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Exploring the formation of the first galaxies with VISTA and JWST

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Lay Summary

In order to understand how galaxies evolve we need to understand how the very first galaxies formed. Due to the finite speed of light, the more distant a galaxy is to us, the further back in time we observe that galaxy to be. Therefore, by observing the most distant galaxies we can observe the very first galaxies and study their properties.

With the successful launch of *JWST*, galaxies can be detected to within approximately 300 million years after the Big bang, when the Universe was $\sim 3\%$ of it's current age. In this thesis I measure the abundances of these early galaxies over cosmic time using data from *JWST* which allows this research to be carried out to increasingly early times.

Prior to the launch of *JWST* there was significant uncertainty over whether the galaxy population continued to decline at a smooth rate at times earlier than ~ 700 Myr after the Big Bang or if it more rapidly declined. In this thesis I show that *JWST* supports a continued smooth decline out to ~ 300 Myr showing that galaxy formation was already under way at such early cosmic times. I also investigate the properties of these galaxies by fitting models of the light emitted at different wavelengths to measure the ages and masses of the stars within the galaxies.

Finally, I construct a theoretical model to understand what drives the evolution of the earliest population of galaxies. This reveals that a simple model where only the age of the stellar population evolves is sufficient to explain the build up of early galaxies where the stellar age gets increasing younger at earlier times. These ages all point to a common formation time approximately ~ 300 Myr after the Big Bang potentially suggesting that this is the point in cosmic time where the first population of galaxies began to emerge.

Abstract

With the successful launch of *JWST*, there is now the ability to robustly detect galaxies at $z \geq 10$ for the first time due to the sensitivity of the NIRCam instrument at $\lambda > 2\mu\text{m}$.

I first reduce and analyse the initial available *James Webb Space Telescope* (JWST) ERO and ERS NIRCam imaging (SMACS0723, GLASS, CEERS) in combination with the latest deep ground-based near-infrared imaging in the COSMOS field (provided by UltraVISTA DR5) to produce a new measurement of the evolving galaxy UV luminosity function (LF) over the redshift range $z = 8 - 15$. This yields a new estimate of the evolution of UV luminosity density (ρ_{UV}), and hence cosmic star-formation rate density (ρ_{SFR}) out to within < 300 Myr of the Big Bang. My results confirm that the high-redshift LF is best described by a double power-law (rather than a Schechter) function up to $z \sim 10$, and that the LF and the resulting derived ρ_{UV} (and thus ρ_{SFR}), continues to decline gradually and steadily up to $z \sim 15$ (as anticipated from previous studies which analysed the pre-existing data in a consistent manner to this study).

I then utilise *JWST* NIRCam medium-band imaging centered on the Hubble Ultra Deep Field (HUDF) to search for extreme redshift ($z \geq 9.5$) galaxy candidates. My search reveals 6 robust candidates, 3 of which have recently been spectroscopically confirmed. One of these 3 is the previously controversial $z \simeq 12$ galaxy candidate UDF-22980, which now has a secure photometric redshift of $z_{\text{phot}} = 11.6 \pm 0.2$. I determine the physical properties of the 6 galaxies by fitting the 14-band photometry with BAGPIPES finding stellar masses of $\log(M_{\star}/M_{\odot}) \simeq 7.5 - 8.7$ and star-formation rates of $\log(\text{SFR}/M_{\odot}^{-1}\text{yr}^{-1}) \simeq 0.3 - 5.0$. Despite the relatively small cosmological volume covered by the HUDF itself and the second NIRCam module imaging, I find that the existence of these galaxies is fully consistent with the latest measurements of both the UV luminosity function and cosmic star-formation rate density at $z \simeq 11$.

I then present a new determination of the evolving galaxy UV LF over the redshift range $8.5 < z < 15.5$ using a combination of several major Cycle-1 *JWST* imaging programmes - PRIMER, JADES and NGDEEP. I select a sample of 2548 galaxies with a significant probability of lying at high redshift ($p(z > 8.5) > 0.05$) to undertake a statistical calculation of the UV LF. My measurements yield a new estimate of the early evolution of the UV LF and cosmic star-formation rate density (ρ_{SFR}) confirming the gradual decline deduced from early *JWST* studies, at least out to $z \simeq 12$. Finally I show that the observed early evolution of the galaxy UV LF (and ρ_{SFR}) can be reproduced in a Λ CDM Universe, with no change in dust properties or star-formation efficiency required out to $z \simeq 12$. Instead, a progressive trend towards younger stellar population ages can reproduce the observations, and the typical ages required at $z \simeq 8, 9, 10$, and 11 all converge on $\simeq 380 - 330$ Myr after the Big Bang, indicative of a rapid emergence of early galaxies at $z \simeq 12 - 13$.

Since the launch of *JWST* there have been a number of surprising results concerning galaxy evolution at $z > 6$ which are in apparent tension with a number of theoretical models. Here I further develop a simple theoretical model to reproduce the observed evolution of the galaxy stellar mass function (GSMF) and the UV luminosity function (UVLF) at $z \geq 6$. A constant star-formation efficiency model is able to both match the latest *JWST* measurements of the GSMF at $z = 6 - 8$ and the UV LF at $z = 6 - 13$ in contrast to some suggestions in the literature. I find no evidence for the removal of feedback in high-mass halos ($> 10^{11.7} \text{ M}_{\odot}$) from the observed GSMF at $z \geq 6$ and number density of sub-millimetre galaxies. Instead the bright-end of the UV LF at $z \geq 6$ is fully reproducible with dust attenuation given a consistent relationship between UV attenuation and stellar mass with redshift. Finally, the combination of my models of the UV LF with the latest constraints on the escape fraction of Lyman continuum radiation and the production efficiency of ionising photons in galaxies, is fully able to match observational measurements of the timeline of reionization and completion redshift of $z \simeq 5.5$.

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 the following papers which are near identical to Chapters 3, 4, 5 respectively: [Donnan et al. \(2023a\)](#), [Donnan et al. \(2023b\)](#) and [Donnan et al. \(2024\)](#).

(Callum T. Donnan, December 2024)

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Chapter 1

Introduction

1.1 The history of the Universe

The Universe is thought to be approximately 13.7 billion years old and in that time it has undergone many changes. It began with the Big Bang and over time led to the structures we see in the local universe - stars, planets, galaxies and the cosmic web. The earliest light observed in the universe comes from approximately 380,000 years after the Big Bang at the epoch of recombination. This is when the hot plasma of electrons and protons that existed after the Big Bang combined to form hydrogen atoms as the Universe expanded and cooled. Prior to this epoch, photons were continually scattered due to the dense field of free electrons in the early Universe. With recombination, these photons were finally “freed”, propagating through the Universe. We can detect these photons today in what is known as the Cosmic Microwave Background (CMB) which has an average temperature of 2.73K. The temperature of the CMB is not completely identical at different spatial positions due to small density fluctuations in the early Universe. After this epoch the Universe entered the cosmic “dark-ages” where the newly formed hydrogen and helium atoms exist in an expanding and cooling dark Universe. During this time, the small density fluctuations that were imprinted in the very early Universe start to collapse under their own gravity. Over time this increase in the density of these hydrogen clouds ultimately leads to temperatures high enough to initiate nuclear fusion. This marks the formation of the first stars as the Universe is illuminated by star-light for the first time. These first stars would be free of heavy elements, being composed of mostly hydrogen and helium

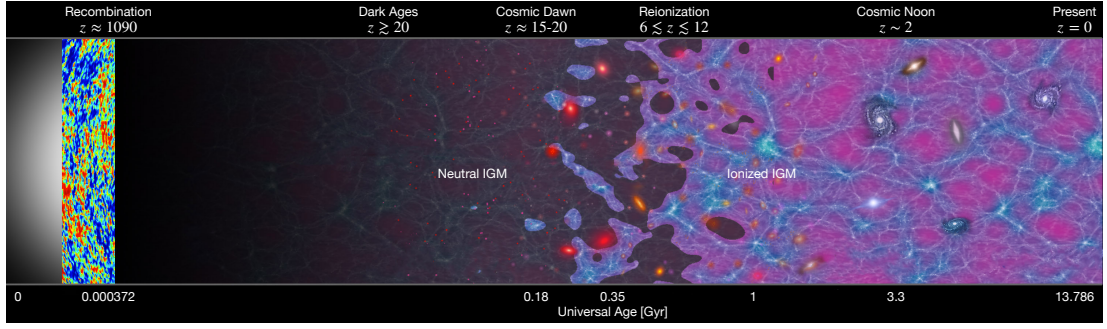


Figure 1.1 *Overview of cosmic history highlighting key epochs. Approximately 380,000 years after the Big Bang the light observed as the CMB was emitted at the epoch of recombination. This was followed by the cosmic dark ages which ended at $z \geq 20$ with the formation of the first stars. These form the first galaxies which reionised the natural hydrogen in the IGM over the epoch of reionization ending at $z \sim 6$. Figure taken from [Robertson \(2022\)](#).*

and therefore would be metal free. However, the first stars are thought to be short-lived due to their large masses and therefore rapidly enrich their surroundings with these heavier elements. Over approximately the next 1 billion years, early star formation is thought to reionize the neutral hydrogen in the intergalactic medium (IGM) due to the powerful ultraviolet (UV) photons emitted from these stars. This process likely started in the densest regions, carving out bubbles of ionised gas until the entire IGM became ionised by $z \sim 6$. The end-point of reionization is still a major area of research with recent results using the Gunn-Peterson trough in high-redshift quasars showing it concludes at $z \simeq 5.5 - 6$ ([Robertson et al., 2015](#); [Aird et al., 2015](#); [Bosman et al., 2021](#)). Fig. 1.1 illustrates these various epochs of cosmic history.

1.2 The expanding Universe

The Universe has been expanding since the Big Bang which causes distant astronomical sources to appear to be moving away from us. This stretches the emitted light from the source meaning that the observed light is “redshifted” compared to when it was emitted. The redshift (z) of a galaxy can be expressed by

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} \quad (1.1)$$

where λ_{obs} is the observed wavelength and λ_{emit} is the wavelength of the emitted light. It should be noted that there are multiple phenomena that can cause the redshifting of astronomical sources such as peculiar velocities (where a galaxy is physically being accelerated by a gravitational potential) and gravitational redshift (where light is stretched as it exits a strong gravitational potential). However, in practice the dominant redshift for distant sources is cosmological redshift (caused by the expansion of the Universe) and therefore in this thesis this is what I mean when referring to “redshift”. This can be related to the expansion of the universe by the scale factor, $a(t)$, which defines how much the universe has expanded between a time t_0 and the present time t_{obs} ,

$$a(t) = \frac{R(t_{\text{obs}})}{R(t_0)} \quad (1.2)$$

where R is the scale length. Redshift as a function of the scale factor is given by,

$$1 + z = \frac{a(t_{\text{obs}})}{a(t_0)} \quad (1.3)$$

The Λ cold dark matter (CDM) cosmological model is the concordant model of the expansion and large-scale structure of the universe. This framework has developed over the last ~ 100 years of astronomy based on ever improving observational tests of cosmology. The Λ CDM model describes a universe with dark matter (matter that does not interact with light) and includes a cosmological constant Λ . The fractional quantities of the universe (Ω) in this model at the present day are,

$$\Omega_R \simeq 0, \Omega_m = 0.3, \Omega_\Lambda = 0.7, H_0 = 70 \text{ km/s/Mpc}^3 \quad (1.4)$$

where Ω_m and Ω_Λ are the fractional amounts of matter (dark and baryonic) and dark energy respectively and Ω_R is the fractional quantity of radiation. H_0 is the Hubble constant for the present day Universe which relates recession velocity to distance for local galaxies. However, the Hubble *parameter*, H , is time dependent with it's time dependence described by the Friedmann equation,

$$H^2(t) = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3} \quad (1.5)$$

where G is the gravitational constant, k is the curvature of the universe ($k = 0$ for a flat universe), c is the speed of light and Λ is the cosmological constant.

This equation can be expressed in terms of the fractional quantities described above giving,

$$H^2(z) = H_0^2[\Omega_R x^4 + \Omega_M x^3 + \Omega_\Lambda + (1 - \Omega_0)x^2], \quad x = 1 + z \quad (1.6)$$

where $\Omega_0 = \Omega_R + \Omega_M + \Omega_\Lambda$. In the Λ CDM model $\Omega_0 \simeq 1$ based on the values expressed in Equation 1.4, as the universe is flat in this model.

As galaxies with increasing redshift are increasingly distant from the observer and are therefore seen further back in time, we can derive relationships between distance and time with redshift. The time-redshift relation is given by,

$$dt = -\frac{dz}{(1+z)H(z)} \quad (1.7)$$

This can be integrated to give the lookback time to a galaxy at a redshift z ,

$$t_0 - t_e = \int_0^z \frac{1}{H(z')} \frac{dz'}{(1+z')} \quad (1.8)$$

To then solve for a given galaxy, assuming a Λ CDM model, $H(z')$ can be substituted using Equation 1.6 with the given parameters for the Λ CDM model. The distance, r , travelled accounting for the expansion of the universe is given by,

$$r = \int \frac{cdt}{R(t)} \quad (1.9)$$

which can be substituted with the time-redshift relation to give the total distance travelled by light, D_0 ,

$$D_0 = R_0 r = \int_0^z \frac{cdz'}{H(z')} \quad (1.10)$$

However, the concept of distance is more complex than would be the case in an non-expanding universe. In an non-expanding universe the relation between the measured brightness (flux; f), the intrinsic luminosity of the source, L , and distance to it, d , is straightforward given by,

$$f = \frac{L}{4\pi d^2} \quad (1.11)$$

However in an expanding universe this is not the case as photons are redshifted which reduces the flux by a factor $1+z$ and photons arrive at a slower rate which also reduces flux by a factor $1+z$. In the case of the expanding universe Equation 1.11 becomes,

$$f = \frac{L}{4\pi a_0^2 r_0^2 (1+z)^2} = \frac{L}{4\pi d_L^2} \quad (1.12)$$

where we define the luminosity distance, d_L as $d_L = a_0 r_0 (1+z)$. Here $a_0 r_0$ describes the proper distance as r_0 is the comoving distance to the source. This flux is the bolometric flux (flux integrated over full wavelength/frequency range) which is the energy per unit time that passes through a unit area. When the light from a distant source is received at a specific frequency, we need to integrate the received power over the total solid angle of a sphere (4π). Due to the expansion of the Universe, this is not the same power that was emitted. This therefore introduces an additional factor of $1+z$ giving the flux density,

$$f_\nu = \frac{L_\nu (1+z)}{4\pi d_L^2} \quad (1.13)$$

The luminosity distance is important to consider when calculating the intrinsic luminosity and therefore absolute magnitude of distant galaxies. To convert between apparent magnitude (m) and absolute magnitude (M) for a cosmological source (i.e a distant galaxy) we use,

$$M = m - 5 \log\left(\frac{d_L}{10}\right) + 2.5 \log(1+z) \quad (1.14)$$

Throughout this thesis I assume a Λ CDM cosmological model with the parameters assumed in Equation 1.4.

1.3 An overview of galaxy evolution

In this section I will describe the different stages of galaxy evolution and the ways in which they can be measured. I will first describe the dark matter halo mass

function and then describe the fundamental scaling relations that can be used to measure how the galaxy population evolves. These scaling relations encode the physical processes that drive galaxy evolution and can be measured using observations at different wavelengths which can then be compared to simulations. Although this thesis focuses on the formation and evolution of the first galaxies, in this section I will provide an overview of galaxy evolution across cosmic time as it is important to establish what can be learned about galaxy evolution at more recent cosmic times before focusing on the earliest epochs.

1.3.1 The halo mass function

In Section 1.1 I described the underlying cosmology of the Universe. Although this underlying dark matter structure can be described as the “cosmic web” consisting of dense nodes connected by filaments, the basic unit of structure of relevance to galaxy formation is defined by the dark matter halo. It is within dark matter halos that galaxies form and then evolve. Therefore before defining the key scaling relations that govern galaxy evolution, we must first define what a dark matter halo is. Halos are gravitationally bound structures of dark matter which have collapsed and detached from the background expansion of the universe. The masses of these halos range across multiple orders of magnitude with low mass halos predicted to be significantly more abundant than higher mass halos. The distribution of their masses can be expressed by the halo mass function which describes the number density of halos of a given mass per unit co-moving volume. As the dark matter halo mass cannot be directly measured, models of the halo mass function are often used and can be generated using N-body simulations (e.g. [Sheth et al., 2001](#); [Reed et al., 2007](#)). The shape of this distribution is defined by the assumption of a cosmological model and therefore given that Λ CDM is the standard model of cosmology, in this thesis a Λ CDM halo mass function is assumed throughout. An illustration of the evolution of the halo mass function (HMF) using the [Reed et al. \(2007\)](#) model over the redshift range $z = 0 - 14$ is shown in Fig 1.2. The shape of the HMF is characterised by a steeply declining function to high masses with a stronger evolution towards higher masses with decreasing redshift, likely due to the gravitational growth of high-mass halos over large periods of cosmic time.

It is within these dark matter halos that gas can cool and condense to form stars and galaxies. Stars can only form if their infalling gas can cool sufficiently

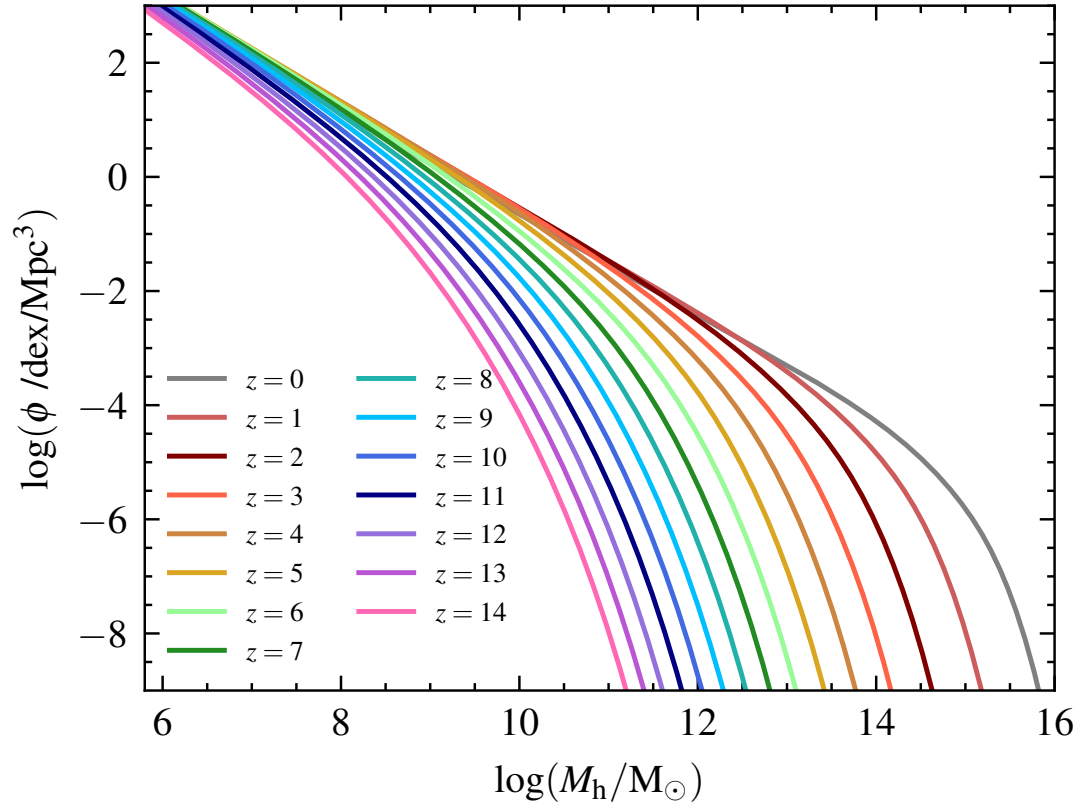


Figure 1.2 The evolution of the [Reed et al. \(2007\)](#) halo mass function model from $z = 0 - 14$.

to create a dense core which allows nuclear fusion to begin with the condition being that the cooling timescale is less than the dynamical timescale (Rees & Ostriker, 1977). There is significantly less baryonic matter than dark matter in the universe with the universal baryonic fraction given by $f_b = 0.167$. Therefore, in a given dark-matter halo mass, on average, the maximum allowed stellar mass is $0.167M_h$. The fraction of total dark matter halo mass that can be formed into stars is therefore simply given by $M_*/M_h = \epsilon(M_h)f_b$ where $\epsilon(M_h)$ describes the star-formation efficiency as a function of halo mass and f_b is the universal baryon fraction. This is shown by the stellar-to-halo mass relation (SHMR) which reveals two key characteristics. Firstly the form of the SHMR is characterised by a peak at a given halo mass ($M_h \simeq 10^{12}M_\odot$) with a declining slope at low-masses and high-masses. Secondly, the SHMR demonstrates that galaxy formation is a generally inefficient process with a maximum efficiency of $\simeq 17\%$ in the local universe. The SHMR from a number of different models and observational constraints at $z = 0$ is shown in Fig. 1.3.

The decrease in this function to both low and high halo masses is indicative of strong feedback processes which reduce the star-formation efficiency. At high masses this feedback is thought to be dominated by active galactic nuclei (AGN) feedback. This is where AGN heat the gas within the halo, preventing the gas from cooling and forming stars (Silk & Rees, 1998). At lower masses, the dominant feedback is thought to come from massive stars which drive powerful winds during their lifetime and can eject even more powerful winds from supernovae. This can eject gas from the halo preventing star formation (Dekel & Silk, 1986). These feedback processes are crucial for regulating star-formation and hence the stellar masses of galaxies.

1.3.2 The galaxy stellar mass function

Similar to how the distribution of dark matter halos masses can be characterised by a mass function, so too can the stellar masses of the galaxies that form within them. The galaxy stellar mass function (GSMF) defines the number density of galaxies that have a given stellar mass per co-moving cosmological volume. This has an overall similar trend to the HMF in that low-mass galaxies are significantly more abundant than high-mass galaxies. However, given the feedback processes that cause the star-formation efficiency to change as a function of halo mass, the shape of the GSMF differs from that of the HMF. The GSMF has a significantly

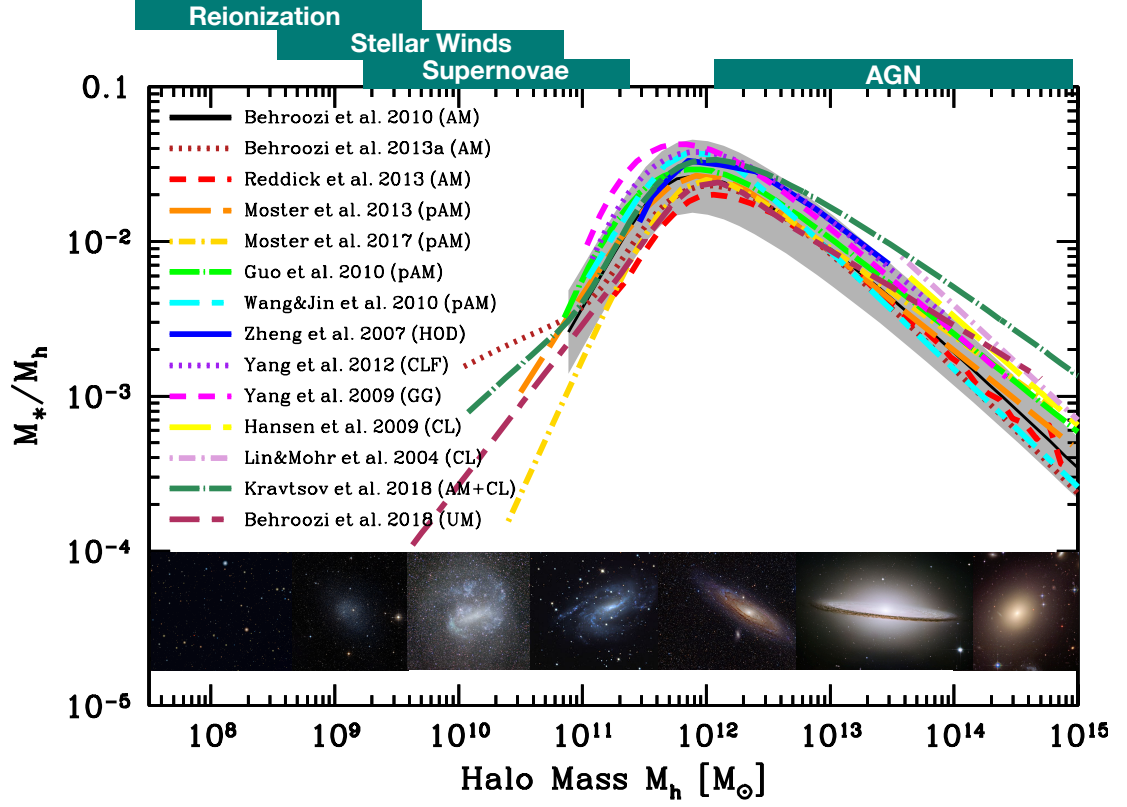


Figure 1.3 From *Wechsler & Tinker (2018)*: The stellar-to-halo mass relation of central galaxies at $z = 0$ showing a number of different constraints from the literature based on different methods of measurement. The dominating forms of feedback which reduce star-formation efficiency are shown at the top of the figure over their relevant halo mass range. Images of the typical galaxies at each halo mass are shown at the bottom.

flatter low-mass slope due to decreasing star-formation efficiency with decreasing stellar mass at low halo masses. At high masses the GSMF also exhibits a steeper decline compared to the HMF due to (presumably AGN) feedback at high halo masses. The GSMF is therefore a very useful measurement of the galaxy population as it directly traces the star-formation efficiency as a function of mass as well as the sum of past star formation. The evolution of this function has been measured from $z = 0 - 4$ fairly robustly (e.g. Baldry et al., 2012; Grazian et al., 2015; McLeod et al., 2021), with *JWST* now able to extend this to $z \simeq 8$ due to the improved sensitivity at $\lambda \geq 2 \mu\text{m}$. The current constraints at $z = 0$ primarily come from large spectroscopic redshift surveys (e.g. SDSS, GAMA; Baldry et al., 2012) and show that the local GSMF, $\phi(M)$, is best fitted by a double Schechter (1976) function:

$$\phi(M) = \ln(10)e^{-10(M-M^*)} (\phi_1^*[10^{(M-M^*)}]^{\alpha_1+1} + \phi_2^*[10^{(M-M^*)}]^{\alpha_2+1}) \quad (1.15)$$

where M^* is the characteristic mass, ϕ_1^* and ϕ_2^* are the characteristic densities and α_1 and α_2 are the low-mass slopes.

McLeod et al. (2021) extended this analysis to $z = 4$ showing that a double Schechter function is the preferred functional form out to $z \simeq 3.25$. The evolution in the GSMF from $z = 0 - 4$ is shown in Fig 1.4 with their best-fitting double Schechter functions. In Section 1.5.2 I outline the current constraints on the GSMF at $z > 4$ and the implications for the properties of high-redshift galaxies.

The GSMF can also be measured separately for the star-forming and quiescent galaxy populations to trace how these different populations evolve with redshift. McLeod et al. (2021) performed this analysis at $z = 0 - 4$ to provide separate measurements of the GSMF for star-forming and quiescent galaxies. This showed that star-forming galaxies dominate the galaxy population at $z > 4$ and evolve more slowly at $z < 3$, while a strong increase is seen in the number density of quiescent galaxies at $z < 3$.

1.3.3 The luminosity function

The galaxy luminosity function (LF) describes the number of galaxies per unit co-moving volume for a given luminosity. This function can be determined at different wavelengths where the evolution of this function encodes various

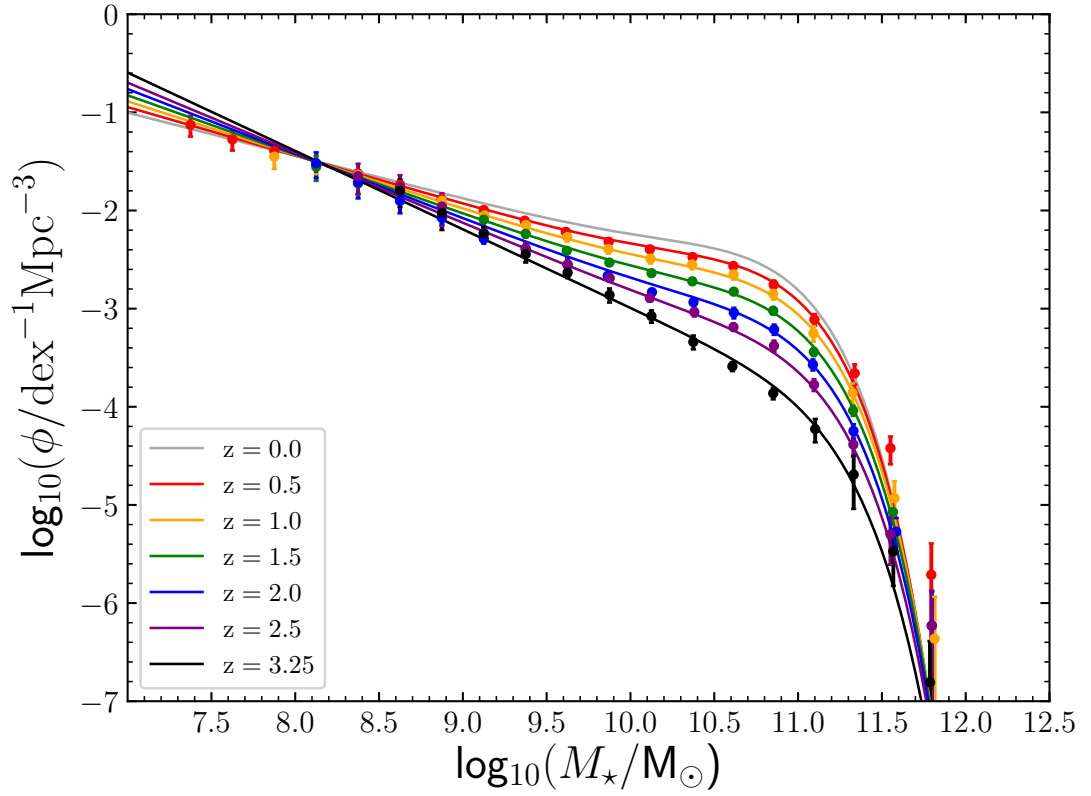


Figure 1.4 From [McLeod et al. \(2021\)](#): The galaxy stellar mass function (GSMF) from $z = 0 - 3.25$ with the data points and best-fitting double Schechter functions.

elements of the physics of galaxy evolution. Specifically, for studies of high-redshift galaxies, the UV luminosity function is of most interest as it is most easily observable (due to the redshifting of the rest-frame UV to the optical and infrared) and measures the flux from star-formation activity within the galaxy population. The galaxy UV LF is described in significant detail in Section 1.7 as this forms much of the main focus of this thesis. Another useful luminosity function to measure at high-redshift is the IR luminosity function which measures the flux emitted from the dust in the galaxy population and can be used to determine the fraction of dust-obscured star-formation activity (e.g. [Barrufet et al., 2023](#)).

1.3.4 Galaxy bi-modality

With the advent of large low- z galaxy redshift surveys (e.g. SDSS), a notable bi-modality in the galaxy population was observed (e.g. [Strateva et al., 2001](#); [Baldry et al., 2004](#)). By plotting galaxy colour against magnitude a distinct population of red quiescent galaxies was identified. These galaxies have little-to-no active star formation and lack dust and gas. The clear bi-modality in the colour-magnitude diagram selected quiescent galaxies to be simply based on their photometry. [Williams et al. \(2009\)](#) introduced the now commonly used UVJ selection criteria which selects quiescent galaxies based on this observed bi-modality which has since been implemented by many other studies (e.g. [Pacifci et al., 2016](#); [Merlin et al., 2018](#); [Hamadouche et al., 2022](#)). However, alternative methods of selecting quiescent galaxies have been introduced using SED fitting to determine the specific star-formation rate (sSFR) of a galaxy. This is given by:

$$\text{sSFR} = \frac{\text{SFR}}{M_{\star}} \quad (1.16)$$

where SFR is the star-formation rate and $M_{\star}$ is the galaxy’s stellar mass. Quiescent galaxies can then be selected by defining a sufficiently low sSFR threshold (e.g. [Leja et al., 2019](#); [Carnall et al., 2020](#)).

Using a UVJ selection, [McLeod et al. \(2021\)](#) measured the evolution of the quiescent galaxy stellar mass function from $z = 0.5 - 3.5$. This shows a dramatic decrease in the number density of quiescent galaxies from $z = 0.5$ to $z = 3.25$ with the star-forming population dominating at $z > 3$ even for the most massive galaxies ($\geq 10^{11} M_{\odot}$). Prior to the launch of *JWST* there had been difficulty in identifying quiescent galaxies at $z > 4$ with photometry (e.g. [Merlin et al., 2018](#);

Carnall et al., 2020; Marsan et al., 2022). The steep evolution in the quiescent stellar mass function could explain this apparent lack of galaxies. However, pre-*JWST* there was a lack of deep imaging data at $\lambda > 2\mu\text{m}$ and therefore the number density of quiescent galaxies at $z > 4$ was unconstrained. *JWST* is able to reveal if there is a significant population of quiescent galaxies at $z > 4$. However, in any plausible scenario, by $z \simeq 6$, the number density of quiescent galaxies is expected to be negligible. Therefore, given the focus of this thesis is galaxies at $z \geq 6$ we are only focused on star-forming galaxies.

1.3.5 The mass metallicity relation

Another key property is the metallicity of a galaxy. This quantifies the fraction of elements in a galaxy that have an atomic number greater than helium. Metals are present in a galaxy within the atmospheres of their stars as well as in the gas in the interstellar medium (ISM). This traces the formation of chemical elements within stars and how they are then distributed into the ISM through supernovae and stellar winds. Therefore, tracing the chemical evolution of galaxies allows a probe of their star-formation histories as well as the physical processes affecting the ISM (e.g. inflows and outflows of gas). Measuring the metallicity of galaxies requires spectroscopy. The stellar metallicity of a galaxy can be measured by the absorption features in a galaxy spectrum. This is however extremely challenging (especially at high- z) due to the long integration times required. Therefore, until recently there have only been a small number of detections at high- z (e.g. Sommariva et al., 2012). Nonetheless, the latest spectroscopic surveys (e.g. VANDELS; McLure et al., 2018b) have been able to yield measurements of the stellar mass-stellar metallicity relation (Cullen et al., 2019; Calabrò et al., 2021) however. Determining the gas-phase metallicity of high- z galaxies is considerably easier as this is measured using emission lines (often orders-of-magnitude brighter than the stellar continuum) which arise due to ionisation of the ISM by stellar radiation. Observational measurements of the gas-phase metallicity are usually expressed in terms of the logarithm of the oxygen abundance: $12 + \log(\text{O}/\text{H})$. The gas-phase metallicity is thought to be governed by multiple physical processes (e.g. Finlator & Davé, 2008; Lilly et al., 2013; Maiolino & Mannucci, 2019). Star formation increases the metallicity of the ISM due to the formation of heavy elements in stars and then subsequent ejection of these metals into the ISM. Conversely, the accretion of metal-poor gas from the intergalactic medium (IGM) can “dilute” the gas in the ISM lowering the metallicity. Outflows can

also regulate the metallicity through ejection of metal enriched gas from the ISM.

Using the Sloan Digital Sky Survey (SDSS), [Tremonti et al. \(2004\)](#) presented the first robust determination of the gas-phase mass-metallicity relation (MZR) at $z = 0$ which showed that metallicity increases with stellar mass, albeit with significant scatter. Since this study there have been a number of measurements up to $z \simeq 3$ finding a consistent shape of the MZR but with a decreasing normalization with increasing redshift (e.g. [Cullen et al., 2014](#); [Curti et al., 2020](#); [Sanders et al., 2020](#)). More recently, measurements have been made of both the gas-phase oxygen abundance (O/H) and the stellar iron abundance (Fe/H) (e.g. [Cullen et al., 2019](#); [Stanton et al., 2024](#)). These measurements can be combined to determine the oxygen to iron abundance (O/Fe) which has been observed to be enhanced relative to the solar abundance. This effect is known as α -enhancement. This ratio is determined by the star-formation timescales because oxygen is produced on short timescales by core-collapse supernovae (CCSNe) whereas iron is produced on longer timescales by CCSNe and type 1A supernovae ([Kobayashi et al., 2020](#)).

1.3.6 Galaxy spectral energy distribution

The spectral energy distribution (SED) of a galaxy describes the flux emitted as a function of wavelength and contains many features which can be measured to determine a wealth of different galaxy properties. A galaxy SED represents the sum of different sources of flux emitted from a galaxy as a function of wavelength and can be defined as being made up of a “continuum” which describes the general shape with emission lines added to the continuum and absorption lines subtracted from the continuum. In the rest-frame UV to infrared this continuum is typically dominated by the flux emitted from stars and therefore is the sum of the flux emitted from the total stellar population in a galaxy. The specific intensity emitted from a star per unit frequency, $B_\nu(T)$, follows a black body given by:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{hc}{k_B T}} - 1} \quad (1.17)$$

where ν is the frequency, h is Planck’s constant, c is the speed of light, k_B is the Boltzmann constant and T is the effective temperature of the star.

This relates the spectrum of a star to simply its temperature with the peak of the spectrum moving to shorter wavelengths at increased temperatures. The most hot and massive stars are O and B type stars which have temperatures of $T \simeq 10000 - 30000K$ the spectra from which peaks in the rest-frame UV. Stars similar to that of the Sun (G type) have effective temperatures of $T \simeq 5500 - 6000K$ with spectra that peak in the rest-frame optical. The coolest dwarf stars ($T \simeq 500K$) have spectra which peak in the infrared.

The initial distribution of stellar masses within a galaxy is called the initial mass function (IMF) and is a crucial component in modelling the SED of a galaxy. This distribution describes the probability of a star within a galaxy having a certain mass and follows the general trend of a greater probability towards lower masses (i.e. the stellar population is dominated by low mass stars). The distribution of masses then evolves with cosmic time due to the evolution of stars as they retire from the main sequence. The exact shape of the IMF is important when modelling the SED as the stellar mass and star-formation history of a galaxy is particularly sensitive to the choice of IMF. [Salpeter \(1955\)](#) introduced a simple power-law form of the IMF described as $dn/dM \propto M^{-2.35}$ but more complex forms are now accepted as they are more representative of the IMF in the Milky Way such as those described by [Kroupa \(2001\)](#) and [Chabrier \(2003\)](#).

A galaxy SED also features absorption and emission lines. Absorption lines arise due to the presence of metals in stellar atmospheres. This is where flux emitted from the star is absorbed at specific wavelengths corresponding to the energy level gap within the metals. This also acts as an important cooling mechanism within the star and is often known as line cooling. Emission lines arise due to the presence of gas in the interstellar medium (ISM) of galaxies. Radiation from stars is absorbed by the ISM gas causing electrons to transition to higher energy levels. This causes the *emission* of photons with a wavelength corresponding to this energy ($E = hc/\lambda$). In order to generate this phenomenon, the incoming radiation must be sufficiently high energy in order to emit photons from the gas as well as of course requiring the presence of gas initially. Therefore the presence of emission lines is typically reserved for star-forming galaxies or those with active galactic nuclei (AGN). The emission lines from the ISM gas are typically emitted in the rest-frame UV to the far-infrared and their strength is sensitive to the chemical properties of gas within the ISM.

The ISM of a galaxy can also contain interstellar dust which consists of small “grains” (5nm–250nm) produced in stellar atmospheres or supernovae ([Draine,](#)

2011). Interstellar dust can be categorised into two main types - carbonaceous and silicate. Dust grains in the ISM have a significant effect on a galaxy’s SED where it both emits a continuum and emission features at infrared wavelengths because it can absorb and redden the SED in the UV and optical and then re-emit this energy at longer wavelengths. This is because dust grains absorb UV and optical photons and re-emit in the infrared which results in a dust continuum while also reducing the flux at shorter wavelengths. Importantly, the absorption becomes increasingly more significant with decreasing wavelength which results in the SED changing shape with “redder” colours. The relationship between the level of dust attenuation and wavelength is known as the dust attenuation curve and constraining this is vital to ensure accurate dust corrections when trying to measure certain galaxy properties (e.g. star-formation rate). This curve is usually given by $A_\lambda(\lambda)$ which describes the attenuation in the form of magnitudes. Therefore the observed apparent magnitude of a galaxy is given by:

$$m_{\text{obs}} = m_{\text{int}} + A_\lambda \quad (1.18)$$

where m_{int} is the intrinsic magnitude and m_{obs} is the observed magnitude. Here the attenuation curve can be expressed by a number of models. A comparison of the most frequently used models which have been derived from different observations are shown in Fig 1.5.

The most often used attenuation curve for high-redshift galaxies is the Calzetti et al. (2000) curve which was derived for local starburst galaxies and is often therefore assumed to apply for high redshift galaxies in general. This notably does not contain the 2175Å bump which is present in a number of other attenuation curves, in particular that derived for the Milky Way.

1.4 Selection of galaxies at high-redshift

There are a number of techniques that have been used to detect the rare number of high-redshift galaxies in the sky. The primary method is the Lyman break technique. This is where there is an distinct “step” in the SED of a galaxy due to the attenuation of flux shortward of $\lambda_{\text{rest}} = 912 \text{ \AA} - 1216 \text{ \AA}$. There are 2 key energy level transitions in the hydrogen atom to explain this process. The energy of an emitted photon, E_{photon} , from a hydrogen atom is given by:

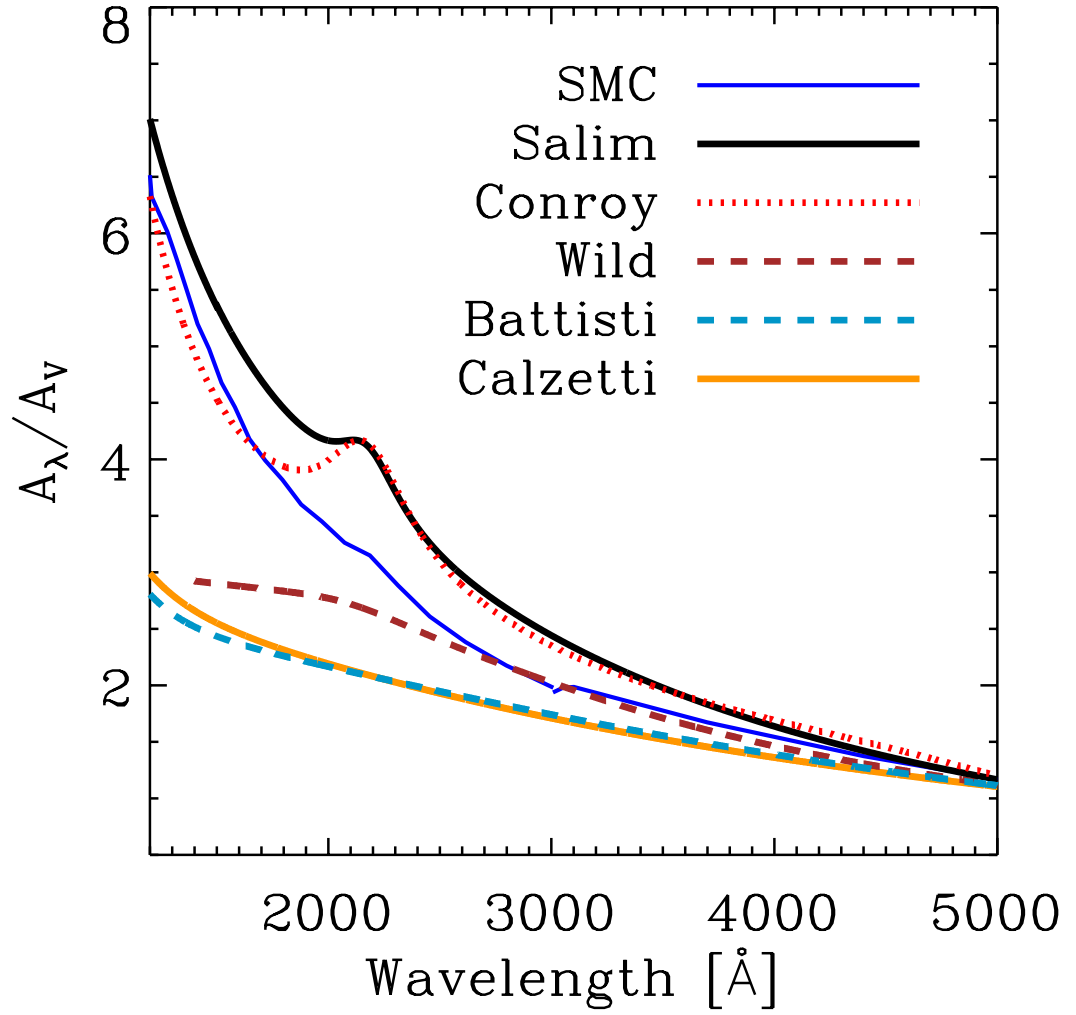


Figure 1.5 From *Salim & Narayanan (2020)*: The dust attenuation curves from *Calzetti et al. (2000)*; *Wild et al. (2011)*; *Conroy & Gunn (2010)*; *Battisti et al. (2016)*; *Salim et al. (2018)* in comparison to the average Small Magellanic Cloud (SMC) extinction curve.

$$E_{\text{photon}} = 13.6 \text{ eV} \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right) \quad (1.19)$$

where an electron transitions from an upper level, n_2 , to a lower level, n_1 . The $n = 2$ to $n = 1$ transition in hydrogen corresponds to a wavelength of $\lambda = 1216 \text{ \AA}$ (where $E_{\text{photon}} = hc/\lambda$) which is known as Lyman- α . The Lyman limit is given by $\lambda = 912 \text{ \AA}$ and corresponds to the $n = \infty$ to $n = 1$ transition. Star-forming galaxies emit strongly in the UV due to the presence of young, massive O and B type stars. This flux is absorbed by neutral hydrogen in the interstellar medium (ISM) shortward of the Lyman break. One of the strongest emission lines in star-forming galaxies is the Lyman- α line. However, these photons have a large interaction cross section making them easily absorbed by neutral hydrogen. When Lyman continuum radiation is emitted by a galaxy it can be absorbed by clouds of neutral hydrogen in the line-of-sight at lower redshifts as Lyman- α in absorption. This causes absorption features to appear at wavelengths shortward of $1216 \text{ \AA}$ in the spectrum of the original emitter. These wavelengths correspond to the redshifts of the neutral hydrogen clouds which absorb the photons. This phenomenon is known as the Lyman- α forest and is most obviously visible in the spectra of bright quasars at $z > 5$. This is shown in Fig. 1.6 for a sample of bright quasars from [Fan et al. \(2006\)](#).

This absorption shortward of $1216 \text{ \AA}$ becomes stronger with increasing redshift with almost complete absorption seen by $z \sim 6$. This is known as the “Gunn-Peterson trough” ([Gunn & Peterson, 1965](#)). This is also shown in Fig 1.6 where it can be seen that this absorption at $\lambda < 1216 \text{ \AA}$ becomes increasingly strong by $z = 6$. This suggests that rather than the presence of individual clouds of neutral hydrogen, the intergalactic medium (IGM) has reached a few percent neutral. Therefore, measurements of bright quasars can be used to measure precisely when this transition happens and therefore define the end of the epoch of reionization (e.g. [Fan et al., 2006](#); [Bosman et al., 2022](#)) which is now thought to be at $z = 5.3$.

The presence of this feature in the rest-frame UV of a galaxy spectral energy distribution led to the development of the Lyman-break technique to identify galaxies at high redshift. This is not only because the Lyman break can be easily identified from broad-band photometry, but also because the position of this break can give an estimate of the redshift of the galaxy. The Lyman-break method was first successfully applied to select galaxies at $z \sim 3$ ([Guhathakurta et al., 1990](#); [Steidel & Hamilton, 1992](#)). These studies used a “colour-colour”

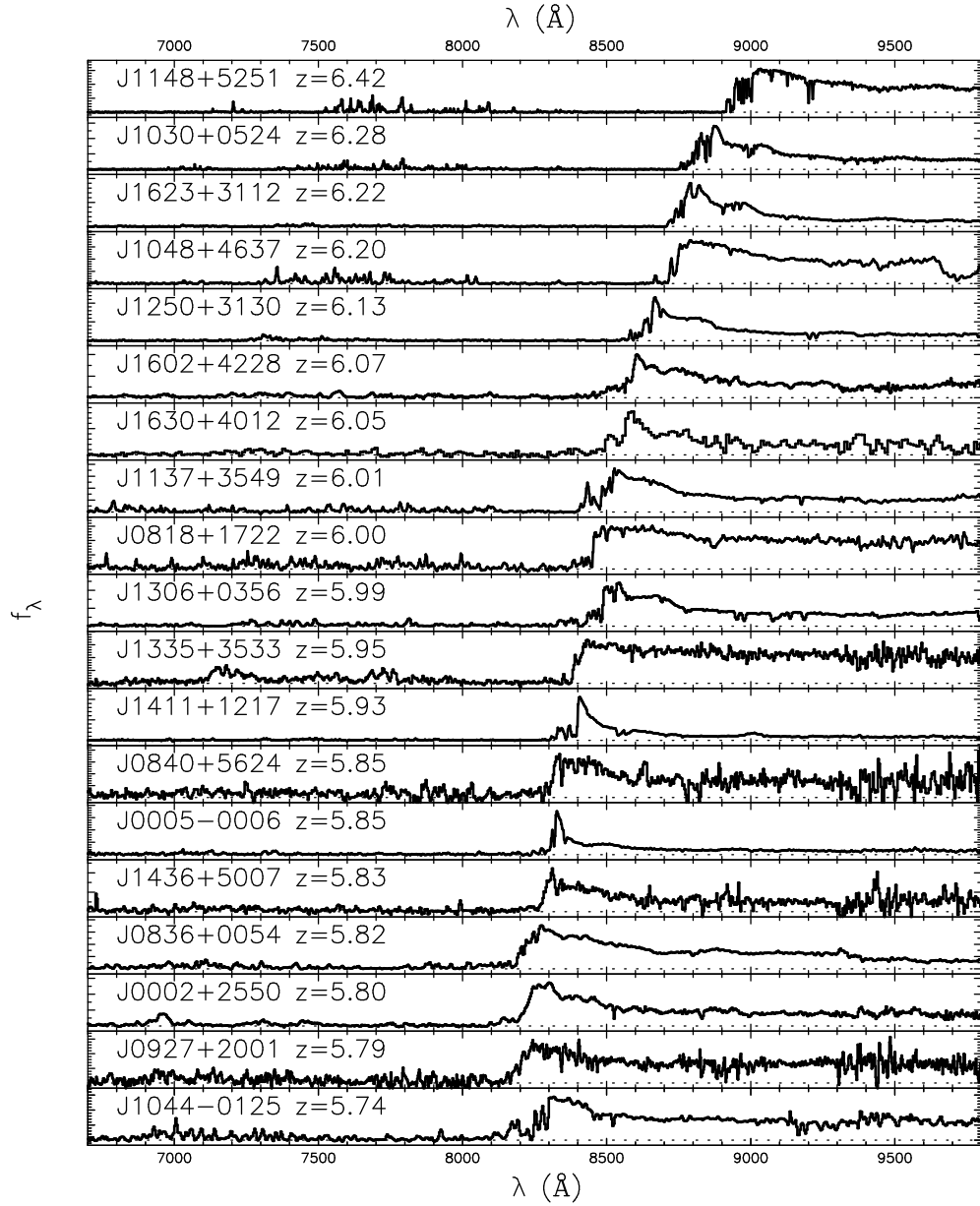


Figure 1.6 From *Fan et al. (2006)*: A sample of bright quasars at $z > 5$. They show bright Ly- α emission with strong “Gunn-Peterson” troughs shortward of 1216 Å. The strength of the troughs increase with increasing redshift indicating an increasingly neutral IGM.

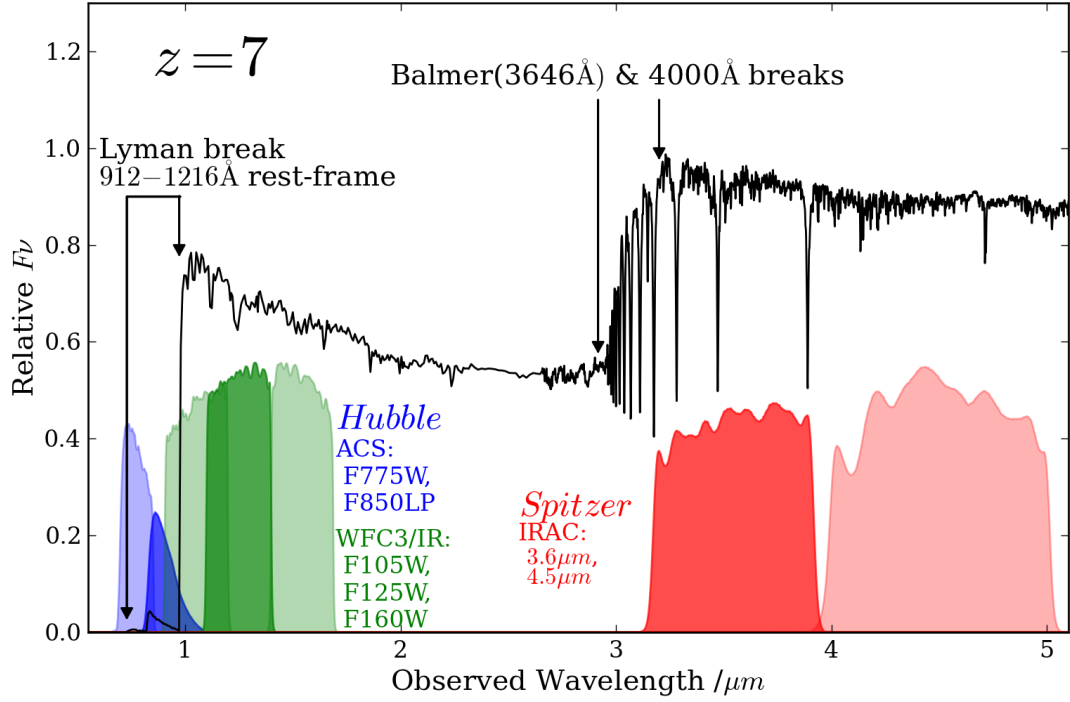


Figure 1.7 From [Dunlop \(2013\)](#): An example star-forming galaxy SED at $z = 7$ redshifted to the near-infrared from the rest-frame UV and optical. The HST and Spitzer/IRAC filters are shown to illustrate how these spectral features can be captured by broadband photometry. The Lyman break at $z = 7$ is present within the HST filters whereas the rest-frame optical features such as the Balmer break, are present within the mid-infrared IRAC filters.

selection of high-redshift galaxies observed in the U, G and R filters in the UV and optical. This technique was first definitively validated when the galaxies in these samples were spectroscopically confirmed by [Steidel et al. \(1996\)](#).

Since this initial selection, this technique has been used repeatedly over the last 3 decades to select galaxies at ever increasing redshift. An example of what a galaxy SED at $z = 7$ selected in *HST* and *Spitzer*/IRAC imaging looks like is shown in Fig. 1.7.

1.4.1 Colour-colour selection

As mentioned above, the most simple approach to applying the Lyman-break technique is a “colour-colour” selection. This involves making a selection where there is a “red” colour (i.e. the flux is greater in the longer wavelength filter)

across the position of the Lyman break and a “blue” colour longward of the Lyman break (where the rest-frame UV continuum flux is sampled). This selection can be implemented using different filters depending on the redshift of target and has a number of advantages and disadvantages. One advantage is that it is simple and reproducible as it simply requires the fluxes of the sources to be measured. However, a significant disadvantage is that it is vulnerable to contamination. In particular, the colours of a high-redshift galaxy can be reproduced by a brown dwarf star or a dusty low-redshift galaxy. This is discussed further in Section 1.4.3. The disadvantages of colour-colour selection are demonstrated in Fig. 1.8 which demonstrates a number of issues highlighted in Finkelstein et al. (2010). Firstly, there are a number of sources which have photometric redshifts of $z_{\text{phot}} > 6$ that would not be selected by the colour-colour selection. There are also a number of galaxies that have $z_{\text{phot}} < 6$ that would be selected here due to their colours. Secondly, and perhaps more crucially, the colour selection employed by Yan et al. (2010) would allow significant levels of brown dwarf contamination. The selection used by Oesch et al. (2009) would allow a number of these contaminants to be removed with the addition of a constraint on the colour longward of the break. However, as can be seen in Fig 1.8, there still persists significant rate of brown dwarf contamination.

1.4.2 SED fitting

The other (and now more commonly) used technique to select high-redshift galaxies is SED fitting. Instead of trying to select the Lyman break purely by the flux difference between the filters that sample the break, SED fitting involves fitting models of the galaxy’s SED to all of the photometric data points. This can be used to measure the photometric redshift of the source as well as a wealth of other galaxy properties. This approach involves first generating a set of galaxy SED templates based on models of the stellar populations within galaxies. Three of the most commonly used models are the BC03 (Bruzual & Charlot, 2003), FSPS (Conroy et al., 2009) and PEGASE (Fioc & Rocca-Volmerange, 1999) models. The model SEDs, are based on an assumed star-formation history and are then subject to an assumed dust attenuation. The SED templates are then tested against the data points, exploring the parameter space of the different properties of the template including, most crucially, the redshift. The result is a probability distribution of the redshift where the peak of this distribution specifies the best-fitting photometric redshift.

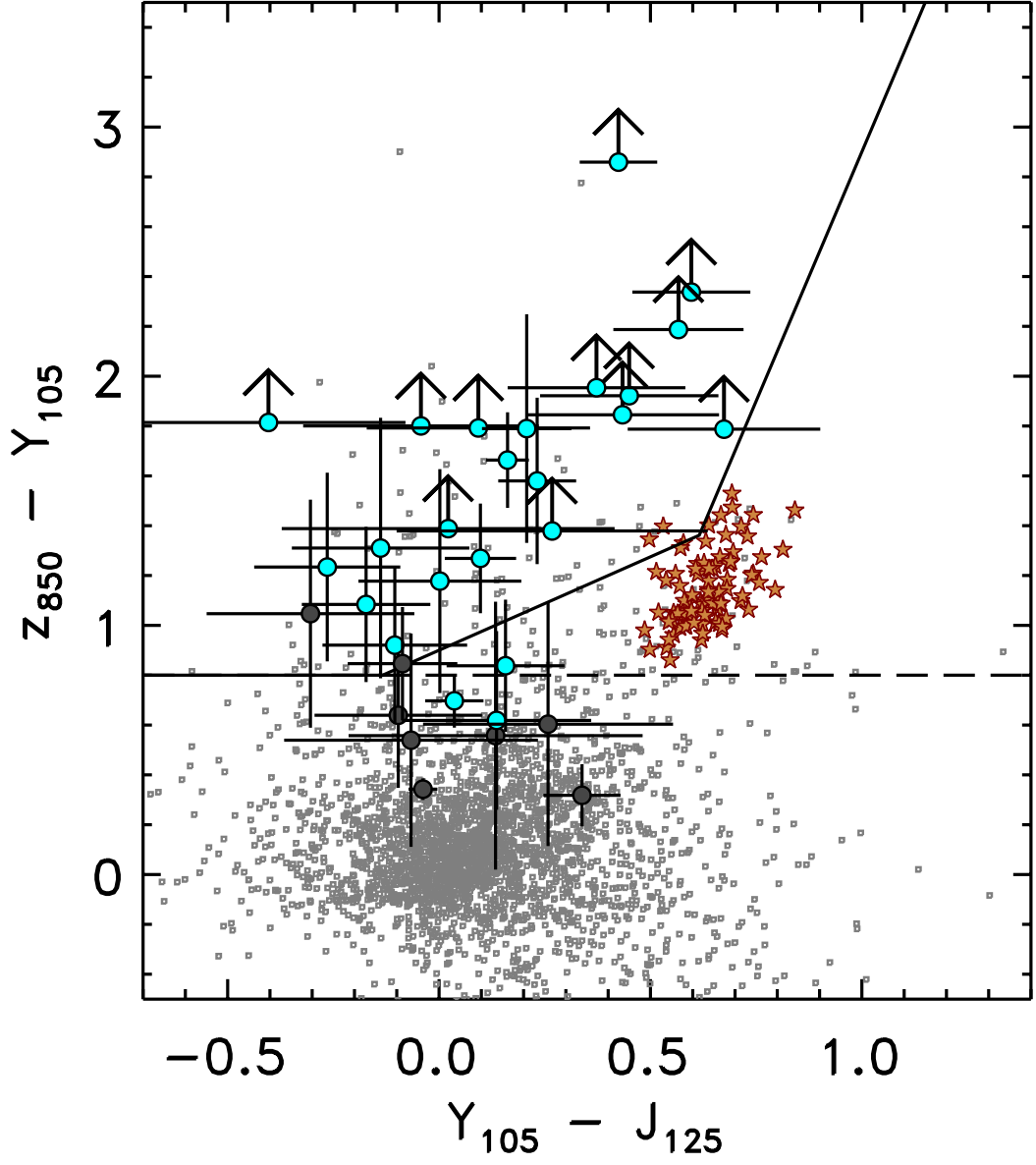


Figure 1.8 From [Finkelstein et al. \(2010\)](#): A demonstration of the limitations of colour-colour selection. The grey squares show galaxies with $z_{\text{phot}} < 6$, the grey circles show galaxies with $6 < z_{\text{phot}} < 6.3$ and the cyan circles show those with $6.3 < z_{\text{phot}} < 7.5$. The brown stars show the colours of a sample of brown dwarfs. The solid black line shows the colour-colour selection from [Oesch et al. \(2009\)](#) and the dashed line shows that adopted by [Yan et al. \(2010\)](#).

The advantage of this technique is that it uses all of the photometric information of a given source simultaneously to determine the redshift of the source. Although the Lyman break will drive the preferred redshift of the source, the photometry longward of the break is crucial for removing low-redshift contaminants.

1.4.3 Potential contaminants

There are a number of potential contaminants that can be found in high-redshift galaxy samples if not carefully removed. Firstly, low-redshift galaxies can be mistakenly identified as high-redshift galaxies. The main factor in this contamination is the confusion between the Lyman break and the Balmer break of a galaxy. The Balmer break arises due to a drop in flux shortward of the Balmer limit $\lambda_{\text{rest}} \simeq 3646 \text{ \AA}$ which is due to the $n = \infty$ to $n = 2$ transition in hydrogen. Similar to the Lyman break, this causes a distinctive “step” in the galaxy SED at this wavelength. Due to this similarity to the Lyman break, a low-redshift galaxy with a Balmer break can produce very similar photometry to a high-redshift galaxy with a Lyman break if there is inadequate signal-to-noise of the photometry. This demonstrates the importance of having sufficiently deep imaging in filters that sample the flux shortward of the Lyman break as with a Balmer break there is still flux emitted shortward of the Balmer break (the break does not generally exceed a factor of 2). Another potential factor in low-redshift contamination is the presence of extreme emission lines in the rest-frame optical. This is of particular concern for the mid-IR photometry which prior to *JWST* was from *Spitzer*/IRAC. This is where the flux measured in the imaging is driven primarily by the detection of strong emission lines rather than the underlying continuum. For example, the continuum could be “red” in colour (which with SED fitting would normally help favour a low-redshift solution), but the emission line could make the resultant photometry “blue” in colour which would imitate a blue UV continuum at high-redshift.

The second potential contaminant is a brown dwarf star. This is particularly important for wide-area ground-based surveys where the aim is to detect rare, bright galaxies at high redshift (e.g. [Stefanon et al., 2019](#); [Bowler et al., 2020](#)). This is because with the lower resolution imaging from ground-based data (compared to *HST* or *JWST*), both stars and high-redshift galaxies appear as point sources. To account for this form of contamination, when SED fitting, the photometry can also be modelled with brown dwarf templates. The quality

of the fit from the best fitting brown dwarf template can then be compared to the best fitting galaxy template (e.g. using the reduced χ^2 value) to deduce the security of the galaxy solution. Having contiguous filter coverage is also important in removing brown dwarf contamination. For example the, *HST* pure-parallel program BoRG has suffered badly from this issue due to the often poor filter coverage in selecting high-redshift galaxies (e.g. [Rojas-Ruiz et al., 2020](#); [Leethochawalit et al., 2023a](#)).

1.5 The properties of high-redshift galaxies

1.5.1 UV spectral slopes

The slope of the UV continuum emission is primarily determined by the flux from the young, blue stellar population of a galaxy. This is an important property of a galaxy as it can reveal information about the properties of the stellar population such as metallicity and age. It is also reasonably straightforward to determine as it can be measured using multi-wavelength photometry. The dust content of a galaxy can also affect the value of the slope as dust attenuation can redden the observed light.

The UV continuum slope is often represented by β where the flux is given by $f_\lambda \propto \lambda^\beta$. For galaxies at $z > 6$, β can be measured from the photometry in the near-infrared. For $\beta = -2$, the spectrum in F_ν is flat which equates to zero colour in AB magnitudes. If the UV slope is sufficiently blue enough (i.e. $\beta = -3$), then this would indicate the presence of a very young, dust-free and metal-free stellar population. Therefore, much effort has been invested in trying to accurately determine β as this method could potentially identify Pop III stars in these early galaxies. An early measurement using *HST* data apparently discovered galaxies with a UV slope of $\beta = -3 \pm 0.2$ ([Bouwens et al., 2010](#)) at $z \sim 7$. However further measurements showed that this study was biased towards bluer slopes (due to a scattering effect of the galaxy fluxes near the detection limit) with a consensus now showing a slope of $\beta \sim -2$ at $z \sim 7$ ([Dunlop et al., 2012, 2013](#); [Bouwens et al., 2014](#)). The value of $\beta \sim -2$ is also aligned with theoretical predictions ([Dayal & Ferrara, 2012](#)). Therefore no convincing evidence was found for extremely blue stellar populations at $z \geq 7$, with the UV slopes appearing to have little evolution from $z \sim 4$ when using *HST* imaging.

The relationship between β and M_{UV} has also been investigated. At $z \sim 5$ there is strong evidence for this relationship, with galaxies displaying steeper UV slopes at lower luminosities (Rogers et al., 2014). At $z \sim 7$ however, there is disagreement on whether this relationship still exists. A number of studies showed a lack of dependence of M_{UV} for β (Dunlop et al., 2012; Rogers et al., 2013; Finkelstein et al., 2012). However, this is in disagreement with other studies which show a linear relation (Bouwens et al., 2014, 2010).

1.5.2 Stellar mass

One of the most important physical properties of a galaxy is its stellar mass. This quantifies the total mass of stars within a galaxy which represents the sum of its star-formation history.

Measurements of the stellar masses of galaxies at high-redshift have been challenging as accurate measurements require observations across a wide wavelength range to sample the flux from the complete stellar population. At $z > 6$ *HST* imaging probes the rest-frame UV which is dominated by the flux from O and B stars. These are rare and short-lived stars which are therefore a good tracer of recent star-formation, but in terms of stellar mass they are not representative of the wider galaxy stellar population. Therefore, if one attempts to measure the stellar mass of a galaxy using rest-frame UV observations alone, the result will be inaccurate. What is therefore required is observations at longer wavelengths ($3 - 5\mu\text{m}$) which at $z > 6$ can be observed using the *Spitzer*/IRAC [3.6] and [4.5] filters. A number of studies attempted to measure the galaxy stellar mass function (GSMF) to $z \sim 7$ utilising the *Spitzer*/IRAC [3.6] and [4.5] imaging to measure stellar masses (e.g. Stark et al., 2013; Duncan et al., 2014; Grazian et al., 2015). This showed a steepening of the GSMF between $z = 4 - 7$ with a low-mass slope of $\alpha \simeq -1.9$ at $z = 7$. Stefanon et al. (2021) attempted to extend the use of *Spitzer*/IRAC to $z \simeq 10$, measuring a low-mass slope of $\alpha \simeq -2$ at $z = 10$. They also conclude that despite a significant change in the stellar mass density ($\times 1000$) from $z = 10$ to $z = 6$, the star-formation efficiency (traced by M_*/M_h) does not change over this redshift range.

However, there are a number of major difficulties in using the *Spitzer*/IRAC imaging to measure the evolving stellar mass function - especially at $z > 6$. Firstly, the angular resolution of the IRAC imaging is poor in comparison to *HST* and even ground-based telescopes (e.g. HSC, VISTA). This means that multiple

sources can become blended together in the IRAC imaging making it difficult to obtain accurate fluxes for the targeted source. Therefore it is often necessary to utilise de-confusion software (e.g. TPHOT; [Merlin et al., 2015](#)) which inevitably introduces additional uncertainties.

Secondly, the presence of strong rest-frame optical emission lines can contaminate the IRAC filters, which due to their breadth can cause difficulty distinguishing between strong emission lines and continuum flux ([Roberts-Borsani et al., 2016](#)). This therefore leads to considerable uncertainty in the stellar masses. Without spectroscopic redshifts for these sources, the emission lines can move through the filters with redshift leading to a broad range of stellar masses at $z \geq 8$ ([Strait et al., 2020](#)). To resolve this issue one can attempt to disentangle the contribution to the observed flux from nebular emission lines and stellar continuum using stellar population synthesis models when fitting the photometry (e.g. [Endsley et al., 2021](#)). Another method is to limit the redshift range of study to that where key emission lines (e.g. [OIII] & H α) lie outside the [3.6] and [4.5] IRAC filters (e.g. [Smit et al., 2014](#)).

By measuring the stellar mass of high-redshift galaxies, the relationship with star-formation rate (SFR) can be established. The result is the star-formation main sequence which describes the star-formation processes that impact the galaxy population. The first measurements of the galaxy star-formation main sequence at $z = 4 - 6$ showed that more massive galaxies emit stronger UV fluxes ([Stark et al., 2009](#)) with little evolution over this redshift range. [Salmon et al. \(2015\)](#) report a star-forming main sequence which follows the form $\text{SFR} \propto M_*^\alpha$ where $\alpha \simeq 0.6$. Measurements of the stellar mass function and the star-formation main sequence at $z > 6$ can be achieved using observations from *JWST*/NIRCam due to the increased sensitivity, resolution and filter coverage over *Spitzer*/IRAC.

1.5.3 Dust content

Another key property of high-redshift galaxies is their dust content which is crucial for understanding the production mechanisms of interstellar dust as well as for correcting the cosmic star-formation rate density (see Section 1.7.1) for dust obscuration. Measurements of the UV continuum slopes (as described in Section 1.5.1) can provide an indirect probe of the dust content of galaxies by measuring the dust attenuated flux from the rest-frame UV. However, more direct probes of the dust content are now observable primarily due to the sensitivity of

The Atacama Large Millimeter/submillimeter Array (ALMA) at submillimeter wavelengths. By measuring the sub-mm continuum of galaxies at $z > 6$ with ALMA, one can directly measure the thermal radiation emitted from the dust grains within the galaxy. ALMA can also observe far-infrared emission lines (e.g. [CII]158 μ m) which can not only give a precise spectroscopic redshift, but also can be used as an indirect tracer of the neutral gas within the galaxy (e.g. [Wolfire et al., 2003](#)).

