Measuring BAO using photometric redshift surveys.

Aurelio Carnero Rosell.
E. Sanchez Alvaro, Juan Garcia-Bellido, E. Gaztanaga, F. de Simoni, M. Crocce, A. Cabre, P. Fosalba, D. Alonso.

10-08-10

Punchline of the talk.

1. We propose a new method to extract the BAO scale from the 2-pt angular correlation function $\omega(\theta)$.

2. The goal is to use this information in order to constrain cosmological parameters using BAO as a standard ruler.

3. Method tested in many different cosmologies and in N-body simulation with photo-z effects.

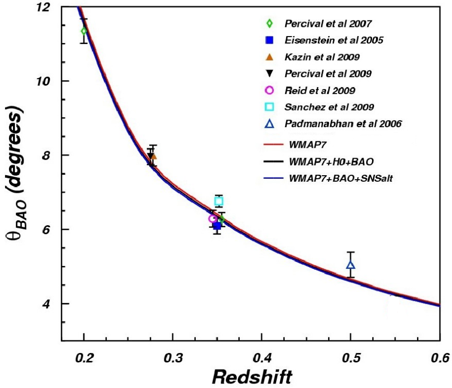
4. Also a systematic errors' study.

Introduction.

BAO detection.

- BAO confirmed in the galaxy power spectrum & correlation function.
- Mainly with spectroscopical data.
- New surveys aiming at the study of Dark Energy.
- Two ways of improvement:

Current status



1. more spectra. Spectroscopic surveys.
2. more volume and statistic. **Photometric surveys**.

Upcoming galaxy surveys.

Spectrocopic surveys

- BOSS, BigBOSS
- WiggleZ
- Hetdex
- WFMOS...

Photometric surveys

- DES
- Pan-Starrs
- HSC
- PAU...

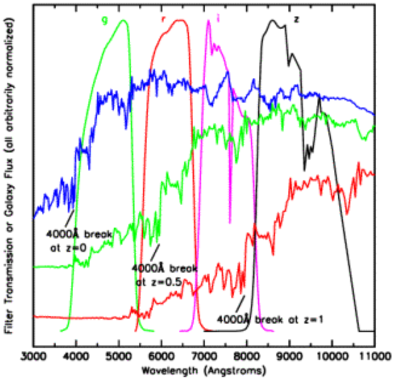
Check other talks in Benasque for more information about these or other surveys

- T.Davis in Wigglez.
- N.Kaiser in Pan-STARRS.
- P.Norberg in Gama.
- J.Frieman in DES.

In photometric surveys.

- Higher accuracy by a larger volume and larger number of observed galaxies even if photo-z have lower precision compared to their spectroscopic counterparts.
- Impossible to infer the true 3-dimensional clustering pattern. The analysis of angular statistics, like the 2-pt angular correlation function $\omega(\theta)$ and the angular power spectrum C_l is required.

Photo-z error depends mostly on the range of wavelengths covered by the filters and number of them.



We propose a new method.

- GOAL: To recover the BAO scale as a function of redshift and obtain the properties of the dark energy from its evolution.
- Generic to any photometric surveys but tuned with DES expectations.
- Use only as a standard ruler. We do not try to use the whole shape of the correlation function or power spectrum.
- Less sensitive to systematic errors.

Most of results are in Arxiv preprint *arxiv:1006.3226* (submitted to MNRAS).

Angular clustering.

Relation between $\xi(r)$ and $\omega(\theta)$:.

$$\omega(\theta) = \int_0^\infty dz_1 \phi(z_1) \int_0^\infty dz_2 \phi(z_2) \xi(r; \bar{z})$$

- No small angle approximation (Limber's approximation).
- $P(k)$ from CAMB. Galaxy bias b=1.

Nonlinearities.

We introduce non-linear matter clustering with RPT (gaussian smoothing):
$P_{NL} = P_L e^{-k^2 \sigma_v^2(z)/2}$ $\quad \sigma_v(z) = [\frac{1}{6\pi^2} \int_0^\infty dk P_L(k; z)]^{-1/2}$
We discard the contribution of the additive mode-coupling term to $P(k)$. $\rightarrow$ For aclarations ask Gaztanaga & Crocce.

