THE DEPENDENCE OF THE MASS ASSEMBLY HISTORY OF COLD DARK MATTER HALOS ON ENVIRONMENT

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ABSTRACT

We show by means of a high-resolution N-body simulation how the mass assembly histories of galaxy–size cold dark matter (CDM) halos depend on environment. Halos in high density environments form earlier and a higher fraction of their mass is assembled in major mergers, compared to low density environments. The distribution of the present–day specific mass aggregation rate is strongly dependent on environment. While in low density environments only ~20% of the halos are not accreting mass at the present epoch, this fraction rises to ~80% at high densities. At z = 1 the median of the specific aggregation rate is ~4 times larger than at z = 0 and almost independent on environment. All the dependences on environment found here are critically enhanced by local processes associated to subhalos because the fraction of subhalos increases as the environment gets denser. The distribution of the halo specific mass aggregation rate as well as its dependence on environment resemble the relations for the specific star formation rate distribution of galaxies. An analogue of the morphology–density relation is also present at the level of CDM halos, being driven by the halo major merging history. Nevertheless, baryonic processes are necessary in order to explain further details and the evolution of the star formation rate–, color– and morphology–environment relations.

Subject headings: cosmology:dark matter — galaxies:formation — galaxies:halos — methods:N–body simulations

1. INTRODUCTION

The build–up of galactic dark matter halos is a crucial ingredient of galaxy formation in the context of the popular hierarchical Λ Cold Dark Matter (ΛCDM) scenario. Many of the present–day galaxy properties are expected to be tightly related to their halo mass assembly process. A simple way to characterize this process is by the halo mass–aggregation history (MAH). The MAH implies both the mass growth by violent major mergers and by quiescent accretion. The influence of the MAHs on the halo and galaxy properties remains imprinted for example on the halo concentration (Avila-Reese et al. 1998; Firmani & Avila-Reese 2000; W echsler et al. 2002), the gas infall and star formation rates in disk galaxies (e.g., Avila-Reese & Firmani 2006; van den Bosch 2002; Murani et al. 2002) and the major merging rate and therefore, the morphology of galaxies (Kauffmann et al. 1993; Baugh et al. 1996; Somerville & Primack 1999; Cole et al. 2000; Springel et al. 2001; Granato et al. 2001; Steinmetz & Navarro 2002; Müller et al. 2005).

The continuous mass growth of isolated halos is a generic process in the hierarchical CDM scenario (e.g., Gunn 1982; Kauffmann et al. 1993; Lacey & Cole 1993). Semi–analytic models and numerical simulations have been used to predict the MAHs of halos of a given present–day mass, starting from a primordial Gaussian density fluctuation field characterized by a power spectrum. On one hand, the results have shown that, due to the stochastic nature of the primordial density field, the MAHs of halos of a given mass at z = 0 span a wide range of “tracks”, influencing galaxy features such as the scatter of the Tully–Fisher, halo concentration–mass and color–magnitude relations (Eisenstein & Loeb 1996; Avila-Reese et al. 1998; Firmani & Avila-Reese 2000; Bullock et al. 2001; Eke et al. 2001; Berlind et al. 2005). On the other hand, the MAHs depend on mass: less massive halos tend to build up a given fraction of their present–day mass on average earlier than the massive ones. This dependence is at the basis of the halo concentration–mass–relation (Navarro, Frenk, & White 1997; Firmani & Avila-Reese 2000; Eke et al. 2001; van den Bosch 2002; Wechsler et al. 2002; Zhao et al. 2003).

To study the general behavior of the MAHs as a function of mass and environment, we introduce the average MAH (AMAH) as $\langle M(a) \rangle = \frac{1}{M_0} \int_0^a \zeta(M) M(t) dt$, where $a$ is the scale factor and $\langle M(a) \rangle$ is the average mass of the most massive progenitors (MMP) of present–day halos of mass $M_0$ at the epoch $a$. It was found that the smooth AMAHs can be approximated by simple (universal) functions, where (1) the main function parameter is related to some typical formation epoch of the halo, and (2) this epoch depends on $M_0$ (Bullock et al. 2001; van den Bosch 2002; Wechsler et al. 2002). On the basis of N–body cosmological simulations, it was also suggested that all the MAHs, independent of $M_0$, present an early phase of fast mass aggregation (mainly by major mergers) and a late phase of slow aggregation (mainly by smooth mass accretion) (Zhao et al. 2003; Salvador-Solé et al. 2005).
We would also like to know if the bimodality of the star morphology, color, star formation rate, etc. on environment. able to explain the observed dependencies of galaxy mor-

CDM halos of similar masses depend on environment in denser regions (Sheth & Tormen 2004; Harker et al. 2004; Smith et al. 2005; Postman et al. 2005). As

other halo property on environment was found by these authors by combining cosmological N–body simulations and semi–analytic modeling of the baryon galaxy processes, a technique pioneered by Kauffmann et al. (1999) and Springel et al. (2001). Although in the pa-

ers that used this technique the galaxy dependencies on environment are intrinsically taken into account, the impact the MAH dependence on environment has on the galaxy properties is not clearly established.

The major observable dependencies with envi-
ente are seen for the morphological mix of elliptical and spiral galaxies (e.g., Dressler 1980; Postman & Geller 1984; Whitmore et al. 1993; Dominguez et al. 2002; Goto et al. 2003; color and specific star formation rate (e.g., Balogh et al. 1998; 2004; Kodama et al. 2001; Tran et al. 2001; Pimbblet et al. 2002; Lewis et al. 2002; Blanton et al. 2003; Gómez et al. 2003; Kauffmann et al. 2004; Hogg et al. 2004; Tanaka et al. 2004; Croton et al. 2005). Besides, there is some evidence that these dependencies evolve, becoming weaker at higher red-
shifts (Treu et al. 2003; Goto et al. 2004; Bell et al. 2004; Smith et al. 2005; Postman et al. 2005). As mentioned above, the morphology of galaxies as well as their colors and star formation rates are certainly related to the assembly history of their halos. Astrophysical external mechanisms, acting mainly in high–density environments, are also important. To disjoint the role of one from the other and to understand which are the drivers of the changes of galaxy properties with environment, it is important to explore and quantify how the CDM halo assembly history depends on environment. N–body cosmological simulations are required for this endeavor.

