

THE GROWTH OF GALAXY STELLAR MASS WITHIN DARK MATTER HALOS

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ABSTRACT

We study the evolution of stellar mass in galaxies as a function of host halo mass, using the “MPA” and “Durham” semi-analytic models, implemented on the Millennium Run simulation. For both models, the stellar mass of the central galaxies increases rapidly with halo mass at the low-mass end and more slowly in halos of larger masses at the three redshifts probed ($z \sim 0, 1, 2$). About 45% of the stellar mass in central galaxies in present-day halos less massive than $\sim 10^{12} h^{-1} M_{\odot}$ is already in place at $z \sim 1$, and this fraction increases to $\sim 65\%$ for more massive halos. The baryon conversion efficiency into stars has a peaked distribution with halo mass, and the peak location shifts toward lower mass from $z \sim 1$ to $z \sim 0$. The stellar mass in low-mass halos grows mostly by star formation since $z \sim 1$, while in high-mass halos most of the stellar mass is assembled by mergers, reminiscent of “downsizing.” We compare our findings to empirical results from the Sloan Digital Sky Survey and DEEP2 surveys utilizing galaxy clustering measurements to study galaxy evolution. The theoretical predictions are in qualitative agreement with these phenomenological results, but there are large discrepancies. The most significant one concerns the number of stars already in place in the progenitor galaxies at $z \sim 1$, which is about a factor of two larger in both semi-analytic models. We demonstrate that methods studying galaxy evolution from the galaxy–halo connection are powerful in constraining theoretical models and can guide future efforts of modeling galaxy evolution. Conversely, semi-analytic models serve an important role in improving such methods.

Key words: cosmology: theory – galaxies: evolution – galaxies: halos – galaxies: statistics – galaxies: stellar content – large-scale structure of Universe

1. INTRODUCTION

In the current paradigm of structure formation, galaxies form within cold dark matter halos. The formation and evolution of these halos are dominated by gravity and can be well predicted from high-resolution cosmological numerical simulations and analytic models. The assembly of the stellar content of galaxies, however, is governed by more complex physics, and the relation between galaxies and dark matter halos and the detailed physical processes of galaxy formation and evolution are only partially understood.

A useful approach to explore galaxy formation within dark matter halos is the semi-analytic modeling (SAM) of galaxy formation (e.g., Cole et al. 1994, 2000; Benson et al. 2003; Croton et al. 2006; Bower et al. 2006). In such models, halos identified from high-resolution N -body simulations are “populated” with galaxies using analytical prescriptions for the baryonic evolution. Within the SAM approach, galaxies change as the original stars evolve and new stars form. They also change their stellar content and increase their mass by merging with other galaxies. Different feedback or pre-heating mechanisms, such as those caused by star formation, active galactic nuclei, or the photoionizing ultraviolet background, also impact at different stages of a galaxy’s life and are implemented in the models at different levels. These models have been successful in reproducing several measured properties including the galaxy luminosity and stellar mass functions (see, e.g., Croton et al. 2006; Bower et al. 2006; Fontanot et al. 2009).

Different phenomenological methods have been developed to connect galaxies with dark matter halos. One commonly used approach is the Halo Occupation Distribution framework (HOD; e.g., Jing et al. 1998; Peacock & Smith 2000; Seljak 2000;

Scoccimarro et al. 2001; Berlind & Weinberg 2002), which characterizes the relationship between galaxies and halos in terms of the probability distribution, $P(N|M)$, that a halo of virial mass M contains N galaxies of a given type, together with the spatial and velocity distributions of galaxies inside halos. The HOD parameters are constrained using galaxy clustering measurements from large galaxy surveys and theoretically known halo clustering. Similar approaches include the conditional luminosity function (see Yang et al. 2003), which describes the average number of galaxies as a function of luminosity that reside in a halo of mass M , and abundance matching schemes (Conroy et al. 2006; Conroy & Wechsler 2009; Moster et al. 2010; Guo et al. 2010; Neistein et al. 2011a; Rodriguez-Puebla et al. 2011), which monotonically connect galaxy luminosity or stellar mass to halo mass by matching the abundances of halos and galaxies.

HOD models have been mostly used to learn about the relationship between galaxies and halos at a fixed epoch (e.g., Bullock et al. 2002; Zehavi et al. 2005, 2011; Zheng et al. 2008, and references therein). Recent studies have started using them to also explore galaxy evolution by combining the inferred galaxy–halo connection at different redshifts with the evolution of dark matter halos provided by theory (Zheng et al. 2007; White et al. 2007; Seo et al. 2008; Wake et al. 2008, 2011). In particular, Zheng et al. (2007, hereafter ZCZ07) develop a phenomenological approach to extract information about galaxy evolution from $z \sim 1$ to $z \sim 0$ by performing HOD modeling of two-point correlation functions of DEEP2 and SDSS galaxies. With the inferred galaxy–halo connection at two redshifts, they establish an evolutionary link using the typical growth of dark matter halos obtained from numerical simulations.

Even with the progress made in establishing the evolutionary link between galaxies and halos, our understanding of the

specifics of stellar mass growth within the dark matter halos is still far from complete. Galaxies can grow their stellar mass by star formation, accretion of smaller satellite galaxies, or major merging. It is important to quantify the contribution of all these processes in order to have a complete picture of the assembly history of galaxies within their host dark matter halos. ZCZ07 derive the mean stellar masses of central galaxies at $z \sim 1$ and $z \sim 0$ as a function of the present-day host halo mass. After roughly accounting for the contribution of merging of central and satellite galaxies, they infer the star formation contribution to the stellar mass assembly. They find that in central galaxies located in relatively low-mass halos ($\sim 5 \times 10^{11} h^{-1} M_{\odot}$) the bulk of the stellar mass results from star formation between $z \sim 1$ and $z \sim 0$, while only a small fraction of stars formed since $z \sim 1$ in central galaxies of halos as massive as $\sim 5 \times 10^{12} h^{-1} M_{\odot}$. For these massive halos, merging becomes more important and constitutes the dominant contribution to the stellar mass growth (see Figure 9 in ZCZ07 for details). The results reflect the so-called downsizing star formation pattern in which the sites of active star formation shift from high-mass galaxies at early times to lower-mass systems at later epochs (e.g., Cowie et al. 1996; Juneau et al. 2005; Fontanot et al. 2009; Avila-Reese & Firmani 2011), manifested in terms of halo mass.

In this paper, we study the theoretical predictions for stellar mass evolution as a function of dark matter halo mass using SAM catalogs. One of the main advantages of the SAMs is that we can trace the full evolution of the individual galaxies within their dark matter halos, allowing an explicit study of the different processes that contribute to the buildup of the stellar content of galaxies. We compare and contrast these predictions with the results of ZCZ07. We gauge the potential of the phenomenological methods to constrain galaxy formation models, as well as test some of the assumptions of such methods. In particular, we check the validity of the simple evolutionary approach presented by ZCZ07.

For these purposes, we use two SAM catalogs, the “MPA” (Croton et al. 2006; De Lucia & Blaizot 2007) and “Durham” (Bower et al. 2006; Font et al. 2008) catalogs produced from the Millennium Run cosmological N -body simulation (Springel et al. 2005). We mainly focus on the stellar mass growth as a function of halo mass since $z \sim 1$ for ease of comparison with ZCZ07. Nonetheless, we briefly study also the stellar mass growth since $z \sim 2$ in the MPA catalog to explore the processes involved in galaxy formation at higher redshifts. These SAM catalogs have been previously used to study the stellar mass evolution in galaxies (e.g., Guo & White 2008; Stringer et al. 2008; Fontanot et al. 2009). However, those studies focus on the integrated stellar mass to make a direct comparison to observations and did not investigate in detail its evolution as a function of halo mass. Most physical processes involved in galaxy formation models depend explicitly on the mass of the dark matter halo. Additionally, the modeling of other observables such as the galaxy–galaxy merger rate strongly relies on the precise knowledge of the galaxy–halo connection (see, e.g., Hopkins et al. 2010). Thus, it is physically meaningful and informative to study galaxy evolution as a function of halo mass.

The paper is organized as follows. Section 2 describes the SAM catalogs that we use and the sample selection. In Section 3, we present and discuss our results for the growth of stellar mass as a function of halo mass. In Section 4, we compare our results to those found by ZCZ07 and we conclude in Section 5.

2. MOCK CATALOGS AND GALAXY FORMATION MODELS

In this work, we use the publicly available mock galaxy catalogs produced with the “MPA” (Croton et al. 2006; De Lucia & Blaizot 2007) and “Durham” (Bower et al. 2006) semi-analytic models of galaxy formation, both based upon dark matter halo evolution in the Millennium Run simulation (Springel et al. 2005). The Millennium Run followed the evolution of $\sim 10^{10}$ dark matter particles in a Λ CDM universe. The simulation uses a periodic box of $500 h^{-1}$ Mpc on a side with mass resolution per particle of $8.6 \times 10^8 h^{-1} M_{\odot}$. The initial conditions of the simulation were generated with cosmological parameters obtained from the combined analysis of 2dFGRS and WMAP1 cosmic microwave background data. The halos in the simulation were identified in each time step using a friend-of-friends algorithm with a linking length of 0.2 times the mean particle separation. More details can be found in Springel et al. (2005).