Angular clustering.

Covariance matrix of $\omega(\theta)$

Is defined as: $Cov_{\theta\theta'} \equiv < \omega(\theta)\omega(\theta') >$. For a given survey can be estimated by:

$$Cov_{\theta\theta'} = \sum_{l\geq 0} \frac{2(2l+1)P_l(cos(\theta))P_l(cos(\theta'))}{(4\pi)^2 f_{sky}} [C(l) + \frac{1}{N/\Delta\Omega}]^2$$

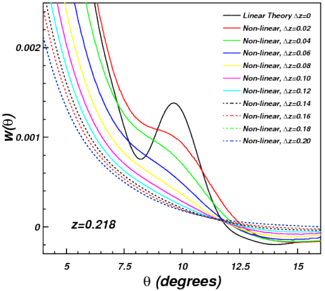
Where f_{sky} is the fraction of the sky covered by the survey and the ratio $N/\Delta\Omega$ is the number of galaxies per unit of solid angle.

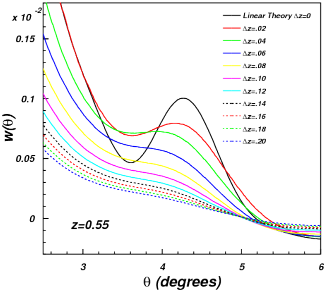
Errors in $\omega(\theta)$ obtained from the covariance matrix.

Reference: Crocce, Cabre, Gaztanaga. Arxiv:: 1004.4640

BAO as a standard ruler.

- The standard ruler method lays in the potential to relate the acoustic peak position in the correlation function of galaxies to the sound horizon scale at decoupling.
- We have to distinguish between $\theta_{BAO} \equiv r_S/\chi(z)$ and θ_{FIT}.





Method to recover θ_{BAO}.

1. Divide the full sample in redshift bins.
2. Compute the angular two-point correlation function in each redshift bin.
3. Parametrize the correlation function using the expression:

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

   and perform a fit to $\omega(\theta)$ with free parameters A,B,C,$\gamma, \theta_{FIT}, \sigma$.
4. The BAO scale is estimated using the parameter θ_{FIT} and correcting it for the projection effect: $\theta_{BAO}(z) = \alpha(z, \Delta z)\theta_{FIT}(z)$
5. Fit cosmological parameters to the evolution of the corrected θ_{BAO} with z.

Tests

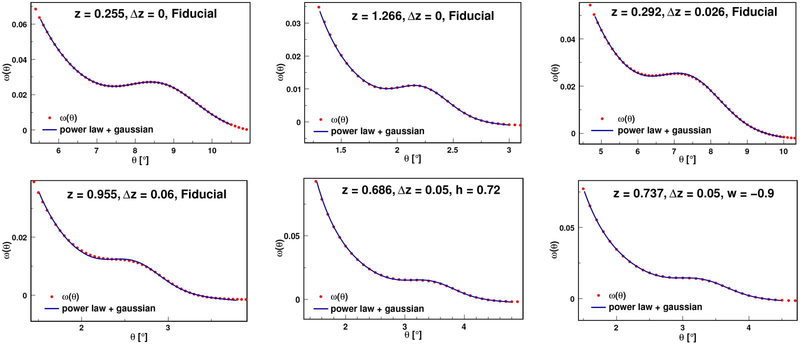
We have tested the method in two steps

1. In theoretical $\omega(\theta)$ in many different cosmologies.
2. In a N-Body Simulation including observational effects.

Calibration on theoretical $\omega(\theta)$

We tested the goodness of this parametrization in various redshifts, ranging from 0.2 to 1.4 for a wide range of widths of the redshift bins and for 14 cosmological models.

- errors in each point of $\omega(\theta)$ is $\sim 1\%$. Less than in any real survey.
- Fits to our parametrization are always $\chi^2/ndof << 1$. Excelent fit!



Calibration on theoretical $\omega(\theta)$

We tested the goodness of this parametrization in various redshifts, ranging from 0.2 to 1.4 for a wide range of widths of the redshift bins and for 14 cosmological models.

- errors in each point of $\omega(\theta)$ is $\sim 1\%$. Less than in any real survey.
- Fits to our parametrization are always $\chi^2/ndof << 1$. Excelent fit!

