Modeling of bispectrum in redshift space

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Origin of accelerated expansion

Dark energy or Modified gravity ? ?

How to distinguish ?

Structure formation history offers cosmological test of gravity

Growth rate

$$f(z) \equiv \frac{d \ln D_+}{d \ln a}$$

a : scale factor

D_+ : linear growth factor of density fluctuation

GR case : $f(z) \simeq \{\Omega_{\rm m}(z)\}^{0.55}$ e.g. Linder ('05)

Redshift-space distortions (RSD) can be unique probe to measure the growth rate

Redshift-space distortions

The apparent anisotropies of galaxy clustering due to peculiar velocity : $\boldsymbol{v}$

redshift space　　　　　　　　　　　　real space

$$\boldsymbol{s} = \boldsymbol{r} + \underline{\frac{v_z(\boldsymbol{r})}{aH(z)}\hat{\boldsymbol{z}}}$$

red-/blue- shift

$\hat{\boldsymbol{z}}$: line of site

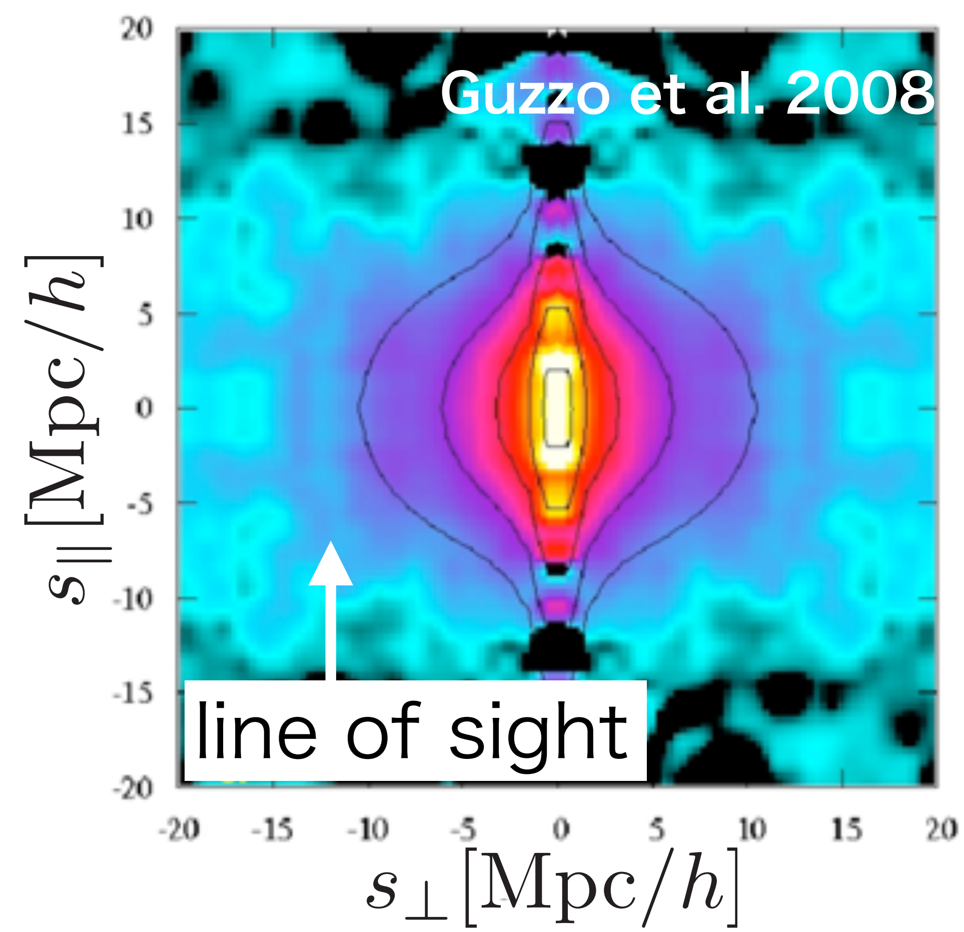
Large scale(~100Mpc)

- Coherent motion
  →make clustering stronger
- strength of distortion proper to velocity $v \propto f(z)$

Around halo (<10Mpc)

