Primordial black holes and how to produce them

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- Primordial black holes are by no means a generic prediction of inflation
- But, they would change the game entirely for early universe cosmology and dark matter
- Strong motivation to check that they're (not) there (with e.g. neutrino observations!)

What is a PBH?

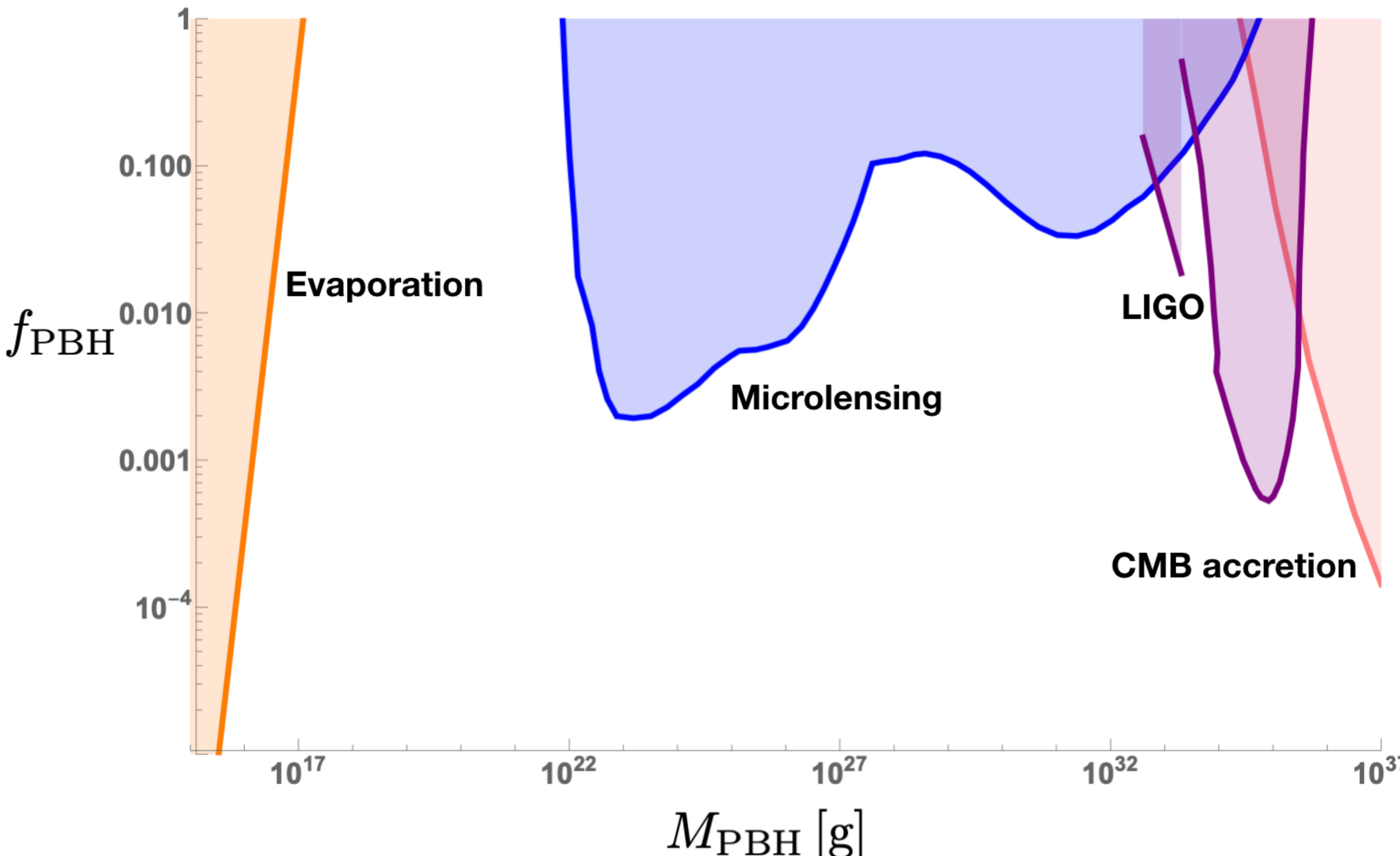
For me, it's a black hole which formed immediately after inflation in the very early Universe.

They can form with any mass, and if they're larger than 10^15g, they'll still be around today.

(Assuming single-field inflation with Gaussian initial fluctuations, however they can form by other means)

Why might we want PBHs?

