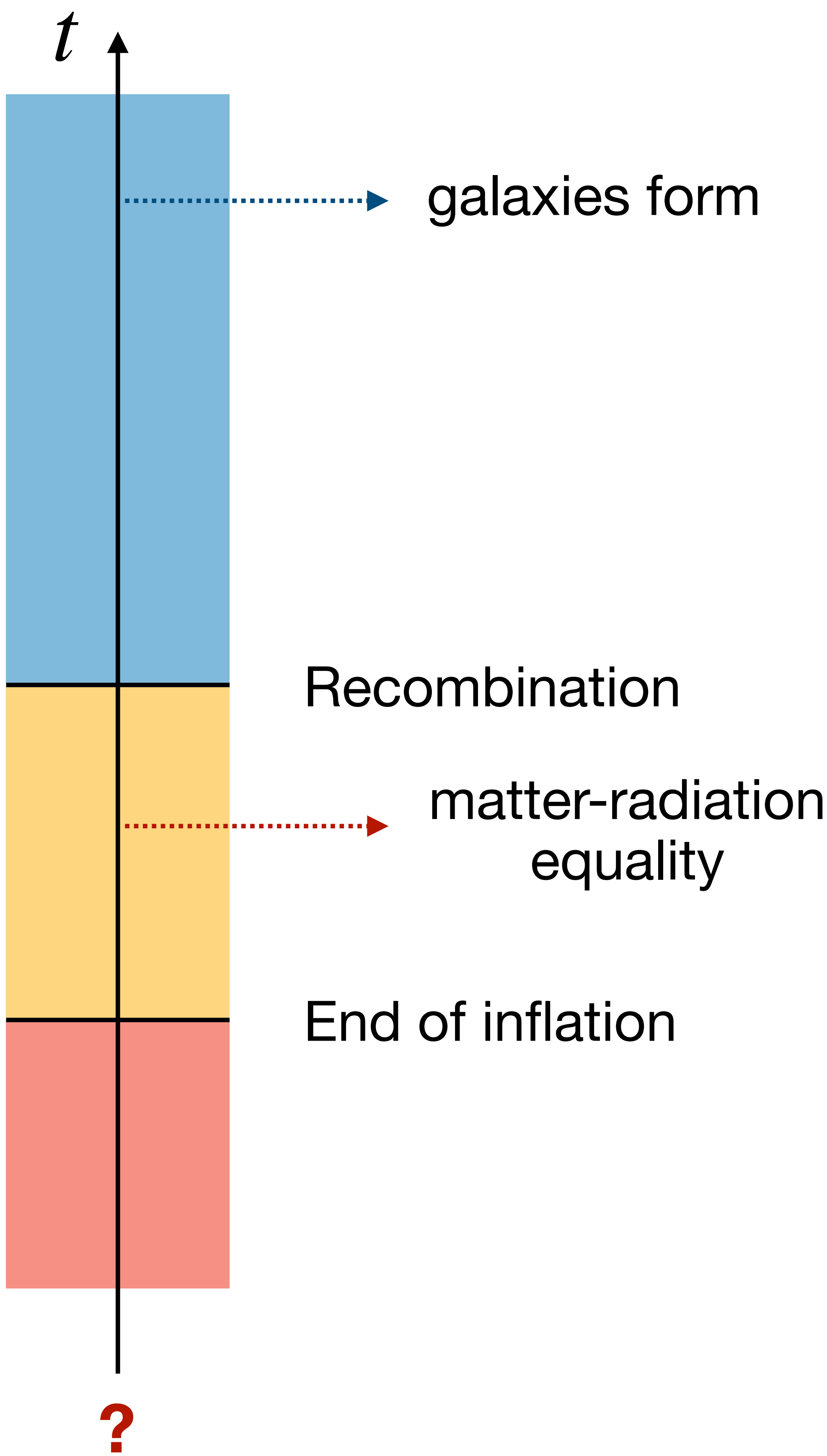
Large-Scale Structure I

Lecture 1

ΛCDM cosmological model



$$\delta_g(\boldsymbol{k}, t)$$

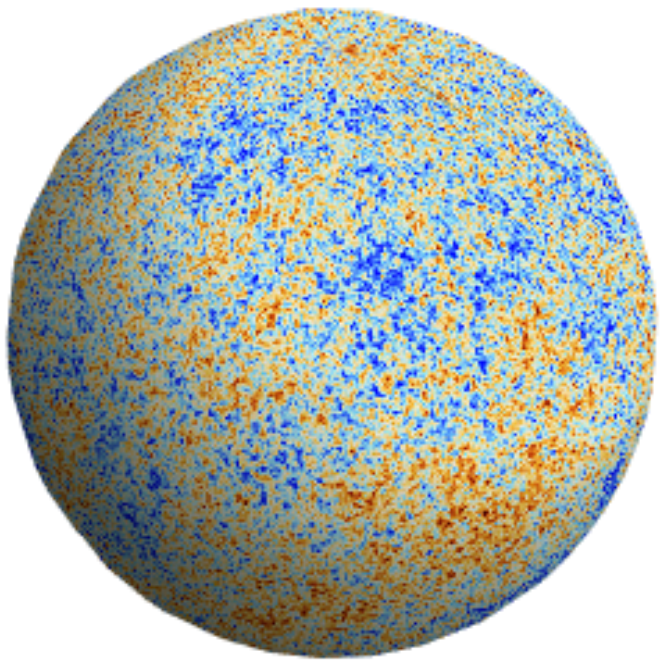
$$\delta_{\text{lin}}(\boldsymbol{k}, t) \sim D(t)\delta_{\text{in}}(\boldsymbol{k})$$

