On Halo Formation Times and Assembly Bias

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ABSTRACT

In this paper we use the “Millennium Simulation” to re-examine the mass assembly history of dark matter halos and the age dependence of halo clustering. We use eight different definitions of halo formation times to characterize the different aspects of the assembly history of a dark matter halo. We find that these formation times have different dependence on halo mass. While some formation times characterize well the hierarchical nature of halo formation, in the sense that more massive halos have later formation, the trend is reversed for other definitions of the formation time. In particular, the formation times that are likely to be related to the formation of galaxies in dark halos show strong trends of “down-sizing”, in that lower-mass halos form later. We also investigate how the correlation amplitude of dark matter halos depends on the different formation times. We find that this dependence is quite strong for some definitions of formation time but weak or absent for other definitions. In particular, the correlation amplitude of halos of a given mass is almost independent of their last major merger time. For the definitions that are expected to be more related to the formation of galaxies in dark halos, a significant assembly bias is found only for halos less massive than $M_*$. We discuss our results in connection to the hierarchical assembly of dark matter halos, the “archaeological down-sizing” observed in the galaxy population, and the observed color-dependence of the clustering strength of galaxy groups and clusters.

Key words: cosmology: theory — galaxies: formation — galaxies: halos — dark matter.

1 INTRODUCTION

The cold dark matter (CDM) scenario has been proven a very successful model for structure formation. In this framework, most mass in the cosmic density field ends up in virialized objects, called dark matter halos, and luminous objects, such as galaxies, are supposed to form and evolve in such halos \citep{WhiteRees1978}. Clearly, the first step in understanding the formation of galaxies is to understand the formation of the dark halo population. Using both $N$-body simulations and semi-analytical methods, many important results have been obtained regarding the properties of dark matter halos in the current CDM paradigm of structure formation, including halo mass function \citep[e.g.][]{Bond1991, LaceyCole1993, ShethTormen1999, ShethTormen2001, Warren2006}, density and sub-halo profile \citep[e.g.][]{NavarroFrenkWhite1997, Bullock2001, Eke2001, Gao2004, Lu2006}, angular momentum property \citep[e.g.][]{BarnesEfstathiou1987, ColeLacey1996, Bullock2001, ChenJing2002}, and clustering property \citep[e.g.][]{MoWhite1996, Jing1998, LemsonKauffmann1999, ShethTaylor1999, ShethTormen2001}. These results have been playing an important role in our understanding of galaxy formation.

One important property of a dark halo is its formation history. In the previous studies, this formation history is usually characterized by a single parameter which is the time when a halo has acquired half of its final halo mass \citep[e.g.][]{LaceyCole1993, LemsonKauffmann1999, vanBosch2002, Gao2003, Wechsler2000}. This definition of halo formation time is useful because it indicates when the main body of a halo is assembled. However, it is unclear if such definition is closely related to how galaxies form in a halo. For example, \cite{vanBosch2003} and \cite{Yang2003} both found that dark halos with masses around $10^{11.5} h^{-1} M_\odot$...
have the lowest mass-to-light ratio, which suggests that star formation is the most efficient in halos with a fixed mass around $10^{11-12} h^{-1} M_\odot$. Thus, for halos with masses much larger than this mass, the half-mass assembly time may have little to do with how galaxies may have formed in such halos. Based on the half mass formation time, more massive halos are expected to form later due to hierarchical clustering. This is in contrast with the recent observations that the stellar population in more massive systems are generally older (Thomas et al. 2005; Nelan et al. 2005). This phenomenon, known as the “archaeological down-sizing”, appears to be in contradiction with the “hierarchical” formation scenario, but may also indicate that the growth of galaxies in a halo does not follow the growth of the halo.

