Galaxy Sizes Since $z = 2$ from the Perspective of Stellar Mass Distribution within Galaxies

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Received 2020 August 13; revised 2020 October 31; accepted 2020 November 3; published 2020 December 28

Abstract

How stellar mass assembles within galaxies is still an open question. We present measurements of the stellar mass distribution on kiloparsec-scales for $\sim 5500$ galaxies with stellar masses above $\log(M_*/M_*) \geq 9.8$ up to redshift 2.0. We create stellar mass maps from Hubble Space Telescope observations by means of the pixel-by-pixel spectral energy distribution fitting method. These maps are used to derive radii encompassing 20%, 50%, and 80% ($r_{20}$, $r_{50}$, and $r_{80}$) of the total stellar mass from the best-fit Sérsic models. The reliability and limitations of the structural parameter measurements are checked extensively using a large sample ($\sim 3000$) of simulated galaxies. The size–mass relations and redshift evolution of $r_{20}$, $r_{50}$, and $r_{80}$ are explored for star-forming and quiescent galaxies. At fixed mass, the star-forming galaxies do not show significant changes in their $r_{20}$, $r_{50}$, and $r_{80}$ sizes, indicating similar growth. Only above the pivot stellar mass of $\log(M_*/M_*) \approx 10.5$ does $r_{80}$ evolve as $r_{80} \propto (1 + z)^{-0.85 \pm 0.20}$, indicating that mass builds up in the outskirts of these systems (inside-out growth). The Sérsic values also increase for the massive star-forming galaxies toward late cosmic time. Massive quiescent galaxies show stronger size evolution at all radii, in particular, the $r_{20}$ sizes. For these massive galaxies, Sérsic values remain almost constant since at least $z \sim 1.3$, indicating that the strong size evolution is related to the changes in the outer parts of these galaxies. We make all the structural parameters publicly available.

Unified Astronomy Thesaurus concepts: Galaxy structure (622); Galaxy evolution (594); Galaxy mass distribution (606); Galaxy radii (617)

Supporting material: machine-readable table

1. Introduction

An open challenge in galaxy evolution is understanding how stellar mass assembles within galaxies. The stellar mass distribution of a galaxy contains a wealth of information on its past evolution and is thought to be able to constrain physical processes that operate on spatially resolved scales. In this paper, we present detailed measurements of the stellar mass distribution on the kiloparsec (kpc) scale for a large sample of galaxies over the past 10 billion years (since redshift $z \approx 2$), focusing specifically on the evolution of galaxy sizes.

A wide range of physical mechanisms is thought to shape both star-forming and quiescent galaxies. While galaxies are forming stars, the gas and the resulting star formation distribution mostly drive the mass growth. This is particularly the case at early cosmic times, when the star formation rates (SFRs) are high relative to the stellar masses ($M_*$), i.e., for galaxies with high specific SFRs (sSFR). A variety of processes can lead to rapid gas inflow into the central region (summarily called “gas compaction”; Dekel & Burkert 2014; Zołotov et al. 2015; Tacchella et al. 2016a), including disk instabilities, mergers, and migration of gas clumps (Hernquist 1989; Noguchi 1999; Dekel et al. 2009; Bournaud et al. 2011; Sales et al. 2012; Wellons et al. 2015). At later cosmic times, when gas fractions and sSFRs are lower, secular processes related to spiral arms and bars (including stellar migration) may contribute to the spatially resolved stellar mass growth (see, e.g., the review by Kormendy & Kennicutt 2004). When galaxies are quiescent, gas-poor mergers and perturbations such as tidal interactions from neighboring galaxies are important in adding and redistributing stellar mass (Naab et al. 2009; Bekki & Couch 2011; Oser et al. 2012).

Different physical mechanisms have distinct imprints on the mass distribution and, hence, the morphological indicators. For example, gas-poor minor mergers preferentially lead to mass growth in the outskirts, leading to an increase in the half-mass radius $r_{50}$ (Bezanson et al. 2009; Naab et al. 2009). On the other hand, gas compaction leads to mass growth in the center, decreasing $r_{50}$ and increasing the stellar mass density within the central kpc ($\Sigma_1$; Bournaud et al. 2007; Elmegreen et al. 2008; Dekel et al. 2009; Tacchella et al. 2016a). These and other processes lead to the large diversity of galaxies today with a structural dichotomy between star-forming and quiescent galaxies: star-forming galaxies are larger, whereas quiescent galaxies have a more prominent bulge component (Cheung et al. 2012; Fang et al. 2013; Bluck et al. 2014; Huertas-Company et al. 2016; Whitaker et al. 2017). Nevertheless, it is not clear how much (or if any at all) morphological transformation takes place when galaxies cease their star formation (Tacchella et al. 2019): the present-day quiescent galaxies were star-forming galaxies in the past when gas fractions were much higher (relative to present-day star-forming galaxies), leading to a higher efficiency of bulge formation.

To better understand and constrain the physical processes involving the total mass growth and mass (re-)distribution within galaxies, it is essential to study their stellar mass profiles. Normally, difficulties in estimating the mass profiles lead to the use of light profiles in most studies. However, it is known that the age, dust, and metallicity of the underlying stellar populations and the star formation history (SFH) within galaxies vary from the central regions to the outskirts and therefore cause mass-to-light ratio ($M/L$) variations (or gradients) as a function of radius (e.g., Franx et al. 1989; Peletier et al. 1990; La Barbera et al. 2005). The
consequence of this is the wavelength dependence of the structural parameters (Kennedy et al. 2015) and introduction of differences between morphological parameters obtained from the light and stellar mass distributions (Fang et al. 2013; Szomoru et al. 2013; Tacchella et al. 2015b). Comparing observed mass profiles with simulations is also more straightforward than a comparison with the light profiles. Mass profiles are therefore better suited and robust for imposing constraints on the physical processes and comparisons.

How do we derive the stellar mass distribution within galaxies? Deriving two-dimensional (2D) stellar mass maps from integral field unit (IFU) spectroscopy is favorable (Bacon et al. 2001). However, IFU data for a large sample of galaxies (in particular at high redshifts) is still expensive (Bacon et al. 2017). The sensitivity of this technique to the bright regions also limits observation to the central regions within galaxies, even if samples were large (Croom et al. 2012; Sánchez et al. 2012; Bundy et al. 2015). A simple solution to this is to make use of photometric multiwavelength observations.

Different approaches have been adopted by authors to convert multiwavelength observations to 2D stellar mass maps and 1D stellar mass profiles. In the majority of these studies, the stellar mass profiles are obtained from 1D light profiles (observed or point-spread function; PSF corrected). These light-based profiles are then converted into mass profiles either with a constant or a radially varying \( M/L \) correction, where the latter usually assumes a simple color-\( M/L \) relation or is based on spectral energy distribution (SED) fitting (van Dokkum et al. 2010; Fang et al. 2013; Patel et al. 2013; Szomoru et al. 2013; Morishita et al. 2015; Tacchella et al. 2015a; Barro et al. 2017; Mosleh et al. 2017, 2018; Suess et al. 2019a). The second approach for deriving stellar mass profiles is to build 2D stellar mass maps by means of pixel-by-pixel SED fitting technique. This technique was first introduced by Abraham et al. (1999) and Conti et al. (2003) and has been used for several purposes, including SFR profiles, color gradients, and testing total stellar masses, galaxy mergers, etc. (Lanyon-Foster et al. 2007, 2012; Zibetti et al. 2009; Hemmati et al. 2014; Cibinel et al. 2015, 2019; Sorba & Sawicki 2015; Abdurro’uf & Akiyama 2018). The structural analysis (parametric and nonparametric) based on the 2D stellar mass maps are studied by Wuyts et al. (2012), Lang et al. (2014), Cibinel et al. (2015), Chan et al. (2016), and Morselli et al. (2019).

In addition to these two different approaches, technical details within these approaches are diverse in the literature as well. In particular, the reliability of these methods over the range of stellar masses and redshifts is not fully examined. In addition to these issues, the number of published catalogs on the structural parameters based on the stellar mass profiles are sparse. Recently, Morselli et al. (2019) published a catalog for a limited (~700) sample of sources within 0.2 < \( z < 1.2 \), and Suess et al. (2019a) presented measurements of Sérsic parameters (half-mass radii and \( n \)) for a sample of ~7000 galaxies at 1.0 < \( z < 2.5 \) with stellar masses of 9.0 ≤ \( \log(M_\text{*/M}_\odot) \) ≤ 11.5 for three high-redshift CANDELS fields. Hence, consistent measurements of the stellar mass-based sizes at 0.3 ≤ \( z \leq 2.0 \) for all CANDELS fields are required. Moreover, adopting a simple method to avoid many prior assumptions about the shape of light or \( M/L \) profiles (Mosleh et al. 2017; Suess et al. 2019a) for estimating the stellar mass density profiles can help to understand uncertainties in the final results.

Therefore we here create stellar mass maps for a large sample (~5500) of galaxies with \( \log(M_\text{*/M}_\odot) \geq 9.8 \) at \( z \leq 2 \) to cover a wider range in redshift and stellar mass, as described in Section 3. The structural parameters (sizes containing 20%, 50%, and 80% of the stellar mass—\( r_{20}, r_{50}, \text{ and } r_{80} \)) are then estimated based on the 1D and 2D stellar mass distributions (Section 4 and Appendix A). We extensively test our method using a large sample of mock galaxies (see Appendix B). We present the size—mass relations (\( r_{20}, r_{50}, r_{80}—\text{stellar mass} \)) for star-forming and quiescent galaxies in Section 5. The final results and their interpretations are discussed in Section 6. For a consistency with recent works, we choose the following cosmological parameters throughout this paper: \( \Omega_m = 0.3, \Omega_{\Lambda} = 0.7, \text{ and } H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}. \)

2. Data and Sample

The sample of galaxies used for this study is based on the publicly available catalogs and imaging data of the 3D Hubble Space Telescope (HST) Treasury Program (Brammer et al. 2012; Skelton et al. 2014) and the Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011). We make use of all five fields (GOODS-South, GOODS-North, COSMOS, UDS, and AEGIS). The total area of these fields is about 900 arcmin\(^2\). Using different fields helps to mitigate cosmic variance effects. The photometry of the sources from all 3D-HST observations and all publicly available data over a wide range of wavelengths (0.3–8 \( \mu m \)) are provided in the catalogs. Using these ancillary data, the stellar masses and photometric redshifts (if no spectroscopic or grism redshift is available) are determined with the FAST (Kriek et al. 2009) and EAZY (Brammer et al. 2008) codes, respectively.

