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GALICS – V: Low- and high-order clustering in mock Sloan Digital Sky Surveys

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ABSTRACT

We use the GALICS hybrid model of galaxy formation to explore the nature of galaxy clustering in the local Universe. We bring the theoretical predictions of our model into the observational plane using the MOMAF software to build mock catalogues which mimic Sloan Digital Sky Survey (SDSS) observations. We measure low- and high-order angular clustering statistic from these mock catalogues, after selecting galaxies the same way as for observations, and compare them directly to estimates from the SDSS data. Note that we also present the first measurements of high-order statistics on the SDSS DR1. We find that our model is in general good agreement with observations in the scale/luminosity range where we can trust the predictions. This range is found to be limited (i) by the size of the dark matter simulation used – which introduces finite volume effects at large scales – and by the mass resolution of this simulation – which introduces incompleteness at apparent magnitudes fainter than $r \sim 20$.

We then focus on the small-scale clustering properties of galaxies and investigate the behaviour of three different prescriptions for positioning galaxies within haloes of dark matter. We show that galaxies are poor tracers of either DM particles or DM substructures, within groups and clusters. Instead, SDSS data tells us that the distribution of galaxies lies somewhat in between these two populations. This confirms the general theoretical expectation from numerical simulations and semi-analytic modelling.

Key words: methods: N -body simulations – methods: observational – galaxies: statistics – large-scale structure of Universe.

1 INTRODUCTION

Understanding galaxy biasing has become one of the most exciting challenges of galaxy formation theories, especially due to the overwhelming data sets that are being acquired at many wavelength, for example, with the Sloan Digital Sky Survey (SDSS, York et al. 2000), and other large-scale or deep surveys. Comprehension of galaxy biasing can help us in using large-scale structure (LSS) surveys to constrain cosmological parameters. Or, the other way around, assuming that the cosmology is known, galaxy clustering sets fundamental constraints on models of galaxy formation. It is the second line that this paper follows.

Two fundamentally different approaches are being used to investigate galaxy clustering from a theoretical viewpoint. The first

one consists in running cosmological simulations that describe both the dark matter and the baryonic components of the Universe (e.g. Pearce et al. 1999; Cen & Ostriker 2000; Pearce et al. 2001; Yoshikawa et al. 2001; Weinberg et al. 2004). This method, although describing in the most realistic manner the processes of galaxy formation in the cosmological context, suffers from its computational expenses. As a result, large-scale clustering can only be explored at the price of small scales, or, in other words, one has to choose between volume and mass resolution. It, however, remains the only way to describe DM and baryons in a fully consistent manner (up to the resolution limits). The second approach gathers a large variety of implementations of the so-called *halo model*. As is well illustrated by Peacock & Smith (2000), the philosophy here is that galaxy clustering stems from three ingredients only, namely, (i) halo clustering properties, (ii) halo occupation distribution (HOD) and (iii) spatial distribution of galaxies within haloes. While

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modelling the spatial distribution of haloes has become routine with the increasing number of N -body simulations, the way to populate these haloes with galaxies is still a matter of debate. One can basically distinguish two routes among the methods for populating DM haloes with galaxies. The first one is based on biasing schemes: given the halo mass, one uses phenomenological bias prescriptions to assign a number of galaxies of given type and luminosity to a halo. Examples of this so-called ‘HOD’ method are for example, Jing, Mo & Boerner (1998), Peacock & Smith (2000), Somerville et al. (2001), Scoccimarro et al. (2001), Scoccimarro & Sheth (2002), Berlind & Weinberg (2002) and Yang et al. (2004). The second route uses semi-analytic models (SAMs) of galaxy formation to produce a physically motivated distribution of galaxies within haloes. The SAM can either be fed with semi-analytic halo merger trees (e.g. Kauffmann, Nusser & Steinmetz 1997; Benson et al. 2000, 2001) or merger trees directly extracted from cosmological DM simulations (e.g. Kauffmann et al. 1999a; Helly et al. 2003; Hatton et al. 2003). In all cases, the spatial distribution of haloes is taken from N -body simulations.

The last unknown in the framework of the halo model is then the spatial distribution of galaxies within the haloes they populate. Much work has recently been done to understand the nature of this distribution relative to the distribution of DM and it now seems clear that galaxies sample subhaloes within clusters in a non-trivially biased manner (e.g. Springel et al. 2001; Gao et al. 2004; Nagai & Kravtsov 2005). The bias arises because subhaloes are stripped much more efficiently than the galaxies they harbour as they orbit within the main halo’s potential well, which gives rise to a steeply decreasing mass-to-light ratio inwards the halo. The HOD and SAM routes then again differ. On the one hand, the HOD formalism distributes galaxies as a function of an instantaneous view of the DM distribution. It is thus not suited to describe the above evolutionary process and HOD implementations usually assume that galaxies are distributed as the DM particles within each halo, with the exception of the most massive galaxy which is forced to lying at the centre of its host halo. Note that Gao et al. (2004) suggested that this is a very good approximation, although Nagai & Kravtsov (2005) found somewhat different results. On the other hand, SAMs generally attempt to predict the galaxy spatial distribution with a more or less detailed modelling of the dynamical processes that shape it. This either involves semi-analytic prescriptions that describe dynamical friction and how halo mergers affect galaxy orbits (e.g. Hatton et al. 2003), or DM-based treatments in which galaxies typically follow the most bound particle of the halo in which they were formed (e.g. Kauffmann et al. 1999a,b; Diaferio et al. 1999, 2001; Mathis et al. 2002; Mathis & White 2002; Helly et al. 2003) or even DM subhaloes¹ (Springel et al. 2001; De Lucia, Kauffmann & White 2004; Gao et al. 2004).

The objective of this paper is to improve on previous theoretical studies of galaxy clustering in the following directions. First, we use the state-of-the-art GALICS model of galaxy formation (Hatton et al. 2003) to populate DM haloes from a cosmological N -body simulation. This model describes galaxy formation with semi-analytic prescriptions applied within halo merger trees extracted from that DM N -body simulation, and thus provides us with a physically motivated HOD. Secondly, we use the MOMAF software (Blaizot et al.

¹ Because of finite mass resolution and efficient tidal stripping of substructures, the subhaloes harbouring galaxies cannot all be followed in practice. A proxy is then necessary: when a subhalo disappears, the galaxy it contained follows the most bound particle of this subhalo, identified before the halo vanishes.

2005, hereafter MOMAF) to construct mock catalogues that mimic the SDSS early data release and DR1, both in geometry and photometric selection. These mock catalogues enable us to carry out a direct comparison of *angular* galaxy clustering statistics with those observed in the SDSS. Note that comparisons of hybrid models and observations have already been performed in the ‘observational plane’ in the past (Diaferio et al. 1999; Mathis et al. 2002). Thirdly, we extend the comparison to high-order statistics such as the three- and four-point angular correlation functions. Fourthly, we investigate how clustering statistics are affected by the spatial distribution of galaxies within haloes, that is, what does the SDSS data tell us about the small-scale distribution of galaxies. To this end, we compare the results obtained with three different galaxy distributions: (i) the one predicted by the ‘progenitor position interpolation’ (PPI) scheme implemented in the standard version of GALICS, (ii) one where galaxies follow dark matter density within haloes and (iii) one where galaxies are distributed as DM substructures. Finally, as part of the GALICS series, a side-output of this paper is the validation of the combined tools GALICS and MOMAF concerning their ability to predict spatial and angular clustering of galaxies in a more general context, that is, in the framework of forthcoming extra-galactic surveys. This is particularly meaningful since all the data used in this paper are available from the GALICS webpage,² in the form of a relational data base (see Blaizot et al. 2005).

This paper is organized as follows. In Section 2, we review the characteristics of GALICS and MOMAF which are relevant to the present study. In Section 3, we discuss the two-point angular correlation. In Section 4, we discuss higher order clustering statistics. We discuss our results and conclude in Section 5.

