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

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based on arXiv:2007.03670

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Outline

- Intrinsic Alignment (IA)
  - Linear alignment model
- 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

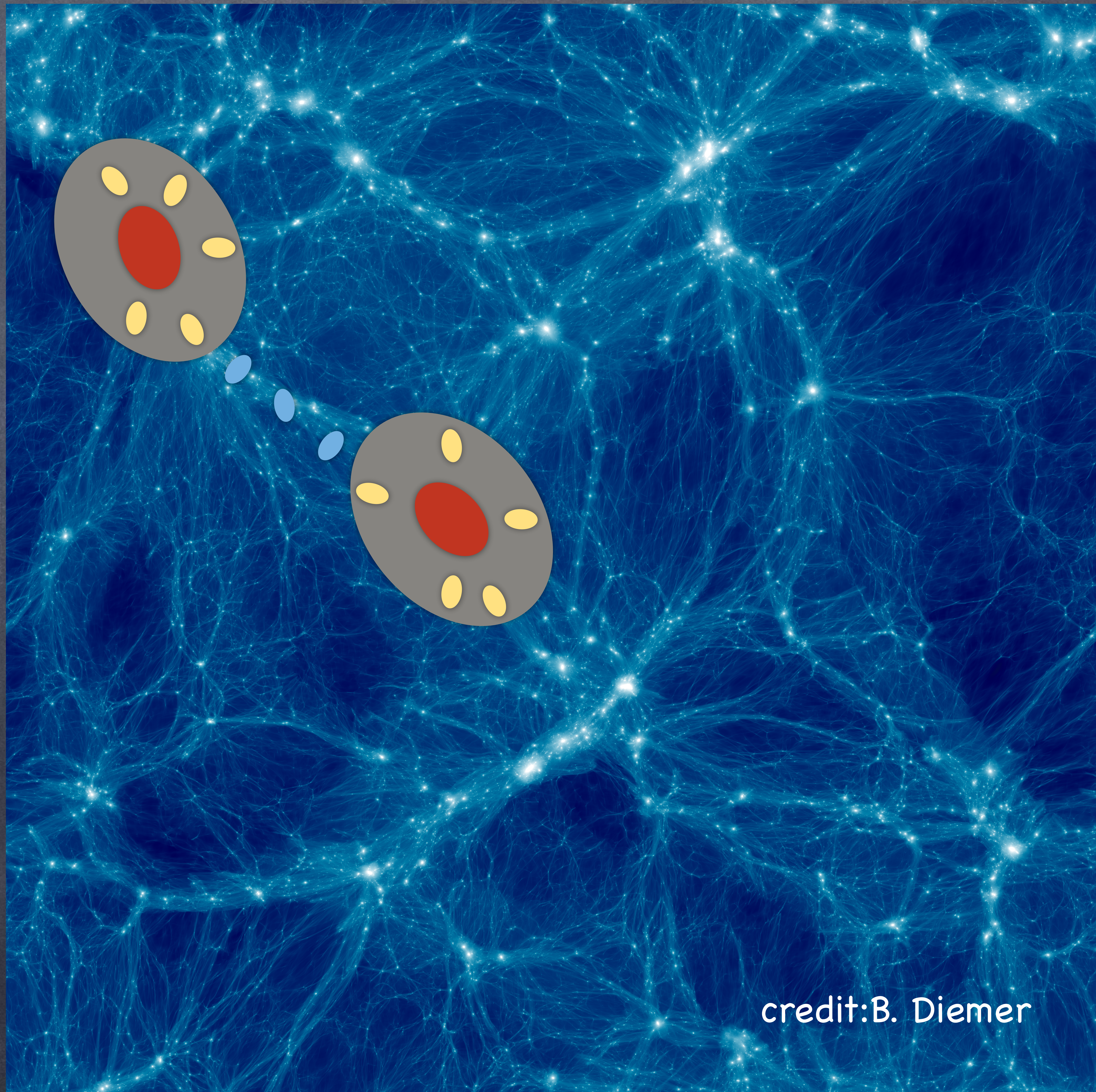
Halo/galaxy clusters

Central galaxy shape

