Morphological Study of a Sample of Massive Quiescent Galaxies at z 1.2 (Postprint)

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Date: 2025-09-28T12:32:54+00:00

Abstract

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Full Text

Preamble

Research in Astronomy and Astrophysics, 25:085011 (9pp), 2025 August reserved. Printed in China. https://doi.org/10.1088/1674-4527/ade027 CSTR: 32081.14.RAA.ade027

Morphological Study of a Sample of Massive Quiescent Galaxies at z 1.2

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Received 2025 April 1; accepted 2025 May 1; published 2025 July 1

Abstract

We present the morphological study of 18,572 massive quiescent galaxies at z 1.2, selected by i − y colors in the Hyper Suprime-Cam (HSC) Deep and UltraDeep fields. The majority of our sample (94.3%) fall in the quiescent region in the rest-frame UVJ diagram. Comparing the five HSC bands and the subsample with HST F160W images, consistent with the decreasing effective radius re, Sérsic index n shows an increasing trend indicating a more bulge-dominant morphology towards the infrared. Even for our massive, quiescent galaxies, which are dominated by typical elliptical galaxies with bulges, the re and n values still vary with the wavelengths.

For instance, there is a systematic drop in n of 0.4 going from y band to F160W, making 20% of the HSC "disk-like"galaxies appear "bulge-like"in the HST images. We suggest to use caution when comparing galaxy morphological types based on images at different resolutions or at different wavelengths, and whenever possible, to apply a re or n correction. More massive quiescent galaxies are systematically larger than the less massive ones, though no mass dependence is found for n measurements. The size-mass relation based on our sample and lower-z control samples show a monotonic increase of re with M*, with a power-law of 0.61 ± 0.01, lower than previously found in similar samples of smaller sizes. Future high-resolution space-based surveys like NGRST will help confirm the possible n evolution, and if the flattening at the low-mass end is a genuine physical trend or limited by the image resolutions.

Key words: catalogs -galaxies: structure -galaxies: evolution

1. Introduction

The transformation of galaxy morphology is closely linked to their history of mass assembly and star formation activity. Observations have shown that galaxy bimodality exists in both color and morphology, with most bulge-like galaxies in the red sequence and disk or irregular galaxies in the blue cloud.

According to the bimodality scenario of galaxy evolution, a galaxy should evolve from the blue cloud, cross the green valley, and ultimately settle down in the red sequence (e.g., Strateva et al. 2001; Kauffmann et al. 2003a, 2003b; Baldry et al. 2004; Willmer et al. 2006). This scenario suggests that a morphological transformation must occur as a galaxy moves from the blue cloud to the red sequence. Additionally, elliptical galaxies in the red sequence, on average, have a larger stellar mass than a star-forming galaxy in the blue cloud.

A merging scenario has been proposed to explain both mass increase and morphological transformation (e.g., Faber et al. 2007). However, even the merging scenario includes multiple paths of galaxy evolution across the green valley. An analysis of galaxy morphology in the massive end of the red sequence could provide insight into how this transformation occurs (Shen et al. 2003; van der Wel et al. 2014).

The distribution of galaxy sizes is a direct measurement of their mass assembly history. Previous surveys have demonstrated that galaxy sizes are correlated with their masses over a wide range of redshifts, from $z = 0$ to $z = 3$ (e.g., van der Wel et al. 2014; Mowla et al. 2019; Kawinwanichakij et al. 2021).

This size-mass relation is likely a consequence of galaxy mass accretion or minor merging events. Galaxies with different morphologies exhibit different slopes in this relation. In particular, bulge galaxies display a much steeper slope than disk galaxies, which suggests that mass growth via accretion or minor merging is inefficient in bulge galaxies, even though their sizes can become significantly larger. Conversely, disk galaxies can experience substantial mass growth without requiring a commensurate increase in size. Previous studies have focused on the size-mass relations for disk galaxies in the blue cloud. However, there are also disk galaxies in the red sequence, such as S0 and Sa galaxies (e.g., McGrath et al. 2008; Stockton et al. 2008; van der Wel et al. 2011). The prevalence of red disk galaxies increases at higher redshifts, suggesting that the mass assembly process for galaxies in the red sequence may differ from that of their blue cloud counterparts, particularly for high-mass galaxies. Kawinwanichakij et al. (2021, hereafter K21) found there is a turning point at log(M*/M) 10.2-10.6, below which the quiescent galaxies have similar slope as star-forming galaxies.

To conduct a comprehensive study of galaxy properties, it is crucial to obtain samples with both spectral energy distribution (SED) identification and morphology classification. High angular resolution images, such as those obtained by the Hubble Space Telescope (HST) or the James Webb Space Telescope (JWST), are typically required for morphological studies of galaxies at z 1.

