Cosmology with high (z>1) redshift galaxy surveys

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Cosmology Seminar, University of California, Berkeley
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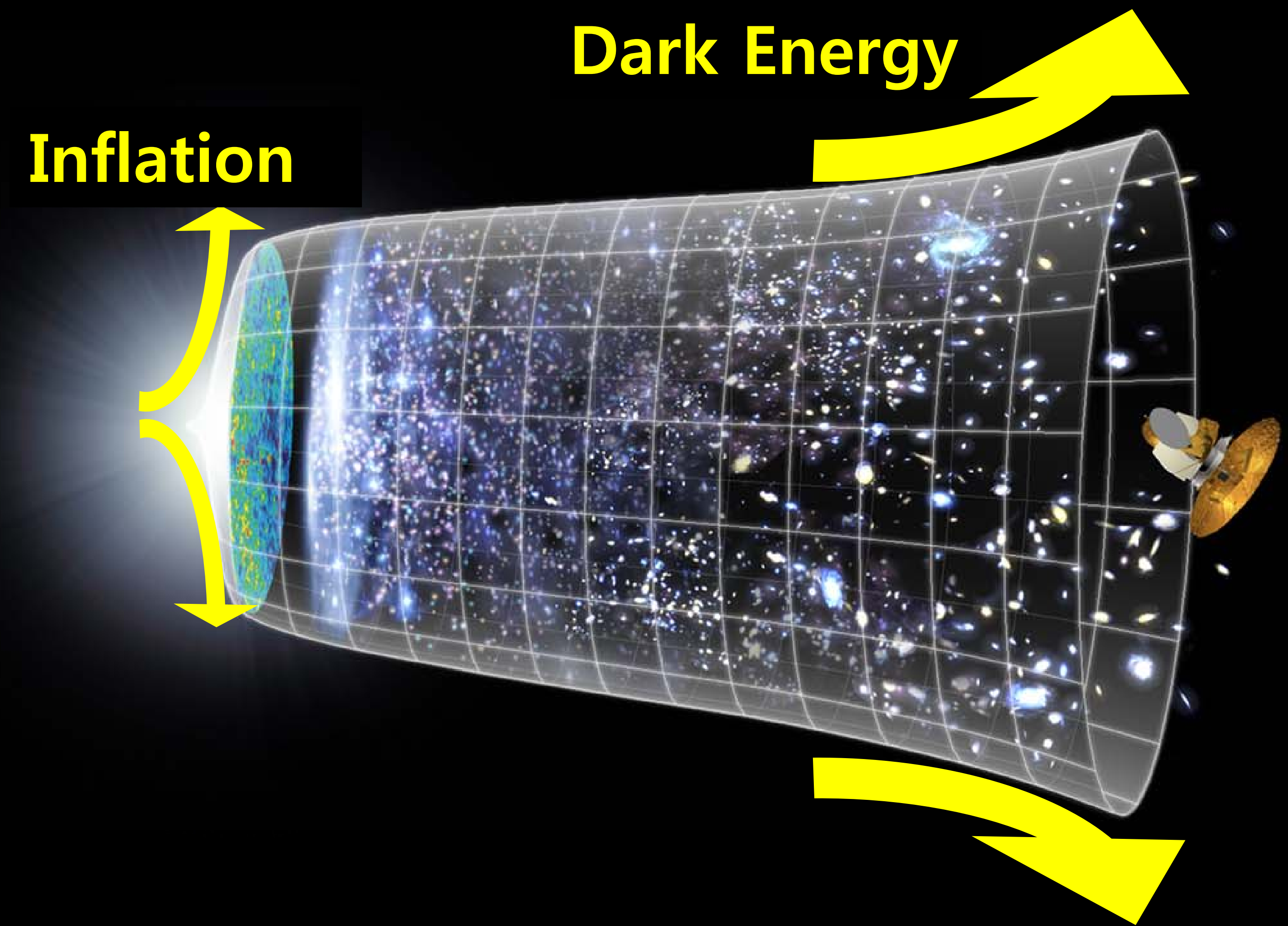
Papers to talk about

- **Jeong** & Komatsu (2006) ApJ 651, 619
- **Jeong** & Komatsu (2009a) ApJ 691, 569
- Shoji, **Jeong** & Komatsu (2009) ApJ 693, 1404
- **Jeong** & Komatsu (2009b) ApJ 703, 1230
- **Jeong**, Komatsu & Jain (2009) [arXiv:0910.1361]
- **Jeong** & Komatsu, in preparation
- **Jeong**, in preparation

I. Introduction

The golden age of cosmology and concordance model:
What's next?

Biggest mysteries in cosmology



Accelerations, past & present

NASA/WMAP Science Team

Inflation: past acceleration

- **Accelerating expansion** at a very early stage of the universe.
- Accelerated the expansion by a factor of at least 10^{27} times, **yielding a flat, homogeneous, and isotropic universe**.
  - The radius of curvature increases by the same factor
  - Physical scales grow faster than the size of horizon
- Stretched the quantum vacuum fluctuations outside of the Hubble horizon which **seed the large scale structure**.

Dark energy: present acceleration

- It is **responsible for the current accelerating expansion of the universe.**
- Two numbers ("WMAP5+BAO+SN")

$$\Omega_{de} = 0.726 \pm 0.015$$

$$1 + w_{de} = -0.006 \pm 0.068$$

- Too many ideas, too few observational clues!

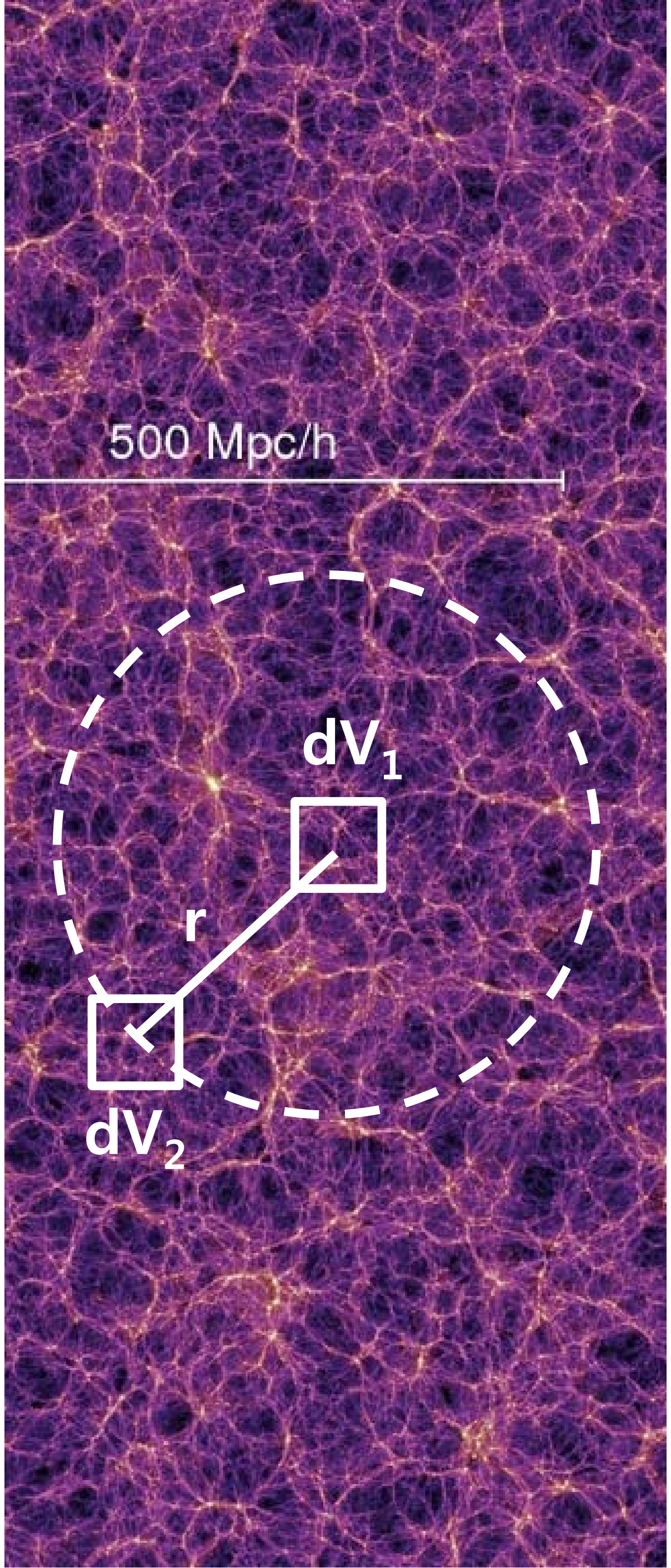
Q: What drove acceleration?

- Gravity is an attractive force for ordinary matter & radiation. Therefore, we need something different.
  - Exotic matter satisfying $w_{de} \equiv P_{de}/\rho_{de} < -1/3$
    - Vacuum energy $w_{de} = -1$
    - Slowly-rolling scalar field (one? two? many?)

$$w_{de} = \frac{(1/2)\dot{\varphi}^2 - V(\varphi)}{(1/2)\dot{\varphi}^2 + V(\varphi)} \approx -1$$

  - Modifying Einstein Equation
    - f(R) gravity (e.g. Brans-Dicke theory)
    - Higher dimensional gravity (e.g. DGP)

How do we test the theory of acceleration?
We use the large scale structure!



I. Power spectrum

- Probability of finding two galaxies at separation r is given by the two-point correlation function

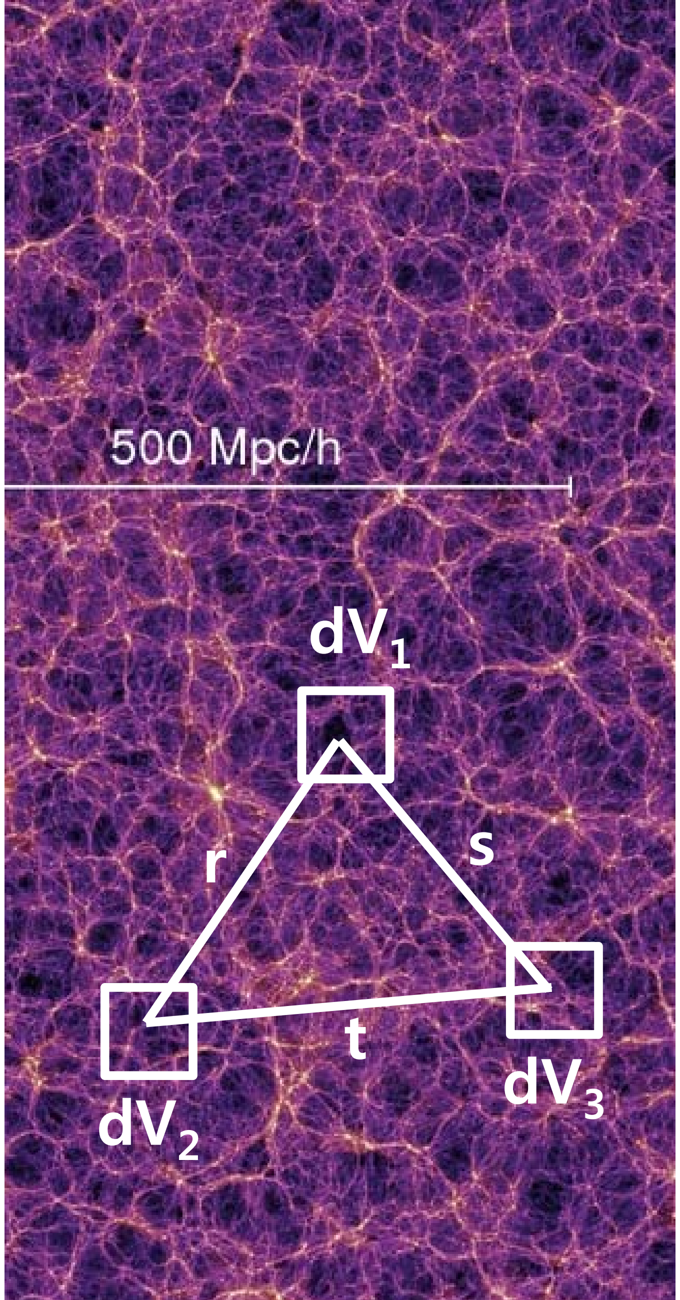
$$P_2(\mathbf{r}) = \bar{n}^2(1+\xi(\mathbf{r}))dV_1 dV_2$$

- P(k) is the Fourier transform of ξ(r)

$$P(\mathbf{k}) = \int d^3 r \xi(\mathbf{r}) e^{-i\mathbf{k}\cdot\mathbf{r}}$$

- Or, in terms of density contrast, δ(k),

$$\langle \delta(\mathbf{k})\delta(\mathbf{k}')\rangle = (2\pi)^3 P(\mathbf{k})\delta^D(\mathbf{k}+\mathbf{k}')$$



II. Bispectrum

- Probability of finding three galaxies at separation (r, s, t) is given by the two, and three-point correlation function

$$
\begin{aligned}
& P_3(r,s,t) \\
= \; & \bar{n}^3(1+\xi(r)+\xi(s)+\xi(t)+\zeta(r,s,t))dV_1 dV_2 dV_3
\end{aligned}
$$

- B(**k**,**k**′) is the Fourier transform of ζ(**r**,**s**).

$$B(\mathbf{k},\mathbf{k}') = \int d^3r \int d^3s \zeta(\mathbf{r},\mathbf{s}) e^{-i\mathbf{r}\cdot\mathbf{k}} e^{-i\mathbf{s}\cdot\mathbf{k}'}$$

- Or, in terms of density contrast,

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

From P(k) & B(k) to acceleration: Simple rules I keep in mind

Inflation sets
the initial condition,
and
dark energy sets
the growth and **the distances**.

Initial condition from inflation

- Seed fluctuations predicted by most inflation models are *nearly* **scale invariant** and obey *nearly* **Gaussian statistics**, which are often parametrized as
  - Initial power spectrum

$$k^3 P_\Phi(k) = A \left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln\left(\frac{k}{k_0}\right)}$$

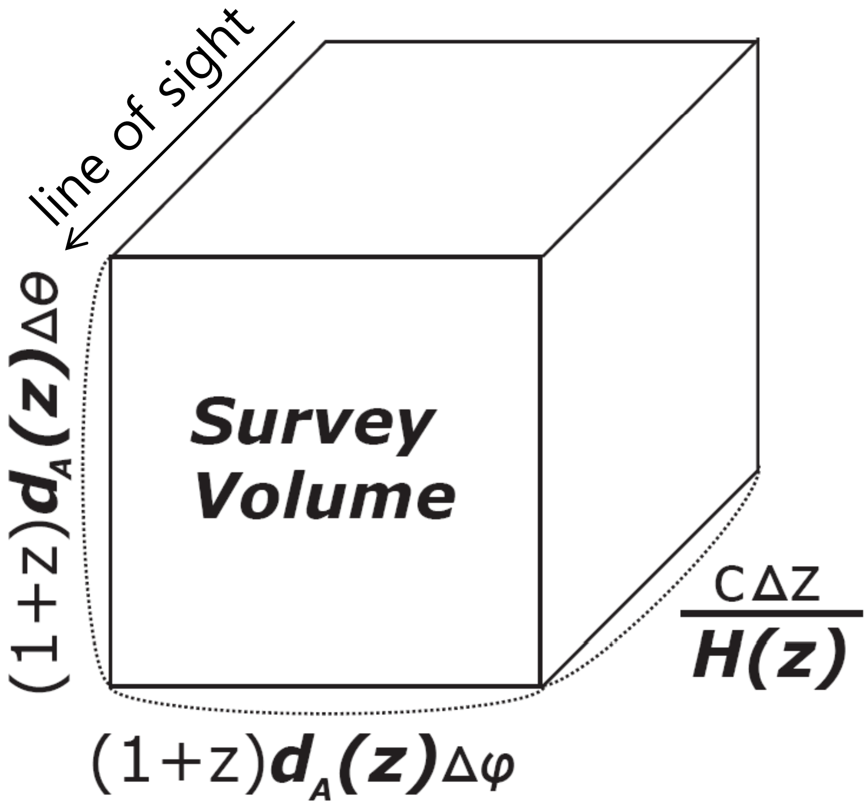
  - Initial bispectrum

$$B_\Phi(k_1, k_2, k_3) = 2 f_{\rm NL} \left[P_\Phi(k_1)P_\Phi(k_2) + P_\Phi(k_2)P_\Phi(k_3) + P_\Phi(k_3)P_\Phi(k_1)\right]$$

Here, primordial curvature perturbation, Φ,is (local type)

$$\Phi(\mathbf{x}) = \phi(\mathbf{x}) + f_{\rm NL}\left(\phi^2(\mathbf{x}) - \langle\phi^2\rangle\right)$$

Distances from dark energy



- In galaxy surveys, we chart galaxies by (θ,φ,z).
- In order to convert them to physical coordinate, we have to *assume* the **Hubble expansion rate, $H_{ref}(z)$**, and the **angular diameter distance, $D_{A,ref}(z)$**.
- **Observed power spectrum** using *reference* cosmology is **rescaled and shifted (in log scale)** relative to the **true power spectrum** :

$$P_{\rm obs}(k_{\rm ref\perp}, k_{\rm ref\parallel}) = \left(\frac{D_{A,\rm ref}}{D_A}\right)^2 \left(\frac{H}{H_{\rm ref}}\right) P_s^g(k_\perp, k_\parallel)$$

$$k_{\rm ref\perp} \equiv \frac{D_A}{D_{A,\rm ref}} k_\perp \qquad k_{\rm ref\parallel} \equiv \frac{H_{\rm ref}}{H} k_\parallel$$

Basic idea

- Use the galaxy data to learn:
  - Initial power spectrum **[Inflation]**

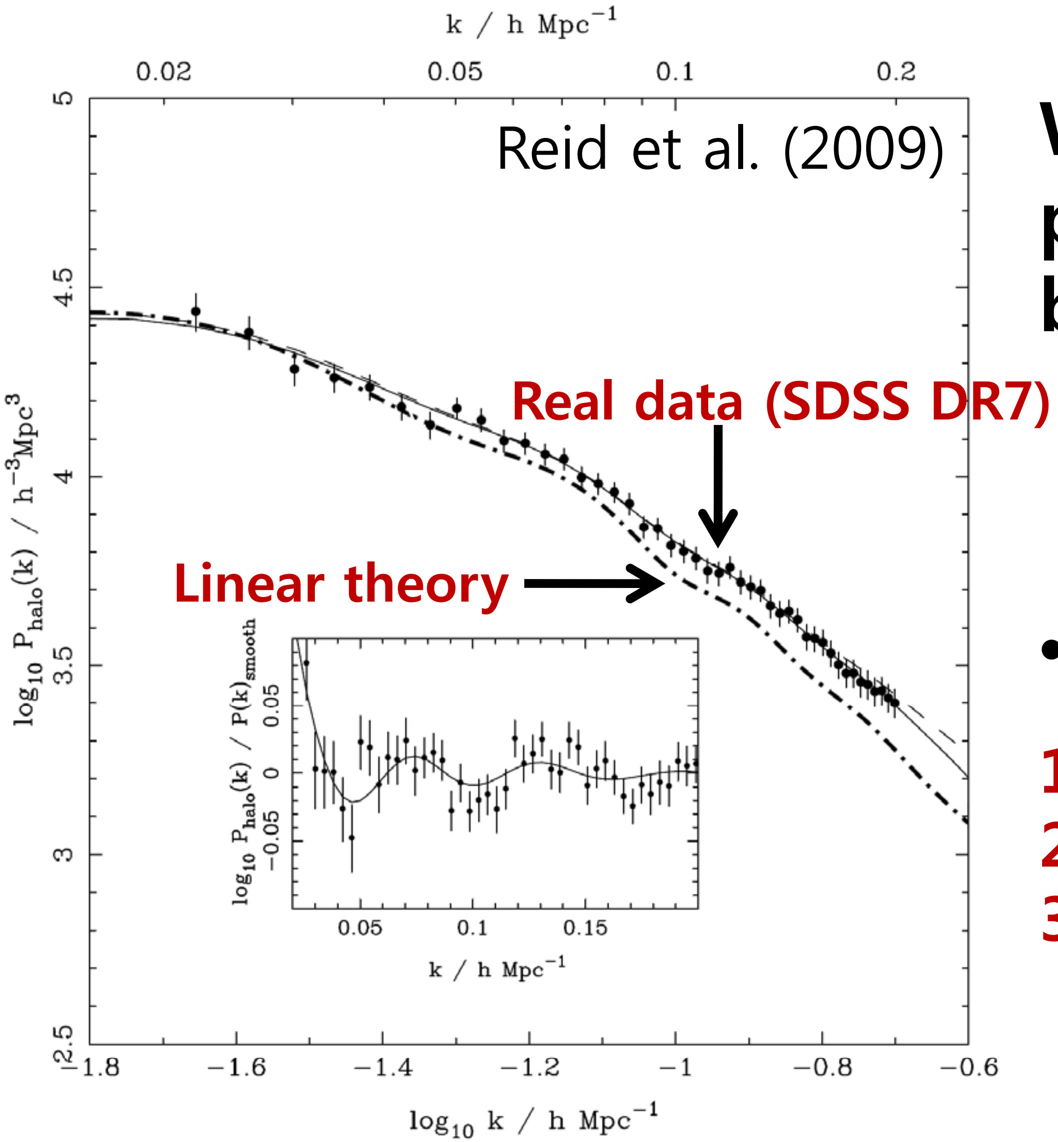
$$k^3 P_\Phi(k) = A\left(\frac{k}{k_0}\right)^{n_s - 1 + \frac{1}{2}\alpha_s \ln\left(\frac{k}{k_0}\right)}$$

  - Initial bispectrum **[Inflation]**

$$B_\Phi(k_1, k_2, k_3) = 2 f_{\rm NL}\left[P_\Phi(k_1)P_\Phi(k_2) + P_\Phi(k_2)P_\Phi(k_3) + P_\Phi(k_3)P_\Phi(k_1)\right]$$

  - Expansion rates, H(z) **[dark energy]**
  - Distances, $d_A(z)$ **[dark energy]**

However, this method works only IF



We can model the galaxy power spectrum & bispectrum.

- Fact : what we measure from galaxy survey is **far from** the linear theory!

- Three nonlinearities :

1) Nonlinear matter clustering
2) Nonlinear galaxy bias
3) Nonlinear redshift space distortion

To exploit the galaxy power spectrum,

- We have to model the non-linear galaxy power spectrum.
- How?
  Solid theoretical framework : **Perturbation Theory (PT)**

  - It is necessary to avoid any empirical, calibration factors.
  - Validity of the cosmological *linear* perturbation theory has been verified *observationally*. (Remember the success of WMAP!)
  - So, we just go one step beyond the linear theory, and include higher order terms in perturbations.
  - **3rd-order perturbation theory (3PT)**

Is 3PT new?

- Not at all! It is more than 25 years old!
- However, it <u>has never been applied to the real data</u> so far, because nonlinearity is too strong to model power spectrum at z~0.
- High-z galaxy surveys are now possible. (e.g.)
  - HETDEX (Hobby-Eberly Telescope Dark Energy Experiment)
  - SUMIRE/LAS (formerly known as WFMOS)
  - JDEM (ADEPT, CIP, …)
- **What's new!**
  - Detailed analysis of high-z power spectrum
  - Unprecedented accuracy (1%) required by data

II. Modeling the nonlinear galaxy power spectrum

Nonlinear clustering
Nonlinear redshift space distortion
Nonlinear galaxy bias

Solving Just Three Equations

- Setting up
  - – Consider large scales, where the baryonic pressure is negligible, but smaller than the Hubble horizon. (i.e. $a_0 H << k << k_J$, where k_J is the Jeans scale.)
  - – Ignore the shell-crossing, so that the rotational velocity is zero : curl(v)=0
- Matter field is described by Newtonian fluid equations.

$$\begin{cases} \dot{\delta} + \nabla \cdot [(1+\delta)\boldsymbol{v}] = 0 \\ \dot{\boldsymbol{v}} + (\boldsymbol{v} \cdot \nabla)\, \boldsymbol{v} = -\dfrac{\dot{a}}{a}\boldsymbol{v} - \nabla\phi \\ \nabla^2\phi = 4\pi G a^2 \bar{\rho}\delta \end{cases}$$

Solution in Fourier space

- In Fourier space, equations become, for $\theta \equiv \nabla \cdot v$.

$$
\begin{aligned}
&\dot{\delta}(\boldsymbol{k},\tau)+\theta(\boldsymbol{k},\tau) \\
&= -\int \frac{d^3k_1}{(2\pi)^3}\int d^3k_2\,\delta_D(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{k})\frac{\boldsymbol{k}\cdot\boldsymbol{k}_1}{k_1^2}\delta(\boldsymbol{k}_2,\tau)\theta(\boldsymbol{k}_1,\tau), \\
&\dot{\theta}(\boldsymbol{k},\tau)+\frac{\dot{a}}{a}\theta(\boldsymbol{k},\tau)+\frac{3\dot{a}^2}{2a^2}\Omega_{\rm m}(\tau)\delta(\boldsymbol{k},\tau) \\
&= -\int \frac{d^3k_1}{(2\pi)^3}\int d^3k_2\,\delta_D(\boldsymbol{k}_1+\boldsymbol{k}_2-\boldsymbol{k})\frac{k^2(\boldsymbol{k}_1\cdot\boldsymbol{k}_2)}{2k_1^2k_2^2}\theta(\boldsymbol{k}_1,\tau)\theta(\boldsymbol{k}_2,\tau)
\end{aligned}
$$

mode-mode coupling

- We solve it perturbatively

$$
\delta(\boldsymbol{k},\tau)=\sum_{n=1}^{\infty}a^n(\tau)\int\frac{d^3q_1}{(2\pi)^3}\cdots\frac{d^3q_{n-1}}{(2\pi)^3}\int d^3q_n\,\delta_D\Big(\sum_{i=1}^{n}\boldsymbol{q}_i-\boldsymbol{k}\Big)F_n(\boldsymbol{q}_1,\boldsymbol{q}_2,\cdots,\boldsymbol{q}_n)\underline{\delta_1(\boldsymbol{q}_1)\cdots\delta_1(\boldsymbol{q}_n)},
$$

$$
\theta(\boldsymbol{k},\tau)=-\sum_{n=1}^{\infty}\dot{a}(\tau)a^{n-1}(\tau)\int\frac{d^3q_1}{(2\pi)^3}\cdots\frac{d^3q_{n-1}}{(2\pi)^3}\int d^3q_n\,\delta_D\Big(\sum_{i=1}^{n}\boldsymbol{q}_i-\boldsymbol{k}\Big)G_n(\boldsymbol{q}_1,\boldsymbol{q}_2,\cdots,\boldsymbol{q}_n)\underline{\delta_1(\boldsymbol{q}_1)\cdots\delta_1(\boldsymbol{q}_n)}
$$

Why 3rd order?

- $\delta = \delta_1 + \delta_2 + \delta_3$
  where, $\delta_2 \propto [\delta_1]^2$, $\delta_3 \propto [\delta_1]^3$

- The power spectrum from the higher order density field :

$$
\begin{aligned}
&(2\pi)^3 P(k)\delta_D(\boldsymbol{k}+\boldsymbol{k}') \\
&\equiv \langle \delta(\boldsymbol{k},\tau)\delta(\boldsymbol{k}',\tau)\rangle \\
&= \langle \delta_1(\boldsymbol{k},\tau)\delta_1(\boldsymbol{k}',\tau)\rangle + \langle \delta_2(\boldsymbol{k},\tau)\delta_1(\boldsymbol{k}',\tau) + \delta_1(\boldsymbol{k},\tau)\delta_2(\boldsymbol{k}',\tau)\rangle \\
&\quad + \langle \delta_1(\boldsymbol{k},\tau)\delta_3(\boldsymbol{k}',\tau) + \delta_2(\boldsymbol{k},\tau)\delta_2(\boldsymbol{k}',\tau) + \delta_3(\boldsymbol{k},\tau)\delta_1(\boldsymbol{k}',\tau)\rangle \\
&\quad + \mathcal{O}(\delta_1^6)
\end{aligned}
$$

Odd products of Gaussian variables vanish.

