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TESTING DM MODELS AGAINST THE CLUSTER DISTRIBUTION

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Abstract

We study the clustering properties of numerical simulations of the cluster distribution, which are based on the Zel'dovich approximation, and compare them with an extended redshift sample of Abell/ACO clusters. A detailed comparison of such simulations with "exact" N–body simulations is also discussed. Within the list of the simulated dark matter (DM) models, we find that only that based on a mixture of Cold+Hot DM (with $\Omega_{hot} = 0.3$) and a low–density ($\Omega_o = 0.2$) CDM model with a cosmological constant term ($\Omega_\Lambda = 0.8$) provide a good fit to the data. The standard CDM, the tilted CDM ($n = 0.7$) and a low Hubble constant ($h = 0.3$) CDM models are ruled out.

1 Introduction

The observed strong clustering of clusters makes them potentially powerful probes of the large–scale structure of the Universe, because their clustering can be detected with high statistical significance on scales where density fluctuations are still in the linear (or quasi–linear) regime. For this reason, the cluster distribution is expected to give hints about the nature of primordial fluctuations. The usual technique to investigate the cosmological consequences of the cluster clustering involves N–body numerical simulations, which are however computationally expensive. On the other hand, the wide variety of proposed dark matter (DM) models calls for a flexible analysis technique, which would allow to easily go through the DM parameter space. Moreover, in order to assess correctly the statistical significance of the results obtained, one should ideally perform a large ensemble of simulations and look at the variation of statistical

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measures across the ensemble. We present results based on an alternative method for simulating cluster samples in cosmological scenarios which is based on the Zel'dovich approximation [1] (hereafter ZA). The ZA, if used appropriately, reproduces the spatial distribution of matter found in fully dynamical N–body simulations at a fraction of the computational cost. We are therefore able to present a study of a large ensemble of realizations of cluster distributions from various cosmological scenarios with realistic estimation of the cosmic variance[2, 3].

2 The simulations

Let $x(t)$ be the comoving position of a particle. In the ZA, the solution to the equations of motion for the fluid particles can be written as the mapping of Eulerian–to–Lagrangian coordinates

$$x(q,t) = q + b(t)\,\nabla\psi(q)\,, \tag{1}$$

where q and x are the initial (Lagrangian) and the final (Eulerian) particle positions respectively, $b(t)$ is the growing mode for the linear evolution of density fluctuations and $\psi(q)$ describes the gravitational potential, which is related to the density fluctuation field by Poisson's equation. According to eq.(1), particles do not feel any gravitational field and, although they are correctly moved by gravity at the beginning, they are not held within the minima of the potential field at later times. A detailed study of how to optimize best the ZA [4] suggests that one should filter the initial power–spectrum with a Gaussian k–space filter with a cut-off of the form $W(k) = e^{-k^2/2k_G^2}$. The optimal value for k_G depends upon the form of $P(k)$. We have chosen k_G so as to fix the average number of streams at each Eulerian point [5] at the value $N_s = 1.1$. We generate a random–phase realization of the smoothed fluctuation spectrum and the corresponding potential $\psi(q)$, appropriate to the model in question, on a 128^3 grid within a box of size $L = 320\,h^{-1}$ Mpc. A particle is putted on each grid point and is shifted according to Eq.(1). Then, we reconstruct the density field on the grid and identify all the local density maxima as cluster candidates. If d_{cl} is the mean cluster separation, the expected number of clusters is $N_{cl} = (L/d_{cl})^3$. Clusters are identified as the N_{cl} highest grid peaks.

We present ZA simulations for six different dark matter models: (1) Standard CDM model (SCDM) with $\sigma_8 = 1$; (2) Tilted CDM (TCDM), with primordial spectral index $n = 0.7$ and $\sigma_8 = 0.5$; (4) A cold–plus–hot DM model (CHDM), with 30% HDM and $\sigma_8 = 0.67$; (5–6) Two low–density, flat CDM models with $\Omega_o = 0.2$, $\Omega_\Lambda = 0.8$, one with a low normalization, $\sigma_8 = 0.8$ (ΛCDM$_1$), and one with $\sigma_8 = 1.3$ (COBE–consistent, ΛCDM$_2$). For each model we generated an ensemble of 50 different random realizations.

