used, including 1500 from the UDSz (ESO Large Programme; PI: Almaini) and archival data detailed in [Simpson et al. \(2012\)](#). The photometric redshifts used in this work are robust, as the normalized median absolute deviation σ_{NMAD} in $(z_{\text{phot}} - z_{\text{spec}})/(1 + z)$ is 0.019.

2.3 Galaxy classification and stellar masses

In this work, we are interested in galaxy properties over the redshift interval $0.5 < z < 3$. In the UDS, galaxies have been classified at these redshifts using the principal component analysis (PCA) of galaxy spectral energy distributions (SEDs) from [Wild et al. \(2014, 2016\)](#), where a detailed description of this method can be found. In this thesis, we outline the main characteristics.

The goal of this technique is to characterise the SED shapes of galaxies by linearly combining a low number of principal components. Stellar population synthesis models from [Bruzual & Charlot \(2003\)](#) (BC03) are used to obtain a model grid of 44 thousand SEDs, to which PCA is applied. This yields a mean spectrum and three eigenspectra, the linear combination of which can account for > 99.99 per cent of the variance in the model library. Each of these eigenspectra contributes to the reproduction of a complete SED for each galaxy, and supercolours (SC) are defined as the coefficients used to quantify their individual contribution and are called SC1, SC2 and SC3. The red-blue slope is determined by SC1, which correlates with mean stellar age, while SC2 corresponds to the strength of the Balmer break, and correlates with both metallicity and the stellar mass which was assembled during the last billion years. Finally, the shape that each SED takes around 4000 Å is determined by SC3, which also separates the two characteristics given by the SC2. Due to these correlations, galaxies can be classified into various types depending on their supercolours. This divides the galaxy population into five populations: star-forming (SF), dusty star-forming, passive, post-starburst (PSB) and low metallicity, but in this work, we only use the SF, PSB and passive populations. In this work the dusty star-forming galaxies were excluded from the star-forming sample. We note, however, that including them had no significant impact on any of the conclusions presented in this thesis, and they represent only a small minority of the star-forming population at all redshifts.

The stellar masses used in this study were also calculated using the PCA method. The Bayesian analysis described in [Wild et al. \(2016\)](#) was used so the degeneracy between physical parameters can be accounted for. Using BC03, a library with tens of thousands of population synthesis models was created, and

fitting these to the supercolours gives a probability distribution for each physical property. The stellar mass for each galaxy in our sample was calculated assuming a Chabrier (Chabrier 2003) initial mass function. Uncertainties in these stellar masses are typically ± 0.1 dex, assuming the BC03 stellar population models and allowing for photometric redshift uncertainties.

After obtaining the mass for each galaxy, we calculated the 95% mass completeness limits for our sample following the method detailed in Pozzetti et al. (2010). A brief description of this method is presented below, but see the original paper for full details. The first step is to calculate the limiting masses (M_{lim}) for our galaxy sample. The limiting mass at a given redshift is defined as the stellar mass a galaxy would have if it had the limiting magnitude of the UDS survey ($K_{\text{lim}} = 23.5$). This is given by

$$\log(M_{\text{lim}}) = \log(M) + 0.4(K - K_{\text{lim}}), \quad (2.1)$$

where M and K are the stellar mass and K -band magnitude of the galaxy, respectively. At a given redshift, we then use the M_{lim} values of the faintest 20 per cent of the respective galaxy population. The 95 per cent mass completeness limit at this redshift is then defined as the 95th percentile of this M_{lim} distribution. This is performed in several redshift bins, and a functional form fit to the resultant values to obtain the 95 per cent completeness curve.

The 95 per cent completeness curves are illustrated in Fig. 2.1. Here, the mass distribution for the entire sample is shown, as well as the completeness curves corresponding to each galaxy type: blue for star-forming, red for passive and black for PSB galaxies. These limits ensure that our sample is > 95 per cent complete and for each redshift interval studied in this work ($0.5 < z < 1$, $1 < z < 2$ and $2 < z < 3$) the mass limit is chosen as the one corresponding to the upper end of the redshift bin. The 95% completeness limits for each galaxy sample at each redshift bin are shown in Table 2.1 and throughout this work, when we refer to a mass complete sample, those are the corresponding limits.

Redshift	SF	Passive	PSB
$0.5 < z < 1$	9.11	9.7	9.4
$1 < z < 2$	9.74	10.4	10.04
$2 < z < 3$	10.1	10.73	10.44

Table 2.1: Values of the 95% mass completeness limits in units of $\log(M^*/M_{\odot})$ for SF, Passive and PSB galaxies in the three redshift bins, calculated using the functions of the curves in Fig. 2.1

For completeness, the number of galaxies in each population for the different redshift bins is shown in Table 2.2. Here the number of galaxies is shown before and after the mass completeness limits were applied (first and last value, respectively).

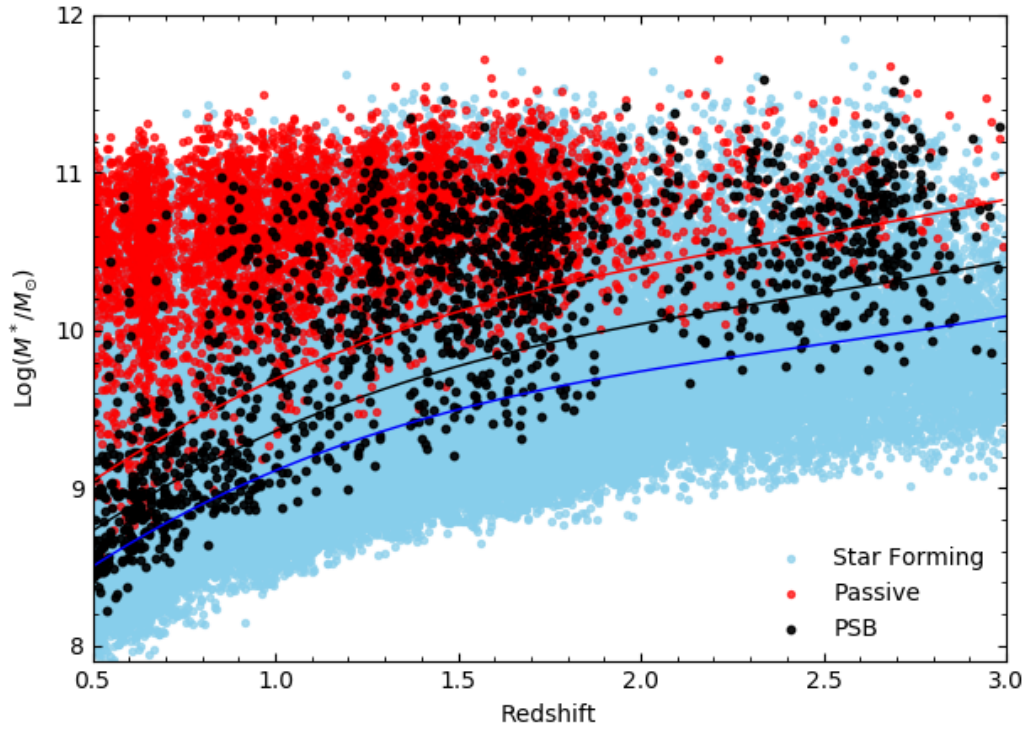


Figure 2.1: *Stellar mass as a function of redshift. The red, black and blue lines represent the 95% completeness limits (calculated following Pozzetti et al. 2010) for the passive, PSB and star-forming galaxies respectively.*

Redshift	SF	Passive	PSB
$0.5 < z < 1$	21349;10315	2080;1933	434;116
$1 < z < 2$	32657;13251	2240;1828	742;529
$2 < z < 3$	10311;3460	247;122	1350;227

Table 2.2: Number of galaxies in each population in the different redshift intervals before and after the mass completeness limits shown in Table 2.1 were applied, For all galaxies, the first number shown is before the completeness limits while the second number shows to the total number of galaxies corresponding to the mass complete sample.

2.4 Size and Sérsic index

Using the UDS DR11 K-band image, the structural parameters that we use in this work were measured by Almaini et al. (2017). In that paper, the GALAPAGOS software (Barden et al. 2012) was used to detect the objects and automatically use GALFIT (Peng et al. 2002) to fit a 2-D Sérsic light profile. The Sérsic light profile is given by:

$$\Sigma(R) = \Sigma_{\text{eff}} \times \exp \left(-\kappa \left[\left(\frac{R}{R_{\text{eff}}} \right)^{1/n} - 1 \right] \right) \quad (2.2)$$

where $\Sigma(R)$ is the surface brightness as a function of the radius R ; Σ_{eff} is the surface brightness at the effective radius, R_{eff} ; n is the Sersic index (Sersic,

1968) and κ is a function of n . The size (effective radius R_{eff}) in image pixels is converted into arcseconds using the plate scale of the UDS K -band image (0.1342 arcseconds/pixel).

The K -band structural parameters used in this work are determined from UKIRT ground-based imaging. However, for a small fraction of our sample (7 per cent), space-based structural parameters are available from the CANDELS-UDS HST H -band imaging (van der Wel et al., 2012). To test the robustness of the K -band structural parameters, Almaini et al. (2017) compared their measurements, where available, with the CANDELS H -band structural parameters. They report a tight relationship between the ground-based K -band and CANDELS H -band sizes. The sizes measured with the CANDELS H -band are systematically ~ 13 per cent larger than the ones measured from the ground-based K -band with a 17 per cent scatter in $\delta R/R$. This confirms the validity of using the ground-based structural parameters in this work. For full details on the K -band structural parameters, see Almaini et al. (2017). For illustrative purposes, a comparison between the effective radius obtained from the UDS (ground based) and CANDELS (space based) is presented in Fig. 2.2.

To determine the physical size of each galaxy, the size (R_{eff}) in arcseconds is converted into kpc using the photometric redshift (z_{phot}) and standard cosmology (see Section 1.6, for the cosmology used). We show how this was done below.

For a given galaxy, the physical size in kpc is determined from its size in arcseconds and the angular scale of the Universe at that redshift (z).

$$R_{\text{eff}}(\text{kpc}) = R_{\text{eff}}(\text{arcseconds}) \times \text{Angular Scale}(z; \text{kpc/arcsecond}) \quad (2.3)$$

The angular scale of the Universe (in kpc/arcsecond) is determined from the angular diameter distance and is presented in Fig. 2.3.

Fig. 2.3 shows the angular diameter distance in kpc/arcsec as a function of redshift. Every object in the catalogue has a value for size and redshift. For each galaxy, the size in kpc is calculated by multiplying the size in arcseconds by the value of Y-axis corresponding to that particular redshift in the catalogue.

2.5 Galaxy environments

The method used to determine the galaxy environments is described in Chuter et al. (2011) and Lani et al. (2013). A short explanation of this technique is described below.