For this study, the PSF-matched mosaic images of these fields, available on the 3D-HST website,\(^4\) are used. These mosaics are available in seven filters (\( B_{435}, V_{606}, r_{775}, z_{850}, J_{125}, H_{140}, \text{ and } H_{160} \)) for GOODS-South and GOODS-North and in five filters (\( V_{606}, R_{814}, J_{125}, H_{140}, \text{ and } H_{160} \)) for COSMOS, UDS, and AEGIS.

For our analysis, we select galaxies with the following criteria:

1. use \texttt{phot} = 1 and flags ≤ 2 (photometric quality and unblended flags in the 3D-HST catalog);
2. \( \log(M_\text{*/M}_\odot) \geq 9.8 \);
3. \( z \leq 2 \) for sources in GOODS-South and GOODS-North;
4. \( z \leq 1.3 \) for COSMOS, UDS, and AEGIS.

The reasons for the chosen stellar mass and redshift ranges are given in the following sections. Briefly, these cuts are based on our simulations (Appendix B) that the results (i.e., the half-mass size measurements) presented in this work are less reliable at \( z > 1.3 \) (\( z > 2.0 \)) and \( \log(M_\text{*/M}_\odot) < 9.8 \) for COSMOS, UDS, and AEGIS (GOODS-South and GOODS-North). With the above criteria, the total number of all selected objects in all CANDELS fields is 5557. However, the stellar masses are more reliable for those that have sufficient wavelength coverage; hence, we imposed an additional constraint for being detected in at least three HST filters. The cost of these constraints is that about 10% of the sources are excluded, which mainly lie in COSMOS and UDS. In addition, we fail to determine the stellar mass maps in ~2% of the sample, usually due to their proximity to the edges of the mosaic images or contamination of very bright stars. This leaves us with a final sample of 4887 galaxies.

\(^4\) http://3dhst.research.yale.edu/Home.html
The histograms in Figure 1 show the distributions of the stellar masses and redshifts (left and middle panels, respectively) for objects in this study. As shown in the histograms of Figure 2, excluding sources with a less sufficient number of filters does not affect the general stellar mass and redshift distributions of the sample. The right panel of Figure 1 also illustrates the distribution of the stellar mass of the sample as a function of redshift. This shows that the sample is complete down to a redshift of ~0.3. Hence, for the results of this paper, we set this redshift as our lower limit.

The star-forming and quiescent galaxies in our sample are selected based on their location in the UVJ color–color diagram (Williams et al. 2009). We use the same criteria as given by Equations (1) to (3) in Mosleh et al. (2017) to separate galaxies on the $U - V$ versus $V - J$ rest-frame color diagrams. Our sample consists of 3524 and 1363 star-forming and quiescent galaxies, respectively.

3. Creating Resolved Mass Maps

3.1. 2D Stellar Mass Maps

We create spatially resolved stellar mass maps by SED fitting each individual pixel (pixel-by-pixel method). We use the PSF-matched mosaic images to identify the same physical region of each galaxy in different filters. For each galaxy, we create postage stamps of $48'' \times 48''$. The segmentation (mask) maps of galaxies, provided by the 3D-HST team, are used to select the pixels that belong to each object. Fluxes of each pixel in all available filters are extracted separately, and their associated flux errors are determined using the empty aperture method (Skelton et al. 2014) of the noise-equalized regions around each object.

The resolved stellar mass maps are derived by finding the best-fit SED model for each pixel. We use iSEDfit, a Bayesian code (Moustakas et al. 2013), to perform the SED fitting. The full grid of 100,000 models is created based on the Bruzual & Charlot (2003) stellar population evolution models with ages between 0.1 and 13.5 Gyr. The star formation history for these models is assumed to be exponentially declining ($\text{SFR} \propto \exp(-t/\tau)$, with an e-folding timescale $\tau$ between 0.01 and 1.0 Gyr) and the Chabrier (2003) initial mass function (IMF) is adopted. We set the metallicity range to 0.004–0.03 and assume the Calzetti et al. (2000) dust attenuation law. For each object, the redshift of all pixels is set to the redshift of the galaxies from the 3D-HST catalog. In Figure 3, color images and the corresponding stellar mass maps of a few example galaxies are shown. The stellar mass maps are relatively smooth compared to the observed images due to the contribution of the old stellar population to the total stellar mass, consistent with earlier findings (Wuyts et al. 2012; Lang et al. 2014; Sorba & Sawicki 2015; Tacchella et al. 2015b). We should note that to reduce the effects of mass loss, the stellar

5 There are some scientific questions, in particular related to the evolution of quiescent galaxies, where it is more useful to adopt the integral of the SFH as the stellar mass because with this definition, the stellar mass of a quiescent galaxy remains constant with time; see Carollo et al. (2013), Fagioli et al. (2016), and Tacchella et al. (2017).
Figure 3. The color ($UJH$) images and the estimated stellar mass maps of a few example galaxies from different fields are shown. The stellar mass maps are derived using the pixel-by-pixel SED fitting method (Section 3). The stellar mass maps are relatively smooth for different types of galaxies. The ID, redshift ($z$), and stellar mass of these galaxies are from the 3D-HST catalog.
mass maps in this study are based on the total masses that are derived from the integrated SFH.

### 3.2. Robustness of the stellar masses

It is important to verify the robustness the stellar mass maps. For this purpose, we first quantify the differences of the total stellar masses from the pixel-by-pixel method and SED fitting of the total fluxes of all pixels. We compare the stellar mass obtained from the integrated photometry (unresolved) and the total stellar mass by summing individual pixels from the mass map (resolved) in Figure 4. For the redshift range of $z < 1.3$ (left panel), the median differences between unresolved and resolved stellar masses for all fields is $\sim 0.06$ dex. The discrepancy increases to $\sim 0.17$ dex for the redshift range of $1.3 < z < 2$ (right panel). This means that the total stellar masses obtained from the integrated photometry of the galaxies (unresolved) are on average less than the resolved total stellar masses from the pixel-by-pixel analysis. This does not depend on the field or the number of filters used. The difference at $z < 1.3$ might be negligible, although at higher redshifts, this difference is more significant. This discrepancy is within the order of the uncertainties of the stellar mass estimates due to the stellar population modeling (Conroy et al. 2009), but the systematic needs to be better understood.

The origin of this difference is still unclear (see, e.g., Zibetti et al. 2009; Sorba & Sawicki 2015; Martínez-García et al. 2017) and is not reported in some studies (e.g., Wuyts et al. 2012). In a recent study, Sorba & Sawicki (2018) argued that this effect depends on the sSFR of galaxies and is caused by the outshining effect on the SED of galaxies, i.e., the contribution of the young massive stars with lower $M/L$ to the total flux of galaxies (Papovich et al. 2001; Maraston et al. 2010). We used the combined UV+IR SFR from the analysis by Whitaker et al. (2014) to test this in Figure 5 for the two redshift ranges and could not see any considerable trend with sSFR for any of these redshift ranges. An almost constant systematic offset exists at all sSFRs in the redshift bin of $1.3 < z < 2$. We should also note that the available HST filters do not cover the rest-frame near-infrared (NIR) wavelength ranges ($\gtrsim 7000$ Å) of the sources beyond redshift of $\approx 1.3$. Many studies emphasized that the NIR SED of galaxies is crucial for determining their robust stellar masses (see, e.g., Maraston et al. 2006; Ilbert et al. 2010), but as shown in Appendix B, this issue mainly increases the uncertainties but does not introduce a significant systematics in this redshift range.

It is worth noting that the assumption of the SFH model might also contribute to this effect (see the recent work by Lower et al. 2020). In this work, the best-fit timescale ($\tau$) varies for each pixel, and hence differs from a single value for the entire galaxy, which can mimic more complex SFHs. As shown in Lower et al. (2020), simplistic (delayed) $\tau$ models underpredict the total stellar mass. Therefore this might contribute to this systematic offset. However, testing this is beyond the scope of this paper.

At fixed stellar mass, comparing the stellar mass density error profiles for different redshift bins shows that uncertainties in the stellar mass estimates increase toward higher redshifts and toward larger radius (see Figure 6). In general, the stellar mass maps for sources beyond $z > 1.3$ might suffer from some
uncertainties due to a combination of different effects such as less coverage of their SEDs, outshining effects, variation in the SFH across the galaxy or a lower signal-to-noise ratio, less coverage of their SEDs, outshining effects, variation in the uncertainties due to a combination of different effects such as Figure 6.

The Astrophysical Journal, roughly 10% in the outskirts.

uncertainties of the stellar mass pro

determined from the mass maps as described above for these galaxies, this method is able to recover the true shape of the mass profiles of these galaxies.

For this purpose, we follow the method used by Maltby et al. (2018). First, the stellar mass surface density profiles are measured using elliptical isophote (isomass for our case) fitting on the 2D stellar mass maps by means of the IRAF task ELLIPSE (Jedrzejewski 1987). This provides 1D stellar mass surface density profiles as a function of radius. The fitting was performed for each galaxy by fixing the same center for all ellipses and assuming ellipticity (e) and position angle (PA) as free parameters. The profiles are then circularized at each radius using $a\sqrt{1-e}$, in which $a$ is the semimajor axis.