In order to test the reliability of the ZA cluster simulations, we run a CHDM PM N–body simulation and compared it with the output of a ZA simulation, having the same initial phases. In Figure 1 we compare the cluster positions in the two simulations at two different epoques, $\sigma_8 = 0.67$ and $\sigma_8 = 1$. It turns out that, while the ZA approach accurately reproduces the "true" cluster positions at the less evolved stage, it is less reliable at the more evolved configuration. This is due to the fact that, as fluctuations depart from linear evolution on the cluster mass scale (i.e., $\sigma_8 \gtrsim 1$), the ZA is not longer efficient at determining the individual cluster positions. Therefore, we expect that our simulation approach will be less reliable for the ΛCDM$_2$ model, while it is adequate for the other models. In any case, these results disprove recent claims for a general inadequacy of the ZA for cluster simulations [6].

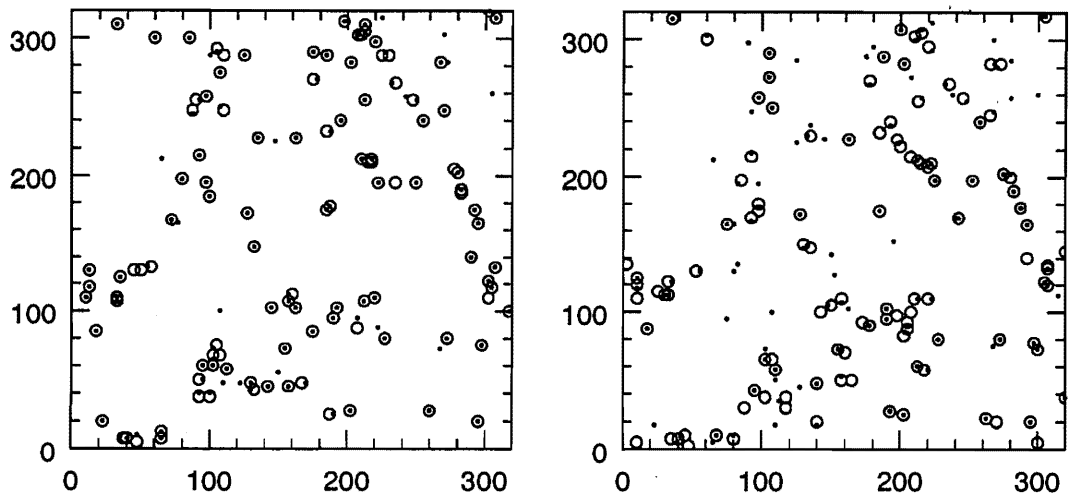

Figure 1: Comparison between ZA and PM cluster simulations, at $\sigma_8 = 0.67$ (left panel) and $\sigma_8 = 1$ (right panel). Open circles are the ZA cluster positions and filled dots give the PM cluster positions.

3 Results

As a test of the clustering developed by the simulated cluster distribution, we analyzed the statistics of the density field traced by clusters. A continuous cluster density field is obtained by smoothing the cluster distribution on a grid with grid–cell width of 20 h^{-1} Mpc with a Gaussian kernel of radius R_g. If $\delta(x_g, R_{sm})$ is the smoothed cluster density fluctuation at the grid-cell position x_g, then its second– and third–order moments,

$$\sigma^2(R_g) = N_{gr}^{-1} \sum_{g=1}^{N_{gr}} [\delta(x_g, R_{sm})]^2 \quad ; \quad \gamma(R_g) = N_{gr}^{-1} \sum_{g=1}^{N_{gr}} [\delta(x_g, R_{sm})]^3 , \qquad (2)$$

