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# Cosmic sound: Measuring the Universe with baryonic acoustic oscillations

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26th June 2006



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## Abstract

We present the results of the power spectrum measurement of the SDSS Luminous Red Galaxy (LRG) sample. The large volume and sufficiently high number density of LRG sample has enabled us to obtain an accurate measure of the clustering power, clearly showing signs of the acoustic oscillations. Using the measured spectrum, we carry out a Markov Chain Monte Carlo (MCMC) maximum likelihood analysis for the cosmological parameters. We briefly discuss the expected performance of the upcoming large galaxy cluster redshift surveys at measuring the clustering signal in comparison to the currently existing SDSS LRG sample.

## 1 Introduction

During the last ten to fifteen years the field of cosmology has witnessed enormous progress. For this progress to continue in the future, it is essential to get a very good handle on all the possible systematic uncertainties that might spoil our conclusions about the underlying cosmology. Thus it is natural to concentrate the observational effort towards the phenomena that are theoretically best understood and also least “contaminated” by complex astrophysical processes or several intervening foregrounds. Currently by far the cleanest cosmological information has been obtained through measurements of the angular temperature fluctuations of the Cosmic Microwave Background (CMB). The typical angular size of the CMB temperature fluctuations is determined by the distance the sound waves in the tightly coupled baryon-photon fluid can have traveled since the Big Bang until the epoch of recombination. A similar scale is also expected to be imprinted in the large-scale matter distribution as traced by, for instance, galaxies or galaxy clusters. Measurements of the peaks in the CMB angular power spectrum fix the physical scale of the sound horizon with a high precision. By identifying the corresponding features in the low redshift matter power spectrum one is able to put constraints on several cosmological parameters. In fact, the acoustic oscillations in the large-scale matter distribution have already been discovered (Eisenstein *et al.*, 2005; Cole *et al.*, 2005; Hütsi, 2005; Hütsi, 2006a), showing great promise for the upcoming large redshift surveys. A comparison of the acoustic features in the CMB angular power spectrum with the ones imprinted onto the LSS is given in Fig. 1.