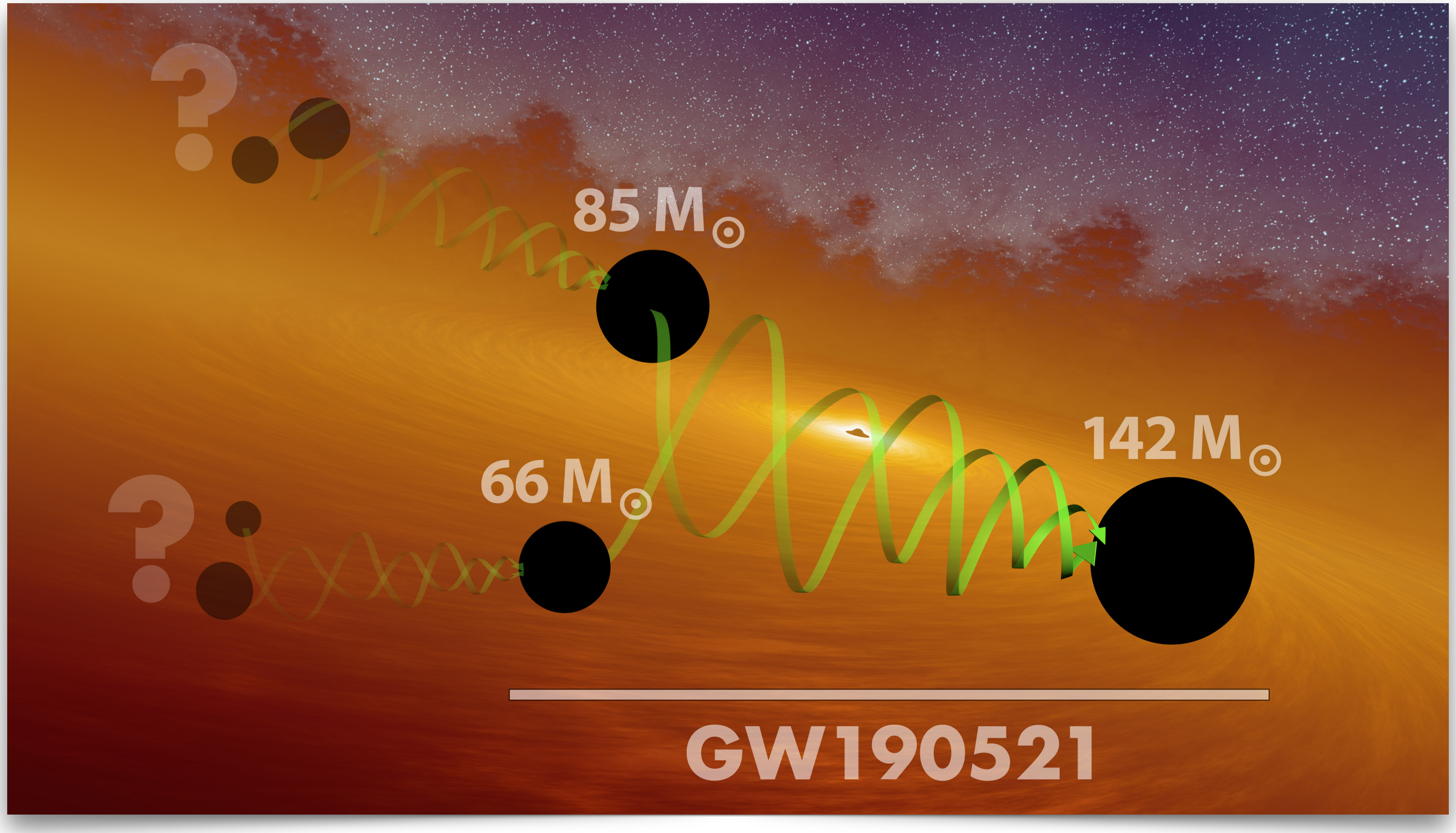
They're a dark matter candidate



Cole, PhD thesis 2020

Why might we want PBHs?

