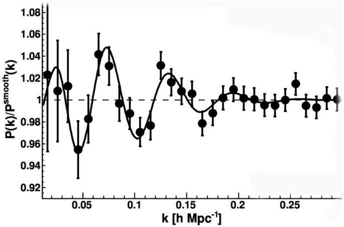
Cosmology from galaxy redshift surveys

Florian Beutler



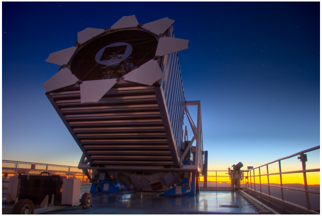
Royal Society University Research Fellow

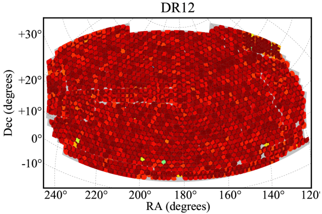
Outline of the talk

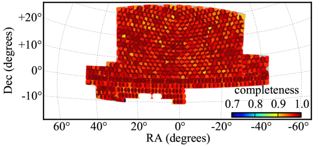
- BOSS DR12 BAO & RSD overview
- The relative velocity effect
- Neutrinos in the BAO phase

The BOSS galaxy survey

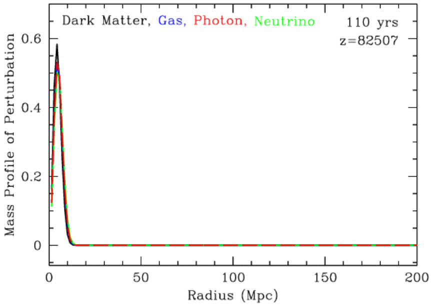
- Third version of the Sloan Digital Sky Survey (SDSS-III).
- Spectroscopic survey optimised for the measurement of Baryon Acoustic Oscillations (BAO).
- The galaxy sample includes 1 100 000 galaxy redshifts in the range $0.2 < z < 0.75$.
- The effective volume is $\sim 6\,\mathrm{Gpc}^3$.
- 1000 fibres/redshifts per pointing.
- The final data release (DR12) covers about $10\,000\ \mathrm{deg}^2$.
- SDSS now moved on to eBOSS.







Baryon Acoustic Oscillations



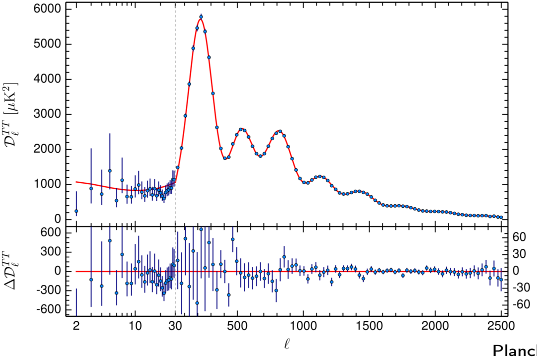
Baryon and photon perturbations in the radiation dominated era follow

$$\ddot{\delta}_{b\gamma} - c_s^2\nabla^2\delta_{b\gamma} = \nabla^2\Phi_+$$

with $\delta_{b\gamma} = A\cos(kr_s + \phi)$.

- Preferred distance scale between galaxies.
- Can be used as a standard ruler using the CMB calibration.
- Can be separated from the broadband signal.

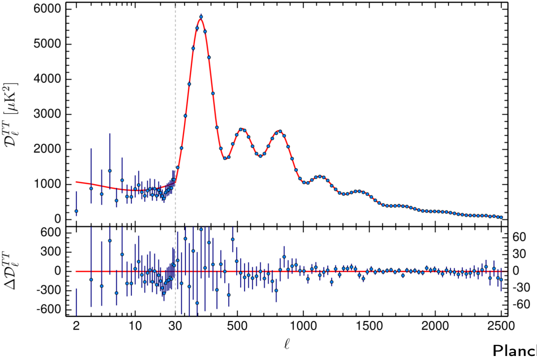
BAO in the photon temperature power spectrum



Planck collaboration

$$r_s(z_d) = 147.34 \pm 0.64\,\mathrm{Mpc} \quad (0.43\%)$$

BAO in the photon temperature power spectrum



Planck collaboration

$$r_s(z_d) = 147.34 \pm 0.64\,\mathrm{Mpc} \quad (0.43\%)$$

With galaxy surveys we measure $\Delta\theta = r_s/D_A(z)$ and $c\Delta z = H(z)r_s$.

