Cosmology with the Baryon Oscillation Spectroscopic Survey (BOSS)

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Collaborators: Hee-Jong Seo, Shun Saito + BOSS collaboration

January, 2016

Lawrence Berkeley National Lab

Outline of the talk

- The **B**aryon **O**scillation **S**pectroscopic **S**urvey (BOSS)
- What are Baryon Acoustic Oscillations?
- BOSS results on BAO and cosmological implications.
- What is the Alcock-Paczynski effect?
- What are Redshift-Space Distortions?
- The BOSS power spectrum multipoles
- BOSS results on RSD and cosmological implications.

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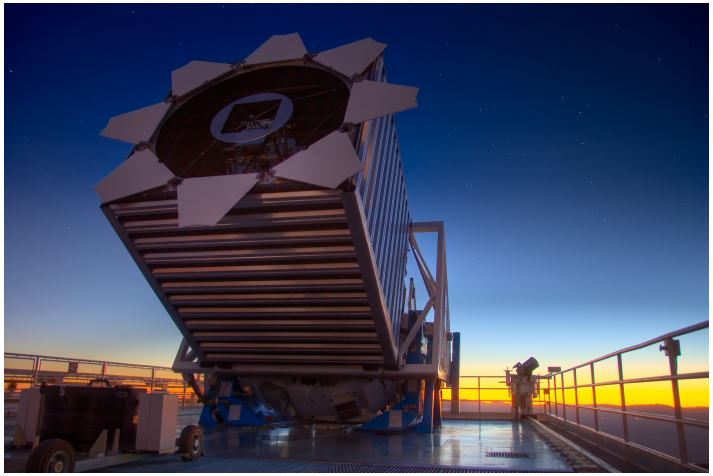
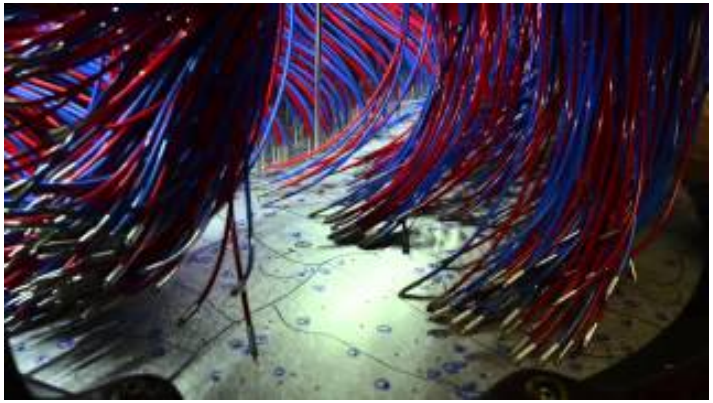
The BOSS galaxy survey

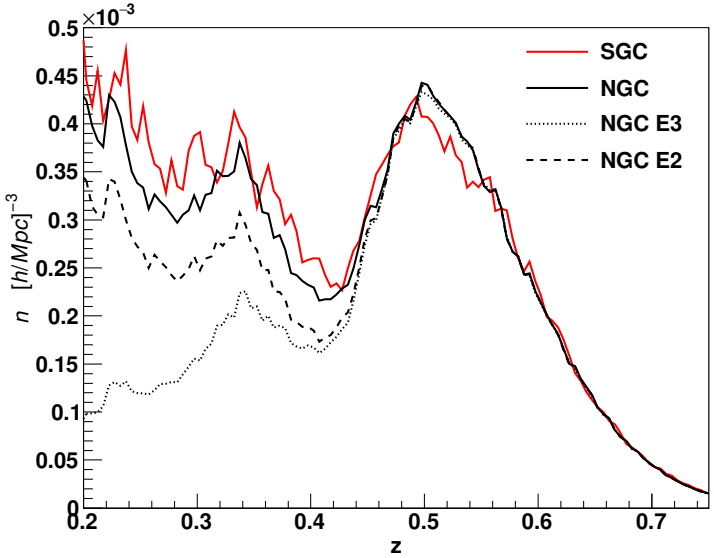
- Third version of the Sloan Digital Sky Survey (SDSS-III).
- Spectroscopic survey optimized for the measurement of Baryon Acoustic Oscillations (BAO).
- The galaxy sample includes 1 100 000 galaxy redshifts in the range $0.2 < z < 0.75$.
- The effective volume is $\sim 6\,\mathrm{Gpc}^3$.
- 1000 fibres/redshifts per pointing

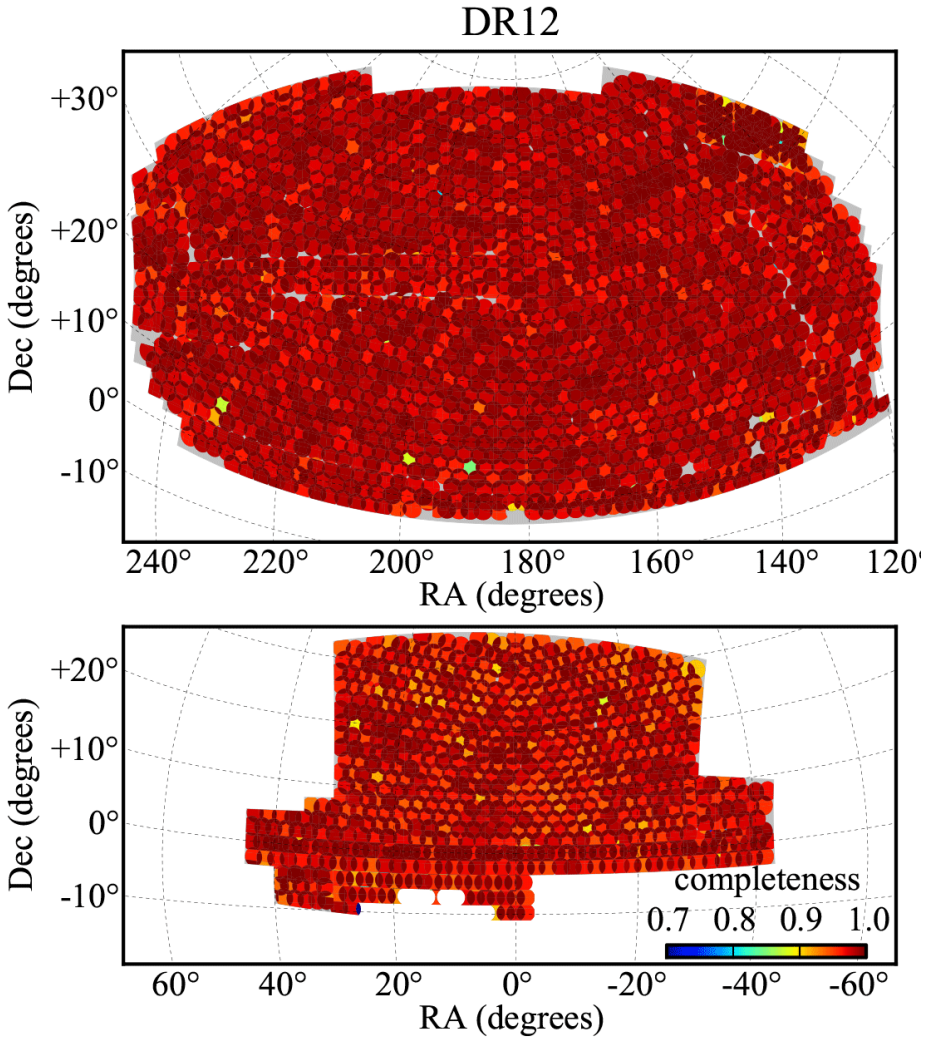




The BOSS galaxy survey

- The final data release (DR12) coveres about 10 000 deg^2.
- The survey is divided in a north galactic patch (NGC) and a south galactic patch (SGC).





Correlation function and power spectrum

The correlation function is defined via the excess probability of finding a galaxy pair at separation r:

$$dP = \overline{n}^2 \left[1 + \xi(r)\right] dV_1 dV_2$$

$\rightarrow$ The correlation function measures the degree of clustering on different scales.

In practice we just count galaxy pairs:

$$\xi(r) = \frac{DD(r)}{RR(r)} - 1$$

The correlation function and the power spectrum are just Fourier transforms of each other

$$P(k) = \int \xi(r) \exp(ik \cdot r) d^3 r$$

$$\xi(r) = \frac{1}{(2\pi)^3} \int P(k) \exp(-ik \cdot r) d^3 k$$

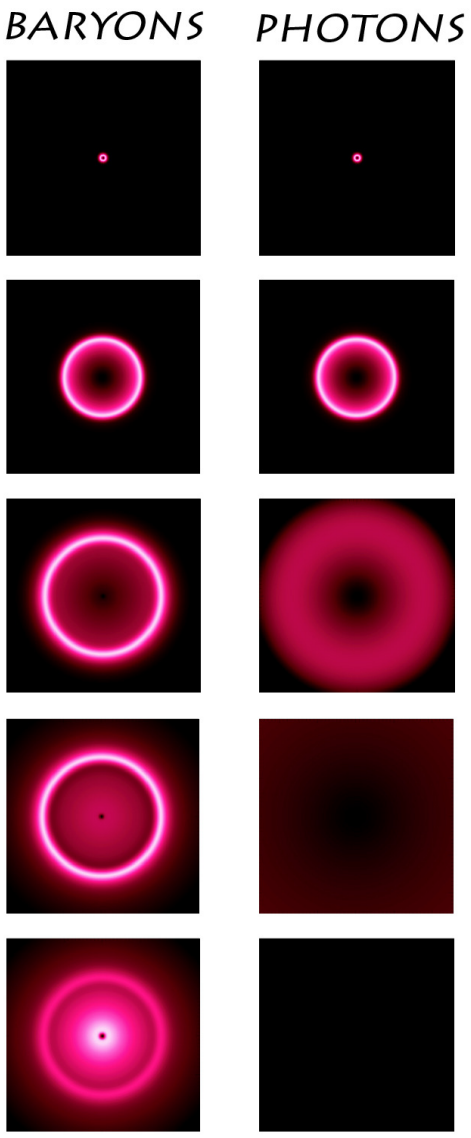
What are Baryon Acoustic Oscillations?

The evolution eq. of baryon and photon perturbations in the radiation dominated era can be written as

$$\ddot{\delta} + 2H\dot{\delta} + \left(\frac{c_s^2 k^2}{a^2} - 4\pi G\overline{\rho}\right)\delta = F$$

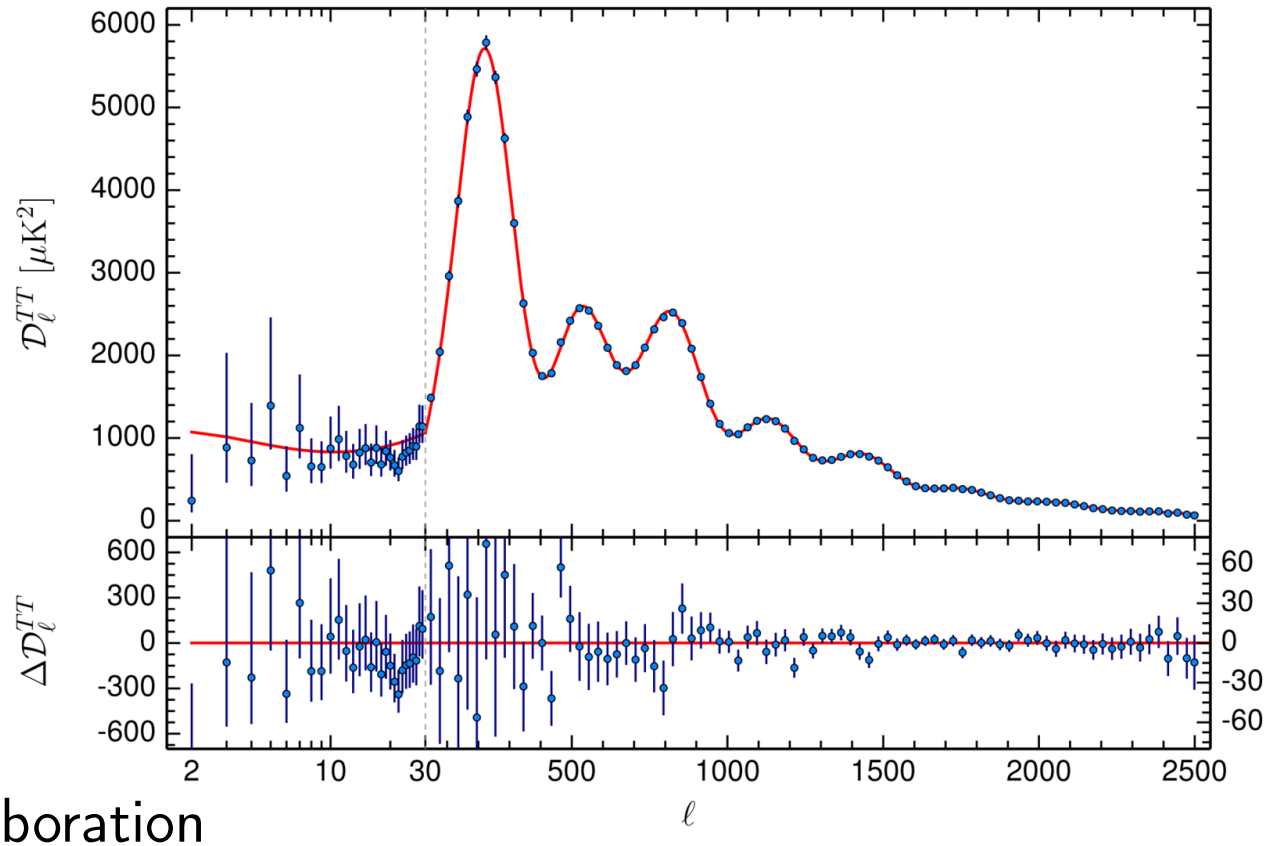
Note that this is a forced and damped harmonic oscillator ($m\ddot{x} + b\dot{x} + kx = F$) with the plane wave solution $\delta \propto A\cos(\omega t - \phi)$, where $\omega^2 = c_s^2 k^2/a^2 - 4\pi G\overline{\rho}$.

