Dark matter halo occupation: environment and clustering

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ABSTRACT
We use a large dark matter simulation of a Λ cold dark matter (ΛCDM) model to investigate the clustering and environmental dependence of the number of substructures in a halo. Focusing on redshift $z = 1$, we find that the halo occupation distribution is sensitive at the tens of per cent level to the surrounding density and to a lesser extent to asymmetry of the surrounding density distribution. We compute the autocorrelation function of haloes as a function of occupation, building on the finding of Wechsler et al. and Gao & White that haloes (at fixed mass) with more substructure are more clustered. We compute the relative bias as a function of occupation number at fixed mass, finding a strong relationship. At fixed mass, haloes in the top 5 per cent of occupation can have an autocorrelation function $\sim 1.5–2$ times higher than the mean. We also compute the bias as a function of halo mass, for fixed halo occupation. We find that for group- and cluster-sized haloes, when the number of subhaloes is held fixed, there is a strong anticorrelation between bias and halo mass. Such a relationship represents an additional challenge to the halo model.

Key words: cosmology: observations – dark matter – large-scale structure of Universe.

1 INTRODUCTION

The halo model of galaxy clustering (see Cooray & Sheth 2002 for a review) takes as one of its usual assumptions that the clustering of a dark matter halo is dictated solely by its mass. Observationally when looking at a cluster or group it is easiest to count galaxies (see e.g. Yang et al. 2005; Hao et al. 2010 for recent cluster and group catalogues), which are usually associated with the population of dark matter subhaloes. The role that the number of subhaloes plays in the clustering of haloes and also how that number is affected by environment has the potential to be linked directly with observations. If halo mass and number of subhaloes affect clustering independently then this is a challenge to a main assumption of the halo model. In this paper we examine the role of the number of subhaloes in a halo on clustering in two different ways, first by studying the environments (nearby overdensity) of haloes and second by computing the correlation function.

Gao, Springel & White (2005) showed that the clustering strength of dark matter haloes depends not only on mass but also on formation time. This result used a high-resolution large volume simulation (the Millennium Simulation of Springel et al. 2005) and was the first of a set of results showing that halo mass is only the first-order driver of halo clustering. Subsequent studies confirmed the result (e.g. Harker et al. 2006; Zhu et al. 2006) and showed that other dependencies exist apart from halo mass, such as concentration (e.g. Wechsler et al. 2006, hereafter W06), and halo spin and shape (Bett et al. 2007). W06 also found a dependence on the number of subhaloes (see also the discussion in Sheth & Tormen 2004), and Gao & White (2007, hereafter GW07) on the substructure fraction, both at fixed mass in that haloes with more substructure are more clustered. It is these relationships that we will be investigating in more detail in this paper.

The clustering of haloes can be probed in a different, related fashion by measuring properties of the local environment. Again in this case to first order the dependence of halo properties on environment was shown to be limited to mass by Lemson & Kauffmann (1999). Advances in simulation size and resolution enabled this type of analysis to be extended to measure smaller effects and different statistics. For example, the abundance of halo substructure in a high-resolution simulation of side length $21.4 \ h^{-1} \ Mpc$ was shown by Ishiyama, Fukusihige & Makino (2008) to be dependent on local overdensity. Wang et al. (2011) find that the large-scale tidal field significantly affects all halo properties they studied (assembly
time, spin, shape and substructure) at fixed mass. White, Cohn & Smit (2010), concentrating on cluster-sized haloes, show that their environment influences and causes physical correlations in many observational probes of mass and richness (e.g. subhalo number, lensing and velocity dispersion).

The analysis in this paper is an extension of some of this prior work, which has already shown in many ways that the subtleties of halo clustering are not explained by the simplest forms of the halo model. Here we use the language of the halo occupation distribution (HOD; Berlind & Weinberg 2002) to examine the environmental dependence of substructure. In looking at clustering, we examine samples of haloes from the point of view of their bivariate distribution (mass and number of subhaloes), which it turns out can lead to some interesting behaviours which may suggest further improvements in the halo model.

The structure of the paper is as follows. In Section 2 we briefly describe the N-body simulation we use to study the subhalo population of haloes along with their large-scale environment. We give our measures of environment and describe our method for computing statistics that depend on halo occupation at fixed halo mass. The environmental dependence of the HOD is examined in Section 3 and a resolution test is carried out. In Section 4 we examine the clustering of haloes, measuring their large-scale bias as a function of mass and subhalo occupation. In Section 5 we summarize our results and discuss their implications for both the theoretical halo model and observational probes of dark matter haloes.

2 SIMULATION

We have used p-GADGET, an upgraded version of GADGET3 (see Springel 2005 for details of an earlier code version) which is being developed for upcoming petascale supercomputer facilities, to run a large dark matter simulation of a Λ cold dark matter (ΛCDM) cosmology. The cosmological parameters used were as follows: amplitude of mass fluctuations, σ8 = 0.8; spectra index, ns = 0.96; cosmological constant parameter ΩΛ = 0.74; and mass density parameter Ωm = 0.26. In the present work we use the simulation output at z = 1, the same as that analysed in our previous paper using that simulation (Khandai et al. 2011). The initial conditions were generated with the Eisenstein & Hu (1998) power spectrum at an initial redshift of z = 159. The basic simulation parameters are as follows: box side length, 400 h−1 Mpc; the number of particles, 24483; the mass of a particle, 3.1 × 108 h−1 M⊙; and the gravitational softening length, 6.5 h−1 kpc. For reference, our simulation volume is roughly half that of the Millennium Simulation (Springel et al. 2005) but our mass resolution is about a factor of 3 better.

