BAO constraints from SDSS III imaging survey.

Hee-Jong Seo

BCCP, UC Berkeley

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

and the SDSS III Collaboration

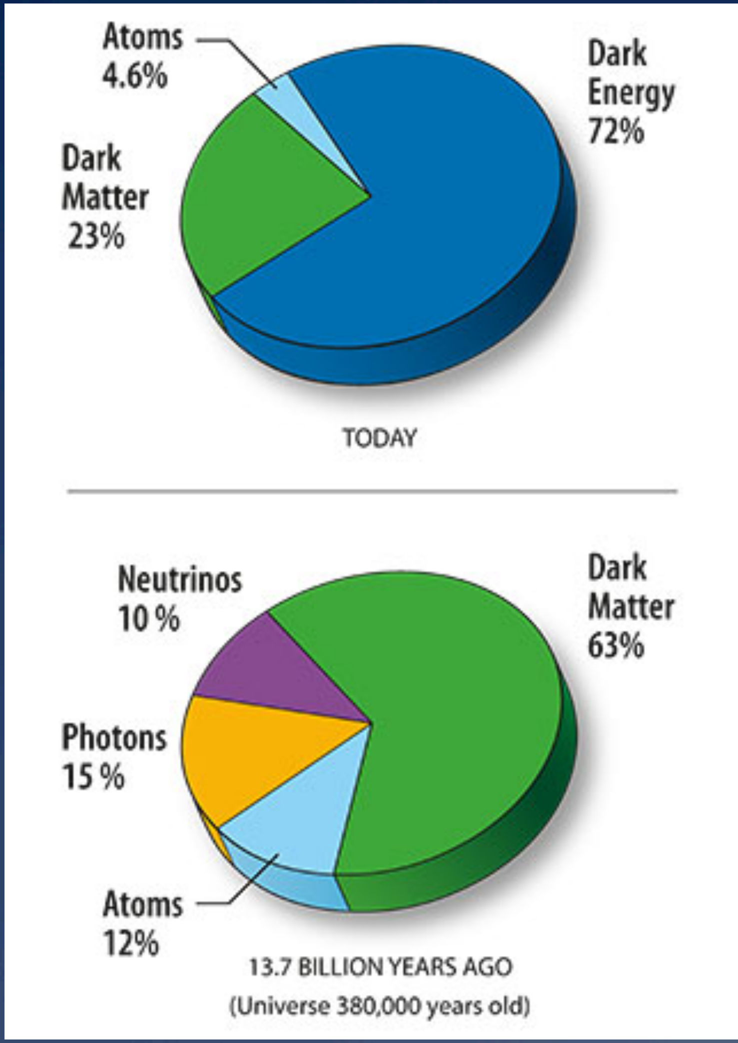
Ho et al. in preparation

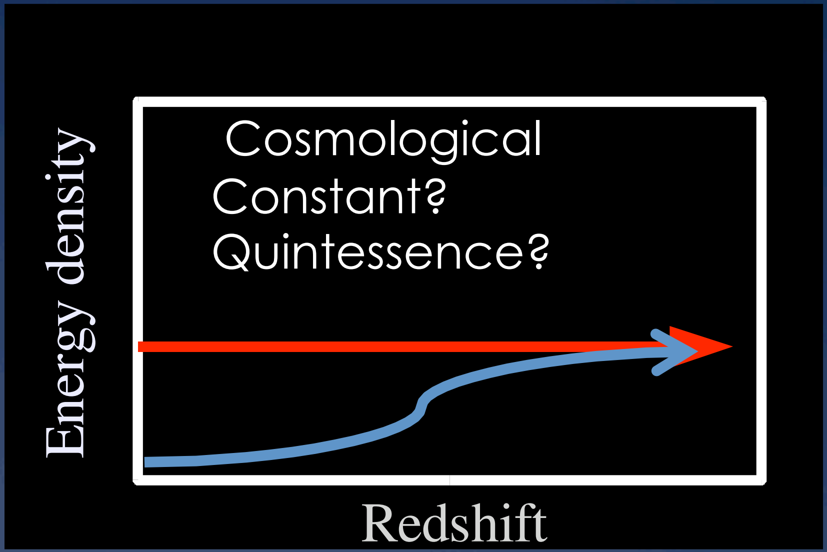
Seo et al. in preparation

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

WKYC, June 29 2011

Probing Dark Energy





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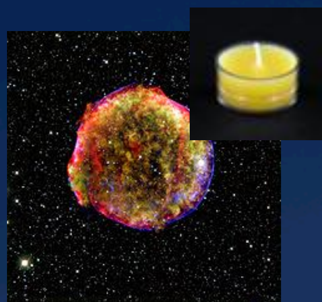
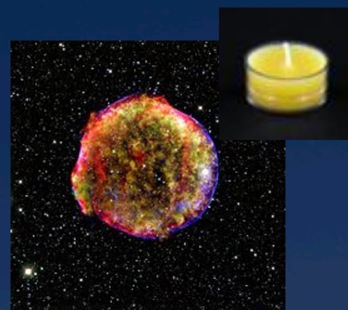
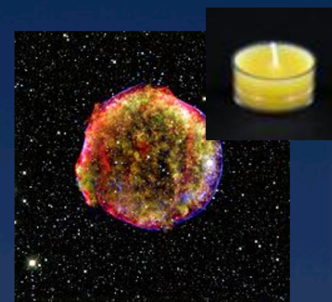
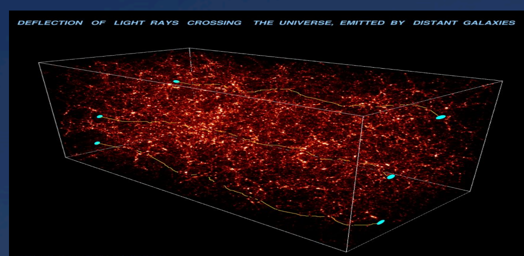


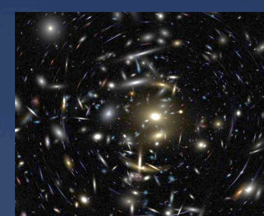




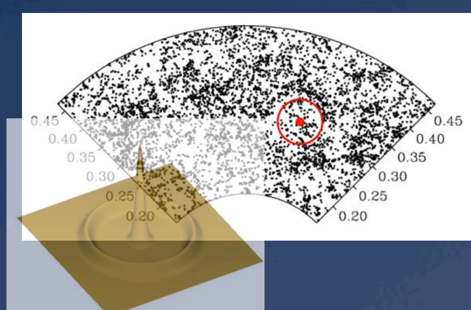
Standard candle
Type Ia SN

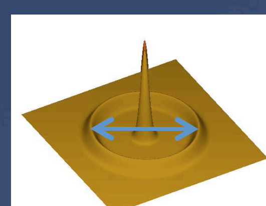


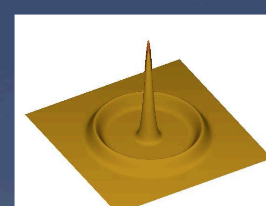
Weak Lensing



Cluster counting



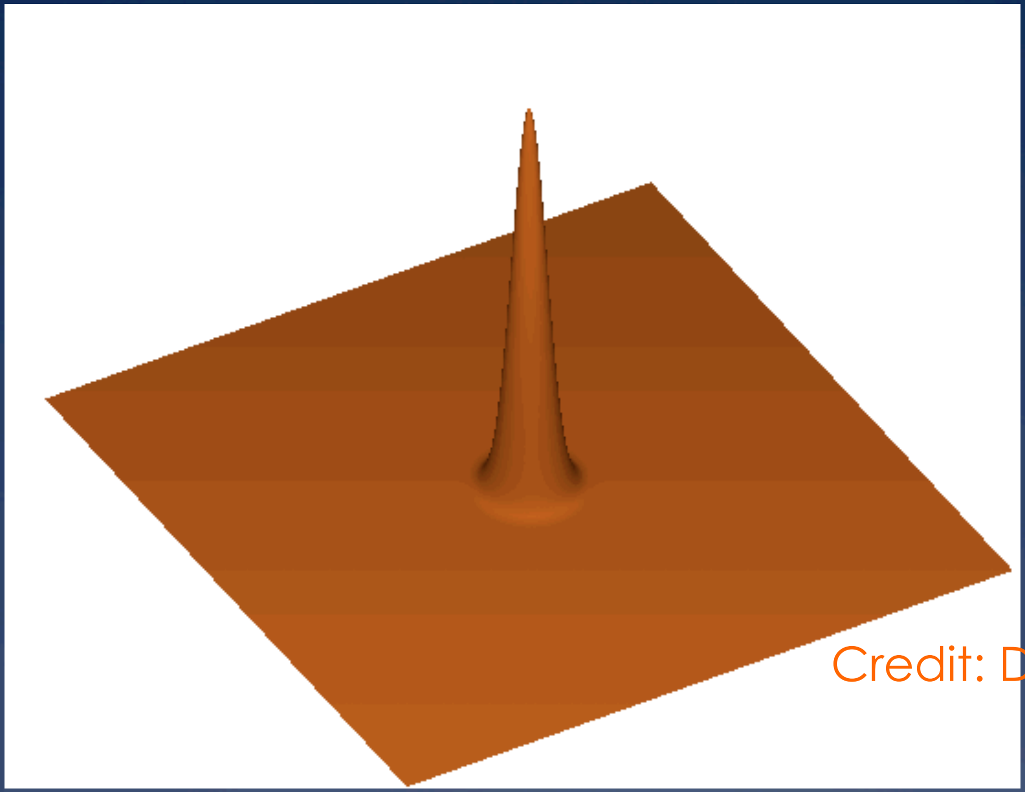




Standard ruler
BAO

z

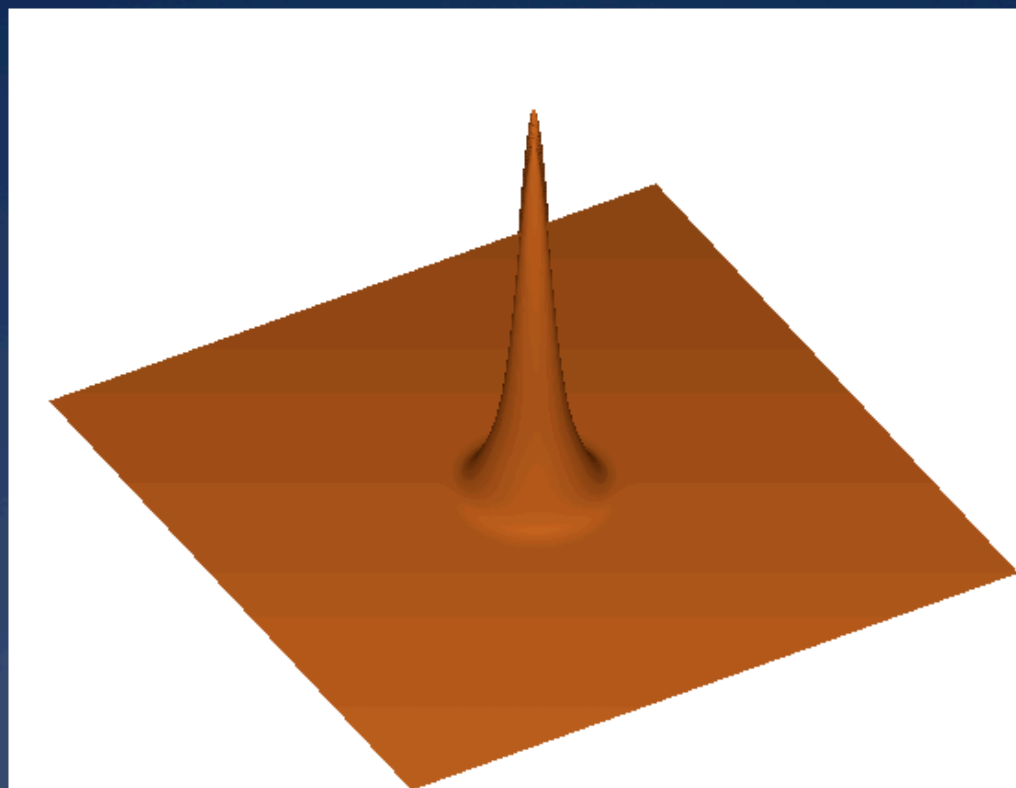
Baryon Acoustic Oscillations (BAO)



Credit: Daniel J. Eisenstein

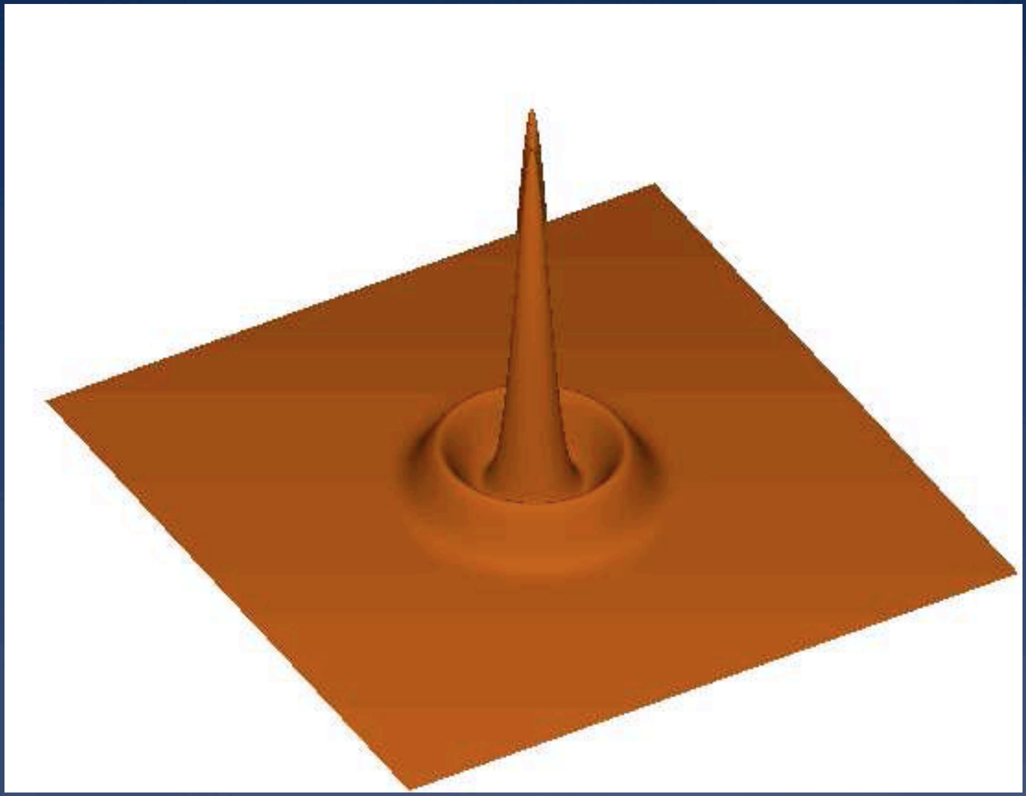
Primordial overdensity peak of dark matter, gas, photons at origin.