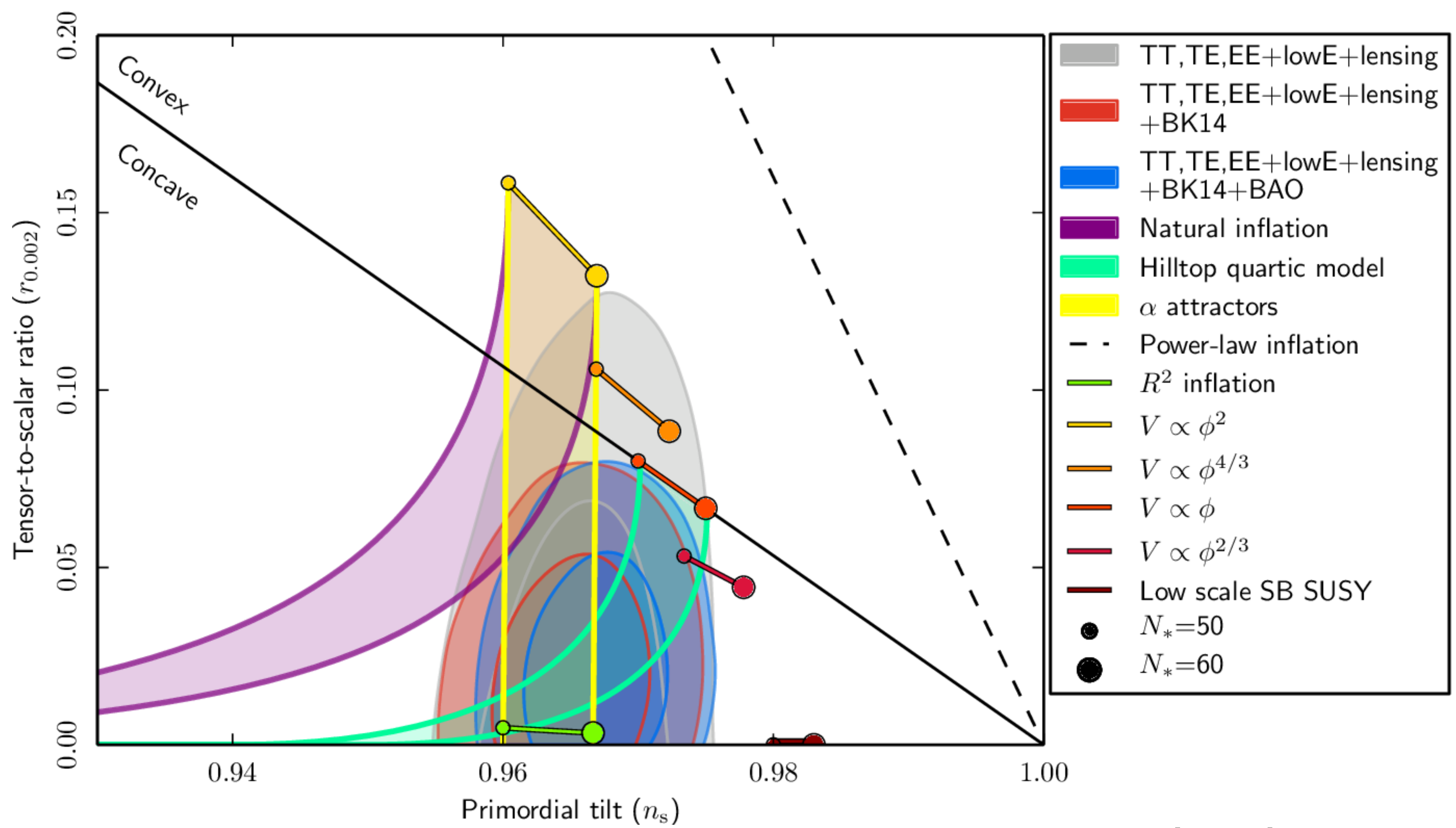
To explain surprising gravitational wave events?



LIGO Collaboration

Why might we want PBHs?

Or, to give our theories of the early Universe some direction (beyond single-field slow-roll inflation)?



