BAO in the angular clustering of SDSS-III photoz LGs.

Hee-Jong Seo

BCCP, LBL and UC Berkeley

Shirley Ho, Martin White, Antonio Cuesta, Ashley Ross, Shun Saito, Beth Reid, Nikhil Padmanabhan, Will Percival,

Roland de Putter, David Schlegel, Nick Ross,

and the SDSS III Collaboration

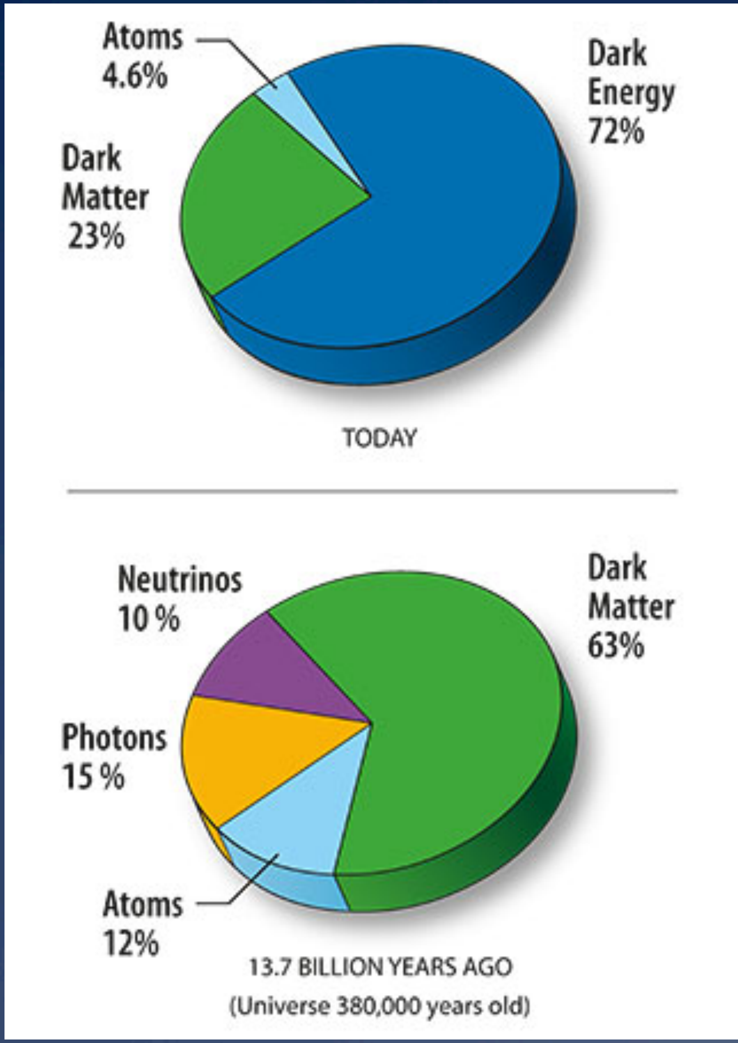
Seo et al. submitted to ApJ

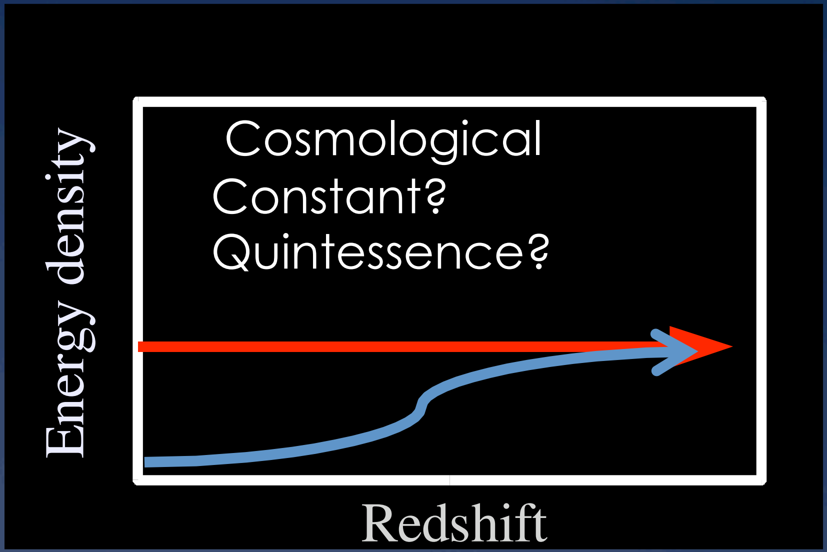
Also, Ho et al. & de Putter et al.

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

INPA, LBL, Dec 16 2011

Probing Dark Energy





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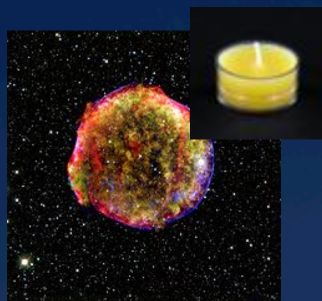
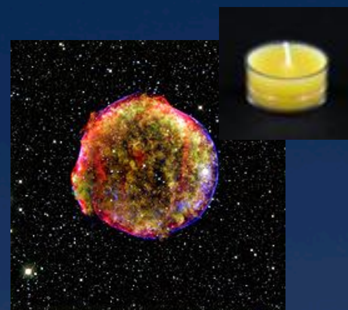
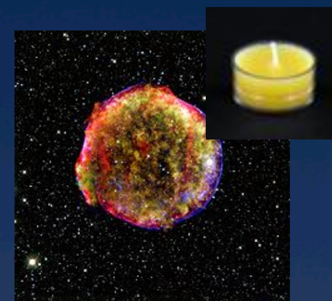
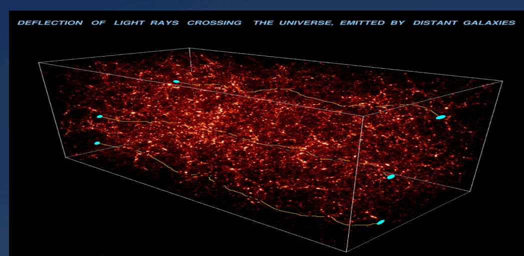
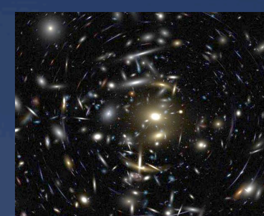




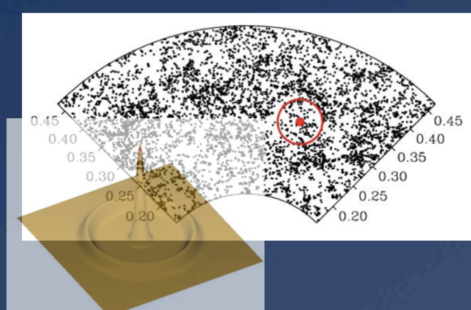
Standard candle
Type Ia SN

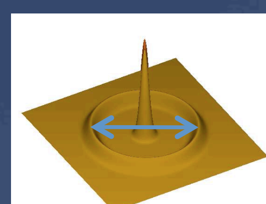
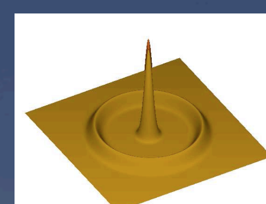


Weak Lensing



Cluster counting

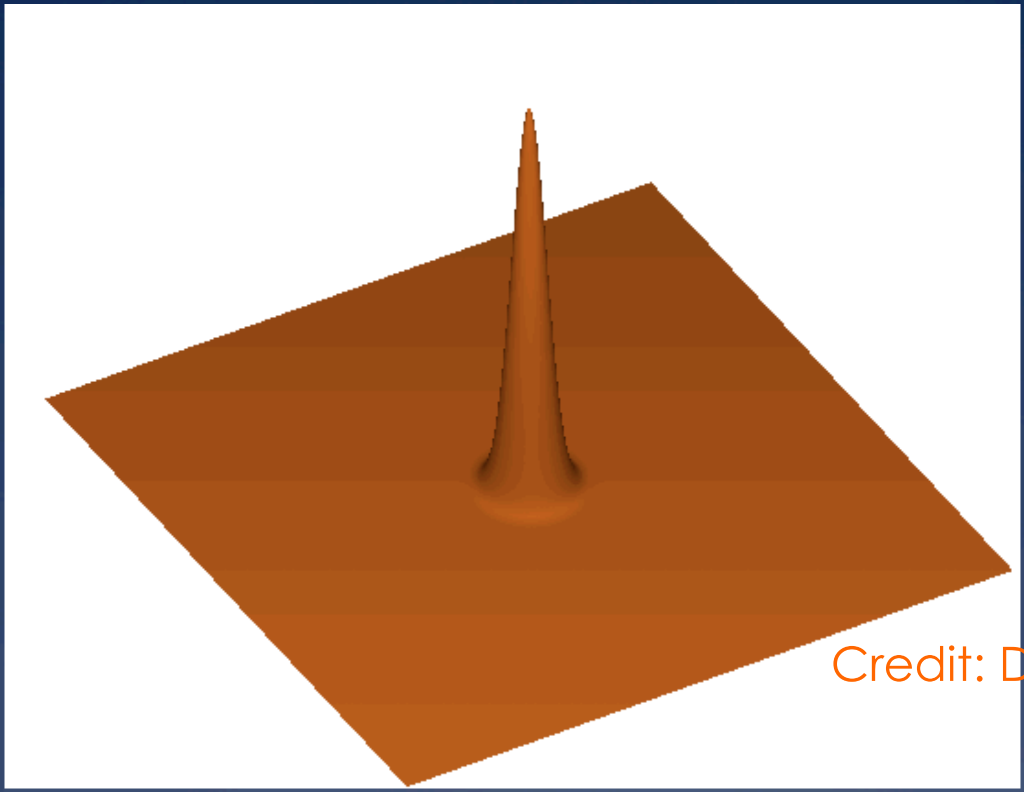


Standard ruler
BAO

z

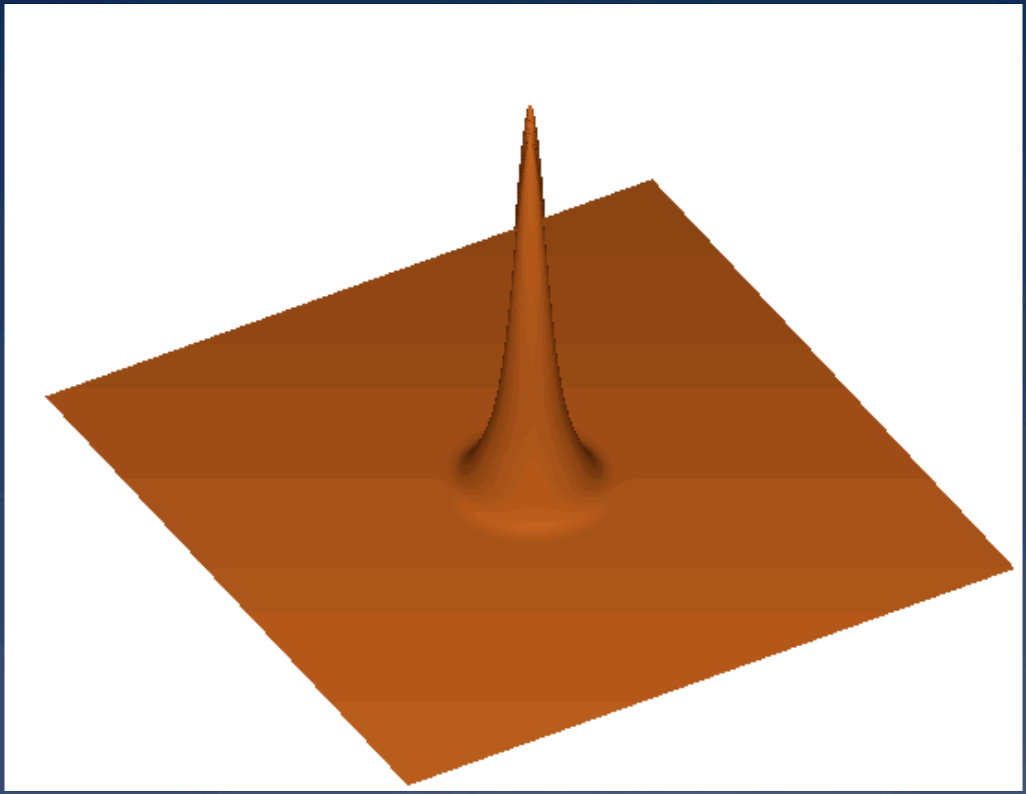
Baryon Acoustic Oscillations (BAO)



Credit: Daniel J. Eisenstein

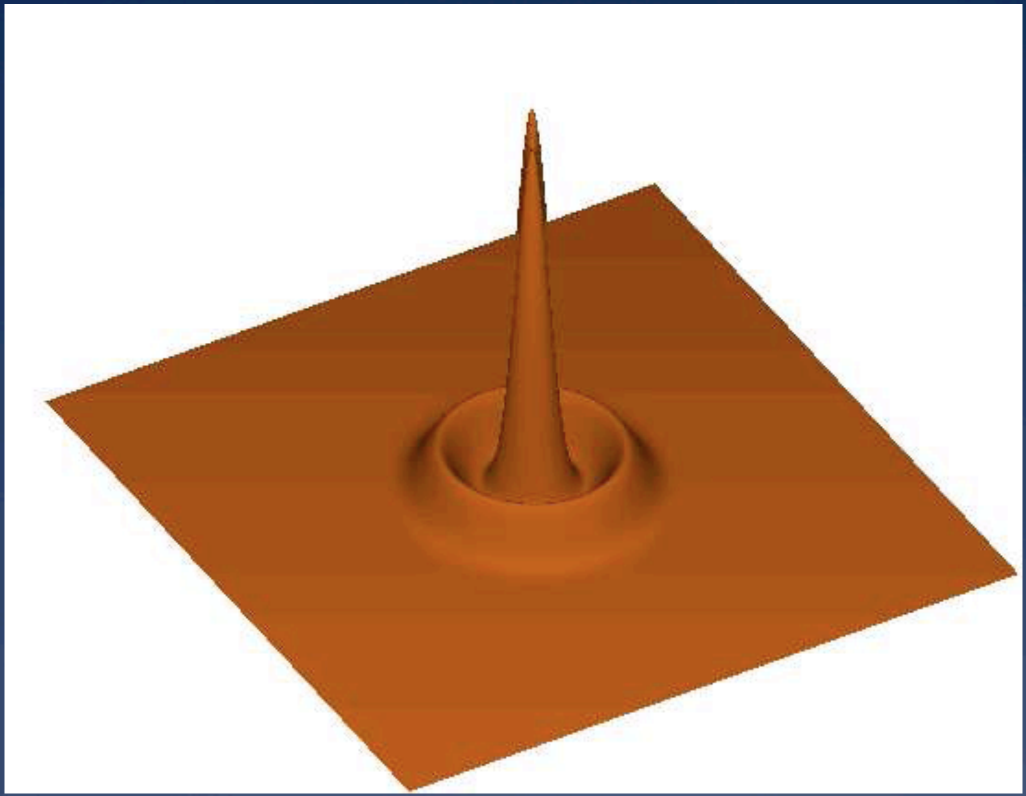
Primordial overdensity peak of dark matter, gas, photons at origin.

Baryon Acoustic Oscillations (BAO)



Overpressured peak initiates a spherical sound wave at $c_s=c/\sqrt{3}$.

Baryon Acoustic Oscillations (BAO)



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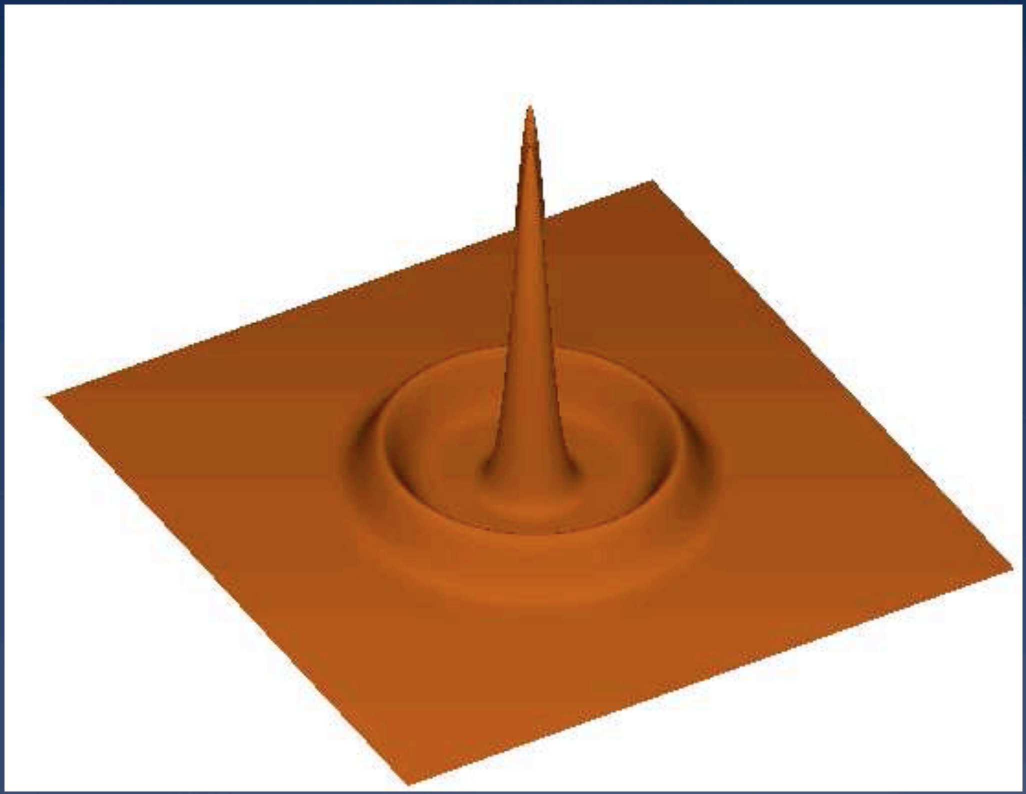