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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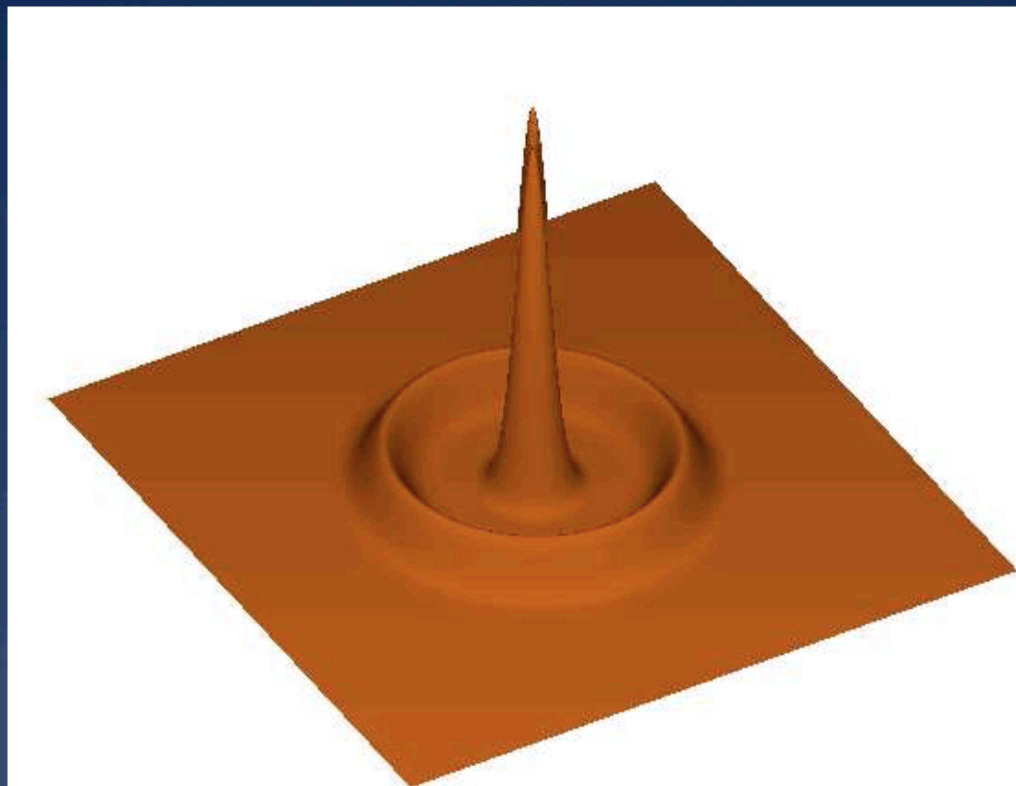

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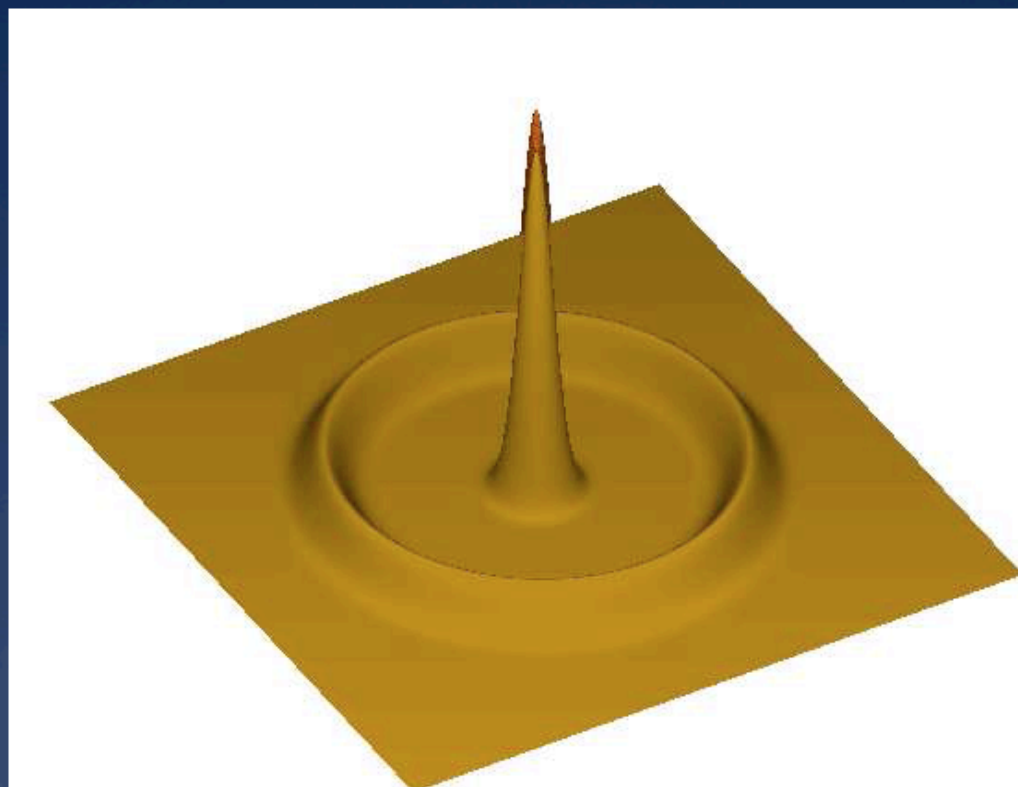

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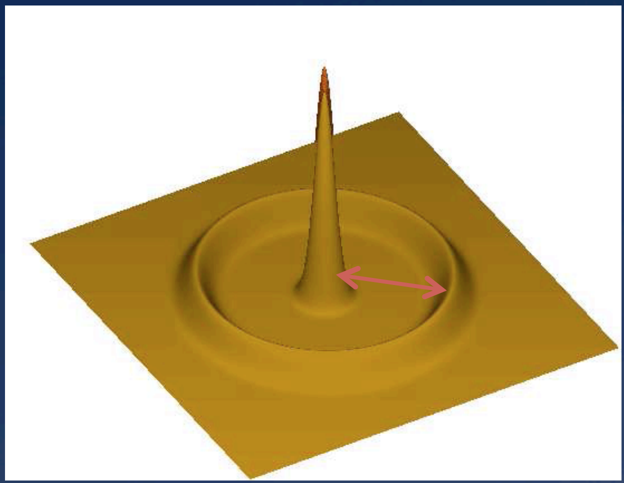


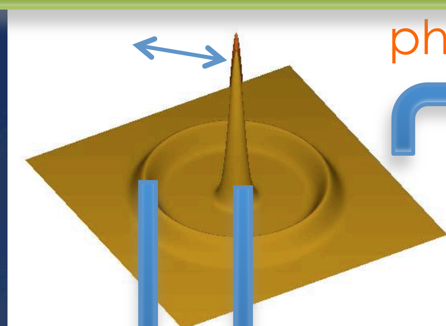
At recombination (z~1000),

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

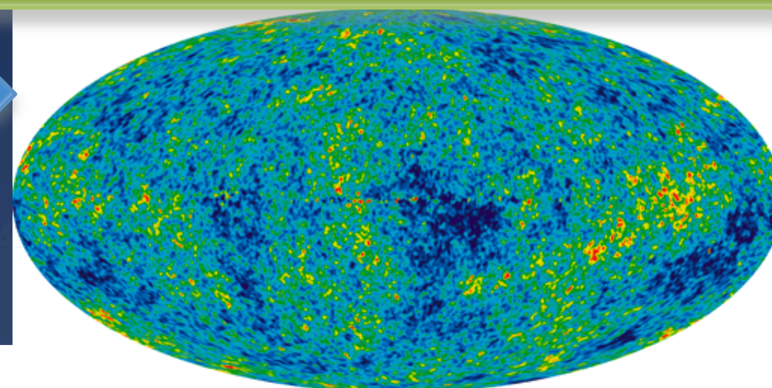
A spherical peak at the distance that the wave has travelled before the recombination
→ **the sound horizon scale** at recombination (150 Mpc).

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).

