Measuring the CMASS galaxy bias using the bispectrum technique

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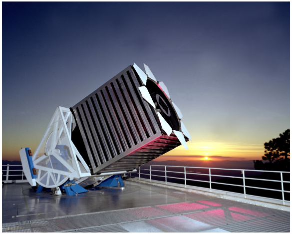
Outline

Introduction to BOSS

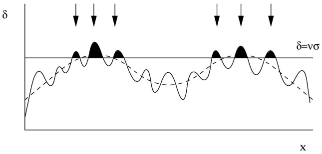
- Apache Point Observatory (APO) 2.5-m telescope for five years from 2009-2014.
- Part of SDSS-III project. BOSS: Baryon Oscillation Spectroscopic Survey
- Map the spatial distribution of luminous red galaxies and quasars
- Total coverage area 10,000 square degrees

- Redshifts of 1.5 million luminous galaxies to $z \simeq 0.7$
- Wavelength: 360-1000 nm



Galaxy Bias

Galaxies are a biased tracers of dark matter.



- Simple bias model

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

- Non-linear local bias model

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

- Non-local bias model (see talks tomorrow)

$$\delta_g = b_1\delta + \frac{b_2}{2}\delta^2 + \gamma_2\mathcal{G}_2$$

Bispectrum of Galaxies

The Bispectrum is sensitive to non-Gaussianities, gravity and biasing.

- Test of General Relativity
- Detect potential primordial non-Gaussianities
- Break degeneracies in the bias parameters

Mocks

Fast synthetic galaxy catalogues.

- What has been included in the mocks is known, so one can work out what are the best estimators, and test systematics.
- As pipelines become complex they are more difficult to capture by theoretical modelling, and mocks a need.
- Covariance matrix require a large number of realisations, the production of fast mock galaxy catalogues may provide them.

Angular & Radial Mask

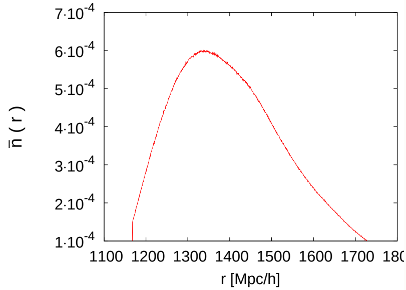
in a Box

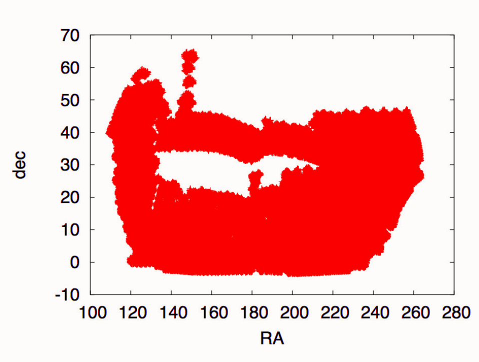
- Constant mean density
- Box with periodic boundary conditions

Real Survey

- z-dependent mean density
- Regions not observed $\rightarrow$ gaps

Angular & Radial Mask





How to deal with it: Power Spectrum

Feldman *et al.* (1994)

$$F_2(\mathbf{r}) \equiv I_2^{-1/2}\left[n(\mathbf{r}) - \alpha n_s(\mathbf{r})\right].$$

where $\alpha \equiv N/N_s$ and $I_i \equiv \alpha^i \int d^3\mathbf{r}\, \bar{n}_s^i(\mathbf{r})$.

FKP estimator

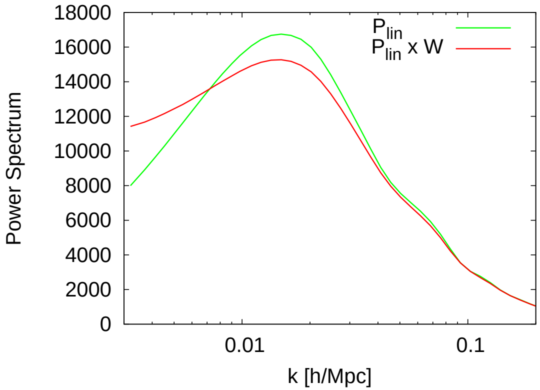
$$\langle |F_2(\mathbf{k})|^2\rangle = \int \frac{d^3\mathbf{k}'}{(2\pi)^3} P_{\rm gal}(\mathbf{k}')|G_2(\mathbf{k}-\mathbf{k}')|^2 + (1+\alpha)\frac{I_1}{I_2}$$

with,

$$G_2(\mathbf{k}) \equiv I_2^{-1/2}\int d^3\mathbf{r}\, \bar{n}(\mathbf{r}) e^{+i\mathbf{k}\cdot\mathbf{r}} \to \delta^D(\mathbf{k})$$