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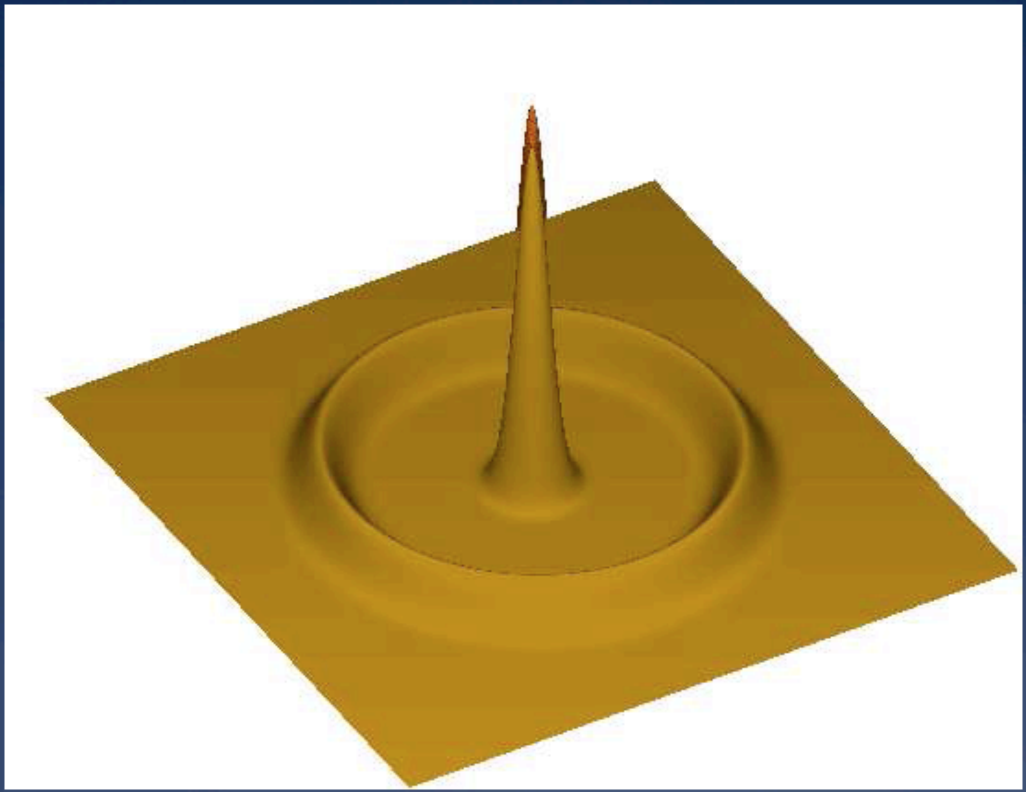

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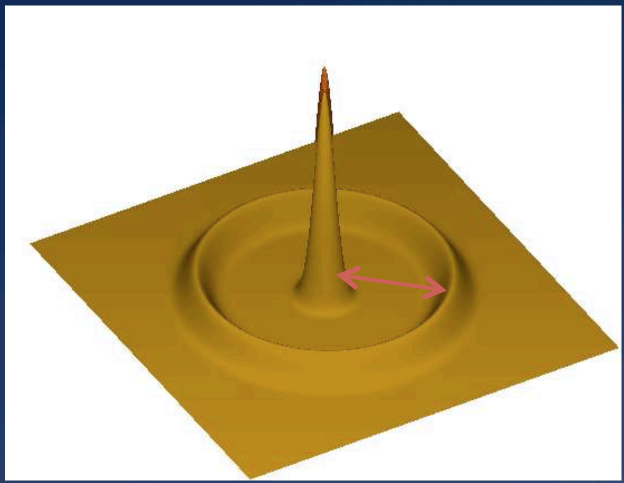
Baryon Acoustic Oscillations (BAO)



At recombination (z~1000),

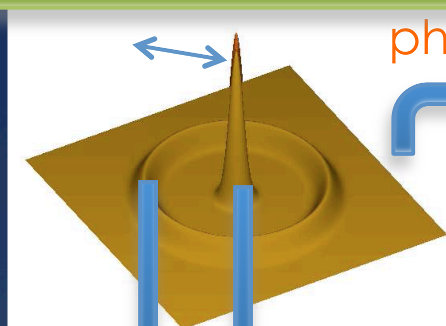
- Optically thick → optically thin
- Baryons decouple from photons.
- Sound speed of gas decreases.
- The traveling wave stalls.

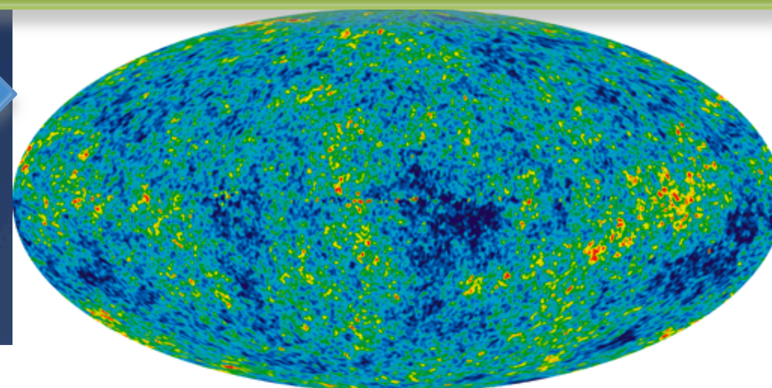
A spherical peak at the distance that the wave has travelled before the recombination
→ **the sound horizon scale** at recombination (150 Mpc).

Baryon Acoustic Oscillations

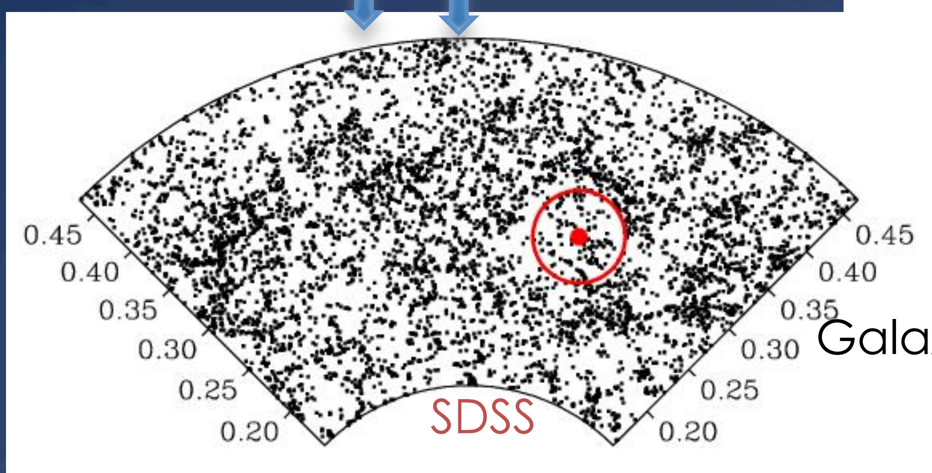
A spherical peak at the distance that the wave has travelled before the recombination
→ **the sound horizon scale** at recombination (150 Mpc).

photons





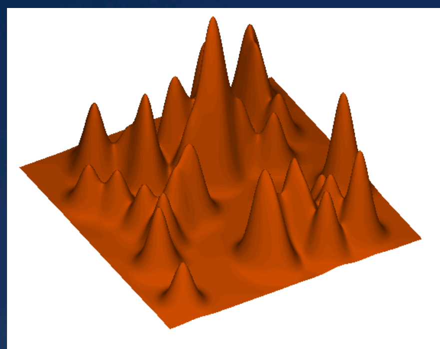
Baryons
+DM



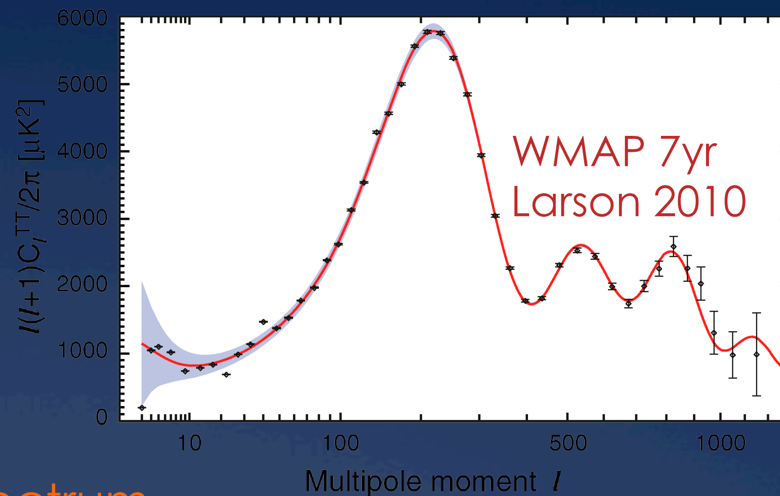
WMAP 7yr
Larson 2010

Galaxy surveys, 21cm surveys

Baryon Acoustic Oscillation



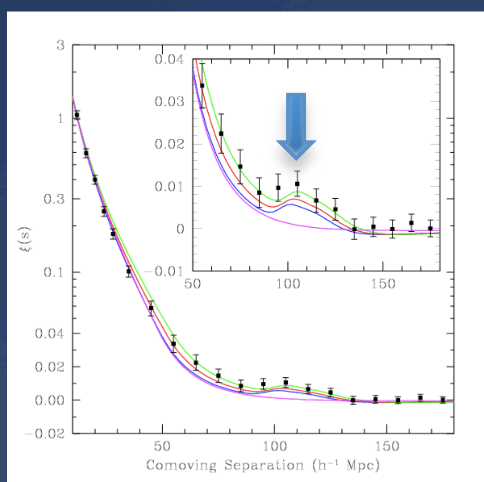
photons

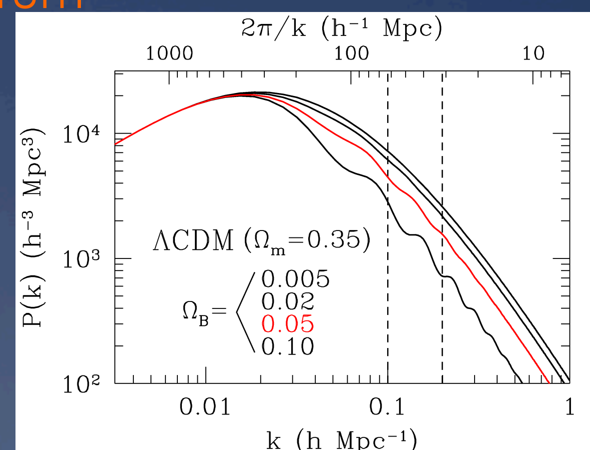


Baryons +DM

Correlation function

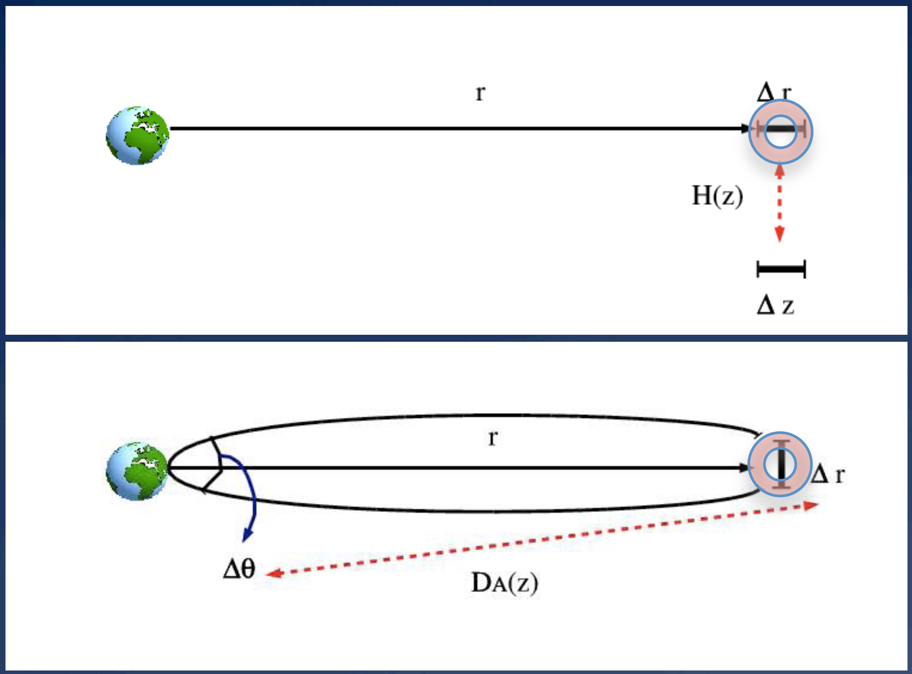
Power spectrum





Eisenstein et al. 2005

Standard ruler test



$$\Delta r_{\parallel} = \frac{c\Delta z}{H}$$

$$\Delta r_{\perp} = (1+z) D_A \Delta\theta$$

$$D_A = \frac{1}{1+z}\int \frac{cdz}{H(z)}$$

Knowing Δr → D_A and H separately measured: **Standard ruler test**

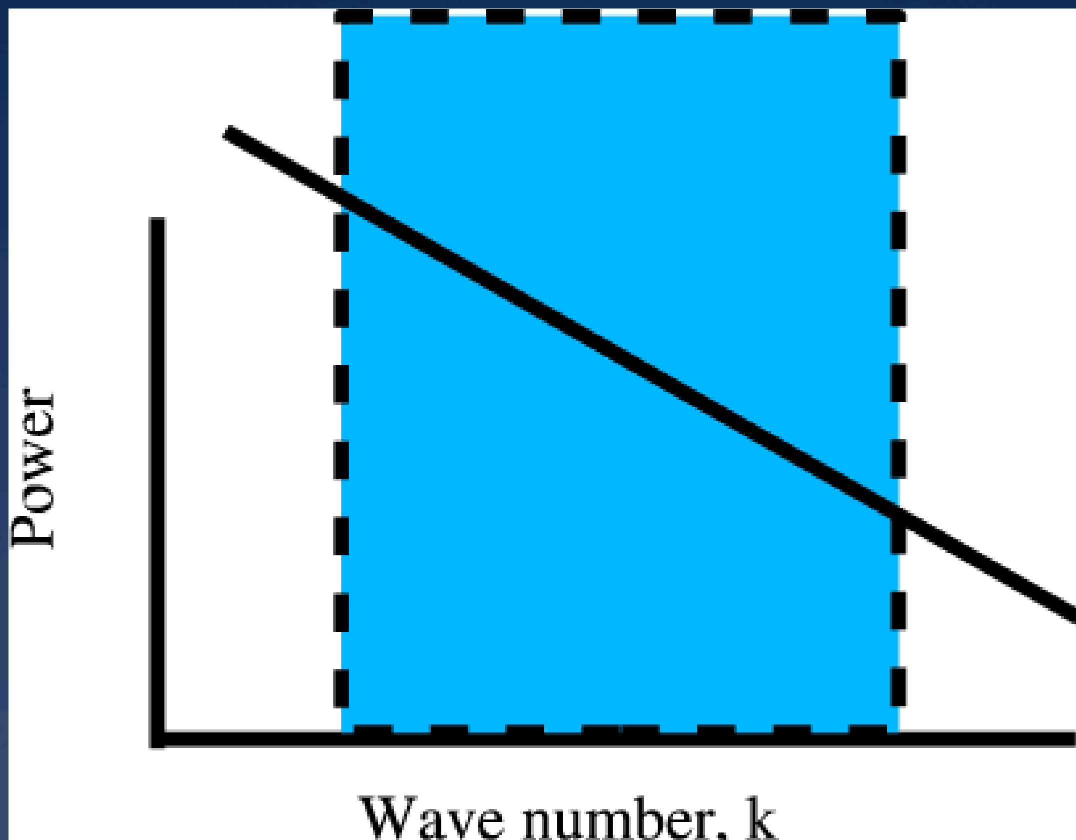
$$\frac{dH}{dz}, \frac{d^2 D_A}{dz^2}$$ → Dark Energy density as a function of redshift → w_0 and w_a

BAO is a good standard ruler

* The sound horizon scale is well determined by CMB measurements -> Then we measure the absolute distance scales.
* Distinct feature – can separate the effect of cosmological distortions from other observational effect such as redshift distortions.

