The growth of galactic bulges through mergers in $\Lambda$CDM haloes revisited. II. Morphological mix evolution

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ABSTRACT
The mass aggregation and merger histories of present-day distinct haloes selected from the cosmological Millennium Simulations I and II are mapped into stellar mass aggregation and galaxy merger histories of central galaxies by using empirical stellar-to-halo and stellar-to-gas mass relations. The growth of bulges driven by the galaxy mergers/interactions is calculated with dynamical prescriptions. The predicted bulge demographics at redshift $z \sim 0$ is consistent with observations (Zavala et al.). Here we present the evolution of the morphological mix (traced by the bulge-to-total mass ratio, $B/T$) as a function of mass up to $z = 3$. This mix remains qualitatively the same up to $z \sim 1$: $B/T \leq 0.1$ galaxies dominate at low masses, $0.1 < B/T \leq 0.45$ at intermediate masses, and $B/T > 0.45$ at large masses. At $z > 1$, the fractions of disc-dominated and bulgeless galaxies increase strongly, and by $z \sim 2$ the era of pure disc galaxies is reached. Bulge-dominated galaxies acquire such a morphology, and most of their mass, following a downsizing trend. Since our results are consistent with most of the recent observational studies of the morphological mix at different redshifts, a $\Lambda$CDM-based scenario of merger-driven bulge assembly does not seem to face critical issues. However, if the stellar-to-halo mass relation evolves too little with redshift, then some tension with observations appear.

Key words: galaxies: formation galaxies: evolution galaxies: high-redshift galaxies: bulges galaxies: interactions galaxies: structure.

1 INTRODUCTION
The two main stellar components of galaxies are the disc and the bulge. The classification of galaxies is tightly related to the luminosity or mass ratio of these components, for example, to the ratio of bulge to total (disc+bulge) mass, $B/T$. Most of the properties of galaxies and relevant aspects of their assembly histories are also tightly related to this ratio. Thus, a key ingredient in the study of galaxy formation and evolution is to understand how is the $B/T$ ratio established as a function of mass and time.

According to the general picture of galaxy formation and evolution in the context of the $\Lambda$ Cold Dark Matter ($\Lambda$CDM) hierarchical scenario, discs form generically inside the evolving CDM haloes, while bulges grow mainly driven by the merger/interaction of discs but also due to intrinsic disc instabilities and by misaligned/perturbed infalling gas.

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The mass accretion and merger histories of CDM haloes as a function of mass and environment are calculated precisely by means of N-body cosmological simulations (e.g. Lacey & Cole 1994; Gottlöber et al. 2001; Wechsler et al. 2002; Maulbetsch et al. 2007; Fakhouri & Ma 2007; Fakhouri et al. 2010; Zhao et al. 2009; Behroozi et al. 2013c). It is common to read in the specialized literature that the predicted $\Lambda$CDM halo merger rates would imply a large population of galaxies with dominant (merger-driven) classical bulges, in conflict with observations (e.g. Weinzierl et al. 2009; Kormendy et al. 2010; Fisher & Drory 2011). However, the connection of halo mass assembly and merger rates to the galaxies they host is complex and should be properly understood in order to account for the growth of bulges.

Recently, several theoretical studies attempted to establish the connection between the halo merger history and the final galaxy $B/T$ ratio. Some of these studies are based on the semi-empirical halo occupation framework.
(e.g. Stewart et al. 2004; Hopkins et al. 2009a, 2010), while others are based on semi-analytic models (Khochar & Silk 2004; Parry et al. 2009; Benson & Devereux 2010; De Lucia et al. 2011; Fontanot et al. 2011). The most relevant conclusions of these works are that: (i) the mapping of halo-halo mergers to stellar galaxy-galaxy mergers is far from linear and strongly depends on mass and redshift, (ii) the inclusion of the galaxy gas content in mergers significantly reduces the final B/T fraction, specially for low-mass galaxies and at high redshifts, and (iii) the B/T fraction predicted in the ΛCDM scenario increases with stellar mass, $M_*$, in a similar way as observations, although there seems to be fewer predicted bulgeless galaxies than observed.

In Zavala et al. 2012 (hereafter Paper I), the merger-driven bulge formation scenario has been revisited by means of a semi-empirical approach based on Hopkins et al. (2009a, 2010). This approach takes into account: (i) the cosmological mass accretion and merger histories of haloes and an estimate for the time of coalescence of the subhaloes in the centre of the main (distinct) halo; (ii) the empirically constrained stellar-to-halo and stellar-to-gas mass relations at different $z$; (iii) a physically-based model for calculating the stellar and gas mass evolution of the satellite galaxies; (iv) dynamical recipes, calibrated with numerical simulations, for calculating the mass growth of the bulges after the merger of the primary galaxy with the accreting satellite galaxy. The results presented in Paper I show that the local bulge demographics and B/T vs $M_*$ correlation down to galaxies of stellar masses $M_* \sim 10^9$ $M_\odot$ are in general consistent with current observational studies. It was also shown that the B/T ratio depends on the way the satellites evolve until they merge with the primary, and that the merger-driven bulges grow in several episodes through concomitant channels of stellar mass acquisition: from the secondaries, from the primary disc and from local starbursts. This produces composite (pseudo + classical) bulges in most of the cases.

The aim of this paper is to extend the analysis of Paper I by analysing the evolution of the morphological (B/T ratio) mix of galaxies as a function of mass, and to compare our predictions with the few (recently appearing) observational determinations of the morphological mix at high redshifts. Some of the questions that we study by means of our semi-empirical model are: Does the morphological mix of galaxies strongly change with redshift? What is the epoch of major changes in this mix? What is the mass dependence of the bulge growth histories of galaxies? Does the assembly of early-type galaxies follow a morphological and mass downsizing trend? Does the morphological transformation to bulge-dominated galaxies happen when galaxies are in their active or passive regime of star formation?

The outline of the paper is as follows. The semi-empirical approach presented in Paper I is summarized in Section 2. In §3.1 results on the evolution of the B/T ratio and the morphological mix as a function of $M_*$ are presented, and in §3.2 the setting of the bulge-dominated galaxy population is discussed. In Section 4 we compare our results with the available observations on morphology and B/T ratios at different $z$. In Section 5 we discuss the implications of a little evolving stellar-to-halo mass relation (SHMR) on the bulge demographics and evolution (§5.1), and whether the merger-driven bulge growth in the context of the ΛCDM cosmology is consistent or not with observations (§5.2). Our conclusions are given in Section 6.

2 THE SEMI-EMPirical MODEL

Our semi-empirical model of galaxy and bulge stellar mass growth is presented in detail in Paper I. Below we summarize its main features.

It is important to remark that we do not model ab initio the physical processes of galaxy evolution (e.g., star formation and feedback), which makes our approach different from semi-analytic models and numerical simulations. Instead, our semi-empirical approach consists in seeding stellar and gaseous masses into the evolving CDM haloes using empirical information. By means of this approach, we can then empirically extend the halo mass aggregation and merger histories of distinct CDM haloes to the corresponding stellar and gaseous mass aggregation histories of central galaxies, including galaxy merger events. The merger-driven growth of bulges in these semi-empirical galaxies is modeled by using dynamical prescriptions calibrated against numerical simulations.

2.1 Subhalo merger histories

Our goal is to analyse the impact of mergers in the growth of the bulges of present-day central galaxies; a central galaxy is defined to be the most massive galaxy in a given main subhalo, i.e. a subhalo that is not contained inside a larger subhalo (known in the literature also as a distinct halo). We therefore extract the merger histories of the principal branches of a population of main subhaloes defined at $z = 0$. We have randomly selected two samples of such subhaloes, having 1347 and 1500 members with masses larger than $1.2 \times 10^{12} M_\odot$ ($10^4$ particles) and $9.4 \times 10^{10} M_\odot$ ($10^4$ particles), from the Millennium (MS-I) and Millennium II (MS-II) simulations, respectively (Springel et al. 2002; Berlín-Kolchin et al. 2009). Both samples (properly normalized to account for the fractional volume they cover relative to the whole simulation boxes) follow the mass function of the full halo population. Combining both samples we can follow up to high redshifts the merger and accretion histories of haloes having a wide mass range at $z = 0$: $10^{10} - 10^{15} M_\odot$.

