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# Modeling bispectrum in redshift space from perturbation theory

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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 : $\boldsymbol{v}$

$$\underbrace{\boldsymbol{s}}_{\text{redshift space}} = \underbrace{\boldsymbol{r}}_{\text{real space}} + \underbrace{\frac{v_z(\boldsymbol{r})}{aH(z)}}_{\text{red-/blue- shift}}\hat{\boldsymbol{z}}$$

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

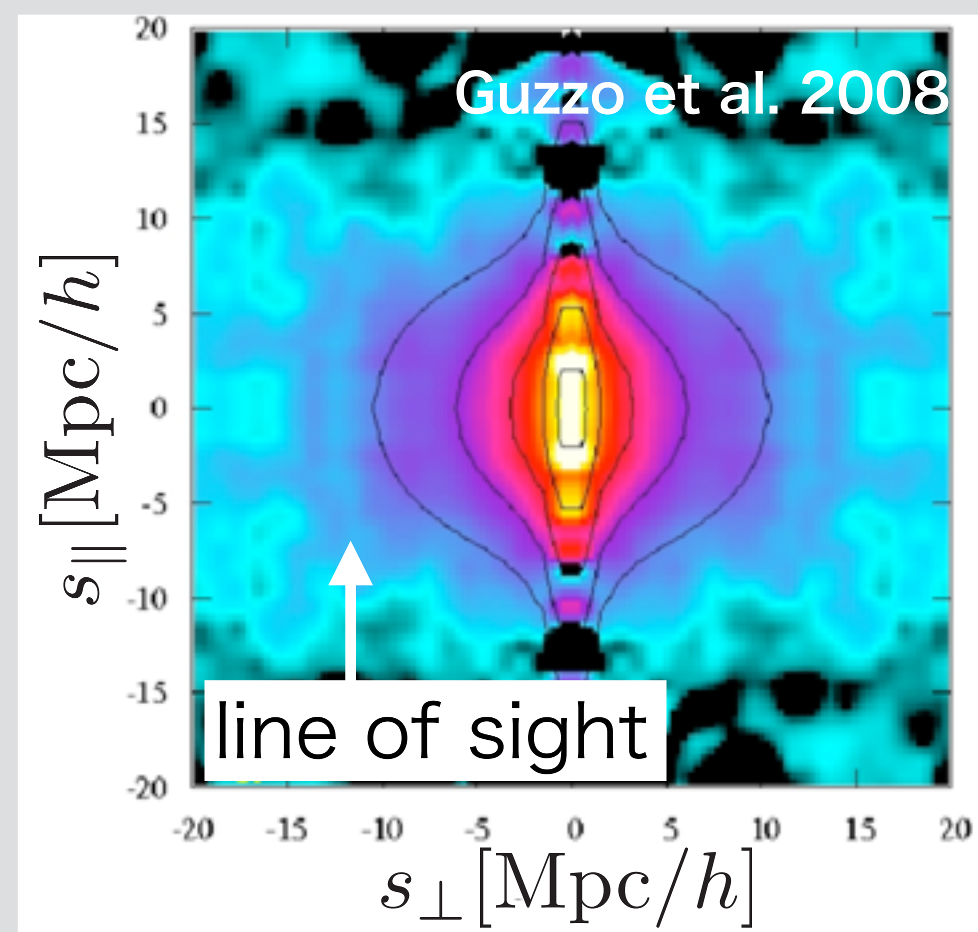
## Large scale( ~100Mpc)