2 SIMULATION AND MOCK CATALOGUES

GALICS is a hybrid model of galaxy formation which combines cosmological DM simulations with a semi-analytic description of baryonic processes. The model is fully described in Hatton et al. (2003), and the version we use here is the same as that used in the previous papers of the GALICS series (Hatton et al. 2003; Blaizot et al. 2004; Devriendt et al., in preparation). We briefly remind the main ingredients in Sections 2.1 and 2.2. We have been lead to change our prescription for positioning galaxies within haloes, since Hatton et al. (2003). We explain our new prescription in Section 2.3 (also read Lanzoni et al. 2005). In this latter section, we present alternative positioning schemes that we will explore in the following sections.

Eventually, GALICS’ outputs are turned into mock catalogues using MOMAF, as explained in Section 2.4. We check in this latter section that the basic properties of these mock catalogues, that is, number counts and redshift distributions, are in agreement with the SDSS data.

2.1 Dark matter

The cosmological N -body simulation (Ninín 1999) we use throughout this paper assumes a flat Cold Dark Matter cosmology with a cosmological constant ($\Omega_m = 1/3$, $\Omega_\Lambda = 2/3$), and a Hubble parameter $h = H_0/[100 \text{ km s}^{-1} \text{ Mpc}^{-1}] = 0.667$. The initial power spectrum was taken to be a scale-free ($n_s = 1$) power spectrum evolved as predicted by Bardeen et al. (1986) and normalized to the present-day abundance of rich clusters with $\sigma_8 = 0.88$ (Eke, Cole & Frenk 1996). The simulated volume is a cubic box of side

² <http://galics.cosmologies.fr/>

$L_b = 100 h^{-1}$ Mpc, which contains 256^3 particles, resulting in a particle mass $m_p = 8.272 \times 10^9 M_\odot$ and a smoothing length of 29.29 kpc. The density field was evolved from $z = 35.59$ to present day, and we outputted about 100 snapshots spaced logarithmically with the expansion factor.

In each snapshot, we identify haloes using a friend-of-friend (FOF) algorithm (Davis et al. 1985) with a linking length parameter $b = 0.2$, only keeping groups with more than 20 particles. At this point, we define the mass M_{FOF} of the group as the sum of the masses of the linked particles, and the radius R_{FOF} as the maximum distance of a constituent particle to the centre of mass of the group. We then fit a tri-axial ellipsoid to each halo, and check that the virial theorem is satisfied within this ellipsoid. If not, we decrement its volume until we reach an inner virialized region. From the volume of this largest ellipsoidal virialized region, we define the virial radius R_{vir} and mass M_{vir} . These virial quantities are the ones we will use later to compute the cooling of the hot baryonic component. Once all the haloes are identified and characterized, we build their merger history trees following all the constituent particles from snapshot to snapshot.

2.2 Lighting up haloes

The fate of baryons within the halo merger trees found above is decided according to a series of prescriptions which are either theoretically or phenomenologically motivated. The guideline – which is similar to other SAMs – is the following. Gas is shock-heated to the virial temperature when captured in a halo’s potential well. It can then radiatively cool on to a rotationally supported disc, at the centre of the halo. Cold gas is turned into stars at a rate which depends on the dynamical properties of the disc. Stars then evolve, releasing both metals and energy into the interstellar medium (ISM), and in some cases blowing part of the ISM away back into the halo’s hot phase. When haloes merge, the galaxies they harbour are gathered into the same potential well, and they may in turn merge together, either due to fortuitous collisions or to dynamical friction. When two galaxies merge, a ‘new’ galaxy is formed, the morphological and dynamical properties of which depend on those of its progenitors. Typically, a merger between equal mass galaxies will give birth to an ellipsoidal galaxy, whereas a merger of a massive galaxy with a small galaxy will mainly contribute to developing the massive galaxy’s bulge component. The Hubble sequence then naturally appears as the result of the interplay between cooling – which develops discs – and merging and disc gravitational instabilities – which develop bulges.

Keeping track of the stellar content of each galaxy, as a function of age and metallicity, and knowing the galaxy’s gas content and chemical composition, one can compute the (possibly extincted) spectral energy distribution (SED) of each galaxy. To this end, we use the STARDUST model (Devriendt, Guiderdoni & Sadat 1999) which predicts the SED of an obscured stellar population from the ultraviolet (UV) to the submm.

The above modelling of galaxy formation provides us with a physically motivated HOD: it tells us how many galaxies one expects in each halo along with the properties of these galaxies. It also predicts the dispersion (and higher orders) of the HOD, as a result of each halo’s individual formation history. In the GALICS model, the number of galaxies that populate a halo results from basically three ingredients. First, gas cools in haloes massive enough compared to the IGM temperature. This is the source term and produces one (central) galaxy per (massive) halo. Secondly, galaxies gather in the same structures when haloes merge. This is the only way to get more

than one galaxy per halo, and tends to yield a number of satellite galaxies proportional to halo mass at high masses. Thirdly, galaxy–galaxy mergers are the only sink term (regardless selection effects). In a paper in preparation, we show that the HOD predicted by GALICS is in good agreement with results from a smoothed particle hydrodynamics (SPH) cosmological simulation, suggesting that the three above ingredients and their implementation properly capture the physics that shape the HOD.

2.3 Galaxy positions

The position \mathbf{p}_g of a galaxy in the simulation volume can be written as $\mathbf{p}_g = \mathbf{p}_h + \delta\mathbf{p}$, where \mathbf{p}_h is the position of the centre of mass of the host halo, and $\delta\mathbf{p}$ the position of the galaxy within this halo. While the positions of haloes are well known from the DM simulation, the spatial distribution of galaxies inside their host haloes is not described by DM-only simulations. One thus needs a model to predict each galaxy’s $\delta\mathbf{p}$. In this paper, we investigate the effect of three such models on the clustering properties of galaxies: (i) the ‘PPI’ implemented in the standard version of GALICS, (ii) a scheme in which galaxies follow DM within haloes (FOF) and (iii) a model in which galaxies are positioned on DM substructures (SUB). Seeing which scheme the SDSS data prefer will hopefully help us understand how galaxies are distributed within DM haloes.

PPI – Because of the spherical symmetry assumption made in GALICS, a galaxy’s position in our model is described only by its orbital radius. We model two processes that can affect a galaxy’s distance to its halo’s centre: (i) dynamical friction brings galaxies to the centre, and (ii) halo mergers heavily perturbate galaxies’ orbits. Because of the frequent mergers, it is the latter process that mostly determines the galaxy distribution. When two haloes merge, the positions of the galaxies within the descendent halo are obtained with an interpolation of the progenitor’s positions using their velocities. In this paper, we use a new prescription to reposition galaxies after halo mergers, which is a modified version of that described in Hatton et al. (2003), designed to better take into account the difference in masses of the merging haloes (see Lanzoni et al., in preparation). In practice, the displacement distance R_j of Hatton et al. (2003, equation 5.1) is now multiplied by a factor of $(1 - M_{\text{prog}}/M_{\text{son}})$, where M_{prog} is the mass of either progenitor, and M_{son} the mass of the descendent. In this way, when a small halo merges with a much more massive one, galaxies’ orbits in the massive halo will change very little, whereas galaxies’ orbits in the small halo will change as before. The effect of this prescription is to yield more concentrated galaxy distributions than the original prescription did. Note, however, that the overall properties of galaxies are almost identical to those presented in Hatton et al. (2003) and Blaizot et al. (2004). An example of the galaxy distribution predicted by the ‘PPI’ model is shown in the upper left-hand panel of Fig. 1, for a halo of mass $8.3 \times 10^{14} M_\odot$, containing 397 galaxies.