In the SAMs, galaxies are assumed to form at the center of dark matter halos. The evolution of the baryonic component of galaxies is modeled using simple but physically motivated analytic prescriptions. These include radiative cooling of hot gas, star formation in the cold disk, supernova feedback, black hole growth, and active galactic nucleus (AGN) feedback through the “quasar” and “radio” epochs of AGN evolution, metal enrichment of the intergalactic and intracluster medium, as well as galaxy morphology shaped through mergers and merger-induced starbursts.

These models are tuned to fit the low-redshift galaxy population and are aimed at reproducing integrated galaxy observables. To that effect, the SAMs recover reasonably well the galaxy luminosity function in different bands (e.g., Croton et al. 2006; Bower et al. 2006) as well as the stellar mass functions for a range of redshifts (e.g., Bower et al. 2006; Fontanot et al. 2009; but see also Li & White 2009; Marchesini et al. 2009). The predictions for the fraction of blue and red central galaxies, however, are not fully correct (see Baldry et al. 2006), and modifications to the treatment of gas cooling (e.g., Viola et al. 2008) and the AGN feedback (e.g., Baldry et al. 2006) have been proposed to alleviate these discrepancies. The SAMs also appear to overestimate the fraction of red satellites (Weinmann et al. 2006; Coil et al. 2008; Kang & van den Bosch 2008; De Lucia 2009; Kim et al. 2009). Note that satellite galaxies in these models are treated differently than central galaxies. Only central galaxies accrete new material by cooling from the hot atmosphere of their halo, direct infall of cold gas, and the merging of satellites. Since no new material accretes onto satellites, their star formation ends when the cold gas is exhausted (see Croton et al. 2006). Satellites are also affected by different environmental processes that change their properties, which are not fully implemented in these models. For example, Kim et al. (2009) suggest that satellite–satellite mergers and tidal dissolution of satellites need to be included to better match the measured luminosity dependence of galaxy clustering.

The different SAMs adopt similar analytical prescriptions to treat the physical processes involved in galaxy formation and evolution. There are still, however, significant differences in the way the MPA and Durham SAMs deal with specific processes, such as the cooling of gas, the cut-off black hole mass for AGN feedback (see Stringer et al. 2008), and the dynamical treatment of the “orphan” satellite galaxies (Gao et al. 2004). Also, the two models are based on different halo merger trees which are

constructed in the post-processing stage of the simulation (see Bower et al. 2006; De Lucia & Blaizot 2007). Even though the halo merger trees are checked to be statistically compatible (G. De Lucia 2010, private communication), differences could arise at the level of individual galaxies, affecting some galaxy properties. See De Lucia et al. (2010) for a comparison of the effect of the different assumptions about gas cooling and galaxy mergers in these models.

The full SAM galaxy catalogs used in this work⁵ contain information for about 8 million galaxies brighter than $M_r = -17$. Several properties are available for each of these galaxies, including positions and velocities, magnitudes in several band passes (Johnson, Bush, 2MASS as well as the five SDSS bands), stellar mass, and mass of the dark matter halo in which the galaxy is located. For the halo mass we use M_{200} , the mass within a radius at which the mean interior density equals 200 times the overall mean matter density. It is important to note that these two SAMs assume different initial mass functions of stars. The MPA model assumes a Chabrier mass function (Chabrier 2003), while the Durham model uses the Kennicutt one (Kennicutt 1983). In order to make a direct comparison between the models, we consistently transform both to a “diet” Salpeter initial mass function (Bell et al. 2003), used also in ZCZ07.

We select from each catalog a random sample of 250,000 present-day central galaxies. For compatibility with the ZCZ07 results, we use in fact the $z \sim 0.1$ snapshot of the catalogs, as this is approximately the value of the median redshift for SDSS galaxies. We hereafter, however, loosely refer to it as $z \sim 0$, in comparison to the evolution since $z \sim 1$ and $z \sim 2$. For each present-day galaxy, we retrieve all its progenitors at $z \sim 1$ (and also at $z \sim 2$ in the MPA SAM) by following the merger tree of each present-day central galaxy. These progenitors can be central galaxies in dark matter halos, satellites located in subhalos or “orphan” galaxies, i.e., satellite galaxies whose parent dark matter subhalo was destroyed below the resolution limit of the simulation by tidal stripping and truncation (see, e.g., Gao et al. 2004). We define the *main* progenitor of a $z \sim 0$ galaxy as the central galaxy located in the most massive dark matter halo at the corresponding higher redshift ($z \sim 1$ for both catalogs and $z \sim 2$ for the MPA only). We have verified that defining the main progenitor as the most massive of the merger tree main branch (e.g., De Lucia & Blaizot 2007) does not change our results. Once all progenitors are identified, we can quantify the different contributions to the stellar mass of central galaxies, namely the stellar mass coming from the main progenitor, from the additional central galaxies (which we loosely call “smaller central galaxies”) and from satellites that merge into the central galaxies. These contributions include then the stellar mass that has formed by $z \sim 1$ in all progenitors. The remaining contribution to the present-day stellar mass in central galaxies arises from more recent star formation (in all progenitors).

3. STELLAR MASS GROWTH AS A FUNCTION OF HALO MASS

In this section, we first examine the ratio of stellar mass to halo mass as a function of host halo mass. We then study the evolution of stellar mass in central galaxies in the semi-analytic models. We also analyze the different contributions to the stellar

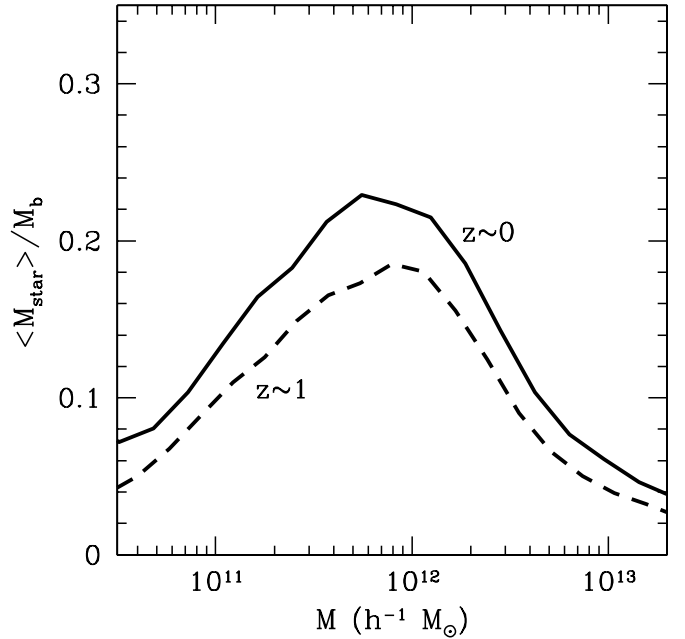


Figure 1. Baryon conversion efficiency in the central galaxies at $z \sim 0$ (solid line) and at $z \sim 1$ (dashed line) as a function of halo mass for the MPA SAM.

mass growth of central galaxies since $z \sim 1$. Finally, we briefly investigate the stellar mass growth since $z \sim 2$.

3.1. Stellar Mass to Halo Mass Ratio

A first fundamental quantity to investigate is the ratio of the central galaxy stellar mass to the hosting halo mass as a function of halo mass. Assuming a universal baryon fraction f_b , this ratio can be translated to the fraction of baryons converted to stars in the central galaxy. We thus define the *baryon conversion efficiency* as the central galaxy stellar mass (M_{star}) divided by the baryon mass $M_b = f_b M$, where M is the mass of the dark matter halo. This conversion efficiency represents the integrated value from the redshift of formation to the epoch in consideration, reflecting the fraction of baryons associated with halos that are converted into stars in that time period. We note that this quantity has also been referred to as the integrated star formation efficiency in some other works (e.g., ZCZ07; Conroy & Wechsler 2009; Wake et al. 2011; cf. Mandelbaum et al. 2006).

Figure 1 shows the baryon conversion efficiency in the central galaxies at $z \sim 1$ and $z \sim 0$ as a function of halo mass predicted by the MPA SAM. The baryon fraction adopted in the MPA SAM is $f_b = 0.17$, though the baryon fraction in any individual halo may vary from the global value. The conversion efficiency has a similar shape at both epochs, peaking at some characteristic mass and dropping toward both low- and high-mass ends. At $z \sim 0$, it peaks at halos of mass $\sim 5 \times 10^{11} h^{-1} M_{\odot}$, while at $z \sim 1$ the peak corresponds to more massive halos ($\sim 10^{12} h^{-1} M_{\odot}$). This trend is reminiscent of “archaeological downsizing” (e.g., Thomas et al. 2005; Neistein et al. 2006; Conroy & Wechsler 2009), shown here as a function of halo mass. Note that these results are direct predictions of hierarchical galaxy formation models. The fraction of baryons converted into stars at the peak is $\sim 23\%$ and $\sim 18\%$ for $z \sim 0$ and $z \sim 1$, respectively. The results for the Durham model are similar.

