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

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## ABSTRACT

We estimate the two-point correlation function of dark matter haloes, with masses $\geq 10^{13}\ h^{-1}\ M_{\odot}$, that have or not significant substructure. The haloes are identified with a friends of friends algorithm in a large $\Lambda$CDM simulation at two redshift snapshots ($z = 0.0$ and 1.0). We find in both epochs a clear and significant, although relatively weak, signal by which haloes 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 $\sim 20h^{-1}$ Mpc. There is also a smooth increase of the halo correlation length with increasing amplitude of the halo substructure. We also find that substructured haloes are typically located in high-density large-scale environments, while the opposite is true for non-substructured haloes. If the haloes 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 haloes, of a similar mass, which form slightly later in the low-density regions. In such a case one would have naively expected that the former (earlier formed) haloes would typically be dynamically more relaxed than the latter (later formed). However, the higher merging and interaction rate, expected in high-density regions, can disrupt their relatively relaxed dynamical state and thus be the cause for the higher fraction of haloes with substructure found in such regions.

*Subject headings:* cosmology: theory – dark matter – galaxies: haloes – galaxies: formation – large-scale structure of universe – methods: N-body simulations.

## 1. INTRODUCTION

In the current cold dark matter picture, structures form via gravitational amplifications of initial density fluctuations. The dark matter (DM) haloes 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 (eg. Dressler 1980; Gómez et al. 2003; Boselli & Gavazzi 2006). Since galaxies form within DM haloes, the "parent" halo properties could influence or even determine the galaxy properties. Therefore, many theoretical studies have investigated in detail the inter-relation of the DM halo properties, among which the halo formation time, their assembly histories, their central concentration, their clustering and their location in the cosmic web. The first studies (eg. Lemson & Kauffmann 1999) found no significant environmental dependence of the various DM halo properties. However, a re-interpretation 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 (eg. Navarro, Frenk & White 1997; Jing 2000; Bullock et al. 2001; Wechsler et al. 2002; Zhao et al. 2003). Sheth & Tormen (2004) showed that haloes in dense regions form at slightly earlier times than similar mass haloes in lower density regions, a result confirmed by Zhu et al. (2006) and Harker et al. (2006) for massive haloes as well.

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

Berlind et al. (2006) confirmed the results of Gao et al. (2005) and Wechsler et al. (2006), and found hints of a possible connection between DM halo age and central galaxy colour for massive haloes. Also Croton, Gao & White (2007) studying the relation between the clustering of DM haloes and their assembly history, using a galaxy formation model applied in the Millennium simulation (Springel et al. 2005), found that the colour 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 haloes, are functions only of the DM halo mass, and not of other properties like its environment.

On the observational side, Berlind et al. (2006) searched for a dependence of the SDSS galaxy groups clustering on

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a second parameter, independent of mass, and found a correlation between the large scale bias of massive groups and their central galaxy $(g-r)$ colour. On larger scales, dynamically active clusters (having significant substructure) are located preferentially in dense large-scale environments (Schuecker et al. 2001; Plionis & Basilakos 2002) and are more clustered with respect to clusters with weak or no substructure (Plionis & Basilakos 2002).

In this letter we address a related issue; ie., 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 sub-haloes, within parent haloes, as an indicator of the parent halo dynamical state, but rather an observationally driven estimator of the halo dynamical state which is based on identifying the amount of halo substructure. Once the halo dynamical state is determined we compute the two-point correlation function and the one-point density distribution function for haloes with and without substructure.

## 2. NUMERICAL SIMULATION & METHODOLOGY

The numerical simulation used in this work was performed using the GADGET2 code (Springel 2005) with dark matter only. We use a ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$, $h = 0.72$, where $\Omega_m$ and $\Omega_\Lambda$ 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 $h^{-1}$ Mpc and $h$ is the Hubble parameter in units of 100km $\mathrm{s}^{-1}\mathrm{Mpc}^{-1}$. The simulation was run in a cube of size $L = 500\ h^{-1}$ Mpc, using $512^3$ particles. The particle mass is $\sim 7.7\times10^{10}\ h^{-1}\ M_\odot$ and the force softening length is $\epsilon = 100\ h^{-1}$ kpc.

