HECTOR GIL-MARIN (ILP-LPNHE)

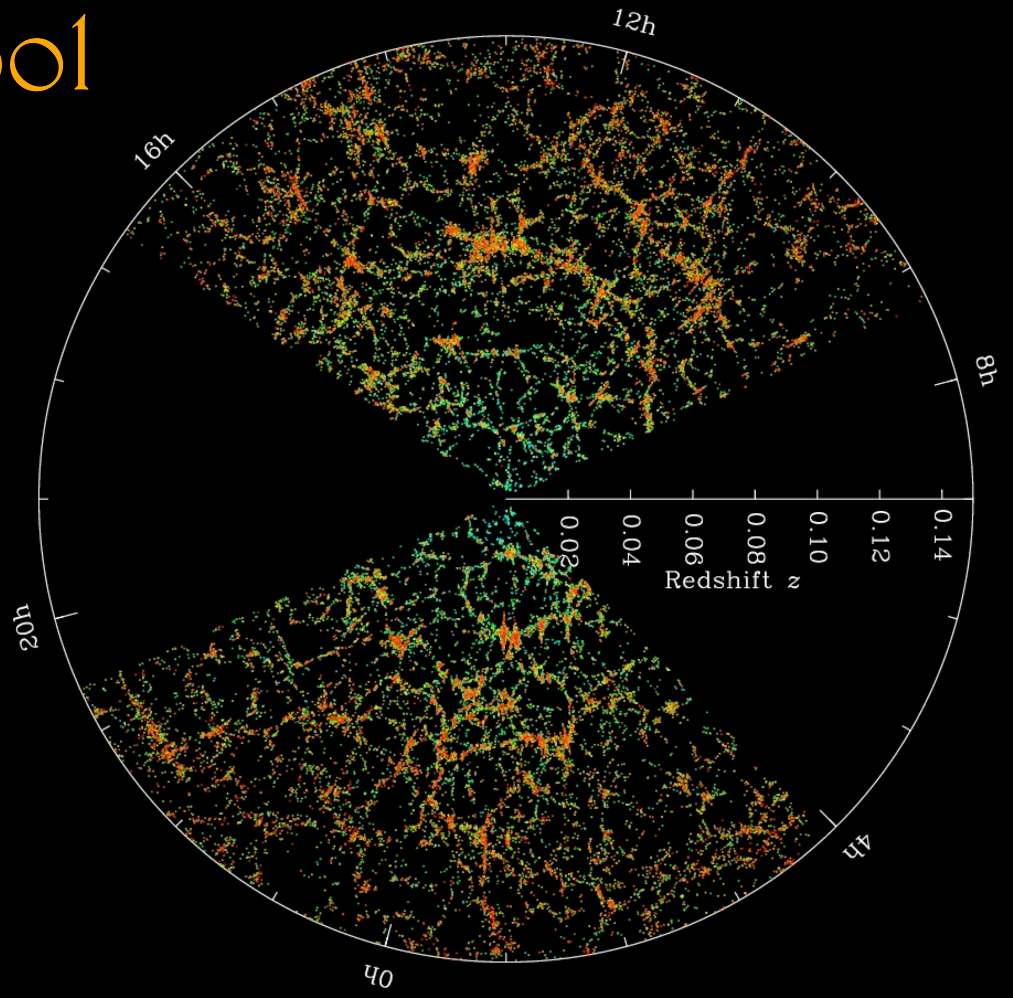
COSMOLOGY WITH GALAXY SURVEYS

Fuerteventura Cosmology School

REDSHIFT SPACE DISTORTIONS

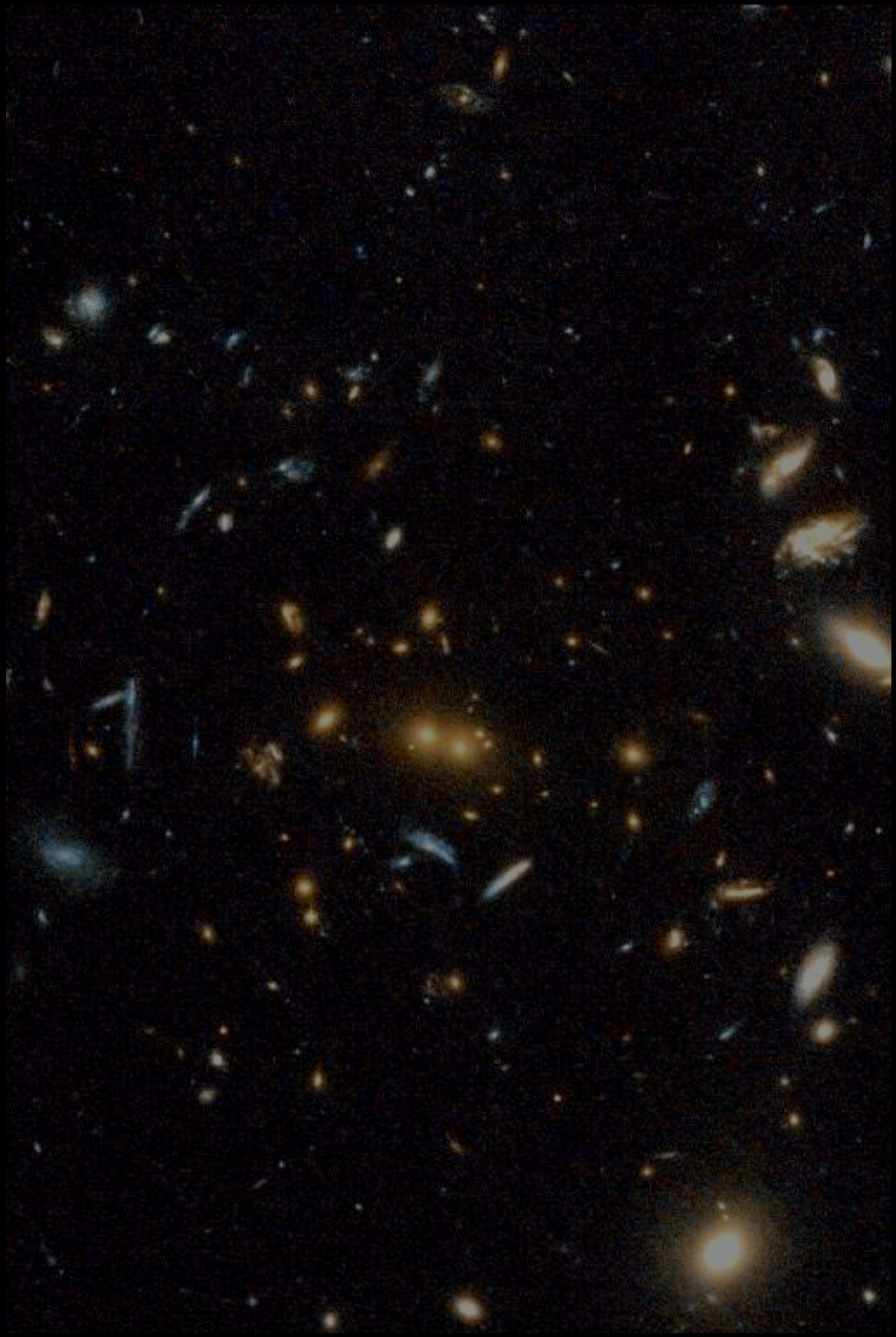
BARYON ACOUSTIC OSCILLATIONS

HIGHER ORDER STATISTICS



Outline

- **P(k) Estimator & Selection Function**
- **RSD & BAO in actual surveys**
- **Bispectrum signal**



Introduction

Dark matter over-density, $\delta(r) \equiv \frac{\rho(r)}{\bar{\rho}} - 1$ $\xrightarrow{\text{FT}}$ $\delta(k) = \int \delta(x) e^{ikx}\, dx$

2-point correlation function (2pCF), $\langle \delta(r)\delta(r+R) \rangle = \xi(R)$

Power Spectrum (PS) $\langle \delta(k)\delta^*(k') \rangle = (2\pi)^3 P(k) \delta^D(k+k')$

The PS and 2-pCF are the *observables* for RSD and BSO

Power Spectrum

Key ingredients for cooking a $f\sigma_8$ / BAO measurement

1. Measure $P^{(0)}(k)$, $P^{(2)}(k)$ from data
2. Survey selection function
3. Model dark matter power spectra
4. Galaxy bias model
5. Covariance (error)

Mix it with a MCMC sampler and serve it cold!

Power Spectrum

Key ingredients for cooking a fσ_8 / BAO measurement

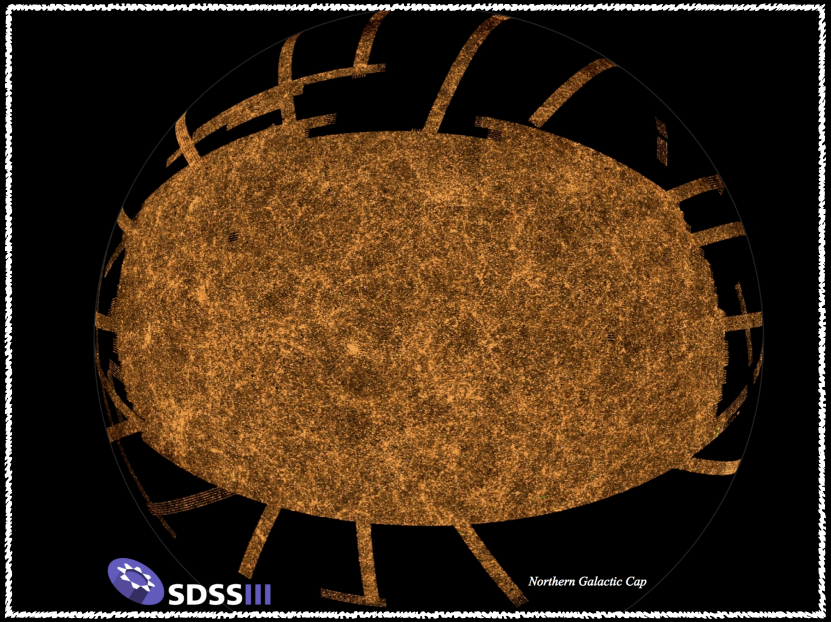
1. Measure $P^{(0)}(k)$, $P^{(2)}(k)$ from data
2. Survey selection function
3. Model dark matter power spectra ← M. Crocce, D. Blas
4. Galaxy bias model ← W. Percival
5. Covariance (error) ← A. Cuesta

Mix it with a MCMC sampler and serve it cold!

Measuring P(k) from surveys

Real life problems

- Non-uniform distribution of galaxies
- Varying photometric conditions
- Fibre limitations



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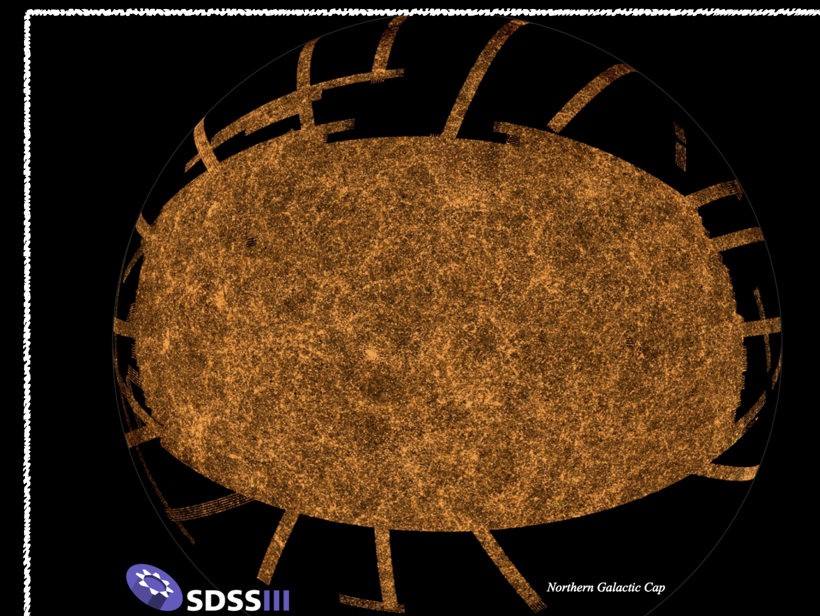

FKP function (Feldman et al. 1994)

$$F_2(\vec{r}) = \frac{w(\vec{r})}{\sqrt{I_2}}[n(\vec{r}) - \alpha n_s(\vec{r})]$$

weight

normalisation

$$I_2 = \int [w(\vec{r})\bar{n}(\vec{r})]^2 d^3 r$$

$$\alpha = N_g / N_s$$

random catalogue

same features than data catalogue but with no clustering structure

actual galaxy catalogue

Measuring P(k) from surveys

Real life problems

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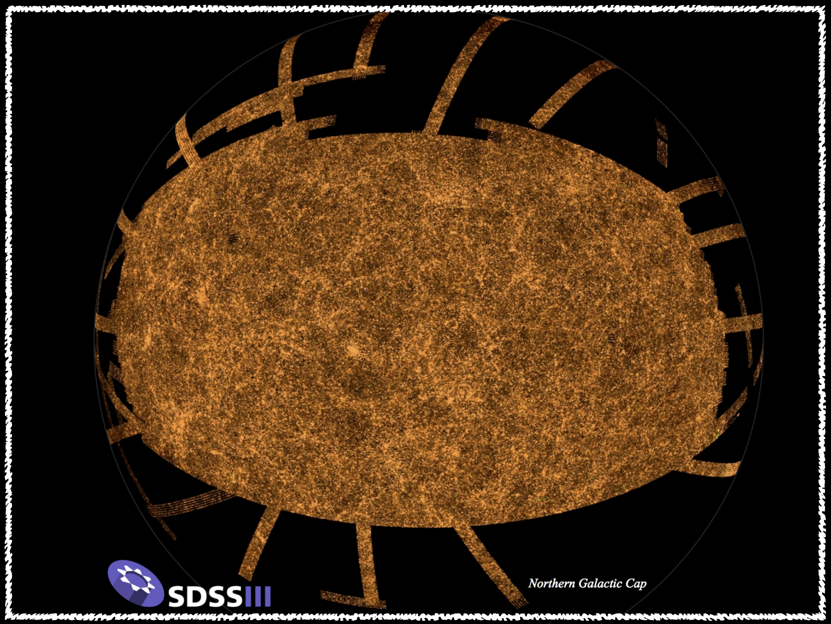


FKP function (Feldman et al. 1994)

$$F_2(\vec{r}) = \frac{w(\vec{r})}{\sqrt{I_2}}[n(\vec{r}) - \alpha n_s(\vec{r})]$$

Yamamoto et al. 2006

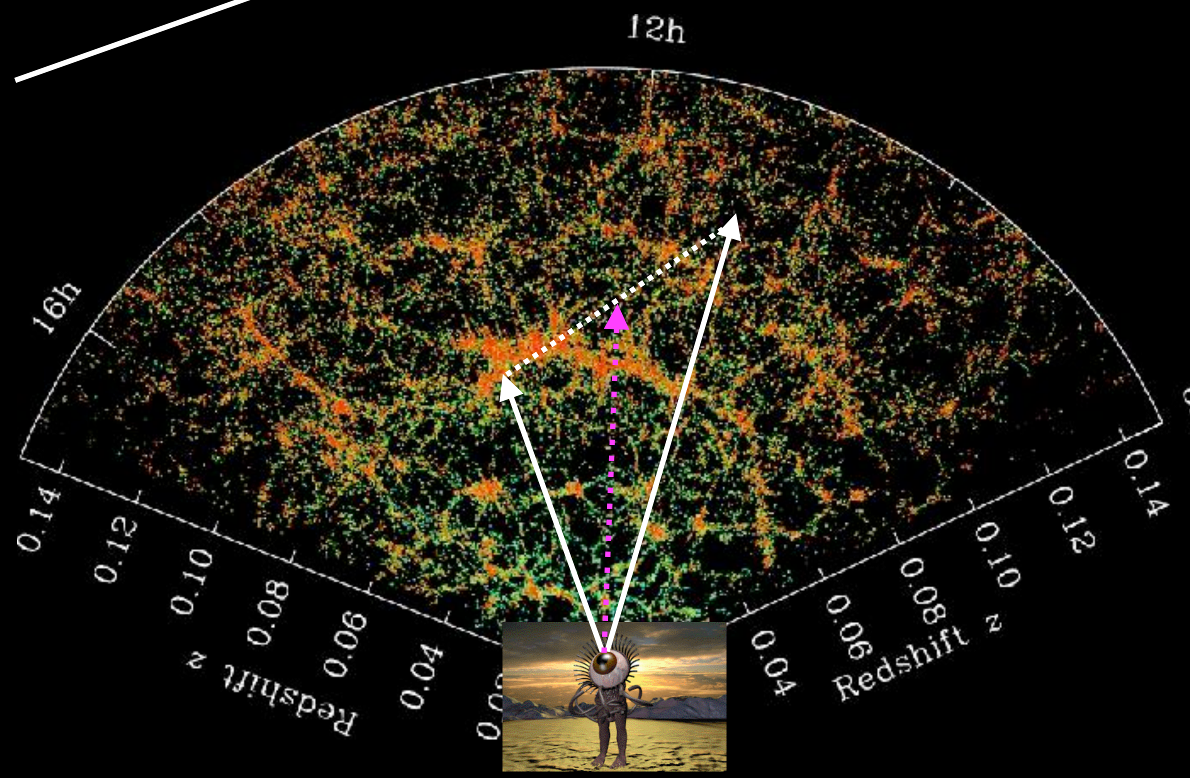
$$\tilde{P}_g^{(\ell)}(k) = (2\ell+1)\int \frac{d\Omega_k}{4\pi}\left[\int d^3r_1 \int d^3r_2 F_2(\vec{r}_1)F_2(\vec{r}_2)e^{i\vec{k}\cdot(\vec{r}_1-\vec{r}_2)}\wp_\ell(\hat{k}\cdot\hat{r}_h) - P_\ell^{noise}(k)\right]$$

line of sight dependence

$$\tilde{P}_g^{(\ell)}(k) = (2\ell+1)\int \frac{d\Omega_k}{4\pi}\left[\int d^3r_1 \int d^3r_2 F_2(\vec{r}_1)F_2(\vec{r}_2)e^{i\vec{k}\cdot(\vec{r}_1-\vec{r}_2)}\wp_\ell(\hat{k}\cdot\hat{r}_h) - P_\ell^{noise}(k)\right]$$

