Constraining cosmological parameters using BOSS data: Power Spectrum and Bispectrum

Héctor Gil-Marín
Collaborators: Will Percival, BOSS GC Team

Laboratoire de Physique Nucleaire et de Hautes Energies
Institut Lagrange de Paris

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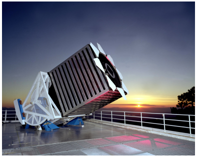
Outline

1. Constrains from the BOSS DR12 Power Spectrum multipoles
   RSD **2016MNRAS.460.4188G**
   BAO **2016MNRAS.460.4210G**
2. Constrains from the BOSS DR12 Bispectrum
   RSD **[arXiv:1606.00439]** (Submitted to MNRAS)

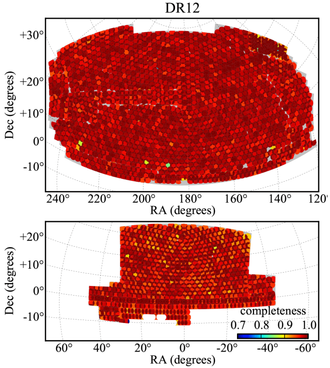
Introduction: the BOSS survey

- Apache Point Observatory (APO) 2.5-m telescope for five years from 2009-2014.
- Part of SDSS-III project. BOSS: Baryon Oscillation Spectroscopic Survey
- Total coverage area about 10,000 square degrees
- Two samples with different target selection: LOWZ and CMASS
- Two patches in the Northern and Southern Hemisphere

- BOSS Galaxies: LRGs.
- $0.15 \leq z \leq 0.43$ LOWZ
- $0.43 \leq z \leq 0.70$ CMASS
- $\sim 1.2 \cdot 10^6$ galaxies



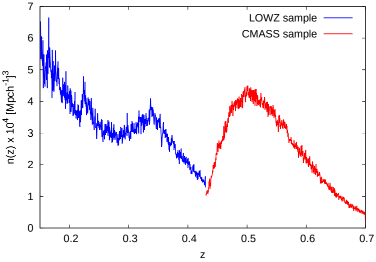
Introduction: LOWZ and CMASS samples



- The two redshift bins have different target selection.
- We treat them as independent galaxy population with different galaxy bias properties.

- CMASS has $\sim$ 3 times the volume that LOWZ

Introduction: LOWZ and CMASS samples



- The two redshift bins have different target selection.
- We treat them as independent galaxy population with different galaxy bias properties.

- CMASS has ~ 3 times the volume that LOWZ

Measurements

1. The **power spectrum** is the Fourier transform of the 2-point function.

$$\langle \delta_{\mathbf{k}1} \delta_{\mathbf{k}2} \rangle = (2\pi)^3 P(\mathbf{k}_1) \delta^D(\mathbf{k}_1 + \mathbf{k}_2)$$

   - It contains information about the clustering.

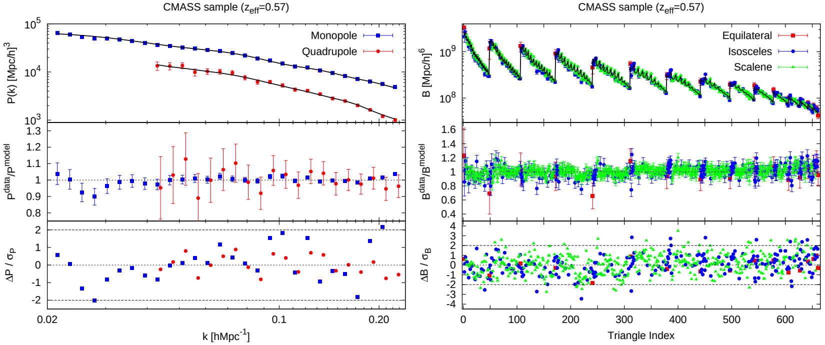
2. The **bispectrum** is the Fourier transform of the 3-point function.

$$\langle \delta_{\mathbf{k}1} \delta_{\mathbf{k}2} \delta_{\mathbf{k}3} \rangle = (2\pi)^3 B(\mathbf{k}_1, \mathbf{k}_2) \delta^D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)$$

   - It essentially contains information about the non-Gaussianities: primordial + gravitationally induced
   - Since is gravitationally sensible $\rightarrow$ Test of GR

Measurements

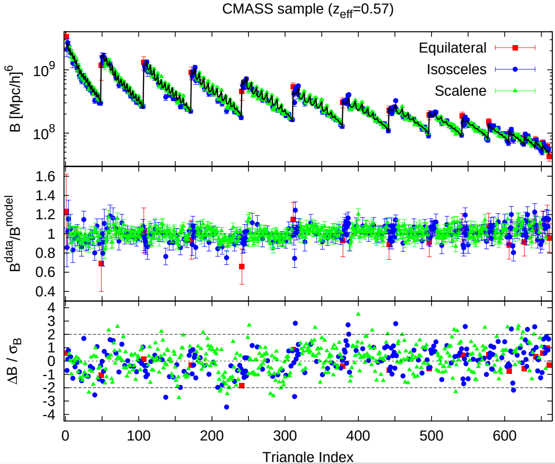
Power spectrum **Monopole**, **Quadrupole** and **Bispectrum** for CMASS sample. (GM et al 2016c, arXiv:1606.00439)



High significant detection of **anisotropy** and **non-Gaussianity**.

