# Chapter I:
# Galaxies and Cosmic Dawn

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# Revelation of Massive Quiescent Galaxies at $z > 3$ from Deep JWST Spectroscopy

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**Abstract.** We present the first results from JWST/NIRSPEC spectroscopy of massive quiescent galaxy candidates at $3 < z < 4$ to complete the spectroscopic survey of Schreiber et al. 2018. In the first six objects targeted (all of which were too faint to secure spectroscopic identifications from the ground) they all are confirmed as yet more massive quiescent galaxies at $3 < z < 4$. The JWST spectra are high signal-to-noise and unambiguous. Most of them have ages of a few hundred Myr from stellar population fits to the spectra and about 1/3 show sign of AGN emission lines. One extraordinary object of stellar mass $1.6 \times 10^{11}$ $M_\odot$ shows a red spectrum with evidence of a 4000Å break and an age of $\gtrsim$ 1Gyr at $z = 3.2$ and forming at $z > 6$.

**Keywords.** galaxies: evolution – cosmology – dark matter

## 1. Introduction

Back in 2017 came the first spectroscopic confirmation of the existence of purely quiescent massive galaxies at $z > 3$ (Glazebrook et al. 2017 [G17]). The galaxy ZF-20115 had a redshift $z = 3.717$ secured using the MOSFIRE spectrograph on Keck purely from absorption lines. It has no emission lines and no sign in the spectral energy distribution (SED) of any star formation. This was a massive object ($\sim 10^{11}$ $M_\odot$) whose Balmer lines indicated it had been quiescent for 500–1000 Myr, i.e. forming at $z > 5$. This galaxy was also extremely compact with an effective radius of 500 pc. Comparing with the abundance of dark matter haloes at this redshift it was shown that $\sim 35\%$ of the expected baryons in the dark matter halo would have to be converted in to stars, compared to 10–20% seen in local galaxies.

Since then a population of these objects have been spectroscopically confirmed (Schreiber et al. 2018, [S18], Forrest et al. 2020a, 2020b, Valentino et al. 2020), either showing strong Balmer absorption lines or weak emission lines. They generally show low molecular gas fractions (Suzuki et al. 2022) consistent with their quiescent nature. Simulations such as Illustris were not able to reproduce their abundance (G17, S18) but more recent simulations with updated AGN feedback at high redshift are able to (Merlin et al. 2019). Kinematic measurements have confirmed their stellar masses dynamically and showing evidence for a lighter initial mass function (IMF) — similar to the Chabrier IMF — than lower redshift quiescent galaxies (Esdaile et al. 2021; Forrest et al. 2022). It appears the IMF may evolve smoothly with redshift, but caution is warranted as these are based on 1D velocity dispersion measurements. 2D kinematics is required to show this definitively.

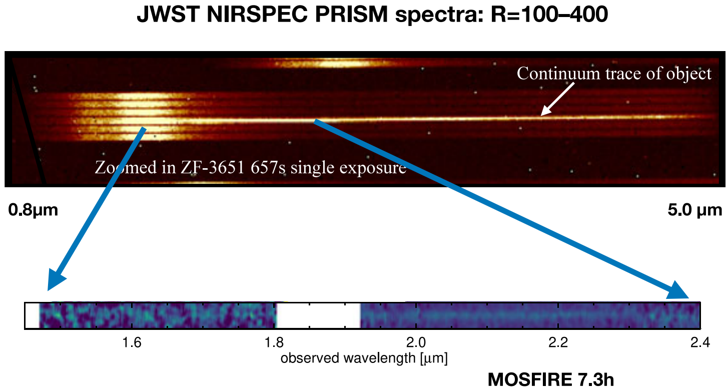


**Figure 1.** Comparison of JWST and MOSFIRE 2D spectra of the same target. The MOSFIRE spectrum is sky-subtracted but the continuum trace is faint and a redshift was not obtained. In contrast the JWST raw data frame, with minimal processing and no background subtraction, shows a strong continuum trace. As expected the low near-infrared background in space permits high signal-to-noise detections and data extending well beyond $2\mu$m. It can also be seen how the NIRSPEC slit is made up of five microshutters.

