Position-dependent power spectrum: a new observable in the large-scale structure

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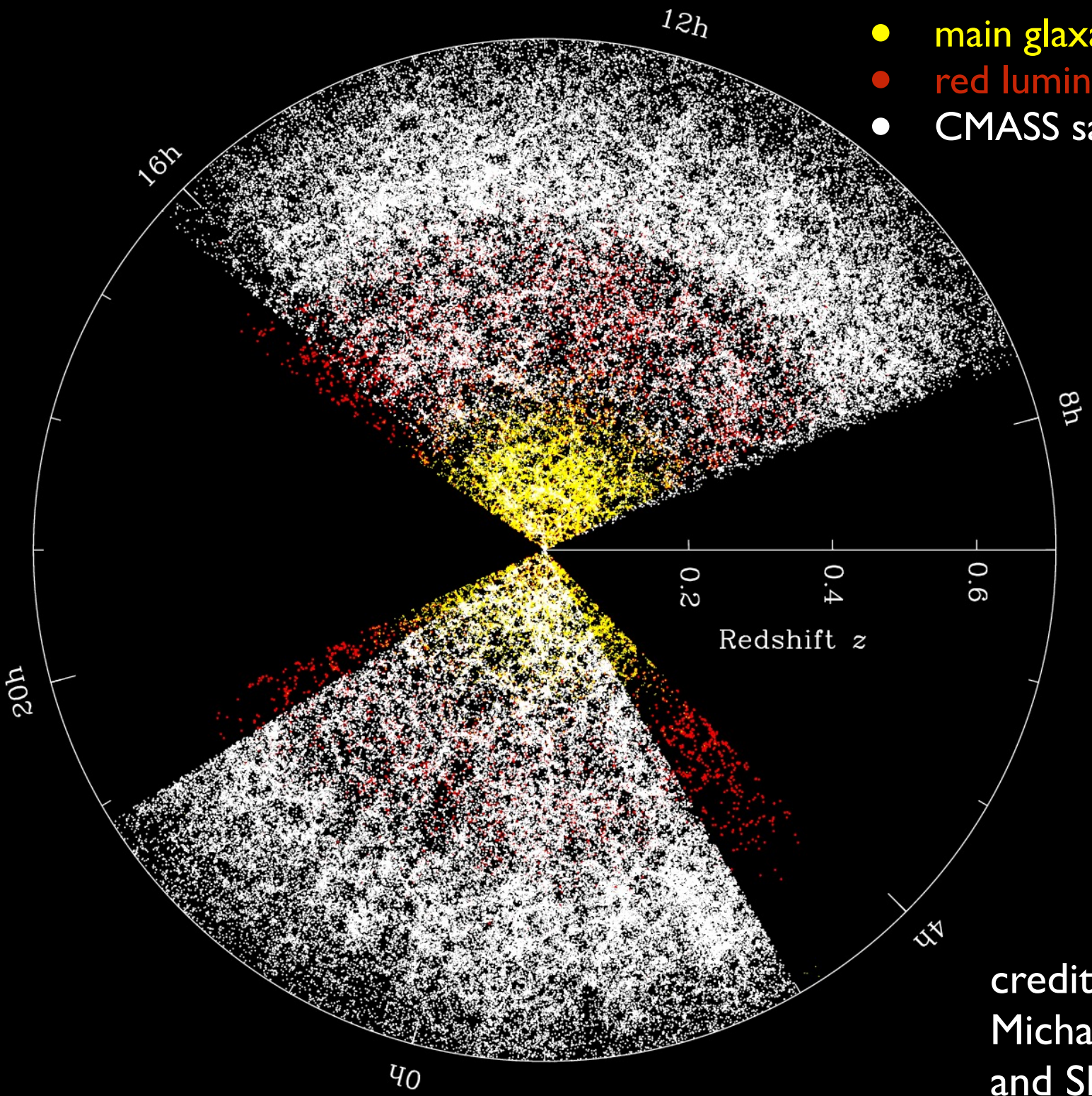


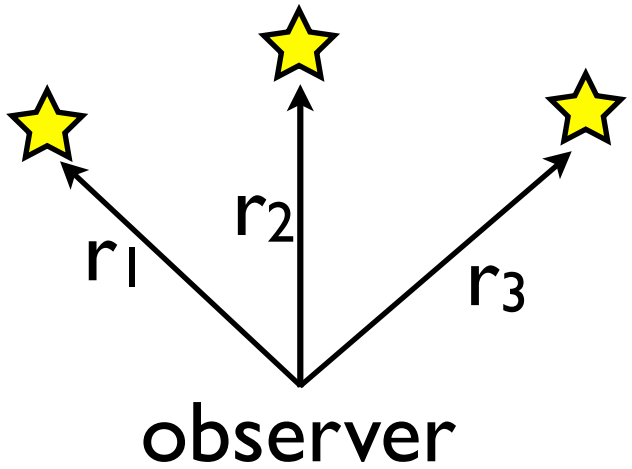
- main glaxay sample
- red luminous galaxy
- CMASS sample

credit:
Michael Blanton
and SDSS

What is the 3-point correlation function and bispectrum?

