

CosKASI-ICG-NAOC-YITP 2017

# The accuracy of a redshift-space bispectrum model based on perturbation theory

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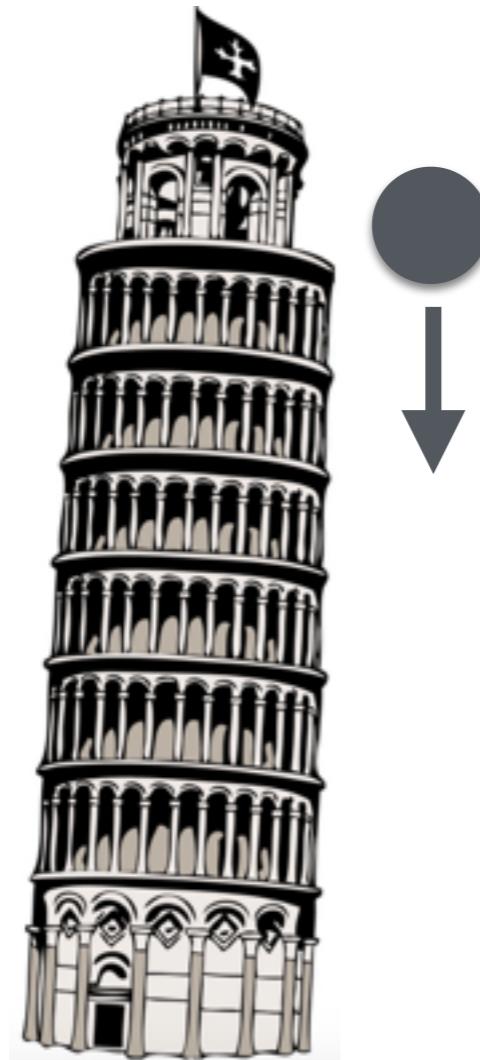
Collaborators :

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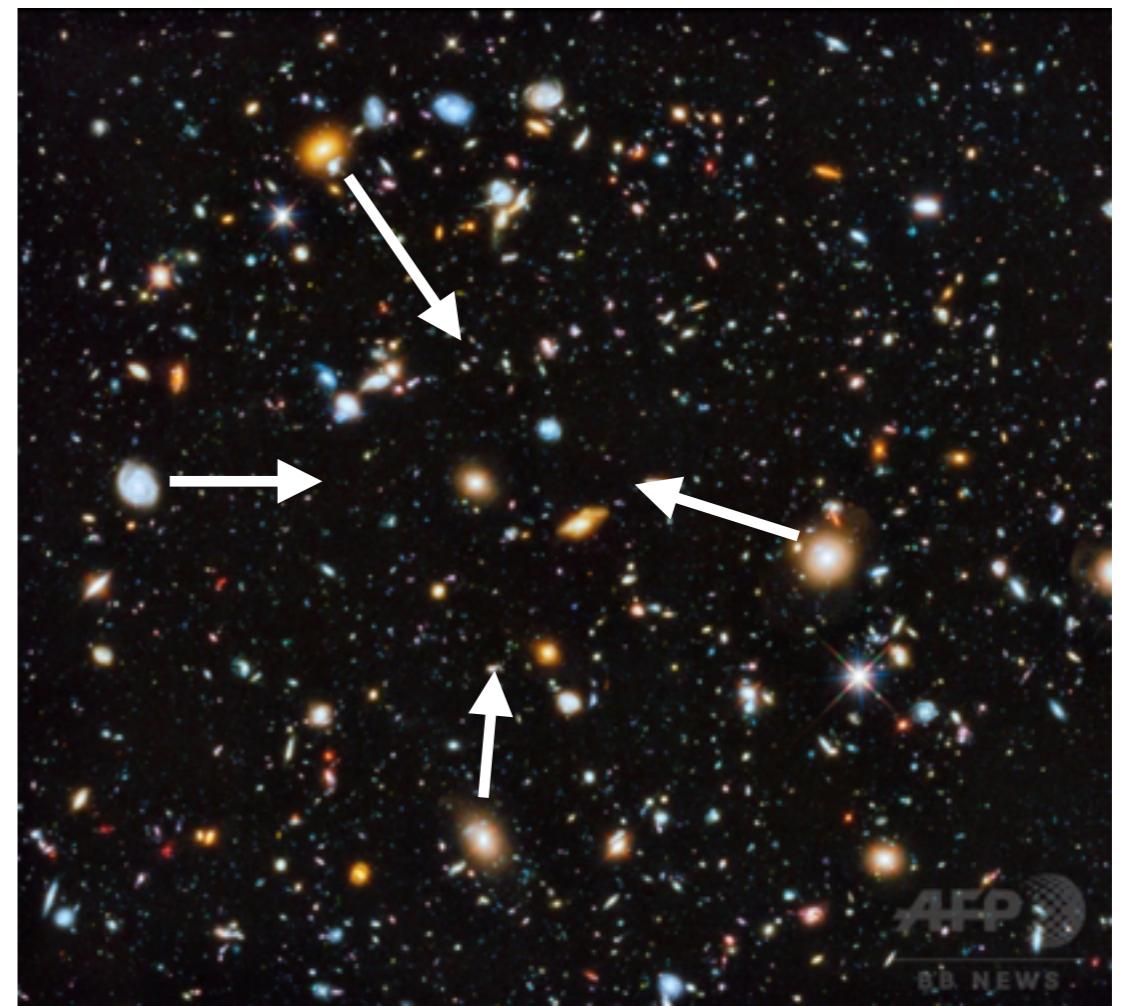
# Origin of accelerated expansion

Dark energy or Modified gravity ??