Based on N–body simulations, Lemson & Kauffmann (1999) concluded that only the halo mass function varies with environment. No significant dependence of any other halo property on environment was found by these authors. Gottlöber, Klypin & Kravtsov (2001) found that the major merging rate histories of CDM halos vary as a function of environment. More recently, Avila–Reese et al. 2005 found that some properties of halos of similar masses (for example, the mean concentration and spin parameter) actually vary systematically between voids and clusters. Also, recently, it was shown that halos of a given mass form statistically earlier in denser regions (Sheth & Tormen 2004; Harker et al. 2006; Gao et al. 2002; Wechsler et al. 2005). Nonetheless, the question of how the mass assembly history of CDM halos of similar masses depend on environment has not been yet explored in detail. Furthermore, we would like to know to what extent this dependence is able to explain the observed dependencies of galaxy morphology, color, star formation rate, etc. on environment. We would also like to know if the bimodality of the star formation rate (SFR) and color distributions, found in large statistical galaxy samples, could be accounted for, at least in part, by the physics of dark matter halos only.

In this Paper we construct the MAHs of ~ 4700 halos with present–day masses larger than 10^{11}h^{-1}M_{⊙} from a 50h^{-1}Mpc box simulation with high–mass res-

olution: m_{p} = 7.75 \times 10^{5}h^{-1}M_{⊙} (§2). We find that several quantities that characterize the halo MAH (the specific mass aggregation rate and merging mass fraction histories, formation times, etc.) change significantly with environment for halos of similar present–day masses (§3). We also explore possible systematical dependences of observational–related quantities on intermediate–scale density, and discuss to what extent these dependences are able to explain the observed galaxy property–density relations (§4). Finally, we highlight the main conclusions of our work (§5).

2. THE SIMULATION

We adopt a flat cosmological model with cosmologi-

cal constant (ΛCDM) and the parameters Ω_{m,0} = 0.3, Ω_{Λ} = 0.7, and h = 0.7. The initial matter power spec-

trum has been calculated using the numerical results of direct integration kindly provided by W. Hu, and it was normalized to σ_{8} = 0.9. The study in this Paper relies on the results from a simulation of box size 50h^{-1}Mpc run with the GADGET–II code (Springel 2005). With 512^3 particles and a particle mass of m_{p} = 7.75 \times 10^{5}h^{-1}M_{⊙} we are able to determine MAHs that extend from z = 0 to redshifts as high as 6 – 9 for halos more massive than 10^{11}h^{-1}M_{⊙} (containing > 1300 particles). In 95 timesteps of ∆z = 0.01 (∼100–160 Myr), halos are identified by a new MPI version of the Bound Density Max-

ima algorithm originally introduced by Klypin et al. 1999. This algorithm allows to detect isolated or ‘parent’ halos (self–bound structures not contained within larger ones) as well as subhalos (self–bound structures contained within larger ones). From these halo catalogues two merger trees were constructed, one for isolated halos alone and one for all halos, including subhalos. At z = 0 there are more than 4700 halos more massive than 10^{11}h^{-1}M_{⊙}.

A halo at redshift z_{1} with n_{j}(z_{1}) particles is identified as the MMP of a halo at z_{0} < z_{1} containing n_{i}(z_{0}) particles if at least a fraction f_{min} = 0.2 of its particles are found in the progenitor and the overlap of particles n_{ov} = n_{i}(z_{0}) \cap n_{j}(z_{1}) divided by n_{max} = max(n_{i}(z_{0}), n_{j}(z_{1})) is maximal. f_{min} is the only free parameter which is chosen to allow for major mergers and early rapid mass growth. MAHs and merger trees only very weakly depend on this parameter. For all progenitors which are merging in a timestep, at least half of their particles are required to be found in the descendant at z_{0}. The algo-

rithm to construct full merger trees from simulations will be described in a forthcoming paper. The construction of MAHs merely requires the identification of the MMP which is straightforward.

The intermediate–scale environment associated to a given halo is defined as the density contrast of dark mat-

ter in a sphere of radius R around the halo center of mass, δ(R) ≡ ρ(R)/ρ_{bg} − 1 (with ρ_{bg} the background density Ω_{θ}\rho_{crit}). The qualitative conclusions are not dependent on the choice of R for 2 < R/h^{-1}Mpc < 8. Since the dependences on environment become weaker for larger R, we will use here δ_{4} ≡ δ(R = 4h^{-1}Mpc). Note that with
the $\delta_4$ criterion, the local environment is smoothed out. For example, the value of $\delta_4$ for most subhalos contained within a given parent halo is the same, notwithstanding whether the subhalo is in the center or in the periphery of its parent halo. We are here interested in exploring the general effects of environment on the halo assembly process. The more local environmental effects are related only to subhalos and have been studied in detail previously (e.g., Kravtsov et al. 2004b; Reed et al. 2004a). In all cases the density contrast is defined at $z = 0$, except for those panels in Figures 8 and 9, where results for $z = 1$ are shown and $\delta_4$ is defined correspondingly at this redshift.

The distribution of the density contrast $\delta_4$ is shown in the upper panel of Fig. 1 for all halos in the three mass bins used hereafter. The vertical lines at $\delta_4 = 5$ and $\delta_4 = 0$ illustrate our definitions of 'high' and 'low' density environments, respectively. Density contrasts $\delta_4 > 5$ correspond to cluster environments, while $\delta_4 < 0$ correspond to the outskirts of filaments and to voids. In the lower panel we show the fraction of subhalos in subsamples selected by mass as a function of $\delta_4$. Whereas in the low density environment only around 1% of the halos with their maximum mass larger than $10^{11}h^{-1}M_{\odot}$ are subhalos, this fraction at high density amounts to about half of all halos. The overall fraction of halos more massive than $10^{11}h^{-1}M_{\odot}$ that are subhalos rises from 7% at $z = 1$ to 14% at $z = 0$.

We also explored the density measure used by Lemson & Kauffmann (1999), which excludes the mass of the halo itself and the close neighborhood, and uses only matter in a spherical shell of inner radius $2h^{-1}\text{Mpc}$ and outer radius 5$h^{-1}\text{Mpc}$ to calculate the density contrast $\delta_{2-5}$. The results presented in the next section virtually do not change when using $\delta_{2-5}$ instead of $\delta_4$. It should be noted that, according to hybrid N–body/semi-analytical models, the galaxy number density is proportional to the mass density (e.g., Kauffmann et al. 1997).

3. RESULTS

3.1. Mass aggregation histories

In Fig. 2 we present and compare the dependences of the AMAH on both mass and environment ($\delta_4$). The AMAHs of isolated halos (left four panels) and all halos (isolated+subhalos, right four panels) are shown in panels A and E for three different mass ranges: $11 \leq \log M_0/h^{-1}M_{\odot} < 11.5$, $11.5 \leq \log M_0/h^{-1}M_{\odot} < 12$ and $12 \leq \log M_0/h^{-1}M_{\odot} < 13$. Further, the AMAHs for the three mass bins, each one divided in our two extreme density contrasts are shown. Dashed and dotted curves correspond to the AMAHs in high–$\delta_4 > 5$ and low–$\delta_4 < 0$ density environments, respectively. These density–dependent AMAHs are shown with mass increasing from panel B to D for isolated halos, and from panel F to H for all halos.

