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Large-scale galaxy correlations as a test for dark energy

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ABSTRACT

We have shown earlier that, contrary to popular belief, Einstein-de Sitter (E-deS) models can still fit the *WMAP* data on the cosmic microwave background provided one adopts a low Hubble constant and relaxes the usual assumption that the primordial density perturbation is scale-free. The recent *SDSS* measurement of the large-scale correlation function of luminous red galaxies at $z \sim 0.35$ has however provided a new constraint by detecting a "baryon acoustic peak". Our best-fit E-deS models do possess a baryonic feature at a similar physical scale as the best-fit ΛCDM concordance model, but do not fit the new observations as well as the latter. In particular the shape of the correlation function in the range $\sim$10−100 h^{-1} Mpc cannot be reproduced properly without violating the CMB angular power spectrum in the multipole range $l \sim 100{-}1000$. Thus, the combination of the CMB fluctuations and the shape of the correlation function up to $\sim$100 h^{-1} Mpc, if confirmed, does seem to require dark energy for a homogeneous cosmological model based on (adiabatic) inflationary perturbations.

Key words. cosmic microwave background – large-scale structure of Universe – cosmological parameters

1. Introduction

The detection by *COBE* of large angular scale fluctuations in the cosmic microwave background (CMB) opened a new era in modern cosmology and established the inflationary model, in which the initial conditions of the present Universe are set by fundamental physical processes occurring in the very early Universe. The subsequent detection of fluctuations on small angular scales and the considerable improvement in the precision of their measurement in the last decade has led to remarkable progress. The flatness of the universe was the first key result to emerge from identification of the "acoustic peak" in the angular power spectrum of the CMB (Lineweaver et al. 1997) which allowed a measurement of the angular distance to the last scattering surface. Together with the observed low matter density of the universe and the cosmic acceleration implied by the Hubble diagram of type Ia supernovae (Riess et al. 1998; Perlmutter et al. 1999), this led to the "concordance model" of cosmology in which the dominant component of the universe is a mysterious dark energy which behaves essentially like a cosmological constant (see e.g. Peebles & Ratra 2003).

This model has been remarkably successful at fitting a large body of cosmological data, in particular of large-scale structure (LSS). However it should be emphasized that *direct* evidence for dark energy, through the detection of the expected correlations between the CMB and LSS induced by the late integrated Sachs-Wolfe effect, still has rather weak ($<3\sigma$) significance (see e.g. Boughn & Crittenden 2004; Padmanabhan et al. 2005). Dimming of distant supernovae by grey dust (Aguirre 1999; Goobar et al. 2002; Vishwakarma 2005) or evolution of their progenitors (Drell et al. 2000; Wright 2002) could well mimic the effects of acceleration in the SN Ia Hubble diagram (see Fig. 7 in Riess et al. 2004). Moreover there are many "degeneracies" in the fitting of cosmological models to CMB and LSS observations which allow rather different parameter combinations to fit the same data. Given the complete lack of theoretical understanding of dark energy, this motivated us to reexamine (Blanchard et al. 2003, BDRS hereafter), whether Einstein-de Sitter (E-deS) models could still be compatible with the extant CMB and LSS data. This required assumptions at odds with current beliefs: we adopted a low value of the Hubble constant (46 km s^{-1} Mpc^{-1}) and, motivated by theoretical ideas about inflation (Adams et al. 1997; Martin & Brandenberger 2003)[1], we relaxed the assumption that the

[1] The "glitches" appearing in WMAP and Archeops data may well be the signature of such new physics (Ringeval & Martin 2004; Hunt & Sarkar 2004).

spectrum of the primordial density perturbation is a simple power-law. The fact that data from WMAP as well as other CMB experiments can be reproduced with E-deS models was a direct demonstration that the CMB data by themselves do *not* require the presence of dark energy.

Moreover we showed that the power spectrum of large-scale structure as measured in the *2dF* galaxy redshift survey, and inferred from observations of the Lyman-α forest, can be adequately reproduced if there is a small component (12%) of unclustered matter e.g. in the form of 0.8 eV mass neutrinos or a pressureless scalar field. This lowers σ_8, the amplitude of matter fluctuations on the scale 8 h^{-1} Mpc, to 0.64 and 0.5 respectively, thus allowing agreement with the values inferred from clusters and from weak lensing for a critical matter dominated universe. In both models, the baryon density is $\Omega_b h^2 \simeq 0.02$, in agreement with the value inferred from primordial nucleosynthesis (see Fields & Sarkar 2004 and Charbonnel & Primas 2005, for recent discussions). Thus it appeared that an E-deS universe could indeed be made consistent with all data, and possibly favored by the evolution of the number density of distant clusters as inferred from *XMM* observations (Vauclair et al. 2003) as well as the baryon fraction in clusters (Sadat et al. 2005).