A given merger event is characterized by three epochs: (a) the start of the merger, $t_{\text{start}}$, i.e., when the subhalo was part of an independent friend-of-friend halo for the last time; (b) the “dissolution” time of the subhalo, $t_{\text{diss}}$, i.e., when the merged subhalo at time $t$, can no longer be resolved in the simulation as an independent self-bound structure at the following time $t_{i+1}$; and (c) the coalescence time of the subhalo center, where the satellite galaxy is supposed to be, with the centre of the main subhalo, $t_{\text{coa}}$. To compute the latter we adopt a dynamical friction time formula applied just after the subhalo has been dissolved (Binney & Tremaine 1987):

$$t_{\text{df}} = \alpha_{\text{fric}}(\Theta_{\text{orb}}) \frac{V_{\text{sub}}^2}{GM_{\text{sub}} \ln \Lambda},$$

where $\alpha_{\text{fric}}(\Theta_{\text{orb}})$ encloses information on the subhalo orbit.

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$V_{	ext{vir}}$ is the virial velocity of the host, $r_{	ext{sub}}$ and $r_{	ext{c}}$ are the mass and position of the subhalo relative to the host just before dissolution, and $\ln \Lambda = (1 + M_{h}/m_{\text{sub}})$ is the Coulomb logarithm with $M_{h}$ the virial mass of the host. We take $\alpha_{\text{vir}}(\Theta_{\text{orb}}) = 1.1717\eta^{0.78}$ (Boylan-Kolchin et al. 2008), where $\eta = j_{c}(E)$ is the orbital circularity of the subhalo relative to the halo center.\footnote{The subhalo has specific angular momentum $j$ and energy $E$, and $j_{c}(E)$ is the specific angular momentum of a circular orbit with the same energy and with a radius $r_{c}(E)$.}

The final cosmic time of the halo-halo central merger, $t_{\text{end}}$, is the sum of $t_{\text{dis}} + t_{\text{dif}}$; we consider that $t_{\text{end}}$ is a good approximation to the actual galaxy-galaxy merger epoch.

We note that the impact of a merger does not depend directly on the halo mass ratio at the start of the merger but rather on the central dynamical masses (inner dark matter, gas and stars) that interact in the final stages of the galactic merger.

### 2.2 Galaxy occupation

To follow the stellar and gas mass assembly of galaxies inside the main haloes, as well as the processes that affect the gas and stellar contents during mergers, we use a semi-empirical approach close to the one in Hopkins et al. (2009a, 2010). This approach yields stellar mass assembly histories that are consistent, by construction, with observational trends. The main steps for each present-day main subhalo in our MS samples are:

1. Extract the main branch of its merger tree;
2. Seed a central galaxy, the primary, at $z_{\text{seed}} \approx 3.5$ with stellar and gas masses given by the semi-empirical relations $M_{\text{s}}(M_{h}, z)$ (Firmani & Avila-Reese 2010) and $M_{g}(M_{h}, z)$ (Stewart et al. 2009), see Appendix A for the analytical formulae;
3. Identify the start of a given merger, $z_{\text{start}}$, along the main branch ($z_{\text{start}} \leq z_{\text{seed}}$) and assign a galaxy to the infalling halo, the secondary, according to the semi-empirical relations $M_{\text{s}}(M_{h}, z_{\text{start}})$ and $M_{g}(M_{h}, z_{\text{start}})$;
4. Follow the evolution of the secondary by means of semi-analytic recipes assuming that the satellite galaxy does not accrete more gas (moderate quenching); for this, its gas mass is distributed in an exponential disc that transforms gas into stars with a local Kennicutt-Schmidt law and ejects gas at each radius due to SN feedback in form of energy-driven outflows (for details see Appendix A3 of Paper I);
5. Compute the galaxy-galaxy (central halo) merging time, $t_{\text{end}} = t_{\text{dis}} + t_{\text{dif}}$;
6. Estimate the bulge (and disc) masses of the primary galaxy after coalescence at $t_{\text{end}}$, using physical recipes for the bulge growth calibrated by numerical simulations (see §§ 2.2 below);
7. Repeat items ii–vi until reaching $z = 0$, taking care of each merger, the bulge growth, and updating at each $z$ the properties of the central galaxy according to the $M_{\text{s}}(M_{h}, z)$ and $M_{g}(M_{h}, z)$ relations.

It is important to remark that in our scheme, after a major merger happens, and the bulge has formed, the mock galaxy will likely continue growing (it depends on the halo mass assembly history and the $M_{\text{s}}(M_{h}, z)$ and $M_{g}(M_{h}, z)$ relations). We assume that this "smooth" growth corresponds to the disc only. Once a new merger happens, the bulge may then grow according to item vi. This is supported by numerical simulations, whence several authors have shown that even after a major merger, the disc may regenerate from the available gas and/or rebuild by late gas accretion (for theoretical works see e.g., Hopkins et al. 2009a, Governato et al. 2004, Hopkins et al. 2009b, Teytavuk et al. 2011, and for observational evidence see Hammer et al. 2009, Puech et al. 2012).

#### 2.2.1 Initial conditions

The empirical relations we use are poorly constrained at $z > 3$ and the mass aggregation and merger histories of the less massive haloes are not reliable for these epochs due to resolution issues. We therefore choose an initial redshift $z_{\text{seed}} \approx 3.5$, where we ought to define an initial condition for the $B/T$ ratio of the seeded galaxies. In Paper I, we assumed that all galaxies are initially pure discs. The galaxy population obtained at $z \sim 0$ is essentially independent of this initial condition because haloes and galaxies grow significantly after more than 10 Gyr of evolution. The $B/T$ ratio of even the most massive bulge-dominated galaxies is mainly established at $z \sim 2$, due to the major merger activity these galaxies suffer at these epochs (see §§ 2.2.2 below).

Because our aim here is to study the morphological mix up to $z \sim 3$, and make comparisons with observations, the initial conditions need to be treated more carefully than in Paper I since it influences the results near this epoch, at least down to $z \sim 1.5$. Thus, we assume that if a given halo at $z_{\text{seed}}$ has a mass larger than the corresponding to a 2-$\sigma$ halo, then its central galaxy is seeded with $B/T=0.9$; otherwise, the galaxy is assumed to start as a pure disc. This implies that only the most massive haloes at $z_{\text{seed}}$ host bulge-dominated galaxies at that epoch.

Both theory and observations indicate that most galaxies should be indeed disc-dominated at redshifts as high as 3–4. For example, the gas fraction-dependent model of Hopkins et al. (2009b) shows a much higher fraction of disk galaxies ($B/T < 0.25$) at different masses compared to bulge-dominated galaxies ($B/T > 0.7$) at $z = 3$. Hydrodynamical simulations constrained to reproduce today a massive spiral galaxy (Eke et al. 2003) and a massive spheroidal galaxy (Naab et al. 2009), show a disk-like structure (with Sérsic index $n < 2.5$) at $z \sim 3$ in both cases. Regarding observations at $z > 2$, several studies of morphology, $B/T$ ratio, Sérsic index, etc. show that disc, late-type galaxies are clearly more abundant, even for massive galaxies (Bruce et al. 2012, Buitrago et al. 2013, Mortlock et al. 2013). In Section 4.2 we discuss in detail many of the results from these works.

Nevertheless, at high redshifts there is also a (small) fraction of massive galaxies that are already bulge-dominated (elliptical) or are in the process of becoming

\footnote{A collapsed structure of mass $M$ is said to have a peak height $\nu = \delta^{2}(z_{\text{col}})/\sigma^{2}(M)$, where $\sigma$ is the linear mass variance and $\delta_c$ is the critical overdensity required for spherical collapse. A 2-$\sigma$ halo of mass $M$ has $\nu = 2$ at $z = z_{\text{col}}$.}
bulge-dominated (sub-millimeter galaxies, SMGs). According to observational studies, the massive, old ellipticals are likely descendants of SMGs (e.g., Hickox et al. 2012; Riechers et al. 2013; Toft et al. 2014), being both associated to massive, clustered, high-\(\sigma\) haloes. Haloes with higher \(\nu\) values (more massive than the average) collapsed earlier than those with lower values, and thus, they have been subjected to a larger number of major mergers (e.g., Lagos et al. 2002). High-\(\sigma\) haloes are associated to high peaks in the density fluctuation field, and high peaks are clustered and surrounded by other peaks, i.e., the whole region has a higher density and collapses earlier than the average region for that scale (Bardeen et al. 1986; Bond et al. 1991). As it will be clear in Section 4.2, the observed fraction of massive bulge-dominated galaxies at \(z = 2 - 3\) is nearly reproduced with our assumption of haloes with \(\nu \geq 2\) at \(z_{\text{seed}} \sim 3.5\) hosting galaxies with \(B/T = 0.9\). We emphasize once again that for most of our results, the initial conditions are already not relevant for \(z \lesssim 1.5\).