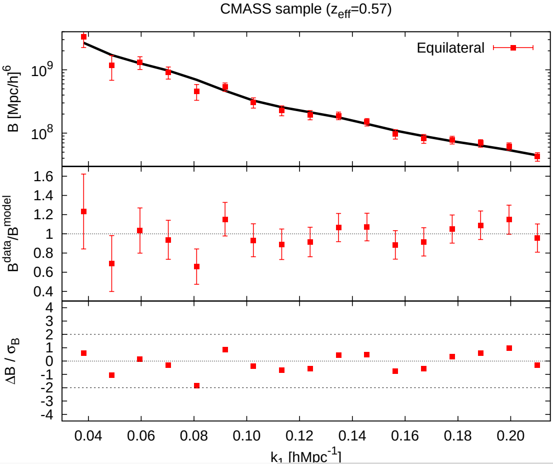
Bispectrum Data

By definition, $k_1 \leq k_2 \leq k_3$



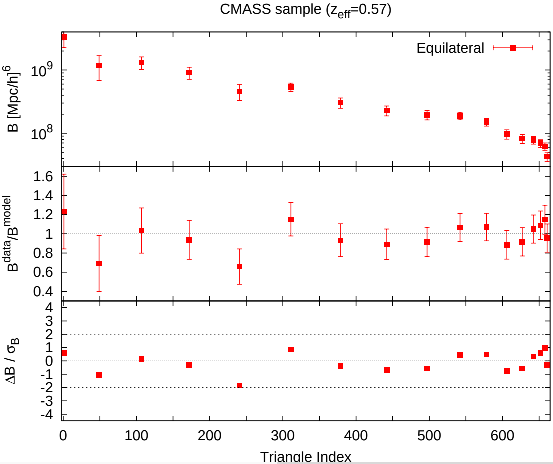
Bispectrum Data

For **equilateral** $k_1 \leq k_2 \leq k_3 \rightarrow k_1 = k_2 = k_3$



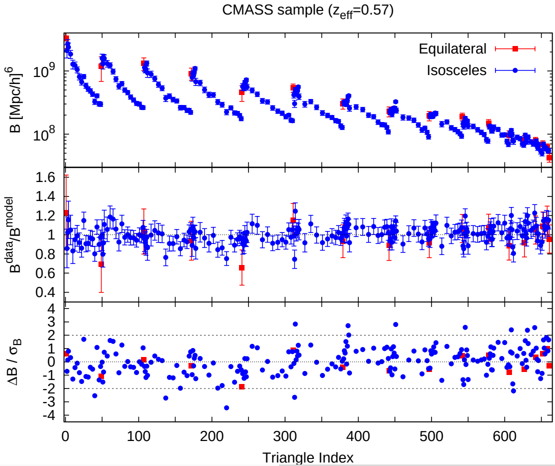
Bispectrum Data

For **equilateral** $k_1 \leq k_2 \leq k_3 \rightarrow k_1 = k_2 = k_3$



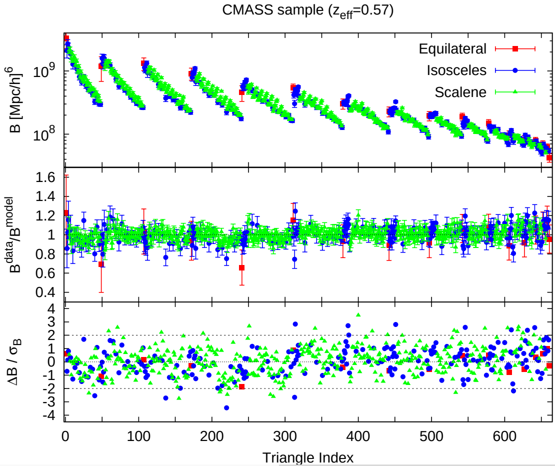
Bispectrum Data

For **isosceles** $k_1 \leq k_2 \leq k_3 \rightarrow k_1 = k_2 < k_3$ & $k_1 < k_2 = k_3$



Bispectrum Data

For **scalene** $k_1 \leq k_2 \leq k_3 \rightarrow k_1 < k_2 < k_3$



Cosmological Constrains from anisotropies

Goal

- To obtain measurements on $f\sigma_8(z_{\rm eff})$, $D_A(z_{\rm eff})$, and $H(z_{\rm eff})$ using the shape and the amplitude of power spectrum and bispectrum in redshift space.

