Galaxies as a window into the Primordial Universe

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Outline

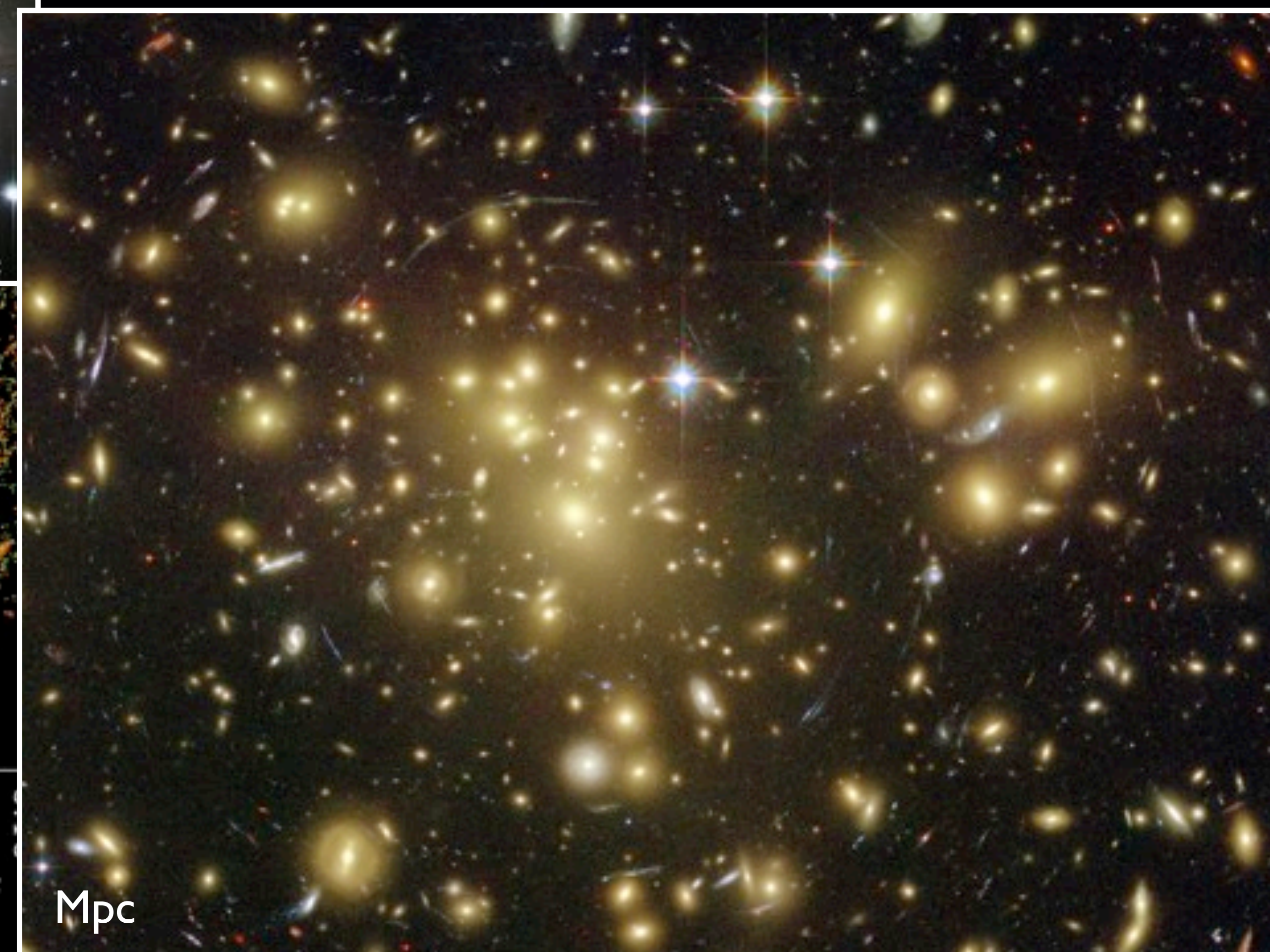
- Galaxy clustering in large scale surveys
- Galaxy biasing: local bias and peak-background split
- Searching for primordial non-Gaussianity in galaxy clustering
- Beyond the standard local bias model

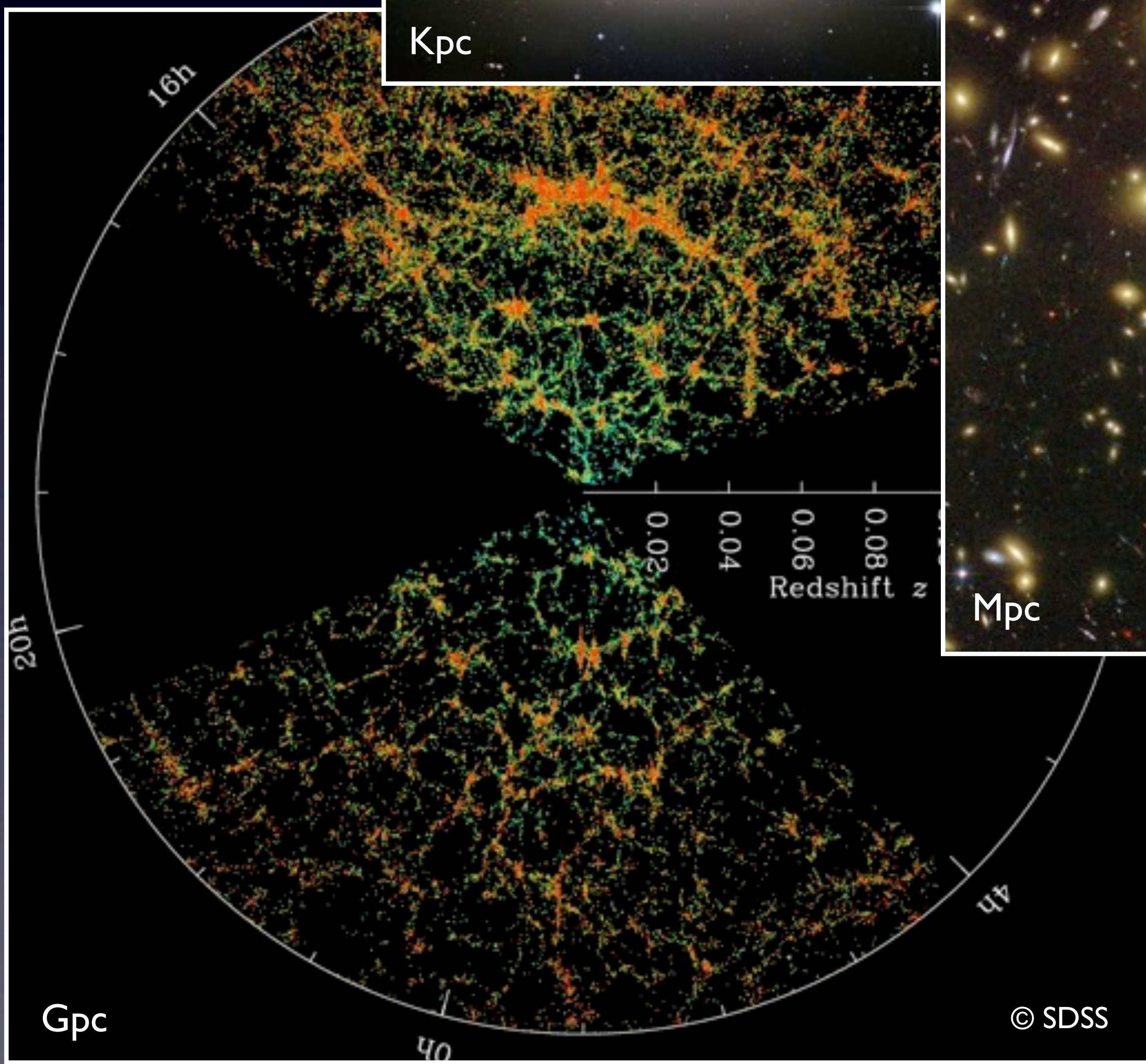
Scales

pleiades

sombrero galaxy

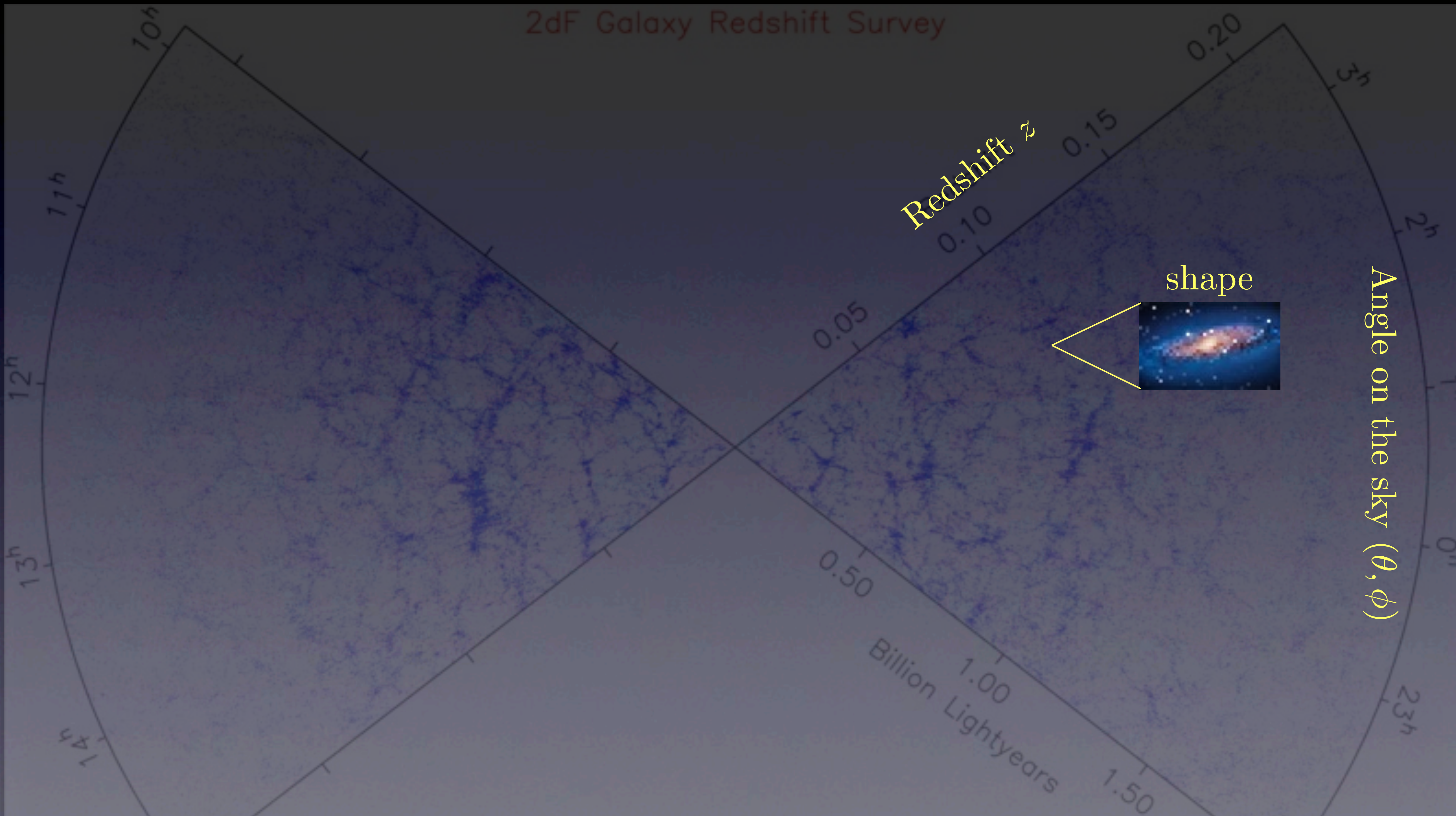
Abell cluster





$$1\text{pc} = 3.086 \times 10^{13}\text{km}$$

Galaxies: what we measure



and also: colors (photo-z's), spectrum (spectro-z's), etc.