The first direct detection of the dust continuum in a galaxy at $z > 4$ was measured by [Watson et al. \(2015\)](#) who detected dust in a strongly-lensed galaxy at $z = 7.5$. Further detections from ALMA from [Capak et al. \(2015\)](#) showed a detection of the dust continuum in 4 galaxies from a sample of 9 galaxies at $z = 5 - 6$. They conclude that the detected flux is $12\times$ lower than seen in galaxies with similar UV properties at $z < 3$, suggesting a potential rapid evolution in the dust content from $z = 3 - 6$. These galaxies also exhibit somewhat redder UV slopes than the average at $z = 5 - 6$ with $\beta \simeq -1.4$ to -0.7 suggesting that the ALMA observations trace the dust-rich galaxy population at these redshifts.

Since the initial results from ALMA there have been a plethora of studies investigating galaxy dust content at $z > 6$. A number of other lensed galaxies have had direct dust detections at $z = 8 - 9$ ([Laporte et al., 2017](#); [Tamura et al., 2019](#); [Bakx et al., 2021](#)). There have also been dust detections from UV-luminous galaxies selected from ground-based surveys ([Bowler et al., 2018](#); [Witstok et al., 2022](#)). Based on these measurements, these galaxies have a strong fraction of obscured star-formation (e.g. $0.2 - 0.6$ [Algera et al., 2023](#)). However, as these galaxies are the most luminous selected, then they likely also have above average stellar masses. Based on the correlation between stellar mass and UV attenuation (e.g. [McLure et al., 2018a](#)), these galaxies likely represent the more dust-rich sources compared to the average population at $z = 7 - 8$. Measurements of the far-infrared luminosity function suggest an obscured fraction of $\simeq 0.1$ at $z = 7$ ([Barrufet et al., 2023](#)). This shows that although there is a rapid build-up in the dust content from $z = 7$ to $z = 3$, there is still a significant level of dust within the first billion years of cosmic time.

ALMA has also shown complex dust morphologies at $z > 6$. In [Bowler et al. \(2022\)](#) they show that for luminous ($M_{\text{UV}} < -22$) galaxies at $z = 7$, there are a range of dust morphologies present. They find both extended dust emission as well as compact emission that is offset from the UV flux.

1.5.4 Spectroscopic redshifts

The redshifts for most galaxies that have been detected at $z > 6$ have been estimated using photometry. This is measured using SED fitting codes such as EAZY (Brammer et al., 2008) to produce a measurement of a photometric redshift. However, photometric redshifts can have large uncertainties as well as degeneracies in their measurements. For example, as explained above, the Lyman break of a galaxy at high redshift creates a similar colour between the appropriate two filters as a Balmer break in a lower-redshift galaxy given photometry of inadequate signal-to-noise. This can lead to confusion as to whether the detected galaxy is really present at high redshift or whether the low-redshift solution is the correct one. The most robust way to measure the redshift of a galaxy is of course through the position of emission lines in the spectra - the spectroscopic redshift. Spectroscopy also allows for a more detailed determination of galaxy properties such as the gas-phase metallicity, and hence connecting galaxy observations with atomic physics.

However, spectroscopy of galaxies at $z > 7$, pre-*JWST* has been challenging, with only a small sample of sources having robust spectroscopic redshifts based on detections of the very strongest emission lines pre-*JWST*. Spectroscopy of galaxies at $z > 7$ has been primarily made using optical/near-infrared telescopes such as the Very Large Telescope (VLT), Keck Observatory and *HST*. These observations have observed rest-frame UV lines such as Ly α (1216Å), NV (1243Å) and CIV (1548, 1550Å). Early progress in spectroscopy of $z > 7$ galaxies came from Ly α measurements (Finkelstein et al., 2013) and a number of galaxies at $7.4 < z < 8$ have yielded Ly α detections in recent years (Oesch et al., 2015; Stark et al., 2017; Endsley et al., 2021). The ability to spectroscopically measure Ly α at $z > 7$ was a significant achievement given the increasingly neutral IGM at $z > 5.5$ which strongly attenuates Ly α emission from galaxies. This required large numbers of high- z targets to attempt to measure Ly α from a small fraction of them. The successful detection of Ly α at $z > 7$ allowed constraints on the Ly α fraction as a function of redshift with a strong decline observed at $z > 6$ decreasing from $\sim 50\%$ at $z = 6$ to $< 5\%$ at $z = 8$ (Schenker et al., 2014).

Pre-*JWST*, the most distant galaxy with a spectroscopic confirmation was the galaxy GN-z11 at $z = 10.957$. This was first measured using *HST* grism spectroscopy (Oesch et al., 2016) and was then further confirmed with *Keck*/MOSFIRE observations of the rest-frame UV [CIII] doublet and [OIII] lines

(Jiang et al., 2021). However, with subsequent *JWST* spectroscopy this results was proven to be inaccurate with the true redshift being $z = 10.6$ (Bunker et al., 2024). This demonstrates the difficulty in using *Keck*/MOSFIRE pre-*JWST* to spectroscopically confirm these extreme redshift sources. Successful spectroscopic measurements of $z > 7$ galaxies have also come in the sub-mm with the Atacama Large Millimeter/submillimeter Array (ALMA). This has, for example, confirmed galaxies at $z = 9.1$ (Hashimoto et al., 2018) and $z = 8.38$ (Laporte et al., 2017) with [OIII] at $88\mu m$ as well as observations with [CII] at $158\mu m$.

JWST NIRSpec revolutionises the ability to perform spectroscopic observations at $z > 6$ with access to the rest-frame optical emission lines and probing much deeper than current facilities free from atmospheric emission and absorption. This will allow spectroscopic confirmation with multiple emission lines and enable the determination of more detailed galaxy properties.

1.6 Cosmic Reionization

As mentioned in Section 1.1, an important period in cosmic history was the epoch of reionization. This occurred within the first billion years after the Big Bang and is thought to have started with the formation of the first stars. Measurements of the Lyman-alpha forest from high-redshift quasars place the end of reionization around $z \sim 6$ (Robertson et al., 2015; Bosman et al., 2021). Measurements of the integrated optical depth of Thomson scattering, τ , can place a stringent constraint on the mid-point of reionization. Using data from the Planck survey (Planck Collaboration et al., 2020a), the optical depth is measured to be $\tau \simeq 0.05$ (Planck Collaboration et al., 2020b) suggesting a mid-point to reionization of $z \simeq 7.5$ indicative of a late and rapid reionization. The process of reionization is where ionising radiation from the first galaxies ionises the neutral hydrogen IGM over time until it is completely ionised. The primary sources of reionization are thought to be young stars in early galaxies due to the strong UV continuum emitted by the massive stars. Active Galactic Nuclei (AGN) also emit strong levels of UV radiation and therefore have been considered as candidates for the agents of reionization. However despite their high escape fractions, the number density of AGN in the epoch of reionization is insufficient to allow for more than a minor contribution to reionization (Parsa et al., 2018). Understanding the process of cosmic reionization is important for our understanding of the underlying cosmology of the universe as well as the properties of early galaxies

as reionization is the imprint left by the formation of the first galaxies.

A useful way of parameterising the process of cosmic reionization is by understanding the rate at which ions are formed,

$$\dot{n}_{\text{ion}} = f_{\text{esc}} \xi_{\text{ion}} \rho_{\text{UV}} \quad (1.20)$$

where f_{esc} is the escape fraction of ionising photons, ξ_{ion} is the number of ionising photons produced per unit star-formation rate and ρ_{SFR} is the cosmic star-formation rate density. Therefore constraining measurements of these three parameters are vital for understanding cosmic reionization. In the following three sections I outline these parameters.

1.6.1 Escape Fraction f_{esc}

The escape fraction of ionizing photons that successfully exit a galaxy, f_{esc} , is one of the important parameters for understanding cosmic reionization. This is because the majority of ionizing flux that is produced by a galaxy is attenuated by the gas within the galaxy itself, leaving only a small fraction able to escape and contribute to cosmic reionization. However, measuring this at $z \geq 6$ becomes very challenging due to the increasingly neutral IGM which attenuates the escaping UV photons that we require to measure in order to determine f_{esc} . There have been a handful of direct detections at moderate redshift using deep spectroscopic observations of reionization era analogues. [Pahl et al. \(2021\)](#) analysed 124 galaxies at $z \sim 3$ with deep Keck/LRIS spectra and found 13 Lyman continuum leakers in this sample. The sample had an average escape fraction of $f_{\text{esc}} = 0.040 \pm 0.006$. However, measurements of f_{esc} within the epoch of reionization rely on indirect measurements. Since the end-point of reionization is known to be at $z \sim 6$, one approach was to use the measurements of ρ_{UV} to calculate what average escape fraction was required of the galaxy population to complete reionization by the required time (e.g. [Finkelstein et al., 2019](#); [Robertson et al., 2015](#)). There is some discrepancy in this with [Robertson et al. \(2013\)](#) finding that an escape fraction of $\sim 10 - 20\%$ is required however [Finkelstein et al. \(2019\)](#) require only $\sim 5\%$. This approach of course depends on a number of assumptions such as the ionising efficiency ([Eldridge et al., 2017](#)) and the luminosity dependence of the production of ionising radiation. It is most common to assume that reionization was primarily driven by faint sources with many studies supporting this conclusion (e.g. [Begley](#)

et al., 2022; Saldana-Lopez et al., 2022a). This is in contrast to the proposal by Naidu et al. (2020) where it was suggested that $\geq 80\%$ of reionization was driven by massive, rare galaxies with high f_{esc} .

Measurements of f_{esc} at low- z indicate a consensus value around $f_{\text{esc}} \simeq 0.05 - 0.07$ based on spectroscopy and photometry at $z \simeq 3 - 4$ (Pahl et al., 2021; Saldana-Lopez et al., 2022a; Begley et al., 2022). A common indirect method of determining the escape fraction at $z > 6$ is the UV continuum slope, β . Chisholm et al. (2022) established a relationship between β and f_{esc} using a sample of 89 galaxies at $z \simeq 0.3$ with direct Lyman continuum measurements. This shows that there is an increase in f_{esc} for increasingly blue UV slopes. Therefore, by measuring the UV slopes of galaxies at $z > 6$ one can obtain an indirect measurement of f_{esc} . As described in Section 1.5.1, the average value is $\beta \simeq -2$ at $z = 6 - 9$ which corresponds to an escape fraction of $f_{\text{esc}} \simeq 0.07$, consistent with the low- z measurements (e.g. Pahl et al., 2021; Begley et al., 2022). With *JWST*, the measurement of UV slopes at $z > 10$ enables constraints of f_{esc} at the earliest stages of reionization.

1.6.2 Photoionization Efficiency ξ_{ion}

The photoionization efficiency, ξ_{ion} , describes how many ionising photons are produced from a galaxy’s stellar population given the level of star-formation activity. The value of ξ_{ion} is dependent on a number of properties such as the initial mass function, star-formation history, stellar metallicity and the evolution of the stellar population. This can be modelled using, for example, the Binary Population and Spectral Synthesis model (BPASS; Eldridge et al., 2017) which describes how ξ_{ion} depends on different galaxy properties.

Pre-*JWST* the typically assumed value for the ionising production efficiency was $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \simeq 25.2$. In Robertson et al. (2015) they suggest that it is possible for reionization to complete using this value of ξ_{ion} in combination with an escape fraction of $f_{\text{esc}} = 0.2$. This value of ξ_{ion} is consistent with observational constraints at low- z . Using near-infrared spectroscopy Shivaiei et al. (2018) measured a lower limit of $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \simeq 25.06 - 25.34$ at $z \simeq 2 - 3$, depending on what dust-attenuation curve was assumed. In Nakajima et al. (2016) they measure a moderately greater value at $z = 3 - 4$ of $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \simeq 25.8$ although the sample was specifically selected by the strength of the galaxy’s emission lines. Therefore, this potentially represents

the upper level of ξ_{ion} values at this redshift. There have also been attempts to measure ξ_{ion} at $z = 4 - 5$ using *Spitzer*/IRAC photometry yielding ξ_{ion} estimates of $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \simeq 25.4 - 25.8$ (Bouwens et al., 2016). However, given the broad *Spitzer*/IRAC filters and limited sensitivity, there is still a significant level of uncertainty.

1.6.3 UV luminosity density ρ_{UV}

The UV luminosity density, ρ_{UV} , describes the total number of UV photons emitted from the galaxy population per unit co-moving volume. This is proportional to the cosmic star-formation rate density, ρ_{SFR} which is the star-formation rate per co-moving volume. This connection between ρ_{SFR} and ρ_{UV} can be made as the UV luminosity of galaxies is primarily attributed to the flux of young, massive O and B type stars and therefore is a tracer of recent star formation. ρ_{UV} can be determined by integrating the UV luminosity function, $\Phi(L)$, weighted by UV luminosity, L , and is given by:

$$\rho_{\text{UV}} = \int_0^\infty \Phi(L)LdL \quad (1.21)$$

whereby the limits in reality are limited by the functional form of $\Phi(L)$, given by the physics of galaxy evolution. This is described in the following section.

1.7 The UV luminosity function

The luminosity function (LF) describes how many galaxies there are at a given luminosity in a given co-moving volume of the universe. In this thesis we focus on the UV LF where the UV luminosity is the luminosity measured at $\lambda_{\text{rest}} = 1500\text{\AA}$. It can be expressed as $\Phi(L)$ but in studies of high-redshift galaxy evolution it is more typical to express the UV LF in terms of absolute magnitude $\Phi(M)$. Therefore it has the units /mag/Mpc³. The UV LF is important for understanding many aspects of galaxy evolution. It's an observationally direct tracer of how the galaxy population evolves as the measurement of galaxy UV luminosity is only dependent on the underlying cosmology of the universe and does not make any assumptions about the physics within the galaxy. This is in contrast the galaxy stellar mass function for example, where the measurement of

stellar mass is model dependent. The UV LF has many physical implications. Firstly, it can be used to calculate the number of available photons to reionize the universe and hence whether the star-forming galaxy population is sufficient to perform this reionization. Secondly, the shape can inform us about what feedback processes are occurring in galaxies such as AGN feedback where star-formation is suppressed. It is also important for measuring how the cosmic star-formation rate density changes over cosmic time as the UV luminosity density is proportional to the cosmic star-formation rate density. It is also useful for informing cosmological simulations as the UV LF is a fundamental relation that can be used as a starting point for simulating the galaxy population.

The most common parameterisation of the UV LF is that of a Schechter function [Schechter \(1976\)](#):

$$\phi(L) = \left(\frac{\phi^*}{L^*}\right) \left(\frac{L}{L^*}\right)^\alpha e^{-L/L^*} \quad (1.22)$$

This describes the LF with a power-law on the faint end and a decaying exponential at the bright end. This function is parameterised by ϕ^* which is the normalisation density, L^* which is the characteristic luminosity, and α which is the faint-end slope. As mentioned above, in optical astronomy the UV LF is typically represented as per unit absolute magnitude rather than luminosity. The Schechter function as a function of absolute magnitude is:

$$\phi(M) = \frac{\ln 10}{2.5} \phi^* (10^{0.4(M^*-M)})^{(\alpha+1)} \exp[-10^{0.4(M^*-M)}] \quad (1.23)$$

The Schechter function is what is typically used to describe the UV LF at $z = 0 - 6$. However, at $z \geq 6$ it has been suggested that a double power law (DPL) is a more appropriate form (e.g. [Bowler et al., 2014, 2020](#)). This is similar to a Schechter function but with a power-law at both the bright and faint-ends are characterised by β and α respectively. This is given by:

$$\phi(M) = \frac{\phi^*}{10^{0.4(\alpha+1)(M-M^*)} + 10^{0.4(\beta+1)(M-M^*)}} \quad (1.24)$$

1.7.1 Observational measurements of the UV LF

Over the past 2 decades there has been much work in pushing the redshift frontier of measurements of the UV LF. This has been mainly due to advances in instrumentation - specifically with improvements in sensitivity at increasingly longer wavelengths. This has allowed the detection and measurement of Lyman-breaks at increasing redshift. In this section I will summarise the progress made in the measurement of the UV LF over this time up to $z \sim 10$, which represents the redshift frontier prior to the launch of *JWST*.

The UV LF at $z = 3 - 6$

The first studies of the UV LF at $z = 3 - 4$ were made possible by deep *HST* imaging. [Steidel et al. \(1999\)](#) analysed 0.23 sq. degrees of *HST* imaging including the Hubble Ultra Deep field (HDF) to measure the UV LF at $z = 3 - 4$, finding little evolution at these redshifts. They fitted their data with a Schechter function finding a faint-end slope of $\alpha = -1.6$. They also found almost no evolution in ρ_{UV} with $\frac{\rho_{\text{UV}}(z=3)}{\rho_{\text{UV}}(z=4)} = 1.1$. However, the lack of faint galaxies in their sample, particularly beyond $z = 3$, forced them to lock the faint-end slope in their measurement of the $z = 4$ UV LF to that of the $z = 3$ value. This is a common practice when fitting the UV LF when there exists insufficient dynamic range in M_{UV} to perform a free-fit to the data points.

It would be a number of years before there were improved constraints on the faint-end slope of the UV LF at $z \geq 4$. In the years following [Steidel et al. \(1999\)](#), there were a number of further studies using both *HST* and ground-based imaging to measure the UV LF at $z = 4 - 5$. [Ouchi et al. \(2004\)](#) analysed the Subaru Deep Field (SDF) and the Subaru/XMM Deep Field (SXDF) to measure the UV LF using a sample of 2600 galaxies at $z = 3.5 - 5.2$. Although still lacking constraints on the faint-end slope they measure an uncertain but steeper $\alpha = -2.2$. In contrast [Giavalisco et al. \(2004\)](#) did not attempt to measure a faint-end slope. Instead they fixed it to the $z = 3$ value from [Steidel et al. \(1999\)](#).

This uncertainty over the faint-end slope at $z = 3 - 6$ could only be resolved with deeper *HST* data that came with the *HST* Advanced Camera for Surveys (ACS). This allowed the faint-end slope to be measured at $z = 4 - 6$ for the first time. [Beckwith et al. \(2006\)](#) presented the Hubble Ultra Deep Field (HUDF) imaging which covered 11 sq. arcmin reaching depths of $m_{\text{AB}} = 29$. [Bouwens](#)

et al. (2007) combined this with imaging from other *HST*/ACS imaging fields to determine how all 3 parameters of the Schechter function evolve from $z = 4 - 6$. They found that the faint-end slope has little evolution between $z = 4 - 6$ with it being consistent with $\alpha = -1.7$ across this redshift range. They also found little evolution in the characteristic density, ϕ^* , whereas there is a stronger evolution in the characteristic magnitude M^* . They found a brightening from $M^* = -20.24$ from $M^* = -20.98$ at $z = 6$ to $z = 4$. Similar results were also found in Oesch et al. (2007). This suggests that between $z = 3 - 6$, the evolution of the UV LF is driven by luminosity evolution rather than density evolution.

At $z = 6$ there have also been measurements using very wide-area surveys from the ground. McLure et al. (2009) measured the bright-end of the UV LF at $z = 5 - 6$ using 0.63 sq. degrees of imaging from the UKIDSS UDS survey. In combination with the fainter constraints from Bouwens et al. (2007), the UV LF was able to be measured over ~ 6 magnitudes from $M_{\text{UV}} \simeq -23$ to $M_{\text{UV}} \simeq -17$. This showed overall a consistent picture with Bouwens et al. (2007) and Oesch et al. (2007) with similar Schechter parameterisations of the UV LF. More recently there have been larger area surveys to push measurements of the UV LF to yet brighter UV magnitudes. In Bowler et al. (2015), they measured the UV LF at $z = 6$ over 1.65 sq. degrees finding yet again a consistent picture with the earlier studies. They conclude that the UV LF at $z = 6$ can be fitted with either a Schechter or DPL. This was made possible by the addition of the UltraVISTA survey (McCracken et al., 2012) in the COSMOS field.

Using the total area of 6 sq. degrees from the COSMOS and XMM-LSS fields Adams et al. (2020) were able to measure the bright-end of the UV LF at $z = 4$ finding a significant contribution of AGN at $M_{\text{UV}} < -23$. Harikane et al. (2022) extended this to investigate the bright-end of the UV LF up to $z = 7$ finding a more rapidly evolving AGN UV LF than the galaxy UV LF over this redshift range.

The UV LF at $z = 7 - 10$

The next major instrumental revolution came in 2009 with the installation of WFC3 on *HST*. This allowed sensitive imaging at $1 - 1.6 \mu\text{m}$ for the first time, enabling the robust detection of galaxies at $z \geq 7$. The first key program was the HUDF09 survey (PI G. Illingworth) which, after the initial release of the data, resulted in a number of papers measuring the UV LF at $z = 7 - 8$. The first

paper was based on a detection of 16 galaxies at $z = 7$ (Oesch et al., 2010) which allowed the first robust measurements of the UV LF at $z = 7$. This was limited however by the small survey area of 4.7 sq. arcmin and therefore the faint-end slope could only be measured with ϕ^* as a fixed parameter. Nonetheless, they measured a consistently steep slope finding $\alpha = -1.77$ at $z = 6$ and argued that the evolution in the UV LF was still driven by an evolution in M^* . McLure et al. (2010) also provided an analysis of the HUDF09 data finding broadly consistent results but suggesting that the evolution between $z = 6$ and $z = 7$ could be explained by an evolution in ϕ^* rather than M^* . However, the biggest limitation which still remained was the small survey area and therefore limited dynamic range. Bouwens et al. (2011b) measured the UV LF at $z = 7$ and $z = 8$ using $\simeq 58$ sq. arcmin of imaging including the full release of the HUDF09 data which reached depths of $m_{AB} \simeq 29.4$. This sample of 132 galaxies at $z = 7 - 8$ yielded a measurement of the UV LF over ~ 4 magnitudes in M_{UV} with a surprisingly steep faint-end slope of $\alpha \simeq -2$. This is significantly steeper than what is observed in the local universe ($\alpha \simeq -1.4$) and what had been previously measured at $z = 7$ from the early release of the HUDF09 data ($\alpha \simeq -1.8$).

This had key implications for our understanding of reionization as the abundance of faint galaxies (which is determined by the steepness of the faint-end slope) strongly effects the ability of the galaxy population to complete reionization by $z = 5.5 - 6$ which is where observations of the quasar Gunn-Peterson trough suggest reionization should have ended (Becker et al., 2007; Bosman et al., 2022). For example, in McLure et al. (2009) they suggest that there were an insufficient number of galaxies to conclude reionization by $z = 6$ whereas with this steeper faint-end slope, Bouwens et al. (2012) suggest that there is a sufficient abundance of faint galaxies which would dominate reionization.

The next big advance was the HUDF12 survey (PIs: R. Ellis & R. McLure) which doubled the exposure time in the WFC3 filters with quadruple exposure time in the F105W filter which was key for accurate selection of galaxies at $z \geq 8$. The first sample from this data was a sample of 8 galaxy candidates at $z > 8.5$ (Ellis et al., 2013). This survey also added the crucial F140W filter which helped improve the SED fitting of the galaxy candidates. This was of particular importance as the non-detection of flux in the F140W filter for a $z \sim 10$ candidate previously discovered (Bouwens et al., 2011a), refined the photometric redshift to $z \sim 12$, making this the most distant galaxy candidate discovered pre-*JWST*. Measurements of the UV LF at $z = 7 - 9$ were produced by these data from

McLure et al. (2013) and Schenker et al. (2013). This showed a steep faint-end slope of $\alpha \simeq -1.9$ at $z = 7$ and $\alpha \simeq -2.0$ at $z = 8$. There was however a lack of dynamic range at $z = 9$ to properly measure the Schechter parameterisation at this redshift. Consistent measurements were found in Bouwens et al. (2015) showing an emergent picture whereby the faint-end slope steepens between $z = 6$ and $z = 8$ but where ϕ^* and M^* can both be allowed to evolve. A summary of the evolution of the Schechter function parameters with redshift are shown in Fig. 1.9.

The final major advances prior to the launch of *JWST* came after the UDF12 survey. The first was the use of wide-area ground-based surveys to measure the bright-end of the UV LF at $z = 7 - 10$. Constraining the bright end of the LF ($M_{\text{UV}} < M_{\text{UV}}^*$) can uniquely help constrain models of galaxy formation and evolution. As bright galaxies are rare, their detection requires wide-area surveys on the sq. degree scale. With *HST* however, it is difficult to observe sufficiently wide areas due to the narrow field-of-view of WFC3. For example, the wide and deep Cosmic Assembly Near-infrared Deep Extragalactic Survey (CANDELS) Grogin et al. (2011) only covered $\sim 0.2 \text{ deg}^2$. Therefore, wide and deep infrared imaging from the ground using the Visible and Infrared Survey Telescope for Astronomy (VISTA) and the UK Infrared Telescope (UKIRT) has been the only viable alternative. Although shallower than deep *HST* imaging, this ground-based imaging has the advantage that it covers areas on the degree scale making it more suitable for the detection of rare, bright star-forming galaxies at $z \geq 7$. Bowler et al. (2014) show that there is an excess of bright galaxies ($M_{\text{UV}} < -22$) compared to an extrapolation of the Schechter function at this redshift. They instead find that a double-power law (DPL) is a more appropriate functional form for the UV LF at $z = 7$. This was extended to $z = 8$ by Stefanon et al. (2019) where they suggested that the UV LF can still be fit by a Schechter function with an $M^* \simeq -21$. However, this would require a strong luminosity evolution between $z = 7 - 8$ to reproduce this. Bowler et al. (2020) also measured the bright-end of the UV LF at $z = 8$ suggesting that a DPL is a more appropriate fit at this redshift. This is shown in Fig. 1.10. They also measured the bright-end of the UV LF at $z = 9$, again preferring a DPL parameterisation over that of a Schechter function. There is thus a growing consensus that the UV LF transitions in shape from that of a Schechter function at $z = 0 - 6$ to that of a DPL at $z \geq 7$.

The second advancement was the use of lensing clusters to attempt to use foreground galaxy clusters as a physical lens to boost the intrinsic depth of *HST*

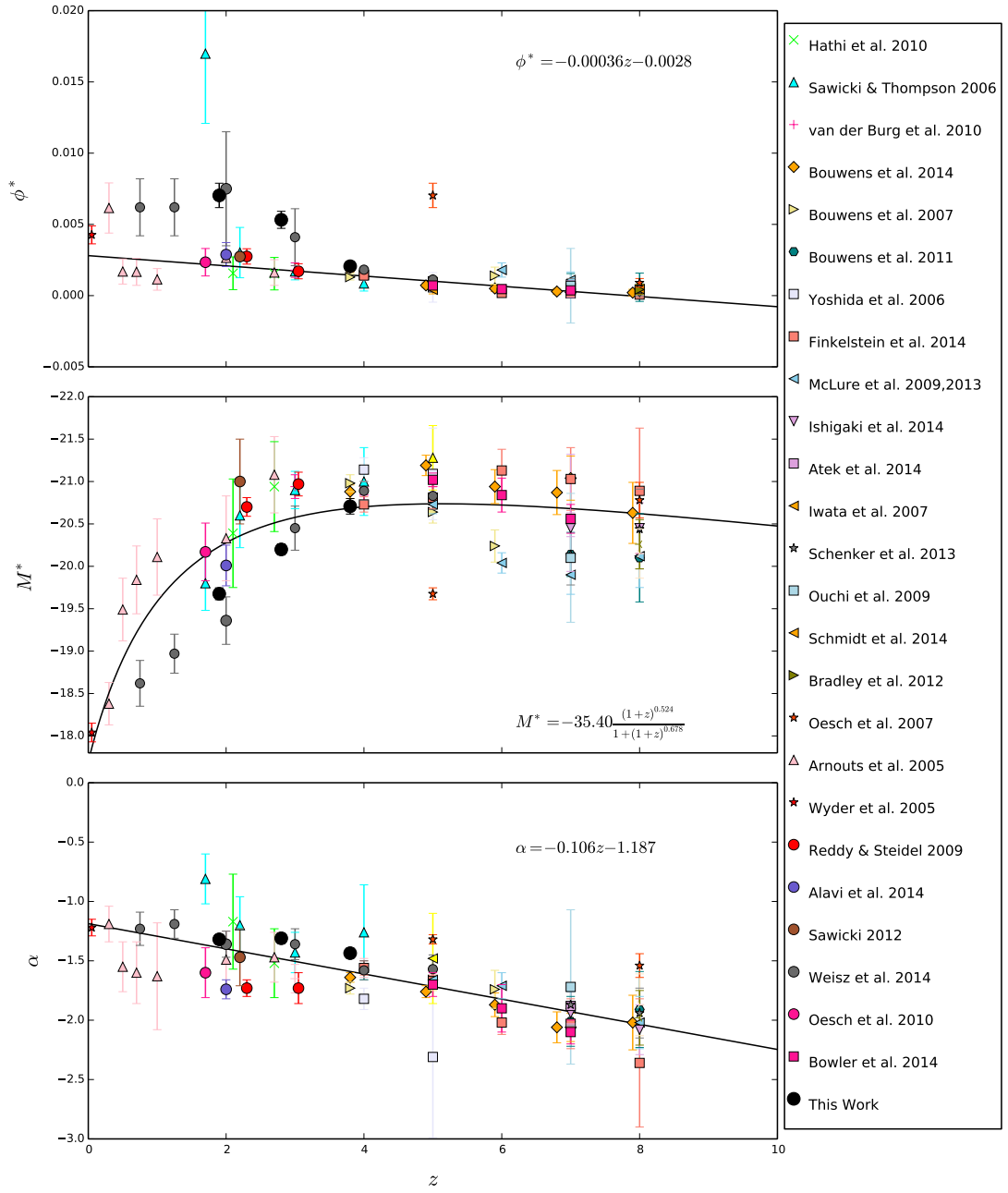


Figure 1.9 From *Parsa et al. (2016)*: The evolution of the three Schechter function parameters (ϕ^* , M^* and α) from fits to UV LF data across the redshift range $z = 0 - 10$.

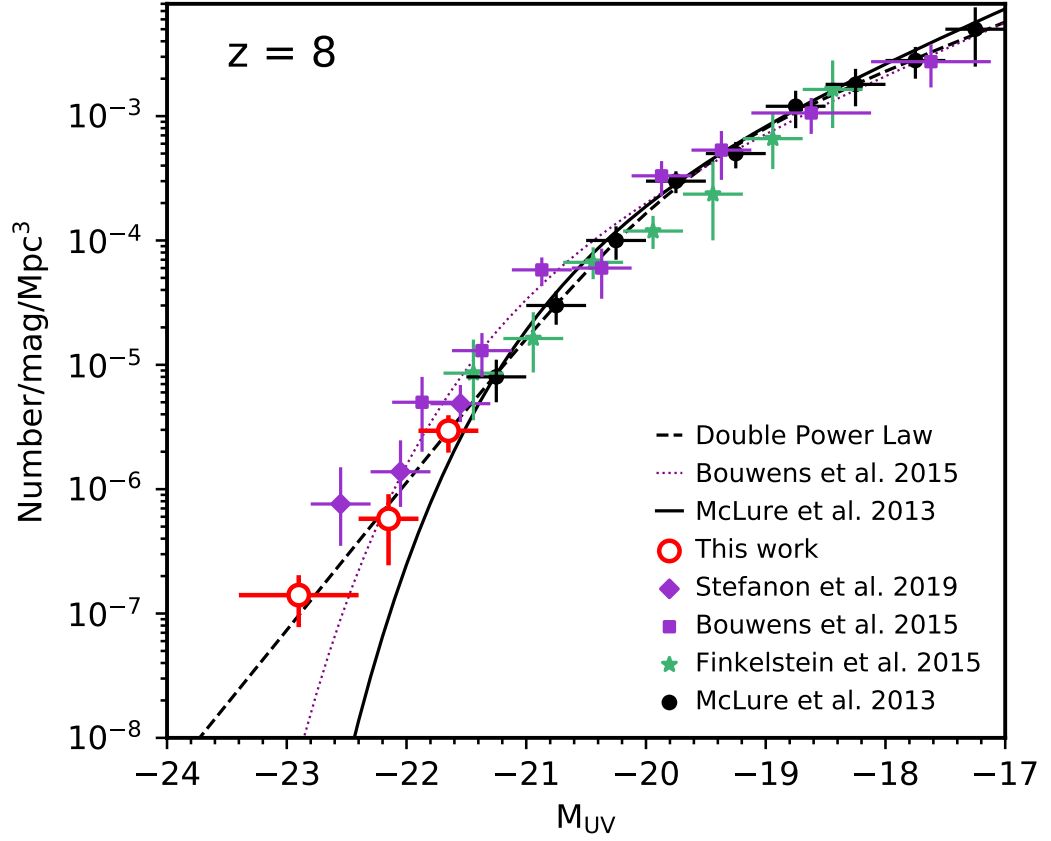


Figure 1.10 From [Bowler et al. \(2020\)](#): The bright-end of the UV LF at $z = 8$ (red data points). The solid black line shows the best-fitting [Schechter \(1976\)](#) fit from [McLure et al. \(2013\)](#) and the dashed black line shows the best fitting DPL. There is an excess in the number density of bright galaxies compared to the expectation of the Schechter fit from [McLure et al. \(2013\)](#).

imaging surveys. The Hubble Frontier Fields (HFF) programme imaged 6 galaxy cluster fields (with 6 parallel fields). The first field imaged was Abell2744 from which were used to detect galaxies at $z = 8 - 10$ and measure the UV LF. [Ishigaki et al. \(2015\)](#) and [Oesch et al. \(2015\)](#) both suggest a rapid decline in the evolution of the UV LF and ρ_{UV} although this was based on a limited area due to only a single HFF field being imaged at this time. This means that although these authors provided measurements of the UV LF and ρ_{UV} at $z = 10$, the results were still highly uncertain. [McLeod et al. \(2015\)](#) followed these papers analysing the first 2 fields and found different result showing strengthened evidence for only a shallow decline to $z = 10$. This debate would continue with subsequent studies analysing the full frontier fields data set. [McLeod et al. \(2016\)](#) analysed the first 4 cluster fields and found yet again evidence for a smooth, shallow decline in ρ_{UV} . Other groups continued to oppose this result finding evidence for a more rapid decline ([Oesch et al., 2018](#)). [Ishigaki et al. \(2015\)](#) analysed the completed 6 cluster fields (and associated parallels) and suggested that the tension over the accelerated decline in ρ_{UV} could be explained by the UV magnitude limit to which ρ_{UV} was calculated. They suggested that in their data using a limit of $M_{\text{UV}} = -15$ would show a smooth decline whereas using $M_{\text{UV}} = -17$ would suggest a more accelerated decline. Ultimately, given the limitations of the data and the difficulty to robustly select galaxies at $z = 10$ with *HST* imaging, this tension could not be resolved until the launch of *JWST*.

Another advantage of the use of gravitational lensing was to constrain the faint-end slope of the UV LF. [Livermore et al. \(2017\)](#) measure the UV LF to a magnitude of $M_{\text{UV}} = -12.5$ at $z = 6$ finding no evidence for a turn-over in the UV LF as had been predicted by theoretical studies ([Shapiro et al., 2004](#)). They find consistent measurements of the faint-end slope as previous studies with a steep $\alpha \simeq -2.1$ at $z = 6 - 8$. However, there are limitations in using gravitational lensing due to the uncertainty that arises from the lensing models (which inform the magnification, μ , of a given galaxy) as well as the limited cosmological volume probed ($V \propto 1/\mu$) especially in regions of high magnification.

Overall, this complementary picture of the UV LF at $z = 3 - 10$ from the ground and space prior to the launch of *JWST* showed a fairly rapid build up in the number density of galaxies over the first ~ 2 Gyr of cosmic history. The latest constraints prior to the launch of *JWST* came from a number of papers analysing all of the available *HST* data from CANDELS, HUDF and the Frontier Fields. [Finkelstein et al. \(2015\)](#) and [Bouwens et al. \(2021\)](#) both perform this analysis

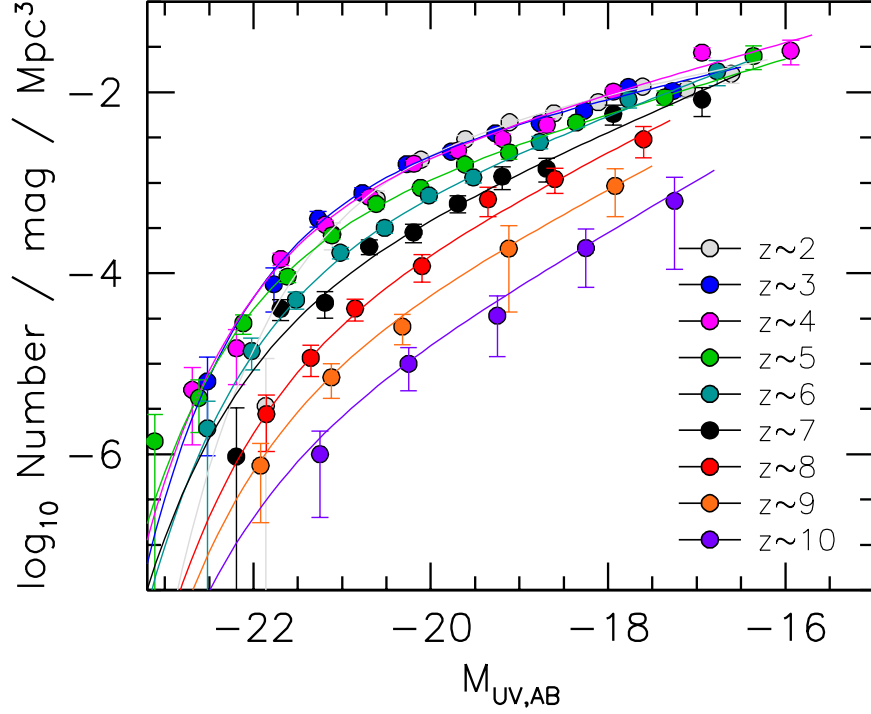


Figure 1.11 From [Bouwens et al. \(2021\)](#): The evolution of the UV LF from $z \sim 2$ to $z \sim 10$ using *HST* data with the best fitting Schechter function shown as the solid lines. The number density decreases at all magnitudes shown with increasing redshift and the UV LF changes shape.

showing a picture whereby the evolution of the UV LF from $z = 3 - 10$ is driven by density evolution where ϕ^* evolves more rapidly than M^* . They also find that α steepens from $\alpha \simeq -1.6$ at $z = 3$ to $\alpha \simeq -2$ at $z = 8$. This has important implications for the UV LF at $z \geq 10$ as if this steepening continues then $\alpha \simeq -2.6$ by $z = 12$. Fig. 1.11 shows their measurements of the UV LF from $z = 2 - 10$ representing the latest constraints prior to the launch of *JWST*.

The cosmic star-formation rate density

As mentioned throughout this thesis, the UV luminosity density, ρ_{UV} , can be calculated from the luminosity weighted integral of the UV LF. As the UV LF traces the flux emitted from massive but short-lived O and B type stars, it is a tracer of the recent star-formation within galaxies. Therefore, ρ_{UV} can be converted into the cosmic star-formation rate density ρ_{SFR} . This describes the total amount of star-formation per unit co-moving volume at a given point in

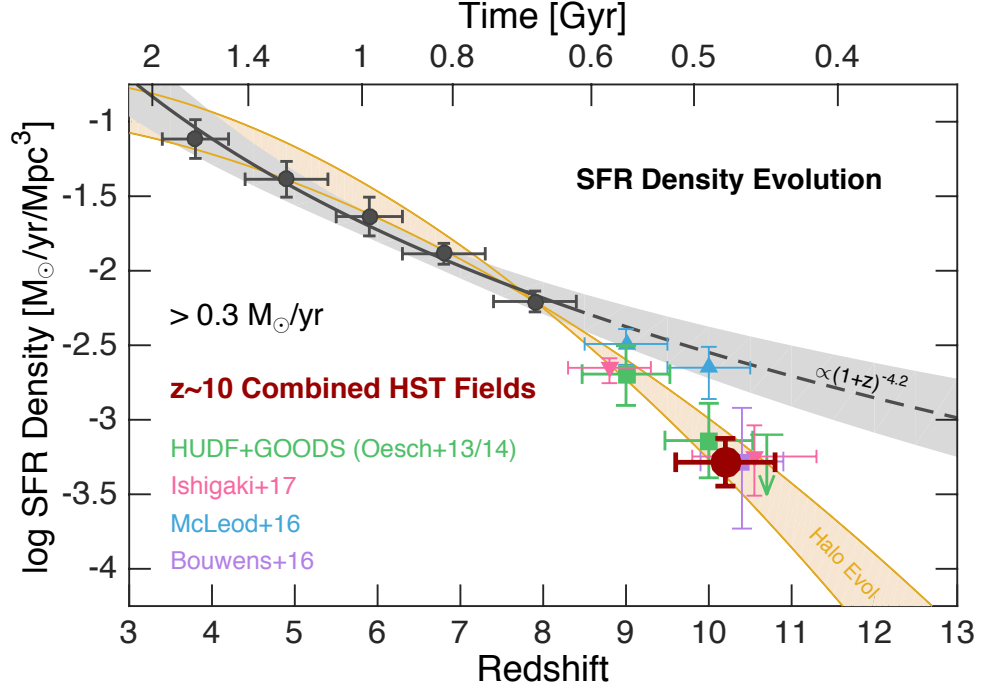


Figure 1.12 From [Oesch et al. \(2018\)](#): The evolution of the cosmic star-formation rate density (ρ_{SFR}) at $z = 3 - 10$. This demonstrates the tension between a rapid decline as supported by the red ([Oesch et al., 2018](#)), green ([Oesch et al., 2013, 2014](#)) and pink ([Ishigaki et al., 2018](#)) data points and the smooth, shallow decline as supported by the blue data points ([McLeod et al., 2016](#)).

cosmic time. As measurements of the UV LF can provide measurements of ρ_{SFR} this can then be used to place data points on the Madau-Lilly diagram ([Madau et al., 1996](#); [Lilly et al., 1996](#); [Madau & Dickinson, 2014](#)). ρ_{SFR} can be calculated from ρ_{UV} using the simple conversion factor from [Madau & Dickinson \(2014\)](#):

$$\rho_{\text{SFR}}/\text{M}_{\odot}\text{yr}^{-1} = 1.15 \times 10^{-28} \rho_{\text{UV}}/\text{erg s}^{-1}\text{Hz}^{-1} \quad (1.25)$$

As described in Section 1.7.1, there was considerable uncertainty in ρ_{UV} and therefore ρ_{SFR} at $z \geq 8$ prior to the launch of *JWST*. This is demonstrated in Fig. 1.12 which shows the inferred measurements of ρ_{SFR} at $z = 8 - 10$ from [Oesch et al. \(2018\)](#).

In summary there are a number of open questions on the evolution of the UV LF prior to the launch of *JWST*. Does ρ_{UV} (and therefore ρ_{SFR}) continue a smooth, shallow decline at $z \geq 8$ or does it decline more rapidly? Does the faint-end slope

continue to steepen at $z \geq 10$ or remain at $\alpha \simeq -2$? What is the abundance of bright galaxies at $z \geq 10$? It is these questions that the work in this thesis investigates using data from the first 2 years of *JWST*.

1.8 Thesis Layout

This chapter has provided an overview of our understanding of galaxy evolution with a focus on the first billion years ($z \geq 6$). I have described how to select high-redshift galaxies as well as a review of the relevant literature. I have summarised our state of understanding of galaxy formation and evolution up to $z = 10$ which represents the limit of our knowledge prior to the launch of *JWST*.

In this thesis I will present my work analysing the first two years of *JWST* data in combination with data from *HST*, *Spitzer* and ground-based imaging data. In Chapter 2 I outline the observational methods used in this thesis including the techniques to measure photometry from imaging data and alternative methods to calculate the UV luminosity function. In Chapter 3 I present a determination of the UV LF at $z = 8 - 15$ by analysing a combination of the first *JWST* images (CEERS, SMACS0723, GLASS) with the latest ground-based data from UltraVISTA. In Chapter 4 I perform a specific test of the abundance of galaxies at $z > 10$ using medium-band imaging from *JWST*/NIRCam in the HUDF where there already exists deep optical data from *HST*/ACS. This yields precise photometric redshifts for a sample of 6 galaxies at $z > 10$, the physical properties of which I also explore in this chapter. In Chapter 5 I then present the most robust measurement of the UV LF at $z = 9 - 15$ using ~ 400 sq. arcminutes of NIRCam imaging from multiple major cycle 1 imaging programs e.g. PRIMER, NGDEEP and JADES. In Chapter 6 I explore the physical drivers of the evolution of the UV LF from $z = 6 - 15$ using a simple theoretical model that can explain the GSMF and the UV LF at $z \geq 6$ simultaneously. Finally, in Chapter 7 I summarise the conclusions of this thesis and outline future work.

Throughout this thesis I use magnitudes in the AB system (Oke, 1974; Oke & Gunn, 1983), and assume a standard cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

Chapter 2

Observational Methods

In this Chapter I describe in detail a number of different techniques used in the analysis of astronomical imaging. Specifically, I describe the techniques I have used in Chapters 3-5 to investigate the formation of the first galaxies. I outline image reduction, how to measure the fluxes of distant galaxies, the identification of distant galaxies, the measurement of their physical properties through SED fitting and different techniques to calculate the UV luminosity function.

2.1 Image processing

When images are first produced from a telescope they are not yet ready for analysis and therefore require processing. In the case of *JWST*/NIRCam the images are reduced using the PRIMER Enhanced NIRCam Image Processing Library (PENCIL; Magee et al. in prep.). This image reduction pipeline is an enhanced version of the default *JWST*/NIRCam pipeline and contains the following stages.

Firstly, stage 1 of the *JWST* pipeline is run where detector-level effects are applied to the individual exposures as they come from the telescope. This is sometimes known as the “ramps-to-slopes” stage as it takes the individual integrations (ramps) and essentially adds them to create a corrected countrate image (units of DN/s), known as a slope. Here DN stands for data number and is the raw signal that is provided from the telescope. The next stage is a custom correction to remove the $1/f$ striping feature in the images. This is run before stage 2 of

the pipeline, where instrumental corrections are applied to create fully calibrated exposures. The next step estimates the background noise of the images and subtracts it from the exposure. The images are then aligned to a world coordinate system (WCS) using an input catalogue of known stellar positions. PENCIL uses GAIA DR3 ([Gaia Collaboration et al., 2023](#)) to create the WCS for the images. Finally the calibrated images are combined into a mosaic producing an image of the full footprint of a given survey in each filter.

PENCIL outputs the processed images in units of MJy/sr. For all imaging used in this thesis I convert the zero-point to ensure the fluxes are measured in units of μJy . This is converted with the following:

$$f_{\nu}/\mu\text{Jy} = 23.504 \times s^2/\text{MJy/sr} \quad (2.1)$$

where s is the pixel scale of the image in arcseconds. For the *JWST* imaging used in this thesis, this is typically $0.03''/\text{pix}$.

2.2 Photometry

In order to detect and study galaxies at high-redshift from imaging data, an accurate measurement of the source’s photometry is required. This allows the accurate determination of galaxy properties from SED fitting such as redshift, stellar mass and UV luminosity. For the work presented in this thesis, photometry is primarily measured using SExtractor ([Bertin & Arnouts, 1996](#)).

SEXTRACTOR is a software package that detects sources in astronomical imaging and measures their fluxes. The first step is to measure and subtract any remaining background and measure the image noise properties. Objects are defined as groups of connected pixels, each of which lies above a defined signal-to-noise threshold. The number of connected pixels and signal-to-noise threshold can be defined in the configuration file. The pixels classified as an object can be seen in the segmentation map. To separate objects from each other the distribution of flux from the pixels are analysed. If this distribution contains two distinct peaks then SExtractor will separate the object into two. Again the threshold for this separation is defined by the user in the configuration file.

SEXTRACTOR allows a number of different methods of measuring the flux of a

detected object and those relevant to the thesis are described below.

2.2.1 Aperture photometry

The primary method for measuring the flux of a source is aperture photometry. This involves the summation of the flux within an aperture of a given size.

When a point source is imaged using a telescope, the distribution of light on the image is known as the point spread function (PSF). For space telescopes the PSF is produced by the optics alone whereas for ground-based telescopes it is also a product of the atmospheric seeing conditions, which typically dominate the PSF. To measure the PSF I define the curve-of-growth, which is the fraction of total flux (defined as the aperture flux at a large radius) as a function of radius and is determined by performing aperture photometry on the two-dimensional PSF in steps of increasing radii. Therefore, the curve-of-growth is essentially a one-dimensional measurement of the width of the PSF. Expressing the PSF in this manner is useful for performing PSF homogenisation (see Section 2.2.2).

To determine the PSF for the telescope filters used in this thesis I select a sample of ~ 15 stars from across the image for which I am attempting to measure the PSF. I select isolated stars that are bright but not saturated to ensure high signal-to-noise and to reduce the impact from contamination of nearby sources. To ensure the stars are accurately stacked, I re-calculate their centroids by fitting a 2D Gaussian function to the star and determining the position of the peak. I then stack these stars and normalise the flux to unity at the central pixel producing a measurement of the PSF for that filter.

The PSF is also typically wavelength dependent and therefore different photometric filters will have different PSFs. This presents a challenge when measuring the flux of a source in different filters, as an aperture of the same size in different filters will enclose a different fraction of the source's flux. There are two common techniques to account for this in order to derive accurate measurements of a sources spectral energy distribution (SED). The first is to simply make point source corrections to the flux measured in each filter. This is the technique I employ in Chapters 3 and 4. This involves determining the percentage of enclosed flux for the given aperture and then correcting it to a common percentage of total for the full filter set. For example, in Chapters 3 and 4, all of the flux is corrected to 76% of total. The correction fraction of 76% was chosen as this is approximately

the fraction enclosed at the chosen aperture size in the F200W filter which was my detection filter. For the *JWST*/NIRCam F444W filter I measure an enclosed flux of 72.36% in a 0.33-arcsec diameter aperture and therefore I multiply the flux measured in that aperture by $\frac{76}{72.36}$ to correct it to 76% of total.

One major disadvantage of this technique is the assumption that the observed source is a point source, as the corrections are derived using the PSF's curve-of-growth. For galaxies at $z > 9$ this is reasonable approximation as sources are generally compact or unresolved. However, with *JWST*/NIRCam a number of sources at these redshifts are resolved.

2.2.2 PSF homogenisation

Another technique to account for PSF differences when performing aperture photometry is PSF homogenisation. The principle here is that instead of correcting the measured flux in each filter to some common fraction of total, I alter the PSF of each image so that all the images share the same PSF *before* performing aperture photometry. This is a technique that I implement in Chapter 5. The advantage of this technique is that a common aperture size can be used, which reduces the systematic uncertainties in measurements of the source's colours and the colours of extended sources are accurately recovered. I always homogenise to the broadest PSF in the chosen filter set which for space-based observations is typically also the longest-wavelength filter. In the case of the standard *JWST*/NIRCam filters this is the F444W filter which has an enclosed flux of $\sim 70\%$ of total in a 0.3-arcsec diameter circular aperture for a point source.

PSF homogenisation is performed by convolving each filter's PSF ($PSF_{\text{unconvolved}}$) with a transfer kernel (K) to produce a new PSF ($PSF_{\text{convolved}}$) that matches the target PSF:

$$PSF_{\text{convolved}} = K \otimes PSF_{\text{unconvolved}} \quad (2.2)$$

This kernel is produced by generating a model using a Moffat profile combined with two Gaussian profiles. This model is then fitted to match the curve-of-growth of the target PSF and is considered acceptable if it is within 5% of the target at the chosen aperture size. I show an example of this in Fig. 2.1 for the *HST*/ACS and *JWST*/NIRCam filters used in Chapter 5.

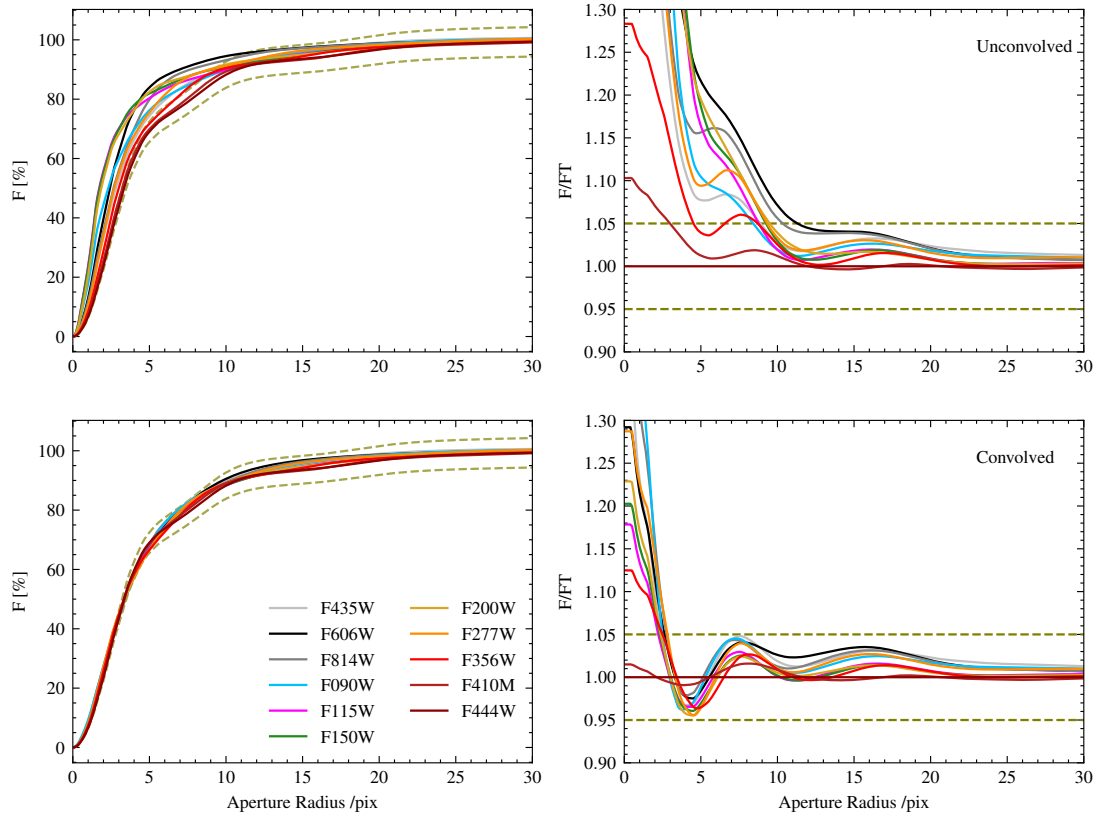


Figure 2.1 *Top: The curve-of-growth for a number of HST/ACS and JWST/NIRCam filters shown as a fraction of total (left) and normalised by the target flux (right). Bottom: The curve-of-growth after PSF convolution. The dashed lines show $\pm 5\%$ of the target PSF. The pixel scale is 0.03-arcsec.*

2.2.3 Isophotal photometry

An alternative to measuring the flux by summing the pixels in a circular aperture is to perform isophotal photometry. This allows the size and morphology of the source to be accounted for when measuring the flux in a given filter. The “isophotal footprint” describes the footprint of the source on the image and is measured using SExtractor given a detection threshold and minimum number of connected pixels. This addresses the problem of missing flux from extended objects when using small circular apertures. However, flux can also be missed using this technique due to the specified detection parameters in SExtractor. Another disadvantage is the wavelength dependence of the size and morphology of galaxies.

2.2.4 Depths

A crucial step in the analysis of astrophysical imaging is accurate measurements of the photometric depths. This is the level of the background noise and is important for evaluating the significance of source detection, as well as providing accurate uncertainties for the flux measurements. When selecting galaxies at high-redshift I employ a range of signal-to-noise criteria. For example I require at the position of the source, for there to be a significance of $< 2\sigma$ (in the appropriate drop-out filters) to eliminate low-redshift contaminants. For this criterion to be implemented correctly, accurate measurements of the depths are required.

To calculate this I place apertures (of the same size used to measure the photometry) across the image in a grid with a single pixel gap between them. Using a segmentation map from SExtractor, all the apertures overlapping with the segmentation map footprint are removed. This leaves a grid of empty sky apertures across the image. The global 1σ depth was then determined as $\sigma_f = 1.4826\text{MAD}$ where MAD is the median absolute deviation of the flux (Equation 2.3) in all the empty apertures across the field. This can then be converted into a 5σ global depth using Equation 2.4 where ZP is the defined zero-point of the image. For images in micro Janskys I use a zero-point of $ZP = 23.9$ to obtain the 5σ global depth in AB magnitudes. The 1σ global depth can be used as a reasonable approximation for the uncertainty on the flux in that filter.

$$\text{MAD} = \text{med}(|f - \text{med}(f)|) \quad (2.3)$$

$$m_{5\sigma} = -2.5 \log(5\sigma_f) + ZP \quad (2.4)$$

However, there are variations in the depth across the image and therefore to obtain more accurate measurements of the flux uncertainties I calculate the local depth for each source. This is done using the same grid as for the global depth but the calculation is only performed on the 200 closest empty apertures to the source. This was implemented using the KDTree function as part of the python `scipy` package. This algorithm defines a tree connecting all the empty apertures which can then be queried for each source to find the nearest 200. The efficiency of this method allows the local depths for a large catalogue of sources to be determined quickly. An example of this for a $z = 8$ candidate in the PRIMER COSMOS F277W imaging is shown in Fig. 2.2. The 1σ local depth is adopted as the uncertainty on the measure photometry.

The depth is correlated with the chosen aperture size. By using smaller aperture sizes, the depth is increased (i.e. a lower 1σ uncertainty on the measured fluxes) which is why it is particularly useful to use small apertures when searching for distant galaxies. The 1σ uncertainty as a function of aperture diameter is shown in Fig. 2.3 for the *HST* and *JWST* filters in a region of PRIMER COSMOS.

In order to obtain accurate uncertainties in the case where isophotal photometry is used, the differing size of the source footprints needs to be taken into account. When the fluxes were measured using isophotal photometry, the depths are calculated using the relation between depth and aperture size. The area of each source in the detection band (where the filters have been PSF homogenised) is determined using the `ISOAREA_IMAGE` parameter outputted from `SExtractor`. The circular radius this corresponds to is then calculated as $\sqrt{\text{ISO area}/\pi}$. The corresponding 1σ aperture depth for that radius shown in Fig. 2.3 is adopted as the 1σ uncertainty for the isophotal flux for that source.

It can also be particularly helpful to produce a map of how the depth varies across an image as different factors can change the depth. For example, imaging of lensing fields where there is a foreground galaxy cluster, will have shallower depths within the cluster (e.g. McLeod et al., 2024). Another example is due to the “wedding-cake” design of some imaging surveys where parts of the field

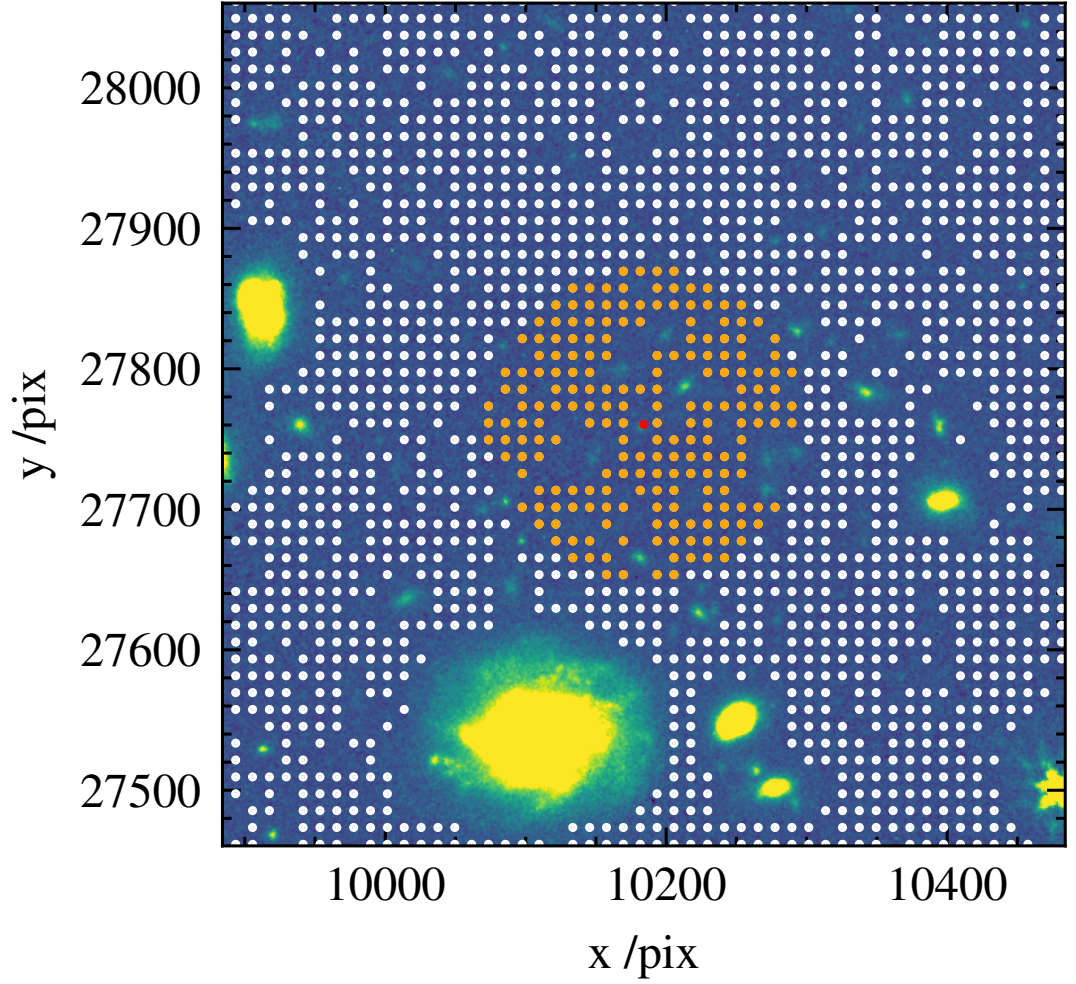


Figure 2.2 *A demonstration of the determination of local depth. For a source at the central position (red) the nearest 200 empty apertures (orange) are found using the KDTree formed from the full grid of empty apertures (white). The background image shows the F277W data in COSMOS from the PRIMER programme. The imaging is on a 0.03-arcsec pixel scale.*

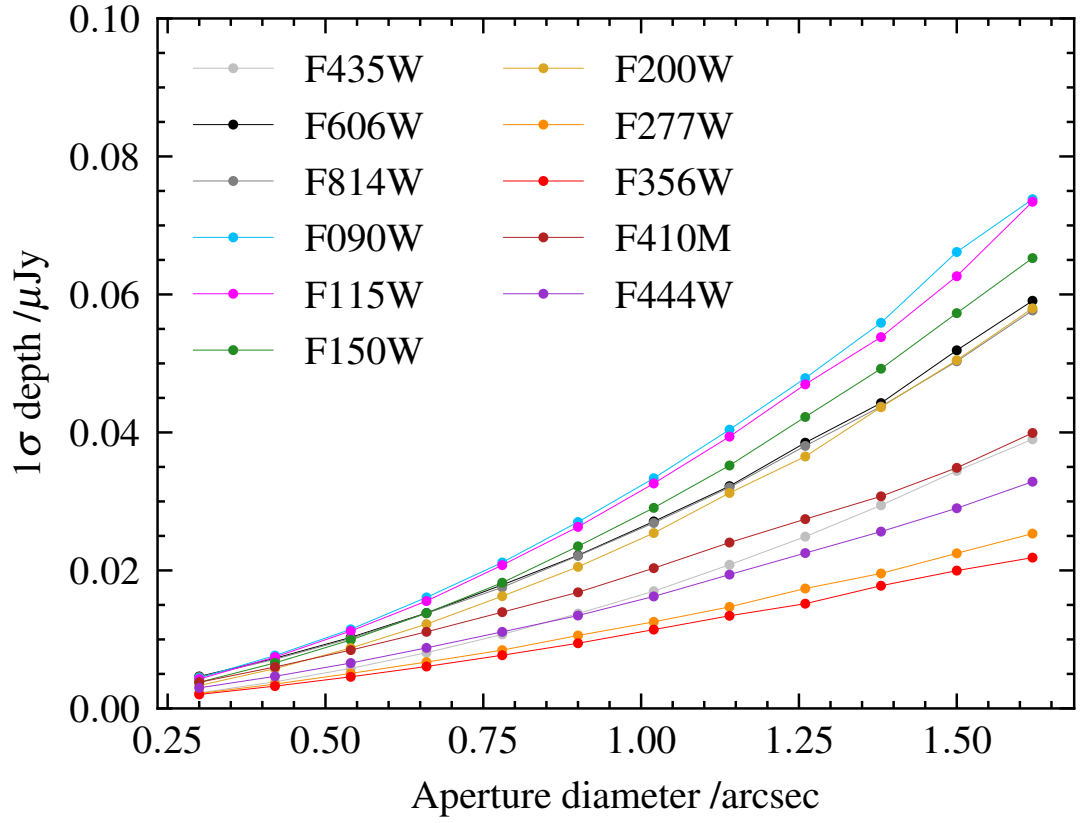


Figure 2.3 *The 1σ global uncertainty as a function of aperture diameter in the COSMOS field using filters from HST/ACS and JWST/NIRCam. The uncertainty increases as a function of diameter for all filters.*

have longer exposure times leading to greater depths. A depth map can be created to identify the different “layers” of this survey design which is needed when calculating the UV luminosity function. The depth map is calculated by measuring the 5σ depth using the same method described above in 3×3 -arcsec regions across the field. This technique is used in Chapter 5 for the PRIMER, JADES and NGDEEP fields. In Fig. 2.4 I show the depth map for the PRIMER COSMOS field, where the deep region can be clearly separated from the surrounding shallower region.

2.3 Identification of high-redshift galaxies

2.3.1 Photometric filters

In order to robustly detect and measure the redshift of a high-redshift galaxy, it is necessary to have photometry in multiple filters at different wavelengths. This is to allow accurate measurement of the shape of the spectral energy distribution (SED) which is vital for accurate measurements of photometric redshifts. The near-infrared camera (NIRCam) on *JWST* enables imaging in 8 broad photometric bands and 12 medium bands. The majority of imaging surveys currently completed with *JWST* primarily make use of the broad bands with some medium bands. For example, PRIMER involves imaging at $\lambda_{\text{obs}} \simeq 0.9 - 4.4 \mu\text{m}$ in the COSMOS and UDS fields using the F090W, F115W, F150W, F200W, F277W, F356W, F410M, F444W filters. In combination with optical imaging from the Advanced Camera for Surveys (ACS) on *HST*, this provides contiguous filter coverage from $\lambda_{\text{obs}} \simeq 0.4 - 4.4 \mu\text{m}$ covering the optical to the mid-infrared. This allows the robust selection of high-redshift galaxies using the Lyman break technique. When selecting galaxies using this technique, I employ signal-to-noise constraints in key filters to remove low-redshift contaminants. This is where I require the flux to be $< 2\sigma$ in all filters short-ward of the position of the Lyman break, with a $> 5\sigma$ detection in the filter closest to, but long-ward of, the Lyman break. I then also require $> 3\sigma$ in the next filter long-ward of the break to rule-out any spurious single-filter detections. This is demonstrated in Fig. 2.5, where model SEDs of galaxies at $z = 8, 10, 12, 16$ are shown together with the *JWST*/NIRCam and *HST*/ACS filter coverage. For selecting a galaxy at $z = 10$ for example, I would require the flux to be $< 2\sigma$ in F090W, F115W and all the *HST*/ACS filters. I also require $> 5\sigma$ detections in F150W and $> 3\sigma$ in F200W.

