Imprint of gravitational waves on large-scale structure in simulations

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Large-scale structure and GWs

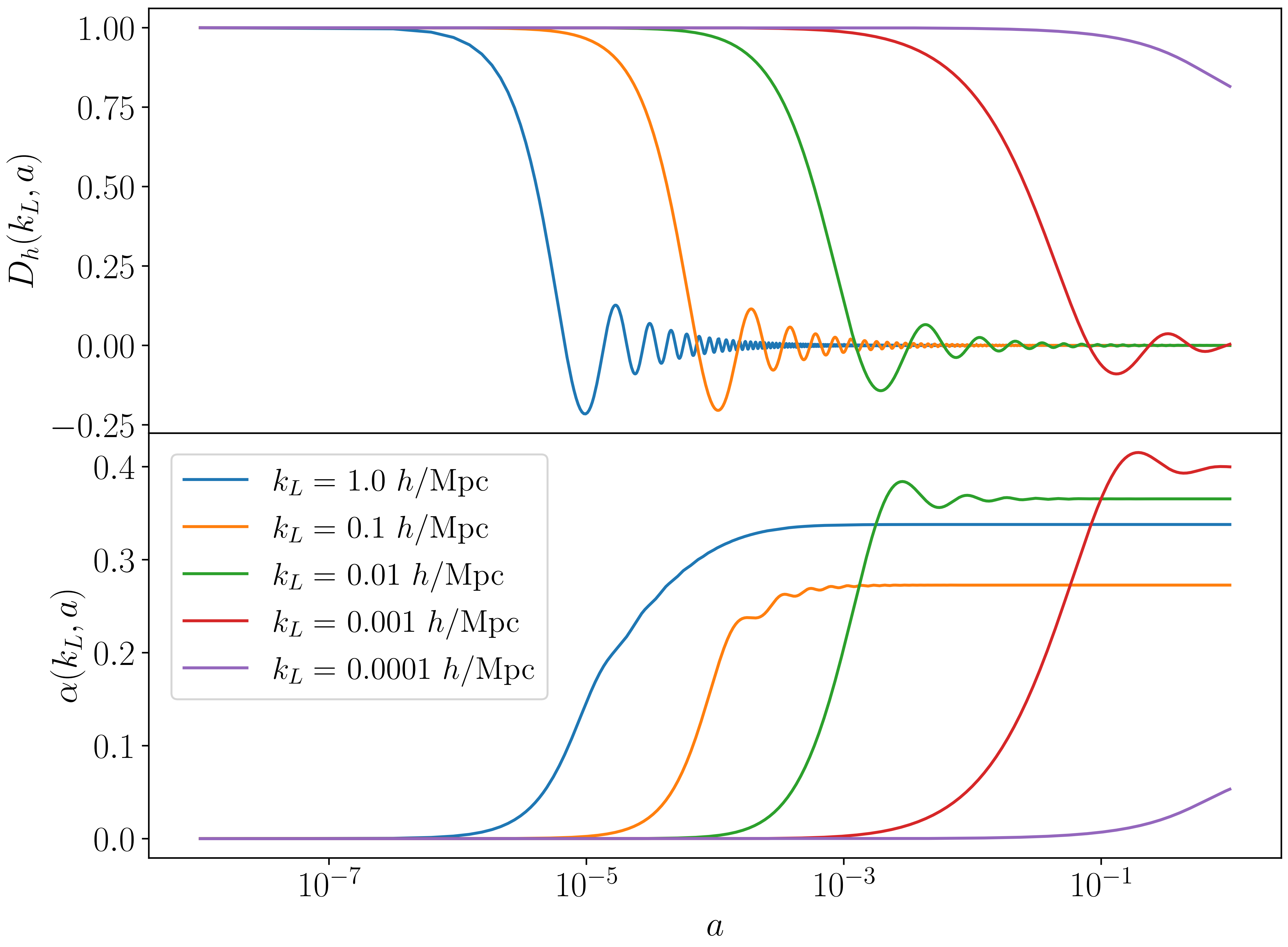
- At 1st order, the density contrast is not affected by GWs.

- 2nd order density field induced by the coupling between GWs and scalar tidal fields:

Dai+13, Schmidt+14

$$\delta^{(2)}(\tau) = \underbrace{\alpha(k_L;\tau)}_{\text{k-dependent}}\underbrace{h_{ij}^{\text{long}}(k_L;\tau_0)}_{\text{GWs at initial time}}\underbrace{\frac{\partial_i\partial_j}{\partial^2}\delta_{\text{short}}^{(1)}(\tau)}_{\text{scalar tidal field}}$$

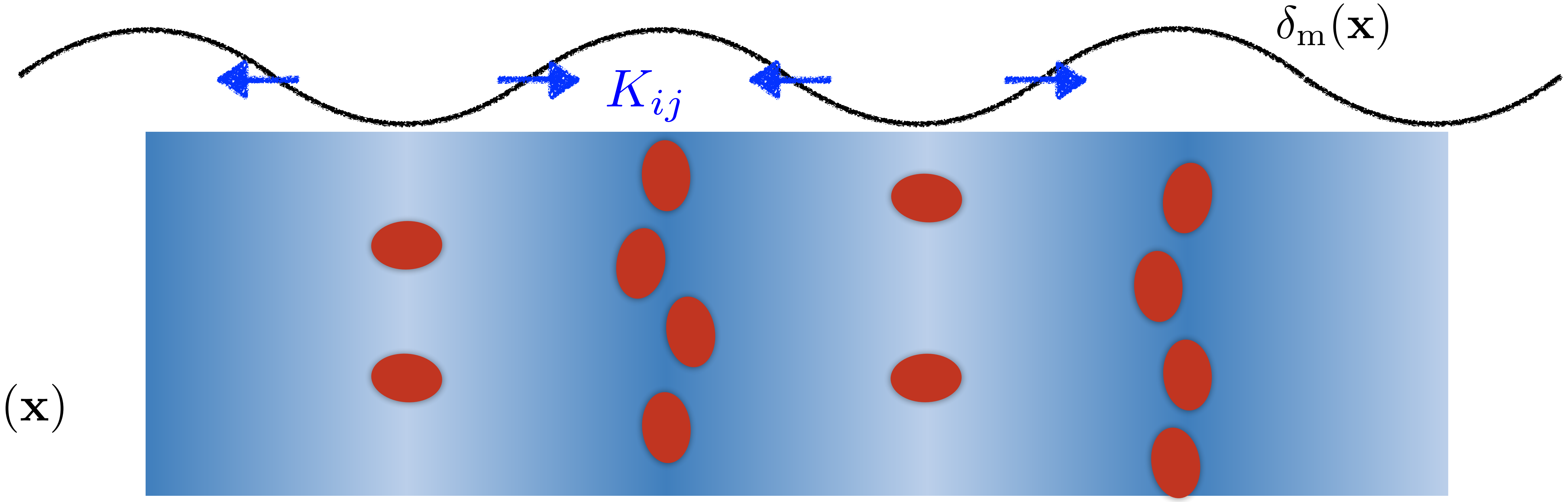
cf. $$\delta^{(2)}(\tau) = \underbrace{\frac{4}{7}\frac{D(\tau)}{D(\tau_0)}}_{\text{k-independent}}\frac{\partial_i\partial_j}{\partial^2}\delta_{\text{long}}^{(1)}(\tau_0)\frac{\partial_i\partial_j}{\partial^2}\delta_{\text{short}}^{(1)}(\tau)$$



- Anything affected by GWs at 1st order?
  - Galaxy/Halo shapes!

Intrinsic alignment (IA) of shapes

- Tidal fields tend to align galaxies/halos. Catelan+00, Hirata, Seljak04, see also Kurita+20



- Linear alignment model:

$$\gamma_{ij} = b^s_K K_{ij}(\mathbf{x})$$

$$K_{ij}(\mathbf{x}) = \left(\frac{\partial_i \partial_j}{\partial^2} - \frac{1}{3}\delta^{\rm K}_{ij}\right)\delta_{\rm m}(\mathbf{x})$$

- Schmidt+14 proposed that GWs also align galaxies/halos.

$$\gamma_{ij} = b^h_K(k_L) h_{ij}(k_L;\tau_0)$$

ansatz: $b^h_K(k_L) = b^s_K \dfrac{7}{4}\alpha(k_L;\tau)$

cf. $$\delta^{(2)} = \alpha(k_L;\tau) h^{\rm long}_{ij}(k_L;\tau_0)\frac{\partial_i\partial_j}{\partial^2}\delta^{(1)}_{\rm short}$$