- 3-point correlation function:

$$\langle \delta(\mathbf{r}_1)\delta(\mathbf{r}_2)\delta(\mathbf{r}_3)\rangle = \zeta(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)$$

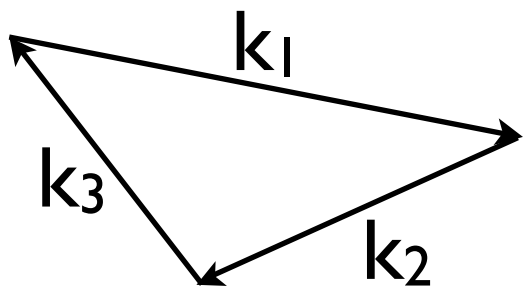


- probability of finding triplets:

$$dP = \bar{n}^3[1 + \zeta(\mathbf{r}_1, \mathbf{r}_2, \mathbf{r}_3)]d^3r_1 d^3r_2 d^3r_3$$

- bispectrum:

$$\langle \delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\delta(\mathbf{k}_3)\rangle$$
$$= (2\pi)^3 \delta_D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B(k_1, k_2, k_3)$$

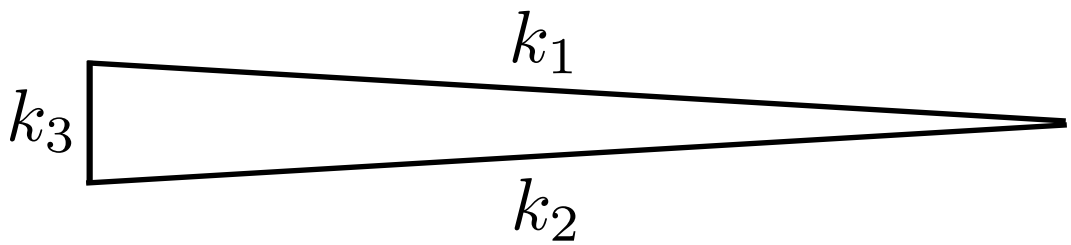


Why study position-dependent power spectrum?

- Direct measurement of the 3-point correlation function (bispectrum) is difficult when the survey geometry and selection function are not ideal.
- There are only a few measurements of the bispectrum for the current large-scale structure surveys (e.g. Gil-Marín et al 2014 for SDSS DR11).
- This motivates us to find a new observable which is easier to model and gives similar information (especially in the squeezed limit).

What is the squeezed-limit bispectrum?

- $\langle \delta(\mathbf{k}_1)\delta(\mathbf{k}_2)\delta(\mathbf{k}_3)\rangle = (2\pi)^3 \delta_D(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B(k_1, k_2, k_3)$
- squeezed limit: $k_1 \approx k_2 \gg k_3$

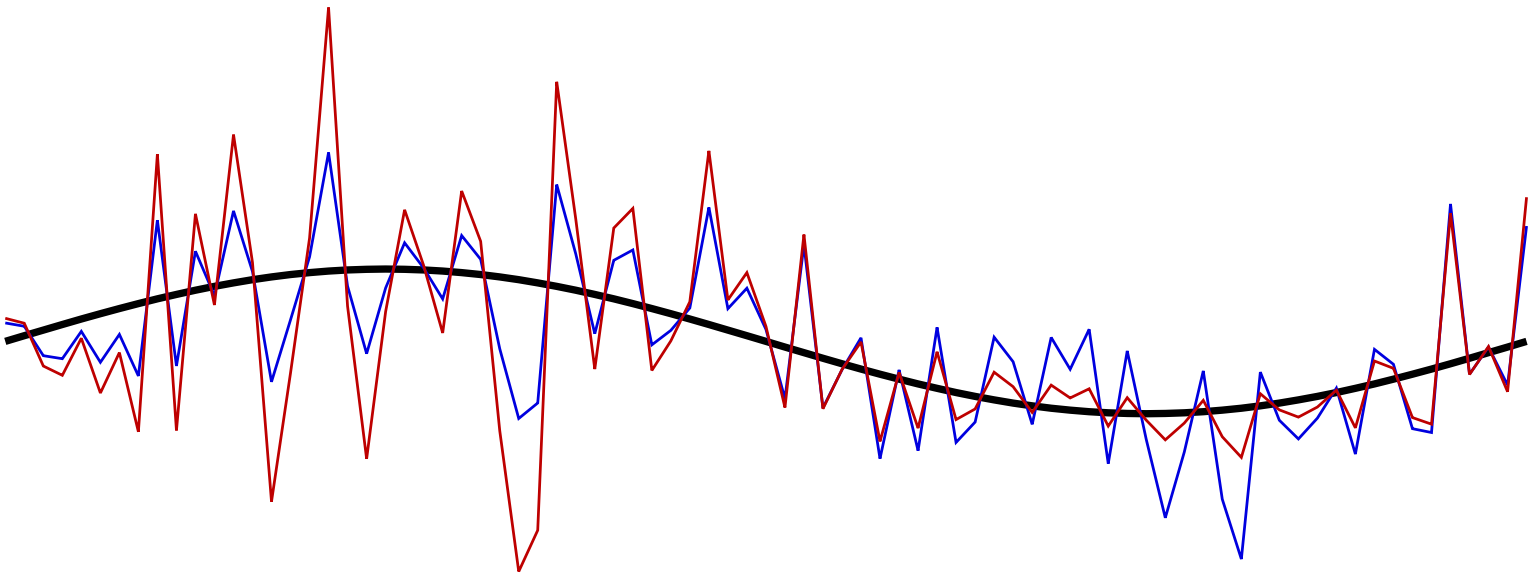


- Squeezed-limit bispectrum measures the correlation of one long-wavelength (small-wavenumber) fluctuation and two short-wavelength (large-wavenumber) fluctuations.

How is the position-dependent P(k,r) modulated by the bispectrum?

vanishing squeezed-limit bispectrum:
no correlation between power spectra and positions

non-vanishing squeezed-limit bispectrum:
correlation between power spectra and positions



overdensity underdensity

How to measure $P(k,r_L)$?

