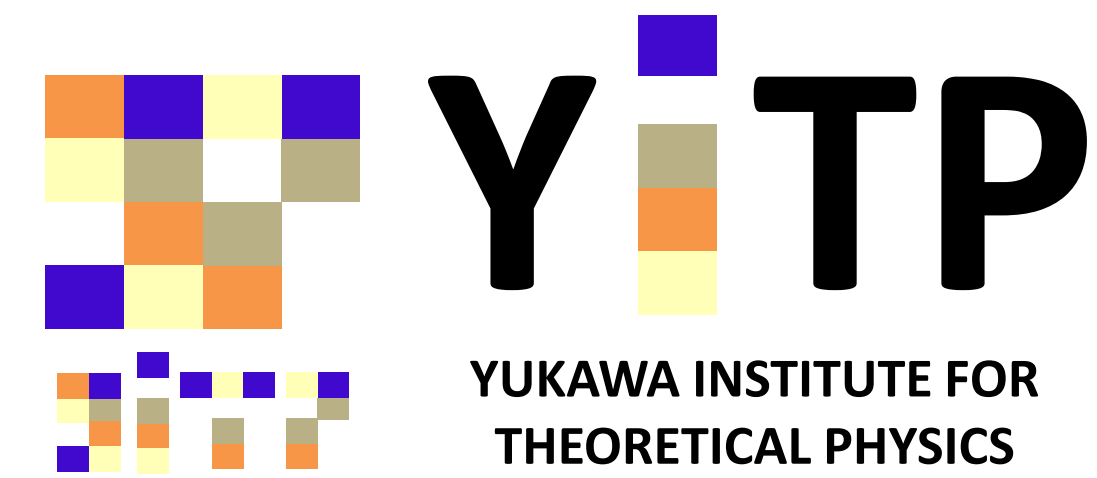


2026 June 22-26
Focused research on the origin
and evolution of the Universe
@ APCPT, Pohang



Galaxy shapes and alignments as a novel probe of cosmology

**Atsushi Taruya
(YITP/KIAS)**

In collaboration with

Toshiki Kurita (MPA), Teppei Okumura (ASIAA), Takahiro Nishimichi (Kyoto Sangyo.U),
Junsup Shim (PNU)

Plan of talk

Intrinsic galaxy shapes and alignments as cosmological probes,
alternative or complementary to conventional galaxy clustering

Motivation

Galaxy ellipticity fields as a novel probe of cosmology :

Measurements & future forecast

Improved modeling in redshift space

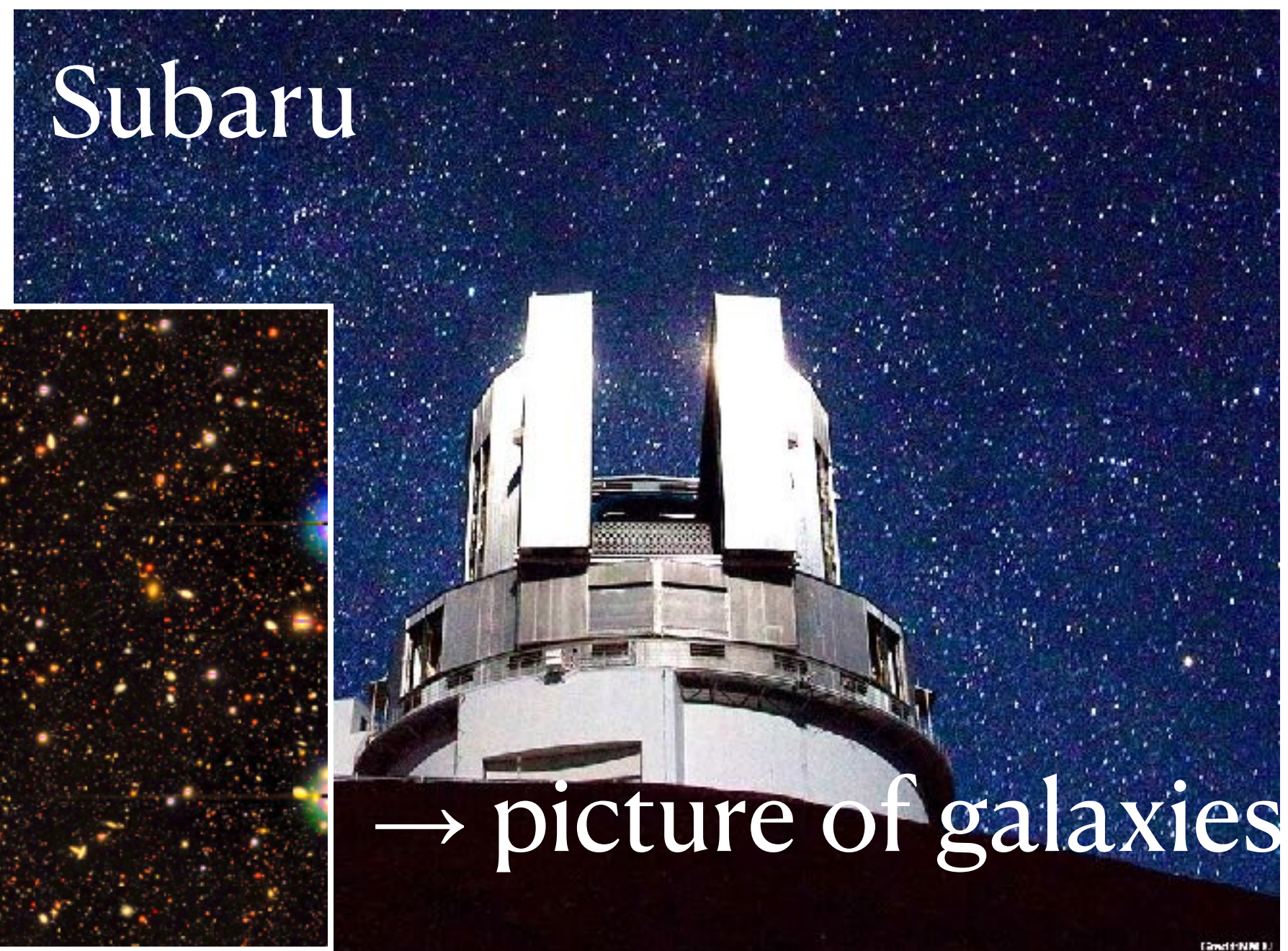
Summary

Mapping large-scale structure

Galaxy surveys play a major role

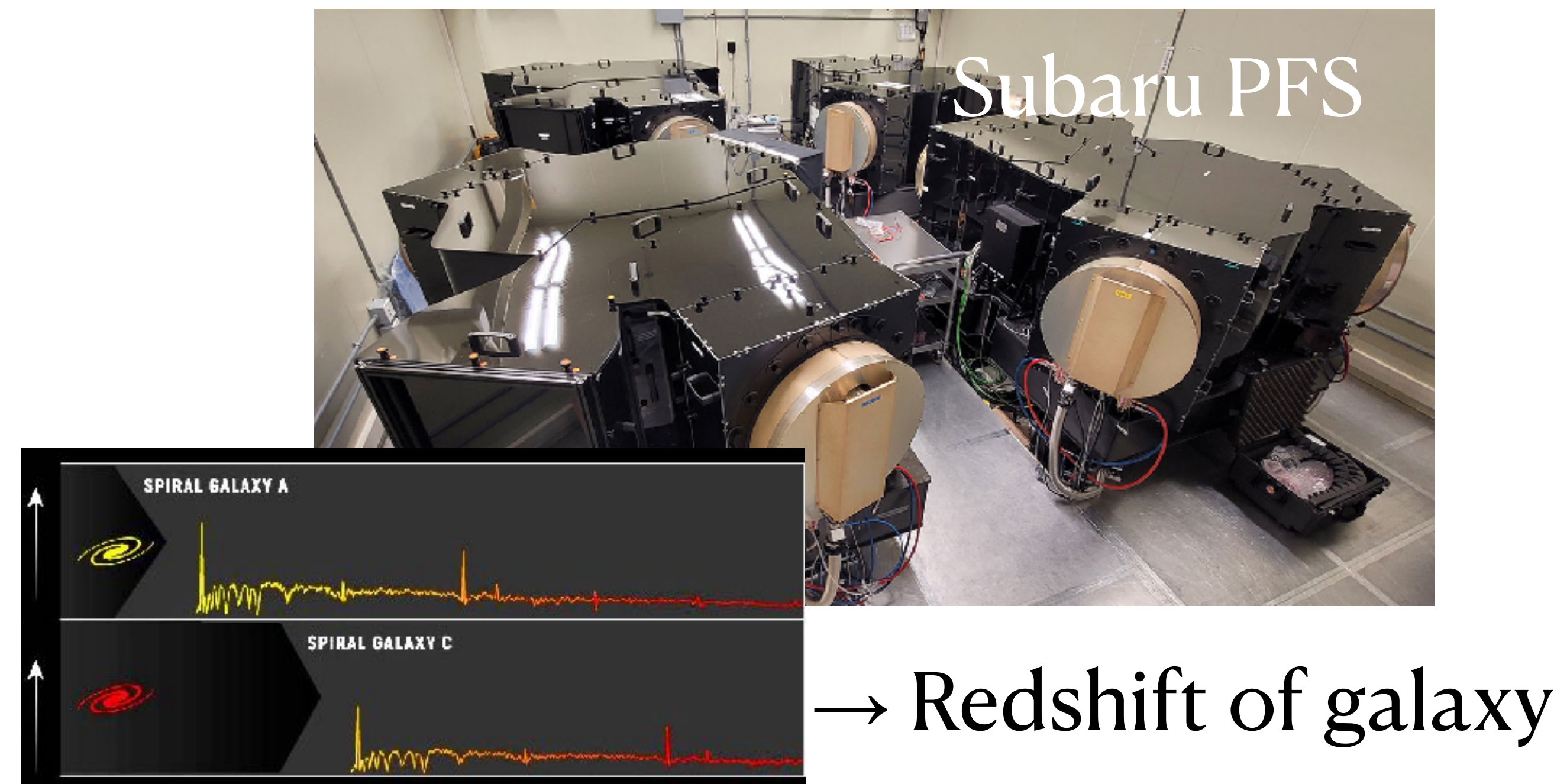
✓ Imaging surveys

(DES, HSC, KiDS, ...)



✓ Spectroscopic surveys

(BOSS, DESI, Euclid, Subaru-PFS,...)



Mapping large-scale structure

Galaxy surveys play a major role

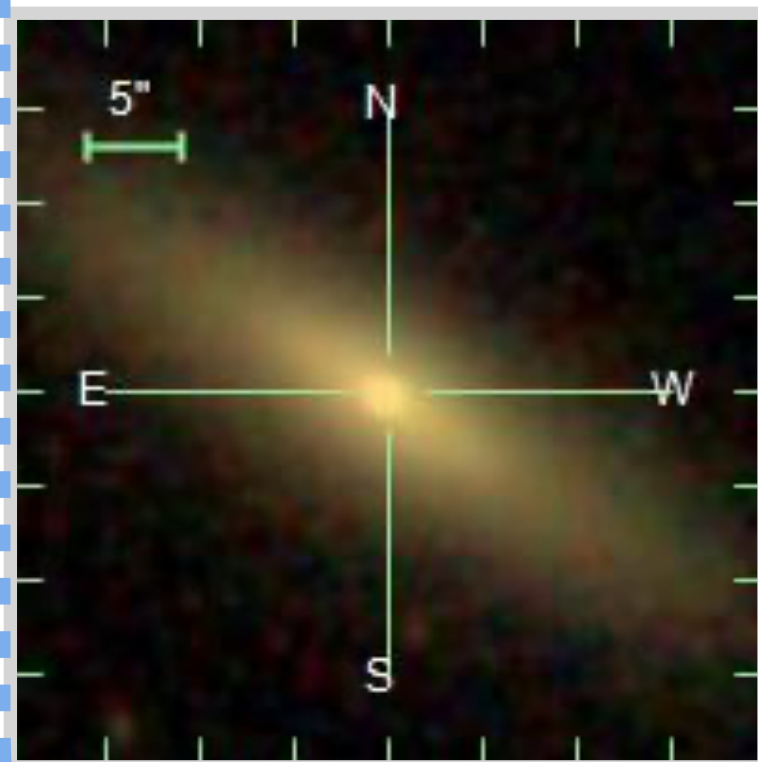
Imaging
surveys

Galaxy
2D map

Redshift

Spectroscopic
surveys

Galaxy
3D map



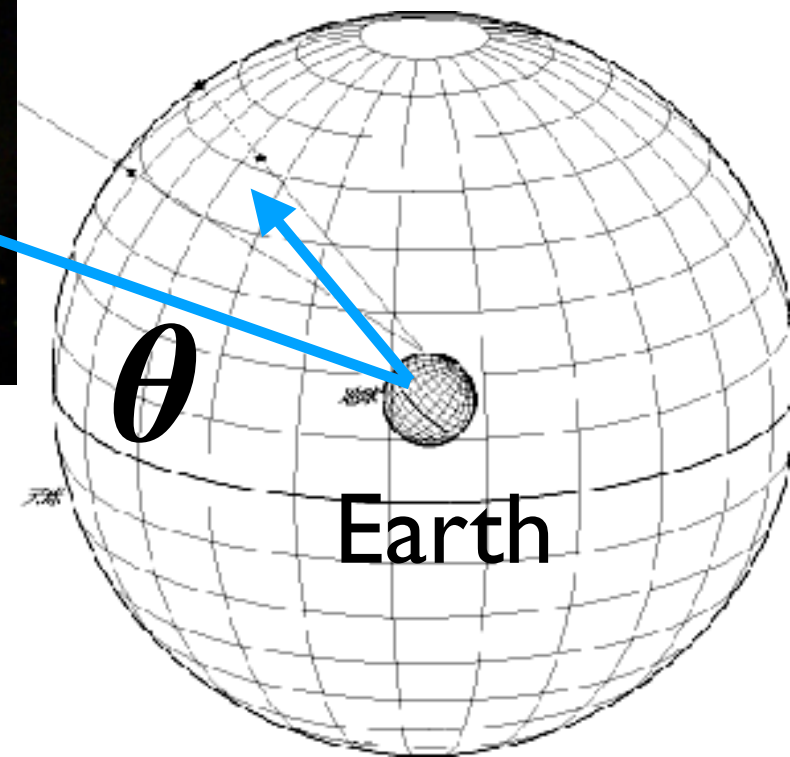
Mapping large-scale structure

Information of LSS we can get

Imaging surveys

2D galaxy density field + *projected* shapes/alignments

(As a function of angular position)

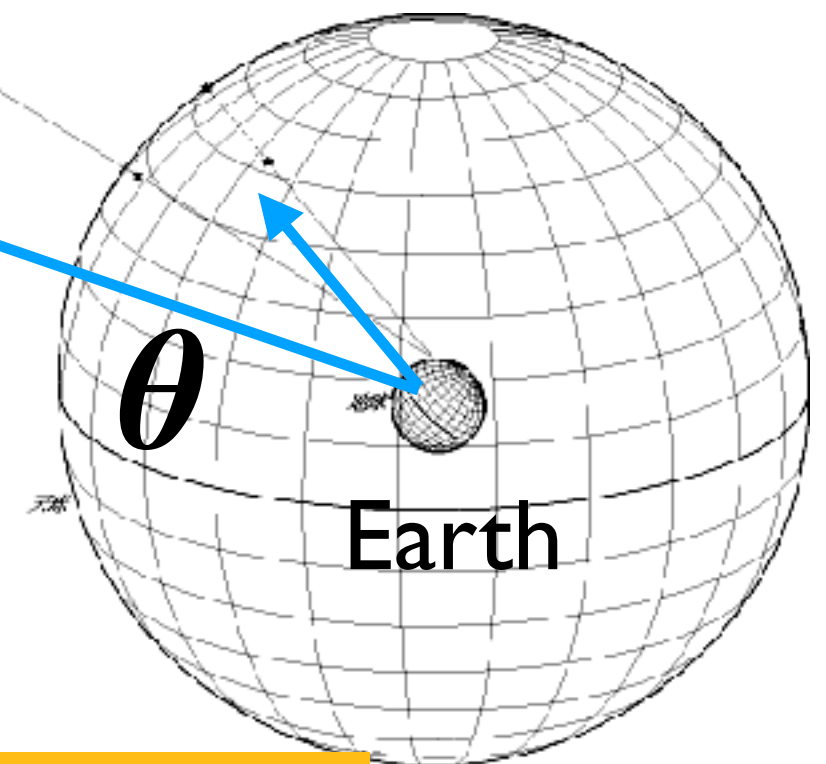


Spectroscopic surveys

3D galaxy density field

(As a function of angular position & redshift)

Redshift z



These information have been so far treated separately

In this talk, we consider the benefit of combining these information

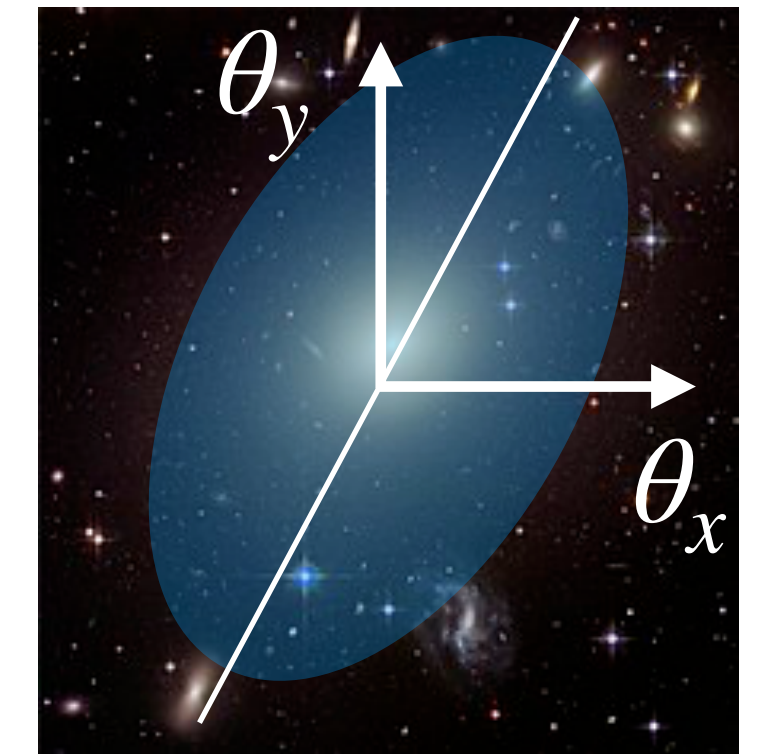
Characterizing galaxy shape/alignment⁶

Galaxies are not circular, are aligned in a certain direction

As a simple characterization,

Second moment
of galaxy image

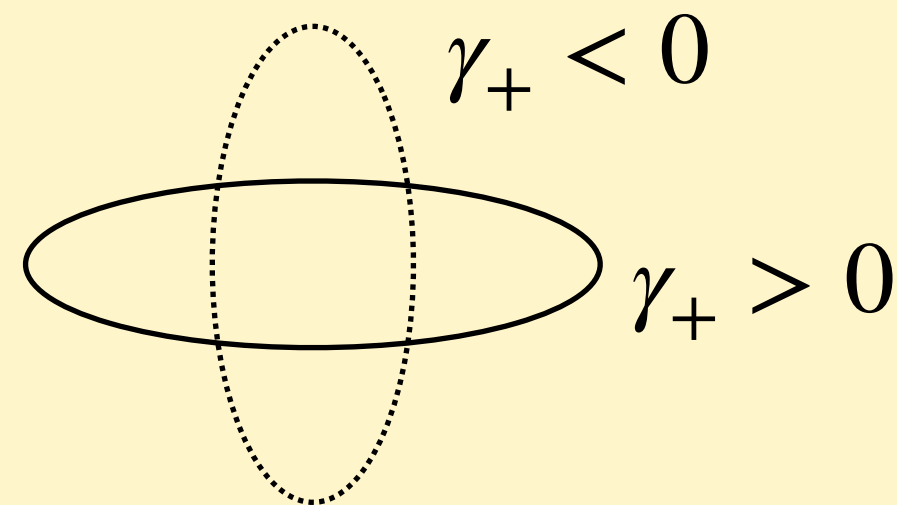
$$I_{ij} \equiv \int d^2\theta \text{Intensity } I_{\text{obs}}(\theta) \theta_i \theta_j$$



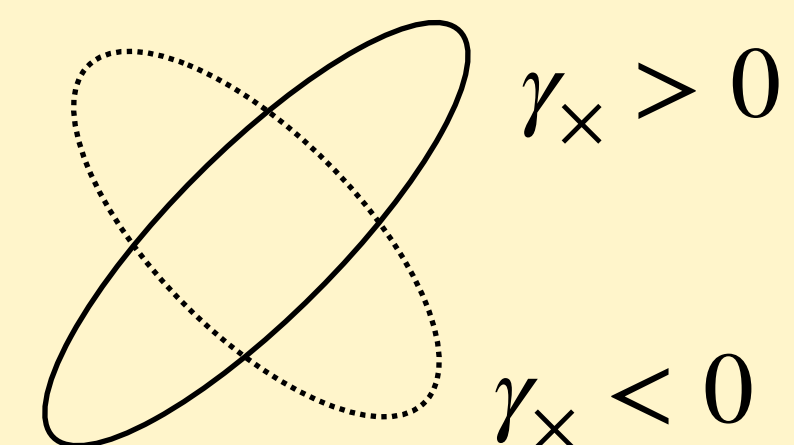
Ellipticity

$$\gamma_+ \equiv \frac{I_{xx} - I_{yy}}{I_{xx} + I_{yy}},$$

(Traceless & offdiagonal)



$$\gamma_{\times} \equiv \frac{2 I_{xy}}{I_{xx} + I_{yy}}$$



→ Have been long used in weak-lensing analysis What is extra benefit ?

