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EXPLORING REDSHIFT-SPACE CLUSTERING WITH COSMOLOGICAL N-BODY SIMULATIONS

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1. Introduction

Cosmological N-body simulations have played an important part in describing and understanding the nonlinear gravitational clustering in the universe. In this context, a paper by Miyoshi and Kihara (1975) is truly pioneering, and should be briefly described here. They carried out a series of cosmological N-body experiments with $N = 400$ *galaxies* (particles) in an expanding universe. The simulation was performed in numerical comoving cube with a periodic boundary condition. As the title of the paper "*Development of the correlation of galaxies in an expanding universe*" clearly indicates, they were interested in understanding why observed galaxies in the universe exhibit a characteristic correlation function of $g(r) = (r_0/r)^s$. In fact, Totsuji and Kihara (1969) had already found that $r_0 = 4.7h^{-1}$Mpc and $s = 1.8$ is a reasonable fit to the clustering of galaxies in the Shane – Wirtanen catalogue. One of the main conclusions of Miyoshi and Kihara (1975) is that "*The power-type correlation function $g(r) = (r_0/r)^s$ with $s \approx 2$ is stable in shape; it is generated from motionless galaxies distributed at random and also from a system with weak initial correlation* ".

Several years after Totsuji and Kihara (1969) published the paper, Peebles (1974) and Groth and Peebles (1977) reached the same conclusion, which seems to have motivated several cosmological N-body simulations all over the world (e.g., Aarseth, Gott and Turner 1979; Efstathiou 1979; Doroshkevich et al. 1980). At present, nearly a quarter century later, the cosmological N-body simulations are armed by (i) significant progress in computational methods and resources (e.g., H.P. Couchman, in these proceedings), (ii) physically motivated initial conditions on the basis of inflationary models and the idea of dark matter dominated universe (e.g., Davis et al. 1985), and (iii) reliable statistical measures to quantify the clustering

of the universe at $z \sim 0$. Naturally they have been established as important tools in exploring the nonlinear gravitational evolution of three-dimensional collisionless system in the expanding universe. Nevertheless it is quite remarkable that all the basic ingredients of cosmological N-body simulations were already fully described in the pioneering paper by Miyoshi and Kihara (1975).

A widely accepted point of view in cosmology is that gravitational instability in a cold dark matter dominated universe is a reasonably successful model of the cosmic structure formation at $z \sim 0$. On the basis of this, it is natural to move from understanding of the *current universe* to exploring the evolution and clustering of the universe *at high redshifts*. The present talk focuses on two topics in this line; cosmological redshift distortion (Matsubara and Suto 1996; Nakamura, Matsubara, and Suto 1998; Magira, Jing, Matsubara and Suto 1998) and cosmological implications of the strong clustering of Lyman-break galaxies at $z \sim 3$ (Jing and Suto 1998).

2. Cosmological redshift distortion

The three-dimensional distribution of galaxies in the redshift surveys differ from the true one since the distance to each galaxy cannot be determined by its redshift z only; for $z \ll 1$ the peculiar velocity of galaxies, typically $\sim (100-1000)$km/sec, contaminates the true recession velocity of the Hubble flow, while the true distance for objects at $z < 1$ sensitively depends on the (unknown and thus assumed) cosmological parameters. This hampers the effort to understand the true distribution of large-scale structure of the universe. Nevertheless such redshift-space distortion effects are quite useful since through the detailed theoretical modeling, one can derive the peculiar velocity dispersions of galaxies as a function of separation, and also can infer the cosmological density parameter Ω_0, the dimensionless cosmological constant λ_0, and the spatial biasing factor b of galaxies and/or quasars, for instance. Here we point out the importance of such redshift distortion induced by the geometry of the universe.

Let us consider a pair of objects located at redshifts z_1 and z_2 whose redshift difference $\delta z \equiv z_1 - z_2$ is much less than the mean redshift $z \equiv (z_1 + z_2)/2$. Then the *observable* separations of the pair parallel and perpendicular to the line-of-sight direction, $s_\parallel$ and $s_\perp$, are given as $\delta z/H_0$ and $z\delta\theta/H_0$, respectively, where H_0 is the Hubble constant and $\delta\theta$ denotes the angular separation of the pair on the sky. The cosmological redshift-space distortion originates from the anisotropic mapping between the redshift-space coordinates, $(s_\parallel, s_\perp)$, and the real comoving ones $(x_\parallel, x_\perp) \equiv (c_\parallel s_\parallel, c_\perp s_\perp)$; $c_\perp$ is written as $c_\perp = H_0(1+z)D_A/z$ in terms of the angular diam-