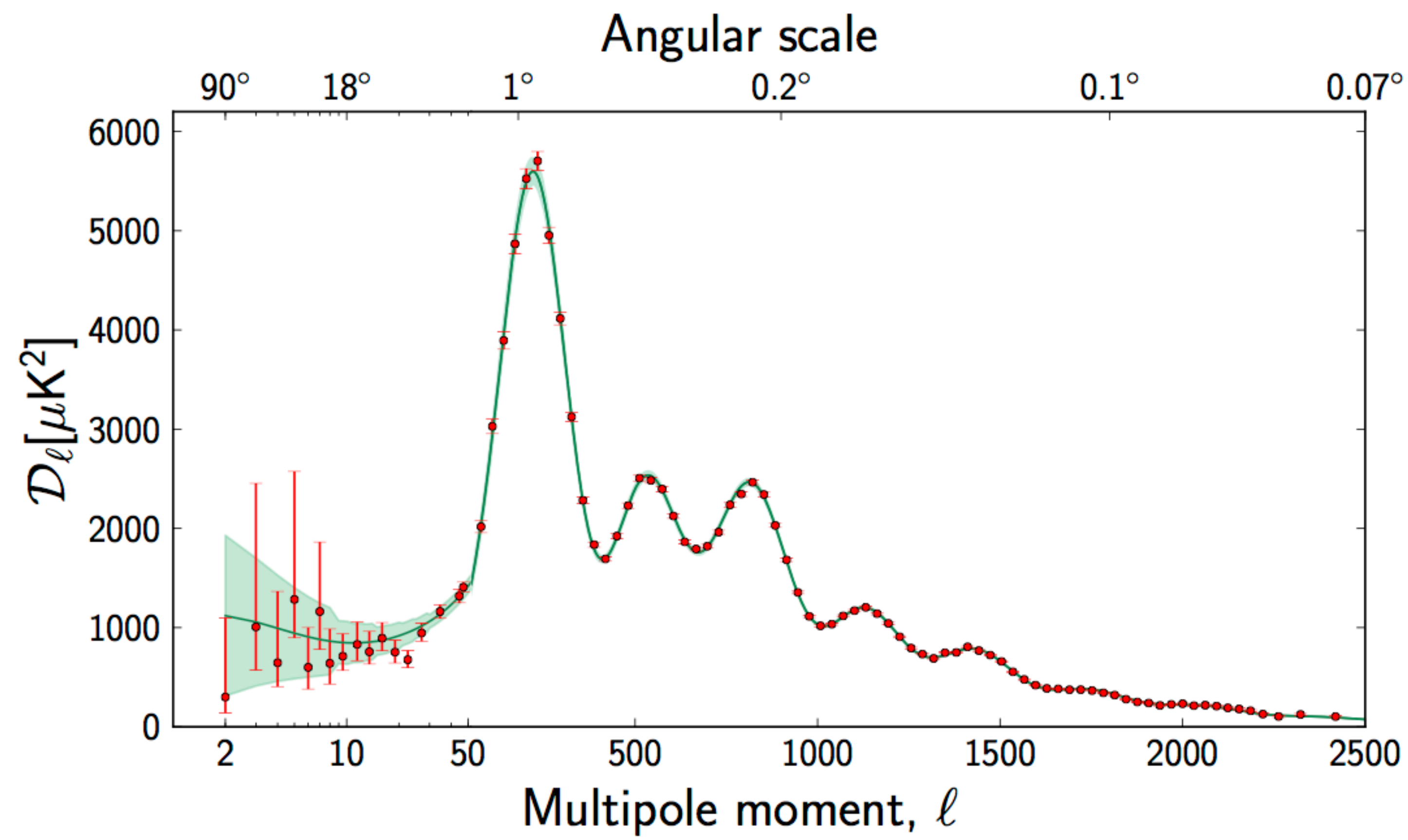
$$\delta_{\text{in}}(\boldsymbol{k}) \sim T(k)\zeta(\boldsymbol{k}) \longrightarrow \frac{\delta T}{T}$$

$$P_\zeta(k) \sim \frac{1}{k^3}\left(\frac{k}{k_*}\right)^{n_s-1}$$

$$|\Omega\rangle$$

Cosmic Microwave Background (CMB)





Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042
H_0	67.36 ± 0.54

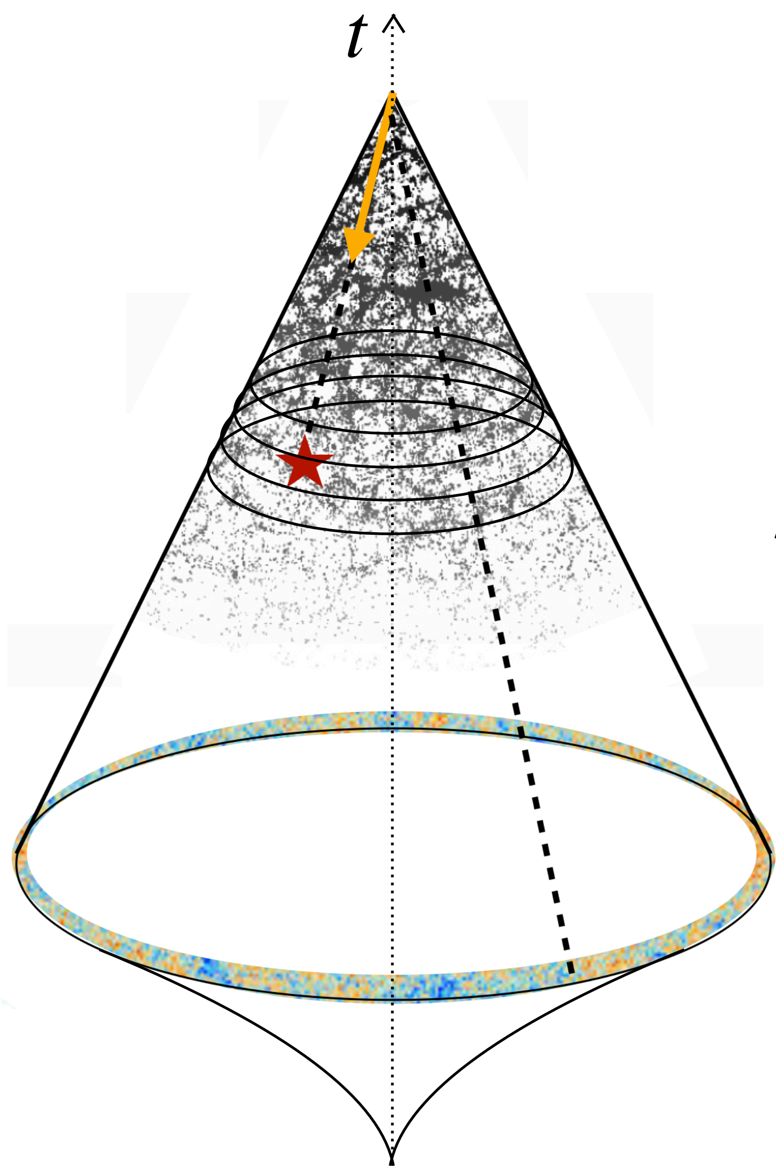
Cosmology and
high-energy physics

Beyond CMB

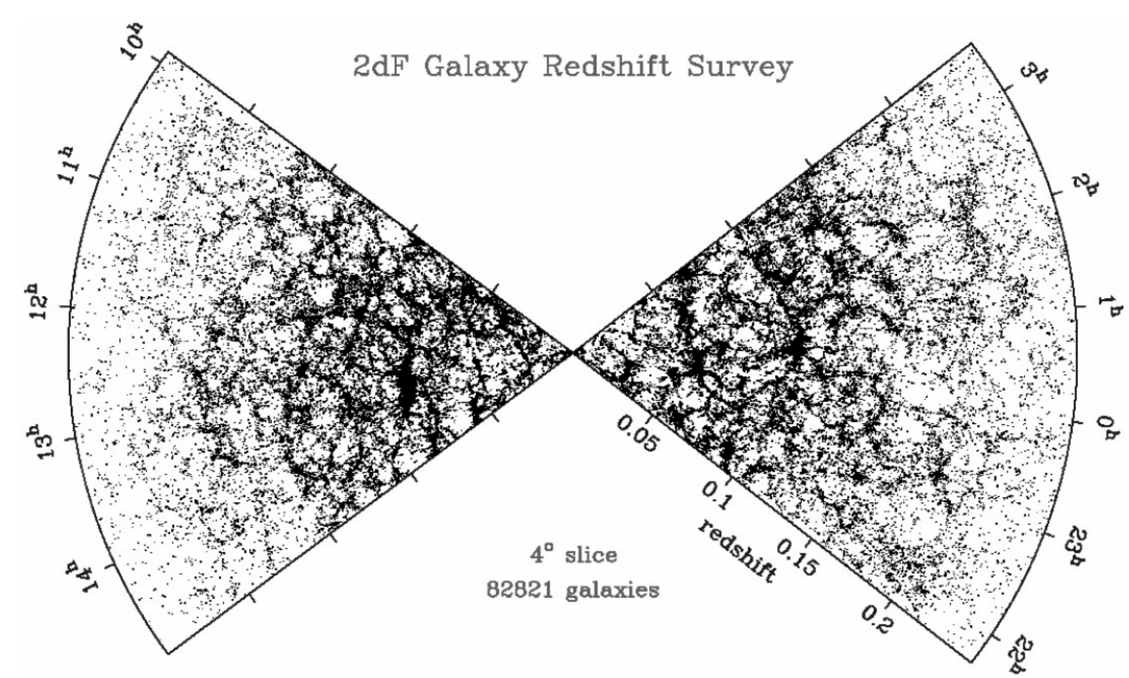
Large-scale structure (LSS)