local mean

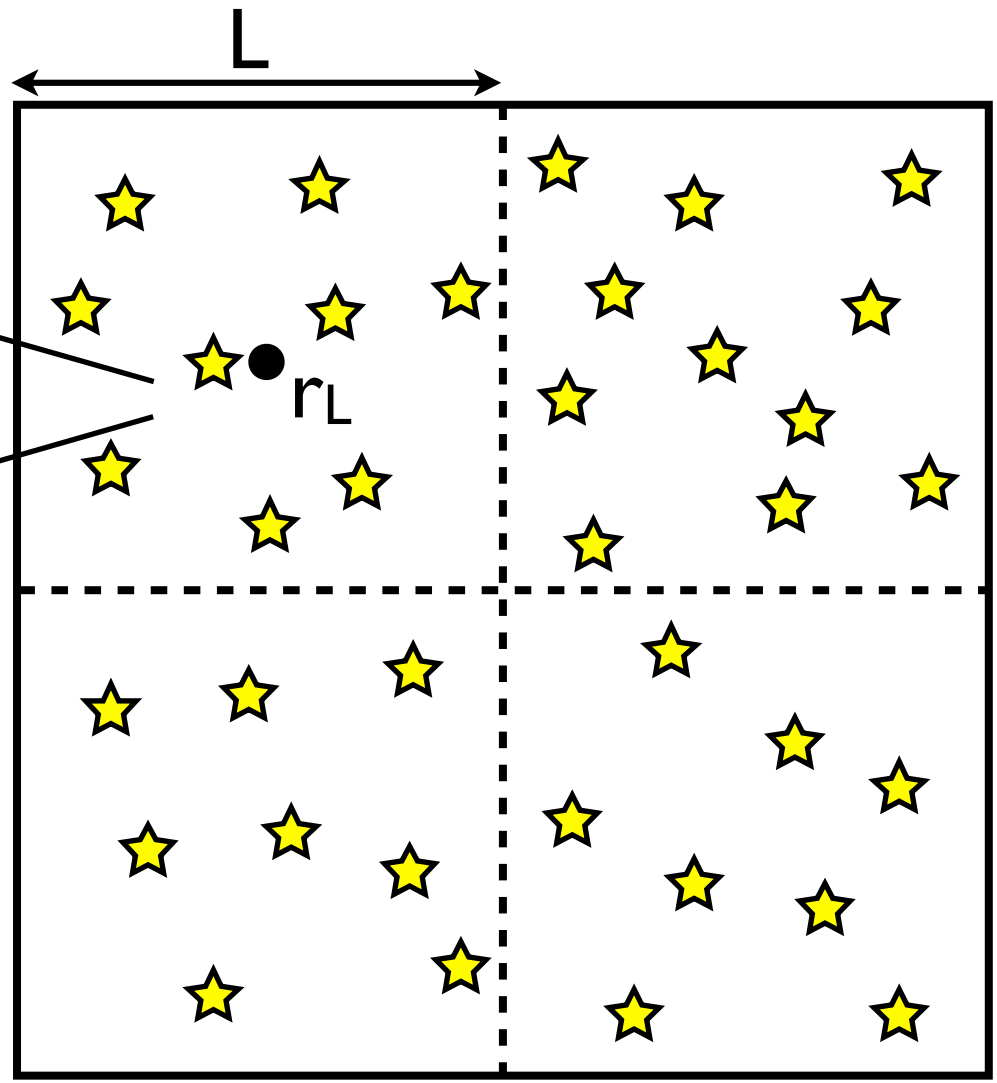
$$\bar{\delta}(\mathbf{r}_L) = \frac{\bar{n}(\mathbf{r}_L)}{\langle n \rangle} - 1$$

global mean

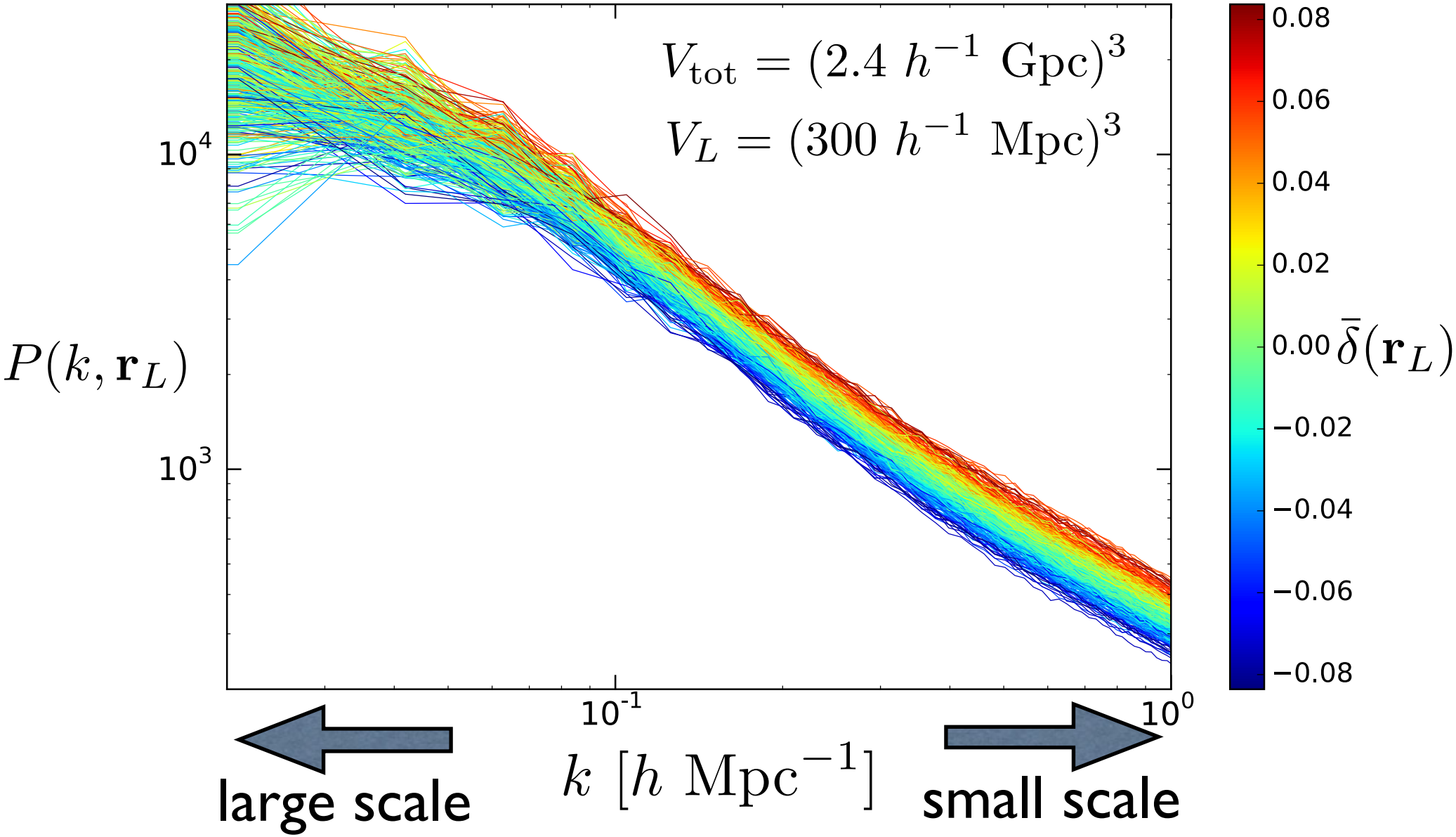
$$P(\mathbf{k}, \mathbf{r}_L) = \frac{1}{V_L} |\delta(\mathbf{k}, \mathbf{r}_L)|^2$$

