This thesis has been submitted in fulfilment of the requirements for a postgraduate degree (e. g. PhD, MPhil, DClinPsychol) at the University of Edinburgh. Please note the following terms and conditions of use:

- This work is protected by copyright and other intellectual property rights, which are retained by the thesis author, unless otherwise stated.
- A copy can be downloaded for personal non-commercial research or study, without prior permission or charge.
- This thesis cannot be reproduced or quoted extensively from without first obtaining permission in writing from the author.
- The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the author.
- When referring to this work, full bibliographic details including the author, title, awarding institution and date of the thesis must be given.
Constraining quenching mechanisms at high redshift: The sizes, masses and star-formation histories of massive galaxies

Massissilia Louisa Hamadouche

Doctor of Philosophy
The University of Edinburgh
February 2024
For my parents and sister
Lay Summary

One of the most important discoveries of the past few decades in extra-galactic astronomy was determined from observations of the local Universe. These data showed that disc-like galaxies are typically blue in colour and star forming, whereas elliptical galaxies are red and no longer forming stars. As a galaxy runs out of the fuel it needs to maintain star formation, the colour of the galaxy transforms from blue to red, albeit over timescales of hundreds of millions of years. Galaxies with bluer colours contain stars that are younger and brighter, whereas redder colours indicate a population of older and fainter stars. This discovery led to a very important question: what causes galaxies to stop forming new stars?

Galaxies that have stopped forming new stars are referred to as quiescent, and are generally massive, red ellipticals. The study of large samples of these galaxies allows us to infer the physical mechanisms which caused the fuel supply for star formation to be shut off, or quenched. In this thesis, I present work which attempts to understand how galaxies quenched by using a range of observational datasets from space-based and ground-based telescopes.

In forthcoming chapters, I explore the relationships between quiescent-galaxy size, stellar mass, age and structure/morphology in order to determine the evolution of these physical properties with time. In Chapter 3, I find that “downsizing” is clearly evident within the massive quiescent galaxy population, whereby the most massive galaxies in the Universe are the oldest. I also find that, at a fixed stellar mass, galaxies with smaller sizes are older than galaxies with larger sizes. Then in Chapter 4, I show that for massive quiescent galaxies, there is a large scatter around the mean relationship between stellar mass and age, suggesting that there are multiple quenching mechanisms at work within the galaxy population.

Finally in Chapter 5, equipped with high-quality data obtained using the space-based telescope JWST, I explore the relationships between various physical and
structural properties of quiescent galaxies, finding evidence for multiple quenching mechanisms for the first time at these cosmic epochs. In the Universe, low-mass galaxies can be quenched by environmental-driven factors, such as being stripped of the gas needed to form new stars as they fall into large clusters of galaxies. In contrast, the quenching of more-massive galaxies appears more consistent with mechanisms that forcefully eject the gas out of the galaxy and cause the rapid quenching of star formation.

In summary, the work presented in this thesis has attempted to provide a coherent narrative of galaxy evolution over \( \sim 10 \) billion years of cosmic history, through the investigation of significant relationships between size, stellar mass, age and morphology. Although many questions remain unanswered, forthcoming datasets from telescopes such as JWST and the Very Large Telescope (VLT) will enable us to significantly advance our current knowledge of galaxy evolution and quenching.
Abstract

Observations of the local and high-redshift Universe have revealed a clear bi-modality in the galaxy population. This is apparent in galaxy colours, morphologies and star-formation rates, with galaxies being categorised into two distinct populations; star-forming and quiescent. The existence of this bi-modality means that one or more mechanisms must be able to cease, or quench, star-formation in galaxies. One of the key questions in extragalactic astronomy is to identify which quenching mechanisms are most important and on what timescales they operate.

In this thesis, I use a combination of photometry and spectroscopy to examine the evolution of the quiescent galaxy population at high redshift in an attempt to piece together a coherent picture of their evolution over the past ten billion years of cosmic history. Some of the foundational results that have shaped our understanding of galaxy evolution are the relationships between galaxy stellar mass, size and age. In addition to the bi-modality observed up to $z \sim 2$, it has also been shown that galaxies which formed earlier in cosmic time are more massive than their later counterparts, a phenomenon often referred to as “downsizing”. In this thesis, ultra-deep spectroscopic data along with $HST$ and $JWST$ imaging from large-scale surveys is used to study the sizes, masses and star-formation histories of massive galaxies from $z = 0.25$ to $z = 2.25$.

Firstly, I present a study exploring the most massive galaxies at $0.6 < z < 1.3$ using ultra-deep spectroscopy and photometry from the VANDELS and LEGA-C ESO public spectroscopic surveys. I investigate the relationships between galaxy stellar mass, physical size and age (using a well-known proxy for age predominant in quiescent galaxy spectra; the $D_n4000$ index), and demonstrate for the first time that downsizing is clearly evident in both our quiescent samples. I present a toy model to explain the size evolution of massive quiescent galaxies from $z = 1.3$ to $z = 0.6$ based on minor mergers.
Next, I present the results of full spectral fitting of the VANDELS quiescent sample at $1.0 < z < 1.3$, examining in further detail the relationship between stellar mass and age, this time using galaxy formation and quenching times. Upon further investigation into these trends, it becomes apparent that there is a sample of quiescent galaxies which appear to have experienced very short periods of star-formation, followed by abrupt quenching. These galaxies indicate higher levels of $\alpha$-enhancement compared to the rest of the quiescent galaxies in my sample. This implies that there is an important mechanism at work which can end star-formation on very short timescales. One galaxy in my sample formed less than a billion years after the Big Bang, experiencing a short episode of star-formation before quickly becoming quiescent, based on star-formation and quenching timescales.

Building on these key results at $z \sim 1$, I investigate whether these trends can be seen at higher redshift using data obtained from the JWST PRIMER and JADES surveys. Due to the improved sensitivity and spatial resolution of JWST imaging, it is possible to examine the sizes and morphologies of star-forming and quiescent galaxies to lower stellar masses than previously possible. Over the redshift range $0.25 < z < 2.25$, I find that low-mass quiescent galaxies in my sample exhibit Sérsic indices and sizes qualitatively consistent with these galaxies quenching by infall into cluster environments. Contrastingly, the sizes and morphologies of more massive quiescent galaxies are consistent with having quenched by internal feedback mechanisms.

In summary, this thesis aims to provide a quantitative investigation of the evolution of quiescent galaxies over cosmic time. The unprecedented size and quality of the datasets used throughout this work have led to many important findings, enabling a deeper understanding of the properties of quiescent galaxies, and the overall formation and evolution of galaxies across time.
Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified.

Parts of this work have been published in Hamadouche et al. (2022) and Hamadouche et al. (2023).

(Massissilia Louisa Hamadouche, February 2024)
Acknowledgements

I would like to express my sincere thanks to my supervisors, Ross and Adam for their constant support and encouragement throughout this PhD. Thank you both for all your words of wisdom; I am a better person and scientist because of them.

To all the people I shared this PhD journey with who became some of my closest friends, thank you so much for your steadfast support over the past few years. Firstly, to the people with whom I started the PhD: Ryan and Rob; thank you for your friendship, for being the best office bud(s), for the good laughs, fun beach days, game nights and beautiful hill walks, and for always believing in me. Arnaz, thank you for the unconditional encouragement and love throughout this PhD, I couldn’t ask for a better friend to share this journey with.

Léa, thank you for living with me, for the late-night Wikipedia trips, seeing Harry Styles with me (twice!!) and all the impromptu beach days, I’m so lucky to be your friend. Maca, Callum and Thomas - thank you for the tea breaks, the great conversation (9/10 times it’s about TS or HS\(^1\)), the friendship and for always encouraging me. Catherine, thank you for always checking in to see how I was doing.

Thank you especially to Hanieh and Hania, who have given me unwavering love and encouragement since we first met during our undergraduate degrees. I love you both very much and I am ever grateful to be able to call you my best friends.

I would also like to express my love and gratitude to my parents who have always supported my dreams and have never once stopped believing in me, I love you both so much. Finally, thank you to my sister Anya, who has always stood by me and has been a constant source of laughter and encouragement. I could not have done this without you, I love you forever.

\(^{1}\)Honestly, Taylor Swift and Harry Styles deserve a special mention, so thank you to them for making brilliant music that 1. kept me sane during the PhD and 2. started many friendships.
Contents

Lay Summary ii

Abstract iv

Declaration vi

Acknowledgements vii

Contents viii

List of Figures xiv

List of Tables xvii

1 Introduction 1

1.1 The Origin of the Universe ........................................ 1

1.1.1 Big Bang Nucleosynthesis ...................................... 2

1.1.2 The cosmic microwave background and large scale structure 3

1.1.3 The Standard Model of Cosmology .......................... 6

1.1.4 The first galaxies and reionization .......................... 8

1.2 Galaxy evolution from observations ............................ 9

1.2.1 The star-formation rate density of the Universe .......... 9

1.2.2 Demographics of the galaxy population .................... 10
1.2.3 The star-forming main sequence of galaxies ..................... 13
1.2.4 The bi-modality of the galaxy population ......................... 15
1.2.5 Galaxy downsizing and stellar population ages ................. 18
1.2.6 Metal enrichment in galaxies ........................................ 20
1.2.7 Alpha-enhancement and formation timescales ................... 25
1.2.8 Galaxy physical sizes and morphology ............................ 27
1.3 Star-formation efficiency and quenching ............................. 31
1.3.1 Reproducing the galaxy bi-modality in simulations ............ 33
1.4 Stellar population synthesis .......................................... 37
1.4.1 Stellar evolution and the initial mass function .................. 37
1.4.2 Dust attenuation and extinction .................................... 40
1.4.3 Nebular emission and the intergalactic medium ................. 44
1.4.4 The star-formation histories of galaxies ......................... 45
1.4.5 Modelling galaxy physical properties ............................. 46
1.5 Open questions and motivations ...................................... 50
1.6 Thesis outline ............................................................. 54

2 Observational data and model fitting ................................. 55
2.1 Observational astronomy ................................................ 55
2.1.1 Photometry ............................................................ 56
2.1.2 Spectroscopy .......................................................... 58
2.2 Imaging datasets ........................................................ 59
2.2.1 The CANDELS imaging survey .................................... 59
2.2.2 The JADES Survey .................................................. 60
3 The evolution of massive quiescent galaxies from $z = 0.6$ to $z = 1.3$

3.1 Introduction

3.2 DATA

3.2.1 The VANDELS spectroscopic survey

3.2.2 The LEGA-C spectroscopic survey

3.3 Method and sample selection

3.3.1 Selection of a mass-complete sample from VANDELS

3.3.2 Selection of a mass-complete sample from LEGA-C

3.3.3 Measuring galaxy sizes

3.3.4 Measuring $D_n4000$

3.3.5 Stacked spectra
3.4 Results ........................................................................................................... 94
3.4.1 The relationship between stellar mass and D₄000 ......................... 94
3.4.2 The VANDELS and LEGA-C mass-size relations ....................... 94
3.4.3 Stellar mass-size trends with D₄000 ................................................ 98
3.5 Discussion ................................................................................................... 100
3.5.1 Evidence of downsizing from stellar mass vs D₄000 ................. 100
3.5.2 Stellar mass-size relations ................................................................. 101
3.5.3 The size-D₄000 relation: changing age or metallicity? .......... 103
3.5.4 A model linking the VANDELS and LEGA-C samples ........... 104
3.6 Conclusions .............................................................................................. 110
4 The connection between stellar mass, age and quenching
  timescale in massive quiescent galaxies at 1.0 < z < 1.3 ................. 112
4.1 Introduction .................................................................................................. 112
4.2 The VANDELS survey ............................................................................... 116
  4.2.1 VANDELS sample selection ............................................................. 116
  4.2.2 VANDELS spectroscopy ................................................................. 117
4.3 Methodology and sample selection .......................................................... 119
  4.3.1 Spectro-photometric fitting ............................................................. 119
  4.3.2 A mass-complete sample ................................................................. 121
  4.3.3 Stacked spectra .................................................................................. 121
  4.3.4 Size measurements ......................................................................... 122
4.4 Results .......................................................................................................... 122
  4.4.1 Trends with rest-frame UVJ colour ............................................. 122
  4.4.2 The relationship between stellar mass and age.......................... 123
4.4.3 The oldest galaxy at $z \sim 1$ ........................................... 126

4.5 Discussion ........................................................................... 128

4.5.1 The formation times of quiescent galaxies ....................... 128

4.5.2 The relationship between colour and age ....................... 135

4.5.3 Quenching timescales .................................................... 136

4.6 Conclusions ......................................................................... 145

5 The sizes and morphologies of star-forming and quiescent galaxies from $z = 0.25$ to $z = 2.25$ 147

5.1 Introduction ...................................................................... 147

5.2 Data ................................................................................ 151

5.2.1 The JADES survey .................................................... 151

5.2.2 The PRIMER survey .................................................. 151

5.2.3 Photometric catalogues ............................................... 152

5.3 Methods and sample selection ................................................ 154

5.3.1 Photometric fitting using BAGPIPES ......................... 154

5.3.2 Selection of mass-complete samples ............................. 155

5.3.3 Size measurements & colour gradients ....................... 156

5.3.4 Final sample selection ................................................. 157

5.4 Results ............................................................................. 159

5.4.1 The galaxy stellar-mass function up to $z \sim 2.25$ ............. 159

5.4.2 Galaxy size-mass relations at $0.25 < z < 2.25$ ............... 159

5.4.3 The evolution of size and Sérsic index ......................... 167
# List of Figures

1.1 Schematic of the timeline of the Universe ........................................ 2
1.2 Map of the CMB showing temperature variations ................................. 3
1.3 The CMB power spectrum ................................................................. 4
1.4 Galaxy clustering from 2dFGRS ......................................................... 5
1.5 The cosmic star-formation rate and stellar-mass density ......................... 11
1.6 The galaxy luminosity function from $z \sim 2$ to $z \sim 10$ ....................... 12
1.7 Star-forming and quiescent galaxy stellar-mass functions ...................... 14
1.8 The galaxy colour bi-modality .......................................................... 16
1.9 $UVJ$ diagram of galaxies from the UKIDSS UDS survey ...................... 18
1.10 Morphologies of galaxies on the $UVJ$ diagram ................................ 19
1.11 The evolution of SFR with redshift ................................................ 21
1.12 Gas-phase mass-metallicity relation from SDSS ................................. 23
1.13 Stellar mass-metallicity relation from VANDELS ............................... 24
1.14 Production timescales of elements for an SSP ................................ 26
1.15 Star-forming and quiescent galaxy size-mass relations up to $z \sim 3$ ...... 27
1.16 Broken-power law size-mass relations for quiescent galaxies ................ 29
1.17 Schematic of the Hubble tuning fork ................................................. 30
1.18 Redshift evolution of size, Sérsic index and axis ratio ......................... 31
1.19 Stellar-to-halo mass ratios for central galaxies .................................. 34
1.20 The Hertzsprung-Russell diagram ................................................... 38
1.21 Isochrones of solar metallicity for different ages ............................... 39
4.1 UVJ diagram of the final sample of VANDELS galaxies . . . . . . . 120
4.2 Stellar mass versus formation redshift & median $z_{\text{form}}$ . . . . . . . 125
4.3 Spectra of potential CN enhanced VANDELS galaxies . . . . . . . 127
4.4 Stellar mass versus formation and quenching redshift . . . . . . . 129
4.5 Comparison of $M_* - z_{\text{form}}$ with similar studies . . . . . . . 132
4.6 Stacked spectra of galaxies based on UVJ position . . . . . . . 134
4.7 Quenching timescale versus stellar mass . . . . . . . . . . . . . . 137
4.8 Stacked spectrum of CN enhanced galaxies . . . . . . . . . . . . . 139
4.9 Histogram showing CN-index distribution . . . . . . . . . . . . . 140
4.10 Star-formation histories of CN enhanced galaxies . . . . . . . 144

5.1 UVJ diagrams for final JADES & PRIMER samples . . . . . . . 153
5.2 Star-forming & quiescent galaxy number densities . . . . . . . . 158
5.3 Size-mass distributions of star-forming & quiescent galaxies . . . 163
5.4 Stellar-mass distributions of star-forming and quiescent samples . 166
5.5 Redshift evolution of median size and Sérsic index . . . . . . . 167
5.6 Size-mass distributions colour-coded by Sérsic index . . . . . . . 170

6.1 Visualisation of non-parametric morphological parameters . . . . 181
6.2 Half-light versus half-mass radii size-mass relations . . . . . . . 182
List of Tables

3.1 Details of parameter ranges & priors for VANDELS & LEGA-C . . 86
3.2 Details of median and stacked D_n4000 values . . . . . . . . . . . . 90
3.3 Median parameter values for VANDELS and LEGA-C samples . . 97

4.1 Details of parameter ranges and priors for VANDELS . . . . . . 118
4.2 Median and stacked D_n4000 values . . . . . . . . . . . . . . . . . . 135
4.3 Physical properties of CN enhanced galaxies . . . . . . . . . . . 141

5.1 Details of parameter ranges & priors for JADES & PRIMER . . . 154
5.2 Mass-completeness limits for JADES & PRIMER samples . . . . 156
5.3 Best-fitting parameters for broken-power law fits . . . . . . . . . 160
5.4 Best-fitting parameters for single-power law fits . . . . . . . . . . 161
5.5 Median size and Sérsic index at each redshift . . . . . . . . . . . 165
Chapter 1

Introduction

1.1 The Origin of the Universe

Our current understanding of the Universe and the origin of galaxies came about in the early twentieth century. In 1918, Vesto Slipher discovered that the spectra of spiral nebulae appeared to be Doppler shifted, and that most of these objects seemed to be receding. However, it was unclear at the time whether or not these nebulae were inside the Milky Way. A few years later, the famous ‘Great Debate’ between Heber Curtis and Harlow Shapley split the scientific community; Shapley believed these spiral nebulae, such as Andromeda, resided within the Milky Way, which he believed to be the entire Universe. In contrast, Curtis contended that the nebulae were extra-galactic based on magnitude measurements of the stars within Andromeda as well as radial velocities of other spiral nebulae. The debate was finally resolved with the subsequent confirmation of distances to Cepheid variables in Andromeda using Henrietta Leavitt’s Period-Luminosity relationship, calibrated against cepheids in the Large Magellanic Cloud, an irregular galaxy, neighbour to the Milky Way.

In the late 1920s, using the 2.5m telescope at Mt. Wilson in California, Edwin Hubble was able to resolve Cepheids in the Andromeda Galaxy (M31) and, correlating these distances to Slipher’s measurements of nebulae redshifts, found there to be a constant of proportionality between the distances and recessional velocities of these systems (Hubble, 1926). These observations were conclusive in that the objects were finally deemed to be located outside our own Galaxy,
Figure 1.1 Diagram presenting the current accepted timeline of the Universe, starting from the Big Bang on the left-hand side.

sparking the beginning of extra-galactic astronomy as a field of research.

1.1.1 Big Bang Nucleosynthesis

The results presented by Hubble sparked the beginning of a decades-long debate on the origin of the Universe, with Big Bang cosmology taking the lead over other cosmological models at the time (e.g. steady-state Universe, Bondi & Gold, 1948). The current standard model of cosmology proposes that $\sim 13.8$ billion years ago, the Universe began with a singularity and was extremely hot and dense (see Fig. 1.1). After the Big Bang, the Universe began to expand and during this expansion, the Universe began to cool. Approximately one second after the Big Bang, the temperature of the Universe had decreased to around $10^{10}$K.

Alpher & Herman (1948) suggested that the primordial Universe consisted of only neutrons, though we now know this was a plasma of free neutrons, protons and electrons. At $\sim 10^{-36} - 10^{-32}$ s after the Big Bang, the Universe then went through a rapid period of inflation, and the Universe continued to expand and cool for a long time after this, albeit more slowly than during inflation. The next stage in the evolution of the Universe is referred to as nucleosynthesis; as the Universe expanded, it cooled sufficiently for thermally stable nuclei to form. This allowed the production of heavier nuclides on timescales comparable to the half-life of neutrons ($\sim 20$ minutes).
1.1.2 The cosmic microwave background and large scale structure

For a long time after nucleosynthesis and inflation, the Universe was fully ionised (see Fig 1.1). This meant that radiation was efficiently scattered by matter, keeping the Universe in a state of thermal equilibrium. However, around 380,000 years after the Big Bang, as the Universe expanded the temperature had cooled to $\sim 3000$ K, lowering the rate of scattering, so that the nuclei which had formed during nucleosynthesis began to recombine with free electrons to form neutral Hydrogen, in an epoch referred to as recombination.

This meant that photons were decoupled from matter and were thus able to propagate freely through the Universe. This period in cosmic history is often referred to as the surface of last scattering, and was first predicted by Gamow in 1946. These photons (which last interacted with matter at $z \approx 1100$) are therefore observed today as the cosmic microwave background (see Fig. 1.2). However, it was not until 1965 that direct evidence of the cosmic microwave background (CMB) radiation was observed as excess noise in a sensitive radio receiver (Holmden Horn Antenna) by Penzias & Wilson (1965) at the Bell Telephone Laboratories.

Sachs & Wolfe (1967) postulated that any density fluctuations at the surface of last scattering would appear as small temperature variations in the observed CMB signal due to relativistic effects attributed to photons interacting with gravitational potentials, known as the Sachs-Wolfe effect. These predicted CMB temperature fluctuations were finally discovered using the COSmic Background Explorer (COBE) satellite (Smoot et al., 1992). Most recently, observations of
Figure 1.3  The power spectrum of the cosmic microwave background (CMB) taken from Schneider (2015). The blue line in both panels shows the best-fitting Λ–CDM model.

the CMB by the Planck satellite have measured the root mean-squared amplitude of temperature variations to be around ±18 μK (see Planck Collaboration et al., 2020).

We can obtain information about the early Universe from the anisotropies observed in the CMB, such as the Sachs-Wolfe effect, the integrated Sachs-Wolfe effect (ISW), and baryonic acoustic oscillations (BAOs). In Fig. 1.3, the strength of the first peak is produced by baryonic acoustic oscillations, which drive the large-scale structure of the early Universe.

In the early 1930s, Hubble discovered that the pattern of galaxies on the sky was non-random, and subsequent observations over the next few decades found that, although on large scales, above 100 $h^{-1}$Mpc, the Universe is uniform, the existence of filaments and voids becomes apparent at smaller scales. The nature of this large-scale structure raised tensions with the current understanding of cosmology at the time. By extrapolating the CMB variations observed at $z \approx 1100$, then large-scale structure formation can be predicted by gravitational instabilities in the high-density regions of gravitationally-bound dark matter (matter that does not interact with the electromagnetic spectrum, but does interact with gravity) referred to as dark-matter halos, where primordial neutral

$^1h$ is the dimensionless Hubble parameter, where $H_0 = h \times 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The current value of $h$ is around $\approx 0.7$. 

4
gas from recombination cools and collapses to form galaxies.

The high- (and low-) density regions observed as temperature fluctuations in the CMB are the seeds of large-scale structure formation in the early Universe. Prior to recombination, the photons and baryons were strongly coupled forming a high-pressure photon-baryon fluid. However, as the baryons are gravitationally attracted to the dark-matter potential wells, the pressure provides a restoring force acting against the baryon-photon fluid, causing the fluid to develop sound waves known as Baryonic Acoustic Oscillations. After decoupling, however, the baryons are pulled into the dark matter potential wells, becoming the building blocks of the early stars and galaxies. The amplitude of the variations is observable in the CMB angular power spectrum and the peaks in Fig. 1.3 represent how the temperature varies between points on the sky for the angular frequency, $l$. Over-plotted in blue is the prediction from $\Lambda$–CDM.

Large area studies of the local Universe by the Sloan Digital Sky Survey (SDSS, York et al., 2000) and the Two-degree Field Galaxy Redshift Survey (2dFGRS, Colless, 1999) provided the first detections of these Baryonic Acoustic Oscillations in the large-scale clustering of galaxies (BAO, see Peacock et al., 2001). The scale of these oscillations can be used to constrain important cosmological parameters.
such as the Hubble parameter (the rate at which the Universe is expanding today) $H_0 = 67.4 \pm 0.5 \text{ km s}^{-1} \text{Mpc}^{-1}$, the matter density of the Universe $\Omega_m = 0.315 \pm 0.007$, and dark energy $\Omega_\Lambda = 0.685 \pm 0.007$ (Planck Collaboration et al., 2020). This theory was observationally tested in Peacock et al. (2001), using redshift determinations of 140,000 galaxies from 2dFGRS and measuring their clustering properties. This provided independent measurements of the power spectrum of galaxy clustering, which were found to be consistent with CMB anisotropies. Fig. 1.4 shows a $4^\circ$ slice of sky from 2dFGRS (Colless, 1999; Peacock et al., 2001), clearly showing clustering features and density variations of the $\sim 60,000$ galaxies within the slice.

1.1.3 The Standard Model of Cosmology

Further observational evidence for an expanding Universe was determined from the use of Type-Ia supernovae (SNe) as standard candles by Riess et al. (1998) and Perlmutter et al. (1999). Type-Ia SNe occur in stellar binary systems where a white dwarf accretes material from a red-giant star until it reaches the Chandrasekhar mass-limit ($\sim 1.4 \text{ M}_\odot$). Due to this mass limit, the phenomenon therefore has a fixed luminosity, which can be used to derive distances. These first studies found that SNe at $z \leq 0.35$ were much fainter than expected, suggesting that the expansion of the Universe had begun to accelerate since $z \sim 0.5$, allowing the first constraints of the dark energy density to be made.

These results lent support to the Big Bang cosmological model (or ‘Standard Model’); suggesting that the Universe started from a singularity (Lemaître, 1927). The expanding Universe causes the wavelength of the light travelling from distant objects to be stretched out, referred to as cosmological redshift, shifting the light from these distant objects towards the red end of the electromagnetic spectrum. Due to the finite speed of light, we observe these objects as they were at earlier times.

In order to properly define the distance to galaxies in the early Universe, it is necessary to introduce a scale factor, $a(t)$ which relates the comoving distance $d_c(t)$, and proper distance $d_p(t)$, of a particle at some time $t$ in the Universe. The comoving distance is defined as the distance between two points along a path which does not change with cosmological time. In contrast, the proper distance is the distance between the same two points in space incorporating cosmological expansion. The two distances are related by the scale factor $a(t)$,
This can also be re-written as

\[ \bar{x}(t) = a(t)\bar{r}(t) \]  

(1.2)

where \( \bar{x} \) is the proper distance and \( \bar{r} \) is the comoving distance between two points in space moving with the Hubble flow (the expansion of the Universe). At the present day, the scale factor \( a(t_0) = 1 \), implying that the comoving and proper distances are the same. As Hubble determined, there is a linear relationship between the recessional velocity of galaxies with distance, and the velocity of a comoving particle can be expressed as

\[
\bar{v}(\bar{r}, t) = \frac{d}{dt} \bar{r}(t) = \frac{da}{dt} \bar{x} = \frac{\dot{a}}{a} \bar{r} = H(t) \bar{r}
\]  

(1.3)

This means that the Hubble constant is related to the scale factor such that \( H(t) = \dot{a}/a \). Due to the fact that we are observing light when it was emitted at a redshift, \( z \), the scale factor at the time the light was originally emitted is

\[ a = \frac{1}{(1 + z)} \]  

(1.4)

due to the cosmological expansion of the Universe. The redshift can be expressed as a function of wavelength of the light emitted by the object

\[ z = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}} \]  

(1.5)

We can also write the (proper) distance light has travelled from a given redshift as

\[ \bar{x}(z) = \int_0^z \frac{c \, dz'}{H(z')} \]  

(1.6)

The observed flux from a distant galaxy is dependent on the cosmological luminosity distance and in turn the angular diameter distance. These two parameters are important in calculating cosmological distances.

The luminosity distance is defined by the relationship between the intrinsic luminosity and the observed flux of an object and is related to the angular
diameter distance by:

\[ d_L = (1 + z)^2 d_A \]  

(1.7)

The angular diameter distance is then defined as the ratio between the physical size of an object to its angular size on the sky, and is given by:

\[ d_A = \frac{x(z)}{(1 + z)} \]  

(1.8)

These parameters are, of course, dependent on the cosmology used, and the expansion history of the Universe. This can be described by the two equations of motion (also known as the Friedmann equations) which follow on from the Einstein General Relativity field equations for a homogeneous and isotropic Universe:

\[ \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho - \frac{k c^2}{a^2} \]  

(1.9)

\[ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} \left( \rho + \frac{3 P}{c^2} \right) \]  

(1.10)

where \( G \) is the gravitational constant, \( c \) is the speed of light in a vacuum, and \( k \) represents the curvature of the Universe today i.e. for a flat Universe, \( k = 0 \) and \( P \) is the pressure component. The density \( \rho \) is the sum of the matter, dark-energy and radiation density of the Universe, and the density parameter, \( \Omega \), is the ratio of the matter or dark-energy density to the critical density, \( \rho_c \), e.g. \( \Omega_m = \rho_m / \rho_c \). The critical density is defined as the mean density of matter in the Universe necessary for gravity to halt its expansion. A universe with a density equal to the critical density is said to be a flat universe (i.e. when \( k = 0 \Rightarrow \rho_c = 3H^2 / 8\pi G \)). Throughout this thesis, I use \( \Omega_{\Lambda} = 0.7, \Omega_m = 0.3 \), and \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

1.1.4 The first galaxies and reionization

The confirmation of large-scale structure in the Universe, and the cosmic microwave background fluctuations were huge steps forward in understanding the formation and growth of the first galaxies in the early Universe. However, the picture was still yet to be completed. After recombination, there was a long period of time called the cosmic Dark Age due to the lack of new photons being
produced (see Fig. 1.1). This ended with the collapse of primordial neutral hydrogen and helium gas into dark-matter halos, forming the very first stars and galaxies in the Universe.

The formation of these very early stellar systems led to the final phase change in the evolution of the Universe, referred to as the *Epoch of Reionization*. These first stars produced UV photons (at $\lambda < 912 \, \text{Å}$) which caused the cold neutral hydrogen gas in the intergalactic medium (IGM) to become ionised, as we observe today. Current data suggests that reionization took place from $z \sim 10 - 15$ to $z \sim 5 - 6$, and early star-forming galaxies are now thought to be the primary source of these ionising photons (see e.g. Robertson et al., 2013, 2015; Begley et al., 2022).

### 1.2 Galaxy evolution from observations

The past few decades have witnessed major advances in astronomical observations owing to the advent of increasingly deep photometric data from surveys such as the Sloan Digital Sky Survey (SDSS, York et al., 2000), the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS Grogin et al., 2011; Koekemoer et al., 2011), Cosmic Evolution Survey (COSMOS Scoville et al., 2007), UKIDSS Ultra Deep Survey (UDS, Almaini et al., in prep.) as well as multi-wavelength imaging from *Spitzer* and *HST*. Additionally, deep spectroscopic surveys such as LEGA-C (van der Wel et al., 2016), VANDELS (McLure et al., 2018b; Pentericci et al., 2018) and zCOSMOS (Lilly et al., 2007; Moresco et al., 2010) have facilitated studies of galaxy evolution and firmly established that up to $z \sim 3$, the galaxy population is bimodal in colour, size and morphology. Most recently, data from *JWST* has shown that star-formation is already underway at very early times ($z > 12$, see e.g. Donnan et al., 2023; Arrabal Haro et al., 2023; Bunker et al., 2023, and references therein).

#### 1.2.1 The star-formation rate density of the Universe

Much effort has been invested in measuring the cosmic star-formation history of the Universe. Up until now, we have been able to trace the cosmic star-formation rate density (SFRD) since the cosmic Dark Ages all the way to the current epoch, and the top panel of Fig. 1.5 shows the SFRD from a compilation
of different studies (from Madau & Dickinson, 2014) measured up to look-back times of \( \approx 12.8 \) Gyr (up to \( z \approx 8 \)) from the UV and IR. This demonstrates a clear trend of rapidly-increasing star-formation from early times until \( z \approx 2 \), after which there is a subsequent steady decline to present day. It is notable that the peak of star-formation at \( z \approx 2 \) also coincides with the peak of AGN activity (e.g. Aird et al., 2015), suggesting that the conditions of the Universe at that epoch were suitable for star-formation and black-hole mass growth.

The bottom panel of Fig. 1.5 shows the stellar-mass build-up of galaxies from \( z \approx 8 \) to the present day and demonstrates a steady increase in the stellar-mass density of galaxies over cosmic time. These observational results point to evidence that some galaxies are beginning to shut off, or quench, their star formation while the overall population continues to build up their stellar mass. These quenched galaxies make up only a small percentage of the stellar-mass budget at \( z \approx 2 \), where actively star-forming galaxies dominate, however at \( z \leq 0.5 \), quenched galaxies dominate the stellar-mass budget (Madau & Dickinson, 2014; McLeod et al., 2021).

1.2.2 Demographics of the galaxy population

One of the most basic statistical measurements of a galaxy population is the abundance of galaxies as a function of luminosity or stellar mass at a given epoch. Therefore, the galaxy luminosity function (LF) or stellar-mass function (GSMF) are crucial in improving our understanding of the evolution of galaxies and stellar-mass build-up throughout cosmic history. Measuring the luminosity functions of different galaxy populations using different selection techniques in different wavelength regimes can provide different information on the galaxies. Since the time-averaged star-formation rate of a galaxy is related to the unobscured rest-frame UV luminosity, the UV luminosity function can shed light on how fast galaxies grow with cosmic time (see Fig. 1.6). By measuring the NIR/IR luminosity functions, we can probe the stellar mass build-up of the population. The galaxy luminosity function is usually fit with a Schechter function (see Schechter, 1976), defined as

\[
\phi(L) = \phi^* \left( \frac{L}{L^*} \right)^\alpha e^{-\frac{L}{L^*}}
\]  

(1.11)
The cosmic star-formation rate density, taken from Madau & Dickinson (2014). The solid black line shows a functional fit to the star-formation rate density from Eq. 15 of Madau & Dickinson (2014).

The stellar-mass density from $z \sim 8$ to the present Universe, taken from Madau & Dickinson (2014). The solid black line shows the best-fitting model to the stellar-mass density, a result of integrating the SFRD function shown in the top figure (Madau & Dickinson, 2014).

Figure 1.5 The cosmic star-formation rate density and the stellar-mass density of the Universe, taken from Madau & Dickinson (2014).
where $\phi$ is the number of galaxies per unit UV luminosity per unit volume, $L^*$ is the characteristic luminosity, $\phi^*$ is the normalisation value and $\alpha$ describes the faint-end slope. By integrating the luminosity function, one can recover the total luminosity density at a specific redshift which can be converted into a star-formation rate density (SFRD). This is key in understanding how galaxies have formed and evolved over time, and tracing this cosmic SFRD has become one of the major observational goals of the past few decades.

The galaxy stellar-mass function is an important tool in interpreting the evolution of galaxies over cosmic time, and if simulations are able to reproduce this, it suggests a better understanding of the baryonic physics of galaxy formation. The stellar-mass function (SMF) is defined as the number density of galaxies per stellar-mass interval. McLeod et al. (2021) derived stellar-mass functions for quiescent and star-forming galaxy populations between $0 < z < 4$, finding that at lower stellar masses, the mass-fraction is dominated by star-forming galaxies (SFGs) at all redshifts, yet the mass budget is only dominated by the highest-mass SFGs from $z = 4$ to $z \sim 1$. Moving to lower redshifts $z < 1$, however, the galaxy stellar-mass budget is dominated by massive quenched galaxies (see also

\textbf{Figure 1.6} The luminosity function constraints from $z \sim 2$ to $z \sim 10$ from Bouwens et al. (2021). The $z \sim 10$ results are taken from Oesch et al. (2018).
e.g. Baldry et al., 2012).

The stellar-mass function for galaxies can be described by a single-Schechter function (for star-forming galaxies), defined as:

\[
\phi(M) = \phi_* \cdot \ln(10) \cdot 10(M - M_*)(1+\alpha) \cdot \exp[-10(M - M_*)] \tag{1.12}
\]

or a double-Schechter function (for quiescent galaxies):

\[
\phi(M) = \ln(10) \cdot \exp[-10(M - M_*)] \\
\cdot 10^{(M - M_*)} \cdot [\phi_*^1 \cdot 10^{(M - M_*)\alpha_1} + \phi_*^2 \cdot 10^{(M - M_*)\alpha_2}] \tag{1.13}
\]

where in both functions, the characteristic stellar mass is given by \(M_*\).

Fig. 1.7 shows the stellar mass functions of the star-forming and quiescent galaxy populations at various redshift ranges as derived by McLeod et al. (2021). The rapid evolution of the quiescent GSMF is highlighted in the plots by the red Schechter functions in contrast to the star-forming GSMF, which is much more slowly evolving in comparison over the redshift range \(0.5 < z < 3.25\). The quiescent stellar-mass function evolves faster than the star-forming galaxy stellar-mass function up to \(z < 2\), which is well-defined by a single-Schechter function while the quiescent GSMF appears to be better-fitted by a double-Schechter function. This suggests that the galaxy stellar-mass function can present important information on the quenching mechanisms of galaxies (see discussion in Section 1.3).

1.2.3 The star-forming main sequence of galaxies

So far, our understanding of galaxy formation in the Universe relies on the \(\Lambda\)–CDM paradigm, in which galaxies reside in dark-matter halos which are hierarchically built up through density perturbations, and stars are formed in galaxies when hot gas radiates away energy and cools, losing pressure support. Galaxies then further evolve via merger activity and star-formation feedback processes, and our current knowledge of galaxy formation and evolution relies heavily on observed relations between properties such as star-formation rate and stellar mass, known as the star-forming main sequence of galaxies.
Figure 1.7 Mass-functions of star-forming (blue) and quiescent (red) galaxies taken from McLeod et al. (2021). The star-forming galaxy stellar-mass function is fit using a single-Schechter function as defined in Eq. 1.12, whereas the quiescent galaxies up to $z \sim 1.5$ are better described by a double-Schechter function.
In Daddi et al. (2007), stellar mass and star-formation rate were found to be proportional for star-forming galaxies at $z = 2$ with little scatter (only about 0.16 dex) in the specific star-formation rate. Brinchmann et al. (2004) find that in the low-redshift universe, the majority of star formation takes place in moderately massive galaxies with masses of $10^{10} - 10^{11} M_\odot$, with a clear correlation between the SFR and $M_*$ in their sample. The evolution of the star-forming main sequence (SFMS) has been studied extensively, and observations suggest that the normalisation of the SFMS decreases significantly, but smoothly, as a function of redshift from $z = 2$ to the local Universe (see e.g. Elbaz et al., 2007; Speagle et al., 2014).

The advent of spectroscopic surveys has given rise to findings showing that this main sequence of star-formation holds from the low-redshift Universe (York et al., 2000; Salim, 2014; Brinchmann et al., 2004) up to $z \sim 2$ (Noeske et al., 2007; Daddi et al., 2007), and in later studies, the relation was confirmed up to at least redshift $z \sim 4$ (Pannella et al. 2009; Peng et al. 2010; Whitaker et al. 2014).