Volume of the light-cone

“Multiple snapshots” of the universe

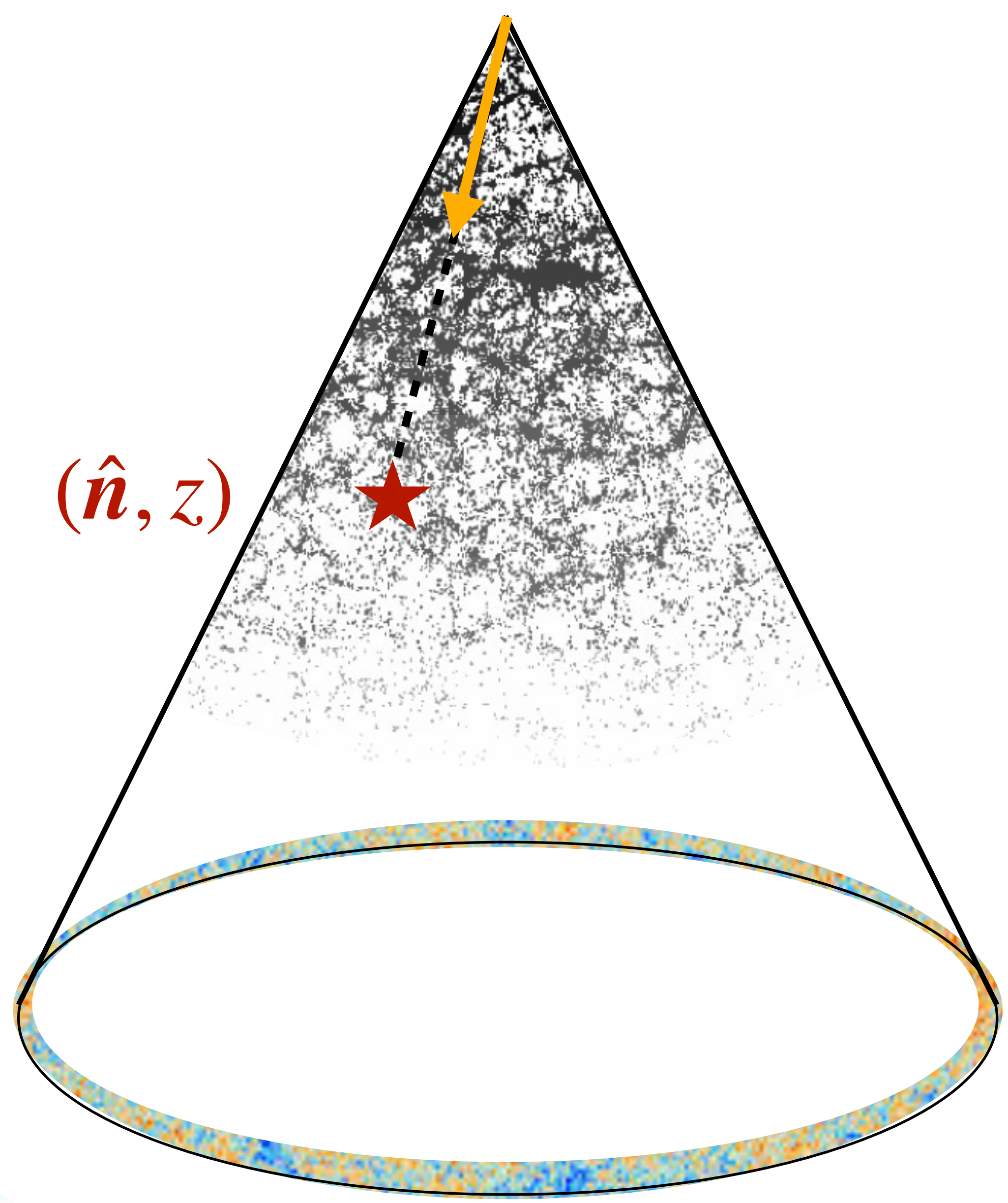


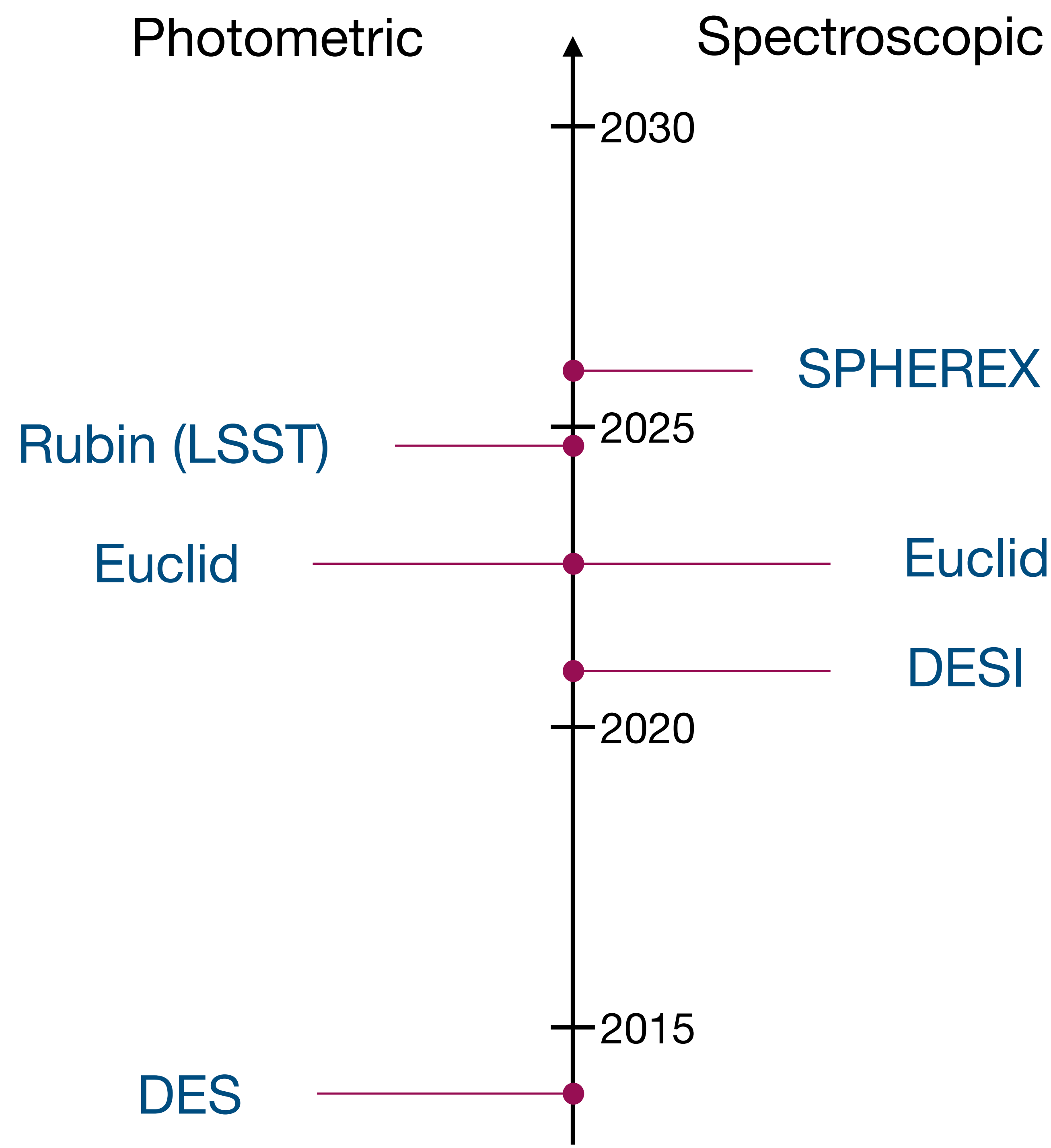
Inflation



Modern galaxy surveys

Image billions and take spectra of ~100 million of objects up to z<5





Open questions

New level of precision, deviations from ΛCDM at $\sim 10^{-3}$ level

1) Properties of the initial conditions

Single “clock”? Speed of inflaton fluctuations less than 1?
“Spectroscopy” of massive/higher spin particles?
Primordial features in the power spectrum?

2) Everything gravitates

Sum of neutrino masses.
Other massive (but light) relics? Ultralight axions?