local Fourier transform

$$\langle P(\mathbf{k}, \mathbf{r}_L) \bar{\delta}(\mathbf{r}_L) \rangle$$



Small-scale power spectra depend on large-scale density fluctuations!



Integrated bispectrum iB(k)

- $$iB(k) = \langle P(k, \mathbf{r}_L)\bar{\delta}(\mathbf{r}_L)\rangle$$
$$= \frac{1}{V_L^2}\int \frac{d^2\hat{k}}{4\pi}\int \frac{d^3q_1}{(2\pi)^3}\int \frac{d^3q_2}{(2\pi)^3}\; B(\mathbf{k}-\mathbf{q}_1, -\mathbf{k}+\mathbf{q}_1+\mathbf{q}_2, -\mathbf{q}_2)$$
$$\times W_L(\mathbf{q}_1)W_L(-\mathbf{q}_1-\mathbf{q}_2)W_L(\mathbf{q}_2)$$

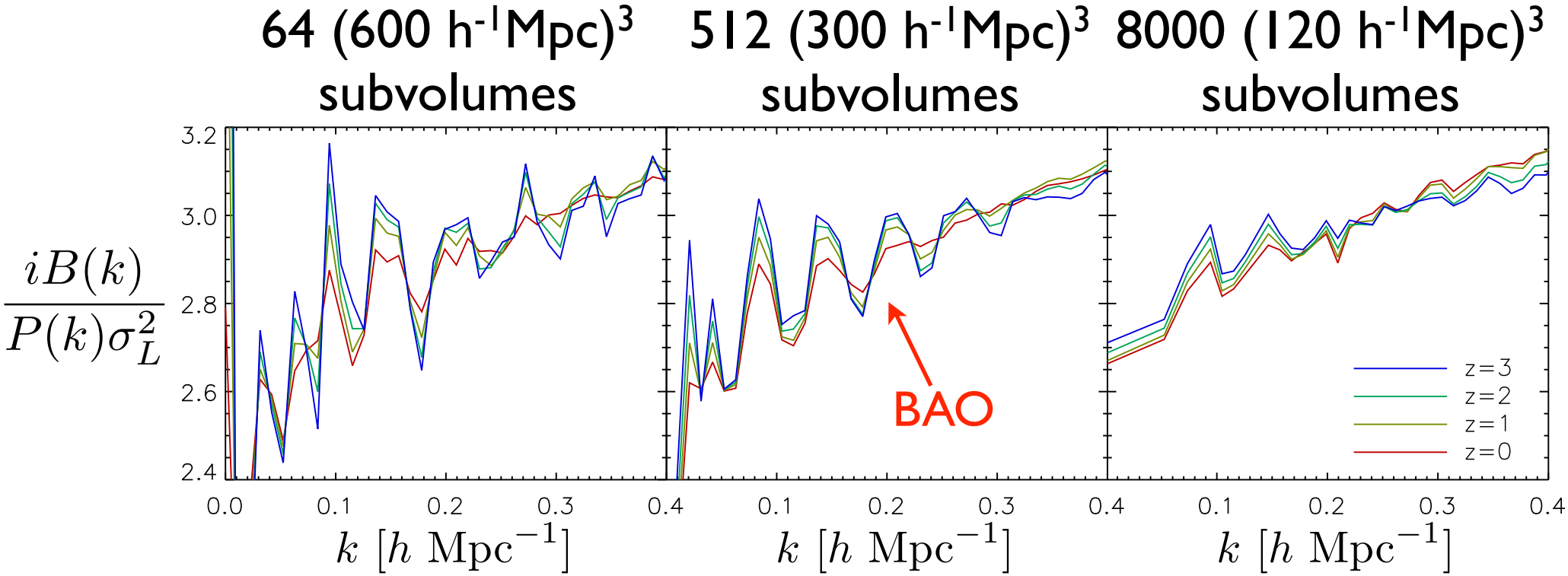
- $$W_L(\mathbf{k}) = V_L\ \mathrm{sinc}\left(\frac{k_xL}{2}\right)\mathrm{sinc}\left(\frac{k_yL}{2}\right)\mathrm{sinc}\left(\frac{k_zL}{2}\right)$$

- squeezed limit: $k \gg 1/L$ (e.g. k=0.3 h Mpc^{-1} and L=300 h^{-1}Mpc)

- normalized integrated bispectrum:

$$\frac{iB(k)}{P(k)\sigma_L^2} \quad \text{where} \quad \sigma_L^2 = \frac{1}{V_L^2}\int \frac{d^3q_2}{(2\pi)^3}\,|W_L(\mathbf{q}_2)|^2 P(q_2)$$

Measured normalized iB(k) from 160 (2.4 h^{-1} Gpc)^3 DM simulations



- BAO is damped more with smaller sub-volume size
- Nonlinear evolution also damps BAO