Planck 2018

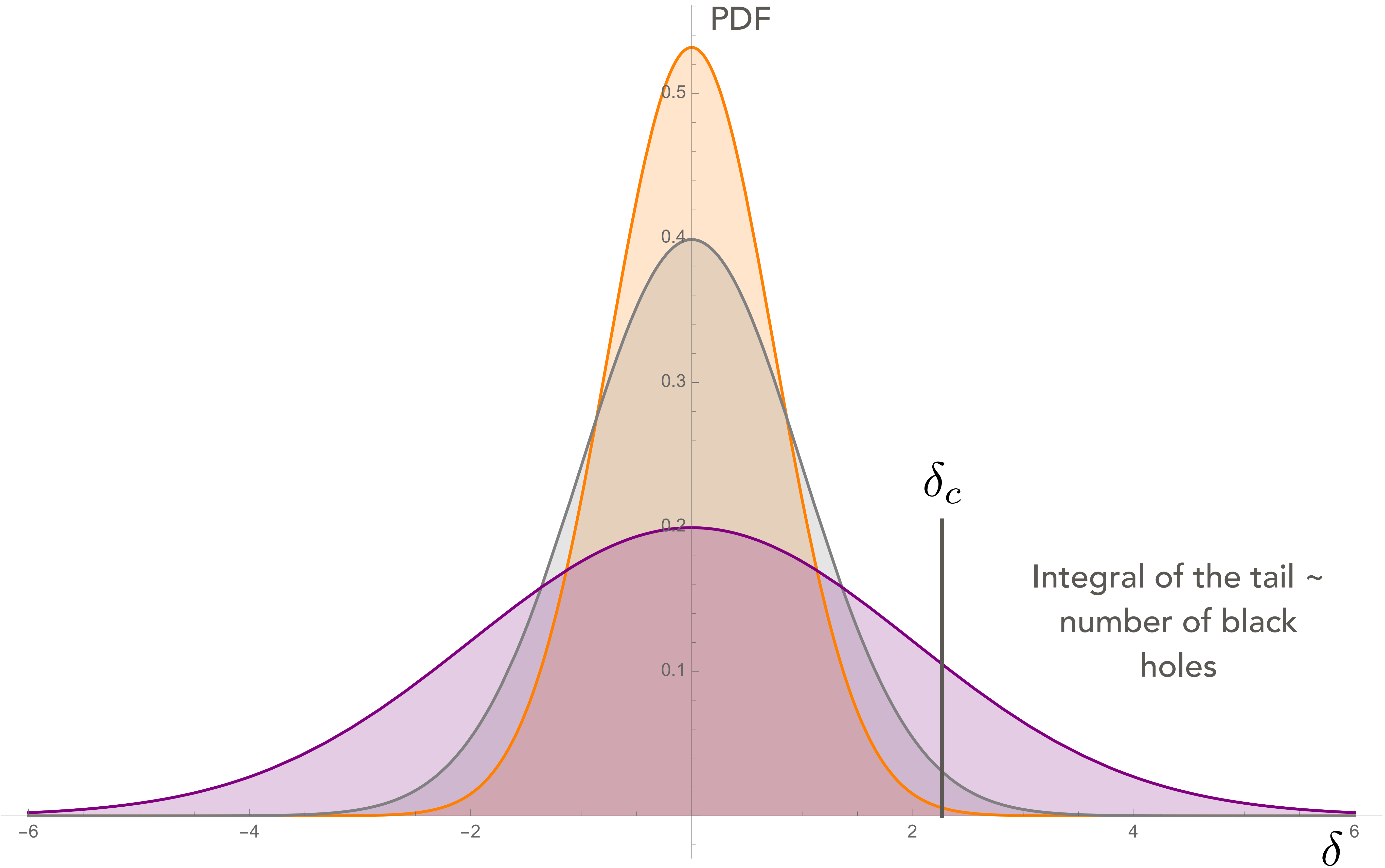
However, it’s super tricky to produce even just 1 single primordial black hole

This is a good thing if we find one, because we’ll congratulate ourselves on all 3 previous points
- explain some of dark matter
- (maybe) explain the LIGO events
- hone in on our early universe theory

This is a bad thing in terms of motivating their existence
(dare I say “fine-tuning” or “naturalness” arguments?)