1. Alcock-Paczynski (AP)
2. Redshift space distortions (RSD)

Issues

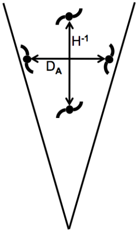
- Galaxy bias may be non-local, non-linear and stochastic
- RSD small scale modelling
- Dark matter small scales modelling: matter and velocity-fields
- Need to include AP parameter to account for inaccuracies when assuming Ω_m

Alcock-Paczynski

Source of anisotropy comes from AP-effect, The co-moving distance to an observed galaxy is given by,

$$d_{\mathrm{comov}}(z) = \int_0^z \frac{cdz'}{H(z')}$$

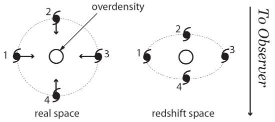
By assuming a wrong cosmological model (Ω_m) we change the line-of-sight clustering respect to the angular clustering, creating a measurable anisotropy: constrains $H(z)$ and $D_A(z)$



This idea is exploited by **RSD** and **BAO** analyses.

Redshift Space Distortions

- Observed redshift depends on the Hubble expansion and peculiar velocities.
- The peculiar velocities are related to the growth of structure.
- Resulting change in redshift is coherent with growth of structure.



As a consequence an enhancement of the clustering along the LOS relative to angular clustering

Quadrupole signal increased relative to the monopole.

RSD vs. AP

There are two main kind of complementary analyses:

1. BAO analysis: Based on the position of the BAO peak
   - Constrain on $D_A(z_{\rm eff})$ and $H(z_{\rm eff})$ through the BAO-feature only.
   - It only requires the modelling of the oscillation, not the shape/amplitude of the broadband signal.
   - Usage of reconstruction algorithm to enhance the significance of the peak.
2. RSD analysis: Based on the PS (and BS) full shape and amplitude signal.
   - Constrain the growth of structure, $f\sigma_8(z_{\rm eff})$, $D_A(z_{\rm eff})$ and $H(z_{\rm eff})$ through the shape and amplitude of a range of scales.
   - It requires a full modelling of the amplitude and shape of the power spectrum multipoles and bispectrum

BAO analysis

1. BAO analysis: Based on the position of the BAO peak

- After the BAO reconstruction $P^{(2)}$ is very suppressed.
- We chose to work instead with $P^{(0)}$ and $P^{(\mu^2)}$, which has the same information content than $P^{(0)}$ and $P^{(2)}$,

$$
\begin{aligned}
P^{(\mu^2)}(k) &\equiv \int_0^1 d\mu \, P_g^{(s)}(k,\mu)\mu^2 \\
P^{(\mu^2)} &= 2/5P^{(2)} + P^{(0)}
\end{aligned}
$$

- $P^{(\mu^2)}$ has the same linear shape than $P^{(0)} \rightarrow$ Easy to model
- $P^{(\mu^2)}$ has better S/N than $P^{(2)} \rightarrow$ BAO results less affected by noise

BAO analysis

- BAO peak position in the CF / PS is related to AP-dilation parameters (Ross, Percival & Manera 2015),

$$\alpha_{\|} = \alpha_0^{-3/2}\alpha_2^{5/2}; \quad \alpha_{\perp} = \alpha_0^{9/4}\alpha_2^{-5/4}$$

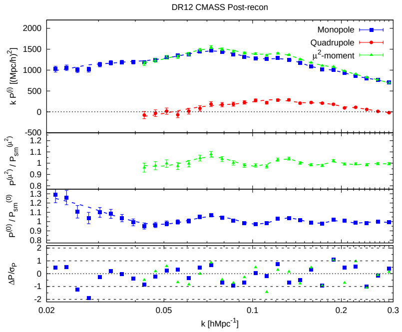
$$P_{\rm model}(k;\alpha_{0,2}) = P_{\rm model,sm}(k)\left\{1 + [O_{\rm lin}(k/\alpha_{0,2}) - 1]e^{-\frac{1}{2}k^2\Sigma^2_{\rm nl}}\right\},$$

$$P_{\rm model,sm}(k) = B^2 P_{\rm lin,sm}(k) + A_1 k + A_2 + \frac{A_3}{k} + \frac{A_4}{k^2} + \frac{A_5}{k^3},$$

- The AP-dilation parameters are related to the cosmological parameters: angular diameter distance D_A and Hubble parameter H,

$$\alpha_{\|}(z) \propto H^{-1}(z) \qquad \alpha_{\perp}(z) \propto D_A(z)$$

BAO analysis



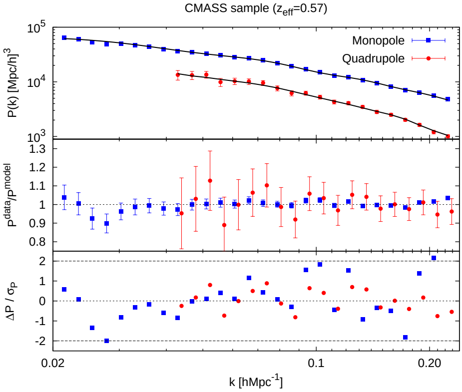
- Comoving BAO wavelength is determined by the comoving sound horizon at recombination: $\sim 110h^{-1}\,\mathrm{Mpc}$, $0.06h\,\mathrm{Mpc}^{-1}$
- Small changes on the radial and angular position of the peak depend on Ω_m.
- Reconstruction technique enhances the significance of the peak