Recently Gao, Springel & White (2005, see also Wechsler et al. 2002; Harker et al. 2006; Jing, Suto & Mo 2007; Gao & White 2007) found that, the half-mass assembly time of a halo is also correlated with halo clustering properties on large scales. Using N-body simulations, these authors find that, for halos of a given present mass that is smaller than $M_*$, the ones that assembled half of their final masses earlier are more strongly clustered in space. On the contrary, for halos more massive than $M_*$, the ones that assembled half of their final masses later are more strongly clustered. If the star formation history is somehow correlated with dark halo formation history, as is expected from current theory of galaxy formation, these results would indicate that galaxy systems, such as clusters and groups, of the same mass but containing different galaxy populations should also show different clustering properties. Observationally, there is evidence to support such connection (e.g. Wang et al. 2007b; Yang et al. 2004; Berlind et al. 2006). Although there is still discrepancy among the different results, most studies show that redder groups are more strongly clustered than bluer groups. In particular, the results of Wang et al. (2007b) suggest that such color dependence is stronger for groups with lower halo masses and becomes insignificant for groups with halo masses above $\sim 10^{13} h^{-1} M_\odot$. This dependence has the same trend as the assembly-time dependence of halo clustering, and it is tempting to link these two types of dependence. However, as mentioned above, the half-mass assembly time may not be a good indicator of the typical formation time of stars in a halo. Indeed, using a “shuffling” technique, Croton et al. (2007) found that, the dependence of halo bias on halo half-mass assembly time can only account for about half of the clustering bias seen in red halos in their semi-analytical catalogue. Clearly, in order to understand the observational results in terms of halo assembly bias, one needs to define halo formation times that are more closely related to the formation of galaxies in dark matter halos.

The main goal of this paper is to systematically study when various characteristic events take place in the halo assembly process and how they are correlated with halo mass and with the large-scale environments. To this end, we define a number of formation times to characterize each halo formation history. We study in detail how each of these formation times is correlated with halo mass and how the halo correlation amplitude depends on these formation times. Our analysis is based on the “Millennium Simulation” (Springel et al. 2005b). The paper is organized as follows. In Section 2, we briefly describe the simulation and the techniques to identify halos and to construct merging trees. In Section 3, we describe our definitions of halo assembly times and how to estimate them from the simulation, and study how they are correlated with halo mass. In Section 4, we present the results on the assembly-time (age) dependence of halo clustering. Finally, in Section 5, we summarize and discuss the implications of our results.

2 THE SIMULATION

In this paper we use the “Millennium Simulation” (MS) carried out by the Virgo Consortium (Springel et al. 2005a). This simulation follows the evolution of $2160^3$ dark matter particles in a cubic box of $500 h^{-1} $Mpc on a side. The particle mass is approximately $8.6 \times 10^9 h^{-1} M_\odot$, which enables us to study the assembly of halos more massive than around $10^{14} h^{-1} M_\odot$ with a reasonable mass resolution. The simulation adopts a flat ΛCDM with $\Omega_M = \Omega_{dm} + \Omega_b = 0.205 + 0.045 = 0.25$, where $\Omega_{dm}$ and $\Omega_b$ stand for the current densities of dark matter and baryons respectively; the linear r.m.s. density fluctuation in a sphere of an $8 h^{-1} $Mpc radius, $\sigma_8$, equals 0.9; and Hubble expansion parameter $h = 0.73$. In total there are 63 snapshot outputs between $z = 0$ and $z = 80$, which are almost evenly placed in ln(1 + $z$) space.

In the MS simulation, the characteristic collapsing mass, $M_*$, defined through $\sigma(M_*) = 1.69$, is about $6 \times 10^{12} h^{-1} M_\odot$. In order to identify dark halos, the Friends-Of-Friends (FOF) algorithm with a linking length $b = 0.2$ times the mean particle separation is used, so that the structures identified (we will call them FOF groups hereafter) have a density approximately 200 times the mean cosmic density. In addition, by smoothing the FOF groups outside-in, each FOF group is also assigned a corresponding “virial halo” with a “virial mass” $M_v$, so that the average density contrast between the “virial halo” and cosmic critical density $\rho_c$, is

$$\Delta_v(z) = 18\pi^2 + 82[\Omega_m(z) - 1] - 39[\Omega_m(z) - 1]^2$$

(1)

(Bryan & Norman 1998). The radius at which the density contrast first reaches $\Delta_v(z)$ defines the virial radius, $R_v$, of the halo. Despite the fact that $M_v$ is slightly (typically 5%) smaller than the corresponding FOF group mass, there are no other significant differences when one studies the accretion history of dark halos. In what follows, we always use “virial halos” in our analysis. Given a cosmological model, we define the virial velocity $V_{\text{vir}}(z)$ of a growing halo at redshift $z$ as

$$V_{\text{vir}}(z) = \sqrt{\frac{GM_v(z)}{R_v(z)}} = \left[\frac{\Delta_v(z)}{2}\right]^{1/2} [M_v(z) H(z)]^{1/3},$$

(2)

where $R_v(z)$ and $H(z)$ are, respectively, the halo virial radius and Hubble expansion parameter at redshift $z$. With this, we can follow the growth of the virial velocity (which is a measure of the halo gravitational depth) using the growth of the halo mass.