Separate universe approach

- The power spectrum in the universe with an infinite-wavelength density perturbation δ_0 is

$$P(k|\delta_0) = P(k)|_{\delta_0=0} + P(k)\frac{d\ln P(k)}{d\delta_0}\bigg|_{\delta_0=0}\delta_0 + \mathcal{O}(\delta_0^2)$$

$$\langle P(k|\delta_0)\delta_0\rangle = iB(k) = P(k)\frac{d\ln P(k)}{d\delta_0}\bigg|_{\delta_0=0}\langle\delta_0^2\rangle$$

- One can then consider the normalized integrated bispectrum as how the power spectrum responds to the density perturbation δ_0, i.e.

$$\frac{iB(k)}{P(k)\sigma_L^2} = \frac{d\ln P(k)}{d\delta_0}$$

Mapping the universe

Ω_m	Ω_m	$\tilde{\Omega}_m$
Ω_Λ	Ω_Λ	$\tilde{\Omega}_\Lambda$
Ω_k	Ω_k	$\tilde{\Omega}_k$
H_0	H_0	$\tilde{H}_0$
ρ_m	$\rho_m(1+\delta_0)$	ρ_m

(e.g. Sirko 2005, Baldauf et al 2011, Sherwin & Zaldarriaga 2012, Li et al, 2014)

Change of P(k) with δ_0

- dilation effect (change of scale):

$$\tilde{P}(\tilde{k},t) \to \left[1 - \frac{1}{3}\frac{d\ln k^3 P(k,t)}{d\ln k}\frac{D(t)}{D(t_0)}\delta_0\right] P(k,t)$$

- reference density effect ($\rho \to \rho(1+\delta_0)$):

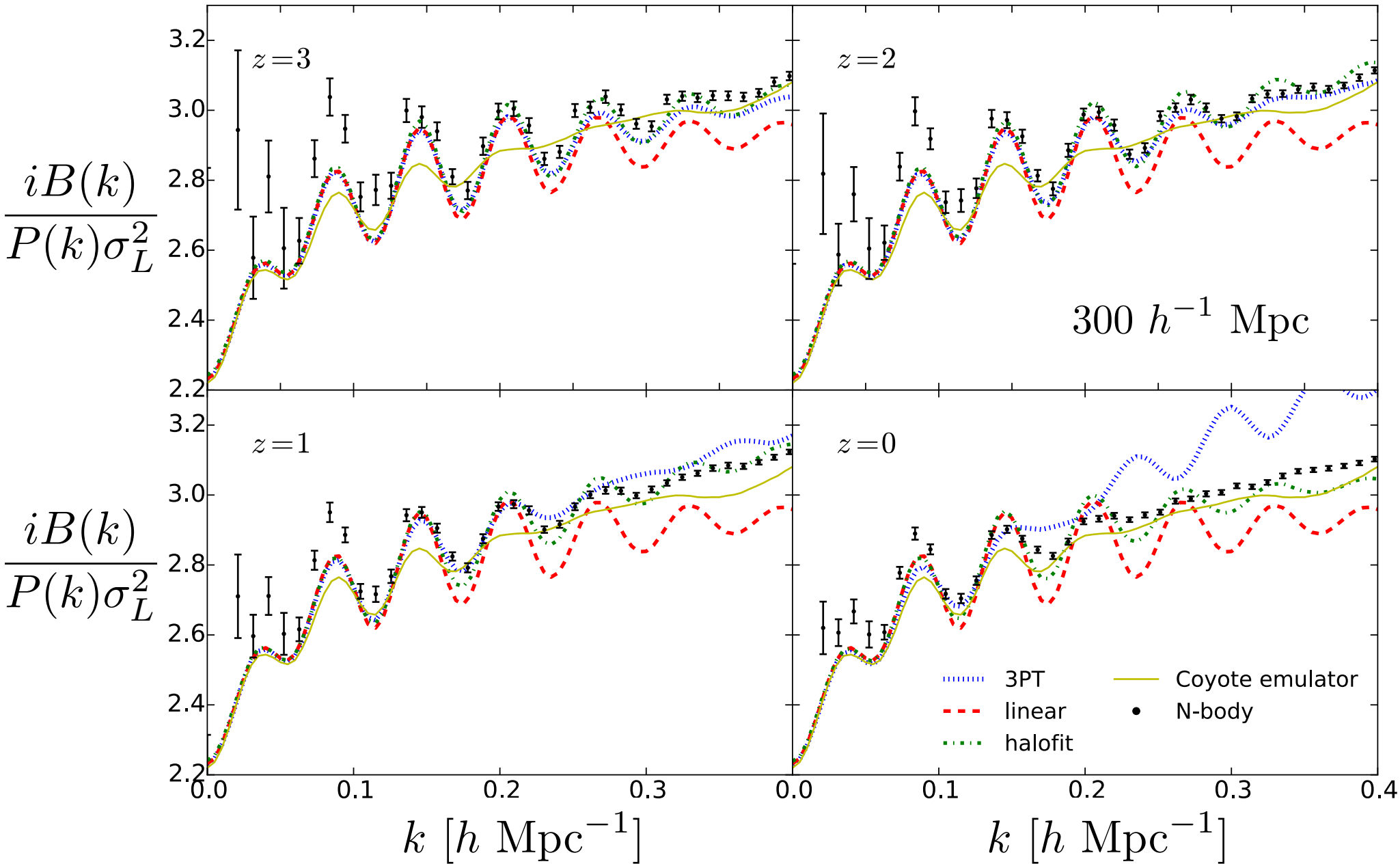
$$\tilde{P}(\tilde{k},t) \to \left[1 + 2\frac{D(t)}{D(t_0)}\delta_0\right] P(\tilde{k},t)$$

- growth effect:

$$\tilde{P}(\tilde{k},t) \to \left[1 + \frac{26}{21}\frac{D(t)}{D(t_0)}\delta_0\right] P(\tilde{k},t)$$ for linear P(k)

separate universe simulations for nonlinear P(k)

Separate universe modeling



Application to the SDSS-III BOSS DR10 CMASS sample

- Correlation function is easier to measure than power spectrum for galaxy surveys.
- Galaxy 3-point function $\zeta_g = b_1^3 \zeta_{\rm SPT} + b_1^2 b_2 \zeta_{b_2}$ is sensitive to the nonlinear bias at the leading order (unlike the 2-point function).

