Measuring BAO in Photometric Redshift Surveys

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CIEMAT

The Nature of the Dark Energy
UAM (Madrid) 2011

E. Sánchez et al. MNRAS 411 (2011) 277
A. Carnero et al. ArXiV 1104.5426 [astro-ph]
M. Crocce et al, ArXiV 1104.5236 [astro-ph]

OUTLINE

Introduction: BAO Measurements and Photometric Surveys

A New Method to Measure BAO

Standard Ruler
Description of the Method
Calibration on Theoretical Calculations

Application to a Cosmological Simulation

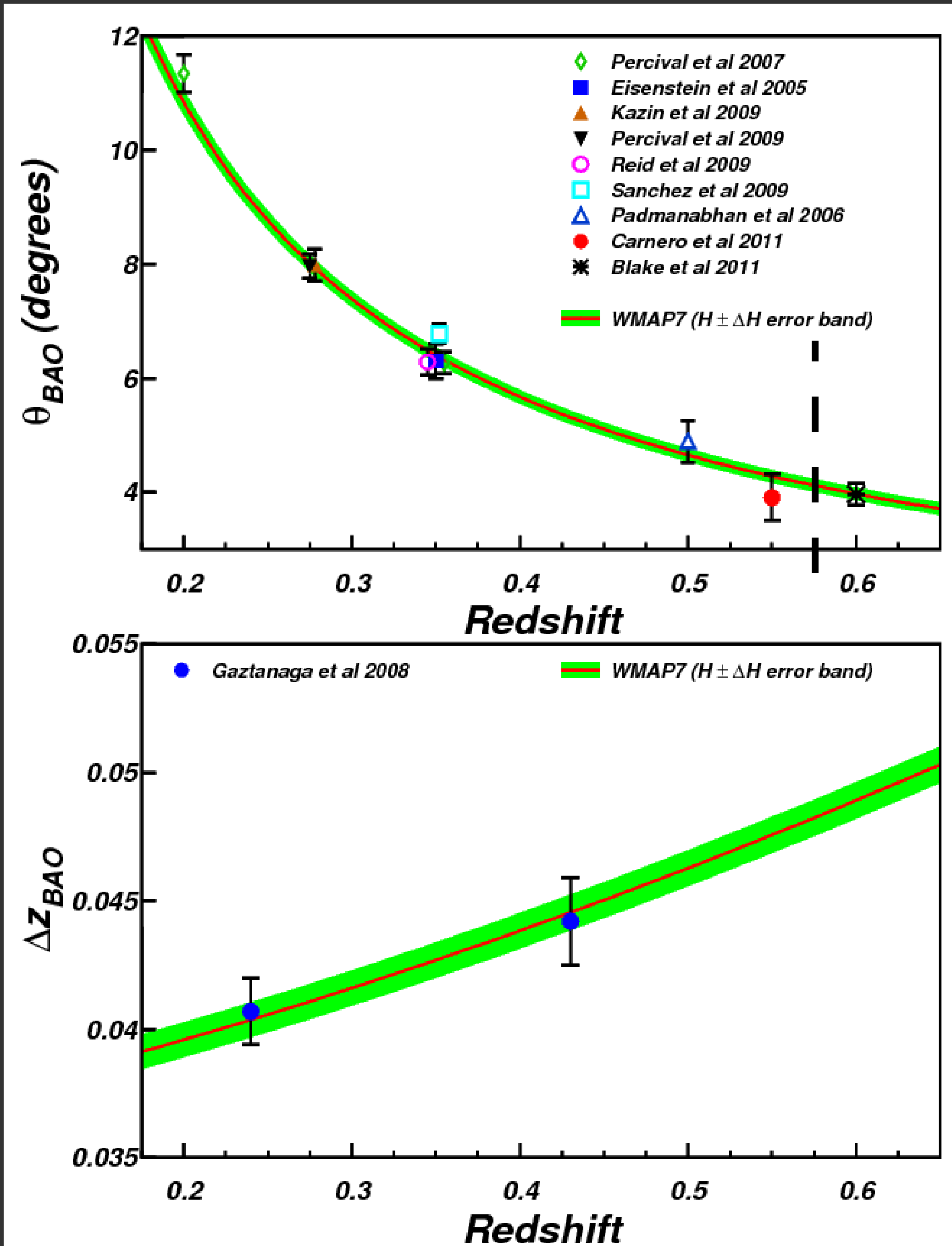
MICE simulation
Photometric Redshift
Correlation Functions
Application of the Method
Results: Forecasts for next surveys

Application to Real Data: SDSS

Selection of the Galaxy Sample
Photometric Redshifts
Correlation Functions
Results

Conclusions

INTRODUCTION



CURRENT SITUATION

Almost all the measurements of the BAO scale have been done using spectroscopic galaxy surveys (except that at z=0.5)

Use a combination of angular and transverse distances

NEW LARGE GALAXY SURVEYS ARE COMING

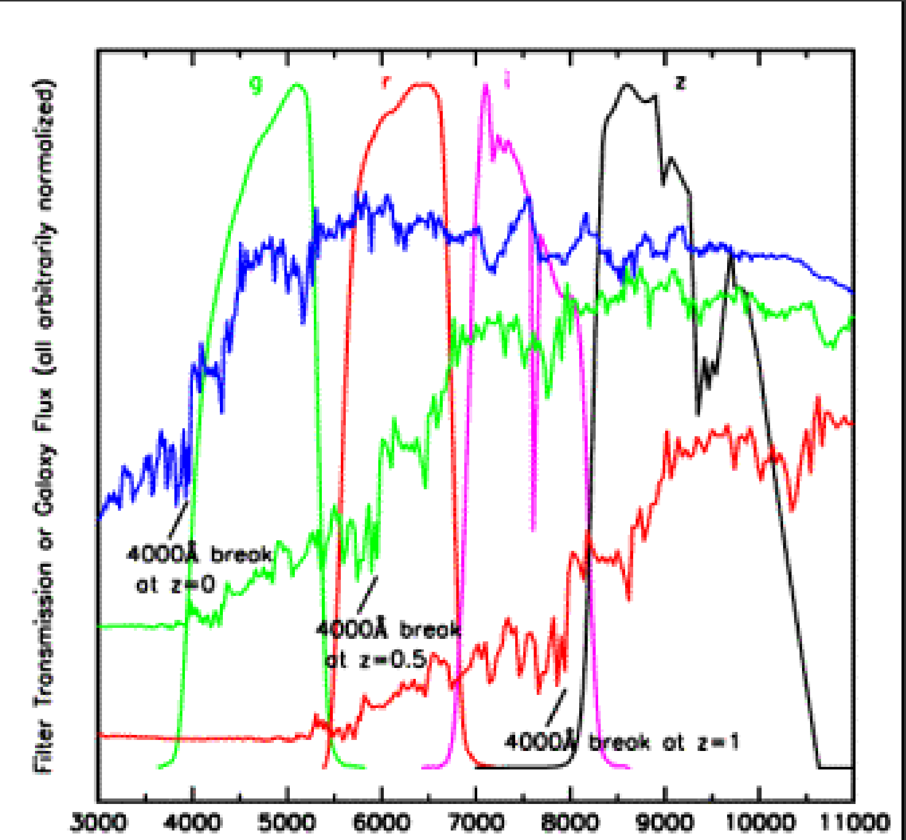
1. Spectroscopic (precision redshifts)
2. Photometric (volume and statistics)

Sensitivity of photometric surveys beyond Fisher matrix: Systematic errors

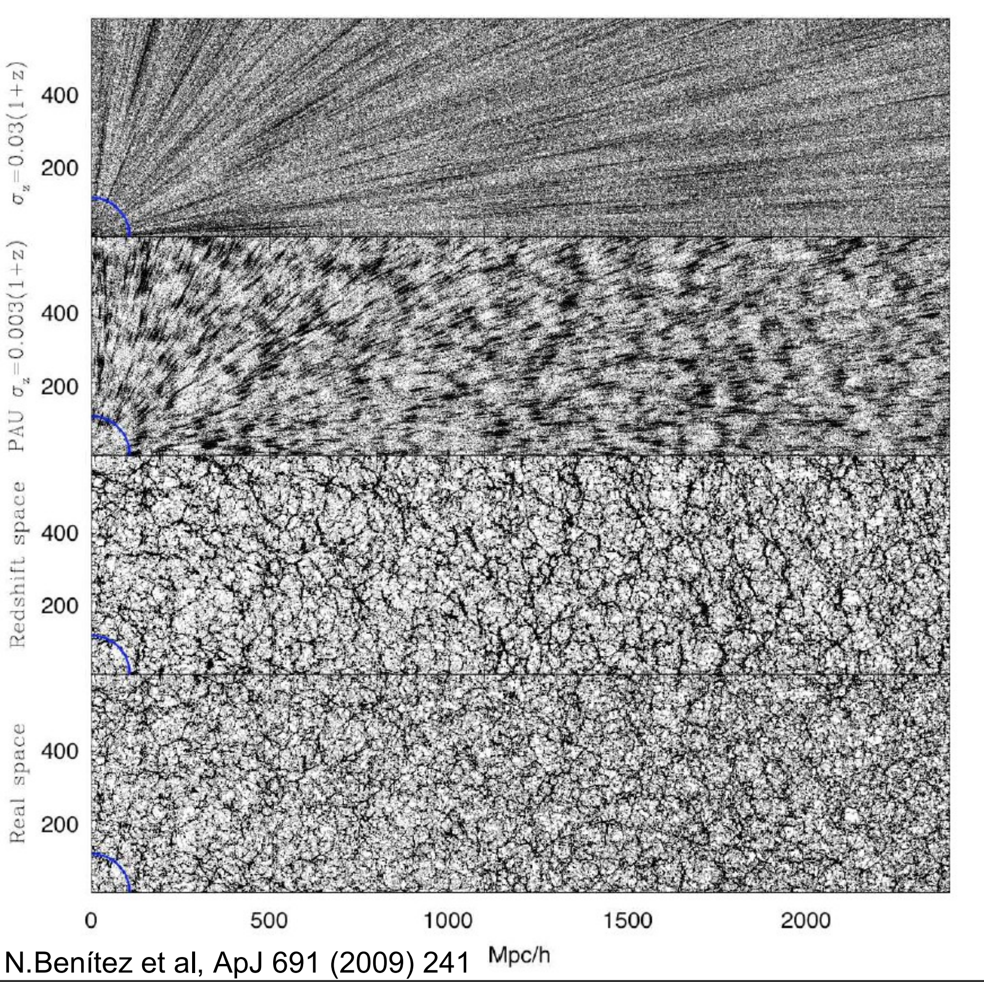
INTRODUCTION
Large Galaxy Surveys

Spectroscopic
BOSS (taking data)
WiggleZ (finished)
BigBOSS...

Photometric
DES (Starting october 2011)
PanStarrs (taking data)
PAU...



From SDSS



N.Benítez et al, ApJ 691 (2009) 241

NEW METHOD TO MEASURE BAO

Try to optimize the power of upcoming photometric galaxy surveys, mainly to study the nature of the dark energy

Use only observable quantities, maintain the method model independent (no fiducial models)

Avoid any bias when constraining exotic cosmological models

Minimize the impact of systematic errors

Use BAO as a standard ruler. Do not try to fully describe the correlation function, but only localize the BAO scale with the maximum precision

ANGULAR CLUSTERING

Angular correlation function of galaxies: Excess joint probability that two galaxies are found in two solid angle elements with angular separation θ compared to a homogeneous Poisson distribution.

PROJECTION OF THE 3D FUNCTION

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

$$\bar{z} = (z_1 + z_2)/2 \qquad r = \sqrt{\chi(z_1)^2 + \chi(z_2)^2 - 2\chi(z_1)\chi(z_2)\cos\theta}$$

$$\xi(r;z) = \int_0^\infty \frac{dk}{2\pi^2} k^2 j_0(kr) P(k;z) \qquad \chi(z) = \frac{c}{H_0}\int_0^z \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}}$$

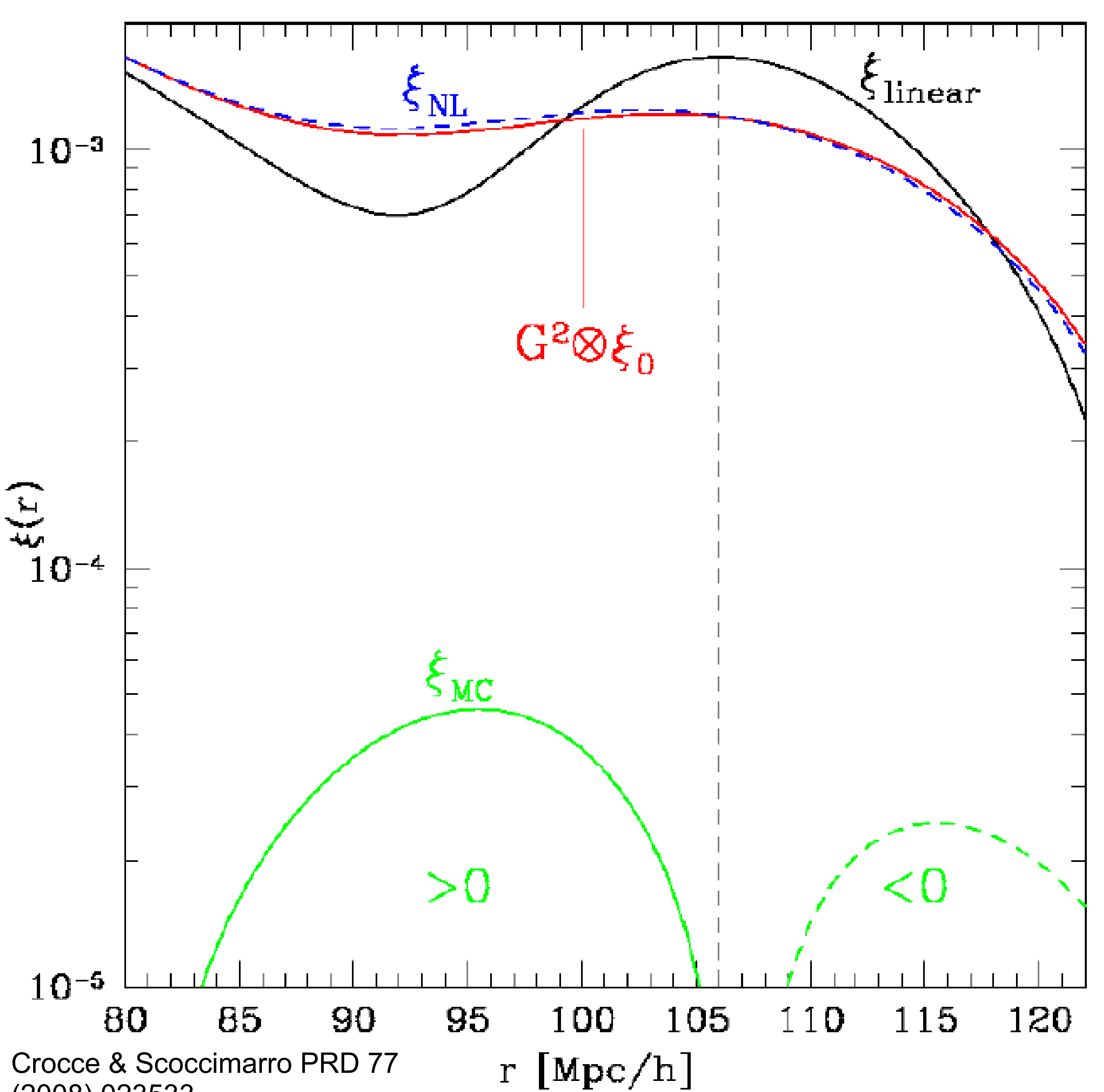
No small angle approximation (Limber)
PL(k) from CAMB.