2.1 Haloes and subhaloes

Haloes and subhaloes are identified on the fly as the simulation runs, the haloes using a standard friends-of-friends (FOF) groupfinder with linking length 0.2 times the mean interparticle separation. The halo masses quoted are the sum of masses of all particles in the FOF group.

We use the SUBFIND code (Springel et al. 2001) to construct a subhalo catalogue and to measure the mass for every subhalo. Groups of particles are retained as a subhalo when they have at least 20 bound particles, which corresponds to a minimum group mass of Msub = 6.3 × 108 h−1 M⊙. We will investigate the dependence of our results on the minimum cut-off mass in the halo and subhalo masses. We also carry out a resolution test in Section 3.2.

The number of FOF haloes in our simulation with mass greater than 1015 h−1 M⊙ is 15.3 million. These FOF haloes contain a total of 18.6 million subhaloes (we do not differentiate between central and satellite subhaloes). Several of the trends we will be looking at are relatively subtle and the statistical power coming from the large number of subhaloes and haloes is needed to make them readily detectable.

We note that other authors have investigated the dependence of substructure on other halo properties (e.g. Jeescs-on-Daniel et al. 2011; Skibba & Maccio 2011) and clustering on substructure (e.g. GW07; Wang et al. 2011). Substructure can be defined in many different ways (such as the mass fraction in subhaloes above a certain mass) and also be counted either within the FOF halo or within a certain radius (GW07 try r200). We use the definition of substructure appropriate to the usual definition of the HOD, the number of subhaloes above a certain mass within the FOF halo. We expect (as shown by GW07 and Bet et al. 2007) that the complex nature of the relationship between detailed halo properties and clustering will mean that different definitions of substructure can yield different results.

2.2 Environment

As a measure of environment we have a number of choices. The most standard is the overdensity within a sphere of fixed radius. We take this, using a fixed radius of 5 h−1 Mpc comoving to be our fiducial measure. We also test other radii, as well as using instead the overdensity in the sphere centred on a halo that encloses a fixed mass 1015 h−1 M⊙. This Lagrangian definition of overdensity has been used before in the context of simulations by e.g. Colberg & Di Matteo (2008), who investigated the relationship between supermassive blackholes and their environments.

We note that the overdensity within either a fixed radius or Lagrangian volume is expected to correlate strongly with halo mass (see e.g. the extensive study carried out by Haas, Schaye & Jeescs-on-Daniel 2011). Haas et al. 2011 show that it is possible to formulate measures of environment that are independent of halo mass. In this paper we have the more limited goal of investigating the dependence of the number of subhaloes (rather than mass) on environment. We can sidestep the mass–environment correlation by either plotting a statistic we are interested in as a function of halo mass directly (the HOD) for different environments, or else by plotting a statistic (the correlation function and its relative bias) as a function of the number of subhaloes for fixed mass. Either way we have removed the dependence on mass for the purposes of our analysis.

2.3 Halo occupation at fixed halo mass: definition

Once we have a halo catalogue and have enumerated the subhaloes per halo, we would like to break up our full sample into high- and low-occupation haloes, where ‘occupation’ is simply the number of subhaloes (we do not differentiate between central subhaloes or satellites).

In order to avoid dependence of properties (such as clustering) on halo mass, we would like to somehow make the sample be effectively at fixed halo mass. One possible approach involves applying an upper and lower mass threshold to the halo sample and then ordering the remaining haloes by occupation. There are two disadvantages with this. First, applying mass cuts in this way will reduce the number of haloes available for study, perhaps dramatically if the mass window allowed is narrow. Secondly, if the mass window is not very narrow one could legitimately worry that dependence on
halo mass will still creep in, as there is obviously a strong dependence of halo occupation and halo mass. This means that for such a mass window, the top say 10 per cent of haloes by occupation could be significantly more massive than the bottom 10 per cent.

We avoid both of these problems by instead breaking our full halo sample into a large number of narrow bins in mass. In each one of the mass bins, we order the haloes by occupation number per unit mass, choosing the top 5 per cent of haloes, top 10 per cent and so on. When making a sample of haloes chosen by occupation we then take the required fraction from each mass bin, so that we are left with a sample that spans the entire mass range, but that was chosen by occupation at fixed halo mass. We have tried varying the width of the mass bins, $\Delta \log_{10}(M)$, finding that below $\Delta \log_{10}(M) = 0.5$ our results are independent of its value [we use $\Delta \log_{10}(M) = 0.2$].

We make first use of our set of haloes ranked by occupation at fixed halo mass in Section 2.4 when plotting their spatial distribution. The main use for this type of subsample will however be in Section 4 when we examine clustering. It will be useful to us to also look at haloes ranked by mass for a fixed number of subhaloes. In this case we will use the same technique, breaking the sample into a large number of narrow bins, but this time in subhalo number.

2.4 Spatial distribution

As an example of our categorization of haloes by occupation we show in Fig. 1 the spatial distribution of high- and low-occupation haloes. Here high-occupation haloes are the top 5 per cent by number of subhaloes per unit mass at fixed mass, using the definition given above (Section 2.3), and the low-occupation haloes are the bottom 5 per cent. For reference, the mean number of subhaloes in the high-occupation sample is 17.6 and the mean mass per halo is $3.8 \times 10^{12} h^{-1} M_\odot$. The mean number of subhaloes for the bottom 5 per cent sample is 4.1 and the mean mass per halo is $3.9 \times 10^{12} h^{-1} M_\odot$.