How to measure $\xi(r,r_L)$?

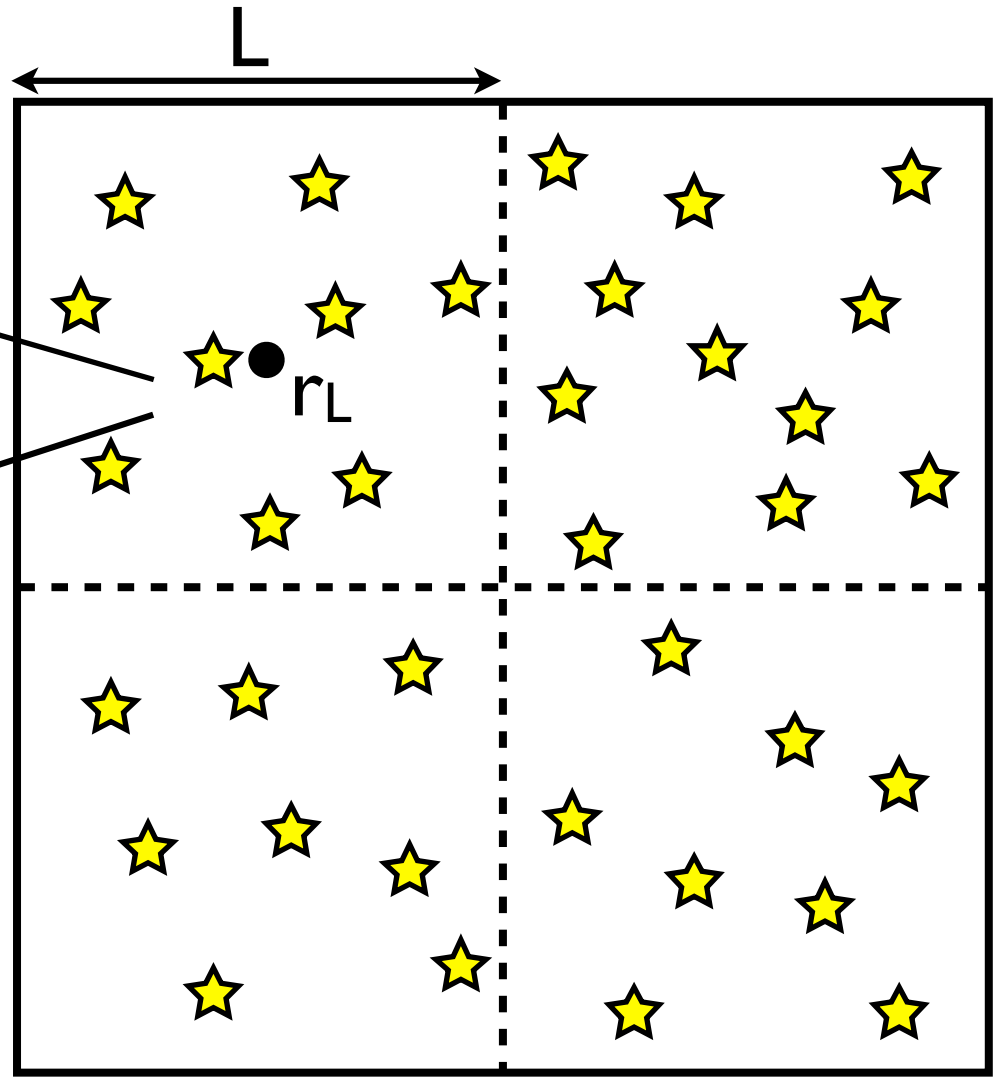
local mean

$$\bar{\delta}(\mathbf{r}_L) = \frac{\bar{n}(\mathbf{r}_L)}{\langle n \rangle} - 1$$

global mean

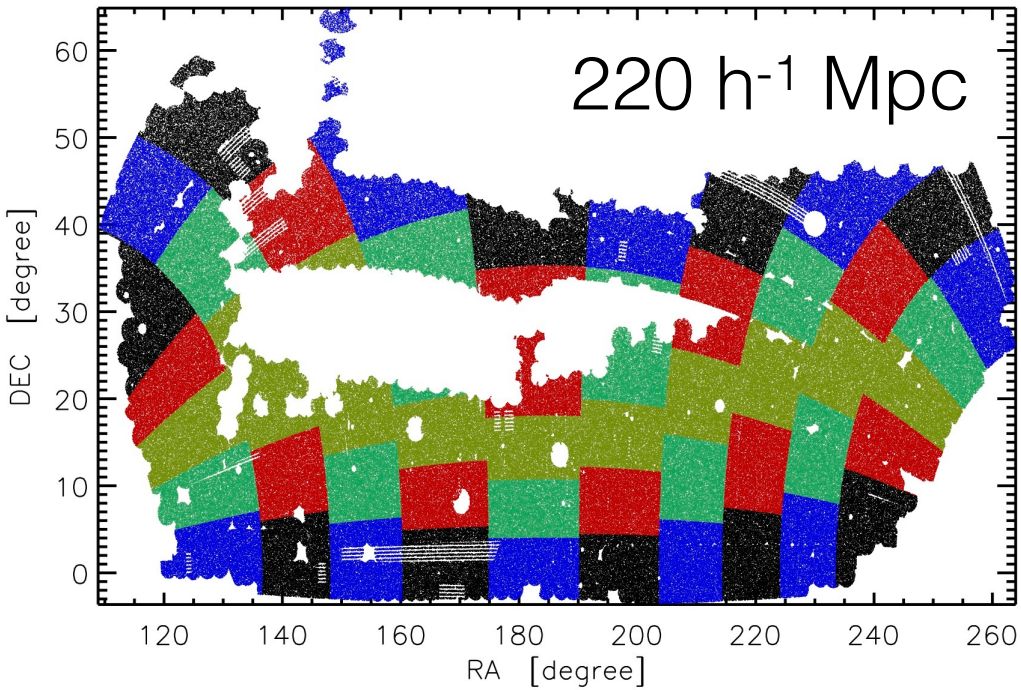
$$\xi(\mathbf{r}, \mathbf{r}_L)$$

$$\langle \xi(\mathbf{r}, \mathbf{r}_L) \bar{\delta}(\mathbf{r}_L) \rangle \equiv i\zeta(\mathbf{r})$$

