$P_g(k)$ near horizon scales: galaxy bias in general relativity and effective f_{NL}

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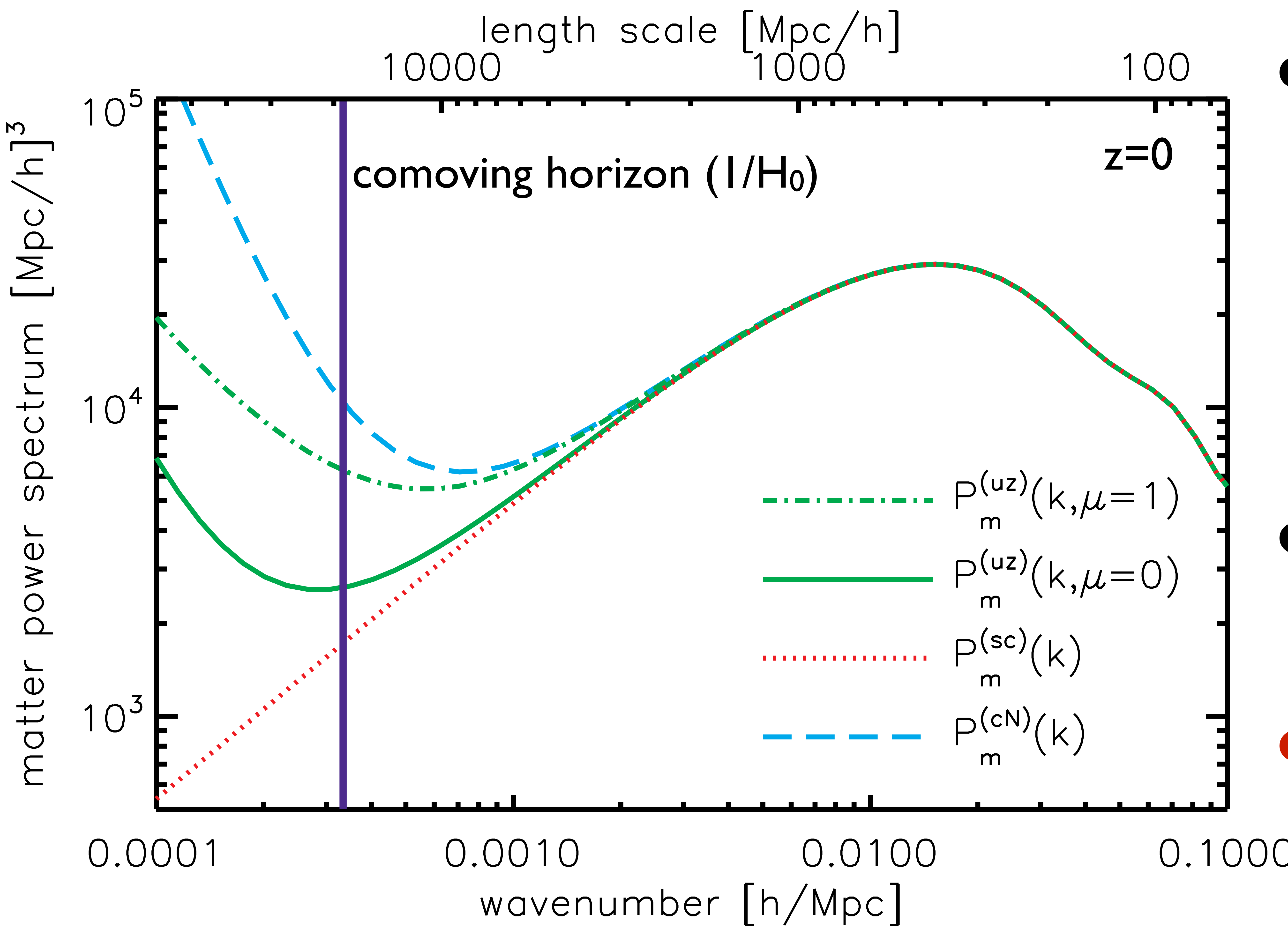
Cosmological non-Gaussianity: observations confront theory workshop
14 May 2011

Work in progress with Fabian Schmidt and Chris Hirata linear bias = linear in matter density

$P_g(k)=b^2P_m(k)$. But, which $P_m(k)$?



- $P_m(k)$ from three gauges
  - conformal Newtonian (cN)
  - synchronous comoving (sc)
  - uniform redshift (uz)
- General covariance says all P(k)s are equally good.
- Q: what is $P_g(k)$ we will measure in the large scale galaxy surveys?