Looking at Fig. 1 we can immediately see that there is a difference in the way the two subsamples are tracing out structures. Lower occupation haloes appear to outnumber the high-occupation haloes in the low-density regions that fill most of space. In the densest areas, there are many more high-occupation haloes. We will see in the following Sections 3.1 and 3.3 that this is borne out quantitatively by considering the HOD in different density environments and also measuring the correlation function for the two samples we are plotting here.

3 HALO OCCUPATION DISTRIBUTION

Many observational measurements of galaxy clustering can be reproduced by theories that include two main ingredients: the clustering of dark matter haloes and a model for the number of galaxies in a halo. The HOD (see e.g. Berlind & Weinberg 2002; Zheng et al. 2002; Kravtsov et al. 2004) is a way of formulating the latter. In the case where galaxies are identified with dark matter subhaloes, the
HOD can be measured from a simulation by simply counting the number of subhaloes as a function of halo mass. In this paper we will only concern ourselves with the mean number of galaxies in a halo, leaving the form of the probability distribution for further work. We note that Boylan-Kolchin et al. (2010) have found that subhalo abundances are not well described by Poisson statistics at low mass, but rather are dominated by intrinsic scatter.

The simplest assumption that can be made about the HOD is that the mean number of subhaloes, \( N_{\text{sub}} \), depends only on halo mass. This assumption has been shown to hold relatively well by Berlind et al. (2003) in (hydrodynamic) simulations and is consistent with the e.g. Yang et al. (2005) observational measurements of galaxy groups. It is known however that substructure fraction does depend on environments in simulations (e.g. Wang et al. 2011). We will see how this translates into changes in the HOD, first by looking at the local overdensity around haloes and then some other measures of the environment.

### 3.1 Density dependence

We measure the density within a radius of each halo centre of mass. We then split up the haloes into 12 mass bins and in each of these we rank the haloes by density. It is necessary to rank the haloes by local density internal to each mass bin to avoid the biases which arise from the presence of a massive halo contributing substantially by itself to the local density. We plot the HOD for the haloes as a function of halo mass for different density subsamples. Results are shown in Figs 2(a) and 2(b), where we show the HOD for the top 5 per cent by density, bottom 5 per cent by density and for the whole sample. In the top panels of that figure we show the fractional difference from the HOD for all haloes. To compute the error bars on the fractional difference, the volume was split into octants, and a jackknife estimator (Bradley 1982) was used to compute the error on the mean from the standard deviation of the jackknife subsamples.

We can see from Fig. 2(a) that the number of subhaloes in a halo does depend on the local density, with the haloes located in the densest (5 per cent) of environments having a difference in halo occupation of up to \( \sim 40 \) per cent more subhaloes than the set of all haloes. This difference increases in prominence as haloes increase in mass. For haloes of masses \( \sim 5 \times 10^{13} h^{-1} M_\odot \) the trend may flatten out (both at high and low overdensity). The error bars become too large however to say if it is inconsistent with the trend continuing or not. One thing that can be seen even at intermediate mass is that the tails of the overdensity distribution do not have more of an effect on the number of subhaloes than moderately overdense regions. This is not true of haloes in underdense regions, which have systematically fewer subhaloes than the mean, with the most underdense regions plotted (the bottom 1 per cent of environments) have up to 50 per cent less.

The environmental dependence continues out to larger radius, as can be seen in Fig. 2(b) where we use density measured within \( 10 h^{-1} \) Mpc to rank haloes. A third method to measure the density is that within a Lagrangian volume with mass \( 10^{15} h^{-1} M_\odot \). This is shown in Fig. 2(c), where the sign of the effect is the same, although the amplitude for the low-density environments is different, being lower. This is likely to do with the fact that the lowest density environments in this Lagrangian picture are being measured out to very large radii and therefore diluting the effect. For example, the mean radius that encloses \( 10^{15} h^{-1} M_\odot \) for the bottom 1 per cent of haloes by overdensity is \( 23 h^{-1} \) Mpc.

The dependence of halo properties on environment has been investigated by many authors (e.g. Ishiyama et al. 2008; Wang et al. 2011). Recently Jeeson-Daniel et al. (2011) have shown that...
environment does not correlate with substructure mass fraction on a halo by halo basis. This appears to be at odds with what we find here, but the definition of environment used by Jeeson-Daniel et al. (2011) is different to ours, being chosen so that it is not dependent on halo mass. Also we count subhaloes by number and not by mass fraction. Wang et al. (2011) on the other hand have found a relationship between local tidal field of a halo and substructure. Jeeson-Daniel et al. and Skibba and Maccio (2011) find that concentration (closely related to age) is more fundamental in setting a range of halo properties than mass.

The destruction of substructure over time in haloes can explain the anticorrelation between age or concentration and substructure. Our minimum mass to be counted as a subhalo is $6 \times 10^9 \, h^{-1} \, M_{\odot}$ (20 particles). In Fig. 3 we show the effect on the environmental dependence (defined as density within 5 $h^{-1}$ Mpc around each halo) of the HOD on changes in this parameter. In Figs 3(a)–(c) we are varying the subhalo mass threshold by factors of 3, 4 and 16. The number of subhaloes at fixed mass obviously decreases sharply as the subhalo mass threshold is raised. We however do not see any noticeable change in the difference between subhalo number in low- and high-mass threshold is raised. We however do not see any noticeable change in the difference between subhalo number in low- and high-mass environments. This is interesting as one may have thought that small mass haloes would be more susceptible to destruction and so there should be more of an effect. This also does not appear to be a resolution effect (we return to this below).