1.2.4 The bi-modality of the galaxy population

Towards the local Universe, observations from SDSS (see Strateva et al., 2001; Baldry et al., 2004) led to the identification of a significant population of passively evolving ‘red and dead’ galaxies and the separation of the galaxy population into distinct categories; the so-called ‘red sequence’ and ‘blue cloud’. More specifically, galaxies in the red sequence are red in colour, and tend to be elliptical, early-type quiescent galaxies. This sub-population appears to consist of older stellar populations and shows little evidence for ongoing star-formation activity. Contrastingly, galaxies in the blue cloud are mainly spiral-like, late-type galaxies with typically younger stellar populations and high star-formation activity. The discovery of this colour bi-modality (shown on the colour-mass plot in Fig. 1.8) points to mechanisms which are able shut off star formation, causing galaxies to transition from star-forming to quiescent, which is referred to as quenching.

Another population of galaxies are those in the so-called ‘green valley’ region of colour-magnitude diagrams and are thought to be galaxies which are transitioning from the star-forming blue cloud to the quiescent red sequence. The low number of galaxies observed in the green valley points to relatively fast quenching timescales.

The observed bi-modality of the galaxy population means that we can separate
Figure 1.8  The galaxy bi-modality, shown as $u - r$ colour versus stellar mass, taken from Schawinski et al. (2014). Early-type galaxies form a tight sequence of higher stellar masses and redder colours, whereas late-type galaxies have bluer colours and lower-stellar masses.
galaxies into their star-forming and quiescent sub-populations, allowing us to investigate their individual properties and provide clues on the reasons star-formation can be shut down in galaxies. Using the rest-frame $U - V$ and $V - J$ colours are the most common way to divide these populations, although, selecting galaxies using e.g. rest-frame $u - r$ colour versus stellar mass is also frequently used (see Fig. 1.8).

Williams et al. (2009) introduced a set of criteria to accurately separate these galaxy populations, which takes into account dusty star-forming galaxies which have redder colours and may contaminate quiescent galaxy selections. These criteria are:

- $U - V > 1.3$
- $V - J < 1.6$
- $U - V > 0.88 \times (V - J) + 0.69$ ($0 < z < 0.5$)
- $U - V > 0.88 \times (V - J) + 0.59$ ($0.5 < z < 1.0$)
- $U - V > 0.88 \times (V - J) + 0.49$ ($1.0 < z < 2.0$)

These criteria are illustrated in Fig. 1.9 on the $UVJ$ diagram for a sample of $K<22.4$ UKIDSS Ultra Deep Survey (UDS) galaxies from Williams et al. (2009) in five redshift bins, where the solid lines show the divisions between the quiescent and star-forming samples. The clear separation of the quiescent and star-forming populations is seen up to $z = 2$, however, beyond that it becomes difficult to divide these populations due to larger uncertainties in the photometry and photometric redshifts, as shown by the error bars in the $z > 2$ bin. Very recently, JWST studies have been able to extend this to higher redshifts ($z > 5$) by using other colour selections and criteria to isolate quiescent galaxies (see e.g. Gould et al., 2023; Antwi-Danso et al., 2023).

The clear division between the star-forming and quiescent populations on the $UVJ$ diagram also provides an insight into their differences in physical and structural properties. Fig. 1.10 shows image stamps of galaxies over the redshift range $0.6 < z < 0.9$, in three stellar-mass bins on the $UVJ$ diagram from Patel et al. (2012). The top figure (central mass bin) clearly demonstrates how the $UVJ$-selected quiescent galaxies (within the region enclosed by the solid black line) appear to be more elliptical, compact early-type systems, whereas the star-forming galaxies
Figure 1.9 The rest-frame $UVJ$ diagram for a sample of galaxies from the UKIDSS UDS galaxy survey, taken from Williams et al. (2009). The figure demonstrates that $UVJ$ selection can still separate star-forming and quiescent galaxies up to $z < 2$.

are mostly disky, late-type spirals and this seems to hold up over the entire stellar-mass range.

1.2.5 Galaxy downsizing and stellar population ages

One of the most intriguing results of the late 20th century was established by Cowie et al. (1996). Using a sample of $\sim 400$ galaxies observed with the LRIS spectrograph on Keck, the authors observed that the maximum $K$-band luminosities of star-forming galaxies drops smoothly from $z \sim 1$ to the present epoch. This trend, coined ‘downsizing’, suggests that the upper end of the luminosity function assembles top-down with decreasing redshift. In a hierarchical galaxy formation scenario, the smallest halos are the first to form. However, this observational evidence pointed to more-massive galaxies forming before less-massive galaxies, and more recent observations have shown that, at any epoch, the most massive galaxies are older and this has been confirmed out to $z \simeq 2$ (see also Fontana et al., 2006; Pacifici et al., 2016). This means that the most massive
Figure 1.10 The morphologies of galaxies positioned on the $UVJ$ diagram over the redshift range $0.6 < z < 0.9$, taken from Patel et al. (2012).

galaxies form within the densest environments and the size of the halo that galaxies begin to form in is important as star-formation is only efficient within
the most massive halos (\( \gtrsim 10^{12} \text{M}_\odot \)), see e.g. Wechsler & Tinker, 2018, and Section 1.3). Within the past few years, empirical studies have found correlations between galaxy stellar masses and spectral age indicators, providing strong constraints on this downsizing trend at \( z \lesssim 1 \) (e.g. Moresco et al., 2011, 2016; Haines et al., 2017; Kim et al., 2018; Wu et al., 2018b).

Based on results from previous work (see e.g. Heavens et al., 2004; Thomas et al., 2005b), Panter et al. (2007) firmly established the downsizing signature for a sample of 300,000 galaxies from SDSS DR3. The star-formation rate of galaxies split by stellar-mass range is presented in Fig. 1.11, showing that the most-massive galaxies formed their stars earlier, and display negligible signs of recent star formation. In contrast, the lower-mass galaxies have higher star-formation rates which continues to the present day.

Building upon the foundations of these empirical results, large spectroscopic datasets have pushed the boundaries of what we can understand from spectral fitting codes, and recent literature have found that within a single redshift range, ages and star-formation & quenching timescales of galaxies vary hugely. At \( z \sim 1 \), the slope of the age-mass relation appears to be much steeper than predicted by simulations such as EAGLE (Schaye et al., 2015; Crain et al., 2015) and SIMBA (Davé et al., 2019), suggesting underlying physics which has yet to be accounted for. Elements such as those produced in core-collapse supernovae (CCSNe), also referred to as \( \alpha \)-elements, have also served as useful star-formation chronometers (Maiolino & Mannucci, 2019). The stellar masses of galaxies at high-redshift have shown strong correlations with the relative abundance of these \( \alpha \) elements, suggesting that more massive galaxies not only formed earlier but much faster than their less-massive counterparts (Thomas et al., 2005b, 2010; Kobayashi et al., 2020).

### 1.2.6 Metal enrichment in galaxies

The chemical properties of galaxies also provide a unique insight into the processes driving their formation and evolution, and are a consequence of a combination of their star-formation history, gas inflows and outflows, and environment. Metallicity can therefore serve as a powerful constraint on the so-called baryon cycle and the enrichment history of galaxies (Maiolino & Mannucci, 2019; Cullen et al., 2021). The metallicity (\( Z \)) of a stellar population is a measure of the fraction of metals relative to hydrogen and helium, and is usually expressed
Figure 1.11  The star-formation rate evolution with redshift of the SDSS galaxies for different stellar mass ranges, taken from Panter et al. (2007). The top panel shows the same as the bottom panel but offset for easier comparison. It is clear from the figure that the most massive galaxies built up most of their stellar mass the earliest and have negligible recent star formation compared to the lower-mass galaxies in the sample.

relative to Solar abundance (Asplund et al., 2009). The Solar metallicity value is $Z_\odot \simeq 0.0142$, meaning that hydrogen and helium contribute $\gtrsim 98$ percent
of the mass of the Sun. Galaxies form in halos consisting mostly of pristine hydrogen (and helium) gas, and as stars form in these environments, the pristine gas becomes polluted by heavier metals over time allowing us to probe the metal enrichment history of the interstellar medium (ISM) of galaxies. There are two main ways to probe the metal enrichment, or metallicity, of a galaxy. Firstly, it is possible to directly probe the stellar metallicity of the galaxy by measuring equivalent widths of prominent absorption features, and secondly, the gas-phase or nebular metallicity can be probed through emission lines. In studies of the interstellar medium, the metallicity refers to the (gas-phase) oxygen abundance (given by \(12 + \log_{10}[O/H]\)), rather than the iron abundance which is used in stellar metallicity studies. This is because oxygen is the most abundant ‘metal’, and so displays strong emission lines in the optical, produced when the hot gas surrounding stars becomes ionised (see Section 1.4.3), and this metallicity is a good tracer of the most recent generation of stars which formed in the galaxy.

The SFRs of quiescent galaxies are very low, meaning there is no nebular emission with which to probe gas-phase metallicities. We can, however, directly probe their stellar metallicities using spectral features such as magnesium and iron absorption lines (e.g. Kriek et al., 2019; Beverage et al., 2021). The stellar metallicity reflects the average metal enrichment history of the galaxy. Typically, due to the faintness of stellar absorption features in higher redshift quiescent galaxies, the [Mg/Fe] and [Fe/H] abundance ratios are measured from stacked spectra, except in the case of very massive quiescent galaxies. For a sample of massive quiescent galaxies at \(z \sim 1.4\), (Kriek et al., 2019) find that [Mg/Fe] is positively correlated with stellar mass, consistent with lower-redshift \((z < 0.7)\) results (e.g. Onodera et al., 2015; Kriek et al., 2016).

Observationally, there are clear scaling relations between stellar mass and metallicity for both star-forming and quiescent galaxies (see e.g. Tremonti et al., 2004; Gallazzi et al., 2005). One of the most important findings in early studies was that more massive galaxies have higher gas metallicities. In a large sample of local star-forming galaxies in SDSS, Tremonti et al. (2004) found a steep relation between gas-phase metallicity (derived from optical nebular emission lines, such as [OII], H\(\beta\), and [OIII]) and stellar mass as shown in Fig. 1.12. This study built on previous work which identified the relationship between the luminosities (as opposed to stellar masses) of galaxies and their metallicities, due to the difficulty at the time in measuring accurate stellar masses. Gallazzi et al. (2005) found a tight mass-metallicity relation using measured stellar metallicities
Figure 1.12 The gas-phase mass-metallicity relation derived from $\sim 53,000$ star-forming galaxies in SDSS, taken from Tremonti et al. (2004).
Figure 1.13  The redshift evolution of the stellar mass-metallicity relation from Cullen et al. (2020) using the VANDELS data.
of local galaxies from SDSS for stellar masses $M_\star / M_\odot > 10^9$. Later work found that the stellar mass-metallicity relation (MZR) was more fundamental than the luminosity-metallicity relation, and more recent studies confirmed the MZR to evolve with redshift. This redshift evolution of the MZR is shown in Fig. 1.13 for a sample of star-forming galaxies in VANDELS taken from Cullen et al. (2020). Results from SDSS (Zahid et al., 2017) are shown on the figure for comparison; the $z \sim 0$ MZR is around 0.6 dex higher than the $z \sim 3$ VANDELS results.

The existence of this tight ($\pm 0.1$ dex) relation between metallicity and stellar mass was found to extend over 3 decades in stellar mass and a factor of 10 in metallicity, with a slight flattening towards higher stellar masses. However, it appears that the observed gas-phase MZR in the local Universe is due to a more general relation between star-formation rate, mass and gas-phase metallicity, commonly referred to as the Fundamental Metallicity Relation (FMR, see Mannucci et al., 2010).

The observation that low-mass galaxies are more metal-depleted is attributed to galactic winds being more effective in removing metals from their potential wells than in more massive galaxies (Leethochawalit et al., 2018). However, as not all the metals in a galaxy are in the gas, there is a degeneracy between inflow, outflow and enrichment rates, which can all work to regulate the metallicity. It was soon found that stellar metallicities are needed to break this degeneracy better constraining models of chemical and metal enrichment (Lu et al., 2015). In quiescent galaxies, the low (near absent) gas content means we can only measure stellar metallicities to constrain the chemical evolution.

1.2.7 Alpha-enhancement and formation timescales

The interstellar medium of galaxies is enriched by their stellar populations via powerful ejecta from core-collapse (Type II) and Type Ia supernovae explosions, or winds from asymptotic giant-branch (AGB) stars (Woosley & Weaver, 1995). Type Ia supernovae arise from the thermonuclear explosion of a C-O white dwarf accreting mass from a non-degenerate star (e.g. a red-giant star), or from the merger of two white-dwarf stars (see Maoz et al., 2014, for a complete review).

These different channels can be well characterised by different abundance patterns and enrich the ISM on different timescales, and since stars retain the abundance pattern of the ISM they were formed in, they provide a fossil record of the formation history of the galaxy. Alpha elements (built up by $\alpha$–particle nuclei)
Figure 1.14 The timescales of production of elements for a single stellar population, taken from Maiolino & Mannucci (2019), showing the relative contributions from Type Ia and core-collapse supernovae and contributions from AGB stars. The top panel shows the production rates of these elements, per mass of formed stars.

are those mainly produced by core-collapse (Type II) supernovae explosions such as O, Mg, Ne, Si, S, Ar, Ca and Ti as well as N and Na (Maiolino & Mannucci, 2019). In contrast, the iron peak elements Fe and Cr are produced in delayed Type Ia supernovae and so the alpha-element ratio, $\alpha/Fe$ is key in measuring the formation history of a galaxy. Fig. 1.14 demonstrates the relative formation timescales and rates for alpha and iron peak elements indicating the relative importance for the CCSNe, SNeIa and AGB production mechanisms; oxygen forms fastest through CCSNe, while nitrogen is primarily formed by AGB stars.
A key finding in recent studies of early-type galaxies is that the $\alpha$/Fe ratio is positively correlated with velocity dispersion and galaxy stellar mass, consistent with the ‘downsizing’ scenario (e.g. Thomas et al., 2010; Segers et al., 2016); massive galaxies produce the bulk of their stars on shorter timescales than low-mass galaxies, meaning that the chemical content of these massive galaxies is dominated by stars enriched by $\alpha$–peak elements.

1.2.8 Galaxy physical sizes and morphology

In addition to correlations with stellar population age, and metallicity, the size of a galaxy is a highly important parameter in identifying the evolutionary trends of galaxies. One of the key results of the past few decades, based on results from SDSS, was that quiescent galaxies follow steeper stellar mass versus size relations than star-forming galaxies in the local Universe (Shen et al., 2003). These authors also showed that these local quiescent galaxies were smaller in size than their star-forming counterparts at stellar masses $\log_{10}(M_*/M_\odot) \lesssim 11$.

![Figure 1.15](image-url) The size-mass relations for star-forming (blue) and quiescent (red) galaxies up to $z \sim 3$. Taken from van der Wel et al. (2014).
In light of these results, McLure et al. (2013) showed this to be true at $z \sim 1.25$, additionally finding that the sizes of quiescent galaxies of a given mass increase from $z \simeq 1.5$ to $z \simeq 0$ by a factor of $\sim 2.5$ (see also e.g. Trujillo et al., 2007; Cimatti et al., 2012). The most common explanation for the growth of galaxy sizes in the Universe is through mergers; dry or minor merger events cause mass and size build-up on the outskirts of the galaxy due to accretion (e.g. van Dokkum et al., 2010; Trujillo et al., 2011; McLure et al., 2013; Belli et al., 2019a), however, this picture may be complicated by progenitor bias at intermediate redshifts; more recently quenched star-forming galaxies joining the quiescent population at later times can make it difficult to compare to samples at higher redshifts (see e.g. van Dokkum & Franx, 1996; Belli et al., 2015). A study by van der Wel et al. (2014) showed that up to $z \sim 3$, quiescent galaxies follow a steeper size-mass relation (van der Wel et al., 2012) - which can be well described by a single power law - with smaller sizes on average than the star-forming population. The normalisation of the size-mass relation for both star-forming and quiescent galaxies has also been demonstrated to show a strong evolution with redshift at fixed stellar masses, with the average size of galaxies increasing towards the local Universe, although there are some physical processes which can cause galaxies to become more compact Zolotov et al. (2015). The study of the size-mass distributions of galaxies at these redshifts was further extended by Mowla et al. (2019), confirming these results at higher stellar masses using data from the COSMOS-DASH survey. However, over a larger dynamical range of stellar masses, the size-mass relation of quiescent galaxies has been suggested to instead follow a ‘broken’ or double power-law (see Fig. 1.16), with a pivot mass at $\log_{10}(M_*/M_\odot) \lesssim 10$ (see e.g. Nedkova et al., 2021; Kawinwanichakij et al., 2021).

At the highest stellar masses, the star-forming and quiescent galaxy populations have similar half-light radii measurements at all epochs. However, based on their median sizes over the whole stellar-mass range, quiescent galaxy sizes have been shown to be more rapidly evolving compared to star-forming galaxies at the same stellar masses (van der Wel et al., 2012; Mowla et al., 2019). These findings suggest that the evolution of quiescent galaxy sizes is more complicated than previously thought; at lower-stellar masses, the flattening of the size-mass relation up $z \sim 2$ points to evidence that quiescent galaxies are quenching via different mechanisms than their higher-mass counterparts. Environmental quenching mechanisms become effective at lower-stellar masses,
Figure 1.16  The size-mass relations of galaxies taken from Kawinwanichakij et al. (2021), demonstrating the double power-law fits to the quiescent (red) and star-forming (blue) galaxies, where the low-mass and high-mass ends are separated by a pivot mass of $\log_{10}(M_*/M_\odot) > 10$. 
and become increasingly important at lower redshift; for example, ram-pressure stripping can modify the SFR and colour of a galaxy without causing significant change to its morphology (e.g. Weinmann et al., 2006; van den Bosch et al., 2008; Kawinwanichakij et al., 2017). At higher-stellar masses, mass (or internal) mechanisms become more efficient for quenching in galaxies (see Section 1.3). Additionally, disk or bar instabilities can strongly affect a galaxy’s morphology, but this happens on much longer timescales compared to merger events (secular evolution, e.g. Kormendy & Kennicutt, 2004).

![Hubble tuning fork diagram](image)

**Figure 1.17** Hubble tuning fork diagram, taken from Cui et al. (2014).

The morphological properties of galaxies can provide deeper insight into the evolution of galaxies over cosmic time. Locally, galaxies have been classified using the Hubble ‘tuning fork’ shown in Figure 1.17, and the system describes how the galaxy population can be classified into elliptical, spiral and irregular types (e.g. Sandage, 1961). Within the past decade, the model has undergone modifications that have introduced more complex morphological classifications to the original Hubble system (e.g. Cappellari, 2017). The simplified model of hierarchical galaxy formation suggests that galaxies which form in isolation produce disk-like structures, whereas those which undergo mergers and other galaxy-galaxy interactions are more elliptical (see also White & Frenk, 1991; Kauffmann et al., 1993).

In Almaini et al. (2017), the authors study a sample of galaxies selected from the UKIDSS UDS survey and find that post-starburst galaxies exhibit similar Sérsic indices to and smaller sizes than the quiescent galaxies in their sample. This points to evidence that the structural transformation of the post-starburst (PSB)
galaxies was already in place prior to quenching, unless the transformation took place on much shorter timescales than the PSB phase ($< 500$ Myr) through an event such as a gas-rich merger after which star-formation is rapidly quenched by a central AGN leading to the compact systems observed.

In Fig. 1.18, the size, Sérsic index and axis ratio of star-forming (blue) and quiescent (red) galaxies are shown to evolve with redshift from Patel et al. (2013). The average properties of the overall galaxy population are shown in black. The first panel in Fig. 1.18 demonstrates the steady increase in sizes for both quiescent and star-forming galaxies, and SFGs have larger effective radii than the quiescent galaxies at each epoch. The middle panel demonstrates the rapid evolution of Sérsic index with redshift for the quiescent galaxies, whereas the star-forming galaxy Sérsic indices evolve less dramatically, and by the present day, quiescent galaxies are massive spheroids.

### 1.3 Star-formation efficiency and quenching

Our current understanding of $\Lambda$–CDM provides the underlying framework for models of galaxy formation and evolution. The accepted theory of galaxy formation relies on work by Silk (1977), White & Rees (1978) and White & Frenk (1991); the first studies to explore the cooling of gas and the hierarchical build-up of dark-matter halos through semi-analytic models. The theory of hierarchical structure formation states that structure grows from Gaussian random-phase perturbations, and non-linear clumps can be identified as over-densities in the linear density field (see Press & Schechter, 1974). Much effort has been invested in improving prescriptions for gas-cooling, supernovae feedback and star-formation processes, which were incorporated into these models.
In the Universe, dark matter can propagate freely through the density distribution due to its collisionless properties. However, due to baryons being collisional, gas cannot propagate freely. As the dark matter halo collapses due to gravity, the potential energy of the gas converts to heat through friction, and the pressure of the gas prevents it from falling directly into the halo. This is dependent on the gas temperature and the halo mass, and this pressure effect is important for low-mass halos at high redshifts.

As the outer part of the DM halo collapses, the gas falls towards the centre of the density distribution, and the infall speed of the gas reaches velocities greater than the sound velocity. This produces a shock front which heats up the gas inside the DM halo, as the kinetic energy of the gas is converted into heat energy, and the gas is therefore shock-heated to the virial temperature (White & Frenk, 1991). The collapsed halo therefore contains hot gas with a temperature that is dependent on the halo mass and size.

In order to form stars within the dark matter halos, the gas must be compressed into dense clouds where star formation can occur, and this can only happen if the mass of the gas cloud is larger than the Jeans mass. However, unless it is able to cool, the pressure of the hot gas can prevent the gas from condensing. This requires the gas to release enough of its energy via radiation (e.g. bremsstrahlung, or collisional excitation), and for optically thin gas, photon emission can cool the gas enough to prompt efficient star-formation (see e.g. Sutherland & Dopita, 1993).

For primordial gas, i.e. gas only made of hydrogen or helium, there is only a small range of stellar masses and temperatures where the cooling of gas is efficient enough to lead to star formation. In this case, the efficiency of gas cooling is described as when the cooling time of the gas is shorter than the free-fall time of a gas particle falling into a dark matter halo. At $z > 5$, star-formation is only efficient at halo masses of $M_h \approx 10^{12}M_\odot$ and gas temperature below $T \lesssim 10^6$K (e.g. White & Frenk, 1991; Navarro et al., 1997; Kereš et al., 2005; Dekel & Birnboim, 2006). At the low-mass end, gas cooling and star formation are only efficient if the dark-matter halos formed early enough in time, corresponding to very high densities, making the stars in these low-mass halos very old. This gives rise to the downsizing scenario; more massive systems formed earlier and built up their stellar masses quickly, whereas galaxies which formed later have lower stellar masses.
1.3.1 Reproducing the galaxy bi-modality in simulations

The existence of massive quiescent galaxies, and the observed bi-modality of the galaxy population, point to processes which prevent gas from cooling and forming new stars. In the $\Lambda$-CDM cosmological model, galaxies form within dark matter halos, and the efficiency of forming stars (star-formation efficiency, SFE) within these galaxies is determined by the halo mass.

The consensus appears to be that the process of star formation in galaxies is an inefficient one (e.g. Fukugita et al., 1998); the efficiency of converting gas into stars in galaxies peaks at $\sim 20 - 30\%$ of the universal baryon fraction for halo masses of $10^{12} M_\odot$ and is even less for lower and higher halo masses (Wechsler & Tinker, 2018). This missing baryon problem suggests that there are mechanisms at play which prevent star formation within galaxies. Figure 1.19 shows the stellar mass-to-halo mass ratio for galaxies at $z = 0$, demonstrating the peak at $M_h = 10^{12} M_\odot$. The decrease in star-formation efficiency for low and high halo masses points to physical processes responsible for suppressing star formation in galaxies.

Current theories suggest there are two distinct processes of “mass” and “environment” quenching, and their effects are separable up to at least $z \lesssim 2$ (see Peng et al., 2010). Mass (sometimes referred to as internal, e.g. Somerville & Davé 2015a) quenching refers to the shutting down of star formation via internal feedback processes, and appears to be more important at earlier times, and happens on relatively shorter timescales (of the order of a few hundred Myr to 1 Gyr). Environmental quenching comes into effect at lower redshift and lower stellar masses than mass quenching, and concerns galaxy-galaxy interactions and the interactions between galaxies and their immediate surroundings.

Our current understanding of quenching is heavily reliant on simulations of galaxy formation, and more recently, they have been able to replicate the observed bi-modality of the galaxy population up to $z \sim 2$ (Croton et al., 2006; Somerville & Davé, 2015a; Davé et al., 2017). Simulations without any type of quenching mechanism appear to produce colour-magnitude diagrams which are inverted; massive luminous galaxies are star-forming and blue, and these diagrams do not show signs of any bi-modality in the galaxy population (e.g. Gabor et al., 2011).

A key issue in early galaxy simulations was the over-cooling problem (Cole, 1991; White & Frenk, 1991; Balogh et al., 2001); given the rate at which gas can cool
The stellar-to-halo mass ratios for central galaxies at $z = 0$, with processes which suppress star-formation at the high- and low-halo mass ends indicated at the top of the figure (taken from Wechsler & Tinker 2018, adapted from Behroozi et al. 2013).

The bi-modality of the galaxy population shows a characteristic stellar mass, $M_{s,\text{crit}} \simeq 3 \times 10^{10} M_\odot$, below which corresponds to the ‘blue’ (star-forming) sequence, while more massive galaxies form the ‘red’ (passive) sequence (see Fig. 1.8). This characteristic stellar mass corresponds to a dark-matter halo mass of $M_{\text{crit}} \lesssim 10^{12} M_\odot$. In the theoretical framework of galaxy formation, the cooling
time of gas in a halo will be shorter than the free-fall time for low halo masses. As the halo becomes more massive, the cooling time will be greater than the free-fall time, and the gas cannot fall onto the central galaxy leading to a regime where the gas forms a pressure-supported ‘hot halo’, so any new gas accreted onto this hot halo will be shock heated. The creation of this hot halo is seen as the dominant criterion for quenching in simulations up to $z < 2$ (Hopkins et al., 2008).

Quenching via feedback processes

Dekel & Birnboim (2006) introduced the idea that the origin of the galaxy bi-modality is driven by thermal properties of in-flowing gas and their connection with feedback and clustering processes. For halos with masses between $10^{11} - 10^{12} \, M_\odot$, streams of cold gas can travel along filaments into the centre of the halo, through the virial-shocked hot gas medium, thus enabling new star-formation and disc growth at early times. Supernovae (SNe) feedback, stellar winds and reionization are then needed to regulate star formation in galaxies at lower halo masses.

For halos with masses above $10^{12} \, M_\odot$, and at later times, the cold streams of gas along filaments are suppressed due to the hot halo, and the in-flowing gas is further shock heated to the virial temperature, prompting star-formation to be shut down as the residual cold gas is used up in the galaxy. In order to maintain the hot halo to produce the red galaxies we observe today, feedback from active galactic nuclei (AGN) is incorporated into many simulations and models.

The first generation of semi-analytic models that included AGN feedback to quench galaxies were able to produce qualitatively the observed bi-modality in specific star-formation rate (sSFR) and colour (e.g. Croton et al., 2006). By introducing AGN feedback into the models, galaxies can be quenched by suppressing the cooling of gas necessary for star formation; e.g. by heating the gas (thermal feedback), driving winds which can eject it out of the system (kinetic feedback) or ionising or photo-dissociating the gas (radiative feedback) (Somerville & Davé, 2015a).

In early generations of SAMs, jet-mode AGN feedback was the primary mechanism for ensuring that the gas halo was heated continually to ensure the cold gas supply was shut off, and these models produced results in agreement with
simulations where cooling was shut off above a specified dark matter halo mass (e.g. Cattaneo et al., 2006). Croton et al. (2006) showed that quenching can take place by maintaining a hot halo via a radio-mode AGN that accretes at a lower rate, and requires a super-massive black hole (SMBH) at the centre of the galaxy. In the radio mode, the AGN drives (radio) jets that heat the circumgalactic gas and maintain the hot halo. In this case, the dominant criterion for quenching is still the formation of the hot halo above a critical halo mass, and the AGN acts to suppress the cooling of the halo gas.

Environmental quenching processes

On the other hand, environmental quenching is generally thought to be associated with galaxy-galaxy interactions, for example, ram-pressure stripping caused by satellite galaxies falling into large dark matter halos. At high redshift, the passive galaxy stellar-mass function is more well-defined by a function similar to the star-forming mass function, which is due to mass-quenching being dominant at high stellar masses and earlier times (Peng et al., 2010). However, at lower redshift, the passive galaxy mass function is best fitted by a double-Schechter function as shown in Fig. 1.7. At low redshift a combination of environmental quenching mechanisms become important, particularly for lower-stellar masses, which can affect the way that the stellar-mass function evolves; the secondary upturn in the passive galaxy stellar-mass function is due to lower-mass galaxies undergoing quenching by environmental processes.

Some of the most important types of interactions between galaxies are merger events. They can be further separated into distinct interactions; gas-rich mergers, which can significantly affect the star formation in each galaxy; and so-called ‘dry mergers’, which usually concern early-type, gas-poor systems. On the other hand, gas-rich major mergers at higher redshift are thought to form the old, red, quenched galaxies that are observed at $z < 2$, disrupting the discs of the progenitor galaxies and destroying the gas reservoirs in the main galaxy by inducing a final burst of star-formation during the merger (Steinmetz & Navarro, 2002).

In Hopkins et al. (2008), using semi-empirical models, the authors showed that quenching associated with mergers for halos below the characteristic shock mass can contribute to the suppression of cooling flows, by either shock heating the halo enough through quasar-mode AGN feedback (accretion onto a black hole at
high Eddington luminosities, and at faster rates than radio-mode AGN feedback) or stellar winds induced by the major merger which act to drive the cool gas out of the host galaxy or reheat the gas to the virial temperature of the hot halo.

Another method of star-formation quenching which involves galaxy-galaxy interactions is ram-pressure stripping; in Gunn & Gott (1972), the authors discussed the possibility that the absence of late-type galaxies in galaxy clusters can be explained by the effects of ram pressure due to the intra-cluster medium (ICM). The ICM is the X-ray emitting gas which exists within galaxy cluster environments, and as galaxies are permeated by this gas as they fall into the cluster centre, they are eventually stripped of most of their cold gas and the remainder is used up in star-formation (Larson et al., 1980).

1.4 Stellar population synthesis

Over the past few decades, significant effort has been devoted to understanding the scaling relations of galaxies, and their evolution over time. The correlations observed between physical parameters such as size, stellar mass, age and metallicity can provide important evidence for various evolutionary pathways. Fundamentally, most of the physical properties we derive from a galaxy come from fitting its spectral energy distribution (SED). Nearly every physical property in a stellar system affects the shape of a galaxy’s SED and in order to extract these physical properties, it is important to include accurate models to correctly represent the observed stellar populations.

To this end, there are a number of factors which need to be considered to ensure that the models we are fitting to galaxy SEDs are realistic. In this section, I will endeavour to explain the fundamental considerations needed in order to obtain accurate information on stellar populations in the distant Universe.

1.4.1 Stellar evolution and the initial mass function

The light we observe from galaxies originates from stars, and so in order to understand the physical properties of a galaxy, it is important to first consider the individual characteristics of their stellar populations. When we observe a spectrum of a galaxy, we assume this is a superposition of the spectra of
stars contained within the galaxy. Therefore we must understand the stars in a galaxy by accounting for spectral type, temperature, stellar mass and chemical composition. As stars evolve as a function of time, the galaxy spectrum we observe is a product of its previous star-formation history. This means that the age of the galaxy’s stellar population and its star-formation history is encoded in the observed galaxy spectrum and that this information can, in principle, be extracted through SED fitting.

The various types of stars are shown on the Hertzsprung-Russell diagram (HRD) in Fig. 1.20 and can therefore provide an overview of the evolutionary phases of stars. Once a star has formed it evolves onto the main sequence - where it spends approximately 90% of its lifetime - the fuel required to sustain the star begins to run out and it splits off onto the giant or super-giant branches on the HR diagram. The fuel that sustains a star is created through nuclear fusion in its core, however, the mechanism which drives this is dependent on the initial mass of the star. In low-mass stars, hydrogen atoms fuse via the proton-proton chain process, whereas above a mass limit of $1.5M_\odot$, stars fuse hydrogen instead via the more complicated Carbon-Nitrogen-Oxygen (CNO) cycle.
In order to gain reliable information from a galaxy, models for stellar atmospheres and evolution are needed. It is therefore useful to compute the evolutionary tracks of stars that start out at different chemical compositions and initial masses. An isochrone is a snapshot of these stars at a given time $t$, and represents a stellar population whose stars are the same age but have different stellar masses and chemical compositions. In Fig. 1.21, each curve (or isochrone) connects the location of stars on the HRD which all have the same age.

In addition to isochrones, an initial mass function (IMF) is needed to understand the initial mass distribution of a stellar population. For an infinitesimal stellar mass range of $m$ to $m + dm$, the number of stars $dN$ is described as

**Figure 1.21** Isochrones for solar metallicity of different ages ranging from $6 < \log(t/\text{yr}) < 10.2$ at intervals of $\Delta \log(t/\text{yr}) = 0.1$ taken from Bressan et al. (2012).
\[ dN = \phi(m) \, dm \tag{1.14} \]

where the initial mass function \( \phi(m) \) is \( \phi(m) \propto m^{-a} \). Typically, the integration limits of the mass function range from \( 0.1M_\odot \) to \( 100M_\odot \). Below the lower mass limit, stars are not able to ignite their hydrogen (brown dwarfs) and more massive stars than the upper limit are not observed, theoretically due to their very short predicted lifetimes, but more reasonably because they would not be structurally stable because of extreme radiation pressure.

An extensive analysis of the initial mass function of stars in the solar neighbourhood was first given by Salpeter (1955) and in recent years it has been widely investigated in a variety of other studies (Kroupa, 2001; Chabrier, 2003). A comparison between different IMFs used in the literature is presented in Fig 1.22. In practical terms, the IMF determines the mass-to-light (M/L) ratio for a stellar population. The Salpeter IMF is commonly used in Milky Way studies, where

\[ \phi(m) \propto m^{-2.35} \tag{1.15} \]

Although this works well for stars with masses similar to Solar, a flatter IMF appears to better describe populations of stars which are less massive. In general, the luminosity of a star is heavily dependent on the initial mass as \( L \propto M^3 \), and so the luminosity of a stellar population is usually dominated by the most massive stars that are on the main sequence at a specific time. This also means that most of the stellar mass in a population is dominated by the low-mass stars.

### 1.4.2 Dust attenuation and extinction

Another important component in stellar population synthesis is the effect of dust on the spectral energy distribution of a galaxy. There are two main types of dust in the Universe, silicates and carbonaceous dust particles, or \textit{grains}, and they are thought to be formed by the condensation of metals in the atmospheres of evolved stars or supernovae remnants (Salim & Narayanan, 2020). These are then ejected into the ISM (Draine, 2003) where they are able to grow in size and mass.

The dust content is a valuable property in tracing the interstellar medium (ISM) and stellar evolution history of a galaxy, and plays a very important role in our understanding of galaxies, and can majorly affect the shape of its observed
Figure 1.22 A comparison between different initial mass functions, taken from Offner et al. (2014).
spectrum (Draine, 2003). It is central in determining how the chemistry and thermodynamics behave and is also crucial in understanding the cosmic star formation rate density in early galaxies (Stark 2016).

![Figure 1.23](image)

**Figure 1.23** Schematic of dust extinction vs. dust attenuation in galaxies, taken from Salim & Narayanan (2020).

There are two major ways to describe the obscuration of light due to dust measured from a galaxy; extinction and attenuation. Extinction reflects the decrease of energy received along a single line-of-sight as a consequence of dust, causing absorption or scattering of photons away from the sight line (see Fig. 1.23). Attenuation includes back-scattering into the line of sight, re-absorption and the contribution to the observed light by unobscured stars (Salim & Narayanan, 2020). In the literature, dust attenuation and extinction are usually used interchangeably, but it should be noted that when describing the effect of dust on a galaxy SED, we are dealing with attenuation rather than extinction.

In the local Universe, the extinction curves for the Small Magellanic Cloud (SMC), Large Magellanic Cloud (LMC) and Milky Way (MW) were notably measured by Prevot et al. (1984), and Fitzpatrick (1985, 1986) and Cardelli et al. (1989), respectively. In Calzetti et al. (2000), the authors study the dust content and average attenuation curve of a sample of 8 nearby ($z < 0.03$) star-forming galaxies using far-infrared (FIR) photometry from the Infrared Space Observatory. They determine that the FIR spectral energy distributions of these galaxies are best fitted by a combination of two modified Planck functions with contributions from warm and cool dust emission, and determine that the cool dust emission contributes up to 60% of the flux in the far-infrared of starburst galaxies. The study improved on an earlier analysis of the average attenuation curve of star-forming galaxies in the local Universe from Calzetti et al. (1994), also known as the Calzetti law, and this attenuation curve is significantly shallower than the extinction curves measured for the Milky Way, SMC and LMC, as shown in Fig. 1.24. The Calzetti attenuation curve is often adopted for SED fitting of high-
redshift galaxies. A thorough review of dust in high-redshift galaxies is given in Calzetti (2001).

![Figure 1.24](image)

**Figure 1.24** Comparison between the SMC extinction curve and the Calzetti et al. (2000) attenuation curve along with the attenuation curves measured for galaxies at $z > 0.5$ from Buat et al. (2012), Kriek & Conroy (2013) and Reddy et al. (2015), taken from Salim & Narayanan (2020).

A common feature in the Milky Way and LMC dust curves is the 2175Å UV extinction bump, first studied by Fitzpatrick & Massa (1986). This feature is not typically observed at high redshifts, and also does not appear in the SMC extinction curve, as demonstrated in Fig. 1.24. Studies find that the peak wavelength and width (FWHM $\simeq$ 350Å) for this extinction feature is variable (at $1\sigma$ of 5Å and 20Å for the peak wavelength and width respectively), with broader bumps associated with denser extinction regions (Zafar et al., 2012; Salim & Narayanan, 2020). The 2175Å bump is currently thought to be caused by carbonaceous dust grains in galaxies, mainly from polycyclic aromatic hydrocarbons (PAHs) which are usually formed in the atmospheres of AGB stars in massive, metal-rich galaxies.

In the ultraviolet/optical regimes, galaxy observations can be strongly affected by dust; in star-forming galaxies the light is attenuated and re-radiated in the far
infrared, causing the spectrum to appear redder. The selection criteria described in Section 1.2.4 take into account the contribution of redder star-forming galaxies, which usually lie in the top right corner of the UVJ diagram (shown in Fig. 1.9), separating these dusty red galaxies from red quiescent galaxies. However, the degeneracy between age, metallicity and dust in galaxies complicates this picture as they all redden the spectrum of a galaxy. A few studies find that the Calzetti attenuation curve describes the high-redshift population well (e.g. Cullen et al., 2018; McLure et al., 2018a), however, due to the complicated dust compositions and orientation angles of galaxies, it has become more common to use a variation of the Calzetti law which includes a deviation from the average curve as described in Salim et al. (2018). This allows the steepness of the attenuation curve to vary, encompassing the range of slopes that are seen locally (see Fig. 1.24) and predicted from simulations (see e.g. Salim & Narayanan, 2020). Another prescription to describe the dust law in high-redshift galaxies is a variable-slope power law, as described in (Charlot & Fall, 2000) that also accounts for the finite lifetime of stellar birth clouds.