Difference in background

- Two coordinate systems (gauge) x_A and x_B [$x=(\tau,x^i)$]

$$n = \bar{n}(x_A) + \delta n(x_A) = \bar{n}(x_B) + \delta n(x_B)$$

Scalar variable

- δn_A with B coordinate variables (gauge transformation):

difference in background

$$\delta n_A = \delta n_B + [\bar{n}(x_A) - \bar{n}(x_B)]$$
$$= \delta n_B + \bar{n}'(x_B)(\tau_A - \tau_B)$$

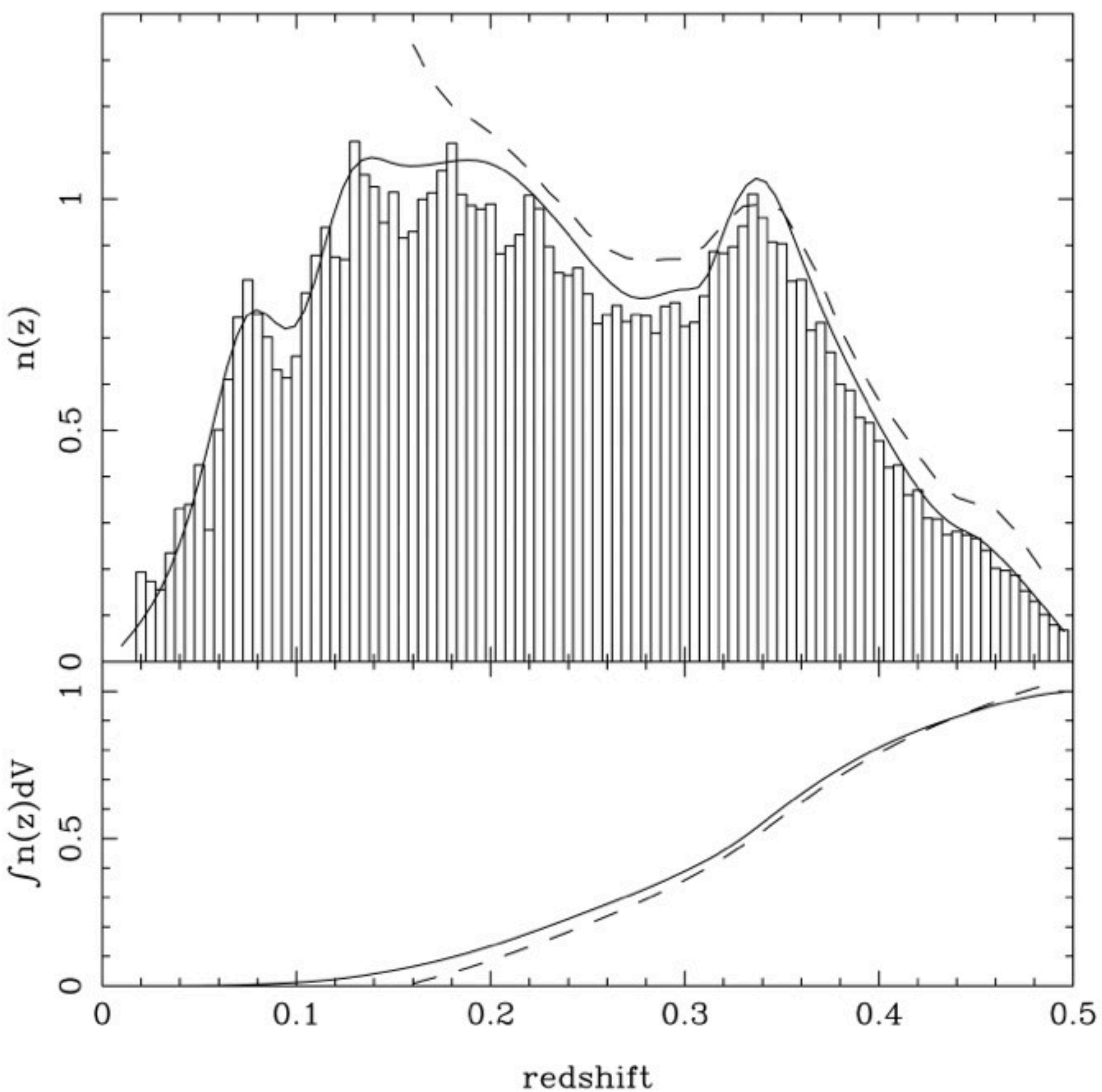
difference in time

- Therefore, it is important to know *in which coordinate frame we observe background density!*

Two central questions

- In which frame we measure the background number density?
- In which frame is the galaxy bias linear in matter density?