Note the convolution between $P_{\rm gal}$ and $|G_2|^2$

How to deal with it: Power Spectrum



How to deal with it: Bispectrum

and for the bispectrum,

$$F_3(\mathbf{r}) \equiv I_3^{-1/3}\left[n(\mathbf{r}) - \alpha n_s(\mathbf{r})\right].$$

FKP estimator

$$\langle F_3(\mathbf{k}_1)F_3(\mathbf{k}_2)F_3(\mathbf{k}_3)\rangle - B_{\rm sn} = \int \frac{d^3\mathbf{k}'}{(2\pi)^3}\frac{d^3\mathbf{k}''}{(2\pi)^3}\, B_{gal}(\mathbf{k}',\mathbf{k}'')Q_3(\mathbf{k}_1-\mathbf{k}',\mathbf{k}_2-\mathbf{k}'')$$

where,

$$Q_3(\mathbf{k}_A,\mathbf{k}_B) \equiv I_3^{-1}\left[I_2^{1/2}G_2(\mathbf{k}_A)\times I_2^{1/2}G_2(\mathbf{k}_B)\times I_2^{1/2}G_2^*(\mathbf{k}_A+\mathbf{k}_B)\right],$$

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FKP estimator

$$\langle F_3(\mathbf{k}_1)F_3(\mathbf{k}_2)F_3(\mathbf{k}_3)\rangle - B_{\rm sn} \quad \simeq \quad B_{gal}(\mathbf{k}_1,\mathbf{k}_2)$$

where,

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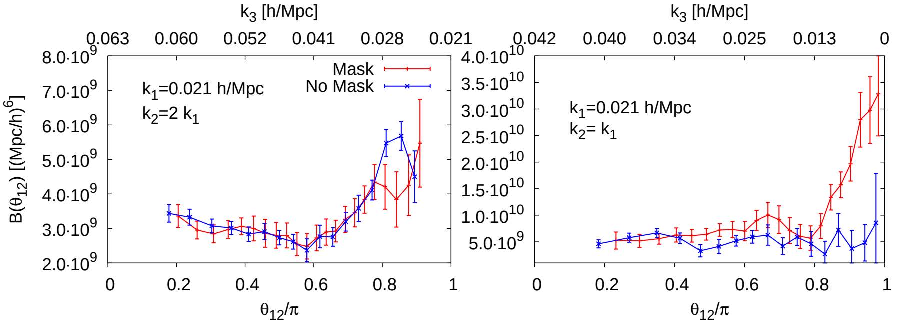
How to deal with it: Bispectrum

We apply the mask geometry to a 2LPT halo periodic box.

- 2LPT haloes: 20 realizations $\times$ 2.4 Gpc/h (unmasked).



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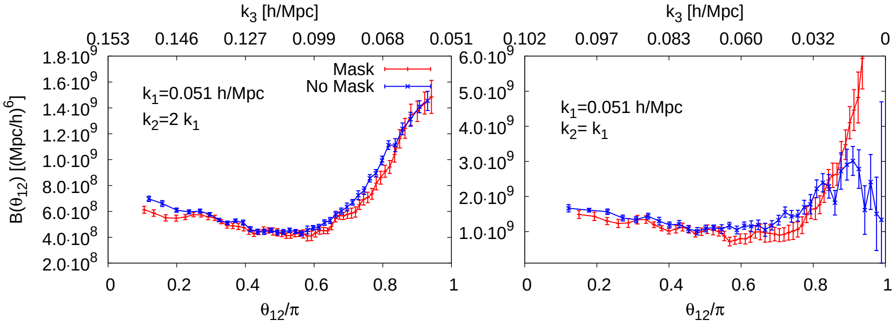