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\gamma(1+z)^4 + \Omega_\Lambda}$$

$$D_A(z) \propto \int_0^z \frac{dz'}{H(z')}$$

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

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

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

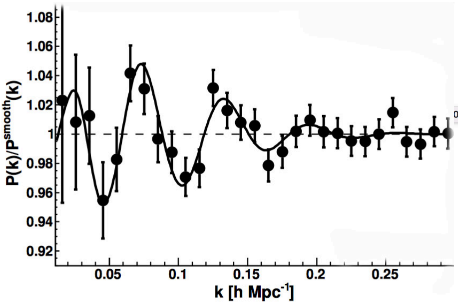
BAO in the two-point matter clustering

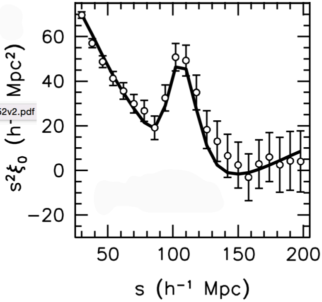
$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \overline{\rho}}{\overline{\rho}}$$

$$\xi(r) = \langle \delta(\vec{x} + \vec{r})\delta(\vec{x}) \rangle$$

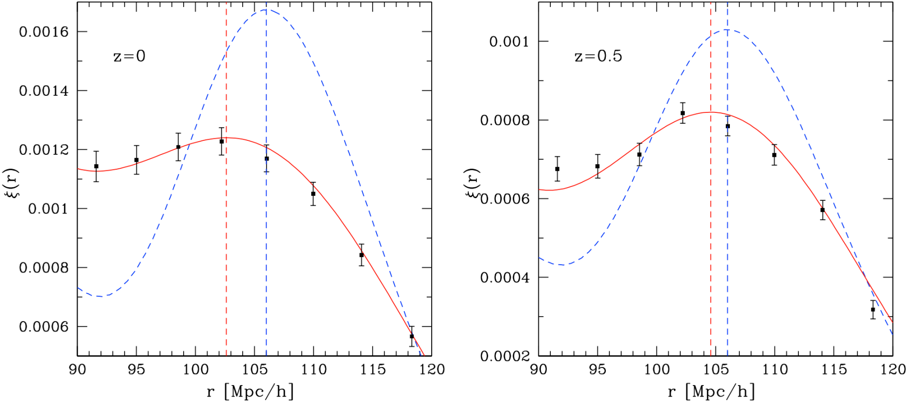
$$P(k) = \langle |\delta(\vec{k})|^2 \rangle$$

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





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

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

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

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

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

$$A(k) = a_1 k + a_2 + \frac{a_3}{k} + \frac{a_4}{k^2} + \frac{a_5}{k^3}$$
$$P^{\rm fit}(k) = B^2 P^{\rm sm,lin}(k/\alpha) + A(k)$$

- Marginalize to get $\mathcal{L}(\alpha)$.

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

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

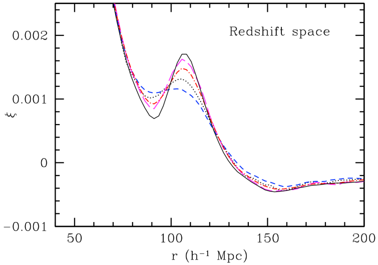
- Solve the Poisson eq. to obtain the gravitational potential

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

- The displacement (vector) field is given by

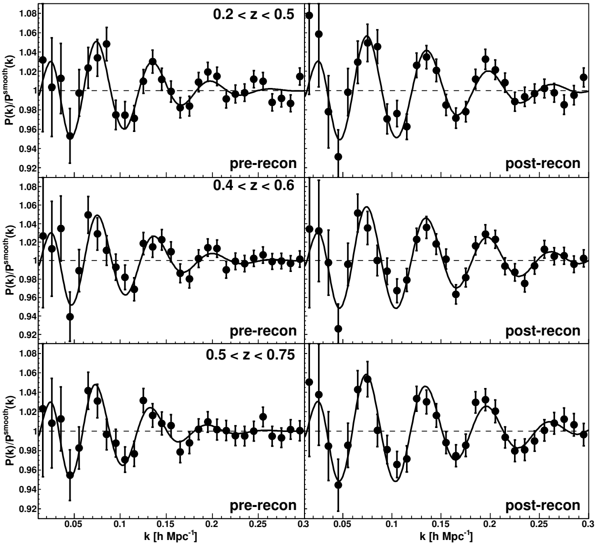
$$\Psi = \nabla\phi$$

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

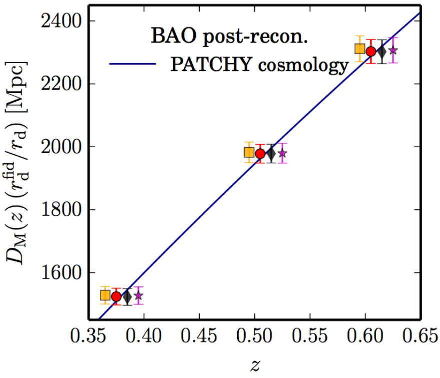


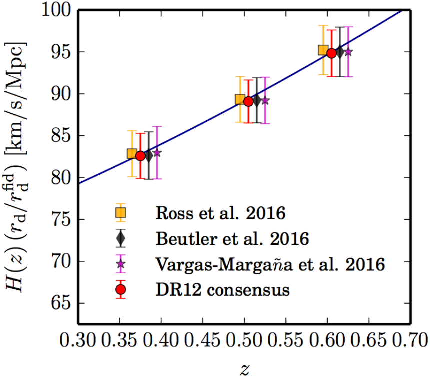
Eisenstein et al. (2007), Padmanabhan et al. (2012)