- Preferred distance scale between galaxies as a relict of sound waves in the early Universe.
- Can be used as a standard ruler.
- The systematic errors are far below the current statistical errors.



credit: Martin White

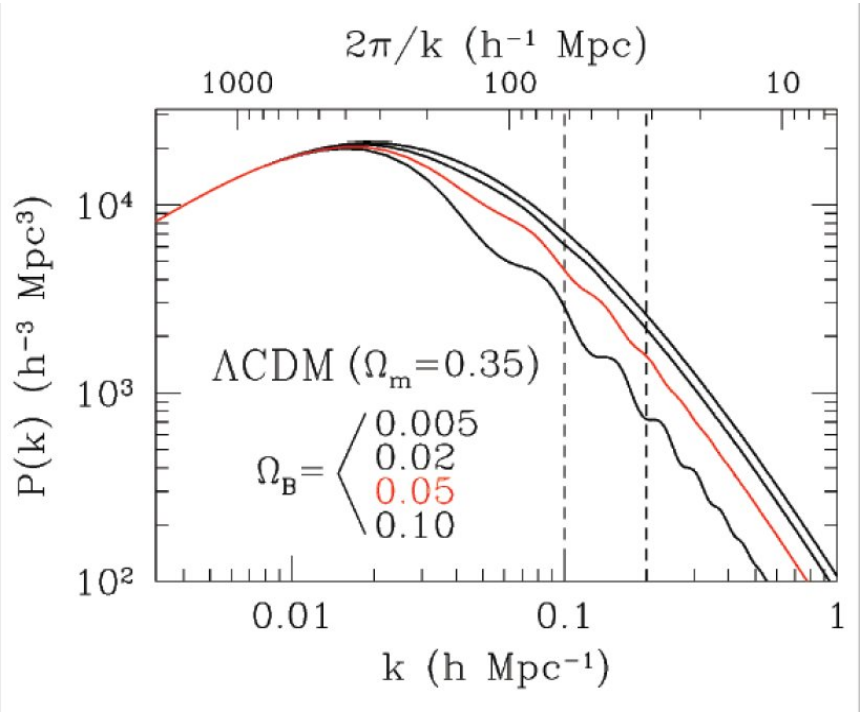
BAO in the photon temperature power spectrum

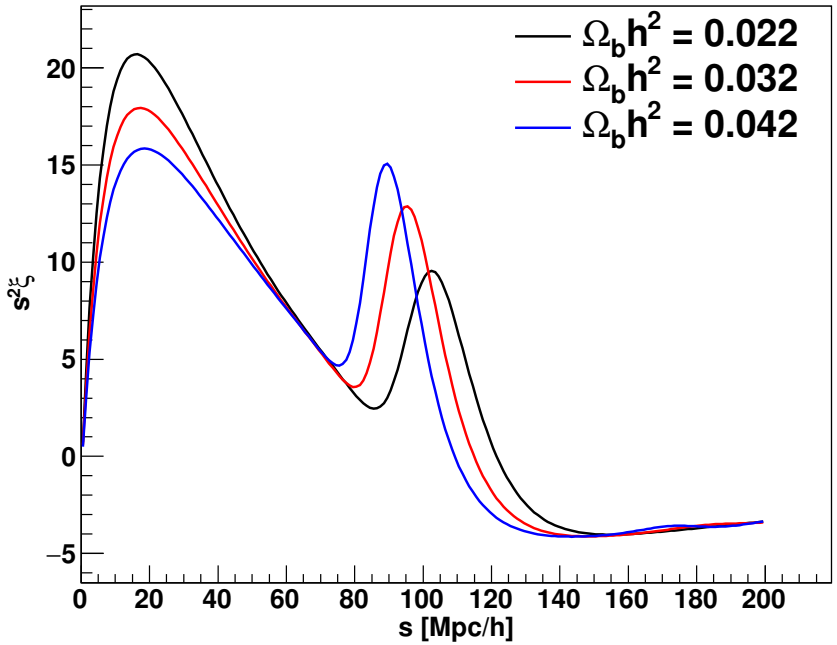


Planck collaboration

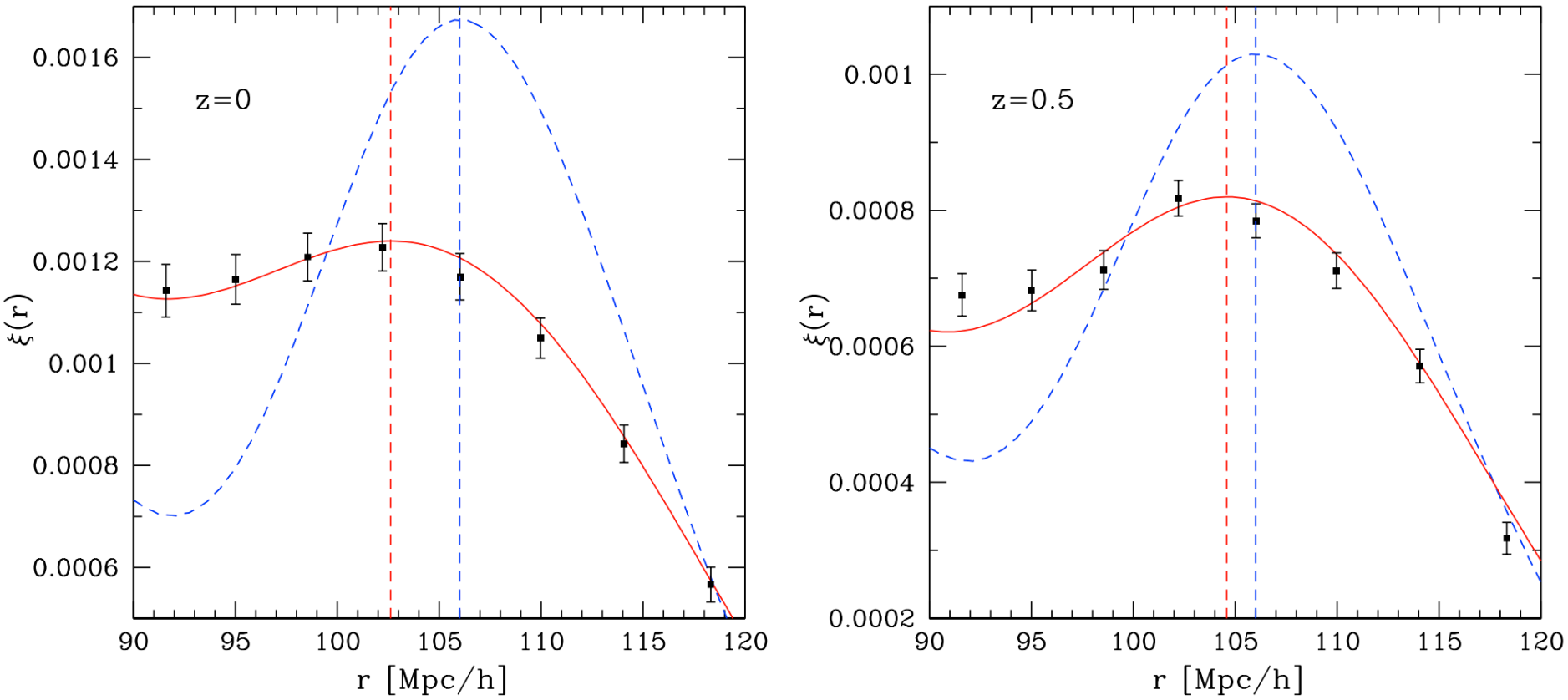
$$r_s(z_*) = 144.75 \pm 0.66\,\mathrm{Mpc} \quad (0.46\%)$$
$$r_s(z_d) = 147.34 \pm 0.64\,\mathrm{Mpc} \quad (0.43\%)$$

BAO in the two-point matter clustering





Non-linear effects on the BAO peak



$$\xi(r,z) = [e^{-r^2/\sigma^2} * \xi_{\rm lin}](r,z) + \xi_{\rm MC}(r,z)$$

Crocce & Scoccimarro (2008)

Non-linear effects on the BAO peak

The matter power spectrum can be written as

$$P_{\rm g}(k,\mu) = \exp\left(-k^2\Sigma^2\right) P_{\rm lin}(k) + P_{\rm MC} + \ldots,$$

The second term represents the power generated by mode-coupling at smaller scales and in standard PT it can be written as

$$P_{\rm MC}(k) \simeq 2\int \left[F_2(k-q,q)\right]^2 P_{\rm lin}(|k-q|)P_{\rm lin}(|q|)d^3q$$

with the second-order PT kernel

$$F_2(k_1,k_2) = \frac{5}{7} + \frac{2}{7}\left(\frac{\vec{k}_1\cdot\vec{k}_2}{k_1k_2}\right)^2 + \frac{\vec{k}_1\cdot\vec{k}_2}{2}\left(\frac{1}{k_1^2}+\frac{1}{k_2^2}\right).$$

Density field reconstruction

- Smooth the density field to filter out high k non-linearities.

$$\delta'(\vec{k}) \rightarrow e^{-\frac{k^2 R^2}{4}} \delta(\vec{k})$$

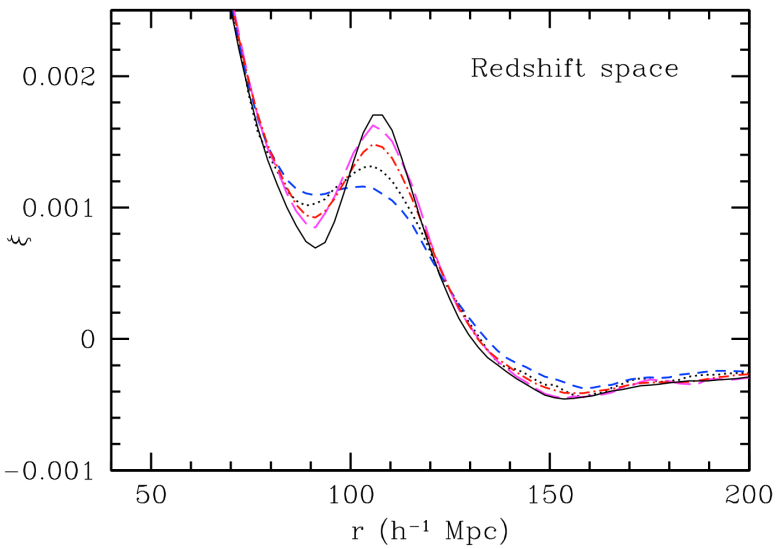
- Solve the Poisson eq. to obtain the gravitational potential

$$\nabla^2 \phi = \delta$$

- The displacement (vector) field is given by

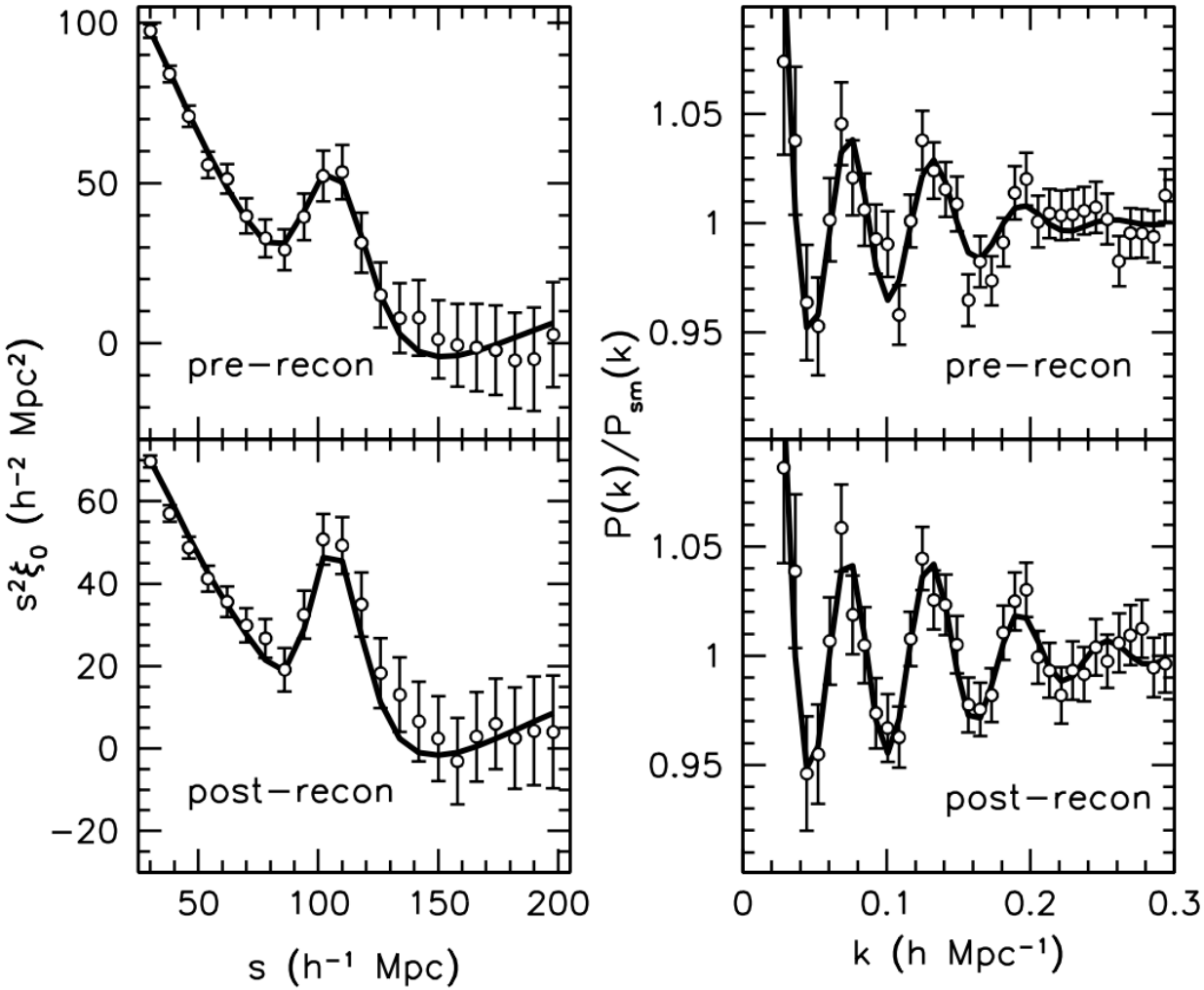
$$\Psi = \nabla \phi$$

- Now we calculate the displaced density field by shifting the original particles.



Eisenstein et al. (2007), Padmanabhan et al. (2012)

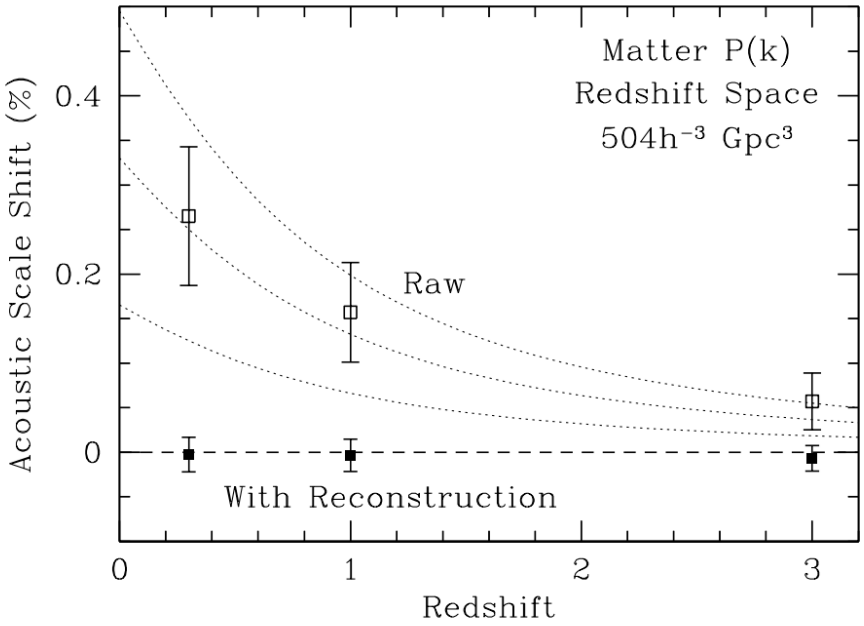
BOSS & BAO

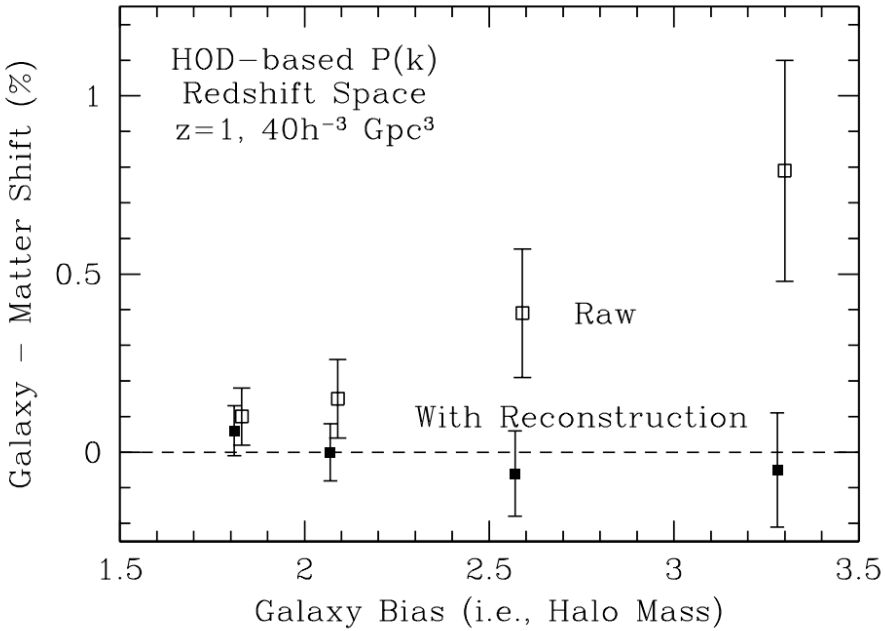


Anderson et al. (2014)

Density field reconstruction

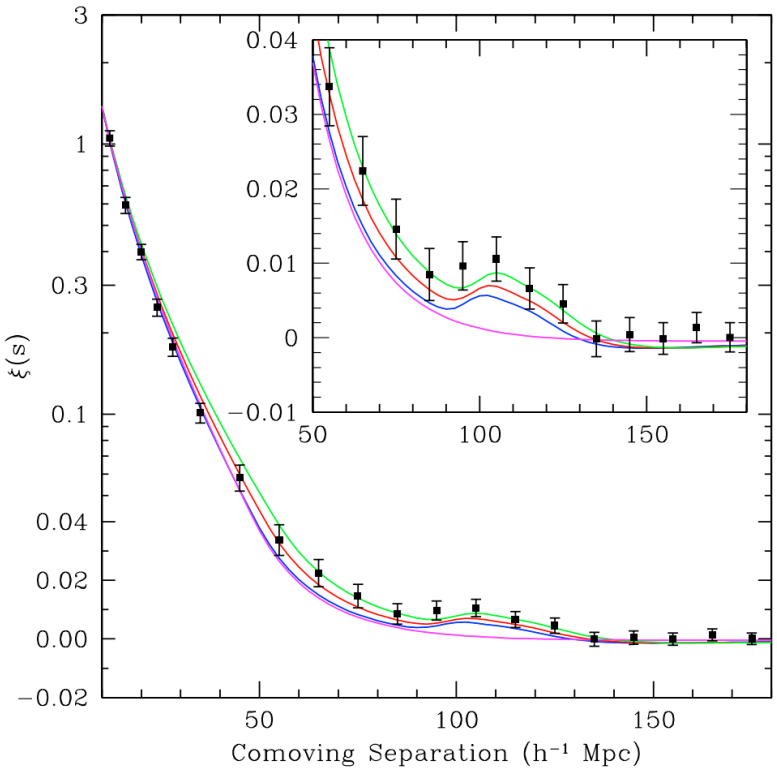
- Density field reconstruction increases the BAO signal and improves the distance constraint by a factor of ~ 2 which corresponds to a increase in survey volume by a factor of ~ 4 (Padmanabhan et al. 2012).
- One can show that reconstruction removes the shift due to the mode coupling term (see e.g. Seo et al. 2010, Mehta et al 2011).