Full shape analysis

2. RSD analysis: Based on the PS (and BS) full shape and amplitude signal.

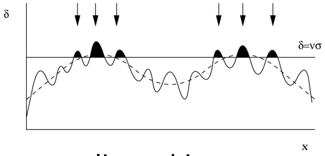
Measure the amplitude and shape of the monopole and quadrupole on the observed galaxies

- Lagrangian local bias (McDonald & Roy 2009)
- 2loop-RPT for $P_{\delta\delta}$, $P_{\delta\theta}$, $P_{\theta\theta}$ (Gil-Marin et al. 2012)
- TNS for RSD in PS (Taruya, Nishimichi & Saito 2010; Beutler et al. 2014)



Galaxy Bias

Galaxies are a biased tracers of DM.



The bias model can be as complex as we want: linear bias, non-linear bias, non-local bias,....

- Eulerian non-local bias model (local in Lagrangian space),

$$\delta_g(\mathbf{x}) = \underbrace{b_1\delta(\mathbf{x})}_{\text{linear Eulerian}} + \overbrace{\frac{1}{2}b_2[\delta(\mathbf{x})^2]}^{\text{non-linear Eulerian}} + \underbrace{\frac{1}{2}[\overbrace{b_{s^2}}^{\frac{4}{7}(1-b_1)}][\overbrace{s(\mathbf{x})^2}^{\text{tidal tensor}}]}_{\text{non-local Eulerian}}$$

McDonald & Roy 2009; Baldauf et al. 2012

Bispectrum: Tree-level

We can model the bias using PT in real and redshift space,

$$B_g(\mathbf{k}_1,\mathbf{k}_2) = \sigma_8^4 b_1^4 \left\{ 2P_{\rm lin}(k_1)\ P_{\rm lin}(k_2)\ \left[\frac{1}{b_1}F_2(\mathbf{k}_1,\mathbf{k}_2) + \frac{b_2}{2b_1^2} + \frac{2}{7b_1^2}(1-b_1)S_2(\mathbf{k}_1,\mathbf{k}_2)\right] + \text{cyc.} \right\},$$

$$B_g^{(s)}(\mathbf{k}_1,\mathbf{k}_2) = \sigma_8^4 \left[2P_{\rm lin}(k_1)\, Z_1(\mathbf{k}_1)\, P_{\rm lin}(k_2)\, Z_1(\mathbf{k}_2)\, Z_2(\mathbf{k}_1,\mathbf{k}_2) + \text{cyc.}\right].$$

$$\begin{aligned} Z_1(\mathbf{k}_i) &\equiv (b_1 + f\mu_i^2) \\ Z_2(\mathbf{k}_1,\mathbf{k}_2) &\equiv b_1\left[F_2(\mathbf{k}_1,\mathbf{k}_2) + \frac{f\mu k}{2}\left(\frac{\mu_1}{k_1}+\frac{\mu_2}{k_2}\right)\right] + f\mu^2 G_2(\mathbf{k}_1,\mathbf{k}_2) + \\ &+ \frac{f^3\mu k}{2}\mu_1\mu_2\left(\frac{\mu_2}{k_1}+\frac{\mu_1}{k_2}\right) + \frac{b_2}{2} + \frac{2}{7}(1-b_1)S_2(\mathbf{k}_1,\mathbf{k}_2) \end{aligned}$$

Bispectrum: Tree-level

Bispectrum monopole,

$$B_g^{(0)}(\mathbf{k}_1,\mathbf{k}_2)=\int d\mu_1 d\mu_2 B_g^{(s)}(\mathbf{k}_1,\mathbf{k}_2)\,.$$

Simplest expression with no-FoG:

$$\begin{aligned} B_g^{(0)}(\mathbf{k}_1,\mathbf{k}_2) &= P_{\rm lin}(k_1)P_{\rm lin}(k_2)b_1^4\sigma_8^4\left\{\frac{1}{b_1}F_2(k_1,k_2,\cos\theta_{12})\mathcal{D}^{(0)}_{\rm SQ1}\right.\\ &+ \frac{1}{b_1}G_2(k_1,k_2,\cos\theta_{12})\mathcal{D}^{(0)}_{\rm SQ2}\\ &+ \left.\left[\frac{b_2}{b_1^2}+\frac{b_{s^2}}{b_1^2}S_2(\mathbf{k}_1,\mathbf{k}_2)\right]\mathcal{D}^{(0)}_{\rm NLB}+\mathcal{D}^{(0)}_{\rm FoG}\right\}+\text{cyc.}\end{aligned}$$