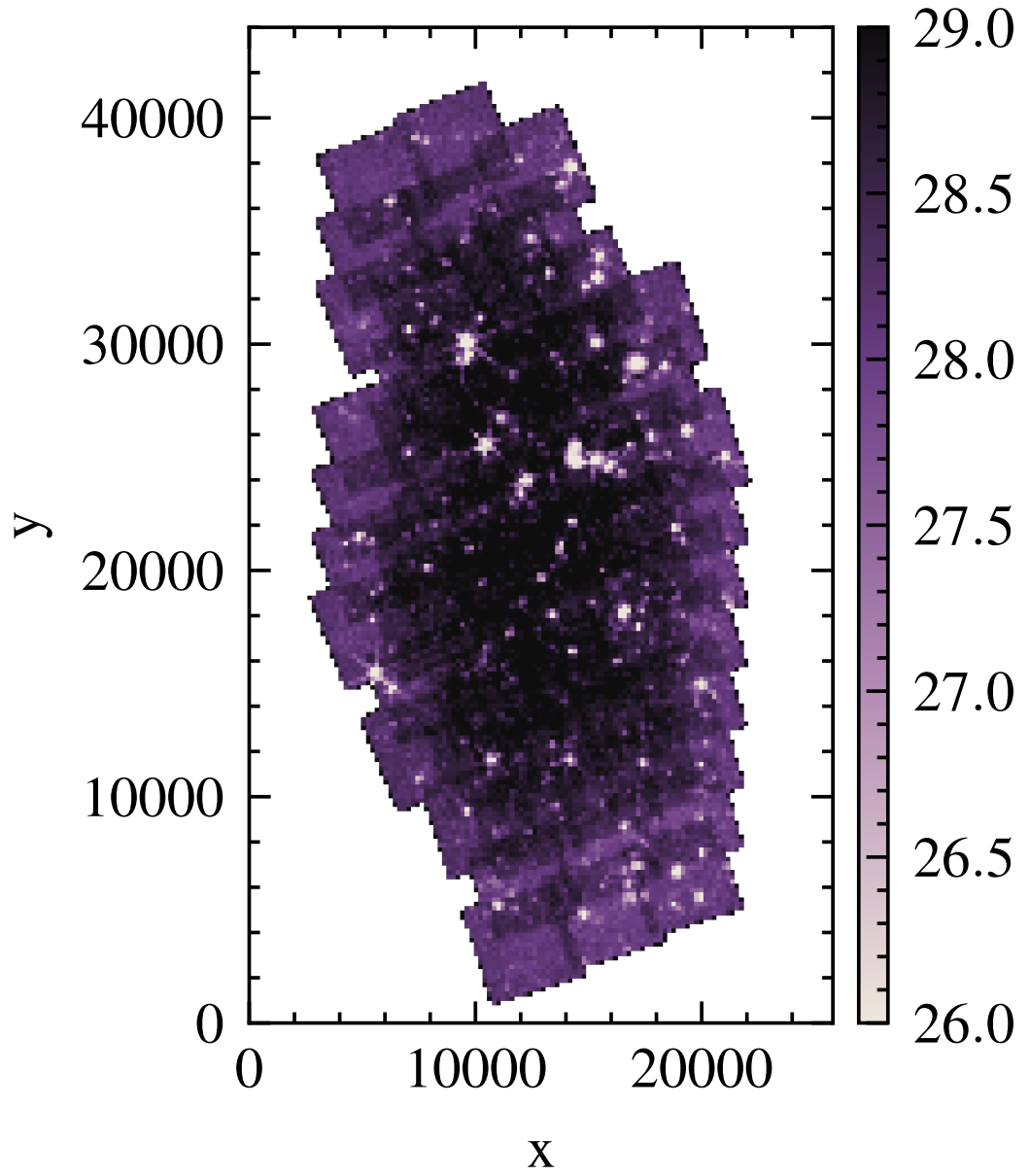


Figure 2.4 *The 5σ depth as a function of spatial position across the PRIMER COSMOS F277W imaging. All depths have been corrected to total assuming a point source correction. The colour-bar shows the scale of the 5σ depth.*

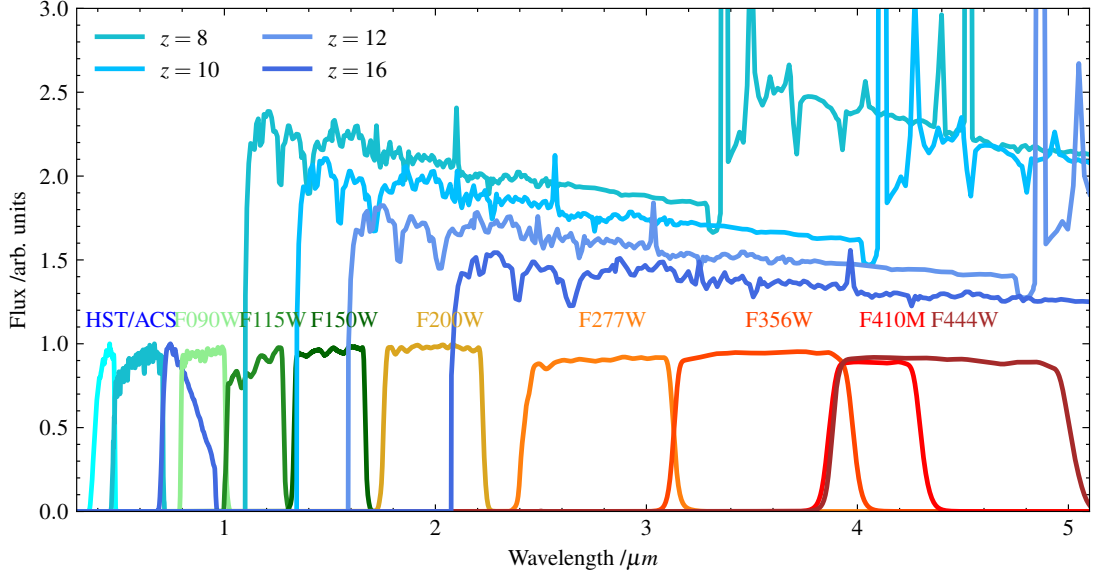


Figure 2.5 *A illustration of model galaxies at $z = 8, 10, 12, 16$ using the PEGASE templates from EAZY. The HST/ACS and JWST/NIRCam filters utilised in the PRIMER survey are shown at the bottom.*

2.3.2 SED fitting

When selecting high-redshift galaxies I also perform template fitting to the galaxy’s SED to measure the photometric redshift. This is primarily done using the code EAZY (Brammer et al., 2008) with the PEGASE (Fioc & Rocca-Volmerange, 1999) templates. This codes operates by stepping through a redshift grid for each source and minimising the χ^2 (shown in Equation 2.5) at each step over N_{filt} filters. $T_{z,i,j}$ is the flux of the i ’th template at a redshift z for filter j . F_j is the observed flux in filter j and δF_j is the uncertainty on that observed flux.

$$\chi_{z,i}^2 = \sum_{j=1}^{N_{\text{filt}}} \frac{(T_{z,i,j} - F_j)^2}{(\delta F_j)^2} \quad (2.5)$$

Although I can measure the photometric redshift of a source using photometric data, there are some caveats to this technique. The low-spectral resolution of broad-band photometry makes this technique vulnerable to low-redshift contamination. For example, the photometry produced by a Lyman break at high-redshift can be reproduced by a Balmer break at lower redshift (Dunlop, 2013). Therefore, when SED fitting to measure a photometric redshift, I also measure the best-fitting solution over the redshift range $0 < z < 6$ to force a low-redshift fit. I define $\Delta\chi^2 = \chi_{\text{low}}^2 - \chi_{\text{primary}}^2$ where χ_{low}^2 is the minimum χ^2 I measure

when fitting over the redshift range $0 < z < 6$ and χ^2_{primary} is the minimum χ^2 I measure over the full redshift range of $0 < z < 25$. In my high-redshift galaxy selection, I require $\Delta\chi^2 \geq 4$ to ensure the robustness of the high-redshift solution as this has been demonstrated to accurately remove low-redshift contaminants as it is a 2σ rejection for a single fitted parameter (e.g. [Bowler et al., 2020](#)).

Using the best-fitting template from EAZY, the absolute UV magnitude, M_{UV} can be determined. This property is of great importance for calculating the galaxy UV luminosity function as described in Section 2.4. This is calculated using a tophat filter centered on $\lambda_{\text{rest}} = 1500 \text{ \AA}$ with a width of $100 \text{ \AA}$. This defines the *apparent* UV magnitude, m_{1500} . Using the redshift the luminosity distance, D_L , is calculated and therefore the absolute UV magnitude can be determined using Equation 2.6.

$$M_{\text{UV}} = m_{1500} - 5 \log_{10} \left(\frac{D_L}{10} \right) + 2.5 \log_{10} (1 + z) \quad (2.6)$$

EAZY is the primary SED fitting code I use in this thesis as it prioritises efficiency of the redshift determination over other galaxy properties. As the redshift and UV magnitude are all that is required to measure the UV LF, this is the optimum choice of SED fitting code for this work. Other codes (e.g. BAGPIPES, Prospector; [Carnall et al., 2018](#); [Leja et al., 2017](#)) can determine further properties such as the stellar mass and star-formation histories of galaxies.

The outputted χ^2 as a function of redshift from EAZY can be converted into a probability distribution, $p(z)$. The normalised $p(z)$ is given in Equation 2.7.

$$\text{Normalised } p(z) = \frac{e^{-\frac{\chi^2(z)}{2}}}{\int_0^\infty e^{-\frac{\chi^2(z)}{2}} dz} \quad (2.7)$$

It is also useful to introduce priors in calculating the probability of a galaxy being at a given redshift. Equation 2.7 assumes no prior information and therefore the probability is purely dependent on the $\chi^2(z)$ outputted from EAZY. In this thesis I do not make use of the prior option within EAZY. A simple prior that can be introduced is the cosmological volume prior. As the co-moving cosmological volume in a given redshift interval decreases with increasing redshift at $z > 2.5$ (i.e. the volume is smaller in $9.1 < z < 9.2$ than $3.1 < z < 3.2$), the probability of a galaxy is weighted according to this volume difference. Fig. 2.6 demonstrates

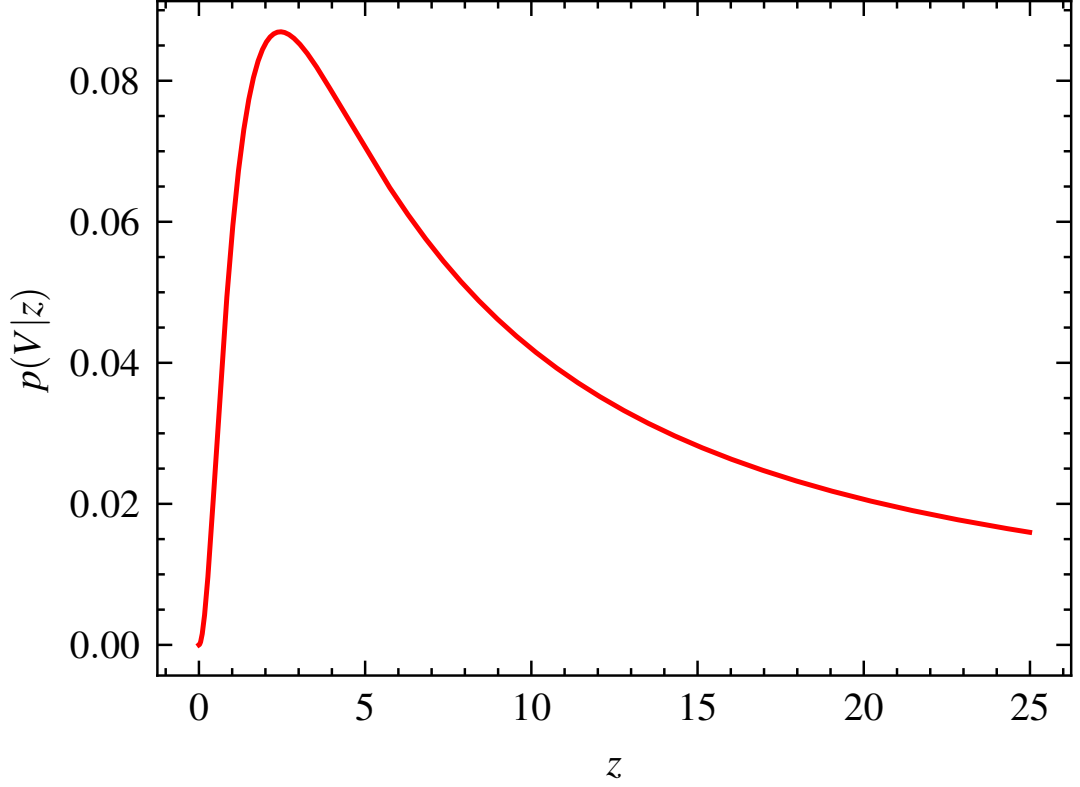


Figure 2.6 *The normalised probability distribution of co-moving volume as a function of redshift.*

how the normalised probability distribution of co-moving volume changes with redshift.

This can have an impact if the preference of the high-redshift solution in terms of $\chi^2(z)$ is marginal. The volume prior weights the low-redshift solution more than would have happened if no prior was assumed, however if the low-redshift solution is at $z < 1$, then the volume prior will likely increase the probability of the high-redshift solution due to the limited accessible volume at $z < 1$.

A more sophisticated prior for determining the $p(z)$ is to use a luminosity function prior. This allows the prior to be a function of the apparent magnitude of the galaxy as well as its redshift and is particularly important for very bright objects. To determine this I require a model of the evolving UV luminosity function from $z = 0 - 20$. [Bouwens et al. \(2021\)](#) provide an evolving LF model from $z = 0 - 9$, however as is discussed in later chapters, one of the key results from early *JWST* studies (e.g. [Donnan et al., 2023a](#)) is that the LF appears to evolve slower at $z > 9$ than some pre-*JWST* models, including the [Bouwens et al. \(2021\)](#) model. This model also assumes a Schechter function parameterisation of the UV LF, which

has been shown to fail to fit the bright end of the UV LF at $z > 7$ (e.g. [Bowler et al., 2014, 2015, 2020](#)). Therefore, I only use the Schechter parameterisation from [Bouwens et al. \(2021\)](#) up to $z = 7$ and I create a new model for the evolving UV LF at $z > 7$ using a double-power law with parameters from [Bowler et al. \(2014, 2017, 2020\)](#); [Donnan et al. \(2023a\)](#); [McLeod et al. \(2024\)](#). Therefore, the complete model for the evolving UV LF is:

$$M^* = \begin{cases} -20.89 - 1.09(z - 2.46) & \text{if } z \leq 2.46 \\ -21.03 - 0.04(z - 6) & \text{if } 2.46 < z < 7.00 \\ -20.95 + 0.11z & \text{if } z \geq 7.00 \end{cases} \quad (2.8)$$

$$\phi^* = \begin{cases} 0.4 \times 10^{-3} \times 10^{(-0.33(z-6)-0.024(z-6)^2)} & \text{if } z < 7.00 \\ 10^{(-0.14z-2.36)} & \text{if } z \geq 7.00 \end{cases} \quad (2.9)$$

$$\alpha = \begin{cases} -1.94 - 0.11(z - 6) & \text{if } z < 7.00 \\ -2.04 \times 10^{-4}z - 2.1 & \text{if } z \geq 7.00 \end{cases} \quad (2.10)$$

$$\beta = 0.138z - 5.13 \quad \text{if } z \geq 7.00 \quad (2.11)$$

To demonstrate the accuracy of the prior I compare to the recent results of the UV LF at $z = 11$ from [McLeod et al. \(2024\)](#) as shown in Fig. 2.7. My double-power law evolving LF model is a more suitable fit to the data at $z = 11$ than extrapolating the evolving Schechter parameterization from [Bouwens et al. \(2021\)](#).

This model was then implemented in the calculation of the $p(z)$ for each galaxy selected in the sample. This was done by calculating the number density for a given redshift and the apparent magnitude of a source over a grid of redshifts. As absolute UV magnitude is a function of redshift, this had to be recalculated at each grid-point in redshift by calculating the apparent m_{1500} for the best-fitting template at each redshift for each source. Fig. 2.8 demonstrates the effect of different prior choices on the $p(z)$ for four example objects selected in the COSMOS field using PRIMER NIRCcam photometry.

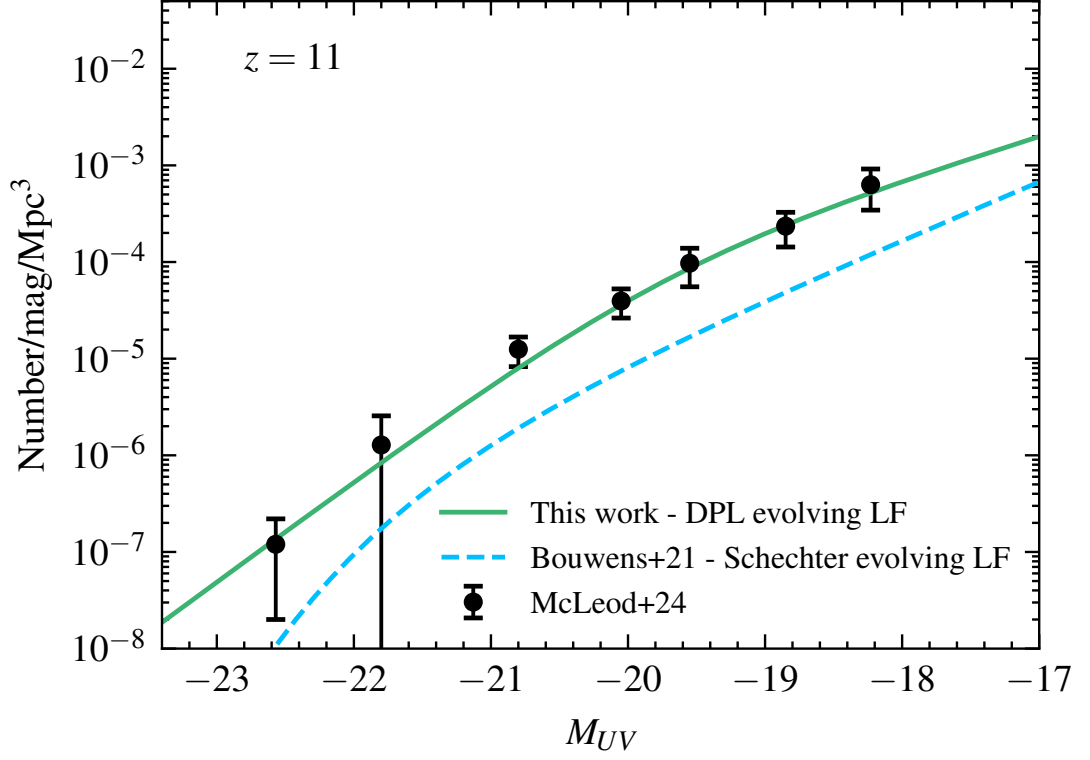


Figure 2.7 *The UV luminosity function at $z=11$ with observational constraints from [McLeod et al. \(2024\)](#) shown by the black data points. My double-power law evolving luminosity function model is shown by the solid green line, whereas the dashed blue line shows the evolving Schechter function from [Bouwens et al. \(2021\)](#).*

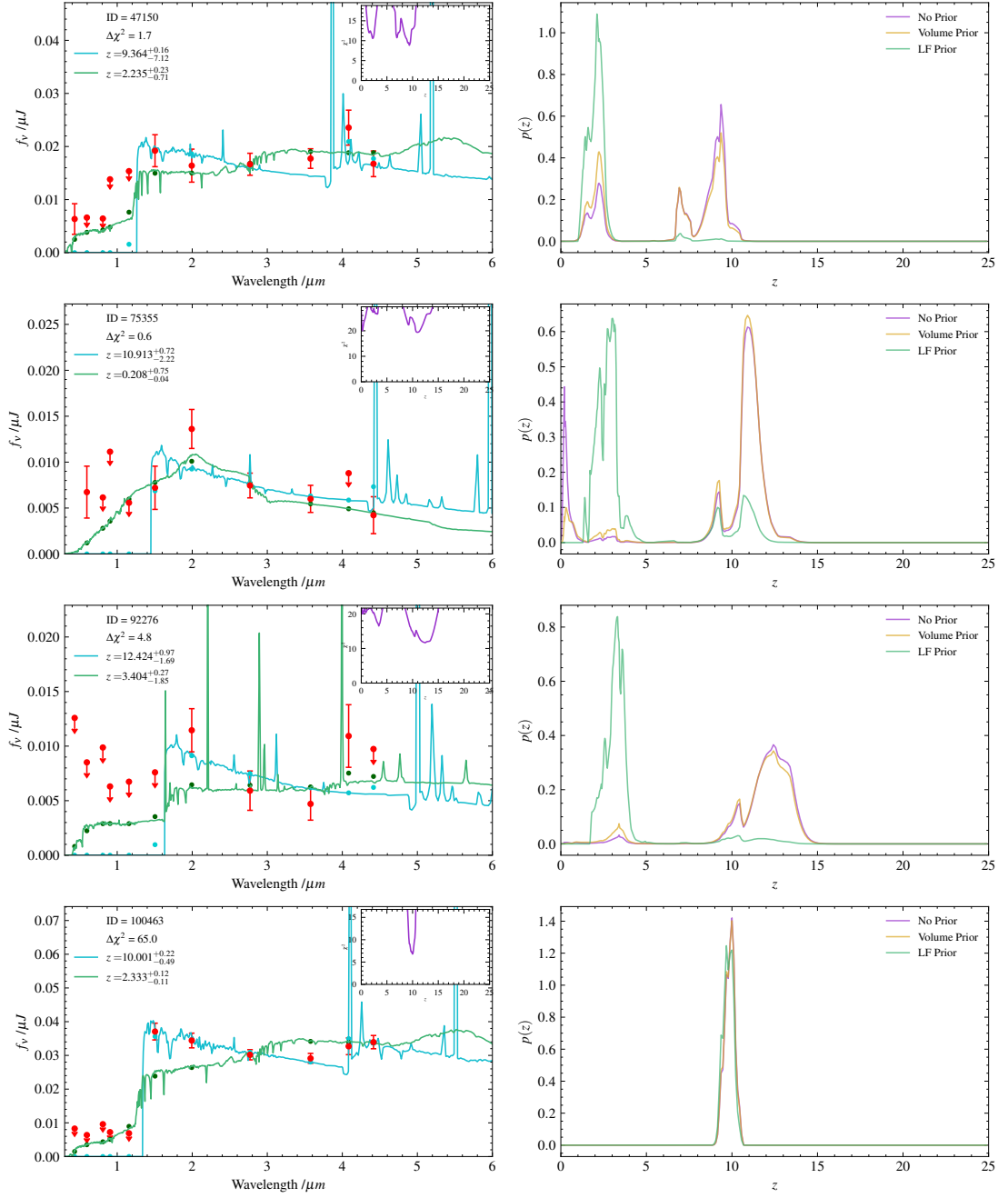


Figure 2.8 *Left: Alternative SED fits using EAZY to four $z > 8.5$ galaxy candidates in PRIMER COSMOS, where the blue line shows the best-fitting template over the redshift range $0 < z < 25$ and the green line shows the best-fitting template at $0 < z < 6$. The inset panel shows the χ^2 as a function of redshift. Right: The probability distribution of redshift with no prior (purple), volume prior (yellow) and a UV luminosity function prior (green). All probability distributions are normalised such that $\int_0^\infty p(z)dz = 1$.*

2.4 Calculating the luminosity function

The UV luminosity function can be calculated in a number of different ways. One crucial component in all the methods is accounting for the sample incompleteness. In this section I outline how the sample incompleteness can be determined and then describe the different methods used to calculate the UV luminosity function.

2.4.1 Completeness

To obtain an accurate measurement of the UV LF, one needs to have a complete sample of the galaxies that exist in a given redshift and magnitude range. In reality, astronomical surveys will always fail to detect every real source in the given redshift and magnitude range. This can be due to obscuration by foreground sources (e.g. bright stars and galaxies), false characterisation of real sources as contaminants or scattering below the detection limit. The latter point is of particular concern for studies of high-redshift galaxies which are often faint, even in the deepest imaging. It is also important to account for sources scattering into the detection image that are, in reality, fainter galaxies than the detection limit. The sample completeness can be determined by running simulations where artificial sources are injected into the real imaging to quantify these effects. The selection algorithm can then be tested on these artificial sources to measure how complete the survey is. This process can have varying degrees of complexity. In this thesis I have implemented two different methods of completeness simulations which are outlined here.

Completeness as a function of apparent magnitude

The first method, implemented in Chapter 3, simply measures the sample completeness as a function of apparent magnitude. This involves injecting artificial sources into the detection image at random positions over a range of apparent magnitudes. The sources are injected as point sources using the measured PSF's of the appropriate filter. This is typically performed ten times in three different regions of the imaging to capture the small variations in completeness that occur over the field. This can be due to differences in exposure time or different density of foreground stars etc. The artificial sources are then recovered using the same detection process as the real objects and matched

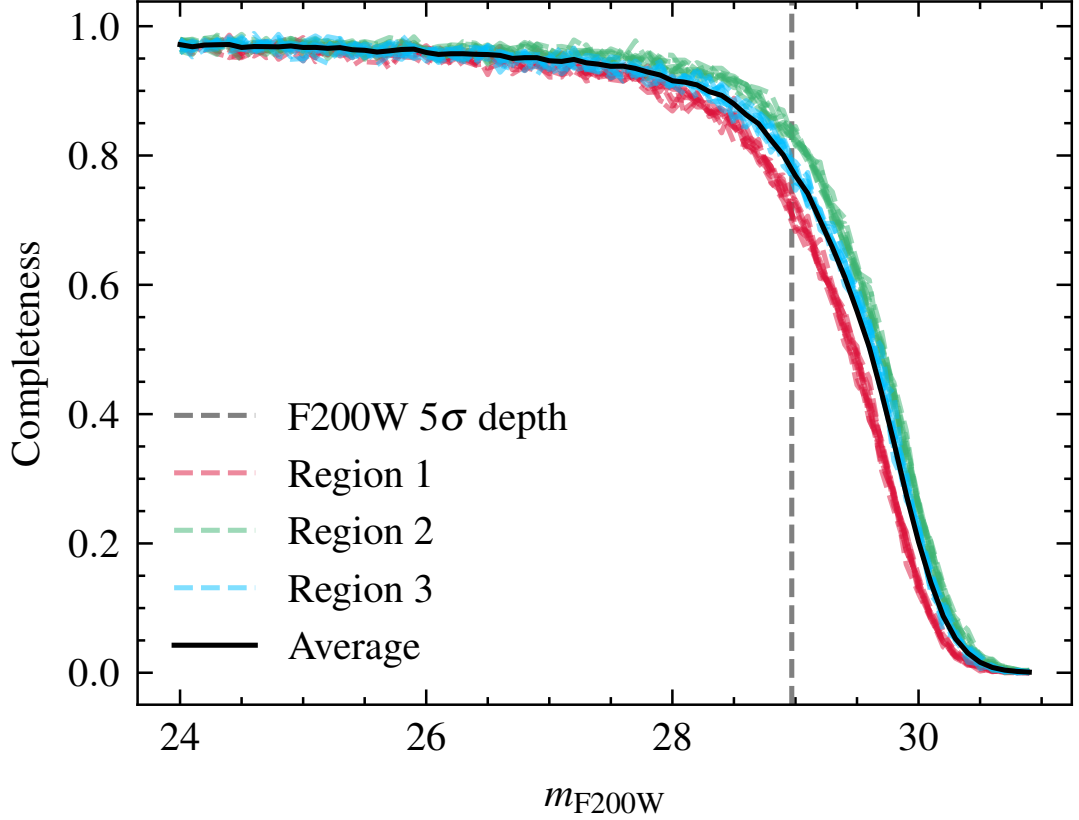


Figure 2.9 *The completeness fraction for the CEERS NIRC*am* imaging as a fraction of the apparent magnitude in F200W. The dashed coloured lines show the outcome of each individual simulation (10 for each region, 30 in total) separated by region. The solid black line shows the average across the 30 runs. The dashed grey vertical line indicates the 5σ global depth of the F200W CEERS imaging.*

to the input catalogue. This yields the completeness fraction as a function of apparent magnitude in the detection image. This is demonstrated in Fig. 2.9 for the CEERS field. This shows how dramatically the completeness starts to drop beyond the 5σ limit of the imaging. It also demonstrates the need for using multiple regions across the imaging to account for the spatial differences in the sample completeness.

Completeness as a function of galaxy properties

In the previous section I outlined the simplest approach to measuring the sample completeness, where completeness is just measured as a function of apparent magnitude in the detection image. A more complex approach is to measure the completeness as a function of the galaxy properties. This involves generating

synthetic galaxy SEDs and injecting the synthetic photometry into each filter of the imaging used. This is the method used in Chapter 5. When determining the UV LF I measure completeness as a function of redshift and UV magnitude, $C(z, M_{\text{UV}})$.

Firstly I generate a $M_{\text{UV}} - z$ grid in steps of 0.5 for both axes in order to define the parameter space over which the synthetic galaxy population will be generated. I use a template with a UV slope of $\beta = -2.3$ as this matches the observational measurements of the UV slope at $z > 8.5$ (Cullen et al., 2024a; Topping et al., 2024a). For $M_{\text{UV}} < -19.5$ there were 100 sources injected into each grid point. At $M_{\text{UV}} > -19.5$, the number of sources in each grid point were defined by the double power-law shape of the UV LF assuming a faint-end slope of $\alpha = -2.1$ consistent with prior measurements (Leung et al., 2023; Pérez-González et al., 2023). To avoid confusion in the recovery of artificial sources, the injection of these sources was split ensuring a low enough density of artificial sources per image. The injected images are then subject to the same detection, catalogue creation and selection process as the real sample. This produces a two-dimensional grid of completeness as a function of M_{UV} and z . This is shown in Fig 2.10 for the PRIMER UDS field. Although I only parameterise completeness here by M_{UV} and z , this method can be used to determine the completeness as a function of any galaxy properties and can be increasingly complex. For example, this method still assumes all sources are point sources and therefore a natural next step would be to simulate a range of galaxy sizes and morphologies. However, this was not included in the work in this thesis as it has been demonstrated to have a negligible impact on the completeness of $z \geq 9$ galaxies (McLeod et al., 2024).

2.4.2 The $1/V_{\text{max}}$ method

One of the most frequently used methods for determining the luminosity function is the $1/V_{\text{max}}$ method (Schmidt, 1968). This involves binning the galaxies in absolute magnitude bins and summing over the N sources in a bin of width ΔM . Therefore the number density in that bin is given by:

$$\Phi(M_{\text{UV}}) = \frac{1}{\Delta M} \sum_{i=1}^N \frac{1}{C_i(m_{\text{AB}}) V_{\text{max},i}} \quad (2.12)$$

where $C_i(m_{\text{AB}})$ is the completeness as a function of apparent magnitude in the

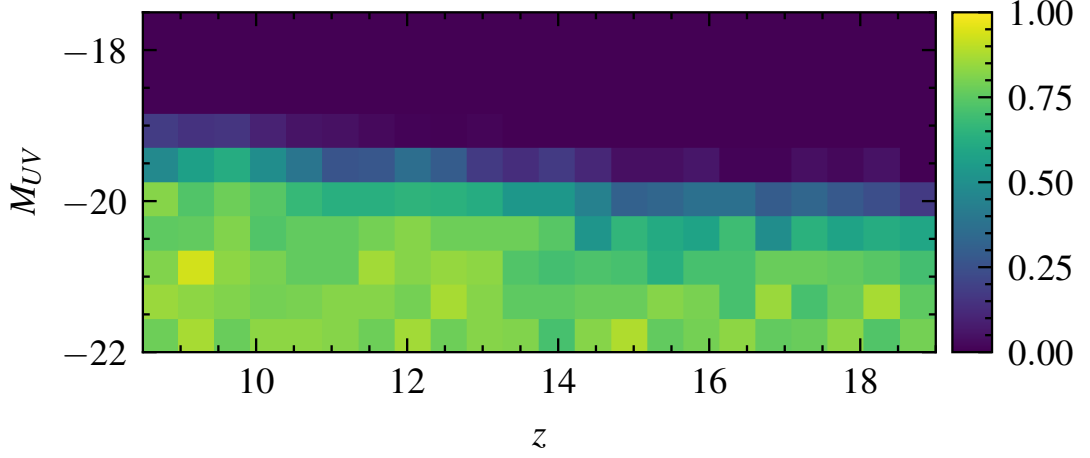


Figure 2.10 *The fraction of recovered injected galaxies in the PRIMER UDS field as a function of M_{UV} and z .*

appropriate detection image and $V_{\max,i}$ is the maximum comoving volume the i 'th galaxy could occupy and still be detected. The comoving volume V_C is given by:

$$V_C = d_H \int d\Omega \int_0^z \frac{d_L^2 dz'}{(1+z'^2) \sqrt{\Omega_M(1+z'^3) + \Omega_k(1+z'^2) + \Omega_\Lambda}} \quad (2.13)$$

where d_L is luminosity distance, $d_H = c/H_0$ where H_0 is the Hubble constant, c is the speed of light Ω_m is the total density of matter, Ω_k is the curvature density, Ω_Λ is the cosmological constant. The integral over solid angle, $d\Omega$, defines the area of the survey on the sky, which is 4π for the full sky.

To determine $V_{\max}$, the comoving volume is calculated at the minimum and maximum redshifts for a given redshift range. For example, for the LF at $z = 9$ the redshift range is $8.5 < z < 9.5$. Therefore the minimum redshift is $z = 8.5$ and the maximum redshift is then determined by calculating how much dimming (ΔM) occurs to the galaxy by redshifting it. This is given by:

$$\Delta M = 5 \log_{10}\left(\frac{d_{L_{\text{new}}}}{d_L}\right) - 2.5 \log_{10}\left(\frac{1+z_{\text{new}}}{1+z}\right) \quad (2.14)$$

where z_{new} is the redshift when the dimming would cause the galaxy to be as faint as the detection limit. If this redshift is beyond the maximum for the LF redshift range ($z = 9.5$ for the $z = 9$ LF), then $z_{\text{max}} = 9.5$ is adopted as the galaxy was bright enough to be detected throughout the full redshift range for this LF bin.

Therefore the maximum volume for each galaxy is defined by:

$$V_{\text{max}} = V_{z_{\text{max}}} - V_{z_{\text{min}}} \quad (2.15)$$

For a determination of the LF where there are multiple survey fields, V_{max} is determined for each field and then summed to give the final V_{max} for that galaxy.

2.4.3 A more statistically robust method

The $1/V_{\text{max}}$ method makes the assumption that the selected galaxies are at their best-fitting photometric redshifts. This assumption holds true when the photometry is of sufficient signal-to-noise such that the $p(z)$ has a clearly defined single solution, ruling out alternative redshift solutions. However, when approaching the detection limit of the imaging, the signal-to-noise of the photometry reduces and therefore multiple redshift solutions become statistically acceptable. Due to the intrinsic shape of the UV LF (i.e. there are more faint galaxies than bright galaxies) the majority of the galaxy sample is comprised of sources close to the detection limit. This is demonstrated in Fig. 2.11 where I show a theoretical example of two different determinations of a high-redshift galaxy $p(z)$. This difference could arise due to different SED fitting codes, different image reductions or different methods of measuring the photometry. When using the $1/V_{\text{max}}$ method, where this information is reduced to simply a peak redshift, these two different determinations of the $p(z)$ lead to very different outcomes. This can be seen in Fig. 2.11 where the two similar $p(z)$'s have very different peak redshifts even though the overall $p(z)$ and the integrated probability of the galaxy to be at $z > 8.5$ is similar. This issue may explain why many of the early *JWST* high-redshift studies had smaller than expected overlap between their galaxy samples (Bouwens et al., 2023b), despite a strong consensus on the determination of the UV LF.

One solution to minimise this issue when using the $1/V_{\text{max}}$ method is to impose a strict signal-to-noise cut on the sample selection. This is what is done in Chapter 3-4 as well as McLeod et al. (2024) where the flux is required to be $> 8\sigma$ in the detection filter. This ensures a clean sample where the $p(z)$ has a clearly preferred high-redshift solution.

In Chapter 5 I implement an alternative method of calculating the UV LF

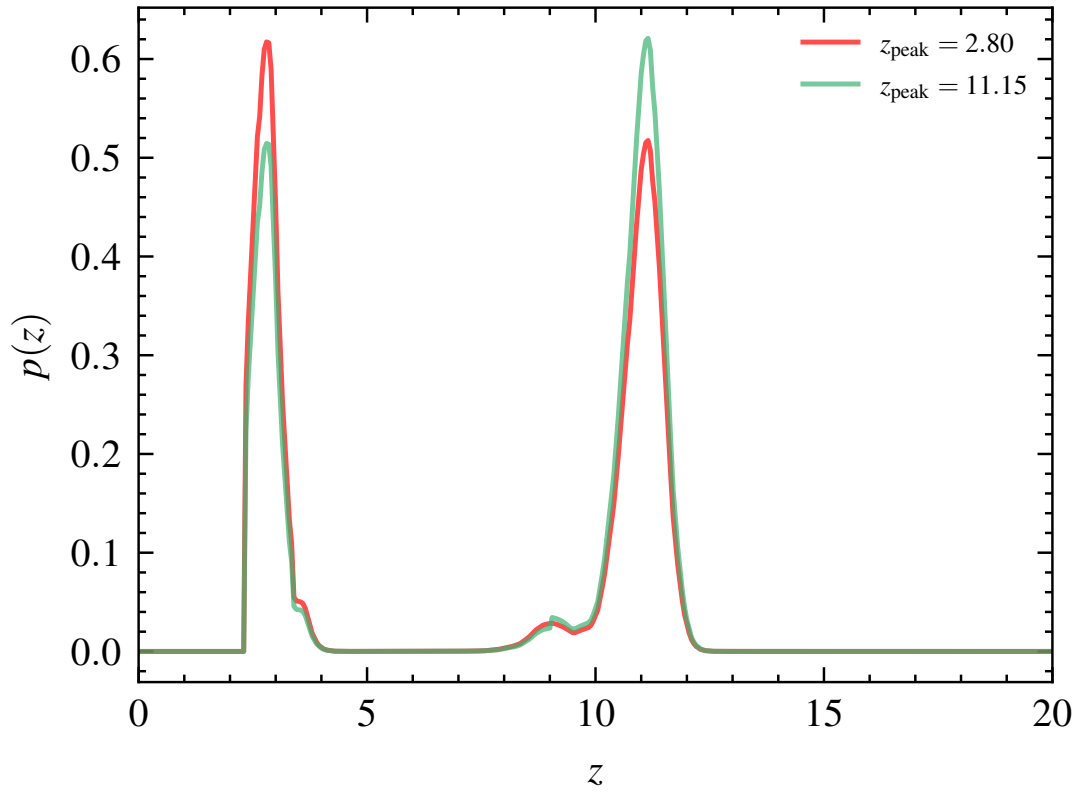


Figure 2.11 *An example of how small differences in a source's $p(z)$ produces dramatic differences if the only measurement taken is the peak redshift, despite the similarity in the integrated $p(z)$.*

that resolves these issues. Instead of selecting galaxies at high-redshift and assuming a specific photometric redshift, I incorporate the full $p(z)$ distribution for each galaxy. This ensures that all galaxies that have any probability of being at high redshift are included. In each redshift and M_{UV} bin, the number of galaxies is calculated by summing the fractional distribution of every galaxy's $p(z)$ distribution within that (M_{UV}, z) bin. This produces a two-dimensional histogram of the number of sources as a function of M_{UV} and z for a given survey field. This can then be used to determine the number density $\Phi(M_{\text{UV}}, z)$, as a function of M_{UV} and z by correcting for completeness and dividing by the cosmological volume. As described in Section 2.4.1, I calculate completeness also as a function of M_{UV} and z on the same grid. This is then used to determine the completeness corrected volume at each M_{UV} and z for a given survey field. I then combine multiple fields using:

$$\Phi(M_{\text{UV}}, z) = \sum_{i=1}^N \frac{p_i(M_{\text{UV}}, z)}{V_i C_i(M_{\text{UV}}, z)} \quad (2.16)$$

where N is the total number of sub-fields; $p_i(M_{\text{UV}}, z)$ is the total probability in a given (M_{UV}, z) bin for a given field; $C_i(M_{\text{UV}}, z)$ is the corresponding completeness and V_i is the cosmological volume provided by that field.

Using this method to calculate the UV LF makes the assumption that I have measured accurate $p(z)$'s for each source. As described in Section 2.3.2 there are a number of choices of prior for this calculation. In this work I use the UV LF prior described in Section 2.3.2.

Chapter 3

The evolution of the galaxy UV luminosity function at redshifts $z \simeq 8 - 15$ from deep JWST and ground-based near-infrared imaging

3.1 Introduction

Over the last decade, major instrumental advances have enabled astronomers to clarify the background cosmology of the Universe and push studies of galaxies back to within a billion years of the Big Bang (see [Dunlop \(2013\)](#), [Madau & Dickinson \(2014\)](#) & [Stark \(2016\)](#) for reviews). In particular, deep near-infrared extragalactic surveys, both from the ground and with the *Hubble Space Telescope* (HST) and *Spitzer* have revealed galaxy evolution extending out to redshifts $z \simeq 10$ (e.g. [Ellis et al., 2013](#); [McLure et al., 2013](#); [Oesch et al., 2014, 2018](#); [Bowler et al., 2014, 2015, 2020](#); [Finkelstein et al., 2015](#); [McLeod et al., 2015, 2016](#); [Bouwens et al., 2021, 2023b](#)). It now appears that this growing population of early star-forming galaxies could indeed have bathed the Universe in sufficient high-energy photons to produce cosmic hydrogen reionization ([Robertson et al., 2015](#); [Finkelstein et al., 2019](#); [Aird et al., 2015](#)), especially since μ -wave background measurements now indicate a ‘mean’ redshift of reionization $\langle z \rangle \simeq 7.8 \pm 0.7$ ([Planck Collaboration et al., 2020b](#)). However, analyses combining all available constraints indicate that much of the key ‘action’ has yet to be discovered, with

the ionizing photon budget potentially dominated by low-luminosity galaxies undetected by HST, and early galaxies commencing reionization at redshifts as high as $z > 15$ (Robertson et al., 2015; Robertson, 2022). Testing these predictions is one key goal for the *James Webb Space Telescope* (JWST), given its ability to probe out to $z \simeq 20$.

Although installation of the near-infrared camera WFC3/IR enabled HST to probe beyond $z \simeq 7$ into the first $\simeq$ Gyr, the isolation of secure samples of $z > 7$ galaxies has still been severely hampered by the curtailment of HST wavelength coverage at $\lambda_{\text{obs}} < 1.6 \mu\text{m}$. Robust redshift information benefits greatly not only from identification of the Lyman-break at $\lambda_{\text{rest}} = 1216 \text{ \AA}$, but also from extended/high-quality wavelength coverage above the break to exclude lower-redshift red/dusty interlopers or extreme emission-line objects which can masquerade as very high redshift Lyman-break galaxies. This uncertainty beyond $z \simeq 8$ explains, at least in part, why different authors have reached very different conclusions regarding the very high-redshift evolution of the galaxy LF, and hence the high-redshift decline of cosmic star-formation rate density (ρ_{SFR}). In particular, based on deep HST surveys, McLeod et al. (2015, 2016) concluded in favour of a smooth, exponential decline in ρ_{SFR} out to at least $z \simeq 10$, whereas Oesch et al. (2013, 2014, 2018) deduced the existence of a much more rapid decline/cutoff beyond $z \simeq 8$; the implications of these alternative forms of high-redshift evolution for galaxy formation, and for the prospects of finding galaxies at extreme redshifts, are very different.

For probing beyond $z \simeq 7$, and resolving such uncertainties, the capabilities of the NIRC2 camera on-board JWST are transformative, with complete multi-band imaging now available out to $\lambda \simeq 5 \mu\text{m}$ with unprecedented angular resolution.

Studies of high-redshift galaxy evolution with HST have also been limited by the areal coverage of near-infrared HST imaging, due to the small field-of-view of the WFC3 camera. Consequently, even though heroic efforts have been made to construct large-area HST image mosaics (e.g., CANDELS: Grogin et al., 2011), degree-scale near-infrared imaging from the ground, in particular with the WFCAM camera on UKIRT (Lawrence et al., 2007), and VIRCAM on VISTA (McCracken et al., 2012), has continued to drive our knowledge of the evolution of the brightest galaxies at $z > 6$ (Bowler et al., 2014, 2015). Indeed, the dynamic range (in galaxy luminosity) which can be accessed by combining space-based and ground-based near-infrared galaxy surveys has proved to be invaluable/essential for constraining the evolving form of the galaxy UV luminosity function out to

the highest redshifts, and hence enabling meaningful comparison with theoretical models of early galaxy evolution (Bowler et al., 2020; Adams et al., 2023a).

It is the power of this combined ground-based + space-based approach which I exploit again in this new study of the high-redshift galaxy LF, but now for the first time armed with $\simeq 45 \text{ arcmin}^2$ of deep multi-band NIRCам imaging from the JWST Early Release Observations (ERO) and Early Release Science (ERS) programmes, and $\simeq 1.8 \text{ deg}^2$ of near-homogeneous near-infrared imaging in the COSMOS field provided by Data Release 5 (DR5) from the UltraVISTA survey (McCracken et al., 2012). I have used these brand-new datasets to conduct a new search for galaxies at $z \geq 7.5$ in the three early JWST deep fields (SMACS0723, CEERS and GLASS) and in the COSMOS/UltraVISTA field. The resulting new high-redshift galaxy samples have enabled us to derive a new estimate of the evolution of the galaxy LF, and hence ρ_{SFR} , from $z \simeq 8$ out to $z \simeq 15$, less than 300 Myr after the Big Bang.

The chapter is structured as follows. In Section 3.2 I describe the JWST and ground-based data which I utilised in each field. In Section 3.3 I describe the process of catalogue creation and galaxy selection which yielded the new galaxy sample presented in Section 3.4. Then, in Section 3.5 I describe how the luminosity function was calculated and present my new determination of the evolving, high-redshift, galaxy UV LF, along with the resulting constraints on UV luminosity density, ρ_{UV} , and hence cosmic star-formation rate density, ρ_{SFR} out to $z \simeq 15$. Finally, in Section 3.6 I discuss my results in the context of existing studies, before summarising my conclusions in Section 3.7. Throughout I use magnitudes in the AB system (Oke, 1974; Oke & Gunn, 1983), and assume a standard cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

3.2 Data

3.2.1 Fields

JWST Early Release imaging

I utilise the early deep public imaging data from JWST covering three separate fields. First, the SMACS J0723 cluster was imaged using NIRCcam in the F090W, F150W, F200W, F277W, F356W, F444W filters as part of the Early Release Observations (ERO) ([Pontoppidan et al., 2022](#)). This imaging dataset consists of a single NIRCcam pointing which targets the cluster with one NIRCcam module while the other module delivers imaging in a blank field adjacent to the cluster (hence yielding a "parallel", relatively unlensed survey field). Second, the CEERS Early Release Science (ERS) programme has now observed 4 of the 10 planned NIRCcam pointings in the Extended Groth Strip (EGS) CANDELS field, and here I use the resulting NIRCcam imaging in the F115W, F150W, F200W, F277W, F356W, F410M and F444W filters. Finally, the GLASS ERS programme ([Treu et al., 2022](#)) has already yielded a parallel NIRCcam field consisting of one (two module) pointing imaged in the F090W, F115W, F150W, F200W, F277W, F356W, and F444W filters. However, the GLASS F090W imaging contains an abundance of artefacts across the image making it challenging for use in searching for $z \geq 7.5$ galaxies, and so in this study, for high-redshift galaxy selection, I utilise only the F115W, F150W, F200W, F277W, F356W and F444W imaging (although see [Leethochawalit et al. \(2023b\)](#)). The final combined JWST NIRCcam effective imaging area available for this study totals $\simeq 45 \text{ arcmin}^2$, albeit with the somewhat varied filter coverage described above. This public JWST NIRCcam imaging was reduced using PENCIL (PRIMER enhanced NIRCcam Image Processing Library). The PENCIL pipeline is built on top of STScI's JWST Calibration (v1.6.2) but also includes additional processing steps not included in the standard calibration pipeline. This includes the subtraction of $1/f$ noise striping patterns (both vertical and horizontal) that are not fully removed by the standard calibration pipeline and the subtraction of "wisps" artifacts from the short wavelength filters F150W and F200W in the NRCA3, NRCB3, and NRCB4 detector images.

Additionally, the background sky subtraction is performed by subtracting the median background over a $N \times N$ grid while using a segmentation map to mask

pixels attributed to sources. The image alignment is executed in two passes using the calibration pipeline’s TweakReg step and then using STScI python package TweakWCS: the first pass uses TweakReg to group overlapping images for each detector/filter and perform an internal alignment within the detector/filter group; the second performs alignment against an external catalog using TweakWCS. The external catalog is, if possible, generated from an HST ACSWFC image mosaic which has been registered to the GAIA DR3 catalog. The astrometry of all the reduced images was aligned using SCAMP to GAIA EDR3 and aligned and stacked to the same pixel scale of 0.03 arcsec using SWARP.

COSMOS/UltraVISTA

I utilise near-infrared imaging from the UltraVISTA survey ([McCracken et al., 2012](#)) which provides deep $YJHK_s$ imaging across 1.8 deg^2 in the COSMOS field, taken using ESO’s VISTA telescope in Chile. The UltraVISTA imaging is split into two regions “ultra-deep” and “deep” which cover approximately half the area each. These regions consist of four stripes, each of which alternate between the two depths across the image. In this study I use the fifth data release (DR5) of UltraVISTA which differs primarily from DR4 in providing significant deeper J -band and H -band imaging: $\simeq 1 \text{ mag.}$ deeper in the “deep” stripes, and $\simeq 0.2 \text{ mag.}$ deeper in the “ultra-deep” stripes. Within the central 1 deg^2 I complement the new near-infrared UltraVISTA imaging data with optical imaging from the CFHTLS-D2 field from the CFHT Legacy Survey ([Hudelot et al., 2012](#)) in u^*griz . I also include wider-area optical data covering the full UltraVISTA field from the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) DR2 ([Aihara et al., 2019](#)) in the $GRIZy$ filters as well as in two narrow bands, $NB816$ and $NB921$. All the near-infrared and optical imaging in COSMOS was aligned to the GAIA EDR3 reference frame using SCAMP and re-sampled using SWARP to a common pixel scale of 0.15-arcsec. Finally, I supplemented my ground-based datasets by adding $3.6\mu\text{m}$ and $4.5\mu\text{m}$ photometry from *Spitzer*/IRAC imaging, which experience proves can be invaluable for the refinement of photometric redshifts as well as minimising the level of low-redshift galaxy and dwarf-star contamination in the final high-redshift galaxy sample. The *Spitzer*/IRAC data in $3.6 \mu\text{m}$ and $4.5 \mu\text{m}$ in the COSMOS field was provided by the Cosmic Dawn Survey ([Euclid Collaboration et al., 2022](#)).

3.2.2 Image processing

PSF homogenisation in COSMOS

In order to derive consistent photometry in different filters, the differences in the point spread function (PSF) between filters needs to be accounted for. I corrected for this in the COSMOS imaging by homogenising the PSFs in the different images to one common PSF. As the UltraVISTA *Y* band has the broadest PSF, I chose to use that as the target PSF to which to PSF-homogenise all of the other COSMOS imaging. Firstly, I identified $\simeq 15$ bright but unsaturated stars in each image. I then centroided and stacked these stars to generate a measurement of the PSF in each waveband. Then, using a combination of a Moffat profile with two Gaussian profiles, I generated a series of kernels. These kernels were then convolved with the original PSFs to match the target (*Y*-band) PSF. At a radius of 0.9-arcsec I confirmed that the enclosed flux in every image is within 2% of the target. I then convolved every image with its respective kernel to PSF-homogenise the entire COSMOS imaging dataset.

Image depths

The global depths in all of the ground-based PSF homogenised images were determined using 1.8-arcsec diameter circular apertures placed in all locations within the image that were determined to be source free. The 5σ depth was then calculated via

$$5\sigma = 1.483 \times \text{MAD} \times 5, \quad (3.1)$$

where MAD refers to the median absolute deviation of the flux detected in the empty apertures. These *global* $5\text{-}\sigma$ depths for each ground-based image are listed in Table 3.1 for information. In practice I then re-determined *local* depths for each source detected (see Section 3.3) by determining equation (3.1) on the 200 empty apertures nearest to the source in question, and adopted the 1σ local depth as the uncertainty in the photometry for every source detected.

For the JWST images, the global depths of the SW images were determined using 0.248-arcsec diameter circular apertures placed in all locations within the image that were determined to be source free. I used the same procedure for the LW images, but with 0.341-arcsec diameter apertures. The $5\text{-}\sigma$ depth was then calculated using the procedure described above (equation (3.1)). The *global*

Table 3.1 *The derived 5σ global depths for all the COSMOS images used in this analysis. All depths (quoted in AB Magnitudes) were calculated using 1.8-arcsec diameter apertures on the PSF-homogenised images and corrected to total using a point-source correction.*

Filter	ultra-deep	deep
CFHT u^*	27.00	27.00
CFHT g	27.03	27.03
CFHT r	26.47	26.47
CFHT i	26.17	26.17
CFHT z	25.34	25.34
SSC B	27.16	27.16
SSC z'_{new}	25.95	25.95
HSC G	27.09	27.09
HSC R	26.74	26.74
HSC I	26.46	26.46
HSC Z	26.18	26.18
HSC y	25.42	25.42
HSC $NB816$	25.66	25.66
HSC $NB921$	25.70	25.70
VISTA Y	25.51	24.37
VISTA J	25.55	25.10
VISTA H	25.26	24.96
VISTA K_s	24.96	24.62

Table 3.2 *The derived 5σ global depths for all the space-based images used in this analysis. All depths (given in AB magnitudes) have been corrected to total assuming a point-source correction.*

Filter	SMACS		CEERS	GLASS
	Cluster	Parallel		
F090W	28.30	28.40	-	-
F115W	-	-	28.62	28.75
F150W	28.37	28.70	28.54	28.57
F200W	28.33	28.78	28.70	28.67
F277W	27.65	28.86	28.74	28.77
F356W	28.05	28.89	28.77	28.75
F410M	-	-	29.07	-
F444W	28.27	28.68	28.34	28.79

$5\text{-}\sigma$ depths (corrected to total with the appropriate point-source correction) for all three JWST fields are shown in Table 3.2. In practice, I again determined local depths for each source detected using the 200 empty photometric apertures closest to the source. I adopted the (point-source corrected) $1\text{-}\sigma$ local depth as the uncertainty on my photometry for every source detected.

Spitzer/IRAC fluxes

The *Spitzer*/IRAC imaging at $3.6\mu\text{m}$ and $4.5\mu\text{m}$ has significantly poorer angular resolution than the optical and near-infrared imaging used in this study. Therefore, to extract robust IRAC photometry for the COSMOS field, I utilised the deconvolution software package TPHOT (Merlin et al., 2015). I used the three near-infrared detection images (see below) as the high-resolution priors to generate the TPHOT fluxes which are therefore isophotal. To add this to the PSF-homogenized photometry, I performed a correction to the optical and near-infrared photometry by multiplying the fluxes by $f = D_{iso}/D_{1.8}$ where D_{iso} is the isophotal flux in the corresponding detection image and $D_{1.8}$ is the flux enclosed within the 1.8-arcsec diameter aperture in the detection image.

3.3 Catalogue creation and galaxy selection

To create catalogues in the COSMOS fields I utilised inverse variance weighted stacks of the data in the Y , J , H , and K_s bands to increase the sensitivity of my detections. I constructed stacks of VISTA $Y + J + H + K_s$, VISTA $J + H + K_s$

and VISTA $H + K_s$ imaging. These stacks were chosen to best optimise the detection of $z \sim 6 - 10$ Lyman-break galaxies. The catalogues were created using SExtractor (Bertin & Arnouts, 1996) in dual-image mode with the stacked images as the detection images. A master catalogue was created by combining sources detected in both the detection images, with duplicates removed by retaining the object with the highest signal-to-noise.

For the JWST catalogues I created two rest-frame UV-selected catalogues using SExtractor in dual-image mode with the F200W as the detection image. This was to optimise my catalogue to select $z \geq 8$ galaxies as this filter will encompass the bright UV flux red-ward of the Lyman break. I used 8-pixel diameter (0.248-arcsec diameter) apertures on the imaging taken through the SW filters (F090W, F115W, F150W, F200W) and 11-pixel diameter (0.341-arcsec diameter) apertures on the LW imaging (F277W, F356W, F410M, F444W) as these diameters were found to contain a similar percentage of total flux based on the curve-of-growth ($\sim 76\%$). Further small corrections on the percent level were made to correct to 76% of total flux based on a point-source correction derived from curves of growth determined from the imaging in each JWST NIRCcam filter.

3.3.1 Determination of photometric redshifts

I used the photometric redshift (photo- z) code EAZY (Brammer et al., 2008) for my redshift determination for every object in the COSMOS and JWST catalogues. I ran EAZY using the Pegase set of templates with zero-point offsets calculated based on a set of robust spectroscopic redshifts in COSMOS. This method allows us to refine the SED fitting using spectroscopically confirmed redshifts and assess the performance of the SED fitting by calculating the fraction of catastrophic outliers (f_{outliers}) and the bias, which I define as the median value of $dz = (z_{\text{spec}} - z_{\text{phot}})/(1 + z_{\text{spec}})$. To quantify the accuracy of the photometric redshifts I calculated σ_{dz} using the robust median absolute deviation (MAD) estimator. A comparison of the spectroscopic redshifts vs photometric redshifts for ~ 3700 sources shows that my photometric redshifts are robust, with a $\sigma_{dz} = 0.025$ and an outlier rate of $f_{\text{outliers}} = 2.49\%$. I did not initially include the *Spitzer*/IRAC photometry in the fitting, as this was added after the initial galaxy selection described in Section 3.3.2 to refine the selected sample. Because brown dwarfs are possible contaminants in the search for high-redshift galaxies (especially with ground-based data), I also used EAZY to fit a series M-, L- and

T-dwarf templates from the SpeX prism library¹ to the COSMOS catalogues.

3.3.2 Galaxy selection from the COSMOS UltraVISTA imaging

From the sample of objects detected in the COSMOS field I selected galaxies in redshift bins of width $\Delta z = 1$ around central redshifts of $z = 8, 9$ and 10 . For a source to be accepted into the sample, they must meet the following criteria:

1. $\chi^2_{\nu, \text{galaxy}} < 5$
2. $\chi^2_{\nu, \text{galaxy}} < \chi^2_{\nu, \text{star}}$

where $\chi^2_{\nu, \text{galaxy}}$ and $\chi^2_{\nu, \text{star}}$ represent the reduced χ^2 for the Pegase galaxy templates, and SpeX stellar templates, respectively. Condition (i) ensures that only sources with acceptable galaxy template solutions are included. Condition (ii) removes brown dwarf contaminants by ensuring that the galaxy templates provide a better fit than the brown dwarf templates.

To further refine the sample I use two further SED fitting codes: **LePhare** (Arnouts et al., 1999; Ilbert et al., 2006) with templates from Bruzual & Charlot (2003) and with dust attenuation spanning the range $A_V = 0.0 - 6.0$, and the code described in McLure et al. (2011). I further require all galaxies to have a preferred high-redshift solution produced by these two alternative codes, to ensure that the redshift solution is robust against choice of templates, dust attenuation and photo-z code.

Finally, all candidates were visually inspected to remove objects which could be due to diffraction spikes and any other artefacts.

Cross-talk artefacts

In the COSMOS field, Bowler et al. (2017) identified faint cross-talk in the VISTA $YJHK_s$ imaging. Therefore, to avoid these artefacts I developed a mask based on the positions of all the bright stars in the image from the COSMOS 2020 bright stars mask (Weaver et al., 2022).

¹<http://pono.ucsd.edu/~adam/browndwarfs/spexprism/index.html>

z=8

In COSMOS I require a 5σ detection in the VISTA J or H band. I require non-detections at the 2σ level in all filters blue-ward of the Lyman break up to and including the SSC z' filter. A best-fitting photo- z in the range $7.5 < z < 8.5$ from EAZY is also required.

z=9

In COSMOS I require a 5σ detection in the VISTA J , H or K_s band. I require non-detections at the 2σ level in all filters blue-ward of the Lyman break up to and including the VISTA Y filter. A best-fitting photo- z in the range $8.5 < z < 9.5$ from EAZY is also required.

z=10

In COSMOS I require a 5σ detection in the VISTA H or K_s band. I require non-detections at the 2σ level in all filters blue-ward of the Lyman break up to and including the VISTA Y filter. A best-fitting photo- z in the range $9.5 < z < 10.5$ from EAZY is also required.

3.3.3 Galaxy selection from the JWST NIRCам imaging

I selected galaxies using different ‘dropout’ criteria in the JWST fields. Due to the different filter sets in the three different fields, the same criteria could not be applied to every field. The conditions required to select robust samples of high-redshift galaxies are therefore described below, field by field.

CEERS and GLASS

In the CEERS and GLASS fields I constructed three samples meeting the following criteria. F115W dropouts require a 2σ non-detection in F115W with a 5σ detection in F150W and a 3σ detection in F200W. F150W dropouts were selected by requiring a 2σ non-detection in F115W and F150W, a 5σ detection in F200W and a 3σ detection in F277W. I also included sources where the

Lyman break is partway through the F150W filter: this sample requires a 2σ non-detection in F090W and F115W, a detection between 2σ and 5σ in F150W, a 5σ detection in F200W and a 3σ detection in F277W.

SMACS0723

I performed different dropout selections for sources in SMACS0723 due to the inclusion of F090W imaging and the lack of F115W imaging. F090W dropouts require a 2σ non-detection in F090W with a 5σ detection in F150W and a 3σ detection in F200W. F150W dropouts require 2σ non-detections in F090W and F150W with a 5σ detection in F200W and a 3σ detection in F277W.

For SMACS0723, CEERS and GLASS, every galaxy in the final selected sample was also required to have a $\Delta\chi^2 > 4$ between the best fitting high- z and low- z solution. This helps to ensure that the high- z solution is robust by removing potential low- z contaminants (generally dusty intermediate-redshift galaxies or extreme emission-line objects) from the sample. Consistent with the selection of the ground-based galaxies, I also fitted the sources in the JWST sample with the SED code **LePhare** as well as the code described in [McLure et al. \(2011\)](#), and additionally required preferred high-redshift solutions from both codes. Finally, all candidates were again visually inspected to remove artefacts.

3.4 The final high-redshift galaxy sample

3.4.1 The final COSMOS/UltraVISTA galaxy sample

Using the selection criteria described in Section 3.3.2 I assembled a final combined sample of 16 LBGs at $z > 7.5$ in COSMOS/UltraVISTA field. The objects with their best fitting redshift, M_{UV} and coordinates are listed in Table 3.3 (ranked by photometric redshift). The sample contains 12 sources with a best fitting redshift from EAZY in the range $7.5 < z < 8.5$, 3 sources in the range $8.5 < z < 9.5$ and 1 source in the range $9.5 < z < 10.5$.

There are 16 galaxies in this sample, 8 of which are found in the "Deep" region of UltraVISTA. In previous work searching for bright galaxies at $z > 7.5$ in UltraVISTA, the fraction of the sample that was in the "Deep" region was

Table 3.3 *The best-fitting photometric redshifts from EAZY for the final sample of $z > 7.5$ galaxies found in the COSMOS/UltraVISTA field, ranked by photometric redshift. The first column gives the source ID, with z_{phot} for each object then presented in Column 2. Column 3 gives the derived rest-frame UV magnitude of each galaxy. Column 4 denotes the the sub-region of the UltraVISTA imaging within which each object has been found: ‘U-D’ refers to the ultra-deep stripes while ‘D’ refers to the deep stripes, although as discussed in the text the difference in depth between these two regions has now been largely eliminated at J,H,K_s in UltraVISTA DR5. The coordinates for each source are given in the following two columns. The final two columns list an alternative ID, as appropriate, for those (8) sources which were already detected by Bowler et al. (2020) or were listed in the COSMOS2020 catalogue (Weaver et al., 2022), indicated by B20 and W22, respectively. Interestingly, and as largely anticipated, the new sources reported here almost all lie with the D (deep) stripes, where the UltraVISTA data have been most improved in depth between DR4 and DR5 (effectively doubling the area available in COSMOS for the selection of very high-redshift galaxies).*

ID	z_{phot}	M_{UV}	Region	RA	DEC	B20	W22
334330	$7.58^{+0.87}_{-0.16}$	−21.30	D	10:00:05.27	01:59:05.98	-	-
733875	$7.58^{+0.46}_{-0.31}$	−21.57	D	09:59:52.85	02:34:57.00	-	-
812867	$7.58^{+1.35}_{-0.02}$	−21.02	U-D	10:00:040.8	02:42:16.62	-	1349252
688541	$7.66^{+0.82}_{-0.00}$	−22.15	U-D	10:02:12.55	02:30:45.81	914	1151531
765906	$7.66^{+0.53}_{-0.1}$	−22.61	D	09:58:12.23	02:37:52.61	-	1274544
626972	$7.75^{+0.72}_{-0.24}$	−21.49	U-D	09:57:54.25	02:25:08.40	839	1055131
536767	$8.02^{+0.33}_{-0.40}$	−21.40	D	09:58:17.19	02:17:06.39	-	-
861605	$8.02^{+0.66}_{-0.26}$	−21.33	U-D	09:57:21.37	02:45:57.57	-	1412106
978389	$8.02^{+0.77}_{-0.21}$	−21.68	U-D	10:00:34.56	01:55:17.42	-	-
484075	$8.11^{+1.03}_{-1.03}$	−22.05	D	09:58:032.1	02:12:21.83	-	-
578163	$8.20^{+0.50}_{-0.35}$	−22.35	U-D	09:57:47.91	02:20:43.54	762	978062
458445	$8.38^{+0.28}_{-0.56}$	−21.65	U-D	10:01:47.49	02:10:15.43	598	784810
448864	$8.57^{+0.30}_{-0.69}$	−21.15	D	10:02:46.29	02:09:23.42	-	-
306122	$8.76^{+0.14}_{-0.43}$	−21.76	D	10:02:50.81	01:56:36.49	-	-
892014	$8.96^{+0.11}_{-0.33}$	−22.16	D	10:00:04.23	02:47:59.84	-	-
817482	$9.89^{+1.22}_{-0.20}$	−22.57	U-D	09:57:25.46	02:42:41.21	-	1356755

minimal with 1/16 in the [Bowler et al. \(2020\)](#) sample, and 0/16 in the ([Stefanon et al., 2019](#)) sample.

This demonstrates the (anticipated) impact of the increased depth in the J and H bands delivered in the "Deep" region in UltraVISTA DR5, which effectively doubles the useful area searchable for bright high-redshift galaxies in the COSMOS field.

3.4.2 The final JWST galaxy sample

There are 45 galaxies in the final high-redshift ($z > 8.5$) sample uncovered by my analysis of the ERO/ERS JWST NIRCcam imaging, with 23 found in SMACS0723, 19 in CEERS, and only 3 in GLASS. Two of the high-redshift galaxies I have found here in the GLASS field have been independently discovered by [Naidu et al. \(2022b\)](#) and [Castellano et al. \(2022\)](#), namely GLASS-1698 and GLASS-17487 in my sample which I find to lie at $z = 10.45$ and $z = 12.42$ respectively (consistent with the independently reported photometric redshifts). I fail to recover robust high-redshift solutions for any of the five sources that [Castellano et al. \(2022\)](#) reported in their fainter sample. In SMACS0723, 2 of the $z_{\text{phot}} \sim 9$ galaxies in this sample are known to be at $z < 8.5$ as they have been spectroscopically confirmed at $z = 7.663$ (SMACS-44711) and $z = 7.665$ (SMACS-44566) as noted in [Carnall et al. \(2023\)](#). Therefore, these sources are not included in the LF calculation described in Section 3.5.2. I have also detected the $z \sim 12$ source discovered in [Finkelstein et al. \(2022b\)](#) with a similar redshift of $z = 12.29$ (ID: CEERS-32395_2). The highest redshift galaxy in my sample is CEERS-93316 which sets a new redshift record with a best-fitting redshift of $z = 16.4$. This object is described in more detail in Section 3.6.2.

In Fig. 3.1 I show illustrative examples of the SEDs of 4 of my JWST-selected galaxies, at redshifts $z \simeq 9, 10, 11$ & 12.

The effective area available in which to search for high-redshift galaxies within each field was computed after masking the regions dominated by bright foreground sources, and removing areas of increased noise towards the edge of the imaging. The resulting effective area available for high-redshift galaxy detection/selection in each JWST field is listed in Table 3.4. These areas are also then used consistently in the calculation of the luminosity function in Section 3.5. I make a conservative estimate for the area in SMACS0723, including the removal

Table 3.4 *The derived effective areas available for robust high-redshift galaxy selection in each of three JWST fields used in this work.*

Field	Area [arcmin ²]
CEERS	31.7
GLASS	6.1
SMACS0723	6.3

of the highly-lensed region centred on the cluster. Only 1 of the 23 galaxies found in the SMACS0723 field lay within the excluded area, SMACS-34086, and therefore this is not included in the calculation of the luminosity function (note that this highly-lensed galaxy has been spectroscopically confirmed with NIRSpec at $z = 8.948$; [Carnall et al. 2023](#)).

The UV magnitude of each source was determined and corrected to total assuming a point-source correction (see Section 3.5). I make further corrections to objects that look particularly extended by performing manual aperture photometry in 0.5'' apertures as this is where the curve-of-growth in F200W looks approximately flat. The corrected absolute UV magnitudes for all the sources in my final $z > 8.5$ sample are given in Table 3.5, along with their positions and redshifts. Sources with extra corrections to total are marked with an asterisk.

3.5 The Luminosity Function

Having completed the selection and refinement of my final galaxy samples at $z > 7.5$ I proceed to compute the UV luminosity function at $z = 8, 9$ with a redshift bin width of $\Delta z = 1$ and at $z = 10.5$ with a bin width $\Delta z = 2$ and $z = 13.25$ with a bin width $\Delta z = 3.5$. The UV absolute magnitude was estimated for each galaxy from the best-fitting SED template using a tophat filter centered on $\lambda_{\text{rest}} = 1500\text{\AA}$ with a width of $100\text{\AA}$. This was then converted to an absolute magnitude using

$$M_{UV} = m_{1500} - 5 \log_{10} \left(\frac{D_L}{10} \right) + 2.5 \log_{10} (1 + z), \quad (3.2)$$

where m_{1500} is the apparent magnitude at $\lambda_{\text{rest}} = 1500\text{\AA}$, D_L is luminosity distance in parsecs and z is the best fitting redshift of the source.