Test of gravity has opportunity to distinguish



Small scale : Free fall



Large scale : Galaxies

# Redshift-space distortions

redshift space

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

real space

red-/blue- shift  
due to peculiar velocity

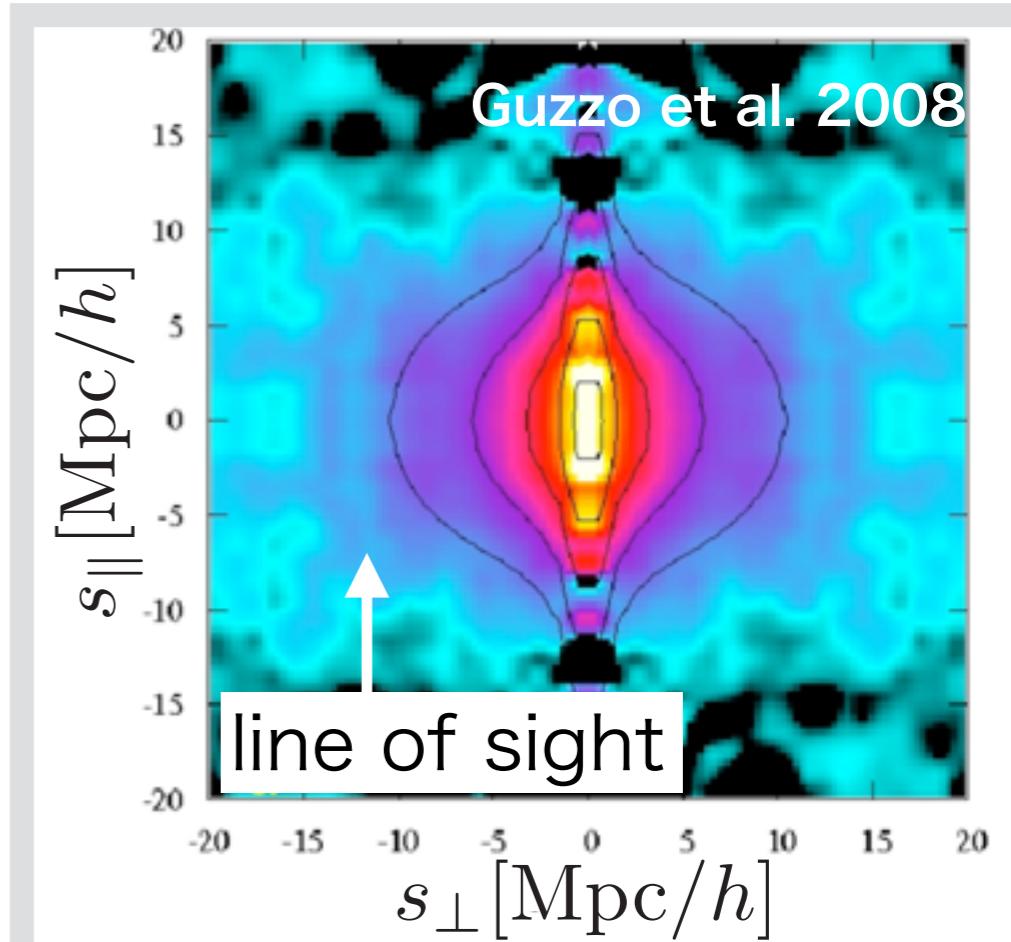
$\hat{z}$  : line of site

## Large scale( ~100Mpc)

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

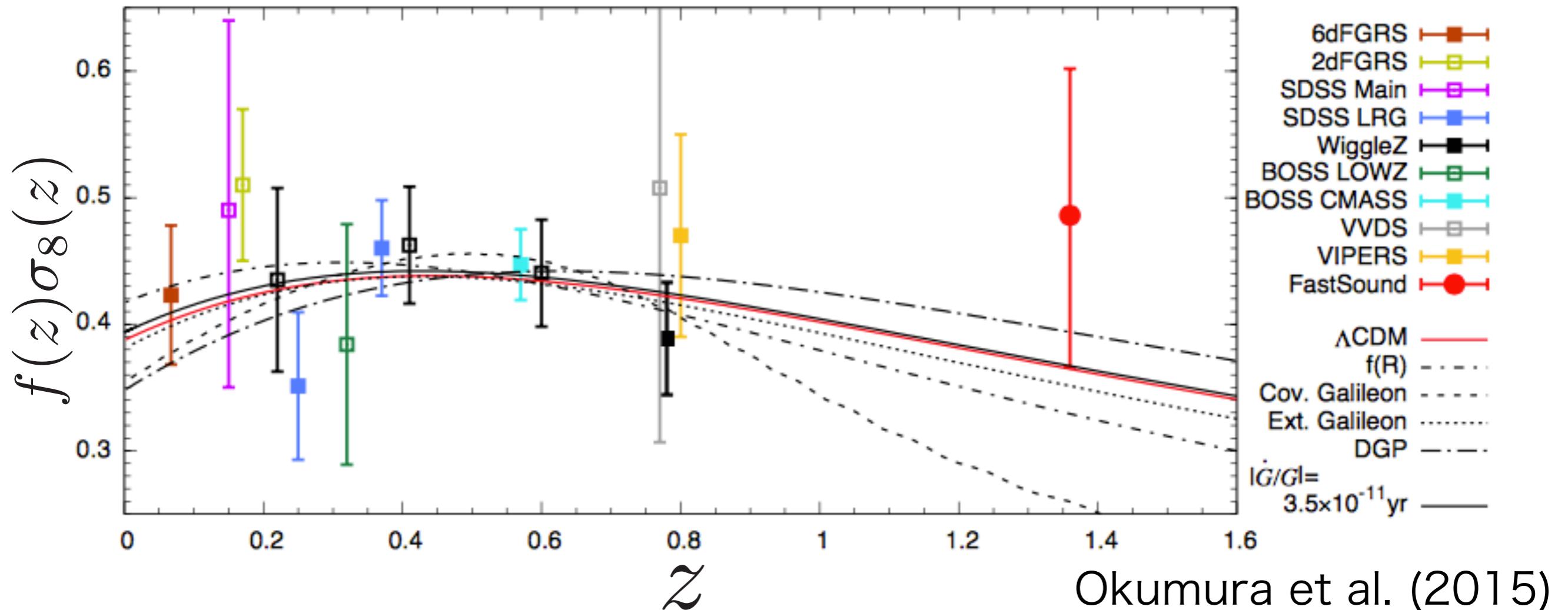
## Around halo ( <10Mpc)

- Random motion with large velocity  
→ make clustering weaker
- Finger-of-God effect (FoG)