Spatial curvature, dark energy?
New energy components in early or late universe?
Probing dark sector, new long-range interactions?

Open questions

How can galaxies be sensitive to all these things?

Large volume — a lot of statistics

Matter does not move much from the ICs

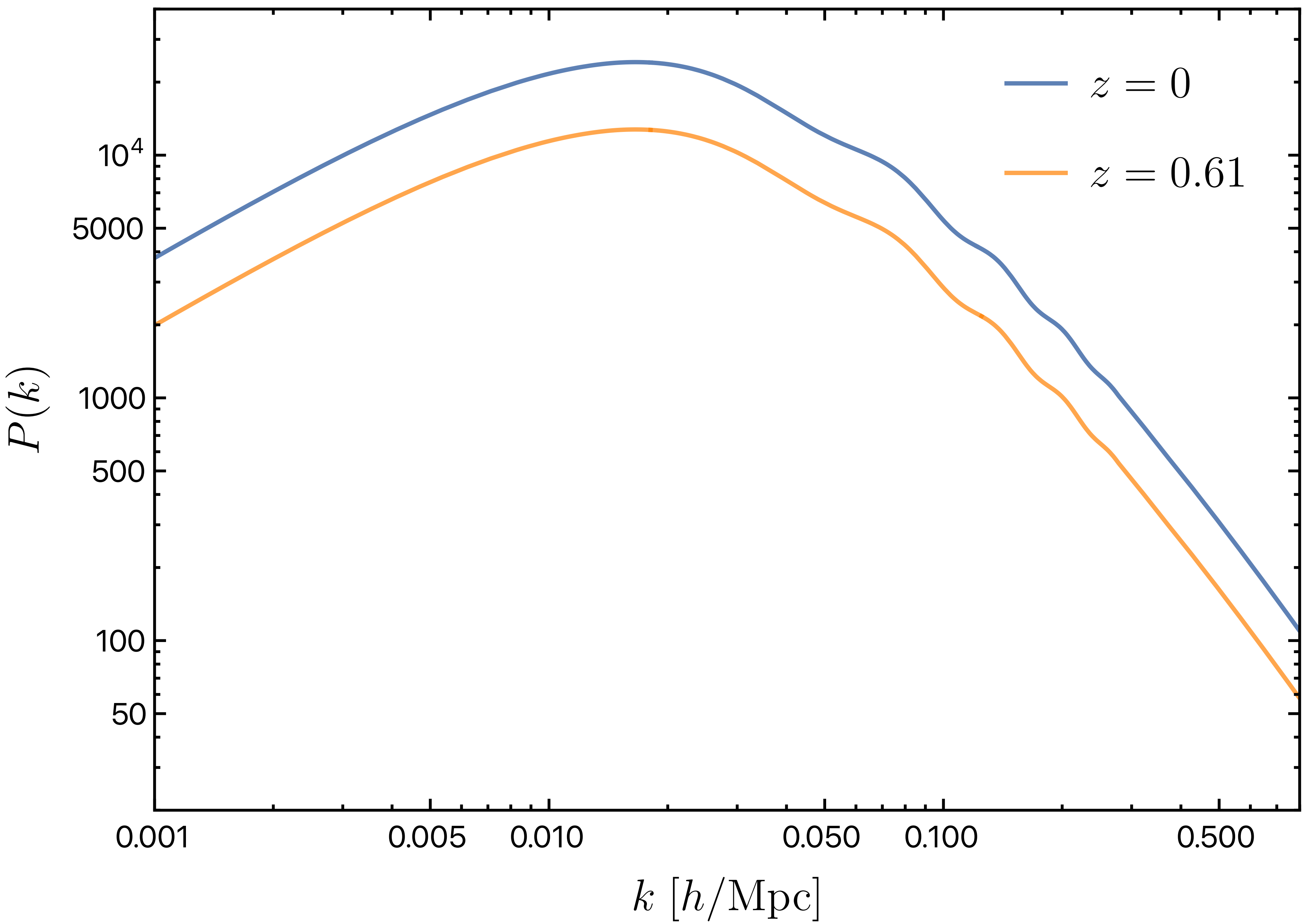
Evolution very sensitive to matter content

The key question: evolution of late-universe fluctuations

The main problem: we do not know galaxy formation physics sufficiently well

Linear matter power spectrum

Let us begin with the linear evolution $\delta_{\rm lin}(\boldsymbol{k}, t) = D(t)\delta_{\rm in}(\boldsymbol{k})$