- Red galaxies
- Shape $\sim$ halo shape
- Tidal alignment

Satellite galaxy

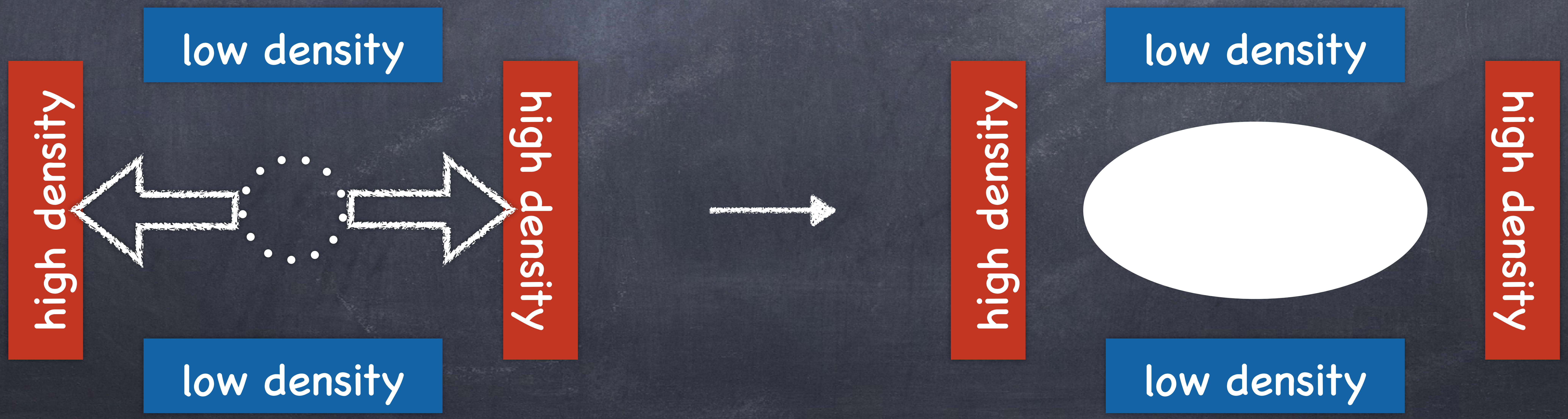
Galaxy on filaments



Tidal alignment (Linear alignment) model

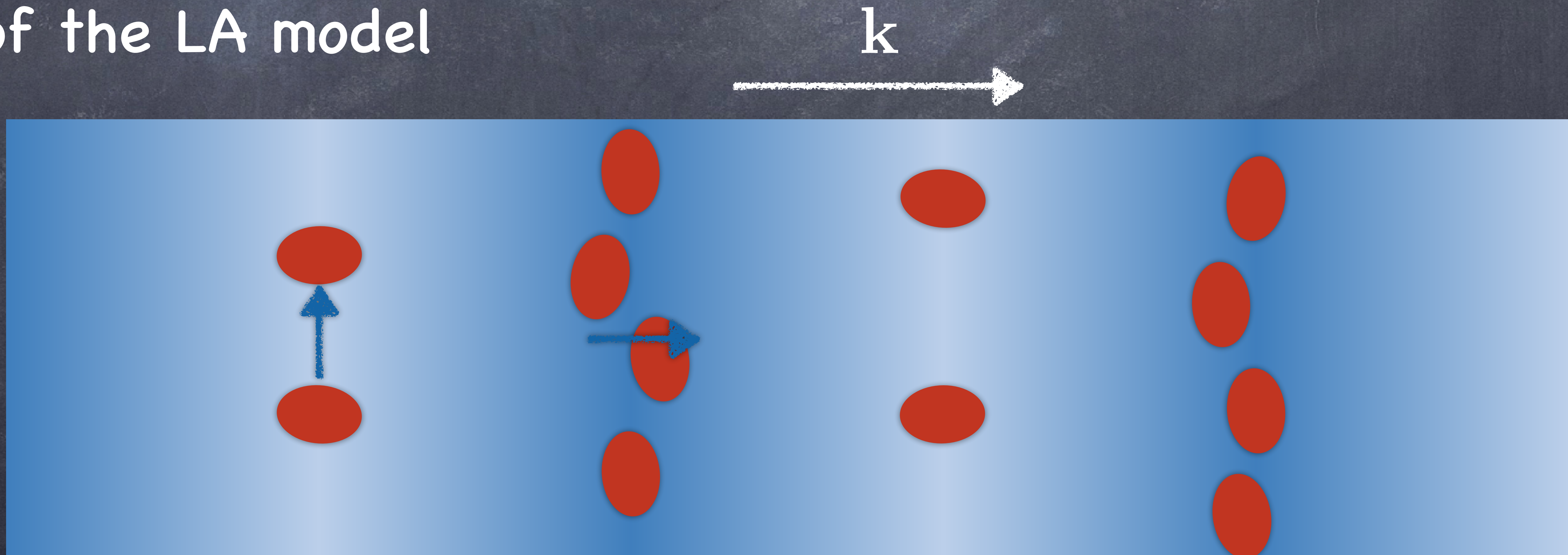
Catelan+ '00, Hirata&Seljak '04

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



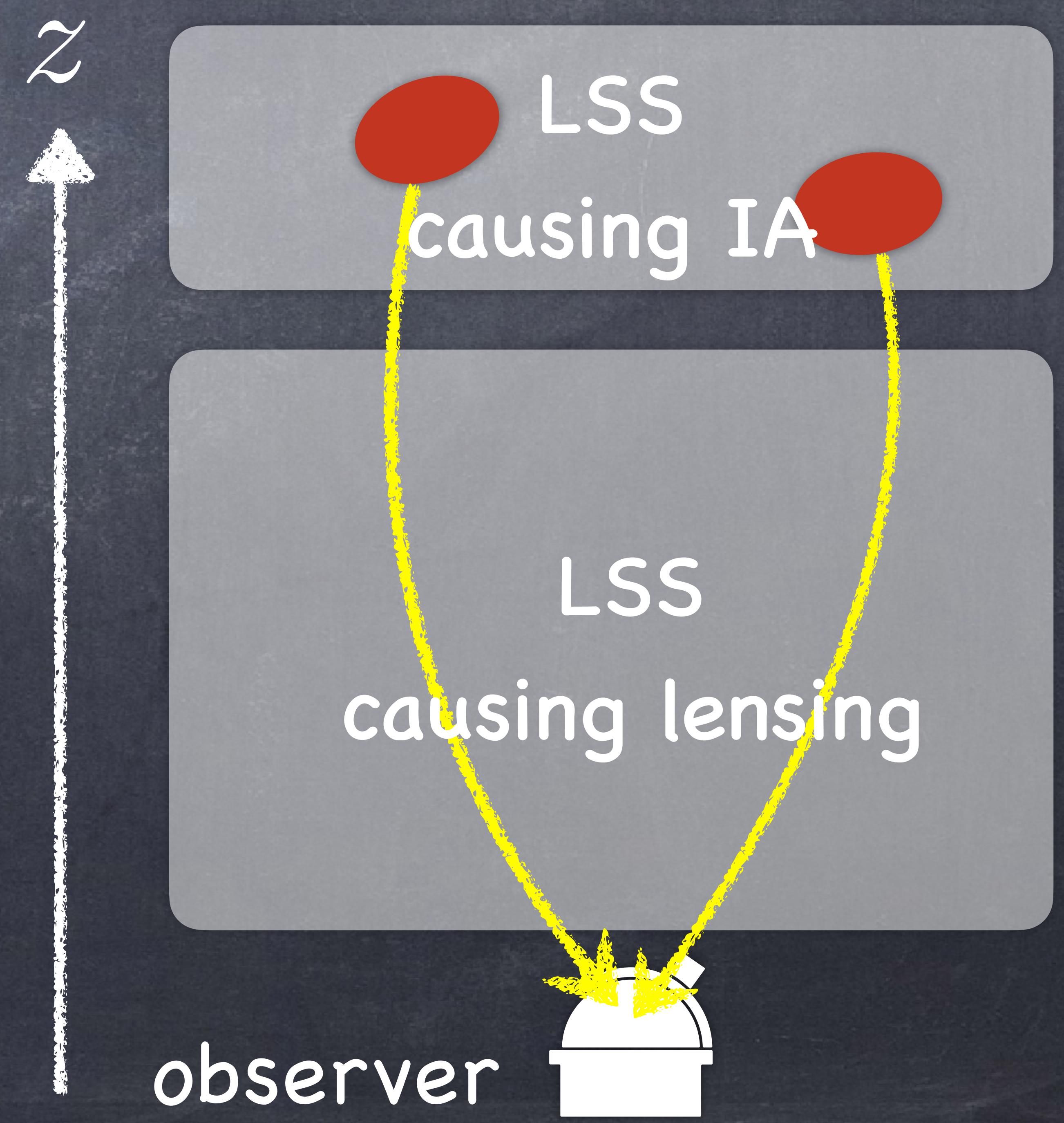
shape as a biased tracer of tidal fields