The environment measure used in this work is defined as a normalised galaxy number density, and were measured by counting the number of galaxies in a fixed aperture with $K_{\text{AB}} < 25$ (where the UDS K -band sample is > 99 per cent complete; see Almaini et al. in preparation). For each galaxy in the survey, we count the number of galaxies in a cylinder centered on the subject galaxy,

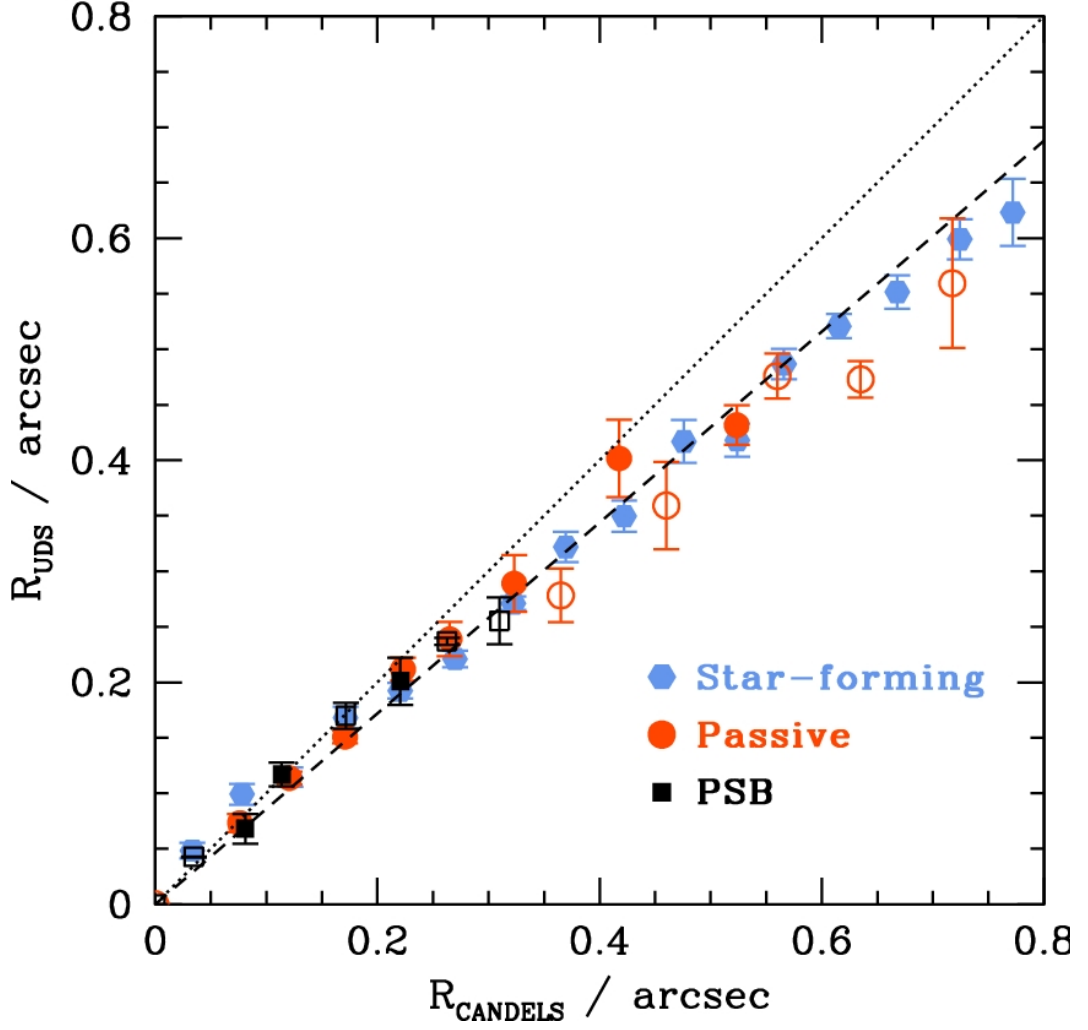


Figure 2.2: Galaxy size measured from the ground-based UDS K-band imaging versus the space-based CANDELS H-band imaging. This is used to check how robust the sizes obtained from the ground-based observations are. This plot is taken from [Almaini et al. \(2017\)](#).

with a radius of either 250 or 400 kpc and a depth of ± 0.5 Gyr in lookback time. The depth of the cylinder is a few times larger than the typical error in the photometric redshifts in order to limit the effect of photometric redshift uncertainty on these measurements.

To obtain our measure of environment (normalised galaxy number density ρ_n), the number of galaxies in the aperture N_g^{aper} is normalised with respect to the expected number counts assuming a random/uniform distribution N_r^{aper} (i.e. the average galaxy density):

$$\rho_n = \frac{N_g^{\text{aper}}}{N_r^{\text{aper}}} \quad (2.4)$$

Using this definition of environment, $\rho_n = 1$ corresponds to the average density of the galaxy distribution, $\rho_n < 1$ to underdense regions (e.g. field galaxies) and $\rho_n > 1$ to overdense regions (e.g. clusters). The expected number counts assuming a random/uniform distribution N_r^{aper} (i.e. the average galaxy den-

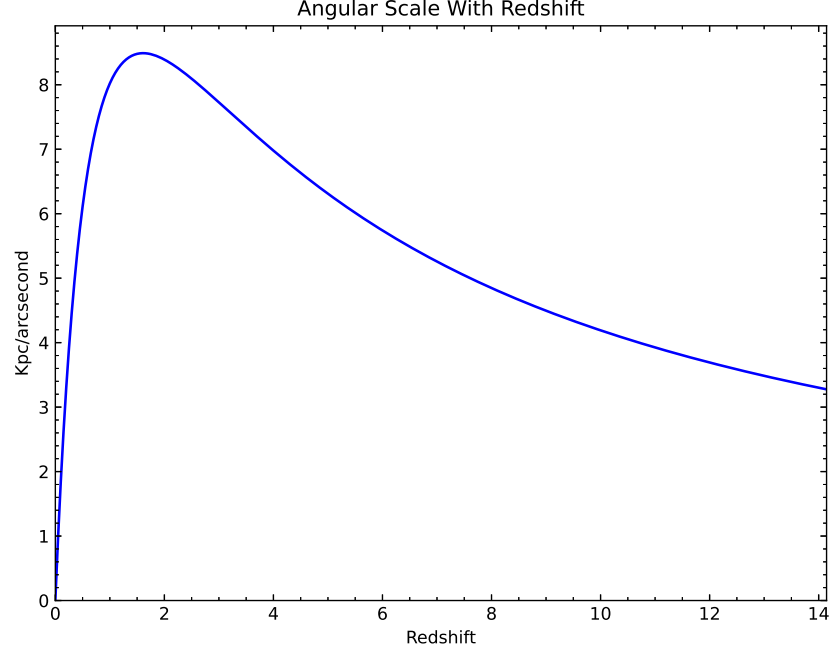


Figure 2.3: Angular scale at a given redshift in *kpc/arcsecond*.

sity) is calculated by

$$N_r^{\text{aper}} = \frac{N_z}{\text{TotalSurveyArea}} \times \text{ApertureArea} \quad (2.5)$$

where N_z is the galaxy counts within the redshift slice used to define the aperture cylinder (± 0.5 Gyr), and the total survey and aperture area take into account the bad pixel masking and limits of the *K*-band image.

In this thesis, we draw direct comparisons between our results and those of [Peng et al. 2010b](#) (see Section 3.1). We note that our environmental measure (ρ_n) is analogous to the overdensity measure ($1 + \delta$) used by [Peng et al. 2010b](#) (i.e. $\rho_n = 1 + \delta$), with the caveat that our environmental measure is determined using projected over-densities based on photometric redshifts.

In Fig. 2.4, we show the resulting galaxy density distribution of both the star-forming and quiescent galaxies. The quiescent population is defined to include both the passive and PSB SC populations. The shaded areas (Q1 to Q4) correspond to the quartiles of the quiescent sample at that redshift. Throughout this thesis, when comparing between high and low density environments, the fourth (Q4) and first (Q1) quartiles are used.

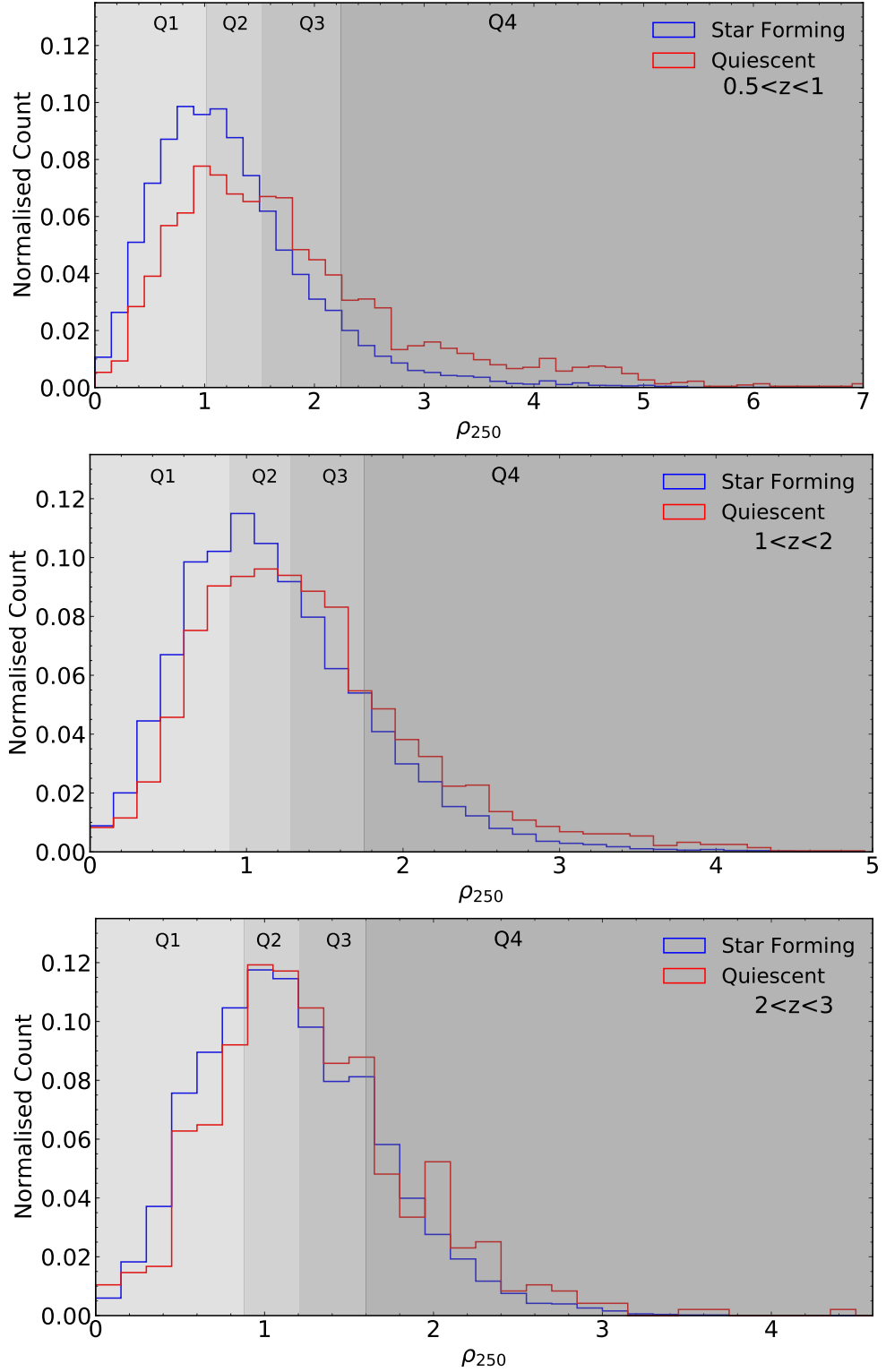


Figure 2.4: Galaxy density histograms measured in a 250kpc aperture for both star-forming and quiescent galaxies in the three redshift bins (Top: $0.5 < z < 1$, Middle: $1 < z < 2$, Bottom: $2 < z < 3$). The quiescent population has both post-starburst and passive galaxies. The shaded areas correspond to the four quartiles Q1, Q2, Q3 and Q4 for the quiescent sample. The mass completeness limits shown in Fig. 2.1 have been applied to the galaxy sample here, so the mass limits for both the quiescent and star forming galaxies correspond to the lines in Fig. 2.1. In this plot the mass of the galaxies does not drop below those curves.

Chapter 3

Results

3.1 Environment and mass

We study the relationship between galaxy environment and the quiescent fraction up to $z \sim 3$, aiming to verify if the trends found at low redshift by Peng et al. (2010b) are also present in the early Universe.

The quiescent fraction is calculated by computing the ratio between the number of quiescent (passive + PSB) galaxies and the number of total galaxies (quiescent and star-forming). In Fig. 3.1, we show the fraction of quiescent galaxies as a function of both mass and overdensity in the three redshift bins explored in this work: $0.5 < z < 1$, $1 < z < 2$ and $2 < z < 3$. This figure is split into two panels, the top panel shows the fraction of quiescent galaxies as a function of both mass and environment, where the colours represent the fraction, following Peng et al. (2010b), and the lower panel shows the quiescent fraction as a function of stellar mass in the highest density bin, the lowest density bin, and the two central bins combined. In the lower panels of Fig. 3.1 the uncertainties were calculated using the binomial error in the fraction. The dashed lines correspond to the 95% mass completeness limit, based on the passive galaxies. As in the previous section, these limits were chosen at the upper limit of the redshift bin, to provide the most conservative limit.

For the lowest redshift bin, our results show that the fraction of quiescent galaxies increases with both mass and overdensity, consistent with the findings presented in Peng et al. (2010b). Furthermore, during this epoch, from the lowest ($\log M^*/M_\odot \sim 9.9$) to the highest ($\log M^*/M_\odot \sim 11.1$) mass, the fraction of quiescent galaxies increases by a factor of 4.

For $1 < z < 2$, in the middle panels of Fig. 3.1, the contour plot also shows some curvature, suggesting that at this epoch, the fraction of quiescent galaxies also increases with both mass and overdensity. Due to the value of the mass completeness limit, the difference between Q1 and Q4 is more evident at higher masses, for $10^{10.9} < M^*/M_\odot < 10^{11.4}$. Nonetheless, the intermediate bins also suggest that the quiescent fraction steadily increases with both stellar mass and overdensity.

