Primordial black holes and how to produce them

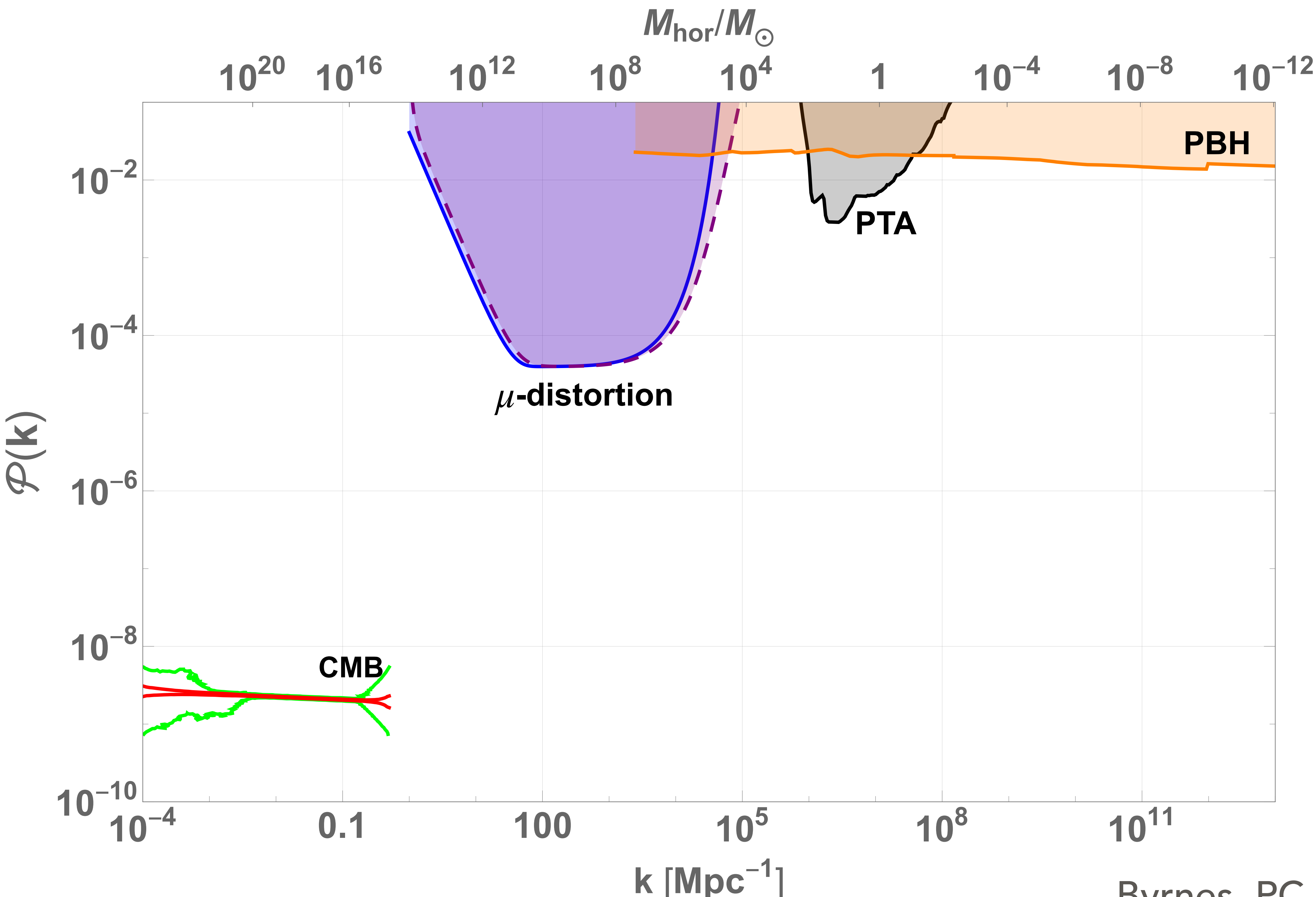
Philippa Cole
University of Sussex, Brighton, UK

with Christian Byrnes (Sussex) and Subodh Patil (Niels Bohr Institute, Copenhagen)

arXiv:1811.11158

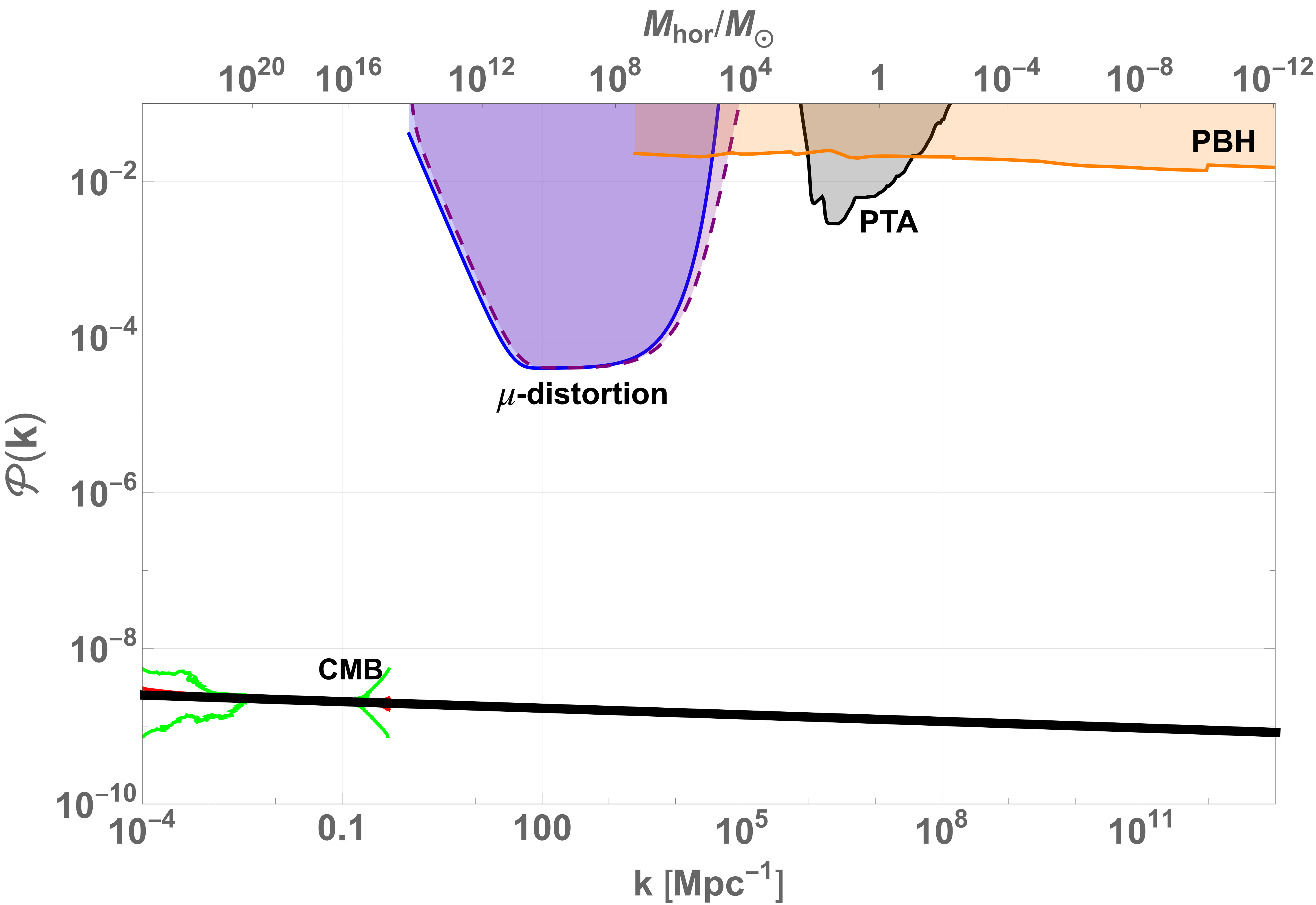
The primordial power spectrum

Measure of how overdense patches of a particular size were at the end of inflation - best 'observable' we have