FOF – The second positioning scheme explored in this paper, and hereafter called ‘FOF’, consists in placing galaxies on random particles of the halo they belong to, with the exception of the most massive galaxy which is forced to lie at the centre of mass of its halo. This is done as a post-treatment of the GALICS outputs and has thus no effect on the physical properties of modelled galaxies. For the same reason, though, the positions of *satellite* galaxies within haloes are not related to their physical properties. The resulting distribution is illustrated in the lower left-hand panel of Fig. 1. Several qualitative differences can be noticed with the PPI distribution: (i) the shape of the distribution is more complex (two cores, etc.), (ii) it is much

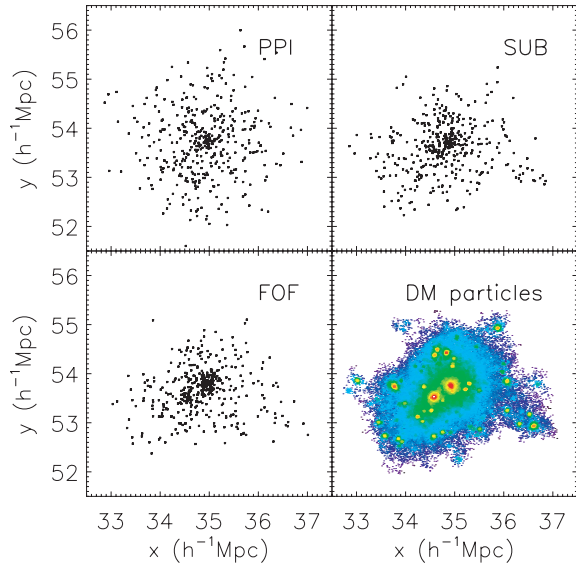


Figure 1. Projected positions of galaxies (dots) in a $8.3 \times 10^{14} M_{\odot}$ halo containing 397 galaxies. The upper left-hand panel (respectively, upper right-hand panel, lower left-hand panel) shows the PPI (respectively, SUB, FOF) galaxy distribution. The lower right-hand panel shows the distribution of dark matter particles, for comparison. The virial radius of this halo is $1.6 h^{-1}$ Mpc.

more concentrated near the core(s). Note that this FOF distribution is the one most commonly used in HOD implementations.

SUB – The third positioning prescription we explore consists in placing galaxies on top of DM substructures (this will hereafter be referred to as ‘SUB’). In this case, we assign galaxies to substructures as a function of their masses: more massive galaxies go to more massive substructures. As a result, the most massive galaxy of a halo naturally ends up at the centre of mass of this halo. This procedure relies on the assumption that the mass of a substructure roughly scales with that of the galaxy it contains. This assumption is definitely questionable, since substructures are much more efficiently tidally stripped – while orbiting within the main halo – than the galaxies they harbour (e.g. Springel et al. 2001; Diemand, Moore & Stadel 2004; Nagai & Kravtsov 2005). We thus expect our procedure to induce a significant depletion of identified galaxies in the cores of massive haloes. This should definitely have some impact on the measurement of the two-point correlation function and higher order statistics at small scales. In particular, we expect that the SUB scheme will lead to an underestimate of the small-scale clustering signal, with respect to what would be found with a full hydro-dynamical treatment as in Nagai & Kravtsov (2005). Still, the exercise is interesting because our SUB and FOF schemes are expected to closely bracket the ‘true’ distribution of galaxies.

Also note that in practice, the number of substructures within a halo may differ from the number of SAM galaxies it contains. This is an issue when there are fewer substructures than galaxies. In this case, the extra (low-mass) galaxies are given the positions of random dark matter particles as in the FOF scheme. Fortunately, for our SDSS mock catalogues, such miss-identifications are rare enough, as shown in Appendix A. The upper right-hand panel of Fig. 1 shows the ‘SUB’ distribution of galaxies in the same halo as before. This distribution lies somewhat in between the FOF and PPI pictures. The identification of substructures is done using the

ADAPATHOP code by Aubert, Pichon & Colombi (2004), as described in Appendix A.

Finally, note that in the three different positioning schemes, we do not allow for galaxies to overlap, that is, we impose a minimum distance between galaxies of twice their sizes.

2.4 Mock catalogues

We use the *random tiling* technique described in MOMAF to build mock observations from the redshift outputs of GALICS. We mimic the SDSS early data release by constructing catalogues of $2.5 \times 90 \text{ deg}^2$, limited in apparent magnitude at $r = 22$. As explained in MOMAF, several different observing cones can be generated from the same set of outputs of GALICS, by changing either the line of sight or the seed for the random tiling. We build 20 cones with seeds and lines of sight chosen randomly for each positioning scheme. These 20 cones allow us to infer some estimate of the dispersion in clustering measurements, that is, the cosmic variance associated to our mock catalogues. However, given the rather small size of the simulation box, $100 h^{-1}$ Mpc on a side, this estimate is likely to be biased and has to be taken as a lower boundary on the cosmic errors.

In Table 1, we give some geometrical characteristics of our mock catalogues. The first line gives the median redshift (z_{med}) of each apparent-magnitude selection. The second and third lines give the angular size (θ_b) of our simulated volume at z_{med} and the corresponding number of boxes required to fill the observing cone in its largest dimension ($N_r \times \theta_b \sim 90^\circ$). Both these quantities give an idea of the importance of finite volume and replication effects, which tend to reduce the amplitude of the N -point correlations functions as well as that of the measured cosmic variance on their estimates [see Blaizot et al. (2005) for a thorough discussion of these effects]. The fourth and fifth lines give similar quantities, this time along the line of sight. The sixth and seventh lines give the completeness limits at z_{med} in terms of absolute rest-frame magnitudes in

Table 1. Summary of the limitations of our simulation, in terms of volume (first five rows), and mass resolution (last three rows). The angular size of our simulation allows us to probe clustering up to scales ranging from $\sim 1^\circ$ to ~ 0.6 from the brightest to the faintest apparent-magnitude bins. Moreover, the mass resolution guarantees that our samples of galaxies are complete in the two brightest magnitude bins, while we certainly miss part of the galaxies at fainter fluxes.

	$18 < r < 19$	$19 < r < 20$	$20 < r < 21$	$21 < r < 22$
z_{med}^a	0.22	0.31	0.41	0.55
θ_b^b	11.2	8.77	7.34	6.26
N_r^c	8	10	12	14
$d_c(2z_{\text{med}})^d$	1170	1567	1957	2429
N_r^e	12	16	20	25
r_{res}^f	−20.0	−20.5	−20.6	−20.3
I_{res}^g	−20.5	−20.8	−20.9	−20.6
M_r^h	−21.3	−21.1	−20.8	−20.6

^aMedian redshift of galaxies in each magnitude bin, as shown by the vertical lines in Fig. 3; ^bangular size of the simulated volume at z_{med} , in degrees; ^cnumber of boxes tiled across the line of sight, in the direction where the observing cone is 90° wide; ^dcomoving distance from the observer to $2 \times z_{\text{med}}$, in h^{-1} Mpc; ^enumber of boxes tiled along the line of sight.

^fcompleteness magnitude limit in the SDSS r band (rest frame); ^gcompleteness magnitude limit in the $F814W$ band from *HST* (rest frame); ^habsolute (observer-frame) magnitudes corresponding to the fainter boundary of each apparent magnitude bin, at the corresponding median redshift.