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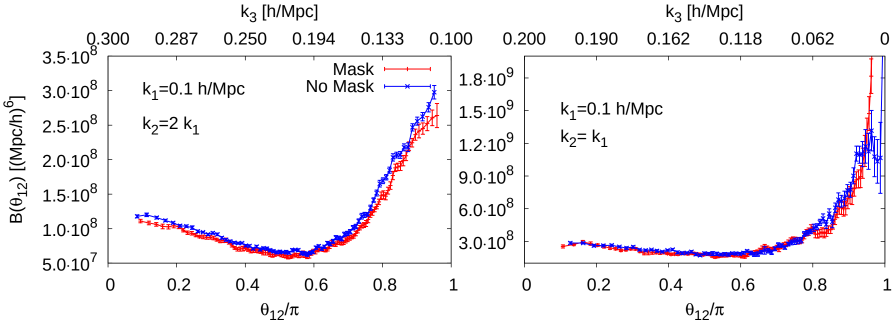


Galaxy Mocks

There are 2 sets of mocks available for the BOSS collaboration.

- 2nd order Lagrangian Perturbation Theory Mocks (2LPT) by Manera et al. 2012, arXiv.1203.6609
- Quick Particle Mesh (QPM) Mocks by White et al. 2013, arXiv.1309.5532

In order to obtain the galaxy mocks,

- Mock-Haloes are produced
- They are populated with galaxies using some prescription, such as HOD

We can compare 2LPT haloes with N-body haloes predictions for the power spectrum and bispectrum to check the validity of the approximation.

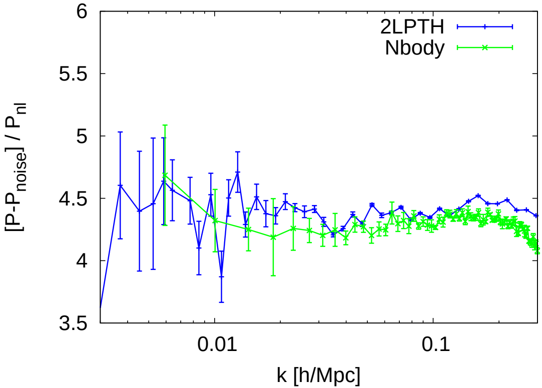
In order to have a similar biasing, we have to limit the mass o haloes to,

- 2LPT haloes: $M_{\rm min} \simeq 5 \times 10^{12}\, M_\odot/h$
- N-body haloes: $M_{\rm min} \simeq 9 \times 10^{12}\, M_\odot/h$

2LPT Haloes: Power spectrum

Halo-halo power spectrum relative to the non-linear matter one.

- 2LPT haloes: 20 realisations $\times$ 2.4 Gpc/h
- N-body haloes: 5 realisations $\times$ 1.5 Gpc/h
- Survey volume $\sim 2\ [\mathrm{Gpc}/h]^3$



2LPT Haloes: Bispectrum

Halo-halo-halo bispectrum.

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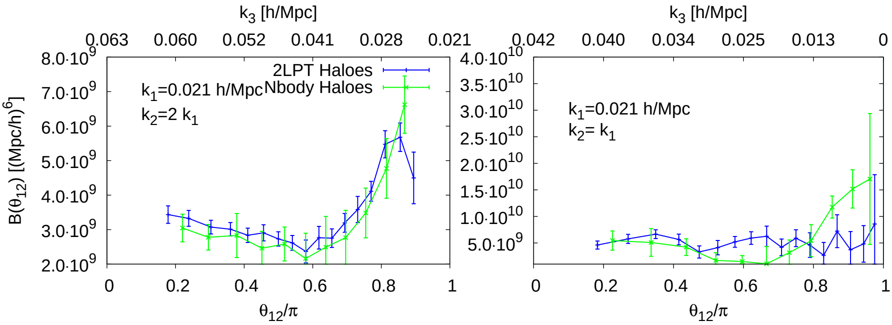