Line of sight dependence through

$$\vec{r}_h = \frac{\vec{r}_1+\vec{r}_2}{2}$$



Legendre Polynomials

$\wp_0(x) = 1$ Monopole

$\wp_2(x) = \frac{1}{2}(3x^2-1)$ Quadrupole

For the **monopole** no-LOS dependence,

$$\tilde{P}_g^{(0)}(k) = \int \frac{d\Omega_k}{4\pi}\left[\int d^3r_1 \int d^3r_2 F_2(\vec{r}_1)F_2(\vec{r}_2)e^{i\vec{k}\cdot(\vec{r}_1-\vec{r}_2)} - P_0^{noise}(k)\right]$$

Integrals are separable

$$\tilde{P}_g^{(\ell)}(k) = (2\ell+1)\int \frac{d\Omega_k}{4\pi}\left[\int d^3r_1 \int d^3r_2 F_2(\vec{r}_1)F_2(\vec{r}_2)e^{i\vec{k}\cdot(\vec{r}_1-\vec{r}_2)}\wp_\ell(\hat{k}\cdot\hat{r}_h) - P_\ell^{noise}(k)\right]$$

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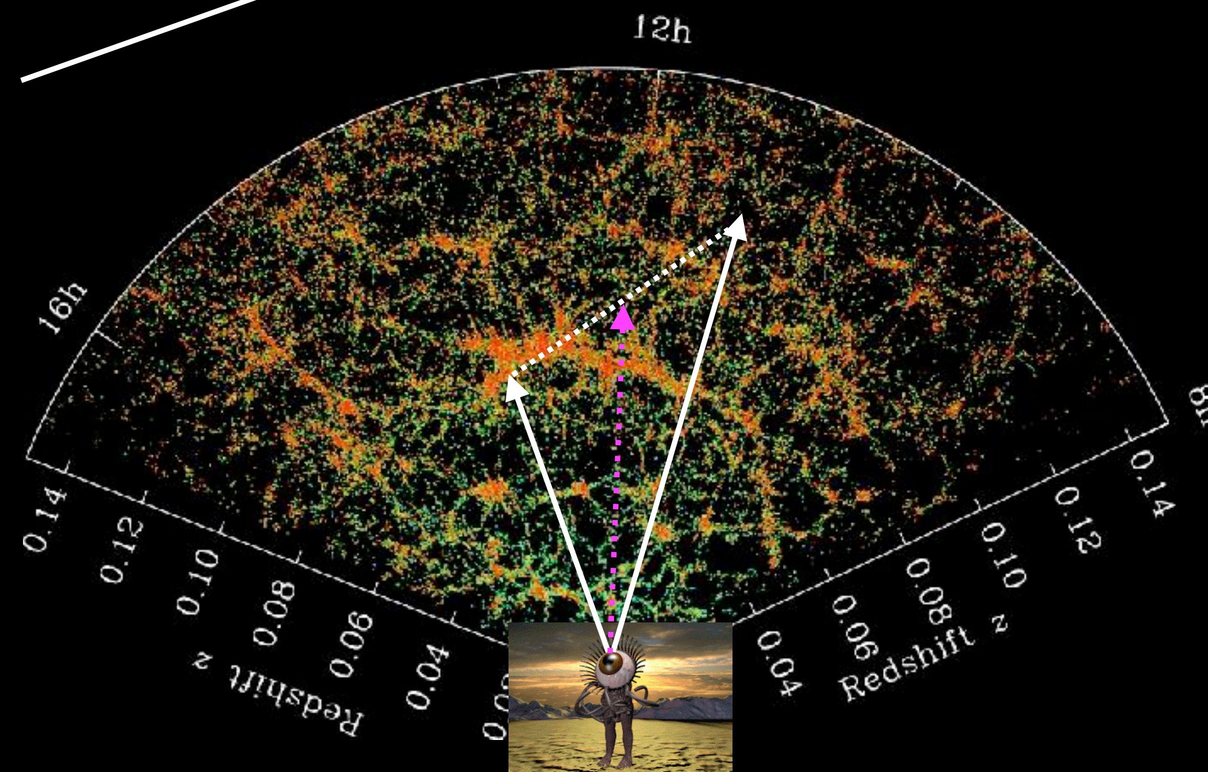

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$$\tilde{P}_g^{(0)}(k) = \int \frac{d\Omega_k}{4\pi}\left[\underbrace{\int d^3r_1 F_2(\vec{r}_1)e^{ik\cdot r_1}}_{\text{FT}} \underbrace{\int d^3r_2 F_2(\vec{r}_2)e^{-ik\cdot r_2}}_{\text{FT}} - P_0^{noise}(k)\right]$$

$$\tilde{P}_g^{(\ell)}(k) = (2\ell+1)\int \frac{d\Omega_k}{4\pi}\Big[\int d^3r_1 \int d^3r_2 F_2(\vec{r}_1)F_2(\vec{r}_2)e^{i\vec{k}\cdot(\vec{r}_1-\vec{r}_2)}\wp_\ell(\hat{k}\cdot\hat{r}_h) - P_\ell^{noise}(k)\Big]$$

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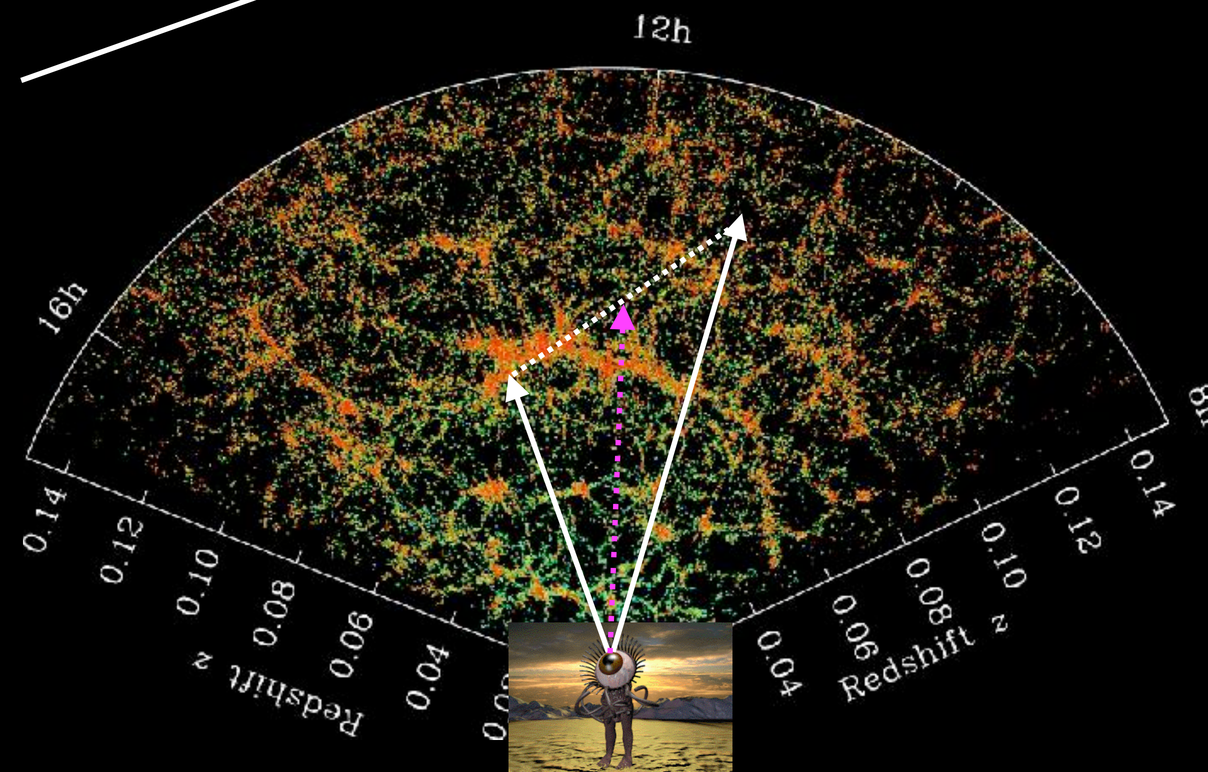

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$$\tilde{P}_g^{(0)}(k) = \int \frac{d\Omega_k}{4\pi}\Big[F_2(\vec{k})F_2^*(\vec{k}) - P_0^{noise}(k)\Big]$$

$$\tilde{P}_g^{(\ell)}(k) = (2\ell+1)\int \frac{d\Omega_k}{4\pi}\left[\int d^3r_1 \int d^3r_2 F_2(\vec{r}_1)F_2(\vec{r}_2)e^{i\vec{k}\cdot(\vec{r}_1-\vec{r}_2)}\wp_\ell(\hat{k}\cdot\hat{r}_h) - P_\ell^{noise}(k)\right]$$

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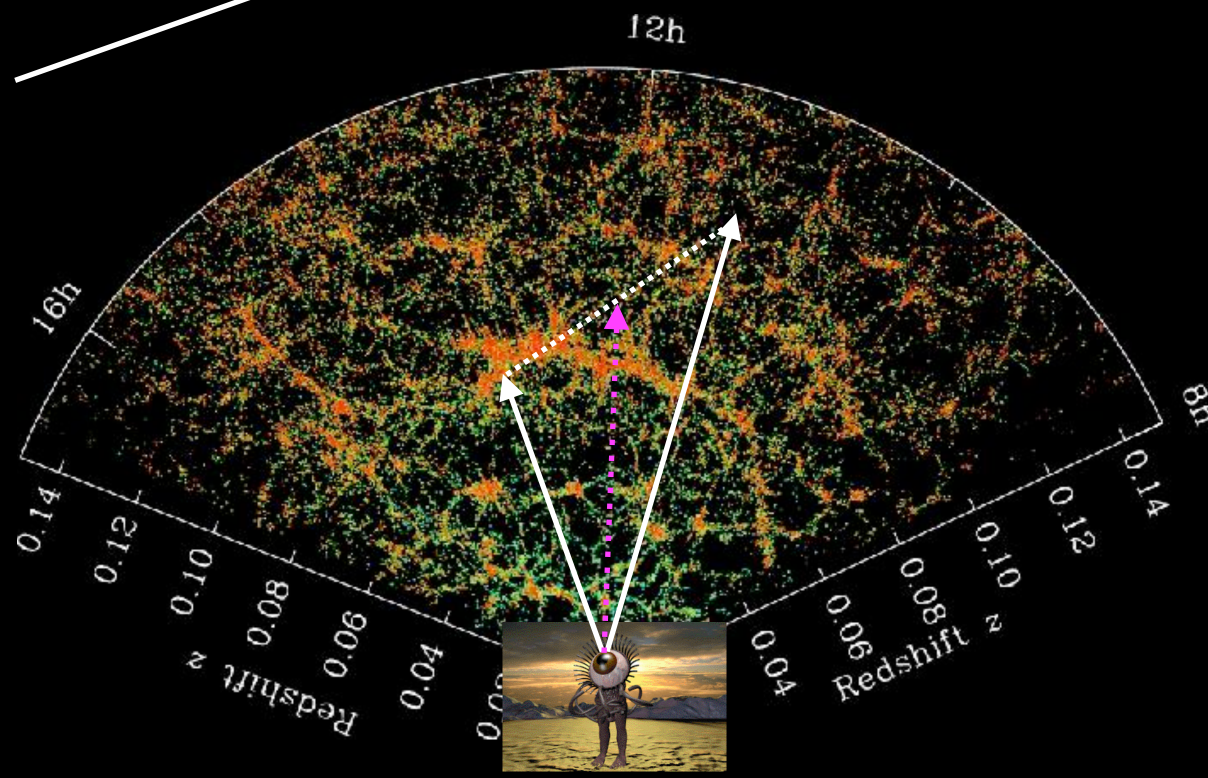

Legendre Polynomials

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For the **quadrupole**,

$$\tilde{P}_g^{(2)}(k) = 5\int \frac{d\Omega_k}{4\pi}\left[\int d^3r_1 \int d^3r_2 F_2(\vec{r}_1)F_2(\vec{r}_2)e^{ik\cdot(r_1-r_2)}\wp_2(\hat{k}\cdot\hat{r}_h) - P_\ell^{noise}(k)\right]$$

Integrals are **not** separable

$$\tilde{P}_g^{(\ell)}(k) = (2\ell+1)\int \frac{d\Omega_k}{4\pi}\left[\int d^3r_1 \int d^3r_2 F_2(\vec{r}_1)F_2(\vec{r}_2)e^{i\vec{k}\cdot(\vec{r}_1-\vec{r}_2)}\wp_\ell(\hat{k}\cdot\hat{r}_h) - P_\ell^{noise}(k)\right]$$

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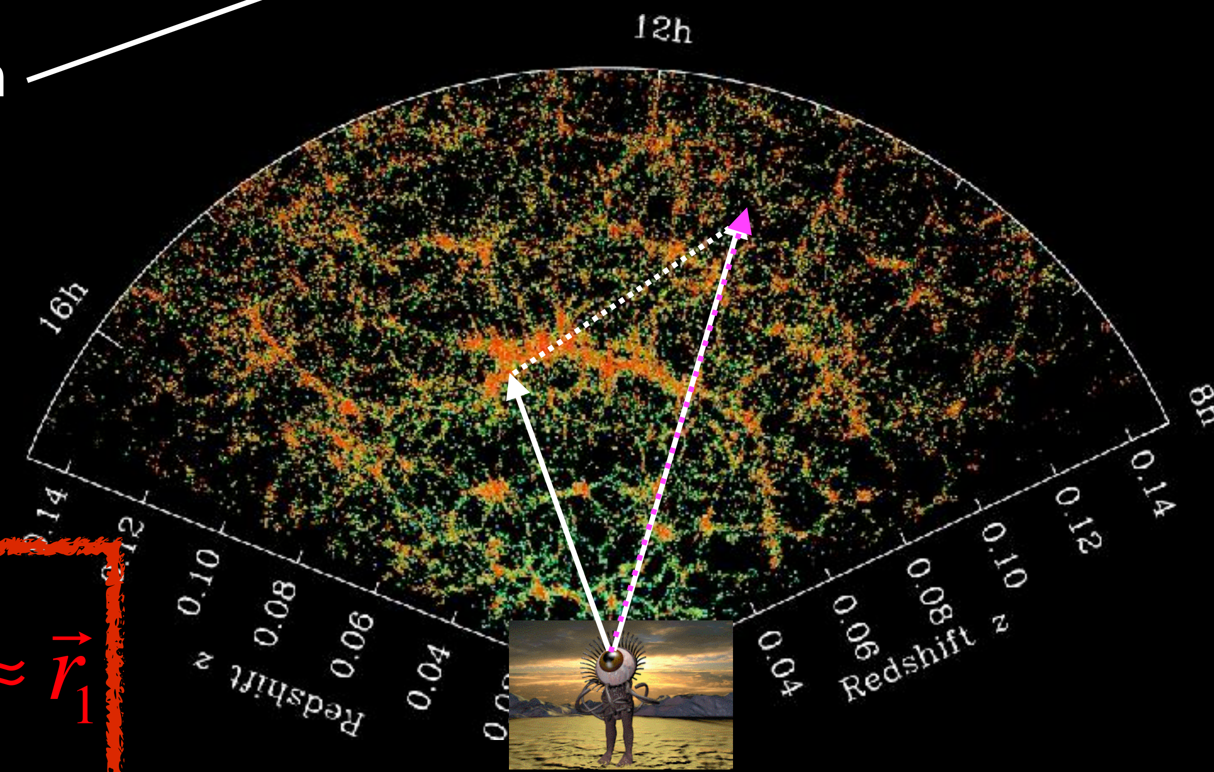

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Integrals are separable

$$\tilde{P}_g^{(\ell)}(k) = (2\ell+1)\int \frac{d\Omega_k}{4\pi}\Big[\int d^3r_1 \int d^3r_2 F_2(\vec{r}_1)F_2(\vec{r}_2)e^{i\vec{k}\cdot(\vec{r}_1-\vec{r}_2)}\wp_\ell(\hat{k}\cdot\hat{r}_h) - P_\ell^{noise}(k)\Big]$$

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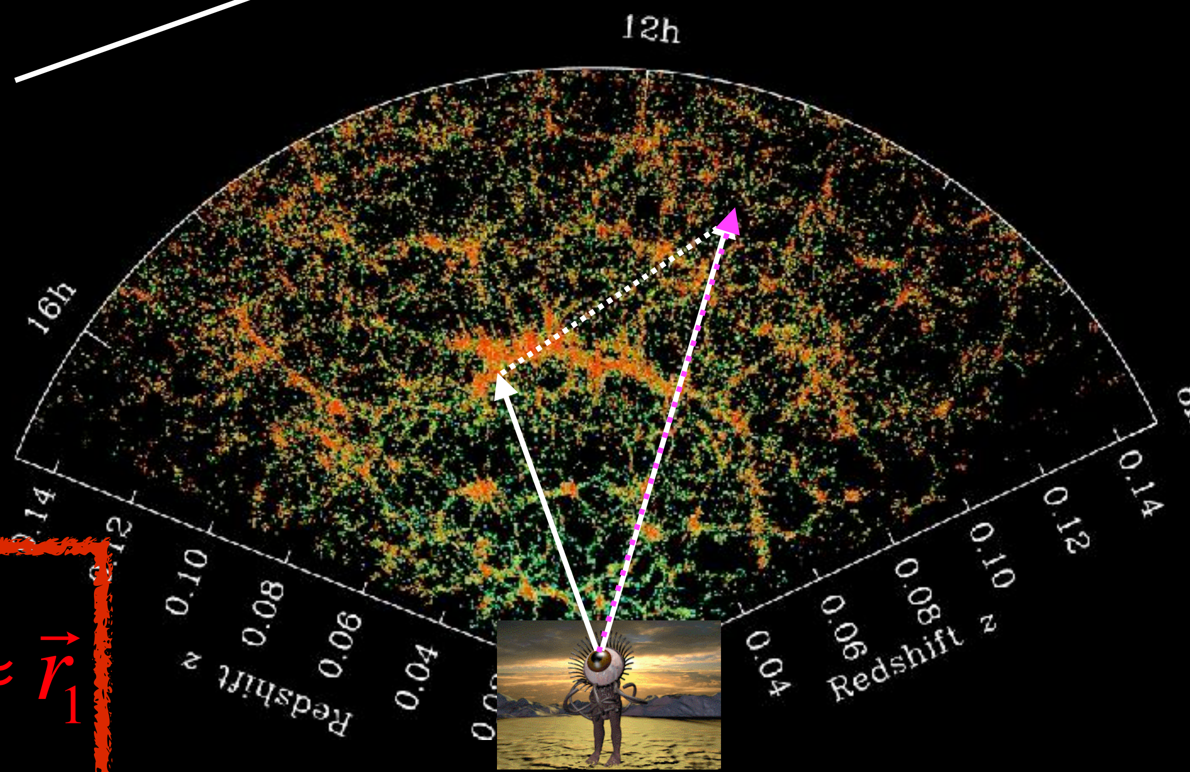


