Models for current LSS observations

Final BOSS data release (DR12)

Florian Beutler

May, 2016

Outline of the talk

- The **B**aryon **O**scillation **S**pectroscopic **S**urvey (BOSS)
- BAO and density field reconstruction
- Cosmological implications
- The Alcock-Paczynski and RSD effects
- Modeling the BOSS 2-point statistics
- Cosmological implications
- Future outlook

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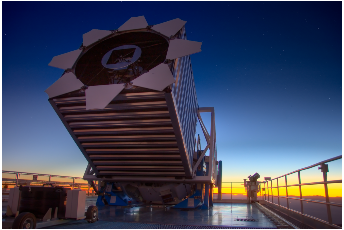
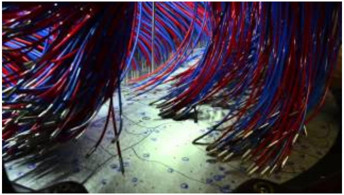
The BOSS galaxy survey

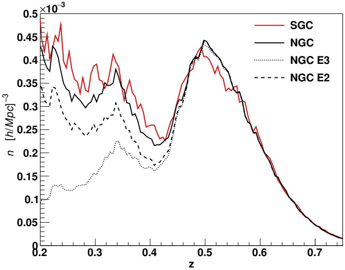
- Third version of the Sloan Digital Sky Survey (SDSS-III).
- Spectroscopic survey optimized for the measurement of Baryon Acoustic Oscillations (BAO).
- The galaxy sample includes 1 100 000 galaxy redshifts in the range $0.2 < z < 0.75$.
- The effective volume is $\sim 6\,\mathrm{Gpc}^3$.
- 1000 fibres/redshifts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

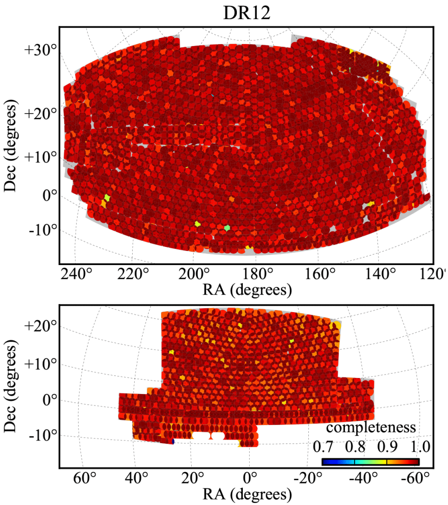




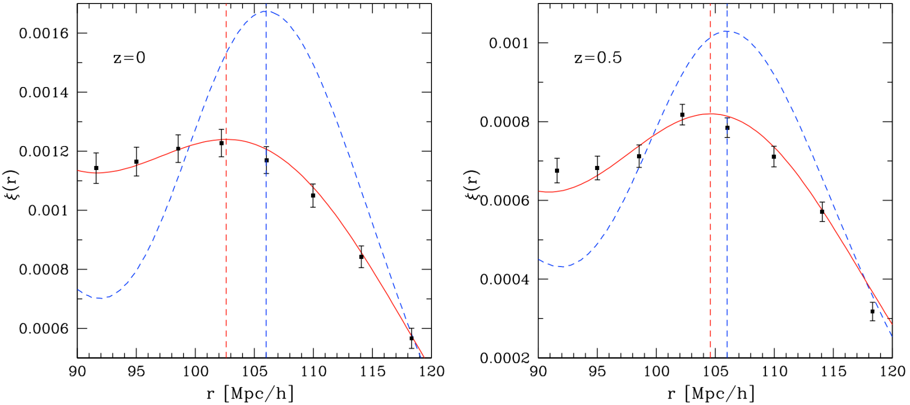
The BOSS galaxy survey

- 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).





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

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

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.

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

- Solve the Poisson eq. to obtain the gravitational potential

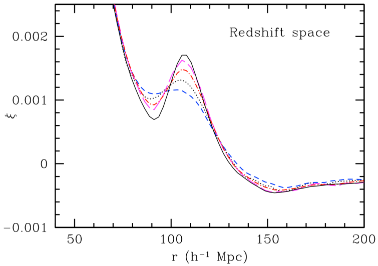
$$\nabla^2\phi = \delta$$

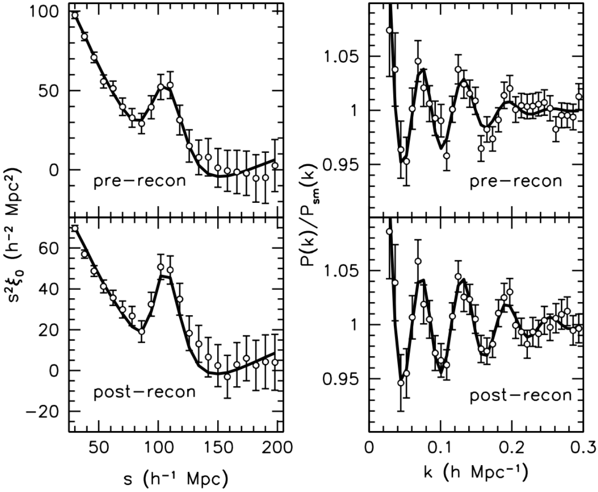
- The displacement (vector) field is given by