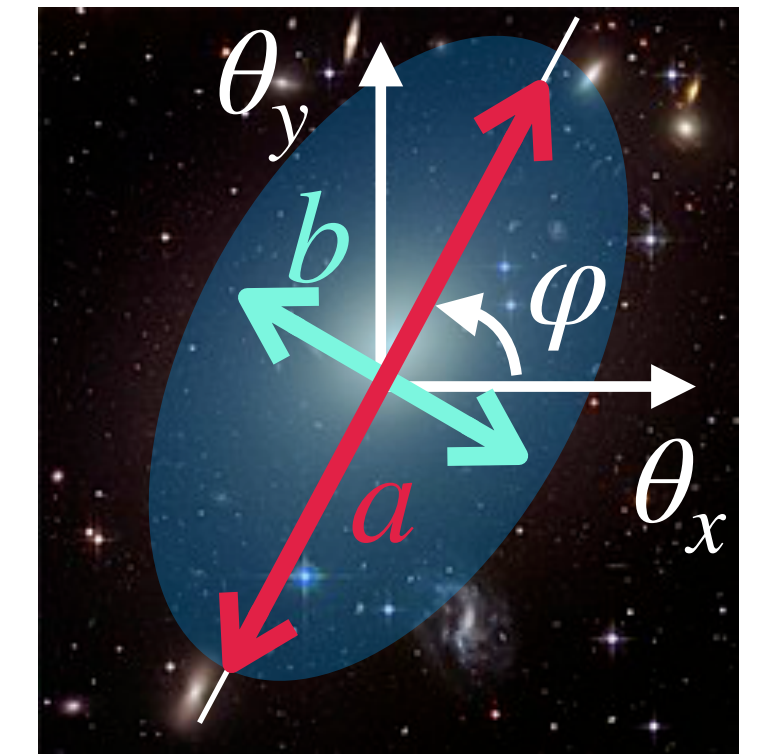
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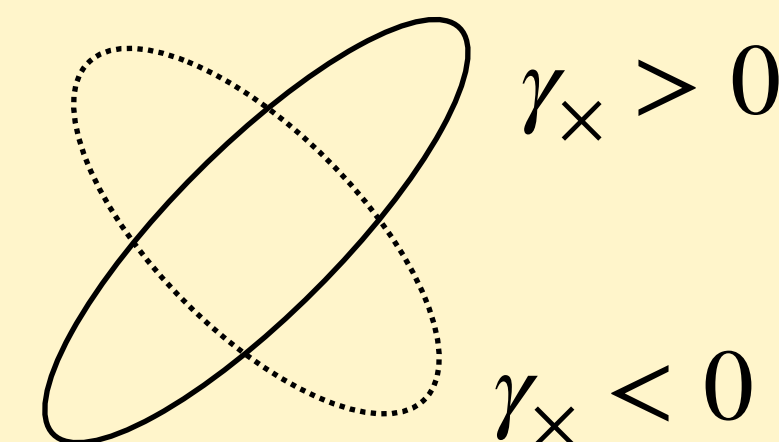
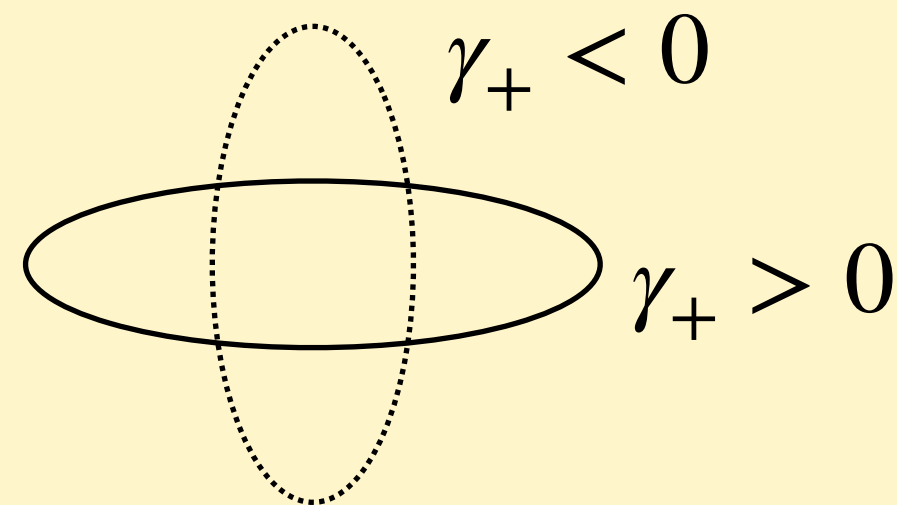
$$I_{ij} \equiv \int d^2\theta \text{Intensity } I_{\text{obs}}(\theta) \theta_i \theta_j$$



Ellipticity

$$\gamma_+ \equiv \frac{1 - (b/a)^2}{1 + (b/a)^2} \cos(2\varphi), \quad \gamma_{\times} \equiv \frac{1 - (b/a)^2}{1 + (b/a)^2} \sin(2\varphi)$$

(Traceless & offdiagonal)



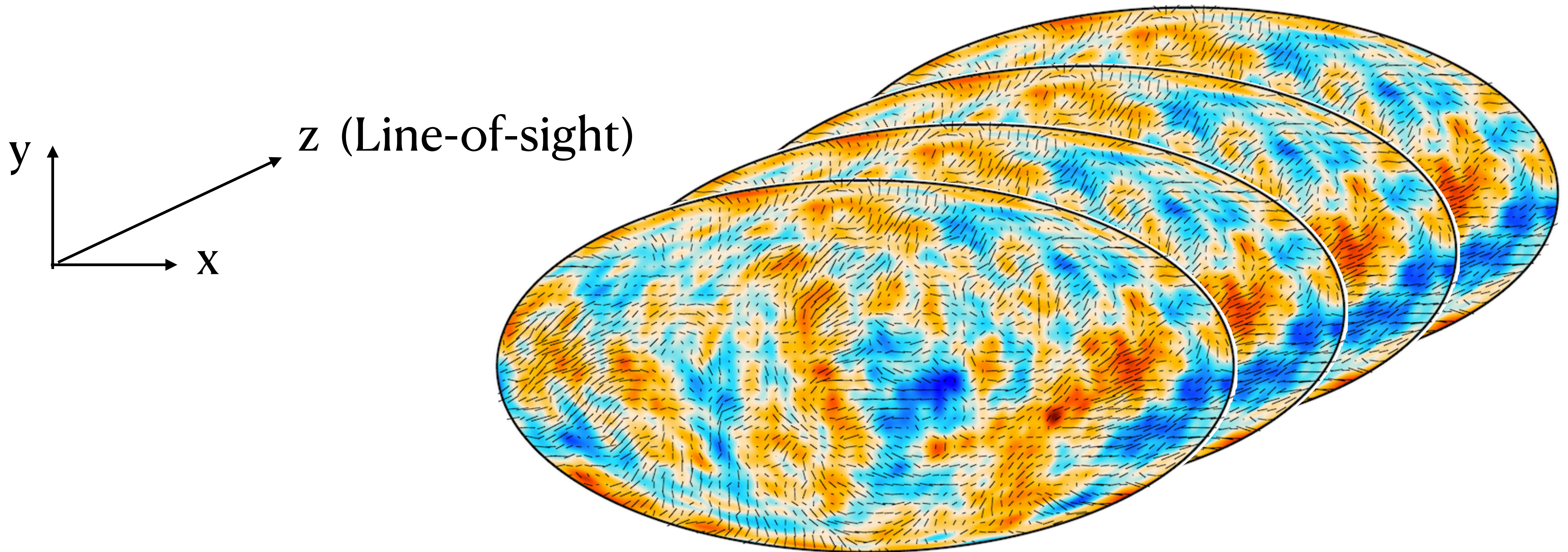
Minor-to-major
axis ratio

→ Have been long used in weak-lensing analysis What is extra benefit ?

Galaxy density & intrinsic ellipticity fields

Galaxy density + ellipticity fields

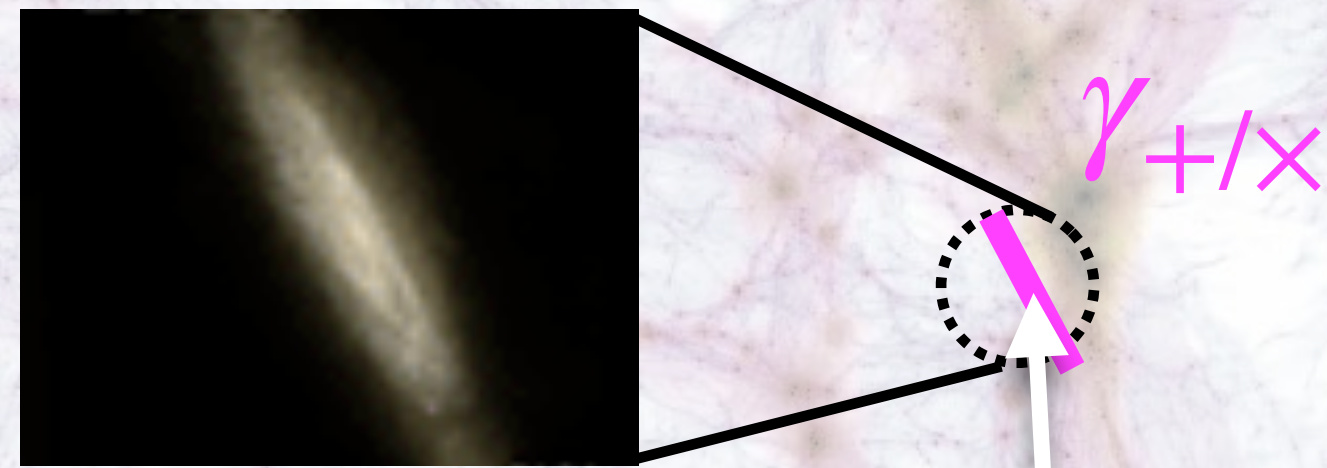
$\approx$ 3D version of CMB anisotropies (temperature & polarizations)



These are supposed to be more informative than CMB

Galaxy density & intrinsic ellipticity fields⁹

Galaxies are known to follow the mass density field of large-scale structure (LSS)



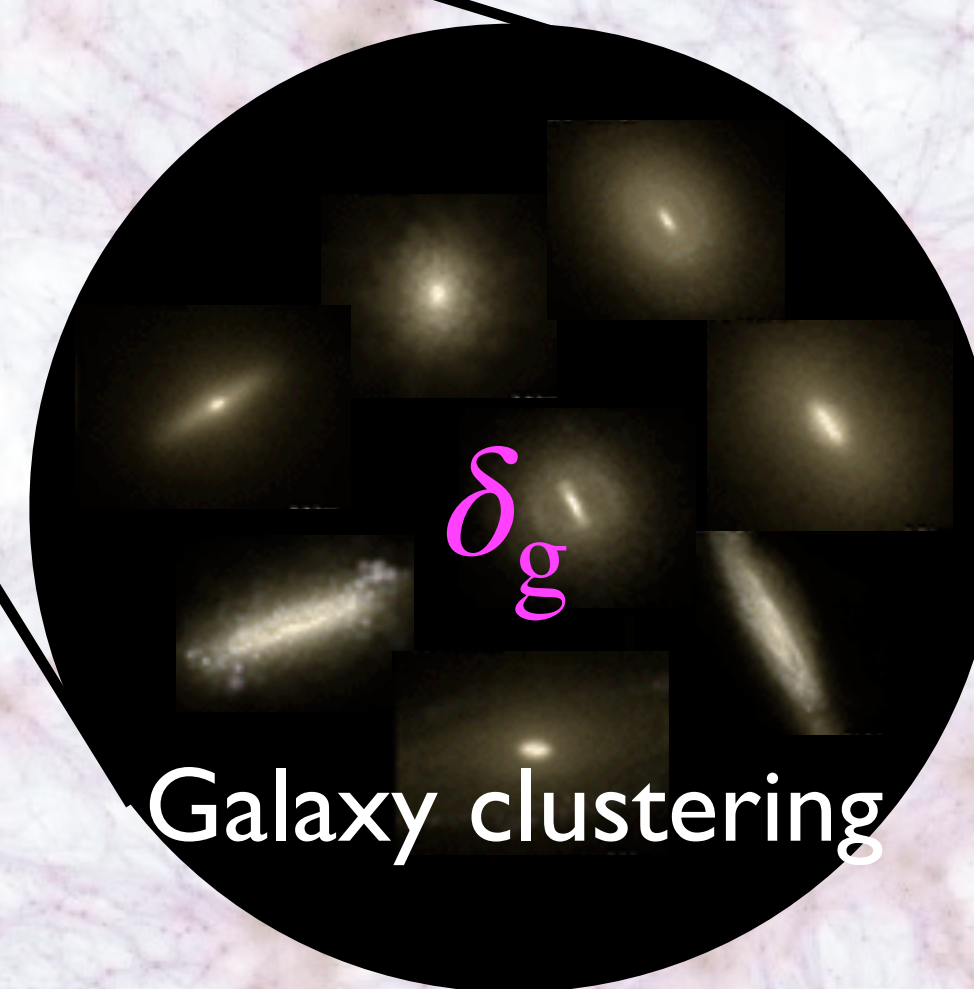
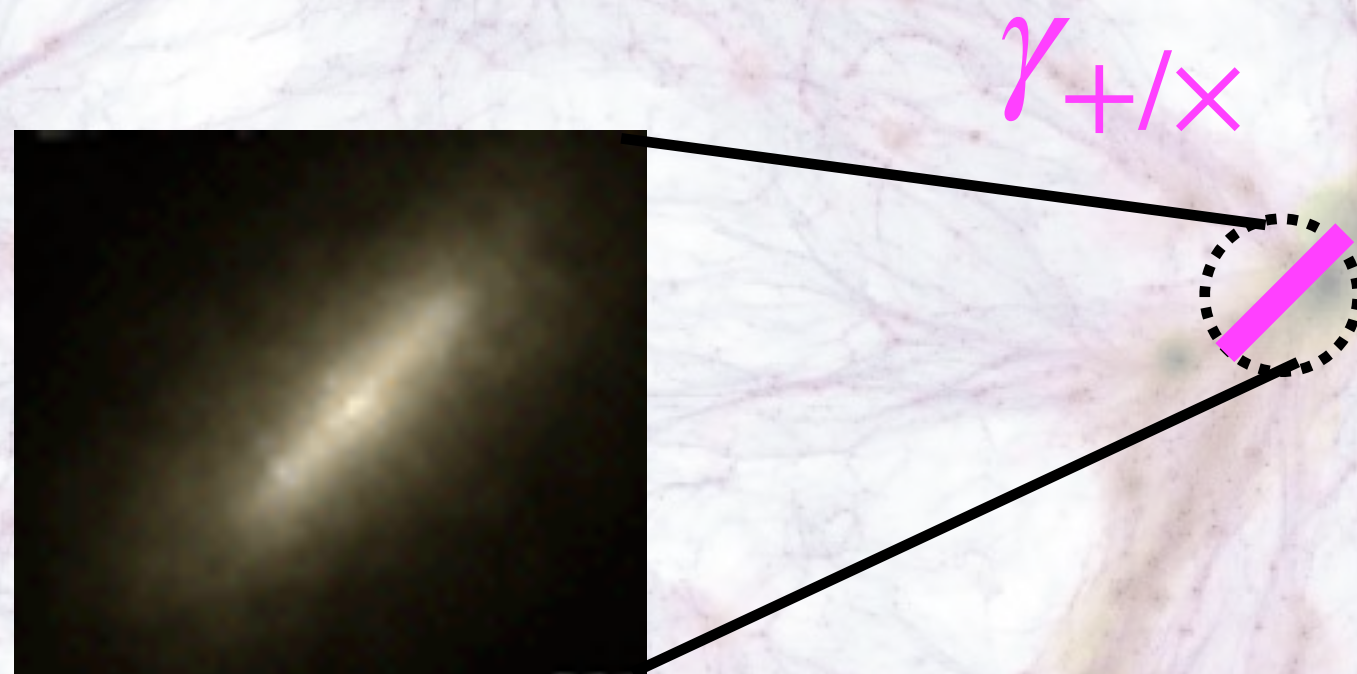
(i.e., δ_g is a tracer field of LSS)

Likewise,

galaxies are supposed to be aligned with the tidal force field of large-scale structure

(i.e., $\gamma_{+/\times}$ is also a tracer field)

Distance



Galaxy clustering

Ellipticity field as cosmological probe

Tightening **cosmological parameter** constraints

Chisari and Dvorkin ('13); AT & Okumura ('20); Okumura & AT ('22); Shim, Okumura & AT ('25ab)

Probing **parity violation** signature

Philcox et al. (2024); Kurita, Jamieson, Komatsu & Schmidt ('26)
(See also Bakx et al. ('26), Shim et al. ('25), Yu, Shim & Song ('26))

Probing **dark matter** self-interaction

Harvey, Chisari, Robertson & McCarthy ('21)

Imprint of **relativistic effects**

Saga, Okumura, AT & Inoue ('23)

Imprint of **primordial Non-Gaussianity (by higher spin fields)**

Schmidt, Chisari & Dvorkin ('15); Kogai, Matsubara, Nishizawa & Urakawa ('18);
Kogai, Akitsu, Schmidt & Urakawa ('21); Akitsu, et al. ('21); Kurita & Takada ('23)

Long-wavelength **gravitational waves**

Schimit & Jeong ('12); Schimit Pajer & Zaldarriaga ('14); Chisari, Dvorkin & Schmidt ('14);
Biagetti M, Orlando G ('20); Akitsu, Li & Okumura ('23)

Long-wavelength **primordial magnetic field**

Saga, Shiraishi, Akitsu & Okumura ('24)

Two-point statistics

Combining the information from imaging & spectroscopic surveys,

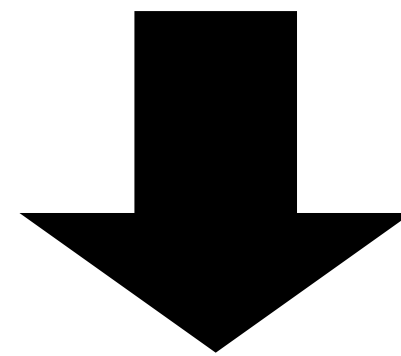
Observables:

$$\delta_g(\mathbf{x})$$

galaxy density field

$$\gamma_{+/\times}(\mathbf{x})$$

galaxy ellipticity field



$\mathbf{x}$: 3D comoving position constructed from angular position θ and redshift z

Two-point
statistics
($\mathbf{r} \equiv \mathbf{x}_1 - \mathbf{x}_2$)

New!

$$\xi_{gg}(\mathbf{r}) \equiv \langle \delta_g(\mathbf{x}_1) \delta_g(\mathbf{x}_2) \rangle$$

GG correlation

$$\xi_{g+}(\mathbf{r}) \equiv \langle \delta_g(\mathbf{x}_1) \gamma_+(\mathbf{x}_2) \rangle$$

GI correlation

$$\xi_{\pm}(\mathbf{r}) \equiv \langle \gamma_+(\mathbf{x}_1) \gamma_+(\mathbf{x}_2) \pm \gamma_{\times}(\mathbf{x}_1) \gamma_{\times}(\mathbf{x}_2) \rangle$$

II correlation

$\xi_{g\times}$ vanishes by symmetry

Other statistics are worth for further investigation (e.g., Minkowski tensors)

Two-point statistics

Combining the information from imaging & spectroscopic surveys,

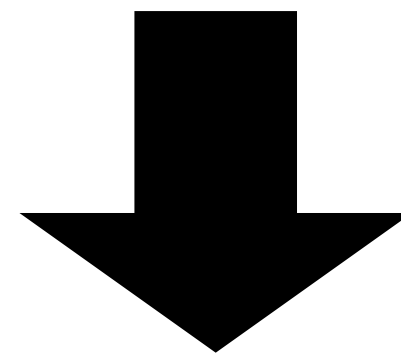
Observables:

$$\delta_g(\mathbf{x})$$

galaxy density field

$$\gamma_{+/\times}(\mathbf{x})$$

galaxy ellipticity field



Fourier counterpart

E/B-mode decomposition

$$\gamma_E + i \gamma_B = e^{-i 2 \phi_k} \{ \gamma_+ + i \gamma_{\times} \}$$

Two-point
statistics

(Power spectra)

P_{gB} vanishes by symmetry

New!

$$P_{gg}(k)$$

$$P_{gE}(k)$$

$$P_{EE}(k), \quad P_{BB}(k) \quad (\simeq 0)$$

GG correlation

GI correlation

II correlation

Other statistics are worth for further investigation (e.g., Minkowski tensors)