In both Figs 2 and 3 we can see that the environmental dependence of the HOD increases as halo mass increases, but may flatten off or at least not increase as much for very high mass host haloes ($m_{\mathrm{halo}} \gtrsim 10^{14} \, h^{-1} \, M_{\odot}$). Some insight into what might be expected can be found in Zentner et al. (2005) and W06, who found that for low-occupation number haloes the environmental trends are those induced by formation time (because for small haloes the abundance of subhaloes reveals a lot about the mass accretion history of the host halo). For larger haloes this relationship is not as strong and consistent with the interpretation of our finding above (see also Kravtsov et al. 2004; Zentner et al. 2005). We do however only find a difference in HOD over a limited range of masses, so that other effects are involved as well.

One thing which is clear is that the halo model of galaxy clustering which assumes a fixed HOD for all environments can be wrong at up to the 40 per cent level in the least dense environments. How this dependence of HOD on environment affects statistics that are measured, such as the correlation function of galaxies is best addressed by computing them directly, which we do in Section 4.

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so one might expect the environmental trend to be less evident also.

### 3.2 Resolution test

As a test of the effect of resolution on our results, we have run a simulation with an identical cosmology but at worse mass resolution, and in a smaller volume. The simulation had 512$^3$ particles in a box of side length 167 $h^{-1}$ Mpc, so that the mass per particle is eight times larger than in our fiducial simulation (the volume is also 14 times smaller). We again identified subhaloes using SUBFIND, and compared the HOD in both simulations where the subhalo mass threshold was 40 particles in the low-resolution run and 320 in the fiducial simulation (the same mass in each).

The results are shown in Fig. 4, where we show the fractional difference between mean number of subhaloes for all haloes and the top and bottom 25 per cent selected by mass, (similar as in the top panels of Figs 2 and 3 except here we show only the top and bottom quartiles because of the small number of haloes in the low-resolution simulation). We can see the pattern again, with more subhaloes in denser regions and a rapid drop-off at high masses in the number of subhaloes in underdense regions. There are not enough haloes with masses above $\sim 10^{14.5} h^{-1} M_\odot$ in the smaller, low-resolution run to be able to compare results, but below that mass there does not appear to be any systematic difference between the $N_{\text{sub}}$ values and those for our standard simulation. If numerical effects were responsible for the destruction of subhaloes in high-concentration regions, one would expect there to be significantly different amounts of substructure. Given that this does not occur despite the large difference in mass resolution is some evidence for the robustness of our results.

**Figure 4.** A resolution test of the effect of local environment on the HOD. We show the fractional difference between the number of subhaloes in all haloes and in the top 25 per cent picked by local density (red) and bottom 25 per cent picked by local density (blue) (similar to top panels of Fig. 2, again ranked by density in each mass bin). Results for our fiducial simulation are shown as small filled points and results for a simulation with eight times worse mass resolution and smaller box size (see Section 3.2) are shown as open circles.

### 3.3 Other environmental factors

Although local overdensity is often used interchangeably with environment, other local measures of the environment of haloes have been shown to affect halo properties. For example, Wang et al. (2011) find that at fixed halo mass, halo properties depend strongly on the local tidal field. The substructure mass fraction in their simulations is particularly affected, although the nature of the dependence is complex. They suggest that haloes in higher density (and higher tidal field regions) have more accretion and so more substructure.

We investigate three measures of local environment apart from the density and look at their effect on the HOD. Again we use a fixed radius of 5 $h^{-1}$ Mpc to define the local region around each halo and we continue to use the ranking of environmental measure that is internal to each mass bin, to avoid possible biases. We look at the asymmetry of the local mass distribution (defined as the offset of the centre of mass and the centre of the halo, divided by 5 $h^{-1}$ Mpc), the mean infall velocity of particles and the mean angular momentum. Of these, the asymmetry has some similarities with the tidal field studied by Wang et al. (2011), and the infall velocity will be strongly related to the overdensity. The results are shown in Fig. 5, where we again plot the HOD for the top and bottom 5 per cent of haloes chosen according to each statistic. Again our fiducial cut-off in subhalo mass is $6 \times 10^9 h^{-1} M_\odot$.

We compute the mean (mass-weighted) infall velocity by summing the mass times the component of the velocity of each particle in the radial direction (towards the centre of the halo) and then dividing by the total mass of particles within the $(5 h^{-1} \text{ Mpc})$ radius. As expected, the high mean infall velocity selected haloes (middle panel) show the same sign of effect in overabundance of subhaloes as seen in highly overdense regions. The size of the positive effect is again close to a maximum 30 per cent difference from all haloes. The negative effect in haloes of low infall velocity is about a maximum of 15 per cent below the result for all haloes, slightly less than the equivalent result for density (left-hand panel of Fig. 2). The asymmetry results are more instructive, with the most asymmetric local regions having fewer subhaloes (by $\sim 2$ per cent) than all haloes, and the least asymmetric $\sim 2$ per cent more. That this is a separate effect to the density effect can be understood by the fact that the most asymmetric regions actually have higher densities (because they have more neighbouring haloes). Looking at the relationship between density and asymmetry (not plotted) we find for the mean asymmetry, $A \sim 0.15 + 0.25 \log \rho_{5 h^{-1} \text{ Mpc}}$, where $\rho_{5 h^{-1} \text{ Mpc}}$ is the density within 5 $h^{-1}$ Mpc. We also find that the mean value of the density $\rho_{5 h^{-1} \text{ Mpc}}$ for the haloes with the top 5 per cent of asymmetry $A$ values, is the same as for the top 7 per cent of haloes ranked by density $\rho_{5 h^{-1} \text{ Mpc}}$. If increased local density is causing the trend, one should therefore expect (based on Fig. 2) to find a 10 per cent increase in the number of subhaloes in the most asymmetric regions, rather than a 2 per cent decrease.