BAO is a good standard ruler

If power spectrum follows a simple power law



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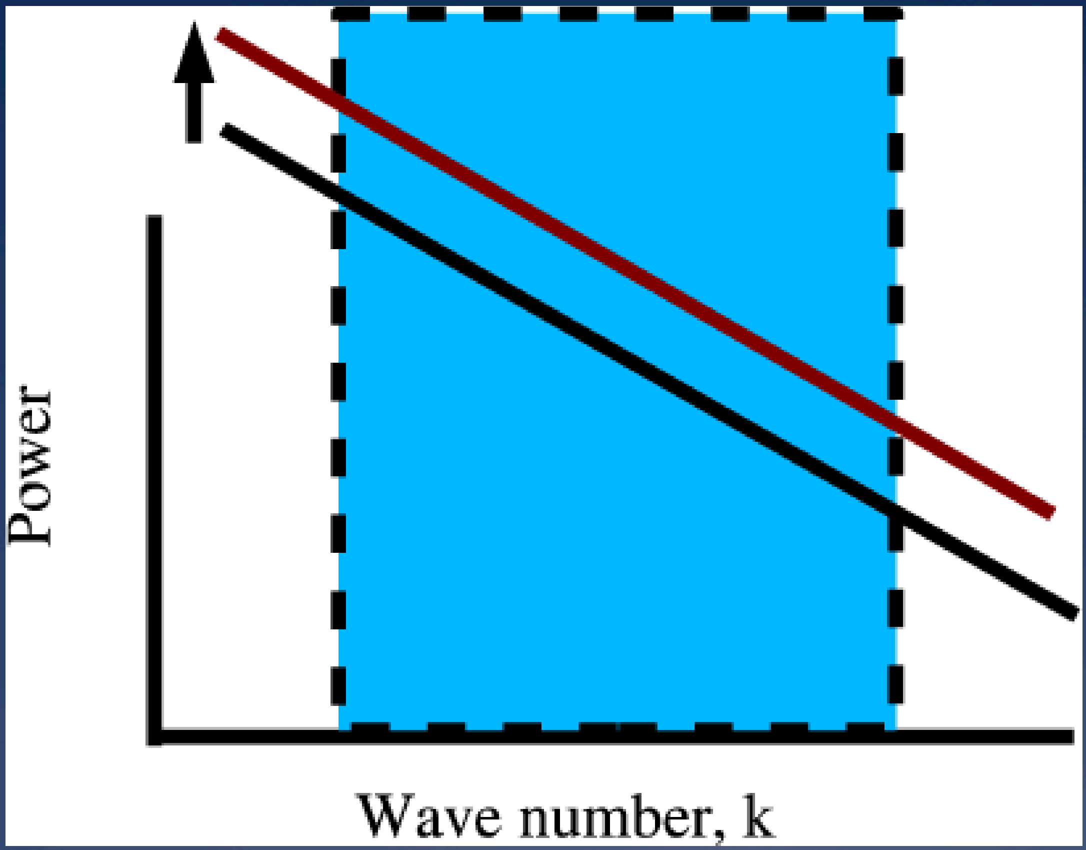

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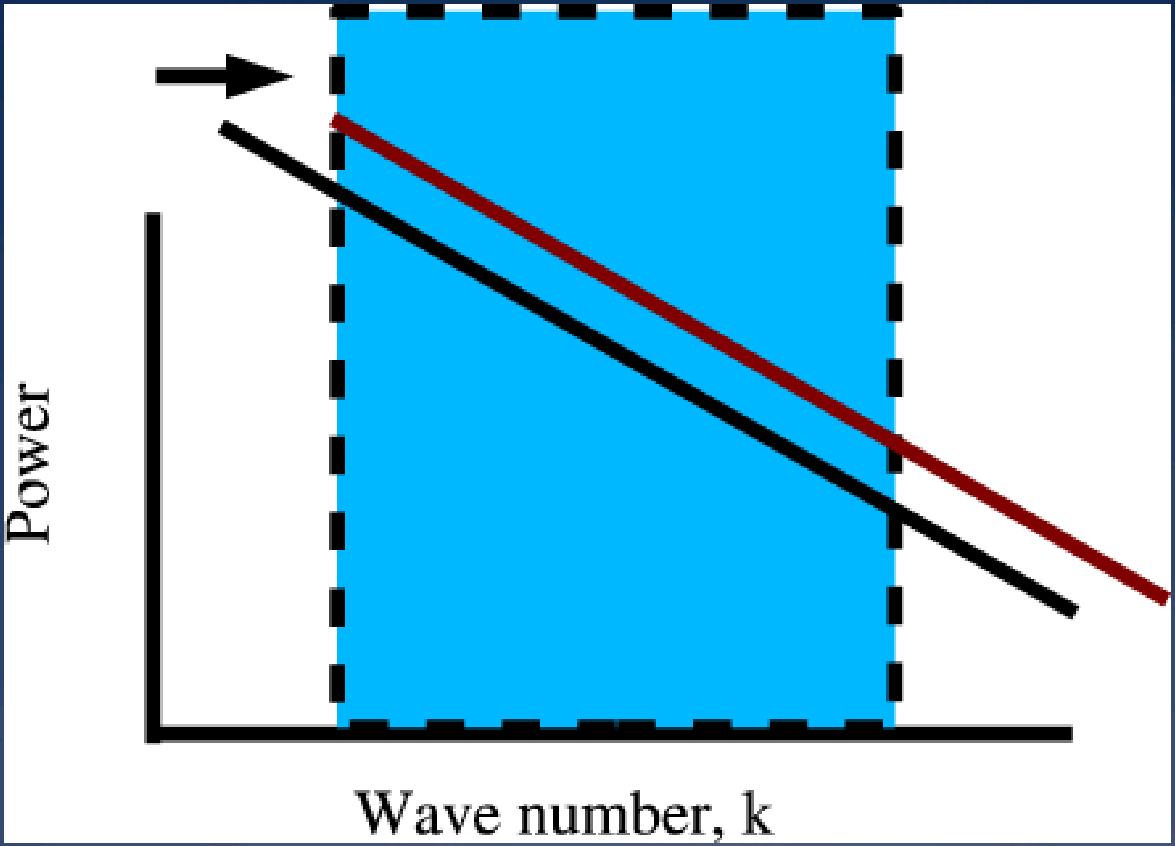
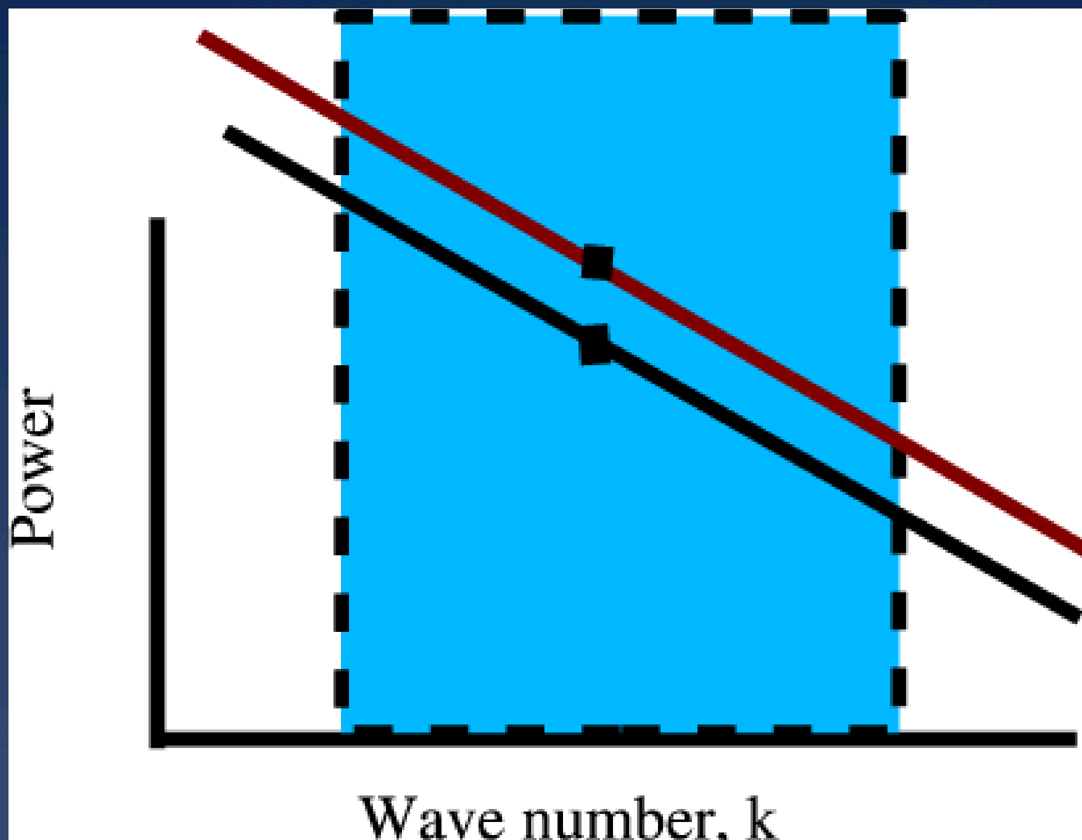


BAO is a good standard ruler

With a distinct signature,



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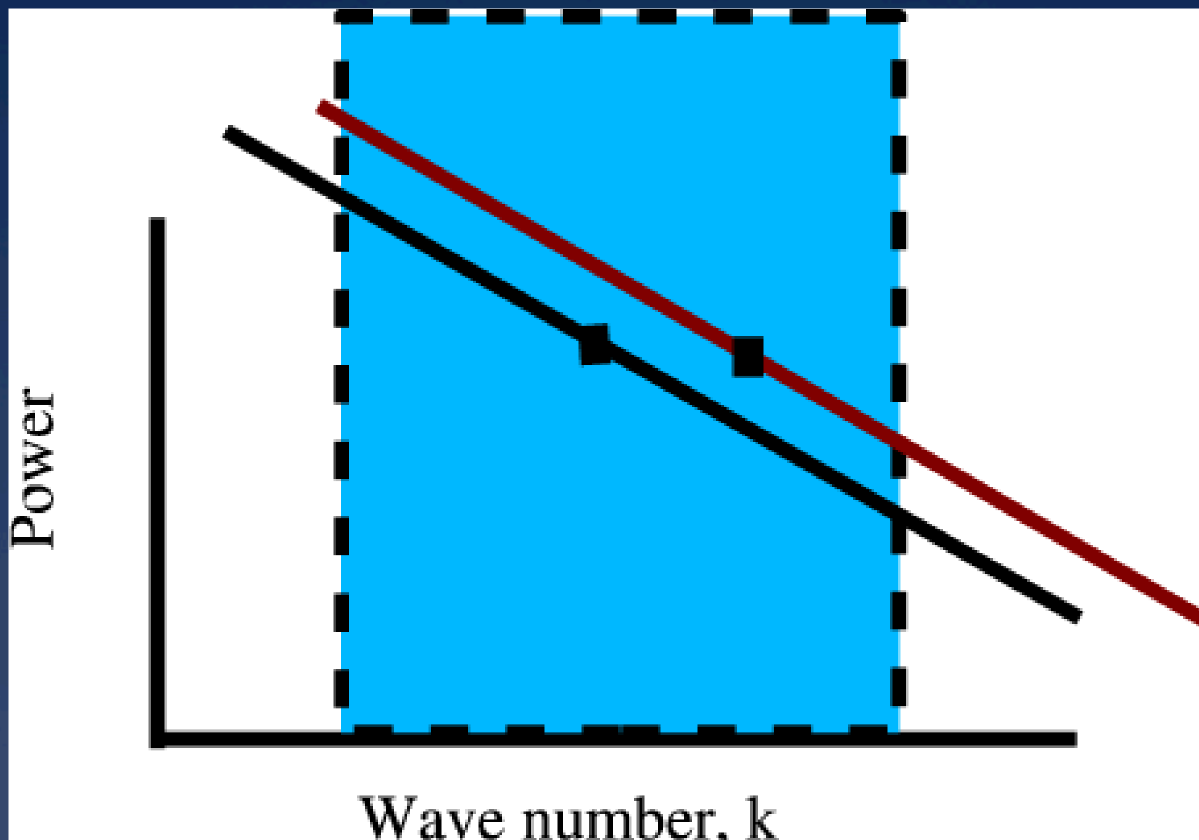

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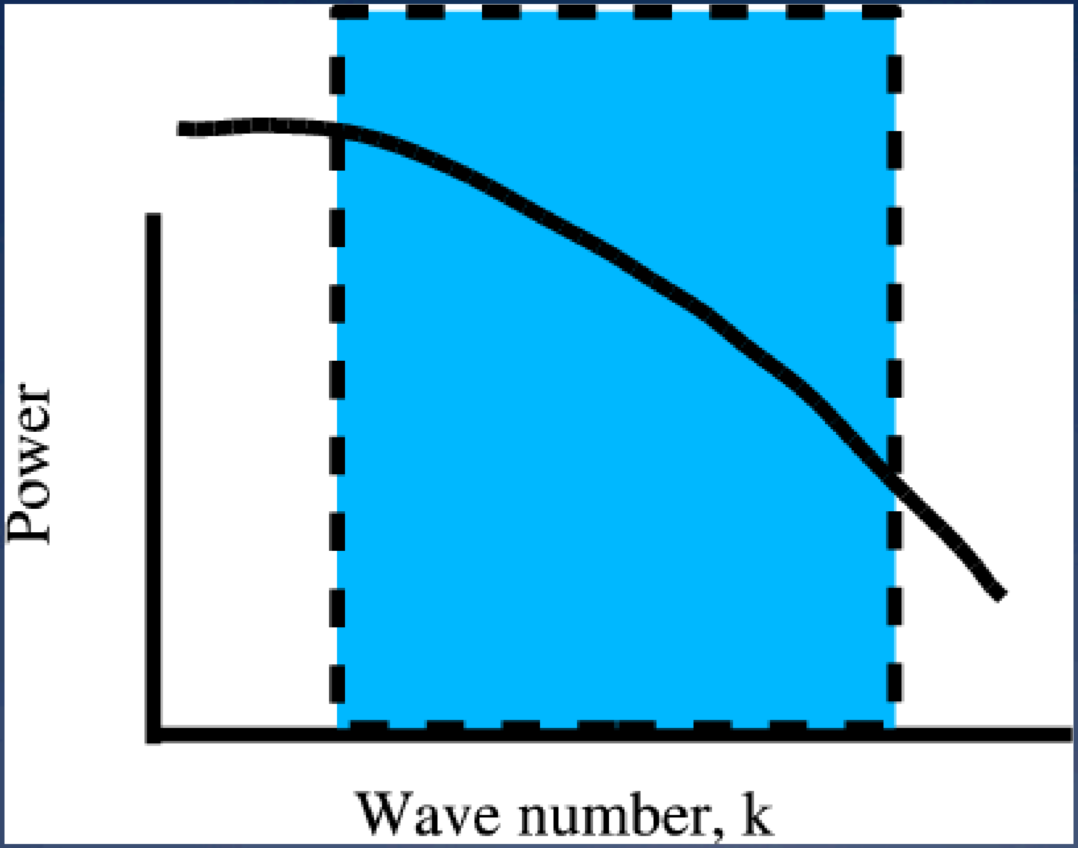

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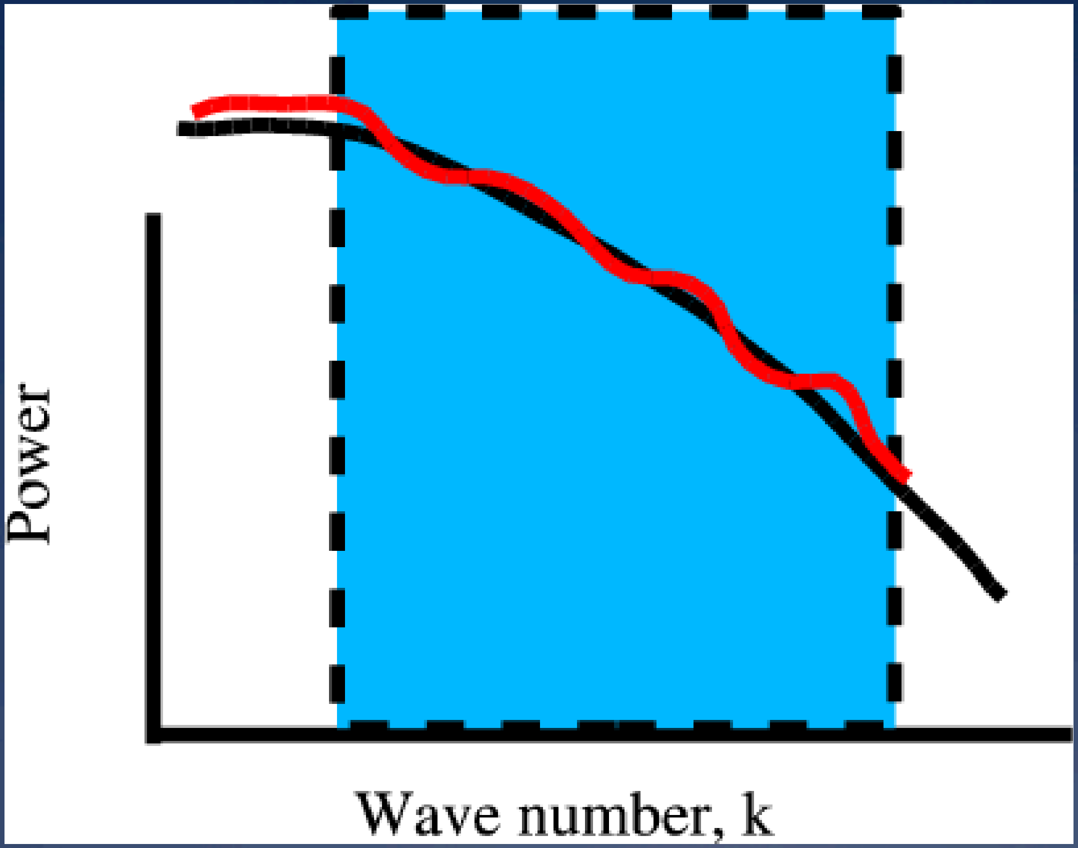


BAO is a good standard ruler

- The sound horizon scale is well determined by CMB measurements -> Then we measure the absolute distance scales.
- Distinct feature – can separate the effect of cosmological distortions from other observational effect such as redshift distortions, galaxy bias, etc.
- A feature on large scales – Nonlinearity effects (damping and shift) are still moderate.
- Internal crosscheck between D_A and ~~H~~.

Not for photo z.

Believed to suffer least systematics among dark energy probes

3D vs 2D BAO

3D (spec z) : accurate redshift determination.
Expensive.
Both $D_A(z)$ and $H(z)$.

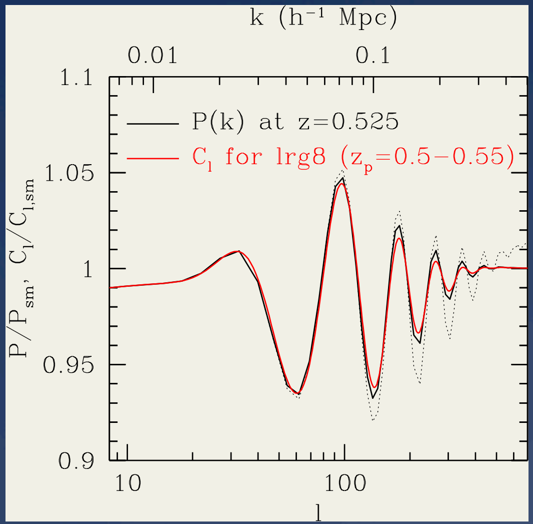
2D (photo z): Multiband imaging surveys.
Cheaper to cover a large Ng and a larger area of sky.
Large error on redshift determination.

BAO from imaging surveys

Due to the larger error on the photometric redshift, we lose the clustering information along the line of sight:

- Almost No H(z) information (Seo & Eisenstein 2003) for σz=0.05

-- mainly 2D information.



