The power spectrum and bispectrum of the CMASS BOSS galaxies

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Theoretical and Observational Progress on LSS of the Universe
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
- Map the spatial distribution of luminous red galaxies and quasars
- Total coverage area 10,000 square degrees

- CMASS BOSS Galaxies: LRGs.
  - $0.43 \leq z \leq 0.70$
  - $\sim 7 \cdot 10^5$ galaxies
  - Volume of $6 \text{ Gpc}^3$
  - 10,000 deg$^2$ area
Introduction: the BOSS survey

CMASS sample with $z_{\text{eff}} = 0.57$.

Anderson et al. (2013)
Previous measurements of the **bispectrum** or **3-PCF** in spectroscopic galaxy surveys,

- 1982, CfA Redshift Survey ($\sim 1,000$ galaxies)
  [Baumgart & Fry (1991)]
- 1995, APM survey ($\sim 1.3 \cdot 10^6$ galaxies)
  [Frieman & Gaztañaga (1999)]
- 1995, IRAS - PSCz ($\sim 15,000$ galaxies)
  [Feldman et al. (2001), Scoccimarro et al. (2001)]
- 2002, 2dFGRS ($\sim 1.3 \cdot 10^5$ galaxies)
  [Verde el al. (2002)]
- 2013, WiggleZ ($\sim 2 \cdot 10^5$ galaxies)
  [Marín et al. 2013]
- 2015 SDSS-III (DR11 BOSS-CMASS) ($\sim 7 \cdot 10^5$ galaxies)
  [HGM et al. 2015a, 2015b]
Introduction: Statistical moments

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

\[ \langle \delta_{k_1} \delta_{k_2} \rangle = (2\pi)^3 P(k_1) \delta^D(k_1 + k_2) \]

- It contains information about the clustering.

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

\[ \langle \delta_{k_1} \delta_{k_2} \delta_{k_3} \rangle = (2\pi)^3 B(k_1, k_2) \delta^D(k_1 + k_2 + k_3) \]

- It essentially contains information about the non-Gaussianities: primordial + gravitationally induced
- Since is gravitationally sensible → Test of GR
- It is essential to break the typical degeneracies between bias parameters, \( \sigma_8 \) and \( f \).
Measurements: Power Spectrum Monopole

HGM et al. 2015a

The power spectrum and bispectrum of the CMASS BOSS galaxies
Measurements: Bispectrum Monopole

HGM et al. 2015a
Measurements: Reduced Bispectrum

HGM et al. 2015a
Galaxy Bias

Galaxies are a biased tracers of dark matter. We chose a non-linear and non-local bias model,

\[ \delta_g(x) = b_1 \delta(x) + \frac{1}{2} b_2 [\delta(x)^2] + \frac{1}{2} b_s^2 [s(x)^2] \]

We choose that the bias is local in Lagrangian space,

\[ \delta_g(x) = b_1 \delta(x) + \frac{1}{2} b_2 [\delta(x)^2] + \frac{1}{2} \left[ \frac{4}{7} (1 - b_1) \right] [s(x)^2] \]

which is in agreement with the synthetic halo and galaxy catalogues for the power spectrum and bispectrum.
The Kaiser (linear order) prediction for the power spectrum multipoles is,

\[ P_g^{(0)}(k) = P_{\text{lin}}(k)\sigma_8^2 \left( b_1^2 + \frac{2}{3} fb_1 + \frac{1}{5} f^2 \right) \]  
Monopole

\[ P_g^{(2)}(k) = P_{\text{lin}}(k)\sigma_8^2 \left( \frac{4}{3} fb_1 + \frac{4}{5} f^2 \right) \]  
Quadrupole

Measuring the amplitude of \( P_g^{(0)} \) and \( P_g^{(2)} \) at large scales respect to \( P_{\text{lin}} \), \( b_1\sigma_8 \) and \( f\sigma_8 \) can be inferred.

In our analysis we use more complex model,

- Real space matter power spectrum is modelled through 2-loop RPT (HGM et al. 2012)
- Redshift space distortions for the power spectrum are modelled using TNS model (Taruya, Nishimichi & Saito 2010)
RSD: Bispectrum