**Correlation function**  
VVDS,  $0.6 < z < 1.2$ ,  $4\text{deg}^2$

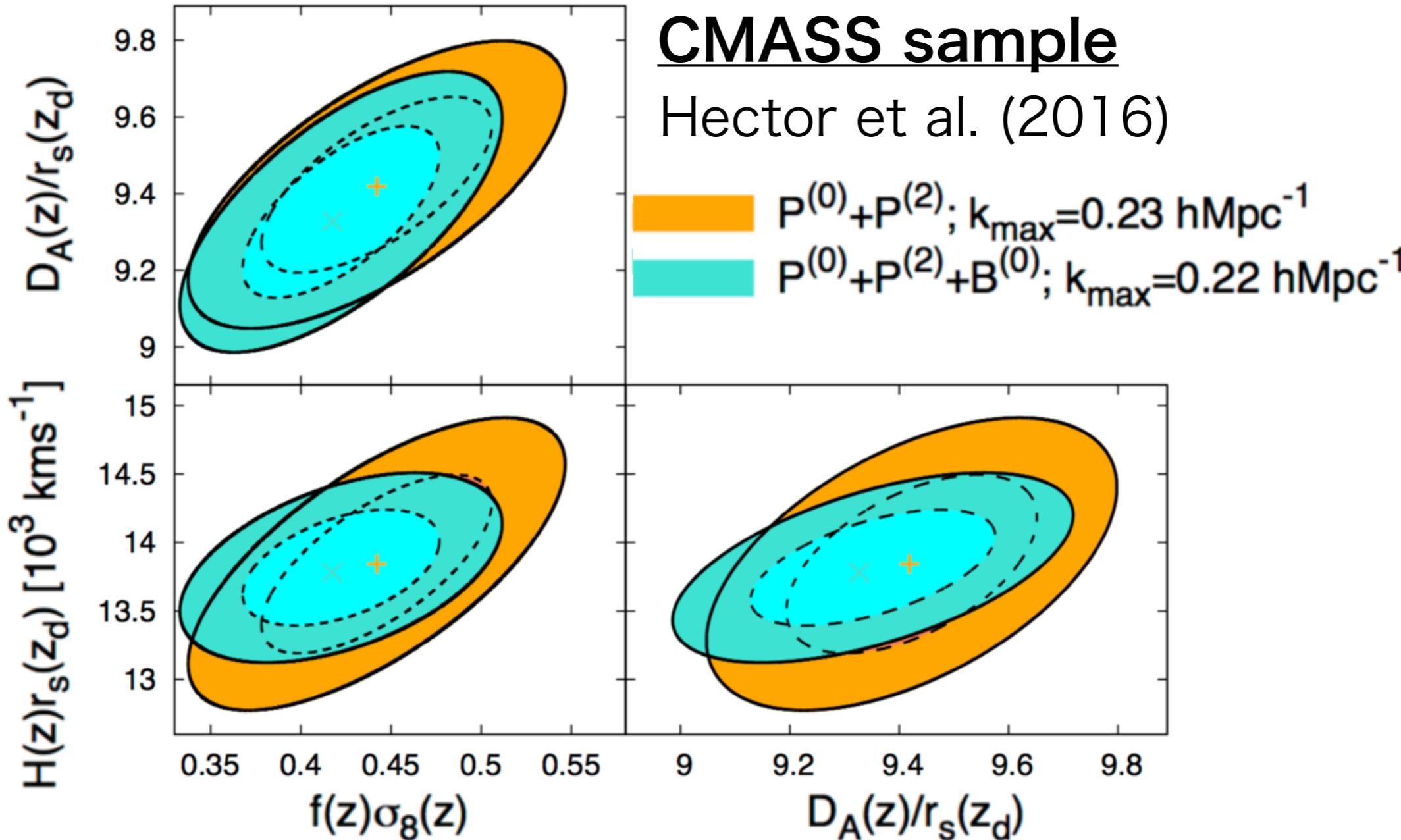
# Current constraints



- Consistent with  $\Lambda$ CDM at ~10% level
- Mostly from the two point correlation or power spectrum

We want to add **redshift-space bispectrum**

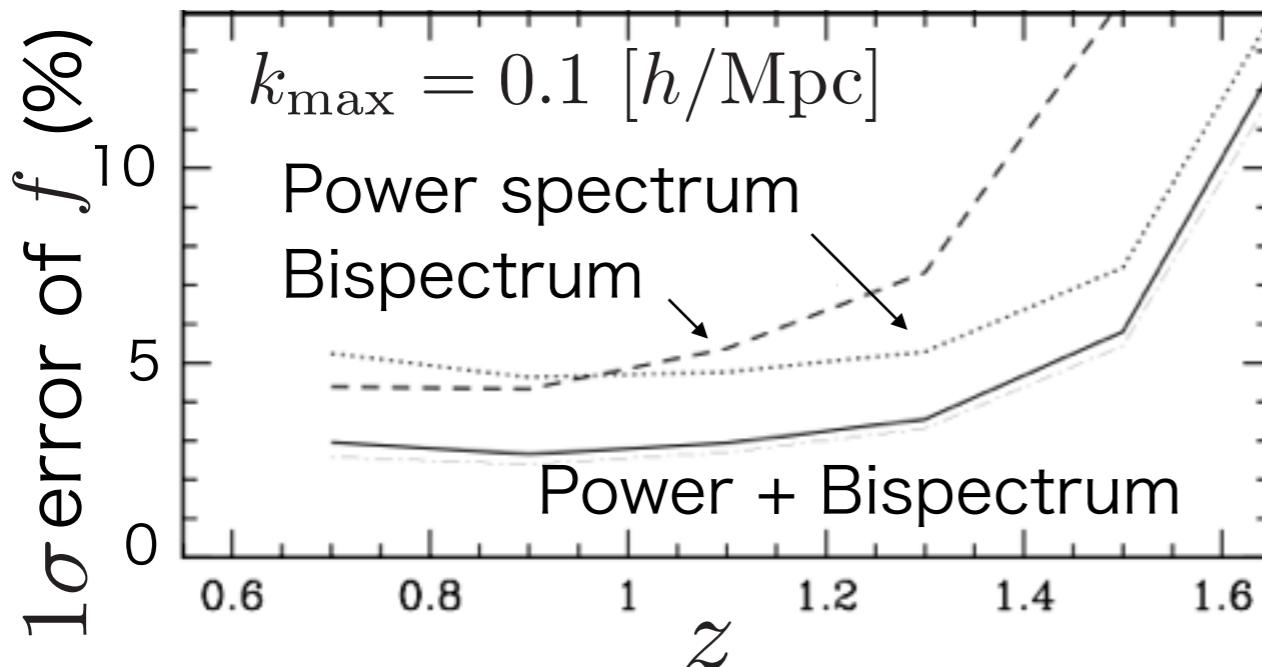
# Constraints from bispectrum



- Bispectrum improves the constraint of  $f\sigma_8$  for  $\sim 15\%$
- Anisotropic information of bispectrum is not included

# Impact of future survey

## Combining bispectrum in future survey



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

Song, Taruya and Oka ('15)

## Aim of this work

- Constructing precise model of bispectrum which can be applied for future survey
- Including the information of bispectrum up to quadrupole moment

# Theoretical models

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## ■ 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
- Investigating the validity of theoretical model by comparing N-body up to quadrupole of bispectrum

# Theoretical model of bispectrum

Exact formula of redshift-space bispectrum

$$B^{(s)}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \int d\mathbf{r}_{13} d\mathbf{r}_{23} e^{i(\mathbf{k}_1 \cdot \mathbf{r}_{13} + \mathbf{k}_2 \cdot \mathbf{r}_{23})} \langle A_1 A_2 A_3 e^{j_4 A_4 + j_5 A_5} \rangle$$

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

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

Expand naively by  $\delta_1 \rightarrow$  standard perturbation theory

Exponential term is expanded as power series

$$\langle e^X \dots \rangle = \langle \underbrace{(1 + X + X^2/2 \dots)}_{\text{orange}} \dots \rangle$$
$$B_{\text{PT}} \simeq \begin{array}{c} B_{\text{tree}} \\ O((\delta_1)^4) \end{array} + \begin{array}{c} B_{\text{1-loop}} \\ O((\delta_1)^6) \end{array} + \dots$$

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

$$B^{(s)}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \int d\mathbf{r}_{13} d\mathbf{r}_{23} e^{i(\mathbf{k}_1 \cdot \mathbf{r}_{13} + \mathbf{k}_2 \cdot \mathbf{r}_{23})} \langle A_1 A_2 A_3 e^{\underline{j_4 A_4 + j_5 A_5}} \rangle \text{ Damping effect}$$

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

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

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

Exponential term is divided by cumulant expansion

$$\langle \underline{e^X} \cdots \rangle = \frac{\exp\{\langle e^X \rangle_c\} \{\langle \cdots \rangle_c \cdots\}}{\text{Taruya et al. ('10)}}$$

Our model



Calculate up  
to 1-loop level

$$B^{(s)}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \frac{D_{\text{FoG}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)}{\text{ }} \frac{B'_{\text{PT}}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)}{\text{ }}$$

# Comparing with N-body

Hashimoto  
et al. ('17)

## Dark Energy Universe Simulation (DEUS)

Box size: 1312.5 Mpc/h, # of particles: 512<sup>3</sup>,  
# of realizations : 512