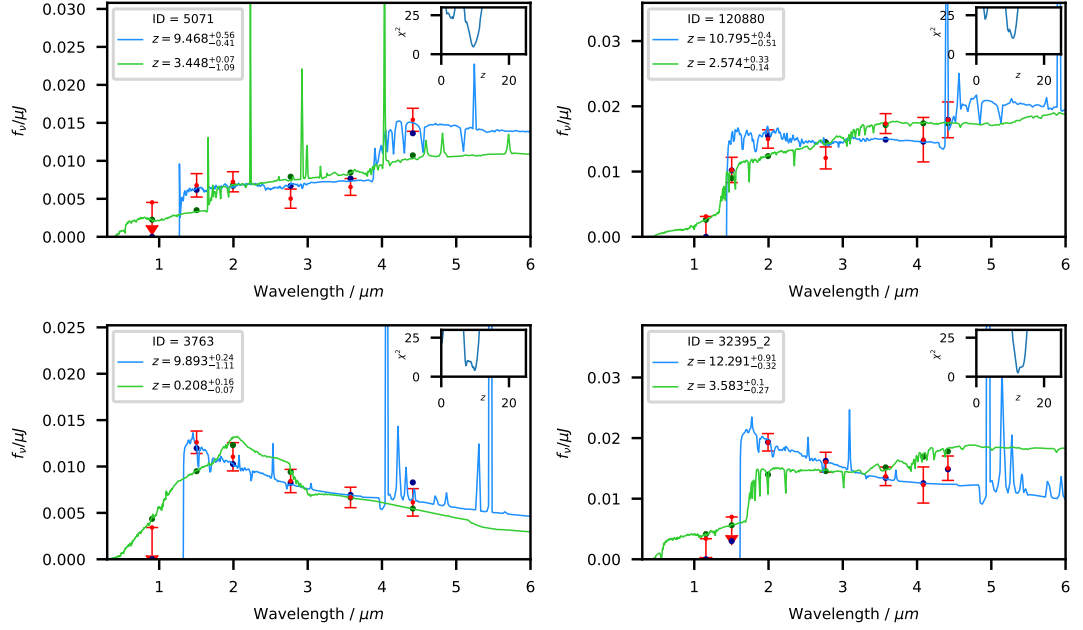


Figure 3.1 *Spectral Energy Distribution (SED) fits for 4 example galaxies selected from within the final JWST high-redshift sample. The blue line shows the best-fitting (preferred) high-redshift solution, the green line shows the best-fitting (alternative) low-redshift solution, and the red points show the measured photometry (at 76% of total flux). The solid blue and green circles represent the model photometry of the best fitting high and low redshift templates respectively. The χ^2 as a function of redshift is shown in the inset panels. These four galaxies have been chosen to be illustrative of the SEDs displayed by the galaxies found at redshifts $z \sim 9, 10, 11, 12$.*

Table 3.5 *The best-fitting photometric redshifts from EAZY for the final sample of high-redshift ($z > 8.5$) galaxies found in the combined JWST fields, ranked by photometric redshift. The first column gives the source ID, with z_{phot} for each object then presented in Column 2. Column 3 gives the derived rest-frame UV total magnitude of each galaxy. The coordinates for each source are given in the final two columns. I note here that sources 1698 and 17487 have also been independently discovered in the GLASS imaging by [Naidu et al. \(2022b\)](#) and [Castellano et al. \(2022\)](#) and sources 34086, 44711 and 44566 have been spectroscopically confirmed at $z = 8.498$, $z = 7.663$ and $z = 7.665$ respectively ([Carnall et al., 2023](#)). The total UV magnitudes of sources indicated with an asterisk incorporate an additional correction to account for extended flux.*

ID	z_{phot}	M_{UV}	RA	DEC
43031	$8.57^{+0.65}_{-1.15}$	-18.43	07:23:27.86	-73:26:19.66
29274_4	$8.86^{+1.37}_{-0.60}$	-18.41	14:19:27.39	52:51:46.90
1434_2	$9.16^{+1.30}_{-0.27}$	-18.82	14:19:26.11	52:52:52.38
44085	$9.26^{+0.20}_{-0.24}$	-18.25	07:23:26.72	-73:26:10.54
38697	$9.36^{+0.38}_{-0.25}$	-18.86	07:23:27.84	-73:26:19.91
5071	$9.47^{+0.56}_{-0.41}$	-18.02	07:22:56.86	-73:29:23.50
44711*	$9.47^{+0.24}_{-0.20}$	-20.14	07:23:20.16	-73:26:04.32
43866	$9.47^{+0.38}_{-0.30}$	-18.14	07:23:25.60	-73:26:12.43
34086	$9.47^{+0.27}_{-0.38}$	-17.87	07:23:26.24	-73:26:57.00
14391	$9.47^{+0.36}_{-0.21}$	-18.81	07:22:47.73	-73:28:28.32
12682	$9.57^{+0.50}_{-0.63}$	-18.95	07:22:38.95	-73:28:30.40
44566*	$9.68^{+0.14}_{-0.25}$	-20.68	07:23:22.74	-73:26:06.26
22480	$9.68^{+0.36}_{-0.47}$	-18.50	07:22:45.81	-73:27:46.60
15019	$9.68^{+0.12}_{-2.14}$	-18.67	07:22:58.27	-73:28:19.56
12218	$9.68^{+0.59}_{-0.62}$	-19.28	07:22:35.06	-73:28:33.00
3398	$9.68^{+0.10}_{-2.33}$	-18.21	07:22:35.37	-73:29:38.64
6200	$9.79^{+0.24}_{-2.17}$	-18.52	07:22:41.51	-73:29:10.64
7606	$9.89^{+0.20}_{-2.17}$	-18.08	07:22:29.56	-73:29:05.69
3763	$9.89^{+0.24}_{-1.11}$	-18.99	07:22:49.14	-73:29:31.18
1698*	$10.45^{+0.26}_{-0.16}$	-20.62	00:14:02.86	-30:22:18.62
20976_4	$10.45^{+0.52}_{-0.96}$	-18.80	14:19:36.30	52:50:49.18
6647	$10.45^{+0.40}_{-0.92}$	-18.88	14:19:14.67	52:48:49.76
3710	$10.45^{+0.33}_{-0.68}$	-19.06	14:19:24.03	52:48:28.98

Table 3.5 *Continued.*

ID	z_{phot}	M_{UV}	RA	DEC
4063	$10.45^{+0.44}_{-2.45}$	−18.03	07:22:52.31	−73:29:32.39
30585	$10.56^{+0.25}_{-0.52}$	−19.35	14:19:35.34	52:50:37.87
73150	$10.56^{+0.29}_{-1.10}$	−19.07	14:19:26.78	52:54:16.59
21071_2	$10.68^{+0.28}_{-1.70}$	−19.27	14:19:36.72	52:55:22.63
20757	$10.68^{+0.49}_{-1.14}$	−17.88	07:23:12.47	−73:28:01.74
6415	$10.79^{+0.45}_{-0.66}$	−19.13	00:14:00.28	−30:21:25.87
120880	$10.79^{+0.40}_{-0.51}$	−19.43	14:20:10.56	52:59:39.51
26598	$10.79^{+0.26}_{-1.68}$	−18.47	07:22:50.56	−73:27:37.89
61486	$11.15^{+0.37}_{-0.35}$	−19.61	14:19:23.73	52:53:00.98
622_4	$11.27^{+0.48}_{-0.60}$	−18.92	14:19:16.54	52:47:47.36
33593_2	$11.27^{+0.58}_{-0.28}$	−19.58	14:19:37.59	52:56:43.82
77241*	$11.27^{+0.39}_{-0.70}$	−19.60	14:19:41.47	52:54:41.49
5268_2	$11.40^{+0.30}_{-1.11}$	−19.16	14:19:19.68	52:53:32.11
127682	$11.40^{+0.59}_{-0.51}$	−19.07	14:19:59.25	53:00:21.34
26409_4	$11.90^{+1.60}_{-0.70}$	−18.84	14:19:38.48	52:51:18.12
8347	$11.90^{+0.27}_{-0.39}$	−19.09	07:22:56.36	−73:29:00.52
10566	$12.03^{+0.57}_{-0.26}$	−19.70	07:23:03.47	−73:28:46.99
32395_2	$12.29^{+0.91}_{-0.32}$	−19.89	14:19:46.35	52:56:32.82
1566	$12.29^{+1.50}_{-0.44}$	−18.77	07:22:39.16	−73:30:00.83
17487	$12.42^{+0.27}_{-0.14}$	−20.89	00:13:59.76	−30:19:29.07
27535_4	$12.56^{+1.75}_{-0.27}$	−19.42	14:19:27.31	52:51:29.23
93316*	$16.39^{+0.32}_{-0.22}$	−21.66	14:19:39.49	52:56:34.94

3.5.1 Determining completeness

An accurate derivation of the UV LF requires a reliable estimate of how complete the samples are near to the magnitude limits of the imaging data. To calculate this I ran completeness simulations to estimate the fraction of galaxies I expect to recover as a function of observed magnitude in the detection images. This was done by injecting fake point sources (based on the measured PSF in the imaging) into three different regions of the different detection images. The sources were injected in steps of apparent aperture magnitude and the fraction of successfully recovered sources was measured at each step. This was performed 10 times in each of the three regions and a median was taken of the resulting 30 simulations. For COSMOS I treated the "Deep" and "Ultra-Deep" regions as separate fields. This produced the completeness as a function of apparent AB magnitude and was performed for each detection image in all of the fields analysed in this work. For GLASS and CEERS, 3 cutouts were made in random areas of the fields and sources were injected into each. From F200W (AB) = 24 – 31 in steps of 0.1, 800 sources were injected into each area at each step. Therefore, a total of 336,000 sources were injected into both fields combined. For SMACS0793 there were 2 larger cutout areas with one covering the cluster field and one covering the parallel field with 1000 sources inserted in each area at each step. Therefore, a total of 140,000 sources were injected into SMACS0793. This was then implemented in the determination of the UV LF as described in Section 3.5.2.

3.5.2 Determining number density

The binned co-moving number density of sources per absolute magnitude, $\Phi(M_{UV})$, was determined using the $1/V_{\max}$ method (Schmidt, 1968). The equation for $\Phi(M_{UV})$ is given by

$$\Phi(M_{UV})\Delta M = \sum_{i=1}^N \left(\frac{1}{C(m_{AB})V_{\max}} \right), \quad (3.3)$$

where N is the number of galaxies in each bin, $C(m_{AB})$ is the completeness as a function of m_{AB} in the detection image, and $V_{\max}$ is the maximum volume the galaxy could occupy and still be detected in the appropriate filter for the given redshift. This was determined by redshifting each galaxy from its measured photo- z until it could no longer be detected in the appropriate detection filter

(at a redshift z_{max}). The volume, V_{max} , is the difference in co-moving volume between the co-moving volume at z_{max} and at the minimum redshift for that sample (i.e. for the $z = 8$ sample the minimum redshift is $z = 7.5$). In the case of the SMACS0723 field, the volume was adjusted by the magnification factor which was computed from GLAFIC (Oguri, 2010). As mentioned in Section 3.4.2, the SMACS0723 sources included in the LF calculation lie outside the most magnified region. Therefore the magnification values of the sources used in the LF calculation are $\lesssim 2$.

The completeness factor, $C(m_{\text{AB}})$, takes into account how incomplete the given galaxy sample is at the apparent AB magnitude in the detection image. This then leads to a value for the number density of galaxies in the given UV absolute magnitude bin. The Poisson uncertainties were calculated using the confidence intervals from Gehrels (1986).

Our determinations of the UV LF at $z = 8, 9, 10.5, 13.25$ are shown in Fig. 3.2 and tabulated in Table 3.6. The combined dataset from the ground and space allows for increased dynamic range in my LF determination although this is only possible up to $z \sim 11$ due to the limited wavelength range accessible from the ground. At $z = 8$ the new data contributing to the LF is purely from the COSMOS sample and therefore I place new constraints on the bright end alone. My results are in good agreement with Bowler et al. (2020) and show a clear deviation from the McLure et al. (2013) Schechter function at the bright end. At $z = 9$ my results at the bright end are in also good agreement with Bowler et al. (2020) and my faint-end bins determined using the JWST sample are in good agreement with McLeod et al. (2016). My JWST results at $z = 9$ are also in good agreement with Bouwens et al. (2021). At $z = 10.5$ my new source from the UltraVISTA imaging allows us to compute a bin at the bright end of this LF and my JWST sample provides a fainter bin. The $z = 13.25$ LF was calculated from the JWST sample alone as this redshift range cannot be probed from the ground. This shows a modest evolution from $z = 9$ to $z = 10.5$ and then further decline to $z = 13.25$.

Luminosity function fitting

As shown by this work, and the results of Bowler et al. (2014, 2015, 2020), a double-power law (DPL) function is a more suitable fit to the UV LF at $z \geq 8$. Therefore, I fit a DPL to all the new high-redshift luminosity function data derived here. The fitting was done using the Scipy (Virtanen et al., 2020) `curve_fit`

Table 3.6 *Computed UV LF data points using the derived sample of $z > 7.5$ galaxies from UltraVISTA and JWST. The columns show redshift, the central UV absolute magnitude of the bin, the bin width and the source number density within the bin, along with uncertainties.*

z	M_{UV} [mag]	ΔM [mag]	ϕ [$10^{-6}/\text{mag}/\text{Mpc}^3$]
8	-22.17	1.0	$0.63^{+0.50}_{-0.30}$
8	-21.42	0.5	$3.92^{+2.34}_{-1.56}$
9	-22.30	1.0	$0.17^{+0.40}_{-0.14}$
9	-21.30	1.0	$3.02^{+3.98}_{-1.95}$
9	-18.50	1.0	1200^{+717}_{-476}
10.5	-22.57	1.0	$0.18^{+0.42}_{-0.15}$
10.5	-20.10	1.0	$16.2^{+21.4}_{-10.5}$
10.5	-19.35	0.5	$136.0^{+67.2}_{-47.1}$
10.5	-18.85	0.5	$234.9^{+107}_{-76.8}$
10.5	-18.23	0.75	630.8^{+340}_{-233}
13.25	-20.35	1.7	$10.3^{+9.98}_{-5.59}$
13.25	-19.00	1.0	$27.4^{+21.7}_{-13.1}$

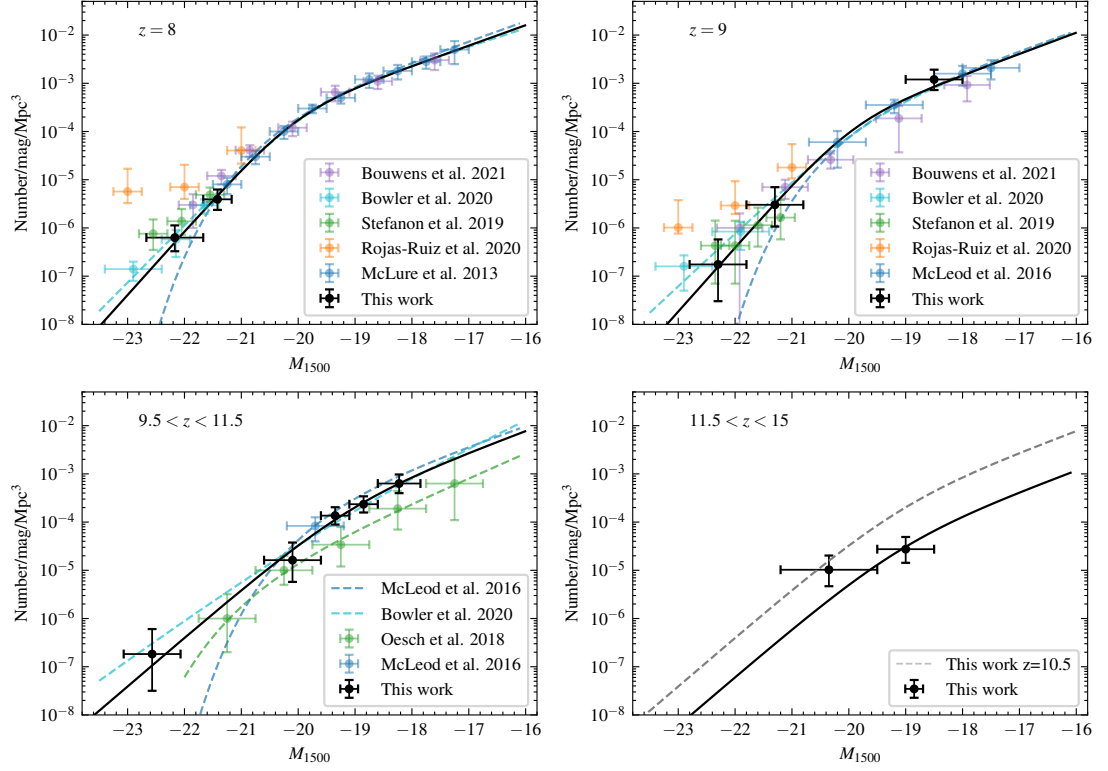


Figure 3.2 *The rest-frame UV LF at $z = 8, 9, 10.5$ and $z = 13.25$ shown as black points. I include data points from [McLure et al. \(2013\)](#); [McLeod et al. \(2016\)](#); [Bouwens et al. \(2021\)](#); [Oesch et al. \(2018\)](#). The best-fitting Schechter functions from [McLure et al. \(2013\)](#) and [McLeod et al. \(2016\)](#) are shown as the dashed blue lines at $z = 8, 9, 10.5$. The best-fitting Schechter function from [Oesch et al. \(2018\)](#) at $z = 10$ is shown as the dashed green line. My best-fitting double power laws are shown as solid black lines with the best-fitting double power laws from [Bowler et al. \(2020\)](#) at $z = 8, 9, 10.5$ shown as dashed cyan lines.*

Table 3.7 *The derived parameter values for the best-fitting double power-law (DPL) models fitted to my data over the redshift range $8 < z < 15$. The LF fits derived at $z = 8$ and $z = 9$ utilised the new data presented here along with the data-points presented by [McLure et al. \(2013\)](#) and [McLeod et al. \(2016\)](#). At higher redshifts the fits are based purely on the new analysis and galaxy samples presented in this work. The first column gives the central redshift of the binned LF. This is followed by the values of the best-fitting characteristic density ϕ^* , the best-fitting or fixed characteristic absolute magnitude M^* , the fitted or assumed faint-end slope α , and the fitted or adopted bright-end slope β (see text for details). In the case where a parameter was fixed, the value is denoted with an asterisk.*

z	ϕ^* [$10^{-4}/\text{mag}/\text{Mpc}^3$]	M^* [mag]	α	β
8	3.30 ± 3.41	-20.02 ± 0.55	-2.04 ± 0.29	-4.26 ± 0.50
9	2.10 ± 1.68	-19.93 ± 0.58	-2.10^*	-4.29 ± 0.69
10.5	3.32 ± 8.96	-19.12 ± 1.68	-2.10^*	-3.53 ± 1.06
13.25	0.51 ± 0.22	-19.12^*	-2.10^*	-3.53^*

function which uses a least-squares method to fit the data. At $z = 8$ and $z = 9$ I combine my data points with the data points from [McLure et al. \(2013\)](#) and [McLeod et al. \(2016\)](#), respectively. In these two redshift bins, my DPL fits are consistent with those previously derived by [Bowler et al. \(2020\)](#). At $z = 9$ and $z = 10.5$ I fix the faint-end slope to $\alpha = -2.10$ which is the value derived in [Bowler et al. \(2020\)](#). At $z > 11.5$ I lose dynamic range due to the lack of ground-based objects and limited sample size. Therefore, for my fit at $z = 13.25$ I also fix the bright-end slope to $\beta = -3.53$ and $M^* = -19.12$, the best-fitting values obtained at $z = 10.5$, and allow only ϕ^* to vary as a free parameter. With these constraints, the best-fitting DPL function for each redshift is shown as the solid black line in Fig. 3.2. The best fitting parameters for my DPL fits are listed in Table 3.7.

Comparison to the results of HST pure parallel imaging

There have been many recent attempts to use pure-parallel imaging with HST to try to determine the bright end of the galaxy UV luminosity function at high redshifts. To illustrate this I over-plot in Fig. 2 the LF points produced by [Rojas-Ruiz et al. \(2020\)](#), which are in close agreement with the results reported by [Leethochawalit et al. \(2023a\)](#) (see also [Bagley et al. 2024a](#)), derived from SuperBORG, the largest-area HST pure-parallel survey covering $\simeq 1000 \text{ arcmin}^2$.

However, it is well known that the limited wavelength coverage available in much/most of the HST pure-parallel imaging makes high-redshift galaxy samples derived from surveys such as SuperBORG extremely vulnerable to contamination. It is thus perhaps unsurprising that their derived number densities are completely inconsistent with my estimates of the bright end of the UV LF. For example, assuming the number density of the brightest bin from [Rojas-Ruiz et al. \(2020\)](#) at $z = 8$, I would have expected to find ~ 50 galaxies in my brightest luminosity bin, whereas in fact I only find 4 galaxies. At $z = 9$ the results from HST pure parallel studies are also inconsistent with my findings at the bright end of the LF. At $M_{UV} = -22.3$, assuming the number density from [Rojas-Ruiz et al. \(2020\)](#), I should have found ~ 21 galaxies and assuming the number densities from [Finkelstein et al. \(2022a\)](#) and [Bagley et al. \(2024a\)](#) I should have detected ~ 17 galaxies. In this study I only find 1 galaxy in this bin.

3.5.3 The cosmic SFRD at $z \geq 8$

The evolution of the UV luminosity density and cosmic star-formation rate density at $z > 8$ has been a point of contention in recent HST-based studies, with [Oesch et al. \(2018\)](#) concluding in favour of a rapid decline at $z > 8$, whereas [McLeod et al. \(2016\)](#) presented evidence for a much smoother, gradual decline extending out to higher redshifts. Using my new estimates of the evolving UV LF at $z = 8, 9, 10.5$ & 13.25 , I perform a luminosity-weighted integral of my best-fitting double-power law fits to determine the evolution of UV luminosity density, ρ_{UV} . I integrate down to $M_{UV} = -17$ and use the same limit to integrate the LFs from [Oesch et al. \(2014, 2018\)](#) and [McLeod et al. \(2016\)](#). The UV luminosity density is converted to the cosmic star-formation rate ρ_{SFR} using the conversion factor $\mathcal{K}_{UV} = 1.15 \times 10^{-28} \text{ M}_{\odot} \text{ yr}^{-1}/\text{erg s}^{-1} \text{ Hz}^{-1}$ ([Madau & Dickinson, 2014](#)). The results are shown in Fig. 3.3. I also perform a log-linear fit to my data points (motivated, in part, by the analytical work of [Hernquist & Springel \(2003\)](#)) and find that the evolution of ρ_{UV} with redshift is well described by:

$$\log_{10}(\rho_{UV}) = (-0.231 \pm 0.037)z + (27.5 \pm 0.3). \quad (3.4)$$

I also plot a rapidly descending halo evolution model from [Oesch et al. \(2018\)](#). This is shown as the shaded blue region. My results are inconsistent with this function.

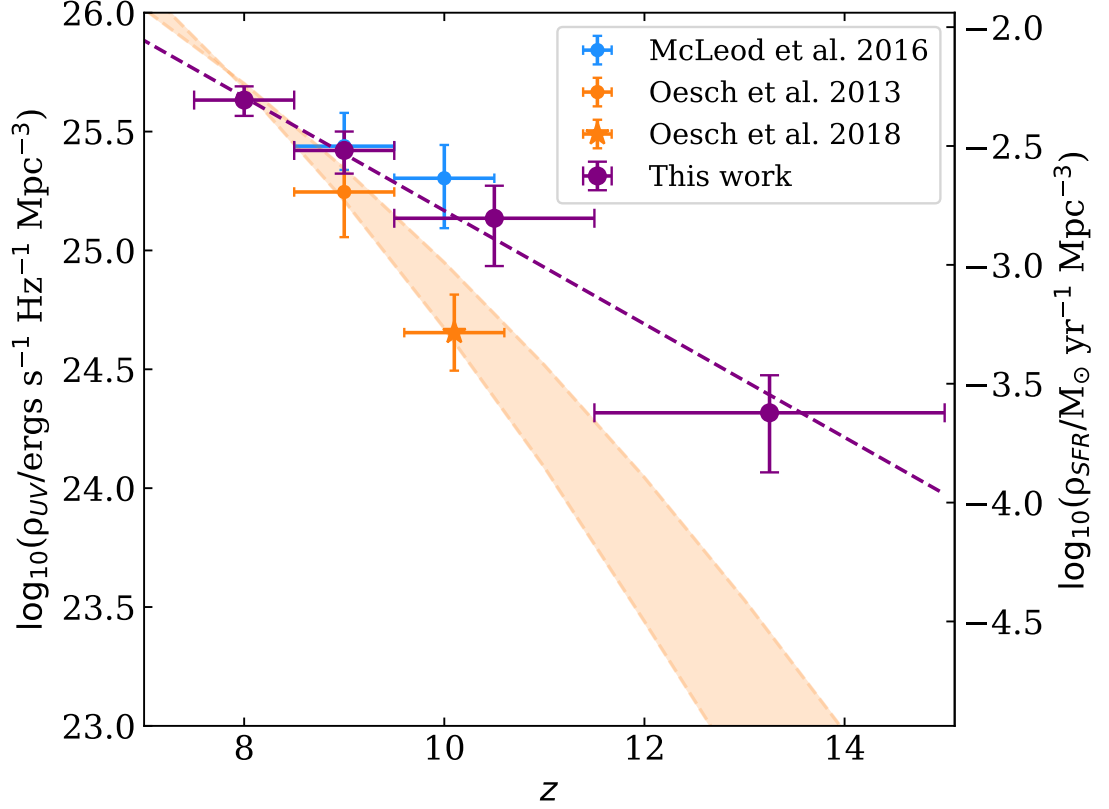


Figure 3.3 *The redshift evolution of the UV luminosity density ρ_{UV} and therefore the cosmic star-formation rate density ρ_{SFR} at $z > 7$ with my new measurements at $z = 8$, $z = 9$, $z = 10.5$, and $z = 13.25$ (purple circular data points). Estimates at $z \simeq 9 - 10$ from [Oesch et al. \(2013, 2018\)](#) and [McLeod et al. \(2016\)](#) are shown by the orange and blue data points respectively. All values were determined using a limit of $M_{UV} = -17$ in the luminosity-weighted integral. The dashed purple line shows a log-linear fit to my data points with the solution $\log_{10}(\rho_{UV}) = (-0.231 \pm 0.037)z + (27.5 \pm 0.3)$. The shaded orange region shows the halo evolution model from [Oesch et al. \(2018\)](#). In contrast to the [Oesch et al. \(2018\)](#) claim of a rapid fall-off in ρ_{UV} at $z > 8$, my data favour a steady, exponential decline in ρ_{UV} up to $z \simeq 15$ (consistent with the result of [McLeod et al., 2016](#)).*

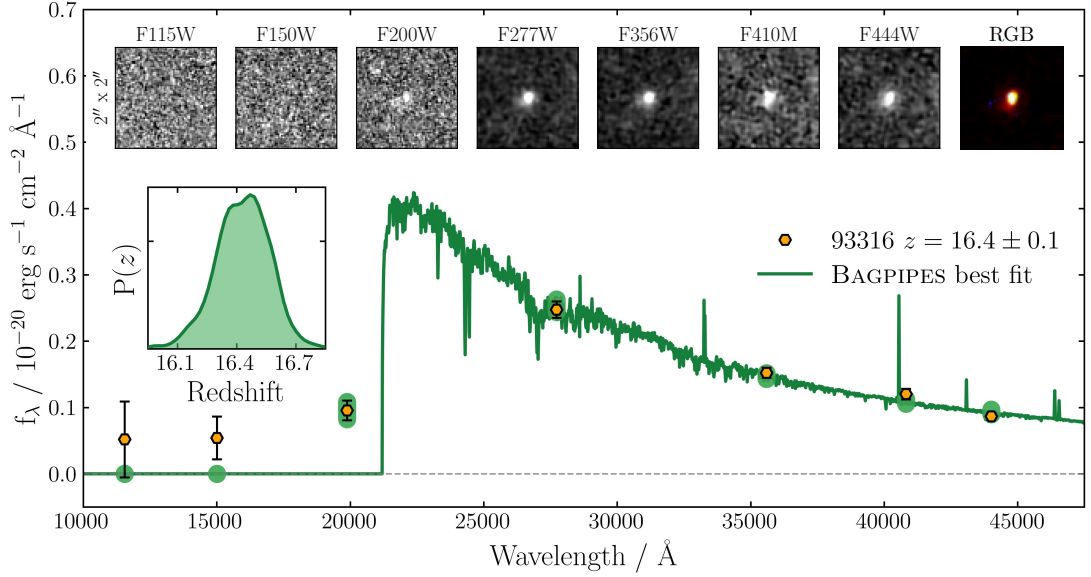


Figure 3.4 *The highest-redshift object in my sample, CEERS-93316. The NIRCam photometric measurements are plotted in the SED plot as golden hexagons, while $2'' \times 2''$ postage-stamp images in each band are shown above the SED. The **BAGPIPES** model I fit in Section 3.6.2 is shown in green. The posterior distribution for redshift is shown in the inset panel, which is centred on $z = 16.4$, and is fully consistent with the value of $z = 16.4$ quoted in Table 3.5 from EAZY. The fortuitous positioning of the F200W and F277W bands relative to the Lyman break allows such a precise redshift estimate. The rest-frame near-UV slope, $\beta = -2.06 \pm 0.25$ indicates no evidence for an unusual (i.e. Population III dominated) stellar population. The galaxy has a stellar mass of $\log_{10}(M_*/M_{\odot}) = 9.0^{+0.4}_{-0.5}$*

3.6 Discussion

3.6.1 The early growth of galaxies and cosmic star-formation

The results of this study provide dramatic, early confirmation of the long-anticipated power of JWST to chart the evolution of galaxies back to within < 300 Myr of the Big Bang. In addition to independently uncovering the 2 bright galaxies at redshifts $z \simeq 10.5$ and $z \simeq 12.5$ recently reported by [Naidu et al. \(2022b\)](#) and [Castellano et al. \(2022\)](#) from the GLASS NIRCам imaging, I here report the discovery of an additional 43 galaxies at $z > 8.5$ from the combined SMACS0723+GLASS+CEERS ERO/ERS JWST NIRCам imaging, covering a total effective area of $\simeq 44$ arcmin².

This analysis also reaffirms the importance of large dynamic range (in galaxy luminosity) for properly constraining the form of the evolving galaxy luminosity function (LF), here provided by the addition of the $\simeq 2$ deg² of deep near-infrared imaging now delivered by UltraVISTA DR5. Here I report the discovery of 16 bright galaxies in the redshift range $7.5 < z < 10.5$ from this relatively wide-area ground-based imaging: providing crucial information on the bright end of the galaxy LF, at least out to $z \simeq 10$. To fill in the luminosity/volume gap between UltraVISTA and the early small-area JWST surveys, to extend the study of brighter/rarer objects to $z \geq 10$, and to improve the statistical robustness of my results, forthcoming larger-area deep JWST imaging surveys, such as PRIMER (GO 1837)², will be key.

Encouragingly, even with the existing ground-based+JWST dataset I am able to draw a number of firm conclusions. First, I am able to settle the long-standing uncertainty/dispute over the evolution of UV luminosity density, ρ_{UV} (and hence star formation rate density, ρ_{SFR}) at redshifts beyond $z \simeq 8$. Contrary to the conclusion reached by [Oesch et al. \(2014, 2018\)](#) that ρ_{UV} falls off rapidly at $z > 8$, the results shown in Fig. 3.3 support the conclusion of [McLeod et al. \(2016\)](#) (in line with the long-standing analytical prediction of [Hernquist & Springel \(2003\)](#)), that ρ_{UV} continues to display a steady, exponential decline with increasing redshift out to at least $z \simeq 12$. Clearly, galaxy formation commenced at even higher redshifts ($z > 15$).

Second, armed with the UltraVISTA DR5 and JWST ERO/ERS imaging, I am

²<https://primer-jwst.github.io/>

able to reaffirm the findings of [Bowler et al. \(2020\)](#) that, at the highest redshifts ($z \geq 7$) the galaxy LF can no longer be adequately described by a Schechter function, but instead evolves into a more gently declining double power-law, a functional form that more closely mirrors the shape of the underlying dark-matter halo function. As described in [Bowler et al. \(2020\)](#), and then discussed further in [Adams et al. \(2023a\)](#), this is arguably as expected, as we look back into an era when neither mass-quenching, AGN feedback, nor significant dust-obscuration are able to curtail the luminosities of the brightest galaxies.

Third, while less surprising, and hence undoubtedly less important, it is worth noting that I can completely rule out the very high number densities of bright high-redshift galaxies reported from recent pure-parallel HST studies (e.g. [Rojas-Ruiz et al., 2020](#)). If the conclusions of such studies were valid, I would have detected an order-of-magnitude more bright galaxies at $z > 7$ in UltraVISTA than were actually revealed by the data. There are several obvious lessons here, including a timely reminder of the importance of insisting on a sufficient number of photometric bands to properly constrain galaxy photometric redshifts and basic physical properties.

3.6.2 A galaxy candidate at $z = 16.4$

Finally, in addition to the other sources discussed earlier in this work, I highlight the apparent discovery of an object with a well-constrained photometric redshift of $z = 16.4$, corresponding to a time just $\simeq 250$ Myr after the Big Bang. This object was selected as a F150W dropout in the CEERS imaging data. However, it is much brighter in F277W and the longer-wavelength filters than in F200W, indicating that the Lyman break lies towards the red end of the F200W filter. This fortuitous alignment of filters produces a particularly well-constrained photometric redshift, with all three of the photometric redshift codes discussed above returning consistent values at $z = 16.3 - 16.5$ and no plausible secondary low-redshift solutions.

Since my first-reported discovery of this extreme redshift source, some follow-up studies have discussed the plausibility of an alternative, lower-redshift solution. In particular, [Naidu et al. \(2022a\)](#) propose a extreme emission line solution from a passive or dusty star-forming galaxy. They argue this solution becomes plausible from SED fitting when arbitrarily boosting the uncertainties on the fluxes to 20% due to zero-point uncertainty. However, as discussed here, the robustness

of the high redshift solution is unchanged with updated zero-points. Secondly as described in [Naidu et al. \(2022a\)](#), the extreme, arguably unphysical nature of the $z \sim 5$ solution and very limited redshift range required to reproduce the photometry, imply that the $z \sim 5$ solution is still less plausible than the $z \sim 16$ solution. This is consistent with my secondary solution from **EAZY** which is at $z = 4.9$ but, even with the revised NIRCam photometric zeropoints, still has a much higher χ^2 than the best fitting $z = 16.4$ solution ($\Delta\chi^2 = 20.3$).

The object is also clearly resolved in the NIRCam imaging data, and so cannot be a low-mass star or unobscured active galactic nucleus. I have re-calculated the photometry for this object using a variety of aperture sizes, but this does not change my recovered redshift. Having searched extensively, I am currently unable to find any plausible explanation for this object, other than a galaxy at a new redshift record of $z = 16.4$.

In order to constrain the physical properties of this galaxy candidate, I fit my photometric data using the **Bagpipes** spectral fitting code ([Carnall et al., 2018](#)). I use the same configuration described in [Carnall et al. \(2020, 2023\)](#), including the 2016 updated version of the [Bruzual & Charlot \(2003\)](#) stellar population models with the MILES stellar spectral library, an emission line prescription calculated using the **Cloudy** photoionization code ([Ferland et al., 2017](#)), the [Salim et al. \(2018\)](#) dust attenuation model and a constant SFH model. The time before observation at which stars began forming is varied from 1 Myr to the age of the Universe with a logarithmic prior.

The results of my spectral fitting analysis are shown in [Fig. 3.4](#). I obtain a photometric redshift of $z = 16.4 \pm 0.1$, in good agreement with the other three codes discussed above. I also measure a stellar mass, $\log_{10}(M_*/M_\odot) = 9.0^{+0.4}_{-0.5}$ (assuming a [Kroupa \(2001\)](#) initial mass function), with the large uncertainty due to the lack of rest-frame optical data. I recover $\log_{10}(\text{SFR}/M_\odot\text{yr}^{-1}) = 1.0^{+0.3}_{-0.5}$ and a (mass-weighted) mean stellar age of 20^{+40}_{-10} Myr. Assuming my constant SFH model, I find that star formation first began in this object between 120 and 220 Myr after the Big Bang ($z = 18 - 26$).

By separate analysis, I recover a rest-frame UV spectral slope, $\beta = -2.06 \pm 0.25$. In combination with my **Bagpipes** fit finding dust attenuation, A_V , consistent with zero, this suggests no evidence for an unusual (i.e., Population III dominated) stellar population.

An important consideration is whether this new, relatively massive galaxy

candidate at such an extreme redshift is consistent with the Λ -CDM halo-mass function. I consider this object in the context of the analysis presented by Behroozi & Silk (2018), which provides cumulative number density thresholds for high-redshift galaxies in Λ CDM under the assumption that all gas available to halos is converted into stars. Across my survey volume of $\simeq 10^5 \text{ Mpc}^3$ from $15 < z < 17$ I find that my object falls close to, but does not significantly exceed the Λ CDM limit calculated by Behroozi & Silk (2018). Since initial publication of this work as a preprint, this finding has subsequently been validated by several other authors (Boylan-Kolchin, 2023; Lovell et al., 2023).

These comparisons with the halo-mass function are strongly dependent on my stellar-mass estimate of $\log_{10}(M_*/M_\odot) = 9.0^{+0.4}_{-0.5}$, which assumes a Kroupa (2001) IMF. At high redshift, some theoretical and observational evidence points towards a more top-heavy IMF (e.g. Sneppen et al. 2022), which would lead to a reduction in my implied stellar mass, moving the object further from the Λ CDM limit.

Another potential issue that could impact my stellar mass estimate is binary stellar evolution. This extends the lifetimes of very massive stars, increasing the luminosity of young stellar populations (e.g. Eldridge et al. 2017), potentially resulting in a reduction of my stellar mass estimate. As an additional test, I re-fit this galaxy with `bagpipes` using the Binary Population and Spectral Synthesis (BPASS) models (v2.2.1; Stanway & Eldridge 2018), including binary evolution, with an upper IMF mass limit of $300 M_\odot$. Under the assumption of these alternative stellar models, I recover a $\simeq 0.2$ dex lower stellar mass of $\log_{10}(M_*/M_\odot) = 8.8^{+0.4}_{-0.4}$.

Given the apparent robustness of the SED fitting and extreme redshift of this candidate, it is essential that spectroscopic verification was obtained. Since the publication of this work in 2023, I was involved in follow-up spectroscopy with *JWST*/NIRSpec to spectroscopically verify the redshift of this galaxy candidate. In Arrabal Haro et al. (2023b), we presented the $\simeq 5$ hour exposure to produce a NIRSpec PRISM spectrum of this galaxy refuting the proposed $z \simeq 16.4$ solution in favour of the secondary solution at $z_{\text{spec}} = 4.912 \pm 0.001$. This reveals that the true solution is a galaxy with moderate dust-attenuation ($A_v \simeq 2.3$) and strong rest-frame optical emission lines ($\text{H}\alpha$, and OIII) which imitate a Lyman-break and blue UV continuum at $z \simeq 16.4$. This is particularly driven by the strong $\text{H}\alpha$ emission line which sits in the small wavelength window where the F356W, F410M and F444W NIRCcam filters overlap and therefore contributing significantly to the observed flux in those filters. The *JWST*/NIRSpec spectrum and corresponding

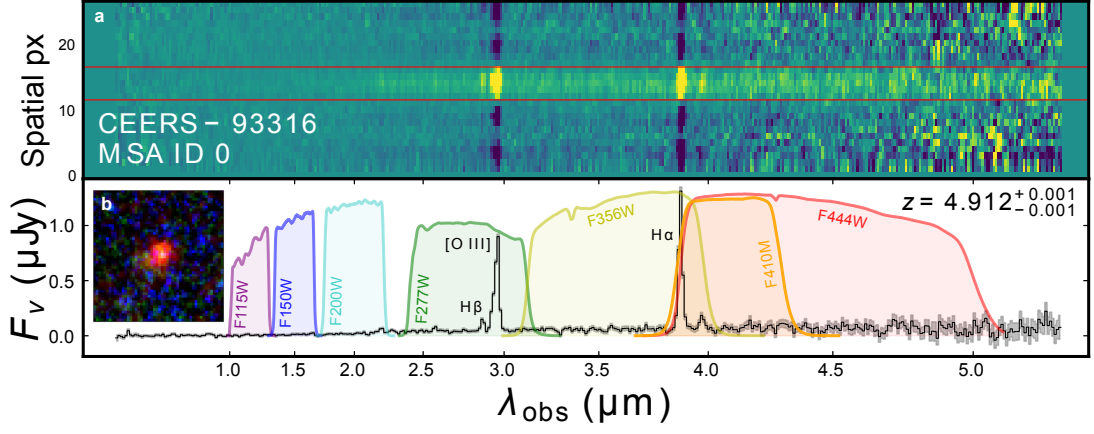


Figure 3.5 *The JWST/NIRSpec PRISM spectrum of CEERS-93316 showing definitive confirmation of the redshift as $z_{\text{spec}} = 4.912 \pm 0.001$ from Arrabal Haro et al. (2023b). Panel a shows the 2D PRISM spectrum with the red lines denoting the extraction region. Panel b shows a F150W+F200W+F277W cutout of the galaxy. Panel c shows the extracted 1D spectrum overlaid onto the JWST/NIRCam filters from the CEERS survey.*

JWST/NIRCam filters are shown in Fig. 3.5. This result demonstrates the importance of spectroscopic verification of extreme redshift sources, while also highlighting the need to account the true nature of CEERS-93316 in SED models to accurately select galaxies at $z \simeq 16$.

3.7 Conclusions

I have re-reduced and analysed the early public *James Webb Space Telescope* (JWST) ERO and ERS NIRCam imaging (SMACS0723, GLASS, CEERS) in combination with the latest deep ground-based near-infrared imaging in the COSMOS field provided by UltraVISTA DR5, with the aim of producing a new sample of galaxies at $z > 7.5$ to probe early galaxy evolution. Through careful galaxy candidate selection, and the use of a range of photometric redshift codes, I have assembled a combined sample of 61 high-redshift galaxies, 47 of which are reported here for the first time.

I have exploited this new sample, in tandem with pre-existing results from HST, to produce a new measurement of the evolving galaxy UV luminosity function (LF) over the redshift range $z = 8 - 15$. The luminosity-weighted integral of the evolving LF then yields a new estimate of the evolution of UV luminosity density

(ρ_{UV}), which I then convert into an estimate of declining cosmic star-formation rate density (ρ_{SFR}) out to within < 300 Myr of the Big Bang.

Our results confirm that the high-redshift LF evolves into a form that is best described by a double power-law (rather than a Schechter) function (at least up to $z \sim 10$ as shown by the COSMOS analysis), and that the LF and the resulting derived ρ_{UV} (and thus ρ_{SFR}), continues to decline gradually and steadily over this redshift range (as anticipated from previous studies which analysed the pre-existing data in a consistent manner).

I provide details of the 61 high-redshift galaxy candidates, with full photometry, SED fits, and multi-band postage-stamp images presented in Appendices A and B. my sample contains 6 galaxies at $z \geq 12$, one of which is the galaxy at $z = 12.4$ independently reported by [Naidu et al. \(2022b\)](#) and [Castellano et al. \(2022\)](#). However, the most distant object is one which appears to set a new redshift record as an apparently robust galaxy candidate at $z \simeq 16.4$. Given the apparently extreme nature of this source, I consider its physical properties and plausibility in detail as well as subsequent spectroscopy showing it is in fact a $z = 4.9$ galaxy where strong optical emission lines imitate a blue UV continuum at $z \simeq 16.4$.

The advances presented here emphasize the importance of achieving high dynamic range in studies of early galaxy evolution, and re-affirm the enormous potential of forthcoming larger JWST programmes to transform our understanding of the young Universe.

Chapter 4

The abundance of $z \gtrsim 10$ galaxy candidates in the HUDF using deep JWST NIRCам medium-band imaging

4.1 Introduction

The study of galaxies at the highest redshifts is crucial to unveiling the earliest stages of galaxy formation and evolution. Observations of high-redshift galaxies are vital for improving our understanding of the formation of the first stars and black holes and quantifying the role of galaxies in cosmic reionization (see [Dunlop 2013](#) and [Stark 2016](#) for reviews).

Until recently, the observational frontier was defined by galaxies that could be selected and studied using a combination of deep near-infrared imaging with *HST* and shallower mid-infrared imaging with *Spitzer*. This combination of facilities led to significant improvements in our understanding of galaxy evolution out to $z \simeq 9$ (e.g. [Ellis et al., 2013](#); [McLure et al., 2013](#); [Oesch et al., 2014, 2018](#); [Finkelstein et al., 2015](#); [McLeod et al., 2016](#); [Bouwens et al., 2021, 2023b](#)). Due to its long-wavelength limit of $1.7\,\mu\text{m}$, *HST* imaging can only identify galaxies out to $z \simeq 12$, and even then only with single-band detections in the F160W filter. Prior to the launch of the *James Webb Space Telescope* (*JWST*), the most distant

spectroscopically-confirmed galaxy had a redshift of $z = 10.957 \pm 0.001$: GN-z11 (Oesch et al., 2016; Jiang et al., 2021), a source that was originally selected using *HST* F160W imaging combined with non-detections at shorter wavelengths.

The landscape of high-redshift galaxy studies has now been dramatically changed with the advent of *JWST*, which has enabled a new era of extragalactic astronomy. The extended wavelength coverage of NIRCam imaging to $\lambda \simeq 5 \mu\text{m}$ has facilitated the robust detection of galaxies at $z \geq 10$ for the first time (e.g. Finkelstein et al., 2022b, 2023; Adams et al., 2023b; Castellano et al., 2022; Naidu et al., 2022b) including galaxy candidates at $z \simeq 16$ (Donnan et al., 2023a; Harikane et al., 2023a). Early *JWST*-based studies of the evolving galaxy UV luminosity function imply a smooth and steady decline in the cosmic star-formation rate density (ρ_{SFRD}) out to $z \simeq 15$ (Donnan et al., 2023a; Harikane et al., 2023a), as anticipated from some previous *HST*-based studies (e.g. McLeod et al., 2016).

Although GN-z11 was the highest redshift, spectroscopically-confirmed galaxy prior to *JWST*, another even higher-redshift galaxy candidate was identified in the *HST* UDF12 imaging of the HUDF (Ellis et al., 2013; McLure et al., 2013) with a best-fitting redshift of $z_{\text{phot}} = 11.9^{+0.3}_{-0.5}$. This galaxy (UDF12-3954-6284) is the highest-redshift candidate ever identified from *HST* imaging. In fact it was originally noted as a potential $z \simeq 10$ galaxy (UDFj-39546284) from the UDF09 imaging of the HUDF (Bouwens et al., 2011a), based on a F160W detection and non-detections in F125W, F105W and the HUDF ACS optical imaging. However, following the UDF12 *HST* imaging campaign, the galaxy was also found to be undetected in the F140W filter which, given the substantial overlap between the F140W and F160W filters, favoured a significantly higher redshift of $z \simeq 11.9$ (Ellis et al., 2013).

Robertson et al. (2023) and Curtis-Lake et al. (2023) have recently reported *JWST* NIRCam and NIRSpec observations of 4 galaxies within the GOODS-S field from the JADES survey, including spectroscopic confirmation of UDFj-39546284 at $z_{\text{spec}} = 11.58 \pm 0.05$. They also report a galaxy at $z_{\text{spec}} = 13.20^{+0.04}_{-0.07}$ which now overtakes Gn-z11 as the highest redshift spectroscopically-confirmed galaxy. In addition, they derive stellar masses, star-formation rates and mean stellar ages for these 4 objects, finding results consistent with expectations at these redshifts.

Bouwens et al. (2023b) used *JWST* NIRCam medium band imaging to measure

the evolution of the UV luminosity function in the redshift range $z = 8\text{--}15$ using high-redshift galaxy candidates selected from within the HUDF area alone. Consistent with other studies (e.g. [Donnan et al., 2023a](#); [Harikane et al., 2023a](#)) their results do not support the previously suggested rapid decline in the cosmic star-formation rate density (ρ_{SFR}) beyond $z \sim 8$ ([Oesch et al., 2018](#)). However, their measurements of ρ_{SFR} at $z \gtrsim 11$ are in fact significantly higher than what was derived in Chapter 3. They also measure an absolute UV magnitude, M_{UV} , that is $\simeq 1$ magnitude brighter than reported by [Robertson et al. \(2023\)](#) for the spectroscopically confirmed $z_{\text{spec}} = 11.58 \pm 0.05$ source.

Motivated by the continued uncertainty over the nature of the UV luminosity function and cosmic star-formation rate density at $z \gtrsim 10$, I analyse a combination of the ultra-deep *HST* ACS+WFC3/IR data available in GOODS-S/UDF with the full area available from *JWST* NIRCam medium-band imaging at $\lambda \simeq 2\,\mu\text{m}$ and $\lambda \simeq 4.5\,\mu\text{m}$ to search for galaxy candidates at $z \geq 9.5$. Crucially, the new NIRCam imaging (ID 1963; PI Williams) is the first publicly available data in the HUDF red-ward of $\lambda \simeq 1.6\,\mu\text{m}$ with sufficient sensitivity to robustly detect candidates at $z \geq 9.5$. The aim of this study is to exploit the new *JWST* imaging data to derive secure photometric redshifts for $z \geq 9.5$ galaxy candidates and provide further constraints on the galaxy UV luminosity function and hence luminosity density at $z \geq 9.5$. I also employ Spectral Energy Distribution (SED) fitting to derive the basic properties of the stellar populations in these early galaxies.

The chapter is structured as follows. In Section 4.2 I describe the imaging data and source catalogue creation. In Section 4.3 I explain the sample selection and the measurement of the physical properties of the galaxies. In Section 4.4 I present my derived luminosity function and the resulting inferred high-redshift dependence of the cosmic star-formation rate density. In Section 4.5 I discuss my results in the context of other recent observational studies and the predictions of various theoretical/numerical models of galaxy formation. Finally, in Section 4.6 I summarise my conclusions. Throughout I use magnitudes in the AB system ([Oke, 1974](#); [Oke & Gunn, 1983](#)), and assume a standard cosmological model with $H_0 = 70\text{ km s}^{-1}\text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

4.2 Data

4.2.1 Imaging

I utilise deep imaging from *HST* and *JWST* in the HUDF. From *HST* I use data covering the wavelength range $\lambda \simeq 0.4 - 1.6 \mu m$ from ACS F435W, F606W, F775W, F814W, F850LP and WFC3 F105W, F125W, F140W and F160W imaging. I utilise new *JWST* imaging from the HUDF medium-band survey (ID 1963; PI Williams) which contains deep NIRCcam imaging through the F182M, F210M, F430M, F460M and F480M filters (Williams et al., 2023). The 5σ global depths for F182M and F210M are $m_{AB} \simeq 29$ and for F430M, F460M and F480M they are $m_{AB} \simeq 28.5$. The data were reduced using the Primer Enhanced NIRCcam Image Processing Library (PENCIL; Magee et al., in prep) software, a customised version of the *JWST* pipeline v1.8.0. The CRDS context used was “jwst_1011.pmap”, which includes the most recent NIRCcam zero-point corrections and in-flight calibrations. An extended description is available in Chapters 2-3.

4.2.2 Catalogue creation and photometry

I perform a search for galaxies using SExtractor (Bertin & Arnouts, 1996) in dual-image mode. I use the F182M band image as the detection image as it is the deepest imaging sampling flux long-ward of the Lyman break. For the photometry in the *JWST* NIRCcam imaging, I use a similar technique to Chapter 3, with 0.24 arcsec-diameter apertures in the SW filters (F182M, F210M) and 0.3 arcsec-diameter apertures in the LW filters (F430M, F460M, F480M). I also use 0.3 arcsec-diameter apertures in the HST ACS and WFC3 filters. All of the photometry was then corrected to 76% of total (as this is approximately the flux enclosed by the apertures utilised for F182M) using a point-source correction based on the curve-of-growth of each filter’s PSF. I adopt the 1σ local depth as the error on the fluxes measured through each filter. This was determined by $1.483 \times \text{MAD}$ where MAD is the median absolute deviation of the flux in the closest 200 empty apertures to the source.

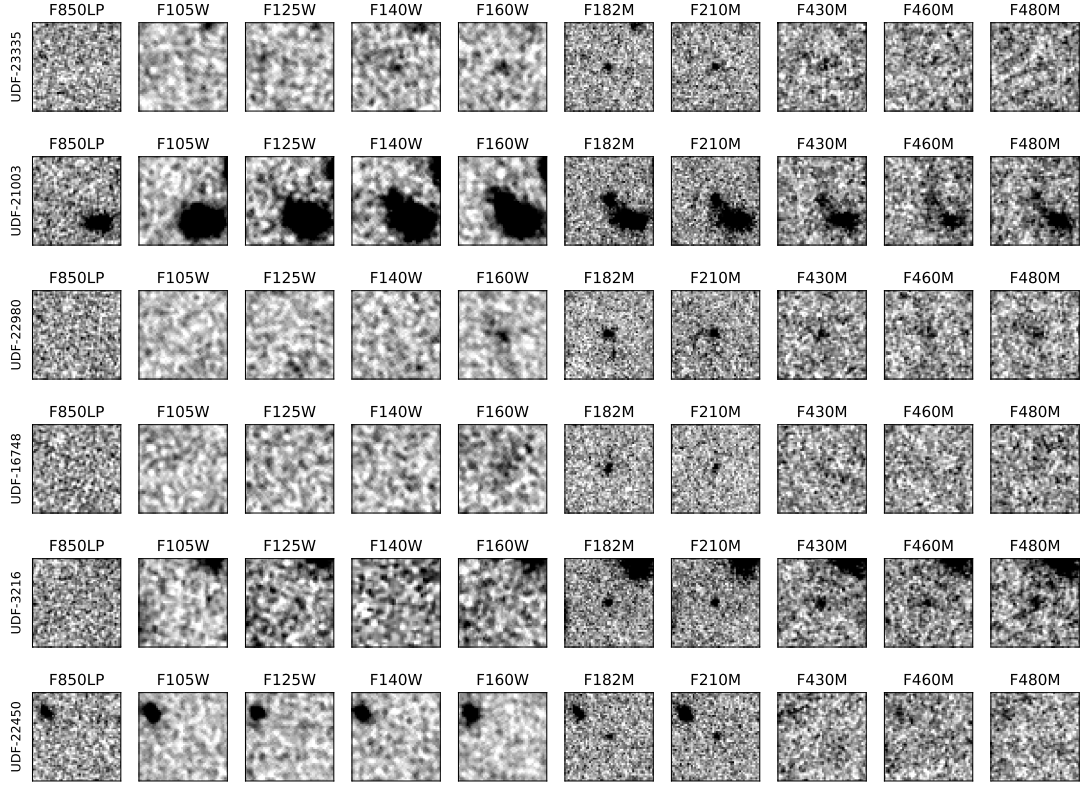


Figure 4.1 *Postage-stamp greyscale images of the six $z \geq 9.5$ galaxy candidates from my sample in the HST and JWST imaging. The imaging is ordered by increasing wavelength from left to right. Each postage-stamp image is 1.5×1.5 arcsec in size, with North to the top and East to the left.*

4.3 Galaxy sample

4.3.1 Sample selection

I use the photometric redshift (photo-z) code EAZY (Brammer et al., 2008) for my primary redshift determination, fitting with the PEGASE (Fioc & Rocca-Volmerange, 1999) set of templates which include nebular emission lines. I determine the primary solution by allowing templates to vary over the redshift range $0 < z < 25$ and a secondary low-redshift solution by restricting the redshift range to $0 < z < 6$. I select my sample by requiring a best-fitting photometric redshift at $z \geq 9.5$ with a threshold value of $\Delta\chi^2 \geq 4$ between the primary and secondary solution. Due to the position of the Lyman break, I require the flux to be $< 2\sigma$ in all the ACS filters. I also require the flux to be $> 5\sigma$ in either F160W or F182M with the next reddest filter at 3σ to ensure a robust detection long-ward of the Lyman break. I visually inspect the final sample to remove artefacts and diffraction spikes. To verify the robustness of the photometric redshifts, I also fitted the photometry using two further SED fitting codes: LePhare (Arnouts et al., 1999; Ilbert et al., 2006) with templates from Bruzual & Charlot (2003) and with dust attenuation spanning the range $A_V = 0.0 - 6.0$, and also the code described in McLure et al. (2011). I require all candidates in the final sample to have significantly preferred high-redshift solutions from all three codes.

4.3.2 Final sample

The final sample contains 6 galaxies at $z \geq 9.5$. The measured photometry, corrected to total, is listed in Table 4.1 and the photometric redshifts of the galaxy candidates are listed in Table 4.2. Out of these 6 sources, one is UDFj-39546284 (UDF-22980 in this study) which is the previously-detected source at $z \simeq 12$ (e.g. Bouwens et al., 2011a; Ellis et al., 2013) with recent spectroscopic confirmation at $z_{\text{spec}} = 11.58$ (Curtis-Lake et al., 2023). My best-fitting photo-z for this galaxy from EAZY is in excellent agreement with this, yielding $z = 11.65^{+0.17}_{-0.21}$, with a $\Delta\chi^2 = 40$ between the primary solution and the low-redshift secondary solution ($z = 2.9^{+0.1}_{-0.1}$), indicating a clear preference for the primary (higher) redshift. This is consistent with the photo-z from (Ellis et al., 2013; McLure et al., 2013) which at the time was based on only a F160W detection (combined with non-detections through other *HST* and *Spitzer* filters).

Table 4.1 *The observed photometry for the galaxies in the JWST-selected sample in AB magnitudes. The first column lists the ID of the object. The following columns show the photometry in each of the relevant ACS, WFC3 and NIRC2 filters. In the case of a non-detection at the 2σ level the photometry is shown as an upper limit.*

ID	F850LP	F105W	F125W	F140W	F160W	F182M	F210M	F430M	F460M	F480M
23335	>30.40	>31.20	$30.49^{+0.45}_{-0.32}$	$29.71^{+0.18}_{-0.15}$	$29.41^{+0.14}_{-0.12}$	$28.94^{+0.14}_{-0.13}$	$29.10^{+0.21}_{-0.18}$	$28.85^{+0.41}_{-0.3}$	>28.95	>29.25
21003	>30.41	$30.68^{+0.36}_{-0.27}$	$29.27^{+0.12}_{-0.1}$	$28.09^{+0.06}_{-0.05}$	$27.77^{+0.06}_{-0.05}$	$27.84^{+0.06}_{-0.05}$	$27.94^{+0.06}_{-0.05}$	$28.00^{+0.2}_{-0.17}$	$27.89^{+0.21}_{-0.17}$	$28.26^{+0.22}_{-0.18}$
22980	>30.48	>31.37	>31.00	>30.93	$29.04^{+0.1}_{-0.09}$	$28.33^{+0.09}_{-0.08}$	$28.32^{+0.08}_{-0.08}$	$28.37^{+0.2}_{-0.17}$	$28.02^{+0.19}_{-0.17}$	$28.21^{+0.23}_{-0.19}$
16748	>30.16	>30.93	>30.50	>30.54	$29.68^{+0.29}_{-0.23}$	$28.93^{+0.18}_{-0.15}$	$29.10^{+0.4}_{-0.29}$	$29.15^{+0.62}_{-0.39}$	29.24	$29.24^{+0.67}_{-0.41}$
3216	>28.87	>29.69	>29.49	>28.03	>29.22	$28.69^{+0.1}_{-0.09}$	$28.75^{+0.13}_{-0.11}$	$28.33^{+0.23}_{-0.19}$	$28.30^{+0.25}_{-0.21}$	$28.39^{+0.15}_{-0.13}$
22450	>30.28	>31.39	>30.69	>30.99	>31.01	$29.29^{+0.19}_{-0.16}$	$28.99^{+0.22}_{-0.18}$	>29.16	>29.20	>29.26

UDF-21003, with a photo- z of $z = 9.8_{-0.1}^{+0.2}$, is a newly-detected source which is in fact the most robustly detected candidate in the sample. It was previously undetected likely due to the close positioning of a low-redshift nearby source. UDF-3216 is newly-detected candidate at $z = 12.6 \pm 0.7$ which is located in the second/parallel NIRCcam module. Multi-waveband postage-stamp images of the 6 galaxies in the sample are shown in Fig. 1, while the photometric data for the sample along with the two alternative (high-redshift and low-redshift) SED fits for each galaxy are shown in Fig. 4.2.

Robertson et al. (2023) reported photometric properties of 4 galaxies with spectroscopic confirmation in a companion paper (Curtis-Lake et al., 2023) using data from the JADES survey. I recover 3 of the 4 galaxies in their sample (the fourth source is positioned outside the medium band imaging) with my photometric redshifts broadly consistent with their spectroscopic redshifts. These are noted in the final column in Table 4.2.

Bouwens et al. (2023b) also recently searched for galaxies using the JWST UDF medium band survey and found 4 galaxies at $z \geq 9.5$. I recover 3 of these candidates in my sample as indicated in Table 4.2. The 4th source, XDFH-2334046578 in Bouwens et al. (2023b), is not included in this sample as it failed the visual inspection stage due to an unusual positional offset of the source in F160W. Therefore I was not confident in the strength of the break between the F160W and F182M filters. For the 3 I recover, I find good agreement overall in the photometric redshifts. However, for UDF-22980 I measure a moderately lower redshift. I also find a significantly fainter absolute UV magnitude for this source of $M_{UV} = -19.4$ compared to the value of $M_{UV} = -20.2$ reported by Bouwens et al. (2023b). It is unclear what the cause of this discrepancy is. My value of M_{UV} is in close agreement to that given by Robertson et al. (2023) which exploits the additional constraints provided by the broadband NIRCcam imaging in the JADES survey.

Our sample contains 2 galaxy candidates at $z > 12.5$, UDF-3216 and UDF-22450 which have best fitting redshifts of $z = 12.6_{-0.7}^{+0.6}$ and $z = 13.5_{-0.8}^{+0.3}$ respectively. Despite the photometric redshift relying on detections in only 2 filters, my photometric redshift measurement of UDF-22450 is in close agreement with the spectroscopic redshift of $z_{\text{spec}} = 13.20$ recently reported by Robertson et al. (2023).

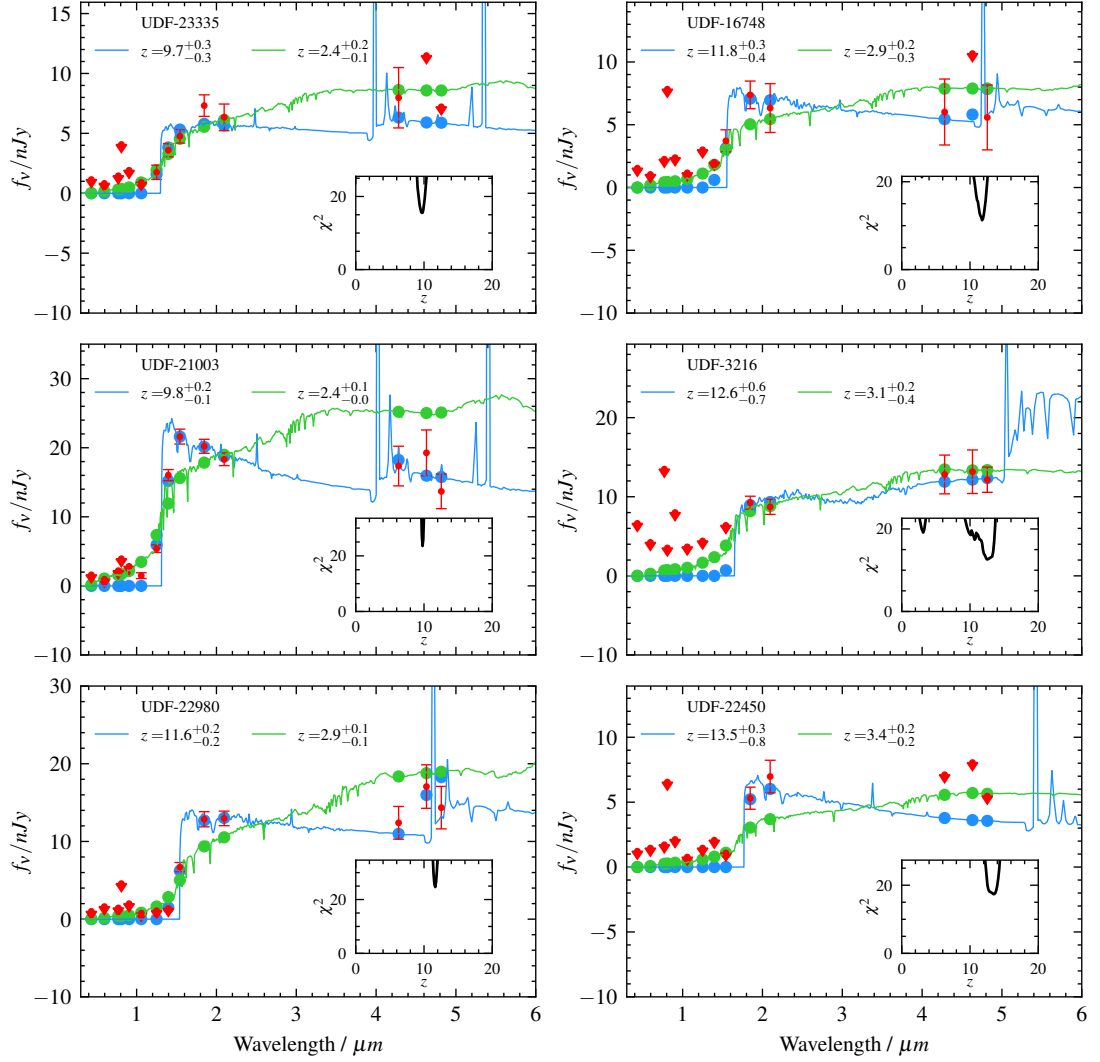


Figure 4.2 *Alternative Spectral Energy Distribution (SED) fits for the six $z \geq 9.5$ galaxies in the sample. The blue line shows the best-fitting (preferred) high-redshift solution, the green line shows the best-fitting (alternative) low-redshift solution, and the red points show the measured photometry (at 76% of total flux). The red arrows show upper limits in the case of a non-detection at the 2σ level. The solid blue and green circles represent the model photometry of the best-fitting high and low-redshift templates respectively. The value of χ^2 as a function of redshift is shown for each source in the inset panel.*

Table 4.2 *The best-fitting photometric redshifts and derived physical properties of the six $z \geq 9.5$ galaxy candidates. The first column shows the ID of the object followed by the best-fitting photometric redshift from EAZY. The following columns show the UV slope (β), stellar mass, star-formation rate and mean stellar age from BAGPIPES, the absolute UV magnitude and the coordinates of each object. The penultimate column notes if the source was also reported by Bouwens et al. (2023b) and the final column shows, where available, the spectroscopic redshift from Curtis-Lake et al. (2023).*

ID	z_{phot}	β	$\log(M_{\star}/M_{\odot})$	$\log(\text{SFR}/M_{\odot}/\text{yr})$	$t_{\star}/\text{Myr}$	M_{UV}	RA	Dec	B22	z_{spec}
23335	$9.68^{+0.28}_{-0.28}$	-0.8 ± 0.6	$7.5^{+0.4}_{-0.2}$	$0.3^{+0.5}_{-0.1}$	7^{+38}_{-5}	-18.13	03:32:38.12	-27:46:24.56	Yes	10.38
21003	$9.79^{+0.15}_{-0.13}$	-2.5 ± 0.2	$8.1^{+0.2}_{-0.3}$	$1.3^{+1.0}_{-0.7}$	34^{+48}_{-25}	-19.63	03:32:42.13	-27:46:50.28	-	-
22980	$11.65^{+0.17}_{-0.21}$	-2.3 ± 0.5	$8.3^{+0.4}_{-0.6}$	$2.4^{+2.5}_{-1.9}$	44^{+104}_{-36}	-19.36	03:32:39.55	-27:46:28.62	Yes	11.58
16748	$11.77^{+0.29}_{-0.44}$	-3.3 ± 1.6	$7.9^{+0.4}_{-0.5}$	$0.8^{+0.9}_{-0.6}$	41^{+115}_{-33}	-18.71	03:32:40.47	-27:47:33.93	Yes	-
3216	$12.56^{+0.64}_{-0.66}$	-2.4 ± 1.1	$8.7^{+0.4}_{-0.7}$	$5.0^{+7.8}_{-3.9}$	40^{+107}_{-31}	-19.13	03:32:29.20	-27:49:48.46	-	-
22450	$13.54^{+0.28}_{-0.76}$	-1.6 ± 2.1	$7.8^{+0.4}_{-0.5}$	$0.7^{+0.6}_{-0.5}$	52^{+87}_{-39}	-18.73	03:32:35.97	-27:46:35.39	-	13.20

4.3.3 Physical properties

All the fluxes were corrected to total assuming a point source correction based on the curve-of-growth. I then use the BAGPIPES spectral fitting code (Carnall et al., 2018) to further constrain the physical properties of the galaxies in my sample. I run BAGPIPES using the configuration described in Carnall et al. (2020, 2023), which includes the 2016 updated version of the Bruzual & Charlot (2003) stellar population models with the MILES stellar spectral library, an emission line prescription calculated using the Cloudy photoionization code (Ferland et al., 2017), the Salim et al. (2018) dust attenuation model and a constant SFH model. The recovered stellar masses and mass-weighted mean stellar ages for all 6 galaxies are noted in Table 4.2. I find that these galaxies have relatively low stellar masses ($\log(M_*/M_\odot) \simeq 7.5 - 8.7$) and star-formation rates in the range $\log(\text{SFR}/M_\odot\text{yr}^{-1}) \simeq 0.3 - 5.0$. The limited detections longward of the Balmer break prevent any conclusive constraints on the stellar ages of these galaxies. Nevertheless, the mean stellar ages derived from BAGPIPES are moderate (~ 40 Myr), and for those with spectroscopic confirmation, are consistent with ages derived using the more extensive filter coverage in the JADES survey (Robertson et al., 2023).

Using the filters long-ward of the Lyman break I determine the rest-frame UV continuum slope, β (where flux $f_\lambda \propto \lambda^\beta$) with the technique described in Cullen et al. (2023) which involves fitting a power-law to the photometry. Due to the limited number of filters beyond the Lyman break, the UV slope remains relatively unconstrained for most of these objects. However, I measure a robust UV slope for UDF-21003, finding $\beta = -2.5 \pm 0.2$. This represents a very blue UV continuum indicating the presence of a young, low-metallicity stellar population. However, I note that Cullen et al. (2023) found a median UV slope of $\beta = -2.29 \pm 0.09$ at $8 < z < 16$, indicating that UDF-21003 is fully consistent with the average UV slope found at these redshifts.

4.4 Luminosity function

I compute the UV luminosity function at $z \simeq 11.2$ using objects detected at 8σ in F182M in a redshift bin spanning $9.5 \leq z \leq 13.5$ (with the upper redshift limit set by the fact the Lyman break cuts into the F182M filter at $z \simeq 13.5$).

Four galaxies are selected using this condition which are contained within a bin centred at $M_{\text{UV}} = -19.2$ with a width of 1 magnitude. The use of a redshift bin spanning $\Delta z = 4$ reduces the impact of photo-z uncertainties on my derivation of the LF.

The binned co-moving number density of sources per absolute magnitude, $\Phi(M_{\text{UV}})$, is determined using the $1/V_{\text{max}}$ method (Schmidt, 1968). The volume, V_{max} , is defined as the difference in co-moving volume between the volume at $z = 9.5$ and the maximum redshift that the galaxy could be detected at 8σ in F182M with a limit at $z = 13.5$ for this selection. I find that 2 of the sources are detectable to $z = 13.5$ whereas the 2 fainter sources are only detectable to $z \simeq 11.8$ and $z \simeq 12.6$. Therefore the average redshift of the limited volumes is $z \simeq 11.2$. In order to account for incompleteness in the galaxy sample, I perform completeness simulations using the same method as described in Chapter 3, with point sources injected into the F182M imaging in 3 regions across the 2 modules. From $m_{\text{AB}} = 24\text{--}31$ in steps of 0.1, 800 sources are injected into each region and the rate of recovery measured. This process is repeated 10 times for each region which therefore results in a total of 1,680,000 sources injected into the imaging. This generates the completeness as a function of apparent magnitude in the detection image, F182M.

As the UV LF is derived here using a relatively small cosmological volume (in Chapter 3 I use a $\sim 5\times$ larger volume), my results are more vulnerable to cosmic variance. To account for this I use the cosmic variance calculator from Trenti & Stiavelli (2008). I measure an uncertainty of 27% due to cosmic variance which is smaller than the uncertainties arising from the small sample size. The cosmic variance uncertainty was factored into the final uncertainty on the number density. The resultant galaxy number density in this bin is shown in Fig. 4.3 where $\Phi(M_{\text{UV}} = -19.2) = (1.03^{+0.86}_{-0.57}) \times 10^{-4} \text{ mag}^{-1} \text{ Mpc}^{-3}$.

This new estimate at $z \simeq 11.2$ is fully consistent with the evolution of the UV LF from $z \sim 10.5$ to $z \sim 13.25$ in Chapter 3. I fit a double-power law (DPL) using the same technique described in Chapter 3 where I fix α , β and M_* to -2.10 , -3.53 , -19.12 respectively. These are the best fitting values at $z \sim 10.5$ (Donnan et al., 2023a) and therefore I allow only ϕ_* as a free parameter. This results in a best-fitting DPL model with $\phi_* = (2.36 \pm 1.60) \times 10^{-4} / \text{mag} / \text{Mpc}^3$. I then perform a luminosity-weighted integral of the best-fitting DPL model to derive the comoving UV luminosity density (ρ_{UV}) and therefore cosmic star-formation rate density (ρ_{SFR}). This is shown as the red point in Fig. 4.4 which is in good

agreement with the log-linear relation from [Donnan et al. \(2023a\)](#), solid black line) and is therefore consistent with a steady, exponential decline in ρ_{UV} to $z \sim 15$. My results are inconsistent with the result at $z \sim 12.6$ from [Bouwens et al. \(2023b\)](#) as they predict a significantly higher ρ_{UV} as shown by the green point at $z \sim 12.6$ in Fig. 4.4. This is possibly impacted by their estimate of M_{UV} for UDF-22980 which is ~ 0.8 mag brighter than derived here (see Section 4.3.2). They also restrict their search to the HUDF area alone and therefore probe a smaller cosmological volume than utilised in this search, which, as they mention, also makes their measurement of the UV LF somewhat more sensitive to cosmic variance. They report a cosmic variance uncertainty of $\sim 52\%$ using the [Trenti & Stiavelli \(2008\)](#) calculator which is notably larger than I calculate for my LF ($\sim 27\%$). [Bouwens et al. \(2023b\)](#) also use a significantly steeper value of the faint end slope of $\alpha = -2.71$. As ρ_{UV} is particularly sensitive to α , their steeper faint-end slope also contributes to this increased value of ρ_{UV} .