Observed mean galaxy density



SDSS DR7 Reid et al. (2010)

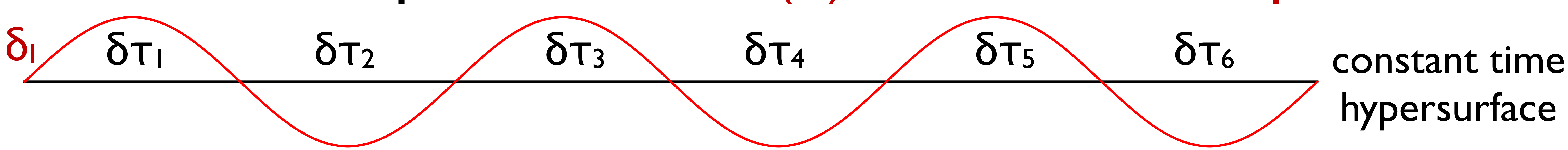
- In galaxy surveys, we estimate the background number density by angular averaging samples in a redshift bin.
- That is, we observe the galaxy density contrast reference to the constant-observed-redshift slicing (we call uniform-redshift (uz) gauge).

Linear bias, reconsidered

- In peak-background split, we get bias from (e.g. Fabian's talk)

$$\delta_g(M,\tau) = \frac{\bar{n}(M,\delta_c - \delta_l,\tau)}{\bar{n}(M,\delta_c,\tau)} - 1 \simeq -\frac{\partial \ln \bar{n}(M,\delta_c,\tau)}{\partial \delta_c}\delta_l$$

- Hidden assumption: τ, or $\sigma_R(\tau)$, is constant in space.



- Therefore, bias is linear iff the constant time hyper-surface shares same σ_R (for any given scale R), or evolutionary stage, or conformal time! → Synchronous comoving (sc) gauge!

For other argument why we need to do it in (sc) gauge, see, e.g. Wands & Slosar (2009), Bartolo et al. (2010).

Adding up two answers

- δτ = time difference between (sc) and (uz) gauge

$$\delta z^{(\mathrm{uz})} = 0 = \delta z^{(\mathrm{sc})} + aH\delta\tau$$

- With the same time change, the density contrast of galaxies are transformed as

$$\delta_g^{(\mathrm{uz})} = \delta_g^{(\mathrm{sc})} - \frac{\partial \ln \bar{n}}{\partial \tau}\delta\tau = b\delta_m^{(\mathrm{sc})} + \frac{1}{aH}\frac{\partial \ln \bar{n}}{\partial \tau}\delta z^{(\mathrm{sc})}$$

galaxy density contrst in uniform redshift gauge

Variables in synchronous comoving gauge (where bias is linear in matter density) spatial metric in (sc) gauge $\longrightarrow$ $g_{ij} = a^2(\tau)\left[(1+2D)\delta_{ij} + 2\left(\partial_i\partial_j - \frac{1}{3}\delta_{ij}\partial^2\right)E\right]$

One more step

- Assuming the universal mass function (f=dlnD/dlna)

$$\frac{\partial \ln \bar{n}}{\partial \tau} = \frac{\partial \ln \bar{n}}{\partial \sigma_R}\frac{\partial \sigma_R}{\partial \tau} = aH\delta_c f(b-1)$$

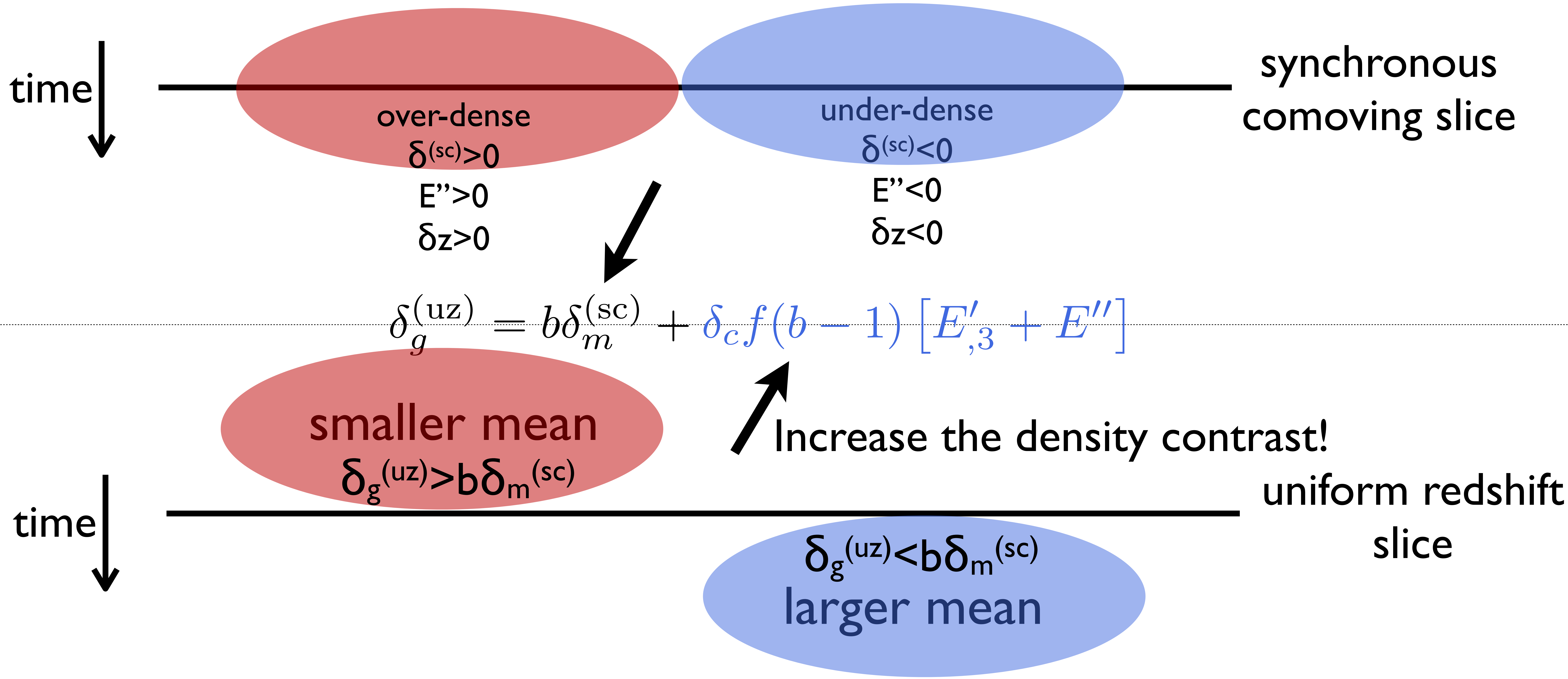
- redhisft perturbation in synchronous comoving gauge

