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THE DARK AND STELLAR MASS ASSEMBLY OF GALAXIES

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RESUMEN

De acuerdo al cuadro empírico del ensamblaje de masa estelar ($M_{\rm s}$) de las galaxias, el establecimiento de la población de galaxias procede de arriba a abajo en $M_{\rm s}$. Conectando galaxias con halos ΛCDM y sus historias se infieren trazas individuales de $M_{\rm s}$. Estas trazas muestran que galaxias masivas ensamblaron su $M_{\rm s}$ más temprano mientras más masivo es el halo, y que galaxias menos masivas aún están creciendo activamente, más mientras menos masivo es el halo. Predicciones hechas en base a estas trazas coinciden con observaciones directas lo cual implica que el escenario ΛCDM es consistente con dichas observaciones. El reto es explicar cómo es que el ensamblaje de $M_{\rm s}$ se desvía sistemáticamente del ensamblaje de la masa del halo correspondiente.

ABSTRACT

The emerging empirical picture of galaxy stellar mass ($M_{\rm s}$) assembly shows that galaxy population buildup proceeds from top to down in $M_{\rm s}$. By connecting galaxies to ΛCDM halos and their histories, individual (average) $M_{\rm s}$ growth tracks can be inferred. These tracks show that massive galaxies assembled their $M_{\rm s}$ the earlier the more massive the halo, and that less massive galaxies are yet actively growing in $M_{\rm s}$, the more active the less massive is the halo. The predicted star formation rates as a function of mass and the downsizing of the typical mass that separate active galaxies from the passive ones agree with direct observational determinations. This implies that the ΛCDM scenario is consistent with these observations. The challenge remains in explaining how the $M_{\rm s}$ assembly (downszing) systematically shifts from the corresponding halo mass assembly (upsizing).

Key Words: cosmology: theory — galaxies: evolution — galaxies: formation

1. INTRODUCTION

One of the current challenges in the study of galaxies is determining and understanding how did they assemble their stellar and dark halo masses. The main observational imprint of the complex galaxy assembling processes is probably the stellar-to-dark mass ratio, $F_s \equiv M_{\rm s}/M_{\rm h}$, as a function of mass and redshift z. The growth of $M_{\rm s}$ can be due (1) to local star formation (SF) fed by available or infalling gas and/or (2) to capture of other stellar systems. In the former case, SF is driven by internal physics, mainly by self-regulation processes in the galaxy disk (e.g., Firmani & Avila-Reese 2000), or is induced by external interactions and mergers – mainly those with high gas content. In the latter case, $M_{\rm s}$ can grow by accretion of small satellites or by major mergers. Even more, the mentioned processes imply feedback effects, like SN-driven outflows and AGN-driven intrahalo gas reheating/ejection effects that inhibit further $M_{\rm s}$ growth. *Which of these channels and their respective feedback effects did dominate in the $M_{\rm s}$ growth of galaxies as a function of their halo masses, types, and environment? How does proceed the stellar and dark mass assembly of galaxies?*

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2. DIFFERENT APPROACHES TO GALAXY FORMATION AND EVOLUTION

2.1. *The inductive or 'archaeological' method*

The approaches for studying galaxy formation and evolution have changed over time. In the past, the main approach was the 'archaeological' method: ages and star formation rate histories of our and other local galaxies are reconstructed by means of stellar population synthesis and chemical evolution models from the observed spectro-photometric and chemical properties. The application of this method to modern data and large galaxy surveys have allowed to obtain key constraints to galaxy mass assembly as a function of mass, galaxy type, and environment (e.g., Thomas et al. 2005; Panter et al. 2007; Asari et al. 2007).

2.2. *The deductive or ab initio method*

With the consolidation of the popular Λ Cold Dark Matter (ΛCDM) cosmology in the last twenty years, a powerful theoretical background for galaxy formation and evolution appeared. According to this framework, cosmic structures emerged from the gravitational evolution of CDM-dominated primordial perturbations. The distributions, inner properties, and evolution of the collapsed CDM structures (halos) were predicted in detail by cosmological N-body simulations. Ab initio (deductive) models, as well as full numerical simulations including hydrodynamics, were developed in order to follow the complexity of baryon physics during the process of galaxy formation and evolution inside the growing CDM halos. Several of the physical ingredients and parameters of the models, as well a some of the subgrid parameters of the simulations, are actually determined/calibrated from mainly local observations. The deductive approach has enormously contributed to our understanding of galaxy formation and evolution in the cosmological context though many questions remain yet unsolved, including the validity of the backbone of this approach itself: the existence of the elusive CDM.