BOSS & BAO



Beutler et al. (2017)



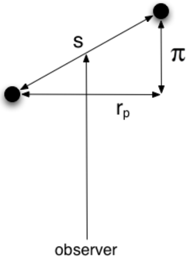


Alam et al. (2016)

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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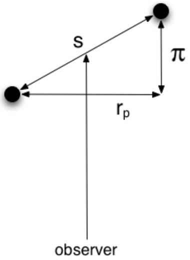

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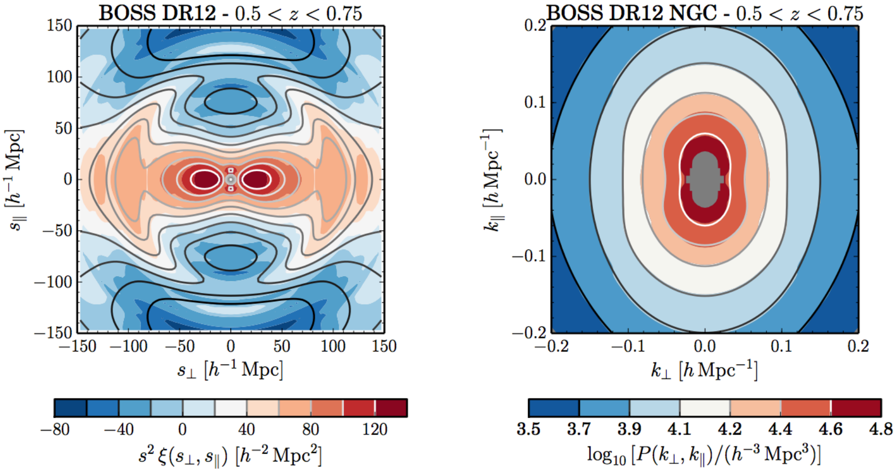
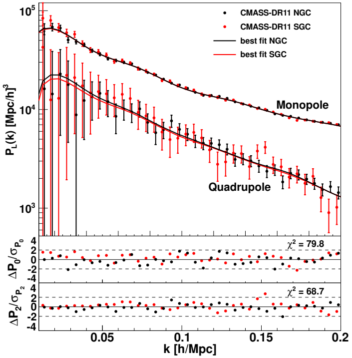
The matter clustering is normalized by the r.m.s. mass fluctuation amplitude in spheres of $8\,\mathrm{Mpc}/h$ (σ_8). Since we only measure the galaxy clustering we are sensitive to $b_1\sigma_8$ and therefore our observable is

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

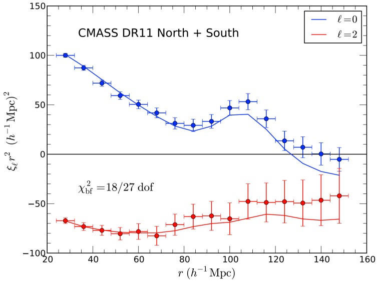


Alam et al. (2017)

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



Beutler et al. (2014)



Samushia et al. (2014)

Power spectrum modelling

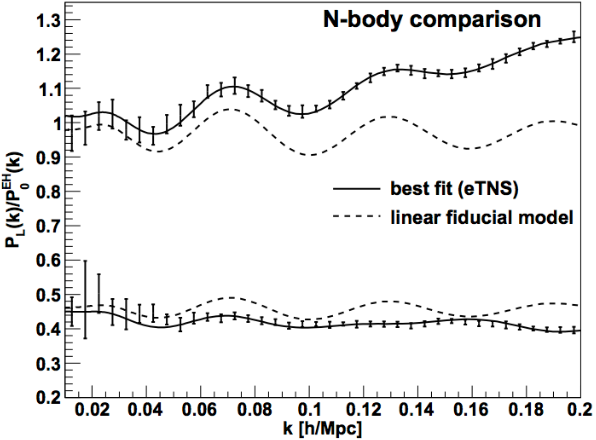
Our power spectrum model is based on renormalized perturbation theory (Taruya et al. 2011, McDonald & Roy 2009)

