Beyond the standard Baryon Acoustic Oscillation measurement

Florian Beutler

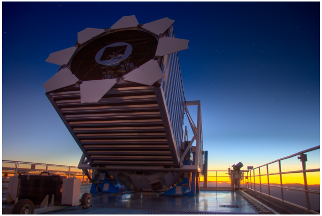
20 April, 2018

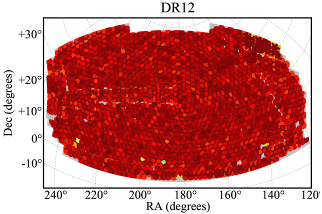
Outline of the talk

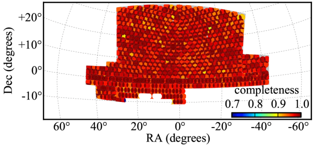
- BOSS DR12 BAO measurement.
- First Measurement of Neutrinos in the BAO Spectrum.
- A complete FFT-based decomposition formalism for the redshift-space bispectrum.

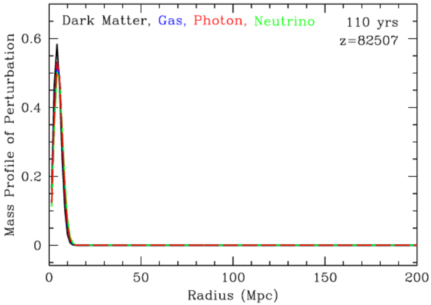
The BOSS galaxy survey

- 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 deg^2.
- SDSS now moved on to eBOSS (see Hector's talk).







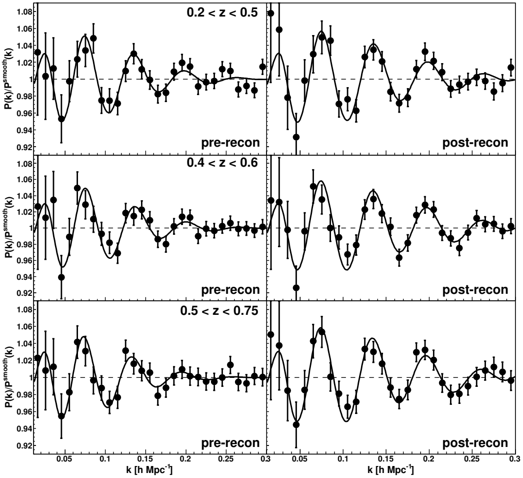


Baryon and photon perturbations in the radiation dominated era follow

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

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.



Beutler et al. (2017)

$$D_A \sim 1.5\%$$
$$H \sim 2.5\%$$
$$D_V \propto \left[D_A^2/H\right]^{1/3} \sim 0.9\%$$

Fitting the BAO

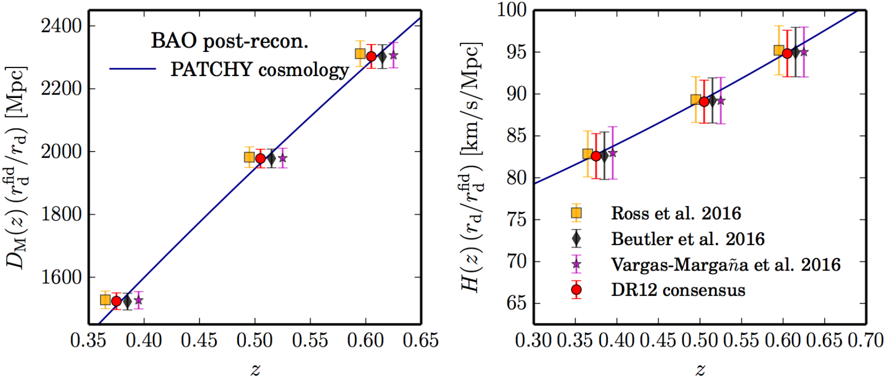
- Start with linear $P(k)$ and separate the broadband shape, $P^{\rm sm}(k)$, and the BAO feature $O^{\rm lin}(k)$. Include a damping of the BAO feature:

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

- Add broadband nuisance terms

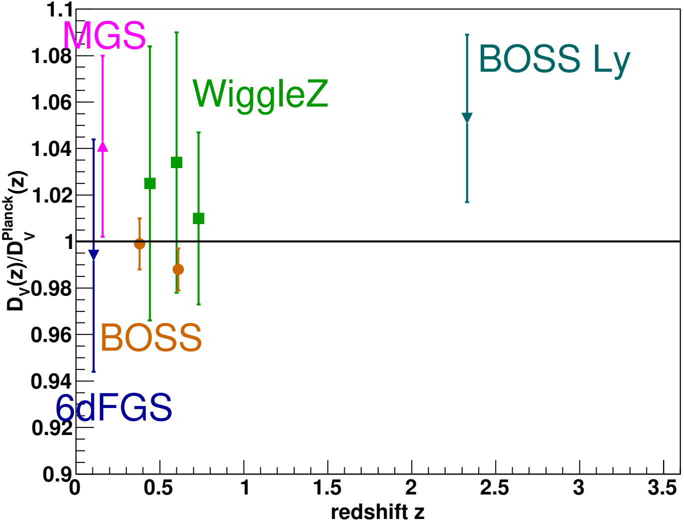
$$A(k) = a_1 k + a_2 + \frac{a_3}{k} + \frac{a_4}{k^2} + \frac{a_5}{k^3}$$
$$P^{\rm fit}(k) = B^2 P^{\rm sm,lin}(k/\alpha) + A(k)$$

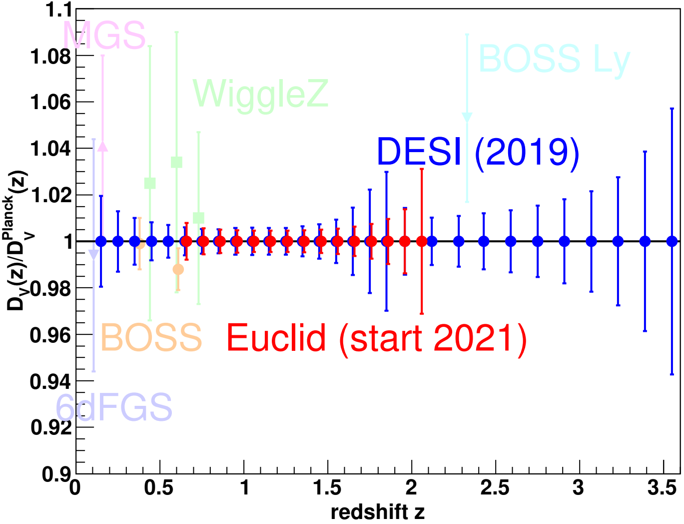
- Marginalize to get $\mathcal{L}(\alpha)$.



Alam et al. (2016)

Future of galaxy surveys

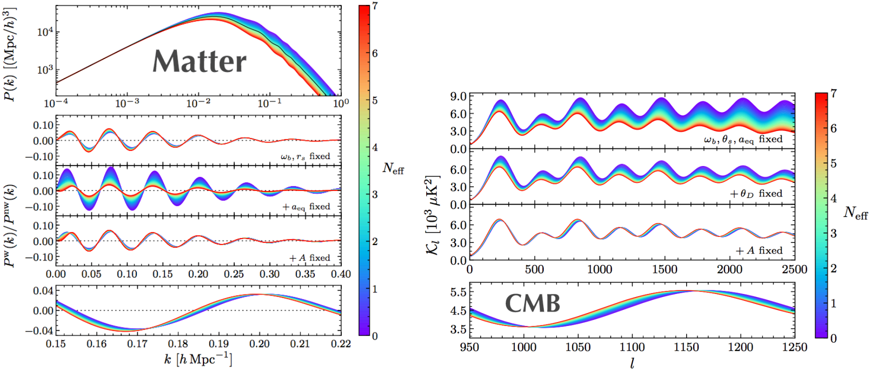



MGS
WiggleZ
BOSS Ly
DESI (2019)
BOSS
Euclid (start 2021)
6dFGS
$D_V(z)/D_V^{Planck}(z)$
redshift z
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.9
0
0.5
1
1.5
2
2.5
3
3.5

