GALAXY DOWNSIZING EVIDENCED BY HYBRID EVOLUTIONARY TRACKS

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ABSTRACT

The stellar–dark halo mass relation of galaxies at different redshifts, \( M_\ast(M_h, z) \), encloses relevant features concerning their physical processes and evolution. This sequence of relations, defined in the range \( 0 < z < 4 \), together with average \( \Lambda \) cold dark matter (ΛCDM) halo mass aggregation histories (MAHs), is used here for inferring average galaxian hybrid evolutionary tracks (GHETs), where “hybrid” remarks on the combination of observational (\( M_\ast \)) and theoretical (\( M_h \)) ingredients. As a result of our approach, a unified picture of stellar and halo mass buildup, population migration, and downsizing of galaxies as a function of mass is presented. The inferred average \( M_\ast \) growth histories (GHETs) of the highest and lowest mass galaxies are definitively quite different from the average MAHs, \( M_h(z) \), of the corresponding dark halos. Depending on how a given \( M_h(z) \) compares with the mass at which the \( M_\ast \)-to-\( M_h \) ratio curve peaks at the epoch \( z, M_{\rm tri}(z) \), two evolutionary phases are evidenced: (1) galaxies in an active regime of \( M_\ast \) growth when \( M_h < M_{\rm tri} \) and (2) galaxies in a quiescent or passive regime when \( M_h > M_{\rm tri} \). The typical \( M_\ast \) at which galaxies transit from the active (star-forming) to the quiescent regime, \( M_{\rm tri} \), increases with \( z, \log(M_{\rm tri}/M_\odot) \approx 10.30 + 0.55z \), making evident a population downsizing phenomenon. This result agrees with independent observational determinations based on the evolution of the galaxy stellar mass function decomposition into blue and red galaxy populations. The specific star formation rate (SSFR) predicted from the derivative of the GHET is consistent with direct measures of the SSFR for galaxies at different redshifts, though both sets of observational inferences are independent. The average GHETs of galaxies smaller than \( M_{\rm tri} \) at \( z \approx 0 \) (\( M_\ast \approx 10^{10.3} M_\odot \), \( M_h \approx 10^{11.8} M_\odot \)) did not reach the quiescent regime, and for them, the lower the mass, the faster the later \( M_\ast \) growth rate (downsizing in SSFR). The GHETs allow us to predict the transition rate in the number density of active to passive population; the predicted values agree with direct estimates of the growth rate in the number density for the (massive) red population up to \( z \approx 1 \). We show that ΛCDM-based models of disk galaxy evolution, including feedback-driven outflows, are able to reproduce the low-mass side of the \( M_\ast-M_h \) relation at \( z \approx 0 \), but at higher \( z \) strongly disagree with the GHETs: models do not reproduce the strong downsizing in SSFR and the high SSFR of low-mass galaxies.

Key words: cosmology: theory – galaxies: evolution – galaxies: halos – galaxies: high-redshift – galaxies: spiral – galaxies: star formation

Online-only material: color figures

1. INTRODUCTION

According to the popular hierarchical clustering \( \Lambda \) cold dark matter (ΛCDM) scenario, galaxies form and grow inside evolving dark matter haloes. A central question emerges then about what is the galaxy stellar mass, \( M_\ast \), associated on average with a given halo of mass \( M_h \), i.e., the \( M_\ast \)-\( M_h \) relation. The change with redshift of this relation, \( M_\ast(M_h, z) \), resumes the key astrophysical processes of galaxy stellar mass assembly in the context of the ΛCDM scenario.

With the advent of large galaxy surveys in the last years, a big effort has been made in constraining the local \( M_\ast \)-\( M_h \) relation (1) directly by estimating halo masses with galaxy–galaxy weak lensing, with kinematics of satellite galaxies, or with X-ray studies and (2) indirectly by linking the observed statistical galaxy properties (e.g., the galaxy stellar mass function GSMF, the two-point correlation function, galaxy group catalogs) to the theoretical halo mass function (hereafter HMF; for recent reviews on all of these methods, see Moster et al. 2010; Behroozi et al. 2010; More et al. 2010, and references in these papers). The latter approach is less direct than the former one, but it allows us to cover larger mass ranges and it can be extended up to the redshifts where observed GSMFs are reported (for recent results, see Conroy & Wechsler 2009; Moster et al. 2010; Wang & Jing 2010; Behroozi et al. 2010).

In Moster et al. (2010) and Behroozi et al. (2010, hereafter BCW10), the \( M_\ast(M_h, z) \) functionality has been constrained up to \( z \approx 4 \). In each case, different observational data sets for the GSMFs and different methods for statistically assigning halo masses to the galaxies were used. The \( M_\ast \)-\( M_h \) relation at \( z \approx 0 \) is similar in both works (see also Baldry et al. 2008; Drory et al. 2009; Guo et al. 2010; Wang & Jing 2010). However, the change with \( z \) of this relation, \( M_\ast(M_h, z) \), particularly for \( z \gtrsim 1 \), is different in both cases.

Although the uncertainties in the inferences of \( M_\ast(M_h, z) \) are still significant, the current determinations can be used for preliminary explorations of the galaxy mass assembly process. An original approach has been introduced by Conroy & Wechsler (2009, hereafter CW09), who proposed a parametric form for GSMF as a function of \( z \) constrained by both some observational reports of this function and the star formation rate (SFR)–\( M_\ast \) relations to \( z \approx 1 \). Then, the cumulative GSMFs at each \( z \) were matched to the cumulative HMFs in order to infer the \( M_\ast \)-\( M_h \) relations at different \( z \) (abundance matching formalism, the simplest of the indirect methods; e.g., Marinoni & Hudson 2002; Kravtsov et al. 2004; Vale & Ostriker 2004; see Section 2). Finally, the obtained \( M_\ast \)-\( M_h \) relations at different \( z \) were
connected by using simple parameterizations of the average halo mass aggregation histories (MAHs) in order to infer the average stellar mass buildup of galaxies as a function of mass.

The previous approach has the advantage (1) of being flexible enough as to allow for explorations covering large mass and redshift ranges and (2) of providing a bridge between observational results and theoretical work. One of the bases of this approach is the statistical abundance matching formalism, which has shown to give robust results in agreement with direct inferences of the local $M_*=M_h$ relation or with other indirect inferences based on observations of the two-point correlation functions or galaxy group catalogs (see Moster et al. 2010; BCW10; More et al. 2010; Dutton et al. 2010a).

From a purely empirical point of view, recent studies are posing a new starting point in our understanding of galaxy stellar mass assembly. For example, Drory & Alvarez (2008) used empirical GSMFs up to $z \sim 5$ (Drory et al. 2005) to infer the $M_*$ assembly of large galaxies, and in combination with available observations of the SFR–$M_*$ relation at different $z$, they constrained the contribution of star formation (SF) and merging to stellar mass buildup in galaxies. From this and other studies (e.g., Bundy et al. 2006, 2009; Hopkins et al. 2007; Pozzetti et al. 2009), the trend of downsizing (Cowie et al. 1996) is clearly shown in the sense that the mass at which the SFR starts to drop strongly increases with time (from $M_* \sim 10^{12} M_\odot$ at $z > 4$ to $M_* \sim 10^{10}$ $M_\odot$ at $z \sim 0.5$, according to Drory & Alvarez 2008). This result combined with observationally inferred merger rates led the latter authors to conclude that the (massive) red sequence is built up from top to down. This phenomenon was originally dubbed as “archaeological downsizing” (Thomas et al. 2005; for related results see also, e.g., Daddi et. al 2004, 2007; Drory et al. 2004; Bundy et al. 2005, 2006; Conselice et al. 2007; Marchesini et al. 2009; Pérez-González et al. 2008, and references therein), and it seems that its main drivers are internal galaxy processes that efficiently quench SF in massive galaxies (e.g., Bundy et al. 2006; Peng et al. 2010).

The latter result has been confirmed by recent decompositions of the GSMF by galaxy type (based on color, SFR, morphology, etc.) up to $z \sim 1$ (e.g., Borch et al. 2006; Bell et al. 2007; Drory et al. 2009; Ilbert et al. 2010; Pozzetti et al. 2009; for a compilation of early observations, see Hopkins et al. 2007). A systematic result obtained in these works is that blue/late-type (active) galaxies migrate to the red/early-type (passive) population involving a sequence of masses that decreases with time, a result in line with the archaeological downsizing phenomenon. The environment also plays an important role. Recent observational studies, where the GSMF has been divided not only by galaxy types but also by environment, show that the population migration happens more efficiently and earlier in denser environments (e.g., Peng et al. 2010).