- Due to the projection of different physical scales onto the same l, BAO is additionally damped in 2D:

~ 30% increase in the damping scale for σz=0.05.

Therefore, photoz needs a much larger volume (~10 times) than spec-z for the equivalent performance.

3D vs 2D BAO

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2D (photo z): Multiband imaging surveys.
Cheaper to cover a large Ng and a larger area of sky.

DES, LSST, Pan-STARRS

3D vs 2D BAO

3D (spec z) : Many BAO measurement reports
Eg., Eisenstein et al. 2005, Cole at al. 2005, Percival 2007, 2010, Blake at al. 2011, etc.

2D (photo z): Only a couple.

Padmanabhan et al. 2007: 6.5%
(DR3, 3528 square degrees, 900,000 gals)

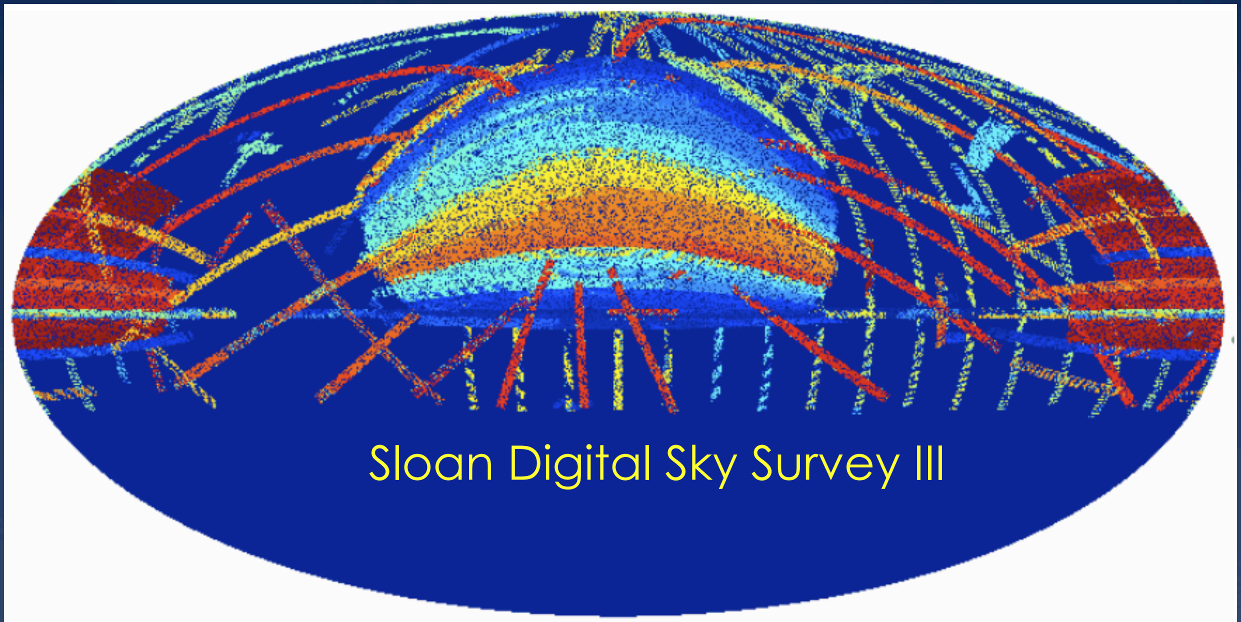
Carnero et al. 2011: 10%
(DR7, 7136 square degrees, $0.5<z<0.6$, 610,000 gals)

We want to design a robust approach for measuring the location of BAO using the imaging surveys.

BAO from SDSS-III photoz LGs (DR8)

Total Area: 14,555 sq deg

1.5 million LGs: 0.4<z<0.7



Full Mask thanks to Michael Blanton

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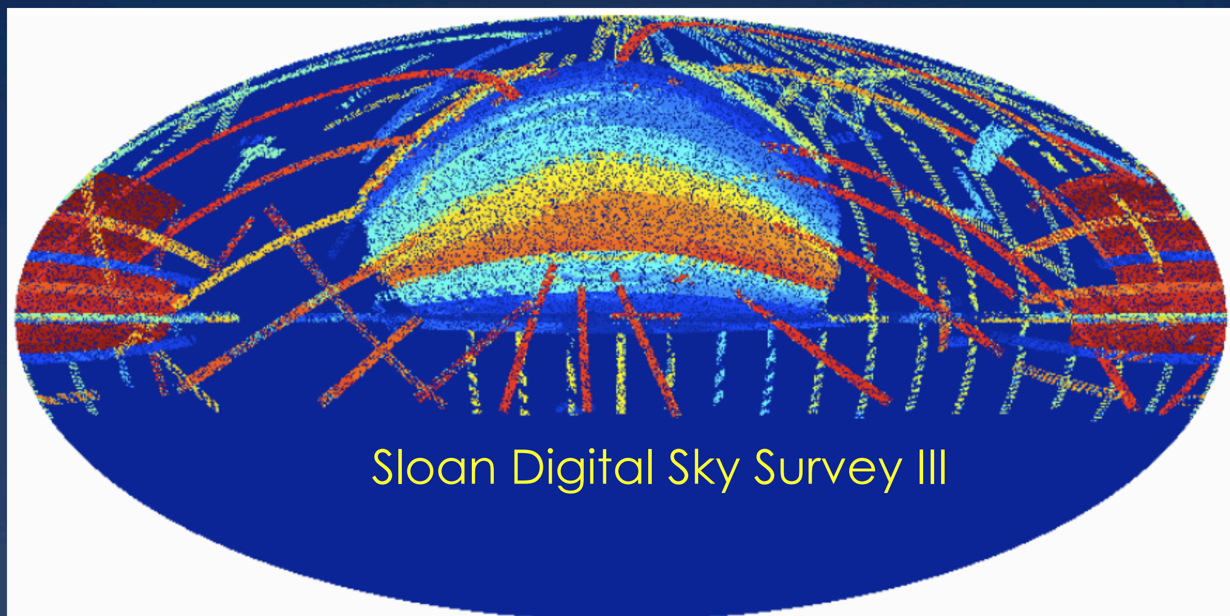
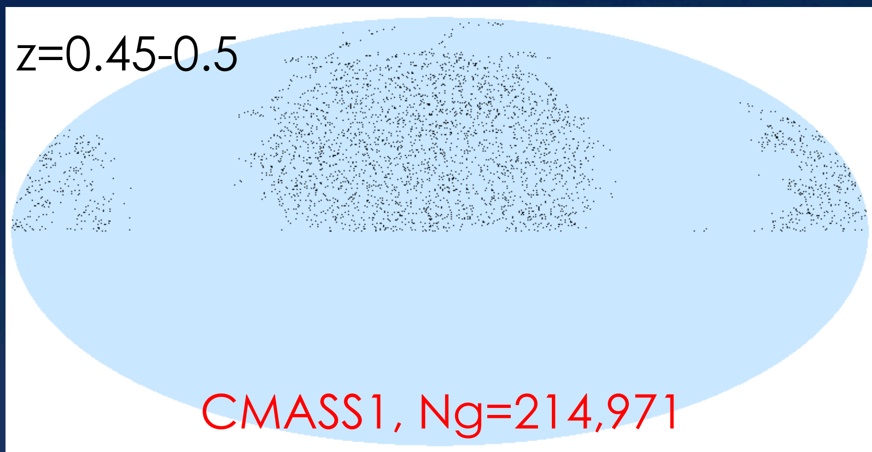
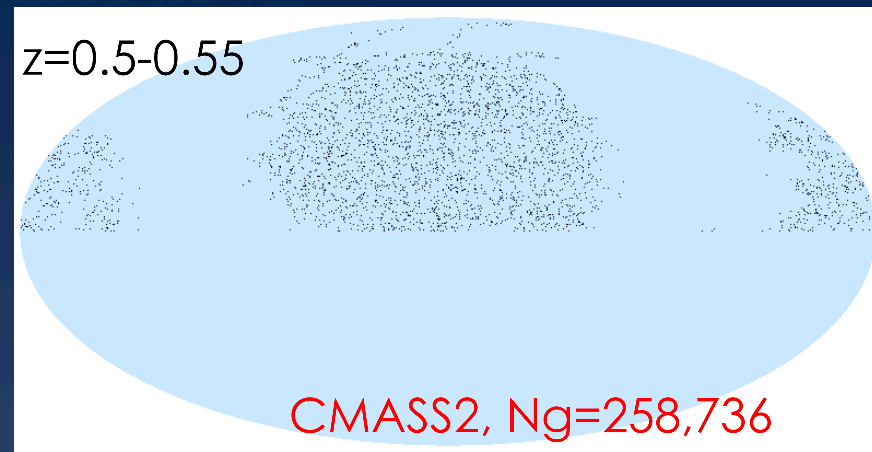


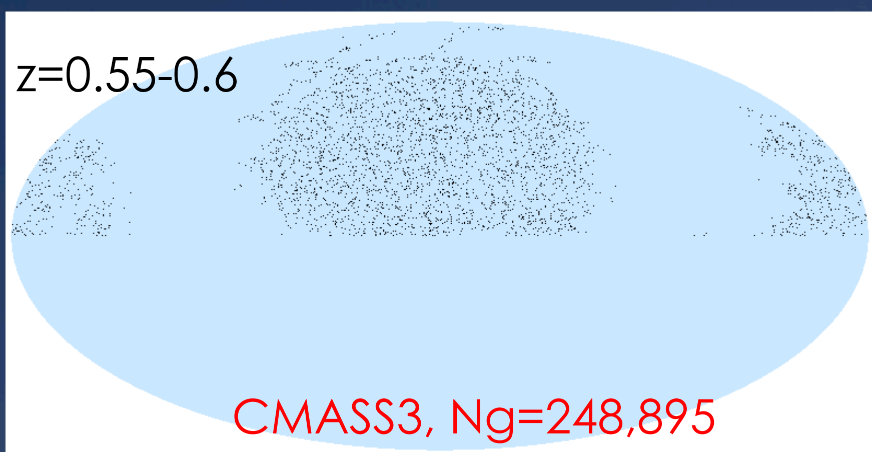
Final photo z sample (CMASS) : ~10000 degree^2 with ~ 0.8 million galaxies at 0.45<z<0.65 (Photoz catalog from Ross et al. 2011).

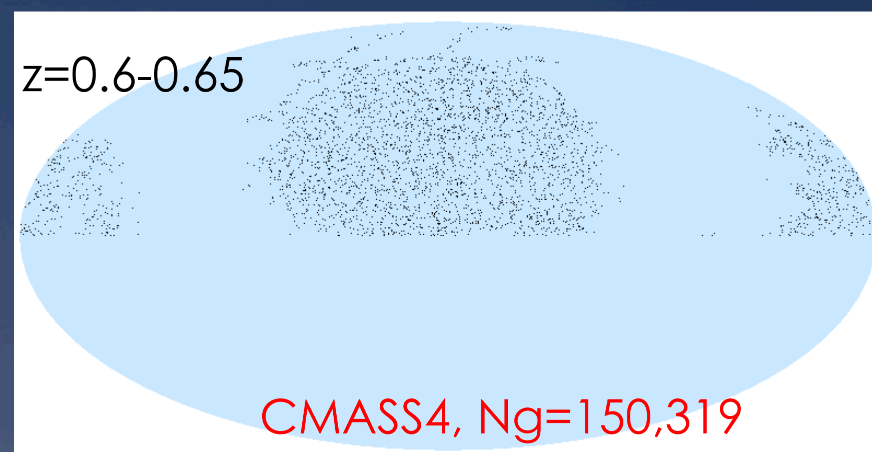
The largest sky area/volume ever for a BAO analysis.

Multiple photo-z redshift bins with dz=0.05



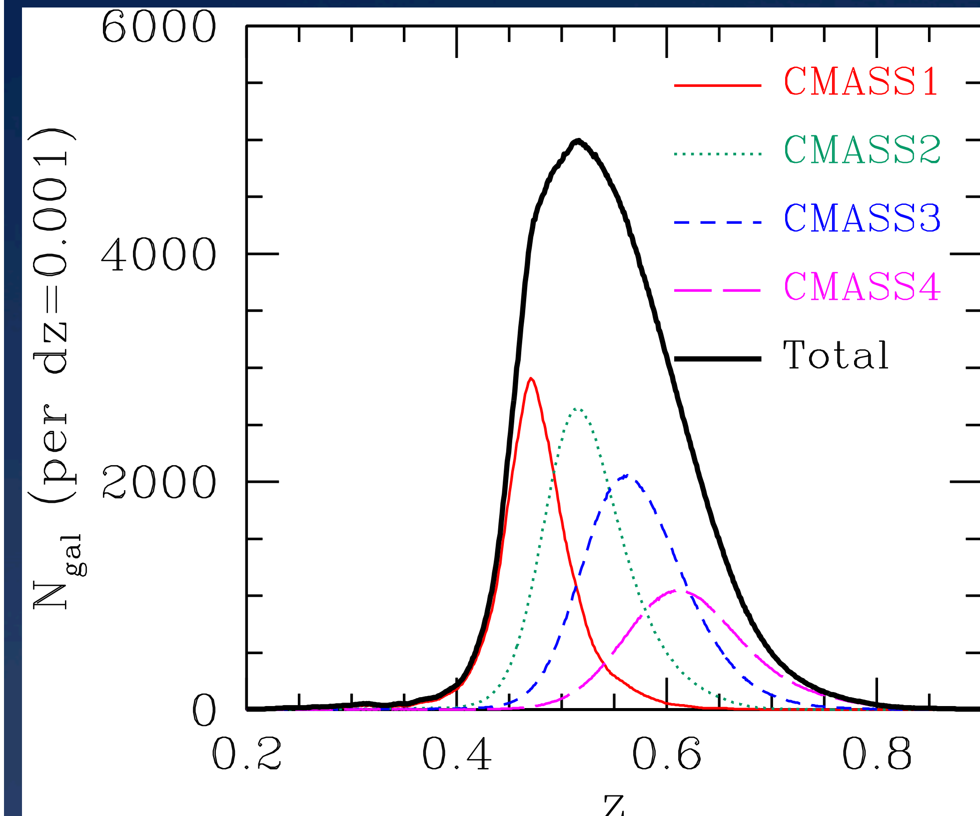






Ho et al. in preparation

Multiple photo-z redshift bins with dz=0.05



Median/Mean redshift = 0.54

TABLE 1
THE FOUR PHOTOMETRIC REDSHIFT BINS.

bins	z_{ph} range	N_{gal}	$\sigma_{z_{ph}}$	z_{median}	z_{mean}
CMASS1	0.45-0.50	214,971	0.043	0.474	0.475
CMASS2	0.50-0.55	258,736	0.044	0.523	0.526
CMASS3	0.55-0.60	248,895	0.052	0.568	0.572
CMASS4	0.60-0.65	150,319	0.063	0.617	0.621
Total	0.45-0.65	872,921		0.541	0.544

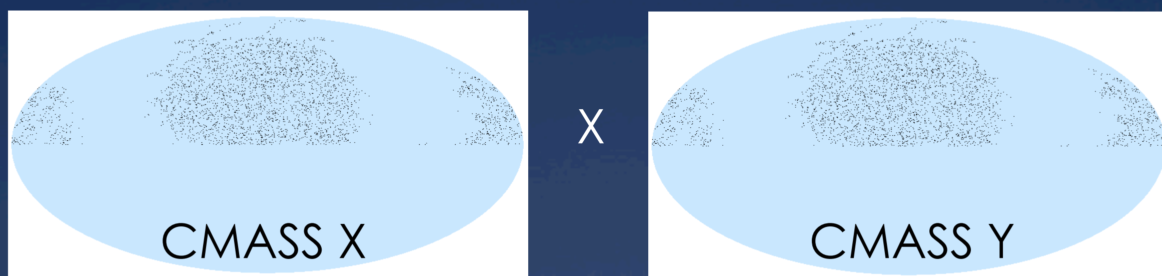
NOTE. — N_{gal} is the effective number of galaxies after weighting each object by p_{sg}, which is the probability that an object is a galaxy. The value of $\sigma_{z_{ph}}$ is the dispersion in redshift for each photo-z bin.

Photometric redshift catalog from Ross et al. 2011.

Angular power spectrum estimation using an Optimal Quadratic Estimator

Ho et al. in preparation,

- We derive auto and cross-power spectra between different redshift bins.



$$C_l^{gg}(\mathrm{DATA})$$

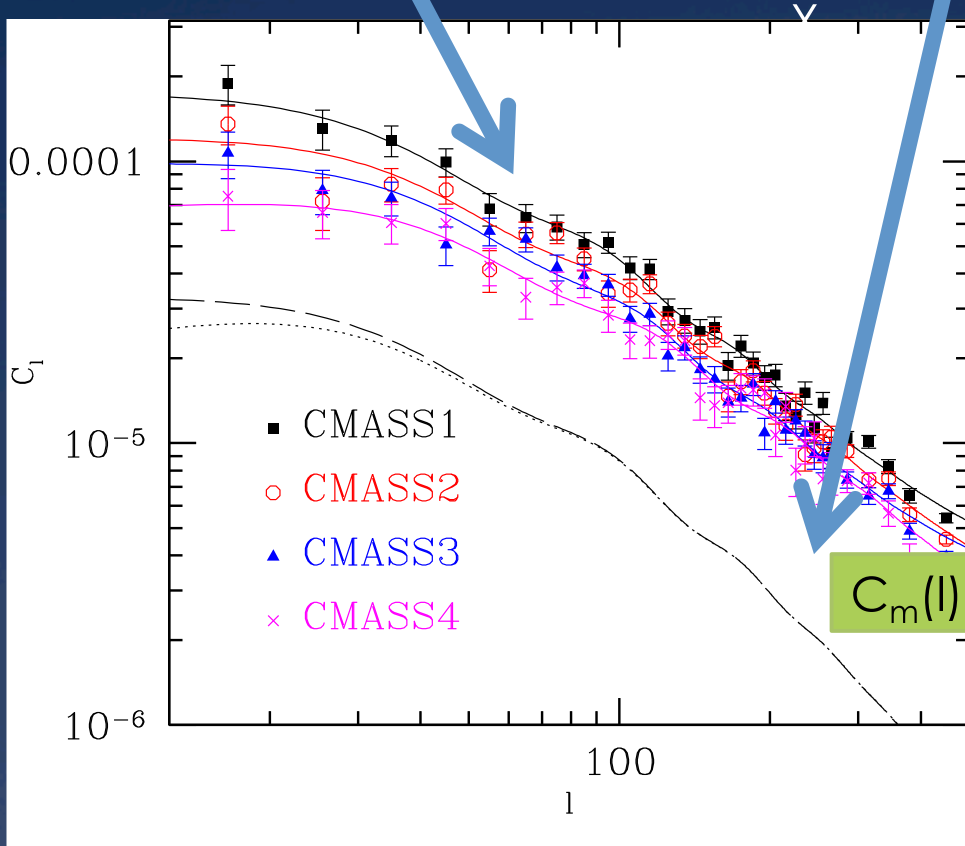
- Returns an unbiased Minimum variance measurement of the parameters if the field is Gaussian (eg. Padmanabhan 2007).