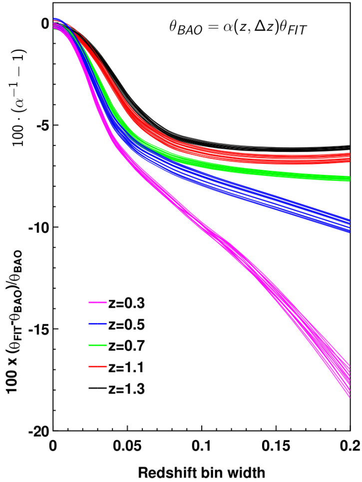
h	Ω_M	Ω_b	Ω_k	w_0	w_a	n_s
0.70	0.25	0.044	0.00	−1.00	0.0	0.95
0.68						
0.72						
	0.20					
	0.30					
		0.040				
		0.048				
			+0.01			
			−0.01			
				−0.90		
				−1.10		
					−0.1	
					+0.1	
						1.00

KEY POINT!

Projection effect can be corrected independently of cosmology.

Correcting for projection effects.

1. Applying parametrization to all 770 $\omega(\theta)$:
2. We can correct θ_{FIT} to obtain θ_{BAO} independent of cosmology.
3. In each band there are 14 cosmological models. Half width of band is the error in the correction.
4. Observe this is relative offset. In absolute, θ_{BAO} is different for each model.

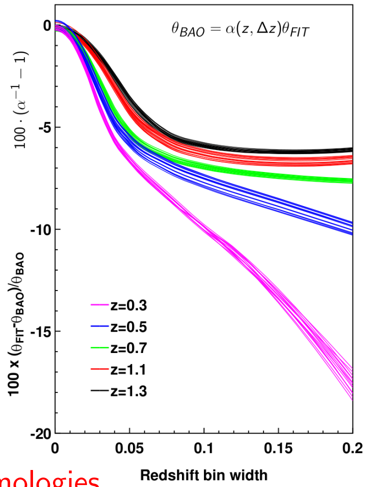


KEY POINT!

Projection effect can be corrected independently of cosmology.

Correcting for projection effects.

1. In a infinitesimal bin width, we recover the exact theoretical value of θ_{BAO} for all cosmologies with an error of the order of 10^{-3}.
2. The correction is greater for low redshifts and for wider bins.

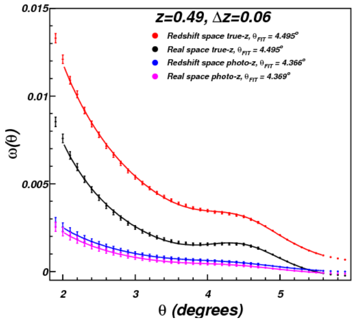


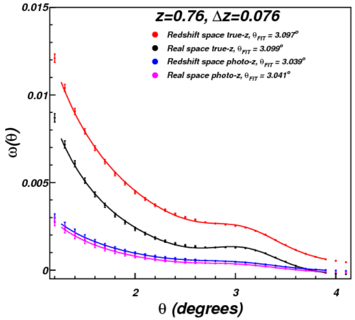
Caveat: Only tested in FRW Cosmologies

Redshift-space distortions.

Redshift Space Distortions in photometric surveys.

- Redshift-space distortions are important in redshift bins analysis and need to be considered. Percival's talk.
- The main effect is an increase in overall amplitude.
- Nonetheless, doesn't move θ_{FIT} with our parametrization to the level of 10^{-3}. The other parameters absorb RSD.
- True-z vs Photo-z



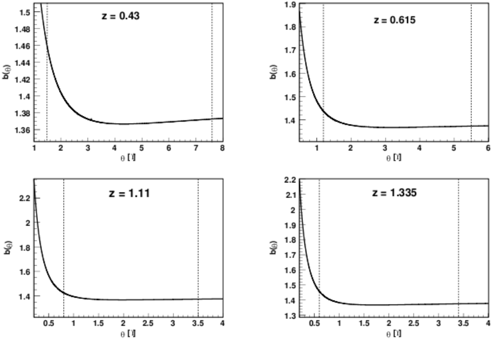


Galaxy bias

We have also studied the effect of galaxy bias in our results:

- **Scale independent bias**: $\omega(\theta)_b = b(z)^2\omega(\theta)$. errors are rescaled correspondingly. Results in θ_{FIT} do not change.