- 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

- Intrinsic alignment(IA): galaxy shape correlation before lensing distortions
  - Galaxy shape ~ lensing + intrinsic alignment + noise(random)
  - lensing : Large-scale structure (LSS) between us and source galaxy
  - IA : Tidal field (LSS) surrounding source galaxy
    - $\langle \gamma\gamma \rangle = \langle \gamma_{\rm lens}\gamma_{\rm lens} \rangle + \langle \gamma_{\rm IA}\gamma_{\rm IA} \rangle + \langle \gamma_{\rm noise}\gamma_{\rm noise} \rangle$
    - $\langle \gamma\delta_g \rangle = \langle \gamma_{\rm IA}\delta_g \rangle \sim b_K b_1 \langle \delta_{\rm m}\delta_{\rm m} \rangle$



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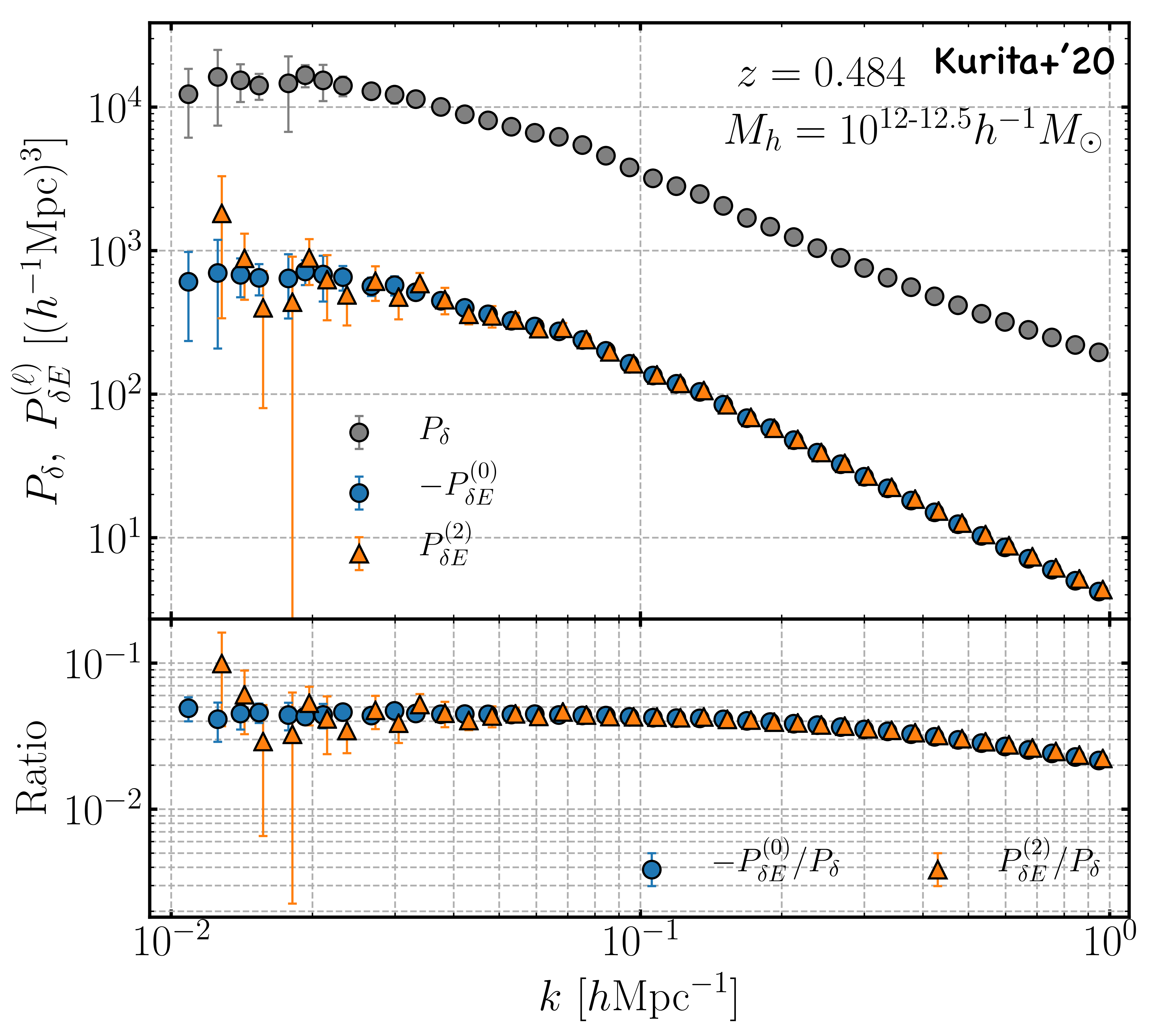


Primordial non-Gaussianity (PNG)

- The primordial perturbation 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

