The intrinsic alignment as a new cosmological probe

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based on arXiv:2007.03670, arXiv:2009.05517, and arXiv:2011.06584

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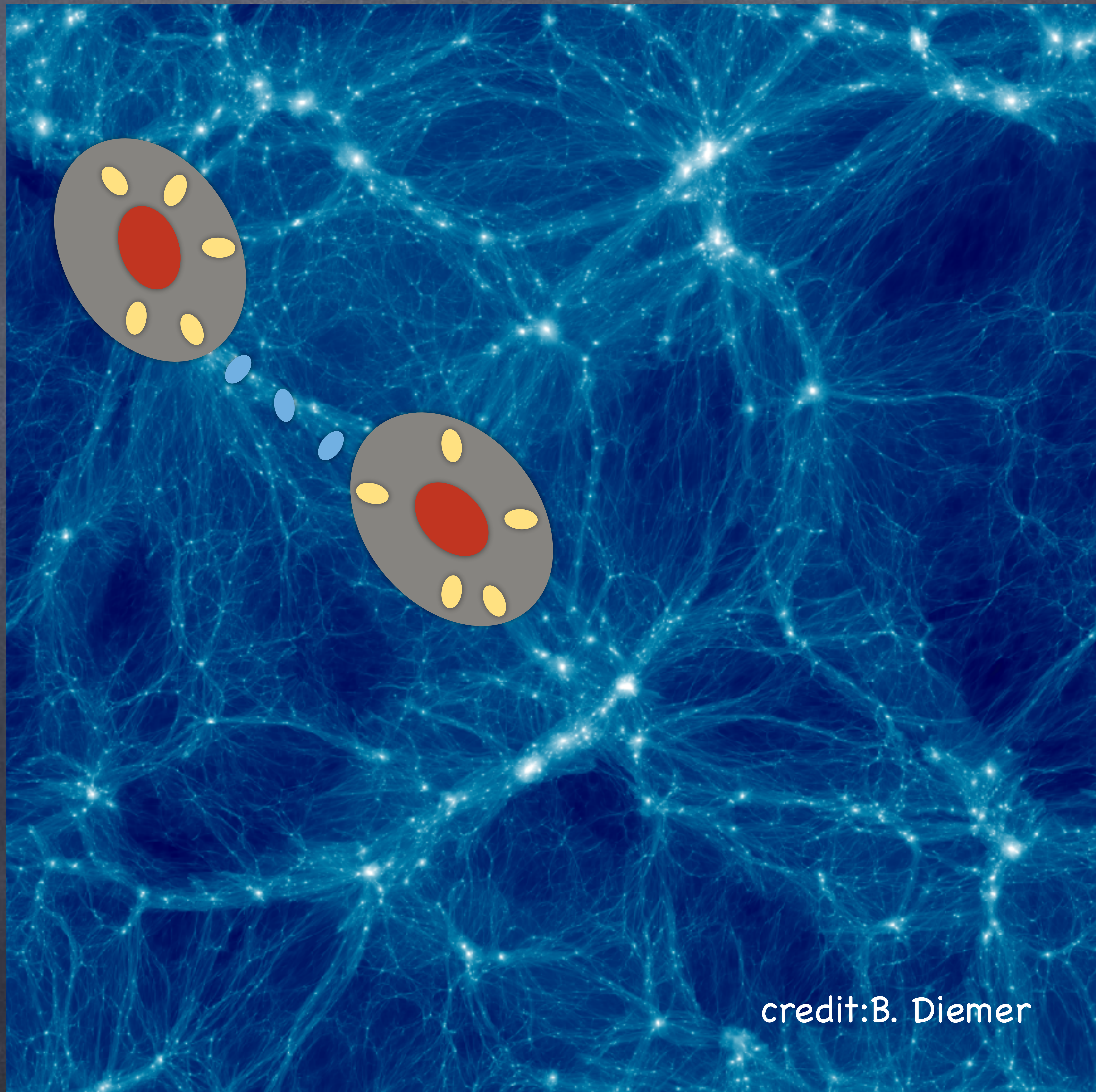
Outline

- Intrinsic Alignment (IA)
  - Linear alignment model
  - 3D power spectrum of IA
- Shape assembly bias
  - Dependence of the IA coefficient on the halo concentration
- Imprint of angular-dependent PNG on IA
  - Scale-dependent bias in the IA power spectrum

Intrinsic alignment : a big picture

- Halo/galaxy clusters
- Central galaxy shape
  - Red galaxies
  - Shape $\sim$ halo shape
  - Tidal alignment
- Satellite galaxy
- Galaxy on filaments



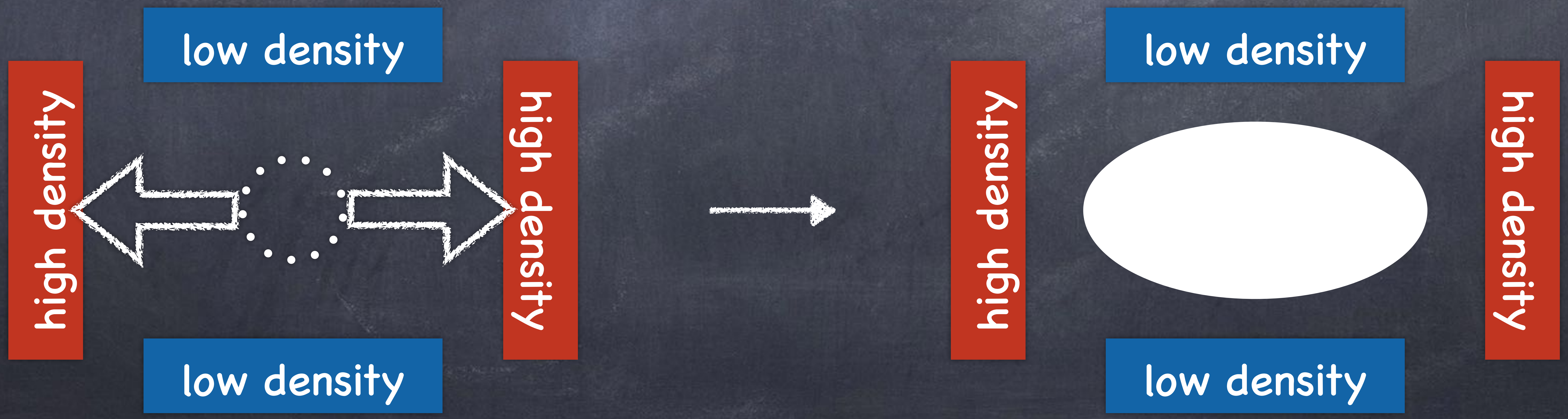
Intrinsic Alignments (IA) = Physical correlations between shapes of galaxy or halos though LSS

- **Intrinsic** correlation before the weak lensing effect   Catelan+ '00
  - weak lensing : **extrinsic** effect
- Source of systematic errors in weak lensing   Hirata&Seljak '04
  - $\gamma_{ij}^{\rm obs} = \underbrace{\gamma_{ij}^{\rm G}}_{\rm WL} + \underbrace{\gamma_{ij}^{\rm I}}_{\rm IA} \quad \rightarrow \quad C_\ell^{\gamma\gamma} = C_\ell^{\rm GG} + \underbrace{C_\ell^{\rm GI} + C_\ell^{\rm IG} + C_\ell^{\rm II}}_{\rm Contaminations}$
- New cosmological signal   Today's talk

Tidal alignment (Linear alignment) model

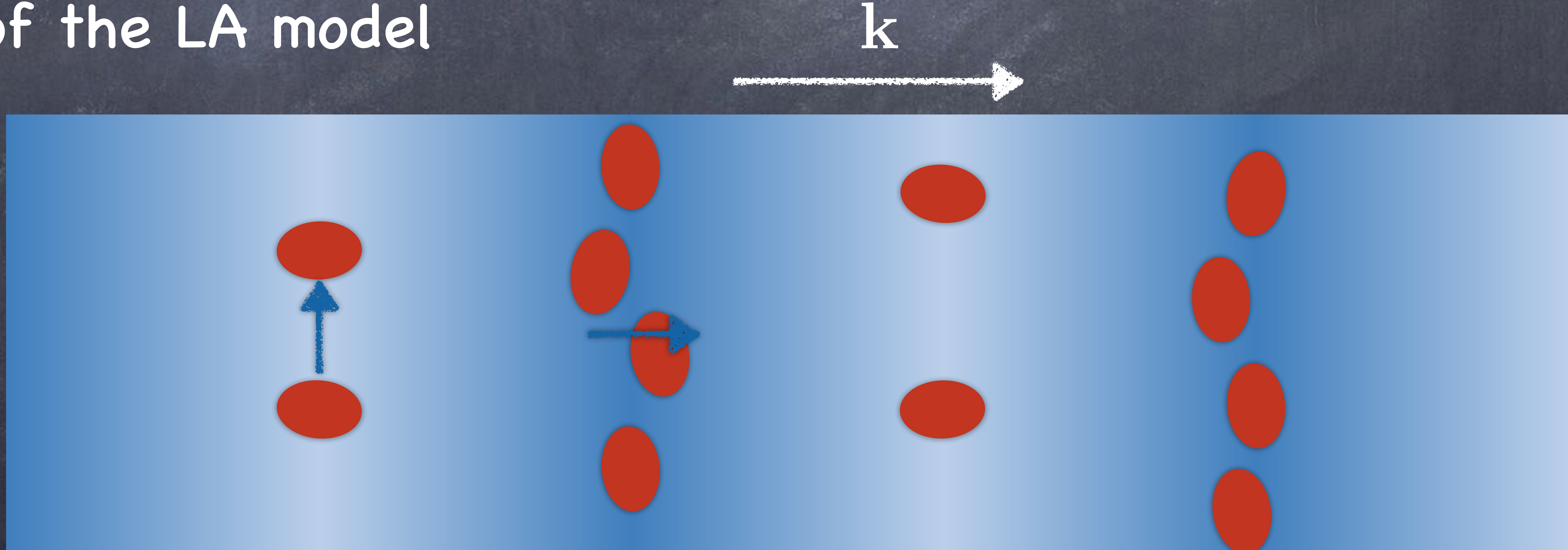
Catelan+ '00, Hirata&Seljak '04

- Origin of IA : interaction with the gravitational tidal field
  - similar to the polarization of CMB photon
  - Quadrupole ~ tidal field



