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第10回観測的宇宙論ワークショップ

Galaxy projected size fluctuations as a cosmological probe

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Take-home message

Galaxy/halo projected ***size***

carries ample cosmological information

$\parallel$ Trace part of the galaxy quadrupole image/shape

(which we usually ignore)

c.f. Intrinsic galaxy/halo alignments

Traceless part of the galaxy quadrupole image/shape

- It is spatially *fluctuating*

  → sensitive to large-scale structure & its tidal field

- It exhibits *anisotropies*:

  → combining conventional galaxy clustering data,

  it greatly helps improving BAO & RSD measurements

Akitsu & AT ('21, in prep.)

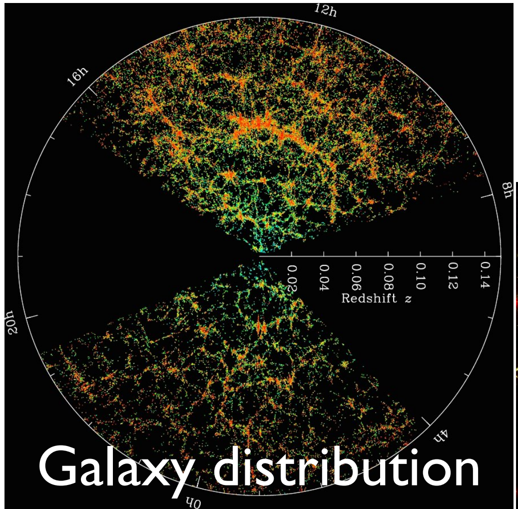
Motivation

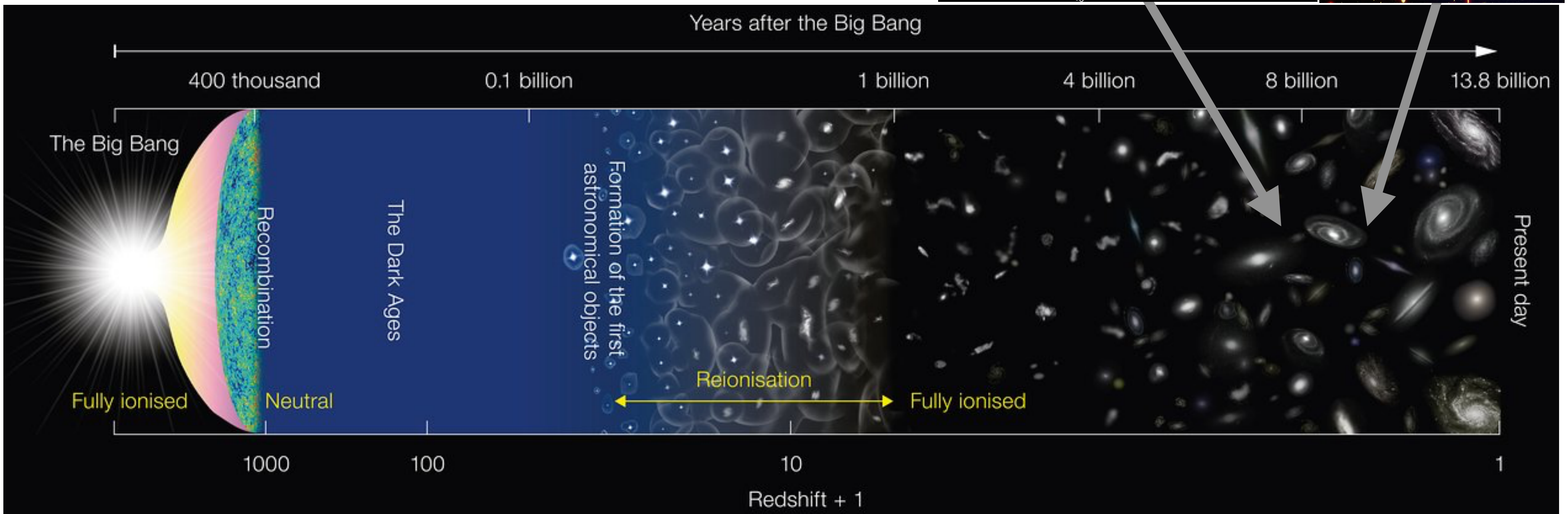
To better test & constrain cosmology,

How well we can maximize the cosmological information from <u>observational data</u> ?

Particularly,

Large-scale structure observations





Mapping the large-scale structure

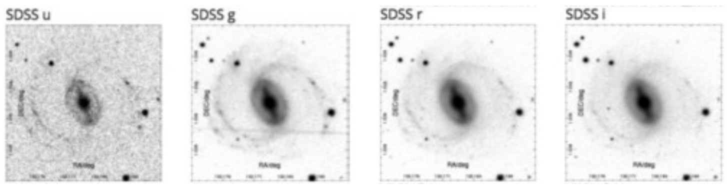
Large-scale matter distribution over Mpc~Gpc carry information on

- Cosmic expansion
- Structure formation driven by gravitational instability

These information can be obtained via

✓ **Imaging/photometric surveys**

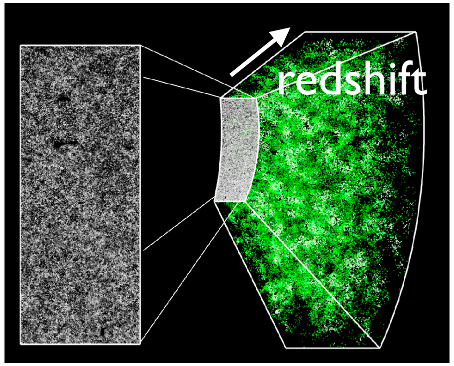
(angular position + galaxy shape)



2D map + shape (+ photo-z)

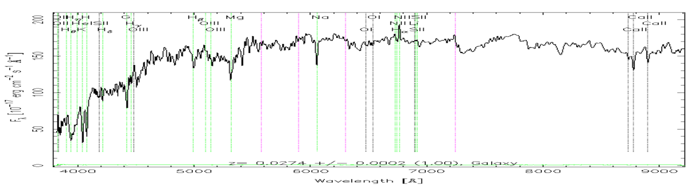
→ Weak lensing observations

→ 3x2pt analysis



✓ **Spectroscopic surveys**

(angular position + spectrum)



3D map

→ Baryon acoustic oscillation (BAO)

→ Redshift-space distortions (RSD)