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

## Around halo ( <10Mpc)

- Random motion with large velocity
  →make clustering weaker

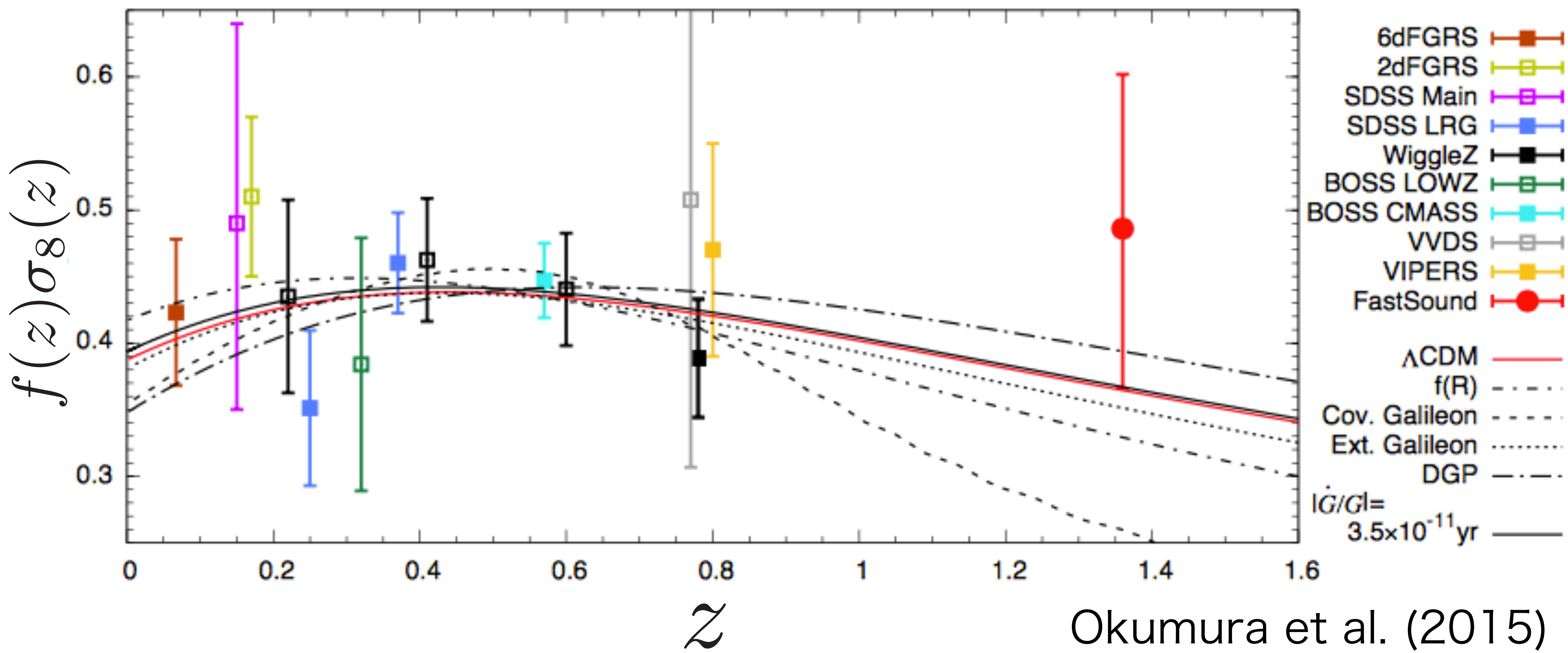
Finger-of-God effect (FoG)