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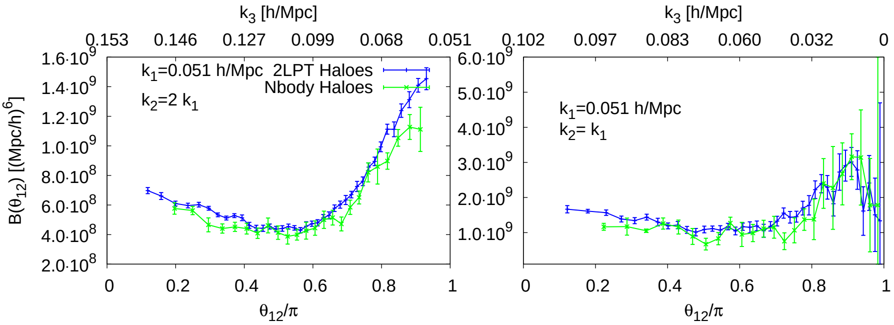

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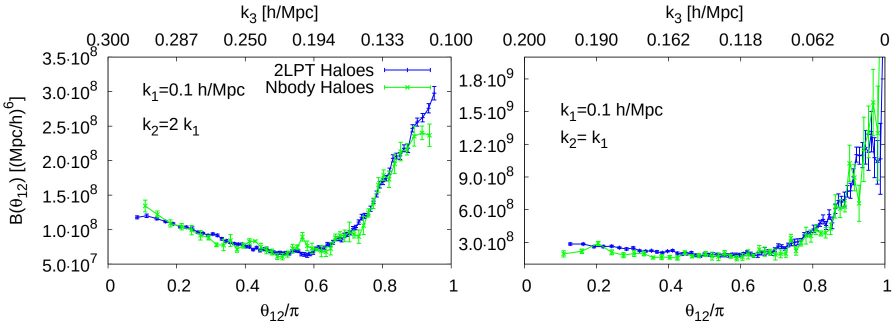


Bias Formalism

We stay at the local bias model with two free parameters: b_1 and b_2.
Bias model chosen

$$\delta_{\rm h}(\mathbf{x}) = b_1\delta(\mathbf{x}) + \frac{1}{2}b_2[\delta(\mathbf{x})^2 - \sigma_2].$$
$$\delta_{\rm h}(\mathbf{k}) = b_1\delta(\mathbf{k}) + \frac{1}{2}b_2\int\frac{d\mathbf{q}}{(2\pi)^3}\,\delta(\mathbf{q})\delta(\mathbf{k}-\mathbf{q}).$$

Power Spectrum,

$$P_{\rm hh}(k) \simeq b_1^2 P(k) + b_1 b_2\int\frac{d\mathbf{q}}{(2\pi)^3}\,B(\mathbf{k},\mathbf{q}) + \dots$$
$$b_{\rm eff}^2(k) \equiv \frac{P_{\rm hh}(k)}{P(k)} = b_1^2 + \frac{b_1 b_2}{P(k)}\int\frac{d\mathbf{q}}{(2\pi)^3}\,B(\mathbf{k},\mathbf{q})$$

Bias Formalism

Bispectrum,

$$B_{\rm hhh}(k_1,k_2,k_3) = b_1^3 B(k_1,k_2,k_3) + \left[b_1^2 b_2 P(k_1)P(k_2) + {\rm cyc.}\right] + b_2^2 \text{ terms}$$

Tree level approximation,

Halo Bispectrum

$$B_{\rm hhh}(k_1,k_2,k_3) = \left[b_1^3 P(k_1)P(k_2) 2F_2(\mathbf{k}_1,\mathbf{k}_2) + b_1^2 b_2 P(k_1)P(k_2)\right] + {\rm cyc.}$$

We write $B_{\rm hhh}$ as a function of $P_{\rm hh}$.

$$\begin{aligned} B_{\rm hhh}(k_1,k_2,k_3) &= \left[\frac{b_1^3}{b_{\rm eff}^2(k_1) b_{\rm eff}^2(k_2)} 2P_{\rm hh}(k_1)P_{\rm hh}(k_2)F_2(\mathbf{k}_1,\mathbf{k}_2) + \right. \\ &+ \left. \frac{b_1^2 b_2}{b_{\rm eff}^2(k_1) b_{\rm eff}^2(k_2)} P_{\rm hh}(k_1)P_{\rm hh}(k_2)\right] + {\rm cyc.} \end{aligned}$$

For simplicity we assume that $b_{\rm eff}$ is k-independent.