2.2.2 Satellite galaxies and merger rates

Regarding the fate of galaxies once they become satellites, the semi-analytical model used to follow them implies that their stellar mass growth is only slightly less healthy than the one of centrals of the same mass (Paper I). Semi-empirical studies seem to confirm this behavior (Watson & Conroy 2010; Puech et al. 2012). Here we use also relevant for of the primary, of dynamical mass (Hopkins et al. 2010; Puech et al. 2012). Here we use also the haloes mass relation (hereafter SHMR), \(M_h(M_\ast, z)\), given in (Rodríguez-Puebla et al. 2013; Wetzel et al. 2013). In Paper I we have explored also the case of extreme satellite quenching (the stellar and gas masses of the satellites do not change since the time of accretion), and obtained an unrealistically low fraction of classical-like bulges.

We highlight that, as shown in Paper I, the stellar major merger rates as a function of \(z\) obtained with our \(\Lambda\)CDM-based semi-empirical fiducial model are in good agreement with several observational inferences (see also Hopkins et al. 2010; Puech et al. 2012). Here we use also this fiducial model, which corresponds to the stellar-to-halo mass relation (hereafter SHMR), \(M_h(M_\ast, z)\), given in Firmani & Avila-Reese (2010) and the evolving satellite case described above. In \(\S4.1\) we discuss the effects on our results when varying the SHMR evolution.

2.3 Bulge growth channels

The bulge growth in our scheme is driven by galaxy mergers, but this growth is not limited only to the acquisition of stars from the secondaries. The three channels of stellar mass bulge growth used in (vi) of the previous section are:

- (a) incorporation of all the stars of the merged secondary;
- (b) disc instability-driven transport of a fraction of stars in the primary galaxy, \(f_{\text{relaxed}}^{\text{p+s}}\);
- (c) newly formed stars in central starbursts produced by a fraction of the gas from both merging galaxies, \(f_{\text{burst}}^{\text{p+s}}\).

In the last stages of coalescence, the surviving dynamical mass of the secondary \(M_2\) collides with the central region of the primary, of dynamical mass \(M_1\). The dynamical mass is defined as the sum of dark, stellar, and gas masses inside the halo scale radius, \(r_s\), where the halo mass distribution is approximated by the NFW density profile (Navarro et al. 1997). Thus, \(r_s = r_{\text{crit}}/c\), where \(c\) is the halo concentration; the \(c(M_{\ast}, z)\) relation of (Gao et al. 2008) is used. During coalescence, the collisionless components of both systems are subject to rapid changes of the gravitational potential that broaden their energy distributions leading towards an equilibrium state. This relaxation process drives the stars originally rotating in discs towards random orbits forming a spheroidal remnant. A simple dynamical argument shows that the stars in the primary disc affected by the action of the secondary are those within a radius enclosing the mass corresponding to \(\sim M_2/2\); the stars at larger radii in the disc are also perturbed but likely they are re-arranged into final configurations that are not far from the original ones. Thus, the fraction of the primary stellar disc that relax into the central spheroid, \(f_{\text{relaxed}}^{\text{p+s}}\), is roughly given by the dynamical mass ratio, \(\mu_{\text{eff}} \equiv M_2/M_1\). A large set of numerical simulations performed by (Hopkins et al. 2009a) confirm this approximation, but in more detail, they suggest a slightly non-linear dependence on \(\mu_{\text{eff}}\): \(f_{\text{relaxed}}^{\text{p+s}} \approx \mu_{\text{eff}} \times 2(1+\mu_{\text{eff}})^{-1}\), with \(a = 0.3 - 0.6\) (Hopkins et al. 2009b). We adopt this correction and use \(a = 0.3\) for our fiducial model.

During final coalescence, the interaction generates also a non-axisymmetric response in the galactic discs that morphologically resembles a bar. The resulting stellar and gaseous bars are however out of phase because gas is collisional and stars are not. Because of this, the stellar bar torques the gas bar draining its angular momentum. In this way, the cold gas is effectively removed from the original discs and transformed into stars, during a starburst, in the bulge of the remnant. This process is efficient within a region inside a critical radius \(r_{\text{crit}}\), which depends on the merger mass ratio and relative orientation and orbit of the progenitors, as well as their stellar and gaseous content. A parametrization of this ratio \(r_{\text{crit}}\), obtained from numerical simulations, is given in Hopkins et al. 2009a; we use this parametrization to calculate \(f_{\text{burst}}\) (see details in Paper I).

As showed in Paper I, bulges are composite, i.e., their stars are acquired by the three channels. However, for massive galaxies, \(M_\ast > 10^{11}\ M_\odot\), channel (a) dominates; for smaller galaxies, channel (b) dominates; and channel (c) contributes with only a minor fraction (<10\%) of the bulge mass in all the cases. Note that we do not account for intrinsic secular disc instabilities, which typically are associated with the formation of pseudo-bulges. However, our channel (b) can be associated also with the formation of pseudo-bulges (stars come from the same disc), while channel (a) will likely give rise to a classical bulge.

The dominion of a given channel as a function of \(M_\ast\) is closely related to the merger history of individual galaxies and their gas fractions. Most of the massive galaxies assembled a significant fraction of their stellar masses by major stellar mergers with small gas fractions, which leads to the growth of prominent bulges dominated by stars from the secondaries (see middle panels of Fig. 3 in Paper I). For less massive galaxies, minor/minuscule stellar mergers with high gas fractions dominate, which leads to (small) bulges formed mainly from dynamically perturbed stars of the primary disc (the stellar mass merger ratio is very small but the dynamical mass merger ratio -due to the high gas fraction- is large.
enough to produce the disc instability; see right panels of Fig. 3 in Paper I).

3 RESULTS

We now present the results of the semi-empirical approach described above for the case of the fiducial model. We recall that: (i) the analysed mock galaxies have been defined at $z = 0$ to be in distinct haloes; therefore these galaxies are centrals; and (ii) the evolutionary trends shown below refer to the evolution of these present-day central galaxies. If a halo (galaxy) is distinct (central) at $z = 0$, then the it is very likely that it was distinct (central) in the past as well. Thus, we are confident that our results refer mostly to distinct haloes and central galaxies at all redshifts, and that the populations of our “evolved” central galaxies at different redshifts describe well the overall population of central galaxies at a given redshift. For example, we have checked that the Galaxy Stellar Mass Function at $z = 0$ agrees well with the measured one from observations.

3.1 Evolution of the morphological mix as a function of mass

A notable prediction of the semi-empirical model is the strong dependence of the $B/T$ ratio on stellar mass at $z = 0$, with central galaxies smaller than $M_* \sim 10^{10} M_\odot$ having typically $B/T < 0.2$, and larger central galaxies having higher $B/T$ values as $M_*$ increases (Paper I; see also Hopkins et al. 2009). The median $B/T$ ratio versus $M_*$ and the $1\sigma$ regions of the distribution are plotted for $z = 0$ galaxies in the upper panel of Fig. 1 (black solid line and diagonal-line dashed area). In this figure we also plot observational inferences that will be discussed in Section 4. In the lower panel we show the model data at $z = 0$ (black solid line and diagonal-line dashed area) and $z = 2$ (red dashed line and vertical dashed area). We can appreciate two main results regarding the evolution of the $B/T-M_*$ relation: (i) From $z = 0$ to $z = 1$, the average of the $B/T-M_*$ relation almost does not change, while from $z = 1$ to $z = 2$ a significant reduction of the $B/T$ ratio is observed at all masses. (ii) The scatter in the $B/T$ distribution is lower at $z = 0$ than at higher redshifts, showing that the morphology of central galaxies, as traced by the $B/T$ ratio, becomes better defined at later epochs. At a given epoch, for a given $M_*$, the scatter of the semi-empirical galaxies (stars connected by the black line and the shaded area), the means of the observed sample of galaxies from Cibinel et al. 2013 (dots connected by the red line). Lower panel: as in the upper panel for the semi-empirical galaxies but at three redshifts: $z \sim 0$ (black solid line and diagonal-line shaded area), $z \sim 1$ (blue dotted line and dotted shaded area), and $z \sim 2$ (red dashed line and vertical-line shaded area).