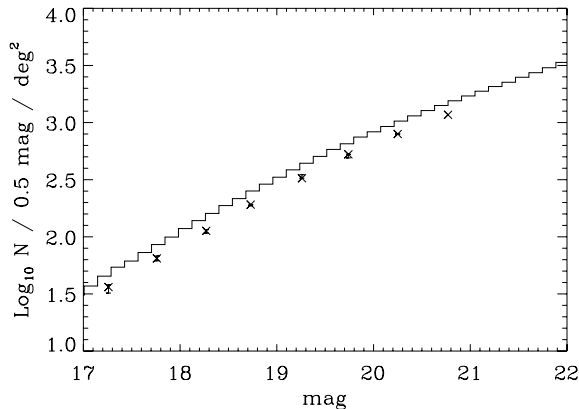


Figure 2. Comparison of number counts from GALICS (solid histogram) with those from the SDSS early data release (crosses with error bars, taken from Yasuda et al. 2001), in the r filter.

the r band (r_{res}) and in the I band (I_{res}). Fainter than these limits, our sample of galaxies is incomplete due to resolution effects: we miss part of the galaxies because they would lie in unresolved DM haloes. The last line of Table 1 gives the observer-frame absolute magnitude corresponding to the faint boundary of the selection at z_{med} in each magnitude bin. This magnitude should be compared to r_{res} at low redshifts and to I_{res} at higher redshifts. Comparison then tells us whether the sample of galaxies we select with the apparent-magnitude cut is complete. As can be seen from the two last columns of Table 1, our samples of galaxies become incomplete faintwards $r \sim 20$.

Before approaching clustering statistics, one should first check that one-point statistics (number counts and redshift distributions) are in agreement with the data. In Fig. 2, we show the comparison of GALICS counts in the r band (solid line) with the SDSS observations (crosses with error bars) taken from Yasuda et al. (2001). These counts were measured on one mock SDSS stripe. Our model slightly overestimates the observed counts at all magnitudes, of ~ 0.1 dex in number or ~ 0.2 mag in magnitudes. The reasons for this overestimate are not obvious. They are partly due to an overestimate of the present-day luminosity function, and possibly to a slightly wrong redshift evolution [although see discussion of $2dF N(z)$ in MOMAF]. The important point here is that the counts match observations well enough for our purposes. We indeed show in Section 3.1 that such a small error in the number counts does not affect our conclusions concerning clustering.

In Fig. 3, we show the redshift distributions of modelled galaxies selected in four apparent-magnitude bins (hereafter ‘standard’ magnitude bins). The solid line shows the redshift distribution of galaxies with apparent r magnitude between 18 and 19, the dashed line is for $19 < r < 20$, the dot-dashed line for $20 < r < 21$, and the dotted line for $21 < r < 22$. The median redshifts of each sample are respectively $z_{\text{med}} = 0.22, 0.31, 0.41$ and 0.55 , as indicated with the vertical lines in Fig. 3. The median redshift of the brightest bin is consistent with $z_{\text{med}} = 0.18$ given by Connolly et al. (2002). Again, these redshift distributions were obtained from a single mock catalogue. The (small) high- z bump seems to be a general trend of our model (it appears in most of our 20 mocks), and not due to a particular superstructure. We have checked that this anomaly has no effect on our clustering estimates by computing $w(\theta)$ with and without galaxies in the high- z tails: results are undistinguishable.

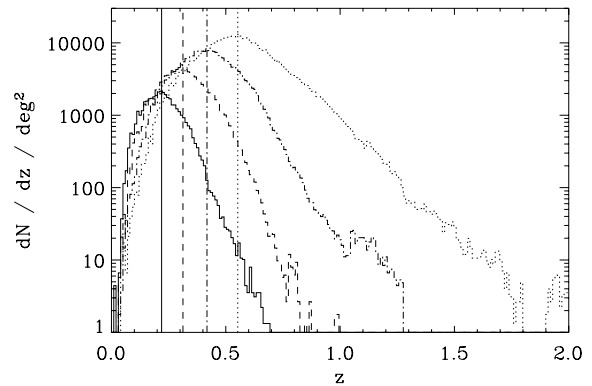


Figure 3. Redshift distributions of modelled galaxies selected in four apparent-magnitude bins. The solid line (respectively, dashed, dot-dashed and dotted) corresponds to $18 < r < 19$ (respectively, $19 < r < 20$, $20 < r < 21$ and $21 < r < 22$).

3 TWO-POINT CORRELATION FUNCTION

In this section, we first show that our clustering results do not depend much on the uncertainty in the counts. Then, we present the angular correlation function (ACF) we obtain with the PPI scheme for positioning galaxies, and discuss its agreement with the SDSS data. Finally, we explore how the three positioning schemes affect the ACF at small scales.

3.1 ACF estimate and robustness

We compute the ACF $w(\theta)$ using the estimator proposed by Landy & Szalay (1993). However, instead of counting pairs, we use a fast Fourier transform (FFT) scheme which is much faster when the number of galaxies is large (Szapudi, Prunet & Colombi 2001b). This method requires one to project the apparent galaxy density on to a grid, the cell-size of which sets a lower limit to the scales one can probe. We therefore project each mock SDSS strip on rectangular grids of 16384×455 cells, which correspond to cells of size ~ 20 arcsec.

We do not attempt to correct for the integral constraint, as Scranton et al. (2002) showed that it is negligible. Moreover, because we mimic the geometry of the SDSS, we are affected by the same integral constraint as observations. A direct comparison of both raw estimates then makes more sense. Also, we do not estimate errors analytically, as they are in principle fully contained in the dispersion of our measurements among the 20 mock catalogues. Remember, however, that we expect this dispersion to give a lower bound on the errors rather than a true estimate, due to the finite size of the simulation box.

As mentioned earlier, the counts from GALICS slightly differ from those given by Yasuda et al. (2001). The significance of this discrepancy is not very clear and could possibly be due to, for example, definition of magnitudes, or pollution by stars (Yasuda et al. 2001; Scranton et al. 2002). A full treatment of photometric errors is, however, beyond the scope of this paper. Instead, we show that our results are not very sensitive to apparent magnitude uncertainties. To do this, we use a single mock catalogue to compute the angular correlation function for galaxies in the four standard magnitude bins ($18 < r < 19$, $19 < r < 20$, $20 < r < 21$ and $21 < r < 22$) and in magnitude bins shifted by -0.2 mag ($17.8 < r < 18.8$, $18.8 < r < 19.8$, $19.8 < r < 20.8$ and $20.8 < r < 21.8$). This shift is about what

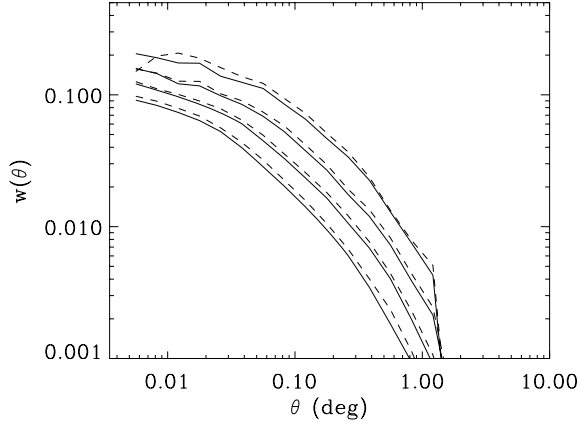


Figure 4. Angular correlation functions of galaxies in different apparent-magnitude bins using the PPI scheme to locate galaxies. The solid lines show the ACF of galaxies with $18 < r < 19$, $19 < r < 20$, $20 < r < 21$ and $21 < r < 22$, from top to bottom. The dashed lines show the ACFs of galaxies with $17.8 < r < 18.8$, $18.8 < r < 19.8$, $19.8 < r < 20.8$ and $20.8 < r < 21.8$, from top to bottom. An uncertainty of 0.2 mag translates in very little changes of $w(\theta)$.

is required for our model counts to fit the SDSS counts. We show the results in Fig. 4 for one of the PPI catalogues. The solid lines correspond to the standard magnitude bins, and the dashed ones to the shifted magnitudes. Naturally, we find that brighter galaxies (the shifted bins) are more clustered than fainter ones. However, the shape of the correlation function is not affected, and the difference in amplitude is very small. Similar results would be obtained with the FOF and SUB schemes to position galaxies. Our conclusions are thus robust in this prospect.