Linear matter power spectrum

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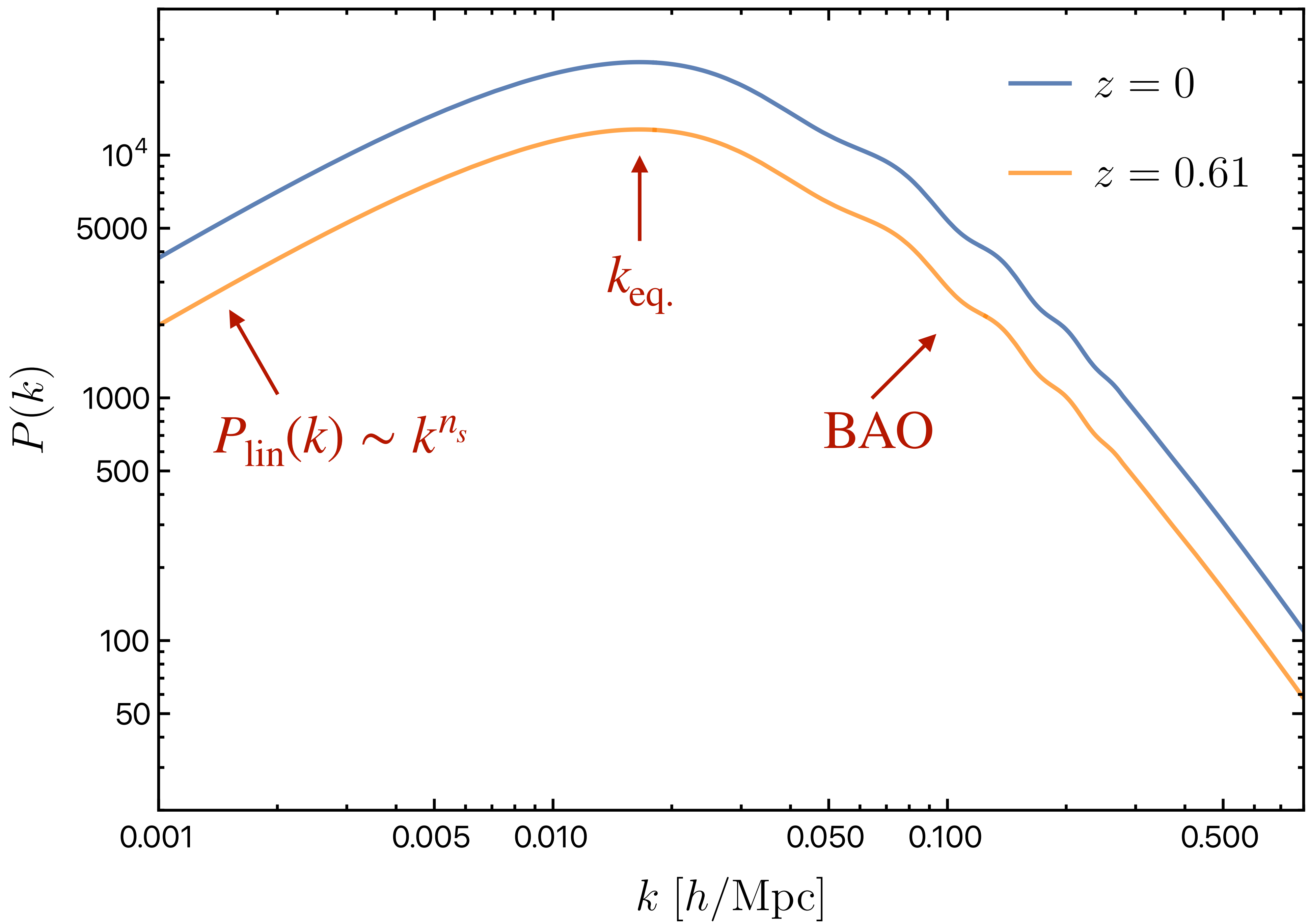
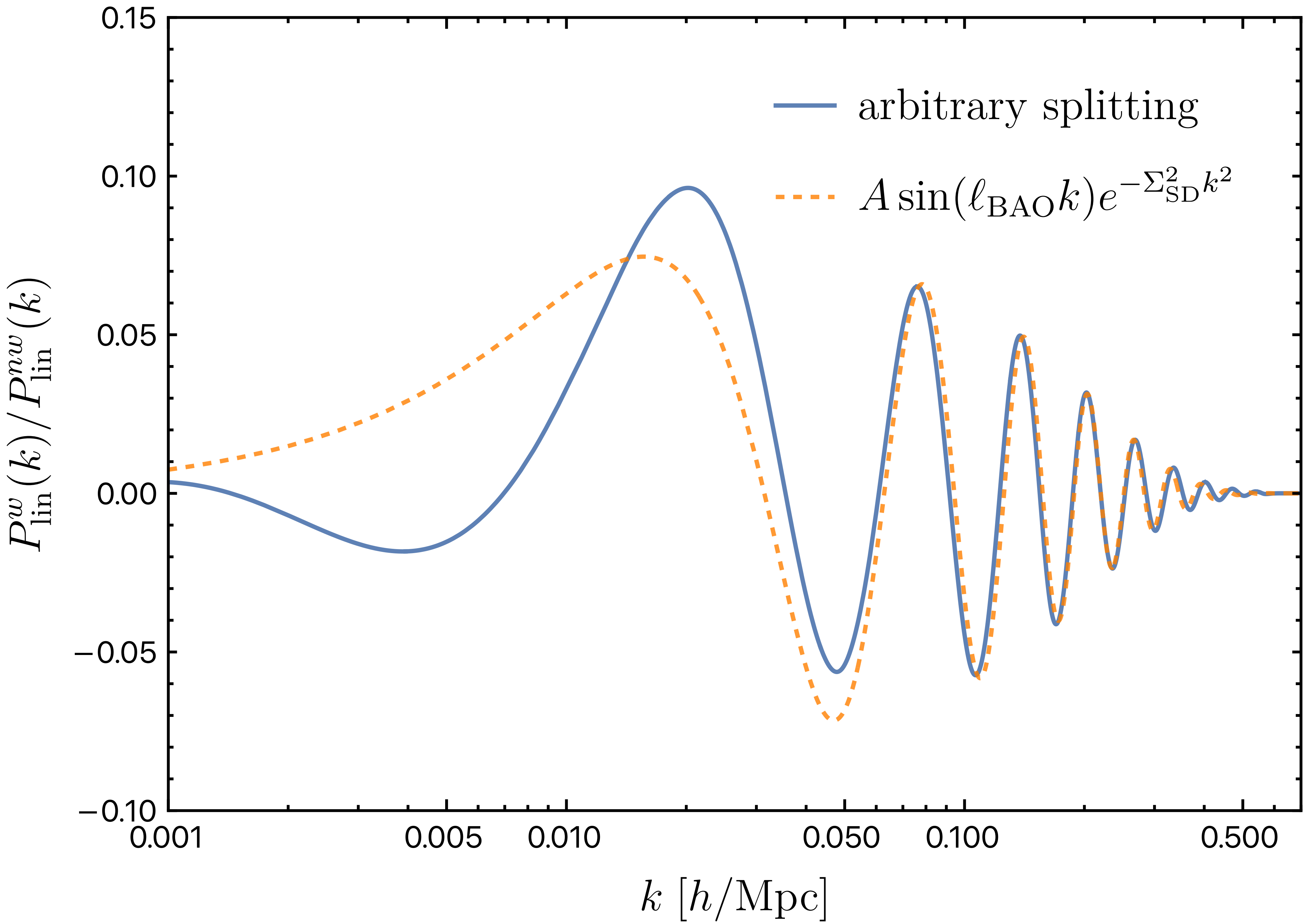
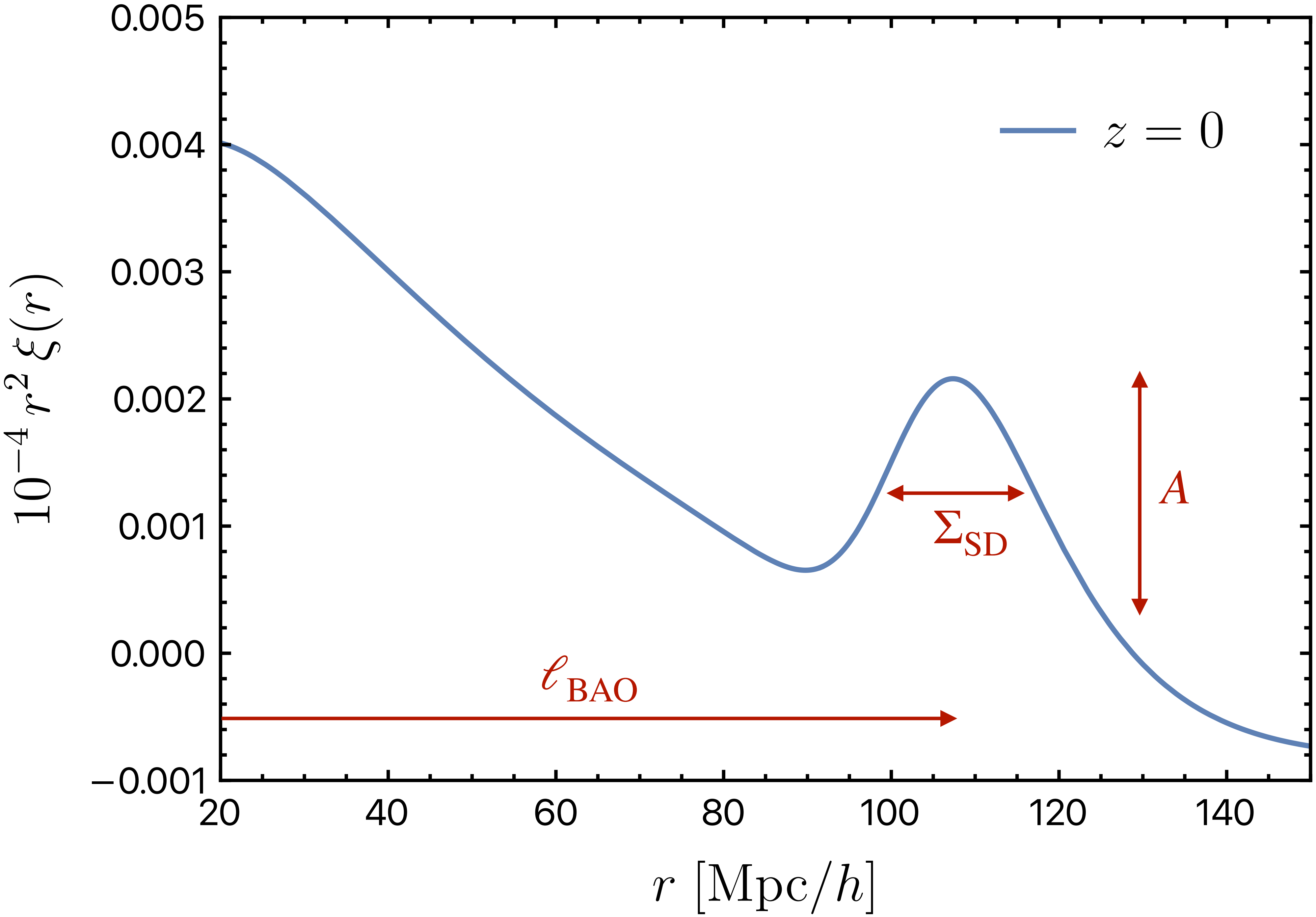