Figure 1. Distributions of the $B/T$ ratio as a function of stellar mass. Upper panel: the median and $1\sigma$ scatter of the semi-empirical galaxies (stars connected by the black line and the shaded area), the means of the observed sample of galaxies from Cibinel et al. 2013 (dots connected by the red line). Lower panel: as in the upper panel for the semi-empirical galaxies but at three redshifts: $z \sim 0$ (black solid line and diagonal-line shaded area), $z \sim 1$ (blue dotted line and dotted shaded area), and $z \sim 2$ (red dashed line and vertical-line shaded area).

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Figure 2 shows the fractional distributions as a function of $M_*$ of the semi-empirical galaxies with $B/T$ ratios $< 0.1$ (red line), between 0.1 and 0.45 (blue line) and $> 0.45$ (black line). This plot can be interpreted as the morphological mix of galaxies if the $B/T$ ratio is assumed to be a good indicator of the distribution. The distributions are shown at 6 redshift bins: 0-0.1, 0.2-0.3, 0.4-0.6, 0.7-1.0, 1.3-1.6, 1.9-2.2, from top-left to bottom-right, respectively. At $z \sim 0$, “bulgeless” ($B/T< 0.1$) galaxies are the most frequent for log($M_*/M_\odot$) $\lesssim 10.3$, disc-dominated galaxies (0.1 $\leq B/T < 0.45$) are the most frequent for 10.3 $\lesssim$log($M_*/M_\odot$) $\lesssim 10.9$, and for larger masses, the bulge-dominated galaxies ($B/T \geq 0.45$) are already the most frequent. For redshifts up to $z \sim 1$, the morphological mix remains qualitatively the same. In more detail, from $z = 1$ to $z = 0$, there are two quantitative differences in the fractional distributions: an increase of bulgeless galaxies at low masses (see below for an explanation of this result), and an increase of galaxies with $B/T > 0.45$ at very high masses. A strong change in the morphological mix is observed at redshifts higher than $z \sim 1$: bulgeless galaxies highly dominate and the bulge-dominated galaxies become rare, even at the largest masses. Since $z \sim 1.5$, the morphological mix is already qualitatively different with respect to lower redshifts. At $z \sim 2$, 73% of all galaxies more massive than log($M_*/M_\odot$)=9 have $B/T < 0.1$, while only $\approx 25\%$ of the galaxies more massive than log($M_*/M_\odot$)=11 are bulge-dominated.

In Fig. 3 we plot the evolution of the $B/T$ ratio of our semi-empirical galaxies, normalized to their present-day...
value. The galaxies are divided into three groups according to their present-day $B/T$ value (as indicated in the figure), and the corresponding median and 1σ regions of the distribution for each $z$ are plotted. The upper and lower panel are for galaxies less and more massive than $M_\star = 3 \times 10^{10} M_\odot$, respectively.

For the less massive galaxies (upper panel), most of those that end today with $B/T < 0.1$ (the majority) had larger $B/T$ ratios in the past (up to $z \sim 1$); this explains what is observed in Figs. 1 and 2. These galaxies have formed a merger-induced bulge by $z \sim 1$, after that their stellar masses kept growing in the smooth (no merger) regime in such a way that their discs grow, making their $B/T$ ratios very small by $z \sim 0$. The very few low-mass galaxies that today have larger $B/T$ ratios, e.g. $B/T > 0.45$, assembled their bulges later on average ($z \sim 0.5$), with almost no change in their morphology since then. For the massive galaxies (lower panel), their $B/T$ ratio becomes defined on average earlier than for less massive galaxies; the trends of the $B/T$ ratio evolution for the different present-day morphologies are similar to those described above for the low-mass galaxies, but much weaker. The massive bulge-dominated galaxies ($B/T > 0.45$ at $z = 0$) acquired their morphology between $z \sim 1.5$ and $0.5$, and since then, their $B/T$ ratios have increased very little.

### 3.2 The setting of the bulge-dominated galaxy population

In Fig. 2 we plot the median of $z_{\text{morph}}$, the redshift at which a present-day bulge-dominated (early-type) central galaxy attained a $B/T$ value larger than 0.45 (solid line), i.e. when it became of early-type; the dashed region shows the 1σ region of the distribution. The plot shows that the less massive the present-day bulge-dominated galaxy is, the later it attained such a morphology. The scatter in $z_{\text{morph}}$ increases for less massive galaxies. However, recall that the fraction of $z = 0$ low-mass bulge-dominated galaxies is very small (Paper I), thus, the large scatter at $M_\star < 7 \times 10^{10} M_\odot$ could be just due to low-number statistics. We also plot the median redshift, $z_{\text{assem}}$, at which 50% of the present-day bulge-dominated galaxy has been dynamically assembled (black dashed line); the black shaded area shows the 1σ region of the distribution. From Fig. 4 we can see that $z_{\text{morph}}$ and $z_{\text{assem}}$ are closely related, which implies that the dynamical mass assembly of the $z = 0$ bulge-dominated galaxies is driven by major mergers (see also Paper I), and their merger histories are such that, on average, the larger the galaxy, the earlier it suffered the last major stellar merger that transformed it into a bulge-dominated one (see also Hopkins et al. 2009b).

Our results show that present-day early-type central galaxies assembled under a ΛCDM merger-driven scenario, follow mass assembly and morphology downsizing trends,
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Figure 3. Evolution of the $B/T$ ratio normalized to the present-day value. The medians and 1σ regions of the distribution of the semi-empirical galaxies grouped in three samples according to their $B/T(z=0)$ value are plotted: blue line and shaded area, green line and shaded area, and red line and shaded area are for $B/T(z=0)$ lower than 0.1, in between 0.1 and 0.45, and higher than 0.45, respectively. The upper (lower) panel is for present-day central galaxies smaller (larger) than $M_*=3\times10^{10}\,M_\odot$.

Figure 4. The median redshift and the 1σ region of the distribution at which present-day bulge-dominated semi-empirical galaxies of mass $M_*$ attained this morphology (magenta solid line and dot-shaded area) and 50% of this mass (black dashed line and diagonal-line shaded area). Galaxies clearly follow a morphological and mass downsizing trend.

i.e., the less massive the early-type galaxy, the later it assembled half its stellar mass and the later it became bulge dominated. Besides, on average, these galaxies transit to bulge-dominated after they attained half their masses, except the most massive ones. The mass assembly downsizing is just a consequence of the halo mass aggregation histories and the empirical SHMRs we have used. From this combination, the larger the present-day $M_*$ is for a given galaxy, the earlier it assembled most of its mass (see e.g., Firmani & Avila-Reese 2010; Behroozi et al. 2013a). The possible physical explanation behind this is that massive galaxies assembled most of their masses by early efficient wet mergers, thus, their growth is slowed down, in spite that their host haloes continue growing. This is because of (i) the long radiative cooling time of the gas in haloes with high circular velocities, and (ii) the efficiency of AGN feedback for massive galaxies (e.g., Croton et al. 2006; Cook et al. 2009).

Several independent observational pieces of evidence show that early-type galaxies follow indeed a mass assembly downsizing (e.g., Cimatti et al. 2006; Thomas et al. 2010; Pozzetti et al. 2010), although probably stronger than in our case. Semi-analytic models obtain an opposite behavior for the dynamical mass assembly of early-type galaxies (for a comparison of several models, see Fig. 18 in Pozzetti et al. 2010). This finding has been used as an argument against the $\Lambda$CDM scenario.