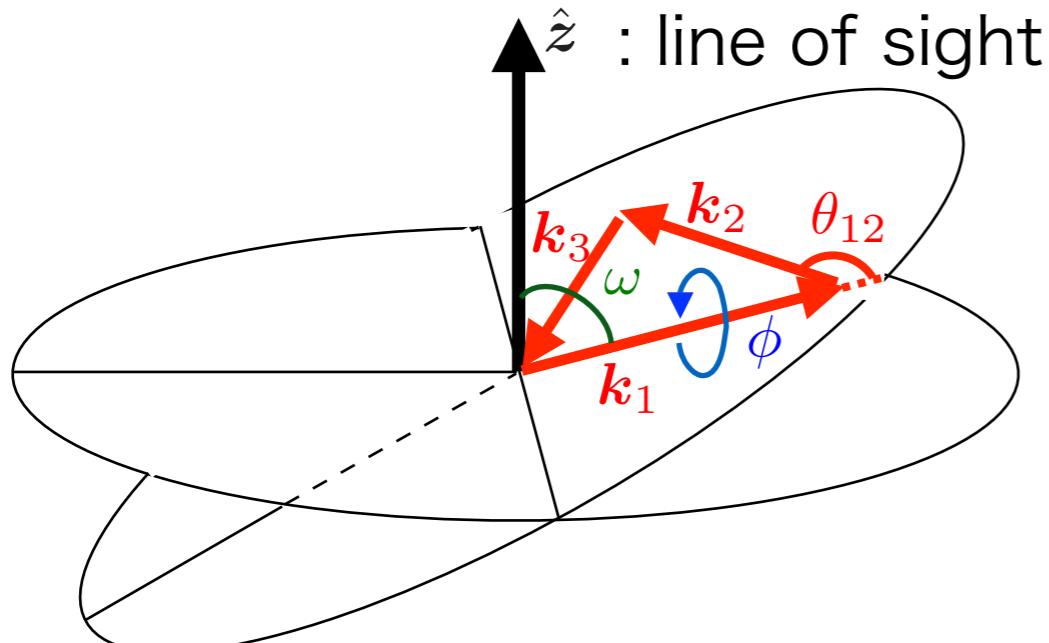
Blot et al. ('14)

### Comparing bispectrum expanded by Legendre polynomial

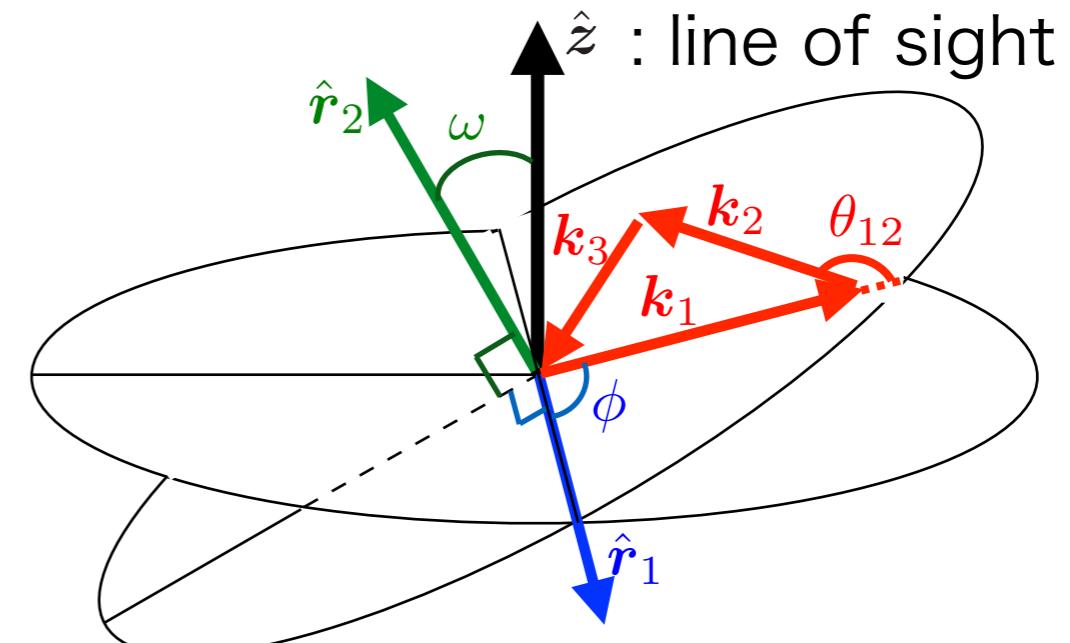
$$\hat{B}_\ell^{(s)}(k_1, k_2, \theta_{12}) = \int_{-1}^1 d\mu \int_0^{2\pi} \frac{d\phi}{2\pi} B^{(s)}(k_1, k_2, \theta_{12}, \mu, \phi) P_\ell(\underline{\mu})$$

$\mu = \cos \omega$

Scoccimarro et al ('98)

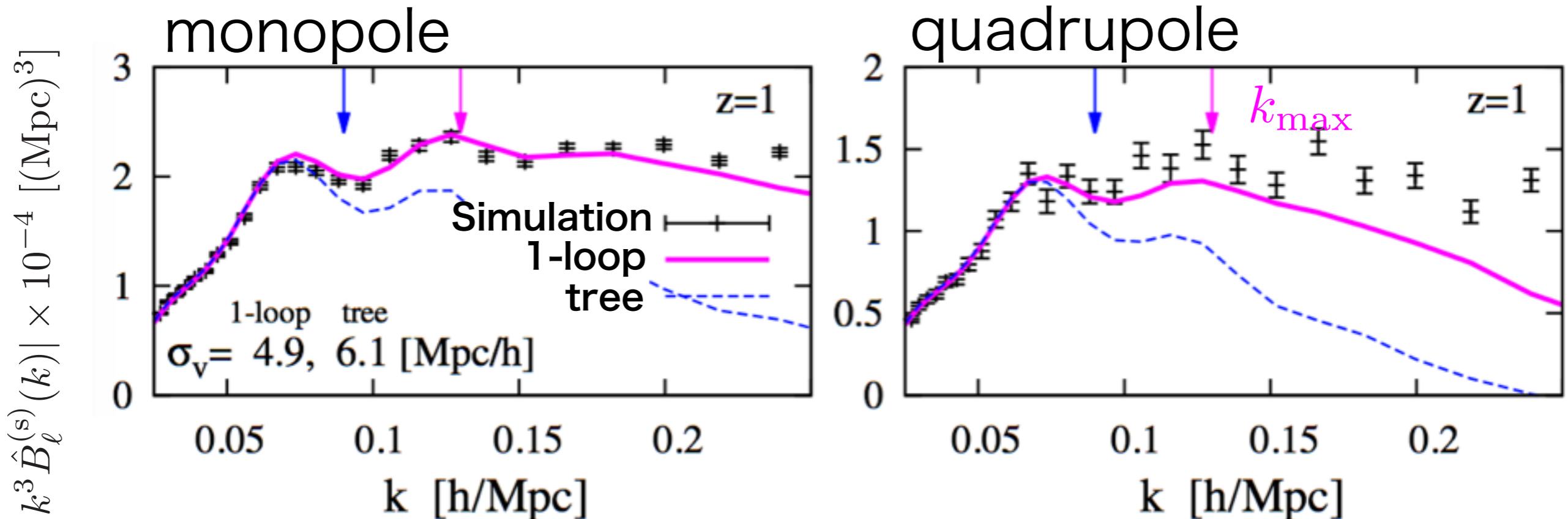


Our definition



# Bispectrum of matter field

Scale dependance of bispectrum ( $k_1 = k_2 = k_3$ )