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

with

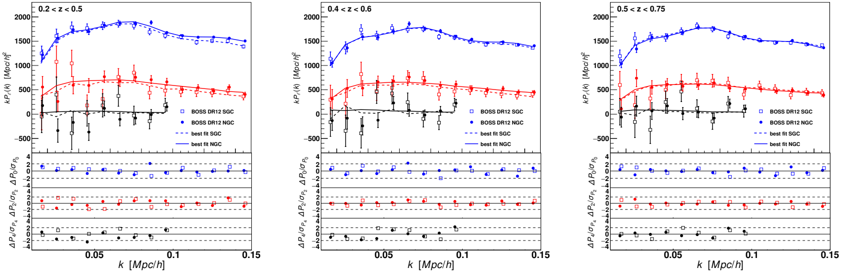
$$
\begin{aligned}
P_{{\rm g},\delta\delta}(k) &= b_1^2 P_{\delta\delta}(k) + 2b_2 b_1 P_{b2,\delta}(k) + 2b_{s2} b_1 P_{bs2,\delta}(k) \\
&+ 2b_{\rm 3nl} b_1 \sigma_3^2(k) P_{\rm m}^{\rm L}(k) + b_2^2 P_{b22}(k) \\
&+ 2b_2 b_{s2} P_{b2s2}(k) + b_{s2}^2 P_{bs22}(k) + N, \\
P_{{\rm g},\delta\theta}(k)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

Clustering measurements – power spectrum

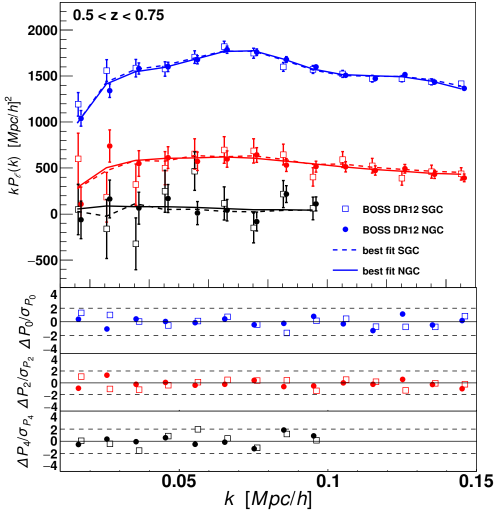


Beutler et al. (2014)

Power spectrum measurement

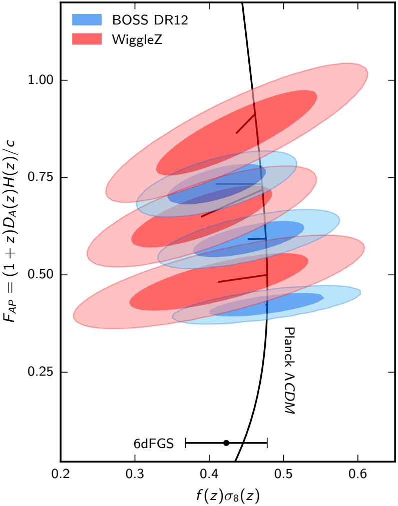


Beutler et al. (2017)



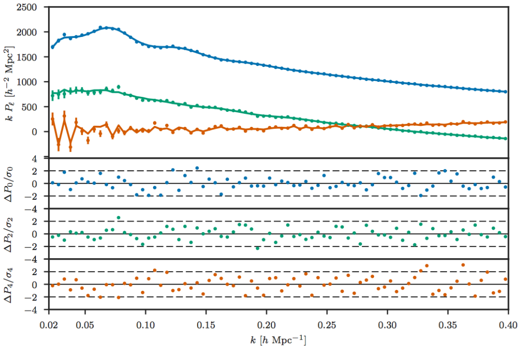
Beutler et al. (2017)

Growth of structure constraints



Beutler et al. (2017)

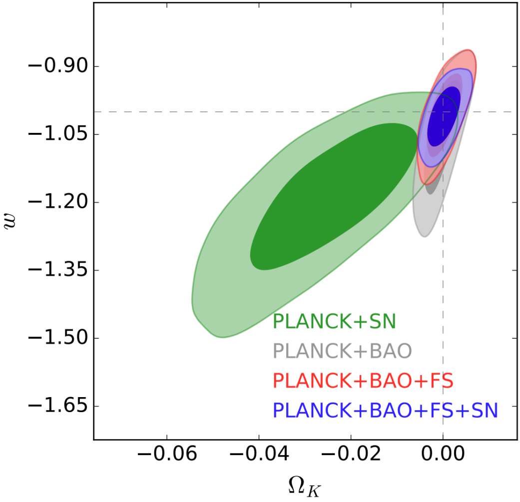
Advances in power spectrum modelling



Hand, Seljak & Beutler (2017)

- Using the power spectrum up to $k_{\mathrm{max}} = 0.4\,\mathrm{Mpc}/h$ only improves the constraints by 20%.
- Including smaller scales does require more PT bias parameters, which absorb some of the cosmological information.
- The bispectrum might help, since its modelling will recycle some of the bias parameters (Sugiyama, Saito, Beutler & Seo 2018).

