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N-body simulations, the halo model, and the distribution of galaxy clusters in Sunyaev-Zeldovich effect surveys

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Abstract. N-body simulations of the formation of the large-scale structure in the Universe have been used to both design and test the halo model, an analytic model which describes the spatial and velocity distribution of galaxies and dark matter halos. Here, we use the halo model to (1) describe the correlation function of galaxies, selected from simulated catalogues, and (2) predict the angular correlation function of galaxy clusters identified in upcoming Sunyaev-Zeldovich (SZ) effect surveys. These are two examples where large N-body simulations have provided crucial ingredients to make the halo model a powerful tool for cosmology.

Key words. galaxy: clusters: general – cosmology: miscellaneous – large-structure of Universe

1. Introduction

In hierarchical clustering scenarios of structure formation, gravitational instability makes the mass aggregate in clumps from small to large scales. At any time, one can therefore think that all the matter in the Universe is in halos of different size and mass. This *halo model*, first suggested by Neyman & Scott (1952) for galaxies alone, has recently been shown to be successful at describing the clustering properties of both dark matter and galaxies in N-body simulations of large scale structure formation (see Cooray & Sheth 2002 for a review). N-body simulations have, on turn, provided important ingredients, which are difficult to model other than phenomenologically, to the halo model. The halo model has thus become a robust framework for interpreting and predicting the large scale distribution of matter in the universe. The halo model is an example of how fruitful the interplay between numerical experiments and analytic description of non-linear physical processes can be. Here, we briefly describe the halo model and its application to the correlation function of galaxies. We then use the model to predict the angular correlation function of clusters in future Sunyaev & Zeldovich (1980) effect surveys.

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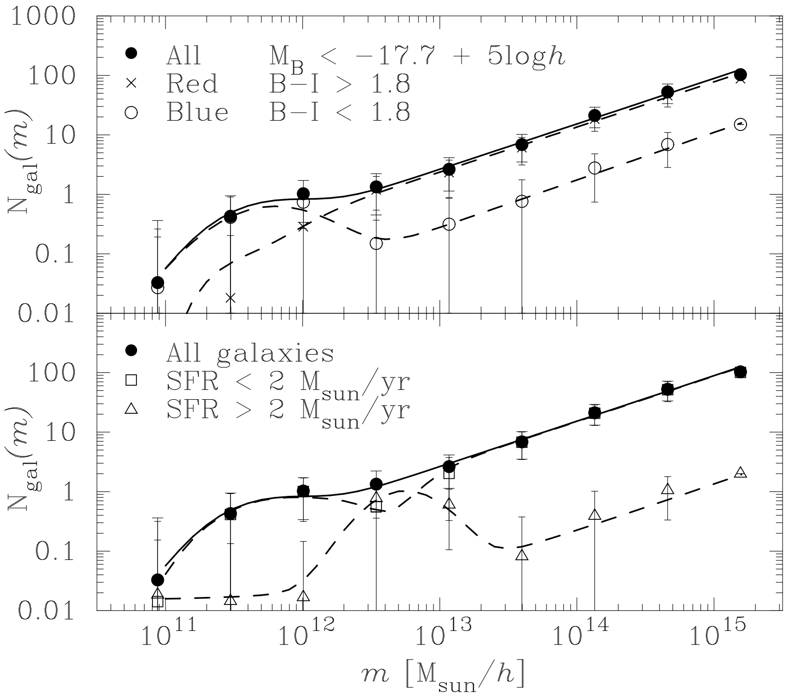

Fig. 1. Mean number of bright galaxies as a function of parent halo mass in the ΛCDM GIF semi-analytic galaxy formation model of Kauffmann et al. (1999). The top panel shows the result of dividing the sample into two based on colour. The bottom panel shows a division based on star formation rate. Crosses, circles, squares and triangles are for objects classified as being red, blue, quiescent and star-forming galaxies respectively.

2. The correlation function of galaxies

The halo model contains two basic ingredients: the galaxy halo occupation distribution, and the halo biasing relation.