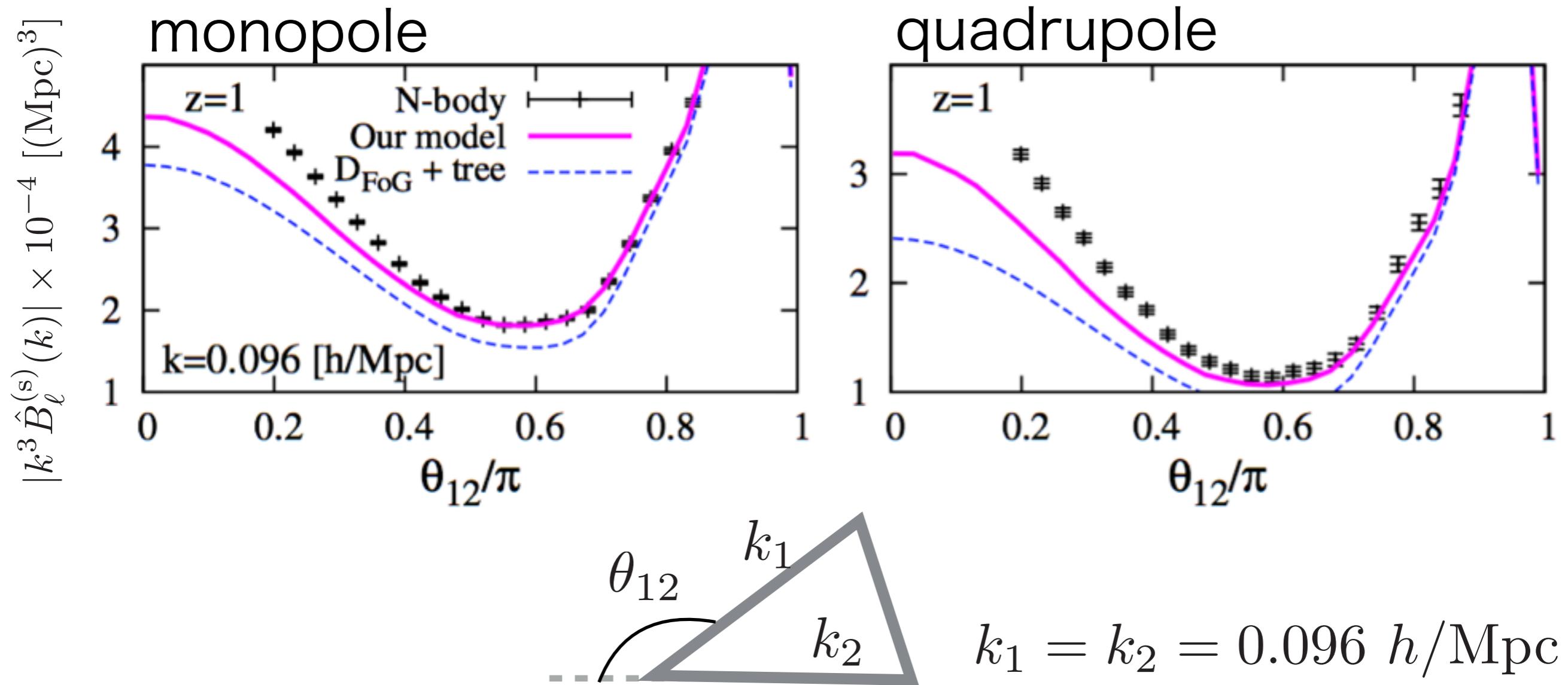
$$D_{\text{FoG}}(q) = e^{-\frac{1}{2}(f\sigma_v q)^2}$$

$$q = k_{1z}^2 + k_{2z}^2 + k_{3z}^2, \quad \sigma_v : \text{fitting parameter}$$