At lower masses the inferences of the $M_*$ assembly are made difficult by the incompleteness limit of the samples as higher is $z$. However, at least for $z \lesssim 1$, current studies show that the specific SFR (SSFR) of low-mass (blue) galaxies is surprisingly high and higher than the SSFRs of more massive galaxies (e.g., Bauer et al. 2005; Noeske et al. 2007; Zheng et al. 2007; Bell et al. 2007; Elbaz et al. 2007; Chen et al. 2009; Damen et al. 2009a, 2009b; Santini et al. 2009; Oliver et al. 2010; Rodighiero et al. 2010). This “downsizing in SSFR” of low-mass galaxies seems to imply a delayed $M_*$ buildup the lower the mass is, something difficult to explain presently by ΛCDM-based models (for models, discussions, and more references, see Noeske et al. 2007; Fontanot et al. 2009; Firman et al. 2010).

Based on the ΛCDM scenario and the new observational inferences discussed above, a unified picture of stellar and halo mass buildup of galaxies of all sizes can be developed. By using $M_*-M_h$ relations constrained by BCW10 from $z \approx 0$ to 4, we generate an analytical $M_*(M_h, z)$ relationship, which is continuous and differentiable at any $z$. This sequence of $M_*-M_h$ relations in $z$ is combined with average halo MAHs in order to

1. calculate the average stellar mass buildup tracks of galaxies, $M_*(z)$, from $z = 4$ up to now (hereafter, galaxian hybrid evolutionary tracks, GHETs) along with their halo MAHs, $M_h(z)$;
2. calculate the average SSFR histories of galaxies from the corresponding specific stellar mass growth rate histories, $M_*(z)/M_*(z)$;
3. determine the typical mass $M_{\text{ran}}$ at each $z$ that marks the transition from active to passive galaxy population (in terms of $M_*$ growth); and
4. infer the transition rate in the number density of active to passive galaxies at each $z$.

Our approach differs from CW09 in several aspects. These authors used observational inferences of the SSFR versus $M_*$ at different $z$ for constraining the evolution of their proposed GSMF (up to $z \sim 1$), which is a partial input of their approach for calculating $M_*(M_h, z)$. Instead, we use more recent and updated direct constraints for this relationship (BCW10), which extends up to $z \approx 4$, and then predict the SSFR histories. In CW09 a simple parameterization for the average MAHs was used, while we generate them by using an extended Press–Schechter formalism that gives results similar to those of large N-body cosmological simulations. We also differ from CW09 in several aims and results.

The inferences of the quantities listed above constrain in general the multiple astrophysical processes participating in the formation and evolution of galaxies. In particular, we will compare the inferred evolutionary tracks (GHETs) to predictions of standard ΛCDM-based semi-numerical models of disk galaxy evolution and explore whether the so-called downsizing in SSFR is really an issue for models.

In Section 2, the method to calculate the GHETs is explained. The inferred average GHETs are presented in different diagrams in Section 3. In Sections 3.1 and 3.2, the evolution of the SSFR as a function of mass, the evolution of the transition mass $M_{\text{ran}}$, and the flow of active to passive galaxies at each epoch are shown and compared with direct observational estimates. The reliability of our approach and the results are discussed in Section 3.3. In Section 4, ΛCDM-based models of disk galaxy evolution are used to calculate evolutionary tracks for low-mass galaxies and see whether they are able to reproduce or not the GHETs, in particular the SSFR downsizing phenomenon. A summary and our conclusions are given in Section 5.

2. THE METHOD

Our inference of the galaxy stellar mass buildup as a function of mass (here called GHETs) consists of two main steps: (1) we find an analytical functionality for $M_*(M_h, z)$ and (2) after generating the halo MAHs, $M_h(z)$, we combine them with $M_*(M_h, z)$ to infer the GHETs, $M_*(z)$. 
2.1. The Stellar Mass–Halo Mass Relations at Different Redshifts

Our starting point is the determination of $M_s(M_h, z)$ up to the highest redshift possible. As mentioned in Section 1, such a relationship has been recently constrained up to $z \sim 4$ by using the statistical formalism of matching one-to-one the cumulative theoretical ΛCDM HMF to the observed cumulative GSMF at different $z$: $n_s(M_h) = n_s(M_s)$ (e.g., Moster et al. 2010; BCW10). Here we will use the results from BCW10, who started from an assumed parametric expression for $M_s(M_h, z)$ and explored the parameter space, including uncertainties and sample variance, with a Monte Carlo Markov Chain technique to fit jointly the GSMFs observed at different $z$ (they actually carried out this analysis separately for two redshift ranges: $0 \lesssim z \lesssim 1$ and $1 \lesssim z \lesssim 4$). The authors have estimated and carefully taken into account all kinds of uncertainties, which introduce significant scatter in the $M_s$–$M_h$ relations and affect even the shape of these relations (see Section 3.3 for a discussion).

The observational input used in BCW10 is the total local GSMF obtained in Li & White (2009) from Sloan Digital Sky Survey (SDSS) data, and the total GSMFs at higher redshifts (up to $z \sim 4$) homogeneously obtained in Pérez-González et al. (2008). For the HMF, BCW10 used the results from N-body cosmological simulations by Tinker et al. (2008). Since these HMFs refer only to distinct halos, a correction by the subhalo abundance was introduced (see details in BCW10). The mass of the subhalo is fixed as that at the time of accretion into the halo, $M_{h,c}$. However, the satellite galaxy’s $M_s$ is associated with the current GSMF, i.e., it is implicitly assumed that the satellite’s $M_s$ will continue to evolve in the same way as for centrals of halo mass $M_{h,c}$ (the effect of fixing instead the satellite mass $M_s$ at the redshift of accretion has virtually no effect on the overall $M_s$–$M_h$ relation as checked in BCW10). Thus, the $M_s(M_h, z)$ relationship used here refers to the overall galaxy population at each epoch, and this includes satellite galaxies, though under the assumptions mentioned above for this sub-population. On the one hand, there are some hints that the $M_s$–$M_h$ relation of only satellite galaxies should not differ significantly from the overall relation (Wang et al. 2006). On the other hand, satellites are not a dominant population at any epoch, in particular at high redshifts. Therefore, even if its $M_s$–$M_h$ relation is quite peculiar, its effect over the average $M_s$–$M_h$ relation is expected to be negligible. For more details on the assumptions and role of uncertainties in the inference of the $M_s(M_h, z)$ relationship we refer the reader to the original work by BCW10 (see also Section 3.3).

It is worth mentioning that BCW10 refer to their $M_s$–$M_h$ relations as corresponding to “central” galaxies. This should be understood in the sense that for each (sub)halo only the $M_s$ of one galaxy is considered, the central one, but not in the sense that the satellite galaxy population has been excluded from the analysis (see above). A (sub)halo may contain more galaxies besides the central one (satellites). Therefore, the total stellar mass within the (sub)halo will be larger if we account for satellites. In BCW10, it was shown that the inclusion of satellites results in a “total” $M_s/M_h$ ratio slightly larger than the “central” one at small masses but significantly larger at high (group and cluster) masses (BCW10; see also Yang et al. 2009). Some of this “excess” stellar mass is expected to end up actually in the central galaxy due to satellite infall and/or tidal stripping of stars (other fractions of this stellar mass may end in the stellar halo or remain in the surviving satellites); this could modify the obtained overall $M_s$–$M_h$ relation. In general, we do not expect that the overall $M_s$–$M_h$ relations inferred by BCW10 will be significantly affected by the (unknown) physics of satellite galaxies, at least for $M_h \lesssim 10^{13} M_\odot$ at any epoch, and for any mass at $z > 0$.

Figure 1 shows the $M_s$–$M_h$ ratio as a function of $M_h$ at $z = 0$, 1, 2, 3, and 4 reported in BCW10 (solid, dashed, dot-dashed, dot-dot-dashed, and dot-dashed-dashed lines) with the respective 1σ uncertainties (error bars, shown only for $z = 0.1, 2$, and 4). Several features regarding galaxy mass assembly can be anticipated from this figure.