$$\delta z^{(\mathrm{sc})} = E'_{,3} + E'' + [\mathrm{ISW}]$$

- Final formula for $\delta_g^{(uz)}$:

$$\delta_g^{(\mathrm{uz})} = b\delta_m^{(\mathrm{sc})} + \delta_c f(b-1)\left[E'_{,3} + E''\right]$$

Meaning of this equation (Einstein de-Sitter Universe)



$$\delta_g^{(\mathrm{uz})} = b\delta_m^{(\mathrm{sc})} + \delta_c f(b-1)\left[E'_{,3} + E''\right]$$

There are more GR effects!

- Effect from volume, magnification in general relativity
  - Yoo et al. (2009), Yoo (2010), and his talk (next)!
- Including all effects + new bias in this work, we have

$$\delta_g^{\rm obs} = (b + f\mu^2)\delta_m^{(sc)} + i\mu a H f \left[\delta_c f (b-1) - \mathcal{C}\right] \frac{\delta_m^{(\rm sc)}}{k}$$

Kaiser (1987) direction dep. time shift (E',3)

additional effects

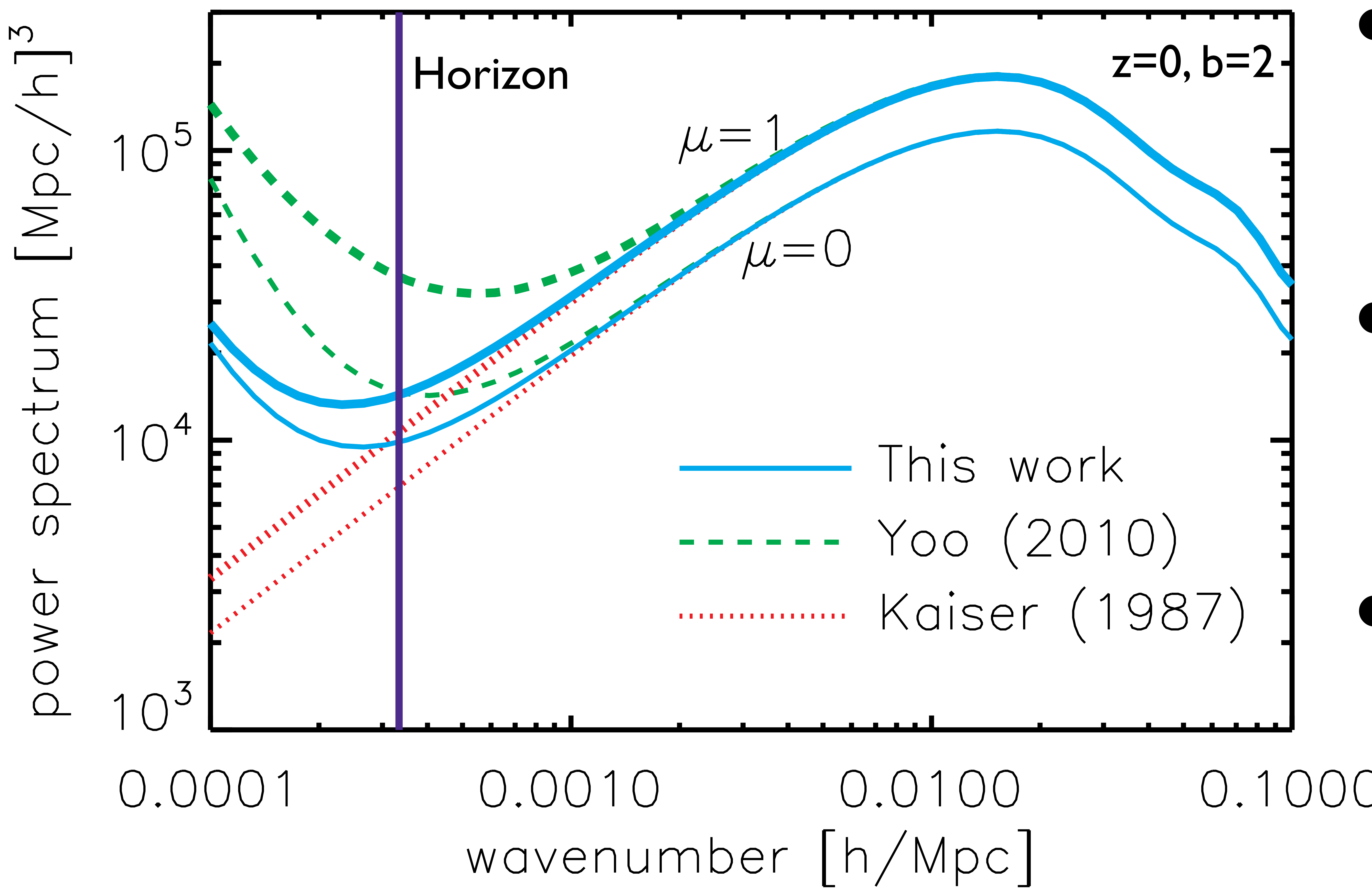
$$+ \frac{3}{2} a^2 H^2 \Omega_m \left[\delta_c f (b-1)\left(1 - \frac{2f}{3\Omega_m}\right) + 2 - (f - \mathcal{C})\right] \frac{\delta_m^{(\rm sc)}}{k^2}$$

