A first look at JWST CEERS: massive quiescent galaxies from $3 < z < 5$

A. C. Carnall1,*, D. J. McLeod1, R. J. McLure1, J. S. Dunlop1, R. Begley1, F. Cullen1, C. T. Donnan1, M. L. Hamadouche1, S. M. Jewell1, E. W. Jones1, C. L. Pollock1, V. Wild2

1 SUPA†, Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK
2 SUPA†, School of Physics and Astronomy, University of St Andrews, North Haugh, St Andrews KY16 9SS, UK

ABSTRACT

We report a robust sample of 9 massive quiescent galaxies at redshift, $z > 3$, selected using the first data from the JWST CEERS programme. Three of these galaxies are at $4 < z < 5$, constituting the best evidence to date for quiescent galaxies significantly before $z = 4$. These extreme galaxies have stellar masses in the range $\log_{10}(M_*/M_\odot) = 10.5 - 11.3$, and formed the bulk of their mass at $6 < z < 9$, with two objects having star-formation histories that suggest they had already reached $\log_{10}(M_*/M_\odot) > 10$ by $z = 8$. We report number densities for our sample, demonstrating that previous work underestimated the number of quiescent galaxies at $3 < z < 4$ by at least a factor of $3 - 6$, due to a lack of ultra-deep imaging data at $\lambda > 2 \mu m$. This result deepens the existing tension between observations and theoretical models, which already struggle to reproduce previous estimates of $z > 3$ quiescent galaxy number densities. Upcoming wider-area JWST imaging surveys will provide larger samples of such galaxies, as well as providing opportunities to search for quiescent galaxies at $z > 5$. The galaxies we report are excellent potential targets for JWST NIRSpec spectroscopy, which will be required to understand in detail their physical properties, providing deeper insights into the processes responsible for quenching star formation during the first billion years.

Key words: galaxies: evolution – galaxies: star formation – methods: statistical

1 INTRODUCTION

Two of the most important outstanding questions in galaxy evolution are: when did the first galaxies begin to form stars, and when did the first galaxies quench their star-formation activity? During the short time since the first data from the James Webb Space Telescope (JWST) were released, remarkable progress has been made towards addressing the first of these questions. We now have good evidence that $\log_{10}(M_*/M_\odot) \approx 8 - 9$ galaxies were already in place by $z \approx 17$, less than 250 Myr after the Big Bang, with preliminary evidence mounting that such objects are more numerous than expected (e.g. Naidu et al. 2022; Castellano et al. 2022; Donnan et al. 2022; Finkelstein et al. 2022). We have also uncovered the unexpectedly rapid growth of these early seeds into massive galaxies with $\log_{10}(M_*/M_\odot) \approx 11$ during the latter half of the first billion years, from $6 < z < 10$ (Labbé et al. 2022).

This extremely rapid assembly of the first massive galaxies is critically important for our understanding of quenching. If $\log_{10}(M_*/M_\odot) \approx 11$ galaxies already exist by $6 < z < 10$, these must equally rapidly quench, to avoid becoming too massive to be accommodated by the lower-redshift galaxy stellar-mass function (e.g. McLeod et al. 2021). This suggests massive quiescent galaxies at least as early as $z \approx 6$.

Currently, the earliest spectroscopically confirmed massive quiescent galaxies are half a billion years later at $z \approx 4$ (e.g. Glazebrook et al. 2017; Valentino et al. 2020; Forrest et al. 2020), and indeed it has proven extremely challenging to identify even robust photometric candidates at $z > 4$ (e.g. Merlin et al. 2018, 2019; Carnall et al. 2020; Esdaile et al. 2021; Stevans et al. 2021; Marsan et al. 2022). It is currently unclear whether this is due to an almost total lack of quiescent galaxies at earlier times, or due to a lack of ultra-deep, high-resolution imaging at $\lambda > 2 \mu m$, with which to constrain the Balmer break at these redshifts.

The number density and passive fraction of high-redshift massive galaxies are, however, key constraints on galaxy formation models, with current simulations unable to reproduce the observed number density of quiescent galaxies at $3 < z < 4$ (e.g. Schreiber et al. 2018; Cecchi et al. 2019). This implies that key physics, capable of giving rise to extremely rapid quenching events, is still missing from these simulations. In this context, more robust constraints on the number density of massive quiescent galaxies at $3 < z < 4$, and confirmation of whether any such objects exist at $z > 4$, are key to our understanding of galaxy formation.