The merging trees of dark halos in the MS are constructed on the basis of sub-halos. In each FOF group, self-bound sub-structures are identified using SUBFIND (Springel et al. 2001). A sub-structure 1 at redshift $z_1$ is considered a progenitor of another sub-structure 2 at $z_2$ ($z_1 > z_2$) if a certain fraction of its most bound particles are in sub-structure 2. In addition to sub-halos, each FOF group contains one and only one “main virial halo”, with
mass $M_*$. In our analysis, we use $M_*$ to construct the mass growth history of the final halo. Since in general $M_*$ accounts for the central part of an FOF group, this treatment naturally avoids the ambiguous case where some accidentally linked sub-halos that do not belong to the halo also contribute to the halo mass.

3 HALO FORMATION TIMES

As mentioned above, the formation of dark halos is a very complicated process. There are two ways to follow the mass growth of a halo with time. First, one can start with a halo at the present time, pick up the most massive progenitor in the adjacent snapshot at higher redshift, and repeat this procedure until the halo mass is so small that it cannot be resolved anymore. The mass accretion history of the halo is then represented by the growth of the progenitor mass along the “main branch”. Alternatively, one can always look up the most massive progenitor at each redshift on the merging tree, and concatenate on these progenitors chronologically. The mass accretion history so obtained reflects the growth of the “maximum progenitor”. Note that the halo main branch does not always represent the maximum progenitor of a halo at each redshift, especially at the early stage of a growing halo (e.g. Gao et al. 2004). Most of the previous studies have been concentrated on the “main branch” when studying the halo assembly histories (e.g. Lacey & Cole 1993; van den Bosch 2002; Gao et al. 2003; Wechsler et al. 2003). In this paper, we use both definitions. We define the following set of parameters to characterize the assembly history of a halo:

(i) $z_{1/2,mb}$: This is the redshift at which the halo main branch has assembled half of its final mass, $M_*(0)$. This formation time has been widely used in the literature, as mentioned before.

(ii) $z_{1/2,tz}$: This is the highest redshift at which half of the final halo mass is contained in progenitors with masses ($M_p$) greater than 0.02$M_*(0)$. The same kind of formation time has been used in Navarro, Frenk & White (1997) to characterize the formation time of a halo and to study how halo concentration is correlated with formation time.

(iii) $z_{1/2,tz}$: This is the highest redshift at which half of the final halo mass has assembled into progenitors more massive than a fixed mass, $M_*=10^{11.5}h^{-1}M_\odot$. As shown by van den Bosch et al. (2003) [see also Yang et al. (2004)], halos with masses $\sim M_*$ have the minimum mass-to-light ratio, and thus are the most efficient in star formation. With $M_*=10^{11.5}h^{-1}M_\odot$, $z_{1/2,tz}$ therefore indicates when star formation starts to prevail the halo assembly history. By definition, only halos more massive than $M_*$ have a well-defined $z_{1/2,tz}$. This formation time is analogous to the formation time, $z_{N06}$, introduced by Neistein et al. (2006). According to Neistein et al. (2006), $z_{N06}$ is the time when the sum of the progenitors above a given minimum mass, reaches half of the present day halo mass.

(iv) $z_{M/L}$: This is the redshift when the progenitors more massive than $M_*$ have assembled a fraction $f$ of $M_*(0)$. Here the definition of $f$ is based on the non-constant mass-to-light ratio of dark matter halos (Yang et al. 2003). For halos more massive than $M_*$, the mass-to-light ratio, $M_*(0)/L$, follows a power law of $M_*(0)$, with power-index $\gamma = 0.32$ (see Yang et al. 2004, table 1). We therefore have,

$$f = \alpha \frac{L}{M_*(0)} = \frac{1}{2} \left( \frac{M_*(0)}{M_*} \right)^{-\gamma},$$

where $\alpha$ is a constant, which is set so that $f = \frac{1}{2}$ for $M_*(0) = M_*$. Thus, $z_{M/L}$ essentially reflects the time when a halo becomes capable of forming a fraction of its total stellar mass. Note again that $z_{M/L}$ can be defined only for $M_*(0) > M_*$. (v) $z_{vmax}$: This is the redshift at which the halo’s main branch assembles a mass of $M_*$. This formation time therefore indicates when a halo is able to host a relatively bright central galaxy.

