ENVIRONMENTAL EFFECTS OF DARK MATTER HALOS: THE CLUSTERING-SUBSTRUCTURE RELATION OF GROUP-SIZE HALOS

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ABSTRACT

We estimate the two-point correlation function of dark matter halos, with masses $\geq 10^{13} h^{-1} M_\odot$, that have or do not have significant substructure. The halos are identified with a friends-of-friends algorithm in a large ΛCDM simulation at two redshift snapshots ($z = 0.0$ and 1.0), while halo substructure is determined using an observationally driven method. We find in both epochs a clear and significant signal by which halos with substructure are more clustered than those with no substructure. This is true for all the considered halo mass ranges, although for the highest halo masses the signal is noisy and present only out to $\sim 20 h^{-1}$ Mpc. There is also a smooth increase of the halo correlation length with increasing amplitude of the halo substructure. We also find that substructured halos are typically located in high-density large-scale environments, while the opposite is true for nonsubstructured halos. If the halos found in high-density regions have a relatively earlier formation time, as suggested by recent works, then they do indeed have more time to cluster than halos of a similar mass, which form later in the low-density regions. In such a case, one would have naively expected that the former (earlier formed) halos would typically be dynamically more relaxed than the latter (later formed). However, the higher merging and interaction rate, expected in high-density regions, could disrupt their relatively relaxed dynamical state and thus be the cause for the higher fraction of halos with substructure found in such regions.

1. INTRODUCTION

In the current cold dark matter (CDM) picture, structures form via gravitational amplifications of initial density fluctuations. The dark matter (DM) halos form hierarchically by the aggregation, via gravitational interactions, of small collapsed structures that merge to form larger ones, eventually forming clusters of galaxies.

Observationally, galaxy properties show a significant variation depending on their local and large-scale environment (e.g., Dressler 1980; Gómez et al. 2003; Boselli & Gavazzi 2006). Since galaxies form within DM halos, the “parent” halo properties could influence or even determine the galaxy properties. Therefore, many theoretical studies have investigated in detail the interrelation of the DM halo properties, including the halo formation time, their assembly histories, their central concentration, their clustering, and their location in the cosmic web. The first studies (e.g., Lemson & Kauffmann 1999) found no significant environmental dependence of the various DM halo properties. However, a reinterpretation of their results and a wealth of new studies point in the opposite direction.

Halo formation time has been found to correlate with halo concentration and with the number of subhalos (e.g., Navarro et al. 1997; Jing 2000; Bullock et al. 2001; Wechsler et al. 2002; Zhao et al. 2003; Zentner et al. 2005). Sheth & Tormen (2004) showed that halos in dense regions form at slightly earlier times than similar mass halos in lower density regions, a result confirmed by Zhu et al. (2006) and Harker et al. (2006) for massive halos as well. Gao et al. (2004), Hahn et al. (2007), and Gao & White (2007) extended the halo “assembly bias” investigation by considering different parent halo properties, among which are concentration, spin, and subhalo mass fraction.

Furthermore, the amplitude of the DM halo two-point correlation function has been found to depend strongly on the halo formation time. Relatively low mass halos ($\leq 10^{13} h^{-1} M_\odot$), which assembled at high redshifts, are more clustered than those that assembled more recently (Gao et al. 2005; Wechsler et al. 2006; Wang et al. 2007; see also Berlind et al. 2006), an effect that strengthens with decreasing halo mass and with decreasing halo separations. However, Wetzel et al. (2007) and Jing et al. (2007) found that very massive halos, which have formed recently, appear to cluster more strongly than older halos of the same mass, which is the opposite of what has been found for lower mass halos (see also Wechsler et al. 2006).

Regarding the dependence of halo clustering on subhalo occupation number, Wechsler et al. (2006), studying only large host halos, found close pairs of halos having an above-average number of satellites. Gao & White (2007), using the Millennium simulation (Springel et al. 2005), demonstrated that halos with a relatively large mass fraction in subhalos are more strongly clustered, confirming Wechsler et al. (2006). Thus, halo occupation by galaxies could be a function of environment. This appears to be in agreement with some observational cluster studies, to the extent to which halo occupation is related to the halo dynamical state. For example, dynamically active clusters (having significant substructure) have been found to be preferentially located in dense large-scale environments (Schuecker et al. 2001; Plionis & Basaklakos 2002), while they are also more clustered with respect to clusters with weak or no substructure (Plionis & Basaklakos 2002).

