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Tracing the sound horizon scale with photometric redshift surveys

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Abstract

We propose a novel method for the extraction of the baryonic acoustic oscillation scale in galaxy photometric surveys. The evolution of this scale can be used as a standard ruler in order to constrain cosmological parameters. The method consists in parametrize the angular correlation function $\omega(\theta)$, with a simple analitical expresion, in order to extract the sound horizon scale. The method has been tested in the MICE simulation, one of the largest N-body simulation to date. We have considered projection effects, non-linearities and observational effects in our analysis, obtaining errors in cosmological parameters in agreement with what is expected in new generation surveys.

1 Introduction

In the early stages of the Universe, interaction between radiation and matter produced primordial perturbations in the photon-baryon fluid until those decouple ($z \approx 1100$). This created a high density region at a characteristic distance given by the sound speed in the primordial fluid. This high density profile shows as a peak in the galaxies spatial two-point statistics and a series of oscillation in Fourier space. These observations, together with WMAP7 and Type Ia supernovae, has yielded the concordance cosmological model: a spatially flat and late time accelerated universe.

In order to achieve higher accuracy, several galaxy surveys are planned in the near future, which will estimate redshifts using photometric data. Some examples are DES [6] or PAU [1]. The photometric redshift resolution depends mostly on the range of wavelengths covered by the filters in which the observations are done, and the number of filters and it will be always worse than its spectroscopic counterparts. That is why in photometric surveys we will generally need the analysis of angular statistics, like the two-point angular correlation function $\omega(\theta)$.

In this work, we introduce a new method based on an empirical parametrization of $\omega(\theta)$ in redshift shells. The goal is to recover the angle corresponding to the BAO scale and use it as a standard ruler in order to constrain properties of dark energy. This method is suitable for any galaxy survey with sufficient etendue.

2 The standard ruler method

The strength of the standar ruler method lays in the potential to relate straightforwardly the acoustic peak position in $\omega(\theta)$ with the sound horizon scale at decoupling. However, these two quantities are not exactly equal [4]. Thus, it's crucial to distinguish between the following two angular scales, $\theta_{\rm BAO} \equiv r_s/\chi(z)$, the angular scale of the BAO at decoupling and θ_p, the location of local maximum in $\omega(\theta)$. The peak position in the linear angular correlation function only approaches the sound horizon scale $\theta_{\rm BAO}$ for infinitesimal redshift shells. But in a photometric survey, there won't be such thing as an infinitesimal shell due to the uncertainty in redshift. It is well known that this induces two effects in the scales of the BAO peak. The first one is that the peak position shifts towards smaller angles with respect to the sound horizon scale (projection effects) and the second is that the amplitude of the peak gets reduced until the local maximum disappears and only a shoulder remains. This suggest that in a photometric survey, the measurement of $\theta_{\rm BAO}$ cannot be based on locating the local maximum in $\omega(\theta)$.

3 Method to recover $\theta_{\rm BAO}$

Adapting the measurement to photometric redshifts, we propose a new method based on an empirical parametrization of $\omega(\theta)$ and including the correction from projection effects. The full recipe is as follows:

- Divide the full galaxy sample in redshift bins.
- Compute the angular correlation function in each redshift bin.
- Parametrize the correlation function in each bin using the expression:

$$\omega(\theta) = A + B\theta^{\gamma} + Ce^{-(\theta-\theta_{\rm FIT})^2/2\sigma^2} \,, \tag{1}$$

  and perform a fit to $\omega(\theta)$ with free parameters A, B, C, γ, $\theta_{\rm FIT}$ and σ.

- The BAO scale is estimated using the parameter $\theta_{\rm FIT}$ and correcting from projection effects.

- Fit $\theta_{\rm BAO}$ as a function of redshift to constrain cosmological parameters.

3.1 Parametrization of $\omega(\theta)$

The correlation function is parametrized using Eq. 1. A power law is used to describe the underlying correlation around the BAO peak and a Gaussian to describe the BAO feature. We have tested the goodness of this parametrization in a redshift interval from $z = 0.2$ to $z = 1.5$ for a wide range of redshift bin widths and in 14 different cosmologies. Values of probabilities for all theoretical $\omega(\theta)$'s, range from 0.9 to 1 when the error in each point is $\sigma_{w(\theta)} \equiv 1\%$, a much better precision than what is expected in any realistic photo-z survey. For further details check Sanchez et al. [5].