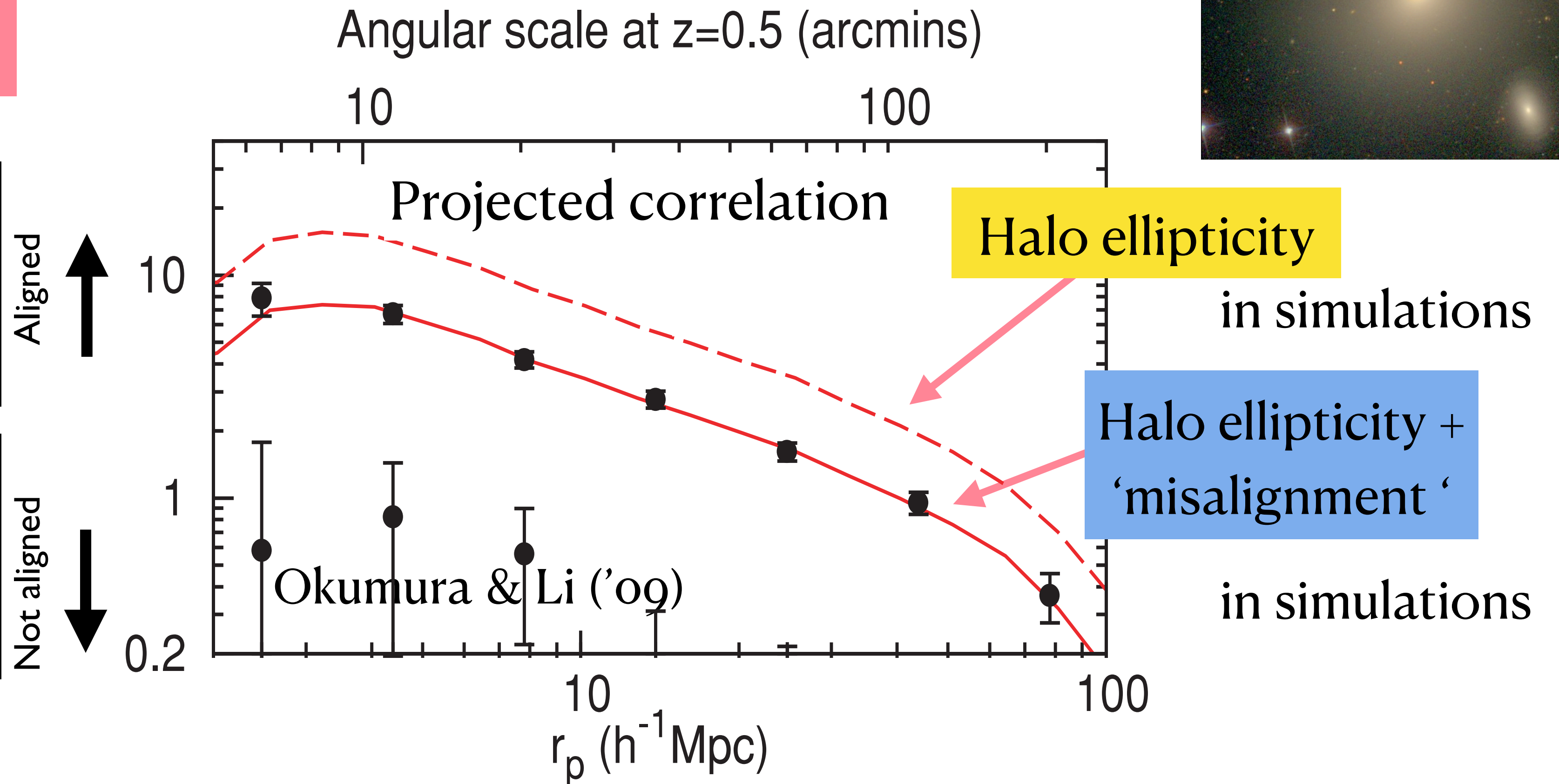
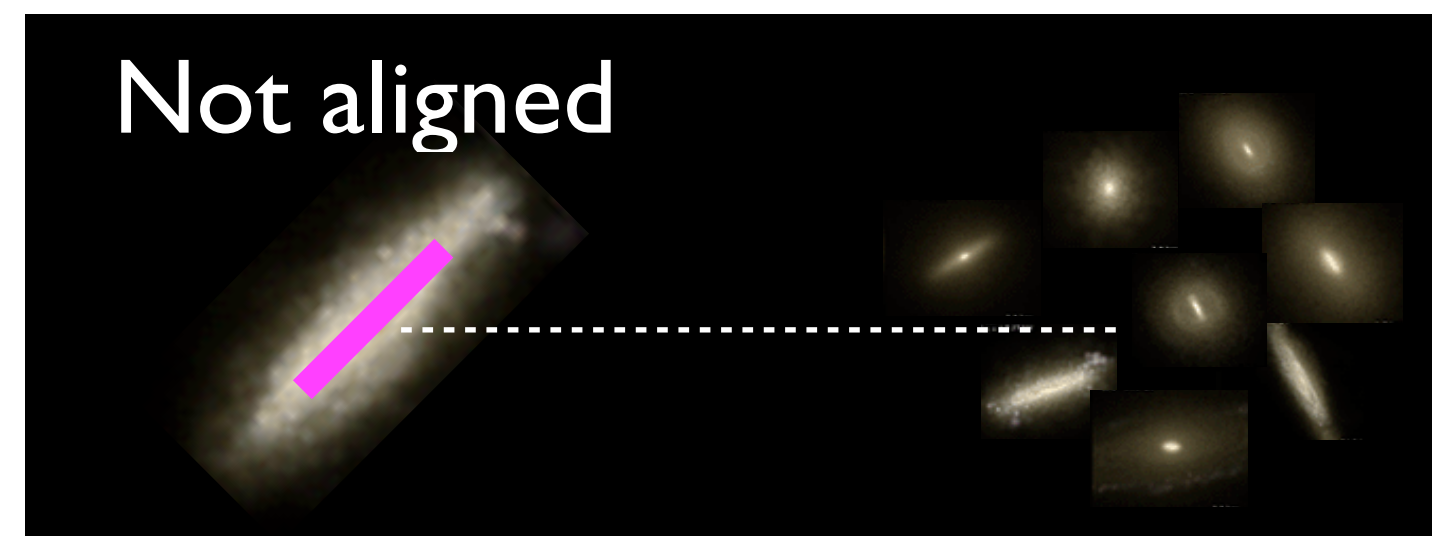
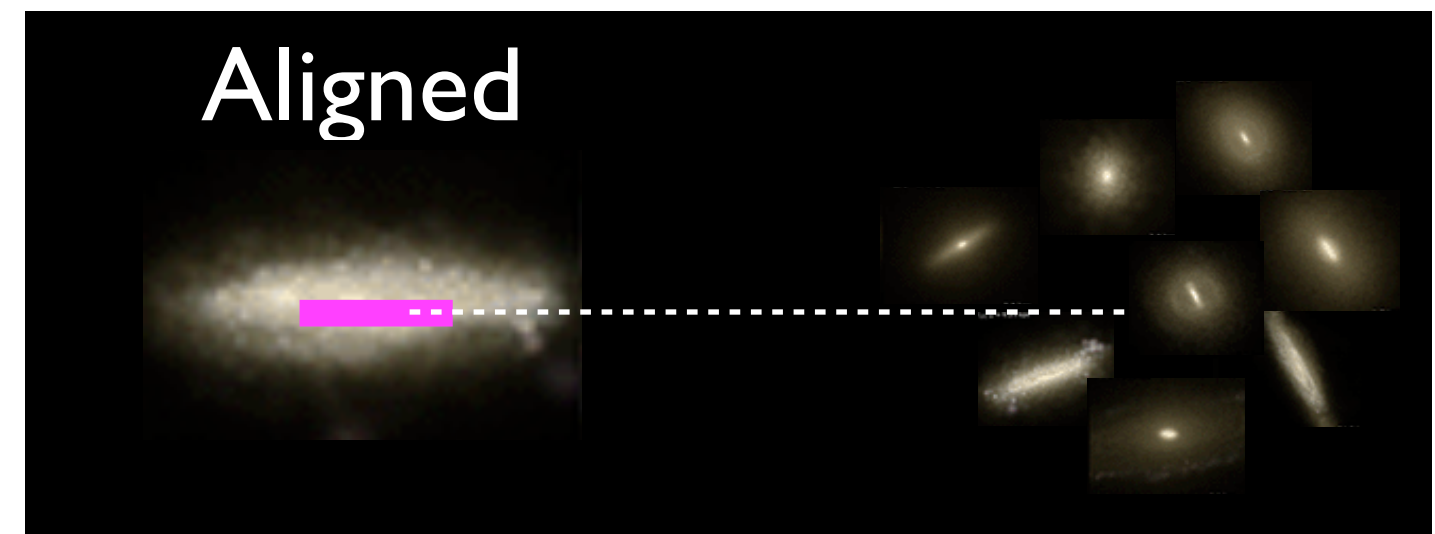
Evidence of gravity-induced ellipticity

Measurement of **GI correlation** for **elliptical** galaxies

SDSS LRG @ $z \sim 0.33$

$$\langle \delta_g \gamma_+ \rangle(r)$$

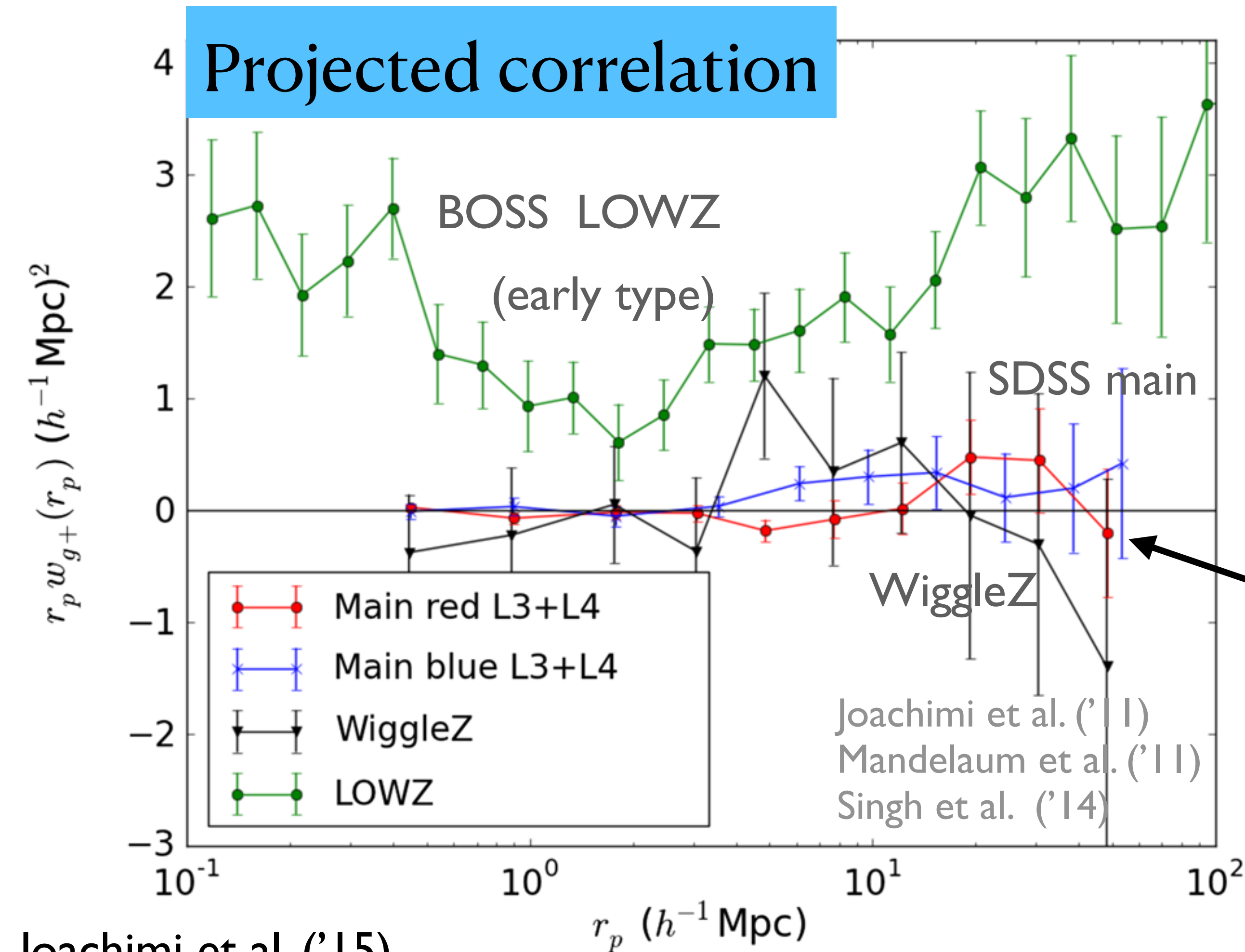
Luminous red galaxy
(LRG)



Galaxy ellipticity is a **tracer** of gravitational tidal force field of large-scale structure

Dependence on galaxy type

Behaviors of IA correlation crucially depend on galaxy type and how you measure IA



Galaxy-IA correlation
(GI correlation)
 $\langle \delta_g \gamma_+^I \rangle$

No clear correlation signal is detected
for late-type galaxies

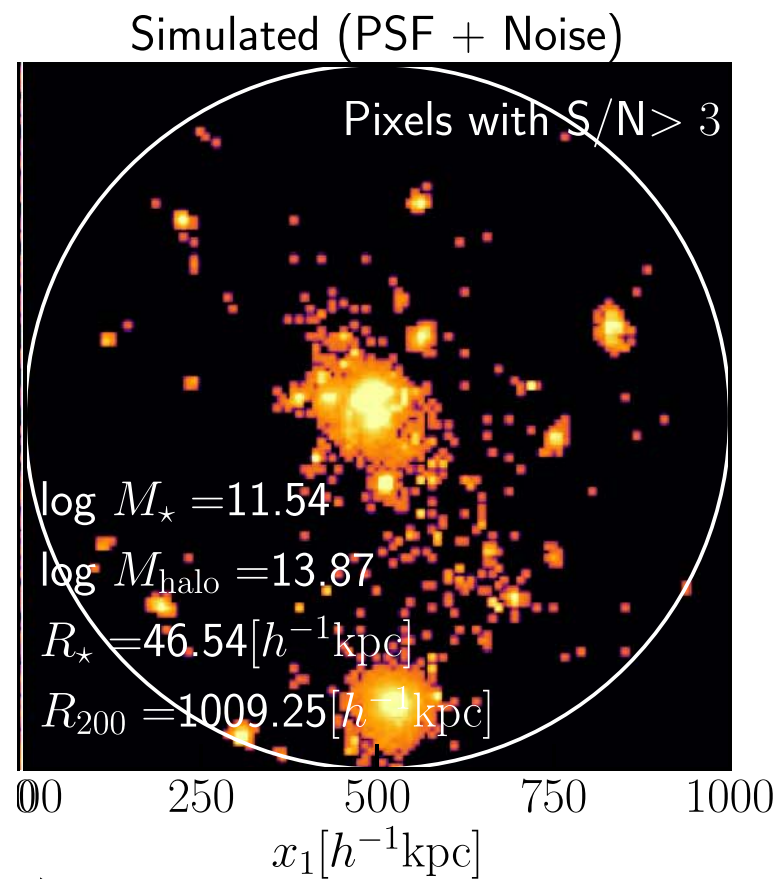


ELG is also the case (but see next slide)

A novel shape estimator

Inertia tensor of building blocks (subhalos):

Shi, Osato, Kurita & Takada ('21)
(see also Ishikawa, AT et al. '24)



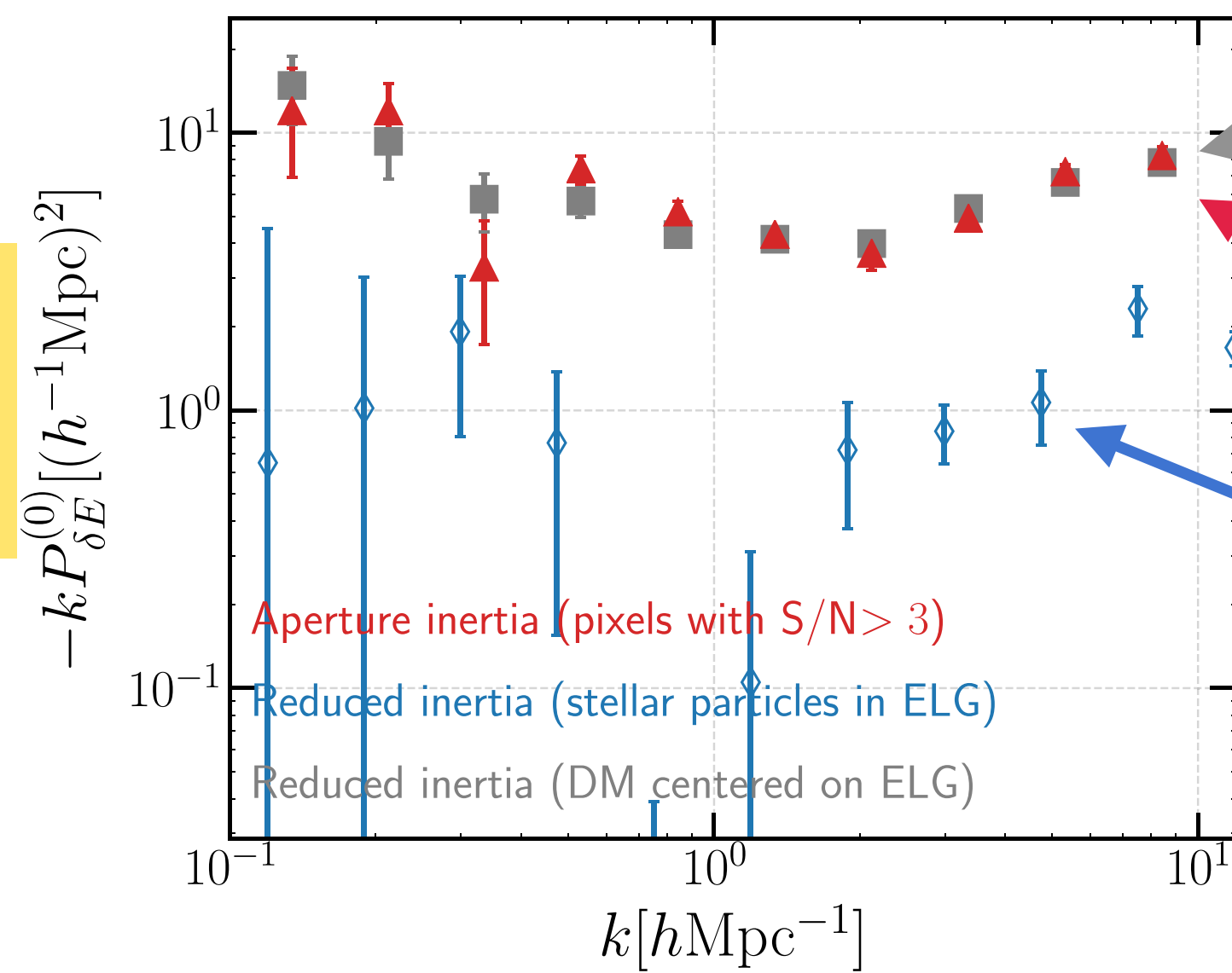
$${}^{\text{new}}I_{ij} \equiv \sum_n w_n x_{ni} x_{nj} ;$$

x_{ni} : 2D position of surrounding building blocks

w_n : weight func. ($\propto$ flux)

➔ Shape measurement can be *extended* to star-forming galaxies (ELG) & clusters

GI cross power spectrum



c.f. Halo shape (dark matter)

New estimator

Conventional

This method is robust even in the presence of mis-identified members (Ishikawa et al. '23)

Anisotropies in ellipticity correlations

Okumura, AT & Nishimichi ('20)

(See also Kurita et al. '21)

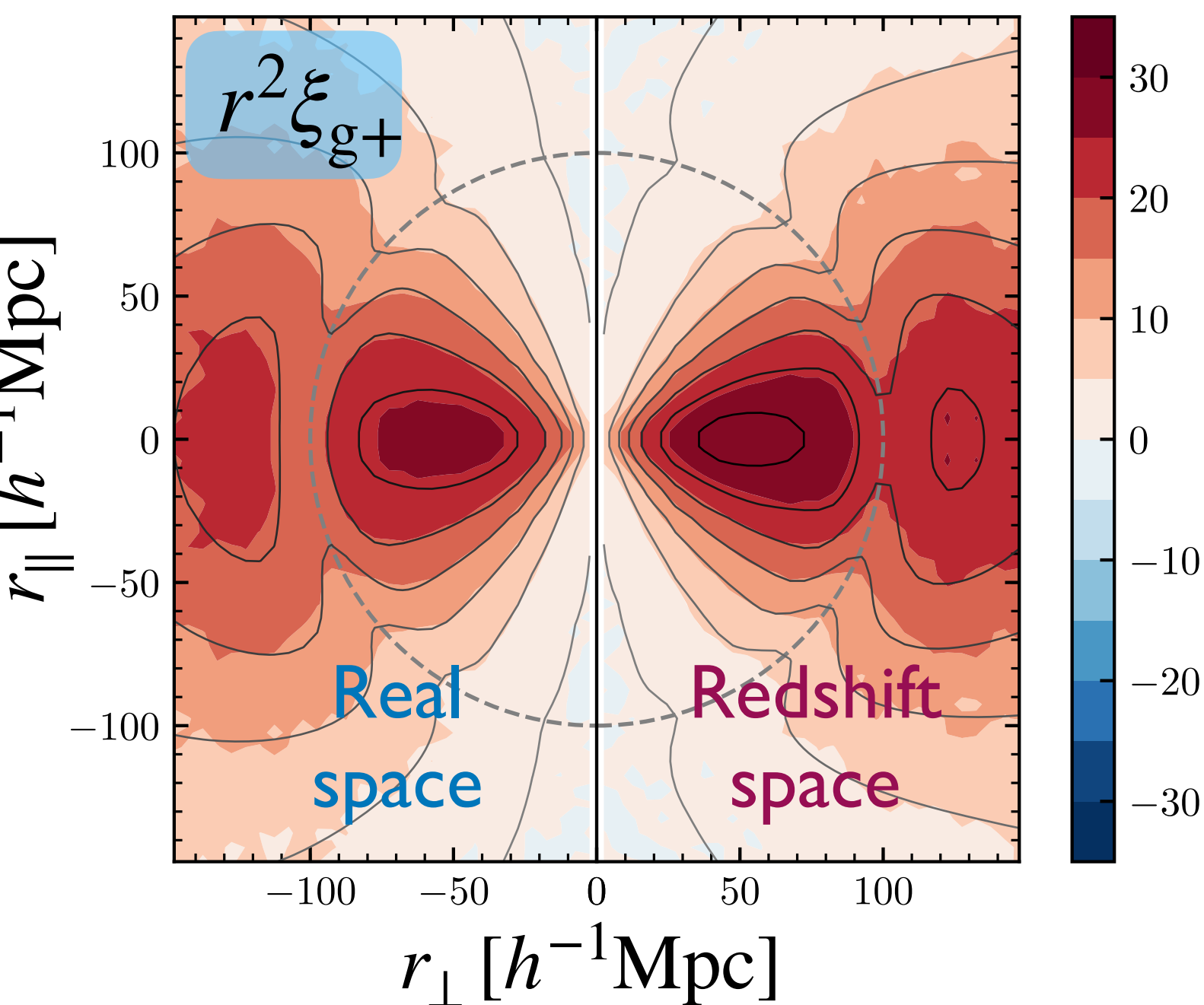
Interesting and important features

GI & II correlations exhibit intrinsic *anisotropies* along the line-of-sight direction