**Correlation function**

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

# Current constraints



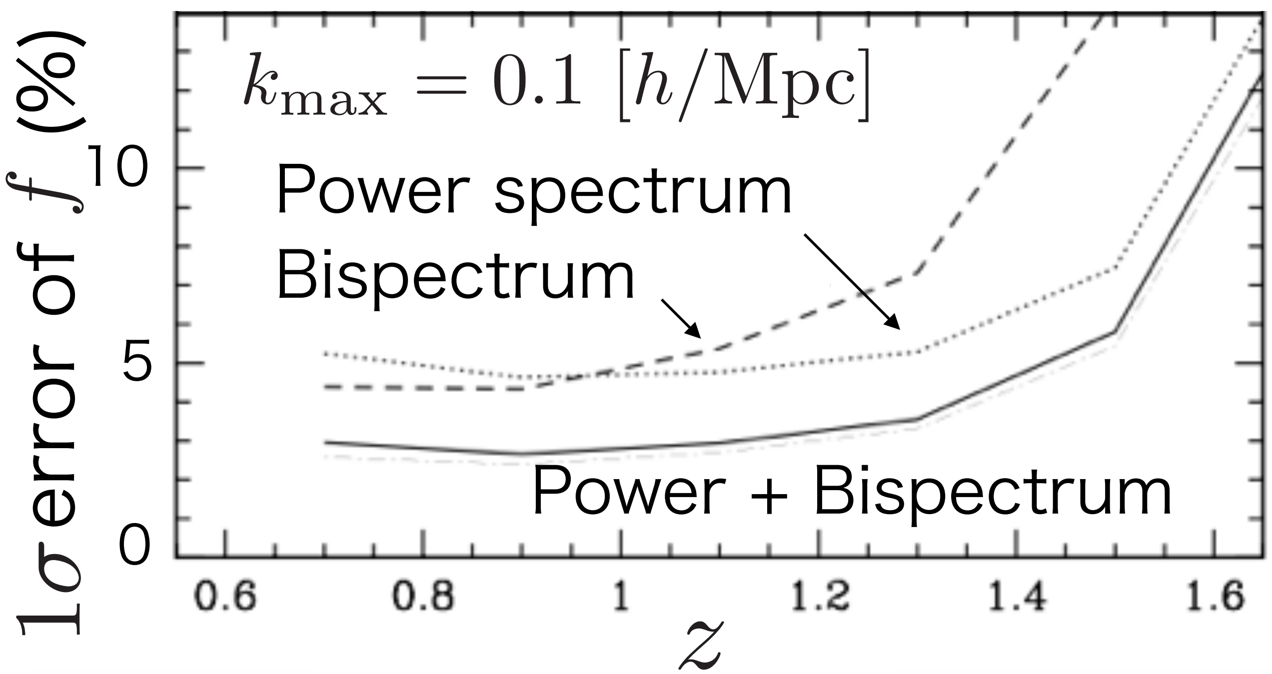

Okumura et al. (2015)

- Consistent with ΛCDM at ~10% level
- Mostly from the measurement of two point correlation or power spectrum

# Aim of this work

**Getting stronger constraint of growth rate by combining redshift space bispectrum**

## Impact of combining bispectrum




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

Song, Taruya and Oka ('15)

In this talk

We construct high precision model of redshift-space bispectrum and compare with simulation

# What's new?

## Previous works

- Scoccimarro, Couchman & Frieman ('98)
- Smith et al. ('07), Yamamoto et al. ('16)
- Gil-Marin et al. ('16,'15)

→ Based on a formula of tree level calculation

## Our work

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

  Non-linear effects: RSD & gravitational growth

- Compering with **DEUS-PUR**

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

  # of realizations :512

Blot et al. ('14)

# Theoretical model of bispectrum

## Exact formula of redshift-space bispectrum

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

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

$$A_4=u_z(\boldsymbol{r}_1)-u_z(\boldsymbol{r}_3),\ A_5=u_z(\boldsymbol{r}_2)-u_z(\boldsymbol{r}_3),\ j_4=-ik_{1z}f,\ j_5=-ik_{2z}f$$

<u>Expand naively by $\delta_1$ → standard perturbation theory</u>

Exponential term is expanded as power series

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

$$B_{\rm PT}\simeq \underset{O((\delta_1)^4)}{B_{\rm tree}}+\underset{O((\delta_1)^6)}{B_{1-{\rm loop}}}+\cdots$$

This model breaks down at large scales even in the case of power spectrum

e.g. Taruya et al. ('10)

# Theoretical model of bispectrum

**Exact formula of redshift-space bispectrum**

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

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Do not expand damping part → **TNS model**

Exponential term is divided by cumulant expansion

$$\langle \underline{e^X}\cdots\rangle=\underline{\exp\{\langle e^X\rangle_{\mathrm{c}}\}}\underline{\{\langle\cdots\rangle_{\mathrm{c}}\cdots\}}$$

Taruya et al. ('10)