It had been emphasized by BDRS that further observations of large-scale structure would provide a key test: *"The most stable difference between our E-deS models and the ΛCDM concordance model is in fact the matter power spectrum shape in the range k ∼ (0.01-0.03) h/Mpc, which galaxy surveys may be able to investigate, provided the possible biasing is reliably understood on these scales."* The recent results in this context from *2dFGRS* (Cole et al. 2005), as well as *SDSS* (Eisenstein et al. 2005) have prompted us to return to this question.

2. Galaxy correlation functions in Einstein-de Sitter models

The most remarkable result that has emerged is the detection of the so called "baryon acoustic peak" in the angular correlation function of *SDSS* luminous red galaxies (LRGs), as well as in the *2dFGRS* power spectrum. The presence of such a feature is a robust prediction (Peebles & Yu 1970) and arises from the summation of several wiggles in the power spectrum (see e.g. Blake & Glazebrook 2003; Matsubara 2004; Huetsi 2005). The first question to examine is whether the position of the peak discriminates between the concordance ΛCDM model and the alternative E-deS models. We have therefore computed the (dark matter) correlation functions of the two best-fit E-deS models discussed by BDRS; these were obtained as direct Fourier transforms of the corresponding power spectra without taking into account corrections due to non-linear effects, redshift space distortions, bias on large scales etc, which are in any case expected to have little effect on the properties of the acoustic peak (White 2005). The correlation functions were normalized to the amplitude of the *SDSS* LRG correlation function on the scale 10 h^{-1} Mpc and are shown in Fig. 1. As one can see the E-deS models exhibit a peak of similar amplitude and location in *physical space* as the

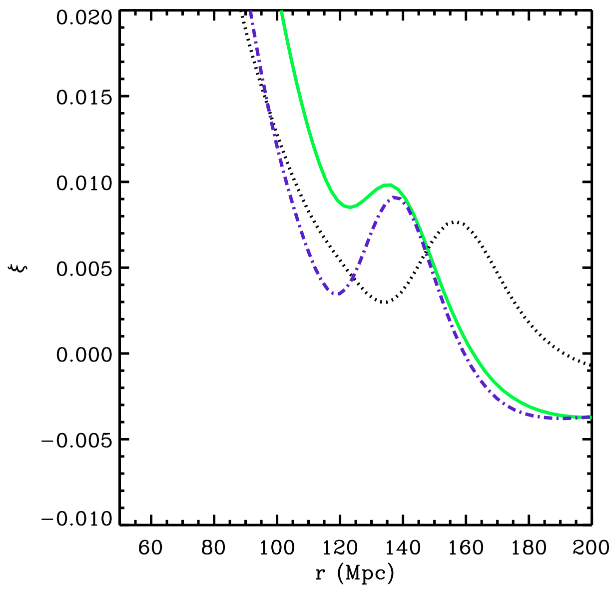

Fig. 1. The correlation function in physical space for the best-fit power-law ΛCDM model (dotted, black line) from Spergel et al. (2003), and for the best-fit Einstein-de Sitter models $\Omega_\Lambda = 0$) from Blanchard et al. (2003) having a neutrino component $\Omega_\nu = 0.12$ (solid, green line) and a pressureless ($w = 0$) quintessence component $\Omega_Q = 0.12$ (dot-dashed, blue line). An acoustic peak is seen for all models, having a similar amplitude and on a similar *physical* scale, as can be anticipated from the physical origin of this peak.

ΛCDM model, the reason for this being that the cold dark matter density $\Omega_m h^2$ and the baryon density $\Omega_b h^2$ have similar values in all these models. Note that the characteristic length scales as $(\Omega_b h^2)^{-0.252}(\Omega_m h^2)^{-0.0853}$ (Hu 2005) making a ∼10% difference between our fiducial models.

However, the position of this peak in *redshift space* differs because of the lower value of the Hubble constant needed to reproduce the CMB power spectrum for the E-deS models. Because of this the peak is shifted to smaller scales in redshift space as seen in Fig. 2. The abscissae of the E-deS models were rescaled by a numerical factor of 1.22, taking into account the dilation at $z \sim 0.35$ in distances according to Eq. (2) of Eisenstein et al. (2005). Although the significance of this peak is not very high, and needs to be confirmed in subsequent surveys, the Einstein-de Sitter models are significantly worse fits (having $\chi^2 \sim 95$ and $\chi^2 \sim 155$ for models in which the bias is optimized, non diagonal terms in the correlation matrix being neglected) than the concordance model ($\chi^2 \sim 20$) for 19 d.o.f. Our concordance model was previously determined as an optimal model for the CMB and is therefore slightly worse than the optimal model of Eisenstein et al. (2005) adjusted directly on the LRG data.

