The power spectrum and bispectrum of the CMASS BOSS galaxies

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arXiv:1407.1836, arxiv:1407.5668, & arxiv:1408:0027

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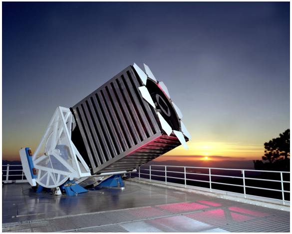
Outline

Introduction: the BOSS survey

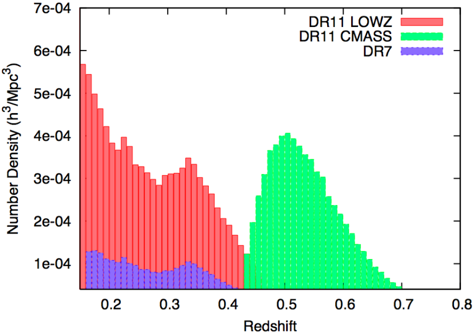
- Apache Point Observatory (APO) 2.5-m telescope for five years from 2009-2014.
- Part of SDSS-III project. BOSS: Baryon Oscillation Spectroscopic Survey
- Map the spatial distribution of luminous red galaxies and quasars
- Total coverage area 10,000 square degrees

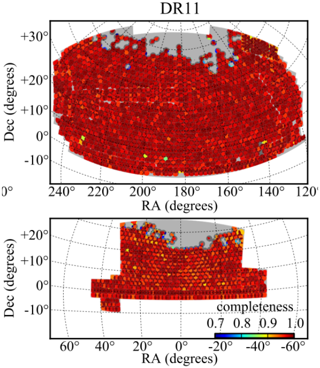
- CMASS BOSS Galaxies: LRGs.
- $0.43 \leq z \leq 0.70$
- $\sim 7 \cdot 10^5$ galaxies
- Volume of $6\,\mathrm{Gpc}^3$
- 10.000 deg^2 area



Introduction: the BOSS survey

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





Anderson et al. (2013)

Introduction: Statistical moments

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.

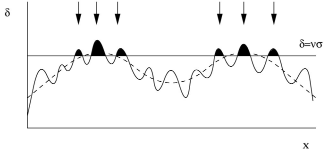
2. The **bispectrum** is the Fourier transform of the 3-point function.

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

   - It essentially contains information about the non-Gaussianities: primordial + gravitationally induced
   - Since is gravitationally sensible → Test of GR
   - It is essential to break the typical degeneracies between bias parameters, σ_8 and f.

Introduction: Galaxy Bias

Galaxies are a biased tracers of dark matter.



- Eulerian linear bias model,

$$\delta_g(\mathbf{x}) = b_1 \delta(\mathbf{x})$$

- Eulerian non-linear, local bias model,

$$\delta_g(\mathbf{x}) = \sum_i \frac{b_i}{i!}(\delta^i(\mathbf{x}) - \sigma_i)$$

- Eulerian non-local bias model,

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

where $s(\mathbf{x})$ is the tidal tensor

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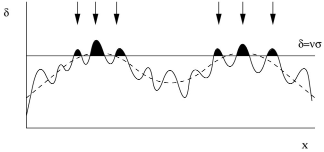

- Eulerian linear bias model,

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- Eulerian non-linear, local bias model,

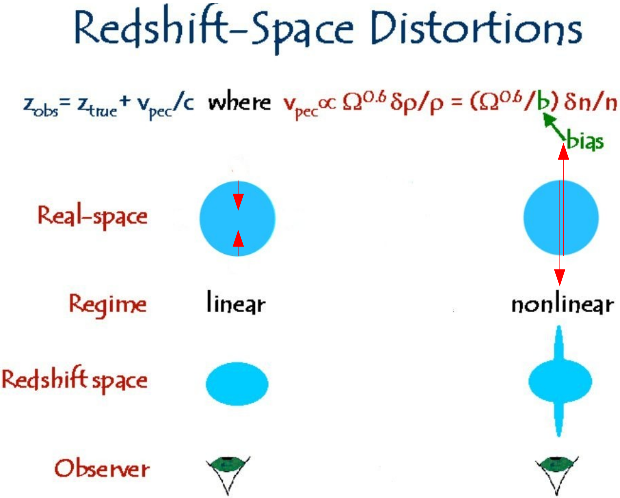
$$\delta_g(\mathbf{x}) = \sum_i \frac{b_i}{i!}(\delta^i(\mathbf{x}) - \sigma_i)$$

