Title: Probing angular-dependent primordial non-Gaussianity from galaxy intrinsic alignments

Speakers: Kazuyuki Akitsu

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Abstract: The primordial non-Gaussianity (PNG) is a key feature to screen various inflationary models and it is one of the main targets in the next generation galaxy surveys. In particular, the local-type of PNG makes the galaxy bias scale-dependent in large-scales, which is known as the scale-dependent bias, allowing to constrain the local-type PNG from galaxy surveys. In this talk, I will present the galaxy shape correlation, called the ``intrinsic alignment", can explore the angular-dependent PNG. Using N-body simulations, we show the angular-dependent PNG induces the scale-dependent bias in the intrinsic alignment, just as the angular-independent PNG leads to the scale-dependent bias in the galaxy number density correlation. By combining photometric and spectroscopic surveys to measure the intrinsic alignment, future galaxy surveys are potentially capable of constraining the angular-dependent PNG better than CMB experiments.

Probing angular-dependent primordial non-Gaussianity from galaxy intrinsic alignments

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based on arXiv:2007.03670 and arXiv:2009.05517

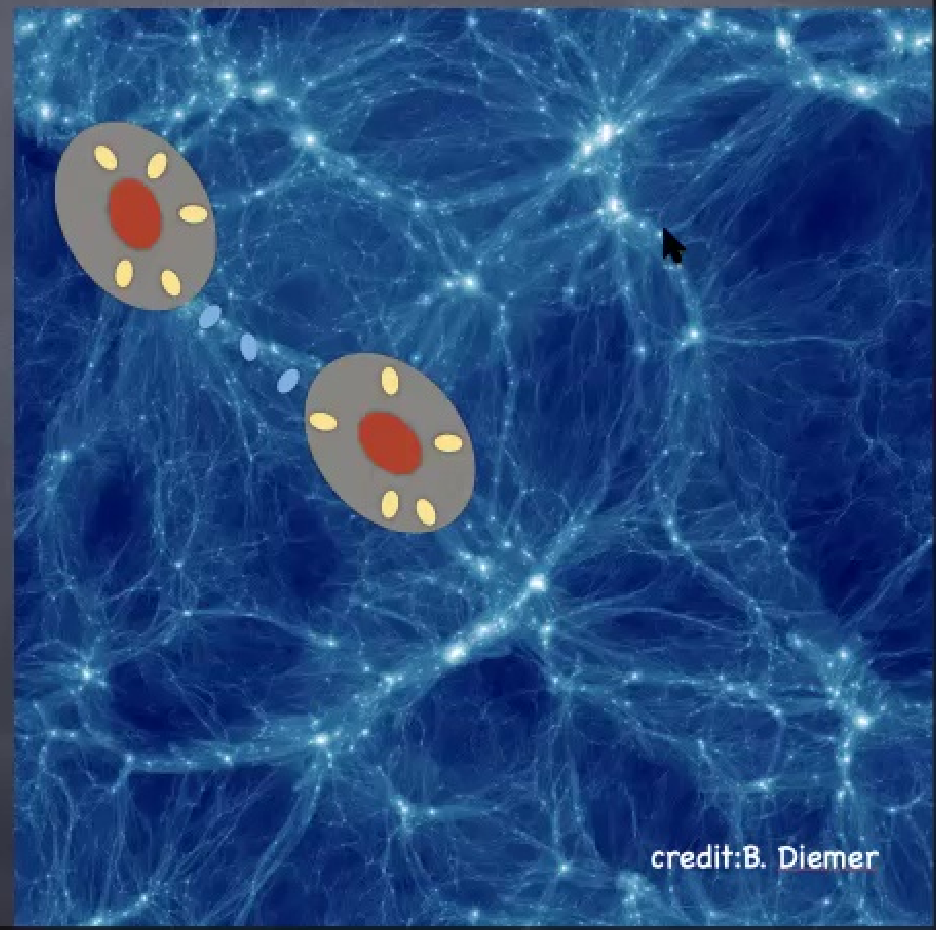
Jan 18th, 2021

Outline

- Intrinsic Alignment (IA)
  - Linear alignment model
  - 3D power spectrum of IA
- Imprint of the primordial non-Gaussianity (PNG) on galaxy clurstering
  - Galaxy bias in the Gaussian universe
  - Scale-dependent bias from the local-type PNG
- Imprint of angular-dependent PNG on IA

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
  - $\underbrace{\gamma_{ij}^{\mathrm{obs}} = \gamma_{ij}^{\mathrm{G}}}_{\text{WL}} + \underbrace{\gamma_{ij}^{\mathrm{I}}}_{\text{IA}} \quad \rightarrow \quad C_\ell^{\gamma\gamma} = C_\ell^{\mathrm{GG}} + \underbrace{C_\ell^{\mathrm{GI}} + C_\ell^{\mathrm{IG}} + C_\ell^{\mathrm{II}}}_{\text{Contaminations}}$
- New cosmological signal Today's talk

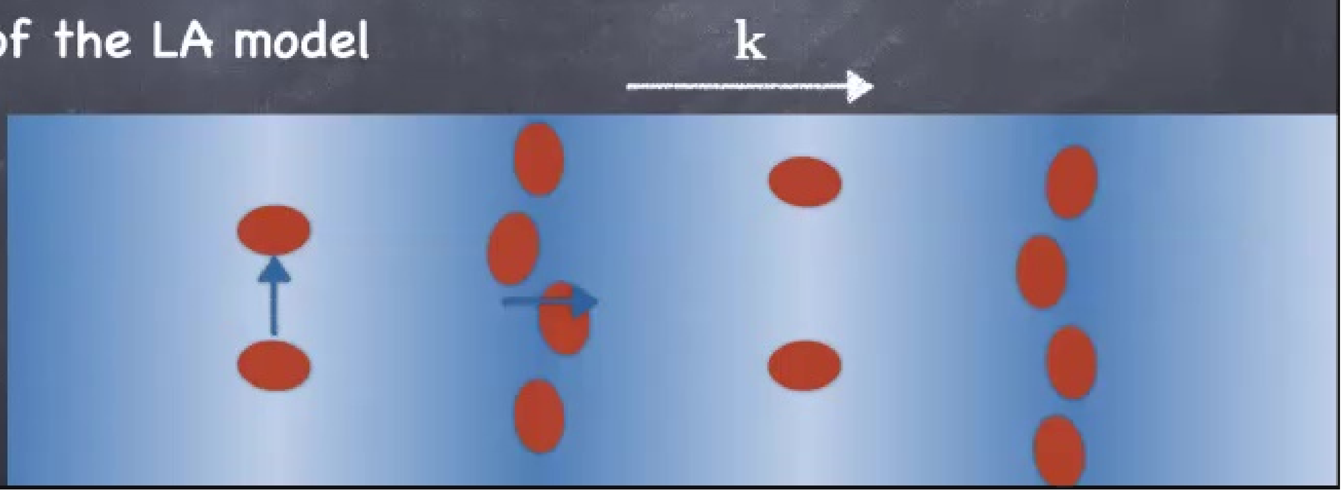
Tidal alignment (Linear alignment) model

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

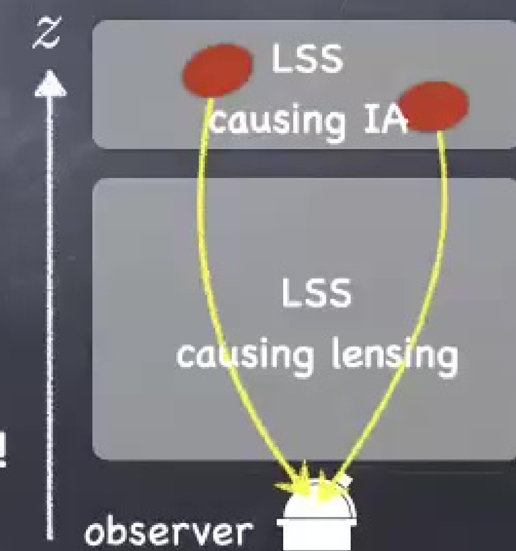
- Galaxy shape ~ Halo shape ~ Tidal field of large-scale structure
  - $\gamma_{ij}(\mathbf{x}) = b_K K_{ij}(\mathbf{x})$ w/ $K_{ij}(\mathbf{x}) = \left(\frac{\partial_i \partial_j}{\partial^2} - \frac{1}{3}\delta^{\mathrm{K}}_{ij}\right)\delta_{\mathrm{m}}(\mathbf{x}) \sim \left(\partial_i \partial_j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