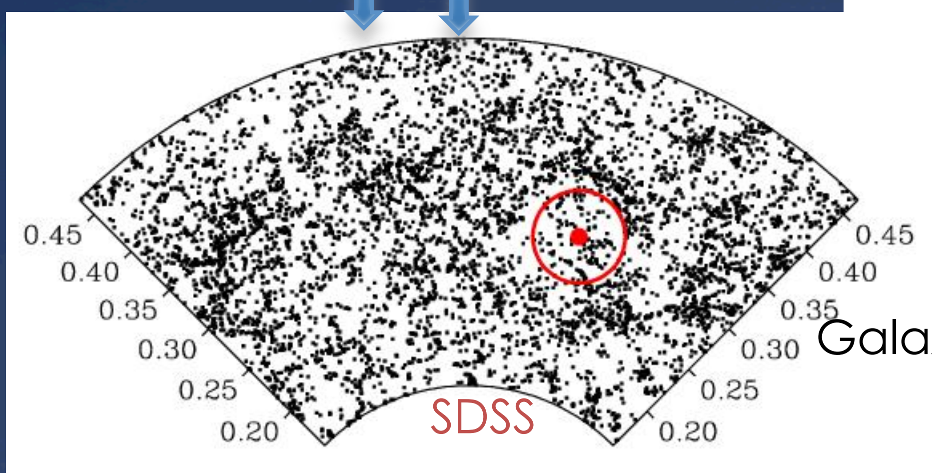


photons



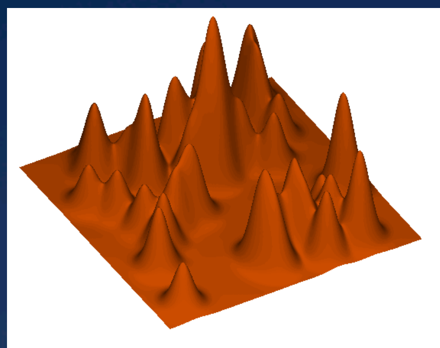
WMAP 7yr
Larson 2010

Baryons
+DM

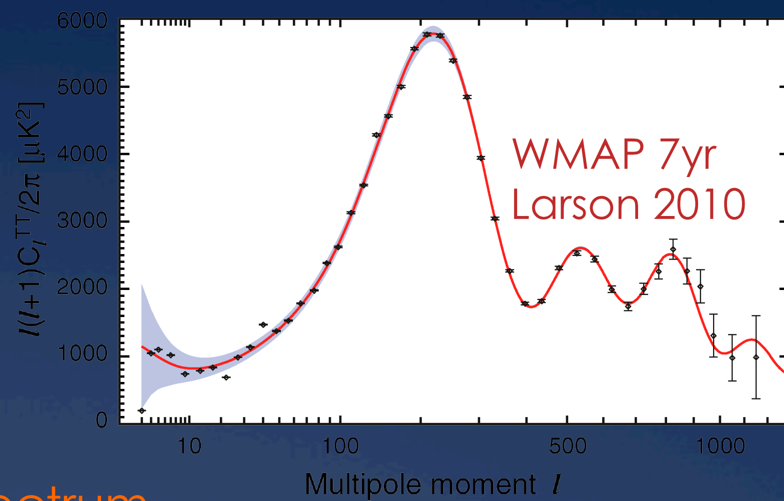


Galaxy surveys, 21cm surveys

Baryon Acoustic Oscillation



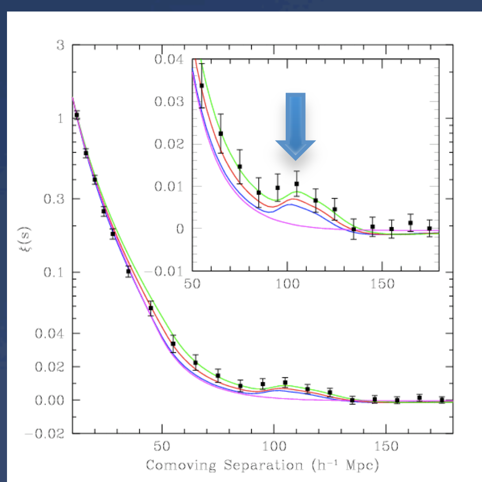
photons



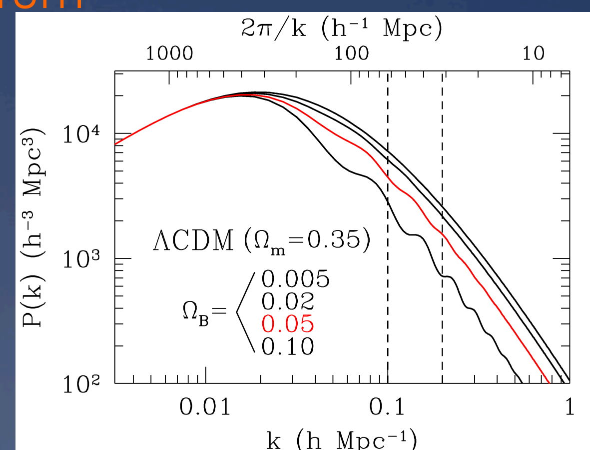
Baryons +DM

Correlation function

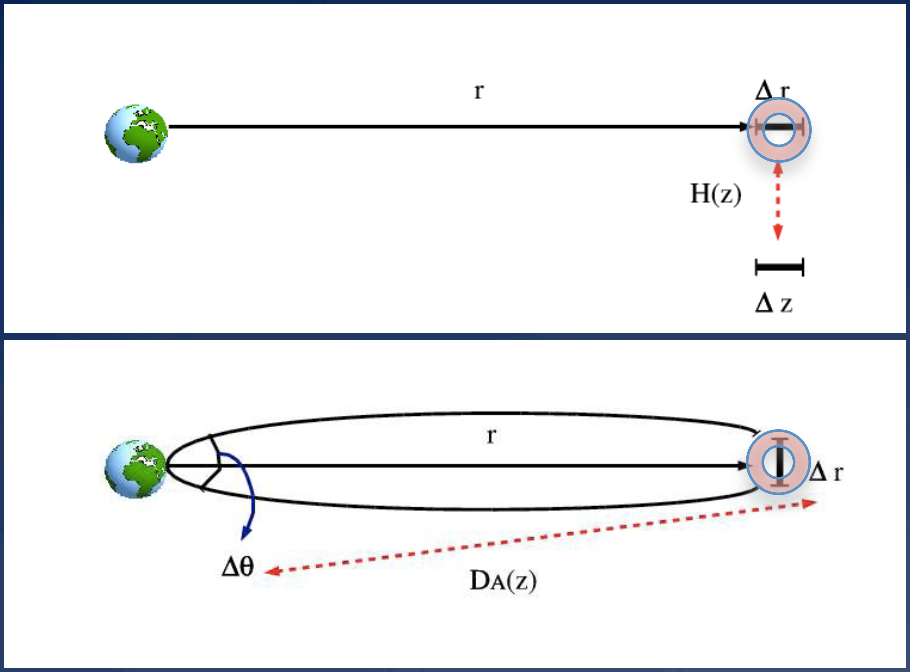
Power spectrum



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**

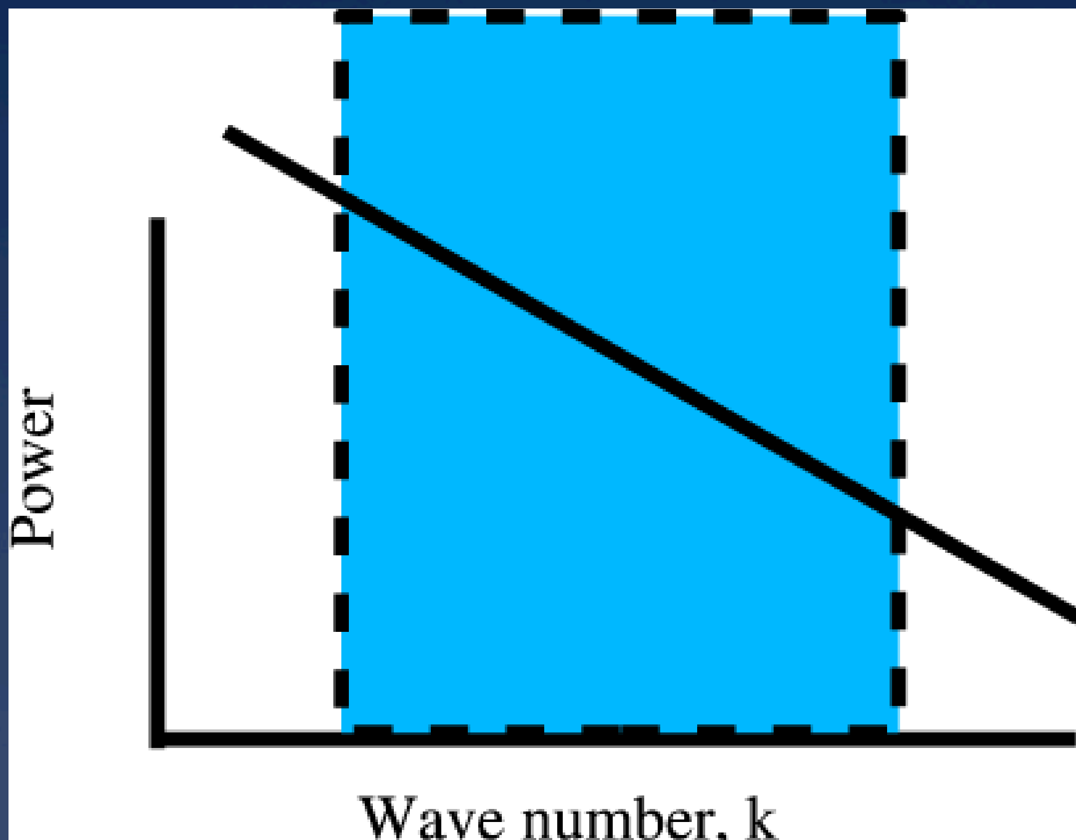
$$\frac{dH}{dz}, \frac{d^2 D_A}{dz^2}$$ → Dark Energy density as a function of redshift → w_0 and w_a

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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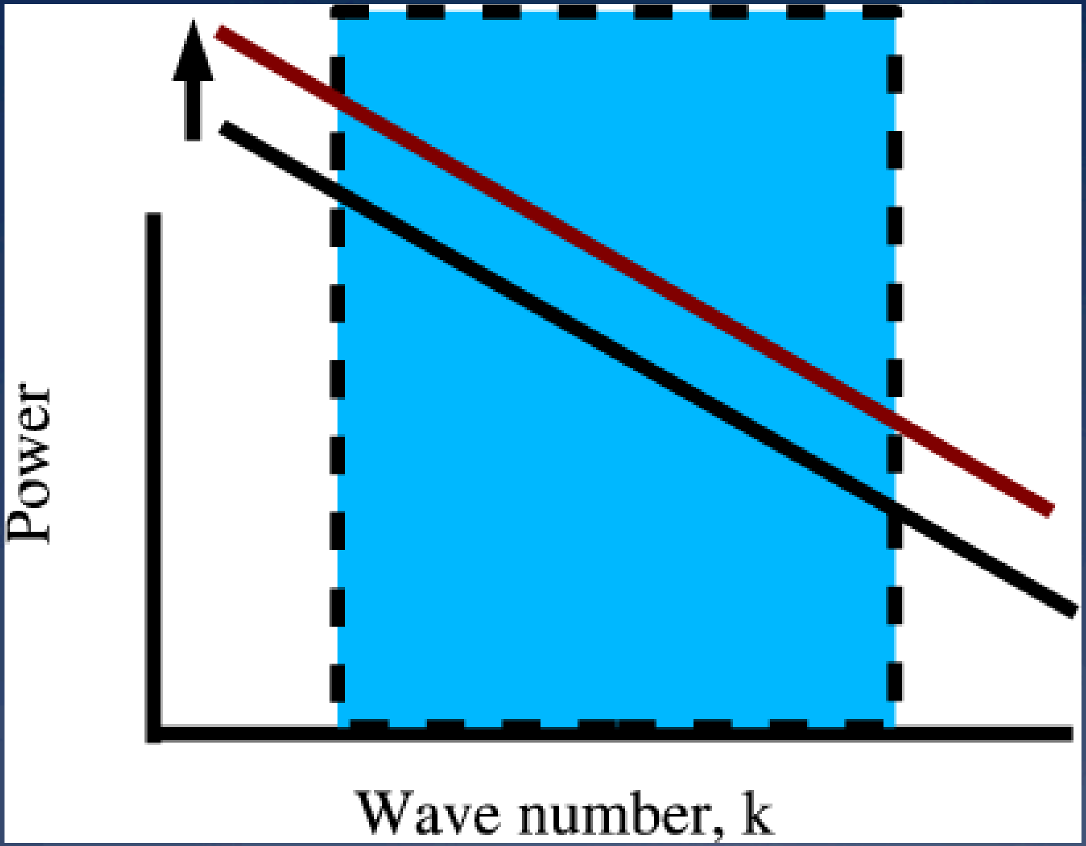

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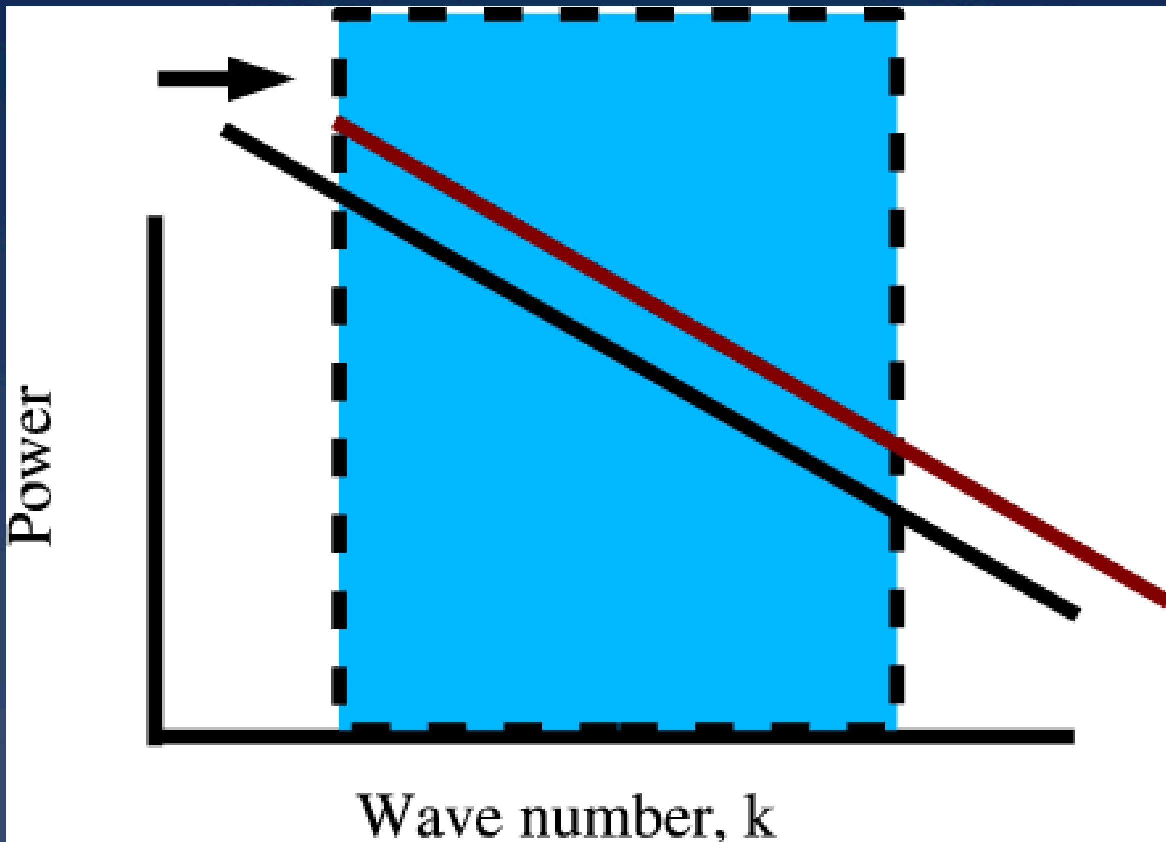
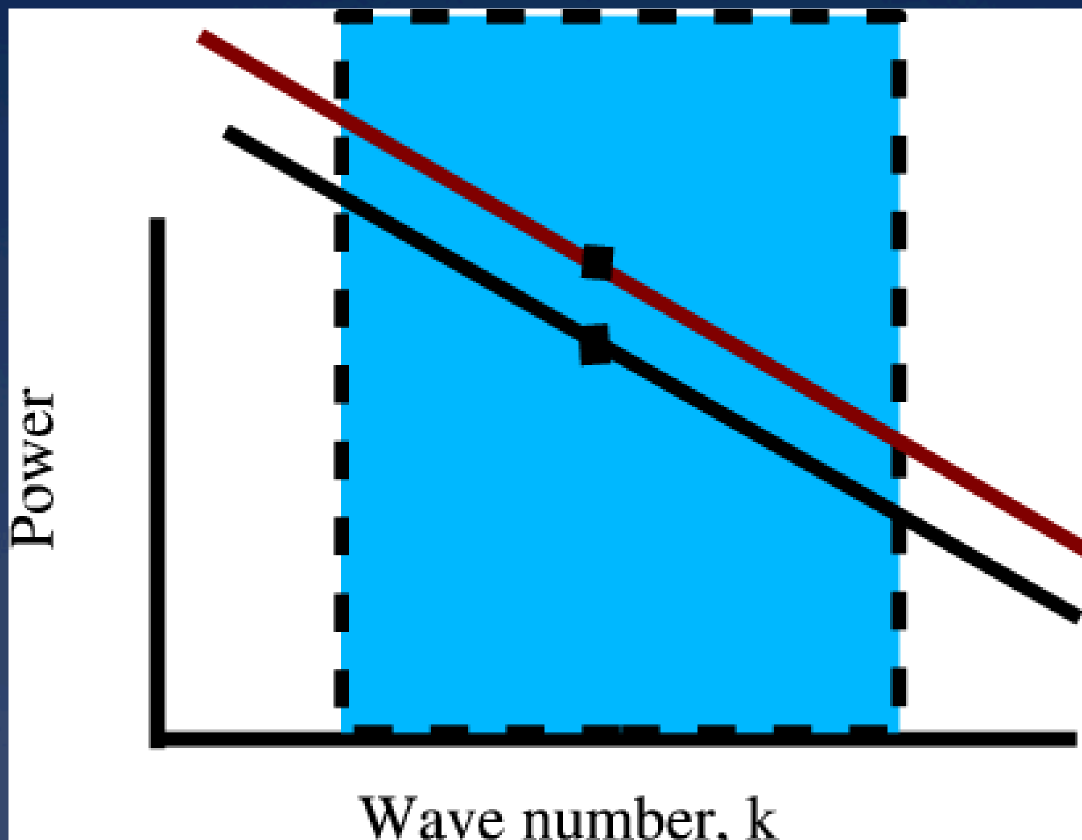