shape as a biased tracer of tidal fields

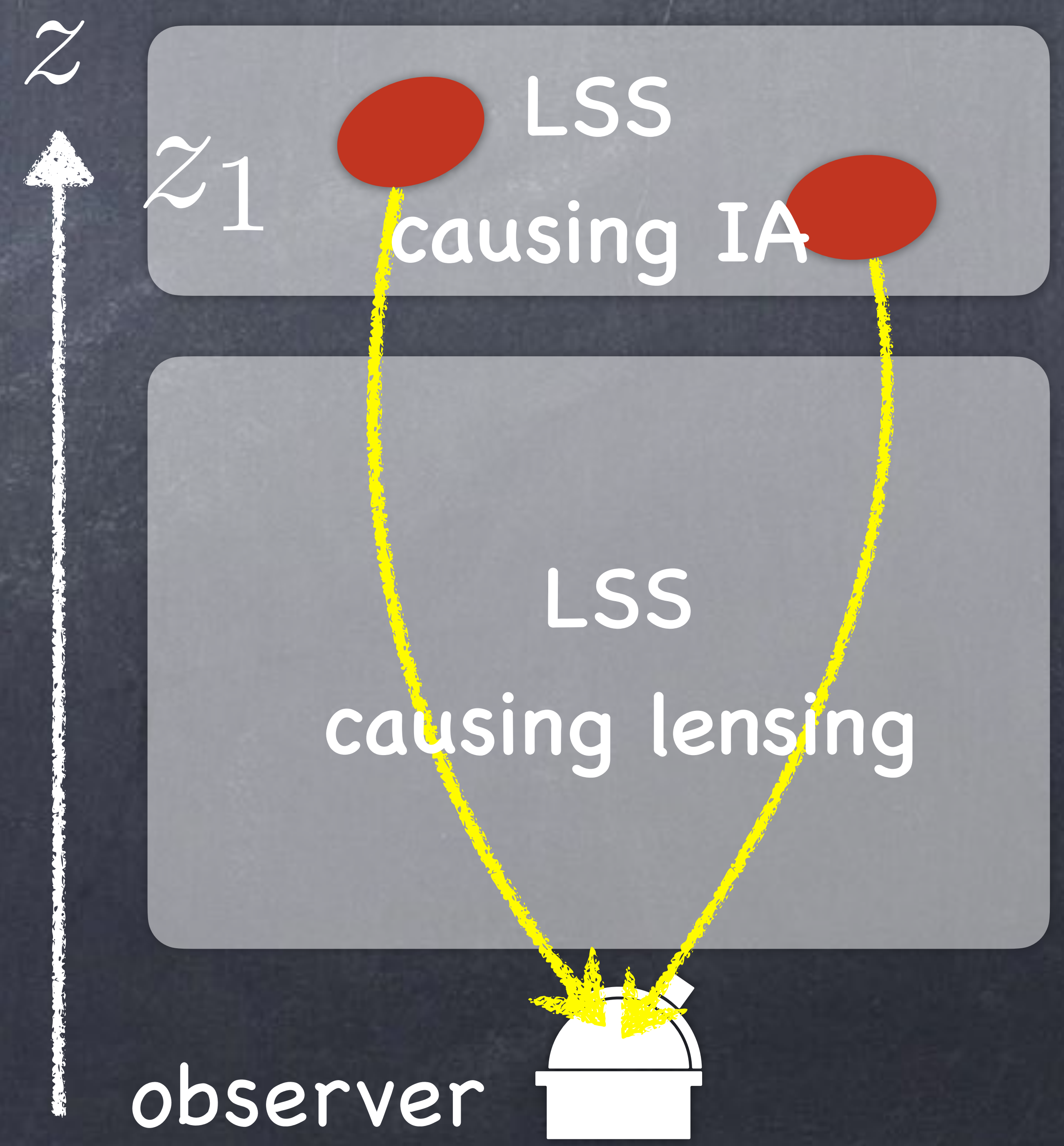
- Galaxy shape ~ Halo shape ~ Tidal field of large-scale structure
  - $\gamma_{ij}(\mathbf{x}) = b_K K_{ij}(\mathbf{x})$ w/ $K_{ij}(\mathbf{x}) = \left(\frac{\partial_i \partial_j}{\partial^2} - \frac{1}{3}\delta^{\rm K}_{ij}\right)\delta_{\rm m}(\mathbf{x}) \sim \left(\partial_i\partial_j - \frac{1}{3}\delta^{\rm K}_{ij}\partial^2\right)\Phi(\mathbf{x})$
  - cf. Galaxy number density ~ matter density field: $\delta_g(\mathbf{x}) = b_1 \delta_{\rm m}(\mathbf{x})$
  - $b_K < 0$: prediction of the LA model
    - $\gamma_{ij} \perp K_{ij}$



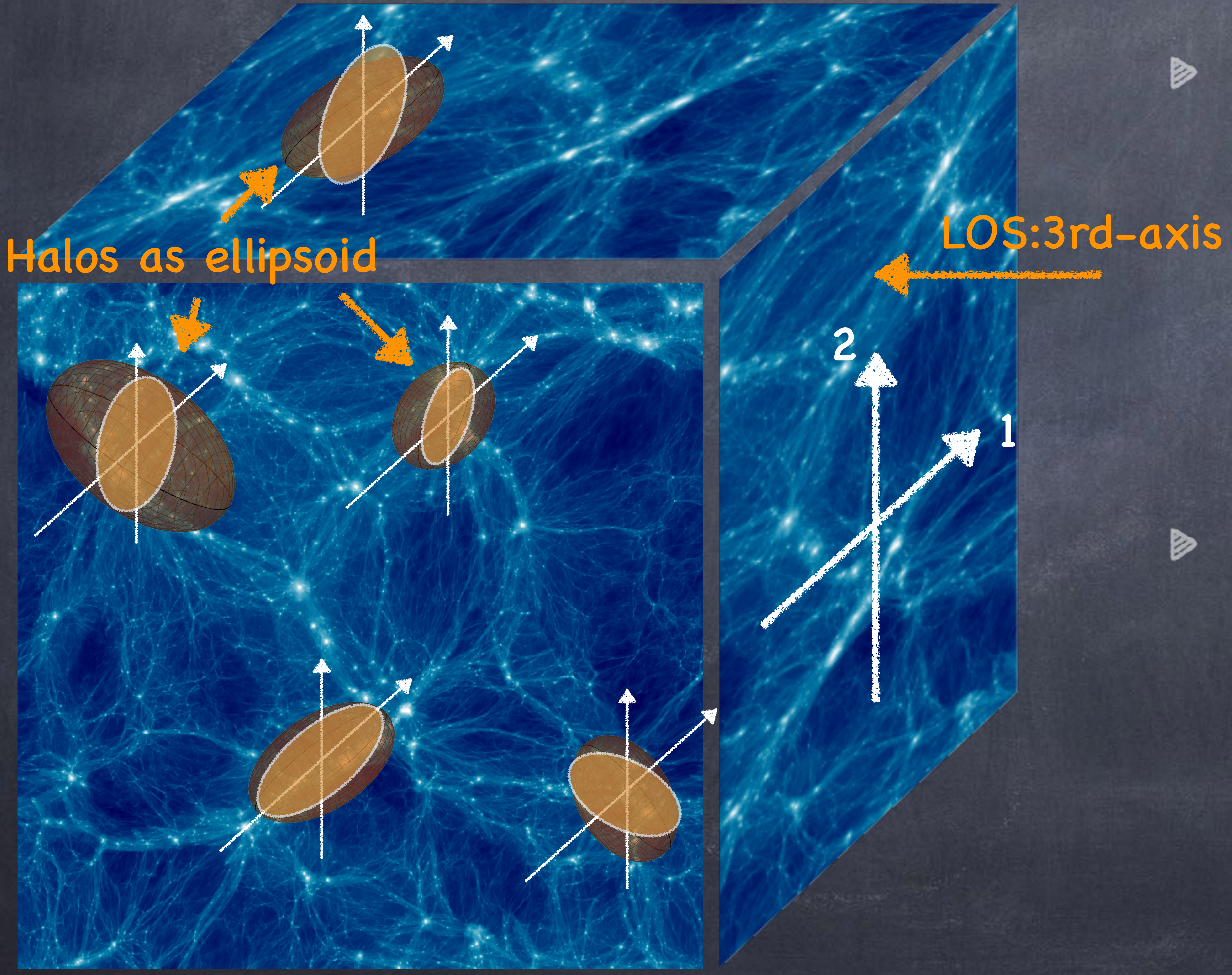
The shape-density correlation as a clean probe of IA

Mandelbaum et al. 2006, Hirata et al. 2007

- How to extract IA signal from observed shapes?
  - $\gamma_{ij}^{\rm obs} = \underbrace{\gamma_{ij}^{\rm G}}_{\text{WL}} + \underbrace{\gamma_{ij}^{\rm I}}_{\text{IA}} + \underbrace{\gamma_{ij}^{\rm N}}_{\text{Noise}}$
  - lensing : LSS between us and source galaxy
  - IA : Tidal field (LSS) surrounding source galaxy
    - $\langle \gamma^{\rm obs}(z_1)\gamma^{\rm obs}(z_1)\rangle \supset \langle \gamma^{\rm G}\gamma^{\rm G}\rangle,\ \langle \gamma^{\rm I}\gamma^{\rm I}\rangle$
    - $\langle \gamma^{\rm obs}(z_1)\delta_g(z_1)\rangle = \langle \gamma^{\rm I}(z_1)\delta_g(z_1)\rangle \sim b_K b_1 P_{\rm m}(z_1)$
  - The shape-density correlation is suite for exploring IA.