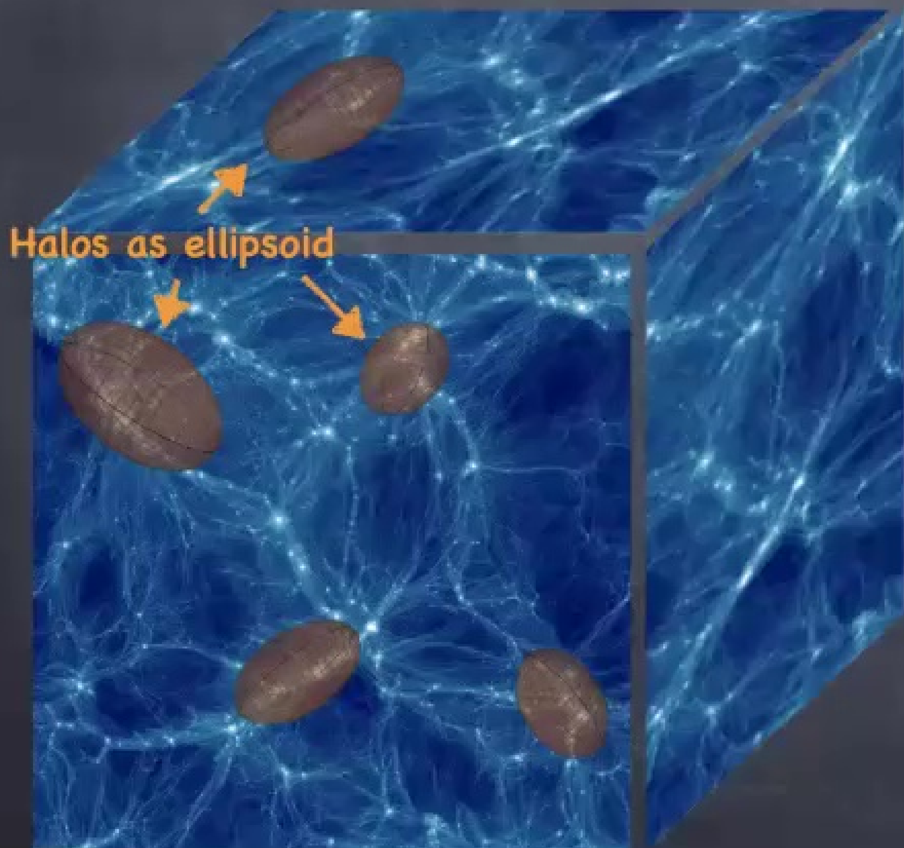
The shape-density correlation as a clean probe of IA

- How to extract IA signal from observed shapes?
  - $\gamma_{ij}^{\rm obs} = \gamma_{ij}^{\rm G} + \gamma_{ij}^{\rm I} + \gamma_{ij}^{\rm N}$

    WL (G term), IA (I term), Noise (N term)
  - lensing : LSS between us and source galaxy
  - IA : Tidal field (LSS) surrounding source galaxy
    - $\langle \gamma^{\rm obs}\gamma^{\rm obs}\rangle = \langle \gamma^{\rm G}\gamma^{\rm G}\rangle + 2\langle \gamma^{\rm G}\gamma^{\rm I}\rangle + \langle \gamma^{\rm I}\gamma^{\rm I}\rangle + \langle \gamma^{\rm N}\gamma^{\rm N}\rangle$
    - $\langle \gamma^{\rm obs}\delta_g\rangle = \langle \gamma^{\rm I}\delta_g\rangle \sim b_K b_1 \langle \delta_{\rm m}\delta_{\rm m}\rangle$
  - The shape-density correlation is suite for exploring IA!



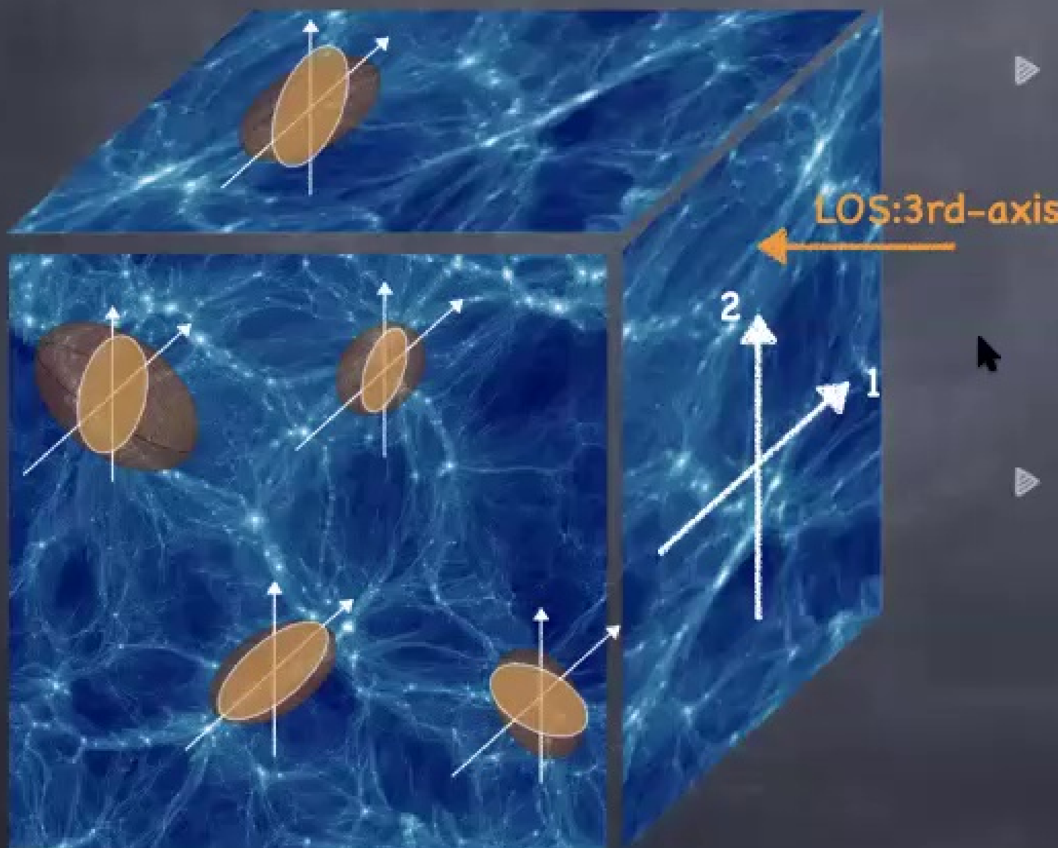
IA in N-body simulations



- L-Gadget2 & Rockstar
- Inertial tensor as halo shape:
  - $I_{ij} = \sum_{p \in \mathrm{halo}} w(|\Delta \boldsymbol{x}_p|)\Delta x_p^i \Delta x_p^j$
  - I_{ij} is the 3D shape tensor

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

Observable = 2D projected shape



- **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**
  - $\gamma_+ = \dfrac{I_{11} - I_{22}}{I_{11} + I_{22}} \qquad \gamma_\times = \dfrac{2I_{12}}{I_{11} + I_{22}}$
  - ${}_{\pm 2}\gamma(\boldsymbol{k}) = \gamma_+(\boldsymbol{k}) \pm i\gamma_\times(\boldsymbol{k})$