For the **quadrupole**,

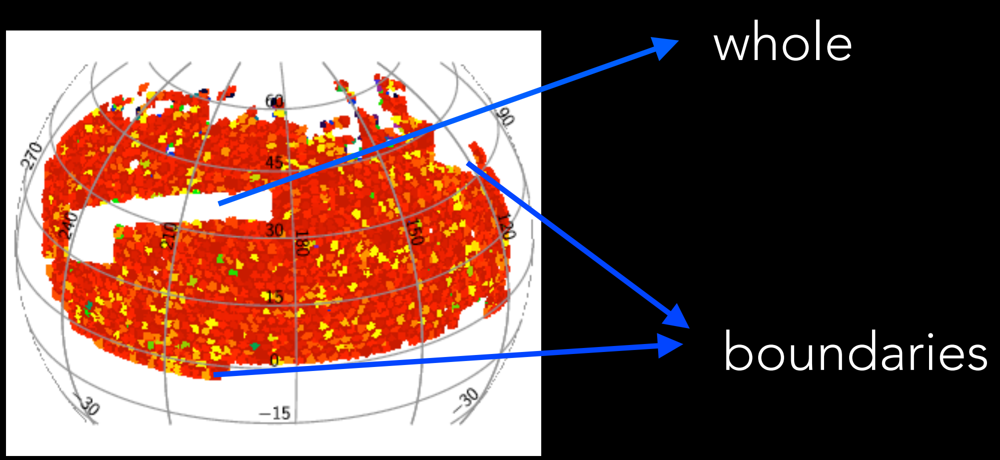
$$\tilde{P}_g^{(2)}(k) = 5\int \frac{d\Omega_k}{4\pi}\Big[\underbrace{\int d^3r_1 F_2(\vec{r}_1)e^{i\vec{k}\cdot\vec{r}_1}\wp_2(\hat{k}\cdot\hat{r}_1)}_{\text{FT-like}}\underbrace{\int d^3r_2 F_2(\vec{r}_2)e^{-i\vec{k}\cdot\vec{r}_2}}_{\text{FT}} - P_0^{noise}(k)\Big]$$

Survey selection function

Issue: Estimators previously presented, $\tilde{P}_g^{(\ell)}(k)$ do not measure the actual underling power spectrum multipoles.

Reason: Non-uniform distribution of galaxies get imprinted inevitably in F(k) after the FT!

Consequence: The estimators $\tilde{P}_g^{(\ell)}(k)$ measure a convolution between the actual underling power spectrum multipoles and the survey geometry function



Survey selection function

Generalization to higher order multipoles: Wilson et al. 2016

Hankel Transforms: $$\hat{P}^{(\ell)}(k) = 4\pi(-i)^{\ell}\int r^2 \hat{\xi}^{(\ell)}(r) j_{\ell}(kr)dr$$

spherical Bessel functions

Survey selection function

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spherical Bessel functions

Masked monopole and quadrupole

$$\hat{\xi}^{(0)}(r) = \xi^{(0)}(r)W_0^2(r) + \frac{1}{5}\xi^{(2)}(r)W_2^2(r) + \frac{1}{9}\xi^{(4)}(r)W_4^2(r) + \ldots$$

$$\hat{\xi}^{(2)}(r) = \xi^{(0)}(r)W_2^2(r) + \xi^{(2)}(r)\left[W_0^2(r) + \frac{2}{7}W_2^2(r) + \frac{2}{7}W_4^2(r)\right] + \ldots$$

Survey selection function

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spherical Bessel functions

HT of the masked PS

HT of the true PS

$$\hat{\xi}^{(0)}(r) = \xi^{(0)}(r)W_0^2(r) + \frac{1}{5}\xi^{(2)}(r)W_2^2(r) + \frac{1}{9}\xi^{(4)}(r)W_4^2(r) + \ldots$$

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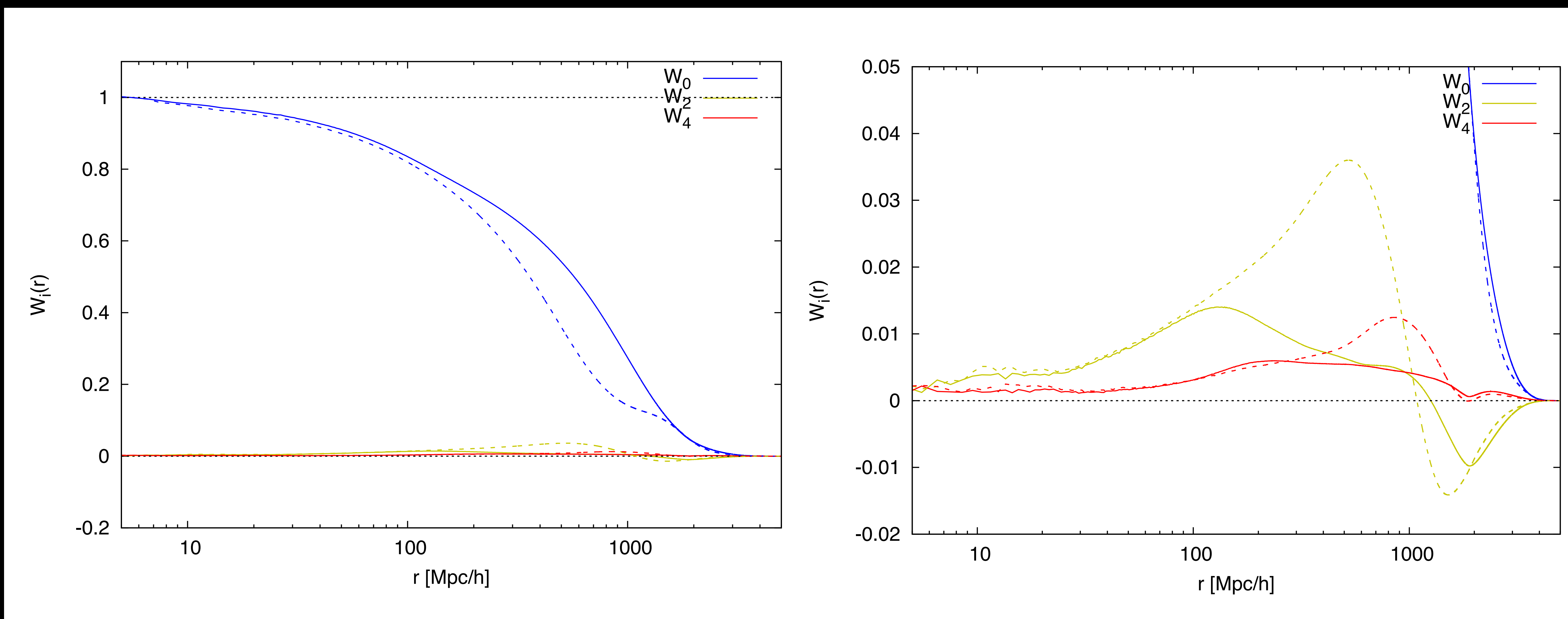
Window Function $\begin{cases} W_0(r) \to 1 \\ W_2(r) \to 0 \\ W_4(r) \to 0 \end{cases}$ when no selection effect

Survey selection function

Generalization to higher order multipoles: Wilson et al. 2016



Survey selection function

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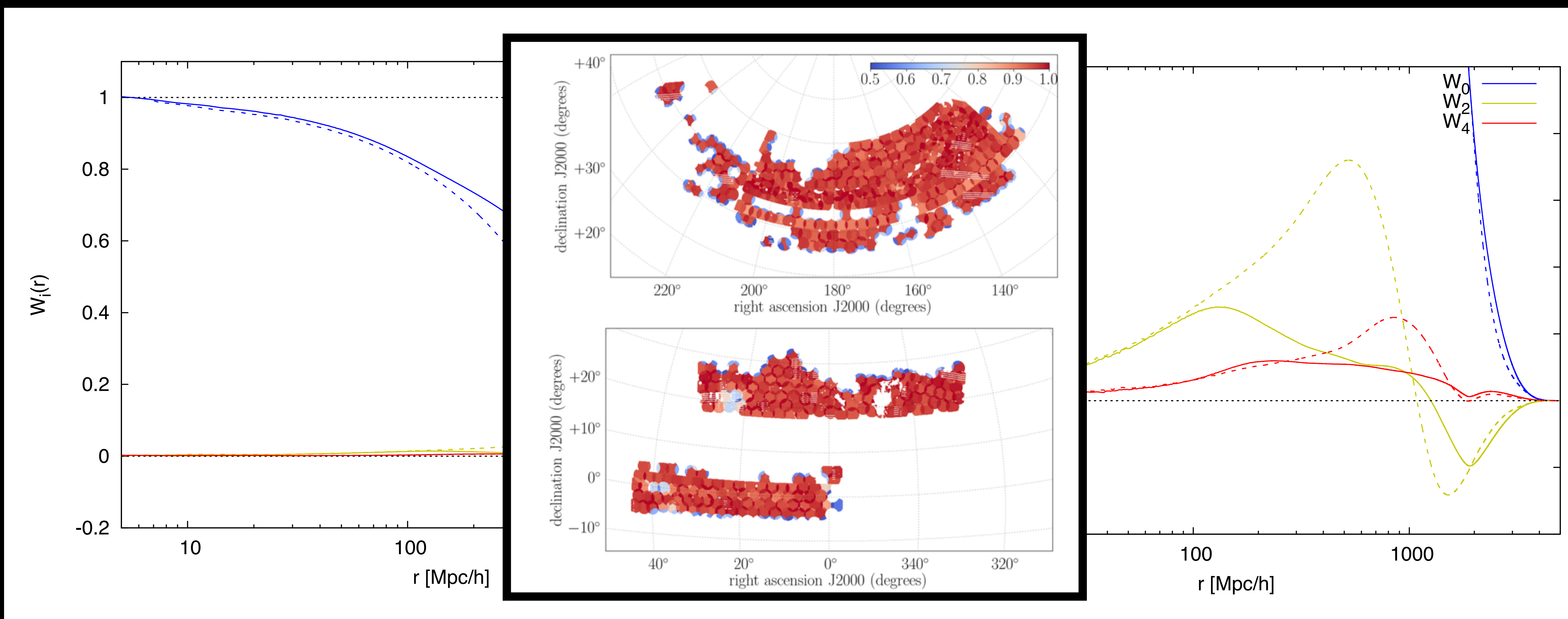
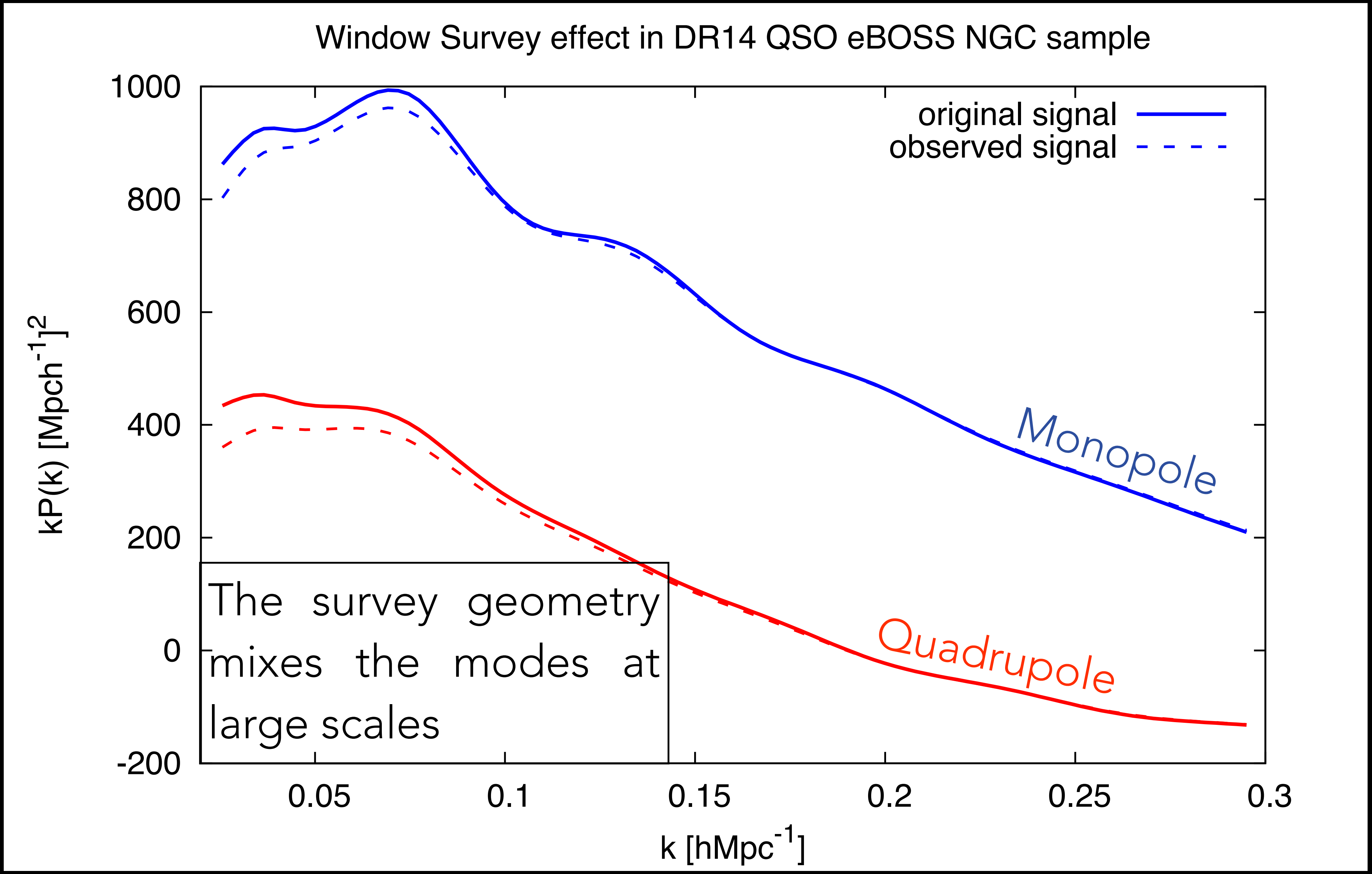


Survey selection function

Importance of the window function for BAO



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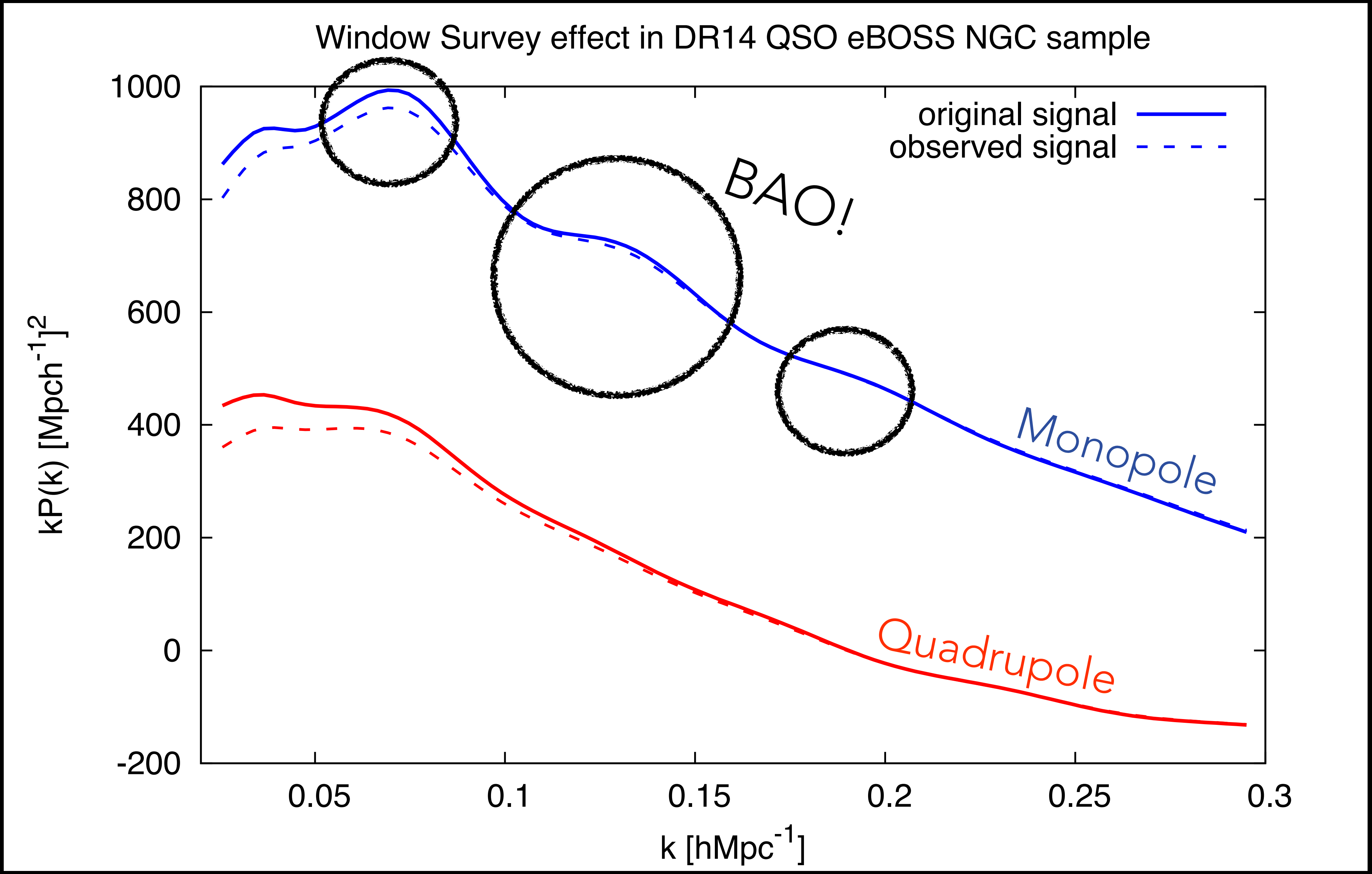