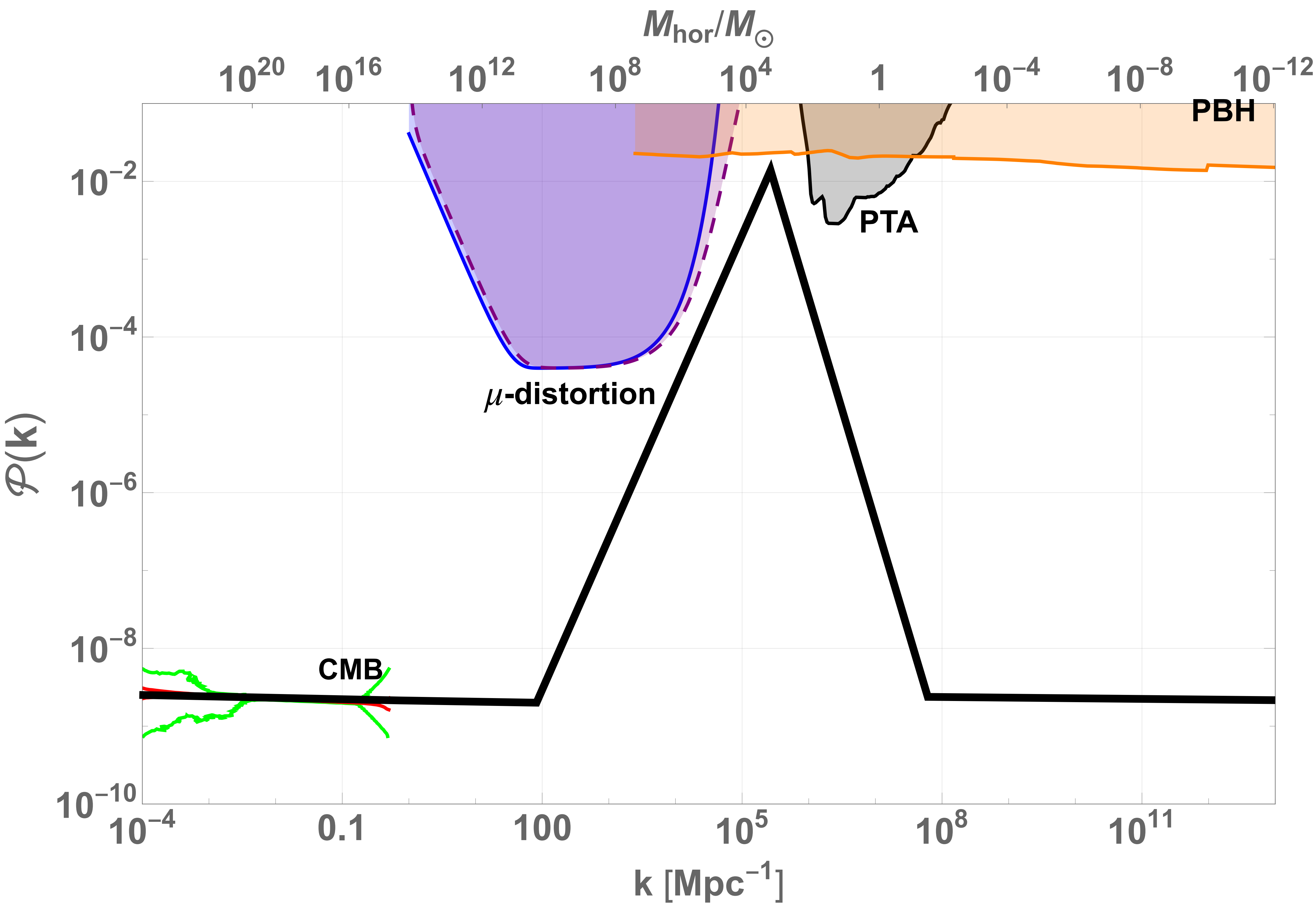


Byrnes, PC, Patil 2018

On CMB scales, the power spectrum is almost scale-invariant with a small amplitude.



But what if we draw a peak or a feature on the smaller scales?

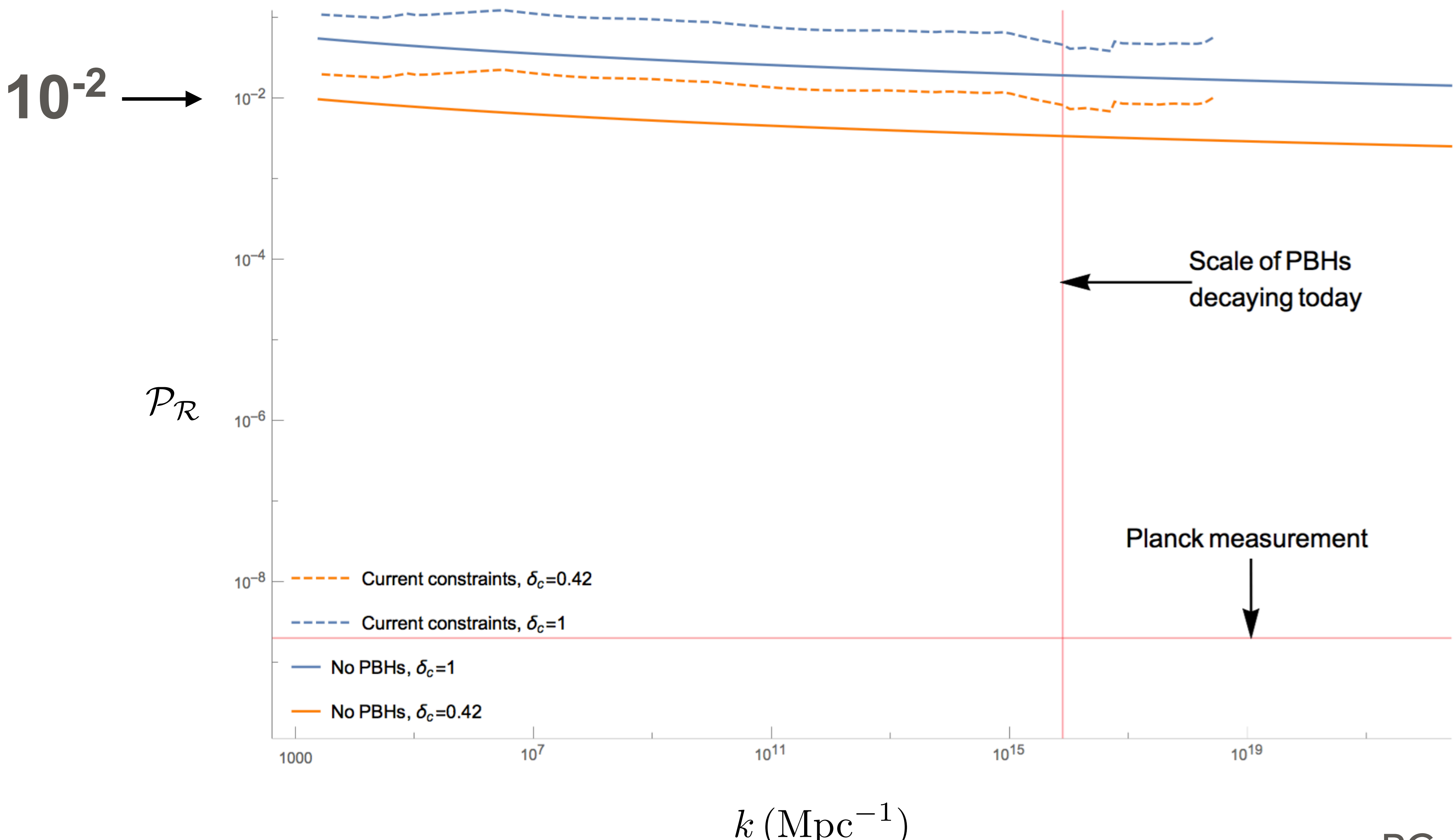


Outline

- Why might we want a peak?
- Why are we interested in PBHs?
- What can we learn about inflation from the shape of the primordial power spectrum?
- Current and future observational constraints

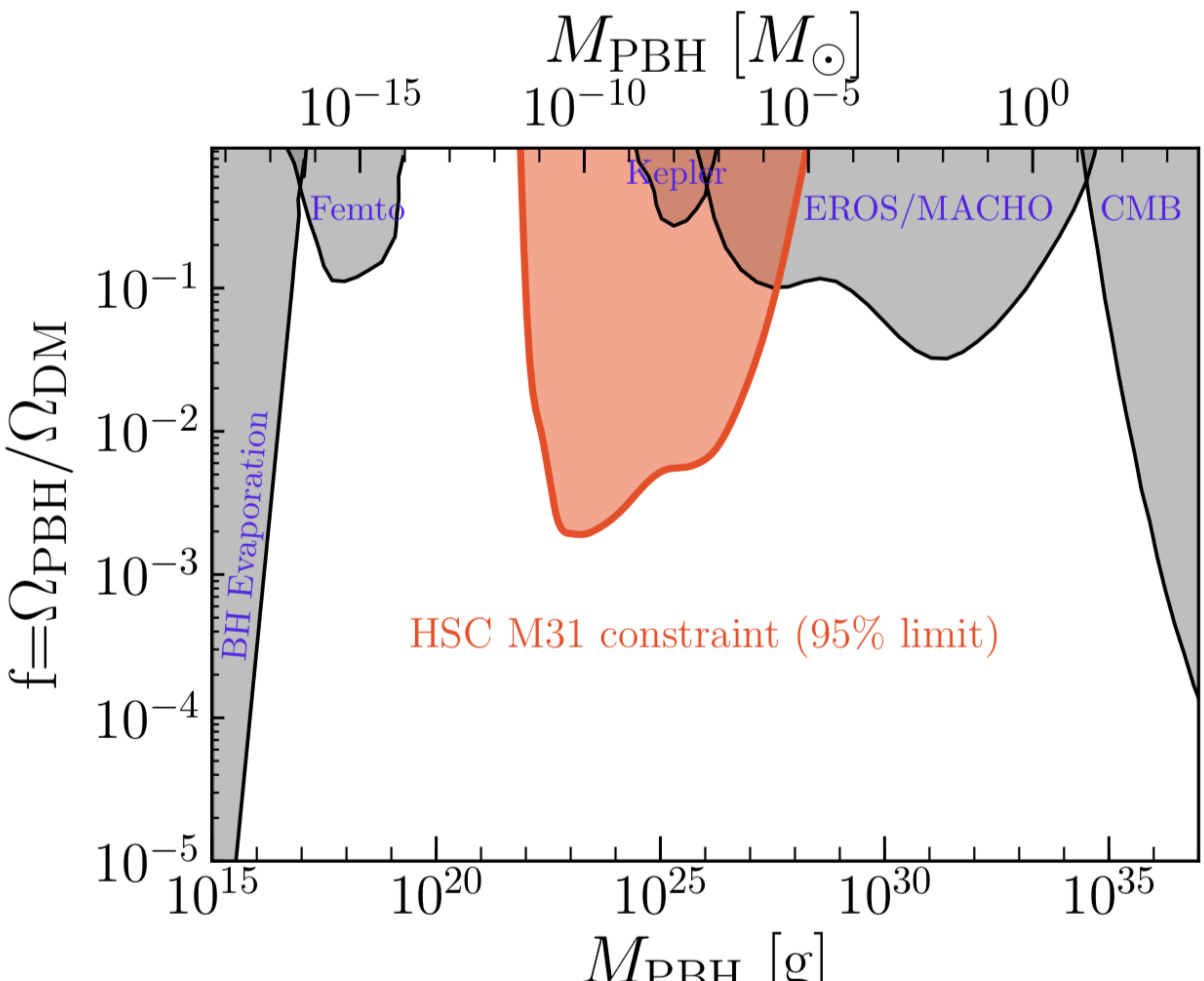
Why might we want a peak?

Primordial black holes can form from large over densities that reenter the horizon after inflation. Assuming Gaussian fluctuations, the power spectrum needs to hit around 10^-2 in order for them to form, so you need a large peak.



PC, Byrnes 2017

Why might we want PBHs?



Niikura et al. 2018 (updated version)

How is inflation related to the power spectrum?