- **Scale dependent bias**: We produce a toy model, i.e.: $\omega(\theta)_b = b(z,\theta)^2\omega(\theta)$. The new values of θ_{FIT} are within 1% variation of the values without any bias
- Bigger effect at low redshift.
- Bias is important at low θ, but model is robust against variations of bias within 20%.



We can neglect the effects of bias in our analysis. In the sense θ_{FIT} doesn't change.

Summary of the method.

- We propose a new method to extract the BAO scale from $\omega(\theta)$:

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

- We can correct θ_{FIT} to obtain θ_{BAO} independent of Cosmology in FRW ones.
- The statistical error in θ_{BAO} comes from the fit to θ_{FIT}.
- effects of redshift-space distortions and bias are crucial if we want a fit to the full shape of $\omega(\theta)$, but not in our parametrization. They are only a small source of uncertainty.

Summary of the method.

- We propose a new method to extract the BAO scale from $\omega(\theta)$:
$$\omega(\theta) = A + B\theta^{\gamma} + Ce^{-(\theta-\theta_{FIT})^2/2\sigma^2}$$
- We can correct θ_{FIT} to obtain θ_{BAO} independent of Cosmology in FRW ones.
- The statistical error in θ_{BAO} comes from the fit to θ_{FIT}.
- effects of redshift-space distortions and bias are crucial if we want a fit to the full shape of $\omega(\theta)$, but not in our parametrization. They are only a small source of uncertainty.

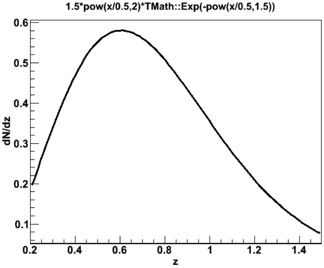
What happens if we include observational effects?: We have studied our parametrization over a large N-body simulation.

MICE Simulation.

http://segre.ieec.uab.es/fosalba/MICE/

Dark Energy Survey Simulation Challenge.

- Publicly available.
- Same volume and σ_z than expected in DES survey.
- 5000sq degrees. 5e7 particles.



Fiducial Cosmology.

MICE Simulation Common Parameters

Baryon density, $\Omega_b = 0.044$

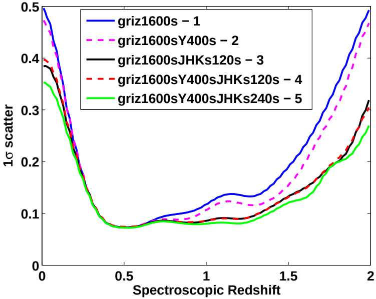
Matter density, $\Omega_m = 0.25$

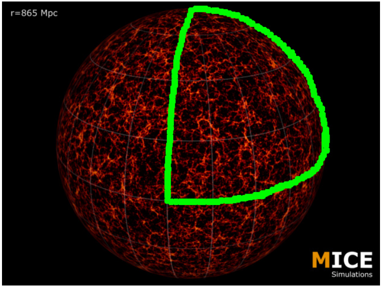
Dark-energy density, $\Omega_\Lambda = 0.75$

Scalar spectral index, $n_s = 0.95$

Rms matter fluctuation amplitude, $\sigma_8 = 0.8$

Hubble paramter (in units of 100 km/sec/Mpc), h = 0.7





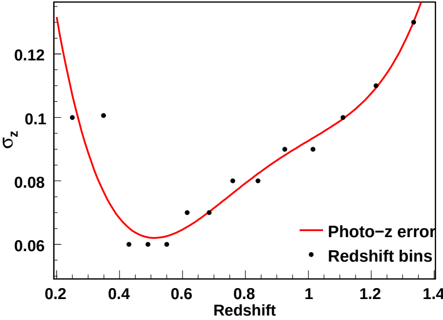
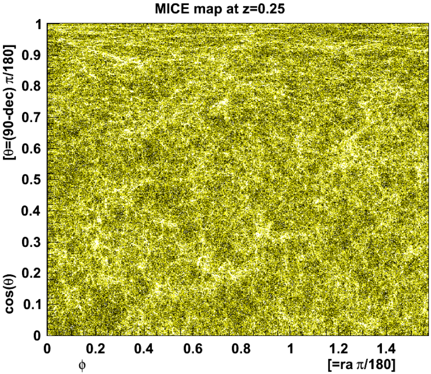