For the construction of the AMAHs we adopt the following definitions. Individual MAHs are normalized to their maximal mass $M_{i,\text{max}}$. For most isolated halos the maximum mass is reached at the present day epoch, $M_{i,\text{max}} = M_i(z = 0)$. If a halo suffers mass loss, we keep $M_i(a)$ fixed until its mass further grows. Therefore all AMAHs have $\bar{M} (a = 1) = 1$. subhalos actually can experience substantial mass loss once they fall into their parent halo. However, it is reasonable to assume that the mass of a galaxy living in a subhalo is proportional to the maximum mass reached by the subhalo rather than to the current stripped halo mass: gas accretion related to the halo mass growth is stopped after the halo falls into a host halo; furthermore, halo tidal stripping is not expected to substantially affect the mass of the galaxy formed at the core of the halo. Therefore the mass of a halo is kept fixed to the mass the halo had at the time it becomes a subhalo ($M_{\text{max}}$), except for those halos that suffer mergers within the host halo, increasing thereby their mass.

When individual MAHs are followed to high redshift, the mass of more and more halos falls below the resolution limit. To avoid a bias in the AMAHs due to this incompleteness, the AMAHs are calculated only down to timesteps when more than 90% of individual MAHs can be followed. This is the reason why e.g., for the lowest mass bin, the curves already end at $\bar{M} \approx 0.1$. Since the slope of the mass function becomes steeper in lower density environments (Lemson & Kauffmann 1999; Gottlöber et al. 2003), their average mass in a given mass bin is lower than for halos in the same mass bin but in high density environments. To exclude this mass effect when comparing different environments the high-density mass environments halos are selected in their mass bin such that the average mass is approximately equal to the bin average mass of halos in the low-density environment. To achieve this we have to exclude a few of the most massive halos in each $\delta_4 > 5$ bin.

Figure 2 shows the well known dependence of AMAHs on mass: low mass halos on average assemble a given mass fraction earlier than massive halos. To get an impression of the scatter in individual MAHs, the 10 and 90 percentiles of the distribution are shown by dot-dashed lines for the middle mass bin ($11.5 \leq \log M_0/h^{-1}M_{\odot} < 12$). This scatter is much bigger than the differences between AMAHs corresponding to the different mass bins, a fact first noted by Avila-Reese et al. (1998).
The new result presented here is the dependence of the average halo MAHs of similar masses on environment. The lower is the density contrast $\delta$, the later on average halos of similar final mass accumulate their mass. This ambiental dependence is already seen for isolated halos (left panels of Fig. 2). However, the dependence becomes much stronger when subhalos are included, as shown in the right four panels of Fig. 2. As we saw in Fig. 1 the fraction of halos that are subhalos is a strong function of environment. On one hand, most subhalos reach their maximum mass at the time they fall into their host halo and have truncated MAHs. On the other hand, the properties of subhalos do not depend significantly on the host halo properties or its environment (De Lucia et al. 2004a). Thus, the main contribution of the MAHs of dark matter halos to the observed environmental dependence of galaxies should result from the dependence of the subhalo fraction on environment.

3.2. Mass aggregation rates

The MAHs can be further characterized by the mass aggregation rate of the halos. We show in Fig. 2 averages of fractional aggregation rates per Gyr normalized to the maximum mass of the given halo, $\dot{M}/M_{\text{max}}$. In building the average $\dot{M}/M_{\text{max}}$, mass loss is not taken into account, i.e. all halos with $dM/dt < 0$ have their aggregation rate set to 0 for the reasons outlined above. The left upper panel compares $\dot{M}/M_{\text{max}}$ for the same mass bins as in Fig. 2. While at high redshift the low mass halos are the ones that accumulate the mass faster, at low redshift we find that the high mass halos have the higher mass aggregation rates. Thus, the maximum of $\dot{M}/M_{\text{max}}$ moves slightly to lower redshifts with increasing mass. However, the differences in the $\dot{M}/M_{\text{max}}$ histories with mass are not so dramatic as with environment (see the rest of the panels of Fig. 2). The average aggregation rates at $z \approx 0$ are much higher in low-density environments than in the high-density ones, but these differences are reversed at redshifts higher than $z \sim 1$. The former is mostly due to the presence of subhalos which can not accrete more mass after falling into their host halo (the only way to increase the mass is through mergers but mergers are very unlikely inside a larger virialized structure).

The distribution of the present–day specific mass aggregation rate, $(\dot{M}/M_{\text{max}})_0$, consists of two parts: 43% of all the halos in the mass range $11.5 \leq \log M_\odot/h^{-1}M_\odot < 12.5$ have $(\dot{M}/M_{\text{max}})_0 \leq 0$ (‘passive’ halos), while the rest has $(\dot{M}/M_{\text{max}})_0 > 0$, with a distribution that peaks at $\sim 0.04\text{Gyr}^{-1}$ (See Fig. 4). The distribution of $(\dot{M}/M_{\text{max}})_0$ changes only little with mass, in the sense that massive halos have a slightly higher rate than the less massive halos (upper panel of Fig. 4). On the other hand, the distribution changes dramatically with environment (lower panel of Fig. 4). In the mass range of $11.5 \leq \log M_\odot/h^{-1}M_\odot < 12.5$, the fraction of ‘passive’ halos is $81\%$ and $22\%$ for the high– ($\delta > 5$) and low– ($\delta < 0$) density environments, respectively. The distribution of $(\dot{M}/M_{\text{max}})_0$ for halos with $(\dot{M}/M_{\text{max}})_0 > 0$ (‘active’ halos) also depends on environment: the median of the distribution is at $(\dot{M}/M_{\text{max}})_0 \approx 0.02\text{Gyr}^{-1}$ and $\approx 0.04\text{Gyr}^{-1}$ for the high– and low– density environments, respectively.