4.5 Discussion

4.5.1 The growth of early galaxies

The early-release NIRCam data demonstrated the ability of *JWST* to detect numerous galaxies at $z > 9$ (e.g. [Adams et al., 2023b](#); [Castellano et al., 2022](#); [Naidu et al., 2022b](#); [Finkelstein et al., 2022b](#)) including a detection of a galaxy candidate at $z \simeq 16$ (see Chapter 3) which has since been verified by multiple studies (e.g. [Harikane et al., 2023a](#); [Finkelstein et al., 2023](#)). This indicates that galaxy formation commenced at $z > 16$ and therefore within < 250 Myr of the big bang. The results from this new study give further support to this conclusion with the detection of 6 galaxies at $9.5 < z \lesssim 13.5$ from within a relatively small cosmological volume. As demonstrated in this analysis, this corresponds to a number density consistent with the evolution of the UV LF derived in Chapter 3. This leads to a value of the UV luminosity density (and cosmic star-formation rate density) at $z \simeq 11.5$ which is fully consistent with the log-linear relation derived in Chapter 3 of:

$$\log_{10}(\rho_{\text{UV}}) = (-0.231 \pm 0.037)z + (27.5 \pm 0.3). \quad (4.1)$$

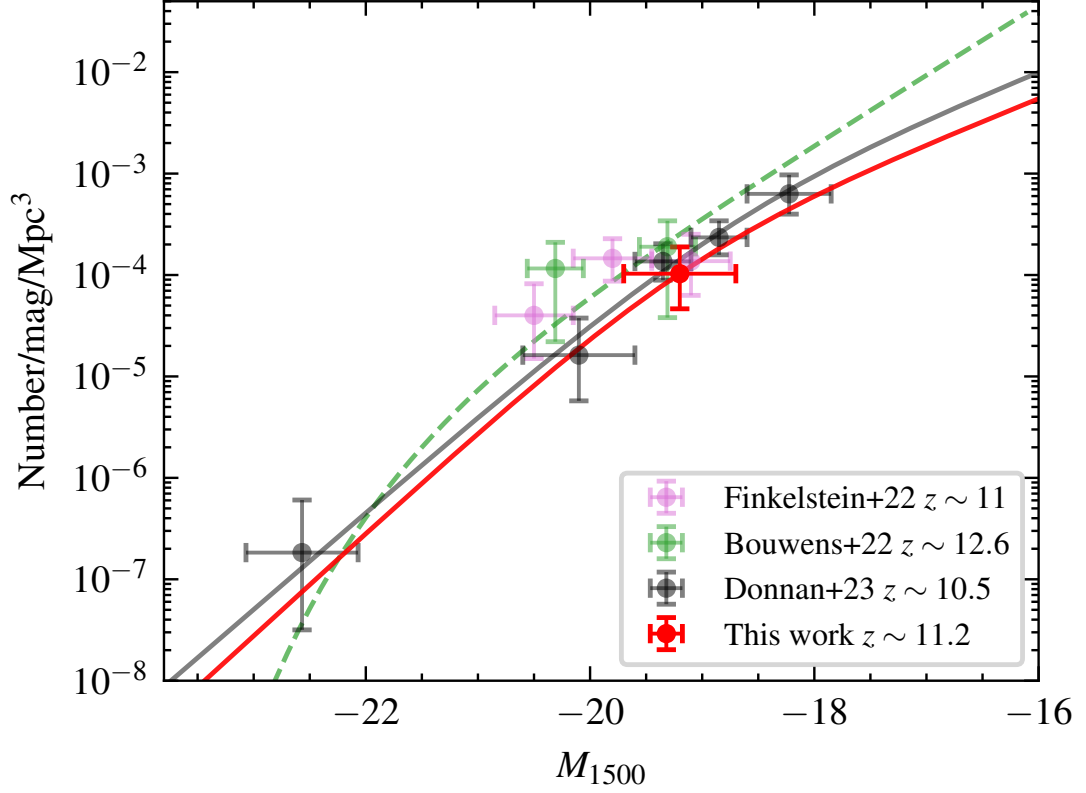


Figure 4.3 *The UV luminosity function (LF) determined from my new sample in the redshift range $9.5 < z < 13.5$ (red point). The rest-frame UV LF at $9.5 < z < 11.5$ from Chapter 3 is shown as black points with the best-fitting double power-law shown as a solid black line. I include data points from [Finkelstein et al. \(2023\)](#) and [Bouwens et al. \(2023b\)](#), with the best-fitting Schechter function from [Bouwens et al. \(2023b\)](#) plotted as the dashed green line. The derived number density based on my new $9.5 < z < 13.5$ galaxy sample is clearly consistent with the evolution of the UV LF derived in Chapter 3.*

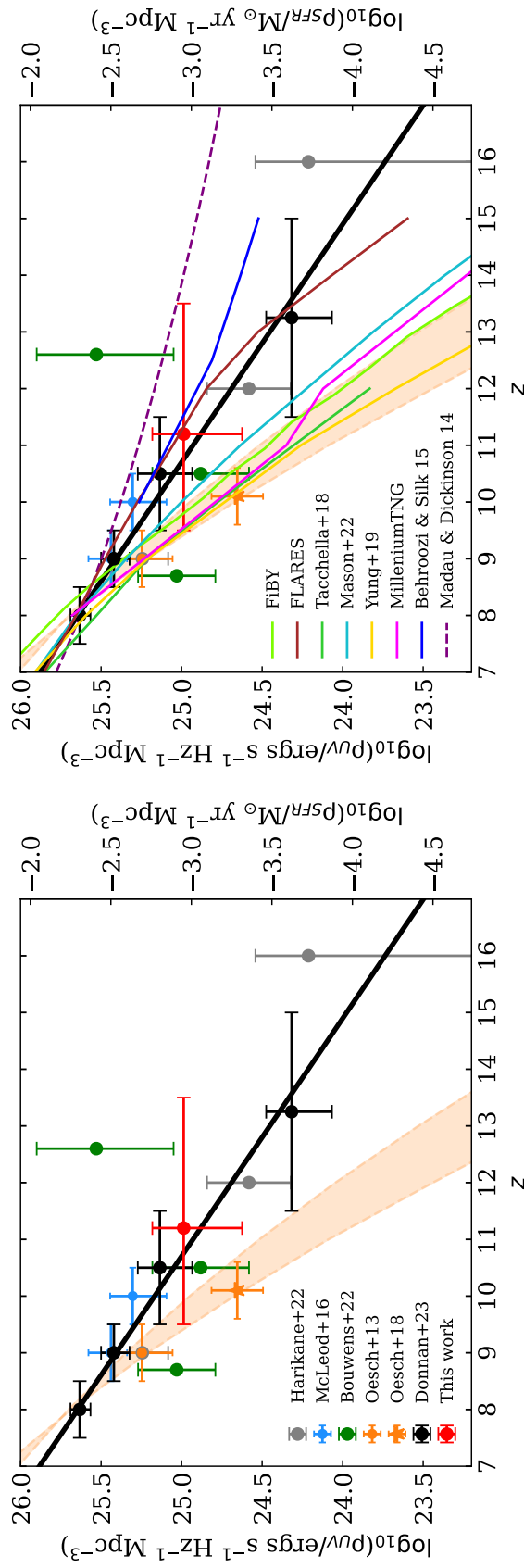


Figure 4.4 The redshift evolution of the UV luminosity density, ρ_{UV} , and hence the inferred cosmic star-formation rate density, ρ_{SFR} , at $z > 7$ with my new measurement at $z \sim 11.2$ (red circular data point). Estimates at $z \simeq 9 - 10$ from Oesch et al. (2013, 2018) and McLeod et al. (2016) are shown by the orange and blue data points respectively. The green and grey points show ρ_{UV} derived from the LFs in Bouwens et al. (2023b) and Harikane et al. (2023a) respectively. All values were determined using a limit of $M_{UV} = -17$ in the luminosity-weighted integral. The black data points and solid line show the results from Chapter 3. The shaded orange region shows the halo evolution model from Oesch et al. (2018). The right-hand panel shows a comparison to theoretical models, again setting the LF integration limit to $M_{UV} = -17$. The green, cyan, blue and yellow lines show semi-analytic models from Tacchella et al. (2018), Mason et al. (2023), Behroozi & Silk (2015) and Yung et al. (2019) respectively. The green, brown and pink lines show the results of hydrodynamical simulations from FIBY (Johnson et al., 2013; Paardekooper et al., 2015), FLARES (Wilkins et al., 2023) and MilleniumTNG (Kannan et al., 2023). The dashed purple line shows an extrapolation at $z \geq 8$ of the $\rho_{UV} \propto (1+z)^{-2.9}$ relation from Madau & Dickinson (2014). My new measurement is fully consistent with the steady, exponential decline in ρ_{UV} up to $z \simeq 15$ described in Chapter 3.

The results of this study thus further support the analytical prediction from [Hernquist & Springel \(2003\)](#) that a steady, exponential decline in ρ_{SFR} is expected with increasing redshift, as illustrated by the solid line in the left-hand panel of Fig. 4.4. In the right-hand panel of Fig. 4.4 I additionally provide a comparison of the new observational constraints on the UV luminosity density with the predictions of various different theoretical/numerical models. Although the observational data points lie below the extreme-redshift extrapolation of the relation provided by [Madau & Dickinson \(2014\)](#), they sit above the predictions from semi-empirical constant star-formation efficiency models as deduced by [Mason et al. \(2023\)](#) and [Tacchella et al. \(2018\)](#). I also compare to the cosmological hydrodynamical simulations FiBY ([Johnson et al., 2013](#); [Paardekooper et al., 2015](#)), FLARES ([Wilkins et al., 2023](#)) and MilleniumTNG ([Kannan et al., 2023](#)). These simulate dark-matter and baryonic physics simultaneously to attempt to provide a more realistic and detailed model of galaxy evolution. However, using cosmological simulations to understand a global scaling relation such as the UV LF is difficult due to many simultaneous physical processes occurring in the simulation. Therefore, disentangling these processes to understand which drives a given simulation’s UV LF is difficult. Overall, it can be seen that there is a wide range in the predictions of the different theoretical models; the new observational constraints sit above most of the theoretical curves but are reasonably in-line with the predictions from FLARES and the semi-analytical model presented by [Behroozi & Silk \(2015\)](#).

4.5.2 Low-redshift solutions for the $z \simeq 12$ candidate

After UDF-22980 was proposed to lie at $z = 11.9$ ([Ellis et al., 2013](#); [McLure et al., 2013](#)), there followed much discussion on the nature of this object, in part informed by a series of follow-up observations. [Brammer et al. \(2013\)](#) used *HST* GRISM spectroscopy and [Capak et al. \(2013\)](#) used Keck MOSFIRE to search for emission lines. No robust emission lines were detected but tentative ($\sim 2\sigma$) detections were reported at $\lambda_{\text{obs}} \simeq 1.6\mu\text{m}$. It was concluded that this could be consistent with an [OIII] $\lambda 4959, 5007$ detection at $z = 2.19$ or [OII] $\lambda 3727, 3729$ at $z = 3.29$. Now, however, with the *JWST* medium band imaging at $\lambda_{\text{obs}} > 1.6\mu\text{m}$ I can robustly constrain the shape of the galaxy SED. I find that, fitting with EAZY and LePhare, the new enhanced photometry is inconsistent with any solution at $z = 2.19$ or $z = 3.29$. When the fit is forced to these redshifts I find that the best-fitting (formally unacceptable) solution is an old passive galaxy which would

not have the strong emission lines required for these low- z solutions. Another inconsistency with the low- z solution is that a strong [OIII] emitter at $z = 2.19$ would likely have strong $H\alpha$ emission at $\lambda_{\text{obs}} = 2.1 \mu\text{m}$. This would result in a substantially smaller flux in F182M than in F210M which is not what is observed. This conclusion is also reinforced by the recent *JWST* spectroscopic observations from the JADES survey, albeit no emission lines were detected with NIRSpec (Robertson et al., 2023; Curtis-Lake et al., 2023).

4.5.3 The power of medium-band imaging

Accurate spectroscopic confirmation of $z \geq 7$ galaxies at optical/near-infrared wavelengths has been, and indeed continues to be a challenge due to the attenuation of $\text{Ly}\alpha$ emission within the epoch of reionization. An alternative route to robust spectroscopic redshifts is provided by the Atacama Large Millimeter/submillimeter Array (ALMA), with spectroscopic redshifts of $z \geq 7$ galaxies now regularly secured at sub-mm wavelengths. For example, ALMA has now been used to confirm galaxies at $z = 9.1$ (Hashimoto et al., 2018) and $z = 8.38$ (Laporte et al., 2017) based on the detection of [OIII] at $\lambda_{\text{rest}} = 88 \mu\text{m}$ as well as observations of [CII] at $\lambda_{\text{rest}} = 158 \mu\text{m}$. As the required observation time with ALMA is strongly dependent on the confidence interval of the photometric redshift (due to the potential requirement for multiple tunings), robust photometric redshifts are required for efficient sub-mm/mm spectroscopic confirmation. The results presented here thus demonstrate that *JWST* NIRCam medium-band imaging can be an invaluable additional tool for refining the photometric redshifts of high-redshift galaxy candidates in preparation for ALMA follow-up spectroscopy.

4.6 Conclusions

I have used a combination of the deepest optical + near-infrared *HST* broad-band imaging with deep *JWST* NIRCam medium-band imaging to detect 6 galaxy candidates at $z \geq 9.5$.

I obtain a robust photometric redshift for 6 candidates including the previously reported $z \simeq 12$ galaxy candidate, UDF-22980, at $z_{\text{phot}} \simeq 11.6$. I find that the previously suggested low- z emission line galaxy solutions indicated from $\sim$

2σ spectroscopic detections at $\lambda_{\text{obs}} = 1.6 \mu\text{m}$ are incompatible with the *JWST* NIRCam photometry which instead re-affirms the $z \simeq 12$ solution and refines the photometric redshift to $z = 11.65^{+0.17}_{-0.21}$. The robustness of the solutions were tested using 4 independent SED fitting codes which all show good agreement.

I also report UV slopes, stellar masses, star-formation rates and mass-weighted mean stellar ages for all 6 candidates. I find stellar masses of $\log(M_*/M_\odot) \simeq 7.5 - 8.7$ and star-formation rates of $\log(\text{SFR}/M_\odot\text{yr}^{-1}) \simeq 0.3 - 5.0$. I am able to measure a robust UV continuum slope for one object, finding a very blue slope of $\beta = -2.5 \pm 0.2$ which is consistent with a young, low-metallicity stellar population.

The galaxy number density and hence cosmic star-formation rate density at $z \simeq 11$ derived from this sample are fully consistent with the current picture of the evolution of the UV LF with a gradual steady decline over the redshift range $z = 8-15$. The resulting inferred gradual (exponential) decline in cosmic star-formation rate density out to at least $z \simeq 15$ is clearly inconsistent with at least some theoretical/numerical models of early galaxy evolution.

This study further demonstrates the power of *JWST* to quickly reveal the true nature of $z \geq 10$ candidates that were first identified by *HST* as well as to detect new galaxy candidates, with the NIRCam medium-band imaging analysed here providing sensitive photometry at $\lambda_{\text{obs}} \gtrsim 1.6 \mu\text{m}$. Robust photometric redshifts are vital for drawing conclusions about the physical properties of $z \geq 10$ galaxies as well as providing a tighter frequency range for ALMA follow-up spectroscopy. Forthcoming *JWST* surveys will primarily target fields that are accessible to ALMA, and were heavily imaged by *HST* such as NGDEEP (GO 2079) and PRIMER (GO 1837) and will therefore benefit from this combination. Therefore, it is likely these surveys will provide large statistically-significant samples of galaxies over a wide redshift range which will yield further constraints on the high-redshift evolution of the UV luminosity function as well as providing numerous extreme-redshift galaxy candidates for follow-up *JWST* and ALMA spectroscopy.

Chapter 5

JWST PRIMER: A new multi-field determination of the evolving galaxy UV luminosity function at redshifts $z \simeq 9 - 15$

5.1 Introduction

The discovery and study of the earliest galaxies is critical for refining my understanding of cosmology and structure formation, and in particular for clarifying the first stages of galaxy formation/evolution and the progress/drivers of cosmic hydrogen reionization (Dunlop, 2013; Stark, 2016). Over the last decade, deep near-infrared surveys with the *Hubble Space Telescope* (*HST*) and *Spitzer* have enabled the evolution of galaxies to be mapped out to redshifts $z \simeq 9$ (e.g. Ellis et al., 2013; McLure et al., 2013; Finkelstein et al., 2015; McLeod et al., 2015, 2016; Oesch et al., 2018; Bouwens et al., 2021, 2023b). Moreover, there is now growing evidence that the UV radiation emitted from these early star-forming galaxies powered cosmic hydrogen reionization, with this phase transition concluding by $z \simeq 5.5 - 6.0$ (Robertson et al., 2015; Aird et al., 2015; Bosman et al., 2021).

The reliable detection of galaxies at $z \geq 7$ was first made possible by the installation of the near-infrared camera WFC3/IR on *HST*. The detection of

galaxies at $z \geq 6$ relies on the robust identification of the Lyman-break due to the attenuation of UV photons short-ward of $\lambda_{\text{rest}} = 1216 \text{ \AA}$ produced by the increasingly neutral intergalactic medium (IGM) at these redshifts. However, as a result of the long-wavelength limit of *HST* at $1.7 \mu\text{m}$, galaxies could only be robustly selected up to $z \sim 10$ with only a small number of more tentative detections reported at higher redshifts (e.g. [Ellis et al., 2013](#); [Oesch et al., 2016](#)) which relied on single filter detections. In parallel with these space-based efforts, wider area (degree-scale) ground-based near-infrared imaging surveys (e.g. UltraVISTA; [McCracken et al., 2012](#)) have revealed an excess of bright galaxies ($M_{\text{UV}} \leq -20$) at high redshifts compared to what is expected from an evolving Schechter function ([Bowler et al., 2020](#); [Varadaraj et al., 2023](#); [Donnan et al., 2023a](#)). When the ground-based and space-based data are combined it is now clear that a double-power law is a more appropriate functional form for describing the UV luminosity function (LF) at $z > 6$.

Now, since summer 2022, the study of early galaxies has been revolutionised by the advent of *JWST*. The NIRCam instrument on *JWST* provides deep multi-band near-infrared imaging out to $\lambda \simeq 5 \mu\text{m}$, and this has enabled the robust detection of galaxies at extreme redshifts ($z \geq 10$) for the first time. Indeed, in just the first year of *JWST* operations, several early NIRCam imaging surveys have already been completed, revealing a significant number of galaxy candidates at $z > 10$ (e.g. [Donnan et al., 2023a,b](#); [McLeod et al., 2024](#); [Adams et al., 2023b](#); [Naidu et al., 2022b](#); [Castellano et al., 2022](#); [Harikane et al., 2023b](#); [Finkelstein et al., 2022b](#); [Austin et al., 2023](#); [Hainline et al., 2024](#)). *JWST* has also been successfully used to spectroscopically confirm the redshift of many of these candidates using the NIRSpec instrument (up to $z_{\text{spec}} = 13.2$) (e.g. [Curtis-Lake et al., 2023](#); [Arrabal Haro et al., 2023b](#); [Harikane et al., 2024](#); [Wang et al., 2023](#); [Castellano et al., 2024](#)). These early spectroscopic results have shown very good agreement with the inferred photometric redshifts for the vast majority of robust targets ([Arrabal Haro et al., 2023a](#); [Bunker et al., 2024](#)).

Out of the galaxy candidates revealed by *JWST* at $z > 10$ there have been a number that are particularly (arguably surprisingly) bright (e.g. [Castellano et al., 2022, 2023](#); [McLeod et al., 2024](#)). This has led to some suggestions that the early *JWST* results in this field present a challenge theoretical models of galaxy evolution, with lower dust attenuation and/or higher star-formation efficiencies, or even primeval (PopIII) stellar populations being proposed as necessary to explain the observations (e.g. [Tacchella et al., 2018](#); [Yung et al., 2019](#); [Mason](#)

et al., 2023; Harikane et al., 2023b).

Prior to the launch of *JWST*, and due primarily to the aforementioned wavelength limitations of *HST*, there was uncertainty over the evolution of the cosmic star-formation rate density (ρ_{SFR}) at $z \geq 9$. This issue has now been largely resolved by the first year of *JWST* observations, with early measurements of the UV LF with *JWST* showing only gradual evolution over the redshift range $z = 8 - 13$ (Donnan et al., 2023a,b; Harikane et al., 2023b; Finkelstein et al., 2023; Bouwens et al., 2023c,a; Adams et al., 2024; McLeod et al., 2024; Leung et al., 2023). This is consistent with the smoother more gradual decline in ρ_{SFR} , consistent with the results/predictions of McLeod et al. (2016).

However, the early high-redshift studies undertaken with *JWST* suffer from several limitations. One limitation is the modest total area coverage and limited availability of deep imaging in the Early Release Science (ERS) and the smaller-scale early Cycle-1 *JWST* NIRCам programmes. As a result there has remained significant uncertainty over the exact shape of the UV LF at $z > 10$. In particular, the constraints on the faint-end slope of the LF are relatively poor, an uncertainty which in turn limits the accuracy with which the cosmic star-formation rate density can be inferred. Moreover, a free fit of the functional form to the UV LF at $z > 10$ has remained challenging due to the limited dynamic range in the UV luminosity (M_{UV}) of the galaxies uncovered at these redshifts in the early *JWST* samples. The limited area of these early studies, as well as inevitably yielding rather small samples, also makes them vulnerable to cosmic variance. In particular, the Abell2744 field imaged by the UNCOVER (Bezanson et al., 2024) and GLASS (Treu et al., 2022) programmes is now known to be highly over-dense at $z \sim 10$ (Castellano et al., 2023).

Another limitation of the early *JWST* studies of high-redshift galaxy evolution has been the methodology used to determine the UV LF. Typically, the $1/V_{\text{max}}$ method (Schmidt, 1968) has been used, which involves selecting galaxies at high redshift using the Lyman break technique and simply adopting the best-fitting photometric redshift (photo- z). However, the redshift of a galaxy is often not very well defined by the multi-band photometry and therefore the photo- z can be unreliable, particularly for galaxies close to the detection limit. This is one possible explanation for the discrepant galaxy samples produced in a number of the early *JWST* studies (Bouwens et al., 2023a).

In this chapter I aim to substantially advance our knowledge of the evolving

galaxy UV LF and hence cosmic star-formation rate density at $z = 9 - 15$. First, I am now able to utilise a number of the more major extragalactic NIRCcam imaging surveys (both public and GTO) which have been largely completed in *JWST* Cycle-1. Second, to do this expanded dataset justice, I have implemented a more statistically robust method of calculating the LF.

Our primary imaging dataset is the Public Release IMaging for Extragalactic Research (PRIMER; Dunlop et al., in preparation) survey which provides imaging over $\simeq 380 \text{ arcmin}^2$ in 8 NIRCcam filters, an order-of-magnitude larger area than covered in the ERS NIRCcam programmes. I also include the ultra-deep imaging from the *JWST* Advanced Deep Extragalactic Survey (JADES; Eisenstein et al., 2023) and the Next Generation Deep Extragalactic Exploratory Public survey (NGDEEP; Bagley et al., 2024b). By taking this multi-field approach, combining surveys with different (and largely complementary) depths and areas (covering a total of $\sim 400 \text{ sq. arcmin}$ while reaching depths of $m_{\text{AB}} \simeq 30$) I now have substantially improved dynamic range in both UV luminosity and redshift compared to previous *JWST*-based studies. As a result of this, and my improved methodology, I am now able to significantly improve the accuracy with which the UV LF can be constrained at extreme redshifts, $z = 8 - 15$.

The chapter is structured as follows. In Section 5.2 I describe the imaging data and the creation of my source catalogues. In Section 5.3 I explain the sample selection and the spectral energy distribution (SED) fitting to the galaxy photometry. In Section 5.4 I present my derived galaxy UV luminosity function as a function of redshift, and the resulting inferred early evolution of the cosmic star-formation rate density. In Section 5.5 I then discuss my results in the context of other recent observational studies and the predictions of various theoretical/numerical models of galaxy formation and evolution. Finally, in Section 5.6 I summarise my conclusions. Throughout I use magnitudes in the AB system (Oke, 1974; Oke & Gunn, 1983), and assume a standard cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

5.2 Data

5.2.1 Survey Fields

We utilise a number of major *JWST* Cycle-1 imaging surveys covering 4 separate fields. Due to the uncertainties and limited cosmological volumes associated with gravitational lensing, I choose to focus on blank/unbiased fields to ensure a robust determination of the UV luminosity function. The largest programme used is the Public Release IMaging for Extragalactic Research (PRIMER, PI: J. Dunlop) survey which images the COSMOS and UDS fields using NIRCcam through the F090W, F115W, F150W, F200W, F277W, F356W, F410M and F444W filters. I also use the first epoch of imaging from the Next Generation Deep Extragalactic Exploratory Public (NGDEEP, PI: S. Finkelstein) survey which provides ultra-deep imaging in the GOODS-South field, specifically targeting the Hubble Ultra Deep Field parallel 2 field (HUDF par. 2). This programme uses the NIRCcam F115W, F150W, F200W, F277W, F356W and F444W filters. Finally I use the *JWST* Advanced Deep Extragalactic Survey (JADES; [Eisenstein et al., 2023](#); [Rieke et al., 2023](#)) NIRCcam data release 2. This programme targets a region within the GOODS-South field centred on the Hubble Ultra Deep Field (HUDF), and uses the same filter set as the PRIMER survey.

These survey fields also have the advantage of deep optical imaging from the *HST*/ACS instrument. The PRIMER UDS and COSMOS fields have been imaged in the *HST* F435W, F606W and F814W filters from the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS; [Grogin et al., 2011](#); [Koekemoer et al., 2011](#)). The JADES and NGDEEP fields also have imaging in these filters with the addition of F775W and F850LP. This imaging was also taken as part of CANDELS as well as through the Great Observatories Origins Deep Survey (GOODS; [Giavalisco et al., 2004](#)). This includes the deepest *HST*/ACS imaging ever taken in the HUDF. The existence of deep optical data is critical for obtaining robust measurements of the redshift probability distributions ($p(z)$) of the sources detected in each field.

The PRIMER and NGDEEP imaging data was reduced using the PRIMER Enhanced NIRCcam Image Processing Library (PENCIL; Magee et al., in preparation) software. For the JADES imaging I use the reductions described in [Rieke et al. \(2023\)](#). The astrometry of all the reduced images was aligned to

GAIA DR3 ([Gaia Collaboration et al., 2023](#)) and stacked to the same pixel scale of 0.03 arcsec.

5.2.2 PSF homogenisation

To create a catalogue with accurate photometry, the differences in the point spread function (PSF) need to be accounted for. This is corrected by homogenising the PSFs produced by the imaging through the different filters to one common PSF, using a similar technique to that which was utilised for the ground-based imaging in Chapter 3. For all of the survey fields used in this study, the F444W imaging is available and has the broadest PSF. The F444W PSF was therefore chosen as the natural target for the homogenisation of the imaging resolution at all other wavelengths. I measured the PSF by selecting $\simeq 20$ bright but unsaturated stars across the PRIMER COSMOS imaging. Each star was then centroided and stacked to generate a measurement of the PSF in each filter. My measured PSFs are comparable to those from WebbPSF ([Perrin et al., 2014](#)) to within $\simeq 1\% - 3\%$. Using a combination of Moffat and Gaussian profiles a series of kernels were produced which, when convolved with the imaging, result in the homogenisation of the imaging through each NIRCcam filter to the PSF at F444W, to within an accuracy of 3 per cent.

5.2.3 Photometric Depths

The global depths for each field were calculated by determining the distributions of fluxes measured in 0.3-arcsec diameter apertures placed within source-free regions of the PSF-homogenised imaging. The 1σ depth is then given by $1.4826 \times \text{MAD}$ where MAD is the median absolute deviation of the flux in the source-free apertures. This gives a global depth, because it is calculated over the full (source-free) area of the imaging. In Fig. 5.1 I show the spatial distribution of the 5σ depth across each field. This illustrates the different depths achieved by the different NIRCcam surveys, as well as revealing the extent of any depth variations across the images. In particular, the “wedding-cake” structure of the PRIMER and JADES surveys can be identified by the distinct regions of differing depth. The depth maps indicate that the NGDEEP and UDS fields are relatively flat whereas the COSMOS and JADES fields have (by design) sub-regions that differ significantly in depth. In COSMOS I found it useful to define 2 individual

sub-regions corresponding to the deeper core and the wider/shallower outer region which I name “COSMOS Deep” and “COSMOS Wide” respectively. In JADES I define 3 distinct sub-regions. “JADES Deep” comprises the deeper stripes in the north of the imaging as well as the deep pointing in the South often labelled as the JADES Origins Field (JOF; [Robertson et al., 2024](#)). “JADES Medium” and “JADES Shallow” define the remaining area. In Table 5.1 I list the 5σ global depths for each field where COSMOS and JADES are divided into their respective sub-regions. The depths have been corrected to total assuming a point source correction. The areas of each region are also stated.

To ensure consistent and robust high redshift galaxy selection, I restricted the analysis (i.e. the source selection) area in each field to those regions in which deep *HST*/ACS F814W and *JWST*/NIRCam F090W imaging is available; this guarantees that there are always a sufficient number of “short”-wavelength filters to confirm the anticipated non-detections for $z \geq 8.5$ galaxy candidates. In practice this requirement only has a significant effect on the NGDEEP and UDS fields, with the useful area of the *JWST* imaging in both these fields being reduced by approximately 1/3. This reduction in usable area has been accounted for in the areas noted in Table 5.1.

Due to the varying depths across much of the imaging, the global depth is a rather poor representation of the uncertainty in the flux of individual objects. To improve on this I have adopted the 1σ *local* depth as the uncertainty of the measured fluxes in each filter for each object. To establish the local depths I use the same technique as utilised In Chapter 3-4 in which the depth is calculated using the 200 empty apertures that lie closest to each detected source.

5.3 Sample selection

For each field I constructed three catalogues using SExtractor ([Bertin & Arnouts, 1996](#)) in dual-image mode. I performed a rest-frame UV selection by using the F150W, F200W and F277W images as the detection images, as these filters sample the flux long-ward of the Lyman break at $9 \lesssim z \lesssim 20$. Master catalogues were constructed from the three single-filter catalogues, removing duplicates by retaining the duplicate with the highest signal-to-noise in its respective detection image. Photometry was measured within $0.3''$ -diameter circular apertures on the PSF homogenised images, corresponding to ~ 70 per

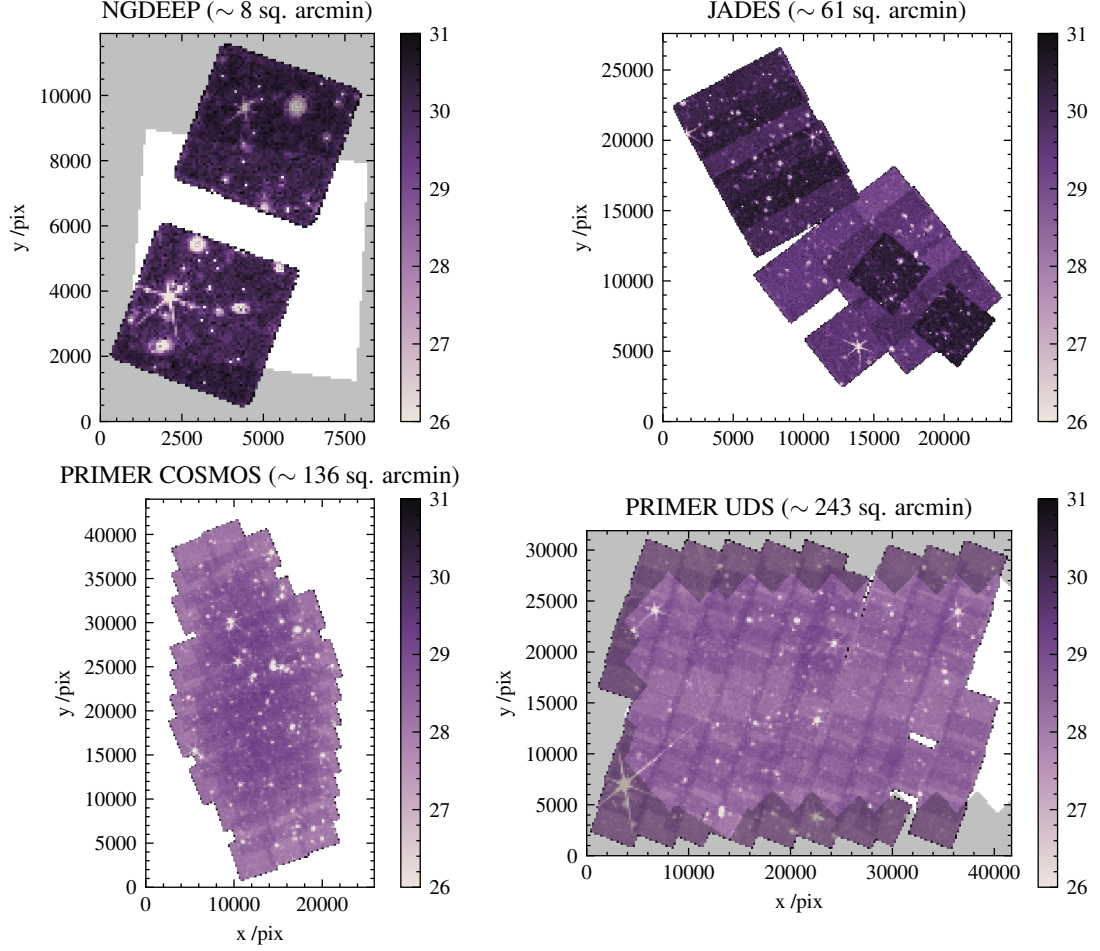


Figure 5.1 *The 5σ depth maps in the $F277W$ filter imaging of each NIRC*am* survey field used in this analysis, demonstrating the variation in depths between the different survey fields, and in some cases within a given field. All images are shown with bins of 200 pixels where the original images are on a 0.03-arcsec pixel scale. The colour-bar shows the 5σ depth in AB mag on the same scale for each field. The grayed out region shows where there is a lack of deep HST/ACS $F814W$ imaging, which only affects the NGDEEP and UDS fields.*

Table 5.1 *The derived 5σ global depths for all the images used in this analysis. All depths (given in AB mag) have been measured in 0.3-arcsec diameter apertures on the PSF-homogenised images and then corrected to total assuming a point-source correction.*

Filter	PRIMER		PRIMER		PRIMER		JADES		JADES		JADES	
	COSMOS Deep	COSMOS Wide	UDS	NGDEEP	Deep	Medium	Shallow	Deep	Medium	Shallow	Deep	Medium
F435W	28.0	27.8	27.2	28.6	28.5	28.4	28.4	28.5	28.4	28.4	28.5	28.4
F606W	27.9	27.8	28.0	29.3	28.9	28.9	28.9	28.9	28.9	28.9	28.9	28.9
F775W	-	-	-	28.9	28.2	28.1	28.2	28.2	28.1	28.2	28.2	28.2
F814W	28.0	27.6	29.0	28.7	28.4	28.4	28.4	28.4	28.4	28.4	28.4	28.4
F850LP	-	-	-	28.2	27.9	27.8	27.8	27.9	27.8	27.8	27.9	27.8
F090W	28.0	27.6	27.6	-	29.4	29.0	28.6	29.4	29.0	28.6	29.4	29.0
F115W	28.3	27.9	27.8	29.1	29.8	29.4	29.0	29.8	29.4	29.0	29.8	29.4
F150W	28.4	28.1	28.1	29.1	29.8	29.4	29.1	29.8	29.4	29.1	29.8	29.4
F200W	28.6	28.2	28.2	29.1	29.9	29.5	29.2	29.9	29.5	29.2	29.9	29.5
F277W	28.7	28.3	28.3	29.5	30.2	29.8	29.3	30.2	29.8	29.3	30.2	29.8
F356W	28.8	28.4	28.3	29.3	30.1	29.7	29.3	30.1	29.7	29.3	30.1	29.7
F410M	28.2	27.7	27.7	-	29.7	29.1	28.7	29.7	29.1	28.7	29.7	29.1
F444W	28.4	28.0	27.9	29.3	29.0	28.8	28.5	29.0	28.8	28.5	29.0	28.8
Area [sq. arcmin]	47.8	84.4	170.7	5.6	19.6	25.3	15.8	19.6	25.3	15.8	19.6	25.3

cent of the total flux for a point source. Based on the individual curves of growth, further corrections of the order $\sim 1 - 2$ per cent were made to correct the imaging through every filter to exactly 70 per cent of the total flux in order to improve the photometric homogenisation.

5.3.1 SED fitting

We used EAZY (Brammer et al., 2008) to perform my initial SED fitting, exploring the redshift range $0 < z < 20$ with the PEGASE (Fioc & Rocca-Volmerange, 1999) template set that includes nebular emission lines.

When computing the UV LF, the standard approach is to adopt the maximum likelihood (i.e. minimum χ^2) photometric redshift solution for each source. However, this approach makes the implicit assumption that the integrated $p(z)$ within the adopted redshift bin is unity. This assumption can hold true when the signal-to-noise of the photometry is sufficient to exclude any alternative redshift solutions as being statistically unacceptable fits to the data. However, this is not the case for a significant number of the sources initially selected, particularly if they are close to the detection limit of the imaging. Consequently, a more robust approach to calculating the UV LF is to consider the full $p(z)$ of each source in the initial catalogue over the entire redshift range $0 < z < 20$.

5.3.2 Posterior probability distributions

For each galaxy, I assume that the posterior probability distribution of the redshift, given the observed fluxes (F), is given by

$$p(z|F) = \mathcal{L}(F|z)p(z|M_{UV}), \quad (5.1)$$

where $\mathcal{L}(F|z)$ is the likelihood of the observed fluxes given the redshift, taken to be

$$\mathcal{L}(F|z) \propto e^{-\chi^2(z)/2}, \quad (5.2)$$

and $p(z|M_{UV})$ is the prior probability of the redshift based on the implied absolute UV magnitude. This prior is based on an evolving model of the UV LF from $z = 0 - 20$. At redshifts $z < 7$ I adopt the evolving Schechter function parameterisation from Bouwens et al. (2021). At $z \geq 7$ I adopt a new parameterisation, designed

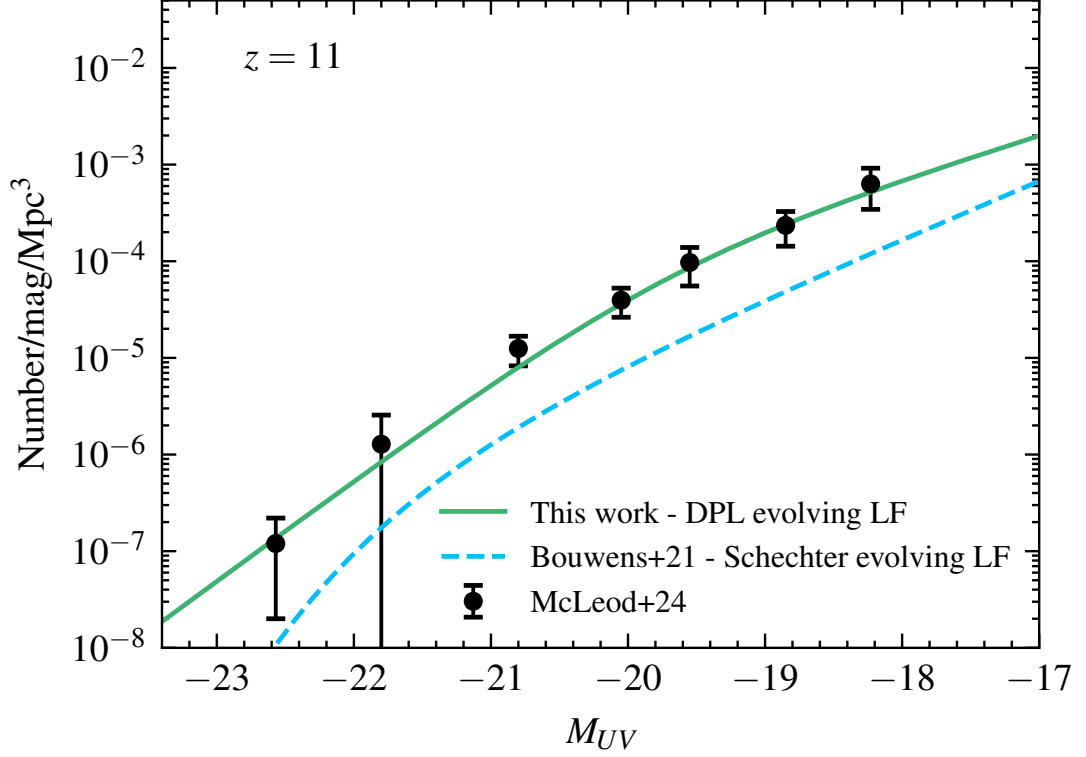


Figure 5.2 *A comparison of my evolving double power-law parameterisation of the $z = 11$ UV LF (green solid line) with the observational data from [McLeod et al. \(2024\)](#) at the same redshift. The prediction of the evolving Schechter function parameterisation of the UV LF from [Bouwens et al. \(2021\)](#) is shown as the dashed blue line.*

to reproduce the double power-law (DPL) fits to the $z \simeq 7 - 11$ UV LF from [Bowler et al. \(2017, 2020\)](#); [Donnan et al. \(2023a\)](#); [McLeod et al. \(2024\)](#). The evolution of the DPL parameters is described as follows:

$$M^* = -20.95 + 0.11z \quad (5.3)$$

$$\phi^* = 10^{(-0.14z - 2.36)} \quad (5.4)$$

$$\alpha = -2.04 \times 10^{-4}z - 2.1 \quad (5.5)$$

$$\beta = 0.138z - 5.13. \quad (5.6)$$

Fig. 5.2 demonstrates that my model of the evolving UV LF is a good fit to the observational data at $z \simeq 11$ from [McLeod et al. \(2024\)](#). In contrast, it can be seen that an extrapolation of the Schechter model from [Bouwens et al. \(2021\)](#) under predicts the latest *JWST* observational data at these redshifts.

The impact of the UV LF prior is particularly important for very bright and/or extreme redshift sources, for which the posterior redshift probability distribution

becomes weighted towards lower redshift *if the photometric data are not deep enough to robustly exclude such solutions*. In Fig. 5.3 I demonstrate the effect of the UV LF prior on the posterior redshift distribution for two different sources: a galaxy uncovered in the HUDF which now has a spectroscopically-confirmed redshift of $z = 11.6$, and an object with a photometric redshift of $z \sim 16$ selected from the NGDEEP survey. I also show their images in a number of filters.

The first source is a galaxy that was initially identified using *HST* data in the HUDF (Bouwens et al., 2011a; Ellis et al., 2013; McLure et al., 2013) with only a single-band detection implying an extreme photometric redshift of $z \simeq 12$. This redshift solution has since been refined first with photometry from *JWST*/NIRCam (Bouwens et al., 2023c; Donnan et al., 2023b; Robertson et al., 2023) and subsequently with spectroscopy from *JWST*/NIRSpec (Curtis-Lake et al., 2023) which yielded a robust redshift of $z = 11.6$. Fig. 5.3 demonstrates that the $p(z)$ I derive for this source (JADES-92420) from fitting my *JWST* photometry is actually unaffected by the UV LF redshift prior due to the robust nature of its photometric redshift. This source is robustly at $z > 8.5$ with an integrated $p(z \geq 8.5) = 0.995$. It most strongly contributes to the $z = 12.5$ UV LF bin as described in Section 5.4 with $p(11.5 < z < 13.5) = 0.97$.

The second source was identified by Austin et al. (2023) to be at $z_{\text{phot}} \simeq 15.6$ (NGD-z15a) which, if correct, would make it one of the most distant galaxy candidates discovered to date. This source was also reported in Leung et al. (2023), with a very similar photometric redshift estimate of $z_{\text{phot}} \simeq 15.8$ (NGDEEP 1369). It can be seen from Fig. 5.3 that, with a flat redshift prior, I would also identify this source (here listed as NGDEEP-3594) as a robust $z \geq 15$ candidate based on my photometry. However, the application of my adopted UV LF prior changes the posterior probability distribution in a way which strongly favours the lower-redshift solution at $z \sim 4$, indicating that, given the available data, this candidate is unlikely to be at ultra-high redshift, with a integrated $p(z \geq 8.5) = 0.054$. Although this candidate does still contribute to the tentative $z = 14.5$ bin described in Section 5.4, it only contributes the equivalent of 0.025 galaxies. This situation may appear similar to that of the very luminous $z \simeq 16$ candidate detected in CEERS (Donnan et al., 2023a; Finkelstein et al., 2023) where subsequent spectroscopy with *JWST*/NIRSpec conclusively revealed that the redshift was in fact $z = 4.9$ (Arrabal Haro et al., 2023b) where the photometry was dominated by strong rest-frame optical emission lines (Harikane et al., 2024). However, the $p(z)$ for this highly-unusual candidate was in fact unaffected by

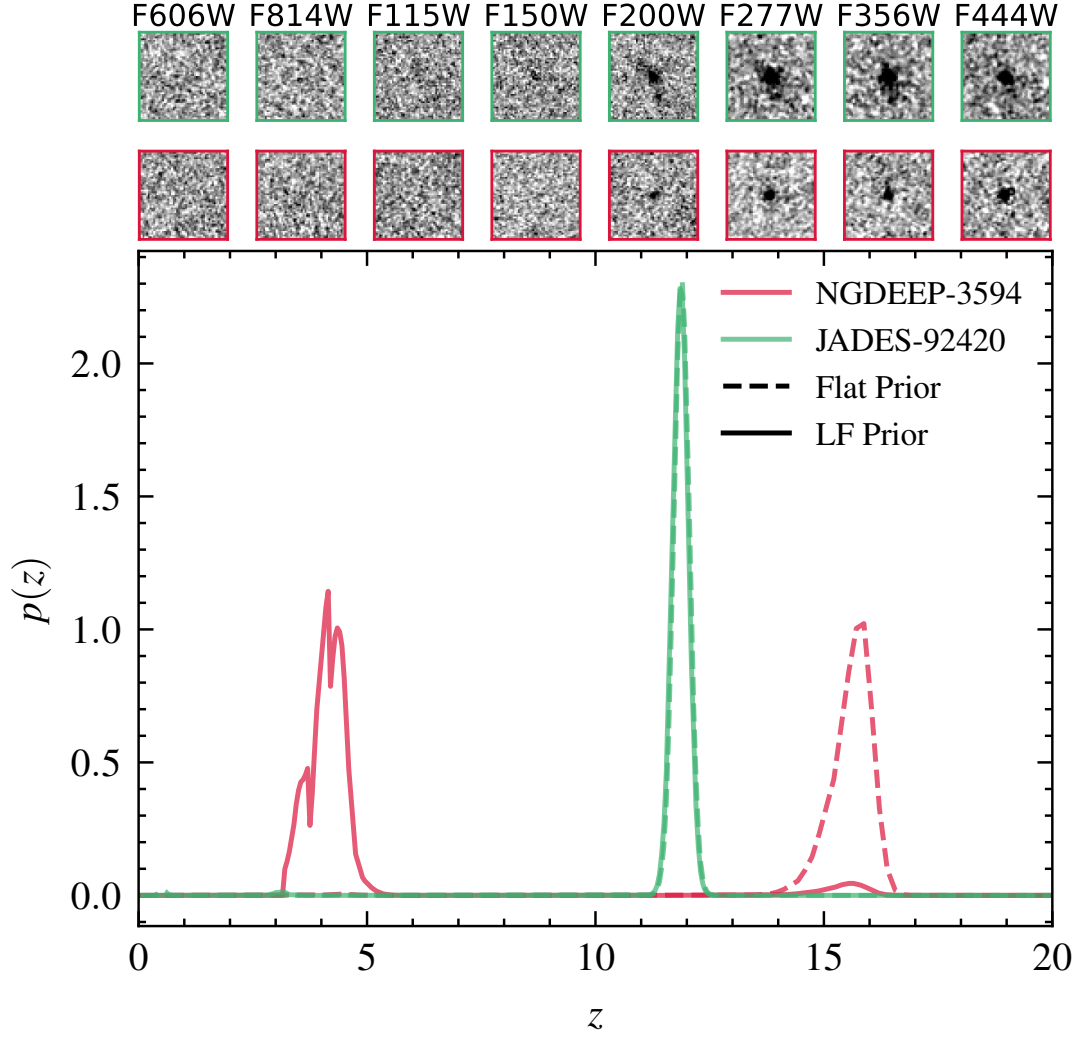


Figure 5.3 The posterior redshift probability distribution for NGDEEP-3594 (red) and JADES-92420 (green) using a flat redshift prior (dashed-lines) and my UV LF prior (solid-lines). The first source is a $z \sim 16$ candidate reported by [Austin et al. \(2023\)](#) and [Leung et al. \(2023\)](#), while the second is a spectroscopically-confirmed galaxy at $z = 11.6$ ([Curtis-Lake et al., 2023](#)). The UV LF prior strongly weights the posterior redshift probability distribution to lower redshift for the less robust source, whereas the redshift solution of the robust high-redshift galaxy is unaffected. The top panel shows cut-out images of the two sources (indicated by their respective border colours) in the HST/ACS F606W, F814W filters and the JWST/NIRCam F115W, F150W, F200W, F277W, F356W and F444W filters.

the application of a UV LF prior, due to the relatively high signal-to-noise of the *JWST* photometry. Instead, the introduction of an extreme emission-line template SED was required to reveal the correct photometric redshift for this particular source.

5.3.3 Selection of galaxy candidates

Based on the master photometric catalogues for each field, I produced initial samples of galaxy candidates at $8.5 < z_{\text{phot}} \lesssim 20$. To be included in my initial samples, objects were required to be $< 2\sigma$ detections in all ACS filters and the F090W NIRCam filter. Objects were also required to be a $\geq 5\sigma$ detection in one of the three detection filters: F150W, F200W and F277W as well as a $\geq 3\sigma$ detection in any one of the other available NIRCam filters. To minimise contamination from artefacts, I masked the low SNR regions around the edges of each field, together with bright stars and their associated diffraction spikes. These further corrections/reductions are accounted for in the areas noted in Table 5.1.

The next step in the selection process was to calculate the posterior redshift distribution for each source (see Eqn. 1), using the UV LF prior. The implementation of the UV LF prior required knowledge of the best-fitting value of M_{UV} at each redshift, which was calculated using a top-hat filter centred on $1500 \text{ \AA}$ in the rest-frame of the best-fitting SED. In order to calculate the total M_{UV} , the aperture-based fluxes were scaled to a Kron aperture flux (Kron, 1980), with an additional correction of 10 per cent to account for extended flux not accounted for by the Kron aperture (McLeod et al., 2024).

All objects with an integrated posterior redshift distribution of $p(z|F) \geq 0.05$ at $z \geq 8.5$ were kept as viable high-redshift candidates. The final stage in the selection process was a visual inspection of the sample in order to remove the small number of remaining artefacts and diffraction spikes.

The apparent magnitude distribution of the final sample in the F277W filter is shown in Fig. 5.4 across the six survey areas employed in this study.

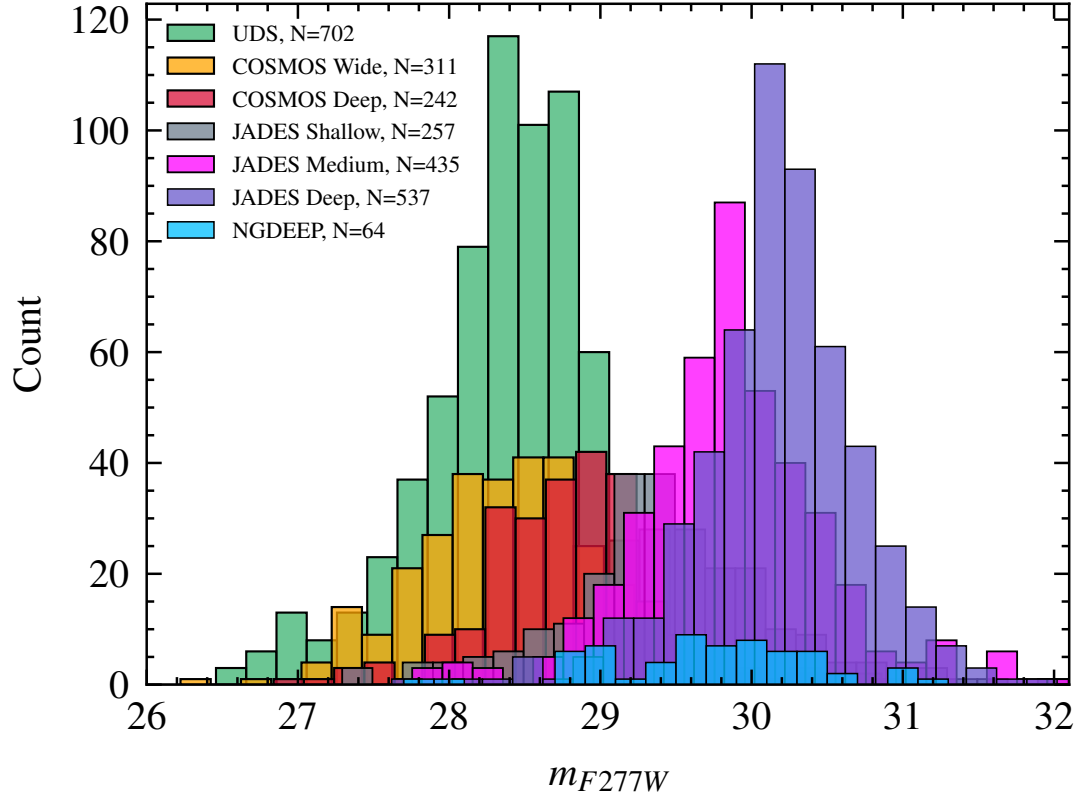


Figure 5.4 *The distribution of apparent magnitude in the F277W filter for the galaxies in the final sample, split by the field in which they reside. The histogram is presented in bins with a width of 0.2 mag and the number of galaxies selected from each field is noted in the legend. The final total combined sample contains 2548 galaxies.*

5.4 UV Luminosity function

The galaxy selection process produced a final sample of 2548 galaxies selected over a total area of $\simeq 369$ square arcminutes of *JWST*/NIRCam imaging. In this section I use this sample to determine the UV luminosity function at $8.5 < z < 15.5$.

5.4.1 Completeness

The accurate determination of the UV LF requires that the incompleteness in the final galaxy sample is accounted for. To achieve this I employed a simulation designed to mimic as closely as possible to real galaxy selection process. In order to calculate the fraction of recovered sources as a function of M_{UV} and z , artificial sources were injected into the real imaging for each of the fields over the range $-22 < M_{\text{UV}} < -17$ and $8.5 < z < 19.5$. This included separating COSMOS and JADES into their respective sub-fields as noted in Section 5.2.3. In steps of $\Delta m = 0.5$ and $\Delta z = 0.5$, sources were injected into all of the available images for each field as point sources, based on an SED template with a UV-slope typical of the $z \geq 8.5$ population ($\beta \sim -2.2$; Cullen et al., 2024b; Morales et al., 2024; Topping et al., 2024b).

By performing the completeness simulation in this way, I am able to test every step of my selection process, ensuring that the recovered completeness is as accurate as possible. Sources were injected as point sources for simplicity, as detailed simulations have shown that modelling the physical size distribution of the sources has a negligible impact on the recovered completeness at these redshifts (McLeod et al., 2024). After injecting the sources, catalogues were extracted from the injected images in the same manner as for the main galaxy sample and then passed through the same selection process. The fractional completeness at each point on the $M_{\text{UV}} - z$ plane was then calculated for each field.

5.4.2 Calculating the UV luminosity function

In order to calculate the UV luminosity function, I populate the $M_{\text{UV}} - z$ plane based on the normalized posterior redshift probability distribution of all galaxies

in the final sample. In practice, I split the $M_{\text{UV}} - z$ plane into bins of dimension $\Delta m = 0.5$ and $\Delta z = 0.5$ within the range $-22 < M_{\text{UV}} < -17$ and $8.5 < z < 19.5$, in order to match the resolution of the completeness simulation. The population of the $M_{\text{UV}} - z$ plane was calculated for each sub-field individually, before the fields were combined to mimic a single survey. The total combined number density at each M_{UV} and z is therefore given by,

$$\Phi(M_{\text{UV}}, z) = \sum_{i=1}^N \frac{p_i(M_{\text{UV}}, z)}{V_i C_i(M_{\text{UV}}, z)} \quad (5.7)$$

where $N = 7$ (the total number of sub-fields); $p_i(M_{\text{UV}}, z)$ is the total probability in a given (M_{UV}, z) bin for a given field; $C_i(M_{\text{UV}}, z)$ is the corresponding completeness and V_i is the cosmological volume provided by that field. When computing the combined UV LF, I conservatively restrict the contribution of each sub-field to the UV magnitude range where it is ≥ 50 per cent complete. The final result provides a continuous expression of the UV LF in two dimensions, from which the one-dimensional UV LF can be extracted over any chosen range in redshift. As a result, and unlike many literature studies, it is not necessary to calculate the UV LF over wide redshift bins in order to counteract the impact of photometric-redshift uncertainties.

We extract and plot (in Fig. 5.5) the one-dimensional UV LF centered on $z = 9, 10, 11$ and $z = 12.5$ using redshift bins spanning $8.5 < z < 9.5$, $9.5 < z < 10.5$, $10.5 < z < 11.5$ and $11.5 < z < 13.5$. The galaxy number densities are tabulated in Table 5.2 along with their corresponding uncertainties. The uncertainties were calculated using Poisson confidence intervals from Gehrels (1986) combined in quadrature with the cosmic variance uncertainty. The cosmic variance was estimated using the calculator from Trenti & Stiavelli (2008) for each of the survey fields using the default cosmological parameters with a $\sigma_8 = 0.9$ and a halo-filling factor of unity. This was then combined using the prescription from (equation (9) in Moster et al., 2011). However, the cosmic variance uncertainty (which ranges from 15% to 25%) in fact has minimal impact on the final uncertainties and including them does not significantly alter my results. For comparison, in Fig. 5.5 I also plot a number of other measurements of the UV LF from the recent literature.

At $z = 9$ my new measurement of the UV LF is consistent with the early *JWST*-based results of Chapter 3, as well as with other recent *JWST* and pre-*JWST* studies (e.g. McLeod et al., 2016; Bouwens et al., 2021). I also find good

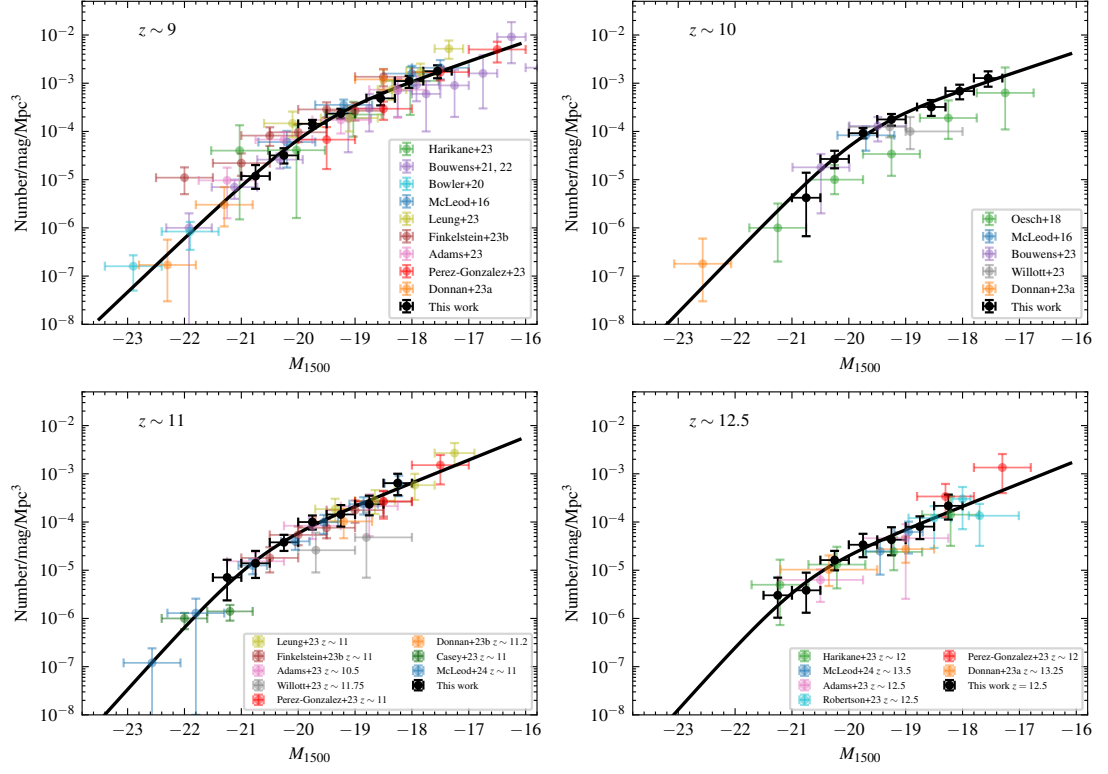


Figure 5.5 Our new measurements of the rest-frame UV LF at $z = 9, 10, 11$ and $z = 12.5$ are shown as the black data points. For comparison I also show data points from *McLeod et al. (2016)*; *Oesch et al. (2018)*; *Bowler et al. (2020)*; *Bouwens et al. (2021, 2023b)*; *Harikane et al. (2023b)*; *Adams et al. (2024)*; *Leung et al. (2023)*; *Donnan et al. (2023a,b)*; *McLeod et al. (2024)*; *Pérez-González et al. (2023)*; *Finkelstein et al. (2024a)*; *Casey et al. (2024)*; *Bouwens et al. (2023a)*; *Willott et al. (2024)*; *Robertson et al. (2024)* with colours indicated in the figure legend. The best fitting double-power law functions are shown as the solid black lines at each respective redshift.

consistency with the faint-end slope measurements from [Bouwens et al. \(2023b\)](#) which were based on an analysis of the available lensing fields from *HST* which enabled a measurement of the UV LF down to $M_{\text{UV}} \simeq -16$ at $z = 9$. At $z = 10$ there is good consistency between my new measurement and the pre-*JWST* measurement from [McLeod et al. \(2016\)](#), as well as an early analysis of *JWST* imaging from [Bouwens et al. \(2023a\)](#). At $z = 11$ I can compare to a significant number of recent *JWST* studies and find that my new measurement of the UV LF is consistent with many of them, in particular the recent wide-area study of [McLeod et al. \(2024\)](#). My determination of the UV LF at $z = 11$ is also consistent with measurements of the faint-end of the $z = 11$ UV LF by [Leung et al. \(2023\)](#) and [Pérez-González et al. \(2023\)](#), who studied a relatively small area ($\simeq 8$ sq. arcmin) covered by the NGDEEP and MIDIS fields, respectively. However, it can be seen that my new measurement of the $z = 11$ UV LF is consistently higher than the recent determination by [Willott et al. \(2024\)](#).

At $z = 9, 10$ and $z = 11$ I am able to achieve a dynamic range of $\simeq 4$ magnitudes ($-21 < M_{\text{UV}} < -17$) due to my multi-field approach, without relying on gravitational lensing. This is transformative compared to the early measurements of the UV LF from *JWST* and, in combination with my large sample size, allows the UV LF to be measured with significantly lower uncertainties. Overall I find a particular lack of evolution at $z = 9 - 11$ which is consistent with previous *JWST* studies (e.g. [Finkelstein et al., 2024a](#)). At $z = 12.5$ I am still able to measure the UV LF over a dynamic range of $\simeq 3$ magnitudes ($-21 < M_{\text{UV}} < -18$), significantly increasing the number of LF bins at this redshift. My new determination of the $z = 12.5$ UV LF is in reasonable agreement with recent *JWST*-based measurements from the literature (e.g. [Adams et al., 2024](#); [Robertson et al., 2024](#)).

With this sample I am able to robustly measure the evolution of the UV LF from $z = 9 - 13$. However, beyond $z = 13.5$ there is a noticeable dearth in the total $p(z)$ and therefore I am unable to precisely measure the UV LF at this redshift. That said, although limited by small-number statistics (the equivalent of $\simeq 1.3$ galaxies), I am able to plot a single bin at $z \simeq 14.5$, spanning the range $13.5 < z < 15.5$. This single bin is shown in Fig. 5.6, where I compare to measurements from other recent studies centred on redshifts from $z \simeq 13 - 15$.

Table 5.2 *Computed UV LF data points shown in Fig. 5.5 at $z = 9, 10, 11, 12.5$ and in Fig. 5.6 at $z = 14.5$. The columns show the central redshift and central UV absolute magnitude of each bin, and then the source number densities within each bin, along with their corresponding uncertainties.*

z	$M_{\text{UV}} / \text{AB mag}$	$\phi / 10^{-6}/\text{mag/Mpc}^{-3}$
9	-20.75	12^{+8}_{-5}
9	-20.25	32^{+13}_{-10}
9	-19.75	144^{+30}_{-28}
9	-19.25	235^{+60}_{-49}
9	-18.55	486^{+157}_{-139}
9	-18.05	1110^{+310}_{-310}
9	-17.55	1776^{+578}_{-510}
10	-20.75	4^{+10}_{-4}
10	-20.25	27^{+13}_{-10}
10	-19.75	92^{+25}_{-20}
10	-19.25	177^{+53}_{-45}
10	-18.55	321^{+127}_{-111}
10	-18.05	686^{+245}_{-223}
10	-17.55	1278^{+486}_{-432}
11	-21.25	7^{+9}_{-5}
11	-20.75	14^{+11}_{-7}
11	-20.25	38^{+16}_{-13}
11	-19.75	100^{+37}_{-30}
11	-19.25	144^{+81}_{-63}
11	-18.75	234^{+118}_{-96}
11	-18.25	641^{+361}_{-281}
12.5	-21.25	3^{+4}_{-2}
12.5	-20.75	4^{+5}_{-3}
12.5	-20.25	16^{+9}_{-6}
12.5	-19.75	34^{+23}_{-15}
12.5	-19.25	43^{+35}_{-22}
12.5	-18.75	80^{+51}_{-36}
12.5	-18.25	217^{+153}_{-104}
14.5	-20.25	3^{+6}_{-2}

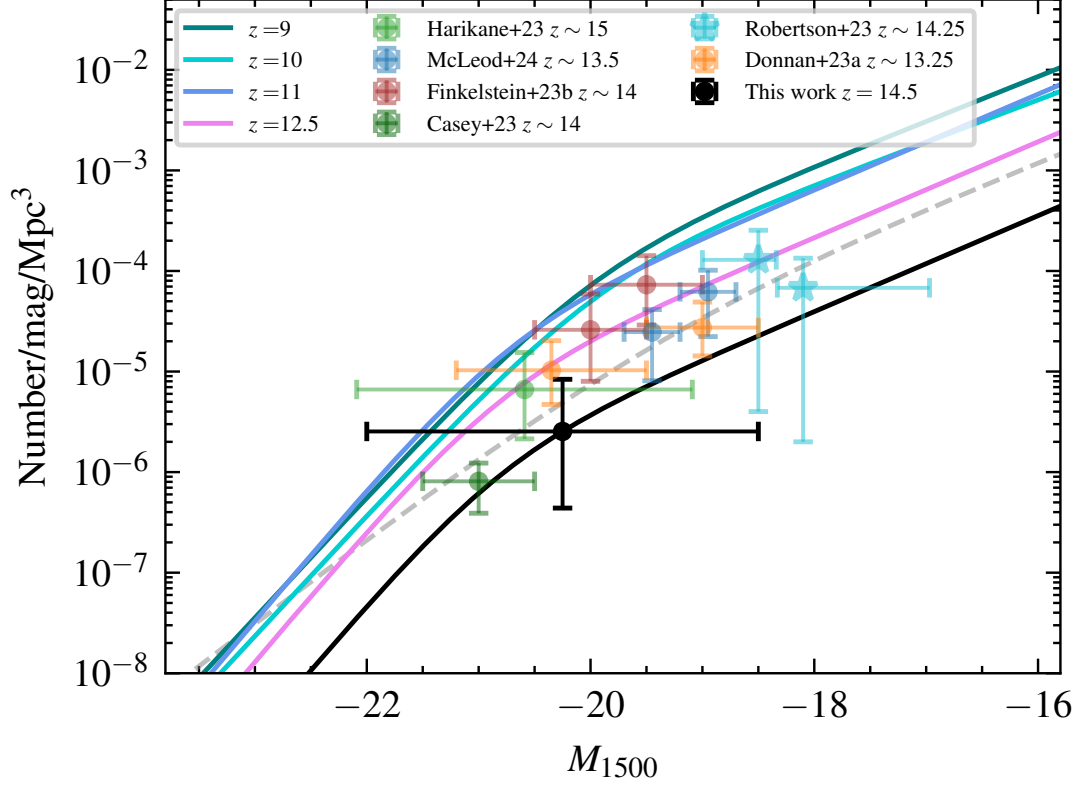


Figure 5.6 Our tentative measurement of the rest-frame UV LF at $z = 14.5$ is shown as the black data point. I include data points from [Harikane et al. \(2023b\)](#); [Donnan et al. \(2023a\)](#); [McLeod et al. \(2024\)](#); [Finkelstein et al. \(2024a\)](#); [Casey et al. \(2024\)](#); [Robertson et al. \(2024\)](#) for comparison. The best-fitting double power-law function is shown as the solid black line, where only the normalisation was allowed to evolve from $z = 12.5$. The dashed grey line shows the prediction from the evolving UV LF model described in Section 5.3.2. The solid coloured lines show my best fitting double power-law fits at $z = 9, 10, 11$ and $z = 12.5$, with colours as indicated in the figure legend.

Luminosity function fitting

It is now typical to fit the UV LF at $z \geq 7$ with a double-power law (DPL) rather than a Schechter function, due to the excess of very bright galaxies that have been detected from large area ground-based surveys (e.g. [Bowler et al., 2017, 2020](#); [Donnan et al., 2023a](#); [Varadaraj et al., 2023](#)). I therefore fit my new observational data points at $z = 9, 10, 11$ and $z = 12.5$ with a DPL parameterisation. I perform the fitting with the SCIPY `curve_fit` function ([Virtanen et al., 2020](#)) using a least-squares method to fit the data. To enhance the dynamic range in UV luminosity, I include in the fits the bright-end data points from [Bowler et al. \(2020\)](#) and Chapter 3 at $z = 9$ and from [McLeod et al. \(2024\)](#) at $z = 11$.

Given the limited constraints on the bright-end of the LF at $z = 10$, I fix the bright-end slope to $\beta = -4.05$, as this is the midpoint between the best-fitting values at $z = 9$ and $z = 11$. Due to the more limited number of data points available at $z = 12.5$, there is insufficient dynamic range in UV luminosity to perform a free-fit to the data. Consequently, I fix the faint-end and bright-end slopes to their best-fitting values at $z = 11$, but keep the LF normalisation (ϕ^*) and the characteristic magnitude (M^*) as free parameters.

The results of the LF fits are shown as the solid black lines in Fig. 5.5 and the best-fitting DPL parameters are reported in Table 5.3. I also fit a DPL to the single bin at $z = 14.5$, fixing M^* , α and β to their best-fitting values at $z = 12.5$, and fitting ϕ^* alone. This fit is shown as the black solid line in Fig. 5.6.

5.4.3 The cosmic star-formation rate density

The UV luminosity density (ρ_{UV}) was calculated by performing a luminosity-weighted integral of my best DPL fits to the data. I integrated down to a limit of $M_{\text{UV}} = -17$ which is consistent with many other *JWST* studies (e.g. [Finkelstein et al., 2024a](#); [Harikane et al., 2023b](#); [Adams et al., 2024](#)). The UV luminosity density was then converted to the cosmic star-formation rate density (ρ_{SFR}) using the conversion factor $\mathcal{K}_{\text{UV}} = 1.15 \times 10^{-28} \text{ M}_{\odot} \text{ yr}^{-1} / \text{erg s}^{-1} \text{ Hz}^{-1}$ ([Madau & Dickinson, 2014](#)) which assumes a [Salpeter \(1955\)](#) initial mass function (IMF). The results are shown in Fig. 5.8.

