Some thoughts on intrinsic alignments (IA) (my talk is for discussion)

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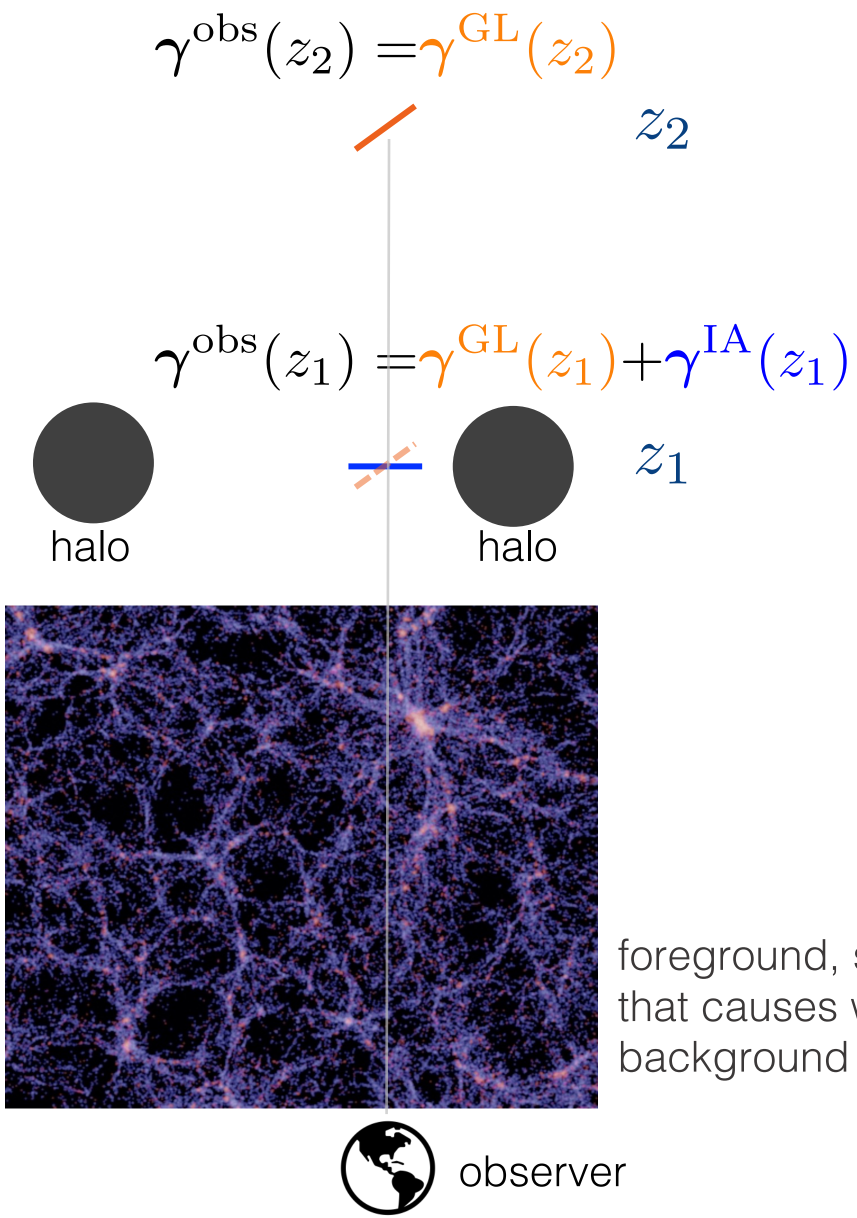
Ken Osato (Kyoto/IAP), Takahiro Nishimichi (Kyoto), Rensei Tateishi

Intrinsic alignment (IA): a contamination to weak lensing



$$\boldsymbol{\gamma}^{\rm obs}(z_2) = \boldsymbol{\gamma}^{\rm GL}(z_2)$$

$$\boldsymbol{\gamma}^{\rm obs}(z_1) = \boldsymbol{\gamma}^{\rm GL}(z_1) + \boldsymbol{\gamma}^{\rm IA}(z_1)$$

foreground, shared large-scale structure (z<z_1)
that causes weak lensing distortions in images of
background galaxies

- Hirata & Seljak (2004)

$$\langle \boldsymbol{\gamma}^{\rm obs}(z_1)\boldsymbol{\gamma}^{\rm obs}(z_2)\rangle = \underbrace{\langle \boldsymbol{\gamma}^{\rm GL}(z_1)\boldsymbol{\gamma}^{\rm GL}(z_2)\rangle}_{\text{cosmic shear}} + \underbrace{\langle \boldsymbol{\gamma}^{\rm IA}(z_1)\boldsymbol{\gamma}^{\rm GL}(z_2)\rangle}_{\text{IA contamination}}$$

$$\langle \boldsymbol{\gamma}^{\rm IA}(z_1)\boldsymbol{\gamma}^{\rm GL}(z_2)\rangle \neq 0 < 0$$

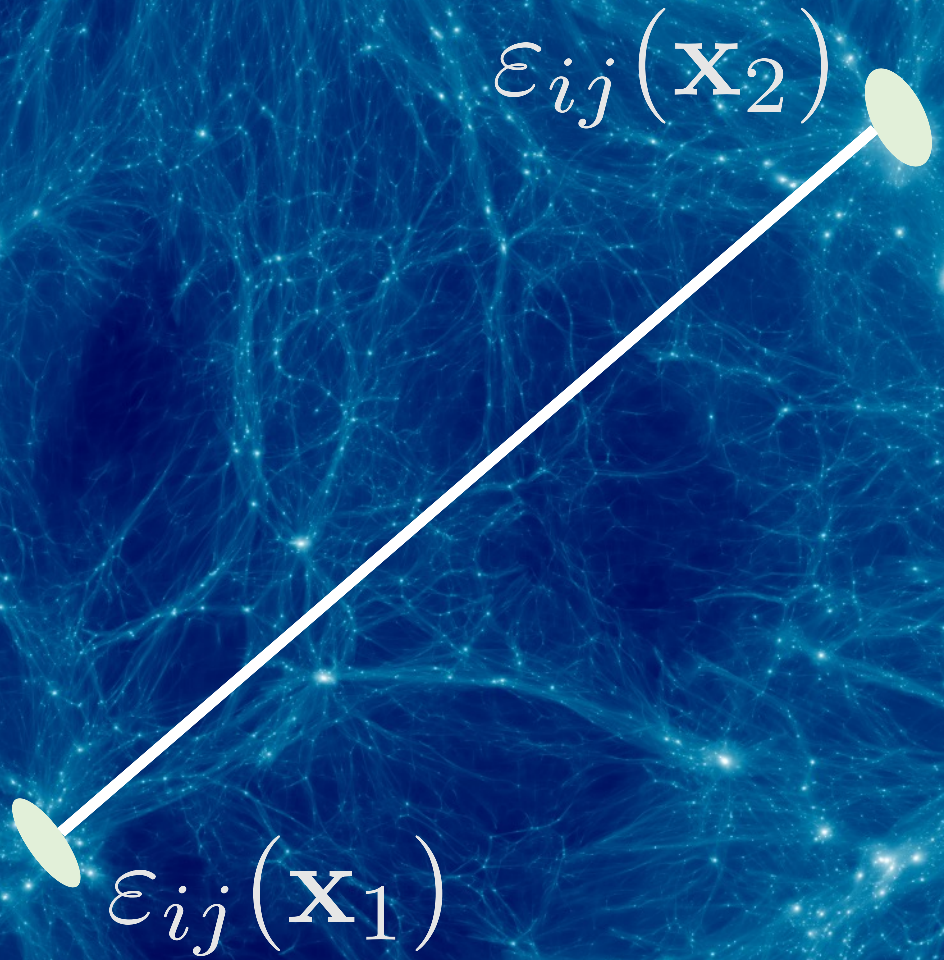
IA contamination needs to be considered in cosmic shear cosmology

- Galaxy-galaxy lensing is NOT contaminated by IA

$$\langle \delta_{\rm g}(\mathbf{x}; z_1)\boldsymbol{\gamma}^{\rm GL}(z_2)\rangle$$

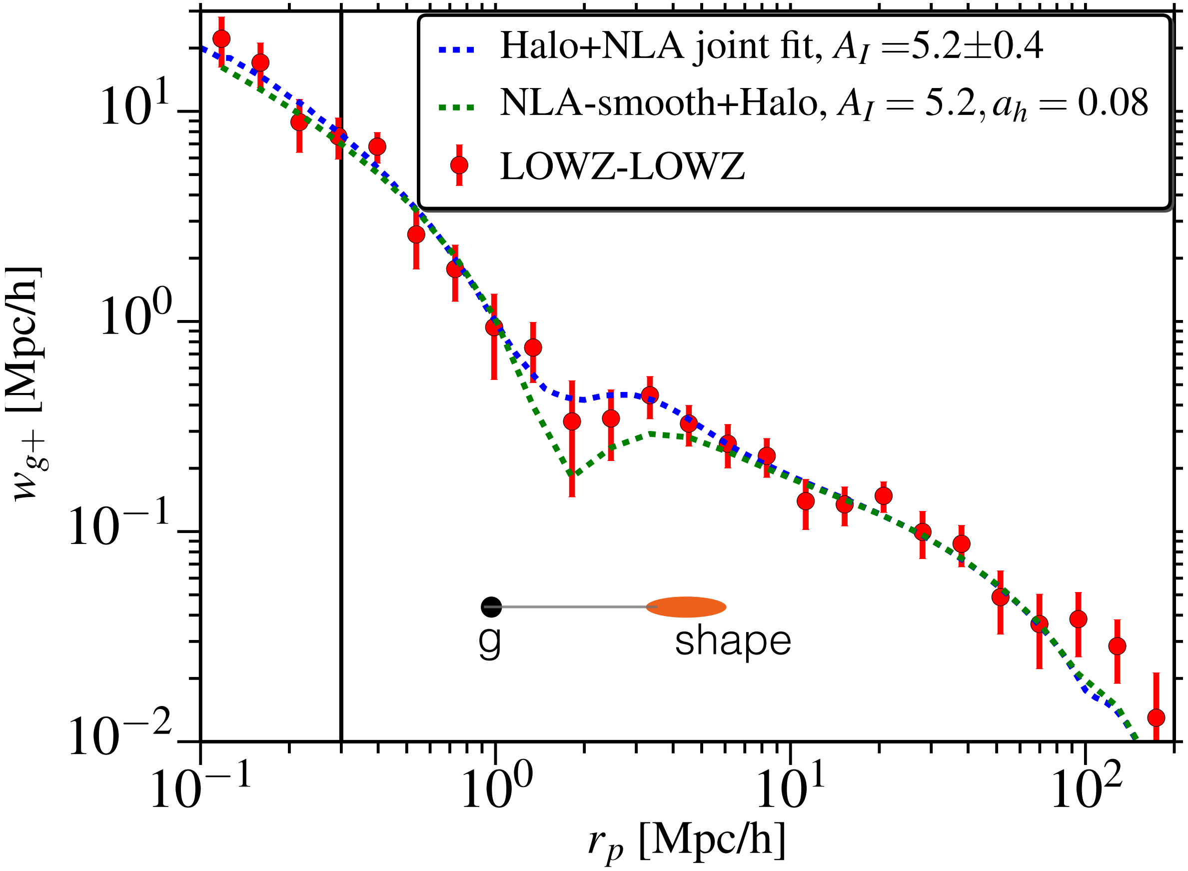
- IA correlation function $\langle \delta_{\rm g}(\mathbf{x}; z_1)\boldsymbol{\gamma}^{\rm IA}(\mathbf{x}'; z_1)\rangle$