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 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)

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

- The gravitational sources on the right 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).
- 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 $+\ \nu$)

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

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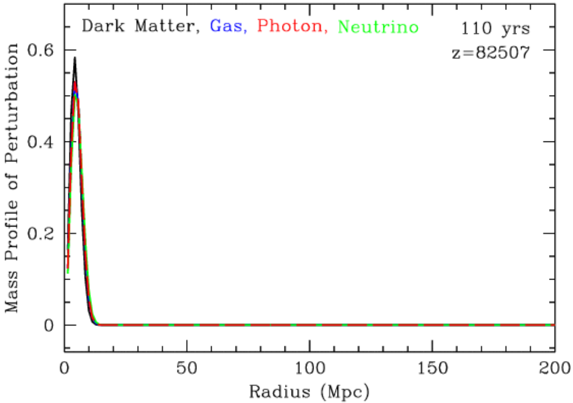
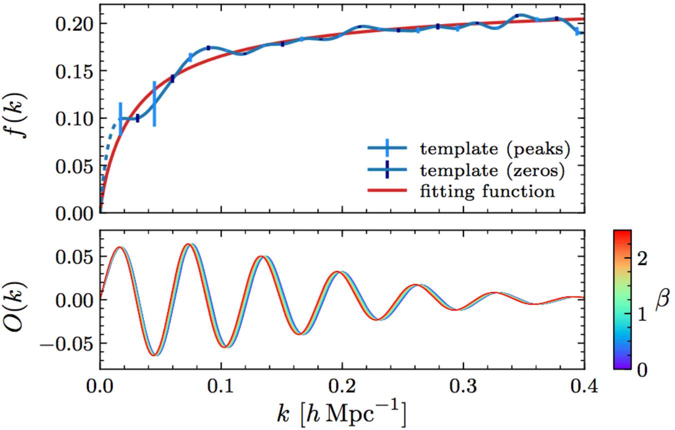
Free-streaming neutrinos overtake the photons, and pull them ahead of the sound horizon.



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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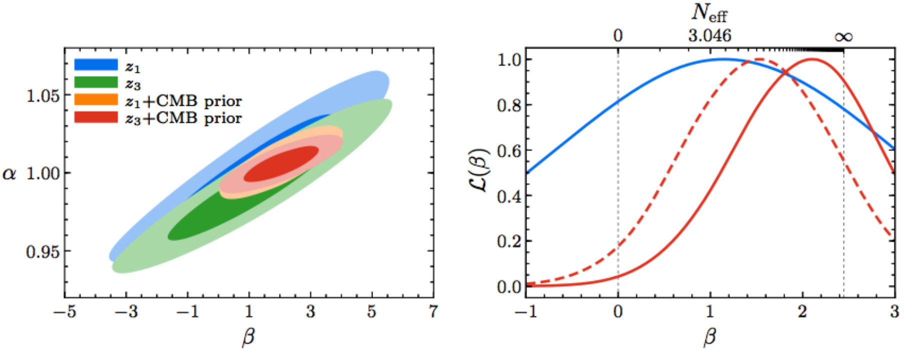
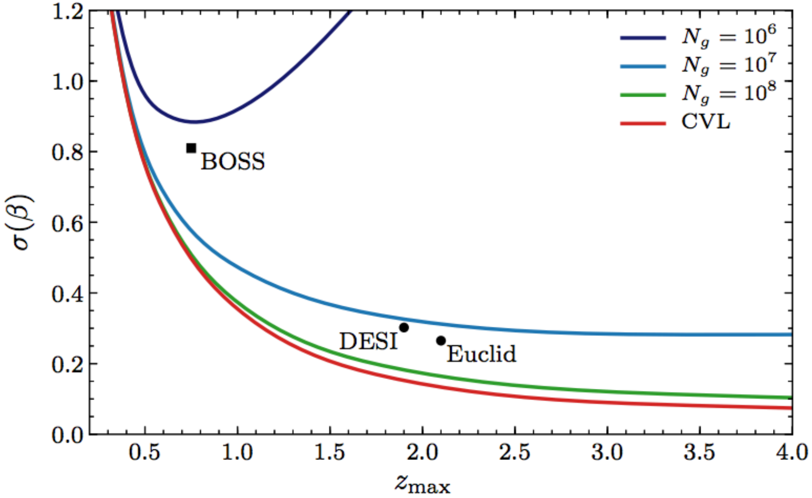