BAO is a good standard ruler

With a distinct signature,



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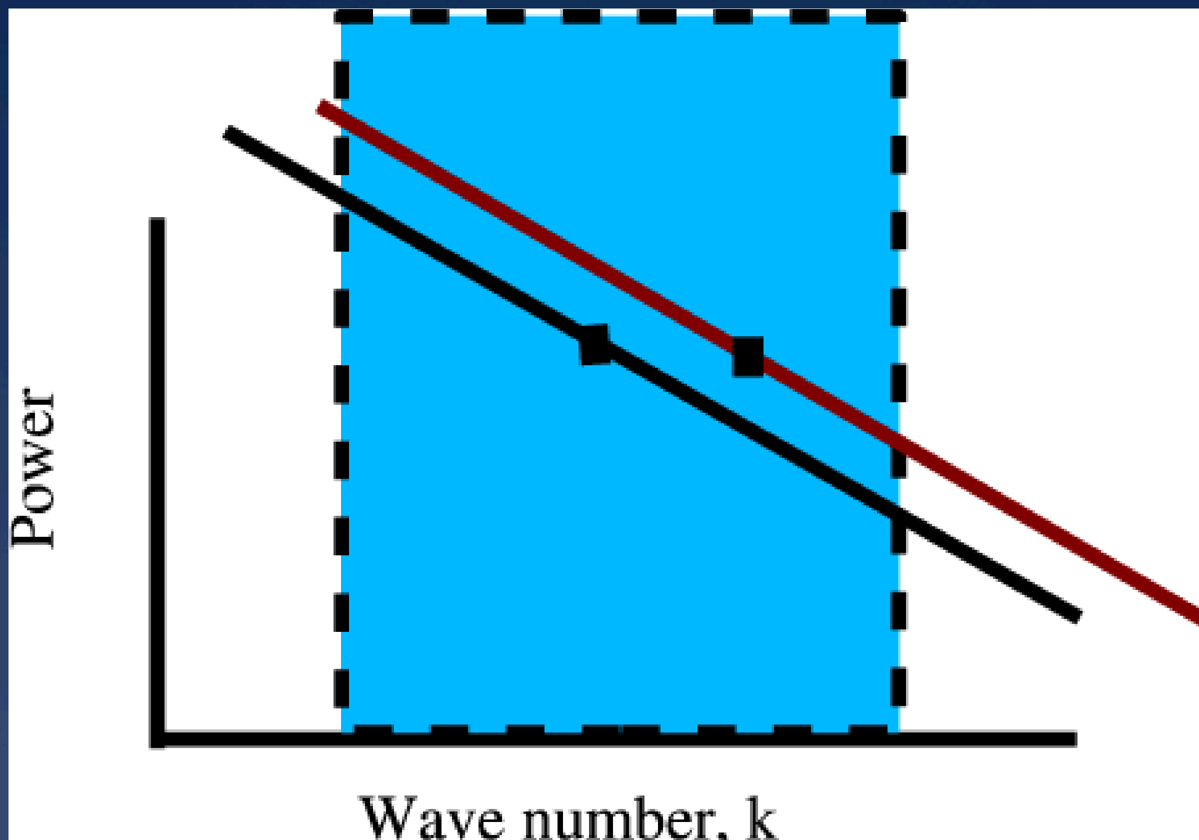

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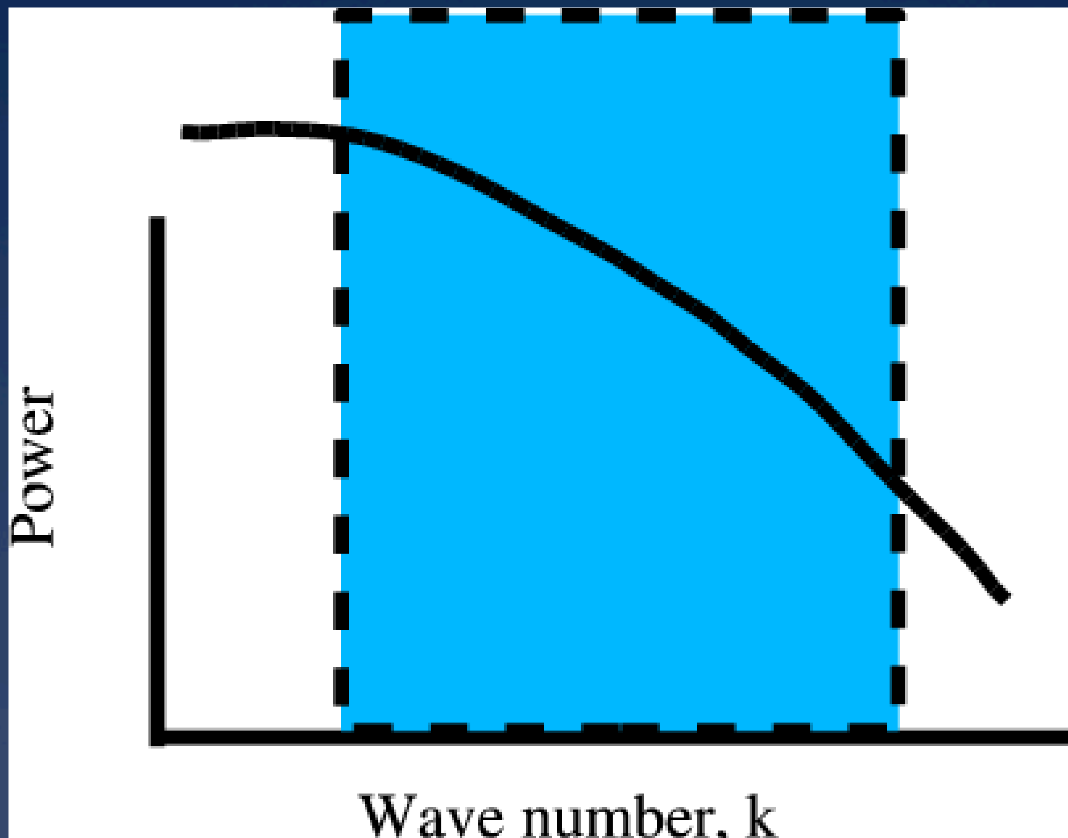

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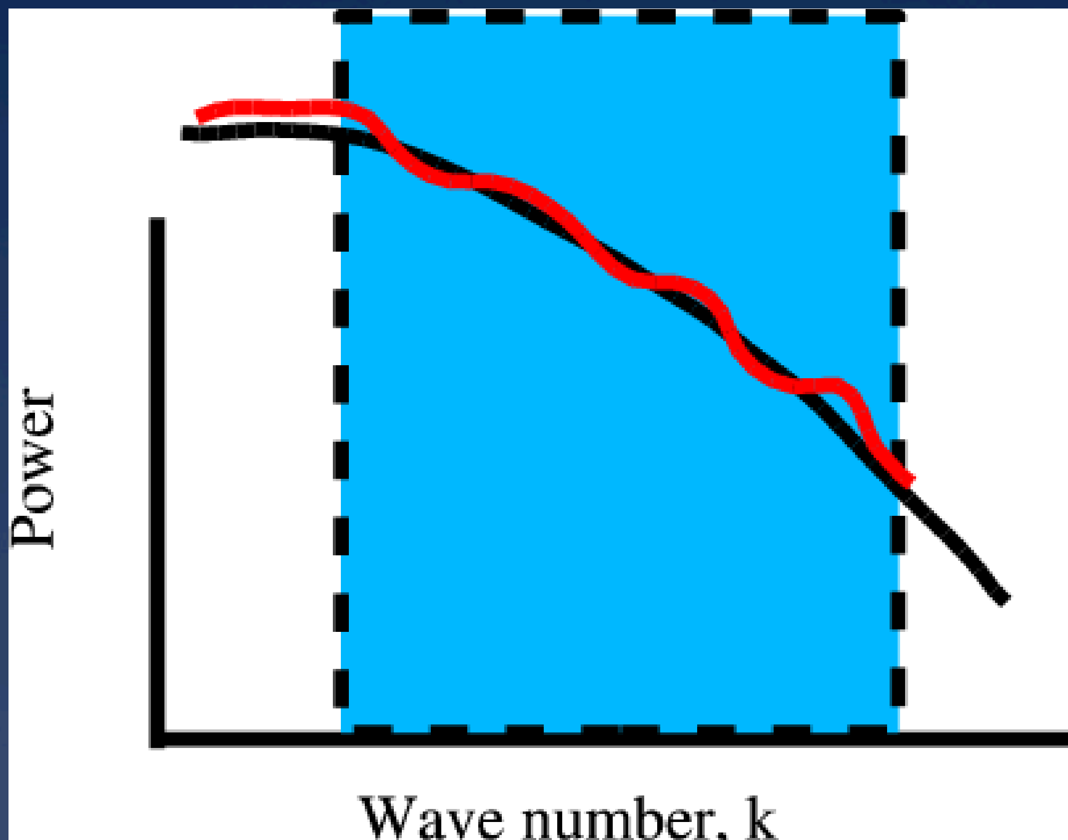


BAO is a good standard ruler

- 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~~.

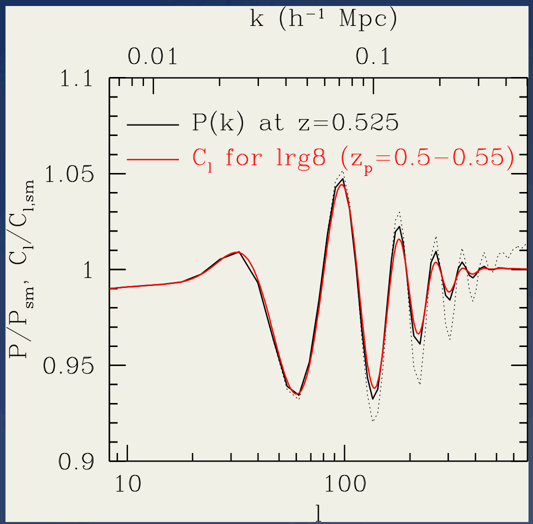
Not for photo z.

Believed to suffer least systematics among dark energy probes

3D vs 2D BAO

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.