- Survey geometry considered appropriately.

Measure the BAO scale using a template

Tailor the method in Seo, Seigel, Eisenstein, & White 2008 to 2D.

$$C_{\rm obs}(l) = B_i(l) C_{m,z_i}(l/\alpha) + A_i(l)$$



$$l_{\rm obs}/\alpha = l_{\rm fid}$$

$C_m(l)$: Template power spectrum

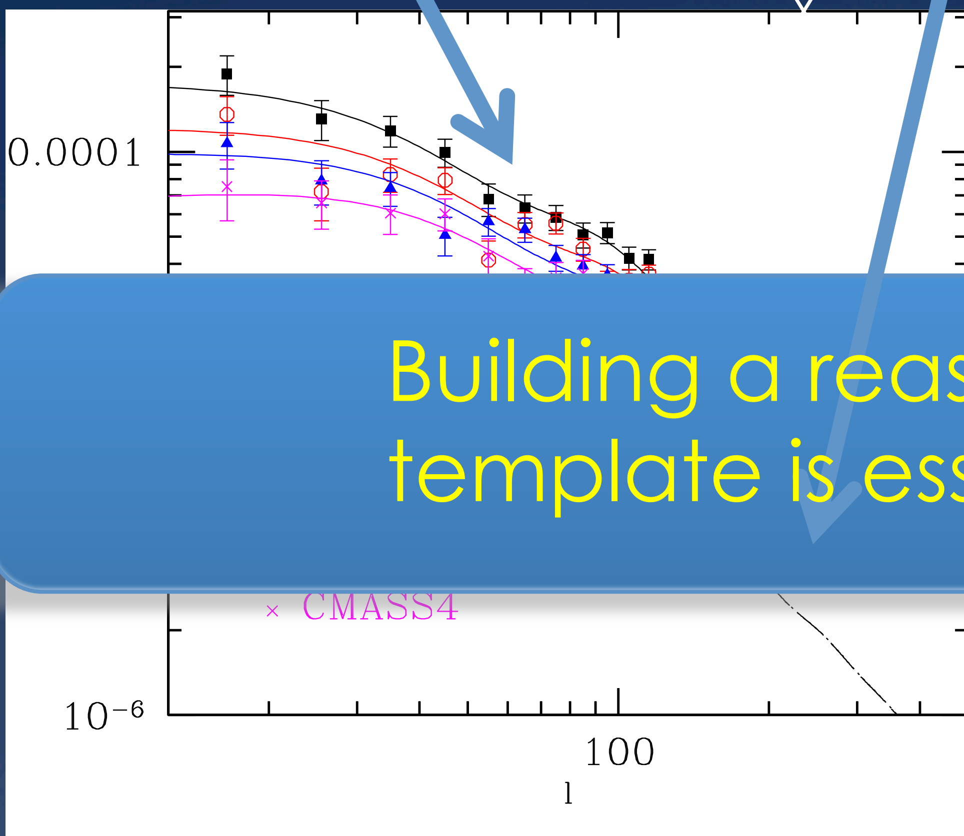
Seo et al. submitted to ApJ

Measure the BAO scale using a template

Tailor the method in Seo, Seigel, Eisenstein, & White 2008 to 2D.

$$C_{\rm obs}(l) = B_i(l) C_{m,z_i}(l/\alpha) + A_i(l)$$

$$l_{\rm obs}/\alpha = l_{\rm fid}$$

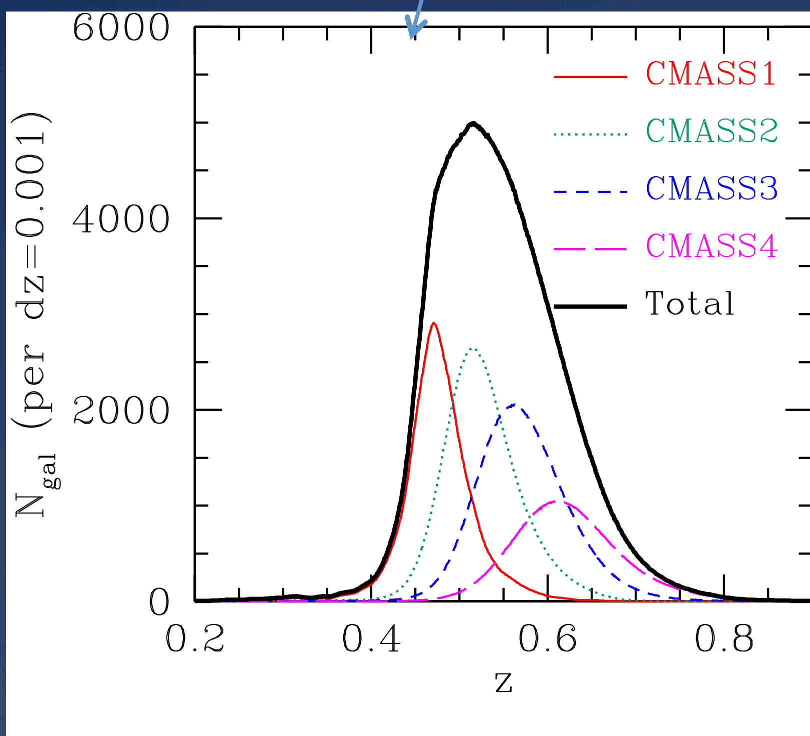


Building a reasonable template is essential!

Template construction: dn/dz from the excellent training set!

Template

$$C_{m,z_i}(\ell) = \frac{2}{\pi}\int \mathrm{d}k k^2 P_m(k, z_i) \left(\int \mathrm{d}z \frac{\mathrm{d}N_i}{\mathrm{d}z} b(z) \frac{D(z)}{D(z=0)} \left[j_\ell\left(k(1+z)D_{A,\mathrm{fid}}(z)\right) - \beta j_\ell''\left(k(1+z)D_{A,\mathrm{fid}}(z)\right)\right]\right)^2,$$



Training sample of 112,778 BOSS CMASS spectra

As small as 0.5% error on dn/dz!

Template construction: "trivial" assumptions

Template (Limber apprx)

$$C_{m,z_i}(l/\alpha) = \int \frac{\mathrm{dz}\;\; H_f(z)}{c[(1+z)D_{A,f}(z)]^2} \left[\frac{dn_i}{dz}\right]^2 [b(z)G(z)]^2 P_m \left(k = \frac{1+1/2}{D_A(z)}\right)$$

Template construction: "trivial" assumptions

Template (Limber apprx)

$$C_{m,z_i}(l/\alpha) = \int \frac{dz \;\; H_f(z)}{c[(1+z)D_{A,f}(z)]^2} \left[\frac{dn_i}{dz}\right]^2 [b(z)G(z)]^2 P_m \left(k = \frac{1+1/2}{\alpha(1+z)D_{A,f}(z)}\right)$$

We assume a fiducial cosmology for $D_A(z)$ and sound horizon.

Then we fit for α to match the observation.

$D_A(z) = \alpha D_{A,fid}(z)$

=> $D_A(z=0.54) = \alpha D_{A,fid}(z=0.54)$

Template construction: "trivial" assumptions

Template (Limber apprx)

$$C_{m,z_i}(l/\alpha) = \int \frac{dz \;\; H_f(z)}{c[(1+z)D_{A,f}(z)]^2} \left[\frac{dn_i}{dz}\right]^2 [b(z)G(z)]^2 P_m \left(k = \frac{1+1/2}{\alpha(1+z)D_{A,f}(z)}\right)$$

We assume a fiducial cosmology for $D_A(z)$ and sound horizon.

Then we fit for α to match the observation.

$[D_A(z)/r_s]_{obs} = \alpha\, [D_{A,fid}(z)/r_s]_{fid}$

$\Rightarrow [D_A(z=0.54)/r_s]_{obs} = \alpha\, [D_{A,fid}(z=0.54)/r_s]_{fid}$

Template construction: "trivial" assumptions

Template (Limber apprx)

$$C_{m,z_i}(l/\alpha) = \int \frac{H_f(z)}{c[(1+z)D_{A,f}(z)]^2} \left[\frac{dn_i}{dz}\right]^2 [b(z)G(z)]^2 P_m\left(k = \frac{1+1/2}{\alpha(1+z)D_{A,f}(z)}\right)$$

Determined based on the fiducial model.

Any deviation is largely marginalized over by B(l).

Essentially does not affect the results.

Fitting range and B(l) and A(l)

$$C_{\rm obs}(l) = B_i(l) C_{m,z_i}(l/\alpha) + A_i(l)$$

For our S/N level, $B_1 l + B_0$ and a constant A_0 for each redshift bin with a fitting range of $30<l<300$, to exclude the non-BAO information as much as we can.

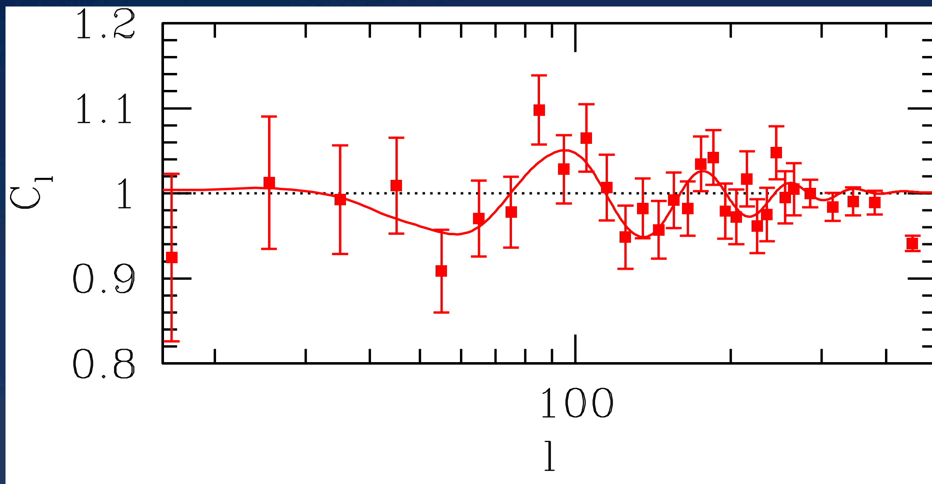
Fit using BAO P_m and No-BAO P_m .

When multiple redshift bins are combined, we fit for a universal α while marginalizing over B_i and Ai for individual redshift bin (A total of 13 parameters).

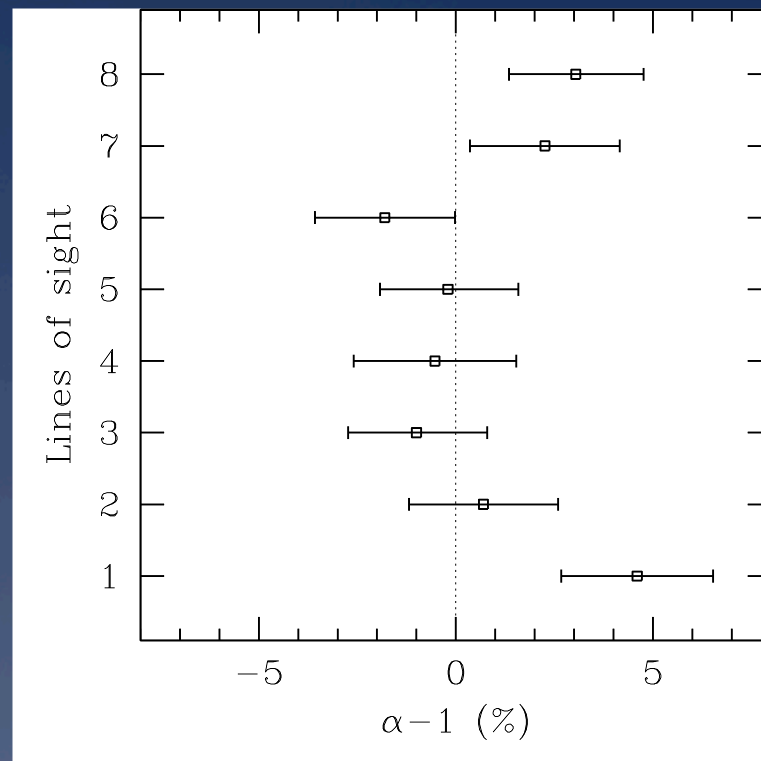
Band window function effect is considered.

Test with Mocks. I

Using Martin White's CMASS mocks, we generate 2D wide-angle projections of uniform dn/dz for a dz=0.05 slice at z=0.525.



Each line of sight ~ 3 sets of the real data.



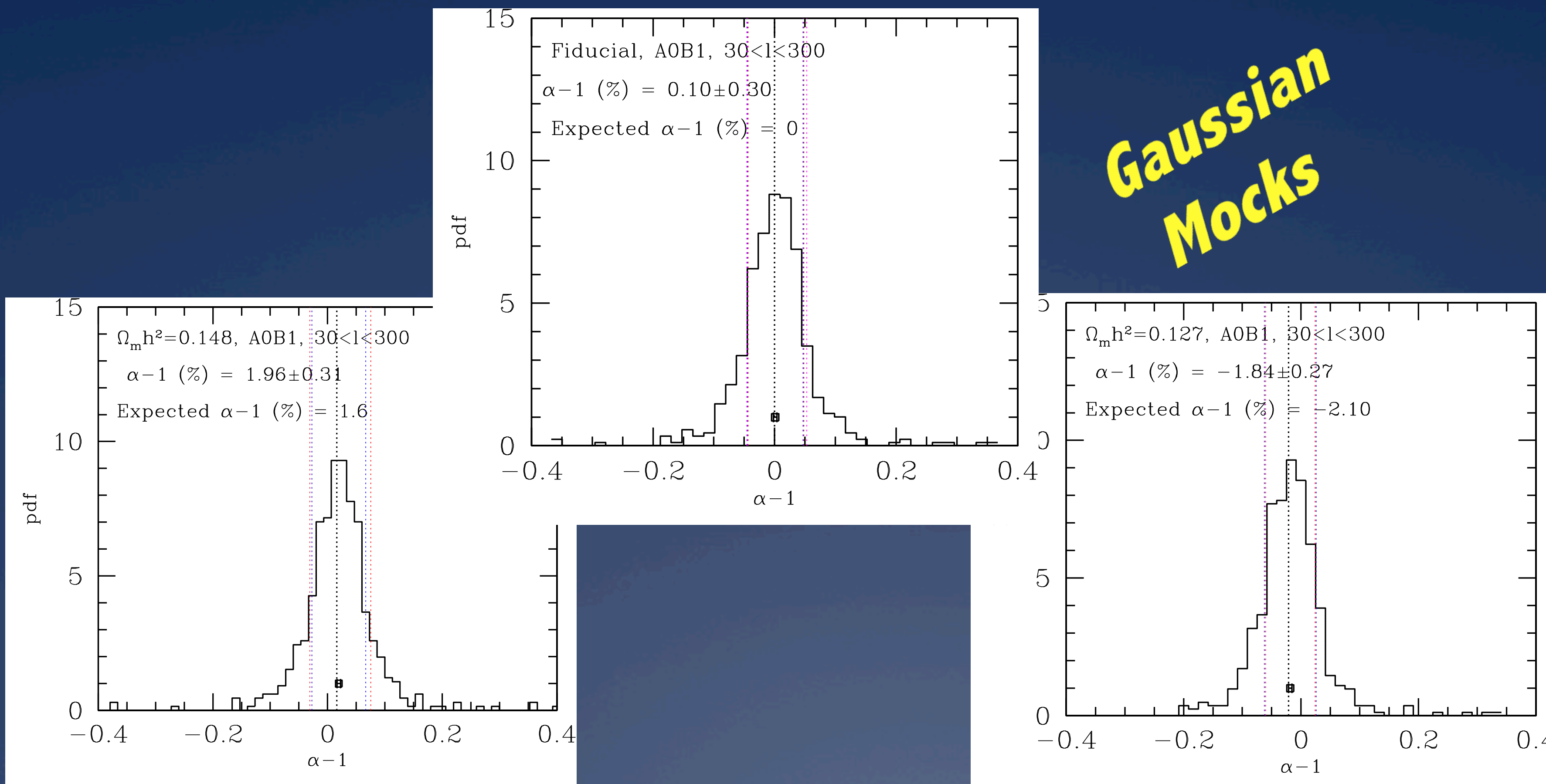
We find no obvious bias on the measured BAO scale.

N-body Mocks

Mock covariance ~ OQE covariance

Test with Mocks. II

Generate Gaussian mock power spectra that mimics the real data
In terms of power spectrum shape as well as the covariance between redshift bins and different scales.
500 samples while each sample includes mock CMASS1, 2, 3, & 4.