Further on the observational side, Blanton & Berlind (2007) found a slight dependence between galaxy colors and measures...
of the surrounding environment on various scales. Berlind et al. (2006), searching for a dependence of the Sloan Digital Sky Survey galaxy groups clustering on a second parameter, independent of mass, found a correlation between the large-scale bias of massive groups and their central galaxy ($g - r$) color as well as hints of a possible connection between the later and DM halo age. Also, Croton et al. (2007), studying the relation between the clustering of DM halos and their assembly history, using a galaxy formation model applied in the Millenium simulation, found that the color of the central galaxy in a DM halo, of a given mass, depends on the halo’s environment.

All these results put into question the simplest form of the excursion-set formalism for galaxy clustering (Bond et al. 1991; Lacey & Cole 1993), which predicts that the properties of galaxies, forming within the DM halos, are functions only of the DM halo mass and not of other properties like its environment. Nevertheless, more elaborate schemes of the excursion-set formalism have been recently proposed that allow more faithful descriptions (Sandvik et al. 2007; Zentner 2007).

In this Letter, we address a related issue, i.e., the relation between DM halo clustering, the halo dynamical state, and its large-scale environment. Note that we do not use the common approach of counting bound subhalos, within parent halos, as an indicator of substructure, but rather an observationally driven estimator of the halo dynamical state that is based on the dynamical measure of halo substructure according to Dressler & Shectman (1988). Once the halo dynamical state is determined, we compute the two-point correlation function for halos with and without substructure, and we also characterize their local environment.

2. NUMERICAL SIMULATION AND METHODOLOGY

The numerical simulation used in this work was performed using the GADGET2 code (Springel 2005) with DM only. We use a ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_L = 0.7$, $\sigma_8 = 0.9$, $h = 0.72$, where $\Omega_m$ and $\Omega_L$ are the present-day matter and vacuum energy densities in units of the critical density, $\sigma_8$ is the present linear rms amplitude of mass fluctuation in spheres of $8 \, h^{-1} \, \text{Mpc}$, and $h$ is the Hubble parameter in units of $100 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$. The simulation was run in a cube of size $L = 500 \, h^{-1} \, \text{Mpc}$, using 512$^3$ particles. The particle mass is $\sim 7.7 \times 10^{10} \, h^{-1} \, M_\odot$, and the force softening length is $\epsilon = 100 \, h^{-1} \, \text{kpc}$.

The DM halos were identified using a friends-of-friends (FOF) algorithm with a linking length $l = 0.17$ times the mean interparticle separation. Given the purpose of this work, we only use halos with at least 130 particles, i.e., with masses greater than $10^{13} \, M_\odot$, which results in a sample of $\sim 58,000$ halos at $z = 0$ and $\sim 32,400$ at $z = 1$. Note that the halo-finding algorithm used provides unique halos that are not subhalos of any other parent halo.

Since we wish to investigate the possible correlation between clustering and the dynamical state of DM halos, we use the Dressler & Shectman (1988) algorithm to estimate the amount of halo substructure. Details for a recent application of this method to simulation data can be found in Ragone-Figueroa & Plionis (2007). Briefly, this method determines the mean local velocity, $\langle V \rangle$, and the velocity dispersion, $\sigma_\text{loc}$, of the nearest $n$ neighbors from each halo particle $i$ and compares them with the mean velocity, $\langle V \rangle$, and the velocity dispersion, $\sigma$, of the whole halo of $N$ particles, defining the following measure:

$$\delta_i^2 = \frac{n}{\sigma^2} [(\sigma_\text{loc} - \langle V \rangle)^2 + (\sigma_\text{loc} - \sigma)^2].$$

Then the quantification of the halo substructure is given by the so-called $\Delta$-deviation, which is the sum of the individual $\delta_i$ over all halo particles $N$: $\Delta = \sum_i \delta_i/N$. The larger the $\Delta$-deviation, the stronger the halo substructure. This statistic depends on the number of nearest neighbors $n$ that is used in the analysis (e.g., Knebe & Müller 2000) and on the number of particles used to resolve a halo as well. Such resolution effects were studied in detail in Ragone-Figueroa & Plionis (2007), who found a monotonic increase of $\langle \Delta \rangle$ with the halo mass, which is clearly due to resolution effects. However, they also found that within relatively small halo mass intervals, the corresponding sorted $\Delta$-deviation distribution can be used effectively to separate substructured from nonstructured halos, by dividing them into those having $\Delta$-deviation above and below the corresponding median or some quantile of the $\Delta$-deviation distribution within each halo mass interval.