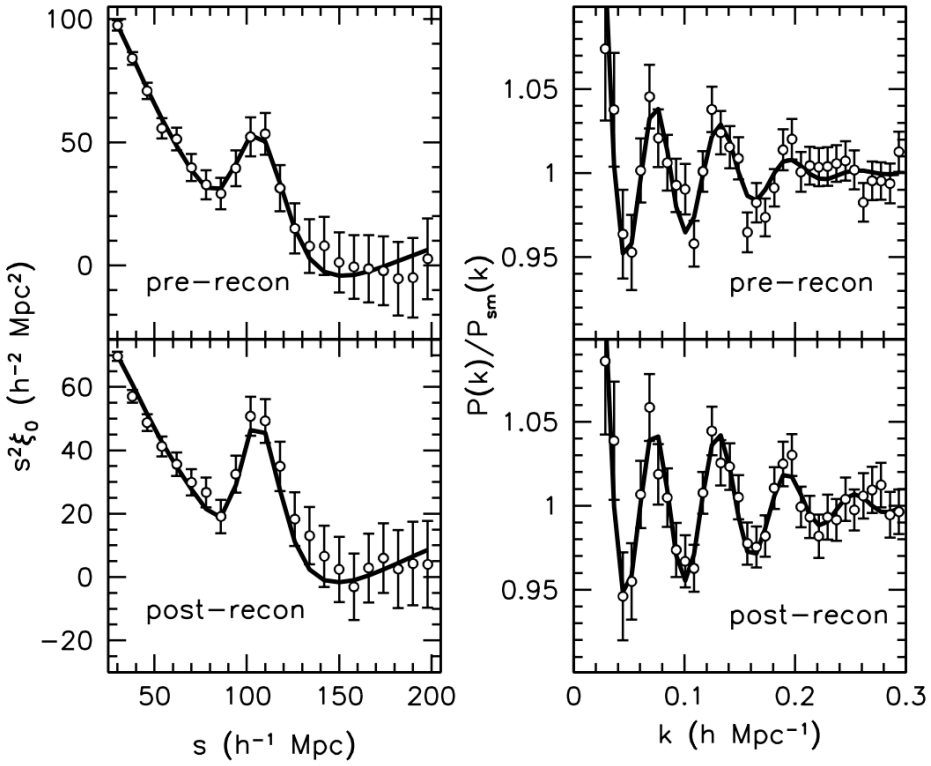


Seo et al. (2010) / Mehta et al. (2011)

BOSS & BAO



Eisenstein et al. (2005)



Anderson et al. (2014)

Fitting the BAO

- Start with linear $P(k)$ and separate the broadband shape, $P^{\rm sm}(k)$, and the BAO feature $O^{\rm lin}(k)$. Include a damping of the BAO feature:

$$P^{\rm sm,lin}(k) = P^{\rm sm}(k)\left[1 + (O^{\rm lin}(k/\alpha) - 1)e^{-k^2\Sigma_{\rm nl}^2/2}\right]$$

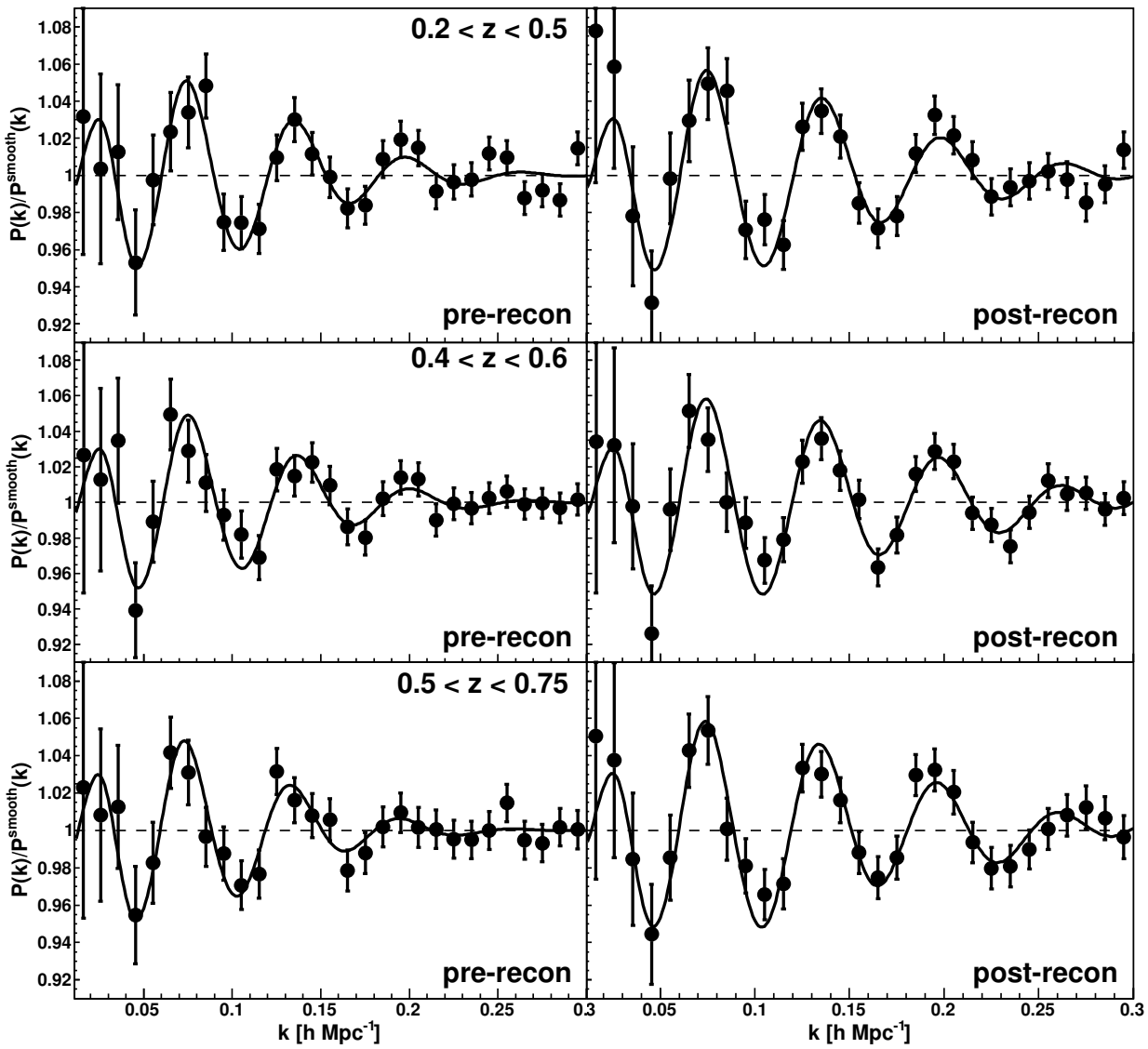
- add broadband nuisance terms

$$A(k) = a_1 k + a_2 + \frac{a_3}{k} + \frac{a_4}{k^2} + \frac{a_5}{k^3}$$

- Marginalize to get P(α)

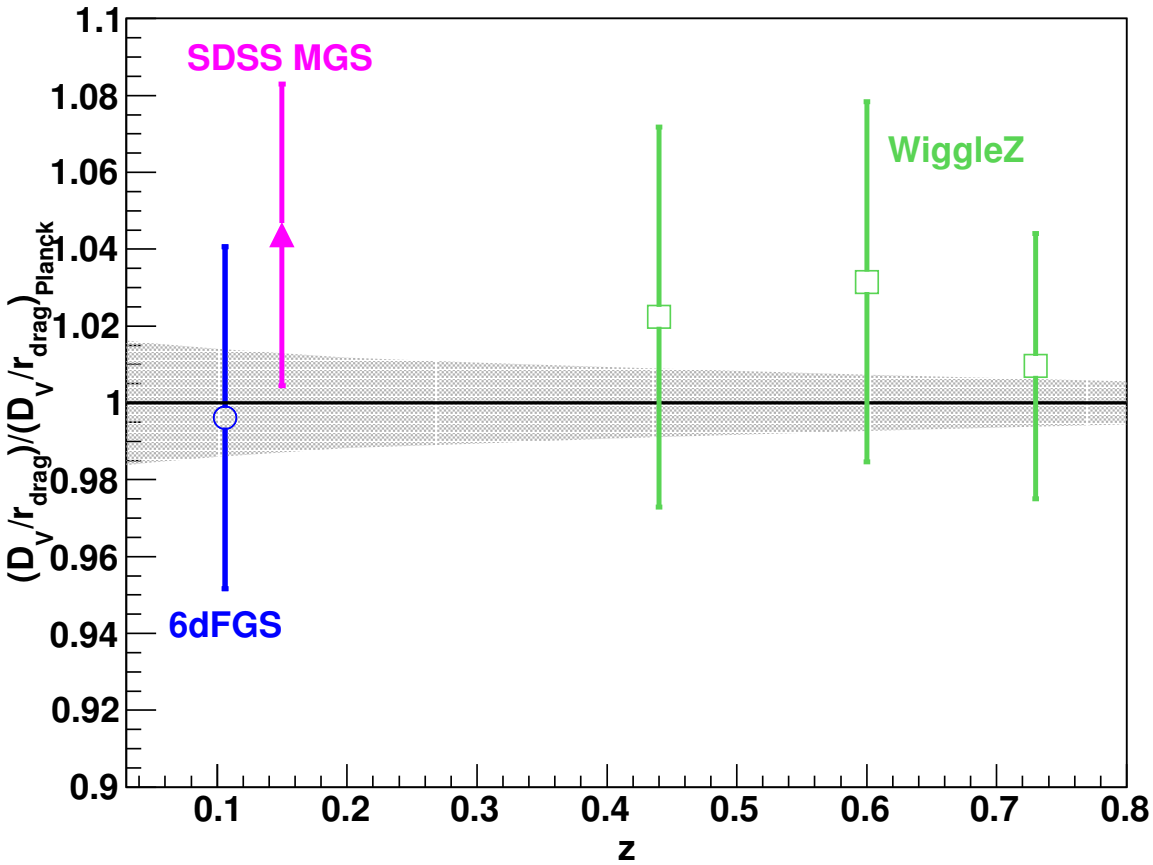
$$P^{\rm fit}(k) = B^2 P^{\rm sm,lin}(k/\alpha) + A(k)$$

BOSS & BAO (preliminary)



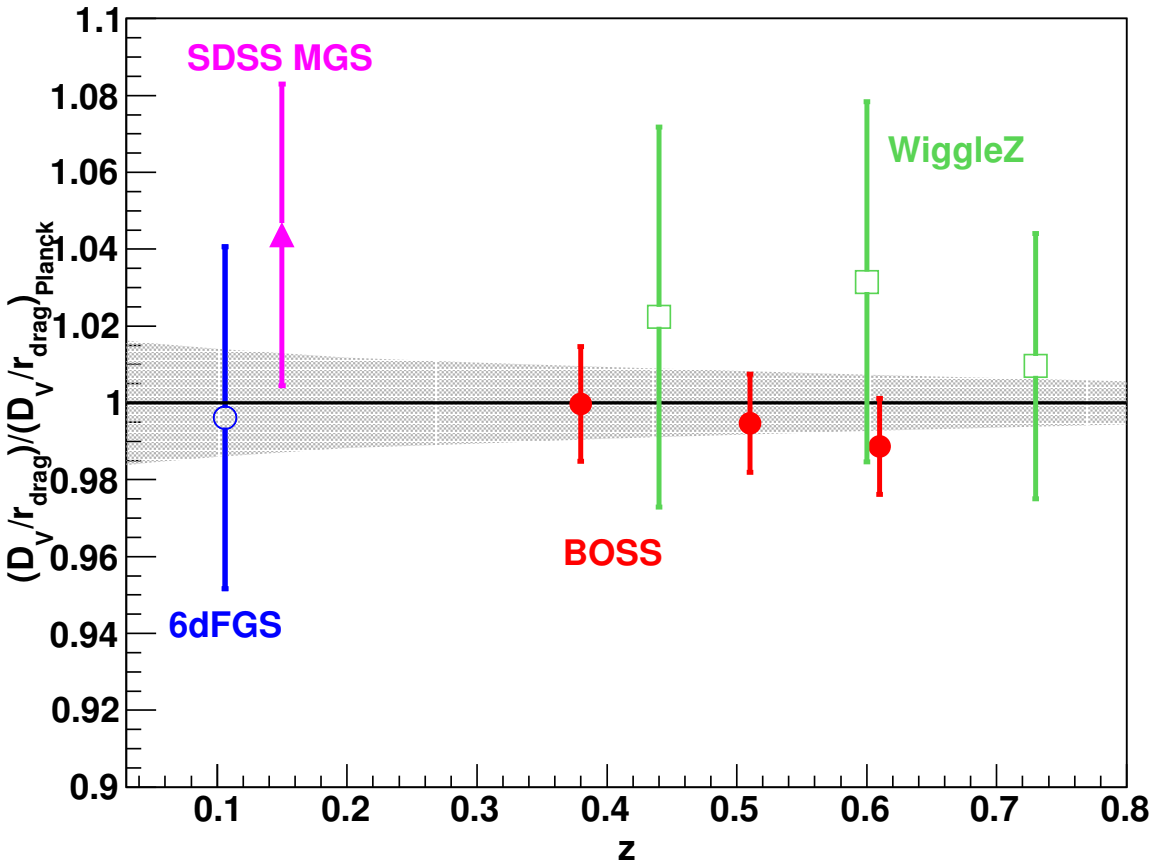
Beutler et al. (in prep.)

