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Constraints on Growth Index from LSS

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Abstract. We utilize the clustering properties of the Luminous Red Galaxies (LRGs) and the growth rate data in order to constrain the growth index (γ) of the linear matter fluctuations based on a standard χ^2 joint likelihood analysis between theoretical expectations and data. We find a value of $\gamma = 0.56 \pm 0.05$, perfectly consistent with the expectations of the ΛCDM model, and $\Omega_{m0} = 0.29 \pm 0.02$, in very good agreement with the latest Planck results. Our analysis provides significantly more stringent growth index constraints with respect to previous studies as indicated by the fact that the corresponding uncertainty is only $\sim 0.09\gamma$.

Keywords. cosmological parameters, dark matter, large-scale structure of universe

1. Introduction

One of the most intriguing problems in Cosmology is to explain the fact that the universe is in a phase of accelerated expansion. In order to deal with this problem, one has to see Dark Energy (DE) either as a new field in nature or as a modification of General Relativity (see for review Copeland *et al.* 2006, Caldwell & Kamionkowski 2009, Amendola & Tsujikawa 2010). An interesting approach to discriminate between the aforementioned is to use the evolution of the linear growth of matter perturbations. Specifically, a useful tool in this kind of studies is the so called growth rate of clustering, which is defined as $f(a) = \frac{d\ln D}{d\ln a} \simeq \Omega_m^{\gamma}(a)$, where $a(z) = (1+z)^{-1}$ is the scale factor of the universe, $\Omega_m(a)$ is the dimensionless matter density parameter, γ is the growth index and $D(a) = \delta_m(a)/\delta_m(a=1)$ is the linear growth factor usually scaled to unity at the present time (Peebles 1993, Wang & Steinhardt 1998). Notice that γ may in general vary with redshift; $\gamma \equiv \gamma(z)$. Theoretically speaking, it has been shown that for those DE models which are within the framework of GR and have a constant Equation of State parameter, the growth index γ is equal to $\gamma \simeq 6/11$ for the ΛCDM model.

Since gravity reflects, via gravitational instability, on the nature of clustering (Peebles 1993) it has been proposed to use the clustering/biasing properties of the mass tracers in constraining cosmological models (see Matsubara 2004, Basilakos & Plionis 2005, Basilakos & Plionis 2006, Krumpe *et al.* 2013) as well as to test the validity of GR on extragalactic scales (Basilakos *et al.* 2012, for a recent review see Bean *et al.* 2013). Using the above notations, the aim of the current study is to place constraints on the (Ω_m, γ) parameter space using the joint analysis of the measured two-point angular correlation function (ACF) of LRGs (Sawangwit *et al.* 2011) and the growth rate of clustering data as collected by Basilakos *et al.* (2013) (see Table 1 of Basilakos *et al.* 2013).

2. Angular Correlation Function

Considering a spatially flat Friedmann-Lemaître-Robertson-Walker (FLRW) geometry, we can easily relate via the Limber's inversion equation the ACF, $w(\theta)$, with the two point spatial correlation function $\xi(r,z)$: $w(\theta) = 2\frac{H_0}{c}\int_0^{\infty}(\frac{1}{N}\frac{dN}{dz})^2 E(z)dz \int_0^{\infty}\xi(r,z)du$, where $1/N\ dN/dz$ is the normalized redshift distribution of the LRGs.

The redshift distribution for this case is given by the relation: $\frac{dN}{dz} \propto (\frac{z}{z_\star})^{(a+2)} e^{-(\frac{z}{z_\star})^{\beta}}$, where $(a,\beta,z_\star) = (-15.53, -8.03, 0.55)$ and $z_\star$ is the characteristic depth of the subsample studied. The spatial correlation function of the mass tracers is given by: $\xi(r,z) = b^2(z)\xi_{DM}(r,z)$, where $b(z)$ is the evolution of the linear bias, and ξ_{DM} is the corresponding correlation function of the underlying mass distribution which is written as $\xi_{DM}(r,z) = \frac{1}{2\pi^2}\int_0^{\infty} k^2 P(k,z)\frac{\sin(kr/a)}{(kr/a)}dk$. Concerning $P(k,z)$, it is $P(k,z) = D^2(z)P(k)$ with $P(k) = P_0 k^n T^2(k)$ denoting the CDM power spectrum of the matter fluctuations. Note that $T(k)$ is the CDM transfer function of Eisenstein & Hu (1998) or this of Bardeen *et al.* (1986) and $n \simeq 0.9671$ following the recent reanalysis of the Planck data by Spergel *et al.* (2013). The variable r corresponds to the physical separation between two sources having an angular separation, θ (in steradians) and $E(z) = H(z)/H_0$, is the normalized Hubble parameter. Non linear effects have been also taken into account through the slope of the power spectrum at the relevant scales: $n_{\rm eff} = d\ln P/d\ln k$ (Peacock & Dodds 1994, Smith *et al.* 2003, Widrow *et al.* 2009).

3. The evolution of linear bias, $b(z)$

The linear bias is defined as the ratio of density perturbations in the mass-tracer field to those of the underling total matter field: $b = \delta_{tr}/\delta_m$. In this analysis we use the bias evolution model of Basilakos *et al.* (2011) and Basilakos *et al.* (2012) which is valid for any DE model (scalar or geometrical) and it is given by:

$$b(z) = 1 + \frac{b_0 - 1}{D(z)} + C_2\frac{\mathcal{J}(z)}{D(z)} \tag{3.1}$$

with $\mathcal{J}(z) = \int_0^z \frac{(1+y)}{E(y)}dy$. The constants b_0 (the bias at the present time) and C_2 depend on the host dark matter halo mass M_h (see Basilakos *et al.*2012).