The drop of the conversion efficiency at the low-mass end is associated with the availability of cold gas in these halos,

⁵ The SAM galaxy catalogs can be downloaded from <http://www.g-vo.org/Millennium/>

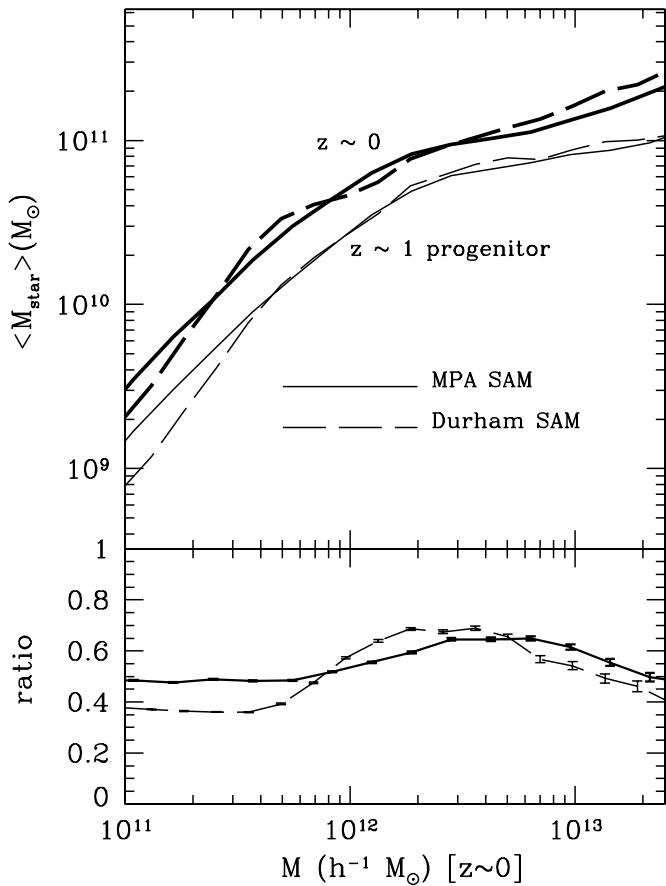


Figure 2. Mean stellar mass in $z \sim 0$ central galaxies and their $z \sim 1$ progenitor central galaxies as a function of the present-day halo mass. Top panel: the mean stellar mass in central galaxies at $z \sim 0$ (thick lines) and that of their $z \sim 1$ main progenitors (thin lines) as a function of the present-day halo mass, predicted by the MPA (solid lines) and Durham (dashed lines) SAMs. Bottom panel: the ratio between the stellar mass at $z \sim 1$ and $z \sim 0$ for the MPA (solid line) and Durham (dashed line) SAMs, representing the fraction of $z \sim 0$ central stellar mass that is in place in the $z \sim 1$ main progenitors. Error bars are the 1σ error in the mean.

which can be affected by photoionization heating and star formation feedback. The drop at the high-mass end is related to gas accretion becoming less efficient due to the high virial temperature and AGN feedback. Additionally, we are only considering here central galaxies, and in high-mass halos the stellar mass contributions from satellite galaxies can be substantial.

3.2. Stellar Mass Growth of Central Galaxies

Figure 2 shows the mean stellar mass in central galaxies at $z \sim 0$ (thick lines) and that of their $z \sim 1$ main progenitors (thin lines) as a function of the present-day halo mass. The results for the MPA catalog (solid lines) and the Durham catalog (dashed lines) are similar. At both redshifts, the stellar mass of the central galaxy increases rapidly with halo mass at the low-mass end and slowly at the high-mass end. The transition halo mass is approximately $10^{12} h^{-1} M_{\odot}$ at $z \sim 0$ and $2 \times 10^{12} h^{-1} M_{\odot}$ at $z \sim 1$.

The bottom panel shows the ratio between the stellar mass at $z \sim 1$ and $z \sim 0$, representing the fraction of the $z \sim 0$ central galaxy stellar mass already in place in the main progenitor galaxies at $z \sim 1$, as a function of present-day halo mass. The error bars on the ratios represent the 1σ error in the mean, and are rather small, due to the large number of galaxies contributing to

each mass bin. The ratios vary slightly with halo mass. For example, for a present-day halo of mass $5 \times 10^{11} h^{-1} M_{\odot}$, on average $\sim 50\%$ ($\sim 40\%$) of the stellar mass in the central galaxy is already in place in the $z \sim 1$ main progenitor for the MPA (Durham) model. The ratio gradually increases to $\sim 65\%$ for halos with mass \sim a few $\times 10^{12} h^{-1} M_{\odot}$, and it starts decreasing toward the highest halo masses probed in this work. The decrease of stellar mass ratio at the highest halo masses is in accord with the predictions for hierarchical assembly of massive galaxies (e.g., De Lucia et al. 2006; De Lucia & Blaizot 2007).

3.3. Different Contributions to the Stellar Mass Growth

The stellar mass in galaxies grows as a consequence of internal star formation or external infall of material (major and minor mergers). For the former, observational estimates (e.g., Salim et al. 2007; Noeske et al. 2007) often come from measuring the average star formation rate as a function of stellar mass and time. The amount of stellar mass gained through accretion is more difficult to measure directly. It is often estimated by simply taking the difference between the growth due to star formation and the total stellar mass at present.

In a SAM based on an N -body cosmological simulation, we have the full merger history of dark matter halos and galaxies. Thus, it is possible to track the complete evolution of the stellar mass due to both mergers and star formation as a function of the halo mass. In particular, following ZCZ07, we account for four different components of the assembly of stellar mass in central galaxies: stars in place in the main progenitor galaxies at $z \sim 1$, stellar mass from smaller central galaxies that merge to the central galaxy, stellar mass from any satellites (of the main progenitor or other smaller central galaxies) that merge with the central galaxy, and recent star formation.

Figure 3 presents the SAM predictions for these different contributions to the $z \sim 0$ central galaxy stellar mass as a function of the present-day halo mass, for both the MPA and Durham models. In each panel, the bottom curve (marked as “A”) denotes the fraction of stellar mass in place in the $z \sim 1$ main progenitor galaxies and is essentially the same ratio shown in the bottom panel of Figure 2. The area between curves “A” and “B” indicates the contribution of smaller central galaxies that have merged into the main progenitor. The area between curves “B” and “C” shows the contribution from satellite galaxies in all progenitor halos at $z \sim 1$ that merge with the $z \sim 0$ central galaxies. Consequently, the remaining stellar mass (from curve “C” to the top of the plot) arises from star formation since $z \sim 1$.

In the SAM data sets, the amount of star formation since $z \sim 1$ can also be estimated by integrating the star formation rate as a function of time. We do a crude calculation of this in the MPA SAM for three specific present-day halo masses and for a small subset of the galaxies, as a sanity check, by integrating the star formation rate for a subsample of main progenitors over 10 snapshots since $z \sim 1$. Accounting for the approximate nature of this calculation, we get consistent results.

The overall trends of stellar mass growth from the two SAMs are similar. It is evident that central galaxies in small halos grow mostly by star formation since $z \sim 1$, while the star formation contribution is small in high-mass halos. This could be explained by the fact that small halos are almost completely assembled by $z \sim 1$, so the new stellar mass must come from star formation. For intermediate halo masses, the contribution from merging becomes more significant, but star formation still contributes most of the stellar mass since $z \sim 1$. For high-mass halos, the contribution from mergers dominates and star formation is

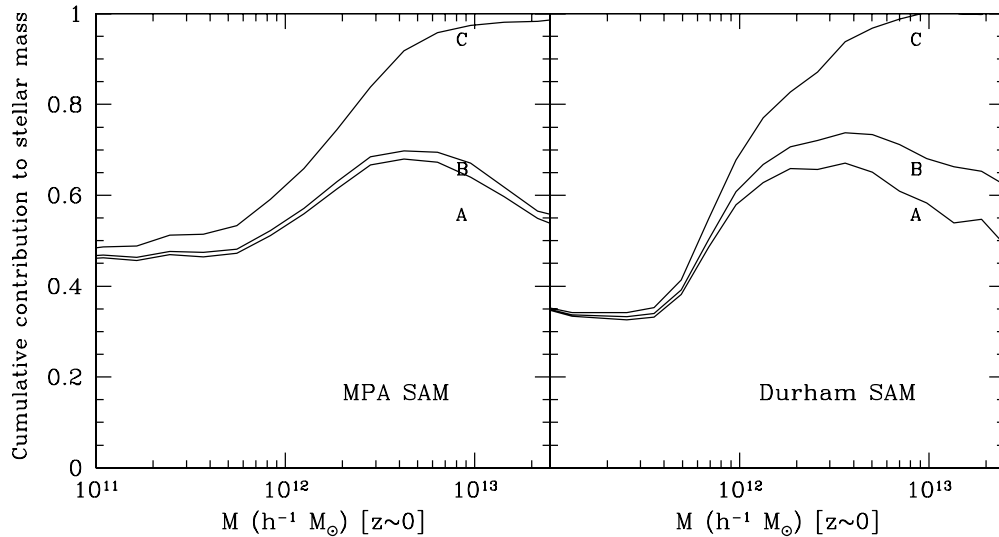


Figure 3. Different contributions to the present-day central galaxy stellar mass as a function of present-day halo mass shown for the MPA (left panel) and Durham (right panel) SAMs. The first curve from the bottom (denoted as “A”) is the stellar mass already in place in the main progenitors at $z \sim 1$. The area between lines “A” and “B” indicates the contribution of the smaller central galaxies that merge with the progenitor central galaxies. The area between curves “B” and “C” denotes the contribution of satellite galaxies. The remainder (from curve “C” to the top of the plot) is the stellar mass gained through star formation since $z \sim 1$.

negligible. This overall behavior is again similar to the observed “downsizing” trends, in this case referring to the fact that more massive galaxies form the bulk of their stars earlier than smaller galaxies (e.g., De Lucia et al. 2006; Stringer et al. 2008; Fontanot et al. 2009).