Intrinsic alignments of galaxy shapes

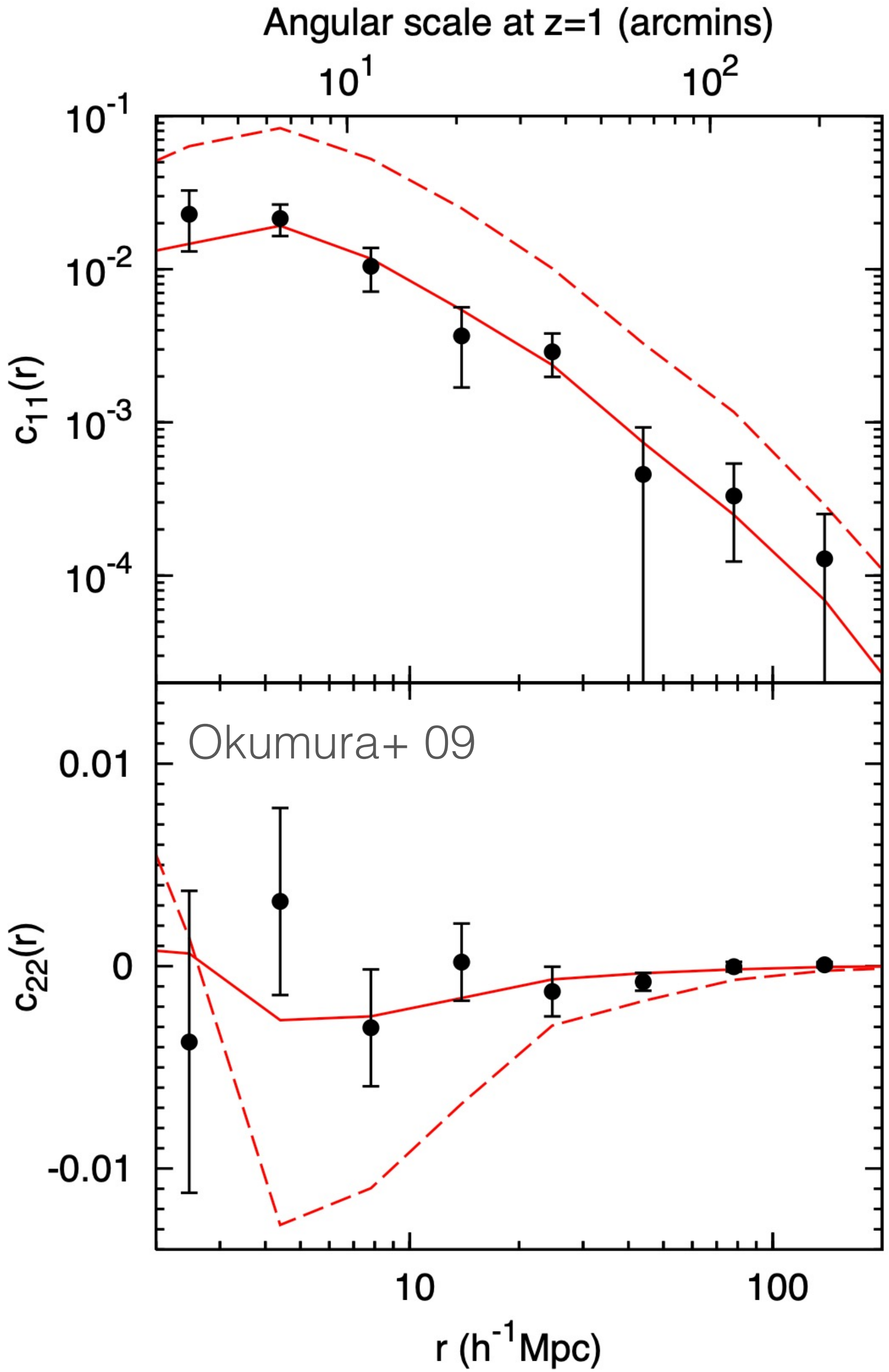


- ✓ Intrinsic alignment = intrinsic correlations of galaxy “shapes” with surrounding large-scale structure
- ✓ Here we want to consider IA up to O(100) Mpc/h ⇒ gravity/primordial origin
- ✓ Galaxy shapes have to be estimated from imaging data
- ✓ Large-scale structure needs to be estimated from spectroscopic data (e.g. using 3D distribution of galaxies)
- ✓ For IA measurements, we need both imaging and spectroscopic data for the same region of the sky

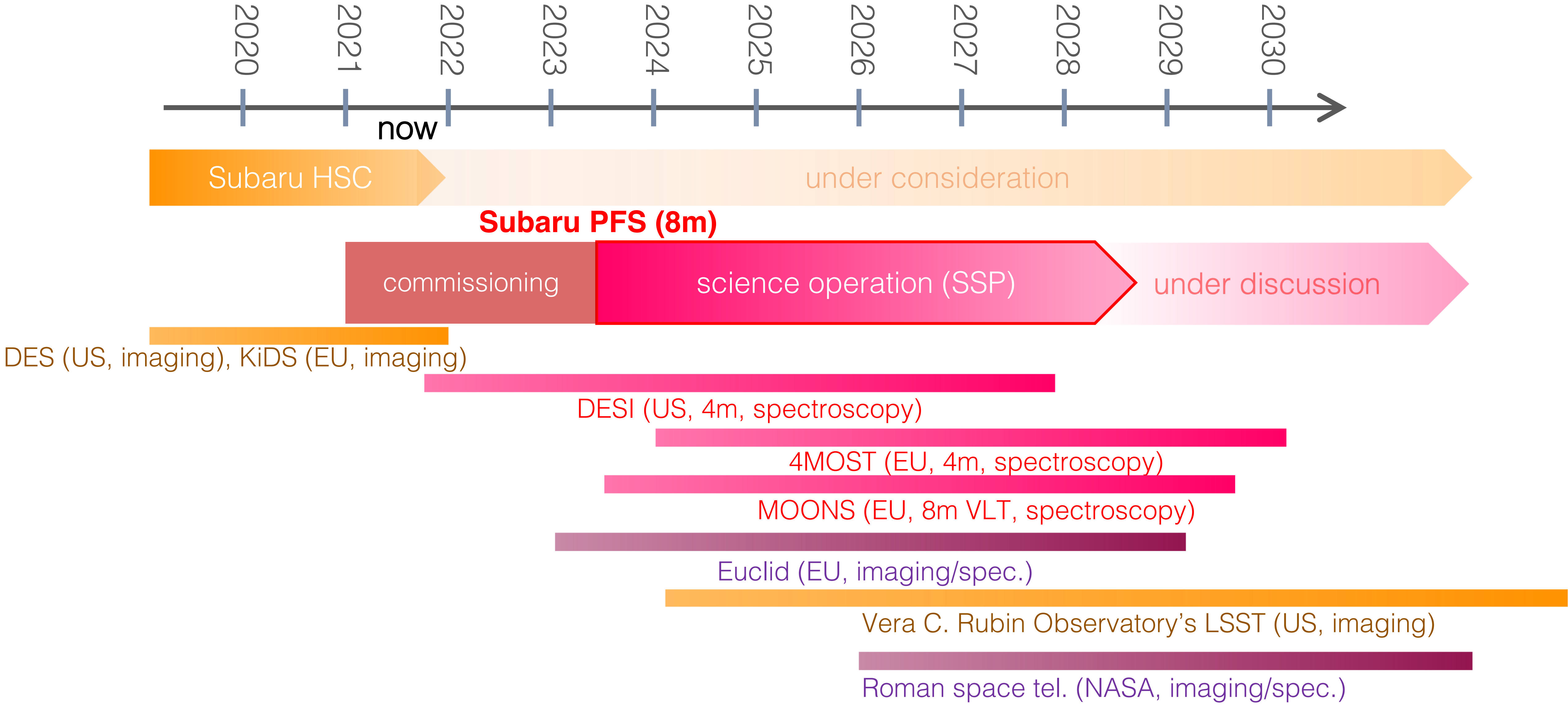
- IA effect has been detected by SDSS data for early-type, red galaxies, NOT for blue, star-forming galaxies
- So far all the measurements are in real (configuration) space
- See Toshiki's (Kurita-san's) talk for an attempt of the Fourier-space measurement



Singh & Mandelbaum 15



Landscapes in 2020s cosmology



2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030

now

Subaru HSC

under consideration

Subaru PFS (8m)

commissioning

science operation (SSP)

under discussion

DES (US, imaging), KiDS (EU, imaging)

DESI (US, 4m, spectroscopy)

4MOST (EU, 4m, spectroscopy)

MOONS (EU, 8m VLT, spectroscopy)

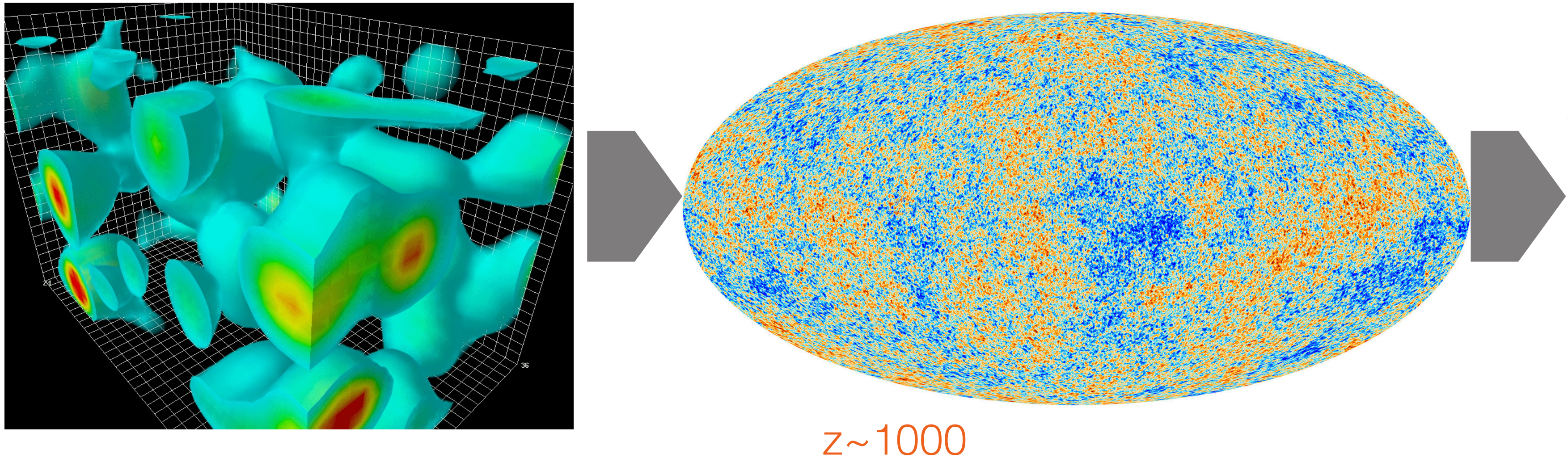
Euclid (EU, imaging/spec.)

Vera C. Rubin Observatory’s LSST (US, imaging)

Roman space tel. (NASA, imaging/spec.)

“adiabatic” ΛCDM model

- All cosmological data are consistent with “adiabatic” ΛCDM model that is predicted by the simplest, single-field inflation model
- “single”-field inflation initial conditions ⇒ a “single” degree of freedom in large-scale structure fields on linear scales



$$\delta\phi_{\rm inf}(\mathbf{k}) \rightarrow \zeta(\mathbf{k})$$

quantum fluctuations

primordial curvature perturbation

z~1000

$$\Theta_\gamma(\mathbf{k}) \equiv \frac{\delta T_\gamma}{\bar{T}_\gamma} = T_\gamma(k)\zeta(\mathbf{k})$$

$$\delta_\nu(\mathbf{k}) = T_\nu(k)\zeta(\mathbf{k})$$

$$\delta_{\rm cdm}(\mathbf{k}) = T_{\rm cdm}(k)\zeta(\mathbf{k})$$

$$\delta_{\rm b}(\mathbf{k}) = T_{\rm b}(k)\zeta(\mathbf{k})$$

In late universe (matter dominated) on large scales (>100Mpc)