- Therefore, $P(k) = P_{11}(k) + P_{22}(k) + 2P_{13}(k)$

3PT Matter power spectrum

Vishiniac (1983); Fry (1984); Goroff et al. (1986); Suto & Sasaki (1991); Makino et al. (1992); Jain & Bertschinger (1994); Scoccimarro & Frieman (1996)

$$P_{\delta\delta}(k,\tau) = D^2(\tau) P_L(k) + D^4(\tau)\left[2P_{13}(k) + P_{22}(k)\right],$$

$$P_{22}(k) = 2\int \frac{d^3q}{(2\pi)^3} P_L(q) P_L(|\boldsymbol{k}-\boldsymbol{q}|)\left[F_2^{(s)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\right]^2$$

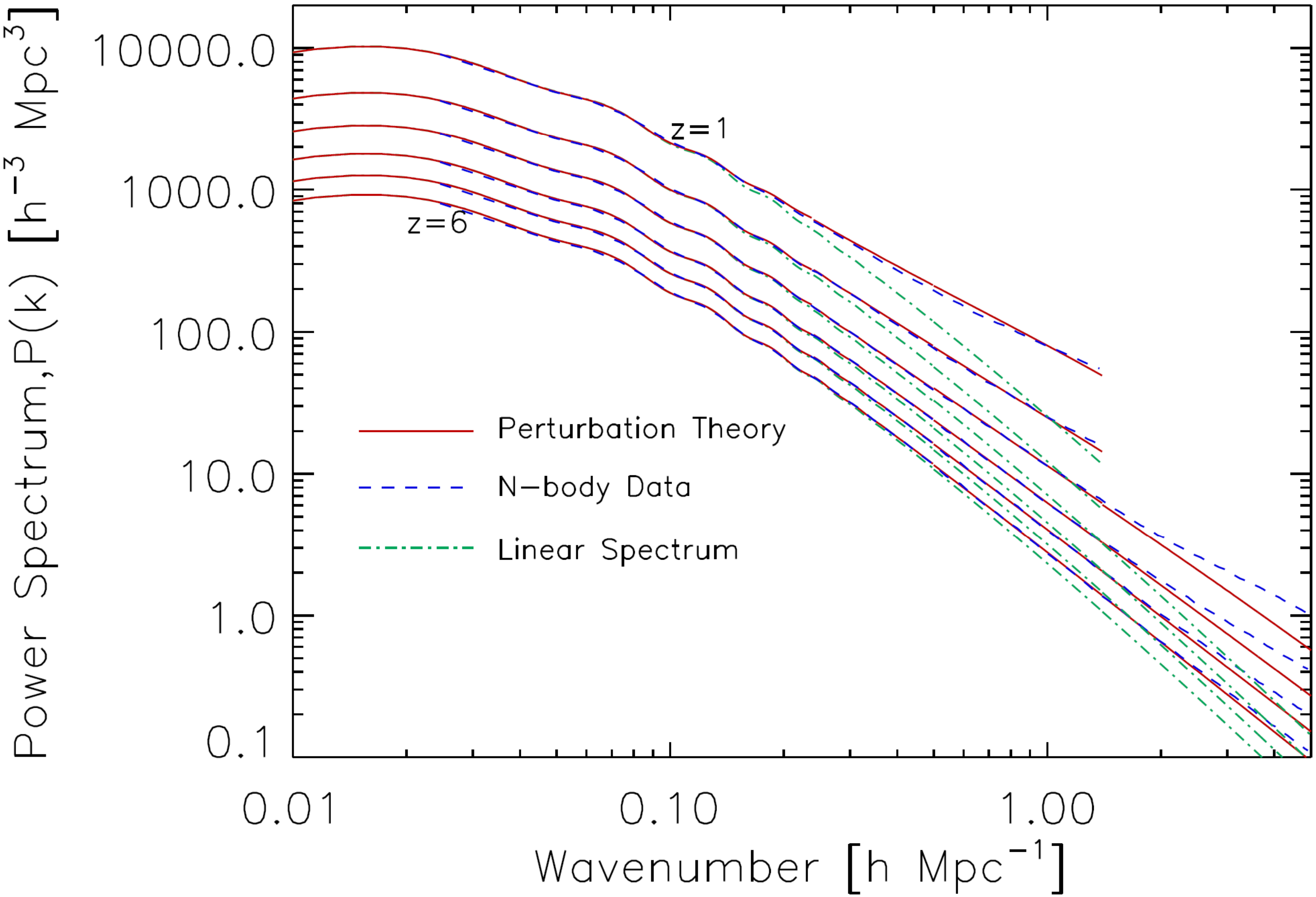
$$\begin{aligned} 2P_{13}(k) &= \frac{2\pi k^2}{252} P_L(k)\int_0^\infty \frac{dq}{(2\pi)^3} P_L(q) \\ &\times \left[100\frac{q^2}{k^2} - 158 + 12\frac{k^2}{q^2} - 42\frac{q^4}{k^4}\right. \\ &+ \left.\frac{3}{k^5 q^3}(q^2-k^2)^3(2k^2+7q^2)\ln\left(\frac{k+q}{|k-q|}\right)\right] \end{aligned}$$

$$F_2^{(s)}(\boldsymbol{q}_1,\boldsymbol{q}_2) = \frac{17}{21} + \frac{1}{2}\hat{\boldsymbol{q}}_1\cdot\hat{\boldsymbol{q}}_2\left(\frac{q_1}{q_2}+\frac{q_2}{q_1}\right) + \frac{2}{7}\left[(\hat{\boldsymbol{q}}_1\cdot\hat{\boldsymbol{q}}_2)^2 - \frac{1}{3}\right]$$

This result is completely analytic!

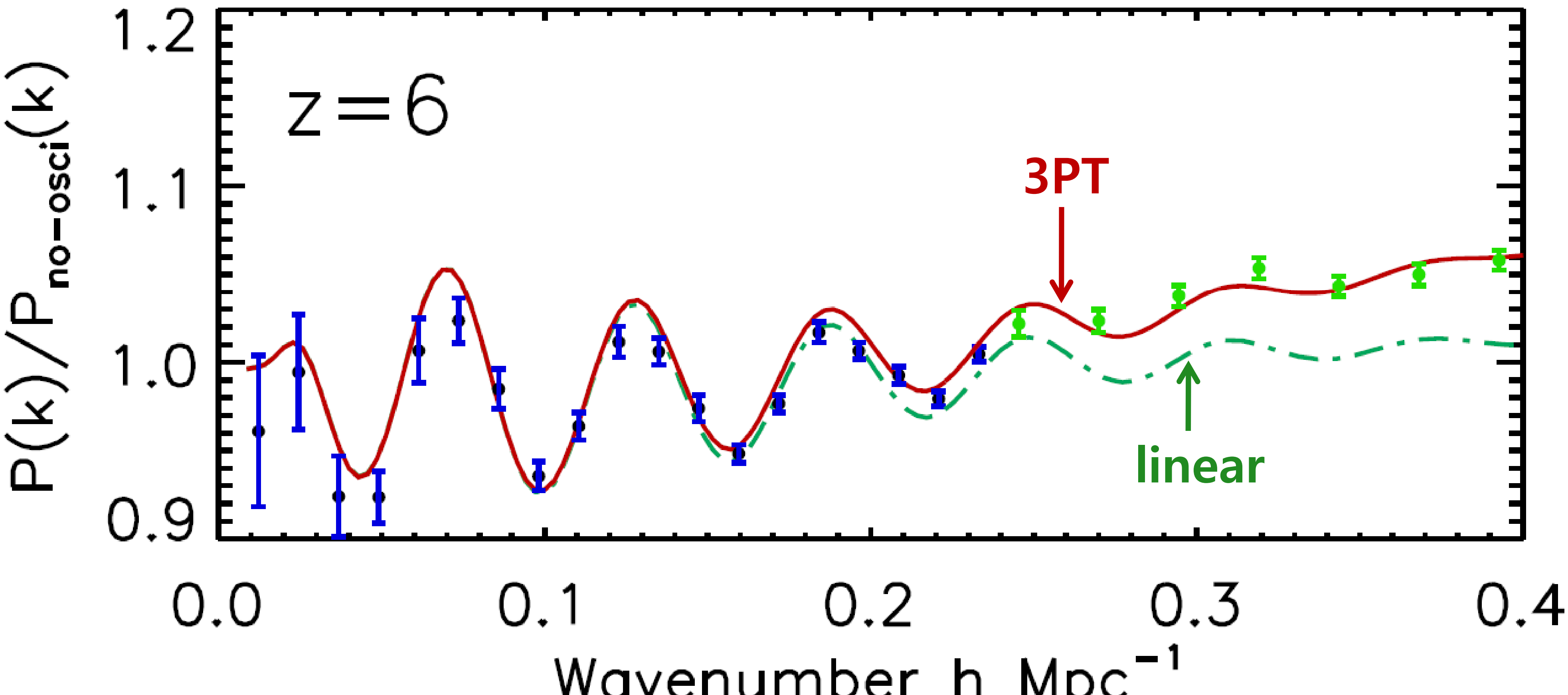
Jeong & Komatsu (2006)

Models Nonlinear matter P(k)



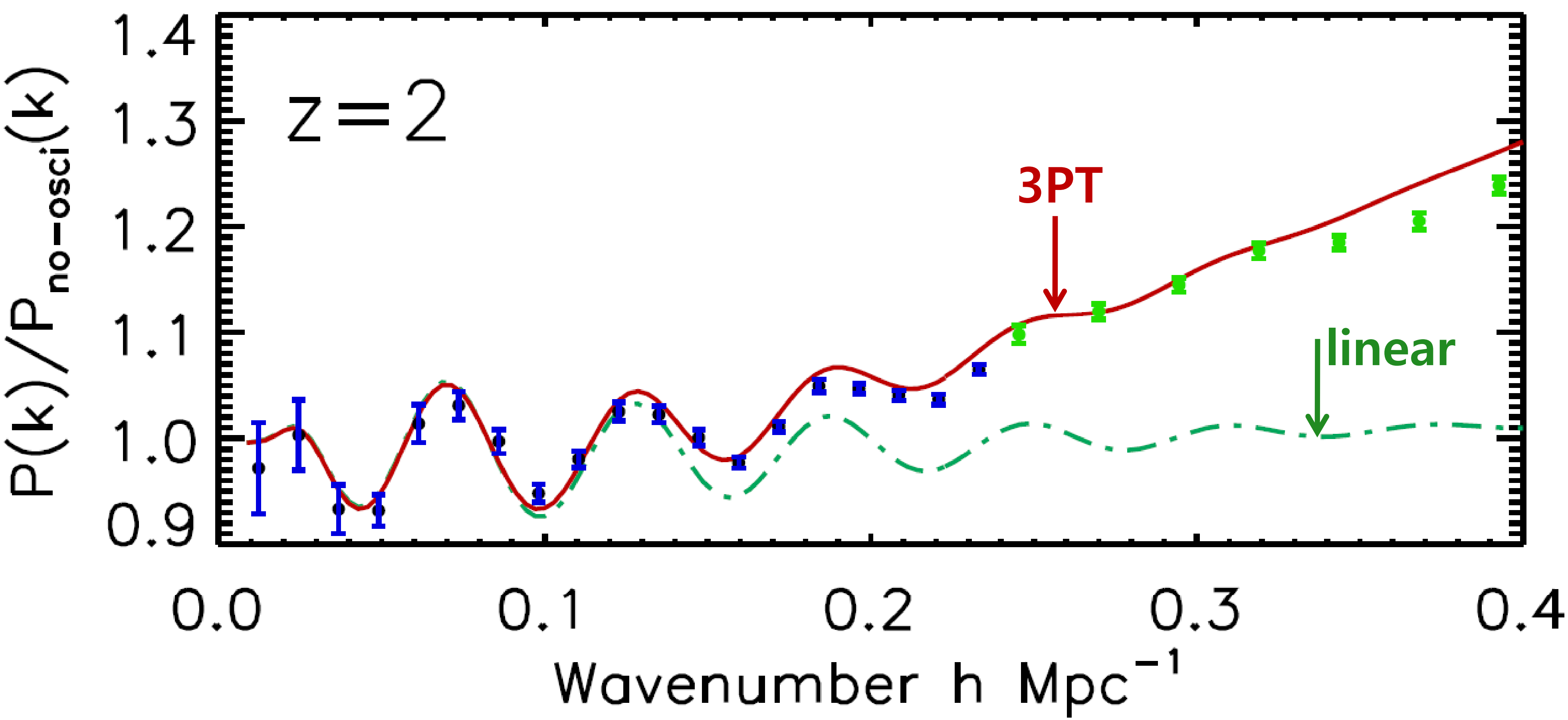
Jeong & Komatsu (2006)

BAO : Matter Non-linearity (z=6)



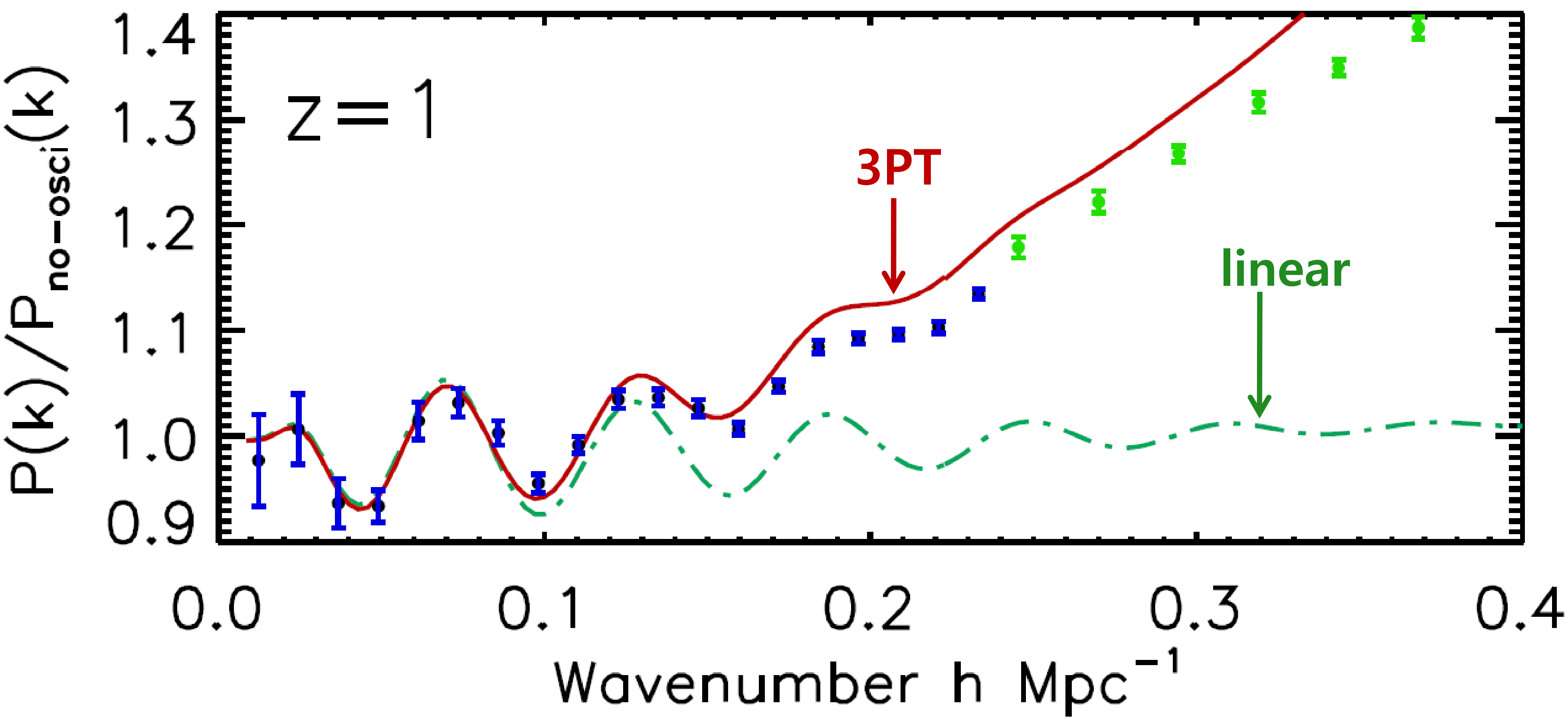
Jeong & Komatsu (2006)

BAO : Matter Non-linearity (z=2)



Jeong & Komatsu (2006)

BAO : Matter Non-linearity (z=1)

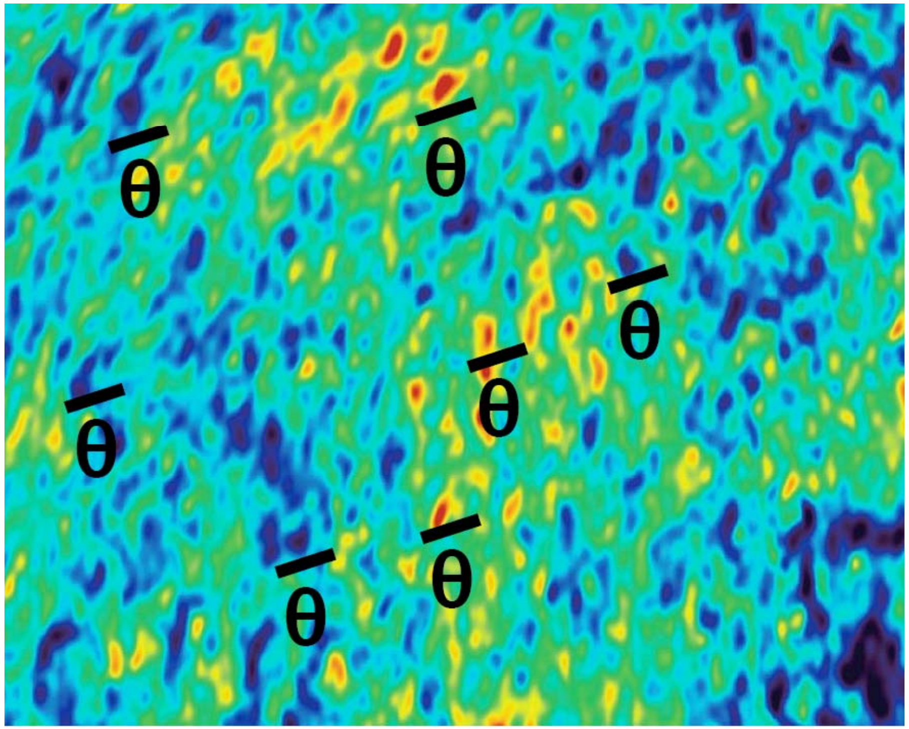


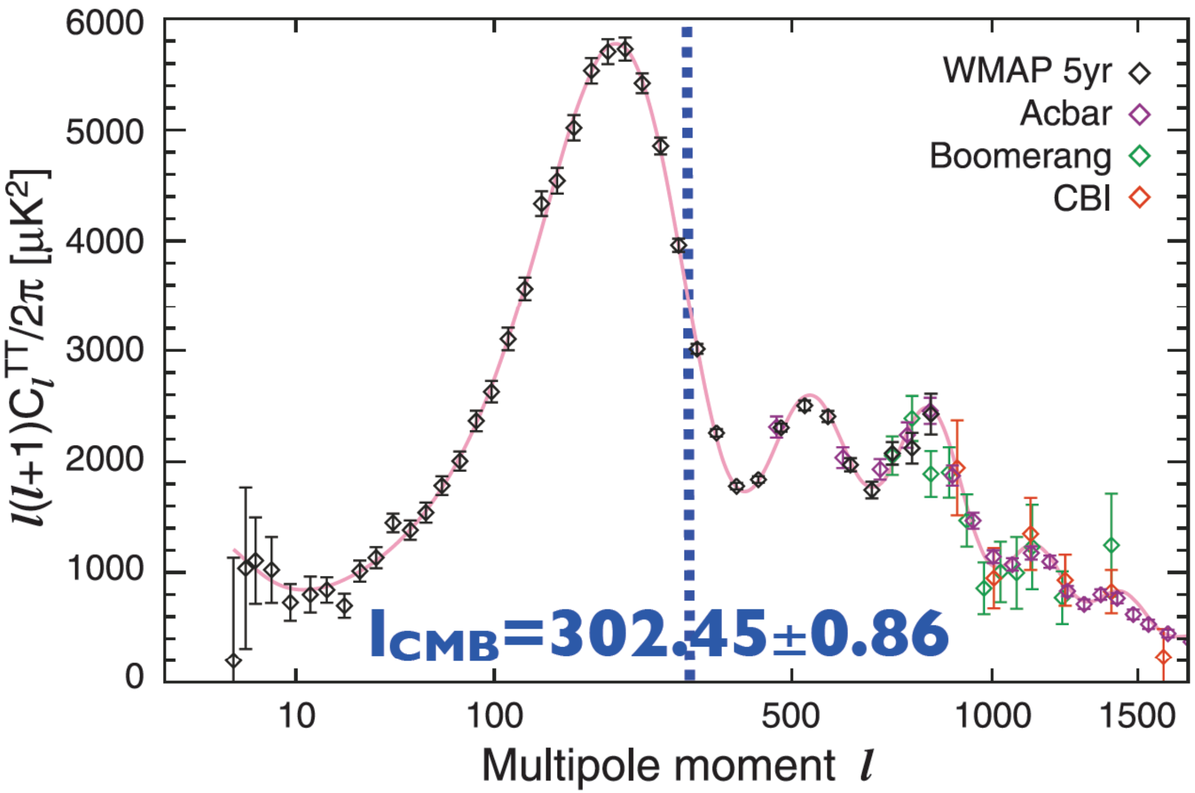
Standard ruler in CMB

- **The standard ruler in CMB angular power spectrum**

  d_{CMB}= **Physical distance traveled by the sound waves** from **the Big-Bang to photon decoupling** at z~1091.51

$$d_{CMB} = 146.8 \pm 1.8 \text{ Mpc (comoving)}$$



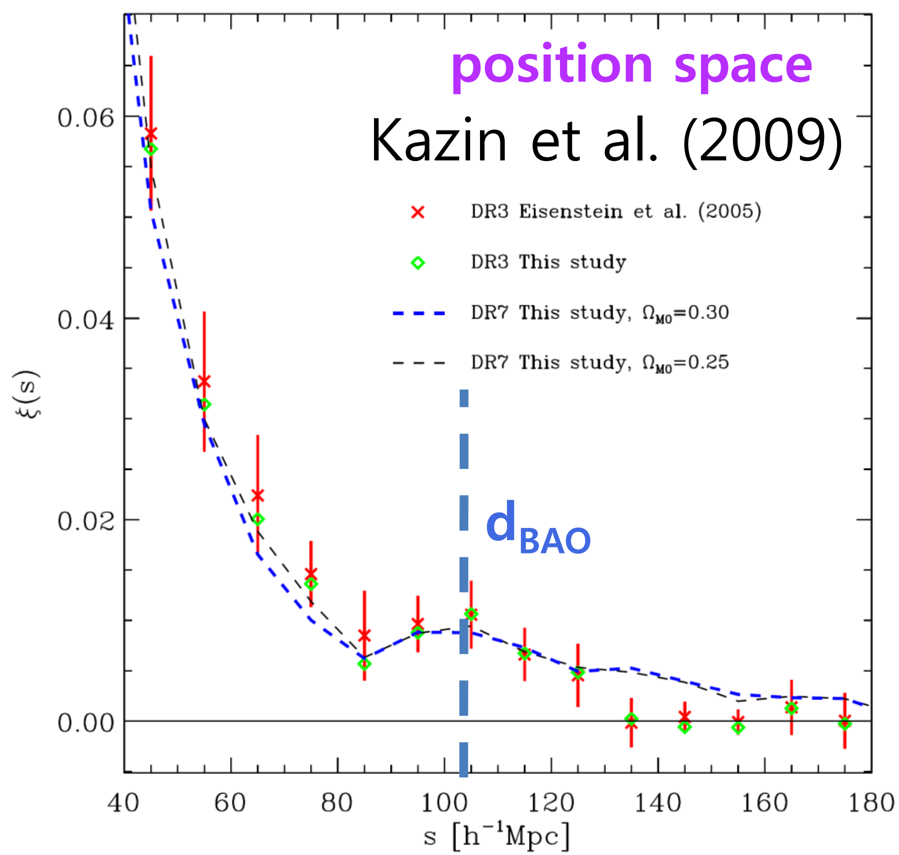


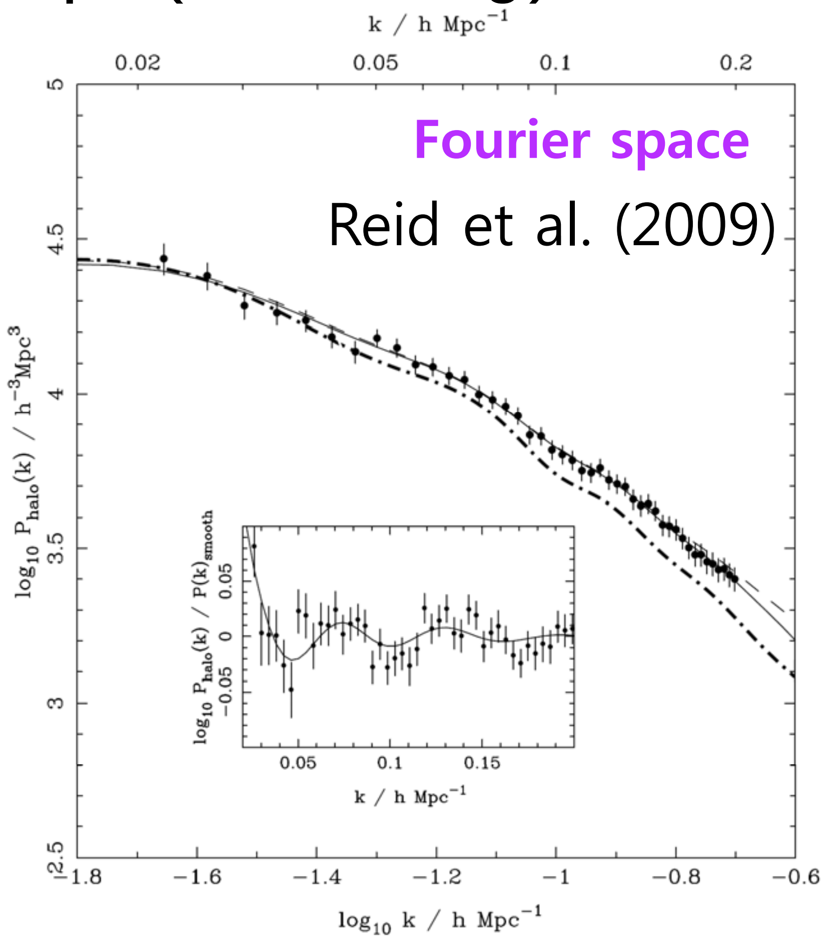
Also imprinted in galaxy P(k)

- **The standard ruler in galaxy two point functions**

d_{BAO}= **Physical distance traveled by the sound waves** from **the Big-Bang to baryon decoupling** at z~1020.5, **MEASURED FROM CMB!!!**