BAO constraints before BOSS (preliminary)



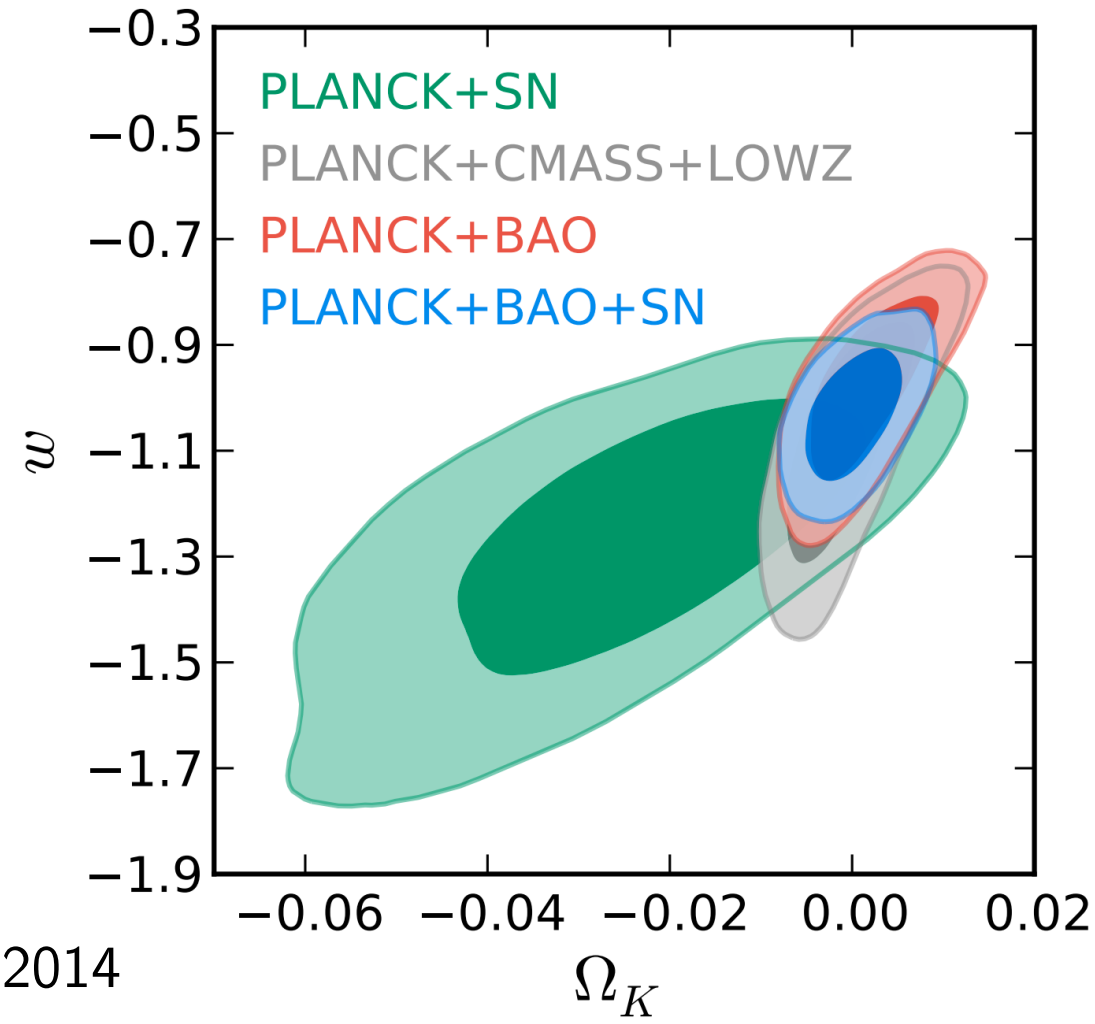
$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

BAO constraints including BOSS (preliminary)



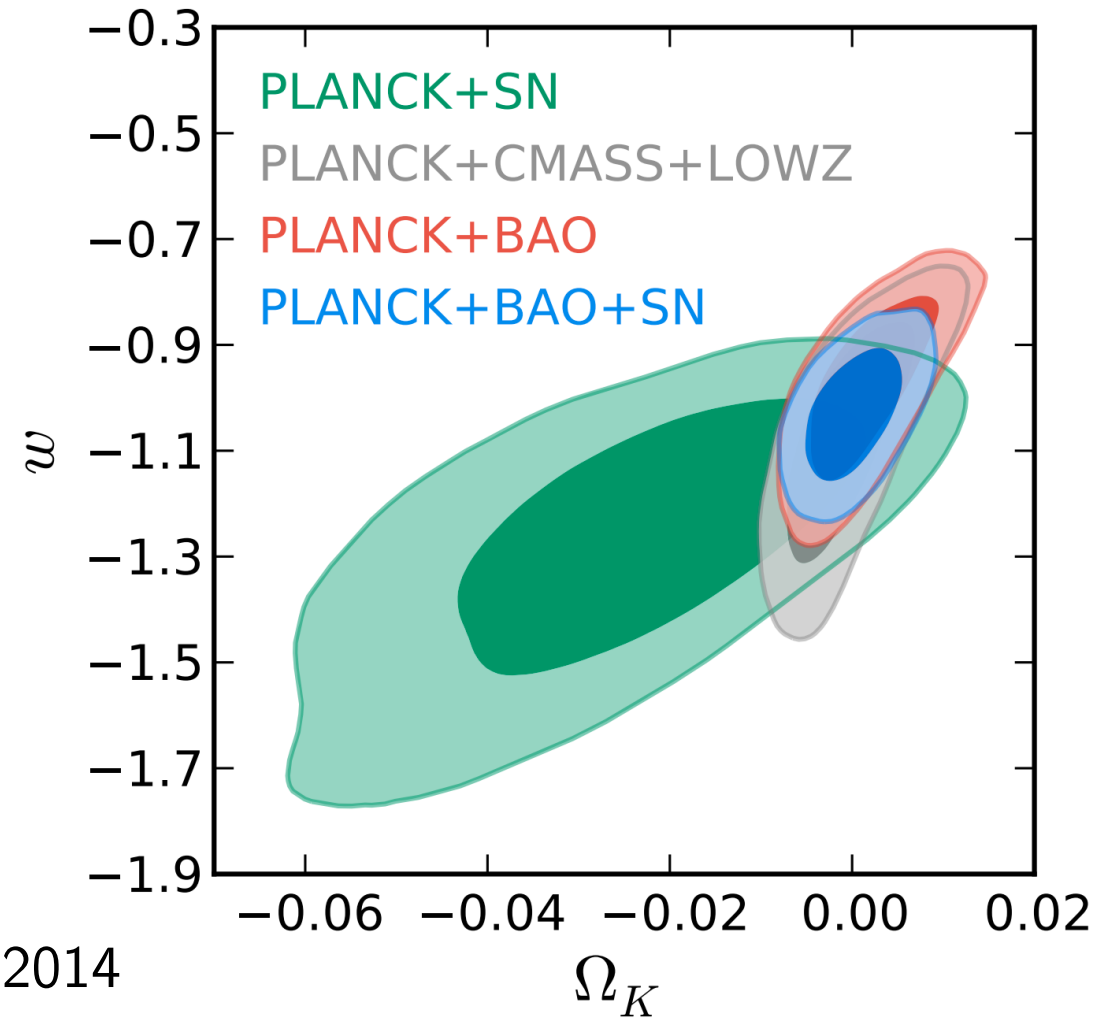
$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

Constraining cosmological parameters



Anderson et al 2014

Constraining cosmological parameters

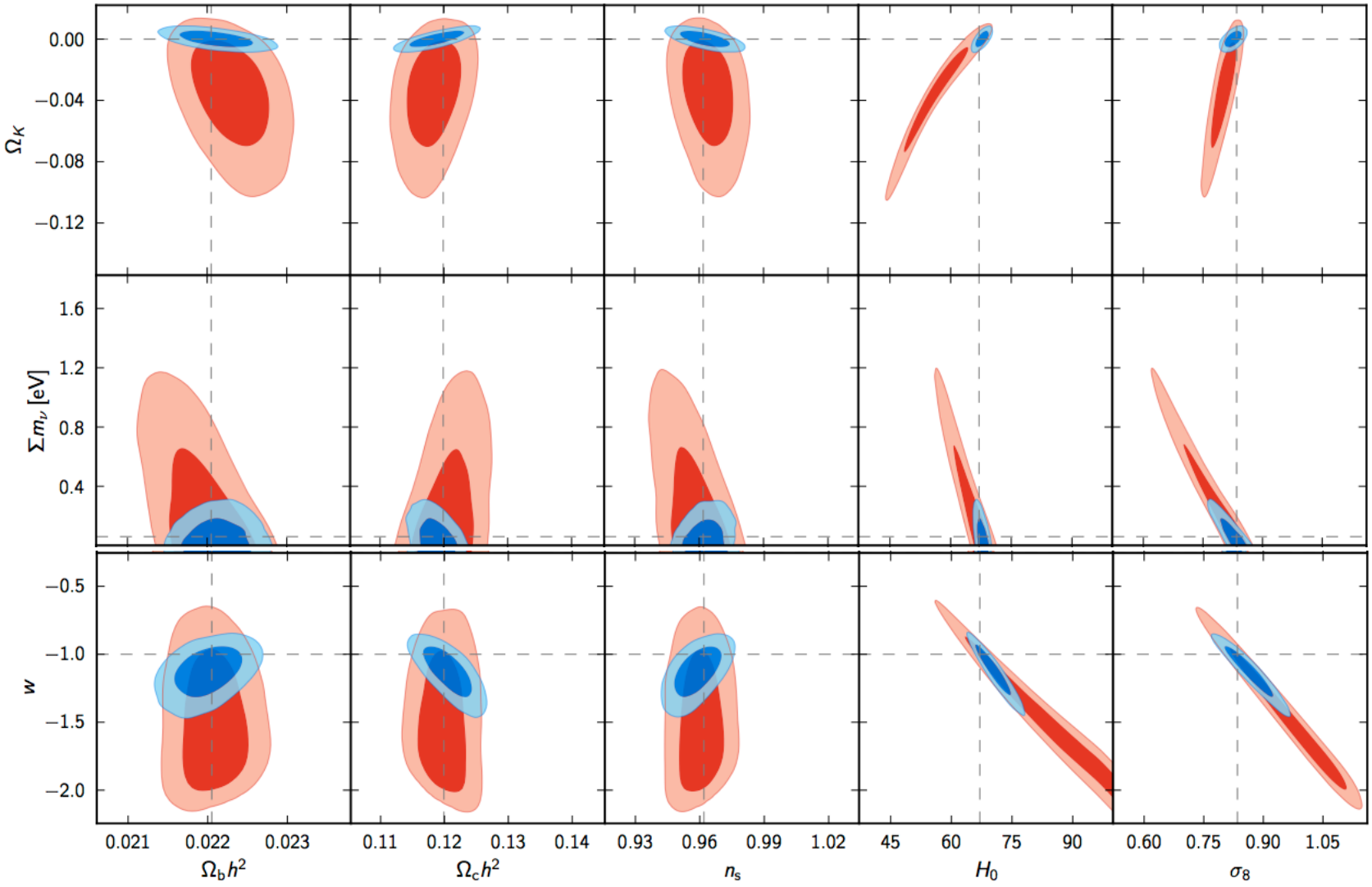


Anderson et al 2014

$$\Omega_k = 0.0002 \pm 0.0034$$

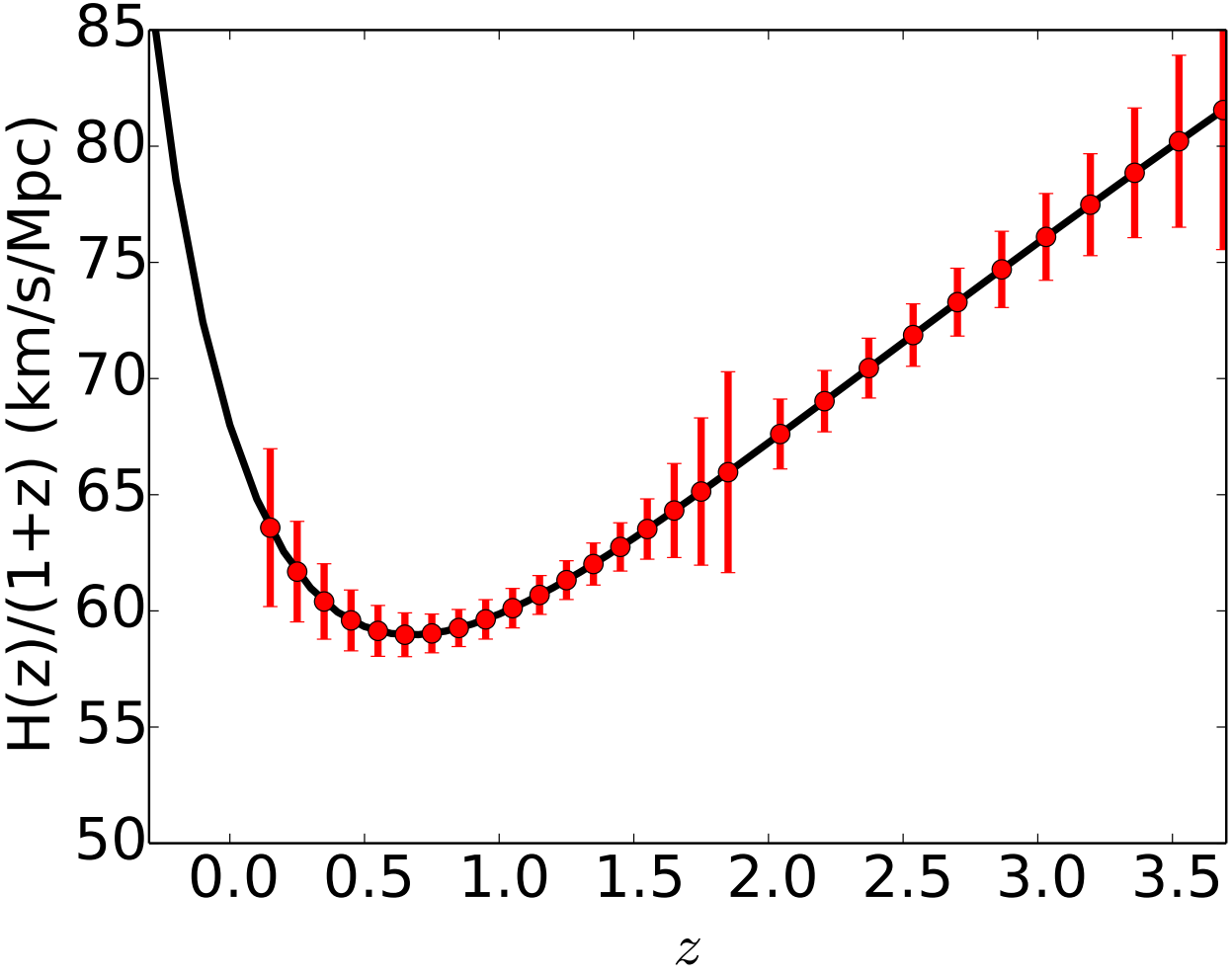
$$w = -1.03 \pm 0.07$$

Next generation BAO (DESI)



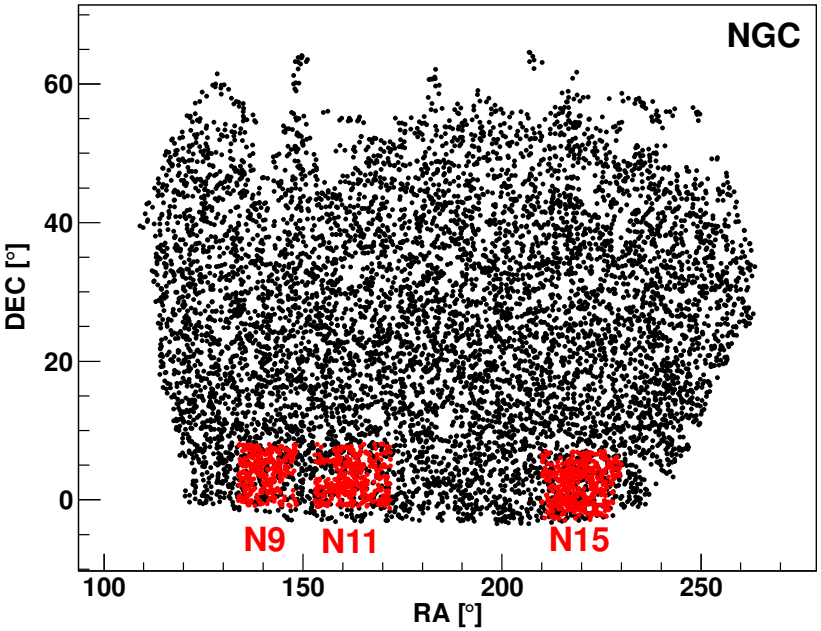
Ade et al. (2015)