By providing unprecedentedly deep infrared imaging at $\lambda > 2 \mu m$, JWST opens up a unique opportunity to address this issue, promising the ability to robustly select representative samples of massive galaxies as far back as just a few hundred Myr after the Big Bang. In addition, its extremely high angular resolution (e.g. Suess et al. 2022) and wide-ranging spectroscopic capabilities (e.g. Carnall et al. 2022b) hold much promise for extending detailed studies of quiescent galaxy physical properties, such as star-formation histories (SFHs),...
Figure 1. Spectral energy distributions and cutout images for our three robust $z > 4$ quiescent galaxies. Our 10-band photometric data from CFHTLS, HST ACS and JWST NIRCam are shown in blue. The posterior median BOPPES models are overlaid in red. Posterior distributions for the redshifts and sSFRs of these galaxies are shown in green to the right of the main panels. The dashed vertical lines in the sSFR panels show the sSFR threshold for inclusion in our quiescent sample at the redshift of each object (see Section 3.2). The inset RGB cutouts are composed of the F444W, F200W and F150W images respectively.
stellar metallicities and sizes, back to the first billion years. This endeavour has previously proven extremely challenging, even at cosmic noon (e.g. Wu et al. 2018; Belli et al. 2019; Carnall et al. 2019a, 2022a; Beverage et al. 2021; Hamadouche et al. 2022).

In this paper, we use extremely deep $I = 1–5 \mu m$ NIRCam imaging from the JWST Cosmic Evolution Early Release Science (CEERS\footnote{https://ceers.github.io}) programme (Finkelstein et al. in prep.) to search for massive galaxies at $z > 3$. In particular, we focus on constraining the number density of galaxies that have already quenched their star-formation activity at this early time, and measuring the SFHs of these galaxies in order to link them with the extreme population of star-forming galaxies currently being uncovered during the first billion years.

The structure of this paper is as follows. In Section 2 we introduce the CEERS and ancillary datasets used in this work. In Section 3 we discuss our spectral energy distribution (SED) fitting methodology and sample selection. In Section 4 we present our results, including the discovery of three robustly identified massive quiescent galaxies at $4 < z < 4.7$. We discuss our results in Section 5 and present our conclusions in Section 6. All magnitudes are quoted in the AB system. For cosmological calculations, we adopt $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$. We assume a Kroupa (2001) initial mass function, and assume the Solar abundances of Asplund et al. (2009), such that $Z_{\odot} = 0.0142$.

## 2 DATA

The primary dataset for this work is comprised of the first observations made as part of the CEERS survey (Finkelstein et al. in prep) in the CANDELS Extended Groth Strip (EGS) field. We use data from the first 4 pointings observed in late June 2022. Imaging is available in 7 NIRCam filters: F115W, F150W, F200W, F277W, F356W, F410M and F444W, with integration times of 2635 seconds per filter, except F115W where the exposure time is doubled. The currently available CEERS data amounts to a total effective area of $\approx 30$ square arcmin (e.g. Donnan et al. 2022).

We perform our own custom reduction of the data, beginning with the Level 1 data products, using the PRIMER Enhanced NIRCam Image Processing Library (PENCIL), a custom version of the JWST pipeline (v1.6.0). We make use of the CRDS_CTX = jwst_0916.pmap version of the JWST calibration files. We align and stack the individual reduced images using the SCAMP and SWARP codes (Bertin 2006, 2010). Our final mosaic images have a pixel scale of 0.031" in all bands.

We employ the SExtractor code (Bertin & Arnouts 1996) to measure object photometry. We run SExtractor in dual image mode, with the F200W mosaic used as the detection image in all cases, as this is the wavelength range in which the SEDs of $z \approx 3–5$ quiescent galaxies peak. Fluxes are measured within 1.25" (40 pixel) diameter circular apertures. This size of aperture is more than sufficient for our purposes, given that massive quiescent galaxies at high redshift are known to be both extremely compact and centrally concentrated (e.g. van der Wel et al. 2014). We cut our catalogue at $F200W = 26.5$, at which magnitude objects have a typical F200W SNR $\approx 20$. This is necessary to ensure objects are reliably detected with high SNR in the other relevant bands, in particular to obtain strong constraints on the Balmer break strength. This results in a parent sample of 10542 objects.

In addition to the NIRCam imaging, we also make use of Hubble Space Telescope (HST) ACS data in the F606W and F814W bands. We use the v1.9 EGS mosaics produced by the CEERS team (Koekemoer et al. 2011), which have a pixel scale of 0.033". We also use $u*$-band imaging from the Canada France Hawaii Telescope Legacy Survey (CFHTLS) T0007 release (Gwyn 2012).

In order to ensure that our analysis is not affected by offsets in relative astrometry whilst using these brand new data products, the HST ACS and CFHTLS data were not included in our SExtractor run. Instead, we produce stacked images in each of these three bands at the positions of bright sources in the SExtractor catalogue, and apply the astrometric corrections required to ensure that the stacks are well centred. These shifts are small, up to a maximum of 0.3".

We then extract photometric fluxes, again in 1.25" apertures, at the positions of each object in our NIRCam catalogue using PhotUtils (Bradley et al. 2020). We measure uncertainties for each object as the standard deviation of fluxes measured in the closest $\approx 100$ blank sky apertures (McLeod et al. 2016), whilst masking out nearby objects, using the robust median absolute deviation (MAD) estimator.