Some differences between the two SAM models are apparent. The stellar mass already in place in the $z \sim 1$ progenitors was compared in the bottom panel of Figure 2. With regard to the other components, the Durham model predicts a larger contribution from smaller central progenitors in halos with present-day mass larger than $\sim 10^{12} h^{-1} M_{\odot}$, while the MPA model produces a slightly larger contribution from satellite galaxies in low-mass halos. These discrepancies likely reflect the variations in the galaxy formation prescriptions of the two models and the underlying halo merger trees. Other contributing factors are the different assumptions regarding galaxy mergers and the treatment of “orphan” galaxies’ dynamics (De Lucia et al. 2010; G. De Lucia 2010, private communication).

3.4. Stellar Mass Growth Since $z \sim 2$

In this section, we explore the SAM predictions for stellar mass growth from higher redshifts, to gain further insight on the processes contributing to galaxy evolution and serve as a reference point for modeling higher-redshift observations. The interpretation of these predictions is complex since observations currently do not provide consistent indicators of stellar masses and star formation rates at these redshifts (see, e.g., Conroy & Wechsler 2009, Section 3.5 for a discussion). Also clustering data at $z \sim 2$ are relatively scarce for ZCZ07-like analyses (but see Wake et al. 2011 for a first attempt along these lines).

We study the stellar mass growth as a function of halo mass since $z \sim 2$ in the MPA catalog, using a smaller sample of 160,000 galaxies. The baryon conversion efficiency at $z \sim 2$ as a function of halo mass exhibits a similar shape and peak location as the $z \sim 1$ results (shown in Figure 1). The overall amplitude is slightly smaller, with a conversion efficiency of $\sim 16\%$ at the peak of the distribution. Our results for the growth of stellar mass are presented in Figure 4. The top panel shows the mean stellar mass in central galaxies at $z \sim 0$ (thick line) and

that of their $z \sim 2$ main progenitors (thin line), as a function of the present-day halo mass. The bottom panel presents the different contributions to the present-day central galaxy stellar mass. The different curves in this plot are the same as those in Figure 3, but referring now to $z \sim 2$, with curve “A” representing the stars already in place in the central galaxies at $z \sim 2$. The results for the Durham model are similar.

The trends are qualitatively very similar to the ones seen for the $z \sim 1$ progenitors in the previous sections. As expected, there is significantly less stellar mass already in place in the main progenitor at $z \sim 2$. The contribution from the smaller central galaxies is more significant than that for the $z \sim 1$ case, while the contribution of the satellites is roughly the same. As less stellar mass is in place at $z \sim 2$, the contribution of star formation from $z \sim 2$ to the present day is substantial, at all halo masses; it is about 10% for central galaxies in the highest mass halos probed and higher for those in lower mass halos.

4. COMPARISON WITH EMPIRICAL RESULTS

Zheng et al. (2007; ZCZ07) perform HOD modeling of the luminosity-dependent projected two-point correlation function for DEEP2 and SDSS galaxies, at $z \sim 1$ and $z \sim 0$, respectively. They infer the relationship between central galaxy luminosity and halo mass at these two redshifts. Stellar masses are derived from the galaxies’ luminosity and color, transforming these into relations between the central galaxy stellar mass and halo mass. Using the typical growth of dark matter halos, central galaxies of a given present-day halo mass are linked to $z \sim 1$ central galaxies residing in the corresponding progenitor halos. This allows for a study of stellar mass assembly over the past ~ 7 billion years as a function of host halo mass. An approximate method is used to estimate the different contributions of mergers and star formation to the growth of the stellar mass of central galaxies. In this section, we use the SAM results to gauge the potential of such phenomenological methods to constrain galaxy formation and evolution models. We first compare the stellar mass growth in central galaxies inferred by ZCZ07 from DEEP2 and SDSS galaxy clustering with that predicted by the

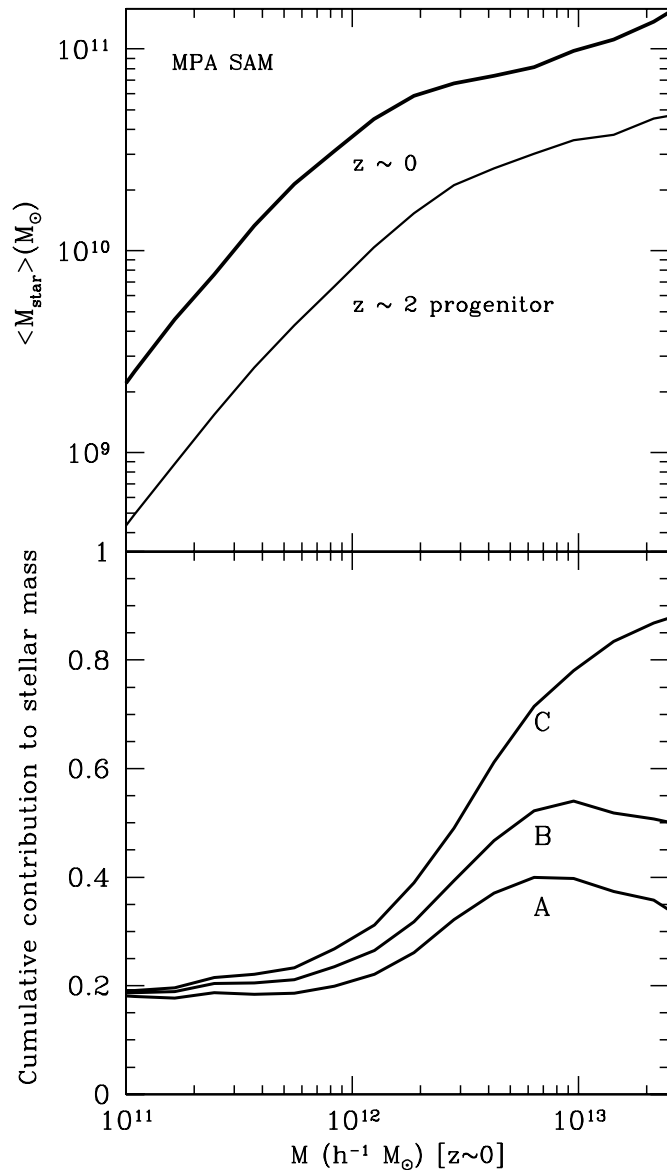


Figure 4. Top panel: mean stellar masses in central galaxies at $z \sim 0$ (thick line) and that of their $z \sim 2$ main progenitors (thin line), as a function of the present-day halo mass, predicted by the MPA SAM. Bottom panel: the different contributions to the present-day central galaxy stellar mass. Curves are the same as in Figure 3, except now referring to stellar mass evolution since $z \sim 2$.

SAM models. We then examine the validity of the assumptions used in the ZCZ07 approach.

4.1. Central Galaxy Stellar Mass Growth

We first examine the baryon conversion efficiency and its evolution from redshift $z \sim 1$ to 0 obtained using the MPA SAM model (our Figure 1) and in ZCZ07 (their Figure 10). Both approaches produce similar general trends with halo mass. They both exhibit peaked distributions at similar halo masses and a shift of the peak toward a higher mass at the larger redshift. The MPA SAM and ZCZ07 also find comparable values for the maximum conversion efficiency at $z \sim 0$. However, at $z \sim 1$, the SAM shows overall higher values than computed in ZCZ07 (peaking at 18% and 12%, respectively), which translates into a larger number of stars by that redshift.

Figure 5 shows the SAM predictions (solid lines) for the stellar mass as a function of halo mass and the results obtained by ZCZ07 (dashed lines), over the halo mass range they probe.

Although the SAMs and ZCZ07 methods produce similar trends, there are important quantitative disagreements between them. The main difference is that the SAMs predict many more stars already in place at $z \sim 1$ in the main progenitor galaxies compared to the ZCZ07 results. The differences are especially pronounced at medium and low halo masses. This may be related to the known fact that the SAMs produce too many M_* and lower-mass galaxies at high redshift (e.g., Kitzbichler & White 2007; Guo et al. 2011). At $z \sim 0$, on the other hand, the agreement is quite good for low-mass halos, while for high-mass halos (larger than $\sim 10^{12} h^{-1} M_\odot$) the SAMs seem to predict less stellar mass in central galaxies than ZCZ07. The AGN “radio mode” feedback becomes important on these mass scales (Bower et al. 2006), which suggests that the SAMs might be overestimating the strength of the feedback.