3.2 Results for the PPI scheme

In Fig. 5, we show the mean ACF (solid line) and its dispersion (dark grey region) from 20 mock catalogues built using the PPI positioning scheme. The light grey areas show the envelopes of

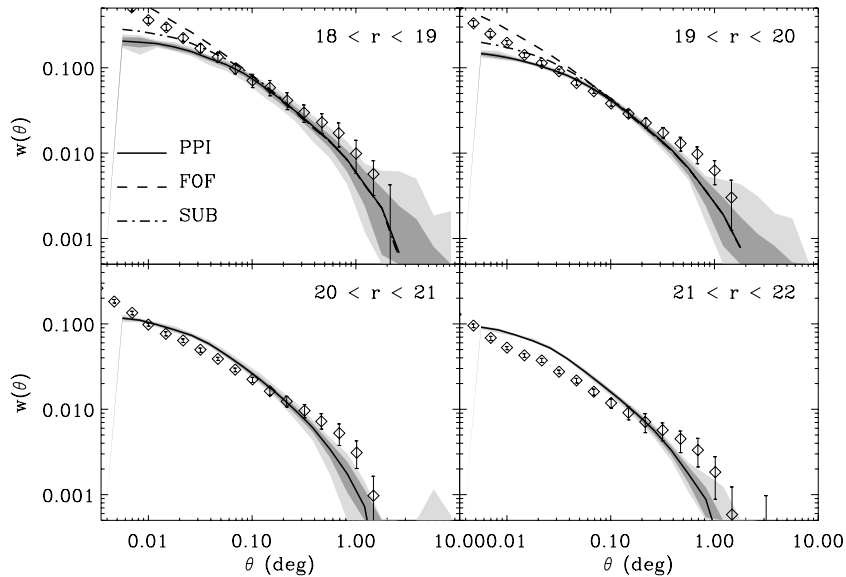


Figure 5. Angular correlation function measured from our mock catalogues for galaxies selected in four apparent-magnitude bins. We computed $w(\theta)$ for 20-independent observing cones of $2.5 \times 90 \text{ deg}^2$. The solid lines show the mean value, the dark grey area shows the dispersion among the 20 cones, and the light-grey region shows the envelope of measures. In each panel, the diamonds with error bars show the SDSS ACF measured by Connolly et al. (2002).

the measurements. The diamonds with error bars are taken from Connolly et al. (2002). Now, some explanations might be useful to understand how *good* the match actually is between our model and the observations.

At large scales, typically larger than $\sim \theta_b/10$, where θ_b is the angular size of our simulated volume at the median redshift of a considered magnitude bin, finite volume effects affect our estimates of the ACF (see Table 1 for numerical values of θ_b). This effect was discussed at length in Blaizot et al. (2005) and is responsible for the (small) underestimate of the ACF at large scales. Interestingly, the finite volume limit of our simulation neighbours that of the observations, since the observed stripe is 2:5 large. The disagreement of our model with data at large scales is thus well understood in terms of finite volume effects, hence it does not point to any failure in the GALICS model.

At faint magnitudes, especially in the two faintest apparent magnitude bins, incompleteness – due to mass resolution – settles in progressively, and is responsible for the increasing amplitude overestimate faintwards. The three bottom lines of Table 1 give us insight on this bias. As discussed in Section 2.4, faint-wards $r \sim 20$, one finds $M_r > I_{\text{res}}$, which means that the samples of galaxies selected in the two faint magnitude bins are incomplete. This incompleteness is such that the selected galaxies inhabit a population of haloes biased towards high masses. Now, as massive haloes cluster more than low-mass ones, increasing incompleteness implies an increasing positive bias in the ACF. This is what happens at $r > 20$. However, our results in the apparent-magnitude range [18;20] are robust, and the amplitude of the ACF found for these samples is in good agreement with observations.

At small scales, typically smaller than the angular size of a group (i.e. $\sim \theta[1 \text{ Mpc}]$ at z_{med}) our predicted ACF underestimates the observed one. We will show in Section 3.3 that this bias can be attributed to an overdiluted distribution of galaxies within haloes of DM.

The discussion above shows that our results are in good agreement with observations, in the rather restricted domain where our model and catalogues are valid. We can nevertheless certainly improve the situation, as we discuss in the following subsection.

3.3 Exploring the small-scale galaxy distribution

The so-called ‘HOD’ formalism has proven to be quite helpful in terms of understanding the origin of the clustering properties of galaxies. In the HOD framework, galaxy clustering is the result of three ingredients: (i) the spatial distribution of haloes, (ii) the number of galaxies per halo and (iii) the distribution of galaxies within haloes. In this study, the distribution of haloes is drawn from a cosmological DM simulation. Except for the very little difference between the ‘concordance model’ and the cosmological parameters we assume, point (i) is thus certainly the least questionable part of this work. The number of galaxies that each halo harbours is a more difficult issue, as it is the result of our complex semi-analytic post-processing. Moreover, this quantity is very difficult to constrain observationally (see, however, van den Bosch, Yang & Mo 2003). In a paper in preparation, we compare the HOD obtained with GALICS to that obtained with a cosmological SPH simulation, and find very good agreement. This, combined with the numerous statistics that have been checked for our model (Hatton et al. 2003; Blaizot et al. 2004; Lanzoni et al., in preparation) gives us confidence in the fact that we predict the right number of galaxies per halo. Then remains point (iii) only to explain the small-scale discrepancy shown in the previous section between our model and observations. One of the interesting results of the HOD formalism is to decompose the correlation function into two terms. A term due to pairs of galaxies located in different haloes (the two-halo term) dominates at large separations, and a term due to pairs of galaxies populating the same halo (the one-halo term) dominates the clustering signal at small scales (see e.g. Berlind & Weinberg 2002). The one-halo term is mainly due to galaxies that lie in groups or clusters, and is sensitive to the way galaxies are spatially distributed within these massive haloes. Already from Fig. 1, one can have a feeling of what is happening: the distribution of galaxies predicted by the PPI scheme within groups and clusters is less concentrated than that obtained with the two other schemes (FOF and SUB). This will naturally lead to an underestimate of the one-halo term, and so to an underestimate of the ACF at small scales.

In the top panels of Fig. 5, we compare the ACFs obtained with the three positioning schemes proposed in Section 2.3. The solid (respectively, dashed, dot-dashed) lines show the mean PPI- (respectively, FOF-, SUB-) ACF from the 20 mock catalogues described in Section 2.4. This comparison tells us many things. First, changing the distribution of galaxies within haloes does indeed change the behaviour of the ACF at small separations, although it leaves unchanged the ACF at large scales, as expected. Secondly, the FOF scheme yields an ACF which overestimates the observed ACF at small scales. If not a well-known result, this is at least a feature which is commonly found in the literature (e.g. Benson et al. 2000; Scoccimarro et al. 2001; Berlind et al. 2003; Weinberg et al. 2004; Yang et al. 2004). Although Yang et al. (2004) interpreted this feature as a hint that the normalization of the power spectrum (σ_8) is overestimated in the concordance model, our analysis suggests another explanation which simply relies on the distribution of galaxies within haloes. This explanation is also supported by the work of Kauffmann et al. (1999a) who found a spatial correlation function in agreement with observations. In their work, the positions of galaxies are obtained following the most-bound particles of the haloes in which they were formed. This is, in essence, similar to following substructures, except that it allows to follow them below mass resolution, and to bypass the expensive identification of substructures. Thirdly, the SUB scheme gives a result intermediate between FOF and PPI, but still not in agreement with the data: it yields a depletion

of the two-point correlation function at small separations, similar to PPI. This was expected, as discussed in Section 2.3, due to the fact that substructures are tidally stripped as they spiral towards the centres of massive haloes. As a result, the number of pairs found at small separations with our SUB scheme is smaller than what we would expect from the real galaxy distribution. This effect is also increased by artificial phase-space heating due to N -body relaxation. In reality, even if a subhalo is tidally stripped, its host galaxy still exists. However, at variance with pure dark matter, galaxies can experience non-trivial collisions that would expectingly reduce slightly their concentration in the centre of rich haloes, which give a likely explanation for the fact that FOF overestimates the ACF at small separations.