However, due to the limited coverage of these space telescopes, the number of massive galaxies in these surveys is relatively small (e.g., coverage less than 1 square degree, CANDELS: Koekemoer et al. 2011).

To obtain a large sample, data from ground-based telescopes are necessary. Most ground-based large galaxy samples have been classified using colors or SEDs to identify their types. Shen et al. (2003) use $u - r$ color to separate early-type galaxies (ETGs) from late-type galaxies (LTGs) with the Sloan Digital Sky Survey galaxy samples. K21 apply optical color $u - r$ versus $r - z$ to classify star-forming and quiescent galaxies at $z < 1$ with the Subaru Hyper Suprime-Cam (HSC) data. Recently, Xu et al. (2020) proposed a simple-color selection method to identify a large sample of massive red galaxies at $z \quad 1.2$ in the HSC deep fields. This selection method is designed for comparable matching with near-infrared (near-IR)/mid-infrared (mid-IR) surveys. The superb seeing conditions of the HSC data enable the study of the morphology of very massive galaxies in large optical surveys.

In this paper, we present a morphological study of a large sample of massive, quiescent (red) galaxies at $z \quad 1.2$, selected from the Subaru Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP). Section 2 provides an overview of our sample selection, while Section 3 describes our methodology for measuring galaxy morphology. Section 4 analyzes the morphological mix of our sample as a function of redshift. Our summary is presented in Section 5. Throughout this paper, the effective radii used in our work are based on circularized measurements, and all magnitudes are in the AB system. We also adopt cosmological parameters of $h \quad H0$ (km s-1 Mpc-1)/100 = 0.70, $\Omega\Lambda = 0.7$, and $\Omega M = 0.3$.

2. Sample Selection

Our massive quiescent samples were selected from the HSC-SSP Public Data Release 2 (PDR2; Aihara et al. 2019), whose Deep and UltraDeep layers cover a total area of 32 deg^2. The Deep and UltraDeep HSC-SSP data used in this study were taken from four fields: the Cosmological Evolution Survey (COSMOS; Scoville et al. 2007), the European Large-Area ISO Survey-North 1 (ELAIS-N1; Oliver et al. 2000), the XMM-Newton Large-Scale Structure (XMM-LSS; Pierre et al. 2004) survey and the Deep Extragalactic Evolutionary Probe 2 field 3 (DEEP2-3; Newman et al. 2013). We used the same method proposed by Xu et al. (2020, hereafter X20) to select massive quiescent galaxies at $z \quad 1.2$.

In brief, we choose the color ($i - y > 1.3$) corresponding to the 4000 Å break to select quiescent galaxies, and set a bright limiting magnitude ($y < 22.5$) to reject contamination from galaxies at high redshifts. The photometric redshift and stellar mass values were provided in the HSC-SSP archive by Nishizawa et al. (2020). However, we note that these photo-z values were estimated using only the HSC-SSP optical photometry (grizy), with a typical accuracy of $\delta z < 0.3$. M. Musin et al. (2025, preparation) compared the photo-z in the HSC-SSP sample before and after adding the near- and mid-IR photometry, and found that including the infrared (IR) photometry significantly reduces the number of photo-z outliers at intermediate redshifts. In addition, adding the IR photometry yields more accurate stellar masses for these galaxies.

Therefore, to ensure reliable redshift estimates, we only consider galaxies with Spitzer IRAC 3.6 m and 4.5 m coverage. We adopt the photo-z and stellar mass estimates from X20, which are briefly summarized below. The photo-z was calculated from the EAZY code (Brammer et al. 2008), and the stellar mass from the FAST code (Kriek et al. 2009), assuming BC03 templates (Bruzual & Charlot 2003) and a Chabrier (2003) initial mass function (IMF) and adopting a least chi square method. The SED consists of the five HSC grizy optical bands and two IRAC IR bands, 3.6 and 4.5 m. For more details please refer to X20. In addition, to focus on only the massive quiescent galaxies, in the following analysis we only include galaxies at log(M/*M) > 10 in our sample. This way we reach a final sample of 18,572 massive quiescent galaxies at z 1.2, with a median mass of logM*/M = 10.9, a typical error of 0.1 dex, and a standard deviation of 0.3 dex.

For comparison, we also constructed two control samples of similar sizes at z 0.4 and z 0.8, respectively, following similar logic (4000 Å break and bright limiting magnitude to reject high-z contamination). Table 1 lists the selection criteria for our main and control samples, and Figure 1 [Figure 1: see original paper] displays their redshift and stellar mass distributions. Our control samples have a comparable stellar mass distribution (10 < log(M*/M) < 12) with our main sample at z 1.2, and only differ in redshift.