1. In the $0 \lesssim z \lesssim 4$ range the peak of the curves shifts from $\log(M_h/M_\odot) \sim 11.8$ to 12.5, while $\log(M_s/M_\odot)$ first declines from $-1.5$ at $z \approx 0$ to $-1.7$ at $z \approx 2$, and then recovers the value $-1.5$ at $z \approx 4$. Taking into account the uncertainty, the shape of the relations is conserved. Around $\log(M_h/M_\odot) \sim 12.5 \pm 0.3$ the curves cross each other.

2. On the left side of the diagram, below the crossing masses (in particular from $z = 1$ to $z = 0.1$), for a given $M_h$, the $M_s$–$M_h$ ratio increases as $z$ decreases, which reveals a strong late growth of $M_s$ for individual galaxies. Hence, this side is expected to be populated mainly by actively growing (blue) galaxies.

3. Just the opposite happens on the right side, above the crossing masses, which means that for individual galaxies, $M_s$ brakes its growth while $M_h$ continues growing. To illustrate this point, we plot in Figure 1 the evolution of $M_s$ with $M_h$ for $z = 0.1, 1, 2, 3, 4$.

\footnote{According to the analysis of Yang et al. (2009), for halos smaller than $M_h \lesssim 10^{13} h^{-1} M_\odot$ at $z \sim 0$, the mass fraction of stars accreted by the central galaxy is negligible, indicating that the latter cannot have grown substantially due to the accretion of satellite galaxy’s stars; rather their growth is dominated by individual evolution (in situ SF). For halos larger than $M_h \approx 10^{13} h^{-1} M_\odot$, the central galaxy $M_s$ may increase late in a significant fraction by satellite accretion (dry mergers); another fraction of the accreted stars end in the stellar halo (intracluster stars).}
The previous considerations confirm the idea that $M_0(M_h, z)$ resumes the key astrophysical processes of galaxy stellar mass assembly and therefore it contains information about the evolution of individual galaxies. Our aim now is to explore the implications of the $M_0(M_h, z)$ relations shown in Figure 1. As we are interested in the properties of $M_0(z)$ up to its second derivative (SSFR and the rate of change of SSFR), we cannot use the double parameterization in $z$ given by BCW10 in the ranges $0 < z < 1$ and $1 < z < 4$, respectively, because discontinuities arise around $z = 1$. Then, starting from the data of Figure 1, we introduce a modified parameterization that is continuous in $z$. The following equations, adapted from BCW10, summarize the model to be used here for $0 < z < 4$:

$$
\log(M_0(M_h)) = \log(M_1) + \beta \log \left( \frac{M_h}{M_{_0}} \right) + \left[ \frac{(M/M_{_0})^{\chi}}{1 + (M/M_{_0})^{\gamma}} \right] - \frac{1}{2},
$$

(1)

The dependence on $z$ is introduced in the parameters of Equation (1) as:

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

$$
\log(M_0(a)) = M_{0,0} + M_{0,a}(a - 1) + \chi (z),
$$

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

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

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

(2)

where $a = 1/(1 + z)$ is the scale factor. The function $\chi (z)$ controls the change with $z$ of the peak value (ordinate) of the curves in Figure 1. If $\chi (z) = 0$, then the curve peak ordinate is independent of $z$. We chose $\chi (z)$ in order to reproduce roughly the evolution of the peak found in BCW10. The first two Equations (2) control the position of the $M_0/M_h$ peak at each $z$ (the value of $M_{0p(z)}$), while the last three control the shape of the $M_0/M_h$-$M_h$ curves. We fix the parameters in Equations (1) and (2) expecting (1) to reproduce well the BCW10 ($M_0/M_h$-$M_h$) relations at the redshift extremes ($z \approx 0$ and $z \approx 4$; see Figure 1); (2) to keep the generated relations at all $z$ within the $1\sigma$ uncertainty given in BCW10, and (3) to have the values of most of the parameters reasonably inside the uncertainties of BCW10 (see their Table 2). The best set of parameters that we have found is reported in Table 1 (for comparison, we reproduce there also the best-fit values from BCW10 for their $0 < z < 1$ case with free systematic parameters $\mu$ and $\kappa$). For the function $\chi (z)$, we use

$$
\chi (z) = -0.181 z (1 - 0.378 z (1 - 0.085 z)).
$$

(3)

The agreement of our model with the BCW10 results can be appreciated in Figure 1 (dotted curves with the same color code as the result from BCW10 at $z = 0, 1, 2, 3, 4$).

Table 1

| Parameter | BCW10 | This Work |
|-----------|-------|----------|
| $M_{0,0}$ | $0.10^{+0.02}_{-0.09}$ | $0.10^{+0.02}_{-0.09}$ |
| $M_{0,a}$ | $0.35^{+0.18}_{-0.17}$ | $-0.80^{+0.18}_{-0.17}$ |
| $M_{1,0}$ | $12.35^{+0.07}_{-0.10}$ | $12.35^{+0.07}_{-0.10}$ |
| $M_{1,a}$ | $0.48^{+0.04}_{-0.06}$ | $-0.80^{+0.04}_{-0.06}$ |
| $\beta_0$ | $0.18^{+0.08}_{-0.04}$ | $0.44^{+0.08}_{-0.04}$ |
| $\delta_0$ | $0.57^{+0.15}_{-0.06}$ | $0.48^{+0.15}_{-0.06}$ |
| $\gamma_0$ | $1.75^{+0.42}_{-0.10}$ | $1.56^{+0.42}_{-0.10}$ |
| $\gamma_a$ | $2.51^{+0.83}_{-0.10}$ | $0.00^{+0.83}_{-0.10}$ |

2.2. The Dark Halo Mass Aggregation History

The $M_0(M_h, z)$ relationship proposed in the previous section allows us to transform an average dark halo MAH, $M_0(z)$, into an average stellar mass growth history, $M_0(M_h(z), z)$ (the GHET). Instead of using a parameterization for the average MAHs as was done in CW09, here we calculate them by using the special extended Press–Schechter formalism developed in Avila-Reese et al. (1998; see also Firmani & Avila-Reese 2000). Under the assumption that the primordial density field is Gaussian, we calculate the overall mass distribution of progenitor halos at a given epoch $z_4$ that will be contained in a halo of mass $M_i$ at a later epoch $z_4$. Thus, after defining the cosmology and the mass power spectrum of fluctuations (as in BCW10, parameters very close to WMAP5 are used here; Komatsu et al. 2009), we start from a given mass at a given time (e.g., $z = 0$) and calculate its mass distribution of progenitors at a previous time step through Monte Carlo trials. The mass of the most massive halo (main progenitor) is used as the conditional for the next time step and so on. In this way, one realization of the MAH is obtained. For each $M_h$ given at $z = 0$, we calculate 20,000 random tracks (MAHs) and then we average among them to get the average MAH for this mass. In spite of the stochasticity, the MAHs present a systematic (hierarchical) trend with mass: the smaller is $M_h(z = 0)$, the earlier is its mass assembly on average (Avila-Reese et al. 1998; van den Bosch 2002; Wechsler et al. 2002). Our average MAHs are not easy to describe by a simple parameterization, but they are in good agreement with those measured in the outcome of cosmological $N$-body simulations (e.g., Fakhouri et al. 2010).

3. GALAXY STELLAR MASS BUILDUP: AVERAGE EVOLUTIONARY TRACKS

The GHETs in the $M_h$ versus $M_h$ diagram, calculated as explained in Section 2, are plotted with red thin solid lines in Figure 2. The blue dashed curves show the $M_h$-$M_h$ relations at the redshift extremes ($z \approx 0$ and $z \approx 4$) for this mass. If the galaxies of the sample that allow us to find the isochrones would be growing in $M_h$, then the arrow would diverge from the $z = 0$ isochrone. Therefore, the fact that the arrow reaches the $z = 0$ isochrone exactly reveals that this side of the diagram is dominated by galaxies with passive evolution.
that inverts the spatial distribution of the $M_\ast$($M_h$, $z$) curves going from the left to the right side of the diagram. The same properties may be derived from Figure 3, where the GHETs are shown as tracks that connect the $M_\ast$/$M_h$–$M_h$ relations. Here the folding is seen in the blue dashed lines as a maximum that shifts to the higher mass side as $z$ increases, making the lines cross each other. Both figures help to understand why the GHETs of massive halos attain a maximum.