$$\Psi = \nabla\phi$$

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

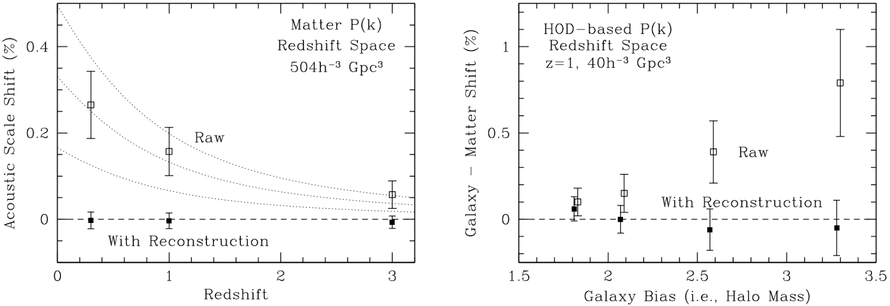
Eisenstein et al. (2007), Padmanabhan et al. (2012), Tassev & Zaldarriaga (2012)





Anderson et al. (2014)

- 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)

Fitting the BAO (isotropic)

- 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)

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

Fitting the BAO (anisotropic)

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

To get the multipoles we integrate over the angle to the line-of-sight

$$P_0(k) = \frac{1}{2}\int_{-1}^{1} P(k,\mu)\mathcal{L}_0 d\mu + A_0(k)$$

$$P_2(k) = \frac{1}{2}\int_{-1}^{1} P(k,\mu)\mathcal{L}_2 d\mu + A_2(k)$$

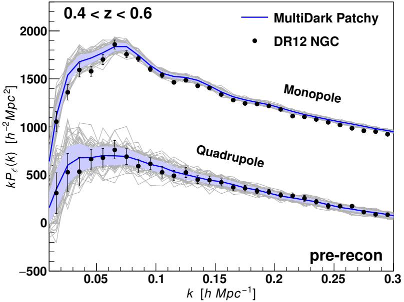
Marginalize to get P($\alpha_{\perp}$, $\alpha_{\parallel}$)

$$P_{\rm sm}(k,\mu) = B^2(1 + \beta\mu 2R)2P_{\rm sm,lin}(k)F_{\rm fog}(k,\mu,\Sigma_s)$$

BOSS mock catalogue

Within BOSS we produced mock catalogues with

- Previous serves like WiggleZ and 6dF used log-normal mock catalogues (Coles & Jones 1991).
- DR9: PThalo mock catalogues (Manera et al. 2012)
- DR10/11: Quick Particle Mesh mock catalogues (White, Tinker & Mcbridge 2014)
- DR12: Patchy mock catalogues (Kitaura et al. 2013)
- Many new methods have been suggested (EZMOCKS, PINOCCHIO, COLA etc.)



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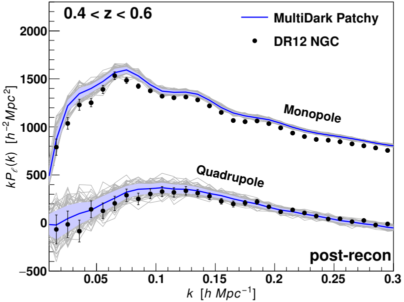
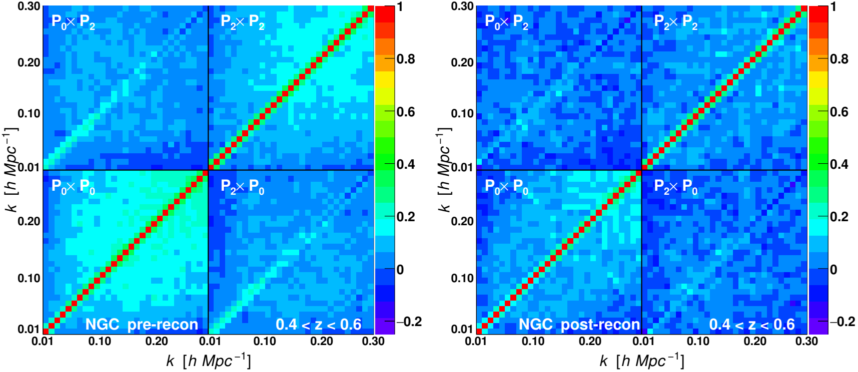
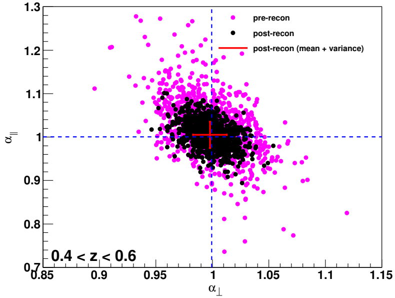
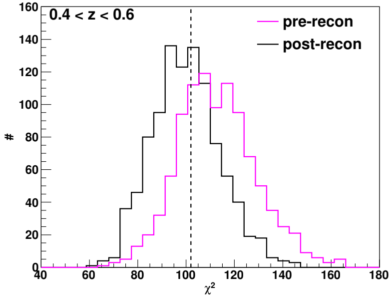


