

Two Distinct Classes of Quiescent Galaxies at Cosmic Noon Revealed by JWST PRIMER and UNCOVER

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(Received XXX; Revised XXX; Accepted XXX)

Submitted to the Astrophysical Journal Letters

ABSTRACT

We present a measurement of the low-mass quiescent size-mass relation at Cosmic Noon ($1 < z < 3$) from the JWST PRIMER and UNCOVER treasury surveys, which highlight two distinct classes of quiescent galaxies. While the massive population is well studied at these redshifts, the low-mass end has been previously under-explored due to a lack of observing facilities with sufficient sensitivity and spatial resolution. We select a conservative sample of robust low-mass quiescent galaxy candidates using rest-frame *UVJ* colors and specific star formation rate criteria and measure galaxy morphology in both rest-frame UV/optical wavelengths (F150W) and rest-frame near-infrared (F444W). We confirm an unambiguous flattening of the low-mass qui-

escent size-mass relation, which results from the separation of the quiescent galaxy sample into two distinct populations at $\log(M_*/M_\odot) \sim 10.3$: low-mass quiescent galaxies that are notably younger and have disk-like structures, and massive galaxies consistent with prolate morphologies and older median stellar ages. These separate populations imply mass quenching dominates at the massive end while other mechanisms, such as environmental or feedback-driven quenching, form the low-mass end. This stellar mass dependent slope of the quiescent size-mass relation could also indicate a shift from size growth due to star formation (low masses) to growth via mergers (massive galaxies). The transition mass between these two populations also corresponds with other dramatic changes and characteristic masses in several galaxy evolution scaling relations (e.g. star-formation efficiency, dust obscuration, and stellar-halo mass ratios), further highlighting the stark dichotomy between low-mass and massive galaxy formation.

Keywords: Galaxy evolution (594); Galaxy structure (622); Galaxy quenching (2040); James Webb Space Telescope (2291)

1. INTRODUCTION

The study of galaxy evolution has long sought how to link a galaxy’s size and morphology to its star-formation history, especially in terms of determining how and why galaxies quench. Previous studies find that quiescent galaxies are more compact than their star-forming counterparts at a given mass out to cosmic noon ($z \gtrsim 2$; e.g., Kriek et al. 2009; Williams et al. 2010; Wuys et al. 2011; van der Wel et al. 2014; Whitaker et al. 2015; Nedkova et al. 2021). At higher stellar masses ($\log(M_*/M_\odot) > 10.5$), quiescent galaxies sizes depend strongly on stellar mass (e.g., Damjanov et al. 2009; van Dokkum et al. 2009; van der Wel et al. 2014; Mowla et al. 2019; Cutler et al. 2022; Ito et al. 2023), possibly due to rapid growth of an outer envelope caused by dry mergers (Bezanson et al. 2009; Naab et al. 2009; Trujillo et al. 2011; Patel et al. 2013; Ownsworth et al. 2014; van Dokkum et al. 2015). Simultaneously, quenching in the massive regime is thought to be primarily caused by galaxies reaching a stellar/halo mass threshold (i.e., mass quenching, Peng et al. 2010b), at which point future star formation is primarily thought to be halted by cosmological starvation (e.g., Feldmann & Mayer 2015), shock heating of circumgalactic gas (e.g., Dekel et al. 2019), or active galactic nuclei (AGN) feedback.

At lower stellar masses ($\log(M_*/M_\odot) < 10$), several recent studies find that the quiescent size-mass relation flattens, with sizes becoming comparable to star-forming galaxies of similar mass (Dutton et al. 2011; Lange et al. 2015; Whitaker et al. 2017; Mowla et al. 2019; Nedkova et al. 2021; Kawinwanichakij et al. 2021; Cutler et al. 2022; Yoon et al. 2023). These galaxies are too low-mass to be quenched by mass-related mechanisms: their halos are below the $\log(M_{\text{halo}}/M_\odot) > 11.8$ limit for shock heating the circumgalactic medium (Dekel et al. 2019) and AGN feed-

back would only temporarily remove gas from the system before it can replenish (Tacchella et al. 2016; Greene et al. 2020). One potential mechanism for quenching these low-mass systems is by rapidly consuming the available gas via central starbursts, either triggered by mergers (Puglisi et al. 2019) or disk/gas instabilities (Dekel & Burkert 2014; Zolotov et al. 2015). However, several studies show that this quenching event is only temporary, with these galaxies returning to the main sequence after the starburst or temporary quenching event (Tacchella et al. 2016; Cutler et al. 2023), likely due to the resumption of cold gas accretion. Simulations also suggest that star formation in these low-mass ($7 < \log(M_*/M_\odot) < 9$) galaxies is bursty at higher redshifts (Ma et al. 2018; Dome et al. 2023), further evidence supporting that galaxies that appear quiescent at the epoch of observation may only be temporarily so. These “mini-quenched” galaxies (e.g., Dome et al. 2023; Looser et al. 2023a; Strait et al. 2023) are likely the result of the interplay between gas inflow (via infalling cold gas streams or mergers) and gas removal (via stellar feedback or environmental interactions) and may be contaminants in finding a population of “fully quenched” low-mass galaxies.

Measurements of galaxy sizes can provide insight into how galaxies form, grow in size, and cease star formation. Previous measurements of the low-mass quiescent size-mass relation are limited by the spatial resolution and depth of observations possible at the time. For example, the Hubble Space Telescope (HST) WFC3 F160W has a half width at half max (HWHM) of 0.65 kpc at $z = 2$, roughly the size at which the quiescent size-mass relation reaches a minimum and begins to flatten (e.g., Nedkova et al. 2021; Cutler et al. 2022). Likewise, robust size measurements have only been available to $\log(M_*/M_\odot) > 9.5$ at $z \sim 1.5$ and $\log(M_*/M_\odot) > 10.5$ at $z \sim 2.5$ with deep HST data (e.g., Hubble Frontier Fields, CANDELS, and COSMOS, Nedkova et al. 2021; Cutler et al. 2022). The wavelength coverage of HST ($\lambda_{\text{rest}} \leq 0.8 \mu\text{m}$ at $z = 1$) also means observed sizes may have biased mass-

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| | UNCOVER | PRIMER-COSMOS | PRIMER-UDS | Total |
|--|-----------|---------------|------------|------------|
| Total Photometric Catalog | 59845 | 58004 | 75914 | 193763 |
| $1 < z < 3$ and $7 < \log(M_*/M_\odot) < 11$ | 4432 | 4610 | 6934 | 15976 |
| UVJ Quiescent ($C_Q > 0.49$ & $t_{50} > 30$ Myr) | 218 | 145 | 266 | 629 |
| Quiescent (UVJ Quiescent & $\Delta MS_{10} < -0.5$ & $SFR_{10} - SFR_{100} < 0.3$) | 108 | 99 | 147 | 354 |
| Quiescent with EA_ZY Color Outliers Removed | 94 | 96 | 142 | 332 |
| Quiescent ($t_{50} > 500$ Myr) | 39 | 69 | 101 | 209 |
| Quiescent ($100 < t_{50} < 500$ Myr) | 27 | 20 | 24 | 71 |
| Quenched ($30 < t_{50} < 100$ Myr) | 28 | 7 | 17 | 52 |

Table 1. Sample size of the low-mass quiescent galaxy sample and sub-samples. The final adopted sample of low-mass $1 < z < 3$ galaxies is shown in bold.

to-light ratios due to “outshining” (Papovich et al. 2001), in which young stars dominate the light from a galaxy such that a significant fraction of the stellar mass can be missed with rest-optical data. Outshining causes light-weighted sizes of quiescent galaxies to be significantly larger than mass-weighted sizes at $\log(M_*/M_\odot) \gtrsim 9.5$, which could artificially lead to larger low-mass sizes should these trends hold (Suess et al. 2019; van der Wel et al. 2023).