NON-LINEARITIES as Renormalized perturbation theory (no mode-mode coupling term)

$$P_L \;\rightarrow\; P_L e^{-k^2\sigma_v^2(z)/2}$$

$$\sigma_v(z) = \left[\frac{1}{6\pi^2}\int_0^\infty dk P_L(k;z)\right]^{-1/2}$$

ANGULAR CLUSTERING



Crocce & Scoccimarro PRD 77 (2008) 023533

ANGULAR CLUSTERING

COVARIANCE (statistical error)

$$\mathrm{Cov}_{\theta\theta'} \equiv \langle \omega(\theta)\omega(\theta') \rangle$$

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

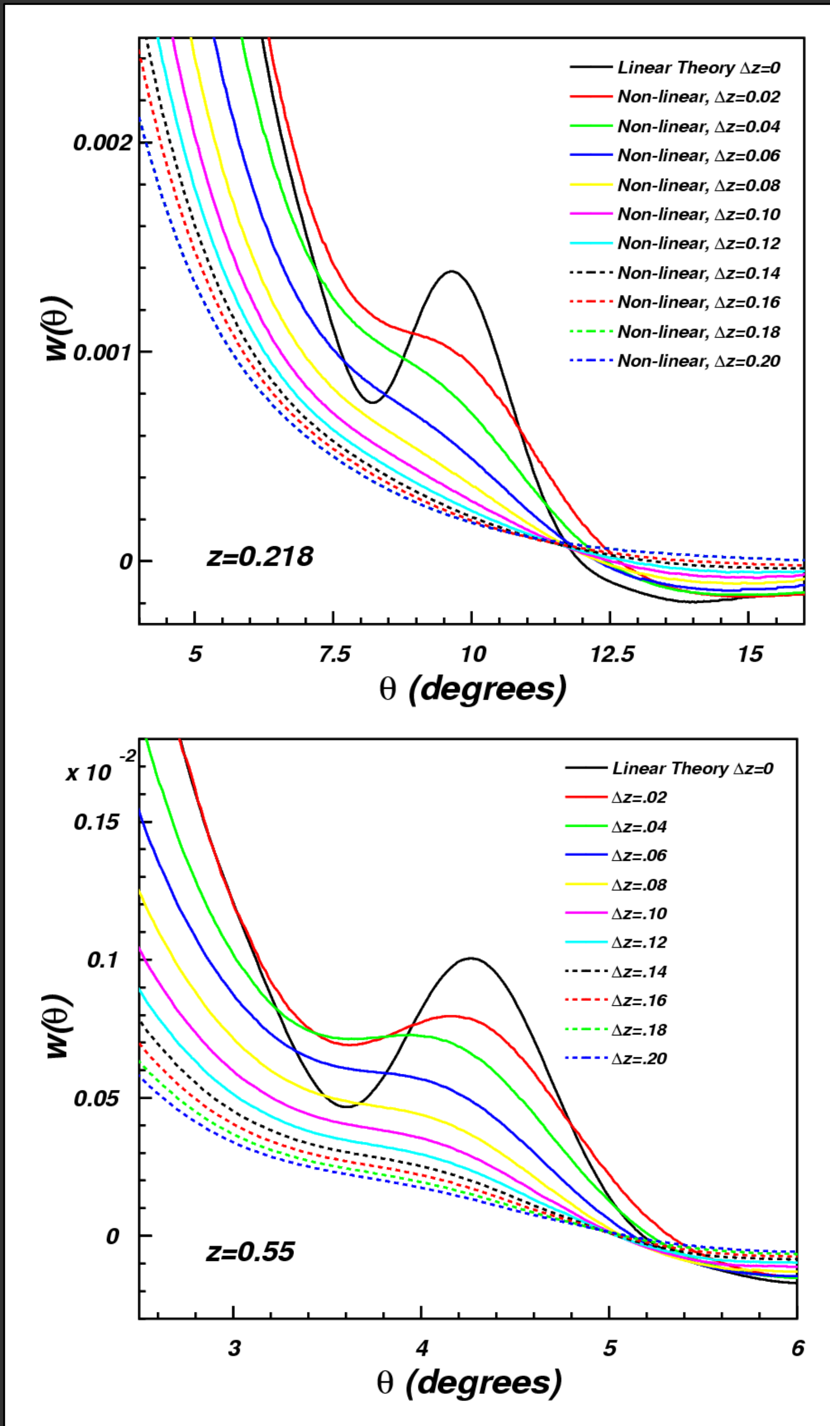
Where f_{sky} is the fraction of the sky covered by the survey and $N/\Delta\Omega$ is the galaxy density

2 main components

Poissonian component related to the number of galaxies (density) of the survey

Cosmic variance, coming from the covered area

PROJECTION EFFECT



The standard ruler method requires to relate the BAO scale with the position of the peak in the correlation function of galaxies

We have to distinguish $\theta_{BAO}=r_{BAO}/\chi(z)$, θ_{FIT} and the local maximum of $w(\theta)$. These three values are DIFFERENT

We propose a method to obtain θ_{BAO} from θ_{FIT}, correcting for observational effects in model independent way

The main correction arises from the projection effect due to the redshift bin width, which has two effects on the correlation function: Makes the amplitude lower and moves the local maximum to smaller values

NEW METHOD TO MEASURE 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,γ, θ_{FIT}, σ.
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.

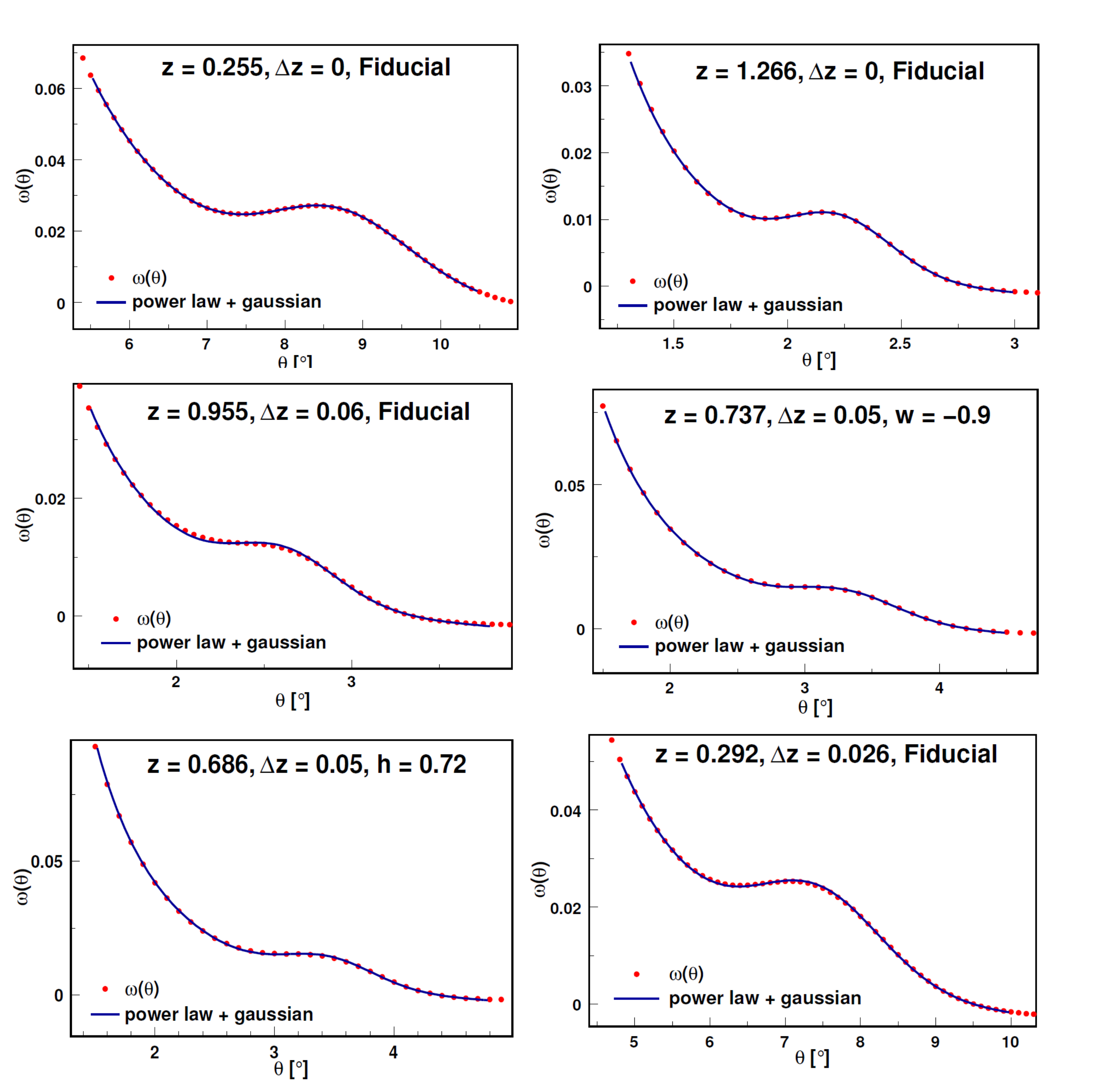
CALIBRATION OF THE METHOD

We have tested the goodness of the parametrization in a redshift range that goes from z=0.2 to z=1.4, for a wide range of bin widths and for 14 cosmological models

The fits to the proposed parametrization have always $0.98 < \chi^2 < 1.01$ with probabilities in the range 0.6 to 0.9, even when the error in each point of $w(\theta)$ is 1%, much smaller than any real survey!

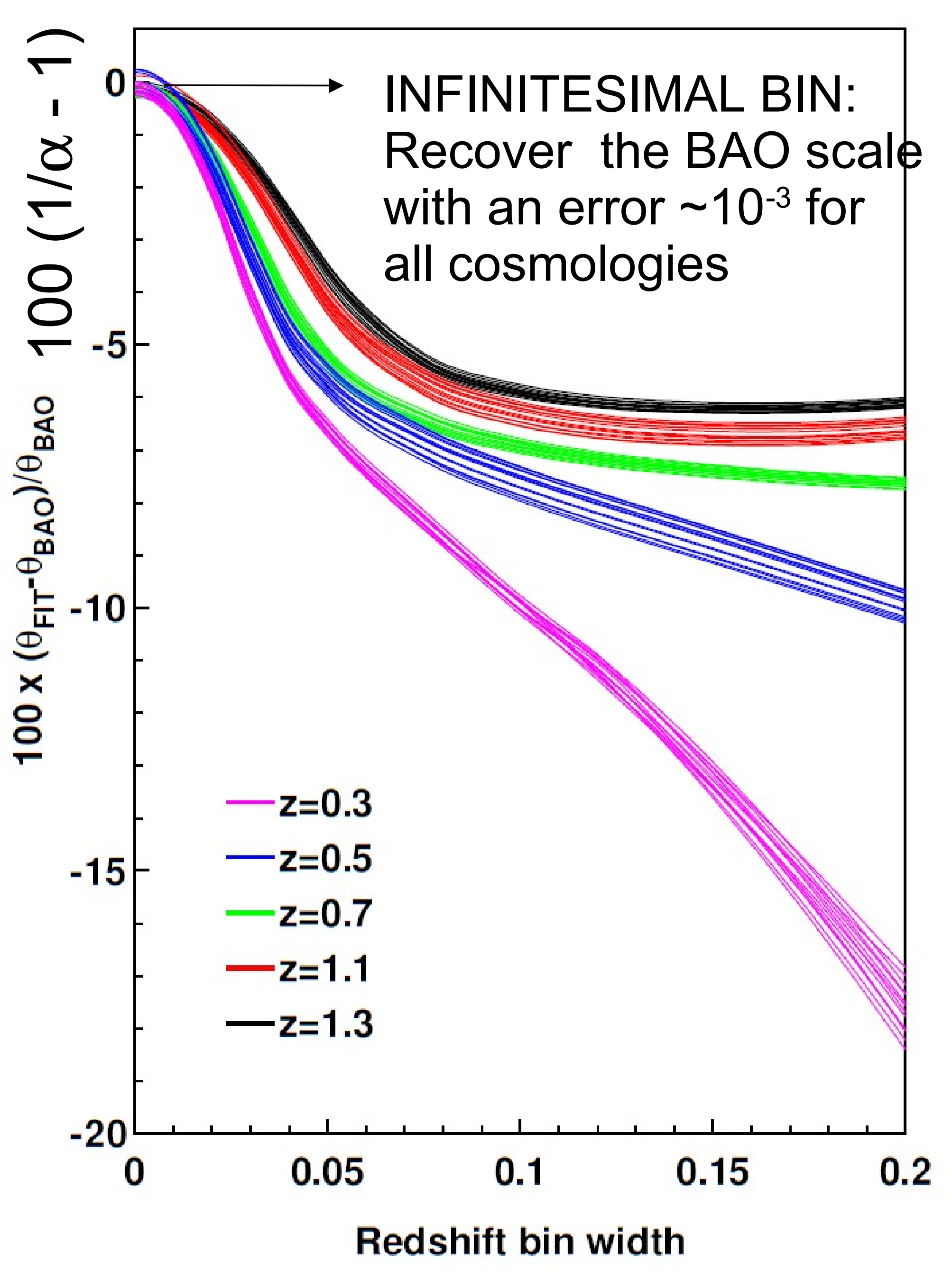
h	Ω_M	Ω_b	Ω_k	w_0	w_a	n_s
0.70	0.25	0.044	0.00	−1.00	0.0	0.95
0.68						
0.72						
	0.20					
	0.30					
		0.040				
		0.048				
			+0.01			
			−0.01			
				−0.90		
				−1.10		
					−0.1	
					+0.1	
						1.00

CALIBRATION OF THE METHOD



CALIBRATION: 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.