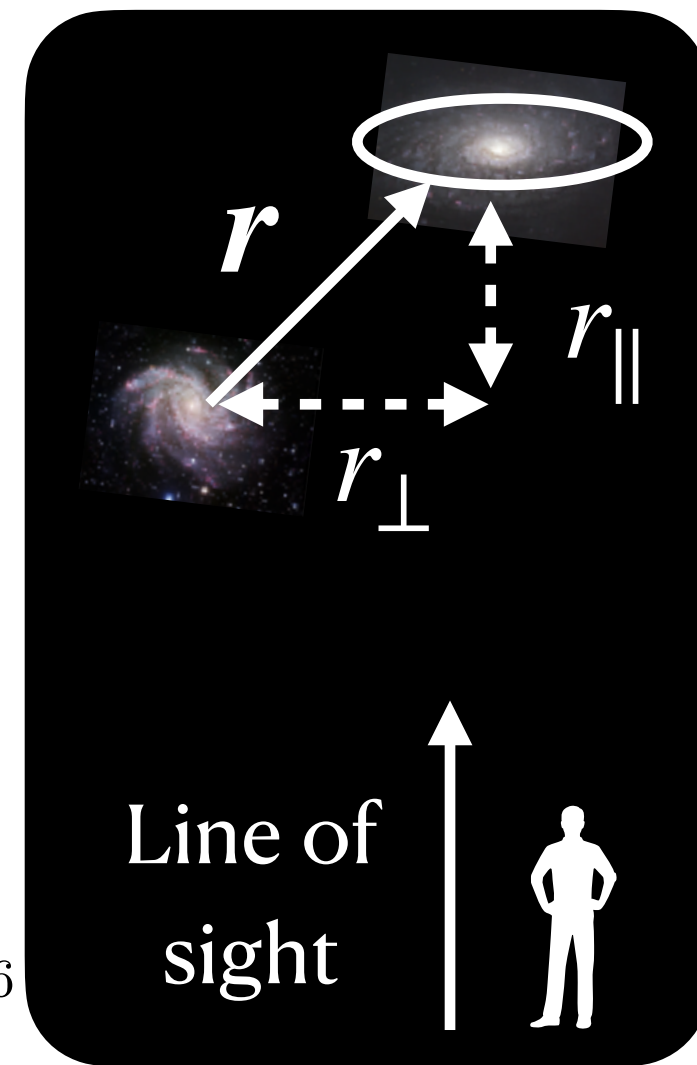
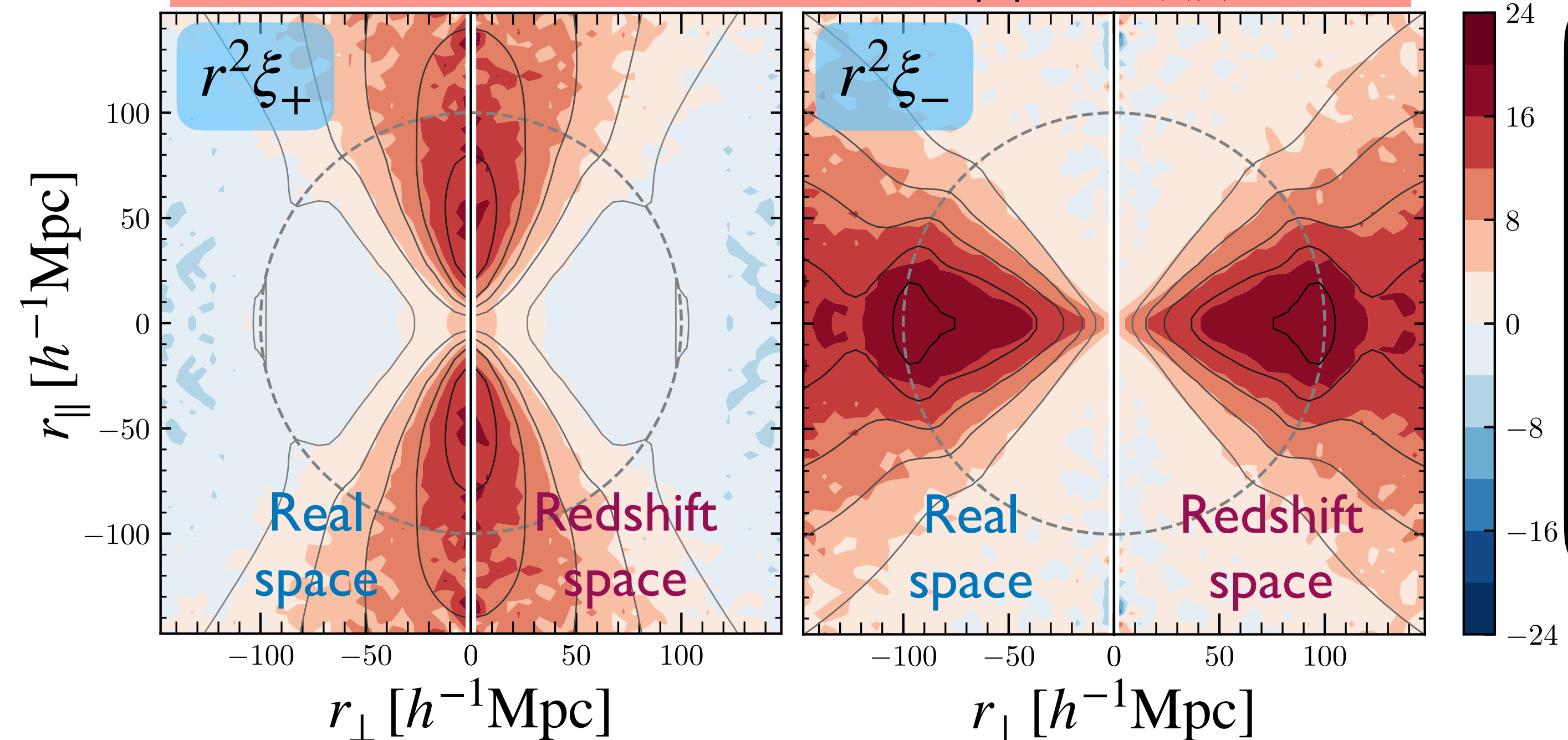
Simulations

GI and II correlations for (sub-)halos in simulations @ $z=0.3$

GI correlation



II correlation ($\xi_{\pm} \equiv \xi_{++} \pm \xi_{xx}$)



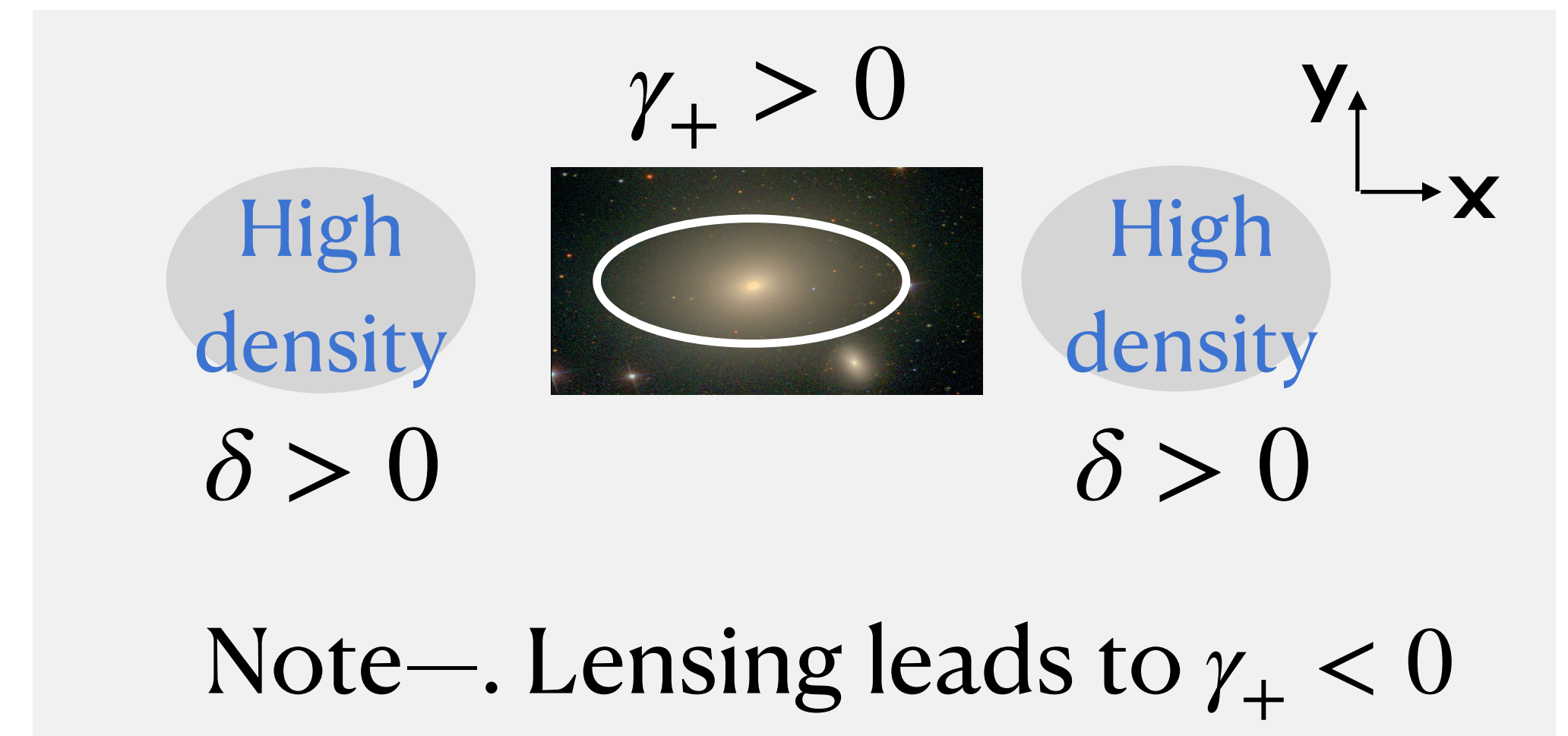
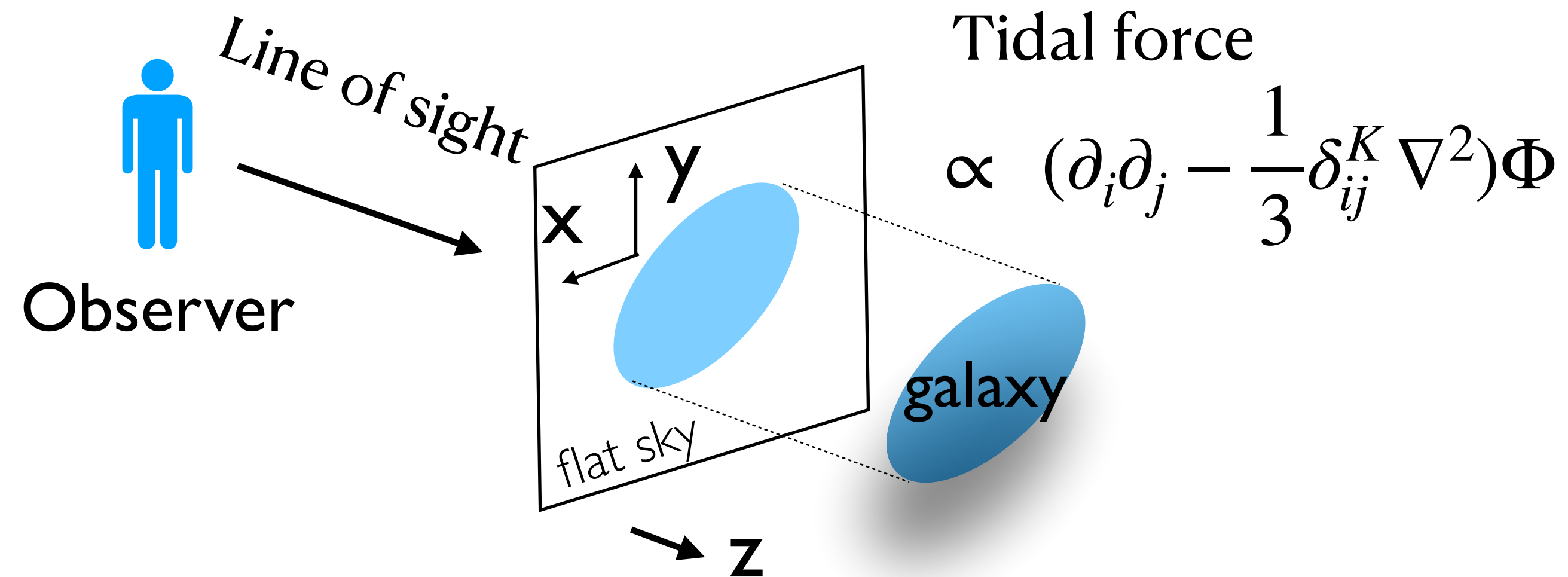
Linear alignment (LA) model

Anisotropic features in simulations can be nicely described by linear model

$$(\gamma_+, \gamma_\times) \propto -(\nabla_x^2 - \nabla_y^2, 2\nabla_x \nabla_y) \Phi$$

Gravitational potential

Catelan et al. ('01)
Hirata & Seljak ('04)



- Anisotropic GI & II correlations can be analytically expressed (Okumura & AT '20)
- Beyond linear order, EFT description has been developed (Vlah et al. '20, '21; Bakx, et al. '23)

Analytical expressions

GI correlation

Okumura & AT ('20)

Real
space

$$\xi_{g+}^R(\mathbf{r}) = -b_K b_b \cos(2\phi) (1 - \mu^2) \Xi_{\delta\delta,2}^{(0)}(r)$$

$$\mu \equiv r_{\parallel}/r$$

ϕ : azimuthal angle in $\vec{r}_{\perp}$

Redshift
space

$$\xi_{g+}^S(\mathbf{r}) = \xi_{g+}^R(\mathbf{r}) - \frac{1}{7} b_K f \cos(2\phi) (1 - \mu^2) \left[\Xi_{\delta\Theta,2}^{(0)}(r) - (7\mu^2 - 1) \Xi_{\delta\Theta,4}^{(0)}(r) \right]$$

Linear growth factor $f \equiv \frac{d \ln D_+}{d \ln a}$

II correlations

Real &
redshift
space

$$\xi_+(\mathbf{r}) = \frac{8}{105} b_K^2 \left[7 \mathcal{P}_0(\mu) \Xi_{\delta\delta,0}^{(0)}(r) + 10 \mathcal{P}_2(\mu) \Xi_{\delta\delta,2}^{(0)}(r) + 3 \mathcal{P}_4(\mu) \Xi_{\delta\delta,4}^{(0)}(r) \right]$$

$$\xi_-(\mathbf{r}) = b_K^2 \cos(4\phi) (1 - \mu^2)^2 \Xi_{\delta\delta,4}^{(0)}(r)$$

For $\xi_{\pm}$, no distinction between real & redshift space (at leading order)

$$\Xi_{XY,\ell}^{(n)}(r) = (a H f)^n \int_0^\infty \frac{k^{2-n} dk}{2\pi^2} P_{XY}(k) j_\ell(kr)$$

$\mathcal{P}_\ell(\mu)$: Legendre polynomials

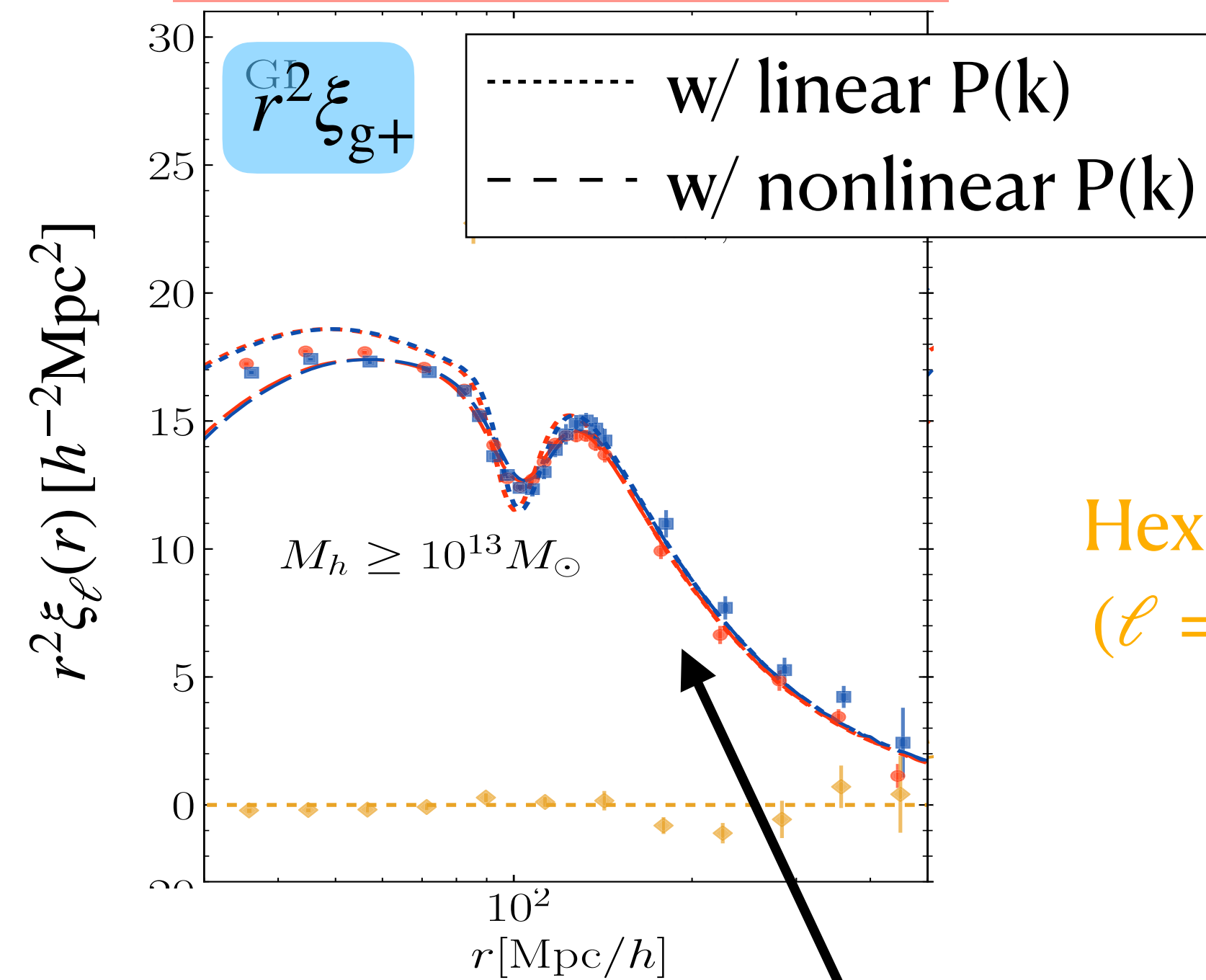
Anisotropies in ellipticity correlations

Okumura, AT & Nishimichi ('20)

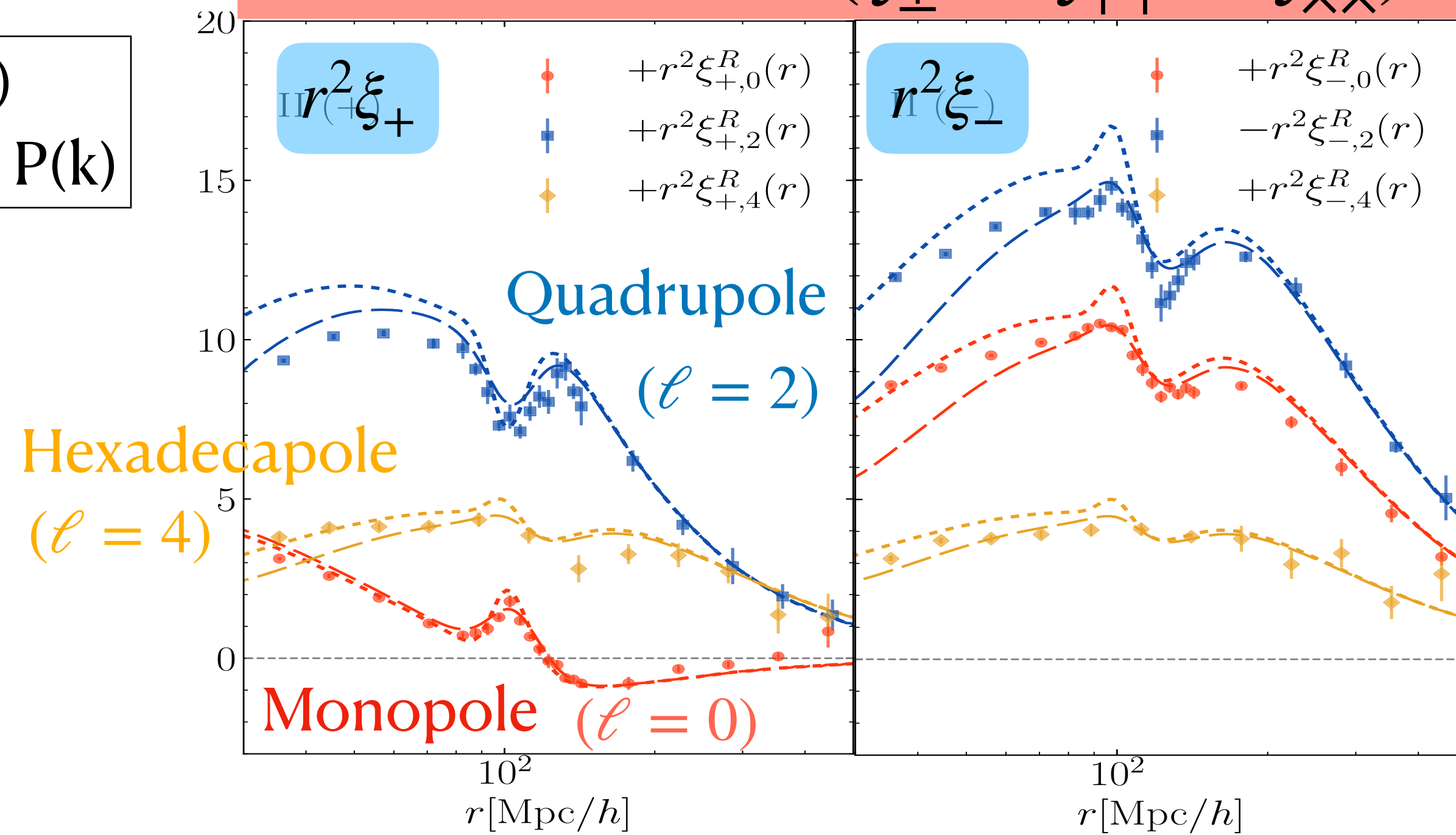
(See also Kurita et al. '21)