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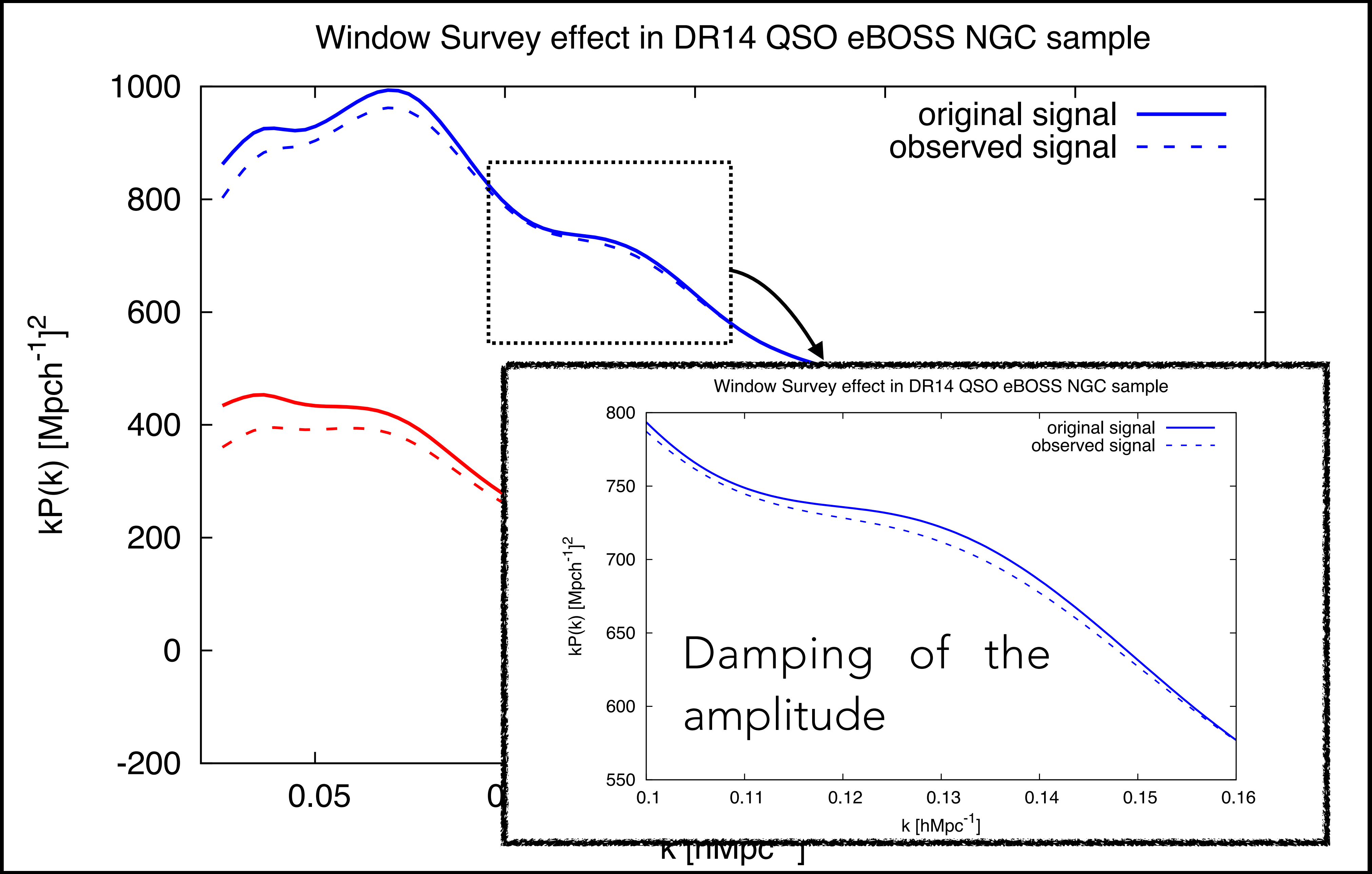
Importance of the window function for BAO



Survey selection function

Importance of the window function for RSD

$$P_g(k,\mu;z)=[b_1(z)+f(z)\mu^2]^2 P_{lin}(k,z_0)[\sigma_8{}^2(z)/\sigma_8{}^2(z_0)]+\dots$$

$$P_g{}^{(0)}(k;z)=\frac{P_{lin}(k;z_0)}{\sigma_8{}^2(z_0)}\sigma_8{}^2(z)\left[b_1(z)^2+\frac{2}{3}f(z)b_1(z)+\frac{1}{5}f^2(z)\right]+\dots$$

$$P_g{}^{(2)}(k;z)=\frac{P_{lin}(k;z_0)}{\sigma_8{}^2(z_0)}\sigma_8{}^2(z)\left[\frac{4}{3}f(z)b_1(z)+\frac{4}{7}f(z)^2\right]+\dots$$

2 Eq. & 2 free param.

$$b_1(z)\sigma_8(z) \qquad\qquad f(z)\sigma_8(z)$$

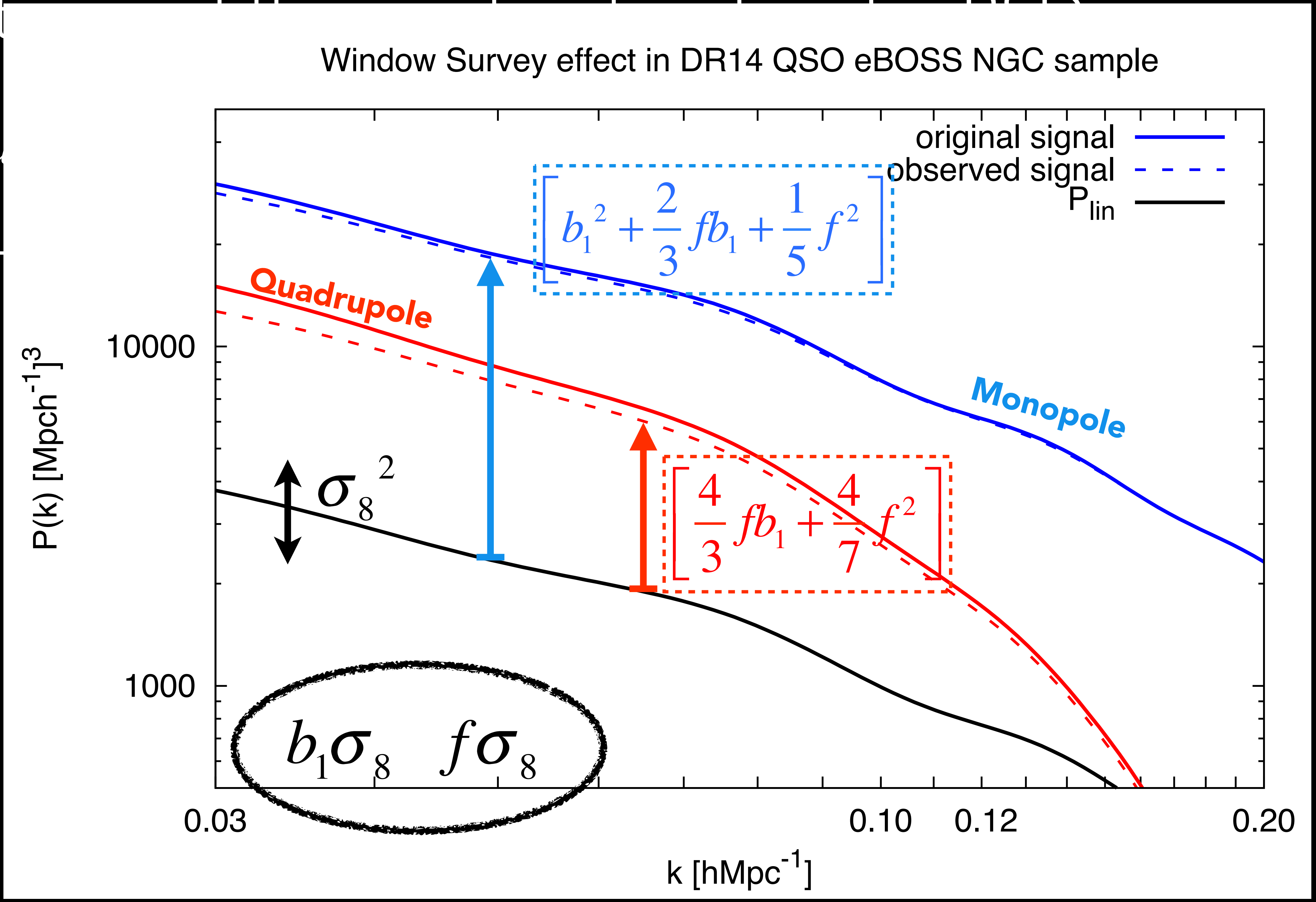
Survey selection function

Import

$P_g(k,\mu$

$P_g^{(0)}(k;$

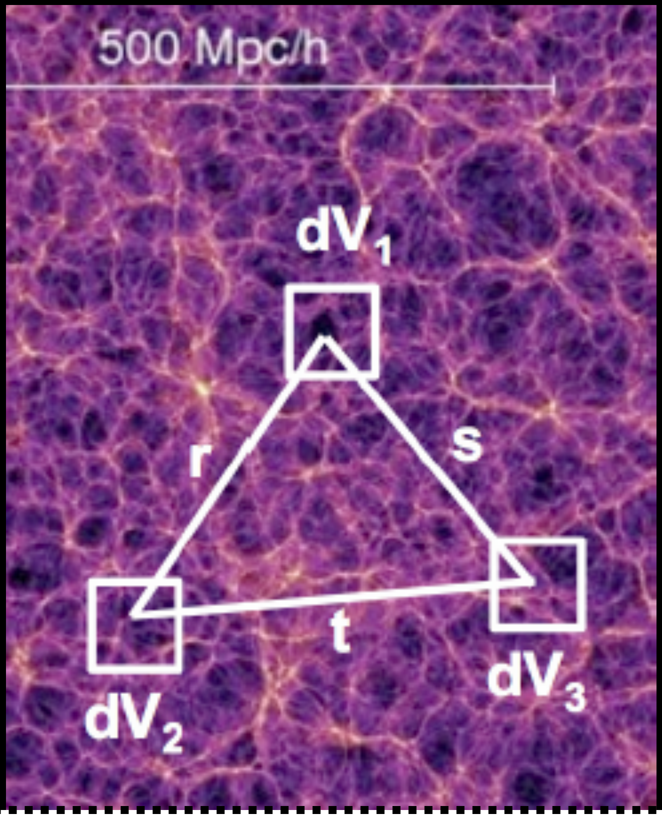
$P_g^{(2)}(k;$



Bispectrum

- Quantity which is essentially non-linear

If all the $\delta(\mathbf{k})$ modes evolve linearly (and the initial conditions are Gaussian) the bispectrum is 0 and all the information on the system of objects/galaxies is described by the power spectrum.



Probability of finding 3 galaxies separated by r, s and t: $P_3(r,s,t) = [1+\xi_2(r)+\xi_2(s)+\xi_2(t)+\zeta(r,s,t)]dV_1\,dV_2\,dV_3$

The bispectrum is defined as the FT of ζ,

$$B(\mathbf{k}_1,\mathbf{k}_2) \equiv \int d\mathbf{r}\,d\mathbf{s}\,\zeta(\mathbf{r},\mathbf{s})e^{-i\mathbf{r}\cdot\mathbf{k}_1}e^{-i\mathbf{s}\cdot\mathbf{k}_2}$$

Since, $\zeta(r,s,t) \equiv \langle\delta(\mathbf{x}+\mathbf{r})\delta(\mathbf{x}+\mathbf{t})\delta(\mathbf{x})\rangle_{\mathbf{x}}$

$$B(k_1,k_2,k_3) = \langle\delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\delta(\mathbf{k}_3)\rangle\delta^D(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)$$

Bispectrum

- Quantity which is essentially non-linear

If all the **δ**(**k**) modes evolve linearly (and the initial conditions are Gaussian) the bispectrum is 0 and all the information on the system of objects/galaxies is described by the power spectrum.

$$\delta(k)=\delta^{(1)}(k)+\delta^{(2)}(k)+\ldots$$

Perturbative expansion
(see. M. Crocce Talk)

$$\delta^{(n)}(\vec{k})=\int \tilde{F}_n(\vec{q}_1,\ldots,\vec{q}_n)\delta^{(1)}(\vec{q}_1)\ldots\delta^{(1)}(\vec{q}_n)d^3q_1\ldots d^3q_n$$

$$\vec{k}=\vec{q}_1+\ldots+\vec{q}_n$$

$\tilde{F}_n(\vec{q}_1,\ldots,\vec{q}_n)$ non-symmetrised kernel of n-order

To be computed from recursive relations

Bispectrum

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Perturbative expansion
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$$\langle\delta(k)\delta(k')\rangle=\langle\delta^{(1)}(k)\delta^{(1)}(k')\rangle+2\langle\delta^{(1)}(k)\delta^{(2)}(k')\rangle+\langle\delta^{(2)}(k)\delta^{(2)}(k')\rangle+2\langle\delta^{(1)}(k)\delta^{(3)}(k')\rangle+\ldots$$

Bispectrum

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$$\delta(k) = \delta^{(1)}(k) + \delta^{(2)}(k) + \ldots$$

Perturbative expansion (see. M. Crocce Talk)

$$\langle \delta(k)\delta(k')\rangle = \langle \delta^{(1)}(k)\delta^{(1)}(k')\rangle + 2\langle \delta^{(1)}(k)\delta^{(2)}(k')\rangle + \langle \delta^{(2)}(k)\delta^{(2)}(k')\rangle + 2\langle \delta^{(1)}(k)\delta^{(3)}(k')\rangle + \ldots$$

linear term: $\langle \delta(k)^2 \rangle$

prim. nG term: $\langle \delta(k)^3 \rangle$

1-loop terms: $\langle \delta(k)^4 \rangle$

Bispectrum

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Perturbative expansion
(see. M. Crocce Talk)

$$\left\langle \delta(k)\delta(k')\delta(k'') \right\rangle = \left\langle \delta^{(1)}(k)\delta^{(1)}(k')\delta^{(1)}(k'') \right\rangle + 2\left\langle \delta^{(1)}(k)\delta^{(1)}(k')\delta^{(2)}(k'') \right\rangle + \ldots$$

Bispectrum

- Quantity which is essentially non-linear

If all the **δ**(**k**) modes evolve linearly (and the initial conditions are Gaussian) the bispectrum is 0 and all the information on the system of objects/galaxies is described by the power spectrum.

$$\delta(k) = \delta^{(1)}(k) + \delta^{(2)}(k) + \ldots$$

Perturbative expansion (see. M. Crocce Talk)

$$\langle \delta(k)\delta(k')\delta(k'')\rangle = \langle \delta^{(1)}(k)\delta^{(1)}(k')\delta^{(1)}(k'')\rangle + 2\langle \delta^{(1)}(k)\delta^{(1)}(k')\delta^{(2)}(k'')\rangle + \ldots$$

primordial nG term
linear term
$\langle \delta(k)^3 \rangle$

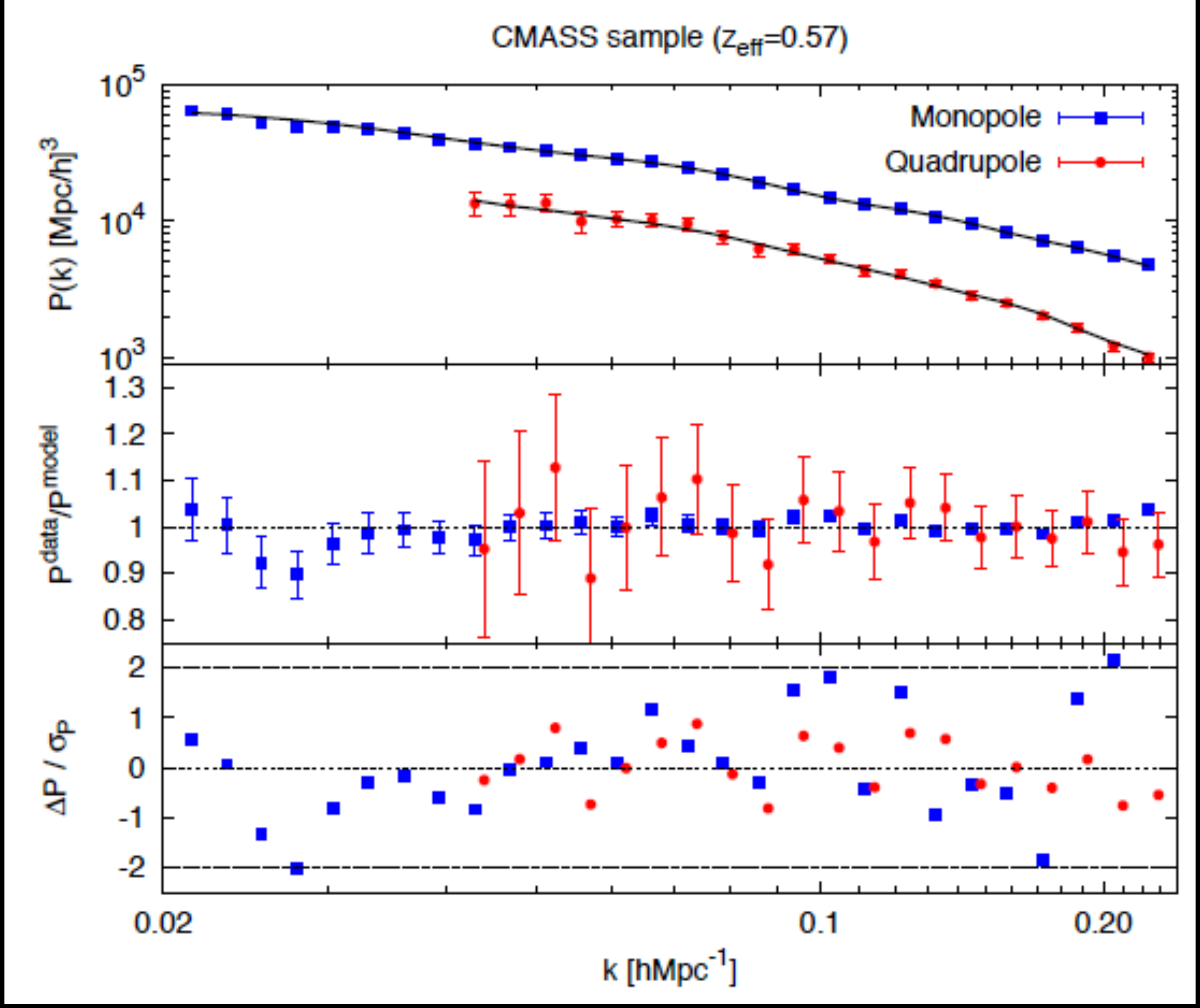
tree-level terms
$\langle \delta(k)^4 \rangle$