CORRECTION IS COSMOLOGY INDEPENDENT

MICE Simulation

One of the largest cosmological simulations ever done.

http://www.ice.cat/mice/

SIMULATION: Dark Energy Survey (DES)

DES Simulation Challenge
Publicly available
Same volume than expected in DES
5000 sq-deg and 50 million galaxies
(dark matter particles)

FIDUCIAL COSMOLOGY

MICE Simulation Common Parameters

Baryon density, $\Omega_b = 0.044$

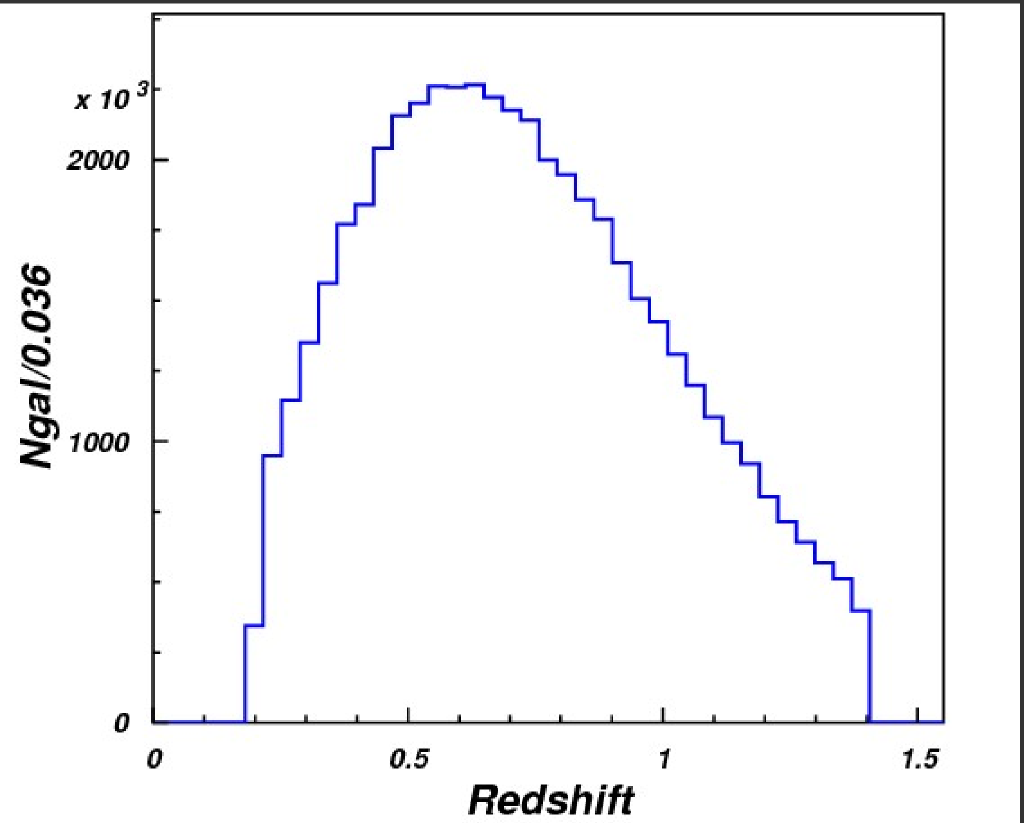
Matter density, $\Omega_m = 0.25$

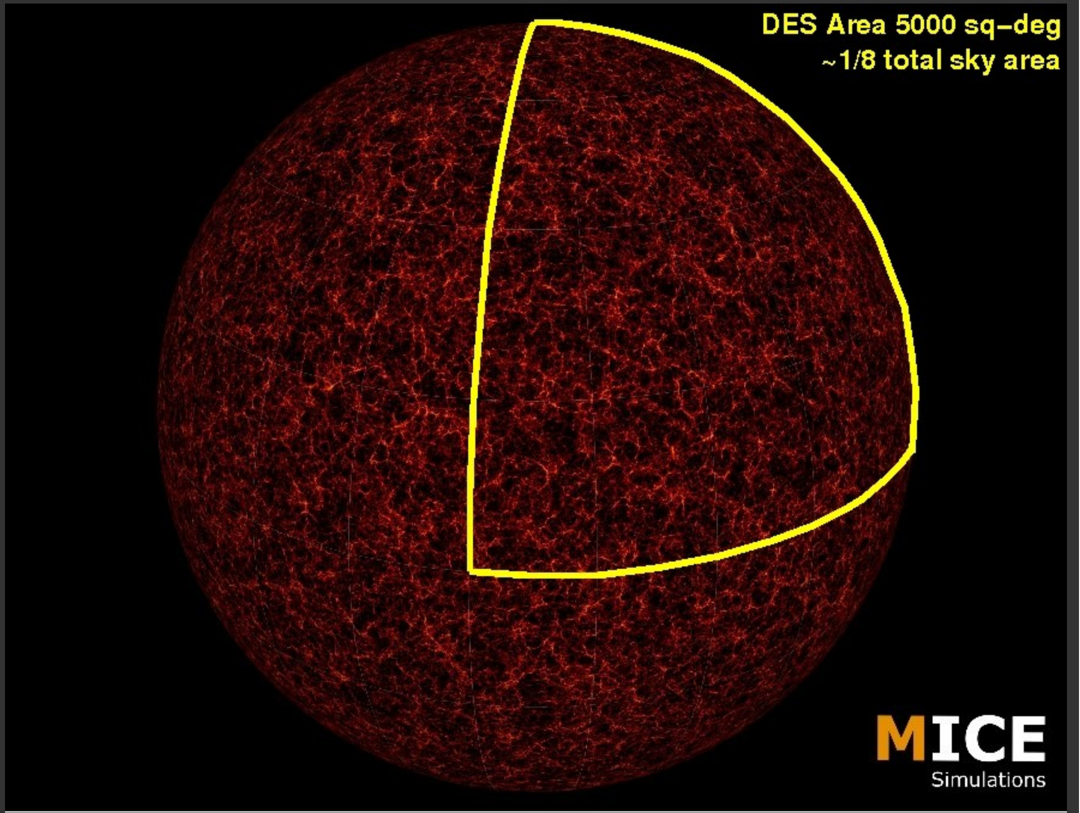
Dark-energy density, $\Omega_\Lambda = 0.75$

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



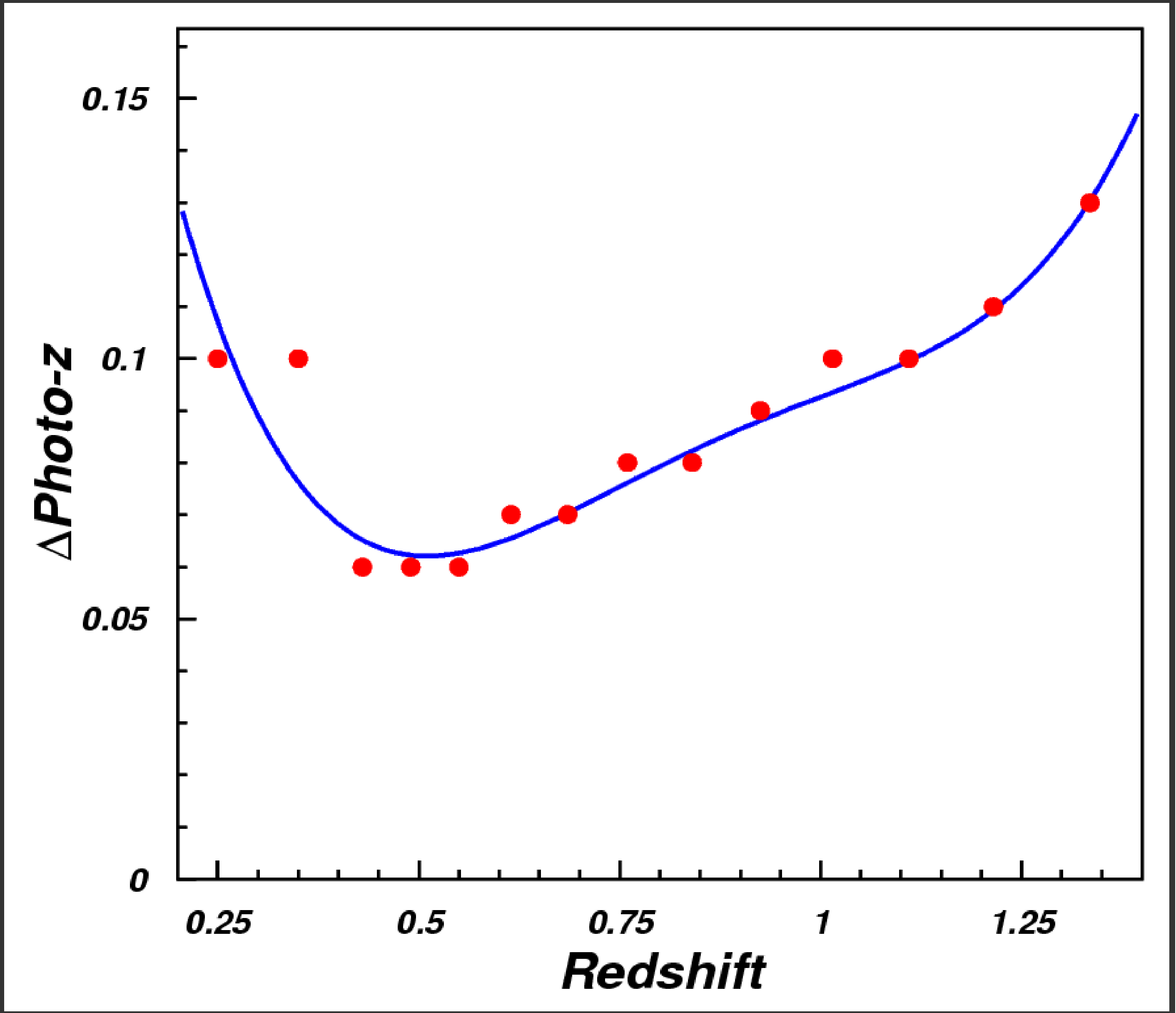


SIMULATION: Photoz in DES

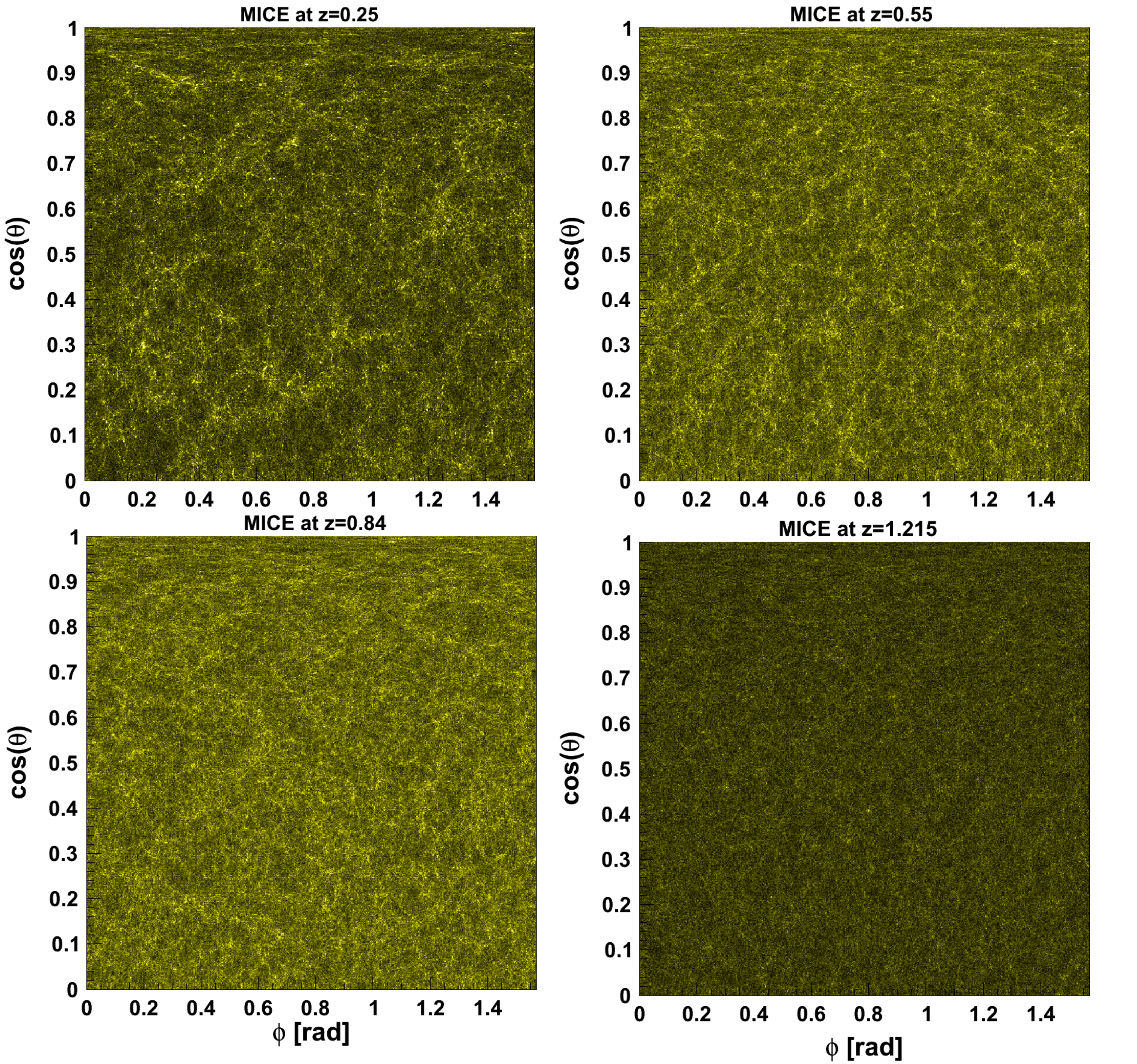
We include the photoz in the simulation smearing the redshift of each galaxy with a gaussian of width Δphotoz

All results include the photoz

We use 14 bins of redshift which follow the photoz error distribution



SIMULATION: Galaxy density Maps



ϕ=ra, θ=90º-dec

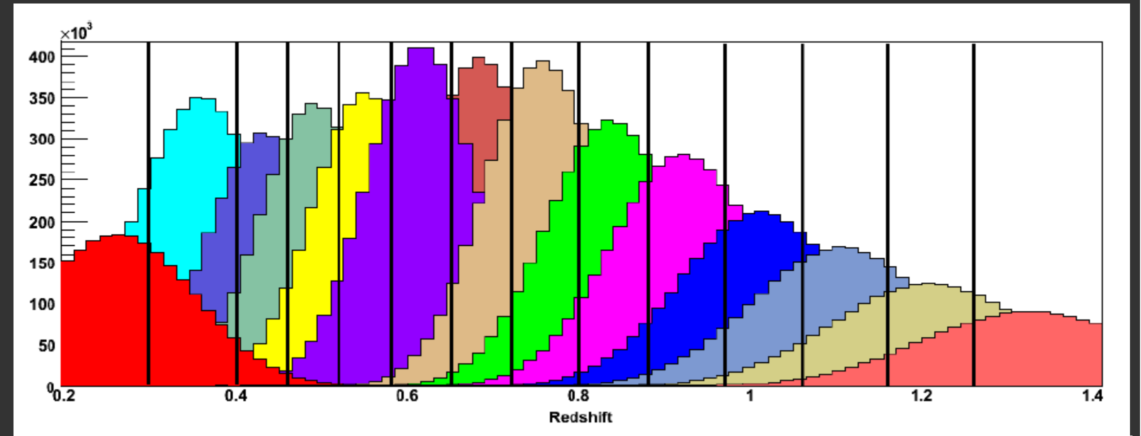
We build a map for each redshift bin

636x636 pixels (equivalent to healpix Nside=512, $\Delta\theta$~0.1º)