$$C_{ij} = \langle P_i P_j \rangle - \langle P_i \rangle \langle P_j \rangle$$

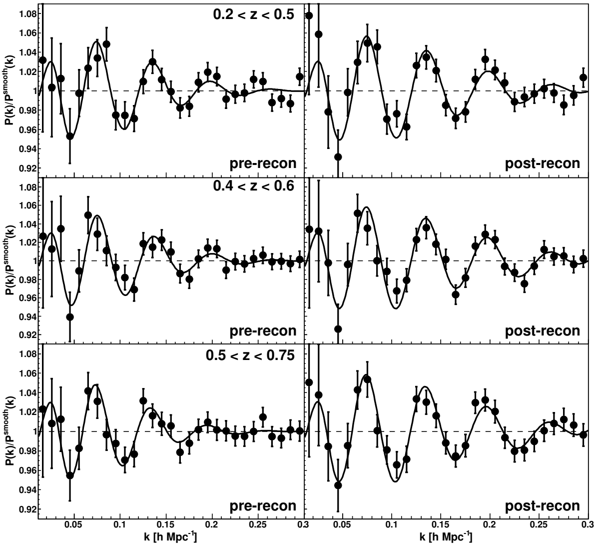


Results for fits to mocks



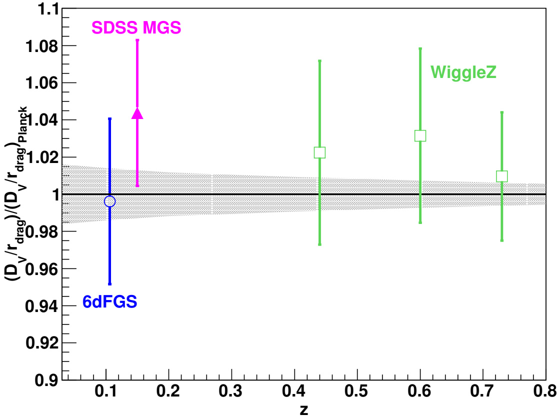


BOSS & BAO (preliminary)



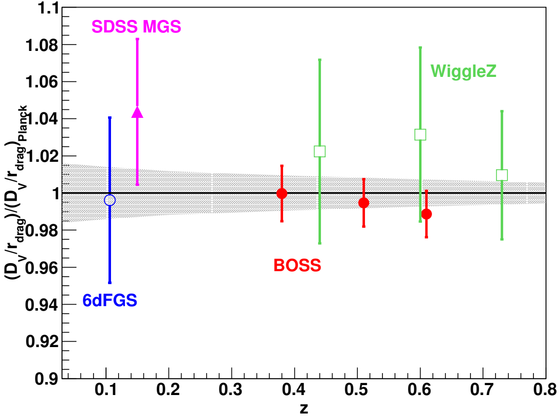
Beutler et al. (in prep.)

BAO constraints before BOSS (preliminary)



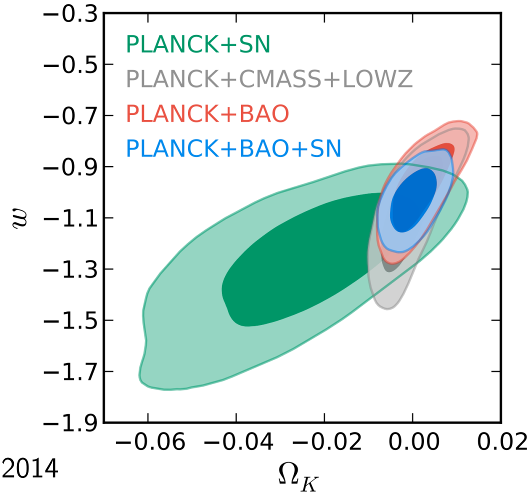
$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

BAO constraints including BOSS (preliminary)