New observations from the James Webb Space Telescope (JWST) NIRCam instrument provide significant improvements in depth, spatial resolution, and redder wavelength coverage over HST (Rieke et al. 2023; Rigby et al. 2023). Several studies have already leveraged these advancements to explore galaxy sizes out to $z \sim 8$ (Ormerod et al. 2023), examine the evolution of the star-forming size-mass relation since $z = 5.5$ (Ward et al. 2023), and investigate the dependence of Sérsic-based measurements on wavelength (Martorano et al. 2023).

In this letter, we measure the sizes of 332 quiescent galaxies from JWST Ultradeep NIRSpec and NIRCam Observations before the Epoch of Reionization (UNCOVER, Bezançon et al. 2022) and Public Release IMaging for Extragalactic Research (PRIMER, Dunlop et al. 2021) in F150W and F444W, using 2D Sérsic fits from GALFIT (Peng et al. 2002, 2010a). We assume a Chabrier (2003) initial mass function and WMAP9 cosmology: $H_0 = 69.32 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.2865$, and $\Omega_\Lambda = 0.7135$ (Hinshaw et al. 2013).

2. DATA AND SAMPLE SELECTION

2.1. Imaging and Catalogs

Our sample is built on the JWST UNCOVER and PRIMER surveys. UNCOVER (JWST-GO-2561) targets 45 sq. arcmin of the Abell-2744 lensing cluster with NIRCam F090W, F115W, F150W, F200W, F277W, F356W, F410M, and F444W and is the deepest-to-date (when augmented by strong lensing) publicly available survey (Bezançon et al. 2022). PRIMER (JWST-GO-1837) is a deep, wide-area survey that covers 378 sq. arcmin. of two HST legacy fields (COSMOS and UDS) with homogeneous depth in the same NIRCam bands as UNCOVER. PRIMER and UNCOVER

are chosen because together they probe a wider range of luminosity and galaxy stellar mass than individually. The deeper imaging of UNCOVER finds more low-mass, faint galaxy populations, while the larger area of PRIMER enables us to detect more of the rarer, higher-mass/brighter galaxies. Moreover, the use of these surveys covers three separate fields, which reduces the impact of cosmic variance. Between $1 < z < 3$, UNCOVER reaches 95% mass-completeness limits of $\log(M_*/M_\odot) \sim 7.3$ (7.8) at $z = 1$ ($z = 3$) for a sample of all galaxies, though older or quiescent galaxy samples may be less complete. In both surveys, samples are selected from a F277W-F356W-F444W detection image, with F444W down to $m_{5\sigma} = 29.21$ ABmag in UNCOVER and 28.17 ABmag in PRIMER.

Imaging is from the v7¹ mosaics reduced by GRIZLI (Brammer 2023) and rescaled to a 40 mas pixel scale in both F150W and F444W. The UNCOVER mosaics with bright cluster galaxy, intracluster light, and sky background subtraction are used (Weaver et al. 2023a), while additional sky background is subtracted from the PRIMER science mosaics. Sample galaxies are selected from the UNCOVER (Weaver et al. 2023a) and PRIMER photometric catalogs as follows. The PRIMER catalogs (both COSMOS and UDS) are built using the APERPY² aperture photometry code, with settings identical to Weaver et al. (2023a). Both the UNCOVER and PRIMER catalogs are PSF-matched to F444W. Redshifts and stellar populations properties for the UNCOVER³ and the PRIMER photometric catalogs are inferred following Wang et al. (2023a), using the PROSPECTOR- β model (Wang et al. 2023b) within the PROSPECTOR (Johnson et al. 2021) Bayesian inference framework. PROSPECTOR- β provides robust photometric redshifts, rest-frame colors, and key stellar population properties, including stellar masses and non-parametric star-formation histories (SFHs). For the Abell

¹ <https://dawn-cph.github.io/dja/imaging/v7/>

² <https://github.com/astrowhit/aperpy>

³ The catalog and related documentation are accessible via the UNCOVER survey webpage (<https://jwst-uncover.github.io/DR2.html#SPSCatalogs>) or Zenodo (doi:10.5281/zenodo.8401181)