All pixels have the same area

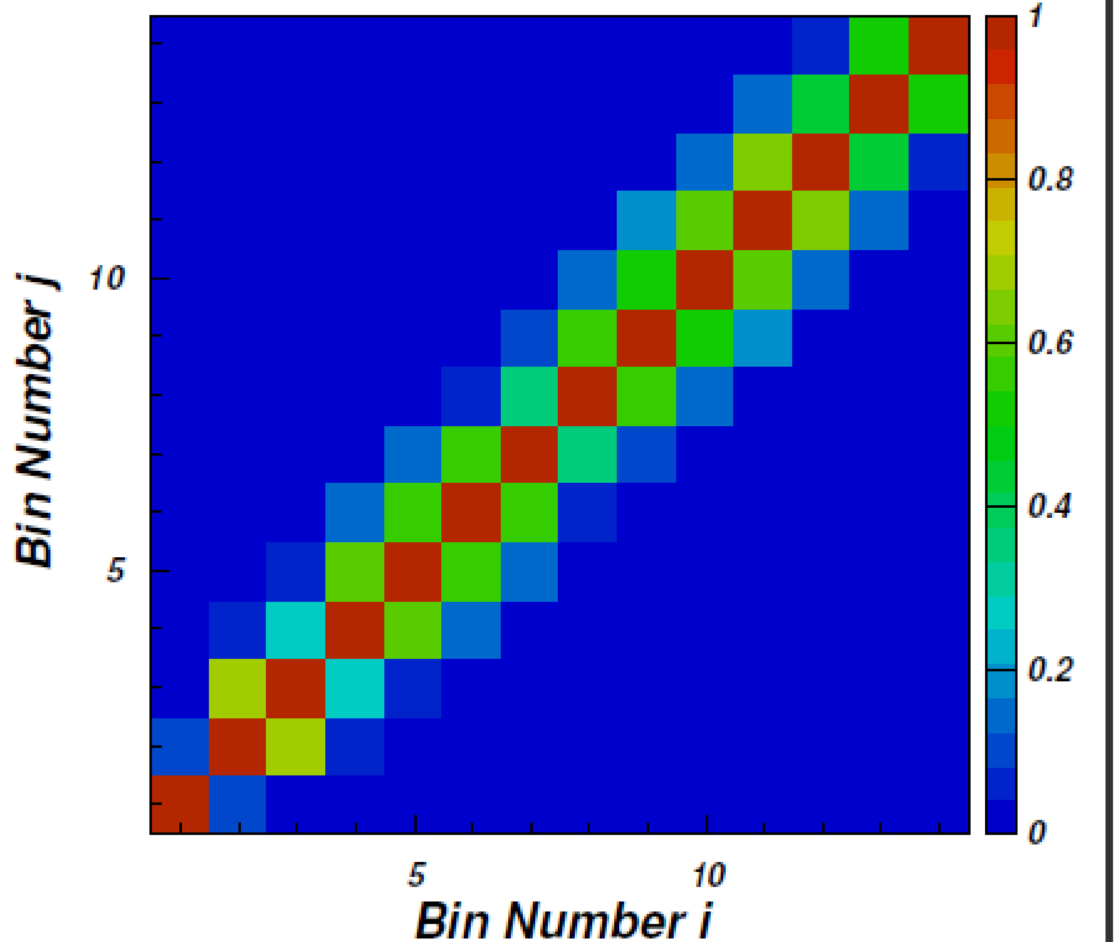
SIMULATION: Photoz resolution and correlations

The resolution in the measurement of photoz produces galaxy migration between bins



The correlation matrix between bins is directly related to the migration matrix

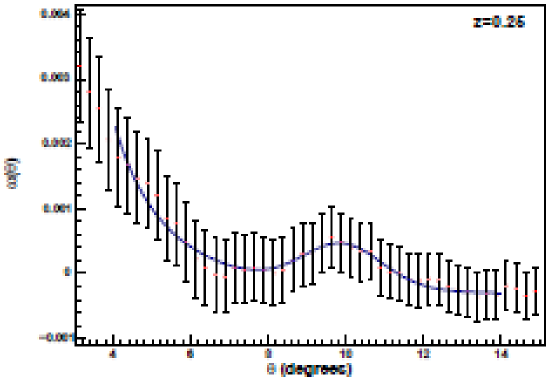
We calculate and use the covariance matrix, including correlated and uncorrelated errors in the measurement of the BAO scale



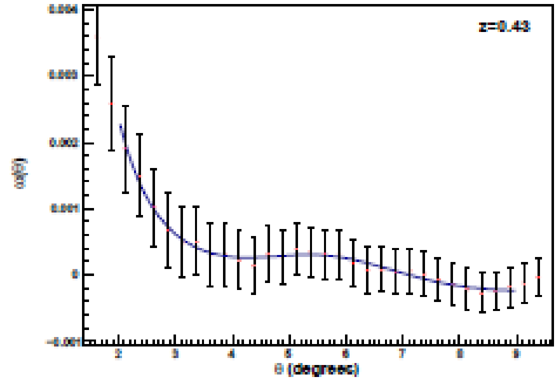
$$C_{ij} = < w_i^O(\theta) w_j^O(\theta') > = \sum_{k=1}^{N_{bins}} (r_{ik}^2 r_{jk}^2) \frac{(N_k^T)^4}{(N_i^O)^2 (N_j^O)^2} \mathrm{Cov}_{\theta\theta'}$$

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.

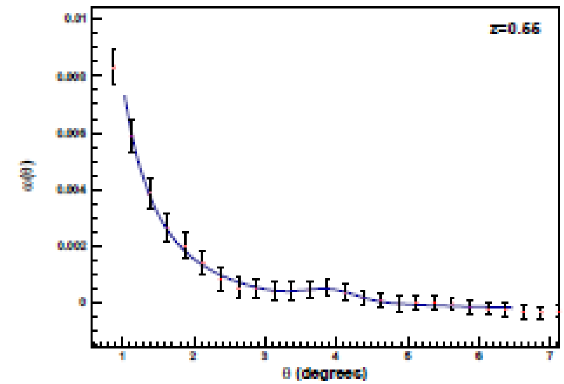
SIMULATION: Angular correlation functions



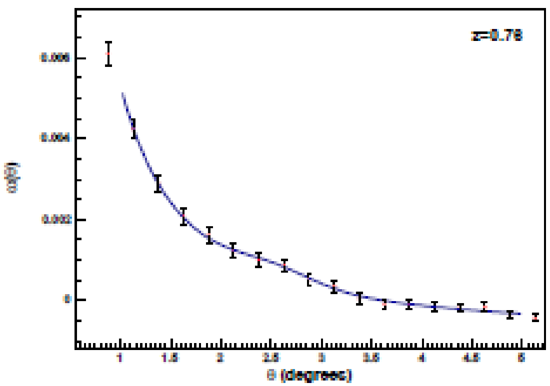
$\chi^2/dof = 0.1 \quad Prob = 1$



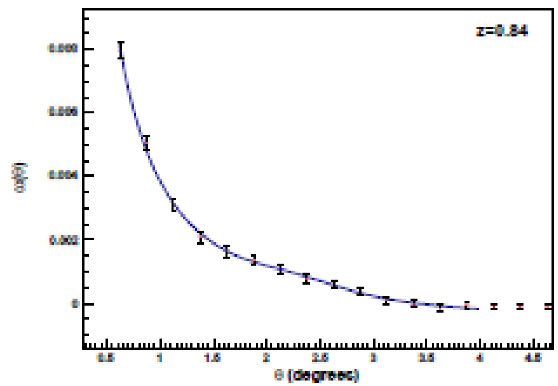
$\chi^2/dof = 0.15 \quad Prob = 1$



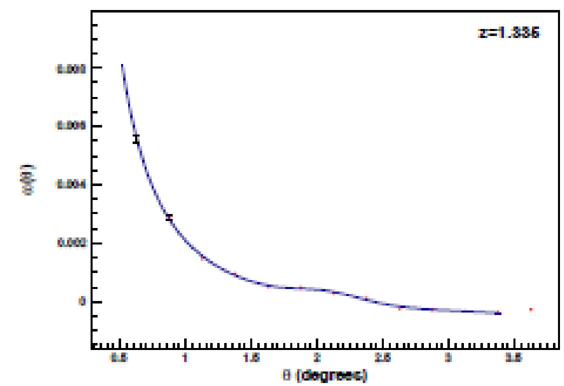
$\chi^2/dof = 0.4 \quad Prob = 0.97$



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



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



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

Compute w(θ) using the Landy-Szalay estimator

Statistical error from C matrix, including correlation between redshift bins

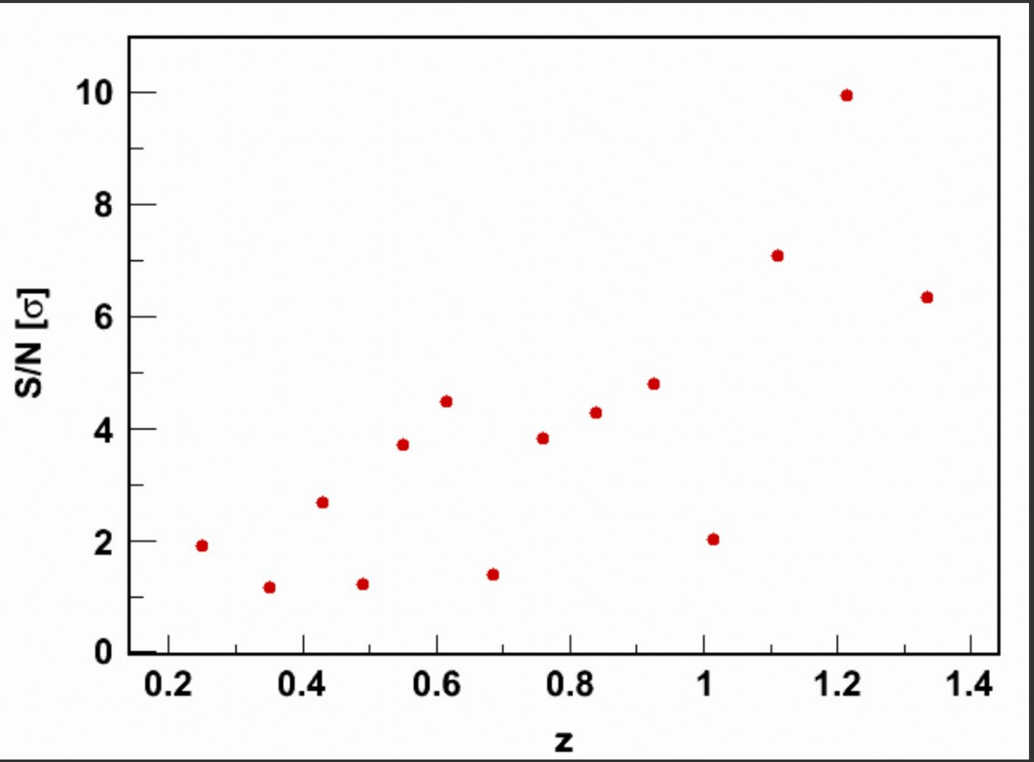
In each bin we apply the fit to the parametrization arounf the BAO peak

The correction is applied using the true redshift bin width, taking into account the photoz resolution