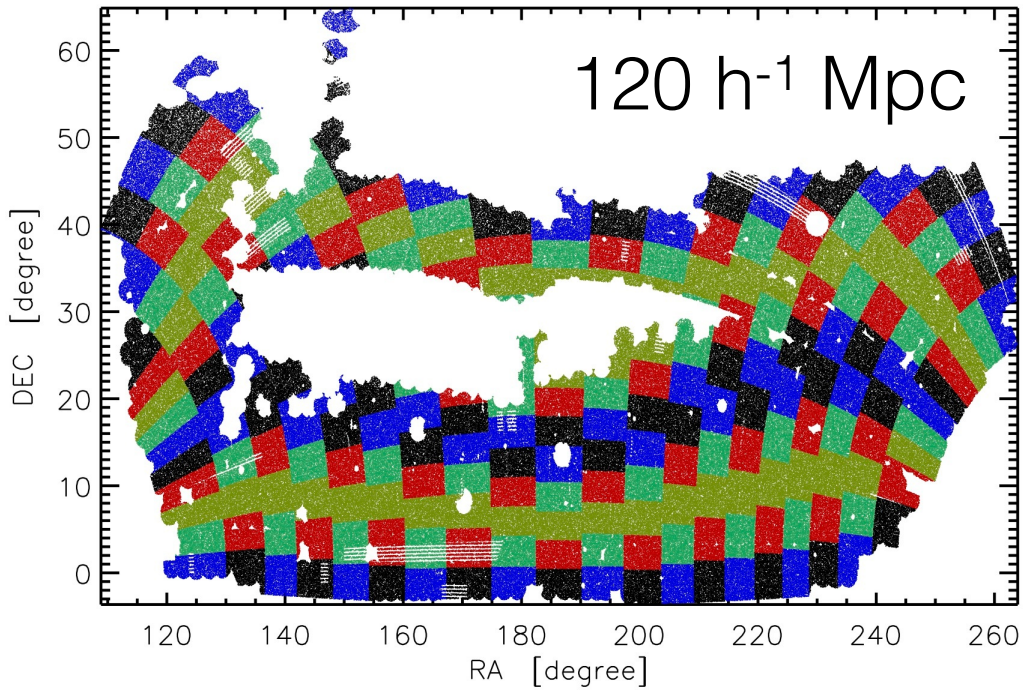


Divide the sample in NGC

- ~400,000 galaxies at 0.43<z<0.7 (~ 2 h^{-3} Gpc^3)
- weighting: $w = (w_{\rm cp} + w_{\rm zf} - 1) w_{\rm star} w_{\rm see} w_{\rm FKP}$
- 600 PTHalos mock catalogs (Manera et al 2014)