As for the fraction of stellar mass in place in the $z \sim 1$ progenitor central galaxies, the SAMs prediction is about twice that inferred by ZCZ07, as shown in the bottom panels of Figure 5. The error bars in the SAMs denote the 1σ scatter of the distribution around the mean, reflecting the stochasticity involved (in the halo mass–progenitor mass relation and in the merging and star formation history for halos at fixed present-day mass). Note that this discrepancy could be less dramatic, as there might be $\sim 25\%$ underestimation in the ZCZ07 calculation of the stellar mass at $z \sim 1$ due to DEEP2 red galaxy incompleteness (see ZCZ07 for details). This effect is shown by the dotted lines in the bottom panels. Even with this potential correction, the discrepancy is significant.

We note that these discrepancies are present at roughly the same level for *both* SAMs, indicating that their cause is of a more fundamental origin not reflected in the differences between the two models. It is also worth mentioning that the major discrepancy between the SAM and ZCZ07 predictions for the stellar mass growth appears to be present already at redshift 2. From the results presented in Section 3.4, we see that the number of stars in place in central galaxies by $z \sim 2$ predicted by the MPA SAM is of the order of the phenomenological results for the number of stars in place by $z \sim 1$.

The top panels of Figure 6 compare the predictions of the SAMs (solid lines) to the ZCZ07 results for the *total* stellar mass acquired through merging of smaller central and satellite galaxies on top of that already in place at $z \sim 1$, normalized by the final stellar mass at $z \sim 0$. For ZCZ07, we plot both the standard estimation (dashed line in each panel) and the conservative estimate including the possible 25% correction of the stellar mass at $z \sim 1$ (dotted line). Here the agreement is better, especially at high halo masses. The difference between these total contributions and the stellar mass at present day in halos of a given mass is essentially the contribution arising from star formation since $z \sim 1$.

Finally, the bottom panels of Figure 6 contrast the individual contributions to the stellar mass assembly in the SAMs (solid lines) and ZCZ07 (dashed lines), showing the relative contributions to the final central galaxy from mergers of smaller central galaxies (thick lines) and satellite mergers (thin lines). The individual contributions from these models are strikingly different. In ZCZ07, the main merger contribution to present-day central galaxies comes from mergers of the smaller central progenitor galaxies, while in the SAMs a larger contribution comes from satellite galaxies. As mentioned already in Section 3.3, the contribution from smaller central progenitor galaxies in the MPA model is particularly minor, while it is somewhat larger in the Durham model (see also De Lucia et al. 2010). These

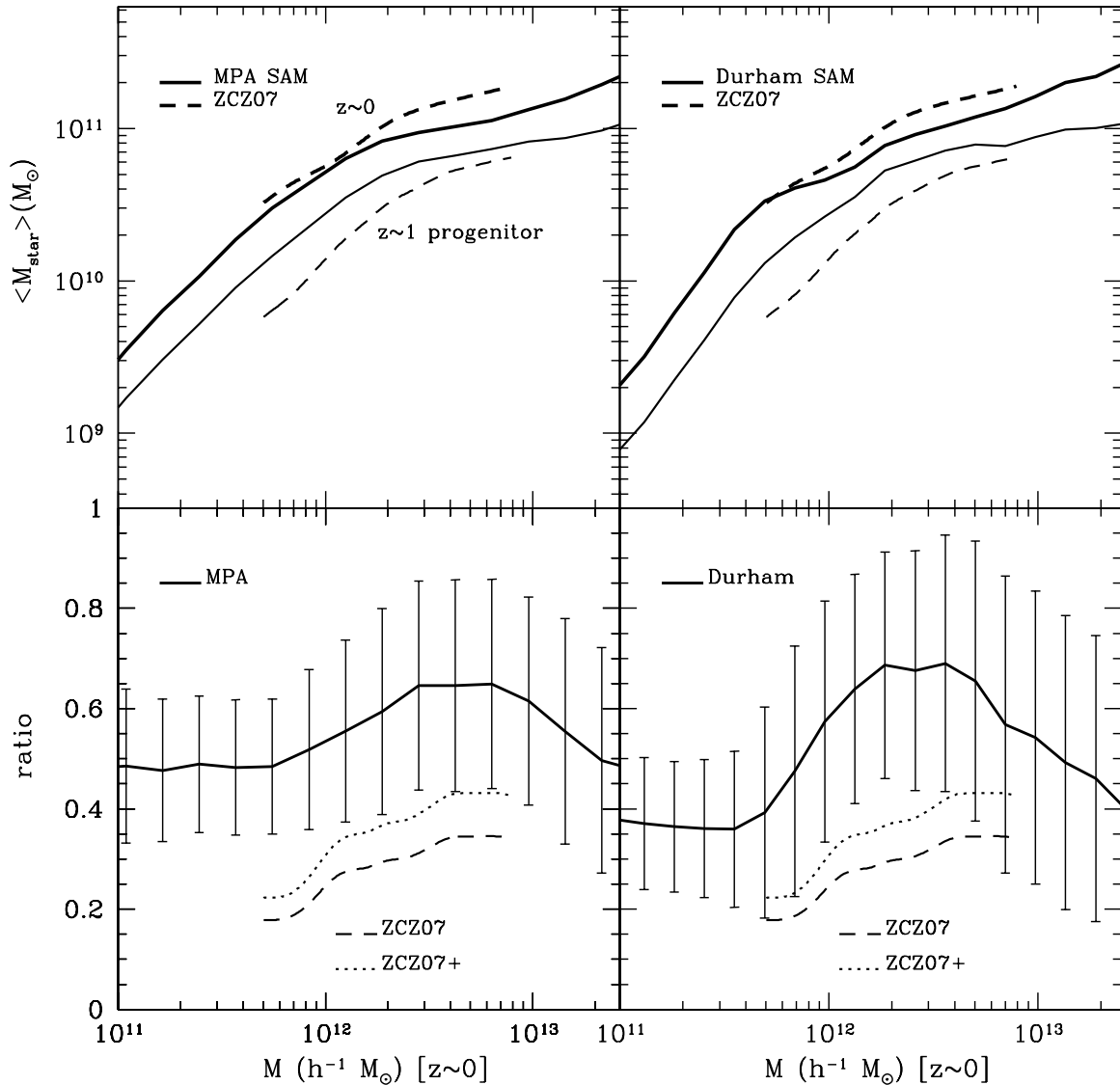


Figure 5. Top panels: comparison of the MPA (left, solid lines) and Durham (right, solid lines) SAMs with the ZCZ07 results (dashed lines) for the mean stellar mass in central galaxies at $z \sim 0$ and $z \sim 1$, as a function of present-day halo mass. Bottom panels: comparison of the SAMs (solid lines) and ZCZ07 results for the ratio of central galaxy stellar mass at $z \sim 1$ and $z \sim 0$ as a function of present-day halo mass. Error bars in the SAM predictions are the 1σ scatter of the distribution around the mean. The dashed line (denoted as “ZCZ07”) represents the standard ZCZ07 result. The dotted line (labeled as “ZCZ07+”) is the conservative estimation, assuming a 25% correction of the stellar mass in the DEEP2 sample (see the text for details).

differences are also related to the simplifying assumptions made in ZCZ07 discussed below.

4.2. Examining Assumptions in the ZCZ07 Approach

In this section, we use the SAM catalogs to test the validity of some of the assumptions adopted in the ZCZ07 method. We note that these tests can be done despite the discrepancies found between the SAMs and ZCZ07.

In ZCZ07, an evolutionary link is established between galaxy populations at the two epochs via the theoretically predicted growth of dark matter halos in which these galaxies reside. The first assumption we examine is related to the statistical nature of any such relation. ZCZ07 use the average relation between masses of present-day halos and that of their main progenitors at $z \sim 1$, obtained by the PINOCCHIO code (Monaco et al. 2002), with no accounting for the intrinsic scatter. This could, in principle, impact the estimation of the stellar mass growth.

Using the SAMs, where the full merger tree is known, it is possible to test this. For each individual $z \sim 0$ central galaxy, the SAM catalog provides its present-day stellar mass and host halo mass as well as its main progenitor stellar mass and host halo mass at $z \sim 1$. Based on these, we derive the stellar mass of central galaxies and that of the main progenitor galaxies as a function of the present-day halo mass, which by construction includes the scatter in the halo mass and progenitor halo mass relation. With the SAM catalog, we can also follow the ZCZ07 procedure to obtain the above relations by using the *average* growth of dark matter halos.