→ This is a proof of principle for extracting information on light relics from galaxy clustering data.

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



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

A complete FFT-based decomposition formalism for the redshift-space bispectrum

N. Sugiyama, S. Saito, F. Beutler & H-J. Seo (2018)

New decomposition formalism for the bispectrum

The estimator is based on the spherical harmonics expansion proposed in Sugiyama et al. (2017), Hand et al. (2017)

$$\begin{aligned}\widehat{B}_{\ell_1\ell_2L}(k_1,k_2) = H_{\ell_1\ell_2L} &\sum_{m_1 m_2 M} \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & M \end{pmatrix} \\ &\times \frac{N_{\ell_1\ell_2L}}{I} \int \frac{d^2\hat{k}_1}{4\pi} y_{\ell_1}^{m_1 *}(\hat{k}_1) \int \frac{d^2\hat{k}_2}{4\pi} y_{\ell_2}^{m_2 *}(\hat{k}_2) \\ &\times \int \frac{d^3k_3}{(2\pi)^3} (2\pi)^3 \delta_{\mathrm{D}}\left(\vec{k}_1 + \vec{k}_2 + \vec{k}_3\right) \\ &\times \delta n(\vec{k}_1)\, \delta n(\vec{k}_2)\, \delta n_L^M(\vec{k}_3)\end{aligned}$$

were y_L^{M*}-weighted density fluctuation

$$\delta n_L^M(\vec{x}) \equiv y_L^{M*}(\hat{x})\, \delta n(\vec{x})$$

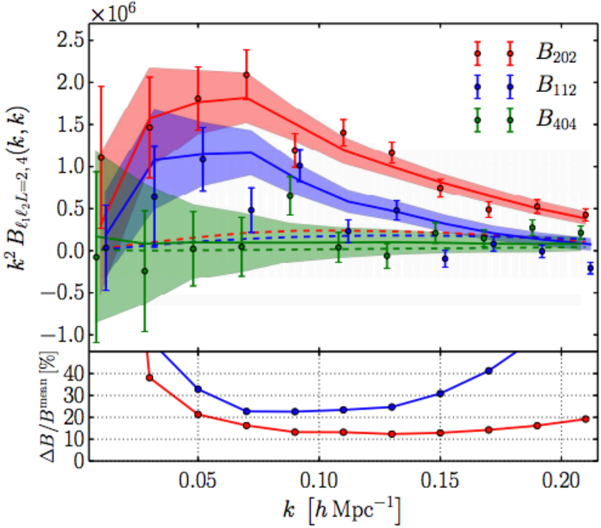
$$\delta n_L^M(\vec{k}) = \int d^3x \mathrm{e}^{-\mathrm{i}\vec{k}\cdot\vec{x}} \delta n_L^M(\vec{x})$$

and $y_\ell^m = \sqrt{4\pi/(2\ell+1)}\, Y_\ell^m$.