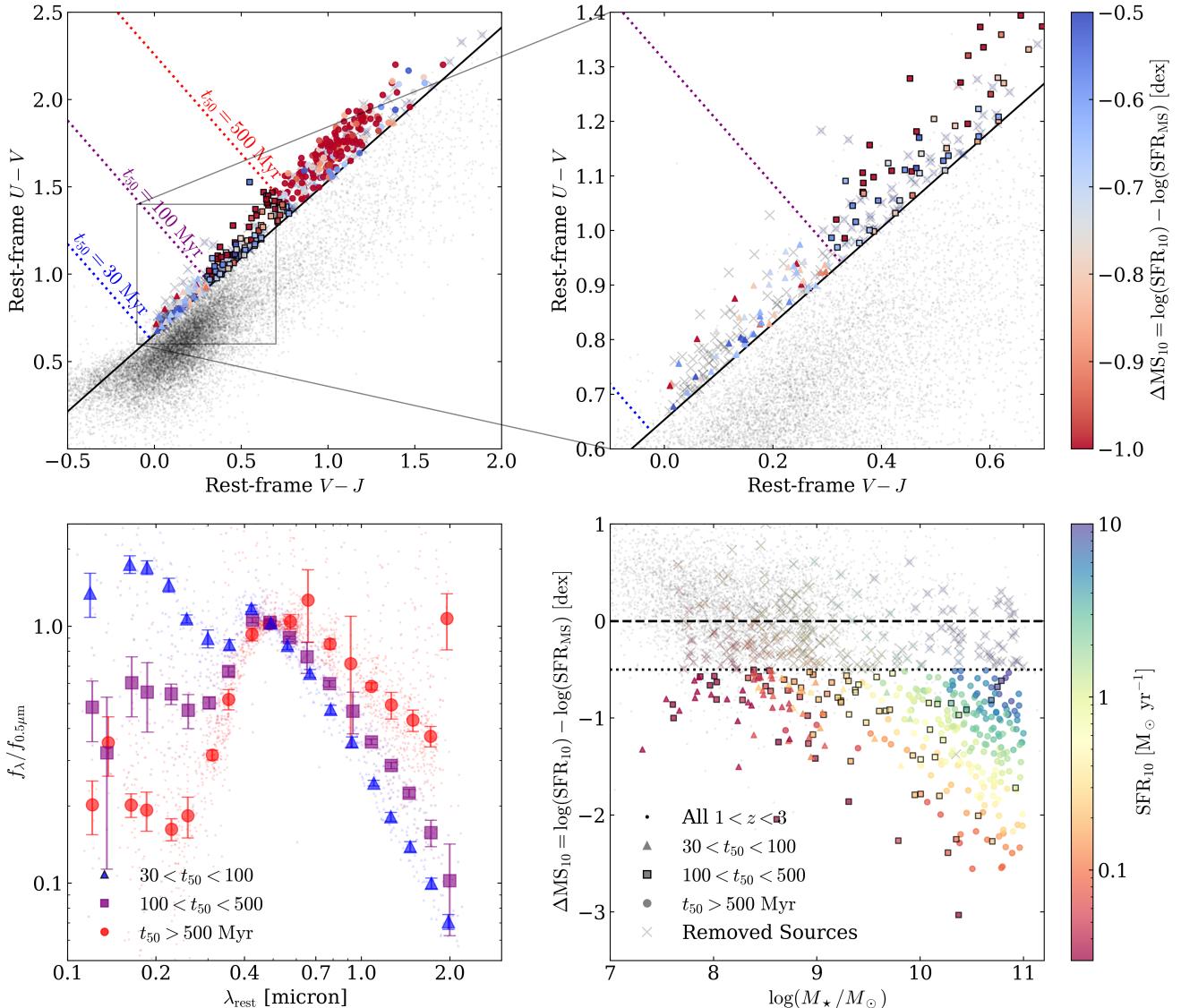


Figure 1. Rest-frame colors and physical properties of the 281 quiescent galaxies at $1 < z < 3$ with $\log(M_*/M_\odot) < 11$, as defined in Section 2. Sources are identified as $t_{50} > 500$ Myr quiescent (circles), 100–500 Myr quiescent (squares), or 30–100 Myr quenched galaxies (triangles), respectively, relative to the parent sample at $1 < z < 3$ (small black points). The top row shows rest-frame UVJ colors from best-fit SPS models, with an inset (top right) to show more detail, colored by ΔMS_{10} (Eqn. 3). Solid black and dotted lines show the UVJ selections for general quiescent galaxies and cuts selecting galaxies of varying median age, respectively. Composite SEDs (bottom left) demonstrate that each sub-population has fundamentally different spectral shapes. The degree of quiescence for the sample is captured by difference in SFR relative to the average SFMS (dashed line), ΔMS_{10} , colored by the SFR at 10 Myr (bottom right). Galaxies 0.5 dex below the SFMS (dotted line) are considered quenched. Sources marked with black x's are potential contaminants and have been removed from the sample.

2744 field, we adopt the strong lens model from Furtak et al. (2023). Note that the redshifts and stellar populations properties are inferred jointly, and that since the magnification factor depends on redshift, we account for lensing modification consistently during model fitting (see Section 3.1 in Wang et al. 2023a for details). This way, the scale-dependent priors (i.e., the mass function prior and dynamic SFH prior introduced in Wang et al. 2023b) used to optimize the inference for JWST surveys, can also be properly applied. However,

we neglect the uncertainty in the lens model itself, which will be explored in future works.

2.2. Sample Selection

We create an initial ‘‘Cosmic Noon’’ sample of robustly photometered galaxies using all sources with USE_PHOT=1 (see Weaver et al. 2023a) and $S/N > 10$ in both F150W and F444W between $1 < z_{\text{phot}} < 3$ and $7 < \log(M_*/M_\odot) < 11$ using SPS photometric redshifts and stellar masses (Wang et al.

2023b), as shown in Table 1. To ensure accurate $U-V$ colors and recent SFRs, we restrict our sample to sources that have photometric coverage (regardless of S/N) in at least one filter blueward of rest-frame 3500 Å. Quiescent galaxies are then selected using rotated UVJ coordinates from Belli et al. (2019):

$$\begin{aligned} S_Q &= 0.75(V-J) + 0.66(U-V) \\ C_Q &= -0.66(V-J) + 0.75(U-V). \end{aligned} \quad (1)$$

Physically, S_Q measures the net slope of a spectrum while C_Q approximates the spectrum's curvature, the difference in slope above and below 4000 Å (Fang et al. 2018). The age of a quiescent galaxy has been shown to increase with S_Q due to the transition from Balmer break- to 4000 Å break-dominated spectra (Whitaker et al. 2012, 2013; Belli et al. 2019). This can be used to infer the median stellar age of a galaxy via:

$$\log(t_{50}/\text{yr}) = 7.03 + 1.12 S_Q. \quad (2)$$

In this work, we investigate galaxies with $C_Q > 0.49$ (defined as quiescent by Belli et al. 2019) and $t_{50} > 30$ Myr, indicated by solid black and dotted blue lines, respectively, in the UVJ diagram shown in the top two panels of Figure 1. This extension to the traditional quiescent box has been proven to capture rapidly-quenched and post-starburst galaxies (e.g., Park et al. 2023).

In order to remove potential star-forming contaminants from our sample of color-selected quiescent galaxies, we also examine a galaxy's distance from the star-forming main sequence (SFMS) using SPS modeling from PROSPECTOR- β . The distance from the SFMS is calculated via

$$\Delta MS_t(M_*, z) = \log(SFR_t) - \log(SFR_{MS}(M_*, z)), \quad (3)$$

where t is the lookback time over which the SFH is averaged, and $SFR_{MS}(M_*, z)$ is the SFR of the SFMS at stellar mass M_* and redshift z from Leja et al. (2022). Any galaxy more than 0.5 dex below the SFMS at 10 Myr ($\Delta MS_{10} < -0.5$) in our color-selected sample is retained. Selecting quiescent galaxies with ΔMS_{100} instead of ΔMS_{10} does not significantly impact our results. Moreover, in order to exclude any potentially rejuvenated galaxies, we exclude sources where the SFR increases by more than 0.3 dex between lookback times of 100 and 10 Myr ($\log(SFR_{10}) - \log(SFR_{100}) > 0.3$). The number of galaxies in this selection is shown in Table 1, of which only a single source (0.3%) was removed for potentially being rejuvenated. We show how ΔMS_{10} changes with stellar mass for galaxies in our sample in the bottom left panel of Figure 1. Galaxies are also colored by their ΔMS_{10} in the UVJ diagrams shown in the top panels of Figure 1.

From the UVJ/SFR sample of quiescent galaxies, we compare rest-frame $U-V$ colors measured by PROSPECTOR- β

and EAzY (Brammer et al. 2008). Any outlier sources that differ by > 0.2 mag in $U-V$ color, which is unphysical if the 4000 Å break is sufficiently sampled, are removed from the sample due to untrustworthy SPS models. 22 total sources are removed for outlier $U-V$ colors (6.2%). With color outliers removed, we select 94 galaxies in UNCOVER and 238 galaxies in PRIMER (bold counts in Table 1).

2.3. Separating Quiescent Galaxies by Age

Lastly, we separate our primary sample into specific types of quiescent galaxies: $t_{50} > 500$ Myr quiescent, $100 < t_{50} < 500$ Myr quiescent, and $30 < t_{50} < 100$ Myr quenched galaxies, where “quenched” is used to indicate galaxies that are observed with colors and measured SFRs consistent with low star-formation activity, but may not be permanently quiescent. $t_{50} > 500$ Myr quiescent galaxies are predominantly high-mass ($\log(M_*/M_\odot) > 10$), while the $30 < t_{50} < 100$ quenched sub-sample is almost exclusively low-mass (Fig. 1, bottom right). The required quality selections ($S/N > 10$, rest-U coverage) may impact our ability to detect $t_{50} > 500$ Myr quiescent galaxies at $\log(M_*/M_\odot) < 9.5$. We note the measured size and structural trends do not change significantly if we apply a USE_PHOT=1 selection only. Moreover, the fraction of the sample with $t_{50} > 500$ Myr is roughly unchanged, both in the overall sample and at low masses. Although we expect our source detection strategy to only detect $\sim 50\%$ of these old, red sources at low masses in the first place (discussed more in Section 5), it is clear that our additional quality cuts do not disproportionately remove older quiescent galaxies from the sample.

Final number counts of each sub-population are shown in Table 1. Composite spectral energy distributions (SEDs) of each subsample (Fig. 1, bottom left) show that each population has distinct spectral shapes. $t_{50} > 500$ Myr quiescent galaxies (circles) have strong Balmer breaks with very little ultraviolet (UV) flux and more infrared (IR) flux. $30 < t_{50} < 100$ Myr quenched galaxies have smaller breaks and more UV flux, indicating their star formation only ceased recently, while $100 < t_{50} < 500$ Myr quiescent galaxies occupy an intermediate region between the two.

3. ANALYSIS

We adapt the GALFIT (Peng et al. 2002, 2010a) one-component Sérsic fitting methods from van der Wel et al. (2012). Galaxies are fit in both the F150W and F444W filters: F150W is chosen due to its high spatial resolution and comparable wavelength coverage to HST/WFC3 F160W, while F444W provides the longest wavelength coverage available. All science images are processed in the same way as follows.