The DM haloes were identified using a friends-of-friends (FOF) algorithm with a linking length $l = 0.17$ times the mean inter-particle separation. Given the purpose of this work, we only use haloes with at least 130 particles, ie., with masses greater than $10^{13}M_\odot$, which results in a sample of $\sim$ 58000 haloes at $z = 0$ and $\sim$ 32400 at $z = 1$. Note that the halo finding algorithm used provides unique haloes that are not sub-haloes of any other "parent" halo.

Since we wish to investigate the possible correlation between clustering and the dynamical state of DM haloes, 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, $\langle \mathbf{v}_{\rm loc}\rangle$, and the local velocity dispersion, $\sigma_{\rm loc}$, of the nearest $n$ neighbours from each halo particle $i$ and compares them with the mean velocity, $\langle \mathbf{V}\rangle$, and the velocity dispersion, $\sigma$, of the whole halo of $N$ particles, defining the following measure:

$$\delta_i^2 = \frac{n}{\sigma}[(\langle \mathbf{v}_{\rm loc}\rangle - \langle \mathbf{V}\rangle)^{\mathbf{2}} + (\sigma_{\rm loc} - \sigma)^{\mathbf{2}}] \ . \qquad (1)$$

Then the quantification of the halo substructure is given by the so-called Δ-*deviation*, which is the sum of the individual $\delta_i$'s over all halo particles $N$: $\Delta = \sum_N \delta_i/N$. The larger the Δ-deviation the stronger is the halo substructure. This statistic depends on the number of nearest neighbours $n$ which is used in the analysis (eg., Knebe & Müller 1999) 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 Δ-deviation distribution can be used effectively to separate substructured from non-substructured haloes, by dividing them in those having Δ-deviation above and below the corresponding median or some quantile of the Δ-deviation distribution within each halo mass interval.

Therefore, the total halo sample was divided in 3 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:
(a) $10^{13}\ h^{-1}M_\odot \le M < 3\times10^{13}h^{-1}M_\odot$,
(b) $3\times10^{13}\ h^{-1}M_\odot \le M < 10^{14}\ h^{-1}M_\odot$,
(c) $M \ge 10^{14}\ h^{-1}M_\odot$.
We compute the DM halo two-point correlation function, $\xi(r)$, separately for the substructured haloes (dynamically active) and non-substructured haloes (virialized), within each mass range, and to emphasize their possible clustering differences we separate haloes having Δ-deviation values larger than the 67% and lower than the 33% quantile of the Δ-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 $4 \lesssim r \lesssim 30\ h^{-1}$ 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 $h^{-1}$ Mpc size and compare the total DM mass (using haloes with $M > 10^{13}h^{-1}M_\odot$) within each cell, $M_i$, to its mean value, $\bar{M}$, ie., estimating: $\delta M/M \equiv (M_i - \bar{M})/\bar{M}$. 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 haloes that have or not significant substructure. We have verified that this local density estimator is equivalent with the 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 haloes with and without substructure, for the three mass intervals and for both redshifts epochs. The errors shown are the propagated quasi-Poissonian uncertainties, estimated by: $\delta\xi(r) \simeq \sqrt{[1+\xi(r)]/\mathrm{DD}(r)}$, where DD$(r)$ are the halo-halo pairs within separation $r \pm \delta r$. It is evident that $R(r)$ is significantly less than 1, indicating that the former haloes indeed have a significantly higher correlation function than the latter ones. For $z = 0$ we have $R(r) < 0$ for all $r$'s, while for $z = 1$ and for the most massive haloes this is true for separations $\lesssim 20$ $h^{-1}$ Mpc. Note, however, that the size of our simulation does not allow us to probe effectively this halo mass range. For completness we list in Table 1 the correlation length, $r_0$, and the exponent $\gamma$ of the power-law $\xi(r)$ fit to the individual correlation functions.