We check the resulting photometry in the $u*$, F606W and F814W bands by cross-checking with the CANDELS catalogue produced by Stefanon et al. (2017), finding good agreement. We also cross-check the NIRCam F115W and F150W imaging against the HST WFC3 F125W and F160W fluxes included in the Stefanon et al. (2017) catalogue, again finding close agreement.

| Component | Parameter | Symbol / Unit | Range | Prior | Hyper-parameters |
|-----------|-----------|---------------|-------|-------|------------------|
| General   | Redshift  | $z$           | (0, 20)| Uniform|                  |
|           | Total stellar mass formed | $M_*/M_\odot$ | (1, $10^{13}$) | Logarithmic |      |
|           | Stellar and gas-phase metallicities | $Z / Z_\odot$ | (0.2, 2.5) | Logarithmic |      |
| Star-formation history | Double-power-law falling slope | $\alpha$ | (0.01, 1000) | Logarithmic |      |
|           | Double-power-law rising slope | $\beta$ | (0.01, 1000) | Logarithmic |      |
|           | Double power law turnover time | $\tau / \text{Gyr}$ | (0.1, $t_{\text{obs}}$) | Uniform |      |
| Dust attenuation | $V$–band attenuation | $A_V / \text{mag}$ | (0, 8) | Uniform |      |
|           | Deviation from Calzetti et al. (2000) slope | $\delta$ | ($-0.3, 0.3$) | Gaussian | $\mu = 0$, $\sigma = 0.1$ |
|           | Strength of 2175Å bump | $B$ | (0, 5) | Uniform |      |
3 METHOD

3.1 Spectral energy distribution fitting

The SED-fitting analysis in this work makes use of the Bagpipes spectral fitting code (Carnall et al. 2018), and is based on the method used to search for $2 < z < 5$ massive quiescent galaxies in CANDELS UDS and GOODS South in Carnall et al. (2020).

The model we fit to our photometric data makes use of the Bruzual & Charlot (2003) stellar population models, in particular the 2016 updated version (Chevallard & Charlot 2016) using the MILES stellar spectral library (Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011) and the updated stellar evolutionary tracks of Bressan et al. (2012) and Marigo et al. (2013).

Nebular line and continuum emission are included in our model using an approach based on the Cloudy photoionization code, outlined in section 3 of Carnall et al. (2018), following Byler et al. (2017). We assume an ionization parameter, $U = 10^{-3}$, and a lifetime for stellar birth clouds of 10 Myr.

Dust attenuation is included using the model of Salim et al. (2018), which has a variable slope, parameterised with a power-law deviation, $\delta$, from the Calzetti et al. (2000) model. We allow the V–band attenuation, $A_V$, to vary from 0 – 8 magnitudes. We further assume that light from stars still enclosed in stellar birth clouds and resulting nebular emission is attenuated by twice the $A_V$ experienced by older stars within the wider interstellar medium (ISM) of the galaxy (e.g. Charlot & Fall 2000).

We assume a double-power-law SFH model, as introduced in Carnall et al. (2018, 2019b), which has been shown to reproduce well the SFRs of massive quiescent galaxies in the Mufasa simulation (Davé et al. 2016). The stellar and nebular metallicities of galaxies are assumed to be identical, and are varied with a uniform prior in logarithmic space from $-0.7 < \log_{10}(Z/Z_\odot) < 0.4$. Intergalactic medium absorption is included using the model of Inoue et al. (2014). We vary redshift in our model with a uniform prior over the redshift range $z = 0 – 20$. A full list of the 9 free parameters of our model and their associated prior distributions is given in Table 1.

We fit our Bagpipes model to the data using the MultiNest nested sampling algorithm (Skilling 2006; Feroz et al. 2019), accessed via the PyMultiNest interface (Buchner et al. 2014).

3.2 Selection of massive quiescent galaxies

We begin our selection process by requiring that objects have a posterior median redshift greater than $z = 3$. We also require that 97.5 per cent of the redshift posterior for each object lies above $z = 2.75$. This is in order to exclude objects with significant secondary low-redshift solutions, whilst retaining objects with narrow redshift posteriors that extend marginally below $z = 3$.

The sample is then cleaned by visual inspection of all 10 photometric bands, as well as the fitted Bagpipes SEDs. We exclude objects that fall close to the edges of the NIRCam detector, objects for which coverage is only available in some bands, and various kinds of NIRCam detector artefacts (Rigby et al. 2022). We further exclude objects that are visible in short-wavelength imaging, below the position of the Lyman break at the Bagpipes fitted redshift (which strongly implies the fitted redshift is incorrect). At the end of this process, we have a total of 421 galaxies at $z > 3$.