Constraining the neutrino mass

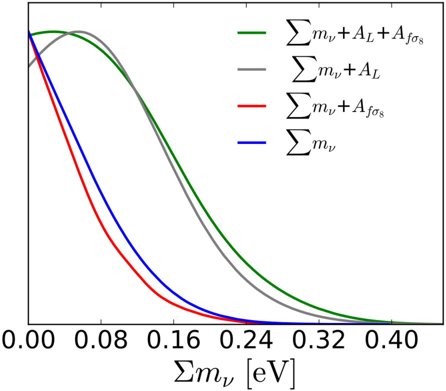


Alam et al (2017)

$$\Omega_k = 0.0002 \pm 0.0023$$

$$w = -1.01 \pm 0.04$$

Constraining the neutrino mass



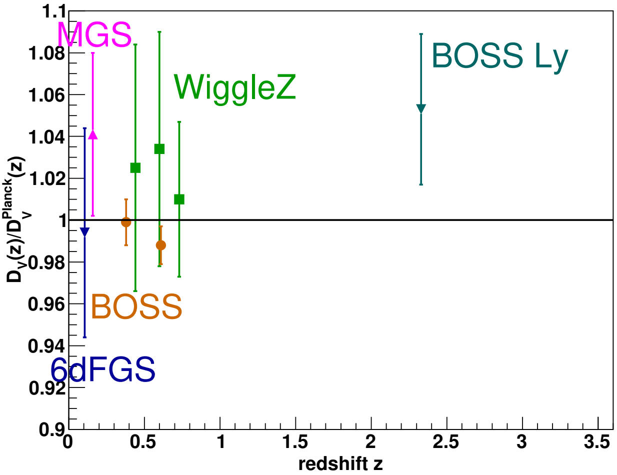
Alam et al (2017)

$$\Lambda CDM + \sum m_\nu < 0.16\, eV$$

$$\Lambda CDM + \sum m_\nu + A_L < 0.23\, eV$$

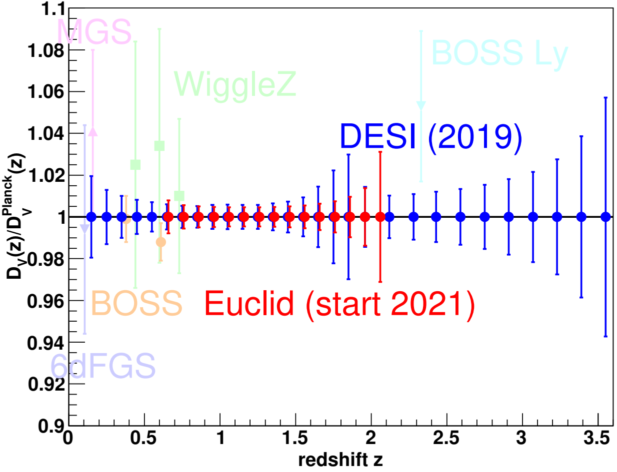
$$\Lambda CDM + \sum m_\nu + A_{f\sigma_8} < 0.15\, eV$$

$$\Lambda CDM + \sum m_\nu + A_L + A_{f\sigma_8} < 0.25\, eV$$



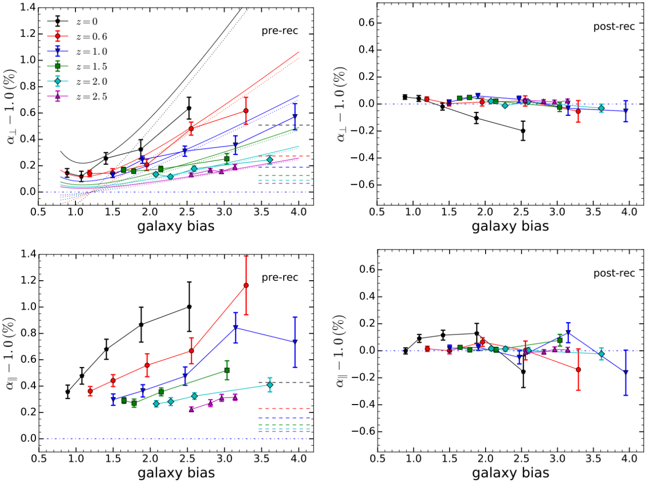
$$D_V \propto D_A^2 / H(z)$$

Future of galaxy surveys



$$D_V \propto D_A^2/H(z)$$

BAO robustness tests



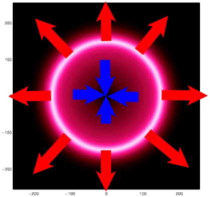
Ding et al. (2018)

The baryon - cold dark matter relative velocity

Beutler, Vlah & Seljak (2016)

Schmidt & Beutler (2017)