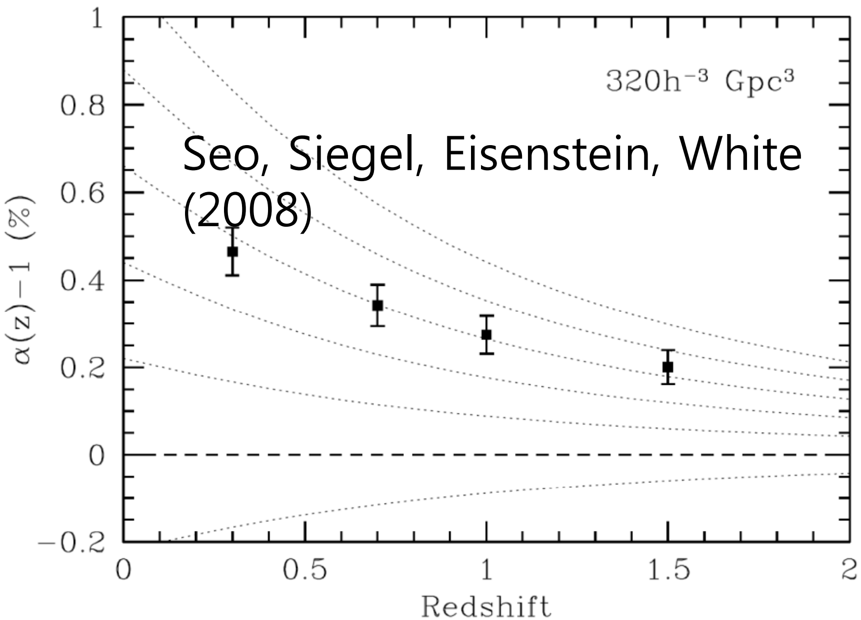
$$d_{BAO} = 153.3 \pm 2.0\ \mathrm{Mpc\ (comoving)}$$





BAO will save us, because

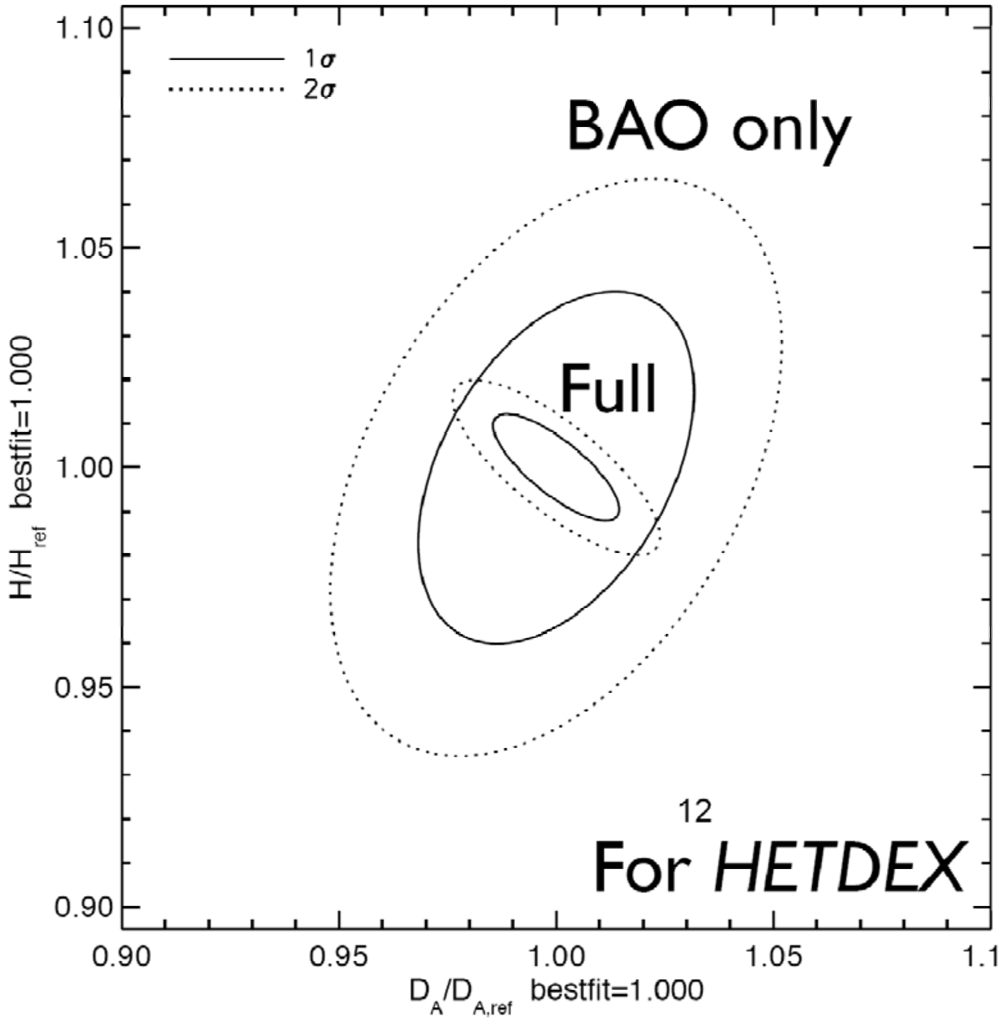
- Its location is **NOT very sensitive to the nonlinear evolution**, according to Dan. Eisenstein.
- Nonlinear shift of BAO phase (lines are growth_factor^2)



Therefore, we would probably have to rely only on BAO when nonlinearities are too strong. (e.g. z~0)

What if we model the nonlinearities?

- It will improve upon the determination of both D_A and H by **a factor of two**, and of the area of ellipse by **more than a factor of four**!
- Plus, we can extract many other information from power spectrum.
    - Growth of structure
    - Shape of the primordial power spectrum
    - Neutrino mass



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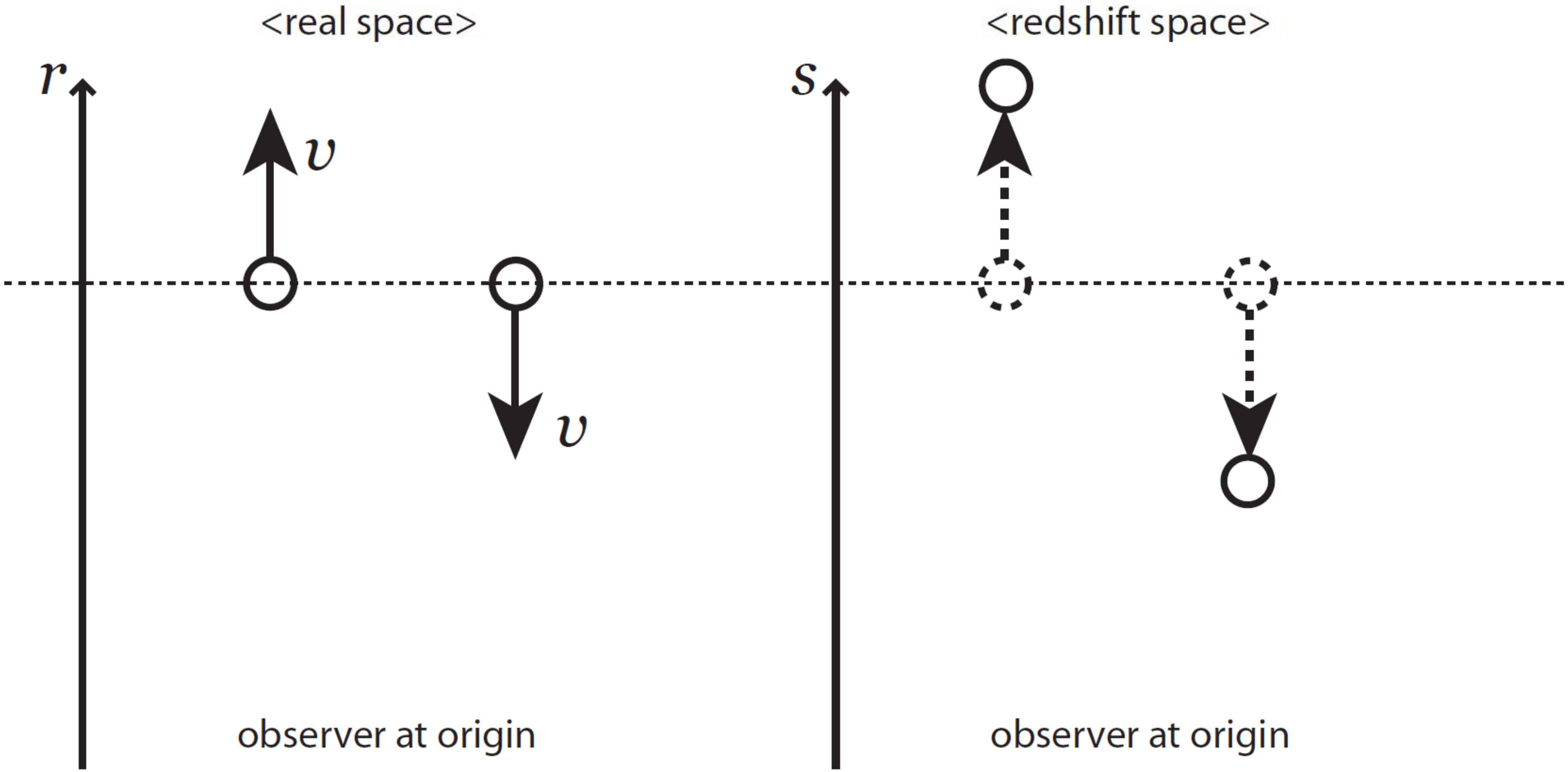
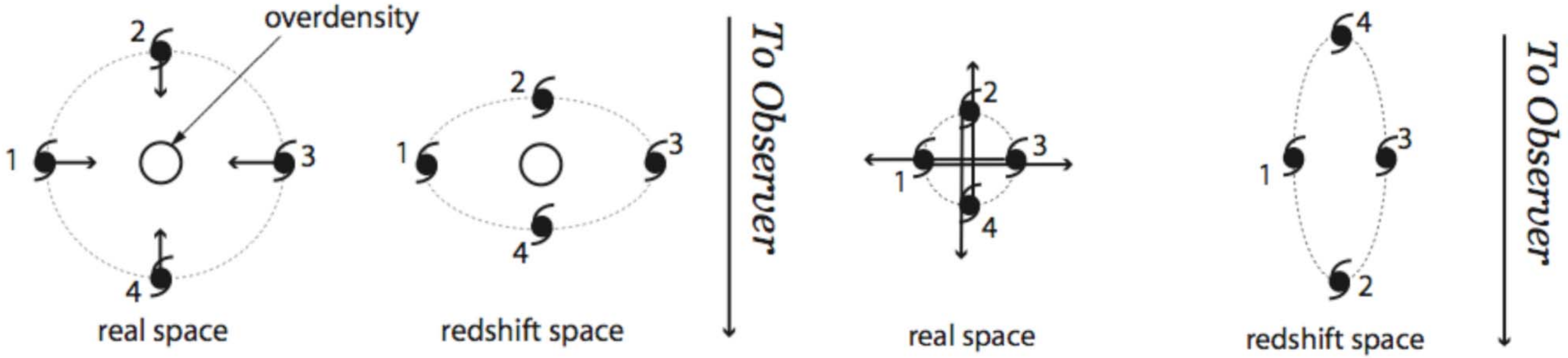
Shoji, Jeong & Komatsu (2008)

Redshift space distortion

- What is the issue?
  - Peculiar velocities, which further shift the spectrum on top of the Hubble flow, systematically shift the inferred radial distance to the object.



Two limits



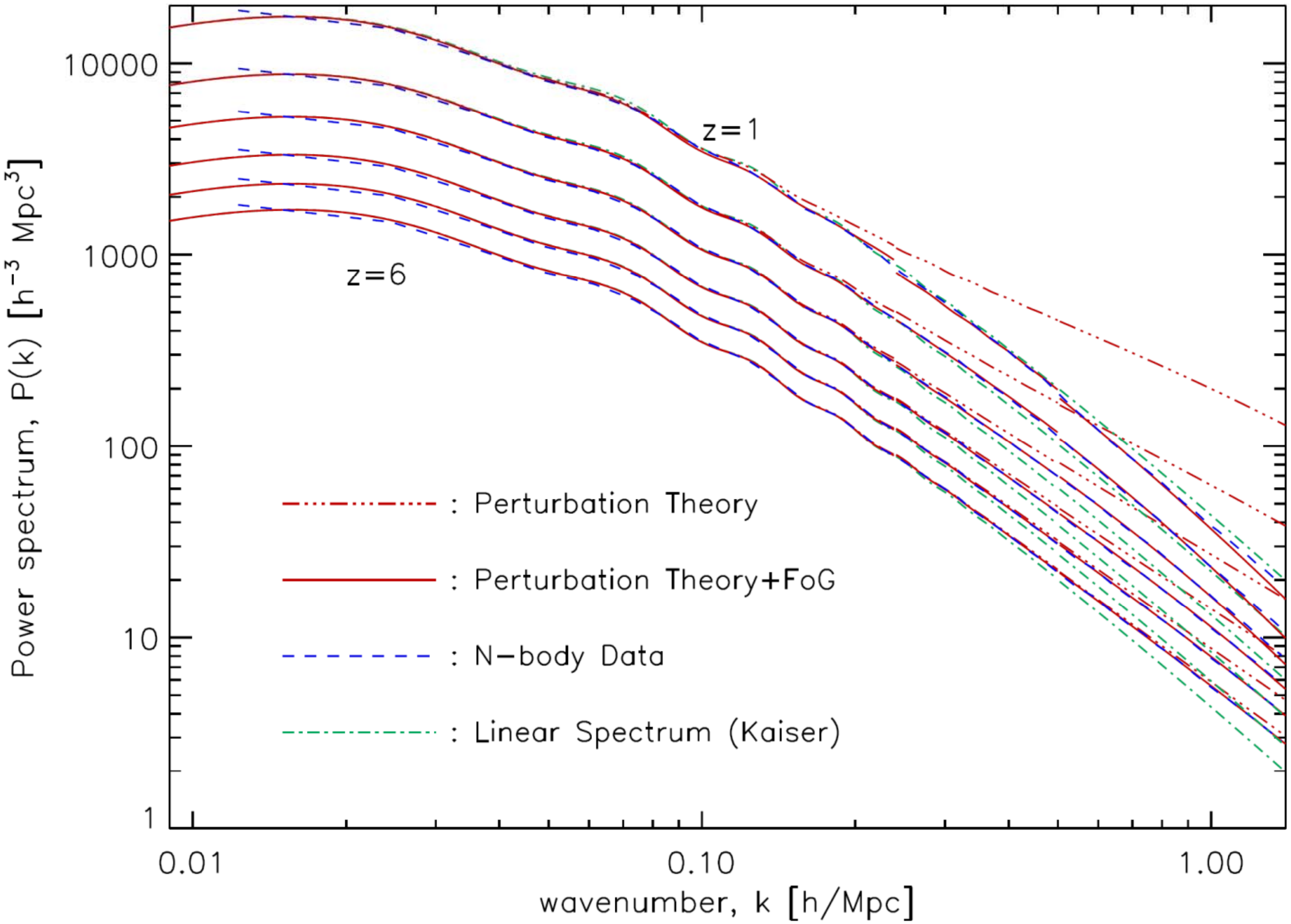
- (Left) Coherent velocity field => Clustering **enhanced** along the line of sight
    - "Kaiser" effect
- (Right) Virial-like random motion => Clustering **diminished** along the line of sight
    - "Finger-of-God" effect

Jeong in preparation

Power spectrum in redshift space

- Nonlinear Kaiser effect (up to 3rd order) can be calculated analytically by PT. (You don't want to see the formula.)
- We fit **Finger-of-God effect** by Lorenzian damping.

$$\frac{P_{red}(k_{\parallel}, k_{\perp}, z)}{1 + k_{\parallel}^2 \sigma_v^2}$$

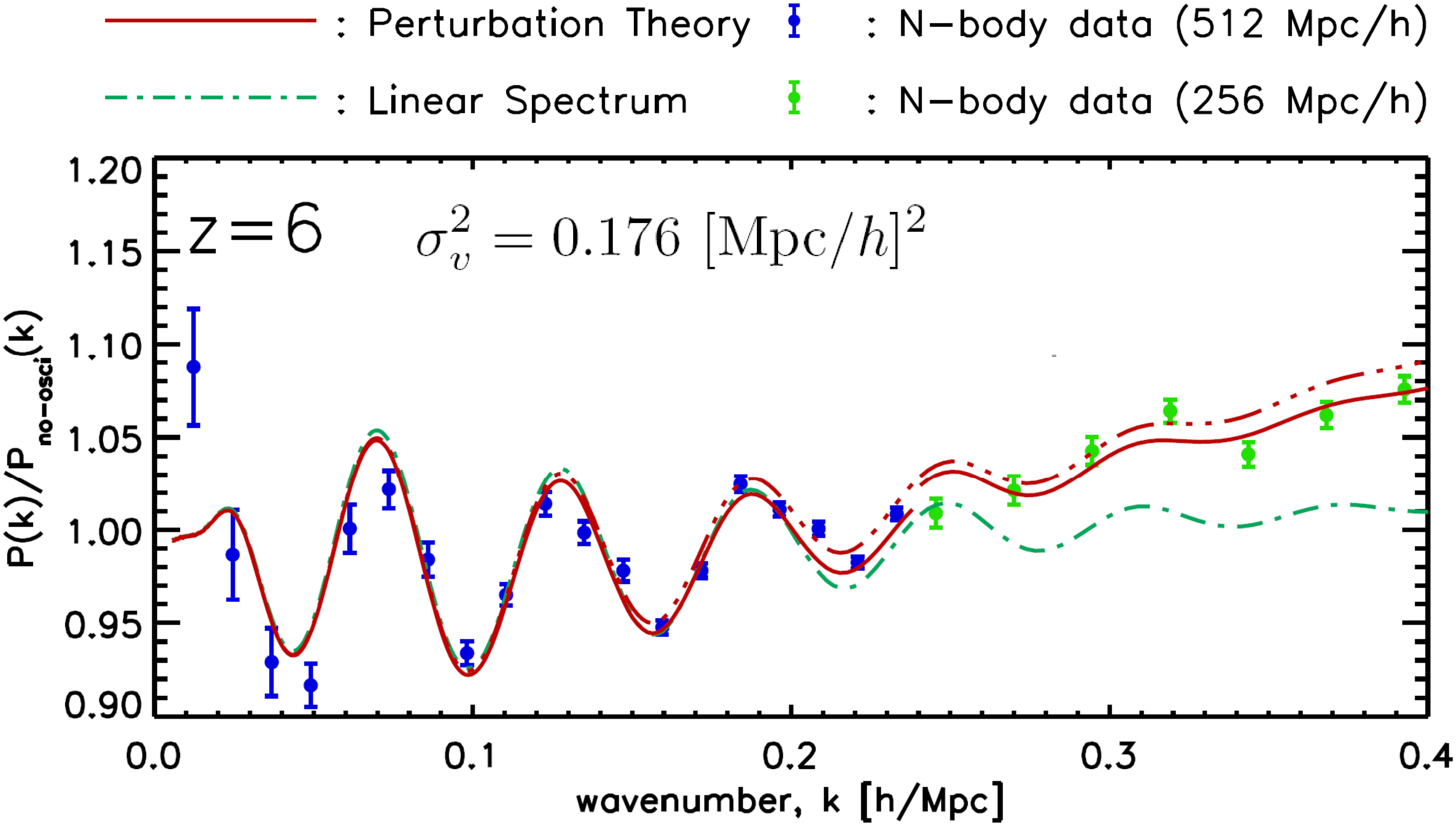


Note!!

$$\frac{1}{1 + k_{\parallel}^2 \sigma_v^2}$$ is the Fourier transform of exponential velocity distribution within halos.

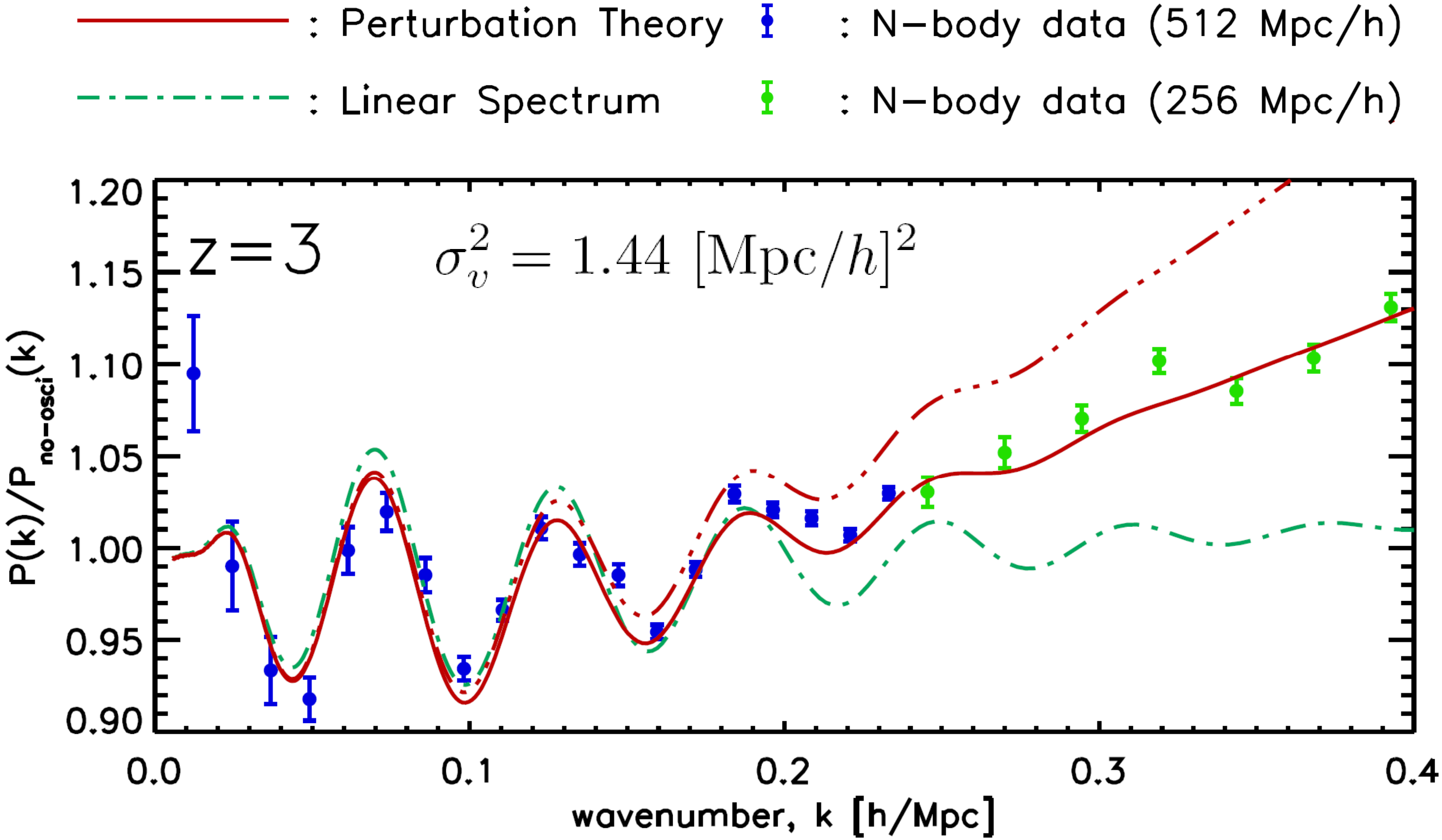
Jeong in preparation

BAO: in redshift space (z=6)



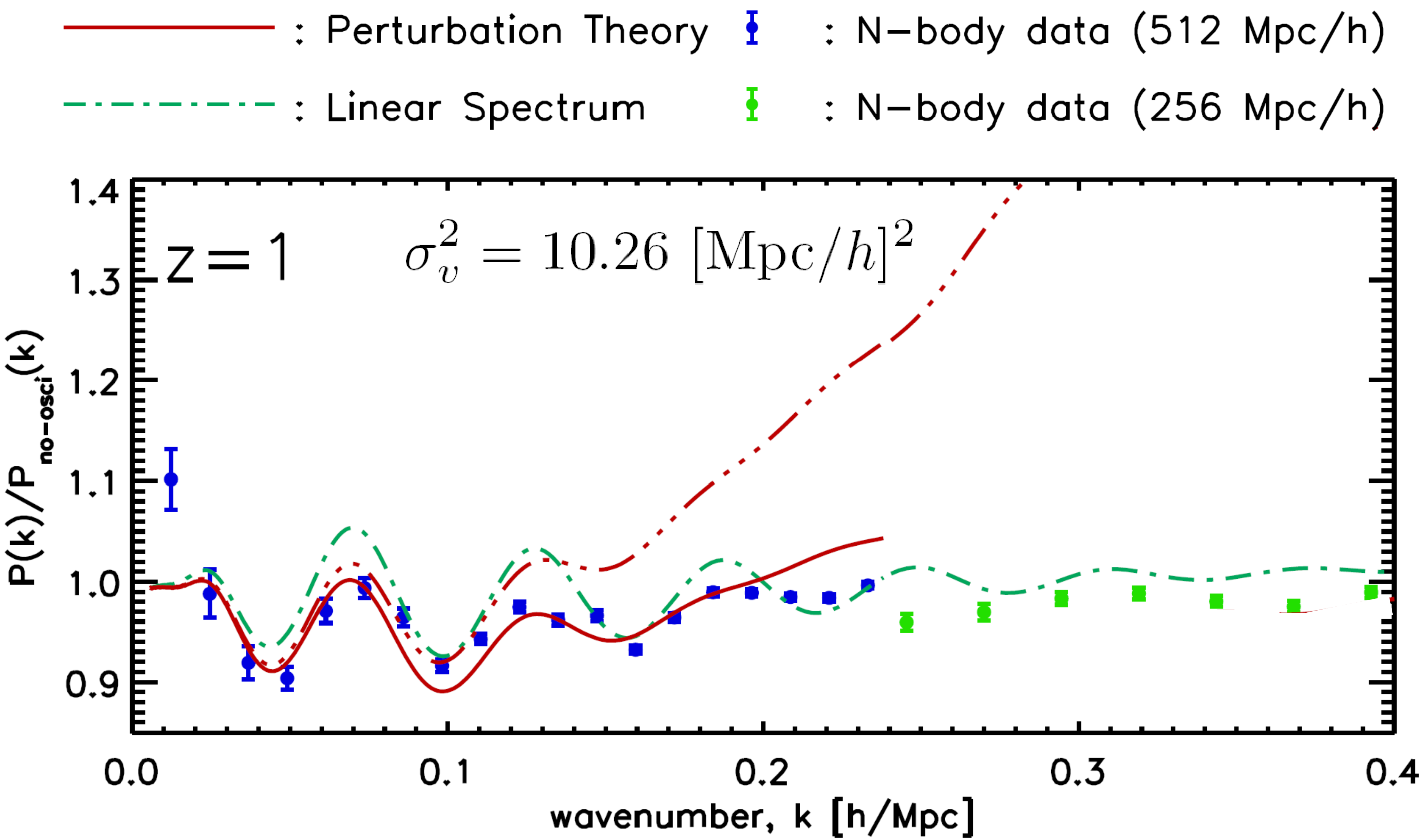
Jeong in preparation

BAO: in redshift space (z=3)



Jeong in preparation

BAO: in redshift space (z=1)



3PT Galaxy power spectrum

- Facts
  - The distribution of galaxies is not the same as that of matter fluctuations.
- Assumption
  - **Galaxy formation is a local process**, at least on the scales that we care about.

$$\delta_g(\mathbf{x}) = \epsilon + b_1\delta(\mathbf{x}) + \frac{1}{2}b_2\delta^2(\mathbf{x}) + \frac{1}{6}b_3\delta^3(\mathbf{x}) + \dots$$