Our results are not complete if we do not estimate the accuracy in the measurement of the mass aggregation
rates and the fractions of passive/active halos. The former measurement is done by the estimate of the halo mass at two different output times. Therefore, its accuracy is related to the accuracy of the measurement of the halo mass in the simulation. The main source of error can be due to the halo finder (BDM). Since the initial seeds are chosen randomly and then moved iteratively to the centers of candidate halos, the resulting radii and masses of halos can in general be different. Differences due to a changing particle configuration can only be detected if they are greater than the differences introduced by the random seeds in BDM. We rerun the halo finder on the last timestep with different sets of initial seed centers for the halos. If \( M_1 \) and \( M_2 \) are two different mass determinations of the same halo, we find for the variance of \( (M_1 - M_2)/M_1 \) for all halos in the mass range \( 11.5 < \log(M/h^{-1}M_\odot) < 12.5 \) the value 0.00225, and hence for the error in \( (\dot{M}/M_{\text{max}})_0 \) a value of 0.0045. Therefore, except for the two lowest bins with \( \log(\dot{M}/M_{\text{max}})_0 < -2.3 \), Fig. 4 is not affected by these errors. The fraction of halos with \( 0 < (M/M_{\text{max}})_0 < 0.0045 \) is 1.4%. However, we recall that the MAHs we are using in our analysis are not allowed to decrease with time. If we use the actual MAHs instead, we find that ~5% of the halos in the above mass range have \( -0.0045 < (M/M_{\text{max}})_0 < 0.0045 \). We consider that this percentage represents the maximum error in the passive halo fraction determination.

Related to the mass error, there is also a systematical uncertainty in our estimate of the passive halo fraction. As explained and justified above, we used MAHs that are kept constant if the actual mass is falling. When using the actual mass in the two timesteps \( z = 0 \) and \( z = 0.1 \), the fraction of passive halos is 36% instead of 43%. On the one hand, the actual mass does not suffer from a temporary wrong assignment of a too high mass value in the past, as does the ‘non-decreasing’ MAHs. On the other hand, the actual mass gives not necessarily a better estimate of the passive halo fraction, since the actual mass is ignoring the possibility that the halo could have reached its maximum mass in the past and therefore is passive at present.

Summarizing, our method in general allows us only to find a possible range for the fractions of passive halos. For all the halos in the mass range \( 11.5 < \log(M/h^{-1}M_\odot) < 12.5 \) this lies between \((36 \pm 5)\%\) and \((43 \pm 5)\%\).

### 3.3. Formation times

Another way to characterize individual MAHs is by their formation time. Here we use the time when the MMP in the MAH reaches half of its maximum mass. To isolate the ambiental effect from the known mass differential effect we use as variable for the formation time the scaled formation redshift, \( \tilde{z}_{1/2} \). This quantity “absorbs” the dependence of \( z_{1/2} \) on mass \( \tilde{z}_{1/2} = [\delta_c(z_{1/2}) - \delta_c(z_0)]/\left[\sqrt{\sigma^2(M_0/2) - \sigma^2(M)}\right] \), where \( \delta_c(z) \) is the critical density threshold for collapse at \( z \) and \( \sigma^2(M) \) is the linear theory variance of density fluctuations at mass \( M \).

In Fig. 5 the distribution of \( \tilde{z}_{1/2} \) for isolated halos...
3.4. Major mergers

Major mergers are believed to play a crucial role in shaping galaxies and leading to an environmental dependence of galaxy morphology. We study here further the question of the halo major-merging dependence on environment. Earlier results by Gottlöber, Klypin & Kravtsov (2001) showed that such a dependence exists. We define a major merger when the relative mass increase (MMP complement), $\Delta M/M$, is larger than 0.2 in a timestep of $\Delta a = 0.01$. Results do not change qualitatively by fixing another reasonable mass fraction increase. We choose this criterion to be able to find mergers at high redshifts, where $\Delta M$ can still be determined for small halos but no secondary progenitor would be found. However, for subhalos we have found that the number of major mergers is overestimated when using $\Delta M$ to define a major merger.

Since the radius and mass of a subhalo can fluctuate due to the temporary incorrect assignment of particles to a halo, by using the $\Delta M/M > 0.2$ criterion more than half of the subhalos at $z = 0$ that were more massive than $10^{11.5} h^{-1} M_\odot$ at infall, get a merger assigned while they were subhalos. However, no secondary progenitor is found for these subhalos. To overcome this problem of incorrect major-merger counting associated to the uncertain mass determination of subhalos, we use an alternative criterion for subhalos: a major merger is counted when $M_{2\text{mm}}/M > 0.2$, where $M_{2\text{mm}}$ is the mass of the second most massive progenitor. Note that to meet this condition the second most massive progenitor should have more than 800 particles for halos with $M > 10^{11.5} h^{-1} M_\odot$. Using this criterion, now only 5% of all subhalos that survive until $z = 0$ suffered a major merger once they enter in a bigger halo.

With these definitions we find that halos in high-density environments suffered on average more major mergers than their counterparts in low-density environments. The average number of major mergers, counted since the mass of the halo is $M_i(a) > 0.05 M_{i,\text{max}}$, and the standard deviations are $4.8 \pm 1.4$ and $3.9 \pm 1.3$ for high- and low-density environments, respectively. The difference in the averages is highly significant according to Student’s $t$-test. This difference is established mainly at $z > 3$. For all the sample, we measure a mean of $4.3 \pm 1.4$ major mergers per halo, similar to the values reported in Li et al. (2005). As these authors showed, the major merging statistics does not depend significantly on halo mass.

From the pure number of major mergers it is difficult to estimate the effect mergers had on a halo, since early mergers only contribute a small fraction to the final halo mass. Therefore we also measured for every halo the fraction of mass accreted in major merger events. For the sample including subhalos and in the mass range $11.5 \leq \log M_0/h^{-1} M_\odot < 12.5$, Fig. 4 shows averages of the major-merger mass fraction, $f_{\text{mm}} = M_{\text{mm}}/M$, vs $a$ for all halos (solid line), and for halos in the high- ($\delta_i > 5$, dashed line) and low- ($\delta_i < 0$, dotted line) density environments. At a given epoch $a$, $M$ and $M_{\text{mm}}$ are the current halo mass and the mass assembled in major mergers until $a$, respectively. The encapsulated panel shows the corresponding distribution of $f_{\text{mm}}$ at $z = 0$. The denser is the environment, the higher and broader...
FIG. 6.—Evolution of the average fraction \( f_{\text{mm}} \) of mass accreted in mergers \( (\Delta M / M > 0.2) \) is shown for all halos in the mass range \( 11.5 < \log M_{0} / h^{-1}M_{\odot} < 12.5 \) as solid line. Halos in high and low density environments are shown by dashed and dotted lines, respectively. The evolution of \( f_{\text{mm}} \) for isolated halos is indicated by thin lines. The encapsulated panel shows the distributions of \( f_{\text{mm}} \) at \( z = 0 \) for all halos. The averages and scatter of \( f_{\text{mm}} \) at \( z = 0 \) are given in the main panel.