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

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

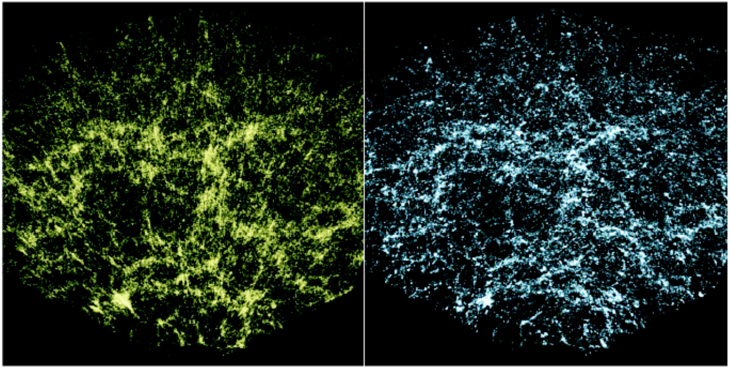
where $s(\mathbf{x})$ is the tidal tensor

Redshift space distortions: Introduction



Redshift space distortions: Introduction

Redshift space **Real space**



Redshift space distortions: Linear order

For the power spectrum, the linear term can be modelled analytically (Kaiser 1984),

$$P_g^{(s)}(k,\mu) = \left[b_1 + f\mu^2\right]^2 \sigma_8^2 P_{\rm lin}(k)$$

$P^{(s)}(k,\mu)$ can be expressed in the Legendre polynomial basis, $P^{(\ell)}$, defined as,

$$P_g^{(\ell)}(k) = \frac{(2\ell+1)}{2}\int_{-1}^{1} d\mu\, P_g^{(s)}(k,\mu)L_\ell(\mu),$$

Redshift space distortions: Linear order

where L_ℓ are the Legendre polynomials of order ℓ.

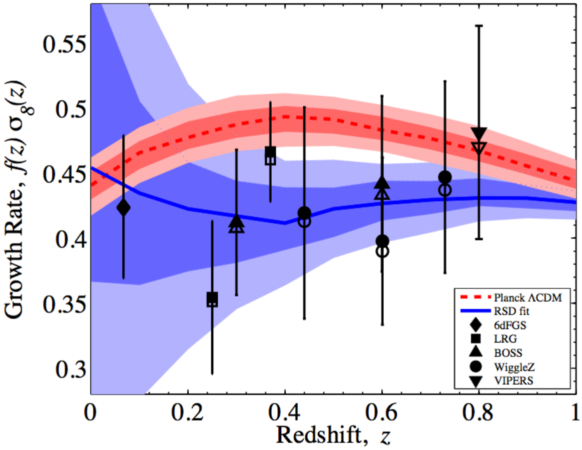
$$P_g^{(0)}(k) = P_{\rm lin}(k)\sigma_8^2\left(b_1^2 + \frac{2}{3}fb_1 + \frac{1}{5}f^2\right) \qquad \text{Monopole}$$

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

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

Following this idea, but with more complex modelling for non-linear scales, $f\sigma_8$ has been measured from the DR11 CMASS BOSS galaxies: *Beutler et al. (2013), Chuang et al. (2013), Sanchez et al. (2013), Samushia et al. (2013)*

But $1-2\sigma$ tension with the CMB...



Macaulay, Wehus & Eriksen (2013)

Bispectrum: History

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]
- 2014 SDSS-III (DR11 BOSS-CMASS) ($\sim 7 \cdot 10^5$ galaxies) [HGM et al. 2014b, 2014c]

Bispectrum: Tree-level

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

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

and in redshift space

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

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

Bispectrum: Tree-level

Bispectrum monopole,

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

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

Scoccimarro et al. (1999)

Bispectrum: Tree-level

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

$$
\begin{aligned}
\mathcal{D}^{(0)}_{\rm SQ1} &= \frac{2(15+10\beta+\beta^2+2\beta^2x^2)}{15}, \\
\mathcal{D}^{(0)}_{\rm SQ2} &= 2\beta\left(35y_{12}^2+28\beta y_{12}^2+3\beta^2y_{12}^2+35+28\beta+\right. \\
&+ 3\beta^2+70y_{12}x_{12}+84\beta y_{12}x_{12}+18\beta^2y_{12}x_{12}+14\beta y_{12}^2x_{12}^2+12\beta^2y_{12}^2x_{12}^2 \\
&+ \left.+14\beta x_{12}^2+12\beta^2x_{12}^2+12\beta^2y_{12}x_{12}^3\right)/[105(1+y_{12}^2+2x_{12}y_{12})], \\
\mathcal{D}^{(0)}_{\rm NLB} &= \frac{(15+10\beta+\beta^2+2\beta^2x^2)}{15}, \\
\mathcal{D}^{(0)}_{\rm FoG} &= \beta\left(210+210\beta+54\beta^2+6\beta^3+105y_{12}x+189\beta y_{12}x_{12}+\right. \\
&+ 99\beta^2y_{12}x_{12}+15\beta^3y_{12}x_{12}+105y_{12}^{-1}x_{12}+189\beta y_{12}^{-1}x+99\beta^2y_{12}^{-1}x_{12}+ \\
&+ 168\beta x_{12}^2+216\beta^2x_{12}^2+48\beta^3x_{12}^2+36\beta^2y_{12}x_{12}^3+20\beta^3y_{12}^{-1}x_{12}^3+ \\
&+ \left.36\beta^2y_{12}^{-1}x_{12}^3+20\beta^3y_{12}x_{12}^3+16\beta^3x_{12}^4\right)/315,
\end{aligned}
$$