There appears to be little dependence of halo substructure on angular momentum of the surrounding region (third panel), although the error bars are large.

### 4 CLUSTERING

Given that the environment on at least 5 and 10 $h^{-1}$ Mpc scales noticeably affects the number of subhaloes in a halo at fixed mass, a natural progression is a study of the clustering properties of haloes. As described in Section 2.3 we have constructed samples of haloes with varying numbers of subhaloes and fixed halo mass, as well as...
Figure 5. The halo occupation distribution as a function of environment for different measures of environment (all measured from matter in a 5 $h^{-1}$ Mpc sphere surrounding the halo). The panels from left to right show, respectively, the asymmetry of the matter distribution (quantified by the difference between the centre of mass of the matter with 5 $h^{-1}$ Mpc and the centre of the halo), the mean infall velocity of matter, and the total angular momentum of matter. As in Fig. 2 the black lines in the bottom panels show the HOD for all haloes and the red and blue lines show the HOD for the top 5 per cent of haloes ranked by the environmental measure in question and for bottom 5 per cent, respectively. As with previous HOD plots, the haloes were ranked by environmental measure within each mass bin. The top panels show the fractional differences from the HOD for all haloes.

4.1 Autocorrelation function

In Fig. 6, we show the autocorrelation function $\xi(r)$ of dark matter haloes at fixed mass (Section 2.3) for different halo occupations. We show different lower mass limits on the halo mass in the panels from left to right. In each lower frame, $\xi(r)$ for all haloes above the mass limit is shown as a solid line and dashed and dotted lines are used to denote $\xi(r)$ for the top and bottom 5 per cent of haloes ranked by occupation. The top frames show the relative bias $b_{\text{HOD/all}}(r)$ obtained by dividing the curves for the top and bottom 5 per cent of haloes ranked by occupation by the curve for all haloes.

Figure 6. The autocorrelation function $\xi(r)$ of dark matter haloes at fixed mass (Section 2.3) for different halo occupations. We show different lower mass limits on the halo mass in the panels from left to right. In each lower frame, $\xi(r)$ for all haloes above the mass limit is shown as a solid line and dashed and dotted lines are used to denote $\xi(r)$ for the top and bottom 5 per cent of haloes ranked by occupation. The top frames show the relative bias $b_{\text{HOD/all}}(r)$ obtained by dividing the curves for the top and bottom 5 per cent of haloes ranked by occupation by the curve for all haloes.
of haloes. The results for the middle panel (lower mass limit of $10^{12} \, h^{-1} M_\odot$) therefore correspond to the haloes plotted in Fig. 1. We can see that in each panel the autocorrelation function of the high-occupation haloes is significantly enhanced with respect to that of all haloes (also shown). The low-occupation haloes, on the other hand, have a slightly lower amplitude of clustering.

We examine this relative bias in the top panels of Fig. 6, where we plot the relative bias with respect to all haloes, as a function of scale, e.g. for high-occupation haloes,

$$b_{\text{HOD/all}}(r) = \sqrt{\xi_{\text{sub}} - \xi_{\text{all}}}.$$

We can see in Fig. 6 that the relative bias is close to flat as a function of $r$ for low-occupation haloes, and for high-occupation haloes it is flat on large scales, $r > 5 \, h^{-1} \text{Mpc}$ for all mass bins. The effect of high occupation is more pronounced for haloes of larger mass, with the $>10^{12} \, h^{-1} M_\odot$ haloes having a relative bias $b_{\text{HOD/all}} \sim 1.4$ on large scales (an amplitude of $\xi$ ~ twice that of all haloes), and the low mass cut-off haloes $m > 10^{11} \, h^{-1} M_\odot$ having $b_{\text{HOD/all}} \sim 1.2$ on these scales.

Just as we expected from the plot of halo positions, there is a substantial clustering difference between haloes of different occupation at fixed mass. How exactly this bias is related to halo occupation and mass can be examined by working with measurements of the large scale (flat part) of the bias directly, which we do below.

### 4.2 Large-scale bias versus mass and occupation

Because a focus of this paper is on the link between clustering and halo occupation and mass we compute bias for a grid of values of these two parameters. To measure the large-scale bias $b$ between haloes and dark matter we use $\xi(r)$ data points with $r > 5 \, h^{-1} \text{Mpc}$.

We describe our jackknife estimator for computing the error on $b$ below. In Fig. 7 we show results for $b$ on a colour scale, as a function of halo mass and subhalo number along the two axes. The plane of the figure is not filled, but the relatively large scatter about the mean relation between $N_{\text{sub}}$ and halo mass means that there are data for a substantial fraction of parameter space that lies off this relation. For example, at low mass and low $N_{\text{sub}}$ there are $10^{12} \, h^{-1} M_\odot$ haloes with only 1 subhalo of mass greater than our threshold ($6 \times 10^9 \, h^{-1} M_\odot$), as well as some haloes of similar mass but with $N_{\text{sub}}$ a factor of 15 larger.