Photo-z in MICE

- We introduce photo-z in MICE by smearing each galaxy redshift by the expected $\sigma(z)$ distribution.
- All results include this photo-z distribution.
- Following $\sigma(z)$ distribution we construct 14 bins of redshift, from $z = 0.2$ to $z = 1.5$.

MICE MAPS

- 14 bins: In each one construct galaxy map.
- x-axis is ϕ and y-axis is $cos(\theta)$ so all pixels have same area in a square grid.
- 636x636 pixels. (equivalent to a healpix $N_{side} = 512$: $\Delta\theta \approx 0.1°$).



Building the angular correlation function $\omega(\theta)$.

- From maps, compute $\omega(\theta)$ using the Landy & Szalay estimator:

$$\omega(\theta) = \frac{DD(\theta) - 2DR(\theta) + RR(\theta)}{RR(\theta)}$$

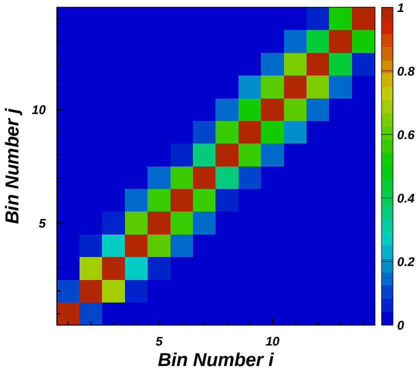
- We build random maps with same number of galaxies (no limited by shot-noise).

BAO "extraction"

- In each $\omega(\theta)$ we apply fit to the parametrization around the peak.
- We correct $\theta_{BAO} = \alpha(z, \Delta z)\theta_{FIT}$, where $\Delta z_{true} = \sqrt{2\pi}\Delta z_{phot}$. Where Δz_{true} is the true redshift width such as the amplitude of $\omega(\theta)$ in z_{true} is the same as in z_{phot}.
- Statistical error in $\omega(\theta)$ is given by $Cov_{\theta\theta'}$ and including correlations between redshift bins.

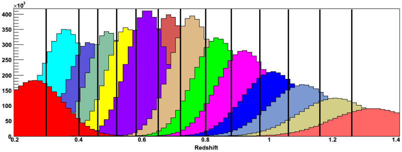
Covariance matrix

- Due to photo-z uncertainty there is galaxy migration between bins.
- Using the mixing matrix (by counting galaxies in bins of true-z and photo-z) and correlations between θ's, we obtain correlation matrix for θ_{BAO}.
- We calculate the covariance matrix, including correlated and uncorrelated errors in θ_{BAO}.

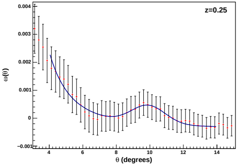


$$C_{ij} =< w_i^O(\theta) w_j^O(\theta') >= \sum_{k=1}^{N_{bins}} (r_{ik}^2 r_{jk}^2) \frac{(N_k^T)^4}{(N_i^O)^2 (N_j^O)^2} \mathrm{Cov}_{\theta\theta'}$$

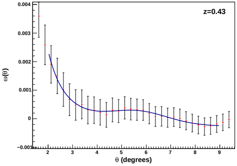
Where r_{ij} are the mixing matrix elements, N_i^T are the number of galaxies with true-z in bin i and N_i^O are the number of galaxies with photo-z in bin i.