Scoccimarro et al. (1999)

Bispectrum: Tree-level

$$
\begin{aligned}
\mathcal{D}^{(0)}_{\rm SQ1} &= \frac{2(15+10\beta+\beta^2+2\beta^2x_{12}^2)}{15}, \\
\mathcal{D}^{(0)}_{\rm SQ2} &= 2\beta\left(35y_{12}^2+28\beta y_{12}^2+3\beta^2y_{12}^2+35+28\beta+\right. \\
&+ 3\beta^2+70y_{12}x_{12}+84\beta y_{12}x_{12}+18\beta^2y_{12}x_{12}+14\beta y_{12}^2x_{12}^2+12\beta \\
&+ +14\beta x_{12}^2+12\beta^2x_{12}^2+12\beta^2y_{12}x_{12}^3\left.\right)/[105(1+y_{12}^2+2x_{12}y_{12})], \\
\mathcal{D}^{(0)}_{\rm NLB} &= \frac{(15+10\beta+\beta^2+2\beta^2x_{12}^2)}{15}, \\
\mathcal{D}^{(0)}_{\rm FoG} &= \beta\left(210+210\beta+54\beta^2+6\beta^3+105y_{12}x+189\beta y_{12}x_{12}+\right. \\
&+ 99\beta^2y_{12}x_{12}+15\beta^3y_{12}x_{12}+105y_{12}^{-1}x_{12}+189\beta y_{12}^{-1}x+99\beta^2y_1 \\
&+ \ldots
\end{aligned}
$$

$(\beta\equiv f/b_1;\ x_{12}\equiv\cos(\theta_{12});\ y_{12}\equiv k_1/k_2)$,

Bispectrum: Beyond tree-level

Tree level only provides an accurate description at large scales and at high redshifts.

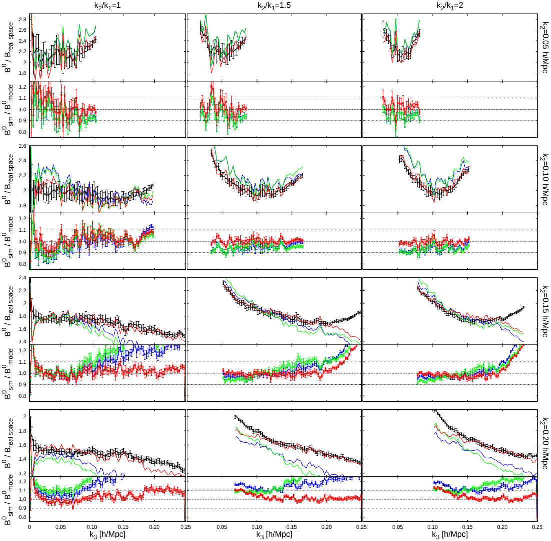
Empirical improvement of this formula through effective kernels method (Scoccimarro & Couchman (2001))

- $F_2 \to F_2^{\rm eff}$ (G-M et al. 2012) **JCAP...02..047G**
- $G_2 \to G_2^{\rm eff}$ (G-M et al. 2014) **JCAP...12..029G**

9 free parameters each kernel to be fitted from dark matter N-body simulations. Independent of scale or redshift, weakly dependent with cosmology.

dark matter particles
$z = 0.5$

- $F_2^{\rm eff}$ & $G_2^{\rm eff}$ in $Z_2^{\rm eff}$
- $F_2^{\rm eff}$ & G_2 in $Z_2^{\rm eff}$
- F_2 & G_2 in Z_2



Parametrization

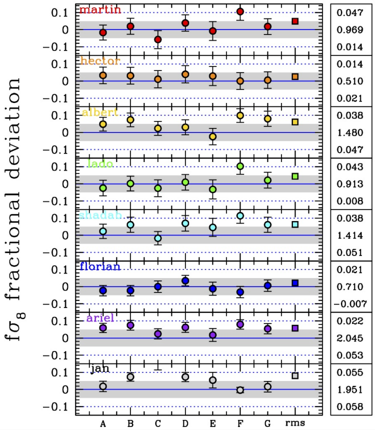
The total number of free parameters of the model is,

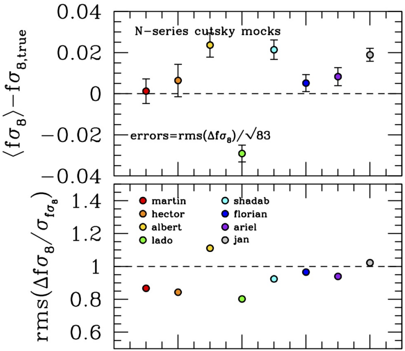
- Bias Parameters: b_1, b_2
- **Cosmology Parameters:** f, σ_8
- **AP parameters:** $\alpha_{\|}$, $\alpha_{\perp} \rightarrow D_A/r_s(z_d)$ and $H(z)r_s(z_d)$
- Fingers-of-God: σ^P_{FoG}, σ^B_{FoG}
- Shot noise amplitude A_{Noise}

8/9 free parameters $\rightarrow$ 4 cosmological, 4/5 "nuissance"
Use of Covariance matrices estimated from PATCHY mocks (2048 realizations) by (Kitaura et al. 2016)
Correction from Hartlap et al. 2007.