1.4.3 Nebular emission and the intergalactic medium

As discussed above, the emission received from galaxies is a combination of gas, stars and intervening dust emission. In galaxies, young stars reside in their birth clouds and this surrounding gas is ionized by the stellar radiation, producing HII regions. This produces nebular emission which can contribute up to 60% of broadband flux in the youngest galaxies (Byler et al., 2017) implying that it is important to model these effects in spectral fitting.

The nebular emission from galaxies is composed of the nebular continuum and nebular line emission. The former is a continuous emission spectrum of free-free (or bremsstrahlung), free-bound, and two-photon emission. Nebular emission lines are generally produced from permitted recombination lines or forbidden (collisional) lines; recombination lines arise when atoms are ionized by radiation from a hot, young star and free-electrons end up being (re)-captured by ions. When the electrons drop down energy levels, the radiation they release produces recombination lines. Forbidden lines (e.g. [OIII]) are low probability lines and can only occur in very low-density gas, which means their detection in galaxy spectra can provide information on the gas density of the galaxy. Analysing the strength of these lines enables us to probe the temperature, density and chemical
composition of the nebular gas in these photo-ionization regions, and currently, there are multiple codes which allow the modelling of nebular emission effects for spectral fitting e.g. CLOUDY (Ferland et al., 2017b), MAPPINGS V (Binette et al., 1985; Sutherland & Dopita, 1993; Sutherland et al., 2018) and M³ (Jin et al., 2022). The CLOUDY (Ferland et al., 2017b) photo-ionization code is used frequently in the literature and is used throughout this thesis when performing spectral fitting of galaxies.

The intergalactic medium (IGM) is the medium of largely ionised gas that exists between galaxies; as rest-frame far-UV radiation is emitted from sources, it is absorbed by the neutral hydrogen left within the IGM following cosmic reionization (McQuinn, 2016). Attenuation takes place due to the increasing number of atomic transitions, as one approaches shorter wavelengths, in the Lyman series of hydrogen and reaches a maximum value at 912 Å also known as the Lyman limit. This wavelength corresponds to the energy required to ionise hydrogen from the ground state.

As one moves to higher redshifts, the IGM attenuation increases up to around redshift \(z > 6\) where almost all of the light emitted short-ward of 1216 Å from the galaxy has been attenuated. Along an observer’s line of sight, there are several systems that contribute to the absorption lines seen in spectra of distant objects; the Lyman-\(\alpha\) forest (LAF, due to the absorption of Ly\(\alpha\)), Lyman limit systems (LLSs) and damped Ly\(\alpha\) systems (DLAs). A notable model for IGM attenuation was given by Madau (1995) as a function of wavelength and redshift and the separate contributions for the aforementioned features were included. These features are generally found in spectra of high-redshift objects and so are useful in selecting objects photometrically using the ‘drop-out’ method, where the flux from a galaxy disappears in a filter due to the absorption of neutral hydrogen (e.g. Steidel et al., 1996; Madau et al., 1996). An updated version of the model for attenuation of the IGM was provided by Inoue et al. (2014) using improved statistics from more recent observations and is now typically adopted as the IGM attenuation model in SED fitting, building upon the previously popular Madau (1995) model.

1.4.4 The star-formation histories of galaxies

The star-formation history (SFH) is perhaps one of the most important components to consider in understanding the evolution of a galaxy. Star-formation
histories tell us how the star-formation rate $SFR(t)$ of a stellar population has evolved over time.

In order to derive SFRs and stellar masses using stellar population synthesis, a simple parametric form of a SFH is typically used, and traditionally in the form of an exponentially-declining function, which is advantageous for its speed in fitting. The drawback of using this SFH though, is that it is less applicable at higher redshifts (Maraston et al., 2010; Reddy et al., 2012). An improvement on the exponentially declining SFH is one that incorporates rising and falling slopes of the SFH, such as a double power-law SFH, which allows the modelling of a slow rise and rapid decline in star formation, which is ideal for modelling for example rapidly quenched systems. In recent years there have been many proposed functional forms which are well-matched to the SFHs of simulated (Vogelsberger et al., 2014; Simha et al., 2014; Diemer et al., 2017) and real galaxies (Gladders et al., 2013; Abramson et al., 2015; Leja et al., 2019a) some of which are demonstrated in Fig. 1.25. In the upper panel of Figure 1.25, the photometric data provides limited insight into the star-formation history. Conversely, the spectroscopic data reveals subtle distinctions among the best-fit models for the star-formation histories, offering more indication of the SFH.

In contrast, non-parametric star-formation histories do not explicitly assume a functional form. These can consist of adaptive time binning (e.g. Tojeiro et al., 2007), adding constant piece-wise functions (e.g. Leja et al., 2017) or directly taken from models of galaxy formation (e.g. Finlator et al., 2007; Pacifici et al., 2012). However, non-parametric SFH models are very computationally expensive due to the large number of free parameters being fitted, and so are better suited to smaller datasets than the ones which will appear in this thesis. A double-power law SFH is consistently used throughout this thesis when fitting galaxies with Bagpipes (see Chapter 2).

1.4.5 Modelling galaxy physical properties

In this section, I have described the many components which, when combined, can provide a complete picture of an evolving stellar population.

As mentioned previously, the first step in constructing a model of galaxy evolution is to build models for the stellar spectra present in the galaxy. This is facilitated by introducing simple stellar populations (SSP) to create model spectra of
Figure 1.25 The best-fit models for six different SFHs (bottom panel, coloured lines) for an example galaxy at $z = 1.666$ from the MOSFIRE sample presented in Belli et al. (2019b). The observed MOSFIRE photometry (black points) and spectrum (black line) are shown in the top and middle panels of the figure. In the bottom panel, the grey lines are a random subset of the SFH drawn from the posterior distribution and the median SFH is shown in black.
galaxies using pre-defined input physics such as stellar evolution theory in the form of spectral libraries (e.g. Conroy, 2013). To construct an SSP model, it is first necessary to compile the spectra of stars for a range of metallicities at a given position on the HR diagram, and for a given SSP model, the isochrone for each age that is needed is selected. This is then combined with a stellar IMF, and these are combined to form the SSP model, as demonstrated in Fig. 1.26.

However, in order to construct more realistic and complex models for galaxies, it is important to incorporate the fact that galaxies are complicated by their stars having different ages and metallicities. This means that a model of a galaxy must contain: stars with a range of ages given by the galaxy SFH; metallicities given by the metallicity probability distribution; dust attenuation and chemical enrichment histories.

These more complex models are referred to as composite stellar populations (CSP) and are the building blocks of SED fitting. There are currently a number of SED codes which use a range of complex techniques to fit models to the galaxy observations. The FAST (Kriek et al., 2009a), LePHARE (Ilbert et al., 2006; Arnouts et al., 1999), PROSPECTOR (Johnson et al., 2021a) and Bagpipes (Carnall et al., 2018) SED fitting codes are commonly used in the literature, however, throughout this thesis I use Bagpipes to extract physical parameters of the galaxy samples presented in the forthcoming science chapters. This choice is based on Bagpipes’ ability to simultaneously fit galaxy spectroscopy and photometry using advanced Bayesian methods.
Figure 1.26  Diagram to demonstrate stellar population synthesis modelling taken from Conroy (2013). To model SSPs, the IMF, isochrones and stellar spectra are taken as initial inputs. Combining these SSPs with dust, star-formation histories and chemical evolution allows one to extract the composite stellar population (CSP) and therefore the physical properties of a galaxy from its spectral energy distribution.
1.5 Open questions and motivations

The previous sections of this Chapter have touched upon the main observational results of the past century that have shaped our understanding of the Universe as a whole, and in particular, the formation and evolution of galaxies. In recent years, the study of the high-redshift universe has seen a significant improvement in observational capabilities, largely due to advancements in telescope power. The Very Large Telescope (VLT), Keck, and the Hubble Space Telescope (HST) have contributed to many significant discoveries, many of which have been discussed previously in this section. More recently, the successful launch of JWST has pushed the limits of our observations, allowing for the detection, and analysis, of fainter and more distant star-forming (e.g. Donnan et al., 2023; Arrabal Haro et al., 2023) and quiescent (Carnall et al., 2023) galaxies than ever before.

Advancements in spectral fitting of galaxies have enabled us to explore the physical processes in galaxies which have shaped their evolutionary history. The observation and analysis of significant relationships between stellar mass with metallicity, age and size points to the processes which the galaxy population has experienced; older galaxies are more massive, with the most massive galaxies forming the earliest, and fastest, in the Universe. Efforts to constrain galaxy ages using empirical indicators are complicated by a bias with metallicity, making a galaxy appear older and more metal poor. However, one of the most important questions is: what mechanisms cause star formation to be quenched in galaxies?

At high redshift, the quiescent population is negligible, with only very few quiescent galaxies being observed above $z > 3$, and only contributing to around 10% of the total mass budget. However, studies of the galaxy stellar mass function have revealed that the quiescent galaxy population significantly dominates the global mass budget of the Universe at $z < 0.5$ (e.g. Fontana et al., 2006; Muzzin et al., 2013b; McLeod et al., 2021). The existence of quiescent galaxies and the bi-modality of the galaxy population is still not fully understood and attempts to quantify the origin of this and the mechanisms through which galaxies cease star formation are ongoing.

Mechanisms which cause star-formation quenching have been linked to the internal processes of a galaxy and the environment within which a galaxy resides; for example, internal quenching can be associated with AGN feedback (e.g. Croton et al., 2006), whereas external quenching processes may arise from
interactions between nearby galaxies or the intra-cluster medium (Gunn & Gott, 1972). Although much progress has been made in this area in regards to the mechanisms which have been suggested to explain quenching on various timescales (see Section 1.3), it has proven difficult to identify the key processes responsible for the quenching of star-formation in galaxies, and their relative importance at different epochs. In the local Universe, the effects of environmental and internal quenching processes are clearly separable, however, it is unclear whether these are separable at higher redshifts.

One of the most basic ways to probe quenching processes in galaxies is to perform robust spectro-photometric SED fitting on the galaxy population, allowing us to constrain fundamental physical properties such as age, stellar mass, metallicities and SFHs. Improved SED fitting methods have already unveiled significant correlations between physical properties based on improved measurements of galaxy SFHs, stellar masses and metallicities, and in this thesis, I present results based on sophisticated spectroscopic and photometric fitting of large datasets using the Bagpipes (Carnall et al., 2018) SED fitting code, which I describe in detail in Chapter 2.

In recent years, much effort has been invested in improving fitting methods to ensure that the models we use to describe the galaxy population are realistic. Bayesian Analysis of Galaxies for Physical Inference and Parameter EStimation (Bagpipes) is a sophisticated spectral energy distribution fitting code, incorporating up-to-date methods to explore a wide area of parameter space and return posterior model spectra, star-formation histories and other physical properties which are fundamental in describing the galaxy population. The advantage of using Bagpipes over other SED codes is that it possesses the unique ability to fit the spectroscopy and photometry of a galaxy simultaneously, with the aim of breaking degeneracies which arise when fitting only photometric data.

Previous studies using Bagpipes have managed to constrain the SFHs and metallicities of massive quiescent galaxies at $z \sim 1$ (see Carnall et al., 2022b), and these updated constraints on the quiescent population have been incorporated into some of the work that is presented in this thesis. More recently, the spectroscopic confirmation using JWST NIRSpec of a massive quiescent galaxy at $z = 4.658$ (GS-9209) and its subsequent analysis using Bagpipes has provided tighter observational constraints on the physical processes which cause quenching in the very early Universe. Full spectral fitting of the galaxy revealed the presence
of a super-massive black hole (SMBH) residing in the centre of the galaxy, inferred from broad-line H\textalpha emission in the spectrum and a high narrow-line [NII]/H\textalpha ratio. The mass of the SMBH points to evidence that the galaxy was most plausibly quenched via AGN feedback. The observed spectrum and model from BAGPIPS are shown in the top panel of Fig. 1.27, demonstrating the strong Balmer-absorption lines typical of a massive quiescent galaxy. The lower panel shows the BAGPIPS-fitted AGN-model component.

The sizes and morphologies of galaxies are also very important in providing information on the processes by which star-formation quenches in galaxies. Studying the relationships between the sizes and physical properties such as ages, stellar masses or metallicities can also provide evidence of merger events, and in turn, can shed light on how star formation was quenched in galaxies. Significant progress has been made using large spectroscopic surveys to try to understand the relationships between the sizes and stellar masses of both star-forming and quiescent galaxies in order to place constraints on quenching. A key result in the literature is that while quiescent galaxies on average display smaller sizes than star-forming galaxies up to $z < 3$, less-massive quiescent galaxies have similar morphologies to star-forming galaxies at the same stellar mass and redshift, pointing to a significant flattening of the quiescent size-mass relation and suggesting that more-massive and less-massive quiescent galaxies have quenched via different channels (Kawinwanichakij et al., 2021; Nedkova et al., 2021).

However, larger sample sizes and deeper data are needed to confirm these trends to lower stellar masses and higher redshifts. Robust measurements of the sizes and morphologies of galaxies using high-resolution HST and JWST imaging can further our understanding of the physical processes contributing to the size growth of quiescent galaxies in the Universe and, combined with sophisticated SED fitting, can place important observational constraints on galaxy evolution models.

Recently, large imaging and spectroscopic surveys have facilitated studies of large samples of star-forming and quiescent galaxies. Throughout this thesis, I make use of ultra-deep spectroscopy from the recently completed VANDELS (McLure et al., 2018b; Pentericci et al., 2018) survey, in addition to HST and JWST imaging from public surveys to study large samples of star-forming and quiescent galaxies from $z = 1$ to $z = 3$, aiming to address the aforementioned outstanding issues in the literature.
(a) The *JWST* NIRSpec observations of the galaxy GS-9209. The inset figure shows a zoomed-in region of the spectrum, highlighting the strong Balmer-absorption lines present in the galaxy.

(b) The BAGPIES model with the AGN component shown in red. Prominent absorption features are also shown, and the Gaussian component fits to the narrow-line Hα and [NII] are shown in green.

Figure 1.27 The observed (blue) *JWST* NIRSpec and BAGPIES model (black) spectra for the massive quiescent galaxy $z = 4.658$, taken from Carnall et al. (2023).
1.6 Thesis outline

The structure of this thesis is as follows: in Chapter 2, I present a detailed explanation of the methods used throughout the thesis, focusing on the SED fitting code Bagpipes and size-morphology code Galfit. I also provide an overview of the spectroscopic (LEGA-C and VANDELS), and imaging (JADES and PRIMER) surveys, whose datasets I use throughout this thesis.

In Chapter 3, I present the work published in Hamadouche et al. (2022), which utilised data from the ultra-deep spectroscopic VANDELS and LEGA-C surveys in order to analyse the relationships between size, mass and age within the quiescent galaxy samples. Then in Chapter 4, I present the results of full spectrophotometric fitting on the VANDELS quiescent sample, most of which is published in Hamadouche et al. (2023). I explore the connection between age, stellar mass, and quenching and star-formation timescales, finding a sub-sample of galaxies which tentatively indicate increased levels of $\alpha-$enhancement compared to the rest of the sample.

I present an analysis of quiescent and star-forming galaxies selected from the JWST JADES and PRIMER surveys in Chapter 5. I provide updated size-mass relations over the redshift range $1 < z < 3$ over a wide stellar-mass range and discuss whether the size-mass relations for quiescent galaxies up to $z \sim 3$ are well-described by a broken power-law as suggested by Nedkova et al. (2021) and Kawinwanichakij et al. (2021). I then present morphological constraints on the two sub-samples of galaxies, and discuss these results in the context of the effect of quenching mechanisms on the observed physical properties of the galaxies.

Finally, In Chapter 6, I discuss how the results I have presented in Chapters 3, 4 and 5 are important in the context of galaxy evolution and how they contribute to our current understanding of quenching. I conclude this thesis by presenting directions for future research.
Chapter 2

Observational data and model fitting

In this Chapter, I discuss the observational datasets and model-fitting techniques employed throughout the rest of this thesis. I begin by providing a brief overview of the basics of photometry and spectroscopy.

2.1 Observational astronomy

Photometry and spectroscopy are the two fundamental techniques for measuring the properties of objects in the night sky. Photometry describes the process of measuring the brightness and colours of objects from imaging obtained through a set of filters, either broad-band or narrow-band. The latter covers a narrow wavelength range of a particular region (typically $\Delta \lambda \simeq 50 - 100 \, \text{Å}$) and is commonly used to search for objects emitting bright emission lines. In contrast, in broadband imaging ($\Delta \lambda \simeq 1000 - 4000 \, \text{Å}$), filters are used to isolate wider wavelength ranges and the information from multiple filters provides information on the physical properties of the objects. Measuring the physical properties of galaxies from photometry by fitting models to them is usually referred to as spectral energy distribution (SED) fitting and can provide photometric redshifts, stellar masses and ages (see Section 2.4).

Although imaging data and photometry can provide important information on the stellar masses, sizes and morphologies, more detailed analysis of the stellar
populations of galaxies requires spectroscopy, as photometry only provides a low-resolution view of a galaxy SED, with typically $\lesssim 20$ photometric data points.

Spectroscopy takes the light from an object and disperses it through a prism (low resolution), or a grating (high resolution). As the light within a wavelength region is dispersed, spectroscopic features such as absorption and emission lines become apparent in the spectrum and can be compared with a laboratory spectrum to identify the lines in the rest frame. Spectroscopy provides key information which is not available from photometry, such as the secure identification of known spectral lines that can provide very accurate redshifts, allowing us to measure the distances to galaxies. Moreover, spectroscopic observations allow us to measure the equivalent widths and strengths of specific emission or absorption lines, which can provide important information on gas inflow/outflow as well as the relative velocities, ages and metallicities of different stellar population components.

2.1.1 Photometry

When we measure the apparent fluxes of an object in a filter, it is equivalent to measuring the average flux density over the wavelength range of the filter. The flux density is defined as the energy received from an astronomical source per second, per unit area, per unit frequency (or wavelength). When we measure photometry of objects, the average flux density is related to the number, and energy, of the photons collected by the detector (e.g. charged couple device, CCD) for a specific filter.

It is useful to define the transmission curve of the filter, $T(\lambda)$. Flux measurements from an image taken using a specific filter are averaged over a range of wavelengths weighted by the transmission curve of the system. The average flux density (per unit frequency) for a photon counting system such as a CCD is defined as:

$$\langle f_\nu \rangle = \frac{\int f_\nu \nu^{-1} T(\nu) d\nu}{\int \nu^{-1} T(\nu) d\nu}$$ (2.1)

In $\sim 129$ BCE, Greek astronomer Hipparchos catalogued the brightness of stars he observed, using a scale from 1 to 6 where sixth magnitude stars were the faintest. This method was employed until the 1800s, when astronomer Norman Pogson formalised the magnitude system by realising that stars of the first magnitude were on the order of $\sim 100$ times brighter than sixth magnitude stars, so each
magnitude corresponds to a $10^{1/5}$ change in brightness. This system placed Vega - a bright star in the northern hemisphere - at around zeroth magnitude, making it a useful object to use as a reference zero-point.

The magnitude system represents a logarithmic flux scale for observations, and the *apparent* magnitude of an astronomical object is described by a system of flux measurements; the flux of a source for a certain frequency or wavelength range relative to a standard source with known flux density. The relationship between apparent magnitude and flux density is given by:

$$m = -2.5 \log_{10} \left( \frac{\langle f_\nu \rangle}{\langle f_{\nu 0} \rangle} \right) \quad (2.2)$$

for a source with flux density $f_\nu$, where $f_{\nu 0}$ is the zero-point which is used to calibrate fluxes to a standard magnitude system.

In contrast, the *absolute* magnitude $M$ of an object is defined as the apparent magnitude of an object if it were observed at a distance of 10 parsecs (pc). It follows that:

$$m - M = 5 \log_{10} (d) - 5 \quad (2.3)$$

where $d$ is the distance to the object in parsecs and $m - M$ is often referred to as the *distance modulus*. Until recently, the Vega magnitude system has continued to be widely used, where objects have apparent magnitudes relative to Vega. However, using Vega to calibrate the magnitude system is problematic for several reasons; firstly, the spectral energy distribution of Vega is not flat, and deviates even more from a flat ($f_\nu$) SED at UV/IR wavelengths. Another reason is that Vega is thought to be a δ-scuti star which are known to have variable brightness. It has therefore become more common in recent years to quote measurements using the AB system defined by Oke & Gunn (1983). The AB system defines the zero-point object as a theoretical source which has a flat ($f_\nu$) SED, matched to the flux density of Vega in the V-band. In the AB system, the flux zero-point in every filter is defined to be $f_{\nu 0} = 3631 \text{ Jy}$, where $1 \text{ Jy} = 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}$ in SI units.
2.1.2 Spectroscopy

To isolate the light of an individual galaxy before it gets dispersed, a small aperture, or slit, is employed at the focal plane of the telescope. The light that passes through the slit is then diverted to a diffraction grating by a collimator. The collimated light is then dispersed through a prism or grating, and split into its constituent wavelengths, and this light is then focused onto the detector to produce an image of the spectrum. The dispersion of the grating sets the wavelength range of the spectrum over a given physical range and is typically measured in Å/pix.

The spectral resolution of a spectrum is dependent on the width of the slit. We can define the spectral resolution, or resolving power, of a spectrograph as

\[ R = \frac{\lambda}{\Delta \lambda} \]  

(2.4)

where \( \Delta \lambda \) is the resolution element; the minimum wavelength separation between two features that can be resolved in the spectrum.

Spectra can reveal important information on the velocities of the individual stars in galaxies, as well as gas-inflow and outflow velocities. These physical processes result in both Doppler shifts and broadening of emission and absorption lines in the spectrum of a galaxy. The observed shifts or broadening of emission/absorption features can be related to the corresponding (non-relativistic) velocity and the spectral resolution by

\[ \frac{\Delta \lambda}{\lambda} = \frac{\Delta v}{c} = \frac{1}{R} \]  

(2.5)

The effect of gas flowing towards - or away from - the centre of a galaxy can cause spectral lines to be Doppler shifted from their rest-frame wavelength. For example, for a spectral resolution of \( R = 10000 \), the minimum velocity shift that can be resolved in the spectrum is \( \Delta v = 0.0001c = 30 \text{ km s}^{-1} \). However, it is important to remember that we only observe the velocity component along the line-of-sight. Early-type galaxies, such as those studied in this thesis are dynamically hot systems. For these galaxies, the velocity widths in the galaxy spectrum reflect the superposition of the random velocities of the individual stars which has the effect of broadening emission/absorption line features. The
width of the feature can be described by a Gaussian, and is referred to as the velocity dispersion, \( \sigma_\star \) of the galaxy. Typically, early-type galaxies exhibit velocity dispersions of \( 100 - 300 \text{ km s}^{-1} \).

Due to the need for large datasets in order to perform statistical analyses of full galaxy populations, we require techniques that allow the retrieval of spectra for multiple objects at once. To achieve this, multi-object spectroscopy (MOS) uses slits or fibres that can obtain spectra for a number of objects simultaneously. The two spectroscopic datasets (VANDELS and LEGA-C) I describe in the next part of this Chapter make use of the MOS capabilities of the Visible MultiObject Spectrograph (VIMOS, Le Fèvre et al. 2004) instrument (now decommissioned by ESO) to obtain spectra for large numbers of objects.

### 2.2 Imaging datasets

Throughout this thesis, I draw upon a range of datasets from multiple surveys. While some of the information here will be presented in the forthcoming science chapters, in this section I give an overview of the survey data, before moving on to describe the fitting techniques I employed in the next section.

#### 2.2.1 The CANDELS imaging survey

The Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; Koekemoer et al., 2011; Grogin et al., 2011) is an *HST* imaging survey of five extra-galactic deep fields (shown in Fig. 2.1); the Extended Groth Strip (EGS), Great Observatories Origins Deep Survey-North (GOODS-North) and -South fields (GOODS-South, also known as the Chandra Deep Field South), Ultra-Deep Survey (UDS) and Cosmic Evolution Survey (COSMOS) fields. The total area of the CANDELS survey is 800 square arcminutes. The CANDELS program was aimed at understanding the evolution of galaxies and black holes over the redshift range \( 1.5 < z < 8 \) and the characterisation of Type Ia supernovae (SNe Ia) at \( z > 1.5 \) to probe dark energy. Over the duration of the survey, imaging was carried out using Wide-Field Camera 3/Infra-red (WFC3/IR) onboard *HST* as the prime instrument and the WFC3/UVIS channel, along with the Advanced Camera for Surveys (ACS) for parallel observations.
Figure 2.1 The five CANDELS survey fields in COSMOS, EGS, GOODS-S, GOODS-N and UDS, taken from Grogin et al. (2011). The HST WFC3/IR prime exposures are shown in blue and HST/ACS exposures are shown in pink.

2.2.2 The JADES Survey

JWST was finally launched on the 25\textsuperscript{th} December 2021, reaching its final position orbiting L2 less than a month later. Within only two years of its launch, the telescope has revolutionised the study of galaxy formation and evolution.

In Chapter 5 of this thesis, I make use of data from the JWST Advanced Deep Extragalactic Survey (JADES). The JADES collaboration is a joint effort of the NIRCam and NIRSpec instrument development teams, with the primary aim of providing unparalleled, deep fields in GOODS-North and GOODS-South to provide a deep look at the Universe to the earliest lookback times; when the Universe was $\lesssim 300$ Myr old.
Survey design and instruments

The results presented in the final chapter of this thesis are partly based on observations from the first data release of JADES NIRCam prime imaging in GOODS-South. In this section, I will therefore only discuss the deep prime observations but for a complete description of the survey design, data reduction and medium prime and parallel observations, I refer the reader to Rieke & the JADES Collaboration (2023) and Eisenstein et al. (2023).

The JADES survey footprint is shown in Fig. 2.3, and shows the prime and parallel imaging observations using the JWST NIRCam instrument. In addition to having an abundance of ancillary HST (CANDELS and HST/ACS) data, the JADES survey fields additionally overlap with other Cycle 1 programs, including the First Reionization Epoch Spectroscopically Complete Observations (FRESCO Oesch et al., 2023), the JWST Extragalactic Medium-band Survey (JEMS Williams et al., 2023) and Next Generation Deep Extragalactic Exploratory Public survey (NGDEEP Bagley et al., 2023).

NIRCam Deep Prime observations

The Deep Prime observations targeted GOODS-South centred on the UDF, with 4 NIRCam pointings covering a 4.4′ by 6.1′ field. The NIRCam instrument consists
Figure 2.3  Figure showing the JADES survey area including the NIRCam prime and parallel imaging and the overlapping NIRSpec pointings, taken from Eisenstein et al. (2023).

of two modules (A & B), each of which have a field-of-view covering 2.2' x 2.2', separated by a 45'' gap. This makes a total combined FOV of around \( \sim 9.7 \text{ sq. arcmin} \). Each of the modules, A and B, has four short wavelength (SW) detectors (A1-A4 & B1-B4), tuned for observations over the range 0.6 – 2.3 \( \mu \text{m} \), and one long wavelength (LW) detector (ALONG & BLONG), tuned for observations over 2.4 – 5 \( \mu \text{m} \). For the Deep Prime pointings, nine NIRCam filters were utilised: F090W, F115W, F150W, F200W in the short-wavelength channel; and in the long-wavelength channel; F277W, F335M, F356W, F410M, F444W. In total, this part of the JADES program covers almost 25 arcmin\(^2\), with a total of 229 hours of observing time.
2.2.3 The PRIMER survey

The Public Release IMaging for Extragalactic Research (PRIMER) survey is a major public Treasury Program that provides deep JWST NIRCam + MIRI imaging for the HST CANDELS COSMOS and UDS legacy fields, which consists of \(\approx 400\) sq. arcmin. In this thesis, I make use of the PRIMER data in COSMOS, which covers an area of 144.2 sq. arcmin.

![Figure 2.4](image.png)

**Figure 2.4** JWST PRIMER pointings in the CANDELS HST legacy fields COSMOS (left) and UDS (right) overlaid on the HST WFC3 and ACS imaging.

Survey design and instruments

The PRIMER observations are constructed as prime/parallel observations. Due to the smaller footprint of the MIRI imaging, and the importance of continuous coverage for both instruments, the MIRI pointings were chosen as the prime observations with NIRCam in parallel, and the dither pattern chosen ensures that sub-pixel sampling for both instruments was achieved.

The NIRCam imaging is in eight filters, with F090W, F115W, F150W, and F200W in the short-wavelength channel; and F277W, F356W, F444W, and...
F410M in the long-wavelength channel. In this thesis, I use catalogues selected from the NIRCam imaging in the F356W filter to obtain robust, mass-complete samples of star-forming and quiescent galaxies. Together with deeper JADES data, I measure their sizes from the F356W images (as described in sections 2.5 and 5.3.3) in order to determine the size-mass relations of both the star-forming and quiescent samples to higher redshift and lower masses than previously studied (e.g. see Chapter 5).

**Key science results from JWST**

Early results from JWST revealed that galaxies are forming earlier than previously thought, with the highest-redshift galaxy spectroscopically confirmed to be at \( z = 13.2 \) (see Curtis-Lake et al., 2023). Early data from the JADES survey has provided substantial insight into the formation of early galaxies, and one of the most exciting results to arise from the survey has defied interpretation. A previously discovered luminous galaxy dubbed GN-z11 was spectroscopically confirmed to be at \( z > 11 \) by Oesch et al. (2016), based on low-resolution HST grism spectroscopy. This galaxy was then observed by the JADES survey this year, and spectroscopically confirmed to be at a slightly lower redshift than previously thought, at \( z = 10.6 \) and is an intriguing object as the UV spectrum features emission of highly-ionised nitrogen (Bunker et al., 2023). The detection of high-ionisation lines and C\( \text{II} \) 1335Å emission in the spectrum are typical of broad-line active galactic nuclei, suggesting that GN-z11 hosts an accreting black hole (e.g. see Maiolino et al., 2023; Scholtz et al., 2023).

![Prism spectroscopy of the luminous galaxy GN-z11, confirmed by the JADES survey to be at \( z = 10.6 \) (Bunker et al., 2023).](image)

**Figure 2.5** Prism spectroscopy of the luminous galaxy GN-z11, confirmed by the JADES survey to be at \( z = 10.6 \) (Bunker et al., 2023).

The additional presence of Ly\( \alpha \) emission - detected using the micro-shutter array
(MSA) mode \((R \approx 1000)\) with the G410M grating - is surprising as the IGM is thought to be neutral at these early times and indicates that the surrounding region of GN-z11 represents a candidate proto-cluster core forming at \(\sim 400\) Myr after the Big Bang (Bunker et al., 2023).

In Sandles et al. (2023), the spectroscopic confirmation of a quiescent galaxy at \(z = 2.34\) became the least massive quiescent galaxy discovered at \(z > 2\). The study also confirmed three other low-mass, low-SFR galaxies in the JADES survey area, prompting important questions about the evolution and quenching of galaxies in over-dense environments, and suggesting that the \(z = 2.34\) galaxy is the earliest evidence of environment-driven quenching to date. Low-mass quiescent galaxies are expected to have had their star-formation quenched via external mechanisms rather than internal, as described in Section 1.19. These low-mass quiescent galaxies therefore require environments where mechanisms such as merging, or ram-pressure stripping are possible, and so observations of over-dense regions are key in examining their properties.

### 2.3 Spectroscopic datasets

#### 2.3.1 The VANDELS Spectroscopic Survey

The first two science chapters (Chapters 3 and 4) of this thesis rely on observations from the VANDELS survey, an ultra-deep, medium resolution \((R \sim 600)\) spectroscopic survey of the CANDELS Chandra Deep Field South (CDFS) and Ultra Deep Survey (UDS) fields (see Fig. 2.6). Data were obtained from the VIMOS instrument on the ESO Very Large Telescope (VLT). The survey provided red-optical spectroscopy for \(\sim 2100\) galaxies (McLure et al., 2018b; Pentericci et al., 2018; Garilli et al., 2021) over a redshift range of \(1 < z < 7\) and targeted star-forming galaxies at \(2.5 < z < 5.5\), massive quiescent galaxies at \(1.0 < z < 2.5\) and fainter star-forming galaxies at redshifts \(3.0 < z < 7.0\). VANDELS also targeted a small number of X-Ray/Spitzer selected AGN, as well as galaxies detected by Herschel.
Figure 2.6 Each of the VANDELS VIMOS pointings in both the UDS and CDFS fields are shown in colour (taken from McLure et al. 2018b), overlaid on HST $H$-band imaging from the CANDELS survey (Grogin et al., 2011; Koekemoer et al., 2011) in greyscale in the centre. The lighter greyscale shows the $H$-band imaging from the UKIDSS Ultra-Deep Survey (Almaini et al., 2007) and the VISTA-VIDEO survey (Jarvis et al., 2013).

Parent sample

The parent sample of potential spectroscopic targets in the VANDELS survey consisted of bright star-forming galaxies ($2.4 \leq z \leq 5.5$), LBGs ($3.0 \leq z \leq 7.0$) and passive galaxies ($1.0 \leq z \leq 2.5$) making up about 97% of the total sample, with the remaining $\sim 3\%$ being the AGN and Herschel-detected galaxies.

Figure 2.7 presents the distribution of this sample on the SFR–$M_*$ plane, showing the population of star-forming galaxies (blue) and more massive passive galaxies (red). The blue and green dashed lines show the main-sequence of star-formation determined by Speagle et al. (2014) and Whitaker et al. (2014) at $z \simeq 3$, demonstrating clearly that the star-forming sub-sample of VANDELS galaxies lies on the main-sequence of star-formation. The colour-bars correspond to the number of objects in each 2D bin.
This diagram shows the distribution of star-forming and passive galaxies from the VANDELS parent sample of potential spectroscopic targets. Star-forming galaxies (blue) lie on the main-sequence of star-formation (blue and green dashed lines) and quenched galaxies (red) lie below. Taken from McLure et al. (2018b).

The full details of the VANDELS sample selection and photometric catalogues are described in McLure et al. (2018b), however, I will give a brief description of the photometric catalogues in this section.

In VANDELS, galaxies were drawn from four separate photometric catalogues covering an observed UV-NIR wavelength range of 0.3 – 5 \( \mu \)m. The VANDELS pointings in the CDFS and UDS fields are centred on the CANDELS fields and benefit from the CANDELS HST imaging. For these pointings, the survey makes use of the catalogues produced by the CANDELS team (Galametz et al., 2013; Guo et al., 2013). As the field of view of the VIMOS instrument is larger than the areas imaged by the CANDELS survey, two further photometric catalogues were produced by McLure et al. (2018b) (see Fig. 2.6) constructed from public ground-based imaging. Each of these catalogues underwent extensive SED fitting to produce robust photometric redshifts, rest-frame magnitudes and stellar masses.
Main science goals

The main science goal of VANDELS was to obtain spectroscopy with high enough signal-to-noise to investigate the astrophysics of galaxy evolution in the early Universe; the interplay between interstellar gas outflows and metal enrichment, and AGN feedback which contributes to the quenching of star-formation. In order to achieve this, all objects have a minimum of 20 hours on-source integration time up to a maximum of 80 hours, significantly more than the integration times (∼1–5 hours) that were typical of previous surveys. The quality and availability of ancillary data was also essential in the choice of field for the VANDELS survey. The multiple VANDELS pointings in UDS and CDFS are shown in Fig. 2.6, overlaid on the ancillary *HST* and ground-based imaging.

The resulting ultra-deep spectroscopy from VANDELS, combined with high-quality multi-wavelength photometry, produced a unique dataset providing accurate determinations of stellar masses, star formation rates, star-formation histories, dust attenuation and metallicities (e.g. Cullen et al., 2018, 2020; Carnall et al., 2022a). Fig. 2.8 shows high-SNR median stacked spectra for VANDELS Lyman Break galaxies and quiescent galaxies from the first data release (DR1), highlighting common emission and absorption features (McLure et al., 2018b).

Key science results from VANDELS

The VANDELS survey observations were completed in 2018, with the final data release (DR4: Garilli et al., 2021) providing ultra-deep rest-frame UV spectra for 2079 galaxies.

The VANDELS survey has facilitated detailed investigations into the properties of star-forming galaxies (e.g. Cullen et al., 2020; Begley et al., 2022, 2023) and quiescent galaxies (e.g. Carnall et al., 2019a; Hamadouche et al., 2022, 2023, see also Chapters 3 and 4) due to the high quality of the spectra. One of the key goals for VANDELS was to measure the metallicities of galaxies at high-redshift, and to quantify the evolution of the mass-metallicity relation.

To this end, Cullen et al. (2019) studied a sample of 681 star-forming galaxies at $2.5 < z < 5.0$ from VANDELS, finding a strong correlation between stellar mass and metallicity, with stellar metallicity increasing from $\log_{10}(Z_*/Z_\odot) = -1.04$ to $\log_{10}(Z_*/Z_\odot) = -0.57$ between $\log_{10}(M_*/M_\odot) = 8.5$ and $\log_{10}(M_*/M_\odot) = 10.2$. 
(a) Stacked spectra of 105 Lyman-break galaxies (LBGs) from the first VANDELS data release (DR1). The spectra have robust redshifts in the interval $3.0 \leq z \leq 4.0$, with a median redshift of $z = 3.5$.

(b) Stacked spectrum of the passive galaxies from DR1, in the redshift interval $1.0 \leq z_{\text{spec}} \leq 2.5$, with a median redshift of $z_{\text{spec}} = 1.2$.

Figure 2.8 Stacked spectra of LBGs and passive galaxies from VANDELS DR1, presented in McLure et al. (2018b). Common emission (dot-dashed) and absorption (dotted) line features are shown.
but with no significant redshift evolution over the redshift range $2.5 < z < 5.0$, consistent with results from simulations. The authors also found that the stellar mass-metallicity relation evolves to higher metallicity at a given stellar mass by 0.6 dex from $\langle z \rangle = 3.5$ to $z = 0$. Another key science goal for VANDELS was the investigation of the star-formation histories and quenching of massive quiescent galaxies. Due to the large sample size of quiescent galaxy targets in VANDELS, full spectroscopic fitting was able to be performed on a mass-complete sample at $z > 1$ in Carnall et al. (2019a). This work showed clear signatures of downsizing within the quiescent population, and enabled detailed analysis of the formation and quenching timescales of the quiescent population at these redshifts.

### 2.3.2 The LEGA–C spectroscopic survey

The Large Early Galaxy Census (LEGA–C, van der Wel et al., 2016) is a large, deep ESO Public Spectroscopic Survey, with the goal of obtaining kinematic and stellar population properties of $\sim 3000$ $K$–band selected galaxies over the redshift range $0.6 \leq z \leq 1$. The third and final data release of LEGA–C (van der Wel et al., 2021) contained 3528 spectra with measured velocity dispersions and stellar population properties.