$$\rho_{\rm m} \gg \rho_i$$

$$\delta_{\rm m}(\mathbf{k}) = T_{\rm m}(k)\zeta(\mathbf{k})$$

$$\delta_{\rm galaxy}(\mathbf{k}) = b_{\rm galaxy}\delta_{\rm m}(\mathbf{k})$$

$$\delta_{\rm BH}(\mathbf{k}) = b_{\rm BH}\delta_{\rm m}(\mathbf{k}), \ldots$$

“adiabatic” ΛCDM model

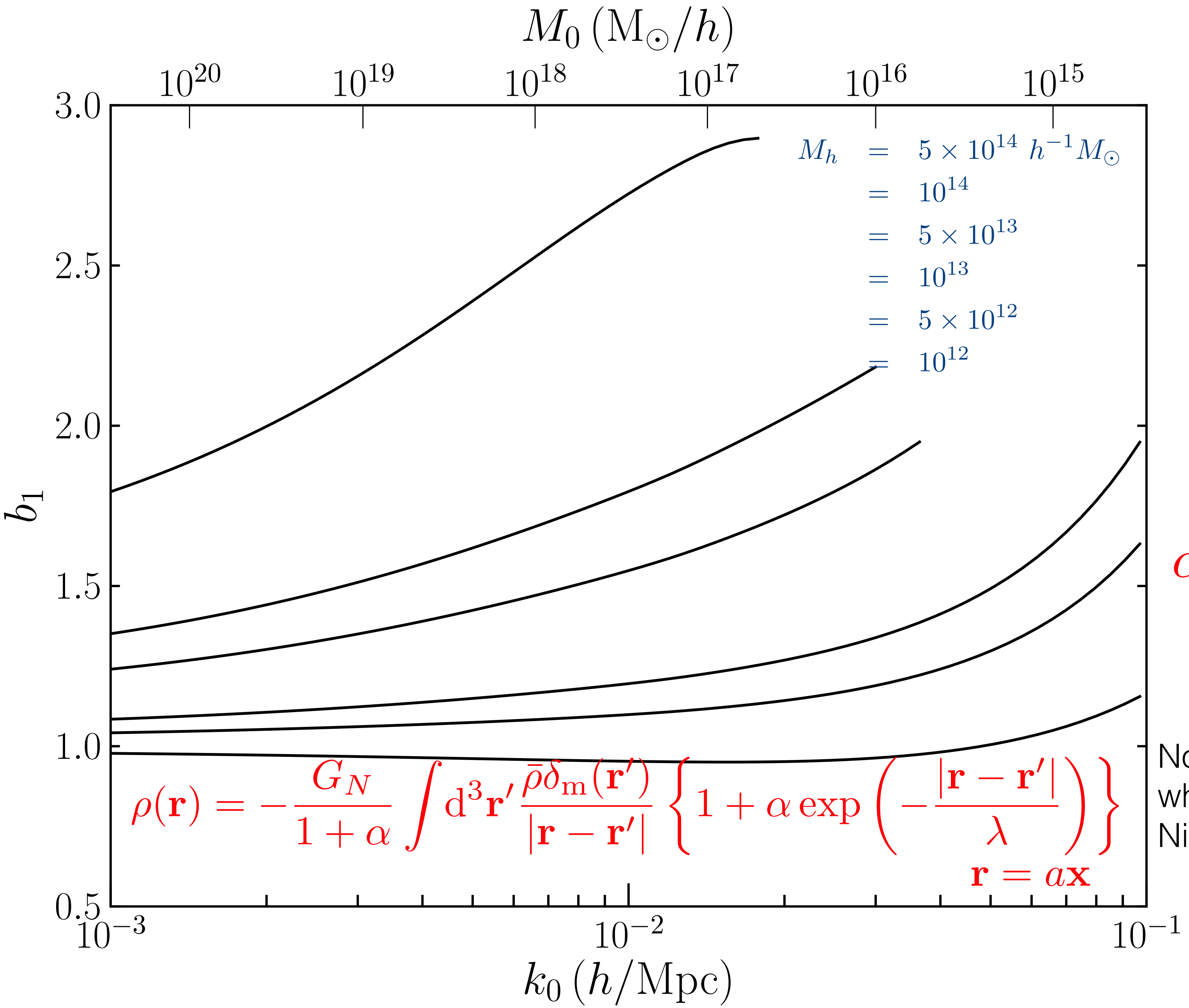
- For any primordial-origin scalar field, its power spectrum (or 2pt correlation function) should obey the following, in the matter dominated era and on linear scales:

$$\frac{\langle F(\mathbf{k})F(-\mathbf{k})\rangle}{\langle \delta_{\rm m}(\mathbf{k})\delta_{\rm m}(-\mathbf{k})\rangle} = \frac{P_{FF}(k)}{P_{\rm mm}(k)} \longrightarrow k^0 \text{ for } k \ll k_{\rm NL}$$

- “m”: weak lensing, RSD. “F” can be any field (galaxy, shape, SZ, kSZ, luminosity, ... AGN jet …): a “correlation” method is very powerful to test the cosmology origin

- Hence if any scale-dependence is observed, it should be a smoking-gun signature of “new physics”, compared to ΛCDM model
  - Secondary primordial field or new degree freedom: e.g., primordial non-Gaussianity and dark energy perturbation
  - Modified gravity
  - … anything else?

Parfrey, Hui & Sheth 11



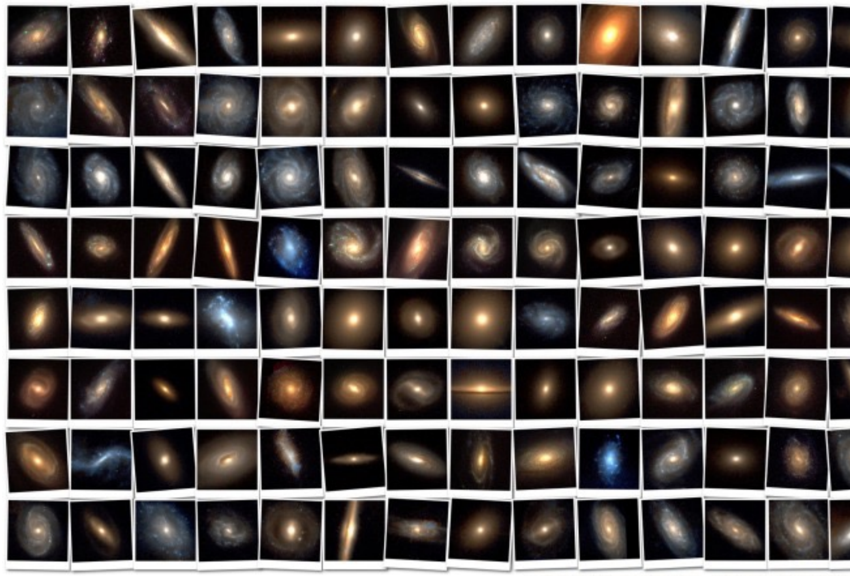
$$\rho(\mathbf{r}) = -\frac{G_N}{1+\alpha}\int \mathrm{d}^3\mathbf{r}'\,\frac{\bar{\rho}\delta_\mathrm{m}(\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|}\left\{1+\alpha\exp\left(-\frac{|\mathbf{r}-\mathbf{r}'|}{\lambda}\right)\right\}$$

$$\mathbf{r} = a\mathbf{x}$$

$$\alpha = 1, \lambda = 10\ h^{-1}\mathrm{Mpc}$$

Note the effect of massive neutrinos, which can be accurately modeled (see Nishimichi-san's talk)

Issue: An estimator of "shapes"



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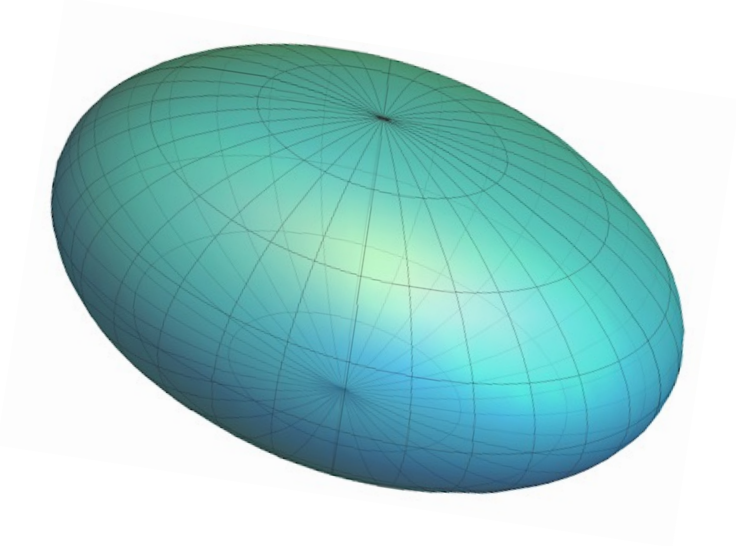
- Need an estimator to quantify "shape" form galaxy images
- E.g., the following is one choice of the estimator (here, to keep generality, it is for "3D" shape, but what is usually observed is a "projected (2D)" shape):

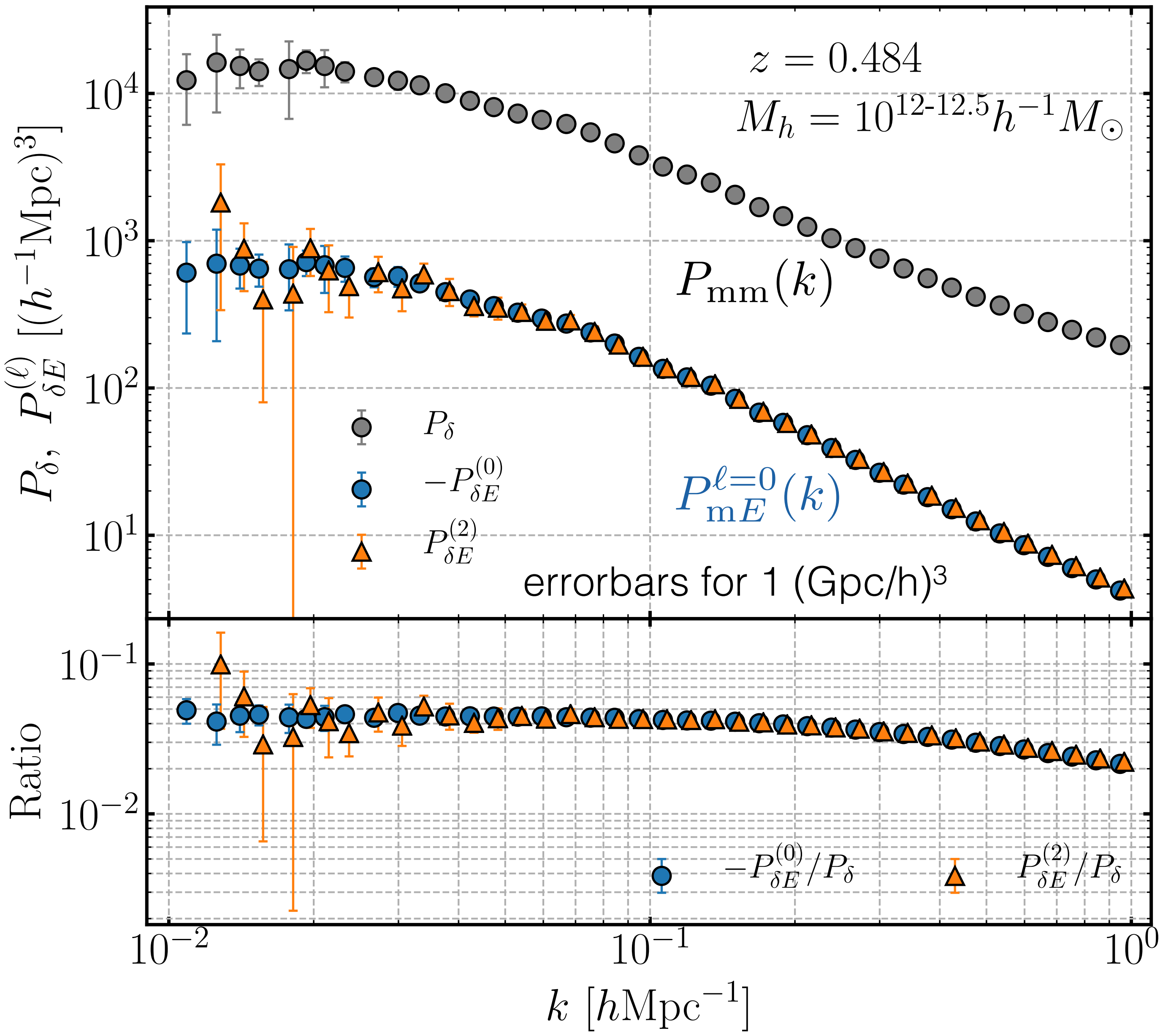
$$I_{ij} \propto \int \mathrm{d}^2\mathbf{r}\ b(\mathbf{r}) w(r) \Delta x_i \Delta x_j$$

e.g. star distribution radial weight



- The 3D shape carries 6 degrees of freedom (Vlah et al. 20): 2 scalar (2 equivalent to 1 scalar in ΛCDM), 2 vector and 2 tensor modes = the same degrees as the metric perturbations (see Kazu Akitsu-san's talk)
- What is an optimal estimator? What is an optimal choice of the weight?
- Note that the estimator needs not be super-accurate unlike weak lensing (the shape bias parameter absorbs an uncertainty in shape estimator; see later)