Bias Formalism

Rewrite the mapping between $B_{\rm hhh}$ and $P_{\rm hh}$ as a function of these new bias parameters: b'_i.

Halo Bispectrum

$$B_{\rm hhh}(k_1,k_2,k_3)=\left[\frac{2}{b'_1}P_{\rm hh}(k_1)P_{\rm hh}(k_2)F_2(\mathbf{k}_1,\mathbf{k}_2)+\frac{b'_2}{b'^2_1}P_{\rm hh}(k_1)P_{\rm hh}(k_2)\right]+\text{cyc.}$$

where the connection to the true bias parameters is,

$$b'_1\equiv\frac{b_{\rm eff}^4}{b_1^3},\qquad b'_2\equiv b_2\frac{b_{\rm eff}^4}{b_1^4}$$

if b_2 very small, $b_{\rm eff}\simeq b_1$ and $b'_i\simeq b_i$. We could measure the bias parameter without any matter information.

Improved Kernel for dark matter

The behaviour of tree level approximation can be improved modifying the 2-point kernel,

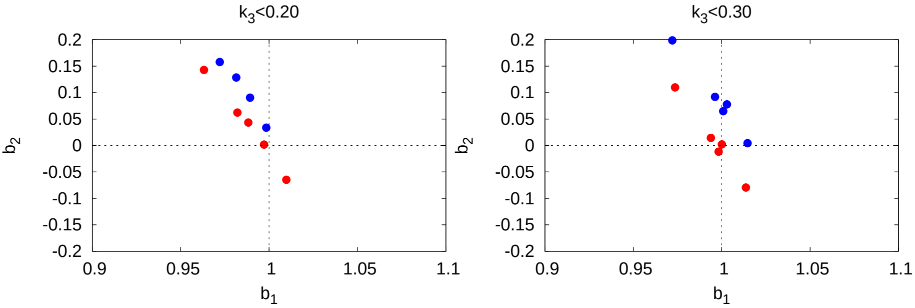
$$
\begin{aligned}
F_2(\mathbf{k}_i, \mathbf{k}_j) &= \frac{5}{7} + \frac{1}{2}\cos(\theta_{ij})\left(\frac{k_i}{k_j} + \frac{k_j}{k_i}\right) + \frac{2}{7}\cos^2(\theta_{ij}), \\
F_2^{\rm eff}(\mathbf{k}_i, \mathbf{k}_j) &= \frac{5}{7}a(n_i, k_i)a(n_j, k_j) + \frac{1}{2}\cos(\theta_{ij})\left(\frac{k_i}{k_j} + \frac{k_j}{k_i}\right) b(n_i, k_i)b(n_j, k_j) \\
&+ \frac{2}{7}\cos^2(\theta_{ij})c(n_i, k_i)c(n_j, k_j),
\end{aligned}
$$

The functions $a(n,k)$, $b(n,k)$ and $c(n,k)$ depend on 9 free parameters that need to be calibrated from simulations. You can find their definition and the values of these free parameters in HG-M *et al.* (2012) arXiv.1111.4477

Improved kernel for dark matter

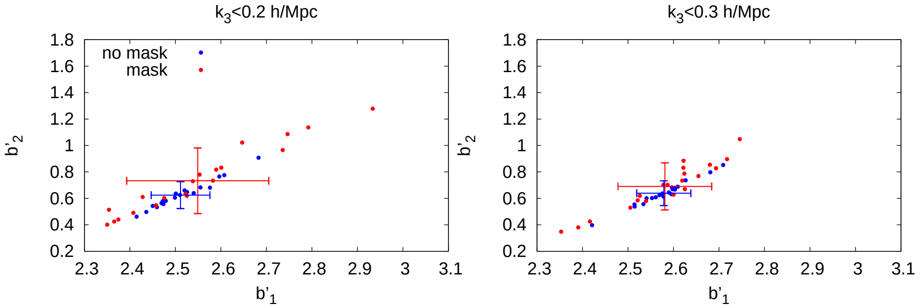
N-body dark matter particles: 5 realisations $\times$ 1.5 Gpc/h.

$$F_2(\mathbf{k}_1,\mathbf{k}_2) \quad \rightarrow \quad \text{SPT kernel}$$
$$F_2^{\rm eff}(\mathbf{k}_1,\mathbf{k}_2) \quad \rightarrow \quad \text{Effective kernel}$$



