Evolution of Galaxy Clustering

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We show that the galaxy correlation function does not evolve in proportion with the correlation function of the underlying mass distribution. Earliest galaxies cluster very strongly and the amplitude of the galaxy correlation function *decreases* from this large value. This continues till the average peaks have collapsed, after which, the galaxy correlation function does not evolve very strongly.

1   The Halo Grail

We begin by addressing the simpler problem of halo correlation. In later sections we will test the model presented here using N-Body simulations. Lastly, we will comment on applying the results for halo clustering to galaxy clustering and discuss some of its implications.

Consider the distribution of halos of mass M, before typical halos of this mass have collapsed. To quantify this, we first define a *bias* parameter $\nu(M) = \delta_c/\sigma(M)$, where $\sigma(M)$ is the (linearly extrapolated) *rms* dispersion in density at mass scale M and $\delta_c = 1.68$ is the linearly extrapolated density contrast at which halos are expected to virialise. We can write the linear correlation function of these halos, for $\nu \gg 1$ and $\frac{\xi(M,r)}{\xi(M,0)} \ll 1$, as [1]

$$\xi_H(M,r) = \exp\left[\nu^2 \frac{\xi(M,r)}{\xi(M,0)}\right] - 1 \tag{1}$$

Here $\xi(M,r)$ is the correlation function of the density field smoothed at mass scale M, evaluated at scale r and ξ_H is the correlation function of halos. It follows from this expression that the halo correlation function is much larger than the mass correlation function in the range of scales where $\nu^2 \frac{\xi(M,r)}{\xi(M,0)} \gtrsim 1$. The evolution of ξ_H for these scales is controlled by the decreasing function ν. *Therefore, at early times, the amplitude of correlation function of halos is a decreasing function of time.* Eqn.(1) gives only the linearly extrapolated correlation function for halos. However, the qualitative behaviour, being exponentially strong, should survive the non-linear evolution.

At later epochs, when $\nu(M) \approx 1$, eqn.(1) is no longer valid. By this time, most halos of mass M have collapsed. In hierarchical models, these halos merge and give rise to more massive halos. As gravity brings halos closer, the

halo correlation function increases. However, the rate of growth of correlation function will be slow as *anti-biased* halos continue to collapse for some time.

2 Simulations

The ideas outlined above are applicable to all models, we tested these using simulations of the SCDM model. We used a 128^3 PM simulation with box size of $90h^{-1}$Mpc. We normalised the power spectrum to reproduce the present day cluster abundance ($\sigma_8 = 0.6$). Halos were identified with the friends of friends (FOF) algorithm, with a threshold linking length of 0.2 grid lengths.

In principle, we should use halos with mass in a narrow range to study the evolution of halo correlation function. However, two reasons force us to use a different strategy. (1) The FOF algorithm is known to link together dynamically distinct halos. This leads to an incorrect estimate of the halo mass and the number of close pairs of halos. (2) Finite mass resolution in numerical simulations leads to the over merging problem [2] and this makes it difficult to estimate the number of halos that survive inside bigger halos. Both of these lead to an underestimate of the halo correlation function. Therefore, we do not consider halos as being one unit each. We assign a weight, proportional to the mass, to each halo. Operationally, this is equivalent to computing the correlation function of particles contained in these halos. This strategy is also appropriate for studying galaxy correlation function as galaxies are known to survive inside clusters of galaxies. Although we ignore the large range in masses of galaxies by using this particular method, we include a realistic contribution of very massive halos.

We describe the clustering properties using the averaged two point correlation function $\bar{\xi}$, defined as

$$\bar{\xi}(r) = \frac{3}{r^3} \int^r x^2 \xi(x) dx \qquad (2)$$

where ξ is the two point correlation function.