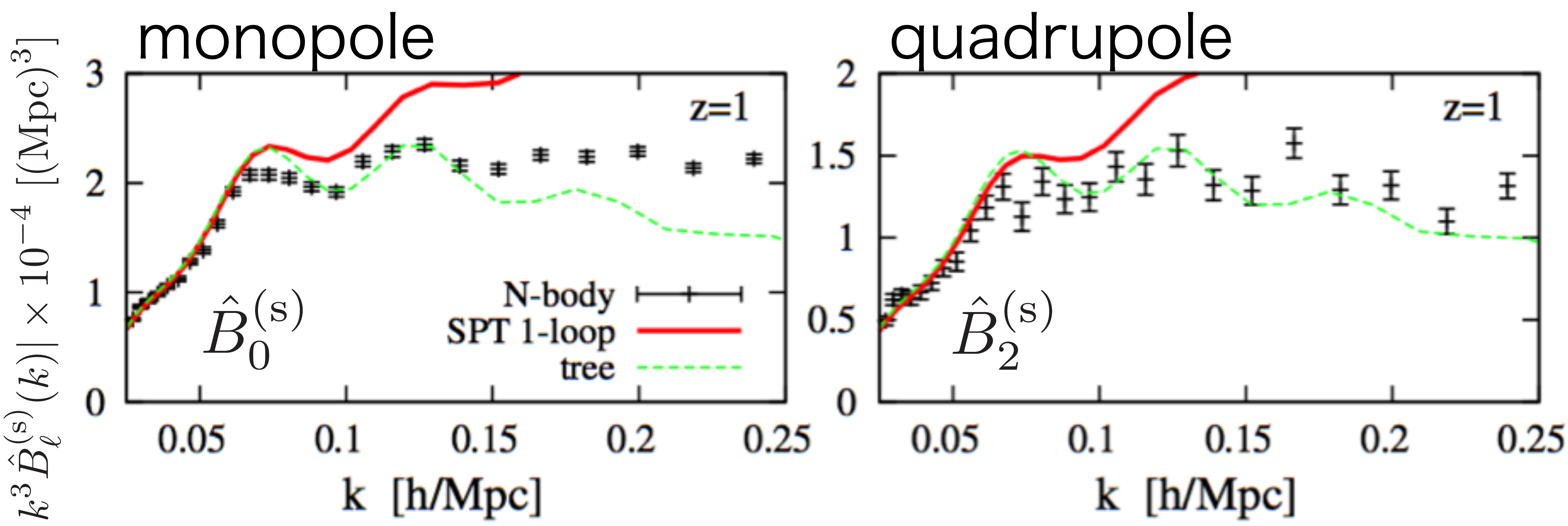
Calculate up to 1-loop level

Our model

$$B^{(\mathrm{s})}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)=\underline{D_{\mathrm{FoG}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)}\,\underline{B'_{\mathrm{PT}}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)}$$

# Bispectrum from SPT

## Scale dependance of equilateral bispectrum

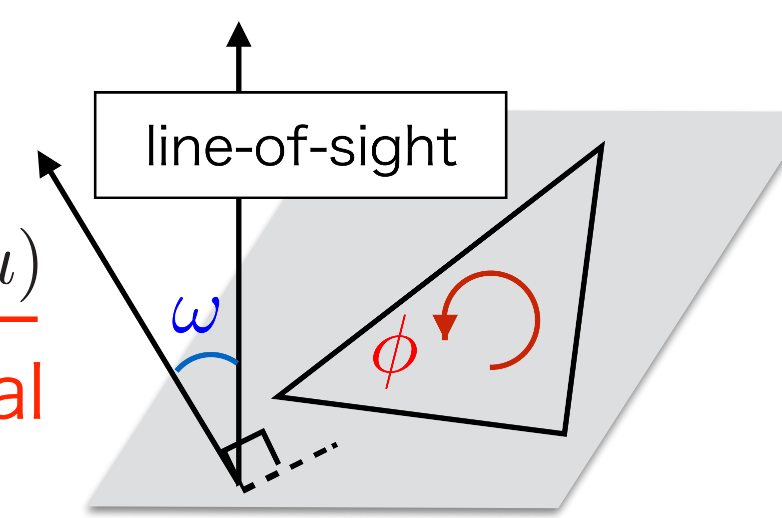



Legendre expansion:

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

$$\mu = \cos\omega$$

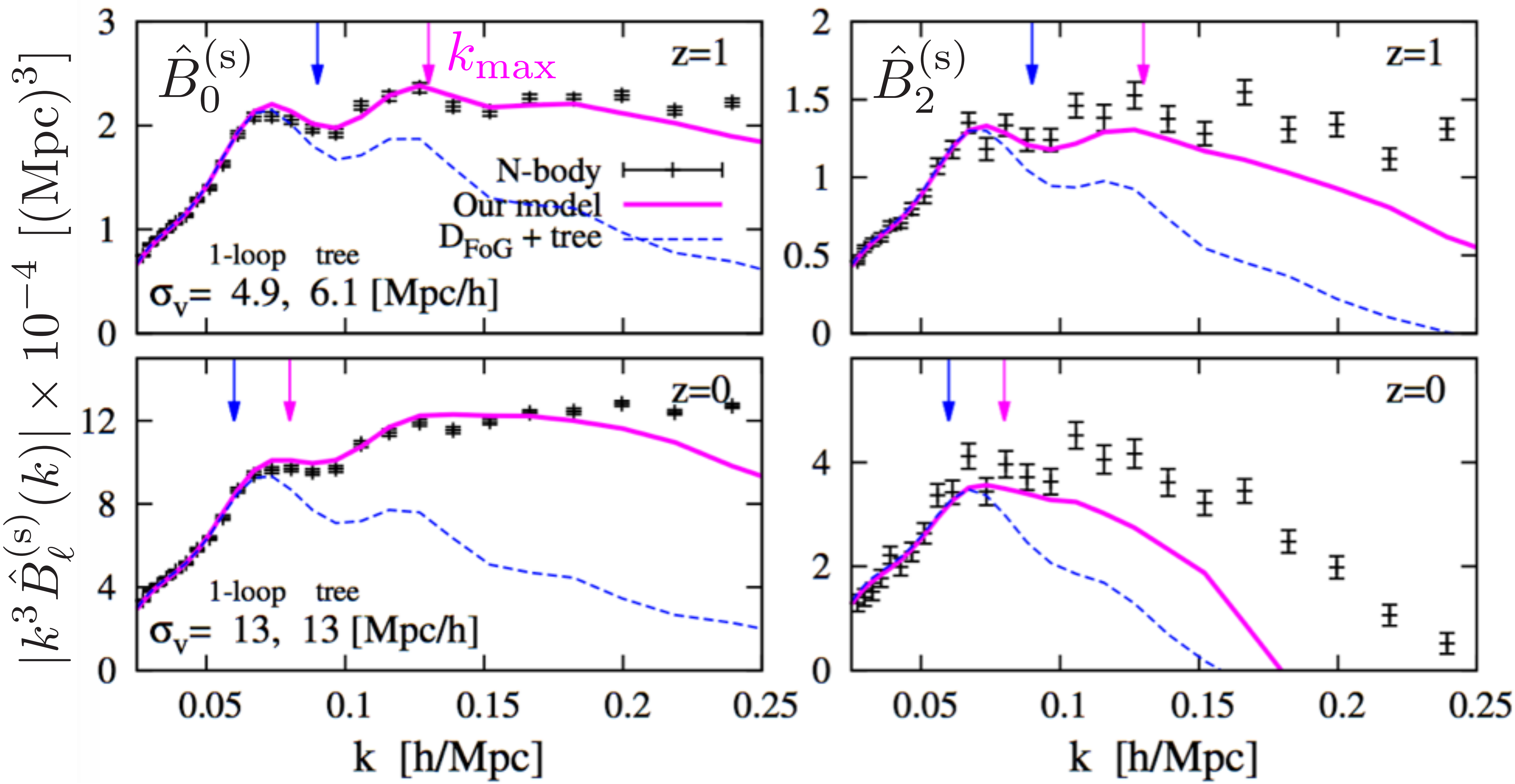
Legendre polynomial



# Bispectrum from our model

Employing Gaussian damping function

$$D_{\rm FoG}(q) = e^{-\frac{1}{2}(f\sigma_v q)^2}\ ,\ q = (k_1^2\mu_1^2 + k_2^2\mu_2^2 + k_3^2\mu_3^2),\, \sigma_v = \langle u_z^2(0)\rangle$$



# What we confirmed

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

## Functional form of damping term

Scocchimarro et al.('98)