The most obvious trend in the $b$ values shown in the plot is the increase in $b$ along the mean relation between $N_{\text{sub}}$ and $M_{\text{halo}}$. Haloes of larger mass tend to cluster more and also on average tend to have more subhaloes. It is also clear at low masses and low subhalo numbers that increasing halo mass but keeping $N_{\text{sub}}$ fixed (moving along rows from left to right) yields an increasing $b$, as does increasing $N_{\text{sub}}$ but keeping $M_{\text{halo}}$ fixed (moving up columns). It is interesting that from this it appears that $N_{\text{sub}}$ and $M_{\text{halo}}$ independently control the amplitude of clustering. This holds in the bottom left of the plot, but when one moves to the top right a trend along rows or up columns is harder to see. By using an averaging technique (see Section 4.3) we will see that it turns out that at high occupation, $b$ is completely independent of $M_{\text{halo}}$ (no trend along rows in Fig. 7) whereas at high masses, $b$ is still correlated with $N_{\text{sub}}$ (still a trend up columns, at least for the mass range shown).

Before examining these trends in $b$ as a function of halo occupation at fixed mass, we will explore the variation of $b$ with halo mass and $N_{\text{sub}}$. The steepness of these trends will allow us to place our later results in context. That halo bias is strongly influenced by halo mass is a result that is at the heart of many analyses of large-scale structure (e.g. Kaiser 1984; Mo & White 1996; Seljak & Warren 2004). In Fig. 8 we show $b$ (in this case the bias of haloes with respect to the dark matter distribution) plotted against mean halo mass in various mass bins, finding qualitatively the same steep relationship seen in e.g. Fig. 8 of Seljak & Warren (2004).

We also plot $b$ against the mean number of subhaloes in a halo, finding a steeper relationship (in that $b$ increases faster for a given increase in $\log N_{\text{sub}}$). Because $N_{\text{sub}}$ increases more slowly than $M_{\text{halo}}$ as $M_{\text{halo}}$ is increased (see e.g. Fig. 2) this behaviour is expected. We show $b$ as a function of $N_{\text{sub}}$ for two different subhalo mass thresholds, finding that $b$ increases faster for a higher threshold mass. This again is expected as for higher mass thresholds the HOD curves stay longer on the shallower initial part of the $N_{\text{sub}}-M_{\text{halo}}$ relationship (see e.g. Fig. 3).

### 4.3 Large-scale bias at fixed halo mass and at fixed occupation

We take samples of haloes which are chosen to have either fixed halo mass or fixed number of subhaloes (as defined in Section 2.3), and compute how the large-scale bias $b_{\text{HOD/all}}$ changes as we vary the other parameters. Our results are shown in Fig. 9, where on the $x-$axis we show the percentiles of the distribution. For example, in the top panel a point at $x = +99$ per cent shows $b_{\text{HOD/all}}$ for the top 1 per cent of haloes by occupation, at fixed halo mass. Likewise a point at $x = -99$ per cent shows $b_{\text{HOD/all}}$ for the bottom 1 per cent of haloes by occupation, at $x = -50$ per cent for the bottom 50 per cent and so on. Points at $x = 0$ show results for all haloes in that
halo mass bin, and the bias $b_{\text{HOD/all}}$ is measured relative to this (as in equation 1). This is different from $b$ computed with respect to the dark matter distribution, and ensures that all curves pass through $b_{\text{HOD/all}} = 1$ at $x = 0$.

In the top panel of Fig. 9, the values of $b_{\text{HOD/all}}$ are shown for variations in the $N_{\text{sub}}$ percentile, at fixed halo mass. We show results for two different halo masses and two different cut-offs in the mass of a subhalo. The mean halo mass $\langle M_{\text{halo}} \rangle$ shown in the figure caption for the curves was computed by averaging over the masses of haloes above a mass threshold. As required, the $\langle M_{\text{halo}} \rangle$ are approximately constant for the different bins of $N_{\text{sub}}$ percentile, and in all cases within 10 per cent of the $\langle M_{\text{halo}} \rangle$ value given. We can see that $b_{\text{HOD/all}}$ does change significantly with $N_{\text{sub}}$ percentile, even though the mean halo mass is the same for all points along the curve. This is what we expect from looking at Figs 1 and 6. We can also see that the steepest change in $b$ occurs for the larger mass haloes. This analysis is equivalent to adding together the trend in $b$ that one gets by moving up different columns in Fig. 7.

If we now turn to the results showing how $b$ varies as $M_{\text{halo}}$ is changed for fixed $N_{\text{sub}}$ (bottom panel of Fig. 9), we can see that the situation is somewhat different. In this plot, the $\langle N_{\text{sub}} \rangle$ values shown are computed from the average number of subhaloes above a threshold in $N_{\text{sub}}$, for each of the bins of $M_{\text{halo}}$ percentile. Here we see that for a low number of subhaloes, $\langle N_{\text{sub}} \rangle = 1.2$, there is a strong trend of $b$ with halo mass, one which is strong for both values of subhalo mass cut-off. However when we increase the $N_{\text{sub}}$ threshold to give a higher value of $\langle N_{\text{sub}} \rangle \sim 8$, we find that there is no dependence of $b_{\text{HOD/all}}$ on $M_{\text{halo}}$ percentile.

This independence of halo clustering and halo mass is interesting enough that we revisit it in Fig. 10, where we now turn to plotting $b$ with respect to dark matter halo clustering. The scale of the effects can then be judged compared to the overall trend of clustering increasing with greater halo mass and with greater $N_{\text{sub}}$.

In order to judge the significance of the comparison, it is useful to put error bars on the points. We have done this by first splitting the simulation into octants and using a jackknife estimator. Using random catalogue we have computed $\xi(r)$ for the halo subsamples and for the dark matter particles, for the simulation volume minus each octant in turn. The value of $b$ was computed for each jackknife subsample, with the error bar coming from their standard deviation.