The assumptions behind ΛCDM

- The variety of structures observed today formed out of tiny, nearly Gaussian fluctuations during an inflationary phase in the primordial Universe
- These fluctuations were amplified by Einstein gravity
- Most of the matter in the Universe is in the form of some unknown, non-relativistic particle or Cold Dark Matter
- The Universe is currently experiencing an accelerated phase of expansion driven by a cosmological constant

Galaxy probes of cosmology

Weak lensing and galaxy clustering, owing to their statistical power, appear as the most promising methods to constrain viable cosmological models from observations of the large scale structure of the Universe

Weak lensing:

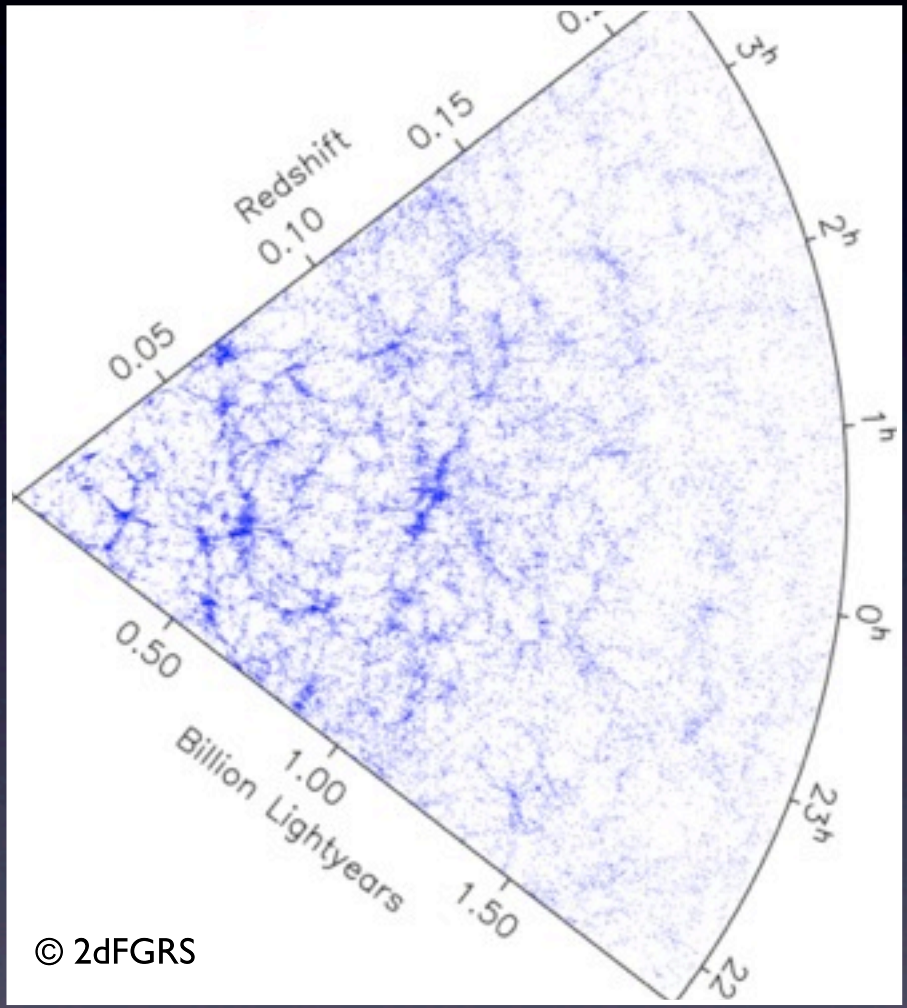
- Galaxy positions + shapes
- Direct probe of the matter density field projected along the line-of-sight (photon path)
- Many systematics (galaxy shapes, intrinsic alignments etc.)

Galaxy clustering:

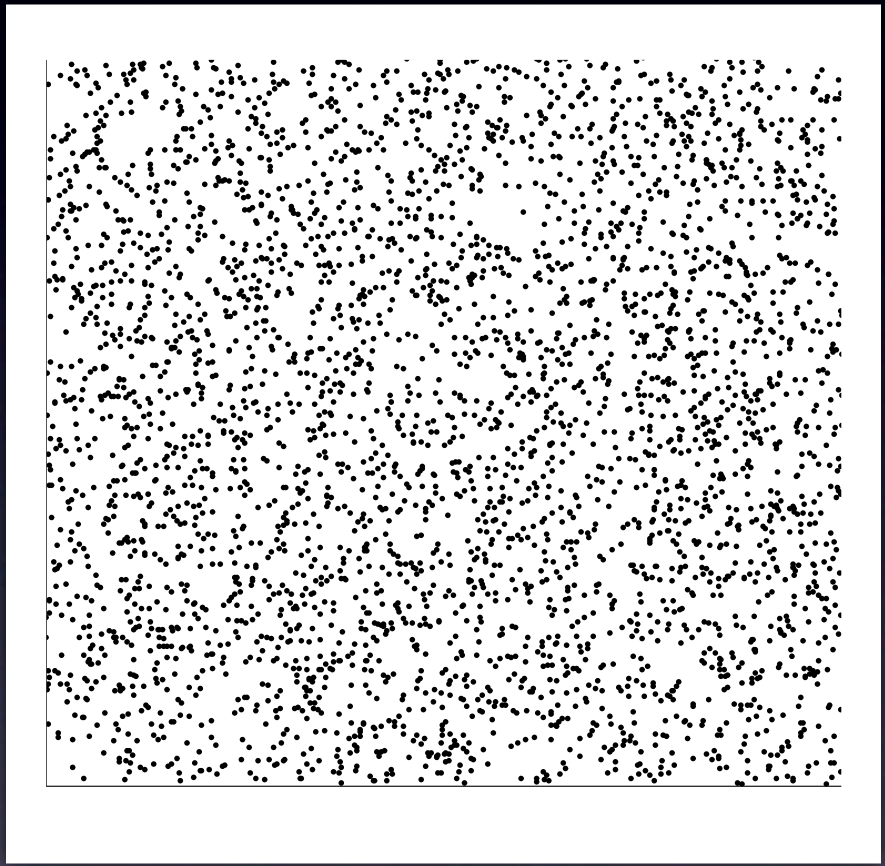
- Galaxy positions
- Issue with the biasing of galaxies
- Mild dependence on the details of galaxy formation

Galaxy clustering

galaxies



random

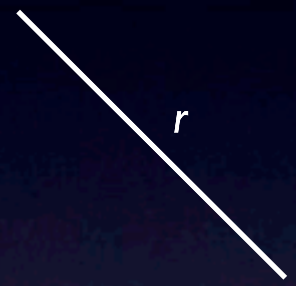


Measure of the probability to find pairs, triplets etc. of galaxies in excess of random

N-point correlation functions

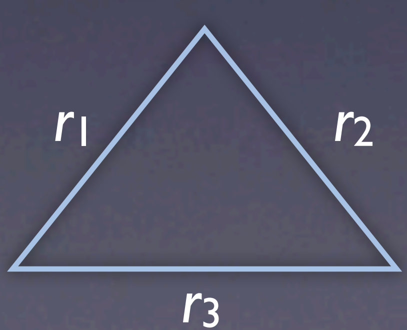
- In a homogeneous and isotropic Universe, homogene, the 2-point correlation function $\xi(r)$ depends solely on the separation r of the galaxy pair. Its Fourier transform is the power spectrum $P(k)$:

$$\xi(r) = \int \frac{d^3k}{(2\pi)^3} P(k) \frac{sin(kr)}{kr}$$

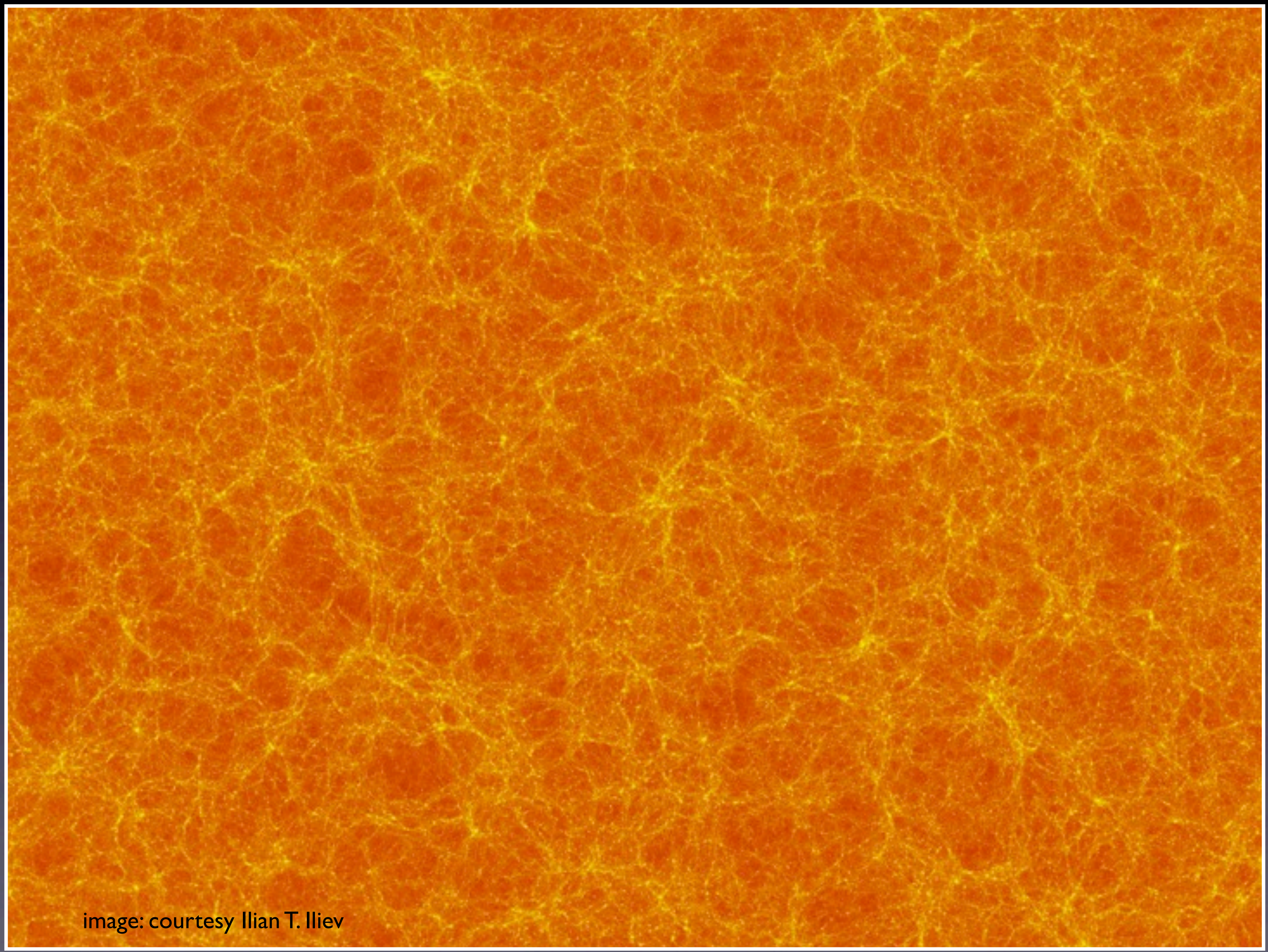


- Analogously, the 3-point correlation function $\zeta(r_1,r_2,r_3)$ only depends on the side lengths of the triplet. Its Fourier transform is the bispectrum $B(k_1, k_2, k_3)$

$$\zeta(r_1, r_2, r_3) = \int \frac{d^3k_1}{(2\pi)^3} \int \frac{d^3k_2}{(2\pi)^3} B(k_1, k_2, |\vec{k}_1 + \vec{k}_2|) e^{i\vec{k}_1\cdot(\vec{r}_3-\vec{r}_1)+i\vec{k}_2\cdot(\vec{r}_3-\vec{r}_2)}$$



The Cosmic Web



Galaxy biasing

Kaiser (1984); ...