Linear power spectrum — BAO wiggles



Linear matter correlation function



Smoothed field and statistics

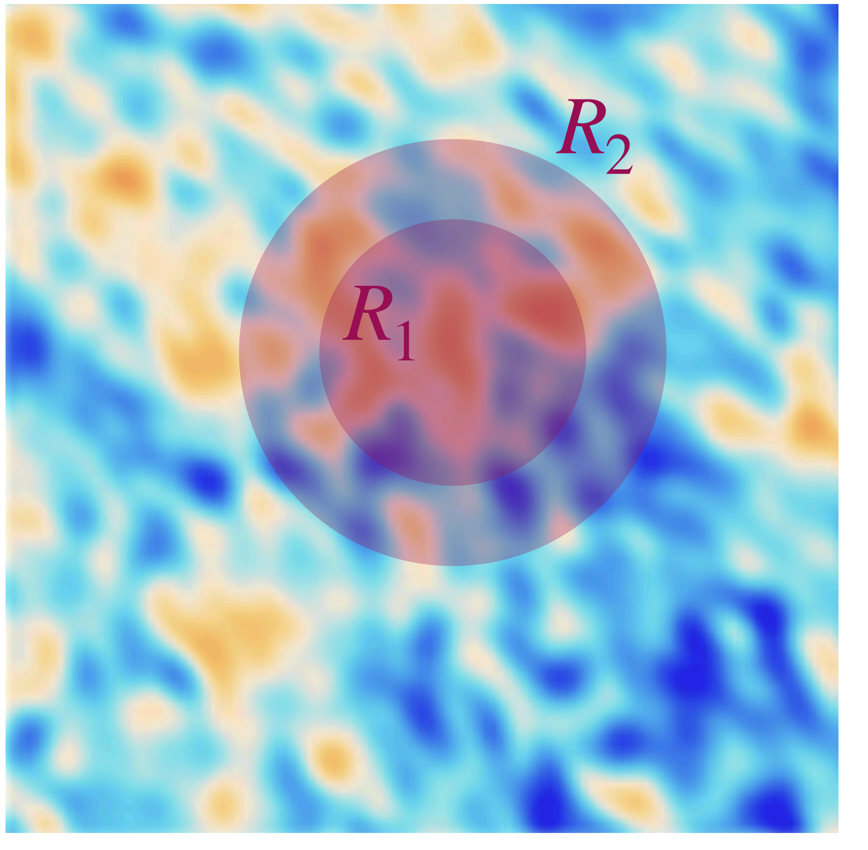
$$\delta_{\mathrm{lin},R}(\boldsymbol{x}) = \int d^3\boldsymbol{x}' W_R(|\boldsymbol{x}-\boldsymbol{x}'|)\delta_{\mathrm{lin}}(\boldsymbol{x})$$

$$\mathrm{Var}(\delta_{\mathrm{lin},R}) = \int \frac{k^2 dk}{2\pi^2} P_{\mathrm{lin}}(k) W^2(kR)$$