We perform such a test with the MPA catalog. Figure 7 compares the stellar mass evolution as a function of present-day halo mass obtained with those two different procedures. The solid lines are the results obtained using the individual halo growth information (presented already by the solid lines in Figure 2), while the dashed lines denote the predictions using the *average* halo growth. There are only negligible differences

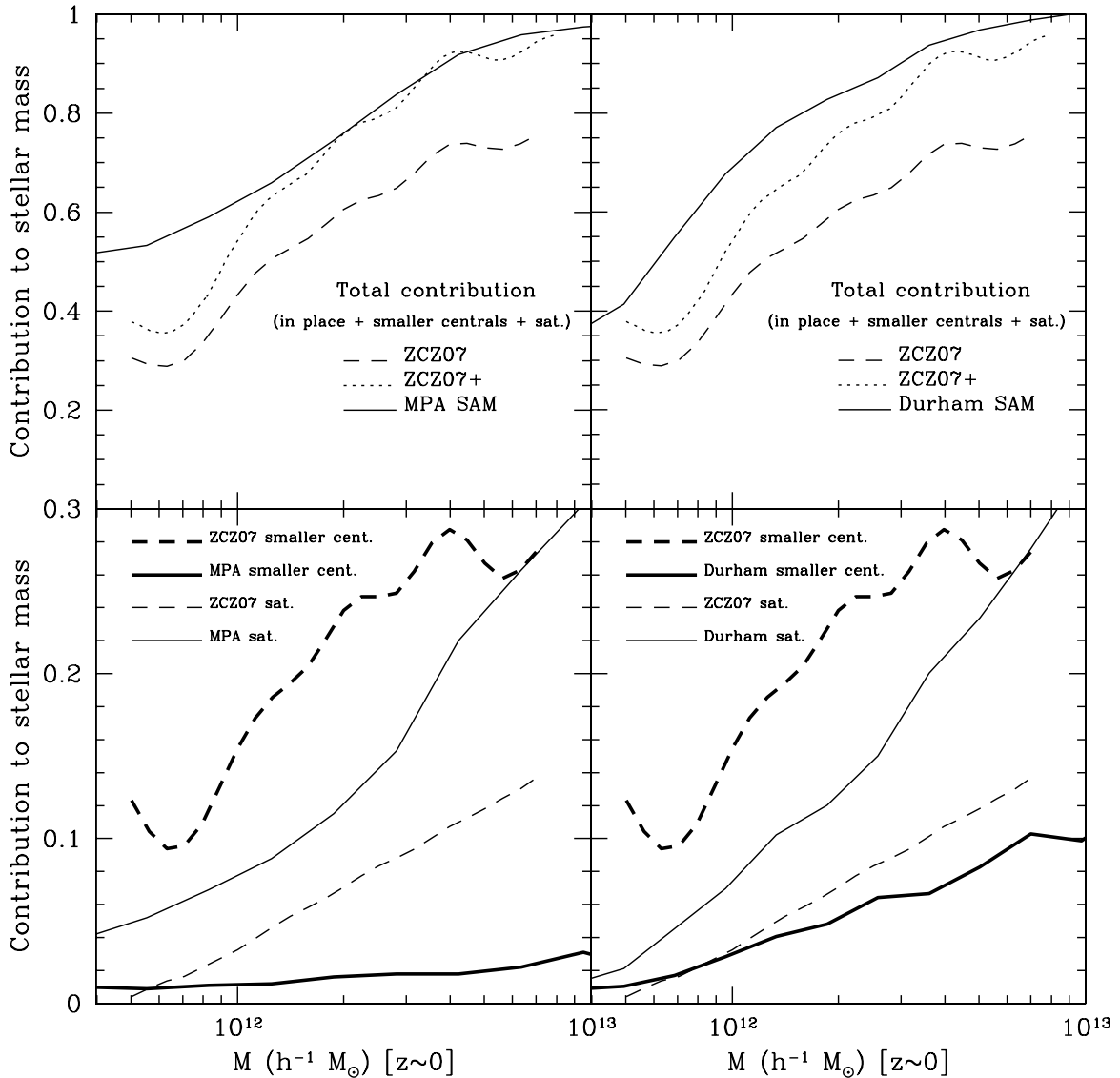


Figure 6. Top panels: predictions of the SAMs compared to the results obtained by ZCZ07 for the *total* stellar mass in central galaxies that was acquired through merging, in addition to that already in place at $z \sim 1$. The stellar mass is normalized by the amount of stellar mass at $z \sim 0$ and presented as a function of present-day halo mass. The left and right panels show the comparison to the MPA and the Durham SAMs, respectively (solid lines). The dashed lines are the standard ZCZ07 result and the dotted lines denote the effect of a tentative 25% correction of the stellar mass at $z \sim 1$ (see the text for details). Bottom panels: comparison between the SAMs (solid lines) and ZCZ07 (dashed lines) for the *individual* contributions from mergers of smaller central galaxies (thick lines) and satellites (thin lines) to the stellar mass in the final central galaxy.

between the two results, with a maximum deviation of about 5%, indicating that the use of the average halo growth to connect galaxies at the two epochs is adequate.

The other assumptions in ZCZ07 are related to the rough estimation of the merger contributions to the stellar mass growth of central galaxies, resulting in the dashed curves shown in the bottom panels of Figure 6. Computing these contributions in a statistical way is not straightforward. In order to estimate the stellar mass contribution from smaller central galaxies, ZCZ07 utilize, for a given dark matter halo mass, the fraction of halo mass already formed at $z \sim 1$ in its main progenitor. This halo has some fraction of stars already formed by that epoch. The assumption is that the ratio of central galaxy stellar mass to halo mass in the other progenitors is the same as that for the main progenitor and that they all will have merged into the main progenitor central galaxy by the present time. For example, a halo of mass $5 \times 10^{11} h^{-1} M_{\odot}$ (at present) has

assembled about 70% of its mass by $z \sim 1$, while the MPA SAM predicts that the corresponding central galaxy has about 50% of the stars already in place by $z \sim 1$. Following the ZCZ07 procedure, the remaining 30% of the halo should contribute $30/70 \times 50\% \sim 21\%$ of the stars. Implicitly, this computation also assumes a constant baryon conversion efficiency (or that the merging halos are of comparable mass).

The assumption that all progenitor central galaxies will have merged with the main progenitor central galaxy by today can be considered in terms of the implied merger time scale and compared to the merger times in the SAMs. Since these mergers occur in between $z \sim 1$ and 0, the merger times implied are shorter than ~ 8 Gyr. These mergers are mostly with halo mass ratio larger than 0.1 (e.g., Parkinson et al. 2008). From Figure 14 of De Lucia et al. (2010), for these halo mass ratios, the merger times are less than two times the dynamical time (about 1 Gyr if estimated at $z \sim 0.5$) in the Durham model and less than

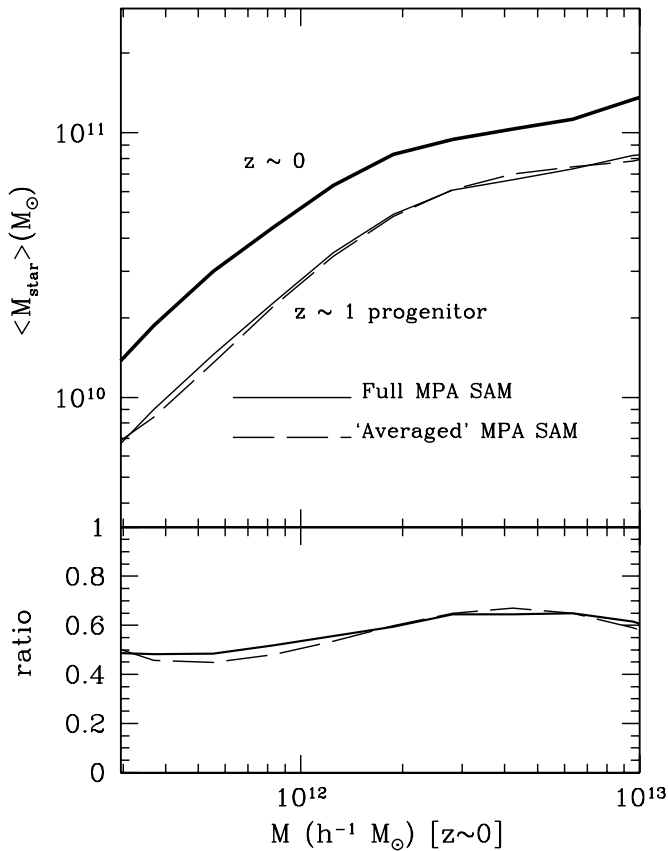


Figure 7. MPA predictions for the mean stellar mass in central galaxies at $z \sim 0$ and that of their $z \sim 1$ main progenitors as a function of the present-day halo mass, calculated using the full halo growth information (solid lines) and the “averaged” relation from the ZCZ07 approach (dashed lines). See the text for details.

ten times the dynamical time for the MPA model. Therefore, the merger timescales of central galaxies implied in ZCZ07 are certainly consistent with these adopted in the Durham model, but perhaps somewhat shorter than the ones in the MPA model.

Obtaining the contribution of satellite galaxies to the final central galaxies is more difficult. ZCZ07 provide a crude estimation based on simplifying assumptions resulting in a linear extrapolation from zero at the low-mass end, where the satellite contribution is expected to be negligible, to 25% of the central galaxies contribution at the high-mass end, where the brightest satellite in each halo is assumed to have merged with the central galaxy (see their Section 6.3 for more details). The implied merger time scale for the brightest satellite is again shorter than 8 Gyr and longer than that for the fainter satellites. For massive halos, the luminosity of the brightest satellite is about a quarter of that of the central galaxy (i.e., a luminosity gap of 1.6 mag, see ZCZ07), indicating a large mass ratio of the brightest satellite to the central galaxy. The corresponding merger timescales in the Durham (MPA) model (De Lucia et al. 2010) are shorter than ~ 2 Gyr (~ 6 Gyr). The ZCZ07 satellite merging timescales are thus consistent with the SAMs predictions, but ZCZ07 ignores the merging of less luminous satellites.