Furthermore, we haven't considered in our theoretical models the effects of redshift space distortions. Those result in an anisotropic correlation function due to the translation of peculiar velocities into redshifts. The resulting angular correlation function can be then different in real and redshift space, althought with our parametrization we are able to absorb these effects and recover the same θ_{FIT} than without redshift space distortions. The same conclusion is applied if we consider a different galaxy bias than $b = 1$. For details check [5].

3.2 Correcting for projection effects

If we want the true BAO scale, it is necessary to correct the observed $\theta_{\rm FIT}$ in order to recover $\theta_{\rm BAO}$:

$$\theta_{\rm BAO} = \alpha\ \theta_{\rm FIT}\ , \tag{2}$$

where the function α could in principle be a function of redshift, bin width and cosmology. However if we want to correct in an unbiased way, it must be cosmology independent. Applying the method described in the previous section on all our theoretical $\omega(\theta)$, we obtain that: the correct BAO scale is recovered for all cosmologies in the case of infinitesimal redshift bin to a precision of $\leq 0.75\%$; and that the shift of $\theta_{\rm FIT}$ with respect to $\theta_{\rm BAO}$ has a universal shape, independent of cosmology. Thus the correction function α depends only on redshift and bin width: $\alpha \equiv \alpha(z, \Delta z)$.

These results are presented in Fig. 1, where we plot the evolution of the shift, taking the angular scale corresponding to the sound horizon scale as a reference, for 5 different redshifts, for several bin widths and for the 14 cosmological models. After this correction, the true value for the BAO scale is recovered for any bin width and cosmology, where the uncertainty is evaluated as the width of the band.

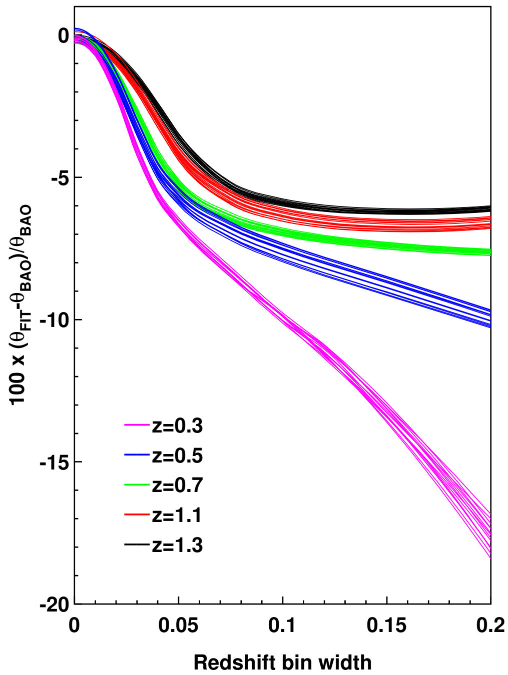

Figure 1: Evolution of the shift of the measured $\theta_{\rm FIT}$ w.r.t. the true value, for different widths and redshifts, for 14 cosmological models.

4 Application to a N-body simulation

We have developed and tested our method to recover the angular scale of the sound horizon using a large N-body simulation capable of reproducing the geometry (e.g. area, density and depth) and specifications of DES [1].

The simulated data was provided by the MICE team and consisted of a distribution of dark matter particles (galaxies, from now on) with the cosmological parameters fixed to a ΛCDM model. The simulation covers 1/8 of sky in the redshift range $0.2 < z < 1.4$, containing 50 million galaxies. More details about this run can be found in [2].

We have inserted the uncertainty in redshift in the simulation by randomly scattering galaxy positions with the expected photo-z uncertainty for DES. Also, the redshift bin widths have been chosen as a compromise between statistics and expected precision in the photo-z. With this prescription, we have set 14 bins up to $z = 1.5$.

We numerically estimate the angular correlation function in each redshift bin with the Landy-Szalay estimator [3]. The resulting correlation functions, together with their parametrizations can be seen in [5]. We have also quantified systematic errors, identifying five main systematics that are summarized in Table 1. For details check [5].