- The primordial power spectrum is related to the inflationary potential:

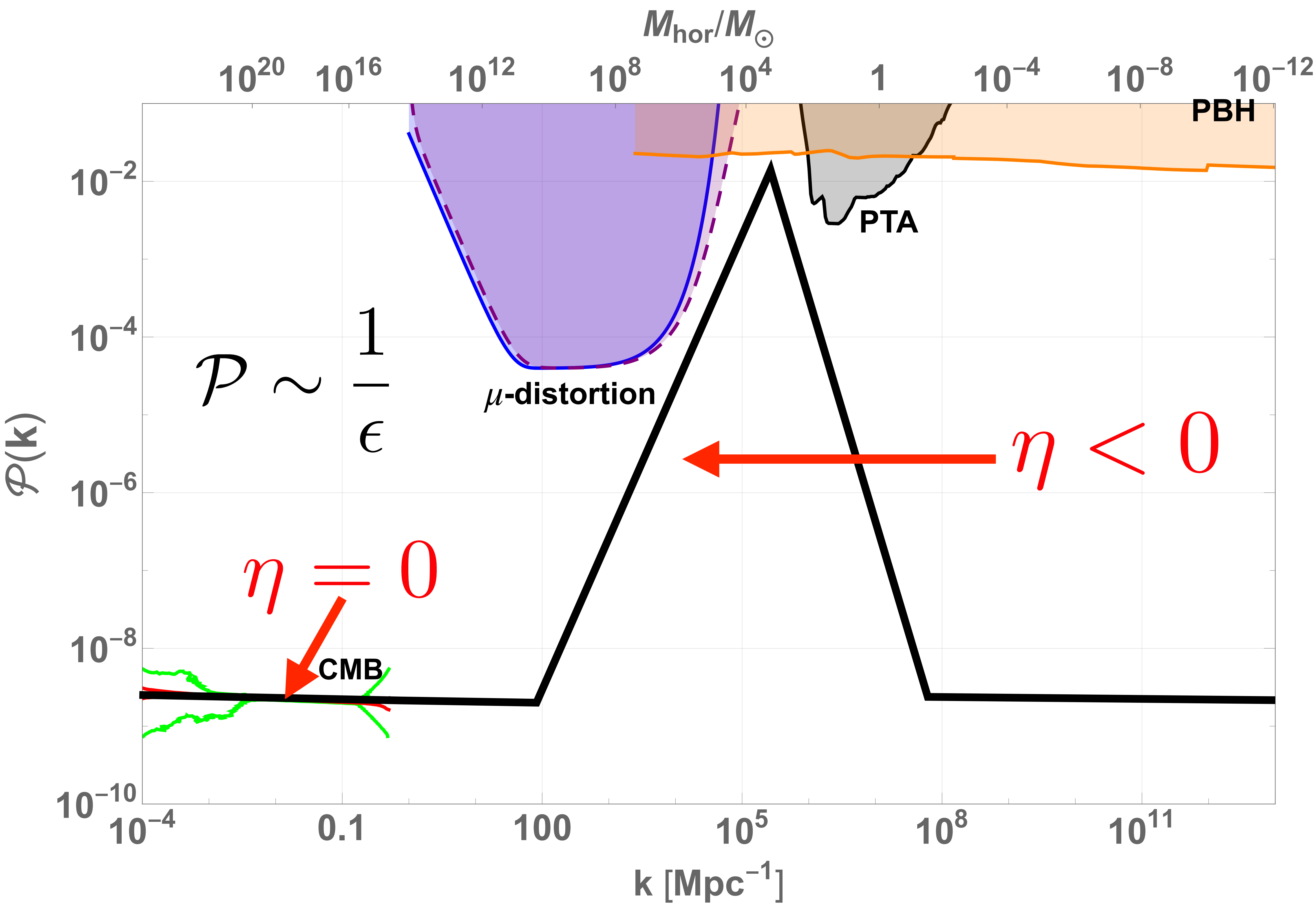
$$\epsilon = -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}^2}{2H^2 M_{\rm pl}^2} \qquad \eta = \frac{\dot{\epsilon}}{\epsilon H}$$

- For the simplest models of inflation:

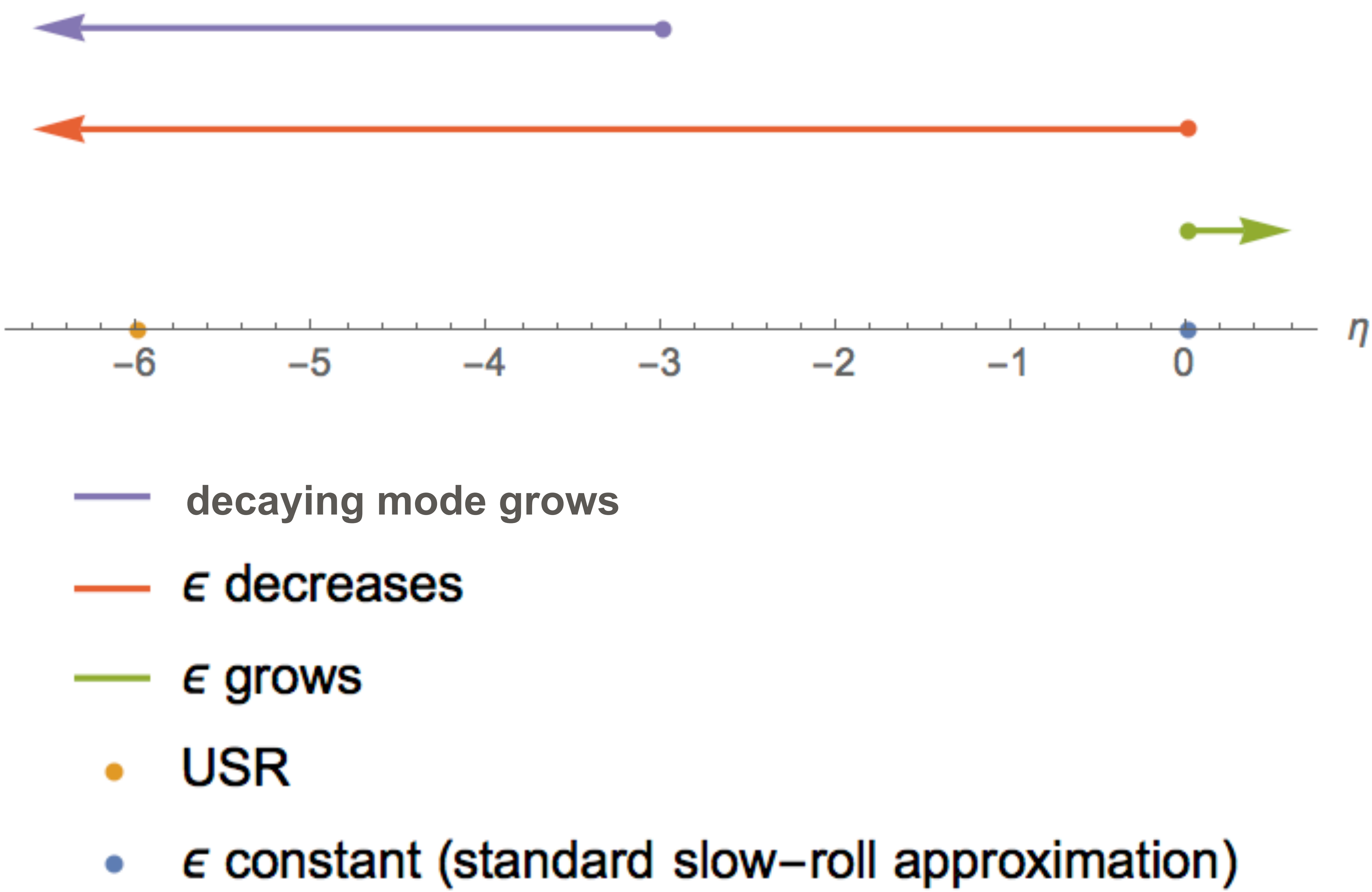
$$\mathcal{P} \sim \frac{1}{\epsilon} \qquad \epsilon_{\rm SR} \sim \left(\frac{V'}{V}\right)^2$$

Slow-roll approximation only valid when ϵ is constant and η ~0

Need to break slow-roll to produce a peak



SR/BSR/USR



η
−6
−5
−4
−3
−2
−1
0
decaying mode grows
ϵ decreases
ϵ grows
USR
ϵ constant (standard slow−roll approximation)