- Random motion with large velocity
  →make clustering weaker

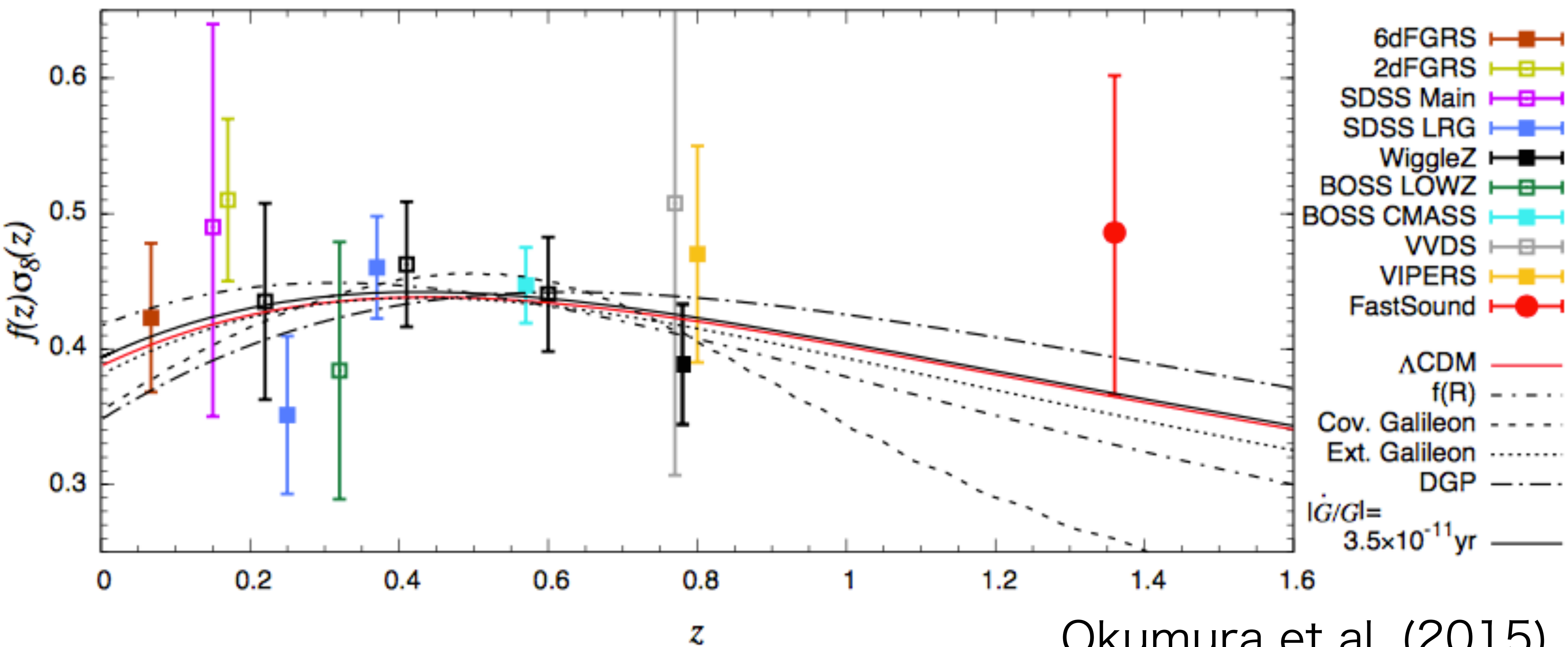
Finger-of-God effect (FoG)



Correlation function

VVDS, $0.6 < z < 1.2, 4\mathrm{deg}^2$

Current constraints

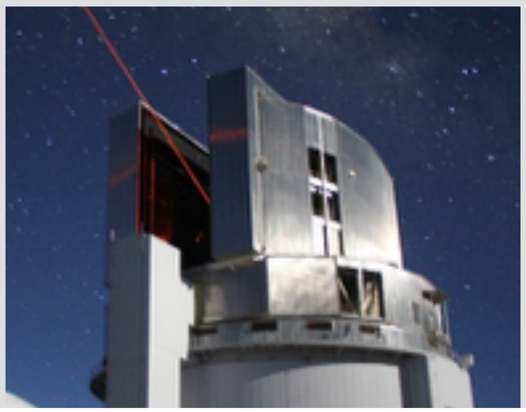


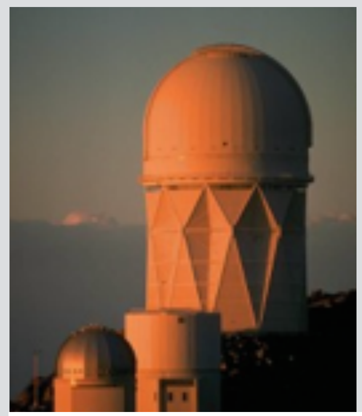
Okumura et al. (2015)

- Constraints are almost ~10% level
- Mostly from the measurement of two point correlation or power spectrum