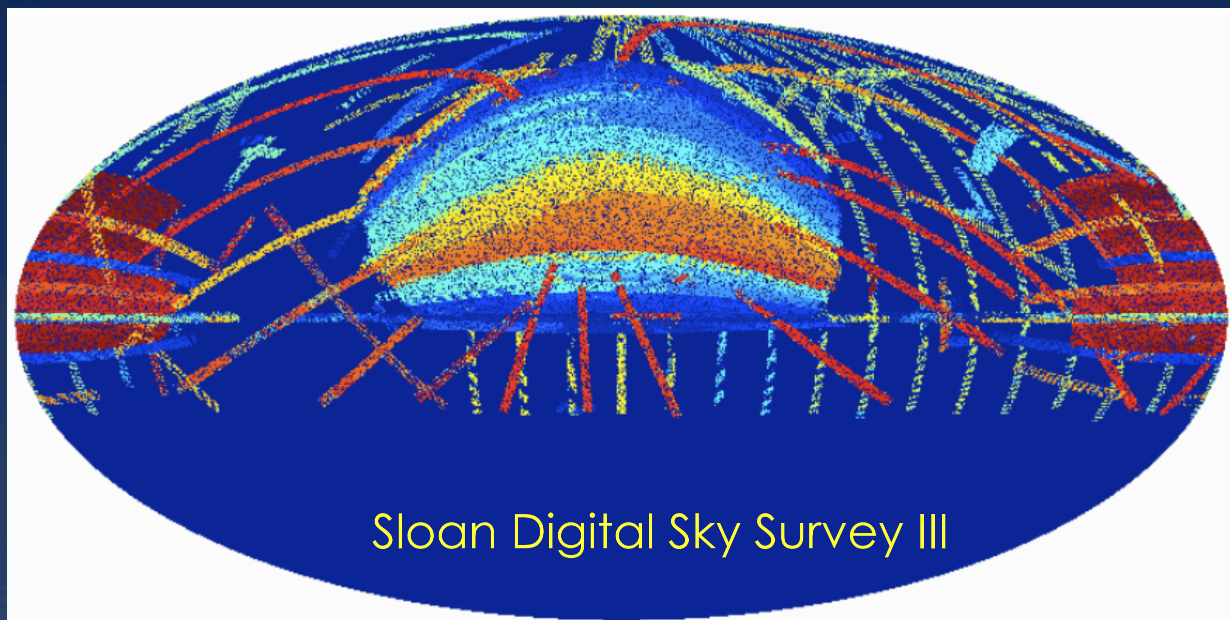
❖ Due to the projection of different physical scales onto the same l, BAO is additionally damped in 2D:
~ 30% increase in the damping scale for σz=0.05.

Therefore, photoz needs a much larger volume (~4x2 times) than spec-z for the equivalent performance.
On the other hand, photoz can acquire a much larger volume and higher number density at cheaper cost (DES, LSST, Pan-STARRS).

BAO from SDSS III photoz LRGs (DR8)

Total Area: 14,555 sq deg

1.5 million LRGs: $0.4<z<0.7$



Full Mask thanks to Michael Blanton

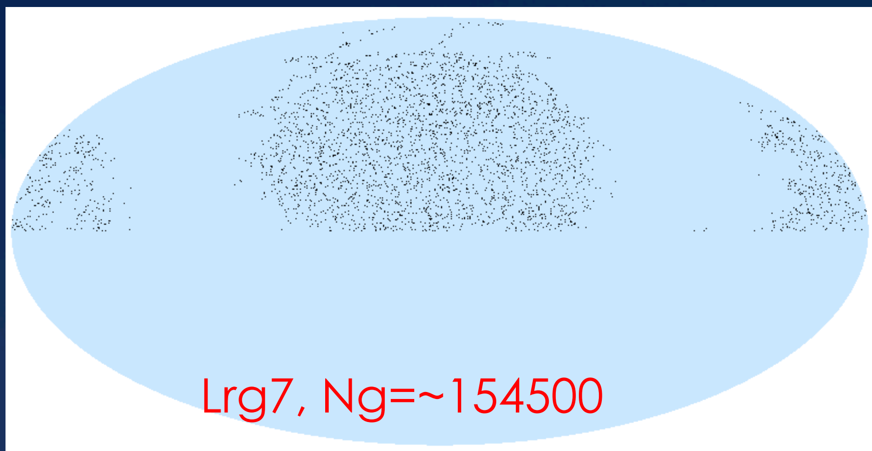
Ho et al. in preparation

note: Colors only indicates the when a certain area of the sky is surveyed.

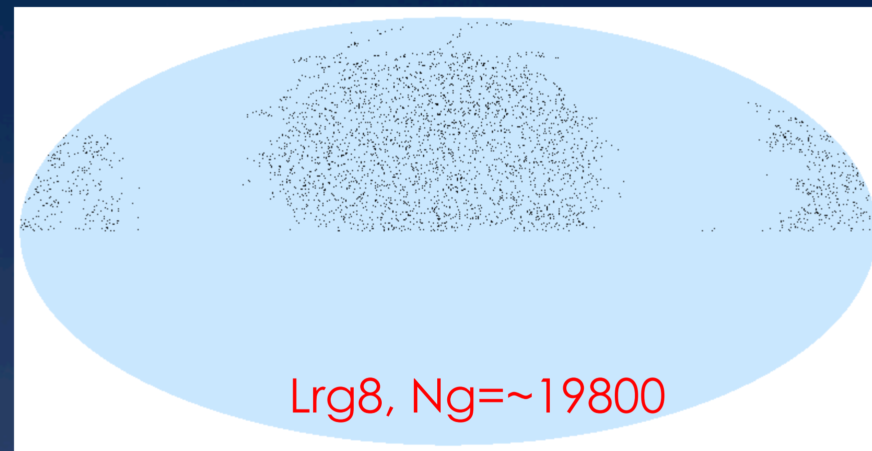
First detected by Padmanabhan et al 2007,
Carnero et al. arXiv:1104.5426 reports 10% of error on the BAO scale from DR7 data using a different approach.

Multiple photo-z redshift bins with dz=0.05

z=0.45-0.5

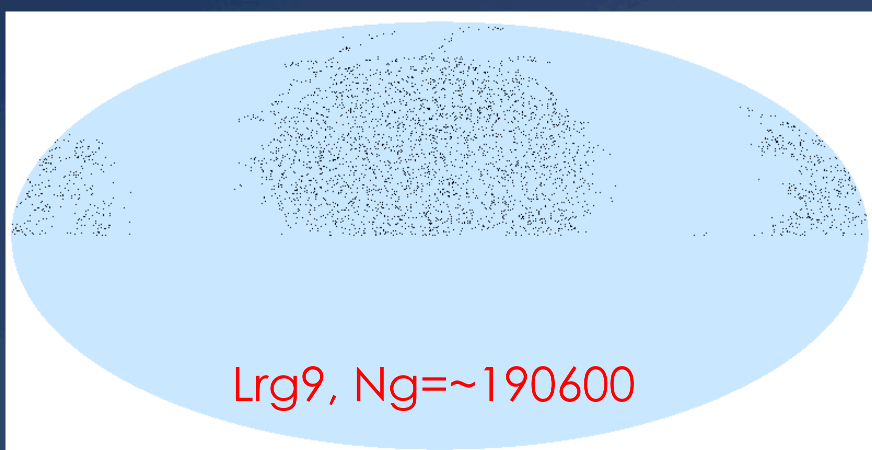


z=0.5-0.55

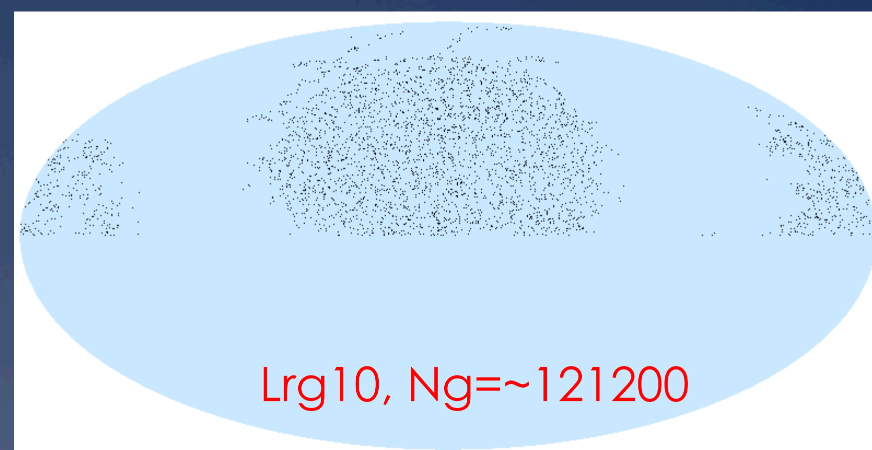


Ho et al. in preparation

z=0.55-0.6



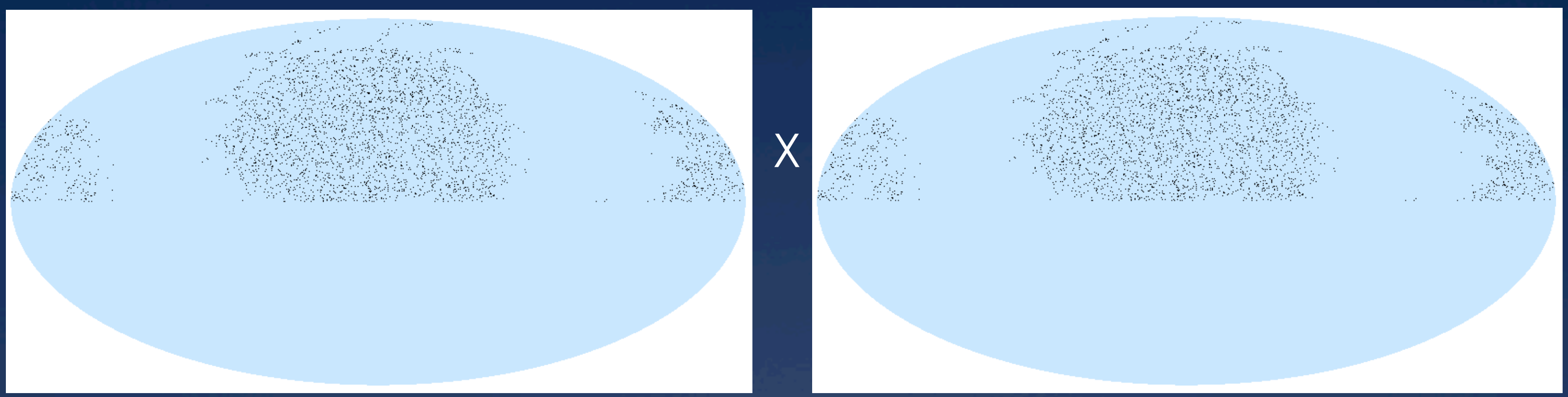
z=0.6-0.65



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

Angular power spectrum estimation using Quadratic estimator

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



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

Ho et al. in preparation

Quadratic estimator

Returns an unbiased Minimum variance measurement of the parameters if the field is Gaussian.

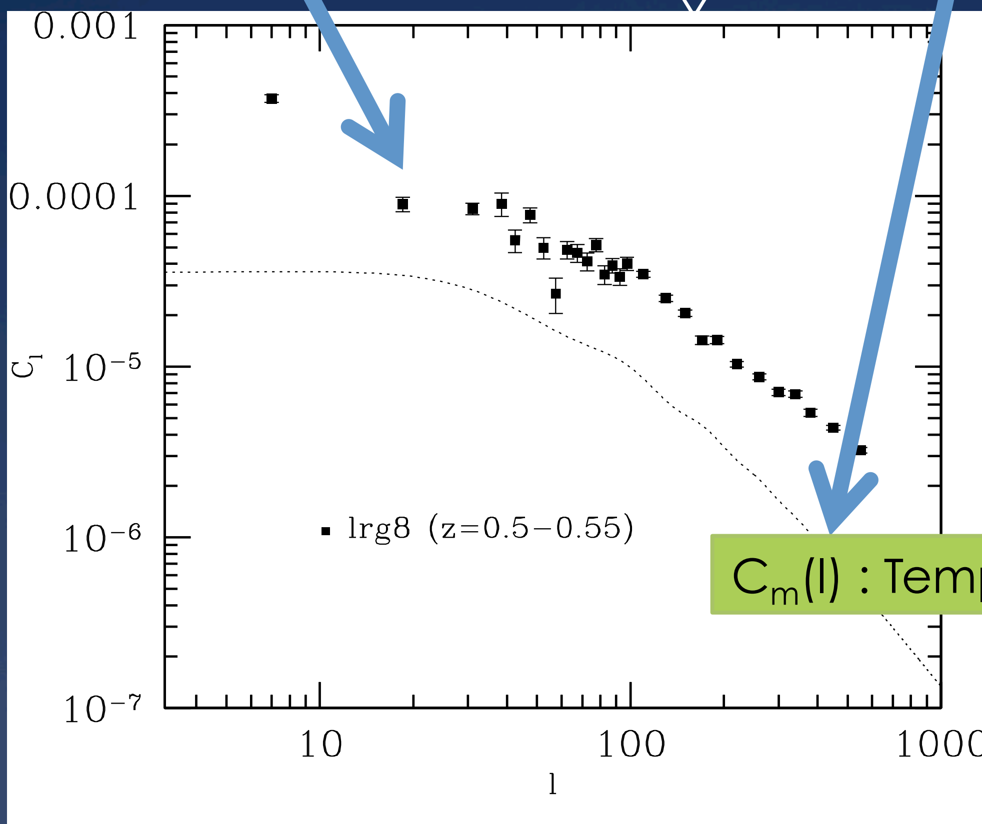
- Previous work on this Quadratic Estimators: Hamilton, Tegmark, Bond, Jaffe and Knox, White, Padmanabhan, Hirata, Blake, et al.