Superhorizon growth

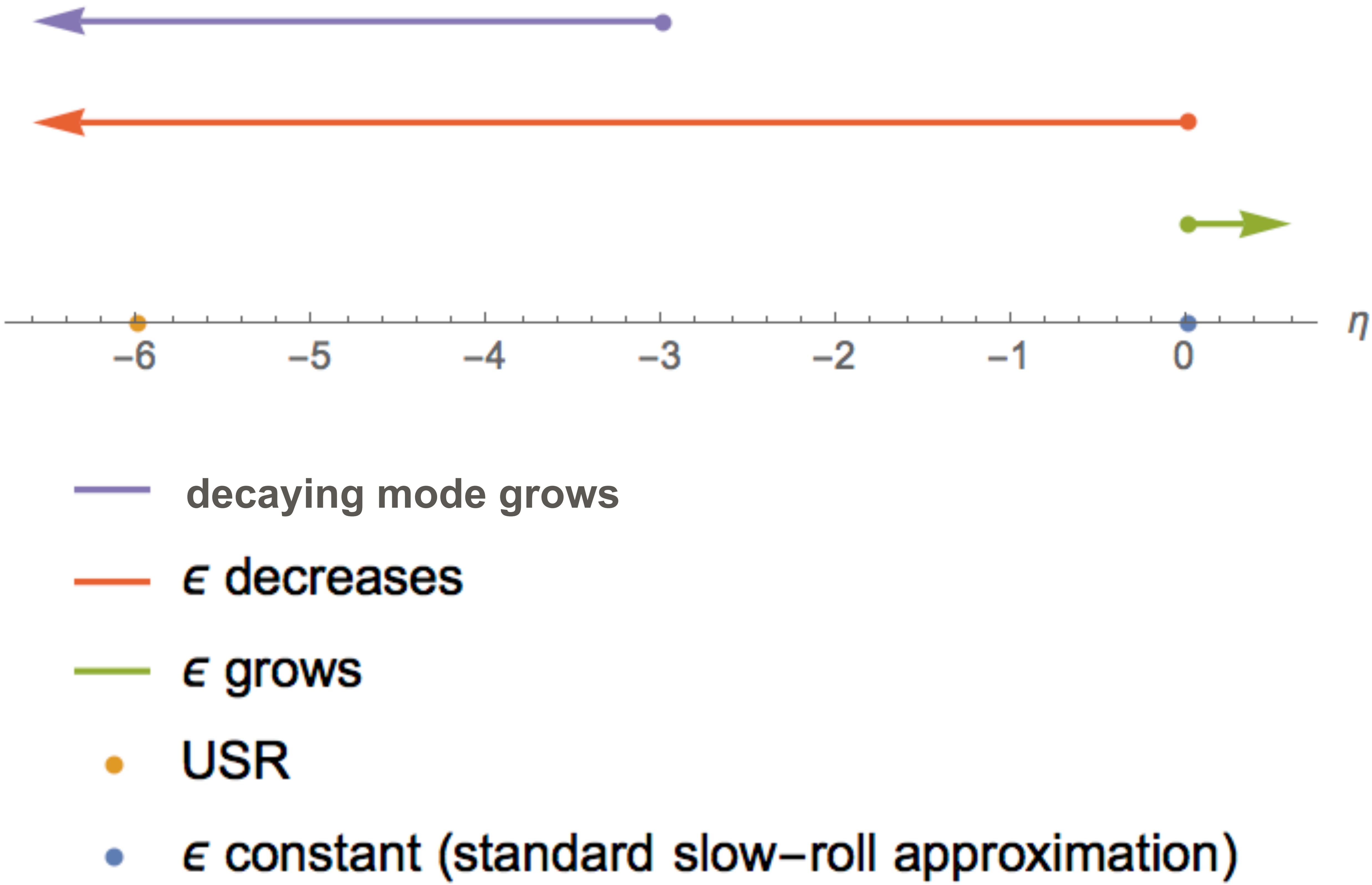
In the slow-roll approximation, everything freezes out after horizon exit. Beyond slow-roll, super horizon growth is possible

Superhorizon growth when ϵ decreases faster than a^3, which is equivalent to $\eta < -3$

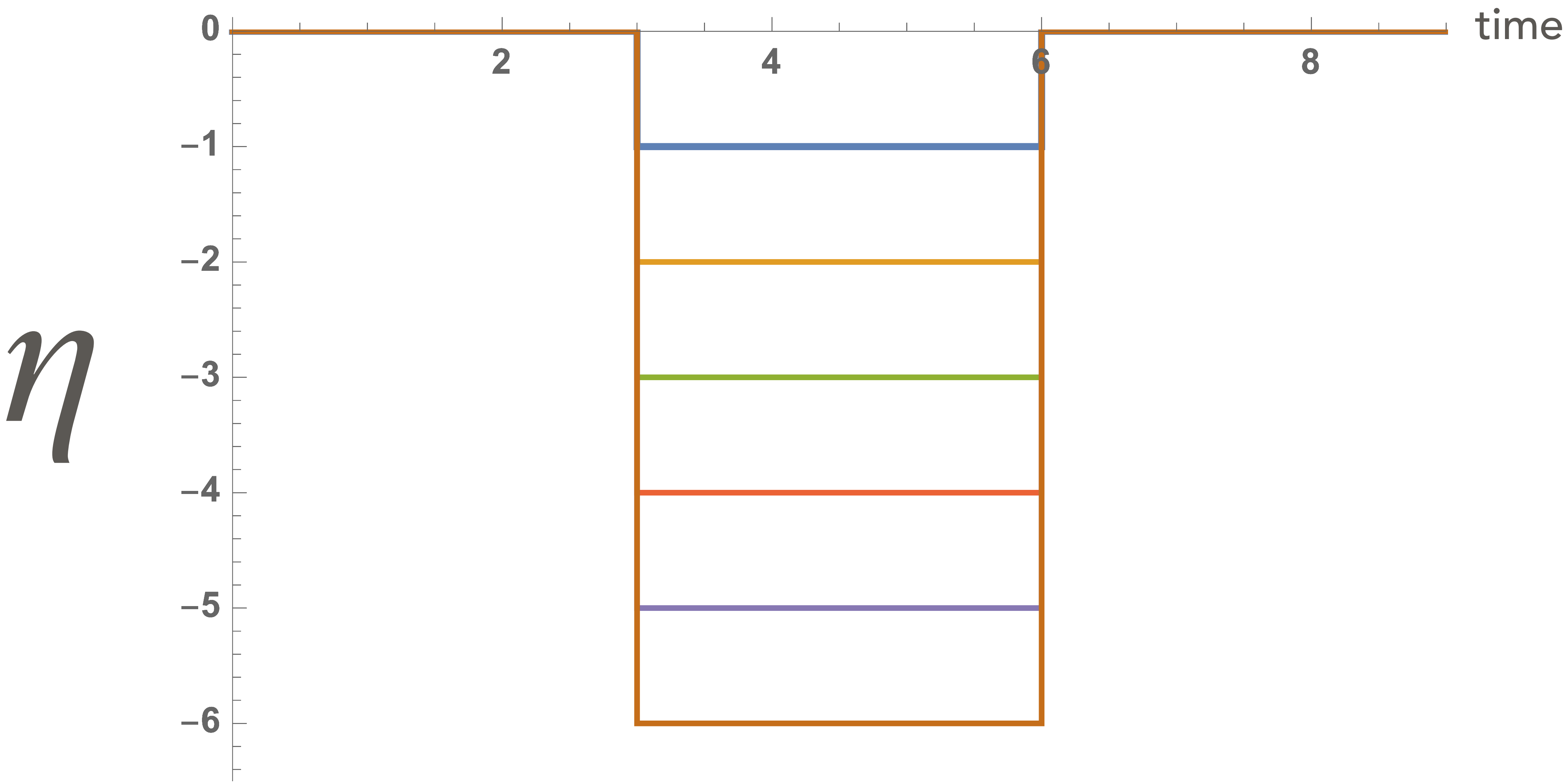
$$\mathcal{R}_{k\to 0} = C_k + D_k \int \frac{dt}{a^3 \epsilon}$$

this is because the previously decaying mode starts to grow

SR/BSR/USR


η
−6
−5
−4
−3
−2
−1
0
decaying mode grows
ϵ decreases
ϵ grows
USR
ϵ constant (standard slow−roll approximation)

Matching

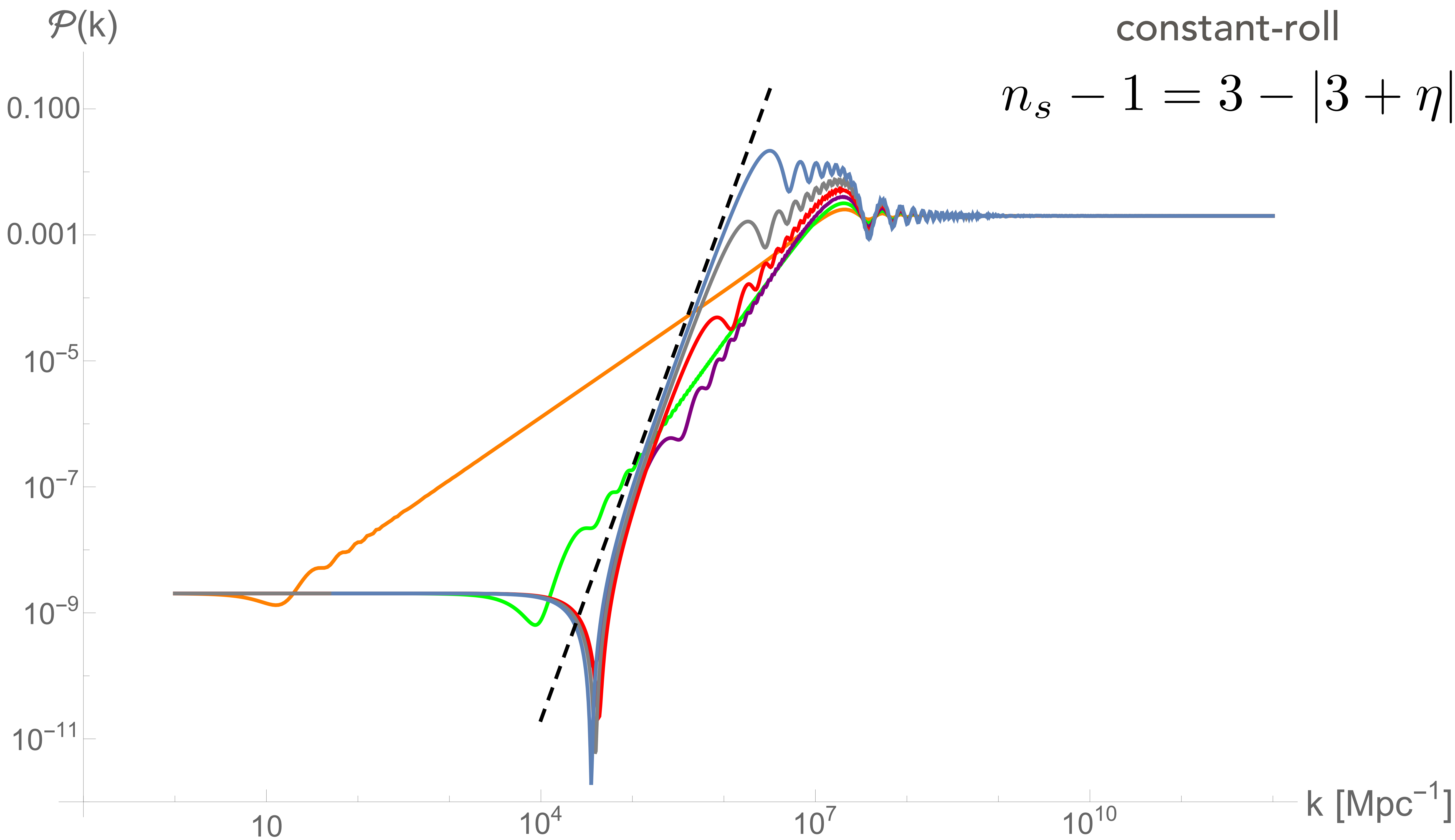


$$\mathcal{R}_k^1(\tau_i) = \mathcal{R}_k^2(\tau_i) \qquad \mathcal{R}_k'^1(\tau_i) = \mathcal{R}_k'^2(\tau_i)$$