In Fig. 10, as in Fig. 9, the top panel shows $b$ as a function of $N_{\text{sub}}$ for fixed halo mass, and the bottom panel shows $b$ as a function of $M_{\text{halo}}$ for fixed $N_{\text{sub}}$. We show results for four different halo masses in the top panel, and the $x$-axis is $N_{\text{sub}}$ instead of $N_{\text{sub}}$ percentile. We can see that even for $M_{\text{halo}} = 4 \times 10^{12} h^{-1} M_{\odot}$ there is a trend of increasing $b$ with increasing $N_{\text{sub}}$. As in Fig. 9, for the smallest $N_{\text{sub}}$, we note that there is some flattening and even a small increase in $b$. For larger $N_{\text{sub}}$ the curves for varying $N_{\text{sub}}$ at fixed halo mass appear to track the black line relatively well, which shows how $b$ varies with $N_{\text{sub}}$ for all haloes.
Figure 10. Large-scale bias (wrt dark matter) for haloes of fixed mean mass but varying $N_{\text{sub}}$ (top panel) and haloes of fixed $N_{\text{sub}}$ but varying $M_{\text{halo}}$ (bottom panel). In the top panel for reference we show $b$ versus $N_{\text{sub}}$ for all haloes as a solid black line. Each set of other lines in the top panel is for a fixed mean halo mass (given in the legend) and shows how $b$ varies with $N_{\text{sub}}$ in that case. In the bottom panel, $b$ versus $M_{\text{halo}}$ is shown as a solid black line. Each of the other lines in the bottom panel is for a fixed mean $N_{\text{sub}}$ (given in the legend) and shows how $b$ varies with $M_{\text{halo}}$. In all cases we apply the usual lower mass limit on the subhalo mass of $6 \times 10^9 h^{-1} M_\odot$.

In the bottom panel, the results for fixed $N_{\text{sub}}$ show a different behaviour. We see that for a sample with $N_{\text{sub}}$ threshold of four subhaloes (with mass $> 6 \times 10^9 h^{-1} M_\odot$) there is no dependence of $b$ on halo mass. To show how different this behaviour is from that usually seen in the halo mass–bias relation (e.g. Seljak & Warren 2004), we can compare to the black line in the bottom panel of Fig. 10 which shows how $b$ varies as a function of halo mass for all haloes. The relative change in $b$ for all haloes is substantial (a change of 35 per cent) over the mass range that is probed by the blue line (where there is no change in $b$).

The behaviour of this relationship is examined for larger haloes in Fig. 11. We show the same bias versus mass plot as in the bottom panel of Fig. 10, but this time for haloes with a lower limit on $N_{\text{sub}}$ varying from 10 to 100. We can see that for fixed subhalo number, the lack of dependence of bias on halo mass seen in Fig. 10 gradually turns into a strong anticorrelation of bias on halo mass.

Figure 11. Large-scale bias (wrt dark matter) for haloes of fixed mean $N_{\text{sub}}$ but varying $M_{\text{halo}}$. This plot is identical in nature to the bottom panel of Fig. 10, but shows results for larger haloes.

This happens between a threshold of $N_{\text{sub}} = 10$ and 20, haloes which have masses of $\sim 10^{13} h^{-1} M_\odot$ and above.

We have seen earlier (Fig. 2) that the environmental dependence of the HOD declines for haloes larger than $\sim 10^{13} h^{-1} M_\odot$. From our clustering results (Fig. 11) one might perhaps have expected a negative environmental dependence which is not seen in Fig. 2. The situation is undoubtedly complex.

5 SUMMARY AND DISCUSSION

5.1 Summary

Using a large, high-resolution dark matter simulation output at redshift $z = 1$, we have investigated the role that the environment of haloes plays on the number of subhaloes they host, and we examined the relationship between clustering and subhalo number. We find the following.

1. At fixed halo mass, the number of subhaloes in a halo is affected by local density, with overdense regions having more substructures over the whole range of halo masses, and underdense regions having less. This effect can be as large as 40 per cent for the most underdense 5 per cent of regions.

2. Our finding (1) is not significantly affected by the mass limit applied to subhaloes, or (in a resolution test) by simulation resolution.

3. At a much smaller level, the asymmetry of the local density (quantified by a centroid shift) affects the subhalo number, so that the most asymmetric haloes have fewer subhaloes, at the per cent level.

4. The clustering of haloes at fixed mass is strongly affected by the number of subhaloes. This is true over the entire mass range tested, from $10^{11}$ to $10^{13} h^{-1} M_\odot$ and for different values of subhalo mass cut-off. As with prior examples of the dependence on clustering of variables other than mass (e.g. age, Gao et al. 2005; concentration, W06), it is thus straightforward to generate samples of haloes which have the same mass but widely different clustering properties.
(5) The clustering of haloes at fixed number of subhaloes is only positively dependent on mass for small haloes. As we increase the size of haloes, we find that for haloes with more than four subhaloes (for a subhalo mass limit of \(6 \times 10^9 \, h^{-1} \, M_\odot\)), at fixed number of subhaloes there is no dependence of clustering strength on halo mass, and then for larger haloes, of group and cluster size, we find that this turns into a strong anticorrelation of clustering amplitude and halo mass. This case, showing first an independence of clustering and halo mass and then an anticorrelation of the two, is perhaps the bluntest expression yet of the shortcomings of the standard halo model when dealing with the subtleties of galaxy clustering.