![Figure 2.9](image.png)

**Figure 2.9** *Left:* Mask design for an example LEGA–C pointing. *Right:* All 32 pointings over the complete survey area, taken from van der Wel et al. (2016). In both panels, the red points are filler targets.

Observations were conducted with the VIMOS spectrograph on the VLT, using the high-resolution grating combined with the GG475 order separation filter,
providing a typical observed wavelength range of 6300 - 8800 Å, with a resolution of $R \simeq 2500$ and a dispersion of 0.6 pix/Å. The whole survey area covered 1.6 sq. degrees of the UltraVISTA footprint (McCracken et al., 2012) in the COSMOS field.

**LEGA-C targets**

The primary parent sample of LEGA–C galaxies was drawn from a $K$–band selected catalogue of targets from the UltraVISTA survey with targets selected to have photometric redshifts of $0.6 < z < 1.0$ (Muzzin et al., 2013a). Spectroscopic targets were selected using a moving $K$–band magnitude limit, ranging from $K < 21.08$ at $z = 0.6$ to $K < 20.36$ at $z = 1.0$. These $K$–band magnitude criteria resulted in a stellar-mass limit of $\log_{10}(M_*/M_\odot) > 10$, and the final sample is dominated by galaxies within a stellar mass range of $10.5 < \log_{10}(M_*/M_\odot) < 11.0$.

Due to the way that the LEGA–C galaxies were selected, a number of biases are introduced. Most importantly, brighter galaxies from the parent sample are preferentially selected for slit observations, and so the probability that a galaxy is included in the survey depends on its $K$–band magnitude. To ensure that the survey presented a statistically representative sample of the galaxy population at these epochs, the LEGA–C team introduce a correction factor in the catalogue to account for this bias.

**Science goals of the LEGA–C survey**

The LEGA–C dataset produced high-resolution spectroscopy for $> 3000$ galaxies at $0.6 < z < 1.0$, with SNR $> 10$ Å per resolution element. A key goal of the LEGA-C survey was to exploit the high-SNR, high-resolution spectra to enable accurate measurements of spectroscopic absorption and emission line strengths, stellar and gas velocity dispersions, and emission line fluxes and equivalent widths.

This was crucial in understanding the physical properties of galaxies at large look-back times; the strength of Balmer absorption features can indicate the underlying physical mechanisms whereby galaxies quench star-formation; e.g. through AGN feedback (see Section 1.2.6). Stellar metallicities derived from iron and magnesium absorption lines constrain the metal content of the stellar population, and structural parameter measurements can provide a detailed investigation into
the evolution of galaxy scaling relations.

**Key science results from LEGA−C**

The LEGA−C survey was the final public spectroscopic survey to be completed with the now-retired VIMOS spectrograph. This survey, whose observations were carried out over the period of December 2014 to March 2018, has produced a number of scientific results which have enhanced our understanding of galaxies at intermediate redshifts. In Wu et al. (2018b) and Barone et al. (2022), ages of quiescent galaxies were found to have a correlation with galaxy size, demonstrating that smaller galaxies are older than larger galaxies at a fixed stellar mass. The high signal-to-noise and high resolution of the spectroscopy from LEGA−C has enabled detailed spectral fitting of quiescent galaxies, providing the capability to measure robust metallicities, and Beverage et al. (2021) find that older quiescent galaxies have lower stellar metallicities than their younger counterparts. These studies have inspired the work which is presented in Chapter 3 of this thesis, where I use the LEGA−C and VANDELS samples to analyse the relationships between size, age and metallicity in the quiescent galaxy population.

In VANDELS, of the 281 quiescent galaxies randomly assigned slits, 269 of those had robust spectroscopic redshifts. These objects were given redshift quality flags of flag 3 or 4 in the VANDELS catalogues, corresponding to 99% probability of being correct. For LEGA-C, the success rate of measuring desired spectroscopic quantities was 97%.

### 2.4 BAGPIPES

In Chapter 1, I introduced the concept of fitting the spectral energy distributions of galaxies in order to obtain meaningful information about their stellar populations. Throughout this thesis, I have made use of the Bayesian Analysis of Galaxies for Physical Inference and Parameter EStimation (BAGPIPES) fitting code (Carnall et al., 2018) to produce the results presented in the next three chapters. BAGPIPES is a Python-based code and possesses the ability to fit spectroscopy and photometry simultaneously within a Bayesian inference framework (see Section 2.4.5). BAGPIPES is also able to sample a wide range of parameter space by using the nested-sampling algorithm MULTINEST (Feroz
For a more detailed description of the Bagpipes SED fitting code, I refer the reader to Carnall et al. (2018) and Carnall et al. (2019b), however, I include a brief summary of the key concepts below.

2.4.1 Stellar population models

Bagpipes incorporates a set of pre-defined stellar population synthesis models generated from the updated 2016 version of the Bruzual & Charlot (2003) (BC03) SPS models. By default, these SPS models include the Medium-resolution Isaac Newton Telescope Library of Empirical Spectra (MILES Falcón-Barroso et al., 2011) which cover a wavelength range of 3450 – 7350 Å. These models are implemented in Bagpipes using a Kroupa (2001) initial mass function (IMF), although Bagpipes has the option to use different IMFs to construct the SPS models.

2.4.2 Modelling dust and IGM attenuation

In the Bagpipes code, the impact of dust attenuation is implemented by calculating the absolute attenuation curve. In galaxies, dust is generally revealed by two effects. It produces emission in the mid/far-infrared part of the spectrum consisting of continuum plus emission and absorption features and also modifies the light from the stellar continuum at all wavelengths. At shorter wavelengths, particularly in the UV/optical regime, attenuation is stronger than at longer wavelengths and so the light from dust-attenuated objects appears redder. This wavelength dependence is defined by

\[ A_\lambda = -2.5 \log_{10}(T_\lambda) \]  

where \( A_\lambda \) is the total attenuation in magnitudes at wavelength, \( \lambda \), and \( T_\lambda \) is the fraction of light transmitted:

\[ T_\lambda = \frac{f_{\lambda}^{\text{obs}}}{f_{\lambda}^{\text{int}}} \]  

The attenuation as a function of \( \lambda \) is defined by the attenuation curve \( A_\lambda/A_V \) and Bagpipes currently implements the Calzetti et al. (2000) dust law for starburst...
galaxies, the Cardelli et al. (1989) Milky Way law, the Charlot & Fall (2000) flexible dust model, the SMC law from Gordon et al. (2003) and the Salim et al. (2018) dust attenuation law. In each case, the normalisation of the dust curve is set relative to the attenuation at 5500 Å.

In Chapters 4 and 5 of this thesis, I make use of the flexible Salim et al. (2018) dust attenuation law, which uses a power-law deviation from the Calzetti et al. (2000) curve to model a wide range of potential dust curves. Additionally, the dust emission models within BAGPIPES are from Draine & Li (2007).

In a similar fashion, attenuation from the IGM is accounted for using the Inoue et al. (2014) model, which is an updated version of the Madau (1995) model. This is calculated for rest-frame wavelengths between $911.8 < \lambda < 1215.7$ Å and the IGM transmission function is assumed to be $T_{IGM} = 0$ below the lower wavelength limit.

### 2.4.3 Nebular emission

In galaxies, particularly young star-forming galaxies, the gas within star-forming regions is heated via photo-ionizing radiation from the stars which excites elements in the gas through photo-excitation or collisions. As the electrons in the excited atoms fall back to the ground state, radiation is released and observed as emission lines.

In BAGPIPES, the nebular-emission model follows the Byler et al. (2017) method, based on the CLOUDY photo-ionization code (Ferland et al., 2017a). CLOUDY is run using pre-computed BC03 Bruzual & Charlot (2003) SSP models as the input spectrum, and varying the ionization parameter, $U$. The (dimensionless) ionization parameter for hydrogen is defined as the ratio of the ionizing photon flux $Q_H$ to the density of hydrogen gas:

$$U = \frac{Q_H}{4\pi r_s^2 n_H c} \quad (2.8)$$

where $n_H$ is the number density of hydrogen atoms, $r_s$ is the radius of the Strömgren sphere and the speed of light, $c$ is introduced to make $U$ dimensionless (see Kewley et al., 2019). The nebular emission is modelled to be the sum of emission from spherical-shell HII regions of varying ages and the metallicity of the ionized gas is assumed to be the same as the stellar metallicity (calculated
from the stars producing the ionizing photons), which is then scaled relative to Solar. In this thesis, I use a constant value of \( \log_{10}(U) = -3 \) which is consistent with values from Kennicutt & Evans (2012) (see Carnall et al., 2018, for details).

### 2.4.4 Star-formation history models

By default, Bagpipes adopts a parametric model for star-formation histories. Possible star-formation history parameterisations consist of burst, constant, log-normal, exponential, delayed-tau and double-power law. It is also possible to input a custom star-formation history as a component in Bagpipes. Throughout this thesis I use a double-power law star-formation history, the parametric form of which is:

\[
SFR(t) \propto \left[ \left( \frac{t}{\tau} \right)^{\alpha} + \left( \frac{t}{\tau} \right)^{-\beta} \right]^{-1} \tag{2.9}
\]

where \( \alpha \) and \( \beta \) define the rising and falling slope respectively, and \( \tau \) is related to (but not the same as) the time of the peak SFR. The double-power law has been shown to accurately model passive galaxy SFHs as described in Section 1.4.4.

### 2.4.5 Model fitting in Bagpipes

Bagpipes uses Bayesian inference methods which rely on Bayes theorem. The theorem relies on defining a likelihood function, along with a prior function in order to calculate the posterior distribution of model parameters. Bagpipes uses the MultiNest (Feroz & Hobson, 2008; Feroz et al., 2009) nested sampling algorithm to obtain posterior distributions and evidence values given a specific model and prior distribution, which allows for efficient exploration of parameter spaces. To calculate the posterior distribution, MultiNest computes the evidence, which is a multidimensional integral over all the model parameters of the prior multiplied by the likelihood. The evidence factor normalises the posterior of the parameter space, and can be used to robustly obtain a ratio of probabilities for two or more models given some observational data. With this information, MultiNest then updates the parameter values to obtain a posterior probability distribution for the parameter. The resulting posterior distribution is post-processed by Bagpipes to return the posterior model spectrum and other
information such as the SFH and physical properties such as stellar masses and metallicities. An example Bagpipes fit to a galaxy in the VANDELS quiescent sample is shown in Fig. 2.10, and the posterior distributions are shown in orange in both panels.

2.5 GALFIT

A fundamental way to characterise the morphology of a galaxy is through its surface-brightness profile (de Vaucouleurs, 1948); disks have surface-brightness profiles which are close to exponential, whereas the light profile of bulges are often described by a de Vaucouleurs profile; \( I \propto r^{1/4} \). However, this is filter dependent; physically, both the size and morphology of a galaxy can change as a function of rest-frame wavelength (e.g. see Suess et al., 2022). With this caveat in mind, parametric fitting of galaxy light profiles has become important in understanding the structural properties of galaxies.

Typically, galaxy light profiles are defined by a Sérsic function, where the
The Sérsic function for a range of Sérsic indices, where $R_e$ and $b_n$ are fixed values Peng et al. (2010).

Luminosity profile goes as:

$$I(r) = I_e \left(-b_n \left[ \left(\frac{r}{R_e}\right)^{1/n} - 1 \right]\right)$$  \hspace{1cm} (2.10)

where $I(r)$ is the surface brightness at a given radius $r$, $R_e$ is the effective radius, $n$ is the Sérsic index, which controls the shape of the galaxy light profile and $I_e$ is the intensity at $R_e$. The Sérsic-dependent coefficient $b_n$ is calculated such that the light within $R_e$ is equal to half the integrated light and $R_e = R_{50}$ (the half-light radius). To a good approximation, one finds $b_n \approx 1.999n - 0.327$. For $n = 4$, the surface-brightness profile represents the de Vaucouleurs profile, and at $n = 1$, the exponential profile is obtained. Higher values of $n$ describe more concentrated light profiles (see Fig. 2.11).

Throughout this thesis I measure galaxy sizes and Sérsic indices using the Galfit program (Peng et al., 2002). Galfit is a two-dimensional fitting algorithm designed to extract structural parameters from galaxy images by modelling their light profiles. The code requires an image cutout centred on the object to be fitted, a point-spread function, a weight map and an (optional) image mask which masks out neighbouring objects depending on their brightness and distance to the
central object. GALFIT determines the best fit through the use of the Levenberg-Marquardt least-squares algorithm, computing the goodness of fit by calculating $\chi^2$ and adjusting the model parameters for the next iteration, until the $\chi^2$ reaches the global minimum.

Although GALFIT provides the functionality for fitting with different types of radial profiles (e.g. Gaussian, Moffat, Nuker), in this thesis I only make use of the single Sérsic profile, an example of which is shown in Fig. 2.12 for one of the objects in the PRIMER sample detailed in Chapter 5. For a single Sérsic profile, the fitting parameters consist of the central position of the object $(x,y)$, the integrated magnitude, Sérsic index $(n)$, axis ratio $(b/a$, the ratio of the semi-minor to semi-major axis), position angle and half-light radius which is measured along the major axis of the object.

![Figure 2.12](image-url)  

**Figure 2.12** Example of a single Sérsic fit using GALFIT for one of the quiescent galaxies in PRIMER, showing the data (left), best-fit model (middle) and residual (right) images. The fitting region is 200 x 200 pixels which is equivalent to 6$''$ on the sky (for a pixel scale of 0.03$''$/pix).
Chapter 3

The evolution of massive quiescent galaxies from $z = 0.6$ to $z = 1.3$

*The material in this chapter was originally published in Hamadouche et al. (2022).*

3.1 Introduction

The formation and quenching of quiescent galaxies is still one of the most debated subjects in extra-galactic astronomy. However, the last 20 years has undoubtedly seen major progress, as a result of ever-expanding and increasingly deep photometric and spectroscopic surveys, such as the Sloan Digital Sky Survey (SDSS; York et al., 2000), zCOSMOS (Lilly et al., 2007), the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al., 2007) and the Cosmic Assembly Near-Infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al., 2011; Koekemoer et al., 2011).

One of the key foundational results that shapes the understanding of galaxy evolution is the galaxy colour bimodality. First quantified in detail using SDSS data in the early 2000s (e.g. Strateva et al. 2001; Baldry et al. 2004), two distinct sub-populations of galaxies were identified. These are commonly referred to as the “red sequence” of quiescent galaxies and “blue cloud” of star-forming galaxies. These two populations are bridged by a smaller number of galaxies in transition
between the blue cloud and red sequence, widely referred to as “green valley”
galaxies. The observation of this sharp divide in the local Universe naturally led
to questions as to when and why galaxies transition to the red sequence.

More recently, deep spectroscopic studies have firmly established that quiescent
galaxies, as well as the colour bimodality, already exist at least as early as redshift, 
\( z \sim 3 \) (e.g. Cimatti et al. 2002; Abraham et al. 2004; Halliday et al. 2008,
Schreiber et al. 2018). However, photometric studies of the galaxy stellar-mass 
function (GSMF) have demonstrated that quiescent galaxy number densities have 
risen rapidly since this time, with quiescent galaxies making up less than 10 per 
cent of the total mass budget at \( z = 3 \), rising to around 75 per cent at \( z = 0 \) (e.g.
Fontana et al. 2006; Muzzin et al. 2013a; Davidzon et al. 2017; McLeod et al.
2021; Santini et al. 2021).

The existence of the colour bimodality across the majority of cosmic history,
coupled with the mass dominance of quiescent galaxies at late times, has 
firmly established quenching as one of the key questions in galaxy evolution 
(e.g. Peng et al., 2010; Somerville & Davé, 2015a). However, despite the 
expanding observational capabilities, it has proven challenging to clearly identify 
the key processes responsible for quenching, and whether their relative importance 
changes as a function of redshift.

A wide range of different potential quenching mechanisms have been discussed in 
the literature. Mechanisms that are directly linked to the internal processes of a 
galaxy (e.g. quasar-mode and radio-mode AGN feedback) are often characterised 
as “internal” or “mass” quenching mechanisms (e.g. Croton et al., 2006; Choi 
et al., 2018). In contrast, mechanisms associated with galaxy-galaxy interaction 
(e.g. mergers, harassment), or interaction between a galaxy and the intracluster 
medium (e.g. ram pressure stripping) are typically described as “environmental” 
or “satellite” quenching.

To understand how these processes each contribute to galaxy quenching, much 
effort has been invested in characterising the physical properties of quiescent 
galaxies across cosmic time, and how these differ from those of star-forming 
galaxies. One of the most critical results, again derived from SDSS data, was 
the discovery that local quiescent galaxies follow a steeper relationship between 
stellar mass and size than local star-forming galaxies, and that, at stellar masses 
\( \log_{10}(M_*/M_\odot) \leq 11 \), quiescent galaxies are smaller than their star-forming 
counterparts (Shen et al., 2003).
Motivated by this, significant progress has been made using deep optical and near-infrared imaging surveys to characterise the relationship between the sizes and stellar masses of both quiescent and star-forming galaxies out to high redshifts (e.g. Daddi et al., 2005; Trujillo et al., 2006; Wu et al., 2018b; Mowla et al., 2019; Suess et al., 2019a,b; Nedkova et al., 2021). These studies have demonstrated that different mass-size relations for quiescent and star-forming galaxies were already in place by $z \sim 3$. In addition, significant growth is observed in the average sizes of quiescent galaxies over time, increasing by a factor of $\sim 2.5$ between $z \simeq 1.5$ and $z = 0$ (e.g. McLure et al., 2013; van der Wel et al., 2014).

It is tempting to interpret increasing average sizes for the quiescent population simply as evidence for the size growth of individual quiescent galaxies, usually assumed to be the result of merger events. However, the situation is complicated by recently quenched star-forming galaxies continuing to arrive on the red sequence over time. As star-forming galaxies are, on average, larger than quiescent galaxies, the addition of these new galaxies to the quiescent population could also plausibly explain this effect (e.g. Belli et al., 2015). Issues of this nature when comparing similarly selected galaxy samples at different redshifts are commonly referred to as “progenitor bias” (e.g. van Dokkum & Franx, 1996).

Because of the challenges introduced by progenitor bias, a variety of more sophisticated methods have been developed to evolve high-redshift galaxy samples down to the local Universe, with the aspiration of defining evolutionary tracks connecting progenitors and descendants (e.g. Zheng et al., 2007; van Dokkum et al., 2010; Cimatti et al., 2012; Shankar et al., 2015; Belli et al., 2019a; Carnall et al., 2019a; Tacchella et al., 2021). A key parameter that can be introduced to break degeneracies in such analyses is the age of a galaxy’s stellar population, or more generally its star-formation history (SFH; e.g. Carnall et al. 2019a, Leja et al. 2019a).

Historically, attempts to constrain the ages of quiescent galaxies have tended to focus on specific spectral features, such as D$_n$4000 and the H$\delta$ equivalent width (e.g. Balogh et al., 1999a; Kauffmann et al., 2003). At $z < 1$, many studies have reported a positive correlation between D$_n$4000 and stellar mass (e.g. Brinchmann et al., 2004; Moresco et al., 2010, 2011, 2016; Haines et al., 2017; Siudek et al., 2017; Kim et al., 2018; Wu et al., 2018a). This has been widely associated with the “downsizing” trend, in which the stellar populations of more massive galaxies formed earlier in cosmic history, with present-day star formation concentrated in lower-mass galaxies (e.g. Cowie et al., 1996; Thomas et al., 2005b).
Recently, the increasing availability of large, representative, spectroscopic samples at intermediate redshifts has facilitated analyses probing how size, age and stellar mass interrelate within the quiescent population. This has been partially motivated by earlier studies, spanning $z = 0 - 2$, that suggest larger galaxies tend to be younger than smaller galaxies within the quiescent population (e.g. van der Wel et al., 2014; Belli et al., 2015; Gargiulo et al., 2017).

At $z \sim 0.7$, Wu et al. (2018b) report a study of $D_n4000$ and H$\delta$ gradients across the stellar mass-size plane for a sample of $\sim$400 H$\beta$-selected quiescent galaxies from the Large Early Galaxy Astrophysics Census (LEGA-C). At fixed mass, a negative correlation is found between $D_n4000$ and size, suggesting that larger galaxies are younger than their smaller counterparts. If confirmed, this result provides an opportunity to quantify progenitor bias within the quiescent population, and hence disentangle this effect from the merger-driven size growth of older galaxies post-quenching.

However, it is also well known that $D_n4000$ has a significant secondary dependence on stellar metallicity (e.g. Bruzual & Charlot, 2003). Recently, Barone et al. (2018, 2022) and Beverage et al. (2021) have reported no correlation between age and size at fixed stellar mass, instead suggesting that the observed correlation between $D_n4000$ and size is driven by a positive correlation between metallicity and the ratio of stellar mass to radius, acting as a proxy for the depth of a galaxy’s gravitational potential well.

Given this renewed discussion in the recent literature regarding the evolution of the quiescent galaxy population on the stellar mass-size plane, in this work I aim to improve our understanding by exploiting the combined statistical power provided by two recently completed surveys: VANDELS (McLure et al., 2018b; Pentericci et al., 2018; Garilli et al., 2021) and LEGA-C (van der Wel et al., 2016, 2021; Straatman et al., 2018). These surveys provide ultra-deep spectroscopy for large, representative samples of quiescent galaxies, and I use them to construct mass-complete subsamples with $\log_{10}(M_*/M_\odot) \geq 10.3$, spanning redshift ranges from $0.6 < z < 0.8$ and $1.0 < z < 1.3$ for LEGA-C and VANDELS, respectively.

I begin by studying the relationship between $D_n4000$ and stellar mass via these new large spectroscopic samples. In particular, VANDELS provides the opportunity to confirm whether the clear $D_n4000$-mass trend seen at lower redshifts was already in place by $z \gtrsim 1$. I then examine how size correlates with $D_n4000$ at fixed mass, and attempt to assess the relative contributions of age and
metallicity to any size-$D_n4000$ trend. Finally, I discuss the level of progenitor bias and merger activity from $z \sim 1.1$ to $z \sim 0.7$, using a simple toy model to explain the observed evolution.

The structure of this chapter is as follows. I first give details of the VANDELS and LEGA-C datasets in Section 3.2. I then describe the sample selection and fitting methods in Section 3.3. I outline my results describing the correlations between size, $D_n4000$ and stellar mass in Section 3.4, then discuss these results in Section 3.5. I summarise my conclusions in Section 3.6. All magnitudes are quoted in the AB system, and throughout the chapter I use cosmological parameters $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$. I assume a Kroupa (2001) initial mass function.

3.2 DATA

3.2.1 The VANDELS spectroscopic survey

The VANDELS ESO Public Spectroscopic survey (McLure et al., 2018b; Pentericci et al., 2018; Garilli et al., 2021) is an ultra-deep, medium-resolution, optical spectroscopic survey, targeting the Chandra Deep Field South (CDFS) and Ultra Deep Survey (UDS) fields. Data were obtained using the Visible Multi-Object Spectrograph (VIMOS; Le Fèvre et al., 2004) on the ESO Very Large Telescope (VLT). The final VANDELS data release (DR4; Garilli et al. 2021) provides spectroscopy for $\sim2100$ galaxies in the high-redshift Universe. VANDELS primarily targeted star-forming galaxies at $z > 2.4$ and massive quiescent galaxies at $1.0 \leq z \leq 2.5$, with quiescent galaxies making up 13 per cent of the final sample. In total, the survey covers an area of $0.2 \text{ deg}^2$.

VANDELS Photometric Catalogues and selection criteria

The galaxies observed by VANDELS were drawn from four separate photometric catalogues, spanning a UV-NIR wavelength range from 0.3–5 $\mu$m. In the central regions of the CDFS and UDS fields, which benefit from CANDELS $HST$ imaging, I make use of the catalogues produced by the CANDELS team (Galametz et al., 2013; Guo et al., 2013). Two further custom ground-based photometric catalogues were produced by McLure et al. (2018b), covering the
areas immediately surrounding the CANDELS footprints.

The VANDELS parent quiescent sample was selected from these photometric catalogues as follows. Objects were required to have $1.0 \leq z_{\text{phot}} \leq 2.5$, as well as $i$-band magnitudes of $i < 25$, and $H$-band magnitudes of $H \leq 22.5$, corresponding to stellar masses of $\log_{10}(M_*/M_\odot) \gtrsim 10$ (McLure et al., 2018b). Quiescent objects were then selected via additional rest-frame $UVJ$ magnitude criteria (e.g. Williams et al., 2009). In summary, the VANDELS parent quiescent sample was selected by:

- $1.0 < z_{\text{phot}} < 2.5$
- $H < 22.5$
- $i < 25$
- $U - V > 0.88 \times (V - J) + 0.49$
- $U - V > 1.3$
- $V - J < 1.6$

These criteria produce a parent sample of 812 galaxies, of which approximately one third were observed as part of VANDELS.

**VANDELS spectroscopic observations**

In this section, I briefly summarise the VANDELS spectroscopic observations. I refer readers to Pentericci et al. (2018) for the full description. From the parent sample of 812 quiescent galaxies (see Section 3.2.1), 281 were randomly assigned slits and observed. Observations were made using the MR grism, which provides a resolution of $R \sim 600$ over a wavelength range from 4800$-$10000 Å. All objects were observed for 20, 40 or 80 hours to obtain SNRs of 15$-$20 per resolution element ($\sim 10$ Å) in the $i$-band. Spectroscopic redshifts, $z_{\text{spec}}$, were measured by the VANDELS team, with redshift quality flags assigned as described in Pentericci et al. (2018). In this work, I use spectra from the VANDELS DR4 final data release (Garilli et al., 2021) and consider only those objects with robust spectroscopic redshifts (i.e quality flags 3 and 4, corresponding to a $\simeq 99$ per cent probability of being correct). This produces an initial sample of 269 galaxies, of which 235 have $z_{\text{spec}} < 1.5$. 

84
3.2.2 The LEGA-C spectroscopic survey

The Large Early Galaxy Astrophysics Census (LEGA-C) is also an ESO Public Spectroscopy Survey, making use of VIMOS on the VLT. The full survey provides high-quality spectra for a primary sample of $\sim 3000$ galaxies between $0.6 \leq z \leq 1.0$, drawn from a $\sim 1.3$ deg$^2$ area within the UltraVISTA (McCracken et al., 2012) footprint in the COSMOS field. A full description of the survey design and data reduction can be found in van der Wel et al. (2016) and Straatman et al. (2018).

LEGA-C photometric catalogues and parent sample

The LEGA-C primary spectroscopic sample is drawn from a parent photometric sample of $\sim 10,000$ galaxies. This parent sample was selected from the UltraVISTA DR1 catalogue of Muzzin et al. (2013a) as follows. Galaxies were first selected to have $0.6 < z < 1.0$, using spectroscopic redshifts where available (primarily from zCOSMOS), or otherwise photometric redshifts measured by Muzzin et al. (2013a). A redshift-dependent $K_s$-band magnitude limit was then applied, ranging from $K_s < 21.08$ at $z = 0.6$, to $K_s < 20.7$ at $z = 0.8$, to $K_s < 20.36$ at $z = 1.0$. This ensures that galaxies in the LEGA-C sample are sufficiently bright in the observed spectroscopic wavelength range, from $\sim 0.6 - 0.9 \mu m$.

LEGA-C spectroscopic observations

All LEGA-C observations were carried out using the high-resolution (HR-Red) grism, covering a typical wavelength range of $\simeq 6000 - 9000$ Å at a spectral resolution of $R \sim 3500$. Each galaxy received $\sim 20$ hours of integration time, resulting in an average continuum SNR of $\sim 20 \AA^{-1}$. The second data release (DR2) consists of 1988 spectra, including 1550 primary targets drawn from the parent sample described in Section 3.2.2. In this work, I make use of the LEGA-C DR2 one-dimensional spectra, as well as $D_n4000$ measurements, sizes and spectroscopic redshifts. The LEGA-C team prioritise spectroscopic targets by $K_s$-band magnitude, introducing an individual, $K_s$-band-magnitude-dependent sample completeness correction factor, $S_{\text{cor}}$, for each object. I account for this by calculating LEGA-C median quantities weighted by these $S_{\text{cor}}$ values throughout
Table 3.1  Details of the parameter ranges and priors adopted for the Bagpipes fitting of both the VANDELS and LEGA-C photometry. Priors listed as logarithmic are uniform in log-base-ten of the parameter.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Symbol / Unit</th>
<th>Range</th>
<th>Prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>Redshift</td>
<td>$z_{\text{spec}}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SFH</td>
<td>Stellar mass formed</td>
<td>$M_*/M_\odot$</td>
<td>$(1, 10^{13})$</td>
<td>log</td>
</tr>
<tr>
<td></td>
<td>Metallicity</td>
<td>$Z_*/Z_\odot$</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Falling slope</td>
<td>$\alpha$</td>
<td>$(0.1, 10^{3})$</td>
<td>log</td>
</tr>
<tr>
<td></td>
<td>Rising slope</td>
<td>$\beta$</td>
<td>$(0.1, 10^{3})$</td>
<td>log</td>
</tr>
<tr>
<td></td>
<td>Peak time</td>
<td>$\tau$/ Gyr</td>
<td>$(0.1, t_{\text{obs}})$</td>
<td>uniform</td>
</tr>
<tr>
<td>Dust</td>
<td>Attenuation at 5500Å</td>
<td>$A_V$/ mag</td>
<td>$(0, 4)$</td>
<td>uniform</td>
</tr>
</tbody>
</table>

my analysis. For full details of the LEGA-C spectroscopic observations, I refer the reader to Straatman et al. (2018).

### 3.3 Method and sample selection

#### 3.3.1 Selection of a mass-complete sample from VANDELS

To construct a mass-complete sample for the analysis, I begin by fitting the available photometric data for the 269 quiescent galaxies with robust spectroscopic redshifts in VANDELS DR4 (see Section 3.2.1), to obtain stellar masses and UVJ colours. I use the Bagpipes code (Carnall et al., 2018), with the 2016 updated version of the Bruzual & Charlot 2003 (BC03) stellar-population-synthesis models (BC16, see Chevallard & Charlot, 2016). I adopt the double-power-law SFH model described in Carnall et al. (2020b), the Calzetti et al. (2000) dust attenuation law, and fixed Solar metallicity for consistency with previous studies (I assume Solar metallicity, $Z_\odot = 0.02$). Details of the parameter ranges and priors used are presented in Table 5.1.

I first impose stricter UVJ criteria using the Bagpipes colours, requiring $U - V > 0.88 \times (V - J) + 0.69$. This criterion has been shown to consistently select objects with sSFRs less than $0.2 t_H^1$ (Carnall et al., 2018, 2019a), where $t_H$
Figure 3.1 The distribution of the mass-complete \((\log_{10}(M_*/M_\odot) > 10.3)\) quiescent galaxy samples on the \(UVJ\) plane, using rest-frame colours from BAGPIPES (Carnall et al., 2018), colour-coded by \(D_n4000\). The VANDELS sample is shown in the left-hand panel, and consists of 137 galaxies (see Section 3.3.1). The 272 LEGA-C galaxies with \(D_n4000\) values are shown in the main part of the right-hand panel, whilst the 105 LEGA-C galaxies without \(D_n4000\) values are shown in the inset (see Section 3.3.2). There is a noticeable trend between \(UVJ\) colour and \(D_n4000\), with galaxies displaying larger \(D_n4000\) values at redder colours.
is the age of the Universe, a widely applied criterion for quiescent galaxy selection (e.g. Pacifici et al. 2016). A total of 209 objects meet this UVJ criterion.

The VANDELS quiescent sample is not mass-complete across the whole redshift range from $1.0 < z < 2.5$, and I therefore impose further spectroscopic-redshift and stellar-mass limits to define a mass-complete subsample. This means that, for a sample of galaxies randomly drawn from the parent photometric catalogue, the spectroscopic sample provides an accurate representation of the quiescent galaxy population within these redshift and stellar-mass ranges. Following Carnall et al. (2019a), I select only objects with redshifts $1.0 \leq z_{\text{spec}} \leq 1.3$ and stellar masses $\log_{10}(M_*/M_\odot) \geq 10.3$ (see their section 3). This narrows the VANDELS sample down to 138 objects.

In summary, the mass-complete VANDELS sample is selected by:

- $U - V > 0.88 \times (V - J) + 0.69$
- $U - V > 1.3$
- $V - J < 1.6$
- $1.0 \leq z_{\text{spec}} \leq 1.3$
- $\log_{10}(M_*/M_\odot) \geq 10.3$

I finally visually inspect the VANDELS spectra, and remove one further object for which the spectrum is highly contaminated. The final mass-complete sample therefore consists of 137 galaxies. These are shown on the UVJ diagram in the left-hand panel of Fig. 3.1.

### 3.3.2 Selection of a mass-complete sample from LEGA-C

In order to define the final mass-complete LEGA-C quiescent sample, I begin with the 1550 primary objects of the LEGA-C DR2 release (see Section 3.2.2). I first exclude objects flagged by the LEGA-C team as having flawed spectra or unreliable redshift measurements. This produced an initial sample of 1212 star-forming and quiescent galaxies between $0.6 < z < 1.0$.

To generate stellar masses and UVJ colours for the LEGA-C galaxies, I use photometry from the updated UltraVISTA DR2 catalogue of Laigle et al. (2016).
I cross-match the 1212 LEGA-C galaxies with the Laigle et al. (2016) catalogue, finding 1165 matches. I again fit the photometry with Bagpipes, using the same approach described in Section 3.3.1. The stellar masses generated by Bagpipes are fully consistent with the masses calculated by the LEGA-C team based on FAST (Kriek et al., 2009a), as well as the Laigle et al. (2016) masses based on LePhare (Arnouts et al., 1999; Ilbert et al., 2006).

At this point I restricted the redshift range of the LEGA-C sample to $0.6 \leq z \leq 0.8$, meaning that both the VANDELS and LEGA-C samples span similar, $\sim 1$ Gyr, periods of cosmic time. This both limits the amount of evolution taking place within each sample, as well as maximising the time interval between the two samples. LEGA-C is mass complete down to $\log_{10}(M/\text{M}_\odot) \sim 10$, however I impose a slightly higher mass cut to facilitate direct comparisons with the VANDELS sample, again requiring $\log_{10}(M/\text{M}_\odot) \geq 10.3$. These two criteria reduce the sample to 656 star-forming and quiescent galaxies. I then apply the same UVJ selection criteria as described in Section 3.3.1, resulting in a LEGA-C quiescent sample of 377 galaxies. These are shown in the right-hand panel of Fig. 3.1.

Due to the truncation of some LEGA-C spectra at the red end, not all LEGA-C galaxies have $D_n4000$ measurements in the DR2 catalogue. From the sample of 377 objects, 272 galaxies have measurable $D_n4000$ values. One further object has an extremely large uncertainty on $D_n4000$, and is therefore excluded from my analysis. In addition, I remove three galaxies for which reliable sizes could not be obtained with Galfit (see Section 3.3.3), resulting in a final LEGA-C sample of 268 quiescent galaxies with both size and $D_n4000$ information.
Table 3.2  Column one lists the stellar mass range spanned by the three bins employed in Fig. 3.2 and Fig. 3.3. Column two lists the number of VANDELS objects in each bin and column three lists their median stellar mass. Columns four and five list the median $D_n4000$ values for objects in each bin, and the $D_n4000$ values measured from the stacked spectra generated for objects in each bin, respectively. Columns 9 – 12 list the corresponding information for the LEGA-C sample.

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>VANDELS</th>
<th></th>
<th></th>
<th>LEGA-C</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>$\log_{10}(M_*/M_\odot)$</td>
<td>$D_n4000_{\text{med}}$</td>
<td>$D_n4000_{\text{stack}}$</td>
<td>N</td>
<td>$\log_{10}(M_*/M_\odot)$</td>
<td>$D_n4000_{\text{med}}$</td>
<td>$D_n4000_{\text{stack}}$</td>
</tr>
<tr>
<td>$10.3 &lt; \log_{10}(M_*/M_\odot) &lt; 10.7$</td>
<td>46</td>
<td>10.51 ± 0.02</td>
<td>1.52 ± 0.03</td>
<td>1.54 ± 0.01</td>
<td>52</td>
<td>10.57 ± 0.02</td>
<td>1.60 ± 0.02</td>
<td>1.60 ± 0.01</td>
</tr>
<tr>
<td>$10.7 &lt; \log_{10}(M_*/M_\odot) &lt; 11.1$</td>
<td>69</td>
<td>10.90 ± 0.02</td>
<td>1.59 ± 0.02</td>
<td>1.60 ± 0.01</td>
<td>125</td>
<td>10.86 ± 0.01</td>
<td>1.66 ± 0.01</td>
<td>1.64 ± 0.01</td>
</tr>
<tr>
<td>$11.1 &lt; \log_{10}(M_*/M_\odot) &lt; 11.5$</td>
<td>22</td>
<td>11.21 ± 0.03</td>
<td>1.62 ± 0.04</td>
<td>1.62 ± 0.01</td>
<td>87</td>
<td>11.26 ± 0.01</td>
<td>1.72 ± 0.02</td>
<td>1.72 ± 0.01</td>
</tr>
</tbody>
</table>
3.3.3 Measuring galaxy sizes

Size measurements for the final sample of VANDELS quiescent galaxies were derived from single Sérsic fitting of their two-dimensional light profiles using Galfit (Peng et al., 2002). Within the CANDELS footprint, I use HST F160W imaging for both UDS and CDFS objects. Outside the CANDELS footprints, in CDFS I use HST ACS F850LP imaging, and in UDS I use ground-based $H$-band imaging from UKIDSS.

For the HST imaging, the Sérsic index ($n$), effective radius ($r_e$), axis ratio, magnitude and position angle are left as free parameters. For the objects I fitted using the UKIDSS ground-based imaging, I find that the spatial resolution of the $H$-band data is not good enough to confidently constrain the Sérsic index, and I instead assume a constant value of $n = 2.5$ during the fitting process. The rest of the parameters are left free. This results in robust sizes measured for all 137 galaxies in the VANDELS sample.

I cross-check my size measurements against the results of van der Wel et al. (2012, 2014) for common objects, finding good agreement (within ±0.1 dex). In addition, I internally cross-compare the results I obtain for galaxies in each of the four input VANDELS catalogues, demonstrating that the different imaging datasets I employ for size measurement produce consistent results.

For the LEGA-C galaxies, I use the Galfit size information provided by the LEGA-C team as part of the DR2 release. These are derived using the methods described in van der Wel et al. (2012) and van der Wel et al. (2016), and are based on the original HST ACS F814W imaging in COSMOS (Scoville et al., 2007). I note that because the LEGA-C size measurements are based on shorter-wavelength F814W imaging, colour gradients could introduce an offset in sizes relative to those measured for the VANDELS sample. The expected magnitude of this effect is $\simeq 0.05$ dex (e.g. van der Wel et al., 2014), well within my size-measurement uncertainty. This potentially introduces a small systematic uncertainty into the size evolution calculations presented in Section 3.5.