Simulations LA model can describe *anisotropic* features in GI and II correlations

GI correlation



II correlation ($\xi_{\pm} \equiv \xi_{++} \pm \xi_{xx}$)



Real space

Multipole expansion

$$\xi(\mathbf{r}) = \sum_{\ell} \xi_{\ell}(r) \mathcal{P}_{\ell}(r_{\parallel}/r)$$

Legendre polynomials

※ Associated Legendre may provide a more natural basis

Baryon acoustic oscillations (BAO) & redshift-space distortions (RSD) are clearly visible

Anisotropies in ellipticity correlations

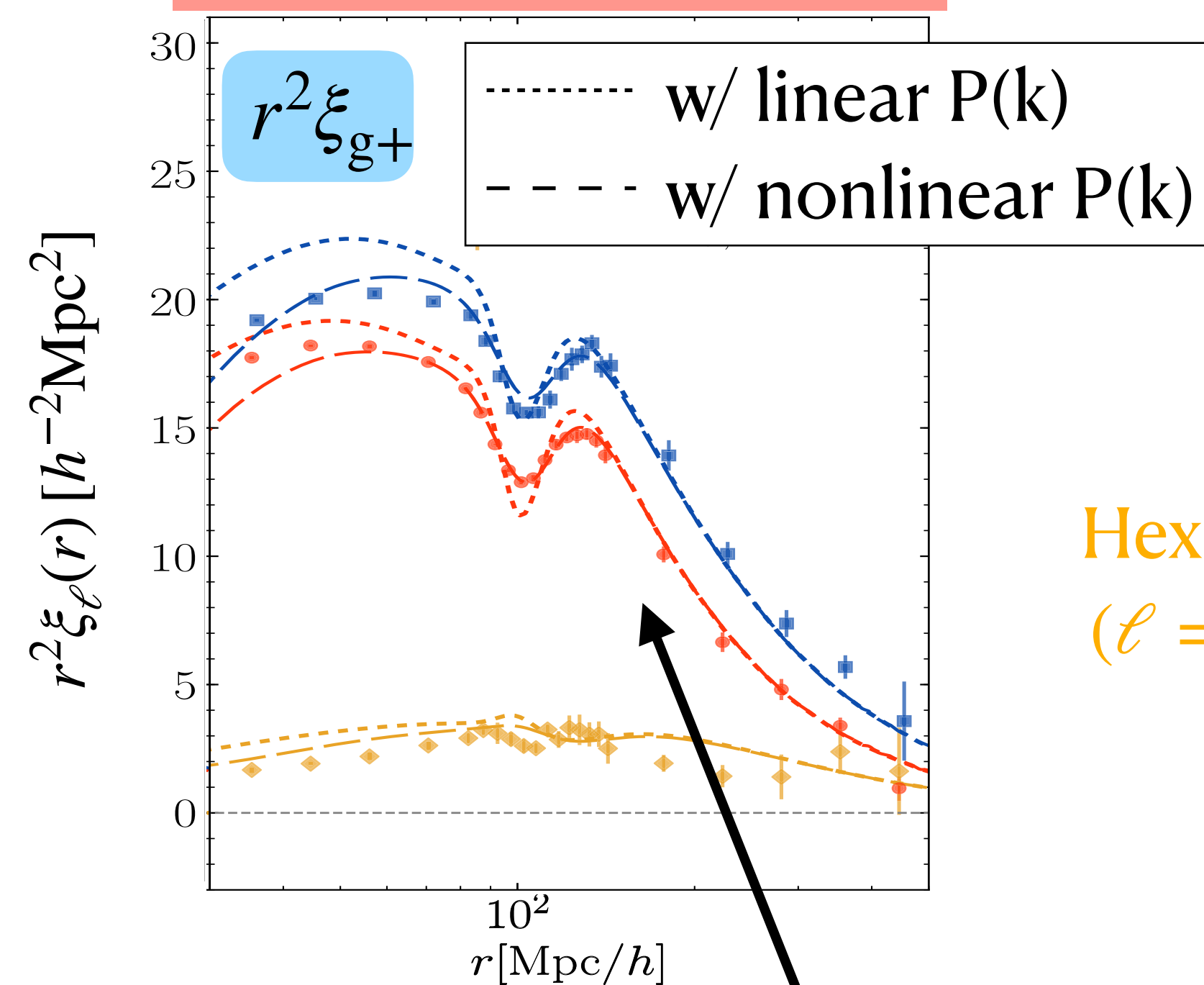
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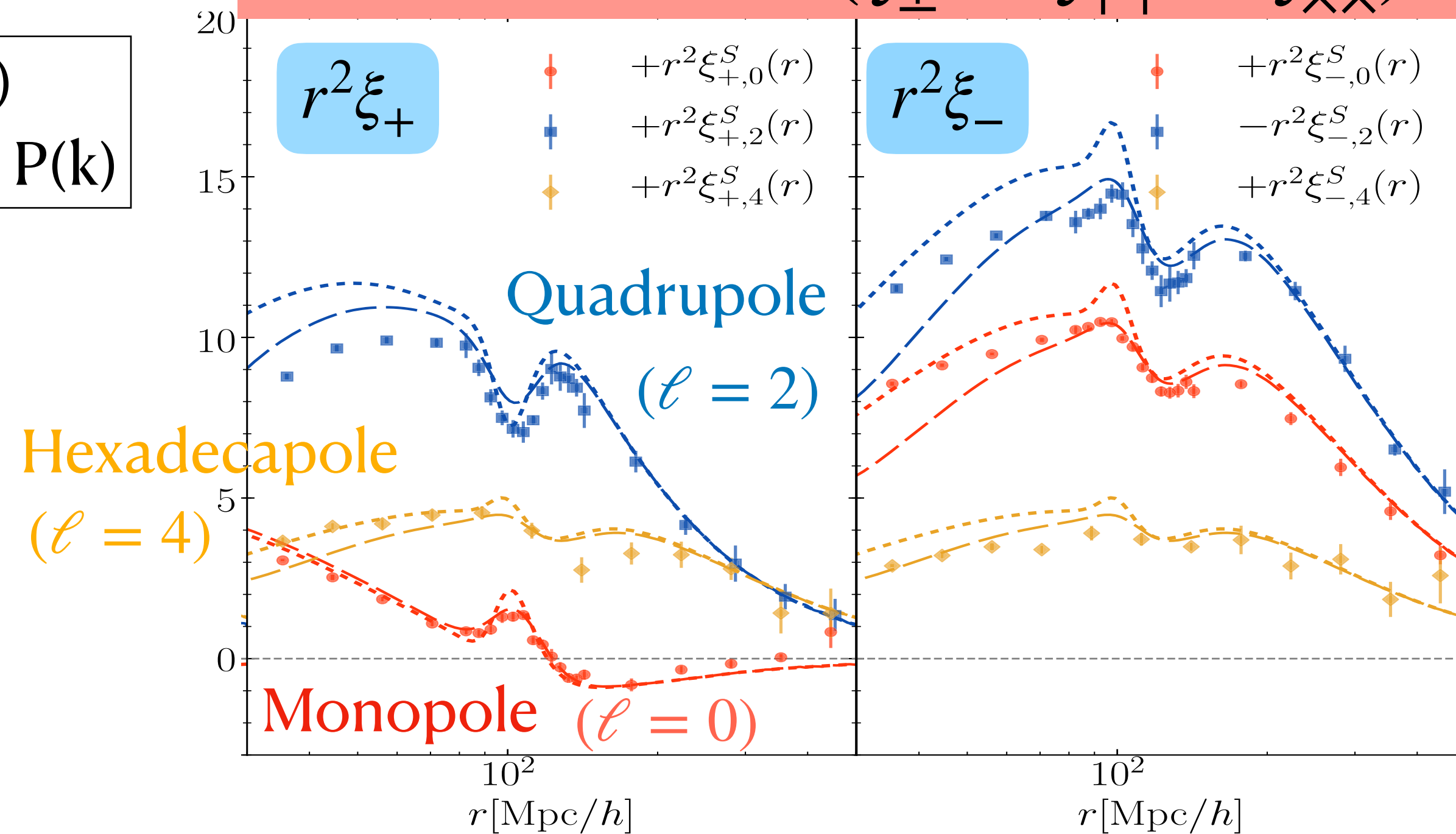
Simulations

LA model can describe *anisotropic* features in GI and II correlations

GI correlation



II correlation ($\xi_{\pm} \equiv \xi_{++} \pm \xi_{xx}$)



Redshift space

Multipole expansion

$$\xi(\mathbf{r}) = \sum_{\ell} \xi_{\ell}(r) \mathcal{P}_{\ell}(r_{\parallel}/r)$$

Legendre polynomials

※ Associated Legendre may provide a more natural basis

Baryon acoustic oscillations (BAO) & redshift-space distortions (RSD) are clearly visible

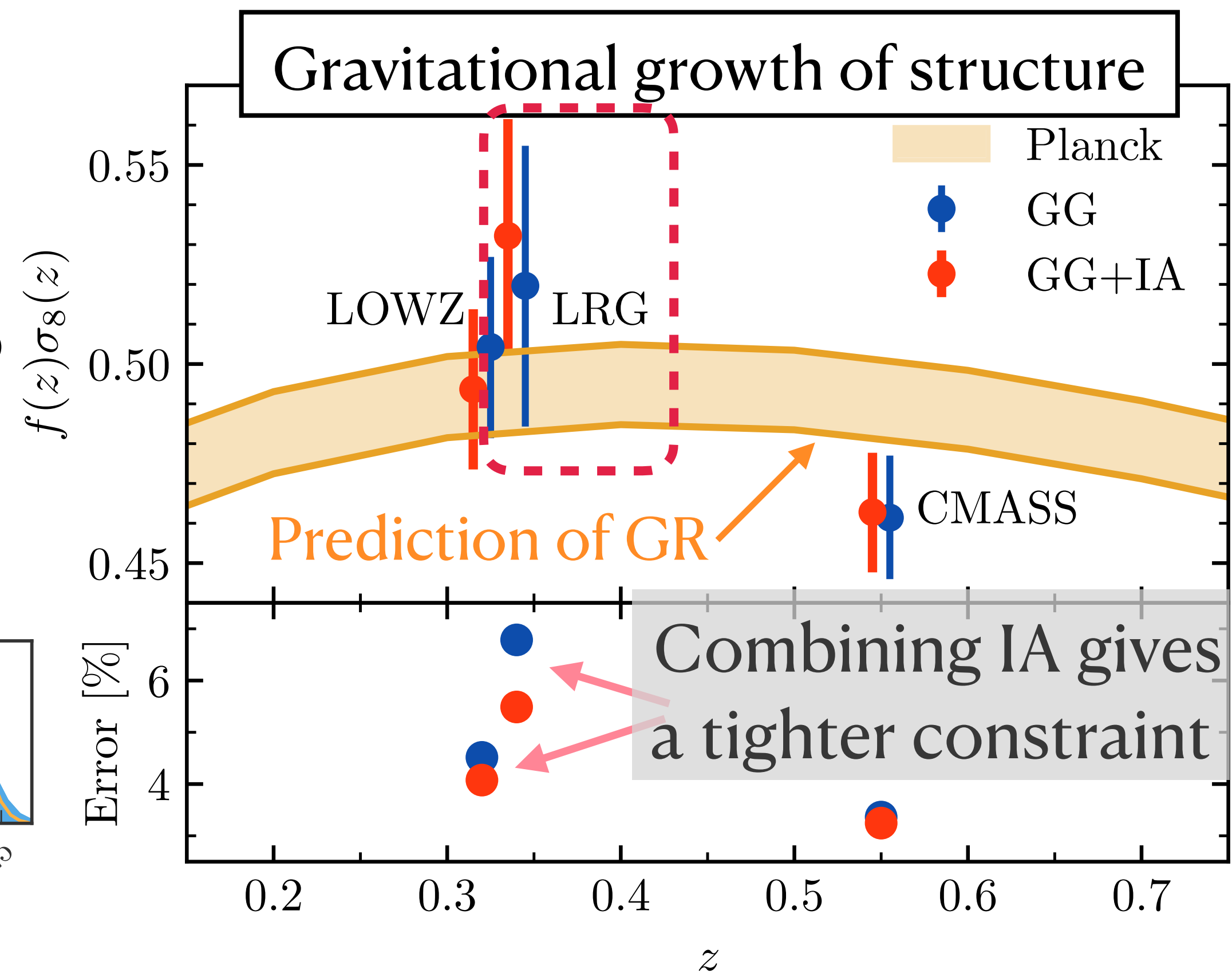
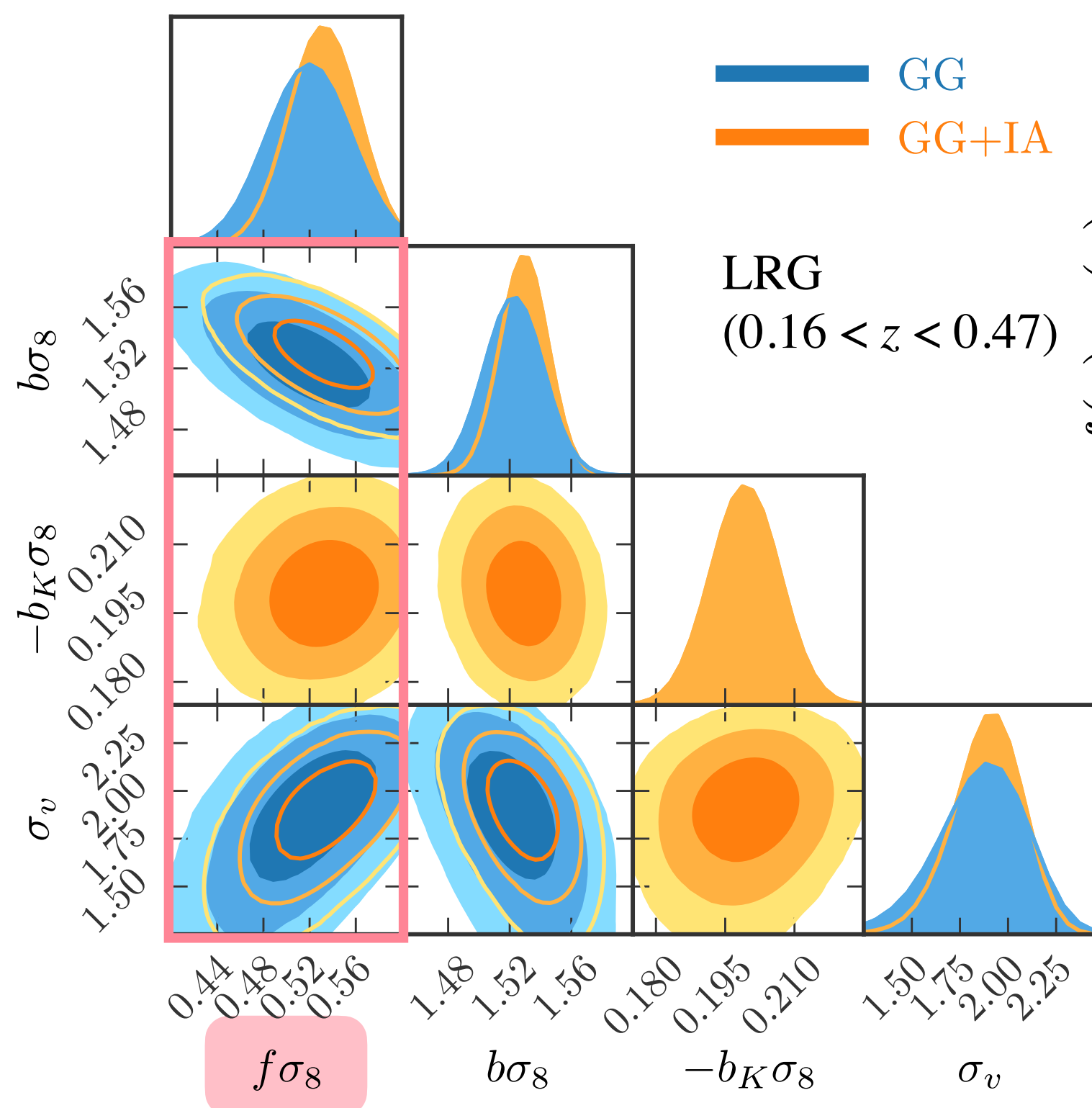
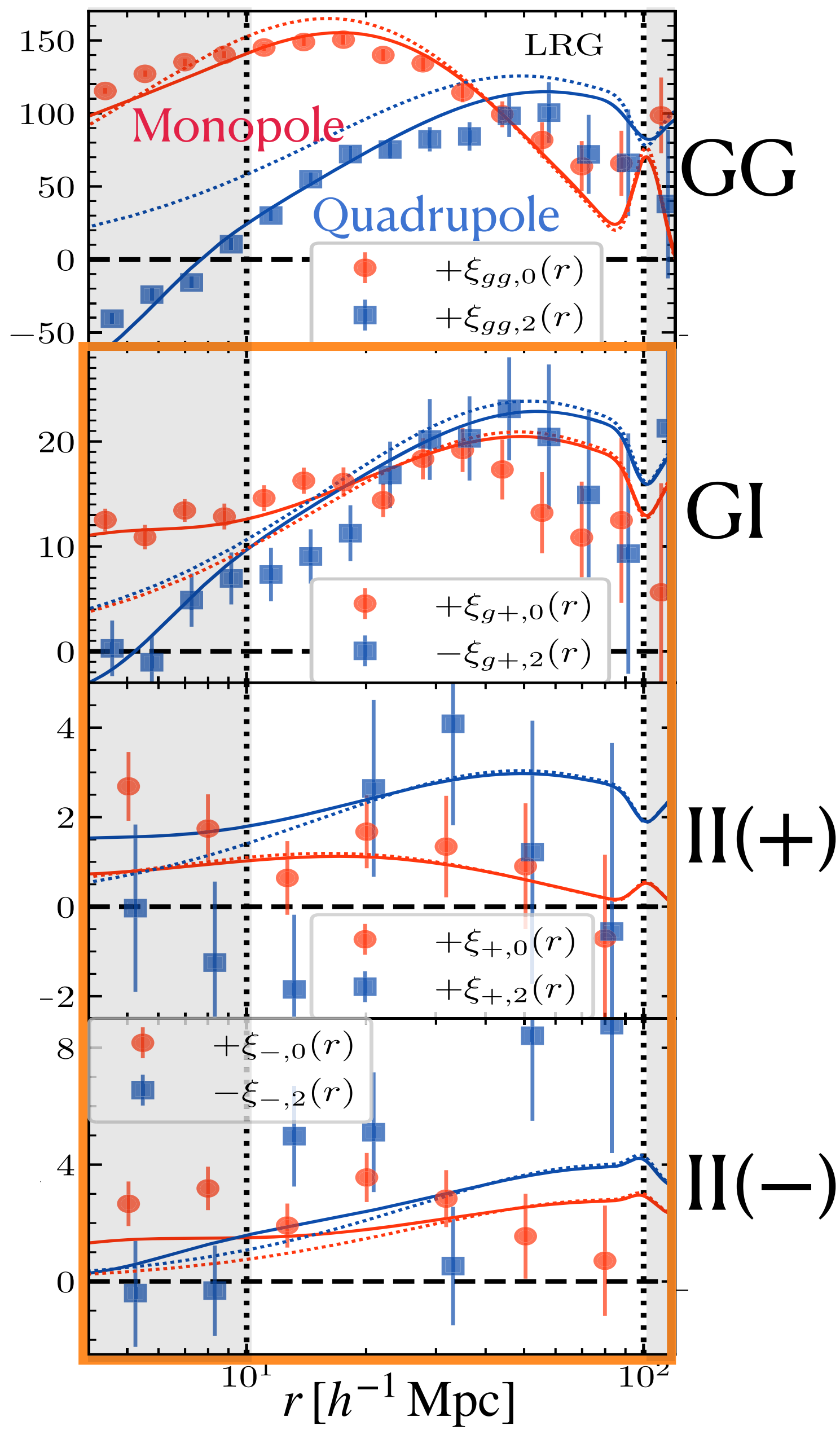
Measurement of redshift-space distortions (RSD)

SDSS LRG

Okumura & AT, ApJL 945, L30 ('23)

A clear detection of RSD

→ growth rate constraint ($f\sigma_8$) (Kaiser '87)