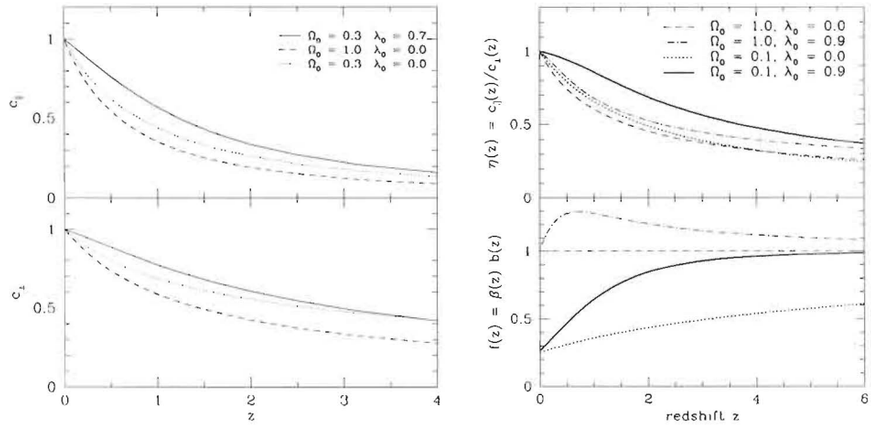

Figure 1. *Left:* Behavior of $c_\parallel(z)$ and $c_\perp(z)$ for $(\Omega_0,\ \lambda_0) = (0.3,0.7)$ in *solid line*, (1.0,0.0) in *dashed line*, and (0.3,0.0) in *dotted line*. *Right:* $\eta(z) = c_\parallel(z)/c_\perp(z)$ (*upper panel*), and $f(z) = \beta(z)b(z)$ (*lower panel*) for $(\Omega_0,\ \lambda_0) = (1.0,0.0)$ in *dashed line*, (1.0,0.9) in *dot-dashed line*, (0.1,0.9) in *dotted line*, and (1.0,0.9) in *thick solid line*.

eter distance D_A, and

$$c_\parallel(z) = \frac{H_0}{H(z)} = \frac{1}{\sqrt{\Omega_0(1+z)^3 + (1-\Omega_0-\lambda_0)(1+z)^2 + \lambda_0}}. \qquad (1)$$

Thus their ratio becomes

$$\frac{x_\parallel(z)}{x_\perp(z)} = \frac{c_\parallel(z)}{c_\perp(z)}\frac{\delta z}{z\delta\theta} \equiv \eta(z)\frac{\delta z}{z\delta\theta}. \qquad (2)$$

Since $x_\parallel/x_\perp$ should approach $\delta z/(z\delta\theta)$ for $z \ll 1$, $c_\parallel(z)/c_\perp(z)$ can be regarded to represent the correction factor for the *cosmological redshift distortion* (upper panel of Fig.1). This was first pointed out in an explicit form by Alcock and Paczyński (1979). Although $\eta(z)$ is a potentially sensitive probe of Ω_0 and especially λ_0, this is not directly observable unless one has an independent estimate of the ratio $x_\parallel/x_\perp$. Here, we propose to use the clustering of quasars and galaxies in z, which should be safely assumed to be statistically isotropic, in estimating $\eta(z)$. Also we take account of the distortion due to the peculiar velocity field using linear theory.

The relation between the two-point correlation functions of quasars in redshift space, $\xi^{(s)}(s_\perp, s_\parallel)$, and that of *mass* in real space, $\xi^{(r)}(x)$, can be derived in linear theory (Kaiser 1987; Hamilton 1992, 1997):

$$\xi^{(s)}(s_\perp, s_\parallel) = \left(1 + \frac{2}{3}\beta(z) + \frac{1}{5}[\beta(z)]^2\right)\xi_0(x)P_0(\mu)$$
$$- \left(\frac{4}{3}\beta(z) + \frac{4}{7}[\beta(z)]^2\right)\xi_2(x)P_2(\mu) + \frac{8}{35}[\beta(z)]^2\xi_4(x)P_4(\mu), \quad (3)$$