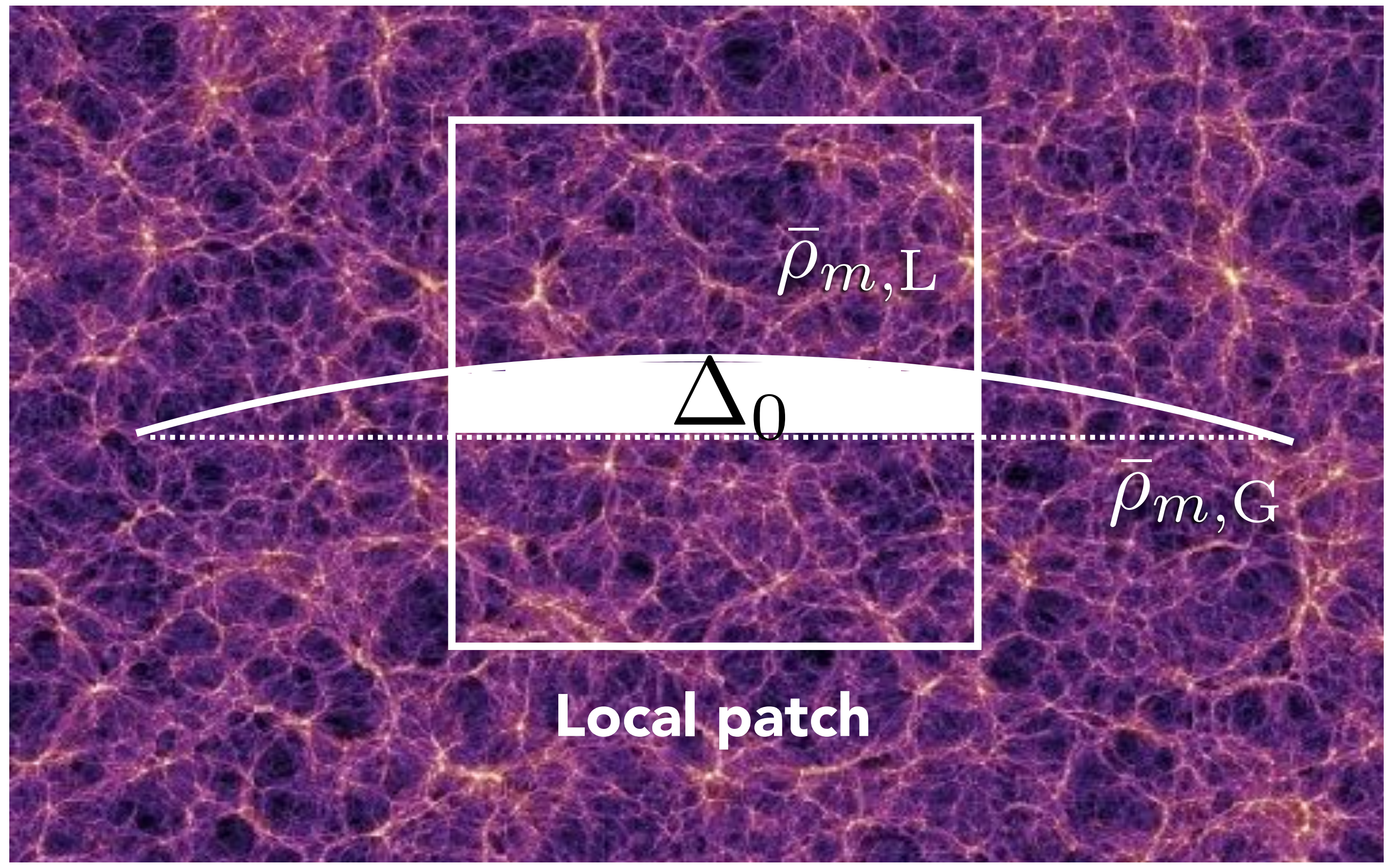
$$\delta^{(2)} = \frac{4}{7}\frac{\partial_i\partial_j}{\partial^2}\delta^{(1)}_{\rm long}\frac{\partial_i\partial_j}{\partial^2}\delta^{(1)}_{\rm short}$$

- Do GWs really induce the IA? If so, how much?

Separate universe simulation

- Long-wavelength perturbations can be absorbed into the background
- For density perturbations (isotropic long-mode)

Sirko+05, Li+14a, Wagner+14, Baldauf+16

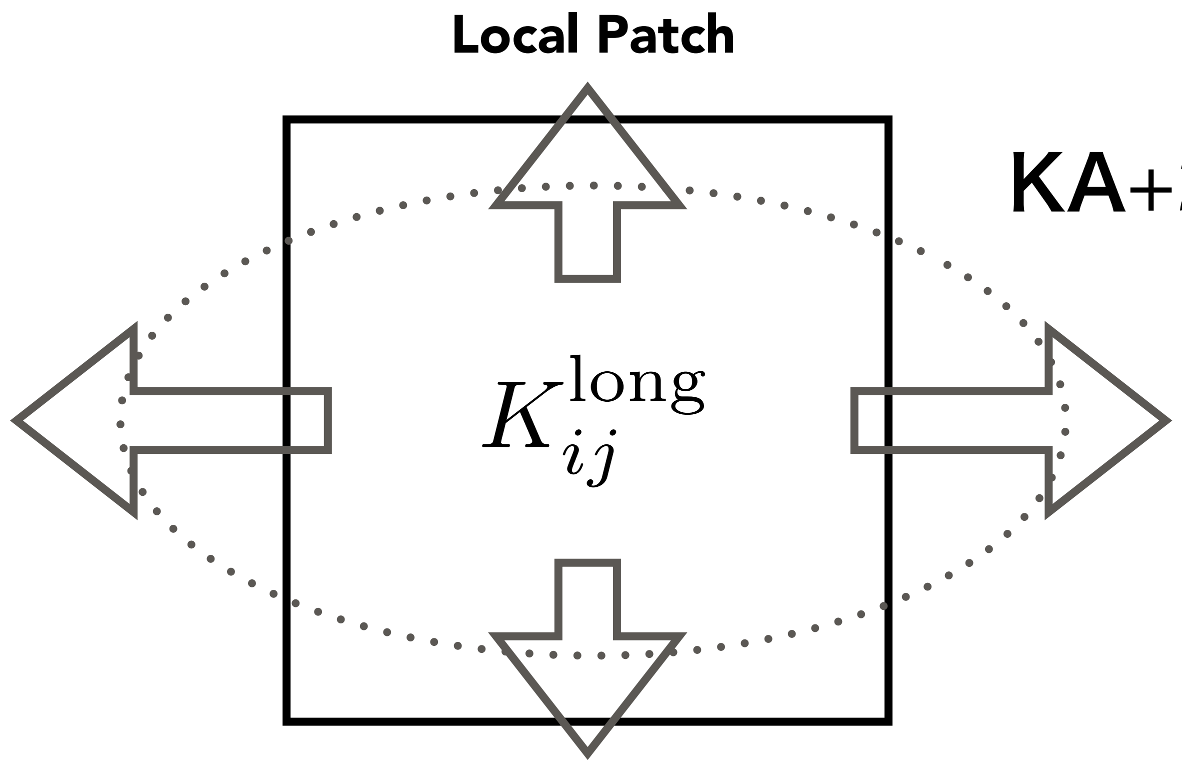


$$\bar{\rho}_{m,\mathrm{L}} = \bar{\rho}_{m,\mathrm{G}}(1+\Delta_0)$$

$$\bar{\rho}_{m,\mathrm{L}} a_{\mathrm{L}}^3 = \bar{\rho}_{m,\mathrm{G}} a_{\mathrm{G}}^3 \rightarrow a_{\mathrm{L}} \simeq a_{\mathrm{G}} \left[1 - \frac{1}{3}\Delta_0\right]$$

- For tidal perturbations (anisotropic long-mode)
  - Anisotropic scale factors

$$a_{\mathrm{L},i} = a_{\mathrm{G}}(1+\Delta_i)$$



KA+20, Stücker+20, Masaki+20

Tidal separate universe sims with GWs

- Long-wavelength GWs are locally seen as (almost) uniform tidal fields

Schmidt+14, Dai+15

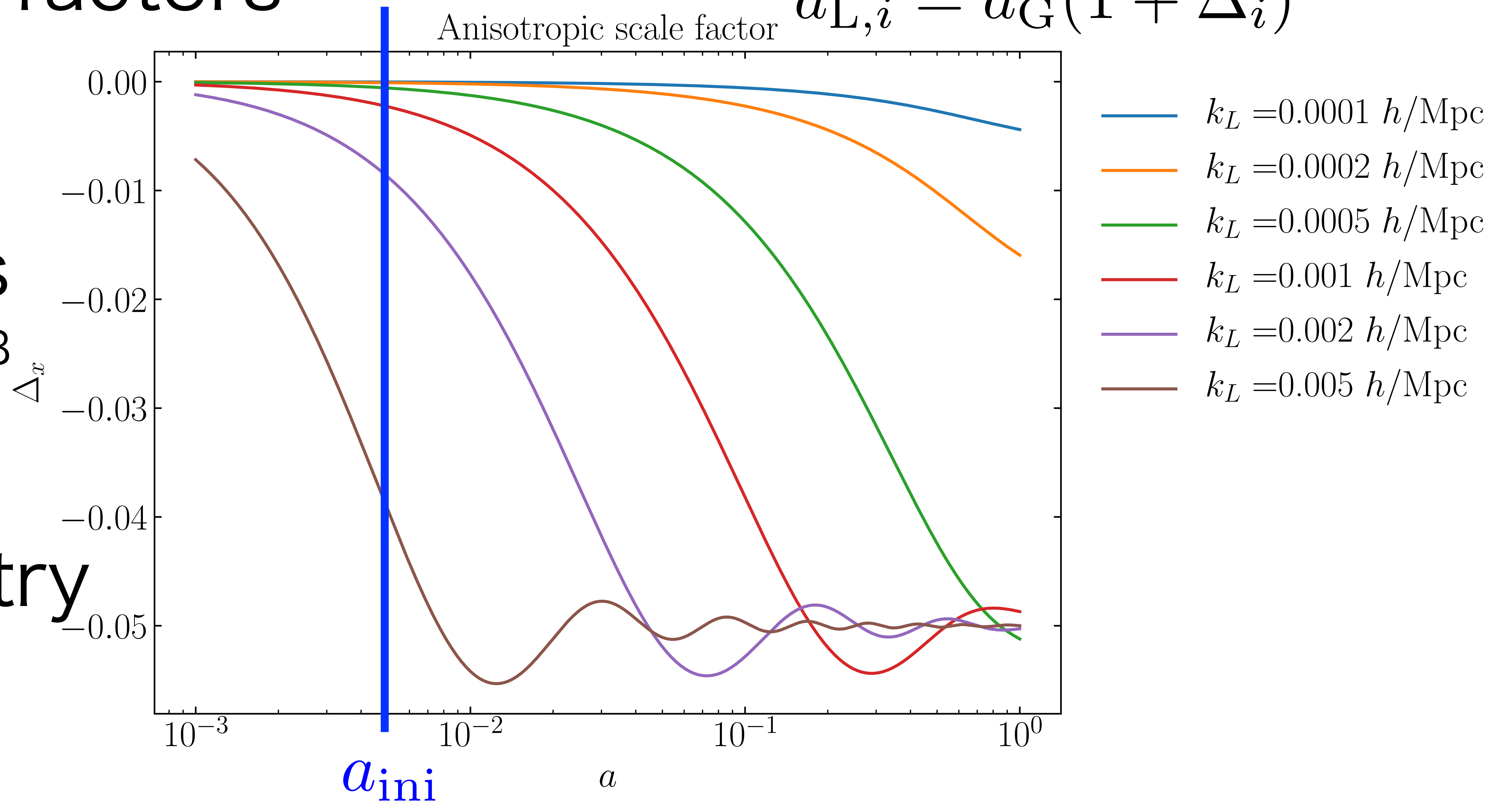
FLRW: $ds^2 = a^2\left[-d\tau^2 + (\delta^{\rm K}_{ij} + h_{ij})dx^i dx^j\right]$ cf. for scalar long-mode: $\tau_{ij} = \partial_i\partial_j\Phi$