Is there a typical mass for those central galaxies that are transiting to bulge-dominated systems ($B/T > 0.45$) at a given epoch? The magenta (cyan) stars joined by a solid line in Fig. 5 show the median of the distribution of stellar masses of galaxies making this morphological transition at a given redshift bin. The shaded area brackets the first and third quartiles of the distribution. Have in mind that this plot takes into account the number of galaxies at each mass. Since most of bulge-dominated galaxies are massive but massive galaxies are not dominant in number, we consider only those with $M_*(z=0)>10^{10}\,M_\odot$, although for completeness, we plot also the median for the case $M_*(z=0)>10^9\,M_\odot$, cyan solid line. The current morphological transition mass does not vary significantly with $z$. The scatter in the distribution of this mass at each $z$ is clearly larger than the possible change with $z$. Note that, despite including all galaxies with $M_*(z=0)>10^9\,M_\odot$, the median morphology transition mass is at all $z$ larger than $M_*=2.5\times10^{10}\,M_\odot$, in agreement with the fact that most of low-mass galaxies were never bulge dominated.

The black solid line in Fig. 5 corresponds to the current “quenching” transition mass given in Firmani & Avila-Reese (2010), based on the connection of the semi-empirical SHMR relations at different $z$’s with the average $\Lambda$CDM halo mass aggregations histories. Using this connection, it is possible to infer the $M_*$ growth histories from the SHMRs. From these histories we can find an active to passive transition mass at each $z$, i.e., the epoch when the stellar mass growth was almost halted. Since here we use the same SHMRs than in Firmani & Avila-Reese (2010), the average transition mass is roughly the same as in that paper. Galaxies above the black solid line in Fig. 5 are on average passive while those below are mostly active.
active (in the sense of stellar mass growth, which can be associated mainly to the star formation activity).

From Fig. 5 we learn that at redshifts higher than \( z \sim 0.5 \), the galaxies in the process of transforming into bulge dominated are mostly still active star forming (blue) galaxies. For lower redshifts, the morphological transitions happen mostly already in the passive regime of these (red) galaxies, likely through dry mergers. This picture may be supported by the observational results of Moresco et al. (2013), see also Pozzetti et al. (2011) at \( z < 1 \). By using different definitions for early-type galaxies, they suggest that these galaxies, at masses \( M_\star < 10^{11} M_\odot \), first experienced a transition in color from blue to red, and then in morphology. On the other hand, at \( z > 1 \), Talia et al. (2013) found that only \( \sim 33\% \) of all their morphological ellipticals are red and passive galaxies, while the rest of these ellipticals are star-forming galaxies. This suggests that morphological transformations at \( z > 1 \) are occurring before the transitions in star formation activity (or color), as indicated in Fig. 6.

4 COMPARISON WITH OBSERVATIONS

Before comparing our results in more detail with direct observations, it should be emphasized that the bulge/disc decomposition of observed galaxies is a very difficult task (see e.g. Graham 2001; MacArthur et al. 2004; Allen et al. 2006; Laurikainen et al. 2007; Fisher & Drory 2008; Tasca & White 2011; Simard et al. 2011). On the other hand, since the \( B/T \) ratio and morphology of a galaxy depend on its luminosity (mass), determinations of the \( B/T \) distribution or the morphological mix are strongly constrained by the completeness of the studied sample. Due to these difficulties, there are only a few studies of bulge/disc decomposition applied to local volume-limited samples that can be used to obtain fair statistics on the \( B/T \) ratio as a function of \( M_\star \). The situation is much worse at higher redshifts (see below). Another possible issue when comparing with observations is that our results are only shown for central galaxies, whereas observational results can also include satellite galaxies. However, the total number fraction of satellites is relatively low (20–25%) at \( z \sim 0.1 \) (Yang et al. 2007). This fraction decreases drastically to higher redshifts (Knobel et al. 2012), so that the contamination of satellites at high \( z \) is not expected to be relevant, specially for massive galaxies. In the following, we attempt to compare our results with the few observational studies on \( B/T \) statistics and evolution as a function of \( M_\star \); at high redshifts, most works report indicators of morphology rather than \( B/T \) ratios, in such a way that we have to roughly associate these indicators with corresponding \( B/T \) values.

4.1 Local galaxies

In Fig. 1 where we plotted the \( B/T \) ratio vs \( M_\star \) at \( z \sim 0 \) for our semi-empirical galaxies, we also reproduce observational results for two local volume-limited samples of galaxies: (i) \( \sim 1000 \) galaxies from the SDSS with \( M_\star \geq 10^{10} M_\odot \) (Gadotti 2009), circles connected by the red line; only their central galaxies were used, see Paper I for details), and (ii) 99 galaxies with \( M_\star \geq 10^{10} M_\odot \) in the local 11 Mpc volume (taken from Fisher & Drory 2011, squares connected by the blue line). Recent determinations of the \( B/T \) ratio for a sample of \( \sim 1100 \) group galaxies (\( z \sim 0.05 \), not from a volume-limited sample) presented in Carollo et al. (2013) and Cibinel et al. (2013) are also shown (\( B/T \) ratio in the \( I \)-band as black circles with error bars). Overall our results follow the same trend than the observational inferences (see also the SDSS results by Skibba et al. 2012), which actually have a large scatter and differ among them. It seems that for \( M_\star \geq 10^{10} M_\odot \), our \( B/T \) ratios are lower on average than observations. A more quantitative comparison is using the \( B/T \) distribution (histogram) for volume-limited samples above a given \( M_\star \); as shown in Paper I our results agree well with the few available observational samples, and even the fractions of classical and pseudo bulges are roughly reproduced. See also Section 3.4.

In a recent paper, using the cross-match of the SDSS and RC3 catalogs given in Wilman & Erwin (2012), Wilman et al. (2013) estimate the local fractions of elliptical galaxies as a function of \( M_\star \). For \( M_\star > 3 \times 10^{10} M_\odot \), the overall fraction is 0.08\( \pm 0.01 \); this fraction raises to \( \approx 0.4 \) for galaxies above \( 6 \times 10^{11} M_\odot \). As these authors suggest, elliptical galaxies can be associated to those with \( B/T > 0.7 \). The fraction of our local galaxies more massive than \( 3 \times 10^{10} M_\odot \) with \( B/T > 0.7 \) is 0.12 \( \pm 0.05 \) and it also increases if the mass threshold is increased.
4.2 High-redshift galaxies

It is only in the last years that a few observational works have appeared reporting reliable morphologies, and even bulge/disc decompositions, for relatively large samples of massive galaxies at high redshifts by using high resolution images, mainly obtained with the Hubble Space Telescope. Unfortunately, the indicators used to define the morphologies are different among different works. Therefore, in order to compare the observational results with the predicted evolution of the B/T ratio, a rough equivalence for these different morphological indicators with the B/T ratio should be established.

Based on ∼8600 galaxies from the zCosmic Evolution Survey (zCOSMOS; Scoville et al. 2007), and using the Zurich Estimator of Structural Types (ZEST), Oesch et al. (2010) studied the evolution of the morphological mix of galaxies at stellar masses $> 5 \times 10^{10} M_\odot$ from $z = 0.2$ to $z = 1$. ZEST is based on structural parameters such as ellipticity, concentration, asymmetry, the second-order moment of the light distribution, $M_{20}$, and the Gini coefficient (Scarlata et al. 2007). Oesch et al. (2010) grouped galaxies into five morphological classes. Here we re-group these galaxies into three broader classes and assign to these classes a range of B/T ratios in order to compare them with our semi-empirical galaxies: elliptical (E) and bulge-dominated (B) galaxies are assigned to a first group with $B/T > 0.45$; spiral galaxies with intermediate bulge properties (S) are assigned to a second group with $0.1 < B/T \leq 0.45$; disc-dominated (D) and irregular (I) galaxies are assigned to a third group with $B/T \leq 0.1$.

Oesch et al. (2010) report the evolution of the mass fractions corresponding to different morphological classes for two mass bins. The medium and bottom panels of Fig. 6 reproduce the Oesch et al. (2010) results re-grouped into the three aforementioned groups; black, blue, and red stars with error bars (connected by dashed lines), respectively. The corresponding mass fractions from the semi-empirical model are shown with black, blue and red solid lines, respectively. The dotted-dashed regions are Poissonian errors in the number counts. In the top panel we show the model predictions for smaller galaxies. The general trends of the mass fractions with $z$ and $M_\ast$ are similar between the predictions and the observational results of Oesch et al. (2010), as can be seen in the medium and bottom panels. The morphological mix from observations changes moderately from $z \sim 1$ to $z = 0.2$: the fraction of bulge-dominated galaxies increases towards lower $z$, while the fraction of other classes decreases. The semi-empirical results show, overall, less relative evolution of the mass fractions with $z$ and $M_\ast$ as can be seen in the medium and bottom panels. The main difference between predictions and observations is that the mass fraction of massive, $M_\ast > 10^{11} M_\odot$, bulge-dominated ($B/T > 0.45$) galaxies is higher by 2-3 $\sigma$ in the model than in observations (bottom panel).