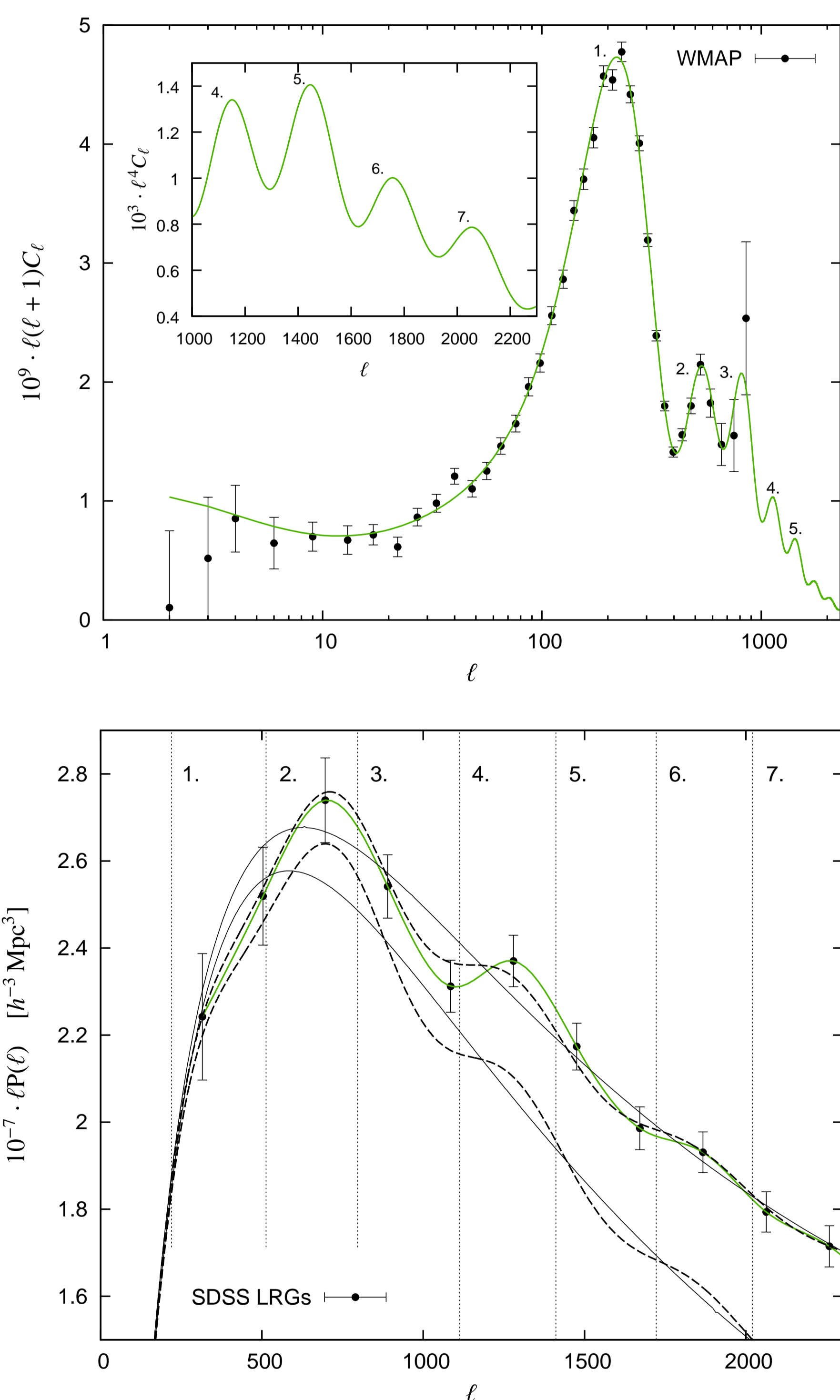


Figure 1: Upper panel: The CMB angular power spectrum as measured by the WMAP team together with the best-fitting  $\Lambda$ CDM model curve. The inset shows the zoom into the damping tail. Due to very strong decline of the CMB angular spectrum at large multipoles the  $y$ -axis is multiplied with an extra factor of  $\ell^2$  in comparison to the main figure. Lower panel: The multiplet spectrum of the SDSS LRGs plotted in a way allowing for a direct comparison with the corresponding CMB spectrum provided in the upper panel. The comoving wavenumber  $k$  was transformed to the multipole number  $\ell$  such that  $\ell \simeq 9940 \cdot k [h \text{ Mpc}^{-1}]$ , where  $9940 h^{-1} \text{ Mpc}$  is the comoving angular diameter distance to the last scattering surface for the best-fit WMAP “concordance” model (Spergel *et al.*, 2003). The solid green line is the cubic spline fitted to the observational data. The lower dashed curve is the linearly evolved matter spectrum corresponding to the best fitting model from the panel above, while the upper dashed line shows the spectrum after incorporating the treatment for the redshift space distortions and nonlinear evolution. The thin solid lines represent the “smoothed” models without baryonic oscillations. All the model spectra here are convolved with a survey window function. The vertical dotted lines mark the positions of the acoustic peaks in the CMB power spectrum.

## 2 Analyzed SDSS LRG sample

We analyze the publicly available data from the SDSS<sup>1</sup> DR4 (Adelman-McCarthy *et al.*, 2006).

Some characteristics of the analyzed LRG sample:

- Sample volume:  $\sim 0.75 h^{-3} \text{ Gpc}^3$ ,
- Sky area covered:  $\sim 3850 \text{ deg}^2$ ,
- Projected number density:  $\sim 12 \text{ deg}^{-2}$ ,
- Total number of galaxies: 51,763,
- Applied redshift cuts:  $z_{\min} = 0.16$  and  $z_{\max} = 0.47$ .

## 3 Power spectrum analysis

In the following we are going to present the measurement of the redshift-space power spectrum of the SDSS LRG sample given in Hütsi (2006a). We estimate the redshift-space “pseudospectrum” (i.e. spectrum convolved with the survey window) using the direct Fourier method of Feldman *et al.* (1994) (FKP). On intermediate scales and in the case where the power spectrum binning is chosen wide enough, FKP estimator gives a good approximation to the true underlying power. In addition to the convolving effect of the survey window there are several other sources that lead to the coupling of the Fourier modes e.g. nonlinear/quasilinear evolution, redshift-space distortions. These significantly complicate the error analysis. Although up to some level it is possible to use purely analytical approximations, we have chosen to estimate the power spectrum covariance using the Monte Carlo method. We generate 1000 mock catalogs having similar clustering amplitude and selection criteria as SDSS LRGs via the Poisson sampling of the large-scale density field generated by the “optimized” 2nd order Lagrangian perturbation scheme (2LPT) (see e.g. Sahni and Coles 1995). The performance of the 2LPT in comparison to the full N-body calculation is presented in Fig. 2.