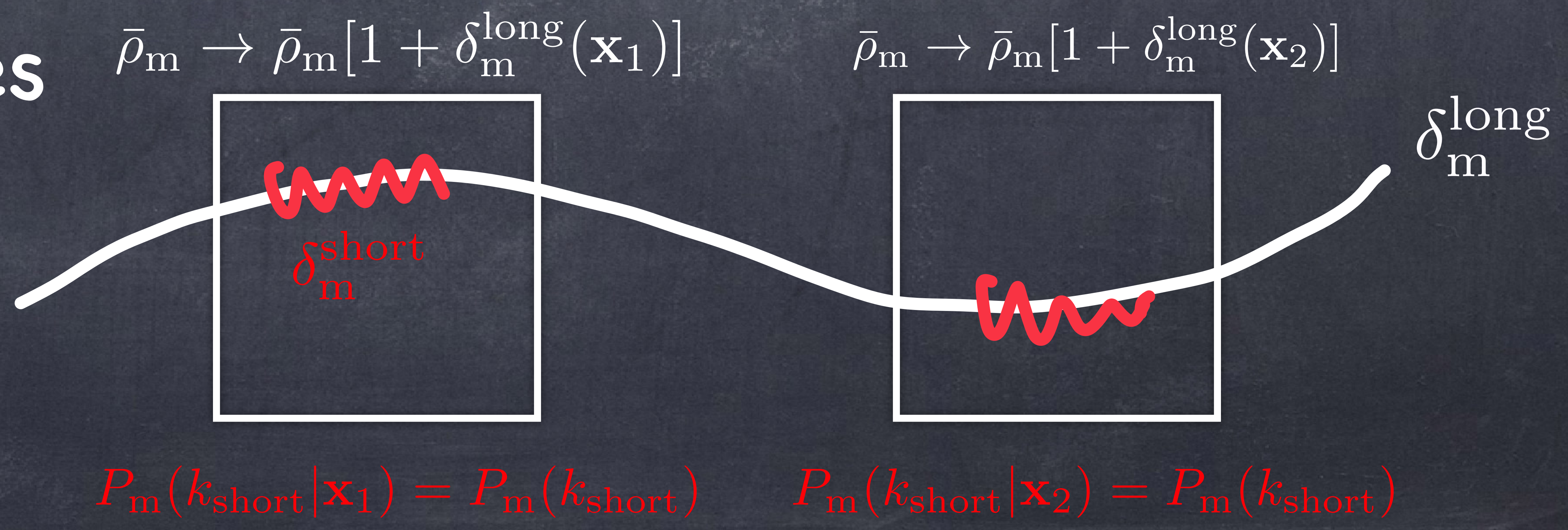
- PNG: the deviation from the Gaussianity (i.e. the standard inflation)
  - its leading order effect is characterized by the bispectrum (3pt function):

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

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

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
  - $b_1 = \dfrac{{\rm d}\ln \bar{n}_g}{{\rm d}\ln \bar{\rho}_{\rm m}} = \dfrac{{\rm d}\ln \bar{n}_g}{{\rm d}\delta_{\rm m}^{\rm long}}$
    - $\delta_g(\mathbf{k}_{\rm long}) = b_1 \delta_{\rm m}(\mathbf{k}_{\rm long})$



Effect of PNG on galaxy number density

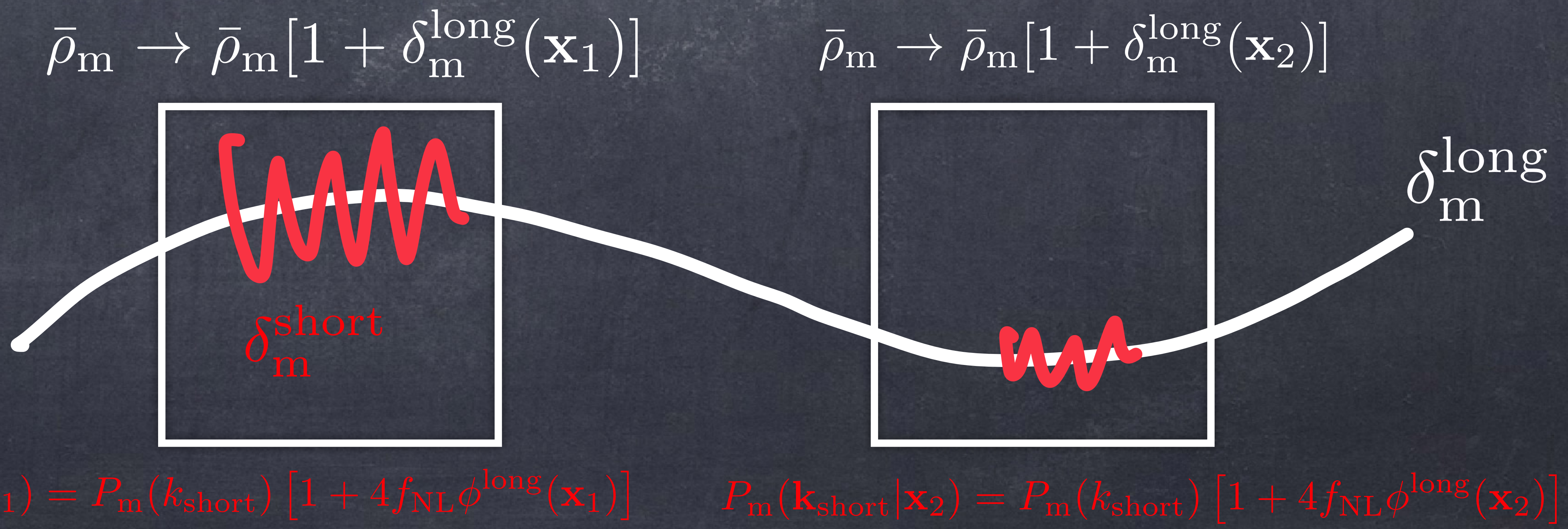
Dalal+'08

- 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 $P_{\rm m}(k_{\rm short}|\mathbf{x}) = P_{\rm m}(k_{\rm short})\left[1+4f_{\rm NL}\phi^{\rm long}(\mathbf{x})\right]$
  - $b_\phi = \dfrac{{\rm d}\ln n_g}{{\rm d}\ln \mathcal{A}_s} = \dfrac{{\rm d}\ln n_g}{{\rm d}\ln \sigma_8} = \dfrac{{\rm d}\ln n_g}{{\rm d}(4f_{\rm NL}\phi^{\rm long})}$
    - $$\begin{aligned}\delta_g(\mathbf{k}_{\rm long}) &= b_1\delta_{\rm m}(\mathbf{k}_{\rm long}) + 4b_\phi f_{\rm NL}\phi(\mathbf{k}_{\rm long}) \\ &= \left[b_1 + 4b_\phi f_{\rm NL}\mathcal{M}^{-1}(k_{\rm long})\right]\delta_{\rm m}(\mathbf{k}_{\rm long})\end{aligned}$$

