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LARGE COSMOLOGICAL N-BODY SIMUALTIONS AND CLUSTERING OF DARK MATTER HALOS

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1. Introduction

Galaxy formation is one of the most important and most challenging problems in astrophysics. In the standard theories of galaxy formation, it is generally believed that the Universe is dominated by dark matters (DM), the early density perturbation generated in the inflationary era is amplified by the gravitational instability, the DM halos form via the collapse of the high density regions, and galaxies are formed from the cooled gas within the DM halos (see, e.g., H. Couchman, Y. Suto, and M. Nonman in these proceedings). Obviously understanding the DM distribution is the first step to a complete understanding of the galaxy formation.

The formation of DM halos or generally the DM distribution on small scales, however, is a strongly non-linear problem. Numerical simulations seem the only way to solve this problem. Although there have been many exciting developments on analytical, semi-analytical or empirical modeling of the DM distribution, these results are generally calibrated with N-body simulations and their validity still depends on the resolution of the simulations used.

In this contribution, I will first describe the N-body simulations carried out at the University of Tokyo. The simulations have similar mass and force resolutions to those the Virgo Consortium (H. Couchman, in these proceedings) has recently obtained (except for their billion-particle simulation for a huge simulation box), but our sample is much larger. These simulations are being used to study many interesting problems of the large-scale structures in the universe. Yasushi Suto (in these proceedings) has already presented our applications of these simulations to the redshift distortion (Magira et al. 1998; in preparation) and to the strong clustering of Lyman Break galaxies at high redshift (Jing & Suto 1998). Here I will present a further interesting application, the bias parameter of the DM halos.

2. N-body simulations

The simulations are generated with my vectorized Particle-Particle-Particle-Mesh (P^3M) code on the the supercomputer VPP300/16R at the National Astronomical Observatory of Japan. Each simulation uses 256^3 simulation particles. The code adopts the standard P^3M algorithm (Hockney & Eastwood 1981; Efstathiou et al. 1985). Twenty one simulations

are generated for three representative cold dark matter (CDM) models of galaxy formation, and eighteen for six scale-free cosmologies. The CDM models are specified completely as regards the DM distribution by the density parameter Ω_0, the cosmological constant λ_0, the shape Γ and the normalization σ_8 of the linear power spectrum. The scale-free models assume an Einstein–de Sitter universe (EdS i.e. $\Omega_0 = 1$ and $\lambda_0 = 0$) and a power-law $P(k) \propto k^n$ for the linear density power spectrum. Table 1 summarize the physical and simulation parameters used for these simulations. The CDM models with the chosen physical parameters are known to reproduce many features observed in the real Universe. The simulations of $100\,h^{-1}$Mpc box size have particle mass $m_p \approx 10^{10} M_\odot$ and force resolution $\eta = 13\,h^{-1}$Kpc (Plummer form), and therefore suit for studying galaxy formation, internal structures of DM halos and clustering of DM halos. The simulations with a larger box size ($300\,h^{-1}$Mpc) are useful for studying the cluster formation and clustering on large scales. Every model (with one box size) have 3 to 4 realizations so the cosmic variance could be properly accounted for. The scale-free models are conceptually simple and possess interesting scaling properties. Therefore they are very powerful for understanding clustering of DM, for testing analytical models, for obtaining fitting formulae, and for quantifying the numerical artifacts. Additional 8 simulations with 200^3 particles are generated for lower density models with $\Omega_0 = 0.1$ for power-law spectra $n = -1$ and $n = -2$, in order to examine the effect of cosmologies on the clustering (cf. the $\Omega_0 = 1$ models). In terms of the mass and force resolution and the number of the realizations for each model, this set of simulations stands as one of the best in the world.

With this large set of high-resolution simulations, many interesting cosmological problems can and will be investigated. As an incomplete list, we are 1) studying the DM distribution in the strongly clustering regime; 2) testing the Press-Schechter extension theories; 3) studying redshift distortion effect and investigating its potential to measure the cosmological parameters; 4) analyzing internal structures of DM halos; 5) investigating galaxy formation by hand-inputing gas physics; 6) applying the simulations to real observations. Some of the above projects are the collaborations with the members of Prof. Yasushi Suto's group at the University of Tokyo.

3. The bias parameter of the dark matter halos

The clustering of the DM halos is the basic block for modeling and understanding the clustering of galaxies and of other extragalactic objects. In my recent work (Jing 1998) I have measured the two-point correlation function of the DM halos for the scale free simulations with $n = -0.5$, -1.0, -1.5, and -2.0. The results confirmed with unprecedent accuracy that the bais of the halos b is linear in the linearly clustering regime. For a scale-free model, the bias parameter b is then expected to depend on the scaled mass $M/M_\star$ only, where $M_\star$ is a characteristic non-linear mass, unless numerical artifacts had destroyed this scaling property. In Fig. 1, I present the $b(M/M_\star)$ for different simulation outputs of each model. The excellent scaling exhibited by the simulation data assures that any numerical artifacts have negligible effect on the results of Fig. 1. The simulation results agree with the analytical formula of Mo & White (1996) only for massive halos with $M/M_\star > 1$, but are significantly higher for much less massive halos. The simulation results could be fit very well by

$$b(M) = (\frac{0.5}{\nu^4} + 1)^{(0.06-0.02n)}(1 + \frac{\nu^2 - 1}{\delta_c}); \qquad \nu = (M/M_\star)^{n+3/6} \tag{1}$$