Significance & Systematic Errors

Statistical significance of the peak detection grows with the redshift

Mainly limited by the area of the survey and the photoz resolution



SYSTEMATIC ERRORS

Photoz

Redshift Space distortions

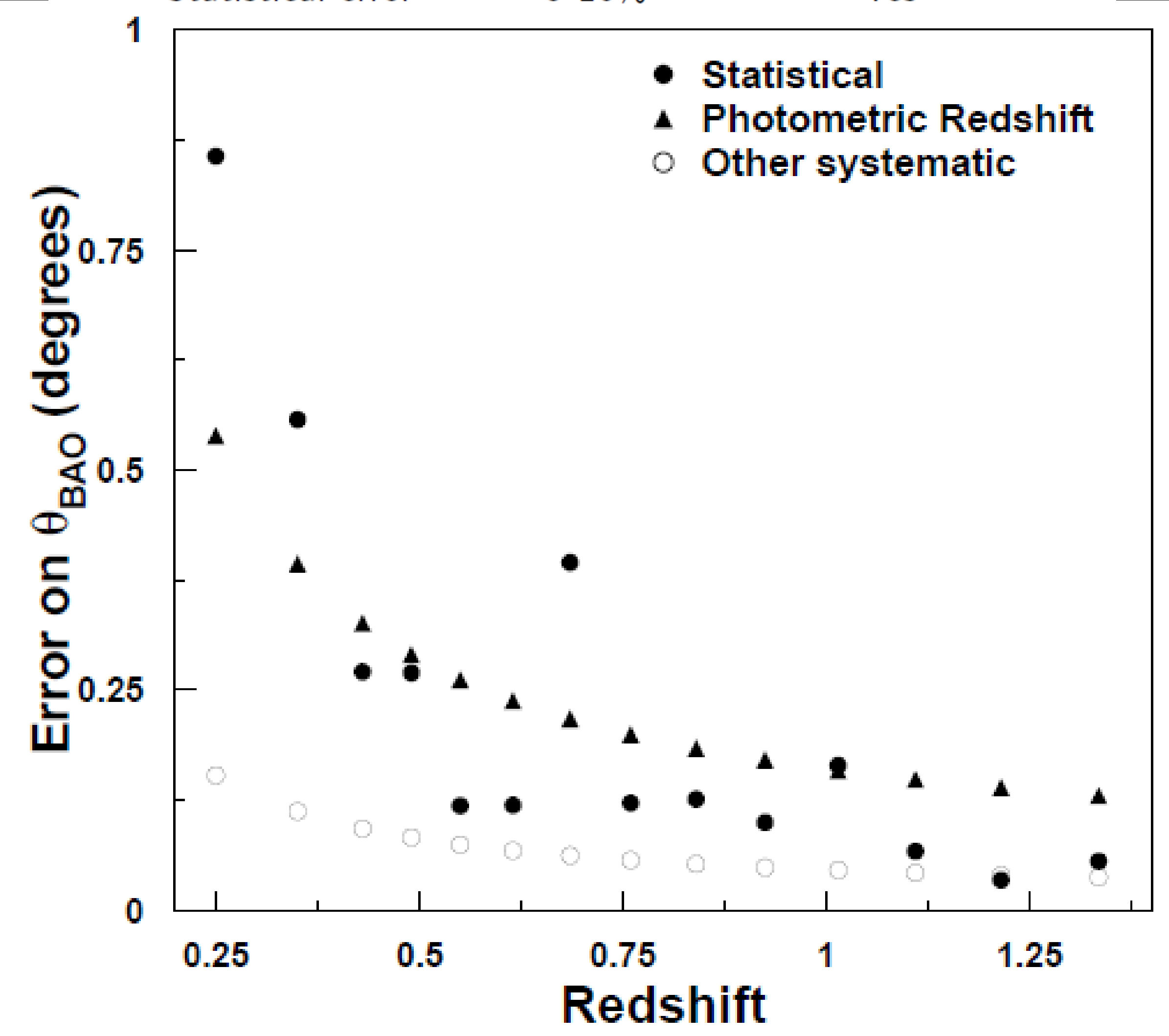
Parametrization

Non-linearities

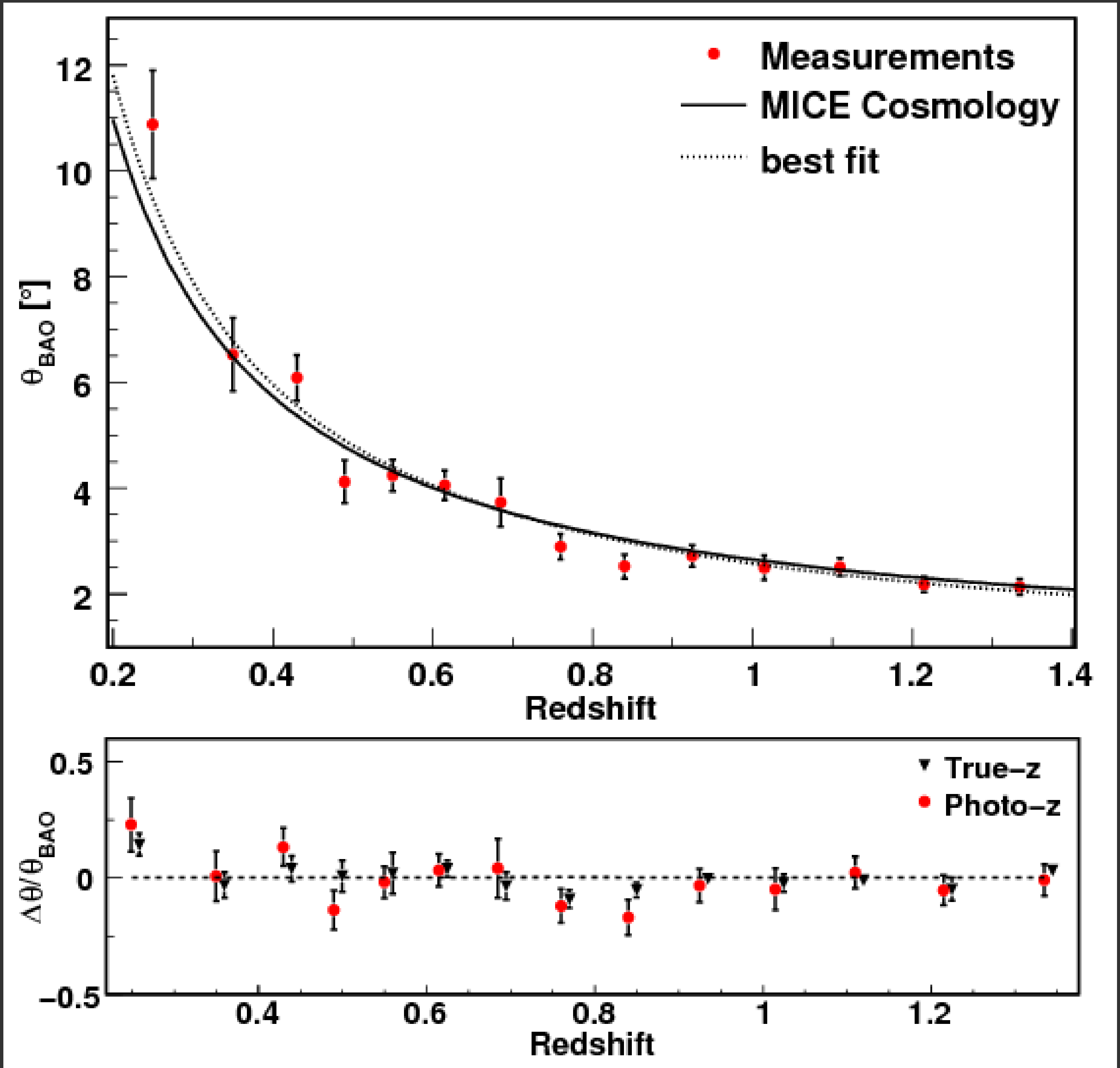
Correction of the projection effect

Systematic 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



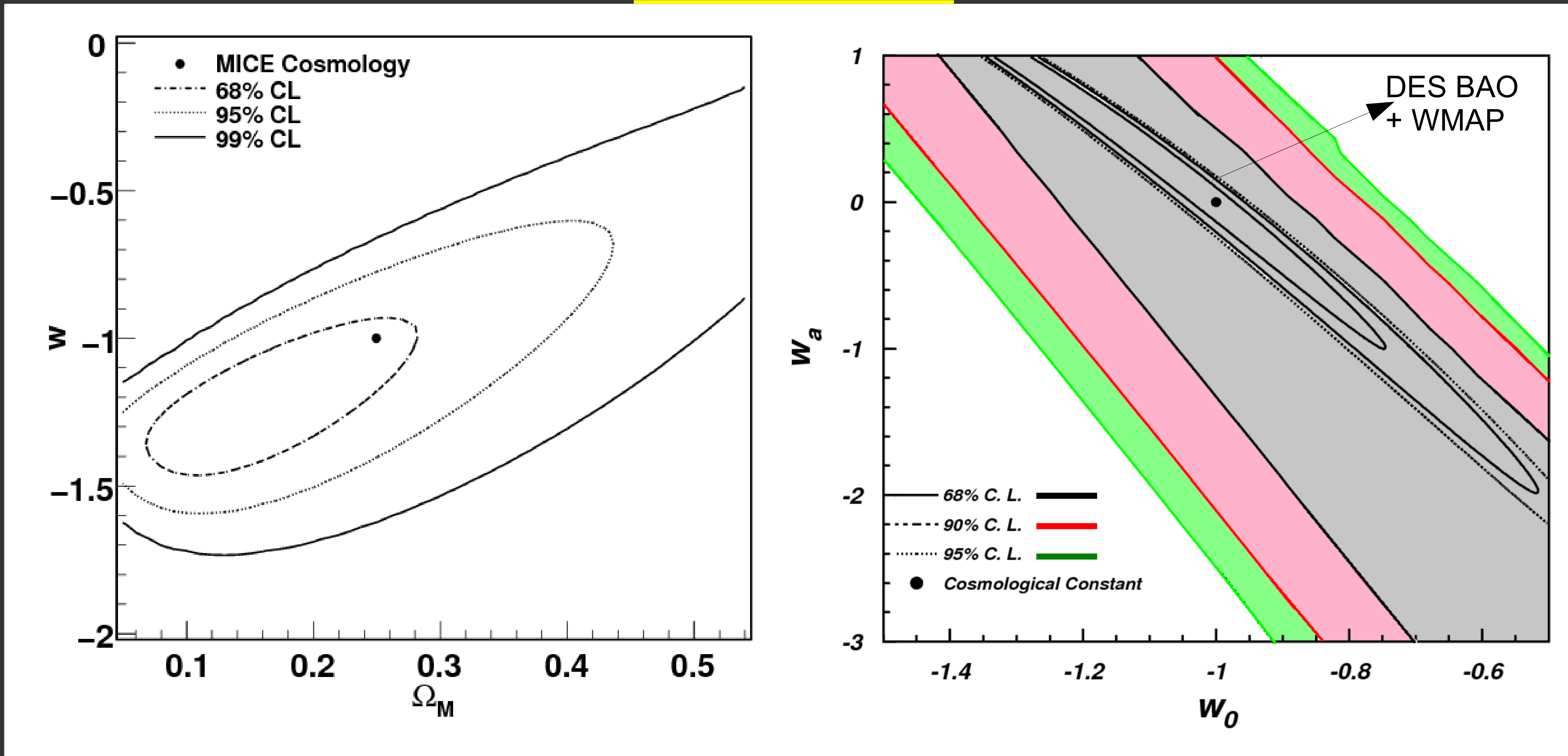
RESULTS



Results in good agreement with the cosmology of the simulation

Also shown the results obtained using the true z

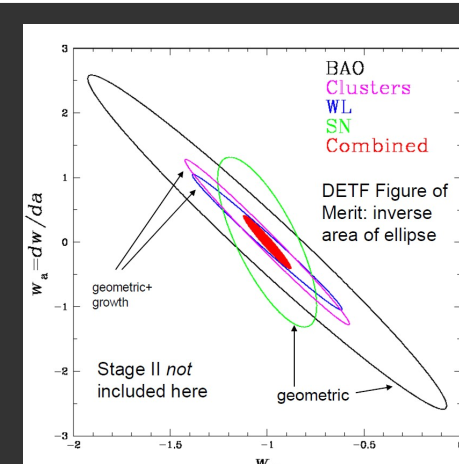
RESULTS



Other parameters fixed to their true values. Cosmology is recovered.

Include correlations between bins

In good agreement with DES expectations



REAL DATA : SDSS

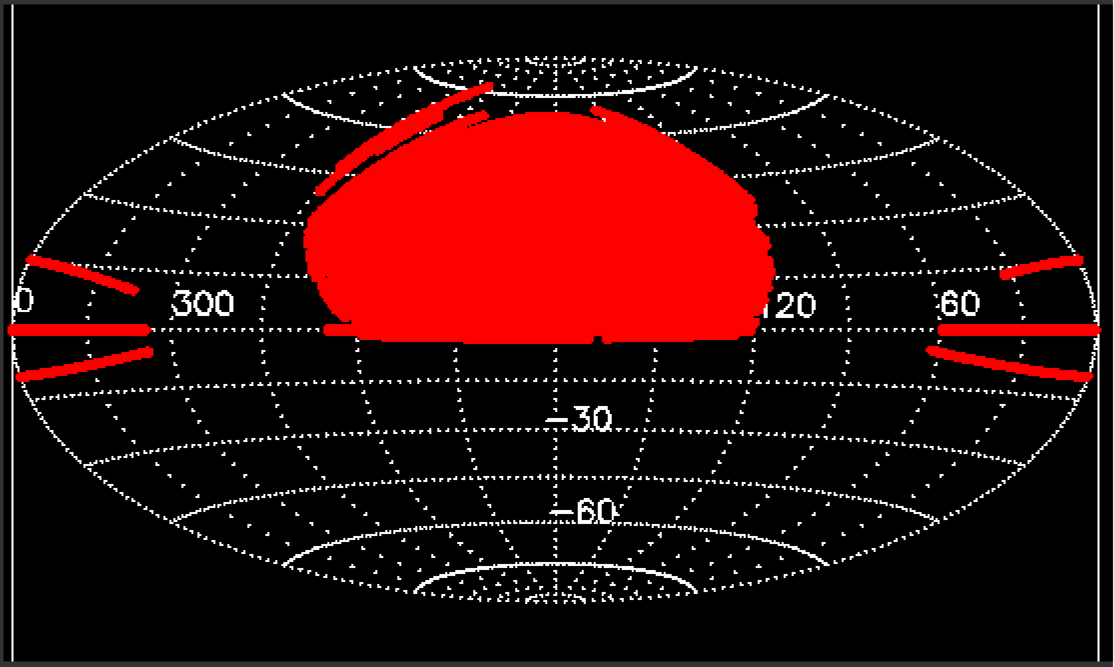
The Sloan Digital Sky Survey (SDSS) has been operating since 2000.

- Dedicated 2.5m telescope at Apache Point (New Mexico)

- 120 Mpx camera (1.5 sq-deg) and 2 spectrographs (640 fibers)

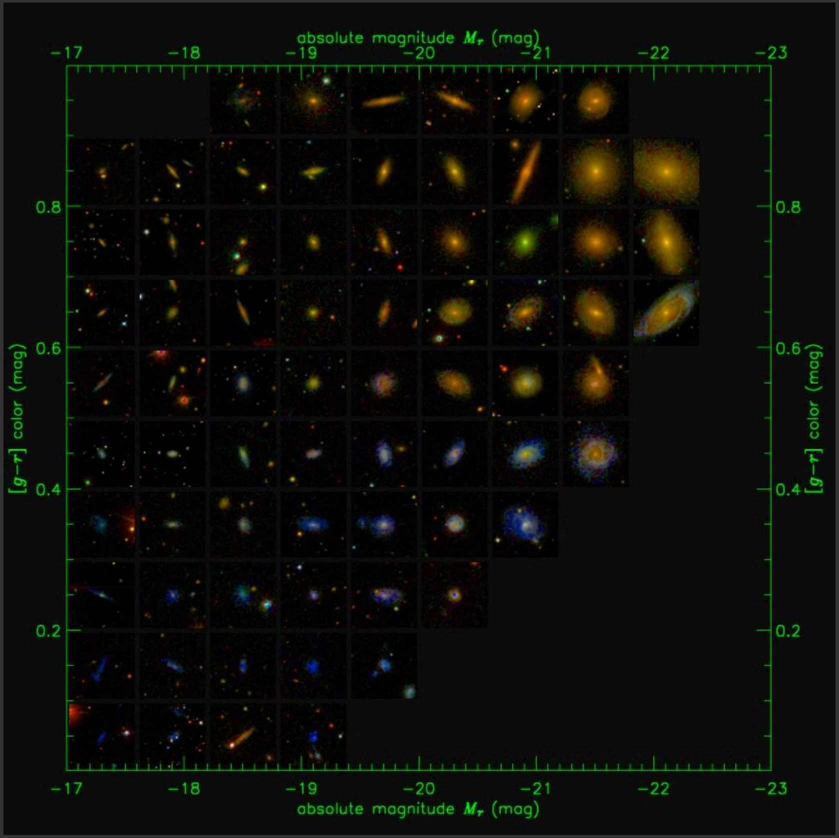
-Final data set (DR7): 230 million objects in 8400 sq-deg and spectra for 930000 galaxies, 120000 quasars and 225000 stars

- Currently in phase SDSS-III (one of the main projects is BOSS, dedicated to dark energy with BAO)