(vi) $z_{vmax}$: This is the redshift at which the most massive progenitor has reached the mass $M_*$. Note that for massive halos, $z_{vmax}$ may be different from $z_{vmax}$. (vii) $z_{vmax}$: This is the redshift at which the halo’s virial velocity $V_{vir}(z)$ reaches its maximum value over the entire mass accretion history. According to equation 2, the value of $V_{vir}(z)$ is expected to increase (decrease) with time, if the time scale for mass accretion is shorter (longer) than the time scale of the Hubble expansion. Therefore, $z_{vmax}$ indicates the time when the halo mass accretion transits from a fast accretion phase to a slow accretion phase (Zhao et al. 2003; Li et al. 2007).

(viii) $z_{1mm}$: Last major merger time. Here we define a major merger as the event when the mass ratio between the smaller halo and the main halo is no less than 1/3. The last major merger time is defined to be the one when the last major merger occurred on the main branch of an assembling halo.

Once the merging history of a halo is given, it is quite straightforward to determine the formation times defined above. The only exception is $z_{1mm}$. Since the mass transfer from the merging halo to the main halo is a gradual process, a merger in general takes several snapshots to complete. Thus, if we used the halo mass increase in one time step, we would find only a small number of events in which the increase in the halo mass in a time step is large enough to be qualified as major mergers. In order to circumvent this problem, we start from one snapshot, and trace the progenitors (including those of sub-halos) back to all the snapshots within a 1-Gyr interval. As long as there is a progenitor with mass exceeding 1/3 of the main-branch halo mass at the same time, a major merger event is identified. The choice of 1 Gyr is not crucial; our tests using 0.5 Gyr or 1.5 Gyr give almost the same results.

As illustration, we plot in Fig. 1 an actual merging history of a typical halo selected from the MS simulation, with all formation redshifts defined above marked. As one can see, the different definitions give very different values of the formation redshift, and they capture quite different aspects of the assembly history of a dark matter halo.

In Fig. 2 we show each of the formation redshifts as a function of halo mass. In each panel, the solid line represents the median in each mass bin, while the dashed lines represent 20% and 80% percentiles, respectively. As one can see, less massive halos generally have higher values of $z_{1/2,mb}$, $z_{1/2,tz}$, $z_{vmax}$ and $z_{1mm}$ than massive ones, i.e. these formation redshifts have a negative correlation with halo mass.
Figure 1. Merging history of a typical MS halo, with all the defined formation times marked. Progenitors greater than $4 \times 10^{10} \, h^{-1} M_\odot$ are output at selected redshifts to avoid crowdness. The radius of each circle is roughly proportional to $M^{1/3}$. Circles filled with hatch lines that are 45° clockwise to the vertical represent the main branch progenitors; while those filled with hatch lines that are 45° counter-clockwise to the vertical represent the maximum progenitors.

Since these formation times are defined in a self-similar manner, i.e., do not involve any particular mass scale, it is not surprising that they show a similar “bottom-up” trend, a consequence of hierarchical clustering. Nevertheless, $z_{1/2,mb}$, $z_{1/2,t_1}$, $z_{vmax}$ and $z_{lmm}$ still represent quite different epochs of halo formation history, which can be seen from their different values and scatter. For all halo masses, both $z_{vmax}$ and $z_{lmm}$ have scatter that is much larger than $z_{1/2,mb}$, $z_{1/2,t_1}$. This indicates that both $z_{vmax}$ and $z_{lmm}$ are more sensitive to the details of the halo assembly history.