The UVJ diagram is a commonly used color-color diagram to separate galaxy populations into different types (i.e., star-forming versus quiescent), based on the rest-frame U − V and V − J colors (e.g., Williams et al. 2009; Muzzin et al. 2013). Figure 2 [Figure 2: see original paper] shows our sample's distribution in the rest-frame UVJ diagram, confirming that our selection effectively (> 95%) selects massive quiescent galaxies at z 1.2. For comparison, the fraction of galaxies that falls in the quiescent regions in the rest-frame UVJ diagram for our control sample are 96.5% (z 0.4) and 98.2% (z 0.8), respectively. The small number statistics of galaxies outside the UVJ quiescent regions should not affect our statistical results in the following chapters.

To compare with the literature results, we further convert our re measurements to re at the rest-frame wavelength of 5000 Å (re,5000) using the following equation:

3. Morphology Measurement

We employed GALFIT, a software that utilizes parametric functions to model objects in digital images (Peng et al. 2002), to perform a single Sérsic profile fit on the surface brightness distribution of each galaxy. The fit was performed on the five HSC band stamp images for each galaxy (grizy, with a pixel scale of 0.168 pixel^{-1} and a typical seeing of 0.7-0.8) (Aihara et al. 2019). The point-spread function (PSF) for each object' s position was generated using the Subaru HSC PSF Picker.[4] We set the fitting ranges to be $0.1 < \mathrm{re} < 143$ pixels for the half-light radius (re), and $0.2 < n < 8$ for the Sérsic index (n).

Given that at different wavelengths, the galaxy' s brightness profile may differ, we check and compare the measured morphological parameters in the five HSC bands in Figures 3 and 4. In both figures, we see a clear trend between the measured re, n and the wavelengths, with re decreasing toward longer wavelengths (more concentrated), and n increasing toward longer wavelengths (more bulge-dominant). A larger re indicates a more diffuse distribution of a galaxy' s surface brightness, which naturally leads to a smaller n value. Despite this, the re and n values are more or less consistent within the five HSC bands. We further divide our sample into massive (logM$/M\ > 11$) *and less massive (10* $<$ *logM*/M < 11) bins. We find larger absolute re in more massive bins, but the overall trends are consistent in different mass bins and with the full sample. For n, there is effectively no significant difference between the massive and less massive bins, though a marginally increasing trend is found toward longer wavelengths.

Therefore, in the subsequent analysis, we employ the fitting results obtained in the y band (closest to the rest-frame 5000 Å for our z   1.2 sample). To compare measurements across different wavelengths, we apply a wavelength correction to re using the empirical relation:

re,5000 = re,obs × (λobs / 5000 Å)^(−0.25)

where re,obs represents the re at the observed wavelength. Here, λobs is the pivot wavelength λpivot of the observed wavelength band (Guo et al. 2011; Kelvin et al. 2012; van der Wel et al. 2014). The pivot wavelength λpivot is calculated using:

λpivot = √(λT(λ)dλ / T(λ)/λ dλ)

where T(λ) represents the filter transmission. The correction to re at 5000 Å is based on empirical relations for quiescent galaxies. For our main and control samples at z   1.2, z   0.8, and z   0.4, the λpivot values used are 9775.07 Å, 7727.01 Å, and 6218.44 Å, respectively.

In addition, for the control samples at $z < 1$, we also calculate the effective radii re,5000 using Equation (2), following the approach of K21, adopting the coefficients at logM*/M = 10.9 for quiescent galaxies at z = 0.2–0.4 and z = 0.6–0.8. We note that the estimated re values are consistent with the results from Equation (1) within 3σ.

3.1. Validations

In this section we utilize HST images from the CANDELS survey (Koekemoer et al. 2011) to verify our surface brightness distribution modeling, and to check if our lower resolution HSC images yield consistent results with the higher angular resolution HST images. We take advantage of a small fraction of our sample covered by the CANDELS survey, which includes 116 galaxies with surface brightness measurements from van der Wel et al. (2012), based on the F160W images (pixel scale = 0.13 pixel^{-1}). For a fair comparison, we convert the F160W re to re,5000 using Equation (1), which matches the definition used in our sample.

Figures 5 and 6 display the comparisons of the converted re and n values between the HSC and HST images. Note that n is not corrected and the comparison is between y and F160W band images. In general, after wavelength correction, re shows good consistency between the HSC and HST images, whose resolutions differ by a factor of 6. This agreement could be attributed to the similar procedure utilized to measure the re (GALFIT), and largely thanks to the re correction applied to convert them into the same band.