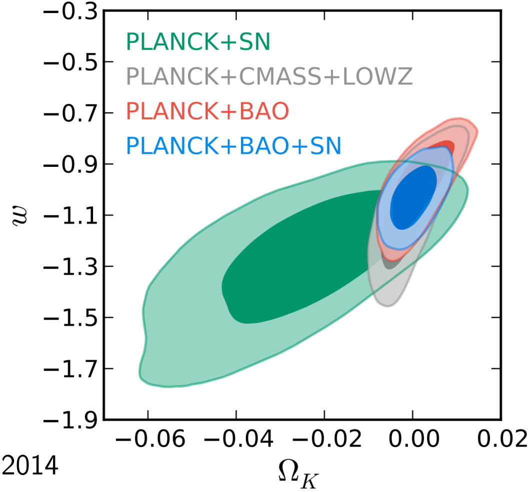


$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

Constraining cosmological parameters



Anderson et al 2014

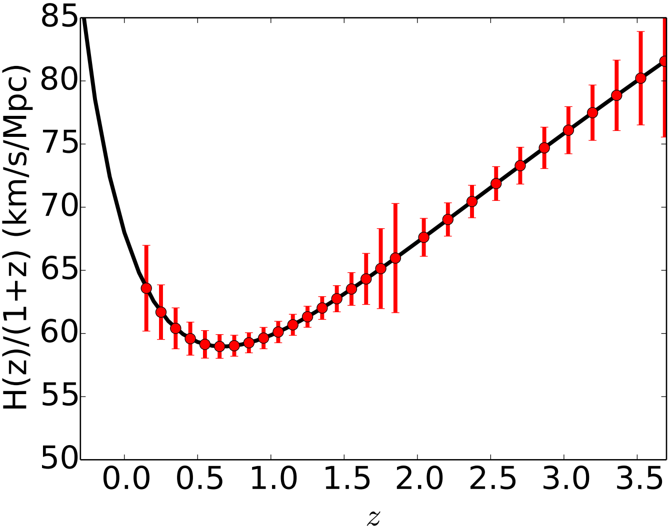


Anderson et al 2014

$$\Omega_k = 0.0002 \pm 0.0034$$

$$w = -1.03 \pm 0.07$$

Future outlook, DESI



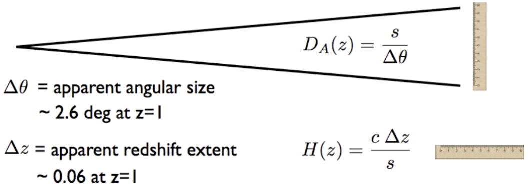
credit: Patrick McDonald

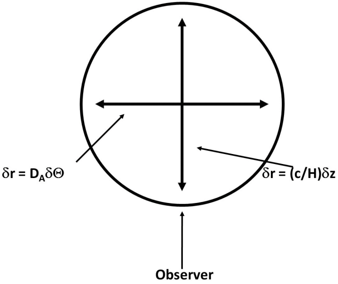
The BAO signal is expected to be isotropic. However, the fiducial cosmological model, which we used to transfer the observables into co-moving distances affects the radial distance differently than the angular distance.

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

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

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

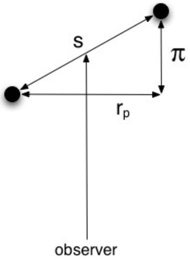




What are redshift space distortions?

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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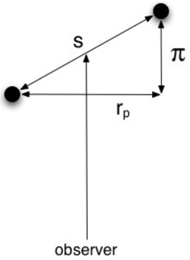

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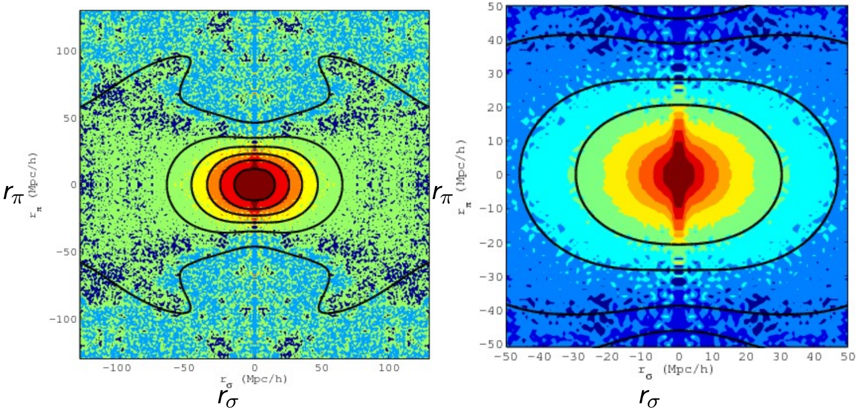
The matter clustering is normalized by the r.m.s. mass fluctuation amplitude in spheres of $8\,\mathrm{Mpc}/h$ (σ_8). Since we only measure the galaxy clustering we are sensitive to $b_1\sigma_8$ and therefore our observable is

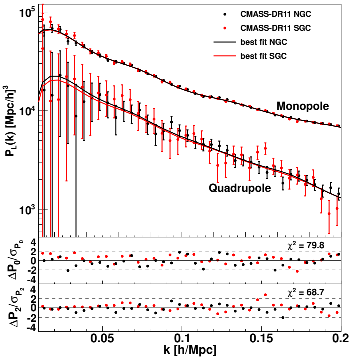
$$b_1\sigma_8 \times \frac{f(z)}{b_1} = f(z)\sigma_8$$

What are redshift space distortions?