To separate star-forming and quiescent galaxies, we use a time-dependent cut in specific star-formation rate (sSFR), as has been widely applied in the literature (e.g. Gallazzi et al. 2014; Pacifici et al. 2016). We define quiescent galaxies as those that have

$$sSFR < \frac{0.2}{t_{\text{obs}}}$$

where $t_{\text{obs}}$ is the age of the Universe at the redshift of the galaxy. This threshold is broadly equivalent to a selection in rest-frame UVJ colour space of $U - V > 0.69 \times (V - J) + 0.69$ (Carnall et al. 2018, 2019b) at all redshifts, which is the $z < 0.5$ quiescent galaxy selection criterion introduced by Williams et al. (2009).

Our full passive sample is defined as those for which the 50th percentile of the fitted Bagpipes sSFR posterior distribution falls
below this threshold. These objects are robustly placed at \( z > 3 \) by our fitting, and are more likely to be quiescent than star forming. However, we cannot confidently exclude star-forming solutions in all cases. Following Carnall et al. (2020), we then further define a “robust” quiescent sub-sample, for which 97.5 per cent of the sSFR posterior is required to fall below the threshold in Equation 1. For these robust objects, we exclude both low-redshift and star-forming solutions with high confidence.

4 RESULTS

From our analysis, we identify a total of 17 quiescent galaxies at \( z > 3 \), of which 9 are members of our robust sub-sample. From these 17 objects, 6 are placed reliably at \( z > 4 \), and 3 of these are robustly identified as quiescent. This is the first clear identification of massive quiescent galaxies significantly beyond \( z = 4 \). We provide coordinates, photometric redshifts, magnitudes and physical properties for the 17 quiescent galaxies we identify in Table 2. We present SEDs for our 9 robust objects in Figs 1 and A1. Cutout images for these 9 robust galaxies are presented in Fig. A2.

4.1 Robust massive quiescent galaxies at \( z > 4 \)

SEDs and colour images for the three \( z > 4 \) objects in our robust sub-sample are shown in Fig. 1. All three of these display a strong Balmer break between the F200W and F277W bands, which provides a very strong constraint on their redshifts. They also exhibit well-constrained red spectral slopes in the rest-frame near-UV, indicating a lack of ongoing star formation, and blue spectral slopes in the longer-wavelength NIRCam bands, strongly ruling our lower-redshift dusty solutions. In this section we briefly discuss the observed properties of each object, before moving on to discuss their SFHs in Section 5.

4.1.1 Galaxy 101962

The highest-redshift robust quiescent galaxy in our sample is object 101962, with F200W = 24.9 and a photometric redshift of \( z \approx 4.7 \). This galaxy, as shown in the top panel of Fig. 1, exhibits the characteristic triangular SED shape of post-starburst (PSB) galaxies at lower redshift (e.g. Wild et al. 2014), implying a recent, rapid fall in SFR (e.g. Wild et al. 2020; D’Eugenio et al. 2021). This is perhaps unsurprising, considering this object is observed just \( \approx 1.3 \) billion years after the Big Bang.

Our sample is shown on the rest-frame UVJ colour diagram in Fig. 2. Galaxy 101962 is the bluest (closest to the bottom-left) robust object shown in the central panel, just below the horizontal edge of the solid UVJ selection box, again highly consistent with lower-redshift PSBs (e.g. Belli et al. 2019; Carnall et al. 2019a).

This object is at a very similar redshift to GOODSS-9209, the highest-redshift candidate identified by Carnall et al. (2020), which is the target of upcoming NIRSpec observations (Carnall et al. 2021). This new galaxy, however, is \( \approx 0.2 \) dex less massive, and more than a magnitude fainter at \( \lambda = 2 \mu \text{m} \) (GOODSS-9209 has \( K_S = 23.6 \)). This is likely related to the fact that 101962 appears older, with considerably less flux in the rest-frame far-UV.

This galaxy has a match within 0.1” in the CANDELS EGS catalogue of Stefanon et al. (2017) (ID: 23297). The median photometric redshift they report (following the method of Dahlen et al. 2013) is \( z = 3.5 \). However, the individual estimates from their different codes display considerable variance, with a 1σ range from \( z = 2.45 - 4.70 \). This galaxy was only previously detected with 3σ significance in the WFCAM \( K_S \) band, meaning virtually no constraint could be placed on the Balmer break. We fit the Stefanon et al. (2017) photometry with BAGPIPES, using the same model described in Section 3.1, and recover an extremely broad photometric redshift posterior distribution from \( z = 3.2^{+1.5}_{-1.4} \). This clearly demonstrates the awesome power of JWST imaging for exploring the high-redshift Universe.

4.1.2 Galaxy 42128

Galaxy 42128 has a slightly lower redshift, \( z \approx 4.5 \), and is brighter, with F200W = 24.3. However, in most respects, this galaxy is very similar to 101962, also exhibiting the characteristic triangular PSB spectral shape. In shorter-wavelength, lower spatial resolution, imaging this object is not distinguishable from the extended structure of the nearby barred-spiral galaxy and therefore does not feature in the Stefanon et al. (2017) CANDELS EGS catalogue. However, the longer wavelength and higher spatial resolution imaging provided by JWST reveal this object as a brighter, redder, highly compact background source.