The halo mass growth in the ΛCDM cosmology is on average hierarchical, from bottom to up. How is the $M_{\rm s}$ assembly of galaxies formed inside the CDM halos and how does it compare with observations? *A sharp test for the ΛCDM scenario may arise from this comparison.* For this, however, several theoretical and observational "biases" should be first well understood. Neither the galaxies trace directly the assembly of their halos –here is implied all the complex baryon physics– nor the observed galaxy populations at different redshifts offer a direct way to determine the individual evolution of galaxies – instead they are inferred and the results are strongly dependent on selection effects and biases. It should be said that misunderstandings and oversimplifications of the scenario have led to some incorrect interpretations. For example, it is common to hear that since in the ΛCDM hierarchical scenario dark halos assemble through violent major mergers ("walnut tree"), therefore galaxy formation is merger-dominated, something that could be in conflict with the observed large abundance of spiral galaxies or the non-negligible fraction of bulgeless galaxies. In fact, most of the mass of galaxy-sized ΛCDM halos (and most of halos) was (were) not assembled by major mergers but by smooth accretion and minor mergers ("pine tree"; Maulbetsch et al. 2007; Genel et al. 2010). Besides, only a fraction of halo-halo mergers end producing galaxy-galaxy mergers. By analyzing the results of the SAM implemented in the Millenium simulation (De Lucia et al. 2005), in De Rossi et al. (2009) it was concluded that only ≈12% of Milky Way-type galaxies experienced a major merger during their lifetimes.

2.3. *The empirical approach*

Thanks to the vertiginous advance of instrumental facilities and multi-wavelength large-area survey programs, the empirical or "look-back time" approach has come to stay. The main photometric and spectral properties of whole galaxy populations obtained at different z allow us to infer $M_{\rm s}$, SF rate (SFR), and other physical properties of galaxies[3]. Given the large numbers and high sensitivities of current surveys, relatively complete samples characterized by the mentioned above properties down to nearly dwarf galaxy masses and out to high redshifts become possible (e.g., $M_{\rm s} \gtrsim 10^8$ at $z \approx 0$ or $M_{\rm s} \gtrsim 3 \times 10^9$ at $z \approx 2$). Thus, progress has been made in determining locally and at higher z: (1) the total galaxy stellar mass function, $GSMF$, and its dissection into blue/star-forming and red/passive components, (2) the SFRs of galaxies as a function of their mass traced by different indicators, from the UV to the radio, and (3) the galaxy rate of merging at different masses and epochs, although with still very large systematic uncertainties. In some works, these determinations have been obtained as a function of environment.

Based on all these observational data, a purely empirical picture of $M_{\rm s}$ assembly as a function of mass, type and environment is emerging now. A general result is that ∼50% of the local stellar mass density was assembled since $z = 1$, and ∼90% since $z = 3.5$ (e.g., Pérez-González et al. 2008). Possibly the main new concept distilled from the empirical picture is that of *cosmic downsizing*, a term coined by Cowie et al. (1996) to describe the decline with cosmic time of the maximum rest-frame $K-$band luminosity of galaxies undergoing active SF. This term has been more recently used to describe a number of trends of the galaxy population as a function of mass that imply in general galaxy buildup from top to down. However, these different trends are actually related to different astrophysical phenomena and galaxy evolutionary stages (Fontanot et al. 2009). From the most general point of view, the many downsizing manifestations can be separated into those that refer to the evolution of:

(A) Massive galaxies, which today are on average red and passive (quenched SF). Observations show

[3]For several of these inferences, stellar population synthesis models should be used. These models had a vigorous advance in the last years, however, several uncertainties remain yet unsolved (for a recent review see Bruzual 2010).

that the high-mass end of the $GSMF$ was in place since high z (e.g., Fontana et al. 2004, 2006; Drory et al. 2005; Cimatti et al. 2006; Marchesini et al. 2009; Perez-Gonzalez et al. 2008), and evidence a decrease with cosmic time of the characteristic mass at which the SFR is quenched or at which the $GSMF$s of early- and late-type galaxies cross, i.e., less and less massive migrate with time to the red sequence (e.g., Bundy et al. 2006; Borch et al 2006; Bell et al. 2007; Hopkins et al. 2007; Drory & Alvarez 2008; Vergani et al. 2008; Pozzetti et al. 2010). This is in line with 'archaeological' inferences for local galaxies that evidence an early and coheval mass assembly for massive ellipticals (e.g., Thomas et al. 2005).

(B) Less massive galaxies, which are on average blue and star-forming. Although the observations of less luminous galaxies suffer incompleteness as z increases due to the flux limits, at least up to $z \sim 1-2$, most of observational studies have found that the specific SFR (SSFR $=$ SFR$/M_{\rm s}$) of galaxies with $M_{\rm s} \lesssim 3\times10^{10}\ M_\odot$, which are mostly late-type, star-forming galaxies, is surprisingly high even at $z \sim 0$ (late mass assembly) and, on average, the lower the mass, the higher the SSFR ('downsizing in SSFR'; e.g., Baldry et al. 2004; Bauer et al. 2005; Zheng et al. 2007; Noeske et al. 2007; Bell et al. 2007; Elbaz et al. 2007; Salim et al. 2007; Chen et al. 2009; Damen et al. 2009; Santini et al. 2009; Oliver et al. 2010; Kajisawa et al. 2010; Rodighiero et al. 2010; Karim et al. 2011; Gilbank et al. 2011).

