Testing general relativity on the scales of cosmology using the redshift-space distortion[1]

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Abstract

As a test of general relativity on cosmological scales, we measure the γ parameter for the growth rate of density perturbations using the redshift-space distortion of the luminous red galaxies (LRG) in the Sloan Digital Sky Survey (SDSS). Assuming the cosmological constant model, which matches the results of the WMAP experiment, we find $\gamma = 0.63 + 2.0 \times (\sigma_8 - 0.8) \pm 0.09$ at 1σ confidence level, which is consistent with the prediction of general relativity, $\gamma \simeq 0.55 \sim 0.56$. Rather high value of $\sigma_8\,(> 0.85)$ is required to be consistent with the prediction of the cosmological GDP model, $\gamma\,(\simeq 0.68)$.

1 Introduction

Modified gravity models, e.g., $f(R)$ gravity, TeVeS theory, DGP model, have been proposed as possible alternatives to the dark energy model. Measurement of the growth of density perturbations will be the key for testing the gravity theory [4]. Several authors have already investigated the growth of density perturbations as a way of constraining these theories [11, 12, 13]. In the future weak lensing statistics will be a promising probe of the density perturbations, while the redshift-space distortions may also be useful for constraining the growth rate of perturbations. Recently, Guzzo et al. have reported a constraint on the growth rate by evaluating the anisotropic correlation function of the galaxy sample from the VIMOS-VLT Deep Survey (VVDS) [14]. The characteristic redshift of the VVDS galaxy sample is rather large. However, the survey area of the VVDS sample is small. This is a disadvantage in detecting the linear redshift-space distortions.

In this work, we used the Sloan Digital Sky Survey (SDSS) luminous red galaxy (LRG) sample from the Data Release 6, whose survey area is around 6,000deg^2. We present the results of the multipole power spectrum analysis for the SDSS LRG sample, and use it to measure the γ parameter for the growth rate of density perturbations.

2 Measurement of the quadrupole spectrum

The peculiar velocity of galaxies contaminates the observed redshift. It leads to the difference in the radial position if the redshift is taken as the indicator of the distance. This causes the difference in the spatial clustering between redshift space and real space, which is called the redshift-space distortion. The power spectrum including the redshift-space distortion can be modeled as (e.g., [8])

$$P\left(k,\mu\right) = \left(b\left(k\right) + f\mu^2\right)^2 P_{mass}\left(k\right) D\left(k,\mu\right),$$

where μ is the directional cosine between the line of sight direction and the wave number vector, $b\left(k\right)$ is the bias factor, $P_{mass}\left(k\right)$ is the mass power spectrum, $D\left(k,\mu\right)$ describes the damping factor due to the finger of God effect.

Thus, the redshift-space distortion causes the anisotropy of the clustering amplitude depending on μ. The multipole power spectra are defined by the coefficients of the multipole expansion [9, 10], $P\left(k,\mu\right) = \sum_{l=0,2,\cdots} P_l\left(k\right)\mathcal{L}_l\left(\mu\right)(2l+1)$, where $\mathcal{L}_l\left(\mu\right)$ are the Legendre polynomials. The monopole

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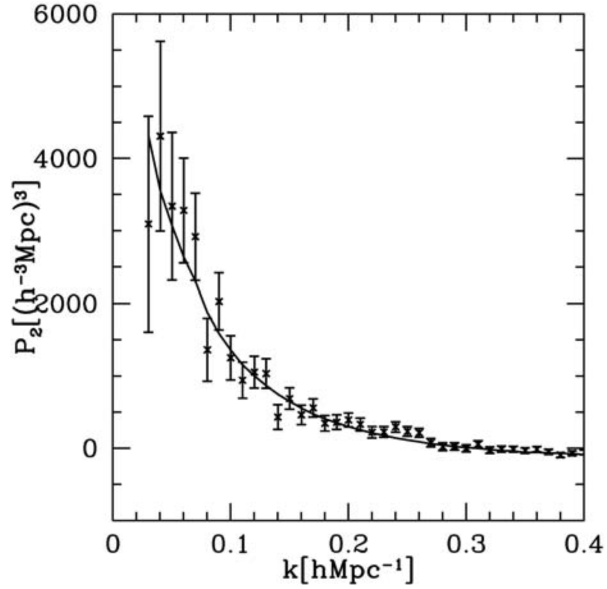

Figure 1: Quadrupole power spectrum. The solid curve is the theoretical curve of the ΛCDM model.