Steepest growth

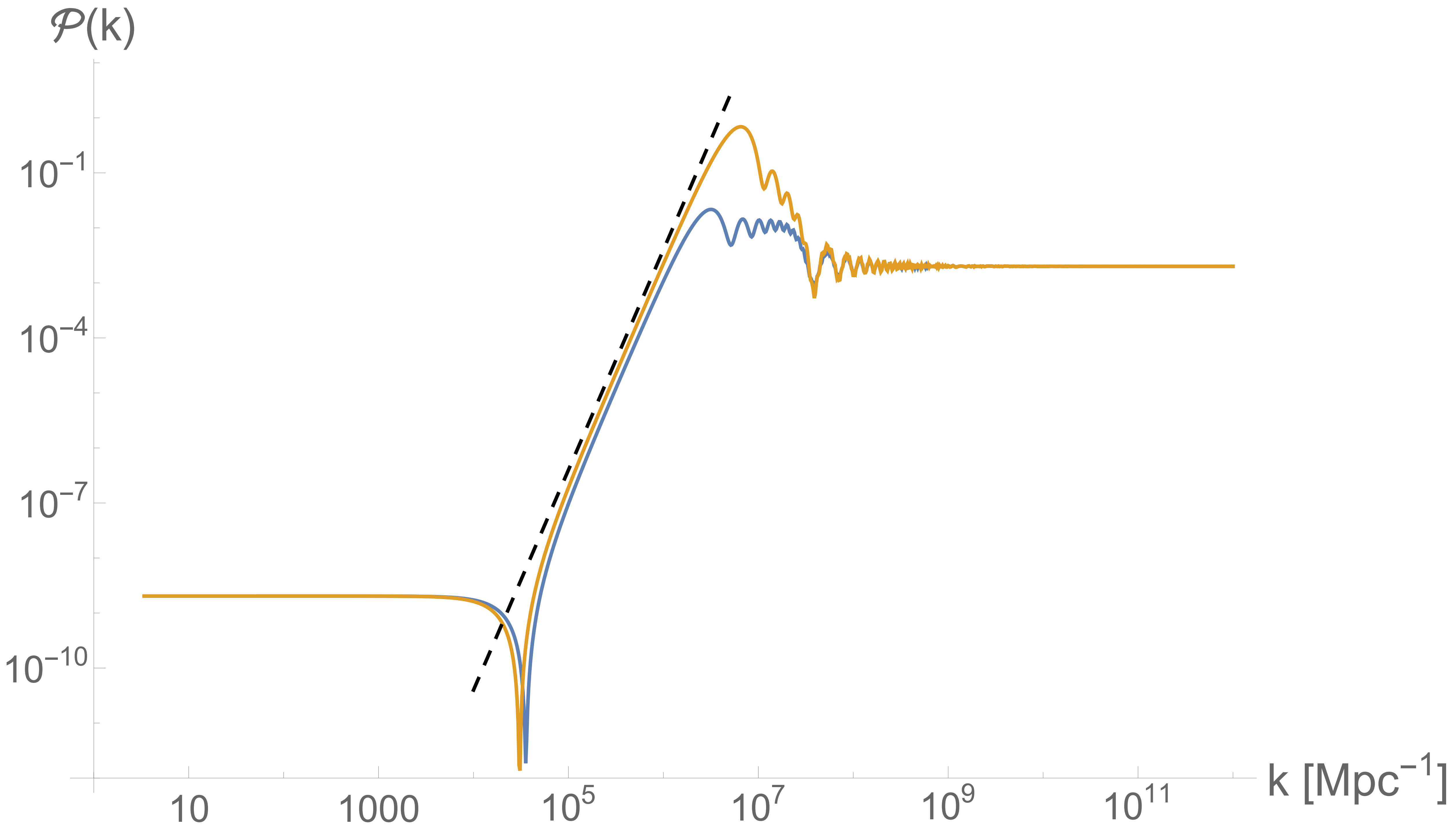
constant-roll

$$n_s - 1 = 3 - |3 + \eta|$$



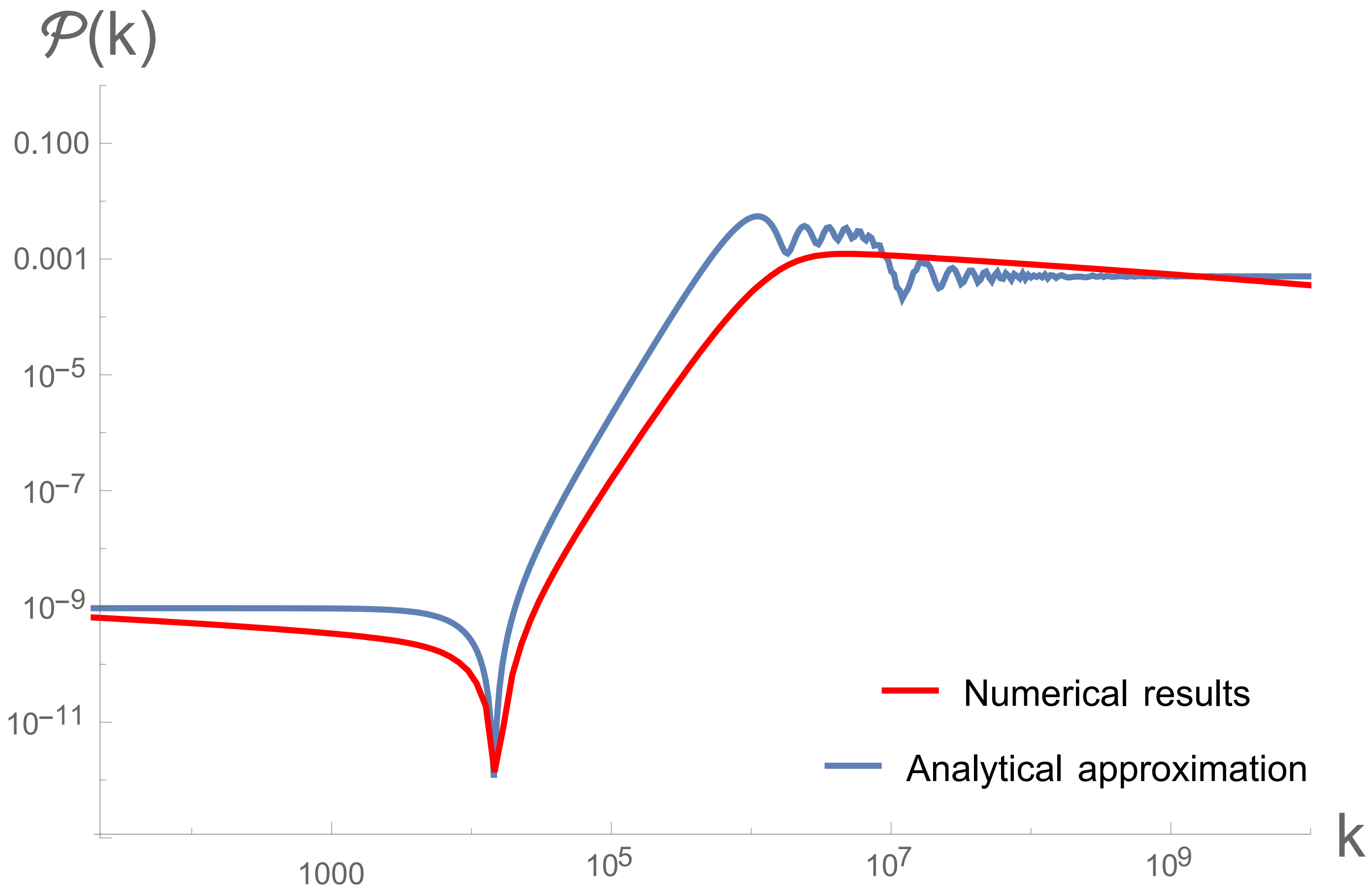
Byrnes, PC, Patil 2018

Rolling up hill

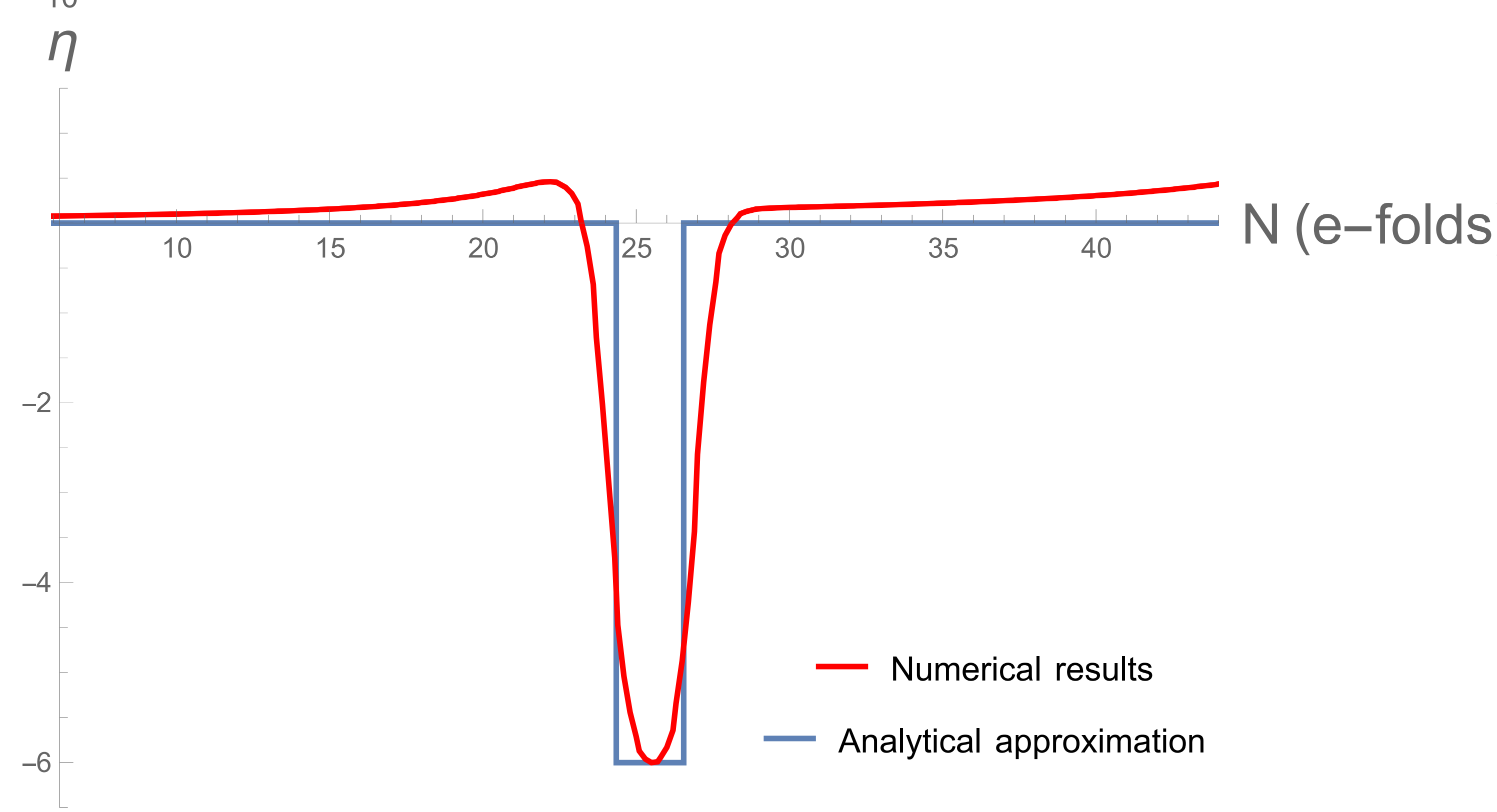