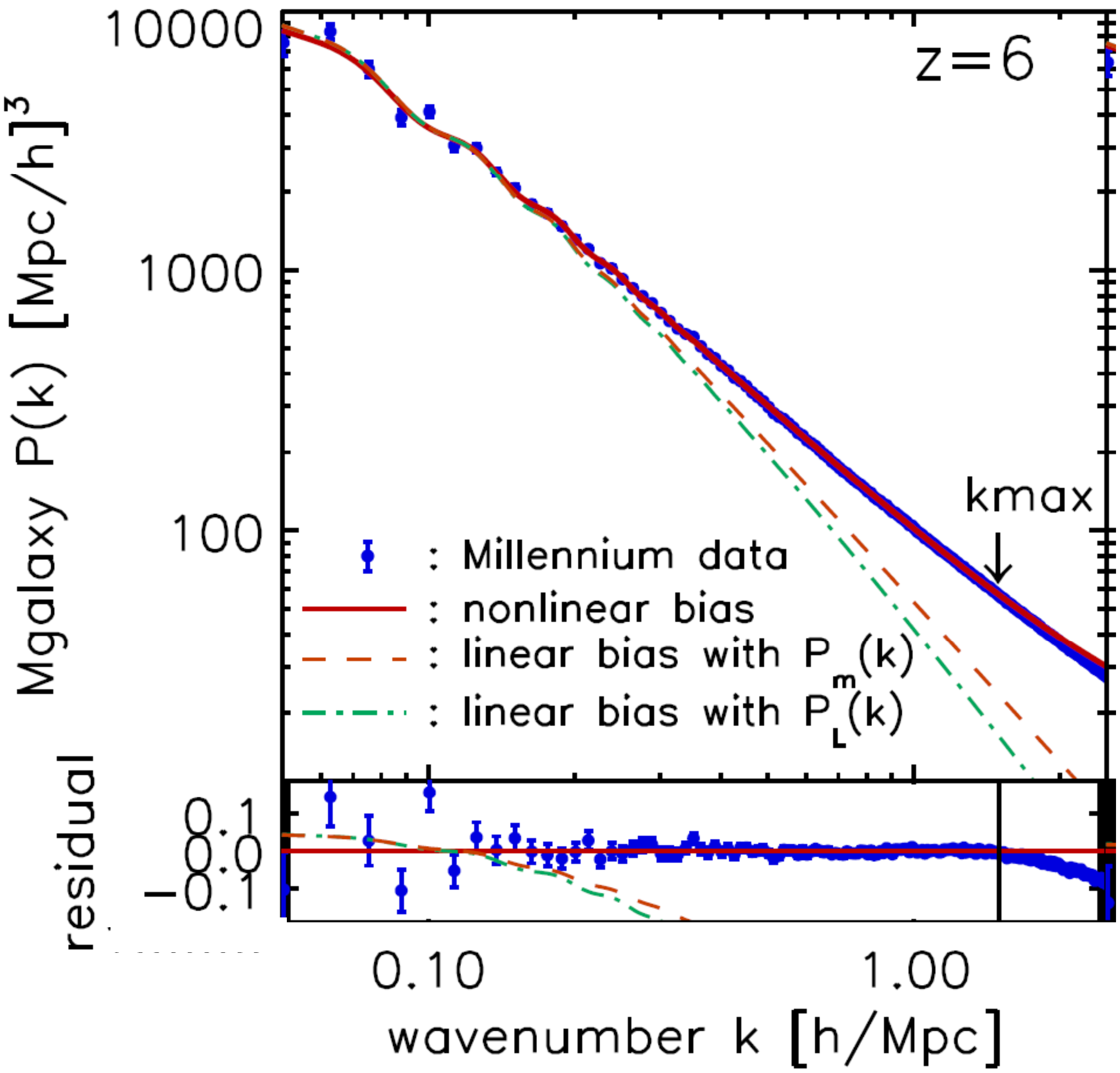
- Result (McDonald, 2006)

$$P_g(k) = P_0 + \tilde{b}_1^2\left[P(k) + \frac{\tilde{b}_2^2}{2}\int\frac{d^3\boldsymbol{q}}{(2\pi)^3}P(q)\left[P(|\boldsymbol{k}-\boldsymbol{q}|) - P(q)\right]\right.$$
$$\left. + 2\tilde{b}_2\int\frac{d^3\boldsymbol{q}}{(2\pi)^3}P(q)P(|\boldsymbol{k}-\boldsymbol{q}|)F_2^{(s)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\right]$$

– b_1,b_2,P_0 are **free parameters** that capture detailed information about galaxy formation!

Jeong & Komatsu (2009a)

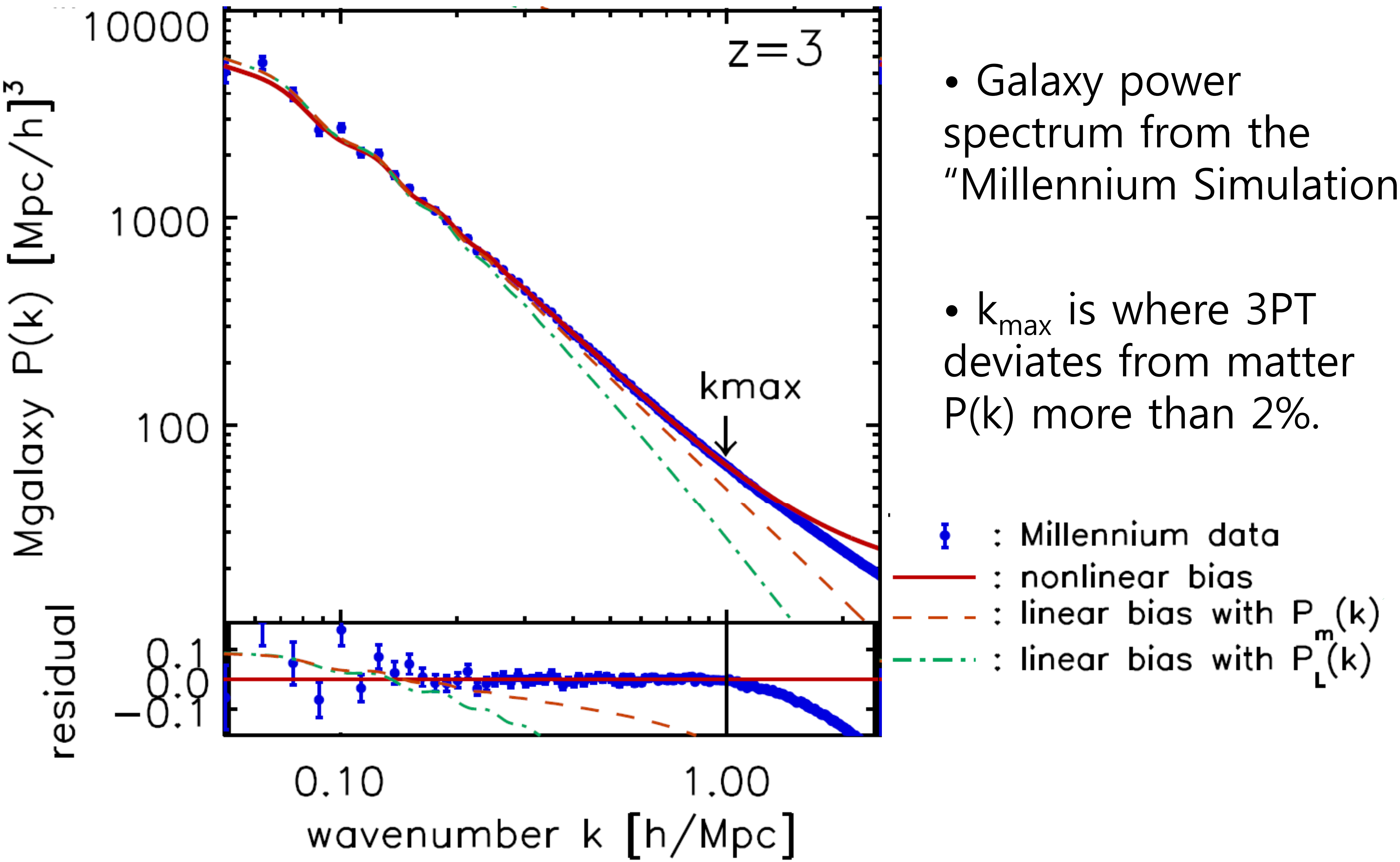
MPA Galaxy power spectrum



- Galaxy power spectrum from the "Millennium Simulation".
- k_{max} is where 3PT deviates from matter P(k) more than 2%.
- Shot noise (1/n) subtracted

Jeong & Komatsu (2009a)

MPA Galaxy power spectrum



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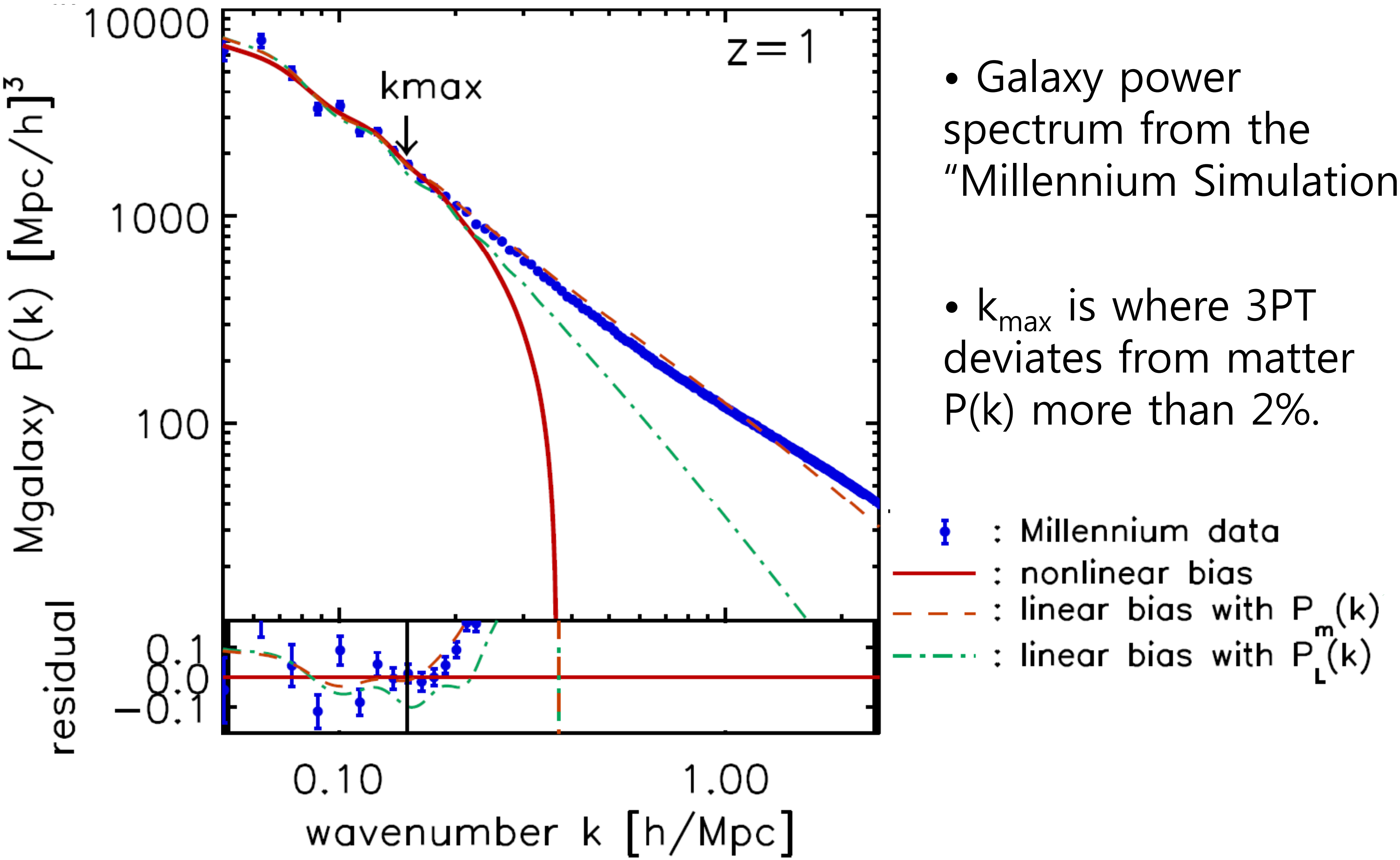
Jeong & Komatsu (2009a)

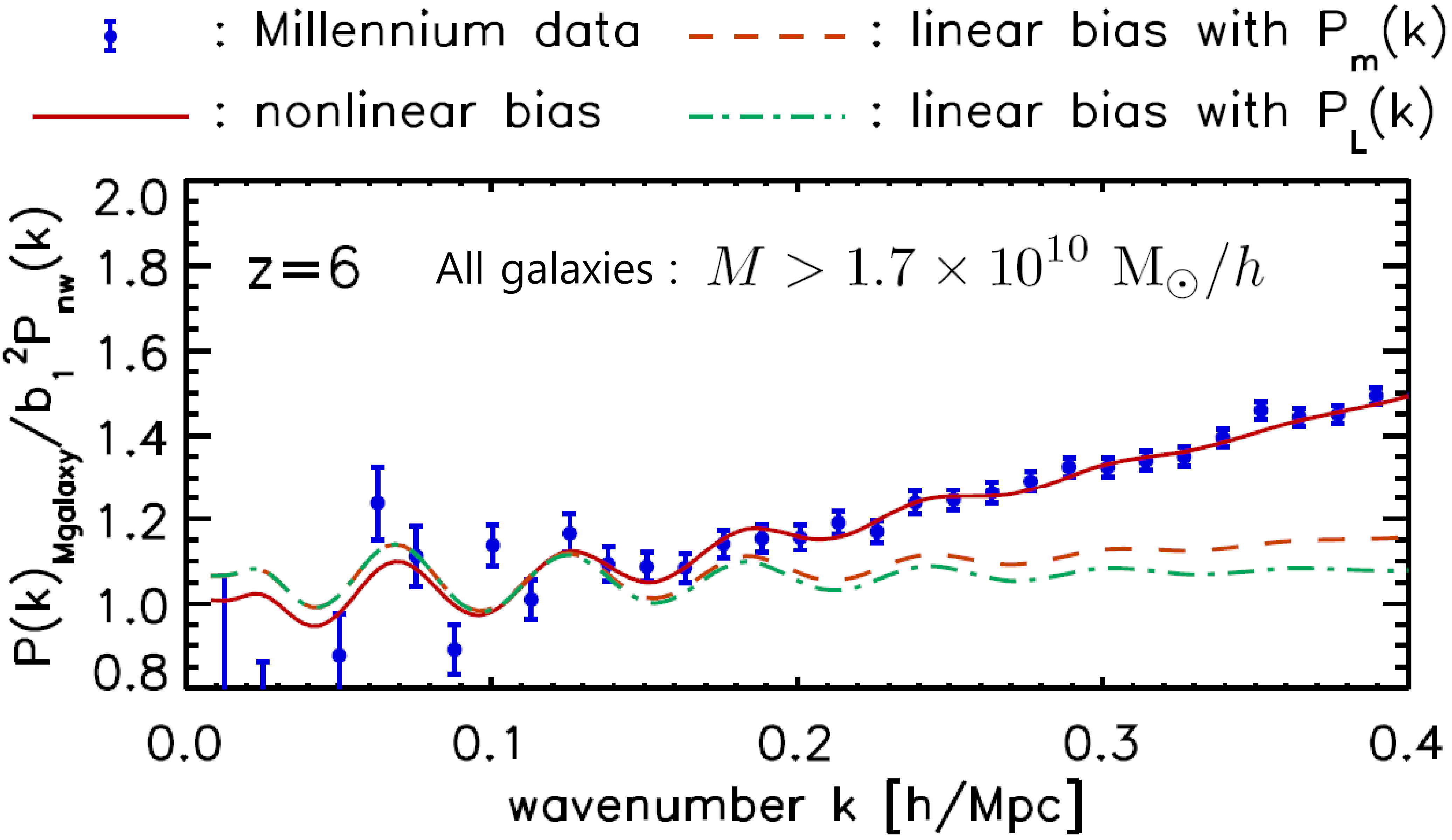
MPA Galaxy power spectrum



- Galaxy power spectrum from the "Millennium Simulation".
- k_{max} is where 3PT deviates from matter P(k) more than 2%.

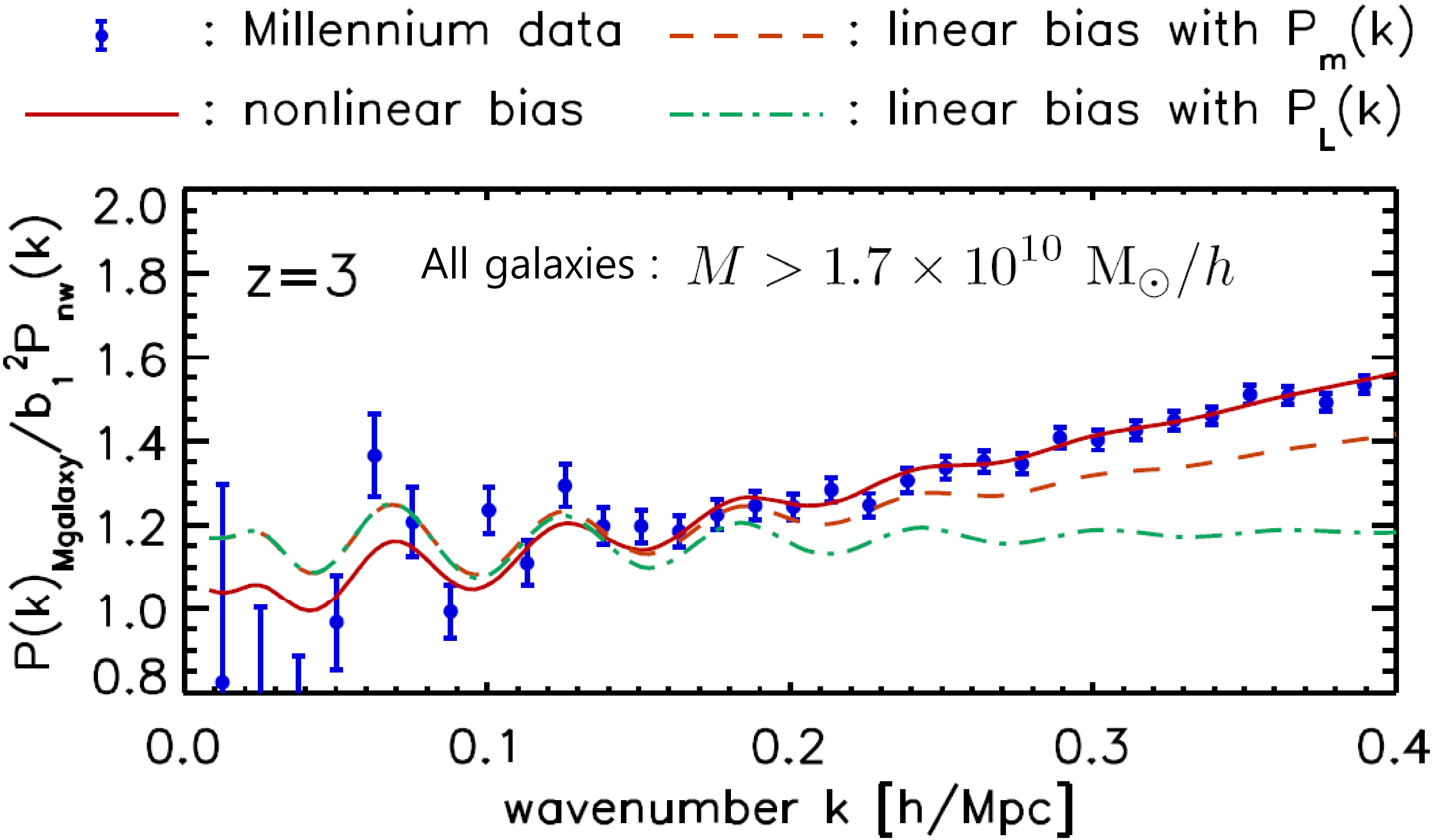
Jeong & Komatsu (2009a)

BAO : Non-linear bias (z=6)



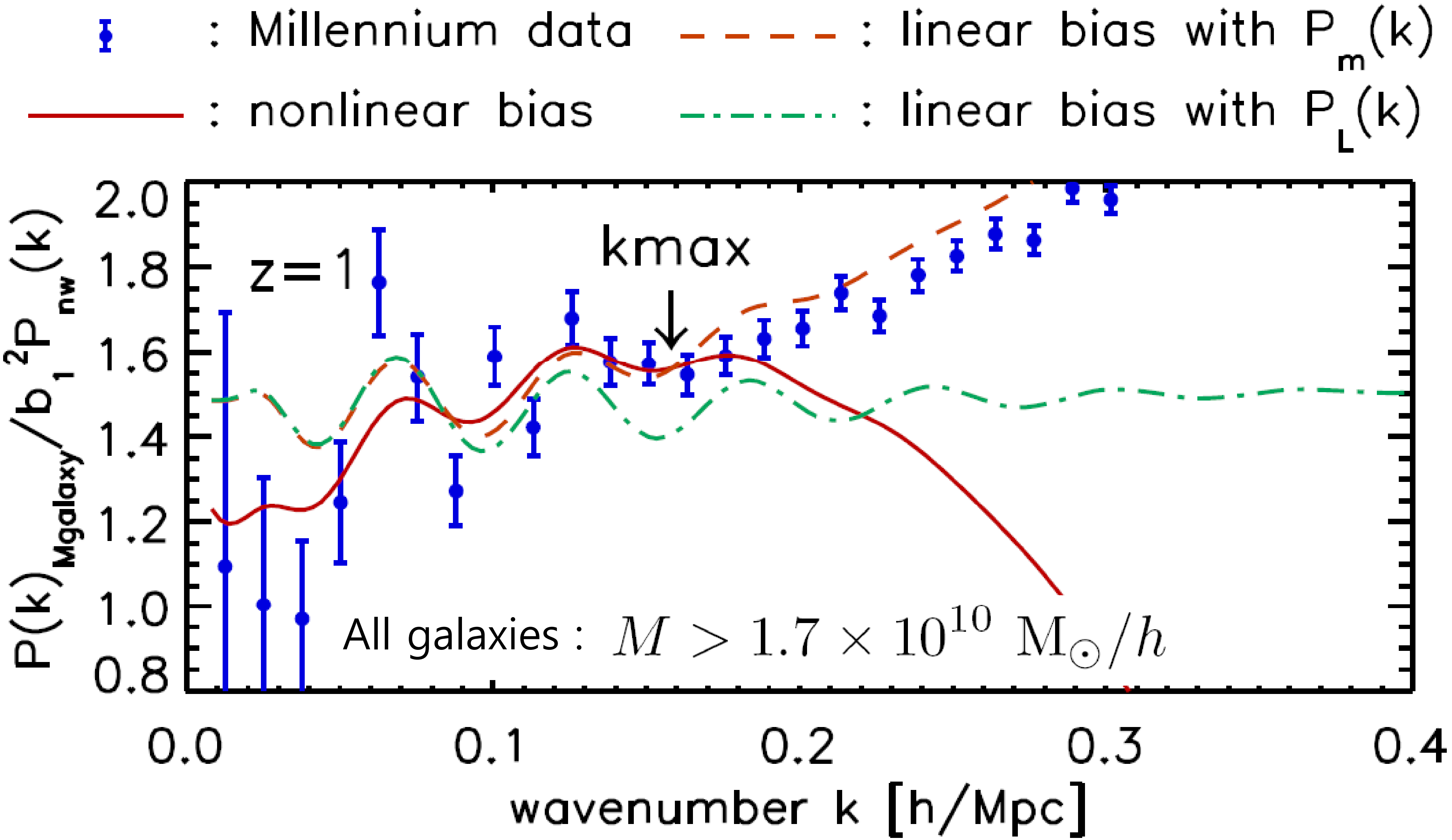
Jeong & Komatsu (2009a)

BAO : Non-linear bias (z=3)



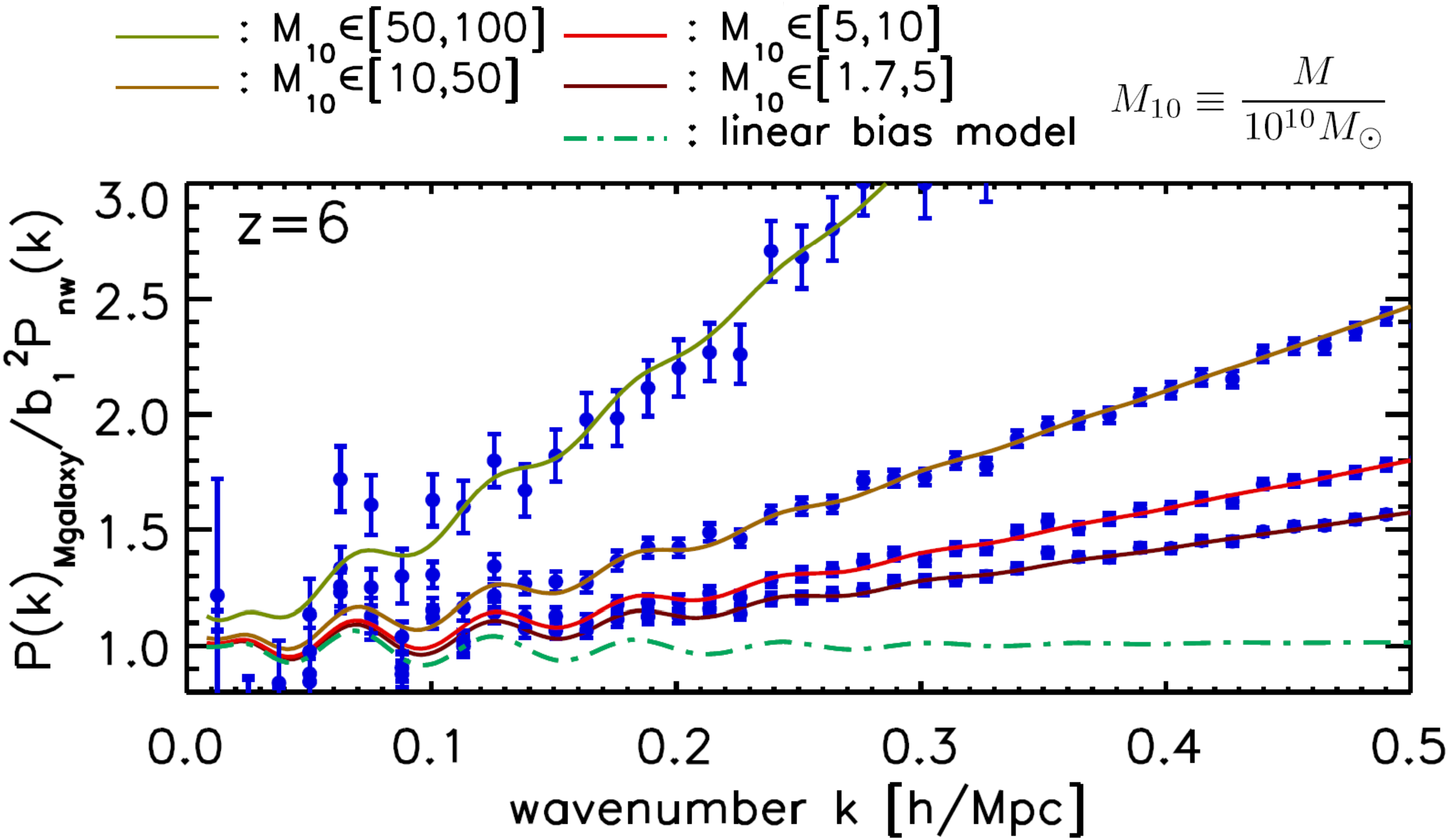
Jeong & Komatsu (2009a)