We have found that the mass assembly histories of galaxy–size CDM halos show marked environmental dependences, though with large scatters. This kind of findings requires numerical simulations due to the complexity that introduces the local and global environment. Popular approaches used for modeling galaxy formation and evolution, as the EPS theory and the halo model of galaxy clustering, assume that the halo evolution and properties depend only on mass but not on environment or formation times. The results of the present paper as well as of recent works Gao et al. 2003 Wechsler et al. 2003, Abbas & Sheth 2005 should be taken into account in these semi–analytical approaches Sheth & Tormen 2003.

In the hierarchical clustering scenario, the evolution of galaxies is tightly related to the assembly history of their halos. In this section we will discuss and attempt to quantify to what extent properties of the observed galaxy population are established already at the level of CDM halos and how the trends with environment found for halos compare to those observed for galaxies.

Over the last years, a number of groups used the technique of grafting semi–analytic models of galaxy evolution on to CDM halo merging trees constructed from large–volume cosmological N–body simulations (e.g., Kauffmann et al. 1999, Diaferio et al. 2001, Springel et al. 2001, Helly et al. 2003, Hatton et al. 2003, De Lucia, Kauffmann & White 2004a, Springel et al. 2005, Kang et al. 2005). In these works, where the properties, distributions and evolution of different galaxy populations were predicted, the spatial distribution of galaxies is explicitly taken into account. However, in most of these works the halo assembly process could only be followed with accuracy for the most massive galaxy–sized halos and, in some cases, subhalos were not included in the analysis at all. On the other hand, it was not quantified explicitly to what extent the obtained galaxy properties and distributions are the result of the CDM halo assembly history.

4. DISCUSSION
To tackle this question, in the following we will consider a simple model, in which galaxy SFRs are proportional to halo aggregation rates and bulge–to–total mass ratios (morphologies) are determined by the $M_{\text{inn}}/M_{\text{max}}$ ratios of halos. Although we are well aware that this is not a realistic model of galaxy formation, the idea is to isolate the environmental effects of CDM and to be able to compare to observations.

### 4.1. The distributions of halo properties

The recently assembled large galaxy redshift surveys such as the Two–degree Field Galaxy Redshift Survey (2dFGRS) and the Sloan Digital Sky Survey (SDSS) have revealed that specific SFRs and colors are not evenly distributed (e.g., Strateva et al. 2001; Blanton et al. 2003; Hogg et al. 2003; Brinchmann et al. 2004; Balogh et al. 2004; Tanaka et al. 2004; Kauffmann et al. 2004; Weinmann et al. 2006 and more references therein). Galaxies are clearly separated into two distinct populations of red, old and 'passive' early–type galaxies, and blue and 'active' star forming late–type galaxies.

The distribution of the mass aggregation rates and its evolution presented in §3.2 seem to lie at the foundation of these observed bimodalities of the galaxy population. While our simplifying assumption that the specific SFR of galaxies is driven mainly by $(\dot{M}/M_{\text{max}})_{0}$ can in general reproduce this bimodality, the aggregation rates at the low and high–mass end of the halo population can not be reconciled with observations. Here, baryonic processes must come into play. The color distribution on the other hand is influenced not only by SFRs and ages of the stellar population, but also by the metal enrichment, i.e. a purely baryonic process.

One may consider that a fraction of the 'passive' halos after truncating their MAHs retain for some Gyr a reservoir of hot coronal gas that may still feed the galaxy with fresh gas through cooling flows. Therefore, the fraction of galaxies formed within the 'passive' halos that are quiescent should be lower than the $\approx 40\%$ of 'passive' halos found in §3.2 (Weinmann et al. 2006). We find for the SDSS sample that roughly $31\%$, $20\%$, and $48\%$ of galaxies belong to their categories of red quiescent, red star–forming, and blue actively star–forming galaxies, respectively. It is interesting to note that these fractions could be roughly explained at the level of CDM halo activity if one takes into account that the $\sim 20\%$ of red star–forming galaxies are formed in some of the 'passive' halos and in those with very low $(\dot{M}/M_{\text{max}})_{0}$ values.

For the low mass halos which have low aggregation rates it is also challenging to explain how they can host galaxies with high specific SFRs (Brinchmann et al. 2004). In these halos cooling and star formation must be delayed with respect to the dark matter assembly. In particular, cold gas may stay in the disk without being consumed immediately by star formation. This is in general expected, as the SFRs of observed galaxies are related to their gas surface mass density (Kennicutt 1998). For the low mass galaxies, high efficient feedback at low gas disk surface density combined with later re-accretion of the gas could result in the high specific SFRs at the present epoch. The disk mass surface density is indeed predicted to be lower as the halo mass decreases (e.g., Dalcanton, Spergel & Summers 1997, Avila-Reese et al. 1998, Mo, Mao & White 1998).

We find that the distribution of $(\dot{M}/M_{\text{max}})_{0}$ is very sensitive to environment: 'passive' halos are the majority in the high density regions, while 'active' halos are the majority in the low density regions (see fractions inside Fig. 4). On the other hand, at least in the mass range studied in our simulation, we do not find a strong mass dependence in the $(\dot{M}/M_{\text{max}})_{0}$ distribution (the fraction of halos with $(\dot{M}/M_{\text{max}})_{0} \leq 0$ for three mass ranges change only by a few percent; see Figs. 4 and 5). The main reason of the environmental dependence of $(\dot{M}/M_{\text{max}})_{0}$ is the fact that halos in higher density regions become subhalos (which means truncation of the mass aggregation process) earlier and much more frequently than halos in lower density regions. As a result, the fractions of 'passive' and 'active' halos in the distribution of the specific mass aggregation rate changes significantly from low– to high–density environment, while the change with mass is only marginal.

The variation of the $(\dot{M}/M_{\text{max}})_{0}$ distribution with environment indeed resembles the corresponding variations observed for SFR tracers (e.g., Kauffmann et al. 2004; Balogh et al. 2004, see in particular Croton et al. 2005, Fig. 2, who use an intermediate–scale environment criterion close to the one used here.). However, the shapes of the $(\dot{M}/M_{\text{max}})_{0}$ distributions of halos with $(\dot{M}/M_{\text{max}})_{0} > 0$ also change with environment. The distribution is more peaked in the low–density regions than in the high–density ones (Fig. 4). These differences are significant according to a K–S test. The medians of $\dot{M}/M_{\text{max}}$ for the halos with positive aggregation rates in our two selected environments are $0.02$ Gyr$^{-1}$ and $0.04$ Gyr$^{-1}$, respectively. This is at variance with the behavior that was reported for the population of star–forming galaxies by Balogh et al. (2004) who found no significant differences for these galaxies with environment.