The GHETs ending at $z = 0$ with masses $8.4 \leq \log(M_\ast/M_\odot) \leq 11.6$ are plotted with red solid lines in Figure 4. The corresponding halo average MAHs are also plotted but, for comparative reasons, each one has been shifted vertically in such a way that $M_\ast(z = 0) = M_h(z = 0)$. The lower and upper dotted curves are model predictions for the evolution of two disk galaxies that end at present with $\log(M_\ast/M_\odot) = 9.40$ and 10.15, respectively (see Section 4 for details). From right to left, the crosses correspond to $z = 0, 1, 2, 3, 4$.

(A color version of this figure is available in the online journal.)

![Figure 2. $M_\ast$–$M_h$ relations (blue dashed lines) at $z = 0$, 1, 2, 3, and 4, from top to bottom (bottom to top) in the left (right) side, respectively, and the inferred average GHETs displayed from $z = 4$ to $z = 0$ (red thin solid lines). The lower and upper dotted curves are model predictions for the evolution of two disk galaxies that end at present with $\log(M_\ast/M_\odot) = 9.40$ and 10.15, respectively (see Section 4 for details). From right to left, the crosses correspond to $z = 0, 1, 2, 3, 4$. (A color version of this figure is available in the online journal.)](image1)

![Figure 3. Same as in Figure 2 but for the $M_\ast$-to-$M_h$ ratio. (A color version of this figure is available in the online journal.)](image2)

to the corresponding halo. Our analysis shows conclusively that the stellar mass growth of galaxies deviates from the halo mass growth, specially for low- and high-mass systems.

Figures 2 and 3 show that the more massive the galaxies, the earlier their GHETs start to slow down their $M_\ast$ growth and at each epoch there is a typical halo or galaxy mass at which this growth stagnates; this typical mass decreases with time. Such a situation can be interpreted as a transition at each epoch from active to passive galaxy populations; a transition at early epochs happens only for the largest galaxies but at later epochs gradually involves smaller galaxies (see Section 3.2 for a more quantitative discussion).

This transition from active to passive regimes is observed in the evolution of the blue and red components of the GSMF. In fact, observations show directly that, despite the stellar mass growth, the blue (late-type) galaxy component of the GSMF is not enriched with massive galaxies with time; on the contrary, within the uncertainty, it seems to become poorer in massive galaxies (e.g., Bundy et al. 2006; Bell et al. 2007; Pozzetti et al. 2009). Such a phenomenon is explained by a migration of galaxies from the blue to the red component of the GSMF; the red (early-type) galaxy component of the GSMF is continuously fed with the galaxies that migrated. Our result, in light of such an interpretation, is remarkable because in our analysis the galaxy color bi-modality never has been taken into account. Studies where the GSMFs were decomposed into blue and red populations support our result independently (e.g., Bell et al. 2007; Drory et al. 2009; Pozzetti et al. 2009).

Note that the prediction of a population transition and the typical mass that separates the two populations at each $z$ depends on the position of the folding in the $M_\ast$–$M_h$–$z$ surface. This feature reveals a fundamental aspect of the GSMF evolution. Therefore, the accurate study of this feature deserves maximum effort from the observational point of view.

The fact that the more massive the systems are, the earlier they finish their $M_\ast$ assembling, transiting from the active to the
passive population, will be called here population downsizing (in the literature the term “archaeological downsizing” has been used to describe a related behavior of galaxies; see, e.g., Fontanot et al. 2009, and references therein).

For systems less massive than $M_\ast \approx 10^{10.5} M_\odot$ at $z = 0$ ($M_\ast \approx 10^{12} M_\odot$), the active (growing) phase still continues at $z = 0$ on average (the population downsizing has not happened), and the smaller the system is, the more delayed and concentrated toward the present the $M_\ast$ growth is. The fact that the less massive the system is, the later its active phase of $M_\ast$ assembling happens is called downsizing in SSFR (see, e.g., Fontanot et al. 2009, Firmani et al. 2010, and references therein).

In the different diagrams plotted in Figures 2–4, we have introduced the corresponding evolutionary tracks (crosses at $z = 0, 1, 2, 3$, and 4 connected with dotted lines) for two (low-mass) galaxies calculated by means of a ΛCDM-based model of galaxy evolution which will be explained in detail in Section 4. Their final stellar masses are $\log(M_\ast/M_\odot) = 9.4$ and 10.1, respectively. We anticipate the rather different behavior of the model “galaxian evolutionary tracks” (hereafter GETs) with respect to the GHETs. For example, the average slope of the former in the $M_\ast$–$M_\odot$ diagram is $\log dM_\ast/d\log M_\ast = 1.4$, much less than the slopes of any GHET, and also less than the lower limit estimated above for the low-mass side of the $M_\ast$–$M_\odot$ relations at each $z$. This means that the model isochrones (defined by connecting crosses of a given $z$) have a distribution and evolution opposite to that of the empirical $M_\ast$–$M_\odot$ relations.

3.1. Stellar Mass Growth Rates as a Function of Mass

The stellar mass buildup of galaxies may happen due to in situ SF or accretion of stars, mainly in dry merger events. Several theoretical (e.g., Maller et al. 2006; Guo & White 2008), semi-empirical (Zheng et al. 2007; CW09; Yang et al. 2009; Wang & Jing 2010), and observational (e.g., Bundy et al. 2006, 2009; Bell et al. 2007; Drory & Alvarez 2008) pieces of evidence show that the former channel completely dominates in low- and intermediate-mass galaxies at all epochs, while the latter may play a moderate role for massive ($M_\ast \gtrsim 10^{11} M_\odot$, mainly red) galaxies at later epochs ($z \lesssim 1$).

As a working hypothesis, we will assume that the stellar mass buildup implied by our derived average GHETs is only due to in situ SF. Therefore, we calculate the SSFR as the time derivative of $M_\ast(z)$ divided by the current mass, $\mbox{SSFR} = dM_\ast/d\log M_\ast$, and divided by $(1 - R)$, where $R = 0.4$ is the gas recycling factor due to stellar mass loss. The obtained SSFRs are then compared with directly observed SSFRs as a function of $M_\ast$ and $z$.

In Figure 5, the evolution of the GHET-based SSFR is plotted (red solid line) for the same cases shown in Figure 4. From top to bottom, the mass of the GHETs increases, except for the minor inversion (track crossing) present in the top right side of the diagram. For all the masses, the SSFR decreases as $z$ decreases. The overall behavior of decreasing SSFR with time agrees, by construction, with the known direct observational inferences of the cosmic stellar mass density history and its time derivative (e.g., Drory et al. 2005; Pérez-González et al. 2008), providing a point of comparison to the observed cosmic SFR density history (Madau et al. 1996; see Hopkins & Beacom 2006 for an extensive compilation of observational inferences).

We test now if the GHET-based SSFR histories as a function of mass are in agreement with direct observational measures. The observations of course do not refer to individual evolutionary tracks. What observers do is determine the SSFRs of galaxy samples in different redshift bins. A commonly reported result is the average of the SSFRs in different $z$ bins corresponding to a given range of $M_\ast$ (the same at all $z$). In Figures 5 and 6, from top to bottom, the curves with thick solid lines connect the tracks at the moment $\log(M_\ast/M_\odot) = 9.5$ (blue), 10 (cyan), 10.5 (green), and 11.0 (red), respectively. The upper and lower black curves are model predictions for the evolution of two disk galaxies that end at present with $\log(M_\ast/M_\odot) = 9.4$ and 10.1, respectively (see Section 4 for details).

(A color version of this figure is available in the online journal.)

Figure 5. Evolution of the SSFR (see the text for its definition) corresponding to the same GHETs shown in Figure 4 (solid red lines). From top to bottom, the curves with thick solid lines connect the tracks at the moment $\log(M_\ast/M_\odot) = 9.5$ (blue), 10 (cyan), 10.5 (green), and 11.0 (red), respectively. The upper and lower black curves are model predictions for the evolution of two disk galaxies that end at present with $\log(M_\ast/M_\odot) = 9.4$ and 10.1, respectively.