Era of precision cosmology

Future redshift surveys will release huge data set


SuMIRe('14~)


DESI('18~)


Euclid('20~)

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Theoretical issues

- Precision theoretical-models reducing nonlinear systematics
- Combining higher-order statistics with power spectrum

<u>In this talk</u>

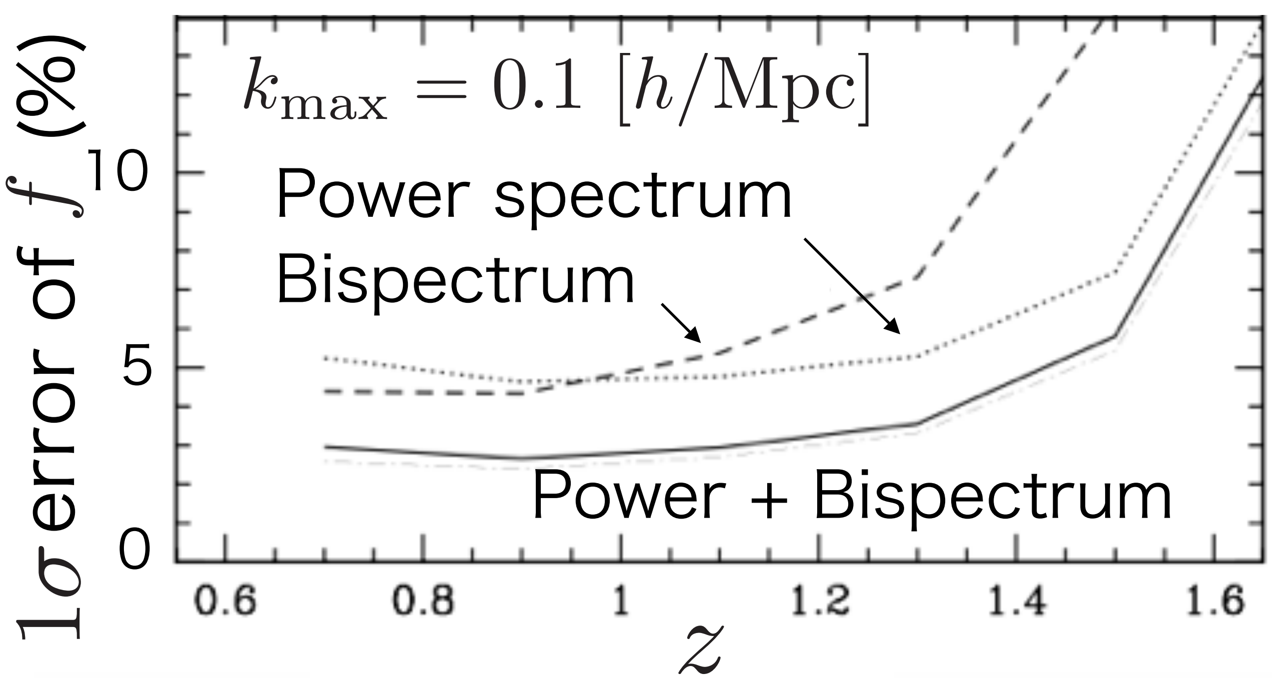
Precision modeling of bispectrum in redshift space

$$\langle \delta^{(\mathrm{s})}(\boldsymbol{k}_1)\delta^{(\mathrm{s})}(\boldsymbol{k}_2)\delta^{(\mathrm{s})}(\boldsymbol{k}_3)\rangle = (2\pi)^3\delta_{\mathrm{D}}(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3)B^{(\mathrm{s})}(k_1,k_2,\theta_{12},\mu,\phi)$$

Aim of this work

We want to get stronger constraint even in quasi non-linear scale where perturbative treatment is usable

Impact of combining bispectrum



Combining bispectrum improves the constraint by a factor of two for DESI

Song, Taruya and Oka ('15)

Precise theoretical model of bispectrum is indispensable for implementing strong constraint

Previous works

Several theoretical models of bispectrum in redshift space were proposed

Scoccimarro, Couchman & Frieman ('98)

- tree level PT + damping function

Smith, Sheth & Scoccimarro ('07)

- Halo model
- Comparing bispectrum monopole with N-body

Gil-Marin et al. ('16)

- tree level PT + Fitting parameters
- Constraining growth rate by combining power spectrum and bispectrum monopole of BOSS

What we did

We constructed bispectrum model of matter distribution and compared with N-body simulation

What's new?