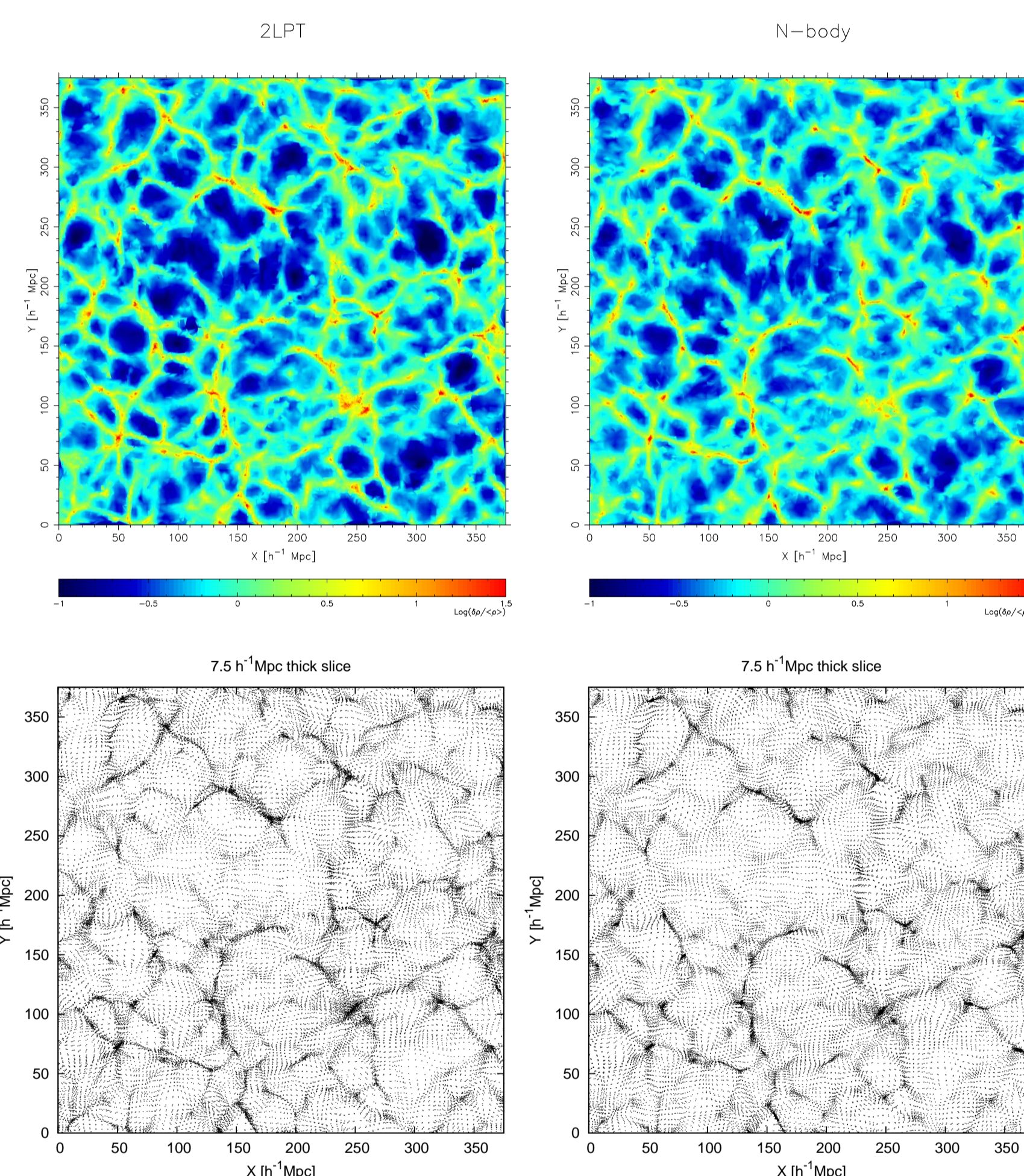


Figure 2: The performance of the “optimized” 2LPT (left-hand panels) with respect to the precise N-body (right-hand panels) calculation. The computational box had a side length of  $375 h^{-1} \text{ Mpc}$  and contained  $256^3$  dark matter particles. The upper panels show the cuts through the 3D density fields, constructed with the 3D Delaunay tessellation field estimator as described in Schaap and van de Weygaert (2000), whereas the lower panels display the corresponding particle distributions inside the  $7.5 h^{-1} \text{ Mpc}$  thick slices at the position of the cuts.