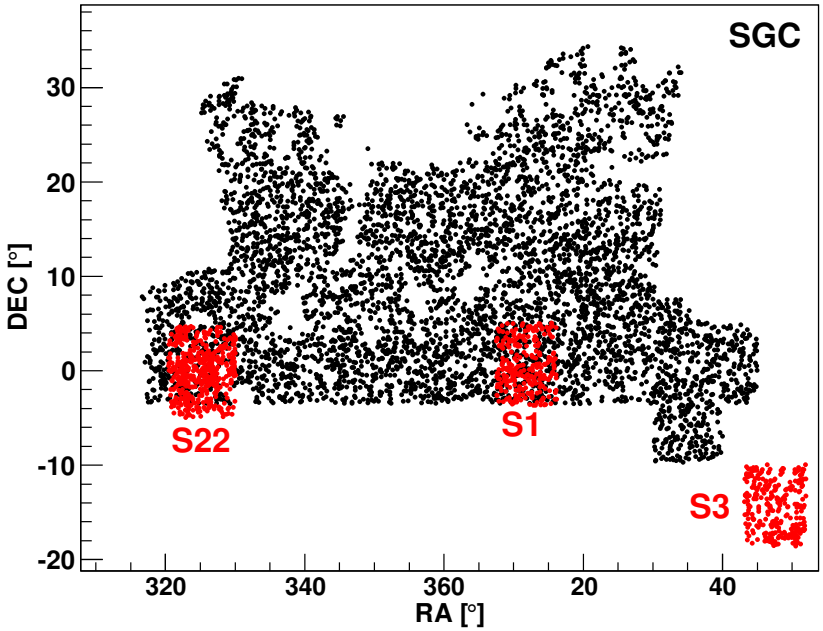
Next generation BAO (DESI)



Patrick McDonald

About BOSS and WiggleZ





Beutler et al. (2015)

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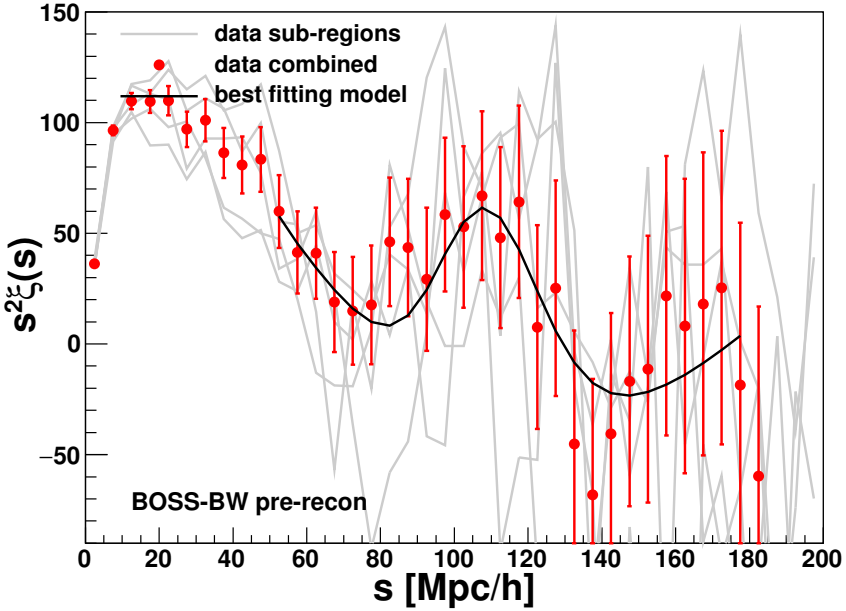
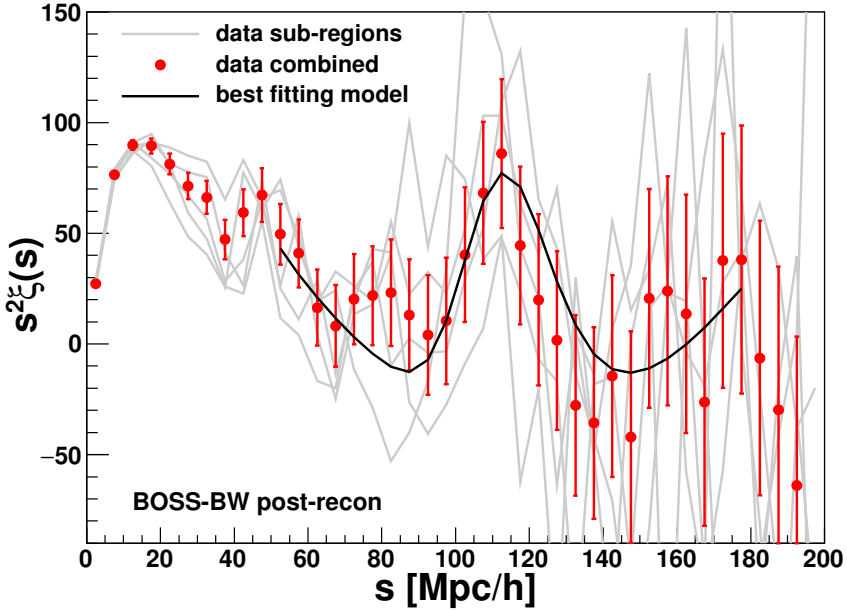
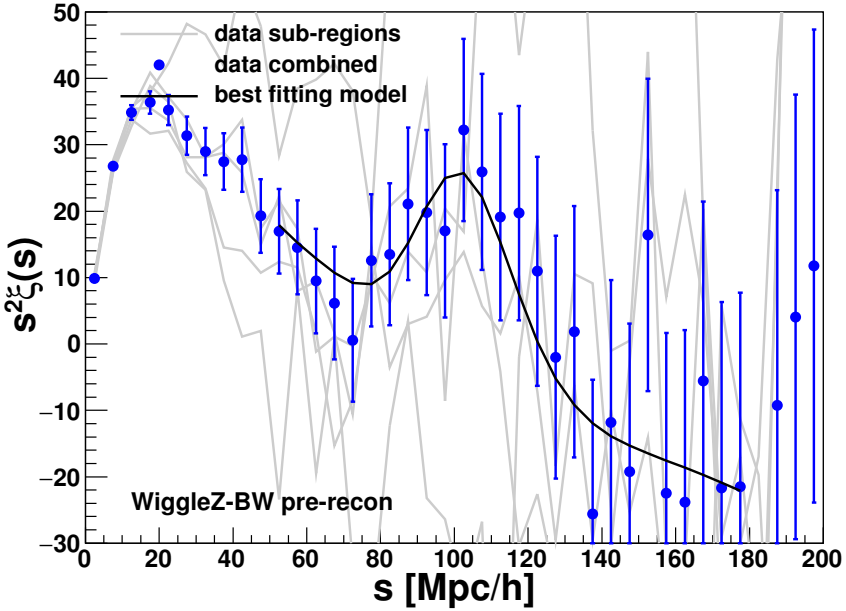


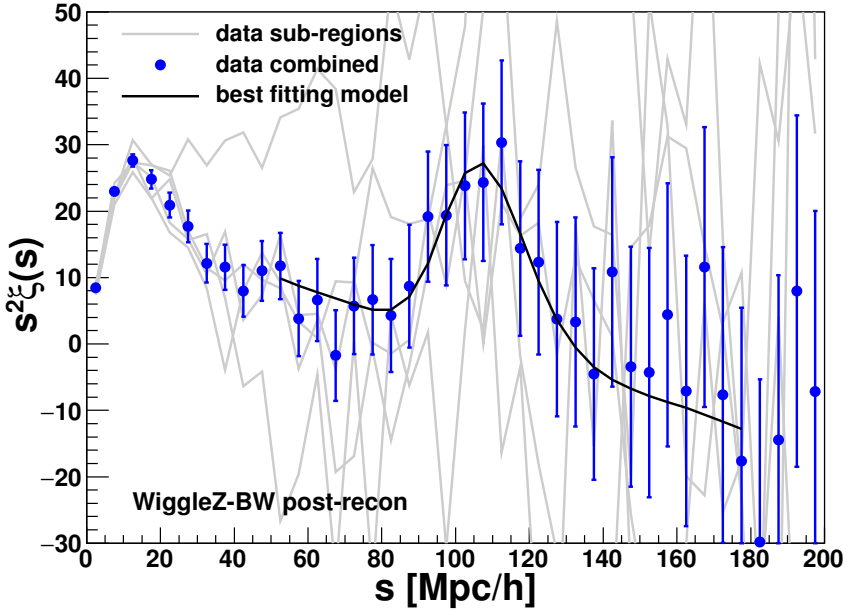


$$D_V/r_s = 2100^{+220}_{-170}\,Mpc \qquad \text{(pre-recon)}$$
$$D_V/r_s = 1970 \pm 45\,Mpc \qquad \text{(post-recon)}$$

Beutler et al. (2015)

About BOSS and WiggleZ

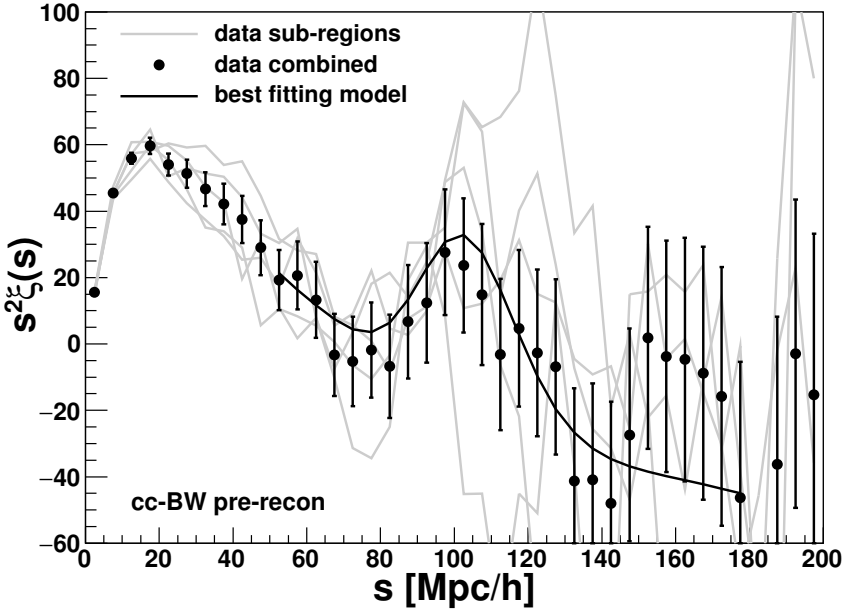


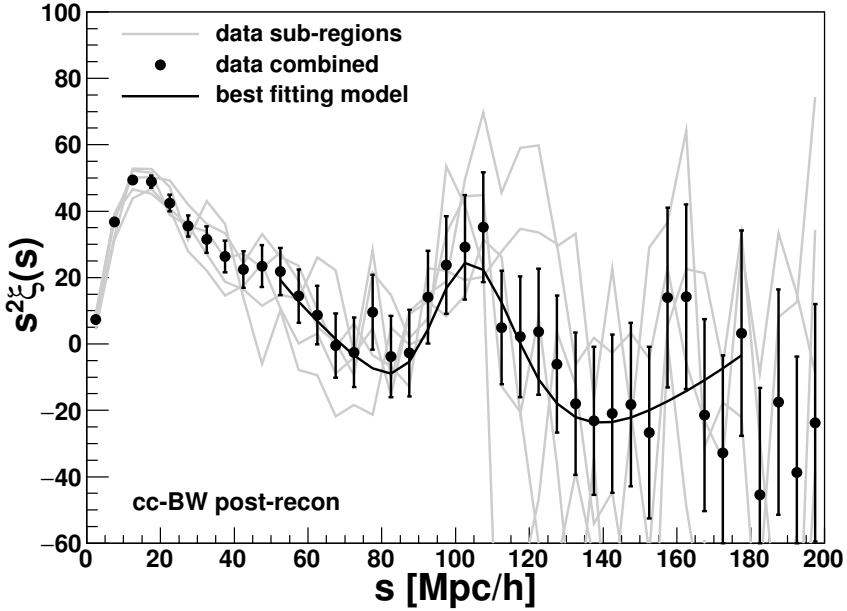


$$D_V/r_s = 2190^{+240}_{-300}\,Mpc \qquad \text{(pre-recon)}$$
$$D_V/r_s = 2100 \pm 200\,Mpc \qquad \text{(post-recon)}$$

Beutler et al. (2015)

About BOSS and WiggleZ





$$D_V/r_s = 2180^{+110}_{-140}\,Mpc \qquad \text{(pre-recon)}$$
$$D_V/r_s = 2132 \pm 65\,Mpc \qquad \text{(post-recon)}$$

Beutler et al. (2015)

About BOSS and WiggleZ

- We use mock catalogues to quantify the correlation between BOSS and WiggleZ leading to the following correlation matrix

$$R_{\mathrm{DR12}} = \begin{pmatrix} 1 & & & \\ 0.039 & 1 & & \\ 0.020 & 0.57 & 1 & \\ 0.014 & 0.39 & 0.51 & 1 \end{pmatrix}$$

  see Cuesta et al. (2015), Beutler et al. (2015)
- This allows to combined BOSS and WiggleZ BAO constraints with the additional information from the cross-correlation function.

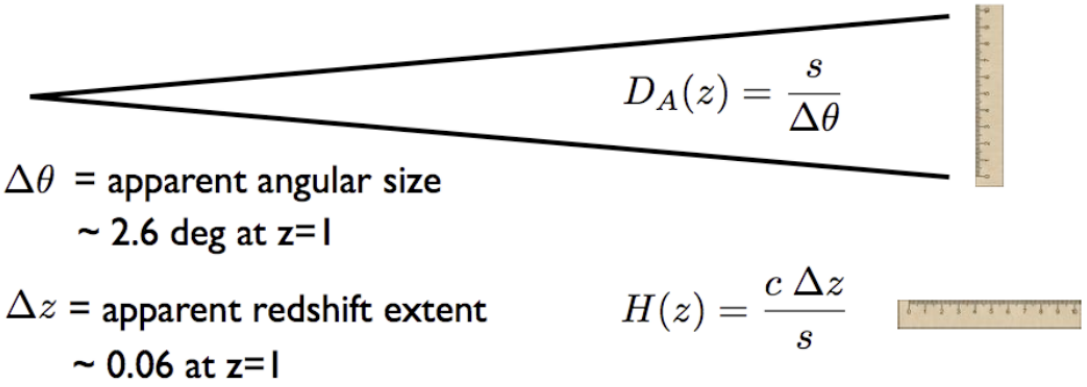
What is the Alcock-Paczynski effect?

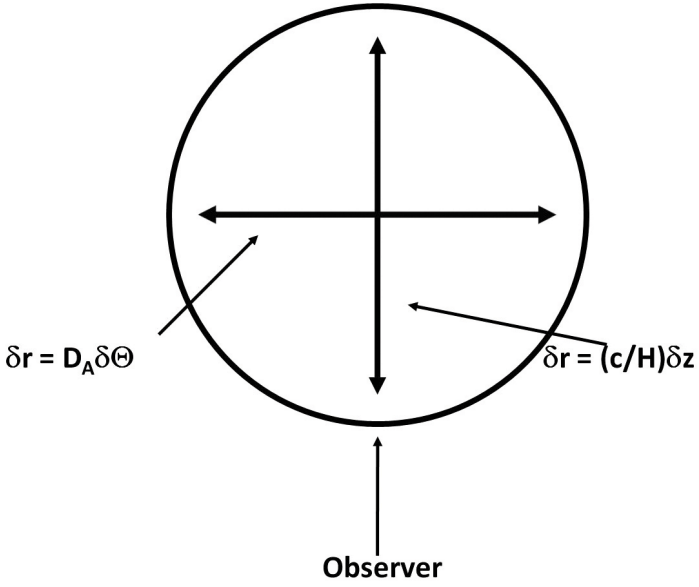
The BAO signal is expected to be isotropic. However, the fiducial cosmological model, which we used to transfer the observables into co-moving distances affects the radial distance differently than the angular distance.