But let’s take a look…

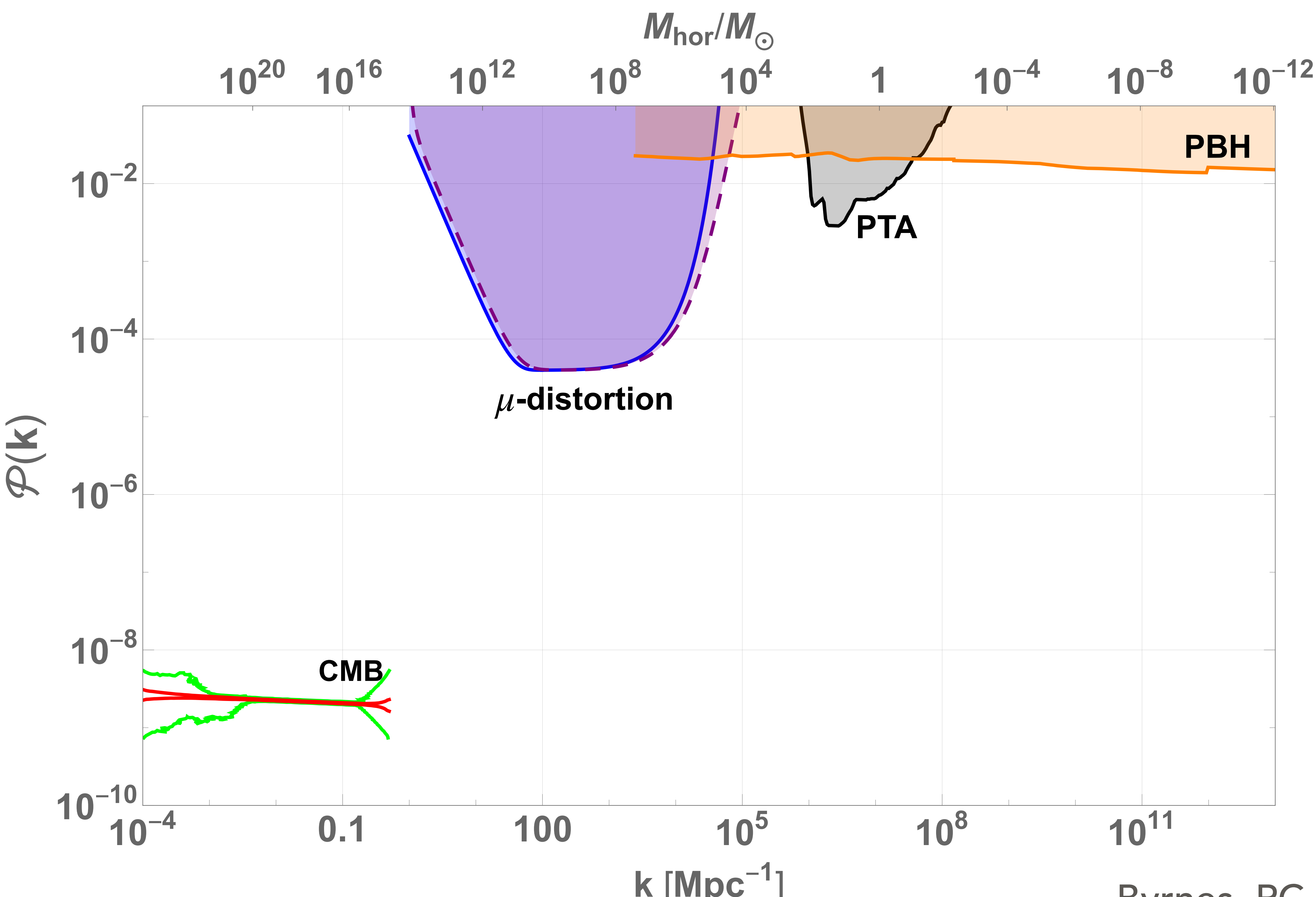
How do they form?