---

1This value was chosen for consistency with the Sérsic indices found for galaxies with HST imaging. Objects with HST F160W imaging have a median Sérsic index of $n = 2.3$, and a mean of $n = 2.7$, suggesting a fixed value of $n = 2.5$ for objects with ground-based imaging is a reasonable assumption.
**Figure 3.2** The relationship between stellar mass and $D_n4000$ for the VANDELS sample. The left-hand panel shows $D_n4000$ as a function of stellar mass. The right-hand panels show median-stacked spectra in the same three mass bins. The dashed pink lines show the median flux in the red band of the $D_n4000$ index. As the spectra have been normalised to the median flux ($f_{\nu}$) in the blue band, the pink lines also correspond to the $D_n4000$ values for each spectrum. I find an increase in $D_n4000$ with stellar mass, of $\simeq 0.1$ over $\simeq 1$ dex in mass, both from the stacked spectra and the median values for individual galaxies (Table 3.2).

**Figure 3.3** Same as Fig. 3.2 for the LEGA-C sample.
3.3.4 Measuring $D_n4000$

In this work, I use the “narrow” definition of the 4000 Å break index, $D_n4000$, which has the advantage of being less sensitive to extinction effects (e.g. Balogh et al., 1999a; Kauffmann et al., 2003; Martin et al., 2007; Silverman et al., 2009). $D_n4000$ is calculated as the ratio between the flux per unit frequency in the red continuum band (4000–4100 Å) and the blue continuum band (3850–3950 Å),

$$D_n4000 = \frac{\langle F^+ \rangle}{\langle F^- \rangle} = \frac{(\lambda_1^- - \lambda_2^-) \int_{\lambda_1^-}^{\lambda_1^+} f_\nu \, d\lambda}{(\lambda_1^+ - \lambda_2^+) \int_{\lambda_2^-}^{\lambda_2^+} f_\nu \, d\lambda}, \quad (3.1)$$

where $\lambda_1^+/-$ are the upper and lower bounds of the blue (−) and red (+) narrow continuum bands defined above.

For all galaxies in the final quiescent VANDELS sample, I calculate my own $D_n4000$ values directly from the VANDELS spectra, obtaining results for all 137 objects. These have an average uncertainty of 0.02. For the LEGA-C galaxies, I make use of the $D_n4000$ values from the LEGA-C DR2 catalogue, which have an average uncertainty of 0.01.

3.3.5 Stacked spectra

In order to investigate the average spectral properties of the galaxies in the VANDELS and LEGA-C samples, I construct several median stacked spectra in bins of size and mass. These stacks are all constructed following the same standard procedure. When constructing a stacked spectrum, I first de-redshift and re-sample the individual spectra onto a common wavelength grid, using the SPECTRES module for spectral re-sampling (Carnall, 2017). I then take the median flux across all the spectra in each pixel, and calculate uncertainties via the robust median absolute deviation (MAD) estimator.

The stacked spectra are normalised by the median flux in the blue continuum band of the 4000 Å break, in units of erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$. This means that the median flux density in the blue band lies at $f_\nu = 1.0$, and the median flux in the red continuum band is equal to the value of the $D_n4000$ index for that stacked spectrum.
3.4 Results

3.4.1 The relationship between stellar mass and $D_n4000$

In Fig. 3.2, I show the relationship between stellar mass and $D_n4000$ for the mass-complete VANDELS sample (see Section 3.3.1). In the left-hand panel, I show $D_n4000$ values for each individual galaxy, highlighting the median values in three 0.4-dex stellar-mass bins. In the right-hand panels, I show median stacked spectra in the same three mass bins. The dashed grey and pink lines indicate the median fluxes in the blue and red bands of the $D_n4000$ index, respectively. Due to the choice of normalisation, the pink lines correspond to the $D_n4000$ values calculated from the stacked spectra. In Table 3.2, I also present the median $D_n4000$ values for galaxies in each mass bin, along with the $D_n4000$ values derived from the stacks.

Fig. 3.3 shows the relationship between stellar mass and $D_n4000$ for the mass-complete LEGA-C sample (see Section 3.3.2), following the same format as Fig. 3.2. The median and stacked $D_n4000$ values shown in Fig. 3.3 for LEGA-C are also listed in Table 3.2.

A clear positive correlation between stellar mass and $D_n4000$ is visible in both the VANDELS and LEGA-C samples, with good agreement found in all cases between the median $D_n4000$ values for individual objects and the values derived from the stacked spectra. For both VANDELS and LEGA-C, the increase in average $D_n4000$ across the mass range I probe is $\approx 0.1$. In addition, similar evolution is observed between VANDELS and LEGA-C at fixed mass in all three bins, with an average evolution in $D_n4000$ of $\approx 0.08$ across the $\approx 2$ Gyr that separates the two samples.

3.4.2 The VANDELS and LEGA-C mass-size relations

I show the VANDELS and LEGA-C samples on the stellar mass-size plane in Fig. 3.4, together with best-fitting relations of the form:

$$\log_{10}\left( \frac{R_e}{\text{kpc}} \right) = \alpha \times \log_{10}\left( \frac{M_*}{5 \times 10^{10} M_\odot} \right) + \log_{10}(A),$$  \hspace{1cm} (3.2)
where $R_e$ is the effective radius, $\alpha$ is the slope, and $A$ is the normalisation (van der Wel et al., 2014). When fitting for the free parameters ($\alpha, A$), I adopt the stellar-mass uncertainties provided by the Bagpipes spectral fits. However, because the formal errors produced by Galfit are known to be significantly underestimated (e.g. Häussler et al., 2007), I adopt a constant error of $\pm 0.1$ dex on the effective radii as a more realistic estimate of the typical uncertainty (e.g. Bruce et al., 2012; McLure et al., 2013).

For the mass-complete sample of 137 VANDELS quiescent galaxies, I find best-fit parameters of $\alpha = 0.72 \pm 0.06$ and $\log_{10}(A) = 0.21 \pm 0.02$. The best-fitting relationship is shown with a dark pink line in the left-hand panel of Fig. 3.4. The 1σ confidence interval is shaded pink. Previous $z \sim 1.25$ results from van der Wel et al. (2014) and Mowla et al. (2019) are shown for comparison.

I perform the same fitting on the LEGA-C sample, using only the 272 objects with $D_n 4000$ values (see Section 3.3.2). I find a shallower slope than the higher-redshift VANDELS sample, with best-fit parameters of $\alpha = 0.56 \pm 0.04$ and $\log_{10}(A) = 0.45 \pm 0.02$. This relationship is shown with a dark blue line in the right-hand panel of Fig. 3.4. The 1σ confidence interval is shaded blue. Recent literature results at $z \sim 0.75$ from van der Wel et al. (2014), Wu et al. (2018a) and Mowla et al. (2019) are shown for comparison.

In order to ensure that the results are not biased by adopting the subset of the LEGA-C sample with $D_n 4000$ measurements, I also fit the full sample of 377 galaxies, obtaining best-fit parameters of $\alpha = 0.59 \pm 0.04$ and $\log(A) = 0.42 \pm 0.02$. The excellent agreement between these results and those quoted above for the $D_n 4000$ subset means that, in the following section, I can compare the VANDELS sample to the LEGA-C subset with $D_n 4000$ measurements, confident that my results are not sensitive to this choice.
Figure 3.4 The mass-size distributions of the VANDELS (left) and LEGA-C (right) UVJ-selected quiescent samples, colour-coded by $D_4000$. Best-fitting mass-size relations, calculated as described in Section 3.4.2, are shown in each panel. The $1\sigma$ uncertainties on the best-fitting relations are shown with translucent filled regions. The grey cross shown in the right-hand panel illustrates the typical uncertainties on size and mass for individual objects in both panels. Previous results from the literature for the mass-size relation at both redshifts are shown in both panels.
For both the VANDELS and LEGA-C samples, I present the median values of stellar mass, $\log_{10}(M_*/M_\odot)$; size, $\log_{10}(R_e/\text{kpc})$, and D$_n$4000 within six mass-size bins. The samples are split, first into three 0.4 dex stellar-mass bins, then into galaxies above and below the best-fitting mass-size relations determined in Section 3.4.2. I also list the number of objects within each bin ($N$), and the value of D$_n$4000 measured from the corresponding stacked spectrum.

### Table 3.3

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>VANDELS</th>
<th>Galaxies above mass-size relation</th>
<th>Galaxies below mass-size relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.3 &lt; $\log_{10}(M_*/M_\odot)$ ≤ 10.7</td>
<td>22</td>
<td>$10.56 \pm 0.03$</td>
<td>$1.56 \pm 0.03$</td>
</tr>
<tr>
<td>10.7 &lt; $\log_{10}(M_*/M_\odot)$ ≤ 11.1</td>
<td>31</td>
<td>$10.86 \pm 0.02$</td>
<td>$1.55 \pm 0.03$</td>
</tr>
<tr>
<td>11.1 &lt; $\log_{10}(M_*/M_\odot)$ ≤ 11.5</td>
<td>7</td>
<td>$11.15 \pm 0.04$</td>
<td>$1.61 \pm 0.08$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>LEGA-C</th>
<th>Galaxies above mass-size relation</th>
<th>Galaxies below mass-size relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.3 &lt; $\log_{10}(M_*/M_\odot)$ ≤ 10.7</td>
<td>24</td>
<td>$10.51 \pm 0.03$</td>
<td>$1.55 \pm 0.03$</td>
</tr>
<tr>
<td>10.7 &lt; $\log_{10}(M_*/M_\odot)$ ≤ 11.1</td>
<td>64</td>
<td>$10.85 \pm 0.02$</td>
<td>$1.62 \pm 0.02$</td>
</tr>
<tr>
<td>11.1 &lt; $\log_{10}(M_*/M_\odot)$ ≤ 11.5</td>
<td>33</td>
<td>$11.28 \pm 0.03$</td>
<td>$1.68 \pm 0.01$</td>
</tr>
</tbody>
</table>
3.4.3 Stellar mass-size trends with $D_n4000$

Having considered the mass-$D_n4000$ and mass-size relations for the samples separately in Sections 3.4.1 and 3.4.2, I now combine these analyses to consider the relationship between galaxy size and $D_n4000$. Given that both quantities depend strongly on stellar mass, it is critical to separate out this dependency as much as possible (e.g. by using narrow stellar-mass bins) in order to delineate any correlation between $D_n4000$ and size.

The VANDELS and LEGA-C samples are shown on the mass-size plane in Fig. 3.4, colour-coded by $D_n4000$. For the LEGA-C sample at $z \sim 0.7$, a vertical trend appears to be visible, with galaxies below the mass-size relation tending to have higher $D_n4000$ values (lighter colours) than galaxies above the relation. For the VANDELS sample, a corresponding trend is not clearly visible. This is perhaps not surprising, given the smaller number of VANDELS objects, and the larger uncertainties on the individual $D_n4000$ measurements due to the lower SNR of the VANDELS spectra.

Motivated by the apparent size-$D_n4000$ trend visible for LEGA-C in Fig. 3.4, I implement an approach similar to that of Section 3.4.1, splitting the VANDELS and LEGA-C samples into the same three 0.4-dex stellar-mass bins, before splitting each mass bin into two size bins. Galaxies are separated in size by their position relative to the best-fitting mass-size relations derived in Section 3.4.2, with those above being separated from those below. This results in three mass bins for galaxies above the mass-size relation, and three mass bins for galaxies below the mass-size relation.

As in Section 3.4.1, I generate stacked spectra for each mass-size bin, from which I measure $D_n4000$ values. The six stacked spectra generated for the VANDELS and LEGA-C samples are shown in Fig. 3.5. The $D_n4000$ values for each stack are listed in Table 3.3, along with median $D_n4000$ values for the individual galaxies entering each stack. From Fig. 3.5 and Table 3.3, it can be seen that LEGA-C galaxies lying below the mass-size relation have significantly higher $D_n4000$ values than those above the relation. Smaller-than-average galaxies have higher $D_n4000$ by $\simeq 0.1$ in the lower two mass bins, whereas the difference is $\simeq 0.05$ in the highest-mass bin. This offset is most significant ($\simeq 4 \sigma$) in the middle-mass bin, where the number of objects is greatest, but is also clearly visible ($\simeq 2 \sigma$ significance) in the highest-mass and lowest-mass bins.
**Figure 3.5** The stacked spectra for galaxies above and below the best-fitting mass-size relations for the VANDELS (left-hand panels) and LEGA-C (right-hand panels) samples, within three 0.4-dex stellar-mass bins. The stacked spectra are created using the methods described in Section 3.3.5. In all panels, the dashed red line corresponds to the $D_n4000$ value calculated from the stacked spectrum below the mass-size relation, and the dashed orange line corresponds to the $D_n4000$ value calculated from the stacked spectrum above the mass-size relation. The uncertainties on the measured $D_n4000$ values are indicated with coloured shading.
For VANDELS, I do not observe a significant difference in average $D_{n4000}$ values above and below the mass-size relation in any of the three stellar-mass bins. This could of course simply indicate that the size-$D_{n4000}$ trend observed in LEGA-C was not in place at $z \sim 1.1$. However, as discussed above, the smaller number of objects in the VANDELS sample, coupled with the individual spectra having lower SNRs, makes it difficult to draw any firm conclusions. For example, it can be seen from the uncertainties quoted in Table 3.3 that, in a given stellar-mass bin, the difference in $D_{n4000}$ above and below the mass-size relation would have to be $≥ 0.15$ in order to be detected with $≥ 2\sigma$ significance in the VANDELS sample.

### 3.5 Discussion

In Section 3.4, I have considered the relationships between stellar mass, size and $D_{n4000}$ for two mass-complete samples of quiescent galaxies with $\log_{10}(M/\text{M}_\odot) > 10.3$, at $0.6 < z < 0.8$ from LEGA-C, and at $1.0 < z < 1.3$ from VANDELS. In this section I discuss these results, with a particular focus on whether the observed trends in $D_{n4000}$ are driven by stellar age or metallicity, and also on understanding the changes in the quiescent population across the $\simeq 2$ Gyr that separates the VANDELS and LEGA-C samples.

#### 3.5.1 Evidence of downsizing from stellar mass vs $D_{n4000}$

In Section 3.4.1, I report a clear relationship between stellar mass and $D_{n4000}$ for both the VANDELS and LEGA-C samples, such that, on average, more massive galaxies have higher $D_{n4000}$. This is in good agreement with previous studies at $z < 1$ (e.g. Kauffmann et al., 2003; Brinchmann et al., 2004; Haines et al., 2017; Kim et al., 2018; Wu et al., 2018a), and has been widely interpreted as evidence that more massive galaxies are older (often referred to as downsizing, or archaeological downsizing). The VANDELS result demonstrates this downsizing signal was already in place at $z ≥ 1$ for the first time using a large, representative, spectroscopic sample.

In this context, the trends between $D_{n4000}$ and stellar mass seen in Fig. 3.2 and Fig. 3.3 can be securely interpreted in terms of stellar populations of different ages, given the broad agreement in the literature that the stellar mass vs stellar
metallicity relation is relatively flat at $\log_{10}(M_*/M_\odot) > 10$ (e.g. Gallazzi et al. 2005, 2014; Panter et al. 2008; Choi et al. 2014; Leethochawalit et al. 2018; Carnall et al. 2021). I also see an increase in $D_n4000$ between VANDELS and LEGA-C, of $\simeq 0.06-0.10$ at fixed stellar mass. This redshift evolution is discussed in Section 3.5.4.

### 3.5.2 Stellar mass-size relations

The stellar mass-size relations followed by both star-forming and quiescent galaxies have been extensively investigated over the past two decades. Over the widest dynamic range in stellar mass, there is now good evidence that quiescent galaxies follow a mass-size relation that is well described by a double power law (e.g. Nedkova et al., 2021; Kawinwanichakij et al., 2021). However, at high stellar masses (i.e. $\log_{10}(M_*/M_\odot) > 10$), it is clear that quiescent galaxies follow a linear $\log_{10}(R_e) - \log_{10}(M_*)$ relation (see Equation 3.2), with a normalisation that evolves rapidly with redshift (e.g. Shen et al., 2003; Buitrago et al., 2008; McLure et al., 2013; van der Wel et al., 2014; Wu et al., 2018b; Mowla et al., 2019). It is much less clear whether the slope of the mass-size relation also evolves with time: most studies report values in the range $0.50 < \alpha < 0.75$, with no clear redshift trend emerging.

The mass-size relations I derive in this work, based on robust, mass-complete, spectroscopically confirmed galaxy samples at $z \sim 0.7$ and $z \sim 1.1$, are consistent with recent literature results based on larger galaxy samples based on photometric redshifts. The results indicate that, at a given stellar mass, massive quiescent galaxies grow by a factor of $\simeq 2$ over the $\simeq 2$ Gyr of cosmic time that separates the two samples.

My results also provide tentative evidence that the slope of the mass-size relation may flatten ($\Delta \alpha = -0.16 \pm 0.07$) over the same interval, although I note that any flattening is only significant at the $\simeq 2\sigma$ level. This tentative flattening of the relation could potentially be explained by larger newly-quenched galaxies, arriving onto the stellar mass-size distribution between $10.3 \leq \log_{10}(M_*/M_\odot) \leq 10.65$. In Section 3.5.4, I explore whether a simple minor-merger model can explain the evolution of the quiescent galaxy mass-size relation suggested by the VANDELS and LEGA-C galaxy samples.
Figure 3.6 The relationship between $D_n4000$, mean stellar age and stellar metallicity. I illustrate the way that $D_n4000$ increases with mean stellar age for six fixed metallicities, assuming 1-Gyr-duration constant star-formation histories. The shaded region shows the difference between the $D_n4000$ values for the two size bins within the middle mass bin of the LEGA-C sample. Within the range of plausible metallicities (i.e. $0.0 < [Z/H] < -0.3$), it can be seen that an age difference of $\simeq 0.5 – 1$ Gyr, or a metallicity difference of $\simeq 0.3 – 0.4$ dex would be required to explain the observed $D_n4000$ offset. Note that I assume a value for Solar metallicity of $Z_{\odot} = 0.02$. 
The spectral index $D_n4000$ is best known as a way of inferring ages for older stellar populations (e.g. Balogh et al. 1999a; Kauffmann et al. 2003). However, the strength of this break is also known to depend somewhat on metallicity (e.g. Bruzual & Charlot, 2003).

In Wu et al. (2018b), the authors report a size-$D_n4000$ relationship for a similar sample of LEGA-C quiescent galaxies, and suggest that this is driven by a difference in the average ages of larger and smaller objects. However, other studies (e.g. Barone et al., 2022; Beverage et al., 2021) have reported a size-metallicity correlation via full spectral fitting analyses, casting doubt as to whether any size-$D_n4000$ trend should be attributed primarily to differences in average age or metallicity.

In Section 3.4.3, I have established that there is a trend between size and $D_n4000$ for the LEGA-C sample, with smaller galaxies having higher $D_n4000$. Averaged over the three mass bins, the mean $D_n4000$ offset is $\approx 0.08$, in good agreement with Wu et al. (2018b).

To investigate the influence of age and metallicity on $D_n4000$ in the context of the LEGA-C sample, I use Bagpipes to run a grid of models with simple, 1-Gyr-duration constant star-formation histories, using the BC03 stellar-population models. In Fig. 3.6, I show the relationship between $D_n4000$ and mean stellar age, for a range of metallicities (note that I assume $Z_\odot = 0.02$). Also shown with indigo shading is the gap between the median $D_n4000$ values above and below the mass-size relation in the middle LEGA-C stellar-mass bin. This mass bin was chosen as it contains the most objects, and hence has the best-constrained median $D_n4000$ values.

Under this simple set of assumptions, and within the range of plausible metallicities (i.e. $0.0 < [Z/H] < -0.3$), it can be seen that the $\Delta D_n4000$ of 0.09 suggests a difference in age of $\approx 0.5 - 1$ Gyr, if the average metallicities in the two size bins are the same (the horizontal distance over which the lines shown move from the bottom to the top of the shaded region). Conversely, if both bins contain objects with the same average ages, a metallicity offset of $\approx 0.3 - 0.4$ dex is required to explain the observed difference in $D_n4000$ values.

Several leading studies have reported that massive, quiescent galaxies at $z \sim 0.7$
exhibit a scatter in metallicity of ≃ 0.2 dex (Gallazzi et al. 2014, Tacchella et al. 2021). Even in the most extreme possible scenario, for which all galaxies above the mass-size relation have below-average metallicities and vice versa, this level of scatter is not sufficient to produce the 0.3–0.4 dex metallicity offset required to fully explain the $\Delta D_n4000 = 0.09$ observed in the middle LEGA-C mass bin. I therefore conclude that the size-metallicity relations found by Barone et al. (2022) and Beverage et al. (2021) cannot fully explain the observed size-$D_n4000$ trend, meaning a size-age relation is likely to also be present in the LEGA-C sample, with a magnitude of $\lesssim 500$ Myr.

As discussed in Section 3.4.3, I do not observe a significant size-$D_n4000$ relation for the VANDELS sample. From Fig. 3.6, it can be seen that any size-$D_n4000$ trend due to a fixed offset in age or metallicity would be smaller in a population of younger galaxies. I therefore would not expect to see clear evidence of a size-age or size-metallicity relation in VANDELS with similar magnitude to the one I observe for LEGA-C, given the larger uncertainties on the binned VANDELS median $D_n4000$ values.

### 3.5.4 A model linking the VANDELS and LEGA-C samples

Having established the level of evolution between the LEGA-C and VANDELS samples in terms of stellar mass, size and $D_n4000$, in this section I investigate whether or not the observed evolution is compatible with the simplest possible toy model. Specifically, I investigate whether the observed size and $D_n4000$ evolution can be explained by passively evolving the VANDELS galaxies by $\sim 2$ Gyr at constant metallicity, with the growth in stellar mass and size being the result of a series of minor mergers.

**Accounting for progenitor bias**

In order to gain an accurate understanding of the relationship between the VANDELS and LEGA-C datasets, I first calculate the fraction of the LEGA-C sample that are likely descendants of the higher-redshift VANDELS galaxies, thus constraining the level of progenitor bias. Based on the original parent samples for both LEGA-C and VANDELS, I estimate that the comoving number densities of quiescent galaxies with $\log_{10}(M_*/M_\odot) \geq 10.3$ at $z \sim 0.7$ and $z \sim 1.1$ are $9.10 \times 10^{-4}$ Mpc$^{-3}$ and $7.62 \times 10^{-4}$ Mpc$^{-3}$, respectively. As a result, I conclude
that the VANDELS sample can account for \( \approx 85 \) per cent of the progenitors of the LEGA-C sample.

Alternatively, I can map the VANDELS comoving number density to a higher-mass subset of the LEGA-C sample. I make the simplifying assumption here that the most massive objects in LEGA-C have been quenched long enough to be descended from the VANDELS sample at \( z \sim 1.1 \). Under this assumption, the VANDELS sample can account for 100 per cent of the progenitors of the LEGA-C sample with stellar masses \( \log_{10}(M_\star/M_\odot) \geq 10.65 \). I adopt this latter assumption throughout the rest of this section, comparing the whole VANDELS sample (\( \log_{10}(M_\star/M_\odot) \geq 10.3 \)) with the LEGA-C sample at \( \log_{10}(M_\star/M_\odot) \geq 10.65 \).

**Modelling the evolution of size, stellar mass and \( D_n4000 \)**

In the left-hand panels of Fig. 3.7, I show size, mass and \( D_n4000 \) histograms for the VANDELS (pink) and LEGA-C (indigo) samples. In order to explore whether the simplest set of assumptions possible can explain the trends observed in the data, I test a model wherein I calculate the shifts required to reconcile the two samples for each parameter, by finding the difference between the median of the VANDELS distribution and the median of LEGA-C galaxies with stellar masses \( \log_{10}(M_\star/M_\odot) \geq 10.65 \) (grey shading). In the right-hand panels of Fig. 3.7, I compare the original LEGA-C distributions to those of the shifted/evolved VANDELS sample, where the shifts applied in \( \log_{10}(R_e/kpc) \), \( \log_{10}(M_\star/M_\odot) \) and \( D_n4000 \) are 0.28, 0.13 and 0.11, respectively.

The application of a two-sample Kolmogorov–Smirnov (KS) test (Hodges, 1958) confirms that the distributions shown in the right-hand panels of Fig. 3.7 are statistically indistinguishable, with \( p \)-values of 0.84, 0.56 and 0.70 for the size, mass and \( D_n4000 \) distributions. In this case, a high \( p \)-value suggests there is no statistical evidence that the two underlying distributions are significantly different. This confirms that, apart from a systematic shift, there is no significant change in the shape of the size, mass and \( D_n4000 \) distributions between the LEGA-C and the VANDELS samples.

Moreover, I can test whether the implied change in the median \( D_n4000 \) value of \( \approx 0.11 \) is plausible, by comparing with the predictions shown in Fig. 3.6. Within the range of plausible metallicities (i.e. \( 0.0 < [Z/H] < -0.3 \)), the tracks shown in
**Figure 3.7** The distributions of size, stellar mass and $D_n4000$ for the VANDELS (pink) and LEGA-C (indigo) galaxy samples. The left-hand panels show the observed distributions. In all panels, the grey shaded region corresponds to the subset of the LEGA-C sample with stellar masses $\log_{10}(M_*/M_\odot) \geq 10.65$. This subset has the same number density as the full VANDELS sample with $\log_{10}(M_*/M_\odot) \geq 10.3$. The right-hand panels show the observed VANDELS distributions shifted to the same median values as the corresponding LEGA-C distribution with $\log_{10}(M_*/M_\odot) \geq 10.65$. The applied shifts are 0.28, 0.13 and 0.11 in $\log_{10}(R_e/kpc)$, $\log_{10}(M_*/M_\odot)$ and $D_n4000$, respectively. The histograms have been normalised by the total number of objects in each sample.
Fig. 3.8 A schematic diagram showing the possible growth paths of the VANDELS galaxies as a result of major (purple) or minor (pink) mergers. The dark pink and indigo lines show the best-fitting mass-size relations derived in Section 4.2 for VANDELS and LEGA-C respectively. The joined orange circles show the median size and mass values for VANDELS galaxies with log\(_{10}(M_\star/M_\odot) > 10.3\), and for LEGA-C galaxies with log\(_{10}(M_\star/M_\odot) > 10.65\) (see Section 3.5.4). It can be seen that the median differences I observe between VANDELS and LEGA-C suggest that the size evolution of quiescent galaxies from \(z \sim 1.1\) to \(z \sim 0.7\) is dominated by minor mergers.

Fig. 3.6 suggest that the change in \(D_n4000\) over 2 Gyr will indeed lie in the range 0.1 < \(\Delta D_n4000\) < 0.2, as required. For massive quiescent galaxies at \(z \sim 0.8\), Tacchella et al. (2021) find a median metallicity of \([Z/H] = -0.27\) (on the Solar abundance scale), suggesting an expected \(D_n4000\) evolution of \(\simeq 0.1\) based on Fig. 3.6. Although encouraging, I note that further spectrophotometric analysis of both datasets will be required to fully understand the evolution in age and metallicity between the two samples.
Interpreting size growth via minor mergers

It has long been accepted that the most likely explanation for the observed size growth of the quiescent galaxy population is via dissipationless, so-called ‘dry’, mergers (e.g. Trujillo et al., 2011; van Dokkum et al., 2010; Cimatti et al., 2012; McLure et al., 2013). The dry merging is usually classified as either ‘major’, with a typical mass ratio of 1:3, resulting in size growth proportional to the accreted mass, or ‘minor’, with a typical mass ratio of 1:10, resulting in size growth proportional to the square of the accreted mass (Cimatti et al., 2012).

The potential growth of the VANDELS galaxies via major and minor mergers is illustrated in the schematic diagram shown in Fig. 3.8. The VANDELS and LEGA-C mass-size relations derived in Section 3.4.2 are again shown, along with representative vectors showing the directions galaxies are expected to move under the minor-merger and major-merger scenarios. The two joined orange points show the median values calculated in Section 3.5.4 for VANDELS galaxies, and for LEGA-C galaxies with stellar masses \( \log_{10}(M_\star/M_\odot) \geq 10.65 \). For context, these median values are also shown overplotted on the whole VANDELS and LEGA-C samples on the mass-size plane in Fig. 3.9.

Fig. 3.8 immediately suggests that the observed evolution between VANDELS and LEGA-C is more consistent with minor mergers. As discussed in the previous section, the observed growth between the VANDELS and LEGA-C samples in terms of stellar mass and size are 0.13 dex and 0.28 dex (factors of 1.35 and 1.91), respectively. This is clearly consistent with a minor-merger scenario (i.e. \( \Delta R_e \propto \Delta M_\star^2 \)). If I assume that minor mergers have a typical mass ratio of 1:10, the observed growth between VANDELS and LEGA-C is consistent with a series of three minor mergers within a time span of \( \simeq 2 \) Gyr.

It is clear from simulations that typical galaxies in the mass range under discussion here are unlikely to experience a major merger over the redshift interval \( 0.7 < z < 1.1 \) (e.g. Hopkins et al., 2010; Johansson et al., 2012). This means that the results are consistent with the expectation that minor mergers are the dominant process driving quiescent galaxy growth at this epoch (e.g. Ownsworth et al., 2014; Buitrago et al., 2017).
Figure 3.9 Evolving the VANDELS galaxies down to $z \sim 0.7$ on the mass-size plane. The left-hand panel shows the VANDELS galaxies (coloured by $D_n4000$) overplotted on the LEGA-C sample (grey circles), both at their respective redshifts of $z \sim 1.1$ and $z \sim 0.7$. The right-hand panel shows the VANDELS galaxies shifted in stellar mass, size and $D_n4000$ by the values shown in the top left-hand corner, derived in Section 3.5.4. In both panels, I also plot the best-fitting mass-size relations determined for the VANDELS and LEGA-C samples in Section 4.2. It can be seen that the mass-size distribution of the shifted VANDELS sample in the right-hand panel is indistinguishable from that of the LEGA-C sample at $\log_{10}(M_*/M_\odot) > 10.65$ (see Section 3.5.4 for discussion).
Evolving the VANDELS sample down to $z \sim 0.7$

The expected future evolution of the VANDELS galaxies on the mass-size plane following the toy-model prescription is illustrated in Fig. 3.9. The left-hand panel shows the VANDELS sample at $z \sim 1.1$, along with the best-fitting mass-size relation determined in Section 3.4.2. In the right-hand panel, I show the location of the VANDELS galaxies after they have been “evolved” down to $z \sim 0.7$, using the average offsets from Section 3.5.4, as indicated in the top-left corner of the panel. The best-fitting mass-size relation for the LEGA-C sample at $z \sim 0.7$ is also shown. Individual LEGA-C galaxies are shown with grey open circles in both panels.

It can immediately be seen from the right-hand panel of Fig. 3.9 that the two-dimensional distribution of the evolved VANDELS sample is well matched to that of LEGA-C (confirmed by a 2D KS test, Peacock 1983; $p = 0.96$). As discussed above, the bottom-right panel of Fig. 3.7 demonstrates the two samples are also well matched in terms of their $D_{n,4000}$ distributions, and that the required $D_{n,4000}$ shift of 0.11 is consistent with 2 Gyr of passive ageing. Taken together, this suggests that the toy model, linking the two populations via a combination of passive evolution and minor mergers, is entirely plausible.

### 3.6 Conclusions

In this work I have explored the relationships between stellar mass, size and $D_{n,4000}$ for samples of quiescent galaxies at $1.0 < z < 1.3$ and $0.6 < z < 0.8$, by utilising high-quality spectroscopic data from the VANDELS and LEGA-C surveys. The main conclusions can be summarised as follows:

1. In Section 3.4.1, I report a positive correlation between $D_{n,4000}$ and stellar mass in both the LEGA-C ($z \sim 0.7$) and VANDELS ($z \sim 1.1$) samples, with a magnitude of $\approx 0.1$ across a $\approx 1$ dex interval in stellar mass. Within the mass and redshift ranges spanned by the two samples, there is little or no correlation expected between stellar mass and metallicity (e.g. Beverage et al., 2021; Borghi et al., 2021). Consequently, this relationship between $D_{n,4000}$ and stellar mass can be interpreted as being primarily driven by a correlation between stellar mass and stellar-population age (downsizing).
2. In Section 3.4.2, I report a new mass-size relation for the VANDELS sample at \( z \sim 1.1 \), and confirm previous determinations of the mass-size relation for the LEGA-C sample at \( z \sim 0.7 \), with best-fitting slopes of \( \alpha = 0.72 \pm 0.06 \) and \( \alpha = 0.56 \pm 0.04 \), respectively. These results provide tentative evidence for a flattening in the slope of the mass-size relation towards lower redshift, although the level of flattening (\( \Delta \alpha = -0.16 \pm 0.07 \)) is only significant at the \( \approx 2\sigma \) level.

3. In Section 3.4.3, I find that, for the LEGA-C sample at fixed stellar mass, galaxies below the mass-size relation display larger \( D_n^4000 \) values than galaxies above the relation. This is in good agreement with the previous analysis of LEGA-C by Wu et al. (2018b). A similar trend is not clearly seen within the VANDELS sample at \( z \sim 1.1 \), although the smaller sample size and lower SNR of the individual VANDELS spectra would make detecting such a trend unlikely.

4. This analysis suggests that the magnitude of the trend between \( D_n^4000 \) and size observed within the LEGA-C sample cannot be fully explained by a relationship between size and metallicity, meaning that a size-age relation must also be present in the data, with a magnitude of \( \lesssim 500 \) Myr (see Section 3.5.3).

5. I find that a simple toy model, based on a combination of passive evolution and minor mergers, can explain the observed evolution in stellar mass, size and \( D_n^4000 \) between the VANDELS and LEGA-C samples. This scenario, assuming each VANDELS galaxy experiences \( \approx 2 \) Gyr of passive evolution, at a constant metallicity, together with a series of \( N \approx 3 \) minor mergers, is sufficient to reproduce the distribution of the LEGA-C sample on the mass-size plane (see Section 3.5.4).

In the near future, there are excellent prospects for improving the understanding of the evolution of size, mass, age and metallicity within the quiescent galaxy population at \( z \geq 1 \). In addition to the unparalleled near-IR imaging and spectroscopic data promised by forthcoming James Webb Space Telescope programmes (e.g. PRIMER; Dunlop et al., 2021), large-scale optical-near-IR spectroscopic surveys, such as MOONRISE (Cirasuolo et al., 2020), will enable detailed studies of the quiescent galaxy population out to the highest redshifts.
Chapter 4

The connection between stellar mass, age and quenching timescale in massive quiescent galaxies at $1.0 < z < 1.3$

The material in this chapter was originally published in Hamadouche et al. (2023).

4.1 Introduction

It is now well established that the local galaxy population is bi-modal in terms of colour, morphology and star-formation rate (SFR). The colour bi-modality was first observed using data from the Sloan Digital Sky Survey (SDSS, York et al., 2000), with galaxies falling into two categories: a star-forming ‘blue cloud’ and a quiescent ‘red sequence’ (e.g. Strateva et al., 2001; Baldry et al., 2004). In general, more-massive galaxies tend to be red spheroids with little ongoing star formation, whilst less-massive galaxies are mainly blue, star-forming discs. Over the past few decades, many studies have aimed to quantify the mechanisms responsible for producing the bi-modality in the galaxy population (e.g. Dekel & Birnboim, 2006; Peng et al., 2010; Gabor & Davé, 2012; Schawinski et al., 2014). However, despite the wealth of ground-based and space-based data available, understanding exactly how the shutting down of star formation relates to this
distinction between galaxy types remains hugely challenging.

Observations have shown that, even within the quiescent population, galaxies demonstrate a range of characteristics. For example, more-massive galaxies are known to have formed earlier in cosmic time and much more rapidly, with clear evidence for younger stellar populations in less-massive galaxies compared to their more-massive counterparts (e.g. Cowie et al., 1996; Thomas et al., 2005b; Fontana et al., 2006; Fontanot et al., 2009; Pacifici et al., 2016). This phenomenon, referred to as ‘downsizing’, is commonly used to describe the relationship between quiescent galaxy stellar mass and age, and indicates that quenching varies as a function of stellar mass and redshift. Empirical spectral age indicators have provided strong constraints on this downsizing trend, with features such as the $D_n4000$ index demonstrating positive correlations with stellar mass at redshift, $z \lesssim 1$ (e.g. Bruzual A., 1983; Balogh et al., 1999b; Kauffmann et al., 2003; Brinchmann et al., 2004; Moresco et al., 2011, 2010, 2016).

In addition to the bi-modality of the galaxy population, one of the most important observational results of the past few decades is the differing evolution of the star-forming and quiescent galaxy stellar mass functions (GSMF) across cosmic time, with the number density of quiescent galaxies apparently increasing by almost an order of magnitude since $z \simeq 2$ (e.g. Cimatti et al., 2002; Abraham et al., 2004; Baldry et al., 2012; Muzzin et al., 2013a; Davidzon et al., 2017; McLeod et al., 2021). However, recent studies also point to a substantial population of massive quiescent galaxies out to $z > 3$ (e.g. Schreiber et al., 2018; Valentino et al., 2020; Carnall et al., 2020a, 2022a). Together, these results allow us to quantify the quiescent galaxy fraction across cosmic time, an important observational constraint on galaxy evolution models (e.g., Somerville & Davé, 2015b).

Another key result was the discovery that the sizes of quiescent galaxies have evolved much more rapidly than their star-forming counterparts since $z \sim 2$, and that quiescent galaxies follow a steeper stellar mass-size relation than star-forming galaxies at all redshifts (e.g. Shen et al., 2003; Trujillo et al., 2006; McLure et al., 2013; van der Wel et al., 2014; Mowla et al., 2019). The physical processes driving the size growth of quiescent galaxies are still not fully understood, although it is widely accepted that minor mergers play an important role in explaining the observed growth from $z \sim 2$ to the local Universe (e.g. see Hopkins et al., 2010; Trujillo et al., 2011; Cimatti et al., 2012; Ownsworth et al., 2014).

Considerable effort has been devoted to understanding which physical mecha-
nisms are required to explain the observed differences in the properties of the star-forming and quiescent galaxy populations. Our understanding of quenching mechanisms relies heavily on simulations of galaxy formation. At $z < 2$, simulations have been able to reproduce the observed bi-modality (see Davé et al., 2017, 2019; Nelson et al., 2018; Akins et al., 2022). However, the situation becomes more complicated at higher redshifts, and it is much more difficult to identify the key physical drivers of quenching. The main mechanisms thought to cause quenching can be categorised into two distinct pathways: ‘mass’ (or ‘internal’, see Somerville & Davé, 2015b) quenching, and ‘environmental’ quenching. Locally, these two pathways are clearly distinguishable, suggesting that multiple mechanisms quench galaxies (e.g., Peng et al., 2010).

Mass quenching is often thought to be associated with feedback processes such as radiative- or jet-mode active galactic nucleus (AGN) feedback (e.g. Croton et al., 2006; Gabor et al., 2011; Choi et al., 2018). Quenching attributed to galaxy-galaxy interactions (often referred to as ‘environmental’ or ‘satellite’ quenching) is thought to be the result of ram-pressure stripping, caused by satellite galaxies falling into larger dark matter halos, or virial shock-heating of the circum-galactic medium (see Dekel & Birnboim, 2006, also referred to as ‘halo’ quenching).