It is then hard to find a way to populate haloes with finite resolution DM simulations only. Even following subhaloes dynamically as in Springel et al. (2001) requires the use of a proxy when subhaloes dissolve: galaxies are then associated to the locally most-bound particle. It is, however, not clear how this proxy behaves once substructures are disrupted – although long relaxation times suggest that the trajectories of once most-bound particles should be a good approximation. In view of this effect, the agreement found by Kauffmann et al. (1999a) can be understood as the result of an average between our FOF and SUB biasing schemes, confirming our above statement that the SUB and FOF prescriptions narrowly bracket the real solution.

To summarize the results, although the accuracy reached in this paper cannot really help us to rigorously disentangle the SUB and FOF schemes, our measurements confirm well-known results of the literature: (i) substructures are non trivially biased tracers of galaxies, and (ii) galaxies are distributed inside haloes very much like dark matter, but in a slightly less concentrated way. In the next section, we explore how this assertion resists the additional constraints from higher order clustering.

4 HIGHER ORDER STATISTICS

Because gravity has long pulled structures harbouring galaxies away from possible initial Gaussianity, the distribution of galaxies is not fully characterized by the two-point correlation function alone. Instead, higher order correlations have become non-zero and encapsulate the details of the small-scale non-linear galaxy distribution. It is thus very important to confront higher order predictions from our model to observational determinations. In this section, we first explain the counts-in-cells method that we used to measure high-order clustering on SDSS DR1 and on mock catalogues. Then, we briefly discuss the estimate made on SDSS DR1. And finally, we compare results obtained with SDSS DR1 and our mocks in order to understand whether this new set of constraints can help discriminate between our SUB and FOF schemes.

4.1 The counts-in-cells method

The probability distribution of counts in cells (CIC), $P_N(\theta)$, is the probability that an angular cell of (linear) dimension θ contains N galaxies. The factorial moments of this distribution are defined by $F_k \equiv \sum_N P_N(N)_k$, where $(N)_k = N(N-1)\dots(N-k+1)$ is the k th falling factorial of N . The factorial moments are closely related to the moments of the underlying continuum random field (which is assumed Poisson-sampled by the galaxies), $\rho = \langle N \rangle (1 + \delta)$, through $\langle (1 + \delta)^k \rangle = F_k / \langle N \rangle^k$ (Szapudi & Szalay 1993), where angle brackets in the last relation denote an area average over cells of size θ . The factorial moments therefore provide a

convenient way to estimate the angular connected moments, $S_p \equiv \langle \delta^p \rangle_c / (\delta^2)^{p-1}$, where the subscript c denotes the connected contribution, and $\langle \delta^p \rangle_c$ denotes the area average (over scale θ) of the p -point angular correlation function. The moments S_3 (skewness) and S_4 (kurtosis) quantify the lowest order deviations of the angular distribution from a Gaussian.

It is straightforward to calculate factorial moments from the distribution of CIC, and one can then use the recursion relation of Szapudi & Szalay (1993) to obtain the S_p 's. This technique is described in more complete detail in Szapudi, Meiksin & Nichol (1996) and Szapudi et al. (2001a). The most delicate and time consuming component of estimating the cumulants S_p 's is then the accurate measurement of CIC distribution.

As shown in Szapudi & Colombi (1996), large-scale measurements are dominated by edge effects which are impossible to correct for exactly – even when using massive oversampling. This stems from the fact that, due to finite cell size, galaxies near the edge of the survey (or near a masked-out region) receive a smaller statistical weight than galaxies away from any edge. This has devastating effect when estimating CIC in galaxy surveys. Typically, across the whole SDSS area, there are over 100 cutout holes per square degree. Consequently, a randomly placed cell of side ~ 0.1 has a high probability of intersecting a mask. Now, because traditional CIC techniques discard such cells, they would not be able provide us with measurements on scales larger than ~ 0.1 . To remedy this situation, we measure the CIC distribution using a new estimator by Colombi & Szapudi (in preparation) and its implementation BMW-PN (for Black-Magic-Weighted-PN). This estimator features a linear, massively oversampling algorithm, and sports a new approximate edge correction scheme.

The recipe implemented in BMW-PN gives approximately equal weight to each galaxies during CIC estimation. While it was shown previously that this is impossible under the most general circumstances, the approximate scheme uses the fact that the CIC distribution is fairly insensitive to cell shape (Szapudi 1998). This empirical fact can be used for edge effect correction for the special case of estimating galaxy CIC in the following way. The data are pixelized on a very fine grid, which will give CIC for the smallest possible scale, the grid step size. The same operation is performed for the masks. On these pixelized data, one considers all the possible square cells of all possible sizes, that are seen as ensembles of pixels. For each of these cells, an effective size is given, corresponding to the valid area it encompasses (overlapping pixelized masks are subtracted). Then the centre of mass of the valid part of the cell is calculated, and one finds the pixel it falls into. With that procedure, a number of cells of a given effective scale will fall on to this same pixel. However, one is interested only in one cell, because one cell per pixel is enough to extract all the available statistical information at the chosen pixelization level. One thus selects the cell which is the most compact one, or, in other words, the initial square cell of smallest possible size before mask area subtraction. This way, one increases the effective area sampled by the cells and the amount of available statistics. Moreover, due to the fact that only one cell at most is allowed to contribute to a pixel, a more even weight is given in practice to galaxies near the edge of the catalogue, which reduces edge effects. It is, however, not easy to demonstrate that analytically: only practical experiments show that it is indeed the case (see Colombi & Szapudi 2006). This is why the method is called ‘Black-Magic Weighting’ (BMW).

A more detailed explanation of this estimator is given by Colombi & Szapudi (2006) who performed a series of tests based on simulated galaxy surveys, and masks lifted from real galaxy surveys. They

have found that the method works with high precision. The control parameter, a number between 0 and 1, determines the fraction of the cell allowed to overlap with a mask. 0 corresponds to no overlap (‘classical’ CIC estimation), while larger numbers turn on the BMW. It was found that even at 75 per cent allowed overlap, the systematic errors introduced are negligible. For a margin of error, we have allowed 50 per cent overlap in all the calculations presented below.

4.2 The SDSS DR1 data set

The first major SDSS data release (Abazajian et al. 2003, DR1) covers 2099 deg² and contains over 53 million objects. In our analysis, we include galaxies of the eight northern stripes 9–12, 34–37 and three southern ones 76, 82 and 86 – that is, all DR1 stripes except the shortest ones, 42 and 43. While we use some data outside the DR1, our area adds up to marginally smaller than the total area of DR1.³ The galaxies were split into four apparent magnitude bins that can be compared to previous results of other surveys as well as the early SDSS measurements by Szapudi et al. (2002). The number of galaxies with dereddened r model magnitudes between 18–19, 19–20, 20–21 and 21–22 are 732 216, 2 047 766, 5 455 559 and 10 890 300, respectively. That is, altogether more than 19.1 million galaxies, which is an order of magnitude more than the largest higher order statistical study to date.

The data base also holds the relevant information about areas on the sky that are to be censored in any type of statistical studies of spatial distribution of galaxies. Bright stars, satellites, airplanes and bad seeing account for approximately 12 per cent loss in the area of DR1. These masked regions on the sky are extremely hard to deal with in CIC measurements, as explained below.