Integral of the tail ~ number of black holes

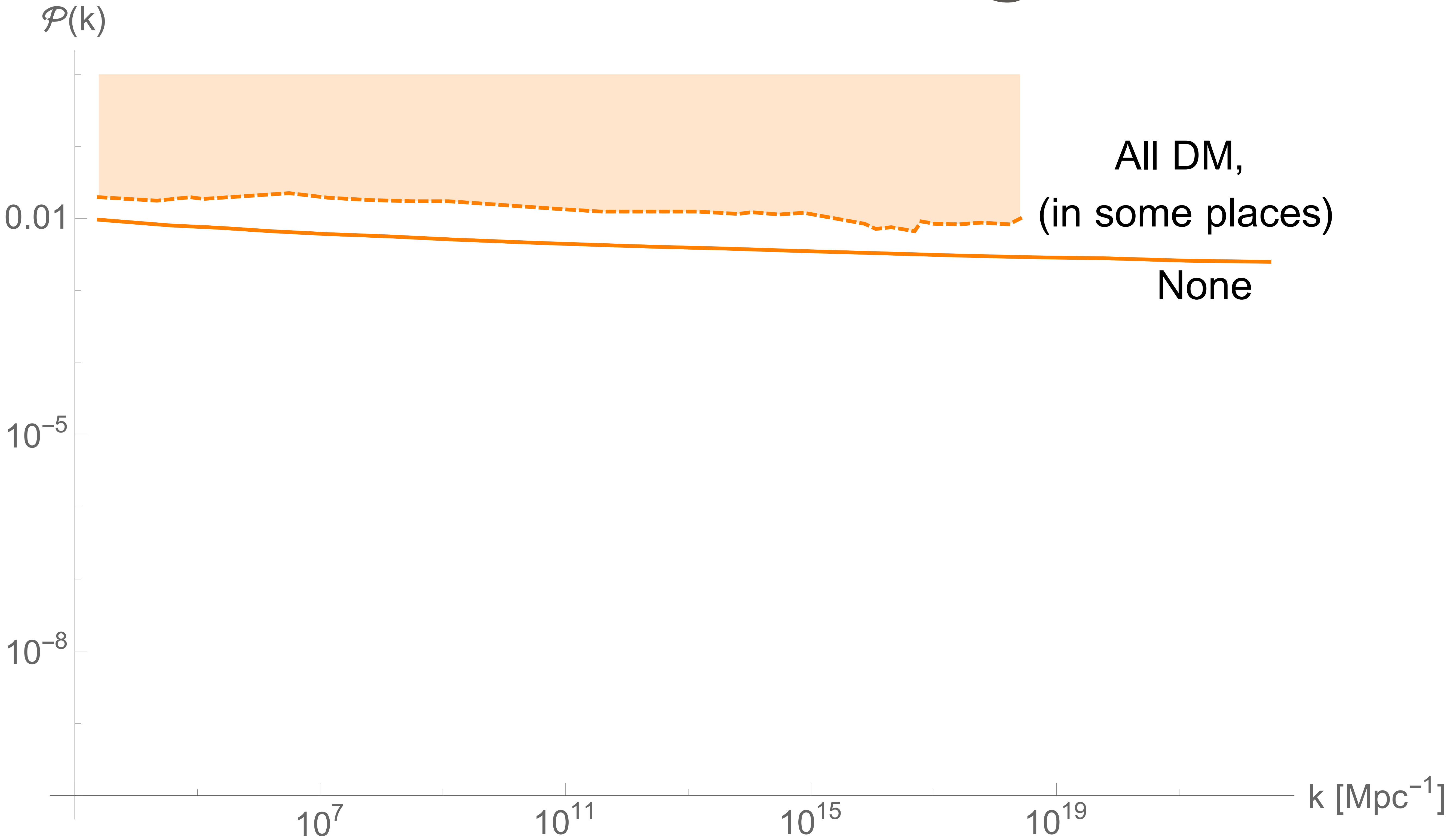
The primordial power spectrum

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