<222>
<114>
<123>
1-loop terms
$\langle \delta(k)^6 \rangle$

Sefusatti et al. 2010

Bispectrum

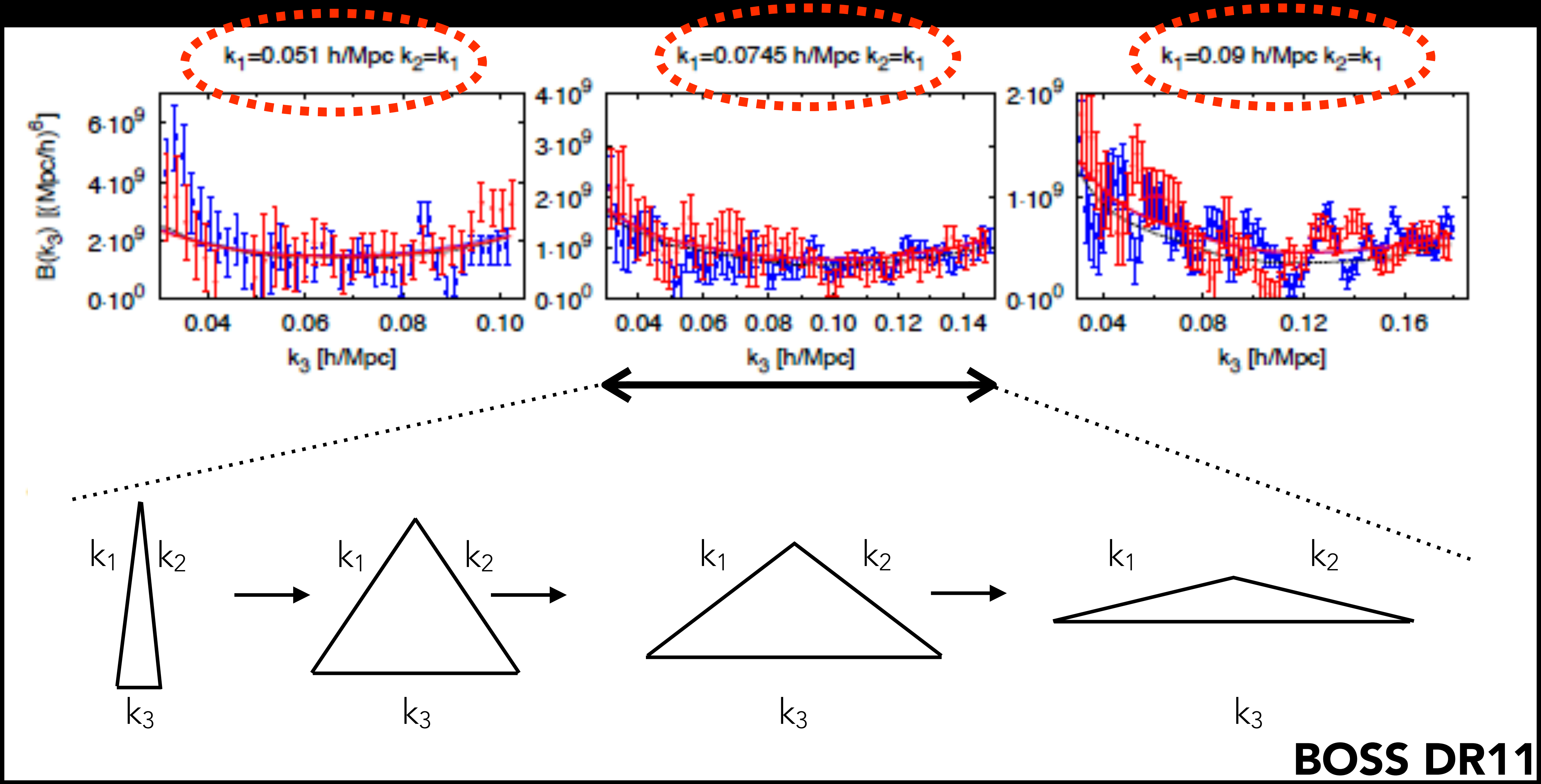
Plotting the Power Spectrum $P(k,\mu) \rightarrow P^{(0)}(k), P^{(2)}(k), \ldots$



Bispectrum

Plotting the Bispectrum

$$B(k_1, k_2, k_3) \rightarrow B(k_3; k_1, k_2)$$



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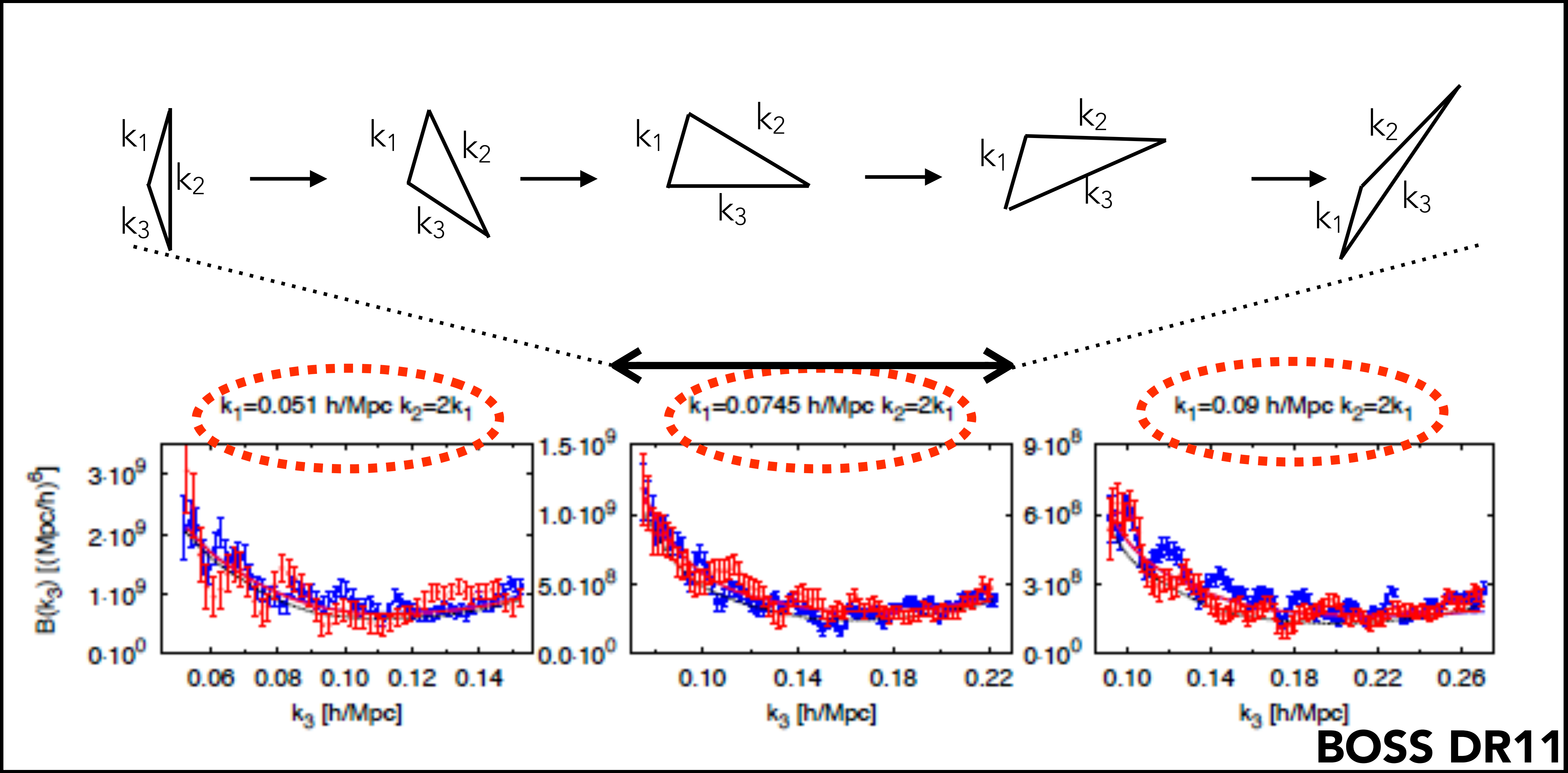
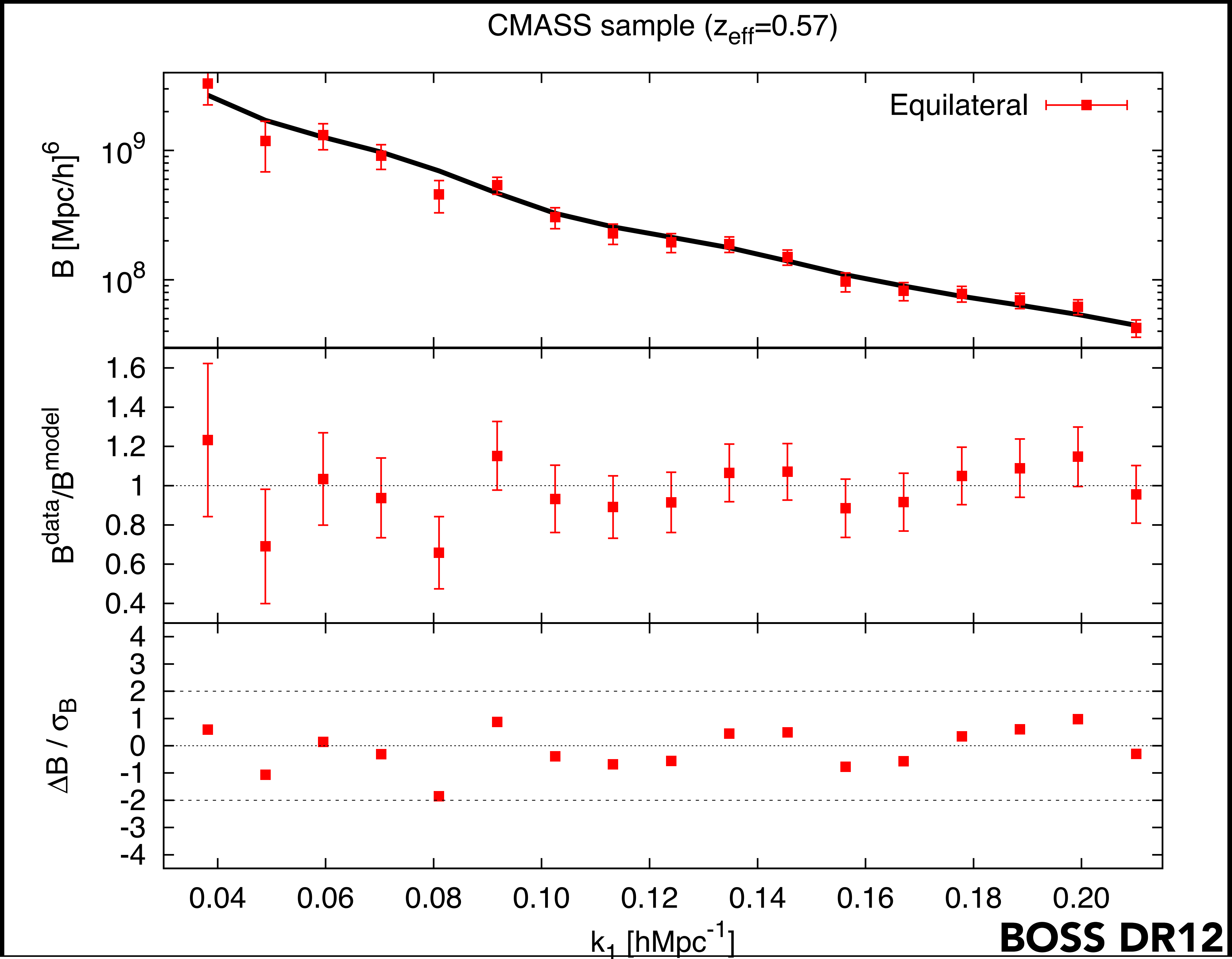


Bispectrum

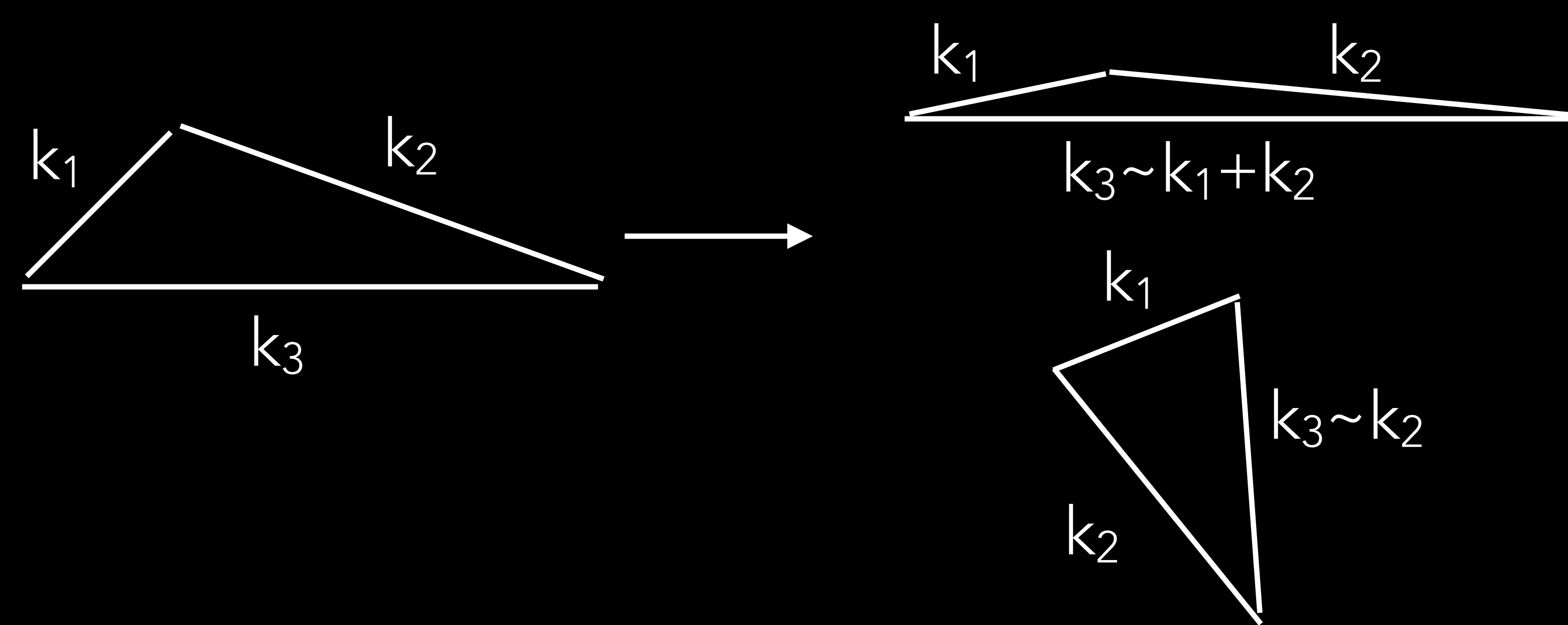
$$B(k_1,k_2,k_3) \rightarrow B^{equi}(k_1)$$