The next step is to build a library of Sérsic models to find the best-fitting ones. To this end, we first generate a table of 29,400 Sérsic models over the size ($r_{50}$)-Sérsic ($n$) parameter space (0.7006 $\leq r_{50}$ $\leq$ 1.58 and 0.3 $\leq n$ $\leq$ 10), using steps of 0.1 for each parameter. The $e$ and PA are assumed to be zero for the models. We then use GALFIT to create 2D model images convolved with the $H_{160}$-band PSFs. To ensure that any field-to-field PSF variation does not affect the results, the models are created for each CANDELS field separately. The 1D density profiles of the models are then determined by fitting ellipses to these 2D galaxy models (fixing the center, PA, and $e$ parameters). This grid of profile models are afterward used to determine the best-fit 1D model. This is done by comparing the normalized 1D mass density profiles of galaxies with all normalized model profiles in the library and finding the minimum $\chi^2$ value. To reduce the uncertainties from the outer regions and the background, the fitting is performed down to a stellar mass surface density of $\Sigma = 10^7 M_\odot \, \text{kpc}^{-2}$. This also ensures that the models catch the main part of the profiles. Our tests show that changing this surface mass density limit does not affect our results. The errors of the parameters are estimated by perturbing the galaxies’ mass profiles within their uncertainties for 100 realizations, and finding their best-fit models. The 1$\sigma$ scatter of the values is then used to estimate their errors.

The blue lines in Figure 7 are the surface stellar mass density profile determined from the mass maps as described above for the same sample of galaxies as shown in Figure 2. The best-fit models for these galaxies are illustrated as orange lines. The gray dashed lines depict the surface density limit of $10^7 M_\odot \, \text{kpc}^{-2}$. The residuals are also shown as blue lines at the bottom of each panel. Despite some noisy features in the outer regions of the stellar mass profiles, this method is able to recover the true shape of the mass profiles of these galaxies.

4. Stellar Mass Structural Parameters

For this study, we use two methods to derive the stellar mass-weighted structural parameters by finding their best-fit Sérsic models (Sérsic 1963). These methods are based on 1D and 2D profile-fitting approaches. As discussed in Appendix A, both methods give consistent results. However, because our 1D method is relatively more robust than the 2D method, we choose this as our fiducial method for the remainder of this paper. We describe this 1D method in detail in this section. The second method and the reliability of these two methods is fully described in Appendices A and B. The key results adopting the second method are presented in Appendix C. The structural parameters from both methods are presented in Table 6 in Appendix C.

4.1. 1D Profile-fitting Method ($M_1$)

In this procedure, we find the best-fit Sérsic models from their 1D stellar mass profiles. The main motivation for using this method is to reduce the effect of uncertainties in the stellar mass maps in the outskirts. Smoothing the stellar mass maps and increasing their S/N by means of smoothing methods such as ADAPTSMOOTH (Zibetti et al. 2009) or the Voronoi binning method (Cappellari & Copin 2003) prior to the SED fitting can introduce biases on the Sérsic parameters and can create large fluctuations (steps) in their mass maps. Converting into the 1D profiles has the advantage of reducing the uncertainties introduced in the 2D method, while preserving the general shape of profiles. In addition, as described below, the procedure of finding the best-fit models for 1D profiles benefits from the evaluation of all models over a wide range of the parameter space. Therefore, this will give us a better constraint on the model parameters. In summary, this method allows us to estimate the sizes robustly.

![Figure 6. Median stacked relative errors of the stellar mass density profiles as a function of radius for different stellar masses and redshift ranges. At fixed mass, the uncertainties of the stellar mass profiles increase toward the outskirts and toward higher redshifts. Typical relative errors are of about 1% in the central region and roughly 10% in the outskirts.](image-url)
Figure 7. Results from the first method to determine the best-fit 1D Sérsic models (orange lines) from the 1D stellar mass density profiles (blue lines) for the objects in Figure 3. The residuals are shown at the bottom of each panel. For this technique, a surface brightness limit of $\Sigma = 10^7 M_\odot$ kpc$^{-2}$ is assumed during the fit. This approach helps to reduce the effect of uncertainties of the stellar mass estimates from the pixel-by-pixel SED method, in particular in the outer parts, and to evaluate all models in a wide range of the $n - r_{50}$ parameter space.
This approach and its reliability are tested with simulated objects in Appendix B. The average recovery rates of reliable size measurements are 96.4% and 91.1% for the low- ($z < 1.3$) and high-redshift ($z > 1.3$) bin, respectively. The majority of this loss is due to galaxies with stellar masses below $\log(M_*/M_*) \sim 10.5$. This mainly affects the size–mass relation of low-mass galaxies at $z > 1$.

4.2. Measuring Sizes: $r_{20}$, $r_{50}$, and $r_{80}$

We use the half-mass radii ($r_{50}$) and Sérsic ($n$) values obtained from the best-fit models to find the radius of galaxies containing 20% and 80% of their total stellar mass ($r_{20}$ and $r_{80}$, respectively). We use Equation (3) of Miller et al. (2019) to convert $r_{50}$ and $n$ into $r_{20}$ and $r_{80}$ as

$$
\frac{r_{20}}{r_{50}}(n) = -0.0008n^3 + 0.0178n^2 - 0.1471n + 0.6294 
$$

$$
\frac{r_{80}}{r_{50}}(n) = 0.0012n^3 - 0.0123n^2 + 0.5092n + 1.2646.
$$

Finally, we note that based on the results from our simulations (Appendix B, the Sérsic indices from the 1D method are underestimated for average values of 12% and 16% in low- and high-redshift bins ($z < 1.3$ and $z > 1.3$), respectively. Therefore, the Sérsic values are corrected to estimate the $r_{20}$ and $r_{80}$.

5. Results

As mentioned in the Introduction, the stellar mass assembly history of galaxies can be traced by the morphological properties such as size and concentration. In this section, we use the measured mass-weighted sizes and concentrations from the stellar mass surface density profiles to explore these quantities for different types of galaxies and their dependence on redshift. First, we quantify and compare the size–mass relation of star-forming and quiescent galaxies. Following this, we measure the size evolution as a function of cosmic time at fixed stellar mass. Finally, we show results on the scatter of the size–mass relation and the Sérsic index.

5.1. Size–Mass Relation

We present the size–mass relation at different cosmic epochs for star-forming and quiescent galaxies in Figure 8. This relation has been explored extensively using light profiles up to high redshifts in many studies (e.g., Mosleh et al. 2012; van der Wel et al. 2014; Holwerda et al. 2015; Allen et al. 2017; Damjanov et al. 2019; Miller et al. 2019; Whitney et al. 2019; Andreon 2020). Mosleh et al. (2017) studied the half-mass size evolution of galaxies at fixed mass based on the 1D stellar mass profiles for the GOODS-North and GOODS-South fields, and Suess et al. (2019a) presented the half-mass size–mass relation for galaxies at $1.0 < z < 2.5$. In this work, we expand this to the different measures of mass-based sizes and study their evolution from $z = 0.3$ to 2.0. This helps to explore how the stellar mass has been assembled in the inner and outer parts of the star-forming and quiescent galaxies over the last 10 Gyr.

In Figure 8 we examine the size–mass relation for the mass-based $r_{50}$ (top panels), $r_{80}$ (middle panels), and $r_{80}$ (bottom panels) sizes, which include 20%, 50%, and 80% of the total stellar mass, respectively. Panels from left to right show bins of increasing redshift. The individual galaxies are shown as blue (star-forming galaxies) and red (quiescent galaxies) points. The large blue and red circles present the median values of sizes as a function of stellar mass for star-forming and quiescent galaxies, respectively. The error bars are the 1σ scatter in each bin. We use a broken power-law relation from Equation (2) of Mowla et al. (2019a) to quantify the size–mass relation,

$$
r = r_p \left( \frac{M}{M_p} \right)^{\frac{1}{2}} \left( 1 + \left( \frac{M}{M_p} \right) \right)^{(\beta - \alpha)/\delta},
$$

where $\alpha$ and $\beta$ are the slopes at the low- and high-mass end, respectively. The variables $r_p$ and $M_p$ are the pivot radius and stellar mass at which the slope transitions from $\alpha$ to $\beta$. We fit the median values with this relation while setting the smoothing factor ($\delta$) to 6. The results of the best-fit values are presented in Tables 1 and 2.

We first focus on the size–mass relation given by $r_{20}$, which is shown in the top panels Figure 8. For the star-forming galaxies, the size–mass relation is relatively flat in all redshift bins. This relation has only a shallow slope at the high-mass end at $z < 1$. The slope at low masses is almost zero, but there is a hint that in the lowest redshift bin that this slope, ($\alpha$) tends to be slightly negative. This indicates that the median $r_{20}$ sizes are almost independent of redshift and stellar mass. The median size of $r_{20}$ is about 1 kpc, which corresponds to the assumed bulge size of the star-forming galaxies in some recent studies (e.g., Cheung et al. 2012; Fang et al. 2013).

Quiescent galaxies have smaller $r_{20}$ sizes than the star-forming ones at all stellar masses, reflecting the higher concentration of these galaxies (see also Section 5.3). For quiescent galaxies, the relation is steeper at high masses above the pivot mass ($M_p$). The existence of the $r_{20}$–mass relation with a larger slope for the massive quiescent galaxies suggests that as the total stellar mass increases, these objects have larger cores and higher stellar mass concentrations. Below the pivot stellar mass, the relation tends to be flatter, at least for the redshift bins of $z < 1$. For the higher redshift bins ($z > 1$), the trends seem to be reversed, although this might be affected by the incompleteness in our sample (see Section 4 and also Section 6.2 for a discussion of whether this trend is reliable). A larger sample of low-mass galaxies with robust stellar mass size measurements at these high-redshift ranges is required to better understand this behavior.

The half-mass size $r_{50}$–mass relations are shown in the middle panels of Figure 8. The half-mass radii of star-forming galaxies are larger than those of quiescent galaxies at fixed stellar mass, consistent with the results based on half-light radii (e.g., Trujillo et al. 2006; Williams et al. 2010; van der Wel et al. 2014). In the high-z bins ($z > 1$), the size–mass relation is relatively flat for star-forming galaxies, while at later epochs, the relation becomes steeper above the pivot mass ($\beta$ increases by about a factor of $\sim 2$). Furthermore, the slope $\beta$ is steeper for quiescent galaxies than for star-forming ones. Moreover, the most massive quiescent galaxies ($\log(M_*/M_*) > 11$) have comparable $r_{50}$ sizes to their star-forming counterparts (Faisst et al. 2017), although the statistic is low at the high-mass end.