## 2. Enter JWST

The launch of the James Webb Space Telescope (JWST) in December 2021 has dramatically improved our ability to do faint near-infrared spectroscopy. In particular we had a program to target faint non-spectroscopically confirmed quiescent galaxies (see Program 2565 web page for full co-investigator list). This program targeted the galaxies in S18 that did not receive spectroscopic confirmation despite extensive MOSFIRE H and K-band spectroscopy. S18 is one of the deepest programs of confirming such objects but even then only 12/24 were confirmed (with two proving to be $z\sim 2$ interlopers). This could be because either lines were not present in the ground-based atmospheric windows or they were simply too faint. It is important to note that being fainter in the K-band does not imply a galaxy might have less mass at $z\sim 3$ — rather it could be significantly older and hence have a higher mass-to-light ratio. These are potentially very interesting objects. A complete set of spectroscopic confirmations is also desirable in order to make a definitive measurement of the number density of massive quiescent galaxies at $3<z<4$ which is by far the most critical test of theories of galaxy assembly. Currently it is assumed that photometric surveys are correct based on the confirmations done so far. However if it turned out that the unconfirmed objects were interlopers at lower redshifts this would reduce the number density inferred by S18 by a factor of 2.5. The JWST program targets all 15 objects in S18 with unknown or uncertain redshifts with NIRSPEC MSA spectroscopy. The first data on six objects in the UDS field was obtained in August 2022.

A simple comparison with the ground (Figure 1) shows the power of JWST. Due to the lower background in space and lack of OH lines the continuum spectrum is easily detected in a short exposure. It also extends to longer wavelengths than are accessible from the ground at these redshifts. Our program used NIRSPEC with the PRISM disperser, so low spectral resolution ($R=100$–$400$) but wide wavelength suitable for the goal of quickly obtaining redshifts.

The data was reduced using the STScI NIRSPEC pipeline. Wavelength calibration proved reliable, absolute flux calibration is still being worked on but a simple flux calibration was determined by using the SEDs of these objects from the ZFOURGE survey (Straatman et al. 2016) as a reference and calibrating with a simple polynomial. The first

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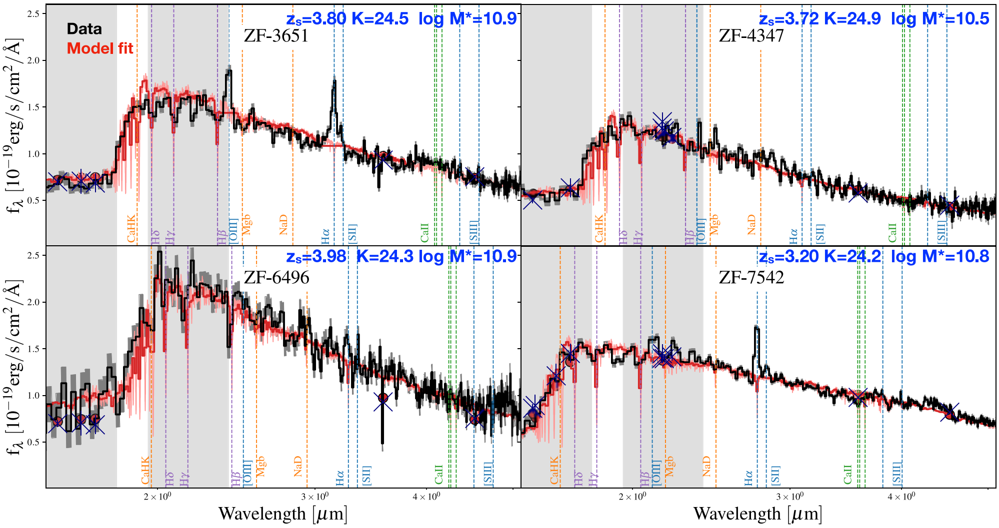


**Figure 2.** JWST NIRSPEC spectra of four UDS targets, comparing the data with a FAST++ model fit. The grey shading shows the ground spectroscopy H and K atmospheric windows. Common emission and absorption lines are marked.