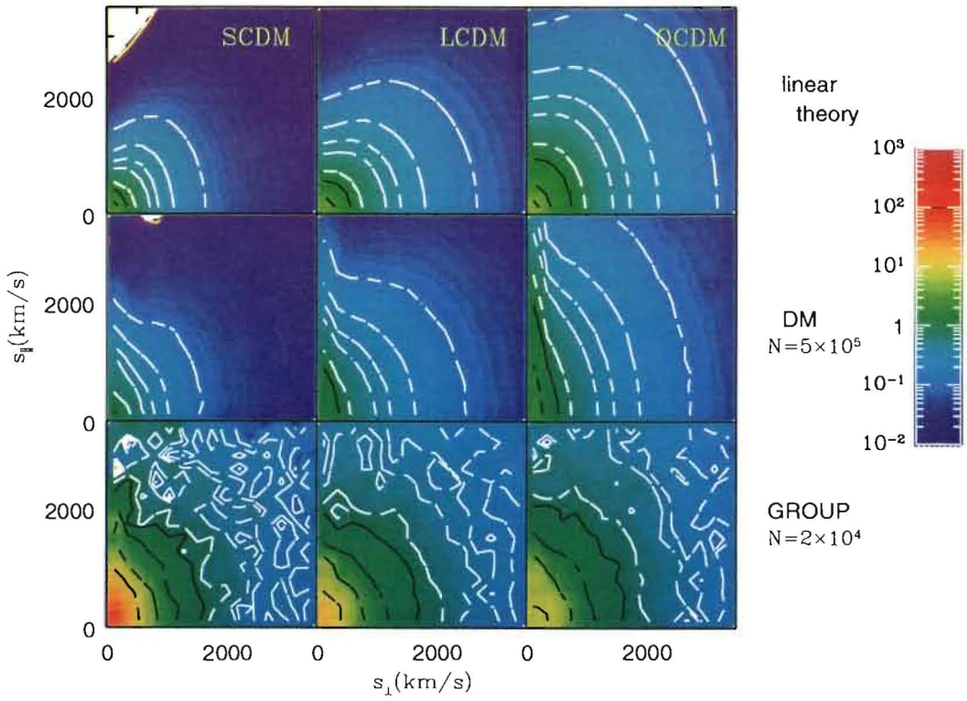

Figure 2. $\xi^{(s)}(s_\perp, s_\parallel)$ from linear theory (*Upper*) and N-body simulations with $N = 5 \times 10^5$ particles (*Middle*) and with $N = 2 \times 10^4$ massive halos of particles at $z = 2.2$ (*Lower*).

where $x \equiv \sqrt{{c_\parallel}^2 {s_\parallel}^2 + {c_\perp}^2 {s_\perp}^2}$, $\mu \equiv c_\parallel s_\parallel / x$, P_n's are the Legendre polynomials,

$$\beta(z) \equiv \frac{1}{b(z)} \frac{d \ln D(z)}{d \ln a}, \quad \xi_{2l}(x) = \frac{(-1)^l}{x^{2l+1}} \left(\int_0^x x dx \right)^l x^{2l} \left(\frac{d}{dx} \frac{1}{x} \right)^l x \xi^{(r)}(x), \quad (4)$$

and $D(z)$ is the linear growth rate (Matsubara and Suto 1996; see also Ballinger, Peacock and Heavens 1996).

In reality, however, the observable two-point correlation functions would be also contaminated by non-linear peculiar velocity as well as statistically limited by the available number of tracer objects. To incorporate the non-linear effect, we compute $\xi^{(s)}(s_\perp, s_\parallel)$ from a series of N-body simulations in CDM models with $N = 256^3$ particles in $(300h^{-1}\mathrm{Mpc})^3$ box (Jing and Suto 1998; Magira et al. 1998; Y.P.Jing, in these proceedings).