- Including non-linear effects up to 1-loop level

  Non-linear effects: RSD & gravitational growth

- Adaptable for the higher-multipole of bispectrum

Result Our bispectrum model reproduce the simulation result in quasi non-linear regime

Bispectrum in redshift space

Exact formula

$$B^{(\mathrm{s})}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = \int d\boldsymbol{r}_{13} d\boldsymbol{r}_{23} e^{i(\boldsymbol{k}_1\boldsymbol{r}_{13}+\boldsymbol{k}_2\boldsymbol{r}_{23})}\langle A_1A_2A_3\underline{e^{j_4A_4+j_5A_5}}\rangle$$

$$A_i = \delta(\boldsymbol{r}_i) + f\nabla_z u_z(\boldsymbol{r}_i) \qquad (i=1,2,3) \qquad u_z = (\boldsymbol{v}\cdot\hat{\boldsymbol{z}})/(aH)$$

$$A_4 = u_z(\boldsymbol{r}_1) - u_z(\boldsymbol{r}_3),\ \ A_5 = u_z(\boldsymbol{r}_2) - u_z(\boldsymbol{r}_3),\ \ j_4 = -ik_1\mu_1 f,\ \ j_5 = -ik_2\mu_2 f.$$

Expand naively → standard perturbation theory

Exponential term is expanded as power series

$$\int dr_{12}dr_{23}\langle \underline{e^X}\cdots\rangle = \int dr_{12}dr_{23}\langle(\underline{1+X+X^2/2\cdots})\cdots\rangle$$

Do not expand damping part → **TNS model** Taruya et al. ('10)

Exponential term is divided by cumulant expansion

$$\int dr_{12}dr_{23}\langle \underline{e^X}\cdots\rangle = \int dr_{12}dr_{23}\,\underline{\exp\{\langle e^X\rangle_{\mathrm{c}}\}}\{\langle\cdots\rangle_{\mathrm{c}}\cdots\}$$

$$\simeq \underline{D_{\mathrm{FoG}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)}\int dr_{12}dr_{23}\{\langle\cdots\rangle_{\mathrm{c}}\cdots\}$$

Detail of our model

Our model of bispectrum in redshift space

$$B^{(\mathrm{s})}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = \underbrace{D_{\mathrm{FoG}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)}_{\text{Damping term}}\,\underbrace{B'_{\mathrm{PT}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)}_{\text{PT part}}$$

Assuming damping function is written for one-variable

$$D_{\mathrm{FoG}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) \to D_{\mathrm{FoG}}(k_1^2\mu_1^2 + k_2^2\mu_2^2 + k_3^2\mu_3^2)$$

e.g. Gaussian: $\exp\left\{-\frac{1}{2}f^2\sigma_v^2(k_1^2\mu_1^2 + k_2^2\mu_2^2 + k_3^2\mu_3^2)\right\}$

$\sigma_v^2 \equiv \langle u_z^2(r)\rangle$: 1-D velocity dispersion (free parameter)

Calculating by PT up to 1-loop level

$$B'_{\mathrm{PT}} \simeq \underbrace{B_{\mathrm{tree}}}_{O((\delta_1)^4)} + \underbrace{B'_{1-\mathrm{loop}}}_{O((\delta_1)^6)} + \cdots$$

Scocchimarro('98) New

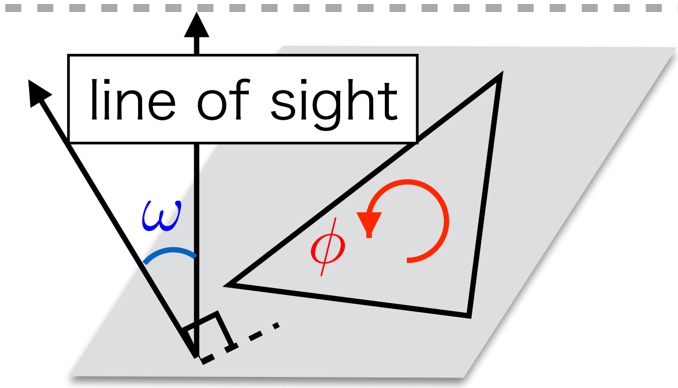
1-loop contribution is different from SPT formulation