Kurita, MT+20

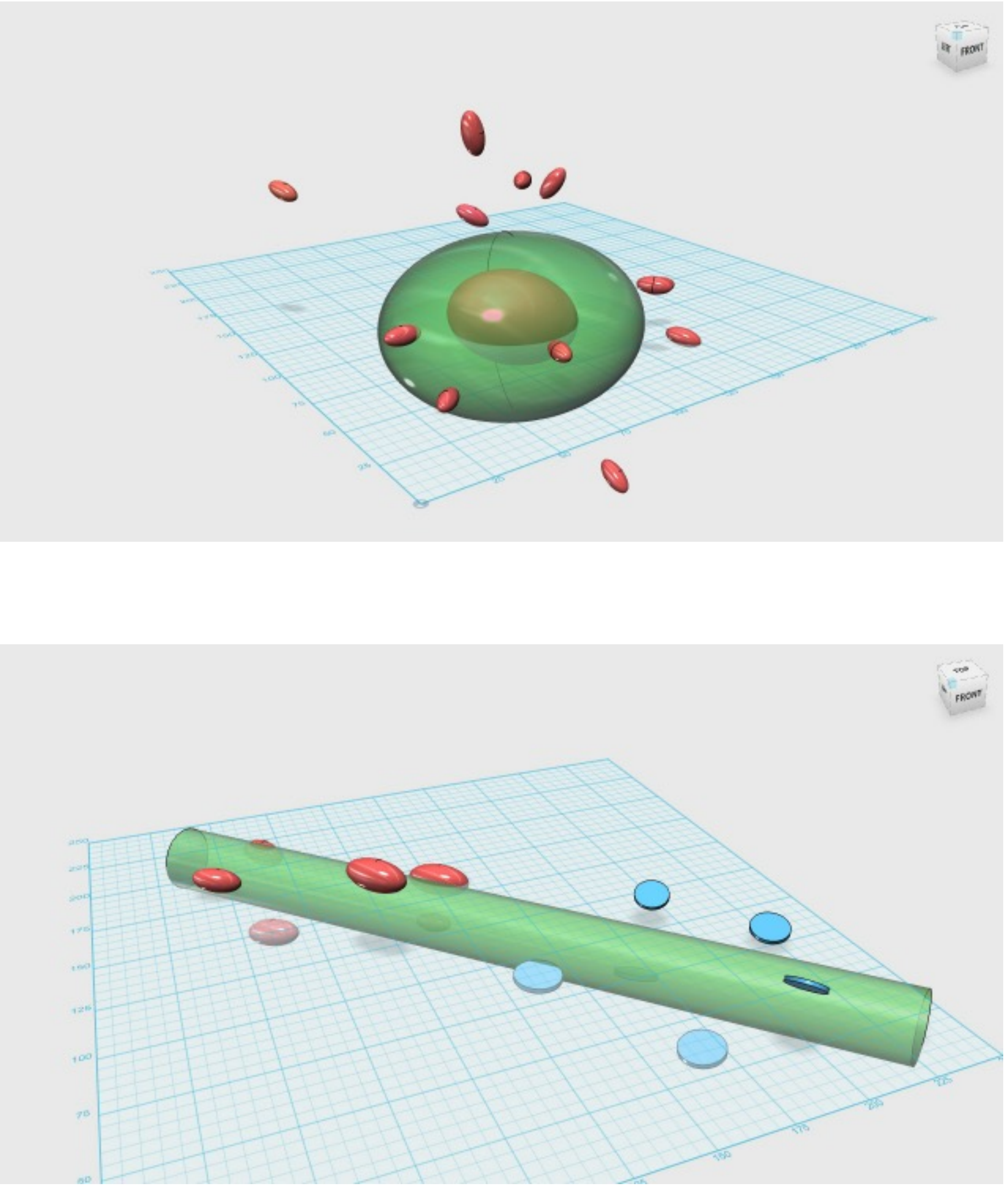


- Run simulation for ΛCDM model
- Identify halos, by Rockstars
- Quantify “shapes” of individual halos (for projected shapes)
- Measure the power spectrum, after E/B decomposition
- Note that the halo shape is measured at the halo position (the density-weighted shape field)

$$\gamma^{\rm obs}_{ij} = (1+\delta_{\rm h})\gamma_{ij}$$

- IA signal gamma~O(0.01), the intrinsic shape O(0.1); noisy on individual halo basis
- Indeed confirmed

$$\frac{P_{{\rm m}E}(k)}{P_{\rm mm}(k)} \to k^0 \ \text{for}\ k \ll k_{\rm NL}$$



Joachimi+15

- What are properties of IA for different types of galaxies?
  - Central vs. satellite galaxies
  - Early-type (quiescent) and late-type (star-forming) galaxies
  - Environments (filaments, voids, nodes)
  - See Jingjing’s talk

Comment on tidal torque theory

- No primordial vector mode in the standard ΛCDM scenario
- A progenitor region of galaxy would acquire angular momentum via coupling between the mass inertia and the surrounding tidal field (White 84; Eisenstein & Loeb 97) ⇒ the origin of “disk” galaxy or galaxy spin

$$\begin{aligned} L_{ij} &\propto I_{ik}T_{kj} \\ &\propto T_{ik}T_{kj} \end{aligned}$$

- Therefore, a correlation of galaxy spins, if exists, should be “non-linear” origined (not primordial-origined)

$$P_{ss}(k) \propto \langle L_{ij}L_{jk}\rangle \propto \langle O(\delta_{\rm m}^4)\rangle \propto (P_{\rm mm}(k))^2$$

$$\frac{P_{ss}(k)}{P_{\rm mm}(k)} \to P_{\rm mm}(k) \to 0 \text{ for } k \to 0$$

Emission line galaxies (main targets for PFS and DESI) are mainly star-forming (disk-like) galaxies ⇒ no IA signal for ELGs? (see Jingjing’s talk)

Linear alignment model

- Intrinsic shapes of galaxies are determined by the tidal field at the time during galaxy formation (matter dominated era) (Catelan, Kamionkowski & Blandford 00; Hirata & Seljak 04)

$$\gamma_{ij}(\mathbf{x};z) = -\frac{C_1}{4\pi G}\left(\partial_i\partial_j - \frac{\delta^K_{ij}}{3}\nabla^2\right)\underline{\Phi_P(\mathbf{x})}$$

primordial gravitational potential field: $\Phi_P(\mathbf{x};z) \propto a^0$

$$\to \boldsymbol{\gamma}^{\rm proj}(\mathbf{k};z) = -A_{\rm IA}C_1\rho_{\rm cr0}\frac{\Omega_{\rm m}}{D(z)}\frac{(k_x^2-k_y^2, 2k_xk_y)}{k^2}\delta_{\rm m}(\mathbf{k},z)$$

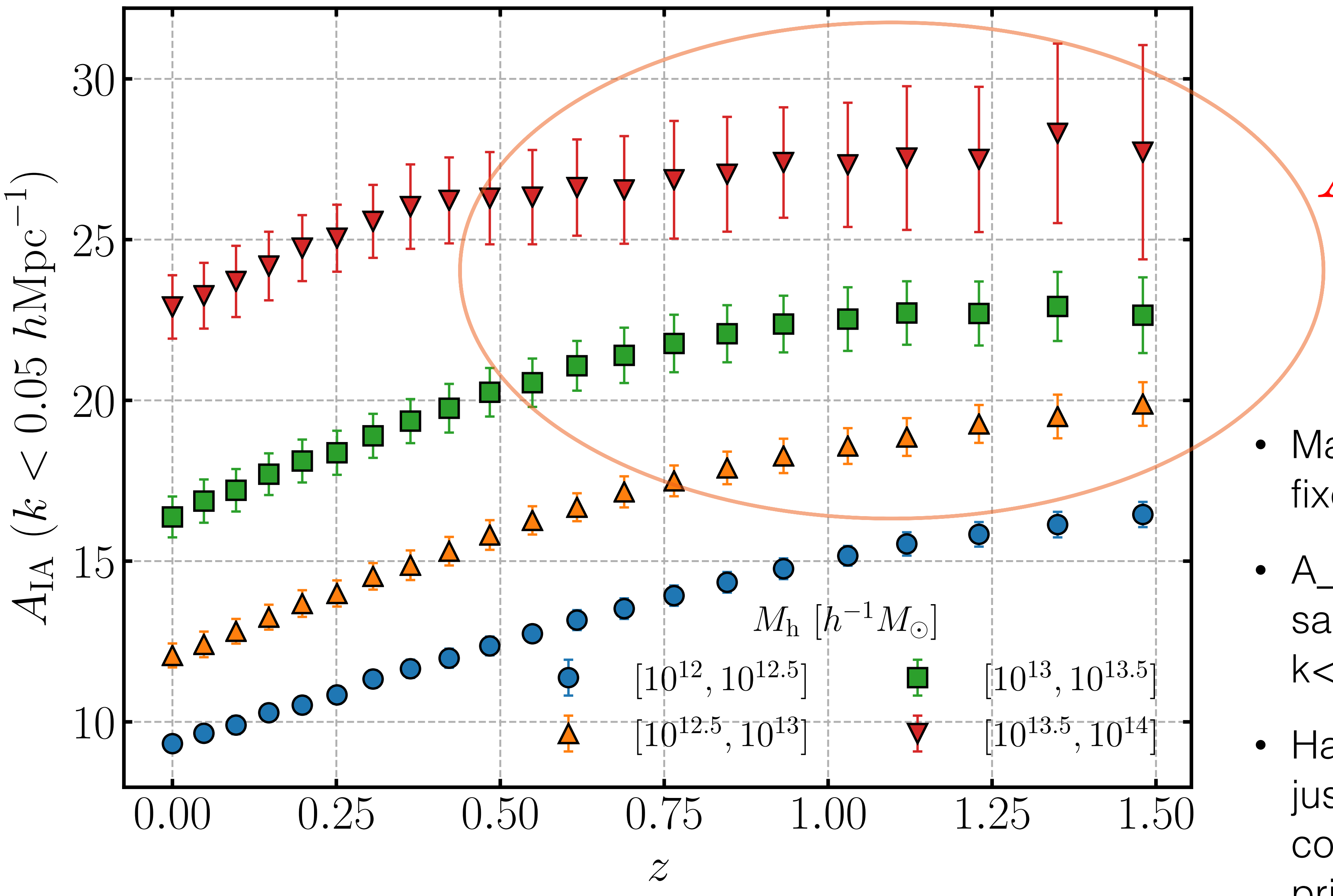
assume that the l.o.s. direction is along z-direction (see Toshiki's talk)

- If the primordial linear IA model is valid, we should find, on linear scales

$$A_{\rm IA} \propto a^0$$

- Q: How do the scale- and redshift-dependences of IA signals look like?

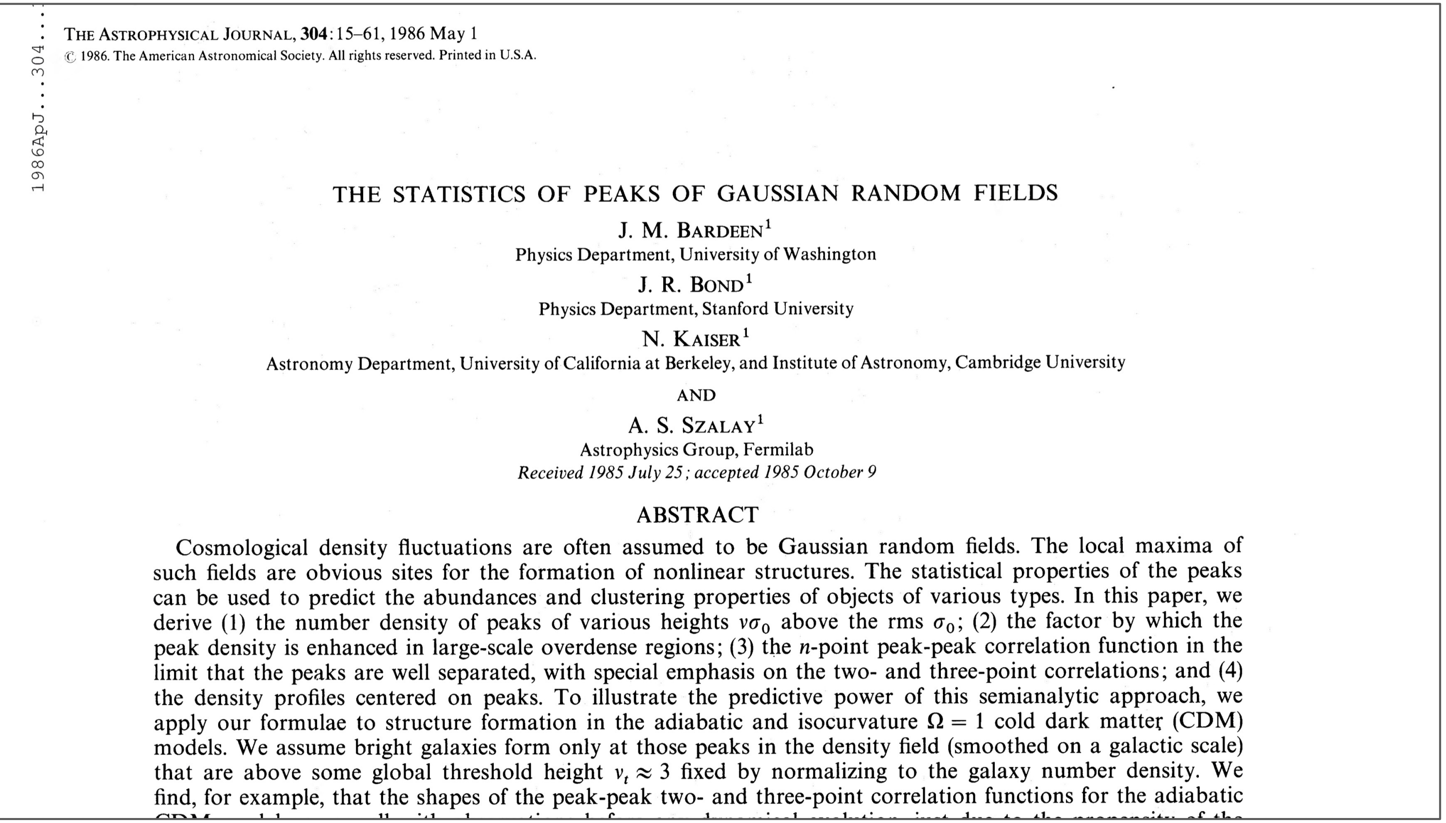
Kurita, MT+20



$A_{\rm IA} \propto a^0$

- Mass-limited halo sample = the fixed Lagrangian volume
- A_IA is estimated for each halo sample, from P_mE(k)/P_mm(k) at k<0.05 h/Mpc
- Halos shapes at higher redshift, just after formed, have the constant IA amplitude; that is, the primordial IA model seems valid