direction indep. time shift (E'')

$$C = \frac{3}{2}\Omega_m + (5p-2)\left(1 - \frac{1}{aH\chi}\right)$$

$dn/dL \propto L^{-(5p/2+1)}$

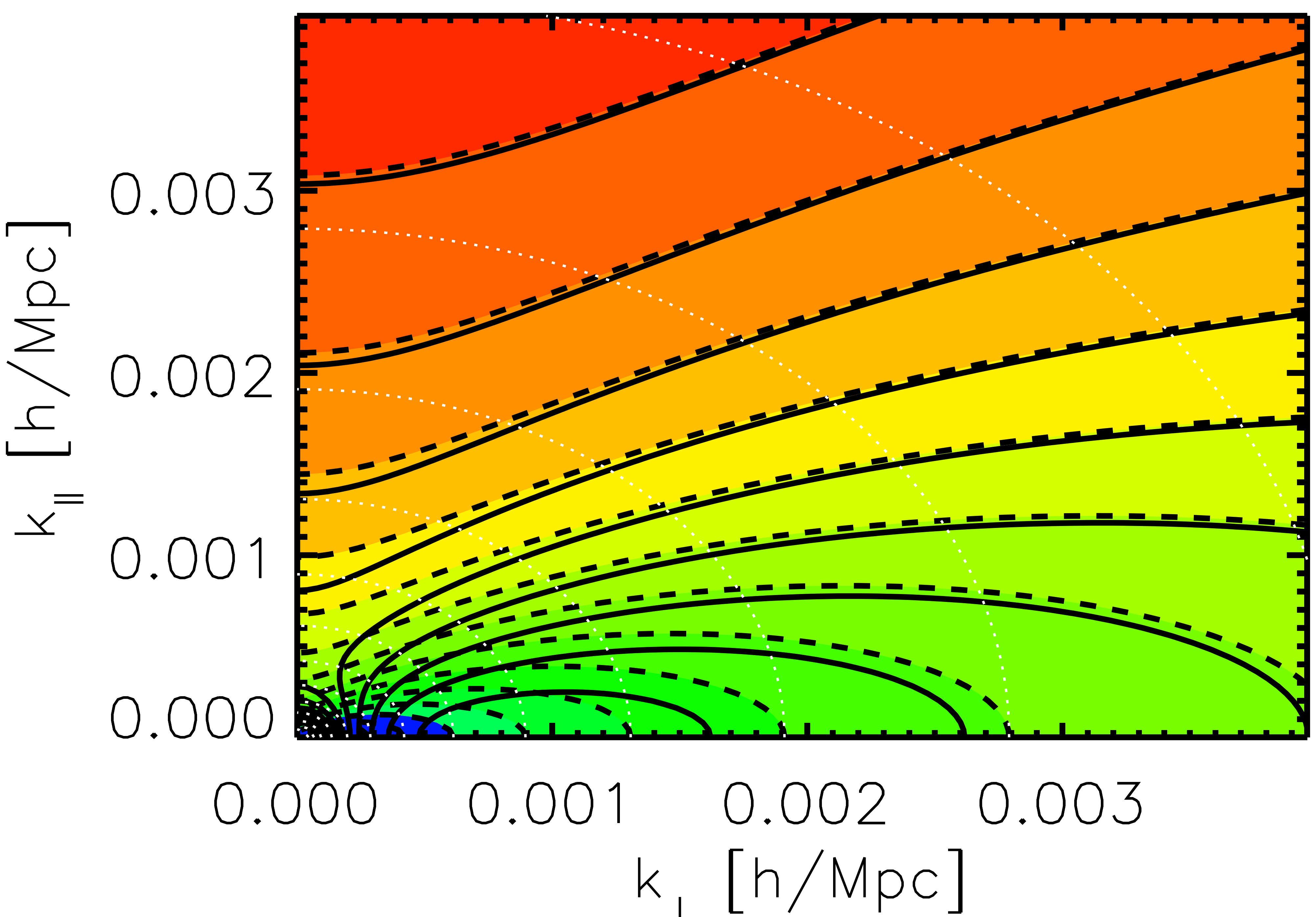
Comp. with previous works