Cutouts of each source are taken from the science, weight, exposure time, and segmentation images. The cutouts have

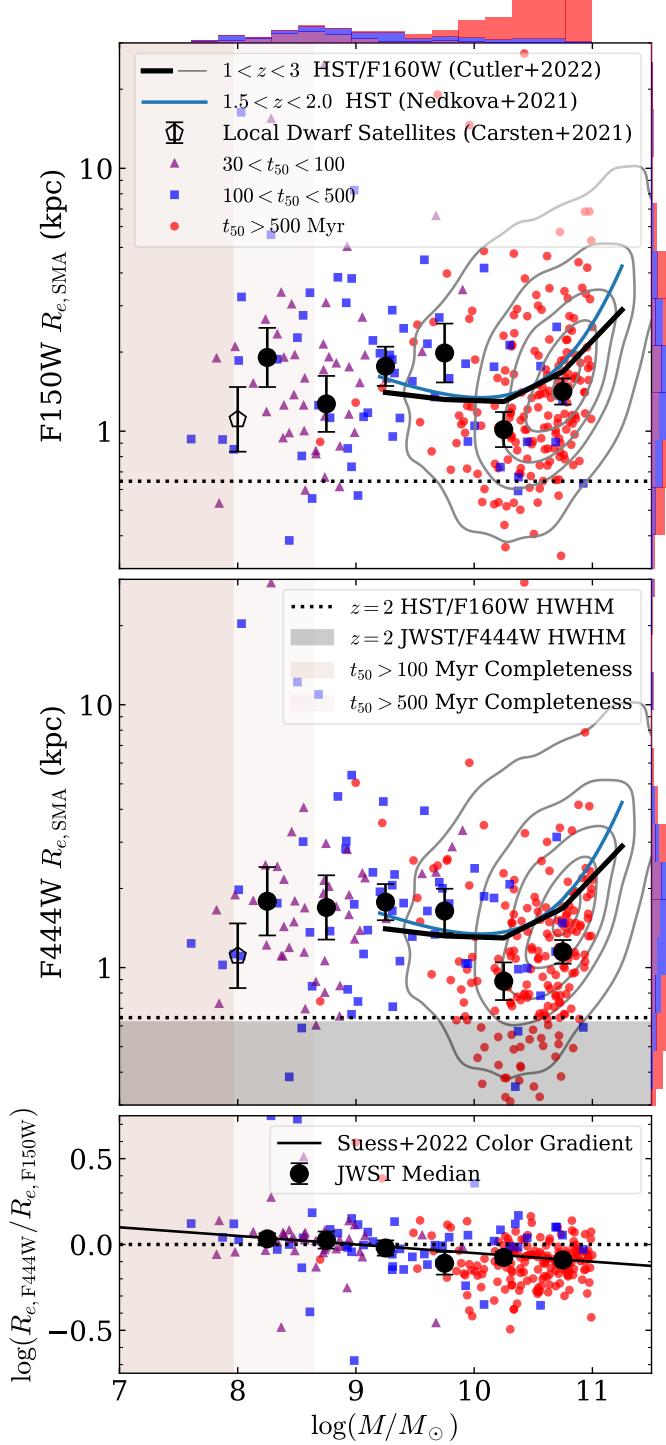


Figure 2. The quiescent galaxy size-mass relation flattens significantly at low masses. Quiescent size-mass relations in both JWST/NIRCam F150W and F444W are shown in the top and middle panels, respectively. The bottom panel shows the ratio of F444W to F150W sizes and exhibits comparable trends to the Suess et al. (2022a) color gradients (thin black line). Purple diamonds, blue squares, and red circles show the individual sizes of $30 < t_{50} < 100$, $100 < t_{50} < 500$, and $t_{50} > 500$ Myr quiescent galaxies, respectively. Marginal histograms show the 1D distributions of galaxy mass and size. In the top and center panels, solid gray contours and the thick black line indicate the $1 < z < 3$ HST/WFC3 F160W sizes of galaxies from COSMOS-DASH (Cutler et al. 2022), while the cyan line shows the $1.5 < z < 2.0$ quiescent size-mass relation from Nedkova et al. (2021). In the top and middle panels, the thin black dotted line shows the HST/WFC3 F160W HWHM and black shading shows the JWST/NIRCam F150W (top) and F444W (middle) HWHMs at $z = 2$. The 50% mass-completeness detection limits of the combined PRIMER and UNCOVER sample for $t_{50} > 100$ and > 500 Myr quiescent galaxies is indicated with dark and light brown shading, respectively.

sides of length $7 \times R_{\text{Kron,circ}}$ or 150 pixels, whichever is larger. Sources where $> 40\%$ of the cutout or the central pixel is empty (zero weight) are removed. Of the 332 galaxies in the sample, 2 (0.6%) are removed by this cut, all of which are located on the edge of the mosaic. The error at a given pixel, σ_i , is estimated using a combination of sky background variance ($1/w$) and Poisson noise (f/t_{exp}):

$$\sigma_i = \sqrt{\frac{1}{w_i} + \frac{f_i}{t_{\text{exp},i}}}, \quad (4)$$

where w_i , f_i , and $t_{\text{exp},i}$ are the weight, flux, and exposure time of a pixel. To mask all other sources in the cutout, nearby-object masks are created from the segmentation map. Empirical JWST point-spread functions (PSFs) are built using stacks of unsaturated stars selected directly from the mosaic, as in Weaver et al. (2023a), and normalized to reported encircled energies from calibration resources⁴ at $4''$.

The science, error, and nearby-object mask cutouts, as well as the empirical PSF, are provided to GALFIT and used to determine the best-fit Sérsic model with free parameters including the object centroid (x_0 , y_0), total magnitude (m), semi-major axis effective (half-light) radius (R_e), Sérsic index (n), axis ratio (q), and position angle (θ). No additional sky background pedestal is fit as we find JWST performs better with external background subtractions (as opposed to HST, Häussler et al. 2007; Cutler et al. 2022), with 5 additional sources being successfully fit when background subtracting is disabled. Standard constraints are imposed on the magnitude (± 3 mag from the photometric catalog value), radius ($0.01 < R_e < 400$ pixels), Sérsic index ($0.2 < n < 10$), and axis ratio ($0.0001 < q < 1$). Sources that have poor mosaic coverage (see above), have best-fit parameters at the constraint values, or cannot be fit by GALFIT (i.e. GALFIT FLAG ≥ 2 in Cutler et al. 2022) are removed from the sample. In total, 40 galaxies (12%) are removed from the sample due to inadequate coverage or GALFIT fitting (4 at $30 < t_{50} < 100$, 11 at $100 < t_{50} < 500$, and 25 at $t_{50} > 500$ Myr, with most $t_{50} > 500$ Myr quiescent galaxies at $\log(M_*/M_\odot) > 10$). To account for the effects of lensing, UNCOVER sizes are scaled by $1/\sqrt{\mu}$ (where μ is the magnification as reported in Furtak et al. 2023). Sources with high magnification $\mu > 3$ are removed from the sample due to possible impacts on the galaxy's size and shape. This removes 7 galaxies (2.4%) from the sample (of which 2 are low-mass, $t_{50} > 500$ Myr sources). If we remove the UNCOVER sample entirely, the overall trends are statistically unchanged, suggesting that lensing effects are minimal.