E/B decomposition of shape fields

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

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

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

$$\langle\delta_{\rm m}(\mathbf{k})E(\mathbf{k})\rangle,\ \langle\delta_{\rm h}(\mathbf{k})E(\mathbf{k})\rangle,\ \langle E(\mathbf{k})E(\mathbf{k})\rangle,\ \cdots$$

  - Linear theory prediction (linear alignment(LA) model) : $\gamma_{ij} = b_K K_{ij}$

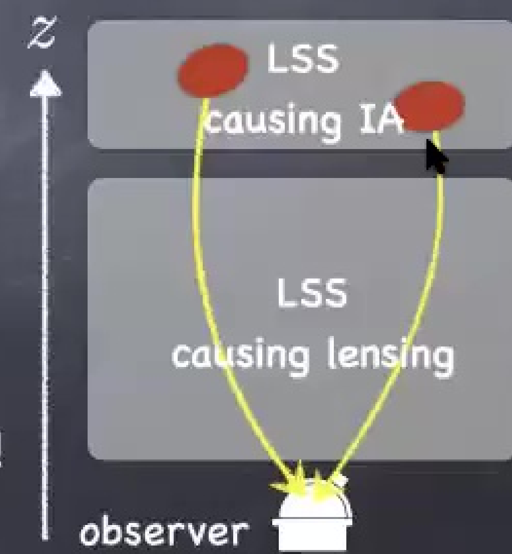
$$P_{{\rm m}E}(\mathbf{k}) = b_K(1-\mu^2)P_{\rm m}(k)$$
$$P_{EE}(\mathbf{k}) = b_K^2(1-\mu^2)^2P_{\rm m}(k)$$
$$(\mu = \hat{k}\cdot\hat{n})$$

cf. Kaiser formula:

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

The shape-density correlation as a clean probe of IA

- How to extract IA signal from observed shapes?
  - $\gamma_{ij}^{\mathrm{obs}} = \underbrace{\gamma_{ij}^{\mathrm{G}}}_{\text{WL}} + \underbrace{\gamma_{ij}^{\mathrm{I}}}_{\text{IA}} + \underbrace{\gamma_{ij}^{\mathrm{N}}}_{\text{Noise}}$
  - lensing : LSS between us and source galaxy
  - IA : Tidal field (LSS) surrounding source galaxy
    - $\langle \gamma^{\mathrm{obs}} \gamma^{\mathrm{obs}} \rangle = \langle \gamma^{\mathrm{G}} \gamma^{\mathrm{G}} \rangle + 2 \langle \gamma^{\mathrm{G}} \gamma^{\mathrm{I}} \rangle + \langle \gamma^{\mathrm{I}} \gamma^{\mathrm{I}} \rangle + \langle \gamma^{\mathrm{N}} \gamma^{\mathrm{N}} \rangle$
    - $\langle \gamma^{\mathrm{obs}} \delta_g \rangle = \langle \gamma^{\mathrm{I}} \delta_g \rangle \sim b_K b_1 \langle \delta_{\mathrm{m}} \delta_{\mathrm{m}} \rangle$
  - The shape-density correlation is suite for exploring IA!



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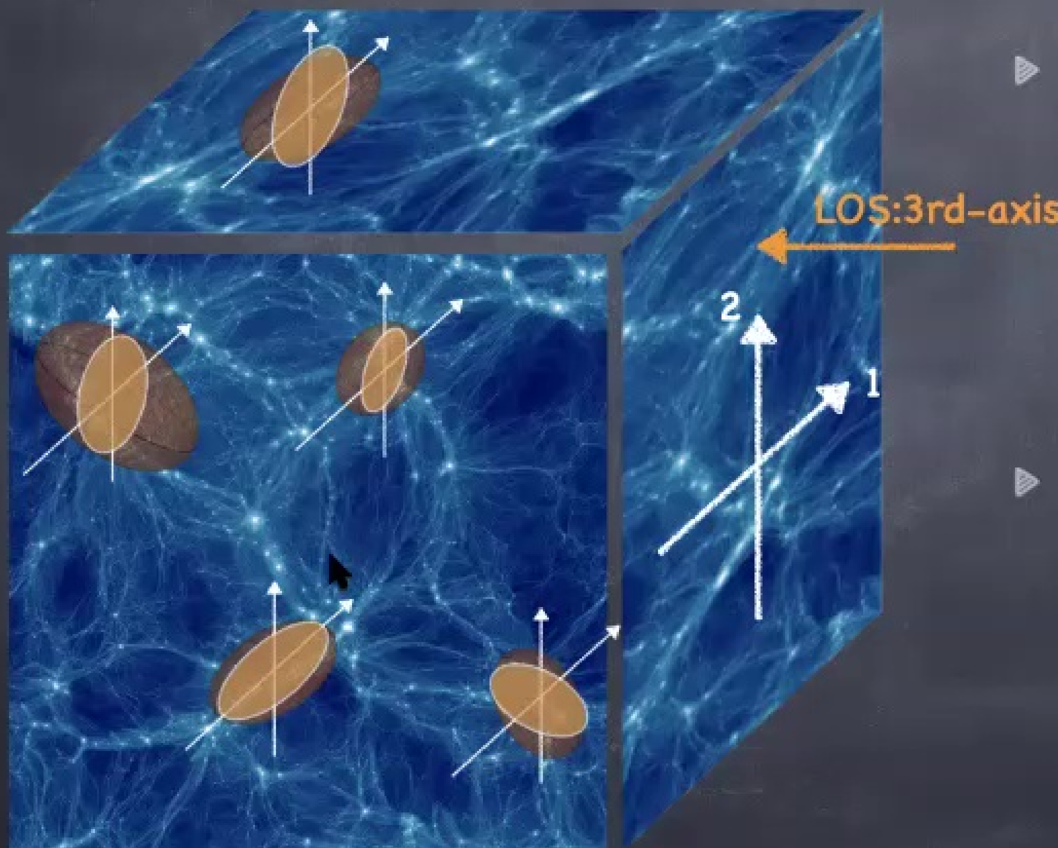

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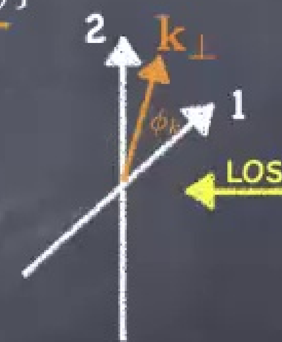