Byrnes, PC, Patil 2018

NUMERICAL COMPARISON



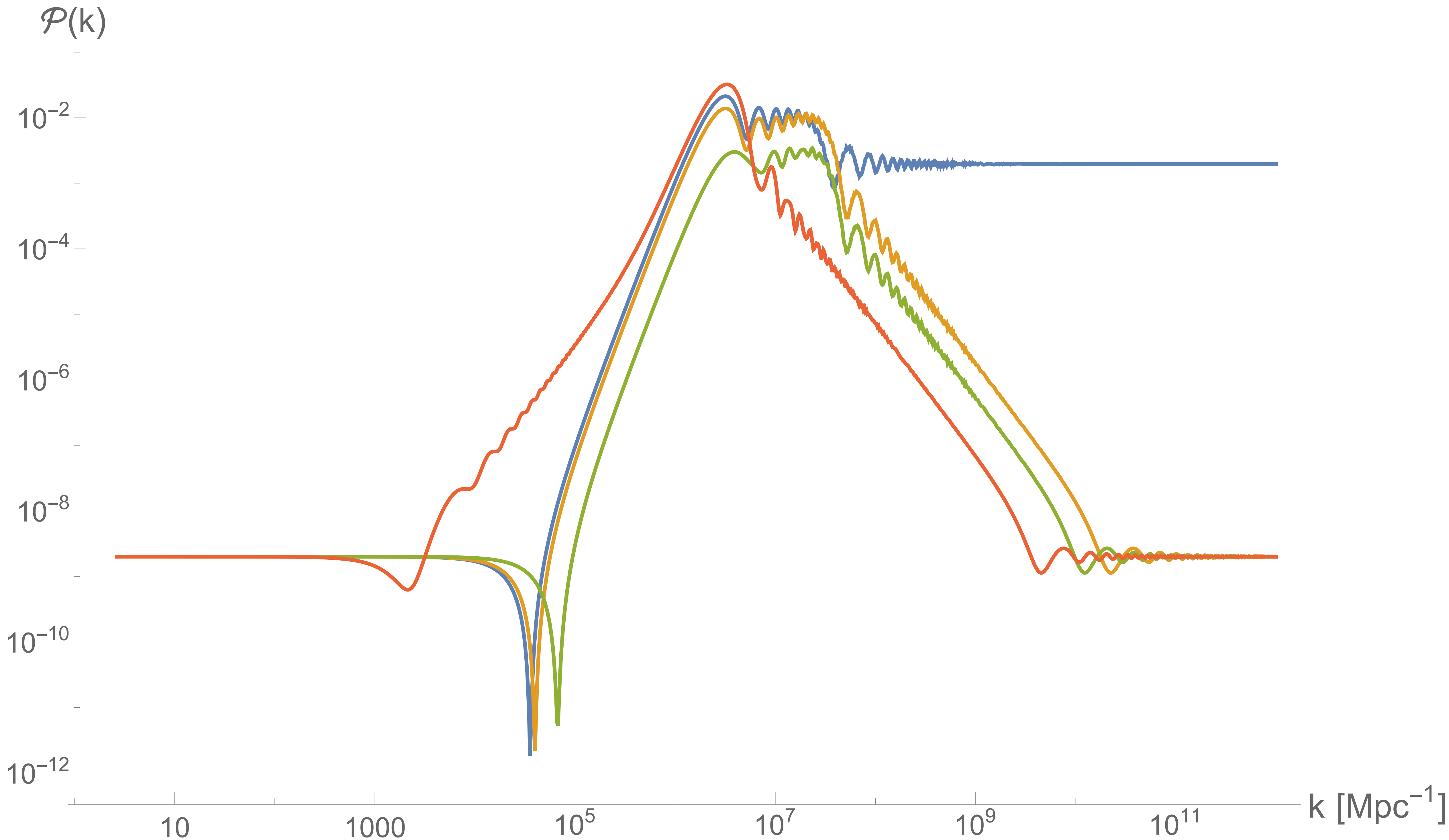
Good approximation of the main features, and dip still there in analytical approximation where epsilon never increases