By combining the evolution of the $GSMF$ with the measured SFR-$M_{\rm s}$ relations at different z, the contribution of local SF and galaxy accretion (mergers) to the stellar mass build up can be constrained (Bell et al. 2007; Drory & Alvarez 2008; Pozzetti et al. 2010). These and some direct –but yet limited– observational determinations of the merging rate (e.g., Lotz et al. 2008; Bundy et al. 2009) show that the former channel completely dominates in low- and intermedium-mass galaxies at all epochs, while (dry) mergers may play a moderate role for massive ($M_{\rm s} \gtrsim 10^{11} M_\odot$, mainly red) galaxies at later epochs ($z \lesssim 1$).

Although important efforts have been made in order to constrain the dynamical evolution of galaxies (e.g., from observational studies at high z of the Tully-Fisher and Faber-Jackson relations, galaxy-galaxy weak lensing, etc.), direct constraints of the galaxy-halo connection as a function of mass are yet very limited. This kind of observations together with those regarding the gas mass of galaxies at high z are necessary to complete the whole picture of galaxy stellar, baryonic, and dark mass assembly. In the meantime, semi-empirical methods were introduced in order to get the whole evolutionary connection in the context of the ΛCDM scenario and constrain in this way the average *individual* trends of the galaxy evolution process as a function of mass (e.g., Conroy & Wechsler 2009; Hopkins et al. 2009; Firmani & Avila-Reese 2010).

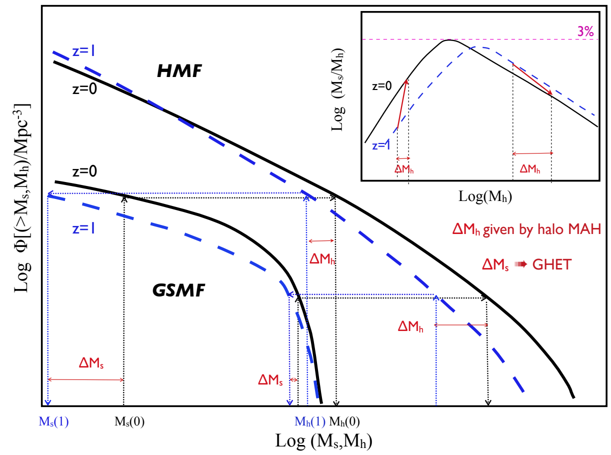

Fig. 1. Halo and galaxy stellar mass cumulative functions at $z = 0$ (solid black curves). Given a $M_{\rm s}$, its corresponding $M_{\rm h}$ is found by matching the mass functions (the dotted black arrows show this for two masses). A relation between $M_{\rm s}$ (or $M_{\rm s}/M_{\rm h}$) and $M_{\rm h}$ is constructed this way (solid black curve in the inset). The same exercise can be repeated at other redshifts (e.g., $z = 1$, dashed blue curves). Given the halo average MAH, the mass at $z = 1$, $M_{\rm h}(1)$, that had a halo of a given mass at $z = 0$, $M_{\rm h}(0)$, can be calculated ($\Delta M_{\rm h}$). Then, by using again the AMT, the $M_{\rm s}(1)$ corresponding to $M_{\rm h}(1)$ is obtained (the dotted blue arrows show this for two masses), and $\Delta M_{\rm s} = M_{\rm s}(0) - M_{\rm s}(1)$ gives the *individual* average $M_{\rm s}$ track (GHET; the red arrows in the inset show two GHET-based tracks in the $M_{\rm s}/M_{\rm h}$–$M_{\rm h}$ diagram).

3. CONNECTING GALAXIES TO DARK HALOS

In the semi-empirical approach, the information provided by direct observations at different epochs is combined in a statistical way with predicted properties for the ΛCDM halos in order: (1) to attain a connection between galaxies and halos, and (2) to infer *individual* galaxy 'hybrid' evolutionary tracks (GHETs). An schematic idea of the approach is shown in Figure 1 and explained below:

(1) Global galaxy-halo connection.- Given the measured cumulative $GSMF$ and the cumulative halo mass function, HMF (both at the same epoch e.g., $z = 0$, black solid curves), and assuming a one-to-one correspondence between $M_{\rm s}$ and $M_{\rm h}$, both functions are matched, $\Phi_g(> M_{\rm s}) = \Phi_h(> M_{\rm h})$, for finding the $M_{\rm h}$ corresponding to a given $M_{\rm s}$ (dotted arrows, for two different masses, in Figure 1), i.e., the $M_{\rm s}$–$M_{\rm h}$ or $F_s \equiv M_{\rm s}/M_{\rm h} - M_{\rm h}$ relations are inferred (solid bell-shaped curve in the inset). This method, called the abundance matching technique (AMT; e.g., Kravtsov et al. 2004; Vale & Ostriker 2004; Behroozi, Conroy & Wechsler 2010, hereafter BCW10, and references therein), makes a minimum of assumptions and has proven to be effective and practical. The halo masses of galaxies can be actually determined by direct methods as galaxy-galaxy weak lensing and satellite kinematics (e.g., Mandelbaum et al. 2006; More et al. 2011). Nevertheless, in current studies, due to the low signal-to-noise ratios, results can be obtained only by stacking a large number of galaxies; this introduces biases and significant statistical uncertainties in the inferences, and limits these inferences to relatively small mass ranges. However, in the mass ranges where comparisons are feasible, these direct methods, the model-dependent indirect methods (e.g., the Halo Occupation Model and the Conditional Luminosity Function formalism), and the AMT, give local F_s-$M_{\rm h}$ relations compatible among them within a factor of $\sim$2 (see BCW10; Moster et al. 2010; Guo et al. 2010; More et al. 2011; Rodríguez-Puebla et al. 2011).