The measured power spectrum in a somewhat unusual form is given in the lower panel of Fig. 1.

Some results of the power spectrum analysis:

- We find evidence for a series of acoustic features in the LRG power spectrum down to scales of  $\sim 0.2 h \text{ Mpc}^{-1}$ , which corresponds to the 6th-7th peak in the CMB angular power spectrum. After correcting for nonlinearities and redshift-space distortions, the best-fit WMAP<sup>3</sup> cosmological model was found to produce a very good match to the determined LRG power spectrum. This should be considered as another great success of the current cosmological “concordance” model.
- Under the assumption of adiabatic initial conditions and a distance-redshift relation given by the best-fit WMAP cosmology, the low redshift acoustic scale was measured to be  $(105.4 \pm 2.3) h^{-1} \text{ Mpc}$ . Using WMAP data together with the prior on the Hubble parameter from the HST Key Project<sup>4</sup>,  $H_0 = 72 \pm 8 \text{ km/s/Mpc}$ , the corresponding scale would be predicted to be in the range  $(107 \pm 20) h^{-1} \text{ Mpc}$ , showing that our measurement provides approximately an order of magnitude improvement over that prediction.
- The models with baryonic features are favored by  $3.3\sigma$  over their “smoothed-out” counterparts without any oscillatory behavior, i.e. the acoustic features are detected at a relatively high confidence level.

## 4 Constraints on cosmological models

Using the obtained low redshift acoustic scale and also the full SDSS LRG power spectrum we have carried out the maximum likelihood cosmological pa-

rameter estimation via the MCMC techniques in Hütsi (2006). In this analysis we focused on adiabatic, spatially flat models with negligible massive neutrino and tensor perturbation contributions. The simplest 6-parameter cosmological model was extended with the dark energy effective equation of state parameter  $w_{\text{eff}}$ . To break the parameter degeneracies additional data from the WMAP experiment was included.

- The most remarkable result is the constraint obtained for the Hubble parameter  $H_0 = 70.8^{+1.9}_{-1.8} \text{ km/s/Mpc}$ .
- This precise measurement helped to break several parameter degeneracies and allowed us to measure the density parameters like  $\Omega_{\text{cdm}}$ ,  $\Omega_b$ , and also the dark energy equation of state parameter  $w_{\text{eff}}$  with significantly higher accuracy than available from the WMAP + HST data alone.
- Through the determination of these parameters we were able to constrain the low redshift expansion law of the Universe. Particularly, we found that a decelerating Universe is ruled out at the confidence level of  $5.5\sigma$ .

For other constraints obtained see Hütsi (2006).

## 5 Prospects for the future cluster redshift surveys

In the near future several SZ-cluster (Sunyaev and Zeldovich, 1980) surveys will be performed. These include shallow and wide surveys as provided by PLANCK satellite<sup>5</sup> or deep and narrower ( $\sim 10\%$  of the sky) surveys such as SPT<sup>6</sup>. The performance of these surveys along with the planned X-ray cluster surveys with a yield of up to 100,000 galaxy clusters<sup>7</sup> is given in Fig. 3. (For further details see Hütsi 2006b.) There the spectrum bin size  $\Delta k = 0.005 h \text{ Mpc}^{-1}$  was assumed. It is also useful to note that for the “concordance” cosmological model the relative amplitude of the acoustic features in the power spectrum is  $\sim 5\%$ .

There are a few advantages of using galaxy clusters rather than galaxies:

- With relatively small cluster samples it is possible to probe large cosmological volumes (thus reducing cosmic variance).
- The clustering signal of galaxy clusters is amplified with respect to that of galaxies.
- The relation with respect to the underlying dark matter field is rather well understood and also redshift space distortions are manageable since “fingers of god” could be avoided.