The above trends are still found in the highest redshift bin, even though the

quiescent fraction is quite small and there are fewer quiescent galaxies when compared to lower redshifts. The lower-right panel of Fig. 3.1 shows that galaxy overdensity is still important out to $z \sim 3$. The completeness limit at this redshift is high, restricting the number of useful data bins.

In the highest redshift bin we note an unexpected excess of quiescent galaxies in the lower-right corner of the contour plot. We performed several analysis to identify the possible origin of the double peak. At this redshift the post-starburst population might be contaminated with star-forming galaxies that are misclassified at this epoch. Naturally, we investigated whether the PSB population could be responsible for this double peak and we did this by removing them from the quiescent sample. These results are shown in Fig. B.1 and we refer the reader to this appendix for more detail on this analysis. We find that removing the PSB population does not have a significant effect on the plots, and the apparent excess of quiescent galaxies is still present in the lower right corner. Instead, we believe this feature is caused by the mass completeness limit in this redshift range. Due to this limit, galaxies of $\sim 10^{11} M_{\odot}$ are detected, but any neighbours of significantly lower mass will be missed; this will lead to an artificially low average density if a given galaxy is the most massive object within its halo. We conclude that the dual peak in the quiescent fraction is mainly due to the low number of data points available at this redshift and the high mass completeness limits.

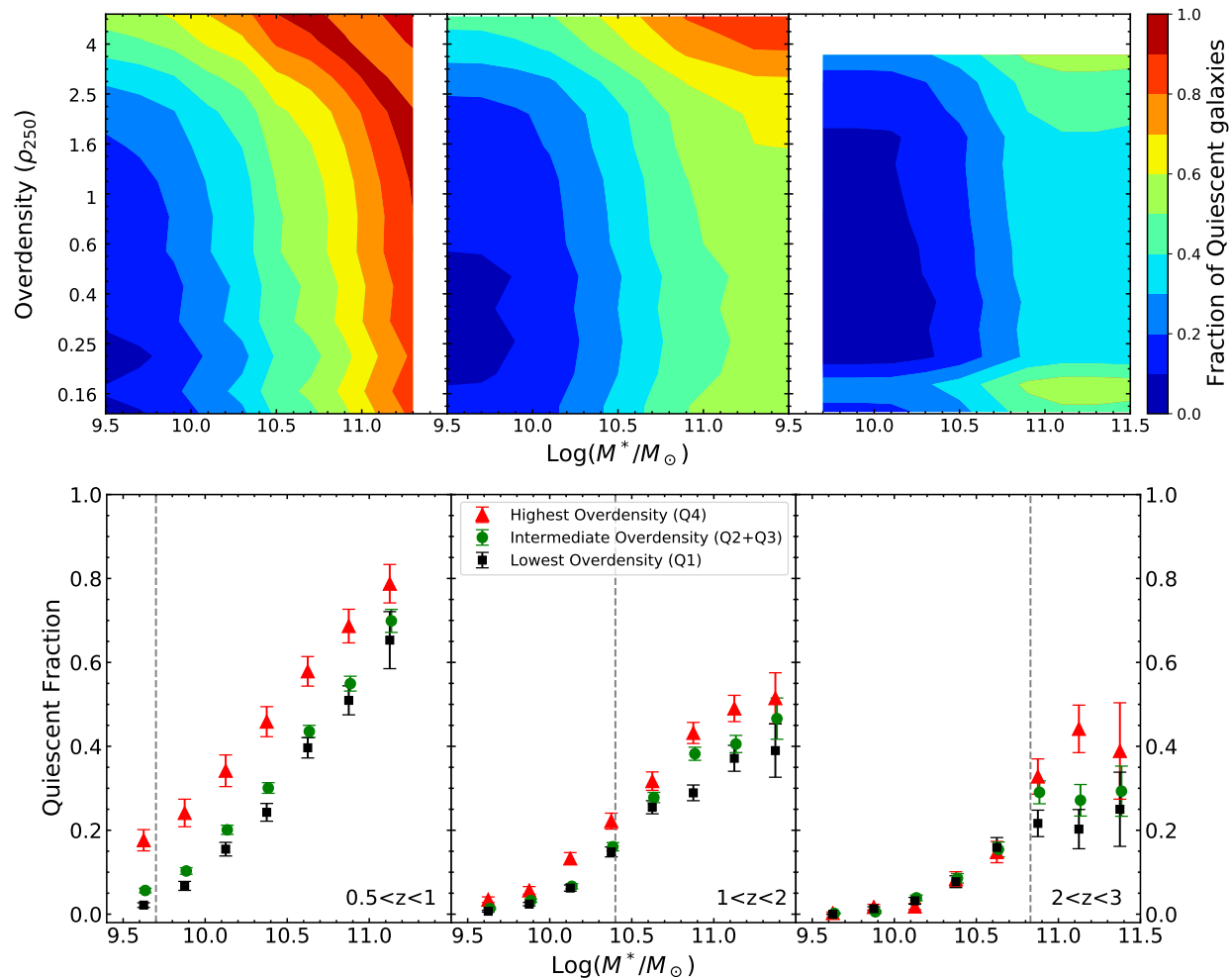


Figure 3.1: Fraction of quiescent galaxies as a function of both mass and overdensity. Top: fraction of quiescent galaxies as a function of mass and environment. Bottom: Quiescent fraction as a function of mass in three overdensity bins. Q1 is the lowest quartile (black squares), Q2+Q3 is the two intermediate quartiles (green circles) and Q4 is the highest quartile (red triangles). The errors were calculated using the fractional binomial error. The left, middle and right panels represent galaxies in $0.5 < z < 1$, $1 < z < 2$ and $2 < z < 3$, respectively. Our quiescent sample includes both passive and PSB galaxies. The vertical dashed lines represent the 95% completeness limits corresponding to the passive galaxies. Fig. ?? shows the definition of the quartiles used in the bottom plots.

3.2 Average density of galaxies

To explore the influence of environment in more detail, in this section we investigate the average density of galaxies as a function of both stellar mass and classification. We separate the quiescent population into older passive galaxies and the post-starburst population, using the classification scheme described in Section 2.3.

In Fig. 3.2, we show the average density of SF (blue), passive (red) and PSB (black) galaxies in three redshift bins from $z = 0.5$ to $z = 3$. The dashed lines correspond to the 95% mass completeness limits calculated in Section 2.3 applied at the highest redshift value for each bin. We find that for each epoch, at constant mass, the passive sample is found in the densest environments while the star-forming galaxies occupy the lowest densities and the PSBs are generally found between the star-forming and passive populations.

We find that PSB galaxies exhibit different trends with environment for low ($z < 1$) and high ($z > 1$) redshift. At $0.5 < z < 1$, low mass PSBs appear to reside in very dense environments while higher mass galaxies are found in significantly less dense regions. On the other hand, for $1 < z < 3$ this trend changes significantly; here the difference between high and low mass is not as steep and the relationship between mass and environment follows a trend similar to the passive sample.

These trends add to the growing evidence for two distinct quenching routes for PSB galaxies (e.g. Maltby et al., 2018, Wild et al., 2016), and will be discussed further in Section 4.

3.3 Size-mass relation

In Figs. 3.3 and 3.4 we explore the mass-size relation for the star-forming, passive and PSB galaxies across three redshift intervals: $0.5 < z < 1$, $1 < z < 2$ and $2 < z < 3$. Fig. 3.3 shows the general mass-size relation while Fig. 3.4 displays the average size of galaxies as a function of mass. Each coloured dashed line represents the 95% mass completeness limit for each sample.

Star-forming galaxies display a shallow mass-size relation in the interval $0.5 < z < 1$. During the same epoch, high mass passive galaxies ($\log M^*/M_\odot > 10.5$) show a very strong relationship between size and mass. Low mass passive galaxies have a slope similar to the one of the SF population, this is because at low mass, passive discs dominate the morphology of the red galaxies; The opposite is true for higher mass, where passive spheroids dominate. The top right panel shows that PSB galaxies are compact objects and have a weak mass-size relation.

Consistent with many previous studies (e.g. Buitrago et al., 2008, Trujillo et al., 2007), we confirm that star-forming galaxies display a shallow mass-size relation at all redshifts, with only modest evolution with redshift. In contrast, massive passive galaxies ($\log M^*/M_\odot > 10.5$) display a very steep relationship between size and mass, and they are significantly smaller at earlier times.

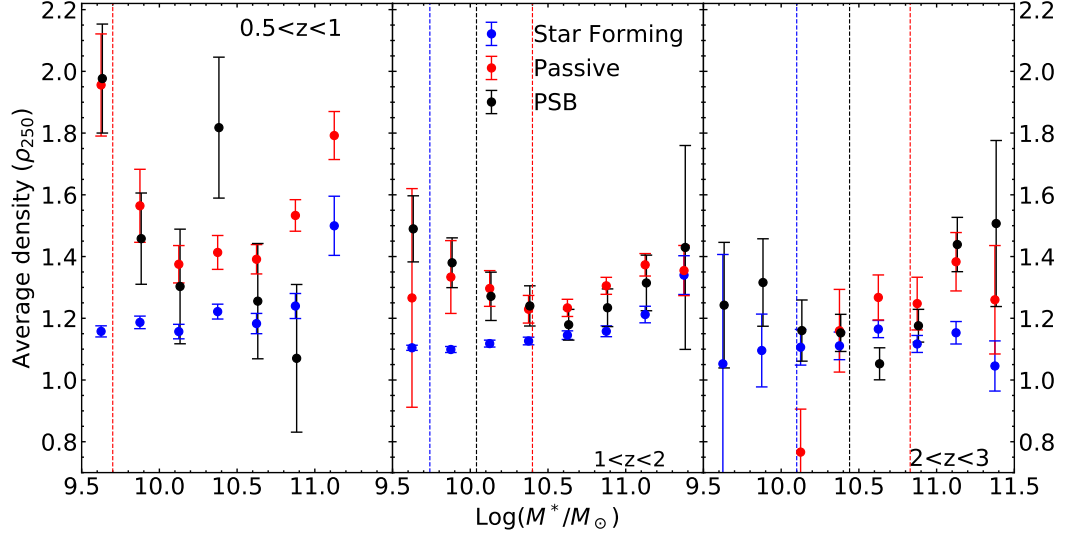


Figure 3.2: Average density (ρ_{250}) as a function of stellar mass for star-forming (blue), passive (red) and PSB (black) galaxies for $0.5 < z < 1$ (left-hand panel), $1 < z < 2$ (centre panel) and $2 < z < 3$ (right-hand panel). The three dashed lines represent the 95% mass completeness limits for each population. The errors were determined using the standard error in each bin. The points were offset so that the error bars do not overlap. In this plot the average density is calculated using the median density for each galaxy population.

A detailed exploration of this size evolution with cosmic time is beyond the scope of this thesis, though in Fig. B.2 we present the size evolution separately for each population.

The middle panels of Figs. 3.3 and 3.4 are a direct comparison to the study conducted by Almaini et al. 2017, using an updated version of the same sample. In Almaini et al. 2017 the DR8 was used to investigate the size-mass relation for star-forming, passive and PSB galaxies in the $1 < z < 2$ interval. Overall, our results agree with what was found in that paper, confirming that PSB galaxies are compact at this redshift.

In this work, however, we extend the study of the PSB mass-size relation to $z = 3$ for the first time. We confirm that massive ($\text{log } M^*/M_\odot > 10.5$) PSB galaxies are exceptionally compact at all epochs, and significantly more compact than the older “red nugget” passive galaxies of the same stellar mass. These general findings build upon other recent studies (e.g. Maltby et al., 2018, Yano et al., 2016). We also find the first tentative evidence that massive PSBs at high redshift are more compact than their counterparts at lower redshift (Fig. B.2).