$P_0(k)$ represents the angular averaged power spectrum and is usually what we mean by the power spectrum. $P_2(k)$ is the quadrupole spectrum, which gives the leading anisotropic contribution. The usefulness of the quadrupole spectrum for the dark energy is discussed in [7].

Within the linear theory of density perturbations, the quadrupole spectrum is given by $P_2(k) = \left[4b(k)f/3 + 4f^2/7\right] P_{mass}(k)/5$. Thus, we can measure the growth rate from the quadrupole spectrum. However, we need other independent information for the clustering bias $b(k)$.

By using the quadrupole spectrum, we perform a simple test of the gravity theory. We focus on the γ parameter, which is introduced to parameterise the growth rate as $f \equiv d\ln D_1(a)/d\ln a = \Omega_m(a)^\gamma$, where $\Omega_m(a) = H_0^2\Omega_m a^{-3}/H(a)^2$, $H(a) = \dot{a}/a$, $H_0(= 100h\mathrm{km/s/Mpc})$ is the Hubble parameter. Measurement of γ provides a simple test of the gravity theory. Within general relativity, even with the dark energy component, γ takes the value around $\gamma \simeq 0.55$ [4]. However, γ may take different values in modified gravity models. For example, $\gamma \simeq 0.68$ in the cosmological DGP model including a self-acceleration mechanism. Thus, the measurement of γ is a simple test of general relativity.

In the present work we measured the monopole and quadrupole power spectra in the clustering of the SDSS DR6 luminous red galaxy sample. The galaxy sample used in our analysis consists of 82,000 galaxies overs the survey area of 6,000deg^2 and redshift range $0.16 \leq z \leq 0.47$ [3]. We have excluded the southern survey stripes since these just increase the sidelobes of the survey window without adding much of the extra volume. We have also removed some minor parts of the LRG sample to obtain more continuous and smooth chunk of volume.

We need to take the clustering bias and the finger of God effect into account. For the finger of God effect we adopt the following form of $D(k,\mu)$, the damping due to the nonlinear random velocity, $D(k,\mu) = 1/[1 + (k\mu\sigma_v/H_0)^2/2]$, where σ_v is the one dimensional pairwise velocity dispersion. (e.g., [6]). This form of damping assumes an exponential distribution function for the pairwise peculiar velocity. In order to determine the clustering bias, we use the monopole spectrum. If σ_8 is fixed, and the cosmological parameters and the bias are given, we can compute the monopole spectrum $P_0^{theor}(k)$, where we use the Peacock and Dodds formula for the mass power spectrum $P_{mass}(k)$ [8]. We determine the clustering bias $b(k)$ through the condition $P_0^{obs}(k) = P_0^{theor}(k)$ using a numerical method. Here $P_0^{obs}(k)$ is the measured value of the monopole, and $P_0^{theor}(k)$ is the corresponding theoretical value. We used the monopole spectrum to determine the bias, and the quadrupole spectrum to obtain constraints on γ and σ_v. Since the galaxy sample covers rather broad redshift range, $0.16 \leq z \leq 0.47$, the effect of the time-evolution should be considered properly [2]. However, for simplicity, we here evaluated the theoretical spectra at

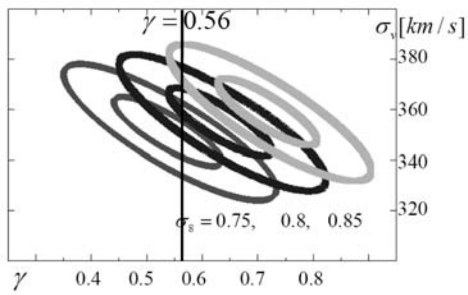

Figure 2: The contour of $\Delta\chi^2$ in the $\gamma - \sigma_v$ plane. We fixed the normalization of the mass power spectrum as $\sigma_8 = 0.75$, 0.80, 0.85. The contour levels are 1-sigma and 2-sigma confidence levels. The other parameters are $h = 0.7$, $n_s = 0.96$, $\Omega_m = 0.28$.