Measure the BAO scale using a template

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

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

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



$C_m(l)$: Template power spectrum

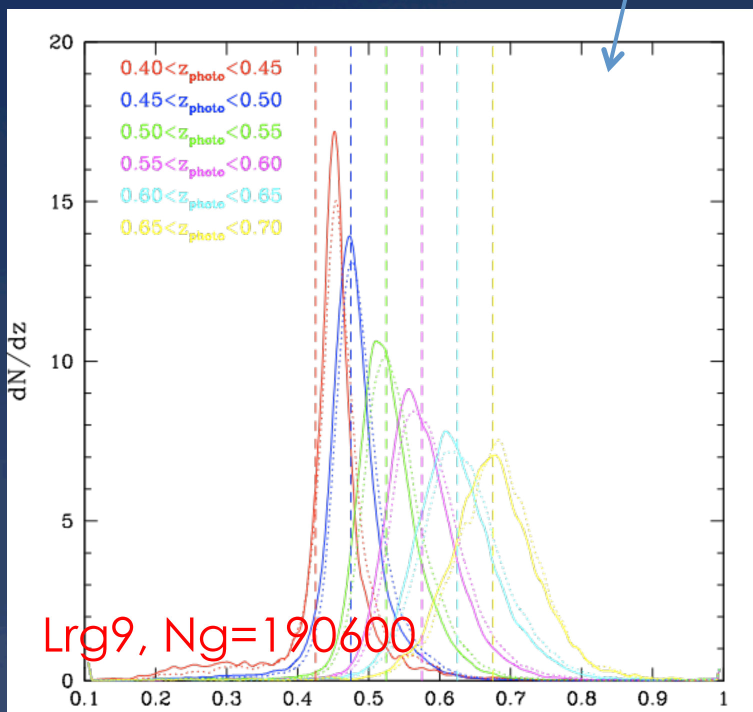
Data from 6 months ago

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

Template

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

10% of the samples have spec z – very little error on pdf(z)



Ross et al. arXiv:1105.2320

Use fiducial cosmology For $b(z)G(z)$, $H(z)$, $D_A(z)$, $Pm(k)$.

When marginalized over $B(l)$ and $A(l)$, the fitting is sensitive only to the shift in the BAO in Pm.

cf. Carnero et al 2011

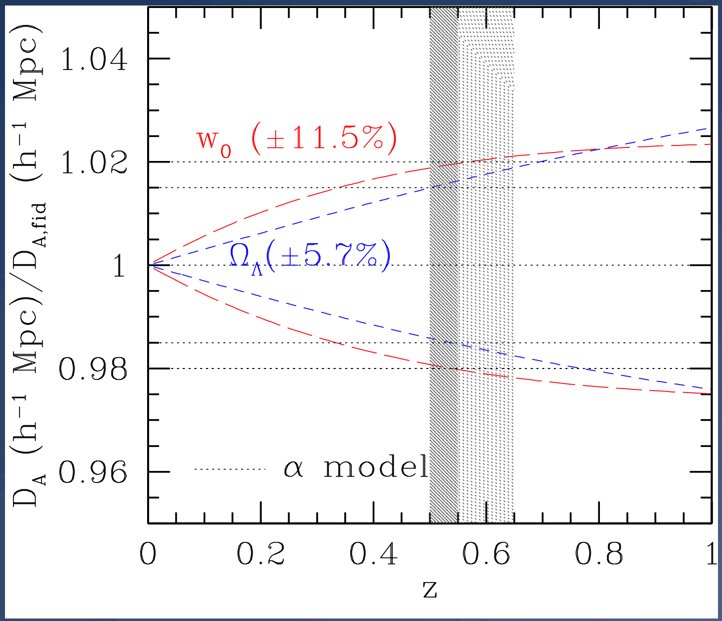
Template construction: "trivial" assumptions

Template

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

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

Then we fit for α, i.e., scale the fiducial D_A to match the observation -- "α model"



For each redshift bin, this α model is very sensitive to the D_A(z_mid) despite a possible difference between the true D_A(z) and $D_{A,f}$ (z), as dn/dz is sharply peaked in each redshift bin relative to the error on D_A

Seo et al. in preparation

Template construction: “trivial” assumptions

Template

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

Therefore we assume a fiducial cosmology for $D_A(z)$ and $H(z)$.

Also an assumption on $b(z)G(z)$ → Not crucial.
Constant bias or constant clustering assumptions both produces essentially the same result.
The true bias evolution will be marginalized over by B(l).

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

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

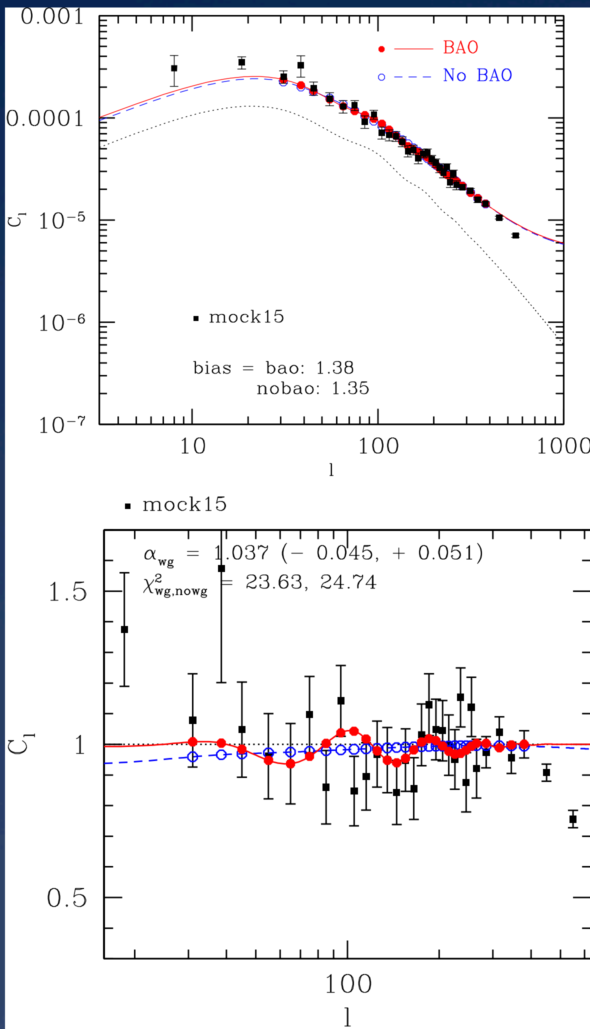
A constant B_i and a constant A_i for each redshift bin with a fitting range of $30<l<300$, to exclude the non-BAO information as much as we can.

Fit using BAO P_m and No-BAO P_m .

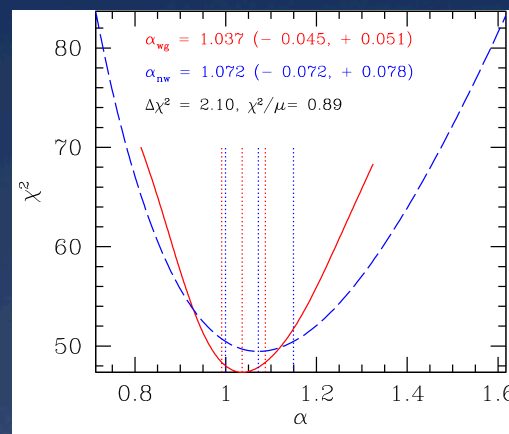
When multiple redshift bins are combined, we fit for a universal α while marginalizing over B_i and Ai for individual redshift bin: i.e., we are deriving an "average" α , and therefore the resulting chi^2 is larger than non-universal α .

Test with Mocks (lrg8)

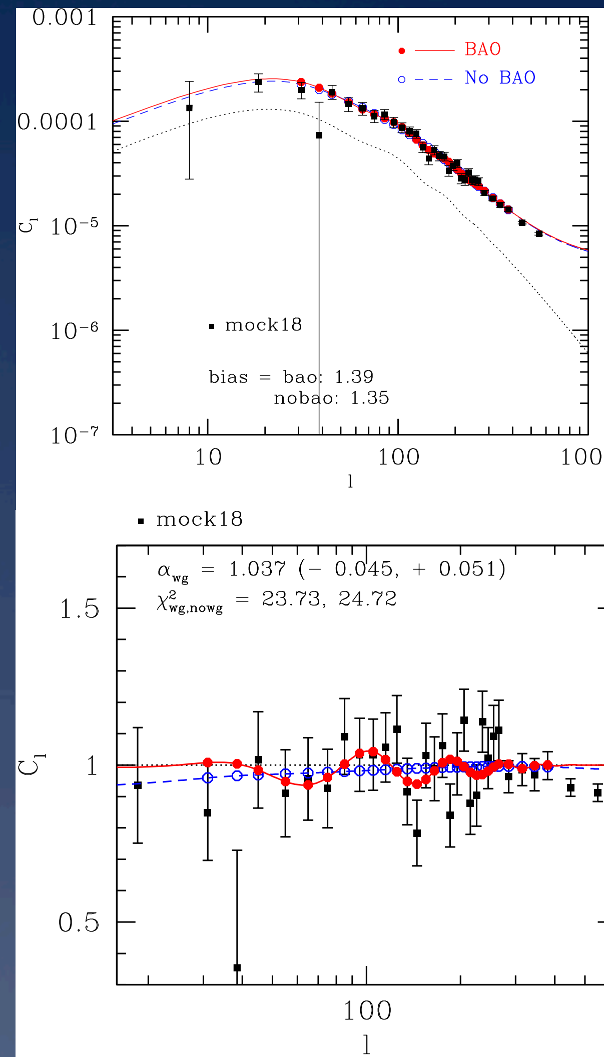
Using Martin White's CMASS mocks, we generate 2D wide-angle projections of uniform dn/dz for a dz=0.05 slice at z=0.525.



Input: WMAP7,
$\alpha=1$

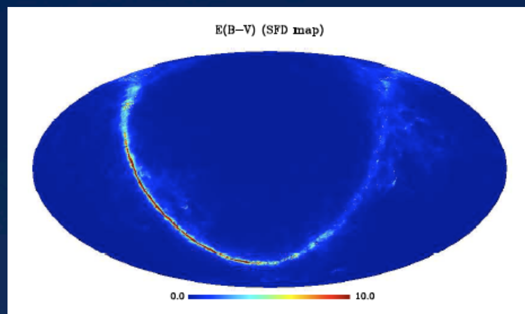


Fit: $\alpha=1.037$
(+-4.8%)
$\Delta\ \chi^2 = 2.1$

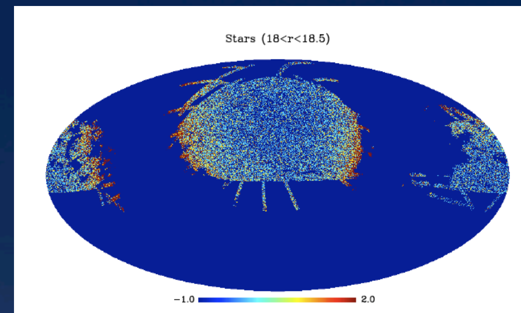


Systematics

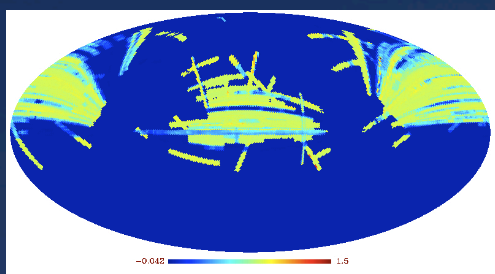
* A real survey is not as favorable as the mock.
* The photoz survey suffers more from various observational systematics such as stars, dust, seeing, offset, and sky brightness.
* In principle, if these effects do not have a preferred scale (i.e., if they have smooth power spectra), we can blindly extract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