➔ Local frame(CFC): $ds_F^2 = -a_F^2\left[1 - \tau_{ij}x_F^i x_F^j\right]d\tau_F^2 + g_{ij}^F dx_F^i dx_F^j$ with $\tau_{ij} = \dfrac{1}{2}a^{-1}(ah'_{ij})'$

- Evolution of local anisotropic scale factors

$$\Delta_i'' + \mathcal{H}\Delta_i' = \frac{1}{2}a^{-1}\left[ah_i'(k_L)\right]'$$

$a_{{\rm L},i} = a_{\rm G}(1+\Delta_i)$



  - depends on wavenumber of GWs

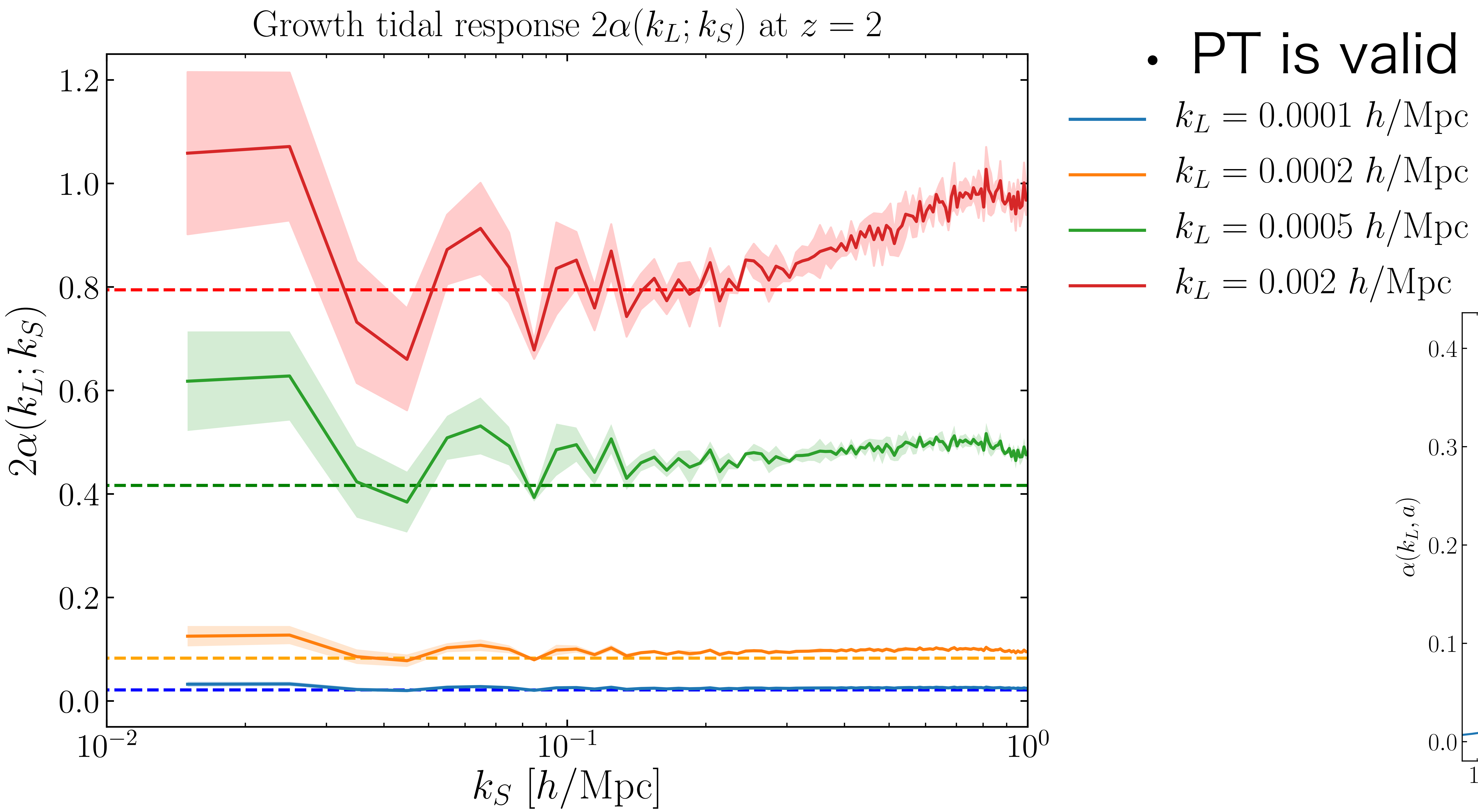
    cf. neutrino separate universe simulations in Chiang+18

  - Anisotropies induced by GWs are nonzero after the horizon entry

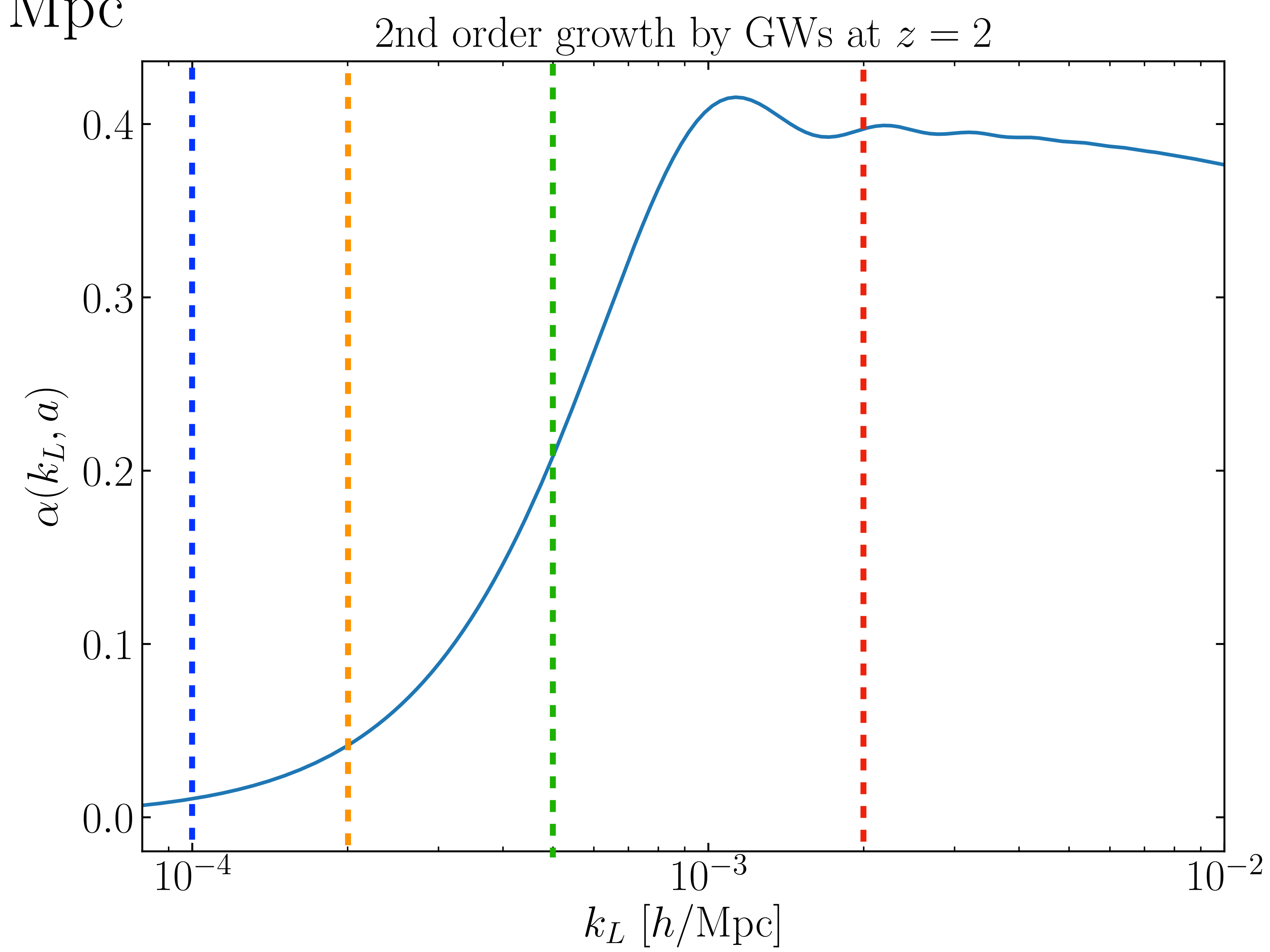
- $z_{\rm ini} = 199, \quad L = 500\ {\rm Mpc}/h, \quad N_{\rm p} = 1024^3$