- Luminous objects - galaxies, quasars etc. - form in dark matter (DM) halos
- DM halos preferentially trace overdense regions of the Universe
- This induces a bias between the luminous tracers and the underlying matter distribution:

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

Complications

- Bias is certainly non-linear, stochastic and scale-dependent
- Luminous tracers are discrete, i.e. they form a point process

Modeling biasing

Two stages modeling: i) biasing of DM halos relative to the mass
ii) distribution of galaxies inside halos

i) e.g., local bias model: (Fry & Gaztanaga 1993; Szalay 1988, ...)

$$\delta_h(\vec{x}) = F\big[\delta(\vec{x})\big] + \epsilon(\vec{x}) = b_1\delta(\vec{x}) + \frac{1}{2}b_2\delta^2(\vec{x}) + \cdots + \epsilon(\vec{x})$$

$$\longrightarrow \quad \xi_h(r) = b_1\xi(r) + \frac{1}{2}b_2^2\big[\xi(r)\big]^2 + \ldots$$

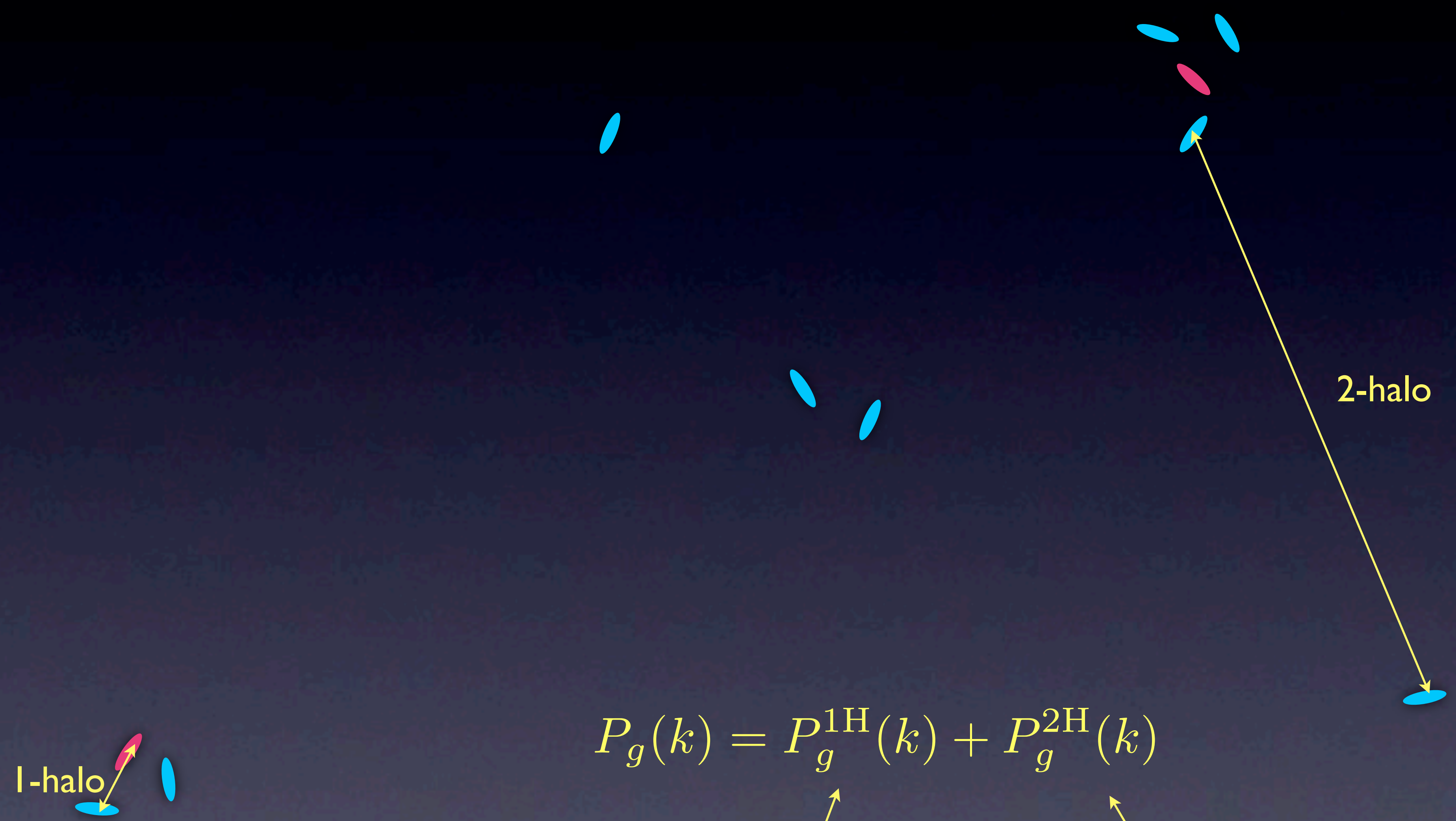
bias factors b_N depend on M_h but not on r

ii) e.g., halo occupation distribution (HOD):

$$P(N_g|M_h) \quad \longrightarrow \quad \langle N_g|M_h\rangle\,, \;\; \langle N_g\,(N_g-1)\,|M_h\rangle \;\; \text{etc.}$$

The halo model

Refine ii) by taking into account halo density profile

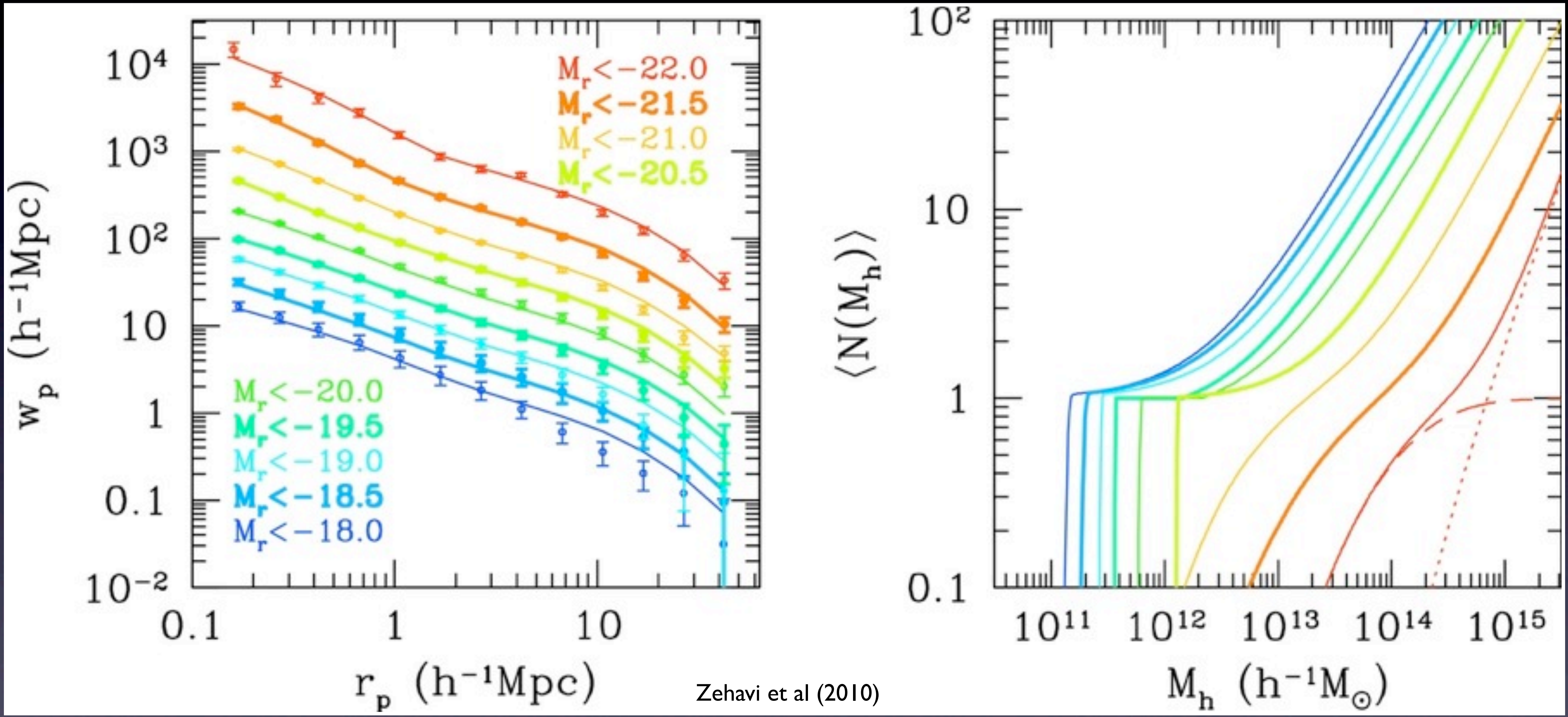


$$P_g(k) = P_g^{1\mathrm{H}}(k) + P_g^{2\mathrm{H}}(k)$$

small scales

large scales

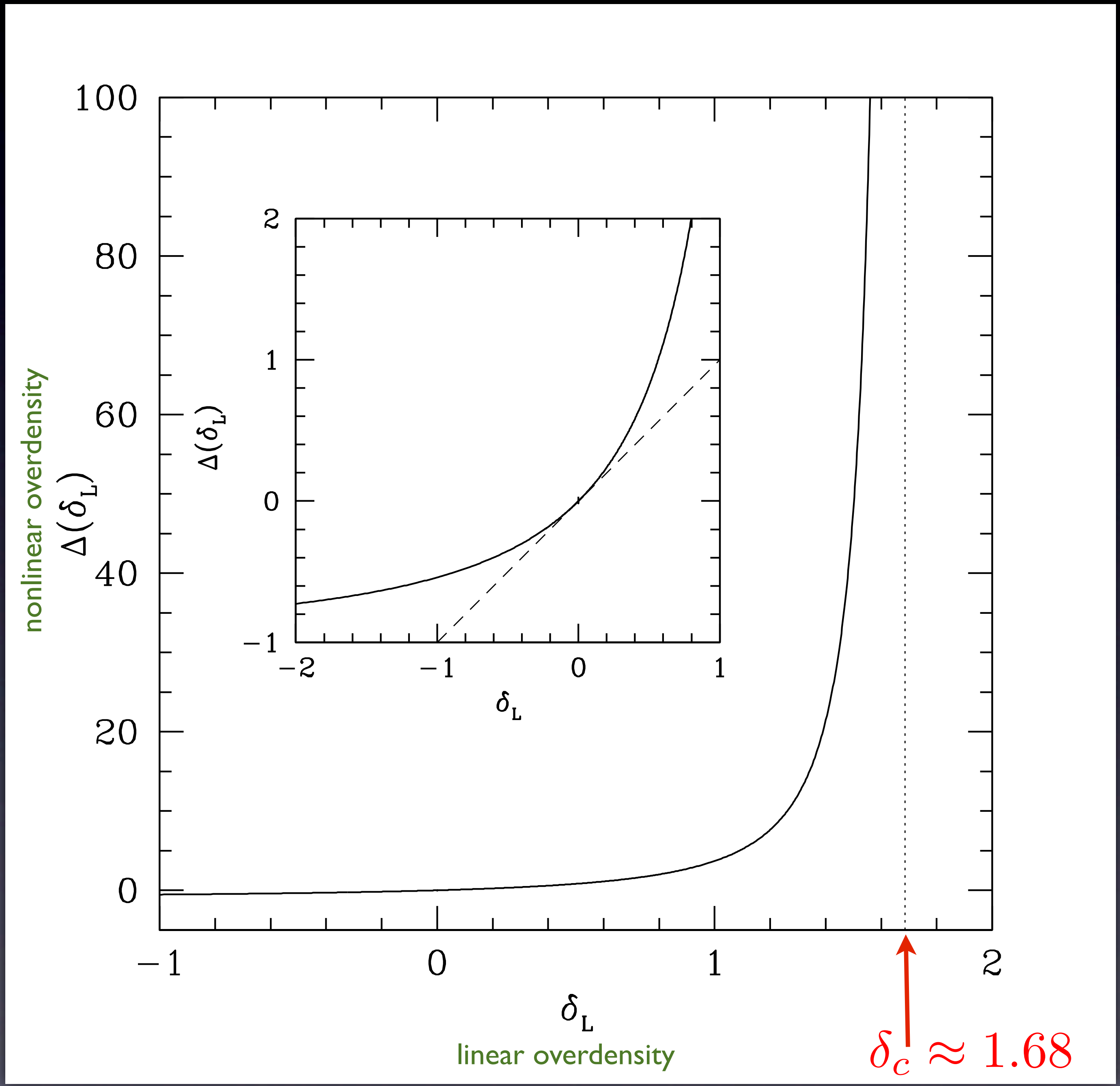
Luminosity dependence of bias



Zehavi et al (2010)

Spherical collapse

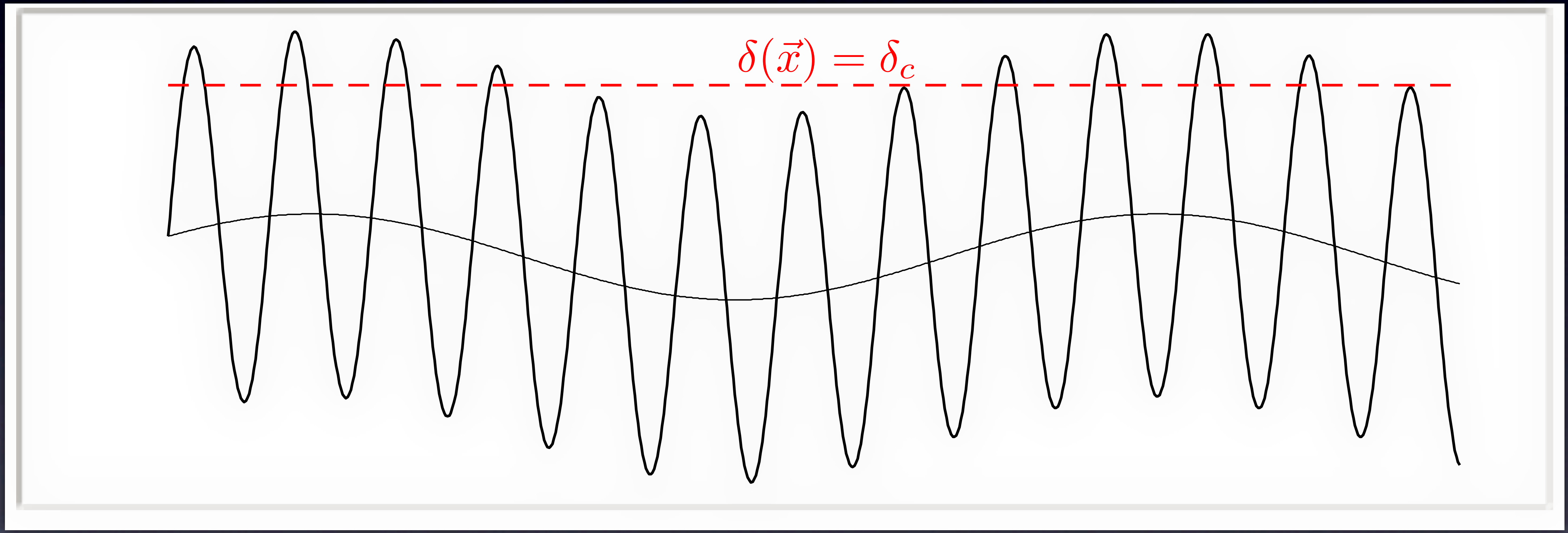
Gunn & Gott (1972)



Peak-background split (PBS)

Kaiser (1984); Bardeen et al (1986); Cole & Kaiser (1989); ...