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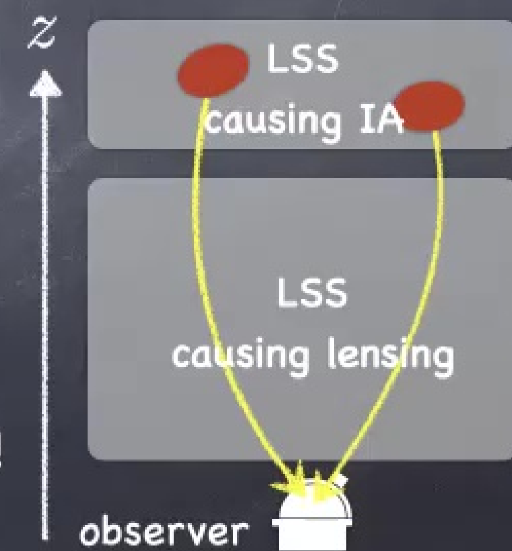
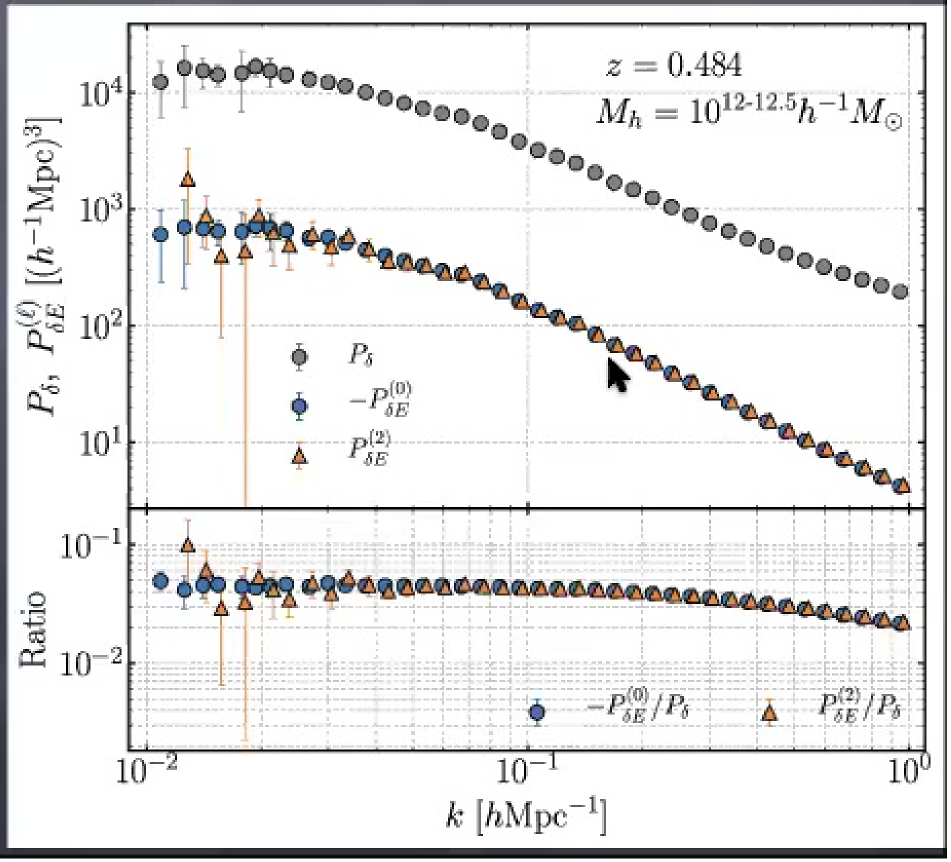


E-mode power spectra from N-body

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

What happens with PNG?

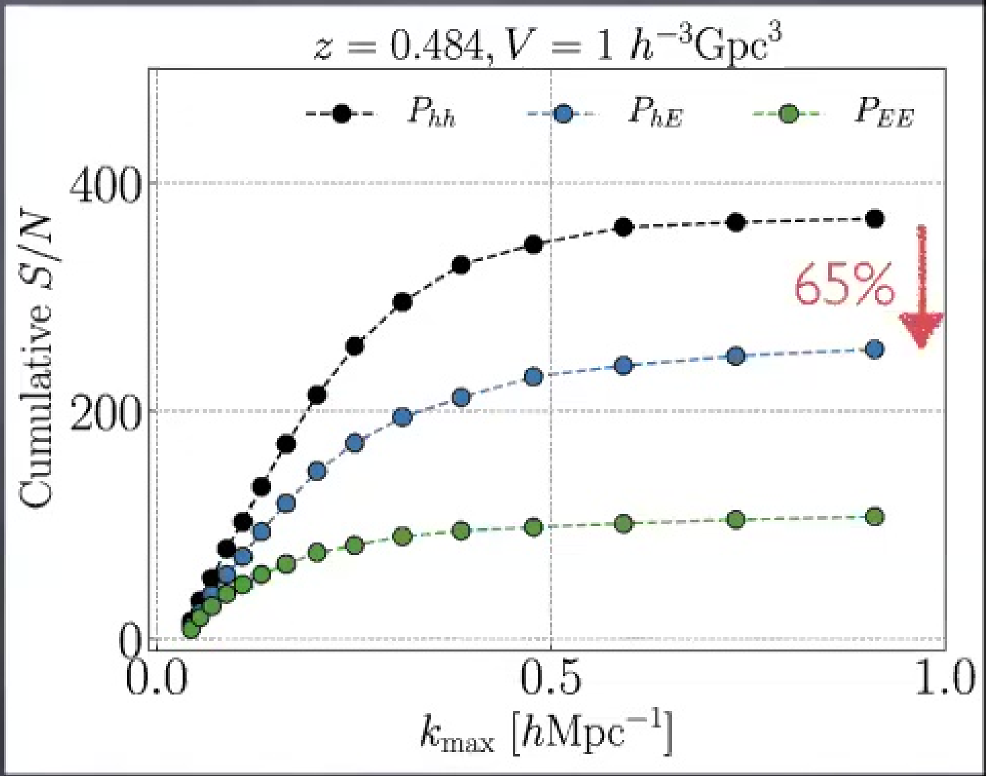


S/N of shape power spectrum

- S/N of P_{hE} 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: $1/\bar{n}_h, \quad \sigma_\gamma^2/n_h$

$$\sigma_\gamma^2 \sim 0.05$$

- For galaxies S/N can be decreased
  - misalignment Okumura+'09

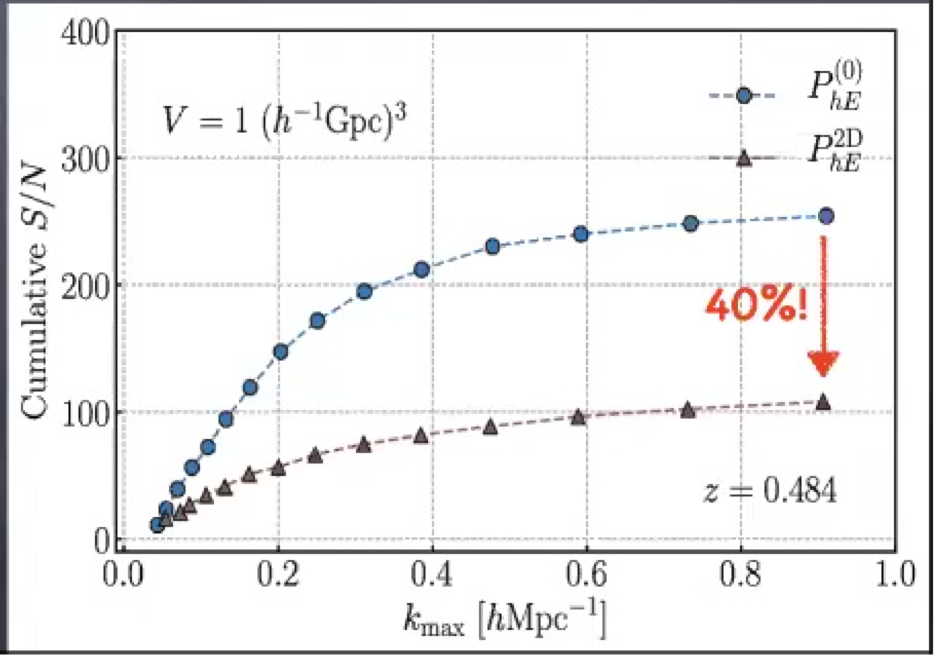


The importance of 3D power spectrum

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

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

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



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):

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

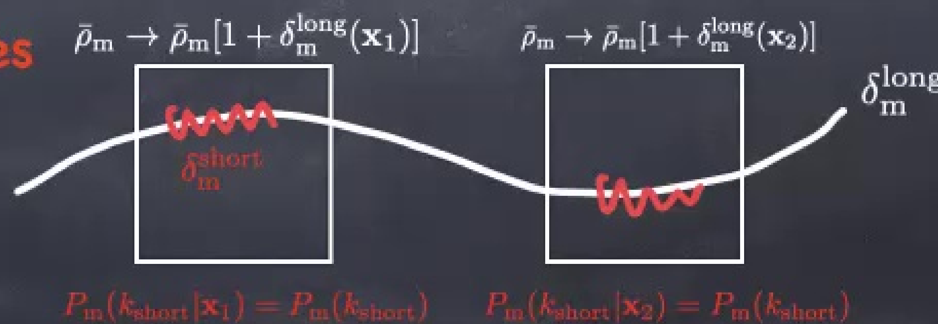
- PNG: the deviation from the Gaussianity (i.e. the standard inflation)
  - its leading order effect is characterized by the bispectrum (3pt function):