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



Scale-dependent bias from the local-type PNG

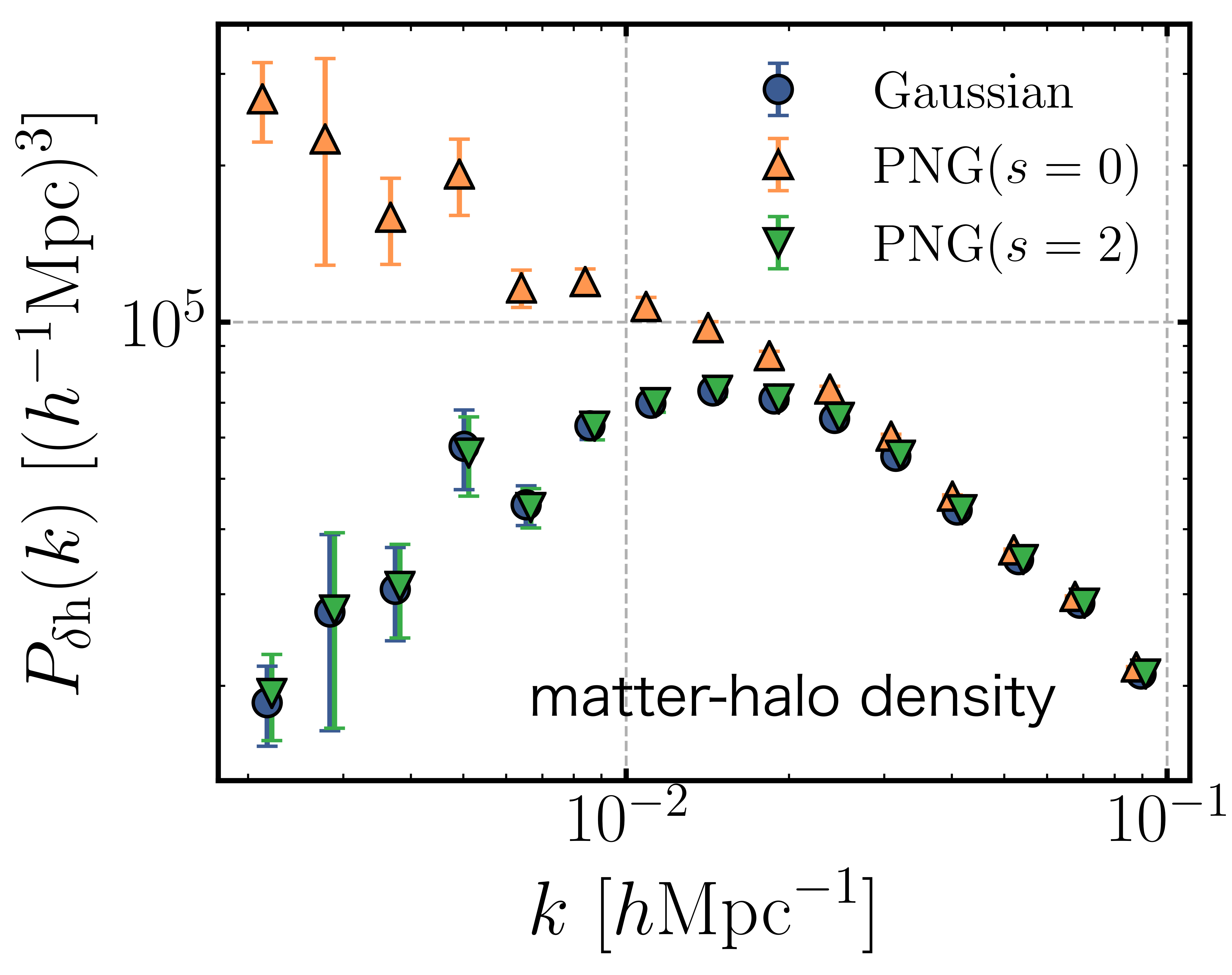
- There appears $1/k^2$ enhancement in galaxy/halo density field on large-scales.
- $\delta_g(\mathbf{k}) = \left[b_1 + 4b_\phi f_{\rm NL}\mathcal{M}^{-1}(k)\right]\delta_{\rm m}(\mathbf{k})$