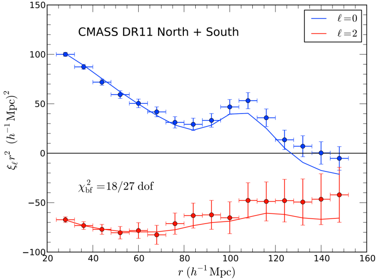


Reid et al. (2012)

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



Beutler et al. (2014)



Samushia et al. (2014)

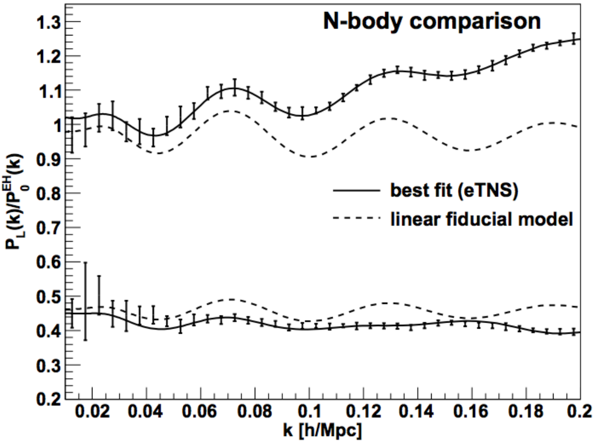
Power spectrum modeling

Our power spectrum model is based on renormalized perturbation theory (Taruya et al. 2011, McDonald & Roy 2009, Saito et al. 2014)

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

with

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



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

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

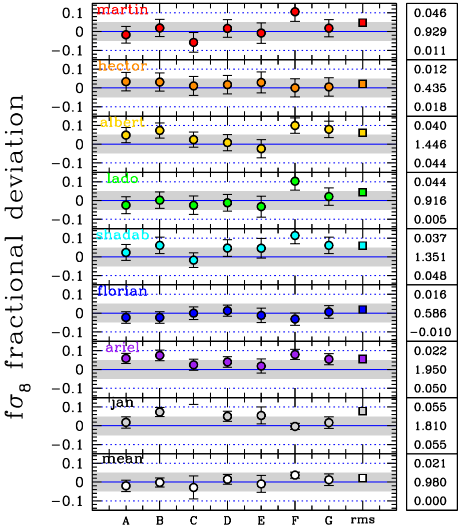
- A straight forward calculation of this integral would have the complexity $\mathcal{O}(N^2_{\rm modes})$. But if the window function is compact, this can be simplified considerably.

Clustering measurements – power spectrum

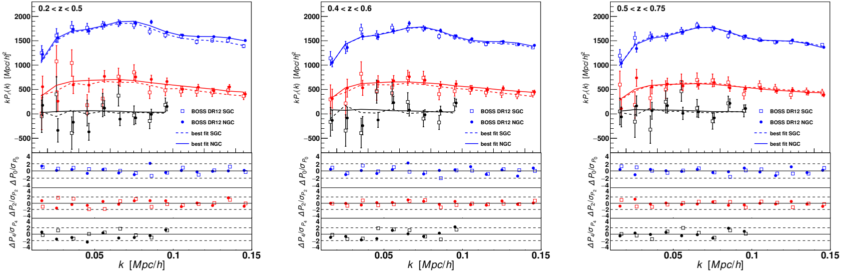
- We can express the window function convolution in terms of the power spectrum multipoles as:

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

- 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.

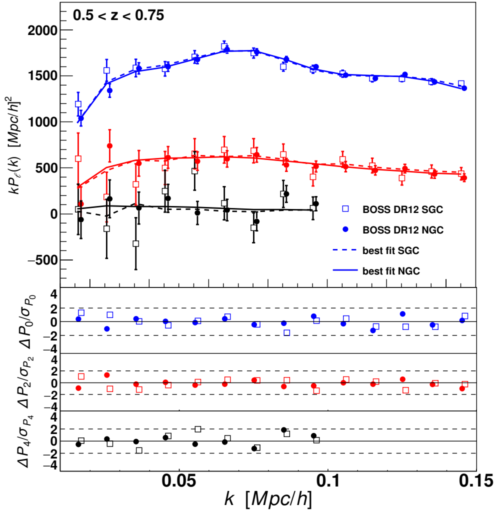


Tinker et al. (in prep.)



