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LOW MASS DARK MATTER HALOS IN VOIDS

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RESUMEN

Utilizando simulaciones numéricas y la aproximación de Sheth-Tormen estudiamos la función de masa de los halos de materia oscura en regiones vacías, Encontramos que la función de masa de las regiones vacías es mucho menor y su forma es distinta de la de los halos del campo. Predecimos que en el modelo estándar LCDM una región vacía con un radio de $10h^{-1}$Mpc debería tener 50 halos con velocidad circular $v_c > 50$ km/s y 600 halos con $v_c > 20$km/s.

ABSTRACT

Using numerical simulations and the Sheth-Tormen approximation we study the mass function of dark matter halos in voids. We find that the void mass function is significantly lower and its shape is different than that of the field halos. We predict that in the standard LCDM model a void with radius $10h^{-1}$Mpc should have 50 halos with circular velocity $v_c > 50$ km/s and 600 halos with $v_c > 20$ km/s.

Key Words: **COSMOLOGY: THEORY — LARGE–SCALE STRUCTURE OF UNIVERSE**

According to the hierarchical structure formation paradigm halos form from small initial density fluctuations by accretion and merging. It is expected that inside the dark matter (DM) halos gas cools and galaxies are formed. Thus, we expect that the distribution of DM halos and their structure are closely related to the observed galaxy distribution. It is also known (e.g., Gottlöber et al. 2001) that the merging history of the DM halos depends on environment. Here we study DM halos in the low density environment of voids.

Cosmological simulations predict many more small DM halos than the observed number of satellites around the Milky Way and Andromeda galaxies. Do we have the same problem for dwarf galaxies in voids? One naively expects a large number because the Press-Schechter mass function steeply rises with declining mass. In contrast, it seems that observations are failing to find a substantial number of dwarf galaxies inside voids (e.g. Popescu et al. 1997). However, the situation is complicated because it is very difficult to detect dwarf galaxies, many of which are expected to have low surface brightness.

We use N-body simulations to make accurate predictions for the expected number of dwarf halos in voids. We have performed a series of high resolution simulations using the ART code (Kravtsov et al. 1997) and the friends-of-friends (FOF) algorithm to identify halos. We investigate a spatially flat cold dark matter model with a cosmological constant (ΛCDM with $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$, and $h = 0.7$). We use a cube of $80h^{-1}$Mpc side length, which is sufficiently large to study the formation of large voids. Because we are interested in the formation of small structure elements inside the voids, we need high mass resolution. Therefore, we perform the simulation in two steps. First, we run a low mass resolution simulation (128^3 particles with mass $m_{\rm part} = 2.0\times10^{10}h^{-1}M_\odot$) and identify 8387 galactic-size halos with masses $> 2.0\times10^{11}h^{-1}M_\odot$. This corresponds to a mean distance of about $4h^{-1}$Mpc between halos. We identify voids in the distribution of the halos. The largest void has a diameter of $24h^{-1}$Mpc. Second, we re-simulate the voids with a formal mass resolution of 1024^3 particles, i.e. $m_{\rm part} = 4.0\times10^7h^{-1}M_\odot$. Thus, we resolve in the voids objects with masses larger than $10^9h^{-1}M_\odot$. By construction, the voids do not have halos with masses larger than $M_{\rm b} = 2.0\times10^{11}h^{-1}M_\odot$.

We re-simulate five voids with radii $R_{\rm void} = 11.6, 10.8, 9.4, 9.1, 9.1\,h^{-1}$Mpc. The underdensity at the centers of these voids is 0.1 – 0.2 of the mean matter density $\Omega_{\rm M}$. In Fig. 1 we compare the mass function of DM halos in voids with the mass function in the whole box. The thin solid line is the analytical prediction based on the Sheth and Tormen (1999) correction to the Press-Schechter mass function

$$n_{\rm ST}(M) = -\left(\frac{2}{\pi}\right)^{1/2} A\left[1+\left(\frac{a\delta_{\rm c}^2}{\sigma^2}\right)^{-p}\right] a^{1/2}\frac{\varrho_{\rm b}}{M} \times \frac{\delta_{\rm c}}{\sigma^2}\frac{{\rm d}\sigma}{{\rm d}M}\exp\left(-\frac{a\delta_{\rm c}^2}{2\sigma^2}\right), \qquad (1)$$