New model vs Simulation

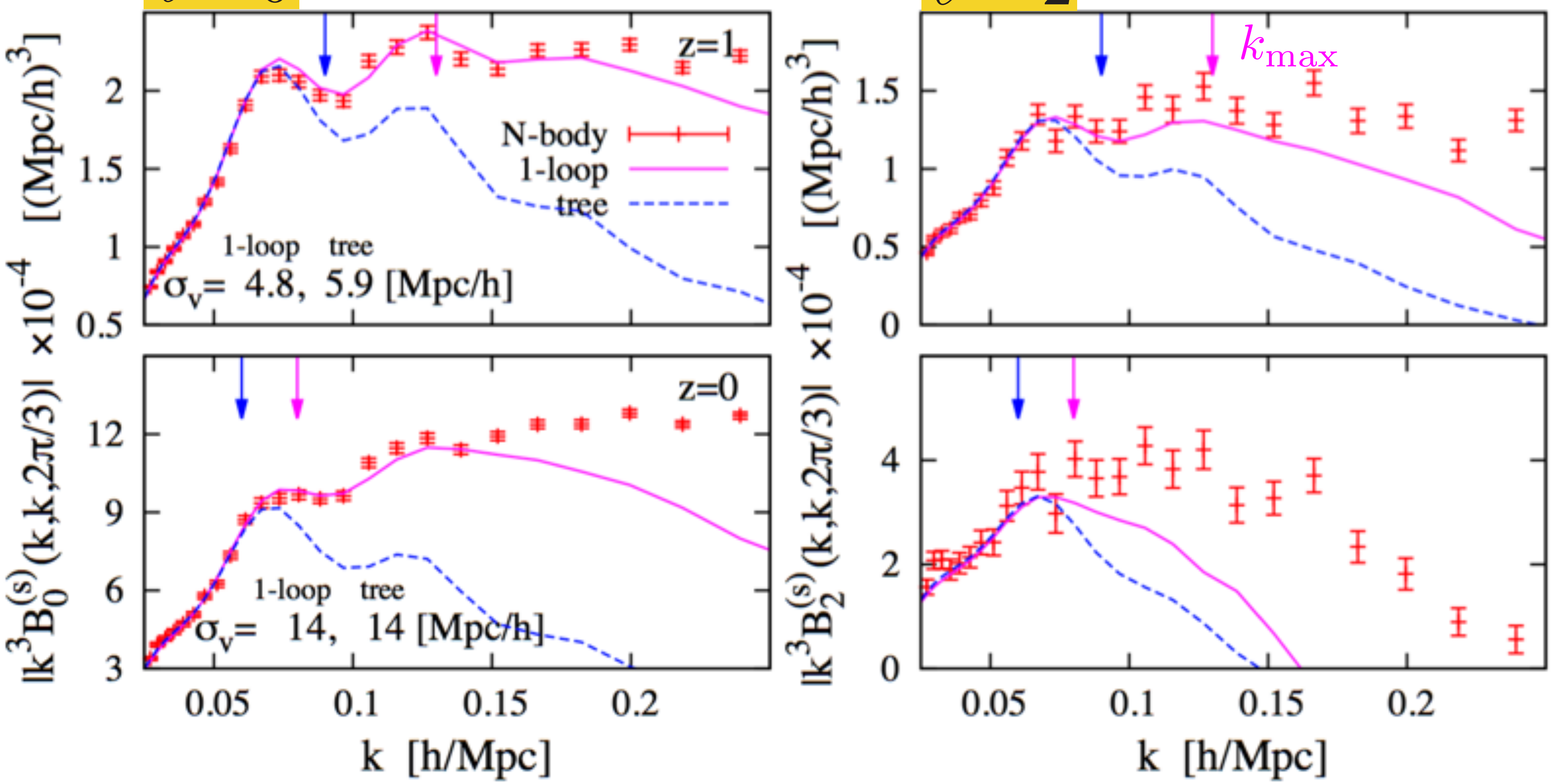
$$\hat{B}_\ell^{(\mathrm{s})}(k_1,k_2,\theta_{12}) = \int_{-1}^{1} d\mu \int_0^{2\pi} \frac{d\phi}{2\pi} B^{(\mathrm{s})}(k_1,k_2,\theta_{12},\mu,\phi)\underline{P_\ell(\mu)}$$