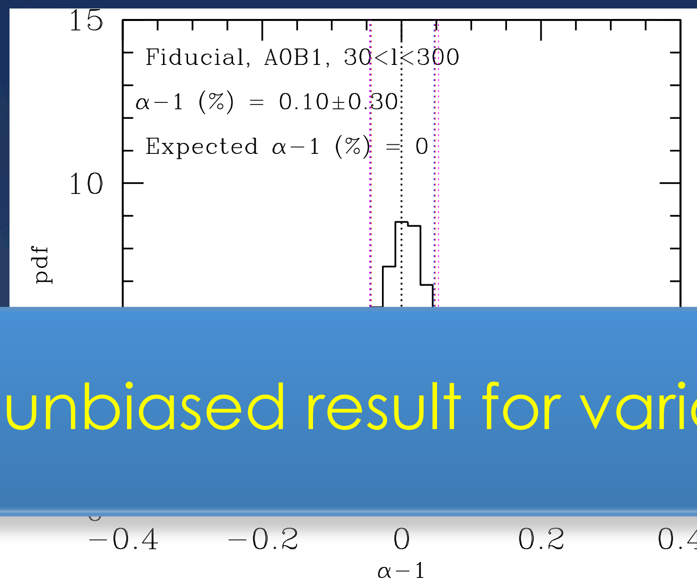


Gaussian Mocks

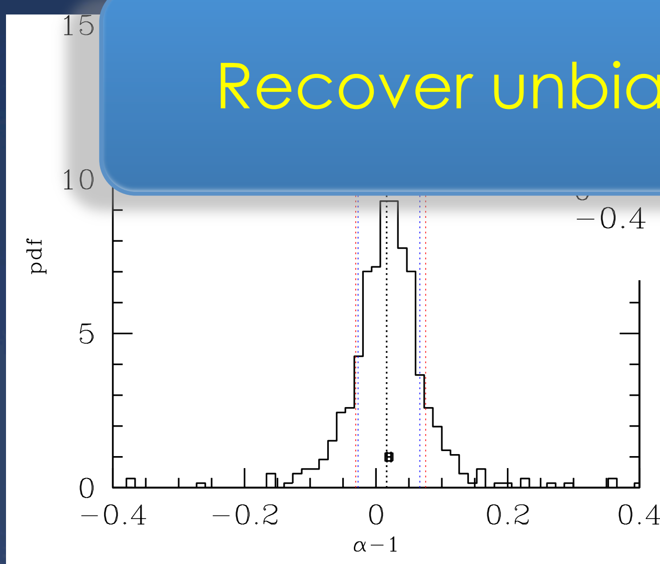
Test with Mocks. II

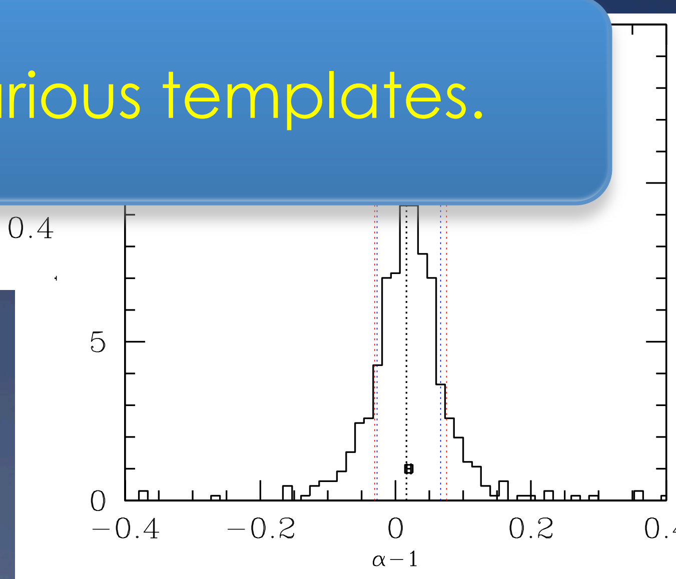
Generate Gaussian mock power spectra that mimics the real data Including the covariance between redshift bins and different scales.

500 samples while each sample includes mock CMASS1, 2, 3, & 4.



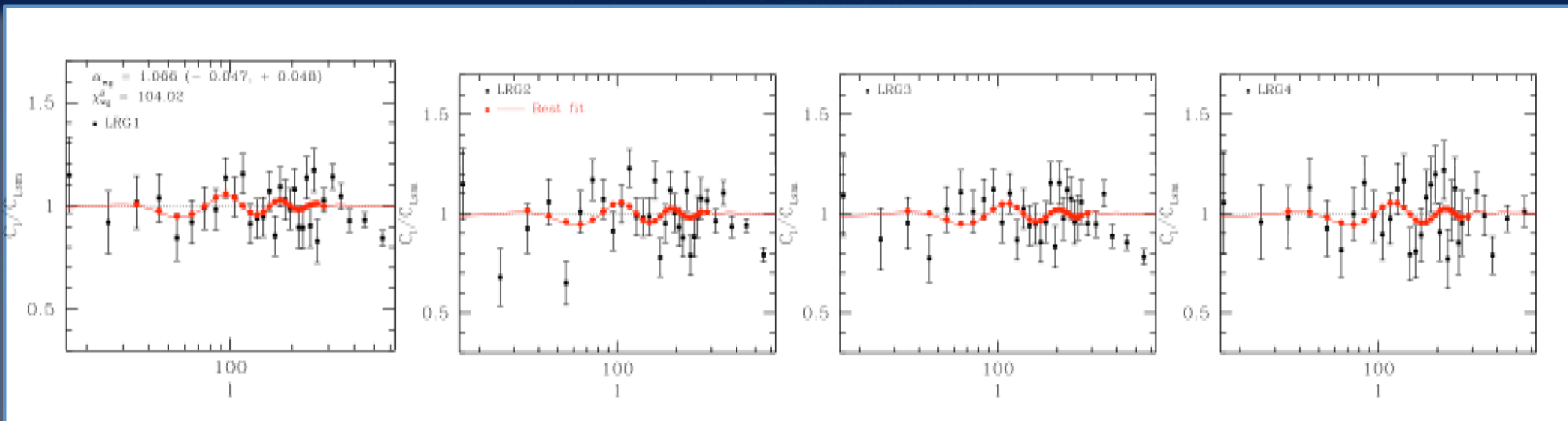
Gaussian Mocks

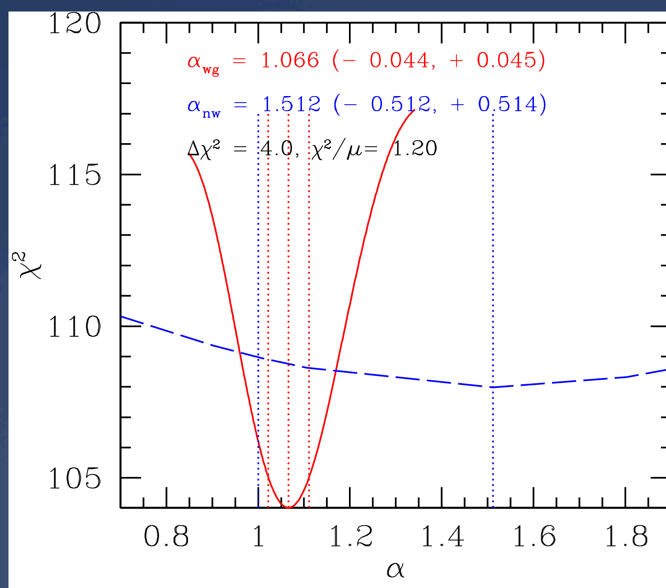




Recover unbiased result for various templates.

Best fit result of DR8





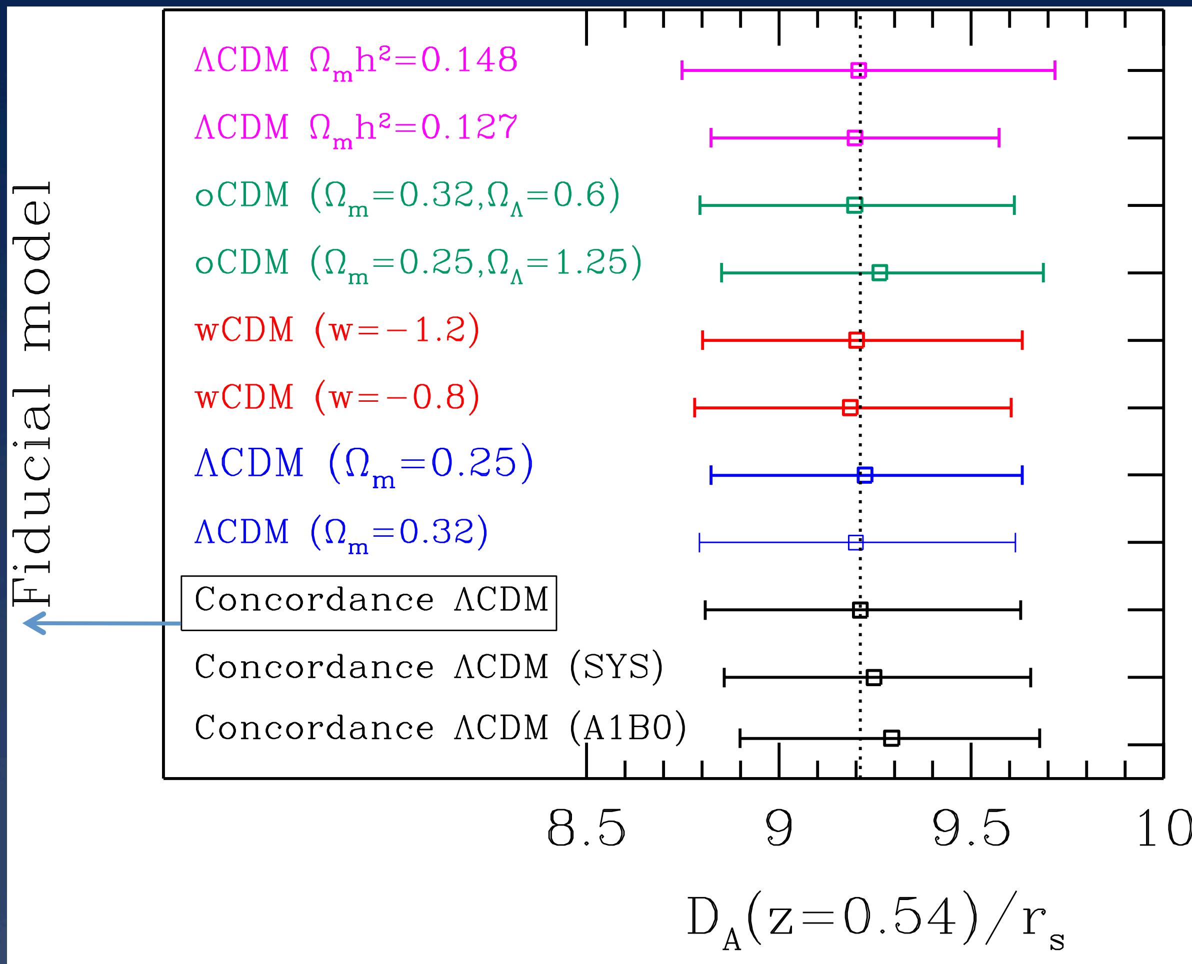
alpha-1 = 6.6 +- 4.7%

Reduced χ^2=1.19

$[D_A(z)/r_s]_{obs}$ = 9.212 +- 0.41 at z=0.54

Seo et al. submitted

Robust result!

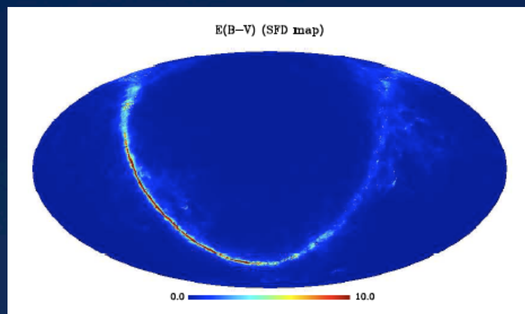


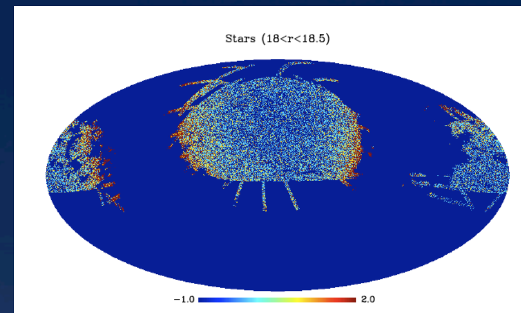
Om=0.274, h=0.7

Does depend little on the assumptions used for building the template. At most 1%.

Systematics

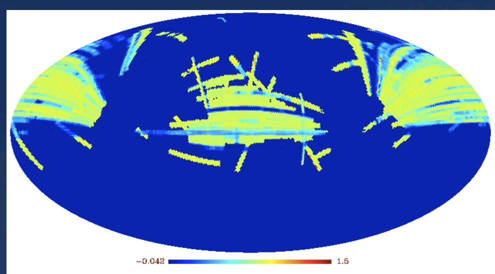
- A real survey is not as favorable as the mock.
- The photoz survey suffers more from various observational systematics such as stars, dust, seeing, offset, and sky brightness.
- In principle, if these effects do not have a preferred scale (i.e., if they have smooth power spectra), we can blindly extract BAO information.

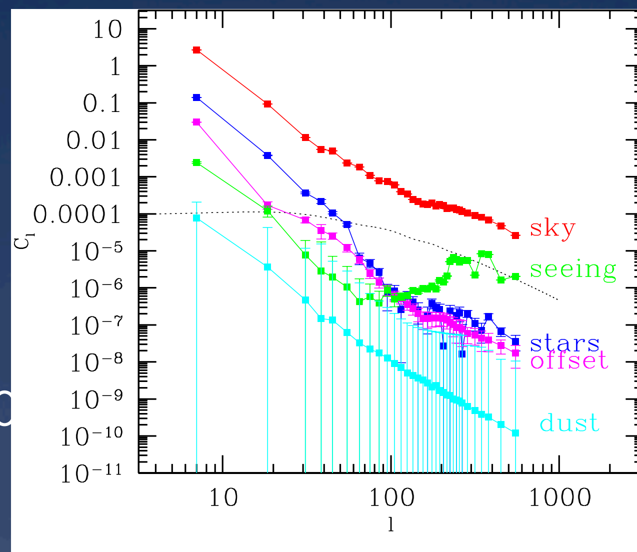


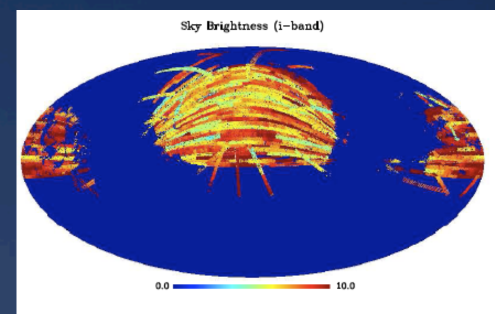


Dust extinction

Stars







Offset (Schlafly et al. 2010

Sky brightness

Ho et al. in preparation

Systematics correction

Ho et al. in preparation

- To get a cleaner angular power-spectrum, we attempt to remove star contamination, dust extinction, and sky brightness effect, etc, assuming that the effect of systematics can be described linearly,

For each l,

$$< \delta_o\delta_o > = < (\delta_g + \sum_i \epsilon_i\delta_i)(\delta_g + \sum_j \epsilon_j\delta_j) >$$

$$= < \delta_g\delta_g > + 2\sum_i \epsilon_i < \delta_g\delta_i > + \sum_i\sum_j \epsilon_i\epsilon_j < \delta_i\delta_j >$$

$$< \delta_o\delta_j > = < (\delta_g + \sum \epsilon_i\delta_i)\delta_j >$$

$$= < \delta_g\delta_j > + \sum \epsilon_i < \delta_i\delta_j >$$

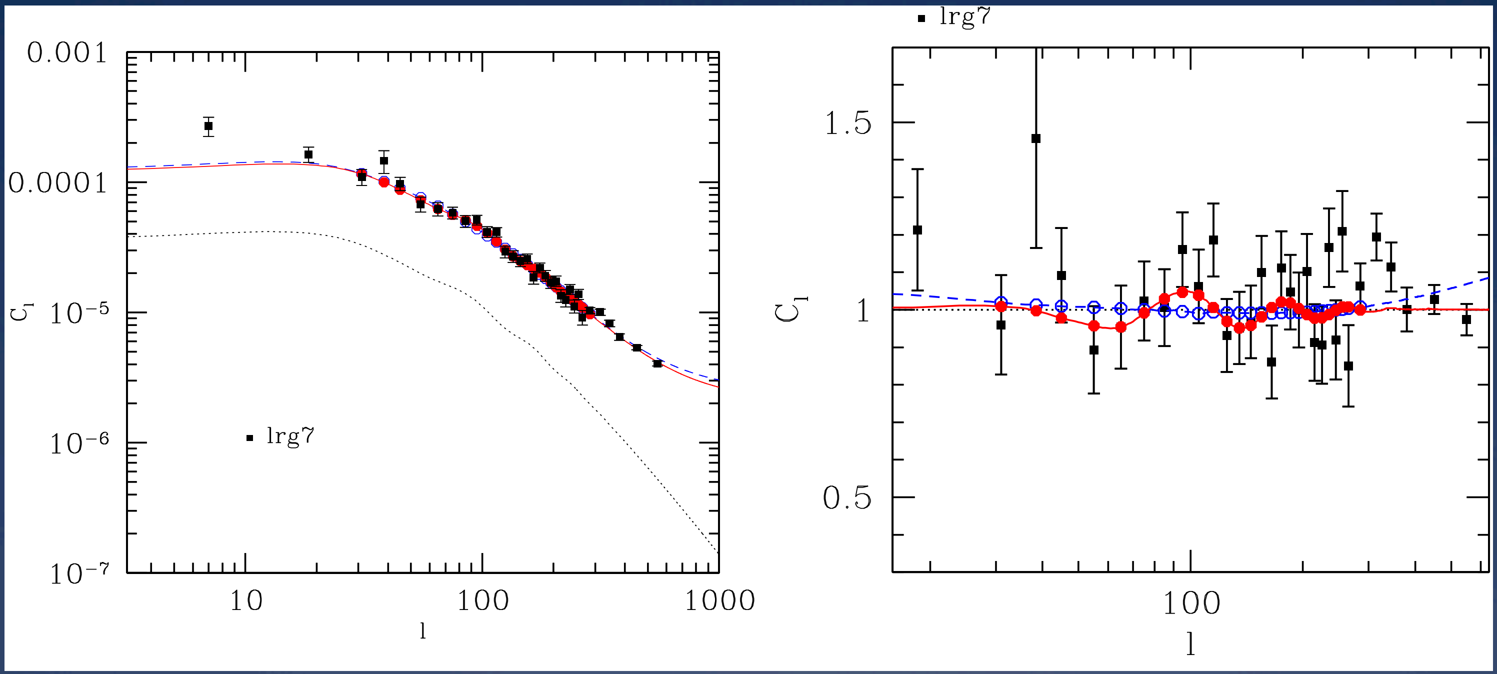
δ_i : dust extinction, star contamination, etc

With the measurements of $<\delta_o \delta_o>$, $<\delta_o \delta_i>$, $<\delta_i \delta_j>$, and $<\delta_i \delta_j>$, it is solvable for $<\delta_g \delta_g>$, if there is no intrinsic correlation bet galaxy and systematics.