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 $10^6$ random halo sub-sample 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

$r \lesssim 20\ h^{-1}$ 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, ie., how many times would $R(r)$ be systematically lower at the level observed between the substructured and non-substructured halo sub-samples, then the answer $< 10^{-6}$. We therefore conclude that haloes with substructure are significantly more clustered than haloes without substructure, locally and in high redshifts, in agreement with:
(a) the observational results based on clusters of galaxies (Plionis & Basilakos 2002),
(b) the DM halo occupation number-clustering correlation (Wechsler et al. 2006), and
(c) the weak signal found by Wetzel et al. (2006) that haloes which have undergone a recent major merger (ie., have significant substructure according to our nomenclature) show a slightly enhanced clustering.

To test whether the dependence of the clustering length, $r_0$, on halo substructure is due only to those haloes which experience "major" mergers (as suggested by Wetzel et al. 2006) we have divided our haloes, of each mass range, in 4 equal-number sub-samples 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 sub-samples (the indicated $\Delta$-deviation value corresponds to its median value in each of the 4 ranges). It is evident that the correlation length is growing smoothly and monotonically with increasing $\Delta$-deviation value, a fact which argues against the $r_0 - \Delta$ relation being only due to "major" mergers. A similar result has been found also for real clusters of galaxies (Plionis & Basilakos 2002 - their figure 3).

Now we ask what could the reason be for such an effect? Could it be that haloes having substructure (ie., 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 haloes with no substructure are located in low-density regions, ie., at regions of a later halo formation time (eg. Sheth & Tormen 2004; Zhu et al. 2006; Harker et al. 2006). The higher clustering of substructured haloes indeed points in such a direction, although one would have expected that earlier formed haloes 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 non-substructured haloes (for the two extreme mass ranges, just for economy of space). If both type of haloes traced similar overdensities, this ratio should have been statistically equivalent to one. 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 haloes are typically found in the higher-density regions.

## 4. CONCLUSIONS

In this letter we have investigated the relation between DM halo clustering, halo dynamical state and halo large-scale environment. We identified haloes with a FOF algorithm in a dark matter only $\Lambda$CDM simulation and used haloes with $M \gtrsim 10^{13}\ h^{-1}\ M_{\odot}$, 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 haloes with high and low levels of substructure, finding that the former haloes are slightly but 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 that haloes with high levels of substructure are located typically in higher density regions with respect to haloes with low levels of substructure and this can explain our previous results. The higher clustering of haloes found in high-density large-scale environments should be expected if haloes 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 which is present in such high-density regions.

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TABLE 1
THE CORRELATION LENGTH AND SLOPE OF THE HALO 2-POINT CORRELATION FUNCTION, FOR HALOES WITH AND WITHOUT SUBSTRUCTURE AND FOR 2 REDSHIFT SNAPSHOTS.