Consistent with N-body in wide range for both case,  
monopole and quadrupole

# Bispectrum of matter field

## Shape dependance of bispectrum

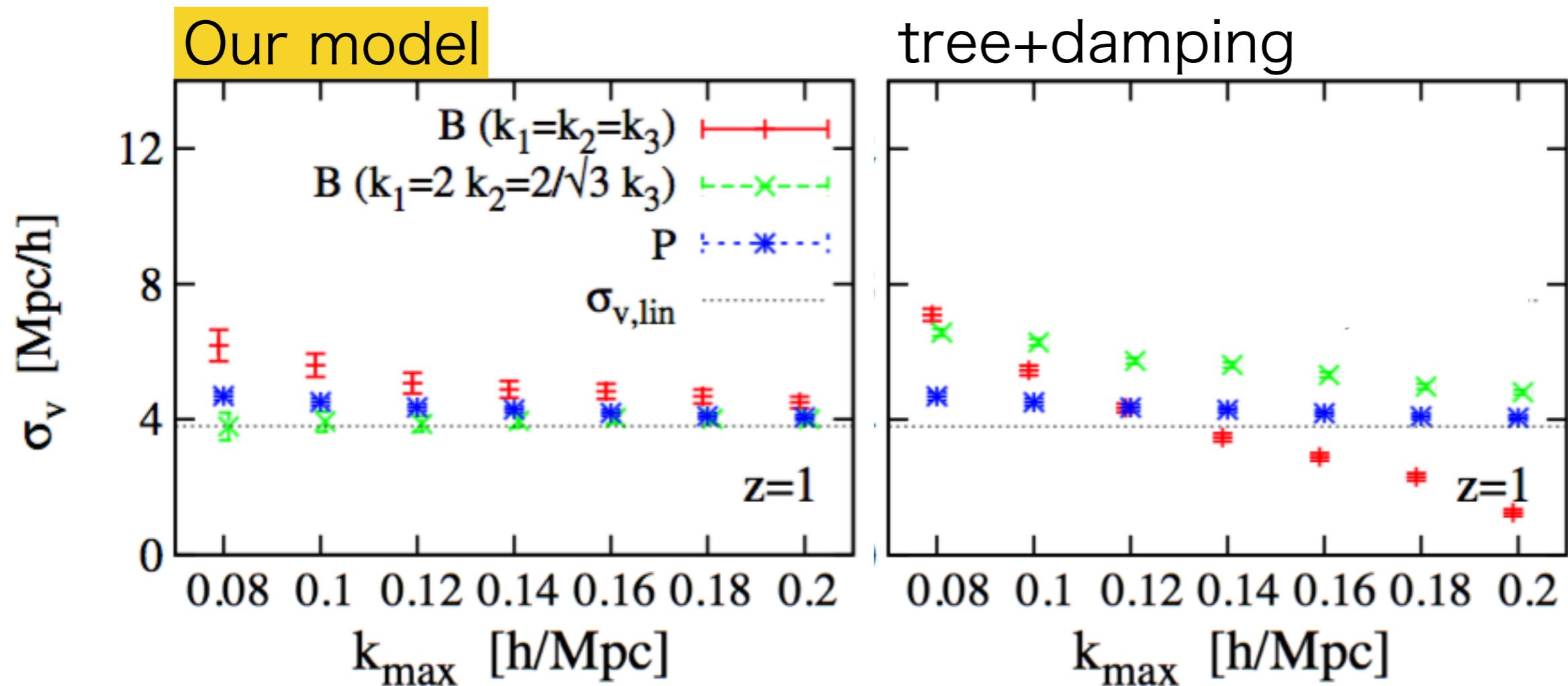


Consistent with N-body in wide range for both case,  
monopole and quadrupole

# 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 in matter field

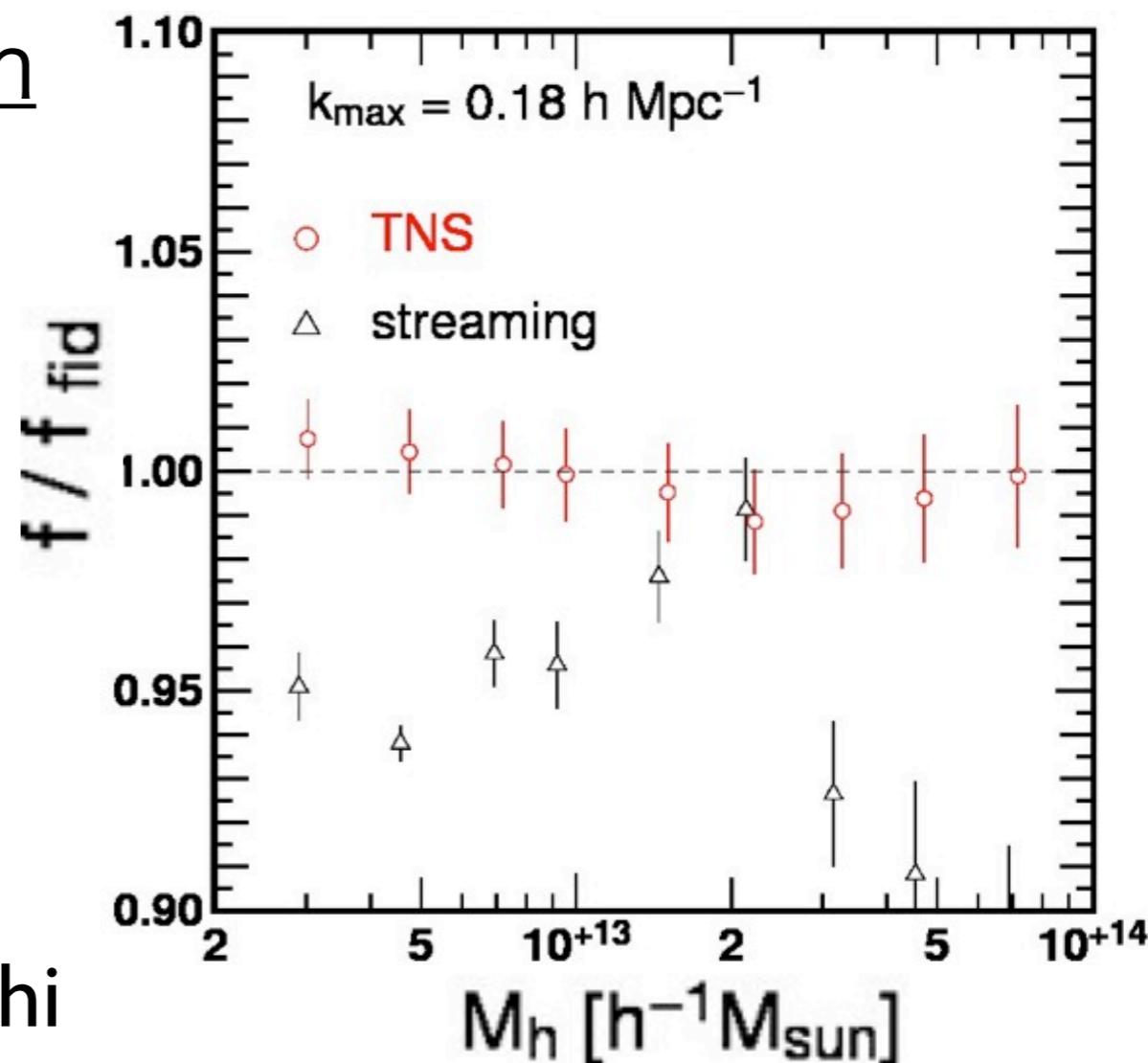
# Next step

- Matter density  $\rightarrow$  Halo number density
- Quantifying systematic error when we estimate cosmological parameters by using our model

In the case of power spectrum

Fitting parameters:  $f, \sigma_v$

We want to do similar test  
in the case of bispectrum



# Method

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1. Construct halo number density field from N-body

**Gadget2** : Box size : 1 [Gpc<sup>3/h</sup>], # of particles: 1024<sup>3</sup>,  
# of realizations : 300

Identifying halos ( $M_h > 10^{-12} M_{\text{sun}}$ ) by using  
**subfind code** Springel et al. (2001)

2. Estimate parameters by our theoretical model

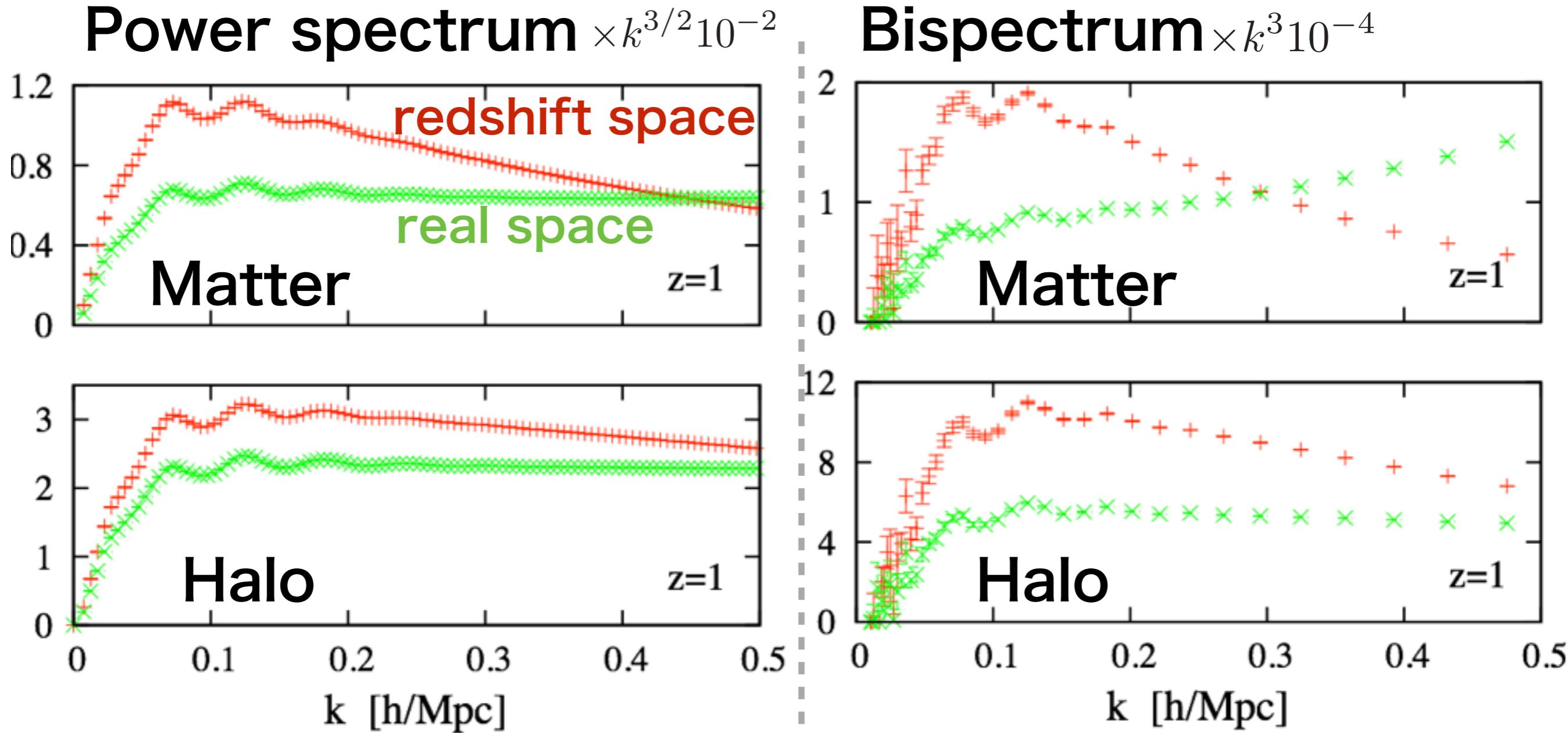
For preliminary test, we employed linear bias model :