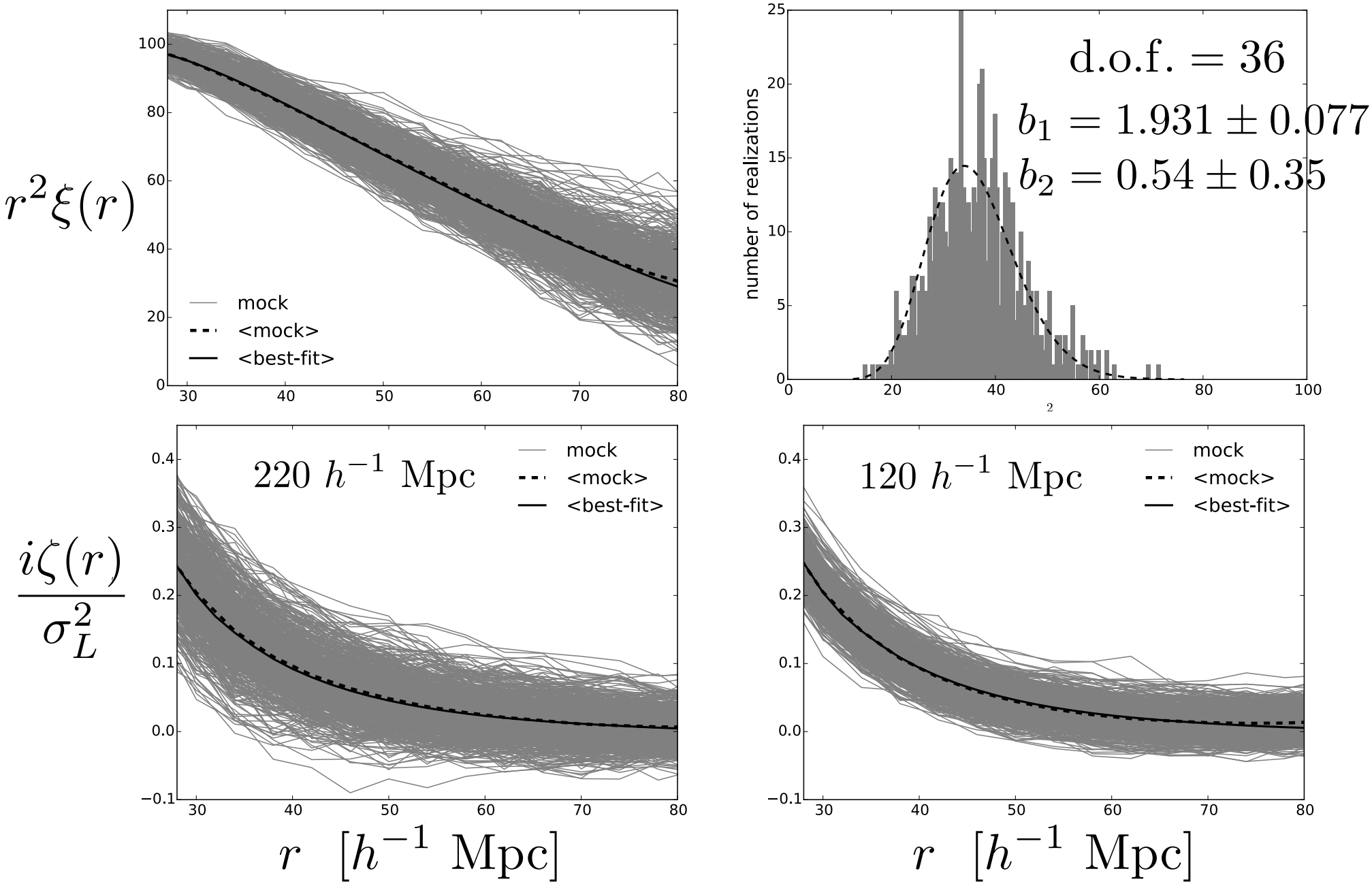


zcut=3
150 subvolumes

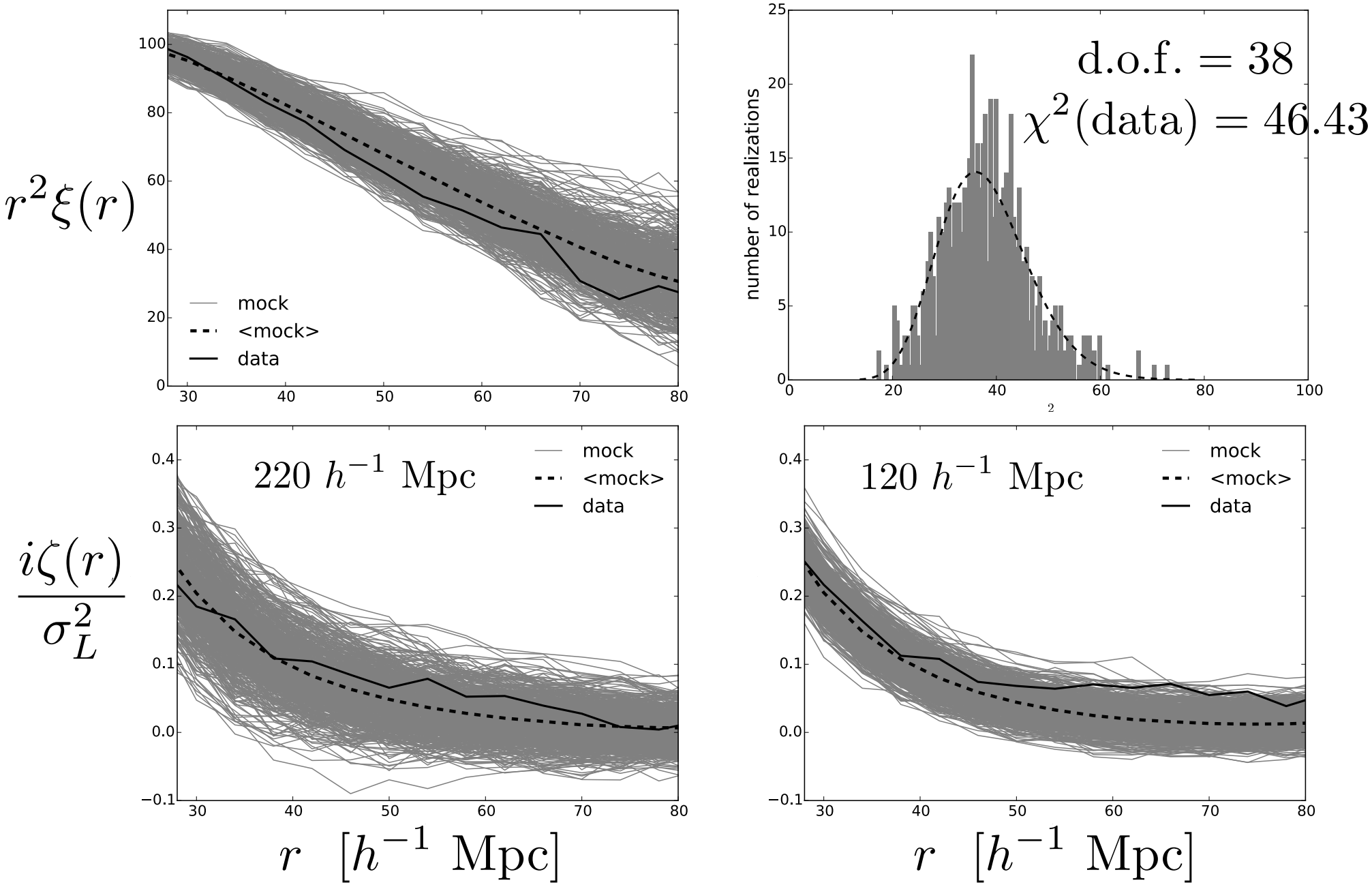


zcut=5
1000 subvolumes

Mocks in redshift space



BOSS DR10 CMASS sample



Combining with other probes

- $i\zeta_g$ is sensitive to b_2 at the leading order
- Anisotropic clustering (Samushia et al 2013): $[(b_1\sigma_8)+(f\sigma_8)\mu^2]^2 \rightarrow (b_1\sigma_8), (f\sigma_8)$
- Weak lensing (More et al 2015): σ_8
- Running MCMC on $i\zeta_g$ with Gaussian priors of $(b_1\sigma_8)$, $(f\sigma_8)$, and σ_8, we obtain $b_2=0.41\pm0.41$ for BOSS CMASS sample.

Conclusions

- Three-point function contains extra information (on top of two-point function) and so can be used to constrain the cosmological parameters.
- Position-dependent power spectrum and correlation function are useful methods to extract the squeezed-limit bispectrum.
- Combining with anisotropic clustering and weak lensing, we can constrain the nonlinear bias of BOSS CMASS sample to be $b_2=0.41\pm0.41$.