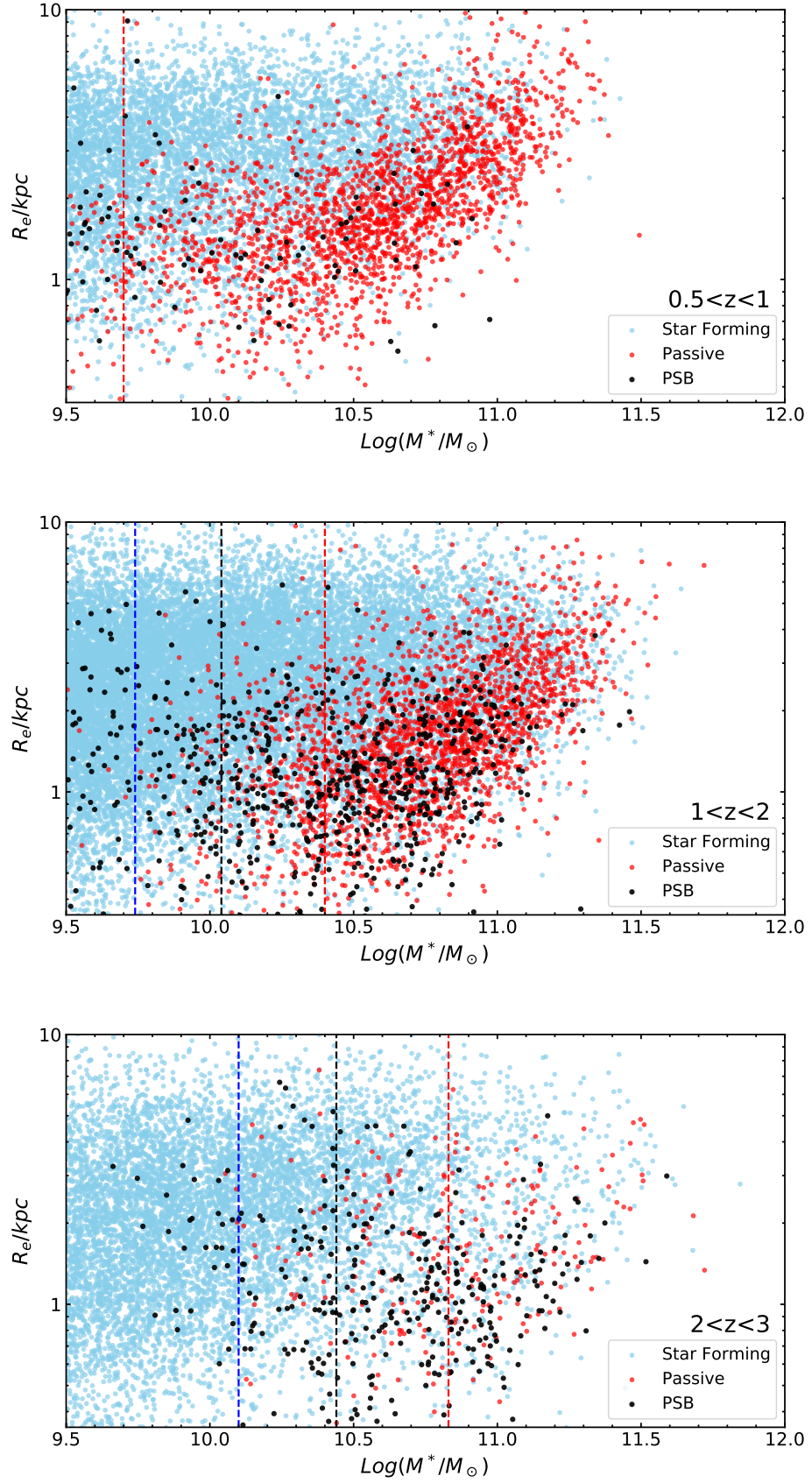


Figure 3.3: Size-mass relation for star-forming (blue), passive (red) and PSB (black) galaxies for $0.5 < z < 1$, $1 < z < 2$ and $2 < z < 3$, top, center and lower panels, respectively. The blue, black and red dashed lines represent the 95% mass completeness limits for each galaxy type.

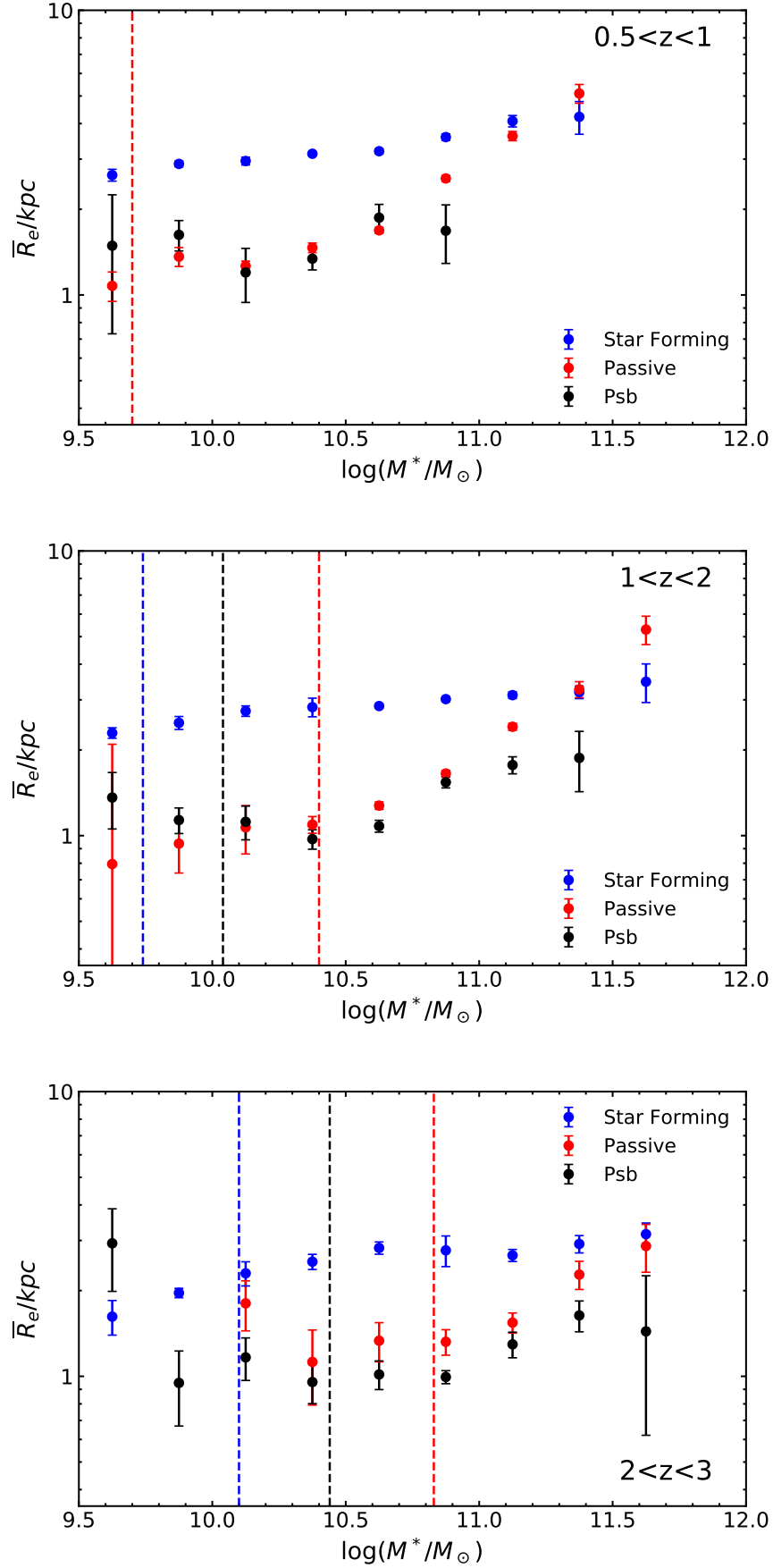


Figure 3.4: Average size of star-forming (blue), passive (red) and PSB (black) galaxies for $0.5 < z < 1$, $1 < z < 2$ and $2 < z < 3$, top, center and lower panels, respectively. The blue, black and red dashed lines represent the 95% mass completeness limits for each galaxy type. This plot derives from Fig. 3.3. The averages in this plot are calculated using the median size for each galaxy population in each mass bin.

3.4 Galaxy size and environment

In this section we combine the measures of environment with the mass-size relation, to investigate the relationship between these three parameters. This work builds on the findings of Lani et al. (2013), which we extend to higher redshift and lower stellar mass. Lani et al. (2013) defined their environments using the same aperture method we describe in Section 2.5, but using a larger 400 kpc aperture. In this Section we have therefore used both aperture diameters (250 kpc and 400 kpc), with the results for the smaller 250kpc aperture shown in the Appendix for completeness (Fig. C.1). The revised overdensity quartiles for the larger aperture (the equivalent of Fig. 2.4) are shown in Fig. A.1. To allow a more direct comparison with Lani et al. (2013) we combine the passive galaxies and PSBs into a single “quiescent” class, although as noted below removing the rarer PSBs has no significant impact on our conclusions.

Fig. 3.5 shows the average size of quiescent (Passive+PSB) galaxies as a function of mass in three overdensity bins: Q1, lowest overdensity, Q2+Q3 showing the intermediate quartiles and Q4, the densest environment. The top, centre and lower plots respectively show the $0.5 < z < 1$, $1 < z < 2$ and $2 < z < 3$ intervals. The dashed lines represent the completeness limit for passive galaxies, as in Fig. 3.1. We find that for the interval $0.5 < z < 1$, quiescent galaxies are, on average, larger in denser environments. This difference is more pronounced in the high-mass end, from $\log M^*/M_\odot > 10.5$. The presence of the intermediate overdensity quartile between Q1 and Q4 suggests that the size of quiescent galaxies constantly increases with environment rather than being a difference only present between the highest and lowest overdensities.

For $1 < z < 2$, our results show that at the low-mass ($\log M^*/M_\odot < 11$) end there is no clear difference between the size of quiescent galaxies in Q4 and Q1. However, for high-mass ($\log M^*/M_\odot > 11$) quiescent galaxies, there is a clear difference between the highest and lowest overdensity; this size growth with environment is also supported by the presence of the intermediate quartiles which lie between the red triangles and the black squares, suggesting a steady increase with galaxy density.

Redshift	ρ_{400}	ρ_{250}
$0.5 < z < 1$	$43 \pm 13\%$	$26 \pm 10\%$
$1 < z < 2$	$52 \pm 14\%$	$44 \pm 13\%$
$2 < z < 3$	$27 \pm 23\%$	$8 \pm 18\%$

Table 3.1: In Figs. 3.5 and C.1 there is evidence that massive quiescent galaxies are larger in denser environments when compared to lower densities. In this table we quantify that difference for both 400 and 250 kpc apertures. The percentages of increase in the size of high mass ($\log M^*/M_\odot > 11$) quiescent galaxies from Q1 to Q4 is shown for each redshift for both ρ_{400} and ρ_{250} . The comparison is only made between the first and fourth quartiles.