We find a similar behavior for star-forming and quiescent galaxies regarding the $r_{80}$–mass plane (bottom panels of Figure 8). In this plane, the scatter of the size distribution decreases slightly, and the average size difference between the star-forming and quiescent galaxies is reduced compared to the $r_{20}$ and $r_{50}$ sizes (see discussion in Section 6). The $r_{80}$ sizes are representative of the radii where the bulk of (80%) of the total stellar mass content of the galaxies are located. Selecting such a
radius can reduce differences of the measured sizes (less sensitive to the Sérsic index), and hence decreases the scatter of the size–mass relation (see also the discussion by Sánchez Almeida 2020 and the recent work by Trujillo et al. 2020). There is a hint that the distances between the median points for different populations (red and blue points) are smaller in the low-redshift bins than the high-redshift ones, but further examination is required.

In Figure 9, the size–mass relations as a function of redshift are plotted for star-forming (left panels) and quiescent (right panels) galaxies. Overall, there is surprisingly little evolution in the size–mass relations for all three size definitions and galaxy types. This can also be seen in Figure 10, where the evolution of the low- and high-mass end slopes ($\alpha$ and $\beta$, respectively) as a function of redshift is shown. The low-mass end slopes are always shallower than the high-mass end slopes. The high-mass slopes are also steeper for quiescent than star-forming galaxies. The variation in the size–mass relation slopes at high and low-mass ends has already been reported for different types of galaxies and was suggested to be related to different...
also be informative to their corresponding pivot mass for each type of galaxies can be also informative to find possible scenarios for the transition between galaxy populations.

For star-forming galaxies, the size–mass relation does not evolve significantly below the pivot mass with cosmic time for all three size definitions, i.e., the normalization as well as the low-mass slope \( \alpha \) remain constant. Even above the pivot mass scale, the \( r_{20} \)-mass relation remains constant. On the other hand, the \( r_{50} \)-mass and \( r_{80} \)-mass relations both steepen above the pivot mass scale with cosmic time (the high-mass slope \( \beta \) increases). The size–mass relation of quiescent galaxies shows little evolution at low masses as well. In particular, the \( r_{50} \)-mass and \( r_{80} \)-mass relations remain roughly constant with cosmic time below the pivot mass scale. Above the pivot mass, sizes are typically larger at later epochs. The \( r_{20} \)-mass relation shows an overall more complex behavior. We discuss the size evolution at fixed stellar mass further in the next section.

We should note that the low- and high-mass end slopes (of the \( r_{50} \) size–mass relation) for both star-forming and quiescent galaxies in the lowest redshift bin are consistent (within the error bars) with the results for the galaxies in the local universe (e.g., Mosleh et al. 2013; Lange et al. 2015).

Finally, the pivot stellar masses for both samples regardless of the size definition increase with redshift, as also depicted in the right panels of the Figure 11. For both star-forming and quiescent galaxies, the pivot radii are almost constant at different redshifts. As we discuss in Section 6, this may be an indication that the mechanisms that drive galaxy structure start to act at lower stellar masses at later cosmic times.

### 5.2. Size Evolution at Fixed Stellar Mass

In this section, we explore the evolution of the mass-based sizes of galaxies at fixed stellar mass over a redshift range of \( 0.3 < z < 2.0 \). We emphasize that this does not trace the size evolution of individual galaxies, rather, this compares the sizes of similar-mass galaxies at different cosmic epochs. We split the samples into four stellar mass bins as shown in Figure 12 (mass bins increase from top to bottom). Similar to the size–mass relation figures, the median values of the star-forming and quiescent galaxies in each redshift bin are illustrated with the blue and red points, respectively. The evolution of sizes are quantified as \( r_m \propto (1 + z)^\gamma \). The best-fit values of \( \gamma \) parameter for different sizes are reported in Tables 3, 4, and 5.

The evolution of the \( r_{20} \) sizes are shown in the left panels of Figure 12. There is no sign for an evolution of the \( r_{20} \) sizes for the star-forming galaxies in all stellar mass bins, consistent with the size–mass relation shown in Figures 8 and 9. There is only a hint that below \( 10^{10.5} M_\odot \) the sizes are smaller at lower redshift, perhaps a sign for building a central concentration.

| Redshift | Size | \( \alpha \)  | \( \beta \)  | \( r_p \) (kpc) | \( \log(M_p/M_\odot) \) |
|----------|-----|-------------|-------------|----------------|------------------|
| 0.3 < z < 0.7 | \( r_{20} \) | -0.234 ± 0.118 | 0.393 ± 0.059 | 0.670 ± 0.050 | 10.566 ± 0.115 |
| 0.7 < z < 1.0 | \( r_{20} \) | -0.066 ± 0.116 | 0.150 ± 0.175 | 0.784 ± 0.065 | 10.648 ± 0.338 |
| 1.0 < z < 1.3 | \( r_{20} \) | -0.189 ± 0.064 | 0.274 ± 0.226 | 0.728 ± 0.043 | 10.842 ± 0.170 |
| 1.3 < z < 2.0 | \( r_{20} \) | -0.203 ± 0.078 | 0.181 ± 0.120 | 0.836 ± 0.039 | 10.731 ± 0.156 |

| Redshift | Size | \( \alpha \)  | \( \beta \)  | \( r_p \) (kpc) | \( \log(M_p/M_\odot) \) |
|----------|-----|-------------|-------------|----------------|------------------|
| 0.3 < z < 0.7 | \( r_{50} \) | -0.131 ± 0.203 | 0.390 ± 0.083 | 1.993 ± 0.212 | 10.373 ± 0.166 |
| 0.7 < z < 1.0 | \( r_{50} \) | -0.023 ± 0.082 | 0.529 ± 0.100 | 2.110 ± 0.196 | 10.694 ± 0.115 |
| 1.0 < z < 1.3 | \( r_{50} \) | -0.091 ± 0.050 | 0.116 ± 0.075 | 2.182 ± 0.071 | 10.668 ± 0.189 |
| 1.3 < z < 2.0 | \( r_{50} \) | -0.043 ± 0.078 | 0.180 ± 0.263 | 2.177 ± 0.181 | 10.825 ± 0.347 |

| Redshift | Size | \( \alpha \)  | \( \beta \)  | \( r_p \) (kpc) | \( \log(M_p/M_\odot) \) |
|----------|-----|-------------|-------------|----------------|------------------|
| 0.3 < z < 0.7 | \( r_{80} \) | -0.021 ± 0.341 | 0.439 ± 0.040 | 4.818 ± 0.775 | 10.212 ± 0.183 |
| 0.7 < z < 1.0 | \( r_{80} \) | 0.067 ± 0.088 | 0.347 ± 0.054 | 4.770 ± 0.488 | 10.483 ± 0.153 |
| 1.0 < z < 1.3 | \( r_{80} \) | -0.059 ± 0.055 | 0.113 ± 0.024 | 5.118 ± 0.128 | 10.433 ± 0.149 |
| 1.3 < z < 2.0 | \( r_{80} \) | -0.026 ± 0.084 | 0.184 ± 0.379 | 4.811 ± 0.500 | 10.887 ± 0.403 |
however, this trend is weak (i.e., $\gamma \sim 0.3 \pm 0.1$). For quiescent galaxies with stellar mass of $10.8 < \log(M_*/M_\odot) < 10.2$, the evolution of $r_{50}$ sizes at fixed mass is significant but positive ($\gamma = 0.85 \pm 0.24$), which can be a sign that the low-mass quiescent galaxies at later epochs have more prominent central densities than their counterparts at high redshifts. The trend can be insignificant if only $z < 1.3$ were assumed (upper left panel of Figure 12). This needs to be confirmed by a large sample of these galaxies with robust size measurement throughout the whole redshift range. The evolution is negligible for galaxies within $10.2 < \log(M_*/M_\odot) < 10.5$ with $\gamma = 0.26 \pm 0.22$. However, for massive quiescent galaxies with stellar masses of $10.8 < \log M_*/M_\odot < 11.2$, the $r_{20}$ sizes decrease with redshift (i.e., $r_{20} \propto (1+z)^{-1.20\pm0.20}$).

The evolution of the half-mass ($r_{50}$) sizes are not significant for massive star-forming galaxies: star-forming galaxies above $10^{10.5}M_\odot$ evolve in size ($r_{50}$) with redshift ($\gamma = -0.45 \pm 0.16$).

The results are consistent with recent studies based on the mass-weighted radii by Mosleh et al. (2017) and Suess et al. (2019b). The evolution reported for the similar mass range by Mosleh et al. (2017) is $\alpha = -0.46 \pm 0.11$. On the other hand, low-mass star-forming galaxies (i.e., $\log(M_*/M_\odot) < 10.5$) have similar half-mass radii at all redshift bins, indicating no size evolution. The slow evolution of $r_{50}$ sizes at low redshifts ($z \leq 1$) has been reported previously based on the half-light radii (Lilly et al. 1998; Simard et al. 1999; Ravindranath et al. 2004; Barden et al. 2005; Dutton et al. 2011; van der Wel et al. 2014; Straatman et al. 2015). However, the slope of the $r_{50}$ evolution obtained in this study is smaller than in most of these works, most probably because other works focused on light-based sizes.

Quiescent galaxies (particularly massive ones with $10.8 < \log(M_*/M_\odot) < 11.2$) show a strong half-mass radii evolution with redshift with $\gamma = -0.96 \pm 0.24$, again consistent with previous studies (Buitrago et al. 2008; Williams et al. 2010; Newman et al. 2012; van der Wel et al. 2014; Mowla et al. 2019b). This size evolution is weaker at intermediate masses ($\gamma \sim -0.58$ for $10.5 < \log M_*/M_\odot < 10.8$), and changes therefore depend on the stellar mass. The origin of the physical processes contributing to these $r_{50}$ evolution for quiescent galaxies might accordingly vary for different stellar masses.

The $r_{50}$ size evolution slightly differs from that of the others (see the right panels of Figure 12 and Table 5). The massive star-forming galaxies show a higher rate of evolution ($\gamma = -0.42 \pm 0.15$ and $-0.85 \pm 0.20$ for the last two massive stellar mass bins, respectively) than the $r_{20}$ and $r_{50}$ sizes, which is related to the pivot mass scale, which is lower for the $r_{50}$-mass relation than for the $r_{50}$-mass relation. This can be an indication that stellar mass has been built up in the outskirts of the star-forming galaxies with stellar mass of $\geq 10^{10.5} M_\odot$ at lower redshifts than for the high-$z$ ones. As we discuss in Section 6.1, this is consistent with accretion of gas onto the outer regions of these galaxies, leading to inside-out disk growth with cosmic time (see, e.g., Nelson et al. 2016a).