These mechanisms can be further categorised as ‘slow’ and ‘fast’ quenching pathways, respectively (Schawinski et al., 2014; Schreiber et al., 2016; Carnall et al., 2018; Belli et al., 2019a). Shorter quenching timescales are thought to be linked with quasar-mode AGN feedback, which is thought to be more prevalent at high redshift (Wild et al., 2016). In contrast, it appears that the key process responsible for quenching at low redshift is the halting of gas accretion, taking place on much longer timescales of several Gyr (e.g. Peng et al., 2015; Trussler et al., 2020).

Large spectroscopic surveys have facilitated increasingly sophisticated, statistical studies of galaxy physical properties at high redshift, with the aim of placing tighter constraints on the physical origins of quenching. The recently completed LEGA-C (van der Wel et al., 2016) and VANDELS (McLure et al., 2018b) surveys provide ultra-deep spectroscopy for hundreds of quiescent galaxies at $0.6 < z < 2.5$. These data sets, coupled with improved spectral energy distribution (SED) fitting methods (e.g. Carnall et al., 2019b; Leja et al., 2019a), have already enabled more-precise measurements of galaxy stellar masses, star-formation histories (SFHs) and stellar metallicities, unveiling significant correlations between these physical properties (e.g. Wu et al., 2018b, 2021;
Beverage et al., 2021; Carnall et al., 2022b).

A key emerging result is the finding that the observed stellar mass vs stellar age relationship for $z \sim 1$ quiescent galaxies is steeper than is predicted by the most recent generation of cosmological simulations (e.g. Carnall et al. 2019a; Tacchella et al. 2022). These new spectroscopic analyses build upon a corpus of earlier work aiming to quantify these relationships, much of which was founded upon the use of elemental abundances as empirical proxies for formation and quenching timescales (e.g. Thomas et al., 2005a; Conroy et al., 2014; Kriek et al., 2019). Despite these advances in the field, continued, in-depth investigation into the physical properties of quiescent galaxies is still needed to build a thorough understanding of quenching and passive galaxy evolution.

In Hamadouche et al. (2022), I investigated the links between stellar mass, age, size and metallicity using quiescent-galaxy samples from the LEGA-C (van der Wel et al., 2016) and VANDELS (McLure et al., 2018b) spectroscopic surveys at $z \simeq 0.7$ and $z \simeq 1.1$, respectively. I examined stellar mass-age trends using the $D_n4000$ index as a proxy for the stellar population age, finding that more-massive galaxies exhibit higher $D_n4000$ values at both redshift ranges, consistent with prior evidence for the downsizing scenario at lower redshifts. In this work, I return to the VANDELS spectroscopic sample, building upon my previous results by employing full spectral fitting to probe the ages and SFHs of massive quiescent galaxies at $z \gtrsim 1$ in detail.

This study makes use of the fully completed VANDELS DR4 sample (Garilli et al., 2021), which includes more than twice the number of quiescent galaxy spectra studied in the initial analysis of Carnall et al. (2019a). Moreover, in this study I implement an improved physical model, along with additional metallicity constraints for the VANDELS sample from Carnall et al. (2022b), to better constrain star-formation histories, stellar masses and formation and quenching times. Motivated by the ongoing challenges in quantifying the correlations between key quiescent galaxy physical properties, I begin by examining the relationship between stellar mass and age in the quiescent sample at $1.0 < z < 1.3$, and discuss these results in the context of downsizing. I then explore the typical quenching timescales of $z \sim 1$ quiescent galaxies, focusing on a sub-sample of galaxies that display spectral features associated with $\alpha$—enhancement.

The structure of this chapter is as follows. I introduce the VANDELS survey in Section 4.2, before providing details of my sample selection and spectral fitting.
technique using the Bagpipes code (Carnall et al., 2018) in Section 4.3. I present my main results in Section 3.4 and discuss them in Section 4.5. Finally, I present my conclusions in Section 4.6. Throughout this chapter, I assume a Kroupa (2001) initial mass function and the Asplund et al. (2009) Solar abundance of $Z_{\odot} = 0.0142$. I assume cosmological parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ throughout. All magnitudes are quoted in the AB system.

4.2 The VANDELS survey

VANDELS is a large ESO Public Spectroscopy Survey (McLure et al., 2018b; Pentericci et al., 2018; Garilli et al., 2021) targeting the CDFS and UDS fields, and covering a total area of 0.2 deg$^2$. The survey data were obtained using the Visible Multi-Object Spectrograph (VIMOS, Le Fèvre et al., 2004) on the ESO VLT. The final data release (DR4; Garilli et al., 2021) provides spectra for a sample of 2087 galaxies, the vast majority of which (87 per cent) are star-forming galaxies in the redshift range $2 < z < 6.2$. However, in this study, I focus on the remaining 281 targets (13 per cent) selected as quiescent galaxies in the redshift range $1 < z < 2.5$.

4.2.1 VANDELS sample selection

The VANDELS spectroscopic sample was originally drawn from a combination of four separate photometric catalogues. Two of these are the CANDELS GOODS South and UDS catalogues (Guo et al., 2013; Galametz et al., 2013), whilst the other two are custom ground-based catalogues (described in McLure et al. 2018b), covering the wider VANDELS area outside of the CANDELS footprints.

The parent quiescent sample was selected from these photometric catalogues as follows. Objects were required to have $H$-band magnitudes of $H \leq 22.5$, corresponding to stellar masses of $\log_{10}(M_*/M_{\odot}) \gtrsim 10$ over the redshift range of $1.0 \leq z_{\text{spec}} \leq 1.3$ we focus on in this work (approximately 98 per cent of the full VANDELS quiescent sample has $z_{\text{spec}} < 1.5$), as well as $i$-band magnitudes of $i \leq 25$. To separate star-forming and quiescent galaxies, rest-frame UVJ criteria were applied following Williams et al. (2009). These criteria result in a sample of 812 galaxies, which I refer to as the VANDELS photometric parent sample.
4.2.2 VANDELS spectroscopy

Here I briefly summarise the VANDELS spectroscopic observations, while referring the reader to Pentericci et al. (2018) for a full description. From the parent sample of 812 quiescent galaxies described in the previous section, 281 were randomly assigned slits and observed as part of the VANDELS survey. Objects were observed for 20, 40 or 80 hours depending on their $i$-band magnitudes. The observations were obtained using the MR grism, providing a median resolution of $R \sim 600$ across a wavelength range from $\lambda = 4800 - 9800$ Å. The VANDELS team manually measured spectroscopic redshifts, assigning redshift quality flags according to Le Fèvre et al. (2013). In this chapter, I only use those galaxies with spectroscopic redshift flag 3 or 4, which has subsequently been shown to correspond to a $\simeq 99$ per cent probability of being correct (Garilli et al., 2021).
Table 4.1  Details of the parameter ranges and priors adopted for the BAGPIPES fitting of the VANDELS photometry and spectroscopy (see Section 4.3.1). Priors listed as logarithmic are uniform in log-base-ten of the parameter.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Symbol / Unit</th>
<th>Range</th>
<th>Prior</th>
<th>Hyperparameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>Redshift</td>
<td>$z_{\text{spec}}$</td>
<td>$z_{\text{spec}} \pm 0.015$</td>
<td>Gaussian</td>
<td>$\mu = z_{\text{spec}} \sigma = 0.005$</td>
</tr>
<tr>
<td>SFH</td>
<td>Stellar mass formed</td>
<td>$M_\star/M_\odot$</td>
<td>$(1, 10^{13})$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td>SFH</td>
<td>Metallicity</td>
<td>$Z_\star/Z_\odot$</td>
<td>$(0.2, 2.5)$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td>SFH</td>
<td>Falling slope</td>
<td>$\alpha$</td>
<td>$(0.1, 10^3)$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td>SFH</td>
<td>Rising slope</td>
<td>$\beta$</td>
<td>$(0.1, 10^3)$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td>SFH</td>
<td>Peak time</td>
<td>$\tau$/Gyr</td>
<td>$(0.1, t_{\text{obs}})$</td>
<td>uniform</td>
<td></td>
</tr>
<tr>
<td>Dust</td>
<td>Attenuation at 5500 Å</td>
<td>$A_V$/mag</td>
<td>$(0, 4)$</td>
<td>uniform</td>
<td></td>
</tr>
<tr>
<td>Dust</td>
<td>Deviation from Calzetti et al. (2000) slope</td>
<td>$\delta$</td>
<td>$(-0.3, 0.3)$</td>
<td>Gaussian</td>
<td>$\mu = 0.0, \sigma = 0.1$</td>
</tr>
<tr>
<td>Dust</td>
<td>Strength of 2175 Å bump</td>
<td>$B$</td>
<td>$(0, 5)$</td>
<td>uniform</td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>Zeroth order</td>
<td>$P_0$</td>
<td>$(0.5, 1.5)$</td>
<td>Gaussian</td>
<td>$\mu = 1.0, \sigma = 0.25$</td>
</tr>
<tr>
<td>Calibration</td>
<td>First order</td>
<td>$P_1$</td>
<td>$(-0.5, 0.5)$</td>
<td>Gaussian</td>
<td>$\mu = 0.0, \sigma = 0.25$</td>
</tr>
<tr>
<td>Calibration</td>
<td>Second order</td>
<td>$P_2$</td>
<td>$(-0.5, 0.5)$</td>
<td>Gaussian</td>
<td>$\mu = 0.0, \sigma = 0.25$</td>
</tr>
<tr>
<td>Noise</td>
<td>White-noise scaling</td>
<td>$a$</td>
<td>$(0.1, 10)$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>Correlated noise amplitude</td>
<td>$b/f_{\text{max}}$</td>
<td>$(0.0001, 1)$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td>Noise</td>
<td>Correlation length</td>
<td>$l/\Delta \lambda$</td>
<td>$(0.01, 1)$</td>
<td>log</td>
<td></td>
</tr>
</tbody>
</table>
4.3 Methodology and sample selection

The VANDELS observations described in Section 4.2 produce an initial sample of 269 quiescent galaxies with robust spectroscopic redshifts, of which 87 per cent have $1 < z_{\text{spec}} < 1.5$. In this section, I describe the selection of the final quiescent sample that I use for my analysis.

4.3.1 Spectro-photometric fitting

I use Bagpipes (Carnall et al., 2018) to simultaneously fit the available spectroscopic and photometric data for my initial sample of 269 quiescent galaxies. I incorporate several improvements to the model used to fit the VANDELS photometric catalogues in Hamadouche et al. (2022) (based on Carnall et al. 2019a), which I briefly describe below.

I use a double-power-law star-formation history model, employing the updated 2016 versions of the BC03 stellar population synthesis models (Bruzual & Charlot, 2003; Chevallard & Charlot, 2016). I also vary the stellar metallicity from $Z_* = 0.2 - 2.5Z_\odot$ using a logarithmic prior. I use the Salim et al. (2018) dust attenuation law, which parameterises the dust-curve shape through a power-law deviation, $\delta$, from the Calzetti et al. (2000) law. Nebular continuum and emission lines are modelled using the Cloudy photoionization code (Ferland et al., 2017b), using a method based on that of Byler et al. (2017). I assume a fixed ionization parameter of $\log_{10}(U) = -3$. Full details of the free parameters and priors used in my fitting are provided in Table 4.1.

I take into account systematic uncertainties in the observed spectra of the galaxies by applying additive noise and multiplicative calibration models (e.g., van der Wel et al. 2016; Cappellari 2017; Johnson et al. 2021b). I follow the approach outlined in Section 4 of Carnall et al. (2019a), by fitting a second-order multiplicative Chebyshev polynomial to account for problems with flux calibration, and an additive Gaussian process model with an exponential squared kernel to model correlated additive noise between spectral pixels in the data.
Figure 4.1 The distribution of the final mass-complete sample of 114 quiescent VANDELS galaxies on the $UVJ$ plane, highlighting trends between the rest-frame $UVJ$ colours and (left to right) $D_n4000$, mass-weighted age and stellar metallicity. The first two panels show that redder rest-frame $UVJ$ colours correlate with higher $D_n4000$ values and older mass-weighted ages, consistent with literature results (e.g., Belli et al., 2019a; Carnall et al., 2019a). The last panel, colour-coded by metallicity, does not demonstrate any significant trend.
4.3.2 A mass-complete sample

To ensure that my final sample is mass complete, I restrict the sample to \( \log_{10}(M_*/M_\odot) \geq 10.3 \) and \( 1.0 \leq z \leq 1.3 \) (see Carnall et al., 2019a). In this context, a mass-complete sample means that for the sample of galaxies that are randomly drawn from the parent VANDELS photometric catalogue, the spectroscopic sample provides an accurate representation of the quiescent galaxy population within the aforementioned redshift and stellar-mass ranges. In addition, I require members of the sample to have \( U - V > 0.88 \times (V - J) + 0.69 \), in order to remove green-valley galaxies. This has been shown to be broadly equivalent to a specific SFR cut of \( \text{sSFR} < 0.2/t_\text{H} \), where \( t_\text{H} \) is the age of the Universe at the relevant redshift (Carnall et al., 2018). These criteria produce a sample of 139 quiescent galaxies.

To clean the quiescent sample of potential X-ray contaminants, I remove five objects with matches in either the Chandra Seven Mega-second catalogue (Luo et al., 2017) or the X-UDS catalogue (Kocevski et al., 2018) that cover the CDFS and UDS fields, respectively. All five galaxies with X-ray matches also display strong [OII] emission in their rest-frame UV spectra. I also search for potential radio-loud AGN using the Very Large Array (VLA) 1.4 GHz data available for both fields (Simpson et al., 2006; Bonzini et al., 2013), finding one additional AGN candidate. This object was not removed from the quiescent sample because it does not display strong [OII] emission.

Finally, I remove one galaxy whose spectrum is highly contaminated (due to a nearby object), leaving a final, cleaned sample of 114 quiescent VANDELS galaxies. This final sample is shown on the UVJ plane in Fig. 4.1, colour-coded by mass-weighted age, \( D_{n4000} \) and stellar metallicity.

4.3.3 Stacked spectra

In the sections of my analysis where I make use of stacked spectra, I use the following standard procedure to produce the stacks. I first de-redshift and then re-sample each individual spectrum onto a uniform 2.5 Å wavelength grid using the spectral re-sampling module SPECTRes (Carnall, 2017). Prior to stacking, I normalise by the median flux across the wavelength range 3500 – 3700 Å. The median flux across all spectra in each pixel is then calculated. Uncertainties in
the stacked spectra are calculated using the standard error on the median.

For stacked spectra where I wish to show correlations with D_n,4000, the spectrum is then normalised by the median flux in the blue continuum band of the D_n,4000 index, such that the median flux density in the red continuum band corresponds to the D_n,4000 index of the stacked spectrum. I calculate D_n,4000 using the same prescription outlined in Section 3.4 of Hamadouche et al. (2022).

### 4.3.4 Size measurements

I use the Galfit (Peng et al., 2002) size measurements from Hamadouche et al. (2022) for 110/114 galaxies in the final sample. For the remaining galaxies I adopted an identical procedure to Hamadouche et al. (2022), using HST F160W images for the three galaxies within the CANDELS footprint and HST ACS F850LP imaging in CDFS for the single galaxy lying outside the CANDELS footprint.

### 4.4 Results

In this section, I present the results obtained from full-spectral fitting of the final quiescent galaxy sample.

#### 4.4.1 Trends with rest-frame UVJ colour

In Fig. 4.1, I show the distribution of the final mass-complete sample of VANDELS quiescent galaxies (see Section 4.3.2) on the rest-frame UVJ diagram, coloured by mass-weighted age, D_n,4000, and stellar metallicity. In the first panel, I see that the galaxies with redder U–V and V–J colours, also tend to have higher mass-weighted ages, consistent with recent literature results (e.g., Belli et al., 2019a; Carnall et al., 2019a). In the next panel, the trend with D_n,4000 is similar; lighter-coloured points indicate higher D_n,4000 values, which is consistent with the trend seen in other samples at similar redshifts (e.g. Whitaker et al., 2013). The final panel of Fig. 4.1 shows the sample coloured by metallicity. There is no obvious trend between metallicity and UVJ colour. The individual metallicities I measure are however consistent with scattering around the median value of
log\(_{10}(Z_*/Z_\odot) = -0.13 \pm 0.08\) determined from an optical+NIR stack at \(z \sim 1.15\) by Carnall et al. (2022b).

### 4.4.2 The relationship between stellar mass and age

I present my results for the stellar-mass vs age relation in Fig. 4.2. I plot redshift of formation, \(z_{\text{form}}\), against stellar mass. The right-hand axis shows the corresponding formation time, \(t_{\text{form}}\), measured forwards from the Big Bang. In this chapter, I take \(t_{\text{form}}\) and \(z_{\text{form}}\) to be the age of the Universe and redshift corresponding to the mass-weighted age of the galaxy. I see a clear negative correlation, albeit with considerable scatter. A trend is also visible between \(t_{\text{form}}\) and \(D_{n4000}\) in Fig. 4.2, with galaxies that have earlier formation times exhibiting higher values of \(D_{n4000}\), as would be expected.

I fit a linear relationship between \(t_{\text{form}}\) and \(\log_{10}(M_*/M_\odot)\), including an intrinsic scatter term, using the nested sampling Monte Carlo algorithm MLFriends (Buchner, 2016, 2019) using the UltraNest package (Buchner, 2021). I derive a best-fitting relation of:

\[
(t_{\text{form}} / \text{Gyr}) = 2.85^{+0.08}_{-0.09} - 1.20^{+0.28}_{-0.27} \log_{10}(M_*/10^{11} \text{ M}_\odot).
\]  

(4.1)

I also find an intrinsic scatter of \((t_{\text{form}} / \text{Gyr}) = 0.51^{+0.09}_{-0.07}\). I show the fit to the data in Fig. 4.2 (purple line) with the shaded region showing the 1\(\sigma\) confidence interval. I also show the result derived by Carnall et al. (2019a), using the VANDELS DR2 sample of 53 galaxies, which is a subset of the new 114-galaxy final VANDELS sample. The slope of my new relation is in good agreement with this previous result, however I recover a \(\sim 300\) Myr offset towards younger ages.

To explore the origin of this offset, I re-fit the linear model to the sub-sample of 53 galaxies used by Carnall et al. (2019a), obtaining a result consistent with theirs. I therefore conclude that this offset is a result of the expanded statistical VANDELS DR4 sample, which contains more galaxies that have high stellar masses and lower formation redshifts with respect to the DR2 subset. I also explore the median relationship between stellar mass and age in my sample by binning the galaxies into equal-width stellar-mass bins of 0.3 dex. This is shown in the right-hand panel of Fig. 4.2, where the relationship is clear up to stellar

\(1\)https://johannesbuchner.github.io/UltraNest/
masses of \( \log_{10}(M_\star/M_\odot) \approx 11.2 \). I discuss this relationship in more detail in Section 4.5.1, making comparisons to relevant literature, which are shown in Fig. 4.5.
Figure 4.2 *Left:* Stellar mass versus formation redshift for my final mass-complete VANDELS DR4 quiescent galaxy sample. The sample is colour-coded by D₄₀₀₀₀, demonstrating a clear preference for higher D₄₀₀₀₀ values at earlier formation times. The relationship I fit in Section 4.4.2 is shown in purple, with the 1σ confidence interval shaded. The relation derived for a smaller sample from VANDELS DR2 by Carnall et al. (2019a) is shown in blue. *Right:* Median formation redshifts for my sample in 0.3-dex bins. The error bars are the standard errors for tf orm / Gyr and log₁₀(Mₘᵣₓ/M☉) in each stellar-mass bin. A clear negative correlation is observed. The final bin contains only ten objects above log₁₀(Mₘᵣₓ/M☉) > 11.2, meaning that the apparent flattening of the relationship is challenging to assess.
4.4.3 The oldest galaxy at $z \simeq 1$

From inspection of Fig. 4.2, it is clear that there is a single galaxy (ID: 111129) which falls significantly below the main stellar mass vs age distribution, with a formation time of $t_{\text{form}} = 0.75^{+0.41}_{-0.29}$ Gyr ($z_{\text{form}} = 7.02^{+3.06}_{-2.07}$), and a quenching time ($t_{\text{quench}}$ is defined as the age of the Universe at which the normalised star-formation rate, $nSFR$ - the current SFR as a fraction of the time-averaged SFR over the whole SFH - as defined in Carnall et al. 2018, first falls below 0.1) of $t_{\text{quench}} = 1.94^{+0.86}_{-0.67}$ Gyr ($z_{\text{quench}} = 3.23^{+1.41}_{-0.93}$) after the Big Bang, respectively. Given recent reports, based on the first data from JWST, of the assembly of significant numbers of massive galaxies during the first billion years (e.g., Labbe et al. 2022), and their subsequent quenching during the second billion years (e.g., Carnall et al. 2022a), this is clearly an object of significant interest.

Upon inspection of the spectrum of this galaxy, and comparison with the best-fit model from my BAGPIPES fitting, I find there is a significant offset between the physical model and observed spectrum in the rest-frame wavelength range $3844 - 3884$ Å. This is consistent with the $\lambda = 3860$ Å CN molecular feature (Smith & Norris, 1983; Balogh et al., 1999b). Motivated by this, I re-inspect the data and best-fit models for my whole sample, finding 10 galaxies in total (including ID: 111129) that clearly demonstrate this feature (see Section 4.5.3). Four example objects from this sub-sample are shown in Fig. 4.3. I discuss the physical interpretation of this feature in Section 4.5.3.
Figure 4.3 Four galaxies in the sample that display enhanced CN absorption. The VANDELS data are shown in grey. The best-fitting full BAGPIPES models (physical + calibration + noise) are shown in purple. The physical + calibration model, excluding the additive Gaussian process noise model, is shown in black. The shaded wavelength region (3844 – 3884 Å) highlights the CN molecular feature.
4.5 Discussion

In Section 4.4, I report the relationship between stellar mass and age from full spectral fitting of the mass-complete VANDELS quiescent sample. In this section, I discuss my results, focusing on relationships between age, $UVJ$ position, $D_n4000$ and metallicity evident within the sample. I also explore a subset of galaxies which appear to exhibit spectral features associated with significant $\alpha$—enhancement.

4.5.1 The formation times of quiescent galaxies

Over the past decade, extensive research has been conducted into the star-formation histories and ages of quiescent galaxies. This has revealed a sub-population of extremely old galaxies, which formed very early in cosmic history (e.g., Glazebrook et al. 2017; Schreiber et al. 2018; Valentino et al. 2020). These galaxies tend to have higher stellar masses and more compact morphologies than is typical for the quiescent population. In order to constrain the build-up of the quiescent population across cosmic time, and reveal the fate of these oldest, most extreme systems, detailed knowledge of the stellar mass vs stellar age relationship as a function of observed redshift is required. The stellar mass vs stellar age relation presented in Section 4.4.2 is based on the robust, mass-complete VANDELS spectroscopic sample. In this section, I compare these results with similar studies in the literature, across a broad redshift range.

My results are placed into the context of recent literature in Fig. 4.5, which shows results derived by Gallazzi et al. (2005, 2014); Choi et al. (2014); Onodera et al. (2015); Schreiber et al. (2018); Belli et al. (2019a); Carnall et al. (2019a); Merlin et al. (2019); Estrada-Carpenter et al. (2020) and Tacchella et al. (2022), with the stellar mass vs age relations derived in various observed redshift ranges over-plotted. For several data-sets shown in the figure, no average relationship between stellar mass and age is calculated by the authors. In these cases, I perform a fit to the individual galaxy masses and ages, using the same method outlined in Section 4.4.2.
Figure 4.4 Stellar mass versus formation redshift and quenching redshift (in the top and bottom panels respectively) for my final sample of VANDELS quiescent galaxies. The galaxies are colour-coded by $D_n4000$, highlighting that higher values of $D_n4000$ are observed for galaxies with earlier formation times. Circled galaxies are those that display enhanced CN absorption in their spectra (see Sections 4.4.3 and 4.5.3).
Slopes of the observed relationships

The slope of the stellar mass vs age relationship is intimately connected to the physics of quenching in massive galaxies. I derive a slope for the VANDELS DR4 sample of $1.20^{+0.28}_{-0.27}$ Gyr per decade in mass. As can be seen from Fig. 4.5, this is in good agreement with the other literature relationships shown. At the highest redshifts, the sample of Schreiber et al. (2018) at $3.0 < z < 4.0$ displays a slope consistent with my result at $z \approx 1.1$ to within $2\sigma$. In the local Universe, the results of Gallazzi et al. (2005) also display a very similar slope. This suggests the slope of the stellar mass vs age relationship for massive quiescent galaxies remains broadly constant across cosmic history.

As can be seen from Fig. 4.5, the results of Belli et al. (2019a), who study a sample of 23 massive quiescent galaxies at $1.5 < z < 2.5$ using data from the Keck-MOSFIRE spectrograph, suggest a steeper relation between stellar mass and age. I perform a fit to their galaxies on the stellar mass-age plane, finding a slope of $1.73^{+0.40}_{-0.40}$ Gyr per decade in mass. Whilst this is a steeper slope than my result, it is not strongly in tension, owing to the relatively small samples involved.

In Carnall et al. (2019a) and Tacchella et al. (2022), the authors compare the observed stellar mass vs age relationship with the predictions of cosmological simulations. Carnall et al. (2019a) derive this relationship from snapshots of the 100 $h^{-1}$ Mpc box runs of SIMBA (Davé et al., 2019) and ILLUSTRIS TNG (Nelson et al., 2018) at $z = 0.1$ and $z = 1.0$. They find that these simulations predict slopes of $\approx 1.5$ Gyr per decade in mass in the local Universe, but much shallower slopes at $z \sim 1$, with Tacchella et al. (2022) reporting similar findings for ILLUSTRIS TNG at $z \sim 0.7$.

My results are consistent with the predicted slopes of $\approx 1.5$ Gyr per decade in mass from these two simulations in the local Universe ($z \sim 0.1$). However, my results again suggest that simulations should seek to reproduce the same, steeper stellar mass vs age relationship for massive quiescent galaxies throughout cosmic history.

Normalisations of the observed relationships

The redshift evolution of the average age of quiescent galaxies at fixed stellar mass is influenced primarily by the quenching of new galaxies that join the quiescent
population over time (e.g. McLeod et al. 2021). This effect is sometimes known as progenitor bias. The expected evolution of the relationships shown in Fig. 4.5 due to progenitor bias would be a steady increase in normalisation from high to low redshift. The rate of this decrease in formation redshift with decreasing observed redshift is also highly sensitive to the effects of merger and rejuvenation events.

Unfortunately, this idealised smooth upward evolution with decreasing redshift is not observed in Fig. 4.5. Whilst studies of galaxy samples at the highest observed redshifts typically return the highest formation redshifts, and the local-Universe study of Gallazzi et al. (2005) returns the lowest, there is confusion between these extremes. I report later average formation times than all studies targeting higher-redshift galaxy samples; however, both Gallazzi et al. (2014) and Tacchella et al. (2022) also report earlier average formation times than this study, despite analysing samples at lower observed redshifts ($z \approx 0.7$, as opposed to $z \approx 1.1$ for my sample).

As has been discussed in several recent works (Tacchella et al., 2022; Carnall et al., 2022b), these differences are likely the result of methodological differences between studies. The two most important of these are different definitions of age (mass-weighted vs light-weighted), and differences between parametric and non-parametric SFH models, the latter of which typically return older stellar ages (Carnall et al., 2019b; Leja et al., 2019a,b). For this reason, a clear understanding of the redshift evolution of the normalisation of this relationship requires a study applying the same methodology to observed samples at a wide range of redshifts.
**Figure 4.5** Stellar mass versus formation redshift for massive quiescent galaxies, taken from a range of studies across a wide range in observed redshift. My sample of VANDELS DR4 quiescent galaxies are shown as circles, and my best-fit line is over-plotted. For some studies that do not report best-fitting relationships between stellar mass and age, I have fitted their results for individual galaxies using the methodology described in Section 4.4.2. These studies broadly agree on the slope of the relationship, which is found to be consistent at $\simeq 1.5$ Gyr per decade in mass across cosmic history. The normalisation of these relationships does not follow the expected smooth evolution with observed redshift, likely due to methodological differences (see Section 4.5.1).
Number density of the oldest galaxies at $z \simeq 1$

Fig. 4.4 shows the formation and quenching redshifts of the VANDELS quiescent sample versus stellar mass, in the top and bottom panels, respectively. A significant number of galaxies have formation redshifts of $z_{\text{form}} > 3$, all of which have stellar masses of $\log_{10}(M_*/M_\odot) \geq 10.6$. Only one galaxy has a formation redshift of $z_{\text{form}} > 5$ (see Section 4.4.3).

Only two galaxies in this sample have quenching redshifts $z_{\text{quench}} > 3$. These objects are of particular interest, given that current simulations seem to underpredict the numbers of galaxies that quenched at these very early times (see Schreiber et al., 2018; Cecchi et al., 2019; Tacchella et al., 2022), possibly due to an additional mechanism capable of causing a rapid early shutdown of star formation, not yet included in simulations. I calculate the number density of galaxies in my VANDELS sample that have $z_{\text{quench}} > 3$, recovering a value of $1.12^{+1.47}_{-0.72} \times 10^{-5}$ Mpc$^{-3}$ (with Poisson uncertainties calculated using the confidence intervals presented in Gehrels, 1986). This is consistent with the results of Schreiber et al. (2018), who calculate a number density for quiescent galaxies observed at $3 < z < 4$ of $(1.4 \pm 0.3) \times 10^{-5}$ Mpc$^{-3}$. This preliminary agreement is encouraging, though my sample of such old quiescent galaxies is very small. My result is consistent with neither rejuvenation or mergers having a significant impact on this population from $1 < z < 3$. For example, if there were no quiescent galaxies with $z_{\text{quench}} > 3$ in my sample, this would suggest that the majority of $z > 3$ quiescent galaxies experience mergers and/or rejuvenation by $z \simeq 1$. However, much larger samples will be necessary to conduct detailed comparisons of this nature.
Figure 4.6 The stacked spectra of my final sample of galaxies (for galaxies with $\log_{10}(M_*/M_{\odot}) \geq 10.6$) in two bins based on their position on the UVJ-diagram. The galaxies are split into blue UVJ and red UVJ populations (see inset) following a method similar to the one adopted by Whitaker et al. (2013). As detailed in the main text, I see an increase in $D_n4000$ and median mass-weighted age with increasing UVJ colour (from blue to red).
Table 4.2  The D_n4000 values calculated from the stacked spectra shown in Fig. 4.6. I also report median values in each of the three bins for D_n4000 and mass-weighted age, where N represents the number of galaxies in each bin.

<table>
<thead>
<tr>
<th>UVJ position</th>
<th>N</th>
<th>D_{n4000}^{stack}</th>
<th>D_{n4000}^{med}</th>
<th>age / Gyr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue UVJ</td>
<td>45</td>
<td>1.57 ± 0.01</td>
<td>1.58 ± 0.03</td>
<td>2.45 ± 0.14</td>
</tr>
<tr>
<td>Red UVJ</td>
<td>47</td>
<td>1.66 ± 0.02</td>
<td>1.63 ± 0.04</td>
<td>2.80 ± 0.12</td>
</tr>
</tbody>
</table>

4.5.2  The relationship between colour and age

Next, I consider the relationship between galaxy stellar age and position on the UVJ diagram, performing a stacking analysis of my sample using two bins in rest-frame colour. Following the approach of Whitaker et al. (2013), I divide the sample into two bins on the UVJ diagram, separated using the criteria:

\[(U - V) = -1.14 \times (V - J) + 3.10, \quad (4.2)\]

as illustrated in the inset panel of Fig. 4.6 by the dot-dashed line. In order to minimise the impact of the correlation between stellar mass and age, I additionally restrict both UVJ bins to only include galaxies with \(\log_{10}(M_*/M_\odot) \geq 10.6\). Adopting these criteria produces bins containing similar numbers of objects and comparable median stellar masses; \(\log_{10}(M_{\text{med}}/M_\odot) = 10.86 \pm 0.03\) and \(11.00 \pm 0.04\) for the blue and red UVJ bins, respectively.

In the main panel of Fig. 4.6, I show stacked spectra constructed from the objects in each UVJ bin and in Table 2, I present D_n4000 values calculated from the stacked spectra, together with the median D_n4000 values and stellar ages of the objects in each bin. It is clear from these results that galaxies within the red UVJ bin display larger D_n4000 values and older stellar ages than their counterparts within the blue UVJ bin. This is consistent with the expected correlation between age and UVJ colour (e.g., Whitaker et al., 2013; Belli et al., 2019a), and with the trends observed in the centre panel UVJ diagram in Fig. 4.1, which is colour-coded by mass-weighted age from the Bagpipes fits. This stacking experiment independently confirms and quantifies the age-colour trend, given the offset in median D_n4000 values calculated for the red and blue UVJ colour bins. I note that Whitaker et al. (2013) find ages of \(0.9^{+0.2}_{-0.1}\) Gyr and \(1.6^{+0.5}_{-0.4}\) Gyr for their blue and red UVJ sub-samples, based on stacked grism spectra of quiescent galaxies.
at $1.4 < z < 2.2$. Within the large uncertainties, this difference of $0.7 \pm 0.5$ Gyr is fully consistent with the difference of $0.4 \pm 0.2$ Gyr I find from my analysis.

### 4.5.3 Quenching timescales

As discussed in the introduction, recent studies of the star-formation histories of quiescent galaxies point to the existence of multiple quenching channels (e.g., Belli et al., 2019a; Carnall et al., 2019a; Tacchella et al., 2022). In general, the star-formation histories I derive for the VANDELS quiescent sample are consistent with this picture, displaying a range of formation and quenching times. However, to investigate this issue in more detail it is interesting to define a quenching timescale parameter: $\Delta t_{\text{quench}}$. In this work, $t_{\text{quench}}$ is defined as the age of the Universe at which the normalised star-formation rate ($\text{nSFR}$; see Carnall et al. 2018) falls below 0.1, corresponding to the time after the Big Bang at which a galaxy is labelled as quiescent by my selection criteria. Therefore, the quenching timescale is naturally defined as:

$$\Delta t_{\text{quench}} = t(z_{\text{quench}}) - t(z_{\text{form}}).$$

In Fig. 4.7, I plot quenching timescale versus stellar mass for the VANDELS quiescent galaxies. It is clear that within my sample there is not a significant correlation between quenching timescale and stellar mass, with some of the highest mass galaxies having quenching timescales of $2 - 3$ Gyr, while others quench in significantly less than 1 Gyr. The mean quenching timescale for my full sample is $\Delta t_{\text{quench}} = 1.4 \pm 0.1$ Gyr.

Although the large scatter observed within the VANDELS sample in Fig. 4.7 may be a result of intrinsic galaxy-to-galaxy variations, it is still important to note the fact that properties such as star-formation histories, ages and quenching times can be affected by the fitting method (see e.g. Pforr et al., 2012; Carnall et al., 2019b; Leja et al., 2019a).

Throughout this chapter, I have used a double-power law parametric SFH, which is more flexible than other parametric SFHs (due to it allowing independent rising and falling phases) and is also a better estimator of stellar masses and ages (Carnall et al., 2018). Although parametric SFHs (such as the double-power law) appear to describe the majority of simulated galaxy populations well, they are
not without fault; for example, parametric SFHs fail to model sharp transitions in SFR as accurately as non-parametric SFHs (Leja et al., 2019a).

For non-parametric models, SFR and ages have been shown to be more dependent on the priors used, than e.g. stellar masses (Leja et al., 2019a), however, the errors on these parameters are larger and thus more realistic than the smaller errors produced by parametric SFHs. In Fig. 4.7, the quenching timescales of the galaxies appear to be well-constrained, however these error bars may not be truly representative of the uncertainty on this parameter due to these SFH modelling effects. In future work, I will extend my methodology to extract quenching timescales from quiescent galaxy samples using non-parametric SFHs, in order to explore the effects of different approaches to modelling star-formation histories. This will allow for a more quantitative understanding of the mechanisms by which these galaxies have quenched, and give further insight into their evolution since quenching.

Figure 4.7 Quenching timescale ($\Delta t_{\text{quench}}$) versus stellar mass for the full VANDELS quiescent galaxy sample. The value of the Dn4000 index is shown by the colour bar.
The CN molecular feature

In Section 4.4.3 I highlighted the object (ID: 111129) with the earliest formation time \((t_{\text{form}} = 0.75^{+0.41}_{-0.29} \text{ Gyr}; \ z_{\text{form}} = 7.02^{+3.06}_{-2.07})\) in the VANDELS sample. I also noted that this object displayed a significant offset between the BAGPIPES physical model and the observed spectrum around the CN molecular feature at \(\lambda = 3860 \ \text{Å}\).

Within the context of constraining the star-formation histories of quiescent galaxies, the CN molecular features are of interest because their strength is known to increase with stellar population age (e.g., Nantais et al., 2013; Choi et al., 2014) and they have also been identified as an indicator of \(\alpha-\)enhancement (Thomas et al., 2003).

Historically, the CN molecular features at \(\sim 3860 \ \text{Å}\) and \(\sim 4125 \ \text{Å}\) have been used to infer Nitrogen abundances in chemically peculiar stars, with the strength of the CN feature at 4125 Å quantified by the Lick indices CN\(_1\) and CN\(_2\). The anomalous strength of the CN absorption seen in globular clusters within the Local Group is attributed to enhanced Nitrogen abundance, with many studies finding anti-correlations between CN and CH (which traces the carbon abundance) (e.g., Smith & Norris, 1983; Burstein et al., 1984; Smith, 1987). Moreover, fitting the Lick indices of 20 extra-galactic globular clusters with SSP models, Proctor et al. (2004) highlight the poor fits to CN indices caused by enhanced Nitrogen abundance.

Studying a sample of elliptical galaxies and globular clusters, Thomas et al. (2003) find that a Nitrogen abundance enhancement of a factor of \(\sim 3\) with respect to other alpha elements is required to reproduce the observed CN\(_1\) and CN\(_2\) indices. Interestingly, this study also shows that CN absorption strength increases with \(\alpha-\)enhancement at fixed total metallicity, mainly due to an anti-correlation with iron abundance. As a result, the strength of the CN absorption features could provide important information on the typical star-formation timescales of high-redshift quiescent galaxies (e.g., Thomas et al., 2002, 2010).

Recent studies of passive galaxies at \(z \simeq 1\) show no clear evidence for evolution in the level of \(\alpha-\)enhancement over the last \(\simeq 8 \ \text{Gyr}\), typically finding values of \([\text{Mg/Fe}] \simeq 0.2\) (Kriek et al., 2019; Carnall et al., 2022b), consistent with observations in the local Universe (Conroy et al., 2014). Although some studies have identified a small number of objects with significantly higher \(\alpha-\)enhancement (e.g., Kriek et al., 2016; Jafariyazani et al., 2020), this has been
attributed to their extreme stellar masses ($\log_{10}(M_*/M_\odot) \geq 11.5$), consistent with our current understanding that more-massive early-type galaxies are more $\alpha$—enhanced than their less-massive counterparts, due to their shorter formation timescales.