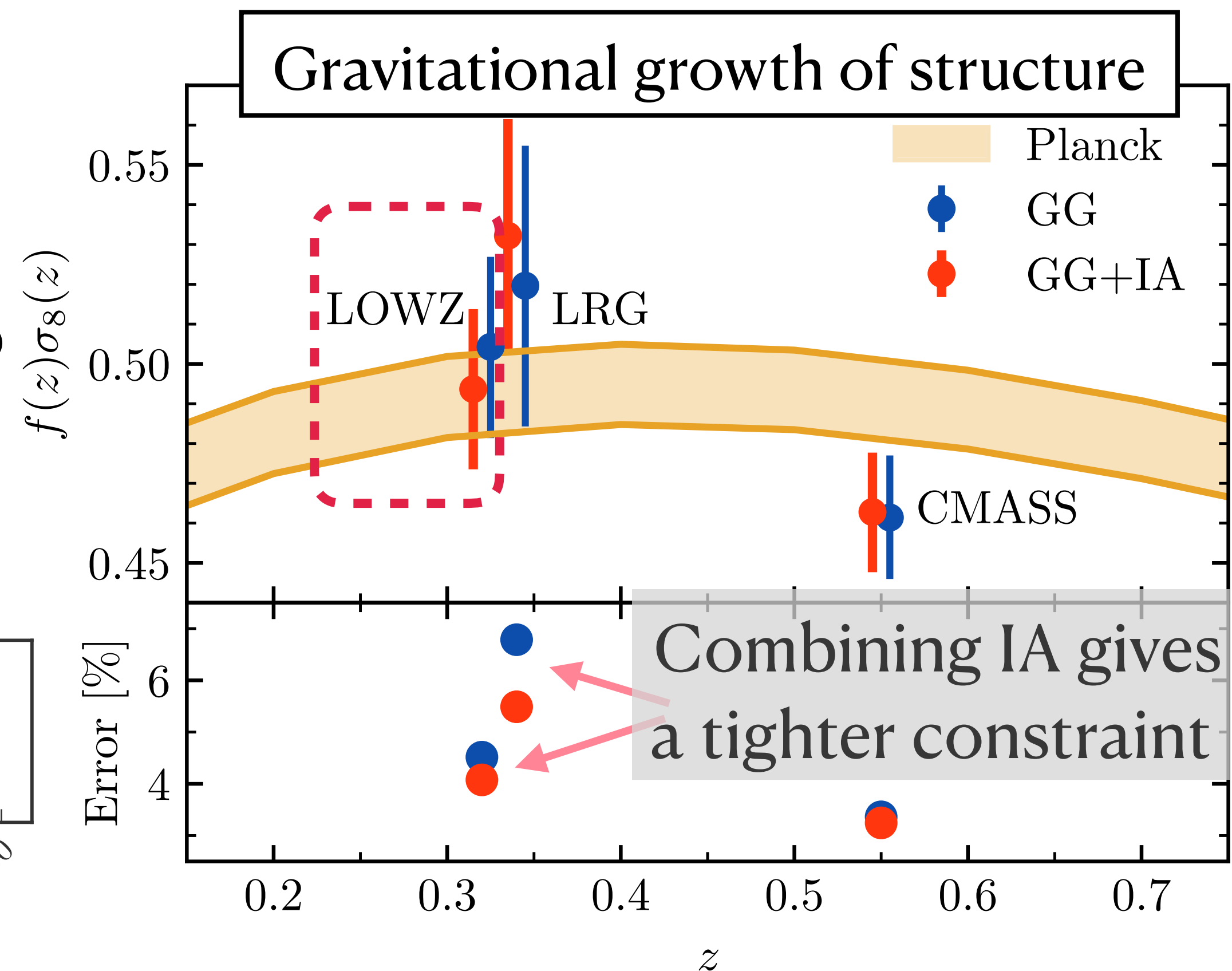
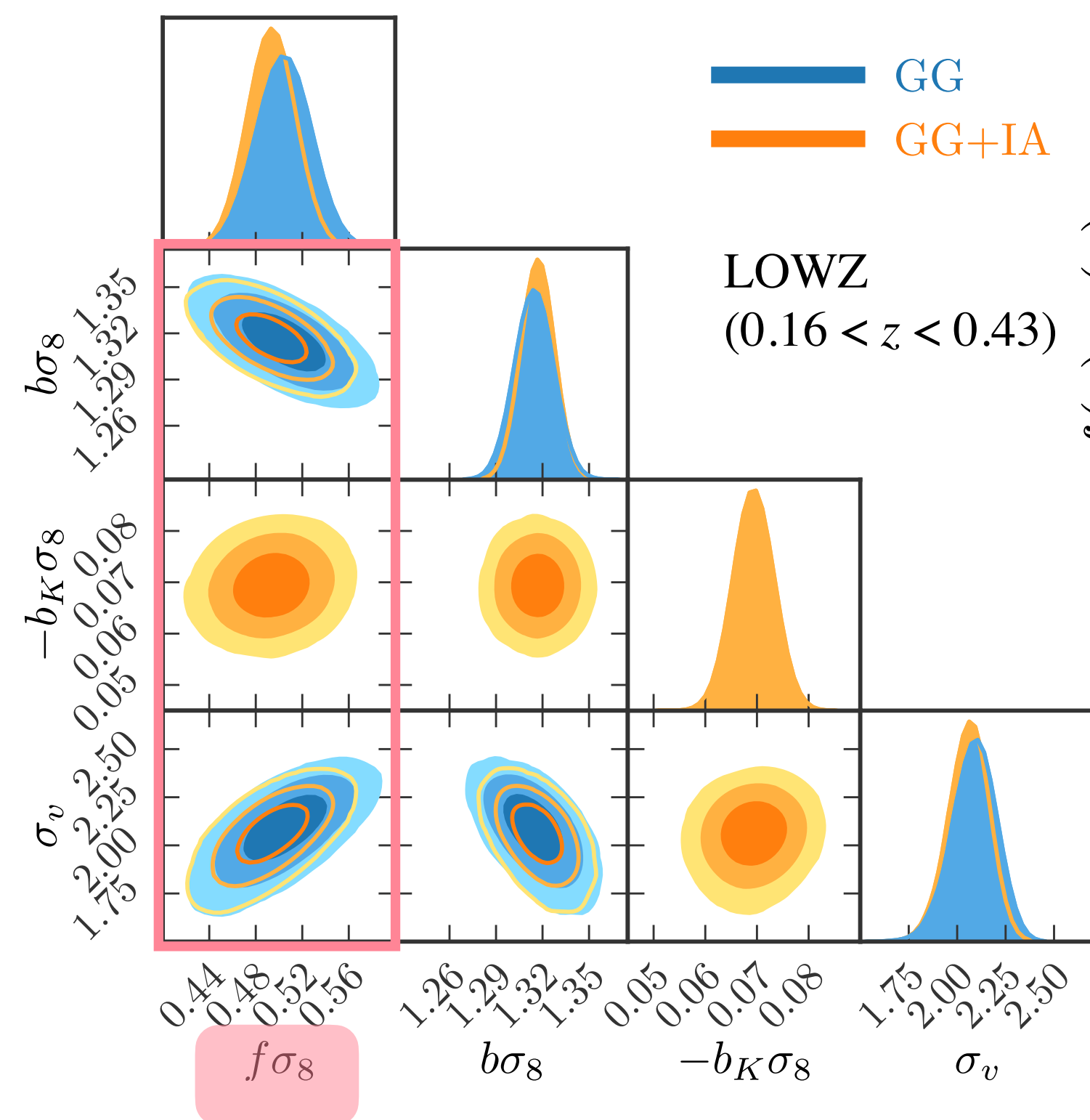
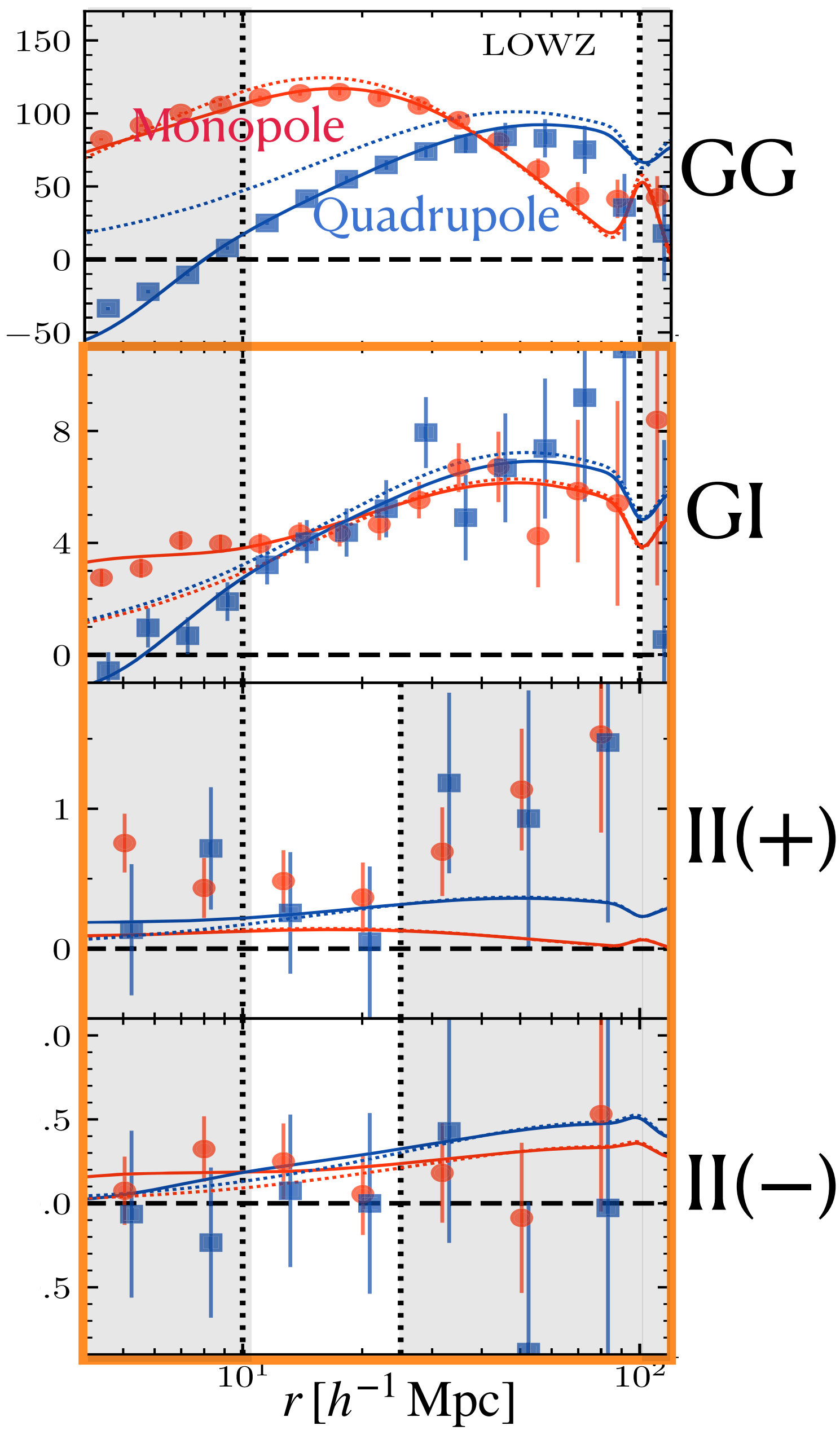
Measurement of redshift-space distortions (RSD)

BOSS LOWZ

Okumura & AT, ApJL 945, L30 ('23)

A clear detection of RSD

→ growth rate constraint ($f\sigma_8$) (Kaiser '87)



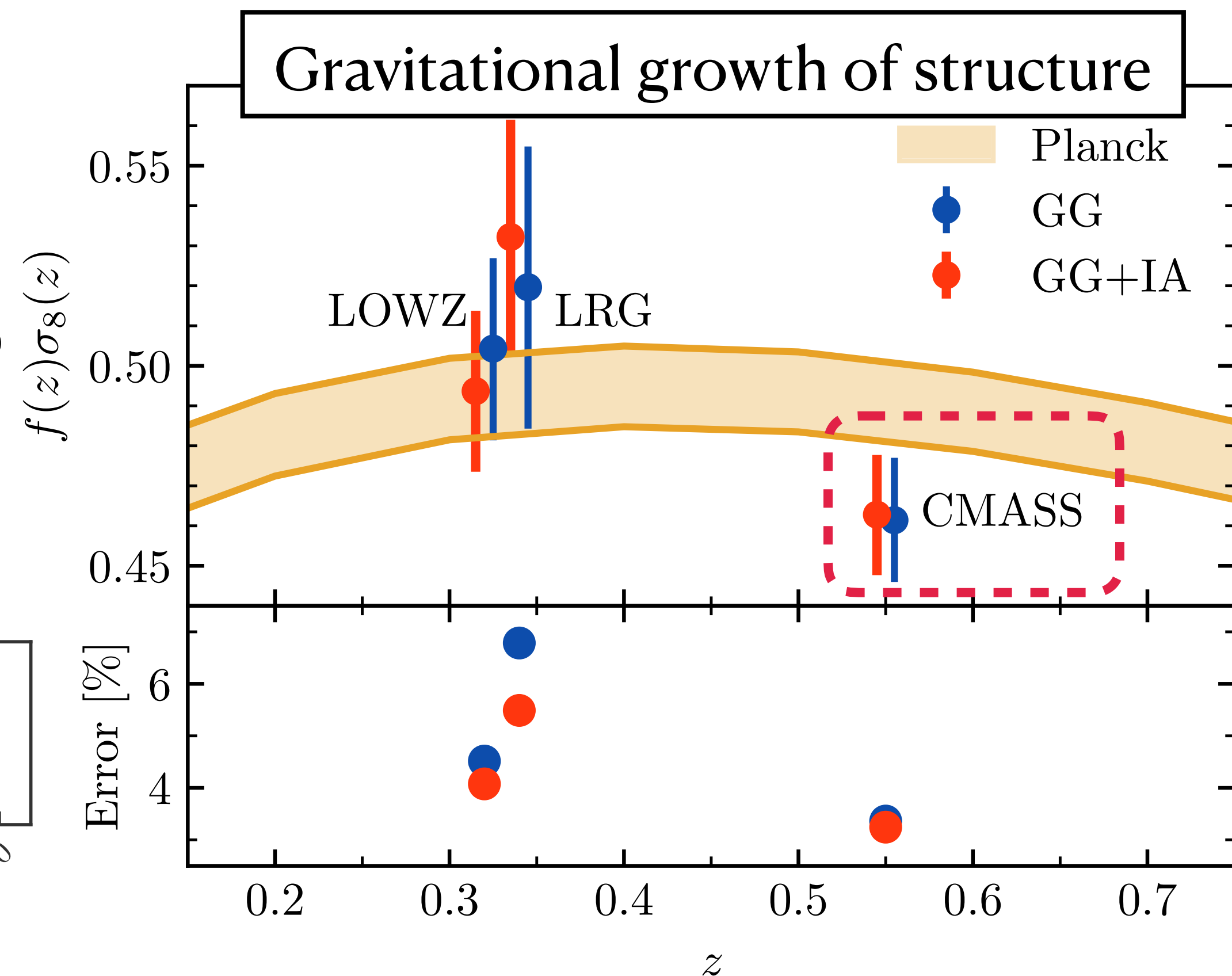
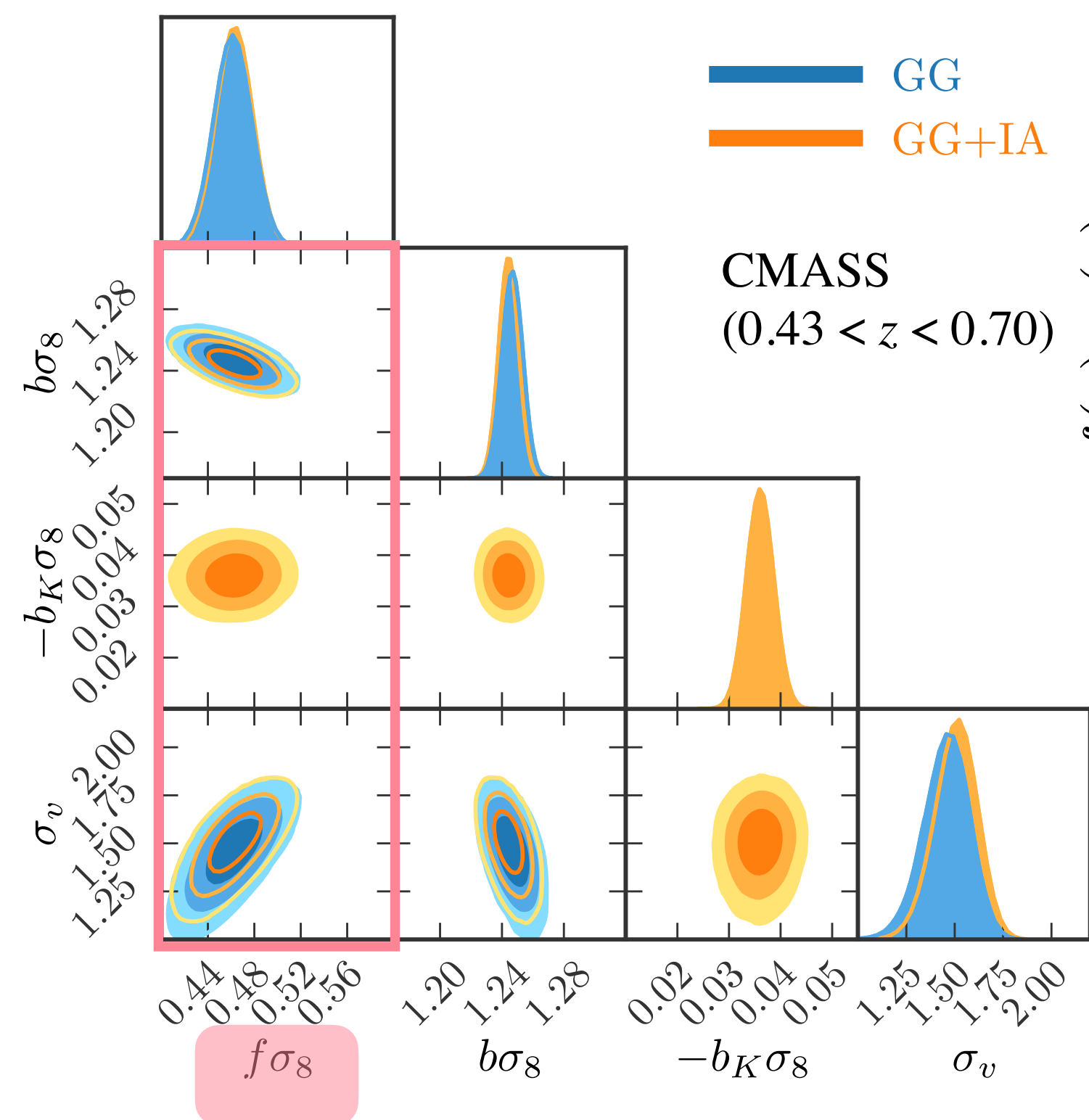
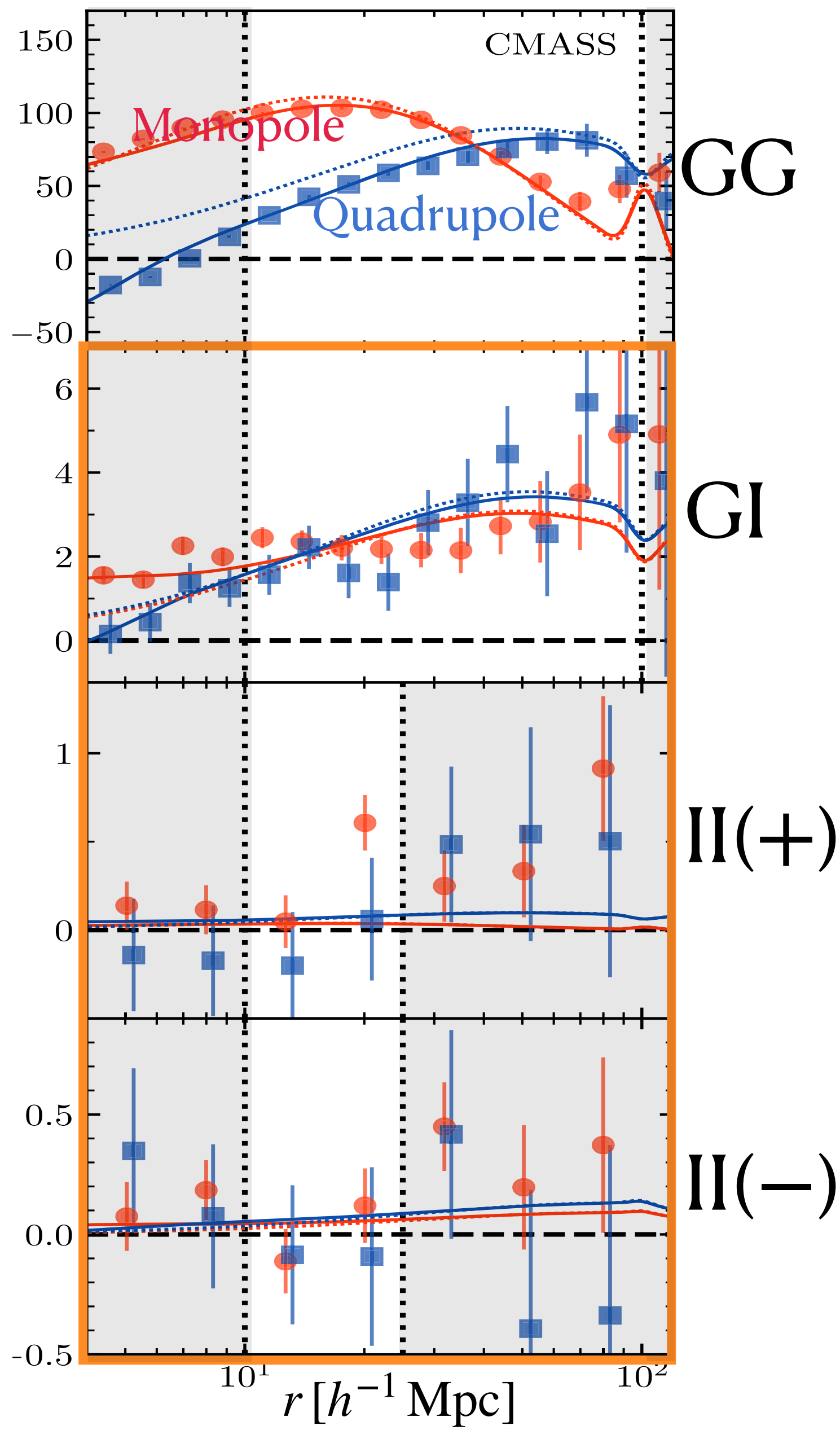
Measurement of redshift-space distortions (RSD)