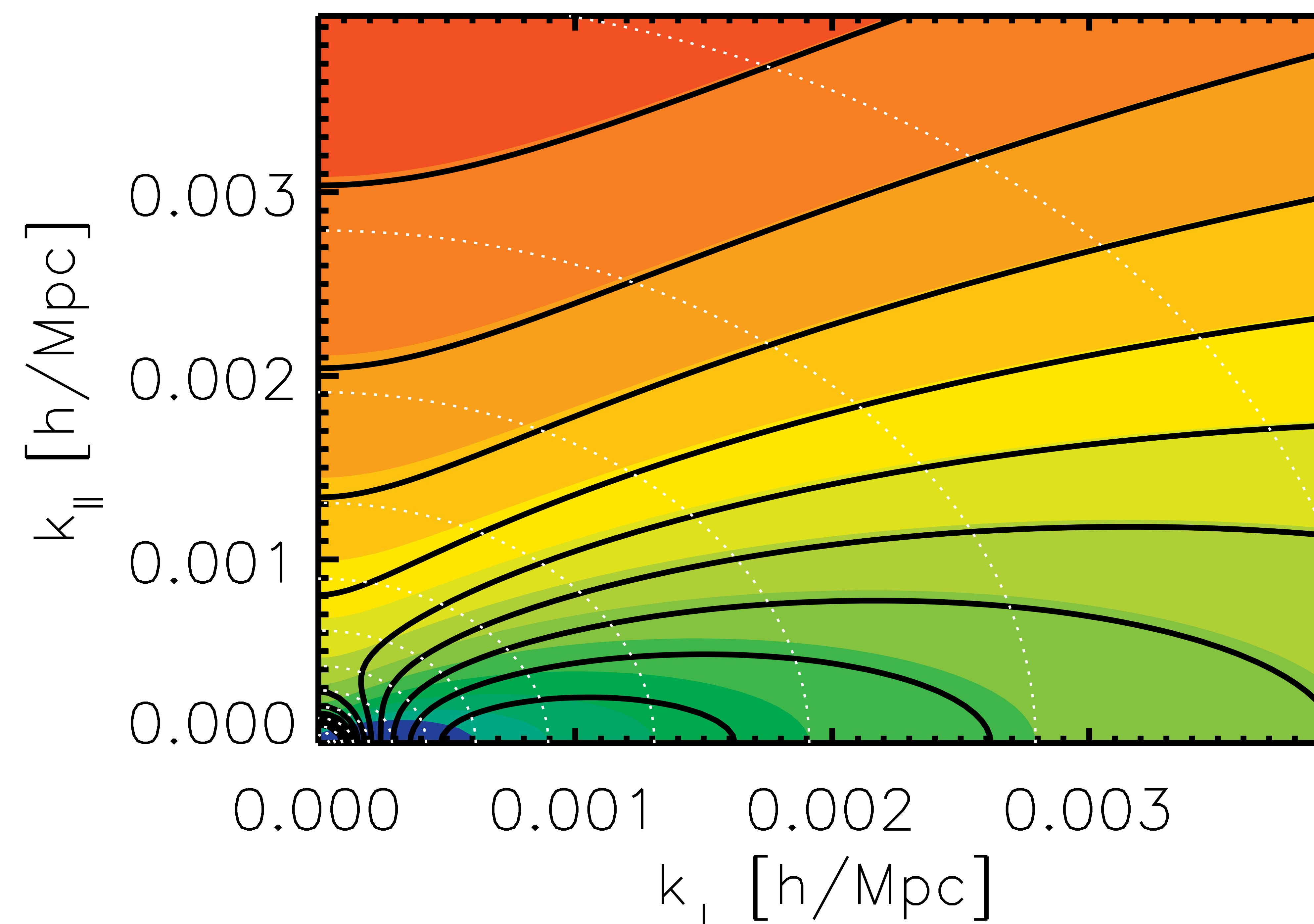
- Red = linear bias with linear redshift space distortion
- Green = linear bias in the uniform redshift gauge
- Blue = linear bias in the synchronous comoving gauge

galaxy power spectrum (2D)