Bispectrum

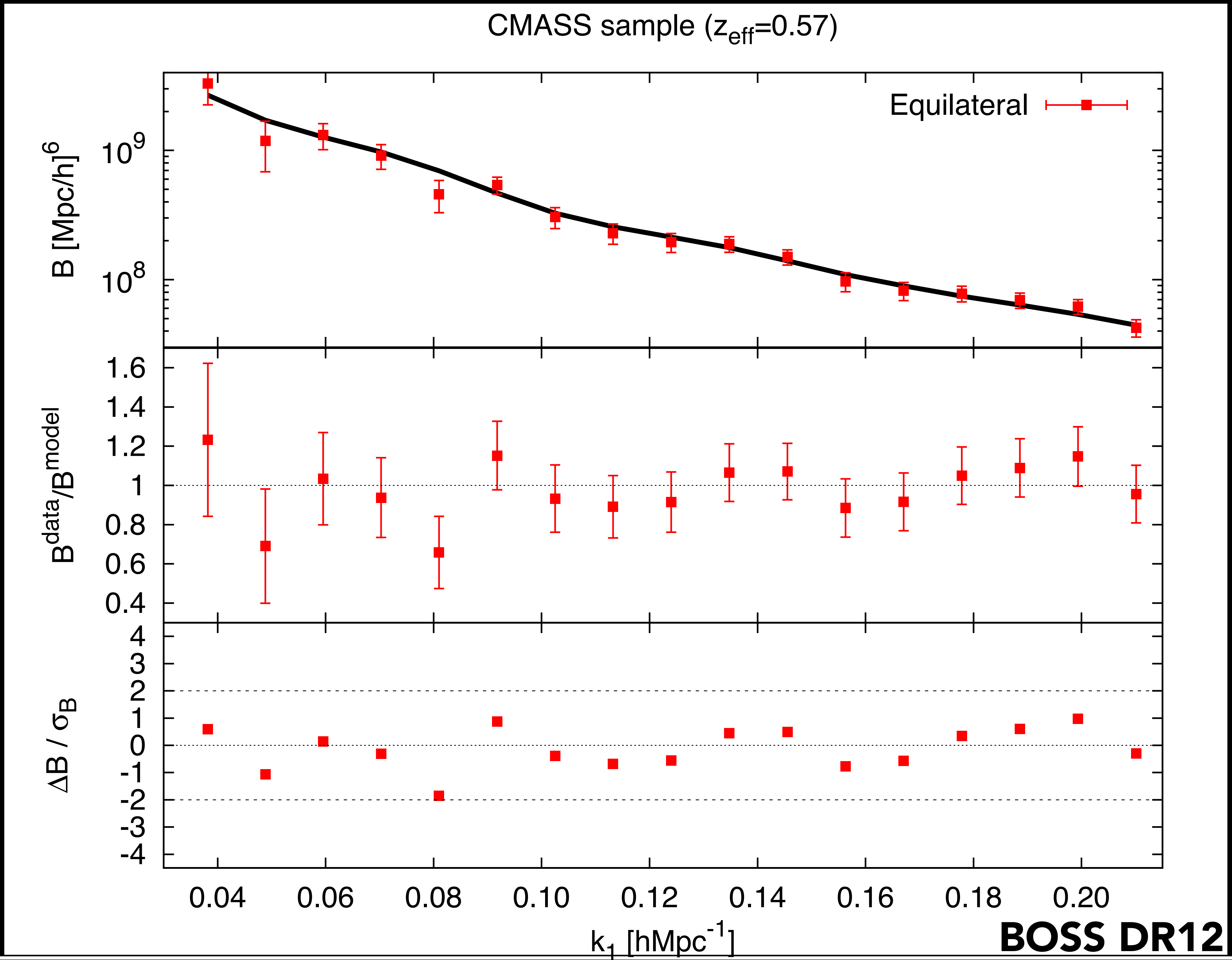
Without loss of generality $k_1 \leq k_2 \leq k_3 \longrightarrow k_1 + k_2 \geq k_3 \geq k_2$

index	k_1	k_2	k_3
1	0.01	0.01	0.01
2	0.01	0.01	0.02
3	0.01	0.02	0.02
4	0.01	0.02	0.03
5	0.01	0.03	0.03
6	0.01	0.03	0.04
…	…	…	…
i	0.02	0.02	0.02
i+1	0.02	0.02	0.03
i+2	0.02	0.02	0.04
i+3	0.02	0.03	0.03
…	…	…	…
n	k_{max}	k_{max}	k_{max}



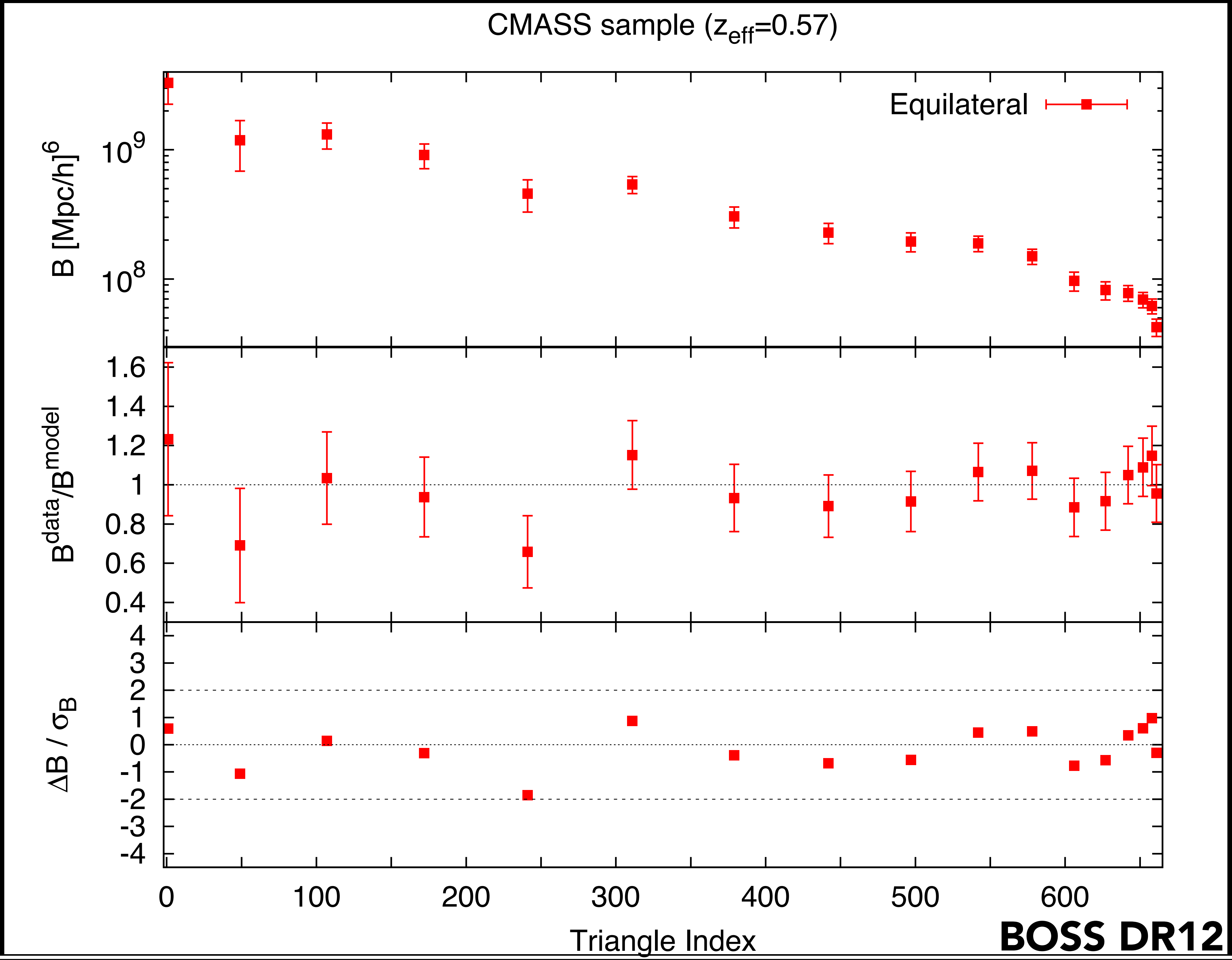
Bispectrum

$$B(k_1, k_2, k_3) \rightarrow B^{equi}(k_1)$$



Bispectrum

$$B(k_1, k_2, k_3) \rightarrow B(I)$$



Bispectrum

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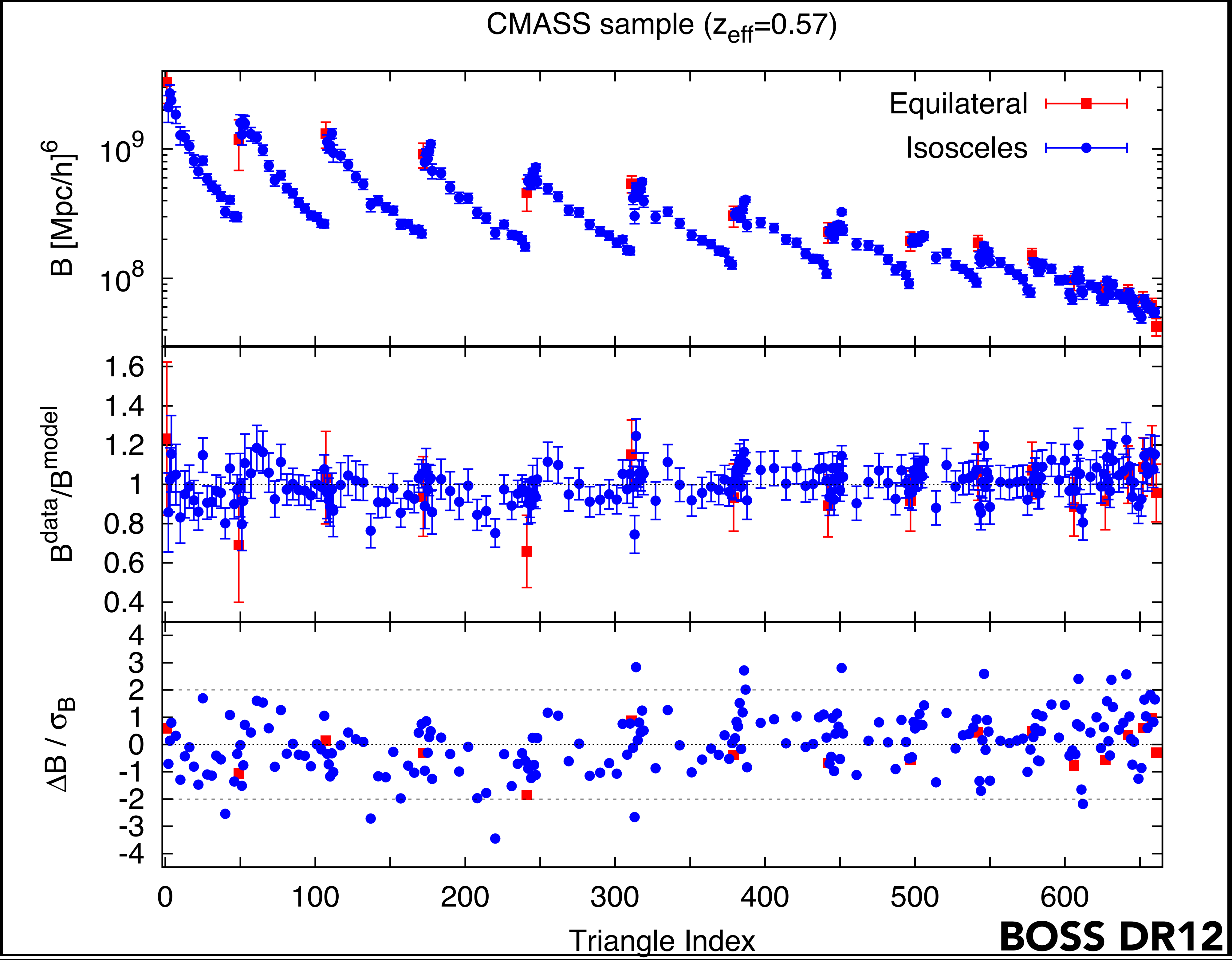

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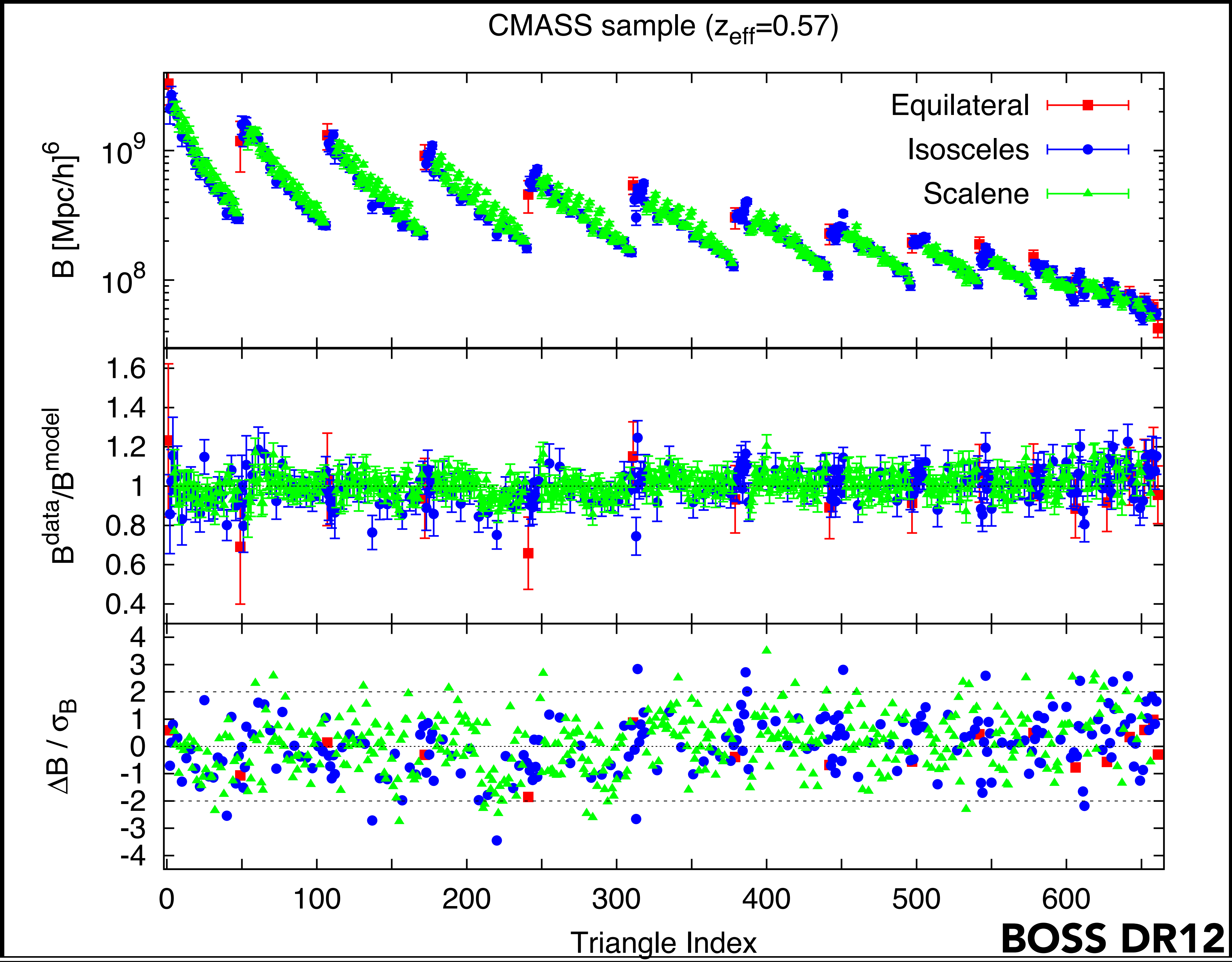

Bispectrum of dark matter

For a Gaussian initial conditions,

$$\langle\delta(k)\delta(k')\delta(k'')\rangle = 2\langle\delta^{(1)}(k)\delta^{(1)}(k')\delta^{(2)}(k'')\rangle + \dots$$

$$B^{tree}(\vec{k}_1,\vec{k}_2) = 2P_{lin}(k_1)P_{lin}(k_2)\tilde{F}_2^{(s)}(\vec{k}_1,\vec{k}_2) + cyc.$$

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where…

$$F_2^{(s)}(\vec{k}_i,\vec{k}_j) = \frac{5}{7} + \frac{1}{2}\cos(\alpha_{ij})\left[\frac{k_i}{k_j} + \frac{k_j}{k_i}\right] + \frac{2}{7}\cos^2(\alpha_{ij})$$

→ derived for a EdS

Weak dependence on **Ω**, but sensitive to modifications of GR

↓

Leading order term in **bispectrum** is sensitive to GR

Bispectrum of dark matter

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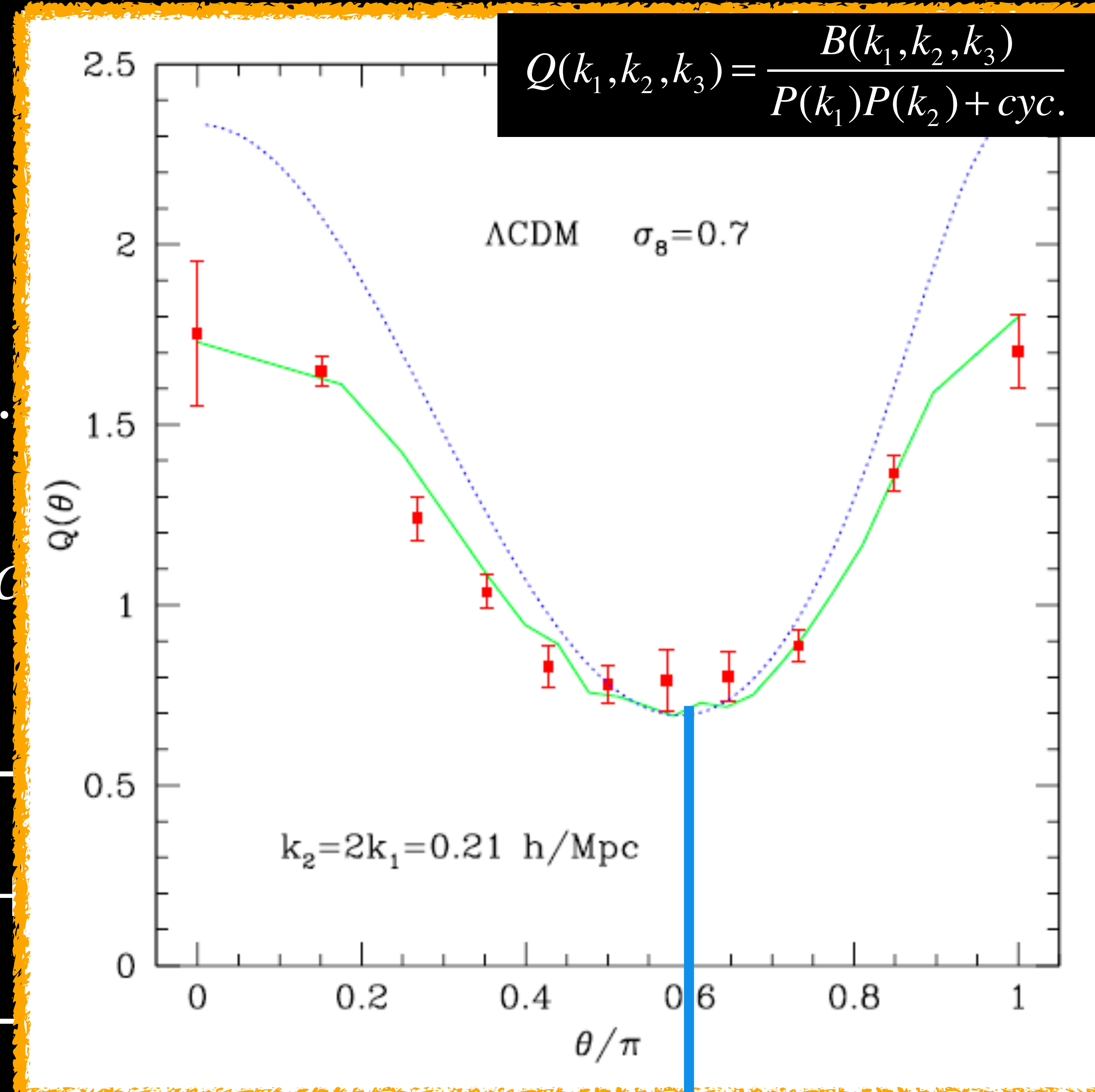