REAL DATA : SELECTION OF THE SAMPLE

Homogeneous and bright sample: LRG
Use the SDSS-II legacy catalogue DR7



Color based selection

1) Region of color-color space populated by LRGs

(r-i) > (g-r)/4 + 0.36

(g-r)>-0.72 (r-i) + 1.7

2) Minimise star contamination

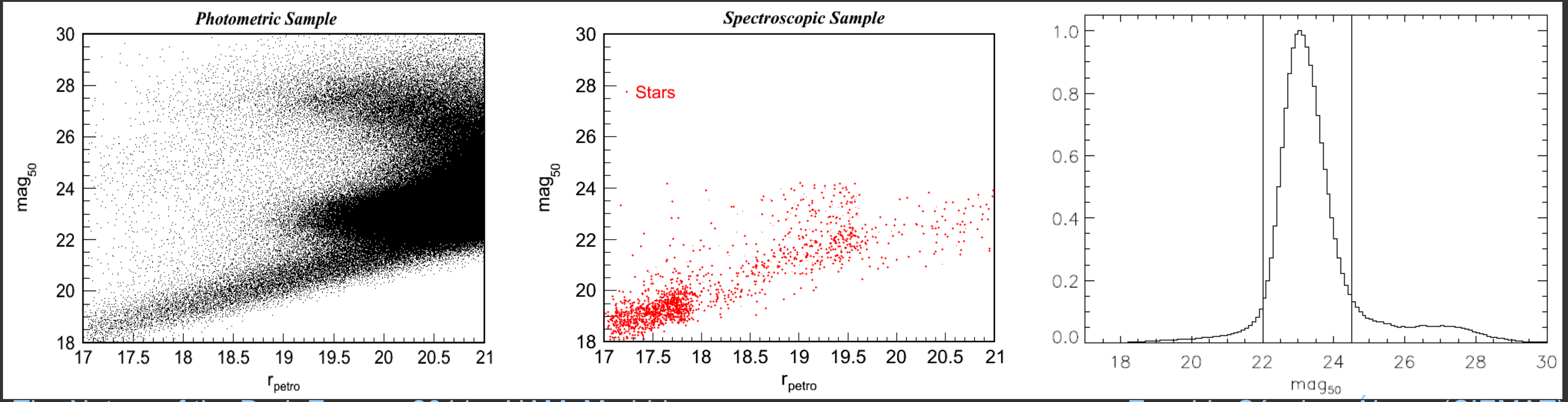
17 < petror < 21

0 < err_petror < 0.5

0 < r-i < 2

0 < g-r < 3

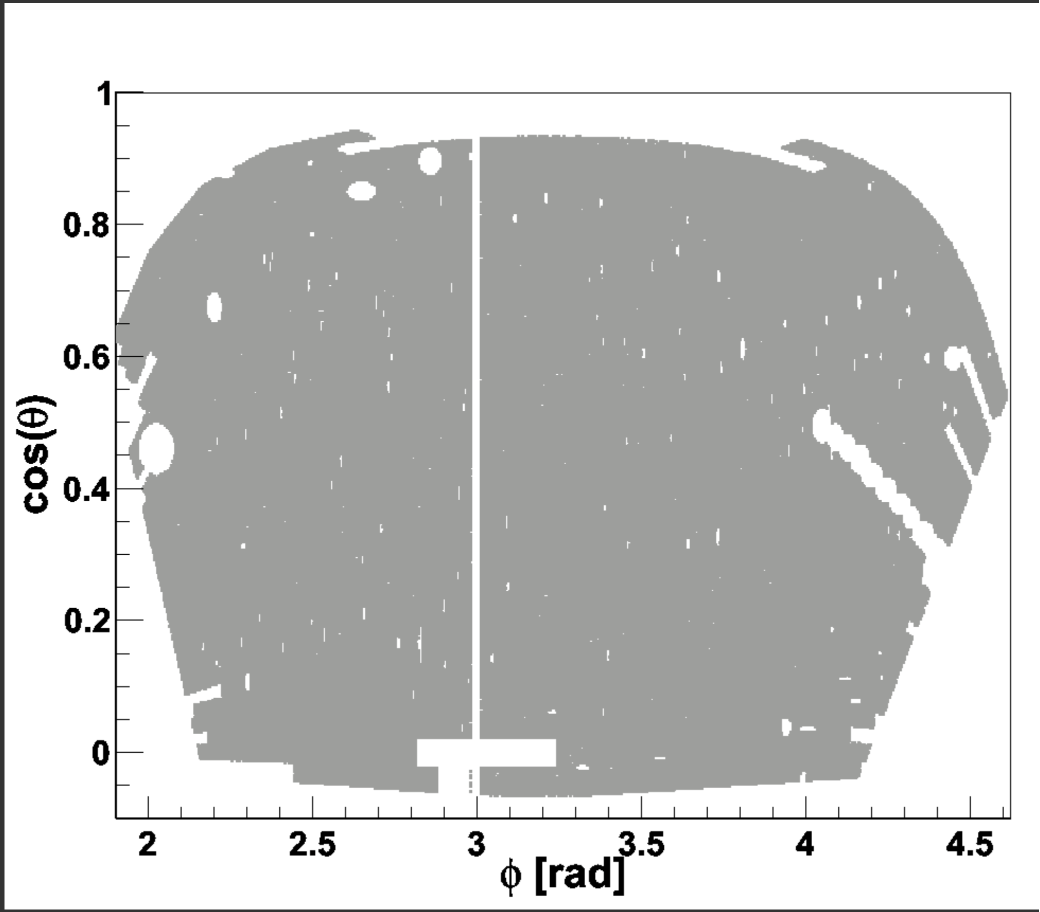
22 mag/arcsec^2 < mag50 < 24 mag/arsec^2

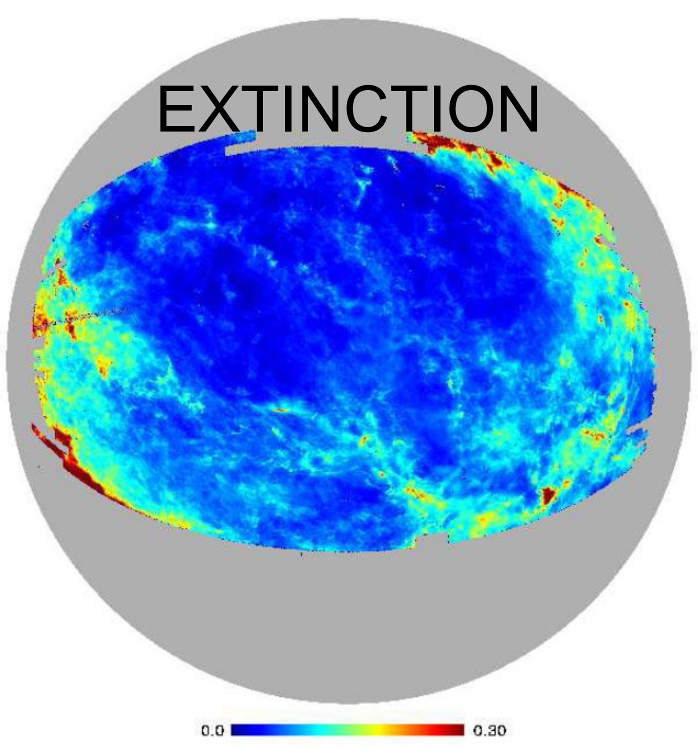


REAL DATA : SELECTION OF THE SAMPLE

Mask out:

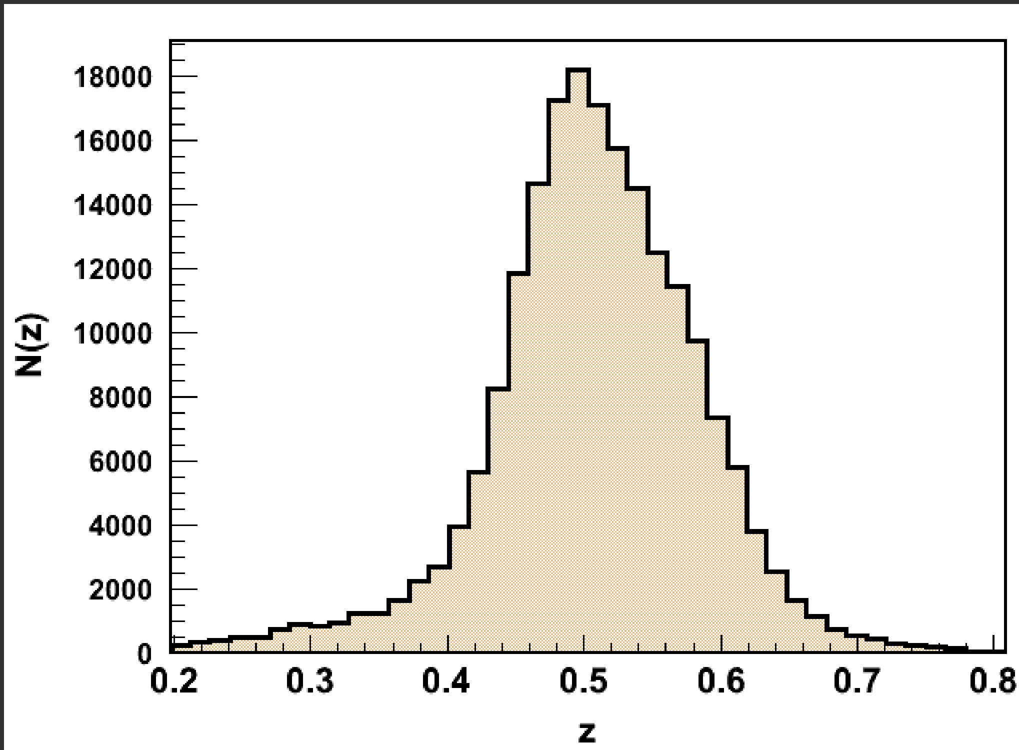
Areas of no observation
Areas with bad photometry
Bright stars
Bad photoz





Total analysed area
7136 sq-deg

REAL DATA : PHOTOMETRIC REDSHIFT



Photoz from the value added catalogue of the Chicago Group (Cunha et al. 2009, Lima et al. 2008)

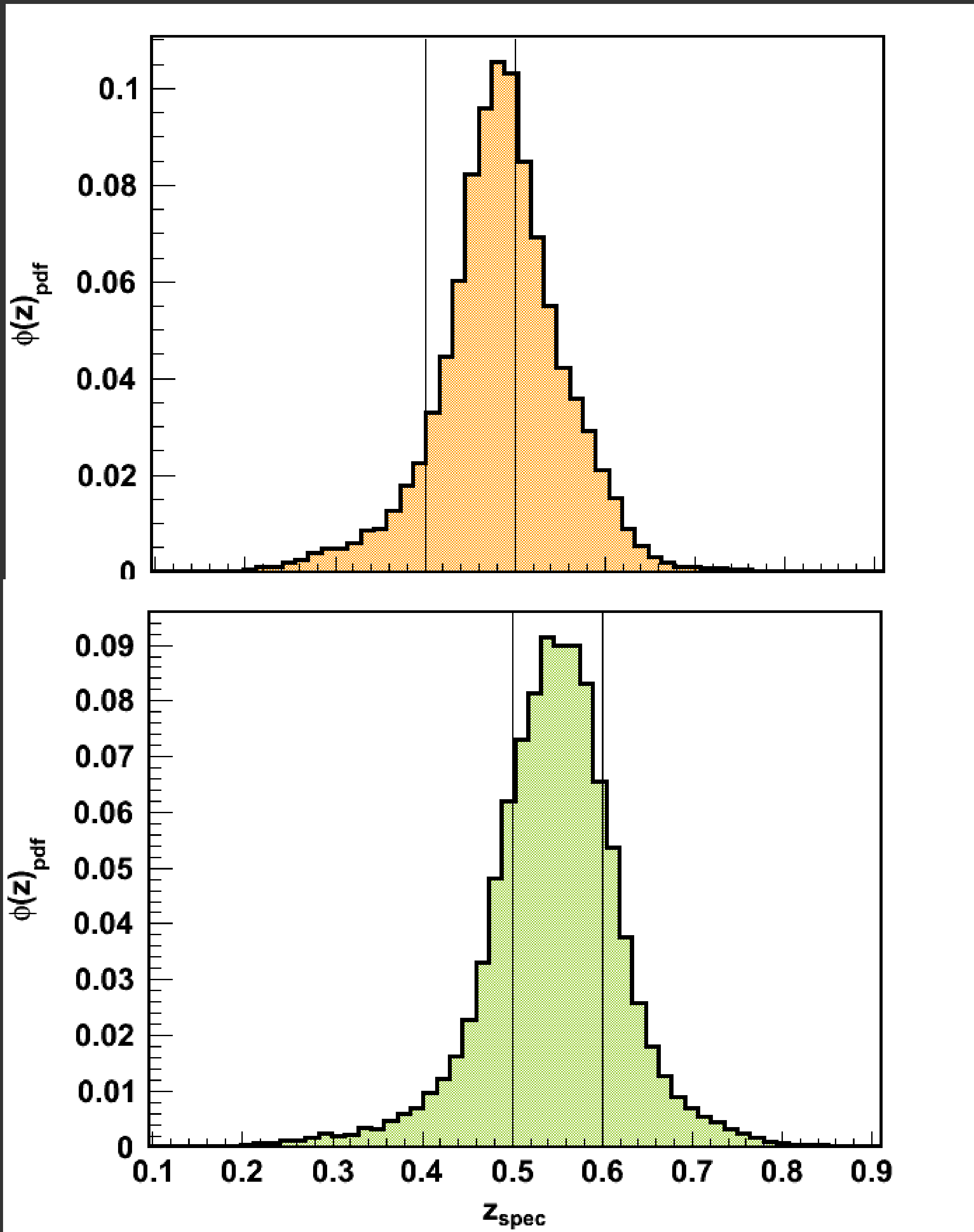
Gives accurate estimates of the probability distribution p(z) for each galaxy

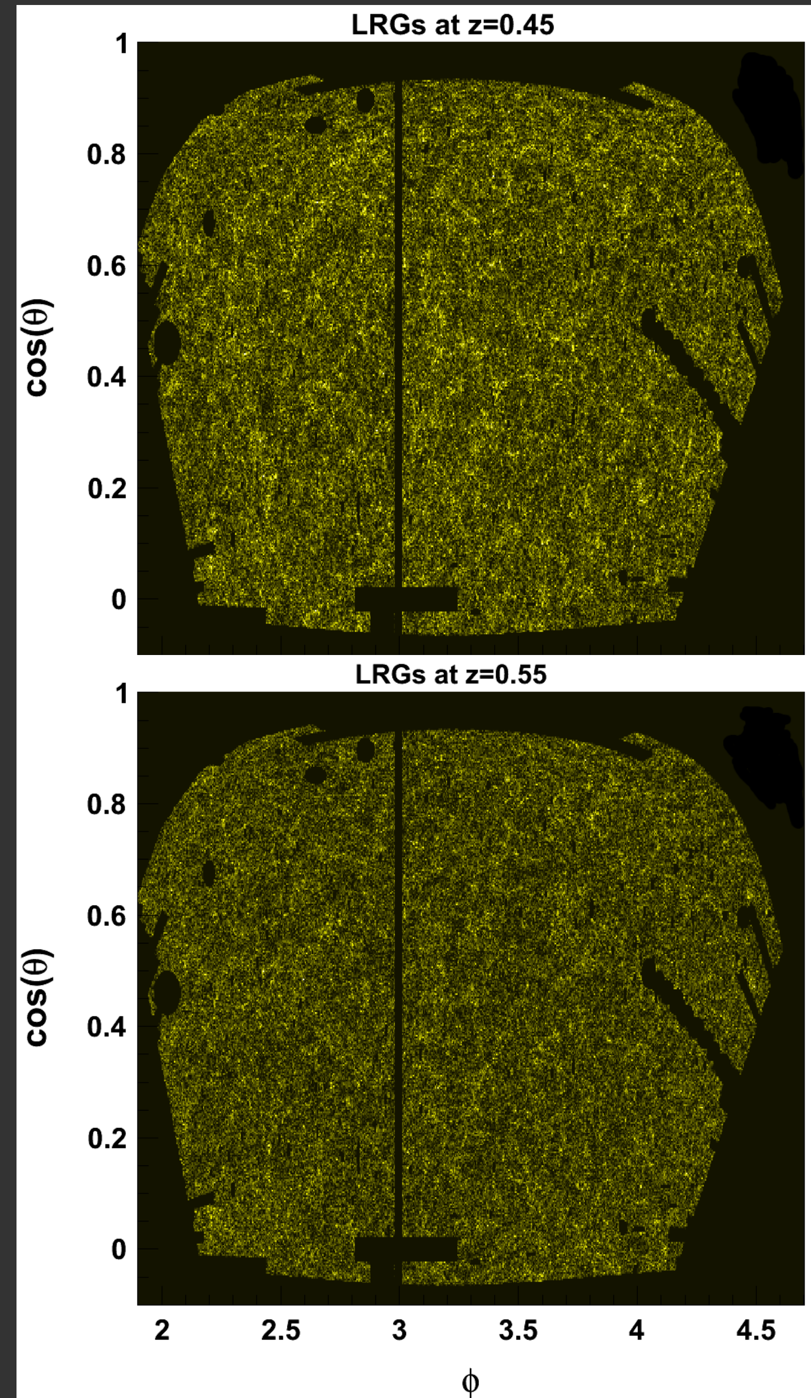
We estimate the redshift as the maximum of p(z) and compute N(z) using the full distribution p(z)