On the other hand, the other four formation redshifts, $z_{M/L}$, $z_{1/2,t_2}$, $z_{core,mb}$ and $z_{core,mp}$, all show positive correlation with the halo mass, in the sense that more massive halos experience these events earlier. For massive halos, $z_{core,mb}$ is lower than $z_{core,mp}$ and has larger scatter, which is due to the fact that for some massive halos, the most massive progenitors are not in the main branch. The trend is particularly strong for $z_{M/L}$, $z_{core,mp}$ and $z_{core,mb}$. A halo of $10^{12} h^{-1} M_\odot$ assembles a progenitor of mass $10^{11.5} h^{-1} M_\odot$ typically at $z \sim 1$, while such a progenitor forms at $z \sim 5$ for halos with masses $\gtrsim 10^{14} h^{-1} M_\odot$. Since $z_{M/L}$, $z_{core,mb}$ and $z_{core,mp}$ are the redshifts that characterize when a halo was able to host a relatively bright galaxy, the results shown here suggest that massive galaxies can form much earlier in massive halos than in low-mass halos. If star formation in these massive galaxies was eventually quenched as their stellar masses reach to some value, as is the case in the current AGN feedback model, or as they merge into a massive halo where radiative cooling becomes inefficient (e.g. Churazov et al. 2005; Croton et al. 2006; Cattaneo et al. 2008), one would expect that the star formation activity shifts with the passage of time from high-mass systems to the low-density field.
This may be related to the observed “down-sizing” effect that massive galaxies in present-day clusters in general have old stellar populations with little star formation activities, and most star formation activities at the present time have shifted to low-mass systems. This shift is perfectly consistent with the hierarchical formation of dark matter halos, provided that there are some mechanisms that can quench star formation in massive galaxies. As we have shown, more massive halos indeed assemble their masses later, but the formation of massive galaxies can actually start earlier in their progenitors.

As mentioned before, the formation redshift \( z_{1/2} \) defined here is similar to the formation time \( z_{\mathrm{NOB}} \) introduced by Neistein et al. (2006). However, the halo mass-dependence we obtain here is quantitatively different from theirs. At the massive end, the results of Neistein et al. (2006) show continuous increase of the formation redshift with halo mass, while ours show a flattened relation. Note that Neistein et al. (2006) used the extended Press-Schechter formalism to generate halo merging trees, while we obtain halo merging trees directly from N-body simulations. We suspect that the discrepancy may be due to the finite mass resolution of the simulation, because small progenitors cannot all be resolved for halos that are too small.

![Figure 2](image-url)

**Figure 2.** Formation time v.s. halo mass. Solid line represents the median of each mass bin, while dashed lines represent 20% and 80% quantiles, respectively. Note that in the panels for \( z_{1/2,t_1} \) and \( z_{\mathrm{vmax}} \), the slight drop at the low mass end (to the left of the vertical dashed line) is due to the finite mass resolution of the simulation, because small progenitors cannot all be resolved for halos that are too small.

4 THE DEPENDENCE OF HALO CLUSTERING ON FORMATION TIMES

Halos are biased tracer of the dark matter distribution. On large scales the auto-correlation function of dark halos, \( \xi_{\mathrm{hh}} \), is expected to be parallel to that of the mass, \( \xi_{\mathrm{mm}} \), so that one can write

\[
\xi_{\mathrm{hh}}(M,r) = b^2 \xi_{\mathrm{mm}}(r),
\]

where \( b \) is the so-called halo bias factor. Analytical models and N-body simulations have shown that the halo bias factor depends strongly on halo mass. Halos more massive than \( M \) are more strongly clustered than the underlying mass (i.e. \( b > 1 \)), while low-mass halos are less clustered than the mass (i.e. \( b < 1 \)) (e.g. Mo & White 1992; Jing, Suto & Mo 2007; Jing, Suto & Mo 1993; Sheth & Tormen 1999; Sheth, Mo & Tormen 2001).

More recently, using N-body simulations, Gao et al. (2003) found that for halos with a fixed mass, the halo bias factor \( b \) also depends on the time when the halo first assembles half of its mass, i.e. on \( z_{1/2,\mathrm{mb}} \), in the sense that halos with higher \( z_{1/2,\mathrm{mb}} \) are more strongly clustered (i.e. have a higher bias factor). This assembly bias is found to be stronger for halos of lower mass. Subsequent investigations using different simulations have confirmed this result (e.g. Wechsler et al. 2006; Harker et al. 2006; Zhu et al. 2006; Jing, Suto & Mo 2007), and theoretical models have been proposed to understand the origin of such assembly bias (e.g. Wang, Mo & Jing 2007a; Sandvik et al. 2007; Hahn et al. 2007).
Figure 3. Compare $z_{\text{core,mb}}$ and $z_{\text{core,mp}}$ with $z_{1/2,\text{mb}}$. Each line represents the result for halos with the mass marked aside. For each point, horizontal axis is the binned $z_{1/2,\text{mb}}$, and vertical axis is the average $z_{\text{core,mb}}$ or $z_{\text{core,mp}}$ in the bin; error bars represent the standard deviation. More massive halos generally have lower $z_{1/2,\text{mb}}$ but higher $z_{\text{core,mb}}$ or $z_{\text{core,mp}}$. Error bars in the right panel are generally smaller than in the left panel, indicating that the maximum progenitor could substantially deviate from the main branch, especially for massive halos at early time.