BOSS CMASS

Okumura & AT, ApJL 945, L30 ('23)

A clear detection of RSD

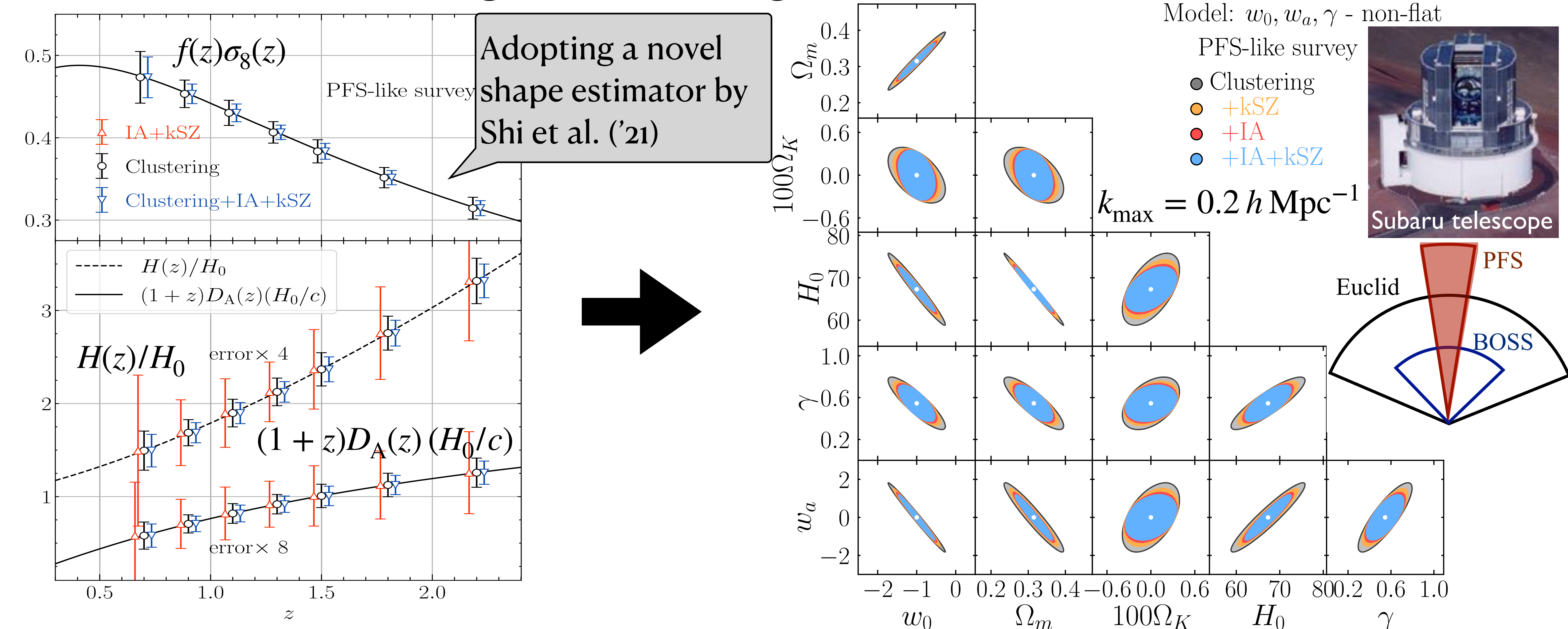
→ growth rate constraint ($f\sigma_8$) (Kaiser '87)



Fisher forecast for upcoming surveys

Combining GG, GI & II correlations, future BAO & RSD measurements further tighten cosmological constraints

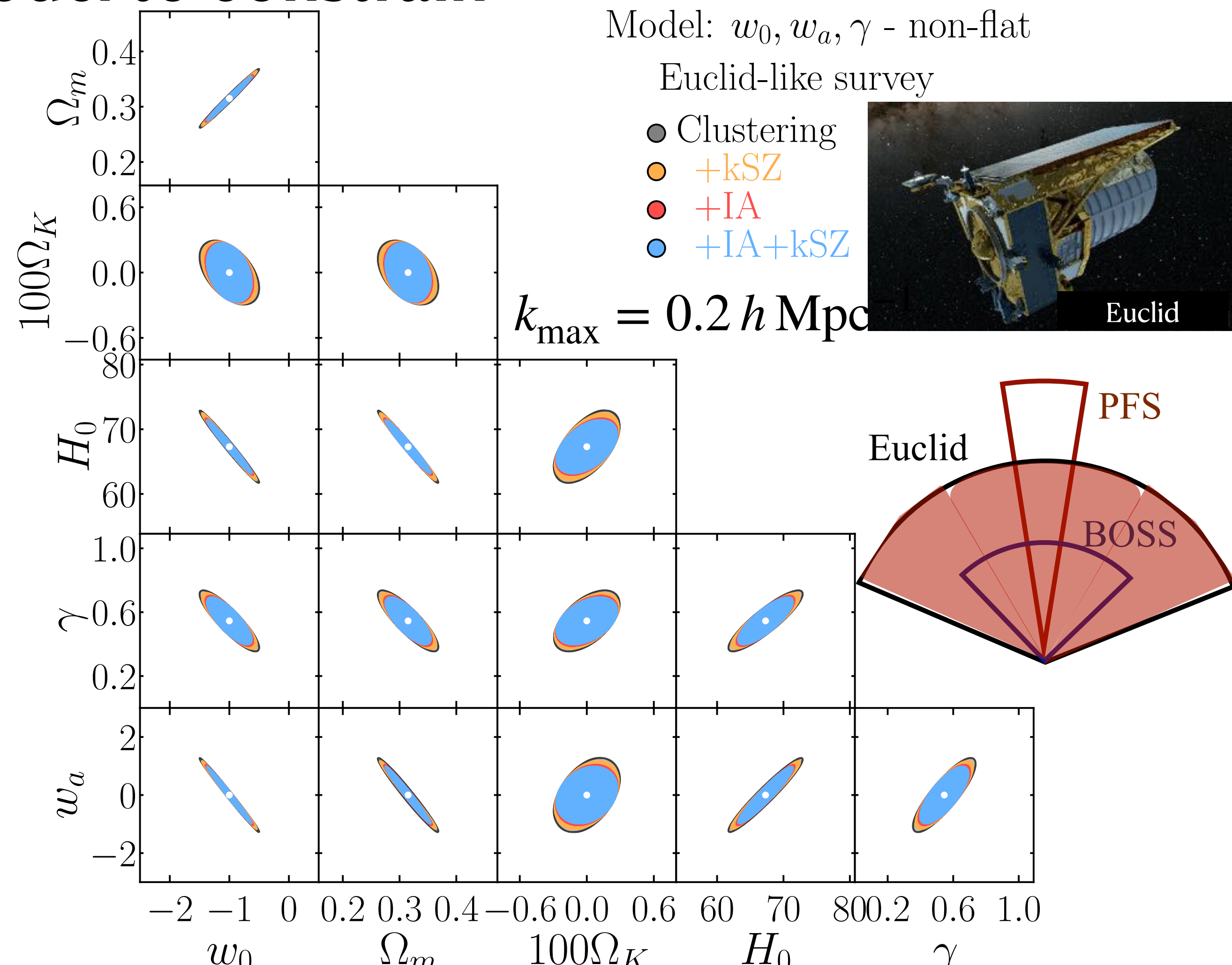
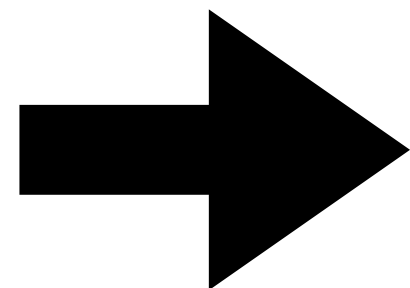
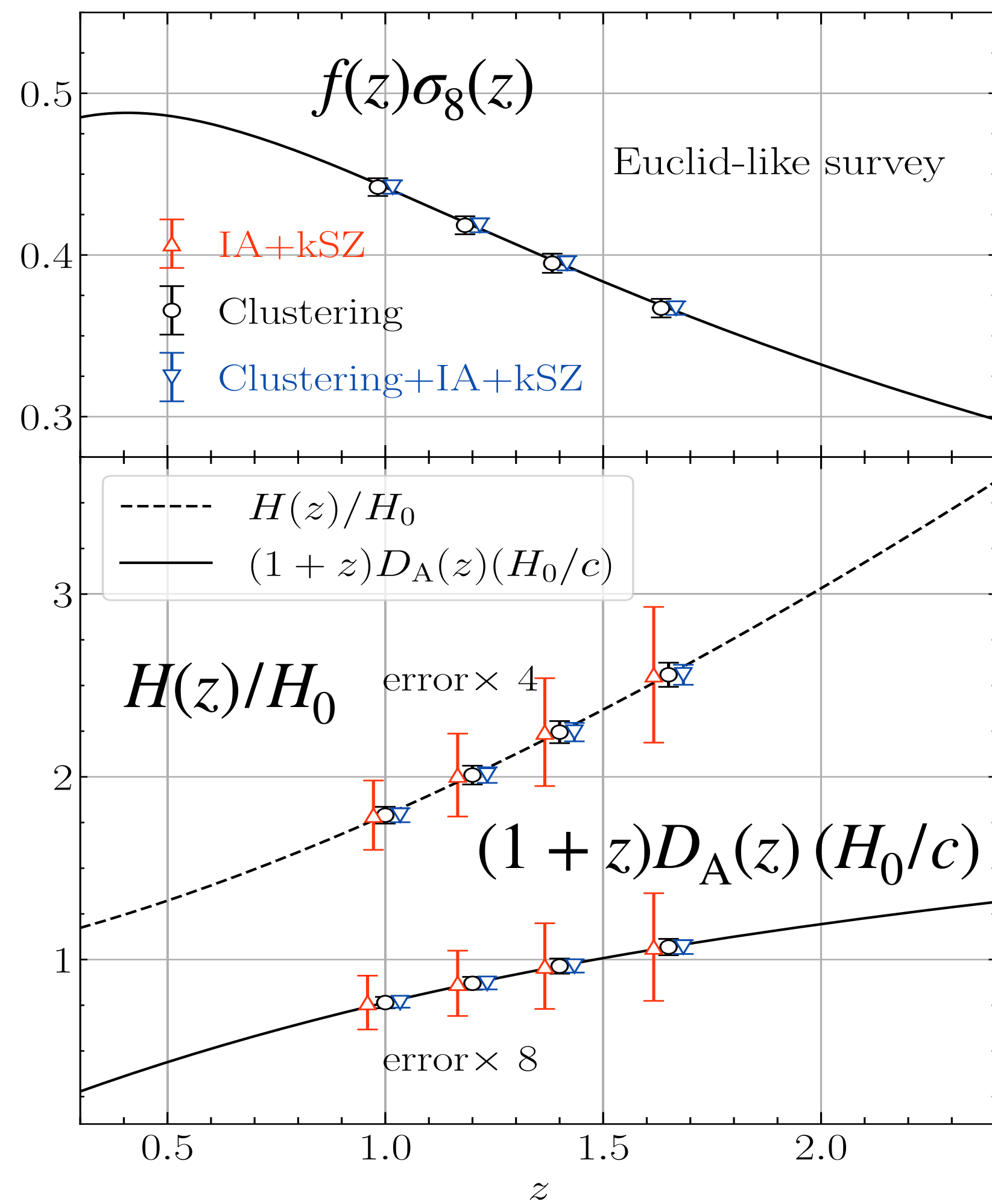
Okumura & AT ('22)



Fisher forecast for upcoming surveys

A benefit of combining IA & kSZ measurements depends
on surveys and cosmological model to constrain

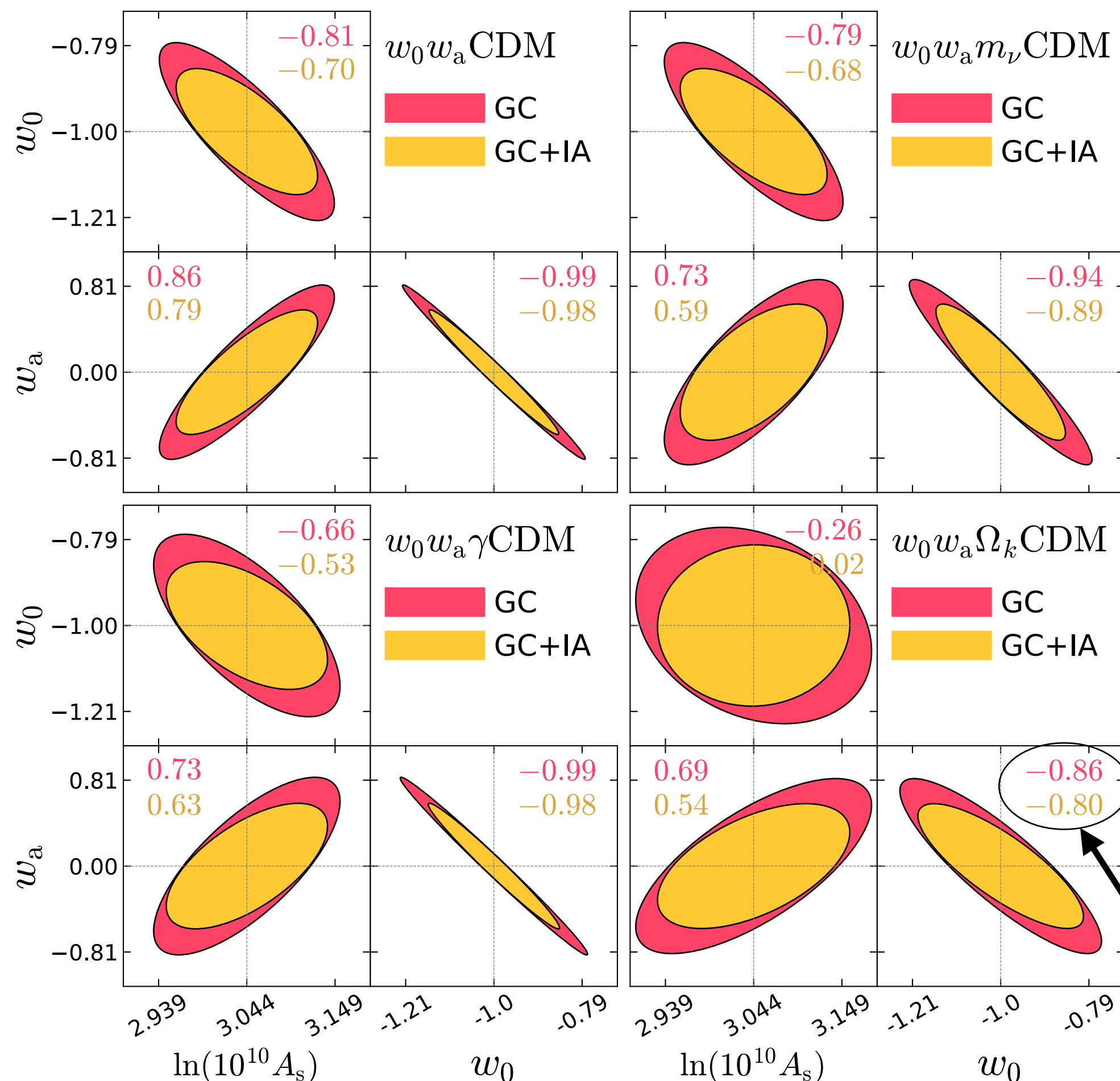
Okumura & AT ('22)



Full-shape analysis

Shim, Okumura & AT ('25a & '25b)

Unlocking the power spectrum shape information, IA statistics can provide significant benefits in tightening cosmological parameters *beyond Λ CDM model*



PFS-like
survey

$$k_{\text{max}} = 0.2 h \text{ Mpc}^{-1}$$

Correlation
coefficient

Improvement factor
 ϵ (%)

	10	20	30
$w_0 w_a$ CDM	19.1	29.1	28.5
+ m_ν	17.8	29.1	26.5
+ γ	13.5	29.9	29.3
+ m_ν, γ	13.5	29.8	26.2
+ Ω_k	18.4	17.9	28.7
+ Ω_k, m_ν	16.7	17.7	25.9
+ Ω_k, γ	13.0	15.0	27.8
+ Ω_k, m_ν, γ	15.5	16.7	25.9
A_s			
w_0			
w_a			

Fractional errors
 σ_i / θ_i

	0.0	0.15	0.30	0.45
$w_0 w_a$ CDM	0.018	0.102	0.388	
+ m_ν	0.019	0.102	0.424	
+ γ	0.021	0.103	0.390	
+ m_ν, γ	0.021	0.104	0.425	
+ Ω_k	0.025	0.130	0.388	
+ Ω_k, m_ν	0.026	0.131	0.427	
+ Ω_k, γ	0.043	0.177	0.401	
+ Ω_k, m_ν, γ	0.044	0.186	0.427	
A_s				
w_0				
w_a				

In particular,

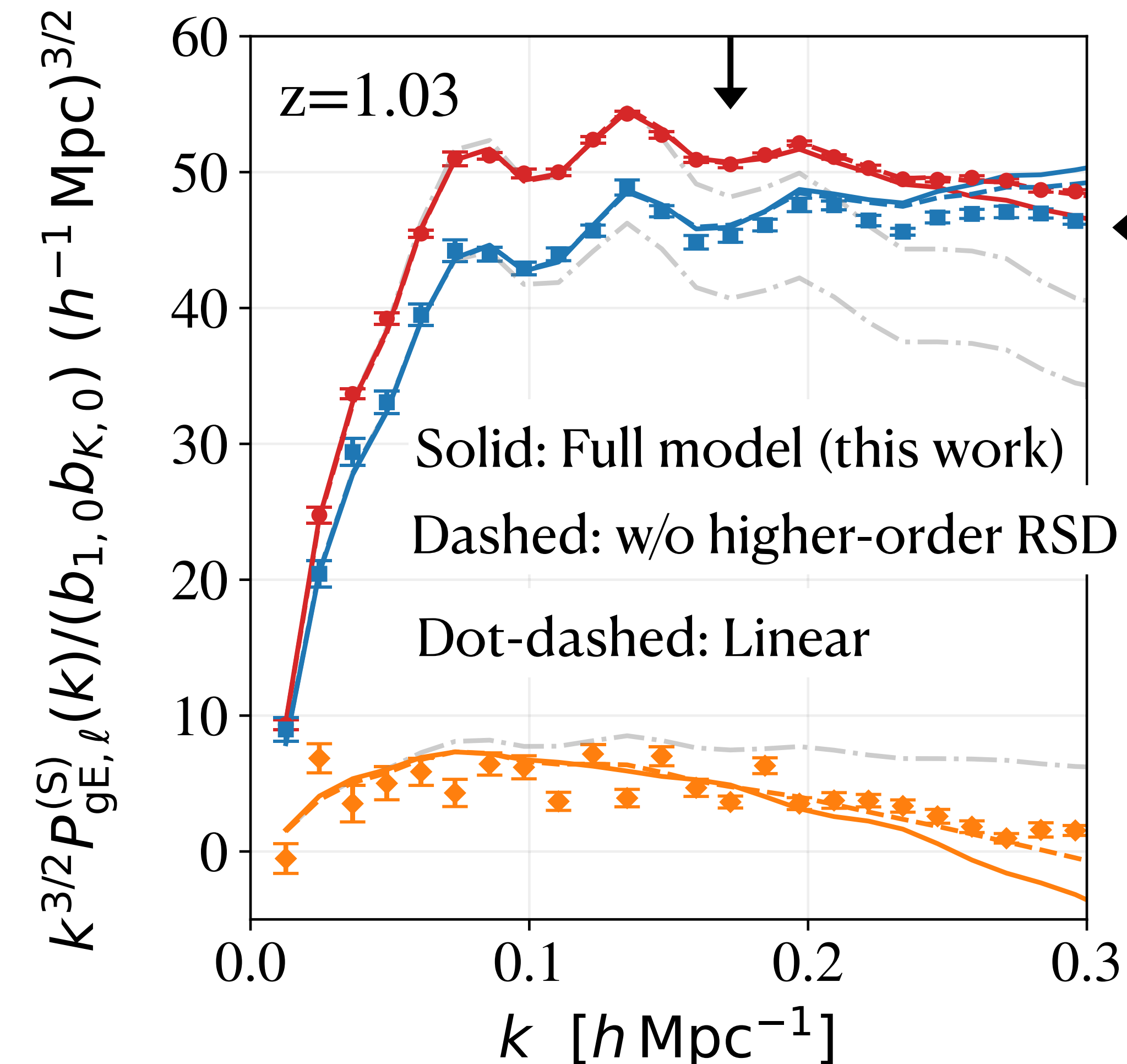
Constraints on dark energy EoS can be improved by **25–30%**

Improving theoretical predictions

AT, Kurita & Okumura ('25)

Nonlinear modeling is the key to extending the analysis to higher k_{max}

particularly in *redshift space*



Redshift-space GI power spectrum
(halo density $\times$ E-mode cross power spectrum)

$$P_{\text{gE}}^{(S)}(k) = \sum_{\ell} P_{\text{gE},\ell}(k) \mathcal{P}_{\ell}(k_{\parallel}/k)$$

Red: $P_{\text{gE},0}$ (monopole)
Blue: $-P_{\text{gE},2}$ (quadrupole)
Orange: $-P_{\text{gE},4}$ (Hexadecapole)