The radial BAO signal is given by $H(z) = c\Delta z/s$.

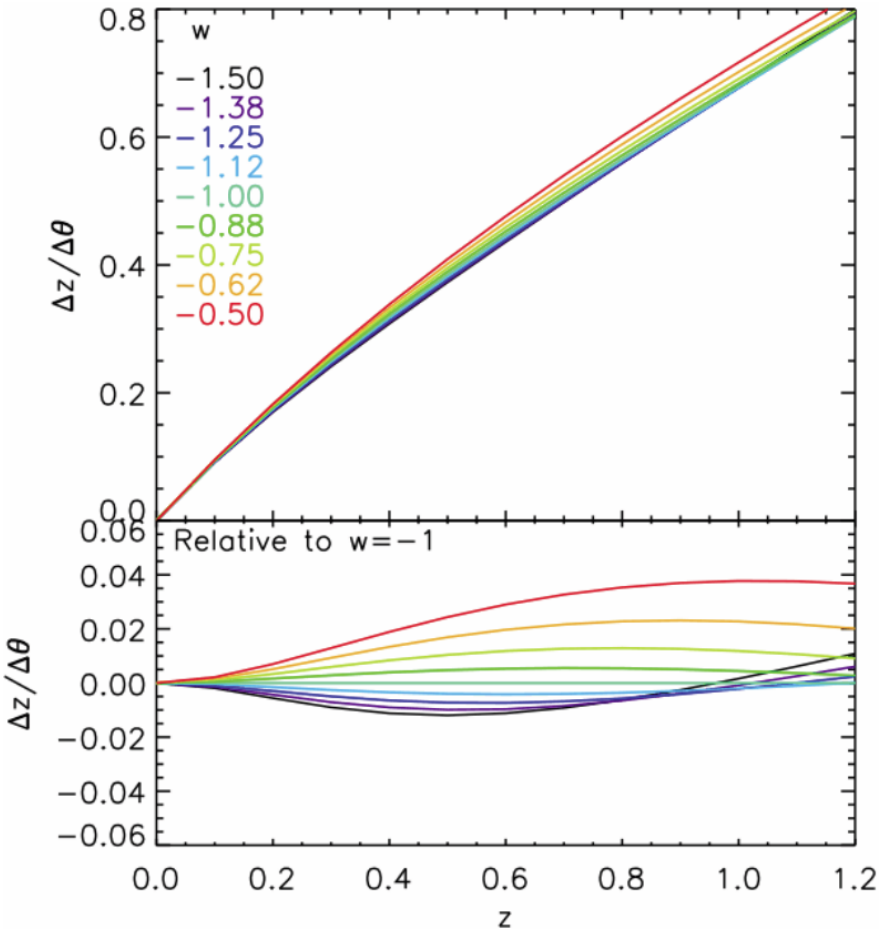
The tangential BAO signal is given by $D_A(z) = s/\Delta\theta$.

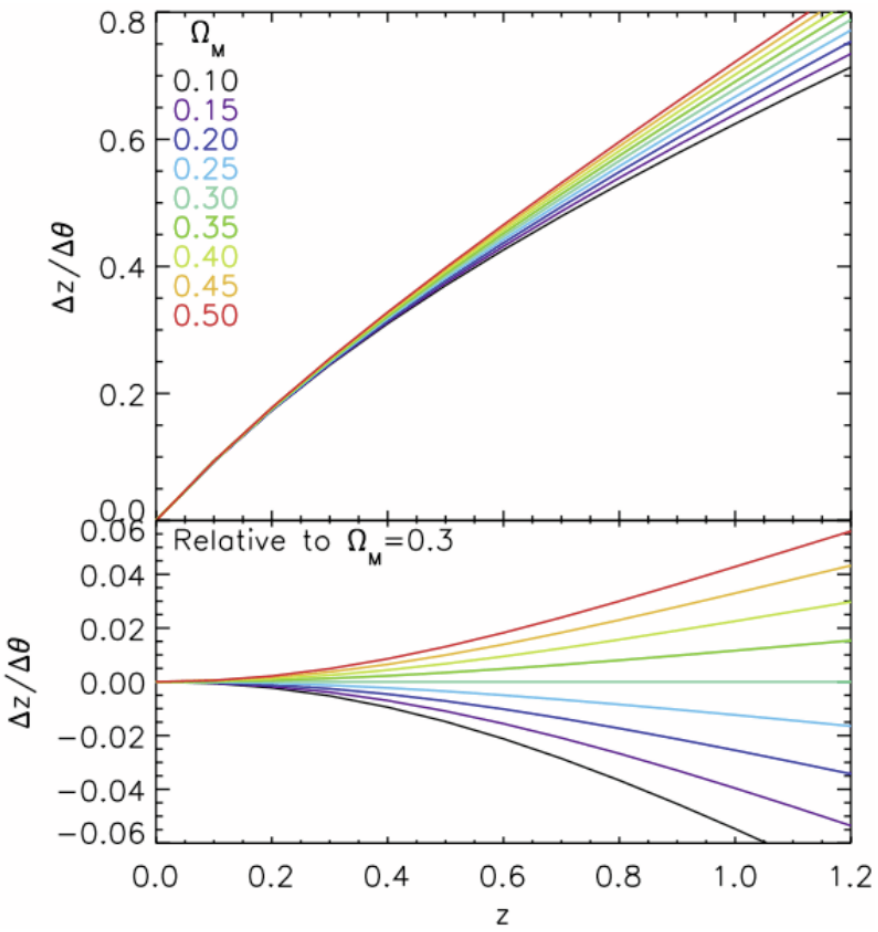
$\rightarrow \delta z/\delta\theta \sim D_A(z)H(z) \sim F_{\mathrm{AP}}$





What is the Alcock-Paczynski effect?





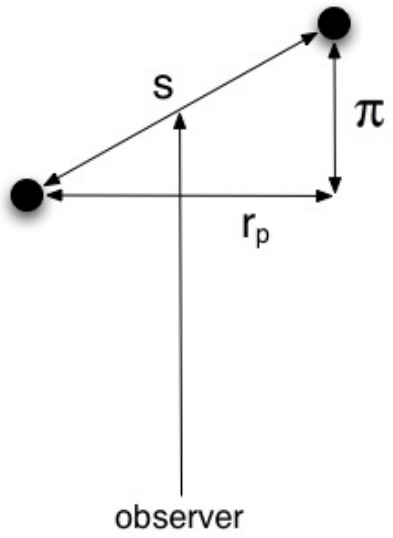
$$\Omega_\Lambda/(1+z)^{1+w}$$

$$H(z) = H_0\left[\Omega_m/(1+z)^{-3} + \Omega_{\mathrm{DE}}/(1+z)^{-3(1+w)}\right]^{1/2}.$$

What are redshift space distortions?

The redshift of a galaxy has two velocity components which we can't distinguish

$$\vec{s} = \vec{r}\left(1 + \frac{u(\vec{r})}{r}\right).$$



The effect is proportional to the growth rate

$$\frac{f(z)}{b_1} = \frac{\Omega_m^{0.55}(z)}{b_1}$$

f = growth rate, b_1 = linear bias, $\Omega_m = \frac{\rho_m}{\rho_0}$

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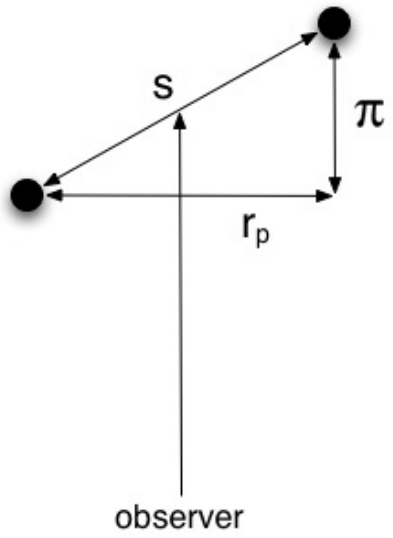

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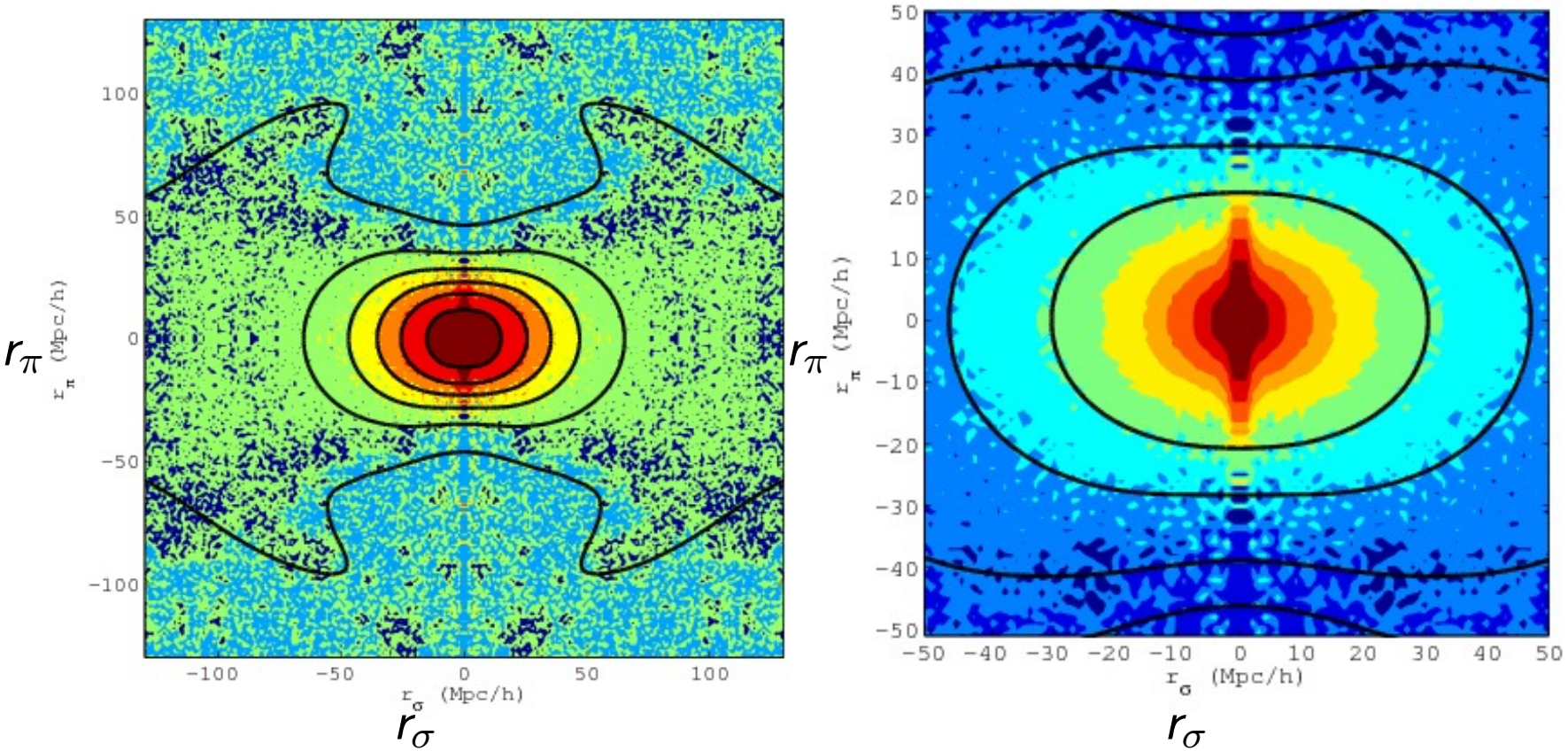
$$\frac{f(z)}{b_1} = \frac{\Omega_m^{0.55}(z)}{b_1}$$

f = growth rate, b_1 = linear bias, $\Omega_m = \frac{\rho_m}{\rho_0}$

The matter clustering is normalized by the r.m.s. mass fluctuation amplitude in spheres of $8\,\mathrm{Mpc}/h$ (σ_8). Since we only measure the galaxy clustering we are sensitive to $b_1\sigma_8$ and therefore our observable is

$$b_1\sigma_8 \times \frac{f(z)}{b_1} = f(z)\sigma_8$$

What are redshift space distortions?

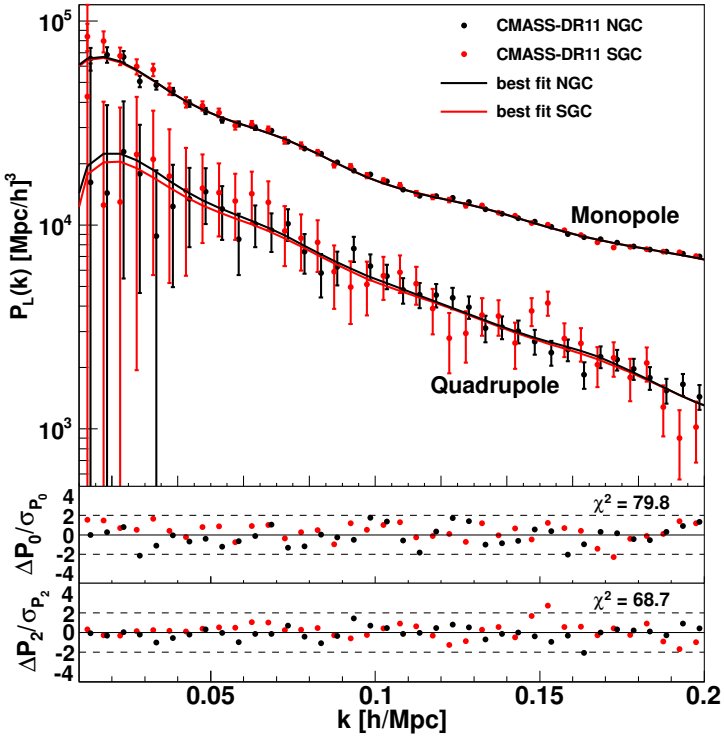


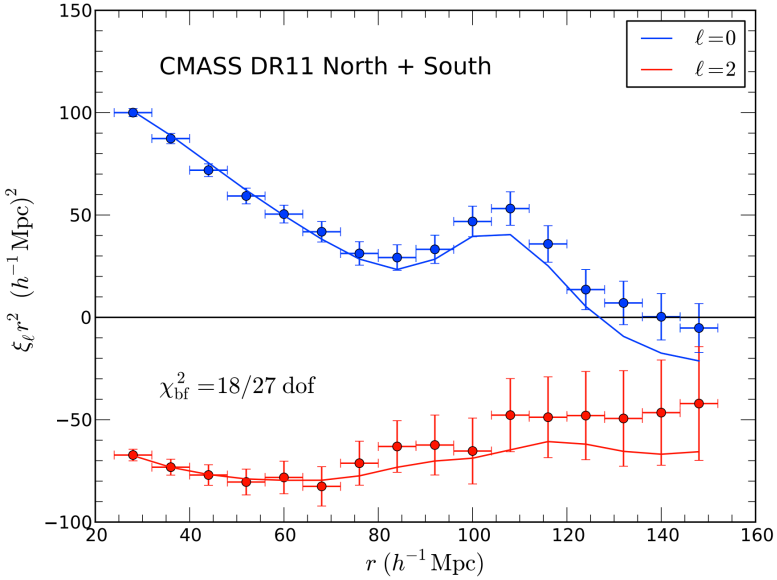
Reid et al. (2012)