The largest IA signal should be from "shapes" of primordial density peaks that lead to galaxies (halos) at later epochs, for the standard ΛCDM model



1986ApJ...304...

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THE STATISTICS OF PEAKS OF GAUSSIAN RANDOM FIELDS

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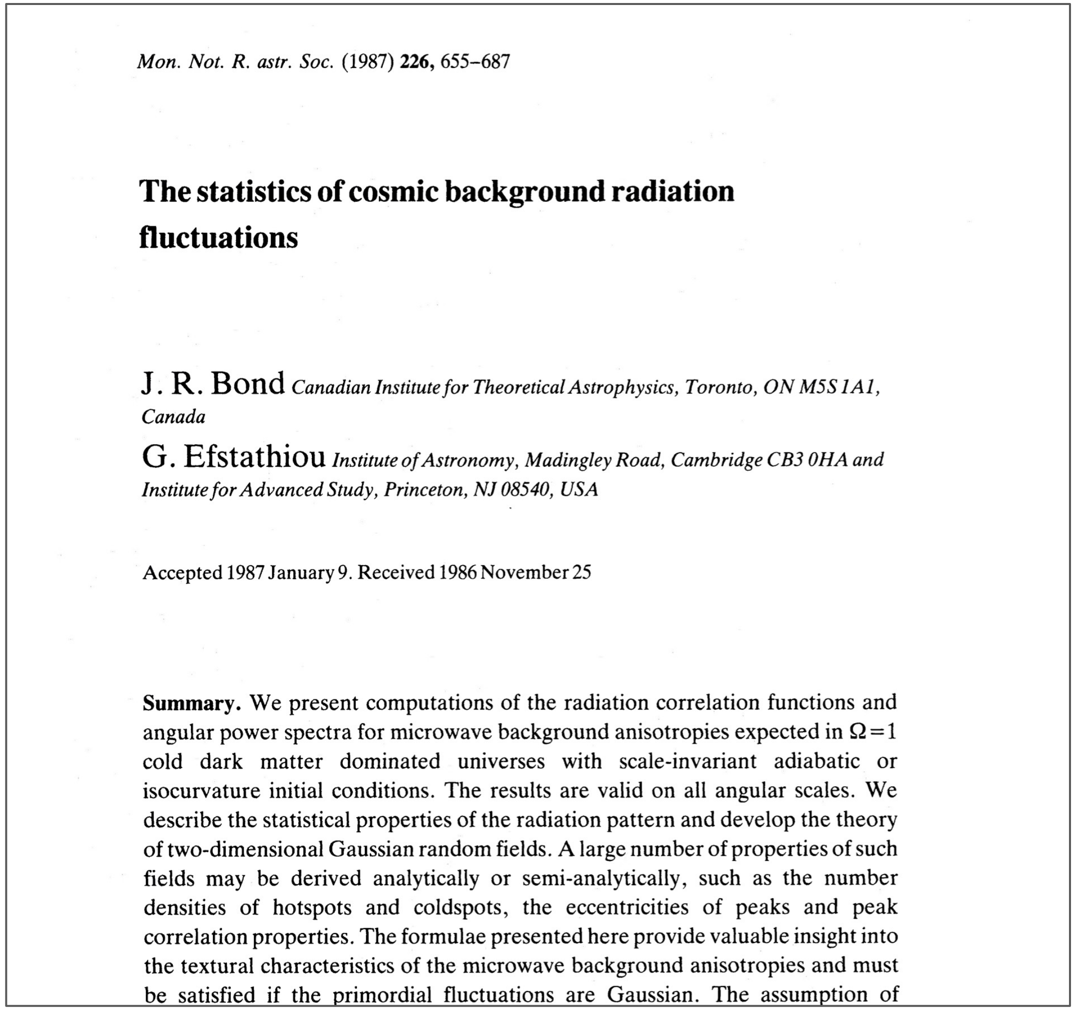
ABSTRACT

Cosmological density fluctuations are often assumed to be Gaussian random fields. The local maxima of such fields are obvious sites for the formation of nonlinear structures. The statistical properties of the peaks can be used to predict the abundances and clustering properties of objects of various types. In this paper, we derive (1) the number density of peaks of various heights $\nu\sigma_0$ above the rms σ_0; (2) the factor by which the peak density is enhanced in large-scale overdense regions; (3) the n-point peak-peak correlation function in the limit that the peaks are well separated, with special emphasis on the two- and three-point correlations; and (4) the density profiles centered on peaks. To illustrate the predictive power of this semianalytic approach, we apply our formulae to structure formation in the adiabatic and isocurvature $\Omega = 1$ cold dark matter (CDM) models. We assume bright galaxies form only at those peaks in the density field (smoothed on a galactic scale) that are above some global threshold height $\nu_t \approx 3$ fixed by normalizing to the galaxy number density. We find, for example, that the shapes of the peak-peak two- and three-point correlation functions for the adiabatic



Mon. Not. R. astr. Soc. (1987) **226,** 655–687

The statistics of cosmic background radiation fluctuations

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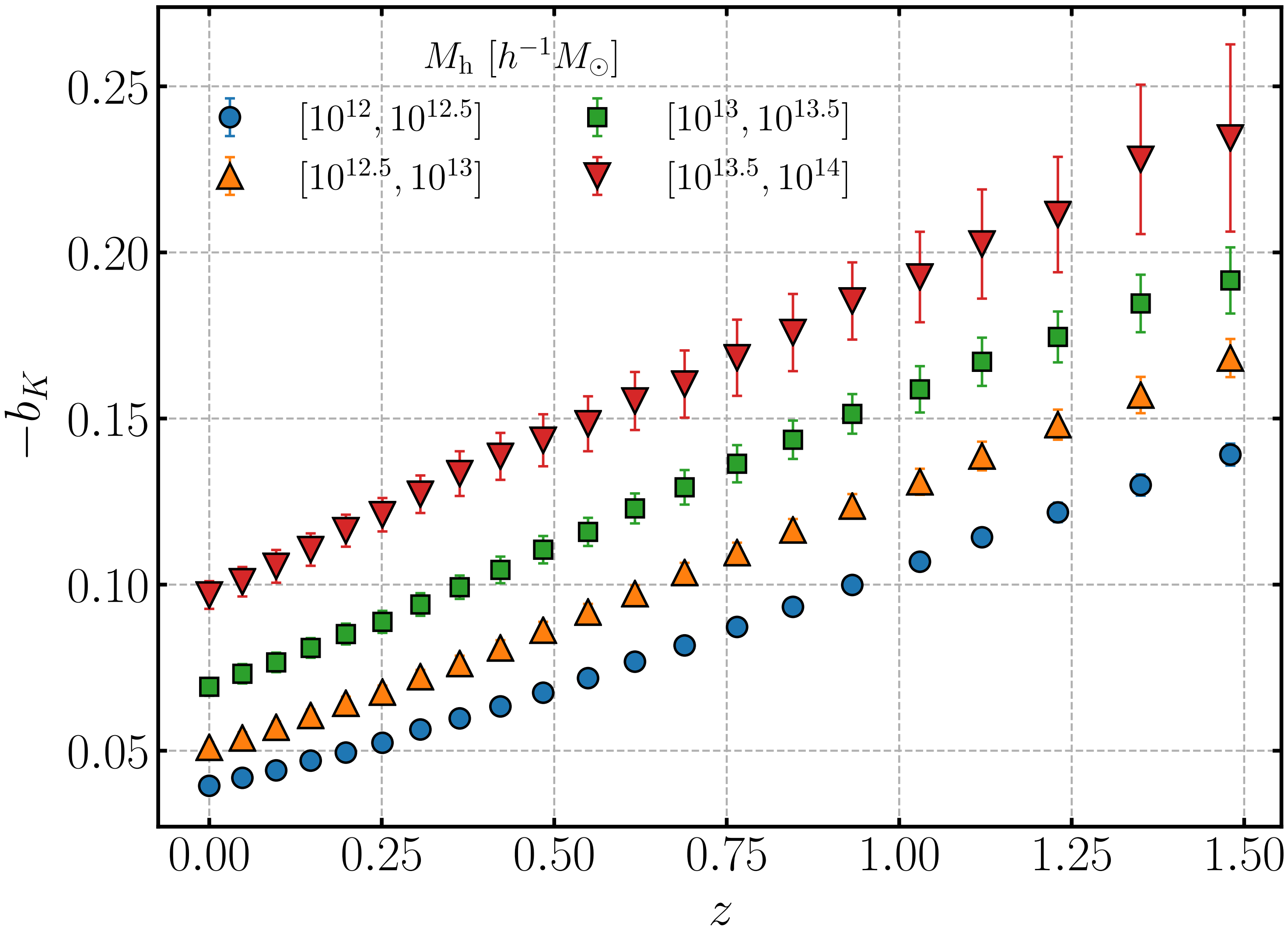
Summary. We present computations of the radiation correlation functions and angular power spectra for microwave background anisotropies expected in $\Omega = 1$ cold dark matter dominated universes with scale-invariant adiabatic or isocurvature initial conditions. The results are valid on all angular scales. We describe the statistical properties of the radiation pattern and develop the theory of two-dimensional Gaussian random fields. A large number of properties of such fields may be derived analytically or semi-analytically, such as the number densities of hotspots and coldspots, the eccentricities of peaks and peak correlation properties. The formulae presented here provide valuable insight into the textural characteristics of the microwave background anisotropies and must be satisfied if the primordial fluctuations are Gaussian. The assumption of

BBKS 86
Bond & Efstathiou 87

Comment: linear "shape" bias parameter

Kurita, MT+20



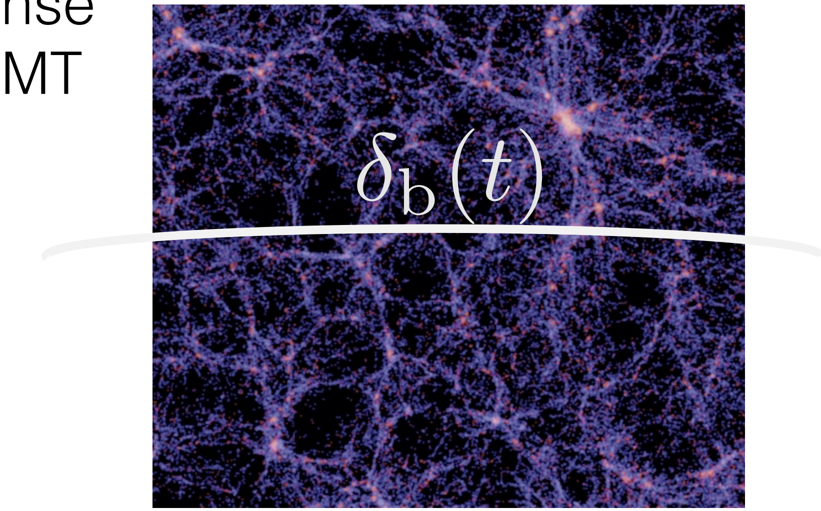
- Other commonly-used definition, just like the linear density bias (Schmidt+15; Vlah+20); on linear scales

$$\gamma_{ij}^{\mathrm{IA}}(\mathbf{x}) = b_K \partial^{-2}\left(\partial_i\partial_j - \frac{\delta_{ij}^K}{3}\nabla^2\right)\delta_\mathrm{m}(\mathbf{x})$$