| Mass range $h/M_{\odot}$ | # | $\Delta$ | $r_{\circ}$ $h$/Mpc | $\gamma$ |
|---|---|---|---|---|
| | | **z = 0** | | |
| $10^{13} \leq M < 3 \times 10^{13}$ | 12802 | $> \Delta_{0.67}$ | 7.9±0.3 | -1.75±0.03 |
| " | " | $< \Delta_{0.33}$ | 6.0±0.3 | -1.78±0.04 |
| $3 \times 10^{13} \leq M < 10^{14}$ | 4847 | $> \Delta_{0.67}$ | 10.5±0.8 | -1.82±0.06 |
| " | " | $< \Delta_{0.33}$ | 8.6±0.5 | -1.79±0.04 |
| $M > 10^{14}$ | 1460 | $> \Delta_{0.67}$ | $17.3^{+3.4}_{-2.8}$ | -2.06±0.15 |
| " | " | $< \Delta_{0.33}$ | $13.1^{+2.9}_{-2.3}$ | -1.59±0.13 |
| | | **z = 1** | | |
| $10^{13} \leq M < 3 \times 10^{13}$ | 8397 | $> \Delta_{0.67}$ | 9.7±0.5 | -1.80±0.04 |
| " | " | $< \Delta_{0.33}$ | 7.5±0.5 | -1.71±0.06 |
| $3 \times 10^{13} \leq M < 10^{14}$ | 2041 | $> \Delta_{0.67}$ | 14.0±1.4 | -2.00±0.08 |
| " | " | $< \Delta_{0.33}$ | 12.5±2.0 | -1.70±0.12 |
| $M > 10^{14}$ | 237 | $> \Delta_{0.67}$ | $25.9^{+13.2}_{-8.6}$ | -1.95±0.28 |
| " | " | $< \Delta_{0.33}$ | $22.4^{+17.2}_{-10.3}$ | -1.72±0.33 |

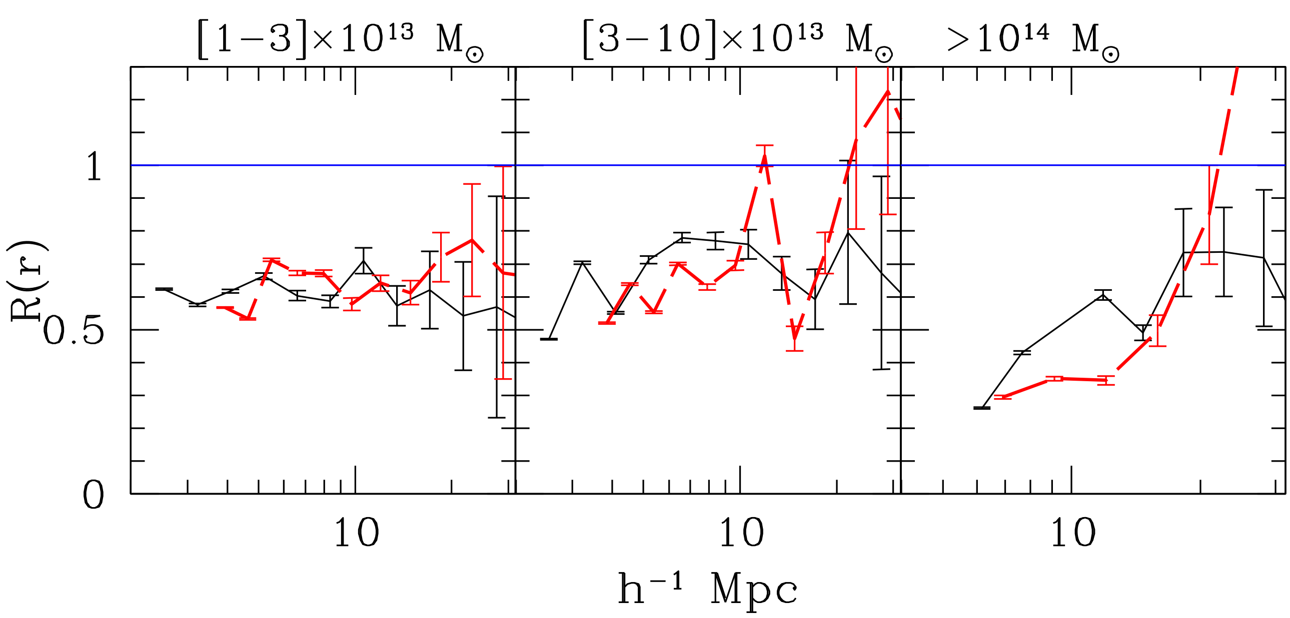


FIG. 1.— The ratio of the 2-point correlation functions of haloes with and without substructure for both redshifts epochs. The continuous lines corresponds to $z = 0$, while the dashed lines to $z = 1$. The errors shown are the propagated quasi-Poissonian $\xi(r)$ uncertainties.