Galaxy shape information in 3D

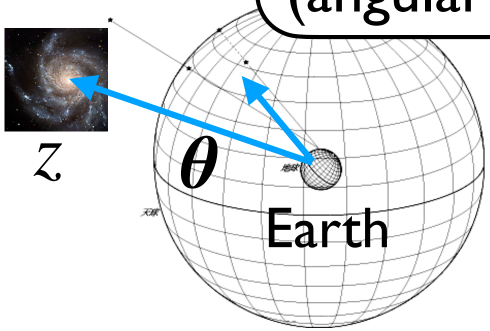
To maximize the cosmological information, one crucial aspect is

a synergy between imaging & spectroscopic surveys

Spectroscopic survey
3D galaxy position
(angular position + redshift)

+

Imaging survey
2D galaxy shape



3D map of projected galaxy shape

→HSC/PFS is powerful

In particular,

intrinsic alignments of galaxies has been recognized as a sensitive cosmology probe, tracing tidal field of large-scale structure

(Okumura-san & Kurita-san's talks)

Intrinsic alignment (IA) of galaxy

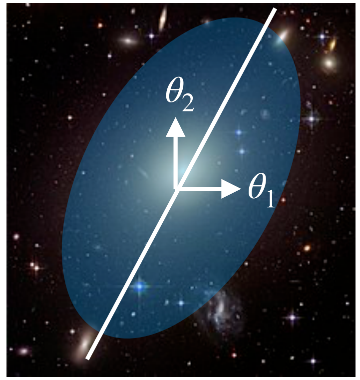
Projected orientation of observed galax/halo shape

In general, galaxy/halo has elliptical shape, aligned to some directions:

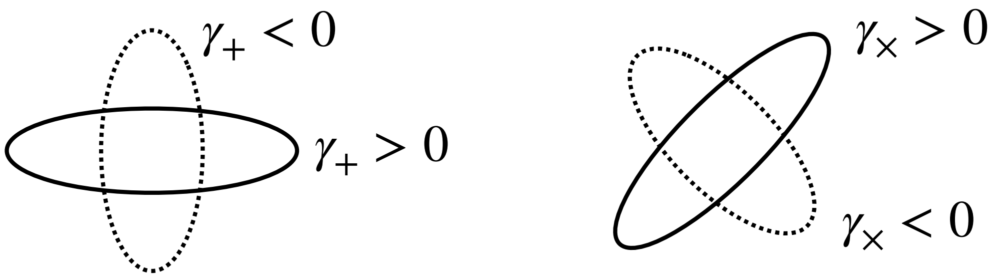
Quadrupole moment of galaxy image

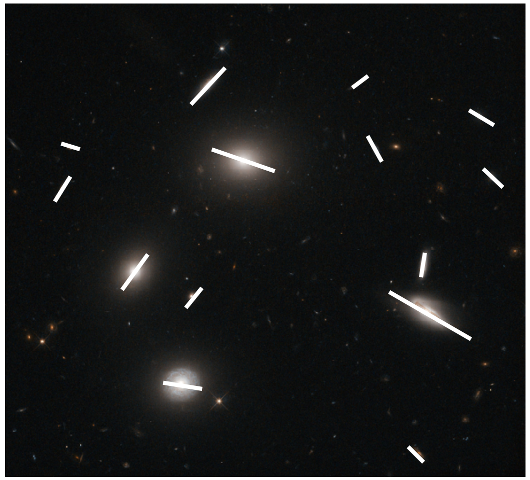
$$I_{ab} \equiv \frac{\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})\, \theta_a\, \theta_b}{\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})} \qquad (a, b = 1,2)$$

intensity



Ellipticity :
$$\gamma_+ \equiv \frac{I_{11} - I_{22}}{I_{11} + I_{22}}, \qquad \gamma_\times \equiv \frac{2\, I_{12}}{I_{11} + I_{22}}$$





This is indeed the quantity to measure weak lensing effect

IA as a cosmological probe

IA has been long considered as a contaminant of lensing signal

However, considering its 3D spatial correlations,

II correlation $\langle \gamma_a(\boldsymbol{x}_1)\,\gamma_b(\boldsymbol{x}_2)\rangle$ GI correlation $\langle \delta_{\rm g}(\boldsymbol{x}_1)\gamma_a(\boldsymbol{x}_2)\rangle$

$(a, b = +\,\mathrm{or}\times)$

- IA can produce a rather *large* signal, dominating the lensing signal

(Okumura, Jing & Li '09)

- IA exhibits *anisotropic* nature, on which BAO is clearly imprinted

Also, RSD can be measured from the GI correlation

(Okumura & AT '20, Okumura, AT & Nishimichi '20, Kurita et al. '20)

- IA is sensitive to a distinct type of primordial non-Gaussianity

(Schmidt, Chisari & Dvorkin '15, Kogai et al. '18, Akitsu et al. '21)

Unlocking *full* shape information

Galaxy IA is now considered as a promising cosmology probe, but we may not yet unlock the *full* power of galaxy shape information

$$I_{ab} \equiv \frac{\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})\, \theta_a \theta_b}{\int d^2\boldsymbol{\theta}\, I_{\rm obs}(\boldsymbol{\theta})} \quad (a, b = 1{,}2) \quad \Rightarrow \quad \gamma_+ \equiv \frac{I_{11} - I_{22}}{I_{11} + I_{22}}, \qquad \gamma_\times \equiv \frac{2I_{12}}{I_{11} + I_{22}}$$

One component is missing !
(trace part)

Focus of this work

Consider the following estimator for the trace part:

New !

$$\kappa \equiv \frac{I_{11} + I_{22}}{\langle I_{11} + I_{22} \rangle} - 1$$

$\langle \cdots \rangle$: ensemble average

Q Is this quantity a sensitive cosmology probe ?