**Selection of the CN enhanced sub-sample**

In order to investigate the prevalence of the CN molecular feature in the VANDELS sample, I now proceed to calculate a CN index. During the spectral fitting with BAGPIPES, once the model has been calibrated for systematic effects by the multiplicative polynomial model, any remaining mismatch to the data around the CN feature is accounted for by the Gaussian process correlated noise model. Therefore, within the wavelength range $3844 - 3884$ Å, I define the CN index as the ratio of the median flux in the data and the median flux of the BAGPIPES physical model multiplied by this polynomial but excluding the Gaussian process noise model. This is the ratio of the black model and grey data in Fig. 4.3 within the shaded wavelength range. In Fig. 4.9 I show a histogram of this CN index for the final VANDELS quiescent galaxy sample. It can be seen that the distribution of the CN index has a median value of 1.05, offset from unity, and shows a tail towards higher values. For comparison, the green shaded histogram shows the equivalent index calculated within a featureless continuum region short-ward of the CN feature, from $3450 - 3490$ Å. As expected, the distribution of index values in this comparison spectral region is symmetric.
Figure 4.9 Histogram of the CN index (see main text in Section 4.5.3) calculated within the wavelength range $3844 - 3884\,\text{Å}$ (solid line). The green shaded histogram shows the equivalent index calculated on a nearby continuum region free from spectral features. The dashed and dashed-dotted lines correspond to the mean values of the two distributions (see text for discussion).

and centred on unity. This corresponds to a zero average correction being made by the Gaussian process correlated noise model over this comparison wavelength range, whereas on average a negative Gaussian process correction is required to explain the data within the CN index wavelength range.

To define the sub-sample of objects that display enhanced CN absorption, I initially select the 14 objects with a CN index greater than 1.15. Visual inspection of these objects confirms that 10 unambiguously display the CN feature, with the remaining four having spectra that are too noisy in the relevant wavelength range to return robust CN index measurements. I additionally re-inspect the entire sample (an additional 100 objects), but find no further objects that unambiguously display this feature. As a result, I consider the 10 unambiguous objects with a CN index greater than 1.15 as my final CN enhanced sub-sample.
Table 4.3  Relevant physical properties of the galaxies within the CN enhanced sub-sample (ordered by $t_{\text{form}}$).

<table>
<thead>
<tr>
<th>ID</th>
<th>$z_{\text{spec}}$</th>
<th>$Z_{\ast}/Z_{\odot}$</th>
<th>$\log_{10}(M_{\ast}/M_{\odot})$</th>
<th>$t_{\text{form}}$/Gyr</th>
<th>$t_{\text{quench}}$/Gyr</th>
<th>Dn4000</th>
<th>$f_{\text{mod}}/f_{\text{data}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>018951</td>
<td>1.093</td>
<td>$0.66_{-0.06}^{+0.10}$</td>
<td>$10.38_{-0.05}^{+0.08}$</td>
<td>$3.89_{-0.27}^{+0.17}$</td>
<td>$4.27_{-0.17}^{+0.22}$</td>
<td>1.72 ± 0.01</td>
<td>1.16</td>
</tr>
<tr>
<td>005756</td>
<td>1.251</td>
<td>$0.55_{-0.06}^{+0.08}$</td>
<td>$10.58_{-0.11}^{+0.04}$</td>
<td>$3.60_{-0.10}^{+0.35}$</td>
<td>$3.98_{-0.26}^{+0.24}$</td>
<td>1.60 ± 0.03</td>
<td>1.20</td>
</tr>
<tr>
<td>018916</td>
<td>1.094</td>
<td>$0.68_{-0.09}^{+0.11}$</td>
<td>$10.75_{-0.04}^{+0.05}$</td>
<td>$3.08_{-0.73}^{+0.33}$</td>
<td>$4.85_{-0.13}^{+0.19}$</td>
<td>1.74 ± 0.01</td>
<td>1.15</td>
</tr>
<tr>
<td>140204</td>
<td>1.118</td>
<td>$0.54_{-0.08}^{+0.09}$</td>
<td>$11.27_{-0.05}^{+0.03}$</td>
<td>$2.57_{-0.29}^{+0.34}$</td>
<td>$3.17_{-0.43}^{+0.60}$</td>
<td>1.70 ± 0.01</td>
<td>1.17</td>
</tr>
<tr>
<td>003647</td>
<td>1.097</td>
<td>$0.65_{-0.07}^{+0.12}$</td>
<td>$11.09_{-0.04}^{+0.03}$</td>
<td>$2.56_{-0.47}^{+0.38}$</td>
<td>$3.48_{-0.59}^{+0.66}$</td>
<td>1.84 ± 0.01</td>
<td>1.19</td>
</tr>
<tr>
<td>138449</td>
<td>1.127</td>
<td>$0.62_{-0.05}^{+0.07}$</td>
<td>$11.37_{-0.04}^{+0.04}$</td>
<td>$2.40_{-0.46}^{+0.34}$</td>
<td>$2.94_{-0.42}^{+0.48}$</td>
<td>1.77 ± 0.01</td>
<td>1.17</td>
</tr>
<tr>
<td>102698</td>
<td>1.221</td>
<td>$0.58_{-0.05}^{+0.07}$</td>
<td>$10.92_{-0.03}^{+0.03}$</td>
<td>$2.17_{-0.25}^{+0.38}$</td>
<td>$3.59_{-0.94}^{+0.38}$</td>
<td>1.67 ± 0.01</td>
<td>1.17</td>
</tr>
<tr>
<td>197547</td>
<td>1.096</td>
<td>$0.73_{-0.08}^{+0.10}$</td>
<td>$11.04_{-0.05}^{+0.04}$</td>
<td>$2.09_{-0.42}^{+0.37}$</td>
<td>$4.02_{-0.35}^{+0.30}$</td>
<td>1.80 ± 0.01</td>
<td>1.18</td>
</tr>
<tr>
<td>018419</td>
<td>1.221</td>
<td>$0.96_{-0.16}^{+0.21}$</td>
<td>$11.18_{-0.05}^{+0.04}$</td>
<td>$2.07_{-0.29}^{+0.63}$</td>
<td>$4.58_{-0.22}^{+0.17}$</td>
<td>1.73 ± 0.01</td>
<td>1.21</td>
</tr>
<tr>
<td>111129</td>
<td>1.130</td>
<td>$0.86_{-0.10}^{+0.10}$</td>
<td>$11.15_{-0.03}^{+0.04}$</td>
<td>$0.75_{-0.29}^{+0.41}$</td>
<td>$1.94_{-0.67}^{+0.86}$</td>
<td>1.86 ± 0.01</td>
<td>1.21</td>
</tr>
</tbody>
</table>
Physical properties of the CN enhanced sub-sample

In Fig. 4.8 I show a stacked spectrum of the CN enhanced sub-sample and compare it to a stacked spectrum of the remaining galaxies in the full VANDELS quiescent galaxy sample. This figure clearly illustrates the enhanced absorption within the CN index wavelength range, which, as discussed in Section 4.5.3, has been linked to older stellar populations and α—enhancement. Relevant physical parameters returned by my Bagpipes fitting to the 10 objects within the CN enhanced sub-sample are displayed in Table 3.

As discussed above, multiple previous studies at low redshift have associated enhanced CN absorption with old stellar populations. For the VANDELS sample of quiescent galaxies at $z \simeq 1.1$, the median mass-weighted age of the CN enhanced sub-sample is $2.81 \pm 0.34$ Gyr, compared to $2.48 \pm 0.10$ Gyr for the main body of the VANDELS sample. It is clear that the trend for strong CN absorption to be related to increased stellar population age is present in my $z \simeq 1.1$ sample, although the difference in median ages is not statistically significant. As would be expected, the CN enhanced sub-sample also has a larger median stellar mass ($\log_{10}(M_\star/M_\odot) = 11.06 \pm 0.12$) compared with the rest of the sample ($\log_{10}(M_\star/M_\odot) = 10.86 \pm 0.03$) but again, the difference is not strongly significant. The CN sub-sample does have a significantly higher median value of $D_n4000$ ($1.73 \pm 0.03$ compared to $1.56 \pm 0.01$), but unfortunately this is somewhat inevitable, given that the CN index lies within the blue continuum band of the $D_n4000$ index.

Overall, it appears that the ten objects comprising the CN enhanced sub-sample are consistent with being older and higher mass than the average member of the $z \simeq 1.1$ sample of quiescent galaxies, although small number statistics prevents us from drawing any firm conclusions.

Star-formation histories of the CN enhanced sub-sample

In Fig. 4.10 I show the posterior star-formation histories of the CN enhanced sub-sample returned by Bagpipes. With the exception of a single galaxy (ID: 111129), which appears to be an isolated case of a very early formation and quenching time (see Section 4.4.3), the majority of the CN enhanced sub-sample have formation redshifts of $z_{\text{form}} = 2 - 3$ and display relatively short quenching timescales.
Given that $\alpha-$enhancement should be associated with short star-formation timescales, it is interesting to compare the star-formation timescales of the CN enhanced sub-sample with those of the sample as a whole. Defining the star-formation timescale as the width of the posterior SFH between the 16th and 84th percentiles, I find the CN sub-sample to have a median timescale of $1.15 \pm 0.34$ Gyr, compared to a median timescale of $1.52 \pm 0.10$ Gyr for the rest of the sample. Although the difference in star-formation timescale of $\approx 400$ Myr is clearly not statistically significant, it is consistent with enhanced CN absorption being connected with $\alpha-$enhancement.

Finally, it is interesting to note that the two youngest members of the CN enhanced sub-sample (ID: 018951 and ID: 005756) have stellar masses that are in the lowest quartile of the full VANDELS sample. This combination of relative youth and low stellar mass would not identify them as obvious candidates to display enhanced CN absorption. However, as can be seen from Fig. 4.10, both objects have very short star-formation timescales, consistent with them both being $\alpha-$enhanced.

In order to gain further insight into the physical properties and SFHs of the CN enhanced sub-sample, and the $z \approx 1.1$ VANDELS sample as a whole, it is clear that near-IR spectroscopy is required. In addition to placing significantly tighter constraints on the SFHs and overall metallicities (Carnall et al., 2022b), such rest-frame optical spectroscopy would allow access to several indices sensitive to $\alpha-$enhancement and Nitrogen abundance (e.g. CN$_1$, CN$_2$, Ca4227 and Mgb). Over the next few years, the MOONS spectrograph (Cirasuolo et al., 2020) will be able to provide the necessary near-IR spectroscopy for large samples of passive galaxies out to $z \approx 2.5$, while NIRSpec on JWST can in principle provide access to the full set of Lick indices out to $z \approx 6.5$. 

143
Figure 4.10  Star-formation histories for the 10 quiescent galaxies in my final sample which show enhanced CN absorption. The grey lines in the background are the SFHs for the rest of the galaxies in the sample ($N = 104$).
4.6 Conclusions

In this chapter, I have explored the relationships between stellar mass, age, star-formation history and quenching timescales for a robust spectroscopic sample of quiescent galaxies at $1.0 < z < 1.3$. The main results and conclusions can be summarised as follows:

1. I derive significantly improved constraints on the relationship between stellar population age and stellar mass for quiescent galaxies at $z \approx 1.1$. From the full VANDELS sample I derive an age-mass relation which has a slope of $1.20^{+0.28}_{-0.27}$ Gyr per decade in stellar mass.

2. Comparing to previous studies in the literature, I find good agreement on the slope of the age-mass relation for quiescent galaxies from the local Universe out to $z \approx 4$. The observed slope is in good agreement with the prediction from simulations at $z \approx 0$, but significantly steeper than simulations predict at $z \geq 1$.

3. The results of my spectro-photometric fitting predict that the number density of already quenched galaxies at $z \geq 3$ with stellar masses $\log_{10}(M_*/M_\odot) \geq 10.6$ is $1.12^{+1.47}_{-0.72} \times 10^{-5}$ Mpc$^{-3}$. Although subject to large uncertainties due to small-number statistics, this estimate is in good agreement with the latest measurements at $3 < z < 4$. The implication is that rejuvenation or merger events are not playing a major role in modulating the number density of the oldest massive quiescent galaxies within the redshift interval $1 < z < 3$, although they cannot be ruled out entirely.

4. I confirm previously reported results that quiescent galaxies with redder $UVJ$ colours are systematically older than their bluer counterparts, finding an off-set of $0.4 \pm 0.2$ Gyr in the median age of mass-matched samples.

5. The VANDELS sample of $z \approx 1.1$ quiescent galaxies displays a wide range of formation and quenching redshifts. I find that the median star-formation timescale is $1.5 \pm 0.1$ Gyr, where the timescale is defined as the width of the posterior SFH between the 16th and 84th percentiles. I find that the mean quenching timescale is $1.4 \pm 0.1$ Gyr, where $\Delta t_{\text{quench}} = t(z_{\text{quench}}) - t(z_{\text{form}})$. The oldest galaxy within the VANDELS sample (ID: 111129) has $z_{\text{form}} = 7.02^{+3.06}_{-2.07}$ and $z_{\text{quench}} = 3.23^{+1.41}_{-0.93}$.
6. I identify a small sub-sample of galaxies which exhibit enhanced absorption in the CN molecular feature at $\lambda = 3860 \text{ Å}$, which has previously been identified to correlate with old stellar population age and $\alpha-$enhancement. This CN-enhanced subsample displays older ages, higher stellar masses and shorter star-formation timescales than the rest of the sample, consistent with expectations for $\alpha-$enhancement. However, due to small number statistics, none of the differences between the CN sub-sample and the full sample are statistically significant, making it difficult to draw firm conclusions from this dataset alone.

Future studies using data from surveys such as PRIMER (Dunlop et al., 2021) and the JWST Advanced Deep Extragalactic Survey (JADES), as well as near-infrared ground-based spectroscopy from the MOONS spectrograph on the VLT will provide higher SNR and larger samples of quiescent galaxies out to $z \simeq 2.5$. Combining these data with more sophisticated galaxy fitting methods (e.g. non-parametric SFHs) will enable a better understanding of quiescent galaxy properties and quenching mechanisms out to higher redshift.
Chapter 5

The sizes and morphologies of star-forming and quiescent galaxies from $z = 0.25$ to $z = 2.25$

5.1 Introduction

One of the key observational results of the past few decades was derived using data from the Sloan Digital Sky Survey (SDSS York et al., 2000). These data revealed that the galaxy population is bimodal in colour, with galaxies being categorised into a ‘blue cloud’ and ‘red sequence’ (Strateva et al., 2001; Baldry et al., 2004). Observations show that galaxies with blue colours are mainly less-massive, star-forming discs, whereas red galaxies tend to be more-massive, quiescent spheroids.

Deep photometric studies of the galaxy stellar-mass function (GSMF) also established that at $z \lesssim 0.5$, quiescent galaxies come to dominate the global stellar-mass budget, increasing from 10 per cent at $z \simeq 3$ to 75 per cent at $z = 0$ (Peng et al., 2010; Muzzin et al., 2013b; McLeod et al., 2021). Quiescent galaxies are commonly separated from their star-forming counterparts based on rest-frame $UVJ$ colours up to $z \sim 2$ (Williams et al., 2009). More recently, significant effort has been invested into improving methods for robustly finding and selecting quiescent galaxies out to higher redshifts ($z < 3$, see Gould et al., 20147...
2023; Antwi-Danso et al., 2023) and recent spectroscopic studies have revealed the existence of quiescent galaxies out to the highest redshifts (3 < z < 5, see Carnall et al., 2023; Valentino et al., 2023).

With this in mind, there have been many studies aiming to explain the bimodality of the galaxy population, and how the mechanisms that quench star-formation are dependent on stellar mass and redshift. Galaxy evolution simulations have revealed that feedback mechanisms at early times are necessary to prevent star-formation and reproduce the bi-modality of the observed galaxy population (e.g. Somerville & Davé, 2015a, and references therein). At lower halo masses (between $10^{11} - 10^{12} \, M_\odot$), supernovae feedback, stellar winds and reionization are required to sustain gas-heating in the halo at early times. In contrast, at higher halo masses, active galactic nuclei (AGN) sustain the hot halo at later times. The first models incorporating AGN feedback into simulations were able to reproduce the observed bi-modality in star-formation rate and colour (Croton et al., 2006).

At lower redshift, environmental-quenching mechanisms become important and are thought to be most important at low-stellar masses (Peng et al., 2010). Investigations of galaxy number densities find evidence for a significant low-mass upturn in the quiescent GSMF up to $z \simeq 1.5$, indicative of environment-driven mechanisms thought to be caused by interactions between galaxies and their immediate surroundings (Muzzin et al., 2013b; McLeod et al., 2021). For example, ram-pressure stripping can strip the galaxy of the cold gas it needs to maintain star formation (Gunn & Gott, 1972), and gas-rich mergers are able to drive the majority of cold gas out of the galaxy (see e.g. Gabor & Davé, 2012; Hopkins et al., 2010). Alternately, without continuous gas accretion, the gas in the galaxy will eventually be used up in star formation, resulting in quiescent galaxies with higher stellar metallicities (Peng et al., 2015).

Unfortunately, it has been difficult to disentangle the effects of various quenching mechanisms and evolutionary channels on the sizes and morphologies of quiescent galaxies. However, over the past decade, deep spectroscopic surveys have enabled the study of statistically representative samples of star-forming and quiescent galaxies to derive robust physical properties and scaling relations (van der Wel et al., 2014; Barone et al., 2022; Beverage et al., 2021). Towards the local Universe, in a large sample of star-forming and quiescent galaxies, Shen et al. (2003) found that at fixed stellar mass, quiescent galaxies display smaller sizes on average and steeper size-mass relations than star-forming galaxies.
Studies of massive quiescent galaxies suggested that the growth in size can be explained by minor mergers, and this is thought to be true to at least $z < 2$ (e.g. Trujillo et al., 2007; Cimatti et al., 2012; Kriek et al., 2009b; van der Wel et al., 2014). McLure et al. (2013) found that quiescent galaxies grow in size by a factor of 1.5 from $z \simeq 1$ to $z \simeq 0$ at fixed stellar mass, citing a combination of minor and major mergers to explain this growth. In more recent work, Mowla et al. (2019) pushed studies of the size-mass relation to higher stellar masses by combining updated HST imaging with 3D-HST data, finding size-mass relations for massive galaxies broadly consistent with van der Wel et al. (2014).

Nevertheless, investigations of the quiescent galaxy size-mass relation for a larger dynamical range of stellar mass paint a more complicated picture; less massive quiescent galaxies have sizes more akin to star-forming galaxies at fixed stellar mass. As a result of this, many studies suggested that the size-mass relation of quiescent galaxies is better described by a smoothly broken- or double-power law (see e.g. Peng et al., 2010; Lange et al., 2015; Nedkova et al., 2021; Kawinwanichakij et al., 2021), with a pivot mass at $\log_{10}(M_*/M_\odot) \simeq 10$, which accounts for the flattening of the quiescent galaxy size-mass relation (e.g. van der Wel et al., 2014). In the context of quenching, these observations highlight an important result; the flattening of the size-mass relation indicates that environmental quenching mechanisms may be coming into effect, particularly in the low-redshift regime and these may have significant consequences for the morphologies of quiescent galaxies (e.g. van den Bosch et al., 2008; Kawinwanichakij et al., 2017).

The morphological properties of galaxies are important in understanding the processes which suppress star-formation. Sérsic index is closely correlated to the concentration of flux in galaxy surface-brightness profiles; higher Sérsic indices $n > 2.5$ correspond to more concentrated light profiles. Star-forming galaxies are observed to have more disc-like morphologies, with an average Sérsic index closer to $n \sim 1$ and it was previously common to select samples of SFGs at $n < 2.5$ and quiescent galaxies at $n > 2.5$ (e.g. Rowlands et al., 2012; Kuchner et al., 2017). Interestingly, Almaini et al. (2017) find evidence that post-starburst galaxies exhibit Sérsic indices similar to quiescent galaxies, albeit with smaller sizes, suggesting a rapid quenching mechanism formed these compact objects. Patel et al. (2013) find that the Sérsic index of quiescent galaxies is strongly evolving with redshift from $z \simeq 3$ to $z \simeq 0$, in contrast to the much less dramatic evolution in Sérsic index for star-forming galaxies.
JWST has allowed for deeper rest-frame optical/near-infrared imaging of the galaxy population than ever before. However, it is still unclear how the structural properties of galaxies depend on rest-frame wavelength. Suess et al. (2022) study a large sample of massive galaxies from the JWST CEERS survey at $z \sim 2$, and measure sizes at $4.4 \, \mu m$ ($\lambda_{\text{rest}} \sim 1.45 \, \mu m$). Comparisons with $1.5 \, \mu m$ measurements demonstrate that the rest-frame near-infrared sizes of massive ($\log_{10}(M_*/M_\odot) > 11$) galaxies are $\sim 30\%$ smaller than their rest-frame optical sizes, complicating our current understanding of how massive galaxy sizes evolve with redshift. This highlights the necessity of rest-frame infrared sizes to capture the true morphological evolution of massive galaxies (see also, Huertas-Company et al., 2023; Kartaltepe et al., 2023).

In Hamadouche et al. (2022), I selected robust samples of quiescent galaxies from the VANDELS (McLure et al., 2018b; Pentericci et al., 2018) and LEGA-C (van der Wel et al., 2016) spectroscopic surveys to investigate the evolution of the galaxy size-mass relation for massive ($\log_{10}(M_*/M_\odot) > 10.3$) quiescent galaxies. I found a tentative flattening of the size-mass relation from $z \simeq 1.3$ to $z \simeq 0.7$, suggesting that minor mergers can explain the observed evolution in stellar mass and size over this redshift range.

In this chapter, motivated by previous findings and the near-infrared capabilities of JWST, I investigate the relationships between size, stellar mass and Sérsic index for large samples of star-forming and quiescent galaxies to lower stellar masses and higher redshifts, using publicly available data from the JWST JADES (Eisenstein et al., 2023) and PRIMER (Dunlop et al., 2021) surveys. I present new size-mass relations for star-forming and quiescent galaxy samples, exploring whether or not the size-mass relation of quiescent galaxies over the full stellar-mass range can be better described by a smoothly-broken or double-power law, as suggested in the literature (Peng et al., 2010; Nedkova et al., 2021; Kawinwanichakij et al., 2021). I discuss the implications of my results in the context of the physical mechanisms that drive the quenching of star-formation in galaxies.

The structure of this chapter is as follows. I first give details of the JADES and PRIMER datasets in Section 5.2, and then discuss fitting methods and the sample selection in Section 5.3. I then present my results on the relationships between size, stellar mass and morphology in Section 5.4, and discuss my findings in Section 5.5. Finally, I summarise my main conclusions in Section 5.6. Throughout this chapter, I quote all magnitudes in the AB system, and assume cosmological
parameters of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$. I use a Kroupa (2001) initial mass function and the Asplund et al. (2009) Solar abundance of $Z_{\odot} = 0.0142$.

## 5.2 Data

In this section, I give a brief overview of the survey data I make use of throughout this chapter.

### 5.2.1 The JADES survey

The JWST Advanced Deep Extragalactic Survey (JADES) is a JWST Guaranteed Time Observations (GTO) program, providing deep imaging and spectroscopy of the HST GOODS-North and GOODS-South fields using the Near-infrared Camera (NIRCam) and Near-infrared Spectrograph (NIRSpec) on JWST. For a more detailed description of the survey design, I refer the reader to Chapter 2 and Eisenstein et al. (2023). I provide a brief description of the survey below, focusing on the data I use later on in this chapter.

The GOODS-S deep prime NIRCam pointings cover a total of 25 sq. arcmin and consist of around 229 hours of observation time. The JADES deep prime observations make use of NIRCam JWST filters covering a wavelength range of $0.9 - 5 \mu m$ over the short- and long-wavelength channels.

### 5.2.2 The PRIMER survey

The Public Release IMaging for Extra-galactic Research (PRIMER) is a Cycle 1 Treasury Program, providing deep JWST NIRCam imaging of the COSMOS and UDS CANDELS legacy fields. The full coverage of the shallow PRIMER pointings for the COSMOS region is $\sim 144$ sq. arcmin of NIRCam imaging, where objects received on-source integration times of approximately $\sim 14 - 28$ mins. The deeper central regions receive $42 - 84$ mins of integration. The wavelength coverage is similar to JADES, with eight filters covering the wavelength range $0.9 - 5 \mu m$. 

151
5.2.3 Photometric catalogues

For both the JADES and PRIMER datasets, multi-wavelength catalogues were constructed using SOURCEEXTRACTOR (Bertin & Arnouts, 1996) in dual-image mode by other members of the Edinburgh team following the method described in McLeod et al. (2021, 2024). In order to facilitate selection of quiescent galaxies up to $z \sim 3$, F356W is used as the primary detection image. Isophotal photometry is performed on the PSF-homogenised images (PSF-matched to F444W) and each of the catalogues requires a $5\sigma$—detection in the detection image, and a $3\sigma$—detection in at least one other band in order to minimise spurious detections. These catalogues were tested using various photo−$z$ codes, with final catastrophic outlier rates for JADES and PRIMER of < 2%. I use these photometric redshifts during my BAGPIPES fitting, discussed in the next section.
Figure 5.1  $UVJ$ diagrams for the final, mass-complete JADES (top panel) and PRIMER (bottom panel) samples. Star-forming galaxies are the blue points while quiescent galaxies are red.
5.3 Methods and sample selection

5.3.1 Photometric fitting using Bagpipes

I use Bagpipes (Carnall et al., 2018) to fit the available photometric data for all galaxies in the initial PRIMER and JADES catalogues. A double-power-law star-formation history model is employed, incorporating the updated 2016 versions of the BC03 stellar population synthesis models (Bruzual & Charlot, 2003; Chevallard & Charlot, 2016). I also vary the stellar metallicity from $Z_* = 0.2 - 2.5 Z_\odot$ using a logarithmic prior.

I use the Salim et al. (2018) dust attenuation law, which parameterizes the dust-curve shape through a power-law deviation, $\delta$, from the Calzetti et al. (2000) law, as used in Hamadouche et al. (2023). Nebular continuum and emission lines are modelled using the CLOUDY photo-ionization code (Ferland et al., 2017b), using a method based on that of Byler et al. (2017). I assume a fixed ionization parameter of $\log_{10}(U) = -3$. Full details of the free parameters and priors used in my fitting are provided in Table 5.1.

<table>
<thead>
<tr>
<th>Component</th>
<th>Parameter</th>
<th>Symbol / Unit</th>
<th>Range</th>
<th>Prior</th>
<th>Hyper-parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>Redshift</td>
<td>$z_{\text{phot}}$</td>
<td>$z_{\text{phot}}$ ($\pm 0.015$)</td>
<td>Gaussian</td>
<td>$\mu = z_{\text{phot}}$, $\sigma = 0.005$</td>
</tr>
<tr>
<td>SFH</td>
<td>Stellar mass formed</td>
<td>$M_*/M_\odot$</td>
<td>$(1, 10^{13})$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Metallicity</td>
<td>$Z_*/Z_\odot$</td>
<td>$(0.2, 2.5)$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Falling slope</td>
<td>$\alpha$</td>
<td>$(0.1, 10^3)$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rising slope</td>
<td>$\beta$</td>
<td>$(0.1, 10^3)$</td>
<td>log</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peak time</td>
<td>$\tau$/Gyr</td>
<td>$(0.1, t_{\text{obs}})$</td>
<td>uniform</td>
<td></td>
</tr>
<tr>
<td>Dust</td>
<td>5500 Å attenuation</td>
<td>$A_V$/mag</td>
<td>$(0, 4)$</td>
<td>uniform</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deviation from Calzetti</td>
<td>$\delta$</td>
<td>$(-0.3, 0.3)$</td>
<td>Gaussian</td>
<td>$\mu = 0.0$, $\sigma = 0.1$</td>
</tr>
<tr>
<td></td>
<td>2175 Å bump strength</td>
<td>$B$</td>
<td>$(0, 5)$</td>
<td>uniform</td>
<td></td>
</tr>
</tbody>
</table>
5.3.2 Selection of mass-complete samples

I first impose a $\chi^2_{\text{phot}} < 50$ cut on the SED fits to remove spurious fits (e.g. fits which have hit the edges of the priors) and strict $UVJ$ criteria to select quiescent galaxies in my samples, as described in Williams et al. (2009). I use the rest-frame colours from Bagpipes to separate the star-forming and quiescent galaxies, requiring:

- $U - V > 0.88 \times (V - J) + 0.69$
- $U - V > 1.3$
- $V - J < 1.6$

Additionally, to determine the effective stellar-mass limits of my JADES and PRIMER samples, I follow the procedure proposed in Pozzetti et al. (2010). For each galaxy in my full sample, I calculate the limiting stellar mass that a galaxy would have if its apparent magnitude was equal to the limiting $5\sigma$ magnitude of the survey. Thus, the limiting stellar mass, $\log(M_{\text{lim}})$, of a single galaxy is given by

$$\log(M_{\text{lim}}) = \log(M) + 0.4(m_{F356W} - m_{\text{lim}})$$

(5.1)

where $m_{F356W} - m_{\text{lim}}$ is the difference between the apparent F356W magnitude of the galaxy and the $5\sigma$ magnitude limit. I thus define the 90% mass-completeness limit for the full sample at each redshift as the minimum stellar mass below which 90% of the individual limiting stellar masses lie.

The PRIMER COSMOS field has a variable depth due to the shallow, medium and deep regions. I therefore use a median depth of 28.5 magnitudes in F356W for calculating the mass-completeness limits in PRIMER; the COSMOS catalogue is robust down to this magnitude for each of the shallow, medium and deep regions. The JADES $5\sigma$ magnitude limit is 29.5 magnitudes in F356W. The 90% mass-completeness limits for $UVJ$-selected star-forming and quiescent galaxies for both surveys are presented in Table 5.2.
Table 5.2 Details of the mass-completeness limits for the star-forming and quiescent galaxies for JWST JADES and PRIMER (detailed in Section 5.3) in each 0.5-wide redshift bin. \(N\) represents the number of galaxies in each population that lie above the corresponding mass-completeness limit.

<table>
<thead>
<tr>
<th>Redshift Bin</th>
<th>N (JADES)</th>
<th>(\log(M_{\text{lim}}))</th>
<th>N (JADES)</th>
<th>(\log(M_{\text{lim}}))</th>
<th>N (JADES)</th>
<th>(\log(M_{\text{lim}}))</th>
<th>N (JADES)</th>
<th>(\log(M_{\text{lim}}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 &lt; (z) &lt; 0.75</td>
<td>1136</td>
<td>6.74</td>
<td>1845</td>
<td>6.98</td>
<td>1551</td>
<td>7.18</td>
<td>1462</td>
<td>7.31</td>
</tr>
<tr>
<td>0.75 &lt; (z) &lt; 1.25</td>
<td>179</td>
<td>6.94</td>
<td>85</td>
<td>7.21</td>
<td>16</td>
<td>7.41</td>
<td>8</td>
<td>7.55</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Redshift Bin</th>
<th>N (PRIMER)</th>
<th>(\log(M_{\text{lim}}))</th>
<th>N (PRIMER)</th>
<th>(\log(M_{\text{lim}}))</th>
<th>N (PRIMER)</th>
<th>(\log(M_{\text{lim}}))</th>
<th>N (PRIMER)</th>
<th>(\log(M_{\text{lim}}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25 &lt; (z) &lt; 0.75</td>
<td>3946</td>
<td>7.13</td>
<td>6727</td>
<td>7.36</td>
<td>4621</td>
<td>7.57</td>
<td>4361</td>
<td>7.74</td>
</tr>
<tr>
<td>0.75 &lt; (z) &lt; 1.25</td>
<td>442</td>
<td>7.37</td>
<td>330</td>
<td>7.63</td>
<td>137</td>
<td>7.88</td>
<td>90</td>
<td>8.05</td>
</tr>
</tbody>
</table>

5.3.3 Size measurements & colour gradients

I use Galfit (Peng et al., 2002) to measure the sizes of galaxies in my sample. I adopt a similar procedure to Hamadouche et al. (2022), using the JWST F356W images to measure sizes for all galaxies in my sample. The choice of using this filter to fit sizes is based on the depth and resolution compared to F444W and F277W. F356W is half a magnitude deeper than F444W, and has higher spatial resolution than the F444W image. At longer wavelengths, we are probing the redder regions of the galaxy, usually associated with the bulge component, which is mainly formed of older stars. The majority of the disc is formed of younger stars, and so at shorter wavelengths, galaxies with a disc component will have lower Sérsic indices (Lange et al., 2015). As suggested by Suess et al. (2022), results in the rest-frame optical do not capture the actual stellar-mass distribution in galaxies, and so the near-infrared is needed to assess the mass-weighted structural evolution of galaxies.

The choice of measuring structural properties in F356W (as opposed to e.g. F277W) therefore removes the concern of colour gradients in this work. Even at the highest redshifts we are probing the near-infrared; over the chosen redshift range 0.25 < \(z\) < 2.25, the F356W filter samples rest-frame wavelengths of 2.85 \(\mu\text{m} < \lambda_{\text{rest}} < 1.09 \mu\text{m}.

I set up an automated fitting routine (in PYTHON) which takes the ID of a galaxy
in my catalogues and uses the magnitude in F356W, the half-light radius ($r_{50}$), and centroid position determined by SourceExtractor (Bertin & Arnouts, 1996) as inputs in the Galfit parameter file. I also generate cutouts for the data, segmentation and weight image of the specified galaxy.

Nearby neighbours within the target galaxy image stamp are masked out using the segmentation map, unless they are within ±2.5 magnitudes of the input galaxy magnitude and within 3″ of the target galaxy in the centre of the image, in which case they are fitted along with the target galaxy. I restrict the image-cutout size to 200 x 200 pixels, which is ~6″ on the sky; the F356W images have pixel scales of 0.03″/pix. For both JADES and PRIMER I use an isolated, unsaturated star in the F356W image as the point-spread function (PSF).

For each galaxy, the automated fitting routine creates an input parameter file and constraints file, and runs Galfit. A fits file containing the data, model and residual image is created and the best-fit parameters from the models are then saved to a catalogue for use in the analysis.

5.3.4 Final sample selection

I remove galaxies which have failed in the size fitting i.e. due to contamination by nearby stars, bright objects or objects that are at the edges of the image, and visually inspect the quiescent galaxy cutouts, taking care to remove any artefacts. These Galfit failures include objects whose fits do not converge (i.e. $n = 0.2$, $n = 8$). These bad fits amount to 12% of the whole sample (~2200 objects). I also perform a magnitude cut of $m_{F356W} < 28$ for all galaxies, ensuring that objects have high enough signal-to-noise to measure good sizes. This leaves a final robust quiescent sample of 687 quiescent galaxies over the redshift range $0.25 < z < 2.25$. The final JADES and PRIMER samples are presented in the top and bottom panels of the UVJ diagrams in Fig. 5.1, respectively.
Figure 5.2  Number densities of star-forming and quiescent galaxies from the PRIMER (filled circles) and JADES (open circles) surveys within the redshift range $0.25 < z < 2.25$. The solid and dashed lines are the quiescent and star-forming galaxy stellar-mass functions, respectively, from McLeod et al. (2021).
5.4 Results

In this section, I present the results obtained from my SED fitting and size measurements for my final JADES and PRIMER samples of star-forming and quiescent galaxies over the redshift range $0.25 < z < 2.25$.

5.4.1 The galaxy stellar-mass function up to $z \simeq 2.25$

In this study, I extend previous work on the galaxy stellar-mass function down to lower stellar masses through the use of deep near-infrared imaging from JWST, improving on previous studies using ground-based and HST imaging. I derive robust stellar masses from BAGPIPES, and calculate number densities for my star-forming and quiescent galaxy samples in JADES and PRIMER. Fig. 5.2 presents the number densities of star-forming and quiescent galaxies between $z = 0.25$ and $z = 2.25$, in 0.5–wide redshift bins. Over-plotted in each panel are the galaxy stellar-mass functions derived by McLeod et al. (2021).

In McLeod et al. (2021), the quiescent GSMF up to $z = 1.75$ is fitted with a double-Schechter function, in contrast to the star-forming galaxies, which instead follow a smooth single-Schechter. The number densities I calculate for my galaxy samples are in good agreement with those presented in McLeod et al. (2021). Fig. 5.2 demonstrates the strong evolution of the galaxy stellar-mass function; the low-mass upturn in the quiescent GSMF can be seen clearly in my data up to $z < 1.75$. This is also tentatively observed in the highest-redshift bin, providing additional constraints on the quiescent GSMF at earlier times. However, my highest-redshift bin is affected by small number statistics, so this is only significant at the 1σ level.

5.4.2 Galaxy size-mass relations at $0.25 < z < 2.25$

I fit size-mass relations for my mass-complete samples derived from the PRIMER and JADES surveys for each redshift bin, described in Section 5.3.2. Similar to Hamadouche et al. (2022), I fit a single-power law relation as a function of galaxy mass such that:

$$
\log_{10}\left(\frac{R_e}{\text{kpc}}\right) = \alpha \times \log_{10}\left(\frac{M_*}{5 \times 10^{10} M_\odot}\right) + \log_{10}(A)
$$

(5.2)
where \( R_e \) is the effective radius of the galaxy, \( \alpha \) is the slope and \( \log_{10}(A) \) is the normalisation of the relationship. I choose to fit a single power law and a broken power law over the entire stellar-mass range for quiescent galaxies and two linear relations for each of the high- and low-mass samples, in order to test which better describes the quiescent galaxy population. The smoothly-broken power law is defined as:

\[
R_e = R_p \left( \frac{M_*}{M_p} \right)^\alpha + \left[ \frac{1}{2} \left( 1 + \left( \frac{M_*}{M_p} \right)^\delta \right) \right]^{\beta - \alpha/\delta}
\]

(5.3)

where \( \alpha \) and \( \beta \) are the low- and high-mass broken power law slopes, \( M_p \) is the pivot mass and \( R_p \) is the corresponding size for a given pivot mass.

When fitting the size-mass relations, I choose a constant uncertainty on galaxy sizes of 0.1–dex, due to the uncertainties provided by Galfit being significantly underestimated (Häussler et al., 2007). The F356W images provide physical resolution almost the same as the \( H \)-band images used to measure sizes in (Hamadouche et al., 2022). In that work, I found that size-measurements agreed between VANDELS quiescent galaxies and van der Wel et al. (2012, 2014) within ±0.1-dex. The constant error adopted for the fitting presented in this chapter therefore provides a more realistic estimate of the typical uncertainty in galaxy sizes (e.g. McLure et al., 2013; Hamadouche et al., 2022).

**Table 5.3** The best-fitting parameters for the broken-power law fit to the quiescent galaxy size-mass distributions. As described in Kawinwanichakij et al. (2021), I use a constant \( \delta = 6 \) which is related to the sharpness of the transition from the high-mass slope to the low-mass slope. Due to the low numbers of quiescent galaxies below \( \log_{10}(M_*/M_\odot) < 10 \) above \( z > 1.25 \), I do not measure relations in the two highest redshift bins. The intrinsic scatter, \( \sigma_{re} \), of the size-mass relation is given in the final column.