The relative velocity effect



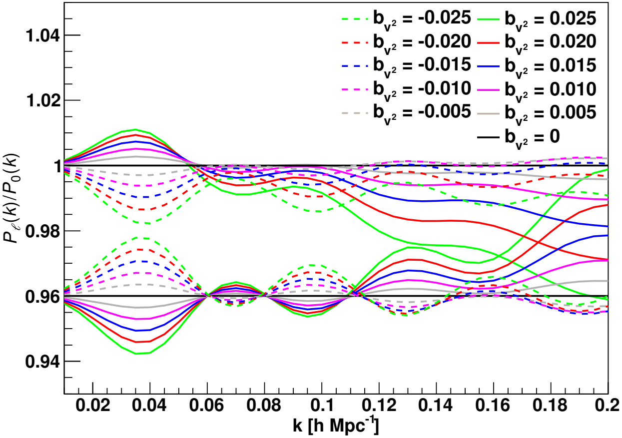
- Before decoupling dark matter perturbations grow, while baryon perturbations only oscillate.
- Baryon and dark matter perturbations start with different initial conditions including a relative velocity (Tseliakhovich & Hirata 2010).
- This relative velocity has large scale variations on the sound horizon scale (Dalal et al. 2010, Yoo & Seljak 2011).
- Baryons can escape the dark matter potential at places where v_{bc} is large (e.g. Asaba, Ichiki & Tashiro 2016).
- The relative velocity impacts galaxy formation and has been put forward as one potential solution to the missing satellite problem (Bovy & Dvorkin 2013).

The relative velocity effect

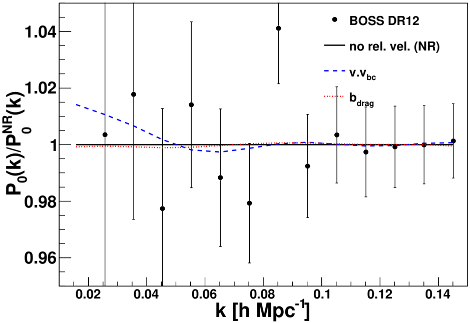
Based on Yoo & Seljak (2011), Schmidt (2015) & Blazek et al. (2014)

$$
\begin{aligned}
P_g(k,\mu) = P_{\rm g,NL}(k,\mu) + b_{v^2}\Big[& b_1 P_{\delta|v^2}(k) + b_2 P_{\delta^2|v^2}(k) \\
& + b_s P_{s^2|v^2}(k) + b_{v^2} P_{v^2|v^2}(k)\Big] \\
& + b_1 b_{v^2} P_{\rm adv|\delta}(k) + 2 b_1 b_\delta^{\rm bc} P_{\delta|\delta_{\rm bc}} + 2 b_1 b_\theta^{\rm bc} P_{\delta|\theta_{\rm bc}} \\
& - 2f\mu^2 \Big[b_{v^2}\left(b_1 P_{\delta|v^2 v_\parallel}(k) + P_{\rm adv|v_\parallel}(k)\right) \\
& - b_\theta^{\rm bc} P_{\delta|\theta_{\rm bc}} + b_\delta^{\rm bc} P_{\delta|\delta_{\rm bc}} \\
& + b_{v^2}\left(P_{v^2|v_\parallel}(k) + P_{v^2|\delta v_\parallel}(k)\right)\Big] \\
& + f^2\mu^4 b_{v^2} P_{v_\parallel|v^2 v_\parallel}(k) \\
& - f^2\mu^2 b_{v^2}\left[I_1(k) + \mu^2 I_2(k)\right],
\end{aligned}
$$

Beutler, Vlah & Seljak (2016)



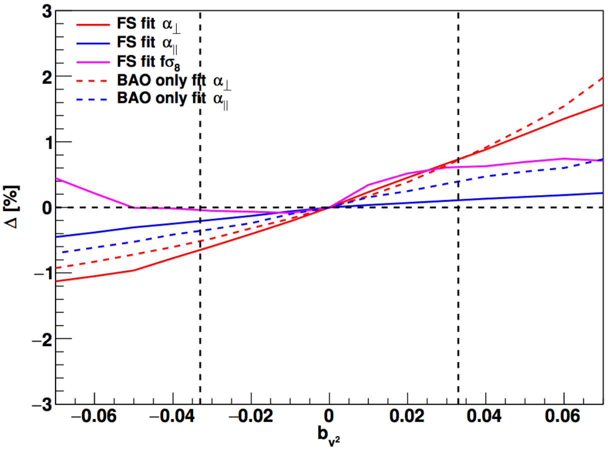
Beutler, Vlah & Seljak (2016)



Schmidt & Beutler (2017)

BOSS, 68% (95%) confidence levels:

- $b_{v^2} = 0.012 \pm 0.015(\pm 0.031)$
- $b_\delta^{\rm bc} = -1.0 \pm 2.5(\pm 6.2)$
- $b_\theta^{\rm bc} = -114 \pm 55(\pm 175)$
- $b_{\rm drag} = 140 \pm 1700(\pm 4500)$
- $b_{\rm drag,bc} = -10 \pm 10(^{+51}_{-28})$