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))

- $F_2 \to F_2^{\rm eff}$ (HGM et al. 2012) **[arXiv:1111.4477]**
- $G_2 \to G_2^{\rm eff}$ (HGM et al. 2014a) **[arXiv:1407.1836]**

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

Bispectrum: Estimating the parameters

The PS and BS models we considered here have 7 free independent parameters:

- The bias parameters: b_1, b_2 (local Lagrangian bias, $b_{s2} = -4/7[b_1 - 1]$),
- Dark matter power spectrum amplitude, σ_8^2: $P_{lin}(k) \to \sigma_8^2 P_{lin}(k)$
- Growth rate of structure $f = \frac{d \log \delta}{d \log a}$
- Fingers of God damping functions: σ_{fog}^P, σ_{fog}^B
- Shot Noise term amplitude term, $A_{\rm noise}$: $A_{\rm noise} > 0$ (sub-Poisson); $A_{\rm noise} < 0$ (super-Poisson).

Bispectrum Estimating the parameters

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

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

$\langle \mathbf{\Psi}_{\rm i} \rangle$ is a **non-optimal and unbiased** estimator of $\mathbf{\Psi}_{\rm true}$, (see Verde et al. 2001)

$$\mathbf{\Psi}_{\rm true} \simeq \langle \mathbf{\Psi}_{\rm i} \rangle \pm \sqrt{\langle \mathbf{\Psi}_{\rm i}^2 \rangle - \langle \mathbf{\Psi}_{\rm i} \rangle^2}$$

1σ-error is given by the dispersion of mocks around to their mean.

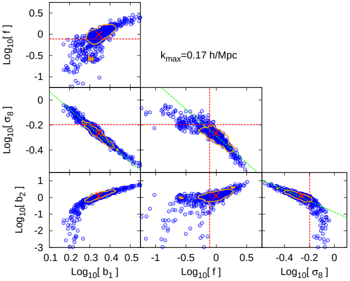
Measurements: Degenerations

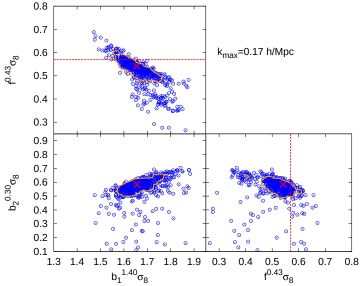
Power Spectrum Monopole + Bispectrum Monopole.