Weak dependence on **Ω**, but sensitive to modifications of GR

Characteristic U-shape

Leading order term in **bispectrum** is sensitive to GR

Bispectrum of dark matter

For a Gaussian initial conditions,

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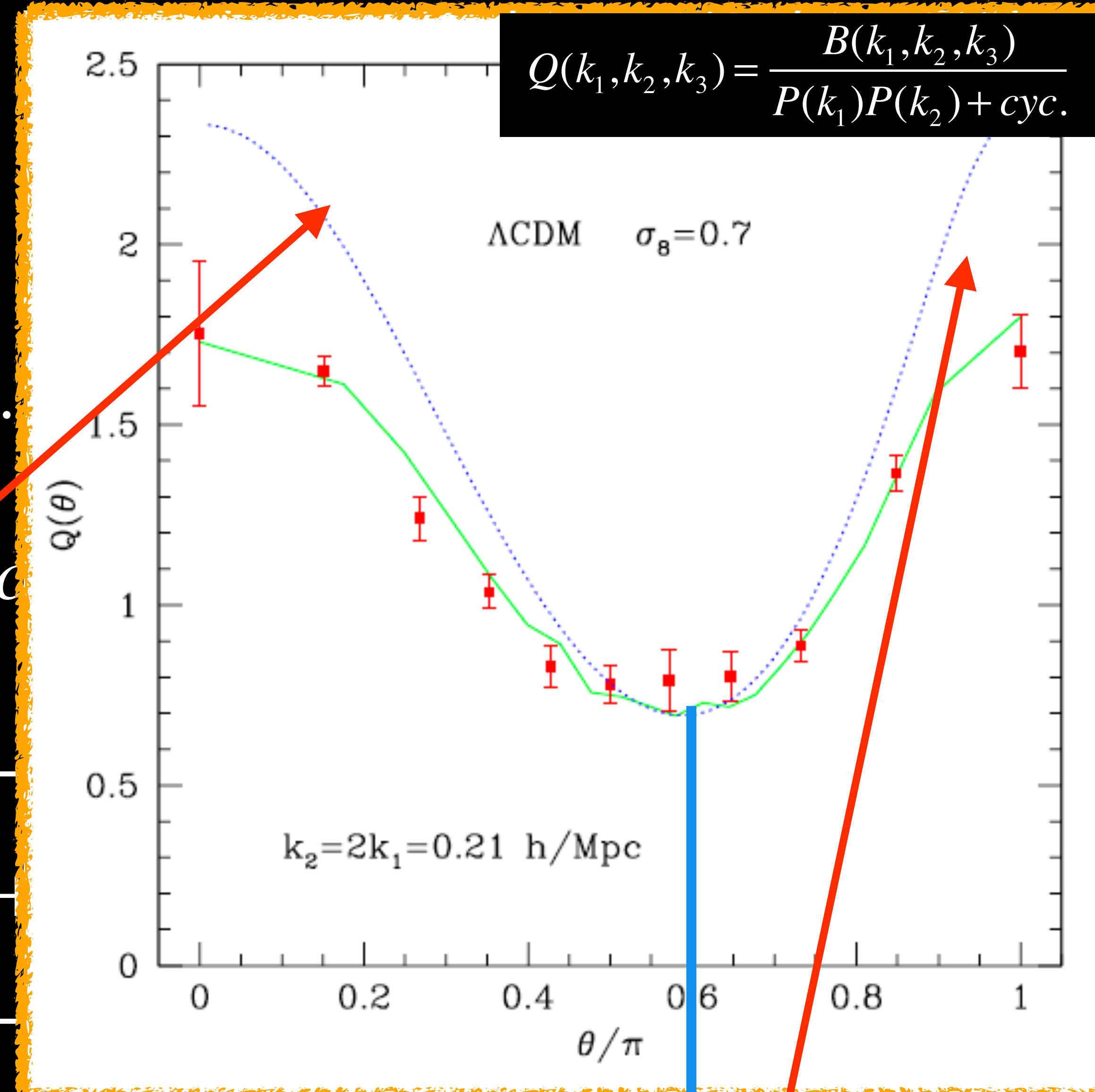

Weak dependence on **Ω**, but sensitive to modifications of GR

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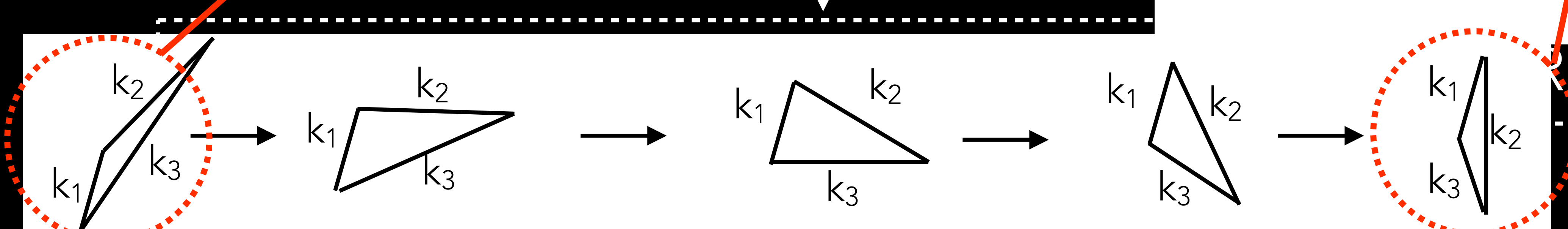


Bispectrum of galaxies

Do PT but on $\delta_g(\mathbf{k})$

Bias model (McDonald & Roy 2009)

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

PT expansion

$$\delta(k) = \delta^{(1)}(k) + \delta^{(2)}(k) + \ldots$$

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

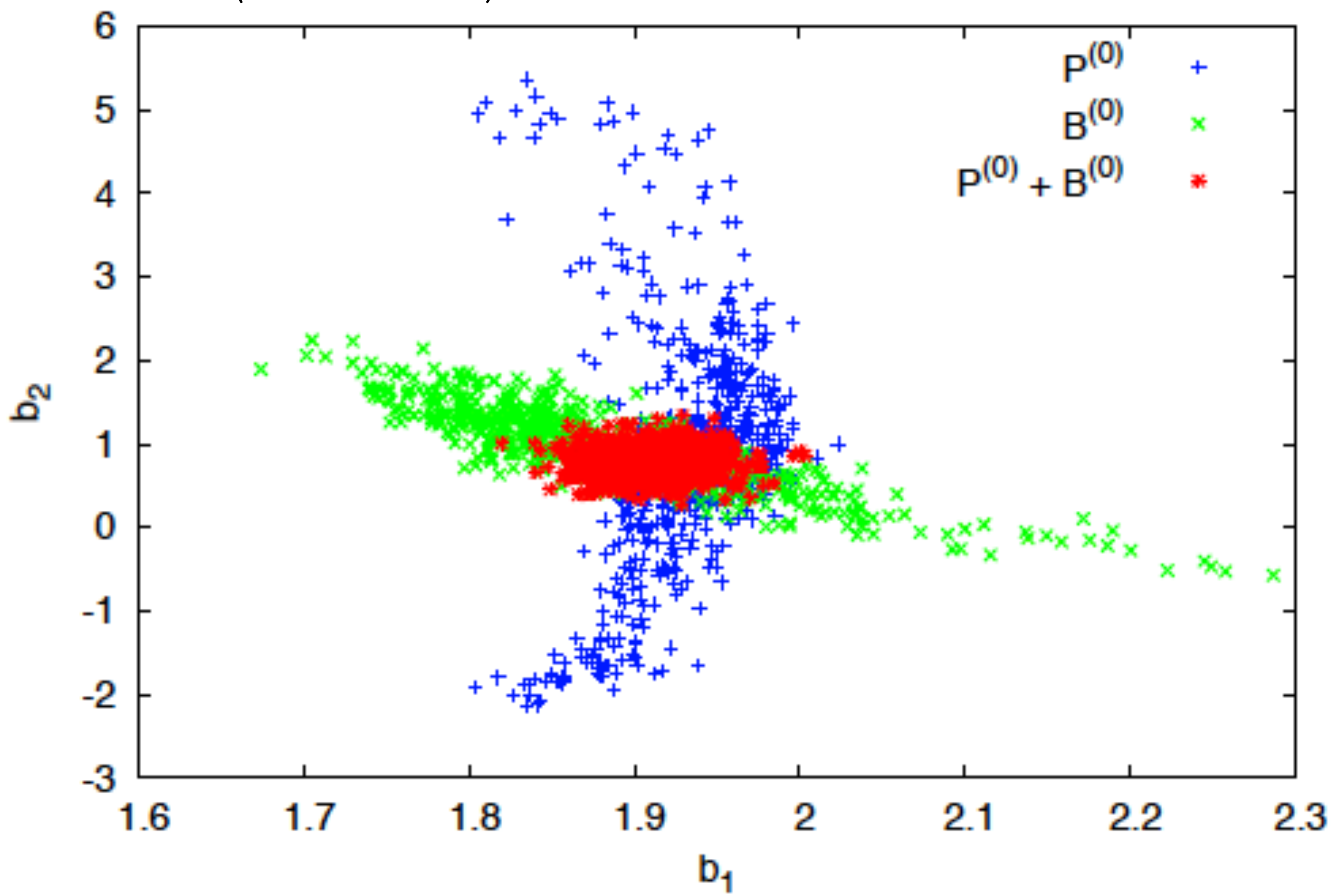
↓

Shape dependence sensitive to $\mathbf{b_2}$ (non-linear term)
Shape dependence sensitive to $\mathbf{b_{s2}}$ (tidal tensor term)

Bispectrum of galaxies

Do

600 PTHalo mocks (DR11 CMASS)



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dal tensor

$s(\mathbf{x})^2$]

ulerian

$\delta($

$B_g($

Sha ... erm)

Shap ... erm)

Bispectrum of galaxies in redshift space

Bispectrum of galaxies in configuration space

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

Redshift space Kernels $\begin{cases} F_1 \to Z_1 \\ F_2 \to Z_2 \end{cases}$

$Z_1(\vec{k})=(b_1+f\mu^2)$ Kaiser like

$$Z_2(\vec{k}_i,\vec{k}_j)=b_1\left[F_2(\vec{k}_1,\vec{k}_2)+\frac{f\mu k}{2}\left(\frac{\mu_1}{k_1}+\frac{\mu_2}{k_2}\right)\right]+f\mu^2G_2(\vec{k}_1,\vec{k}_2)+\frac{f^3\mu k}{2}\mu_1\mu_2\left(\frac{\mu_2}{k_1}+\frac{\mu_1}{k_2}\right)+\frac{b_2}{2}+\frac{2}{7}(1-b_1)S_2(\vec{k}_1,\vec{k}_2)$$

velocity kernel

Bispectrum of galaxies in redshift space

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

Bispectrum of galaxies in redshift space

60 Nbody DM simulations

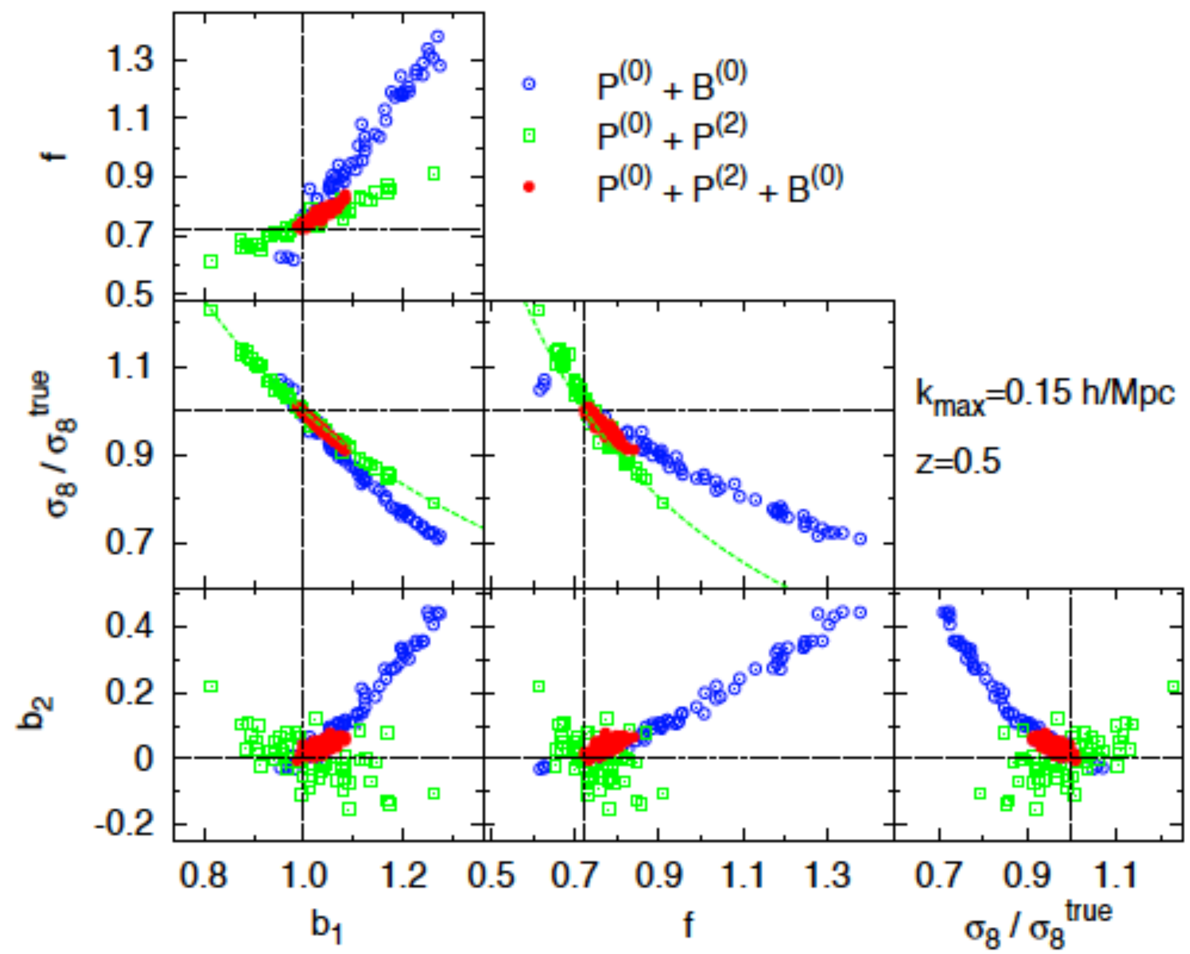

Figure 10. Best-fitting parameters for dark matter simulations in redshift space at $z = 0.5$ for $k_{\rm max} = 0.15$ when different statistics are used: blue points correspond to $P^{(0)} + B^{(0)}$, green points to $P^{(0)} + P^{(2)}$ and red points to $P^{(0)} + P^{(2)} + B^{(0)}$ as indicated. The dashed black lines mark the true values. The green dashed lines mark the $b_1 \propto \sigma_8^{-1}$ and the $f \propto \sigma_8^{-1}$ relations. Note that b_1, b_2, f, σ_8, σ_0^P, σ_0^B are varied as free parameters, although only b_1, b_2, f and σ_8 are shown for clarity.

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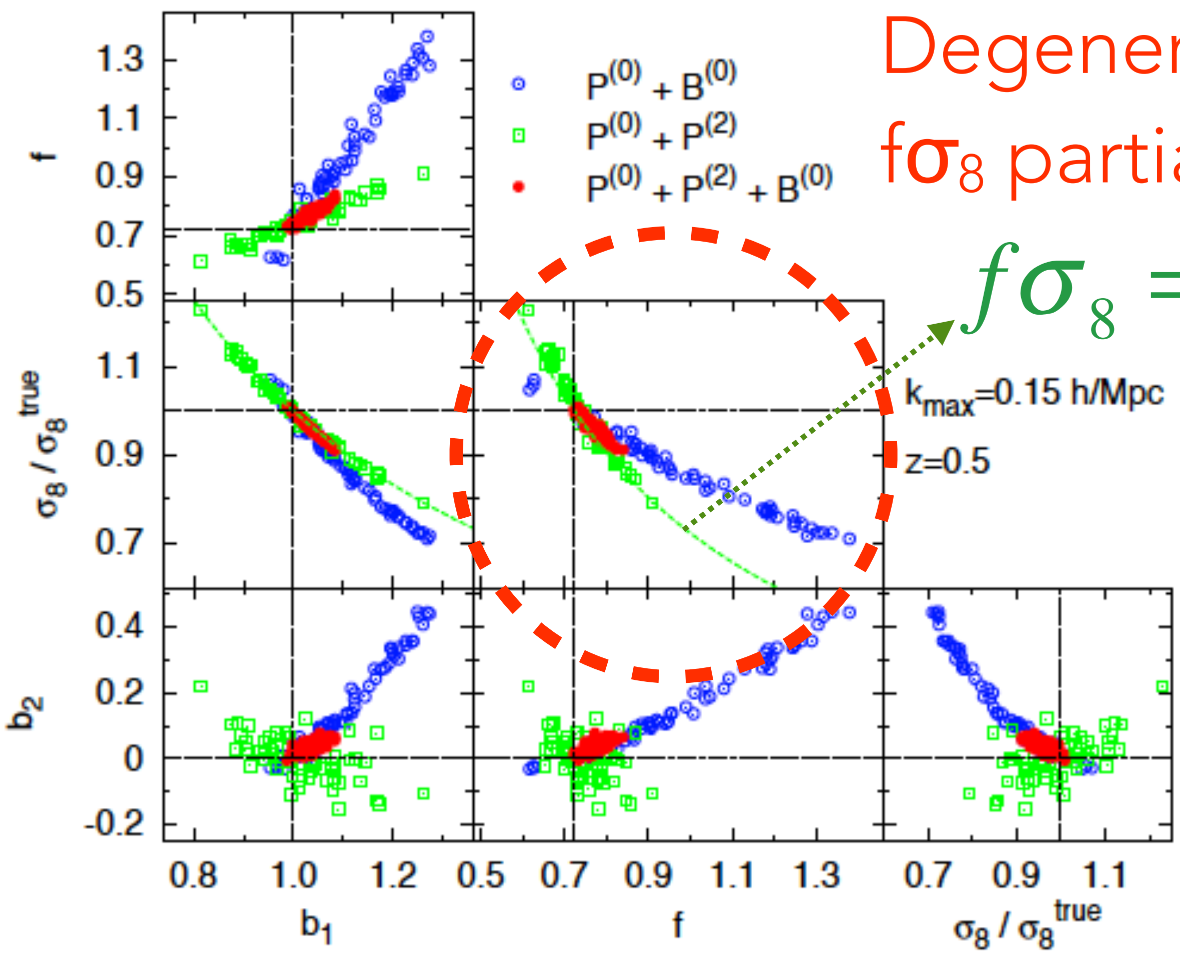
Bispectrum of galaxies in redshift space

60 Nbody DM simulations



Degeneracy between $f\sigma_8$ partially broken

$f\sigma_8 = \text{constant}$

Figure 10. Best-fitting parameters for dark matter simulations in redshift space at $z = 0.5$ for $k_{\rm max} = 0.15$ when different statistics are used: blue points correspond to $P^{(0)} + B^{(0)}$, green points to $P^{(0)} + P^{(2)}$ and red points to $P^{(0)} + P^{(2)} + B^{(0)}$ as indicated. The dashed black lines mark the true values. The green dashed lines mark the $b_1 \propto \sigma_8^{-1}$ and the $f \propto \sigma_8^{-1}$ relations. Note that b_1, b_2, f, σ_8, σ_0^P, σ_0^B are varied as free parameters, although only b_1, b_2, f and σ_8 are shown for clarity.