The $r_{50}$ sizes of massive quiescent galaxies evolve as $\gamma = -0.90 \pm 0.29$, which is similar to the $r_{50}$ size evolution. Again, the $r_{50}$ size evolution of intermediate-mass quiescent galaxies ($10.5 < \log(M_*/M_\odot) < 10.8$) is with $\gamma = -0.79 \pm 0.22$ stronger than the evolution seen by $r_{50}$. This is an indication for the assembly of the stellar masses in the outskirts via minor mergers at large radii (Oser et al. 2012; Matharu et al. 2019).

We summarize these evolutionary trends in Figure 13, where we plot the size evolution of galaxies at fixed mass for star-forming and quiescent galaxies. In all panels, the median of the sizes for each stellar mass bin are depicted with different symbols. The best-fit size evolutions are also shown for the two most massive bins. This figure highlights that the median size of the star-forming galaxy population only evolves weakly with cosmic time: low-mass star-forming galaxies show little evolution, while higher mass galaxies have slightly larger $r_{50}$ and $r_{80}$ sizes at late epochs. Quiescent galaxies at low masses also have similar sizes at all epochs, while the median-size massive quiescent galaxies show significant evolution with cosmic time.

5.3. Evolution of the Sérsic Index at Fixed Stellar Mass

We show in Figure 14 the redshift evolution of the median Sérsic index for four different mass bins (same bins as previous figures). Star-forming galaxies and quiescent galaxies are shown
in the top and bottom panel, respectively. By construction, the Sérsic index is tightly correlated with the previously shown sizes, i.e., $r_{20}$, $r_{50}$ and $r_{80}$ are related to $n$ via Equations (1) and (2). Therefore it is not surprising that Figure 14 shows a consistent picture with Figures 8–13.

Specifically, Figure 14 shows that the median Sérsic index for low-mass star-forming galaxies does not evolve significantly between redshift 0.3 and 2.0. The median Sérsic index is $n \approx 2$, consistent with what is expected for a disk-dominated galaxy with a small bulge component. The median Sérsic index for higher mass star-forming galaxies ($\log(M_*/M_*) > 10.5$) increases with cosmic time: above $z \sim 1$, $n$ is roughly 2 (consistent with lower mass galaxies), and it increases at $z < 1$ to about 4.

The median Sérsic index for quiescent galaxies is consistent with no evolution, with $n \approx 4–6$ at all masses and redshifts. There is a weak trend that higher mass galaxies on average have a higher Sérsic index.

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Figure 10. Left panels: the evolution of the low-mass end slope of the size–mass relation ($\alpha$) with redshift for star-forming and quiescent galaxies (top and bottom panels, respectively). Right panels: the same as in the left panels, but for the high-mass end slope ($\beta$). The exact values are given in Tables 1 and 2. Low- and high-mass end slopes depend only weakly on redshift for both star-forming and quiescent galaxies. The strongest trend with redshift can be found for the high-mass end slope of star-forming galaxies: the size–mass relation steepens toward low redshifts for star-forming galaxies.

Figure 11. Evolution of the pivot radius and pivot stellar mass (left and right panels, respectively) of the size–mass relation as a function redshift. The top and bottom panel are for star-forming and quiescent galaxies, respectively. The exact values are given in Tables 1 and 2. We find that the pivot radius does not evolve with redshift, while the pivot stellar mass increases with redshift. Interestingly, this holds for all three sizes ($r_{20}$, $r_{50}$ and $r_{80}$).
Note. Galaxies do not change with redshift, however, the size of low redshifts. Middle panel: (Q) quiescent galaxies, in particular massive ones. Right panel: considerable evolution with redshift.

Figure 12: Left panel: size ($r_{20}$) evolution of galaxies with redshift for different stellar masses, increasing from top to bottom panels. The $r_{20}$ sizes of the star-forming galaxies do not change with redshift, however, the size of $r_{20}$ increases for massive quiescent galaxies, and become closer to the $r_{20}$ sizes of the star-forming galaxies at low redshifts. Middle panel: same as the left panel, but for the $r_{50}$ size evolution of galaxies at different stellar masses. This evolution is more significant for the quiescent galaxies, in particular massive ones. Right panel: $r_{50}$ size evolution of galaxies at different stellar masses. Massive quiescent and star-forming galaxies show considerable evolution with redshift.

Table 3

| Sample | $9.8 < \log(M_*) < 10.2$ | $10.2 < \log(M_*) < 10.5$ | $10.5 < \log(M_*) < 10.8$ | $10.8 < \log(M_*) < 11.2$ |
|--------|--------------------------|--------------------------|--------------------------|--------------------------|
| SF ($M_f$) | $0.375 \pm 0.082$ | $0.320 \pm 0.113$ | $0.132 \pm 0.160$ | $-0.123 \pm 0.195$ |
| SF ($M_D$) | $0.236 \pm 0.093$ | $0.014 \pm 0.170$ | $0.072 \pm 0.200$ | $-0.645 \pm 0.279$ |
| Q ($M_f$) | $0.854 \pm 0.243$ | $0.260 \pm 0.219$ | $-0.400 \pm 0.193$ | $-1.197 \pm 0.259$ |
| Q ($M_D$) | $0.103 \pm 0.305$ | $-0.095 \pm 0.289$ | $-1.030 \pm 0.270$ | $-1.675 \pm 0.383$ |

**Note.** The best-fit parameters for the stellar $r_{20}$ size relation for star-forming (SF) and quiescent (Q) galaxies for the first and second method described in the text ($M_f$ and $M_D$). Note that the results of this paper are based on the fiducial size-measurement method ($M_D$, bold numbers).

Table 4

| Sample | $9.8 < \log(M_*) < 10.2$ | $10.2 < \log(M_*) < 10.5$ | $10.5 < \log(M_*) < 10.8$ | $10.8 < \log(M_*) < 11.2$ |
|--------|--------------------------|--------------------------|--------------------------|--------------------------|
| SF ($M_f$) | $0.276 \pm 0.073$ | $0.140 \pm 0.109$ | $-0.117 \pm 0.132$ | $-0.456 \pm 0.166$ |
| SF ($M_D$) | $0.138 \pm 0.073$ | $-0.036 \pm 0.123$ | $-0.169 \pm 0.159$ | $-0.826 \pm 0.234$ |
| Q ($M_f$) | $0.508 \pm 0.192$ | $0.162 \pm 0.176$ | $-0.578 \pm 0.172$ | $-0.959 \pm 0.238$ |
| Q ($M_D$) | $0.231 \pm 0.226$ | $0.322 \pm 0.222$ | $-0.672 \pm 0.222$ | $-0.844 \pm 0.321$ |

**Note.** Same as Table 3, but for $r_{50}$ sizes.

5.4. Scatter of the Size–Mass Relation

In this section, we briefly investigate the scatter of the size–mass relation. From a physical point of view, the distribution of sizes at fixed stellar mass is of interest because it can be related to the angular momentum, velocity dispersion, stellar age, and metallicity of galaxies (Scott et al. 2017; Li et al. 2018; Wu et al. 2018; Díaz-García et al. 2019; Rosito et al. 2019;...
Waló-Martín et al. (2020). In addition, this physical origin of the scatter, effects of projection, and galaxy orientation can also produce scatter (e.g., Price et al. 2017). Furthermore, the measured scatter in sizes at a given mass is a combination of the true intrinsic scatter of the underlying size–mass relation and of the measurement uncertainties of the sizes and stellar masses (e.g., van der Wel et al. 2014). Here, we only consider the measured scatter and postpone a more detailed modeling of the scatter to a future publication.

We show in Section 5.1 that the scatter of the size–mass relation of star-forming and quiescent galaxies depends on the choice of size definition. The scatter decreases toward using radii that encompass larger fractions of the total stellar mass (i.e., \( r_{50} \)). This has also been shown by Miller et al. (2019) for sizes based on light profiles. In Figure 15 we quantify the scatter of all galaxies on the size–mass relation for different redshift bins. In general, the scatter of all galaxies increases if an \( r_{20} \) size is used. The \( r_{20} \) is more sensitive to the Sérsic index, and hence using this radius can be related to the formation of the central regions and star formation activity. There is a hint that the scatter of sizes depends on the stellar mass, but this is not conclusive based on the current analysis.

6. Discussion

We present in this paper detailed measurements of the stellar mass surface density distribution within galaxies. Our galaxy sample lies in the redshift range of \( z = 0.3–2.0 \) and has a stellar mass above \( \log(M_*/M_\odot) > 9.8 \). In the previous section, we quantified the dependence of the sizes \( r_{20}, r_{50}, \) and \( r_{80} \) (containing 20%, 50%, and 80% of the stellar mass) on stellar mass (size–mass relation) and redshift (size evolution at fixed stellar mass with cosmic time). In this section, we discuss the size evolution of individual galaxies and the uncertainties on our measurements.

6.1. Interpretation of the Size Evolution of Star-forming Galaxies

We now use \( r_{20}, r_{50}, \) and \( r_{80} \) measurements to explore how galaxies change their stellar mass density profiles with cosmic time. With this analysis, we will shed light on the physical processes that might drive the stellar mass growth on spatially resolved scales. We first focus on star-forming galaxies. Recently, several studies have measured the distribution of the SFR density within galaxies at \( z = 0.3–2.5 \) (e.g., Tacchella et al. 2015a, 2018; Nelson et al. 2016a; Morselli et al. 2019). These studies found that galaxies with \( \log(M_*/M_\odot) < 10.8 \) on the star-forming main sequence have flat sSFR profiles, indicating that galaxies grow self-similarly. Only at higher masses (\( \log(M_*/M_\odot) > 10.8 \)) do galaxies have a reduced sSFR in their cores relative to their outskirts (Tacchella et al. 2015a).