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

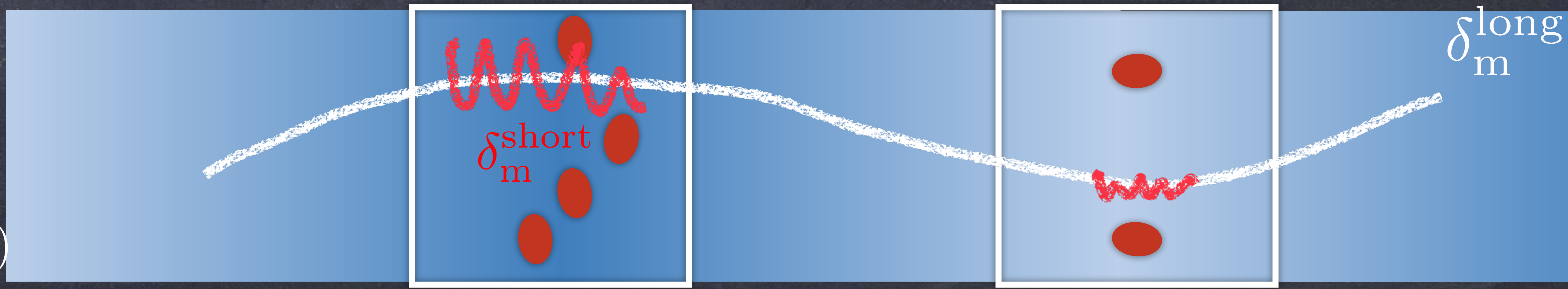
- The quadrupole local-type PNG: $B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = 2 f_{\rm NL}^{s=2} \left[\mathcal{L}_2(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2) P_\Phi(\mathbf{k}_1) P_\Phi(\mathbf{k}_2) + \text{ 2 perms.}\right]$
  - cf. the usual local-type PNG: $B_\Phi(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = 2 f_{\rm NL}\left[P_\Phi(\mathbf{k}_1) P_\Phi(\mathbf{k}_2) + 2 \text{ perms.}\right]$
  - 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: $K_{ij}(\mathbf{x}) = \left(\frac{\partial_i \partial_j}{\partial^2} - \frac{1}{3}\delta^{\mathrm{K}}_{ij}\right)\delta_{\mathrm{m}}(\mathbf{x}) \sim \left(\partial_i\partial_j - \frac{1}{3}\delta^{\mathrm{K}}_{ij}\partial^2\right)\Phi(\mathbf{x})$
    2. The amplitude of small-scale **tidal** fluctuations: anisotropy in $P_{\mathrm{m}}(\mathbf{k}_{\mathrm{short}}|\mathbf{x})$
- Standard (Gaussian&Adiabatic ICs + GR) term: $b_K = \frac{\mathrm{d}\gamma_{ij}}{\mathrm{d}K_{ij}} \to \gamma_{ij}(\mathbf{k}_{\mathrm{long}}) = b_K K_{ij}(\mathbf{k}_{\mathrm{long}})$
- Angular-dependent PNG -> small-scale tidal fluctuations are correlated
    - $P_{\mathrm{m}}(\mathbf{k}_{\mathrm{short}}|\mathbf{x}) = P_{\mathrm{m}}(k_{\mathrm{short}})\left[1 + 4 f_{\mathrm{NL}}^{s=2}\sum_{ij}\psi^{\mathrm{long}}_{ij}(\mathbf{x})\hat{k}^i_{\mathrm{short}}\hat{k}^j_{\mathrm{short}}\right]$ with $\psi^{\mathrm{long}}_{ij} \equiv \frac{3}{2}\left[\frac{\partial_i\partial_j}{\partial^2} - \frac{1}{3}\delta^{\mathrm{K}}_{ij}\right]\phi^{\mathrm{long}}$
    - $b_\psi = \frac{\mathrm{d}\gamma_{ij}}{\mathrm{d}(4 f_{\mathrm{NL}}^{s=2}\psi^{\mathrm{long}}_{ij})}$
        - $\gamma_{ij}(\mathbf{k}_{\mathrm{long}}) = b_K K_{ij}(\mathbf{k}_{\mathrm{long}}) + 4 b_\psi f_{\mathrm{NL}}^{s=2}\psi_{ij}(k_{\mathrm{long}})$
          $= \left[b_K + 6 b_\psi f_{\mathrm{NL}}^{s=2}\mathcal{M}^{-1}(k_{\mathrm{long}})\right] K_{ij}(\mathbf{k}_{\mathrm{long}})$



PNG ICs & simulations

KA+'20

- 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

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

Measurements

- The halo shape is defined by its inertia tensor: $\gamma_{ij} = \sum_p w(r_p)\Delta x_p^i \Delta x_p^j$
- The observable shape is not 3D, but the projected one (2D)
  - $$\gamma_{ij}^{\rm 3D} = \begin{pmatrix} \gamma_{xx} & \gamma_{xy} & \gamma_{xz} \\ \gamma_{yx} & \gamma_{yy} & \gamma_{yz} \\ \gamma_{xz} & \gamma_{yz} & \gamma_{zz} \end{pmatrix} \xrightarrow[\text{with LOS=z}]{\text{Projected onto xy plane}} \gamma_{ij}^{\rm 2D} = \begin{pmatrix} \gamma_{xx} & \gamma_{xy} & 0 \\ \gamma_{yx} & \gamma_{yy} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$
  - 2D shear fields: $\gamma_+ = \gamma_{xx} - \gamma_{yy},\ \gamma_\times = 2\gamma_{xy}$
  - spin-2 fields can be decomposed into E/B fields

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

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

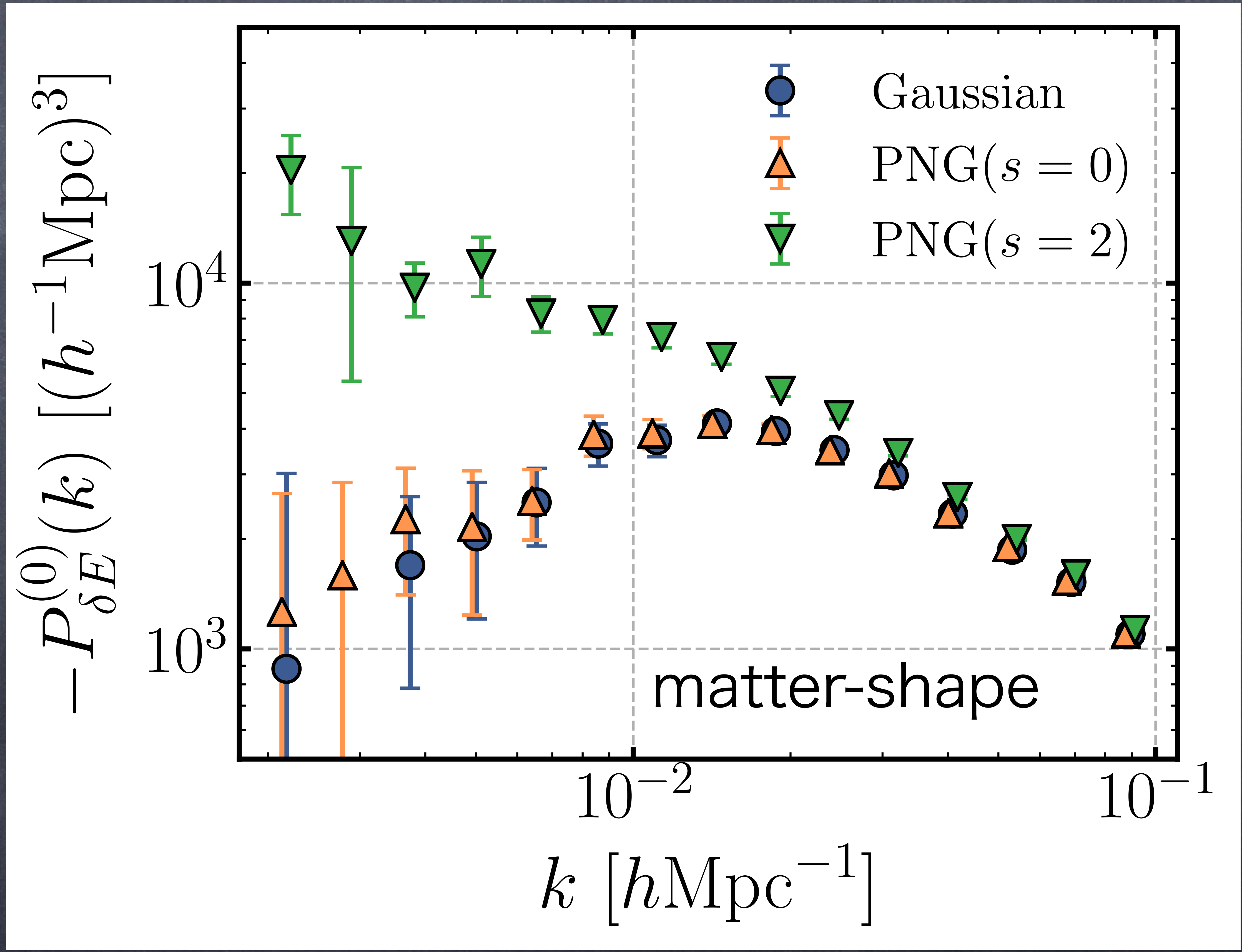
Scale-dependent bias in the IA power spectrum