On the other hand, the comparison of measurements of the Sérsic index n between HST and HSC images shows large dispersions (Figure 6 [Figure 6: see original paper]). The standard deviation (σ) for the difference Δn = nHSC − nHST is 0.38 ± 0.99, implying significantly smaller n measured in the HSC y band than in the HST F160W. In some cases (orange and green dots in Figure 6), this discrepancy could result in different classifications of the galaxy type (i.e., bulge-like in HST and disk-like in HSC, or vice versa), assuming a separation at n = 2.0. Among all HSC disk-like massive quiescent galaxies (n < 2.0), about 71% are classified as bulge-like galaxies in the HST F160W image.

This discrepancy is likely caused by the lack of n correction between different wavelengths, unlike what was done for the re comparison. Although in Figure 4 [Figure 4: see original paper] we did not see a clear wavelength dependence on the n measurement, the range used is still limited, and smaller than the gap between F160W and y band. Despite the consistency in Figure 4, we did observe a marginal increasing trend of the n values toward longer wavelength. A linear fit yields nλ = (1.63 ± 0.58) × λobs + (2.42 ± 0.08) for our sample of massive quiescent galaxies. Given that near-IR bands are more sensitive to an older stellar population as compared to the optical or ultraviolet bands, it is not surprising that the HST F160W image yields higher n values for our sample of massive quiescent galaxies.

Among approximately 71% of the HSC n < 2 quiescent galaxies that are bulge-dominant (n > 2) in the HST images, almost all are located in the quiescent galaxy region of the rest-frame UVJ diagram (Figure 7 [Figure 7: see original paper], green dots). This suggests that the "conflicting" morphological types are more likely genuine quiescent galaxies, instead of being dusty star-forming galaxies, which would otherwise be located along or below the boundary in the UVJ diagram. Compared to the HSC optical images, since our sample is dominated by massive quiescent galaxies, we consider the measurement based on HST F160W images as being more representative of the stellar population.

On the other hand, only 3% of HSC n > 2 galaxies are switched to "disk-like"

($n < 2$) in the HST images. All of them are well inside the "quiescent" region in the UVJ diagram (Figure 7, orange dots). We check the stamp images of these few galaxies (six in total), and find that three hit the fitting lower limits of re in van der Wel et al. (2012), which suggest a very compact morphology. Two of the remaining six have n 1.97, extremely close to the separation line at $n = 2$, while the last one is a relatively faint source at n 1.5. The percentage is small and would not change the statistical properties of the final sample.

Overall, by converting and comparing morphological parameters measured in HSC and HST images, we find that the effective radius (re) is consistent with different measurements, after correcting for the rest-frame 5000 Å wavelength. The majority of our sample of massive quiescent galaxies can be identified as bulge-like galaxies: 77.4% with $n > 2$ in both wavelengths, or 91% with $n > 2$ in either wavelength. We note that the Sérsic index (n) could be systematically smaller in the optical HSC bands than from the near-IR HST bands, suggesting an increasing bulge-dominance toward longer wavelengths.

4. Size-Mass Relation for Massive Quiescent Galaxies

In Figure 8 [Figure 8: see original paper], we present the size-mass evolution as a function of stellar mass for our massive quiescent galaxies, both in the main sample at z 1.2 and in the control samples at z 0.4 and 0.8. Note that our re values are corrected to the rest-frame of 5000 Å. Given the large sizes of our sample (18k-19k per redshift bin), in Figure 8 we only show the density contour and the mean (orange) and median (blue) values. We then follow the method presented in Shen et al. (2003) to derive the size-mass relation as follows:

$$\mathrm{re} = \mathrm{A} \times (\mathrm{M}^*/5 \times 10^{10}\ \mathrm{M}\ )\hat{}\alpha$$

where M* $\mathrm{M}^*/5 \times 10^{10}$ M . This function represents a linear fit relation in the log-log space with an intercept of log(A) and a slope of α. We list the fitting results in Table 2 .

At similar M*, massive quiescent galaxies show comparable slopes of the size-mass relations, though the intercept (i.e., base re) decreases toward higher redshift. This is also reflected in Figure 8, where the median values of re (red crosses) increase toward lower redshift, while the median M* does not see a significant change. This indicates that galaxy quenching may have happened before the size growth (e.g., Cassata et al. 2011). Upcoming large statistical samples that cover near-IR photometry like the Nancy Grace Roman Space Telescope (NGRST, previously WFIRST) would help us confirm if the morphological evolution is prevalent and can explain the size differences of massive quiescent galaxies at different redshifts.