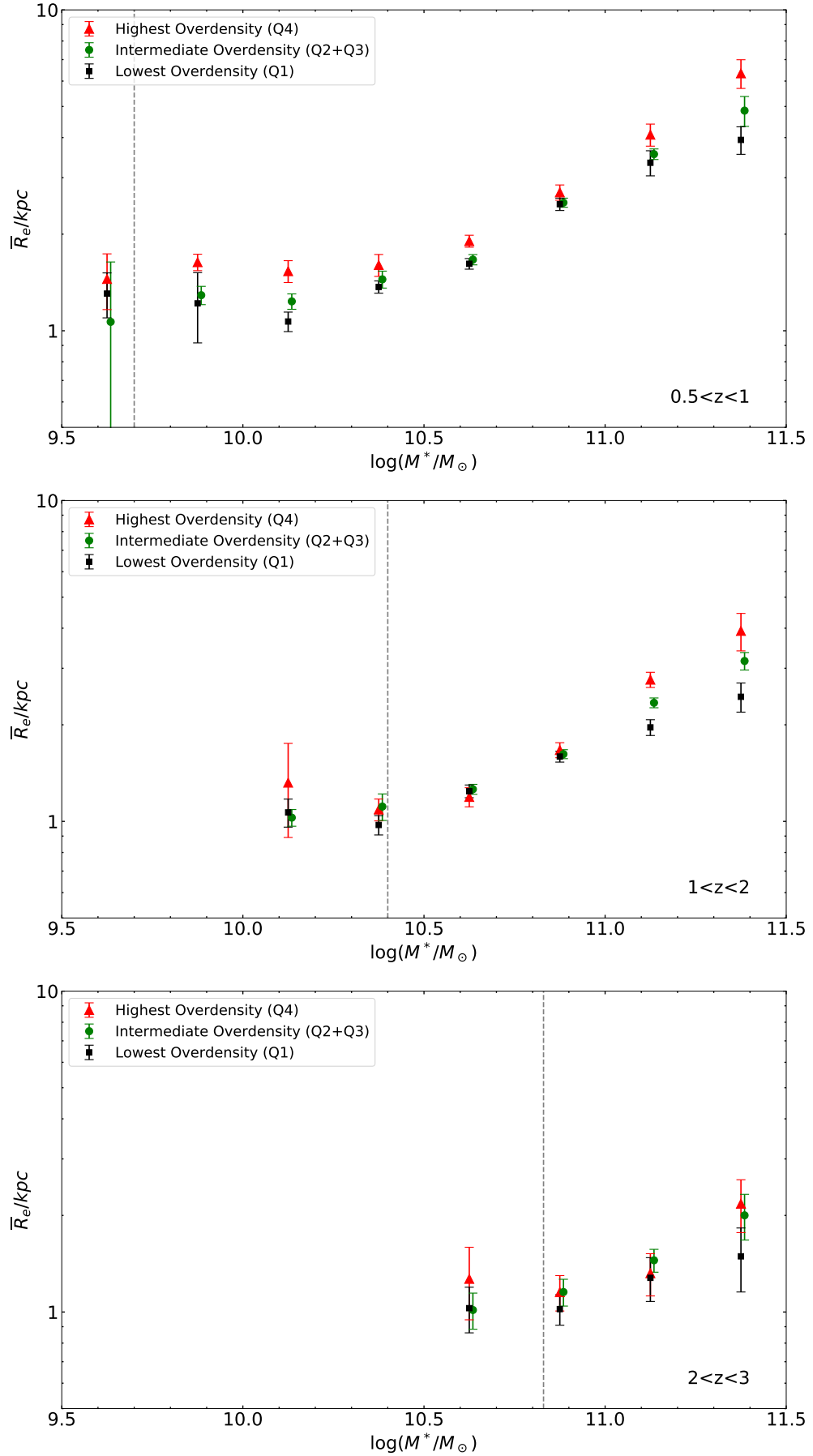


Figure 3.5: Average size of quiescent galaxies as a function of mass in three overdensity bins: first quartile (black squares), second and third quartiles combined (green dots) and fourth quartile (red triangles). In this plot, the aperture used is 400kpc to allow a direct comparison with [Lani et al. \(2013\)](#). Our sample includes both passive and PSB galaxies. The dashed lines represent the 95% completeness limits of the passive population. The points were offset so that the error bars do not overlap.

At the highest redshift bin there is no clear difference in the mass-size relation with environment within the uncertainties, although there remains a tentative trend.

We explored if the difference in the size of quiescent galaxies with environment was due to the presence of PSBs in the sample, which are typically more compact than older passive galaxies (see Section 3.3). Excluding these rare galaxies made no difference to the trends with environment however.

For completeness, we have also investigated if the sizes of star-forming galaxies depend on environment (see Fig.C.2). The analysis was done exactly in the same way, with the density quartiles corresponding to the star-forming sample.

In table 3.1, we show the percentage of increase in the size of quiescent galaxies between the first and fourth quartiles for both 400 and 250 kpc aperture. For the aperture of 400 kpc, in the interval $1 < z < 2$, galaxies in Q4 are 50 percent larger than those in Q1, consistent with the findings by Lani et al. (2013).

Chapter 4

Discussion

4.1 Mass and environment

We have shown that the fraction of quiescent galaxies (passive+PSB) increases with both mass and overdensity up to $z \sim 3$ (Fig. 3.1), increasing with stellar mass at fixed overdensity in addition to increasing with overdensity at fixed stellar mass. This trend is not only present between the highest and lowest quartiles but it is also seen when comparing galaxies within intermediate density quartiles. These results extend the work of Peng et al. (2010b) to higher redshifts, and are broadly consistent with several other studies (e.g. Chuter et al. 2011, Quadri et al. 2012, Darvish et al. 2016, Henriques et al. 2017, Kavinwanichakij et al. 2017, Contini et al. 2019, Contini et al. 2020). In contrast to the conclusions of Darvish et al. (2016), however, we do not find evidence that the quiescent fraction is independent of environment at $z > 1$.

In Fig. 3.2 we explore the environments of PSB galaxies separately, and we find that the mass-density relation for this population at $z > 1$ is different to the lower redshift relation, which suggests that the PSB population has distinct properties at high and low redshift. This observation has also been reported by previous authors, for example Maltby et al. (2018) studied the structure of PSB galaxies in the redshift range $0.5 < z < 2$ and found that the population at $z < 1$ is typically dominated by low-mass ($\log M^*/M_\odot < 10$) disc-like galaxies, while at $z > 1$ high-mass spheroids ($\log M^*/M_\odot > 10$) dominate. In their work, Wild et al. (2016) found that the mass function of PSB galaxies at $z \sim 2$ resembles that of passive galaxies while at $z < 1$ the shape is consistent with SF galaxies. This difference in space density is also apparent in Figure 2.1, which shows that massive PSBs are rare at low redshift. These differences may indicate two different quenching mechanisms are active at different epochs, consistent with Maltby et al. (2018) and Wild et al. (2016).

4.2 Size evolution of galaxies

From the mass-size relation, we find that there is a clear size evolution with redshift, where the most massive ($\log M^*/M_\odot > 11$) passive galaxies have

almost doubled their size from $z \sim 3$ to $z \sim 0.5$. These results are in agreement with many previous studies (e.g. [Trujillo et al. 2007](#), [Buitrago et al. 2008](#), [van Dokkum et al. 2008b](#), [van der Wel et al. 2014](#)).

We also show that out to $z \sim 3$, at the same stellar mass and redshift, PSB galaxies are extremely compact, even more compact than passive galaxies. In their work, [Almaini et al. \(2017\)](#) and [Maltby et al. \(2018\)](#) used the eighth data release from the UKIDSS UDS to study the sizes of PSB galaxies for $1 < z < 2$ and $0.5 < z < 2$, respectively and found that this population is extremely compact across all redshifts ($R_{\text{eff}} \sim 1\text{--}2$ kpc). In this work, we use the final data release of the UKIDSS UDS (DR11) to confirm and extend the results from those works. We also find evidence that massive PSBs at high redshift are more compact than their counterparts at lower redshift (Figure B.2), although larger studies will be required to confirm these findings

Only rapidly quenched galaxies go through a PSB phase. Galaxies that halt their star formation through slow quenching mechanisms such as strangulation do not experience a PSB phase, but instead move slowly from the blue cloud to the red sequence. Some studies have shown that between 30 to 100 per cent of massive galaxies are quenched in a “fast” quenching process and experience a PSB phase (e.g. [Wild et al., 2016, 2020](#)). The compactness of PSB galaxies across all redshifts studied shows that for many massive galaxies, the transition from SF to passive starts with extremely compact galaxies, which then grow into the large passive galaxies we observe in the local Universe (see also [Almaini et al. 2017](#)).

At all redshifts, these massive PSBs are likely to have undergone a highly dissipative event (e.g. merger or disc collapse, see e.g. [Wellons et al. 2015](#), [Zolotov et al. 2015](#), [Almaini et al. 2017](#), [Maltby et al. 2018](#)). But the result of the event is likely to be slightly different depending on the gas availability; the remnants may more compact at higher z since there is more gas around, so the mergers are more gas rich and therefore more dissipative. Our results are consistent with this picture. However, this interpretation may not be valid for low-mass PSB galaxies ($M^* < 10^{10} M_{\odot}$) at lower redshift ($z < 1$), since they are likely to undergo a significantly different evolution. For example, [Socolovsky et al. \(2019\)](#) have proposed that PSBs resulting from low-mass and compact SF galaxies were rapidly quenched via powerful stellar feedback together with the stripping of the halo in dense cluster environments.

Once they reach the red sequence, passive galaxies are expected to undergo satellite accretion, which would result in an expansion of their stellar envelope. This process allows for an effective increase in galaxy size without significantly increase its mass. Our results indicate that the size evolution in galaxies occurs after the PSB phase, suggesting a scenario in which massive galaxies halt their star formation following a highly dissipative event (e.g. gas rich merger), transition into the red sequence, and then increase in size via the successive accretion of satellites. This scenario is consistent with several studies (e.g. [Bezanson et al., 2009](#), [Naab et al., 2009](#), [Oogi et al., 2016](#)).

4.3 Environment and size of quiescent galaxies

We find that across all epochs ($0.5 < z < 3$) massive ($\log M^*/M_\odot > 11$) quiescent galaxies are larger in the highest density environment (Q4) when compared to their counterparts in the lowest density bin (Q1), with massive quiescent galaxies in $1 < z < 2$ being $52 \pm 14\%$ larger in Q4 than in Q1. Across all redshifts in this study, the difference between the typical galaxy size and environment is more significant in the high-mass end, $\log M^*/M_\odot > 11$ (see Figure 3.5).

The findings in this work up to $z \sim 2$ are in agreement with several other works that have investigated the role of environment in the mass-size evolution of galaxies in the same redshift range as in this thesis. For example, Lani et al. (2013) used the UDS DR8 to explore the effect of environment on galaxy sizes. Their environment measurements are the same as used in this work, but with a 400 kpc aperture throughout. They report that galaxy size relates strongly with environment for $1 < z < 2$ where quiescent galaxies are on average larger in denser environments. This difference is greater for the high-mass end when compared with their low-mass counterparts, with massive ($M^* > 2 \times 10^{11} M_\odot$) galaxies in the highest galaxy density being 50 per cent larger when compared to their field counterparts. With the DR11 we are able to probe to much lower stellar masses and higher redshifts than Lani et al. (2013), finding consistent results at $0.5 < z < 2$. We find clear evidence for an environmental dependence in the mass-size relation over the redshift range $0.5 < z < 2.0$, with tentative evidence that this is also present to $z \sim 3$.

Previous work on the influence of environment on galaxy size has produced contradictory findings. Cooper et al. (2012) used data from the DEEP2 and DEEP3 Galaxy Redshift Surveys in the interval $0.4 < z < 1.2$ and found that, for the same stellar mass, ETGs are 25 percent larger in denser environments than those in the field, in broad agreement with Lani et al. (2013). In contrast, Huertas-Company et al. (2012) found that the mass-size relation of quiescent galaxies does not depend on the galaxy environment at $z \sim 1$, although the range of environments probed was relatively limited. Other works, probing at much lower redshifts than this thesis found no evidence for a relationship between the size of quiescent galaxies and environment (e.g. Maltby et al., 2010). Further work may be required to reconcile these studies, although Cappellari (2013) have suggested that some of these contrasting results can be explained by the presence of slow and fast rotators in the samples, where only the former show a strong size increase.

The size growth of quiescent galaxies has been proposed to be mainly due to dry minor mergers as, unlike major mergers, they can effectively increase the size of a galaxy without causing a significant difference in the mass (e.g. Miller & Smith, 1980, Naab et al., 2009, Trujillo et al., 2011). Furthermore, Oogi et al. (2016) investigated how dry mergers affect the size growth of ETGs in high-density environments by making use of simulations. They found that the contribution of dry minor mergers to the growth of massive central ETGs is considerable. This combined with the fact that galaxies evolve faster in denser environment can explain why massive quiescent galaxies follow a steeper size-

mass relation and show a more significant difference in size between high and low density.

Over the redshift range studied in this work the size of the most massive passive galaxies appears to have a stronger dependence on environment but this appears to shift to progressively lower mass at lower redshifts (Figure 3.5). This picture is consistent with these massive galaxies being central galaxies that are growing in size via satellite accretion (minor mergers) within their host halos, with the process occurring first in the most biased regions of the Universe (the most massive halos), and shifting to lower mass halos at lower redshift.

Chapter 5

Conclusions and future work

In this thesis, we use the UDS DR11 to investigate the relationship between the properties of galaxies and their environments at $0.5 < z < 3$. We explore how the fraction of quiescent galaxies relates to both the galaxy environment and stellar mass, we investigate the compact sizes of PSB galaxies at high redshift, and finally we combined both the size of quiescent (passive+PSB) galaxies with environment to study how galaxy size is affected by environment. The key results from our work are:

1. We find that the fraction of quiescent (passive+PSB) galaxies increases with both mass and overdensity. The effects of environment are present out to ($z \sim 3$).
2. The post-starburst (PSB) galaxies provide additional insight into the typical environments where rapid quenching occurs. At low redshift ($z < 1$), PSBs are typically of low mass ($\log M^*/M_\odot < 10$) and inhabit very dense environments, strongly suggesting environmental quenching. At high redshift ($z > 1$) PSBs are typically more massive, and on average inhabit intermediate galaxy environments, between the star-forming and passive populations.
3. Studying the mass-size relation of SF, passive and PSB galaxies, we confirm that PSB galaxies are extremely compact across all epochs. Up to $z \sim 3$, high mass ($\log M^*/M_\odot > 10.5$) PSBs are more compact than older passive galaxies of the same stellar mass.
4. when exploring the effects of environment, we find that quiescent galaxies in denser environments are larger than their counterparts in low density environments up to $z \sim 2$; this difference is more noticeable at high mass ($\log M^*/M_\odot > 10.5$).