4. RESULTS

4.1. The Quiescent Galaxy Size-Mass Relation

If the quiescent size-mass relation really does flatten at low masses, we should expect to see it clearly in both F150W and F444W. In Figure 2, we show the quiescent size mass relation in both F150W (top) and F444W (middle), with a comparison of the sizes of both filters (bottom). There is indeed a significant flattening of the size-mass relation at $\log(M_*/M_\odot) < 10$ that is present in both filters. The median size in the flattened region of the size-mass plot of 1.6 kpc is roughly the same in both filters (as in, e.g., Nedkova et al. 2021; Cutler et al. 2022), as shown in the bottom panel of Figure 2, falling to a minimum at $\log(M_*/M_\odot) \sim 10.3$. The trend then increases with a stronger mass-dependence at higher masses (as in, e.g., van der Wel et al. 2014; Mowla et al. 2019; Cutler et al. 2022; Ito et al. 2023). These trends are apparent well above the JWST resolution limit and the mass completeness limits for different age quiescent galaxies (black and brown shading, respectively).

Also apparent is a bimodality in the overall quiescent galaxy stellar mass distribution of this sample (marginal histogram in Figure 2). This behaviour, combined with the disjoint size-mass relations, indicates low- and high-mass quiescent galaxies may exist in two separate distributions altogether, more in line with proposed star-forming and quiescent growth tracks (e.g., Figure 28 in van Dokkum et al. 2015). We discuss the possible physical causes for the dip in size at $\log(M_*/M_\odot) \sim 10.3$ as well as the distinct distributions of size and mass in Section 5.

There exists a slight difference between earlier HST median sizes (e.g., COSMOS-DASH, Cutler et al. 2022; CANDELS/HFF, Nedkova et al. 2021) and this JWST sample: the median high-mass ($\log(M_*/M_\odot) > 10$) size is smaller in JWST, especially in F444W. With deeper JWST data we can test if this tension is the result of biases in the shallower, noisier HST data. To test this, we remeasure the sizes of the galaxies in our sample with increased noise comparable to the depth of COSMOS-DASH observations ($m_{5\sigma} \sim 25$). We find that while the scatter noticeably increases and fewer low-mass galaxies are successfully fit, there are no biases in the median size that would explain the differences with HST. This effect is also not likely due to the increased spatial resolution of JWST relative to HST. There are noticeably fewer high-mass quiescent galaxies above the HST size-mass relations, so removing sources below the HST HWHM won't significantly increase the median JWST sizes. Moreover, this effect is most significant in F444W, which has a comparable PSF HWHM to HST F160W. Instead, we find that the large discrepancy in F444W is likely due to the negative color gradients in massive quiescent galaxies (Fig 2, bottom), where sources are more compact in the rest-frame near-infrared than the rest-UV/optical (Suess et al. 2022a; van der Wel et al. 2023). The small offset in F150W may be the result of the

⁴ <https://jwst-docs.stsci.edu/jwst-near-infrared-camera/nircam-performance/nircam-point-spread-functions>

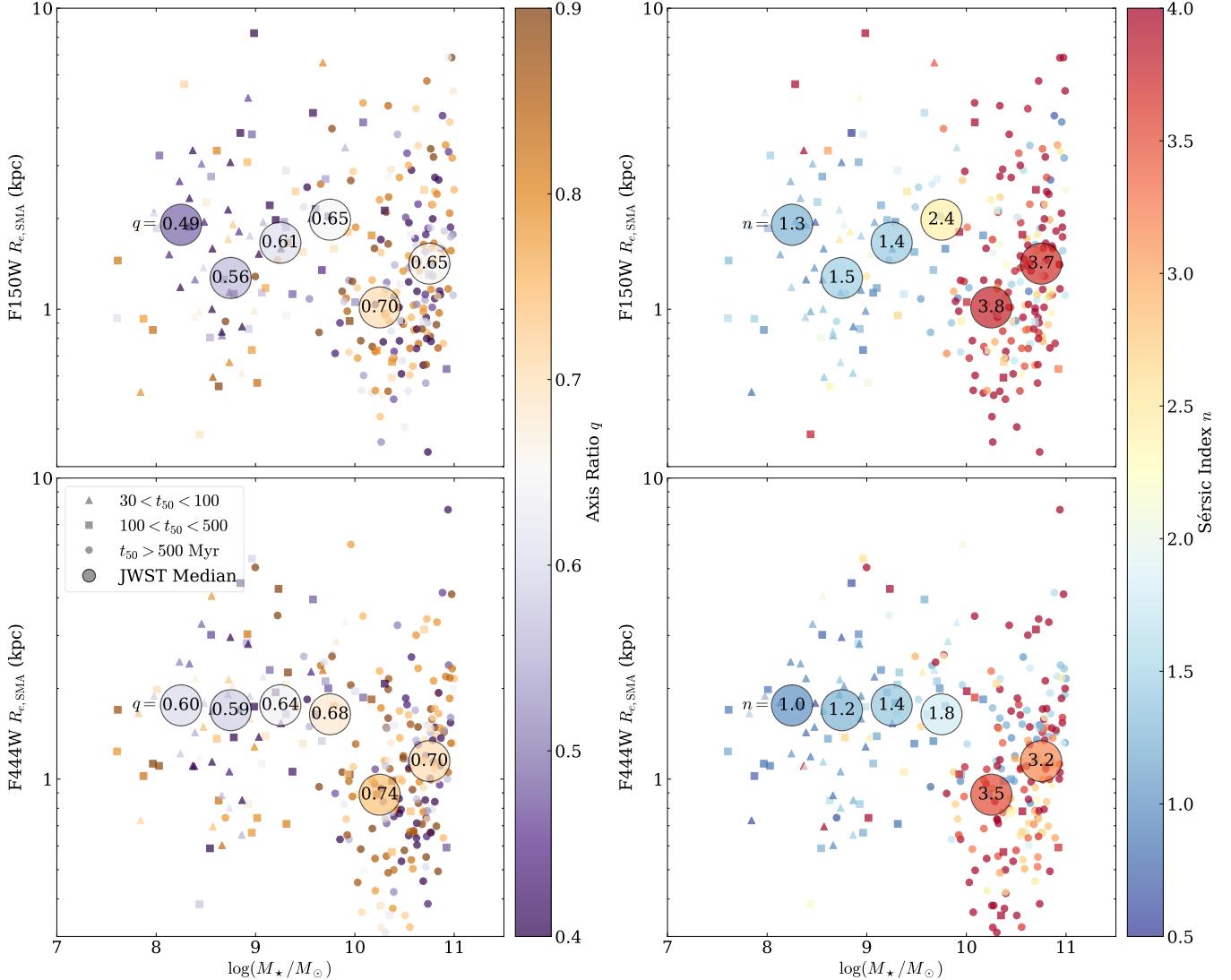


Figure 3. The size-mass relation for galaxies in our sample colored based on the axis ratio (left) and Sérsic index (right) for both F150W (top) and F444W (bottom). Galaxies in the flattened part of the size-mass relation have smaller axis ratios and Sérsic indices. Individual points have the same shape symbols as Figure 2. Large circles indicate the median size-mass for a given stellar mass bin, color-coded by the median axis ratio or Sérsic index. The median axis ratio and Sérsic index are also shown numerically in each point. Typical error bars on axis ratio are ± 0.10 at $\log(M_*/M_\odot) < 10$ and ± 0.04 at higher masses. For the Sérsic index, error bars are typically ± 0.4 .

additional SFR selection we impose on our quiescent galaxy sample: we can recover the high-mass relations of Cutler et al. (2022) and Nedkova et al. (2021) by not implementing SFR cuts, suggesting earlier works possibly had contamination from larger star-forming galaxies.