4.1.3 Galaxy 40015

The third galaxy, 40015, is noticeably different to the other two, being at a lower redshift of \( z \approx 4 \), as well as being significantly brighter, with F200W = 23.5. This object is more than twice as massive as either of the other two, with \( \log_{10}(M_*/M_\odot) \approx 11.3 \). In addition, this galaxy exhibits a different SED shape, more typical of lower-redshift quiescent galaxies. This manifests as a visibly redder colour in the RGB image shown in Fig. 1. This galaxy is also, by some considerable margin, the reddest object on the UVJ diagrams shown in Fig. 2 (nearest the top-right), even when compared with the \( 3 < z < 4 \) robust quiescent galaxies in the left-hand panel.

Intriguingly, this galaxy also appears considerably more extended in the NIRCam imaging than the other two, with evidence for a disk-like structure surrounding a bright core. This is interesting, given that high-redshift massive quiescent galaxies are generally thought to be both extremely compact and highly centrally concentrated (e.g. van der Wel et al. 2014; Mowla et al. 2019; Hamadouche et al. 2022). This observation further demonstrates the huge potential of JWST for delving deeper into the physical structures and resolved properties of galaxies at this early epoch (e.g. Ferreira et al. 2022).

This galaxy also has a match in the CANDELS EGS catalogue (ID: 21378), and is detected with SNR \( > 15 \) in the WFCAM \( K_s \) band. However, despite this, the previous lack of robust photometry at longer wavelengths meant that neither the photometric redshift codes employed by Stefanon et al. (2017), nor our BAGPIPES fitting of their photometry, were capable of correctly identifying the redshift of this galaxy. Stefanon et al. (2017) report a median redshift of \( z = 3.3 \) (with a 1σ range from 2.7 - 3.6), whereas BAGPIPES returns \( z = 2.8^{+1.0}_{-0.7} \).

4.2 Quiescent galaxy number densities at \( 3 < z < 5 \)

In Table 3 we report our estimate of the number density of quiescent galaxies over the redshift range \( 3 < z < 5 \) that meet our F200W < 26.5 selection threshold. We report number densities based on both our full quiescent sample and our robust sub-sample. The numbers based on the robust sub-sample can be interpreted as conservative lower limits. This is the first estimate of the number density of massive quiescent galaxies at \( 4 < z < 5 \).

In Schreiber et al. (2018), the authors report a number density of
whereas for non-robust objects the posterior median solution is quiescent, but we cannot confidently exclude star-forming solutions.

| ID    | RA   | DEC   | F150W | F200W | Redshift | $t_{\text{form}}$ / Gyr | $z_{\text{form}}$ | log10($M_*/M_\odot$) | Robust |
|-------|------|-------|-------|-------|----------|-------------------------|-----------------|----------------------|--------|
| 17318 | 214.808167 | 52.832185 | 27.12 | 25.75 | 4.51±0.9 | 0.77±0.2 | 6.9±1.5 | 10.16±0.05 | False |
| 28251 | 214.870686 | 52.846118 | 26.69 | 25.23 | 4.15±1.1 | 1.03±0.1 | 5.5±1.3 | 10.19±0.05 | False |
| 28316 | 214.871229 | 52.845079 | 23.66 | 22.48 | 3.70±0.9 | 1.28±0.2 | 4.6±1.1 | 10.81±0.05 | False |
| 29497 | 214.760652 | 52.845329 | 23.35 | 22.03 | 3.22±0.9 | 1.29±0.2 | 4.6±1.1 | 11.17±0.05 | True  |
| 36262 | 214.895611 | 52.856508 | 22.95 | 21.84 | 3.26±0.6 | 1.38±0.1 | 4.3±0.4 | 10.96±0.03 | True  |
| 40015 | 214.853948 | 52.861320 | 25.35 | 23.46 | 4.06±0.12 | 0.95±0.2 | 5.8±1.0 | 11.31±0.04 | True  |
| 42128 | 214.850622 | 52.865992 | 25.68 | 24.27 | 4.45±0.08 | 0.63±0.2 | 8.0±2.6 | 10.85±0.04 | True  |
| 46629 | 214.836901 | 52.873427 | 24.62 | 23.47 | 3.44±0.20 | 0.92±0.2 | 6.0±1.9 | 10.57±0.04 | True  |
| 52124 | 214.866029 | 52.884101 | 24.80 | 23.39 | 3.85±0.09 | 1.41±0.1 | 4.2±0.2 | 10.76±0.05 | True  |
| 52175 | 214.866041 | 52.884267 | 23.92 | 22.43 | 3.43±0.09 | 1.28±0.2 | 4.6±0.5 | 10.86±0.02 | True  |
| 53472 | 214.879089 | 52.888077 | 25.45 | 24.13 | 3.47±0.19 | 1.19±0.3 | 4.9±0.8 | 10.33±0.05 | True  |
| 75768 | 214.904836 | 52.935364 | 24.45 | 23.34 | 3.22±0.06 | 1.17±0.3 | 4.9±0.9 | 10.45±0.03 | True  |
| 76507 | 214.931441 | 52.937443 | 26.25 | 25.58 | 4.78±0.13 | 1.03±0.1 | 5.5±0.2 | 9.79±0.03 | False |
| 78374 | 214.899208 | 52.942307 | 24.82 | 24.07 | 3.76±0.10 | 1.48±0.1 | 4.1±0.1 | 9.85±0.04 | False |
| 92564 | 214.957908 | 52.980303 | 25.01 | 23.5 | 3.56±0.11 | 1.35±0.1 | 4.4±0.4 | 10.46±0.03 | True  |
| 97581 | 214.981853 | 52.991229 | 24.12 | 22.77 | 3.34±0.12 | 1.06±0.3 | 5.4±1.7 | 10.76±0.03 | True  |
| 101962 | 215.039116 | 53.002747 | 26.24 | 24.92 | 4.67±0.12 | 0.53±0.2 | 9.1±2.3 | 10.53±0.03 | True  |