The obtained stellar mass fractions, F_s, are very low with respect to the universal baryon fraction ($F_{b,U} \equiv \Omega_b/\Omega_M \approx 0.16$), i.e., galaxy SF inside ΛCDM halos seems to be a very inefficient process. Besides, the efficiency is strongly dependent on mass: it peaks around $M_{\rm h} = 8 \times 10^{11}\ M_\odot$, decreasing significantly towards lower ($F_s \propto {M_{\rm h}}^a, a \approx 1.25$) and higher ($F_s \propto {M_{\rm h}}^b, b \approx -0.6$) masses. The $GSMF$ determinations at higher redshifts allow now to use methods like the AMT to infer the $M_{\rm s}$-$M_{\rm h}$ relation at different epochs (Moster et al. 2010; Wang & Jing 2010, BCW10). The latter authors extended the AMT out to $z \approx 4$ and found that (a) the $M_{\rm h}$ at wich F_s peaks shifts little to higher masses (by ≈ 0.6 dex out to $z \approx 4$), and (b) the peak value remains roughly constant. For masses below (above) the peak at a given epoch, F_s is smaller (slightly larger) than at earlier epochs for a given $M_{\rm h}$ (see Figure 2, dashed blue curves). This implies that galaxy SF in massive halos should have been slightly more efficient in the past, while in low-mass halos it should have been even less efficient. *This is a manifestation of the cosmic downsizing discussed above.*

(2) Individual $M_{\rm h}$ and $M_{\rm s}$ growth tracks.- In the ΛCDM scenario, the individual mass aggregation histories (MAHs) of halos are known. By using

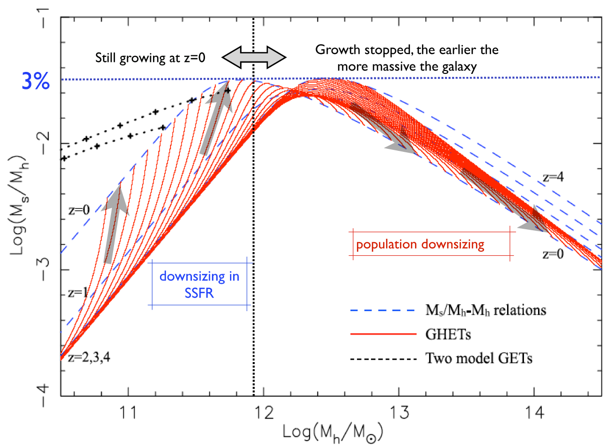

Fig. 2. The $M_{\rm s}/M_{\rm h}$-$M_{\rm h}$ functions inferred by the AMT at four z (dashed blue curves; BCW10, see FA10 for modifications). Solid red curves are the average $M_{\rm s}$ growth tracks inferred in FA10: in small halos, $M_{\rm s}$ assembles faster at late epochs as smaller is $M_{\rm h}$, while in large halos, $M_{\rm s}$ stopped its growth, the earlier the more massive the halo. The two dotted curves are tracks corresponding to two disk galaxy evolutionary models.

them in combination with the semi-empirical $M_{\rm s}$-$M_{\rm h}$ relations at different z, the corresponding $M_{\rm s}$ evolutive tracks (GHETs) can be inferred (red arrows in the inset of Figure 1; Conroy & Wechsler 2009; Firmani & Avila-Reese 2010, hereafter FA10). In FA10, average halo MAHs and a parametrization of the BCW10 $M_{\rm s}$-$M_{\rm h}$ relations up to $z = 4$ were used to infer individual *average* GHETs. The results are encouraging and show that at each epoch there is a characteristic mass that separates galaxies into two populations (Figure 2): (a) galaxies more massive than $M_{\rm s}(z = 0) \approx 3 \times 10^{10}\ M_\odot$ are on average quiescent/passive (their $M_{\rm s}$ growth slowed down or stopped completely), besides the more massive is the galaxy, the earlier it has transited from the active (blue, star-forming) to the passive (red, quenched) population ('population downsizing'); (b) galaxies less massive than $M_{\rm s}(z = 0) \approx 3 \times 10^{10}\ M_\odot$ are on average active (blue), and the less massive the galaxy, the faster its late $M_{\rm s}$ growth, driven likely by local SF ('downsizing in SSFR').