Power spectrum response from GWs

- $\delta^{(2)} = \alpha(k_L;\tau) h_{ij}^{\text{long}}(k_L;\tau_0) \dfrac{\partial_i \partial_j}{\partial^2} \delta^{(1)}_{\text{short}} \longrightarrow P\left(\mathbf{k_S} | h_{ij}(k_L,\tau_0)\right) = P(k)\left[1 + \underline{2\alpha(k_L;k_S)}\hat{k}_S^i \hat{k}_S^j h_{ij}(k_L,\tau_0)\right]$



- PT is valid only if $k_L \ll k_S \ll k_{\text{NL}}$



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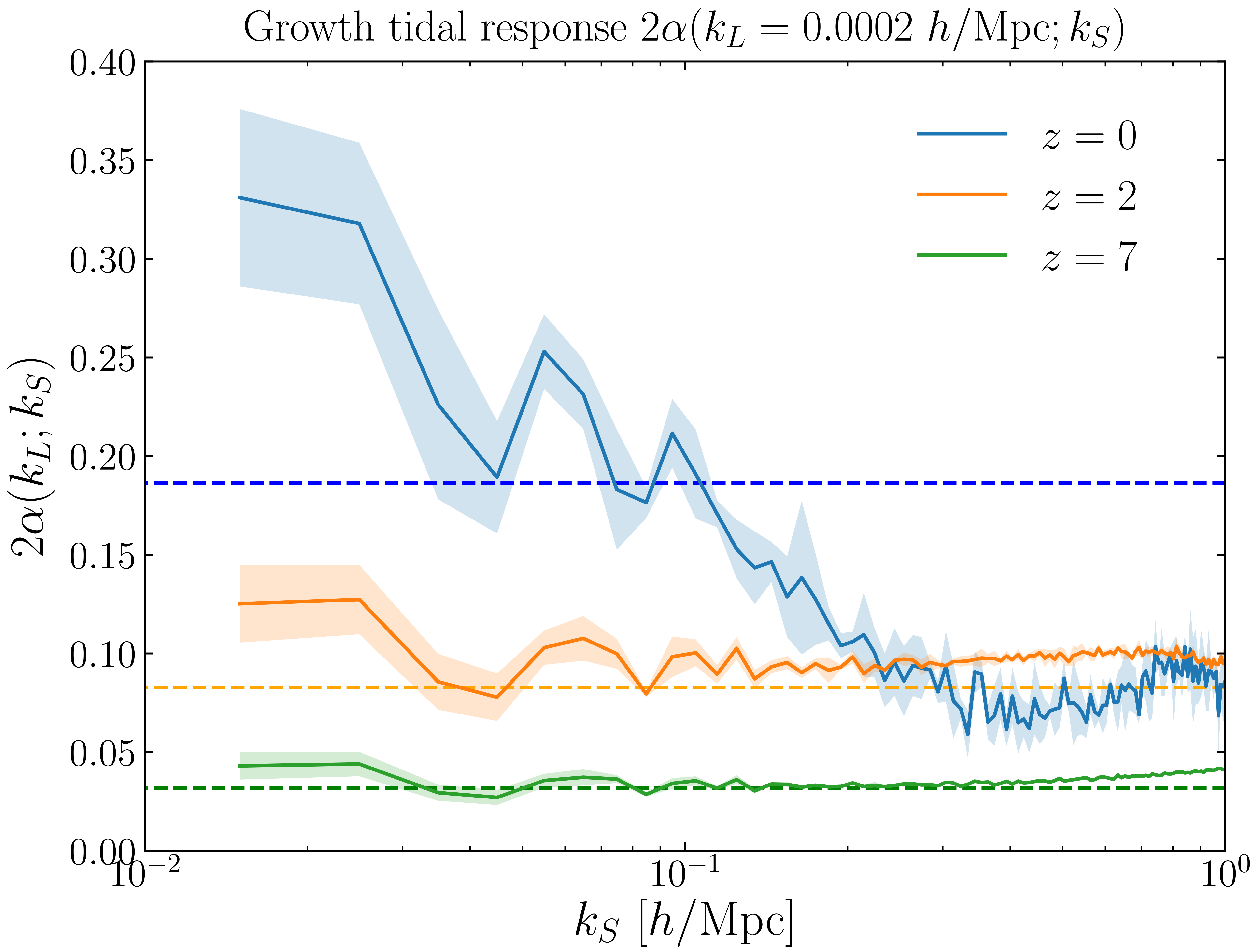

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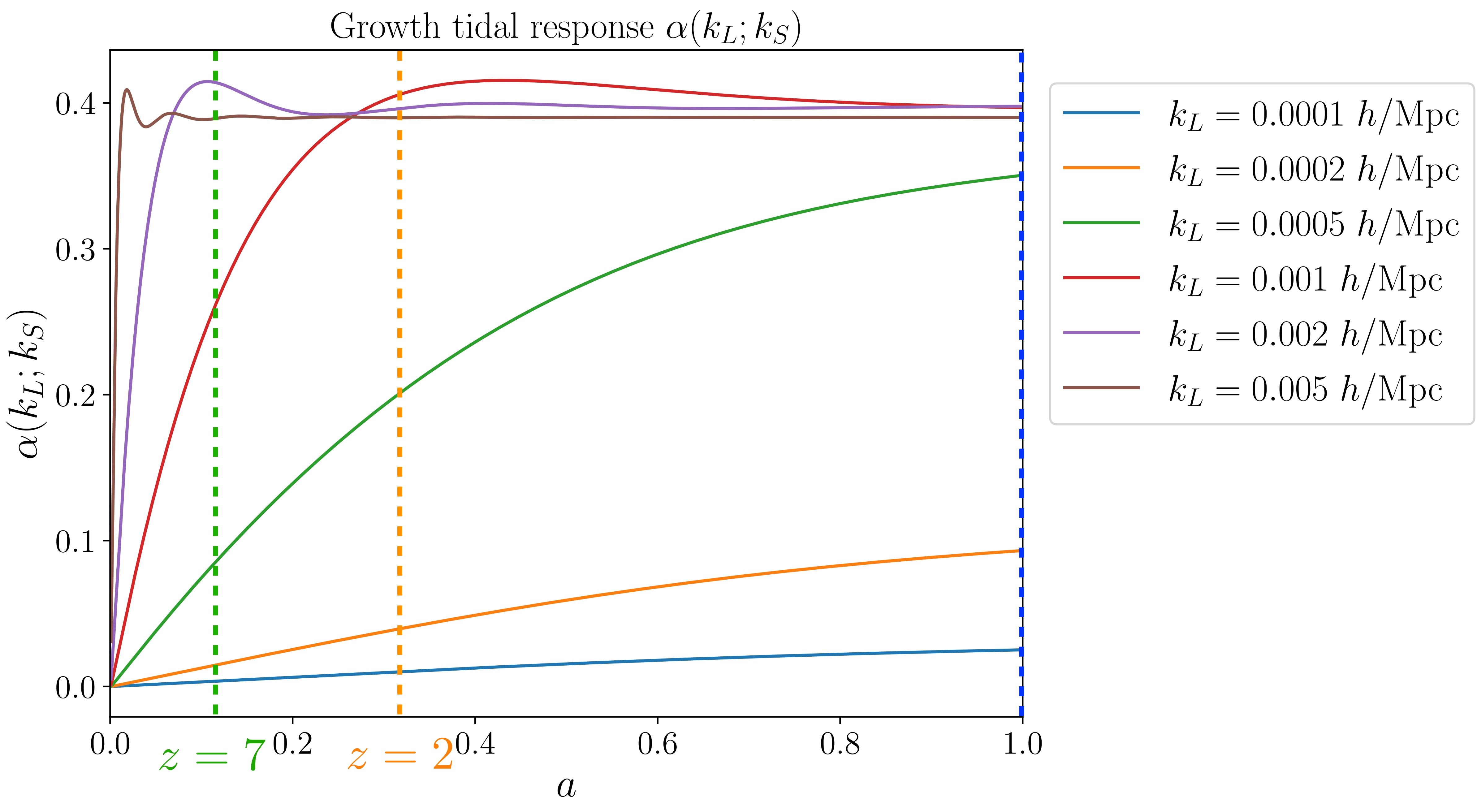