- The linear shape bias parameter has greater amplitude for higher redshifts and more massive halos (Akitsu, Li & Okumura 2021)

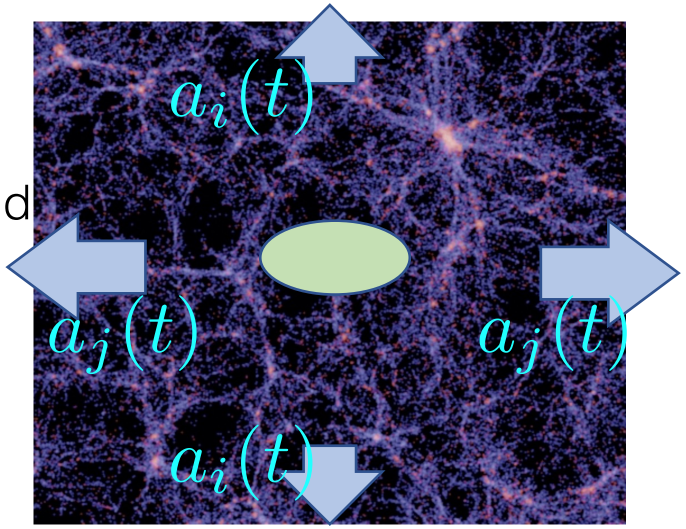
A calibration of linear bias parameters with separate universe simulation

- Recall: a linear halo density parameter is given by the “response” of halo mass function to the large-scale overdensity (Li, Hu &MT 16; Bauldauf+16; Lazeyras+16)



$$b_1^L = \frac{\mathrm{d}\ln n_\mathrm{h}}{\mathrm{d}\delta_\mathrm{b}} \propto \frac{\mathrm{d}\ln n_\mathrm{h}}{\mathrm{d}\Omega_K}$$

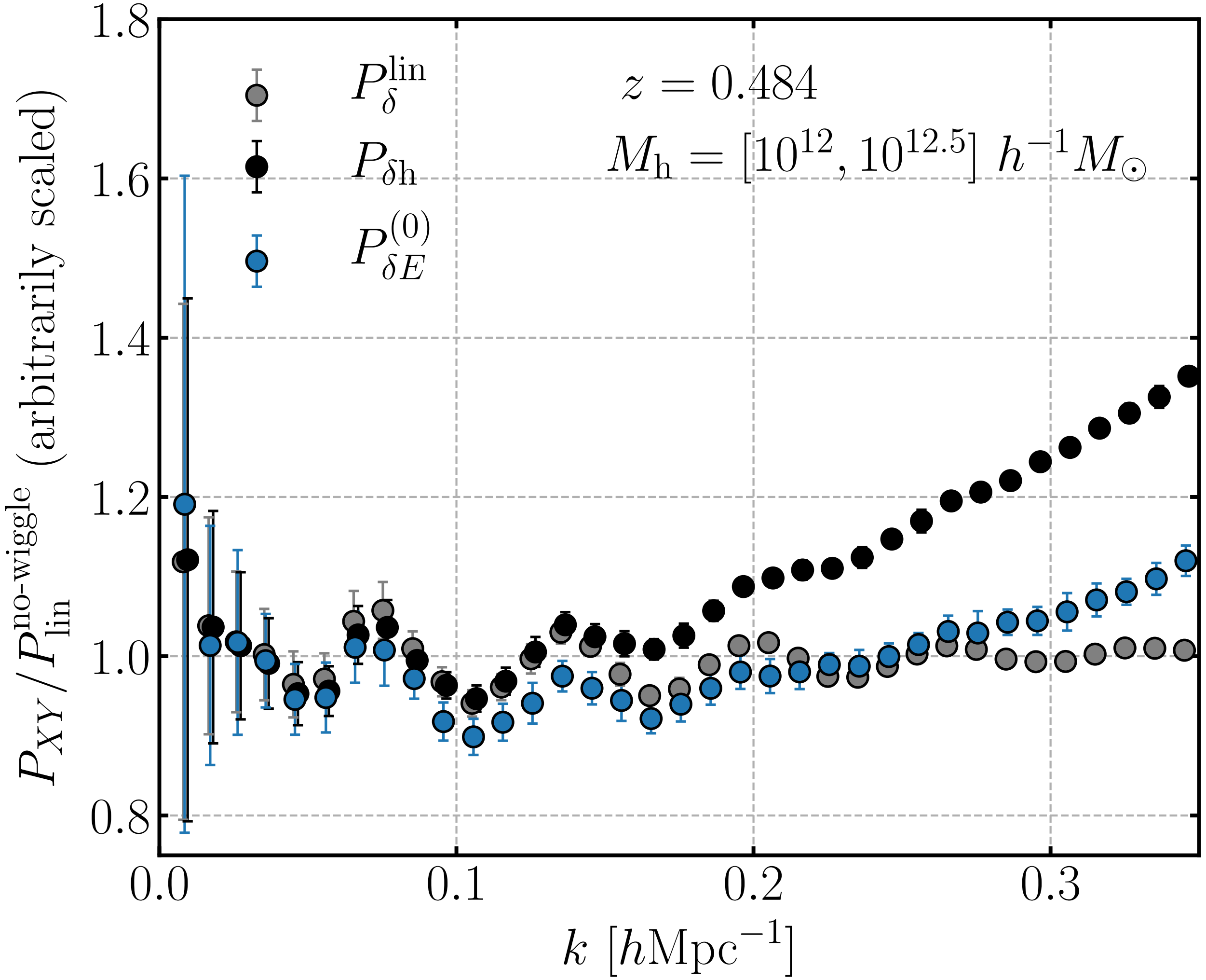
- Linear shape bias parameter is given by the response of halo shapes to the large-scale tidal field (Akitsu, Li & Okumura 21)
  - Large-scale tidal field is described by anisotropic-expansion SU background



$$b_K = \frac{\mathrm{d}\gamma_{ij}}{\mathrm{d}K_{ij}}$$

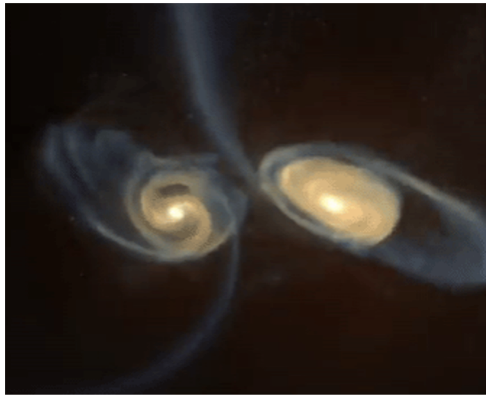
Comment: complementarity between density and IA fields

Kurita, MT+20



- The standard density power spectrum arises more from "high" density field (like galaxy-cluster regions)
- On the other hand, galaxy (subhalo) shapes in high-density regions get randomized due to mass accretion and mergers. Satellite galaxies have smaller IA
- The IA power spectrum would arise more from "isolated" galaxies (halos) or halos in low-density regions (like filaments)

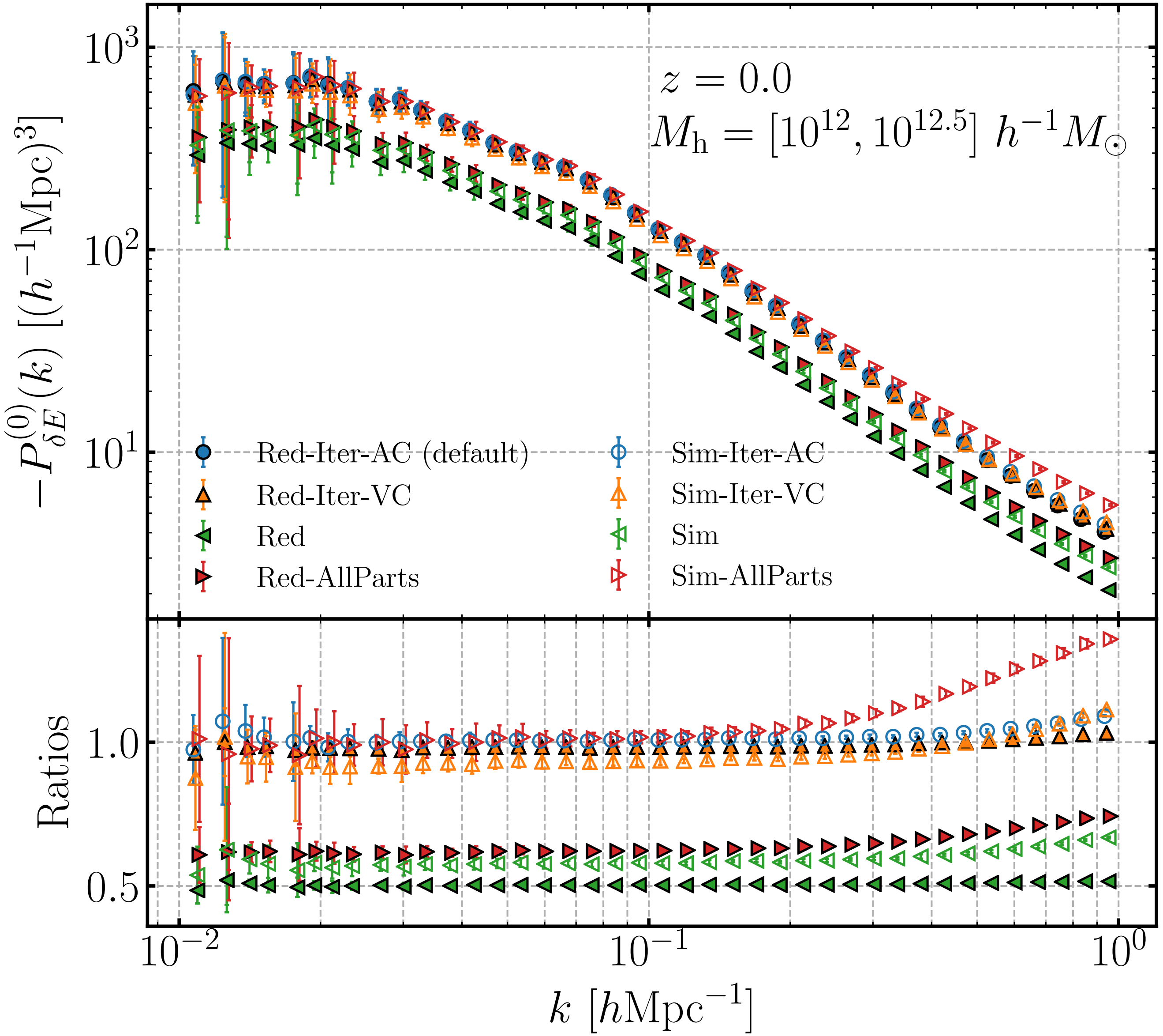
$$P_{\delta E}(k) \leftarrow \langle \delta_{\rm h}(1+\delta_{\rm h})\gamma^{IA}\rangle$$



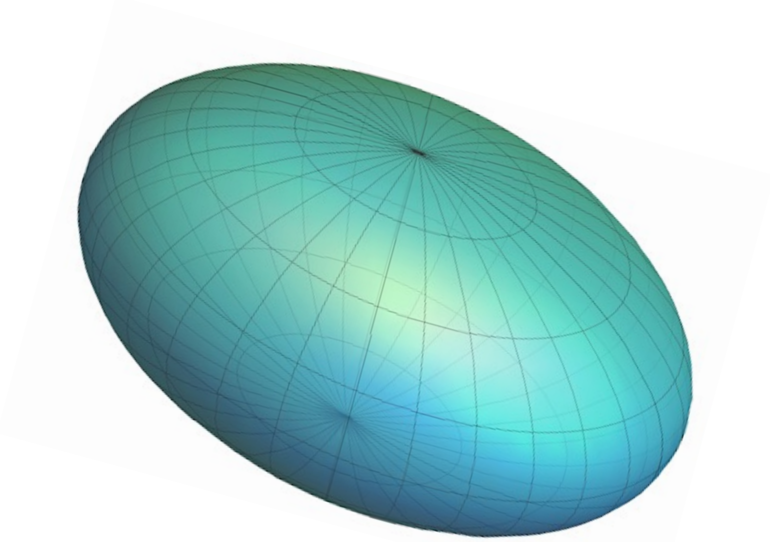
Issue: Any optimal estimator?