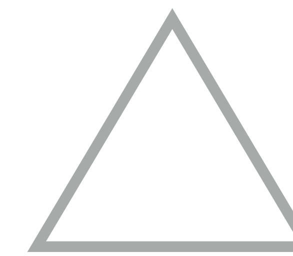
$$\mu = \cos\omega$$

Legendre polynomial



$\ell = 0$ $\ell = 2$

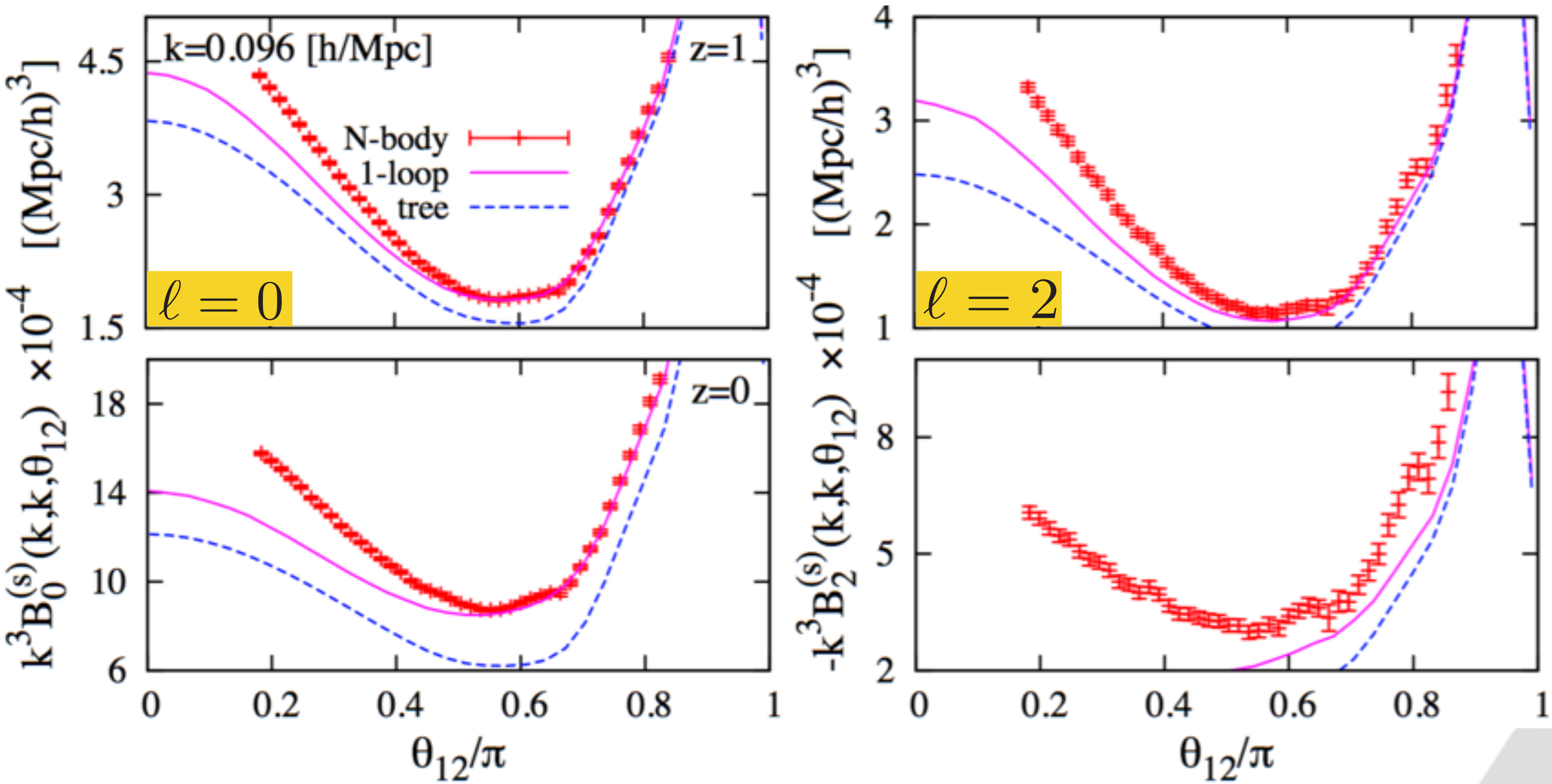


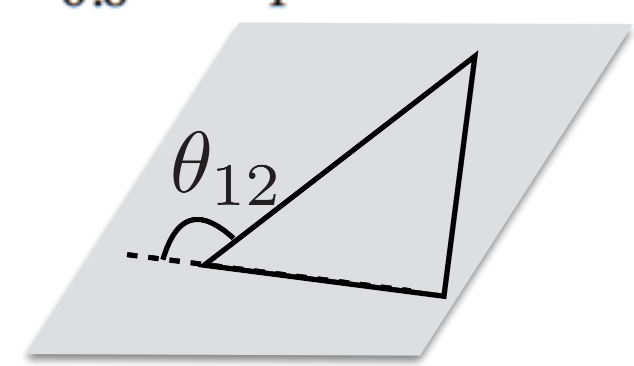


Simulation : Blot et al. ('14)