600 Mocks based on pt-haloes (Manera et al. 2013) at $z_{\rm eff} = 0.57$.

1σ contours from the mocks density of points

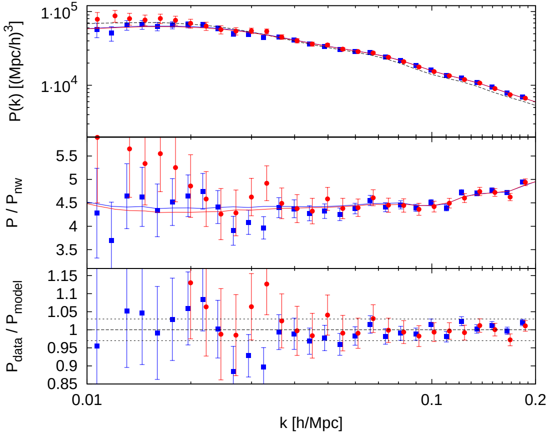
Data from NGC CMASS BOSS galaxies





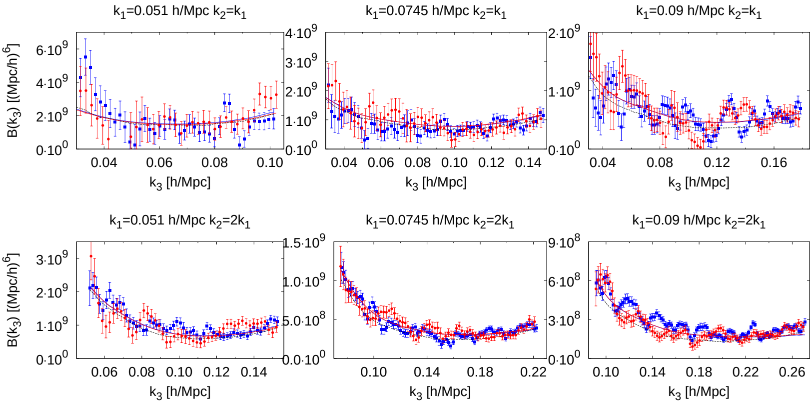
HGM et al. 2014b **[arxiv:1407.5668]**

Measurements: Power Spectrum Monopole



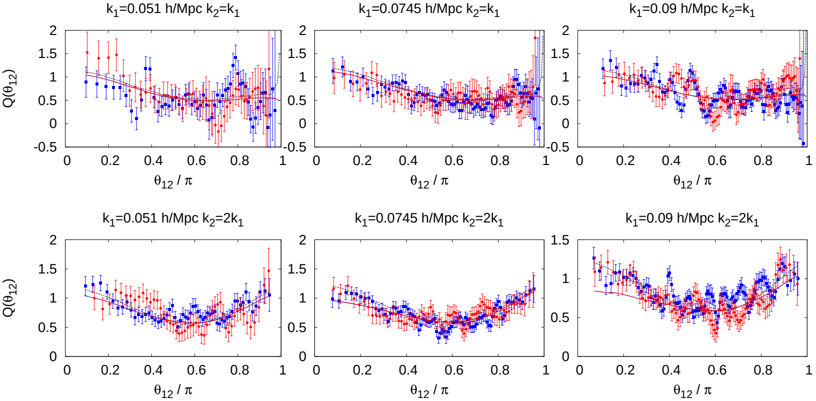
HGM et al. 2014b [arxiv:1407.5668]

Measurements: Bispectrum Monopole



HGM et al. 2014b **[arxiv:1407.5668]**

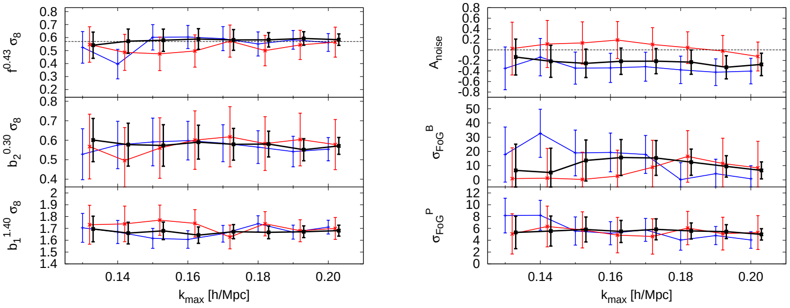
Measurements: Reduced Bispectrum



HGM et al. 2014b **[arxiv:1407.5668]**

Measurements: Dependence with the scale

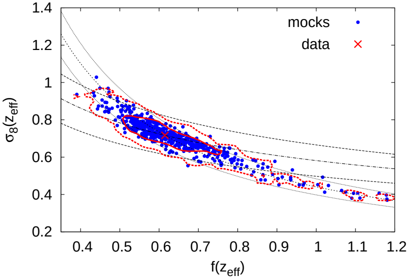
NGC, SGC, NGC+SGC



$$f^{0.43}\sigma_8|_{z=0.57} = 0.582 \pm 0.084\,(14\%) \qquad (k_{\rm max} = 0.17\,h{\rm Mpc}^{-1}).$$
$$f^{0.43}\sigma_8|_{z=0.57} = 0.584 \pm 0.051\,(9\%) \qquad (k_{\rm max} = 0.20\,h{\rm Mpc}^{-1}).$$

Measurements: Breaking f and σ_8 degeneracy

- For constraining f and σ_8 alone we need information from $P^{(0)}$, $P^{(2)}$ and $B^{(0)}$,
- Naively we combine "a posteriori" the measurements on $f^{0.43}\sigma_8$ with $f\sigma_8$ measurements (Samushia et al. 2013)



HGM et al. 2014c **[arxiv:1408:0027]**

$$f\sigma_8|_{z=0.57} = 0.447 \pm 0.028$$

$$f^{0.43}\sigma_8|_{z=0.57} = 0.582 \pm 0.084$$

$$f(z=0.57) = 0.63 \pm 0.16\,(25\%)$$

$$\sigma_8(z=0.57) = 0.710 \pm 0.086\,(12\%)$$

Results to be improved when the combination is "a priori"

Conclusions

This methodology is non-optimal. The errors can be reduced by,

- Including covariance will automatically shrink the error-bars
- Including more triangles will also reduce the error-bars.

Therefore, there is still space for improvement...

Conclusions

- 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 $b^{1.40}\sigma_8$ 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 σ_8 can be estimated separately.

Conclusions

Thank you for your attention!