Observations show a dependence of the bimodality in specific SFR or color on luminosity (or stellar mass). It is possible that this dependence is due to the correlation between the galaxy luminosity function and environment (e.g., Hogg et al. 2003; Croton et al. 2005). The main problem for our simplified model arises for the massive halos in relatively isolated regions: they aggregate mass at a similar or slightly higher rate than the less massive isolated halos, in such a way that the sequence of luminous red quiescent galaxies in the field is not expected; instead an overabundance of luminous blue active galaxies is expected. Observations apparently contradict these expectations: there is evidence of a red sequence of luminous galaxies in low density environments and luminous blue galaxies are rare in any environment (Balogh et al. 2004); it was also found that lower mass field galaxies tend to have higher specific SFRs than higher mass field galaxies, and this trend continues to very high redshifts (Feulner et al. 2005). The solution to this apparent problem may lie in astrophysical processes such as mass–dependent shock heating of the halo gas corona coupled to AGN feedback (e.g., Cattaneo et al. 2006; Bower et al. 2006 and references therein).

### 4.2. Mass aggregation rate dependence on environment and evolution of this dependence

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An interesting question with respect to the environmental dependences is which halo property shows the strongest correlation with environment and if some correlations are more fundamental than others. Recent investigations (Christlein & Zabludoff 2005) show that the SFR–density relation persists, even if stellar mass, mean stellar age and morphology are kept fixed. Also color and magnitude were shown to have the strongest dependence on environment, compared to surface–brightness and concentration (Blanton et al. 2003). Quintero et al. (2005) even find that there is no morphology–density relation at fixed color. To shed some light on the question of the relative strength of these effects and a possible relation, in Figures 8 and 9 we show the specific mass aggregation rates and $M/M_{\text{max}}$ ratios (our proxies for the specific SFR and morphology) as a function of the density contrast $\delta_4$ and the cluster–centric radius, respectively.

The overall dependence of the specific mass aggregation rate, $M/M_{\text{max}}$ on the intermediate–scale density ($\delta_4$) can be appreciated in the upper panels of Fig. 8. Solid and dashed lines show the medians of all halos in the mass ranges $11 < \log M_0/h^{-1}M_\odot < 12$ and $12 < \log M_0/h^{-1}M_\odot < 13$, respectively. Dotted lines are the 25th and 75th percentiles for the former mass range, and the two-dotted-dashed line is the 75th percentile for the latter mass range (the 25th percentile falls outside the plot). Left panel is at $z = 0$ and right panel is at $z = 1$. The median of $M/M_{\text{max}}$ at $z = 0$ anti-correlates weakly with $\delta_4$ up to $\delta_4 \approx 2 - 3$: for halos in higher density environments, the median of $M/M_{\text{max}}$ drops rapidly to 0, i.e. the population of ‘passive’ halos (mostly subhalos) starts to dominate. The differences in these behaviors with mass are small. The more massive halos present slightly higher mass aggregation rates. At $z = 1$, there is almost no correlation of the mass aggregation rate with environment. Especially halos in high density environments are still in their growth phase and no drop of accretion rates at these densities is observed. The $M/M_{\text{max}}$ values at $z = 1$ are systematically higher by a factor of $\sim 4$ than those found at $z = 0$. For the most massive halos, $M/M_{\text{max}}$ even increases slightly with $\delta_4$. The mass aggregation of the latter halos at these epochs happens not only by accretion but also, in a significant fraction, by major mergers, which are common in a dense region that still did not virialize.

Analysis of the SDSS and 2dFGRS surveys showed that SFR tracers, as the Hα line equivalent width, $W$(Hα), correlate with local density of galaxies or with the cluster–centric radius (Lewis et al. 2002; Gómez et al. 2003; Balogh et al. 2003; Tanaka et al. 2004). The qualitative features of these correlations are similar to those presented here for the mass aggregation rate of CDM halos at $z = 0$. Two populations of galaxies, those with significant, on–going SF, and those without SF, are revealed. The distributions of $W$(Hα) or the inferred specific SFR present an abrupt change at some characteristic density $\rho_c$ or cluster–centric radius $r_c$; at densities higher than $\rho_c$ (or radii smaller than $r_c$) there is a near–total lack of star–forming galaxies, while at densities smaller than $\rho_c$ (radii larger than $r_c$), the SF activity tends to increase. These features are well explained if the current SFR of galaxies is associated to the mass infall rate of their halos.

Recent studies show that the galaxy SFR and color bimodality is present at redshifts as high as $\sim 1$, though with significant changes (Bell et al. 2003; Nuijten et al. 2003; Giallongo et al. 2003; Faber et al. 2003; Cooper et al. 2006; Cucciati et al. 2006). Observations show that the density of the galaxy red sequence roughly duplicates since $z \sim 1$ to $z = 0$ with a slight red–dening of the peak of the distribution (Bell et al. 2003; Nuijten et al. 2003). From our simulation, we find that the fraction of ‘passive’ halos with $M/M_{\text{max}} \leq 0$ increases by factor of $\sim 3$ since $z = 1$ to $z = 0$.

To further contrast ‘active’ and ‘passive’ halos, in the upper panels of Fig. 9 we show the fractions of ‘active’ ($M/M_{\text{max}} > 0$, dotted line) and ‘passive’ ($M/M_{\text{max}} \leq 0$, solid line) halos in our simulation at $z = 0$ (left panel) and $z = 1$ (right panel) as a function of cluster–centric radius. The use of cluster–centric radius allows to probe also the radial dependence inside the group/cluster halo where $\delta_4$ remains constant. At $z = 0$ ‘passive’ halos dominate completely inside the virial radius of collapsed structures, $R_{\text{vir}}$. The fraction of ‘passive’ halos decreases beyond $R_{\text{vir}}$ while the fraction of ‘active’ halos increases. In regions as far as $\sim 3R_{\text{vir}}$, the fraction of ‘active’ halos already dominates over that one of ‘passive’ halos. At $z = 1$ (i) the dependences of the fractions of both halo populations on environment become much flatter than at $z = 0$, and (ii) ‘active’ halos dominate over ‘passive’ ones even inside the virial radii of collapsed structures. In a very recent work, Cucciati et al. (2006) have reported a qualitatively similar evolution for the color–density relation by using a sample of thousands of galaxies from the VIMOS-VLT Deep Survey. We remark that the density criterion used by these authors traces
Fig. 9.— The upper two panels show the fractions of ‘passive’ (no accretion) and ‘active’ (accreting) halos at redshifts 0 and 1 as a function of cluster–centric radius. The $M_{\text{inn}}/M_{\text{max}}$ ratio is symbolized with $\beta$. The lower two panels show fractions of merger–dominated halos ($\beta < 0.3$) as dotted lines and of intermediate halos ($0.3 < \beta < 0.5$) as dashed lines. Requiring that accretion–dominated halos had no major merger since $z = 1$ for halos at $z = 0$ or in the last 2 Gyrs for halos at $z = 1$ leads to the thin dotted lines. The additional condition that the last major merger happened more than 2 Gyrs ago for the merger–dominated halos leads to the thin solid lines.