Table 1. List of simulations

Model	N	Ω_0	λ_0	Γ	σ_8	m_p ($h^{-1}M_\odot$)	L (h^{-1}Mpc)	realizations
SCDM100	256^3	1.0	0.0	0.5	0.6	1.7×10^{10}	100	3
OCDM100	256^3	0.3	0.0	0.25	1.0	5.0×10^9	100	3
LCDM100	256^3	0.3	0.7	0.20	1.0	5.0×10^9	100	3
SCDM300	256^3	1.0	0.0	0.5	0.6	4.6×10^{11}	300	4
OCDM300	256^3	0.3	0.0	0.25	1.0	1.3×10^{11}	300	4
LCDM300	256^3	0.3	0.7	0.20	1.0	1.3×10^{11}	300	4
Model	N	Ω_0	λ_0	n				realizations
SF1	256^3	1.0	0.0	1.0				3
SF2	256^3	1.0	0.0	0.0				3
SF3	256^3	1.0	0.0	−0.5				3
SF4	256^3	1.0	0.0	−1.0				3
SF5	256^3	1.0	0.0	−1.5				3
SF6	256^3	1.0	0.0	−2.0				3
SF7	200^3	0.1	0.9	−1.0				2
SF8	200^3	0.1	0.0	−1.0				2
SF9	200^3	0.1	0.9	−2.0				2
SF10	200^3	0.1	0.0	−2.0				2

where $\delta_c = 1.68$. This fitting formula could be equally well applied to the CDM models with only a few simple modifications (Jing 1998). This finding has profound implications for the clustering studies of galaxies. More discussions are given in Jing (1998).

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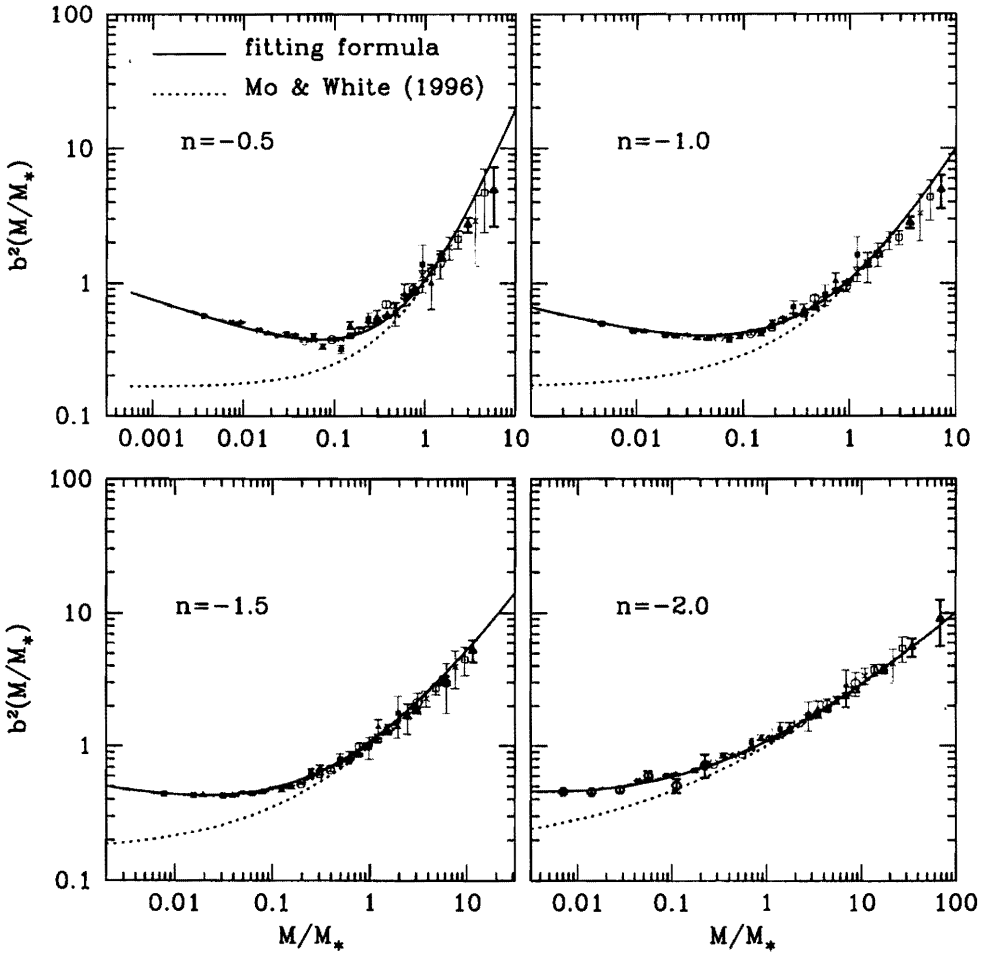

Figure 1. The $b^2(M/M_*)$ for different evolution outputs (different symbols). The dotted lines are the analytical prediction of Mo & White (1996), and the solid lines are my fitting formula Eq. 1 which can accurately fit the simulation results.