Imagine that we split the density field into: $\delta(\vec{x}) = \delta_s(\vec{x}) + \delta_l(\vec{x})$



$$\delta_h(\vec{x}) = \frac{n_h(\vec{x})}{\bar{n}_h} - 1 = \frac{\bar{n}_h\big(\delta_c - \delta_l(\vec{x})\big)}{\bar{n}_h(\delta_c)} - 1 \approx \underbrace{\boxed{\left(-\frac{1}{\bar{n}_h}\frac{d\bar{n}_h}{d\delta_c}\right)}}_{\equiv b_1} \delta_l(\vec{x}) + \frac{1}{2}\underbrace{\boxed{\left(\frac{1}{\bar{n}_h}\frac{d^2\bar{n}_h}{d\delta_c^2}\right)}}_{\equiv b_2} + \ldots$$

Mass function and bias

- The halo mass function (differential number density of halos) is conveniently written as

$$\bar{n}_h(M) \equiv \frac{dn}{dM} = \frac{\bar{\rho}_m}{M^2}\, \nu f(\nu, \ldots)\, \frac{d\ln\nu}{d\ln M} \qquad (M \equiv M_h)$$

- The peak height or significance is

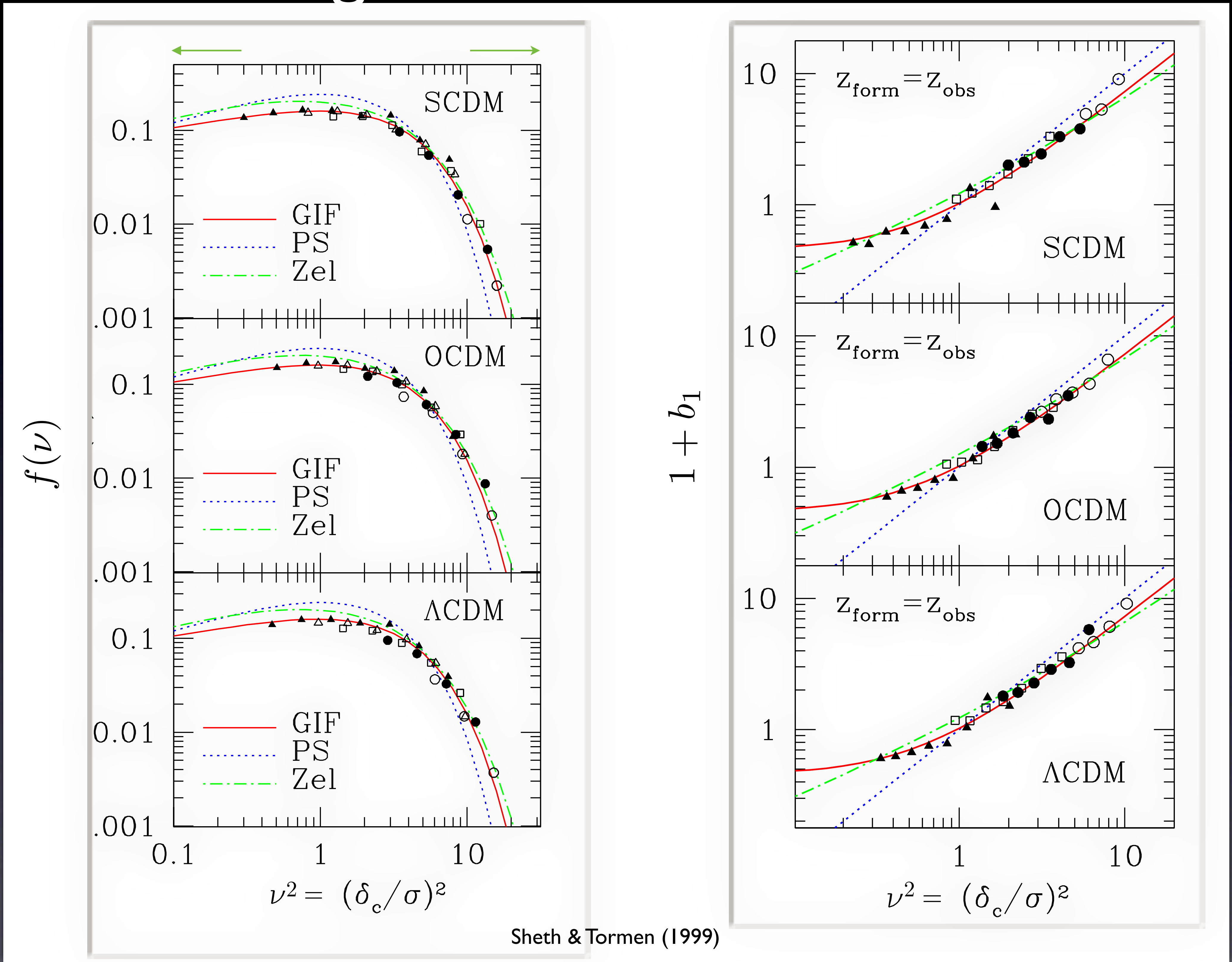
$$\nu = \frac{\delta_c}{\sigma(M)} \approx \frac{1.68}{\sigma(M)}$$

- In the high peak limit, the multiplicity function and bias factors scale as

$$f(\nu) \sim e^{-\nu^2/2}$$

$$b_N \sim \left(\frac{\nu}{\sigma}\right)^N$$

Testing PBS with simulations



Sheth & Tormen (1999)

Inflation

- Explains homogeneity and flatness of the Universe, and provides the seed perturbations that grow to form galaxies
- A plethora of models. How can we distinguish between them ?

Observations are consistent with the simplest single-field slow-roll model:

- Almost scale-invariant (n_s~0.97 ☺), nearly Gaussian (?) spectrum of scalar (curvature ☺) perturbations
- Some tensor perturbations (?)

Primordial non-Gaussianity

- All inflationary models predict some amount of non-Gaussianity (NG) in the statistics of primordial curvature perturbations
- Measure primordial NG to constrain viable inflationary scenarios
- Two probes: CMB or the large scale structure (LSS)

Quantifying primordial NG

$$\Phi(\vec{x}) \;=\; \text{Bardeen's curvature perturbation in matter-dominated era} \;=\; \frac{3}{5}\zeta(\vec{x})$$

Connected (reduced) N-point correlation functions:

$$\langle \Phi(\vec{x}) \rangle = 0$$

$$\langle \Phi(\vec{x}_1)\Phi(\vec{x}_2) \rangle_c$$

$$\langle \Phi(\vec{x}_1)\Phi(\vec{x}_2)\Phi(\vec{x}_3) \rangle_c$$

$$\langle \Phi(\vec{x}_1)\Phi(\vec{x}_2)\Phi(\vec{x}_3)\Phi(\vec{x}_4) \rangle_c$$

...

Example: local primordial NG

$$\Phi(\vec{x}) = \phi_G(\vec{x}) + f_{\rm NL}\phi_G^2(\vec{x}) + g_{\rm NL}\phi_g^3(\vec{x}) + ..., \quad |\phi_G| \sim 10^{-5}$$

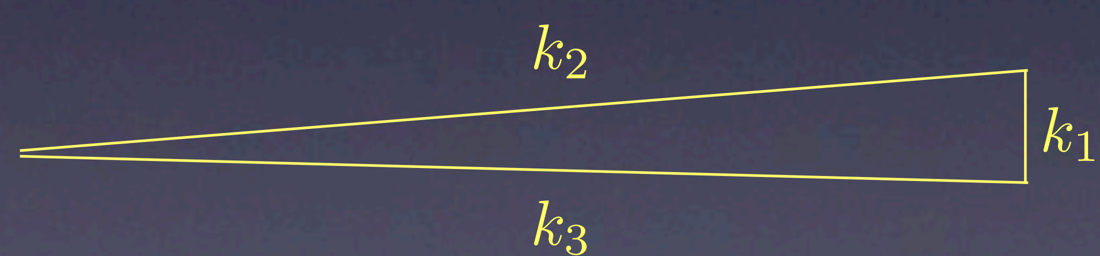
The bispectrum of Bardeen's curvature perturbation is

$$\left\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3) \right\rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B_\Phi(k_1, k_2, k_3)$$

$$B_\Phi(k_1, k_2, k_3) \equiv 2 f_{\rm NL} \left[P_\phi(k_1) P_\phi(k_2) + 2 \text{ cyc.} \right]$$

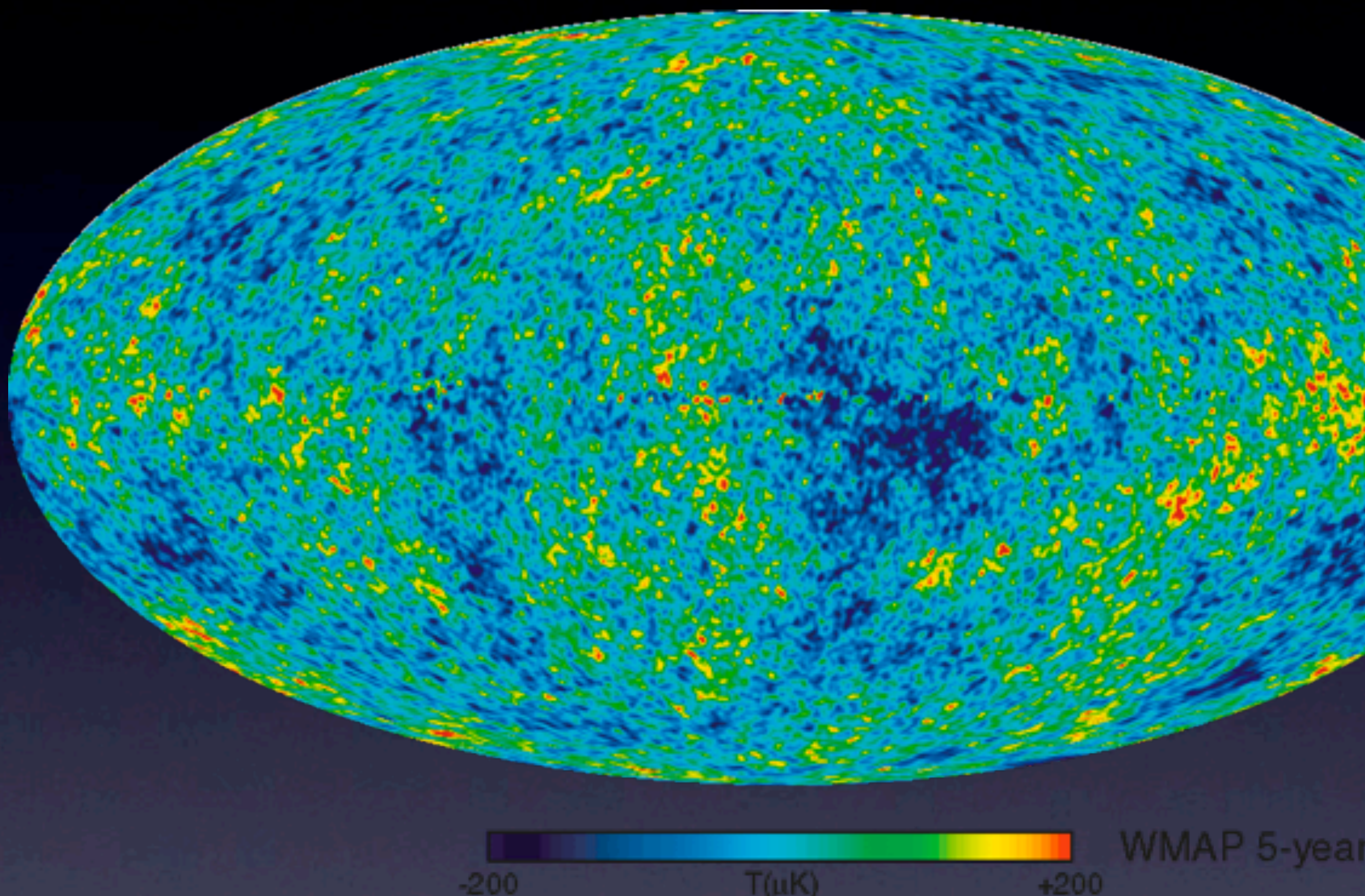
$$P_\phi(k) = \left\langle |\phi_G(\vec{k})|^2 \right\rangle = A_s k^{n_s - 4}$$