Observable = 2D projected shape as a function of 3D position



- Projection: $I^{\rm obs}_{ij}(\boldsymbol{x}) = \mathcal{P}^{\ell}_{i}(\hat{n})\mathcal{P}^{m}_{j}(\hat{n})I^{\rm 3D}_{\ell m}(\boldsymbol{x})$

3D position

$\mathcal{P}_{ij}(\hat{n}) = \delta^{\rm K}_{ij} - \hat{n}_i\hat{n}_j$

2D shape

$$I_{ij}(\boldsymbol{x}) = \begin{pmatrix} I_{11}(\boldsymbol{x}) & I_{12}(\boldsymbol{x}) & I_{13}(\boldsymbol{x}) \\ I_{21}(\boldsymbol{x}) & I_{22}(\boldsymbol{x}) & I_{23}(\boldsymbol{x}) \\ I_{31}(\boldsymbol{x}) & I_{32}(\boldsymbol{x}) & I_{33}(\boldsymbol{x}) \end{pmatrix}$$

- Projected ellipticity: spin-2 field
  - $\gamma_+ = \dfrac{I_{11} - I_{22}}{I_{11} + I_{22}}$ $\quad \gamma_\times = \dfrac{2I_{12}}{I_{11} + I_{22}}$
  - ${}_{\pm 2}\gamma(\boldsymbol{k}) = \gamma_+(\boldsymbol{k}) \pm i\gamma_\times(\boldsymbol{k})$

E/B decomposition of shape fields

Hirata&Seljak '04, Blazak+'11, Blazak+'15

- At each 3D grid, projected 2D shape fields (and density field) are defined.

$$\{\delta_{\rm m}(\mathbf{k}),\ \delta_{\rm h}(\mathbf{k}),\ \gamma_+(\mathbf{k}),\ \gamma_\times(\mathbf{k})\} \longrightarrow \{\delta_{\rm m}(\mathbf{k}),\ \delta_{\rm h}(\mathbf{k}),\ E(\mathbf{k}),\ B(\mathbf{k})\}$$

E/B decomposition

$$E(\mathbf{k}) = \gamma_+(\mathbf{k})\cos 2\phi_k + \gamma_\times(\mathbf{k})\sin 2\phi_k$$
$$B(\mathbf{k}) = \gamma_+(\mathbf{k})\sin 2\phi_k - \gamma_\times(\mathbf{k})\cos 2\phi_k$$

- IA power spectra: 3D power spectra of 2D projected shape field
  - Linear theory prediction (linear alignment(LA) model) : $\gamma_{ij} = b_K K_{ij}$

$$P_{{\rm m}E}(\mathbf{k}) = b_K(1-\mu^2)P_{\rm m}(k)$$
$$P_{EE}(\mathbf{k}) = b_K^2(1-\mu^2)^2 P_{\rm m}(k)$$
$$(\mu = \hat{k}\cdot\hat{n})$$

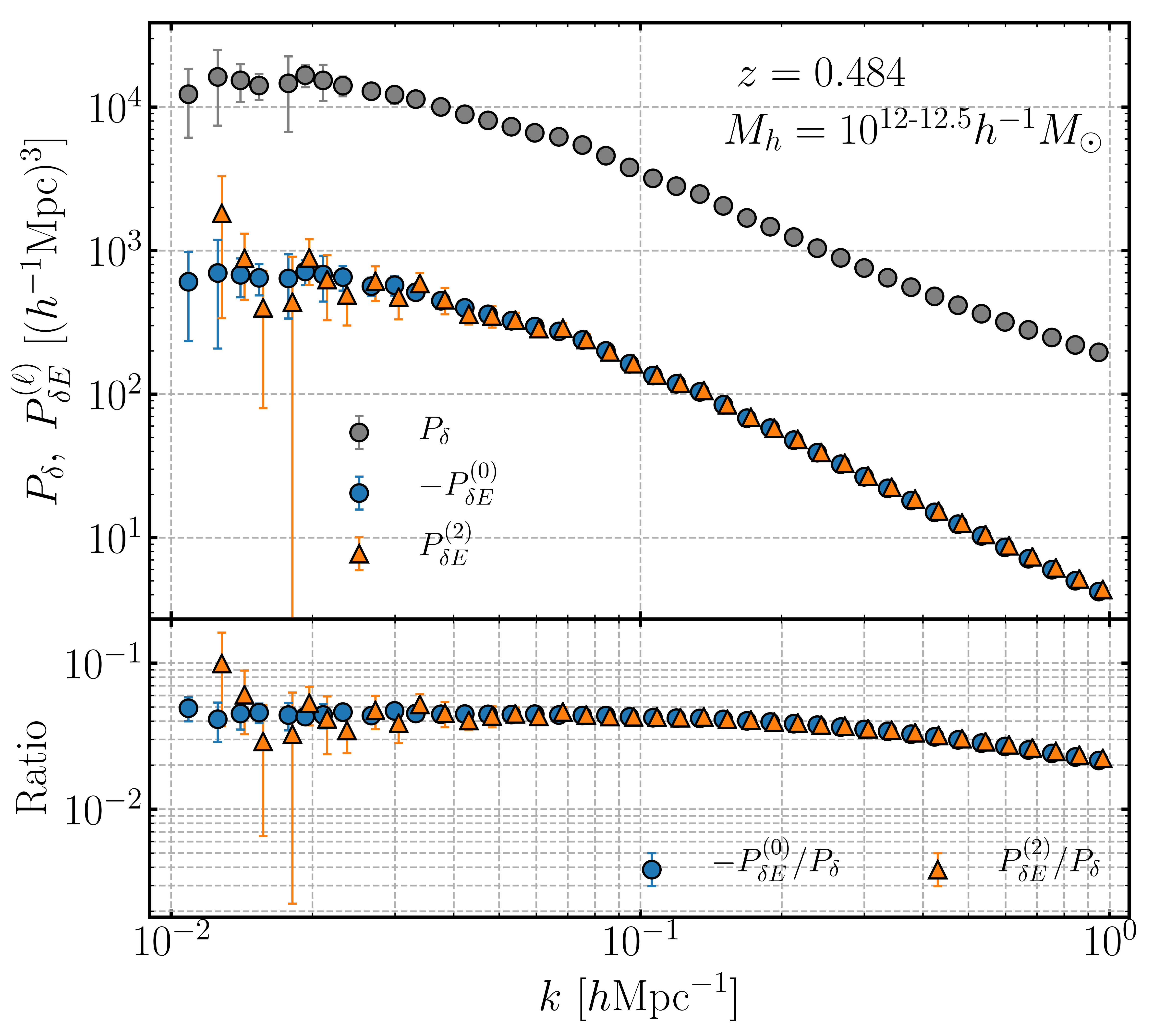
cf. Kaiser's formula:

$$P_{\rm mh}(\mathbf{k}) = (b_1 + f\mu^2)P_{\rm m}(k)$$
$$P_{\rm hh}(\mathbf{k}) = (b_1 + f\mu^2)^2 P_{\rm m}(k)$$

E-mode power spectra from N-body

- LA model works on large scales.
  - Negative correlation $P^{(0)}_{\mathrm{m}E} < 0$
    - $\gamma_{ij} \perp K_{ij}$
  - $P_{\mathrm{m}E} \propto P_{\mathrm{mm}}$ on large-scales
    - $E(\mathbf{k}) \sim b_K \delta_{\mathrm{m}}(\mathbf{k})$ with $b_K \sim -0.1$
- The large-scale constant bias when
  - Equivalence principle
  - Adiabatic&Gaussian ICs

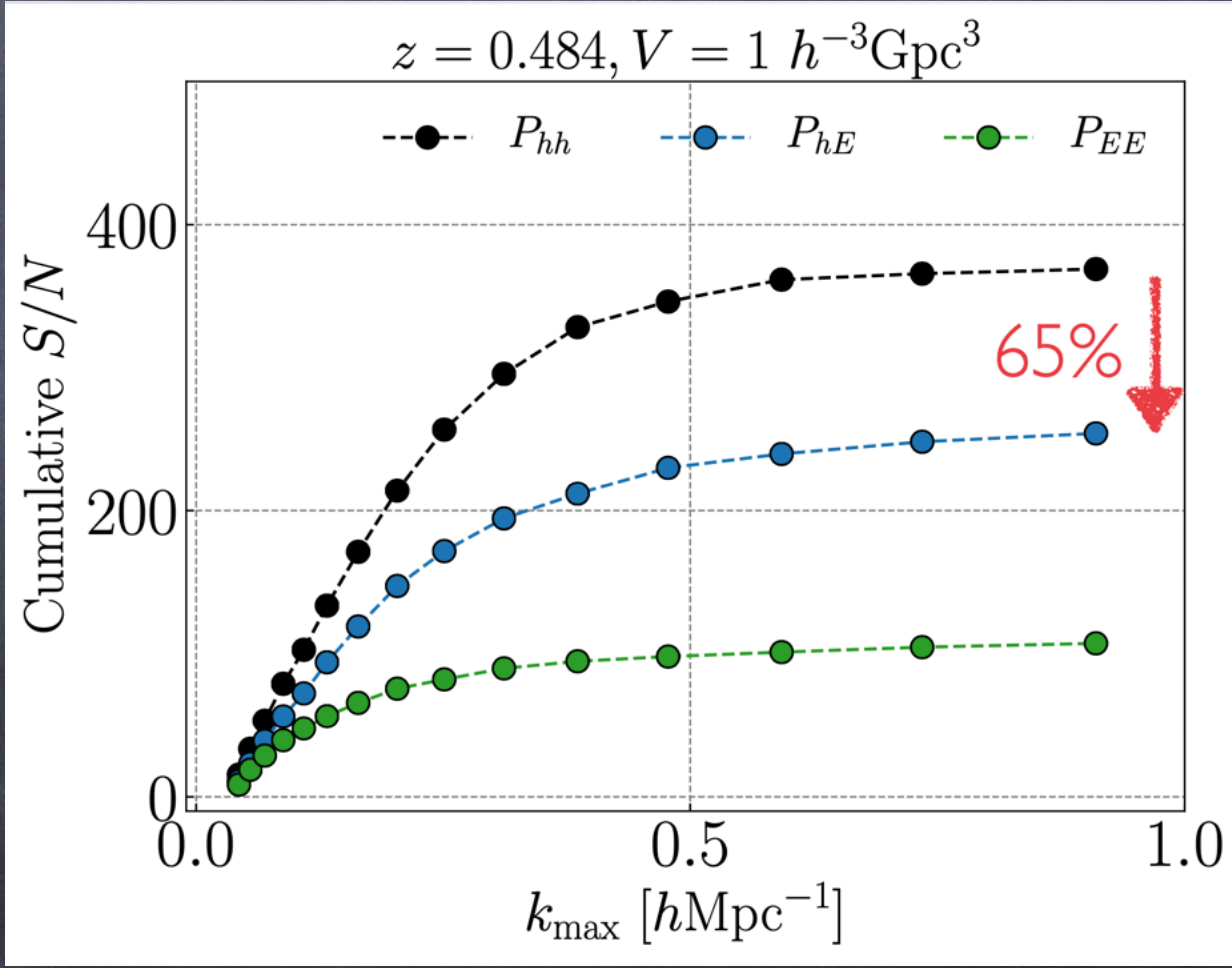
What happens with PNG?