The improved statistics and dynamic range in UV luminosity of this study provide measurements of the UV luminosity density at $z = 9$ to $z = 12.5$ with much lower

Table 5.3

The derived parameter values for the best-fitting double power-law (DPL) models fitted to my data over the redshift range $9 < z < 15.5$. The LF fits derived at $z = 9$ and $z = 11$ utilised the new data presented here along with the data-points presented by [Bowler et al. \(2020\)](#) and [McLeod et al. \(2024\)](#). At $z = 10$ and $z = 12.5$ the fits are based purely on the new analysis and galaxy samples presented in this work. The first column gives the central redshift of the binned LF. This is followed by the values of the best-fitting characteristic density ϕ^* , the best-fitting or fixed characteristic absolute magnitude M^* , the fitted or assumed faint-end slope α , and the fitted or adopted bright-end slope β (see text for details). In the cases where a parameter was fixed, the value is denoted with an asterisk. The final column states the resulting UV luminosity density derived at each redshift.

z	$\phi^*/\text{mag}/\text{Mpc}^{-3}$	$M^*/\text{AB mag}$	α	β	$\log_{10}(\rho_{\text{UV}}/\text{ergs s}^{-1}\text{Hz}^{-1}\text{Mpc}^{-3})$
9	$(23.5 \pm 39.2) \times 10^{-5}$	-19.70 ± 0.96	-2.00 ± 0.47	-3.81 ± 0.49	$25.29^{+0.05}_{-0.05}$
10	$(14.5 \pm 16.4) \times 10^{-5}$	-19.98 ± 0.61	-1.98 ± 0.40	-4.05^*	$25.12^{+0.07}_{-0.08}$
11	$(3.27 \pm 9.86) \times 10^{-5}$	-20.73 ± 1.61	-2.19 ± 0.69	-4.29 ± 1.30	$25.12^{+0.14}_{-0.20}$
12.5	$(0.99 \pm 0.99) \times 10^{-5}$	-20.82 ± 0.71	-2.19^*	-4.29^*	$24.64^{+0.18}_{-0.32}$
14.5	$(0.18 \pm 0.28) \times 10^{-5}$	-20.82^*	-2.19^*	-4.29^*	$23.92^{+0.27}_{-0.81}$

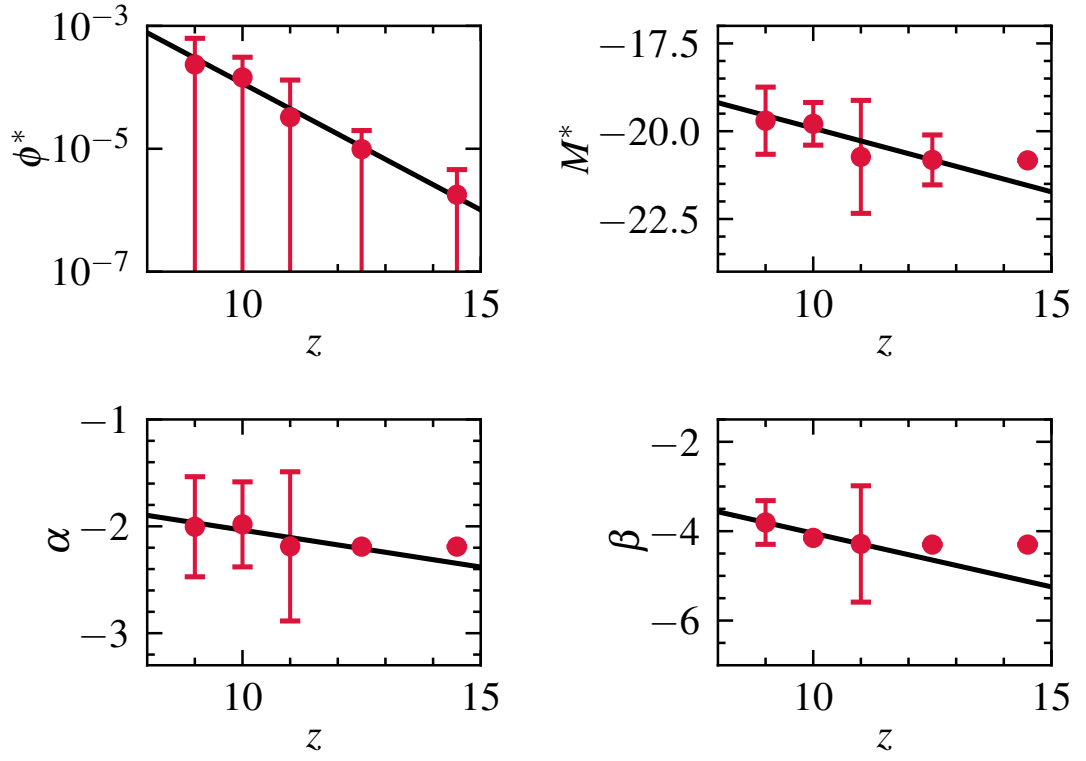


Figure 5.7 *The evolution of the best-fitting double-power law parameters at $z = 9, 10, 11, 12.5$ from my UV LF fitting. The solid black line shows a linear fit to the evolving parameters. Where a parameter was fixed, its value is indicated by a data point with no error bar.*

uncertainties than early *JWST*-based measurements.

In Chapter 3 I performed a log-linear fit to the evolution of ρ_{UV} with redshift, motivated in part by the analytical expression from [Hernquist & Springel \(2003\)](#). An updated log-linear fit to my new data is shown as the solid black line in Fig. 5.8 and has the functional form

$$\log(\rho_{\text{UV}}) = (-0.140 \pm 0.068)z + (26.5 \pm 0.6). \quad (5.8)$$

It can be seen that this expression provides an excellent description of the evolution of ρ_{UV} over the redshift range $8 < z < 12.5$. Interestingly, it is noticeable that an extrapolation of this relation (dashed black line) sits somewhat higher than my tentative measurement of ρ_{UV} at $z = 14.5$.

5.5 Discussion

5.5.1 A multi-field approach to measuring the galaxy LF

By combining the data from the PRIMER, JADES and NGDEEP *JWST* NIRCam surveys I have been able to conduct a relatively wide-area survey which also samples $\simeq 4$ mag of dynamic range in UV luminosity at $z = 9$ to $z = 12.5$. This, coupled with a rigorous, statistically robust methodology, has enabled us to substantially improve our knowledge of the form and evolution of the UV galaxy LF at $z \geq 9$ compared to what was achieved by previous studies.

Firstly, by combining four separate survey fields with a total combined area of $\simeq 370$ sq. arcmin, I have been able to mitigate the impact of cosmic variance on my measurements. Primarily due to the impact of PRIMER, my survey area is an order-of-magnitude larger than that which was available in the initial studies of the high-redshift UV LF undertaken with *JWST* data. For example, the first measurements of the UV LF with *JWST* were derived from early imaging which covered only ~ 40 sq. arcmin ([Donnan et al., 2023a](#); [Finkelstein et al., 2022a](#); [Bouwens et al., 2023a](#)). As *JWST* Cycle 1 progressed, the area of available imaging expanded somewhat, to ~ 100 sq. arcmin ([Harikane et al., 2023b](#); [Adams et al., 2024](#); [Finkelstein et al., 2024a](#)). However, all of these early NIRCam-based studies essentially utilised the same survey fields, notably the CEERS ([Bagley et al., 2024b](#)) ERS imaging of the EGS field (initially covering

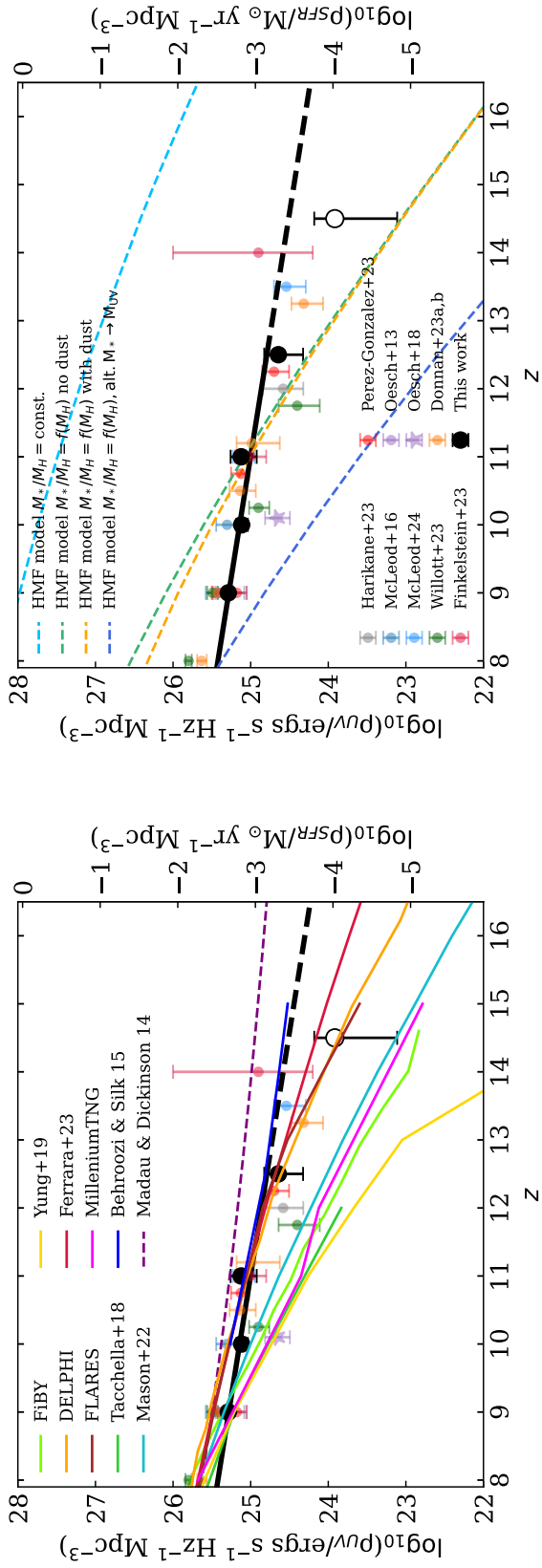


Figure 5.8 The redshift evolution of the UV luminosity density, ρ_{UV} , and hence the inferred cosmic star-formation rate density, ρ_{SFR} , at $z > 8$ with my new measurements at $z \sim 9, 10, 11, 12.5$ (solid black circular data points) and my tentative measurement at $z = 14.5$ (open black circular data point). Estimates at $z \simeq 9 - 10$ from Oesch et al. (2013, 2018) and McLeod et al. (2016) are shown by the purple and blue data points respectively. The green, grey and light red points show ρ_{UV} derived from the LFs in Willott et al. (2024), Harikane et al. (2023b) and Pérez-González et al. (2023) respectively. All values were determined using a limit of $M_{UV} = -17$ in the luminosity-weighted integral. The orange data points show the results from Donnan et al. (2023a,b) (see Chapter 3 and Chapter 4). The solid black line shows the best-fitting linear relation at $z = 9 - 12.5$ with an extrapolation shown by the dashed black line. The left-hand panel shows a comparison to theoretical models, again setting the LF integration limit to $M_{UV} = -17$. The green, cyan, blue and yellow lines show semi-analytic models from Tacchella et al. (2018), Mason et al. (2023), Behroozi & Silk (2015) and Yung et al. (2019) respectively. The red line shows the dust-free model from Ferrara et al. (2023). The green, brown and pink lines show the results of hydrodynamical simulations from FiBY (Johnson et al., 2013; Paardekooper et al., 2015), FLARES (Wilkins et al., 2023), DELPHI (Mauerhofer & Dayal, 2023) and MilleniumTNG (Kannan et al., 2023). The dashed purple line shows an extrapolation at $z \geq 8$ of the $\rho_{UV} \propto (1+z)^{-2.9}$ relation from Madau & Dickinson (2014). The dashed lines in the right panel show the predictions from my halo mass function (HMF) models. I show the HMF model where $\log(M_{*}/M_{\odot}) = 9$ corresponds to $M_{UV} = -22.47$ assuming a constant stellar mass to halo mass ratio (light blue), the same mass-to-light conversion but with a halo-mass dependent stellar mass to halo mass ratio consistent with that at $z = 0$ (green) and then where dust is introduced (orange). The dark blue curve shows the same as the model in green but with an alternative scaling where $\log(M_{*}/M_{\odot}) = 10$ corresponds to $M_{UV} = -22.4$.

$\simeq 35$ sq. arcmin, subsequently expanding to $\simeq 90$ sq. arcmin after programme completion) and the Abell 2744 cluster field which was imaged by the GLASS (Treu et al., 2022) and UNCOVER (Bezanson et al., 2024) programmes. As noted in Castellano et al. (2023), as well as being relatively small (and complicated by gravitational lensing), this latter field has a significant over-density at $z \simeq 10$, severely exacerbating the impact of cosmic variance on LF determinations at these redshifts.

These limitations motivated the work of McLeod et al. (2024), which represents the most extensive study of the UV LF at $z = 11$ completed prior to the present work. This study was based on a combined survey area of $\simeq 210$ sq. arcmin, and the results solidified the earlier measurements of the extreme-redshift UV LF, with the data again supporting a slow, gradual evolution of the LF between $z = 9$ and $z = 11$. The results presented here are in excellent agreement with those derived by McLeod et al. (2024), which is all the more significant because the present study is based on a different set of survey fields, and utilises a different method for calculating the evolving LF. These consistent results, now based on effectively $\simeq 600$ sq. arcmin of NIRCcam imaging, contrast with the evolution of the LF recently presented by Willott et al. (2024). This study used imaging from the CANUCS survey targeting five cluster fields, covering a relatively small total area of $\simeq 50$ sq. arcmin, with the medium-band imaging (a strength of the CANUCS dataset) only covering $\simeq 35$ sq. arcmin. Therefore, as they note, they may have targeted one or more relatively underdense fields, which most likely explains why their results differ somewhat from the higher number densities found here and in other wider area studies (e.g. McLeod et al., 2024; Finkelstein et al., 2024a).

Secondly, my new study benefits from vastly improved statistics, simply because my combined multi-tiered survey has yielded a very large sample of galaxies from which to compute the UV LF over a wide range in UV luminosity and redshift. This has led to a significant reduction in the statistical uncertainties in my measurements as well as enabling us to produce LF measurements in an increased number of redshift bins over the redshift range $z = 9 - 12.5$. By increasing the dynamic range in UV luminosity compared to previous *JWST* studies, I am better able to constrain the shape of the LF and hence explore how the parameters of the adopted DPL function evolve with redshift. In performing the DPL fits, I found that the data were of sufficient quality to enable us to allow the characteristic magnitude, M^* , and the characteristic density, ϕ^* , to be fitted as free parameters at $z = 9 - 12.5$. The results as a function of redshift are

shown in the upper two panels of Fig. 5.7, where it can be seen that the derived evolution in ϕ^* is stronger than that inferred for M^* . This indicates that there is more density evolution than luminosity evolution in the UV LF over the redshift range $z = 9 - 12.5$, consistent with the persistence of relatively bright galaxies out to extreme redshifts (e.g. Castellano et al., 2023; McLeod et al., 2024).

We can also explore the evolution of the faint- and bright-end slopes of the DPL fit. Although the bright-end slope, β , is (by necessity) fixed for the fits at $z = 10$ and $z = 12.5$, I see a lack of evolution between the free fits achieved at $z = 9$ and $z = 11$. The same is also true of the faint-end slope, α , where I find no significant evolution between $z = 9$ (where I obtain $\alpha = -2.00 \pm 0.47$) and $z = 11$ (where I find $\alpha = -2.19 \pm 0.69$). My results are consistent with other recent studies of the faint-end slope, which also observe no significant change over this redshift range (Leung et al., 2023; Pérez-González et al., 2023).

Using wide-area ground-based surveys, such as UltraVISTA, it has been demonstrated that there is little if any evolution in the bright end of the UV LF from $z \simeq 7$ to $z \simeq 10$ (e.g. Stefanon et al., 2019; Bowler et al., 2020; Donnan et al., 2023a). However, due to the wavelength restriction of ground-based telescopes, the bright-end of the UV LF at $z > 10$ can only be measured with wide-area surveys from *JWST*. My results re-affirm the findings of McLeod et al. (2024) and now extend the evidence for the lack of evolution in the bright-end of the LF out to $z \simeq 12.5$. Several previous studies have discussed the potential physical mechanisms that might allow/explain this (arguably unexpected) lack of evolution in the bright galaxy population at early times (e.g. Bowler et al., 2017, 2020; Finkelstein & Bagley, 2022). A decrease in dust attenuation or a lack of AGN feedback have been suggested as contributing factors, while others have inferred that the data imply increased star-formation efficiency in the very young Universe (Harikane et al., 2023b). However, as I discuss further below, while these proposed astrophysical changes may be important, and can certainly not be excluded at present, they are not in fact required to explain the results of the present study.

In the left-hand panel of Fig. 5.8 I compare my new measurements of ρ_{SFR} to a number of theoretical models and cosmological simulations. It can be seen that the model predictions diverge widely beyond $z \simeq 9$, and so the diagnostic power of the new measurements is clear. In particular, the observational data now clearly lie above the constant star-formation efficiency models of Tacchella et al. (2018), Yung et al. (2019) and Mason et al. (2023). However, there is good

agreement between the observations and the predictions of the FLARES (Vijayan et al., 2020; Lovell et al., 2020; Wilkins et al., 2023) and DELPHI (Mauerhofer & Dayal, 2023) cosmological hydrodynamical simulations. My results are also consistent with the predictions of the semi-empirical dust-free model presented by Ferrara et al. (2023), which is discussed further in Section 5.5.3. It should be noted that the DELPHI and Ferrara et al. (2023) dust-free models were both published after initial *JWST* studies suggested a high abundance of luminous galaxies at $z \geq 10$.

5.5.2 The star-formation rate density at $z \geq 13$

The wealth of new deep NIRCam imaging delivered by *JWST* has already enabled a large number of galaxy candidates to be detected up to $z \simeq 12$, and several of these extreme redshift candidates have already been spectroscopically confirmed with NIRSpec (e.g. Harikane et al., 2024; Arrabal Haro et al., 2023b). Indeed, as shown in the present work, the galaxy samples that can now be assembled at $z \simeq 12$ (by combining the major Cycle-1 programmes) are large and robust enough to enable the basic form and amplitude of the UV LF to be well constrained at these redshifts. However, the nature of galaxy evolution at still higher redshifts, $z \geq 13$, remains much more uncertain. Despite the abundance of *JWST* imaging now available, and the absence of any wavelength limitation, there remain very few robust galaxy candidates at $z \geq 13$, with only one spectroscopic confirmation of a faint galaxy at $z = 13.2$ (Curtis-Lake et al., 2023). This has inevitably led to uncertainty in constraining the UV galaxy LF and hence cosmic star-formation rate density at $z \geq 13$.

In Chapter 3 I proposed a log-linear relationship between comoving cosmic star-formation rate density, ρ_{SFR} , and redshift, z , at $z \geq 8$, motivated at least in part by the theoretical expectations articulated by Hernquist & Springel (2003). Indeed, the early *JWST* results did appear consistent with the inferred smooth, gradual decline in ρ_{SFR} to higher redshift, and the results of the present study re-affirm this conclusion, showing that the log-linear relation remains a good fit to my new robust constraints over the redshift range $z = 9 - 12.5$, as shown by the solid black line in Fig. 5.8. However, at some point a departure from this relationship is inevitable as I enter the epoch of the very first galaxies. To explore to yet higher redshifts, as described in Section 5.4, I have attempted to calculate a basic estimate of the galaxy number density at $z = 14.5$ from my data. This

measurement provides some tentative evidence for the onset of a steeper decline in the UV LF between $z = 12.5$ and $z = 14.5$, with the inferred ρ_{SFR} at $z = 14.5$ lying below the extrapolation of the log-linear relation fitted at $z = 9 - 12.5$. However, this measurement is highly uncertain, as indicated by the error bars, and I caution against any strong interpretation of this result given that my UV LF measurement at $z = 14.5$ is based on a total $p(z)$ equivalent to $\simeq 1.3$ galaxies.

[Robertson et al. \(2024\)](#) also recently explored this very early epoch within the $\simeq 8$ sq. arcmin of the JADES Origins Field (JOF). They report 3 candidates at $z > 13.5$ but note that none of them can be regarded as robust. Therefore they discuss two alternative scenarios in which they calculate ρ_{SFR} with and without the 2 highest-redshift candidates (proposed to lie at $z > 14$), yielding the expected result that there is a more rapid decline in ρ_{SFR} with the extreme redshift candidates removed. Although, as noted above, my own measurement of ρ_{SFR} at $z = 14.5$ is somewhat poorly constrained, it is nonetheless more closely aligned with this more rapid decline scenario at $z > 13$. Indeed, consistent with this, my own investigation of the JADES data supports the removal of all 3 of the $z > 13.5$ candidates tentatively reported by [Robertson et al. \(2024\)](#). I recover one of these galaxies in my sample (JADES+53.02868–27.89301) but find a $p(z)$ which peaks at $z \sim 3.5$ (albeit still with a non-negligible probability of lying at $z \sim 13$). The 2 candidates at $z > 14$ tentatively reported by [Robertson et al. \(2024\)](#) do not contribute significantly to my high-redshift LFs because in both cases the bulk of their redshift probability distribution lies at much lower redshifts in my analysis (which I emphasize, however, involves the use of LF priors). This therefore adds to the tentative but growing evidence that there is a change from the gradual evolution in the LF observed at $z = 9 - 13$ to a more rapid decline at $z > 13$. However, still better constraints on the UV LF (and hence ρ_{SFR}) are needed at these extreme redshifts to confirm the existence and/or severity of this transition.

5.5.3 Modelling the growth of the galaxy population at $z > 8$

As discussed above, the initial observations from *JWST* revealed a high abundance of (UV) bright galaxies at $z \geq 10$ which stimulated a number of theoretical attempts to explain their abundance. One natural point of astrophysical interest is the way in which the dust attenuation of galaxies might change (*i.e.* reduce) with increasing redshift. Indeed, [Ferrara et al. \(2023\)](#) have

recently proposed a model in which galaxies are essentially dust-free at very early times, finding good agreement with the first measurements of the UV LF from *JWST*. In this specific model they propose that the dust could have been ejected from the galaxies as a by-product of intense star-formation activity, leading to (temporarily) dust-free galaxies that might populate the bright end of the LF at $z > 10$. This model does indeed provide a good fit to my new observational constraints on ρ_{UV} , as shown by the red solid line in the left-hand panel of Fig. 5.8. There is now also independent observational evidence for a lack of significant dust in galaxies at $z > 10$ as inferred from analyses of the UV continuum slopes, β , displayed by early galaxies. In particular, Cullen et al. (2024b) report that, at $z = 11.5$, the average UV slope plateaus at $\beta \simeq -2.6$, consistent with dust-free stellar populations. This is also consistent with the UV-slope measurements of Morales et al. (2024) and Topping et al. (2024b). It has also been suggested that increasingly stochastic star formation, with spells of enhanced star-formation efficiency, can help to explain the high number densities of galaxies observed in the rest-frame UV at $z \geq 10$ (Mason et al., 2023).

To explore the physical processes which might explain my observational measurements I have constructed a simple model of galaxy evolution based on the evolving dark matter halo mass function (HMF). I first calculated the evolving HMF at $z = 8 - 15$ using `HMFcalc` (Murray et al., 2013) with the model from Reed et al. (2007). This was then converted to an evolving galaxy stellar mass function (GSMF) simply using a form of the mass-dependent stellar-mass to halo-mass ratio consistent with that at $z \simeq 0$ (Behroozi et al., 2010). This step essentially applies the impact of the inferred feedback processes at both high and low halo masses which regulate the shape of the GSMF and, correctly or incorrectly, assumes this is unchanged with redshift. The derived evolving GSMF was then converted to a UV LF at each redshift by a scaling equivalent to assuming that a galaxy with a stellar mass of $\log(M_*/M_\odot) = 9$ has a UV luminosity equivalent to $M_{\text{UV}} = -22.47$. This mass to UV magnitude conversion was determined from a BC03 stellar population model (Bruzual & Charlot, 2003) with a metallicity of $Z/Z_\odot = 0.2$, a Chabrier (2003) IMF and an assumed constant star-formation history with an age of 30 Myr. I compare the predictions of this simple model to the observed evolution of ρ_{UV} in the right-hand panel of Fig. 5.8, and show a detailed comparison of the LF predicted by this model with my observed UV LF at $z = 11$ in the left-hand panel of Fig. 5.9.

We show my primary model by the dashed green line which is consistent with

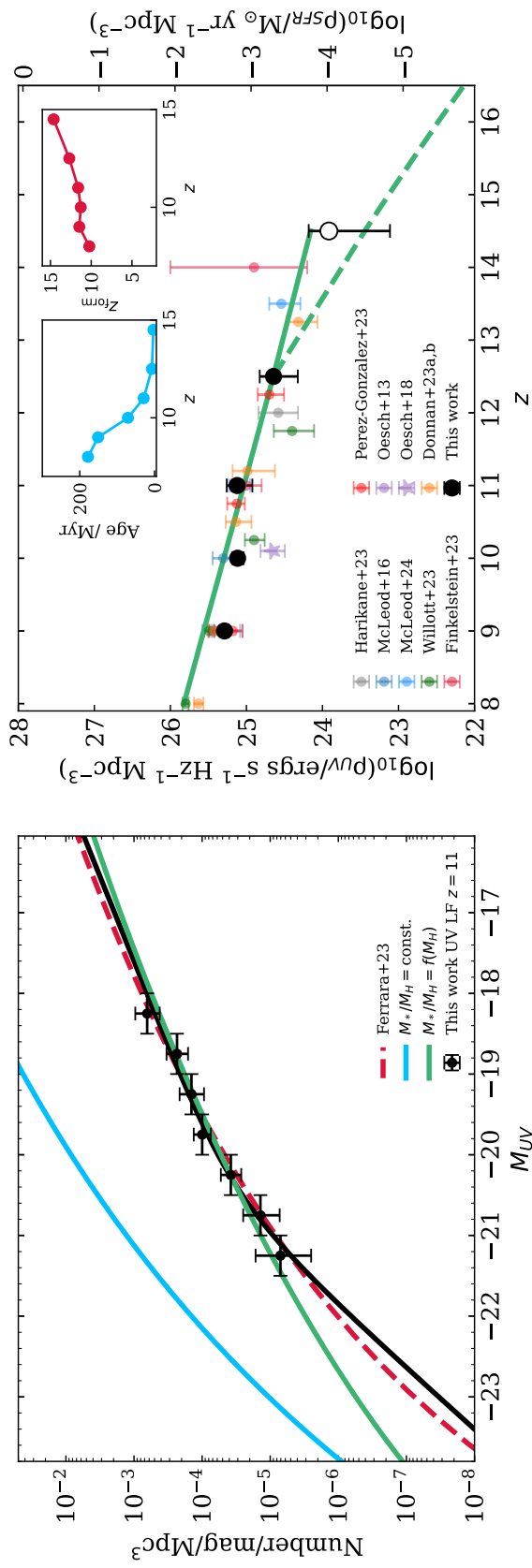


Figure 5.9 Left: The observed UV LF at $z = 11$ compared to my DPL fit (black), my HMF model assuming a constant $M_*/M_H = 1/35$ ($\epsilon \simeq 0.17$, light blue), my HMF model with $M_*/M_H = f(M_H) = f(M_H)$ (solid green), and the dust-free model from Ferrara et al. (2023) (dashed red). Right: The observed evolving UV luminosity density, ρ_{UV} , and cosmic star-formation rate density, ρ_{SFR} , at $z > 8$ compared to the predictions of my model of the HMF in which the typical stellar population age is allowed to be redshift-dependent (solid green line). The dashed green line shows the extreme-redshift prediction of my HMF model if the stellar population age is simply fixed to 10 Myr at $z \geq 12.5$. The two inset panels show the age (left) and inferred formation redshift (right) of the stellar populations required to best fit my evolving HMF model to the UV LF at each redshift.

the data at $z \geq 10$ but overshoots the observations at $z < 10$. To attempt to correct this I introduce a dust component to the model by adding mass-dependent UV dust attenuation, A_{1500} , given by the dust to stellar-mass relation at $z = 2$ derived by [McLure et al. \(2018a\)](#). This model is shown by the orange line in the right-hand panel of Fig. 5.8 which lies slightly below the green dashed line, but still overshoots the data at $z < 10$. This is perhaps unsurprising as galaxies at $z < 10$ are likely to have average ages older than the assumed value of 30 Myr. Moreover, additional feedback at low stellar masses in the reionization era, or reduced halo occupation could also play a role in reducing the predicted ρ_{UV} at $z < 10$.

We also show two secondary models. The first is created by altering the step where I apply feedback at the low- and high-mass ends of the HMF. Instead I simply use $M_*/M_H = 1/35$, which is the peak value found in the present-day Universe, corresponding to the observed maximum in historical star-formation efficiency ($\epsilon \simeq 0.17$). This effectively provides an upper limit on what is physically permitted by the assumed Λ CDM cosmology while assuming that star-formation efficiency has never been more efficient at any mass than for present-day Milky-Way mass galaxies. This simple removal of both high- and low-mass feedback predicts the evolution of ρ_{UV} shown by the dashed light-blue line in the right-hand panel of Fig. 5.8 and the form of the $z = 11$ UV LF shown by the solid light-blue line in the left-hand panel of Fig. 5.9.

Clearly the predictions of this modified model vastly exceed the observational results, demonstrating that my new measurements of the UV galaxy LF certainly do not threaten the viability of the standard Λ CDM cosmological model. I also show another modified model illustrated by the dashed dark-blue line in the right-hand panel of Fig. 5.8. This is the same as the primary model except that it assumes a different mapping from galaxy stellar mass to UV luminosity. Here I assume that a galaxy of stellar mass of $\log(M_*/M_\odot) = 10$ has a UV luminosity equivalent to $M_{UV} = -22.4$ as assumed at $z = 7$ in [Bowler et al. \(2014\)](#). This demonstrates that a much steeper decline is inevitably predicted when fixing the stellar mass to UV luminosity mapping at $z = 7$ assuming no dust obscuration.

The effect of dust at $z > 10$

As mentioned above, [Ferrara et al. \(2023\)](#) have presented a dust-free model of the UV LF and suggest physical mechanisms by which the dust could be expelled

from galaxies at $z > 10$. The galaxy UV LF predicted by this model at $z = 11$ is shown by the dashed red line in the left-hand panel of Fig. 5.9, where it can be seen to be in excellent agreement with my observational data points. However, as shown in the right-hand panel of Fig. 5.8, there is no significant difference in the inferred evolution of ρ_{UV} predicted by models which do or do not include dust obscuration at $z > 10$. This is because the dust-mass relation deduced by McLure et al. (2018a) at $z = 2$ indicates that there is essentially no significant dust attenuation (*i.e.* $A_{1500} \simeq 0$) for stellar masses below $\log(M_*/M_\odot) \simeq 8.4$, and, based on my primary model, the vast majority of the galaxies currently observed at $z > 10$ have stellar masses smaller than this. Indeed, my brightest bin at $z = 11$, corresponding to $M_{\text{UV}} = -21.25$, equates to a stellar mass of $\log(M_*/M_\odot) = 8.5$ according to my adopted mass to UV luminosity conversion. In other words, even assuming a Universe as dusty as observed at $z \simeq 2$ (*i.e.* at "cosmic noon", where dust-obscured star formation dominates ρ_{SFR}) I would not expect any of the galaxies that contribute to my observed UV LF at $z \simeq 11$ to be significantly attenuated by dust in the rest-frame UV. Or, in other words, the stellar-mass range (and hence M_{UV} regime) in which dust, if present at such early times, would have an observable impact has not yet been accessed in this study. Thus, within the range of UV luminosities probed by the *JWST* imaging surveys analysed here, I do not need to invoke any physical mechanism to remove or destroy dust to explain the data, as the observed galaxies are not expected to be massive enough to contain significant quantities of dust at any redshift. Further work, including the exploitation of still larger-area surveys, is thus required to measure the very bright end of the galaxy UV LF ($M_{\text{UV}} \lesssim -21.5$) at $z = 11$, and hence to determine whether dust removal processes are required to explain the properties of higher-mass galaxies at these early times.

Despite this current lack of robust statistical constraints on the bright-end form of the $z \simeq 11$ galaxy UV LF at $M_{\text{UV}} < -21.5$, a few 'bright' galaxy candidates have been uncovered in this luminosity regime at $z > 10$. These include the spectroscopically-confirmed $M_{\text{UV}} \simeq -21.8$ galaxy at $z = 10.6$ reported by Bunker et al. (2023) and Tacchella et al. (2023). Interestingly, these authors report a modest dust attenuation of $A_V = 0.17$ for a stellar mass of $\log(M_*/M_\odot) = 8.73$, consistent with the stellar mass-to-UV magnitude mapping and dust-mass relation used in my primary model. In addition I note that Casey et al. (2024) have reported an initial sample of more luminous ($M_{\text{UV}} \lesssim -21$) galaxy candidates from the first half of the COSMOS-Web programme (Casey et al., 2023), derived from imaging covering $\sim 0.28 \text{ deg}^2$. This yields an estimate

of the LF at $z = 11$ indicated by the dark-green data-points in the bottom-left panel of Fig. 5.5. These inferred number densities are consistent with my best-fitting DPL and suggests that there may indeed be galaxies massive enough to require dust-removal mechanisms at these extreme redshifts. However, the lack of contiguous filter coverage in the COSMOS-Web programme may result in more significant numbers of low-redshift contaminants in the high-redshift galaxy samples, in turn leading to more uncertain and potentially biased estimates of the bright end of the galaxy UV LF at extreme redshifts. Spectroscopic verification of these luminous high-redshift candidates is therefore required to accurately constrain their abundance.

An age-dependent model

Finally, I alter my primary model to introduce a stellar population age-dependence which creates a redshift-dependent mapping of stellar mass to UV luminosity. This was determined by adjusting the typical stellar age at a given redshift to best map the GSMF onto the UV LF at $z = 8 - 14.5$. This model is shown by the green solid line in the right-hand panel of Fig. 5.9. Unsurprisingly, and largely by design, this provides an excellent representation of the evolution of ρ_{UV} out to $z \simeq 13$. Also unsurprising, and physically sensible, are the relatively young inferred ages of the stellar populations at each redshift which dominate the rest-frame UV light, as tabulated in Table 5.4.

The required stellar ages are consistent with those obtained from fitting SED models to the *JWST*/NIRCam photometry. For example, Robertson et al. (2023, 2024) derive stellar ages of $t_* \simeq 10 - 70$ Myr for galaxies at $z \geq 10$. This trend of younger stellar ages at increasing redshift is also consistent with theoretical predictions, where increased gas accretion rates at high redshift lead to increased star-formation rates for fixed stellar mass (Mason et al., 2015, 2023). Therefore at fixed stellar mass, galaxies at higher redshifts have greater UV luminosities and younger stellar ages, consistent with the results of my model. What is more surprising, and potentially very interesting, is the extent to which, for $z = 8, 9, 10$, and 11 , the required stellar population ages converge on a common formation time corresponding to $\simeq 380$ Myr after the Big Bang (equivalent to a formation redshift $z_f \simeq 12$). This is again tabulated in Table 5.4, with the results of this analysis shown in the two inset panels in the right-hand panel of Fig. 5.9. I note that my fit quality and overall conclusion is unchanged with different choices

Table 5.4 *The age-dependent UV magnitude mapping to stellar mass as a function of redshift for my age-dependent model. This model is based on a BC03 stellar population model (Bruzual & Charlot, 2003) with a metallicity of $Z/Z_{\odot} = 0.2$. The first column is the redshift. The second column is the UV magnitude, M_{UV} , that is mapped to a stellar mass of $\log(M_*/M_{\odot}) = 9$ determined by the age given in the third column. The fourth column is the formation time after the Big Bang associated with this age and the final column is the formation redshift.*

z	$M_{\text{UV}} / \text{AB mag}$	Age / Myr	$t_{\text{form}} / \text{Myr}$	z_{form}
8	−20.68	178	451	10.23
9	−20.92	151	386	11.46
10	−21.65	71	395	11.28
11	−22.47	29	380	11.60
12.5	−23.33	7	336	12.69
14.5	−24.18	3	276	14.61

of the HMF in the model, with only a modest increase in the required stellar ages resulting from the adoption of a Sheth & Tormen (1999) HMF (pushing the galaxy emergence epoch back slightly to $z \simeq 12.5$) or decrease for a Tinker et al. (2008) HMF. My adopted model from Reed et al. (2007) is positioned in the middle of the scatter between different models of the HMF at $z > 8.5$.

Obviously the small number of galaxies discovered at $z \geq 13$ require a still higher formation redshift (albeit with now very young stellar ages, corresponding to a formation redshift $z_f \leq 14$), but there is nothing in my analysis which would *a priori* have required an inferred common epoch of formation for the galaxy populations observed over the redshift range $z \simeq 8 - 11$. These results indicate not only that the observed high-redshift evolution of the UV galaxy LF (and hence ρ_{SFR}) can be explained without requiring any changes to cosmology, star-formation efficiency, or indeed dust, but intriguingly they also point towards the rapid emergence of early galaxies at $z \simeq 12 - 13$, consistent with the first suggestions of a steeper decline in galaxy number density at $z \geq 13$ seen here in Fig. 5.8.

In this context, to illustrate what is *expected* to happen once ever-younger stellar populations can no longer offset the rapid decline of the halo mass function back to earlier times, I also plot a green dashed line in the right-hand panel of Fig. 5.9 which shows the extreme-redshift prediction of my model when the stellar population age is simply fixed to 10 Myr at $z \geq 12.5$. The prediction is that, unless the inevitable extreme-redshift decline in the halo mass function

is offset by more extreme/exotic stellar populations or enhanced star-formation efficiency, UV luminosity density is expected to decline more rapidly, by roughly two orders-of-magnitude from $z \simeq 13$ to $z \simeq 16$.

5.6 Conclusions

I have completed an analysis of the major Cycle-1 *JWST*/NIRCam imaging surveys PRIMER, JADES and NGDEEP, covering a total area of $\simeq 370$ sq. arcmin and reaching a $5\text{-}\sigma$ depth of $\simeq 30$ AB mag in the deepest regions. Rather than simply selecting galaxy candidates at high redshift by their "best" photometric redshift, I selected all galaxies that have at least a 5 per cent probability of lying at $z \geq 8.5$ and consider their $p(z)$. Through careful selection of galaxies I have derived the $p(z)$ for 2548 galaxies using a UV LF prior and hence calculated the evolution of the galaxy UV LF at $8.5 < z < 15.5$. My multi-field approach has allowed new constraints to be placed on the form of the UV LF spanning a UV luminosity range corresponding to $\simeq 4$ AB mag over the redshift range $z = 9 - 12.5$. This has allowed us to reach a number of conclusions.

First, the large dynamic range in UV luminosity resulting from my multi-field approach has enabled us to define the shape of the UV LF at $z = 9 - 12.5$ from $M_{\text{UV}} \simeq -21$ to $M_{\text{UV}} \simeq -17$. I have fitted my new measurements with a double-power law (DPL) functional form and explored how the parameters evolve with redshift. I find a lack of evolution in the bright- and faint-end slopes as well as at most only modest evolution in the characteristic magnitude, M^* . Much stronger evolution is seen in the LF normalisation suggesting that the evolution of the LF at $z = 9 - 12.5$ is dominated by density evolution rather than luminosity evolution.

Second, my new measurements of the UV LF have yielded improved constraints on the evolution of cosmic star-formation rate density, ρ_{SFR} , at $z \geq 9$. I find good agreement with prior work showing a smooth, slow evolution over the redshift range $z = 9 - 12.5$ which can be described with a log-linear relationship. Indeed, in the present study there is very little evolution between $z = 9$ and $z = 11$. I have also presented a tentative measurement of the galaxy number density at $z = 14.5$ which suggests the onset of a steeper decline in ρ_{SFR} , below the extrapolation of the log-linear relation to these extreme redshifts. This, albeit still necessarily uncertain result, hints at a more rapid build-up of galaxies at very early times

corresponding to $z > 13$.

Finally, I explore the evolution in the UV LF and ρ_{SFR} at $z \geq 8$ through simple modelling based on the halo mass function. I demonstrate that my measurements are fully consistent with a Λ CDM cosmology, and moreover currently require no change to the star-formation efficiency or the dust properties of galaxies as observed in the low-redshift Universe. Rather, I show that a simple evolution in the ages of the stellar populations can explain my measurements, with (unsurprisingly) the typical age of the galaxies which populate the UV LF decreasing with increasing redshift. Intriguingly I find that the typical ages required at $z \simeq 8, 9, 10$, and 11 all converge on a time $\simeq 380 - 330$ Myr after the Big Bang, equivalent to a formation redshift $z \simeq 12 - 13$. This is consistent with the aforementioned first signs of a steeper drop-off in the galaxy population I find beyond $z \simeq 13$, as expected given the very rapid evolution of the halo mass function at earlier times.

Chapter 6

A simple model of the galaxy stellar mass function and UV luminosity function at $z \geq 6$

6.1 Introduction

In only its first two years of operation, *JWST* has already significantly advanced our knowledge of galaxy evolution back into the first 500 million years of cosmic time, producing a wealth of new observational results which have revolutionized, and in some cases challenged our understanding of early galaxy formation and growth.

Thanks to its sensitivity and extended near-infrared wavelength coverage (out to $\lambda \simeq 5\mu\text{m}$) the NIRCам instrument on *JWST* has produced the first robust detections of significant numbers of galaxies at redshifts $z > 10$ (e.g. [Castellano et al., 2022](#); [Naidu et al., 2022b](#); [Donnan et al., 2023a,b](#); [Adams et al., 2023a](#); [Finkelstein et al., 2023](#); [Harikane et al., 2023b](#)). This has in turn enabled the first robust measurements of the evolving galaxy UV luminosity function (LF) at $z = 9 - 15$, revealing a perhaps surprisingly gradual evolution of the LF over this redshift range (e.g. [Finkelstein et al., 2024a](#); [Pérez-González et al., 2023](#); [McLeod et al., 2024](#); [Adams et al., 2024](#); [Donnan et al., 2024](#)). A number of the new high-redshift galaxy candidates have also been spectroscopically confirmed using the NIRSpec instrument (now up to $z \simeq 14.2$) (e.g. [Curtis-Lake et al., 2023](#); [Bunker](#)

et al., 2024; Arrabal Haro et al., 2023b; Carniani et al., 2024) as well as ALMA (Schouws et al., 2024). Although the relatively slow evolution of the galaxy population out to extreme redshifts is consistent with some pre-*JWST* predictions from simulations (Wilkins et al., 2023) and observational extrapolations (McLeod et al., 2016), it is undeniably in tension with a number of pre-*JWST* models, particularly at the bright end (e.g. Mason et al., 2015; Tacchella et al., 2018; Yung et al., 2019).

Several alterations to the physical properties of galaxies at early times have been proposed in order to explain the high-redshift evolution of the galaxy UV LF. Firstly, changes in the star-formation efficiency as a function of redshift have been invoked. For example, Harikane et al. (2023b) suggest that a constant efficiency model (based on that from Harikane et al. (2023a)) is unable to match the cosmic star-formation rate density (ρ_{SFR}) at $z > 10$. The implication is that an increase in star-formation efficiency with increasing redshift is required in order to match the observed prevalence of UV-luminous galaxies at $z \geq 10$.

Secondly, much reduced dust attenuation has been suggested to explain the bright-end of the UV LF at $z = 11$ (e.g. Ferrara et al., 2023) with it being proposed that any dust created in early galaxies could possibly (at least temporarily) be ejected due to the extreme physical conditions associated with early galaxy formation. A lack of dust at extreme redshifts is also arguably consistent with measurements of the UV continuum slopes of galaxies at $z = 11$ (derived from *JWST*/NIRCam photometry) which are, on average, consistent with $\beta \simeq -2.5$ (e.g. Topping et al., 2024b; Morales et al., 2024; Cullen et al., 2024b).

Another fundamental scaling relation is the galaxy stellar mass function (GSMF) which directly traces the product of star formation across cosmic time. By measuring the GSMF, one can obtain a direct probe of past star formation which, given the relatively short timescales involved at high redshifts, can be related to star-formation efficiency as a function of dark matter halo mass. Precise measurement of the GSMF requires photometry of the rest-frame optical light from galaxies in order to provide accurate stellar mass measurements for individual galaxies. Using *HST* as well as ground-based observations, the GSMF was previously measured up to $z \simeq 3$ by a number of studies (e.g. Muzzin et al., 2013; Mortlock et al., 2015; McLeod et al., 2021; Weaver et al., 2023). However, at $z \geq 3$, measurement of the GSMF proved more challenging because, prior to the launch of *JWST*, this could only be achieved by utilising relatively low resolution *Spitzer*/IRAC observations to probe the rest-frame optical at higher redshifts

(e.g. [Grazian et al., 2015](#); [Song et al., 2016](#); [Stefanon et al., 2021](#)). However, now *JWST* has enabled a number of new measurements of the GSMF, with the sensitivity and exquisite angular resolution of NIRC*am* at $\lambda \simeq 1 - 5\mu\text{m}$ enabling the first robust measurements of the GSMF over the redshift range $z = 3 - 8$ ([Weibel et al., 2024](#); [Harvey et al., 2024](#); [Shuntov et al., 2024](#)). The discovery of at least some very massive galaxies at these early times has again led to the suggestion that increases in star-formation efficiency (e.g. $\epsilon \sim 0.2$; [Chworowsky et al., 2024](#)) are required to explain their existence, with some authors even suggesting that the most extreme examples present a challenge to the standard ΛCDM cosmological model (e.g. $\epsilon \sim 0.8 - 1.0$; [Labbé et al., 2023](#); [Glazebrook et al., 2024](#); [Shuntov et al., 2024](#)).

Finally, there have been suggestions that there is an ionizing photon budget crisis ([Muñoz et al., 2024](#)) in the sense that some recent *JWST* results appear to imply that too many ionizing photons were produced at early times to be consistent with measurements of the evolving neutral fraction of the intergalactic medium (e.g. [Tang et al., 2024](#); [Nakane et al., 2024](#)) including the requirement that reionization is not fully completed until $z \simeq 5.5$ ([Bosman et al., 2021](#)).

Given the recent advances in the observational determinations of both the UV LF and the GSMF, it is clearly important to generate a theoretical framework that can simultaneously explain the form and evolution of both of these fundamental scaling relations. In this chapter I expand upon and further develop the model introduced in [Donnan et al. \(2024\)](#) to explore whether a simple theoretical model can reproduce the *JWST* constraints on the UV LF, the GSMF, and the timeline of reionization at $z = 6 - 13$. This can be viewed as a test of the extent to which current observational data really do require the introduction of more complex/changing astrophysics to explain the new results on early galaxy evolution emerging from *JWST*.

The chapter is structured as follows. In Section [6.2](#) I initially model the GSMF and compare to the latest observational constraints. In Section [6.3](#) I further develop the model to generate the UV LF at $z = 6 - 13$. In Section [6.4](#) I then introduce dust attenuation to my model of the UV LF and present the implied UV attenuation–stellar mass relation. In Section [6.5](#) I then explore the predictions of my model for the progress of cosmic hydrogen reionization. In Section [6.6](#) I then discuss the implications of my theoretical model for star-formation efficiency, high-mass feedback, dust attenuation and the ionizing photon budget. Finally, in Section [6.7](#) I summarize my conclusions. Throughout I use magnitudes in

the AB system (Oke, 1974; Oke & Gunn, 1983), a Chabrier (2003) initial mass function, and assume a standard cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

6.2 Modelling the stellar mass function

6.2.1 The star-formation efficiency

I begin by constructing a model of the galaxy stellar mass function (GSMF) which I describe in this section. To construct this simple model I first calculate the evolving dark-matter halo mass function (HMF) using HMF_{CALC} (Murray et al., 2013) where I use the model of Reed et al. (2007). A number of alternative models of the HMF are available which scatter across a range of ~ 0.15 dex at $z = 0$. This scatter increases with redshift with a ~ 0.35 dex scatter at $z = 10$ rising to a scatter of ~ 0.45 dex at $z = 13$. I adopt the Reed et al. (2007) model specifically because this lies in the centre of this scatter over the halo mass range of concern. The Reed et al. (2007) model was also specifically determined by simulating halos at $z = 10 - 30$ making it ideal for this work.

I model the star-formation efficiency as a function of halo mass, $\epsilon(M_h)$ through the stellar-to-halo mass relation (SHMR). This relates the stellar and halo masses, incorporating the universal baryon fraction, $f_b = 0.167$, through the relation

$$\frac{M_*}{M_h} = \epsilon(M_h) f_b \quad (6.1)$$

which assumes that the efficiency, ϵ , is purely dependent on the mass of a galaxy's host dark-matter halo. I then adopt a functional form for $\epsilon(M_h)$ using the double power-law relationship from Tacchella et al. (2018):

$$\epsilon(M_h) = 2\epsilon_0 \left[\left(\frac{M_h}{M_c} \right)^{-\beta} + \left(\frac{M_h}{M_c} \right)^{\gamma} \right]^{-1} \quad (6.2)$$

where ϵ_0 is the peak efficiency, M_c is the characteristic mass (the mass at ϵ_0), β is the low-mass slope and γ is the high-mass slope. I initially use $(\epsilon_0, M_c, \beta, \gamma) = (0.16, 10^{11.7}, 0.9, 0.65)$, as this is the parameterisation used in Donnan

et al. (2024). This relation is shown by the solid red line in Fig. 6.1. I also show in Fig. 6.1 the observational constraints on the $z \simeq 0$ SHMR as compiled by Wechsler & Tinker (2018) with the uncertainty captured by the gray shaded region.

I then also compare my initial adopted relation to the predictions from a number of alternative models. These alternative models cover a large range of efficiencies and include some that are clearly inconsistent with the $z = 0$ relation. It can be seen that Tacchella et al. (2018) assume a significantly greater efficiency (~ 1 dex) whereas the model from Mason et al. (2015) is moderately lower and the models from Sun & Furlanetto (2016) and Harikane et al. (2023a) are significantly lower. For the semi-analytical model from Yung et al. (2019), I plot their $z = 10$ relation. Another feature of these models is that they assume a rather low efficiency for massive dark-matter halos ($M_h > 10^{11.7} M_\odot$) compared to both my initially adopted model and indeed the relation at $z = 0$. These models had been specifically designed to model the UV LF at $z = 4 - 10$. However, the UV LF is not a direct tracer of star-formation efficiency as the UV luminosity of a galaxy is dictated by more than simply its stellar mass (e.g. stellar age, star-formation history). Therefore, although these models all assume significantly different star-formation efficiencies, they often still yield similar final UV LFs at $z = 4 - 10$ due to these degeneracies. This is important to note since, as discussed later in Section 6.6.1, these models have led to claims that a constant star-formation efficiency model fails to reproduce the now well-constrained UV LF at $z > 10$ (e.g. Harikane et al., 2023b; Tacchella, 2024). However, I re-emphasize here that, as demonstrated in Fig. 6.1, there are in fact very substantial differences in what form any proposed constant star-formation efficiency is assumed to take.

6.2.2 Observational constraints on the GSMF

Given that there are such significant differences between the star-formation efficiency relations assumed by different models, breaking the degeneracy between any evolution in the efficiency function and, for example, changing mass-to-light ratios in galaxies requires direct tests of the evolving GSMF predicted by the different models. Using the $\epsilon(M_h)$, halo mass can be converted to a stellar mass, M_* , by:

$$M_* = \epsilon(M_h) f_b M_h \quad (6.3)$$

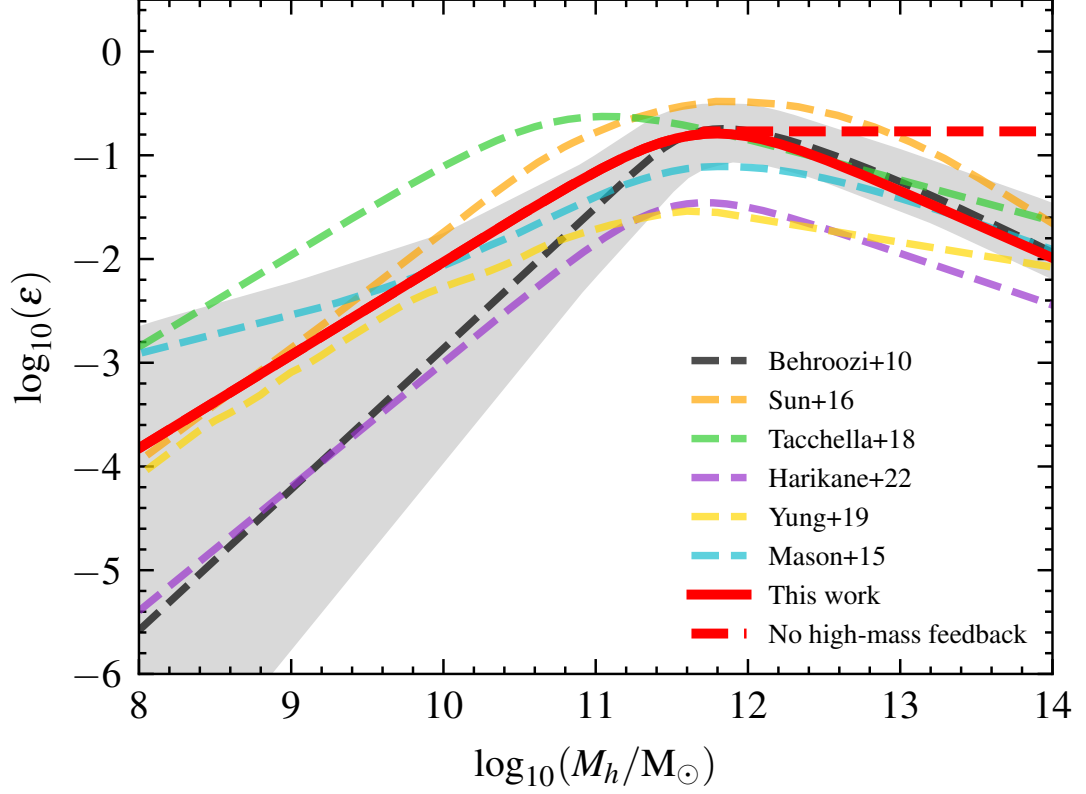


Figure 6.1 *The adopted (redshift independent) star-formation efficiency (ϵ) as a function of halo mass in my model from [Donnan et al. \(2024\)](#) (solid red line) compared to the corresponding relations in the models from [Sun & Furlanetto \(2016\)](#), [Tacchella et al. \(2018\)](#), [Harikane et al. \(2023a\)](#), [Yung et al. \(2019\)](#) and [Mason et al. \(2015\)](#). The dashed grey line shows the $z = 0.1$ [Behroozi et al. \(2010\)](#) stellar-to-halo mass relation (SHMR) which is identical to the relation adopted here at high masses. The low-mass form of my adopted relation is chosen to better track the observational constraints on the SHMR at $z = 0$ ([Wechsler & Tinker, 2018](#)), the uncertainty in which is shown here by the gray shaded region. The red dashed line shows my alternative adopted star-formation efficiency (ϵ) model with no high-mass feedback, a model which I explain further in Section 2.3 but ultimately reject in Section 3.*

The galaxy number density as a function of stellar mass is then given by:

$$\frac{dn}{d\log(M_\star)} = \frac{d\log(M_h)}{d\log(M_\star)} \times \frac{dn}{d\log(M_h)} \quad (6.4)$$

Therefore, by assuming a form for the HMF, I can derive a model of the GSMF using a functional form for $\epsilon(M_h)$. This allows measurements of the GSMF to directly establish the star-formation efficiency, hence enabling direct tests of my model as well as those presented in the literature.

With sensitive imaging at $\lambda > 2\mu\text{m}$, *JWST* now allows robust measurement of the GSMF at $z = 6 - 8$. In Fig. 6.2 I compare my model prediction for the evolving GSMF at $z = 6 - 8$ to the latest observational measurements from a number of pre-*JWST* (Song et al., 2016; Stefanon et al., 2021) and now *JWST* measurements (Harvey et al., 2024; Weibel et al., 2024; Shuntov et al., 2024). This demonstrates that my model is able to broadly match the observational data points of the GSMF at $z = 6 - 8$. This also confirms that the simple assumption of a star-formation efficiency function unchanged from that observed at $z = 0$ is sufficient to successfully reproduce the GSMF out to the highest redshifts for which robust measurements have so far been achieved. Crucially, however, Fig. 6.2 also demonstrates that several of the other models in the published literature, while designed to potentially reproduce the $z = 4 - 8$ UV LF, clearly fail this fundamental GSMF test.

6.2.3 The effect of removing high-mass feedback

Although the star-formation efficiency function used in Donnan et al. (2024) is successfully able to broadly match the observational measurements of the GSMF at $z = 6 - 8$, this $\epsilon(M_h)$ was designed primarily to reproduce the UV LF at $z \geq 9$ where the halo masses of interest lie below the peak of the star-formation efficiency relation (i.e. $\log(M_h/M_\odot) \lesssim 11.7$). Therefore, in that work I simply assumed a high-mass slope equal to that of the $z = 0.1$ SHMR from Behroozi et al. (2010) of $\gamma = 0.65$. However, at $z \geq 7$ there have been suggestions that it may make sense to invoke a lack of high-mass feedback at early times to explain the excess in the bright-end of the UV LF (compared to a Schechter function) through increased star-formation rates at a given halo mass (e.g. Bowler et al., 2017, 2020; Stefanon et al., 2019). Given that the GSMF is a more direct probe of the star-formation efficiency and now that it has been better determined at

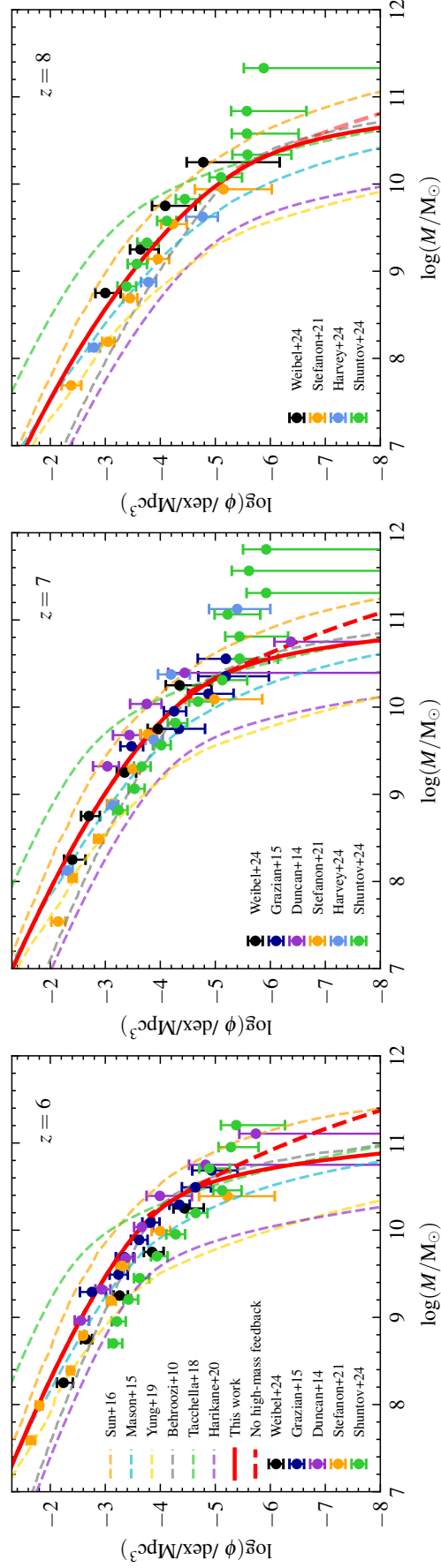


Figure 6.2 My model predictions for the evolving galaxy stellar mass function (GSMF) at $z = 6-8$ based on the two alternative models of $\epsilon(M_h)$ presented in Fig. 6.1 are shown in each panel by the red lines (where the dashed version indicates the removal of high-mass feedback). Also shown by data-points identified in the legend are the latest observational measurements of the GSMF from Duncan et al. (2014); Grazian et al. (2015); Stefanon et al. (2021); Weibel et al. (2024); Harvey et al. (2024); Shuntov et al. (2024). The predictions of the GSMF using the alternative $\epsilon(M_h)$ relations shown in Fig. 6.1 from Tacchella et al. (2018), Harikane et al. (2023a), Yung et al. (2019), Sun & Furlanetto (2016), Mason et al. (2015) and Behroozi et al. (2010) are shown by the various fainter coloured dashed lines for comparison. All stellar masses have been adjusted to assume a Chabrier (2003) initial mass function.

$z = 6 - 8$, I am able to test if the high-redshift form of the GSMF does indeed required less high-mass feedback than at later times. To explore this I introduce an alternative form of $\epsilon(M_h)$ in which a constant value of $\epsilon(M_h) = 0.17$ is assumed for $\log(M_h/M_\odot) > 11.7$, thus essentially removing all feedback within high-mass halos. This modification is illustrated in Fig. 6.1 by the dashed red line which, for simplicity, has the same functional form for $\epsilon(M_h)$ as my original version at lower masses, $\log(M_h/M_\odot) < 11.7$.

From Fig. 6.2 it can be seen that, for the majority of the stellar mass-range probed by the observational measurements of the GSMF, the removal of high-mass feedback has no effect because these observations probe modest halo masses of $\log(M_h/M_\odot) < 11.7$. However, the highest-mass bins at $z = 7$ in particular are more closely matched by my model with high-mass feedback removed. Therefore, one might conclude that there is tentative evidence in favour of the removal of high-mass feedback at $z = 7$. However, caution is required.

Firstly, the high-mass end of the GSMF is vulnerable to Eddington bias (Eddington, 1913). When measuring the GSMF, each galaxy in the sample has a stellar mass measurement with an associated uncertainty. This means that when measured, galaxies scatter above and below the true stellar mass value. Since there are a lot more low-mass galaxies than high-mass galaxies (as the GSMF declines steeply at high mass) then more of the low-mass galaxies scatter upwards than high-mass galaxies scatter downwards, resulting in an artificial boosting of the number densities of galaxies in the high-mass bins.

Secondly, the galaxy number densities in the highest-mass bins are inevitably highly uncertain because they are often based on a very small number of galaxies, or in extreme cases even the proposed presence of a single high-mass source. This is particularly true for the high-mass bins from Shuntov et al. (2024). Therefore, even a small number of contaminants (e.g. due to erroneous photometric redshifts) can drastically change the measured number density at $\log(M_\star/M_\odot) \gtrsim 10.6$. Ultimately, there are not yet enough confirmed galaxies with $\log(M_\star/M_\odot) \gtrsim 10.6$ at $z \geq 6$ to place meaningful constraints on the GSMF in this mass range, and hence properly constrain the high-mass form of the SHMR at early times. Increased survey areas with enhanced filter coverage are required to robustly test the need for high-mass feedback through direct comparison with the high-redshift form of the GSMF. In Section 6.3 I present another test of the need for high-mass feedback using my model of the intrinsic UV luminosity function.

6.3 The galaxy UV luminosity function

6.3.1 Observational measurements of the UV LF at

$$z = 6 - 13$$

The next stage of the model is to convert the GSMF into a galaxy UV luminosity function (LF) in order to compare my model to observational measurements of the UV LF at $z = 6 - 13$.

The UV LF at $z \geq 6$ has primarily been measured using photometric surveys from space-based telescopes (e.g. *HST*, *JWST*). Prior to the launch of *JWST*, there existed a general consensus over the measured form of the UV LF at $z = 6 - 8$, as described by an evolving Schechter function with a fairly steep faint-end slope of $\alpha \simeq -1.8$ (e.g. Bouwens et al., 2007; McLure et al., 2009, 2010; Bouwens et al., 2021). However, *HST* data alone were unable to probe the bright-end of the UV LF ($M_{\text{UV}} \lesssim -21.5$) due to the limited area of *HST* surveys. Fortunately, wider-area ground-based surveys were able to probe this luminosity range, hence enabling measurements of the bright-end of the UV LF, at least out to $z \simeq 9$.

Therefore, in this work I include the latest ground-based constraints on the bright-end of the UV LF in combination with a representative fainter dataset from space-based surveys at each redshift. This forms the dataset that I use to model the UV LF. At $z = 6$ I use the *HST* measurements from Bouwens et al. (2021) with the ground-based data from Bowler et al. (2015). At $z = 7$ I use the data from McLure et al. (2013) in combination with that provided by Bowler et al. (2017) and Varadaraj et al. (2023). At $z = 9$ I use the data from McLure et al. (2013) combined with that from Bowler et al. (2020) and Donnan et al. (2023a). At $z \geq 9$ I use the *JWST* measurements from Donnan et al. (2024) including bright-end constraints at $z = 9$ from Bowler et al. (2020) and Donnan et al. (2023a).

6.3.2 Modelling the UV LF

To convert my model of the GSMF into a predicted UV LF I assume a redshift dependent mass-to-light ratio given by a linear relationship between M_{UV} and

M_* :

$$M_{\text{UV}} = M_{\text{UV},*} - 2.5 [\log_{10}(M_*/M_\odot) - 9] \quad (6.5)$$

where $M_{\text{UV},*}$ is the rest-frame UV absolute magnitude corresponding to $\log_{10}(M_*/M_\odot) = 9$. This relationship is therefore defined by the UV luminosity which is assumed to be produced by a star-forming galaxy with a stellar mass of $M_* = 10^9 M_\odot$. To determine this I perform a χ^2 minimization fit to the faint-end of the UV LF data points ($M_{\text{UV}} > -19$) where, at $z = 6 - 13$, the galaxy population can be reasonably expected to be virtually dust-free and therefore the observed UV flux density from these fainter galaxies can be assumed to be un-attenuated by dust. The resultant $M_{\text{UV},*}$ required for my model to reproduce the UV LF as a function of redshift is noted in the second column of Table 6.1. The M_{UV} for a galaxy of a given stellar mass can then be linked to the age of the stellar population within that galaxy, since a younger stellar population at fixed stellar mass has an increased UV luminosity and hence a more negative absolute magnitude.

To determine the stellar age associated with the required M_{UV} for a stellar mass of $\log_{10}(M_*/M_\odot) = 9$ at each redshift, I employ stellar population synthesis codes. I use two different codes in this work in order to explore the feasibility of and uncertainty in my approach. First I use a BC03 stellar population model (Bruzual & Charlot, 2003) with a constant star-formation history and a metallicity of $Z = 0.2Z_\odot$. Second, I use The Binary Population and Spectral Synthesis code (BPASS; Eldridge et al., 2017) with a constant star-formation history but with a lower metallicity of $Z = 0.05Z_\odot$ which is more typical of the metallicity of galaxies at $z \geq 6$. (e.g. Sanders et al., 2024). The relationships between UV magnitude and the stellar mass-weighted age for a galaxy of $\log_{10}(M_*/M_\odot) = 9$ for each model are shown in Fig. 6.3. This demonstrates that, for galaxies with ages $\gtrsim 3$ Myr, the BPASS model consistently produces fainter UV magnitudes whereas this comparison reverses for ages $\lesssim 5$ Myr. Alternatively, for a given UV magnitude, the BPASS model produces younger stellar ages for $M_{\text{UV}} \lesssim -23$. For the $M_{\text{UV},*}$ at each redshift, the BC03 and BPASS ages are noted in the latter two columns in Table 6.1.

6.3.3 Predictions for high-redshift sub-millimeter galaxies

Using my model of the intrinsic UV LF (i.e. without any dust attenuation) I perform another test of the evidence for and against high-mass feedback in high-

Table 6.1 *The age-dependent UV magnitude mapping to stellar mass as a function of redshift for my model. The first column is the redshift. The second column is the UV absolute magnitude, M_{UV} , that corresponds to a stellar mass of $\log(M_*/M_\odot) = 9$ determined by the mass-weighted age given in the third column for a BC03 stellar population model (Bruzual & Charlot, 2003) with a metallicity of $Z/Z_\odot = 0.2$. The fourth column is the inferred mass-weighted age for a BPASS (Eldridge et al., 2017) model with metallicity of $Z/Z_\odot = 0.05$.*

z	M_{UV} /AB mag	Age (BC03) /Myr	Age (BPASS) /Myr
6	−20.59	140	91
7	−20.99	89	58
8	−21.03	86	56
9	−21.14	75	49
10	−21.76	36	24
11	−22.74	10	7
12.5	−23.27	2.5	3

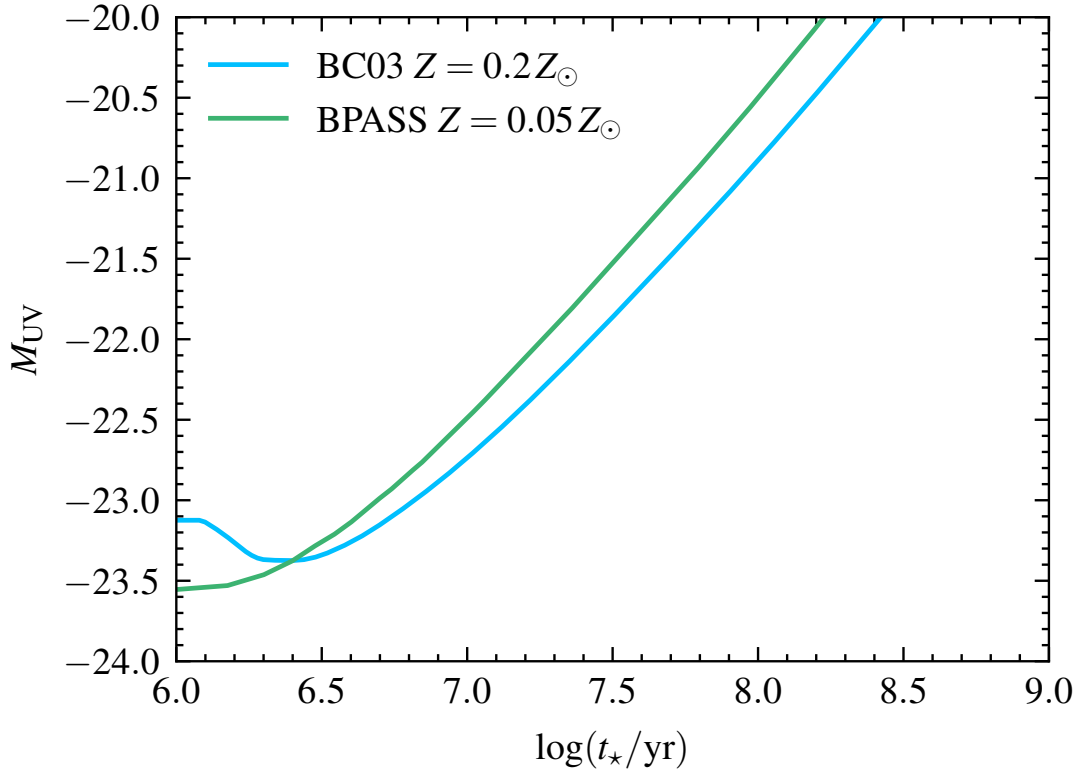


Figure 6.3 *Predicted galaxy UV absolute magnitude as a function of stellar mass-weighted age for a BC03 stellar population model (Bruzual & Charlot, 2003) with a constant star-formation history and a metallicity of $Z = 0.2Z_\odot$ (blue), and alternatively for a BPASS model (Eldridge et al., 2017) with a constant star-formation history and a metallicity of $Z = 0.05Z_\odot$ (green).*

redshift galaxies. In this case I estimate the number of heavily dust-obscured galaxies that would be detectable by sub-mm surveys under either scenario. These are galaxies that contain significant levels of dust attenuation making them extremely faint in the UV and therefore potentially absent from observations of the bright end of the UV LF. However, any such highly star-forming galaxies which are largely attenuated in the rest-frame UV should be revealed at sub-mm wavelengths due to the re-emission of the absorbed UV light by warmed dust grains in the rest-frame far-infrared.