We can model the bias using perturbation theory. In real space tree level,

\[ B_g(k_1, k_2) = \sigma_8^4 b_1^4 \left\{ 2P_{\text{lin}}(k_1) P_{\text{lin}}(k_2) \left[ \frac{1}{b_1} F_2(k_1, k_2) + \frac{b_2}{2b_1^2} \right. \right. \]

\[ + \left. \left. \frac{2}{7b_1^2} (1 - b_1) S_2(k_1, k_2) \right] + \text{cyc.} \right\}, \]

and in redshift space

\[ B_{g}^{(s)}(k_1, k_2) = \sigma_8^4 [2P_{\text{lin}}(k_1) Z_1(k_1) P_{\text{lin}}(k_2) Z_1(k_2) Z_2(k_1, k_2) + \text{cyc.}] . \]

\[ Z_1(k_i) \equiv (b_1 + f \mu_i^2) \]
\[ Z_2(k_1, k_2) \equiv b_1 \left[ F_2(k_1, k_2) + \frac{f \mu k}{2} \left( \frac{\mu_1}{k_1} + \frac{\mu_2}{k_2} \right) \right] + f \mu^2 G_2(k_1, k_2) + \frac{f^3 \mu k}{2} \mu_1 \mu_2 \left( \frac{\mu_2}{k_1} + \frac{\mu_1}{k_2} \right) + \frac{b_2}{2} + \frac{2}{7} (1 - b_1) S_2(k_1, k_2) \]
RSD: Bispectrum

Bispectrum monopole,

\[ B_g^{(0)}(k_1, k_2) = \int d\mu_1 d\mu_2 B_g^{(s)}(k_1, k_2). \]

\[
B_g^{(0)}(k_1, k_2) = P_{\text{lin}}(k_1)P_{\text{lin}}(k_2)b_1^4\sigma_8^4 \left\{ \frac{1}{b_1} F_2(k_1, k_2, \cos \theta_{12})D_{SQ1}^{(0)} 
+ \frac{1}{b_1} G_2(k_1, k_2, \cos \theta_{12})D_{SQ2}^{(0)} 
+ \left[ \frac{b_2}{b_1^2} + \frac{b_s^2}{b_1^2} S_2(k_1, k_2) \right] D_{\text{NLB}}^{(0)} + D_{\text{FoG}}^{(0)} \right\} + \text{cyc.}
\]

Scoccimarro et al. (1999)
RSD: Bispectrum

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

$$
\mathcal{D}^{(0)}_{\text{SQ1}} = \frac{2(15 + 10\beta + \beta^2 + 2\beta^2 x_{12}^2)}{15},
$$

$$
\mathcal{D}^{(0)}_{\text{SQ2}} = 2\beta \left(35y_{12}^2 + 28\beta y_{12}^2 + 3\beta^2 y_{12}^2 + 35 + 28\beta + 3\beta^2 + 70y_{12}x_{12} + 84\beta y_{12}x_{12} + 18\beta^2 y_{12}x_{12} + 14\beta y_{12}^2 x_{12}^2 + 12\beta^2 y_{12}^2 x_{12}^2 + 14\beta x_{12}^2 + 12\beta^2 x_{12}^2 + 12\beta^2 y_{12}^2 x_{12}^3 \right) / [105(1 + y_{12}^2 + 2x_{12}y_{12})],
$$

$$
\mathcal{D}^{(0)}_{\text{NLB}} = \frac{(15 + 10\beta + \beta^2 + 2\beta^2 x_{12}^2)}{15},
$$

$$
\mathcal{D}^{(0)}_{\text{FoG}} = \beta \left(210 + 210\beta + 54\beta^2 + 6\beta^3 + 105y_{12}x + 189\beta y_{12}x_{12} + 99\beta^2 y_{12}x_{12} + 15\beta^3 y_{12}x_{12} + 105y_{12}^{-1}x_{12} + 189\beta y_{12}^{-1}x + 99\beta^2 y_{12}^{-1}x_{12} + 168\beta x_{12}^2 + 216\beta^2 x_{12}^2 + 48\beta^3 x_{12}^2 + 36\beta^2 y_{12}x_{12}^3 + 20\beta^3 y_{12}^{-1}x_{12}^3 + 36\beta^2 y_{12}^{-1}x_{12}^3 + 20\beta^3 y_{12}x_{12}^3 + 16\beta^3 x_{12}^4 \right) / 315,
$$
RSD: Bispectrum

Tree level (already very complex!) only provides an accurate description at large scales and at high redshifts. Empirical improvement of this formula through effective kernels method (Scoccimarro & Couchman (2001))

- $F_2 \rightarrow F_{2}^{\text{eff}}$ (HGM et al. 2012)
- $G_2 \rightarrow G_{2}^{\text{eff}}$ (HGM et al. 2014)

9 free parameters each kernel to be fitted from dark matter N-body simulations. Independent of scale or redshift, weakly dependent with cosmology.
The PS and BS models we considered here have 7 free independent parameters:

- The bias parameters: $b_1, b_2$
- Dark matter power spectrum amplitude, $\sigma_8^2$
- Growth rate of structure $f = \frac{d \log \delta}{d \log a}$
- Fingers of God damping functions: $\sigma_{fog}^P, \sigma_{fog}^B$
- Shot Noise term amplitude term, $A_{\text{noise}}$
Estimating the parameters

Estimation of the best-fit parameters, $\Psi$, and their error.