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

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

Halo/Galaxy bias in a nutshell

- What determines the halo/galaxy abundance in a local region?
  1. The local background matter density : $\bar{\rho}_{\rm m}^{\rm local}(\mathbf{x})$
  2. The amplitude of small-scale fluctuations : $P_{\rm m}(\mathbf{k}_{\rm short}|\mathbf{x})$
- In the standard cosmology (i.e. Gaussian&adiabatic ICs + GR)
  - $\bar{\rho}_{\rm m}^{\rm local}(\mathbf{x}) = \bar{\rho}_{\rm m}^{\rm global}\left[1+\delta_{\rm m}^{\rm long}(\mathbf{x})\right]$ while $P_{\rm m}(\mathbf{k}_{\rm short}|\mathbf{x}) = P_{\rm m}(\mathbf{k}_{\rm short})$
  - No correlation btw long-&short-modes
  - $b_1 = \dfrac{\mathrm{d}\ln \bar{n}_g}{\mathrm{d}\ln \bar{\rho}_{\rm m}} = \dfrac{\mathrm{d}\ln \bar{n}_g}{\mathrm{d}\delta_{\rm m}^{\rm long}}$
    - $\delta_g(\mathbf{k}_{\rm long}) = b_1\delta_{\rm m}(\mathbf{k}_{\rm long})$



Effect of PNG on galaxy number density

Dalal+'08

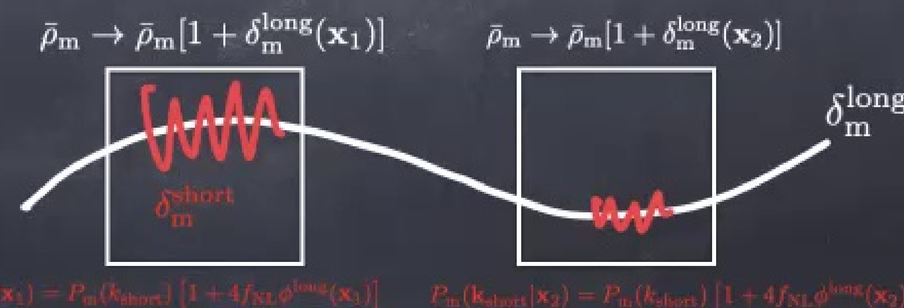
- What if there is the local-type PNG?
  - long-&short-modes are coupled-> the power spectrum is position-dependent.

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

  - Amplitudes of small-scale fluctuations at distant points are now correlated.
  - Now $\bar{\rho}_{\rm m}^{\rm local}(\mathbf{x}) = \bar{\rho}_{\rm m}^{\rm global}\left[1+\delta_{\rm m}^{\rm long}(\mathbf{x})\right]$ and $P_{\rm m}(k_{\rm short}|\mathbf{x}) = P_{\rm m}(k_{\rm short})\left[1+4f_{\rm NL}\phi^{\rm long}(\mathbf{x})\right]$
  - $b_\phi = \dfrac{{\rm d}\ln n_g}{{\rm d}\ln \mathcal{A}_s} = \dfrac{{\rm d}\ln n_g}{{\rm d}\ln \sigma_8} = \dfrac{{\rm d}\ln n_g}{{\rm d}(4f_{\rm NL}\phi^{\rm long})}$
    - $\delta_g(\mathbf{k}_{\rm long}) = b_1\delta_{\rm m}(\mathbf{k}_{\rm long}) + 4b_\phi f_{\rm NL}\phi(\mathbf{k}_{\rm long})$

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

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



Scale-dependent bias from the local-type PNG

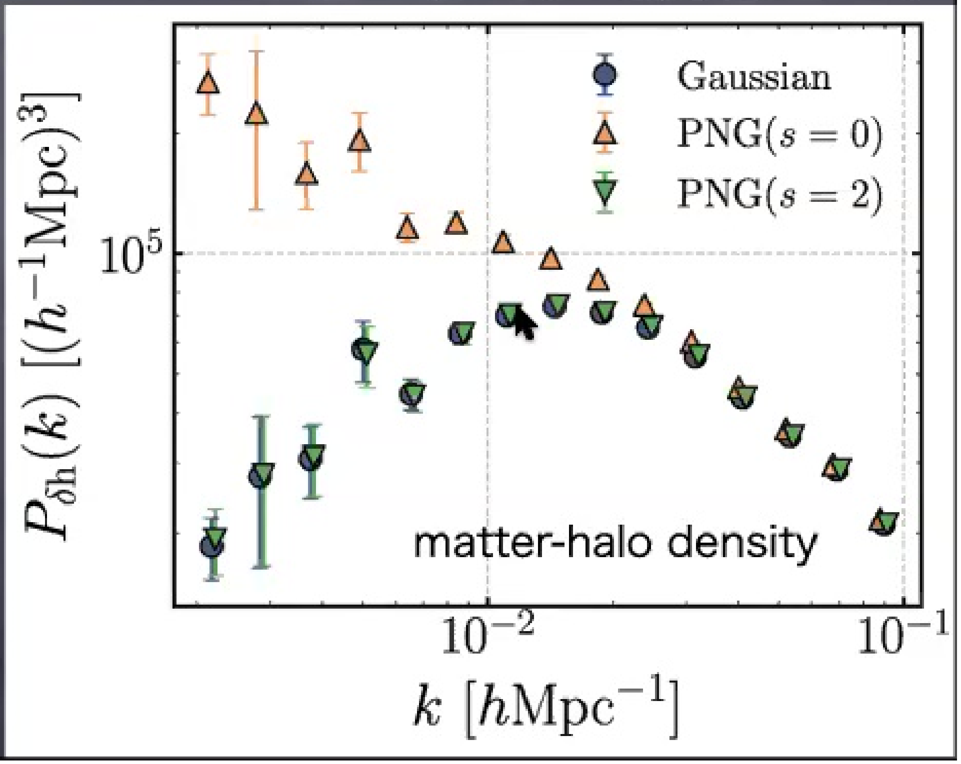
- There appears $1/k^2$ enhancement in galaxy/halo density field on large-scales.
- $\delta_g(\mathbf{k}) = \left[b_1 + 4b_\phi f_{\rm NL}\mathcal{M}^{-1}(k)\right]\delta_{\rm m}(\mathbf{k})$

  → $P_{{\rm m}g}(k) = \left[b_1 + 4b_\phi f_{\rm NL}\mathcal{M}^{-1}(k)\right]P_{\rm m}(k)$
- $\mathcal{M}^{-1}(k) \propto 1/k^2$ 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.Giannantonio+'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

- What determines the halo/galaxy intrinsic shapes in a local region?
    1. The local background **tidal** field: $K_{ij}(\mathbf{x}) = \left(\frac{\partial_i\partial_j}{\partial^2} - \frac{1}{3}\delta^{\rm K}_{ij}\right)\delta_{\rm m}(\mathbf{x}) \sim \left(\partial_i\partial_j - \frac{1}{3}\delta^{\rm K}_{ij}\partial^2\right)\Phi(\mathbf{x})$
    2. The amplitude of small-scale **tidal** fluctuations: anisotropy in $P_{\rm m}(\mathbf{k}_{\rm short}|\mathbf{x})$
- Standard (Gaussian&Adiabatic ICs + GR) term: $b_K = \frac{{\rm d}\gamma_{ij}}{{\rm d}K_{ij}} \to \gamma_{ij}(\mathbf{k}_{\rm long}) = b_K K_{ij}(\mathbf{k}_{\rm long})$
- 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 $\psi^{\rm long}_{ij} \equiv \frac{3}{2}\left[\frac{\partial_i\partial_j}{\partial^2} - \frac{1}{3}\delta^{\rm K}_{ij}\right]\phi^{\rm long}$
    - $b_\psi = \frac{{\rm d}\gamma_{ij}}{{\rm d}(4f_{\rm NL}^{s=2}\psi_{ij}^{\rm long})}$
        - $\gamma_{ij}(\mathbf{k}_{\rm long}) = b_K K_{ij}(\mathbf{k}_{\rm long}) + 4b_\psi f_{\rm NL}^{s=2}\psi_{ij}(k_{\rm long})$
        $= \left[b_K + 6b_\psi f_{\rm NL}^{s=2}\mathcal{M}^{-1}(k_{\rm long})\right]K_{ij}(\mathbf{k}_{\rm long})$