David Seery's CPPTransport for numerical results

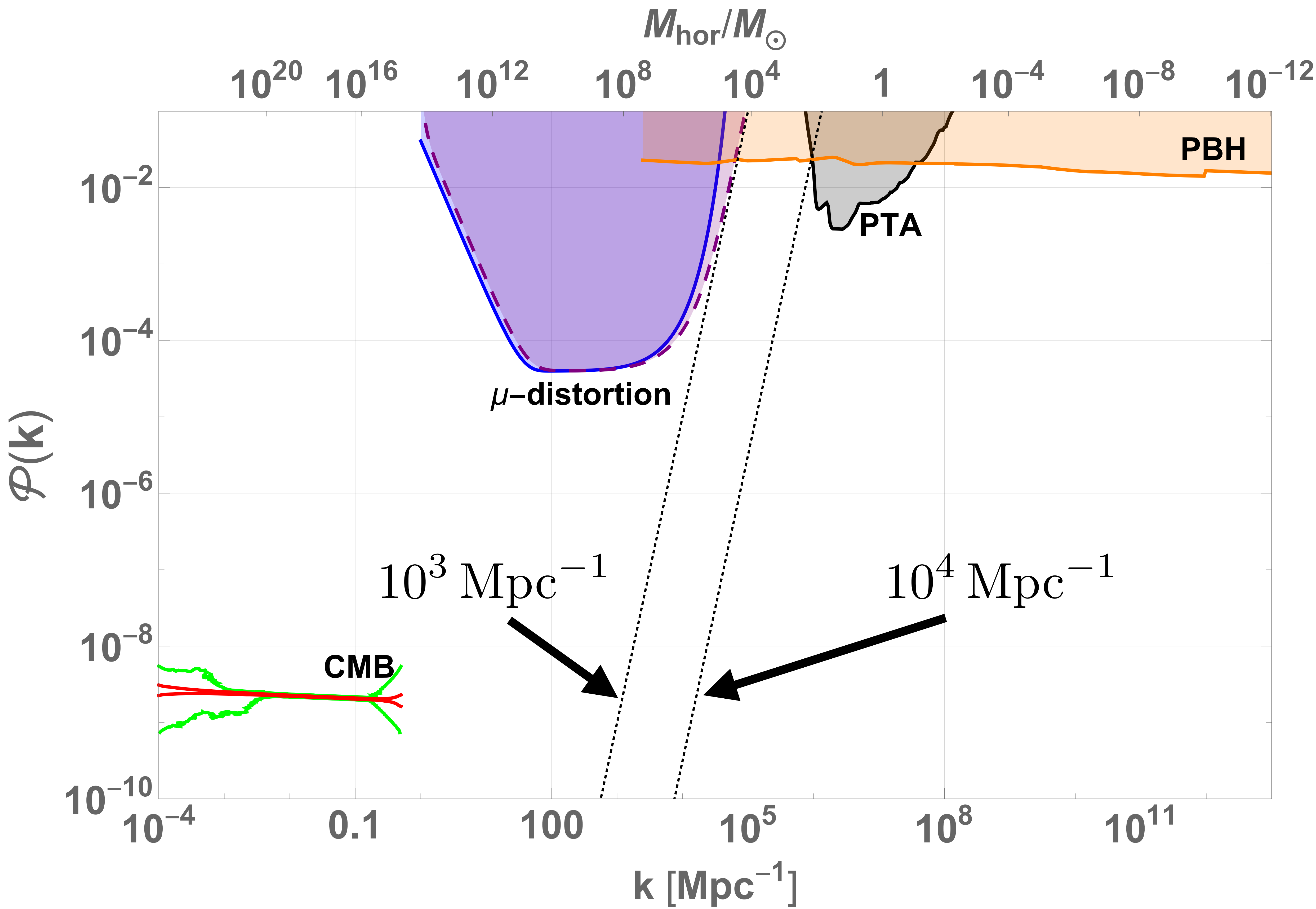
Byrnes, PC, Patil 2018

Multi-matching

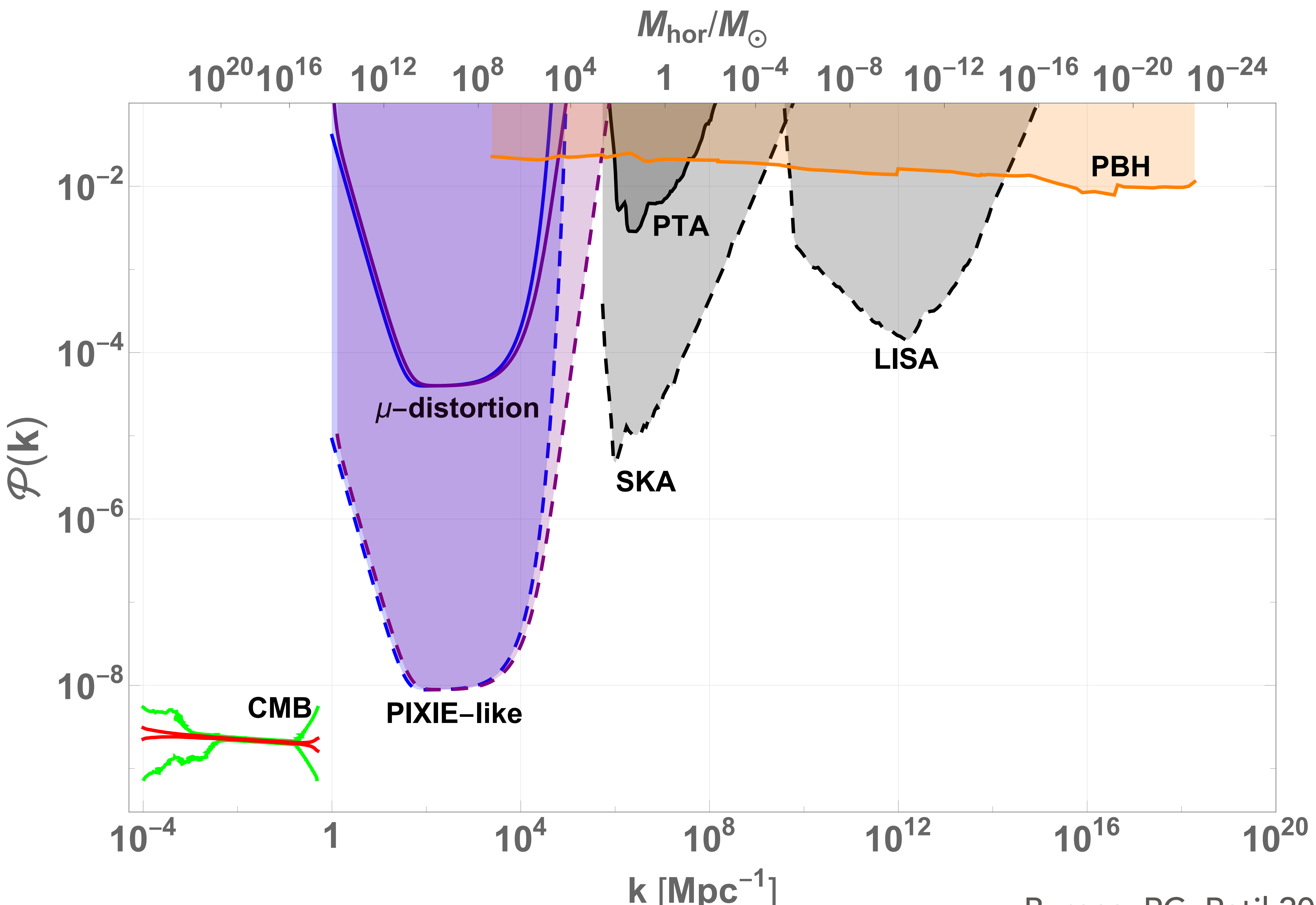


Byrnes, PC, Patil 2018

Consequences for observational constraints



Future forecasts



Byrnes, PC, Patil 2018

Summary

- You need a large peak in the power spectrum to produce primordial black holes (non-Gaussianity or an early matter dominated phase may help you out)

- Primordial black holes are interesting because they could make up all/part of the dark matter, LIGO has a chance of detecting them, and even one is very prescriptive for describing the inflationary potential

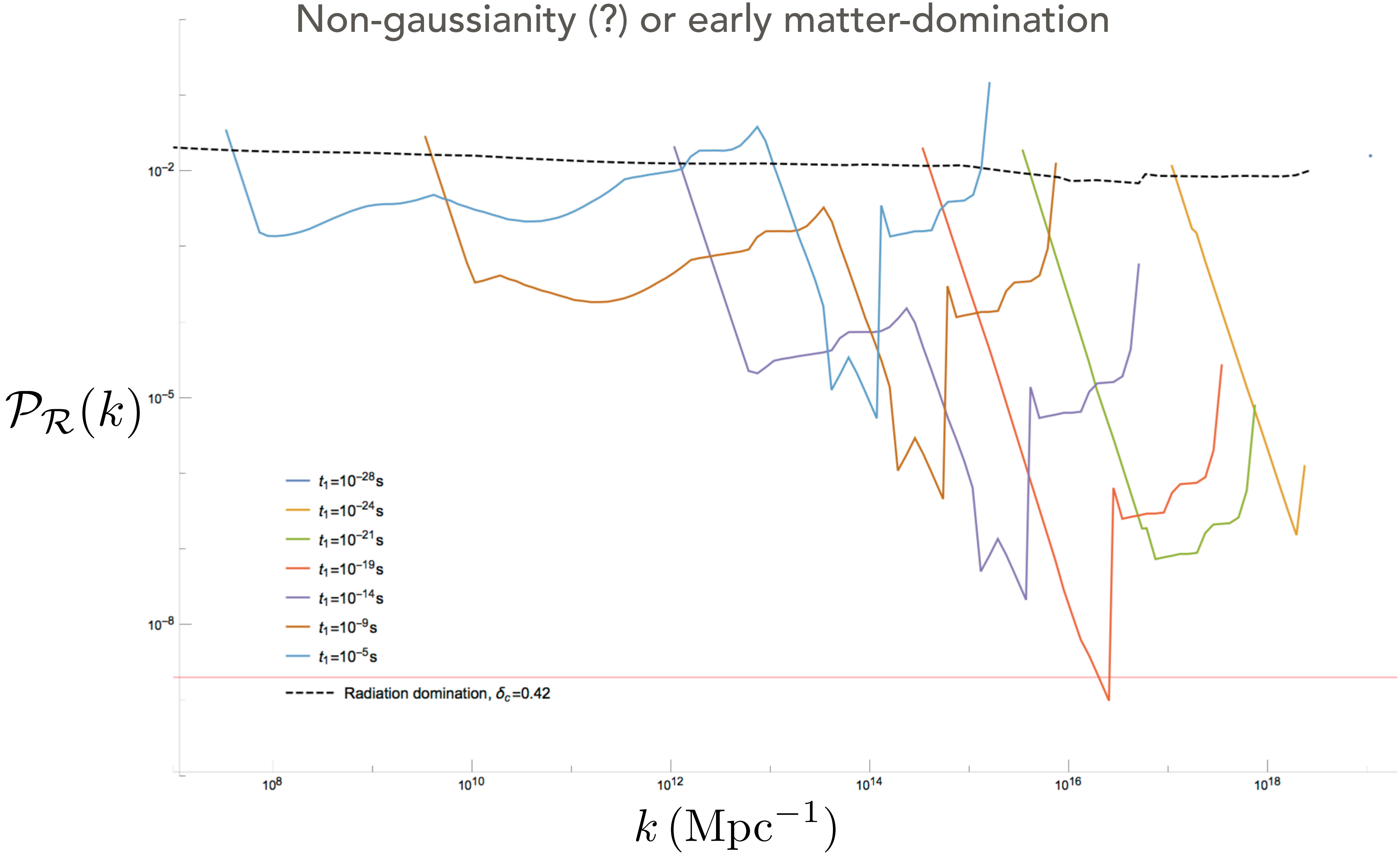
- **The power spectrum can only grow as fast as a spectral index of 4**

- This means that observational constraints on a particular scale actually constrain a wider range because the power spectrum can't jump arbitrarily quickly

- Future forecasts for PIXIE-like experiment and SKA may well shut down the window for solar mass black holes

Do you always need a boost in the power spectrum to produce PBHs?