Potential Systematics on RSD Power Spectrum

Tinker et al in prep.

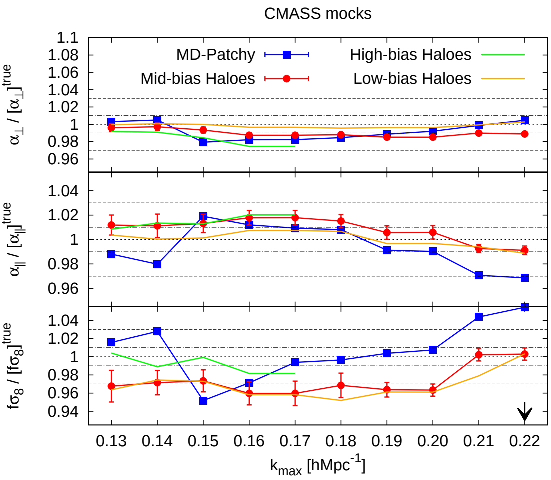




Potential Systematics on RSD Bispectrum

Name	$M^{\rm h}_{\rm min}\,(N_p)$	b_1	b_2	$\bar{n}\times 10^4$
Low-bias N-body	3.80 (50)	1.75	-0.26	6.75
Mid-bias N-body	5.75 (75)	1.90	0.22	4.41
High-bias N-body	8.36 (110)	2.07	0.49	2.90
MD-PATCHY (LOWZ)	-	2.08	0.43	4.0
MD-PATCHY (CMASS)	-	1.97	0.29	4.5
Data (LOWZ)	-	2.08	0.92	4.0
Data (CMASS)	-	2.01	0.68	4.5

Potential Systematics on RSD Bispectrum



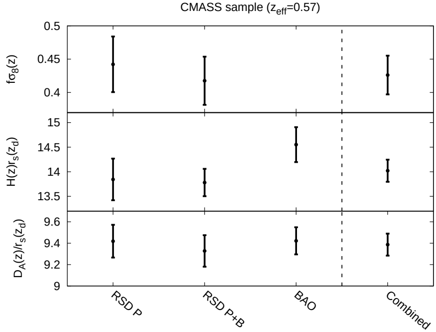
Potential Systematics on RSD Bispectrum

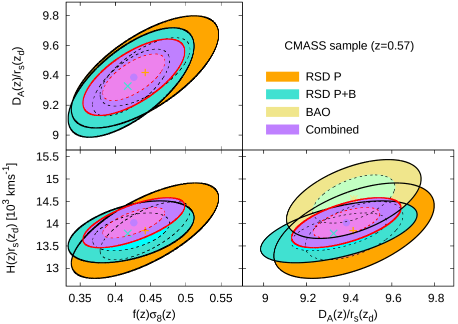
Sum up on systematics

- The systematics in the BAO constrains are negligible if we add them in quadrature with statistical errors (GM et al 2016a.)
- From mock challenge, the full-shape systematics on PS analysis are of order $\lesssim 0.018$ on $f\sigma_8$ (Tinker et al in prep.).
- From N-body haloes & mock challenge, the full-shape systematics on BS analysis are $\lesssim 0.027$ on $f\sigma_8$ and $\sim 1\%$ on α_x.

Combining BAO and RSD analysis

Using the mocks we work out the correlation among $f\sigma_8$, D_A and H estimated from RSD and BAO analyses.





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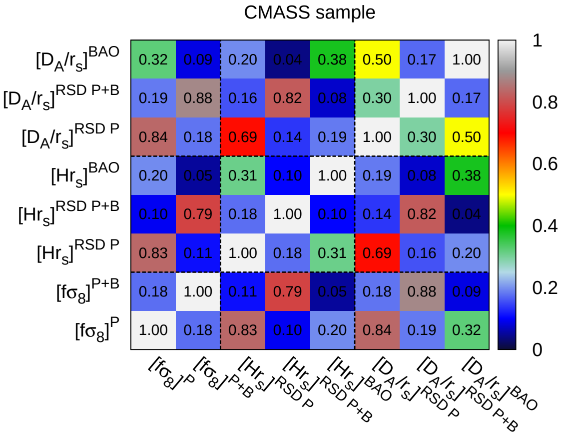


Combining BAO and RSD analysis

Combined BAO + RSD (PS + BS) from DR12 sample.