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: $L = 4.096\ {\rm Gpc}/h,\ N_{\rm p} = 2048^3$
  - $(f_{\rm NL}^{s=0}, f_{\rm NL}^{s=2}) = (0,0)\ ,\ (500,0)\ ,\ (0,500)$

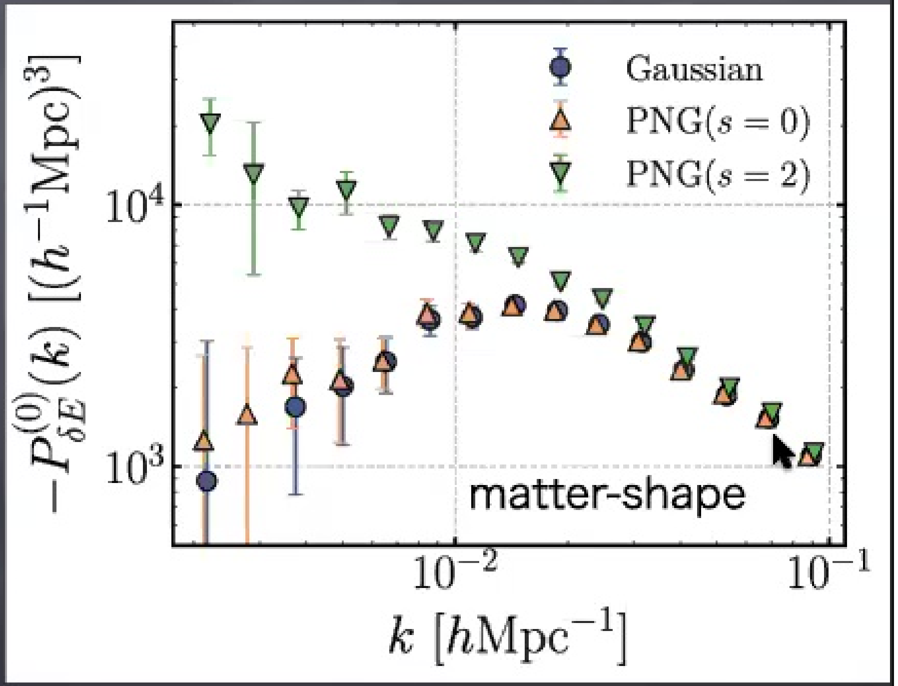
Scale-dependent bias in the IA power spectrum

KA+'20a

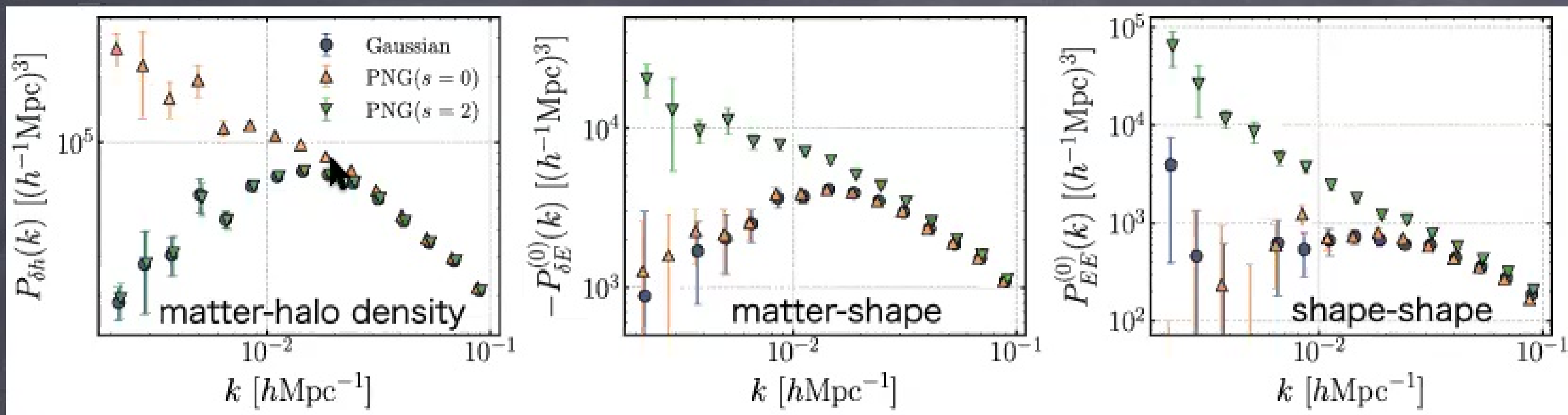
- There appears $1/k^2$ enhancement in galaxy/halo shape field on large-scales.
- $\gamma_{ij}(\mathbf{k}_{\rm long}) = \left[b_K + 6 b_\psi f_{\rm NL}^{s=2} \mathcal{M}^{-1}(k_{\rm long})\right] K_{ij}(\mathbf{k}_{\rm long})$

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

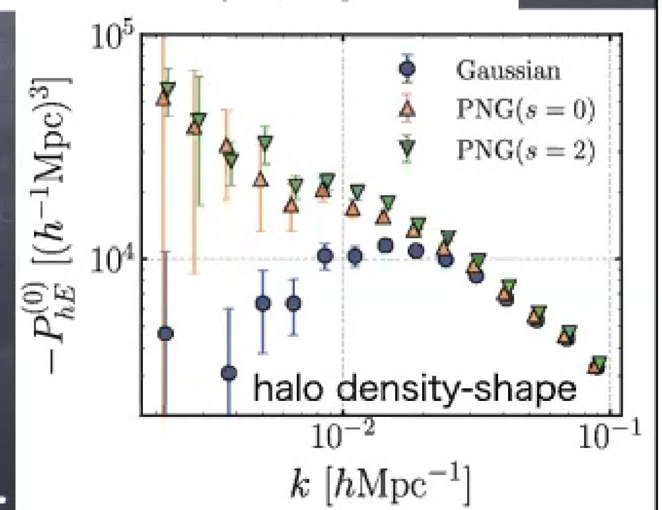
  $\delta_{\rm m}(\mathbf{k}) \sim k^2 \phi(\mathbf{k})$ from Poisson eq.
- The angular-independent PNG has no impact on shape field, i.e. $P_{{\rm m}E}$ & P_{EE}
- The angular-dependent PNG has no impact on density field, i.e. $P_{\rm mh}$ & $P_{\rm hh}$



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_{hE} is affected by both angular-independent&-dependent PNGs
  - P_{hh} responds to only the angular-independent PNG.