3D shape & projected trace field

In principle, the galaxy shape is characterized in 3D space:

3D (symmetric) inertia tensor

e.g., Vlah et al. JCAP 01,025 ('20)

$$I_{ij}(\boldsymbol{x}) \equiv \bar{I}\left[\frac{\delta^{\mathrm{K}}_{ij}}{3}\left\{1 + \underbrace{\delta_{\mathrm{s}}(\boldsymbol{x})}_{\text{trace part}}\right\} + \underbrace{g_{ij}(\boldsymbol{x})}_{\text{trace-free part}}\right] \qquad (i,j = 1,2,3)$$

trace part — trace-free part $\mathrm{Tr}\,[g_{ij}] = 0$

Spatially fluctuating terms

g_{ij} : projecting onto the sky, this is related to IA ($\propto \gamma_{+,\times}$)

δ_{s} : this represents the (3D) size fluctuation **New !**

Then, the *2D* trace part is expressed as

$$\kappa \equiv \frac{I_{11}+I_{22}}{\langle I_{11}+I_{22}\rangle} - 1 \longrightarrow \delta_{\mathrm{s}}(\boldsymbol{x}) - \frac{3}{2}\,g_{zz}(\boldsymbol{x})$$

2D trace field as a tracer of LSS

2D size fluctuation

$$\kappa(\boldsymbol{x}) = \delta_{\rm s}(\boldsymbol{x}) - \frac{3}{2}\,g_{zz}(\boldsymbol{x})$$

Ignoring the tensor/vector modes, these fluctuations *at large scales* are supposed to (*biased*-)trace large-scale matter density field, $\delta_{\rm m}$:

Perturbative expansion $(|\delta_{\rm s}|, |g_{ij}| \ll 1)$

Schmidt et al. Phys.Rep.733, 1 ('18)
Vlah et al. JCAP 01,025 ('20)

$$1 + \delta_{\rm s} = (1+\delta_{\rm g})\left\{1 + b_{\rm s1}\delta_{\rm m} + \frac{b_{\rm s2}}{2}\delta_{\rm m}^2 + \cdots\right\}$$

$\delta_{\rm g}$: galaxy density field

$$g_{ij} = (1+\delta_{\rm g})\{b_{\rm K}K_{ij} + b_{\delta K}\,\delta_{\rm m}\,K_{ij} + \cdots\}$$

$$K_{ij} \equiv \left[\frac{\partial_i\partial_j}{\partial^2} - \frac{1}{3}\delta^{\rm K}_{ij}\right]\delta_{\rm m}$$

At leading order,

$$\kappa(\boldsymbol{x}) \simeq b_{\rm s1}\,\delta_{\rm m} - \frac{3}{2}\,b_K\,K_{zz}(\boldsymbol{x})$$

(Lensing contributions also ignored)

2D trace field as a tracer of LSS

In Fourier space,

Line-of-sight direction

$$\kappa(\boldsymbol{k}) \simeq \left\{b_{\rm s1} - b_K\,\underline{\mathscr{P}_2(\mu_k)}\right\}\delta_{\rm m}(\boldsymbol{k})\,; \qquad \mu_k \equiv \hat{k}\cdot\hat{z}$$

Legendre polynomials

Taking cross-correlation with galaxy density field $\delta_{\rm g} \simeq b_g\,\delta_{\rm m}$

$$P_{\rm g\kappa}(\boldsymbol{k}) = \sum_{\ell} P_{\ell,{\rm g}\kappa}(k)\,\mathscr{P}_\ell(\mu_k)$$

Legendre polynomials

$P_{0,{\rm gE}}(k)$

Multipole expansion

Monopole $\quad P_{0,{\rm g}\kappa}(k) \simeq b_g\,b_{\rm s1}\,P_{\rm mm}(k)$

matter power spectrum

E-mode IA

Quadrupole $\quad P_{2,{\rm g}\kappa}(k) \simeq -\,b_g\,b_K\,P_{\rm mm}(k) \longleftrightarrow -P_{0,{\rm gE}}(k)$

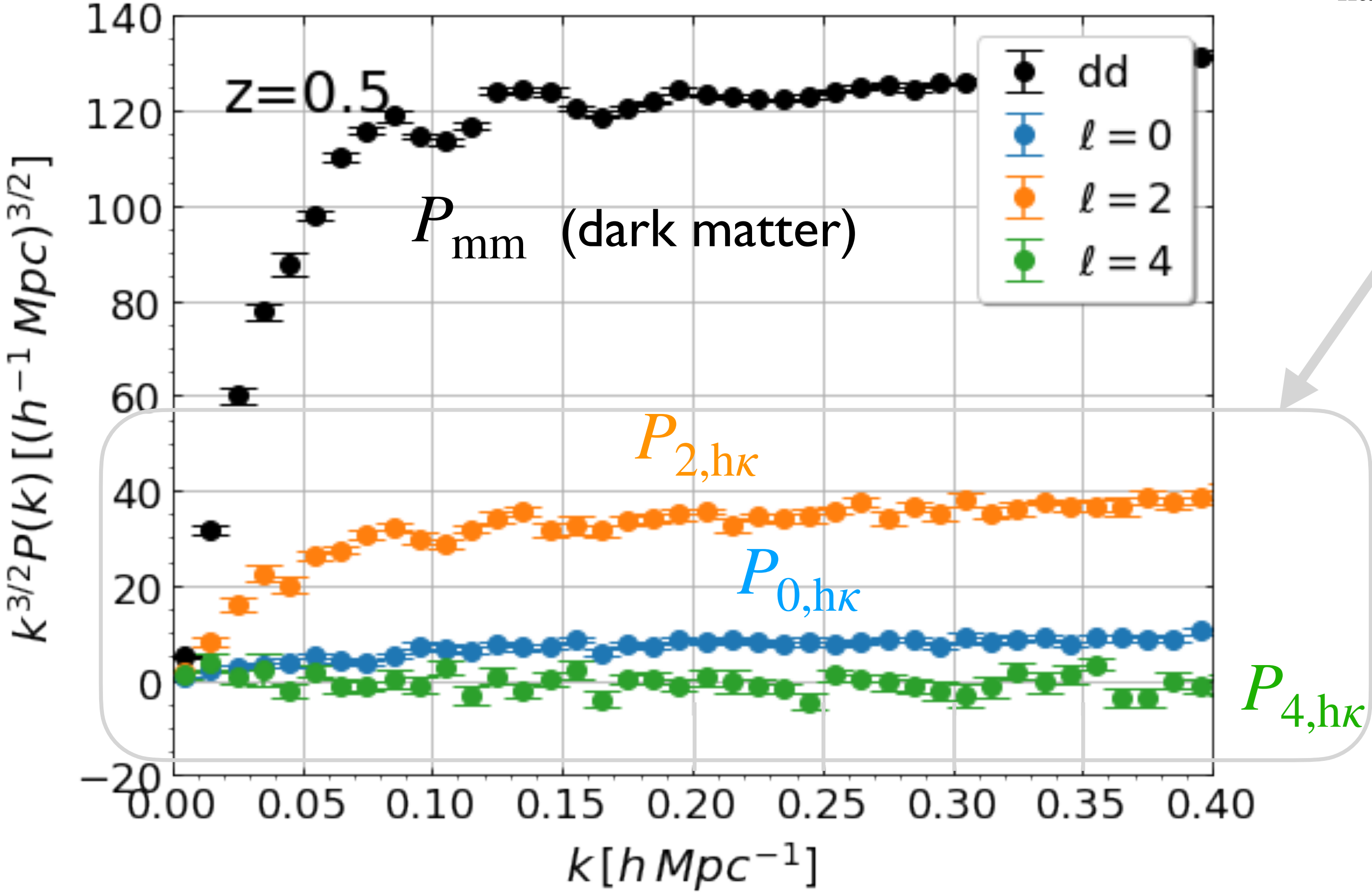
While monopole responds to the size fluctuation, quadrupole responds to IA, *identical* to the GI correlation (monopole)