In order to study the formation-time dependence of halo clustering, we use a 3-dimensional Fast-Fourier-Transform to derive the two-point correlation function of dark matter halos as well as dark matter particles on large scales. We then estimate the halo bias $b$ for a given halo mass, using the square root of the ratio of the two-point correlation function of halos and that of dark matter, averaged over data points in $8 \, h^{-1}\text{Mpc} \leq r < 20 \, h^{-1}\text{Mpc}$. This interval of $r$ is chosen to ensure that the clustering is still in the quasi-linear regime where the linear bias relation is a good approximation. In Fig. 4 we show how halo bias depends on the formation times we have defined for halos of different masses. The dashed line in each panel shows the bias factor of the oldest 20% population among all halos as a function of halo mass, while the solid line shows the corresponding result of the youngest 20%. For comparison, we also show, as the grey line, the results for the total population without separation according to formation time. The errorbar on each data point is estimated through the error propagation function based on the Poisson noise of each data point of the halo two-point correlation in $8 \, h^{-1}\text{Mpc} \leq r < 20 \, h^{-1}\text{Mpc}$.

As one can see, the bias factor of the total population increases with halo mass, and the increase is more rapid at the massive end. This result of mass-dependence of the halo bias factor is in good agreement with the results obtained in earlier investigations. In addition, for halos of a given mass, the bias factor also depends on the formation redshifts, although the strength of the dependence is not always the same for different definitions. The result based on $z_{1/2,\text{mb}}$ is very similar to that obtained by Gao et al. (2005), even though the result here is based on “virial” halos while Gao et al. used FOF groups. With the exception of the case with $z_{\text{lim}}$, where no significant age dependence is found for
any halo masses, the strength of the age dependence in general decreases with increasing halo mass. For halos more massive than $10^{13} M_{\odot}$, we do not see any significant difference between halos of different ages. However, the noise here is too large due to the small number of systems available from the simulation, and so our data is not able to reveal the weak reversed trend, namely that the youngest halos are more strongly clustered, at the very massive end seen in some simulations (e.g. Jing, Suto & Mo 2007; Wetzel et al. 2007). The strongest age dependence is seen in the cases of $z_{1/2,mb}$, $z_{1/2,t_1}$ and $z_{1/2,t_2}$. Note that all these three formation redshifts are based on the properties of half of the final halo masses. This suggests that the assembly of the main parts of halos, especially the low-mass ones, may be affected significantly by large-scale environments. On the other hand, for the definitions that are based on the formation of a progenitor of a fixed mass, such as $z_{core,mb}$ and $z_{core, mp}$, the age dependence is weaker, particularly for halos with masses much higher than the progenitor mass, $M_c$, used in the definition. As shown earlier, such progenitors in massive halos usually form at high redshifts where the large-scale environmental effects may not yet have time to develop. The age dependence based on $z_{vmax}$ is also weaker than that based on $z_{1/2, mb}$, presumably because the halo density involved in defining $z_{vmax}$ is relatively high and so the the mass assembly before $z_{vmax}$ is less affected by the large-scale environment than that before $z_{1/2,mb}$. Fig. 6 also shows that there is almost no dependence of the bias factor on $z_{imm}$. This suggests that major mergers may be controlled by the properties of the local density field, without being strongly modulated by large-scale environments. This is consistent with the result of Percival et al. (2003), who found that, for halos with very recent major mergers (within the past $10^8$ years), there is no difference in the halo bias compared with all the halos of similar mass.