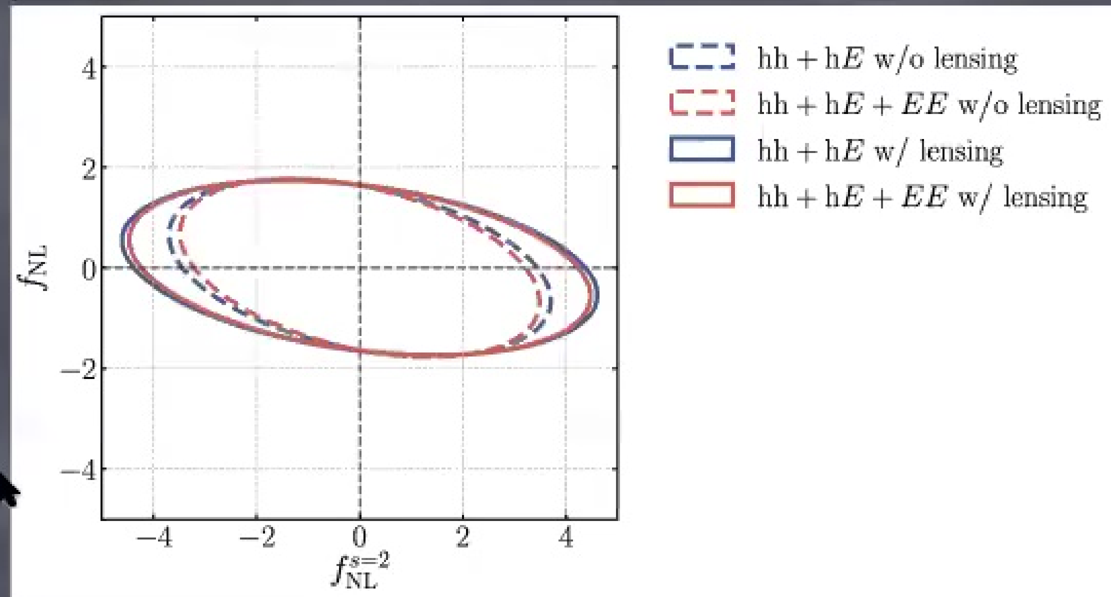
Summary of imprint of various PNGs

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

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

Forecast

- Using both $P_{\rm hh}$ & $P_{\rm h\it E}$
  - $V_{\rm survey} = 69\ ({\rm Gpc}/h)^3$
  - $M_{\rm h} > 10^{13} M_{\odot}/h,\ \bar{n}_{\rm h} = 2.9 \times 10^{-4}\ ({\rm Mpc}/h)^3$
- The current CMB constraints:
  $\sigma(f_{\rm NL}^{s=2}) \simeq 19$
  Planck2018

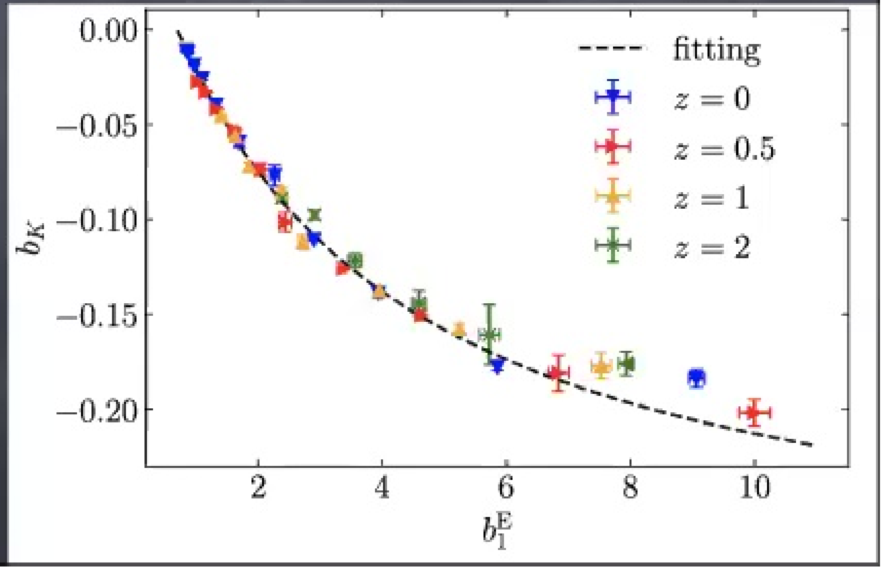


- We need both photo&spec surveys
  - Projected (2D) shapes: photometric survey
  - 3D position of galaxies: spectroscopic survey

Challenge of IA cosmology

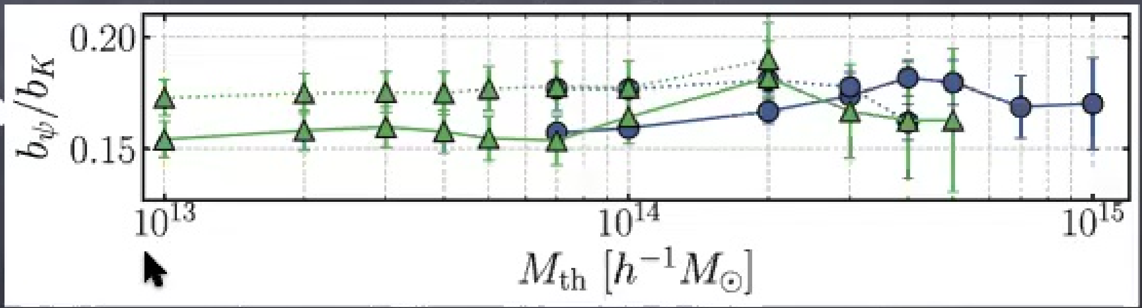
- Complete degenerary between b_ψ and $f_{\rm NL}^{s=2}$ $\quad P_{{\rm m}E}(k) = \left[b_K + 6b_\psi f_{\rm NL}^{s=2}\mathcal{M}^{-1}(k)\right]P_{\rm m}(k)$
  - Density case: $P_{{\rm m}g}(k) = \left[b_1 + 4b_\phi f_{\rm NL}\mathcal{M}^{-1}(k)\right]P_{\rm m}(k)$
    - From peak theory: $b_\phi = 2\delta_{\rm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

KA+'20b



Challenge of IA cosmology

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



Extension to even higher spins

Kogai, KA+'20

- l-th moment of galaxy shape

$$\gamma_{i_1 i_2 \cdots i_\ell}(\mathbf{x}) = \frac{1}{\bar{B} R_*^\ell} \int_{y \le R_*} \mathrm{d}^3\boldsymbol{y}\; y_{i_1} y_{i_2} \cdots y_{i_\ell} B(\mathbf{x}+\mathbf{y})$$ rank-l symmetric tensor

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

Arkani-Hamed&Maldacena'15

- l-th shape moment has only two independent spin components

$$\pm\ell\gamma = m_\mp^{i_1} m_\mp^{i_2} \cdots m_\mp^{i_\ell} \gamma_{i_1 i_2 \cdots i_\ell}$$