5.2 Discussion

The most widely used version of halo model of galaxy clustering has at its heart some very simple premises. It is already well known however from simulation studies that many parameters apart from halo mass are actually at work in the translation of halo clustering into galaxy clustering, including the formation time dependence of clustering (Gao et al. 2005), substructure dependence and concentration dependence (W06). Looking for weak spots in the predictions of the halo model can in principle make the search for better models easier. It can also highlight areas in which for the present non-linear simulations can be a necessary tool in the attempt to make precise predictions of galaxy clustering. The areas we have investigated in this paper may have some observational consequences (as we discuss below), but they also serve to highlight some special cases for which the halo model’s prime assumptions are in direct contradiction with what is seen. These include a sample of haloes of the same mass which have radically different clustering properties based on an internal property (subhalo number) as well as other samples of haloes with very different masses but the same clustering amplitude.

The environmental dependence of the HOD is a relatively subtle effect, as can be seen by the fact that some previous smaller simulations (e.g. Berlind et al. 2003) were consistent with no dependence. Also, the observed correlation function of galaxies can be well modelled by an environmentally independent HOD (Zehavi et al. 2004; Zheng et al. 2009). There are however already signs that some observed galaxy statistics are not well predicted by the halo model, including higher order clustering of Sloan Digital Sky Survey galaxies in low-density environments (Berrier et al. 2011).

As future galaxy surveys move well past the million redshift regime (e.g. Schlegel et al. 2011), we can ask however how well we need to know the HOD and any extra environmentally dependent terms in order to carry out precision cosmology with an HOD approach to galaxy clustering (e.g. Zheng et al. 2002). Further work is needed to determine the effect on, for example, the correlation function of including an environmental term in the HOD. We have also not investigated in this paper the effect of environment on the distribution of the number of haloes at fixed mass (e.g. Kravtsov et al. 2004) which may be strongly affected.

It is also not clear how relevant and how strong the effects that we have seen here with dark matter simulations are on the galaxies that form within the subhaloes. One can clearly enumerate many possible environmental effects that rely on baryonic physics (e.g. luminosities of backsplash galaxies; Pimbblet 2011, etc.), which will further complicate the effect of environment on the HOD and which may even have the opposite sign.

The obvious examples where the number of subhaloes is used to define a set of objects are optical cluster catalogues. The environmental dependence of halo occupation is likely responsible for a fraction of the scatter in the mass–richness relation noted in optical cluster finders (see e.g. Rozo et al. 2011 for different sources of scatter).

The cause of the HOD environmental effect is a complex issue. It has been shown by many authors that a wide range of variables are affected by halo environment such as concentration (e.g. Wang et al. 2011). Internal halo properties such as substructure and shape are nearly all correlated (Jeeson-Daniel et al. 2011; Skibba & Maccio 2011) and the mass function of subhaloes itself correlates with halo concentration, formation time, etc. (Gao et al. 2011). The relative importance of mergers and smooth accretion in building up the mass of halo (Wang 2011) is likely to play a role in the environmental dependence of the HOD. Fakhouri & Ma (2010) have shown that mergers dominate halo growth in overdense regions and diffuse accretion in voids. If they survive the merger and accretion process we therefore expect subhaloes to be more numerous in overdense regions (for haloes of a given mass), as we have found (see also Wetzel et al. 2007). The destruction of subhaloes over time by intrahalo merging and stripping will make this relationship even more difficult to decipher.

Incorporating environmental dependencies into the halo model, making it more complex, but able to deal with phenomena such as those that have been demonstrated here is one avenue which can be pursued. Recently, Gil-Marin, Jimenez & Verde (2011) have presented some first steps in this direction.

Another source of potential uncertainty in the predictions of the halo model is the definition of halo mass. More et al. (2011) have shown that the mass of an FOF halo in a simulation depends on resolution. More et al. state that the influence of substructures (which depend on redshift and cosmology) on the FOF halo boundary will make it difficult to model this effect in general. In our work, the relationship between the number of substructures and environment is likely also influenced by the effect that substructures have on the mass definition.

Direct computation of the dependence of the correlation function of haloes for different occupations shows more of the complex relationship between halo properties and clustering. The bias of haloes of the same mass can vary widely depending on their occupation. For example (from Fig. 10), the lowest 25 per cent of haloes by occupation at fixed mass can have a bias which is 25 per cent lower than that for all haloes. This is similar to the effect seen by GW07 based on substructure fraction within the FOF group (although not within \(r_{200}\)) and appears to be a stronger trend than that based on other properties at fixed mass, such as formation redshift (Gao et al. 2005), concentration (W06) or spin (GW07).

In this paper we have focused on the clustering of haloes of galaxy mass, and also only looked at \(z = 1\). Further work is needed to explore the relationship between clustering and halo occupation in cluster size haloes and those at lower redshift. If the same relationships hold, then this could have interesting consequences for the clustering of galaxy clusters selected in optical surveys. One could make measurements of the dependence of galaxy cluster bias on mass (measured using velocity dispersion or lensing mass) and richness, equivalent to halo occupation. Mapping out the bivariate distribution of bias values as in Fig. 7 would give further clues to the nature of galaxy formation in groups and clusters and how much it is affected by the non-baryonic processes investigated here.

Our final perhaps surprising finding is that one can easily select samples of haloes (by picking a fixed occupation) for which there is either no dependence of clustering on mass or even a strong anticorrelation between the two. This finding is one which could also be tested with observational data on both mass and occupation. It
again points to the complexity of halo clustering and the difficulties of using galaxy clustering measurements for precision cosmology.

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