These measurements of the spatial distribution of star formation is consistent with what we find for the evolution of the mass-based sizes (see Figure 13): star-forming galaxies have similar sizes (all size definitions) at all stellar masses and all redshifts. This is a direct consequence of the self-similar growth. Only for the highest mass bin (Figure 13) do we find that \( r_{50} \) and \( r_{80} \) increase from \( z \approx 1 \) to \( z \approx 0 \). Again, this is consistent with inside-out growth, where sSFRs in the outskirts are higher than in the centers, as expected from inside-out growth.

The constancy for \( r_{20} \) with mass and redshift does not mean that galaxies do not increase their stellar mass in their cores: galaxies do build up dense cores while forming stars, as we can see by looking at the evolution of the Sérsic index (see Figure 14). Massive star-forming galaxies typically have a higher Sérsic index than lower mass star-forming galaxies \( (n \approx 3–4, \text{ increasing toward } z \approx 0) \). This is consistent with previous studies that showed that massive galaxies assemble dense cores already at early epochs (van Dokkum et al. 2010, 2014; Saracco et al. 2012; Barro et al. 2016; Mosleh et al. 2017) and from a bulge on the star-forming main sequence (Lang et al. 2014; Tacchella et al. 2015a, 2018; Tadaki et al. 2017).

The pivot mass scale of the size–mass relation of star-forming galaxies, tracing where the low-mass slope \( \alpha \approx 0 \) transitions to a high-mass slope \( \beta \approx 0.2–0.4 \), decreases from \( \log(M_*/M_\odot) \approx 10.8 \) at \( z \approx 2 \) to \( \log(M_*/M_\odot) \approx 10.3 \) at \( z \approx 0 \) (see Figure 11). This indicates that this transition from self-similar growth to inside-out growth takes place at low masses toward more recent epochs.

Theoretical studies can be used to shed more light onto the physics itself from these observations. The size evolution of galaxies, and in particular the size–mass relation (normalization, slope, and scatter) provide important constraints for numerical simulations (e.g., Furlong et al. 2017; Genel et al. 2018; Rodriguez-Gomez et al. 2019). Cosmological zoom-in simulations can reproduce the aforementioned observed flat sSFR profiles at lower stellar masses on average (Tacchella et al. 2016b). In more detail, Tacchella et al. (2016a) showed that in these simulations, galaxies oscillate about the main-sequence ridge, where bulges are building at the upper envelope of the main sequence (sSFR decrease to the centers), while outskirts are being built when galaxies below the star-forming main sequence (sSFR decrease to the centers)—on average, the sSFR are flat. This is consistent with tidal effects during mergers, misaligned accretion (i.e., counter-rotating gas accretion), and violent disk instabilities leading to gas compaction and the formation of a central spheroidal component (Hernquist 1989; Sales et al. 2012; Dekel & Burkert 2014; Zolotov et al. 2015).

Table 5

| Sample | 9.8 < log(M*) < 10.2 | 10.2 < log(M*) < 10.5 | 10.5 < log(M*) < 10.8 | 10.8 < log(M*) < 11.2 |
|--------|----------------------|------------------------|------------------------|------------------------|
| SF (M20) | 0.144 ± 0.088 | -0.078 ± 0.124 | -0.423 ± 0.149 | -0.847 ± 0.203 |
| SF (M50) | 0.030 ± 0.086 | -0.133 ± 0.142 | -0.389 ± 0.186 | -1.107 ± 0.288 |
| Q (M20) | 0.123 ± 0.227 | -0.037 ± 0.218 | -0.788 ± 0.220 | -0.900 ± 0.294 |
| Q (M50) | 0.302 ± 0.277 | 0.468 ± 0.271 | -0.575 ± 0.271 | -0.436 ± 0.374 |

Note. Same as Table 3, but for \( r_{80} \) sizes.
6.2. Interpretation of the Size Evolution of Quiescent Galaxies

We consider two interesting questions for quiescent galaxies: (i) Do galaxies change their stellar structure when their SFRs cease, i.e., when they move through the “green valley”? (ii) Do galaxies grow in size once they are quiescent? As we discuss below, we cannot provide satisfying answers with our measurements alone. Future studies that include constraints on the stellar ages and SFHs of the galaxies will help answering these questions.

As we mention in the Introduction, although the present-day star-forming and quiescent galaxies have different morphologies, this does not necessarily imply that the morphology of a galaxy needs to change when its star formation ceases because the progenitors of the present-day quiescent galaxies are star-forming galaxies at higher redshifts (e.g., Park et al. 2019; Tacchella et al. 2019). When we compare the morphology of star-forming and quiescent galaxies, a complication arises due to M/L gradients, hence, effects such as disk fading need to be taken into account (e.g., Carollo et al. 2016). Because we work with mass-based quantities, our comparison is straightforward.

Comparing the sizes of star-forming and quiescent galaxies, we find that \( r_{20} \) is on average larger for star-forming galaxies than for quiescent galaxies at all masses and epochs. The average size \( r_{50} \) is larger for star-forming than for quiescent galaxies at low masses, and this reverses at higher masses. We find a similar trend for \( r_{80} \). We note that at fixed mass and \( r_{50} \) sizes, galaxies with higher Sérsic index (\( n \)) are expected to have a smaller \( r_{20} \) but larger \( r_{80} \) sizes. However, this cannot be the only reason why quiescent galaxies are larger than the star-forming galaxies at the high-mass end of \( r_{50} \) and \( r_{80} \)–mass relations, as described in the following paragraphs.

Even though we have these observations at hand, we cannot conclude how galaxy sizes evolve when they cease their star formation. This is because these are average statements over the whole population: the quiescent population at any epoch

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Figure 13. Comparison of the size (\( r_{20} \), \( r_{50} \) and \( r_{80} \)) evolution of star-forming and quiescent galaxies with redshift at fixed stellar mass. The best-fit size evolution is shown for the two massive stellar mass bins in each panel.

Figure 14. Median Sérsic evolution with redshift for star-forming and quiescent galaxies (top and bottom panels, respectively). Each symbol represents a different stellar mass bin.
Figure 15. Comparison of the observed scatter of the size–mass relation as a function of stellar mass for different size definitions. The scatter is slightly reduced as a larger fraction of the stellar mass density profile is considered, i.e., moving from $r_{20}$ to $r_{50}$. The plot is shown for different redshift bins increasing from the top left to the bottom right panel.

consists of galaxies that ceased their SFRs at a range of earlier cosmic epochs. Therefore the evolution of the quantity averaged over the quiescent galaxy population includes evolutionary effects of quiescent galaxies themselves (such as mergers) and the addition of newly quenched galaxies (“progenitor bias,” van Dokkum & Franx 1996; Carollo et al. 2013; Poggianti et al. 2013; Belli et al. 2015; Fagioli et al. 2016). These newly quenched galaxies stem from the star-forming galaxy population, which itself evolves, and during quenching, some morphological evolution might also take place.

Nevertheless, we find that $r_{50}$ and $r_{80}$ is larger for quiescent galaxies than for star-forming galaxies at high masses $\log(M_*/M_\odot) > 11$. Under the assumption of negligible size growth when star-forming galaxies cease their star formation, individual quiescent galaxies indeed need to increase $r_{50}$ and $r_{80}$, i.e., they need to add mass in the outskirts. In addition, the pivot mass in the size–mass relation for quiescent galaxies decreases from $\log(M_*/M_\odot) \approx 10.8$ at $z \sim 2$ to $\log(M_*/M_\odot) \approx 10.2$ at $z \sim 0$ (see Figure 11, similar to star-forming galaxies), which is similar to the mass where the fraction of star-forming galaxies is 50%, indicating that the pivot mass reflects a transition from in situ dissipational to ex situ dissipationless growth (see also Mowla et al. 2019a; Zahid et al. 2019). This is also consistent with the decline in the scatter of sizes toward high stellar masses (see Section 5.4). Finally, the IllustrisTNG simulations also show that the ex situ mass fraction of $\approx 0.2$ decreases from $\log(M_*/M_\odot) \approx 10.9$ at $z = 1.5$ to $\log(M_*/M_\odot) \approx 10.6$ at $z = 0$ (see also Pillepich et al. 2018; Tacchella et al. 2019). In summary, there are indications that merger play a role in setting the size for the most massive systems, which is also consistent with the abundance of slow rotators at the massive end of the mass function (e.g., Bezanson et al. 2009; Cappellari et al. 2013; van Dokkum et al. 2015; Cappellari 2016; van de Sande et al. 2017).

Furthermore, we show in Section 5 that quiescent galaxies have smaller $r_{20}$ sizes than the star-forming ones at all stellar masses, reflecting the higher concentration of these galaxies. For quiescent galaxies, the relation is steeper at high masses above the pivot mass ($M_*$). The existence of the $r_{20}$–mass relation with a larger slope for massive quiescent galaxies suggests that as the total stellar mass increases, these objects have larger cores and higher stellar mass concentrations. Below the pivot stellar mass, the relation tends to be flatter, at least for the redshift bins of $z < 1$. For the higher redshift bins ($z > 1$), the trends seem to be reversed, although this might be affected by the incompleteness in our sample (see Section 4). Nevertheless, if this is real, then the contribution of recently quenched galaxies might affect the trend and cause this relation to be anticorrelated. If different quenching mechanisms can be assumed for galaxies with different stellar masses (e.g., the mass and environmental quenching described in Peng et al. 2010b), then the low-mass galaxies—which quenched via environmental effects—could have been least affected by structural reshaping. Hence, the central regions of the low-mass quiescent galaxies would be similar to star-forming galaxies. Studying the environment and age of these systems might help to test this scenario.