B peaks in the squeezed limit $k_1 << k_2, k_3$



Single-field slow-roll predicts: $f_{\rm NL} = \frac{5}{12}(1 - n_s) \approx 0.017$

Cosmic Microwave Background



$$a_\ell^m = 4\pi(-i)^\ell \int \frac{d^3k}{(2\pi)^3}\, \Phi(\vec{k}) g_{T\ell}(k) Y_\ell^{m\star}(\hat{k})$$

Current CMB constraints

$$A_s \approx 2 \times 10^{-9}, \quad n_s \approx 0.97, \quad -10 < f_{\rm NL} < 74$$

Komatsu et al. (2009)

Gaussian at the 99.9% level

Primordial NG in large scale structure

- Cluster counts:

$$S_3 \sim \int d^3k_1 \int d^3k_2\, B_\Phi(k_1, k_2, |\vec{k}_1 + \vec{k}_2|)$$

- Galaxy power spectrum:

$$\Delta b_1(k) \sim \int d^3k_1\, B_\Phi(k_1, k_1, k), \quad S_3$$

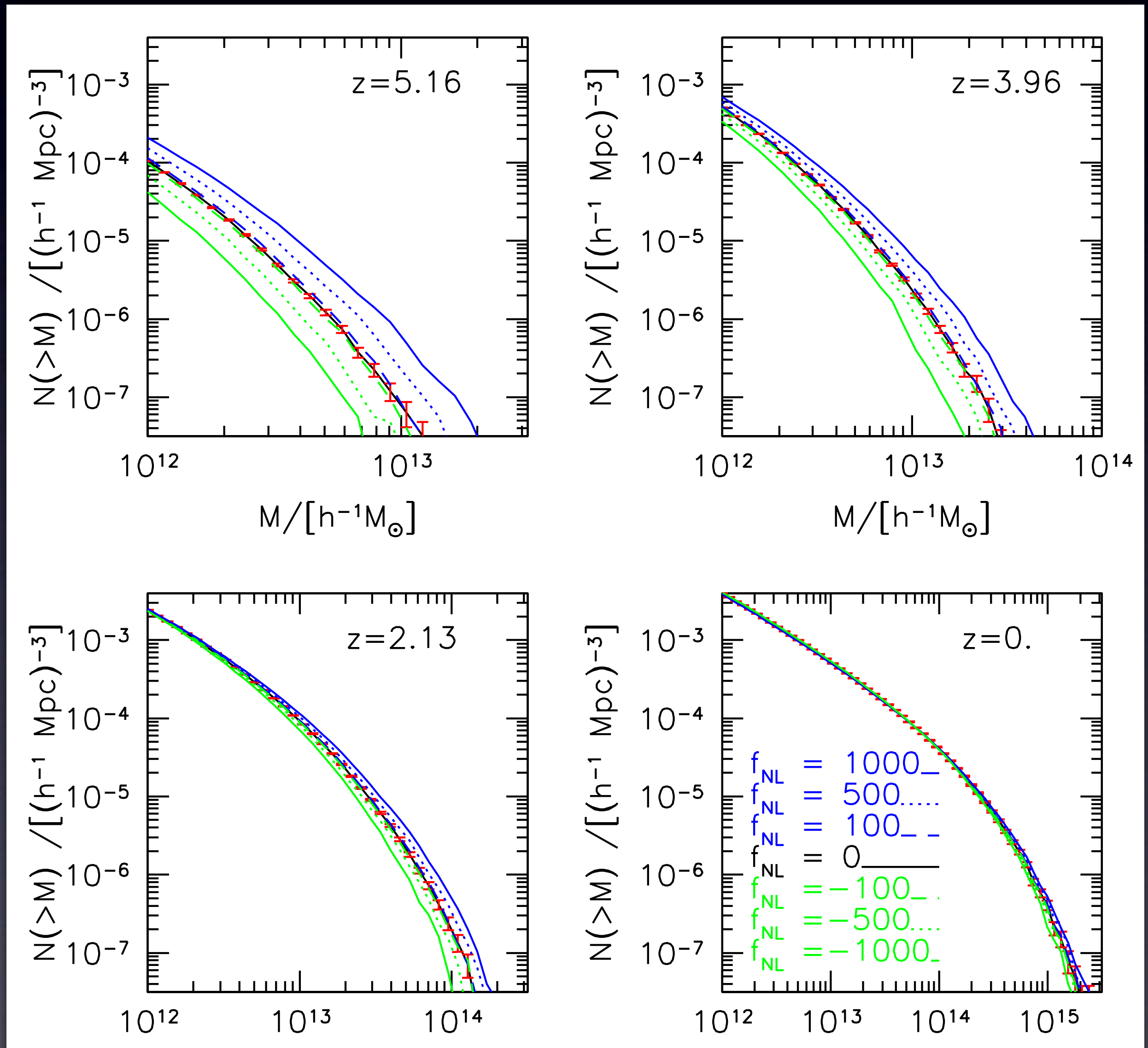
- Galaxy bispectrum:

$$B_\Phi(k_1, k_2, k_3), \; ...$$

Cluster counts

Lucchin & Matarrese 1988; Matarrese, Verde, Jimenez 2000; Sefusatti et al. 2007; Lo Verde et al. 2008 ...

- Non-Gaussian ICs can significantly affect the abundance of massive DM halos
- Complications: mass measurement, degeneracy with σ_8 ...

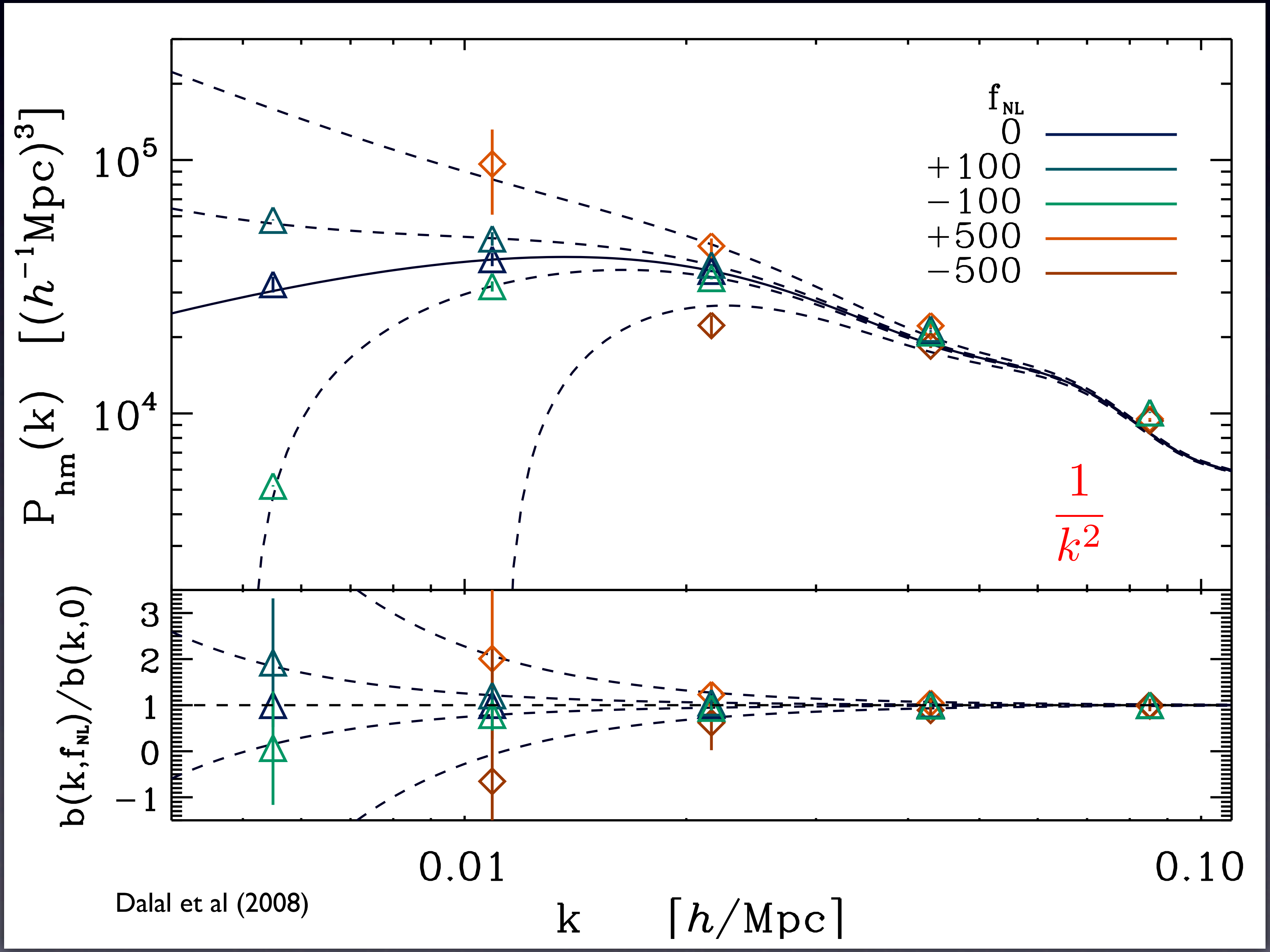


Grossi et al. (2007)

Non-Gaussian bias

Dalal et al. (2008); ...

Local primordial NG induces a scale-dependent bias $\Delta b_1(k) \propto \frac{b_1 f_{\rm NL}}{k^2}$



A PBS interpretation

Slosar et al. (2008); Schmidt & Kamionkowski (2010); VD, Jeong & Schmidt (2011)

Scale-dependent modulation of the amplitude of small-scale density fluctuations

$$\Phi(\vec{x}) = \phi(\vec{x}) + f_{\rm NL}\phi^2(\vec{x})$$

$$\phi(\vec{x}) = \phi_l(\vec{x}) + \phi_s(\vec{x})$$

$$\longrightarrow \quad \Phi = \left(\phi_l + f_{\rm NL}\phi_l^2\right) + \phi_s\left(1 + 2f_{\rm NL}\phi_l\right) + f_{\rm NL}\phi_s^2$$

$$\downarrow$$

$$\sigma_s \to \sigma_s\left(1 + 2f_{\rm NL}\phi_l(\vec{x})\right)$$

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$$\downarrow$$

$$\sigma_s \to \sigma_s\big(1 + 2f_{\rm NL}\phi_l(\vec{x})\big)$$

$$\delta_h(\vec{x}) \approx \frac{\bar{n}_h\Big[\delta_c - \delta_l(\vec{x}), \sigma\big(1 + 2f_{\rm NL}\phi_l(\vec{x})\big)\Big]}{\bar{n}_h(\delta_c, \sigma)} - 1$$

$$\approx \left(-\frac{1}{\bar{n}_h}\frac{d\bar{n}_h}{d\delta_c}\right)\delta_l(\vec{x}) + 2f_{\rm NL}\left(\frac{\sigma}{\bar{n}_h}\frac{d\bar{n}_h}{d\sigma}\right)\phi_l(\vec{x}) + \ldots$$