The $M_{\rm s}(z)$ average tracks (GHETs) inferred in FA10 are shown in Figure 3 (solid red curves). Their corresponding halo MAHs are also plotted (dot-dashed blue curves) but for comparative reasons, they were shifted vertically in such a way that each MAH coincides with its related GHET at $z = 0$. The shapes of the average stellar and halo mass assembling histories are quite different. For galaxies with

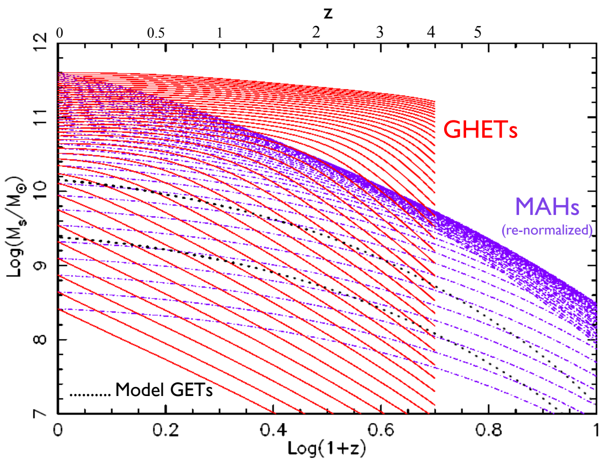

Fig. 3. Average $M_{\rm s}$ growth tracks (GHETs) as a function of z (solid red curves) and their corresponding halo MAHs (dot-dashed purpure curves) shifted vertically in order $M_{\rm s}(z=0)$=$M_{\rm h}(z=0)$. Galaxies and halos assemble their masses in a very different way. Adapted from FA10.

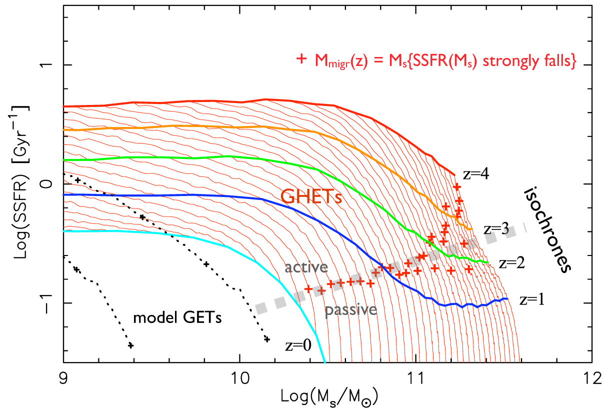

Fig. 4. Predicted average SSFR-$M_{\rm s}$ tracks (assuming negligible $M_{\rm s}$ growth by mergers; solid thin red curves, from FA10). The thick solid curves connect the individual tracks at a given z (isochrones). The crosses show when a given track strongly falls – the galaxy becomes passive. The mass $M_{\rm s}$ at this epoch is called $M_{\rm migr}$.

$M_{\rm s}(z)$ $<$ 3×10^{10} $M_\odot$, their halo MAHs at later epochs grow slightly slower as smaller is the mass, while their stellar GHETs grow much faster. For $M_{\rm s}(z=0)$$>3\times10^{10}$ $M_\odot$, as the system is more massive, the stellar assembly of the galaxy occurs earlier in time with respect to the corresponding halo.

3.1. *Predictions*

SSFR histories.- By using the GHETs, the specific $M_{\rm s}$ growth rate histories, $\dot{M}_{\rm s}(z)/M_{\rm s}(z)$, can be calculated. If as a working hypothesis one assumes that the $M_{\rm s}$ growth of a given galaxy is only due to local SF, then its SSFR history is $\dot{M}_{\rm s}(z)/M_{\rm s}(z)$ divided by $(1-R)$, where $R\approx0.4$ is the gas recycling factor due to stellar mass loss. In Figure 4 we reproduce the individual average SSFR tracks in the SSFR vs $M_{\rm s}$ diagram as obtained in FA10 (thin red solid lines): the SSFR of low-mass galaxies decreases with time slowly, their late $M_{\rm s}$ growth being very fast, while for large galaxies, the SSFR decreases very fast and their $M_{\rm s}$ growth practically stops at late epochs.

The thick solid lines correspond to isochrones at $z=0,1,2,3$ and 4, from bottom to top, respectively. These isochrones are the SSFR-$M_{\rm s}$ relations at the given z and can be compared with the direct determinations mentioned in § 2.3. Within the current large uncertainties and sample selection effects, the GHET-based and directly determined average SSFR-$M_{\rm s}$ relations out to $z\sim2$ are in reasonable agreement. If any, the former are shallower than the latter at the low-mass side; at low z, the predicted SSFRs for intermediate masses ($M_{\rm s}\sim0.7-2\times10^{10}$ $M_\odot$) are slightly larger than the averages of those directly measured. It is important to note that the fast decreasing in the SSFR-$M_{\rm s}$ relations (isochrones) seen at the high-mass side is associated to passive (red) galaxies. Most of the SSFR-$M_{\rm s}$ relations presented in the literature refer to only star-forming (blue) galaxies; for masses lower than $M_{\rm s}\approx2-3\times10^{10}M_\odot$, blue galaxies by far dominate in number, but at high masses passive (red) galaxies become dominant (e.g., Bell et al. 2003; Salim et al. 2007; Pozzetti et al. 2010). In the works where the samples were partitioned by color, the SSFR-$M_{\rm s}$ relation of the red galaxies is inferred indeed very steep (e.g., Bell et al. 2007; Karim et al. 2011).