KA+'20

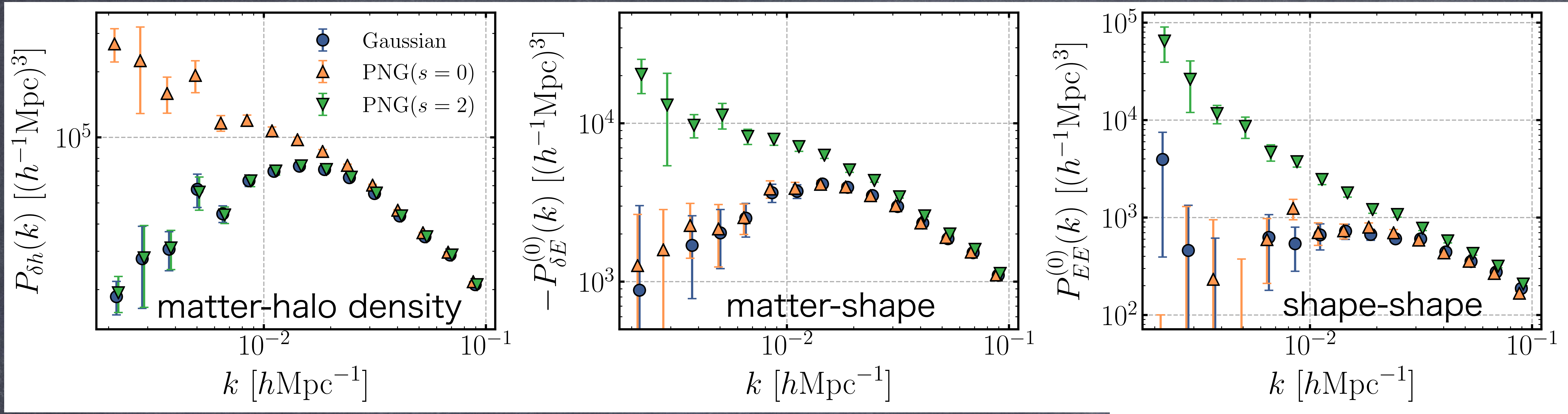
- There appears $1/k^2$ enhancement in galaxy/halo shape field on large-scales.
- $\gamma_{ij}(\mathbf{k}_{\rm long}) = \left[b_K + 6b_\psi f_{\rm NL}^{s=2}\mathcal{M}^{-1}(k_{\rm long})\right] K_{ij}(\mathbf{k}_{\rm long})$