Why using this formalism

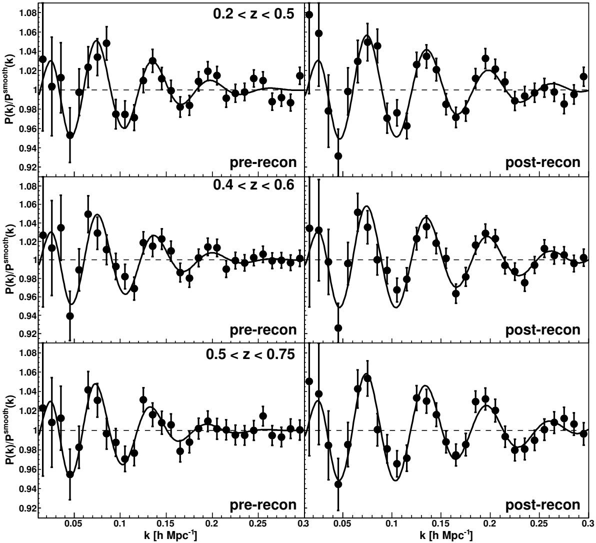
- This decomposition compresses the data into 2D quantities $B_{\ell_1\ell_2L}(k_1, k_2)$ rather than 3D quantities like other decompositions $B_\ell^m(k_1, k_2, k_3)$. This reduces the size of the connected covariance matrix.
- This decomposition allows for a self consistent inclusion of the survey window function.
- The RSD information is clearly separated into the L multipoles.
- The complexity of our estimator is $\mathcal{O}((2\ell_1 + 1)N_b^2 N \log N)$.
- Only some multipoles are non-zero: (1) $\ell_1 > \ell_2$ (2) L $=$ even (3) $|\ell_1 - \ell_2| \leq L \leq |\ell_1 + \ell_2|$ and (4) $\ell_1 + \ell_2 + L =$ even.

First detection of the anisotropic bispectrum



N. Sugiyama, S. Saito, F. Beutler & H-J. Seo (2018)

BOSS & BAO



Beutler et al. (2017)

Density field reconstruction

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

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

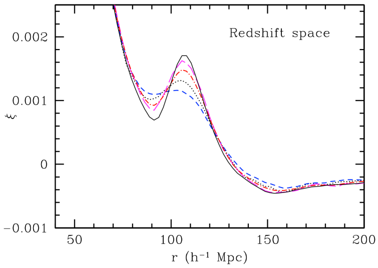
- Solve the Poisson eq. to obtain the gravitational potential

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

- The displacement (vector) field is given by

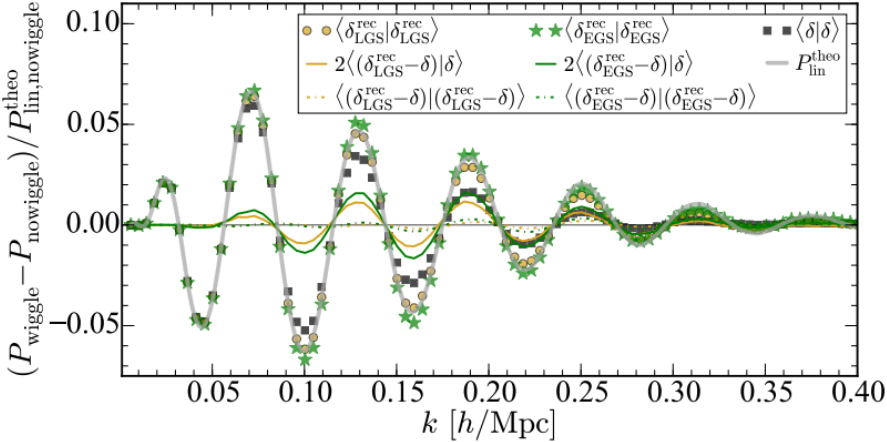
$$\Psi = \nabla\phi$$

- Now we calculate the displaced density field by shifting the original particles.
- Reconstruction decorrelates modes and removes/lowers higher order terms.