6.3. Uncertainties in Parameter Measurements

In this study, we created the stellar mass maps of the galaxies with $\log(M_*/M_\odot) \geq 9.8$ at $0.3 \leq z \leq 2$ to measure their mass-based structural parameters. Converting multwavelength images into the stellar mass maps and measuring the structural parameters is associated with several uncertainties. First, in our method, all pixels are treated independent during the SED fitting. Usually, pixels within central regions have sufficient S/N. However, the stellar mass estimates of pixels in the outer regions with low S/N will be associated with large uncertainties. The pixel-binning methods used in some studies such as Wuyts et al. (2012) degrade the resolution and introduce step-like profiles, which is not suitable for analyzing the morphology of galaxies. Some authors (e.g., Lang et al. 2014; Morselli et al. 2019) tried to use $H_{160}$-band images and multiplied them to the estimated (pixel-binned and smoothed) $M/L$ maps. As discussed in Sorba & Sawicki (2015), this might reduce outshining effects and might therefore change the shape of the true stellar mass profiles. The concerns about the effects of low S/N pixels on the results of this study are examined by means of the simulated galaxies (Appendix B). Although the outer regions of the stellar mass maps are slightly noisy (see, e.g., Figure 6), the overall shape of these maps (in particular, the outer regions) are within the expected range of the stellar mass densities. In addition, conversion of the 2D stellar mass maps into the 1D density profiles reduces the effect of these low S/N pixels in the outskirts of galaxies, while recovering the true profiles. Our approach of using a formalism that considers a wide range of models also helps to mitigate issues regarding
the fitting procedure. The results of this paper are therefore probably robust concerning low S/N pixels in the outskirts.

The second concern is related to the choice of the SFH model of the SED fitting. In this work, an exponentially declining SFH is assumed. Different assumptions such as additional random burst and constant or delayed SFH can alter the estimated stellar masses. This has been tested in Mosleh et al. (2017) for the 1D stellar mass profiles. Although there might be some systematic on the stellar mass estimates (e.g., Madau & Dickinson 2014; Leja et al. 2019), Mosleh et al. (2017) were unable to find any effects on the mass-based size measurements. Testing different SFH models is beyond the scope of this work, and this has to be examined in future studies. Nevertheless, we expect that this will not have significant effects on the general results of this paper; we recall that the stellar masses used in this work are the integral of the SFH, which includes remnant and mass returned to the interstellar medium. It is worth noting that the variation in IMF as a function of radius or redshift (see, e.g., La Barbera et al. 2016; Eftekhar et al. 2019, and references there in) can also affect the stellar mass maps. In this work, we only assume the Chabrier (2003) IMF for all radii and redshifts and the possible consequences due to the changes of the IMF are not studied. Clear pictures of the dependence of the IMF on redshift and radius will be valuable to test its effect on the structural analysis.

Another source of uncertainty is due to the effect of dust on the stellar mass maps, in particular for massive star-forming galaxies and also its dependence on galaxy inclination (Hemmati et al. 2015). Understanding the radial variation of the dust attenuation (Nelson et al. 2016b; Wang et al. 2017; Tacchella et al. 2018) and its effect requires a detailed spectroscopic analysis for a large sample of galaxies. Hence, using a limited number of wavelength bands at short rest-frame filters can be problematic in estimating the dust attenuation. A better coverage at short rest-frame wavelengths might be a first step to test the effects on our final results. We have examined this by exploiting the new ultraviolet (UV) imaging data from the Hubble Legacy Fields (HLF) on the GOODS-South field (Whitaker et al. 2019). We apply our method for deriving the stellar mass maps to about 300 galaxies in common with 3D-HST at $0.5 < z < 1.3$, using 13 bandpass observations in HLF, including rest-frame UV. This allows us to estimate the stellar mass and $A_V$ profiles of these galaxies and compare the profiles with rest-frame UV and without rest-frame UV coverage. Overall, we did not see any significant differences between the stellar mass profiles of star-forming galaxies. The largest difference ($\sim 0.2$ dex) is found for the central regions (within 1 kpc) of the most massive bin in the redshift range of $1 < z < 1.3$. This might affect $r_{20}$ sizes. Therefore we expect in general that the effect of dust does not have notable consequences on our final results (except for the most massive star-forming galaxies at $z > 1$). Nonetheless, future studies with a better wavelength coverage are required to test this further.

The number of galaxies (especially massive ones) declines toward lower redshifts ($z \lesssim 0.5$). Hence, in the lowest redshift bin, the analysis might suffer from low statistics. Using the five fields of 3D-HST has reduced this issue, but a large sample of galaxies is still required to trace the structural evolution at fixed mass at these low redshifts (such as Damjanov et al. 2019).

In addition, galaxies are observed to consist of bulge and disk components out to high-$z$ (Margalef-Bentabol et al. 2016). It has been shown that fitting profiles with single-component models can change the slope of the size–mass relation (Mosleh et al. 2013; Bernardi et al. 2014). However, using simulated data, Mosleh et al. (2013) showed that for high-redshift galaxies ($z \sim 1$), a single-Sérsic model is sufficient to recover their true sizes (see also Davari et al. 2016). Therefore, the result of this paper is not expected to be affected by our assumption of a single-Sérsic model for high-$z$ galaxies. In spite of this, the sizes of galaxies at the lowest redshift range of $z \sim 0.2$–0.4 might be slightly under- or overestimated. Investigating this issue is beyond the scope of this paper, but needs to be considered in complementary studies.

Finally, our strategy was to derive the stellar mass density profiles as straightforwardly as possible without resorting to the light profile-fitting in each filter prior to the SED fitting (Szomoru et al. 2013), or any additional assumption on the $M/L$ profiles (e.g., Suess et al. 2019a). This will reduce many sources of uncertainties on converting the light into mass profiles and measuring structural parameters. Our first and second method described in Section 4 and Appendix A are complementary to each other, and they have been tested via creating a large sample of mock galaxies to ensure that the results are not biased. To the best of our knowledge, this is one of the most comprehensive tests for this type of studies. The method also helps to estimate the PSF-corrected morphological parameters based on the stellar mass maps. However, as discussed in the text, using an SED fitting method to derive mass-based structural parameters of galaxies beyond $z > 1.3$ could be accompanied with another uncertainty because effects such as low S/N and lack of rest-frame NIR coverage are combined. Hence, based on the currently available data, this redshift range should be treated with caution. From our simulated objects, the stellar mass limit of $\log(M_*/M_\odot) \sim 9.8$ is obtained, below which the uncertainties on the parameter measurements increase significantly (see Appendix B).

7. Conclusions

In this paper, we created the stellar mass maps of a sample of $\sim 5557$ galaxies up to $z = 2$ from the CANDELS/3D-HST observations to measure mass-based structural parameters. We used pixel-by-pixel SED fitting to construct these maps. These maps are used to derive mass-based sizes ($r_{20}$, $r_{50}$, and $r_{80}$ that enclose 20%, 50%, and 80% of the total stellar mass, respectively) and Sérsic indices. These measurements are made available to community as an online table (Table 6).

The methods used in this study to derive the stellar mass maps and structural parameters are tested via creating a sample of $\sim 3000$ mock galaxies. Based on the results of these simulations, we show that the analysis is robust for galaxies with stellar mass $> 10^{9.8} M_\odot$ and up to a redshift of $z \sim 2.0$. Beyond this redshift, the robustness of mass maps and sizes is reduced.

We constrain the size–mass relations for all mass-based $r_{20}$, $r_{50}$ and $r_{80}$ sizes. The scatter of size–mass relations depends on the size definition; it is considerably reduced for $r_{80}$ sizes. We use the different size definition to understand how centers and outskirts build up stellar mass as a function of cosmic time and redshift.

The sizes of star-forming galaxies are similar at all mass and redshifts, regardless of the size definition ($r_{20}$, $r_{50}$ and $r_{80}$).
Table 6
Structural Properties for 5557 Galaxies in the CANDELS Fields

| Column Name | Descriptions | Comments |
|-------------|--------------|----------|
| ID          | identification number for each source | from the v4.1 3D-HST catalogs |
| Field       | name of the CANDELS Field | from the v4.1 3D-HST catalogs |
| R.A.        | R.A. (degree) | from the v4.1 3D-HST catalogs |
| Decl.       | decl. (degree) | from the v4.1 3D-HST catalogs |
| z           | Redshift | from the v4.1 3D-HST catalogs |
| LMASS       | total stellar mass of sources in log(M_*/M_☉) | See Appendix B for corrections. |
| r₁₅₀M      | best-fit Sérsic parameter and associated errors from the first method | use flag₁₅₀M = 0 to select reliable ones |
| r₂₀₀M      | best-fit half-mass (r₁₅₀) parameter and associated errors from the first method | |
| r₂₅₀M      | best-fit r2₀ parameter and associated errors from the first method | |
| r₅₀₀M      | best-fit r8₀ parameter and associated errors from the first method | |
| flag₁₅₀M  | quality flag for the first method | |
| r₁₅₀₂₀₀  | best-fit Sérsic parameter and associated errors from the second method | |
| r₁₅₀₅₀₀  | best-fit half-mass (r₁₅₀) parameter and associated errors from the second method | |
| r₂₀₀₅₀₀  | best-fit r2₀ parameter and associated errors from the second method | |
| r₅₀₀₅₀₀  | best-fit r8₀ parameter and associated errors from the second method | |
| flag₂₀₀M  | quality flag for the second method | use flag₂₀₀M = 0 to select reliable ones |
| flag₅₀₀M  | quality flag for the second method | |

Note. The Sérsic parameters from the first approach (r₅₀₀M) should be corrected based on the results from the simulations (see Appendix B).

(This table is available in its entirety in machine-readable form.)

Only r₁₅₀ and r₂₀₀ of the most massive star-forming galaxies increase weakly toward lower redshifts. This leads to a picture that below a pivot stellar mass of \( \sim 10^{10.5} M_☉ \), star-forming galaxies have similar stellar mass profiles and grow self-similarly. This is consistent with flat SSFR profiles from other observations. Above the pivot stellar mass of \( \sim 10^{10.5} M_☉ \), the outskirts of star-forming galaxies grow slightly faster than the inner region. This is consistent with sSFR profiles that rise toward the outskirts.

Quiescent galaxies at low masses also have similar sizes at all epochs. At high masses, the size–mass relation steepens. Furthermore, massive quiescent galaxies, on the other hand, show a strong size evolution at fixed mass, regardless of the size definition. We argue that progenitor bias and accumulation of the stellar masses via minor or major mergers contribute to the evolution.

We thank the anonymous referee for the comments that helped to improve the manuscript. This work is based on observations taken by the 3D-HST Treasury Program (GO 12177 and 12328) with the NASA/ESA HST, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. S.T. is supported by the Smithsonian Astrophysical Observatory through the CfA Fellowship.