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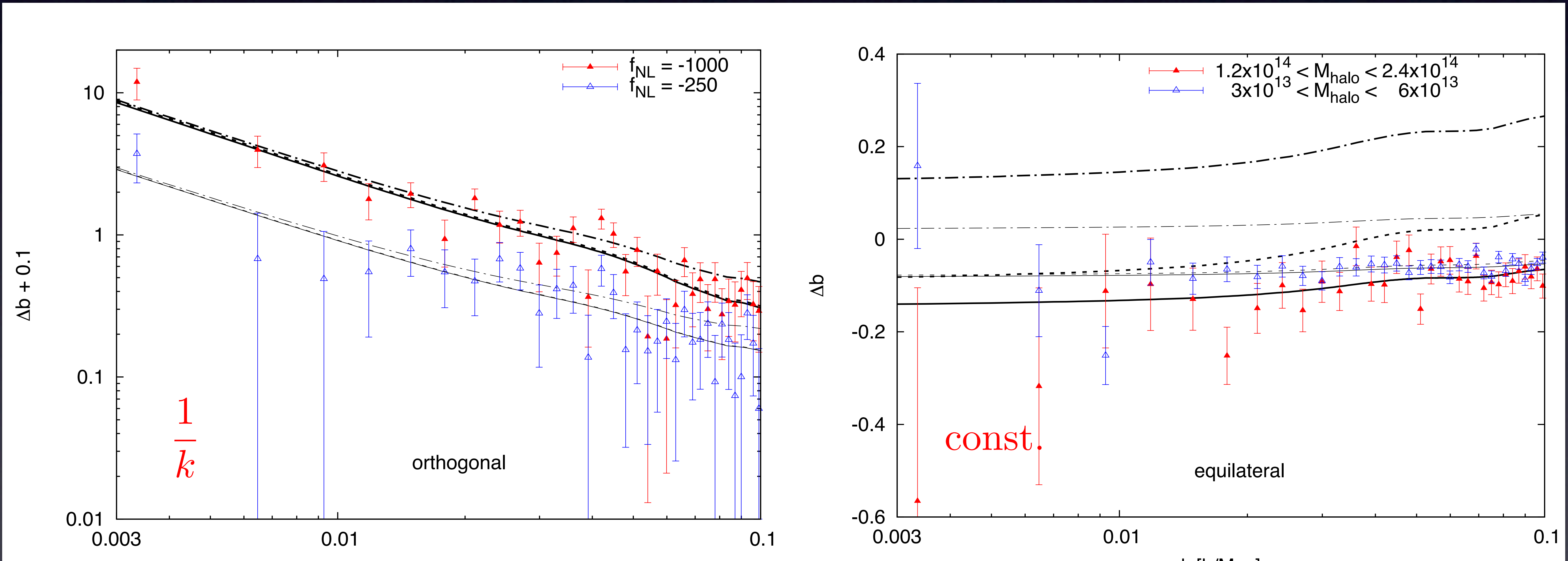
Fourier transform and use $\delta_l(\vec{k} = \mathcal{M}(k)\phi_l(\vec{k})$ with $\mathcal{M}(k) = \dfrac{2k^2T(k)D(z)}{3\Omega_m H_0^2}$:

$$\delta_h(\vec{k}) = \left[b_1 + 2f_{\rm NL}\left(\frac{\partial\ln\bar{n}_h}{\partial\ln\sigma}\right)\mathcal{M}^{-1}(k)\right]\delta_l(\vec{k}) + ...$$

Bispectrum shape

- Approximate the bispectrum of certain class of inflationary models by templates
- Can be implemented in initial conditions of LSS formation
(Wagner & Verde 2011; Scoccimarro et al 2012)



Wagner & Verde (2011)

Generic formula

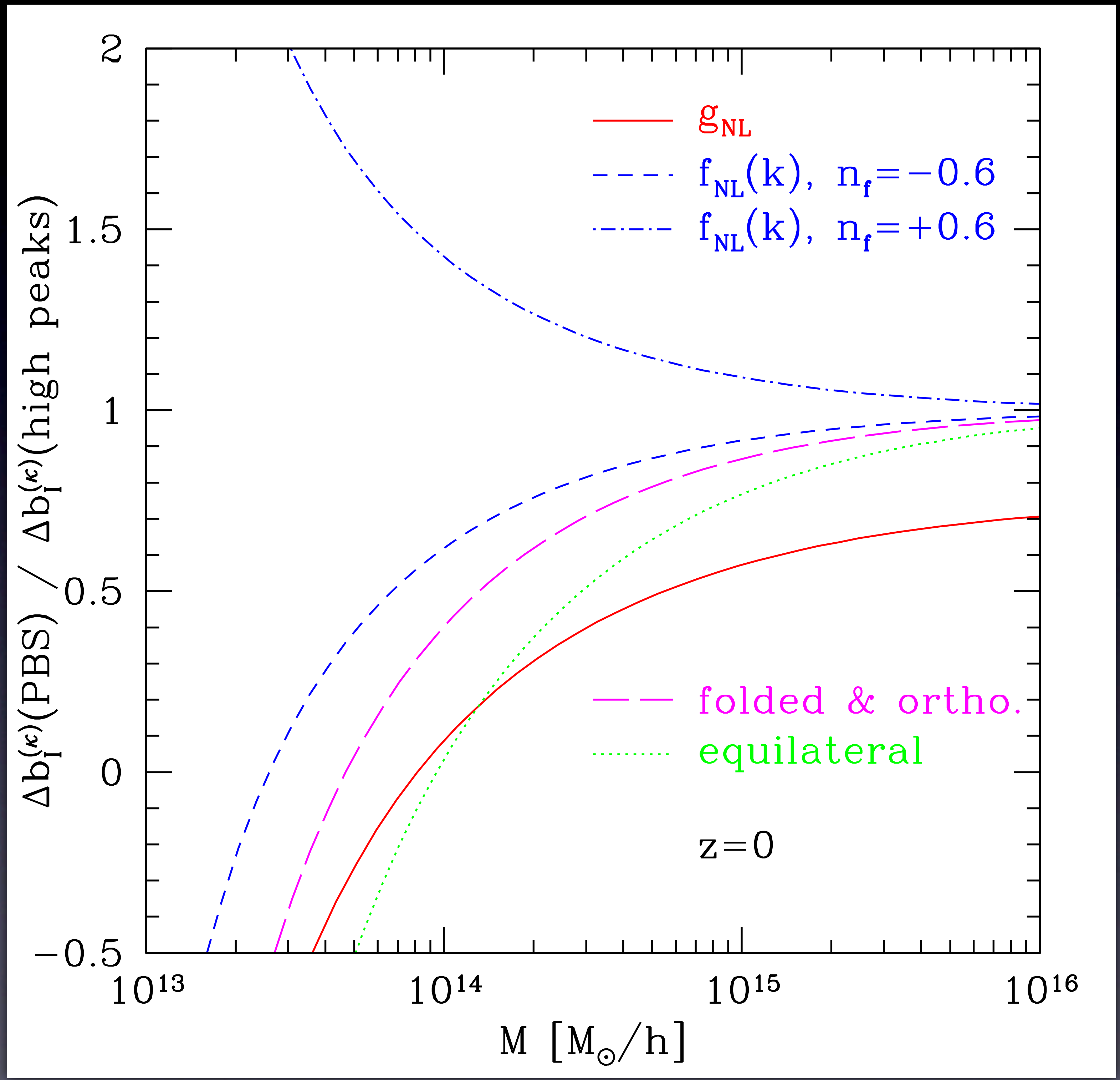
VD, Jeong & Schmidt (2011)

$$\Delta b_1(k) = \frac{4}{(N-1)!}\left\{ b_{N-2}\delta_c + \boxed{b_{N-3}\left[N-3+\frac{\partial \ln \mathcal{F}^{(N)}(k)}{\partial \ln \sigma}\right]}\right\}\mathcal{F}^{(N)}(k)\mathcal{M}(k)^{-1}$$

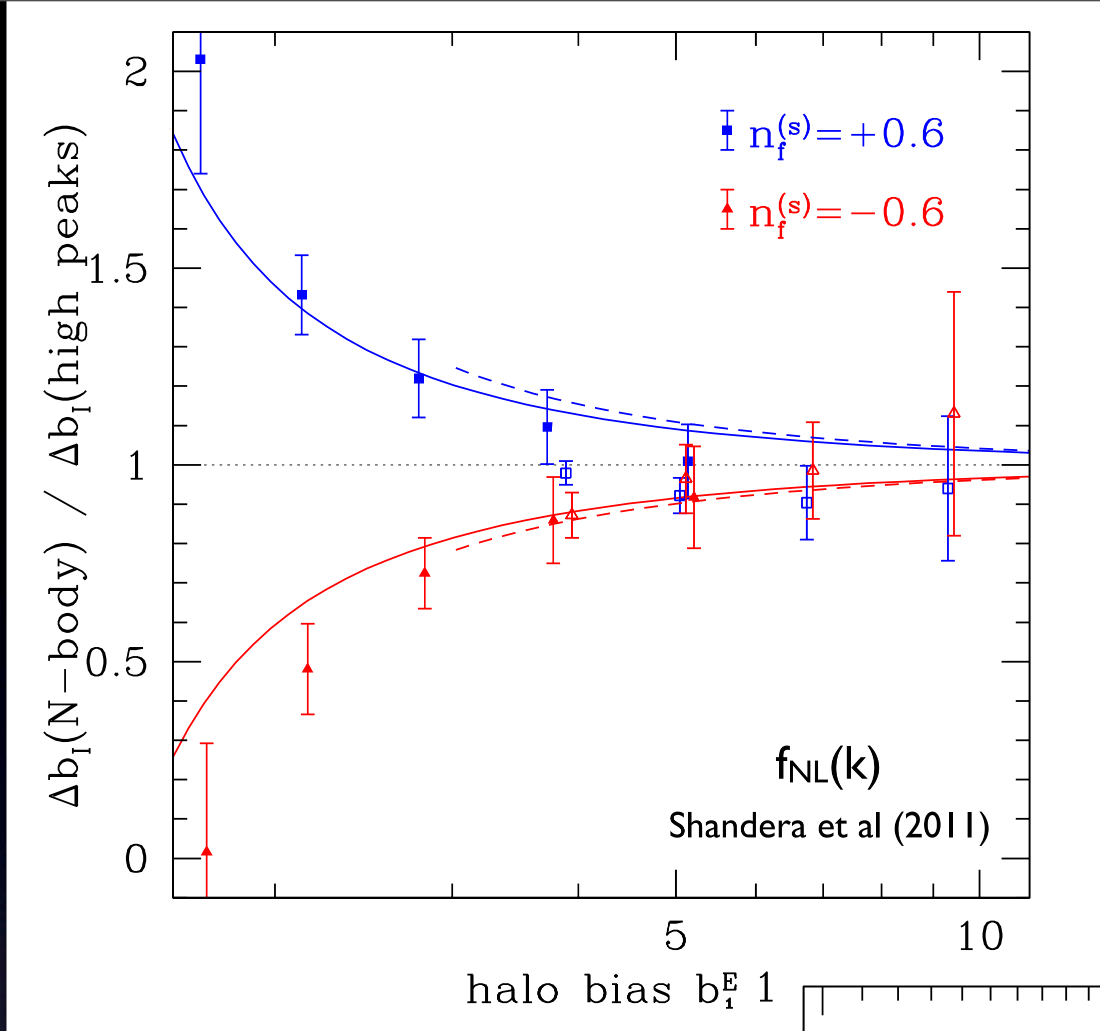
missing in the high peaks approximation

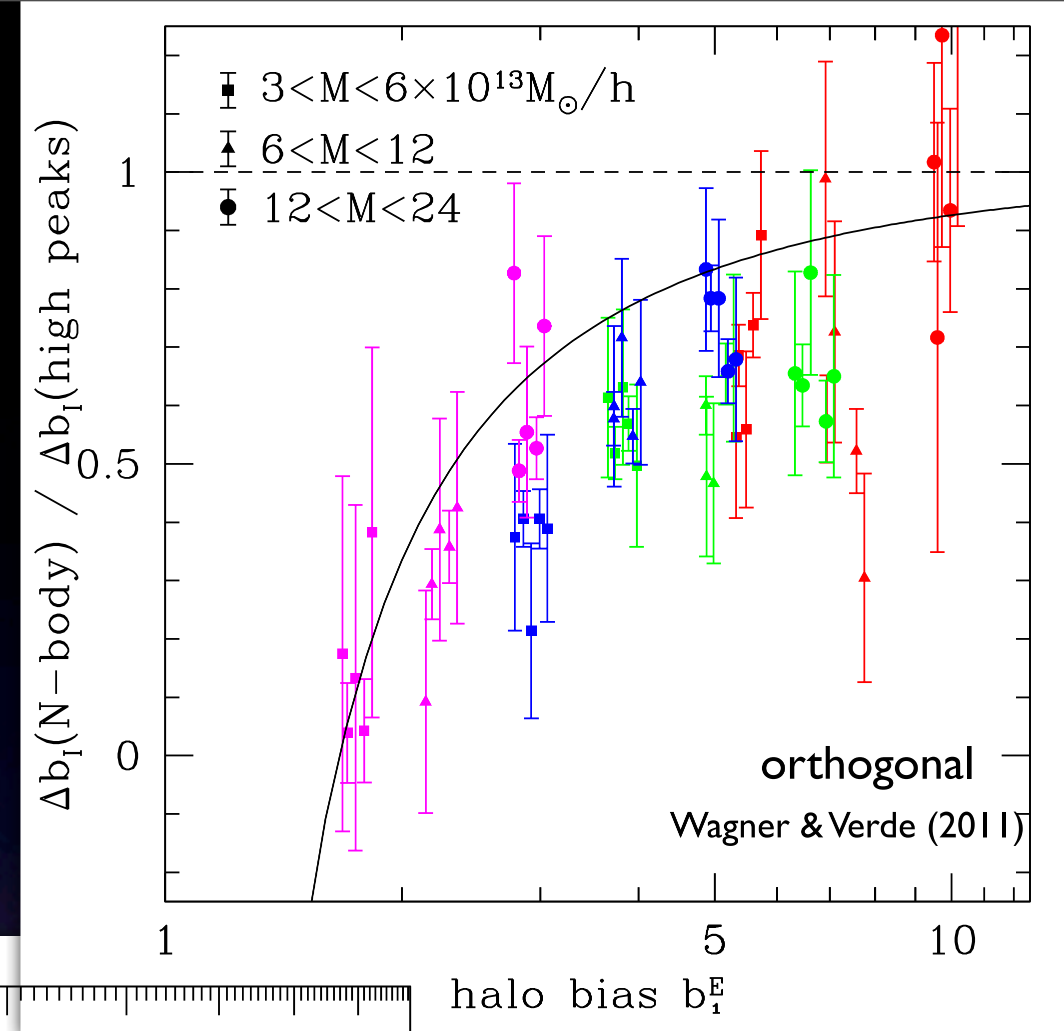
$$\mathcal{F}^{(N)}(k) = \frac{1}{4\sigma^2 P_\phi(k)}\left\{\prod_{i=1}^{N-2}\int\frac{d^3k_i}{(2\pi)^3}\mathcal{M}(k_i)\right\}\mathcal{M}(q)\xi_\Phi^{(N)}(k_1,...,k_{N-2},q,k)$$