Table 2. Properties of the 17 massive quiescent galaxies at $z > 3$ we identify in this work. We define $t_{\text{form}}$ as the age of the Universe corresponding to the mass-weighted age of each galaxy, and $z_{\text{form}}$ as the corresponding redshift. For objects labelled robust, we can confidently exclude star-forming solutions, whereas for non-robust objects the posterior median solution is quiescent, but we cannot confidently exclude star-forming solutions.

Table 3. Number densities derived for our quiescent galaxy sample in integer redshift bins spanning $3 < z < 5$. Uncertainties were calculated as the Poisson noise on the number of objects found (Gehrels 1986). The full quiescent sample includes quiescent galaxies for which we cannot rule out secondary star-forming solutions, whereas the robust sub-sample includes only those galaxies for which we can confidently exclude star-forming solutions.

| Redshift range | $N_{\text{galaxies}}$ | $n / \text{Mpc}^{-3}$ | $n / \text{Mpc}^{-3}$ | $n / \text{Mpc}^{-3}$ |
|----------------|----------------------|----------------------|----------------------|----------------------|
| F200W < 26.5  | F200W < 26.5  | F200W < 24.5  | F200W < 26.5  | F200W < 26.5  | F200W < 24.5  |
| $3 < z < 4$   | 11       | 11.6±3.4×10^{-5}   | 11.6±3.4×10^{-5}   | 7.0±2.8×10^{-5}   |
| $4 < z < 5$   | 6        | 6.3±3.4×10^{-5}    | 6.3±3.4×10^{-5}    | 3.5±1.1×10^{-5}   |

2.0±0.3×10^{-5} Mpc^{-3} for a spectroscopic sample of quiescent galaxies at $3 < z < 4$ with $K_s < 24.5$. We compare our results with Schreiber et al. (2018) by calculating the number of F200W < 24.5 quiescent galaxies in our sample at $3 < z < 4$, as this filter is closest in wavelength coverage to the $K_s$ band. These numbers are reported in the right-hand column of Table 3.

The number density we find for our robust sub-sample at F200W < 24.5 is approximately a factor of 3 larger than the result of Schreiber et al. (2018), whereas the result from our full quiescent sample is approximately a factor of 6 larger. We attribute this significant increase in the number of $z > 3$ quiescent galaxies to the much deeper, redder imaging now available from JWST, which allows physical properties to be reliably inferred for faint, red galaxies such as these.

From our 11 quiescent galaxies at $3 < z < 4$, a total of 9 have matches within 0.25 Mpc in the Stefanon et al. (2017) CANDELS EGS catalogue. All 9 of these have CANDELS photometric redshifts in the range from $3 < z < 4$, and by fitting the Stefanon et al. (2017) photometry with BAGPIPES we recover similar results. However, just 3 of these objects would be included in our quiescent sample given the CANDELS photometry, as their SFRs are far less well constrained by these data. Just 2 of these 3 would be identified as robust.

It is therefore likely that, had we designed a spectroscopic follow-up campaign similar to that of Schreiber et al. (2018) based on fitting only CANDELS EGS data, we would have arrived at a very similar number density for $3 < z < 4$ quiescent galaxies to the one they obtain. Indeed, our result based on fitting CANDELS UDS and GOODS South photometry in Carnall et al. (2020) arrived at a number density of $1.7 ± 0.3 × 10^{-5}$ Mpc^{-3} for $3 < z < 4$ quiescent galaxies with $K_s < 24.5$, fully consistent with Schreiber et al. (2018).