Therefore, the total halo sample was divided into three mass ranges, and the analysis was performed in each individual subsample and for each of the two redshift snapshots ($z = 0$ and 1.0). These halo mass ranges are:

1. $10^{13} \, h^{-1} \, M_\odot \leq M < 3 \times 10^{13} \, h^{-1} \, M_\odot$,
2. $3 \times 10^{13} \, h^{-1} \, M_\odot \leq M < 10^{14} \, h^{-1} \, M_\odot$,
3. $M \geq 10^{14} \, h^{-1} \, M_\odot$.

We compute the DM halo two-point correlation function, $\xi(r)$, separately for the substructured halos (dynamically active) and nonsubstructured halos (virialized), within each mass range, and to emphasize their possible clustering differences we separate halos having $\Delta$-deviation values larger than the 67% and lower than the 33% quantile of the $\Delta$-deviation frequency distribution function.

The measured halo two-point correlation function is also fitted to a power law, $\xi(r) = (r/r_0)^{\gamma}$, in the range $4 \, h^{-1} \, \text{Mpc} \leq r \leq 30 \, h^{-1} \, \text{Mpc}$, using a $\chi^2$ minimization procedure. Furthermore, we estimate the halo mass one-point overdensity distribution function, dividing the simulation box in grid cells of $5 \, h^{-1} \, \text{Mpc}$ size and compare the total DM mass (using halos with $M > 10^{13} \, h^{-1} \, M_\odot$) within each cell, $M_i$, to its mean value, $M$, i.e., estimating: $\delta M/M \equiv (M - M_i)/M$. We then assign to each halo the $\delta M/M$ value that corresponds to the grid cell in which it is located and derive the corresponding frequency distribution separately for halos that have or do not have significant substructure. We have verified that this local density estimator is equivalent with that traditionally used, estimated in spheres centered on each individual halo.

3. RESULTS AND DISCUSSION

In Figure 1, we show the ratio, $R(r)$, of the two-point correlation functions of halos with and without substructure, for the three mass intervals and for both redshift epochs. The errors shown are the propagated quasi-Poissonian uncertainties, estimated by $\delta R(r) = [(1 + \xi(r)/DD(r))^{1/2}]$, where $DD(r)$ are the halo-halo pairs within separation $\delta r \pm r$. It is evident that $R(r)$ is significantly less than 1, indicating that the former halos indeed have a significantly higher correlation function than the latter ones. For $z = 0$, we have $R(r) \leq 0.8$ for all $r'$, while for $z = 1$ and for the most massive halos this is true for sep-
arations \leq 20 \, h^{-1} \text{ Mpc}. Note, however, that the size of our simulation does not allow us to probe effectively this halo mass range.

In order to assign a probability to the events shown in Figure 1, we use a Monte Carlo procedure by which we derive \( R(r) \) for each of \( 10^5 \) random halo subsample pairs of the same size as those of our main analysis (and for each mass range and redshift bin). We then ask how many times is \( R(r) \) consistently less than 1, for all \( r' \)'s (or for \( r \leq 20 \, h^{-1} \text{ Mpc} \) in the case of \( z = 1 \) and the higher mass bins), to find that in all cases the probability is \( < 0.0009 \). If we now ask a more restrictive but more accurate question, i.e., how many times would \( R(r) \) be systematically lower at the level observed between the substructured and nonsubstructured halo subsamples, then the answer is \( < 10^{-6} \). We therefore conclude that halos with substructure are significantly more clustered than halos without substructure, locally and in high redshifts, in agreement with

1. the observational results based on clusters of galaxies (Plionis & Basilakos 2002),
2. the DM halo occupation number-clustering correlation (Wechsler et al. 2006; Gao & White 2007), and
3. the weak signal found by Wetzel et al. (2007) that halos that have undergone a recent major merger (i.e., have significant substructure according to our nomenclature) show a slightly enhanced clustering.