4. Fitting Theoretical Models to the data

A standard χ^2 minimization statistical analysis is implemented in order to provide constraints in the (Ω_{m0},γ) parameter space. It is defined as follows:

$$x_t^2 = \sum_{i=1}^{n}\left[\frac{X_{obs} - X_{th}}{\sigma_i^2}\right]^2$$

where the index t stands for the clustering data of LRGs or the growth data, X is the angular correlation function or the fσ_8 respectively and σ_i is the corresponding uncertainty. We perform a joint likelihood analysis of the two cosmological probes using:

$$x^2 = x^2_{LRGs} + x^2_{gr}$$

The joint result of the analysis for the case of Eisenstein & Hu (1998) transfer function is $(\Omega_{m0},\gamma) = (0.29 \pm 0.02, 0.56 \pm 0.05)$, which is the strongest (to our knowledge) joint constraint appearing in the literature. The results are shown in Table 2. For a more

Table 1. Results in the $(\Omega_{m0}, \gamma, M_h, n_{\rm eff})$ parameter space for the different $T(k)$ and σ_8.

$T(k)$	Ω_{m0}	γ	$M_h/10^{13}M_\odot$	$n_{\rm eff}$	$\chi^2_{t,\rm min}/df$
$\sigma_8 = 0.797\,(0.30/\Omega_{m0})^{0.26}$ Hajian *et al.* 2013					
Eisenstein & Hu (1998)	0.29 ± 0.02	0.56 ± 0.05	1.90 ± 0.10	0.10 ± 0.20	16.36/23
Bardeen et al (1986)	0.29 ± 0.01	0.56 ± 0.10	1.80 ± 0.30	$-0.10^{+0.30}_{-0.10}$	16.56/23
$\sigma_8 = 0.818\,(0.30/\Omega_{m0})^{0.26}$ Spergel *et al.* 2013					
Eisenstein and Hu (1998)	$0.29^{+0.03}_{-0.02}$	$0.58^{+0.02}_{-0.06}$	1.70 ± 0.20	0.30 ± 0.20	15.90/23
Bardeen et al (1986)	$0.29^{+0.02}_{-0.03}$	0.56 ± 0.10	1.60 ± 0.4	$0.0^{+0.10}_{-0.20}$	16.13/23

detailed analysis, as well as for the case of a varying growth index with redshift $\gamma = \gamma(z)$, see Pouri *et al.* (2014).

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References

Copeland, E. J., Sami, M., & Tsujikawa, S. 2006, *Int. J. of Mod. Phys. D.*, 15, 1753

Caldwell, R. R. & Kamionkowski, M. 2009, *Ann. Rev. Nucl. Part. Sci.*, 59, 397

Amendola, L. & Tsujikawa, S. 2010, *Dark Energy: Theory and Observations, Cambridge University Press, Cambridge UK*

Peebles, P. J. E. 1993, *"Principles of Physical Cosmology", Princeton University Press, Princeton, New Jersey*

Wang, L. & Steinhardt, P. J. 1998, *ApJ*, 508, 483

Matsubara, T. 2004, *ApJ*, 615, 573

Basilakos, S. & Plionis, M. 2005, *MNRAS*, 360, L35

Basilakos, S. & Plionis, M. 2006, *ApJ*, 650, L1

Krumpe, M., Miyaji, T., & Coil, A. L. 2013, *arXiv:1308.5976*, 650, L1

Basilakos, S., Dent, J. B., Dutta, S., Perivolaropoulos, L., & Plionis, M. 2012, *Phys. Rev. D.*, 85, 123501

Bean, R., *et al.* 2013, *arXiv:1309.5385*

Sawangwit, U., *et al.* 2011, *MNRAS*, 416, 3033

Basilakos, S., Nesseris, S., & Perivolaropoulos, L. 2013, *Phys. Rev. D.*, 87, 123529

Eisenstein, D. J. & Hu, W. 1998, *ApJ*, 496, 605

Bardeen, J. M., Bond, J. R., Kaiser, N., & Szalay, A. S. 1986, *ApJ*, 304, 15

Spergel, D., Flauger, R., & Hlozek, R. 2013, *arXiv:1312.3313*

Peacock, J. A. & Dodds, S. J. 1994, *MNRAS*, 267, 1020

Smith, R. E., *et al.* 2003, *MNRAS*, 341, 1311

Widrow, L. M., Elahi, P. J., Thacker, R. J., Richardson, M., & Scannapieco, E. 2009, *MNRAS*, 397, 1275

Basilakos, S., Plionis, M., & Pouri, A. 2011, *Phys. Rev. D.*, 83, 123525

Hajian, A., Battaglia, N., Spergel, D. N., Bond, J. R., Pfrommer, C., & Sievers, J. L. 2013, *JCAP*, 11, 64

Pouri, A., Basilakos, S., & Plionis, M. 2014, *arXiv:1409.0964*

Nesseris, S., Basilakos, S., Saridakis, E. N., & Perivolaropoulos, L. 2013, *Phys. Rev. D.*, 88, 103010

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