Using the zCOSMOS data and ZEST, Kovač et al. (2010) determined the number fraction of early-type galaxies (E+B types), $f_{\text{early}}$, as a function of $M_\ast$ at different redshifts and in different environments. As above, we assume that E+B types correspond to $B/T > 0.45$ and plot the Kovač et al. (2010) results for field galaxies in the panels of Fig. 2 with the closest $z$ bins to those reported by these au-
series of massive galaxies (Avila-Reese et al. 2012). The dot-shaded areas bracket the Poisson errors of the number counts. The triangles with error bars connected by short-dashed lines correspond to $B/T$ ratios measured from galaxies observed from $z \sim 1$ to $z \sim 3$ by Bruce et al. (2012).

Figure 7. Number fraction of the semi-empirical galaxies more massive than $10^{11} M_\odot$ according to their $B/T$ values (indicated by the color code in the legend) as a function of $z$ (solid lines). The dot-shaded areas bracket the Poisson errors of the number counts. The triangles with error bars connected by short-dashed lines correspond to $B/T$ ratios measured from galaxies observed from $z \sim 1$ to $z \sim 3$ by Bruce et al. (2012).

Figure 8. Number fraction of bulge- and disc-dominated semi-empirical galaxies (purple and cyan colors, respectively) as a function of $z$, from $z \sim 0$ to $z \sim 3$. The upper (lower) panel is for galaxies of masses $10^{10} - 3.16 \times 10^{10} M_\odot$ ($> 10^{11} M_\odot$). The dot-shaded areas bracket the Poisson errors of the number counts. The squares with error bars connected by short-dashed lines correspond to observations by Buitrago et al. (2013).

According to Fig. 7, the trends in the morphological mix evolution of the semi-empirical and observed massive galaxies are quite similar. One can say that the redshift range $2 < z < 3$ is the era of massive discs. In this redshift range, a substantial fraction of both our semi-empirical (see Fig. 2) and observational (see Bruce et al. 2012) massive galaxies are almost pure discs, $B/T < 0.1$. In the range $1 < z < 2$, the fraction of massive pure discs systems falls dramatically in favor of disc+bulge systems. At $z \sim 1$, while bulge-dominated systems are on the rise, galaxies comparable to present-day giant ellipticals are a minority. Note that from $z \sim 2$ to $z \sim 1$, the fraction of systems with $B/T > 0.7$ ($B/T < 0.3$) increases (decreases) more in the observational sample than in our case. However, at $z < 1$ the fraction of semi-empirical massive galaxies with $B/T > 0.7$ rises strongly.

Buitrago et al. (2013) reported the morphological mix evolution from $z = 3$ to $z \sim 0$ for massive galaxies, $M_* > 10^{11} M_\odot$, using a statistically representative sample of nearly 1000 galaxies from the SDSS, the Palomar Observatory Wide-field InfraRed/DEEP2, and the GOODS NICMOS surveys. These authors applied a qualitative visual morphological classification in addition to a quantitative estimate based on the Sérsic index $n$. The latter parameter is well correlated with $B/T$ in the sense that higher $n$ val-
ues correspond to higher $B/T$ ratios (Bruce et al 2012). In the lower panel of Fig. 8, we reproduce the number fraction evolution of the Buitrago et al. (2013) sample divided in two groups, disc-dominated galaxies ($n < 2.5$; cyan squares with error bars) and bulge-dominated galaxies ($n > 2.5$; purple squares with error bars). We identify the former objects as those with $B/T < 0.45$ and the latter as those with $B/T > 0.45$ and plot the corresponding fractions as a function of $z$ for our semi-empirical sample of galaxies (cyan and purple lines, respectively). The corresponding dot-shaded areas show the Poisson errors of the number counts.

The agreement in the morphological evolution of massive galaxies between our semi-empirical model and the observations reported in Buitrago et al. (2013) is remarkable. The fraction of bulge-dominated galaxies among the massive galaxy population has increased from $20-30\%$ at $z = 3$ to $\sim 80\%$ at $z = 0$. Bulge-dominated galaxies have been the predominant morphological class for massive galaxies only since $z = 1$ (see also Fig. 2). From the visual morphological classification, Buitrago et al. (2013) find that a fraction of their sample are merging/peculiar galaxies; this fraction is very low at low redshifts but it increases from $\sim 10\%$ at $z = 1$ to $\sim 35\%$ at $z \sim 3$. Most of these galaxies seem to correspond to those with $n < 2.5$. In the case of the massive semi-empirical galaxies, we find that the fraction of those suffering a major merger is similar to the one reported in Buitrago et al. (2012, see Paper I and elsewhere for detailed comparisons with observations).

The upper panel of Fig. 8 is analogous to the lower one but for the semi-empirical galaxies in the $10^{10} < M_\star/M_\odot < 3 \times 10^{10}$ mass bin. The fraction of bulge-dominated galaxies increases from virtually $0\%$ at $z = 3$ to $20\%$ at $z \sim 1.5$ and then again decreases, reaching $\sim 5\%$ at $z = 0$. As has already been seen in Figs. 2 and 3, a fraction of the low-mass galaxies may have attained a significant $B/T$ ratio by $z \sim 1 - 1.5$ but afterwards, the major merger rates at these scales are negligible in such a way that the posterior (significant) $M_\star$ growth happens only for the disc.

In a recent paper, Mortlock et al. (2013) extended the morphological classification of galaxies to lower masses ($M_\star > 10^{10}$ $M_\odot$) at $z > 1$ by using the Sérsic index $n$ reported by van der Wel et al. (2012) for $\sim 1100$ galaxies from the CANDELS/UDS field. The number fractions of bulge-dominated ($n > 2.5$) and disc-dominated ($n < 2.5$) galaxies with masses $10^{10} < M_\star/M_\odot < 3 \times 10^{10}$ remain roughly constant from $z \sim 3$ to $z \sim 1$. These fractions are approximately $70\%$ and $25\%$ for the former and latter galaxy types, respectively. A small fraction of galaxies ($\sim 5\%$) have undetermined $n$ index. These results are qualitatively similar to those shown in the upper panel of Fig. 8 although the fractions of bulge-dominated (disc-dominated) are higher (lower) for the observations than for the models. For masses larger than $3 \times 10^{10}$ $M_\odot$, Mortlock et al. (2013) find that the disc-dominated galaxies are more abundant than the bulge-dominated ones down to $z \sim 1.5 - 2$. At lower redshifts, the bulge-dominated galaxies start to be more abundant, in agreement with Bruce et al. (2012) and Buitrago et al. (2013), and therefore with our results.

![Figure 9. The SHMR relation at four redshifts as indicated in the legends. Solid lines are for the “moderately evolving” SHMR (Firmani & Avila-Reese 2010) and dashed lines are for the “slowly evolving” SHMR, resembling closely the results by Behroozi et al. (2013a).](image-url)

5 DISCUSSION

5.1 The case of a “slowly evolving” SHMR

An important ingredient in our scheme is the empirically constrained SHMR that we use at each redshift to assign stellar masses to the distinct haloes from the Millennium simulations (Section 2). We have used the SHMR parametrization given and constrained by Behroozi et al. (2011) and slightly modified by Firmani & Avila-Reese (2010) in order to make it continues from $z = 0$ to $z = 4$ (see Appendix A).

Several new constraints on the SHMR at different redshifts have appeared recently (e.g. Yang et al. 2012, Leauthaud et al. 2012, Wake et al. 2011, Moster et al. 2013, Behroozi et al. 2013a, Behroozi et al. 2013b, Wang et al. 2013). Some of them present a stronger evolution with $z$ than the SHMR used here, while others evolve less. According to Behroozi et al. (2013a), the SHMR changes little from $z = 0$ to $z = 4$. In order to explore the effects of the adopted SHMR evolution on the demographics and evolution of the $B/T$ ratio, we obtained new results changing the evolution of the Firmani & Avila-Reese (2010) SHMR parameters in such a way that the Behroozi et al. (2013a) SHMRs are closely reproduced from $z = 0.1$ to $z \sim 4$ in the halo mass range $10^{11} < M_h/M_\odot < 10^{13}$ (dashed lines in Fig. 9; see Appendix A for the parameter values of this SHMR).