Box size : 1312.5 Mpc/h, # of particles : 512^3, # of realizations : 512

New model vs Simulation





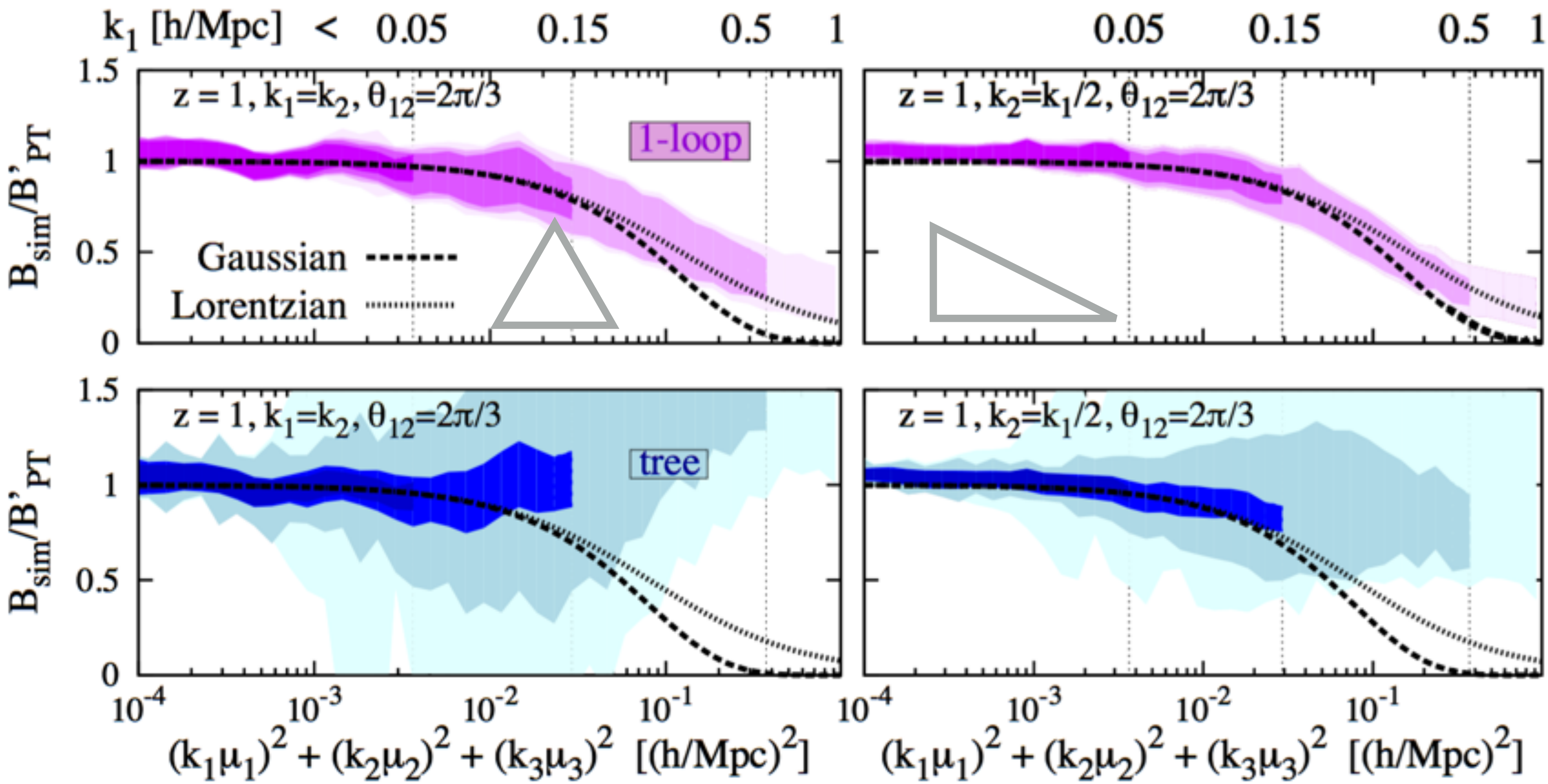
Simulation : Blot et al. ('14)
Box size : 1312.5 Mpc/h, # of particles : 512^3, # of realizations : 512