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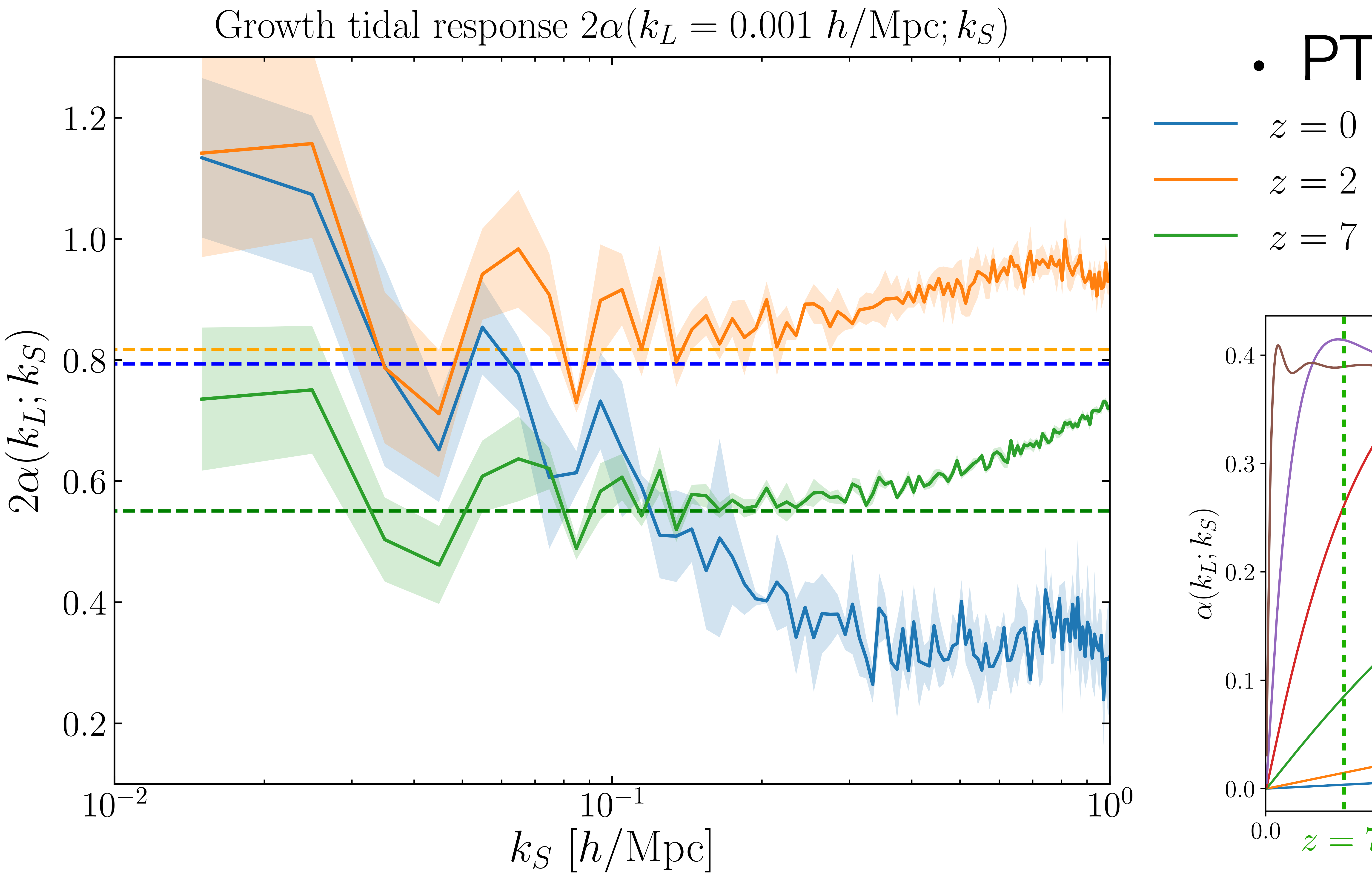

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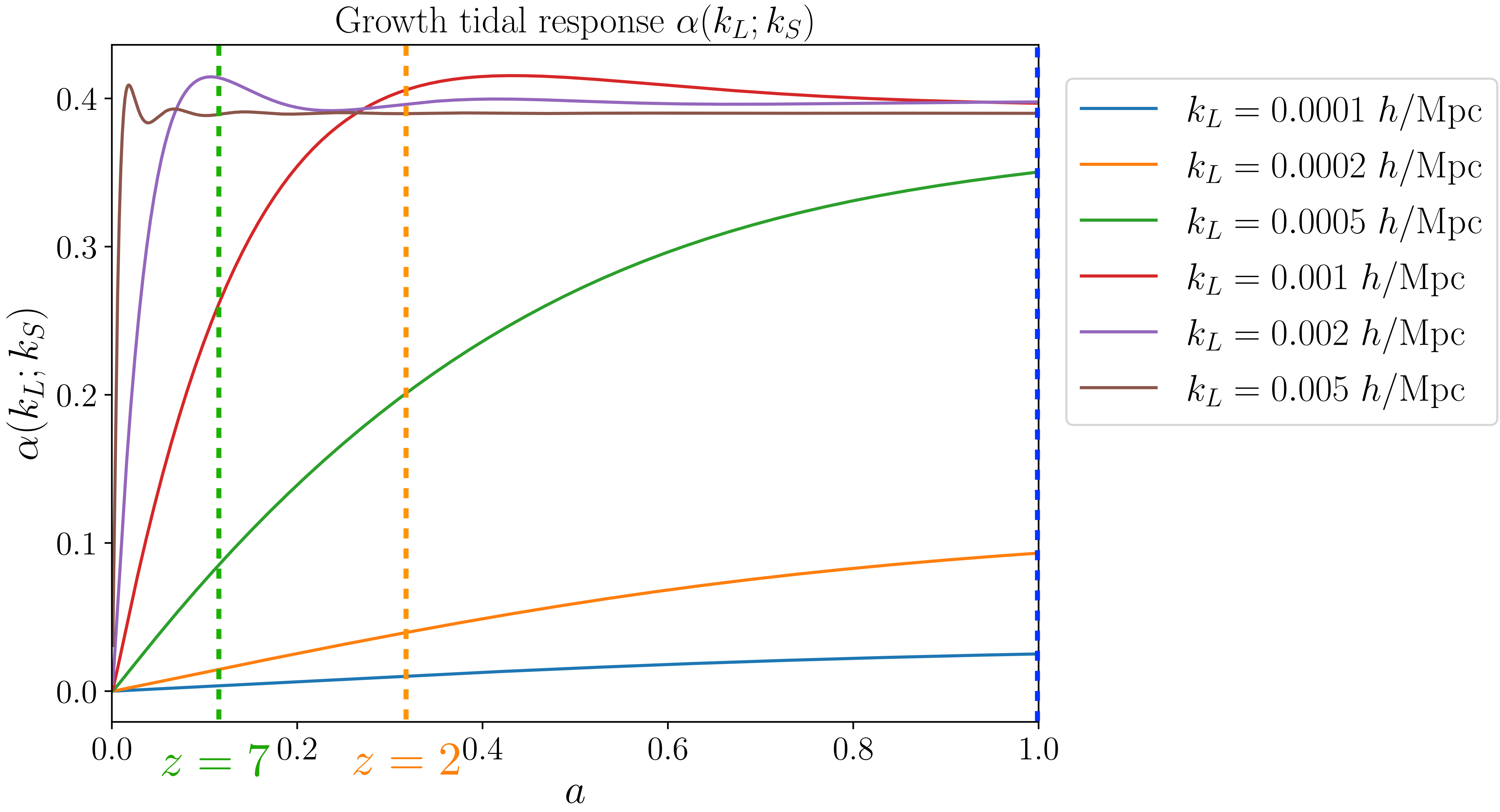
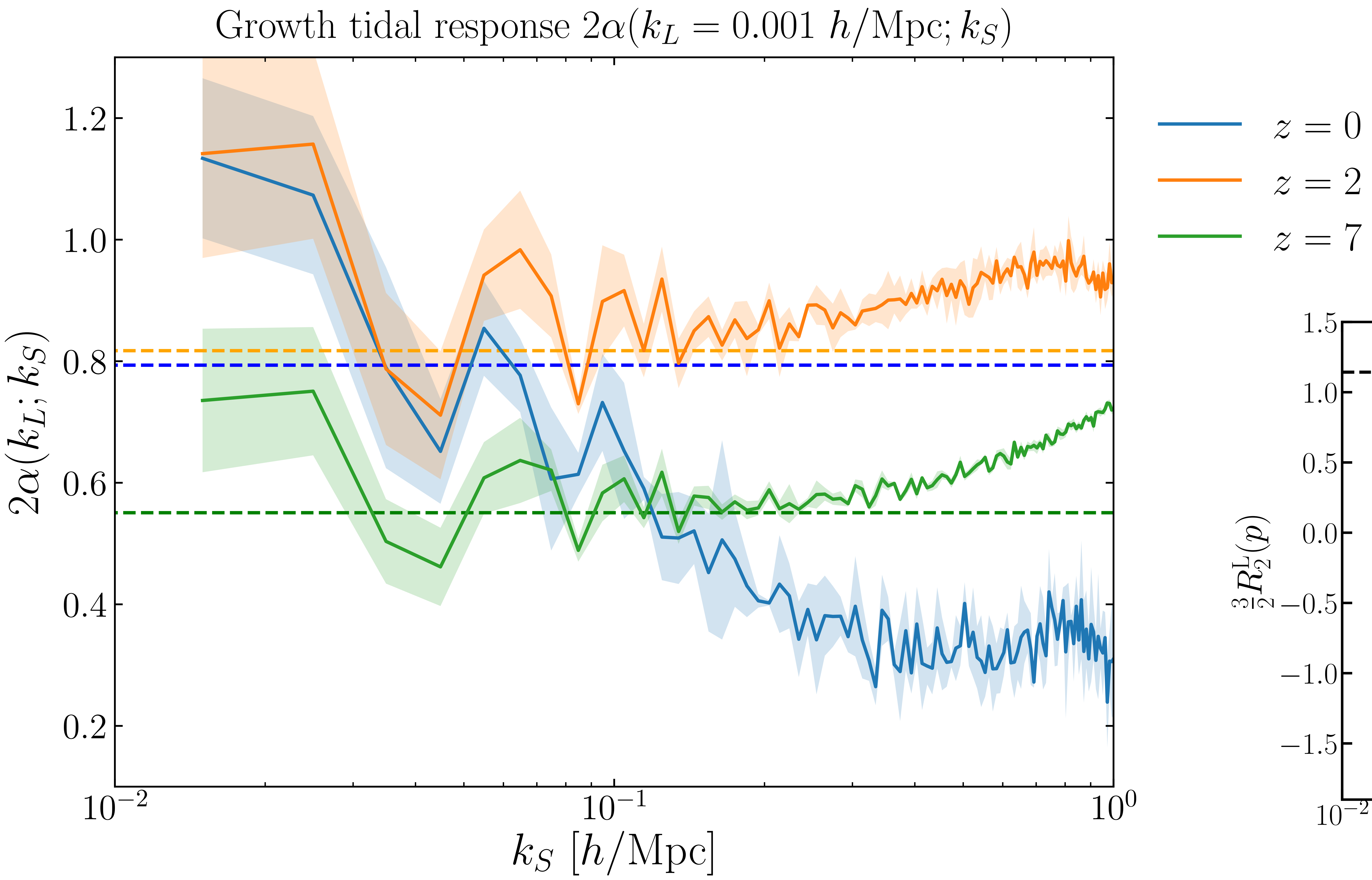
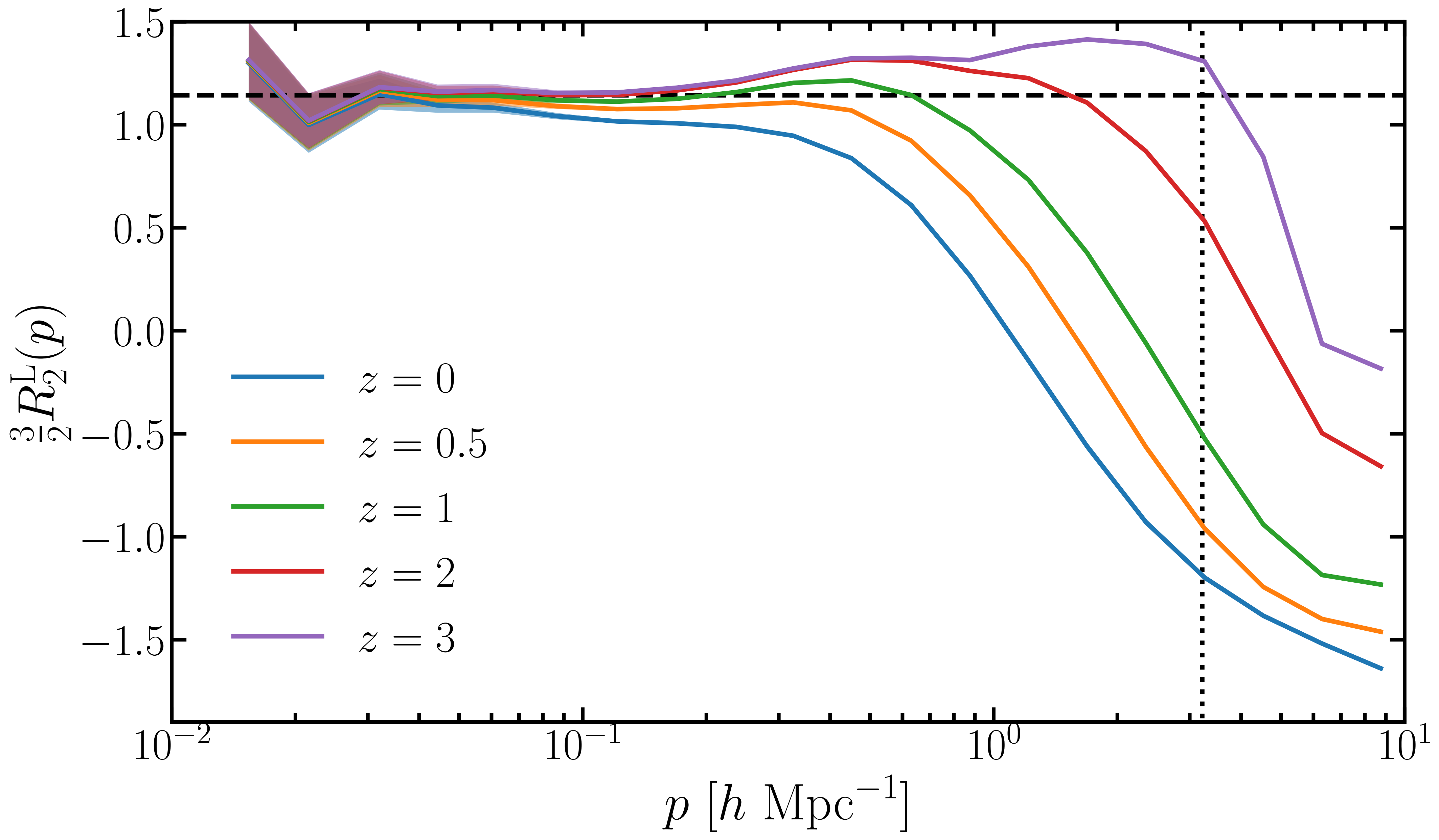