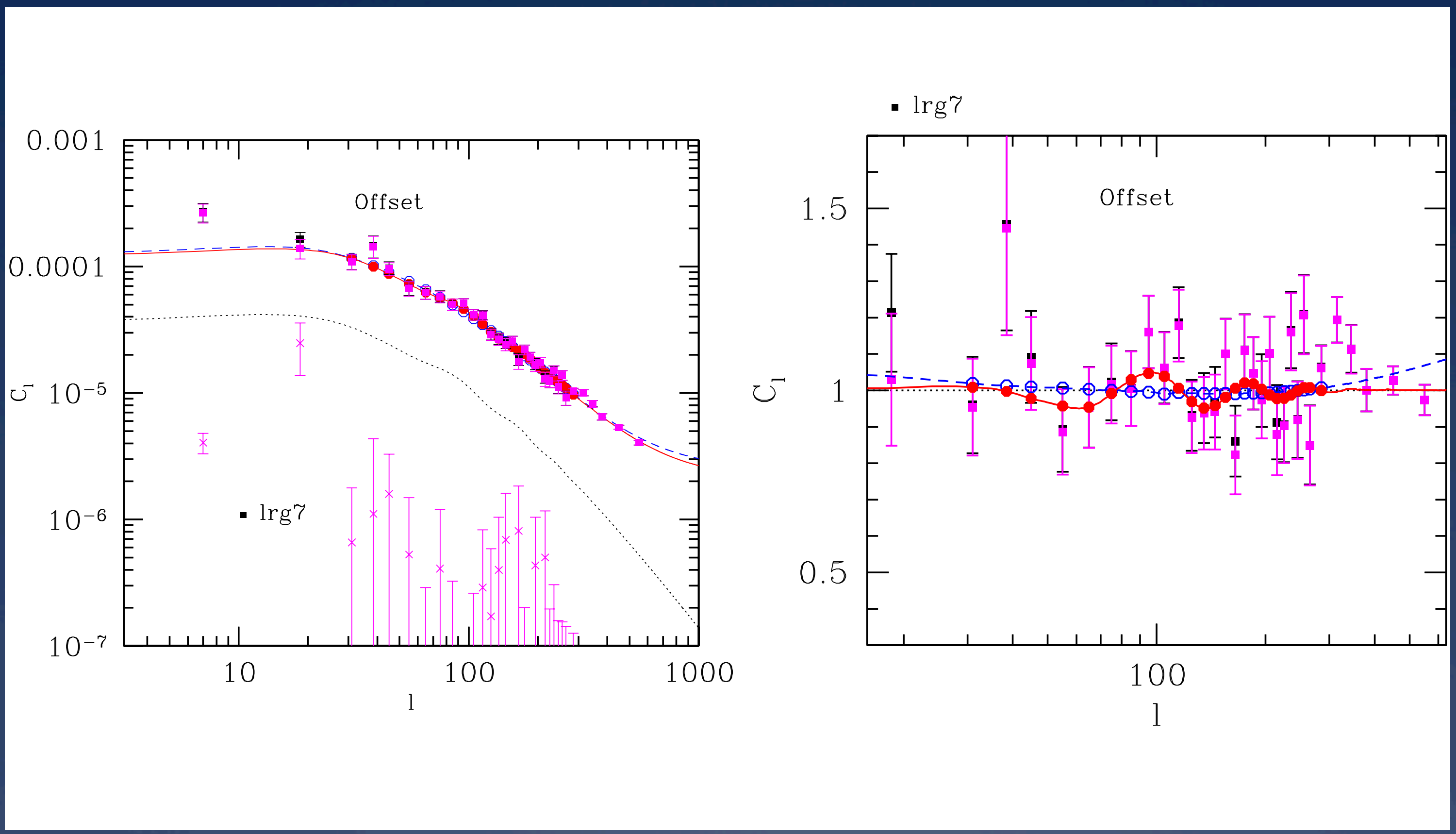
Ross et al. 2011 for correlation function