Testing linear theory predictions

Real-space power spectra

Measured from halos of

$10^{13} \leq M_{\rm halo}/(h^{-1} M_\odot) \leq 3.16 \times 10^{13}$



Cross power spectrum between *halo density & 2D trace*

$P_{\ell,{\rm h}\kappa}(k)$

The amplitudes are rather smaller than $P_{\rm mm}$, but the monopole & quadrupole moments of $P_{{\rm h}\kappa}$ are clearly non-zero, and seems to trace $P_{\rm mm}$

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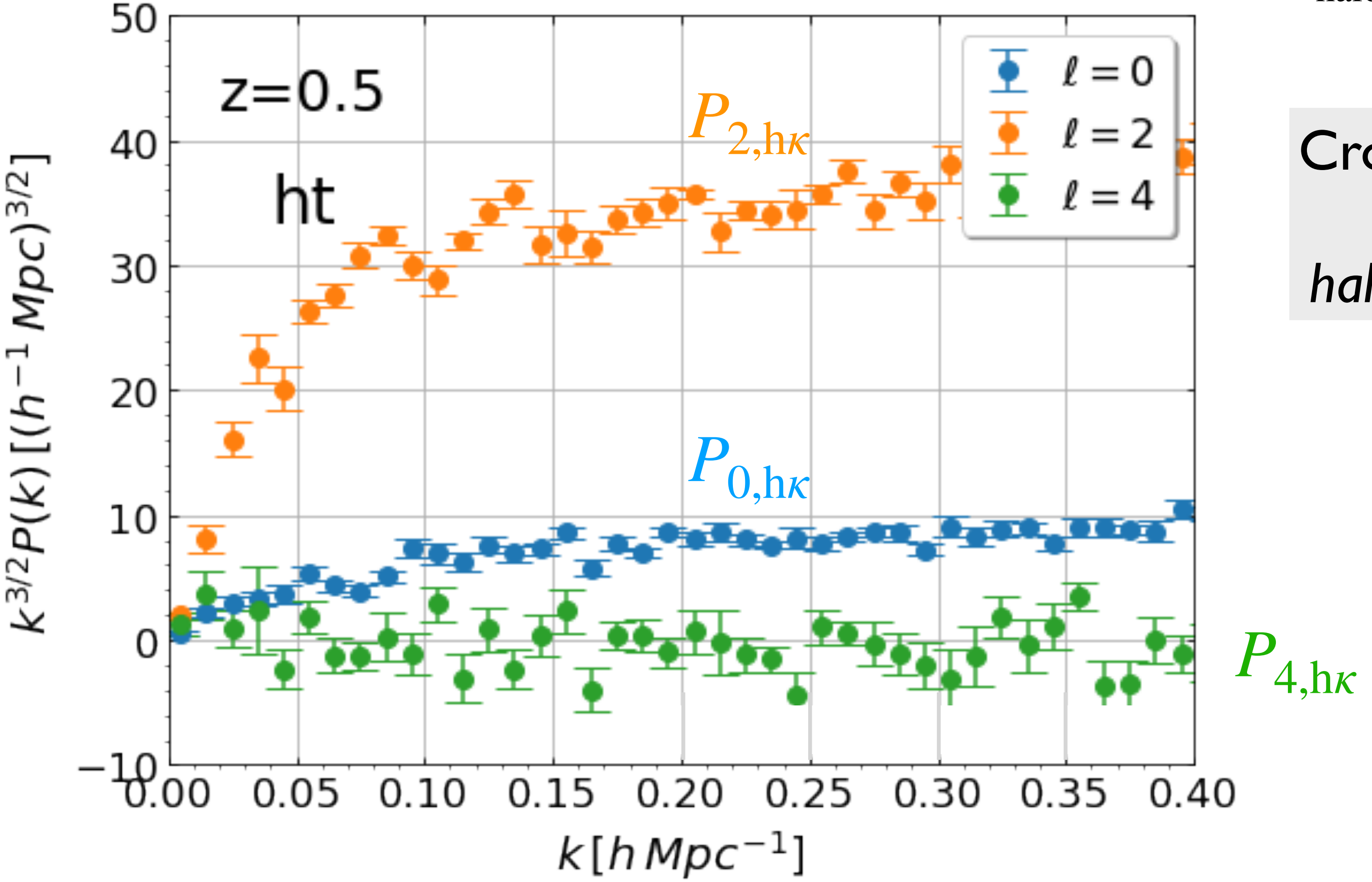
Real-space power spectra



Cross power spectrum between *halo density & 2D trace*

$P_{\ell,\mathrm{h}\kappa}(k)$

BAO feature is clearly visible in $P_{2,\mathrm{h}\kappa}$, while it is subtle for $P_{0,\mathrm{h}\kappa}$.
On the other hand, hexadecapole ($P_{4,\mathrm{h}\kappa}$) is consistent with zero