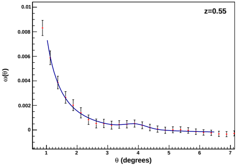
Results for MICE Simulation



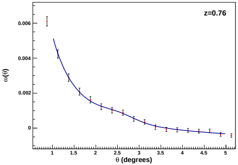
$\chi^2/dof = 0.1 \quad Prob = 1$



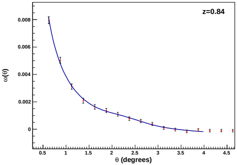
$\chi^2/dof = 0.15 \quad Prob = 1$



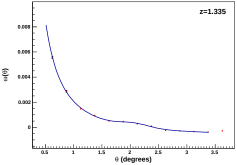
$\chi^2/dof = 0.4 \quad Prob = 0.97$



$\chi^2/dof = 0.5 \quad Prob = 0.8$



$\chi^2/dof = 0.87 \quad Prob = 0.5$



$\chi^2/dof = 1.6 \quad Prob = 0.13$

Main systematics errors.

- Photo-z.
- Redshift space distortions.
- Parametrization
- Theory (non-linearities) and projection correction error.

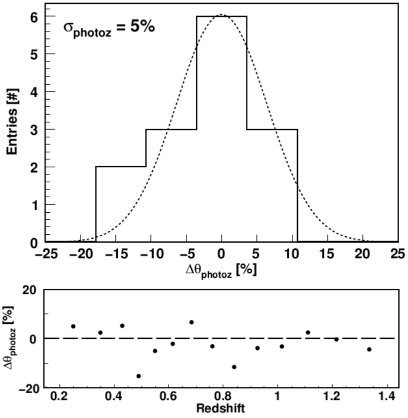
Not considered.

- Selection of galaxies.
- Sample contamination.
- Masking.
- These are small effects (In progress).

Systematic errors.

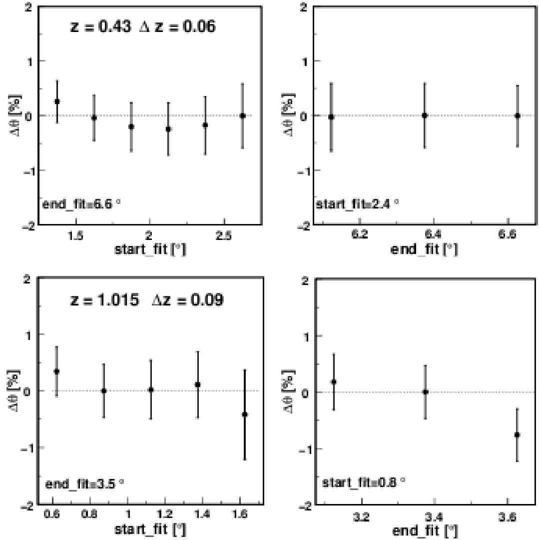
Photo-z error

- By redoing the analysis with true redshift, for same bins, we can compare to photo-z. Look at the difference in θ_{FIT} for true-z and photo-z.
- Its dispersion associated to σ_{photoz}. For our set of bins and $\sigma(z)$: $\sigma_{photoz} = 5\%$
- To study z dependence we would need many mock catalogues.
  $\rightarrow$ In progress.
- It's the greatest source of error in θ_{BAO}.
- Correlated between redshift bins.



Systematic errors.

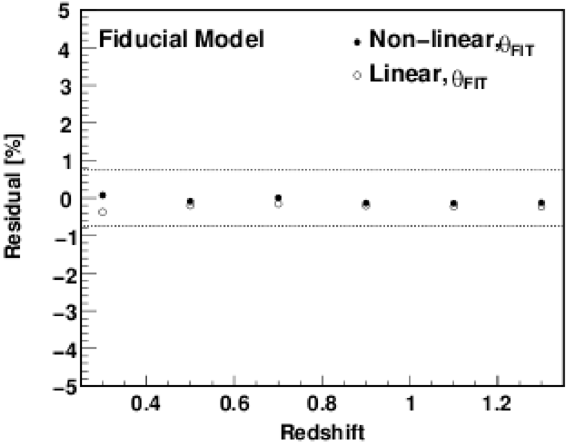
Parametrization error: Error coming from the decision of the region where we perform the fit in $\omega(\theta)$.



Systematic errors.

Uncorrelated systematics

- Theory: Uncertainties in the theory coming from the implementation of non-linearities.



Systematic errors.