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

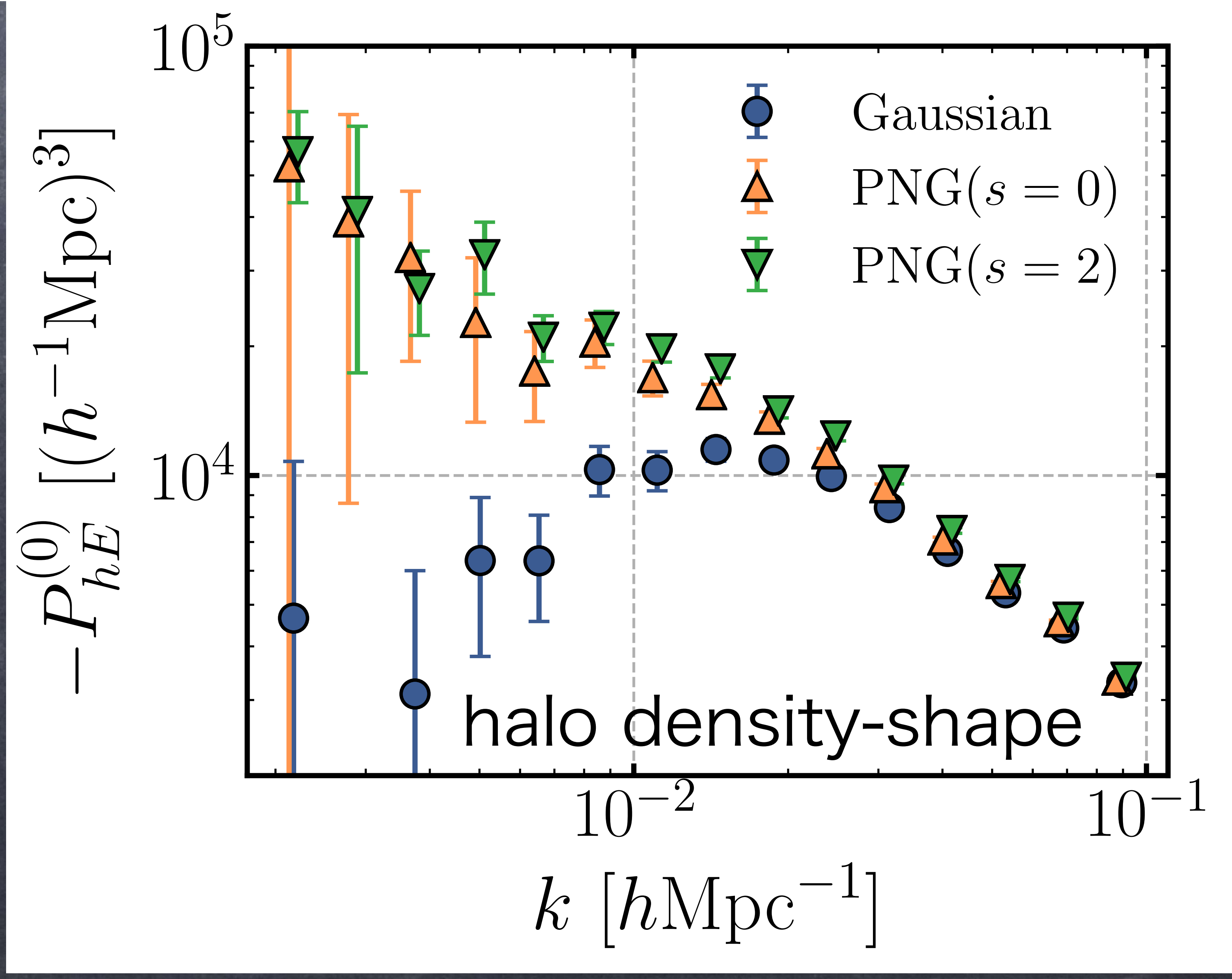
  $\delta_{\rm m}(\mathbf{k}) \sim k^2\phi(\mathbf{k})$ from Poisson eq.
- The angular-independent PNG has no impact on shape field, i.e. $P_{{\rm m}E}$ & P_{EE}
- The angular-dependent PNG has no impact on density field, i.e. $P_{\rm mh}$ & $P_{\rm hh}$



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.

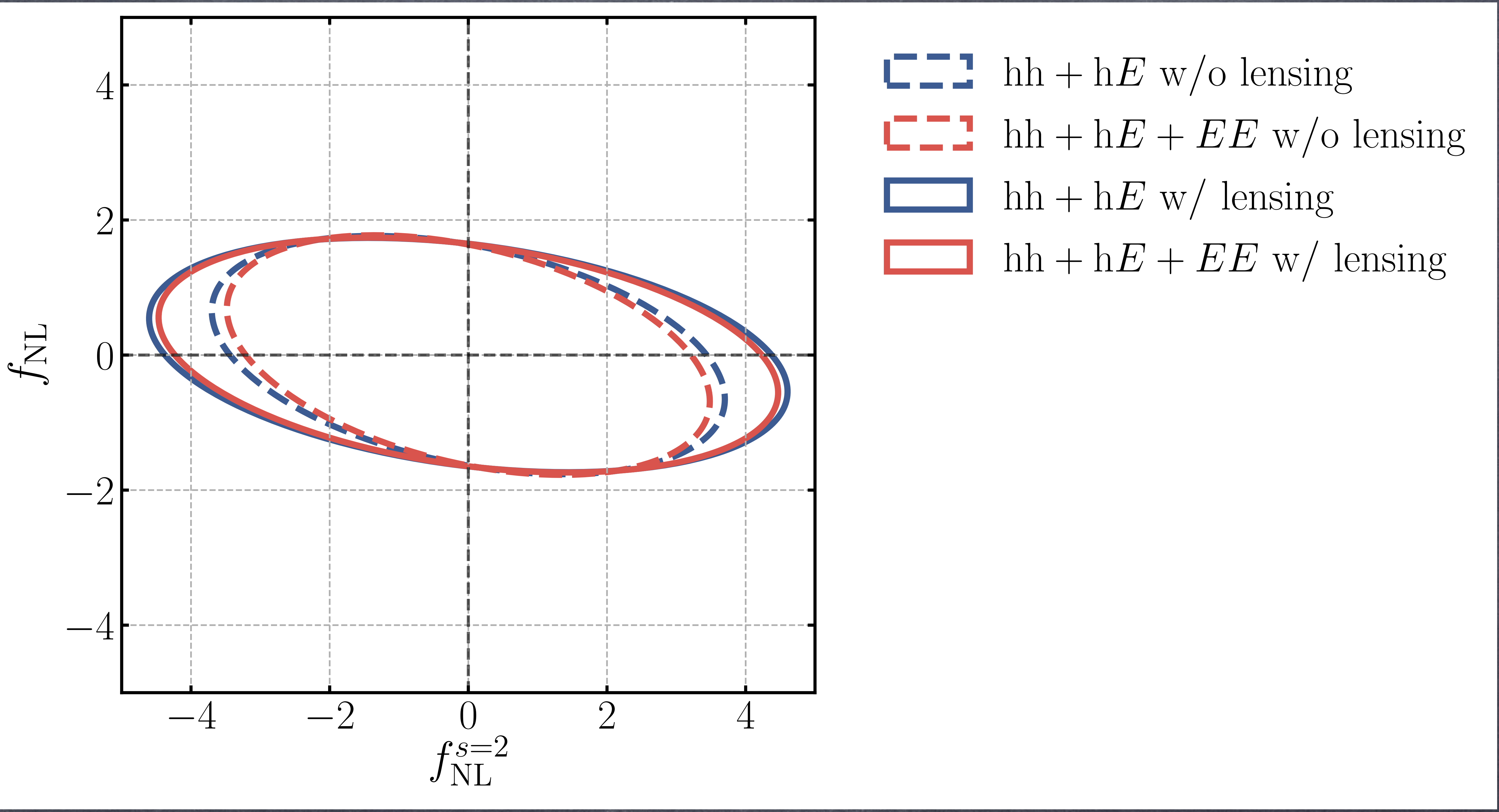


Forecast

- 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

Summary

- 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 works: including bispectrum information, scale-dependent PNG, etc.