$$
\chi^2_{\text{diag.}}(\Psi) = \sum_{k-\text{bins}} \frac{\left[ P^{\text{meas.}}(k) - P^{\text{model}}(k, \Psi; \Omega) \right]^2}{\sigma_P(k)^2} + \\
+ \sum_{\text{triangles}} \frac{\left[ B^{\text{meas.}}(k_1, k_2, k_3) - B^{\text{model}}(k_1, k_2, k_3, \Psi; \Omega) \right]^2}{\sigma_B(k_1, k_2, k_3)^2},
$$

$\langle \Psi_i \rangle$ is a non-optimal and unbiased estimator of $\Psi_{\text{true}}$, (see Verde et al. 2001)

$$
\Psi_{\text{true}} \simeq \langle \Psi_i \rangle \pm \sqrt{\langle \Psi_i^2 \rangle - \langle \Psi_i \rangle^2}
$$

1$\sigma$-error is given by the dispersion of mocks around to their mean.
Cosmological parameters: \( f \) vs. \( \sigma_8 \)

Power Spectrum Monopole + Bispectrum Monopole.

600 Mocks based on PTHALOS (Manera et al. 2013) at \( z_{\text{eff}} = 0.57 \).

1\( \sigma \) contours from the mocks density of points.

Data from NGC CMASS BOSS galaxies.

\[ \begin{align*}
\log_{10}[f] & \quad \log_{10}[\sigma_8] \\
\log_{10}[b_2] & \quad \log_{10}[b_1] \\
\log_{10}[f] & \quad \log_{10}[\sigma_8] \\
\log_{10}[b_2] & \quad \log_{10}[b_1]
\end{align*} \]

\( k_{\text{max}} = 0.17 \) h/Mpc

HGM et al. 2015a
Cosmological parameters: $f$ vs. $\sigma_8$

The power spectrum and bispectrum of the CMASS BOSS galaxies

$k_{\text{max}} = 0.17 \, \text{h/Mpc}$
Cosmological parameters: $f$ vs. $\sigma_8$

- Dependence with the minimum scale
- Breaking $f$ and $\sigma_8$ degeneracy
- Comparison with CMASS DR11 $f\sigma_8$ measurements

The power spectrum and bispectrum of the CMASS BOSS galaxies
Measurements: Dependence with the scale

No significant dependence with minimum scale used up to
\( k_{\text{max}} = 0.17 \, h\text{Mpc}^{-1} \),

\[
\begin{align*}
\sigma_8^{f0.43} |_{z=0.57} & = 0.582 \pm 0.084 \\
\sigma_8^{b1.40} |_{z=0.57} & = 1.672 \pm 0.060 \\
\sigma_8^{b0.30} |_{z=0.57} & = 0.579 \pm 0.082
\end{align*}
\]
Measurements: Breaking $f$ and $\sigma_8$ degeneracy

- For constraining $f$ and $\sigma_8$ alone we need information from $P^{(0)}$, $P^{(2)}$ and $B^{(0)}$.
- We combine “a posteriori” the measurements on $f^{0.43}\sigma_8$ with $f\sigma_8$ measurements (Samushia et al. 2013)

\[
\begin{align*}
f\sigma_8|_{z=0.57} &= 0.447 \pm 0.028 \\
f^{0.43}\sigma_8|_{z=0.57} &= 0.582 \pm 0.084 \\
f(z = 0.57) &= 0.63 \pm 0.16 (25\%) \\
\sigma_8(z = 0.57) &= 0.710 \pm 0.086 (12\%)
\end{align*}
\]

Results to be improved when the combination is “a priori”
Assuming a $f_{\text{Planck}} = 0.777$, we can project $f^{0.43}\sigma_8$ bispectrum result into $f\sigma_8$ plane to compare with $P^{(0)} + P^{(2)}$ DR11 CMASS results:

$$[f\sigma_8]_{\text{est.}} \equiv [f^{0.43}\sigma_8]f^{0.57}_{\text{Planck}}$$

\[f\sigma_8\]_{\text{est.}} = 0.504 \pm 0.069
We have combined the power spectrum monopole with the bispectrum monopole to set constrains in the cosmological parameters.

Using the galaxy mocks we have determined that $b_1^{1.40}\sigma_8$, $b_2^{0.30}\sigma_8$ and $f^{0.43}\sigma_8$ are the parameters less affected by degenerations.

The results on $f^{0.43}\sigma_8$ are robust under changes in the minimum scale used for the fit.

Combining $f^{0.43}\sigma_8$ measurements with $f\sigma_8$ measurements from the same galaxy sample, $f$ and $\sigma_8$ can be estimated separately.
Conclusions

Future work for DR12 sample,

- Include full covariance of $P$ and $B$
- Include power spectrum quadrupole and perform a full fit $P^{(0)} + P^{(2)} + B^{(0)}$ in order to constrain $f$ and $\sigma_8$.
- Improve modelling for RSD in the bispectrum.
Conclusions

Thank you for your attention!