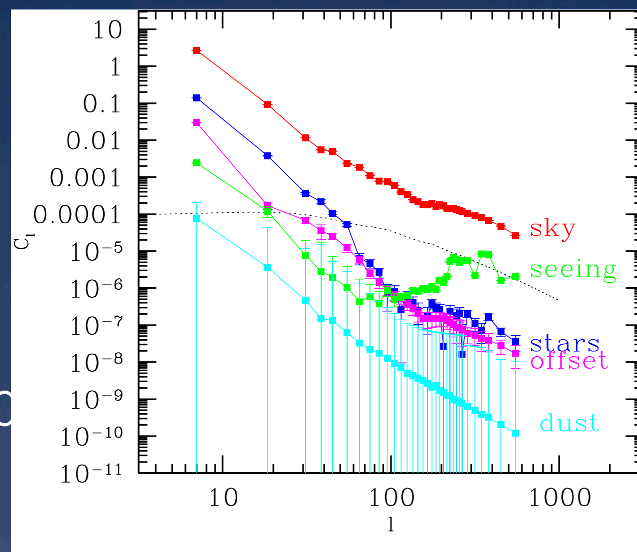
Dust extinction

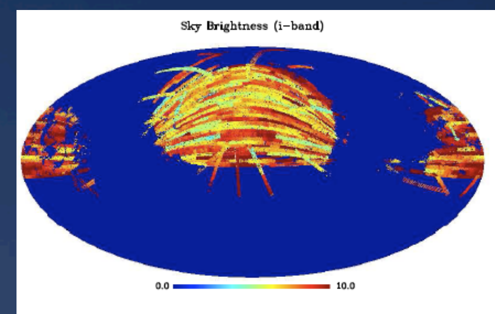


Stars



Offset (Schlafly et al. 2010





Sky brightness

Ho et al. in preparation

Systematics correction

Ho et al. in prep

- 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,

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

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

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

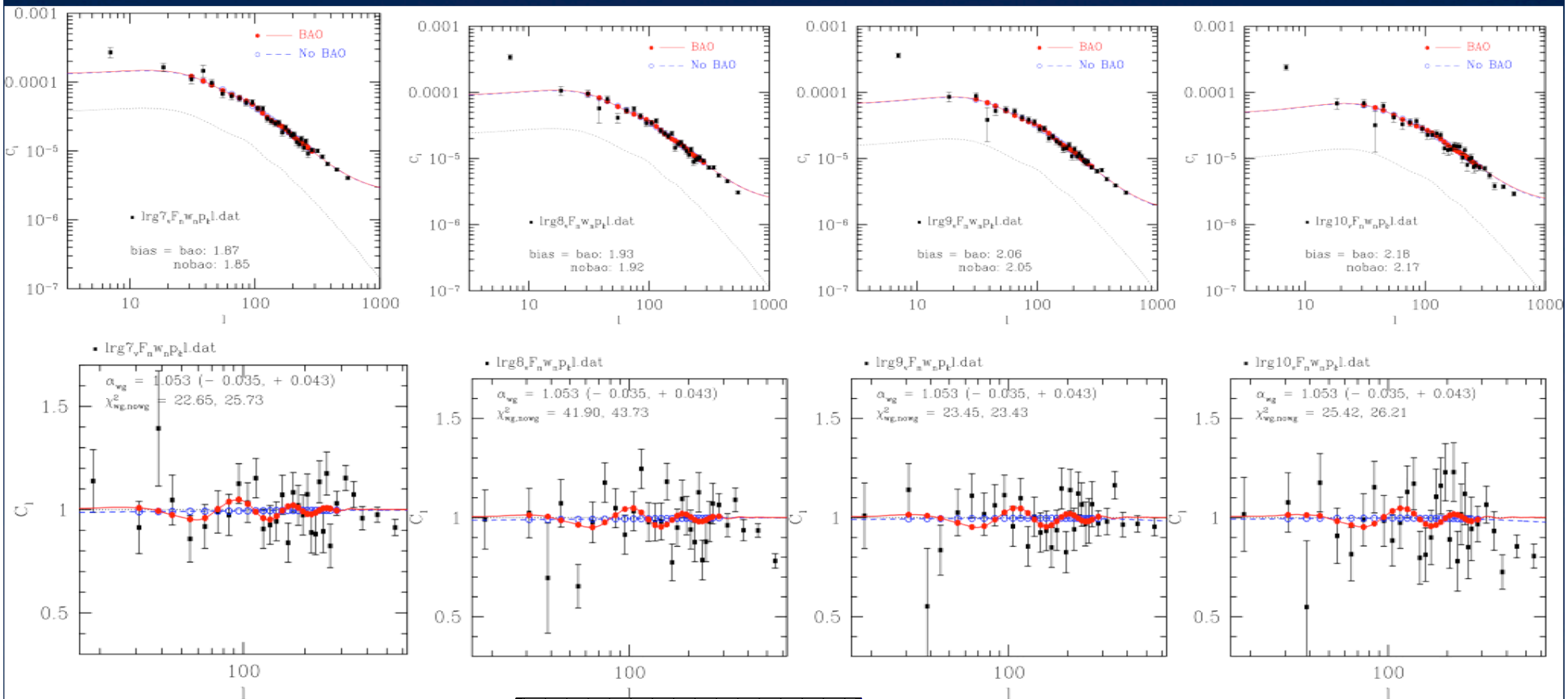
$$= < \delta_g \delta_j > + \sum \epsilon_i < \delta_i \delta_j >$$

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.

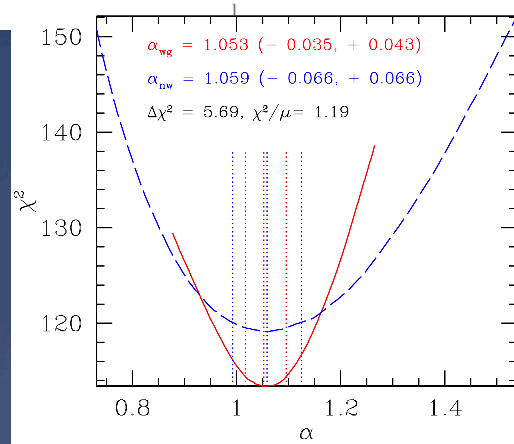
Ross et al. 2011 for correlation funciton

Preliminary results before Sys. correction



Fisher matrix: ~4%

Seo et al. in preparation



α_{wg} =1.053(-0.035+0.043)

α_{nw} =1.059(-0.066+0.066)