4.3. The morphology–density relation and its evolution

The $M_{\text{inn}}/M_{\text{max}}$ ratio distributions for all (isolated + sub–) halos in the mass range $11.5 \leq \log M_0/h^{-1}M_\odot < 12.5$, and for the subsamples of halos in the high– and low–density environments were presented in Fig. 8. The $M_{\text{inn}}/M_{\text{max}}$ ratios are systematically larger for higher environmental densities, similar to the observational trends for the galaxy bulge–to–total luminosity ratio. However, the fraction of halos with large $M_{\text{inn}}/M_{\text{max}}$ (thought to be associated to elliptical galaxies) is very small, even in the high-density (cluster) environment. This suggests, even in the high-density (cluster) environment, that astrophysical processes able to prevent further gas accretion onto big spheroids are necessary to explain the observed fractions of elliptical and S0 galaxies (see above).

The bottom panels of Fig. 8 show the median and quartiles of the $M_{\text{inn}}/M_{\text{max}}$ distribution as a function of $\delta_4$ at $z = 0$ (left) and $z = 1$ (right). The line code is as in the top panels. At $z = 0$, there is a weak but continuous increase of the $M_{\text{inn}}/M_{\text{max}}$ ratio with $\delta_4$. The correlation is nearly independent of mass (if any, massive halos have slightly larger $M_{\text{inn}}/M_{\text{max}}$ ratios than the less massive halos) and it has roughly the same slope for different percentiles. Unlike the $\dot{M}/M_{\text{max}}$ distribution, there is no sharp change in the values of $M_{\text{inn}}/M_{\text{max}}$ when passing from high– to low-density regions. In other words, the halo $M_{\text{inn}}/M_{\text{max}}$–density relation extends smoothly from high to low densities. In the case of observed galaxies, the bulge–to–total mass ratio (morphology) indeed changes with environment more smoothly than the SFR (Christlein & Zabludoff 2003). However, the morphology (mostly of faint galaxies) changes more abruptly at a certain density (typical of clusters outskirts) than our halo $M_{\text{inn}}/M_{\text{max}}$ ratio (Tanaka et al. 2004), suggesting that baryonic processes should play also a role here.

At $z = 1$, the dependence of the current $M_{\text{inn}}/M_{\text{max}}$–ratio on intermediate–scale density is almost absent (see lower right panel of Fig. 8). This plot can be interpreted as follows: in dense environments (protoclusters), the $M_{\text{inn}}/M_{\text{max}}$ ratio is practically established at these early epochs, while in less dense environments, the halos still grow by mass accretion so that the $M_{\text{inn}}/M_{\text{max}}$ ratios decrease with time. The galaxies inside these halos will grow still blue disks. However, some baryonic mechanisms that are effective in the field or poor groups can reduce the decrease of the bulge–to–total mass ratio (and SFR) as the density is lower. These processes are for instance (Tanaka et al. 2004) the low velocity interactions between galaxies, able to trigger SF and consume the gas, and strangulation (halo–gas stripping).

In the bottom panels of Fig. 9 the fractions of merger–dominated halos ($M_{\text{inn}}/M_{\text{max}} > 0.5$), intermediate halos ($0.3 < M_{\text{inn}}/M_{\text{max}} < 0.5$), and accretion–dominated halos ($M_{\text{inn}}/M_{\text{max}} < 0.3$) are shown as a function of the cluster–centric–radius for redshifts $z = 0$ (left panel) and $z = 1$ (right panel). The fraction of halos with high $M_{\text{inn}}/M_{\text{max}}$ ratios decreases continuously from $\sim 0.4$ in the center of virialized host halos to $\sim 0.2$ at $4 - 5 R_{\text{vir}}$. The fraction of halos with low $M_{\text{inn}}/M_{\text{max}}$ ratios is small in the centers of virialized host halos ($\sim 0.25$), but it continuously increases from the periphery to regions of low density where it attains a value of $\sim 0.5$. The fractions of halos with low and high $M_{\text{inn}}/M_{\text{max}}$ ratios become comparable at $\sim 1 R_{\text{vir}}$. Intermediate halos are more abundant inside virialized host halos than in low–density regions.

The observed morphology–density (e.g., Dressler 1980; Postman & Geller 1984; Dressler et al. 1985; Goto et al. 2003) and morphology–cluster–centric radius (e.g., Whitmore & Gallagher 1991; Domínguez et al. 2002; Goto et al. 2003) relations for galaxies are in qualitative agreement with the trends obtained here for halos. The fraction of intermediate–type galaxies (mostly S0’s) increases from the outskirts of clusters to intermediate cluster radii, while the fraction of late–type galaxies decreases. In the densest regions (cluster centers), the intermediate– and late–type galaxy fractions decrease, while the early–type fraction increases. In the sparse regions (far from clusters), the morphology–density relation flattens, i.e. the fractions of different galaxy types only slightly change with density or cluster–centric radius, and the fraction of late–type galaxies dominates. Probably, the main difference with halos is that the fractions of merger– and accretion–dominated halos continue depending on cluster–centric radius (or on density) in these low–density environments (see Fig. 9). However, there are several baryonic processes that could work in the correct direction to “flatten” the morphology–density relation (see above).
At $z = 1$ the fraction of halos with high $M_{\text{imm}}/M_{\text{max}}$ values in the inner parts of clusters is higher ($\sim 0.6$) than at $z = 0$ ($\sim 0.4$). The existing groups/clusters at $z = 1$ just formed and contain still a large fraction of halos that suffered a major merger very recently (large $M_{\text{imm}}/M_{\text{max}}$ ratios). At $z = 0$ a large part of those halos has merged with the parent halo and is replaced with new subhalos that had more time to aggregate mass by smooth accretion before they became subhalos, resulting in a higher fraction of halos with smaller $M_{\text{imm}}/M_{\text{max}}$ ratios than at higher redshift. In regions outside virialized groups/clusters, most of the halos continue accreting mass until the present epoch, so that their $M_{\text{imm}}/M_{\text{max}}$ ratio decreases more and more, increasing therefore drastically the fraction of halos with small $M_{\text{imm}}/M_{\text{max}}$ ratios (compare also Fig. 6).