Comparison of power spectrum responses

- $\delta^{(2)} = \alpha(k_L;\tau)h_{ij}^{\rm long}(k_L;\tau_0)\frac{\partial_i\partial_j}{\partial^2}\delta^{(1)}_{\rm short} \longrightarrow P\left(\mathbf{k_S}|h_{ij}(k_L,\tau_0)\right) = P(k)\left[1+\underline{2\alpha(k_L;k_S)}\hat{k}_S^i\hat{k}_S^j h_{ij}(k_L,\tau_0)\right]$



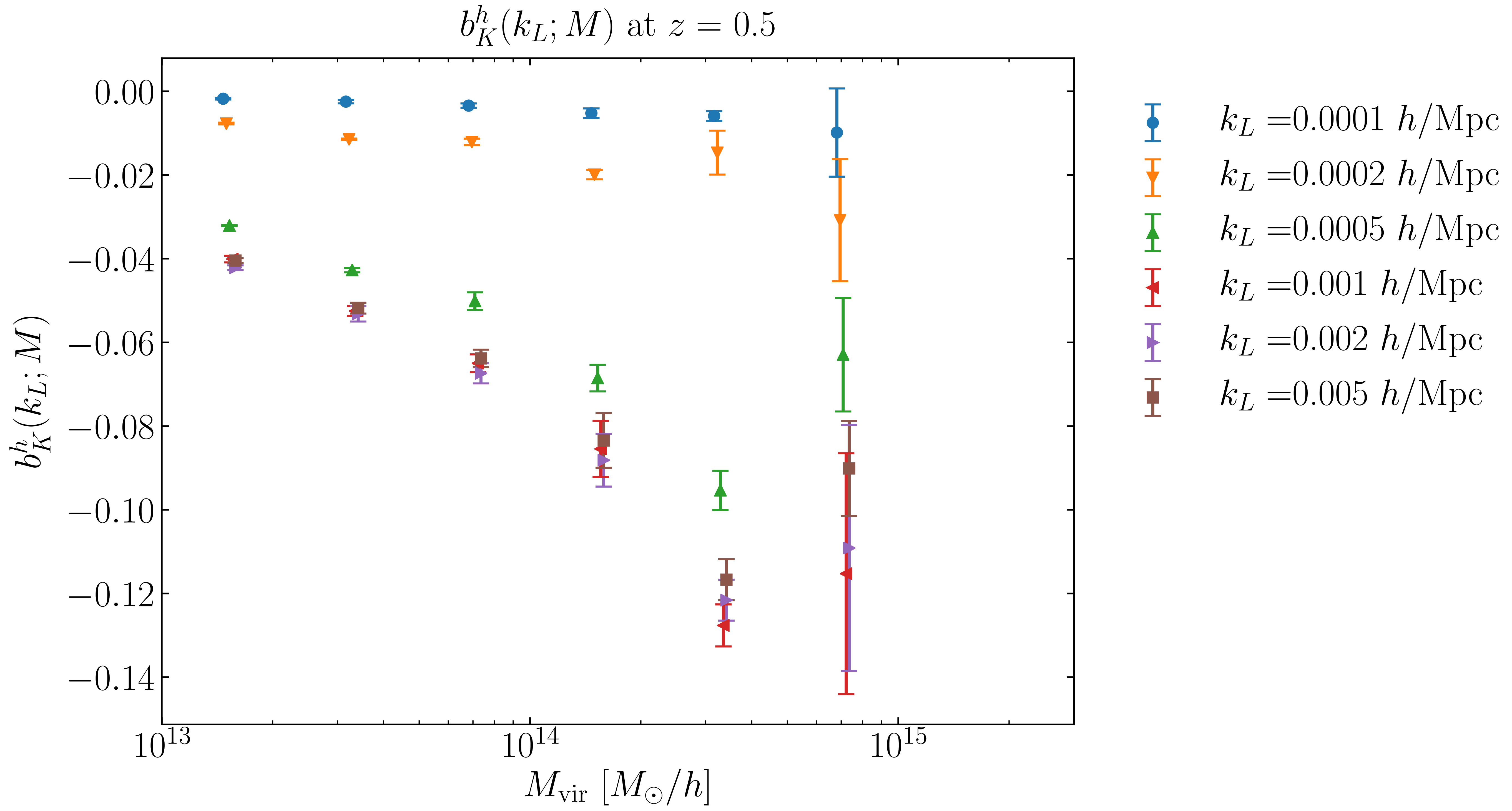
- Similar trend to scalar case on non-linear scales