The formation-time dependence of the halo bias presented above may have important implications. Previous studies suggest that the halo assembly bias may introduce observable effects in the large-scale clustering of galaxies (e.g. Neistein et al. 2004; Croton et al. 2007). Using a large group catalogue constructed from the SDSS, Wang et al. (2007b) found that groups with a redder central galaxy or a redder average color of member galaxies show stronger clustering (see also Yang et al. 2008). Because of the complexity of halo assembly, it is unclear which aspects of the halo formation history are more closely related to the colors of the galaxies that form in halos. By “shuffling” galaxies contained in halos of similar mass or formation time $z_{1/2,mb}$, Croton et al. (2007) found, in their semi-analytical model, that the $z_{1/2,mb}$-dependence of halo clustering can account for most half of the clustering bias of red galaxies. This implies that the difference in $z_{1/2,mb}$ alone may not be sufficient to account for the colors of galaxies. This result is not surprising, because the assembly history of a halo is quite complicated and it is not expected that $z_{1/2,mb}$ can provide a full characterization of such history. As demonstrated above, each of the eight formation times defined in this paper catches a different aspect of the halo formation history. It would be interesting to if see some combinations of these formation times are better correlated with the properties of galaxies. As we have shown, the assembly bias becomes insignificant for halos more massive than $10^{13} h^{-1} M_{\odot}$ for most of the definitions of the assembly times. This may be the reason why the color-dependence of galaxy group clustering is significant only for groups less massive than $\sim 10^{13} h^{-1} M_{\odot}$ (Wang et al. 2007b).

![Figure 4](image-url)  
Figure 4. Age dependence of halo bias. Formation time used is indicated in each panel. Dashed lines are for oldest 20% halos while solid lines are for youngest 20% halos; the thick gray lines represent the bias of all the halos regardless of their ages. Error bar shows the Poisson error.
Our results also show that there is virtually no dependence of halo bias on \( z_{\text{lim}} \), the redshift of last major merger. In the literature, it has been suggested that major merger may effectively shut off the star formation in a galaxy (e.g., Hernquist 1989; Mihos & Hernquist 1996; Springel, Di Matteo & Hernquist 2005b). This suggests that major mergers alone cannot explain the red color of central galaxies. It is possible that the reddening of a central galaxy is the accumulative effect of a series of events triggered by, say, minor mergers, rather than a dominant major merger (e.g., Georgakakis et al. 2008).

5 DISCUSSION AND CONCLUSIONS

In this paper we examine the complexity of dark halo mass assembly history using the MS and using different formation times to characterize the various aspects of halo formation histories. We find that, formation times defined according to the assembly of a fixed fraction of the halo final mass characterize the hierarchical clustering, in the sense that halos of higher masses on average have later formation time. On the other hand, formation times defined by the formation of progenitors of a fixed mass where star formation is expected to be efficient, clearly show “anti-hierarchical” behavior, in the sense that halos of higher masses have earlier formation time. If some feedback processes can terminate the star formation in these progenitors, we would expect that galaxies in massive halos are redder, consistent with observation. We would also expect that the star-formation activities should shift with time from high-mass to low-mass halos, and so the observed “down-sizing” in star formation is not in conflict with hierarchical clustering.

We also study how the clustering of dark matter halos depends on the various formation times defined in this paper. We find that halo bias shows a strong positive correlation with halo mass, in good agreement with earlier results. For fixed halo mass, our results confirm a positive correlation between halo formation time, \( z_{\text{lim}} \), and halo clustering strength (e.g., Gao et al. 2005; Wechsler et al. 2005). The strength of this dependence increases with decreasing halo mass. For halos more massive than \( 10^{14} h^{-1} M_\odot \), we do not find a clear reversal of the assembly bias. In general, for halos less massive than \( 10^{14} h^{-1} M_\odot \), there is a positive correlation between the various formation times defined and halo clustering strength, with the correlation being stronger for lower halo masses. However, the correlation amplitude is quite different when different formation time is considered. The strongest age dependence of halo clustering is seen on \( z_{1/2,1} \) and \( z_{1/2,2} \). There is virtually no age dependence of halo clustering on halo last major merger time, \( z_{\text{lim}} \), and the dependence on \( 2M/L \), \( z_{\text{core,mb}} \), \( z_{\text{core,mp}} \) is moderate. If the typical age of stars in a halo is correlated with halo assembly history in some way, then halos with fixed mass but containing redder member galaxies are expected to be more strongly clustered, and this color-dependence is expected to be weaker for more massive systems. This is consistent with recent observations. However, since there is virtually no dependence of halo clustering on \( z_{\text{lim}} \), the typical color of galaxies in a halo is not expected to be determined by the last major merger time of its host halo.

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