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

e.g. Gaussian,

$$D_{\rm FoG}(q) = e^{-\frac{1}{2}(f\sigma_v q)^2},$$

Lorentzian

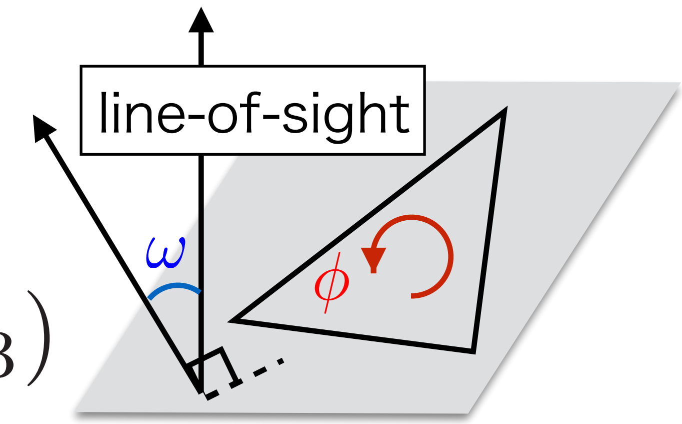
$$D_{\rm FoG}(q) = 1/(1+(f\sigma_v q)^2/2)$$

## Consistency for power spectrum

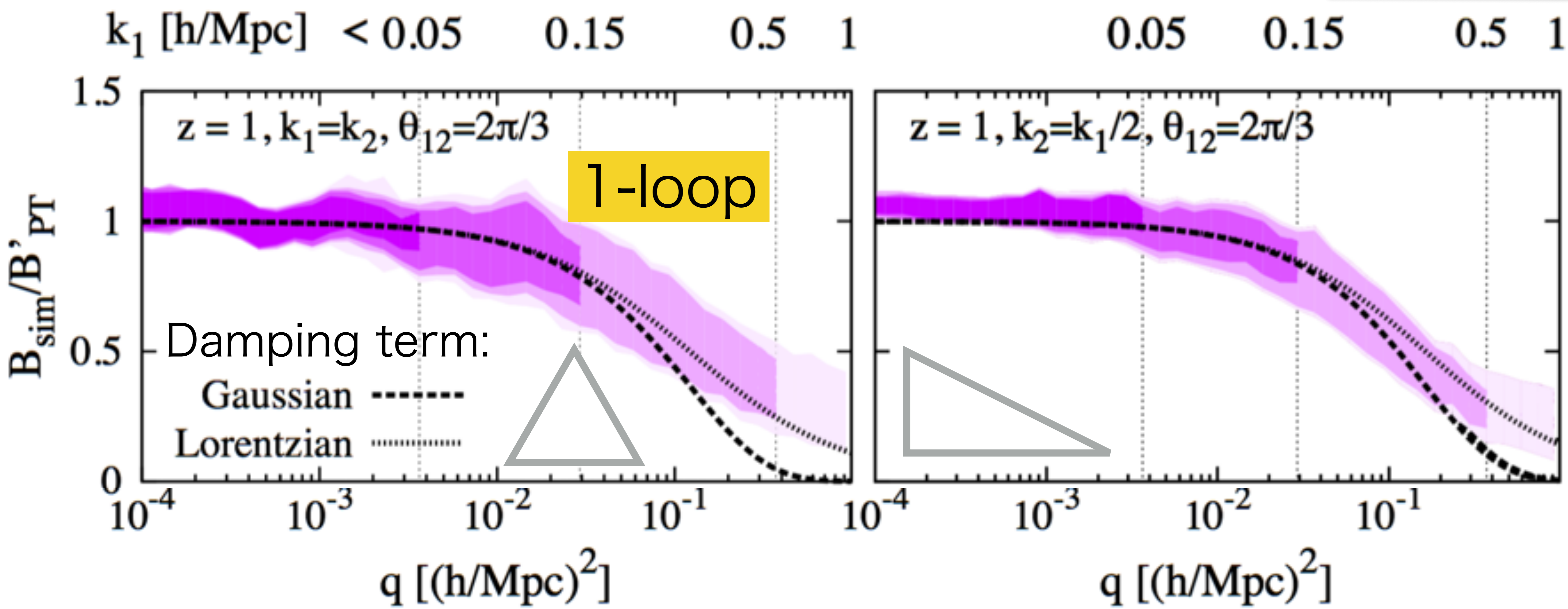
If the value of $\sigma_v$ is consistent with power spectrum from TNS, parameters degeneracy can be solved

# Validity of damping term

**Variance of $B_{\rm sim}/B'_{\rm PT}$ for various $\omega, \phi$ .**




1 variable $D_{\rm FoG}(q)$ ⟷ 5 variables $B_{\rm sim}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)/B'_{\rm PT}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)$