LRGs concentrate in $0.4 < z < 0.6$
Use 2 bins, centred at 0.45, 0.55 and of width 0.1

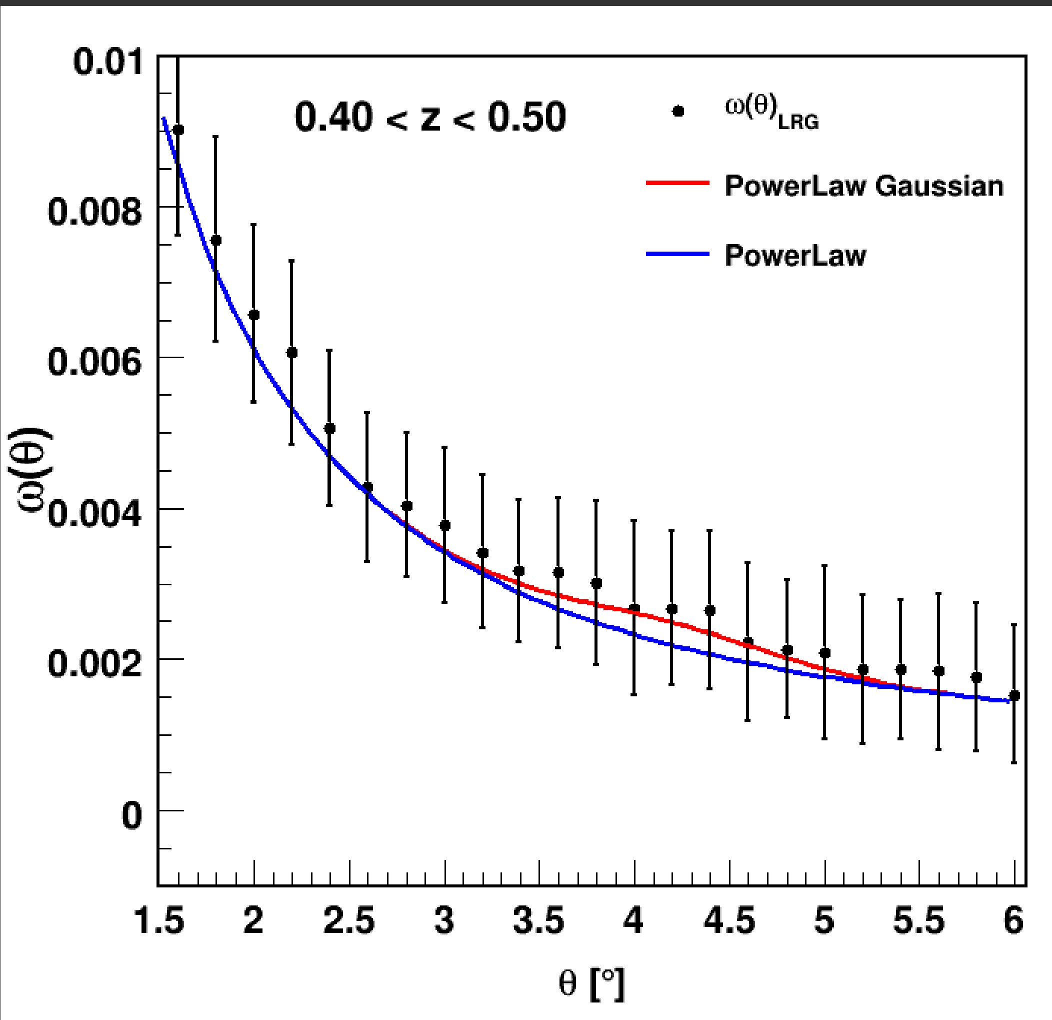
Much narrower bins do not enhance the sensitivity, due to the dilution effect of the photoz. Much wider bins make the amplitude of the correlation functin too small to detect the BAO signal due to the projection effect