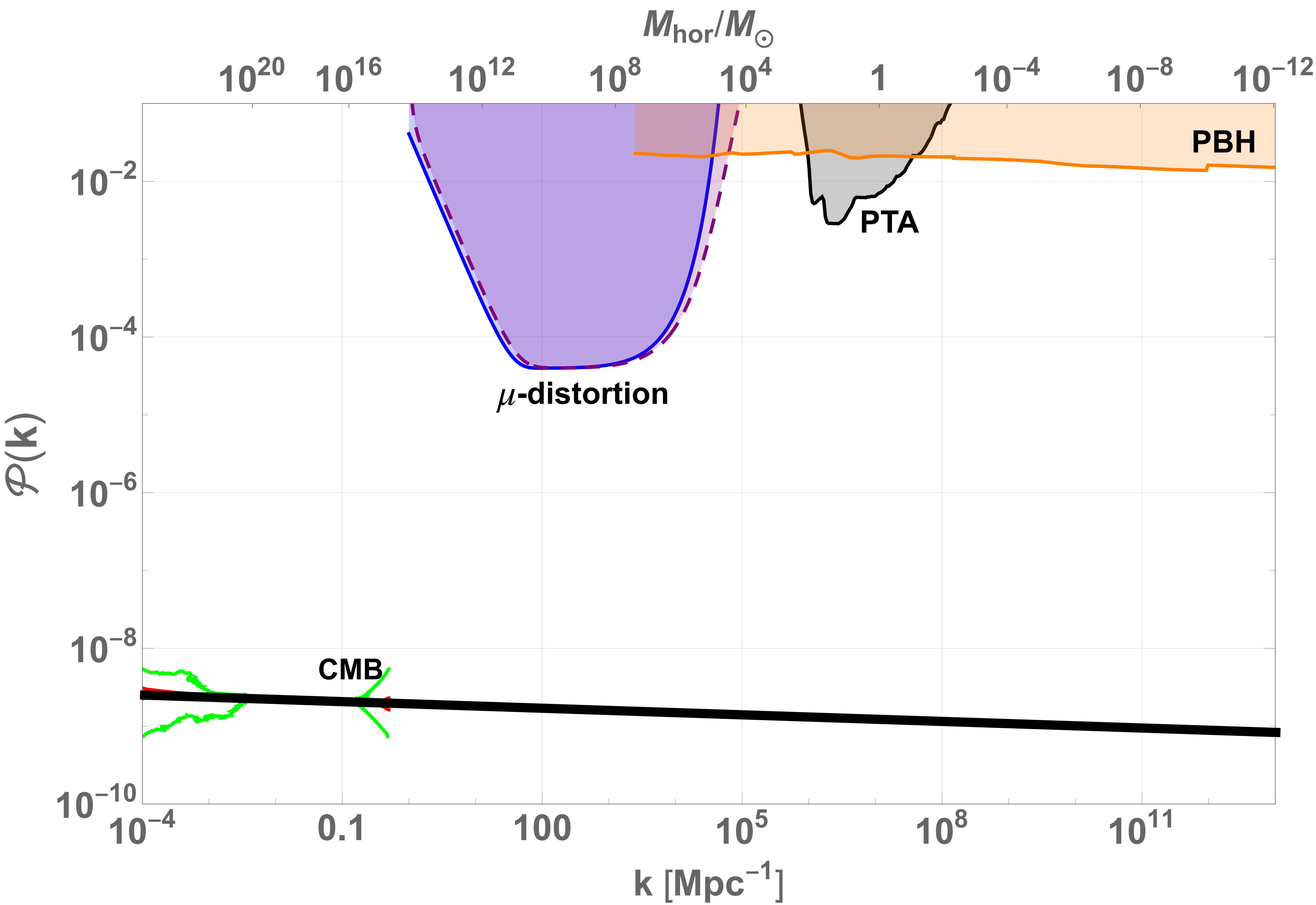
Byrnes, PC, Patil 2018

All or nothing

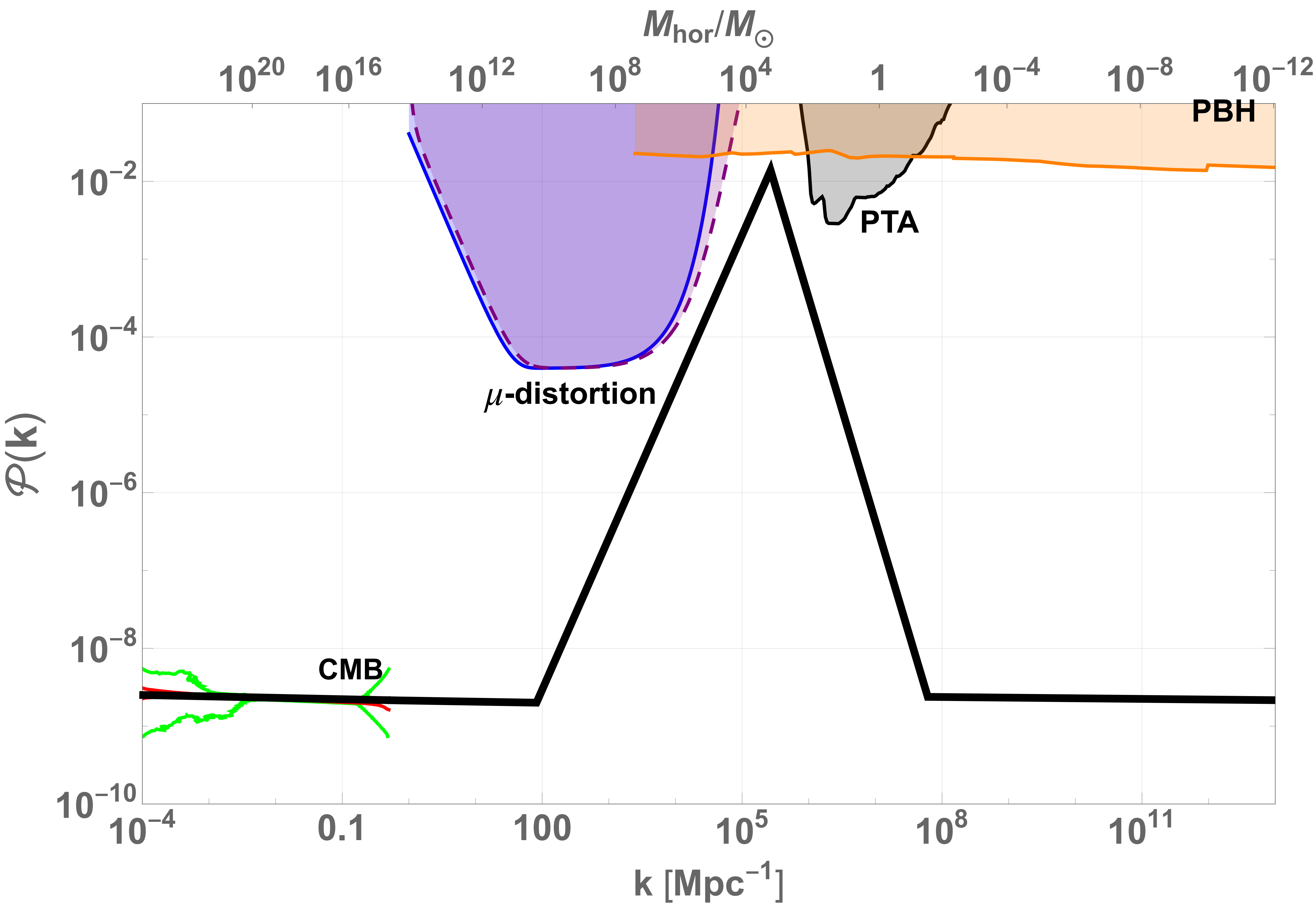


Adapted from Cole, Byrnes 2017

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?