We can also use the full halo and galaxy merging histories provided in the SAMs to test the global effect of these assumptions regarding the contribution from smaller central galaxies and from satellites. The top panels of Figure 8 show for both SAMs the predicted contribution of smaller central galaxies to the final stellar mass obtained by applying the simple estimation proposed by ZCZ07 (dashed lines). The exact contribution in the

SAMs is shown by the solid lines. It is apparent that the approximate approach overestimates the “real” contribution by a large amount. Recall that the SAMs appear to predict a large excess of stars that already assembled in the central progenitors at $z \sim 1$ (Figure 5), which might translate to an overestimation of the estimated contribution. The shorter merger timescales implied by ZCZ07 compared to the MPA model may also contribute to the overestimation in this model.

Another important issue is that the estimation assumes that all the remaining halo mass accreted carries with it the same fraction of stellar mass. This may be reasonable for the merging smaller halos; however, there is also a significant contribution from smooth “diffuse” accretion of dark matter particles to the final halo. In the Millennium Simulation, we obtain that this component accounts for $\sim 30\%$ of the final halo mass since $z \sim 1$ (see also Guo & White 2008; Fakhouri & Ma 2010; Genel et al. 2010). Even though smooth accretion carries baryons that will be added to the hot gas available for cooling (De Lucia et al. 2004), it does not contribute to the existing stellar mass. When accounting for this, we find that the contribution from smaller central galaxies is considerably reduced (the dot-dashed lines in top panels of Figure 8) and is in better agreement with the SAM predictions (particularly for the Durham model). This approximated contribution, however, still appears to be somewhat overestimated, especially in the MPA model, where the measured contribution of smaller central galaxies is tiny.

As mentioned already, the simplified estimate also implicitly assumes a constant fraction of stellar mass for the merging halos, which in reality does vary with halo mass (see, e.g., Figure 1 in this work and Figure 10 in ZCZ07). This can affect the contribution from smaller central galaxies in two ways: for a halo whose mass is around the peak of the conversion efficiency or smaller, this assumption might overestimate the contribution, while for higher-mass halos it can result in an underestimation (which will result in a stronger trend with halo mass).

The bottom panels of Figure 8 compare the rough estimation of the merger contribution from satellites to the stellar mass of the central galaxy (dashed lines) with the SAMs’ exact predictions (solid lines). The estimation is computed in the same halo mass range used in ZCZ07, to facilitate the comparison. In this case, we see that the approximation underestimates the merger contribution of satellites to the final stellar mass, especially at the highest halo masses probed. This may arise due to the merging of additional satellites to the brightest one in each progenitor halo (see above) and may again lead to a stronger trend. We note that the behavior of the estimated satellite merger contribution goes in the opposite direction than that of smaller central galaxies. This leads to a partial cancellation such that the estimate of the total merger contribution is reasonable, which also implies that the inferred contribution from recent star formation is not strongly affected by the approximate nature of the above method. These trends also likely explain some of the differences seen in the individual contributions shown in the bottom panels of Figure 6.

It is hard to draw definitive conclusions from all these tests given the intrinsic uncertainties in both the SAMs and the ZCZ07 estimations. It is worth stressing that the latter assumptions investigated here are related only to estimating the total contributions of central and satellite mergers to the stellar mass assembly. The robust result regarding the fraction of stellar mass already in place in central galaxies at $z \sim 1$ is unaffected by these uncertainties. More care should certainly be given to these assumptions, taking into account smooth accretion and

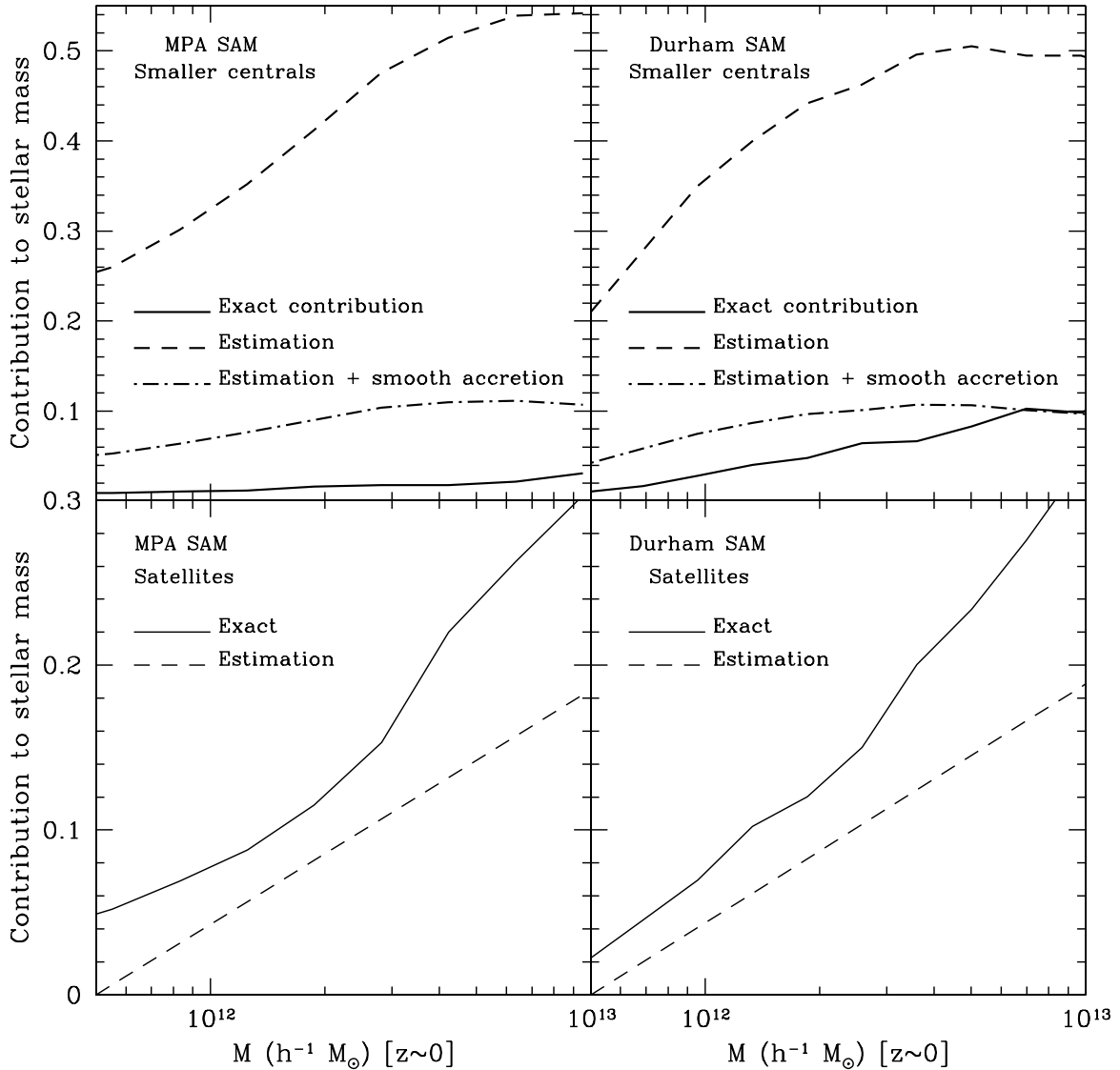


Figure 8. Testing ZCZ07 assumptions regarding the contribution to the central galaxy stellar mass from mergers of smaller central galaxies and satellites since $z \sim 1$ with the MPA SAM (left) and Durham SAM (right). The contribution is normalized by the total amount of stellar mass at $z \sim 0$ and presented as a function of present-day halo mass. Top panels: the solid line in each panel denotes the “exact” stellar mass contribution from the merging of smaller central galaxies. The predictions for this contribution using the ZCZ07 assumptions applied to the SAMs are shown as the dashed lines (marked as “Estimation”). The dot-dashed lines incorporate the effect of “smooth accretion” (see the text). Bottom panels: the same now for the stellar mass contribution from merging satellites. In each panel, the solid line shows the exact contribution from mergers of satellites into the final central galaxy, while the dashed line is the estimated contribution using the ZCZ07 approximation.

incorporating better treatment of central and satellite dynamics determined from analytic models (e.g., Zentner et al. 2005) or from simulations (e.g., Wang et al. 2006; White et al. 2007; Wake et al. 2008). Nonetheless, we expect the qualitative results of ZCZ07 to still be valid (or even somewhat strengthened with these corrections, as discussed above) and believe that such phenomenological methods can provide powerful constraints on theories of galaxy formation and evolution.

5. SUMMARY AND DISCUSSION

In this paper, we study theoretical predictions for the evolution of stellar mass in galaxies as a function of their host halo mass, using semi-analytic galaxy formation models based on the Millennium simulation. We utilize two different SAM implementations, the MPA (Croton et al. 2006; De Lucia & Blaizot 2007) and Durham (Bower et al. 2006) models. We

investigate the different contributions to the growth of stellar mass, and the role of mergers and star formation in the stellar mass assembly from $z \sim 1$ to the present. Such an investigation with SAMs is timely and important as several recent studies have started to explore the galaxy–halo connection and related inferences on galaxy evolution (e.g., ZCZ07; White et al. 2007; Conroy & Wechsler 2009; Wake et al. 2011; Wang & Jing 2009; Behroozi et al. 2010; Firmani & Avila-Reese 2010; Guo et al. 2010; Leauthaud et al. 2011a, 2011b, 2011c; Neistein et al. 2011a). These studies employ different phenomenological approaches utilizing observed statistical properties of galaxies, such as correlation functions, abundances of galaxies, and stellar mass functions. In our study, we particularly compare the SAM predictions to the methodology and results presented in ZCZ07, to assess the potential of such studies to constrain galaxy formation models and to guide future efforts of modeling galaxy evolution.