2D clustering

$$P_\ell(k) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\; P(k,\mu)\mathcal{L}_\ell(\mu)$$

$$\xi_\ell(r) = \frac{2\ell+1}{2}\int_{-1}^{1} d\mu\; \xi(r,\mu)\mathcal{L}_\ell(\mu)$$





Beutler et al. (2014)

Samushia et al. (2014)

Power spectrum modeling

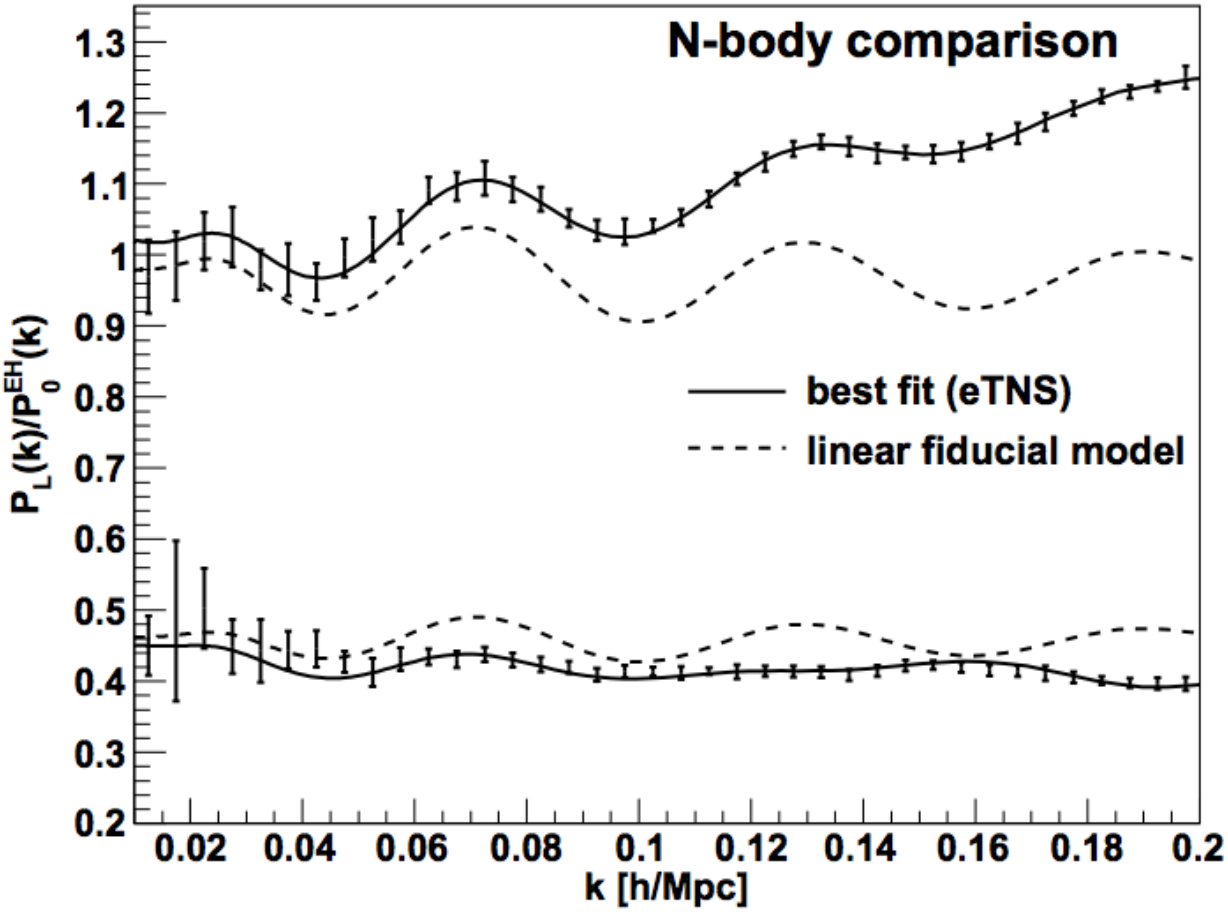
Our power spectrum model is based on renormalized perturbation theory (Taruya et al. 2011, McDonald & Roy 2009)

$$
\begin{aligned}
P_{\mathrm{g}}(k,\mu) = \exp\left\{-(fk\mu\sigma_v)^2\right\} \big[& P_{\mathrm{g},\delta\delta}(k) \\
& + 2f\mu^2 P_{\mathrm{g},\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) \\
& + b_1^3 A(k,\mu,\beta) + b_1^4 B(k,\mu,\beta)\big],
\end{aligned}
$$

with

$$
\begin{aligned}
P_{\mathrm{g},\delta\delta}(k) &= b_1^2 P_{\delta\delta}(k) + 2b_2 b_1 P_{b2,\delta}(k) + 2b_{s2} b_1 P_{bs2,\delta}(k) \\
&\quad + 2b_{3\mathrm{nl}} b_1 \sigma_3^2(k) P_{\mathrm{m}}^{\mathrm{L}}(k) + b_2^2 P_{b22}(k) \\
&\quad + 2b_2 b_{s2} P_{b2s2}(k) + b_{s2}^2 P_{bs22}(k) + N, \\
P_{\mathrm{g},\delta\theta}(k) &= b_1 P_{\delta\theta}(k) + b_2 P_{b2,\theta}(k) + b_{s2} P_{bs2,\theta}(k) \\
&\quad + b_{3\mathrm{nl}} \sigma_3^2(k) P_{\mathrm{m}}^{\mathrm{lin}}(k),
\end{aligned}
$$

Clustering measurements – power spectrum



Beutler et al. (2014)

Clustering measurements – power spectrum

- Since the survey window multiplies the configuration density field, it results in a convolution in Fourier-space.
- To account for the window function effect we can deconvolve the data or convolve the model.
- The convolution integral is

$$P^{\mathrm{conv}}(\vec{k}) = \int d\vec{k}' P^{\mathrm{true}}(\vec{k}')|W(\vec{k}-\vec{k}')|^2 - \frac{|W(\vec{k})|^2}{|W(0)|^2} \int d\vec{k}' P^{\mathrm{true}}(\vec{k}')|W(\vec{k}')|^2$$

- A straight forward calculation of this integral would have the complexity $\mathcal{O}(N^2_{\mathrm{modes}})$. But if the window function is compact, this can be simplified considerably.

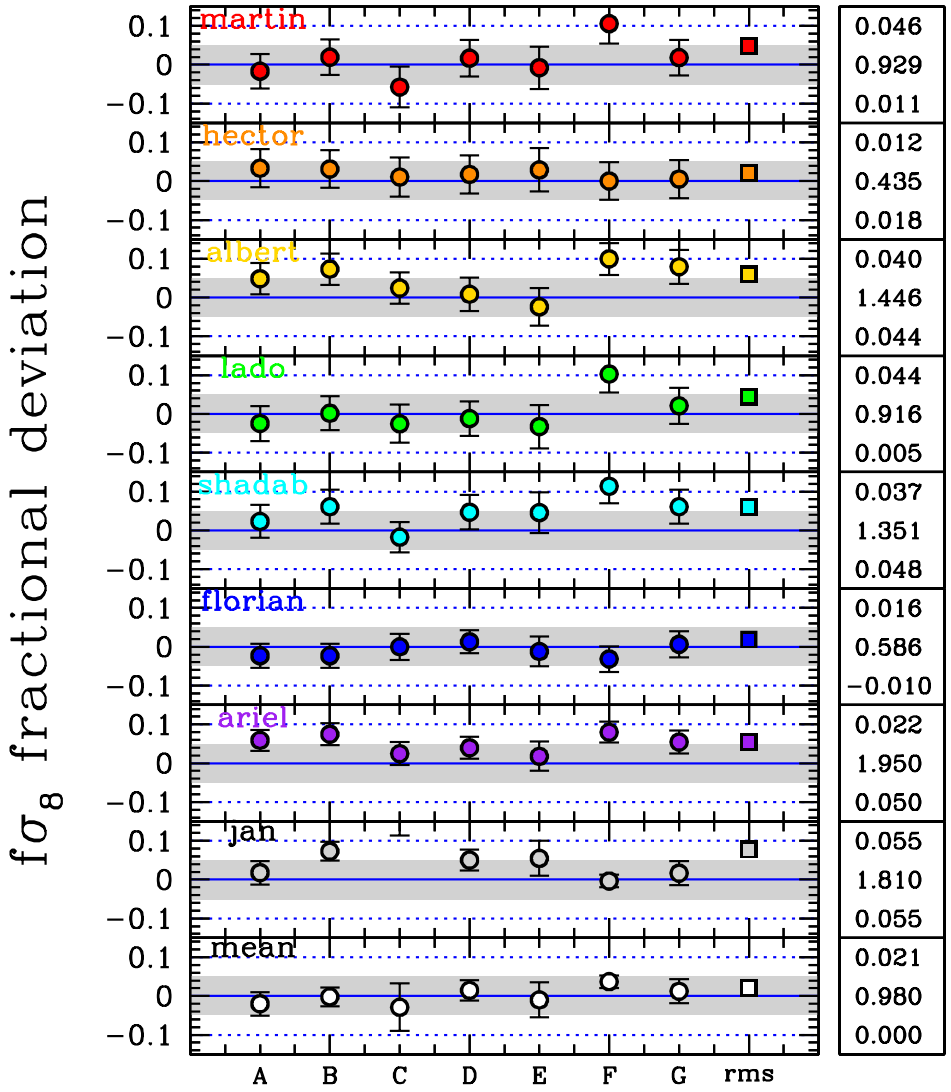
Clustering measurements – power spectrum

- We can express the window function convolution in terms of the power spectrum multipoles as:

$$P_\ell^{\rm conv}(k) = 2\pi \int dk' k'^2 \sum_L P_L^{\rm true}(k') |W(k,k')|^2_{\ell L}$$
$$- 2\pi \frac{|W(k)|^2_\ell}{|W(0)|^2_0} \int dk' k'^2 \sum_L P_L^{\rm true}(k') |W(k')|^2_L \frac{2}{2L+1}$$

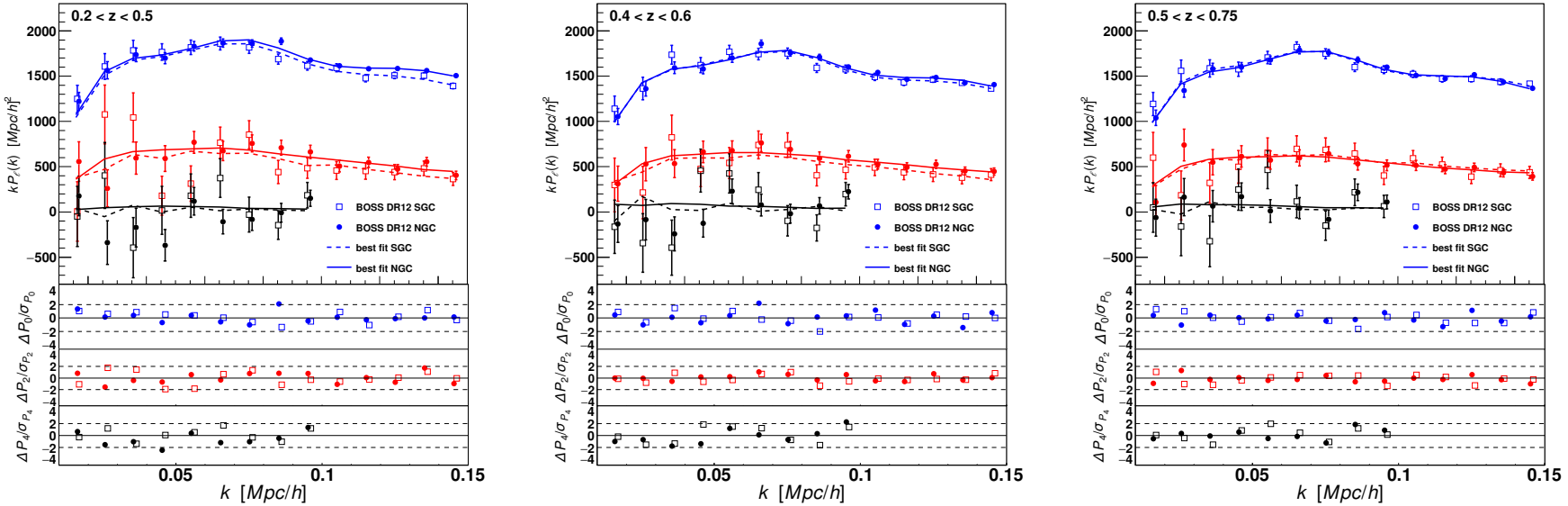
- The equation above only contains the mode amplitude $|\vec{k}|$ instead of the mode vector.
- The integral constraint comes from the fact that we assumed that the mean density of the survey is equal to the mean density of the Universe. Sample variance tells us that this is wrong...
- Therefore our measured power spectrum has the condition $P(k \to 0) = 0$ by design.
- The window function couples the $k = 0$ mode with larger modes, depending on the width of the window function.

Clustering measurements – blind mock challenge



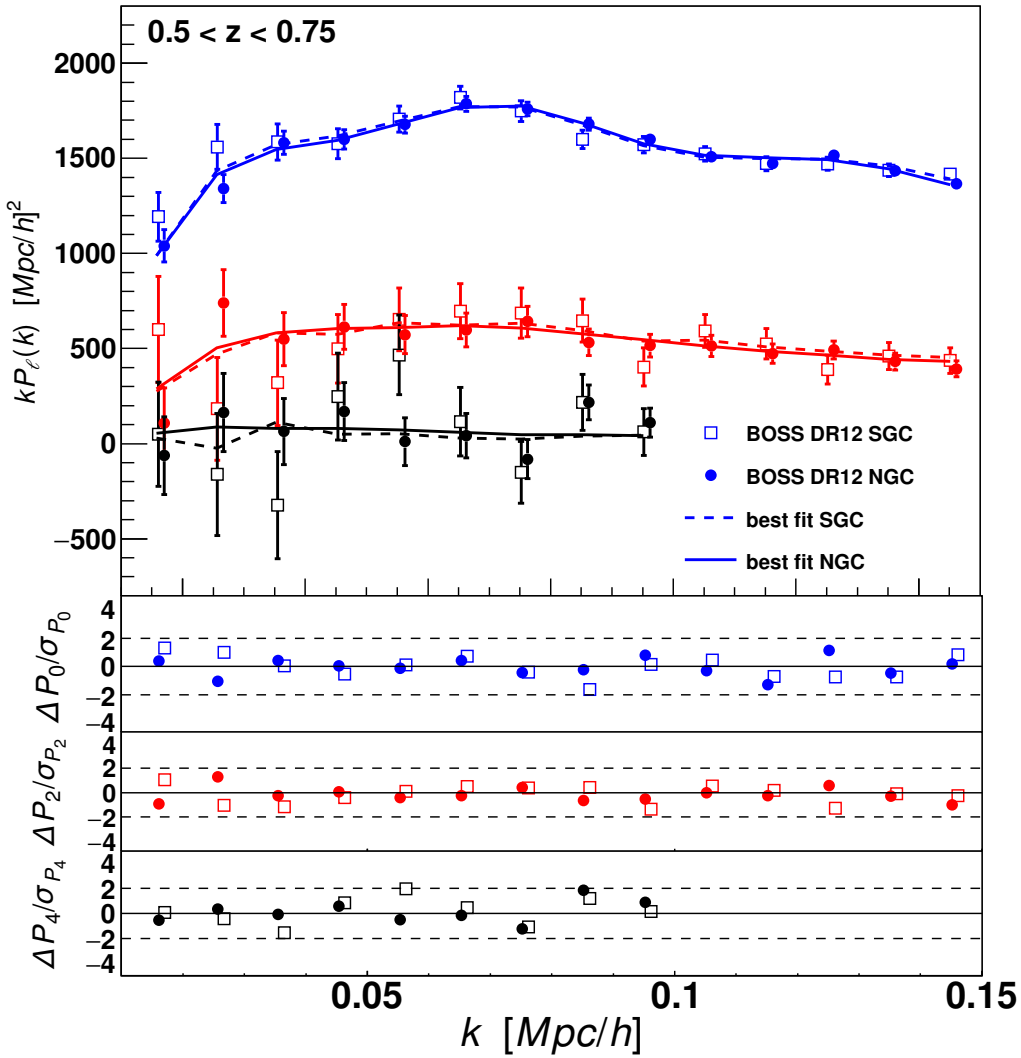
Tinker et al. (in prep.)