$$I_{ij} \propto \int \mathrm{d}^2\mathbf{r}\ b(\mathbf{r}) w(r) \Delta x_i \Delta x_j$$

Kurita, MT+20



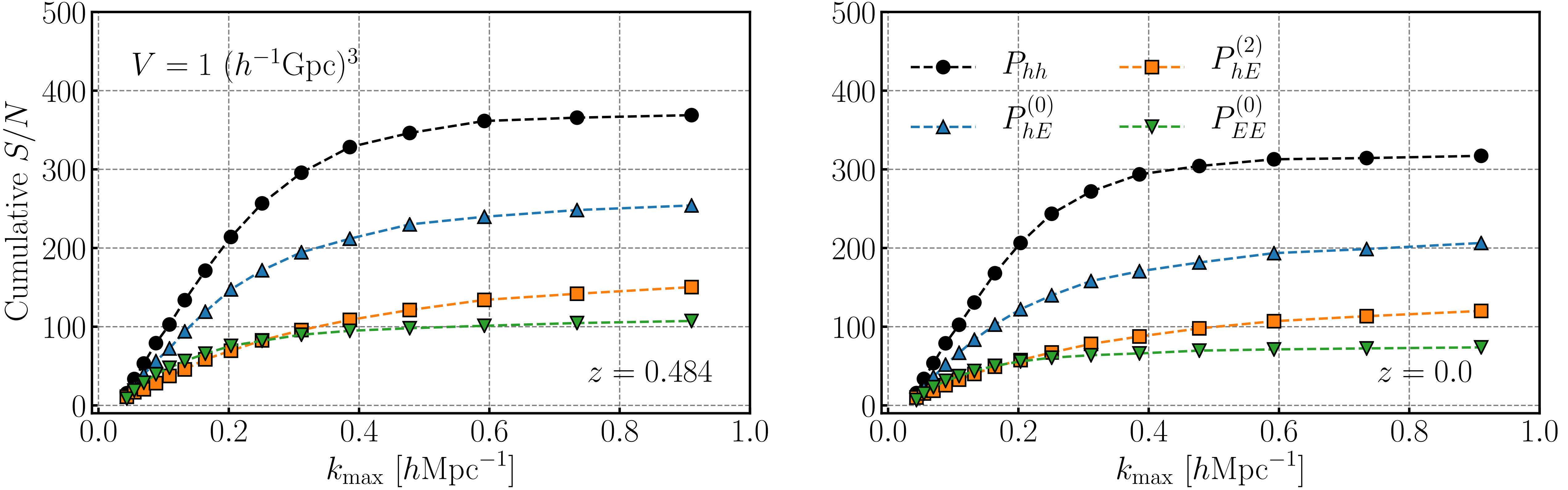
- A choice of "weight": w(r) ∝ r^0 or r^-2
- A choice of the integration range: spherical or ellipsoid
- Changes in the IA power spectrum due to the different shape definitions are absorbed by changes in the linear shape bias amplitudes



Expected signal-to-noise ratios

Kurita, MT+20

LRG/CMASS-like sample



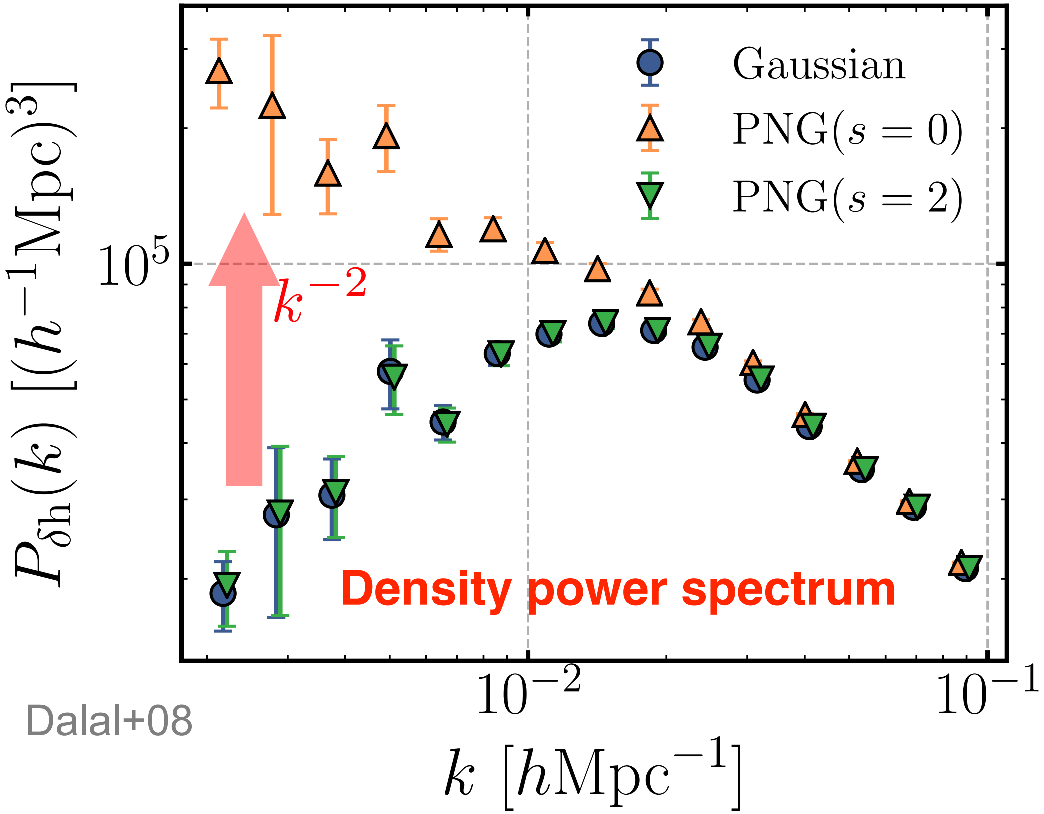
IA power spectrum carries descent signal-to-noise ratios (about 60% of density power spectrum)

IA: a new probe of primordial anisotropic non-Gaussianity

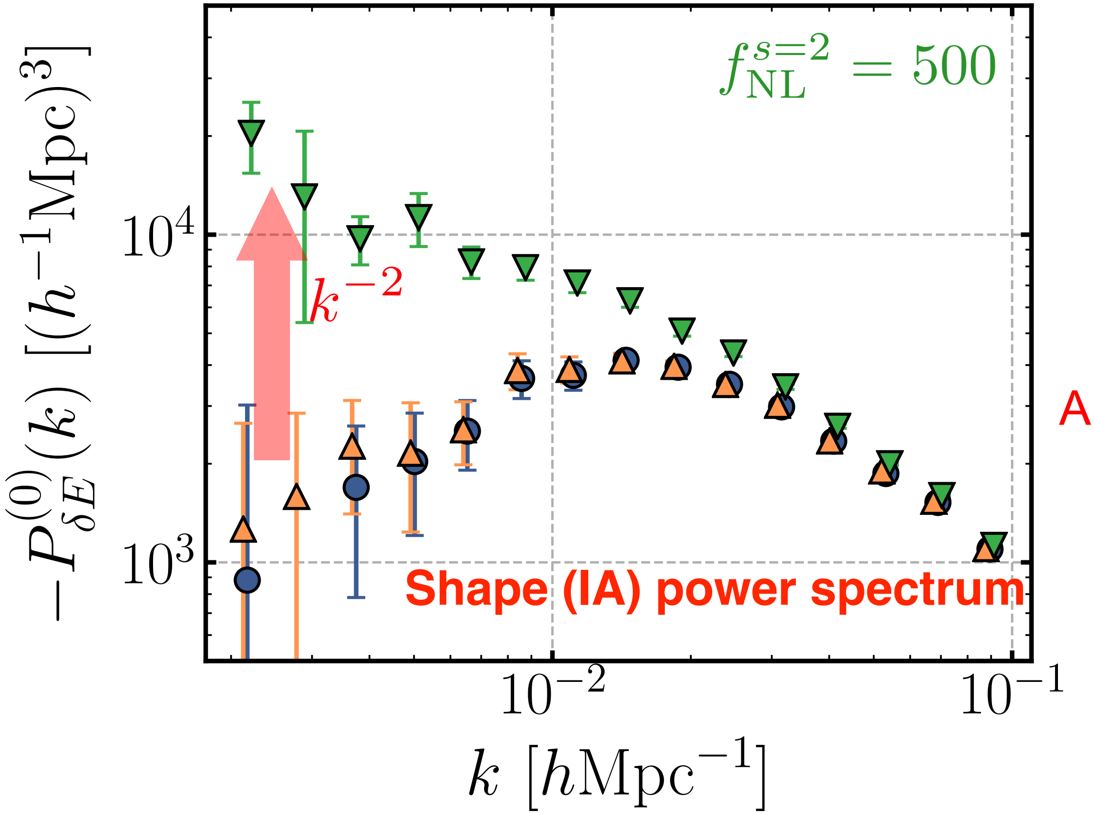
- Tests of different types of primordial non-Gaussianity (ΛCDM predicts f_NL<1)

$$\zeta^{\rm NG}(\mathbf{x}) = \zeta(\mathbf{x}) + f_{\rm NL}\left[\zeta(\mathbf{x})^2 - \langle\zeta^2\rangle\right]$$

$$\zeta^{\rm NG}(\mathbf{x}) = \zeta(\mathbf{x}) + f_{\rm NL}^{s=2}\left[(\psi_{ij})^2 - \langle(\psi_{ij})^2\rangle\right] \qquad \psi_{ij}(\mathbf{x}) \equiv \nabla^{-2}\left(\partial_i\partial_j - \frac{\delta^K_{ij}}{3}\nabla^2\right)\zeta$$