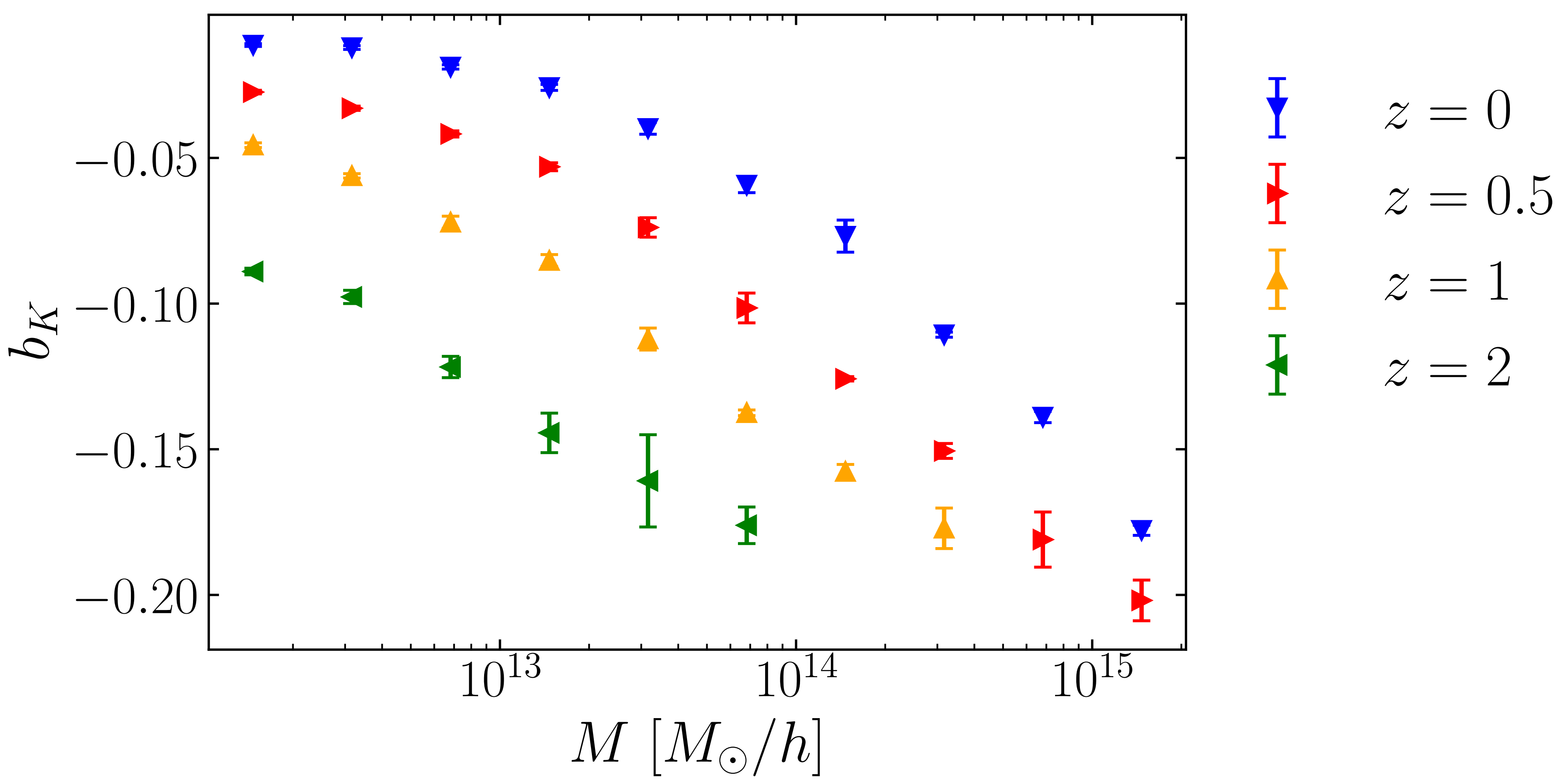
GWs induce the alignment of shapes!

- $\gamma_{ij}(M) = b^h_K(k_L; \underline{M})h_{ij}(k_L; \tau_0)$

- The mass dependence is similar to that of scaler tidal field case



cf. $\gamma_{ij}(M) = b^s_K(M)\dfrac{\partial_i\partial_j}{\partial^2}\delta$



Scale-dependent shape bias from GWs

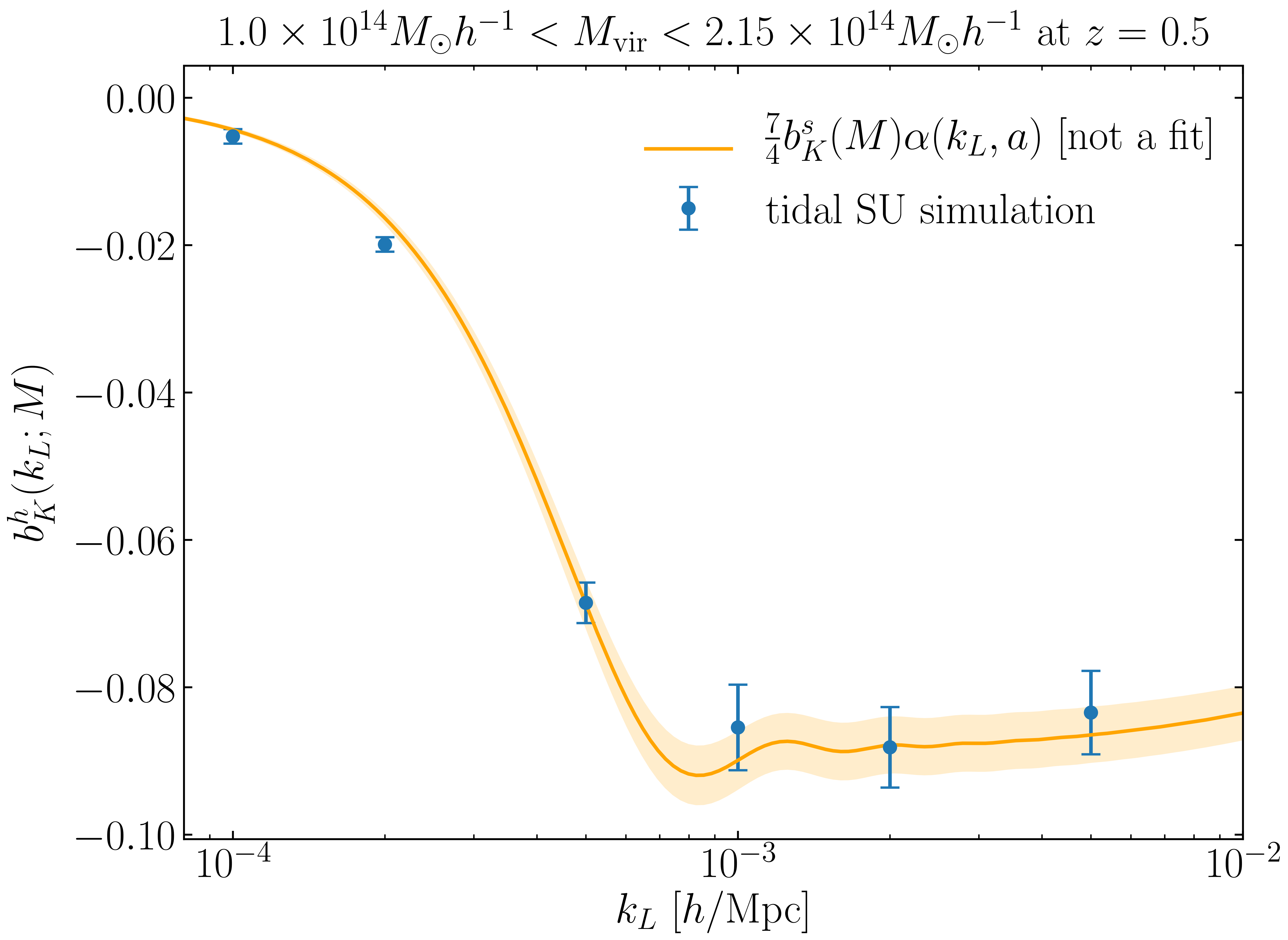
- $\gamma_{ij}(M) = b_K^h(k_L; M) h_{ij}(k_L; \tau_0)$
  - Schmidt+14's ansatz:

$$b_K^h(k_L; M) = b_K^s(M)\frac{7}{4}\alpha(k_L; \tau)$$

- Surprisingly(?), the simple ansatz works well!

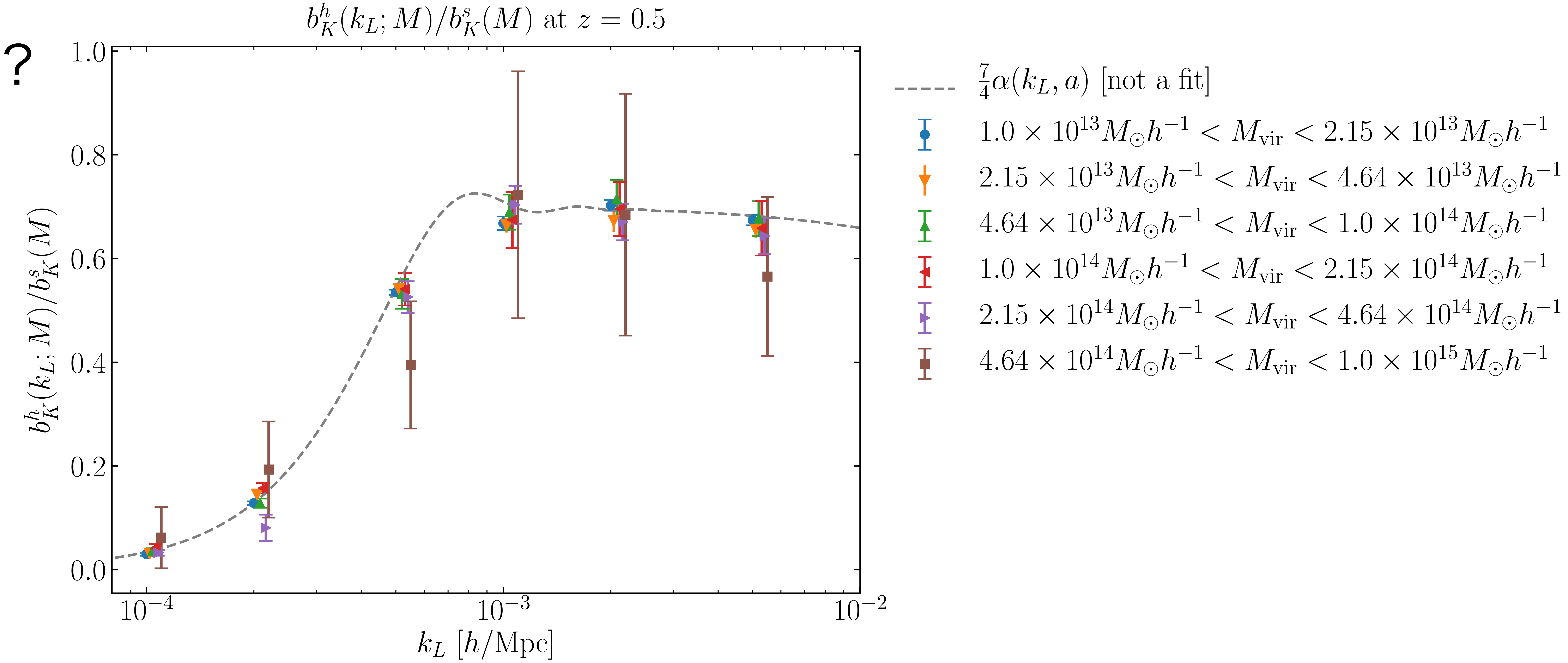
- For scalar perturbations, $b_K^s(M)$ is constant.