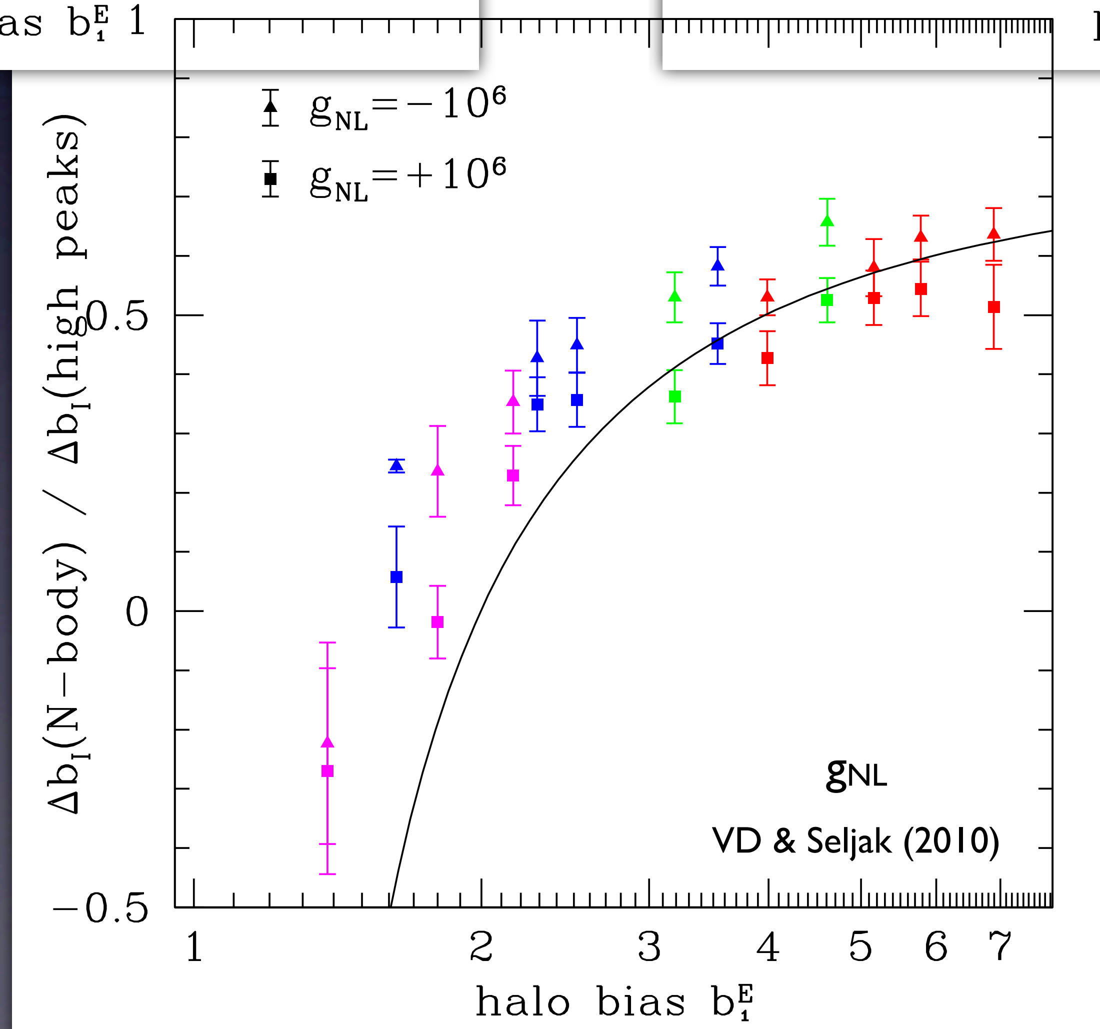
$$\vec{q} = -\vec{k}_1 - ... - \vec{k}_{N-2} - \vec{k}$$



g_{NL}
$f_{NL}(k),\ n_f=-0.6$
$f_{NL}(k),\ n_f=+0.6$
folded & ortho.
equilateral
z=0
$\Delta b_I^{(\kappa)}(\mathrm{PBS})\ /\ \Delta b_I^{(\kappa)}(\mathrm{high\ peaks})$
$M\ [M_\odot/h]$
2
1.5
1
0.5
0
−0.5
10^{13}
10^{14}
10^{15}
10^{16}







$$b_1^{\rm E} = 1 + b_1$$

(VD, Jeong & Schmidt 2011)

Current LSS limits on primordial NG

$$-29 < f_{\rm NL} < 69$$

(Slosar et al 2008)

$$-3.5 \times 10^5 < g_{\rm NL} < 8.2 \times 10^5$$

(VD & Seljak 2010)

$$-419 < f_{\rm NL}^{\rm Eq} < 625$$

$$-179 < f_{\rm NL}^{\rm Ortho} < 6$$

$\times 2$

(Xia et al. 2011)

Stochasticity

A measurement of the galaxy power spectrum implies two sources of error:

- Cosmic variance (at wavenumber k, the number $N(k)$ of observables modes is finite)
- Shot noise (arises due to the discreteness of the tracers)

Limits the precision to which we can measure f_{NL}

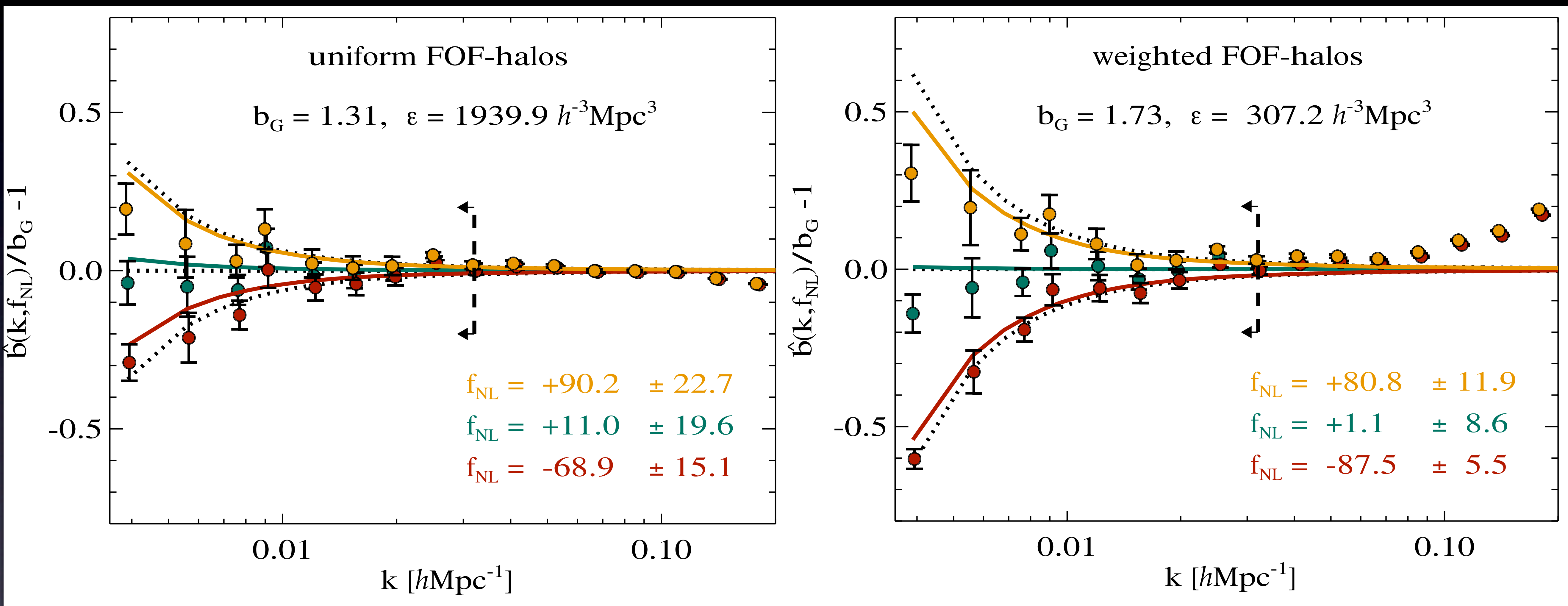
Mitigating stochasticity

Seljak, Hamaus & VD 2009; Hamaus et al. 2010; Hamaus, Seljak & VD 2011

Combine different tracers of the same surveyed volume and weight them in some optimal way

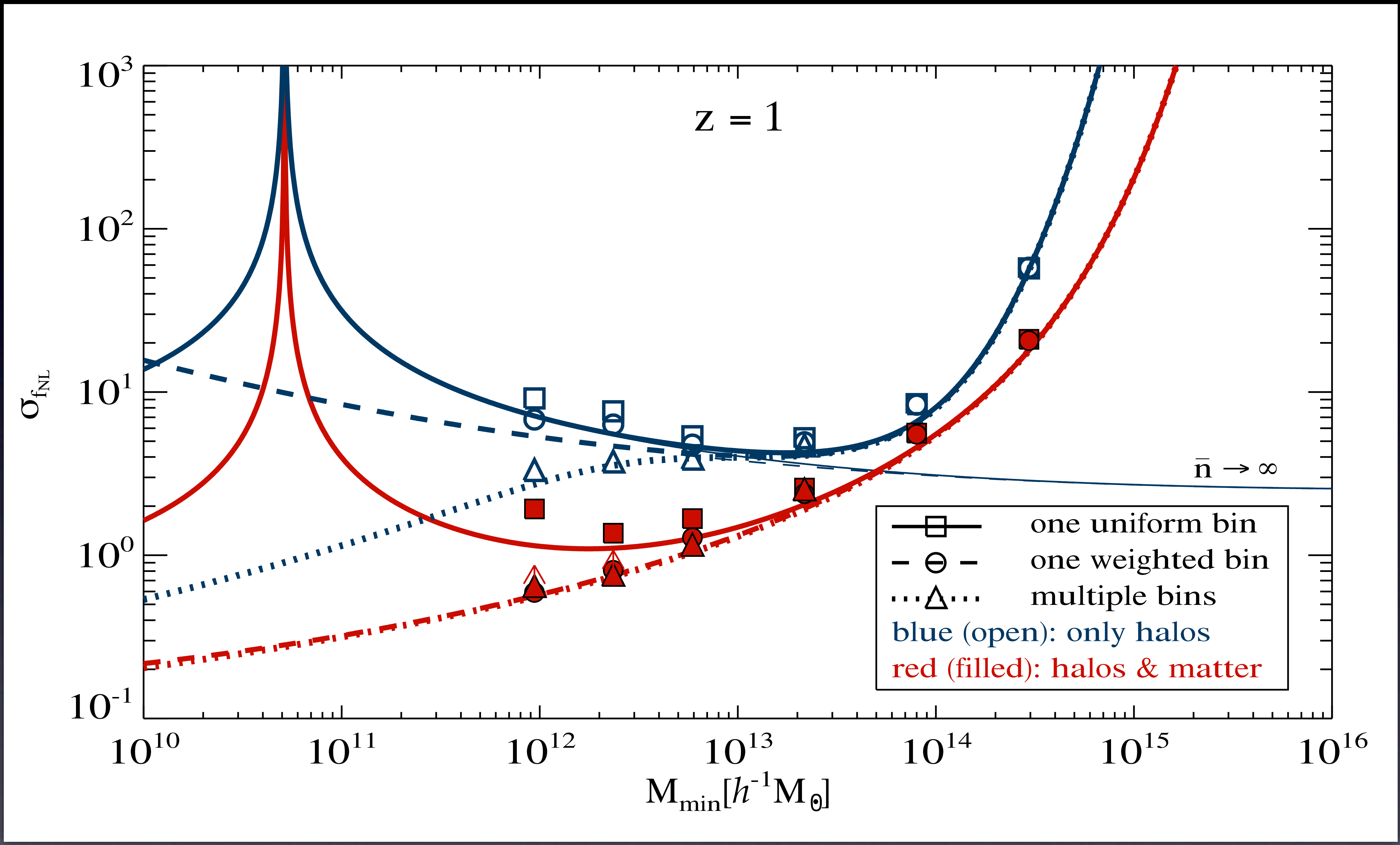
Test with N-body simulations

optimal weight ≈ mass weighting



Hamaus, Seljak & VD (2011)