For the largest mass bin ($M_\ast$ about $10^{11} M_\odot$, lower red curves), the GHETs imply clearly lower SSFRs than the directly measured SSFRs of star-forming (blue) galaxies at $z \lesssim 1$. This is expected since, as discussed above, the most massive galaxies show evidence to have early on transited to the passive population. For the galaxy mass $M_\ast \approx 10^{11} M_\odot$, the transit to the passive, red sequence happens at $z \approx 1.3$ (see Figure 8) as indicated by a vertical mark over the curve. Bell et al. (2007) reported the estimated SSFRs also for the red sequence galaxies. Their estimates for $M_\ast \approx 10^{11} M_\odot$ (red circles) and $10^{10.5} M_\odot$ (green circles) are plotted in Figure 6. The directly measured SSFRs of massive (red) galaxies are very low, decreasing their values as $z$ decreases in the same manner as our predictions show. While it is only speculative at the moment due to the large uncertainties, the fact that the values of our inferred SSFRs are systematically higher than the direct measures of red massive galaxies could be interpreted as an evidence of the contribution of stellar accretion (dry mergers) to the stellar mass growth of these galaxies at late epochs (see Section 2.1 for a discussion of this possibility).
SSFR up to redshift at which these masses transit from active to passive phases. Note that Figure 6.
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and the small squares connected by dashed lines were inferred from Bell et al. (2007) for their sample of blue galaxies; in both cases, the (average) masses are the same as the GHET-based masses. The filled circles are also inferences from Bell et al. but for their sample of red galaxies and only for log(M/M⊙) = 11.0 (red filled circles) and 10.5 (green filled circles). The vertical marks over the log(M/M⊙) = 11.0 and 10.5 curves indicate the typical redshift at which these masses transit from active to passive phases. Note that the end of the 10^{11} M⊙ GHET-based curve (when these masses are already in the passive phase) agrees well with the SSFR of red rather than blue galaxies; the end of the 10^{10.5} M⊙ GHET-based curve is in between the red and blue galaxy samples. The dot-dashed line shows the curve 1/(t_H(z) − 1 Gyr)(1 − R) corresponding to a constant SFR.

(A color version of this figure is available in the online journal.)

Recently, Damen et al. (2009a) presented estimates of the SSFR up to z ≈ 2.8 for massive galaxies (M_i > 10^{10.5} M⊙) in the same Chandra Deep Field South used in Bell et al. (2007). As mentioned above, for redshifts z ≥ 1 galaxies of M_i ≈ 10^{11} M⊙ or smaller are on average in their active (SF-driven) growth regime. The results by Damen et al. are in rough agreement at these redshifts with our predictions. If any, the GHET-based SSFRs are slightly lower than the averages of the directly measured SSFRs.

For the intermediate-mass bin (M_i ≈ 10^{10.5} M⊙, green curves), the agreement between the average SSFRs inferred from the GHETs and those measured directly for the star-forming (blue) galaxies (Bell et al. 2007) is satisfactory, given the spread of data in SSFR. If any, the SSFR from the GHETs is slightly lower, in particular at low z. Again, due to the population downsizing, active (blue) galaxies of masses M_i ≈ 10^{10.5} M⊙ transit to the passive (red) population at z ≈ 0.35 (see Figure 8) as indicated by the mark over the green curve, so that their SSFRs at lower z should be in between those measured for the blue and red sequences. The agreement in the mass range around 10^{10.5} M⊙ with the Damen et al. (2009a) observational inferences up to z ≈ 2.8 is also good, though the samples of these authors do not separate galaxies in early- and late-type ones. For z > 0.5 the slope of the SSFR(M_i ≈ 10^{10.5} M⊙)−(1 + z) relation for our prediction and for direct observations is about 3.3.

For the lowest mass bins (M_i ≈ 10^{10.0} and 10^{9.5} M⊙, blue and cyan curves), the agreement between GHET-predicted and directly measured SSFRs is reasonable if takes into account (1) the large intrinsic spread of the observational inferences (1σ width of ~0.5 dex around the mean in the relation log(SSFR)−logM_i at z ~ 0, Salim et al. 2007; for higher redshifts, the typical reported intrinsic 1σ widths are of ~0.2−0.3 dex, Noeske et al. 2007; Zheng et al. 2007; Damen et al. 2009a, 2009b) and (2) the sample incompleteness, which increases as z is higher (for such small masses, this may bias the observational average estimates toward larger values for z > 0.3−0.5). If any, the predicted SSFR(M_i = const)−(1 + z) curves for these low masses decrease slower (are shallower) than the curves inferred from direct observations for z < 1 (see also Damen et al. 2009a). Better observational estimates for both the low-mass GSMF and SSFRs at high redshifts are needed to attain more conclusive results.

The dot-dashed line in Figure 6 shows the curve 1/(t_H(z) − 1 Gyr)(1 − R) corresponding to a constant SFR. Galaxies above (below) this curve are currently forming stars at a rate higher (lower) than the past average.

In Figure 7, the evolution of SSFR versus M_i for the same GHETs of previous figures is plotted (red solid lines). This plot exhibits the fact that small galaxies maintain high SSFRs and grow fast at late epochs, while very large galaxies had high SSFR and rapid growth in the remote past, being passive at later epochs. In Figure 7, from bottom to top the thick (cyan, blue, green, orange, red) lines connect the individual tracks at the redshifts z = 0, 1, 2, 3, and 4 (isochrones, respectively). Each of these isochrones corresponds to the average SSFR−M_i relations at a given z and can be compared with direct observational inferences of SSFR versus M_i at different z bins. These inferences for samples at different epochs (from z ~ 0 up to z ~ 2) show that galaxies (mainly star-forming ones) are ordered in the log SSFR−logM_i diagram along sequences of intrinsic widths 1σ ≲ 0.3−0.5 dex (e.g., Bauer et al. 2005; Salim et al. 2007; Schiminovich et al. 2007; Noeske et al. 2007; Bell et al. 2007; Drory & Alvarez 2008; Damen et al. 2009a, 2009b; Santini et al. 2009; Oliver et al. 2010; Rodighiero

![Figure 6. Same curves connecting the GHETs at four values of M_i = constant (indicated inside the panel) as shown in Figure 5 (solid thick lines). The filled squares at z ~ 0 are estimates from SDSS by Salim et al. (2007), and the small squares connected by dashed lines were inferred from Bell et al. (2007) for their sample of blue galaxies; in both cases, the (average) masses are the same as the GHET-based masses. The filled circles are also inferences from Bell et al. but for their sample of red galaxies and only for log(M/M⊙) = 11.0 (red filled circles) and 10.5 (green filled circles). The vertical marks over the log(M/M⊙) = 11.0 and 10.5 curves indicate the typical redshift at which these masses transit from active to passive phases. Note that the end of the 10^{11} M⊙ GHET-based curve (when these masses are already in the passive phase) agrees well with the SSFR of red rather than blue galaxies; the end of the 10^{10.5} M⊙ GHET-based curve is in between the red and blue galaxy samples. The dot-dashed line shows the curve 1/(t_H(z) − 1 Gyr)(1 − R) corresponding to a constant SFR.](image)

![Figure 7. Same GHETs as shown in Figure 4 but in the SSFR vs. M_i(z) diagram (thin solid red lines). From bottom to top, the curves with thick solid lines connect the tracks at a given epoch (isochrones): z = 0 (cyan), 1 (blue), 2 (green), 3 (orange), and 4 (red), respectively. The red crosses indicate the points where the GHET slope declines below −5. The lower and upper dotted curves are model predictions for the evolution of two disk galaxies that end at present with log(M_i/M⊙) = 9.40 and 10.15, respectively (see Section 4 for details).](image)
et al. 2010). The averages of these sequences are such that the smaller $M_c$ is, the higher the SSFR. However, due to the sample incompleteness limit, which increases from a few $10^8 M_{\odot}$ to several $10^{10} M_{\odot}$ from $z \sim 0$ to 1, respectively, these averages at low masses might be overestimated. The isochrones showed in Figure 7 are in general within the 1σ width of the intrinsic spread of the observational SSFR–$M_c$ relations. At low masses (where observational samples with measured SFRs are below the completeness limit), the isochrones tend to be below the direct observational estimates of the SSFR at the given epoch but at intermediate masses the agreement is rather good, i.e., at low masses, the GHET-based SSFR–$M_c$ relations tend to be shallower than those constructed from direct observations.

At the high-mass end, our isochrones fall faster than the averages of the observed SSFR–$M_c$ sequences, which typically are reported for star-forming (blue) galaxies. Keeping in mind that our results refer to average trends, in this sense the average high-mass galaxies in our case already transited to the passive (red) population. In fact, the SSFR–$M_c$ relation at a given $z$ should be constructed separately for active (blue) and passive (red) galaxies. Therefore, in the SSFR–$M_c$ diagram two sequences would appear: at low masses a sequence dominated by blue galaxies and at high masses the sequence dominated by red galaxies. From the point of view of the GHET analysis, the characteristic mass that divides both sequences is related to the transition mass inferred from the GHETs at each $z$ (see Section 3.2). As seen in Figure 7, the average slope of the passive sequence (high-mass side) at any $z$ is steeper than that of the active sequence (low-mass end). Interestingly enough, this is the trend actually revealed in those observational works where the SSFR–$M_c$ relations at different $z$ (out to $z \sim 1.0–1.5$) are plotted separately for red and blue galaxies (Bell et al. 2007; Oliver et al. 2010).