A.1. Estimation of the Background Level

Before we describe this method, it is important to mention that estimating the background level is crucial for this fitting approach. Therefore we need to estimate the background level of the stellar mass maps. The 3D-HST mosaic images are background subtracted, but these images have surface brightness limits down to which extended sources can be detected. We find the corresponding stellar mass density limit to those surface brightness limits around each source. We measure the 1σ scatter of the background pixels in the 48” × 48” postage stamps for all filters. We perform SED fitting of the background assuming the same redshift as the galaxy. The estimated stellar masses of the background pixels are then perturbed randomly by their errors assuming a Gaussian distribution and are then added to the background pixels in the galaxy stellar mass maps. We stress that the method has been tested extensively using simulated objects, as discussed in Appendix B.

A.2. 2D Profile-fitting Method (M_B)

In this method, we use the 2D stellar mass maps and use GALFIT v3 (Peng et al. 2010a) to perform 2D χ² fitting. We use the H₁₆₀-band PSFs because all images are convolved to the H₁₆₀ resolution. We therefore assume that the resolution is not affected during the pixel-by-pixel SED fitting process. We follow a similar procedure as in Mosleh et al. (2012) and treat the background as a free parameter during the fitting process. In Figure 16, we show for the same objects as in in Figure 3 the mass maps, the best-fit 2D Sérsic models, and the associated residuals. In order to test the reliability and limits of this method, a set of mock galaxies is required, and we refer to Appendix B for more details. As explained and examined in that section, the fraction of galaxies with reliable sizes drops significantly (by \( \sim 20\% \)) beyond a redshift of \( z \sim 1.3 \) as the uncertainties of the stellar mass maps increase. For these sources, GALFIT fails.
to converge, or it converges to the set boundaries. Below this redshift, on average only $\sim 6\%$ of the sources are returned with unreliable size estimates. We should note that in order to be consistent with the first method and to reduce the effects of ellipticity, the sizes are also circularized (e.g., Trujillo et al. 2006).

A comparison between the $r_{50}$ sizes estimated from the first and the second method is illustrated for the two redshift ranges in Figure 17. In general, the results from both methods are consistent with a median offset of $\Delta (r_{50}) < 0.02$ dex for both redshift ranges and a scatter of $\lesssim 0.11$ and $\lesssim 0.13$ dex for the low- and high-redshift bin, respectively. We have also compared the half-mass sizes for $\sim 700$ galaxies that are in common with Suess et al. (2019a) in Figure 18. There is a tendency that the sizes from Suess et al. (2019a) are larger than those from this work. The overall differences between both measurements is small ($\sim 0.04$ dex), however, the scatter with $\sim 0.2$ dex is substantial.
Appendix B
Simulations

We perform extensive simulations to test the reliability of our methods for deriving stellar mass maps and sizes of galaxies. The results of this section will help to constrain the stellar mass and redshift limits to which our methods are robust. We first describe how the models are created, and then we test the size measurement methods using these simulated data.

B.1. Models

First, we create a catalog of mock galaxies by randomly selecting objects from the 3D-HST catalog. We then create single-Sérsic models (using GALFIT) with the same structural parameters \((n, r_{50}, b/a, \text{ and PA})\) in each filter. The range of properties is selected to be within a similar range of the observed galaxies in the stellar mass–size plane (see Figure 23). The models are all convolved to the same \(H_{160}\)-band PSF. Assuming the same shape in all filters will ensure that the shape of simulated galaxies at different wavelengths is the same (i.e., removing any color gradients), and hence, there will not be any inherent bias between the light- and mass-based sizes for these mock galaxies. To ensure that the total stellar mass is conserved, the total flux of the model in each filter corresponds to flux from that randomly chosen real object. The models are then added to the empty regions of the mosaic images. We then run the SExtractor (Bertin & Arnouts 1996) to create segmentation maps for each mock galaxy. We use the same procedure as described in Section 3.1 to derive the stellar mass maps of these simulated galaxies. The stellar mass maps of a few simulated galaxies are shown in Figure 19. The simulated mass maps are similar to real objects (see Figure 3) with higher surface densities in the center and a relatively smooth distribution.

For these simulations, we created about 3000 mock galaxies, in which two-thirds were added to the GOODS-South field (7 HST filter coverage) and the rest to the COSMOS and UDS fields (5 HST filter coverage). The redshift range of the simulated object in the GOODS-South field is between \(0.5 \leq z \leq 2.0\), and for the other fields, it was chosen to be \(0.5 \leq z \leq 1.3\).

B.2. Testing the Total Stellar Masses

As a first step, we check the differences between the input (original) stellar mass and the output total unresolved stellar mass for these simulated galaxies. Overall, there is a very good consistency: the median differences are smaller than \(\sim 0.04\) dex at all redshifts (see the top panels of Figure 20). This indicates that the total stellar masses (regardless of the number of filters) are recovered without any systematic offset. Therefore the method for estimating the stellar mass maps is robust.

Next, we compare the total stellar mass from the unresolved and resolved (pixel-by-pixel) methods for the two redshift ranges (below and above \(z \sim 1.3\)). The differences are shown in the bottom panels of Figure 20. For simulated objects at \(z < 1.3\), there is no systematic offset in the median values (green points) at all stellar masses above \(\log M_\odot = 9.8\). Above \(z \sim 1.3\), the uncertainties and biases increase, similar to the real objects (see Figure 4), but the systematic differences are smaller (\(\sim 0.07\) dex) than for the real objects (\(\sim 0.17\) dex). This might be due to our choice of rather simplistic models without any color gradients for these mock galaxies. Nevertheless, at redshifts beyond \(z = 1.3\), the resolved total stellar masses start.
to deviate from the resolved ones. As discussed in Section 3, the origin of this deviation has been attributed to several effects such as dusty regions, SFHs, outshining effects, or S/N issues. The next generation of (space) telescopes and high-resolution instruments will assist in resolving this issue by studying the rest-frame NIR of these high-z galaxies.

**B.3. Testing the Mass Profile Parameters**

We used two methods to measure the sizes and Sérsic parameters of galaxy stellar mass maps, which are based on 1D and 2D, as described in Section 4. We apply the same techniques to the simulated stellar mass maps. In Figure 21, the best-fit 1D Sérsic models are shown for the objects in Figure 19.
Figure 19. The results for the 2D fitting method are also illustrated in Figure 22 for the same objects. For both methods, the true shapes of the profiles have been recovered by their best-fit models.

We examine this further by studying the relative difference (between input and measured) of the $r_{50}$ sizes in the stellar mass–size plane. The top panels of Figure 23 show the distributions of the simulated galaxies on the size–mass plane for the two redshift bins of $0.5 < z < 1.3$ (left panel) and $1.3 < z < 2$ (right panel). The symbols are color-coded according to the relative difference of input and output sizes ($\Delta r_{50}/r_{50}$) from the first method (1D fitting). For the redshift range of $0.5 < z < 1.3$, the relative differences of the sizes are small (middle left panel). In spite of this, the median relative differences of the Sérsic indices at this redshift range show a small systematic offset of 12%, i.e., the output values of the Sérsic indices are smaller than the inputs. This might be due to limitations of ellipse fitting in the very central regions of the objects.
stellar mass maps caused by the pixel resolution. The systematic offset of the median relative sizes in the high-redshift sample ($z > 1.3$) is about 12% (middle right panel of Figure 23), but the scatter is also considerable. Moreover, a systematic offset in the recovery of the Sérsic parameter exists at this redshift bin (16%), and the scatter is also large.

Identical tests for the second method (2D profile-fitting) are presented in Figure 24. From this figure, it is clear that for objects with $r_{50}$ smaller than 0.5 kpc (gray shaded regions), the size measurement is not reliable. The median relative differences of the sizes and Sérsic index are robust for the studied stellar mass range at $z < 1.3$ and objects with mass-based sizes $>0.5$ kpc. However, the scatter increases for the galaxies below $\log M_\odot \sim 10$ (see the middle and lower panels of Figure 24). For the sources at the redshift of $1.3 < z < 2$, the uncertainties of the output parameters are large, and the systematic differences in sizes can be seen for massive sources, but we do not see a significant systematic difference in the recovery of the Sérsic parameters.

The relative size ($r_{50}$) differences for the simulated galaxies as a function of redshift are shown in Figure 25. In this figure, the symbols are color-coded according to their stellar masses. For both methods, the scatter increases significantly beyond $z \sim 1.3$. In addition, the fraction of sources that have been fitted without any failure in their fitting procedure drops significantly beyond $z > 1.3$, but the systematic differences are smaller for the 1D method. For the first and second methods,
98% and 95% of the simulated galaxies within $0.5 < z < 1.3$ have been recovered without failure, respectively. However, this drops to about 92% and 73% for objects at $1.3 < z < 2$ mainly because fewer robust and noisier stellar mass maps are available. From this analysis, we conclude that our methods for deriving the stellar mass sizes and Sérsic indices are reliable for stellar masses beyond $10^{9.8} M_\odot$ and up to the redshift of $z \sim 1.3$ (for the 2D method) and $z \sim 2.0$ (for the 1D method). Beyond these redshift limits, the uncertainties of the size estimates increase, although the systematics are small. Moreover, the first method covers the full size–mass plane and redshift range better. We therefore treat this as our fiducial size measurement method for the main analysis of this work. The results based on the second method are presented in Appendix C.

Appendix C
Results Based on Sizes from Method ($M_{II}$)

We used our second method (2D fitting approach) to explore the size–mass relations, similar to the first method. The results are shown in Figure 26. There is a general agreement between size–mass relations when this is compared with Figure 9 from the 1D method. Star-forming galaxies have shallower slopes than quiescent galaxies in all redshift bins, regardless of the size definition. The strong size evolution at fixed mass takes place for those above the pivot stellar mass. The evolution of sizes is also illustrated in Figure 27. We note that the results based on this second method ($M_{II}$) are noisy at $z > 1.3$, as also shown in the simulations above.

Figure 26. Size–mass relation of star-forming and quiescent galaxies at different redshift, similar to Figure 9, but based on sizes obtained from the second method. In general, there is a good agreement between the results of the two methods.

Figure 27. Size evolution of galaxies with redshift for different size definitions and galaxy types, similar to Figure 13. The slopes are reported in Tables 3, 4, and 5.