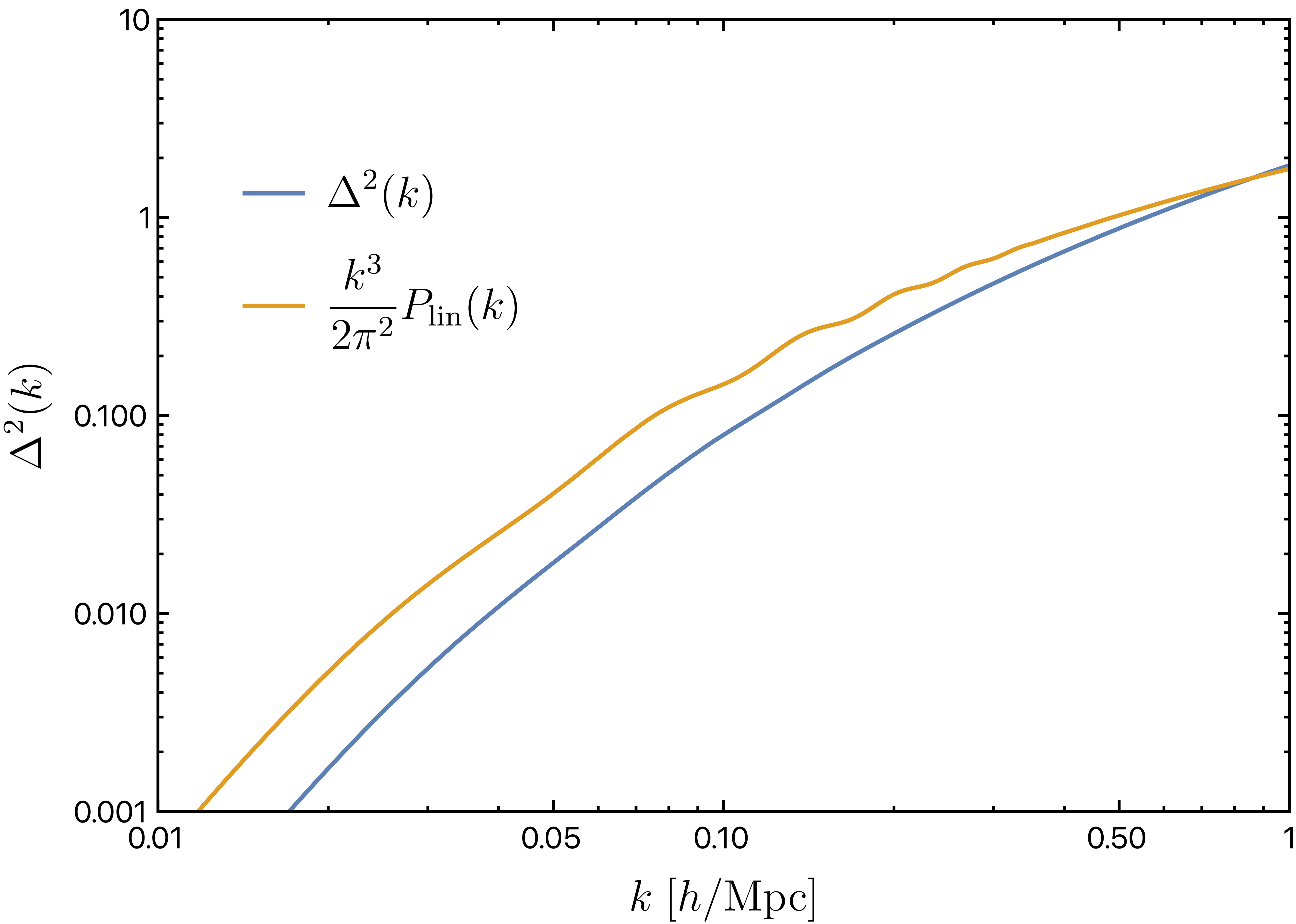
$$\Delta^2(k) \equiv \int_{q<k} \frac{d^3\boldsymbol{q}}{(2\pi^3)} P_{\mathrm{lin}}(q)$$