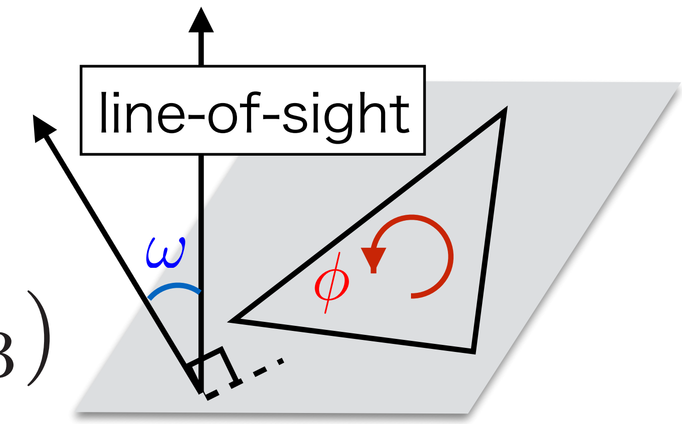



$$q = (k_1^2\mu_1^2 + k_2^2\mu_2^2 + k_3^2\mu_3^2)$$

The ratio converge to the single variable function

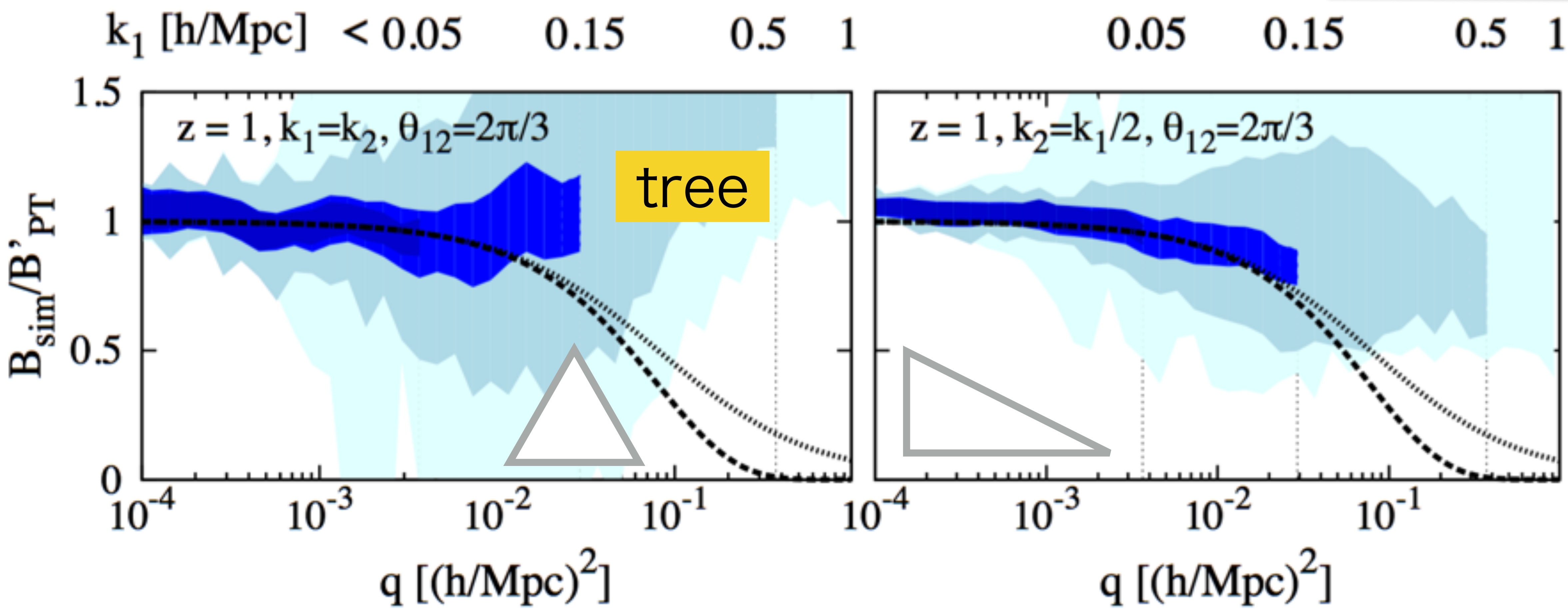
# Validity of damping term

**Variance of $B_{\rm sim}/B'_{\rm PT}$ for various $\omega, \phi$ .**




1 variable $\qquad$ 5 variables

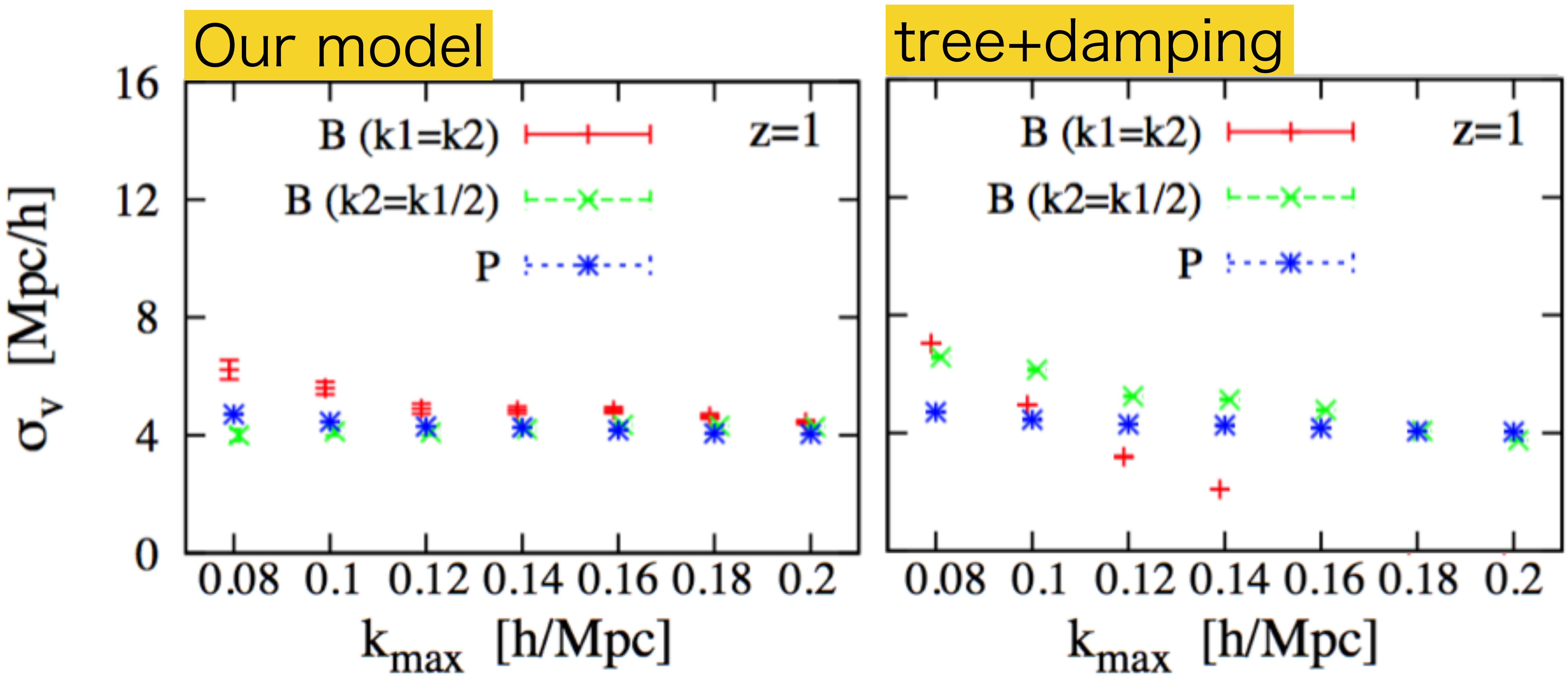
$D_{\rm FoG}(q) \longleftrightarrow B_{\rm sim}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)/B'_{\rm PT}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)$



# Consistency for power spectrum

**$k_{\max}$ dependance of $\sigma_v$ .**

The result of fitting bellow $k_{\max}$




In our model, $\sigma_v$ is consistent with power spectrum

# 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
- $\sigma_v$ of bispectrum is consistent with that of power spectrum