Assume that the matter in the universe is made up of dark matter particles and these particles are arranged in clumps of different mass and size. Each clump contains a number of galaxies of different luminosity, color, star formation rate (SFR), and so on. In order to describe the clustering properties of galaxies we need to know how many galaxies each halo of mass M hosts on average, and how large the scatter around this mean is. To model the first and the second moment of this distribution, we used N-body simulations where galaxies were formed and evolved with a semi-analytic procedure (Kauffmann et al. 1999). Figure 1 shows that the mean number of galaxies is roughly proportional to the halo mass M

$$\langle N_{\rm gal}|M\rangle \propto M^{\alpha}, \quad 0 < \alpha < 1 \tag{1}$$

and the scatter $\langle N_{\rm gal}(N_{\rm gal}-1)|M\rangle$ can be expressed as a function of the first moment $\langle N_{\rm gal}\rangle$ (Sheth et al. 2001). Equation (1) is actually more complicated and depends on

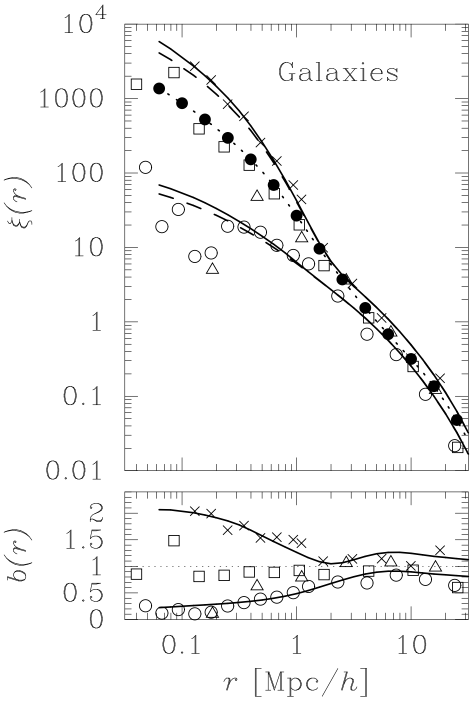

Fig. 2. Correlation functions of different tracers of the dark matter density field in the ΛCDM GIF semi-analytic galaxy formation model. Filled circles are for the dark matter, crosses are for red galaxies, squares for galaxies which have low star formation rates, triangles for galaxies with high star formation rates, and open circles for blue galaxies. The two solid curves show our model predictions for the red and blue galaxies, and the dashed curves show what happens if we use the second factorial moment of the galaxy counts, rather than the second moment when making our model prediction (see Sheth et al. 2001 for details). For comparison, the dotted curve shows the predicted dark matter correlation function.

the selection criteria of the galaxy population.

Let the correlation function $\xi_g(r)$ describe the probability of finding two galaxies at separation r in excess to the Poissonian probability. $\xi_g(r)$ is the sum of two terms: the contribution from pairs whose members are in the same halo and the contribution from pairs whose members are in different halos. The first term depends on $\langle N_{\rm gal}(N_{\rm gal}-1)\rangle$; the second term depends on $\langle N_{\rm gal}\rangle$. Moreover, the first term can be derived by knowing the density profiles of dark matter halos (Navarro, Frenk & White 1997). For the second term, we need a model for the correlation function of halos. This can be written in terms of the correlation function of dark matter particles, $\xi_m(r)$, and a biasing relation $b(M)$:

$$\xi(r, M_1, M_2) = b(M_1)b(M_2)\xi_m(r) \tag{2}$$

where M_1 and M_2 are the masses of the two halos. A quantity which is more convenient to measure, both in the N-body simulations and observationally, is the correlation function of halos with mass larger than a given mass threshold $M_{\rm th}$. Sheth & Tormen (1999) provide an analytic expression for a scale-independent biasing relation $b_{\rm ST}(M)$, which yields the effective bias

$$b_{\rm ST,eff}(M_{\rm th}) = \left[\int_{M_{\rm th}}^{\infty} \frac{dn}{dM} dM\right]^{-1} \times \\ \times \left[\int_{M_{\rm th}}^{\infty} b_{\rm ST}(M)\frac{dn}{dM}dM\right] \qquad (3)$$

where $dn(M,z)/dM$ is the halo mass funtion.

By combining all these ingredients we obtain the correlation functions shown in figure 2 for different observable properties of the galaxies. The model is in excellent agreement with the data from the N-body simulations. We emphasize that the N-body calibration shown in figure 1 has been crucial for making such an agreement quantitatively valid.

3. Angular correlation function of clusters

Upcoming space mission and ground based interferometers will observe the sky at different wavebands between $\sim$ 10 GHz and $\sim$ 400 GHz, with the aim of detecting clusters. In these experiments, clusters are identified thanks to the effect that free electrons in the intracluster plasma produce on the surface brightness of the cosmic microwave background (CMB) (Sunyaev & Zeldovich 1980). This SZ effect has the advantage of being independent of the cluster distance; therefore, a flux limited cluster survey is basically a mass limited survey. These catalogues will be a gold mine for constraining the cosmological model, the gravitational instability paradigm, and the model of cluster formation.