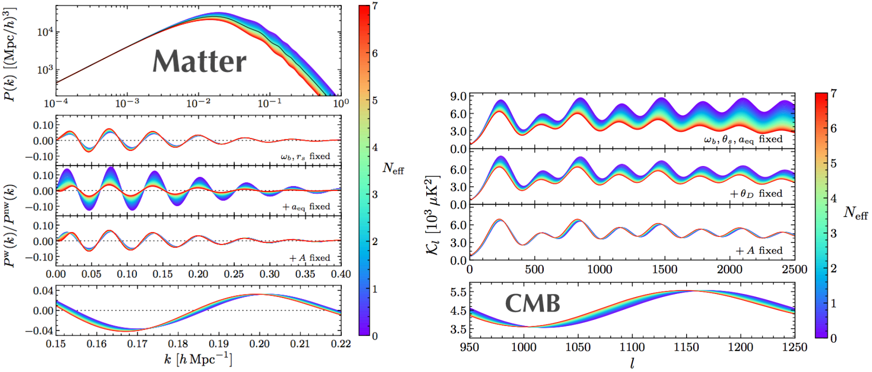


- Given these limits, potential shifts in the BAO measurements of BOSS are constrained to 0.53σ, 0.50σ and 0.22σ for $D_A(z)$, $H(z)$ and $f\sigma_8$, respectively

First Measurement of Neutrinos in the BAO Spectrum

D. Baumann, F. Beutler, R. Flauger, D. Green, M. Vargas-Magana, A. Slosar, B. Wallisch & C. Yeche (2018)

The main effect of neutrinos is to increase the damping of the spectrum (degenerate with helium fraction).



D. Baumann, D. Green & B. Wallisch (2017)

Neutrinos in the BAO Spectrum

The oscillation have been imprinted during radiation domination

$$\ddot{\delta}_{b\gamma} - c_s^2 \nabla^2 \delta_{b\gamma} = \nabla^2 \Phi$$

with solutions (Φ sourced by γ, DM, baryons)

$$\delta_{b\gamma} = A\cos(kr_s)$$

- γ, DM, baryons only impact A, but they cannot change the phase (Bashinsky & Seljak 2003, Baumann et al. 2015).
- Any fluctuation in the grav. potential which travels faster than the baryon-photon plasma can generate a phase shift (free streaming neutrinos $c_\nu > c_\gamma$).
- Planck allowed the first detection of the phase shift in the CMB with $N_{\rm eff} = 2.8^{+1.1}_{-0.4}$ (Follin et al. 2015).
- Using all information in Planck: $N_{\rm eff} = 3.04 \pm 0.18$
- BBN measured 3.28 ± 0.28 (Cooke et al. 2015)
- The phase is immune to the effects of nonlinear evolution (Baumann, Green & Zaldarriaga 2017)

Neutrinos in the BAO Spectrum

The oscillation have been imprinted during radiation domination

$$\ddot{\delta}_{b\gamma} - c_s^2 \nabla^2 \delta_{b\gamma} = \nabla^2 \Phi$$

with solutions (Φ sourced by γ, DM, baryons $+ \nu$)

$$\begin{aligned} \delta_{b\gamma} &= A\cos(kr_s) + \delta B \sin(kr_s) \\ &= A\cos(kr_s + \phi) \end{aligned}$$

- γ, DM, baryons only impact A, but they cannot change the phase (Bashinsky & Seljak 2003, Baumann et al. 2015).
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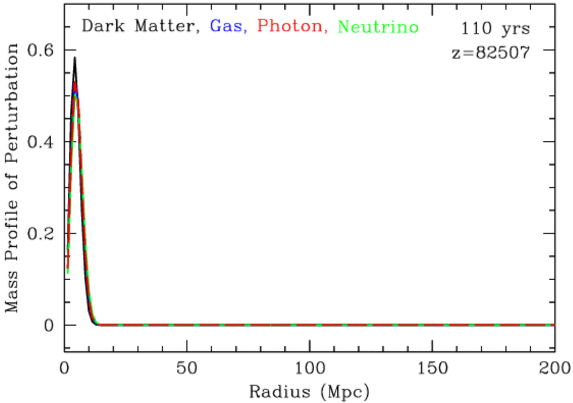
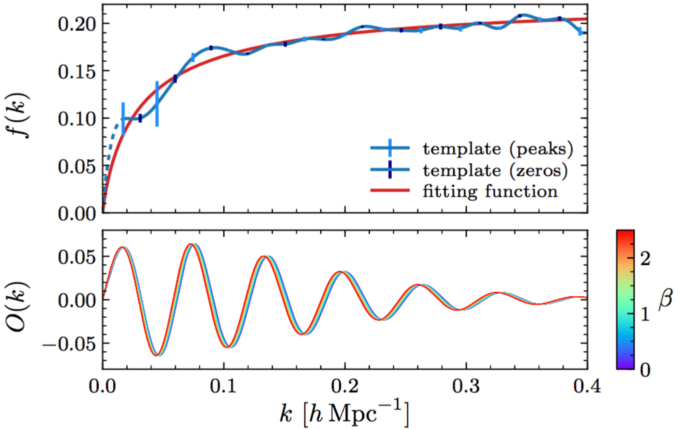
Free-streaming neutrinos overtake the photons, and pull them ahead of the sound horizon.