($N_{gr} = (16)^3$ is the total number of grid points) are the variance and the skewness, respectively. In Figure 2 we plot the relation between σ^2 and γ for each realization of the six considered models, at two different smoothing scales, $R_g = 20\,h^{-1}$ Mpc and $R_g = 30\,h^{-1}$ Mpc. The crosses are the results of the same analysis on a sample of Abell and ACO clusters [7]. At $R_g = 20\,h^{-1}$ Mpc the models which perform better are CHDM and ΛCDM$_1$, while almost no realizations of the other four models are consistent with the observational result. At $R_g = 30\,h^{-1}$ Mpc the increase of the cosmic variance makes SCDM, LOWH and TCDM marginally consistent, while the excess clustering of ΛCDM$_2$ generates too large σ^2 and γ values. Note, however, that for this model we expect the ZA to be in trouble in describing the cluster distribution. Following indication from N–body simulations that cluster correlations are almost independent of σ_8 [3, 6], one would instead conclude that the ΛCDM model substantially agrees with the observed cluster correlation.

As a general conclusion, the ZA approximation is shown to give an excellent representation of the cluster clustering at a very low computational cost. Therefore, it represents a very useful instrument to investigate in detail the parameter space of DM models.

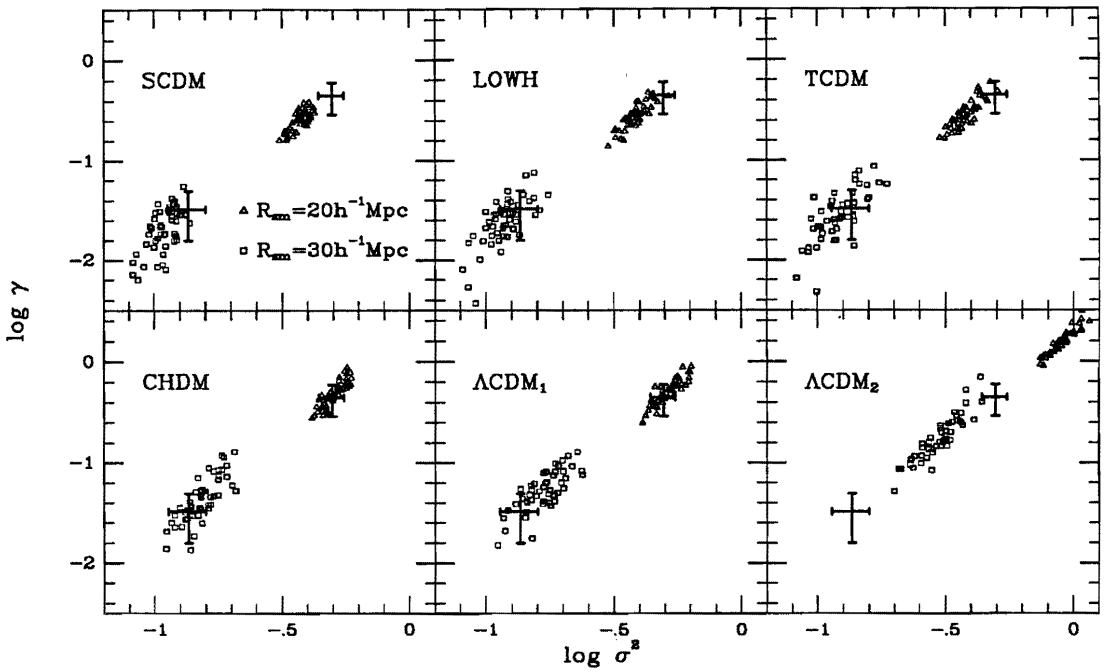

Figure 2: Variance–skewness relation for the six models at two smoothing scales, R_{sm}, as compared to observational results based on the Abell–ACO cluster sample [7].

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