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

Where does the information come from?



M. Schmittfull, Y. Feng, F. Beutler, B. Sherwin & M. Chu (2015)

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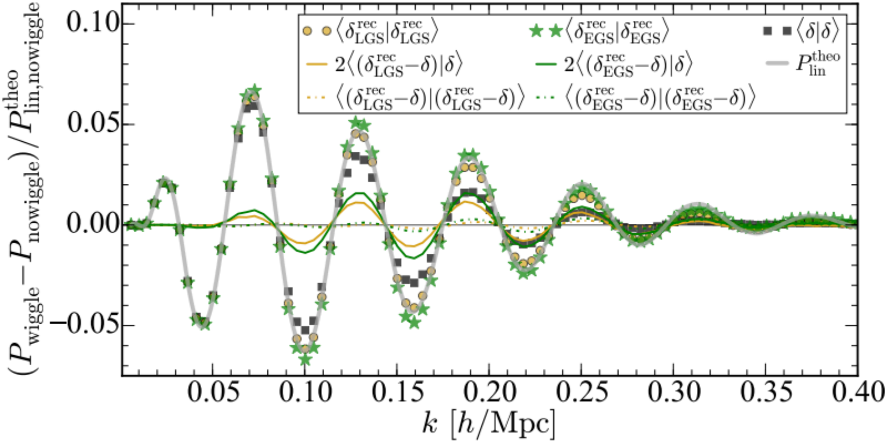
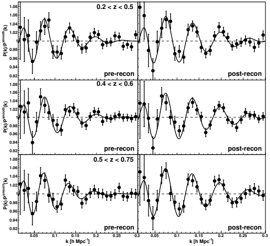
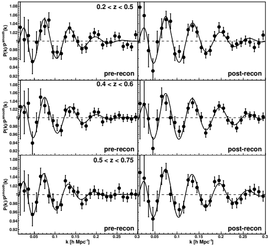


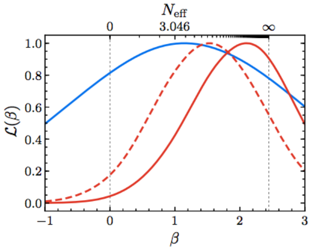
$$P(k) + B(k_1, k_2, k_3) \simeq P(k) + \text{ reconstruction}$$

M. Schmittfull, Y. Feng, F. Beutler, B. Sherwin & M. Chu (2015)



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.





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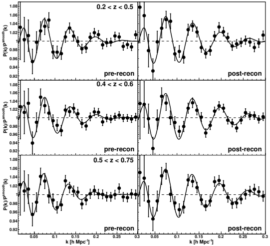
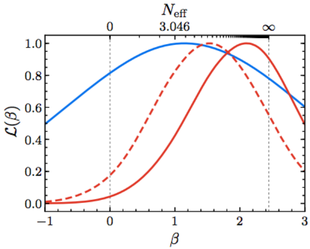
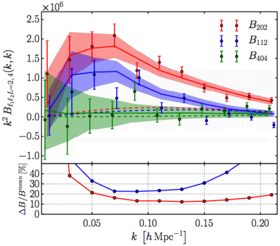
2. The phase of the BAO carries information about the cosmic neutrino background. We report the first detection of this signature to the BAO phase using BOSS data. This the first use of the BAO signal beyond the standard ruler.

Summary







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2. The phase of the BAO carries information about the cosmic neutrino background. We report the first detection of this signature to the BAO phase using BOSS data. This the first use of the BAO signal beyond the standard ruler.
3. We developed a new estimator for the galaxy bispectrum and have the first detection ($> 14\sigma$) of the anisotropic bispectrum with BOSS data.