Our results suggest that environment plays a complex role in shaping galaxy evolution. At low redshift, environmental quenching may be the dominant mechanism responsible for the rapid quenching of low-mass galaxies. At high redshift the role of environment in quenching is less clear, but the most recently quenched high mass galaxies are certainly the most compact, and their subsequent growth in size appears to be strongly related to environment. We

propose a scenario in which high-redshift massive galaxies collapse to an ultra-compact phase immediately prior to being quenched. The resulting compact PSBs gradually accrete satellites at a rate that depends on their environment, before gradually becoming the massive central passive galaxies we observe today.

5.1 Limitations of this work

In this work, I have investigated the role of environment in the evolution of galaxies up to $z \sim 3$. Below I describe some of the potential limitations of this work, and discuss how this area of research might be improved in the future.

1. The uncertainties in the photometric redshifts become higher as the galaxies become fainter (high- z). The accuracy of the classification of galaxies as well as their stellar masses depends on the accuracy of the photometric redshifts. Therefore, galaxies in the interval $2 < z < 3$, carry a larger uncertainty than those at lower redshift ranges. This could be improved upon with deeper data, and also with more accurate galaxy templates to provide a better representation of galaxies at these early epochs. The growing high-redshift spectroscopic samples in the UDS will also help in the calibration of our photometric redshifts.
2. For the highest redshift interval it is more difficult to distinguish between the different populations of galaxies (Wild et al., 2014, 2020). Correctly classifying galaxies as either passive or PSB becomes quite challenging, in part due to the limited number of photometric wavebands around the crucial Balmer break and D4000 regions. As noted above, this is an area that could be improved upon with improved galaxy templates, and also with growing spectroscopic samples to test our classification methods.
3. For $2 < z < 3$, the number of usable data points for the quiescent (passive+PSB) population is very reduced when compared to lower redshifts and the mass limit extremely high ($\log M^*/M_\odot \sim 10.73$, see Table 2.1), so we are only able to probe at significantly large masses. Deeper data would allow us to probe lower stellar masses, and provide a more robust measure of environment (e.g. by allowing us to detect the satellites of these massive galaxies).

Another key limitation is that our PSB classification method is arguably untested at $z > 1.4$ in our current optical spectroscopy. This is primarily because the characteristic $H\delta$ absorption feature moves to the near-infrared at higher redshift. The James Webb Space Telescope (JWST) will have the ability to provide deep near-infrared spectroscopy to probe these features for the first time, with the potential for revolutionising studies of quenching in the early Universe. For the brightest PSBs we are also obtaining ground-based infrared spectroscopy with the Japanese Subaru telescope.

Another way to reduce the errors is to increase the sample size. The COSMOS survey is similar to the UDS, but it covers a larger area (1.5 compared to 0.62

square degrees after masking), though to slightly less depth in K. Supercolour classifications have recently been obtained in the COSMOS field (Wilkinson et al., submitted), which may allow us to extend the work of this thesis to a new and independent field.

In the longer-term future, ESA’s EUCLID mission will conduct a wide-area survey of $> 10^9$ galaxies across 15,000 square degrees (Laureijs et al., 2011), which will allow complementary studies in the more local Universe.

EUCLID will also conduct a “deep” survey over 40 square degrees to depths comparable to the UDS, which will provide an ideal probe of environments in the more distant Universe.

Bibliography

- Abell G. O., 1965, [ARAA](#), **3**, 1
- Almaini O., et al., 2017, [MNRAS](#), **472**, 1401
- Andreon S., 2013, [A&A](#), **554**, A79
- Andreon S., 2018, [A&A](#), **617**, A53
- Baldry I. K., Glazebrook K., Brinkmann J., Ivezić Ž., Lupton R. H., Nichol R. C., Szalay A. S., 2004, [ApJ](#), **600**, 681
- Balogh M. L., Schade D., Morris S. L., Yee H. K. C., Carlberg R. G., Ellingson E., 1998, [ApJL](#), **504**, L75
- Balogh M., et al., 2004, [MNRAS](#), **348**, 1355
- Bamford S. P., et al., 2009, [MNRAS](#), **393**, 1324
- Barden M., Häußler B., Peng C. Y., McIntosh D. H., Guo Y., 2012, [MNRAS](#), **422**, 449
- Bassett R., et al., 2013, [ApJ](#), **770**, 58
- Bell E. F., 2008, [Astrophys. J.](#), **682**, 355
- Belli S., Newman A. B., Ellis R. S., 2015, [ApJ](#), **799**, 206
- Bezanson R., van Dokkum P. G., Tal T., Marchesini D., Kriek M., Franx M., Coppi P., 2009, [ApJ](#), **697**, 1290
- Blanton M. R., et al., 2003, [ApJ](#), **592**, 819
- Brammer G. B., van Dokkum P. G., Coppi P., 2008, [ApJ](#), **686**, 1503
- Brammer G. B., et al., 2009, [ApJL](#), **706**, L173
- Brooks A. M., Governato F., Quinn T., Brook C. B., Wadsley J., 2009, [ApJ](#), **694**, 396
- Bruce V. A., et al., 2012, [MNRAS](#), **427**, 1666
- Bruce V. A., et al., 2014, [MNRAS](#), **444**, 1001
- Bruzual G., Charlot S., 2003, [MNRAS](#), **344**, 1000

- Buitrago F., Trujillo I., Conselice C. J., Bouwens R. J., Dickinson M., Yan H., 2008, [ApJL](#), **687**, L61
- Buitrago F., Trujillo I., Conselice C. J., Häußler B., 2013, [MNRAS](#), **428**, 1460
- Cappellari M., 2013, [ApJL](#), **778**, L2
- Cappellari M., 2016, [Annual Review of Astronomy and Astrophysics](#), **54**, 597
- Carollo C. M., et al., 2013, [The Astrophysical Journal](#), **773**, 112
- Cassata P., et al., 2008, [A&A](#), **483**, L39
- Cebrián M., Trujillo I., 2014, [MNRAS](#), **444**, 682
- Chabrier G., 2003, [PASP](#), **115**, 763
- Chevalier R. A., Clegg A. W., 1985, [NATURE](#), **317**, 44
- Chuter R. W., et al., 2011, [MNRAS](#), **413**, 1678
- Contini E., Gu Q., Kang X., Rhee J., Yi S. K., 2019, [ApJ](#), **882**, 167
- Contini E., Gu Q., Ge X., Rhee J., Yi S. K., Kang X., 2020, [ApJ](#), **889**, 156
- Cooper M. C., et al., 2012, [MNRAS](#), **419**, 3018
- Daddi E., et al., 2005, [APJ](#), **626**, 680
- Damjanov I., et al., 2009, [ApJ](#), **695**, 101
- Damjanov I., et al., 2011, [ApJL](#), **739**, L44
- Darvish B., Mobasher B., Sobral D., Rettura A., Scoville N., Faisst A., Capak P., 2016, [ApJ](#), **825**, 113
- Davis M., Efstathiou G., Frenk C. S., White S. D. M., 1985, [ApJ](#), **292**, 371
- Dekel A., Sari R., Ceverino D., 2009, [ApJ](#), **703**, 785
- Delaye L., et al., 2014, [MNRAS](#), **441**, 203
- Diamond-Stanic A. M., Moustakas J., Tremonti C. A., Coil A. L., Hickox R. C., Robaina A. R., Rudnick G. H., Sell P. H., 2012, [ApJL](#), **755**, L26
- Dressler A., 1980, [ApJ](#), **236**, 351
- Dressler A., Gunn J. E., 1983, [ApJ](#), **270**, 7
- Dressler A., et al., 1997, [ApJ](#), **490**, 577
- Faber S. M., Jackson R. E., 1976, [ApJ](#), **204**, 668
- Fabian A. C., 1994, [ARAA](#), **32**, 277
- Fall S. M., Efstathiou G., 1980, [MNRAS](#), **193**, 189
- Fan L., Lapi A., De Zotti G., Danese L., 2008, [ApJL](#), **689**, L101

- Franx M., van Dokkum P. G., Förster Schreiber N. M., Wuyts S., Labbé I., Toft S., 2008, [ApJ](#), **688**, 770
- Furusawa H., et al., 2008, [ApJS](#), **176**, 1
- Gallazzi A., Brinchmann J., Charlot S., White S. D. M., 2007, [MNRAS](#), **383**, 1439
- Gómez P. L., et al., 2003, [ApJ](#), **584**, 210
- González-García A. C., Balcells M., 2005, [MNRAS](#), **357**, 753
- Granato G. L., Silva L., Monaco P., Panuzzo P., Salucci P., De Zotti G., Danese L., 2001, [MNRAS](#), **324**, 757
- Gunn J. E., Gott J. Richard I., 1972, [ApJ](#), **176**, 1
- Haas M. R., Schaye J., Jeesson-Daniel A., 2012, Monthly Notices of the Royal Astronomical Society, **419**, 2133
- Hashimoto Y., Augustus Oemler J., 2000, [ApJ](#), **530**, 652
- Hashimoto Y., Oemler Augustus J., Lin H., Tucker D. L., 1998, [ApJ](#), **499**, 589
- Henriques B. M. B., White S. D. M., Thomas P. A., Angulo R. E., Guo Q., Lemson G., Wang W., 2017, [MNRAS](#), **469**, 2626
- Hubble E. P., 1926, [ApJ](#), **64**, 321
- Hubble E., Humason M. L., 1931, [ApJ](#), **74**, 43
- Huertas-Company M., et al., 2012, [MNRAS](#), **428**, 1715
- Icke V., 1985, AA, **144**, 115
- Ilbert O., et al., 2013, [A&A](#), **556**, A55
- Jarvis M. J., et al., 2013, [MNRAS](#), **428**, 1281
- Kauffmann G., et al., 2003, [MNRAS](#), **341**, 33
- Kauffmann G., White S. D. M., Heckman T. M., Ménard B., Brinchmann J., Charlot S., Tremonti C., Brinkmann J., 2004, [MNRAS](#), **353**, 713
- Kawinwanichakij L., et al., 2017, [ApJ](#), **847**, 134
- Kelkar K., Aragón-Salamanca A., Gray M. E., Maltby D., Vulcani B., De Lucia G., Poggianti B. M., Zaritsky D., 2015, [MNRAS](#), **450**, 1246
- Kereš D., Katz N., Fardal M., Davé R., Weinberg D. H., 2009, [MNRAS](#), **395**, 160
- Kormendy J., 1977, [ApJ](#), **218**, 333
- Kuchner U., Ziegler B., Verdugo M., Bamford S., Häußler B., 2017, [A&A](#), **604**, A54

- Lacey C., Cole S., 1993, [MNRAS](#), **262**, 627
- Lani C., et al., 2013, [MNRAS](#), **435**, 207
- Larson R. B., Tinsley B. M., Caldwell C. N., 1980, [ApJ](#), **237**, 692
- Laureijs R., et al., 2011, arXiv e-prints, p. [arXiv:1110.3193](#)
- Lawrence A., et al., 2007, [MNRAS](#), **379**, 1599
- Lee J. H., Lee M. G., Park C., Choi Y.-Y., 2008, [MNRAS](#), **389**, 1791
- Lee B., et al., 2013, [ApJ](#), **774**, 47
- Longhetti M., et al., 2007, [MNRAS](#), **374**, 614
- López-Sanjuan C., et al., 2012, [A&A](#), **548**, A7
- Madau P., Dickinson M., 2014, [ARAA](#), **52**, 415
- Maltby D. T., et al., 2010, [MNRAS](#), **402**, 282
- Maltby D. T., et al., 2016, [MNRAS](#), **459**, L114
- Maltby D. T., Almaini O., Wild V., Hatch N. A., Hartley W. G., Simpson C., Rowlands K., Socolovsky M., 2018, [MNRAS](#), **480**, 381
- Martig M., Bournaud F., Teyssier R., Dekel A., 2009, [ApJ](#), **707**, 250
- Masters K. L., et al., 2010, [MNRAS](#), **405**, 783
- McGrath E. J., Stockton A., Canalizo G., Iye M., Maihara T., 2008, [ApJ](#), **682**, 303
- McLure R. J., et al., 2013, [MNRAS](#), **428**, 1088
- Mihos J. C., Hernquist L., 1996, [ApJ](#), **464**, 641
- Miller R. H., Smith B. F., 1980, [ApJ](#), **235**, 421
- Montero-Dorta A. D., et al., 2009, [MNRAS](#), **392**, 125
- Moore B., Katz N., Lake G., Dressler A., Oemler A., 1996, [Nature](#), **379**, 613
- Morishita T., Ichikawa T., Kajisawa M., 2014, [ApJ](#), **785**, 18
- Moustakas J., et al., 2013, [ApJ](#), **767**, 50
- Muldrew S. I., et al., 2012, [MNRAS](#), **419**, 2670
- Naab T., Johansson P. H., Ostriker J. P., Efstathiou G., 2007, [ApJ](#), **658**, 710
- Naab T., Johansson P. H., Ostriker J. P., 2009, [ApJL](#), **699**, L178
- Oemler Augustus J., 1974, [ApJ](#), **194**, 1
- Oogi T., Habe A., Ishiyama T., 2016, [MNRAS](#), **456**, 300