Despite the different selection criteria, i.e. color-magnitude selection in the HSC-SSP Deep/UltraDeep regions versus UVJ-selected quiescent galaxies in HST CANDELS, our fitting results show a general consistency with the W14 results (α 0.6-0.7) at $z < 1.0$, which was based on smaller samples of ETGs at similar redshifts. As affirmed in Figure 2, our color-magnitude selection is effective in selecting UVJ quiescent galaxies (90% consistency). Therefore, it is not surprising to see comparable slopes and intercepts. However, at z 1.2, our slope of 0.61 is significantly ($>3\sigma$) flatter than previously found in CANDELS. We suspect this is due to our selection of a magnitude cut to select only massive galaxies ($>10^{10}$ M), which leaves out the possible population of lower mass, compact quiescent galaxies. Inclusion of the fainter, compact quiescent galaxies could steepen the observed slope.

In some references (e.g., K21), a double power-law provides better fits, with a pivot stellar mass at log(M*/M) 10.2–10.6 at $z < 1$. Above the pivot stellar mass, the slope for quiescent galaxies significantly steepens from 0.1 to 0.6–0.7. In contrast, a single power-law would provide a flatter slope of only α 0.3–0.4. This is likely due to the different completeness of the two samples. At $z < 1$, K21 has an i band magnitude cut at 24.5, two magnitudes deeper than our control samples, and a mass cut at 10^9 M , one order of magnitude lower as well. Inclusion of less massive, quiescent galaxies without better image resolution would naturally result in a flatter slope at the low-mass end of the size-mass relation. Although K21 stops at $z < 1.0$, their trend is actually consistent with our findings of a flatter slope at the lower-mass end for our main sample at z 1.2. Future high-resolution space-based surveys like NGRST are needed to confirm if the flattening at the low-mass end is a genuine physical trend or limited by the image resolutions.

5. Summary

We measure the morphological parameters effective radius re and Sérsic index n for a sample of 18,572 color-magnitude selected massive quiescent galaxies at z 1.2 in the HSC-SSP Deep and UltraDeep fields. The majority of our color-selected quiescent galaxies also fall in the quiescent region in the rest-frame UVJ diagram, confirming their passive nature.

We then compare the re measured at different HSC bands (grizy) and for a subsample with HST coverage, the HST F160W band. We find that regardless of stellar mass, the re decreases as the wavelength increases, confirming their bulge-dominant nature. This also alerts us about the use of absolute re values, which should be converted to a standard wavelength (e.g., rest-frame 5000 Å) before making a fair comparison. At similar wavelengths, the re values for massive galaxies are systematically larger than the less massive ones, as expected from their monotonic size-mass relation.

For the Sérsic index n evolution, however, there is yet no conversion between different bands or for different mass bins. In the subsamples with both HST and HSC coverage, we find a common jump from disk-like ($n < 2$) to bulge-like ($n > 2$) galaxies adopting n from near-IR images. This again confirms the bulge-dominant nature of massive, quiescent galaxies. We suggest to use caution when comparing galaxy morphological types based on images at different resolutions or at different (rest-frame) wavelengths, and whenever possible, to apply an n correction if necessary. Future high-resolution space-based surveys like NGRST will be needed to confirm the n evolution along wavelength and across various redshifts.

In general, the size-mass relation based on our statistical main sample (z 1.2) and lower-z control samples show a monotonic increase of re with M*. A single power-law fit yields a slope of 0.61 ± 0.01 for our z 1.2 main sample, $>3\sigma$ lower than previously found in van der Wel et al. (2014, W14) for a smaller sample of UVJ selected quiescent galaxies. For our control samples at lower z, the size-mass relation agrees well with the W14 results, but are steeper than the single power law slope reported in Kawinwanichakij et al. (2021), which includes more fainter and less massive objects of similar image qualities. Future high-resolution space-based surveys like NGRST will help confirm if the flattening at the low-mass end is a genuine physical trend or limited by the image resolutions.

Acknowledgments

We thank the anonymous referee for their comments that helped improve the presentation of the paper. We are grateful to Piaoran Liang for assisting with grammar and vocabulary corrections. This work is sponsored by the National Key R&D Program of China (MOST) with grant No. 2022YFA1605300, and the National Natural Science Foundation of China (NSFC, grant Nos. 12273051 and 11933003). Support for this work is also partly provided by the Chinese Academy of Sciences (CAS) through a grant to the South America Center for Astronomy (CASSACA). This work is based in part on data collected at the Subaru Telescope and retrieved from the HSC data archive system, which is operated by the Subaru Telescope and Astronomy Data Center at National Astronomical Observatory of Japan. This work is based in part on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

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