In general, for the “slowly evolving” SHMR, the $B/T$ ratios are higher (specially at low masses) and the bulges assemble earlier than for the “moderately evolving” SHMR (fiducial case, Sections 3 and 4). Fig. 10 shows the $B/T$ distribution for the mock galaxies with $M_\star \geq 10^{10}M_\odot$ in these two cases. Observations from the Fisher & Drory (2011) sample are also shown with blue symbols with error bars. It is clear that the “slowly evolving” case is at odds with this observational sample, producing too few bulgeless galaxies,
contrary to the “moderately evolving” case that is in remarkable agreement with the Fisher & Drory (2011) observations (Paper I). However, at intermediate masses (10^{10} < M_*/M_⊙ < 10^{11}), the “slowly evolving” case is in slightly better agreement than the fiducial case with the observational results from Gadotti (2009) and Cibinel et al. (2013). For massive galaxies, M_*>10^{11} M_⊙, the “slowly evolving” SHMR produces too many bulge-dominated galaxies compared to the results of Buitrago et al. (2013) and Bruce et al. (2012), specially from z=3 to z~1.5 (see Fig. 11). For this case, the period 2<z<3 is not the era of massive discs as observations suggest. The mass fractions of galaxies with B/T > 0.45 (0.1 < B/T < 0.45) from z=1 to z=0.2 are also significantly higher (lower) than the observational results of Oesch et al. (2010); in particular, at z~1, the fraction of B/T > 0.45 galaxies in the mass range 5×10^{10} < M_*/M_⊙ < 10^{11} is two times higher than in Oesch et al. (2010).

Let us understand why the “slowly evolving” SHMR produces results different to the “moderately evolving” SHMR used in Section 3. For a given M_*, at the high-mass end of the SHMR and at high redshifts, the halo mass is significantly larger for the former than for the latter (see Fig. 9). This implies a larger fraction of high B/T galaxies at high z because of two effects: (i) the merger rate is higher for more massive haloes (see Paper I), and (ii) for a given z, the peak height of the density fluctuations corresponding to more massive haloes is higher, thus, there is a larger fraction of haloes with ν > 2 at zseed. Recall that we impose as our initial condition that if ν > 2 at zseed for a given halo, then its central galaxy is born with B/T=0.9 (see subsection 2.2.1).

In the low-mass side of the SHMR, M_h < 10^{12} M_⊙, the galaxies grow increasingly faster with time towards lower masses (downsizing in sSFR; Firmani & Avila-Reese 2010). This behavior is more dramatic for the “moderately evolving” SHMR used in the previous sections than for the “slowly evolving” SHMR. Therefore, while the discs continue growing in the former case, making the B/T ratios smaller, in the latter case the low-mass galaxies grow less, keeping their relatively high B/T ratios, acquired early during the active merging epochs. As a result, for low-mass galaxies formed in the “slowly evolving” SHMR case: (i) their B/T ratios are higher today and (ii) the morphological mix changes much less since z~1 than in the case of the “moderately evolving” SHMR used in previous sections as our fiducial case.

5.2 Is the ΛCDM-based bulge growth consistent with observations?

The semi-empirical model of bulge growth presented in Paper I and here is based on the cosmological ΛCDM scenario, specifically, it rests on the merger rates as a function of time that galaxies suffer insider the growing CDM haloes, with the spheroidal component (bulges) assembling as the result of merger-driven processes. Bulges acquire their stars from the merged secondaries, from the primary disc due to instabilities induced by the mergers (even those that almost do not contribute with stars but perturb the disc with their dynamical masses), as well as through stars formed in situ from the gas that is funneled to the center during mergers. These different channels may give rise to classical- and pseudo-like bulges residing in the same galaxy, i.e., bulges...
can be actually composite, with the pseudo bulge component being the product of merger-driven instabilities. By means of numerical simulations of 50 galaxies, Eliche-Moral et al. (2013) have shown that intermediate and major mergers indeed trigger significant internal secular evolution in the discs (difficult to isolate from the purely intrinsic disc instabilities), which is seemingly able to preserve the structural coupling of the bulge and the disc.

It is important to mention that in our model the galaxies formed in rare high-$\alpha$ massive haloes at $z_{\text{seed}} \sim 3.5$ are seeded as bulge dominated (see subsection 2.2.1), resembling a monolithic scenario rather than the hierarchical one. Since the stellar masses of massive galaxies almost do not grow further according to the semi-empirical SHMRs, the assumed high $B/T$ ratios for these galaxies remain in most of cases as such until the present day.

In Section 4 we have compared the semi-empirical results corresponding to our fiducial case with currently available direct observational studies of the morphological mix of galaxies at different redshifts. All the observed general trends of the fractions of galaxies with a given $B/T$ ratio as a function of $M_*$ and $z$ are in good agreement with our results. At this level, the ΛCDM-based semi-empirical approach we have used here to estimate the growth of bulges does not seem to face critical issues. At a quantitative level, our results are in most cases consistent with these observations, within the large systematic and statistical uncertainties.

However, we have found also a few quantitative discrepancies that should be discussed. Before that, it is worth noting that (i) observational studies at high redshifts typically report different morphological classes rather than $B/T$ ratios, and (ii) a criterion of morphological classification in the local universe is not always useful at high redshifts. For example, Talia et al. (2013) found that the parameters of asymmetry and $M_{20}$ are not effective in distinguishing morphologies at $z > 1$, in contrast to what is observed at $z \sim 0$. A similar result is found by Mortlock et al. (2013), thus suggesting that high $z$ galaxies are structurally different from their counterparts at low $z$. In general, disc galaxies are misclassified as spheroids due to the lower resolution of the images at high redshift, which removes the signatures of a disc structure. Therefore, it is possible that the observational fractions of bulge-dominated galaxies are overestimated at high redshifts.

The most noticeably quantitative difference among the semi-empirical galaxies and observations is in the mass fractions of massive galaxies, $M_* > 10^{11} M_{\odot}$, between $0.2 < z < 1$ (bottom panel of Fig. 5) observations from Oesch et al. (2010). Although qualitatively for both, models and observations, the mass fraction of massive objects is dominated by galaxies with an important bulge component, quantitatively, the mass fraction of model galaxies with $B/T > 0.45$ ($0.1 < B/T < 0.45$) is higher (lower) than that of the corresponding observed morphological class by 2-3σ. This discrepancy diminishes at lower redshifts. Note that the mass fraction takes into account the number fraction and the number density of galaxies. Since massive galaxies are rare, cosmic variance has probably an important role in their number densities. For the same zCOSMOS sample, the number fractions of bulge-dominated massive galaxies as reported in Kováč et al. (2010) are actually larger than in our case (see Fig. 2).

At intermediate masses, $10^{10} < M_*/M_{\odot} < 3.2 \times 10^{11}$, our fiducial model predictions show that the number fraction of disc-dominated galaxies completely dominates at all redshifts (upper panel of Fig. 3). This is in qualitative agreement with the observational results of Mortlock et al. (2013) reported at $1 < z < 3$. However, the model predicts a fraction greater than 0.8 for galaxies with $B/T < 0.45$, while the fraction of observed galaxies with Sérsic index $n < 2.5$ (disc-dominated systems) is not higher than 0.8 at any $z$. Finally, at low redshifts, the model seems to predict slightly lower $B/T$ ratios of galaxies of intermediate masses than observations (see Fig. 4 and the middle panel of Fig. 6); there is also a possible slight excess of pseudo-bulges over classical bulges as compared with the local observations (Paper I).

Interesting enough, the ΛCDM-based semi-empirical fiducial model, instead of predicting an excess of high $B/T$ classical bulge galaxies at intermediate masses with respect to observations, it seems to predict a slight deficit of them. Recently, alternative mechanisms of bulge formation have been proposed. For example, the fragmentation of the gas-rich disc into clumps that migrate towards the centre can form a large spheroid in intermediate-mass galaxies at $z \sim 1 - 2$ (Dekel et al. 2009; Perez et al. 2013). According to the latter authors, this spheroid has the features of a classical bulge. This extra mechanism could perfectly fit in our scheme, increasing the fraction of higher $B/T$ intermediate-mass galaxies from $z \sim 3$ to $z \sim 1$. If the bulges thus formed of some of these galaxies do not increase much more down to $z = 0$, then they will contribute to the classic-bulge dominated population today.