Beutler et al. (in prep.)

Power spectrum measurement (preliminary)



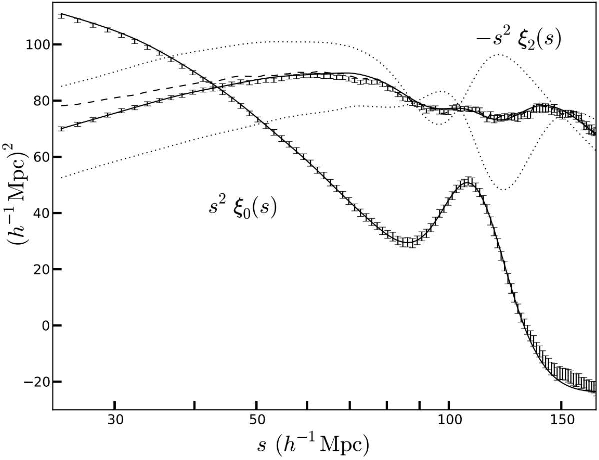
Beutler et al. (in prep.)

Streaming models combine (linear) theory with approximate descriptions for the random motion of galaxies within collapsed objects (e.g. Peacock, 1992).
In BOSS we also used the streaming model (see Reid & White 2011).
Convolution of a real-space correlation function template with the probability distribution function of the infall velocity of a galaxy pair along the line-of-sight.

$$1 + \xi^{\rm s}(s_{\|}, s_{\perp}) = \int \left[1 + \xi^{\rm r}(r_{\|}, r_{\perp})\right] P(s_{\|} - r_{\|}) dr_{\|}$$

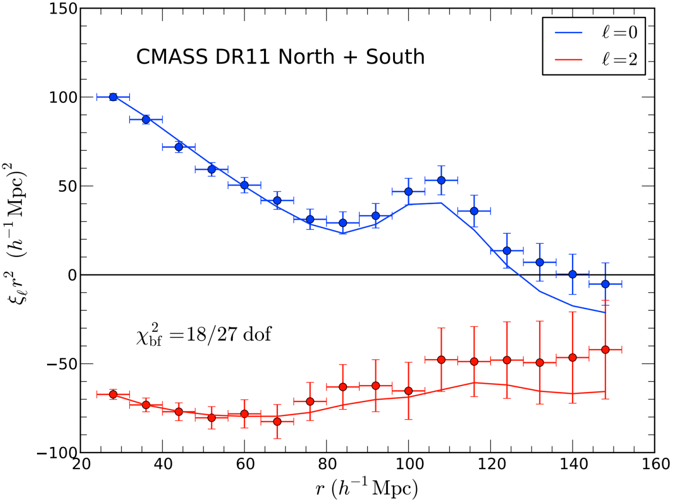
with

$$P(\Delta) = \frac{\exp\left(-\left[\Delta - \mu\nu_{\rm in}(r,\mu)\right]^2 / 2(\sigma^2_{\rm in}(r,\mu) + \sigma^2_{\rm FoG})\right)}{\sqrt{2\pi(\sigma^2_{\rm in}(r,\mu) + \sigma^2_{\rm FoG})}}$$



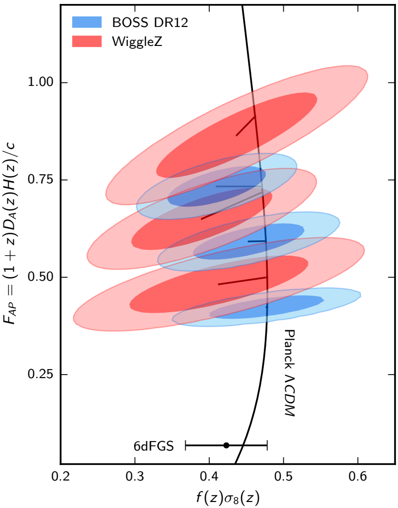
Reid et al. 2012

Correlation function modeling



Samushia et al. 2014

Growth of structure constraints (preliminary)



Beutler et al. (in prep.)