$$\Delta^2(k) \approx \frac{k^3}{2\pi^2} P_{\mathrm{lin}}(k)$$

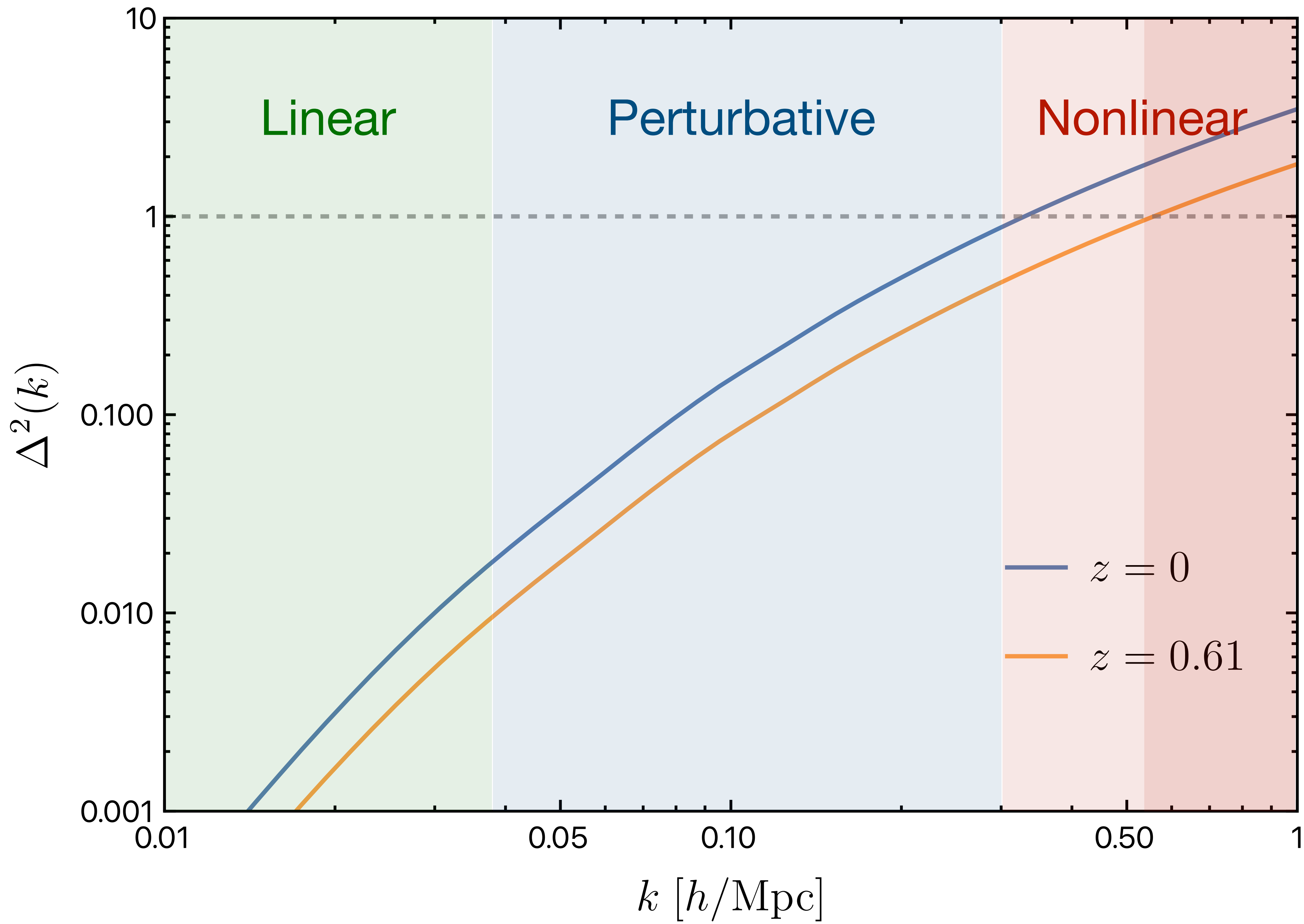
Smooth the field on the scale R



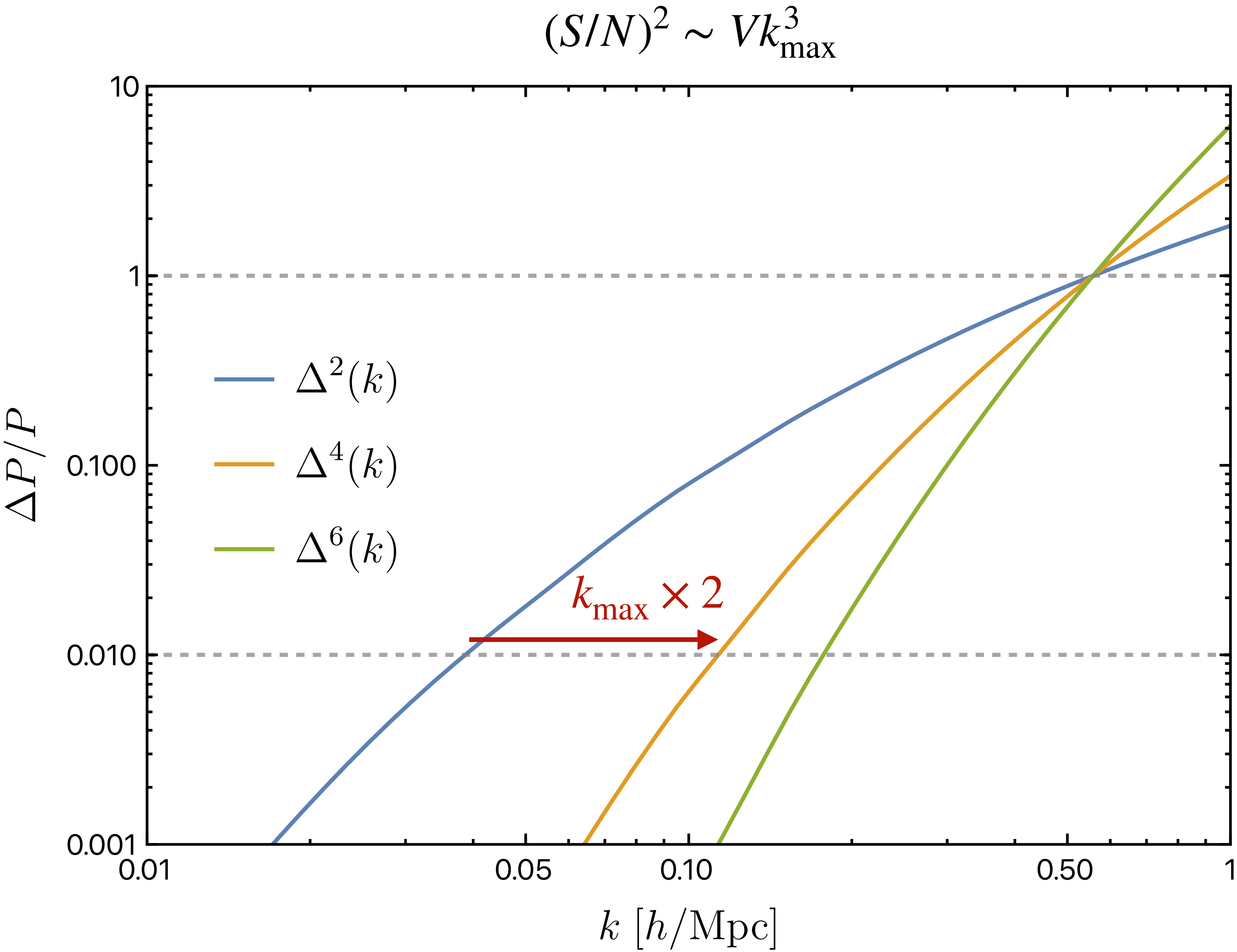
Variance of the linear matter density field



Variance of the linear matter density field

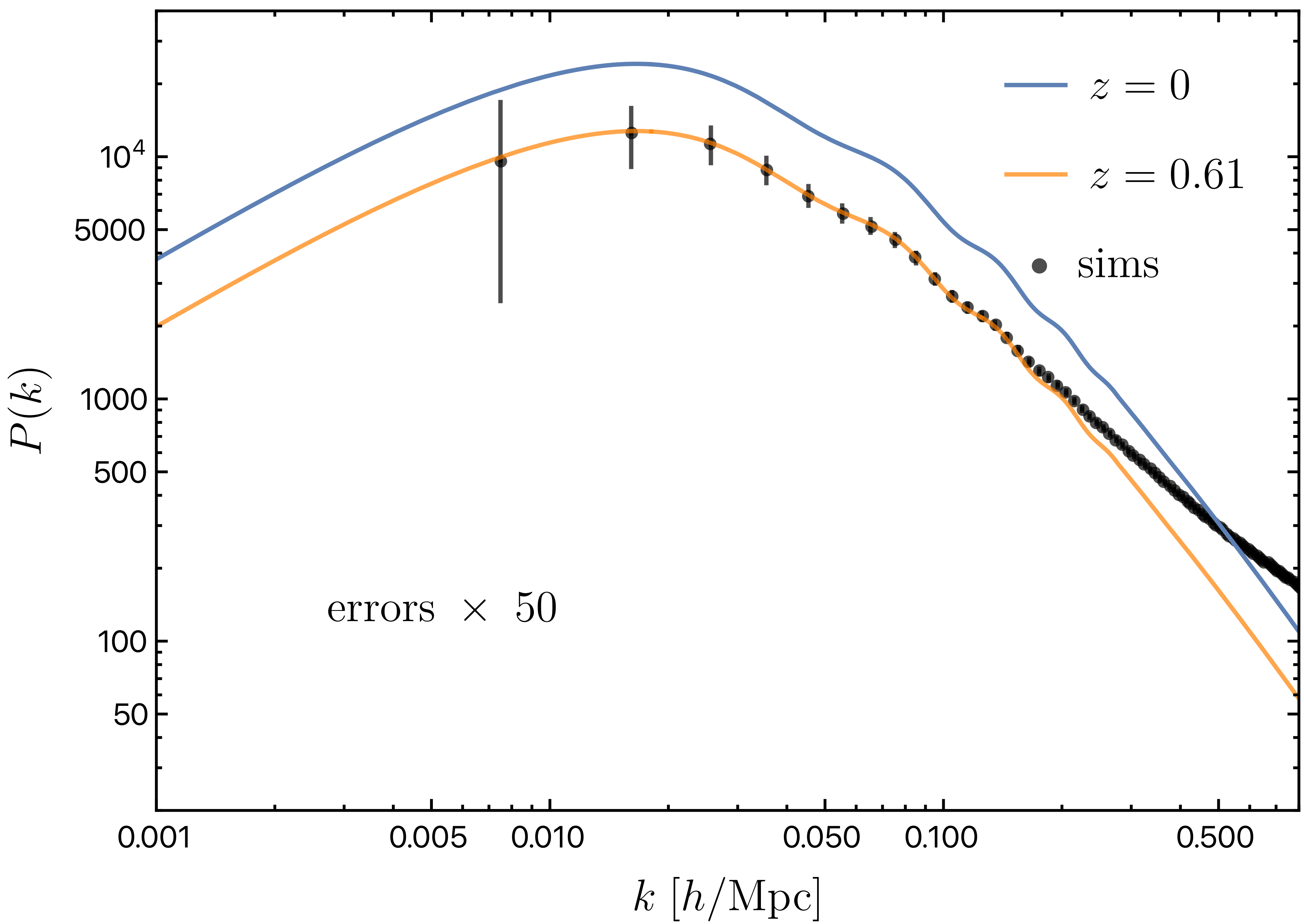


Motivation for perturbation theory



Motivation for perturbation theory

Nishimichi et. al. (2020) — PT Challenge Simulations



Motivation for perturbation theory

In the next couple of lectures, we will make this plot look much better