In general, we conclude that the SSFRs at different $z$ and as a function of $M_c$ predicted on the basis of our GHETs are reasonably consistent with recent observational studies based on direct measures of the SSFRs of galaxies at different $z$ (especially those that divide galaxies into blue and red ones). This consistency is particularly important because the observational information concerning SFR never enters in our scheme. Therefore, on the one hand, this result is an independent test for the whole approach presented here (it predicts the mean SSFRs of galaxies at different epochs consistent with direct observational estimates). On the other hand, it supports our hypothesis that the stellar mass buildup given by the average GHETs is driven by in situ SF. This does not mean, however, that the growth of $M_c$ by accretion of stellar systems (dry mergers) may not happen, but it suggests that it is less dominant than the SF channel (our approach and the accuracy of current estimates of SSFRs at different redshifts do not allow for quantitative inferences of the contributions of one or another channel of galaxy mass growth).

A natural question arises about the information the GHETs provide on the stellar initial mass function (IMF). We have outlined the agreement between our SSFR derived from the stellar mass growth and the directly inferred SSFR. The latter inference is highly sensitive to the assumption of a universal IMF. In this sense, we can say that such an agreement is congruent with a universal IMF. Nevertheless, the uncertainties are still large, making it premature to draw such a conclusion as sufficiently robust.

Finally, the results mentioned above confirm and integrate into a unified picture two key facts of galaxy stellar mass assembly: (1) the downsizing in SSFR of low-mass galaxies and (2) the population downsizing of massive galaxies. The former will be discussed in light of CDM-based models in Section 4. The latter is quantified in the next section.

3.2. Evolution of the Characteristic Mass that Separates Active from Passive Population

Our method reveals the existence of a characteristic stellar mass at each $z$, $M_{\text{tran}}(z)$, at which the growth rate of the average GHET sharply declines. We interpret this as a transition from the active to the quiescent regime of SFR, the onset of the migration from the star-forming blue to the passive red population (population downsizing). We may estimate $M_{\text{tran}}(z)$ quantitatively by identifying the mass at a given $z$ corresponding to the GHET that started to strongly decrease its SSFR, for example, when the slope of the track in SSFR versus $M_c$ (see crosses in Figure 7) becomes steeper than $-5$ (the measured SSFR at this point increases from log(SSFR/Gyr$^{-1}$) = $-0.8$ at $z \sim 0$ to $-0.5$ at $z \sim 3$). The stellar $M_{\text{tran}}$ calculated this way is plotted versus $z$ in Figure 8 (diagonal crosses). The function

$$log(M_{\text{tran}}/M_{\odot}) = 10.30 + 0.55z$$

(4)

offers an approximate description of the results up to $z \sim 2$ (solid line).

The focus now is to compare our result with independent observational pieces of evidence for a transition mass from active to quiescent/passive population as a function of $z$. Nowadays, as mentioned in Section 1, it is possible to follow...
the evolution of the early (red) and late-type (blue) GSMFs separately. In one of the most recent and complete works, based on the zCOSMOS survey, Pozzetti et al. (2009) determined the mass where the early- and late-type GSMFs cross (different estimators for these two populations are used, see figure caption) from $z \approx 1$ to $z \approx 0.2$. Such a crossing mass, $M_{\text{cross}}$, is interpreted namely as the typical mass of late-type galaxies migrating to early-type ones (see also Bell et al. 2007).

The agreement between the Pozzetti et al. (2009) results for $M_{\text{cross}}$ (circles with error bars connected by different dashed lines) with our $M_{\text{tran}}(z)$ is satisfactory as can be seen in Figure 8. Local estimates of $M_{\text{cross}}$ by Bell et al. (2003, filled triangle) and Baldry et al. (2004, filled square) are also plotted, as well as the law inferred by Drory & Alvarez (2008), for the mass above which the SFR as a function of $M_s$ begins to drop exponentially, $M_{\text{tran}}/M_\odot = 10^{10.43}(1+z)^{-1}$. Our result also agrees qualitatively with other observational studies, with different definitions of the characteristic mass above which the passive (red) population of galaxies dominates in number density (e.g., Bundy et al. 2006; Hopkins et al. 2007; Vergani et al. 2008).

We may also predict the flow of galaxies transiting from active to passive populations at each $z$ per unit of comoving volume. At each redshift interval $z$, $z + dz$ (time interval $t$, $t + dt$), there are GHETs transiting from the active to the passive regime, whose associated halo masses are in the interval $M_h$, $M_h + dM_h$. The transition rate in number density is then given by the abundance of halos in such a mass interval divided by $dt$, $\Phi(M_h, z) \times dz$ log $M_h/dt$. For the abundance of halos at each $z$ we use the HMFs given in Tinker et al. (2008) adapted to our cosmology and corrected to include subhalos according to the functions given in BCW10.

The result is shown in Figure 9. The transition rate in the comoving number density of active to passive galaxies up to $z = 1$ scatters around $(1.0 - 5.5) \times 10^{-4}$ gal Gyr$^{-1}$ Mpc$^{-3}$ without any clear trend with $z$ (the scatter is mainly due to the discretization of the MAHs in mass and $z$). At $z \approx 0.3$, the rate is $(3.7 \pm 1.2) \times 10^{-4}$ gal Gyr$^{-1}$ Mpc$^{-3}$. The obtained passive population growth rates can be compared with estimates reported in the same work by Pozzetti et al. (2009). They found an average growth rate in number density of the red population integrated above log($M_s/M_\odot$) = 9.8 of $6.8(\pm 1.2) \times 10^{-4}$ gal Gyr$^{-1}$ Mpc$^{-3}$ for a redshift interval centered in $z = 0.34$ (solid triangle with error bar in Figure 9); this value is in reasonable agreement with our results. Note that the flow of galaxies in our case is related to a small mass range around the transition mass $M_{\text{tran}}$ given by the average GHETs, while the direct observational determination takes into account a large range of masses. The fact that the latter is only slightly larger than the former implies that indeed most of the galaxies becoming red are those of masses close to the average transition mass.

### 3.3. Reliability of the Results

The results presented above are based mainly on the evolution of the $M_s$–$M_h$ relation. An important question is then how general and reliable is the $M_s(M_h, z)$ relationship used here. A comprehensive analysis of the statistical and systematical uncertainties in $M_s(M_h, z)$ and how they affect the shape of the $M_s$–$M_h$ relations at different $z$ has been carried out by BCW10. These authors separate the uncertainty sources into three classes: uncertainties (1) in the observational inference of GSMF, (2) in the dark matter HMF, and (3) in the matching process arising primarily from the intrinsic scatter between $M_s$ and $M_h$. They found that by far the largest contributor to the error budget of the local $M_s$–$M_h$ relation comes from assumptions in converting galaxy luminosity into $M_s$, which amounts to uncertainties of $\sim 0.25$ dex in the normalization of the relation (see the error bars in Figure 1). The contribution from all other sources of error, including uncertainties in the cosmological model, is much smaller, ranging from 0.02 to 0.12 dex at $z = 0$ and from 0.07 to 0.16 dex at $z = 1$. At high redshifts ($z > 1$), statistical uncertainties grow, becoming as significant as the systematic ones. On the other hand, the intrinsic scatter in $M_s$ given $M_h$ and the random statistical error in $M_s$ inferences have a significant effect on the shape of the $M_s$–$M_h$ relation at the massive end (taken into account in BCW10).

At $z \sim 0$, the results from most direct and indirect studies to infer $M_s(M_h, z \sim 0)$, in spite of the different methods and different local GSMFs used, agree well, especially if the uncertainties are taken into account (see BCW10 for a comparison). The systematic shift of the ($M_s$/$M_h$)–$M_h$ curves to higher $M_h$ as $z$ increases (see Figures 1 and 3) is also a generic result obtained by all the authors (CW09; Wang & Jing 2010; Moster et al. 2010; BCW10). This implies that the trend reported here of downsizing in SSFR for galaxies less massive than $M_h \approx 3 \times 10^{10} M_\odot$ is robust; the downsizing can be respectively stronger or weaker depending on whether the low-mass end of the curves shifts more or less with $z$. As the completeness of the samples at low masses improves, the estimate of the GSMFs at their low-mass end will be better, and hence the evolution of the $M_s$–$M_h$ relation at lower masses will be more accurately constrained.