$$\delta_h = b \delta_m$$

3. Compare fiducial and estimated parameters

Fitting parameters:  $f, \sigma_v, b$

# Statistics of halo field

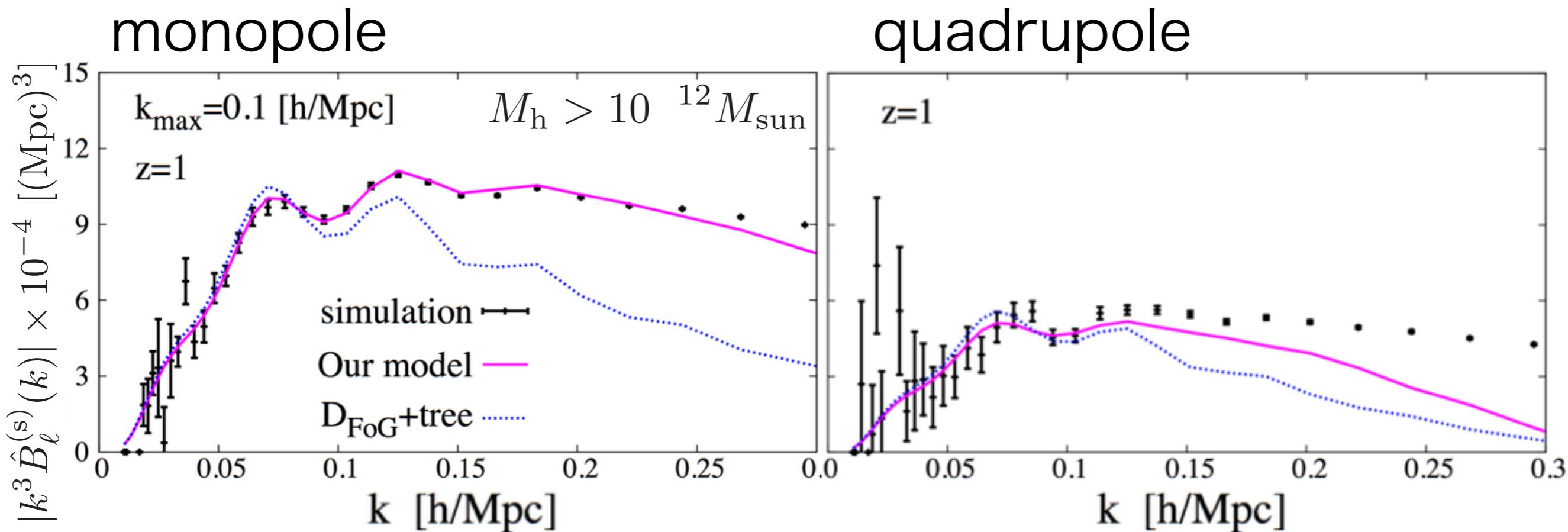


In halo number density field, FoG effect becomes weaker than in matter density field

# Preliminary results

## Scale dependance of bispectrum ( $k_1 = k_2 = k_3$ )

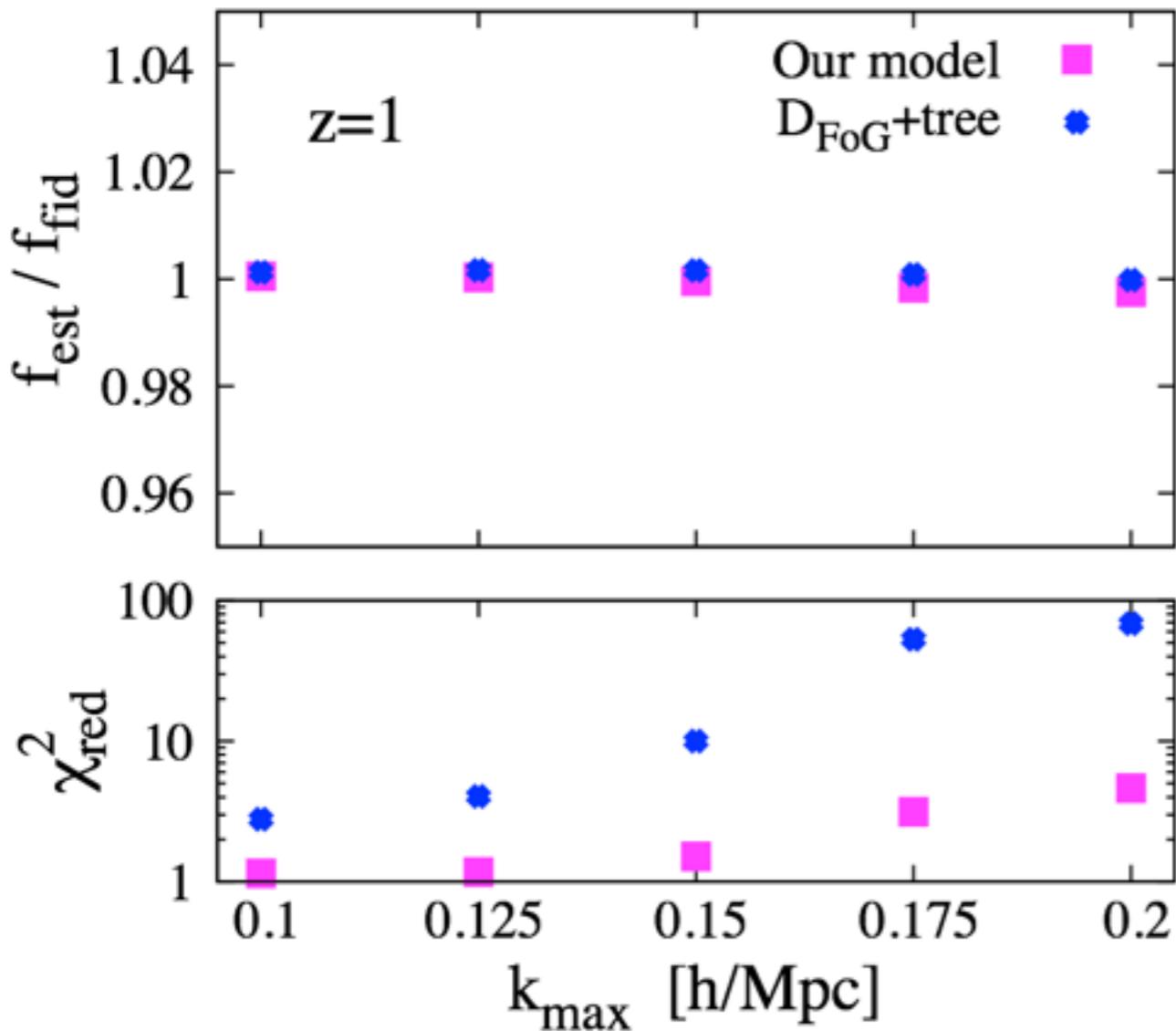
Fitting parameters:  $f, \sigma_v, b$



Even linear bias model, our theoretical model  
regenerate simulation results in high accuracy