Testing linear theory predictions

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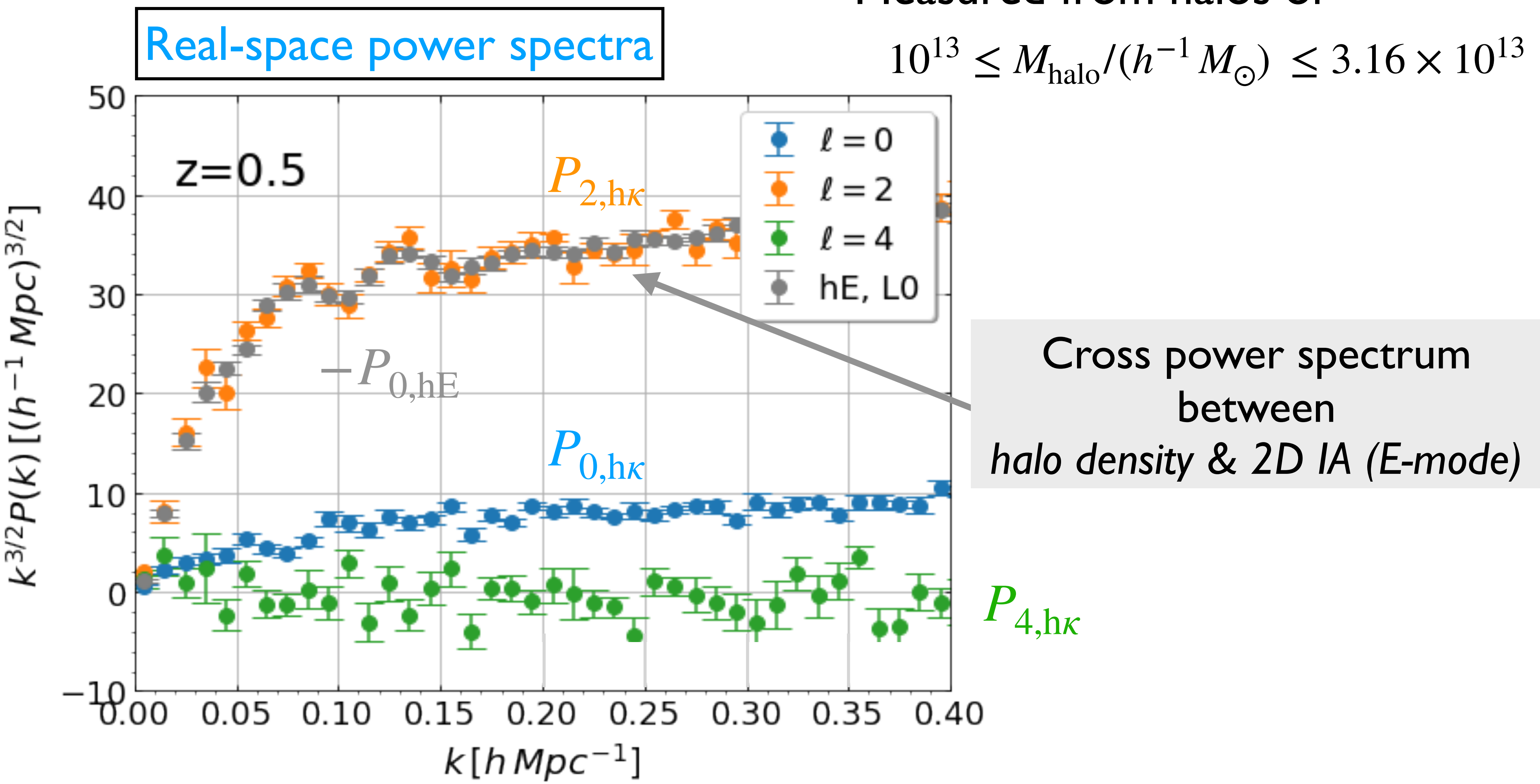

Quadrupole moment, $P_{2,\mathrm{h}\kappa}$, quantitatively match GI monopole ($-P_{0,\mathrm{gE}}$)

All consistent with linear theory !

Testing linear theory predictions

Measured from halos of

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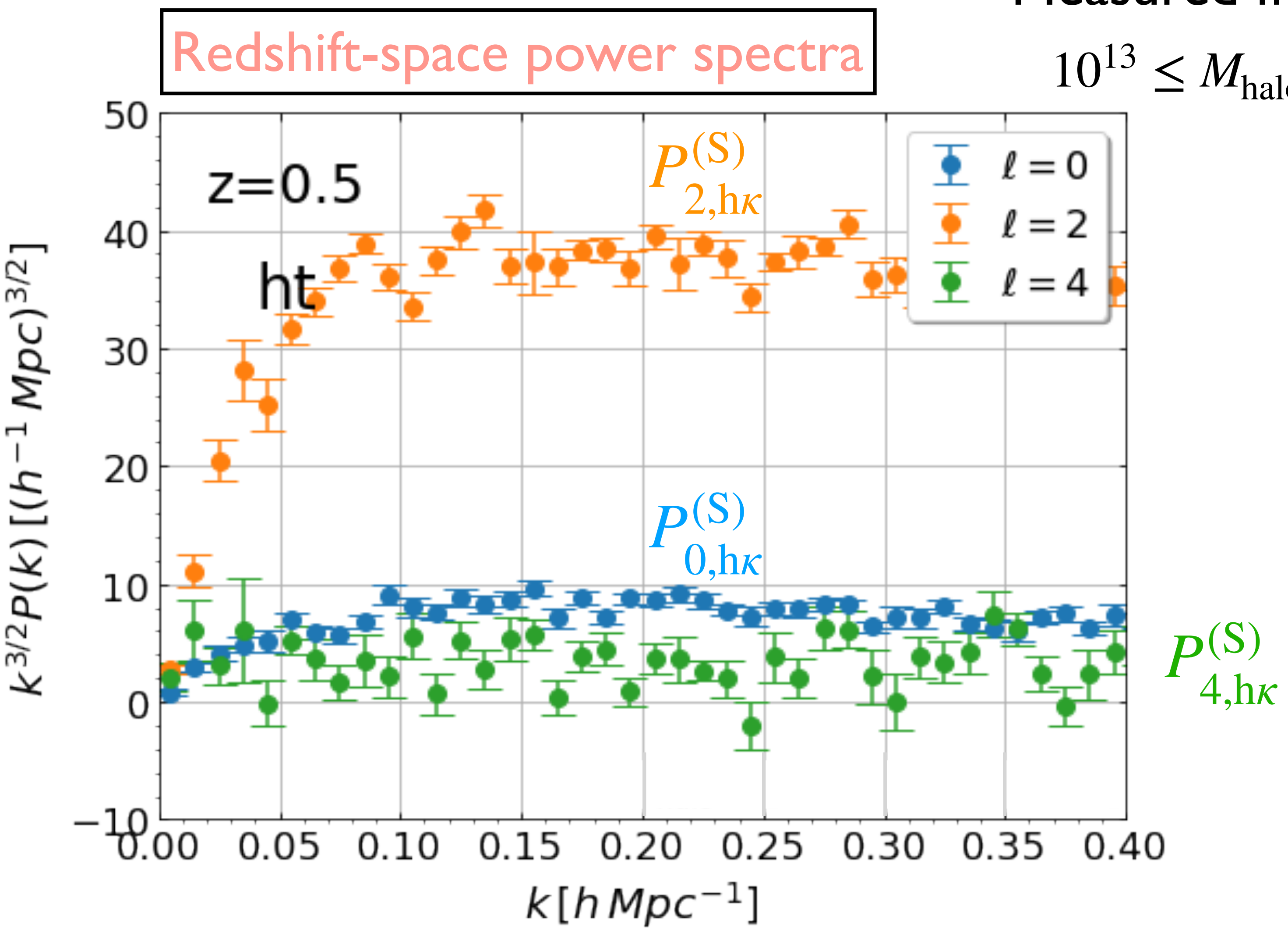