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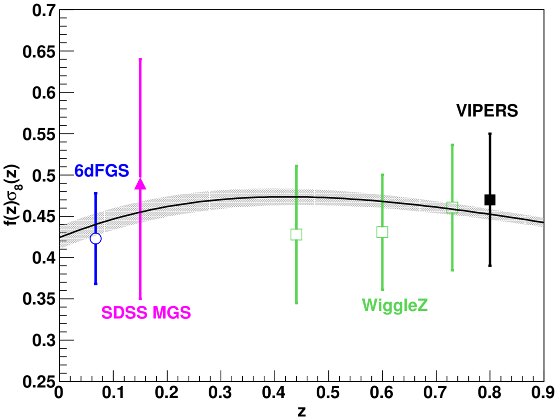
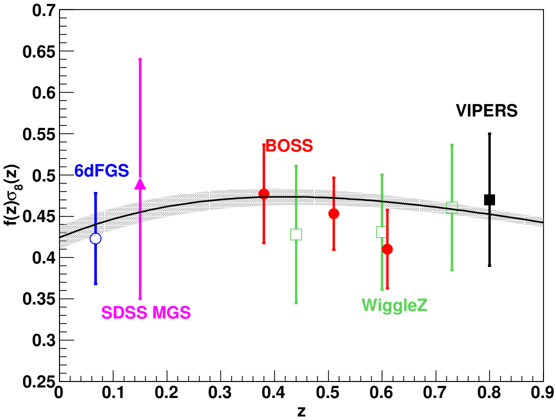


$$f(z) = \frac{\partial \ln D(a)}{\partial \ln a}$$

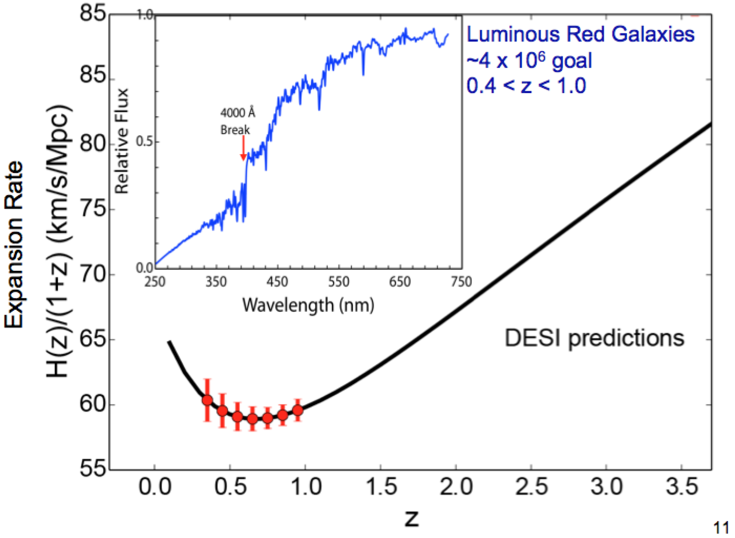
Growth of structure constraints (preliminary)



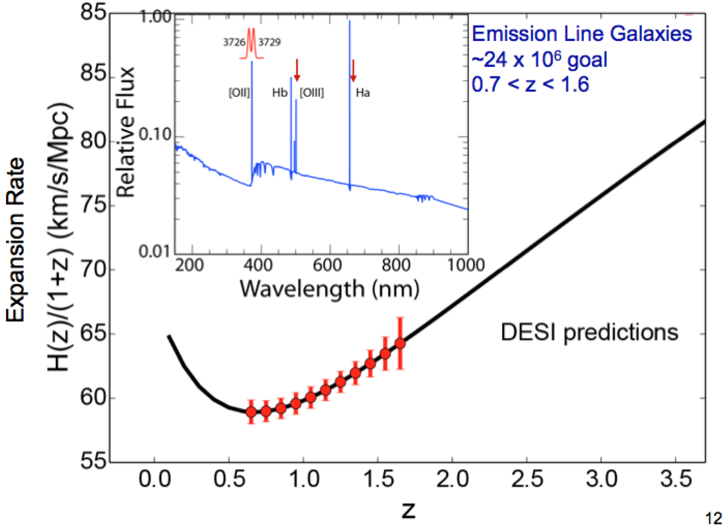
$$f(z) = \frac{\partial \ln D(a)}{\partial \ln a}$$

Future outlook, DESI and Euclid

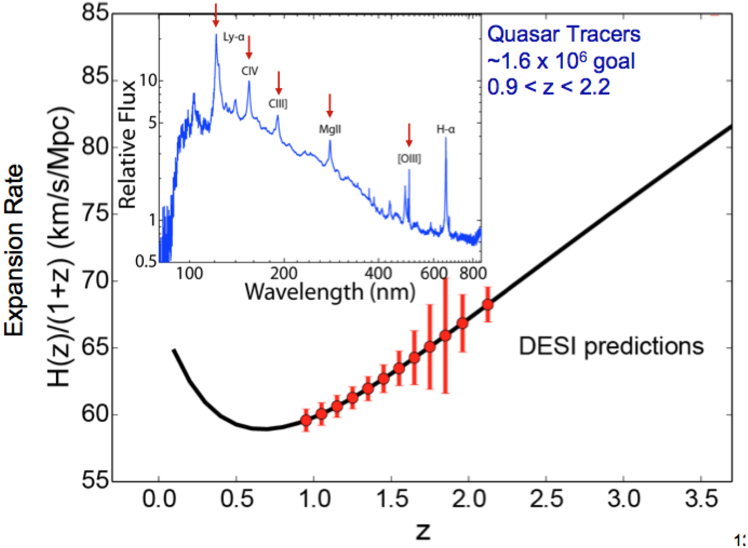
- An imaging (targeting) survey over 14 000 deg^2.
  - g-band to 24.0 mag
  - r-band to 23.6 mag
  - z-band to 23.0 mag
- A spectroscopic survey over 14 000 deg^2.
  - 4 million Luminous Red Galaxies
  - 23 million Emission Line Galaxies
  - 1.4 million quasars
  - 0.6 million quasars at $z > 2.2$ for Lyman-alpha-forest
- Covering a volume of $50h^{-3}\text{Gpc}^3$, compared to $6h^{-3}\text{Gpc}^3$ in BOSS.
- 5000 fibres compared to 1500 fibres in BOSS (automatic fibre positioner).