	LOWZ	CMASS
$f\sigma_8(z_{\rm eff})$	0.427 ± 0.056 [13%]	0.426 ± 0.029 [6.8%]
$H(z_{\rm eff})r_s(z_d)$ $[10^3 \mathrm{km} s^{-1}]$	11.55 ± 0.38 [3.2%]	14.02 ± 0.22 [1.6%]
$D_A(z_{\rm eff})/r_s(z_d)$	6.60 ± 0.13 [2.0%]	9.39 ± 0.10 [1.0%]

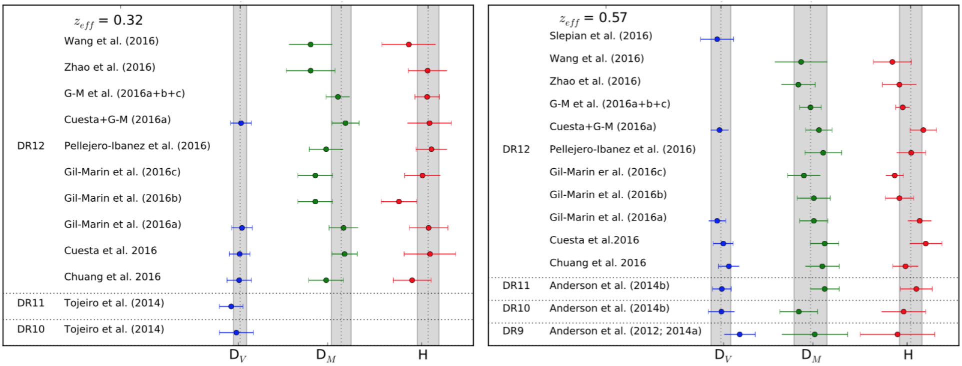
Combining BAO and RSD analysis

RSD (PS + only) from DR12 sample.

	LOWZ	CMASS
$f\sigma_8(z_{\rm eff})$	0.394 ± 0.067 [17%]	0.444 ± 0.041 [9.4%]
$H(z_{\rm eff})r_s(z_d)$ $[10^3 \mathrm{km} s^{-1}]$	11.41 ± 0.56 [4.9%]	13.92 ± 0.44 [3.1%]
$D_A(z_{\rm eff})/r_s(z_d)$	6.35 ± 0.19 [3.0%]	9.42 ± 0.15 [1.6%]

Comparison with DR12 analyses

Alam et al. 2016



Comparison with DR12 analyses

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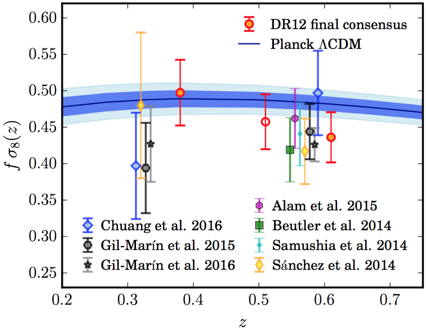
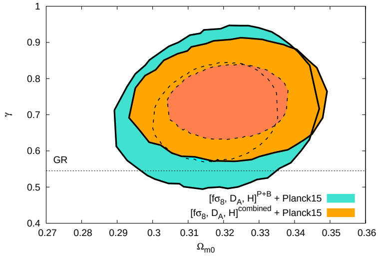


- Mild tension between GR+Planck and RSD analyses from different surveys
- Using LOWZ and CMASS data points only yields to a $\sim 2.7\sigma$! tension on γ ($f = \Omega_m^\gamma$) w.r.t. GR predictions

GR-γ test

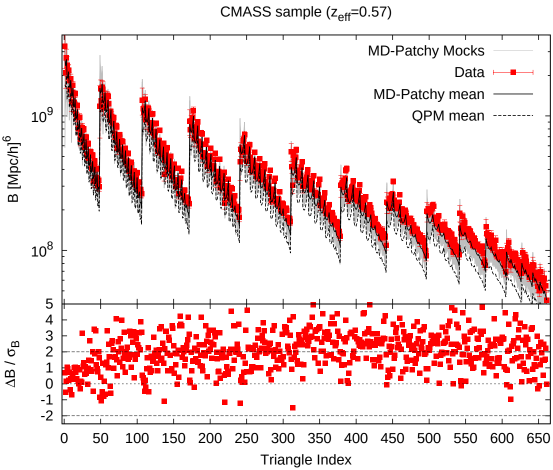


Assumptions	γ	Ω_{m0}
$[f,\ D_A,\ H]^{\mathrm{P+B}}$	$0.80^{+0.31}_{-0.23}$	$0.20^{+0.14}_{-0.10}$
$[f\sigma_8,\ D_A,\ H]^{\mathrm{P+B}}$	$0.33^{+0.41}_{-0.47}$	$0.330^{+0.058}_{-0.064}$
$[f\sigma_8,\ D_A,\ H]^{\mathrm{combined}}$	$0.18^{+0.29}_{-0.34}$	$0.341^{+0.045}_{-0.046}$
$[f,\ D_A,\ H]^{\mathrm{P+B}}+Planck15$	$0.95^{+0.26}_{-0.23}$	0.315 ± 0.012
$[f\sigma_8,\ D_A,\ H]^{\mathrm{P+B}}+Planck15$	$0.701^{+0.088}_{-0.093}$	$0.318^{+0.012}_{-0.011}$
$[f\sigma_8,\ D_A,\ H]^{\mathrm{combined}}+Planck15$	$0.733^{+0.068}_{-0.069}$	$0.320^{+0.011}_{-0.012}$