<table>
<thead>
<tr>
<th>Redshift, ( z )</th>
<th>( \alpha )</th>
<th>( r_p )</th>
<th>( \beta )</th>
<th>( M_p )</th>
<th>( \sigma_{re} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0.25 &lt; z &lt; 0.75 )</td>
<td>0.07 ± 0.03</td>
<td>1.74 ± 0.21</td>
<td>0.59 ± 0.07</td>
<td>10.36 ± 0.12</td>
<td>1.10 ± 0.10</td>
</tr>
<tr>
<td>( 0.75 &lt; z &lt; 1.25 )</td>
<td>0.04 ± 0.03</td>
<td>1.55 ± 0.17</td>
<td>0.73 ± 0.08</td>
<td>10.60 ± 0.08</td>
<td>0.82 ± 0.10</td>
</tr>
</tbody>
</table>
Table 5.4  The best-fitting parameters for the galaxy size-mass relations as described in Section 5.4.2. Due to the low numbers of quiescent galaxies in the two highest redshift bins, I do not measure relations in these bins. The intrinsic scatter of the size-mass distribution is given in the third column, $\sigma_{re}$, for each population.

<table>
<thead>
<tr>
<th>Redshift, $z$</th>
<th>star-forming</th>
<th>low-mass Q</th>
<th>high-mass Q</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha$</td>
<td>$\log(A)$</td>
<td>$\sigma_{re}$</td>
</tr>
<tr>
<td>$0.25 &lt; z &lt; 0.75$</td>
<td>$0.21 \pm 0.01$</td>
<td>$0.64 \pm 0.01$</td>
<td>$0.05 \pm 0.01$</td>
</tr>
<tr>
<td>$0.75 &lt; z &lt; 1.25$</td>
<td>$0.16 \pm 0.01$</td>
<td>$0.53 \pm 0.01$</td>
<td>$0.06 \pm 0.01$</td>
</tr>
<tr>
<td>$1.25 &lt; z &lt; 1.75$</td>
<td>$0.13 \pm 0.01$</td>
<td>$0.43 \pm 0.02$</td>
<td>$0.04 \pm 0.01$</td>
</tr>
<tr>
<td>$1.75 &lt; z &lt; 2.25$</td>
<td>$0.15 \pm 0.01$</td>
<td>$0.43 \pm 0.02$</td>
<td>$0.04 \pm 0.01$</td>
</tr>
</tbody>
</table>
Star-forming galaxies

In the top panel of Fig. 5.3, I present the size-mass distributions and relations for star-forming galaxies from $z = 0.25$ to $z = 2.25$ in 0.5–dex stellar-mass bins. From Fig. 5.3, and the results presented in Table 5.4, it is clear that the normalisation of the star-forming size-mass relation decreases with increasing redshift, consistent with galaxies possessing larger sizes at later times. However, the slope does not change significantly from $z = 2.25$ to $z = 0.25$, suggesting no strong evolution in the slope of the star-forming galaxy size-mass relation from $z = 2.25$ to $z = 0.25$, consistent with previous literature results that also fit the size-mass relation, with a shallow slope of $\alpha \simeq 0.2$ (e.g. van der Wel et al., 2014; Mowla et al., 2019). The sizes of star-forming galaxies increase by $\sim 0.1$–dex between $z = 2.25$ and $z = 0.25$ (see Section 5.4.3 and Fig. 5.5).

Quiescent galaxies

As mentioned previously, I fit both single and double power-law size-mass relations for both low- and high-mass quiescent galaxies up to $z < 2.25$. I report the results of my size-mass fitting in Tables 5.3 and 5.4. I first demonstrate how a single linear fit does not capture the true size-mass distribution of quiescent galaxies in the second row of Fig. 5.3. The low-mass quiescent galaxies dominate the size-mass fitting, resulting in a slope of $\alpha = 0.14 \pm 0.04$ at $z \sim 0.5$, and $\alpha = 0.08 \pm 0.05$ at $z \sim 1.0$. The size-mass distribution of high-mass quiescent galaxies are not accounted for by the single power-law fit.

In the third row of Fig. 5.3, I present my smoothly-broken power law fits to the size-mass relations for the entire quiescent galaxy distribution. These fits could only be performed in the lowest redshift bins, due to low numbers at higher redshifts. In the lowest redshift bins there is a clear flattening of the quiescent galaxy size-mass relation, consistent with similar studies at the same redshift (e.g. van der Wel et al., 2014; Nedkova et al., 2021; Kawinwanichakij et al., 2021).

I confirm that quiescent galaxies above $\log_{10}(M_{\star}/M_\odot) > 10$ demonstrate steeper size-mass relations than star-forming galaxies at $0.25 < z < 2.25$. In contrast, the slope of the size-mass relation for low-mass quiescent galaxies up to $z \sim 1.25$ is similar to that of star-forming galaxies, with no significant evolution observed between $z \simeq 1.25$ to $z \simeq 0.25$. I discuss the implications of these results in Section 5.5.3.
Figure 5.3  The size-mass distributions of star-forming and quiescent galaxies over $0.25 < z < 2.25$, over-plotted with the size-mass relations presented in Table 5.3 and Table 5.4.2, as well as single-power law fits to all the quiescent galaxies up to $z \sim 1.25$. 
However, upon inspection, I find that these fits do not accurately describe the quiescent galaxy population as a whole. Although the slopes of the broken-power law relations from Nedkova et al. (2021) and Kawinwanichakij et al. (2021) agree broadly with my fits, they do not account for the galaxies in the low-mass end of the high-mass sample, and the apparent stellar-mass gap between the low- and high-mass quiescent galaxies.

I therefore perform single-power law fits on each of the low- \( \log_{10}(M_\text{⋆}/M_\odot) < 10 \) and high-mass \( \log_{10}(M_\text{⋆}/M_\odot) > 10 \) quiescent galaxy samples, in order to capture the true underlying distribution of these galaxies. If low and high-mass quiescent galaxies are indeed quenching via different mechanisms and thus undergoing different evolutionary pathways, it is plausible to treat these sub-populations separately (see e.g. Maltby et al., 2018). The results of my fitting are presented in the bottom panel of Fig. 5.3.

The results of the fitting, shown in Fig. 5.3, suggest that the quiescent galaxy population is separated into sub-populations. This is consistent with results from studies of the quiescent galaxy stellar-mass function, and the results presented in Section 5.4.1; the upturn in the galaxy stellar-mass function reflects environmental quenching mechanisms becoming important at low stellar masses \( \log_{10}(M_\text{⋆}/M_\odot) < 10 \), signifying two distinct evolutionary channels for low and high-mass quiescent galaxies.

As shown in the bottom panel of Fig. 5.3, the slope of the low-mass quiescent galaxy size-mass relation is shallower than the higher-mass relation. The low-mass slope mirrors that of the star-forming galaxies, albeit with a lower normalisation, and is consistent with quiescent galaxies displaying smaller sizes than star-forming galaxies at fixed stellar mass. This may point to the progenitors of these low-mass quiescent galaxies being star-forming galaxies that are smaller on average than the overall star-forming population. In contrast, the slope of the size-mass relation for higher-mass quiescent galaxies is steeper than lower-mass quiescent and star-forming galaxies; the high-mass slope of the double-power law and the single-power law fits agree \( (\alpha \simeq 0.5) \), within 1σ, and are consistent with recent studies of the size-mass relations of massive quiescent galaxies at \( z > 1 \) (see e.g. van der Wel et al., 2014; Mowla et al., 2019; Hamadouche et al., 2022). The findings indicate that star-forming and low- and high-mass quiescent galaxies occupy distinct regions of the size-mass plane. In Section 5.5.2, I investigate possible quenching mechanisms which could reproduce the observed trends.
Table 5.5  The median Sérsic index and effective radius in kpc for each 0.5–dex redshift bin.

<table>
<thead>
<tr>
<th>Star-forming</th>
<th>all</th>
<th>Low-mass</th>
<th>High-mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redshift, $z$</td>
<td>$n$</td>
<td>$R_e$/kpc</td>
<td>$n$</td>
</tr>
<tr>
<td>0.25 &lt; $z$ &lt; 0.75</td>
<td>$1.11 \pm 0.00$</td>
<td>$1.51 \pm 0.01$</td>
<td>$1.08 \pm 0.01$</td>
</tr>
<tr>
<td>0.75 &lt; $z$ &lt; 1.25</td>
<td>$1.12 \pm 0.00$</td>
<td>$1.42 \pm 0.01$</td>
<td>$1.09 \pm 0.01$</td>
</tr>
<tr>
<td>1.25 &lt; $z$ &lt; 1.75</td>
<td>$1.10 \pm 0.00$</td>
<td>$1.33 \pm 0.01$</td>
<td>$1.09 \pm 0.01$</td>
</tr>
<tr>
<td>1.75 &lt; $z$ &lt; 2.25</td>
<td>$1.19 \pm 0.01$</td>
<td>$1.31 \pm 0.01$</td>
<td>$1.17 \pm 0.01$</td>
</tr>
<tr>
<td>Quiescent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redshift, $z$</td>
<td>$n$</td>
<td>$R_e$/kpc</td>
<td>$n$</td>
</tr>
<tr>
<td>0.25 &lt; $z$ &lt; 0.75</td>
<td>$1.58 \pm 0.01$</td>
<td>$1.12 \pm 0.01$</td>
<td>$1.54 \pm 0.01$</td>
</tr>
<tr>
<td>0.75 &lt; $z$ &lt; 1.25</td>
<td>$1.85 \pm 0.01$</td>
<td>$1.16 \pm 0.04$</td>
<td>$1.48 \pm 0.01$</td>
</tr>
<tr>
<td>1.25 &lt; $z$ &lt; 1.75</td>
<td>$2.08 \pm 0.03$</td>
<td>$1.19 \pm 0.07$</td>
<td>$1.50 \pm 0.04$</td>
</tr>
<tr>
<td>1.75 &lt; $z$ &lt; 2.25</td>
<td>$2.59 \pm 0.05$</td>
<td>$1.05 \pm 0.05$</td>
<td>$2.13 \pm 0.13$</td>
</tr>
</tbody>
</table>
Figure 5.4 Histograms showing the distribution of stellar masses for the star-forming (blue) and quiescent (purple) galaxy populations from $z = 0.25$ to $z = 2.25$. Quiescent galaxies exhibit a potential bimodality in stellar mass, with a gap between $9 < \log_{10}(M_*/M_\odot) < 10$. 
5.4.3 The evolution of size and Sérsic index

In Fig. 5.3, the quiescent galaxies appear to display a bi-modal distribution in stellar mass, separated at \( \log_{10}(M_*/M_\odot) \sim 10 \), consistent with the pivot mass below which the quiescent galaxy size-mass relation appears to flatten. This bimodality in stellar mass is also displayed in Fig. 5.4; the quiescent galaxy population exhibits an apparent ‘gap’ between stellar masses of \( 9 < \log_{10}(M_*/M_\odot) < 10 \), with the number of less-massive quiescent galaxies increasing to lower redshift as environmental quenching mechanisms may begin to dominate over internal mechanisms. As demonstrated in Fig. 5.6, out to \( z \sim 1.5 \), higher-mass quiescent galaxies exhibit values of Sérsic index higher than those at lower-stellar masses. The lower-mass quiescent galaxies in the samples display values of \( n \sim 1.3 \), only slightly higher than the overall star-forming population up to \( z \sim 1.5 \), whose Sérsic indices are more consistent with disc-like morphologies (van der Wel et al., 2014; Kawinwanichakij et al., 2021). These results may suggest that the Sérsic indices displayed by the lower-mass quiescent galaxies are associated with morphologies transitioning from disc-like to lenticular (e.g. S0).

![Figure 5.5](image)

**Figure 5.5** The redshift evolution of median size and Sérsic index from \( z \simeq 2 \) to \( z \simeq 0.5 \). Massive quiescent galaxies exhibit higher values of Sérsic index and faster size evolution at all redshifts compared to star-forming and less-massive quiescent galaxies.

In Fig. 5.5, I show the evolution of median size and Sérsic index from \( z = 2.25 \) to \( z = 0.25 \), measured in 0.5-wide redshift bins, and present these values in Table 5.5. The sizes of the low mass-quiescent galaxies are smaller than the star-forming galaxies at all redshifts, and smaller than higher-mass quiescent galaxies, although
our final two redshift bins are affected by low number statistics, so it is difficult to confirm how significant these values are at \( z > 1.25 \). Star-forming galaxies increase in size on average by \( \simeq 0.1\)–dex (below \( \log_{10}(M_*/M_\odot) < 10 \)) and massive quiescent galaxies increase in size by \( \simeq 0.24\)–dex. At higher stellar masses, star-forming galaxies exhibit more size-evolution with redshift, corresponding to a \( 0.18\)–dex increase in size from \( z \simeq 2 \) to \( z \simeq 0.5 \). The overall size evolution for star-forming and massive-quiescent galaxies is consistent with previous results from the literature, for example, for \( \log_{10}(M_*/M_\odot) > 10.0 \), van der Wel et al. (2014) find that star-forming galaxies increase by \( 0.15\)–dex and quiescent galaxies increase by \( 0.25\)–dex over a similar redshift range as studied in this work.

In the high-mass quiescent galaxy samples, the increase in \( R_e \) from \( z = 2.25 \) to \( z = 0.25 \) may be explained by minor merger activity. Dry minor mergers can increase the sizes of galaxies without significantly increasing their stellar masses (e.g. see McLure et al., 2013; Ownsworth et al., 2014; Buitrago et al., 2017; Hamadouche et al., 2022) and over the redshift range \( 0.5 < z < 1.5 \), galaxies are unlikely to experience major mergers. However, the true size evolution between different redshift bins may be complicated by progenitor bias (van Dokkum & Franx, 1996), where more recently quenched galaxies that are larger in size enter the quiescent population at later times.

5.5 Discussion

In Section 5.4, I report new size-mass relations for my star-forming and quiescent galaxy samples in JADES and PRIMER. In this section, I focus on the relationships between stellar mass, size and Sérsic index, within the context of galaxy quenching mechanisms.

5.5.1 The evolution of the galaxy stellar-mass function from \( z = 0.25 \) to \( z = 2.25 \)

In Section 5.4.1, I presented the number densities of quiescent and star-forming galaxies derived from the JWST JADES and PRIMER surveys. These results are in very good agreement with previous wide-area studies of the galaxy population up to \( z \sim 3 \) (see McLeod et al., 2021), especially given the small field of view; the total area covered by the samples presented here is just \( \sim 160 \) sq. arcminutes,
compared to the 3 sq. degrees of the study presented in McLeod et al. (2021). The star-forming galaxy stellar-mass function does not show strong evolution over my entire redshift range, consistent with a range of literature studies over similar redshift ranges (Fontana et al., 2006; Muzzin et al., 2013b; Davidzon et al., 2017).

At the highest redshifts, I am able to place new constraints on the quiescent galaxy mass function; Fig. 5.4.1 demonstrates that even up to \( z = 2.25 \), the quiescent GSMF is better described by a double-Schechter function, and this appears to be true over the entire redshift range. The quiescent GSMF is also rapidly evolving over the redshift range, particularly between \( z \approx 1.75 \) and \( z \approx 0.25 \), and the double-Schechter describes the low-mass upturn of the quiescent galaxy stellar mass function better than a single-Schechter. The two components of the quiescent GSMF are due to higher numbers of low-mass quiescent galaxies entering the population at \( z = 2.25 \) and potentially reflects the two distinct mechanisms by which galaxies quench; environmental quenching, which is independent of mass, and internal quenching, which is proportional to the galaxy stellar mass (Peng et al., 2010).

The data presented in this chapter extends 1-dex lower in stellar mass than McLeod et al. (2021), providing the first demonstration of an environmental upturn at \( z = 1.5 \). However, the number density of low-mass galaxies drops off at the highest redshifts (1.75 < \( z < 2.25 \)), and so it is difficult to confirm whether or not the upturn suggested by the data is robust at \( z > 1.5 \). Wider-area JWST surveys will provide larger samples of quiescent galaxies to probe the effect of environmental quenching at the highest redshifts.
Figure 5.6 The size-mass distributions for all galaxies in the samples, colour-coded by Sérsic index. Star-forming galaxies are shown in the top panel, and quiescent galaxies are on the bottom row with the star-forming population shown in grey for each redshift range. On a galaxy-by-galaxy basis, high-mass quiescent galaxies clearly exhibit higher Sérsic indices than low-mass quiescent galaxies up to $z \approx 1.75$. Star-forming galaxies do not appear to show any evolution in Sérsic index with stellar mass or size.
5.5.2 Environmental or internal quenching?

Extreme events such as mergers, or interactions involving high-speed fly-bys between galaxies, can affect the morphology of galaxies and increase their Sérsic indices as they transform from disc-dominated to spheroid-dominated (Moore et al., 1998). Disc instabilities in galaxies can also present ways to increase Sérsic index; gravitational instabilities redistribute angular momentum, causing material to be pushed towards the centre and resulting in a bulge-dominated galaxy (e.g. Kormendy & Kennicutt, 2004; Brennan et al., 2015).

There is a clear bi-modality in the size-mass distributions of the quiescent population in this work, and higher-mass quiescent galaxies demonstrate different morphologies than lower-mass quiescent galaxies. In Fig. 5.6, I again show the galaxies on the size-mass plane, instead coloured by Sérsic index. The star-forming galaxies in the samples do not show any significant correlation between stellar mass and Sérsic index or size and Sérsic index. Although I find that the average $n$ for more-massive star-forming galaxies is higher than the overall star-forming population at all redshifts, the evolution of Sérsic index is still less dramatic than the observed distinction between the low- and high-mass quiescent galaxies. The highest-mass star-forming galaxies may be consistent with the formation of a more prominent bulge component than at lower-stellar masses, explaining the increase in $n$ for these more massive systems. However, the evolution of Sérsic index with stellar mass for star-forming galaxies is much less strong than seen in the quiescent galaxies in the samples, making it unlikely that the difference in $n$ between the two quiescent sub-populations is purely a result of increasing stellar mass.

In Sandles et al. (2023), the authors found evidence for a very low-mass quiescent galaxy within an over-density at $z \sim 2$ (with a stellar mass of $\log_{10}(M_*/M_\odot) \sim 9.0$), as well as two other more massive candidate quiescent galaxies in the nearby region, with properties consistent with environment-driven quenching. Their results demonstrate that environment can still be responsible for quenching at early times, and these observations lend support to the tentative result of an environment-driven upturn in the quiescent GSMF at $z \sim 2.0$. In addition, Taylor et al. (2023) find evidence for a significant number of galaxies quenching in dense environments and link this to the build-up of the quiescent galaxy mass function since $z < 2$. Together, these studies suggest that the observed distribution in Sérsic index is linked to different evolutionary pathways for low-mass and high-
mass quiescent galaxies.

Feedback processes

The high-mass quiescent galaxies in the sample have stellar masses and sizes consistent with quenching via AGN feedback. Dubois et al. (2013) find that using Adaptive Mesh Refinement code RAMSES, AGN feedback can reproduce the observed scaling relations up to $z \sim 2$. Similarly, Dubois et al. (2016) examined the role of AGN feedback on galaxy morphology over a range of redshifts using the hydrodynamical cosmological simulation, HORIZONAGN, with and without an AGN component. The authors found that incorporating AGN feedback reproduces the observed size-mass relation of massive quiescent galaxies, albeit with a shallower slope than found by van der Wel et al. (2014) and broadly consistent with the one found in this work. The lack of star-forming galaxies with comparable Sérsic indices to the high-mass quiescent galaxies in my sample (see Fig. 5.6) indicate that internal quenching mechanisms are likely responsible for the high values of $n$ observed for massive quiescent galaxies.

More extreme interactions between galaxies involve mergers, and gas-rich mergers have been suggested as potential drivers of quenching star-formation in galaxies. A gas-rich merger may also transform galaxies from disky to elliptical, or S0, depending on the relative sizes and the gas dynamics of the progenitor galaxies, however, an added complication of gas-rich mergers is that the gas may lead to the stellar remnant rebuilding its disc, and continuing star-formation. In simulations, while mergers can lead to gas being evacuated from a galaxy, radio-mode feedback (also called maintenance mode, as it maintains the hot halo needed to keep gas from cooling) is responsible for keeping the galaxy quenched (Croton et al., 2006; Bower et al., 2006). Mergers may induce a starburst in the galaxy which can cause the gas to be quickly used up, however, Gabor & Davé (2012) show that merger quenching can only temporarily quench galaxies, and eventually star-formation is reignited via accretion of gas.

In-fall into cluster environments

At lower-redshifts, the progenitors of low-mass quiescent galaxies are proposed to be star-forming galaxies that quenched in high-density environments (Boselli & Gavazzi, 2006). As discussed in Kuchner et al. (2017), galaxies in high-density
environments such as clusters are affected by the intra-cluster medium (ICM); as a galaxy falls into a cluster, the pressure of the ICM is greater than the gravitational force between the gas and stellar disc within the galaxy, and gas will be stripped (ram-pressure stripping, Gunn & Gott, 1972). This results in the disc of the galaxy fading and reddening over time as the stars within it age, and galaxies falling into cluster centres are expected to have quenched within 1-3 Gyr (at most, 6 Gyr) of entering the dense environment (see e.g. Wetzel et al., 2013; Hirschmann et al., 2014; Wright et al., 2019). This explains the lower SFRs and older stellar populations possessed by low-mass quiescent galaxies in high-density environments.

In cluster environments, galaxies close to the centre of the cluster have had more time to lose their star-forming outskirts, resulting in smaller sizes as observed in the optical, due to the reddening of the disc. However, tidal stripping is also effective at removing some of the loosely-bound matter (stars) from the outskirts of galaxies (Boselli & Gavazzi, 2006), and together these processes can work to quench the galaxy outside-in, where the remaining gas towards the centre of the galaxy is used up in star-formation, with the galaxy eventually becoming red and passive but still possessing a (now slightly smaller) disc component. This scenario is consistent with the galaxies transforming from disc/spirals to S0-type, and may explain the large number of red, S0-type galaxies in clusters (e.g. Abraham et al., 1996; D’Onofrio et al., 2015).

In my sample of JADES and PRIMER galaxies, I observe that low-mass quiescent galaxies have smaller sizes and higher Sérsic indices on average than star-forming galaxies at fixed stellar mass, lending support to the idea that low-mass star-forming galaxies undergo small morphological transformations as they are quenched, resulting in quiescent galaxies with more-concentrated light profiles and slightly smaller sizes. This suggests that, at least qualitatively, the morphological and size evolution of the low-mass quiescent galaxies in my samples appear to be consistent with infall into cluster environments.

5.5.3 Implications for star-forming and quiescent galaxy evolution

In Fig. 5.6, I show the size-mass distributions of the quiescent galaxies, colour-coded by Sérsic index. From the figure, it is clear that higher-mass quiescent galaxies exhibit higher Sérsic indices on a galaxy-by-galaxy basis and Table 5.5 shows that on average, higher-mass quiescent galaxies display larger Sérsic indices
and smaller sizes than lower-mass quiescent galaxies and star-forming galaxies.

In contrast, low-mass quiescent galaxies exhibit Sérsic indices akin to the star-forming population. However, it is known that Sérsic index is positively correlated with stellar mass, and is also positively correlated with the dark-matter halo mass of star-forming and quiescent galaxies (e.g. Lange et al., 2015; Kuchner et al., 2017; Taylor et al., 2020). I therefore restrict the star-forming and quiescent samples to $\log_{10}(M_*/M_\odot) > 10$ and compare the median $n$ of the two populations. I find that, although the average $n$ of massive star-forming galaxies is higher than that of all star-forming galaxies in the sample, the quiescent galaxies have average Sérsic indices $\Delta n \simeq 2$ higher than the star-forming galaxies at $0.25 < z < 1.25$.

My results demonstrate that by $z \sim 2$, massive quiescent galaxies appear to already have more concentrated light profiles than massive star-forming galaxies and lower-mass quiescent galaxies. In my sample, the Sérsic indices of these high-mass quiescent galaxies increase towards lower redshift. The observed increase in $n$ is consistent with the central galaxy undergoing dry, minor mergers over $z = 1.75$ to $z = 0.25$ as suggested both observationally and from simulations (Trujillo et al., 2011; Buitrago et al., 2008; Hilz et al., 2013; McLure et al., 2013).

Additionally, the results show that massive star-forming galaxies appear to slowly become more concentrated from $z = 1.5$ to $z = 0.5$, as presented in Table 5.5. This may be consistent with the idea that massive galaxies build up a bulge component through internal secular evolution (i.e. through disk/bar instabilities, e.g. Kormendy & Kennicutt, 2004); this scenario happens over long timescales, and may explain the evolution from $z \sim 1.75$ to $z \sim 0.25$ for the massive star-forming galaxies in the sample.

### 5.6 Conclusions

In this work I have explored the relationships between stellar mass, size and morphology at $0.25 < z < 2.25$ for samples of quiescent and star-forming galaxies by utilising high-quality photometric data and imaging from the JWST JADES and PRIMER surveys. The main conclusions can be summarised as follows:

1. I find that the number densities of both quiescent and star-forming galaxies in the JWST PRIMER and JADES surveys are in very good agreement
with previous studies of the galaxy stellar-mass function over the redshift range $0.25 < z < 2.25$. The results provide new constraints on the quiescent-galaxy stellar-mass function at high-redshifts; I present the first demonstration of a reliable environmental quenching upturn in the quiescent GSMF at $z \sim 1.5$, and provide tentative evidence that this may be present at $z \sim 2.0$.

2. In Section 5.4.2, I report new size-mass relations for the combined JWST PRIMER and JADES samples at $0.25 < z < 2.25$, and confirm that the slope of the size-mass relation for star-forming galaxies does not evolve significantly with cosmic time, with the normalisation consistent with decreasing sizes toward higher redshift, in agreement with previous literature results. At all redshifts, quiescent galaxies display smaller sizes on average than the star-forming galaxy population at fixed stellar masses.

3. The slope of the size-mass relation for low-mass quiescent galaxies also does not evolve significantly over time. Similar to the star-forming galaxies in our sample, the normalisation of low-mass quiescent galaxies is also consistent with decreasing sizes towards earlier times. In contrast, the high-mass quiescent slope appears to become shallower towards later times, possibly due to the effects of either minor mergers or larger, more recently quenched galaxies being added to the quiescent population (progenitor effect).

4. In Section 5.4.2, I also find that high and low-mass quiescent galaxies are separable populations of galaxies likely being quenched by different processes. Low-mass quiescent galaxies display properties better associated with quenching via environmental mechanisms. In contrast, higher-mass quiescent galaxies have morphologies and sizes consistent with quenching via internal processes such as AGN feedback and Sérsic index/size-growth via dissipationless minor mergers, in agreement with results from previous observations and simulations.

In this chapter, I have presented detailed studies of the structural properties of star-forming and quiescent galaxies up to $z = 2.25$. Using deep near-infrared imaging from the PRIMER and JADES surveys I have shown for the first time that the quiescent-galaxy stellar-mass function exhibits the low-mass upturn associated with environmental-driven quenching mechanisms. I have also demonstrated that the high-mass quiescent galaxy sizes are strongly
evolving with redshift, with morphologies consistent with quenching via internal mechanisms and size growth via minor mergers. Low-mass quiescent galaxies in my sample exhibit size-mass relations and morphologies qualitatively consistent with quenching via infall into cluster environments. In summary, this chapter presents one of the first in-depth studies of quiescent galaxies complete down to lower stellar masses than previously possible, providing further constraints on quenching over a wide redshift range.
Chapter 6

Conclusions and future work

6.1 Final conclusions

In this section, I provide a brief summary of the overall conclusions of this thesis and potential directions for future work.

Throughout this thesis, I have attempted to understand how and why star-formation is quenched in galaxies, and examined the evolution of the quiescent galaxy population at high redshift. I used a combination of photometry and spectroscopy to investigate the key results which have shaped our understanding of galaxy evolution thus far, and extended these methods to galaxies over a wide range of redshifts. The ultra-deep spectroscopic data and deep \textit{HST} and \textit{JWST} imaging from large surveys have provided me with the ability to study the relationships between galaxy stellar mass, size and age in unprecedented detail.

In the sections that follow, I present the main conclusions for each of my science chapters.

6.1.1 Size-mass evolution of massive quiescent galaxies

In Chapter 3, I explore the relationships between stellar mass, size and $D_n4000$ for samples of quiescent galaxies at $1.0 < z < 1.3$ and $0.6 < z < 0.8$, by utilising high-quality spectroscopic data from the VANDELS and LEGA-C surveys. Using sophisticated SED fitting methods, and robust measurements of the spectral age
indicator $D_n4000$, I find that the downsizing signature is already in place by $z \simeq 1.1$, with $D_n4000$ increasing by $\simeq 0.1$ between $z \simeq 1.1$ to $z \simeq 0.7$. I then investigate the evolution of the quiescent galaxy stellar mass-size relation over this redshift range, finding that the median size increases by $1.9 \pm 0.1$ at fixed stellar masses, and also observed a tentative flattening of the relation between $z = 1.3$ to $z = 0.6$.

I split galaxies above and below the size-mass relation for each redshift, finding that at $z \sim 0.7$ galaxies with smaller sizes are older (higher $D_n4000$ values, using $D_n4000$ as a proxy for stellar population age) than larger galaxies at the same stellar mass. However, this relationship between size and age is not observed within the VANDELS galaxies, possible due to the smaller numbers and lower SNR spectra.

Given concerns that metallicity may drive the size-$D_n4000$ relationship in the galaxies at $z \sim 0.7$, I consider a range of plausible metallicities that could explain the difference in $D_n4000$ between the galaxies above and below the size-mass relation, within the stellar-mass bin containing the most objects in LEGA-C. I find that metallicity differences cannot plausibly explain the relation between stellar-age and size, meaning that galaxies with smaller sizes are older than larger galaxies. I also find that the size growth of quiescent galaxies between $z \sim 1.1$ and $z \sim 0.7$ can be explained by minor mergers, and that the increase in $D_n4000$ is consistent with passive evolution over 2 Gyr.

6.1.2 The connection between stellar mass, star-formation histories and quenching timescales

In Chapter 4, I explore the relationships between stellar mass, age, star-formation history and quenching timescales for a spectroscopic sample of quiescent galaxies from the VANDELS survey at $1.0 < z < 1.3$. Using robust spectro-photometric fitting methods, I derive a new stellar-mass versus stellar-age relation, finding a slope of $1.20^{+0.28}_{-0.27}$ Gyr per decade in stellar mass.

The slope of this relation is consistent with recent literature results over a wide range of redshifts, indicating that the slope is constant over $0 < z < 4$. I find that the normalisation of the slope differs between studies, possibly due to differences in definitions of stellar age (e.g. light-weighted versus mass-weighted), and using parametric versus non-parametric star-formation histories.
I also find tentative evidence of \(\alpha\)-enhancement through increased absorption of the CN molecular feature at \(\sim 3860\) Å within a small subset of galaxies in the VANDELS sample. The CN feature is commonly associated with older stellar population ages, consistent with the star-formation histories extracted for these galaxies, and provides evidence that these galaxies had shorter formation timescales than the rest of the quiescent sample on average.

### 6.1.3 The sizes, masses and morphologies of quiescent galaxies

In Chapter 5, I build on my results at \(z \sim 1\) to investigate whether the same trends can be seen at higher redshift, using data taken from the JWST PRIMER survey in the COSMOS field and the JADES survey in the GOODS-South field. I explore the relationships between stellar mass, size and morphology at \(0.25 < z < 2.25\) for samples of quiescent and star-forming galaxies by utilising high-quality photometric data and imaging.

I find that the number densities of both quiescent and star-forming galaxies in the JWST PRIMER and JADES surveys are in very good agreement with previous studies of the galaxy stellar-mass function over the redshift range \(0.25 < z < 2.25\), and provide new constraints on the quiescent-galaxy stellar-mass function in the highest redshift bin, \(1.75 < z < 2.25\), demonstrating for the first time, the upturn in the quiescent GSMF associated with environmental quenching mechanisms.

I also report new size-mass relations for the combined JWST PRIMER and JADES samples at \(0.25 < z < 2.25\), and confirm that the size-mass relation for star-forming galaxies does not evolve significantly with cosmic time, with the normalisation consistent with decreasing sizes toward higher redshift. At all redshifts, quiescent galaxies display smaller sizes than star-forming galaxies at a fixed stellar mass.

I also find that high- and low-mass quiescent galaxies are separable populations, quenching via different mechanisms; low-mass quiescent galaxies display properties better associated with quenching via environmental processes such as ram-pressure stripping as the galaxy falls into a cluster environment. In contrast, the higher-mass quiescent galaxies are more concentrated than their lower-mass counterparts, and more consistent with quenching via internal processes such as AGN feedback.
This thesis has attempted to build upon the extensive literature on quiescent galaxies, and improve our understanding of the main drivers of quiescence through detailed investigation of their sizes, stellar masses, ages and metallicities. The work presented in this thesis has provided a clear narrative of the evolution of quiescent galaxies over time and the physical markers left behind by the processes that caused these galaxies to quench.

6.2 Future work

Throughout this thesis, I have presented work that provides evidence for various quenching processes and evolutionary channels that star-forming galaxies undergo to transform into the red, dead galaxies we observe up to $z \sim 3$. In this section, I discuss a number of directions for future work, endeavouring to explain the physical drivers of quenching and the subsequent passive evolution of quiescent galaxies.

6.2.1 The non-parametric morphologies of quiescent galaxies

My previous work has measured physical and structural properties from robust parametric fitting using the SED fitting code Bagpipes and size-fitting code Galfit, respectively. However, while they take more time per galaxy to run and may be prone to degeneracies, non-parametric methods can provide a more unbiased approach to studying the star-formation history and structural evolution of galaxies. Building on previous work, and using public imaging data from PRIMER, JADES and COSMOS-WEB, I can increase the numbers of quiescent galaxies in my samples, providing a more statistically representative view of the quiescent galaxy population to higher redshifts.

Using non-parametric structural fitting code Statmorph, I will be able to extract additional morphological parameters such as the CAS parameters (concentration, asymmetry and smoothness/clumpiness) in order to determine how distinct the morphologies of quiescent galaxies within various stellar-mass ranges and redshifts are, and exploring evidence for mergers to provide new insights into quenching.

These results can be readily compared to simulations; for example, Rodriguez-Gomez et al. (2019) use Statmorph on 27,000 simulated galaxy images from
the hydrodynamic cosmological ILLUSTRIS{TNG} simulations, designed to match observations from Pan-STARRS of massive galaxies at $z \sim 0.05$. The authors extract sizes and CAS parameters from their simulated galaxies (as shown in Fig. 6.1), finding good agreement with the sizes and morphologies of observed galaxies. The JWST PRIMER data presents a unique opportunity to measure structural properties of galaxies to higher redshifts with improved spatial resolution, enabling in-depth studies of the morphological imprints left behind by various quenching mechanisms.

6.2.2 Galaxy quenching from colour gradients and half-mass radii

It has been established that the sizes of quiescent galaxies evolve much faster from $z < 2$ to the local Universe than their star-forming counterparts, with quiescent galaxies possessing much steeper size-mass relations as demonstrated in Chapter 5, McLure et al. (2013), van der Wel et al. (2014) and Hamadouche et al. (2022). Additionally, results up to $z \sim 2.5$ find strong positive colour gradients in ‘transition’ galaxies, pointing to evidence of fast and slow quenching channels (Suess et al., 2021). Interestingly quiescent galaxies display negative colour gradients, suggesting these galaxies quench inside out. In order to fully quantify
the effects of colour gradients, and effectively probe quenching mechanisms, it is necessary to obtain half-mass radii through spatially-resolved SED fitting. As alluded to in Chapter 5, the near-infrared capabilities of JWST now allow us to probe the mass-weighted structural properties of galaxies.

Additionally, to complement the work presented in Chapter 5, comparisons between measures of half-mass and half-light radii offer the ideal opportunity to fully investigate the size-redshift evolution of quiescent and star-forming galaxies. This will confirm if the relationship between size and redshift is more strongly evolving when using half-light radii, as shown in Fig. 6.2, allowing us to probe how galaxies build up their stellar mass (see e.g. Suess et al., 2019a,b, 2021). While this has been achieved with CANDELS data, it is now possible to probe these relations to higher redshifts than before, using spatially-resolved SED fitting to probe the mass-profiles of galaxies with improved spatial resolution data from JWST. PRIMER offers the ideal dataset to obtain physical and structural properties for statistically representative samples of the star-forming and quiescent galaxy populations, and address the main drivers of quenching in galaxies through studies of colour gradients.

6.2.3 Understanding galaxy evolution through $\alpha$–enhancement

Spectroscopic observations of the distant Universe have revealed a wealth of information, and data from public release surveys such as LEGA-C and VANDELS have demonstrated the power of ultra-deep spectroscopic observations.
In work presented in Chapter 4, I found a subset of VANDELS quiescent galaxies which tentatively indicated \( \alpha \)–enhancement via stronger absorption of CN at \( \sim 3860 \) Å. This feature is of particular interest in galaxy evolution as its strength can be used to constrain the star-formation history of a galaxy (Thomas et al., 2010); higher abundances of \( \alpha \)–elements (such as nitrogen) in galaxies can point to shorter formation timescales (see 1.2.6).

In the near-infrared, it is possible to examine more prominent and better-calibrated indicators of \( \alpha \)–enhancement. Observing these features at higher-redshifts will be invaluable in shedding light on formation timescales and the metallicity histories of galaxies. The LEGA-C spectra have a resolution of \( R \sim 3500 \) at 6000 – 9000 Å, making this data-set an obvious choice for investigating these features at lower-redshift. Additionally, MOONS (Cirasuolo et al., 2020) will be able to provide the necessary near-IR spectroscopy for large samples of quiescent galaxies out to \( z \simeq 2.5 \), while NIRSpec can provide access to the full set of Lick indices out to \( z \simeq 6.5 \). Combining these data will result in a more complete picture of the metal-enrichment and star-formation histories of quiescent galaxies.
Bibliography

Alpher R. A., Herman R. C., 1948, Physical Review, 74, 1737
Bouwens R. J., et al., 2021, AJ, 162, 47


Cirasuolo M., et al., 2020, The Messenger, 180, 10


Colless M., 1999, 357, 105


Curtis-Lake E., et al., 2023, Nature Astronomy, 7, 622
D’Onofrio M., Marziani P., Buson L., 2015, Frontiers in Astronomy and Space Sciences, 2, 4


189
Hodges J. L., 1958, Arkiv för Matematik, 3, 469
Kewley L. J., Nicholls D. C., Sutherland R. S., 2019, ARA&A, 57, 511
Lemaître G., 1927, Annales de la Société Scientifique de Bruxelles, 47, 49
Maiolino R., Mannucci F., 2019, A&ARv, 27, 3
McQuinn M., 2016, ARA&A, 54, 313


Salim S., 2014, Serbian Astronomical Journal, 189, 1
Stark D. P., 2016, Annual Review of Astronomy and Astrophysics, 54, 761


Thomas D., Maraston C., Bender R., 2005a, Highlights of Astronomy, 13, 189


de Vaucouleurs G., 1948, Annales d’Astrophysique, 11, 247