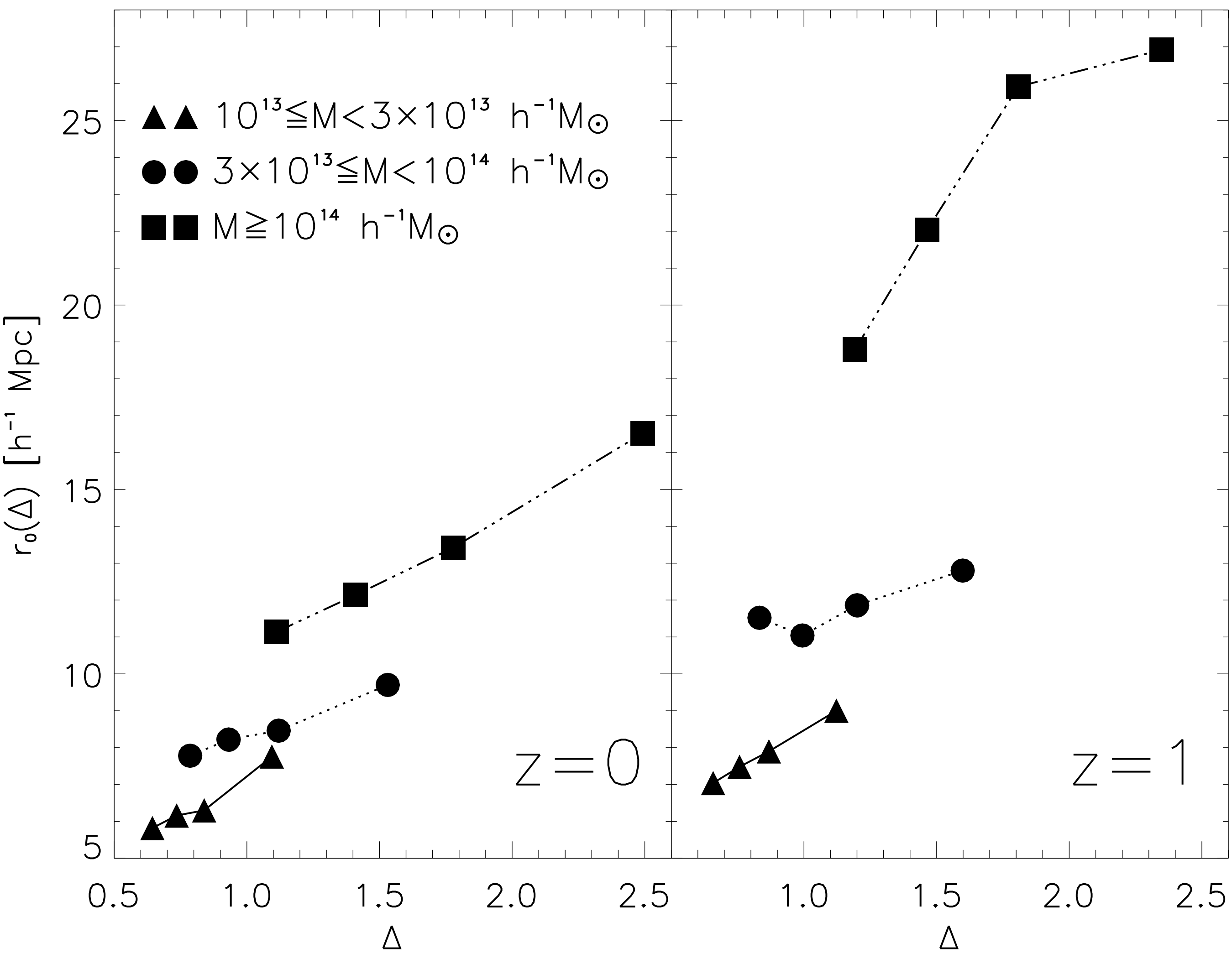


FIG. 2.— Correlation length, $r_0$, as a function of halo $\Delta$-deviation for the three halo mass ranges and for two redshift snapshots (*left panel:* $z = 0$ and *right panel:* $z = 1$). The different halo mass ranges are indicated by the different symbols.