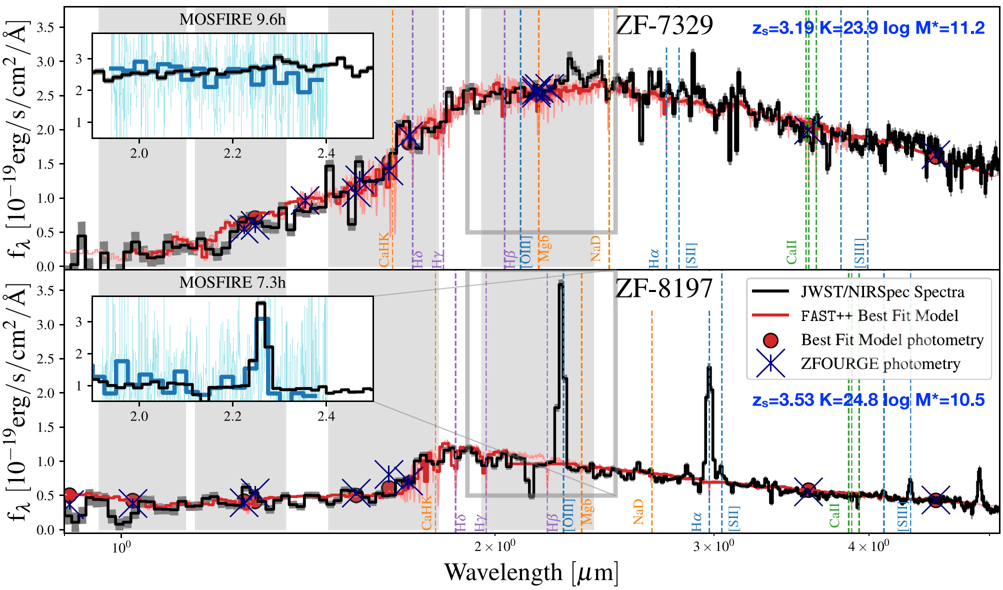


**Figure 3.** A further two UDS targets of particular interest, ZF-7329 appears to be much older (see discussion in text) and ZF-8197 was a MSA filler with a previous MOSFIRE emission line redshift. The MOSFIRE spectrum is shown in blue for comparison in the inset with darker blue being binned to match JWST resolution.

six spectra from the UDS field are shown in Figure 2 and Figure 3. Fits to the spectra were made using the code FAST++ (S18) using an identical star formation history modelling framework to S18 for easy comparison. Further details are given in Nanayakkara et al. 2023. Several key points are apparent:

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(1) *All of the six galaxies presented here* are confirmed to be at $3 < z < 4$ and are more massive quiescent galaxies. This suggests the number densities of S18 are indeed robust, and the execution of the remaining program is likely to verify this.
(2) Most of them show well developed Balmer breaks and Balmer absorption lines putting their ages at several hundred million years.
(3) Several of them show emission lines that were outside the ground windows for those which eluded ground confirmation. Given the line ratios they would seem to be consistent with AGN. The prevalence of AGN could be a smoking gun for the mechanism that quenched star formation in these objects.
(4) The galaxy ZF-7329 confirmed at $z = 3.188$ is particularly interesting as it is significantly redder than the rest. The older SED in S18 was noted and hence we secured an additional 3 hour exposure XSHOOTER spectra but still failed to get a redshift. NIRSPEC now shows the break appears to be more of a 4000Å break rather than a Balmer break. This is exciting as the 4000Å feature starts to develop at $\sim 800$ Myr in a post-burst population. The FAST++ fits confirms this, with an age of at least 1 Gyr implying it forms rapidly at $z > 6$. Forming a galaxy of this mass at this redshift is an extreme challange to ΛCDM cosmology (c.f. discussion in Labbé et al. 2023 which finds very high mass star forming galaxies at $z > 7$).

## 3. Discussion

The 100% success rate of our JWST spectroscopy (so far) in confirming massive quiescent galaxies that were previously too faint from the ground points to an epoch of rapid formation of quiescent galaxies very quickly. The age of ZF-7329 is particularly interesting. Our model fitting returns age solutions (time since quenching) in the range 1.0–1.5 Gyr, i.e. a redshift range of 6–11. An obvious question (e.g, G17) is — are their sufficient dark matter host haloes with sufficient mass to host these early galaxies? If following G17 we assume a cosmic baryon fraction of 16%, then with 100% conversion efficiency of baryons in to stellar mass the minimum dark matter halo mass is $1.0 \times 10^{12}$ $M_{\odot}$. Using the Watson et al. (2013) halo mass function fits we find a space density of $2.5 \times 10^{-6}$ Mpc$^{-3}$ at $z = 6$ and $\sim 10^{-12}$ Mpc$^{-3}$ at $z = 10$ for halos of this mass or greater. Similar densities are given by the halo mass function of Tinker et al. 2008. We can roughly consider the space density of galaxies like ZF-7329 by dividing the quoted space density in S18 by 24 (for 1 in 24 objects), this gives $6 \times 10^{-7}$ Mpc$^{-3}$. Clearly this is compatible with the lower end of the age range, but not the upper due to the extremely rapid evolution of the abundance of high mass halos. At $z = 10$ there is less than one massive halo per Hubble Volume, essentially impossible. We note star forming massive galaxies with slightly smaller stellar masses $\sim 10^{10}$ M$_{\odot}$ and a similar space density to our quiescent galaxies have been photometrically identified at $z \sim$8–9 by Labbé et al. 2023. This could be a possible ancestral population if spectroscopically confirmed.