The results of different authors may differ regarding the exact location of the $M_s$–$M_h$ (or $M_s/M_h$–$M_h$) curves at different $z$, especially for $M_h \gtrsim 10^{10.5} M_\odot$. For example, in Moster et al. (2010), the peaks in ($M_s$/$M_h$)–$M_h$ significantly decrease with $z$ in such a way that the curves intersect only at very high masses. This implies that the GHETs keep growing until $z = 0$ even for large galaxies, the transition to passive population happening only for the most massive ones. In a similar way, CW09 concluded from their analysis that out to $z \sim 1$ and for $M_h < 10^{11} M_\odot$ there is no characteristic mass at which the growth rate of galaxies is truncated. However, this is in conflict with independent observations that instead show strong population downsizing (see Section 3.2 and Figure 8).
In the case of BCW10, the peaks in \((M_*/M_h) - M_h\) slightly decrease out to \(z \sim 1\) and for higher \(z\), they increase, attaining at \(z \approx 4\) the same level as at \(z \approx 0\) (Figures 1 and 3). However, the uncertainties in the determination of the \((M_*/M_h) - M_h\) curves are large and other behaviors with \(z\) are allowed. The relationship used here closely resembles the BCW10 results as discussed in Section 2.

In order to probe the robustness of the conclusions presented here, we have performed our analysis by using \(M_*/(M_h + z)\) relationships different from the one assumed in Section 2 but still within the uncertainties of the BCW10 inferences. For example, we explored a \(M_*/(M_h + z)\) relationship such that the peaks of the \((M_*/M_h) - M_h\) curves remain at the same level for all redshifts (i.e., \(\chi(z) = 0\) in Equation (2)). The obtained GHETs are qualitatively similar to the ones presented here and Equation (4) slightly changes to \(\log \left( \frac{M_{\text{cen}}}{M_\odot} \right) = 10.2 + 0.6z\). It is noteworthy that the high-mass GHETs in Figure 4, presenting a stagnation in their \(M_*\) growth, show shapes that are a little sensitive to the parameter \(\delta_a\). By assuming \(\delta_a = 0\) in Equation (2), the most massive GHETs, after reaching a maximum stellar mass at approximately the same \(z\) as presented in Figure 4, decline in mass but not by more than 0.1 dex.

We conclude that the main results reported here are robust at least for the range of variations in the \(M_*/(M_h + z)\) relationship that remains within the current uncertainties in the inference of this relationship.

4. MODEL PREDICTIONS VERSUS HYBRID EVOLUTIONARY TRACKS

Any model of galaxy formation and evolution within the hierarchical ΛCDM scenario should predict how the \(M_* - M_h\) ratios (the “galaxy formation efficiency”) of individual galaxies evolve. Several complex astrophysical processes intervene in shaping the evolution of this ratio. Most of the semi-analytical and semi-numerical models—as well as the numerical simulations regarding subgrid physics—introduce physical schemes for modeling these processes and for reproducing the present-day \(M_* - M_h\) relation (or the luminosity function) and other properties/correlations of galaxies. The question now is whether such models are able to reproduce the whole evolution outlined here. Different approaches to explain population downsizing have been recently proposed, while SSFR downsizing is just starting to be recognized as a problem (e.g., Fontanot et al. 2009; Firmani et al. 2010; Colín et al. 2010).

In each one of the figures where the GHETs were presented in this paper, we have plotted the GETs corresponding to the two low-mass disk galaxy models that end at present with \(\log(M_*/M_\odot) = 9.40\) and 10.15 (\(\log(M_*/M_\odot) = 11.25\) and 11.73; dotted lines). The models were calculated with a semi-numerical method that self-consistently solves dynamical and hydrodynamical equations of halo mass virialization given the MAH, disk formation in centrifugal equilibrium inside the growing halo, gravitational drag of the disk over the halo inner regions, SF triggered by gravitational instability and self-regulated by a vertical energy balance between energy input due to SNe and turbulent energy dissipation, and SN-driven mass outflows (Firmani & Avila-Reese 2000; Firmani et al. 2010). The main assumptions implicit in the models are spherical and cylindrical symmetries for the halo and disk, respectively, gas infalling on dynamical time scales (“cold mode”), adiabatic invariance during halo contraction, and detailed angular momentum conservation for the infalling gas.

The baryon fraction is assumed initially as the universal one, but the feedback-driven outflow reduces significantly this fraction. The parameters of the outflow model are fixed in such a way that the (low-mass) \(M_* - M_h\) relation at \(z \sim 0\) is reproduced. In Firmani et al. (2010), we have shown that this happens only in the case of the so-called energy-driven outflow and for a high SN energy-transfer efficiency. Because the exploration in this paper is only at the level of average trends, the halo MAHs used in the models are the averages among 20,000 realizations for each given mass, and the used halo spin parameter \(\lambda\) was fixed to 0.03 at all \(z\), a value slightly smaller than the mean of \(z = 0\) relaxed halos in N-body cosmological simulations (e.g., Bett et al. 2007). On the one hand, the N-body simulations show that \(\lambda\) does not significantly change with time for halos growing in the accretion mode (e.g., Peirani et al. 2004; D’Onghia & Navarro 2007). On the other hand, our models show that the radius evolution of disk galaxies agrees with observational inferences when the gas parameter \(\lambda\) is roughly constant in time (Firmani & Avila-Reese 2009).

The GETs in Figure 4 show that the stellar mass growth is roughly proportional to the halo MAH as \(z\) decreases. The model GETs and the GHETs in the \(M_* - M_h\) diagram (Figure 2) are very different; the average slopes of the GETs are \(d \log M_*/d \log M_h \approx 1.4\), much less than the slopes of the corresponding GHETs. The model \(M_* - M_h\) ratio in Figure 3 decreases toward the past due mainly to the feedback-driven outflow effect, but only slightly, while the GHETs of the same masses evidence a very fast decrease. The \(M_* - M_h\) and \(M_*/M_h\)-\(M_h\) relations (Figures 2 and 3, respectively) predicted by the model GETs at low masses change with \(z\) (\(M_*\) slightly increases with \(z\) for a fixed \(M_h\) in the opposite direction with respect to the empirically inferred observations. This discrepancy represents a serious problem for all the theory behind the models.

The dramatic differences between the GETs and GHETs are also seen in the SSFR evolution plots (Figures 5 and 7). We remark here the downsizing aspect. The GET-based SSFRs of the two galaxies evolve almost parallel (with a law SSFR \(\propto (1+z)^{1.2-2.2}\)) with the SSFR of the larger galaxy slightly higher due to higher \(z\) (weak upsizing). Instead, the GHET-based SSFRs cross each other at high \(z\) (see the upper side of Figure 5) in such a way that larger galaxies have higher SSFR at very high \(z\), but at lower \(z\), the situation is inverted in such a way that as \(z \to 0\), the smaller the galaxy is, the higher the SSFR (downsizing). The comparison of theoretical models with the GHET-based SSFRs suggests that some astrophysical mechanism not considered up to now should systematically delay the onset of SF activity the smaller the halo is.

The low SSFRs (early stellar mass assembly) of small galaxies predicted by the models, which include energy-driven outflows, are actually generic to all ΛCDM-based models. This issue has been reported in different ways by the semi-analytic models. Most of these models show that the stellar population of small galaxies (\(M_* \approx 10^9-10^{10.5} M_\odot\)) is assembled too early, with these galaxies becoming older, redder, and with lower SSFRs at later epochs than the observed galaxies in the same mass range (e.g., Somerville et al. 2008; Fontanot et al. 2009; Santini et al. 2009). The problem is both at the level of satellite and central galaxies. For example, it was shown that models typically overpredict the observed stellar population ages (Pasquali et al. 2009) and stellar masses (Liu et al. 2010).

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4 If the possibility of late re-accretion of the lost gas is taken into account, then in Firmani et al. (2010) it was found that the momentum-driven outflow is the one that best can help to reproduce the \(z = 0\) \(M_*/M_h\) relation.
of central galaxies in low-mass halos. By means of a galaxy evolutionary model similar to ours, Dutton et al. (2010b) also find that the SSFR of model low-mass galaxies is below the average of observations, specially at redshifts \( z \sim 1 \), suggesting that their models are able to reproduce roughly the main features of the observed SFR sequence.