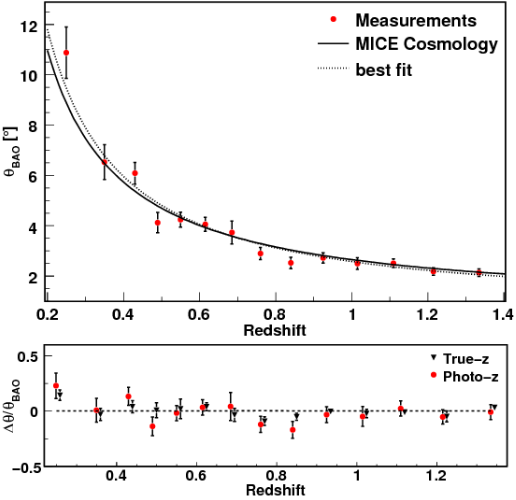
Uncorrelated systematics

- Projection effect: Uncertainty coming from the error in the parameter α:
- Redshift Space Distortions: Difference in θ_{FIT} by including RSD.
- All these four effects are subdominant. We have set them to 1% CONSERVATIVE.

Errors

Systematic error	$\Delta\theta_{BAO}$	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
Statistical error	5-10%	Yes

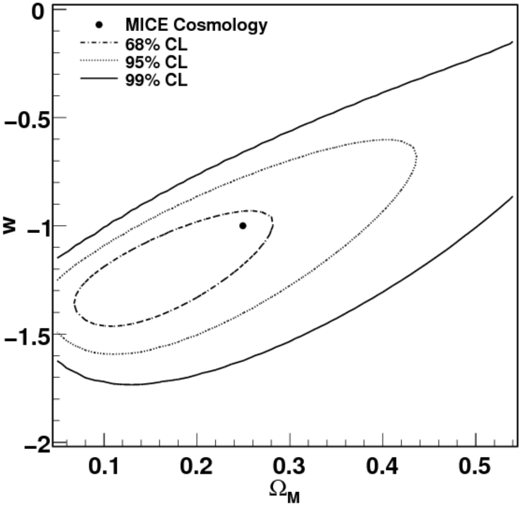
θ_{BAO} vs z



- Total error is $\sigma(\theta_{BAO})^2 = \sigma^2_{stats} + \sigma^2_{sys}$
- Also shown, results obtained without photo-z (*true-z*).
- Minimize χ^2 w.r.t. Ω_M & w:

$$\chi^2 = (\theta_{BAO} - \frac{r_S}{\chi(z)})_i C^{-1}_{ij} (\theta_{BAO} - \frac{r_S}{\chi(z)})_j$$

Cosmological constrains



- Other parameters fixed to their true values.
- Include correlations between bins.
- In good agreement with DES expectations.

if $\Omega_M = 0.25$ $w = -1.05 \pm 0.14$ and if $w = -1$ $\Omega_M = 0.23 \pm 0.05$

Conclusions.

1. We have propose a new method to use BAO's as a standard ruler in photo-z surveys. The shift due to projection is cosmology independent to 0.75%.
2. Method tested in many different cosmologies and in N-body simulation with photo-z effects.
3. We recover the input cosmology.
4. The dominant systematic error comes from photo-z precision. We have also studied bias, RSD effects.
5. Next step: Test method with real survey data.

True-z results.

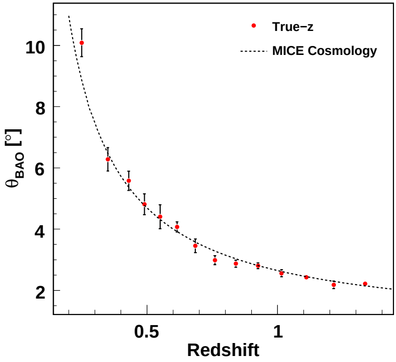


Figure: Plot of θ_{BAO} vs z. True-z.

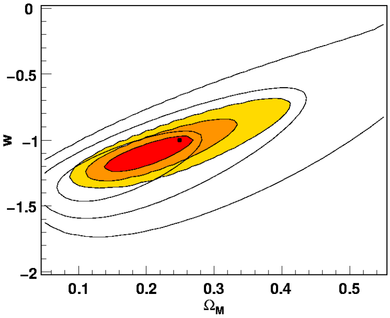


Figure: Contours for true-z, covariance is diagonal.