4.2. Trends with Structural Parameters

Figure 3 shows the JWST size-mass relations from Figure 2 color-coded by axis ratio, q (left), and Sérsic index, n (right). In both filters, we see clear trends with n . In the low-mass, flattened region of the size-mass relation, galaxies have much smaller Sérsic indices ($n < 2$). At the high-mass, steeply growing end, Sérsic indices are in the tradi-

tionally “elliptical” regime ($n > 2.5$). At $\log(M_*/M_\odot) > 9.5$, axis ratios are generally higher than at lower masses. This higher median q in this older, more massive population, combined with the larger Sérsic indices is likely indicative of a spheroidal population, compared to the lower-mass sample that appears consistent with a more oblate population. Unusually, in all mass bins, F444W Sérsic fits find higher values for q and lower values for n than F150W, contrary to Martorano et al. (2023). Despite this, the F444W–F150W color gradients are comparable to Suess et al. (2022a) (solid black line in Figure 2, bottom).

Figure 4 compares the stellar mass, R_e , n , and q distributions for $30 < t_{50} < 100$, $100 < t_{50} < 500$ and $t_{50} > 500$ Myr

quenched/quiescent galaxies. Quiescent galaxies with low Sérsic indices ($n < 2.5$) have been observed with a roughly flat distribution of axis ratios (e.g., Chang et al. 2013; Cutler et al. 2022). However, we see a peak in the axis ratios of $30 < t_{50} < 100$ quenched and $100 < t_{50} < 500$ Myr quiescent galaxies (which predominately have $n < 2.5$) at $q \sim 0.4$ and 0.6, respectively. These distributions, combined with the smaller median Sérsic indices we measure, likely indicate that the younger ($t_{50} < 500$ Myr), low-mass quiescent galaxies are oblate and disk-like. This is in agreement with Tan et al. (2022), who find that disk-like structures dominate the low-mass ($8.5 < \log(M_*/M_\odot) < 9.5$) quiescent galaxy population in the Hubble Frontier Fields. For $t_{50} > 500$ Myr quiescent galaxies, the q distribution peaks significantly at $q \sim 0.8$. This peak also coincides with a higher Sérsic index ($n > 4$), which strongly suggests these galaxies are predominantly spheroidal.

5. DISCUSSION

The distinct size-mass relations in the quiescent size-mass relation (no size evolution at low masses and increasing size with mass at high masses) potentially indicates two separate evolutionary paths. These paths may be caused by separate quenching mechanisms and/or different physical processes driving size growth.

At high masses, compaction is often associated with quenching (e.g., Cheung et al. 2012; Barro et al. 2017; Whitaker et al. 2017; Lee et al. 2018; Ji & Giavalisco 2022); several studies have even proposed morphological changes, specifically bulge formation and compaction, as potential mechanisms for quenching in massive elliptical galaxies (e.g., Martig et al. 2009; Tacchella et al. 2018; Tadaki et al. 2020). These structural changes would result in the smaller R_e and larger n seen in $10 < \log(M_*/M_\odot) < 11$ quiescent galaxies in Figures 2 and 3.

At low masses, quenching could instead be primarily driven by mechanisms that mostly leave structure and size intact, similar to star-forming galaxies at comparable masses. Environmental quenching such as stripping of gas in and around a low-mass galaxy (e.g., Weinmann et al. 2006), is a viable explanation. Yoon et al. (2023) find at nearby redshifts ($0.01 < z < 0.04$), the quiescent size-mass relation flattens at $\log(M_*/M_\odot) < 10$ for galaxies in denser environments, while isolated low-mass quiescent galaxies are smaller and their size-mass relation does not flatten. They also find low-mass quiescent galaxies in high-density environments have more disk-like structure (smaller n), which could be due to environmental gas stripping without significant morphological changes. The existence of known cosmic noon overdensities in the observed fields (COSMOS: Spitler et al. 2012; Chiang et al. 2014, UDS: Chuter et al. 2011; Guaita et al. 2020) suggests that environmental quenching is a likely explanation for

the resulting structure of low-mass quiescent galaxies in our sample.

While simulations find that low-mass satellites of the Milky Way and M31 can be efficiently quenched (Fillingham et al. 2018), these studies also suggest that low-mass field galaxies are unlikely to be quenched by galaxy-galaxy interactions, and that they are more likely quenched by efficient feedback mechanisms (e.g., Fitts et al. 2017). The choice of feedback model has also been shown to impact the overall size-mass relation at low masses (e.g., Pillepich et al. 2018), with the caveat that the sample isn't separated into star-forming and quiescent populations. At higher redshifts, supernovae have been proposed as potential driver of low-mass galaxy quenching, though they have been shown to not impart sufficient energy to halt star formation in the Looser et al. (2023b) or Strait et al. (2023) high-redshift mini-quenched galaxy candidates (Gelli et al. 2023a,b). Quenching via environmental interactions would result in minimal structural changes to the stellar light of low-mass galaxies, while stellar feedback quenching makes galaxies larger (Übler et al. 2014). This would explain the similar size-mass relation to low-mass star-forming galaxies, as well as the Sérsic indices closer to an exponential disk light profile. While we can only speculate, our data is consistent with low-mass quenching being driven by stellar feedback, environmental interactions, or both.

The suggested quenching mechanisms for both mass regimes do not explain all of the trends in the quiescent size-mass relation. The steeper size-mass slope of massive quiescent galaxies (e.g., Mowla et al. 2019) cannot be explained by compaction/bulge formation. Moreover, it isn't clear why the disjoint transition between these populations occurs at $\log(M_*/M_\odot) \sim 10.3$. These effects could be explained by a change in the dominant mechanism behind size-growth at this transition mass. At lower masses, galaxies can only grow in size via star formation (prior to quenching), whereas at higher masses, dry mergers rapidly increase the size of previously-quenched galaxies (van Dokkum et al. 2015). At $1 < z < 3$, the quiescent mass function peaks at $\log(M_*/M_\odot) \sim 10.5$ (Muzzin et al. 2013; Santini et al. 2022; Weaver et al. 2023b), which is also the location of the size-growth transition found herein. Since quiescent galaxies at this mass are most abundant, they are the most likely candidates for mergers and a clear starting point for the steeper growth found at the high-mass end. Galaxies below this mass are also more likely to merge with a higher mass galaxy, which prevents steep size growth from occurring at $\log(M_*/M_\odot) < 10.5$ as they are subsumed.

Merger-dominated growth at high masses could also explain the dip in the quiescent size-mass relation at $\log(M_*/M_\odot) \sim 10.3$: galaxies in this mass regime may be in a compact, non-virialized state following the merger. More-