To estimate the prevalence of bright sub-mm sources at high redshifts, inferred from the need to effectively remove them from the bright end of the UV LF through dust obscuration, I proceed as follows.

For simplicity, I consider only galaxies at $z = 6 - 8$ which my model predicts to have an intrinsic unobscured UV absolute magnitude brighter than $M_{\text{UV}} = -24.98$. This choice was made in order to capture the number density of galaxies which have a $\text{SFR} \geq 300 \text{ M}_{\odot} \text{ yr}^{-1}$ according to the conversion factor given by [Madau & Dickinson \(2014\)](#). Specically, I use the relation:

$$\text{SFR} = \mathcal{K}_{\text{UV}} \mathcal{L}_{\text{UV}} \quad (6.6)$$

where $\mathcal{K}_{\text{UV}} = 0.70 \times 10^{-28} \text{ M}_{\odot} \text{ yr}^{-1} / \text{erg s}^{-1} \text{ Hz}^{-1}$ (adjusted to a [Chabrier \(2003\)](#) initial mass function) and L_{UV} is the UV luminosity.

Next, I exploit the work of [Dunlop et al. \(2017\)](#) who derived a relationship between the infrared-visible SFR and observed flux density at $\lambda = 1.3 \text{ mm}$ ($S_{1.3}$) by fitting the characteristic spectral energy distribution (SED) of the ALMA-detected sources in the HUDF across the wavelength range $24 \mu\text{m} - 1.3 \text{ mm}$ giving:

$$\text{SFR} / \text{M}_{\odot} \text{ yr}^{-1} \simeq 0.3 S_{1.3} / \mu\text{Jy} \quad (6.7)$$

I then simply assume that the intrinsic UV-derived SFR is equal to the actual infrared-inferred SFR to determine the flux density at 1.3 mm (a very reasonable assumption for highly-obscured star-forming galaxies). For $\text{SFR} \simeq 300 \text{ M}_{\odot} \text{ yr}^{-1}$ I derive a 1.3 mm flux-density estimate of $S_{1.3} \simeq 1.0 \text{ mJy}$. I then assume a functional form for the shape of the far-IR SED such that $f_{\nu} \propto \nu^3$ to determine the equivalent flux density at $\lambda_{\text{obs}} = 850 \mu\text{m}$. This results in a value of $S_{850} \simeq 3.6 \text{ mJy}$ which enables comparison to SCUBA-2 surveys which have typically achieved 4-

σ detections and hence published source catalogues down to this $850\mu\text{m}$ flux density (e.g. S2COSMOS, AS2UDS; [Simpson et al., 2019](#); [Dudzevičiūtė et al., 2020](#)).

Finally, I then integrate my model of the intrinsic UV LF at $z = 6 - 8$ to a limit of $M_{\text{UV}} = -24.98$ to determine the number of galaxies that would be detectable in a $850\mu\text{m}$ survey down to a flux density of $S_{850} = 3.6\text{mJy}$.

I compare my model predictions to the AS2UDS survey which detected 364 SMGs across ~ 1 sq. degrees in the UDS field with $S_{850\mu\text{m}} \geq 3.6\text{mJy}$ based on ALMA follow-up of the original SCUBA-2 Cosmology Legacy Survey of the UDS field ([Dudzevičiūtė et al., 2020](#)). They report that 2 of these sources at $z > 5.5$ indicating a number density of ~ 2 galaxies per sq. degree with $S_{850\mu\text{m}} = 3.6\text{mJy}$ at $z > 5.5$. This is consistent with the more recent *JWST* analysis of the S2COSMOS sample in COSMOS-Web ([Casey et al., 2023](#)) which revealed 2 sources (at $z = 5.5 - 8.5$) across 0.54 sq. degrees with a flux density $S_{850} > 2\text{mJy}$ ([McKinney et al., 2024](#)). In this case these two sources have been specifically noted in the literature with AzTECC71 at $z_{\text{phot}} = 5.7 \pm 0.6$ ([McKinney et al., 2023](#)) and MAMBO-9 at $z_{\text{spec}} = 5.850$ ([Casey et al., 2019](#)). Their measurements therefore suggest $\sim 3 - 4$ sources with $S_{850} > 2\text{mJy}$ per sq. degree. Given the somewhat increased depth used in this study compared to my calculation and the presence of an over-density at $z = 6$ in which one of these sources apparently resides ([Brinch et al., 2024](#)), it is consistent with the number density from the AS2UDS survey. I note however, that both the proposed $z > 5.5$ sources in the AS2UDS survey only have photometric redshifts, and that my own photometric redshift analysis of this same sample in fact yields no sources with $z > 5.5$. Meanwhile, of the 2 claimed $z > 5.5$ sources in S2COSMOS sample, only the redshift of AzTECC71 can be considered secure. It is thus reasonable to adopt an estimate of 1 source per sq. degree with $z > 5.5$ at the $S_{850\mu\text{m}} = 3.6\text{mJy}$ level.

My model, including continued high-mass feedback (as seen at low redshift) at high redshift yields a prediction of $\simeq 0.3$ galaxies with $S_{850} > 3.6\text{mJy}$ per sq. degree, completely consistent with the available sub-mm survey results. However, with high-mass feedback removed, I predict $\simeq 4$ galaxies with $S_{850} > 3.6\text{mJy}$ per sq. degree, less consistent with the data. Accepting the unavoidable crudeness of this comparison, this demonstrates that the number density of bright sub-mm galaxies can be used to place constraints on the star-formation efficiency in high-mass halos ($M_{\text{h}} \gtrsim 10^{11.7}$) at early times. In this case the available evidence continues to support the necessity of high-mass feedback, at least out to $z \simeq 6$, or

at the very least provides no motivation for increasing efficiency at high masses.

6.4 Dust attenuation

Given that the intrinsic, dust free, model is able to successfully reproduce submillimeter number counts, I now consider whether the introduction of a physically plausible relationship between stellar mass and dust attenuation can accurately reproduce the observed UV LF. In [Donnan et al. \(2024\)](#), I accounted for the impact of dust by assuming the $A_{1500} - M_\star$ relation derived for star-forming galaxies at $2 < z < 3$ by [McLure et al. \(2018a\)](#). In this study, I attempt to directly measure the $A_{1500} - M_\star$ relation as a function of redshift by forcing agreement between the intrinsic, dust free, UV LF model and the observed data.

To determine the level of UV attenuation as a function of stellar mass, I calculate the difference between the intrinsic model of the UV LF and the observational data at the corresponding number density. The resulting predictions for the $A_{1500} - M_\star$ relation as a function of redshift are shown in [Fig. 6.5](#), along with the $z \simeq 2.5$ relation from [McLure et al. \(2018a\)](#).

Due to the DPL functional form used to fit the observed UV LF, my adopted method produces a physically unrealistic turn-over in the derived $A_{1500} - M_\star$ relation at stellar masses of $\log(M_\star/M_\odot) \simeq 10$, corresponding to absolute UV magnitudes well beyond the bright end of the observed UV LF data. Consequently, at each redshift, I implement a horizontal extrapolation at stellar masses greater than the peak of the derived $A_{1500} - M_\star$ curve. This extrapolation, shown as the dashed lines in [Fig. 6.5](#), begins at $\log(M_\star/M_\odot) \simeq 10$ for redshifts $z = 6 - 9$ and at $\log(M_\star/M_\odot) \simeq 9.9, 9.8, 9.6$ for $z = 10, 11$ and 12.5 , respectively. The final UV LF models, incorporating the derived dust attenuation at each redshift, are plotted as the solid green lines in [Fig. 6.4](#). By design, there is good agreement between the models and the observational data points across the range of UV magnitudes constrained by the available data.

The individual redshift relations for $A_{1500} - M_\star$ shown in [Fig. 6.5](#) do not display a clear monotonic evolution with redshift although, at fixed stellar mass, there is a tentative trend towards lower dust attenuation at earlier times. This trend is made clearer when considering the mean $A_{1500} - M_\star$ relations in the range $6 \leq z \leq 9$ and $10 \leq z \leq 12.5$, shown as the solid blue and red curves,

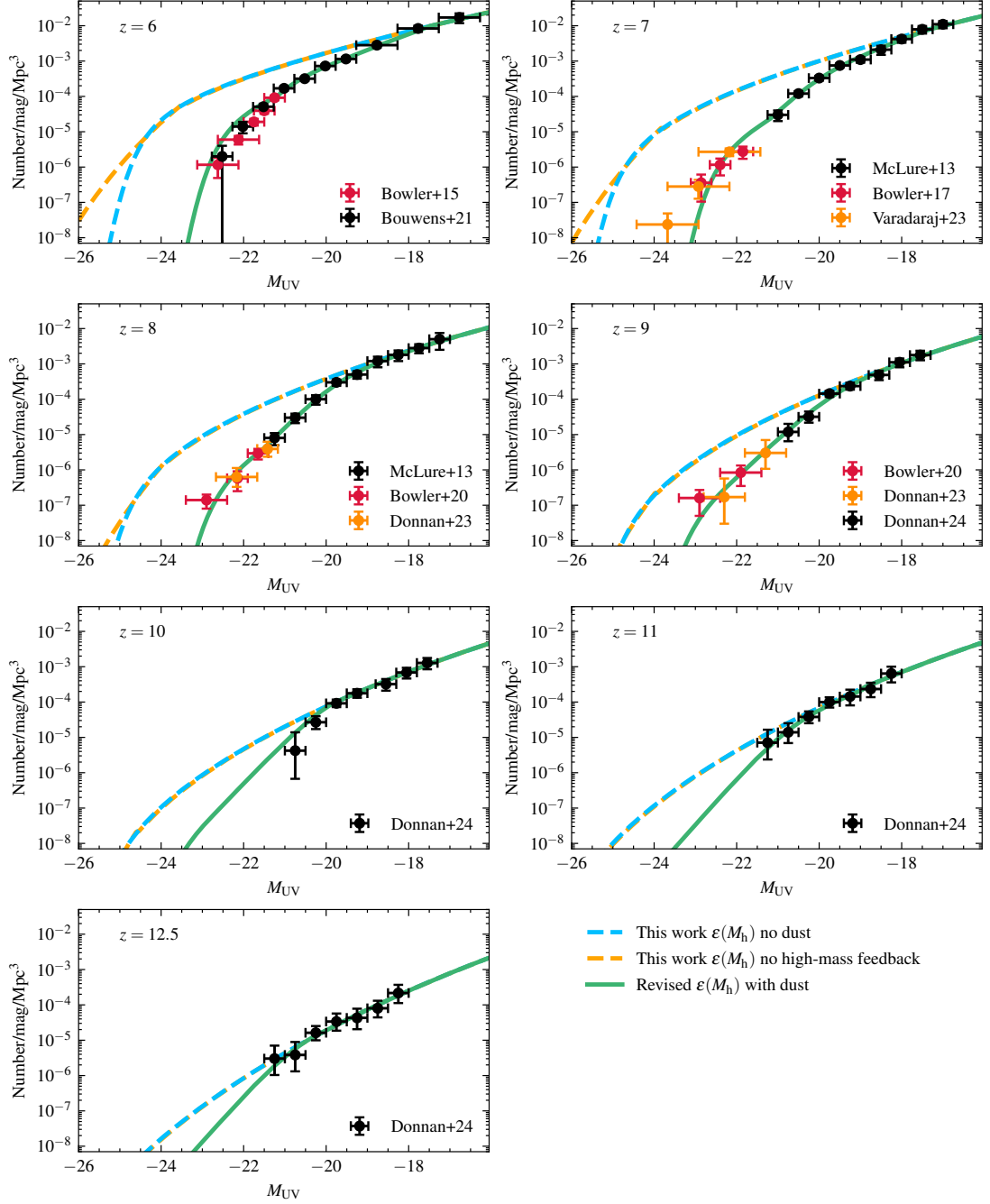


Figure 6.4 A comparison of my models of the UV luminosity function (UV LF) to observational measurements from [McLure et al. \(2013\)](#); [Bowler et al. \(2015\)](#); [Bouwens et al. \(2021\)](#); [Varadaraj et al. \(2023\)](#); [Donnan et al. \(2023a, 2024\)](#). The dashed blue line shows my intrinsic dust free model assuming the form of star-forming efficiency $\epsilon(M_h)$ established by [Donnan et al. \(2024\)](#). The dashed orange line shows the dust-free model assuming the [Donnan et al. \(2024\)](#) $\epsilon(M_h)$ model is altered to contain no high-mass feedback. The solid green line shows the final model with dust attenuation.

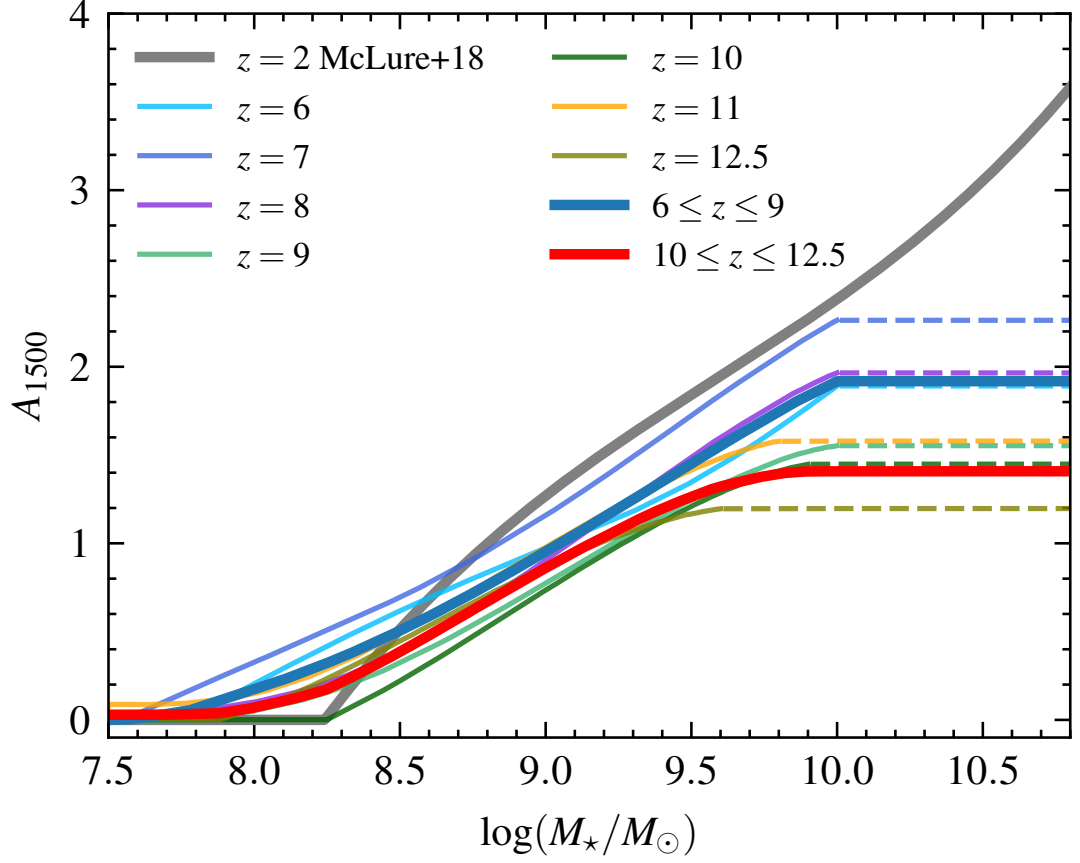


Figure 6.5 *The UV dust attenuation at $\lambda_{\text{rest}} = 1500 \text{ \AA}$ as a function of stellar mass derived in my model at each redshift. The $z = 2$ relation from [McLure et al. \(2018a\)](#) is shown by the solid gray line. The dashed lines show the horizontal extrapolation at high stellar masses. The thick solid blue line shows the mean $A_{1500} - M_*$ relation at $6 \leq z \leq 9$ whereas the thick solid red line shows the mean $A_{1500} - M_*$ relation at $10 \leq z \leq 12.5$.*

respectively. Given the uncertainties involved, it is difficult to draw any firm conclusions on the functional form of the derived $A_{1500} - M_{\star}$ relations. However, they appear physically plausible and, at least within the stellar-mass range that is best constrained by the available data (i.e. $8.5 \leq \log(M_{\star}/M_{\odot}) \leq 9.5$), have a similar gradient to the $z \simeq 2.5$ relation from [McLure et al. \(2018a\)](#); derived using a completely different method.

6.5 Cosmic hydrogen reionization

Constraining the timeline of reionization continues to be a key goal of extragalactic astronomy. Although there is general consensus that reionization was completed by $z \simeq 5.5 - 6$ ([Robertson et al., 2015](#); [Bosman et al., 2021](#)), the evolution of the neutral hydrogen fraction (X_{HI}) at higher redshifts is still open to question. Fundamentally, the timeline of reionization is governed by the balance between the rate at which ionizing photons are produced and escape into the IGM and the hydrogen recombination rate. The rate at which ionizing photons escape into the IGM is given by:

$$\dot{n}_{\text{ion}} = f_{\text{esc}} \xi_{\text{ion}} \rho_{\text{UV}} \quad (6.8)$$

where f_{esc} is the escape fraction of Lyman continuum radiation, ξ_{ion} is the ionizing photon production efficiency and ρ_{UV} is the UV luminosity density. Consequently, by performing a luminosity-weighted integral of my UV LF models to measure ρ_{UV} , it is possible to estimate $\dot{n}_{\text{ion}}$ as a function of redshift, based on assumed values of f_{esc} and ξ_{ion} . When calculating ρ_{UV} , I integrate my UV LF models to a common limit of $M_{\text{UV}} = -15$, as this is the faintest UV magnitude any measurements of the UV LF have been able to obtain (e.g. [Parsa et al., 2016](#); [Atek et al., 2018](#)).

Pre-*JWST*, a canonical value of $\xi_{\text{ion}} \simeq 10^{25.2} \text{Hz erg}^{-1}$ was typically assumed for reionization calculations (e.g. [Robertson et al., 2015](#); [Bouwens et al., 2016](#); [Matthee et al., 2017](#)). In contrast, initial *JWST* results suggested that high-redshift galaxies displayed higher efficiencies; $\xi_{\text{ion}} \simeq 10^{25.8} \text{Hz erg}^{-1}$ (e.g. [Atek et al., 2024](#); [Simmonds et al., 2024a](#)). However, more recent *JWST*-based studies have tended to revise-down estimates of ξ_{ion} , closer to typical pre-*JWST* values ([Simmonds et al., 2024b](#); [Pahl et al., 2024](#); [Begley et al., 2024](#)). In order to span the range of observational constraints, in my calculations I adopt three different

values of ξ_{ion} with $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.2, 25.5, 25.8$.

In a similar fashion, I also consider three different values of f_{esc} . At the highest redshifts where it is possible to directly measure f_{esc} (i.e. $3 < z < 3.5$), recent studies based on both photometry and spectroscopy have suggested typical values of $f_{\text{esc}} \simeq 0.05$ (e.g. [Pahl et al., 2021](#); [Begley et al., 2022](#)). At higher redshifts, estimates of f_{esc} are typically based on the relationship between f_{esc} and the UV slope (β) established at low-redshift ([Chisholm et al., 2022](#)). [Cullen et al. \(2024b\)](#) report an average UV slope of $\beta = -2.22$ at $z \simeq 10$, corresponding to $f_{\text{esc}} = 0.07$ using the relationship from [Chisholm et al. \(2022\)](#). They also report an average UV slope of $\beta = -2.6$ at $z \simeq 11.8$, indicating an increase in escape fraction with redshift to $f_{\text{esc}} = 0.19$. Given this range of escape fractions, I determine my model of the neutral fraction as a function of redshift for three fixed values of $f_{\text{esc}} = 0.05, 0.10, 0.20$. In addition, I also consider an evolving f_{esc} model, based on the UV slope measurements from [Cullen et al. \(2024b\)](#).

Armed with my calculated values of $\dot{n}_{\text{ion}}$, I determine the neutral fraction of the IGM using the [Madau et al. \(1999\)](#) prescription for the ionizing photon output required to maintain a given neutral fraction:

$$\dot{n}_{\text{ion}} = 10^{47.4} (1 - X_{\text{HI}}) C_{\text{HII}} (1 + z)^3 \text{ s}^{-1} \text{Mpc}^{-3} \quad (6.9)$$

where C_{HII} is the IGM clumping factor, which I assume follows the redshift-dependent form provided by [Shull et al. \(2012\)](#). The evolution of X_{HI} with redshift corresponding to my different parameter choices is shown in [Fig. 6.6](#), along with the latest observational constraints from the literature.

It can be seen from [Fig. 6.6](#) that different choices of f_{esc} and ξ_{ion} have a significant impact on the timeline of reionization. For $f_{\text{esc}} = 0.2$, I find that reionization completes by $z = 7$, even for the lowest ionizing production efficiency ($\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.2$). For $f_{\text{esc}} = 0.1$, reionization is still able to complete by $z \simeq 6$ for $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.2$. In contrast, if $f_{\text{esc}} = 0.05$ is assumed, reionization completes by $z \simeq 6$ only for an ionising production efficiencies of $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \geq 25.5$. Using the more realistic, evolving prescription for f_{esc} , reionization also ends by $z \simeq 6$ for $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.5$, consistent with the latest observational estimates of ξ_{ion} and the optical depth from the cosmic microwave background (CMB; [Planck Collaboration et al., 2020a](#)).

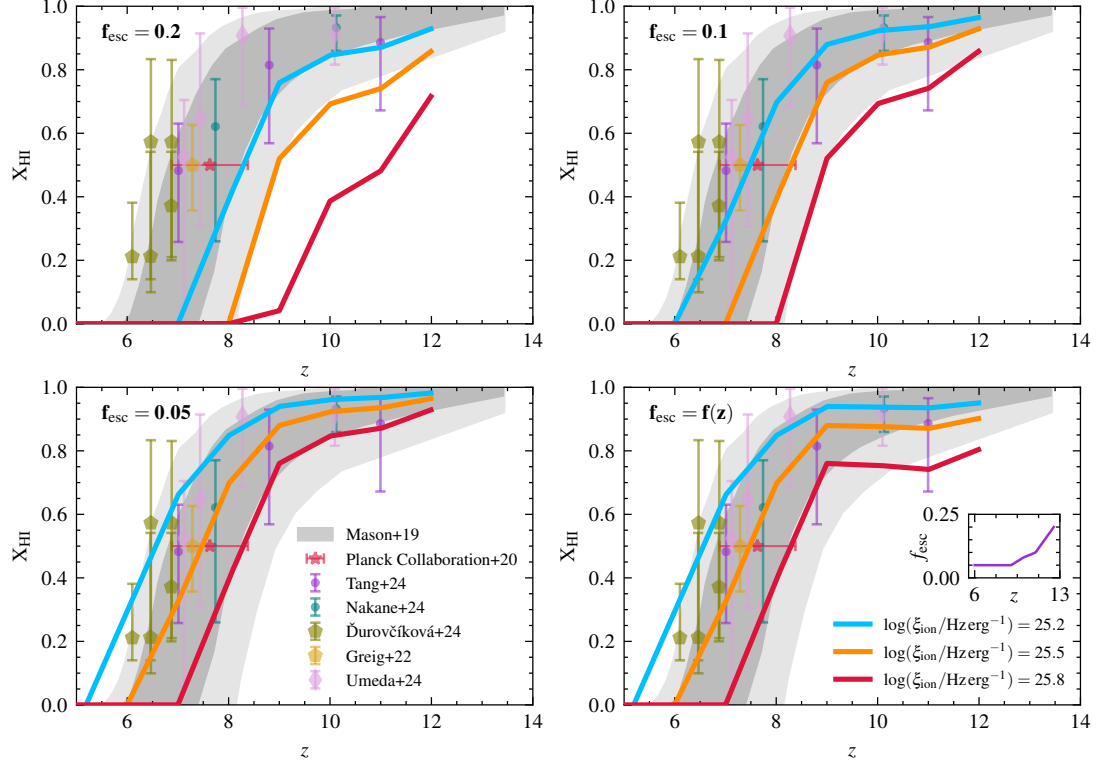


Figure 6.6 The redshift evolution of the hydrogen neutral fraction of the intergalactic medium with my model predictions given by the solid blue, orange and red lines for $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.2, 25.5, 25.8$ respectively where the UV LF is integrated to a limit of $M_{\text{UV}} = -15$. In each panel the models are computed using different escape fractions with $f_{\text{esc}} = 0.2$ (upper left), $f_{\text{esc}} = 0.2$ (upper right), $f_{\text{esc}} = 0.05$ (bottom left) and for an evolving f_{esc} as function of redshift (bottom right and inset). Observational measurements of the neutral fraction are shown for the CMB (Planck Collaboration et al., 2020a), Ly α equivalent widths (Tang et al., 2024; Nakane et al., 2024), QSO damping wings (Greig et al., 2022; Āurovčíková et al., 2024) and for LBG damping wings (Umeda et al., 2024). The grey shaded region shows the model from Mason et al. (2019) (dark grey: 68th percentile; light grey: 95th percentile)

6.6 Discussion

6.6.1 A constant star-formation efficiency

I have presented a simple theoretical model which is able to match the observational constraints on both the GSMF at $z = 6 - 8$ and the UV LF at $z = 6 - 13$ (i.e. out to the highest redshifts for which robust measurements of these two key scaling relations currently exist). This was achieved using a redshift independent form of the stellar-to-halo mass relation and therefore a redshift independent form of the star-formation efficiency (as function of halo mass) that is consistent with that observed at $z = 0$. I first describe this model in the context of the GSMF and then the UV LF.

Modelling the GSMF with constant star-formation efficiency

Firstly, I tested my constant efficiency model against recent measurements of the evolving GSMF, finding good consistency with the observationally derived data points. The viability of a non-evolving star-formation efficiency is also consistent with several pre-*JWST* measurements of the GSMF obtained through abundance matching (Behroozi et al., 2013; Stefanon et al., 2021) as well as the predictions of at least some simulations (Feldmann et al., 2024). However, arguments have also been advanced in support of a redshift-dependent star-formation efficiency, based both on new observations (Shuntov et al., 2024) and alternative simulations (Ceverino et al., 2024). Nonetheless, across most of the mass range, the evolution with redshift that has been suggested has been relatively mild, with even the evolving efficiency functions generally lying within the scatter of the $z = 0$ relation.

Recently, however, claims have been advanced that the GSMF requires significantly increased star-formation efficiency at $z > 6$ for the most massive galaxies. In particular, Shuntov et al. (2024) make the dramatic claim that, at the highest redshifts, star-formation efficiency rises to $\epsilon = 0.8 - 1.0$ for $\log(M_*/M_\odot) > 10.8$. However, this conclusion is based on highly uncertain high-mass data points which are particularly vulnerable to contamination and bias, for example due to incorrect photometric redshifts (especially likely in this study due to the currently limited filter set of the COSMOS-Web imaging). In addition to the positive bias

at the high-mass end resulting from even a tiny number of incorrect photometric redshifts, and the inevitability of Eddington bias (Eddington, 1913), it has also been demonstrated that the use of NIRCам alone can result in the stellar masses of galaxies being over-estimated by up to $\simeq 0.5$ dex (Wang et al., 2024).

Finally, while the robust measurement of the GSMF is currently limited to $z \leq 8$ due to the requirement of sufficiently long wavelength coverage red-ward of the Lyman break, I note that this has not deterred several authors from providing measurements at $z = 9 - 11$, which have again in some cases been used to argue for increased star-formation efficiency (Harvey et al., 2024; Weibel et al., 2024; Shuntov et al., 2024). Although these "results" are not shown in Fig. 6.2, I have checked that, within the observational uncertainties, my model does in fact successfully reproduce the proposed form of the GSMF at $z = 9$ and $z = 11$.

I therefore conclude that, at present, the available observational constraints on the evolving GSMF provide no clear evidence for a significant increase in star-formation efficiency in massive galaxies at $z \geq 6$.

Star-formation efficiency and the UV LF at $z = 6 - 13$?

Using a similar type of model to the one considered here, Harikane et al. (2023b) concluded that the assumption of constant star-formation efficiency was able to reproduce the UV LF out to $z \simeq 10$, but that an increased efficiency was required at still higher redshifts. There have also been a number of other studies suggesting that increased star-formation efficiency is required to explain the form of the UV LF at $z > 10$, especially at the bright end (e.g. Dekel et al., 2023).

Of course, the difficulty in using the UV LF as a measurement of the star-formation efficiency is that the UV luminosity of a galaxy does not simply depend on its stellar mass. Even at early times, a galaxy of a given stellar mass can have a range of UV luminosities dependent on its star-formation history and the age/metallicity of the stellar population that dominates the rest-frame UV. Indeed, in the simple model discussed here I have demonstrated that the assumption of constant star-formation efficiency can be maintained by appealing to ever younger stellar populations to produce an increasing average UV luminosity with increasing redshift beyond $z \simeq 8$. It is only through the flexibility of decreasing typical age at extreme redshifts that my constant-efficiency model is able to explain the UV LF at $z = 10 - 13$.

Somewhat surprisingly, the idea of decreasing characteristic age at extreme redshifts is not regularly cited as an explanation for the observed modest evolution of the UV LF (and hence ρ_{SFR}) from $z \simeq 8$ out to $z \simeq 13$. Nevertheless, at some stage young ages become inevitable as we are rapidly running out of time at these redshifts, and indeed my approach is vindicated by the observed consistency of my model (without modification), with measurements of the GSMF (which offers a more direct probe of star-formation efficiency).

Finally, I note that while my simple constant-efficiency model can reproduce the UV LF at $z > 10$, more extensive spectroscopy of galaxies at $z > 10$ is required to investigate the physical properties of early galaxies in detail, including the ages of their stellar populations. To date, only a handful of galaxies at such extreme redshifts (extending up to $z = 14.2$) have been observed with NIRSpec (e.g. [Bunker et al., 2024](#); [Arrabal Haro et al., 2023b](#); [Castellano et al., 2024](#)) and ALMA ([Schouws et al., 2024](#); [Zavala et al., 2024](#)), and so it remains unclear how typical their properties are of the wider emerging galaxy population at these early times. Fortunately, in Cycle 3 *JWST* is set to observe an order-of-magnitude more galaxies at $z > 10$ with NIRSpec, through a series of major spectroscopic surveys (e.g. CAPERS GO 6368).

6.6.2 No evidence for removing feedback in high-mass halos

A number of studies have presented evidence for an excess of bright galaxies ($M_{\text{UV}} \lesssim -21$) at $z \geq 6$ compared to expectations based on the assumption (well justified at lower redshifts) that the LF follows the exponentially declining form of a Schechter function (e.g. [Bowler et al., 2014, 2020](#); [Stefanon et al., 2019](#)).

One possible explanation for this phenomenon is the weakening or removal of high-mass feedback at early times. With feedback reduced or even non-existent at high masses, galaxies can rapidly assemble larger stellar masses and therefore produce greater UV luminosities, thus potentially explaining the observed slow evolution in the bright-end of the UV LF. High-mass feedback is typically explained by the impact of AGN in massive galaxies whereby their jets expel gas from the galaxy therefore quenching further star formation, potentially permanently ([Hopkins et al., 2006](#)). Alternatively, halo quenching can also act as a feedback mechanism, with the shock-heating of gas in massive halos effectively removing the reservoir of cold gas required for star formation ([Somerville et al., 2008](#); [Gabor & Davé, 2015](#)).

It might reasonably be expected that both of these high-mass feedback mechanisms would be less effective at extreme redshifts, with super-massive black holes and high mass dark-matter halos requiring time to grow. However, as I discussed in, Section 6.3.3 there exists no clear evidence for the removal of high-mass feedback at $z \geq 6$ given the current observational constraints on the evolving GSMF.

This motivated my test of the sub-mm galaxy counts using my model of the intrinsic form of the UV LF. This is a useful test of the high-mass end of star-formation efficiency because it is now well established that the most massive star-forming galaxies are heavily obscured by dust and are thus unlikely to feature even at the bright end of the UV LF (despite obviously still appearing at the high-mass end of the GSMF). I have found that the number of bright high-redshift galaxies observed in current sub-mm surveys (e.g. Simpson et al., 2019; McKinney et al., 2024) also provides little evidence for any decline in high-mass feedback at early times, with the observed prevalence of bright sub-mm galaxies ($\simeq 1$ per square degree at $z > 5.5$ forming stars at a rate $\geq 300 M_{\odot} \text{yr}^{-1}$) being completely consistent with the predictions of my fiducial model. Furthermore, in Section 6.4 I demonstrated that I obtain physically plausible relationships between the UV attenuation and stellar mass for $z \geq 6$ (discussed further in Section 6.6.3) with an unchanged high-mass star-formation efficiency.

Although in my model the bright end of the UV LF can be fully explained by the level of dust attenuation, and the sub-mm galaxy counts provide some further constraining power, the precise differentiation between weakening star-formation efficiency and increasing dust attenuation will require further observational measurements. Direct measurements of the dust content of galaxies at $z \geq 6$ with ALMA and NOEMA will help determine the relationship between stellar mass, UV luminosity and dust attenuation in these galaxies. This requires both sufficient depth (to be able to detect or robustly constrain the dust continuum) and surveys covering sufficient area in order to detect a statistically significant number of galaxies with stellar masses of $\log(M_{\star}/M_{\odot}) > 10$ at $z \geq 6$.

While my tests of the high-redshift sub-mm galaxy counts do not provide any strong support for the removal of high-mass feedback at early times, currently I cannot precisely determine the normalisation and form of the high-mass end of the stellar-to-halo mass relation at $z \geq 6$. This would require improved measurements of the high-mass end of the GSMF which can only be enabled by yet wider-area NIRCam surveys with *JWST*.

Progress is being made in this direction. To date [Harvey et al. \(2024\)](#) have presented measurements of the GSMF using $\simeq 187$ sq. arcmin of NIRCcam imaging, while [Weibel et al. \(2024\)](#) used a larger area of $\simeq 500$ sq. arcmin from PRIMER ([Dunlop et al., 2021](#)), JADES ([Eisenstein et al., 2023](#)) and CEERS ([Bagley et al., 2024b](#)). More recently, [Shuntov et al. \(2024\)](#) have presented measurements of the GSMF based on the Cosmos-Web program ([Casey et al., 2023](#)) which significantly expands the available survey area to $\simeq 0.5$ sq. degrees. However, as discussed above, the COSMOS-Web survey is currently limited to only 4 NIRCcam filters (F115W, F150W, F277W, F444W) which results in significantly less robust photometric redshifts and estimated stellar masses. The upcoming *JWST* Cycle-3 COSMOS-3D program (PI: Kakiichi) will provide F200W and F356W imaging across ~ 0.33 sq. degrees of the COSMOS-Web footprint therefore providing contiguous NIRCcam wavelength coverage from $1 - 4.4\mu\text{m}$ which should provide significantly improved stellar mass constraints for the galaxies detected in this field.

Finally, another important consideration is the wavelength coverage of the observations. Interestingly, [Wang et al. \(2024\)](#) used MIRI imaging at $7.7\mu\text{m}$ to extend the wavelength coverage used to measure galaxy stellar masses beyond that which can be accessed with NIRCcam. They concluded that this has an important impact in the sense that the inclusion of the MIRI data results in a significant reduction in the observed number densities of massive galaxies. Therefore, the robust determination of the GSMF at $z > 6$ will require further expansion of the existing *JWST* imaging surveys, ideally with substantial NIRCcam and MIRI overlap (as was designed for PRIMER).

6.6.3 The evolution of the UV attenuation - stellar mass relation

My derived models of the $A_{1500} - M_\star$ relation at $z \geq 6$ show some evidence for a shallow redshift evolution with a lower normalisation than the $z = 2$ relation from [McLure et al. \(2018a\)](#). A lack of dust attenuation in bright ($M_{\text{UV}} \lesssim -21$) galaxies at $z > 10$ has been suggested as an explanation for their observed luminosity (e.g. [Ferrara et al., 2023](#)). There is also observational evidence from analysis of the UV continuum slopes indicating sufficient steepness in the observed slopes such that there is a requirement for a lack of dust attenuation (e.g. [Topping et al., 2024b](#); [Morales et al., 2024](#); [Cullen et al., 2024b](#)). In the model presented in Chapter 5,

I concluded that the galaxy population was largely dust-free due to the low stellar masses of the galaxies in the luminosity range probed by the observational measurements. However, in Chapter 5 I simply adopted the $z = 2$ dust-mass relation from [McLure et al. \(2018a\)](#) where $A_{1500} = 0$ at $\log(M_\star/M_\odot) \lesssim 8.4$. In the more detailed model presented in this work, I derive a relationship between dust attenuation and stellar mass at $z = 11$ (albeit with lower normalisation). This shows that with an established relationship between dust attenuation and stellar mass at $z = 11$, the observational measurements of the UV LF are still fully explainable. This is also still consistent with the conclusions of Chapter 5 and the observational measurements of the UV slopes as again the majority of galaxies in my model have insufficient stellar masses to have significant levels of dust attenuation. The brightest observational measurement of the UV LF at $z = 11$ is at $M_{UV} = -21.25$ and as shown in Fig. 6.4, this is consistent with both my dust and dust-free models. Therefore, there is insufficient evidence from measurements of the UV LF to remove dust attenuation entirely at $z = 11$.

As the brightest bin ($M_{UV} = -21.25$) corresponds to a stellar mass of $10^{8.4}M_\odot$, the $A_{1500} - M_\star$ relation at $z = 11$ for $\log(M_\star/M_\odot) > 8.4$ is simply an extrapolation of the difference between my intrinsic model of the UV LF and the best fitting DPL to the data. It is therefore entirely consistent with the UV LF for yet more massive galaxies at $z = 11$ to contain some level of dust attenuation. Yet wider area surveys are required to measure the UV LF to brighter UV magnitudes which will precisely confirm if there is a requirement to remove dust or if they are fully consistent with my derived $A_{1500} - M_\star$ relation.

6.6.4 Is there an ionising photon budget crisis?

Recent *JWST* results have suggested that there is an ionising photon budget crisis ([Muñoz et al., 2024](#)) where there are too many ionising photons emitted from the galaxy population at $z > 6$ leading to completion of reionization too early. This suggestion was based on the assumption of the three parameters in Equation 6.8 which define the history of reionization.

JWST has unlocked the ability to measure ξ_{ion} at $z > 6$ for the first time. Early *JWST* results indicated that ξ_{ion} increased as a function of redshift perhaps reaching significantly higher values of $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \simeq 26$ at $z > 6$ ([Simmonds et al., 2024a](#); [Atek et al., 2024](#)). This was suggested due to increased burstiness of star-formation leading to increased production of ionising photons.

However, recent deeper surveys reveal lower values more typical of what had been seen at low- z pre-*JWST* (Simmonds et al., 2024b; Pahl et al., 2024; Begley et al., 2024) showing a mild redshift evolution with an average efficiency of $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) \simeq 25.3$. This may be because the galaxies in earlier studies were selected due to the strengths of key emission lines (e.g. $\text{H}\alpha$, [OIII]) and therefore only provided measurements of ξ_{ion} for galaxies in the strongest bursts of star-formation.

The second assumption that led to the suggestion of an ionising photon budget crisis is the escape fraction, f_{esc} . In Muñoz et al. (2024) they use an initial assumption of $f_{\text{esc}} = 0.2$ as this is the previously assumed value suggested in Robertson et al. (2015) that was required to complete reionization by $z \simeq 5.5$. Using $f_{\text{esc}} = 0.2$, as shown in the upper left panel of Fig. 6.6, I find consistency with the suggestion from Muñoz et al. (2024) of an excess of ionising photons with reionization completing too early, with even the lowest ξ_{ion} model completely ionising the IGM by $z \simeq 7$. However, pre-*JWST* observational measurements of f_{esc} indicate a significantly lower value from low- z measurements of $f_{\text{esc}} \simeq 0.05$ (Pahl et al., 2021; Saldana-Lopez et al., 2022b; Begley et al., 2022). Using the $\beta - f_{\text{esc}}$ relation from Chisholm et al. (2022) in combination with recent measurements of β up to $z \simeq 13$, I calculate a more realistic redshift evolving form of f_{esc} . Although the measurements of the UV slopes suggest $f_{\text{esc}} \simeq 0.2$ at $z = 12$, this rapidly decreases to $f_{\text{esc}} \simeq 0.07$ by $z = 10$ (shown by the inset panel in the bottom right of Fig. 6.6). This removes the tension with observational constraints on the neutral fraction for even modestly large values of the ionising production efficiency ($\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 25.5$). This is because (using the UV slopes), the escape fraction only rises to $f_{\text{esc}} = 0.2$ at $z > 10$ and therefore the majority of the reionization history occurs with significantly lower escape fractions ($f_{\text{esc}} \simeq 0.05$).

The final parameter that could cause an excess in ionising photons is the UV luminosity density, ρ_{UV} . This concern was raised due to the excess in the observed UV LF compared to some pre-*JWST* models at $z > 10$ (e.g. Mason et al., 2015; Yung et al., 2019). My models which closely reproduce the observed UV LF and ρ_{UV} at $z = 6 - 13$ show that, in fact, this is not in tension with observational measurements of the neutral fraction or the precisely constrained end-point of reionization ($z \simeq 5.5$; Bosman et al., 2021). Determination of ρ_{UV} is sensitive to the steepness of the faint-end slope of the UV LF, α . Prior to the launch of *JWST*, there had been an observed steepening in α with increasing redshift.

Table 6.2 *The faint-end slope, α , of my UV LF model at $z = 6 - 12.5$ assuming a power-law functional form. The first column states the redshift of the UV LF. The second column is the best-fitting faint-end slope to the model over the UV magnitude range $-18 < M_{\text{UV}} < -16$ with the final column showing the best-fitting faint-end slope over the range $-17 < M_{\text{UV}} < -15$.*

z	α	
	$-18 < M_{\text{UV}} < -16$	$-17 < M_{\text{UV}} < -15$
6	-1.72	-1.66
7	-1.78	-1.71
8	-1.84	-1.78
9	-1.93	-1.87
10	-2.00	-1.93
11	-2.04	-1.97
12.5	-2.16	-2.08

In [Bouwens et al. \(2021\)](#), they describe this evolution by the linear relationship $\alpha = -1.94 - 0.11(z - 6)$. This provided a prediction of the faint-end slope of the UV LF at $z > 10$ for which *JWST* is now able to measure. Assuming this linear extrapolation would mean that by $z = 11$ there would be a faint-end slope of $\alpha \simeq -2.5$ ([Bouwens et al., 2023c](#)) which is significantly steeper than at $z \simeq 8$ ($\alpha \simeq -2.1$). Early *JWST* measurements of the UV LF were unable to constrain α given the initial lack of ultra-deep NIRC*am* imaging however more recent measurements using the JADES ([Eisenstein et al., 2023](#)) and NGDEEP ([Bagley et al., 2024c](#)) surveys have enabled this measurement with $\alpha \simeq -2.2$ at $z = 11$ ([Leung et al., 2023](#); [Pérez-González et al., 2023](#); [Donnan et al., 2024](#)). This demonstrates that there is a somewhat milder evolution in α with increasing redshift than some pre-*JWST* predictions. This mild evolution in α is matched by my model in this work showing consistency with recent observations. This is demonstrated in Fig. 6.7 where I compare the model to observational constraints on α . The model also predicts that the faint-end slope reduces in steepness to fainter UV magnitudes with a non-linear faint-end to the UV LF. This is demonstrated in Table. 6.2, where I show the faint-end slope of my models over the range $-18 < M_{\text{UV}} < -16$ and $-17 < M_{\text{UV}} < -15$. This is due to the ever decreasing star-formation efficiency with decreasing halo-mass. There is some observational evidence for this shape at $z \simeq 2 - 4$ ([Parsa et al., 2016](#)) but deeper *JWST* imaging is required to measure this at the highest redshifts. Both the milder evolution in α with increasing redshift and the decreasing steepness with fainter UV magnitudes both limit the number density of faint-galaxies able to

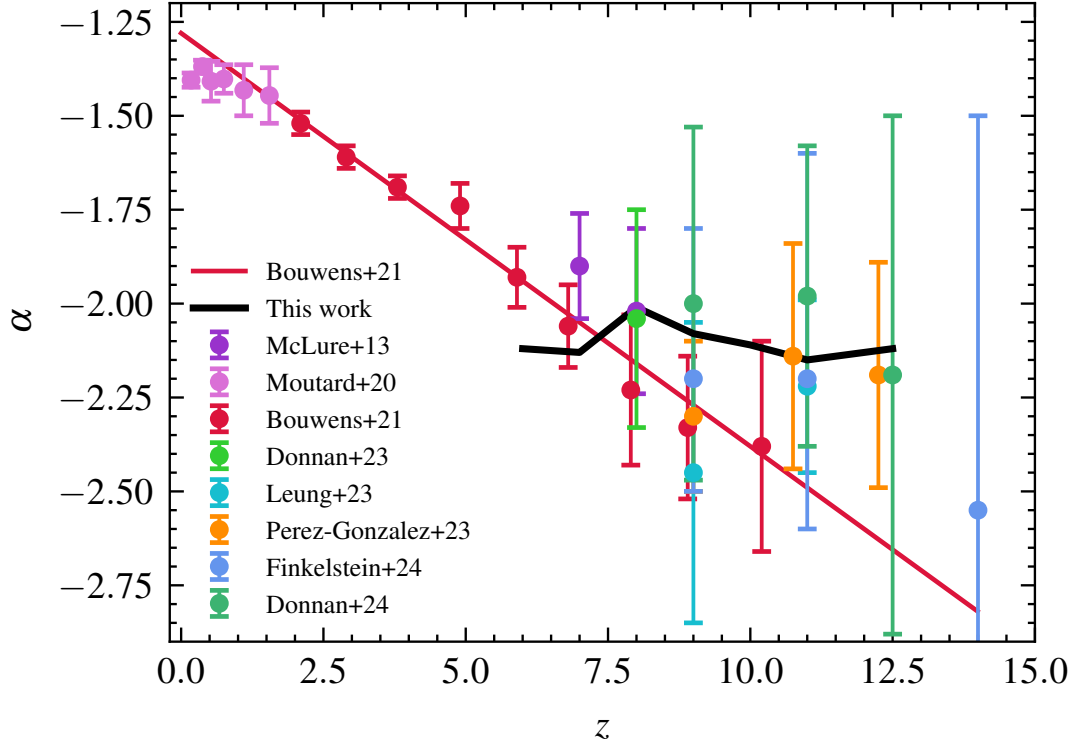


Figure 6.7 *The redshift evolution of the strength of the faint-end slope, α . The solid red line shows the model from [Bouwens et al. \(2021\)](#) whereas the solid black line shows the faint-end slope from my model measured over $-18.5 < M_{UV} < -17.5$. I show a range of observational constraints from [McLure et al. \(2013\)](#); [Moutard et al. \(2020\)](#); [Bouwens et al. \(2021\)](#); [Donnan et al. \(2023a\)](#); [Leung et al. \(2023\)](#); [Pérez-González et al. \(2023\)](#); [Finkelstein et al. \(2024b\)](#); [Donnan et al. \(2024\)](#).*

contribute to reionization.

Overall, using the latest *JWST* constraints on the escape fraction and ionising photon production efficiency along with my models of the UV LF at $z = 6 - 13$, I find no evidence for an excess of the ionising photons and instead find consistency with the observational constraints of the neutral IGM fraction as a function of redshift. In Fig. 6.8 I show the final result of my model for redshift evolution of the neutral fraction assuming the latest constraints on ξ_{ion} , f_{esc} and ρ_{UV} where I assume a redshift dependent form for both ξ_{ion} (Begley et al., 2024) and f_{esc} . This shows excellent consistency with the observational datapoints and specifically the required termination of reionization at $z \simeq 5.5$.

6.7 Conclusions

I have developed a simple theoretical model to test whether more complex physical phenomena are necessary to explain the UV LF, GSMF and reionization history at $z \geq 6$ as has been proposed by a number of recent studies from *JWST* observations.

Firstly, I assume a constant star-formation efficiency as a function of redshift where efficiency depends only on dark matter halo-mass. This is able to reproduce the GSMF up to $z = 8$ (the maximum redshift where robust measurement is available) and is also able to fully reproduce the UV LF at $z = 6 - 13$. This demonstrates that there is not in fact a requirement for increased star-formation efficiencies to explain the highest redshift measurements of the GSMF or UV LF.

Secondly, I test the need for high-mass feedback as the removal of this has been suggested as an explanation for the excess of bright galaxies observed at $z = 6 - 9$ from ground-based surveys as well as explaining the (highly uncertain) high-mass end of the GSMF. I find from both the GSMF and the number density of sub-millimetre galaxies that there is insufficient evidence to remove high-mass feedback. Yet wider area studies of the GSMF at $z = 6 - 8$ is required to precisely constrain the star-formation efficiencies for massive halos ($M_{\text{h}} > 10^{11.7} M_{\odot}$).

Thirdly, I find that the bright-end of the UV LF at $z \geq 6$ is fully explainable with a moderate level of dust attenuation consistent with a $A_{1500} - M_{\star}$ relation with the same slope but lower normalisation than that at $z = 2$. The abundance of bright galaxies at $z > 10$ is also consistent with the presence of the $A_{1500} - M_{\star}$

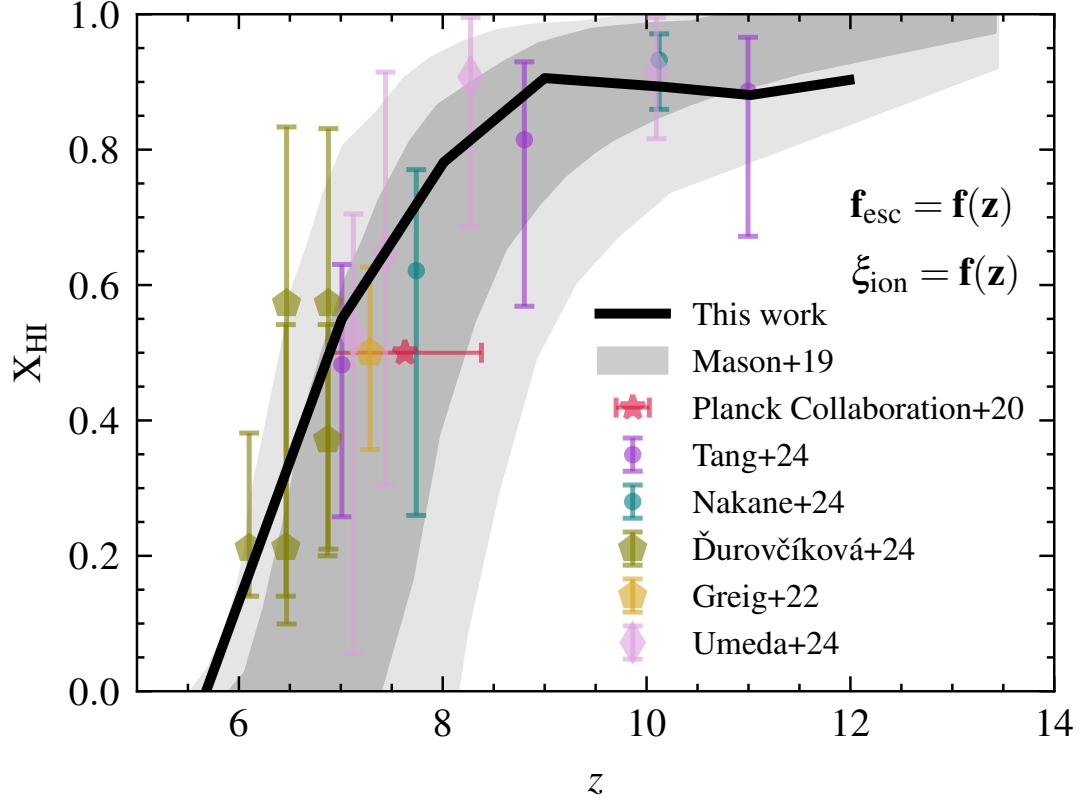


Figure 6.8 *The redshift evolution of the neutral fraction of the intergalactic medium with my final model prediction given by the solid black line where $\log(\xi_{\text{ion}}/\text{Hz erg}^{-1}) = 0.035z + 25.08$ (Begley et al., 2024) and the UV LF is integrated to a limit of $M_{\text{UV}} = -15$. I assume the redshift evolving form of f_{esc} shown by the bottom right inset panel in Fig. 6.6. Observational measurements of the neutral fraction are shown for the CMB (Planck Collaboration et al., 2020a), Ly α equivalent widths (Tang et al., 2024; Nakane et al., 2024), QSO damping wings (Greig et al., 2022; Ďurovčáková et al., 2024) and for LBG damping wings (Umeda et al., 2024). The grey shaded region shows the model from Mason et al. (2019) (dark grey: 68th percentile; light grey: 95th percentile)*

relation, albeit with a lower normalisation.

Finally, I tested the implications of my model on reionization to test if the latest *JWST* observations suggest an ionising photon budget crisis. I find that using the latest measurements of f_{esc} and ξ_{ion} in combination with my model UV LF's, there is no tension with observational measurements of the timeline of reionization or with the completion redshift of $z \simeq 5.5$.

Chapter 7

Conclusions and future work

7.1 Conclusions

In this chapter, I provide a summary of the conclusions of each of the chapters in this thesis. I then discuss potential future work.

My thesis has explored the formation of the first galaxies using both ground and space-based data to measure the evolution of the UV luminosity function at the highest redshifts possible ($z = 8 - 15$) and explore the physical properties of these galaxies. I have then developed a simple theoretical model to interpret the observational results.

7.1.1 The evolution of the galaxy UV luminosity function at redshifts $z \simeq 8 - 15$ from deep JWST and ground-based near-infrared imaging

In Chapter 3 I presented an analysis of the first available *JWST*/NIRCam imaging data from the SMACS0723, GLASS and CEERS surveys in combination with the latest ground-based data from UltraVISTA DR5. I selected a sample of 61 galaxies, 47 of which are newly discovered in this work, to provide an estimate of the UV LF and cosmic star-formation rate density (ρ_{SFR}) at $z = 8 - 15$. My results confirm that the UV LF at $z \geq 8$ is best described by a double power-law instead of a Schechter function. I have shown that ρ_{SFR} declines steadily and

gradually to $z \sim 15$, which is in excess of some pre-*JWST* predictions. The sample contains 6 galaxies at $z \geq 12$, one of which is an apparently robust galaxy candidate at $z \simeq 16.4$. I consider the properties of this galaxy in detail including follow-up spectroscopic observations.

7.1.2 The abundance of $z \gtrsim 10$ galaxy candidates in the HUDF using deep *JWST* NIRCam medium-band imaging

In Chapter 4 I presented a search for $z \geq 9.5$ galaxies using *JWST*/NIRCam medium bands in the Hubble Ultra Deep Field (HUDF) as well as an additional pointing within the GOODS-South field. This search revealed 6 robust galaxy candidates of which 3 have been spectroscopically confirmed. One of these galaxies is the previously controversial $z = 12$ candidate which now has a precise photometric redshift of $z_{\text{phot}} = 11.6 \pm 0.2$ which is in close agreement to the recent spectroscopic measurement. Using the SED fitting code BAGPIPES, I determined the physical properties of these galaxies, finding stellar masses of $\log(M_{\star}/M_{\odot}) = 7.5 - 8.7$ and star-formation rates of $\log(\text{SFR}/M_{\odot}^{-1}\text{yr}^{-1}) = 0.3 - 5.0$. Although this imaging only covers a small cosmological volume with an area of $\simeq 9$ sq. arcmin, we find that the number density at $z = 11$ is consistent with recent *JWST* measurements showing the UV LF and cosmic star-formation rate density following a shallow, gradual decline out to $z \sim 15$.

7.1.3 *JWST* PRIMER: A new multi-field determination of the evolving galaxy UV luminosity function at redshifts $z \simeq 9 - 15$

In Chapter 5 I presented a multifield determination of the UV LF at $z = 9 - 15$ using *JWST*/NIRCam imaging data from three of the major Cycle 1 imaging programmes - PRIMER, JADES and NGDEEP. This results in a sample of 2548 galaxies with a probability of lying at high-redshift of $p(z > 8.5) > 0.05$ selected from $\simeq 370$ sq. arcmin of NIRCam imaging. I presented robust UV LF measurements in 4 different redshift bins at $z = 9, 10, 11, 12.5$ spanning ~ 4 magnitudes of UV luminosity. These measurements demonstrate that the UV LF evolves slowly from $z = 9 - 13$ with little evolution in either the bright or

faint-end slopes.

I then demonstrated that the evolution in the cosmic star-formation rate density can be reproduced with no change to cosmology, dust content or star-formation efficiency out to $z \simeq 12$. Instead, a steady decline in stellar ages with increasing redshift is sufficient to reproduce the evolution in ρ_{SFR} out to $z \simeq 12$. These ages all converge on a formation time of $\simeq 380 - 330$ Myr after the Big Bang. This indicates a potential rapid decline in the number density of galaxies at $z \geq 14$ which is likely driven by the rapid evolution of the halo-mass function.

7.1.4 A simple model of the galaxy stellar mass function and UV luminosity function at $z \geq 6$

In Chapter 6 I presented a simple theoretical model based on the halo-mass function which can reproduce the observed UV LF and galaxy stellar-mass function (GSMF) at $z = 6 - 13$. This model shows that constant star-formation efficiency with redshift is able to reproduce the observed GSMF and UV LF at $z = 6 - 13$. The model also shows that the bright-end of the UV LF at $z = 6 - 13$ is fully explainable with moderate levels of dust attenuation and requires no change in the star formation efficiency in the most massive halos. Finally, I determined the evolution of the neutral fraction of the IGM with redshift based on the UV LF models finding consistency with the observational constraints on cosmic reionization indicating that there is no “ionising photon budget crisis”.

7.2 Future work

This thesis has focused on using photometry, primarily from *JWST*/NIRCam, to understand the formation of the first galaxies through the evolution of the UV LF. This has provided valuable insight on the global build-up of galaxies in the early Universe. However, to truly understand the physics within the first galaxies, we require follow-up spectroscopy of these galaxies.

7.2.1 Spectroscopic confirmation of the UV LF at $z \geq 10$

As described throughout this thesis, I have used photometric measurements of galaxies to determine the UV LF at $z = 8 - 15$. However, without spectroscopic verification there is still uncertainty over these measurements of the UV LF. I am a leading member of the large Cycle 3 *JWST*/NIRSpec programme CAPERS which will finish observing by June 2025 providing spectroscopic confirmation of > 100 galaxies at $z > 9.5$ using (at least) the precise detection of the Lyman- α break (e.g. [Curtis-Lake et al., 2023](#)) and 2000 galaxies at $4 < z < 9.5$ using emission-line detections, transforming the sample size of spectroscopically confirmed galaxies at these redshifts. Currently there are tentative spectroscopic measurements of the UV LF (e.g. [Harikane et al., 2024](#)). However, these are based on a limited sample and therefore only provide lower limits on the UV LF. Using CAPERS there will be an order-of-magnitude increase in the sample size will therefore enable a definitive confirmation the UV LF at $z = 8 - 15$ for the first time. This will be especially true for the bright-end of the UV LF where we will obtain spectroscopic measurements for a complete sample of galaxies. This is the luminosity regime where there is the most tension with many existing theoretical models with the number density of such sources apparently $\sim 10\times$ their predictions (e.g. [Yung et al., 2019](#); [Mason et al., 2023](#)). Therefore I will test the spectroscopic measurements against these literature models as well as my own model.

In [Donnan et al. \(2024\)](#) I showed tentative evidence that there is a more rapid decline in ρ_{SFR} at $z > 13$. However, selecting galaxies at $z > 13$ is very challenging with the currently available NIRCам photometry. Also there are only 3 galaxies spectroscopically confirmed at this redshift ([Curtis-Lake et al., 2023](#); [Carniani et al., 2024](#)) and therefore there is significant uncertainty on the abundance of galaxies at $z > 13$. Using CAPERS I will further constrain the abundance of galaxies at $z > 13$ by targeting these extreme redshift galaxies over hundreds of sq. arcminutes. This will not only accurately constrain their abundance (and reveal if there truly is a more rapid decline at $z > 13$) but also reveal their physical properties to understand the nature of such extreme redshift sources.

7.2.2 The UV spectral properties of galaxies at $z \geq 10$

The next stage in using spectroscopy to understand the properties of galaxies at $z > 10$ is measuring their chemical abundances. *JWST*/NIRSpec has revealed

elevated nitrogen and carbon abundances for a small number of bright galaxies at $z > 10$ implying a rapid chemical enrichment that cannot be explained with standard nucleosynthesis. [Cameron et al. \(2023\)](#) measured an unusually high N/O abundance in a $M_{UV} = -21.5$ galaxy at $z = 10.6$ (GN-z11) using NIRSpect observations. [Castellano et al. \(2024\)](#) also measure a high N/O abundance in a $M_{UV} = -20.5$ galaxy at $z = 12.34$ (GHZ2) but also detect an extremely strong C IV $\lambda 1549$ line with an equivalent width of $\simeq 46\text{\AA}$. This is in contrast to GN-z11 which has a CIV equivalent width of $\simeq 3.5\text{\AA}$. GHZ2 and GN-z11 also have a number of other UV emission lines (e.g. CIII, NIII, NeIII) which have vastly different equivalent widths for each galaxy. However, there are also bright galaxies at $z > 10$ with single or no emission-line detections where the upper limits indicate significantly weaker emission lines than GHZ2 and GN-z11 (e.g. [Curtis-Lake et al., 2023](#); [Carniani et al., 2024](#)). Therefore, it is crucial to understand this diversity of rest-frame UV emission line strengths to understand the details of star formation at cosmic dawn. This work can be divided into 2 sub-projects summarised below.

Although these sources suggest a wide range of different chemical properties at $z > 10$, and crucially demonstrate the feasibility of using NIRSpect/PRISM to measure them, there have only been a small number of UV luminous galaxies ($M_{UV} \leq -20$) at $z > 10$ targeted with NIRSpect. To fully understand the diversity of rest-frame UV properties of galaxies at $z > 10$ requires a larger sample of NIRSpect data at these redshifts. Using the CAPERS survey I will improve this with an order of magnitude increase in the number of galaxies at $z > 10$ with measurements of their rest-frame UV emission lines. This will generate a statistically large sample for the first time mapping out the range of chemical properties of these extreme redshift galaxies.

C IV $\lambda 1549$ and C III] $\lambda 1908$ (which are expected to be strong at $z \geq 10$; [Roberts-Borsani et al., 2024](#)), will enable me to measure how their equivalent widths vary with redshift allowing a direct probe of the ionization conditions as these lines are correlated with the metallicity and ionization conditions of star-forming galaxies ([Mingozzi et al., 2024](#)). Also the ratio of C IV $\lambda 1549$ /C III] $\lambda 1908$ will allow measurements of the ionization parameter in these galaxies. The detection of [Ne III] $\lambda 3868$ will also enable a measurement of the oxygen abundance using the [Ne III] $\lambda 3868$ /[O II] $\lambda 3727$ calibration ([Maiolino et al., 2008](#)) and the detection of O III] $\lambda 1663$ will also enable the measurement of the carbon and nitrogen abundances through the C III] $\lambda 1908$ /O III] $\lambda 1663$ and N III] $\lambda 1750$ /O III]

$\lambda 1663$ ratios respectively (e.g. [Berg et al., 2019](#)). There is also the possibility to detect $\text{Ly}\alpha$ in this sample as, although rare due to the neutral intergalactic medium (IGM), it has been detected at $z \simeq 11$ ([Bunker et al., 2024](#)) and $z \simeq 13$ ([Witstok et al., 2024](#)). I will also stack the spectra to enable line detection in galaxies where the CAPERS spectra are unable to sufficiently provide detection in individual galaxies. In summary, I will measure a number of important galaxy properties using rest-frame UV emission lines for a statistically significant sample of galaxies at $z \geq 10$, providing new insights into the nature of star formation at cosmic dawn.

Appendix A

The First Appendix

A.1 SEDs and postage-stamp images

The SEDs and postage-stamp images of all 55 sources are provided in this Appendix. In Figs. [A.1-A.2](#) I show the best-fitting SEDs for the 16 COSMOS galaxy candidates. In Figs. [A.3-A.7](#) I show the best-fitting SEDs for the 45 JWST-selected galaxy candidates. The postage-stamp images for the galaxies in the COSMOS sample are presented in Figs. [A.8-A.9](#). The postage-stamp images of the JWST-selected galaxies are shown in Figs. [A.10-A.15](#).

A.2 Photometry tables

The multi-wavelength photometry for the galaxies in the COSMOS/UltraVISTA sample is listed in Table [A.1](#), with the photometry for the JWST-selected galaxies listed in Table [A.2](#).

A.3 JWST Zero-point calibrations

Since the initial release of the JWST imaging there have been updates to the NIRCам calibrations from in-flight tests ([Rigby et al., 2023](#)). However, comparison to existing imaging data (both HST and ground based) shows that

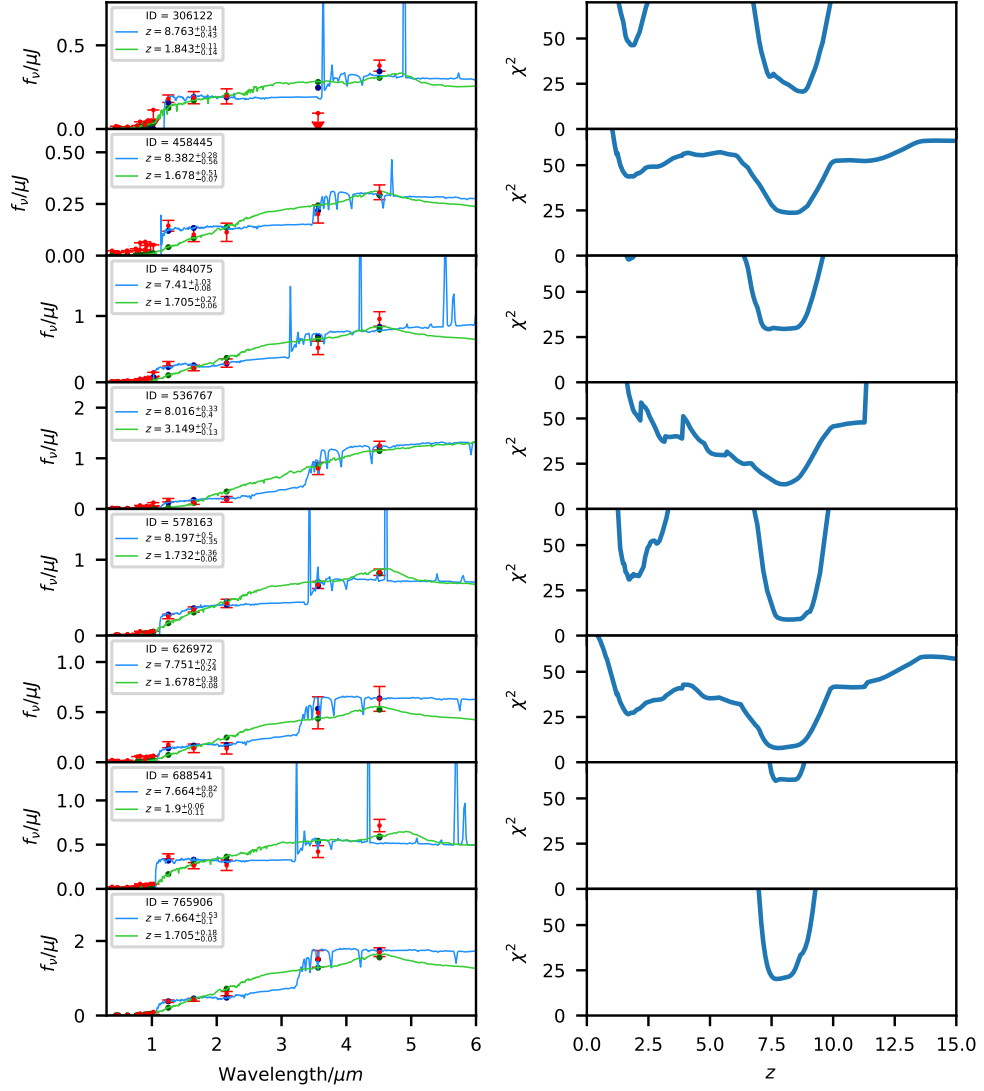


Figure A.1 *The measured photometry and best-fitting SED from EAZY for the $z > 7.5$ galaxies found the COSMOS/UltraVISTA field. For each object the best-fitting high-redshift solution is shown in blue with the best-fitting alternative low-redshift solution plotted in green. Non-detections at the 2σ level are shown as downward arrows. The solid blue and green circles represent the model photometry of the best fitting high and low redshift templates respectively.*

The panels in the right-hand column show χ^2 as a function of redshift for each object.