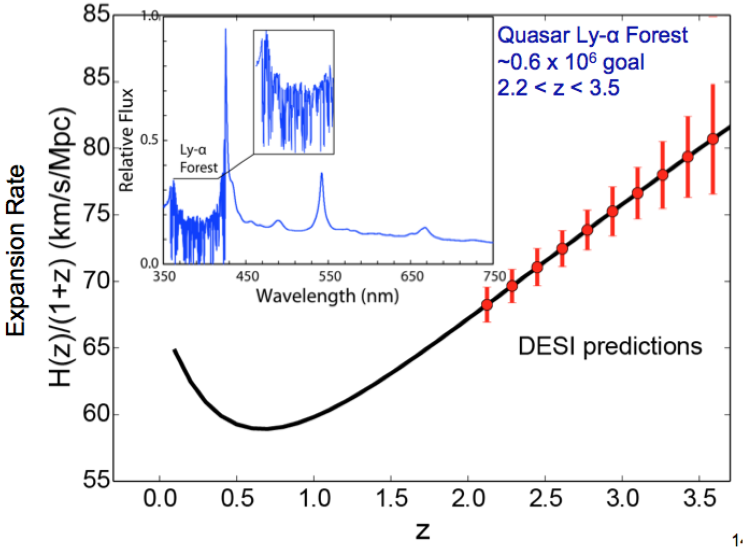

Expansion Rate
H(z)/(1+z) (km/s/Mpc)
85
85
80
75
70
65
60
55
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
z
Relative Flux
1.0
0.5
0.0
4000 Å
Break
250
350
450
550
650
750
Wavelength (nm)
Luminous Red Galaxies
~4 x 10^6 goal
0.4 < z < 1.0
DESI predictions
11

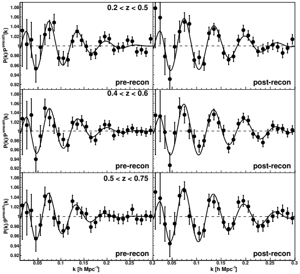
Future outlook, DESI and Euclid



Future outlook, DESI and Euclid

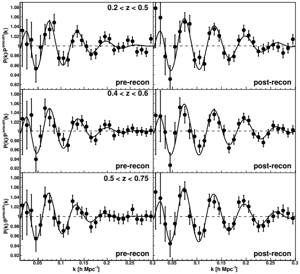


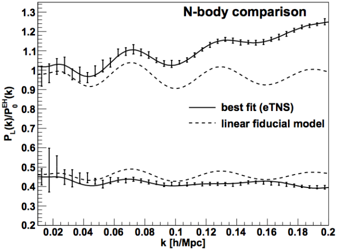

Quasar Ly-α Forest
~0.6 x 10⁶ goal
2.2 < z < 3.5
DESI predictions
Expansion Rate
H(z)/(1+z) (km/s/Mpc)
z
85
85
80
75
70
65
60
55
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Relative Flux
Wavelength (nm)
Ly-α
Forest
1.0
0.5
0.0
350
450
550
650
750



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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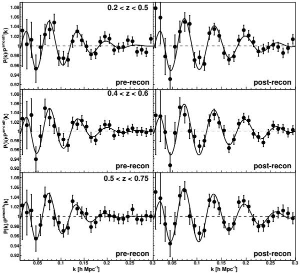
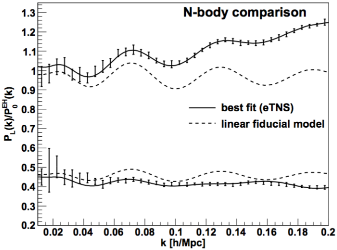
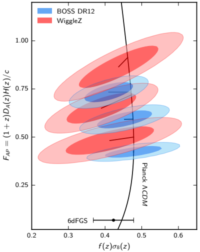
2. We use a PT based model as well as a streaming model to fit the two-point multipoles.







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 use a PT based model as well as a streaming model to fit the two-point multipoles.
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.