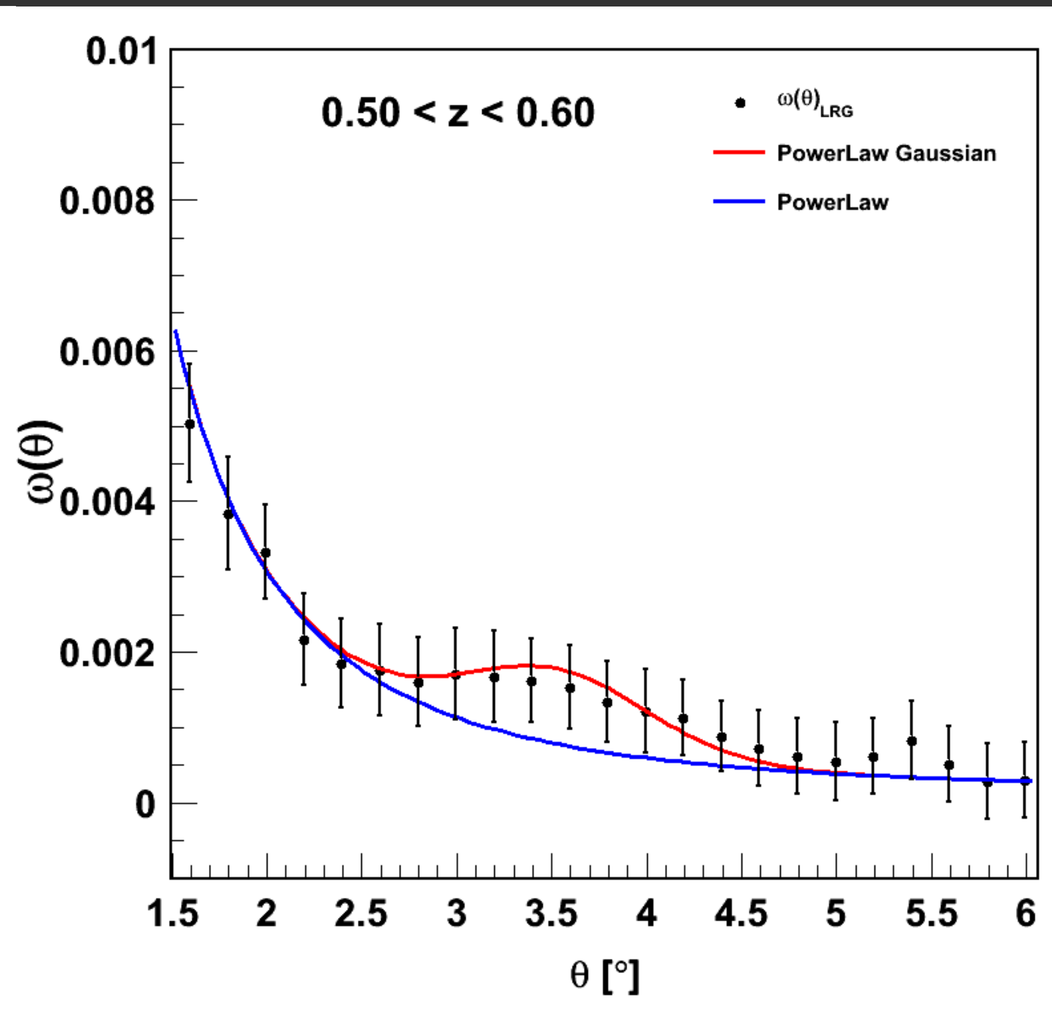
REAL DATA : PHOTOMETRIC REDSHIFT





CORRELATION FUNCTIONS & FITS

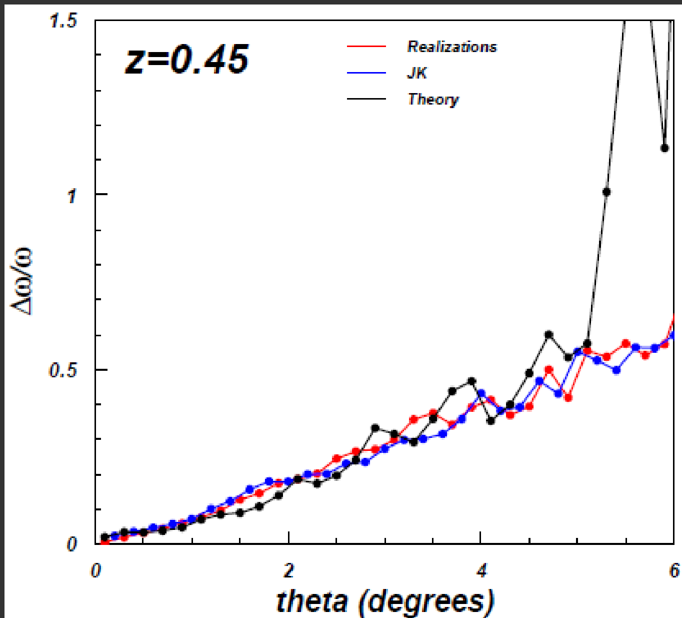


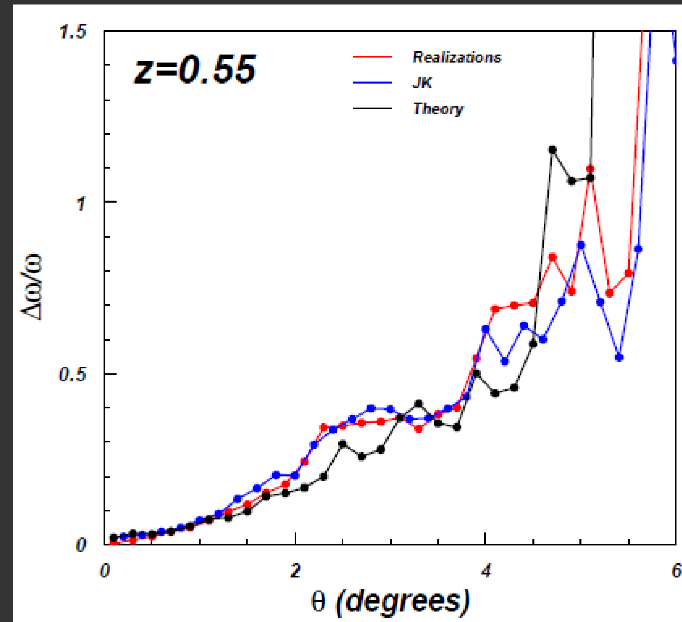


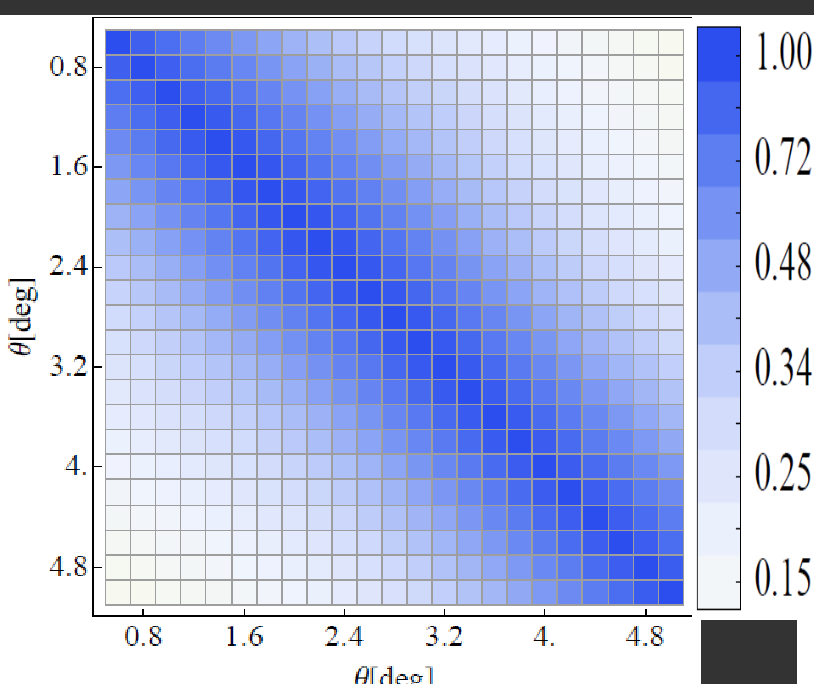
NO DETECTION
Bad quality of the photoz

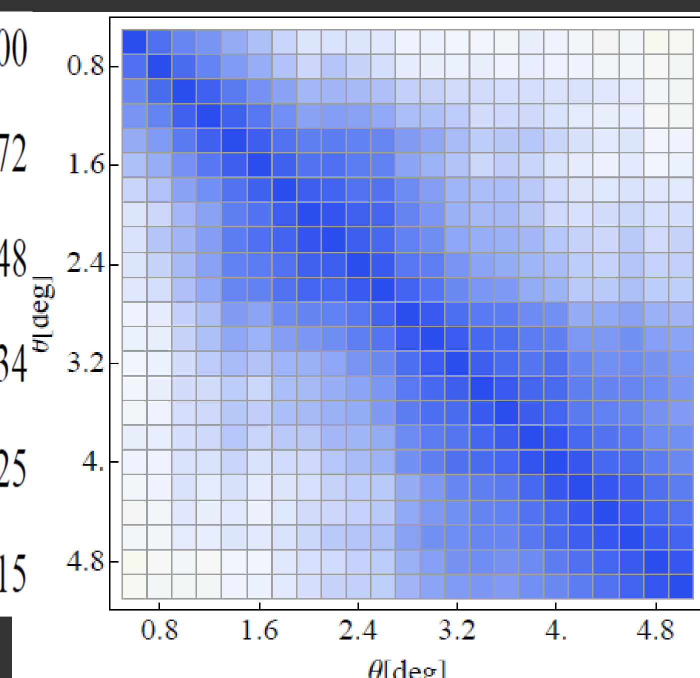
DETECTED SIGNAL
Significance = 2.6 σ

STATISTICAL ERROR WELL UNDER CONTROL









3 different methods of estimating the error perfectly agree

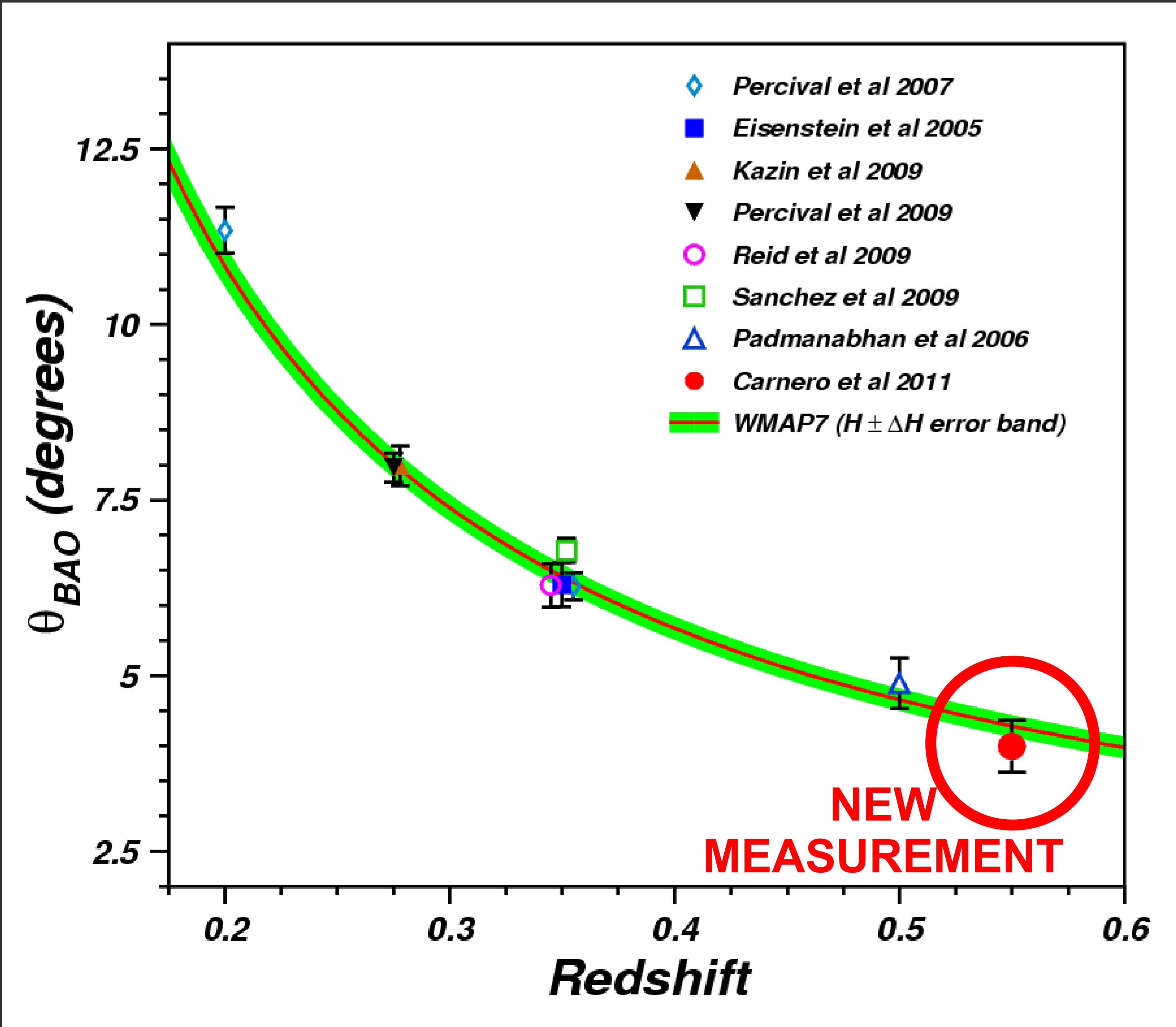
Theory, Jack knife, artificial realizations

Not only the errors, but the full covariance matrix

SYSTEMATIC ERRORS

Systematic Error	$\Delta\theta_{BAO}$
Parametrization	1%
Photoz	5%
Redshift Space Distortions	1%
Theory (non-linearities)	1%
Projection Effect	1%
Photoz non-gaussianity	2%
Selection	2.5%
Mask	2%

RESULTS



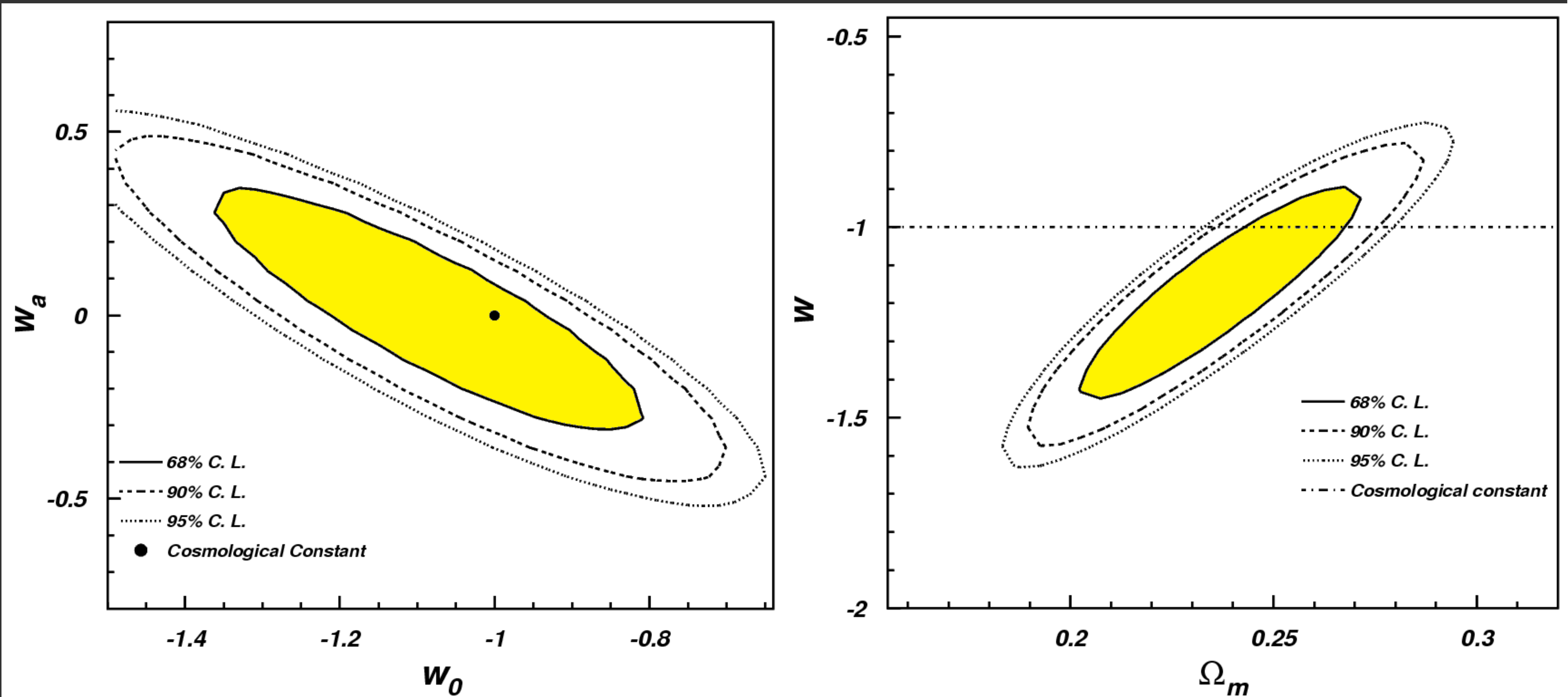
θ_{BAO} (z=0.55) = (3.98 ± 0.40)º

Systematic errors are included

Dominant error sources are the cosmic variance and the photometric redshift

In good agreement with the WMAP7 cosmology

RESULTS



COMBINATION OF ALL BAO MEASUREMENTS (ANGULAR AND RADIAL)

except wigglez

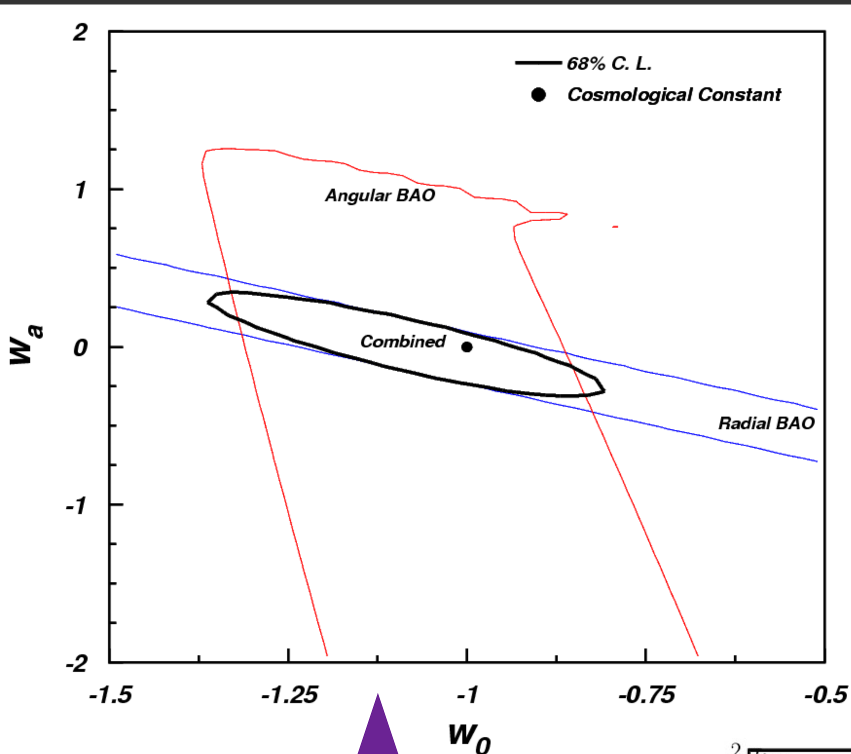
Results compatible with dark energy being a cosmological constant

w_0 = -1.03 +/- 0.16

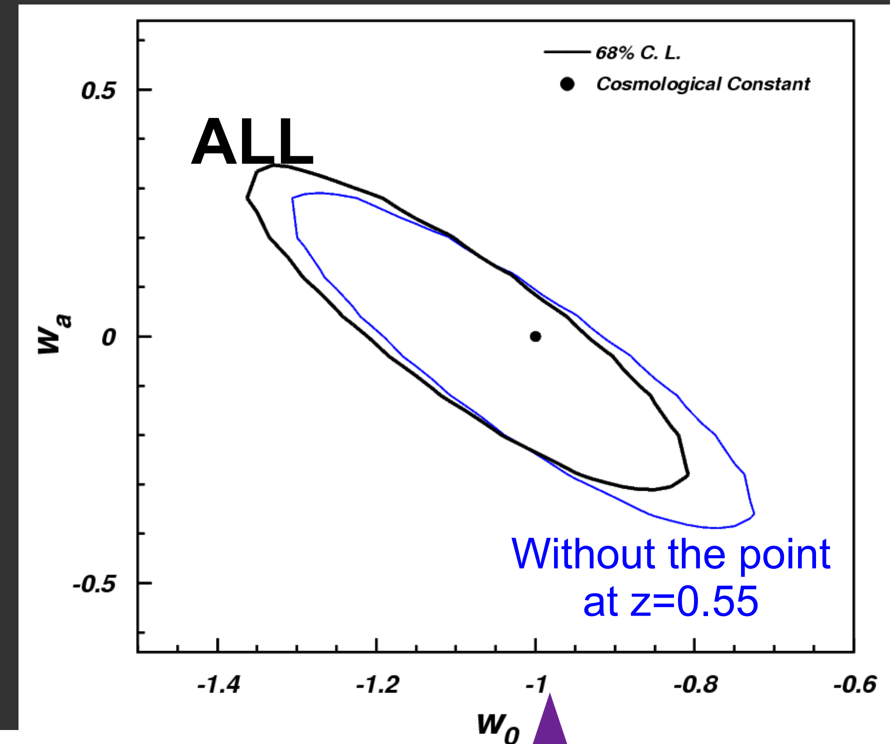
w_a = 0.06 +/- 0.22

Ω_M = 0.26 +/- 0.04

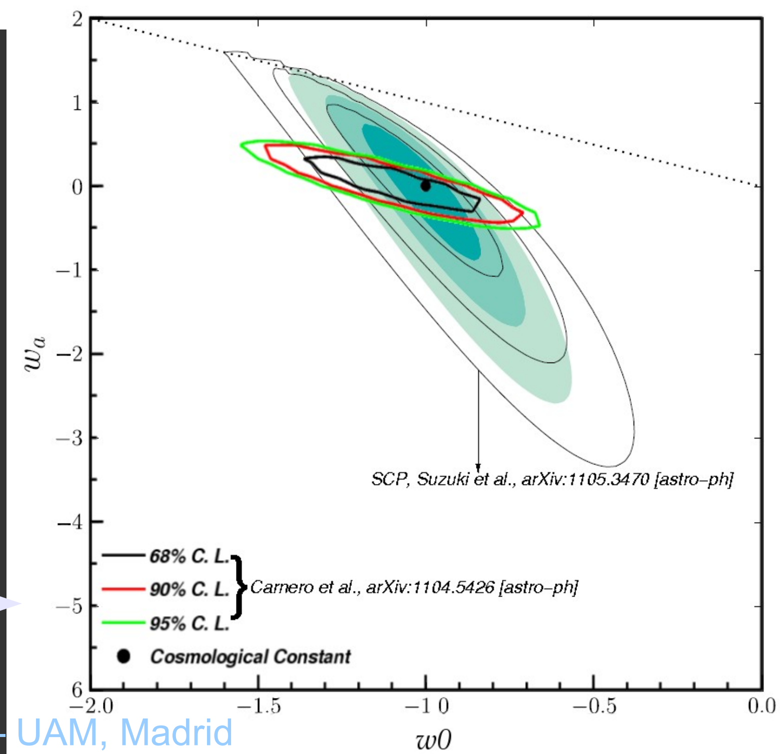
RESULTS



Contribution of angular and radial BAO



Contribution of the measurement at z=0.55



Comparison with SNIa

CONCLUSIONS

We have developed a new method to measure with precision the BAO scale in photometric (also spectroscopic) survey, working only with observable quantities

It has been intensively tested and calibrated on different cosmological models, recovering the BAO scale with precision better than 1% in a model independent way

The method has been applied to a N-body simulation with the DES survey features, including the main systematic effects. The BAO scale is recovered within the scientific requirements of the survey (including the systematic errors)

Finally the method has been applied to the LRG DR7 sample of the SDSS survey.

We have measured the BAO scale to the highest redshift to date z=0.55 in a real photometric survey, demostrating the feasibility and sensitivity of the method

The result is compatible with dark energy being a cosmological constant to a 20% precision