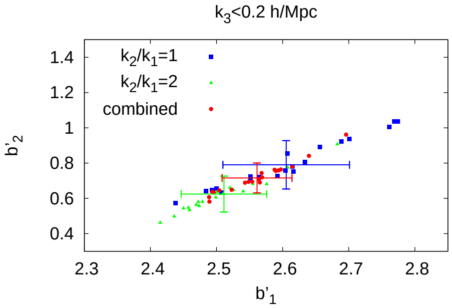
Mask Effect

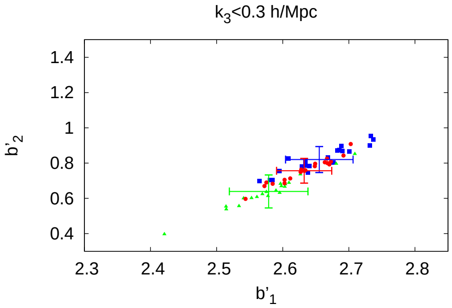
- 2LPT Haloes. $F_2^{\rm eff}$ used.
- 20 realizations $\times$ 2.4 Gpc/h (unmasked)
- Error-bars correspond to 1σ dispersion of 1 single realization.



Best Triangle Configuration

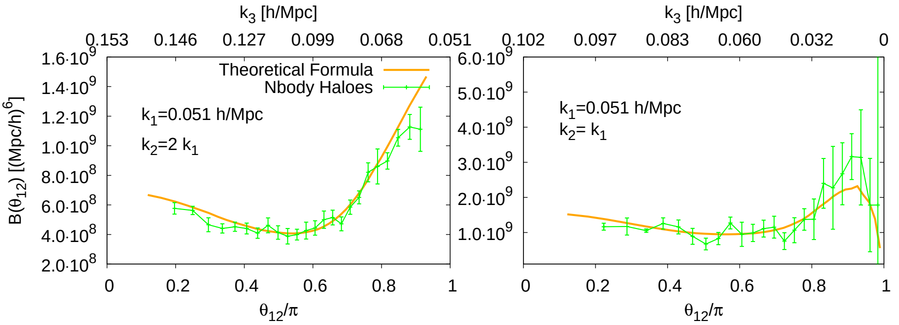
- 2LPT Haloes. $F_2^{\rm eff}$ used.
- 20 realizations $\times$ 2.4 Gpc$/h$.
- Error-bars correspond to 1σ dispersion of 1 single realization.





Fitting Formula

$$F_2^{\text{eff}}(\mathbf{k}_i,\mathbf{k}_j) = \frac{5}{7}a(n_i,k_i)a(n_j,k_j) + \frac{1}{2}\cos(\theta_{ij})\left(\frac{k_i}{k_j}+\frac{k_j}{k_i}\right)b(n_i,k_i)b(n_j,k_j) + \frac{2}{7}\cos^2(\theta_{ij})c(n_i,k_i)c(n_j,k_j),$$



Fitting Formula

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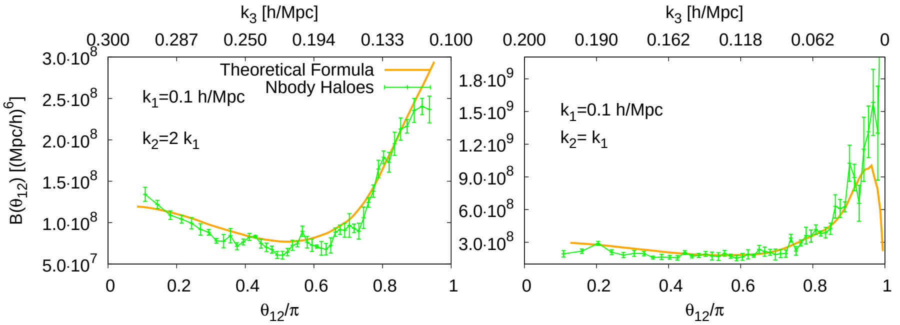
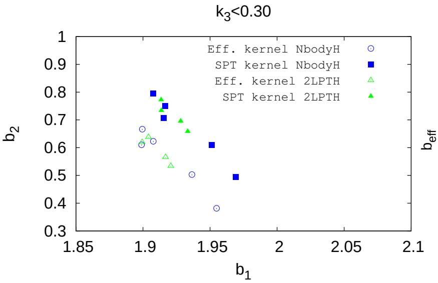
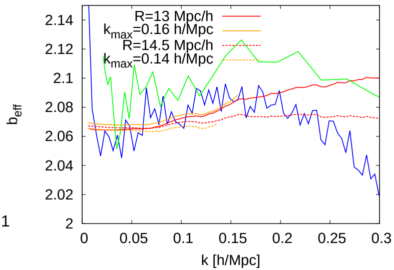