Since we have measured CIC in 11 virtually independent SDSS stripes, we were able to estimate the variance in a fairly robust fashion, by taking the unbiased dispersion over the 11 stripes and dividing the corresponding error by a factor of $\sqrt{11}$ (see e.g. Colombi, Szapudi & Szalay 1998). All error bars have been determined this way. For the mock catalogues, the errors are determined from the dispersion obtained from 20 random stripes without further renormalization: the error estimated this way assumes only one stripe. Indeed, the simulation used to generate the mock catalogues is too small to have fair estimate of the errors on a full 11 stripes catalogue.

We performed a series of measurements on the DR1 data set, using the CIC method. We extracted S_3 – S_5 from the CIC statistics. All the measurements were carried out with masks corresponding to seeing limit full width at half-maximum ($FWHM$) = 1.7, 1.8, 1.9 and 2.0 arcsec.

We have found that seeing has only minor effects for the most part, therefore we present measurements for $FWHM$ = 1.7 only (shaded areas in Fig. 6).

4.3 Mocks versus DR1

In Fig. 6, diamonds (respectively, stars, triangles) show the mean values of S_3 (respectively, S_4, S_5), obtained from the 20 mock catalogues. The symbols connected with continuous (respectively, dashed, dot–dashed) lines correspond to the PPI (respectively, FOF,

³ Note that DR4 is now publicly available. We, however, still use DR1 because it is largely sufficient for the level of detail we wish to reach, given the size of the simulation used.

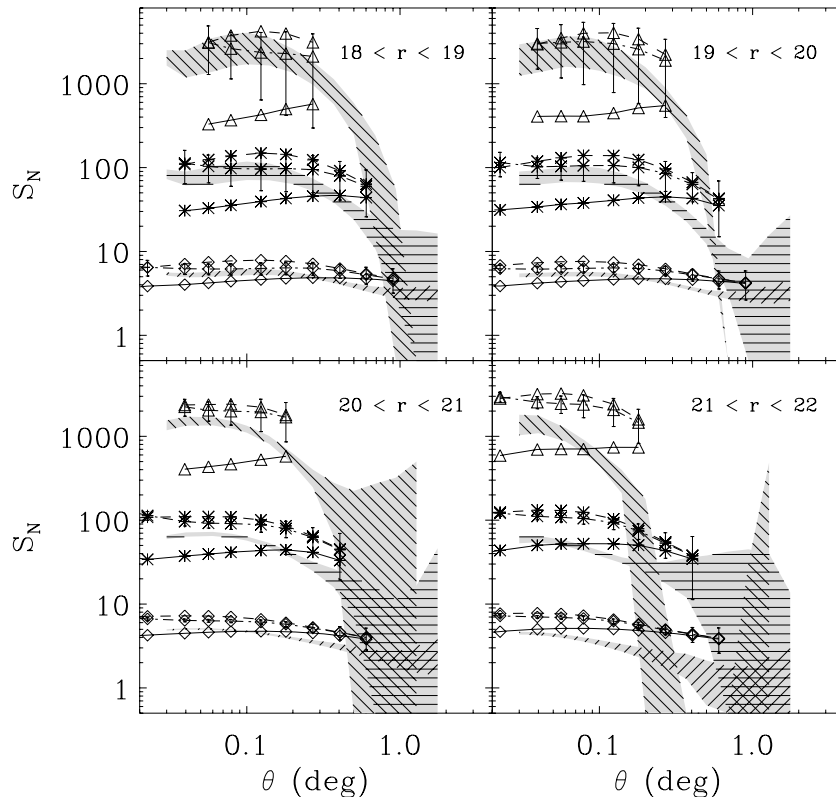


Figure 6. Third (respectively, fourth, fifth) order cumulants measured in 20 mock catalogues are shown as diamonds (respectively, stars, triangles). Solid (respectively, dashed, dot–dashed) lines connect symbols corresponding to the PPI (respectively, FOF, SUB) scheme. The error bars associated with symbols show the dispersion around the average estimate. The four panels correspond to different apparent magnitude selections, as in Fig. 5. The shaded regions show the locus of SDSS measurements.

SUB) schemes for positioning galaxies within haloes. The dispersion of S_n estimates are shown with error bars for the SUB case only, for the sake of clarity. Measurements from the SDSS DR1 are shown with the shaded and hatched areas. These were obtained with the 1.7-arcsec seeing masks. Note that errors computed for the predictions are larger than for the data. As already mentioned above, the reason for that is that for the first case, the errors are obtained from the dispersion over the 20 simulated stripes, while the errors in the second case take into account the fact that there are 11 stripes in the DR1 survey, hence corresponding to errors $\sim\sqrt{10} \sim 3$ times smaller. Note that some data points are not shown from the model at large and small scales. Points were removed when the associated error bars became too large.

As for the two-point angular correlation, model results in the two faintest magnitude bins are strongly affected by incompleteness. This again leads to an overestimate of the S_n coefficients, increasing with apparent magnitude. Similarly, large scales are affected by finite volume effects. The poor agreement between the models and the observations at large scales, even on the upper panels of Fig. 6 can thus certainly be blamed on finite volume/edge effects as mentioned earlier. It remains quite acceptable given the error bars. The fact that cumulants from the three different positioning schemes converge only at rather large-scales – larger than for the two-point correlation function – is just because these quantities are cell averages, that is, integrated from 0 to θ . At brighter magnitudes ($r < 20$), the model’s predictions are robust, as discussed for the ACF. Fig. 6 then tells us the following.

(i) The FOF and SUB schemes show a similar good agreement with observations and are almost indistinguishable from each other given the level of uncertainty on the measurements. In principle, one might expect significant differences between FOF and SUB at small scales, as found for the two-point correlation function, but the effect seems to be of the same order of magnitude on $\langle \delta^N \rangle_c$ and $\langle \delta^2 \rangle^{N-1}$ and thus disappears in the normalization.

(ii) We recover in the two upper panels of Fig. 6 the fact found in the previous section, that the PPI scheme leads to an expected strong underestimate of the observed S_n coefficients. The effect is the strongest at small scales, while PPI converges to FOF and SUB at large-scales, when data points are available.

(iii) Finally, the agreement of GALICS with the DR1 estimates is quite a success, provided that modelled galaxies are distributed as substructures or DM within haloes.

5 CONCLUSIONS

In this paper, we have used a novel technique for constructing mock SDSS-like observations from the predictions of a hybrid model of galaxy formation (Hatton et al. 2003; Blaizot et al. 2005). Although mock observations have been made in the past from hybrid models of galaxy formation (e.g. Diaferio et al. 1999; Mathis et al. 2002), we emphasize that our method is general and can readily be used to reproduce *any* type of extra-galactic survey. We have used these mock observations to carry out a detailed comparison of the clustering properties of galaxies observed in the SDSS to those predicted by a state-of-the-art implementation of the hierarchical galaxy

formation scenario. We have carefully investigated the limitations of our model, which are mostly due to mass resolution and finite volume of the DM simulation. Mass resolution directly translates into incompleteness at faint apparent magnitudes, such that the selected galaxies inhabit haloes biased towards high masses. This in turn leads to an increasing overestimate of the clustering statistics faintwards. Our predictions are robust, though, at magnitudes brighter than $r \sim 20$. The finite volume of the simulation introduces a negative bias in clustering statistics at large scales, well known as the ‘integral constrain’ problem. We have shown in Blaizot et al. (2005), how this affects angular correlation function estimates from mock catalogues, and can thus safely define a safe validity scale range for our predictions, which typically extends up to a tenth of the apparent size of the simulated volume at the median redshift of the selected sample. Within the rather restricted domain where the model predictions are valid, we find a good agreement with the observed angular two-point correlation function.