When attempting to connect our results with observations of galaxy populations, we should have in mind that the halo last major merger may have happened very recently. In this case a high $M_{\text{imm}}/M_{\text{max}}$ value does not imply a residing early–type galaxy, but rather a star–bursting one. If we impose the extra condition that the last major merger happened more than 2 Gyr ago, then the fraction of merger–dominated halos decreases, mainly at $z = 1$ (thin solid lines in lower panels of Fig. 6). Nevertheless, this fraction is still larger at $z = 1$ than at $z = 0$, contrary to the observational inferences (Smith et al. 2003; Postman et al. 2003). Since the “morphological” fractions reported here for halos at $z = 0$ are comparable to those observed for galaxies, the main disagreement actually occurs at $z = 1$.

On one hand, at high redshifts and in dense environments, most of the halos are still actively growing, with a significant mass fraction aggregated in mergers. Therefore, a part of the high–density halo population with $M_{\text{imm}}/M_{\text{max}} > 0.5$ at $z = 1$ is expected to harbour actually blue, star–forming galaxies. On the other hand, the strong increase of the fraction of accretion–dominated halos since $z = 1$ to $z = 0$, especially at large cluster–centric radii, contrasts with the corresponding decrease in the observed late–type galaxy fraction (Smith et al. 2003; Postman et al. 2003). As discussed above, baryonic processes in the field and poor groups may work to decrease the present–day fraction of late–type galaxies in the low–density accretion–dominated halos. However, it is not easy to explain the observed high fraction of late–type galaxies in low–density environments at high redshifts as compared to the low fraction of accretion–dominated halos in these environments. Selection effects could be affecting the observational inferences of the morphological mix. Detailed galaxy modeling inside the evolving ΛCDM halos is necessary to understand better the evolution of the morphology –cluster–centric radius and –density relations.

Finally, by comparing the strenght of the environmental dependence of the aggregation rate and the $M_{\text{imm}}/M_{\text{max}}$ ratio presented in Figures 8 and 9, we conclude that $M_{\text{imm}}/M_{\text{max}}$ shows a much weaker dependence on environment than the aggregation rate, $\dot{M}/M_{\text{max}}$. It could be, however, that the difference between the strength of the observed morphology–density relation and our $M_{\text{imm}}/M_{\text{max}}$–density relation is caused by processes influencing both, SFRs and morphology, at the same time.

5. CONCLUSIONS

In previous works it was shown that the present–day mass function (Lemson & Kauffmann 1999) and internal properties (Avila-Reese et al. 2003) of ΛCDM halos change systematically with environment. In the present paper we investigated environmental dependences of the mass assembly process of ΛCDM halos. Our results suggest that a significant part of the relations observed between galaxy properties and environment can be explained by the environmental dependences of the halo assembling process. Our main findings are as follows:

- The MAHs of the ΛCDM halos change with intermediate–scale environment: the lower the density contrast $\delta_1$, the later on average a given fraction of the maximum halo mass is assembled. The averages of the specific present–day mass aggregation rate, $(\dot{M}/M_{\text{max}})_0$, are 4–5 times higher for halos in low–density environments ($\delta_1 < 0$) than for halos in high–density environments ($\delta_1 > 5$). These differences are smaller at higher redshifts, at $z \sim 1$ disappear, and for $z \gtrsim 1$ the trends are reversed. The average MAHs and mass aggregation rates also depend on halo mass, but to a much lesser degree than on environment.

- The distribution of $(\dot{M}/M_{\text{max}})_0$ has two parts: $\approx 40\%$ of all the halos in the mass range $1.5 \lesssim \log M_0/h^{-1}M_\odot < 2.5$ do not aggregate mass, i.e. $(\dot{M}/M_{\text{max}})_0 \leq 0$, while the rest has a distribution of $(\dot{M}/M_{\text{max}})_0$ peaked at $\sim 0.03 - 0.04$ Gyr$^{-1}$. The distribution changes little with mass but dramatically with environment: the fraction of halos with $(\dot{M}/M_{\text{max}})_0 \leq 0$ increases to $\approx 81\%$ and reduces to $\approx 22\%$ for the high– and low–density environments, respectively. The distribution of the halo formation time, also changes with environment: for instance, halos of $\sim 10^{12} h^{-1}M_\odot$ assemble half of their maximum mass approximately $1.5$ Gyr earlier in the high–density regions than in the low–density ones.

- Using only isolated halos, the dependences of halo MAHs on environment are weak, showing that the intermediate–scale density around halos affects only partially their mass assembling process. The strongest effects of environment appear when subhalos are included. Although the effect due to subhalos is local, the fraction of halos with masses above $10^{11} h^{-1}M_\odot$ that become subhalos increases as the environment gets denser. The two main effects that a halo suffers when it becomes subhalo of a larger host virialized structure are: (i) its MAH is suddenly truncated (the mass growth is even reversed to mass loss due to tidal stripping), and (ii) the major merging probability drops drastically due to the high velocity dispersions inside the virialized host halo.

- Present–day halos in high–density environments suffered more major mergers on average and assembled a larger fraction of their mass in major mergers than halos in low–density regions. Halos in dense regions become subhalos at $z \lesssim 1$ much more frequently than those in low–density regions. For these halos the (high) major merging mass fractions and (large) last major merger mass-to-current mass ratios, $M_{\text{imm}}/M_{\text{max}}$, become defined at the epoch of their infall. On the other hand, halos in low–density environments continue growing mainly
mass accretion, thus, their major merging mass fraction and \( M_{\text{imm}}/M_{\text{max}} \) ratio continuously decrease.

We have shown that the distribution of \( (M/\text{max})_0 \) and the strong dependence this distribution presents with environment could explain partly the observed bi-modal distributions of specific SFR and color for galaxies and their systematical dependences on environment. The main difficulty for this direct halo–galaxy connection would be to explain the existence of the population of red luminous galaxies in low–density environments, and the high fraction of blue star forming galaxies among low mass galaxies. Astrophysical processes related to baryonic matter should be invoked here.

The morphology–density relation can be partly explained if the halo \( M_{\text{imm}}/M_{\text{max}} \) ratio is used as measure of the bulge–to–total mass ratio (morphology). However, even close to the cluster center, the fraction of halos with \( M_{\text{imm}}/M_{\text{max}} \) as high as to harbour elliptical galaxies is too small at \( z = 0 \). This suggests the need of astrophysical processes able to avoid gas accretion onto the early formed spheroids. The main trends of the observed morphology–density and cluster–center radius relations at \( z = 0 \) agree with the trends of the halo \( M_{\text{imm}}/M_{\text{max}} \) ratio with environment reported here.

Future comparisons of observations with models that include the astrophysical processes of galaxy formation in highly resolved evolving ACDM halos will tell us whether or not the ACDM paradigm agrees with observations, and what are the key ingredients at the basis of the morphology-, color-, and star formation–density correlations. Our results suggest that the halo assembly process and its dependence on environment should be a main ingredient.

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