S/N of shape power spectrum

- S/N of $P_{\mathrm{h}E}$ is about **65%** compared with halo clustering P_{hh}
  - bias: $b_h \sim \mathcal{O}(1), \quad b_K \sim \mathcal{O}(0.1)$
  - Noise: $1/\bar{n}_h, \quad \sigma_\gamma^2/n_h$

    $\sigma_\gamma^2 \sim 0.1$
- For galaxies S/N can be decreased
  - misalignment Okumura+'09



The importance of 3D power spectrum

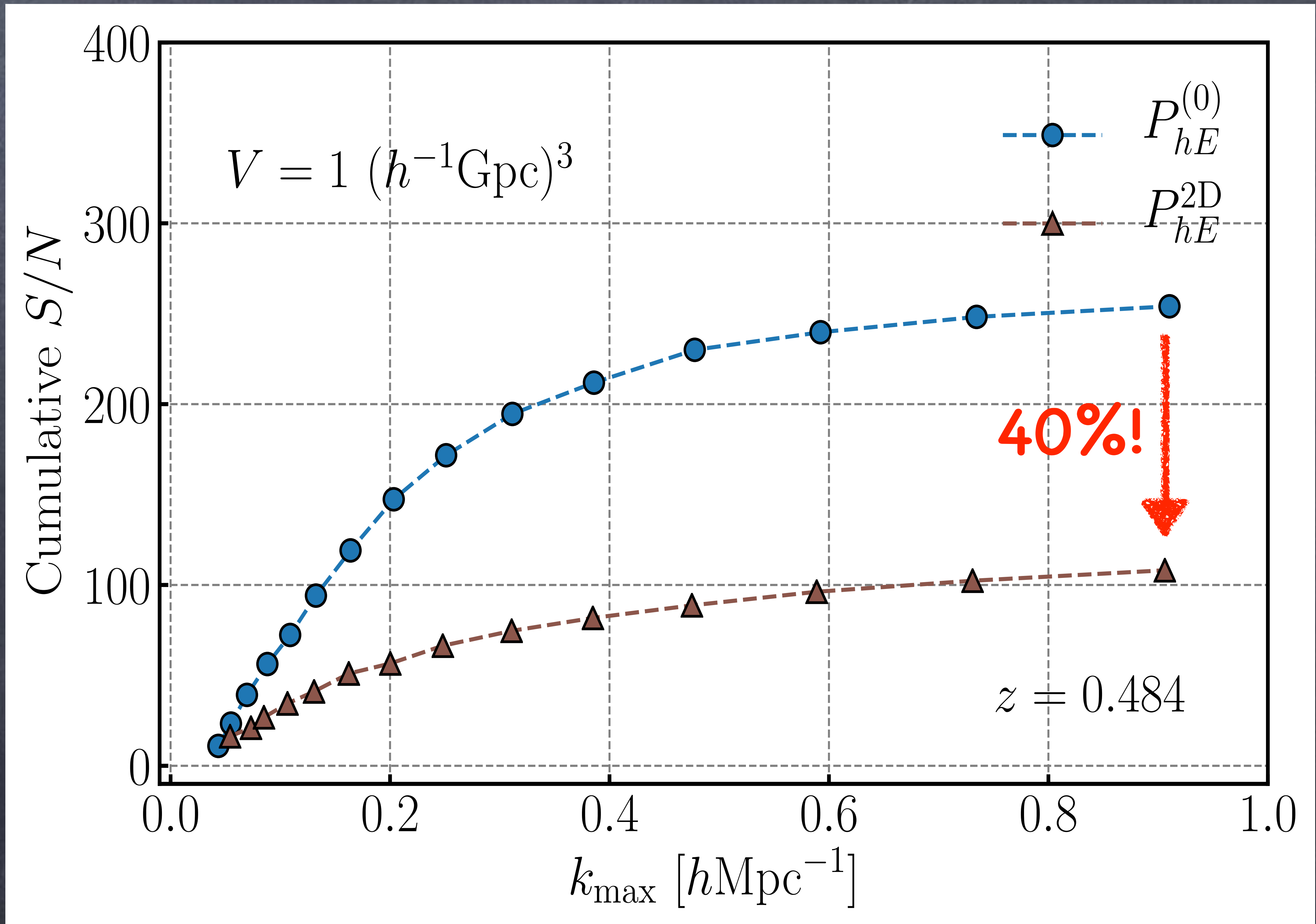
$$\gamma_{ij}(\boldsymbol{x}) = \begin{pmatrix} \gamma_{11}(\boldsymbol{x}) & \gamma_{12}(\boldsymbol{x}) \\ \gamma_{21}(\boldsymbol{x}) & \gamma_{22}(\boldsymbol{x}) \end{pmatrix}$$

- 2D shape components from imaging
- 3D position from spectroscopy
- What if only using imaging survey?

$$\gamma_{ij}^{2D}(\boldsymbol{x}_\perp) = \int_{\bar{\chi}-\Delta\chi/2}^{\bar{\chi}+\Delta\chi/2} dx_3 \; \gamma_{ij}(\boldsymbol{x}_\perp, x_3)$$

2D position

- $\Delta\chi$ corresponds to $\sigma_z \sim 0.04$



The linear alignment coefficient b_K from the tidal separate universe simulation

Separate universe simulation

Sirko'05, Baldauf+'11, Li+'14a, Wagner+'14, Baldauf+'16, Lazeyras+'16

- Long-wavelength perturbation can be absorbed into the local background

Perturbed flat FLRW Universe

curved FLRW Universe (Unperturbed)
= Separate Universe

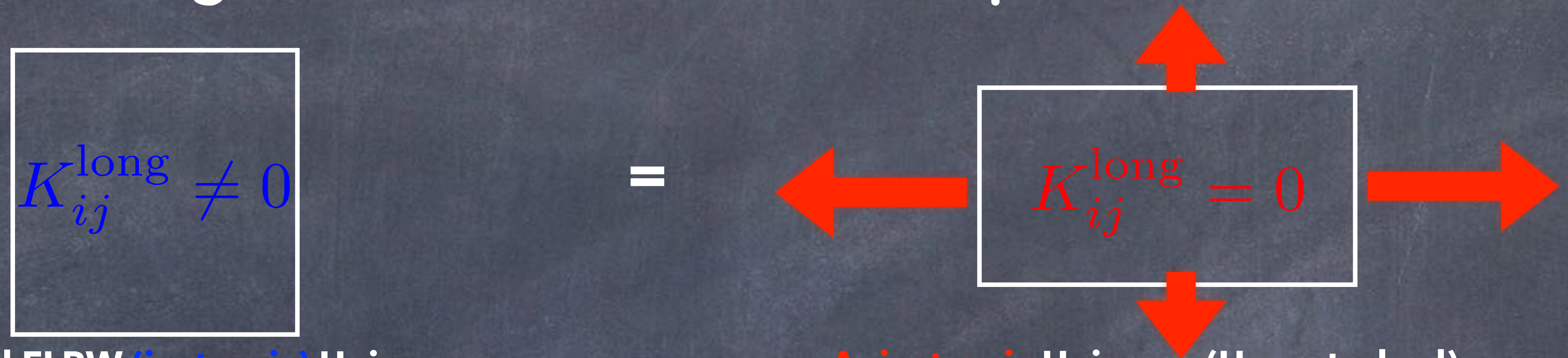
- Mass conservation: $a^3 \bar{\rho}_{\rm m}[1+\delta_{\rm b}] = a_W^3 \bar{\rho}_{{\rm m}W} \quad \rightarrow \quad a_W \simeq a\left[1 - \frac{1}{3}\delta_{\rm b}\right]$
- From the same initial seeds
- Halo biases can be well calibrated by using this technique.

$$b_1 = \frac{{\rm d}\ln \bar{n}_h}{{\rm d}\ln \bar{\rho}_{\rm m}} = \frac{{\rm d}\ln \bar{n}_h}{{\rm d}\delta_{\rm b}}$$

Tidal separate universe simulation

KA+'20, see also Stucker+'20 and Masaki+'20

- Including long-wavelength tidal field: anisotropic scale factor



Perturbed FLRW (isotropic) Universe | **Anisotropic Universe (Unperturbed)**

$$a_x = a_y = a_z = a$$

$$a_x = a[1 - K_x]$$
$$a_y = a[1 - K_y]$$
$$a_z = a[1 - K_z]$$

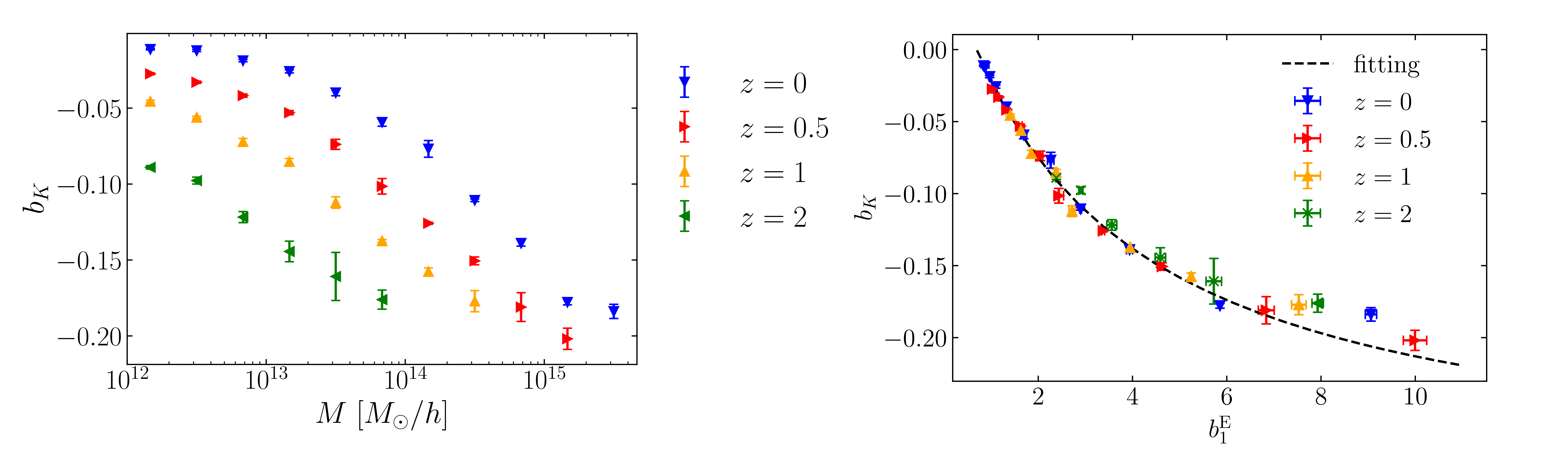
- The shape bias can be well calibrated by this simulation.