At small scales – typically $< 1 h^{-1}$ Mpc – our standard PPI positioning scheme is found to underestimate the two-point correlation function. This can be explained by the fact that this modelling of galaxy positions within haloes yields too diluted a distribution of galaxies within groups and clusters. We thus investigated the impact of changing the spatial distribution of galaxies within haloes on the ACF and found that observations can be explained if galaxies have a distribution somewhere between that of DM particles and DM substructures, as suggested by the early results of Kauffmann et al. (1999a).

Moving to higher order statistics, we can robustly rule out the PPI scheme. The uncertainty on the measurements does not allow to discriminate between the FOF and SUB schemes. This work shows that modelling the distribution of galaxies within massive haloes is a difficult task. In particular, the instantaneous view of the DM distribution is not enough (yet) to populate haloes, because (i) the positions of galaxies are the result of an evolutionary process and (ii) the substructures that harbour them dissolve if prohibitively high resolution is not used. A straightforward biasing scheme based either on DM particles or on DM substructures is thus, as already found in the literature, a poor proxy for positioning galaxies, and we show that it leads to an overestimate (respectively, an underestimate) of the clustering signal at small separations. Existing attempts to follow the dynamics of galaxies within DM-only simulations still suffer from resolution effects (Springel et al. 2001). As a result, most galaxies in the core regions of massive haloes are attached to particles (once most-bound) rather than substructures. This makes it necessary for HOD models to incorporate in some way the evolution of the subhaloes, for example, by keeping track of once most-bound particles, just like in SAMs.

Most of the limitations of this work are due to the rather small range where our model’s predictions are robust, which is in turn mainly due to the properties of the DM simulation we use. Namely, mass resolution and finite volume effects do not allow us to make full use of the wealth of data obtained by the SDSS. One obvious way to improve the situation is to use bigger simulations. In this prospect, the so-called ‘millennium simulation’ from the Virgo consortium⁴ will undoubtedly help us progress on the interpretation of the clustering properties of galaxies in the nearby Universe. The mass resolution of this simulation is about 10 times better than that of the simulation used in this work. This should allow us to make better use of the observations in the apparent-magnitude range

$20 < r < 22$. And the volume of the millennium simulation is 125 times larger, which should allow (i) better estimates of cosmic variance, and (ii) robust characterization of the large-scale distribution of galaxies (alleviating finite volume effects). The sheer statistics from this simulation should also allow us to carry out a more subtle study of the dependence of galaxy clustering on various galaxy properties (e.g. luminosities, colours, age, morphological types, etc.), thereby allowing to set constraints on the baryonic physics of galaxy formation.

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⁴ <http://www.virgo.dur.ac.uk/>

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APPENDIX A: SUBSTRUCTURES

A1 Identification

We identified substructures in our DM simulation using the ADAPATHOP code (Aubert et al. 2004, appendix B.), which is an extension of the HOP halo finder (Eisenstein & Hut 1998). This algorithm exploits basic principles of the Morse theory to extract a tree of structures (the haloes) and substructures from a distribution of DM particles. It proceeds in four steps, which are the following.

(i) One needs to estimate the local density associated to each DM particle using the SPH interpolation over N_{SPH} neighbours. Here, we take $N_{\text{SPH}} = 20$ in order to match the FOF halo population, as explained below. During this process, one should store the N_{HOP} nearest neighbours for later use. In this paper, we take $N_{\text{HOP}} = 16$ as advocated by Eisenstein & Hut (1998).

(ii) One locates the ‘leaves’ of the tree, that is, the most elementary substructures, by associating groups of particles to local SPH density maxima. This step is performed by a walk from particle to particle, the next particle being the one with the maximum SPH density among the particle itself and its N_{HOP} neighbours.

(iii) One can then establish the connectivity between these ‘peak-patches’ by locating saddle points at the boundaries of the above regions.

(iv) Finally, one builds the tree of structures and substructures as a function of density threshold using the saddle points to determine if two substructures are connected or not.

Note that we use a criterion relying on local Poisson noise in order to assess a substructure’s statistical significance: basically, a structure of density ρ and with N particles must be at a 4σ level compared to local background, ρ_b , to be significant: $\rho > \rho_b \times (1 + 4/\sqrt{N})$.

A2 Cross-match with FOF groups

Our FOF haloes being identified with a linking-length parameter $b = 0.2$, we identify haloes with ADAPATHOP as connected regions of SPH density larger than $\rho_{\text{th}} = 81$ (e.g. Eisenstein & Hut 1998). An additional fine-tuning of the match between FOF and ADAPATHOP halo populations requires using $N_{\text{SPH}} = 20$, in agreement with the minimum number of particles allowed in FOF haloes. Still, the haloes produced by ADAPATHOP are unfortunately slightly different from the FOF ones. We thus associate ADAPATHOP substructures to FOF haloes according to one simple rule: a substructure is associated to the FOF halo which contains most of its particles. This prescription has the advantage to avoid mis-identifications, especially in rich environments, nearby massive groups or clusters.

Also, because of mass resolution, nothing guarantees a priori that we detect enough substructures to fit in all galaxies detectable by the SDSS. We address this issue in Fig. A1 for galaxies with $18 < r < 19$ (left-hand-side plot) and $19 < r < 20$ (right-hand-side panel). The solid lines show the fraction of haloes containing more detected galaxies than substructures in one of our mock catalogues. Only haloes actually containing at least one galaxy were considered for the normalization of this fraction. The upright-hatched region shows the redshift distribution of haloes containing at least one detected galaxy. Considering this region and the solid curve, one sees that about 1 per cent of the haloes do not contain enough substructures in both magnitude ranges. The dashed line shows the fraction of

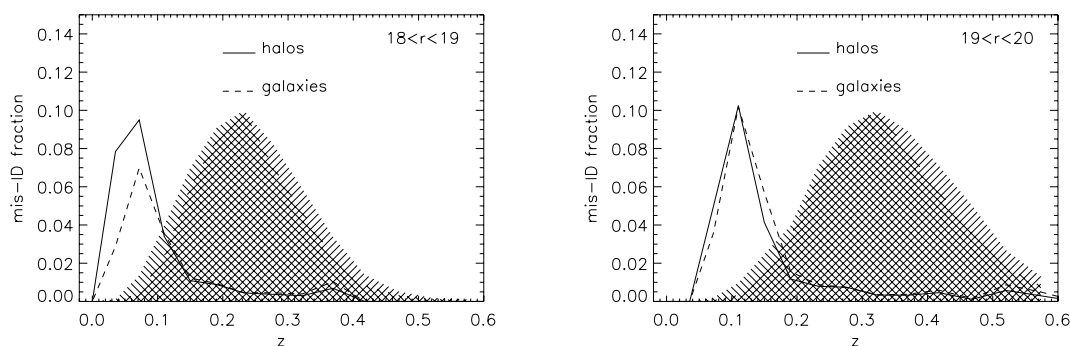


Figure A1. Dashed lines show the fraction of selected galaxies which are not associated with a substructure. Solid lines show the fraction of haloes containing more detected galaxies than substructures. The hatched area shows the arbitrarily scaled redshift distribution of galaxies (downright hatches) and haloes (upright hatches) in the catalogue. Less than 1 per cent of galaxies are not associated with substructures in our catalogues, at $r < 20$. NB: in the right-hand-side panel, the truncation of the redshift distributions is only an artefact of the plotting routine.

galaxies which are not associated to substructures in the same mock catalogue, that is, the fraction of galaxies that we have to distribute on random halo particles. The redshift distribution of galaxies in the same catalogue is shown with an arbitrary normalization with the downright hatches. Again, about 1 per cent of detected galaxies only are not associated with substructures. These two plots show

that the level of contamination of the SUB scheme by particles is at the ~ 1 per cent level at most. In other words, the clustering signal obtained with the SUB scheme does indeed come from substructures.

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