Downsizing of the migration (quenching) mass.- The GHET-based SSFRs can be used to calculate the z at which the SSFR as a function of $M_{\rm s}$ for a given track decreases dramatically (the galaxy migrates to the passive sequence). The crosses in Figure 4 show, for each track, the $M_{\rm s}$ attained by the galaxy at this epoch, i.e., at each epoch there is a mass $M_{\rm migr}$ at which galaxies on average came to be passive (Figure 5). The solid line in Figure 5 is a by-eye linear fit to the data: $\log(M_{\rm migr}/M_\odot)$ = $10.30+0.55z$, i.e., the population migration progresses from massive systems at high z to less massive systems at lower z ('population downsizing'). Is there evidence from direct observations of a migration mass to the passive population as a function of z? As mentioned in § 2.3, observations allow now

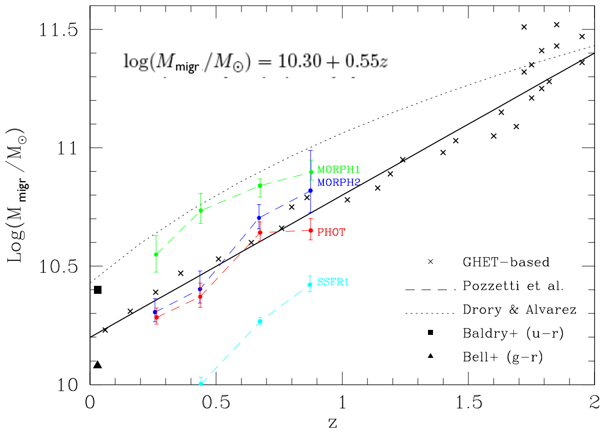

Fig. 5. Typical mass at which galaxies migrate on average to the passive sequence at a given z (crosses, see Figure 4). The solid line is a eye-fit to the crosses. The dashed lines correspond to the mass $M_{\rm cross}$ at which the late- and early-type $GSMF$s crosses, where different morphological, photometrical and SSFR criteria were used to separate the sample into late- and early-type galaxies (Pozzetti et al. 2010). See text for more details.

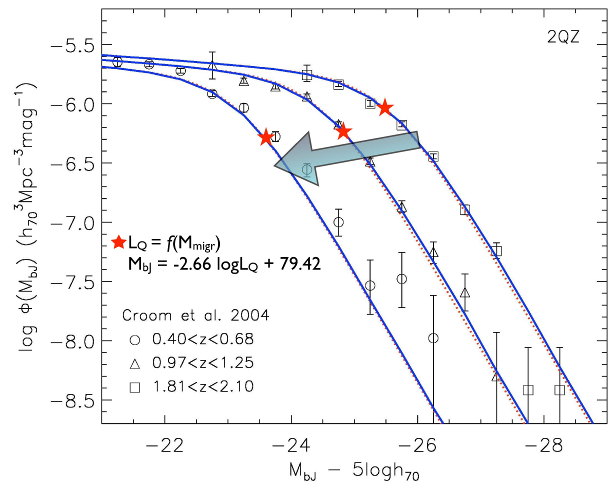

Fig. 6. The $M_{\rm migr}$ mass and its abundance translated to a quasar luminosity, L_Q, and abundance at three redshifts ($z = 0.5, 1$, and 2, filled stars). The obtained results are showed over the luminosity function plots of quasars at the three z bins indicated in the panel (Croom et al. 2004; Croton 2009; see text for details). The masses and abundances of galaxies in the migration process roughly coincide with the characteristic L_Q of the quasar luminosity functions at the same redshifts.

to determine the $GSMF$ at different epochs decomposed into early- (red) and late-type (blue) galaxies. For example, based on the zCOSMOS survey, Pozzetti et al. (2010) determined the mass at which the early- and late-type $GSMF$s cross (different estimators for these two populations are used) from $z \approx 1$ to $z \approx 0.2$. Such a crossing mass, $M_{\rm cross}$, is interpreted namely as the typical mass of late-type galaxies migrating to early-type ones (see also Bell et al. 2007). Local estimates of $M_{\rm cross}$ 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 $M_{\rm s}$ begins to drop exponentially, $M_{\rm quench}/M_\odot = 10^{10.43}(1+z)^{2.1}$. It is remarkable the agreement between direct estimates of different definitions of the characteristic mass above which the passive (red) population of galaxies dominates in number density (see also Bundy et al. 2006; Hopkins et al. 2007; Vergani et al. 2008) and the semi-empirical inferences of FA10.