6 CONCLUSIONS

The mass aggregation and merger histories of a subsample of present-day distinct haloes from the Millennium Simulations are used to calculate the stellar mass growth and merger histories of galaxies. Galaxies are seeded at the centre of the distinct haloes (and in subhaloes at the accretion time) by means of the stellar-to-halo and gas-to-stellar mass relations constrained by observations at different redshifts. The merger-driven bulge growth of these galaxies is calculated by using physically motivated recipes, which account for three channels of bulge mass acquisition: stars from the merged secondary, stars transferred from the primary disc due to instabilities induced by the merger, and stars formed from gas funneled from both merging galaxies. At intermediate-mass, the first and second channels combine in such a way that the bulges are actually composite (Paper I). At small masses, the second channel dominates by far, producing pseudo-like bulges, while at large masses, the first channel dominates, producing classical-like bulges.

Our semi-empirical model offers a transparent way to map the ΛCDM halo mass accretion and merger histories to the stellar mass growth of the galaxies and their bulges. In the following, we present the main results and conclusions obtained with this semi-empirical model using a SHMR that moderately changes with $z$.

- The morphological ($B/T$ ratio) mix at different stellar masses remains qualitatively the same since $z \sim 1$, while for $z > 1 - 1.5$, it changes towards a larger population of disc-dominated and bulgeless galaxies. In the $0 < z < 1$ period,
the most abundant galaxies are: bulgeless \((B/T < 0.1)\) at low masses, \(M_\ast \lesssim 10^{10} M_\odot\); disc-dominated \((0.1 < B/T \lesssim 0.45)\) at intermediate masses, \(10^{10} \lesssim M_\ast/M_\odot \lesssim 8 \times 10^{10}\), and bulge-dominated \((B/T > 0.45)\) at large masses, \(M_\ast \gtrsim 8 \times 10^{10} M_\odot\). In the 1 < \(z < 3\) period, galaxies with \(B/T \lesssim 0.45\) dominate by far at masses below \(M_\ast \sim 10^{11} M_\odot\), and for \(z > 2\), galaxies with \(B/T < 0.1\) dominate at all masses.

- For massive galaxies, \(M_\ast > 10^{11} M_\odot\), the fraction of bulge-dominated systems rises systematically with cosmic time, becoming the dominant population at lower redshifts.

Taking this into consideration, we have compared our model to semi-analytical model predictions, this is in agreement with observations. The dominant channel of bulge growth for the massive galaxies is the acquisition of stellar mass from the secondary(ies) in major mergers.

- At \(z > 1\), the galaxies that become bulge-dominated (their \(B/T\) ratios overcome 0.45) are on average still actively growing in mass, presumably by in situ star formation. At \(z \lesssim 0.5\), a significant fraction of the galaxies in transition to bulge domination are already passive, in such a way that the merger(s) they subsequently suffer to become bulge-dominated are presumably dry.

- The predicted local bulge demographics as a function of mass is in agreement with observations (see also Paper I). At higher redshifts, the few observational studies available use instead of the \(B/T\) ratio, other morphological definitions. Taking this into consideration, we have compared our models to observations from Oesch et al. (2010), Kováč et al. (2010), Bruce et al. (2012), these authors actually measure the \(B/T\) ratio, Buitrago et al. (2013), and Mortlock et al. (2013). We found that, within the large observational systematic and statistical uncertainties, the trends of the fractions of galaxies with a given \(B/T\) as a function of \(M_\ast, z\) are in agreement. It is particularly remarkable the excellent agreement with Buitrago et al. (2013) in the fractions of bulge- and disc-dominated massive galaxies from \(z = 3\) to \(z \sim 0\).

- According to our merger-driven bulge growth predictions, the \(\Lambda\)CDM scenario does not face the problem of producing a deficit of bulgeless or disc-dominated galaxies at intermediate/low masses. If any, it seems to predict slightly more of such galaxies with respect to local and high \(z\) observations. Thus, there is room for including intrinsic (not induced by mergers) mechanisms of bulge growth, for instance, the central migration of gas-rich clumps produced by instabilities of the gaseous discs at \(z \sim 1 - 2\), and the secular bar formation and dissolution in evolved stellar discs.

We note that our semi-empirical model results depend on the way the SHMR evolves. For a "slowly evolving" SHMR (e.g. Behroozi et al. 2013a), the predicted bulge demographics and evolution of the morphological mix are in tension with observations: the predicted \(B/T\) ratios of low mass galaxies are too high, and the bulge assembly of bulges in massive galaxies is predicted to occur too early.

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APPENDIX A: THE SEMI-EMPIRICAL RELATIONS

The shape of the SHMR used here has been proposed by Behroozi et al. (2010) on the basis of its ability to map the halo mass function into a Schechter-like Galaxy Stellar Mass Function down to \(M_\ast \sim 10^9 M_\odot\). Behroozi et al. (2010) constrained with observations the parameters of this SHMR from \(z = 0\) to \(z = 1\) and from \(z = 1\) to \(z = 4\) independently. Firmani & Avila-Reese (2010) slightly modified the Behroozi et al. (2010) SHMR in order to describe its evolution in a continuous way from \(z = 0\) to \(z = 4\). The analytical formula is as follows:

\[
\log(M_h(M_\ast)) = \log(M_1) + \beta \log \left( \frac{M_\ast}{M_*^0} \right) + \frac{\log \left( \frac{M_\ast}{M_*^0} \right)}{1 + \left( \frac{M_\ast}{M_*^0} \right)^\gamma} - \frac{1}{2}. \tag{A1}
\]

The dependence on \(z\) is introduced in the parameters of eq. A1 as:

\[
\log(M_1(a)) = M_{1,0} + M_{1,a} (a - 1),
\]

\[
\log(M_*^0(a)) = M_{*,0} + M_{*,a} (a - 1) + \chi(z),
\]

\[
\beta(a) = \beta_0 + \beta_a (a - 1),
\]

\[
\delta(a) = \delta_0 + \delta_a (a - 1),
\]

\[
\gamma(a) = \gamma_0 + \gamma_a (a - 1),
\]

where \(a = 1/(1 + z)\) is the scale factor. The function \(\chi(z)\) controls the change with \(z\) of the peak value of the \(M_\ast\)-to-\(M_h\) ratio. Firmani & Avila-Reese (2010) defined \(\chi(z)\) in order to roughly reproduce the peak evolution found in Behroozi et al. (2010):

\[
\chi(z) = -\chi_0 z (1 - 0.378 z (1 - 0.085 z)); \tag{A3}
\]

if \(\chi = 0\), then the peak of the \(M_\ast\)-to-\(M_h\) ratio remains the same at any \(z\). The first two formulae in eq. A2 control the position of the \(M_\ast/M_h\) peak at each \(z\), while the last three control the shape of the \(M_\ast/M_h\) curves. The set of parameter values reported in Firmani & Avila-Reese (2010) and used here are reproduced in the second column of Table A1.

In Section 5.1 we experimented with a slowly evolving SHMR, based on the recent constraints by Behroozi et al. (2013a). By keeping the same parametrization given by eqs. A1 and A2, the parameter values that closely reproduce

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the Behroozi et al. (2013a) SHMRs are reported in the third column of Table A1.

The $M_\ast-M_{\text{gas}}$ relation and its change with redshift used in our model (see Section 2.2) has been proposed by Stewart et al. (2009) as a fit to the available data at $z \sim 0$ and at higher redshifts:

$$\frac{M_{\text{gas}}}{M_\ast}(z) = 0.04 \left( \frac{M_\ast}{4.5 \times 10^{11} M_\odot} \right)^{-\alpha(z)}, \quad (A4)$$

where $\alpha(z) = 0.59(1+z)^{0.45}$. For small masses, $M_{\text{gas}}/M_\ast$ can be very large, particularly at higher redshifts. Given the high degree of observational uncertainty in this regime, we opt to set $M_{\text{gas}}/M_\ast \leq 100$, which is the maximum observed value reported in Stewart et al. (2009).

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