$$b_K = \frac{\mathrm{d}\ln \bar{I}_{ij}}{\mathrm{d}K_{ij}}$$

Similarity to the linear bias

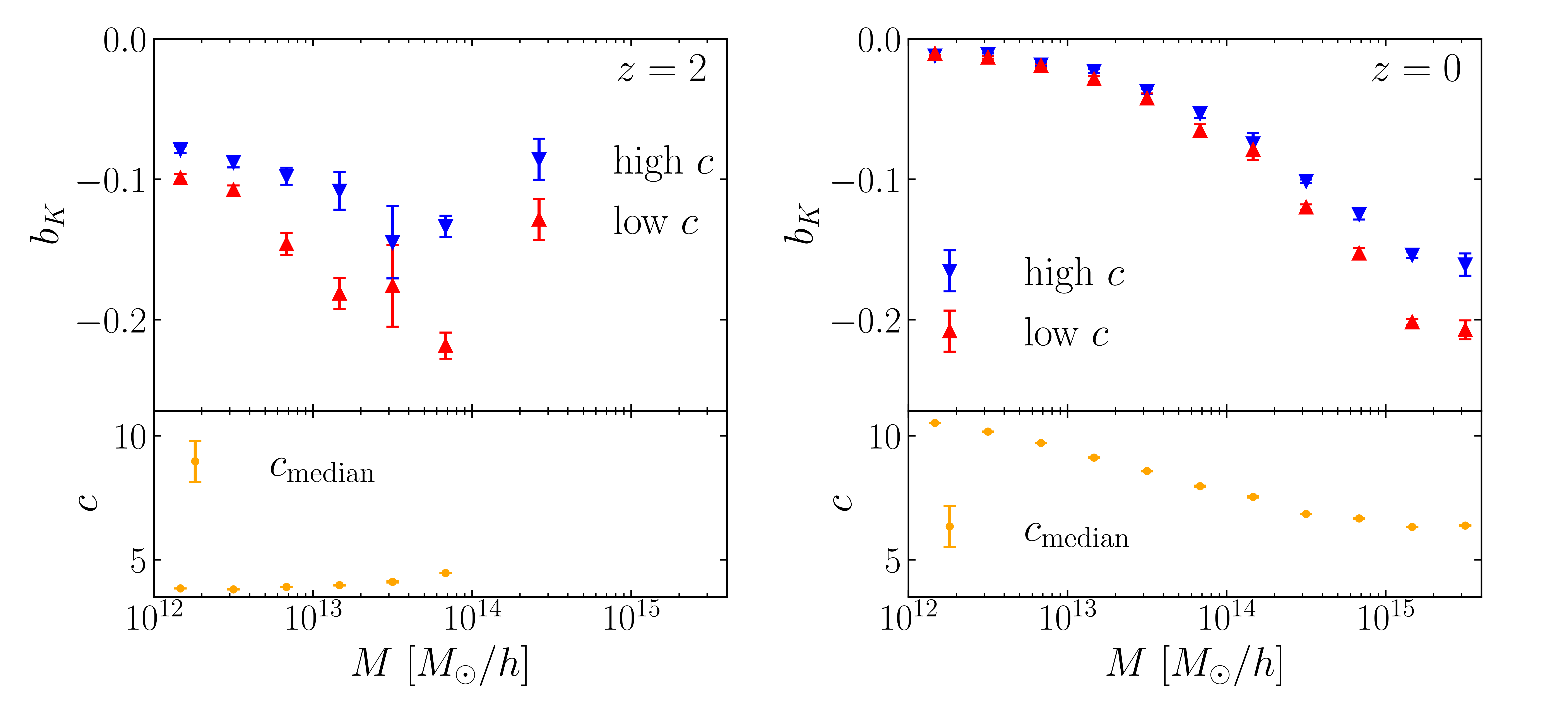
KA+'20

- Similar dependence on halo mass and redshift to the linear bias
  - Hint for a theory of bK?



Shape assembly bias: concentration

- The shape bias depends on the halo concentration.
- High peak is less affected by large-scale tides?



The intrinsic alignment as a probe of the angular-dependent PNG

Primordial non-Gaussianity (PNG)

- The primordial perturbations obey the Gaussian distribution
  - predicted by the standard (single field & slow roll) inflation
  - completely described by the power spectrum (2pt function):

$$\langle \Phi(\mathbf{k_1})\Phi(\mathbf{k_2})\rangle = (2\pi)^3 \delta_{\rm D}^3(\mathbf{k}_1+\mathbf{k}_2)P_\Phi(\mathbf{k}_1)$$: No mode-coupling

- PNG: the deviation from the Gaussianity (i.e. the standard inflation)
  - its leading order effect is characterized by the bispectrum (3pt function):

$$\langle \Phi(\mathbf{k_1})\Phi(\mathbf{k_2})\Phi(\mathbf{k_3})\rangle = (2\pi)^3 \delta_{\rm D}^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

  - Local-type: $B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = 2 f_{\rm NL}\left[P_\Phi(\mathbf{k}_1)P_\Phi(\mathbf{k}_2) + 2\ \text{perms.}\right]$

Effect of PNG on galaxy number density

Dalal+'08

- What if there is the local-type PNG?
  - long-&short-modes are coupled-> the power spectrum is position-dependent.

$$P_{\rm m}(k_{\rm short}) \to P_{\rm m}(k_{\rm short}|\mathbf{x}) = P_{\rm m}(k_{\rm short})\left[1+4f_{\rm NL}\phi^{\rm long}(\mathbf{x})\right] \quad \leftarrow B_\Phi(\mathbf{k}_{\rm short},\mathbf{k}_{\rm short},\mathbf{k}_{\rm long}) \simeq 4f_{\rm NL}P_\Phi(\mathbf{k}_{\rm short})P_\Phi(\mathbf{k}_{\rm long})$$

  - Amplitudes of small-scale fluctuations at distant points are now correlated.
  - $\delta_g(\mathbf{k}_{\rm long}) = b_1\delta_{\rm m}(\mathbf{k}_{\rm long}) + 4b_\phi f_{\rm NL}\phi(\mathbf{k}_{\rm long})$

$$= \left[b_1 + 4b_\phi f_{\rm NL}\mathcal{M}^{-1}(k_{\rm long})\right]\delta_{\rm m}(\mathbf{k}_{\rm long})$$

with $\delta_{\rm m}(\mathbf{k}) = \mathcal{M}(k)\phi(\mathbf{k})$

$$b_\phi = \frac{{\rm d}\ln n_g}{{\rm d}\ln \mathcal{A}_s} = \frac{{\rm d}\ln n_g}{{\rm d}\ln \sigma_8} = \frac{{\rm d}\ln n_g}{{\rm d}(4f_{\rm NL}\phi^{\rm long})}$$

$\bar{\rho}_{\rm m} \to \bar{\rho}_{\rm m}[1+\delta_{\rm m}^{\rm long}(\mathbf{x}_1)]$ $\quad$ $\bar{\rho}_{\rm m} \to \bar{\rho}_{\rm m}[1+\delta_{\rm m}^{\rm long}(\mathbf{x}_2)]$

$P_{\rm m}(\mathbf{k}_{\rm short}|\mathbf{x}_1) = P_{\rm m}(k_{\rm short})\left[1+4f_{\rm NL}\phi^{\rm long}(\mathbf{x}_1)\right]$ $\quad$ $P_{\rm m}(\mathbf{k}_{\rm short}|\mathbf{x}_2) = P_{\rm m}(k_{\rm short})\left[1+4f_{\rm NL}\phi^{\rm long}(\mathbf{x}_2)\right]$

Scale-dependent bias from the local-type PNG

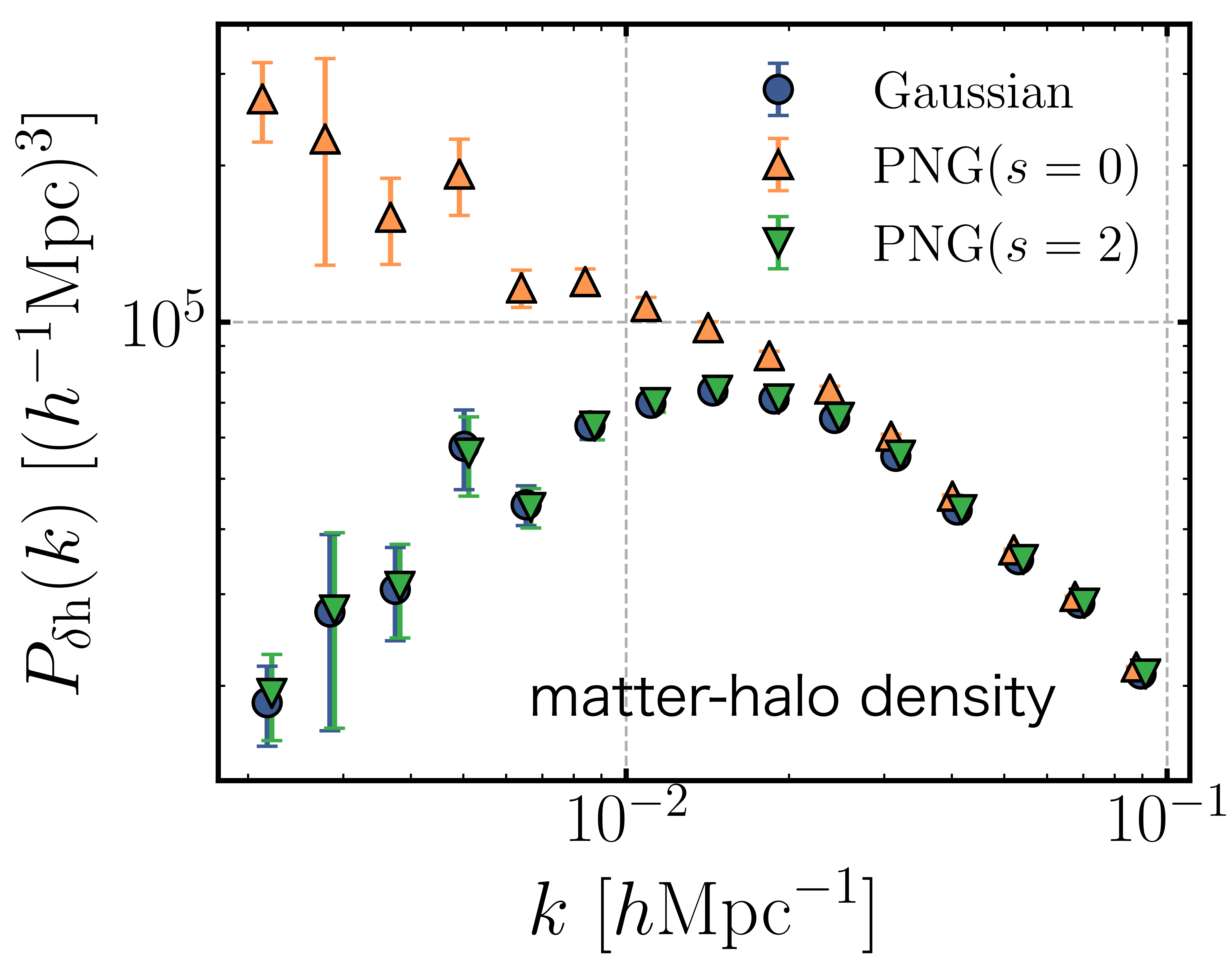
- There appears $1/k^2$ enhancement in galaxy/halo density field on large-scales.
- $\delta_g(\mathbf{k}) = \left[b_1 + 4b_\phi f_{\rm NL}\mathcal{M}^{-1}(k)\right]\delta_{\rm m}(\mathbf{k})$