BAO : Non-linear bias (z=1)

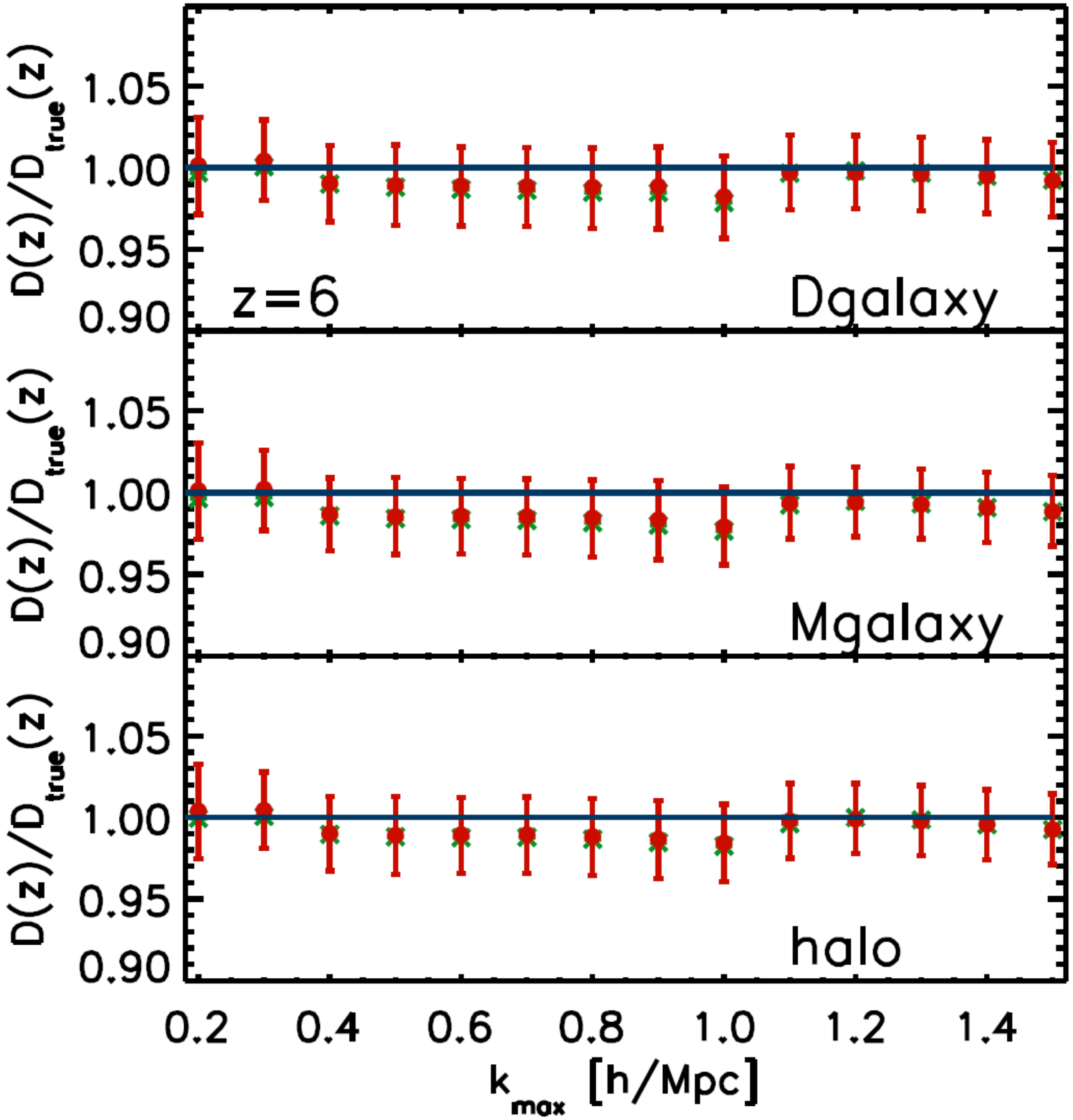


Jeong & Komatsu (2009a)

BAO from different halo mass



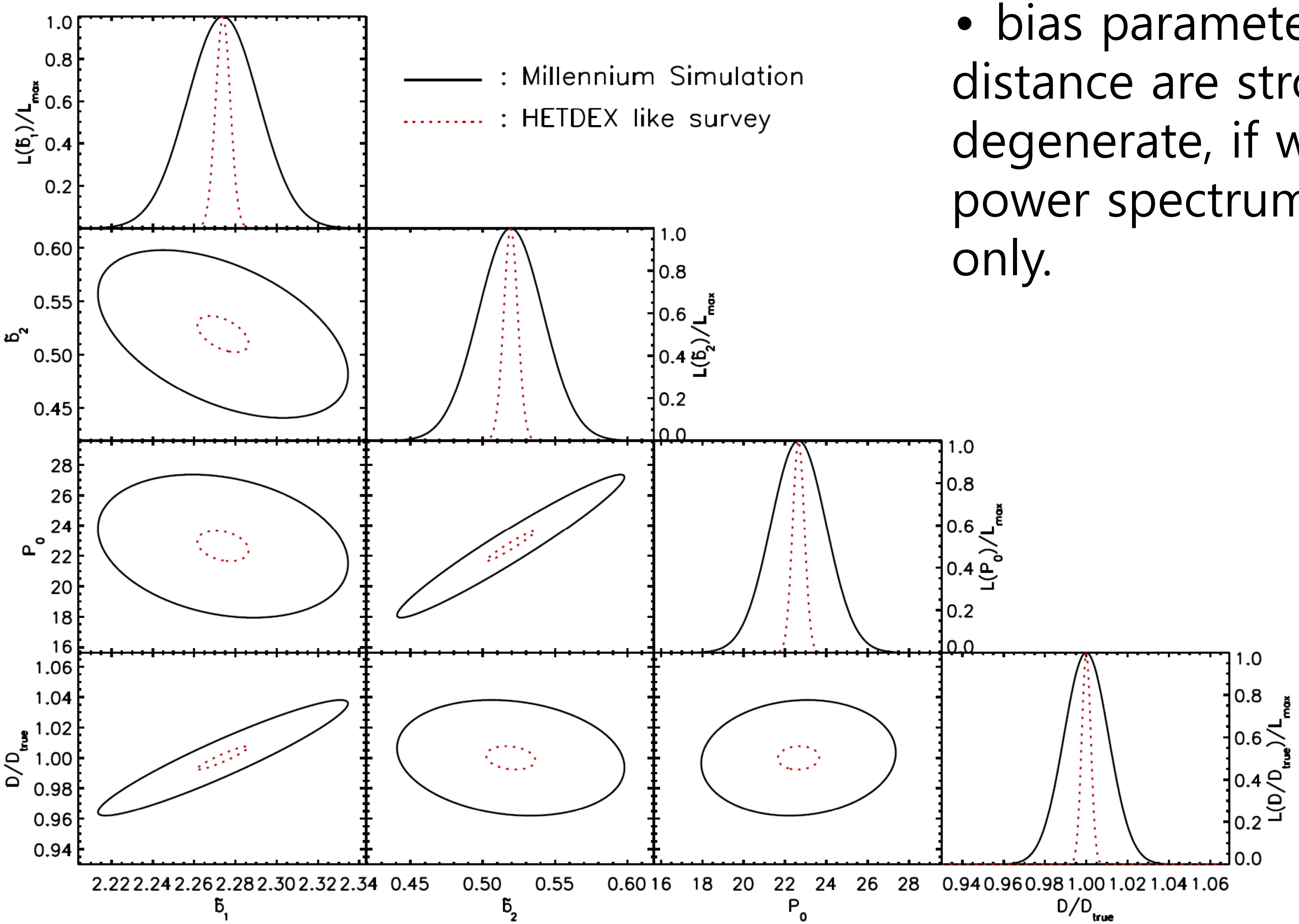
Distance from galaxy P(k) (z=6)



- With 3PT, we succeeded in measuring $D_A(z)$ from the "observed" power spectra in the Millennium Simulation at z>2.

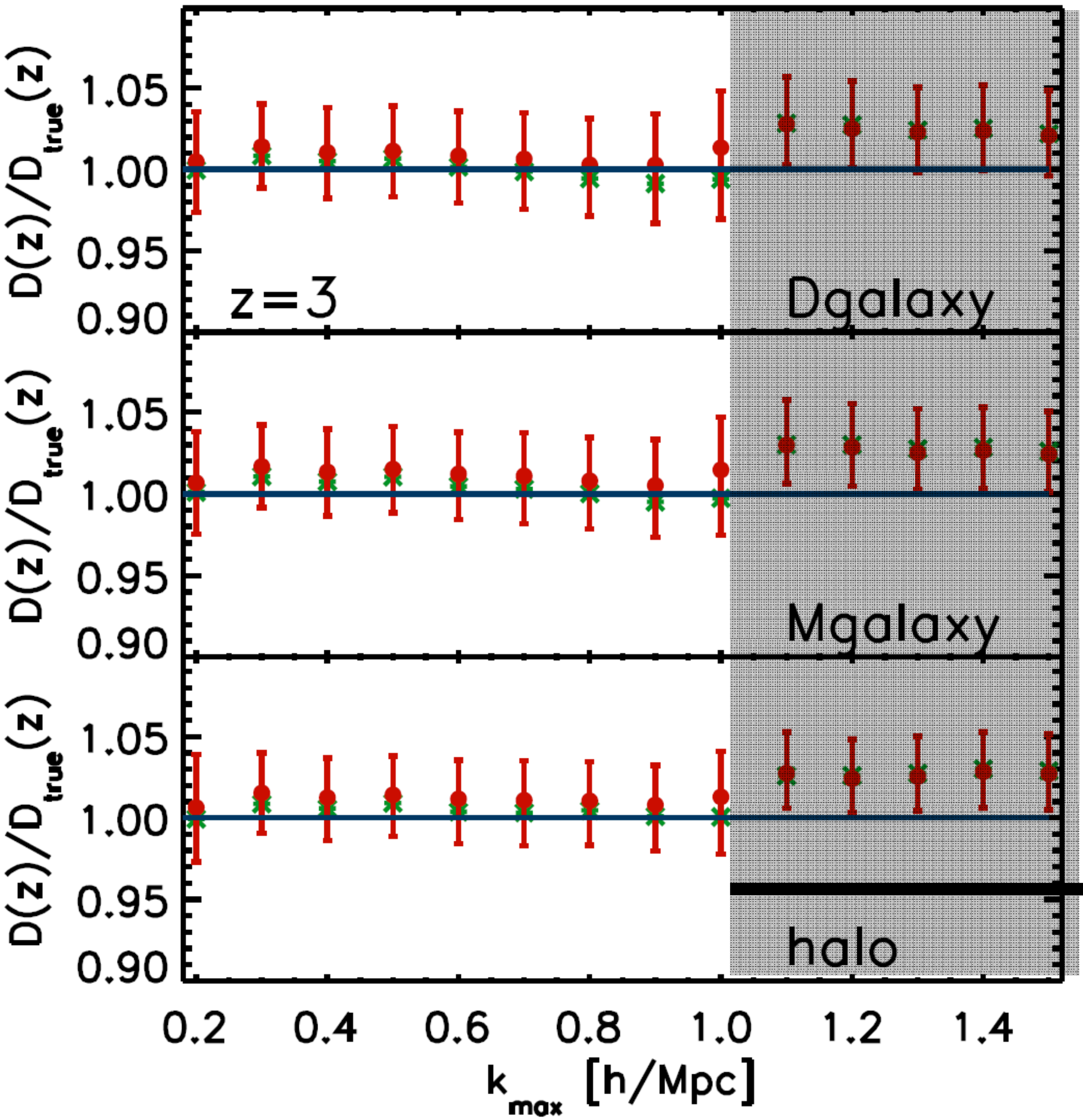
Jeong & Komatsu (2009a)

So Much Degeneracies



- bias parameters and the distance are strongly degenerate, if we use the power spectrum information only.

Distance from galaxy P(k) (z=3)

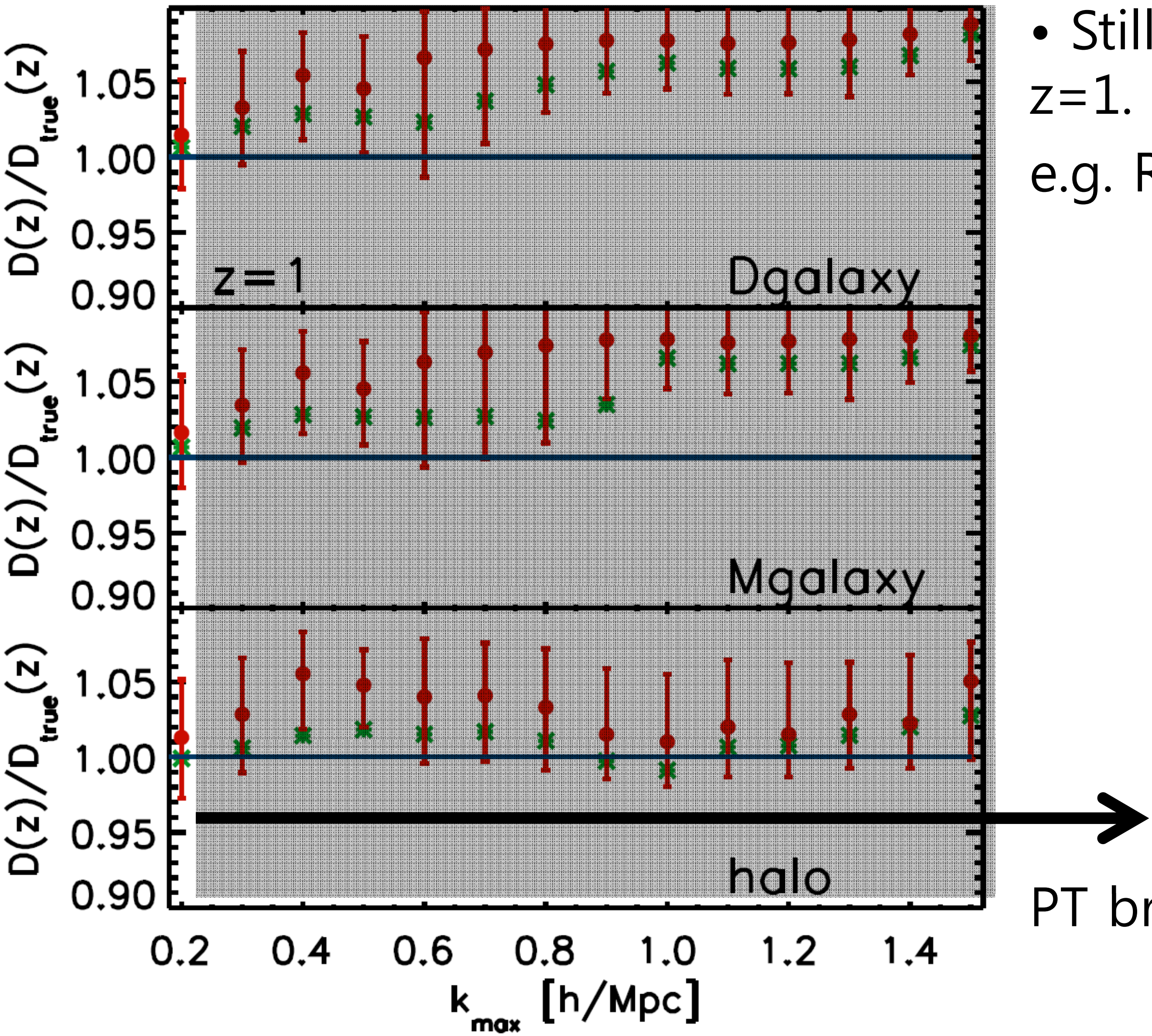


- With 3PT, we succeeded in measuring $D_A(z)$ from the "observed" power spectra in the Millennium Simulation at z>2, below k_{max}.
- Note that k_{max} (z=3)=1 [h/Mpc]

PT breaks down!

Jeong & Komatsu (2009a)

Distance from galaxy P(k) (z=1)



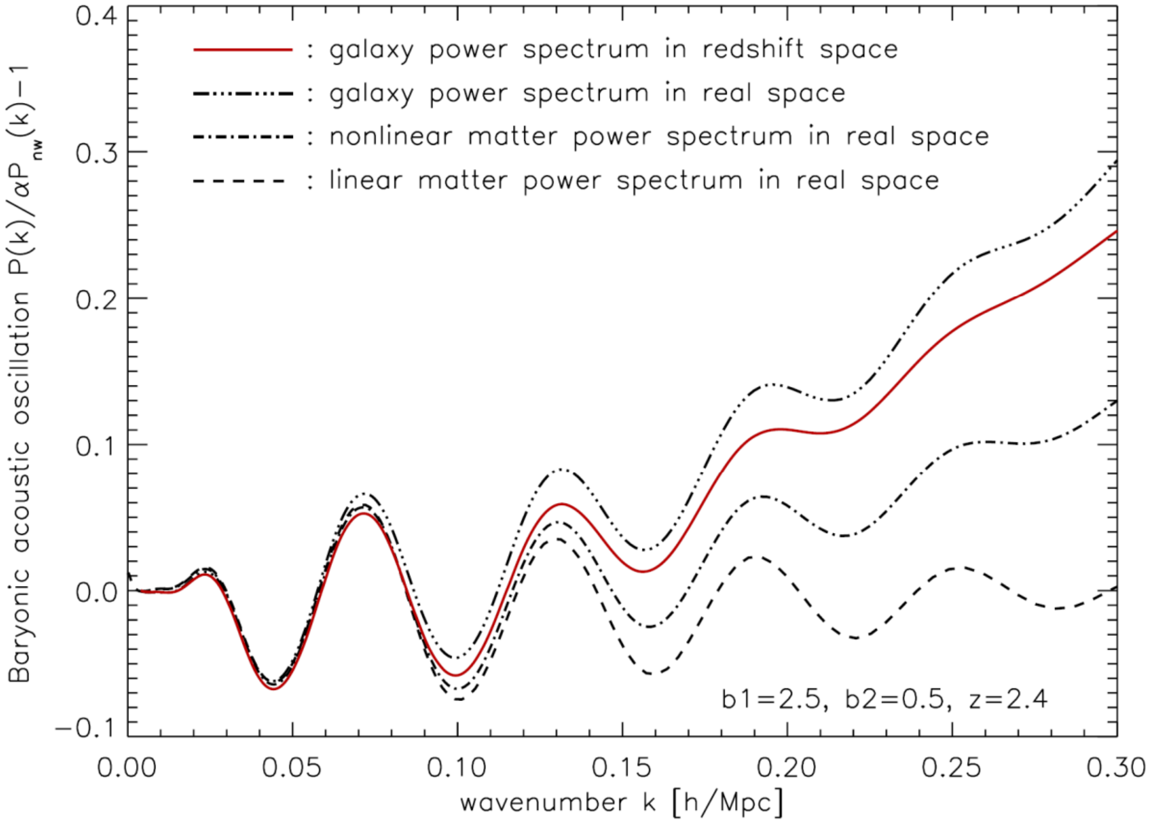
- Still seems challenging at z=1. Better PT is needed!

e.g. Renormalized PT

PT breaks down!

Summary so far

- We have modeled the non-linear galaxy power spectrum in redshift space one by one.
- 4 parameters : σ_v, b_1, b_2, P_0
- BAO is also distorted by non-linearities. But, we can model the distortion.
- **Redline (New)** includes all three effects! (Jeong, in prep.)



Cross check I:
Bias from Galaxy Bispectrum

- We can measure the non-linear bias parameters from the galaxy bispectrum.
- The galaxy bispectrum depends on b_1 and b_2 as

$$B_t(k_1, k_2, k_3) = \tilde{b}_1^3 \left[B_m(k_1, k_2, k_3) + \tilde{b}_2 \left\{ P(k_1)P(k_2) + (\text{cyclic}) \right\} \right]$$

where B_m is the matter bispectrum.

	V	n_g	z	k_{max}	b_1	b_2	Δb_1	Δb_2
SDSS	0.3	30		0.09	1.19	−0.10	0.270	0.151
LRG	0.72	1	0.35	0.11	2.14	0.96	0.209	0.348
APO-LSS	3.8	4	0.35	0.11	1.69	0.21	0.069	0.068
WFMOS1	1.6	5	0.7	0.14	1.87	0.45	0.076	0.096
	2.4	5	1.1	0.18	2.16	1.00	0.047	0.081
	combined						...	...
ADEPT	45	1	1.25	0.20	2.97	3.44	0.020	0.063
	55	1	1.75	0.26	3.44	5.43	0.017	0.066
	combined						...	...
WFMOS2	0.5	5	2.55	0.38	3.27	4.64	0.058	0.220
	0.5	5	3.05	0.48	3.64	6.39	0.056	0.253
	combined						...	...
HETDEX	0.68	5	2.25	0.34	3.05	3.70	0.051	0.172
	0.69	5	2.75	0.42	3.42	5.32	0.049	0.199
	0.67	5	3.25	0.53	3.79	7.16	0.050	0.237
	0.64	5	3.75	0.65	4.14	9.20	0.053	0.291
	combined				...	...	...	...
CIP	1.26	50	4	0.71	3.16	4.12	0.010	0.036
	1.13	50	5	1.03	3.72	6.76	0.010	0.047
	1.02	50	6	1.46	4.26	9.90	0.011	0.066
	combined				...	...	...	...

Cross check from data themselves!

Sefusatti & Komatsu(2007)

Cross check II: Bias from CMB lensing

- We can also measure the non-linear bias parameters from the galaxy-CMB lensing cross correlation.
- The galaxy-CMB lensing cross correlation depends on bias as

$$C_\ell^{\kappa-\Sigma} = \frac{3}{2} b \Omega_m H_0^2 \int d\eta \frac{W(\eta)}{a(\eta)} P\left(\frac{\ell}{d_A}, \eta\right) \frac{d_A(\eta_0 - \eta)}{d_A(\eta) d_A(\eta_0)}$$

where P is the matter power spectrum.

Galaxy Survey	$\hat{n}$	$A/10^3$	z_c	b	CMB Expt.	(S/N)	$\Delta b/b$ (%)
					PLANCK	5.8	17.3
SDSSLRG	12.4	3.8	0.31	2	PACT	11.4	8.8
					IDEAL	20.4	4.9
					PLANCK	10.8	9.3
BOSS1	40.	10	0.3	2	PACT	25.5	3.9
					IDEAL	52.5	1.9
					PLANCK	17.0	5.9
BOSS2	110.	10	0.6	2	PACT	39.4	2.5
					IDEAL	78.2	1.3
					PLANCK	52.8	1.9
ADEPT	3500	27	1.35	1	PACT	107.5	0.9
					IDEAL	228.3	0.4

Cross check from data themselves!

Acquaviva et al. (2008)

III. Non-Gaussianity

Galaxy bispectrum and primordial non-Gaussianity
Weak lensing and primordial non-Gaussianity

Primordial non-Gaussianity, revisited

- Well-studied parameterization is "local" non-Gaussianity :

$$\underbrace{\Phi(\boldsymbol{x})}_{\text{Primordial curvature perturbation}} = \underbrace{\phi(\boldsymbol{x})}_{\text{Gaussian random field}} + f_{NL}(\phi^2(\boldsymbol{x}) - \langle\phi^2\rangle)$$

- Current best measurement of f_{NL}
  - From CMB (Smith et al, 2009)

$$f_{\rm NL} = 38 \pm 21 \ (68\% \text{ C. L.})$$

  - From SDSS power spectra (Slosar et al, 2009)

$$f_{\rm NL} = 31^{+16}_{-27} \ (68\% \text{ C. L.})$$

- Therefore, initial condition is **Gaussian to ~0.04% level!** Thus, I am talking about a very tiny non-Gaussianity!