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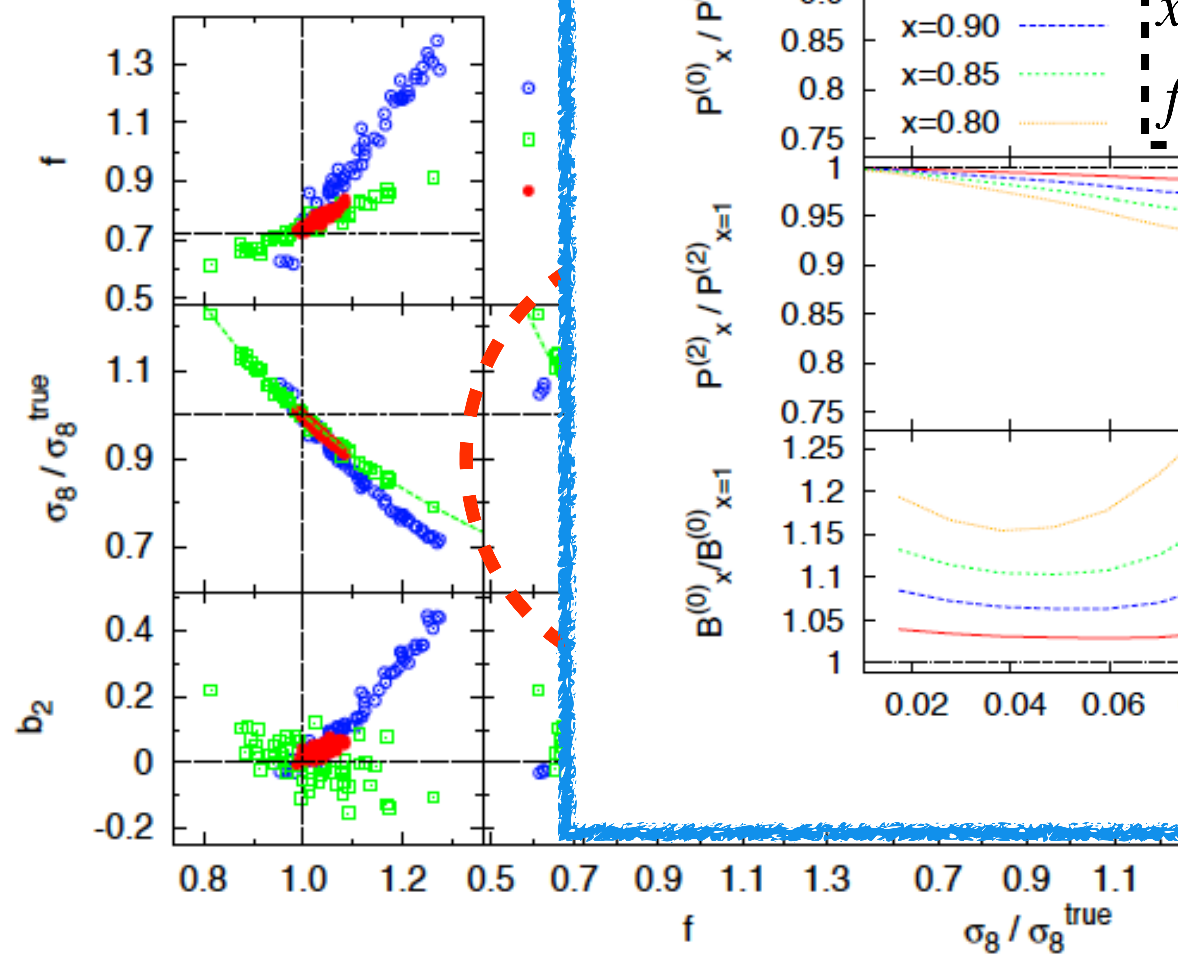
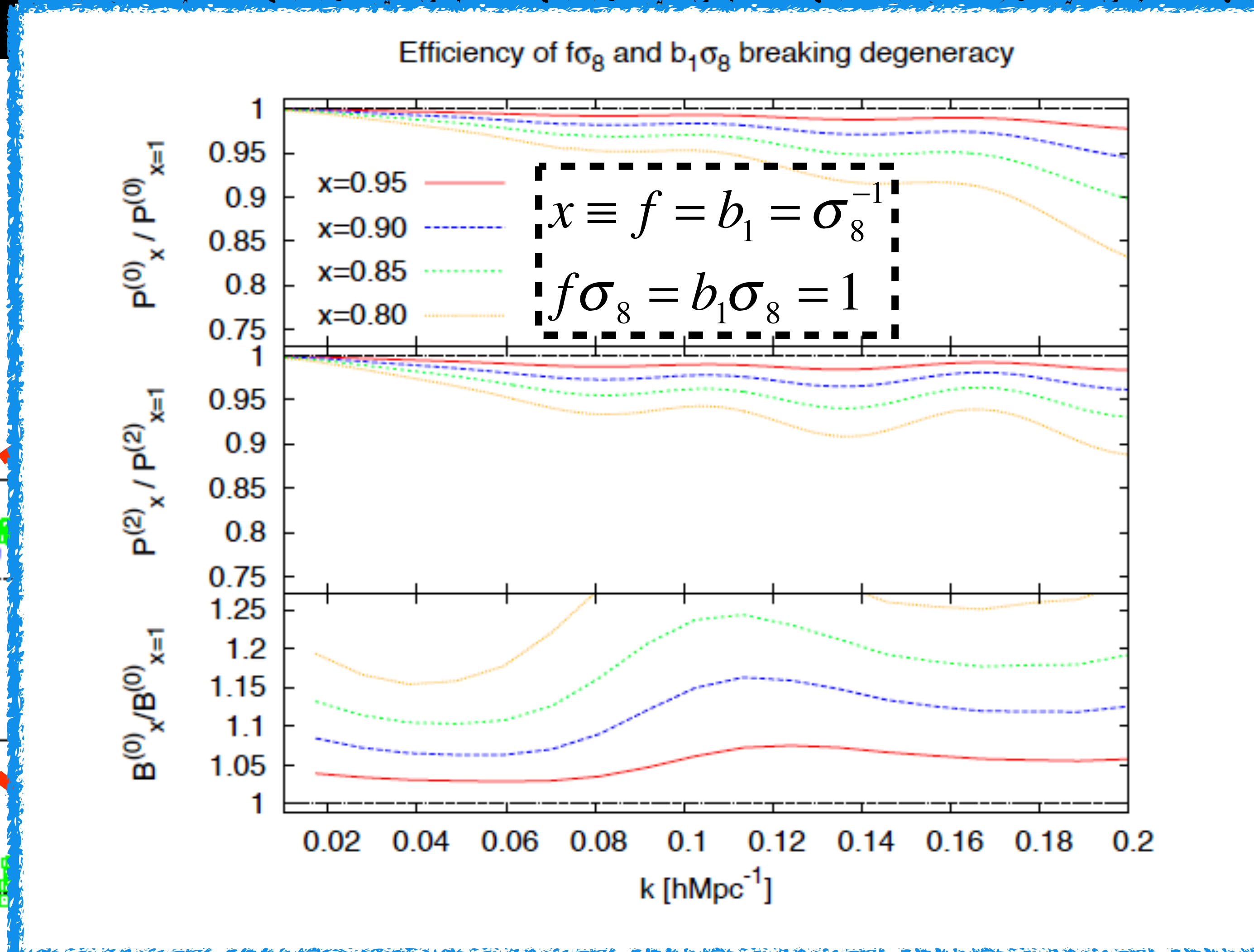
Bispectrum of galaxies in redshift space

60 Nbody DM simulations





Remember…

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

$$P_g^{(2)}(k) = P_{lin}(k)\sigma_8^2\left[\frac{4}{3}fb_1 + \frac{4}{7}f^2\right] + \ldots$$

r dark matter simulations in redshift space at $z = 0.5$ for $k_{max} = 0.15$ points correspond to $P^{(0)} + B^{(0)}$, green points to $P^{(0)} + P^{(2)}$ and red l. The dashed black lines mark the true values. The green dashed lines ılations. Note that b_1, b_2, f, σ_8, σ_0^P, σ_0^B are varied as free parameters, wn for clarity.

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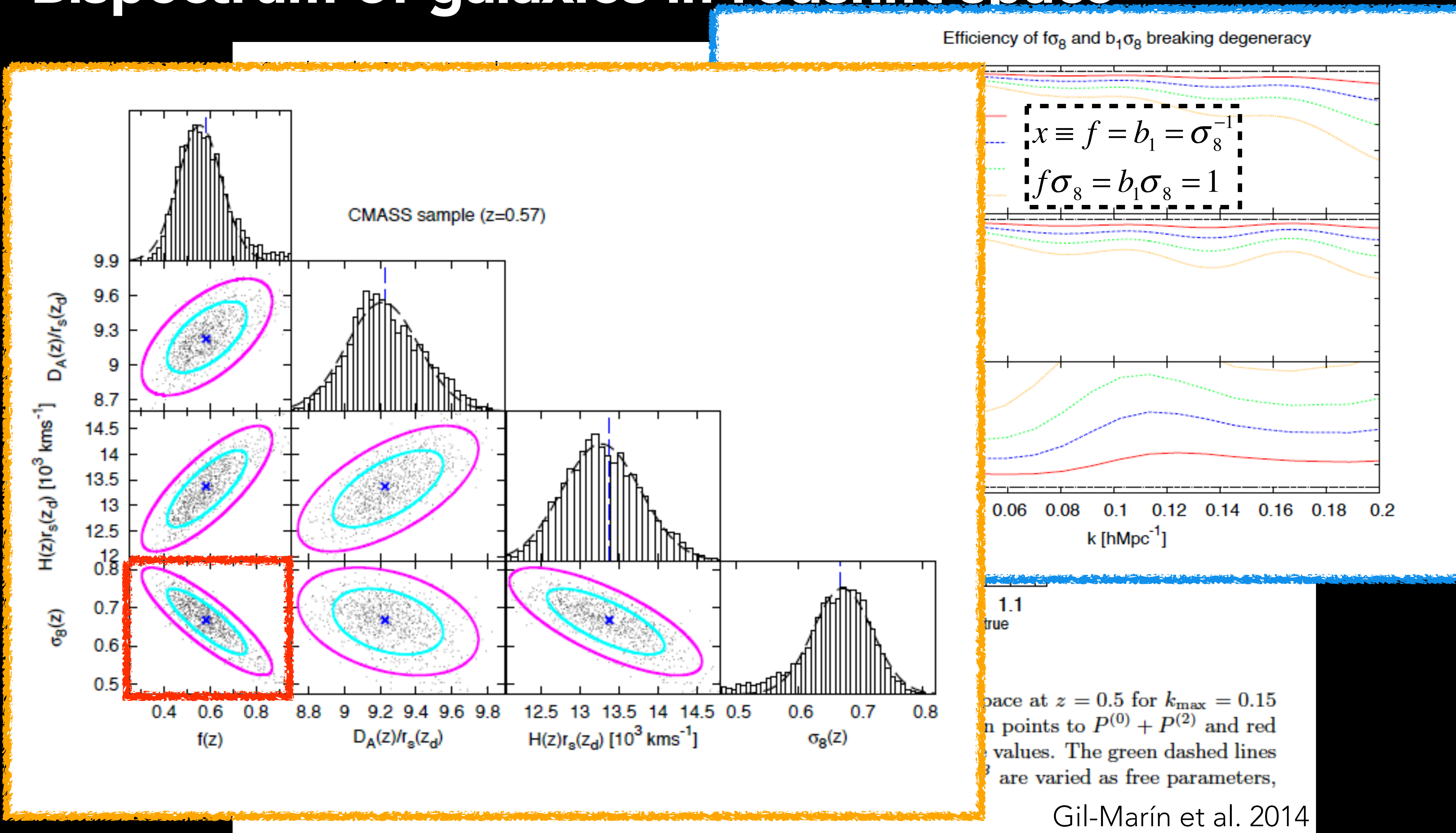
Bispectrum of galaxies in redshift space



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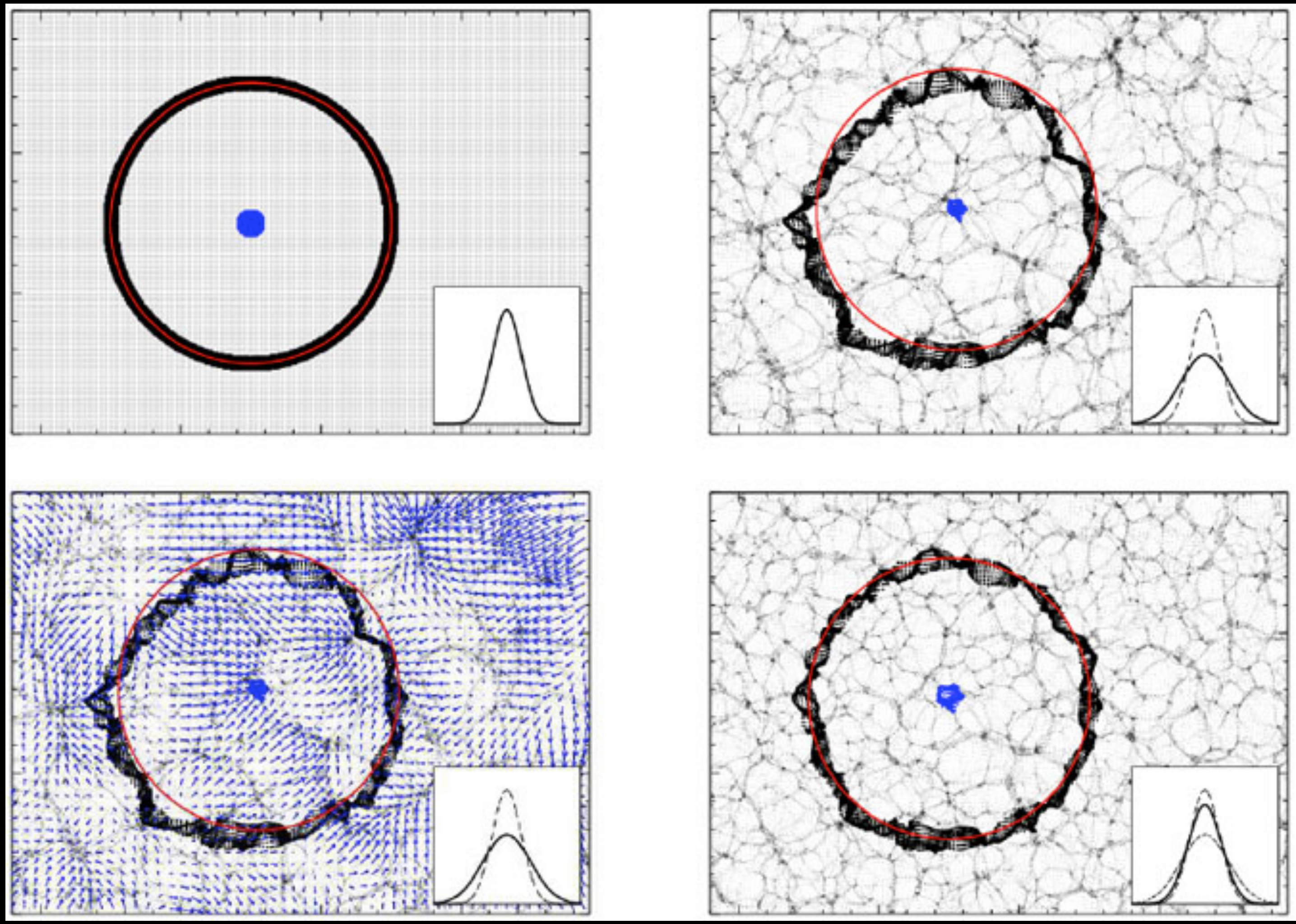
Bispectrum and BAO

- Bispectrum as an alternative to reconstruction techniques.
- After reconstruction the bispectrum signal is significantly reduced to 0
- Reconstruction is pulling information from B back into P
- By measuring P and B in the pre-reconstructed field we can recover post-reconstruction BAO information without assuming GR nor $\mathbf{\Omega_m}$



(see W. Percival talk)

Bispectrum of galaxies in redshift space

Conclusions

- Bispectrum is a non-linear quantity (even at first order)
- Leading order term in **bispectrum** is sensitive to GR
- Shape dependence sensitive to $\mathbf{b_2}$ (non-linear term) and $\mathbf{b_{s2}}$ (tidal tensor term)
- f and σ_8 can be measured independently