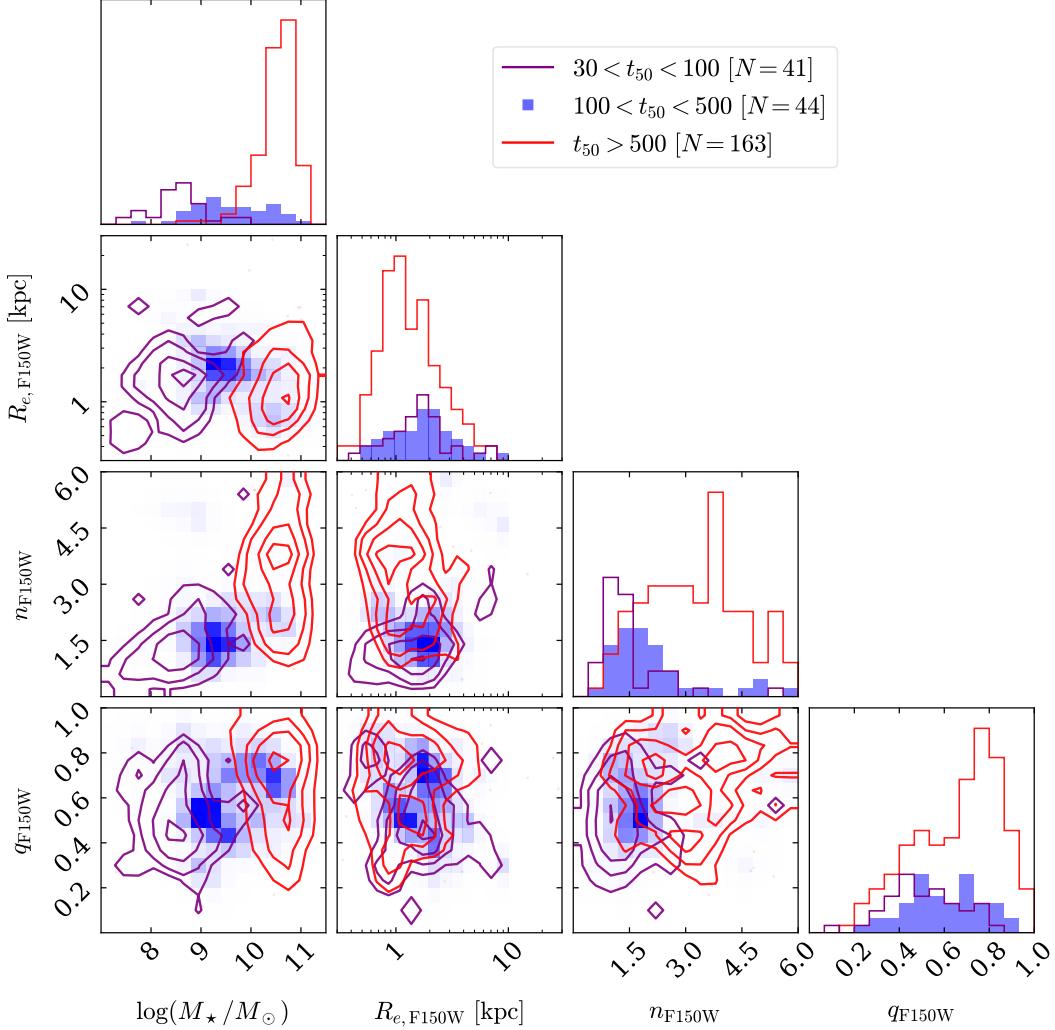


Figure 4. Structural parameters differ dramatically between low- and high-mass quiescent galaxies. Corner plots showing correlations between mass and structural parameters (R_e , n , q) for F150W. Individual distributions of $30 < t_{50} < 100$, $100 < t_{50} < 500$, and $t_{50} > 500$ Myr quiescent galaxies are shown with purple, blue and red contours/shading, respectively. The sample size of each population is indicated in the legend.

over, the mass where these two populations diverge coincides with several other significant transitions in galaxy evolution. At $\log(M_*/M_\odot) \sim 10.3$, observations show the SFMS slope flattens (e.g., Whitaker et al. 2012; Leja et al. 2022) and star-forming galaxies transition from mostly unobscured to dusty (Martis et al. 2016), and simulations indicate the stellar-halo mass relation and star-formation efficiency peak (e.g., Behroozi et al. 2013; Genel et al. 2014). These results, combined with new information about the quiescent size-mass relation presented herein, imply galaxy formation differs dramatically above and below $\log(M_*/M_\odot) \sim 10.3$.

The stark flatness of the quiescent size-mass relation at low-masses is also potentially due to a combination of halted galaxy growth after quenching (in the absence of mergers) and progenitor bias (which is pronounced for low-mass galaxies, Ji & Giavalisco 2023), as suggested by the age gra-

dient in the low-mass quiescent galaxy population. In the flattened region, more massive galaxies are older and thus formed earlier in the universe, which makes them smaller and more dense than more recently formed galaxies (Mo et al. 2010; Ji & Giavalisco 2023). Meanwhile, the younger, low-mass galaxies formed later and are intrinsically larger than older galaxies when they quench. In the absence of mergers at $\log(M_*/M_\odot) < 10$, the sizes of quiescent galaxies should remain the same, meaning the young, low-mass galaxies have roughly the same size as the older, more massive galaxies.

The potential existence of dramatically different high- and low-mass quiescent galaxy evolutionary paths is compounded by a significant paucity in the number of $1 < z < 3$ quiescent galaxies between $9 \lesssim \log(M_*/M_\odot) \lesssim 10$ (mass histograms in Figures 2 and 4). This deficit is likely a real physical effect and not an artifact of our stellar population model-

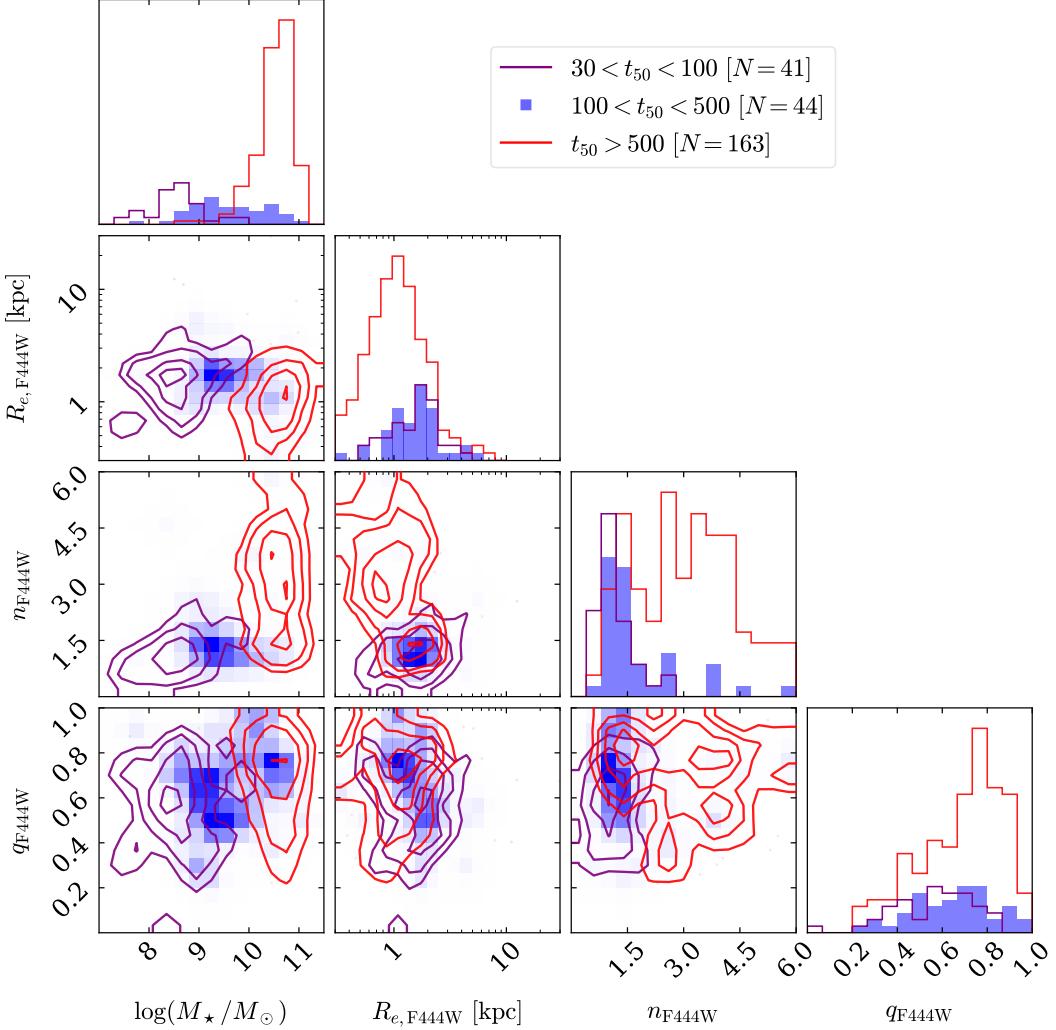


Figure 4. Continued for F444W.

ing or sample selection, as it exists separately in UNCOVER and PRIMER (for larger, less curated quiescent galaxy selections) and using stellar population parameters derived independently with EAzY and PROSPECTOR. Previous studies have missed this effect at these redshifts simply due to mass completeness. In particular, the COSMOS2020 quiescent mass function is only complete to $\log(M_*/M_\odot) \sim 9$ at $z \sim 1$, although it does hint at a local minimum in the number of quiescent galaxies between $9 \lesssim \log(M_*/M_\odot) \lesssim 10$ (San-tini et al. 2022; Weaver et al. 2023b). This effect could be a sign that low-mass quenching mechanisms, such as environmental interactions, become less effective at these masses, making galaxies at $\log(M_*/M_\odot) < 9$ more abundant. At slightly higher masses ($\log(M_*/M_\odot) > 10$), merger-driven growth ensures that these galaxies are more abundant.