# Preliminary results

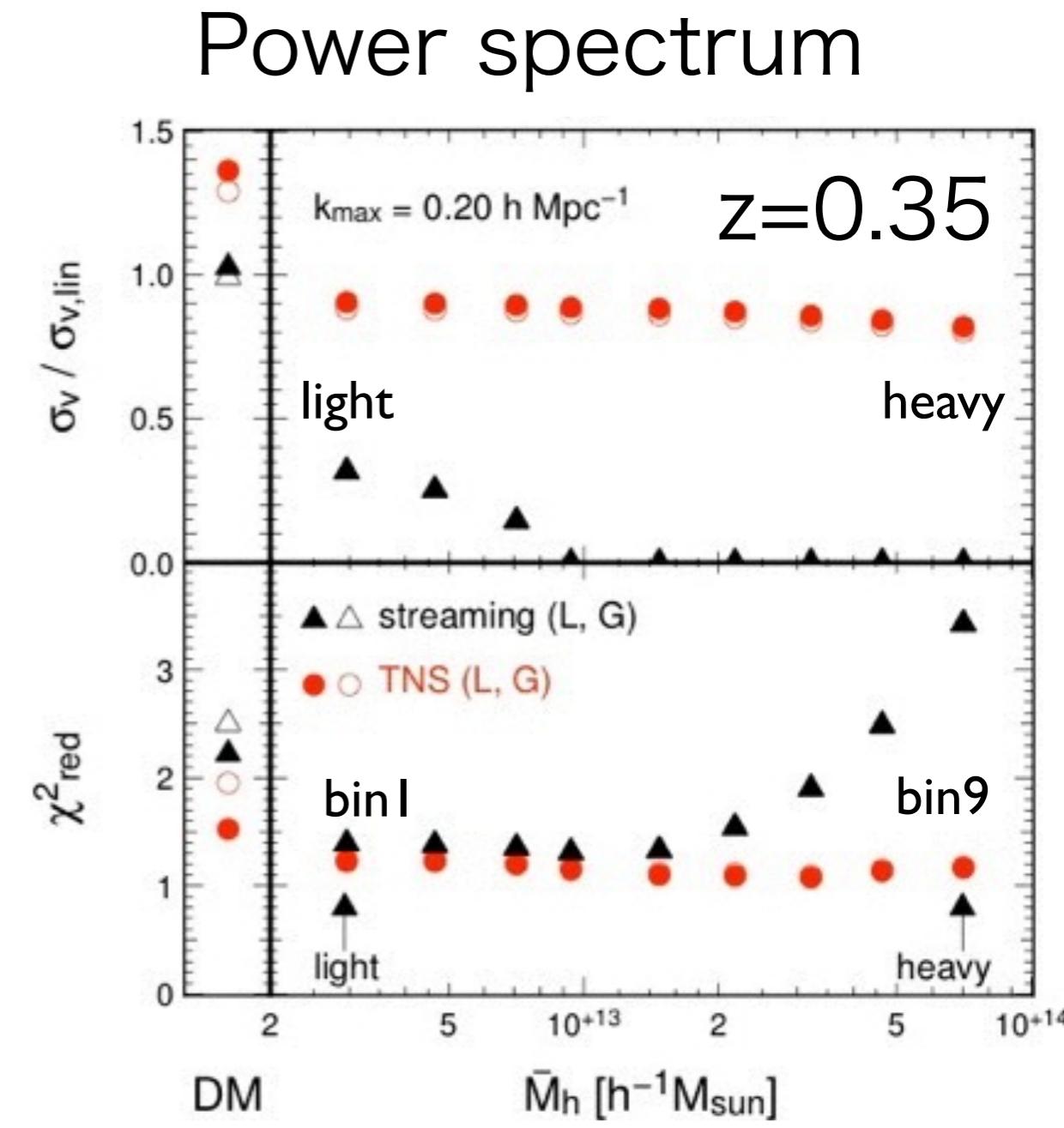
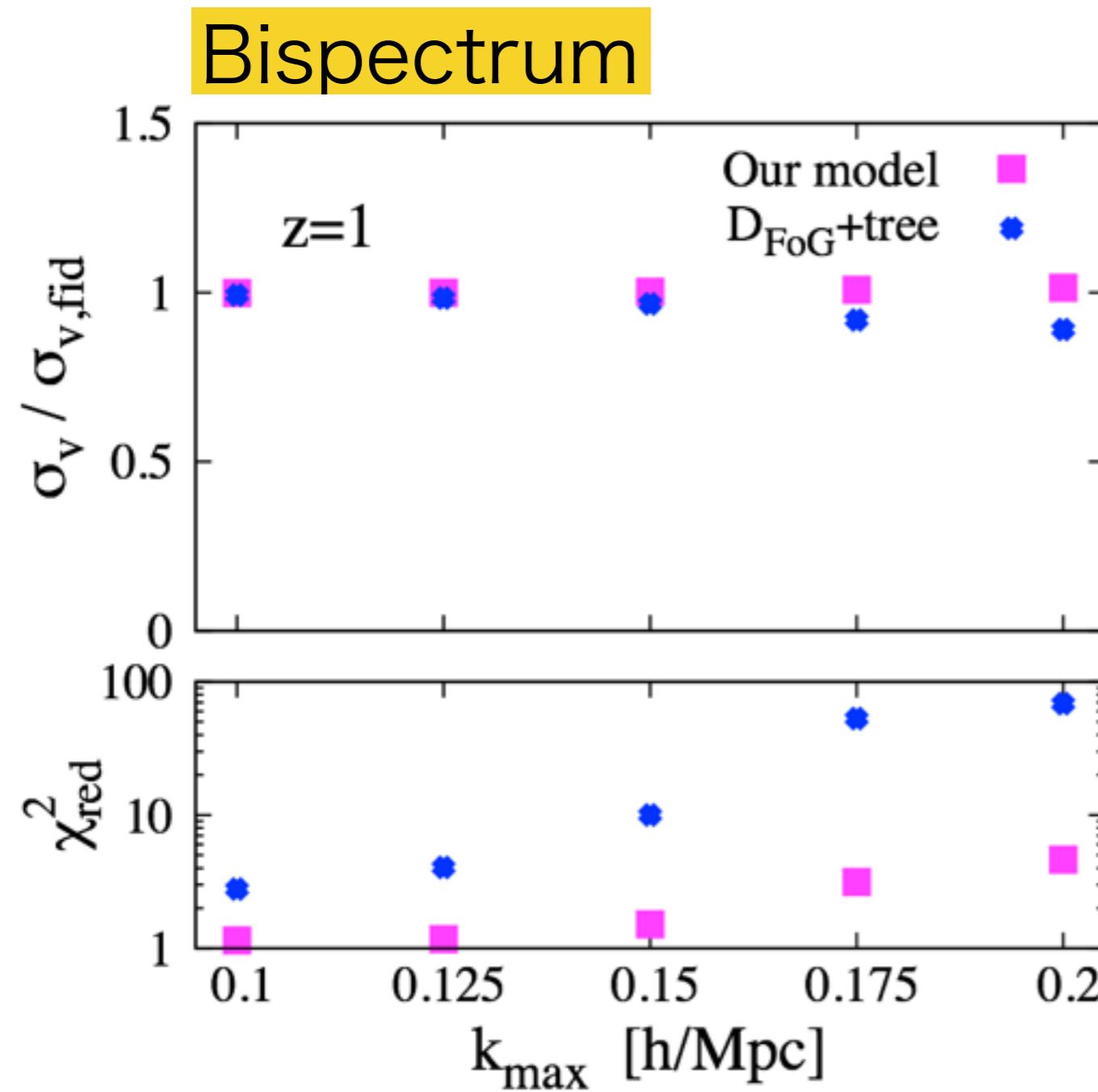
## Growth rate



- Best fit values are well consistent with fiducial
- $\chi^2_{\text{red}}$  of our model is  $O(1)$  even at large  $k_{\text{max}}$
- We should add error bars

# Preliminary results

## Velocity dispersion



# Summary

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## ■ What we did

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

## ■ Result

- Our model produce bispectrum in quasi non-linear regime in matter and halo number density field
- Best fit value of  $f$  is well consistent with fiducial value
- $\sigma_v$  of bispectrum is consistent with that of power spectrum

## ■ Future work

- Including proper bias model
- Investigating the error of estimated parameters