Redshift-space cross power spectra, $P^{(S)}_{\ell,g\kappa}$, are all non zero at $\ell \le 4$, and their amplitudes are slightly enhanced (due to the Kaiser effect on $\delta_{\rm m}$)

Shape-density bias relation

Bias relationship measured from simulated halo catalogs

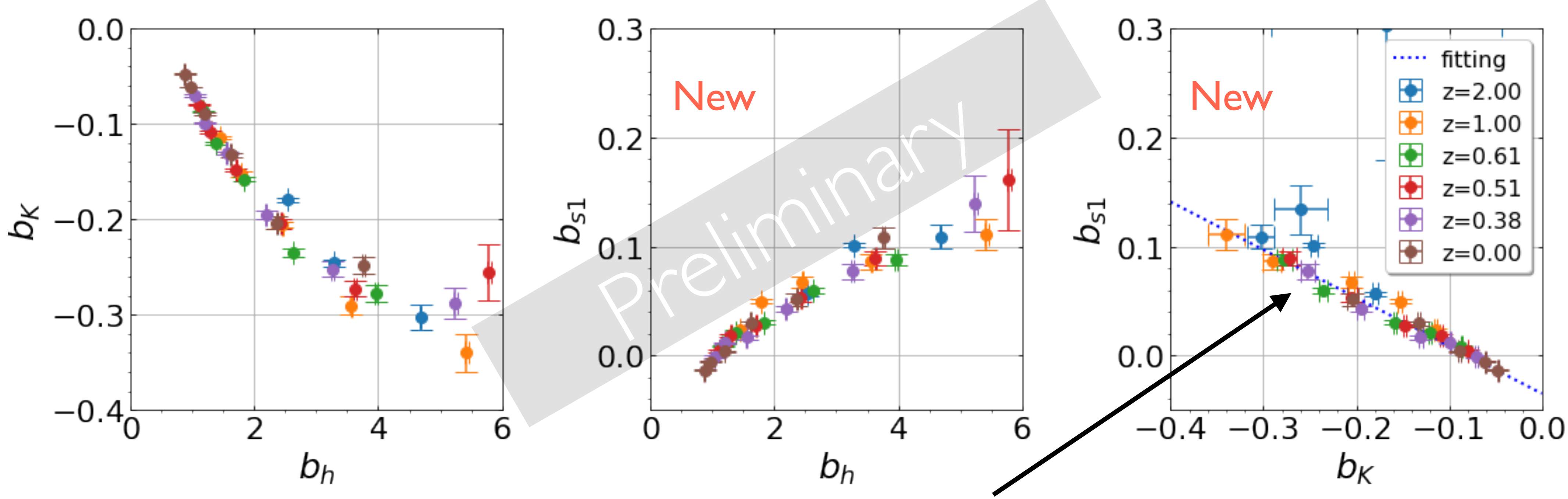
$M_{\rm halo}/(h^{-1}M_\odot) = [10^{12}, 10^{15}]$

Density : $\delta_{\rm h}(\boldsymbol{k}) = \boxed{b_h}\,\delta_{\rm m}(\boldsymbol{k})$

E-mode IA : $\gamma_{\rm E}(\boldsymbol{k}) = \boxed{b_K}\,\mathscr{P}_2(\mu_k)\,\delta_{\rm m}(\boldsymbol{k})$

New !

Trace IA : $\kappa(\boldsymbol{k}) = \{\boxed{b_{s1}} - \boxed{b_K}\,\mathscr{P}_2(\mu_k)\}\,\delta_{\rm m}(\boldsymbol{k})$