We find that the conversion efficiency, the fraction of baryon mass that has converted into stars in the central galaxies, as a function of halo mass has a peaked distribution, with a maximal value of $\sim 23\%$ at $z \sim 0$ and $\sim 18\%$ at $z \sim 1$. The location of the peak shifts toward lower halo mass with time. Both SAM models produce similar results for the growth of stellar mass in central galaxies from $z \sim 1$ to 0 as a function of the present-day halo mass. At both redshifts, the central galaxy stellar mass increases rapidly with halo mass for relatively low-mass halos (below $\sim 2 \times 10^{12} h^{-1} M_{\odot}$) and at a lower rate for more massive halos. The fraction of stellar mass already in place at $z \sim 1$ also varies with final halo mass: it is about 50% (40%) for the MPA (Durham) model at the low-mass end, increasing with halo mass to about 65% for halos with mass $\sim a \text{ few } \times 10^{12} h^{-1} M_{\odot}$, and decreases somewhat at the highest halo mass probed.

The SAM predictions for the different contributions to the stellar mass assembly since $z \sim 1$ indicate that star formation is more important in low-mass halos ($\sim a \text{ few } \times 10^{11} h^{-1} M_{\odot}$), while accretion through mergers dominates at the high-mass end ($\sim 10^{13} h^{-1} M_{\odot}$), where star formation is negligible. In the intermediate regime both these processes contribute. The two SAMs provide similar results, differing mostly in their predictions for the contribution of smaller central galaxies merging with the main central galaxy. This likely arises from differences in the galaxy formation prescriptions and in the merger trees of these models.

We also study the predictions of the MPA SAM for the stellar mass growth since $z \sim 2$. The trends found are very similar to those for $z \sim 1$. As expected, much less stellar mass is already in place in the main progenitors compared to $z \sim 1$ and the contribution from merging of smaller central galaxies is considerably larger. Furthermore, the contribution from star formation is important at all halo masses, even at the high-mass end.

Our study is motivated by ZCZ07 who develop a novel phenomenological approach to study galaxy evolution by connecting galaxy clustering results at different epochs through the growth of the hosting halo mass. Such applications can potentially provide important constraints for galaxy formation models as a function of the host halo mass, which is a fundamental parameter in such models. We compare our findings to those of ZCZ07. We find that the SAMs and ZCZ07 produce qualitatively similar trends for the stellar mass assembly in halos and for the baryon conversion efficiency. We note that the SAMs produce similar downsizing-like trends as seen in the empirical data, confirming that they are in accord with hierarchical structure formation predictions.

There are, however, significant quantitative differences between the SAM predictions and the ZCZ07 results. With regard to the baryon conversion efficiency, the main discrepancy appears at $z \sim 1$ where the MPA SAM predicts a $\sim 50\%$ higher conversion efficiency than ZCZ07. The differences are also apparent when contrasting, for these two approaches, the stellar mass content of halos at the two epochs as a function of present-day halo mass (Figure 5). While the overall trends are in qualitative agreement, there are striking differences. Again, the most significant difference is that the SAMs predict a larger stellar mass content at $z \sim 1$ for all halo masses (with a bigger discrepancy for lower-mass halos). The results from the SAMs and ZCZ07 are in better agreement at $z \sim 0$; however, the SAMs underestimate the stellar mass in central galaxies in present-day halos more massive than $\sim 10^{12} h^{-1} M_{\odot}$. Note that for halos larger than this characteristic

mass, AGN feedback starts to play an important role (see, e.g., Stringer et al. 2008), suggesting its effect might be overestimated within these models, resulting in overquenching stellar mass growth.

When looking at the fraction of stellar mass in present-day central galaxies that is already in place at $z \sim 1$, there is a factor of two disagreement between both SAMs and the ZCZ07 results. For example, ZCZ07 obtain that about 30% of the stars in halos of $\sim 3 \times 10^{12} h^{-1} M_{\odot}$ are formed by $z \sim 1$, while the SAMs predict about 60%. The discrepancy is significant even when conservatively accounting for a possible underestimation of the DEEP2 stellar masses. Note also that these differences are already present at higher redshifts, as we find that the ratio of stellar mass in central galaxies at $z \sim 2$ in the MPA SAM is comparable to the one predicted by ZCZ07 at $z \sim 1$. Our results are in agreement with previous works that studied SAM predictions, which found an excess of stars already in place by $z \sim 1$ (e.g., Croton et al. 2006; Kitzbichler & White 2007; Guo et al. 2011). Those, however, were focused on integrated properties and not explicitly as a function of halo mass as we show here. The discrepancy seems to be a fundamental one, not reflected in current differences between variant SAM models. Low-mass galaxies form too early in these models, reflecting our limited understanding of what regulates their star formation at high redshift. We note that such discrepancies are also apparent in hydrodynamics simulations (e.g., Simha et al. 2009; Avila-Reese et al. 2011).

The SAM predictions for the total number of stars acquired through merging on top of that already in place at $z \sim 1$ are, at first order, in good agreement with ZCZ07 results. However, the individual contributions to the stellar mass of the central galaxies from mergers of smaller central galaxies and satellite mergers are markedly different. In ZCZ07 the significant merger contribution arises from the other central progenitors. In contrast, the SAMs predict a large contribution from mergers of satellites. It is the partial cancellation of these opposing differences that leads to a reasonable agreement of the total merger contribution. As a whole, the SAMs and the ZCZ07 results lead to a similar behavior of the star formation contribution with halo mass.

While the comparison between the ZCZ07 observational results and the SAM predictions is informative, there are some simplified assumptions in the former. ZCZ07 apply the method as a proof of concept and point out that there is room for improvement with more sophisticated applications. With the SAMs, we are able to examine different working assumptions employed by ZCZ07 and guide these efforts. For instance, to link galaxies at two epochs, ZCZ07 use the average relationship between the present-day halo mass and the mass of the main progenitor at $z \sim 1$, neglecting the individual scatter among halos. We test the validity of this assumption, using the full assembly information available in the SAMs, finding that it results in negligible differences.

On the other hand, some of the assumptions made by ZCZ07 to estimate the overall contribution from mergers and star formation can certainly be improved. In particular, the original ZCZ07 estimation does not take into account the smooth accretion of dark matter particles to the final halo mass. In the Millennium Simulation the smooth accretion since $z \sim 1$ accounts for about $\sim 30\%$ of the final halo mass. It is difficult, however, to estimate the contribution of stellar mass from very small halos, below the resolution of current numerical simulations. If smooth accretion is as significant in

the real universe, it will certainly need to be included in such approximations. More realistic dependencies on halo mass can also be implemented to improve the estimation method.

Conroy & Wechsler (2009) present related calculations for the evolution of stellar masses and star formation. They use abundance matching to monotonically link galaxies to halos. They predict similar, but more dramatic trends than both the SAMs and the ZCZ07 approach. For instance, they suggest that galaxies in lower mass halos ($\sim 10^{11} h^{-1} M_{\odot}$) grow their stellar mass purely by star formation, while essentially all of the mass is already in place by $z \sim 1$ in present-day halos of $10^{13} h^{-1} M_{\odot}$. Their results support a picture in which stellar mass grows only via star formation, suggesting that the stellar mass from smaller progenitors does not merge into the central galaxy, but remains as satellites or diffuse light. Additional studies are needed to fully clarify their differences with the results presented here and in ZCZ07. Recently, Neistein et al. (2011b) have critically studied the assumptions made in the abundance matching method using SAM catalogs and found important differences, indicating that environmental processes may be important.

We have demonstrated that phenomenological methods such as ZCZ07 are powerful for studying galaxy formation and evolution. They provide key constraints for theoretical models, such as the SAMs, as a function of halo mass. By highlighting remaining shortcomings of galaxy formation models, they can guide the improvement of theoretical predictions at high redshift and increase our understanding of the complex picture of galaxy formation and evolution. At the same time, while ZCZ07 is useful as a proof of concept, future work should use more sophisticated methods applied to better data, and the SAMs can serve an important role in developing and testing such methods.

Future work will also explore the role of environment in the buildup of stellar mass within the host halos. One of the main assumptions in the current HOD framework is that the galaxy content in halos depends only on the halo mass and is independent of the large-scale environment where the halo is located. Recent theoretical studies have shown that the clustering properties of dark matter halos depend on the large-scale environment (the so-called halo assembly bias; Gao et al. 2005; Wechsler et al. 2006; Croton et al. 2007; Jing et al. 2007). This environmental effect might also impact galaxy properties and galaxy clustering (Zhu et al. 2006; Zu et al. 2008). Using the SAMs, we may be able to test the effect of large-scale environment on stellar mass assembly and galaxy evolution (cf. Hoyle et al. 2011). Moreover, we could use SAM results to incorporate environmental effects into phenomenological methods such as ZCZ07, increasing the constraining power of galaxy clustering data on galaxy formation models.

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