Appendix: Accounting for the survey window

We can estimate the survey window very similar to the bispectrum estimator

$$
\begin{aligned}
Q_{\ell_1\ell_2L}(r_1, r_2) = H_{\ell_1\ell_2L} & \sum_{m_1 m_2 M} \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & M \end{pmatrix} \\
& \times \frac{N_{\ell_1\ell_2L}}{I} \int \frac{d^2\hat{r}_1}{4\pi} y_{\ell_1}^{m_1*}(\hat{r}_1) \int \frac{d^2\hat{r}_2}{4\pi} y_{\ell_2}^{m_2*}(\hat{r}_2) \\
& \times \int d^3x_1 \int d^3x_2 \int d^3x_3 \\
& \times \delta_{\mathrm{D}}\left(\vec{r}_1 - \vec{x}_{13}\right) \delta_{\mathrm{D}}\left(\vec{r}_2 - \vec{x}_{23}\right) \\
& \times y_L^{M*}(\hat{x}_3)\, \bar{n}(\vec{x}_1)\, \bar{n}(\vec{x}_2)\, \bar{n}(\vec{x}_3).
\end{aligned}
$$

We can now follow the steps of Wilson et al. (2015)/Beutler et al. (2017) to include the window function in the analysis pipeline.

1. Hankel transform to the three-point function
2. Multiply with the window function
3. Hankel transform back

Step 1 & step 3: The Hankel transform for the bispectrum - three point function is given by

$$
\begin{aligned}
B_{\ell_1\ell_2L}(k_1,k_2) &= (-i)^{\ell_1+\ell_2}(4\pi)^2\int dr_1 r_1^2\int dr_2 r_2^2 \\
&\times \quad j_{\ell_1}(k_1r_1)j_{\ell_2}(k_2r_2)\zeta_{\ell_1\ell_2L}(r_1,r_2) \\
\zeta_{\ell_1\ell_2L}(r_1,r_2) &= i^{\ell_1+\ell_2}\int\frac{dk_1k_1^2}{2\pi^2}\int\frac{dk_2k_2^2}{2\pi^2} \\
&\times \quad j_{\ell_1}(r_1k_1)j_{\ell_2}(r_2k_2)B_{\ell_1\ell_2L}(k_1,k_2),
\end{aligned}
$$

Step 2: Multiply the three-point function with the survey window

$$
\begin{aligned}
&\left\langle \widehat{\zeta}_{\ell_1\ell_2L}(r_1, r_2) \right\rangle \\
&= N_{\ell_1\ell_2L} \sum_{\ell_1'+\ell_2'+L'=\mathrm{even}} \; \sum_{\ell_1''+\ell_2''+L''=\mathrm{even}} \\
&\times \begin{Bmatrix} \ell_1'' & \ell_2'' & L'' \\ \ell_1' & \ell_2' & L' \\ \ell_1 & \ell_2 & L \end{Bmatrix} \left[\frac{H_{\ell_1\ell_2L} H_{\ell_1\ell_1'\ell_1''} H_{\ell_2\ell_2'\ell_2''} H_{LL'L''}}{H_{\ell_1'\ell_2'L'} H_{\ell_1''\ell_2''L''}} \right] \\
&\times Q_{\ell_1''\ell_2''L''}(r_1, r_2)\, \zeta_{\ell_1'\ell_2'L'}(r_1, r_2) \\
&- \quad Q_{\ell_1\ell_2L}(r_1, r_2)\, \bar{\zeta},
\end{aligned}
$$

Appendix: The three-point function using the same formalism

We can apply the same formalism to the three-point function

$$\zeta_{\ell_1\ell_2L}(r_1, r_2) = H_{\ell_1\ell_2L} \sum_{m_1 m_2 M} \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & M \end{pmatrix} \zeta^{m_1 m_2 M}_{\ell_1\ell_2L}(r_1, r_2).$$