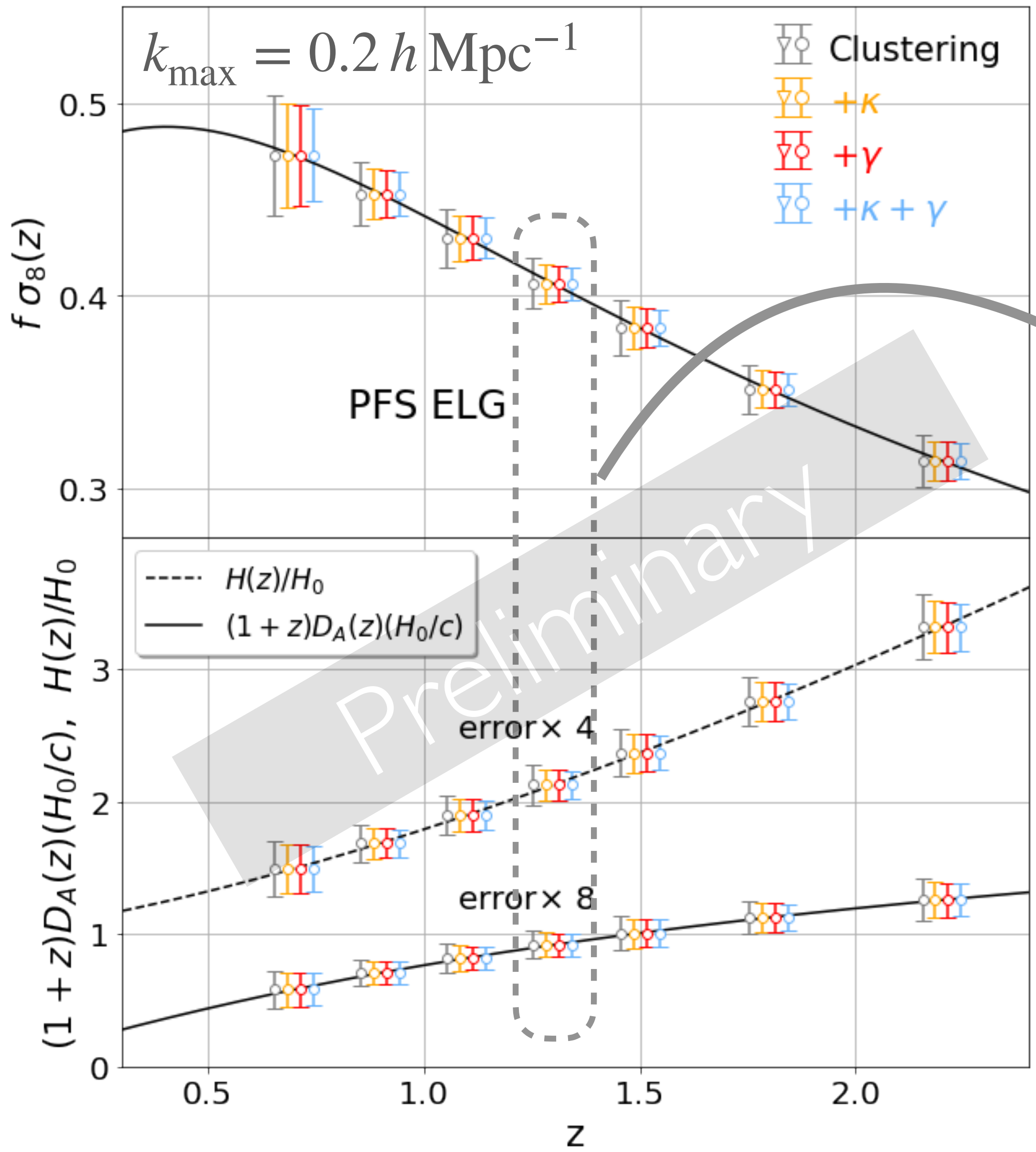


Numerically fitted to a linear relation: $b_{s1} = -0.45\,b_K - 0.035$

→ used to perform Fisher matrix analysis (next)

Forecast results from *all* shape info.

Combining galaxy clustering with *all* shape information

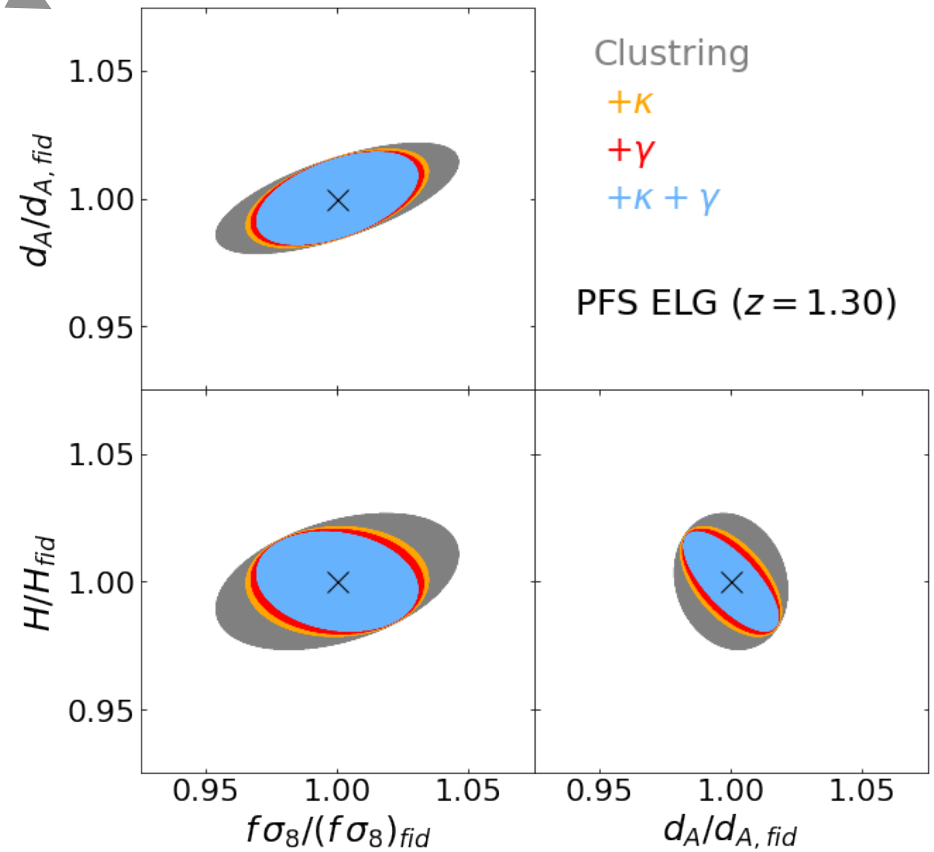


PFS-like survey assumed

(similar to Okumura & AT '21)

Assuming $A_{\rm IA} = 18$ & b_{s1}-b_K relation

(+ lensing systematics)



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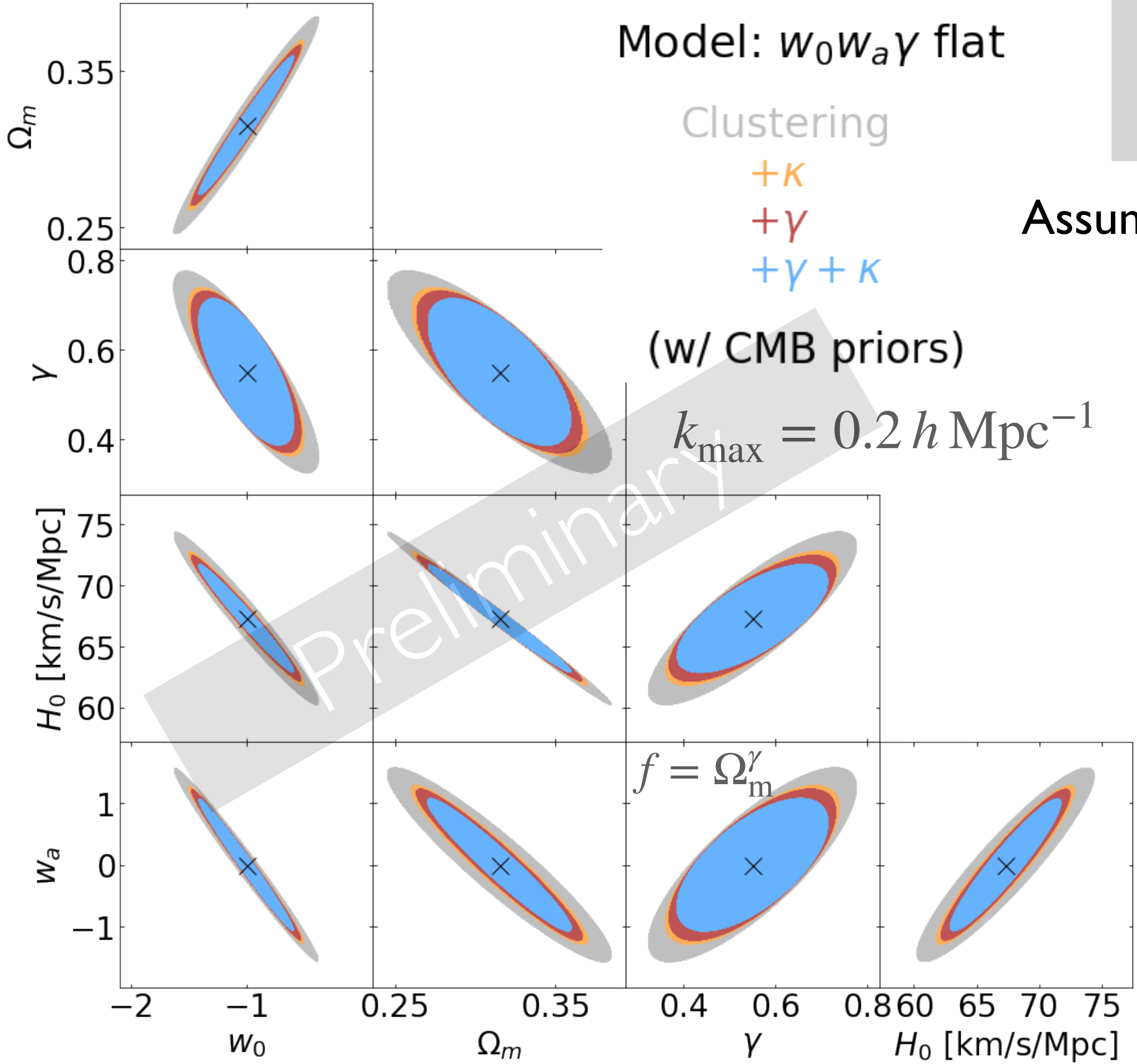