Forecast errors

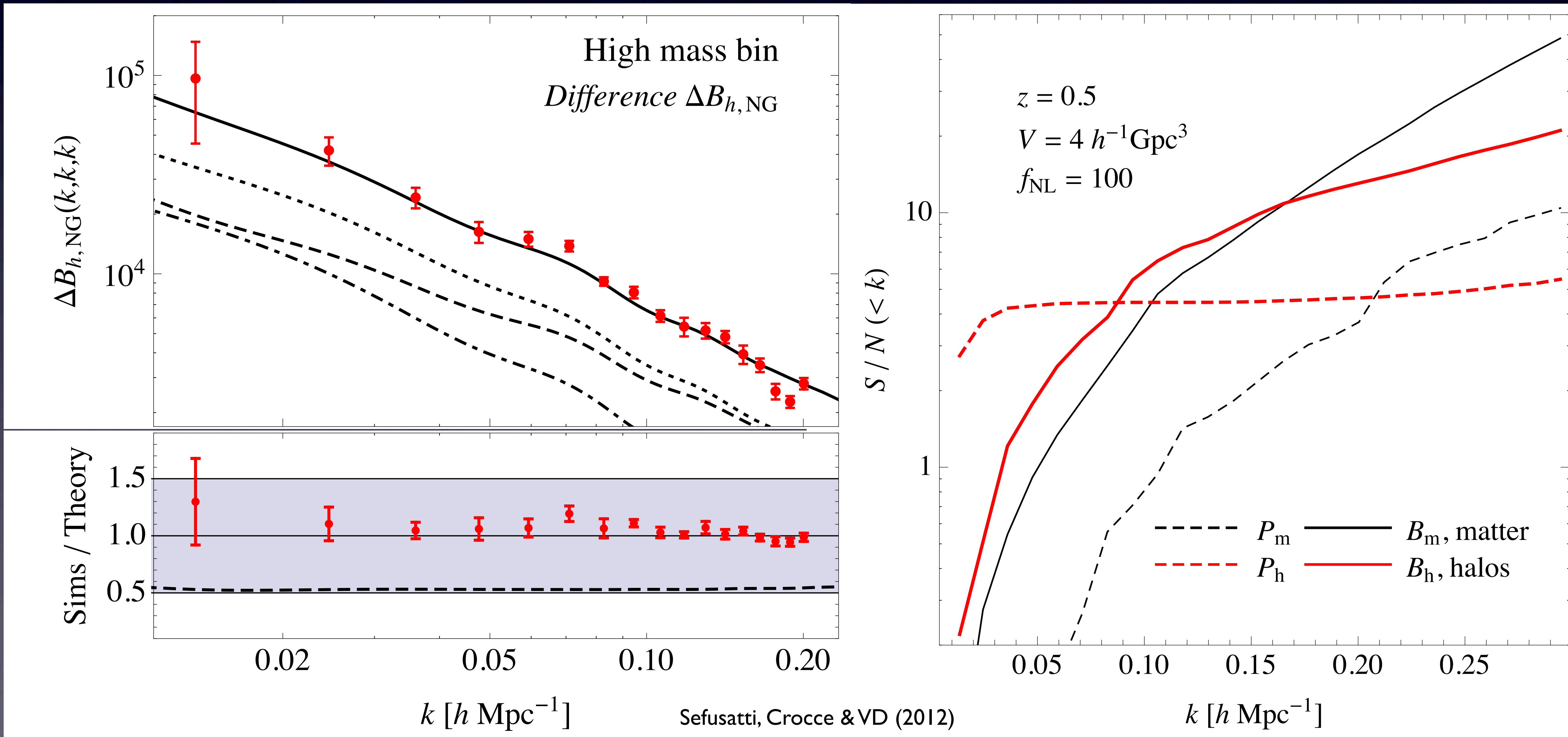


Planck: $\sigma_{f_{\rm NL}} = 5$

Galaxy bispectrum

Frieman & Gaztanaga 1999; Scoccimarro et al .2001; Scoccimarro, Sefusatti & Zaldarriaga 2004; Kulkarni et al 2007;
Sefusatti & Komatsu 2007; Sefusatti 2009; Jeong & Komatsu 2009; ...

Much more sensitive to the shape of the primordial NG, so should be very powerful



Sefusatti, Crocce & VD (2012)

What does local bias predict ?

- Local bias predict the wrong amplitude for the non-Gaussian bias:

$$\langle \delta_h(\vec{x}_1)\delta_h(\vec{x}_2)\rangle \approx b_1^2 \langle \delta(\vec{x}_1)\delta(\vec{x}_2)\rangle + b_1 b_2 \langle \delta^2(\vec{x}_1)\delta(\vec{x}_2)\rangle$$

$$\longrightarrow \quad \Delta b_1(k) \propto \frac{b_2 f_{\rm NL}}{k^2}$$

- So, it seems that we cannot use local bias to predict non-Gaussian corrections to galaxy clustering statistics such as the galaxy bispectrum ...

The peak formalism

- Take discreteness of the tracers into account and assume that DM halos collapse out of initial density maxima
- The peak number density formally is

$$n_{\rm pk}(\vec{x}) = \frac{3^{3/2}}{R_\star^3} \left|\det\zeta(\vec{x})\right| \delta_D\left[\vec{\eta}(\vec{x})\right] \theta_H(\lambda_3)$$

$$\eta_i(\vec{x}) = \frac{1}{\sigma_1}\partial_i\delta(\vec{x}), \quad \zeta_{ij}(\vec{x}) = \frac{1}{\sigma_2}\partial_i\partial_j\delta(\vec{x})$$

$$\sigma_n^2 = \frac{1}{2\pi^2}\int_0^\infty dk\, k^{2(n+1)} P_\delta(k) W^2(kR_s)$$

- Peak correlations functions are obtained from the ensemble averages

$$\langle n_{\rm pk}(\vec{x}_1) \times ... \times n_{\rm pk}(\vec{x}_N)\rangle$$

Bardeen et al. (1986); Regos & Szalay (1995); Matsubara (1999), VD (2008); VD & Sheth (2010); VD et al (2010)

An effective local bias expansion

VD, arXiv:1211.4128

- Peak clustering statistics can be computed from the simple local bias expansion:

$$\delta_{\rm pk}(\vec{x}) = b_{10}\delta(\vec{x}) - b_{01}\nabla^2\delta(\vec{x}) + \frac{1}{2}b_{20}\delta^2(\vec{x}) - b_{11}\delta(\vec{x})\nabla^2\delta(\vec{x}) + \frac{1}{2}b_{02}\left[\nabla^2\delta(\vec{x})\right]^2$$
$$+\chi_{10}\left(\nabla^2\delta\right)^2(\vec{x}) + \frac{1}{2}\chi_{01}\left[3\partial_i\partial_j\delta - \delta_{ij}\nabla^2\delta\right]^2(\vec{x}) + \ldots$$

- The bias parameters b_{ij} and χ_{ij} can be computed from a generalized PBS argument applied to the average peak number density

$$\langle n_{\rm pk}\rangle = \frac{1}{(2\pi)^2 R_\star^3}\, e^{-\nu^2/2}\int_0^\infty du\, f(u)\frac{\exp\left[-\frac{(u-\gamma_1\nu)^2}{2(1-\gamma_1^2)}\right]}{\sqrt{2\pi(1-\gamma_1^2)}}$$

$$u(\vec{x}) = -\frac{1}{\sigma_2}\nabla^2\delta(\vec{x})$$

$$\gamma_1 = \frac{\sigma_1^2}{\sigma_0\sigma_2}$$

Prediction for non-Gaussian bias

VD, Jinn-Ouk Gong, Antonio Riotto, in preparation

- Take into account first-crossing (i.e. that peaks are not included into bigger peaks) Appel & Jones (1990); Manrique & Salvador-Sole (1995); Paranjape & Sheth (2012)

- The halo mass function is

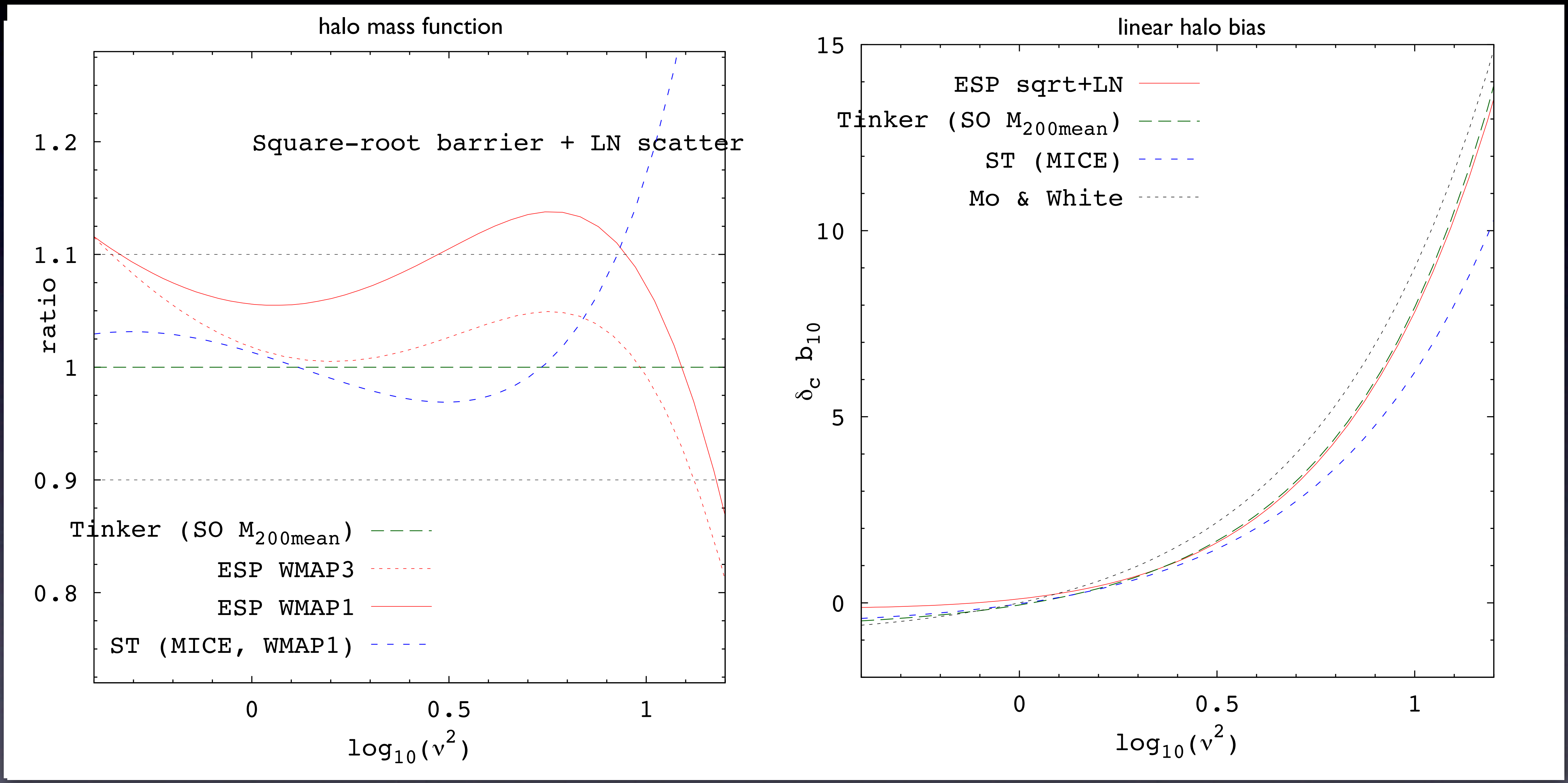
$$\bar{n}_h = \frac{\bar{\rho}}{M^2} \nu f_{\rm ESP}(\nu, \{\sigma_i\}) \frac{d \ln \nu}{d \ln M}$$

- From the effective local bias expansion, we find

$$\Delta b_1(k) = 2 f_{\rm NL} \left(\frac{\partial \ln \bar{n}_h}{\partial \ln \sigma_8} \right) \mathcal{M}(k)^{-1}$$

Gaussian halo mass function and bias

Paranjape, Sheth & VD, arXiv:1210.1483



Conclusions

- Galaxy clustering opens new avenues to constrain the mechanisms that generated the primordial fluctuations
- However, signatures of primordial NG in the large scale structure are expected to be small. Therefore, we must improve our modeling of galaxy biasing
- A local bias expansion in the density only is not enough, but it can be extended to describe the clustering of discrete objects. The resulting non-Gaussian bias is consistent with peak-background split expectations
- This extended local bias approach can be used to compute signatures of primordial NG in the galaxy bispectrum (in progress)
- In the long run, develop a model that can accurately predicts mass function and clustering of tracers for both Gaussian and non-Gaussian ICs