Appendix: Relation to other decompositions

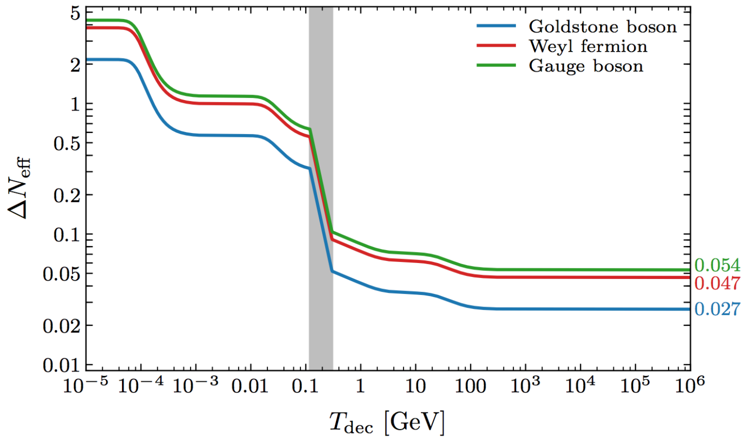
Transformation between Scoccimarro (2015) and our decomposition

$$B_{\ell_1\ell_2L}(k_1,k_2) = \frac{N_{\ell_1\ell_2L}H_{\ell_1\ell_2L}}{\sqrt{(4\pi)(2L+1)}}\int\frac{d\cos\theta_{12}}{2}$$
$$\times\left[\sum_M \begin{pmatrix}\ell_1 & \ell_2 & L\\ 0 & -M & M\end{pmatrix} y_{\ell_2}^{-M*}(\cos\theta_{12},\pi/2)\right]\times B_{LM}(k_1,k_2,\theta_{12})$$

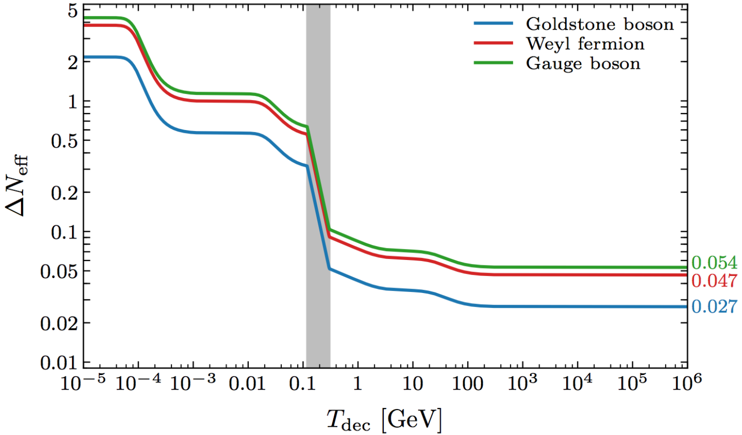
Transformation between Slepian & Eisenstein (2017) and our decomposition:

$$B_{\ell_1\ell_2L}(k_1,k_2) = N_{\ell_1\ell_2L}H_{\ell_1\ell_2L}\sum_m(-1)^m\begin{pmatrix}\ell_1 & \ell_2 & L\\ m & -m & 0\end{pmatrix}$$
$$\times\sqrt{\frac{(\ell_1-|m|)!}{(\ell_1+|m|)!}}\sqrt{\frac{(\ell_2-|m|)!}{(\ell_2+|m|)!}}$$
$$\times\int\frac{d\cos\theta_1\,d\varphi_{12}}{4\pi}\int\frac{d\cos\theta_2}{2}$$
$$\times\cos(m\varphi_{12})\mathcal{L}_{\ell_1}^{|m|}(\cos\theta_1)\mathcal{L}_{\ell_2}^{|m|}(\cos\theta_2)\times B(k_1,k_2,\theta_1,\theta_2,\varphi_{12})$$

Sources of $\Delta Neff$



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



$$\sigma(N_{\rm eff}) = 0.030 \qquad \text{(CMB-S4)}$$

$$\sigma(N_{\rm eff}) = 0.027 \qquad \text{(CMB-S4 + Euclid)}$$

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