Migration rates and the quasar connection.- Another prediction that can be made with the semi-empirical approach is the rate in comoving number density of galaxies migrating from active to passive ones as a function of z. In FA10 it was found that this rate, $\dot{\phi}_g(M_{\rm migr})$, up to $z = 1$ scatters around $(1.0 - 5.5) \times 10^{-4}$ gal/Gyr/Mpc^3 without any clear trend with z. These rates are in agreement with the estimated passive (red) population growth rate per unit of comoving volume determined by Pozzetti et al. (2010) for a redshift bin centered at $z = 0.34$.

If the typical time of galaxy transition (or quenching) is t_Q, then the abundance of galaxies per unit of comoving Mpc in the process of migration, i.e., those of mass $M_{\rm migr}$, is $\phi_{\rm g,migr} \approx \dot{\phi}_g(M_{\rm migr}) \times t_Q$. Let assume $t_Q = 100$ Myr and let estimate the typical luminosity of a bright quasar, $L_Q(z)$ associated to the stellar mass $M_{\rm migr}(z)$ or its corresponding halo mass $M_{\rm h}(z)$ (see e.g., Croton 2009) by making some assumptions ($L_Q = \eta L_{\rm Edd}$, $L_{\rm Edd} = C \times M_{\rm BH}$, $M_{\rm BH}$ is the supermassive black hole mass) and by using the observable correlations of $M_{\rm BH}$ with spheroid velocity dispersion or stellar mass. The result is very encouraging (Figure 6): at each z (up to $z \sim 3$), both $L_Q(M_{\rm migr})$ and its abundance, $\phi_{\rm g,migr}$, match the characteristic luminosity of the two-power law QSO luminosity function and its abundance as determined in Croon et al. (2004) and Robertson et al. (2006). This suggests that the transition from active to passive regime (quenching) in massive galaxies is associated to the QSO active phase.

3.2. *Implications*

In the semi-empirical approach described above, the observational input is the total $GSMF$ measured at different z, while the information provided by the ΛCDM theory allowed to assign halos to galaxies and "individualize" average galaxy M_s tracks as a function of mass. By using the inferred M_s tracks (GHETs), the SSFRs as a function of M_s and z, the evolution of the migration or quenching mass M_{migr}, and the rate per unit of comoving volume of galaxies transiting from active to passive ones were predicted. The fact that these predictions are in reasonable agreement with direct observational measures at different z implies that *both the connection between galaxies and ΛCDM halos, and the predicted halo MAHs are consistent with observations.*

The semi-empirical results imply in a natural way the bimodal distribution of galaxies into active (blue) and passive (red) ones, with a bimodality mass scale that shifts downward as time progress (more galaxies become on average passive), this mass scale being at $z = 0$, $M_s = 2 - 3 \times 10^{10}\ M_\odot$, in agreement with direct observations (e.g., Bell et al. 2003; Kauffmann et al. 2003; Blanton & Moustakas 2009). Therefore, *mass seems to be the main driver of color, SFH, and SF quenching,* though environment is expected to play also a role. Observational studies show indeed that color and SFR are moderately modulated by environment for intermediate-mass galaxies, which assembled more recently, in epochs when larger-scale structures collapse, affecting this those galaxies living in such overdense regions (Cucciati et al. 2010; Peng et al. 2010).

The inference of SSFR (as well as M_{migr}) as a function of z was under the hypothesis that the M_s growth is driven only by local SF, i.e., the growth by accretion of stellar systems (dry mergers) was excluded. The rough agreement between predictions and direct measurements implies that this hypothesis is reasonable or, said in other words, that the former growth channel dominates.

4. CHALLENGES AND CONCLUDING REMARKS

The semi-empirical results imply that *galaxy formation inside the growing ΛCDM halos is consistent in general with observations.* However, these results show that the average M_s assembly histories of galaxies shift from those of their halos in a peculiar way and depending on M_h (Figure 3). The complex astrophysical processes and environmental effects involved in galaxy evolution should explain this. Among the key challenges, we highlight the following ones:

4.1. *Why the M_s assembly of low-mass galaxies is systematically delayed with respect to the assembly of their halos?*

The SAMs introduce efficient SN-driven galaxy outflows for reproducing the shallow faint-end of the luminosity function or, equivalently, the high inclination of M_s/M_h at lower masses (Figure 2). Can galaxy outflows explain also the inefficient galaxy SF in the past as smaller are the halos? By means of self-consistent disk-galaxy evolutionary models, Firmani, Avila-Reese & Rodríguez (2010) have shown that SN-driven outflows, as well as the local SF and ISM feedback processes, may deviate the SFR history of disk galaxies from the associated halo mass aggregation rate history but not enough as to reproduce the semi-empirical and empirical results. In Figures 2, 3, and 4 two evolutionary models of low-mass disk galaxies are plotted (dotted-line curves). The model tracks differ significantly from the GHETs. As seen in Figure 3, the model M_s tracks follow closely those of their halos at late epochs, in disagreement with the systematical shift as the mass is smaller observed for the corresponding GHETs. Although the low M_s/M_h ratios were obtained in the models at $z = 0$ (by assuming very high SN kinetic-energy injection to the outflow, see also e.g., Dutton & van den Bosch 2009), at higher z, model prediction are far from the semi-empirical inferences (Figure 2). The disagreement between models and observations is also evident by comparing the SSFRs: the former predict SSFRs for small galaxies much lower than the observed ones, specially toward lower z.