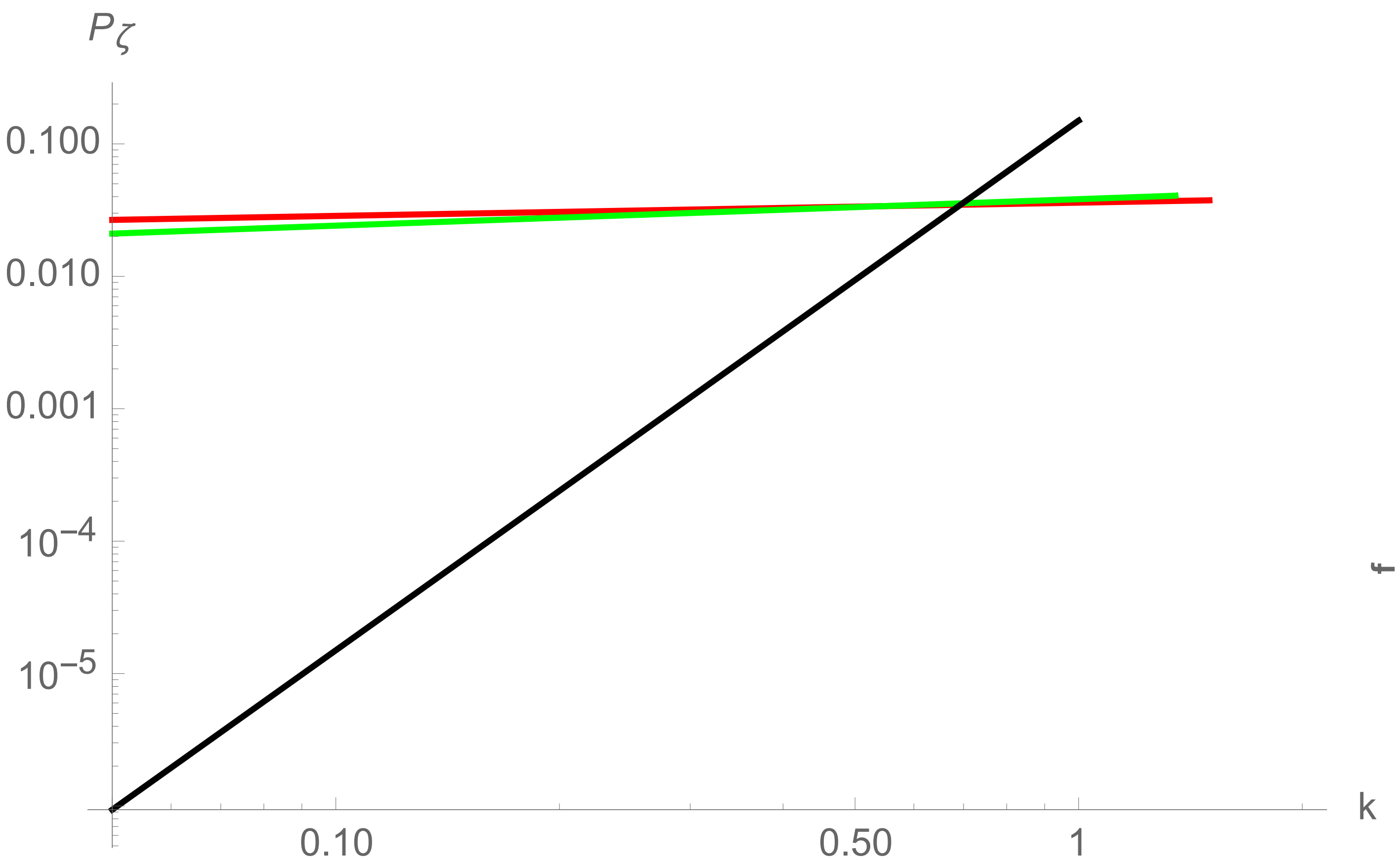
Non-gaussianity (?) or early matter-domination

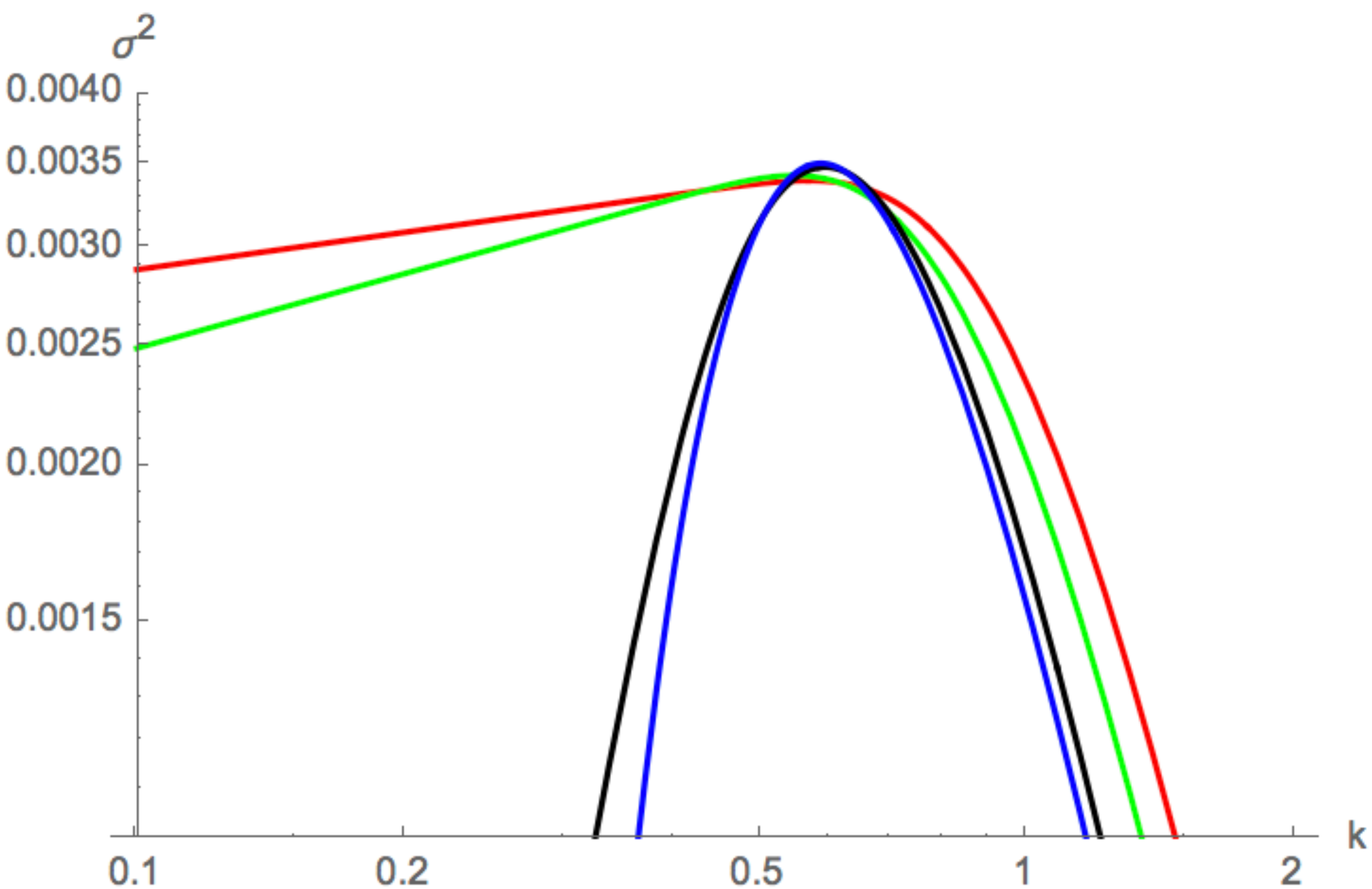


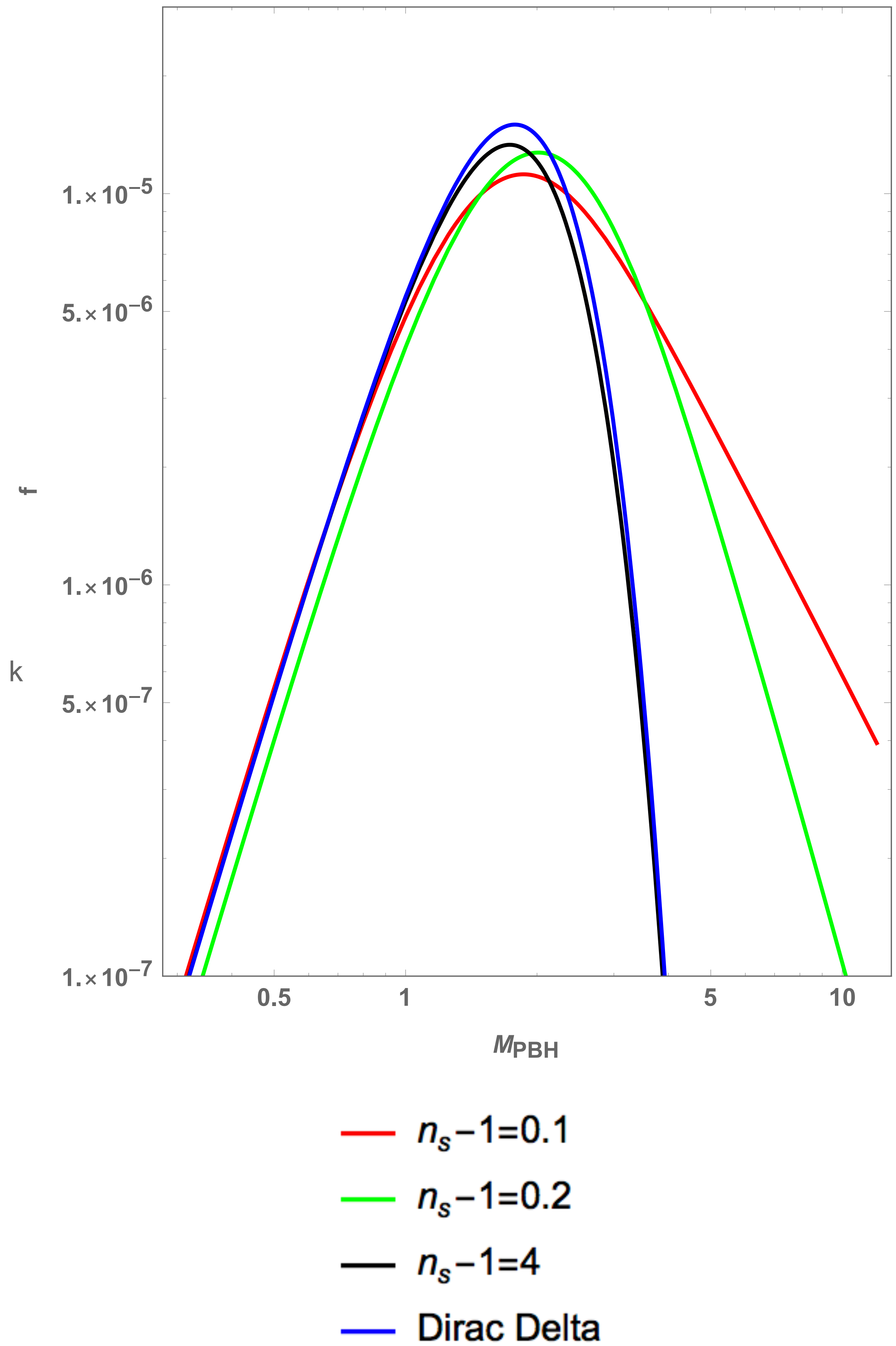
PC, Byrnes 2017

see also Carr, Tenkanen and Vaskonen 2017

Mass function dependence







Assumptions

- Gaussian fluctuations
- Mass of horizon ~ mass of black hole
- Degrees of freedom piecewise
- Gaussian window function
- Delta critical constant for radiation domination
- Monochromatic constraints in some cases
- Quantum diffusion