[1] http://www.darkenergysurvey.org

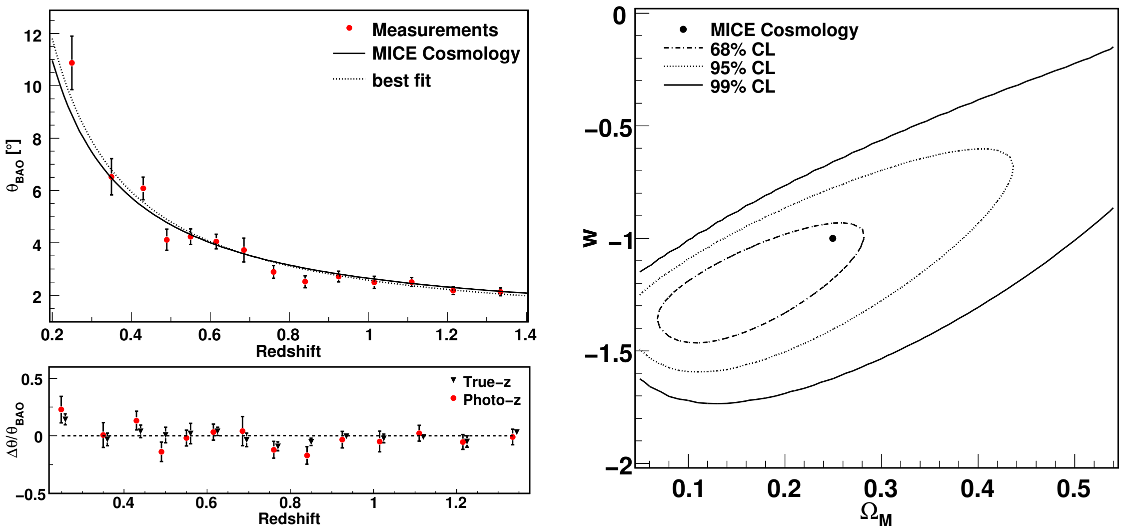

Figure 2: Evolution of the measured $\theta_{\rm BAO}$ with the redshift and comparison of the results obtained using photo-z and the true-z (*left*). Allowed region for the cosmological parameters at 68 (dashed-dotted line), 95 (dashed line) and 99 (solid line) % C. L. The input cosmology, given by the dot, is recovered within 1 σ (*right*).

The recovered values of $\theta_{\rm BAO}$ can be seen in Fig. 2 (left) as a function of redshift. Points include systematic and statistical errors. The input MICE cosmology is also shown as the solid line, and the best fit cosmology as the dashed line. To compare, the same analysis has been applied to the true redshifts catalog (i.e., without photo-z errors). This result is presented in the bottom panel of Fig. 2 (left), as the residual to the input cosmology, together with the photo-z result.

By minimizing χ^2 with respect to w and Ω_M, considering correlations, we are able to recover the input cosmology. The confidence intervals are shown in Fig. 2 (right), where the MICE cosmology is inside the 1σ contours. If we restrict ourselves to a one-dimensional analysis and fix $\Omega_M = 0.25$, we obtain for the equation of state of the dark energy $w = -1.05 \pm 0.14$. These results are in good agreement with the Fisher matrix forecasts for BAO in DES [6].

Table 1: Estimation of systematic errors.

Systematic error	$\Delta\theta_{\rm BAO}$	Correlated between bins
Parametrization	1.0%	No
Photometric redshift	5.0%	Yes
Redshift space distortions	1.0%	Yes
Theory	1.0%	No
Projection effect	1.0%	No

5 Conclusions

We have developed a new method to measure the BAO scale in the angular two-point correlation function of galaxies. This method is adapted to photometric redshift surveys, where the information along the line of sight is lost due to the photo-z precision, and only the angular information survives. Two main results are found. First, the sound horizon scale can be recovered from the non-linear angular correlation functions to a precision $\leq 0.75\%$ applying the parametric fit described in the text, for any cosmological model and also for infinitesimal redshift shells. Second, the shift of the BAO peak due to projection effects has a universal shape, does not depend on the cosmological model, and only depends on the redshift and the redshift bin width. This can be used to correct the result obtained for wide photo-z bins and recover the true sound horizon scale. The method has been tested with a mock catalog built upon a large N-body simulation provided by the MICE collaboration, with characteristics similar to those expected in DES. The input cosmology is recovered within 1σ. The correlation between redshift bins and a preliminary evaluation of the systematic errors have been included in this study, and we find that the most important systematic error arises from the photo-z precision. The method is very promising and very robust against systematic uncertainties.

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