Extension to even higher spins

Kogai, KA+'20

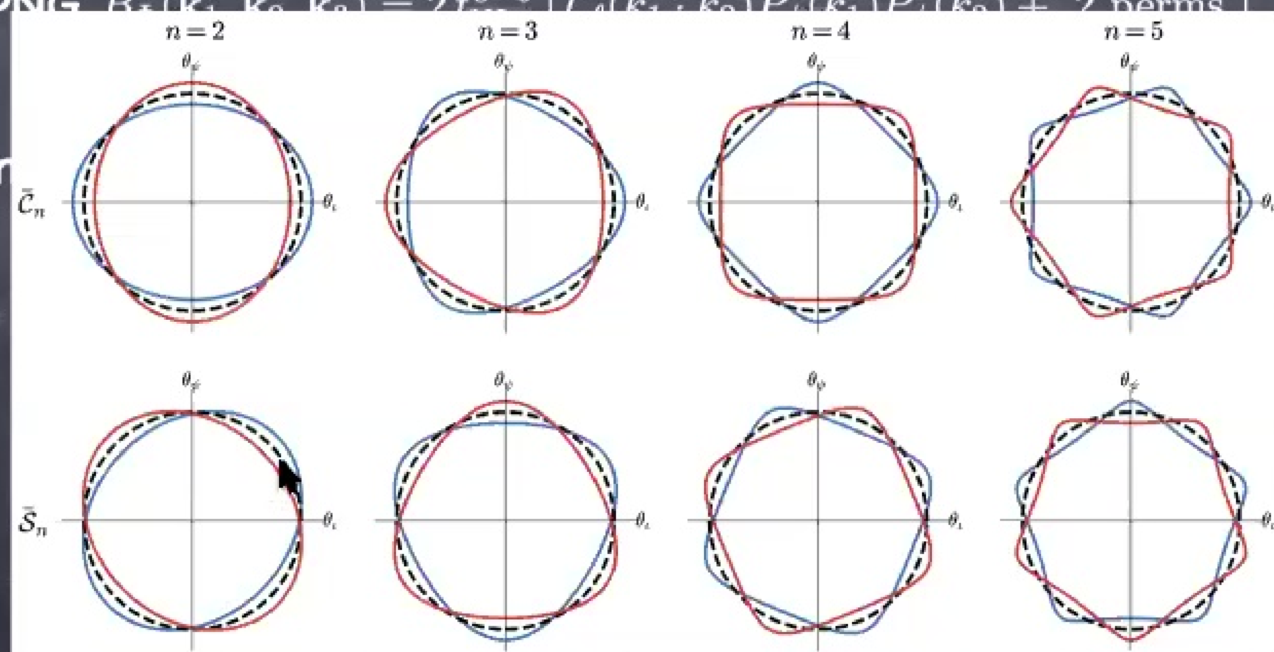
- l-th moment of galaxy shape $\gamma_{i_1 i_2 \cdots i_\ell}(\mathbf{x}) = \frac{1}{\bar{B} R_*^\ell} \int_{y \le R_*} \mathrm{d}^3 y \; y_{i_1} y_{i_2} \cdots y_{i_\ell} B(\mathbf{x}+\mathbf{y})$

  rank-l symmetric tensor

  responds to only s=l PNG $B_\delta(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = 2 f_{\mathrm{NL}}^{s=\ell} \left[\mathcal{L}_\ell(\hat{k}_1 \cdot \hat{k}_2) P_\phi(k_1) P_\phi(k_2) + 2 \text{ perms} \right]$

- l-th shape moment has or

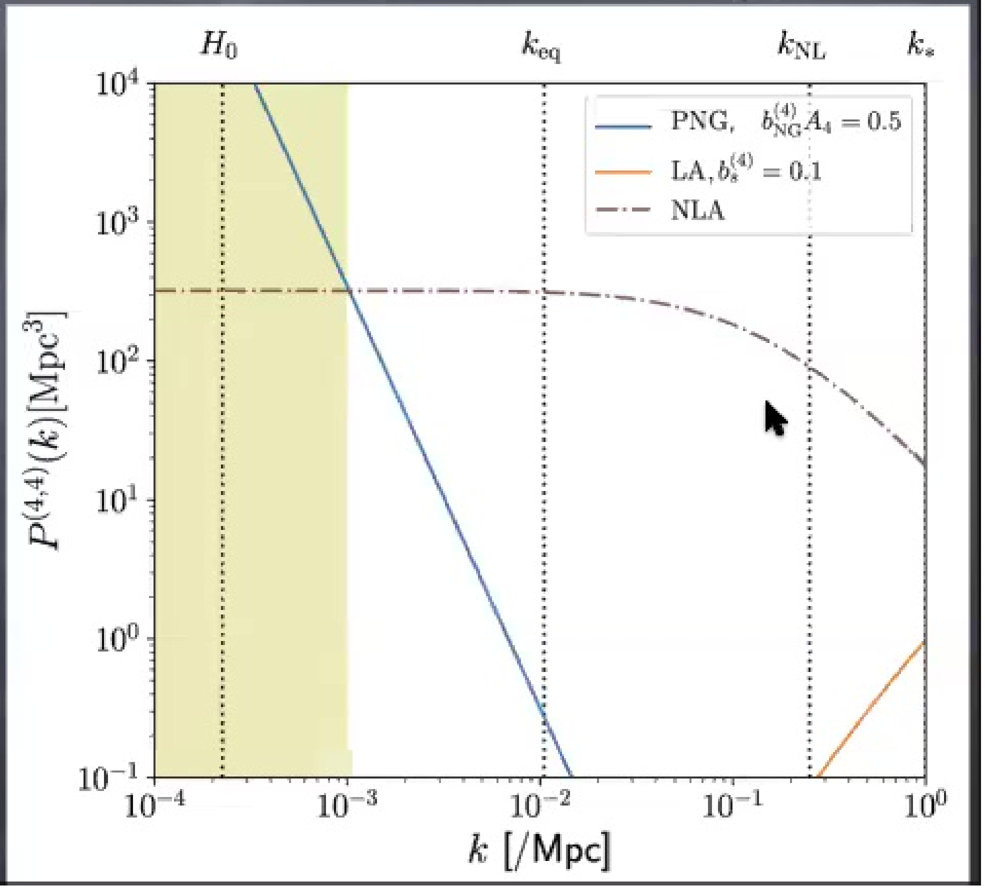
  $_{\pm\ell}\gamma = m_{\mp}^{i_1} m_{\mp}^{i_2} \cdots m_{\mp}^{i_\ell} \gamma_{i_1 i_2 \cdots i_\ell}$



Extension to even higher spins

Kogai, KA+'20

- For 4th moment, no linear term on large scales.
- Uncertainty of shape noise



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
- Extension to higher shape moments Kogai&KA+'20
- Future: theory for the shape bias, including bispectrum information, etc.

Forecast

- Using both $P_{\rm hh}$ & $P_{{\rm h}E}$
  - $V_{\rm survey} = 69\ ({\rm Gpc}/h)^3$
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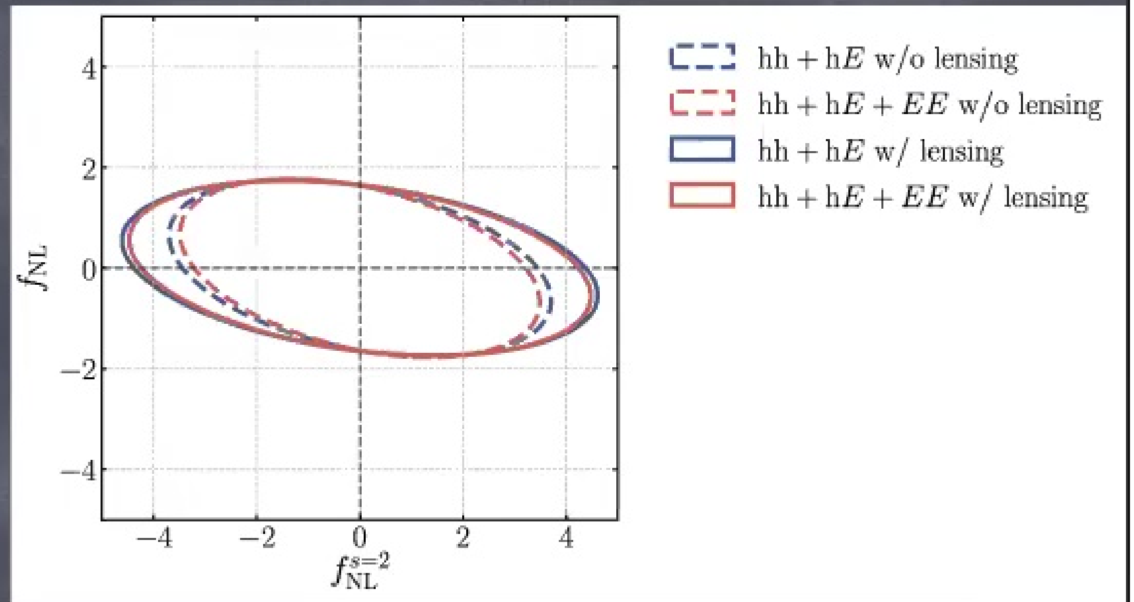

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  - Projected (2D) shapes: photometric survey
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