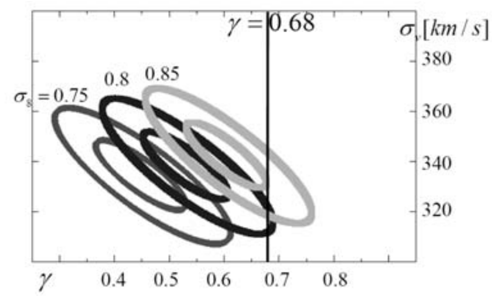

Figure 3: Same as the Figure 2, except here we used the expansion history of the DGP model.

the mean redshift of $z = 0.31$.

Figure 1 plots the quadrupole spectrum. The solid curve is the theoretical curve for the ΛCDM model with $h = 0.7$, $n_s = 0.96$(initial spectral index), Ω_m=0.28, $\sigma_8 = 0.8$, $\gamma = 0.63$, $\sigma_v = 355$km/s.

Figure 2 demonstrates the contour of $\Delta\chi^2$ in the γ versus σ_v parameter plane. We compute χ^2 as $\chi^2 = \sum_i [P_2^{obs}(k_i) - P_2^{theor}(k_i)]/[\Delta P_2^{obs}(k_i)]^2$. Where $P_2^{obs}(k_i)$ and $\Delta P_2^{obs}(k_i)$ are the measured values and errors as plotted in Figure 1. $P_2^{theor}(k_i)$ are the corresponding theoretical value. The curves assume $\sigma_8 = 0.75$, $\sigma_8 = 0.8$, $\sigma_8 = 0.85$. The other parameters are fixed as $h = 0.7$, $n_s = 0.96$, $\Omega_m = 0.28$. In Figure 2 we plot the contour levels in 1-sigma and 2-sigma confidence levels of the χ^2 distribution. We find $\gamma = 0.63 + 2.0 \times (\sigma_8 - 0.8) \pm 0.09$ at 68 percent confidence level, respectively. The value of γ is consistent with general relativity. The result is not sensitive to the inclusion of baryon oscillation in the theoretical power spectrum.

The relation of γ and σ_8 can be understood as the degeneracy between σ_8 and the growth rate f in the following way. As the observed power spectra can be roughly written as $P_0^{obs} \propto b^2(k){\sigma_8}^2 D_1^2(z)/D_1^2(z=0)$ and $P_2^{obs} \propto b(k) f {\sigma_8}^2 D_1^2(z)/D_1^2(z=0)$. The degeneracy between σ_8 and the growth rate f(or γ) in our method is given by $f\sigma_8 D_1(z)/D_1(z=0) = $ constant.

Figure 3 is the analogue of Figure 2, with the expansion history now taken to be that of the spatially flat DGP model, which follows $H^2(a) - H(a)/r_c = 8\pi G\rho/3$, where ρ is the matter density and $r_c = 1/H_0(1 - \Omega_m)$ is the crossover scale related to the 5-dimensional Planck mass. the expansion history in this model can be well approximated by the dark energy model with the equation of state parameter $w(a) = w_0 + w_a(1 - a)$, where $w_0 = -0.78$ and $w_a = 0.32$, as long as $\Omega_m \sim 0.3$ [4]. However the Poisson equation is modified, and the growth history is approximated by the formula with $\gamma \simeq 0.68$. In order to be consistent with $\gamma = 0.68$, Figure 3 requires higher value of σ_8 as compared to the ΛCDM case. We find $\gamma(\simeq 0.68)$ at 68 percent confidence level, which requires $\sigma_8 \geq 0.85$.

3 Conclusion

We measured the monopole and quadrupole spectra in the spatial clustering of the SDSS LRG sample from DR6. Using the spectra, we measured the γ parameter for the linear growth rate and the pairwise peculiar velocity dispersion. The measured value of γ is consistent with general relativity as long as $0.72 \leq \sigma_8 \leq 0.81$. However, it is inconsistent with the cosmological DGP model, $\gamma \simeq 0.68$, as long as $\sigma_8 < 0.85$. If a constraint on σ_8 from other independent sources, we would be able to obtain tighter constraint on the DGP model. The constraint on γ can be applied to other modified gravity models, given that the value of γ which characterises a particular model is found, as discussed by Linder and Cahn [5].

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