Figure 2 shows several examples at $z = 2.2$ for representative CDM models (Table 1). The degree to the extent which one can recover the

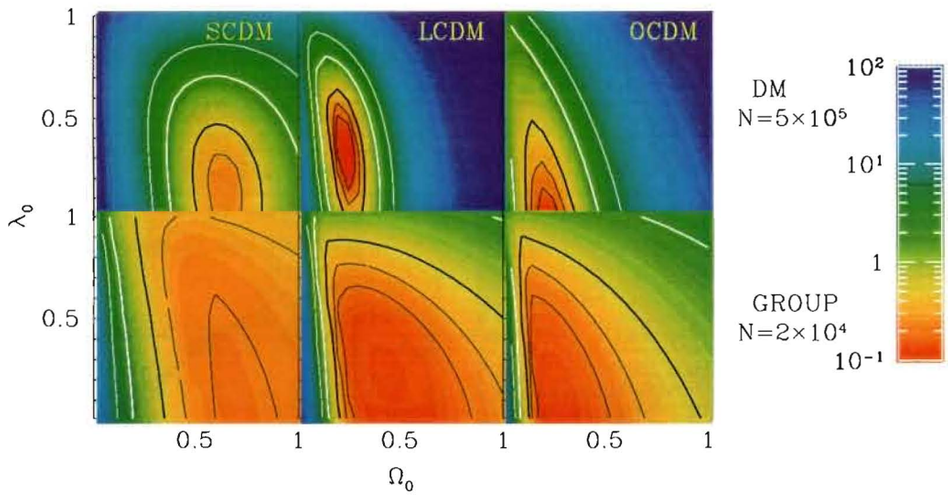

Figure 3. χ^2-contours on Ω_0 - λ_0 plane from the analysis of the data in Fig.2.

underlying correlation of small amplitudes is sensitive to the sampling rate, or the number density of objects. So Figure 2 is plotted for $N = 5 \times 10^5$ randomly selected particles and also for $N = 2 \times 10^4$ massive halos of particles from simulations.

Table 1. Simulation model parameters

Model	Ω_0	λ_0	Γ	σ_8
SCDM	1.0	0.0	0.5	0.6
OCDM	0.3	0.0	0.25	1.0
LCDM	0.3	0.7	0.21	1.0

Figure 3 plots the reduced χ^2 contour from $\xi^{(s)}(s_\perp, s_\parallel)$ of simulations. In computing the χ^2, we exclude the regions with $s_\parallel/s_\perp > 2$ which are likely to be seriously contaminated by nonlinear peculiar velocities. While Figure 3 demonstrates that the current methodology works in principle, the expected S/N is fairly low. This is largely because we adjusted the sampling rate for the high-z QSOs. The situation would be improved, though, if we apply the present methodology to a statistical sample of Lyman-break galaxies, for instance, whose number density is larger and their strong clustering is already observed (Steidel et al. 1998). We will examine the different aspect of strong clustering of the Lyman-break galaxies in the next section.

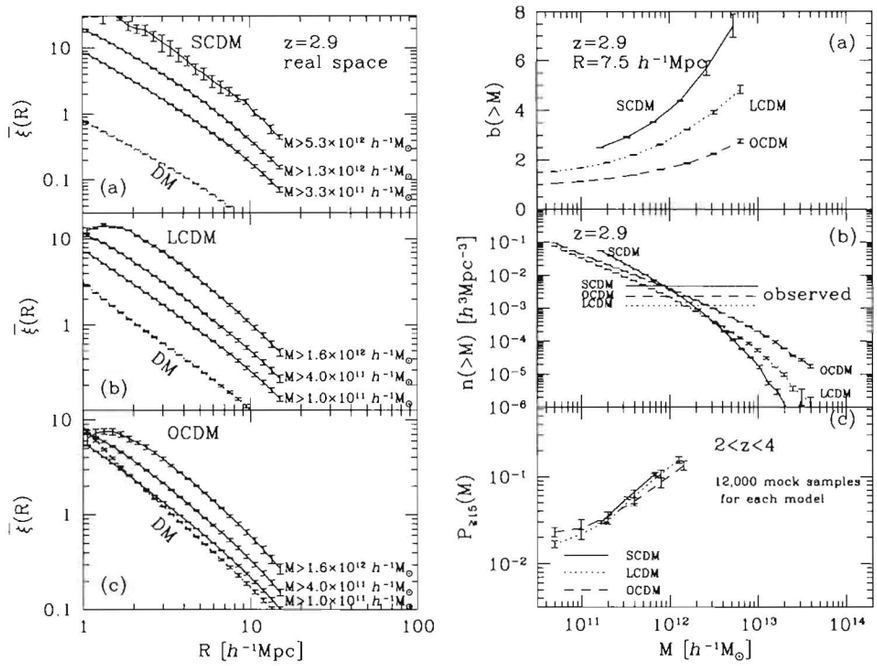

Figure 4. *Left:* Two-point correlation functions of halos at $z = 2.9$ in real space; different curves correspond to the different threshold masses M of the halos in (a) SCDM, (b) LCDM, and (c) OCDM models. Curves labeled by DM correspond to the correlation functions of all particles in the simulation. *Right:* Statistics of the halos as a function of the threshold mass; (a) bias parameter of halos at $z = 2.9$; (b) mean number density of halos in the simulations compared with the observed one of Lyman break galaxies; (c) probability of finding a concentration of at least 15 halos in a bin of $\Delta z = 0.04$.