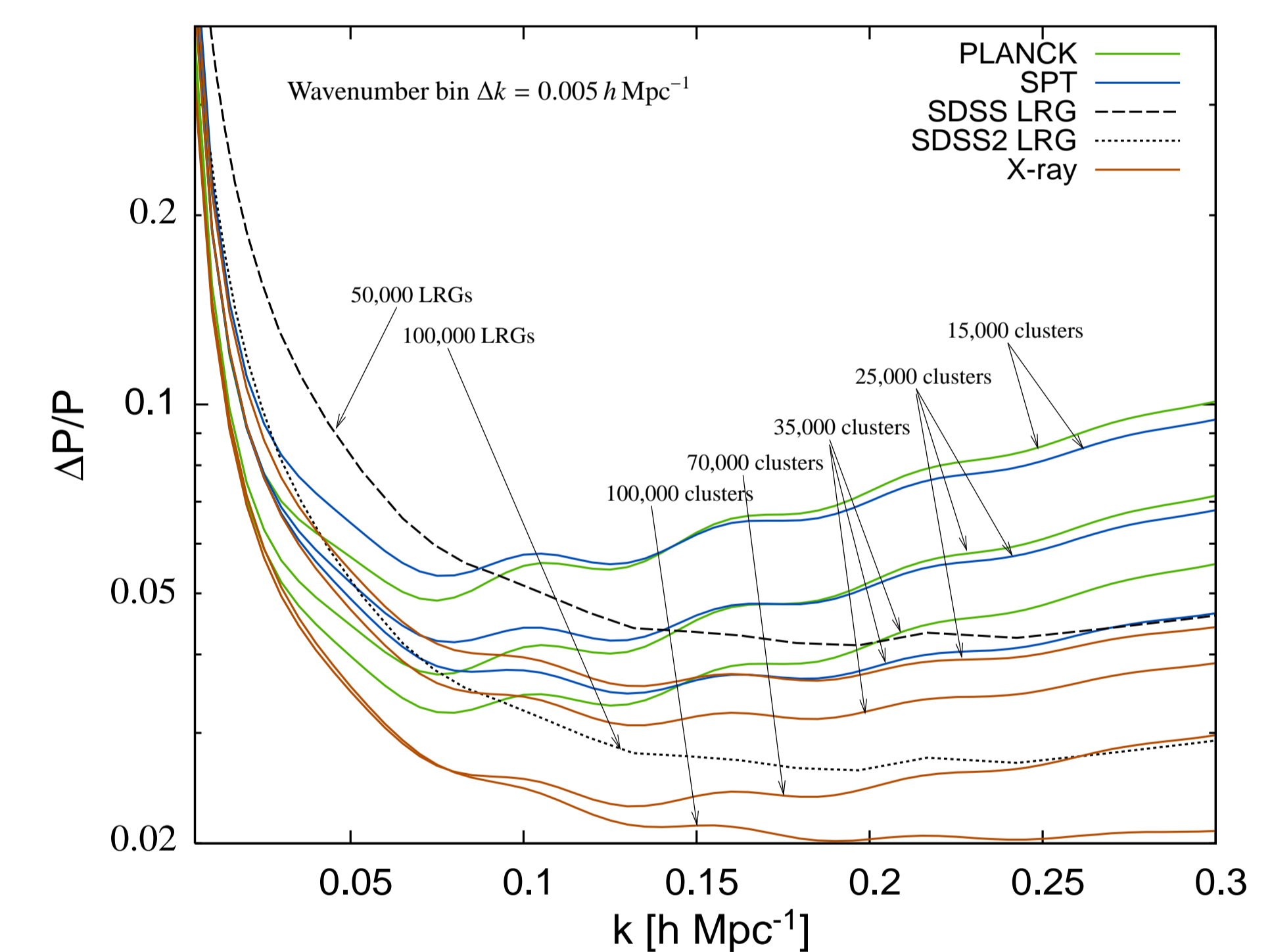


Figure 3: The performance of various cluster surveys in comparison to the SDSS LRG sample. For the SPT and PLANCK-like SZ surveys we have plotted the cases with 15,000, 25,000 and 35,000 detected galaxy clusters. The lines corresponding to the flux-limited X-ray survey represent the cases with 25,000, 35,000, 70,000 and 100,000 detected clusters. With the dotted lines we have also shown the obtainable accuracy of the power spectrum measurement once the SDSS redshift survey is completed within the few coming years. The PLANCK-like, SPT-like, and possible X-ray survey were assumed to cover the full sky, one octant, and 60% of the sky, respectively.

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<sup>1</sup>http://www.sdss.org/  
<sup>2</sup>For the analysis presented here we have excluded the three southern 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 sample to obtain more continuous and smooth chunk of volume.  
<sup>3</sup>http://lambda.gsfc.nasa.gov/  
<sup>4</sup>http://www.ipac.caltech.edu/H0kp/  
<sup>5</sup>http://www.rssd.esa.int/Planck/  
<sup>6</sup>http://spt.uchicago.edu/  
<sup>7</sup>For some information about the planned eROSITA survey see http://www.mpe.mpg.de/erosita/MDD-6.pdf