Also apparent is the lack of $t_{50} > 500$ Myr quiescent galaxies at low masses ($\log(M_*/M_\odot) < 9.5$). This is potentially a

consequence of our “flat” selection function: older galaxies that are bright in F444W only are likely to be missed. We estimate the mass completeness of $t_{50} > 100$ and > 500 Myr quiescent galaxies (brown shading in Fig. 4.1) by scaling the mass and detection (F277W+F356W+F444W) flux of these galaxies to low masses (assuming a constant mass-to-light ratio). At $\log(M_*/M_\odot) \sim 8.6$, we find our sample requirement of $S/N > 3$ only detects 50% of all $t_{50} > 500$ Myr quiescent galaxies. Taking instead the result at face value, one explanation is that low-mass, $t_{50} < 500$ Myr quenched galaxies are the progenitors of today’s dwarf ellipticals, which are roughly 8–12 Gyr old on average (e.g., Rakos et al. 2001; Jerjen et al. 2004), comparable to the range of lookback times from $1 < z < 3$. If this population began to form at these redshifts, it may explain why we do not yet see older, low-mass quiescent galaxies: the progenitor populations don’t exist at higher redshifts. Similarly, the mechanisms driving

low-mass galaxies to quench and become more massive may be rapidly moving quenched galaxies out of the low-mass, disk population and into the massive, spheroidal population on timescales < 500 Myr. For example, if environmental quenching dominates at low masses, perhaps those interactions are also coupled with more frequent mergers, which would rapidly increase the mass of galaxies and move them out of the low-mass population. Alternatively, the potential existence of so-called “mini-quenched galaxies” may explain why $t_{50} > 500$ Myr, low-mass quiescent galaxies are uncommon in our sample: they may be experiencing a temporary quenching event and thus rejuvenate before they reach advanced ages.

While the $30 < t_{50} < 100$ Myr quenched population in our sample appears to be quenched on at least 10 Myr timescales, we cannot rule out that these galaxies may be lower-redshift counterparts of the mini-quenched galaxies recently identified at high redshifts (Looser et al. 2023a; Strait et al. 2023), in which case they will likely resume star formation in the near future. Existing theoretical studies of $z > 4$, $\log(M_*/M_\odot) < 9$ galaxies predict that very bursty SFHs are needed to explain observations (Ma et al. 2018; Dome et al. 2023), but similar studies at lower redshifts do not exist. Moreover, stellar population modeling from broadband photometry alone is largely insufficient to resolve burst durations on time scales shorter than 100 Myr (e.g., Suess et al. 2022b; Wang et al. 2023c), whereas one would need < 40 Myr time scales in order to separate candidate mini-quenched galaxies from recently quenched galaxies (e.g., Dome et al. 2023). Spectroscopy of a sample of these recently quenched galaxies would offer more accurate SFH reconstruction on shorter timescales and allow us to identify observables that isolate mini-quenched galaxies from other low-mass galaxies.

Regardless of the specific processes involved, these results support the idea that low-mass quiescent galaxies differ dramatically from their higher mass counterparts. Below $\log(M_*/M_\odot) \sim 10.3$, quiescent galaxies have a median $R_e \sim 1.6$ kpc, irrespective of their stellar mass which unambiguously transitions to the steeper slope of the massive quiescent size-mass relation seen in previous studies (e.g., Mowla et al. 2019; Nedkova et al. 2021; Cutler et al. 2022). This shift in mass dependence is also accompanied by a dramatic change in the median Sérsic index and axis ratio distribution, indicating that this change is associated with galaxies shifting from disk to more elliptical morphologies. The separation of these populations around $\log(M_*/M_\odot) \sim 10.3$ may indicate that these distinct classes of quiescent galaxies are related to the overall dichotomy between high- and low-mass galaxy formation, as suggested by studies of mass functions, global star-formation rates and efficiencies, and halo-to-stellar mass ratios. In the future, probing environments around low-mass quiescent galaxies will be necessary

for robustly tying their quenching to environmental interactions as opposed to feedback. Moreover, spectroscopic follow up of potential mini-quenched candidates (low-mass, recently quenched galaxies with rapid changes in SFR), as well as theoretical predictions for this population at $z < 4$, is crucial in determining what causes low-mass galaxies to permanently quench as opposed to resuming cold gas accretion and future star formation.

ACKNOWLEDGEMENTS

This work is based in part on observations made with the NASA/ESA/CSA James Webb Space Telescope and the NASA/ESA Hubble Space Telescope obtained from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. The data were obtained from the Mikulski Archive for Space Telescopes at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-03127 for JWST. These observations are associated with programs JWST-GO-2561, JWST-ERS-1324, JWST-DD-2756. HST-GO-11689, HST-GO-13386, HST-GO/DD-13495, HST-GO-13389, HST-GO-15117, and HST-GO/DD-17231. KEW gratefully acknowledges funding from JWST-GO-2561 and the Alfred P. Sloan Foundation Grant FG-2019-12514. BW and JL acknowledge support from JWST-GO-02561.022-A. RP and DM acknowledge funding from JWST-GO-2561. PD acknowledges support from the NWO grant 016.VIDI.189.162 (“ODIN”) and from the European Commission’s and University of Groningen’s CO-FUND Rosalind Franklin program. JSD acknowledges the support of the Royal Society through a Royal Society Research Professorship. FC acknowledges support from a UKRI Frontier Research Guarantee Grant (grant reference EP/X021025/1). Support for this work was provided by The Brinson Foundation through a Brinson Prize Fellowship grant. KG and TN acknowledge support from Australian Research Council Laureate Fellowship FL180100060. Some of the data products presented herein were retrieved from the Dawn JWST Archive (DJA). DJA is an initiative of the Cosmic Dawn Center, which is funded by the Danish National Research Foundation under grant No. 140.

Facilities: JWST (NIRCam)

Software: ASTROPY (Astropy Collaboration et al. 2013, 2018, 2022), EAzY (Brammer et al. 2008) GRIZLI (Brammer 2023, github.com/gbrammer/grizli), GALFIT (Peng et al. 2002, 2010a), PROSPECTOR (Johnson et al. 2021), FSPS (Conroy et al. 2009, 2010; Conroy & Gunn 2010) PYTHON-FSPS Foreman-Mackey et al. (2014) APERPY (Weaver et al. 2023a, github.com/astrowhit/aperpy) SOURCE EXTRACTOR (Bertin & Arnouts 1996), SEP (Barbary 2016), EXTINCTION

(Barbary 2016), SFDMAP (Schlegel et al. 1998; Schlafly & Finkbeiner 2011, github.com/kbarbary/sfdmap), PYPER (Boucaud et al. 2016), PHOTUTILS (Bradley et al. 2022), AS-

TRODRIZZLE (Gonzaga et al. 2012), NUMPY (van der Walt et al. 2011), MATPLOTLIB (Hunter 2007)

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