Single-field Theorem
(Consistency relation)

- For **ANY** single-field inflation models, where there is only one degree of freedom during inflation,
  Maldacena (2003);Seery&Lidsey(2005);Creminelli&Zaldarriaga(2004)

$$f_{\rm NL} \simeq \frac{5}{12}(1-n_s)$$

- With the current limit of n_s=0.96, **f_{NL} has to be ~0.017 for single field inflation.**

Implication of non-Gaussianity

- Therefore, any detection of f_{NL} would **rule out all the single field models** regardless of
  - The form of potential
  - The form of kinetic term (or sound speed)
  - The initlal vacuum state

- We can detect non-Gaussianity from
  - CMB bispectrum
  - High-mass cluster abundance
  - Scale dependent bias
    - Galaxy power spectrum
    - **Galaxy bispectrum** (Jeong & Komatsu, 2009b)
    - **Weak gravitational lensing** (Jeong, Komatsu, Jain, 2009)

From initial curvature to density

Dalal et al. (2008)

$$\Phi(\boldsymbol{x}) = \phi(\boldsymbol{x}) + f_{NL}(\phi^2(\boldsymbol{x}) - \langle\phi^2\rangle)$$

Taking Laplacian

$$\nabla^2\Phi = \nabla^2\phi + 2f_{NL}\left[\phi\nabla^2\phi + |\nabla\phi|^2\right]$$

grad(φ)=0 at the potential peak

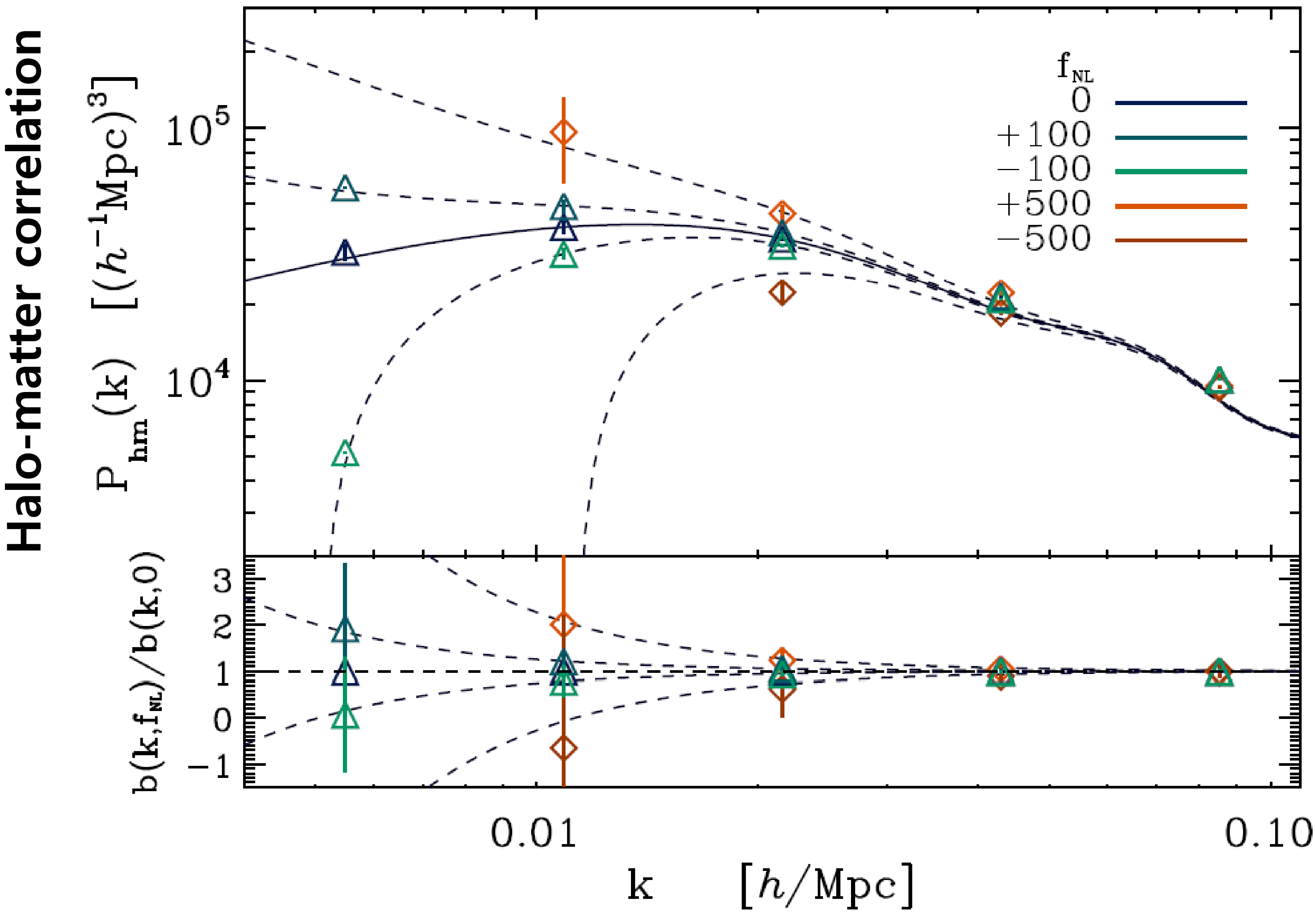
$$\nabla^2\Phi = \nabla^2\phi + 2f_{NL}\phi\nabla^2\phi$$

Poisson equation Laplacian(φ)∝δρ=δ<ρ>

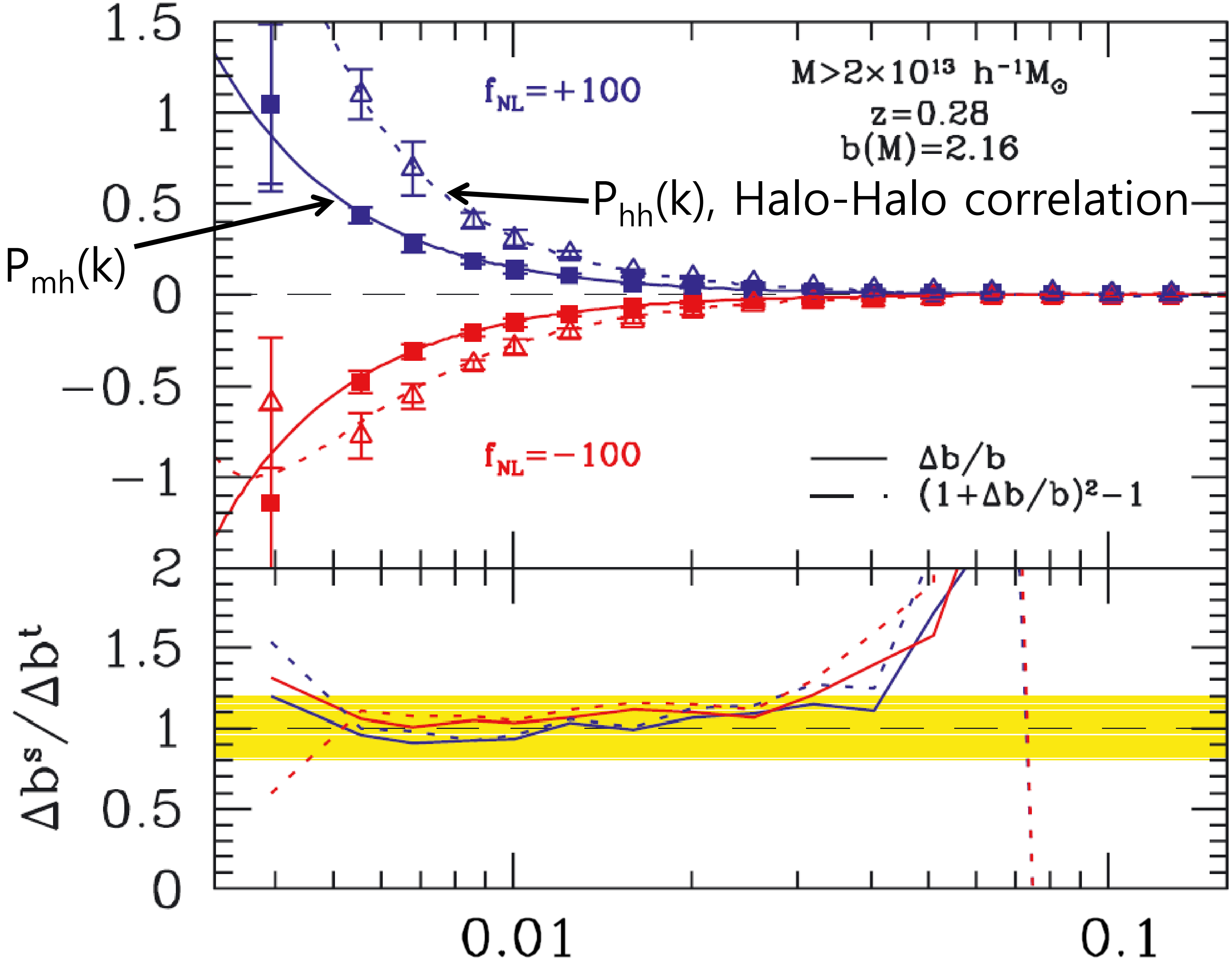
$$\boxed{\delta_{NG} \simeq \delta(1 + 2f_{NL}\phi_p)}$$

Dalal et al.(2008); Matarrese&Verde(2008); Carmelita et al.(2008); Afshordi&Tolly(2008); Slosar et al.(2008);

N-body result I (Dalal et al. 2008)



N-body result II (Desjacques et al. 2009)



Galaxy bias with nG

- The primordial non-Gaussianity changes the galaxy power spectrum by

$$P_g(k) = b_1^2 P_m(k) \rightarrow [b_1 + \Delta b(k)]^2 P_m(k)$$

where change of linear bias is given by

$$\Delta b(k) = \frac{3(b_1 - 1) f_{\rm NL} \Omega_m H_0^2 \delta_c}{D(z) \boxed{k^2 T(k)}}$$

~1/k²

Linear bias depends on the scale!!

$$\delta_{NG} \simeq \delta(1 + 2 f_{NL} \phi_p \qquad P_\phi(k) \propto \frac{1}{k^{4-n_s}}$$

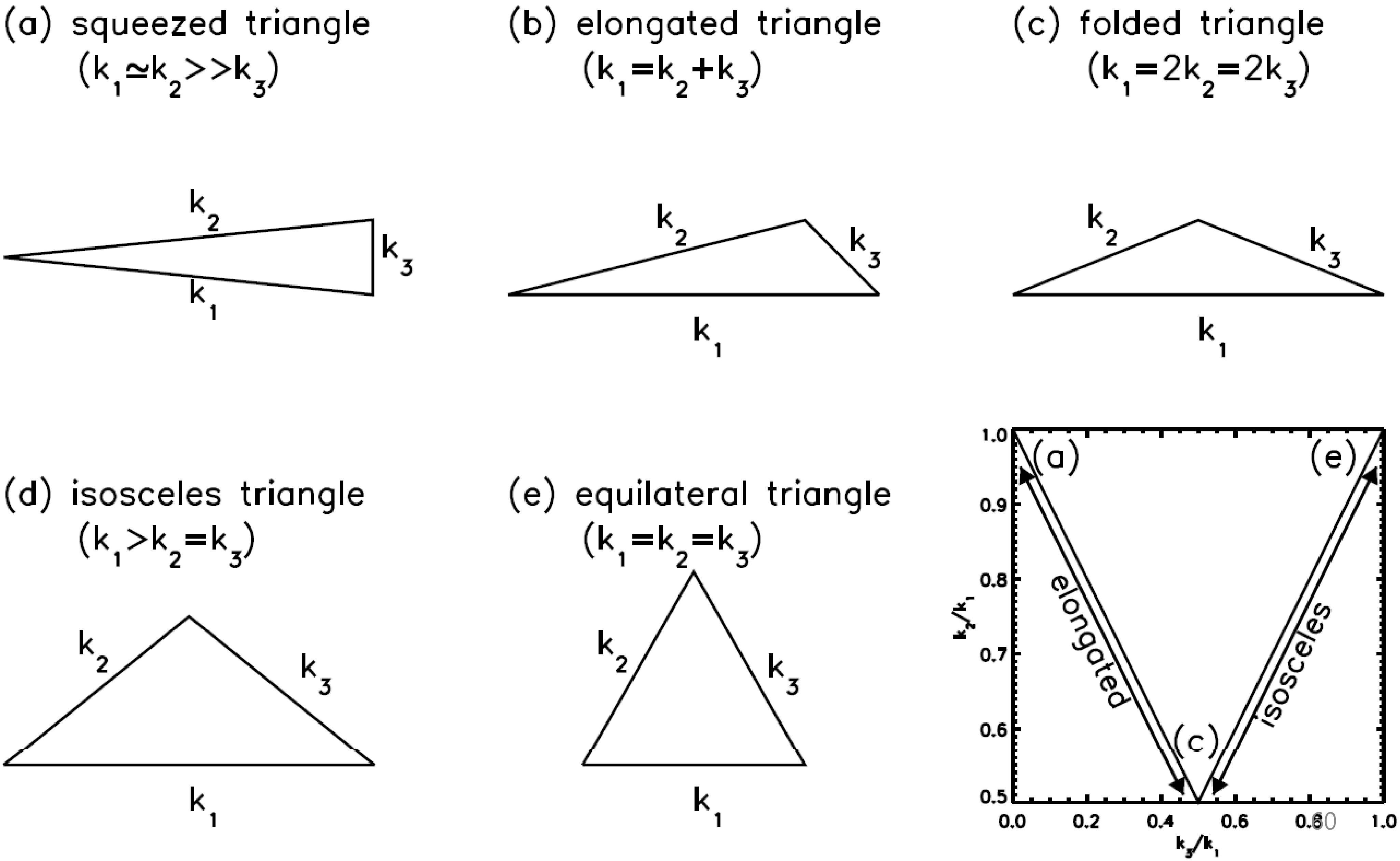
What about galaxy bispectrum?

- For the galaxy, there were previously **three known sources** for galaxy bispectrum (Sefusatti & Komatsu 2007, SK07)
  - I. matter bispectrum due to primordial non-Gaussianity
  - II. Non-linear gravitational coupling
  - III. Non-linear galaxy bias

$$
\begin{aligned}
B_g(k_1, k_2, k_3, z) &= \mathrm{I}\; 3b_1^3 f_{\rm NL} \Omega_m H_0^2 \left[\frac{P_m(k_1, z)}{k_1^2 T(k_1)} \frac{P_m(k_2, z)}{k_2^2 T(k_2)} \frac{k_3^2 T(k_3)}{D(z)} + (2 \text{ cyclic}) \right] \\
&\mathrm{II} \\
&+ 2b_1^3 \left[F_2^{(s)}(\boldsymbol{k}_1, \boldsymbol{k}_2) P_m(k_1, z) P_m(k_2, z) + (2 \text{ cyclic}) \right] \\
&\mathrm{III} \\
&+ b_1^2 b_2 \left[P_m(k_1, z) P_m(k_2, z) + (2 \text{ cyclic}) \right]
\end{aligned}
$$

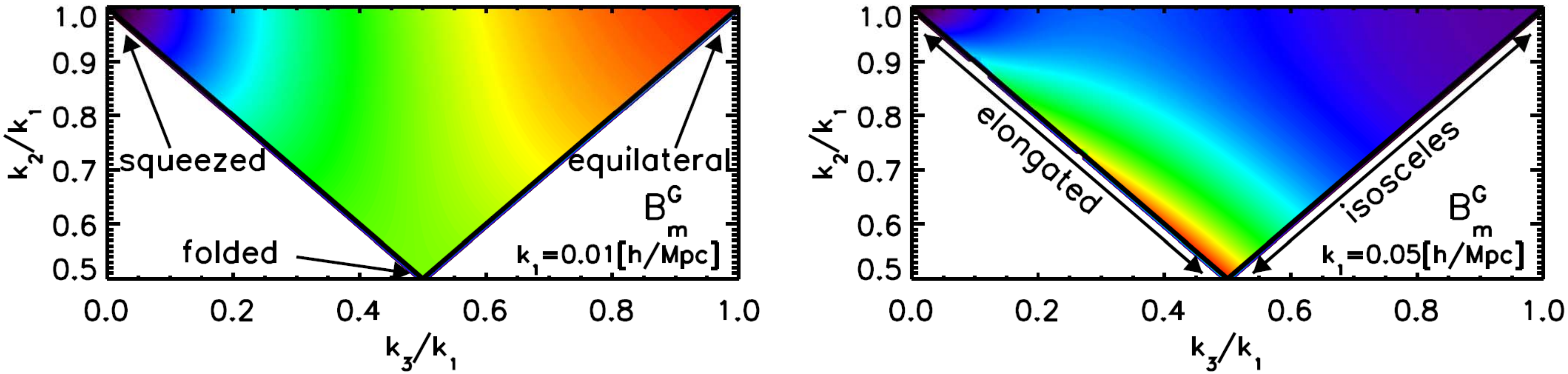
Jeong & Komatsu (2009b)

Triangular configurations

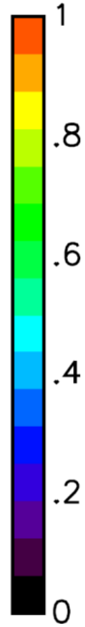


Jeong & Komatsu (2009b)

Known term 1. non-linear gravity



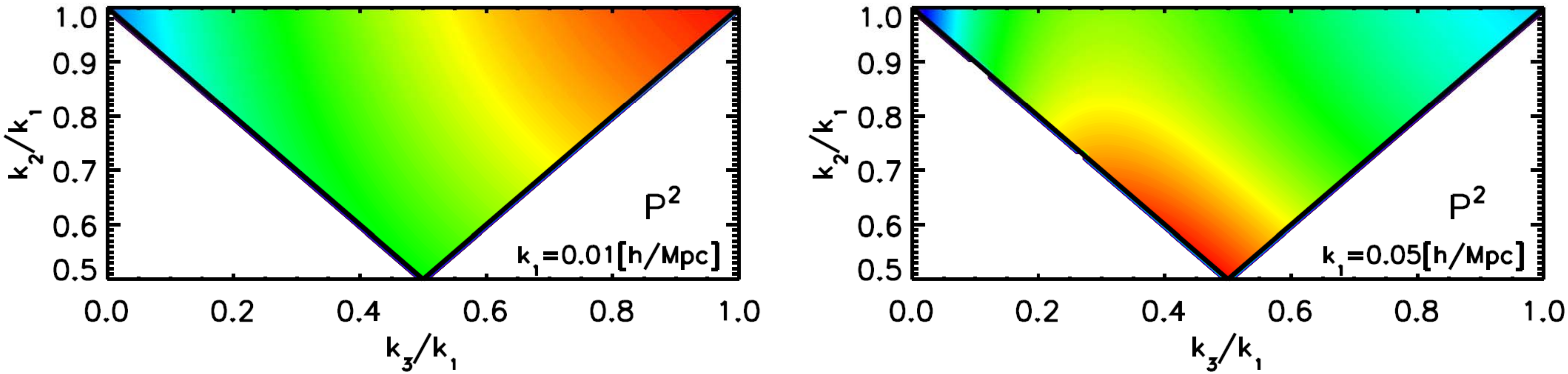
$$2b_1^3\left[F_2^{(s)}(\boldsymbol{k}_1,\boldsymbol{k}_2)P_m(k_1,z)P_m(k_2,z)+(2\ \mathrm{cyclic})\right]$$



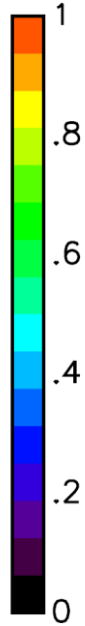
- Non-linear gravity term peaks at **equilateral** (k<0.02 [Mpc/h]), and **folded** triangle (k>0.02 [Mpc/h]) due to the shape of power spectrum and F_2 kernel.

$$F_2^{(s)}(\boldsymbol{k}_1,\boldsymbol{k}_2)=\frac{5}{7}+\frac{\boldsymbol{k}_1\cdot\boldsymbol{k}_2}{2k_1k_2}\left(\frac{k_1}{k_2}+\frac{k_2}{k_1}\right)+\frac{2}{7}\left(\frac{\boldsymbol{k}_1\cdot\boldsymbol{k}_2}{k_1k_2}\right)^2$$

Known term 2. non-linear bias



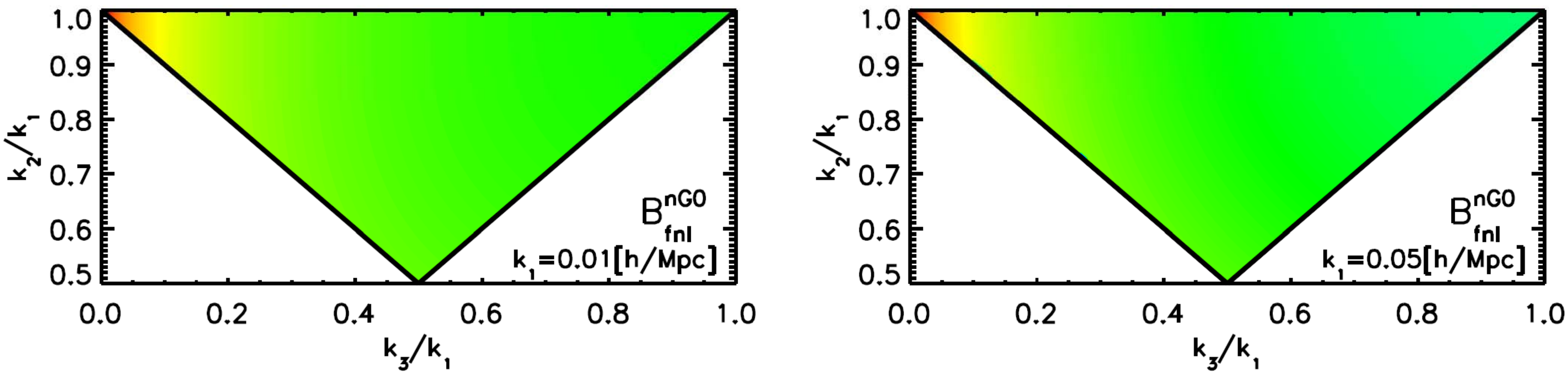
$$b_1^2 b_2 \left[P_m(k_1, z) P_m(k_2, z) + (2 \text{ cyclic}) \right]$$



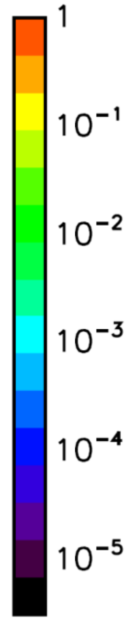
- Non-linear bias term peaks at **equilateral** (k<0.02 [h/Mpc] and **folded** (k>0.02 [h/Mpc]) triangles.
- No F_2 kernel. Less suppression at the squeezed, less enhancement along the elongated triangles.

Jeong & Komatsu (2009b)

Known term 3. non-Gaussianity



$$3b_1^3 f_{\rm NL}\Omega_m H_0^2\left[\frac{P_m(k_1,z)}{k_1^2T(k_1)}\frac{P_m(k_2,z)}{k_2^2T(k_2)}\frac{k_3^2T(k_3)}{D(z)}+(2\ \mathrm{cyclic})\right]$$



- Notice the factor of k^2 in the denominator.
- Sharply peaks at the **squeezed** configuration!

New terms (Jeong & Komatsu, 2009b)

- It turns out that Sefusatti & Komatsu (2007) misses the dominant terms which comes from the statistics of "peaks".
- Jeong & Komatsu (2009b)
  "Primordial non-Gaussianity, scale dependent bias, and the bispectrum of galaxies"
  We present **all** dominant non-Gaussian bispectrum terms on large scales and on squeezed configurations!!

Jeong & Komatsu (2009b)

Bispectrum of galaxies

$$\begin{aligned} & B_h(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3) \\ = \; & b_1^3 \Bigg[B_R(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3) + \frac{b_2}{b_1} \left\{ P_R(k_1) P_R(k_2) + (2 \text{ cyclic}) \right\} \\ & \boxed{+ \frac{\delta_c}{2\sigma_R^2} \int \frac{d^3q}{(2\pi)^3} T_R(\boldsymbol{q}, \boldsymbol{k}_1 - \boldsymbol{q}, \boldsymbol{k}_2, \boldsymbol{k}_3) + (2 \text{ cyclic})} \Bigg]. \end{aligned}$$

- In addition to SK07, galaxy bispectrum also **depends on trispectrum (four point function) of underlying mass distribution!!**

Jeong & Komatsu (2009b)

Matter trispectrum I. T_Φ

- For local type non-Gaussianity,

$$\Phi(\boldsymbol{x}) = \phi(\boldsymbol{x}) + f_{\rm NL}\left[\phi^2(\boldsymbol{x}) - \langle\phi^2\rangle\right] + g_{\rm NL}\phi^3(\boldsymbol{x})$$

- Primordial trispectrum is given by

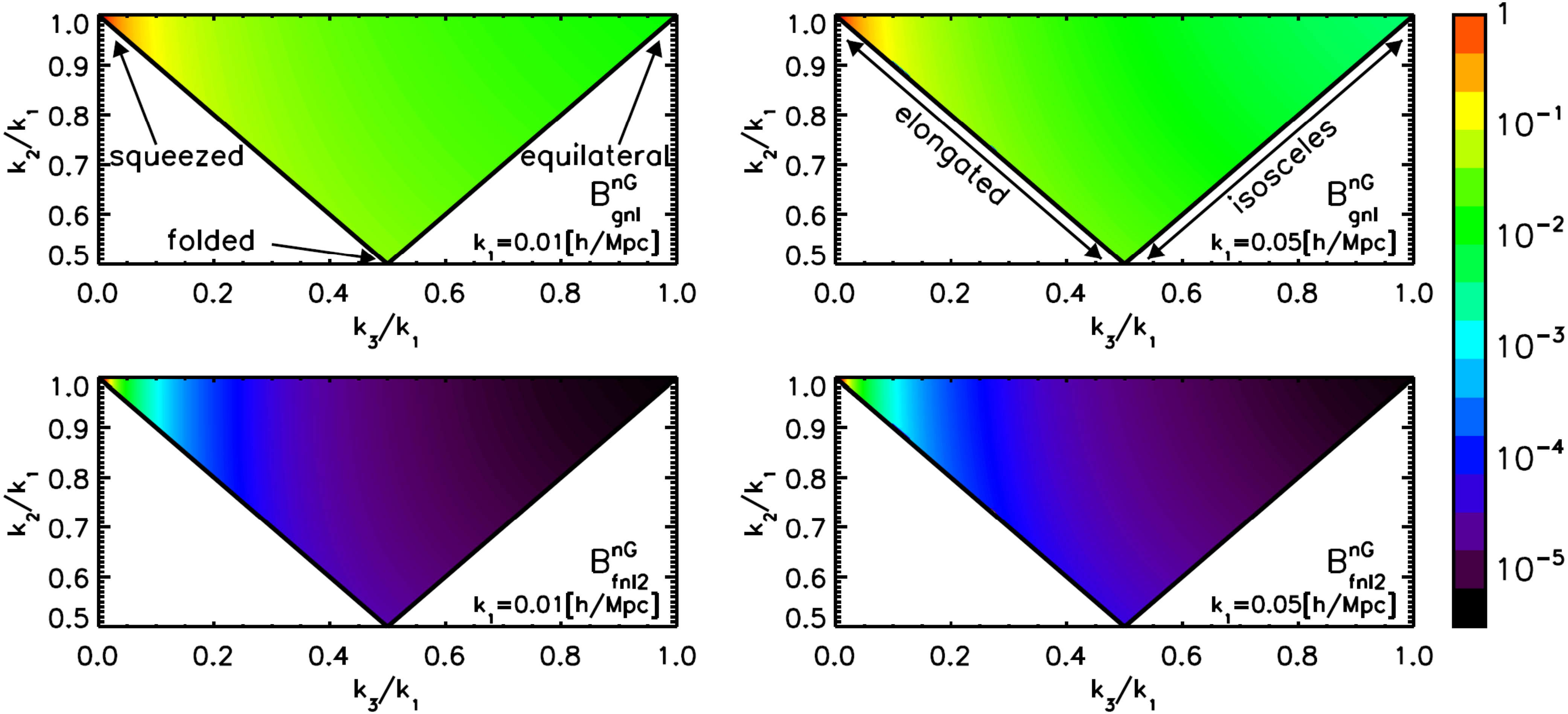
$$\begin{aligned} & T_\Phi(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3, \boldsymbol{k}_4) \\ = \; & 6g_{\rm NL}\left[P_\phi(k_1)P_\phi(k_2)P_\phi(k_3) + (3 \text{ cyclic})\right] + 2f_{\rm NL}^2 \\ & \times \left[P_\phi(k_1)P_\phi(k_2)\left\{P_\phi(k_{13}) + P_\phi(k_{14})\right\} + (11 \text{ cyclic})\right] \end{aligned}$$

- For more general multi-field inflation, trispectrum is

$$\begin{aligned} & T_\Phi(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3, \boldsymbol{k}_4) \\ = \; & 6g_{\rm NL}\left[P_\phi(k_1)P_\phi(k_2)P_\phi(k_3) + (3 \text{ cyclic})\right] + \frac{25}{18}\tau_{\rm NL} \\ & \times \left[P_\phi(k_1)P_\phi(k_2)\left\{P_\phi(k_{13}) + P_\phi(k_{14})\right\} + (11 \text{ cyclic})\right] \end{aligned}$$

Jeong & Komatsu (2009b)

Shape of T_Φ terms



- Both of T_Φ terms peak at **squeezed** configurations.
- f_{NL}^2 term peaks more sharply than g_{NL} term!!