5 DISCUSSION

In this section we discuss the star-formation histories we infer for the 9 robust quiescent galaxies we identify at $z > 3$. We calculate formation times, $t_{\text{form}}$, for each object as the average time at which the stars in the galaxy formed. This is the age of the Universe at the time corresponding to the (mass-weighted) mean stellar age (see Carnall...
et al. 2018, equation 11). We also calculate formation redshifts, $z_{\text{form}}$, which are the redshifts corresponding to $t_{\text{form}}$. These values are reported in Table 2.

Formation redshifts for our 9 robust quiescent galaxies are plotted against the observed redshift of each galaxy in Fig. 3. In addition, the full SFH posteriors for these 9 galaxies are shown in Fig. 4. Their formation redshifts are shown with dashed gray vertical lines.

It can be seen that the 3 robust quiescent galaxies at $z > 4$ formed the bulk of their stellar populations during the first billion years at $z > 6$, with formation redshifts in the range $6 < z_{\text{form}} < 9$. The highest-redshift object, 101962, is also the earliest formed, with the bulk of its stars having formed at $7 < z < 12$. These findings make our $z > 4$ objects highly plausible as descendants of the sample identified by Labbe et al. (2022). Indeed, objects 42128 and 101962 are both predicted to have $\log_{10}(M_*/M_\odot) > 10$ at their formation redshifts of $z_{\text{form}} = 8.0$ and $z_{\text{form}} = 9.1$ respectively. This is fully consistent with the finding of Labbe et al. (2022) that a considerable number of $\log_{10}(M_*/M_\odot) > 10$ galaxies were already in place by $7 < z < 11$.

The 6 robust quiescent galaxies at $3 < z < 4$ formed their stellar populations later in cosmic time, typically with $4 < z_{\text{form}} < 6$. The fact that none of these galaxies is older suggests that the $z > 4$ quiescent galaxies in our sample have not yet reached the end-point of their evolution, and are likely to experience further star formation by $z \approx 3$. However, larger-area JWST surveys will certainly be required to rule out the possibility of $3 < z < 4$ quiescent galaxies with stellar populations dating back to $z > 6$.

It is interesting to reflect on the fact that we do not identify any quiescent galaxies at $z > 5$, despite the fact that our highest-redshift object appears to have quenched by $z > 6$. Apart from the obvious limitations of the relatively small imaging area included in the initial CEERS release, it is currently unclear how the colours of newly quenched galaxies evolve in order to arrive in the UVJ-quiescent
box, and how long this might take after star formation ceases (e.g. Belli et al. 2019; Carnall et al. 2019b; Akins et al. 2022).

Upcoming larger-area JWST imaging surveys, such as Public Release Imaging for Extragalactic Research (PRIMER\(^2\)) are ideally suited to searching for evidence of quiescent galaxies at \(z > 5\), as well as selecting larger samples of \(3 < z < 5\) quiescent galaxies to produce more-robust number densities. Such searches may benefit from the use of catalogues selected in longer-wavelength NIRCam bands, rather than the F200W selection employed in this work, as well as new, JWST-specific colour selection criteria (e.g. Leja et al. 2019; Antwi-Danso et al. 2022).

6 CONCLUSION

In this work we present the results of a search for massive quiescent galaxies at redshifts \(z > 3\), selected from the first NIRCam data taken by the JWST CEERS Early Release Science programme. We identify 17 galaxies in the redshift range \(3 < z < 5\) with robust photometric redshifts and posterior median sSFRs that suggest they are quiescent. For 9 of these galaxies, we can confidently rule out absorption features would unambiguously confirm these objects as quiescent at \(z > 4\), and these objects have stellar masses in excess of \(10^{10}\,\text{M}_\odot\) by \(z \approx 8\), supporting the recent findings of Labbe et al. (2022).

Two of these \(z > 4\) objects have matches in the Stefanon et al. (2017) CANDELS EGS catalogue. However, their photometric redshift posterior distributions were not well constrained by previously available data, with both the CANDELS team and the authors returning posterior median redshifts of \(z \approx 3\) using pre-JWST data.

We calculate number densities for our quiescent sample, as well as for our robust sub-sample (which can be regarded as yielding robust lower limits). We find that the number density of \(3 < z < 4\) quiescent galaxies with \(F200W < 24.5\) is a factor of \(3 \sim 6\) times higher than previously reported by Schreiber et al. (2018). We demonstrate that this difference arises as a result of better constraints from the new NIRCam data, and show that previously available data from CANDELS would have led us to a similar number density to that calculated by Schreiber et al. (2018). This finding poses an additional challenge for simulations of early galaxy formation, which already struggle to reproduce previously reported number densities.

The 9 robust \(z > 3\) massive quiescent galaxies we report, and the 3 at \(z > 4\) in particular, are excellent potential targets for follow up NIRSpec spectroscopy, either as part of CEERS, or via dedicated programmes in JWST Cycle 2 and beyond. The detection of Balmer absorption features would unambiguously confirm these objects as quiescent at \(z > 4\), and full spectral fitting of deep continuum spectroscopic data would provide strong constraints on their SFHs, as well as the ability to probe in detail their physical properties.