Gaussian 2D Pk with GR correction

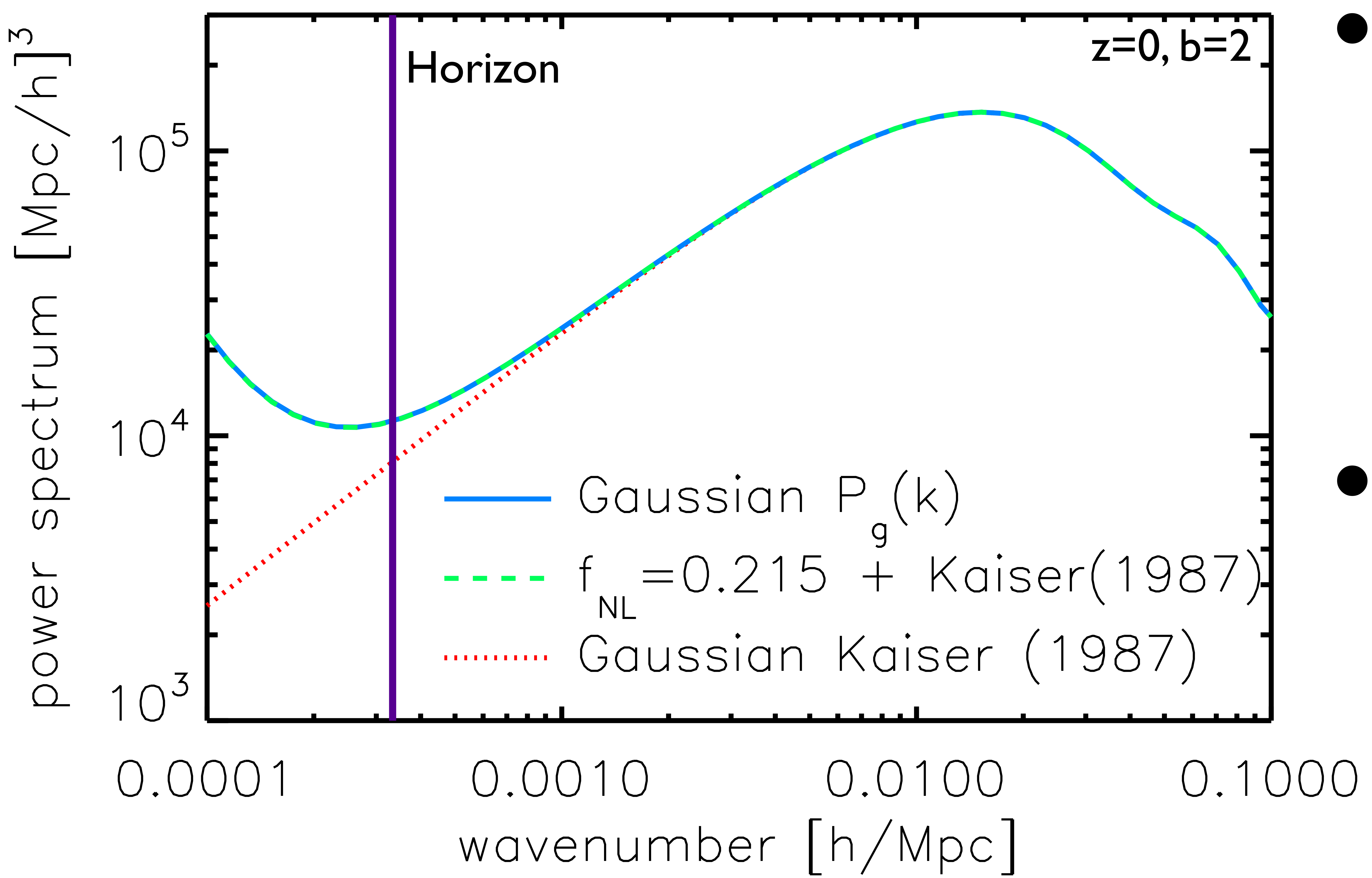


non-Gaussian 2D Pk with f_{NL}=0.215



dashed line = Kaiser effect

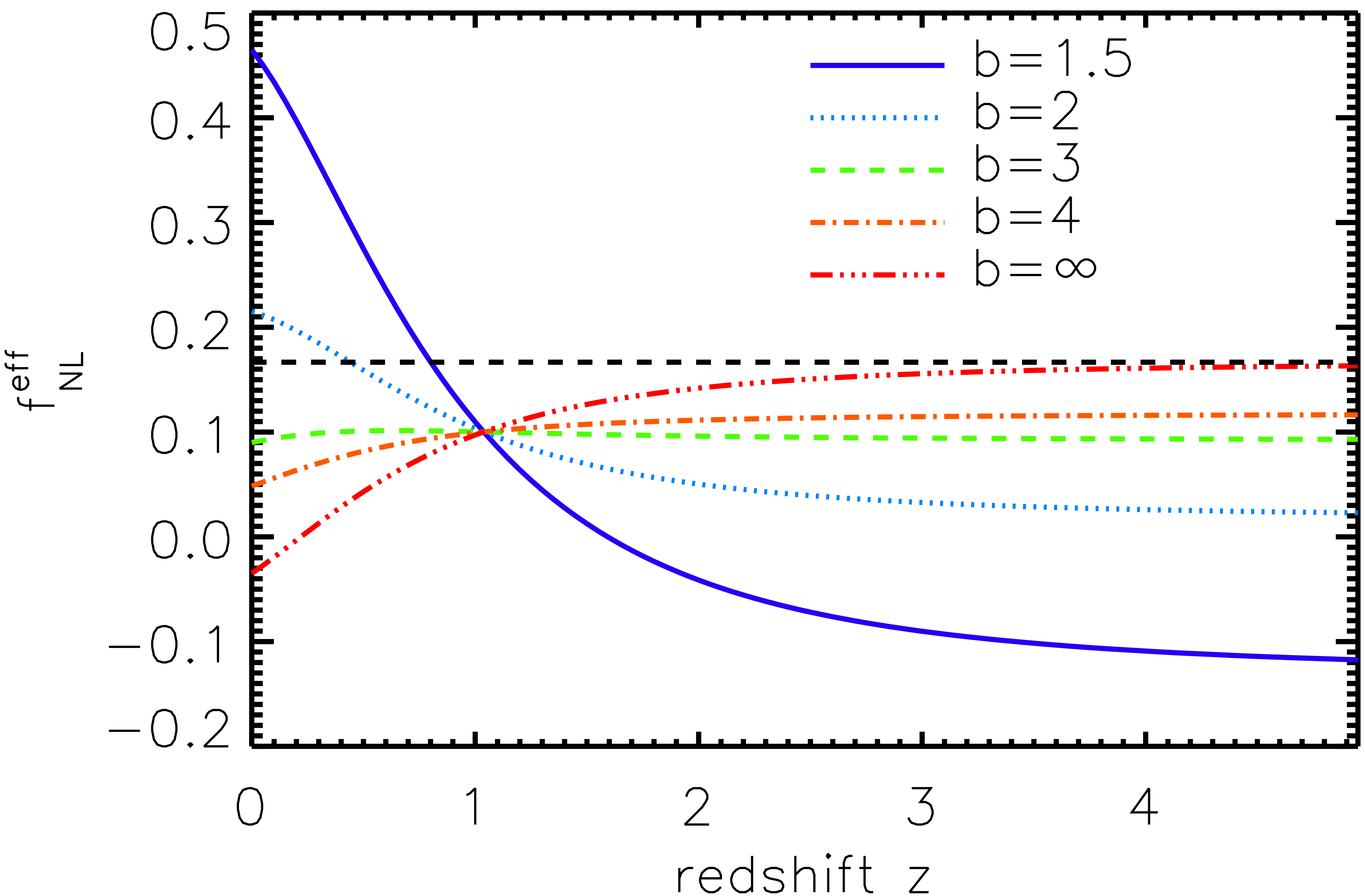
galaxy power spectrum (1D)



- Near Horizon scales, the GR effect is dominate over the linear galaxy power spectrum
- Note: Most of deviation from the volume effect!

Effective local f_{NL}

$$f_{\rm NL}^{\rm eff} = \frac{1}{2} g(a) \left[f \left(1 - \frac{2f}{3\Omega_m} \right) + \frac{2 - (f + 3\Omega_m/2)}{\delta_c (b-1)} \right]$$



- Effective local fNL varies with redshift and bias.
- Approaching 1/6 for high-z, high b
- Note: assumed p=0.4

Conclusion

- Q1: In which frame we measure the background number density?
  - [A1] Uniform redshift gauge
- Q2: In which frame is the galaxy bias linear in matter density?
  - [A2] Synchronous comoving gauge
- Combining two, we calculate the bias relation on horizon scales in synchronous comoving gauge.
- This leads $-0.1 < f_{NL}^{(eff)} < 0.5$, when $p=0.4$, $b>1.5$.