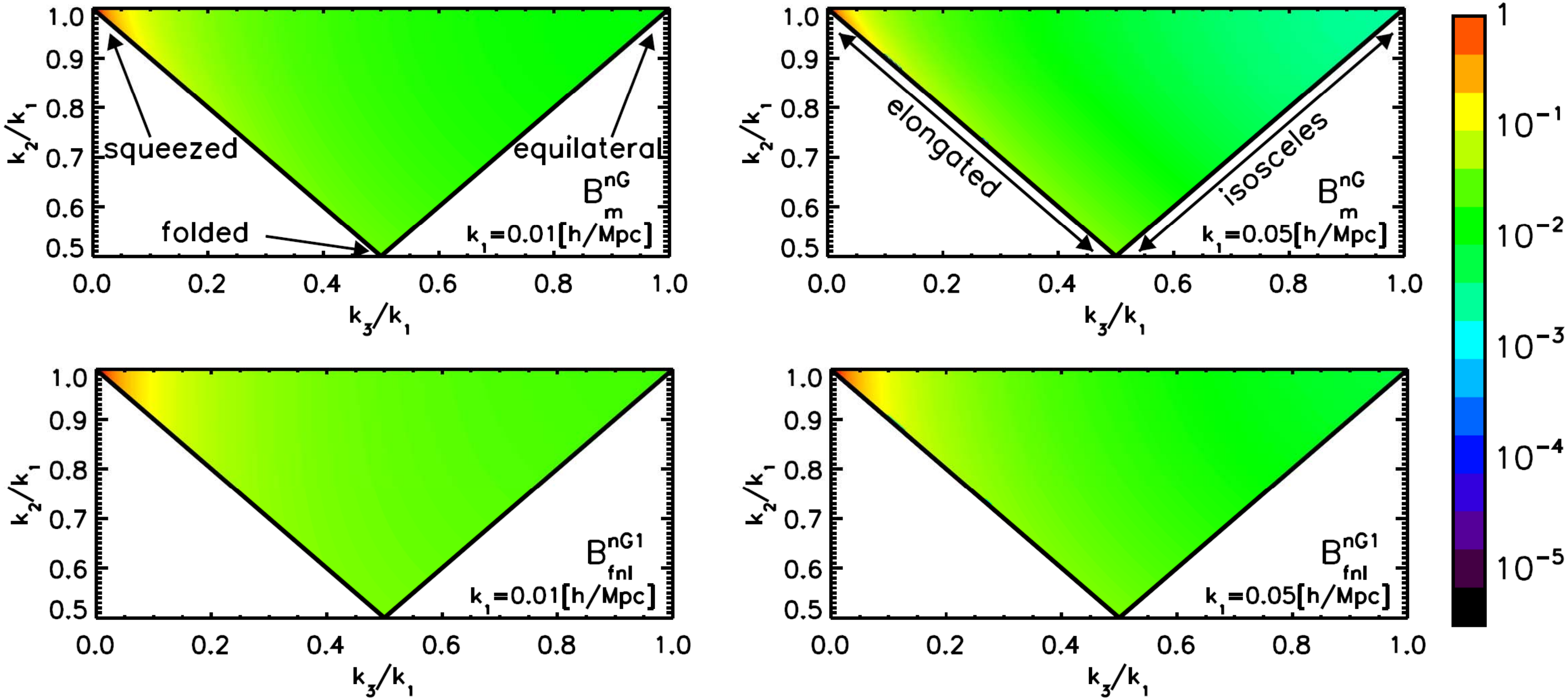
Matter trispectrum II. T^{1112}

- Trispectrum generated by non-linearly evolved primordial non-Gaussianity.

$$
\begin{aligned}
&\langle \delta^{(1)}(\boldsymbol{k}_1)\delta^{(1)}(\boldsymbol{k}_2)\delta^{(1)}(\boldsymbol{k}_3)\delta^{(2)}(\boldsymbol{k}_4)\rangle \\
&= \int \frac{d^3q}{(2\pi)^3} F_2^{(s)}(\boldsymbol{q},\boldsymbol{k}_4-\boldsymbol{q})\langle \delta^{(1)}(\boldsymbol{k}_1)\delta^{(1)}(\boldsymbol{k}_2)\delta^{(1)}(\boldsymbol{k}_3)\delta^{(1)}(\boldsymbol{k}_4-\boldsymbol{q})\delta^{(1)}(\boldsymbol{q})\rangle \\
&= (2\pi)^3\Big[2f_{\rm NL}P_m(k_1)\mathcal{M}(k_3)\int d^3q\mathcal{M}(q)\mathcal{M}(|\boldsymbol{k}_4-\boldsymbol{q}|)P_\phi(q)\left\{P_\phi(|\boldsymbol{k}_4-\boldsymbol{q}|)+2P_\phi(k_3)\right\} \\
&\quad\times F_2^{(s)}(\boldsymbol{q},\boldsymbol{k}_4-\boldsymbol{q})\delta^D(\boldsymbol{k}_{12}) + 4f_{\rm NL}\mathcal{M}(k_2)\mathcal{M}(k_3)\mathcal{M}(k_{14})P_m(k_1)F_2^{(s)}(-\boldsymbol{k}_1,\boldsymbol{k}_{14}) \\
&\quad\times\left\{P_\phi(k_2)P_\phi(k_3)+P_\phi(k_2)P_\phi(k_{14})+P_\phi(k_3)P_\phi(k_{14})\right\} + (\text{cyclic }123)\Big]\delta^D(\boldsymbol{k}_{1234}).
\end{aligned}
$$

Jeong & Komatsu (2009b)

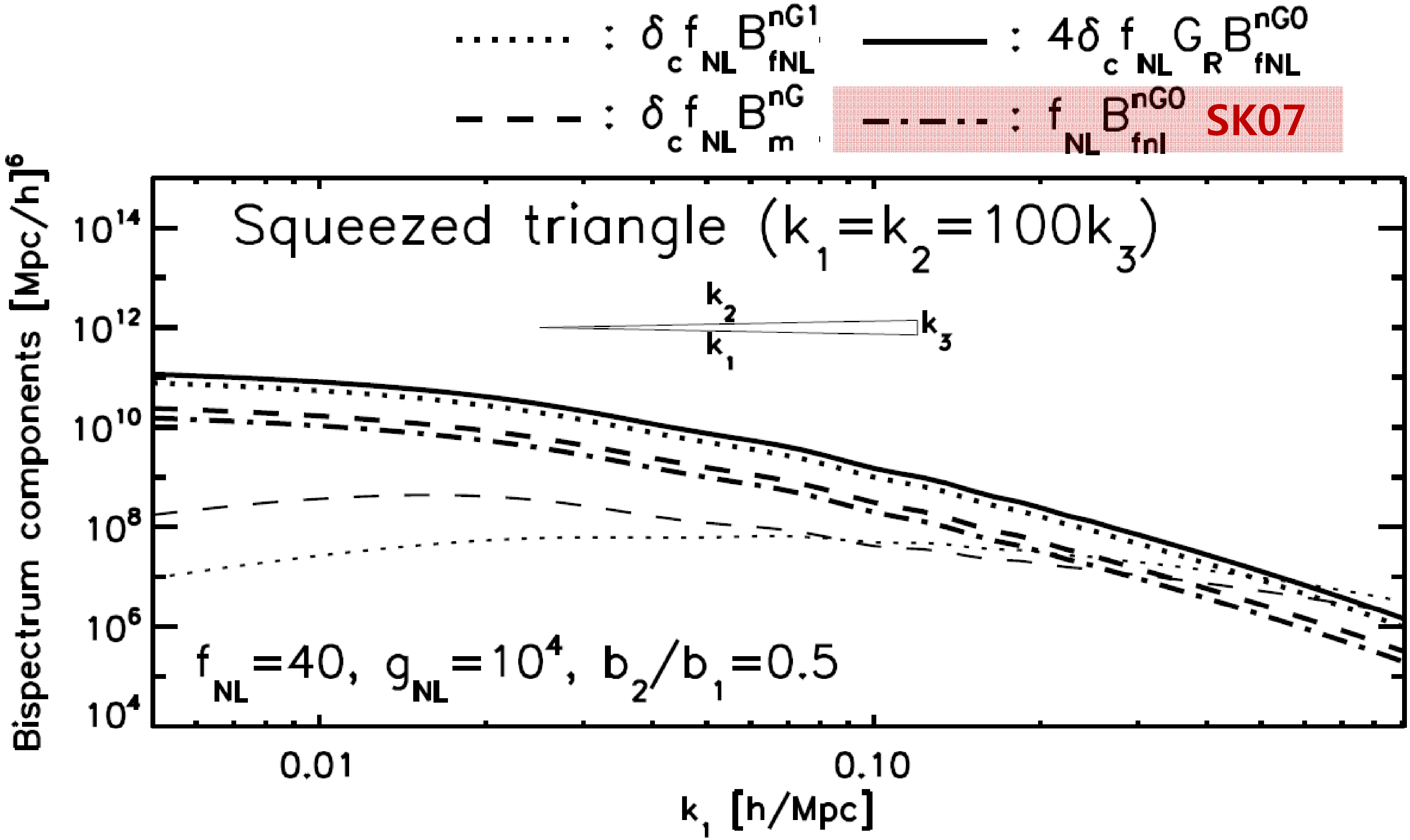
Shape of T^{1112} terms



- T^{1112} terms also peak at **squeezed** configurations.
- T^{1112} terms peak almost as sharp as g_{NL} term.

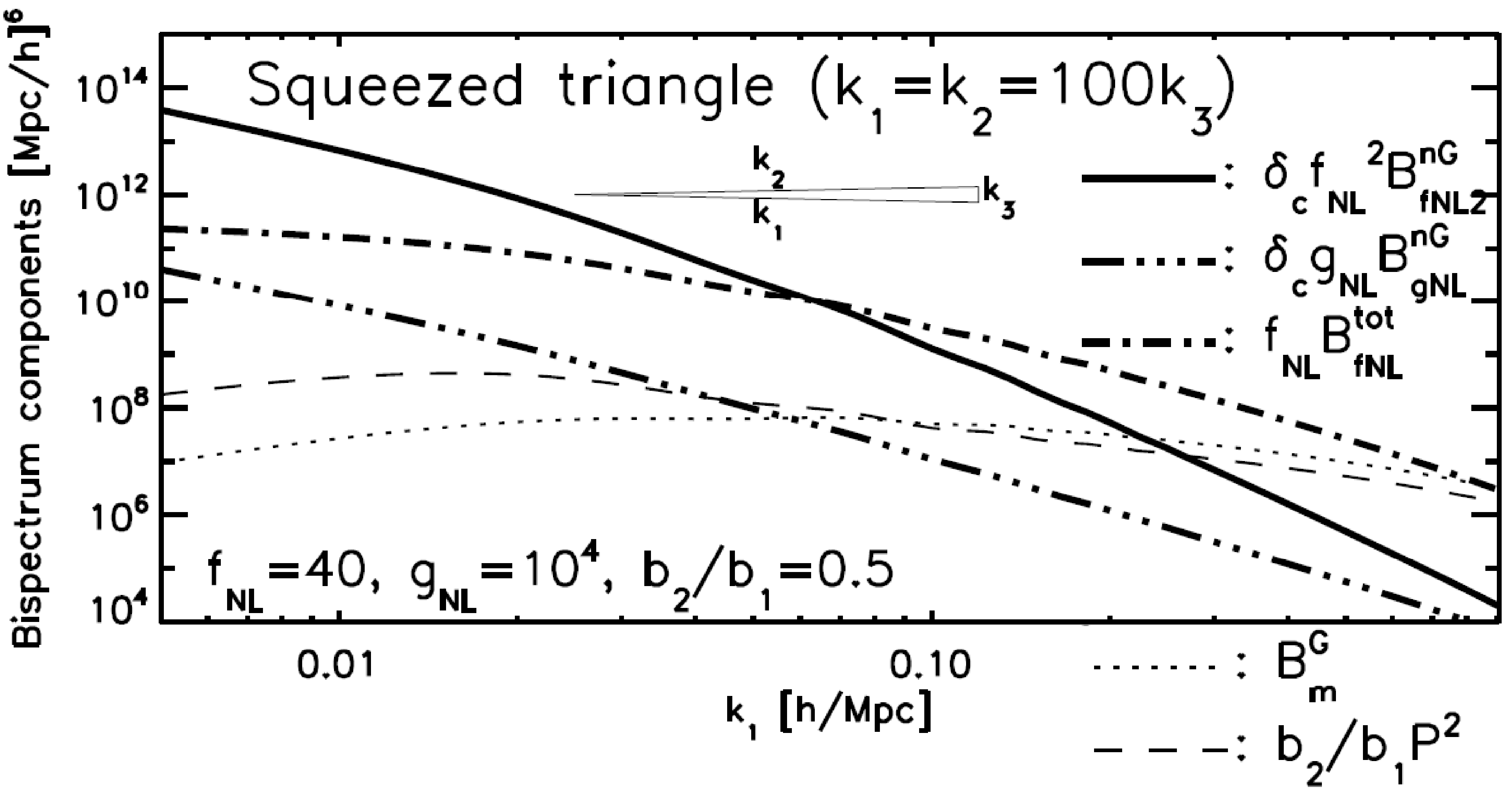
Jeong & Komatsu (2009b)

f_{NL} terms : SK07 vs. JK09



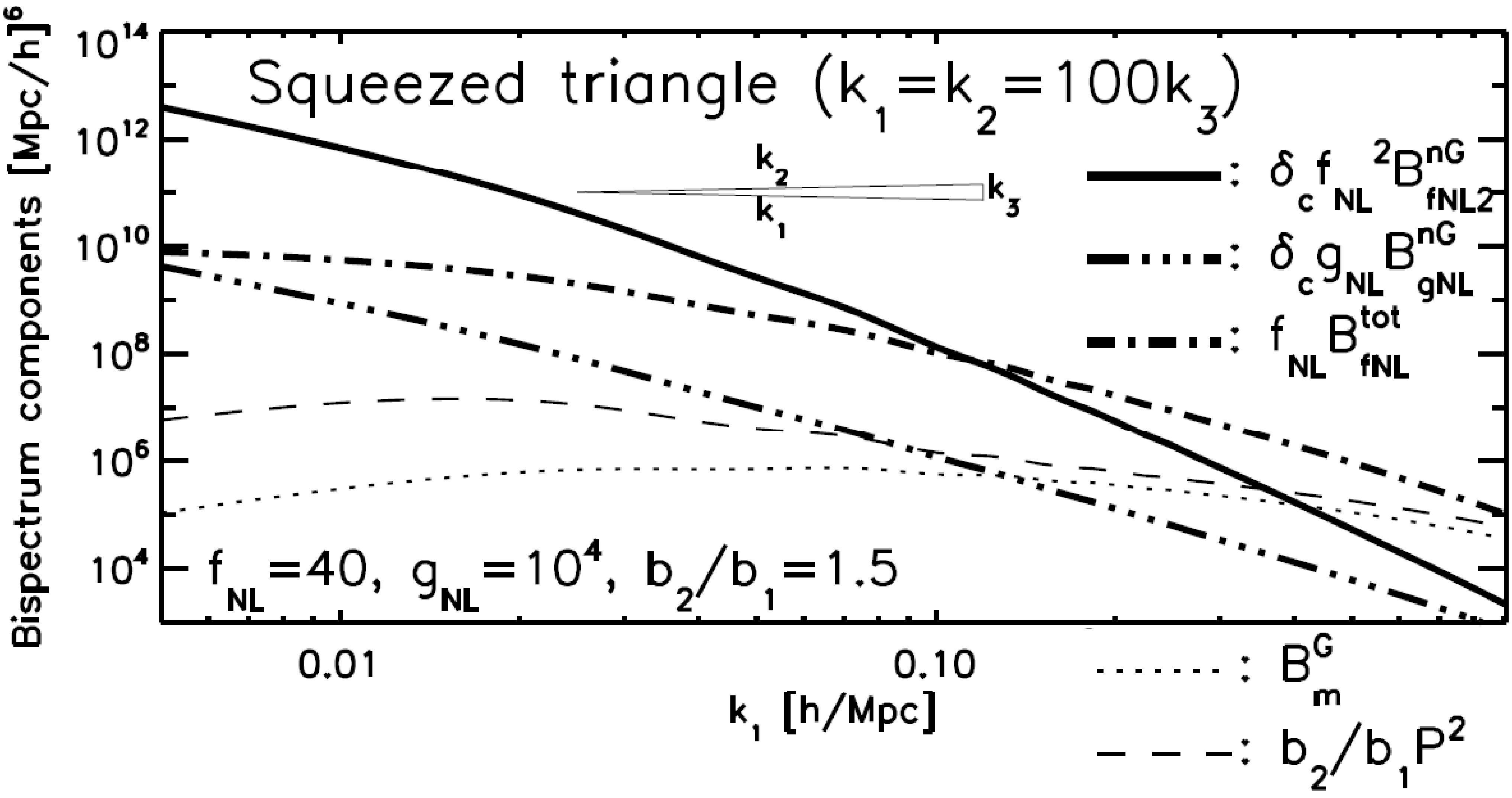
Jeong & Komatsu (2009b)

Are new terms important? (z=0)



Jeong & Komatsu (2009b)

more important at high-z!! (z=3)



Jeong & Komatsu, in preparation

Prediction for galaxy surveys

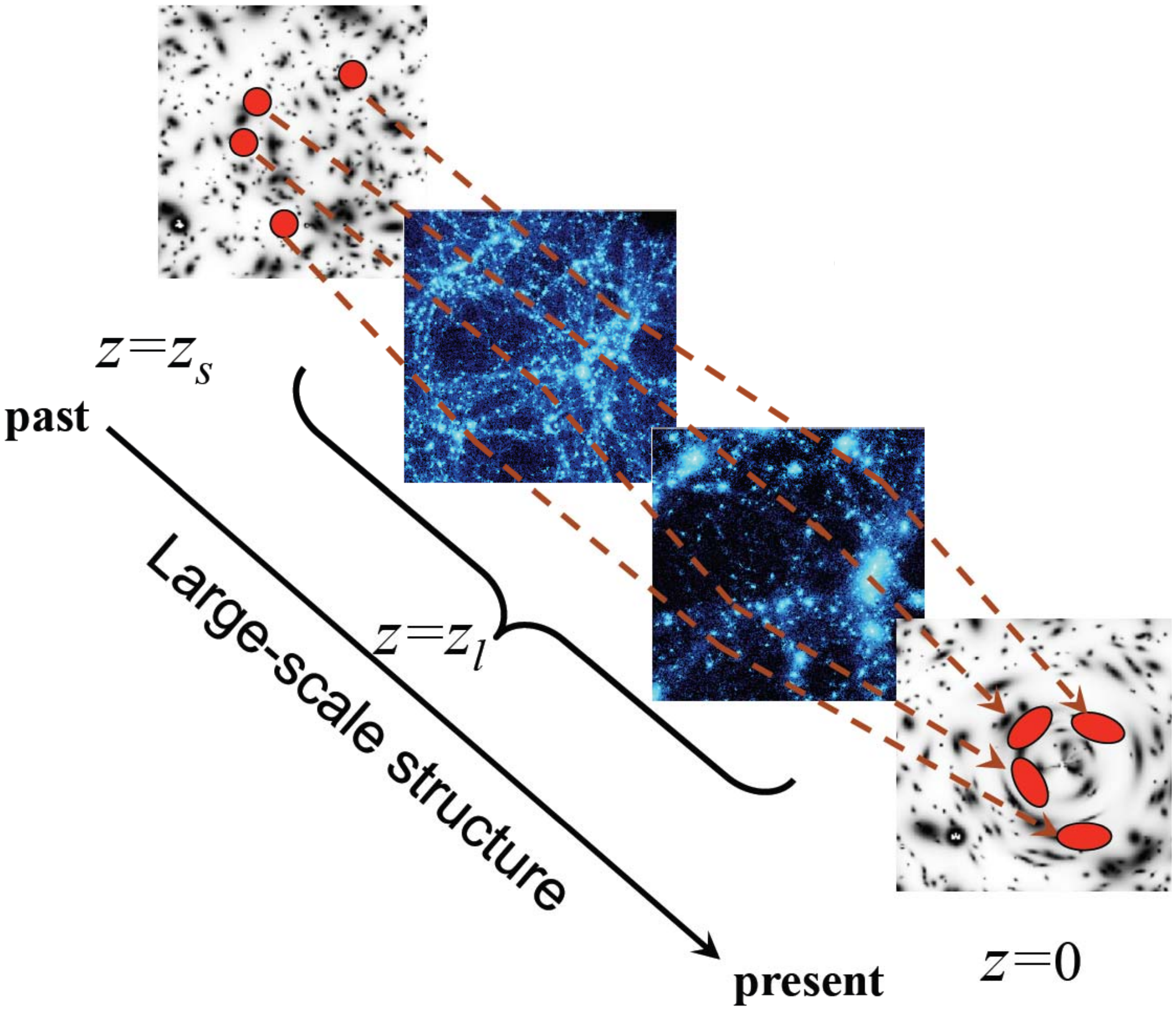
- Predicted 1-sigma marginalized error of non-linearity parameter (f_{NL}) ***from the galaxy bispectrum alone***

	z	V [Gpc/h]^3	n_g 10^{-5}[h/Mpc]^3	b1	Δf_{NL} (SK07)	Δf_{NL} (JK09)
SDSS-LRG	0.315	1.48	136	2.17	60.38	**5.43**
BOSS	0.35	5.66	26.6	1.97	31.96	**3.13**
HETDEX	2.7	2.96	27	4.10	20.39	**2.35**
CIP	2.25	6.54	500	2.44	8.96	**0.99**
ADEPT	1.5	107.3	93.7	2.48	5.65	**0.92**
EUCLID	1.0	102.9	156	1.93	5.56	**0.77**

New!!

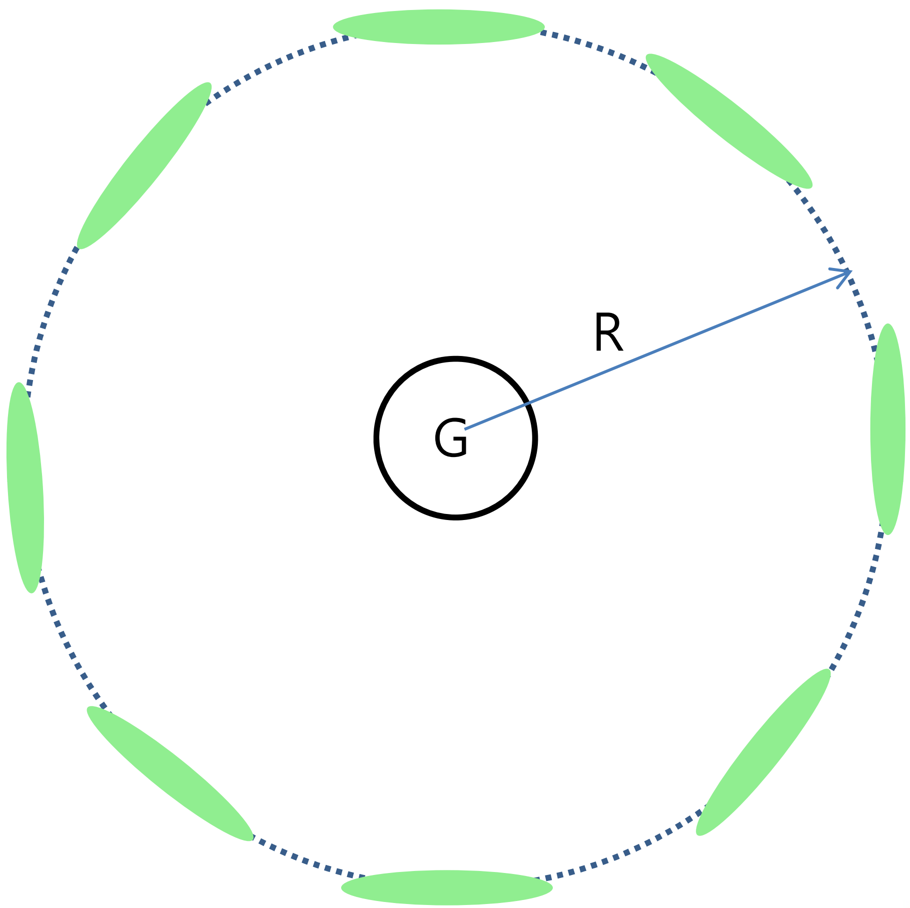
Jeong, Komatsu, Jain (2009), arXiv:0910.1361

f_{NL} from Weak gravitational lensing



Picture from M. Takada (IPMU)

Mean tangential shear



- Mean tangential shear is given by

$$\langle \overline{\gamma}_t^h \rangle (R, z_L) = \frac{\rho_0}{\Sigma_c(z_L)} \int \frac{k dk}{2\pi} P_{hm}(k, z_L) J_2(kR)$$

It is often written as

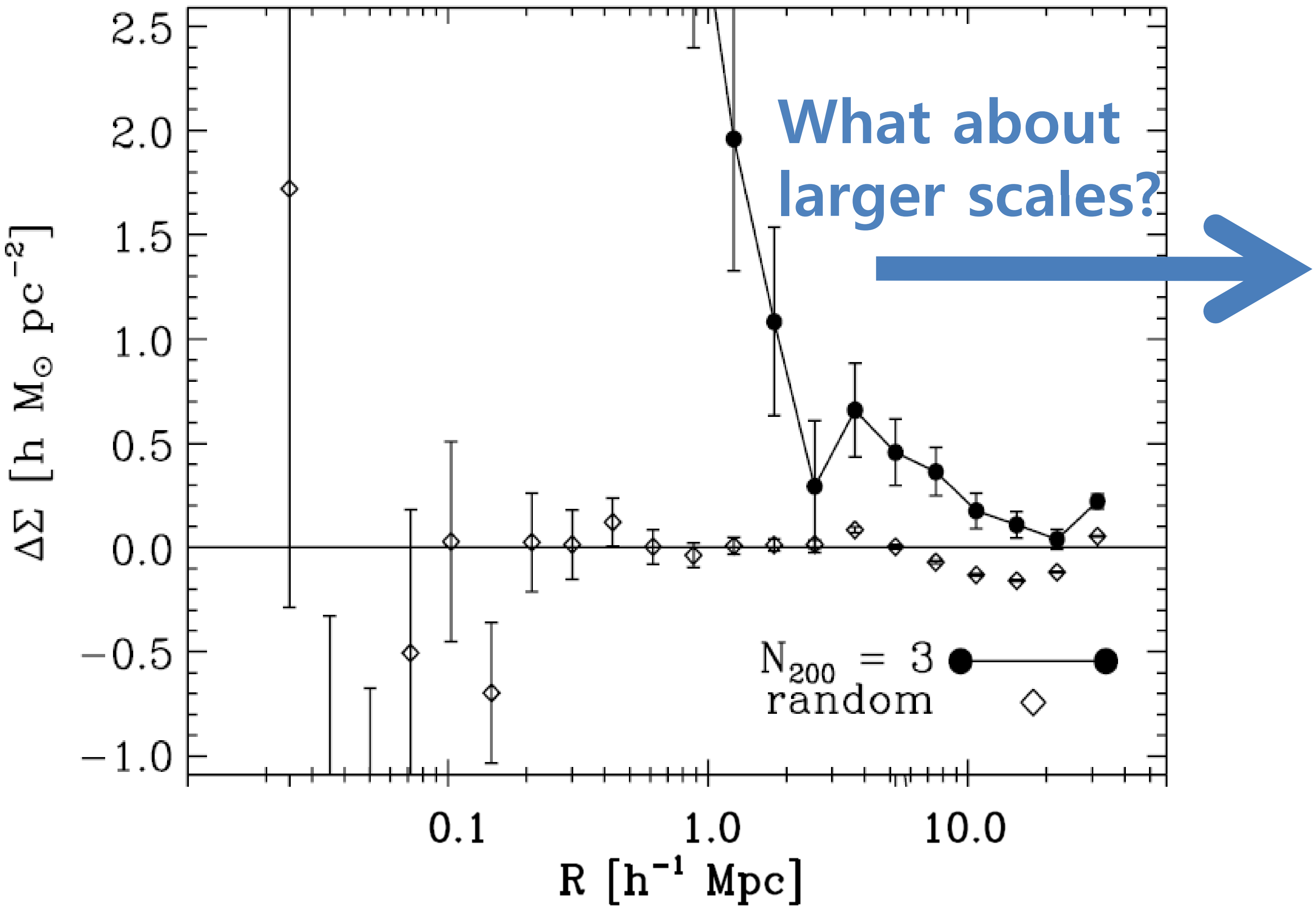
$$\langle \overline{\gamma}_t^h \rangle (R, z_L) = \frac{\Delta\Sigma(R, z_L)}{\Sigma_c(z_L)}$$

where, Σ_c is the "critical surface density"

$$\Sigma_c^{-1}(z_L) = \frac{4\pi G}{c^2}(1+z_L) d_A(0; z_L) \int_{z_L}^{\infty} dz_S \, p(z_S) \frac{d_A(z_L; z_S)}{d_A(0; z_S)}$$