- Papovich C., et al., 2012, [ApJ](#), **750**, 93
- Peng C. Y., Ho L. C., Impey C. D., Rix H.-W., 2002, [AJ](#), **124**, 266
- Peng C., et al., 2010a, [AJ](#), **139**, 2097
- Peng Y.-j., et al., 2010b, [ApJ](#), **721**, 193
- Perlmutter S., et al., 1999, [ApJ](#), **517**, 565
- Pintos-Castro I., Yee H. K. C., Muzzin A., Old L., Wilson G., 2019, [ApJ](#), **876**, 40
- Planck Collaboration et al., 2014, [A&A](#), **571**, A1
- Poggianti B. M., Smail I., Dressler A., Couch W. J., Barger A. J., Butcher H., Ellis R. S., Oemler Augustus J., 1999, [ApJ](#), **518**, 576
- Poggianti B. M., et al., 2013, [ApJ](#), **762**, 77
- Pozzetti L., et al., 2010, [A&A](#), **523**, A13
- Quadri R. F., Williams R. J., Franx M., Hildebrandt H., 2012, [ApJ](#), **744**, 88
- Ravindranath S., et al., 2004, [APJ](#), **604**, L9
- Roberts M. S., 1976, Comments on Astrophysics, **6**, 105
- Roberts M. S., Haynes M. P., 1994, [ARAA](#), **32**, 115
- Rubin V. C., Ford W. K. J., Thonnard N., 1978, [ApJL](#), **225**, L107
- Santini P., et al., 2014, [A&A](#), **562**, A30
- Schawinski K., et al., 2014, [MNRAS](#), **440**, 889
- Sersic J. L., 1968, Atlas de Galaxias Australes
- Silk J., Rees M. J., 1998, [AA](#), **331**, L1
- Simpson C., et al., 2012, [MNRAS](#), **421**, 3060
- Simpson C., Westoby P., Arumugam V., Ivison R., Hartley W., Almaini O., 2013, [MNRAS](#), **433**, 2647
- Smith R., Choi H., Lee J., Rhee J., Sanchez-Janssen R., Yi S. K., 2016, [The Astrophysical Journal](#), **833**, 109
- Socolovsky M., Maltby D. T., Hatch N. A., Almaini O., Wild V., Hartley W. G., Simpson C., Rowlands K., 2019, [MNRAS](#), **482**, 1640
- Spitzer Lyman J., Baade W., 1951, [ApJ](#), **113**, 413
- Strateva I., et al., 2001, [AJ](#), **122**, 1861
- Strazzullo V., et al., 2013, [ApJ](#), **772**, 118

- Szomoru D., Franx M., Bouwens R. J., van Dokkum P. G., Labbé I., Illingworth G. D., Trenti M., 2011, [ApJL](#), **735**, L22
- Takamiya M., 1999, [ApJS](#), **122**, 109
- Trujillo I., et al., 2006, [MNRAS](#), **373**, L36
- Trujillo I., Conselice C. J., Bundy K., Cooper M. C., Eisenhardt P., Ellis R. S., 2007, [MNRAS](#), **382**, 109
- Trujillo I., Ferreras I., de la Rosa I. G., 2011, [MNRAS](#), **415**, 3903
- Tully R. B., Fisher J. R., 1977, *AA*, **500**, 105
- Vulcani B., Poggianti B. M., Finn R. A., Rudnick G., Desai V., Bamford S., 2010, [ApJL](#), **710**, L1
- Weigel A. K., et al., 2017, [ApJ](#), **845**, 145
- Wellons S., et al., 2015, [MNRAS](#), **449**, 361
- Whitaker K. E., et al., 2014, [ApJ](#), **795**, 104
- White S. D. M., Rees M. J., 1978, [MNRAS](#), **183**, 341
- Whitmore B. C., Gilmore D. M., Jones C., 1993, [ApJ](#), **407**, 489
- Wild V., et al., 2014, [MNRAS](#), **440**, 1880
- Wild V., Almaini O., Dunlop J., Simpson C., Rowlands K., Bowler R., Maltby D., McLure R., 2016, [MNRAS](#), **463**, 832
- Wild V., et al., 2020, [MNRAS](#), **494**, 529
- Williams R. J., Quadri R. F., Franx M., van Dokkum P., Labbé I., 2009, [ApJ](#), **691**, 1879
- Wilman D. J., Zibetti S., Budavári T., 2010, [MNRAS](#), **406**, 1701
- Wolf C., et al., 2009, [MNRAS](#), **393**, 1302
- Yano M., Kriek M., van der Wel A., Whitaker K. E., 2016, [ApJL](#), **817**, L21
- Yoon Y., Im M., Kim J.-W., 2017, [ApJ](#), **834**, 73
- Zasov A. V., Saburova A. S., Khoperskov A. V., Khoperskov S. A., 2017, [Physics Uspekhi](#), **60**, 3
- Zolotov A., et al., 2015, [MNRAS](#), **450**, 2327
- Zwicky F., 1933, *Helvetica Physica Acta*, **6**, 110
- van Dokkum P. G., 2005, [AJ](#), **130**, 2647
- van Dokkum P. G., et al., 2008b, [ApJ](#), **677**, L5
- van Dokkum P. G., et al., 2008a, [ApJL](#), **677**, L5

van der Wel A., et al., 2012, [ApJS](#), 203, 24

van der Wel A., et al., 2014, [ApJ](#), 788, 28

von der Linden A., Wild V., Kauffmann G., White S. D. M., Weinmann S.,
2010, [MNRAS](#), 404, 1231

Appendix A

Environment distribution

In this section, we present the environment distribution of both star-forming and quiescent (passive+PSB) galaxies. We show the same as in Fig. 2.4 but using the 400kpc aperture instead. This is to illustrate the quartiles in Fig. 3.5, where we use the 400kpc aperture. The shaded areas correspond to the quartiles of the quiescent sample.

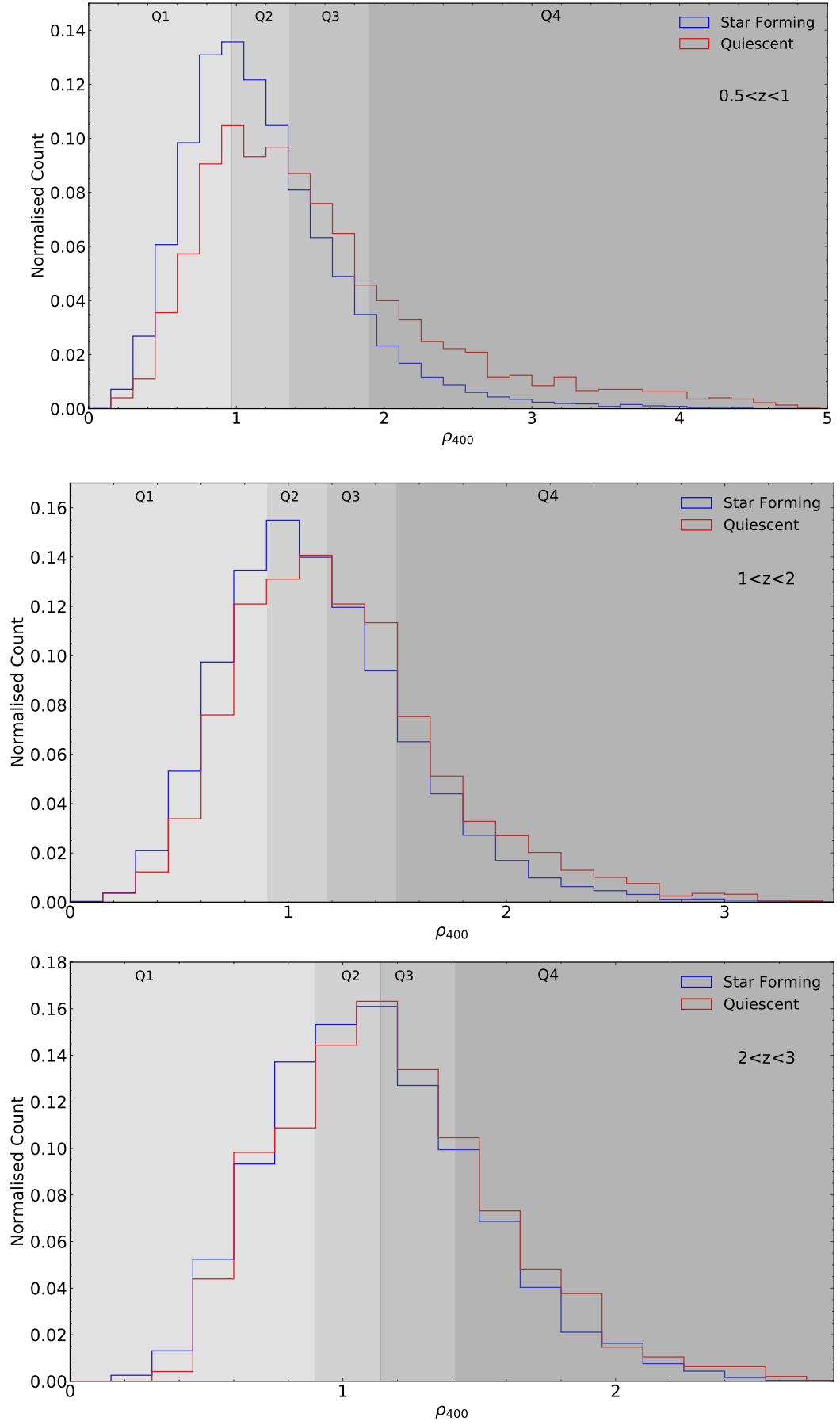


Figure A.1: Galaxy density measured in a 400 kpc aperture for both star-forming and quiescent (passive+PSB) galaxies in three redshift bins: $0.5 < z < 1$ (top), $1 < z < 2$ (centre) and $2 < z < 3$ (bottom). The density quartiles are represented by the shaded areas.

Appendix B

Fraction of quiescent galaxies

In Figure 3.1, we showed how the fraction of quiescent (passive+PSB) galaxies depends on both mass and environment. In this figure, we reported that at $2 < z < 3$ (right-hand side panel), there was a peak in the lower-right corner that should not be there, once the peak is expected to be at the highest stellar mass and overdensity values. As mentioned in the text, we removed the PSB galaxies from the quiescent sample, leaving only the passive galaxies and performed the same analysis shown in Figure 3.1 but using a sample consisting of passive galaxies only, which is illustrated in Figure B.1. After careful examination of this figure, we find that the lower-right corner peak is still present, but the densities are not probed low enough for this to be obvious.

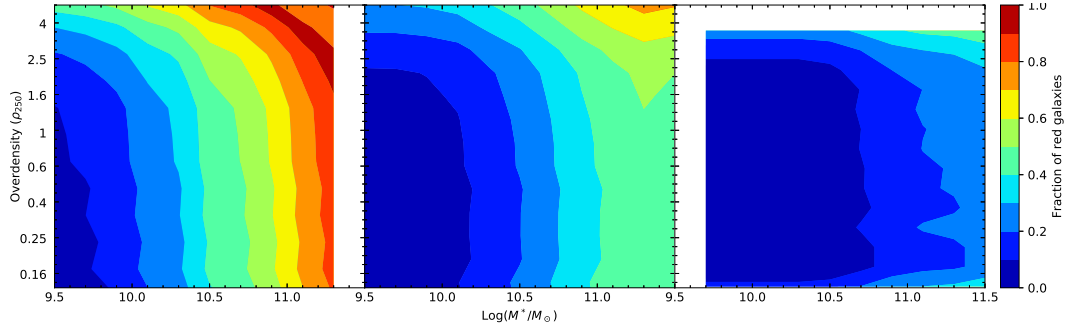


Figure B.1: This plot show the same as Figure 3.1 but the PSB galaxies are eliminated from the sample. The redshift intervals are the same: $0.5 < z < 1$ in the left-hand side, $1 < z < 2$ in the middle panel and $2 < z < 3$ in the right-hand side panel.