Power spectrum measurement (preliminary)



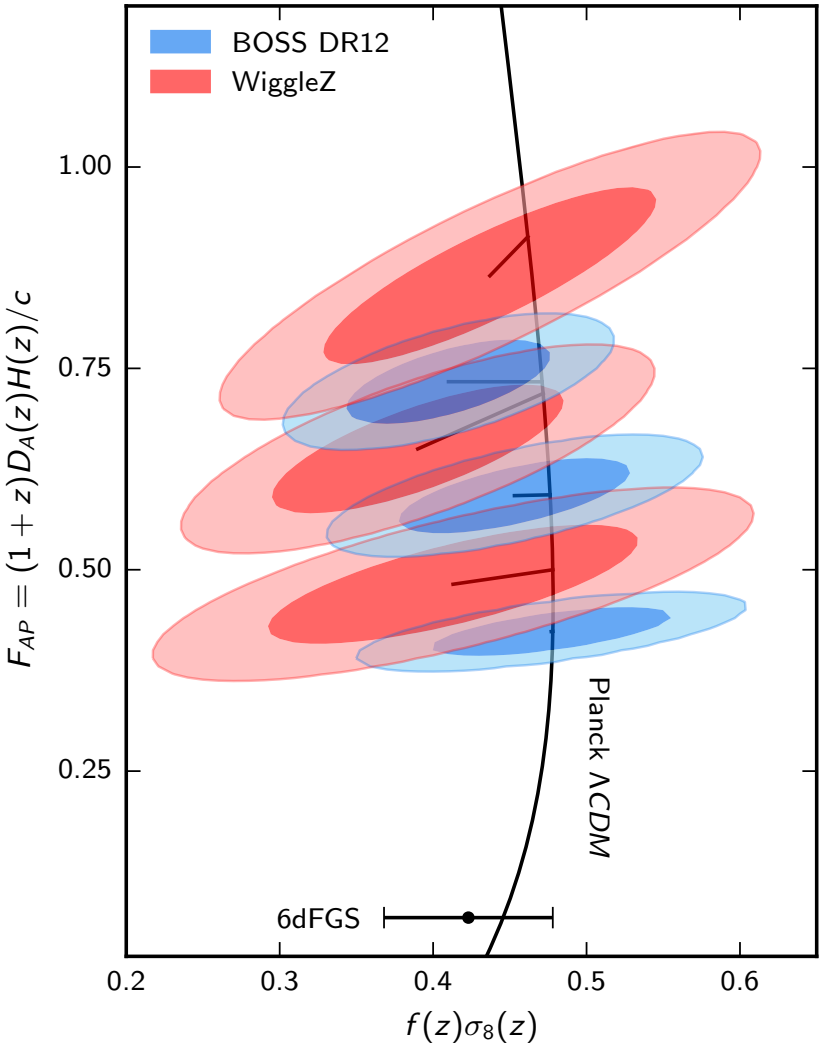
Beutler et al. (in prep.)

Power spectrum measurement (preliminary)



Beutler et al. (in prep.)

Growth of structure constraints (preliminary)



Beutler et al. (in prep.)

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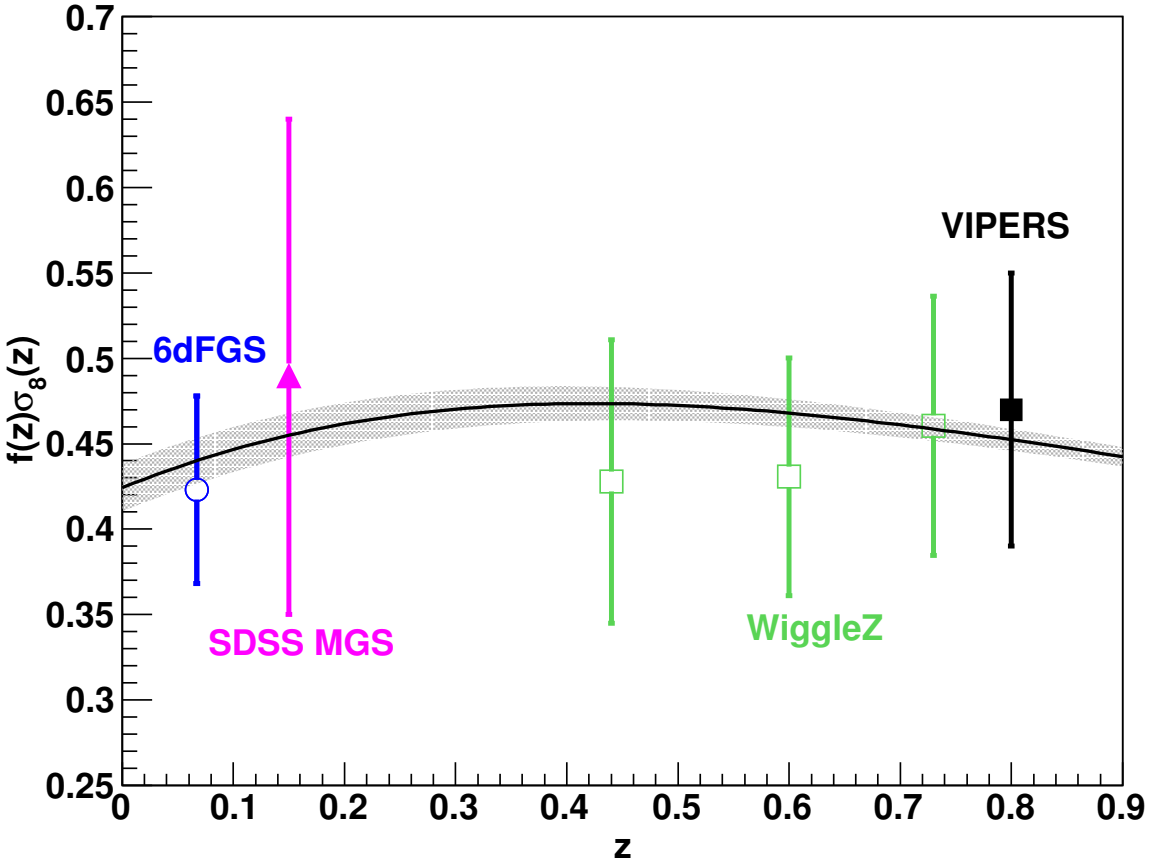
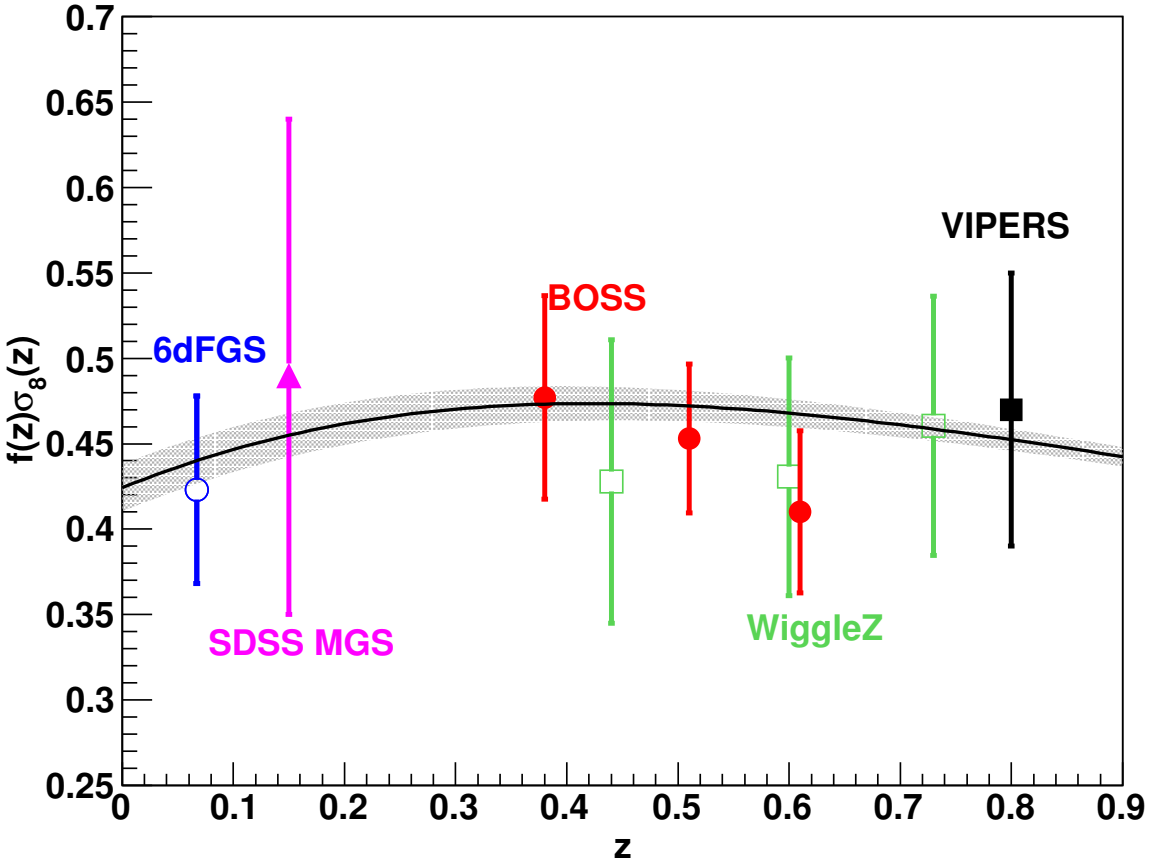


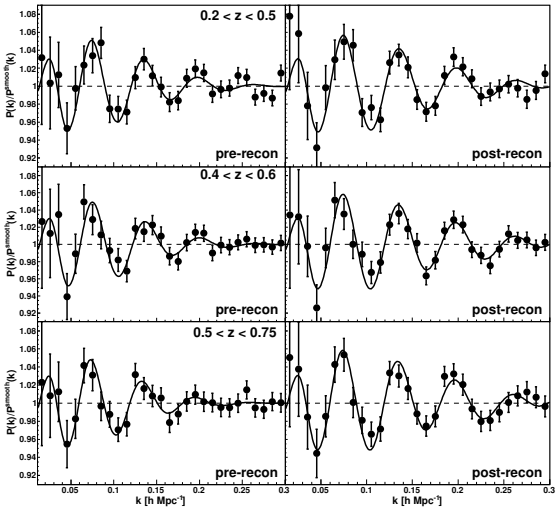
$$f(z) = \frac{\partial \ln D(a)}{\partial \ln a}$$

Growth of structure constraints (preliminary)



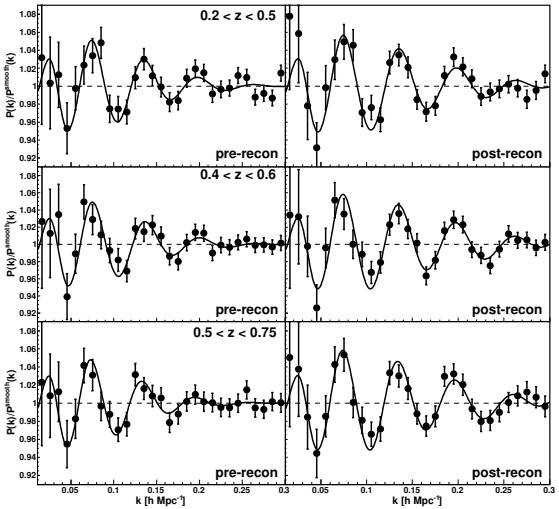
$$f(z) = \frac{\partial \ln D(a)}{\partial \ln a}$$

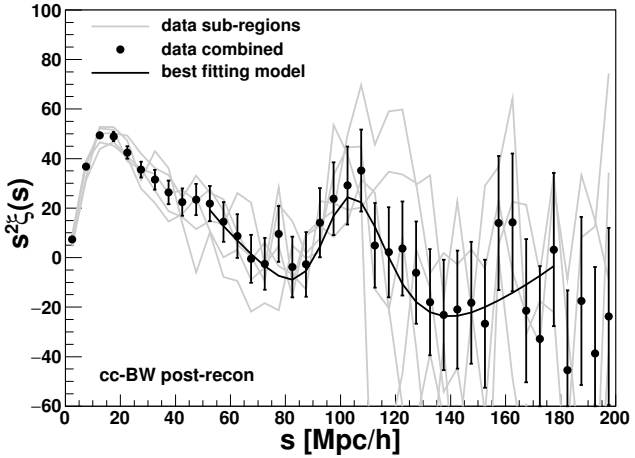
Summary



1. In BOSS we were able to measure the BAO scale in two independent redshift bins ($z = 0.38$ and $z = 0.61$) with an error of 1%, representing the best BAO scale measurements to date.

Summary





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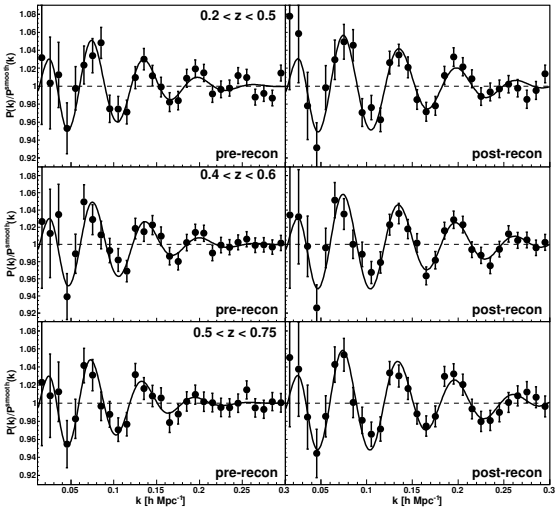
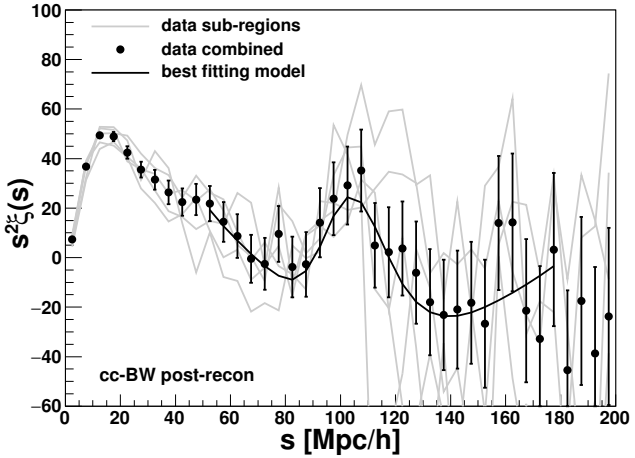
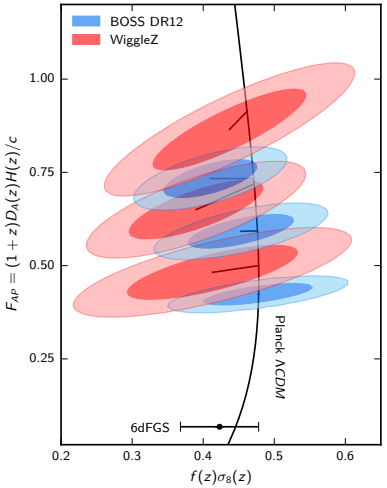
2. We detected the BAO signal in the cross-correlation function of BOSS and WiggleZ leading to a 3% distance constraint.

Summary







1. In BOSS we were able to measure the BAO scale in two independent redshift bins ($z = 0.38$ and $z = 0.61$) with an error of 1%, representing the best BAO scale measurements to date.
2. We detected the BAO signal in the cross-correlation function of BOSS and WiggleZ leading to a 3% distance constraint.
3. We achieved the best constraint on the growth of structure through $f\sigma_8$ with an uncertainty of 11% in two independent redshift bins.