To test whether the dependence of the clustering length, \( r_o \), on halo substructure is due only to those halos that experience “major” mergers (as suggested by Wetzel et al. 2007), we have divided our halos, of each mass range, in four equal-number subsamples based on their sorted \( \Delta \)-deviation values (corresponding to different substructure amplitudes) and computed their individual two-point correlation function. In Figure 2, we present the corresponding correlation lengths as a function of \( \Delta \) for all halo subsamples (the indicated \( \Delta \)-deviation value corresponds to its median value in each of the four ranges). It is evident that the correlation length is growing smoothly and monotonically with increasing \( \Delta \)-deviation value, a fact that argues against the \( r_o \)-\( \Delta \) relation being only due to major mergers. A similar result has been found also for real clusters of galaxies (Plionis & Basilakos 2002, their Fig. 3).

Now we ask, what could the reason be for such an effect? Could it be that halos having substructure (i.e., being dynamically active) are located in high-density environments (see also Ragone-Figueroa & Plionis 2007) and thus at regions of a relatively early halo formation time, while halos with no substructure are located in low-density regions, i.e., at regions of a later halo formation time (e.g., Sheth & Tormen 2004; Zhu et al. 2006; Harker et al. 2006). The higher clustering of substructured halos indeed points in such a direction, although one would have expected that earlier formed halos would typically be dynamically more relaxed than equal-mass later formed ones and would have had less evident substructure features. However, the higher merging and interaction rate, expected in high-density regions, could disrupt the relatively relaxed halo dynamical state.

To attempt to answer the question posed, we present in Figure 3 the ratio of the normalized \( \delta M/M \) frequency distributions of the substructured and nonsubstructured halos (for the two extreme mass ranges, just for economy of space). If both types of halos traced similar overdensities, this ratio should have been statistically equivalent to 1. However, it is evident that it is significantly higher (or lower) than 1 at larger (or smaller) overdensities, for all halo mass ranges and redshifts. As we had anticipated, substructured halos are typically found in higher density regions.

### 4. CONCLUSIONS

In this Letter, we have investigated the relation between DM halo clustering, halo dynamical state, and halo large-scale envi-

![Figure 1](image1.png)

**Fig. 1.—** Ratio of the two-point correlation functions of halos with and without substructure for both redshift epochs. The solid lines correspond to \( z = 0 \), while the dashed lines correspond to \( z = 1 \). The errors shown are the propagated quasi-Poissonian uncertainties. [See the electronic edition of the Journal for a color version of this figure.]

![Figure 2](image2.png)

**Fig. 2.—** Correlation length, \( r_o \) as a function of halo \( \Delta \)-deviation for the three halo mass ranges and for two redshift snapshots (left panel: \( z = 0 \); right panel: \( z = 1 \)). The different halo mass ranges are indicated by the different symbols.

![Figure 3](image3.png)

**Fig. 3.—** Ratio of the normalized \( \delta M/M \) frequency distributions of substructured and nonsubstructured halos. The \( \delta M/M \) fluctuations have been evaluated on a grid with a \( 5 \, h^{-1} \text{ Mpc} \) cell size. Results are shown for two mass ranges and two redshifts. Error bars are propagated individual Poissonian uncertainties. [See the electronic edition of the Journal for a color version of this figure.]
enronment. We identified halos with a FOF algorithm in a DM-only $\Lambda$CDM simulation and used halos with $M \geq 10^{13} h^{-1} M_\odot$, identified at $z = 0$ and $z = 1$. The halo dynamical state was determined by measuring the amount of halo substructure using an observationally driven approach. We then calculated the two-point correlation function for halos with high and low levels of substructure, finding that the former halos are significantly more clustered than the latter, while there is also a smooth increase of the halo correlation length with increasing amplitude of the halo substructure index.

Finally, we find a highly significant signal by which halos with high levels of substructure are located typically in higher density regions with respect to halos with low levels of substructure, and this could be an explanation of our previous results. The higher clustering of halos found in high-density large-scale environments should be expected if halos collapse earlier in such regions and thus have more time to evolve and cluster, while their higher levels of substructure should be probably attributed to the higher rate of halo interactions and merging that is present in such high-density regions.

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