Clusters will be not randomly distributed on the sky: their angular correlation function $w(\theta)$ mirrors the clustering evolution of mass. Here, we use the halo model to predict $w(\theta)$.

Following the classical argument that leads to Limber's equation, one finds that

$$w(\theta) \propto \int_0^{\infty} n(z_1) dV_1 \times \\ \times \int_0^{\infty} n(z_2) b_{\rm eff}(z_1) b_{\rm eff}(z_2)\xi_m(r) dV_2 \qquad (4)$$

where dV is the infinitesimal comoving volume, $n(z)$ is the cumulative halo mass function and $b_{\rm eff}(z)$ is the effective biasing relation.

Equation (4) can be compared with mock observations from the lightcone outputs of the 1-billion particle simulations of the Hubble volume (Evrard et al. 2002; Yoshida et al. 2001). The agreement between the model and the simulations (figure 3) is obtained by introducing a scale dependent biasing relation

$$b(r,z) = b_{\rm ST,eff}(z) \times \\ \times [1 + b_{\rm ST,eff}(z)\sigma(r,z)]^{0.35}\ , \qquad (5)$$

where $\sigma(r,z)$ is the mass variance smoothed over the top-hat radius r at redshift z. Note that equation (5) is fully phenomenological, and we could calibrate it only with the large Hubble volume simulations. $w(\theta)$ is quite sensitive to the scale and time dependence of $b(r,z)$ (Diaferio et al. 2002). So, in principle, one can use the simple measurement of the angular correlation function to constrain $b(r,z)$.

4. Conclusion

Cosmic structure forms by gravitational growth of tiny density perturbations set by quantum fluctuations in the early universe. This model predicts both the formation and the evolution rate of galaxies and clusters and their spatial and velocity distribution. The observation of the CMB power spectrum on small scales will be able to set the fundamental parameters of the cosmological model. To fully constrain the gravitational instability paradigm, one needs to measure other quantities. For example, one

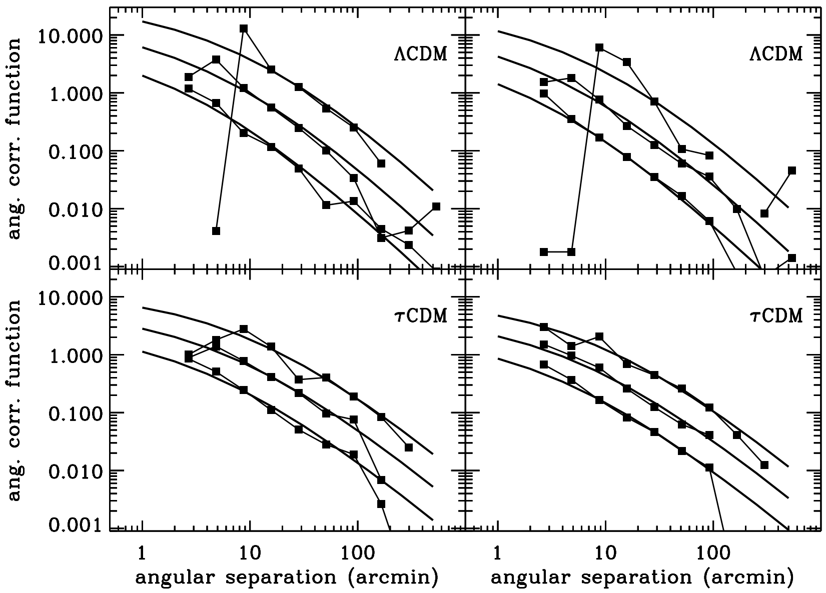

Fig. 3. Angular correlation function of SZ clusters with flux limit $F_\nu^{\rm min} = 200, 50, 10$ mJy (top to bottom) for $\nu = 143$ GHz (left panels) and $\nu = 353$ GHz (right panels). Bold lines are the expected angular correlation function (equation 4); filled squares are the correlation function from the Hubble volume lightcones.

can use the halo model to show that the angular correlation function of clusters in SZ surveys is sensible to the adopted biasing relation between the matter and the cluster spatial distribution (Diaferio et al. 2002). Upcoming catalogues can therefore strongly constrain the halo model and our ideas on how structure formed in the universe.

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