Our model reproduce simulation results in quasi non-linear regime

Validity of the damping model

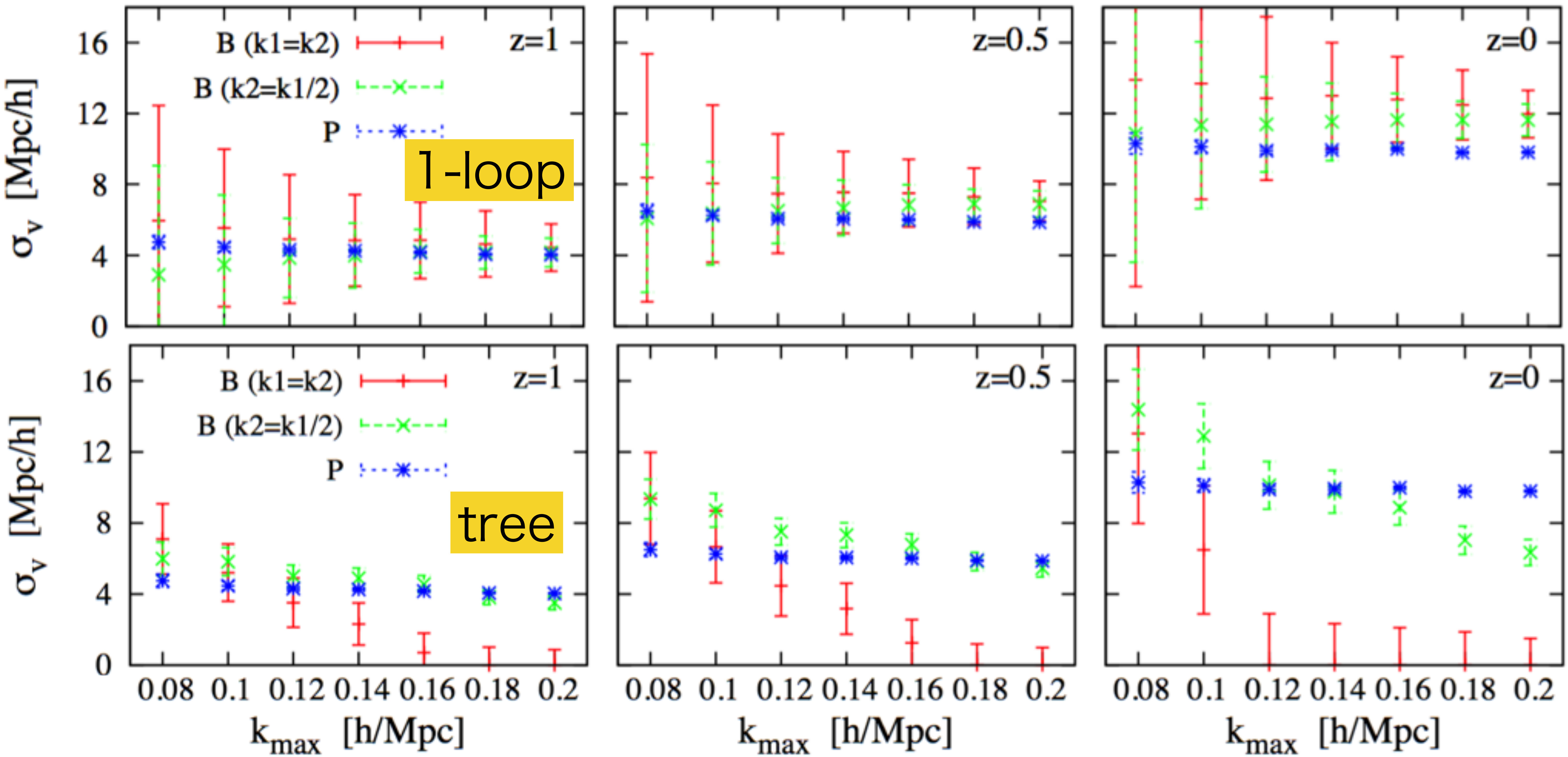
If damping effect is correctly included in our model,

$B_{\rm sim}/B'_{\rm PT}$ should converge on $D_{\rm FoG}(k_1^2\mu_1^2 + k_2^2\mu_2^2 + k_3^2\mu_3^2)$



- 1-loop calculation works well even in small scale
- Damping feature does not depend on bispectrum shapes

Free parameter



σ_v become consistent when we include 1-loop contributions

Summary

Purpose

Constructing the model of redshift-space bispectrum taking account of nonlinear effects on gravity and RSD

What we did

- Expanding TNS model to bispectrum in redshift space
- Checking the validity of the model by N-body simulation

Result

- Our model produce bispectrum in quasi non-linear regime
- Damping model seems relevant in wide range
- σ_v of bispectrum is consistent with that of power spectrum