D. Eisenstein, H.-J. Seo & M. White (2007)

Neutrinos in the BAO Spectrum

$$O(k) = O_{\rm lin}(k/\alpha + (\beta - 1)f(k)/r_s^{\rm fid})e^{-k^2\sigma_{\rm nl}^2/2}$$



D. Baumann, F. Beutler, R. Flauger, D. Green, M. Vargas-Magana, A. Slosar, B. Wallisch & C. Yeche (2018)

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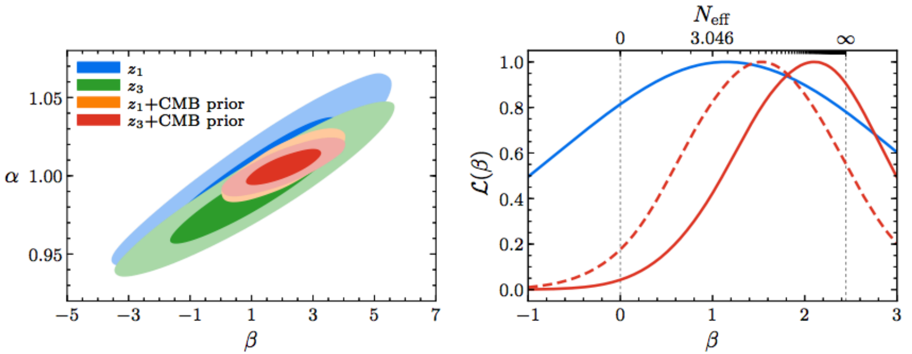

→ This is a proof of principle for extracting information on light relics from galaxy clustering data.

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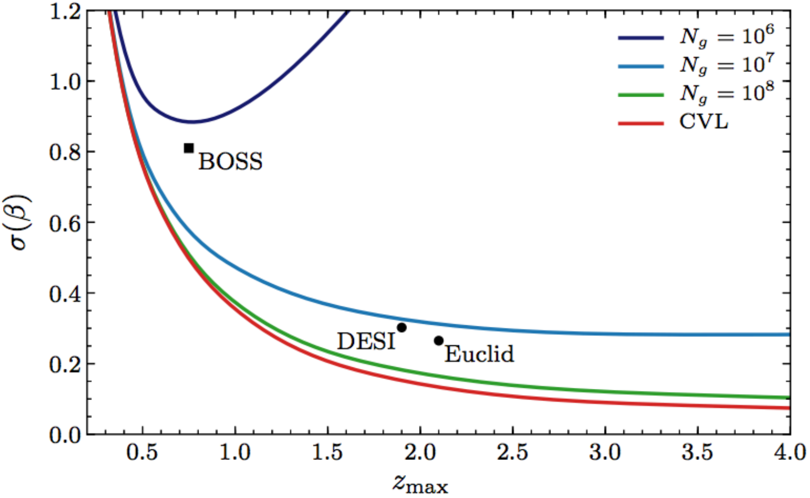

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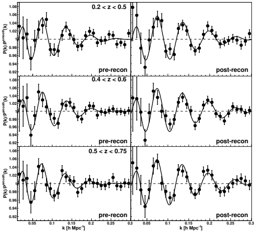
Summary



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%, and the growth of structure with an error of 10%.

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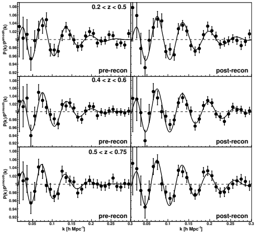

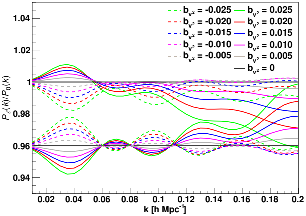

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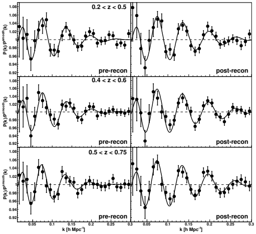

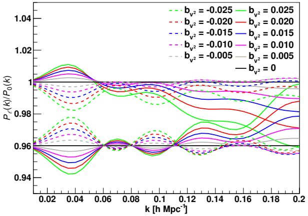

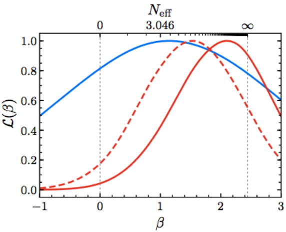

1. In BOSS we were able to measure the BAO scale in two independent redshift bins ($z = 0.38$ and $z = 0.61$) with an error of 1%, and the growth of structure with an error of 10%.
2. The relative velocity between cold dark matter and baryons is a potential systematic for BAO but can be constrained using the power spectrum shape.
3. The phase of the BAO carries information about the cosmic neutrino background. We report the first measurement of this signature in the BAO phase using BOSS data. This is the first use of the BAO signal beyond the standard ruler.