  → $P_{\rm mg}(k) = \left[b_1 + 4b_\phi f_{\rm NL}\mathcal{M}^{-1}(k)\right]P_{\rm m}(k)$
- $\mathcal{M}^{-1}(k) \propto 1/k^2$ on large-scales

  ← $\delta_{\rm m}(\mathbf{k}) \sim k^2\phi(\mathbf{k})$ from Poisson eq.
- Constraints on $f_{\rm NL}$ from galaxy surveys

  $-16 < f_{\rm NL} < 26$ from BOSS T.Glannantonio+'14

  $\sigma(f_{\rm NL}) \sim \mathcal{O}(1)$ in the near future (SPHEREx)
- Note: there is no modulation in $P_{\rm m}(k)$



Angular-dependent PNG

- The quadrupole local-type PNG: $B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = 2 f_{\rm NL}^{s=2} \left[\mathcal{L}_2(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2) P_\Phi(\mathbf{k}_1)P_\Phi(\mathbf{k}_2) + \text{ 2 perms.}\right]$
  - cf. the usual local-type PNG: $B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = 2 f_{\rm NL}\left[P_\Phi(\mathbf{k}_1)P_\Phi(\mathbf{k}_2) + 2\text{ perms.}\right]$
  - Solid inflation, Magnetic fields, Spin-2 particles during inflation

    Endlich+'12 Shiraishi+'13 Arkani-Hamed&Maldacena'15

- The (small-scale) power spectrum becomes position-dependent&anisotropic
  - $P_{\rm m}(\mathbf{k}_{\rm short}|\mathbf{x}) = P_{\rm m}(k_{\rm short})\left[1 + 4 f_{\rm NL}^{s=2}\sum_{ij}\psi_{ij}^{\rm long}(\mathbf{x})\hat{k}^i_{\rm short}\hat{k}^j_{\rm short}\right]$ with $\psi_{ij}^{\rm long} \equiv \frac{3}{2}\left[\frac{\partial_i\partial_j}{\partial^2} - \frac{1}{3}\delta^{\rm K}_{ij}\right]\phi^{\rm long}$
  - cf. angular-independent case: $P_{\rm m}(k_{\rm short}|\mathbf{x}) = P_{\rm m}(k_{\rm short})\left[1 + 4 f_{\rm NL}\phi^{\rm long}(\mathbf{x})\right]$
  - $\hat{k}^i\hat{k}^j\delta_{\rm m} \sim \frac{\partial^i\partial^j}{\partial^2}\delta_{\rm m} \sim \partial^i\partial^j\phi$

Intrinsic alignments with angular-dependent PNG

Schmidt+'15, KA+'20

- Angular-dependent PNG -> small-scale tidal fluctuations are correlated
  - $P_{\rm m}(\mathbf{k}_{\rm short}|\mathbf{x}) = P_{\rm m}(k_{\rm short})\left[1 + 4f_{\rm NL}^{s=2}\sum_{ij}\psi_{ij}^{\rm long}(\mathbf{x})\hat{k}^i_{\rm short}\hat{k}^j_{\rm short}\right]$ **with** $\psi_{ij}^{\rm long} \equiv \frac{3}{2}\left[\frac{\partial_i\partial_j}{\partial^2} - \frac{1}{3}\delta^{\rm K}_{ij}\right]\phi^{\rm long}$
  - $$\begin{aligned}\gamma_{ij}(\mathbf{k}_{\rm long}) &= b_K K_{ij}(\mathbf{k}_{\rm long}) + 4b_\psi f_{\rm NL}^{s=2}\psi_{ij}(k_{\rm long}) \\ &= \left[b_K + 6b_\psi f_{\rm NL}^{s=2}\mathcal{M}^{-1}(k_{\rm long})\right]K_{ij}(\mathbf{k}_{\rm long})\end{aligned}$$

    with $\delta_{\rm m}(\mathbf{k}) = \mathcal{M}(k)\phi(\mathbf{k})$

    $$b_\psi = \frac{{\rm d}\gamma_{ij}}{{\rm d}(4f_{\rm NL}^{s=2}\psi_{ij}^{\rm long})}$$
  - $\delta_g(\mathbf{k}_{\rm long}) = b_1\delta_{\rm m}(\mathbf{k}_{\rm long})$

Angular-dependent PNG ICs & simulations

KA+'20a

- Generating initial condition with angular-dependent PNG
  1. Generate random Gaussian fields $\phi(\mathbf{k})$ with the variance $P_\phi(k)$
  2. Prepare auxiliary fields $\psi_{ij}(\mathbf{k}) = \frac{3}{2}\left[\hat{k}_i\hat{k}_j - \frac{1}{3}\delta^{\rm K}_{ij}\right]\phi(\mathbf{k})$
  3. FT to configuration space and construct non-Gaussian fields according to

     $\Phi(\mathbf{x}) = \phi(\mathbf{x}) + \frac{2}{3}f_{\rm NL}^{s=2}\sum_{ij}\psi_{ij}^2(\mathbf{x})$ (leading to $B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = 2f_{\rm NL}^{s=2}\left[\mathcal{L}_2(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2)P_\phi(\mathbf{k}_1)P_\phi(\mathbf{k}_2) + \text{ 2 perms.}\right]$)

     cf. $\Phi(\mathbf{x}) = \phi(\mathbf{x}) + f_{\rm NL}^{s=0}\phi^2(\mathbf{x})$ (leading to $B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = 2f_{\rm NL}^{s=0}\left[P_\phi(\mathbf{k}_1)P_\phi(\mathbf{k}_2) + \text{ 2 perms.}\right]$)
  4. FT back to Fourier space, then do the 2LPT
- Simulation: $L = 4.096\ {\rm Gpc}/h,\ N_{\rm p} = 2048^3$
  - $(f_{\rm NL}^{s=0}, f_{\rm NL}^{s=2}) = (0,0)\ ,\ (500,0)\ ,\ (0,500)$

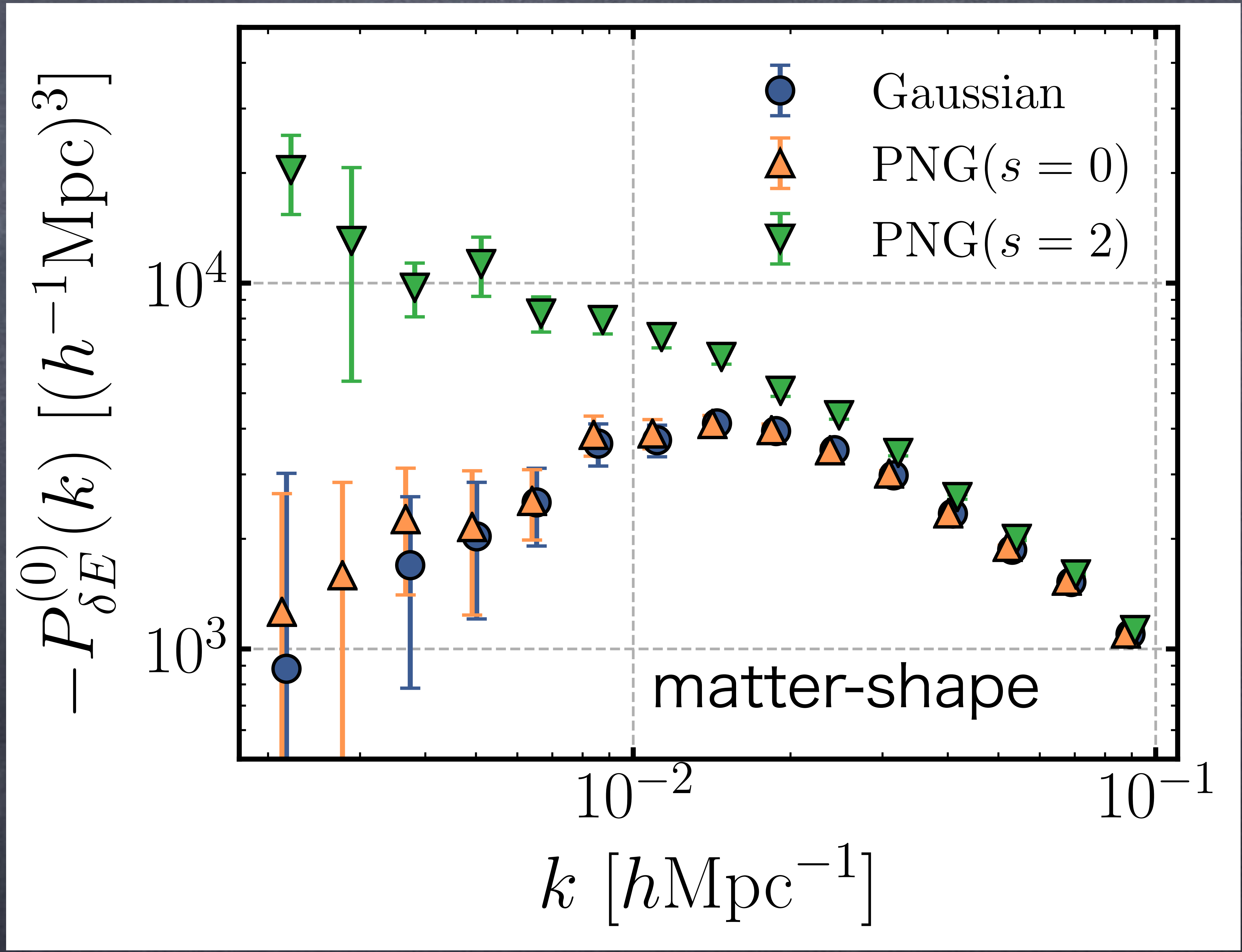
Scale-dependent bias in the IA power spectrum