3. Clustering of Lyman-break Galaxies

Recently Steidel et al. (1998) reported a discovery of a highly significant concentration of galaxies on the basis of the distribution of 78 spectroscopic redshifts in the range $2 \leq z \leq 3.4$ for photometrically selected "Lyman break" objects. We examine the theoretical impact of their discovery in much greater detail using a large number of mock samples from N-body simulations. All the simulations employ 256^3 (≈ 17 million) particles in a $(100h^{-1}\mathrm{Mpc})^3$ comoving box and start at redshift $z_i = 36$. We identify halos of galaxies using the Friend-Of-Friend (FOF) algorithm with a bonding length 0.2 times the mean particle separation, and assume that each halo corresponds to one Lyman break galaxy. Thus our analysis presented here

properly takes account of several important and realistic effects including (i) the survey volume geometry, (ii) redshift-space distortion, (iii) selection function of the objects, (iv) fully nonlinear evolution of dark halos, and (v) finite sampling effect.

Figure 4 (left panels) plots the volume-averaged two-point correlation functions in real space $\bar{\xi}(R; M, z)$ of the halos with mass larger than M at redshift $z = 2.9$. Figure 4 (left panels) indicates that over the scales of interest the correlation functions of halos are enhanced approximately by a constant factor $b^2(M, z)$ relative to those of the dark matter. Figure 4a (right panel) plots this effective bias parameter for halos with mass larger than M, $b(> M) \equiv \sqrt{\bar{\xi}(R; M, z)/\bar{\xi}_{\rm mass}(R; z)}$, calculated at $R = 7.5h^{-1}$Mpc and $z = 2.9$, where $\bar{\xi}_{\rm mass}(R; z)$ is the volume-averaged correlation function of all *particles* in the simulations.

The mean number density of halos of mass larger than M (without applying the selection function) is plotted in Figure 4b (right panel). Three horizontal lines indicate the observed number density of Lyman break galaxies corresponding to our three model parameters. Note that the observed number density should be regarded as a strictly lower limit since some fraction of the galaxies might have been unobserved due to the selection criteria. Since the density of halos falls below the observed one for $M > M_{max}$, we vary the threshold mass of the halos from $10m_p$ up to M_{max} in considering the statistical significance of the clustering. We use a simple algorithm to identify a galaxy concentration in the mock sample following the procedure of Steidel et al. (1998); for each mock sample, we count galaxies within redshift bins of $\Delta z = 0.04$ centered at each galaxy and identify the redshift bin with the maximum count as the density concentration. Then we compute the probability $P_{\geqq 15}(M)$ that a mock sample has a concentration with at least 15 galaxies. Figure 4c (right panel) indicates that while the clustering of such objects is naturally biased with respect to dark matter, the predicted bias $1.5 \sim 3$ is not large enough to be reconciled with such a strong concentration of galaxies at $z \sim 3$ *if one similar structure is found per one field on average.* We predict one similar concentration approximately per ten fields in SCDM and per six fields in LCDM and OCDM. Therefore future spectroscopic surveys in a dozen fields (Pettini et al. 1997) are quite important in constraining the cosmological models, and may challenge all the existing cosmological models *a posteriori* fitted to the $z = 0$ universe.

4. Conclusions

Many cosmological models are known to be more or less successful in reproducing the structure at redshift $z \sim 0$ *by construction.* There are still

several degrees of freedom or *cosmological parameters* appropriately *fit* the observations at $z \sim 0$ (Ω_0, σ_8, h, λ_0, $b(r,z)$). This *degeneracy* in cosmological parameters can be broken by using either accurate observational data with much better statistical significance (e.g., 2dF, Sloan Digital Sky Survey) or the data sample at higher redshifts. To extract all the potential information from the observational data requires predicting the theoretical consequences as quantitatively as possible by combining everything that we know theoretically and state-of-art numerical modeling.

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