Such massive galaxies $> 10^{11}$ M$_{\odot}$ are difficult to produce even at $z = 6$. We can consider the possible systematic errors. Our spectral fitting procedure for the stellar ages marginalises over a broad range of star formation histories, including younger burst populations, and the latter are heavily excluded in all objects. In ZF-7329 there is no evidence for any emission lines such as might be associated with non-stellar sources such as AGN. The spectra are low resolution and we find that the age solutions are heavily dependent on the spectrophotometric calibration as redder continua produce older ages. We are in the process of comparing absolute flux calibration from NIRSPEC to the ZFOURGE survey and to JWST/NIRCAM photometry in the same fields. Higher spectral resolution spectra from NIRSPEC would be a powerful additional test as then we could properly resolve individual age sensitive spectral lines. This would also allow a dynamical mass to be estimated from the velocity dispersion which would guard against possible evolution

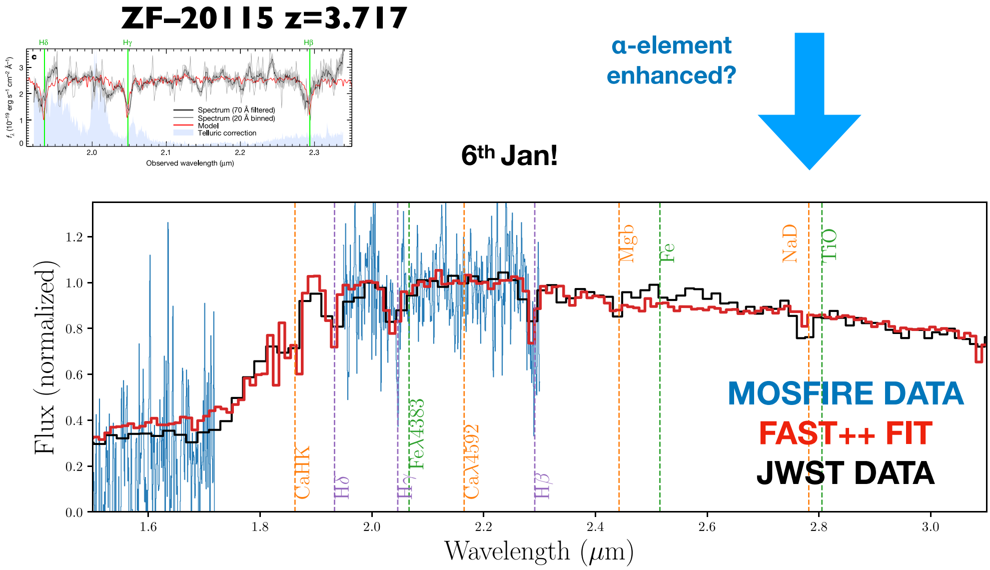


**Figure 4.** A comparison of ZF-20115 original MOSFIRE spectrum as presented in G17 (top) and as seen with JWST NIRSPEC (bottom). The spectra are remarkably consistent. There is tentative evidence for Na D enhancement at 2.8$\mu$m.

in the Initial Mass Function (Esdaile et al. 2021, Forrest et al. 2022). Another possibility is that the stellar mass formed in different lower mass halos that then later merged. However it would seem difficult to get uniformly old stars of similar age if this happened. Finally we could consider more exotic dark matter models that could produce massive halos earlier in cosmic history. Though there is no obvious alternative to vanilla cold dark matter which would clearly do this we note that exotic dark matter models can exert a strong influence on early galaxy formation (Dayal, Mesinger, & Pacucci 2015, Castellano et al. 2019, Maio & Viel 2023, Parashari & Laha 2023).

## 4. A revisit to ZF-20115

Finally, in January 2023 we very recently obtained some spectra of our targets in COSMOS, including the object ZF-20115 originally discussed in G17 which was obtained as a MSA filler. The comparison of JWST and MOSFIRE spectra is shown in Figure 4. The spectra amply confirm the previous MOSFIRE fits and extend substantially redward. Interestingly compared to the model we see tentative hints of a strong Na D absorption line which could be indicative of an $\alpha$-element enhanced stellar population. This would be consistent with with the scenario in G17 where the stellar population formed rapidly though detailed modeling is difficult as standard $\alpha$-enhanced models are not calibrated for stellar populations younger than 1 Gyr (Conroy, Villaume, van Dokkum, & Lind 2018).

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