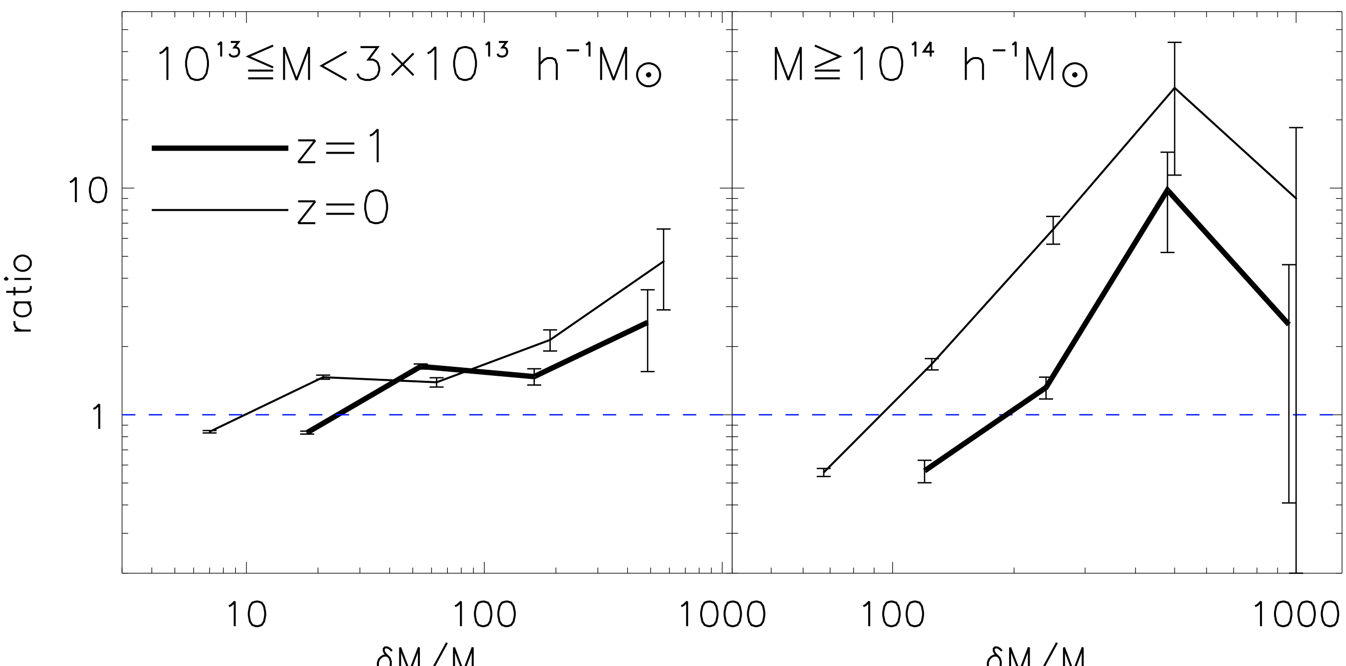


FIG. 3.— The ratio of the normalized $\delta M/M$ frequency distributions of substructured and non-substructured haloes. The $\delta M/M$ fluctuations have been evaluated on a grid with a 5 $h^{-1}$ Mpc cell-size. Results are shown for two mass ranges and two redshifts. Error-bars are propagated individual Poissonian uncertainties.