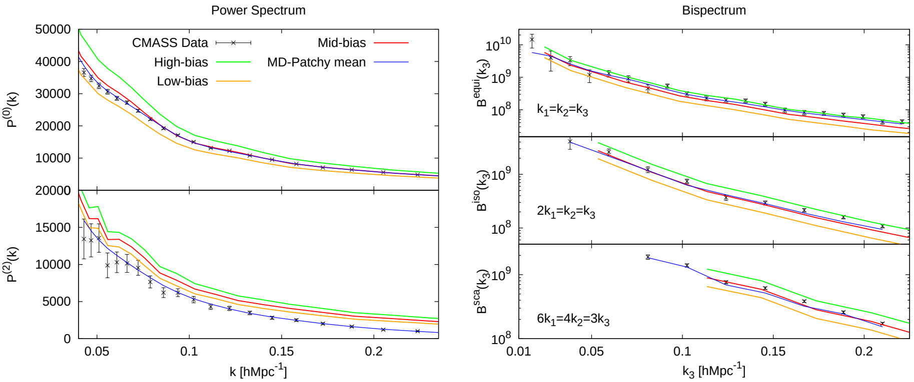
Conclusions

- We have measured the **power spectrum** monopole (isotropic), quadrupole (anisotropic) and **bispectrum** monopole signal from the BOSS DR12 galaxies.
- We have constrained cosmological parameters: the **growth of structure** of the Universe, $f\sigma_8(z_{\rm eff})$, **Hubble Parameter** $H(z_{\rm eff})$ and the **angular diameter distance** $D_A(z_{\rm eff})$.
- We have shown how the bispectrum adds **significant** amount of information in addition to the power spectrum (pre- and post-recon) and therefore is a statistic it must be considered in future surveys such as DESI and Euclid if we want to extract all the information available.

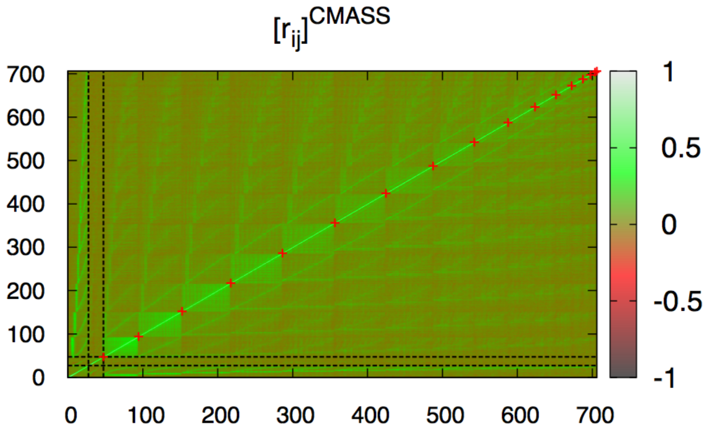
Mocks vs. Data



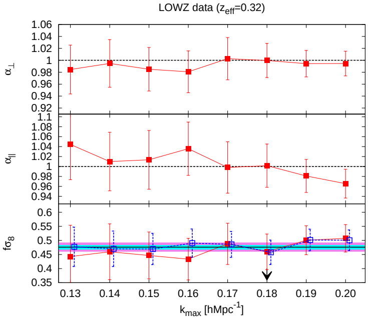
Mocks vs. Data

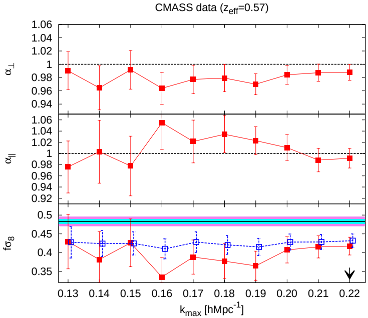


CMASS Covariance



Data vs k_{max}


LOWZ data (z_{eff}=0.32)
$\alpha_\perp$
$\alpha_{||}$
$f\sigma_8$
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
1.1
1.08
0.6
0.55
0.5
0.45
0.4
0.35
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
k_{max} [hMpc^{-1}]


CMASS data (z_{eff}=0.57)
$\alpha_\perp$
$\alpha_{||}$
$f\sigma_8$
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.5
0.45
0.4
0.35
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
0.21
0.22
k_{max} [hMpc^{-1}]

Post-recon Bispectrum