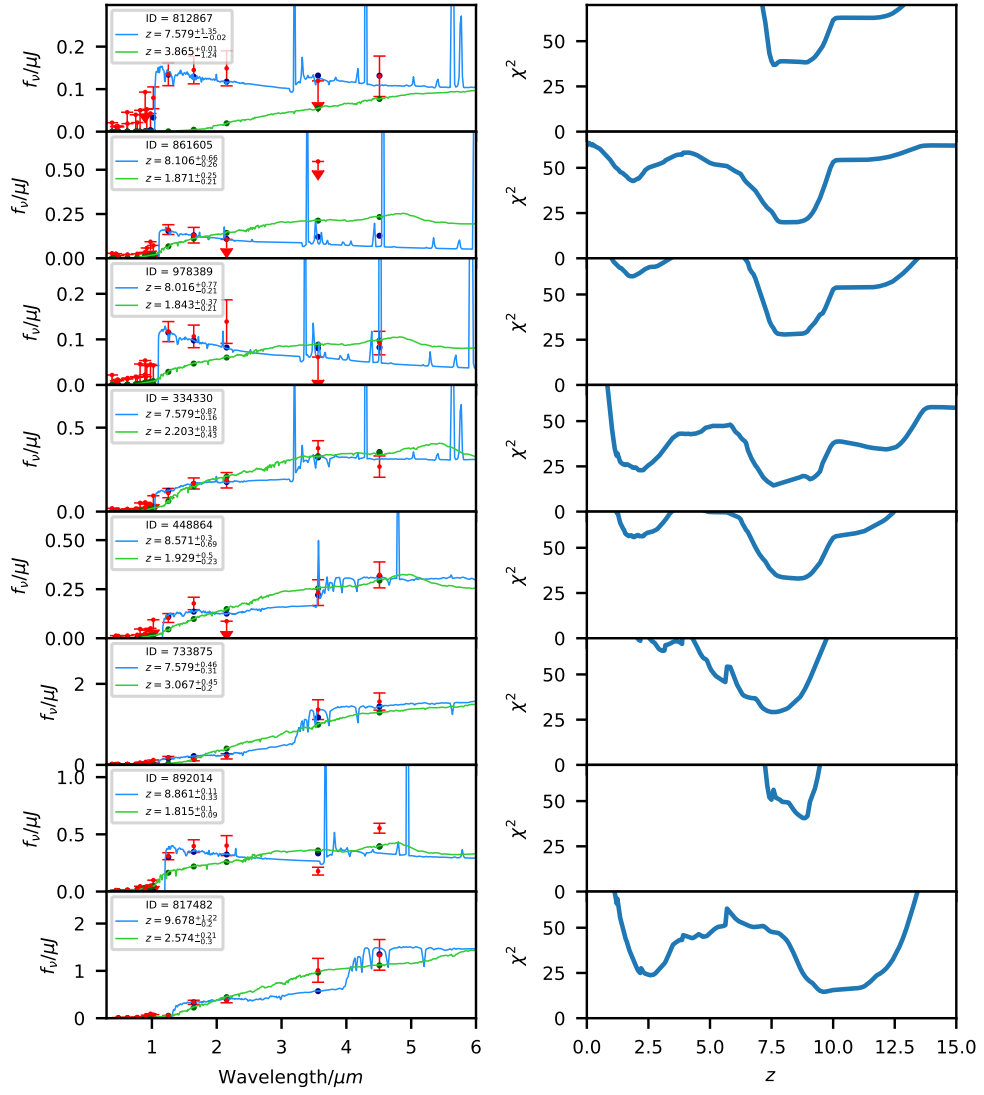


Figure A.2 *Continued.*

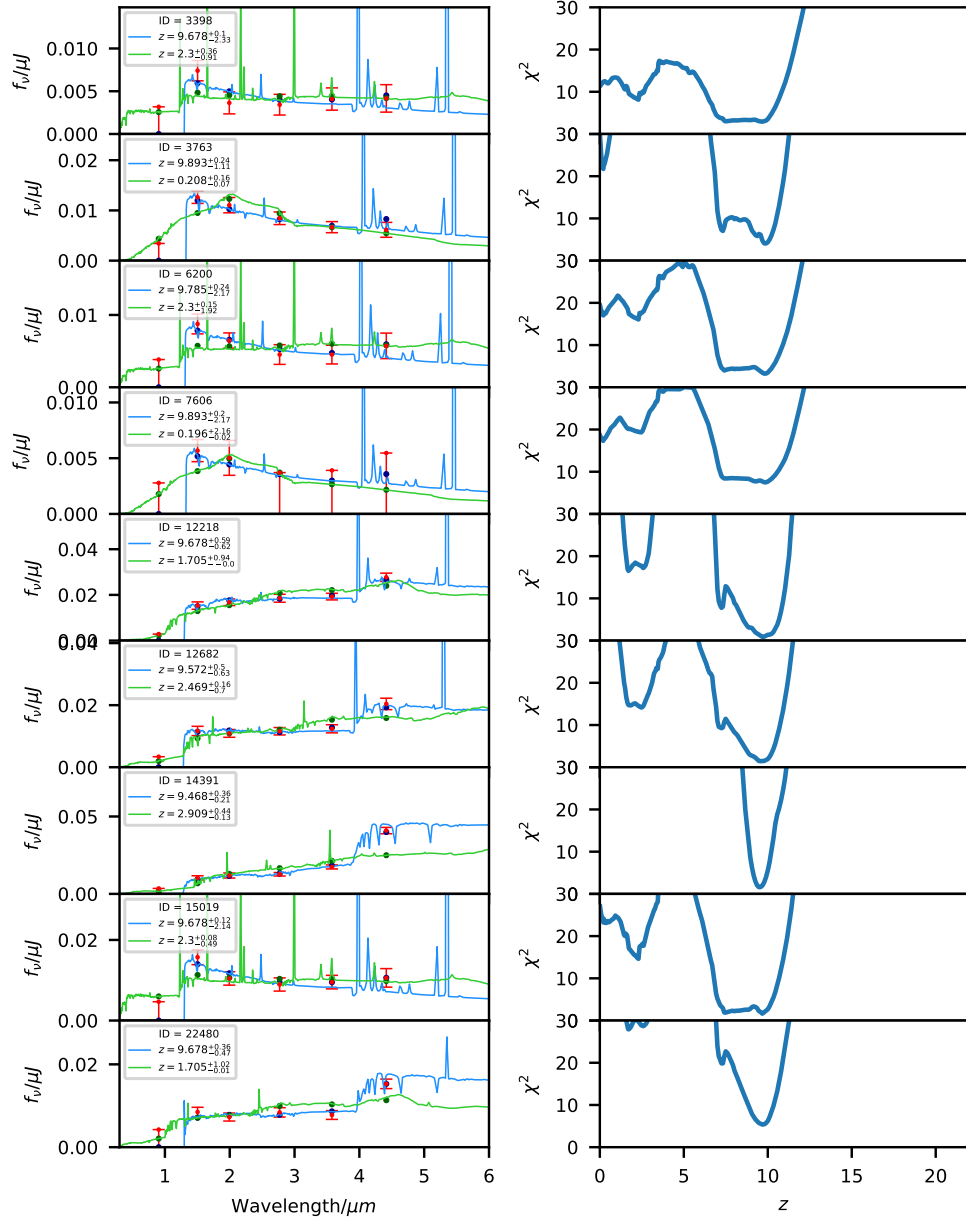


Figure A.3 The measured photometry and best fitting SED from EAZY for the galaxies in the JWST sample. The format is the same as in Fig. A.1.

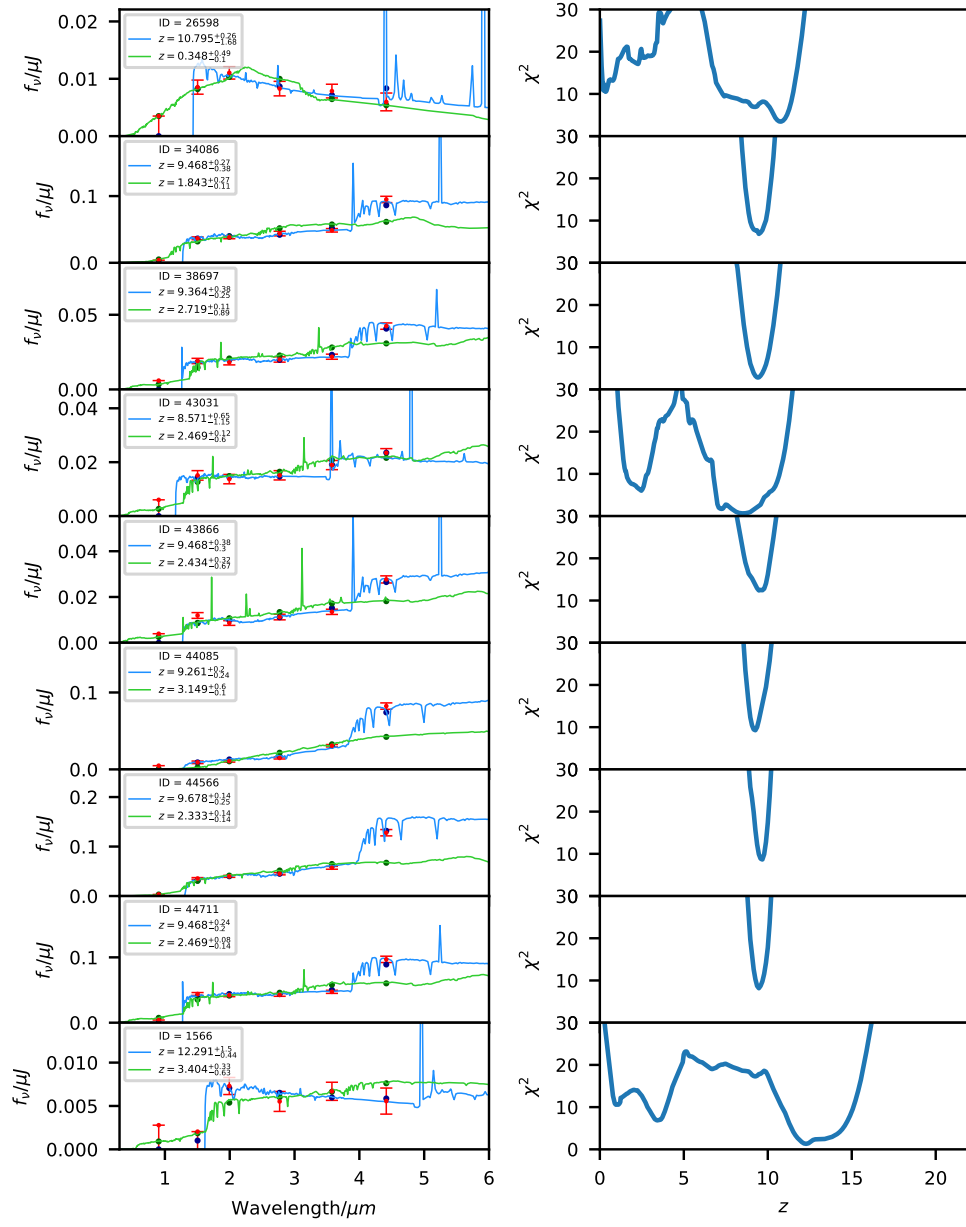


Figure A.4 *Continued.*

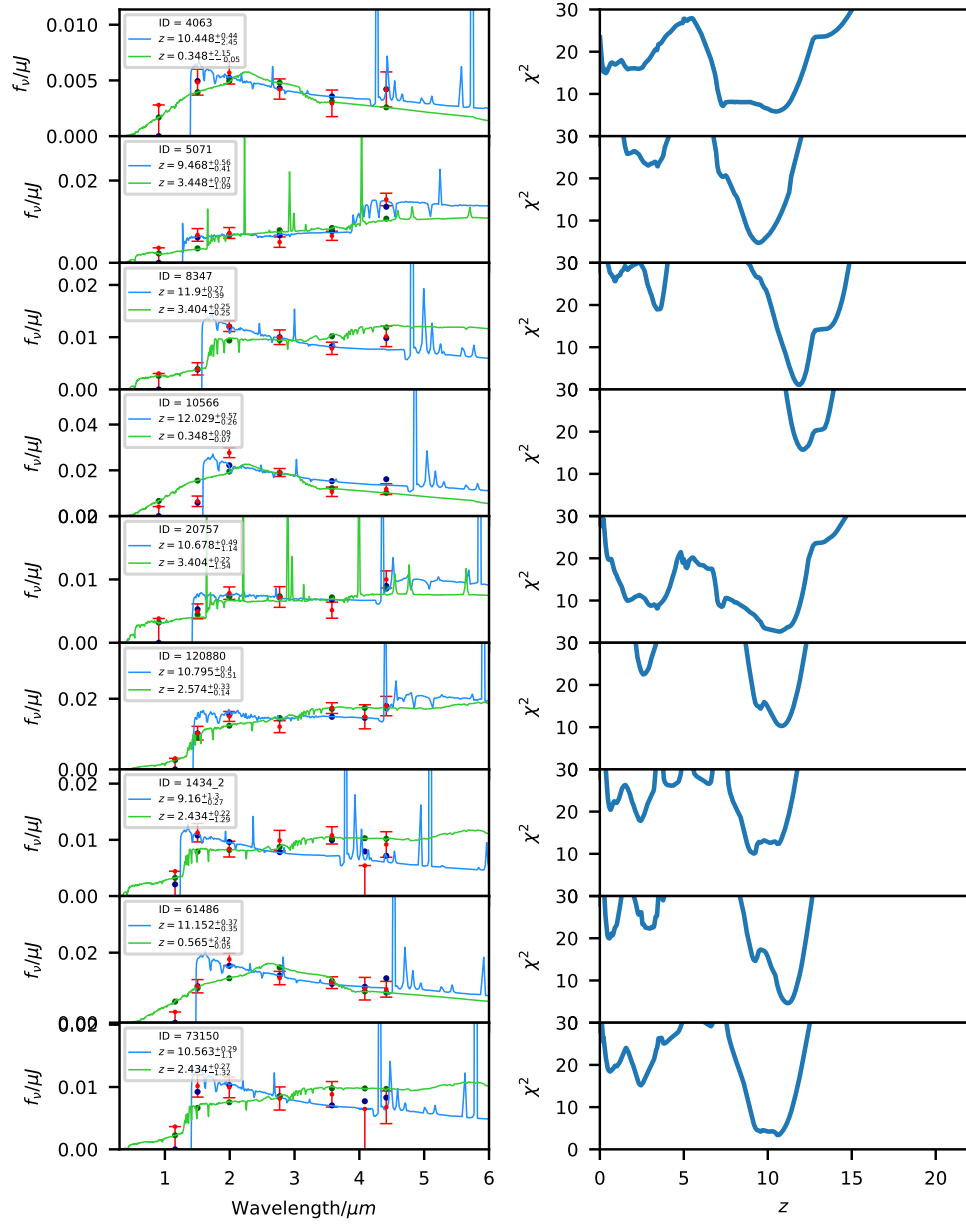


Figure A.5 *Continued.*

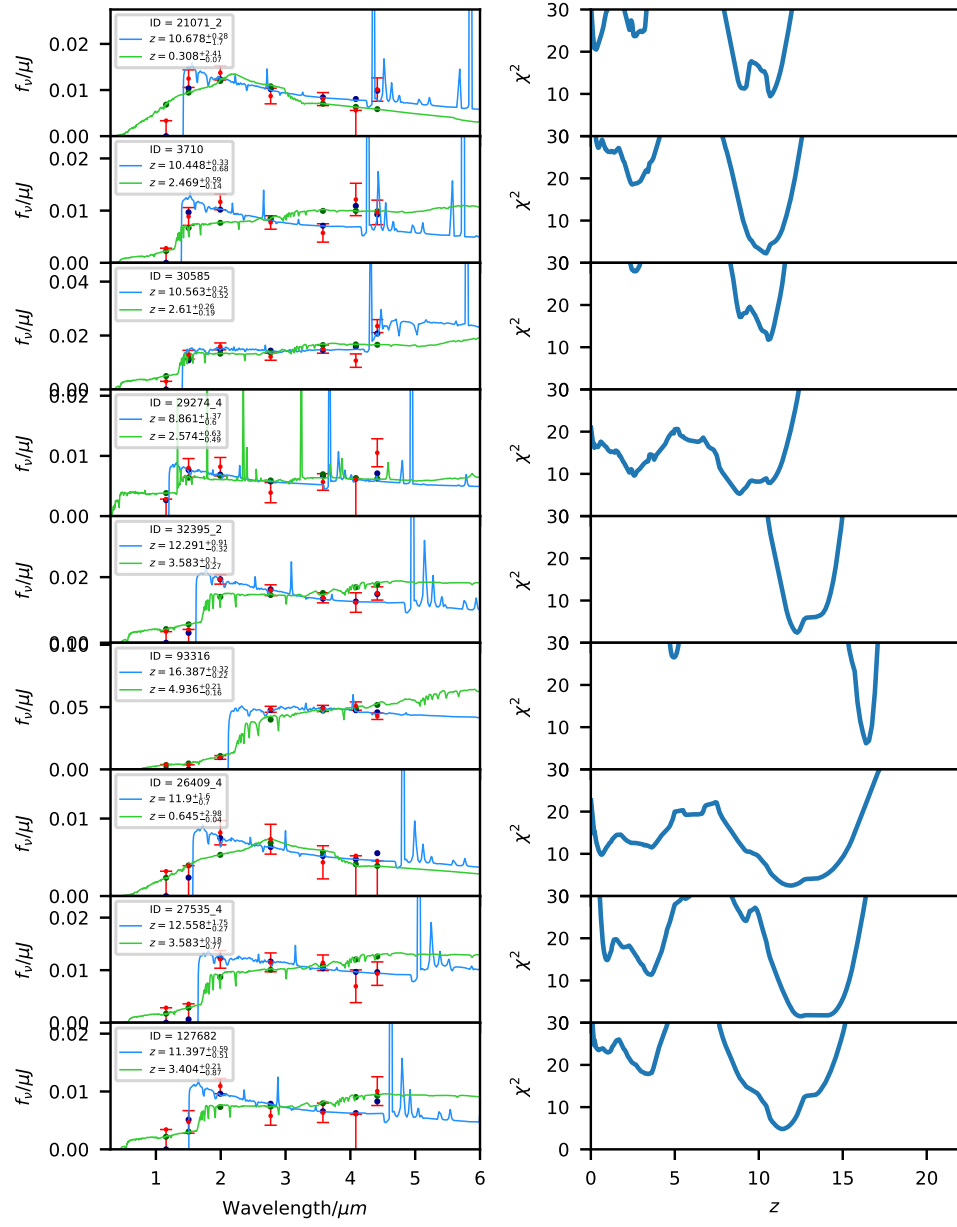


Figure A.6 *Continued.*

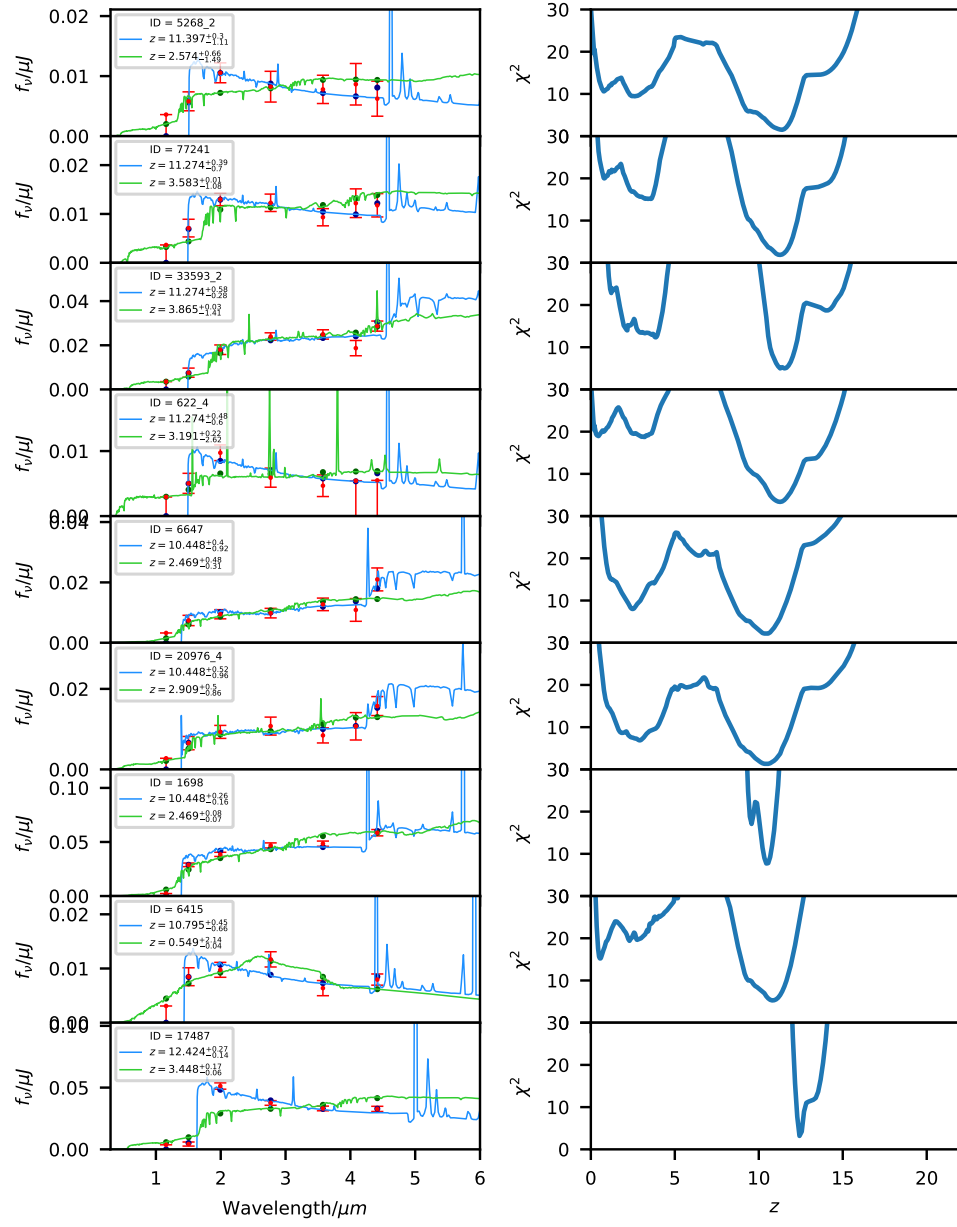


Figure A.7 *Continued.*

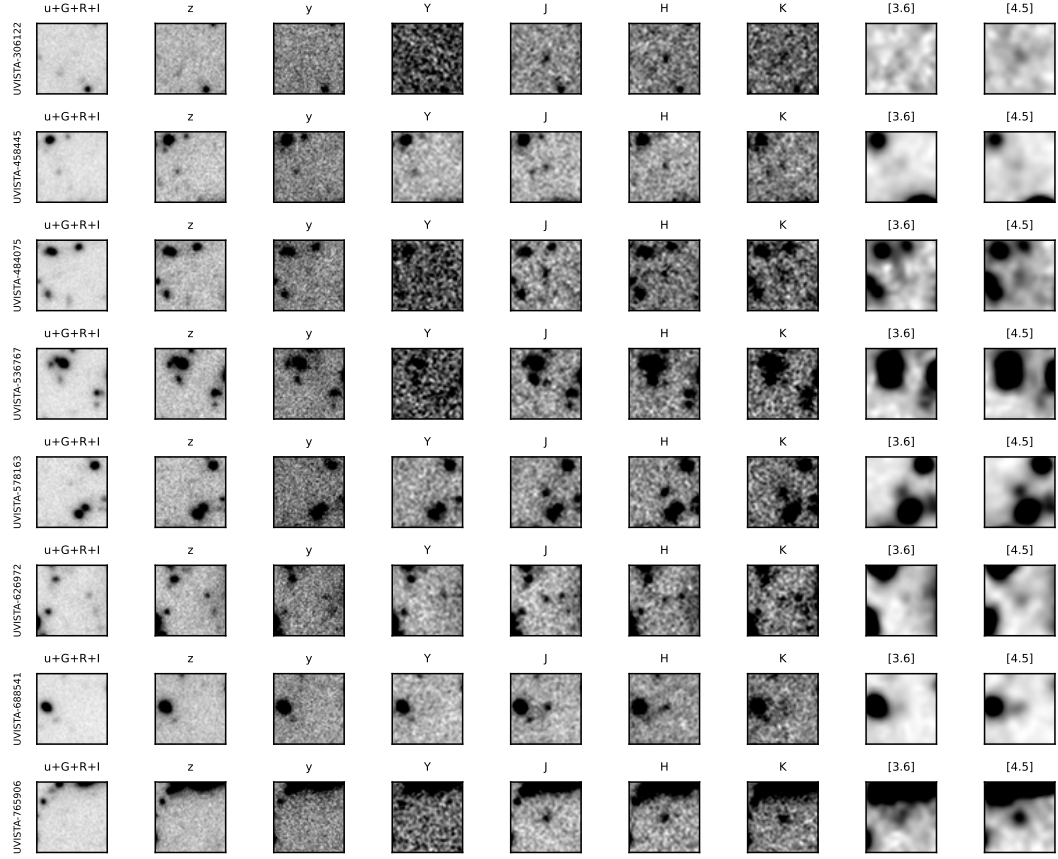


Figure A.8 *Postage-stamp images of the 16 $z > 7.5$ galaxies selected from the COSMOS/UltraVISTA field. Each row shows an individual object, with the imaging ordered by increasing wavelength from left to right. Each postage-stamp image is 10×10 arcsec.*

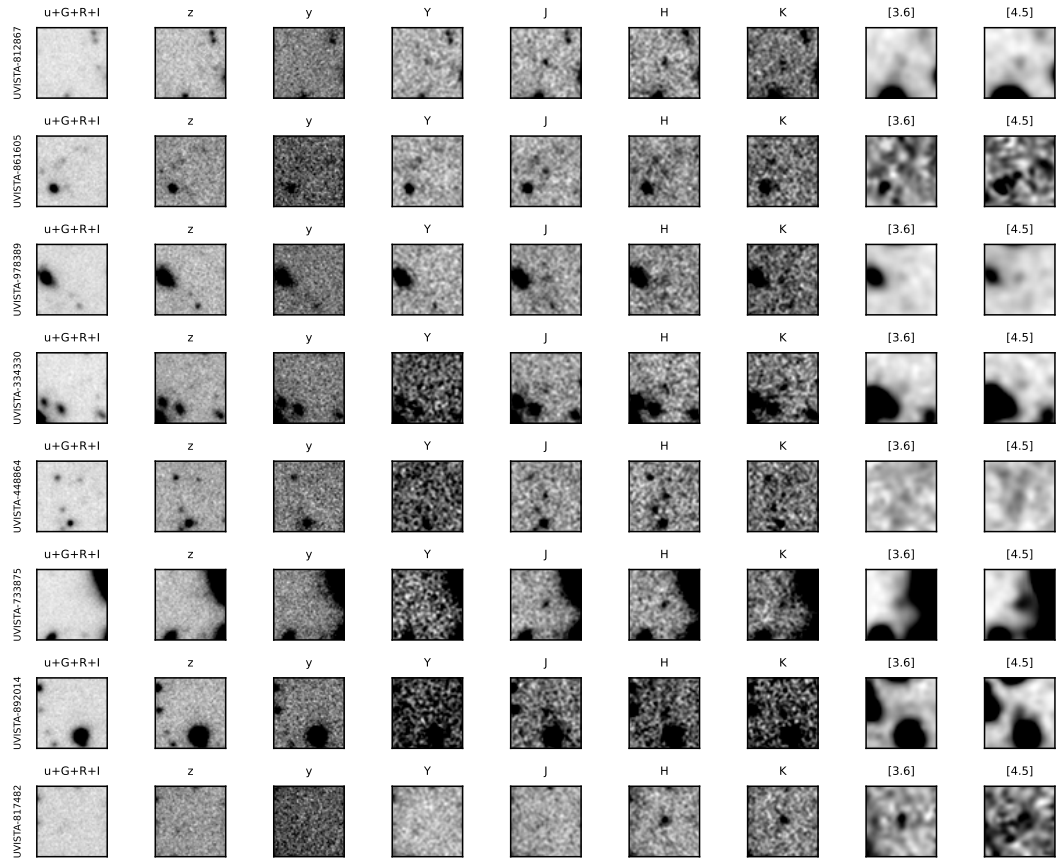


Figure A.9 *Continued.*

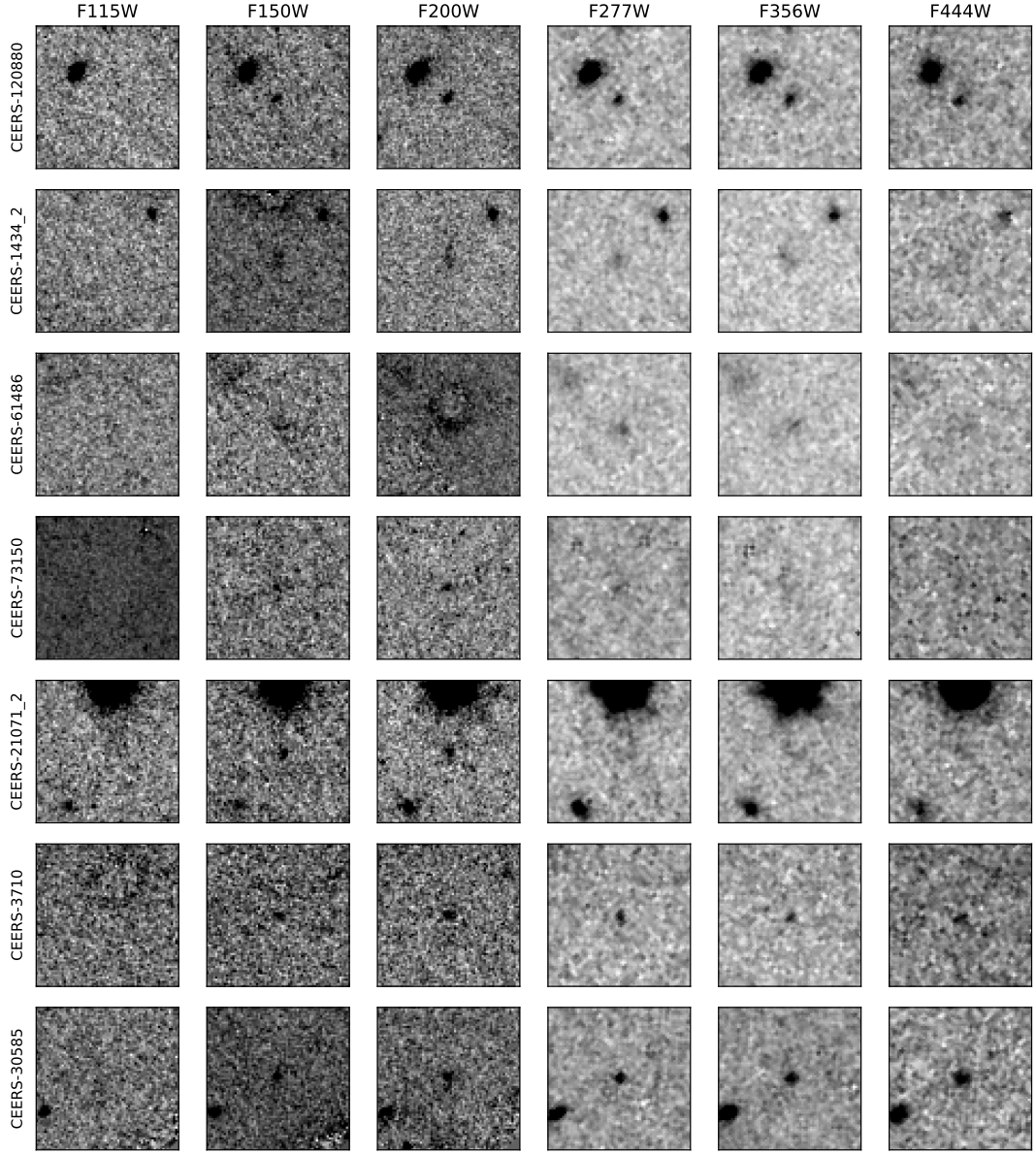


Figure A.10 *Postage-stamp images of the 45 $z > 8.5$ galaxies selected from the combined JWST imaging. Each row shows an individual object, with the imaging ordered by increasing wavelength from left to right. Each postage-stamp image is 2×2 arcsec.*

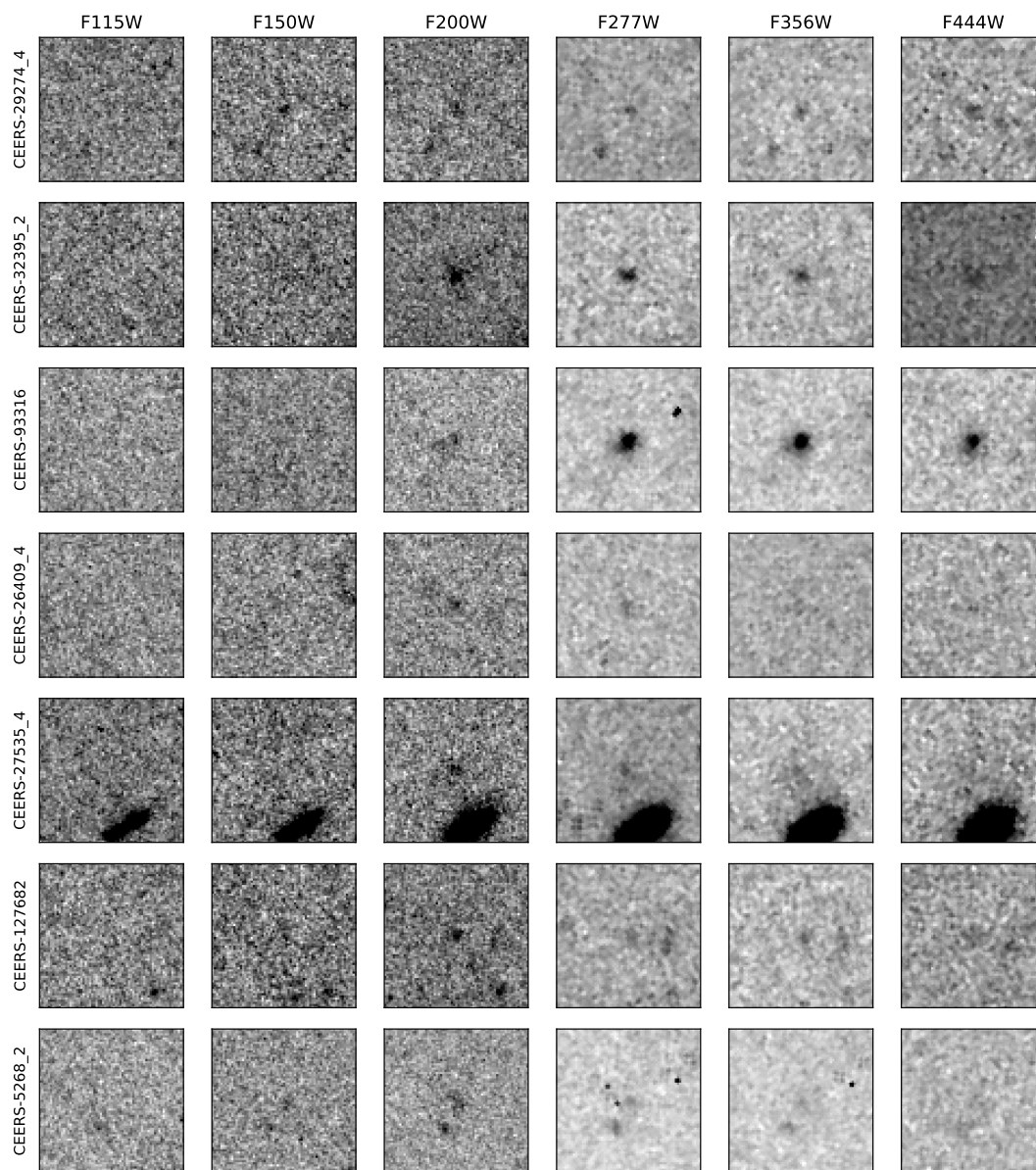


Figure A.11 *Continued.*

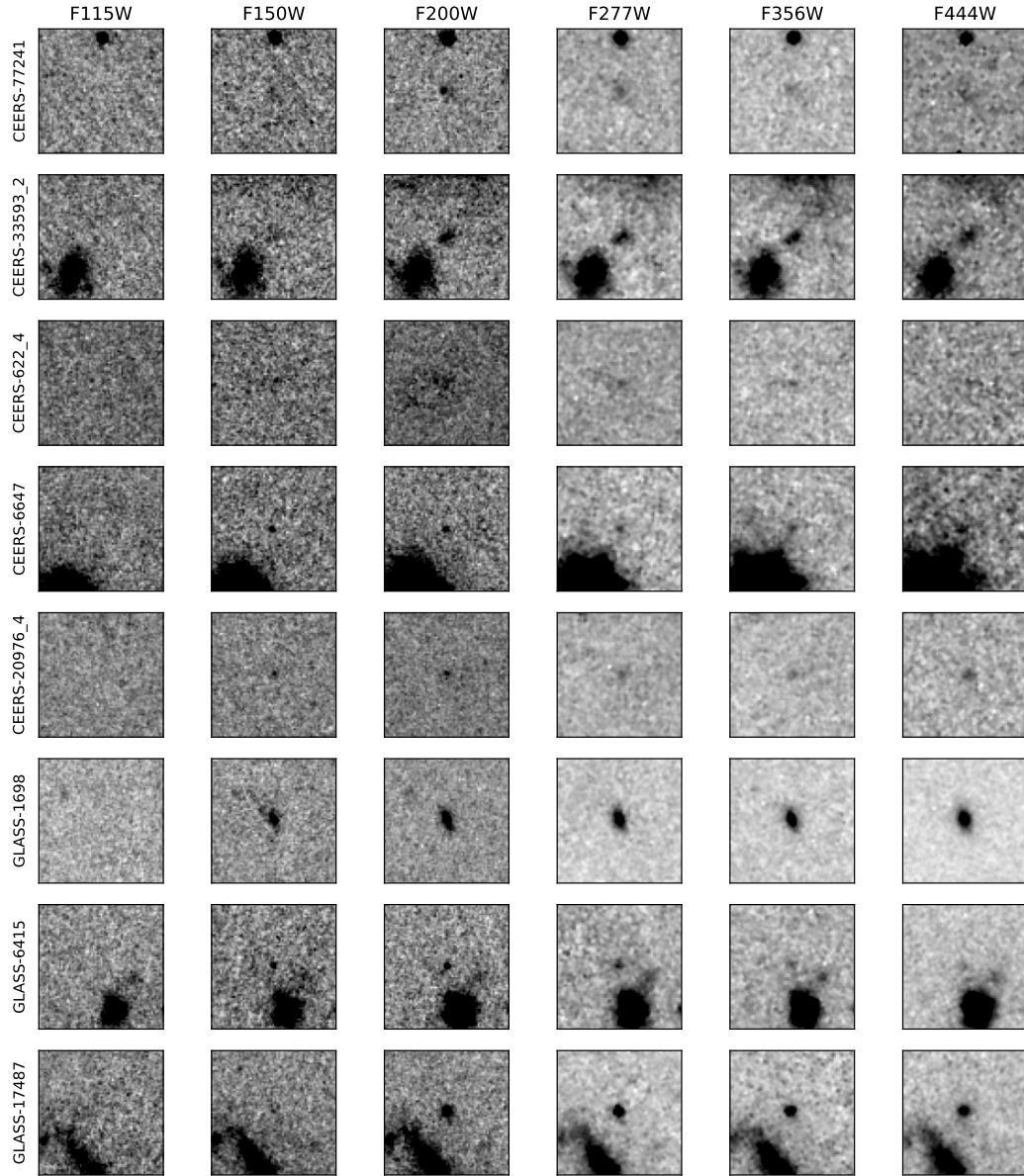


Figure A.12 *Continued.*

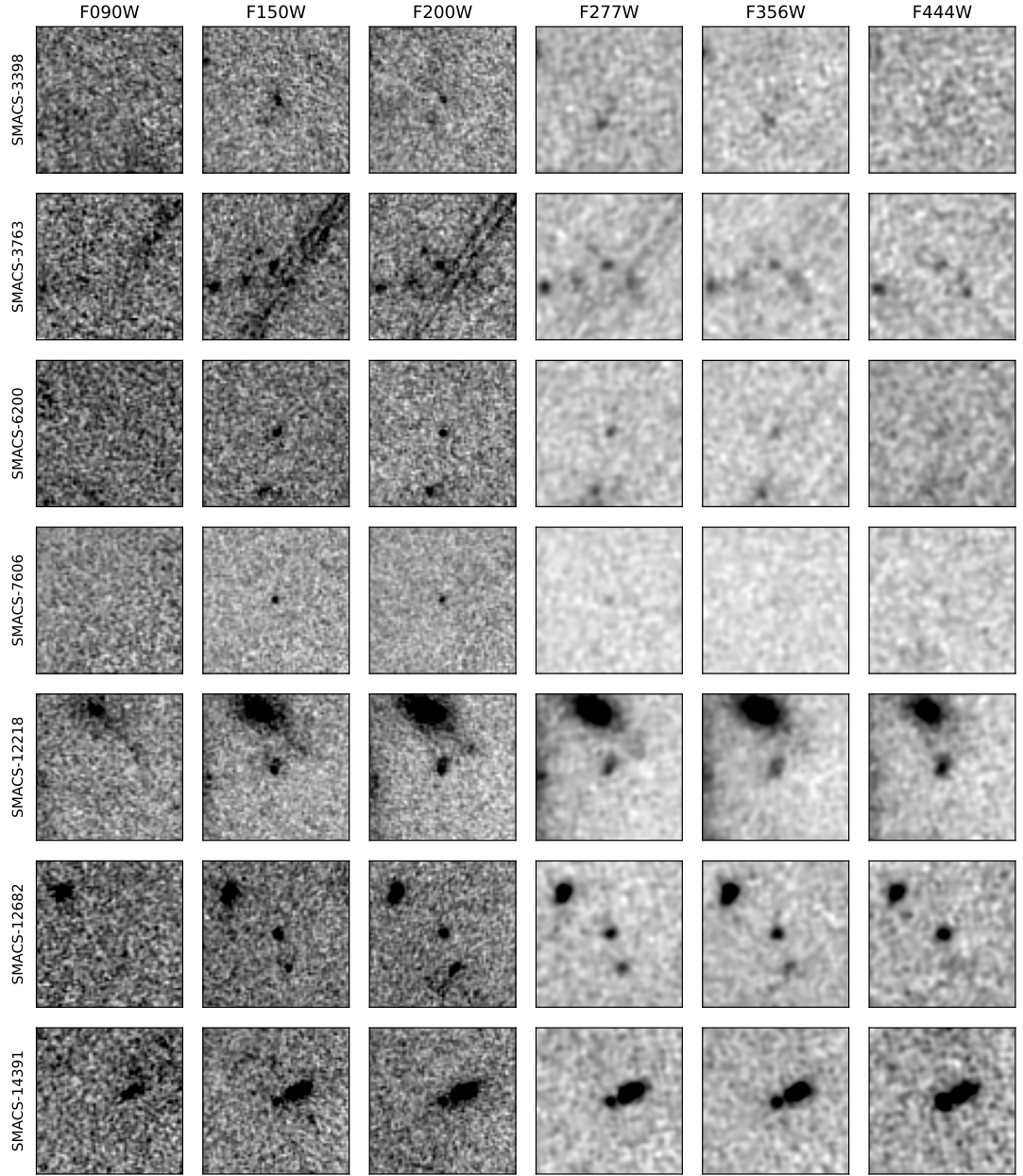


Figure A.13 *Continued.*

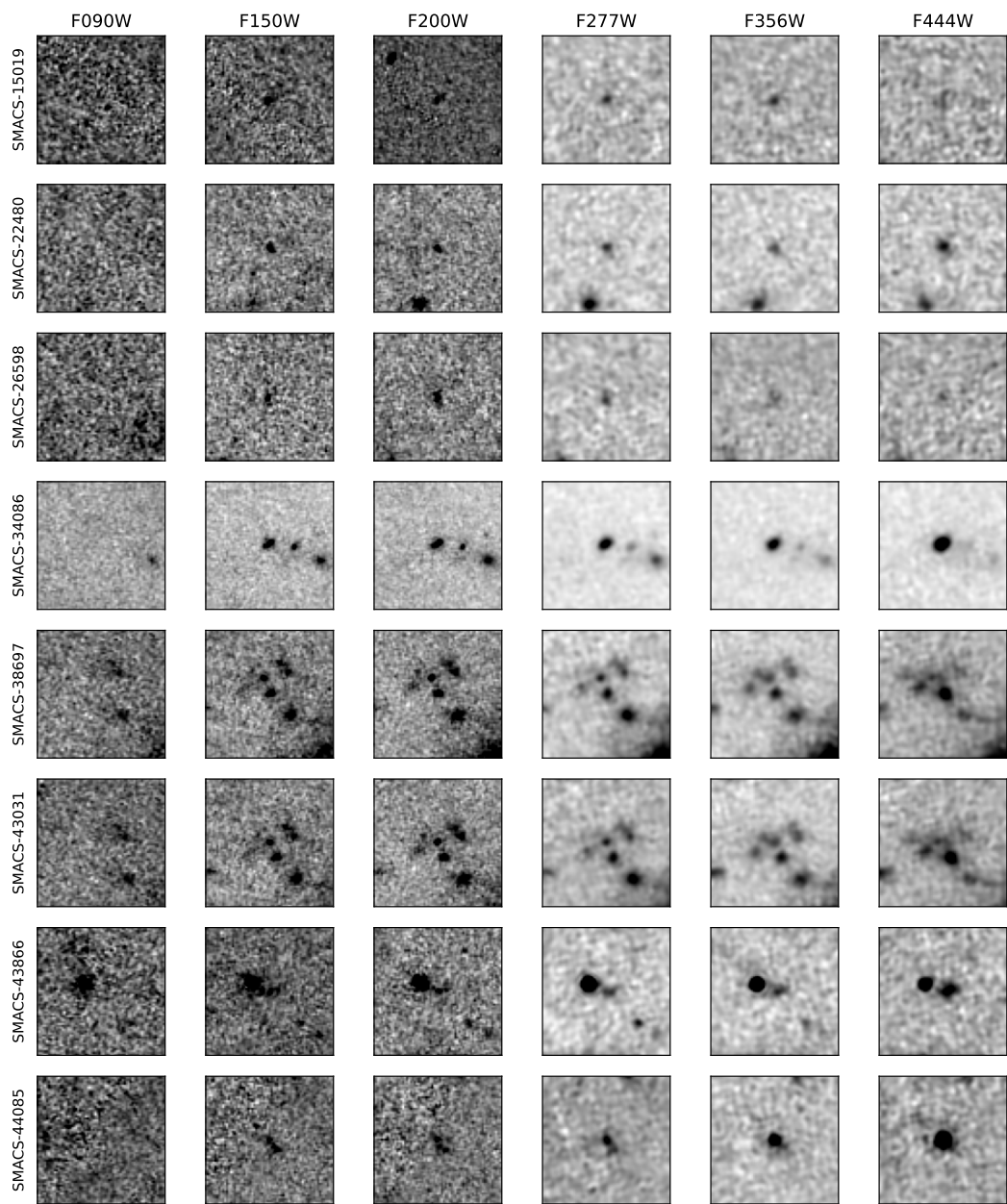


Figure A.14 *Continued.*

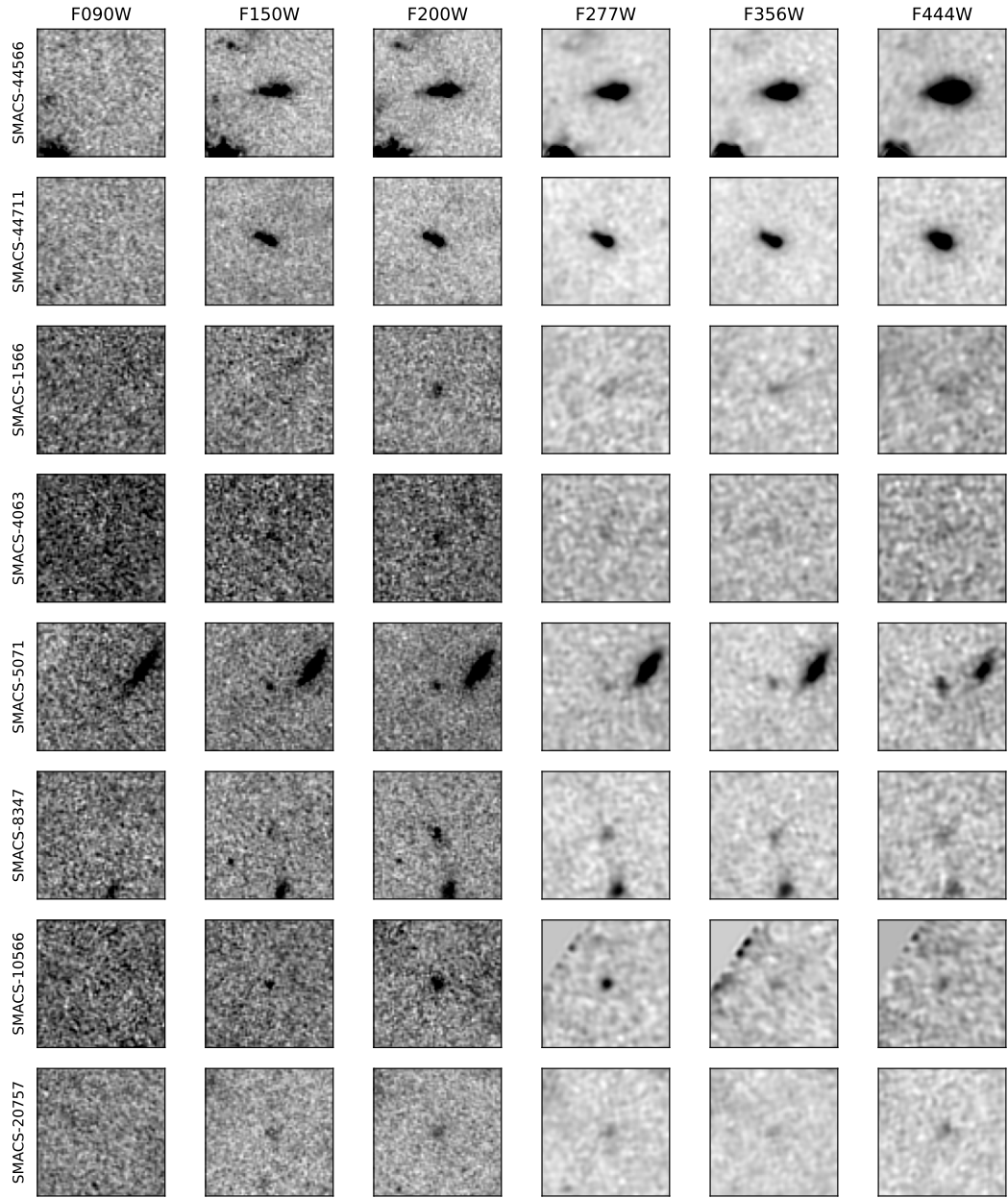


Figure A.15 *Continued.*

Table A.1 *The observed photometry for the galaxies selected from the COSMOS UltraVISTA DR5 imaging. The first column lists the ID of the object followed by the field within which it was identified. The third column shows the HSC z -band magnitude. The following columns show the HSC y magnitude followed by VISTA Y and VISTA J, H, K_s . The final columns show the Spitzer/IRAC magnitudes. In the case of a non-detection, the 2σ upper limit to the photometry is given.*

ID	FIELD	z	y	Y	J	H	K	[3.6]	[4.5]
306122	COSMOS	>27.45	>26.79	>25.85	$25.39^{+0.14}_{-0.13}$	$25.35^{+0.23}_{-0.19}$	$25.30^{+0.29}_{-0.23}$	>26.09	$24.58^{+0.1}_{-0.09}$
458445	COSMOS	>27.33	>26.60	>26.70	$25.63^{+0.22}_{-0.18}$	$26.01^{+0.44}_{-0.31}$	$25.90^{+0.54}_{-0.36}$	$25.27^{+0.26}_{-0.21}$	$24.81^{+0.13}_{-0.12}$
484075	COSMOS	>27.42	>26.53	>25.54	$24.91^{+0.14}_{-0.13}$	$25.19^{+0.23}_{-0.19}$	$24.87^{+0.26}_{-0.21}$	$24.24^{+0.24}_{-0.19}$	$23.58^{+0.13}_{-0.12}$
536767	COSMOS	>27.34	>26.61	>25.75	$25.44^{+0.24}_{-0.2}$	$25.77^{+0.38}_{-0.28}$	$25.34^{+0.39}_{-0.29}$	$23.77^{+0.18}_{-0.15}$	$23.29^{+0.08}_{-0.07}$
578163	COSMOS	>27.49	>26.66	>26.58	$25.03^{+0.14}_{-0.12}$	$24.69^{+0.12}_{-0.1}$	$24.46^{+0.15}_{-0.13}$	$23.97^{+0.08}_{-0.07}$	$23.72^{+0.06}_{-0.05}$
626972	COSMOS	>27.33	>26.52	>26.47	$25.42^{+0.21}_{-0.17}$	$25.67^{+0.4}_{-0.29}$	$25.68^{+0.57}_{-0.37}$	$24.30^{+0.42}_{-0.3}$	$24.03^{+0.24}_{-0.19}$
688541	COSMOS	>27.14	>26.55	>26.65	$24.61^{+0.09}_{-0.08}$	$24.98^{+0.15}_{-0.14}$	$24.96^{+0.27}_{-0.22}$	$24.47^{+0.19}_{-0.16}$	$23.89^{+0.11}_{-0.1}$
765906	COSMOS	>27.21	>26.82	>26.04	$24.57^{+0.1}_{-0.09}$	$24.46^{+0.1}_{-0.09}$	$24.11^{+0.11}_{-0.1}$	$23.07^{+0.17}_{-0.15}$	$22.95^{+0.08}_{-0.07}$
812867	COSMOS	>27.44	>26.87	$26.24^{+0.42}_{-0.3}$	$25.70^{+0.24}_{-0.2}$	$25.62^{+0.28}_{-0.22}$	$25.60^{+0.35}_{-0.27}$	>25.84	$25.74^{+0.49}_{-0.34}$
861605	COSMOS	>27.14	>26.02	>26.33	$25.50^{+0.2}_{-0.17}$	$25.74^{+0.45}_{-0.32}$	>25.96	>24.18	>23.71
978389	COSMOS	>27.59	>26.81	>26.91	$25.86^{+0.23}_{-0.19}$	$25.96^{+0.29}_{-0.23}$	$25.67^{+0.46}_{-0.32}$	>26.56	$26.12^{+0.36}_{-0.27}$
334330	COSMOS	>27.54	>26.85	>26.05	$25.92^{+0.31}_{-0.24}$	$25.47^{+0.24}_{-0.19}$	$25.35^{+0.31}_{-0.24}$	$24.59^{+0.14}_{-0.12}$	$24.96^{+0.29}_{-0.23}$
448864	COSMOS	>27.57	>26.69	>26.05	$26.00^{+0.27}_{-0.22}$	$25.41^{+0.21}_{-0.18}$	>26.18	$25.11^{+0.36}_{-0.27}$	$24.76^{+0.25}_{-0.2}$
733875	COSMOS	>27.33	>26.43	>25.78	$25.39^{+0.2}_{-0.17}$	$25.64^{+0.39}_{-0.29}$	$25.22^{+0.4}_{-0.29}$	$23.19^{+0.21}_{-0.18}$	$23.04^{+0.16}_{-0.14}$
892014	COSMOS	>27.63	>26.68	>26.00	$24.80^{+0.11}_{-0.1}$	$24.53^{+0.16}_{-0.14}$	$24.52^{+0.27}_{-0.21}$	$25.40^{+0.23}_{-0.19}$	$24.17^{+0.09}_{-0.08}$
817482	COSMOS	>27.21	>26.01	>26.30	>26.65	$24.71^{+0.15}_{-0.13}$	$24.60^{+0.15}_{-0.13}$	$23.52^{+0.31}_{-0.24}$	$23.21^{+0.3}_{-0.24}$

Table A.2 *The observed photometry for the galaxies in the JWST-selected sample. The table first presents the photometry for the SMACS0723 candidates followed by the CEERS objects, and then finally the 3 GLASS candidates. The first column lists the ID of the object followed by the name of the field in which it was identified. The following columns show the photometry in each of the relevant NIRCam filters. A dash indicates where that filter was not available for a given field. In the case of a non-detection at the 2σ level the photometry is shown as an upper limit. Extended sources are indicated with an asterisk beside the ID number. These sources have had an extra correction applied to their photometry as a point-source correction is insufficient.*

ID	FIELD	F090W	F115W	F150W	F200W	F277W	F356W	F410M	F444W
3398	SMACS	>29.85	-	28.93 ^{+0.19} _{-0.16}	29.70 ^{+0.47} _{-0.33}	29.76 ^{+0.47} _{-0.33}	29.57 ^{+0.42} _{-0.3}	-	29.55 ^{+0.53} _{-0.35}
3763	SMACS	>29.77	-	28.35 ^{+0.11} _{-0.1}	28.49 ^{+0.16} _{-0.14}	28.79 ^{+0.18} _{-0.15}	29.04 ^{+0.2} _{-0.17}	-	29.13 ^{+0.3} _{-0.23}
6200	SMACS	>29.64	-	28.75 ^{+0.18} _{-0.16}	29.08 ^{+0.19} _{-0.16}	29.46 ^{+0.39} _{-0.29}	29.46 ^{+0.37} _{-0.27}	-	29.21 ^{+0.4} _{-0.29}
7606	SMACS	>29.99	-	29.22 ^{+0.21} _{-0.17}	29.35 ^{+0.4} _{-0.29}	>29.68	>29.62	-	>29.26
12218	SMACS	>29.97	-	28.14 ^{+0.12} _{-0.11}	28.04 ^{+0.1} _{-0.09}	27.93 ^{+0.11} _{-0.1}	27.89 ^{+0.08} _{-0.08}	-	27.50 ^{+0.07} _{-0.07}
12682	SMACS	>29.78	-	28.43 ^{+0.15} _{-0.13}	28.51 ^{+0.13} _{-0.12}	28.44 ^{+0.12} _{-0.11}	28.37 ^{+0.12} _{-0.11}	-	27.83 ^{+0.1} _{-0.09}
14391	SMACS	>29.73	-	28.56 ^{+0.15} _{-0.13}	28.42 ^{+0.16} _{-0.14}	28.34 ^{+0.1} _{-0.09}	28.00 ^{+0.08} _{-0.08}	-	27.07 ^{+0.06} _{-0.05}
15019	SMACS	>29.43	-	28.11 ^{+0.14} _{-0.12}	28.55 ^{+0.19} _{-0.16}	28.72 ^{+0.22} _{-0.18}	28.65 ^{+0.21} _{-0.18}	-	28.54 ^{+0.27} _{-0.21}
22480	SMACS	>29.53	-	28.78 ^{+0.16} _{-0.14}	28.95 ^{+0.15} _{-0.14}	28.79 ^{+0.16} _{-0.14}	28.88 ^{+0.16} _{-0.14}	-	28.14 ^{+0.08} _{-0.08}
26598	SMACS	>29.74	-	28.77 ^{+0.17} _{-0.15}	28.49 ^{+0.11} _{-0.1}	28.81 ^{+0.18} _{-0.15}	28.86 ^{+0.18} _{-0.15}	-	29.16 ^{+0.33} _{-0.25}
34086	SMACS	>29.62	-	27.19 ^{+0.06} _{-0.06}	27.15 ^{+0.06} _{-0.06}	27.00 ^{+0.09} _{-0.08}	26.88 ^{+0.06} _{-0.06}	-	26.16 ^{+0.06} _{-0.05}
38697	SMACS	>29.17	-	27.90 ^{+0.11} _{-0.1}	27.96 ^{+0.11} _{-0.1}	27.85 ^{+0.1} _{-0.09}	27.75 ^{+0.09} _{-0.08}	-	27.03 ^{+0.06} _{-0.05}
43031	SMACS	>29.15	-	28.15 ^{+0.14} _{-0.12}	28.26 ^{+0.15} _{-0.13}	28.15 ^{+0.13} _{-0.12}	27.91 ^{+0.1} _{-0.09}	-	27.67 ^{+0.07} _{-0.07}
43866	SMACS	>29.61	-	28.41 ^{+0.12} _{-0.11}	28.76 ^{+0.14} _{-0.12}	28.48 ^{+0.13} _{-0.11}	28.28 ^{+0.1} _{-0.09}	-	27.50 ^{+0.06} _{-0.06}
44085	SMACS	>29.39	-	28.70 ^{+0.22} _{-0.18}	28.53 ^{+0.14} _{-0.12}	28.17 ^{+0.1} _{-0.09}	27.38 ^{+0.06} _{-0.05}	-	26.31 ^{+0.06} _{-0.05}
44566*	SMACS	>29.84	-	26.24 ^{+0.06} _{-0.05}	26.11 ^{+0.06} _{-0.05}	25.98 ^{+0.06} _{-0.05}	25.72 ^{+0.06} _{-0.05}	-	24.84 ^{+0.06} _{-0.05}
44711*	SMACS	>29.58	-	26.63 ^{+0.06} _{-0.05}	26.68 ^{+0.06} _{-0.05}	26.66 ^{+0.06} _{-0.05}	26.55 ^{+0.06} _{-0.05}	-	25.77 ^{+0.06} _{-0.05}
1566	SMACS	>29.99	-	j30.33	28.94 ^{+0.16} _{-0.14}	29.25 ^{+0.25} _{-0.21}	29.04 ^{+0.18} _{-0.16}	-	29.24 ^{+0.34} _{-0.26}
4063	SMACS	>29.99	-	29.39 ^{+0.3} _{-0.23}	29.22 ^{+0.21} _{-0.18}	29.54 ^{+0.26} _{-0.21}	29.93 ^{+0.56} _{-0.37}	-	29.55 ^{+0.51} _{-0.35}
5071	SMACS	>29.70	-	29.02 ^{+0.28} _{-0.22}	28.95 ^{+0.22} _{-0.18}	29.35 ^{+0.31} _{-0.24}	29.06 ^{+0.2} _{-0.17}	-	28.13 ^{+0.11} _{-0.1}
8347	SMACS	>29.89	-	29.61 ^{+0.38} _{-0.28}	28.39 ^{+0.1} _{-0.09}	28.60 ^{+0.16} _{-0.14}	28.86 ^{+0.18} _{-0.15}	-	28.59 ^{+0.23} _{-0.19}
10566	SMACS	>29.56	-	29.08 ^{+0.47} _{-0.33}	27.50 ^{+0.09} _{-0.08}	27.90 ^{+0.1} _{-0.1}	28.54 ^{+0.23} _{-0.19}	-	28.42 ^{+0.24} _{-0.2}
20757	SMACS	>29.64	-	29.36 ^{+0.29} _{-0.23}	28.87 ^{+0.15} _{-0.13}	28.95 ^{+0.28} _{-0.22}	29.32 ^{+0.31} _{-0.24}	-	28.60 ^{+0.16} _{-0.14}

Table A.3 *Table A.2 continued.*

ID	FIELD	F090W	F115W	F150W	F200W	F277W	F356W	F410M	F444W
120880	CEERS	-	>29.87	$28.58^{+0.23}_{-0.19}$	$28.16^{+0.11}_{-0.1}$	$28.40^{+0.16}_{-0.14}$	$28.00^{+0.1}_{-0.09}$	$28.17^{+0.28}_{-0.22}$	$27.97^{+0.18}_{-0.15}$
1434_2	CEERS	-	>29.49	$28.47^{+0.17}_{-0.15}$	$28.80^{+0.2}_{-0.17}$	$28.62^{+0.22}_{-0.18}$	$28.52^{+0.17}_{-0.14}$	>29.27	$28.70^{+0.31}_{-0.24}$
61486	CEERS	-	>29.88	$28.56^{+0.22}_{-0.18}$	$27.96^{+0.11}_{-0.1}$	$28.34^{+0.18}_{-0.15}$	$28.46^{+0.17}_{-0.15}$	$28.63^{+0.44}_{-0.31}$	$28.65^{+0.29}_{-0.23}$
73150	CEERS	-	>29.70	$28.58^{+0.21}_{-0.17}$	$28.61^{+0.2}_{-0.17}$	$28.82^{+0.28}_{-0.22}$	$28.74^{+0.29}_{-0.23}$	>29.08	$29.03^{+0.53}_{-0.36}$
21071_2	CEERS	-	>29.79	$28.36^{+0.18}_{-0.15}$	$28.26^{+0.13}_{-0.12}$	$28.75^{+0.24}_{-0.19}$	$28.84^{+0.21}_{-0.18}$	>29.23	$28.59^{+0.31}_{-0.24}$
3710	CEERS	-	>29.99	$28.73^{+0.23}_{-0.19}$	$28.43^{+0.15}_{-0.13}$	$28.88^{+0.2}_{-0.17}$	$29.21^{+0.4}_{-0.29}$	$28.39^{+0.32}_{-0.25}$	$28.64^{+0.3}_{-0.24}$
30585	CEERS	-	>29.91	$28.32^{+0.14}_{-0.13}$	$28.09^{+0.09}_{-0.08}$	$28.39^{+0.12}_{-0.11}$	$28.16^{+0.12}_{-0.11}$	$28.53^{+0.29}_{-0.23}$	$27.67^{+0.12}_{-0.11}$
29274_4	CEERS	-	>29.98	$28.84^{+0.24}_{-0.19}$	$28.82^{+0.23}_{-0.19}$	$29.63^{+0.61}_{-0.39}$	$29.22^{+0.3}_{-0.24}$	>29.13	$28.55^{+0.27}_{-0.22}$
32395_2	CEERS	-	>29.78	>29.58	$27.89^{+0.08}_{-0.08}$	$28.09^{+0.12}_{-0.11}$	$28.26^{+0.13}_{-0.12}$	$28.38^{+0.3}_{-0.24}$	$28.16^{+0.16}_{-0.14}$
93316*	CEERS	-	>29.63	>29.68	$28.25^{+0.18}_{-0.16}$	$26.49^{+0.06}_{-0.05}$	$26.48^{+0.06}_{-0.05}$	$26.44^{+0.07}_{-0.07}$	$26.63^{+0.07}_{-0.06}$
26409_4	CEERS	-	>29.84	>29.62	$28.82^{+0.23}_{-0.19}$	$28.94^{+0.33}_{-0.25}$	$29.51^{+0.73}_{-0.43}$	>29.31	>29.46
27535_4	CEERS	-	>29.97	>29.72	$28.40^{+0.16}_{-0.14}$	$28.45^{+0.18}_{-0.16}$	$28.46^{+0.15}_{-0.13}$	$29.00^{+0.65}_{-0.4}$	$28.68^{+0.3}_{-0.23}$
127682	CEERS	-	>29.76	$29.41^{+0.58}_{-0.37}$	$28.50^{+0.14}_{-0.12}$	$29.19^{+0.36}_{-0.27}$	$29.10^{+0.34}_{-0.26}$	>29.15	$28.60^{+0.31}_{-0.24}$
5268_2	CEERS	-	>29.72	$29.19^{+0.34}_{-0.26}$	$28.54^{+0.19}_{-0.16}$	$28.81^{+0.4}_{-0.29}$	$28.87^{+0.39}_{-0.29}$	$28.76^{+0.55}_{-0.37}$	$29.11^{+0.69}_{-0.42}$
77241*	CEERS	-	>29.69	$28.70^{+0.32}_{-0.25}$	$28.05^{+0.11}_{-0.1}$	$28.11^{+0.17}_{-0.15}$	$28.41^{+0.23}_{-0.19}$	$28.12^{+0.3}_{-0.23}$	$28.15^{+0.25}_{-0.2}$
33593_2	CEERS	-	>29.73	$28.90^{+0.35}_{-0.26}$	$27.96^{+0.14}_{-0.12}$	$27.65^{+0.08}_{-0.07}$	$27.61^{+0.1}_{-0.09}$	$27.92^{+0.22}_{-0.18}$	$27.46^{+0.09}_{-0.08}$
622_4	CEERS	-	>29.93	$29.35^{+0.4}_{-0.29}$	$28.63^{+0.14}_{-0.13}$	$29.17^{+0.31}_{-0.24}$	$29.43^{+0.48}_{-0.33}$	>29.26	>29.25
6647	CEERS	-	>29.83	$28.93^{+0.29}_{-0.23}$	$28.66^{+0.19}_{-0.16}$	$28.62^{+0.19}_{-0.16}$	$28.34^{+0.19}_{-0.16}$	$28.51^{+0.46}_{-0.32}$	$27.80^{+0.22}_{-0.18}$
20976_4	CEERS	-	$\lesssim 30.00$	$29.07^{+0.32}_{-0.24}$	$28.68^{+0.21}_{-0.17}$	$28.52^{+0.25}_{-0.2}$	$28.79^{+0.27}_{-0.22}$	$28.53^{+0.42}_{-0.3}$	$28.11^{+0.18}_{-0.15}$
1698*	GLASS	-	$\lesssim 30.19$	$26.89^{+0.06}_{-0.06}$	$26.88^{+0.06}_{-0.05}$	$26.67^{+0.06}_{-0.05}$	$26.63^{+0.06}_{-0.05}$	-	$26.42^{+0.06}_{-0.05}$
6415	GLASS	-	>29.88	$28.78^{+0.24}_{-0.19}$	$28.63^{+0.17}_{-0.14}$	$28.43^{+0.14}_{-0.12}$	$29.09^{+0.27}_{-0.22}$	-	$28.85^{+0.15}_{-0.13}$
17487	GLASS	-	>29.69	$29.52^{+0.53}_{-0.35}$	$26.83^{+0.06}_{-0.05}$	$27.17^{+0.06}_{-0.05}$	$27.30^{+0.06}_{-0.06}$	-	$27.31^{+0.07}_{-0.07}$

there are still offsets in the NIRCcam zero-points which differ between each filter, module and sub-module.

In order to address this problem, I exploited existing imaging data covering the CEERS survey field to derive filter and sub-module specific flux corrections that were applied to my JWST photometric catalogue before the candidate selection process.

We explored two independent approaches to deriving the necessary flux corrections. The first approach was based on SED fitting to a sample of objects with robust spectroscopic redshifts from the DEEP2/3 spectroscopic survey (Cooper et al., 2012; Newman et al., 2013). By fixing the redshift to its spectroscopic value, the difference between the observed fluxes in each filter and the fluxes predicted by the best-fitting SED template provided one estimate of the average flux corrections in each filter/sub-module.

The second approach was based on directly comparing the observed NIRCcam fluxes of compact objects with fluxes measured from existing imaging data taken in overlapping filters (e.g. F125W, F160W, K_s, IRAC CH1, IRAC CH2). During this process, special attention was paid to adopting photometric apertures which enclosed the same fraction of total flux and correcting for average colour terms between filters.

It is clear that different potential biases and systematic errors are likely to affect both methods employed to derive the flux correction factors. Consequently, for the F115W, F150W, F200W, F277W, F356W, F410M and F444W filters I adopted the straight average of the correction factors provided by the two different approaches.

The exception to this rule is the F090W filter, which does not form part of the CEERS data set. The adopted correction factors for this filter were taken from a separate analysis¹. The flux correction factors applied to my JWST photometric catalogue are listed in Table A.4.

¹<https://github.com/gbrammer/grizli/pull/107>

Table A.4 *Zero-point corrections applied to catalogue fluxes for each sub-module within each NIRC*am* filter.*

Filter	Detector	Correction
F090W	NRCA1	0.83
F090W	NRCA2	0.83
F090W	NRCA3	0.76
F090W	NRCA4	0.75
F090W	NRCB1	0.89
F090W	NRCB2	0.84
F090W	NRCB3	0.91
F090W	NRCB4	0.82
F115W	NRCA1	0.88
F115W	NRCA2	0.88
F115W	NRCA3	0.90
F115W	NRCA4	0.86
F115W	NRCB1	0.91
F115W	NRCB2	0.88
F115W	NRCB3	0.94
F115W	NRCB4	0.85
F150W	NRCA1	0.90
F150W	NRCA2	0.91
F150W	NRCA3	0.92
F150W	NRCA4	0.90
F150W	NRCB1	0.93
F150W	NRCB2	0.91
F150W	NRCB3	0.95
F150W	NRCB4	0.87
F200W	NRCA1	0.88
F200W	NRCA2	0.88
F200W	NRCA3	0.87
F200W	NRCA4	0.88
F200W	NRCB1	0.88
F200W	NRCB2	0.88
F200W	NRCB3	0.91
F200W	NRCB4	0.88
F277W	NRCALONG	1.05
F277W	NRCBLONG	0.97
F356W	NRCALONG	1.06
F356W	NRCBLONG	1.01
F410M	NRCALONG	0.99
F410M	NRCBLONG	1.01
F444W	NRCALONG	1.07
F444W	NRCBLONG	1.05

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