KA+'20a

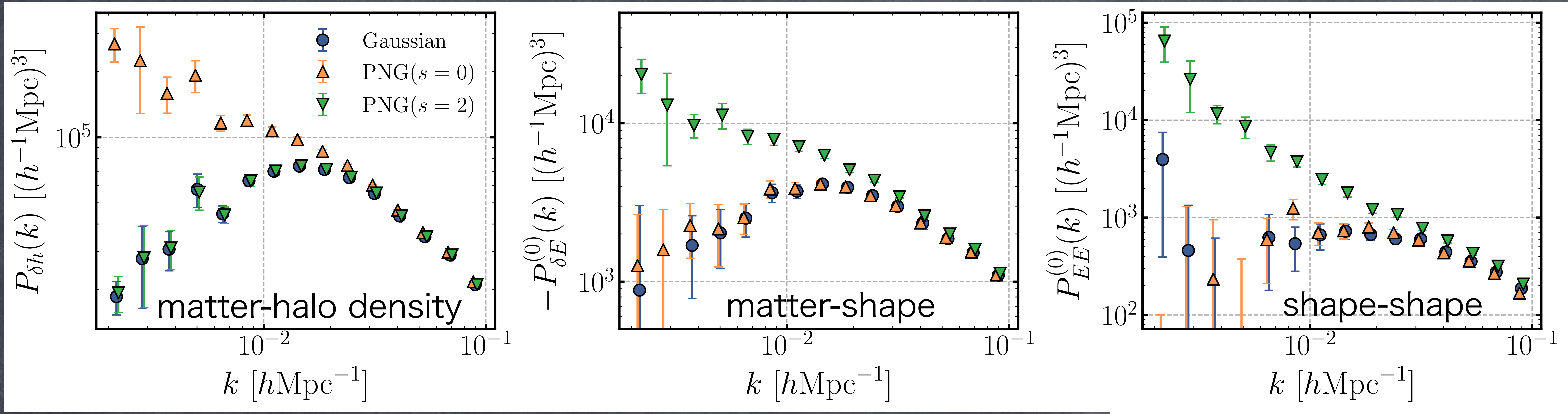
- There appears $1/k^2$ enhancement in galaxy/halo shape field on large-scales.
- $\gamma_{ij}(\mathbf{k}_{\rm long}) = \left[b_K + 6b_\psi f_{\rm NL}^{s=2}\mathcal{M}^{-1}(k_{\rm long})\right] K_{ij}(\mathbf{k}_{\rm long})$

  → $P_{{\rm m}E}(k) = \left[b_K + 6b_\psi f_{\rm NL}^{s=2}\mathcal{M}^{-1}(k)\right] P_{\rm m}(k)$
- $\mathcal{M}^{-1}(k) \propto 1/k^2$ on large-scales

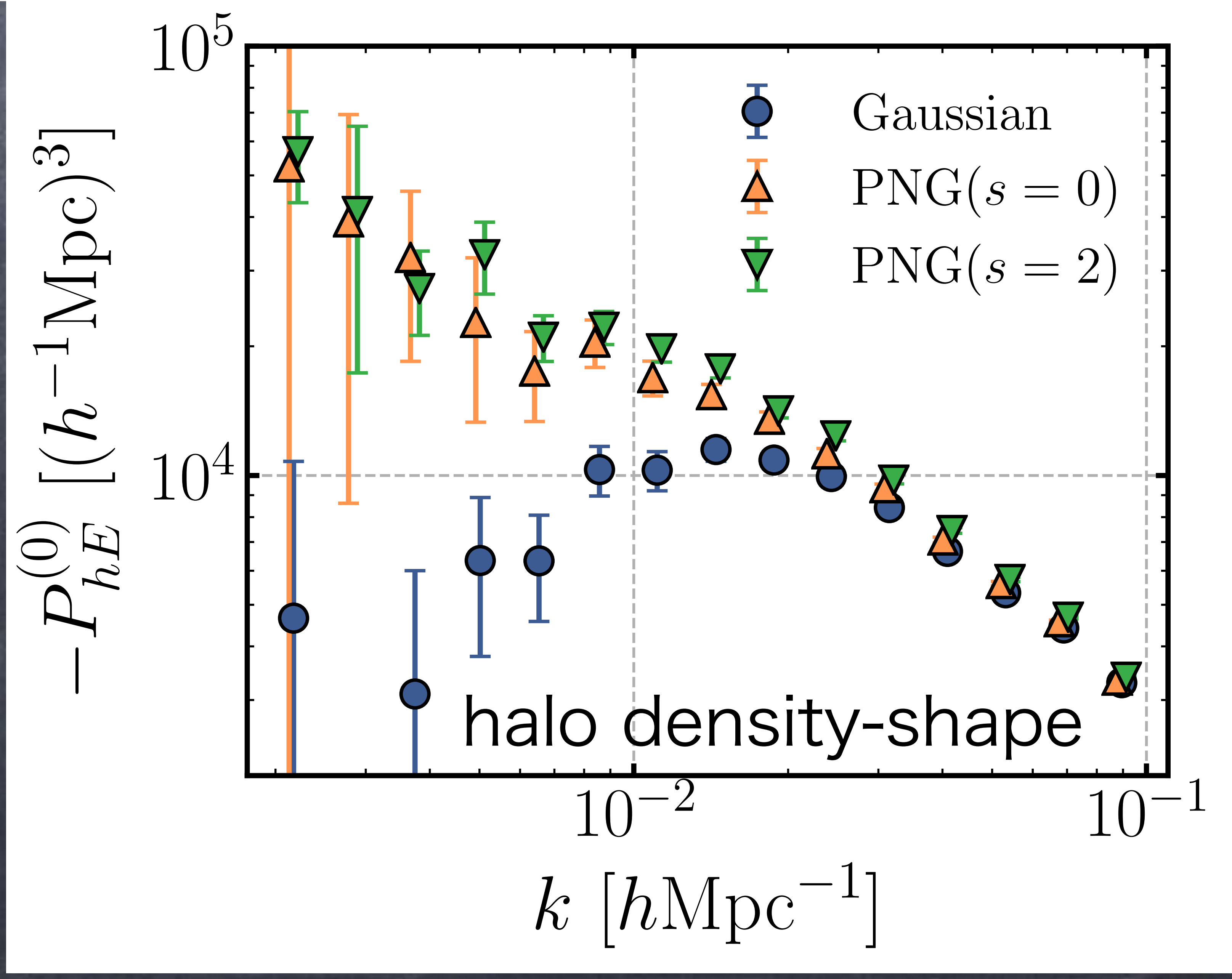
  $\delta_{\rm m}(\mathbf{k}) \sim k^2\phi(\mathbf{k})$ from Poisson eq.
- The angular-independent PNG has no impact on shape field, i.e. $P_{{\rm m}E}$ & P_{EE}
- The angular-dependent PNG has no impact on density field, i.e. $P_{\rm mh}$ & $P_{\rm hh}$



Scale-dependent bias in various power spectrum



- The spin-0 and -2 observables only respond to the s=0 and s=2 PNGs, respectively
- The halo density-shape cross power spectrum $P_{\mathrm{h}E}$ is affected by both angular-independent&-dependent PNGs
  - P_{hh} responds to only the angular-independent PNG.



Summary of imprint of various PNGs

	# density tracer (spin-0 observable) δ	shape tracer (spin-2 observable) γ_{ij}
linear theory	$\delta_g = b_1 \delta_{\rm m}$	$\gamma_{ij} = b_K K_{ij}$
s=0 PNG	$\Phi(\mathbf{x}) = \phi(\mathbf{x}) + f_{\rm NL}^{s=0} \phi^2(\mathbf{x}), \quad P_{\rm m}(\mathbf{k};\mathbf{x}) = P_{\rm m}(k)\left[1 + 4 f_{\rm NL}^{s=0} \phi^{\rm long}(\mathbf{x})\right]$	
	scale-dependent bias	X
s=2 PNG	$\Phi(\mathbf{x}) = \phi(\mathbf{x}) + \frac{2}{3} f_{\rm NL}^{s=2} \sum_{ij} \psi_{ij}^2(\mathbf{x}), \quad P_{\rm m}(\mathbf{k};\mathbf{x}) = P_{\rm m}(k)\left[1 + 4 f_{\rm NL}^{s=2} \psi_{ij}^{\rm long}(\mathbf{x}) \hat{k}^i \hat{k}^j\right]$	
	X	scale-dependent bias

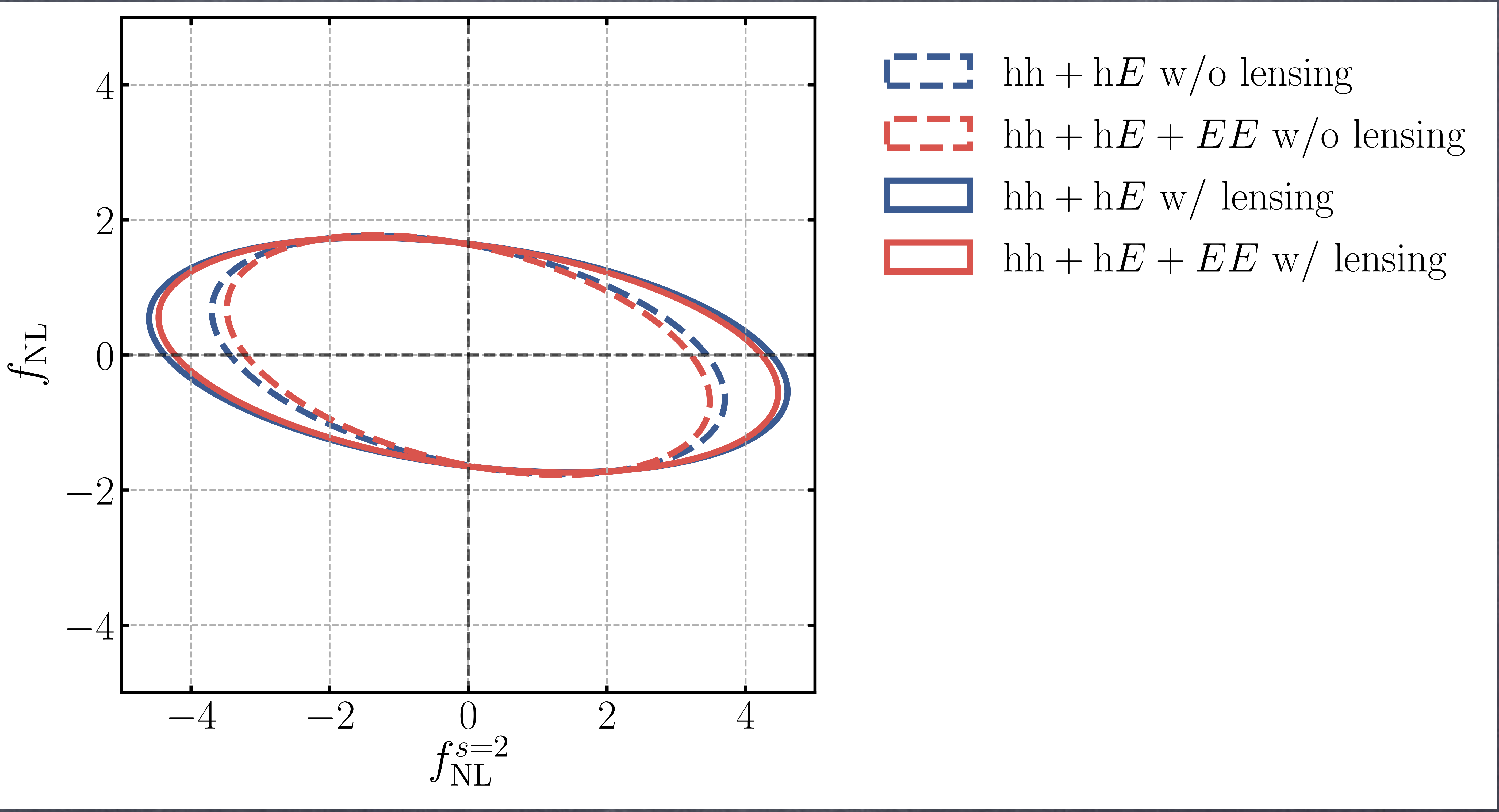
$$B_\Phi(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = 2 f_{\rm NL}^{s=\ell} \left[\mathcal{L}_\ell(\hat{k}_1 \cdot \hat{k}_2) P_\phi(k_1) P_\phi(k_2) + \text{ 2 perms.}\right]$$