For the ΛCDM model, the location of the peak was predicted correctly which should be considered a great success. However, its shape does not appear to be a particularly good fit to the observations. This is also apparent from Fig. 3 in Eisenstein et al. (2005): models which reproduce well the amplitude of the peak have an excessive amplitude on smaller scales (20−50 h^{-1} Mpc). This opens up the possibility that the

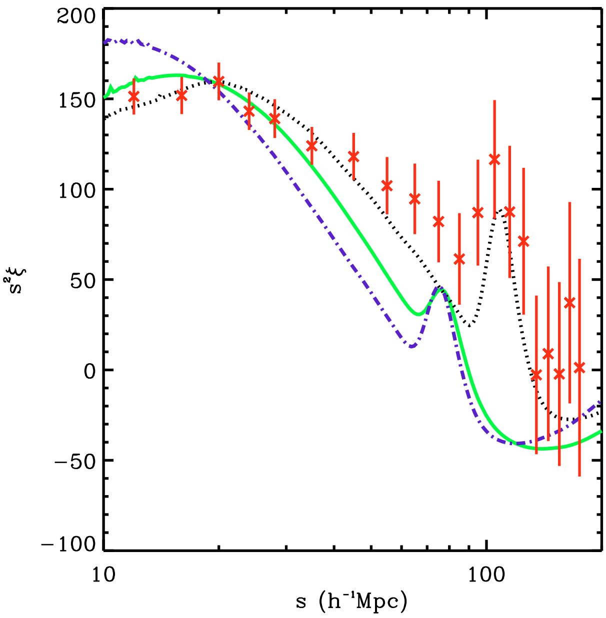

Fig. 2. The correlation function in observed (redshift) space for the same models as in Fig. 1, but with amplitude adjusted to the best fitting value. For Einstein-de Sitter models, the spatial scales are shifted for the geometrical factor (according to Eq. (2) of Eisenstein et al. 2005) relative to a Λ dominated cosmology. The position of the acoustic peak (in h^{-1} Mpc) for E-deS models does not match the observations, unlike the ΛCDM model, because a lower value of the Hubble constant is needed to fit the CMB data. In addition, E-deS models exhibit a lack of power on large scales (30–100 h^{-1} Mpc) when normalized optimally to the observations.

origin of the feature is actually different, perhaps imprinted in the primordial density perturbation. Although this might appear unlikely, physical mechanisms have been proposed which would generate such wiggles in the primordial perturbation spectrum during inflation (Ringeval & Martin 2004; Hunt & Sarkar 2004). It is not our intention here to argue in favor of such a possibility, but rather to examine whether the shape of the correlation function itself can add new information without any prejudice as to the nature of the primordial density perturbation. As BDRS have shown previously, the CMB angular power spectrum at $l \sim 1000$ is directly related to the amplitude of matter fluctuations on the scale $\sim$10 h^{-1} Mpc, therefore the high precision CMB measurements impose a tight constraint on σ_8 in a relative model independent way. Because of the smaller amplitude of the power spectrum on large (redshift) scales, we expect the correlation function in redshift space to reflect this lack of power, as is seen in Fig. 2 for the E-deS models we have previously investigated. Because the amplitude of the CMB anisotropy is well measured in the angular range $l \sim 200{-}1000$ (see e.g. Jones et al. 2005), it follows that the amplitude of the matter correlation function in the corresponding spatial range $\sim$30−100 h^{-1} Mpc cannot be increased without exceeding the observed amplitude of CMB anisotropy on those scales.

We have tried several modifications of the primordial power spectrum but without success in matching the concordance model's ability to reproduce simultaneously the data on CMB anisotropies and the LRG correlation function. There are of course many unknowns apart from the shape of the primordial density perturbation, for instance the possible presence of inflationary tensor modes and of isocurvature modes, the presence of topological defects, the nature of the dark matter etc. It may not therefore be possible to rigorously rule out models in which the CMB anisotropies and the LRG correlation function can be reproduced without any dark energy. However it does appear that the above argument is new evidence in favor of the presence of dark energy, in the standard framework of general relativity and homogeneous cosmological models.

3. Conclusions

Our main conclusion is that the new information contained in the *SDSS* LRG correlation function, in conjunction with observations of CMB anisotropy, in principle allows discrimination between cosmological models with and without dark energy. Although we have shown earlier that Einstein-de Sitter models can indeed fit most cosmological data (with the exception of the SNIa Hubble diagram and the Hubble Key Project value of the Hubble constant), it now appears possible to exclude them by more precise measurements of the correlation function of galaxies on large scales, provided that biasing is well understood. The concordance model does not have any basis yet in fundamental physics and should therefore be regarded as a convenient parameterization of the data in the context of the standard FRW cosmology, rather than as a "Standard Model". In particular there is no physical explanation of why the universe should be embarking on a new inflationary period at this late stage in its history. Nevertheless we acknowledge that the new observations of the galaxy correlation function, jointly with small-angle anisotropies in the CMB which probe the same scales of $\sim$10−100 h^{-1} Mpc, provide a remarkable geometric test of the concordance model which it passes successfully.

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