Finally, it should be said that \( N \)-body + hydrodynamics simulations of individual low-mass galaxies in a cosmological context also face the issue of too low SSFRs (as well as too high stellar and baryonic mass fractions; e.g., Colín et al. 2010). In Firmani et al. (2010), we explored the inclusion in our semi-numeric models of re-accretion of the ejected gas for a broad range of possibilities. As expected, the SSFR of galaxies increases in general due to re-accretion but this increase goes in the opposite direction of downsizing: only moderately for low-mass galaxies and too much for the larger galaxies.

5. SUMMARY AND CONCLUSIONS

Empirically inferred \( M_s-M_h \) relations from \( z \sim 0 \) to \( z \sim 4 \) were connected with average \( \Lambda \)CDM–halo MAHs in order to infer the corresponding individual average stellar mass growth histories, here called GHETs. We have adopted an \( M_s(M_h, z) \) relationship continuous in the 0–4 redshift range and in agreement with the inferences by BCW10, who used the technique of jointly matching the abundances of observed GSFs to the theoretical HMFs at different \( z \). The main results obtained here, which allow us to establish a unified description of average galaxy evolutionary tracks for a large range of masses, are as follows.

1. The folding in the \( M_s-M_h \)–\( z \) surface, reflected mainly as peaks in the \( (M_s/M_h)-M_h \) diagram that shift to higher masses as \( z \) increases, introduces an important feature in the behavior of the GHETs. For masses much smaller than the peak mass at a given \( z \), \( M_{\text{hp}}(z) \), the GHETs are in an active growth phase, whereas masses close to or greater than \( M_{\text{hp}}(z) \) are in a quiescent or completely passive (stagnated) phase (Figures 2 and 3). Therefore, at each \( z \) there is a characteristic stellar mass at which, on average, galaxies slow down their growth and transit from an active (star-forming blue) population to a passive (red) population. This transition mass decreases with time, giving rise to a phenomenon called “population downsizing” here.

2. Galaxies less massive than \( M_{\text{hp}} \) at \( z = 0 \) (\( M_s \lesssim 10^{10.5} M_\odot \)), \( M_h \lesssim 10^{12.0} M_\odot \) still have growing GHETs. Further, the lower the mass, the faster the later \( M_s \) growth, due likely to a delayed and lately active SF phase, a phenomenon called “downsizing in SSFR”.

3. The shapes of the average stellar and halo mass assembling histories are quite different (Figure 4). For galaxies that at \( z = 0 \) have \( M_s < 10^{10.5} M_\odot \), their dark MAHs at later epochs grow slightly slower the smaller the mass is, while their stellar GHETs grow much faster. For \( M_s(z = 0) > 10^{10.5} M_\odot \), the larger the galaxy, the earlier its GHETs attain a stellar mass stagnation; until this epoch, the more massive the galaxy, the faster the \( M_s \) growth with respect to the corresponding \( M_h \) growth.

4. By neglecting any stellar mass growth by accretion (dry mergers), a GHET allows us to find the corresponding SSFR history, SSFR(\( z \)), by calculating \( M_s/M_h \) and correcting by the stellar mass-loss recycling factor \( R \). The inferred SSFRs at different \( z \) and as a function of \( M_s \) (Figures 5–7) are reasonably consistent with recent observational studies based on direct measures of the SSFR of star-forming galaxies at different \( z \). The GHET-based SSFRs corresponding to masses that at a given \( z \) are larger than the transition mass \( M_{\text{tran}}(z) \) are much lower than the measured SSFRs of (rare) luminous blue galaxies, but agree or are even slightly larger than the measured SSFRs of red galaxies. The overall consistency between the GHET-based SSFR–\( M_s \) relations at different \( z \) with direct inferences of these relations suggests that the accretion of stellar systems (mergers) plays a minor role in the \( M_s \) assembling of galaxies, except perhaps those that transited to the passive sequence (the most massive ones).

5. By using the SSFR versus \( M_s \) evolutionary tracks, we calculated the characteristic transition mass at each \( z \), \( M_{\text{tran}}(z) \), above which the average GHET starts to significantly decrease its growth rate, transiting from the active to the passive galaxy population. The result is roughly described by the relation \( \log(M_{\text{tran}}/M_\odot) = 10.30 + 0.55z \) (at least up to \( z \sim 2 \)). This result agrees with recent observational determinations of the evolution of the mass, at which the early- and late-type GSFMs cross each other, from \( z \approx 1 \) to the present (Figure 8).

6. We also determined the transition rate in number density of active (blue) to quiescent (red) galaxy population. At \( z \approx 0 \) such a rate is \( 10^{-3.4 \times 0.2} \text{ gal Gyr}^{-1} \text{ Mpc}^{-3} \) and up to \( z \approx 1 \) the rates are within \( 1.0-5.5 \times 10^{-1} \text{ gal Gyr}^{-1} \text{ Mpc}^{-3} \), in good agreement with direct observational inferences of growth rate in number density of red galaxies.

7. We further explored whether \( \Lambda \)CDM-based models of galaxy evolution are able to predict galaxy evolutionary tracks (here called “GETs”) in agreement with the GHETs, in particular at low masses where the downsizing in SSFR is evidenced by the GHETs. We have shown that while the models with SN energy-driven outflows are able to reproduce the local \( M_s-M_h \) relation (see also Firmani et al. 2010), they fail in reproducing this relation at higher \( z \). The difference between GETs and GHETs at low masses is rather large: the former ones show a fast decrease in SSFR with time almost independent of mass, while for the latter ones, the lower the mass, the slower the late decrease of SSFR (downsizing in SSFR) is.

From these results, we conclude that the general description of stellar mass buildup of galaxies provided by our average GHETs appears rather successful: the predicted SSFR histories as a function of \( M_s \) and the predicted transition mass \( M_{\text{tran}} \) as a function of \( z \), as well as the transition flux at different \( z \), are roughly consistent with direct (but as yet limited) observational estimates of all these quantities. Furthermore, our analysis reveals nicely the existence of a galaxy bi-modality related to the \( M_s \) growth activity; as \( z \) decreases, smaller and smaller masses transit on average from the active (blue star-forming) to the passive (red) population.

An important ingredient of our approach is the connection of \( \Lambda \)CDM halos to the observed galaxies. Therefore, the underlying hierarchical \( \Lambda \)CDM scenario is successful in the sense that the predictions of the model are in agreement with independent observations. The average stellar and dark mass buildup of galaxies were found to be significantly different, specially for low and high masses. This result is in qualitative agreement with CW09 in spite of the differences in the data, method, and redshift range between their and our work. However, the results from both works are different at a quantitative level, which is seen, for example, in the different conclusions regarding the existence of a characteristic mass at each epoch at which the
SSFR of galaxies is truncated. Note that the SSFR and the determination of this characteristic mass ($M_{SSFR}$) are related to the first and second derivatives of the $M_s$ growth, respectively.

Our results put in a unified picture both the population downsizing (related to galaxies with $M_s \gtrsim 3 \times 10^9 M_\odot$ at $z = 0$) and the downsizing in SSFR (related to smaller galaxies). The challenges are now to explain the processes that produce (1) the transition from active to passive regimes in $M_s$ growth associated with a sharp cessation of the SFR in massive galaxies, (2) the fact that the typical mass of SSFR truncation, $M_{ran}$, decreases with cosmic time (population downsizing), and (3) the fact that the smaller the halo is, the more delayed the galaxy’s $M_s$ growth (downsizing in SSFR) is.

Items (1) and (2) seem to find partial explanations in aspects related to the same dark halo clustering (environment) evolution (e.g., Neistein et al. 2006) as well as to the introduction of feedback processes due to the AGNs of massive galaxies (e.g., Silk & Rees 1998; Kauffmann & Haehnelt 2000; Granato et al. 2004; Cattaneo et al. 2005; de Lucia et al. 2005; Bower et al. 2006; Croton et al. 2006). Item (3), as shown here, is a sharp and less understood problem. Later re-accretion of the gas ejected by galaxies due to SN-driven outflows does not account for a solution to this issue (Firmani et al. 2010). A better understanding of the astrophysical processes intervening in galaxy formation and evolution as well as the role of environmental processes is necessary.

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