Mean tangential shear, status

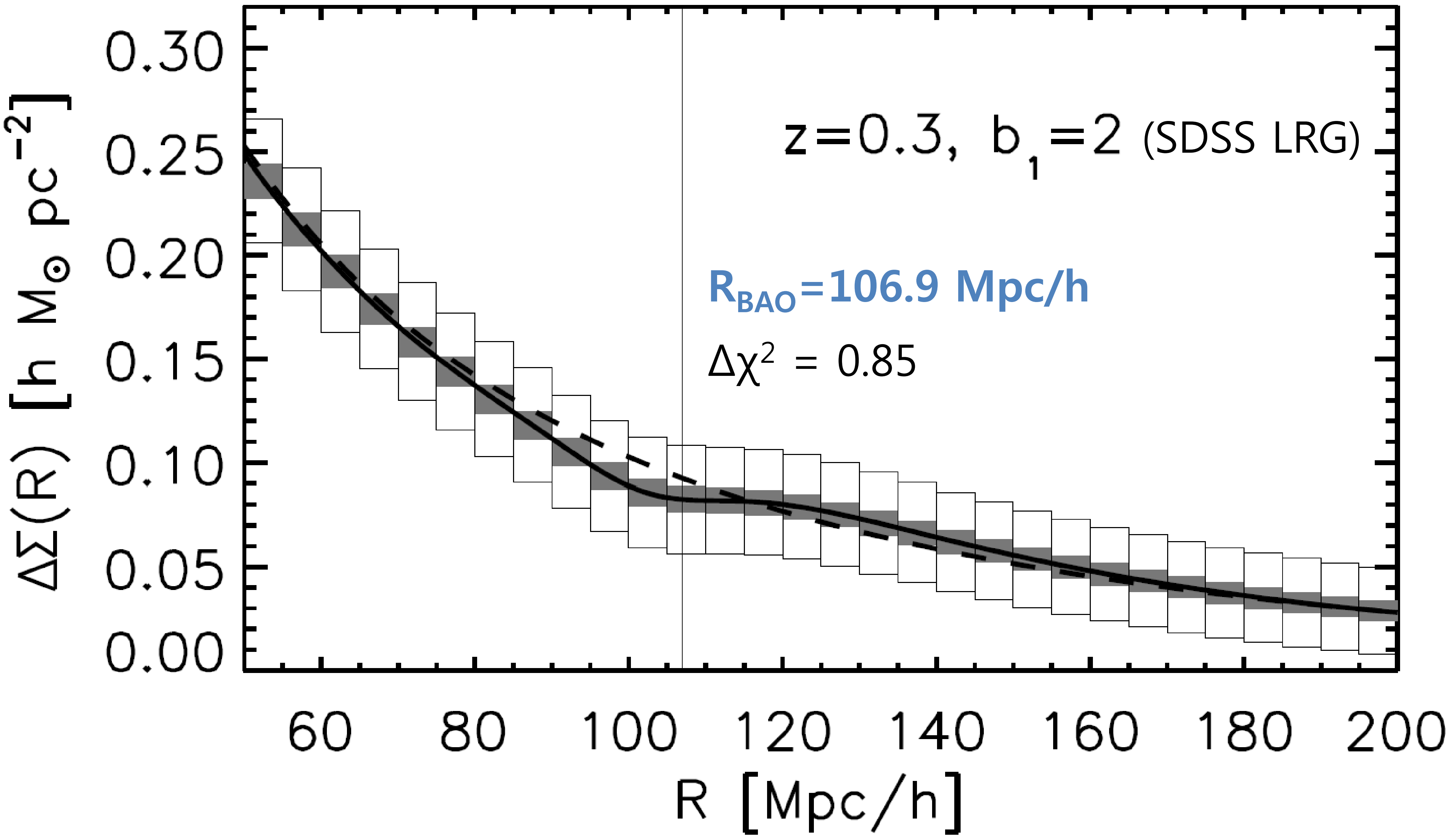
Mean tangential shear from SDSS Sheldon et al. (2009)



Jeong, Komatsu, Jain (2009), arXiv:0910.1361

BAO in mean tangential shear

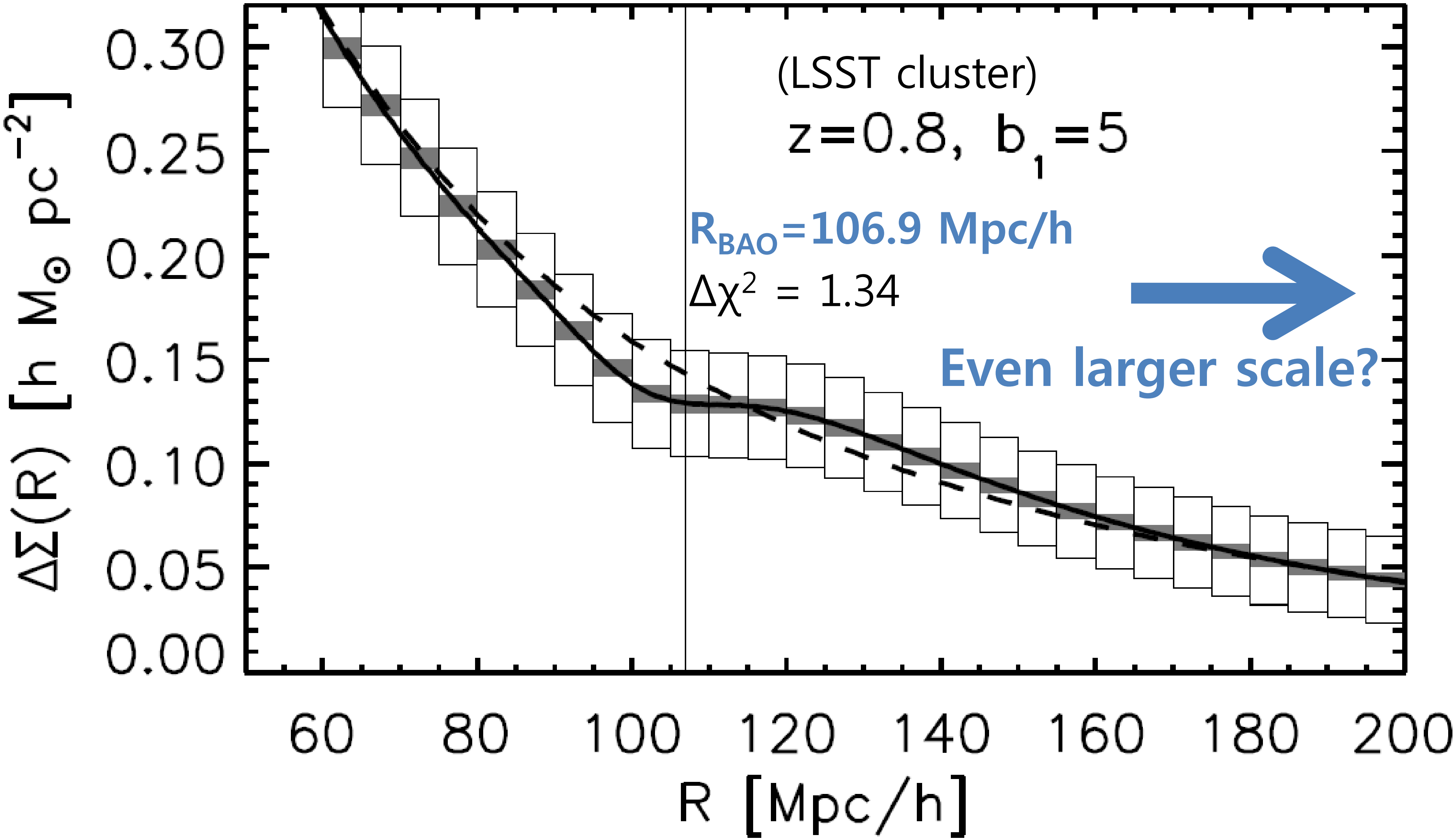
Errors are dominated by cosmic variance.



Jeong, Komatsu, Jain (2009), arXiv:0910.1361

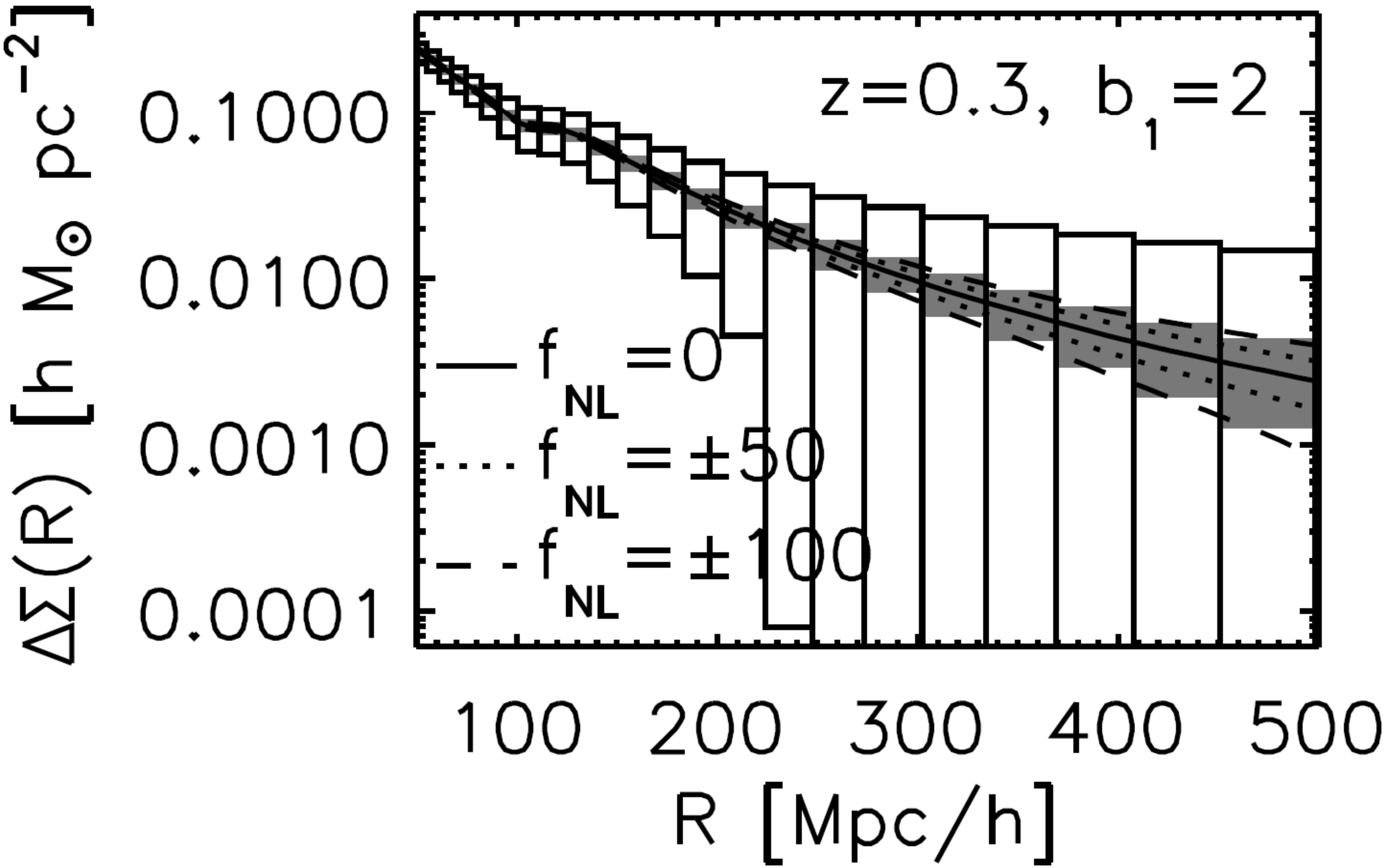
BAO in mean tangential shear

Result from the thin (delta function) lens plane



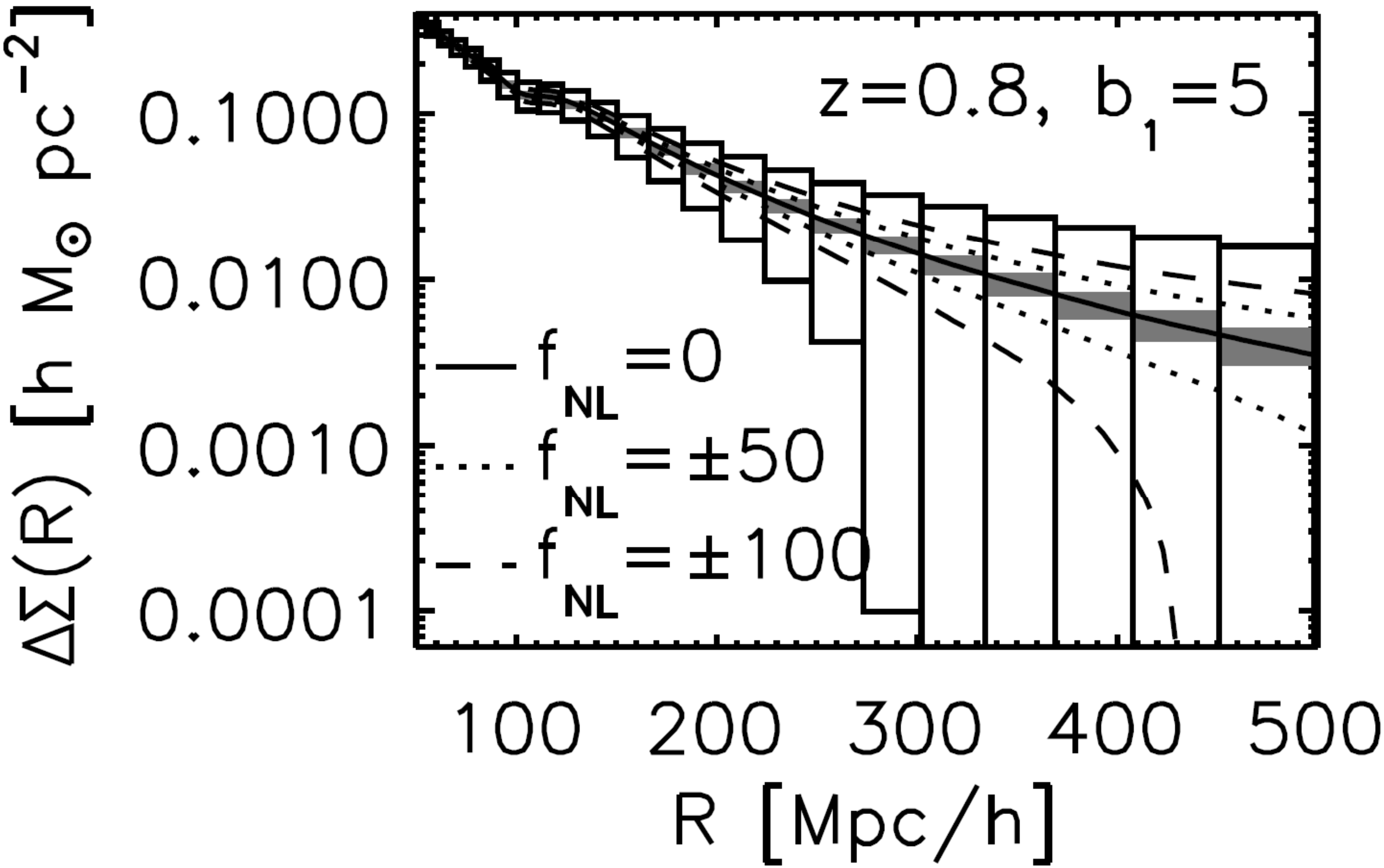
Jeong, Komatsu, Jain (2009), arXiv:0910.1361

f_{NL} in mean tangential shear (LRG)



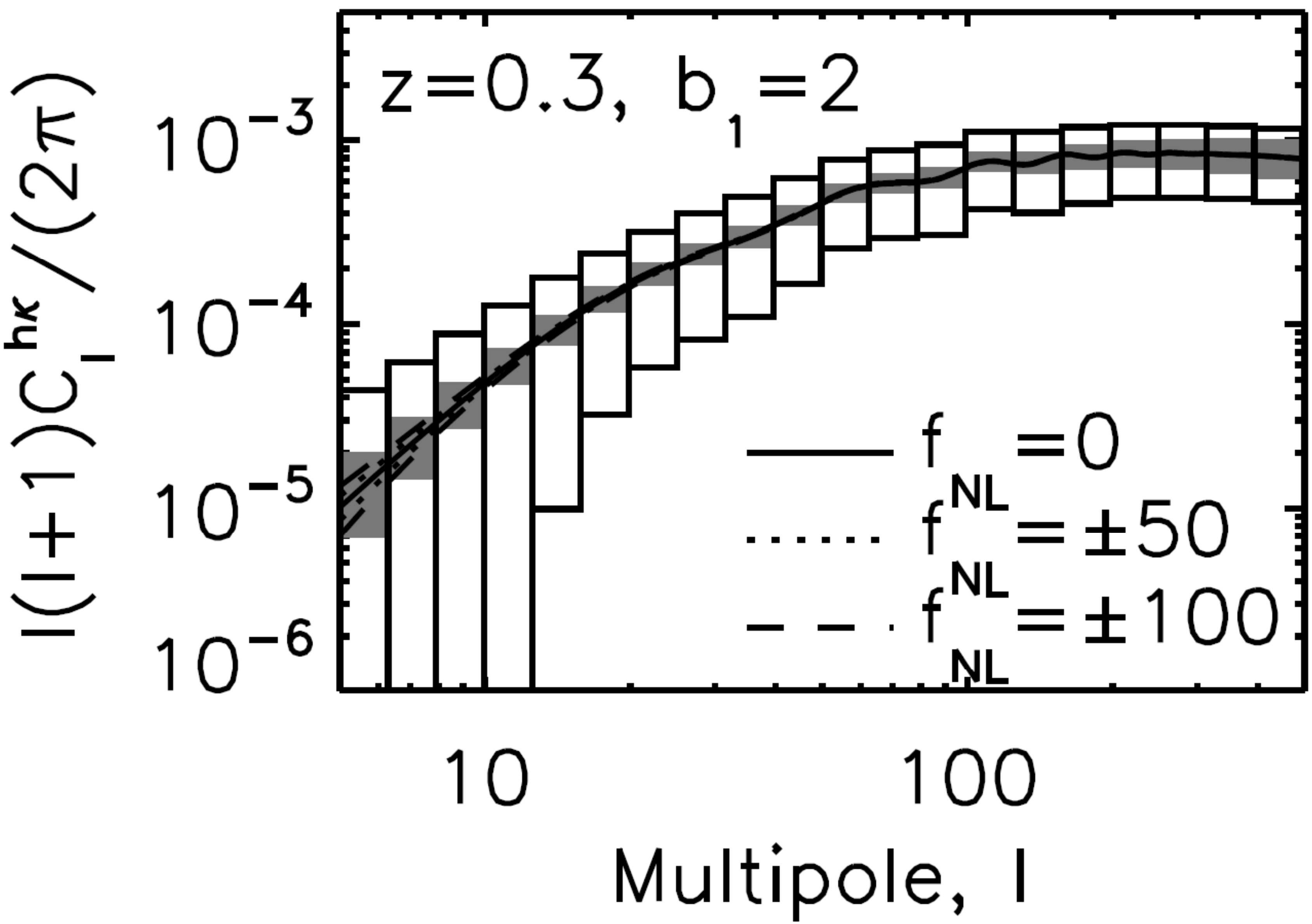
Jeong, Komatsu, Jain (2009), arXiv:0910.1361

f_{NL} in mean tangential shear (LSST)



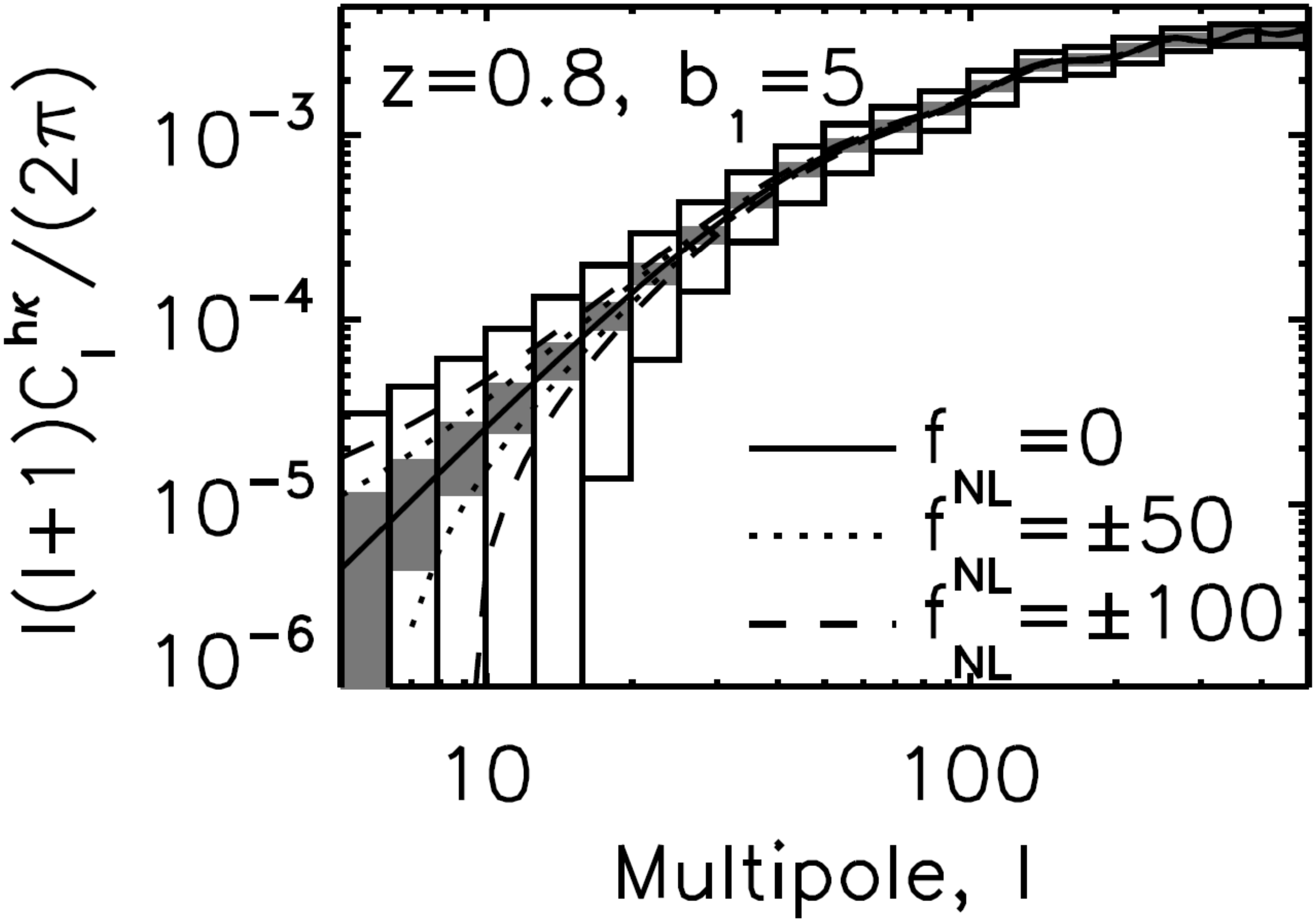
Jeong, Komatsu, Jain (2009), arXiv:0910.1361

Galaxy-CMB lensing, z=0.3



Jeong, Komatsu, Jain (2009), arXiv:0910.1361

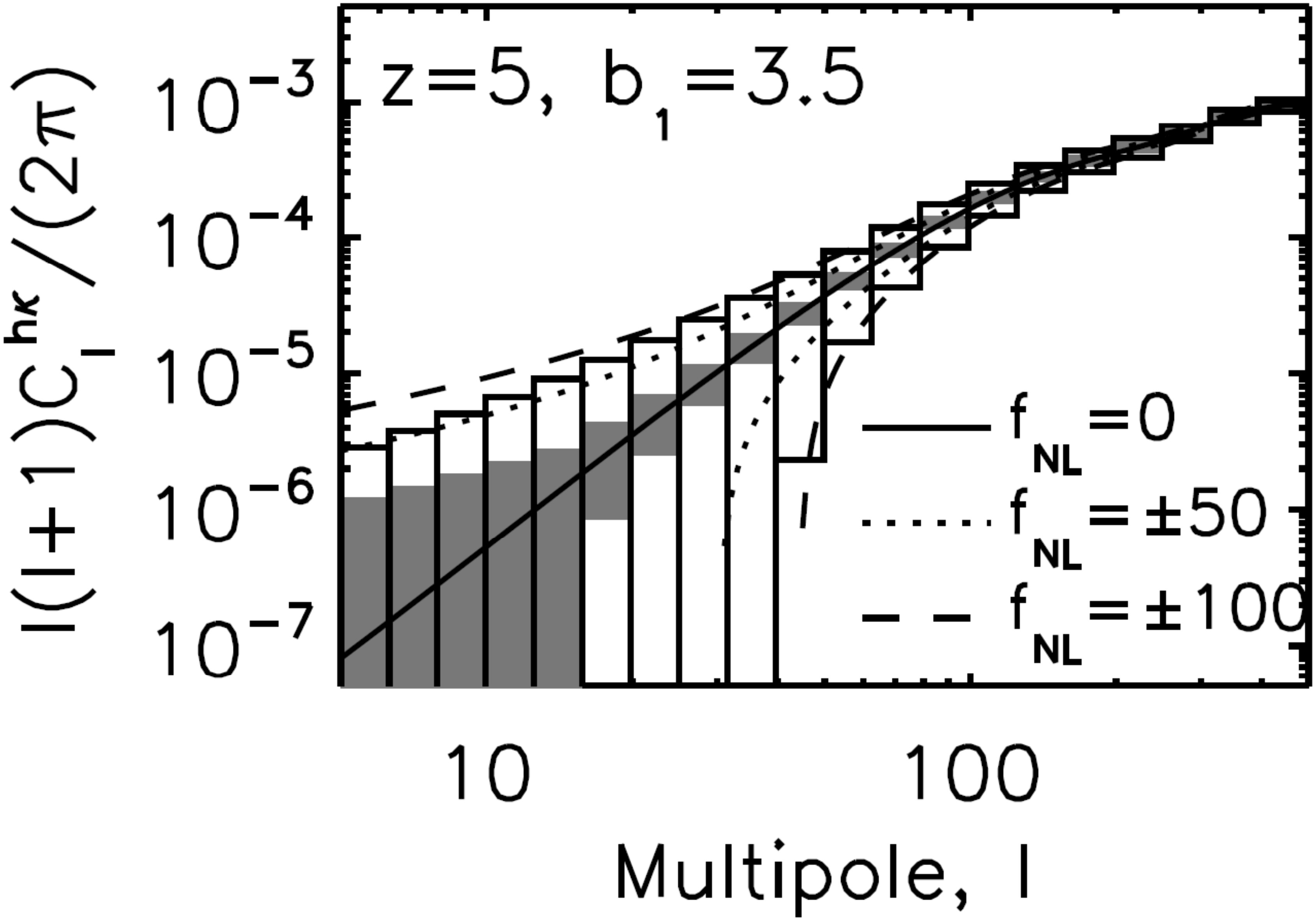
Galaxy-CMB lensing, z=0.8



Jeong, Komatsu, Jain (2009), arXiv:0910.1361

Cluster-CMB lensing, z=5

High-z population provide a better chance of finding f_{NL}.



Conclusion

- In order to exploit the observed galaxy power spectrum, we have to understand the nonlinearities with target accuracy = 1% in P(k).
- We can model the nonlinear galaxy power spectrum at high-z by using the 3rd order perturbation theory.
- Bispectrum provides the nonlinear bias information, as well as information about non-Gaussianity. It is very clean and competitive: $\Delta f_{NL} \sim 1$ is possible!
- Weak gravitational lensing on large scales can provides independent cross-checks of bias and non-Gaussianity.