Effect of systematics correction

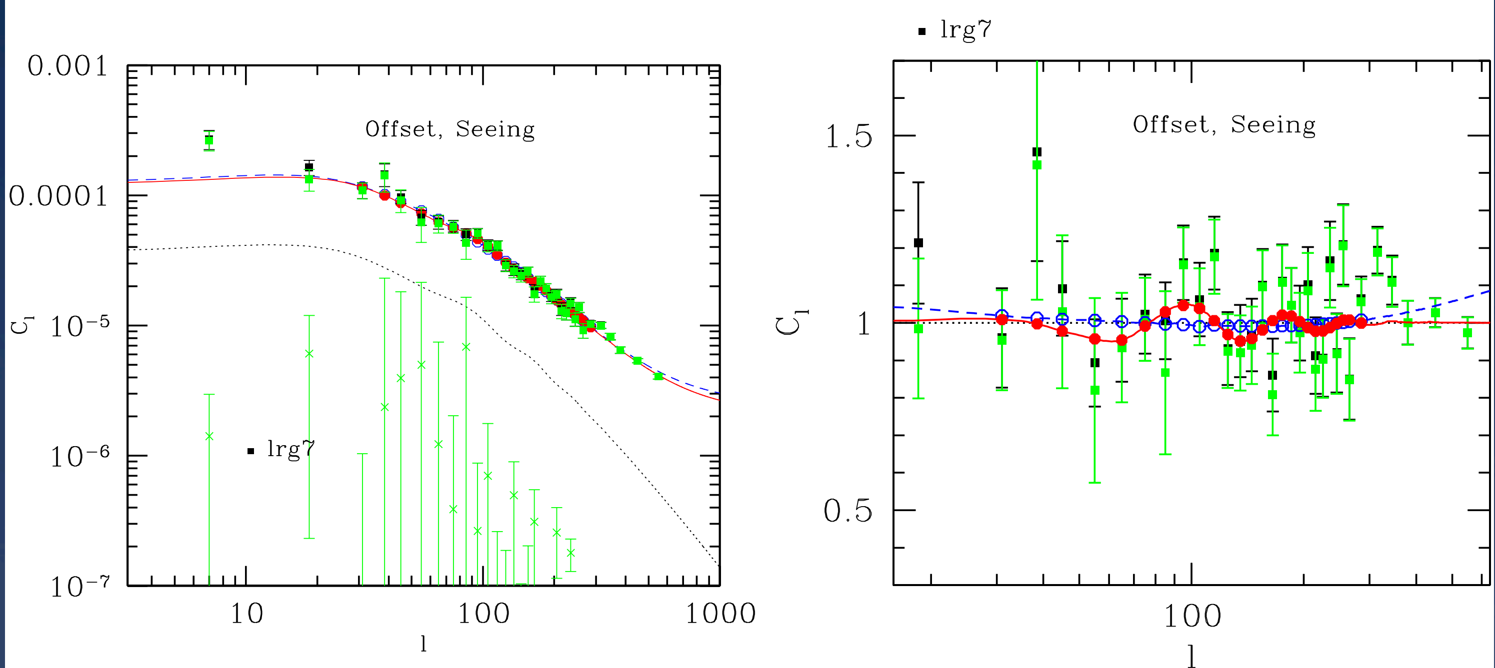
CMASS1



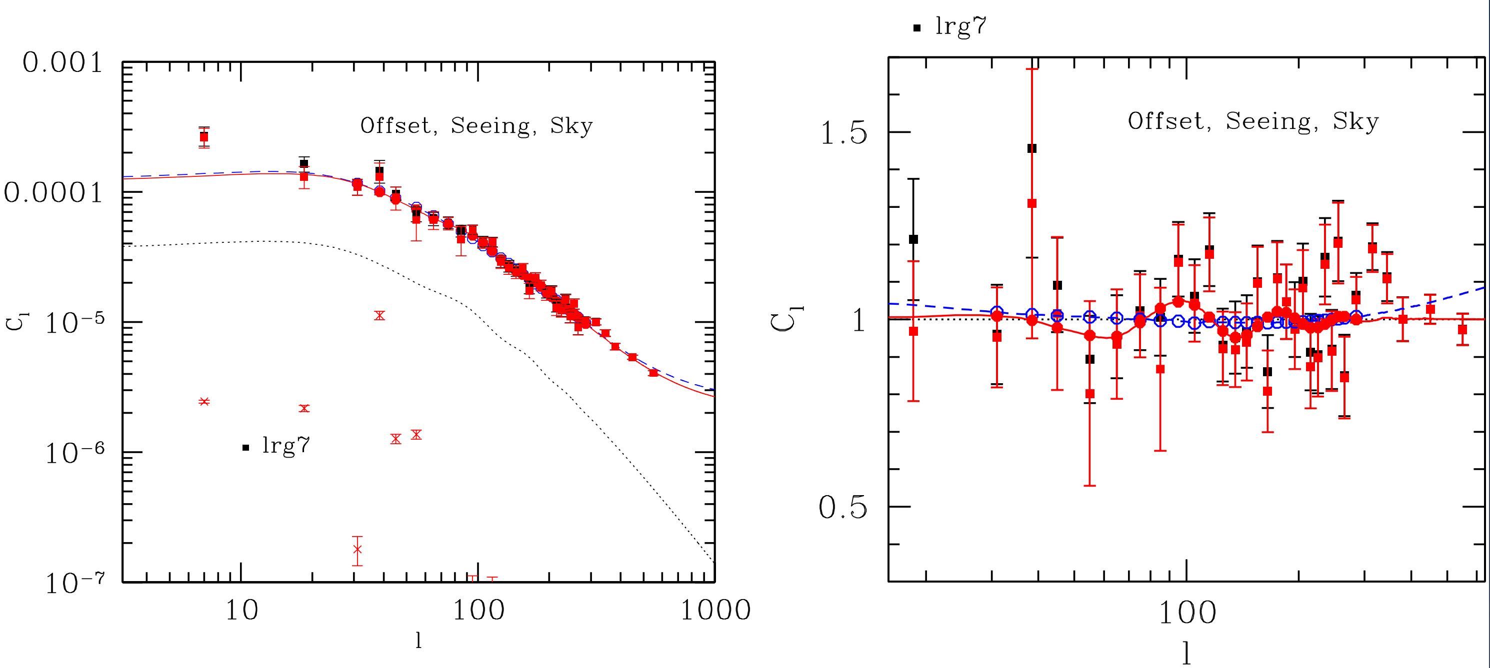
Effect of systematics correction



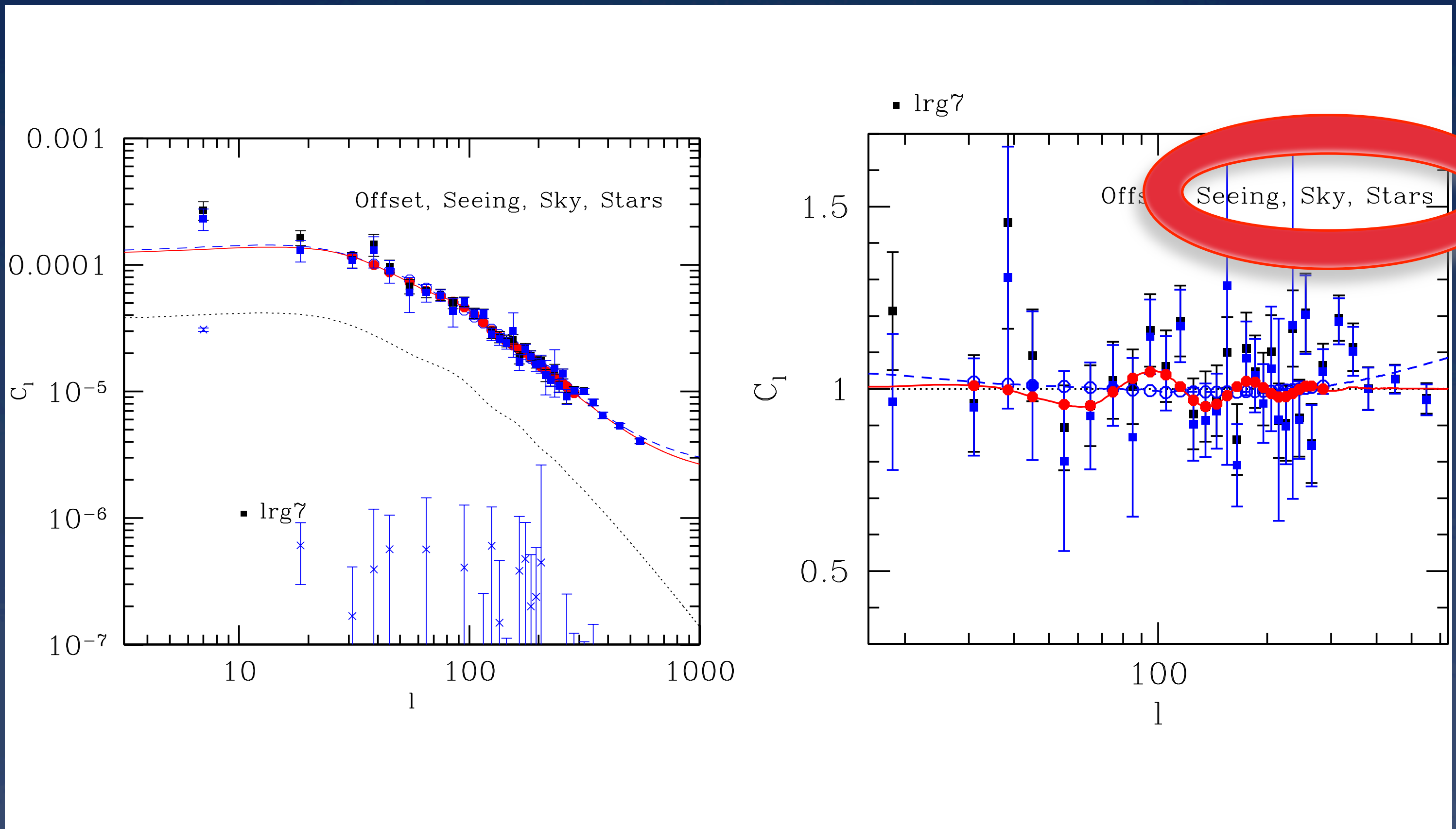
Effect of systematics correction



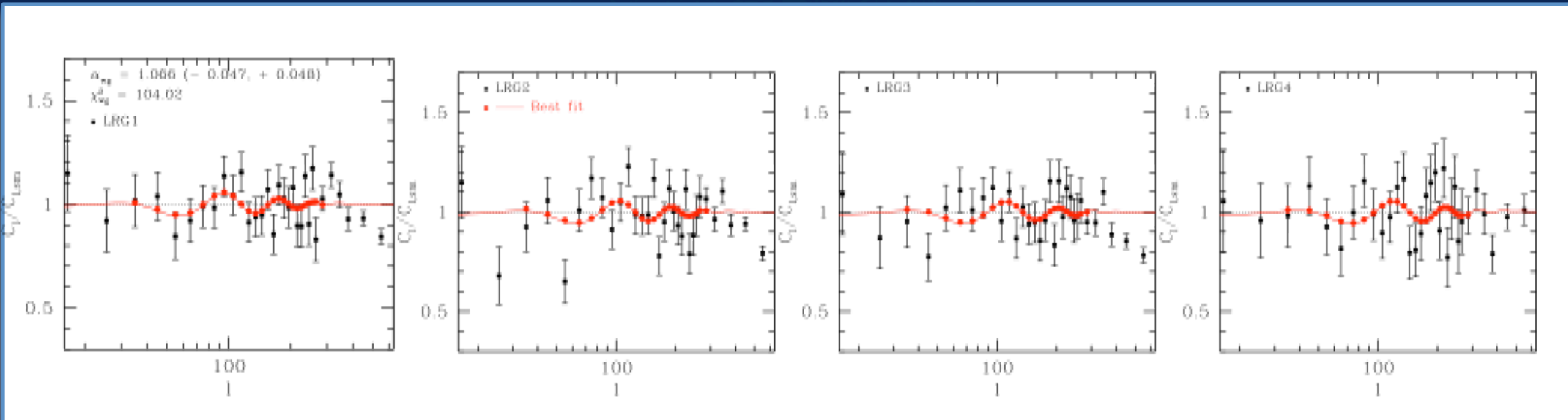
Effect of systematics correction

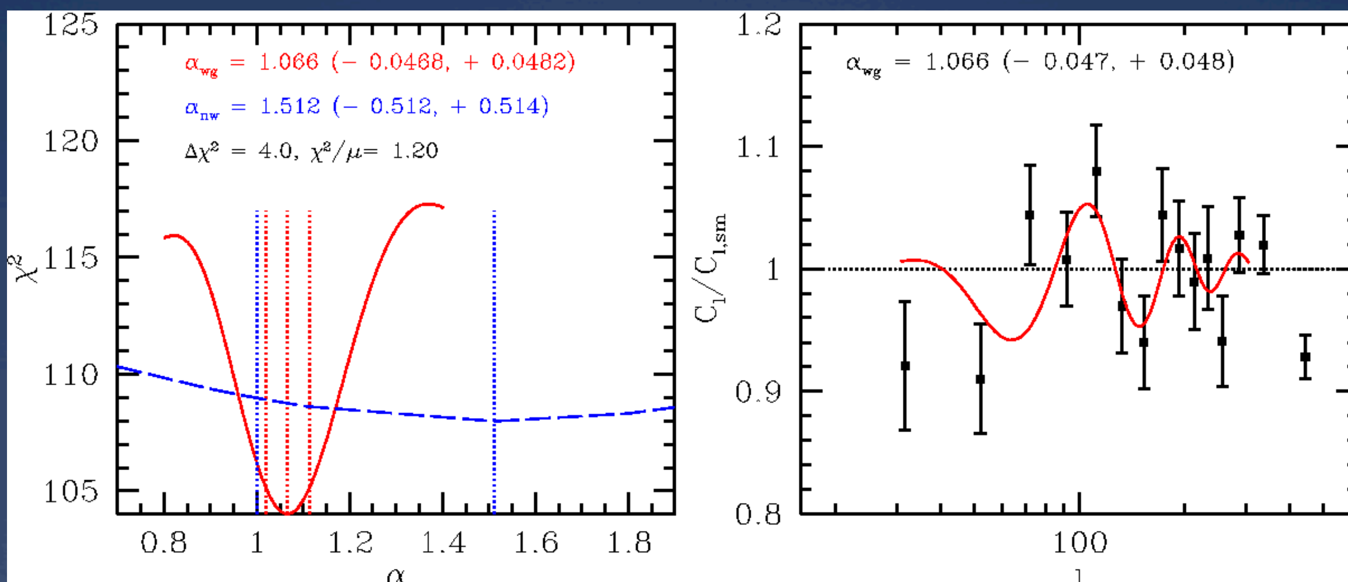


Effect of systematics correction



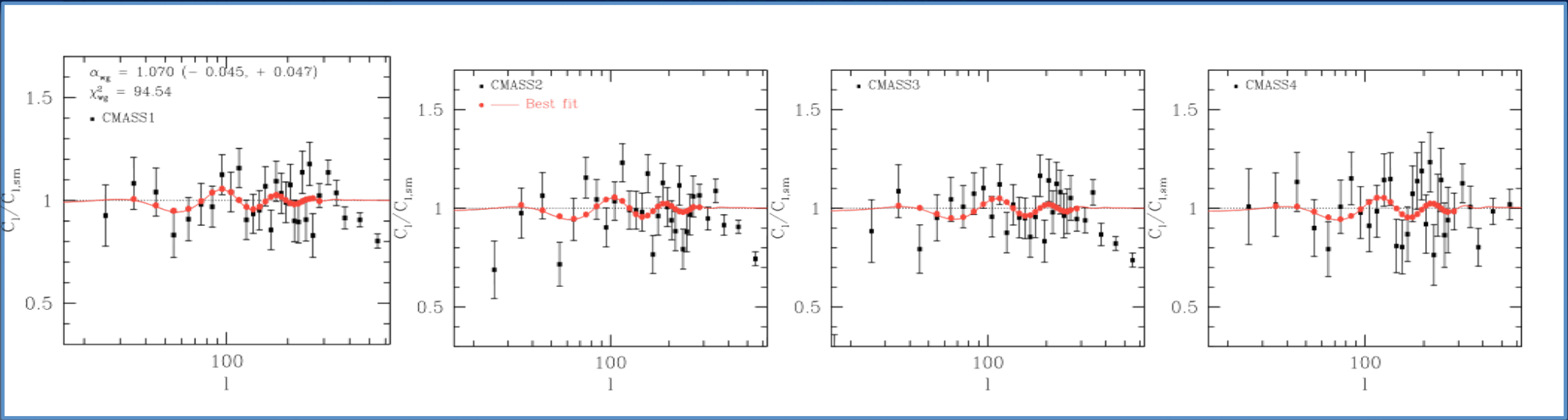
Best fit result of DR8

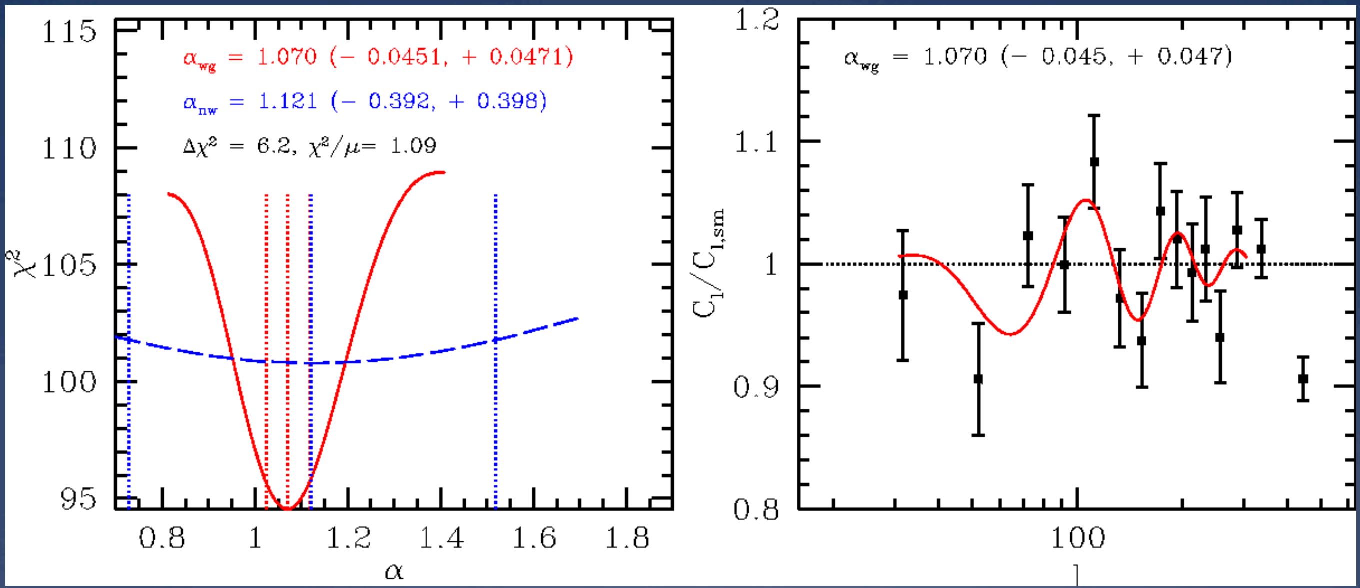




Seo et al.
submitted

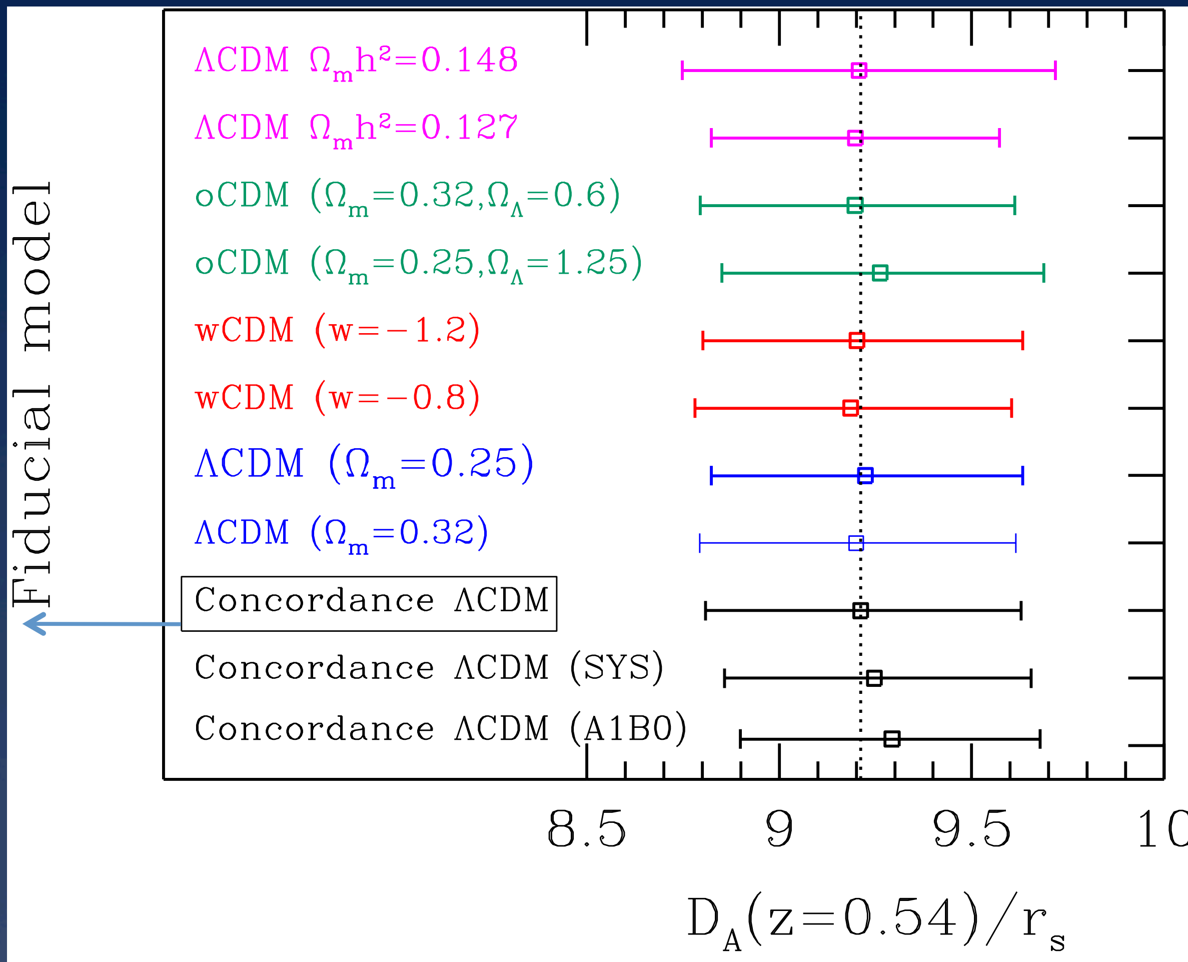
Best fit result of DR8 after systematics correction





Seo et al. submitted

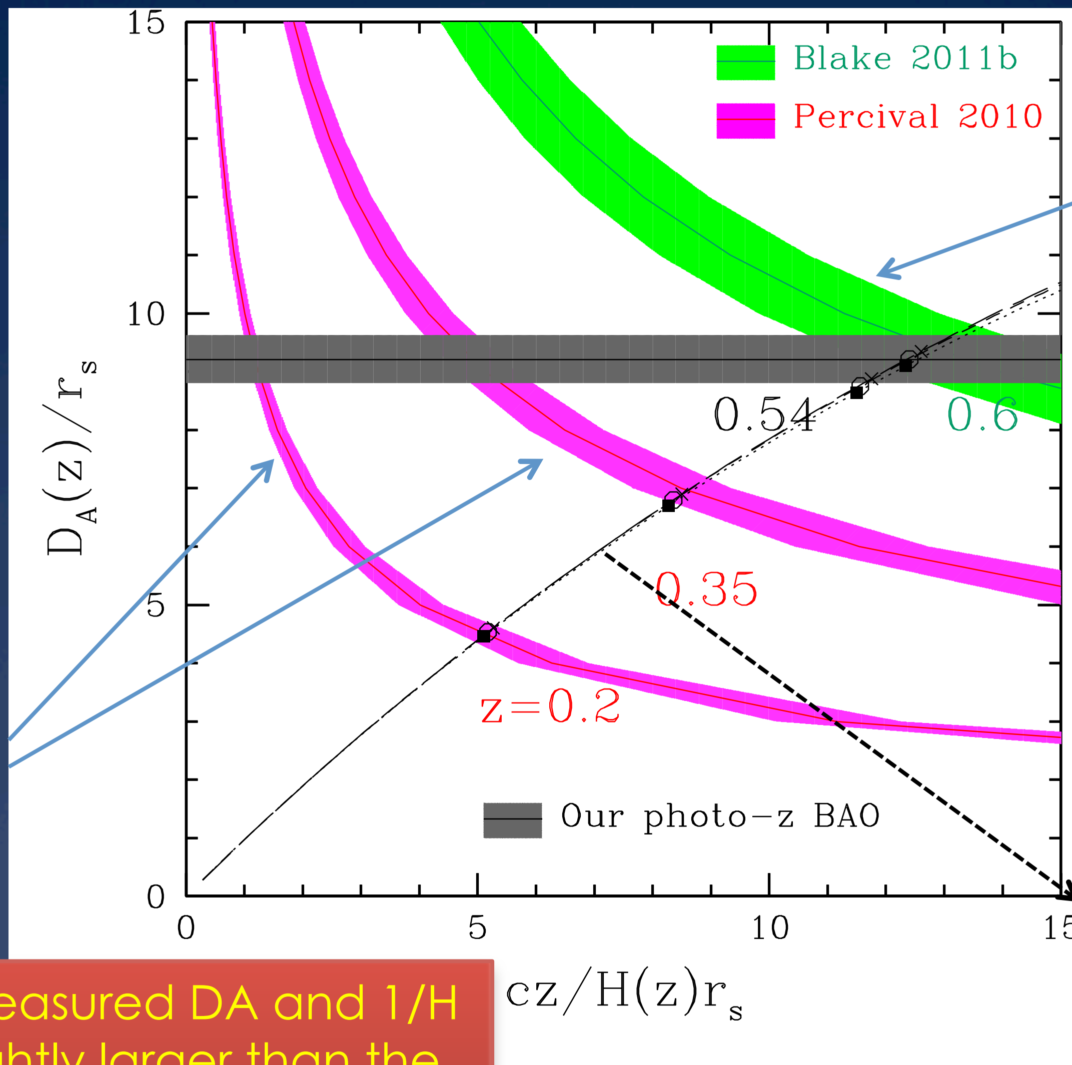
Robust result!



Om=0.274,
h=0.7

Systematics do not hurt BAO

Comparisons



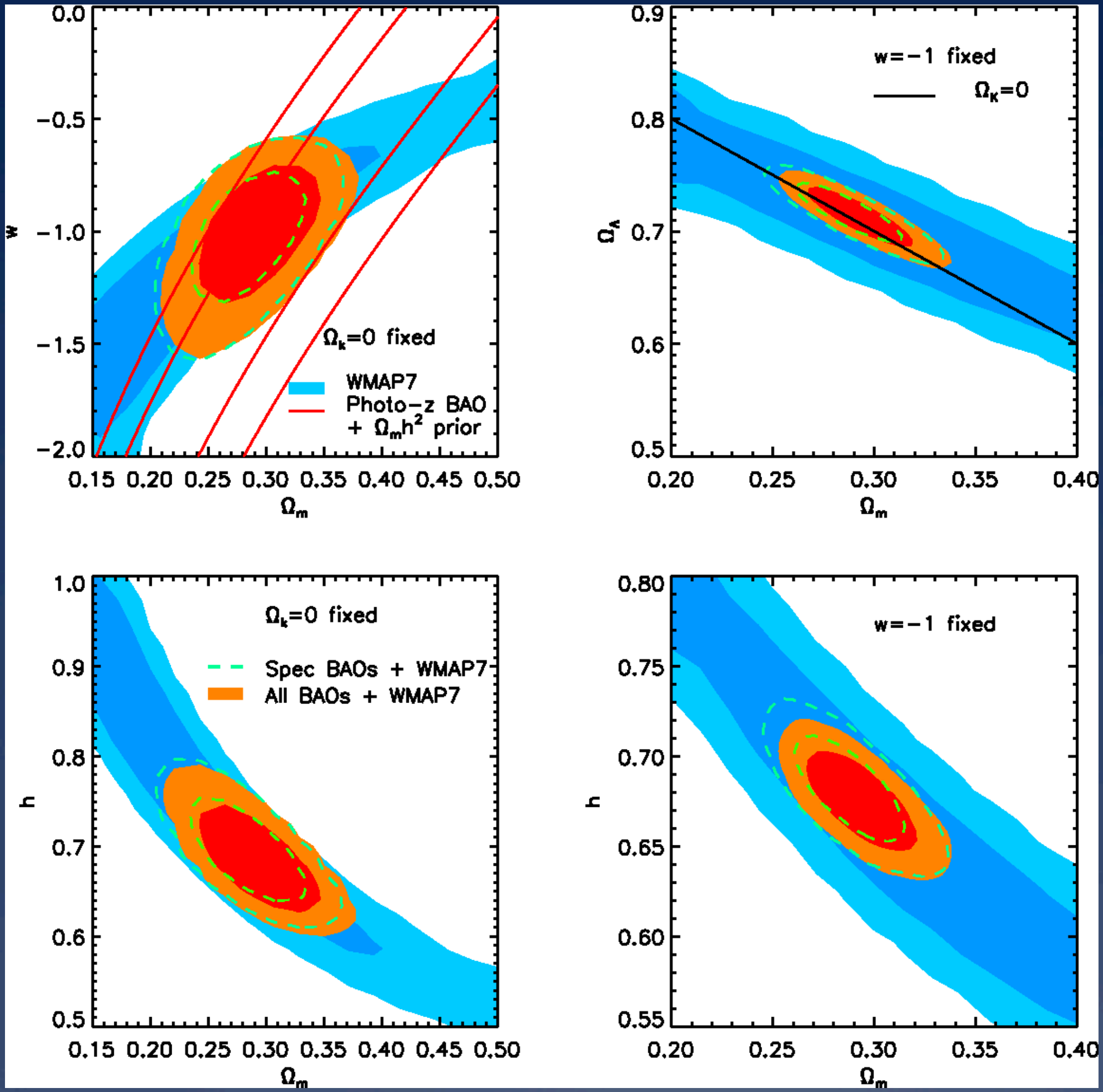
Blake 2011b

Percival 2010

Om=0.274, h=0.7

After z>0.3, measured DA and 1/H tend to be slightly larger than the concordance LCDM.

Cosmological constraints



LCDM

OCDM

Summary

* Data: Largest volume ever used for galaxy clustering: 10,000 sq deg up to z=0.65.
* Use the template fitting method to measure the BAO scale, utilizing the redshift info from the training set.
* Measure the BAO scale within 4.7% at z=0.54. The best photoz BAO precision.
* The best fit scale is slightly smaller (i.e., the distance is slightly larger) than the concordance LCDM → slightly larger Om.
* The result is robust against assumptions made for building the template.