Forecast

- Using both P_{hh} & $P_{\mathrm{h}E}$
  - $V_{\mathrm{survey}} = 69\ (\mathrm{Gpc}/h)^3$
  - $M_{\mathrm{h}} > 10^{13} M_{\odot}/h,\ \bar{n}_{\mathrm{h}} = 2.9 \times 10^{-4}\ (\mathrm{Mpc}/h)^3$
- The current CMB constraints:

  $\sigma(f_{\mathrm{NL}}^{s=2}) \simeq 19$

  Planck2018



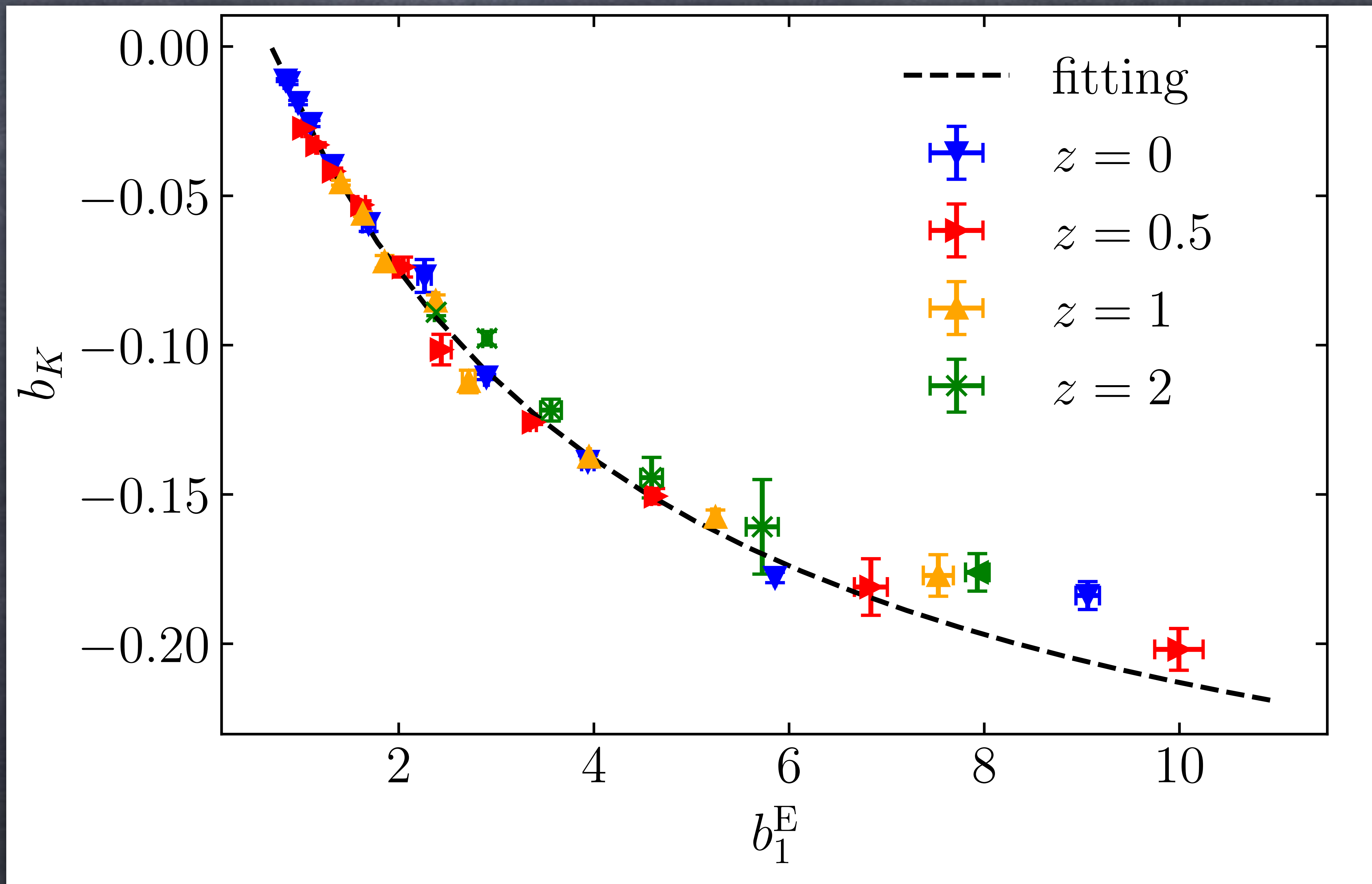
- We need both photo&spec surveys
  - Projected (2D) shapes: photometric survey
  - 3D position of galaxies: spectroscopic survey

Challenge of IA cosmology

- Complete degenerary between b_ψ and $f_{\rm NL}^{s=2}$ $\quad P_{{\rm m}E}(k) = \left[b_K + 6b_\psi f_{\rm NL}^{s=2}\mathcal{M}^{-1}(k)\right] P_{\rm m}(k)$
  - Density case: $P_{{\rm m}g}(k) = \left[b_1 + 4b_\phi f_{\rm NL}\mathcal{M}^{-1}(k)\right] P_{\rm m}(k)$
    - From peak theory: $b_\phi = 2\delta_{\rm cr} b_1^{\rm L} = 2\delta_{\rm cr}(b_1^{\rm E} - 1)$

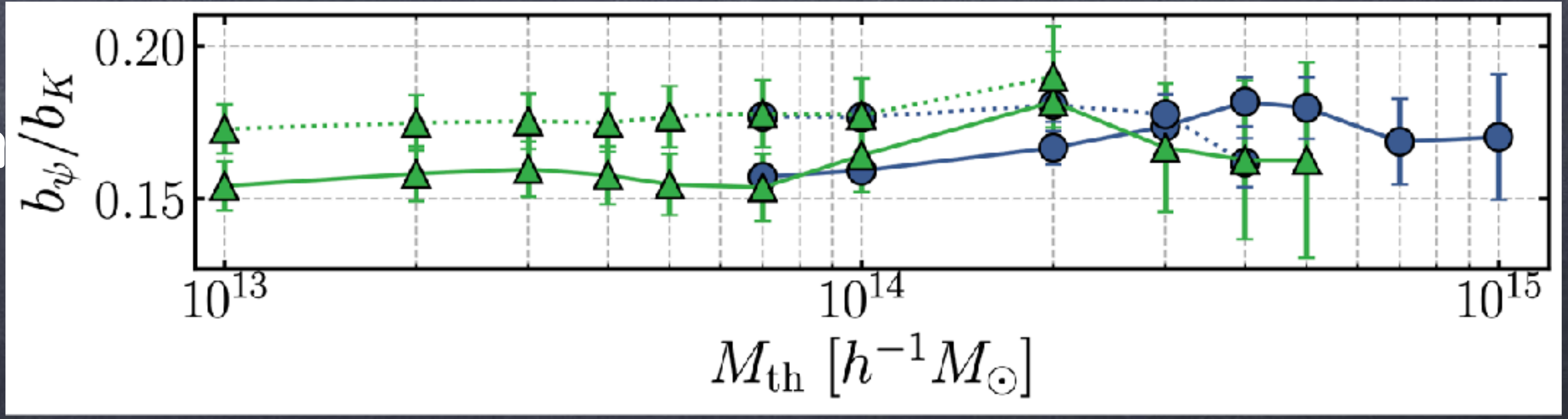
KA+'20b

- need to develop theory on shape bias
  - Some hints:
    - universal relation between b_K and b_1
    - b_ψ / b_K looks constant



Challenge of IA cosmology

- Complete degenerary between b_ψ and $f_{\rm NL}^{s=2}$ $P_{{\rm m}E}(k) = \left[b_K + 6 b_\psi f_{\rm NL}^{s=2} \mathcal{M}^{-1}(k)\right] P_{\rm m}(k)$
  - Density case: $P_{\rm mg}(k) = \left[b_1 + 4 b_\phi f_{\rm NL} \mathcal{M}^{-1}(k)\right] P_{\rm m}(k)$
    - From peak theory: $b_\phi = 2\delta_{\rm cr} b_1^{\rm L} = 2\delta_{\rm cr}(b_1^{\rm E} - 1)$
- need to develop theory on shape bias
  - Some hints:
    - universal relation between
    - b_ψ / b_K looks constant



Summary

- Intrinsic Alignment itself can be seen as new cosmological signal
- The angular-dependent PNG induces the scale-dependent bias in the IA power spectrum
  - But no impact on number density tracers
  - The angular-independent PNG has no impact on IA (while it affects number density tracers)
  - Galaxy surveys (both photo&spec) can constrain $f_{\rm NL}^{s=2}$ better than CMB
- Future: theory for the shape bias, bispectrum etc.