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Geometric & dynamical constraints

$\{f\sigma_8(z_i), D_A(z_i), H(z_i)\}$

⬇

Constraints on

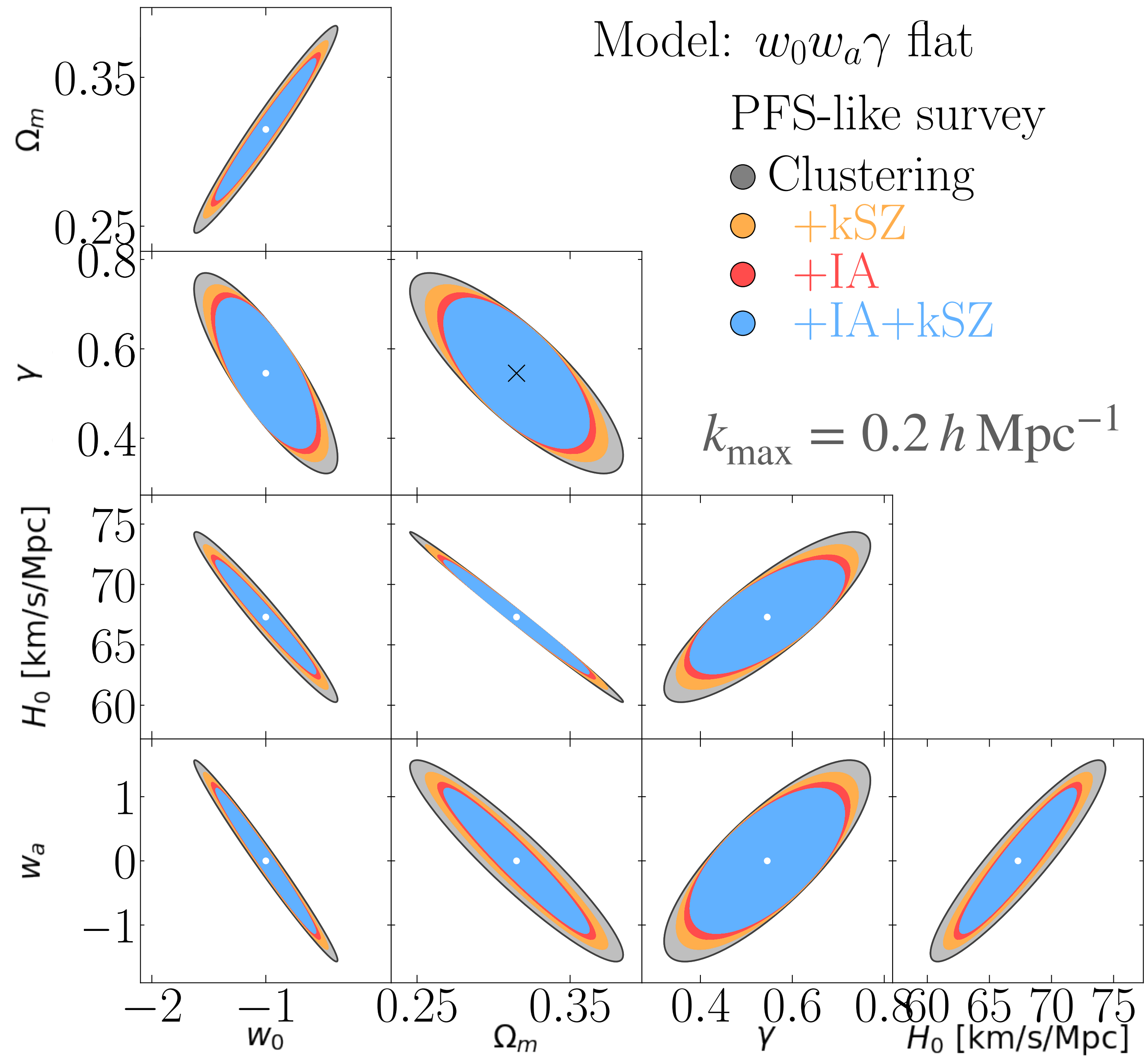
$w_0 w_a \gamma$ flat CDM model

$\{\Omega_{\rm m}, H_0, w_0, w_a, \gamma\}$

With $\sigma_8(0)$ marginalized

c.f. Okumura & AT ('21) arXiv:2110.11127

Combining clustering + IA + kSZ observations



Summary

Galaxy/halo projected ***size***

carries ample cosmological information

$\parallel$

Trace part of the galaxy quadrupole image/shape

(which has been so far ignored)

- It is spatially *fluctuating*

  → sensitive to large-scale structure & its tidal field

- It exhibits *anisotropies*:

  → combining conventional galaxy clustering data,

  it greatly helps improving BAO & RSD measurements

- A more interesting thing happens for the primordial non-Gaussianity

(Akitsu & AT, in progress)