To quantify the differences in evolution of halo distribution and mass distribution, we have plotted the averaged correlation function for these in fig.1. The left panel shows the growth of the mass correlation function and the right panel shows the evolution of the halo correlation function (Minimum halo mass for this simulation is $2 \times 10^{12} M_\odot$). This figure shows that the clustering in mass increases monotonically. In contrast, the amplitude of the halo correlation function is high at early times and decreases rapidly up to $z = 1$. It starts increasing again after $z \simeq 0.5$ which corresponds closely to $\nu(M) \simeq 1$.
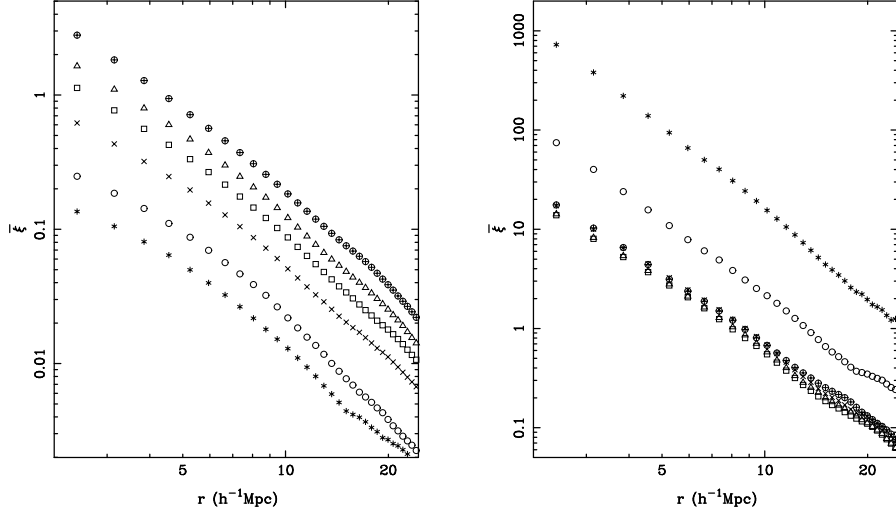
Figure 1: The left panel shows the evolution of clustering in the total mass distribution, $\bar{\xi}$ increases monotonically. Symbols are $*$ ($z = 3$), $\bigcirc$ ($z = 2$), $\times$ ($z = 1$), $\square$ ($z = 0.5$), $\triangle$ ($z = 0.25$) and $\oplus$ ($z = 0$). The halo correlation function, shown in right panel, decreases from its initial high value at $z = 3$, slows down after $z = 1$ and starts increasing after $z = 0.5$.

The halo correlation function varies very little between $z = 1$ and $z = 0$. The value of $\nu(M)$ that corresponds to the minimum amplitude of halo correlation function depends on the local index of the power spectrum[3] and is smaller for negative indices.

3   Discussion

In order to apply the results given above to clustering of galaxies, we must incorporate effects of the mass function of galaxies. The amplitude of halo correlation function starts increasing earlier for low mass halos. As there are many more low mass halos than high mass ones, the epoch at which the amplitude of galaxy correlation function starts increasing will depend on the mass of the smallest galaxies that can be seen at high redshifts[a]. Simulations that combine semi-analytic models of galaxy formation with gravitational clustering can be used to compute galaxy correlation function and for the models where this has been done, the galaxy correlation function follows the same pattern as the halo correlation function.[4] Irrespective of the detailed evolution, we can

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[a]Identifying the *same* population of galaxies at different redshifts is also a problem.

conclude, that at high redshifts, galaxies cluster much more strongly than the underlying mass distribution. Thus, the observed clustering of galaxies at high redshifts [5] is not a strong constraint for most models of structure formation.[6]

Some other implications of strong clustering at high redshifts are: (1) The evolution of galaxy clustering is not a good indicator of cosmological parameters. (2) The shape of the galaxy correlation function is different from the shape of the mass correlation function. Therefore galaxy correlation function is not a very good indicator of the initial power spectrum. (3) Sources responsible for reheating and reionisation of the IGM will have a very non-uniform distribution. This will lead to a patchy structure at early epochs. The scale of patchiness, which may be observable,[7] can be used to constrain galaxy formation scenarios. (4) Formation of many ionising sources in a small region will increase the temperature of the IGM and inhibit collapse of low mass halos in these regions.[8] Therefore, the mass function of galaxies near and away from these ionising centres will be different. (5) If quasars form preferentially in high mass halos then they should show stronger clustering than galaxies. (Recent estimates of quasar correlation function show that it is stronger than the galaxy correlation function.[9,10]) A comparison of the two, and their evolution, can be a useful indicator of the prevalence of AGN activity in galaxies.

Acknowledgements

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