Bispectrum vs. Power Spectrum





SPT: $b_1 \simeq 1.92 \quad b_2 \simeq 0.7$

Eff. : $b_1 \simeq 1.92 \quad b_2 \simeq 0.55$

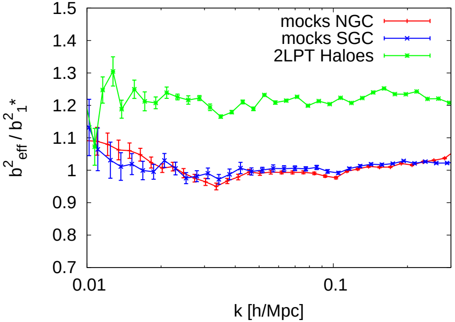
$$b^2_{\rm eff}(k) = b_1^2 + \frac{b_1 b_2}{P(k)} \int d\mathbf{q}\, B(\mathbf{k},\mathbf{q})$$

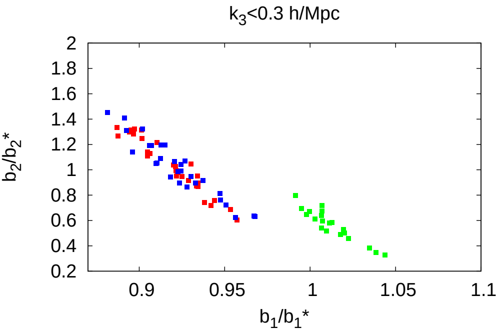
$$B(\mathbf{k}_1,\mathbf{k}_2) = 2P(k_1)P(k_2)F_2(k_1,k_2) + \mathrm{cyc.}$$

Smoothing scale problem.

Galaxy Mocks

Following a HOD prescription galaxies are added into the haloes,





Main effects,

- $b_{\rm eff}$ is reduced
- b_1 is reduced but b_2 increases!

Non-linear bias in z-space

Map the real space kernels into z-space kernels based on perturbation theory,

$$\begin{aligned} b_1 F_1 &\rightarrow Z_1(\mathbf{k}) \equiv (b_1 + f\mu^2) \\ b_1 F_2(\mathbf{k}_1, \mathbf{k}_2) + \frac{b_2}{2} &\rightarrow Z_2(\mathbf{k}_1, \mathbf{k}_2) \equiv b_1 F_2(\mathbf{k}_1, \mathbf{k}_2) + f\mu^2 G_2(\mathbf{k}_1, \mathbf{k}_2) + \\ &+ \frac{f\mu k}{2}\left[\frac{\mu_1}{k_1}(b_1 + f\mu_2^2) + \frac{\mu_2}{k_2}(b_1 + f\mu_1^2)\right] + \frac{b_2}{2}. \end{aligned}$$

$$B^s_{\rm hhh}(\mathbf{k}_1, \mathbf{k}_2) = 2P(k_1)\, Z_1(\mathbf{k}_1)\, P(k_2)\, Z_1(\mathbf{k}_2)\, Z_2(\mathbf{k}_1, \mathbf{k}_2) + \text{cyc.}$$

Work in progress...

Conclusions

1. The bispectrum is the next natural step after the power spectrum to extract information from the large scale galaxy distribution
2. The effects of the mask have to be modeled in order to avoid spurious signals at large scales.
3. 2LPT mocks seem to show good behaviour up to small scales, $k \lesssim 0.3$
4. Since b_2 is not small, we need to assume an underlying $P_{\rm mm}$ to extract b_1 / b_2.
5. Effective kernel need to be used to avoid spurious signals.
6. Stay tuned for upcoming data results!