B.1 Evolution of the mass-size relation with redshift

In this appendix we present the evolution of the mass-size relation with redshift for each galaxy population. In Fig. B.2 we present the average size of galaxies per mass bin in the three redshift ranges, $0.5 < z < 1$ (green), $1 < z < 2$

(grey) and $2 < z < 3$ (blue). The left panel of this figure shows the relation for star-forming galaxies while the passive and PSB populations are shown in the middle and right panels, respectively.

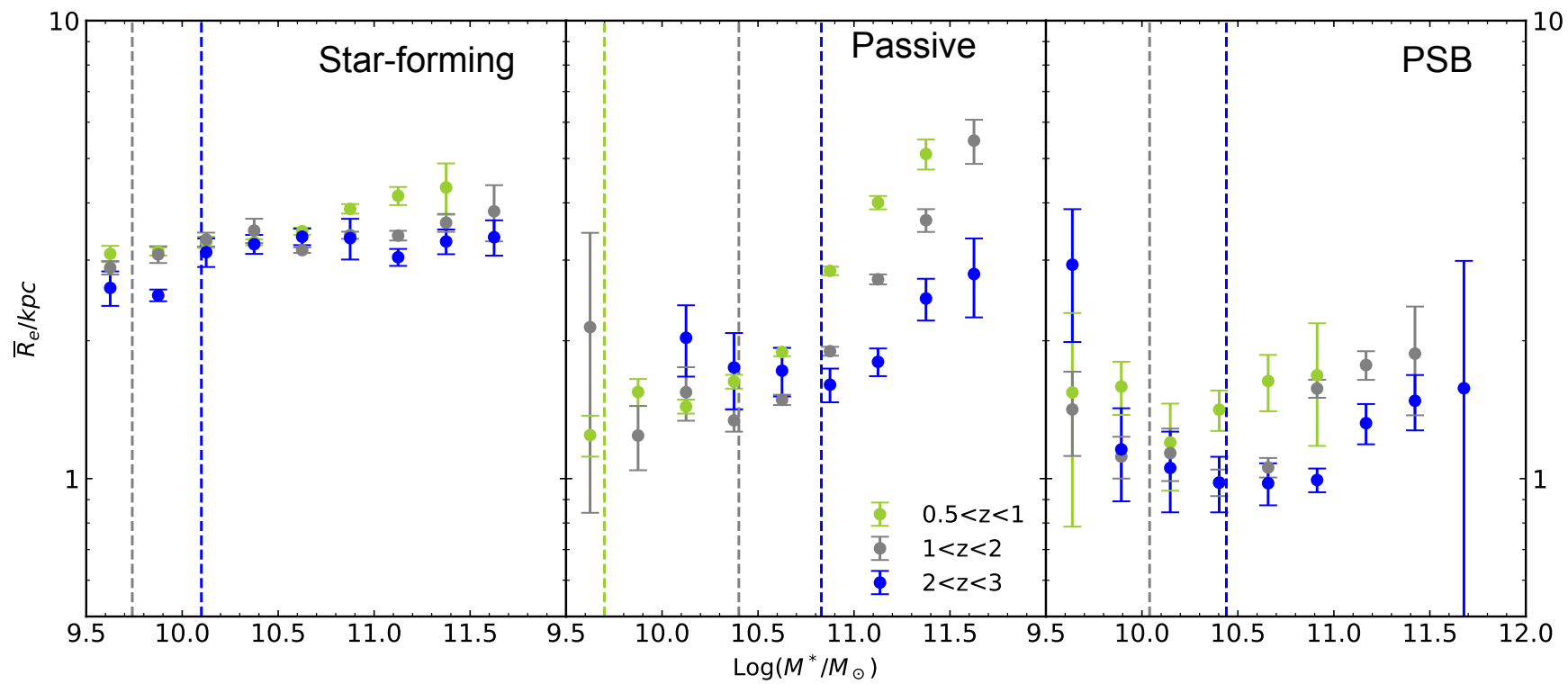


Figure B.2: Size evolution with redshift for the Star-forming, Passive and PSB populations

Appendix C

Mass-size relation with environment

In Fig. C.1 we show the same as in Fig. 3.5 but with the overdensity being measured using the 250kpc aperture rather than 400kpc. When using this aperture, we still find galaxies in denser environments to be larger than those in less dense regions.

In this appendix we also present the average size of galaxies in the highest and lowest overdensity quartiles for star forming galaxies (Fig. C.2). We do not find any significant differences between both environments, however in the highest mass bin for $0.5 < z < 1$, it seems that galaxies in Q1 are larger than those in Q4.

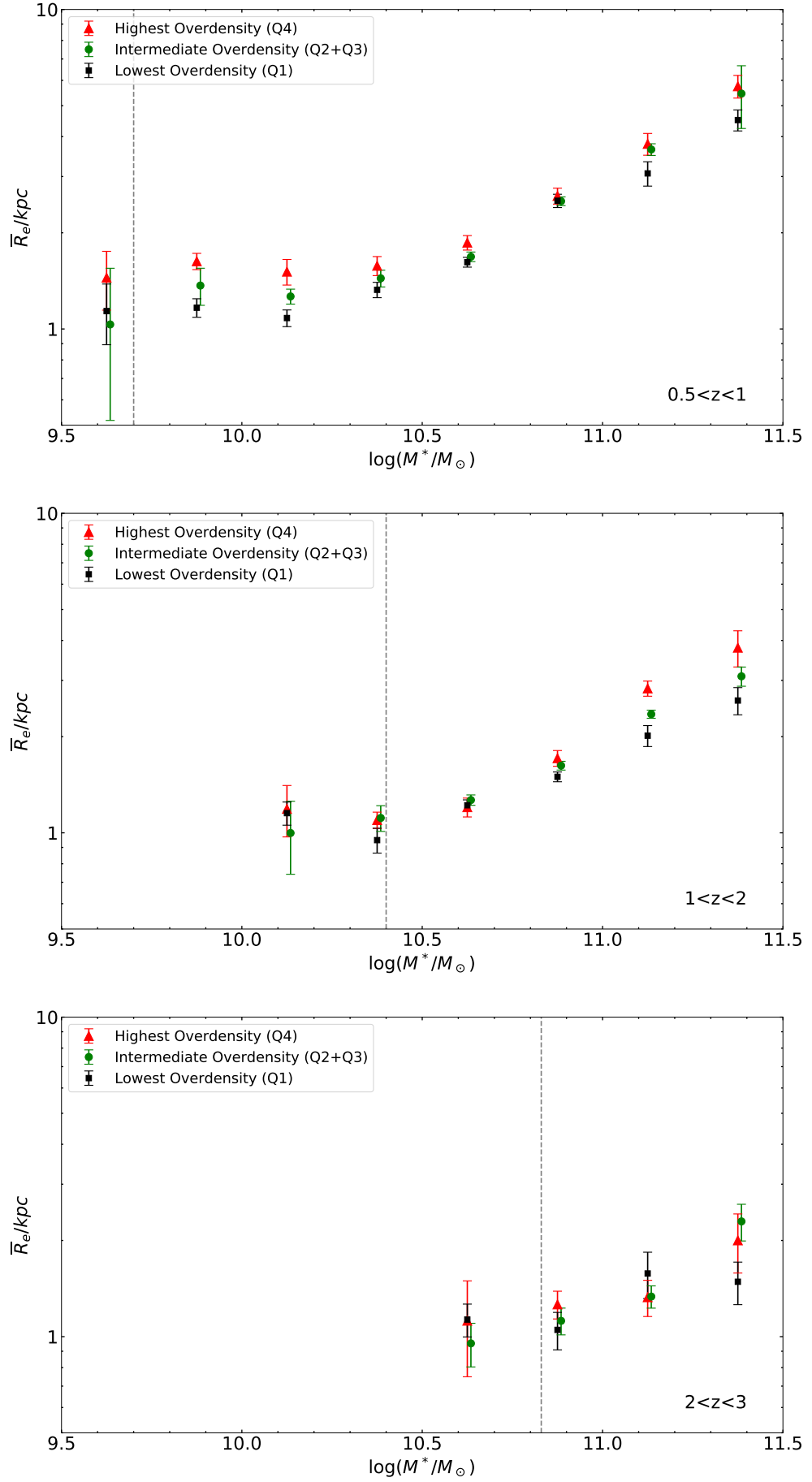


Figure C.1: Average size of quiescent galaxies as a function of mass in three overdensity bins as shown in Fig. 3.5 but using a 250kpc aperture instead.

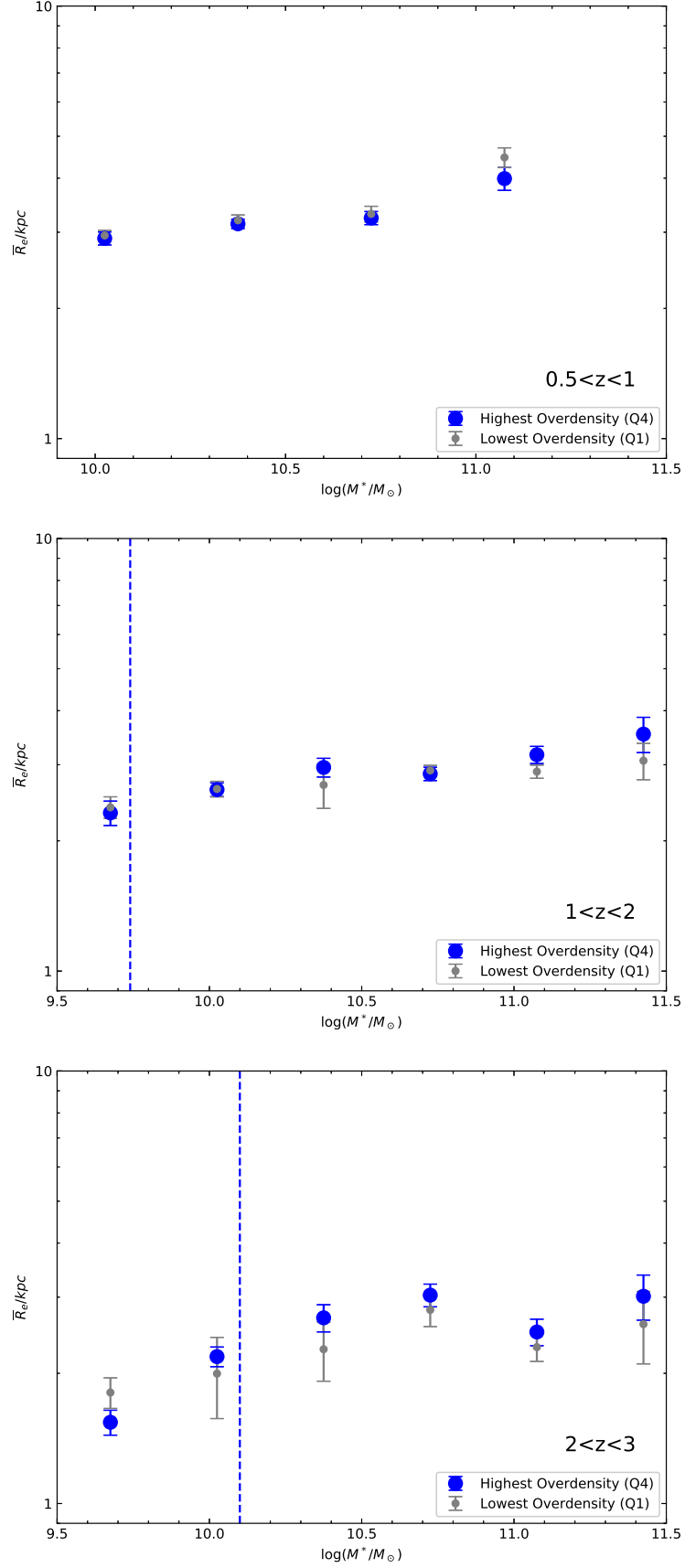


Figure C.2: Size of Star-forming galaxies as a function of mass in the two extreme overdensity bins, first and fourth quartiles, grey and blue dots respectively. Both Q1 and Q2 were calculated from the SF sample applying the same principle as done for the quiescent population. The dashed lines correspond to the 95% completeness limits for the star-forming sample, chosen at the highest redshift value.