Firmani et al. (2010) explored the possibility of later re-accretion of the ejected gas (e.g., Oppenheimer et al. 2010). For reasonable schemes of gas re-accretion as a function of M_h, they found that the SSFR of galaxies increases but in the opposite direction of the downsizing trend: the increase is large for massive galaxies and small for the less massive ones. From the side of SAMs, it was found that the population of small galaxies (both central and satellites) is too old, red, and passive as compared with observations (e.g., Somerville et al. 2008; Fontanot et al. 2009; Santini et al. 2009; Liu et al. 2010), issues that certainly are related to the mentioned-above problem of the M_s buildup of ΛCDM-based sub-M^* model galaxies. N-body + hydrodynamics cosmological simulations of central low-mass galaxies ($0.2 \lesssim M_s/10^9 M_\odot \lesssim 30$ at $z = 0$) show similar problems (Colín et al. 2010; Avila-Reese et al. 2011): (1) the SSFRs are 5–10 times lower than the average of observational determinations at $z \sim 0$, an inconsistency that apparently remains even at $z \sim 1-1.5$, though less drastic; (2) the M_s/M_h ratios are $\sim 5-10$ times larger than the latter at $z \approx 0$ and this difference increases at higher z.

Unless the current observational inferences of M_s, SFR, and their distributions at different z are dominated by strong systematic effects and selection biases (see for discussions BCW10; Firmani et al. 2010; Avila-Reese et al. 2011), *the problems highlighted above pose a sharp challenge to current* Λ*CDM-based models and simulations of low-mass galaxies*. Its solution requires that galaxies smaller than $M_s(z=0) \sim 2 \times 10^{10}$ $M_\odot$ should have significantly delayed their M_s assembly with respect to the assembly of their corresponding ΛCDM halos, besides the smaller the galaxy, the longer should be such a delay. This is in line with the staged galaxy formation picture proposed in Noeske et al. (2007).

4.2. *Why the more massive the galaxy, the earlier assembled most of its M_s?*

Though at first glance contradictory to the ΛCDM picture, this manifestation of downsizing has, at least partially, its natural roots namely in the hierarchical clustering assembly of halos and their progenitors distributions (Neistein et al. 2006, see also Guo & White 2008; Li, Mo, & Gao 2008; Kereš et al. 2009). Besides, red massive galaxies are expected to have been formed in early collapsed massive halos –associated to high peaks, therefore highly clustered– that afterwards become part of groups and clusters of galaxies, leaving truncated therefore the early efficient mass growth of the galaxies associated to these halos. The measured correlation function of luminous red galaxies is indeed very high (e.g., Li et al. 2006). On the other hand, massive galaxies typically hosted in the past AGNs. The strong feedback of the AGN may help to stop gas accretion, truncating further the galaxy stellar growth and giving rise to shorter formation time-scales for the massive galaxies (Bower et al. 2006; Croton et al. 2006; De Lucia et al. 2006). Although all these effects may explain the archeological downsizing, several questions remain yet open and subject to observational testing, among them, whether AGN-feedback is as efficient as required for quenching galaxies.

4.3. *Why galaxies transit from active to passive M_s growth regimes, the more massive earlier than the less massive ones? What does quench the SFR of galaxies?*

These questions are related to the previous one but make emphasis on the continuous and monotonic decreasing of $M_{\rm migr}$ with time. An important question to take into account is the possible link between SFR quenching and morphological transformation; after all, active (blue) and passive (red) galaxies use to be identified with disk- and spheroid-dominated systems, respectively. As numerical simulations show, the main driver of morphological evolution seem to be mergers (e.g., Scannapieco & Tissera 2003; Cox et al. 2006, and more references therein). Mergers can also quench SF through the associated explosive quasar or starburst phase that heats or drive out cold gas in the spheroidal merger remnant. Thus, the scenario where ΛCDM-based mergers drive the formation and quenching of red, early-type galaxies passing by a quasar and/or starburst phase looks promising (Kauffmann & Haehnelt 2000; Hopkins et al. 2008, and more references therein). The connection showed in § 3.1 between $M_{\rm migr}(z)$ and the characteristic luminosity of the quasar luminosity function at each z supports this scenario, at least for the formation of red galaxies more massive than $M_{\rm migr}$ ($M_{\rm migr} \approx 2 \times 10^{10}$ $M_\odot$ at $z=0$).

However, recent observations suggest that the situation could be more complicated, specially for the origin of passive (red) galaxies of smaller masses: nearly 50% of the red-sequence COSMOS galaxies ($z \lesssim 1$) have disk-like morphologies, being bulge-dominated (Bundy et al. 2010), though above $\sim 10^{11}$ $M_\odot$, this fraction is smaller and decreases with time. The authors suggest that passive (red) disks may be a common phase of galaxies transitioning onto the red sequence, and once formed, their transformation into spheroidals is moderately fast (1–3 Gyr), driven likely by minor mergers.

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