$$\gamma_{ij}(M) = b_K^s(M)\frac{\partial_i\partial_j}{\partial^2}\delta$$



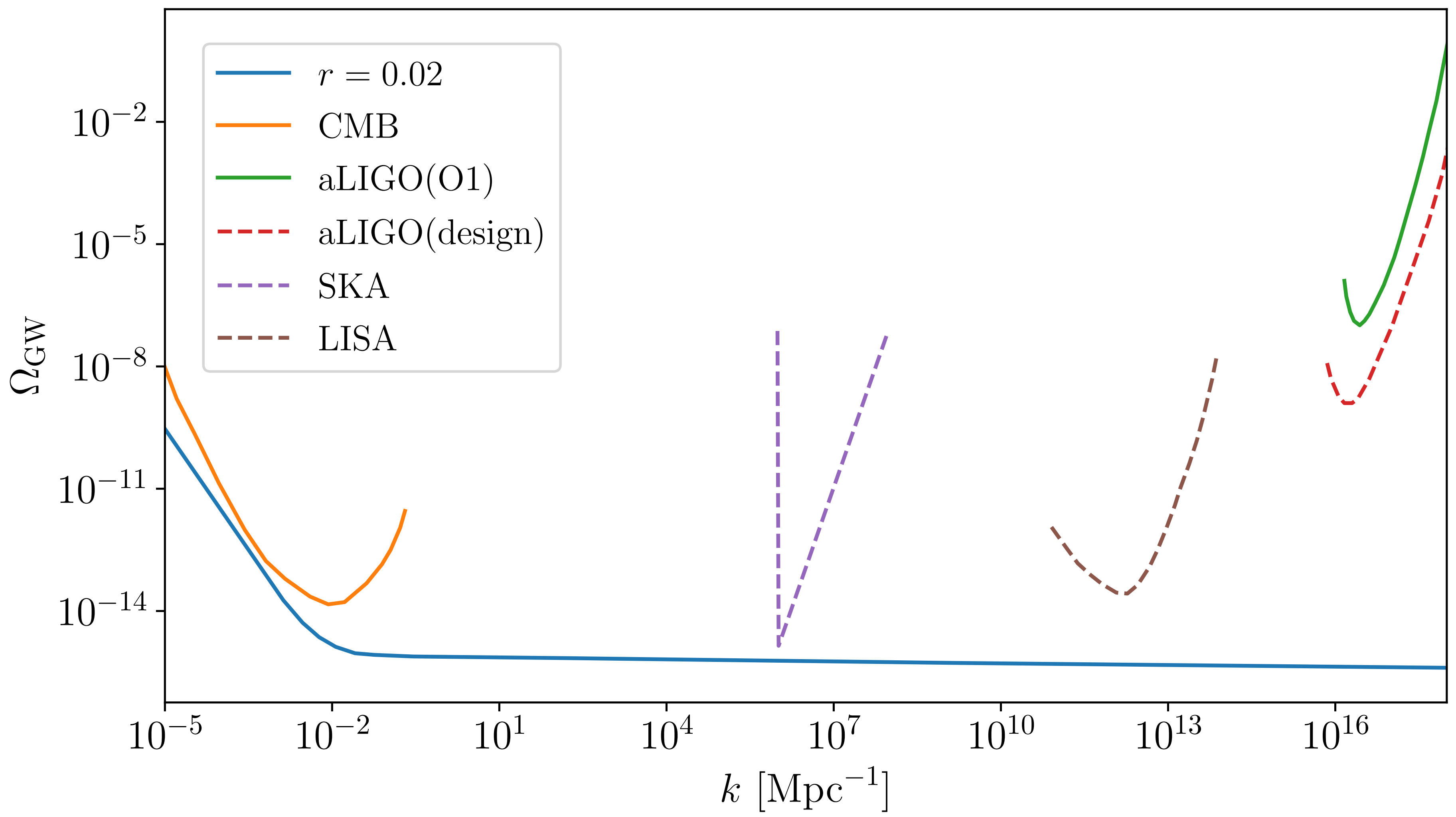
Scale-dependent shape bias from GWs

- $\gamma_{ij}(M) = b_K^h(\underline{k_L}; M) h_{ij}(k_L; \tau_0)$ ansatz: $b_K^h(k_L; M) = b_K^s(M)\frac{7}{4}\alpha(k_L; \tau)$
  - The ansatz seems to work well for all mass range.
  - But, why…?

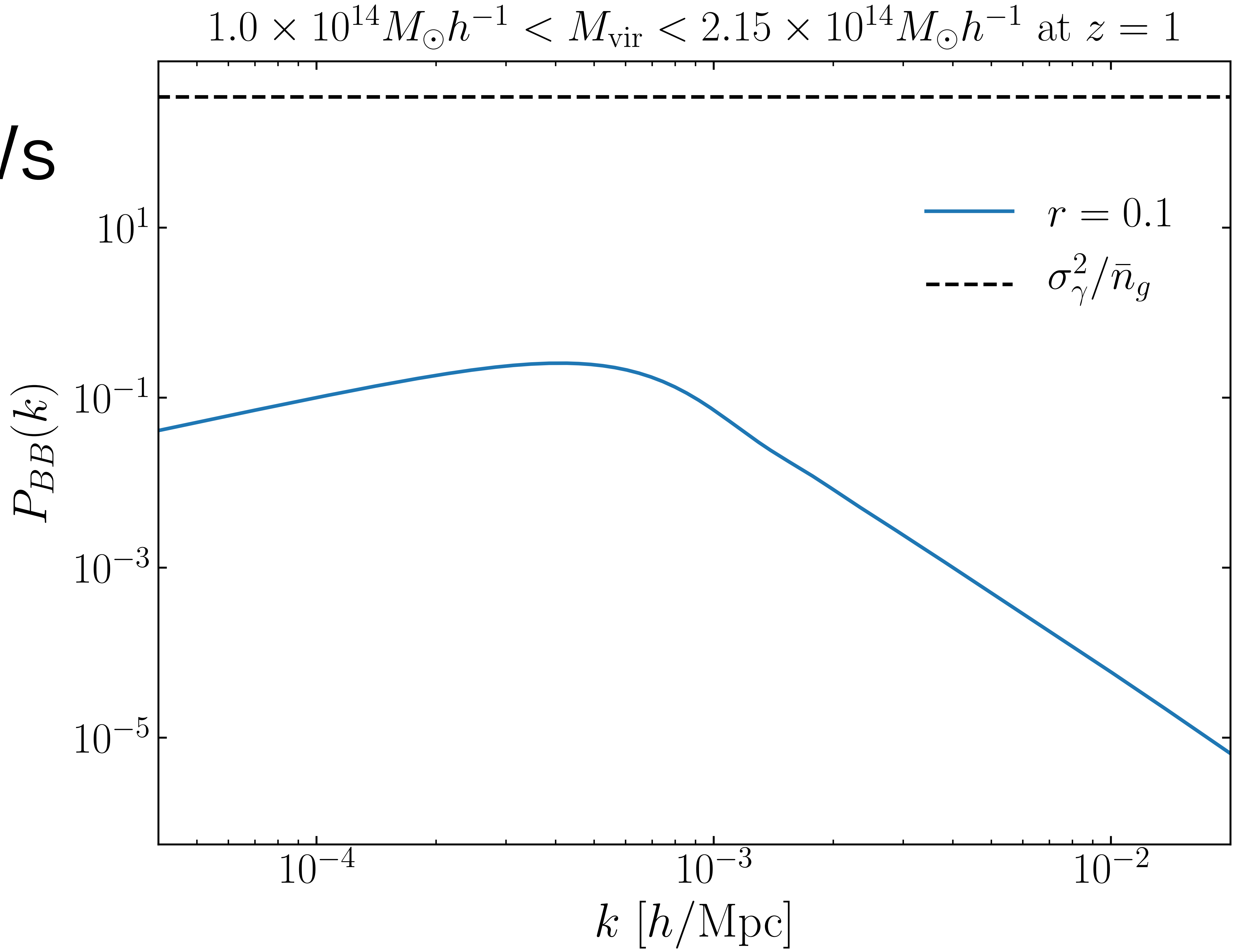


Observational prospects

- For the standard scenario, the shape noise is dominant for the B-mode auto power.
  - but can put the upper limit on GWs



Dodelson 10



- Cross-correlation?

- EB? PNG?

Masui+17, Biagetti&Orlando 20

Summary

- Effect of long-wavelength GWs on LSS can be investigated by tidal separate universe simulations

- The shape bias induced by GWs is scale-dependent.

  - This scale-dependence is in agreement with that of 2nd order density induced by the coupling between GWs and scalar perturbations

- Future works

  - the physical explanation for the simple ansatz

  - improving the quadratic estimator from the density for GWs?

  - other possible observables