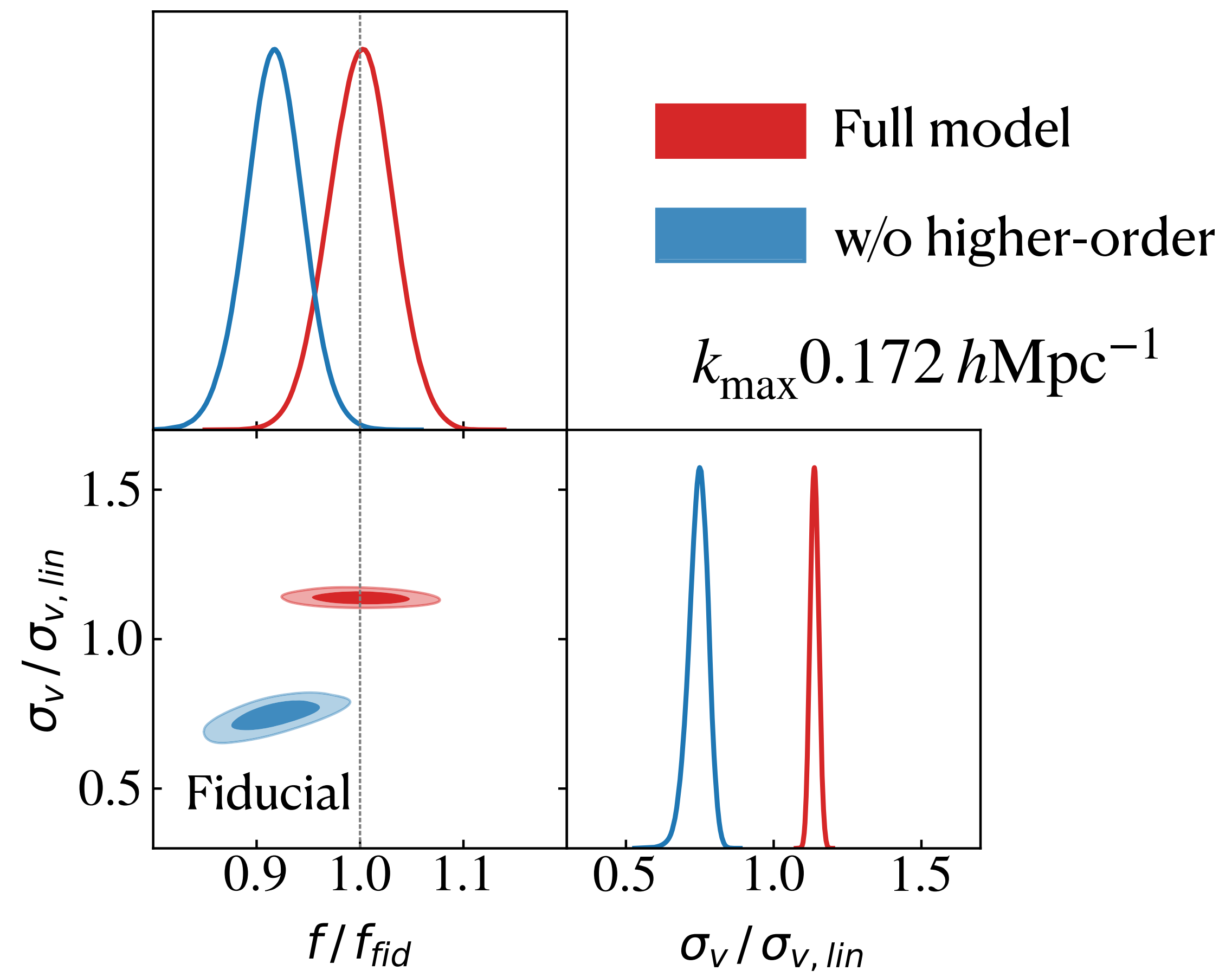
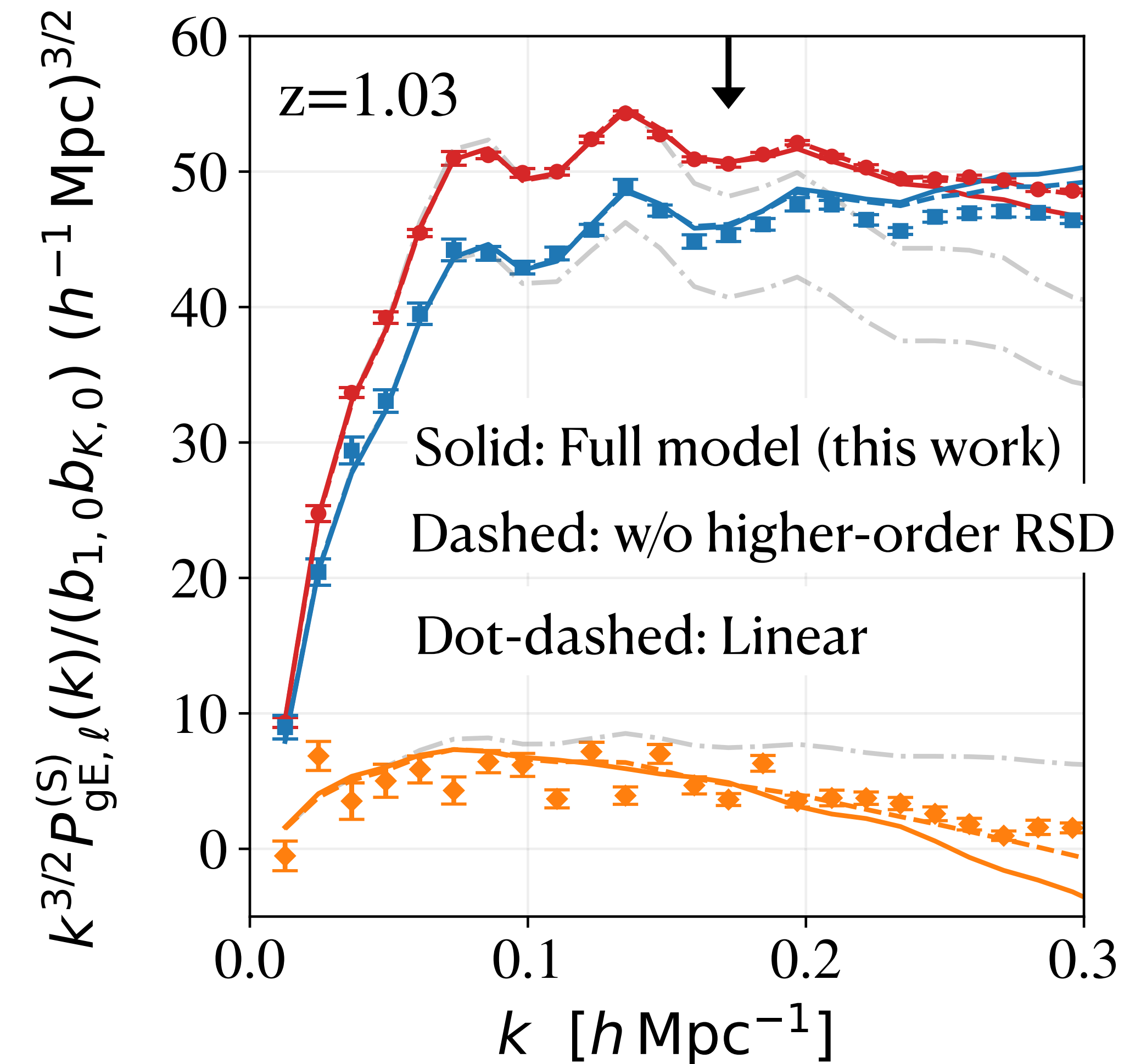
Solid & dashed : one-loop PT predictions
based on *linear alignment model*

Improving theoretical predictions

AT, Kurita & Okumura ('25)

Nonlinear modeling is the key to extending the analysis to higher $k_{\max}$

particularly in *redshift space*

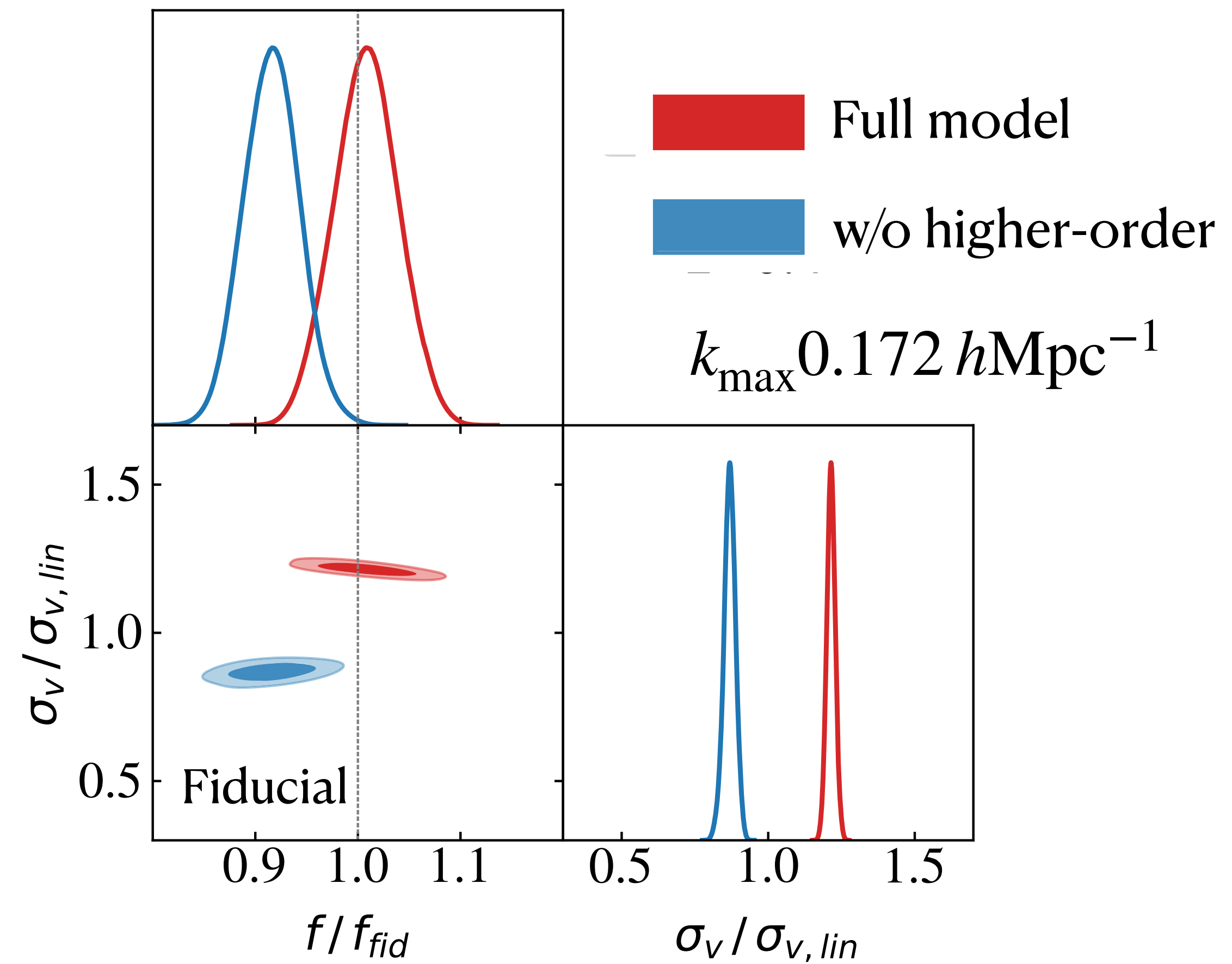
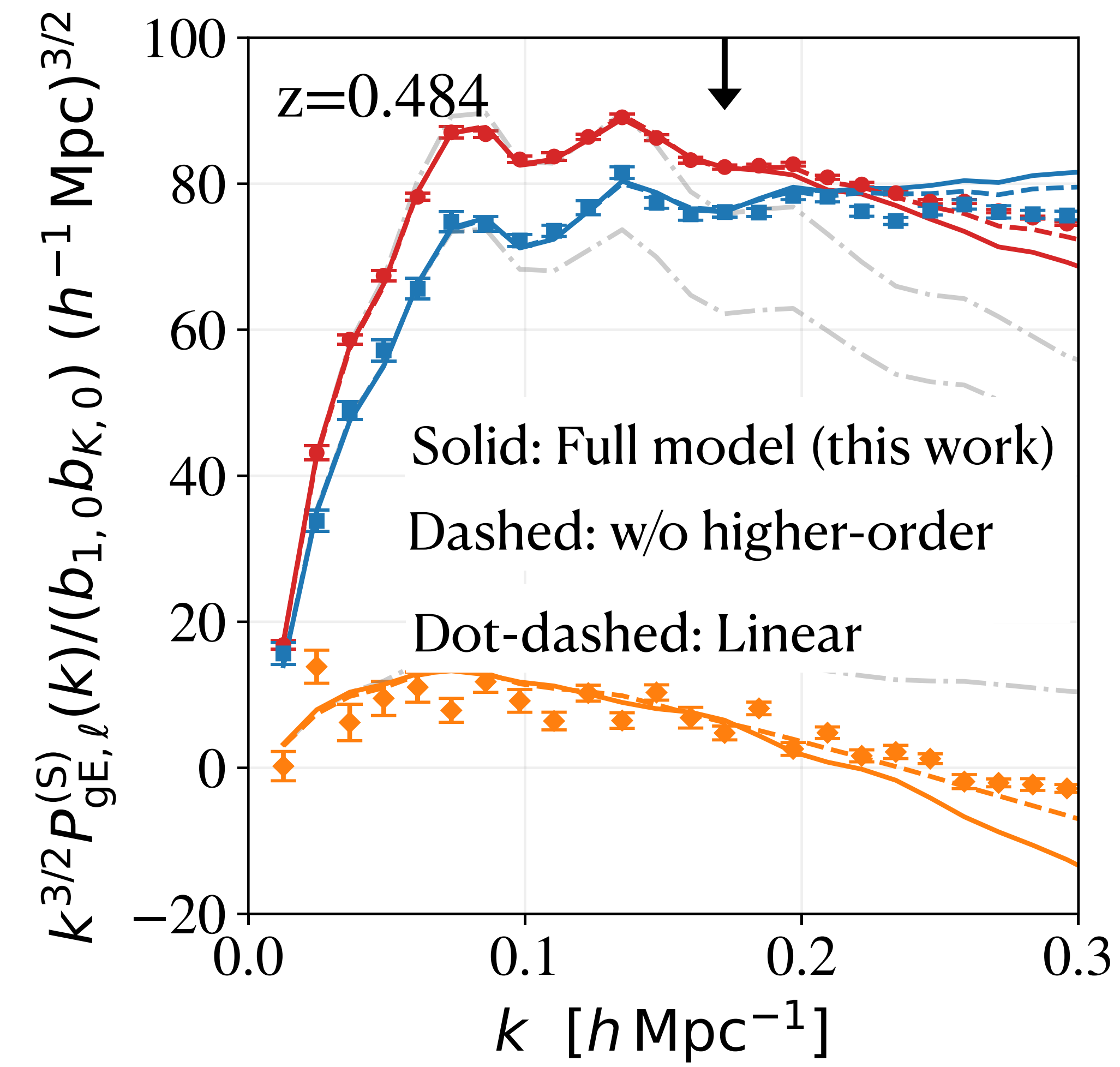


Improving theoretical predictions

AT, Kurita & Okumura ('25)

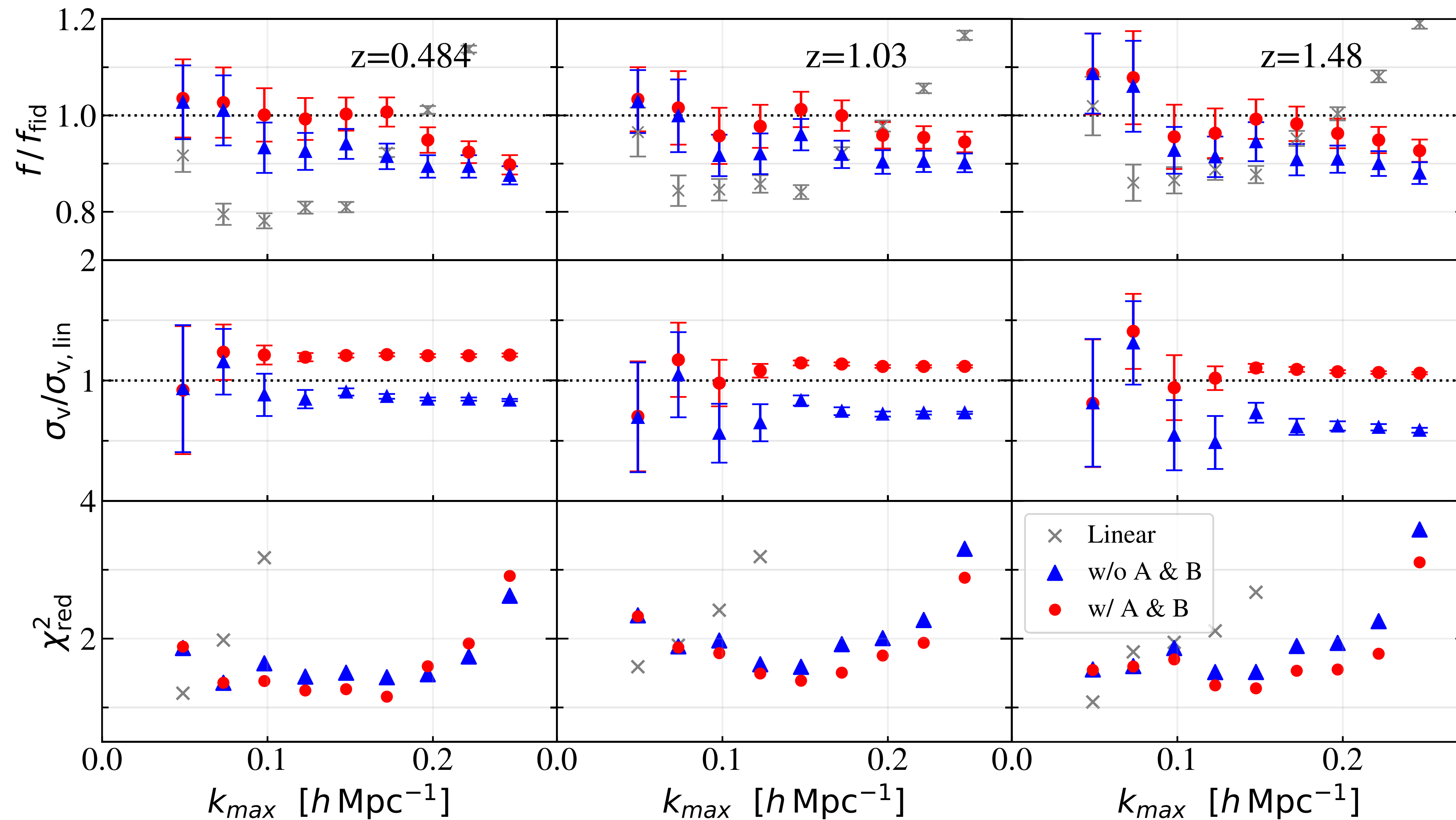
Nonlinear modeling is the key to extending the analysis to higher $k_{\max}$

particularly in *redshift space*



Improving theoretical predictions

AT, Kurita & Okumura ('25)



Linear growth
rate

For large $k_{\max}$, higher-order EFT terms need to be taken into account
(Kurita et al. in progress)

EFT description of ellipticity fields

Ellipticity fields are perturbatively described, in a unified manner, as a **tracer tensor field** constructed with matter density & velocity fields (δ & Θ):

Similar to the description of galaxy density field

$$(\gamma_+^I, \gamma_\times^I) = (g_{xx} - g_{yy}, 2g_{xy})$$

Schmitz et al. ('18)
Blazek et al. ('19)
Vlah et al. ('20ab)
Chen & Kokron ('23)

See also

Bakx et al. ('23)
Akitsu et al. ('23)

Linear order

Tidally induced alignment ($b_K < 0$)

Spin-induced alignment

$$g_{ij}(\mathbf{x}) = b_K K_{ij} + b_{\delta K} \delta(\mathbf{x}) K_{ij}(\mathbf{x}) + b_{K2} \left\{ K_{ik} K_{jk} - \frac{1}{3} \delta_{ij}^K \text{Tr}[K^2] \right\} + b_t t_{ij}(\mathbf{x}) + \dots$$

Second order

Matter density field

Velocity-divergence field of matter

$$K_{ij} \equiv \frac{1}{4\pi G \bar{\rho} a^2} \left[\partial_i \partial_j - \frac{1}{3} \delta_{ij}^K \nabla^2 \right] \Phi = \left[\frac{\partial_i \partial_j}{\partial^2} - \frac{1}{3} \delta_{ij}^K \right] \delta$$

$$t_{ij} \equiv \left[\frac{\partial_i \partial_j}{\partial^2} - \frac{1}{3} \delta_{ij}^K \right] \{ \Theta - \delta \} ; \quad \Theta = -\frac{1}{aH} (\nabla \cdot \mathbf{v})$$

Summary

Intrinsic galaxy shape/alignment carries ample cosmological information complementary to galaxy density field — New frontier of cosmology

◆ Tracer of tidal field of large-scale structure (matter distribution)

- Help tightening cosmological constraints AT & Okumura ('20), Okumura & AT ('22), Shim, Okumura & AT ('25a & '25b)
- First cosmological constraints on growth of structure (Test of gravity) Okumura & AT ('23)
- Precision EFT-based modeling in redshift space AT, Kurita & Okumura ('25), Kurita, AT & Okumura (in prep)

◆ Sensitive probe of cosmological vector/tensor fields

Akitsu et al. ('23), Kurita & Takada ('23), Kurita et al. ('26), ...

Precision modeling & new statistical characterization deserve further investigation