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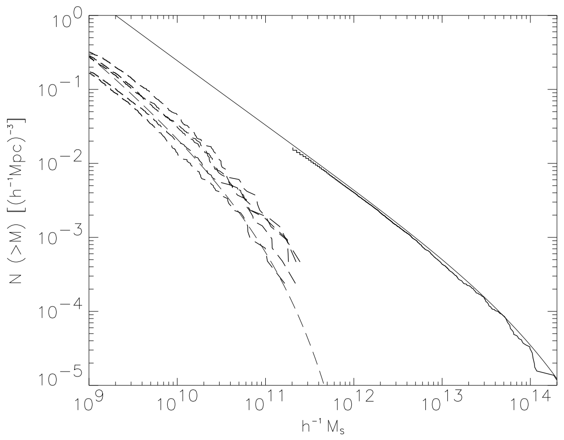

Fig. 1. Mass function of DM halos. The thick full line shows the cumulative mass function $N(>M)$ in the whole $80h^{-1}$Mpc simulation. The thin full curve is the Sheth-Tormen approximation. The mass functions in voids are shown by thick dashed curves. The thin dashed curve is our Sheth-Tormen-type prediction of the void mass function. The mass functions of the voids are different because of the difference in the void underdensity. Note that the normalization *and the shape* of the void functions are different from that of the field population.

where $A = 0.322$, $p = 0.3$, $a = 0.707$, $\varrho_{\rm b}$ is the background density, σ is the rms density fluctuation on scale R corresponding to mass M ($M = 4\pi\varrho_{\rm b}R^3/3$) and $\delta_{\rm c} = 1.676$ for our model. As expected, within the whole mass range covered by the numerical mass function it agrees well with the analytical prediction. Small deviations at $M > 10^{14}h^{-1}M_\odot$ are due to low number of massive objects.

The simulated voids have somewhat different mean (under)densities. This results in different mass functions. The number-density of halos in voids is about an order of magnitude smaller than in the whole box as expected due to lower mean density in voids. However, the shape of the mass function is also different. An analytic approximation to mass function in voids, shown as a thin dashed line in Fig. 1, was obtained by applying the formalism of Sheth and Tormen (2002) for the constrained mass functions

$$\begin{aligned} n_{\rm c,ST}(M) &= -\left(\frac{2}{\pi}\right)^{1/2} \frac{\varrho_{\rm void}}{M} \frac{|T(\sigma^2|\sigma_0^2)|}{(\sigma^2-\sigma_0^2)^{3/2}} \frac{\sigma {\rm d}\sigma}{{\rm d}M} \\ &\times \ \exp\left[-\frac{[B(\sigma^2)-B(\sigma_0^2)]^2}{2(\sigma^2-\sigma_0^2)}\right], \qquad (2) \end{aligned}$$

where

$$T(\sigma^2|\sigma_0^2) = \sum_{n=0}^{5} \frac{(\sigma_0^2-\sigma^2)^n}{n!} \frac{\partial^n[B(\sigma^2)-B(\sigma_0^2)]}{\partial(\sigma^2)^n},$$

and

$$\begin{aligned} B(\sigma^2) &= a^{1/2}\delta_c[1+\beta(a\delta_c^2/\sigma^2)^{-\alpha}], \\ B(\sigma_0^2) &= a^{1/2}\delta_0[1+\beta(a\delta_0^2/\sigma_0^2)^{-\alpha}]. \end{aligned}$$

The parameter δ_0 is the linear underdensity of the void corresponding to the actual nonlinear underdensity δ and is calculated from the spherical top-hat model, while σ_0 is the rms fluctuation at scale $R_0 = (1+\delta)^{1/3}R_{\rm void}$. The parameters $\alpha = 0.615$, $\beta = 0.485$ come from the ellipsoidal dynamics and we have chosen $a = 0.5$ which fits the simulated mass functions better than the value of $a = 0.707$ advertised by Sheth and Tormen. The result shown in Fig. 1 was obtained for $\Omega_{\rm void} = 0.04$ and $R_{\rm void} = 10h^{-1}$Mpc. In an upcoming paper (Gottlöber et al. 2002, in preparation) we discuss the spatial distribution of halos found in numerical simulations of voids and their mass function, and we present a straightforward analytical method to predict the mass function.

In a typical void of radius $10h^{-1}$Mpc we found about 600 halos with circular velocities larger than 20 km/s and about 50 halos with circular velocities larger than 50 km/s. Testing these predictions could be one of the interesting observational tasks of the ongoing SLOAN Digital Sky Survey.

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