ACKNOWLEDGEMENTS

A. C. Carnall thanks the Leverhulme Trust for their support via a Leverhulme Early Career Fellowship. R. Begley, D. J. McLeod, M. L. Hamadouche, C. Donnan, R. J. McLure, J. S. Dunlop, F. Cullen and V. Wild acknowledge the support of the Science and Technology Facilities Council. S. Jewell and C. Pollock acknowledge the support of the School of Physics & Astronomy, University of Edinburgh via Summer Studentship bursaries.

DATA AVAILABILITY

All JWST and HST data products are available via the Mikulski Archive for Space Telescopes (https://mast.stsci.edu). Photometric data and fitted model posteriors are available upon request.

REFERENCES

Akins H. B., Narayanan D., Whitaker K. E., Davé R., Lower S., Bezanson R., Feldman R., Kriek M., 2022, ApJ, 929, 94
Antwi-Danso J., et al., 2022, arXiv e-prints, p. arXiv:2207.0170
Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, ARA&A, 47, 481
Belli S., Newman A. B., Ellis R. S., 2019, ApJ, 874, 17
Bertin E., 2006, in Gabriel C., Arviset C., Ponz D., Enrique S., eds, Astronomical Society of the Pacific Conference Series Vol. 351, Astronomical Data Analysis Software and Systems XV. p. 112
Bertin E., 2010, SWork: Resampling and Co-adding FITS Images Together, Astrophysics Source Code Library, record ascl:1010.068 (ascl:1010.068)
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Beverage A. G., Kriek M., Conroy C., Bezanson R., Franx M., van der Wel A., 2021, arXiv e-prints, arXiv:2105.12750
Bradley L., et al., 2020, astropy/photutils: 1.0.0, doi:10.5281/zenodo.4044744, https://doi.org/10.5281/zenodo.4044744
Bressan A., Marigo P., Girardi L., Salasnich B., Dal Cero C., Rubele S., Nanni A., 2012, MNRAS, 427, 127
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000
Buchner J., et al., 2014, A&A, 564, A125
Byler N., Dalcanton J. J., Conroy C., Johnson B. D., 2017, ApJ, 840, 44
Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682
Carnall A. C., McLure R. J., Dunlop J. S., Davé R., 2018, MNRAS, 480, 4379
Carnall A. C., et al., 2019a, arXiv e-prints, p. arXiv:1903.11082
Carnall A. C., Leja J., Johnson B. D., McLure R. J., Dunlop J. S., Conroy C., 2019b, ApJ, 873, 44
Carnall A. C., et al., 2020, MNRAS, 496, 695
Carnall A. C., et al., 2021, A massive quiescent galaxy at redshift 4.657, JWST Proposal. Cycle 1, ID. #2285
Dahlen T., et al., 2013, ApJ, 775, 93
Davé R., Thompson R., Hopkins P. F., 2016, MNRAS, 462, 3265
Donnan C. T., et al., 2022, arXiv e-prints, arXiv:2207.12356
D’Eugenio C., et al., 2021, A&A, 653, A32
Falcón-Barroso J., Sánchez-Blázquez P., Vazdekis A., Ricciardelli E., Cardiel N., Cenarro A. J., Gorgas J., Peletier R. F., 2011, A&A, 532, A95
Feroz F., Hobson M. P., Cameron E., Pettitt A. N., 2019, The Open Journal of Astrophysics, 2, 10
Ferreira L., et al., 2022, arXiv e-prints, arXiv:2207.09426
Finkelstein S. L., et al., 2022, arXiv e-prints, arXiv:2207.12474
Forrest B., et al., 2020, ApJ, 903, 47
Gallazzi A., Bell E. F., Zibetti S., Brinchmann J., Kelson D. D., 2014, ApJ, 788, 72

\(^{2}\) https://primer-jwst.github.io
APPENDIX A: SEDS AND CUTOUT IMAGES FOR ROBUST QUIESCENT GALAXIES

In Fig. A2 we show 5'' × 5'' HST ACS + JWST NIRCam cutout images for each of the 9 galaxies in our robust z > 3 massive quiescent galaxy sample. In Fig. A1 we show SEDs for the 6 robust quiescent galaxies we identify at 3 < z < 4. SEDs for the 3 robust quiescent galaxies we identify at z > 4 are shown in Fig. 1.
Figure A1. Spectral energy distributions for our 6 robust $3 < z < 4$ quiescent galaxies (SEDs for the three robust galaxies at $z > 4$ are shown in Fig. 1). Our 10-band photometric data from CFHTLS, HST ACS and JWST NIRCam are shown in blue. The posterior median Bagpipes models are overlaid in red. The inset panels show the position of each object on the UVJ diagram.
Figure A2. Cutout images for each of the 9 objects in our robust quiescent sample, in descending order of redshift. Each cutout image is $5'' \times 5''$. 