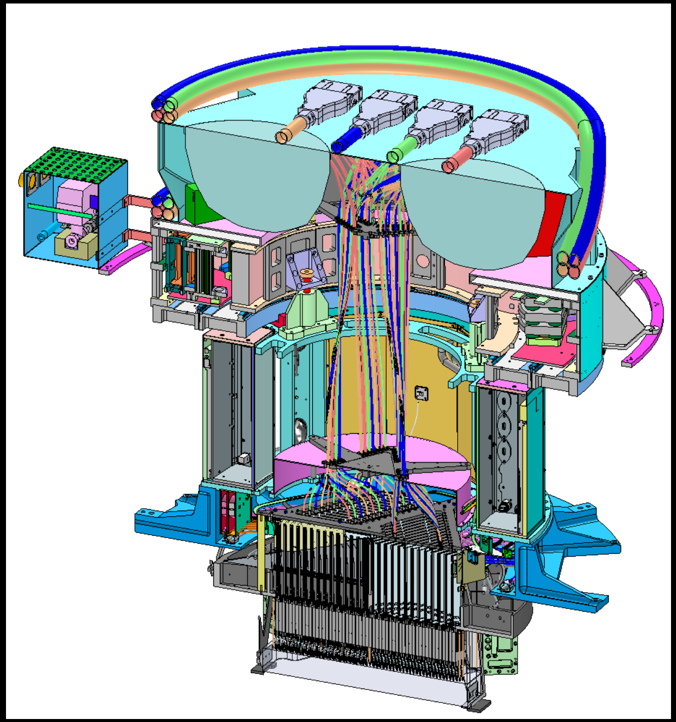
Dalal+08



Akitsu et al. 21

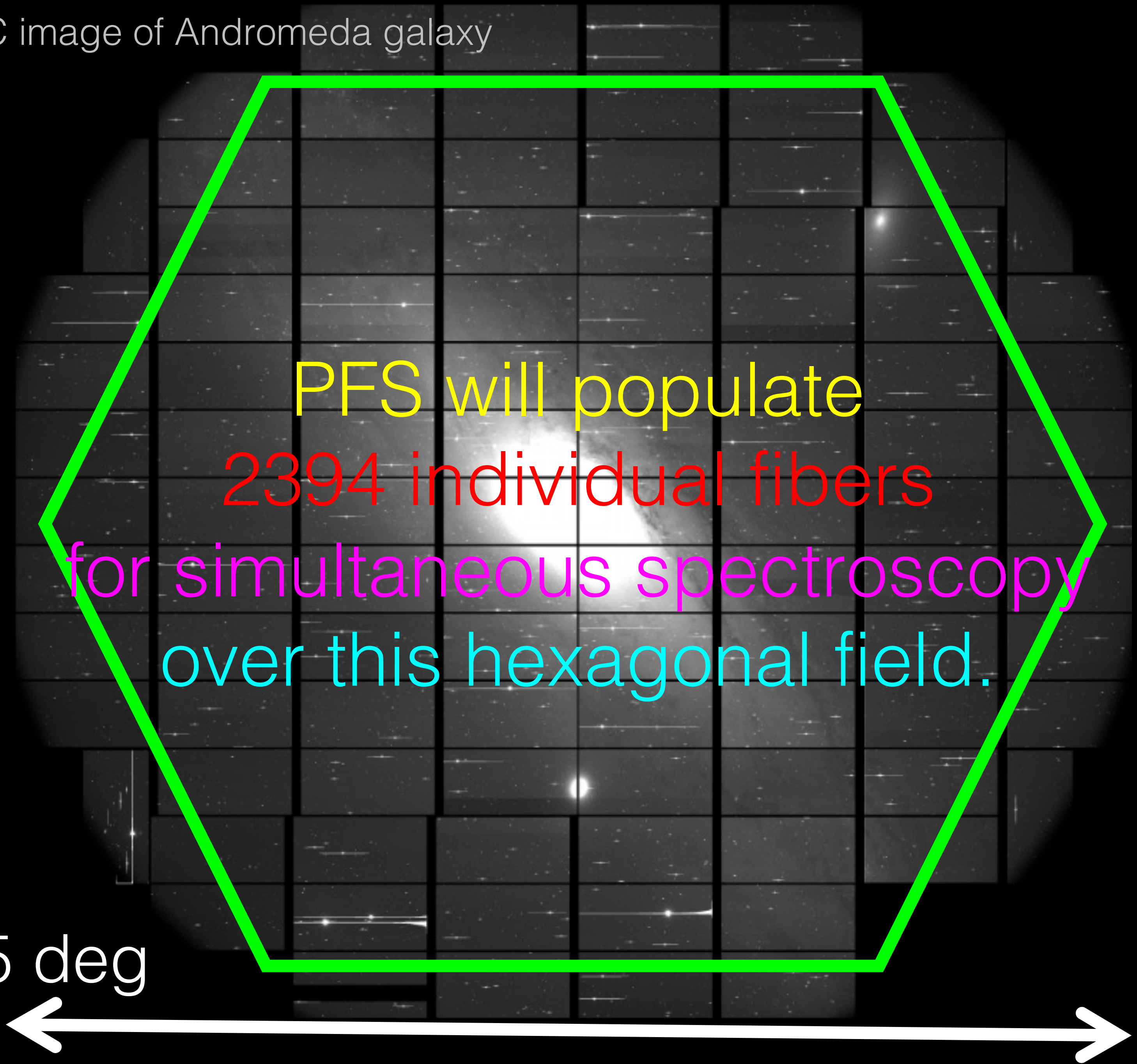
Subaru HSC (imaging) and PFS (spectroscopy)

HSC



PFS (2400 fibers)

HSC image of Andromeda galaxy

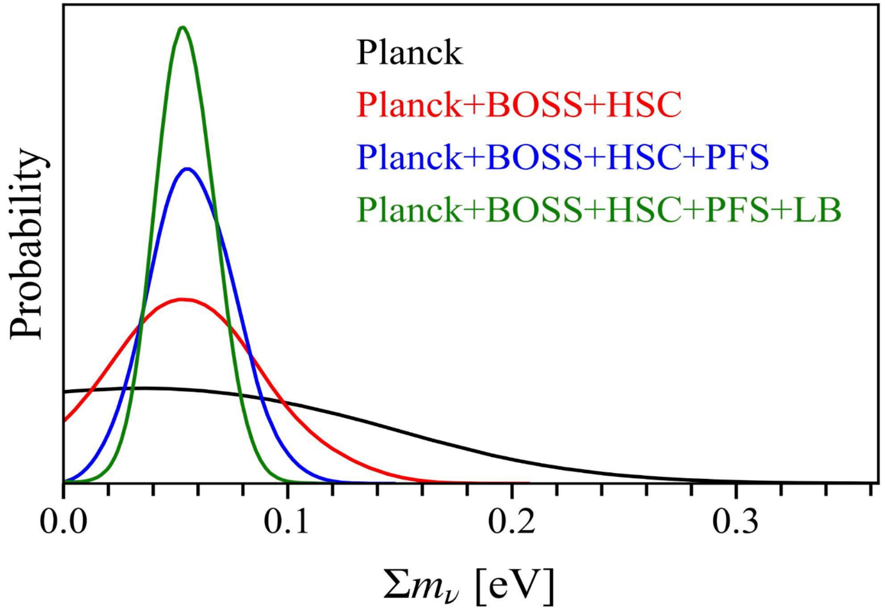


PFS will populate
2394 individual fibers
for simultaneous spectroscopy
over this hexagonal field.

~1.5 deg

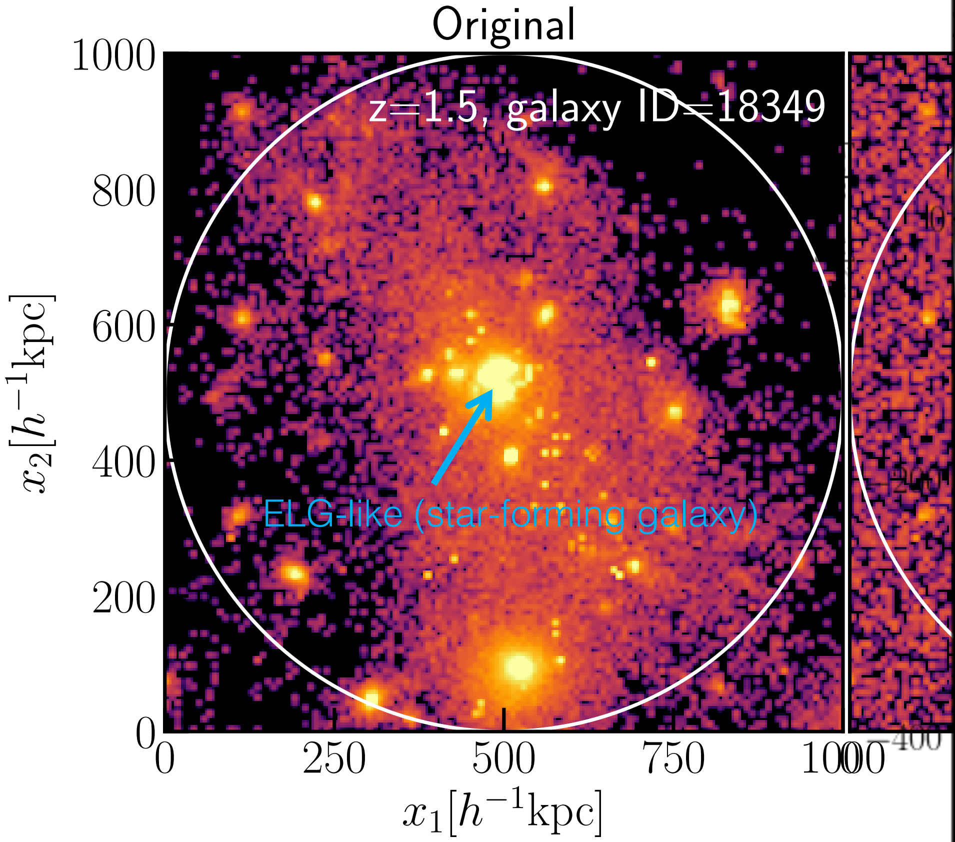
Subaru HSC (2014-) and PFS (2023-) surveys

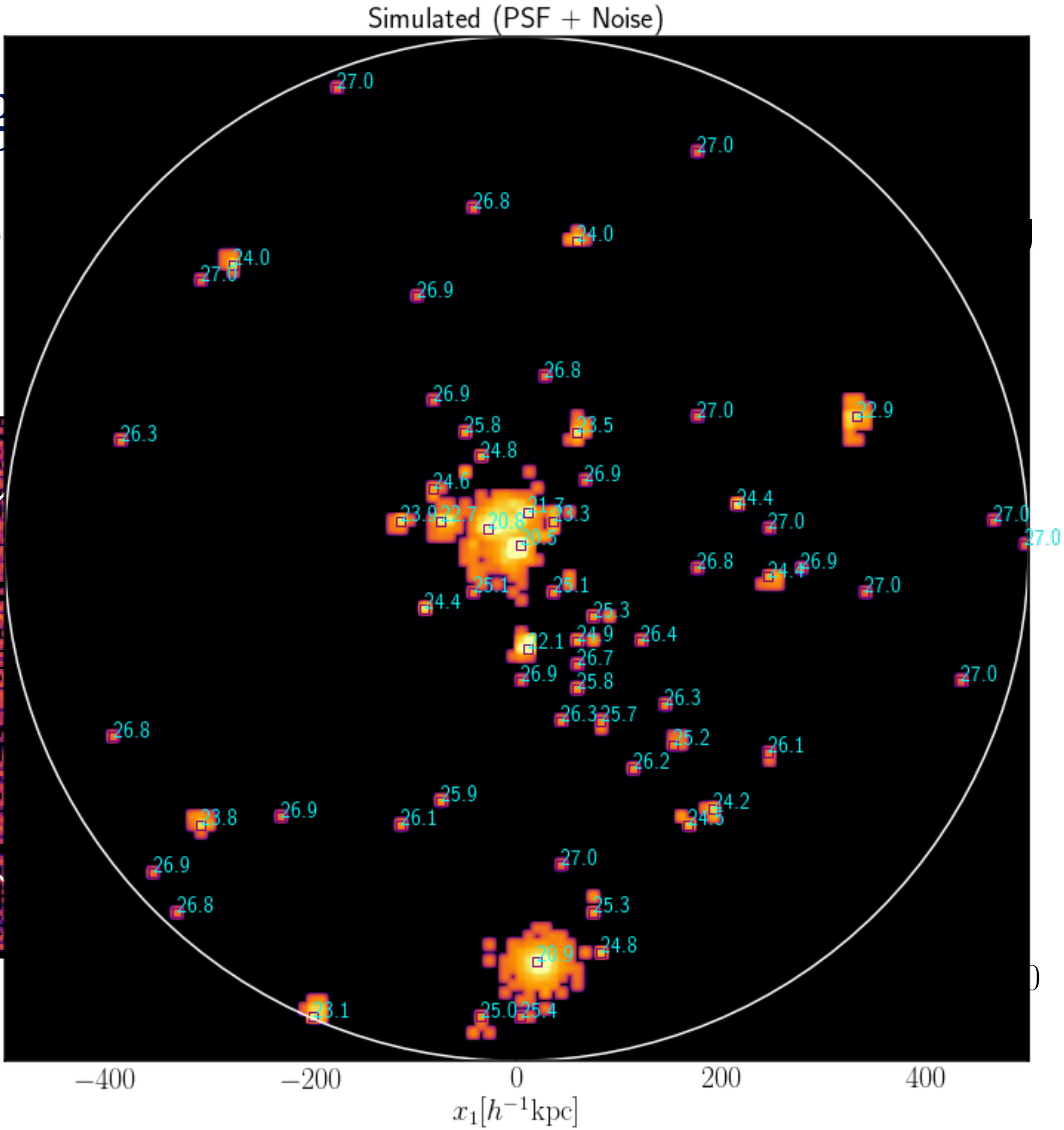
- Subaru Hyper Suprime-Cam survey: thanks to large aperture, wide field-of-view and superb image-quality, the ongoing Subaru HSC will deliver high-quality, deep images of all galaxies (g~26mag for stars) over ~1,200 sq. degrees
- PFS Cosmology survey will carry out a spectroscopic follow-up observation of [OII] emission-line galaxy candidates, selected from the multi-color HSC images, over $0.6<z<2.4$ (~20 arcmin^{-2} HSC galaxies, compared to ~1 arcmin^{-2} PFS ELGs)
- Various, exciting opportunities of many science cases with Subaru HSC and PFS (see Taruya-san and Teppei's talks)
  - Stringent test of ΛCDM models
  - Dark matter & dark energy
  - Neutrino masses
  - PNG



Can we measure IA sig

- Used the Illustris-TNG galaxy to s
Maunakea sky noise, CCD noise,





@z=1.5

Discussion items during WS

- How useful is IA (spin-2 field) signal for cosmology (and galaxy physics), compared to the standard density (spin-0; scalar) information?
- How can we measure the IA signal? (real- vs. Fourier-space, weight, shape measurement method)
- What is an optimal estimator of galaxy “shapes”?
- How can we use the IA signals to do cosmology?
    - Cosmological parameters, primordial non-Gaussianity, anything else?
- Optimal strategy and survey designs for Subaru HSC/PFS (or DESI, Euclid, …) to maximize the scientific returns?