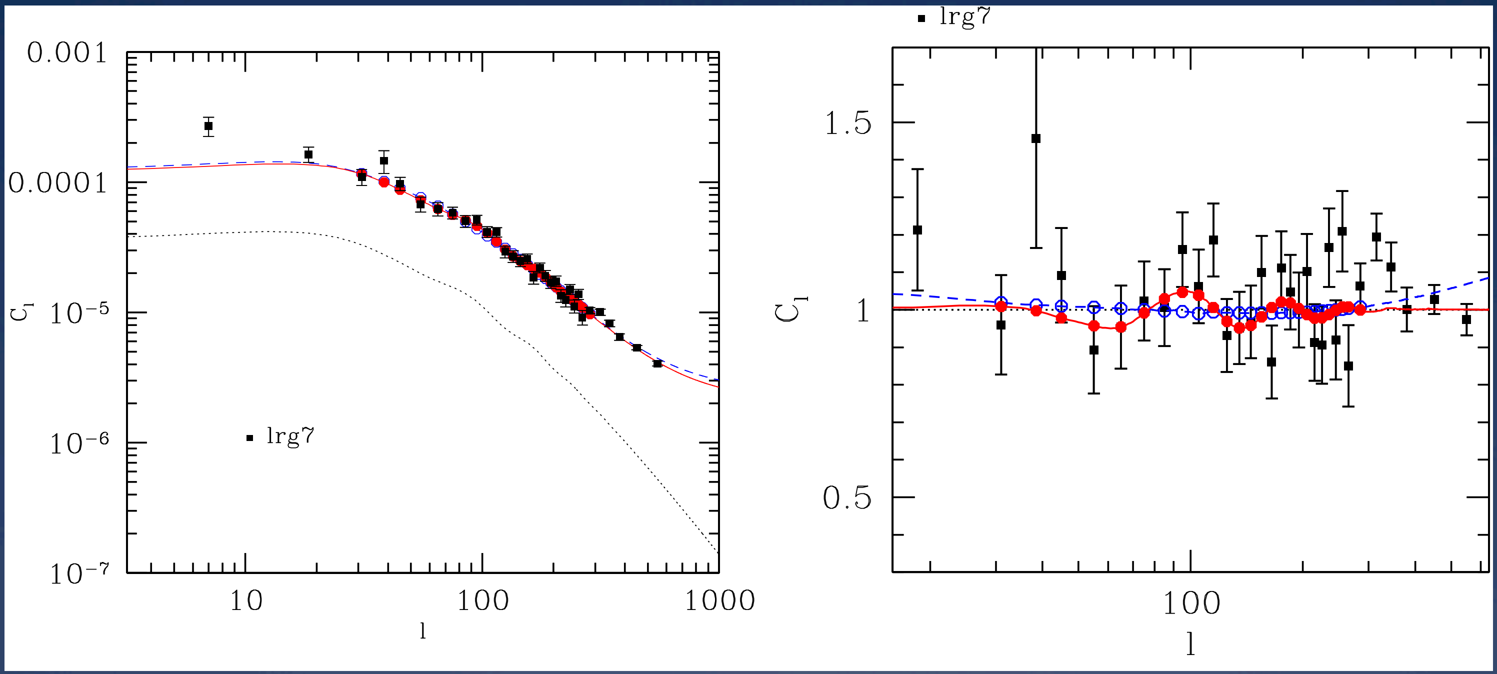
Reduced χ^2=1.19

$[D_A(z)/r_s]_{obs}/[D_A(z)/r_s]_{fid}$ =1.053 +- ~0.04

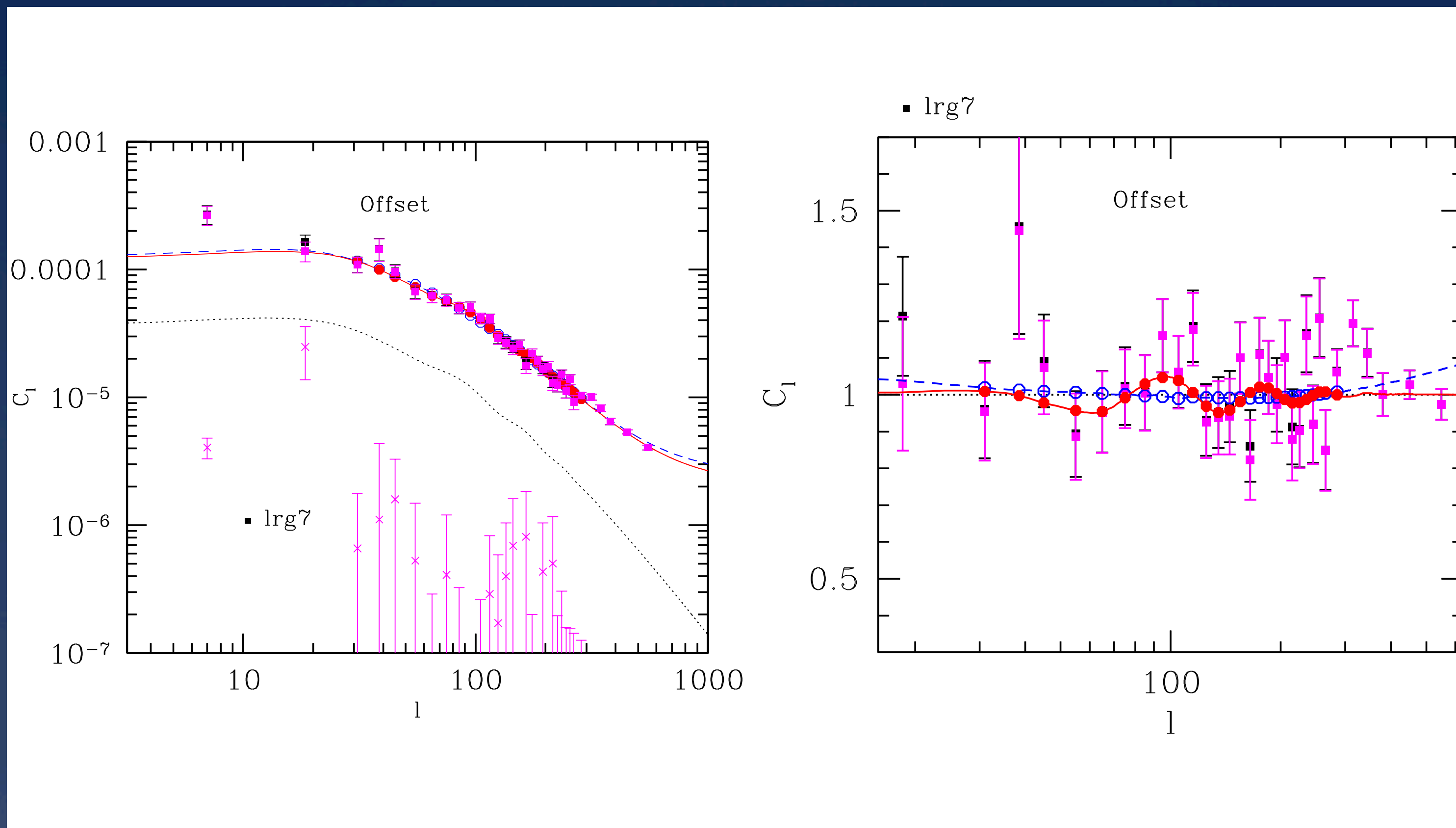
2.4σ detection

Effect of systematics correction
Preliminary result

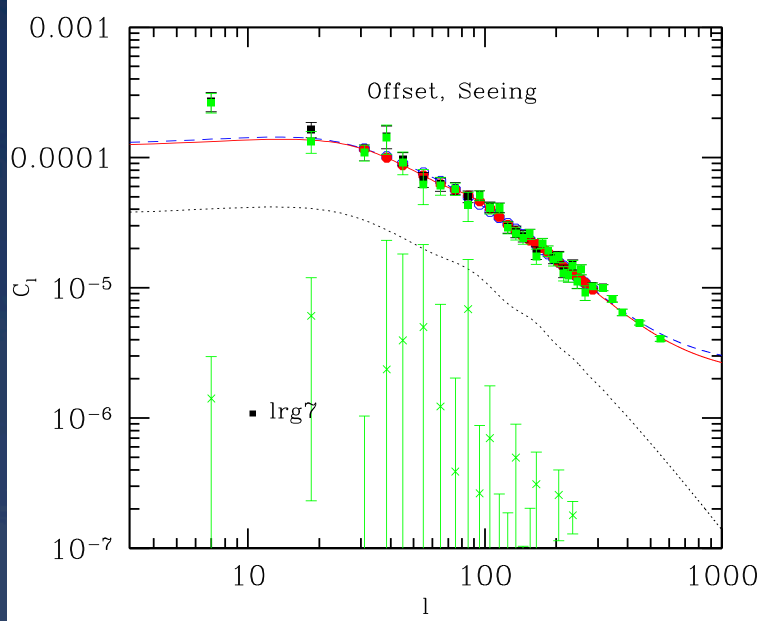
Lrg7

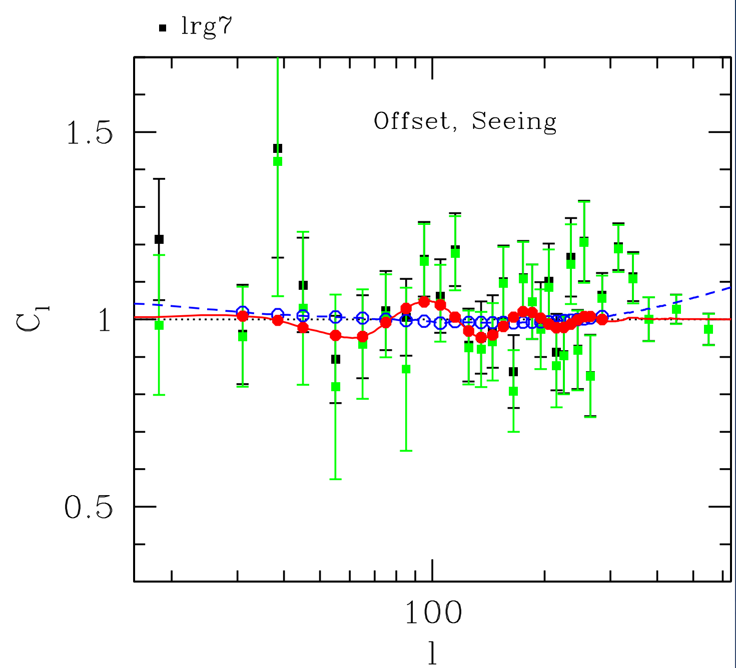


Effect of systematics correction
Preliminary result

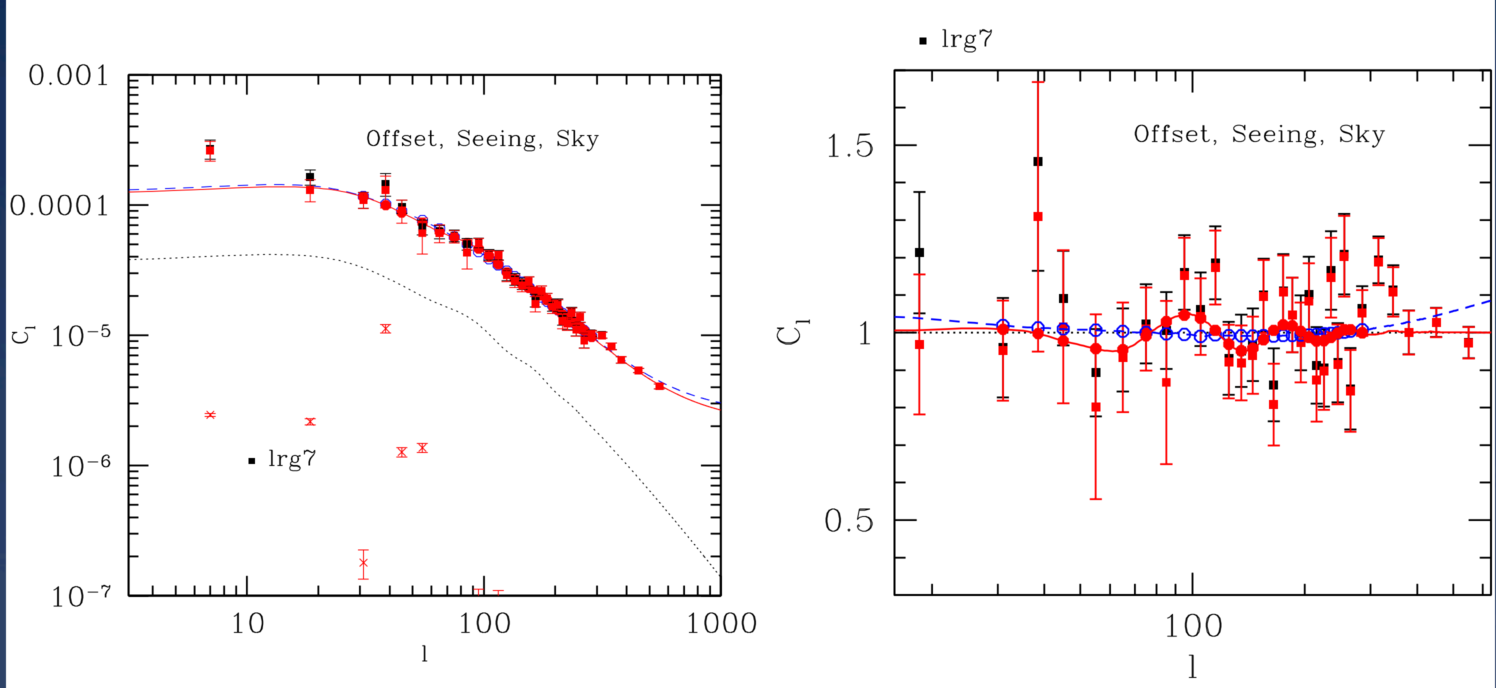


Effect of systematics correction
Preliminary result

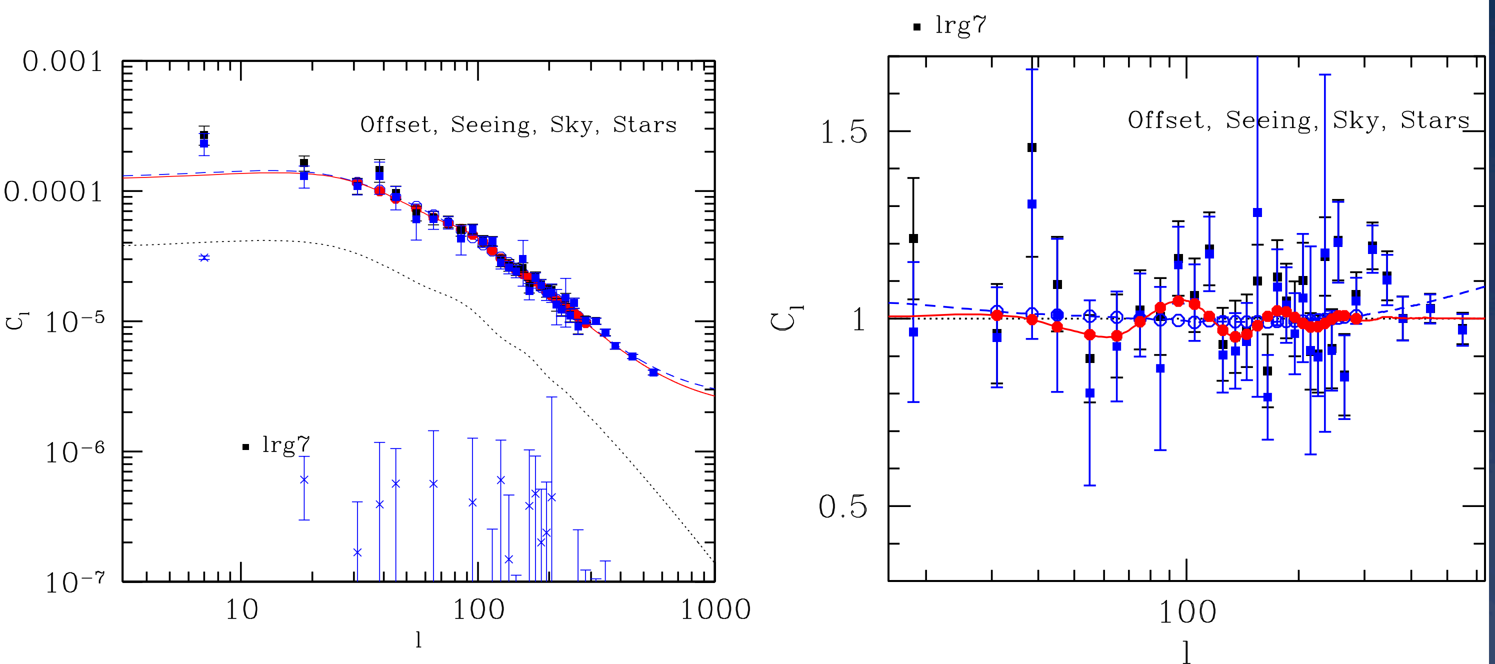




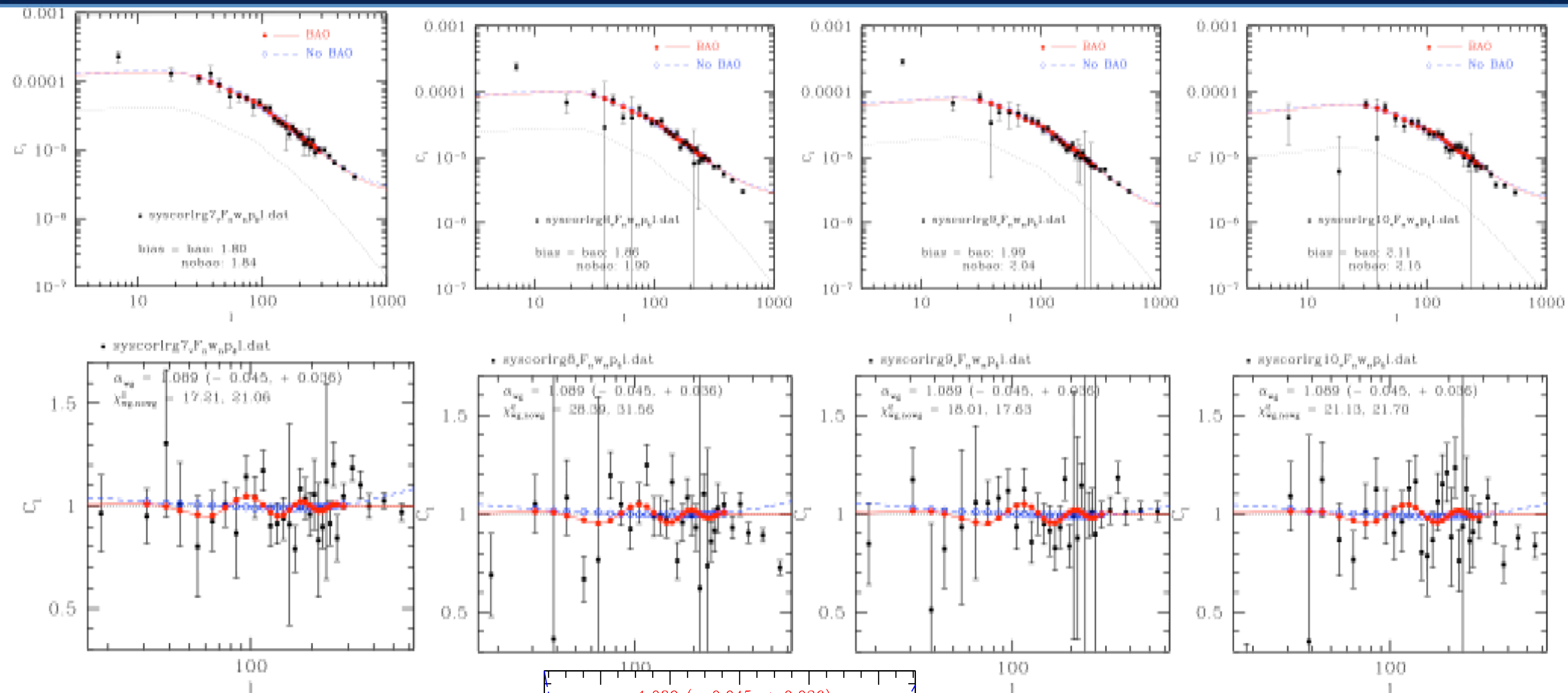
Effect of systematics correction
Preliminary result



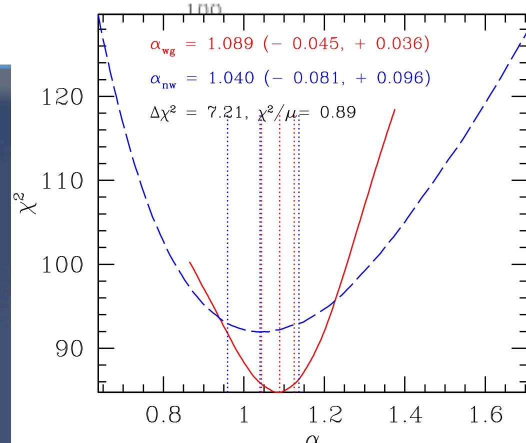
Effect of systematics correction
Preliminary result



After linear systematics correction
Preliminary result



Seo et al. in preparation



α_{wg}=1.089(-0.045+0.036)
α_{nw}=1.040(-0.081+0.096)
Reduced χ^2=0.89
2.7σ detection

Summary

- Data: Largest volume ever used for galaxy clustering: 10,000 sq deg up to z=0.7, this is equivalent to 3(Gpc/h)^3
- Method: First application of Quadratic Estimator on all redshift slices for BAO standard ruler test (while taking into account of all the correlations between different redshift slices of galaxies.)
  - Unbiased minimum variance measurement with various systematics taken into account.
- Detection:
  - First (now second but highest precision) photometric BAO analysis: can be applied to DES, LSST, PanStarrs.
  - This work: Significant Detections at highest redshift range: 0.45<z<0.65 that is complementary to Blake et al. 2011.

Summary

Stacked C_l