How is inflation related to the power spectrum?

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

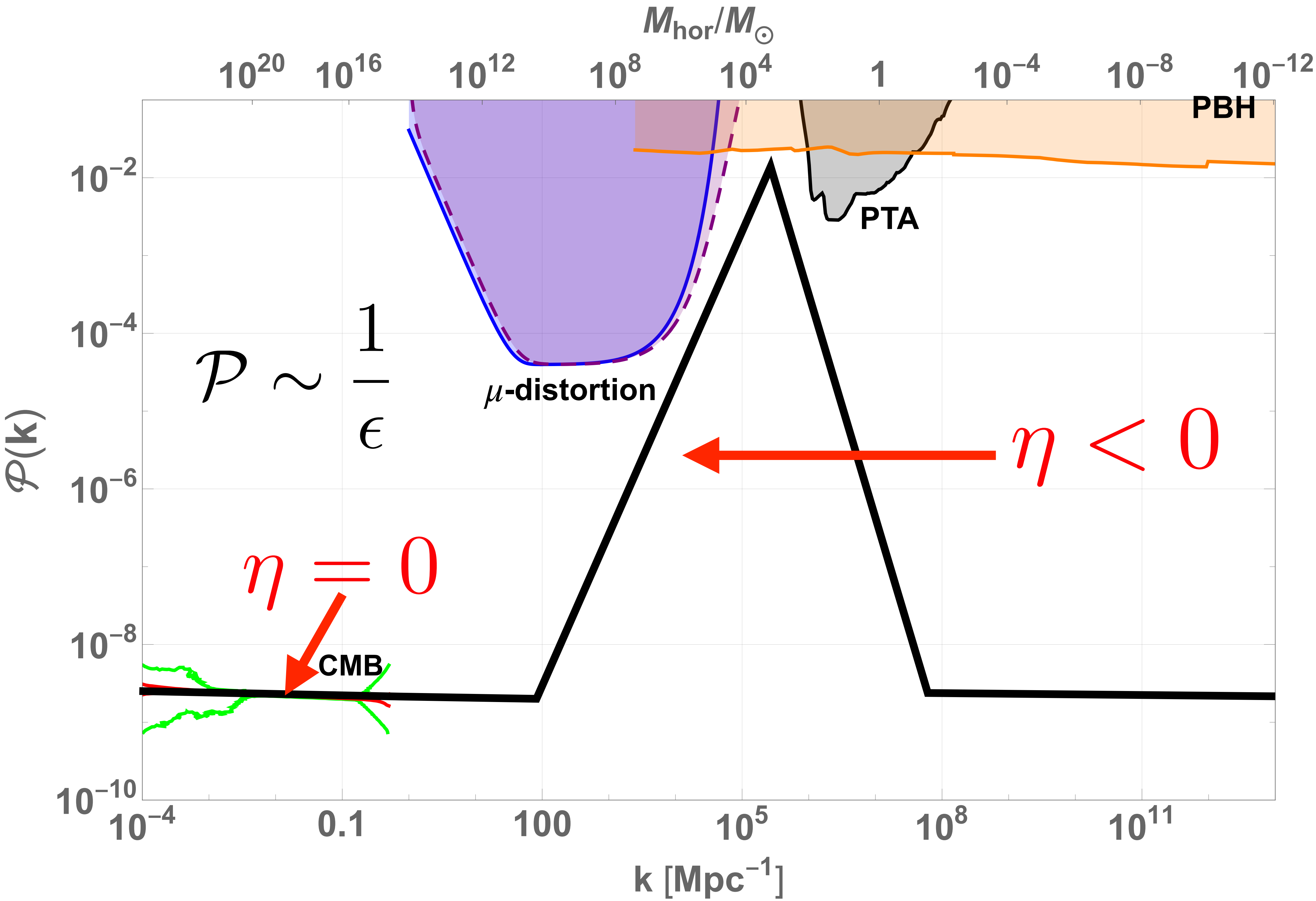
$$\epsilon = -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}^2}{2H^2 M_{\rm pl}^2} \qquad \eta = \frac{\dot{\epsilon}}{\epsilon H}$$

- 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



Tracking the inflaton beyond slow-roll

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\mathrm{d}V}{\mathrm{d}\phi} = 0$$

$$\epsilon = -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}^2}{2H^2 M_{\mathrm{pl}}^2}$$

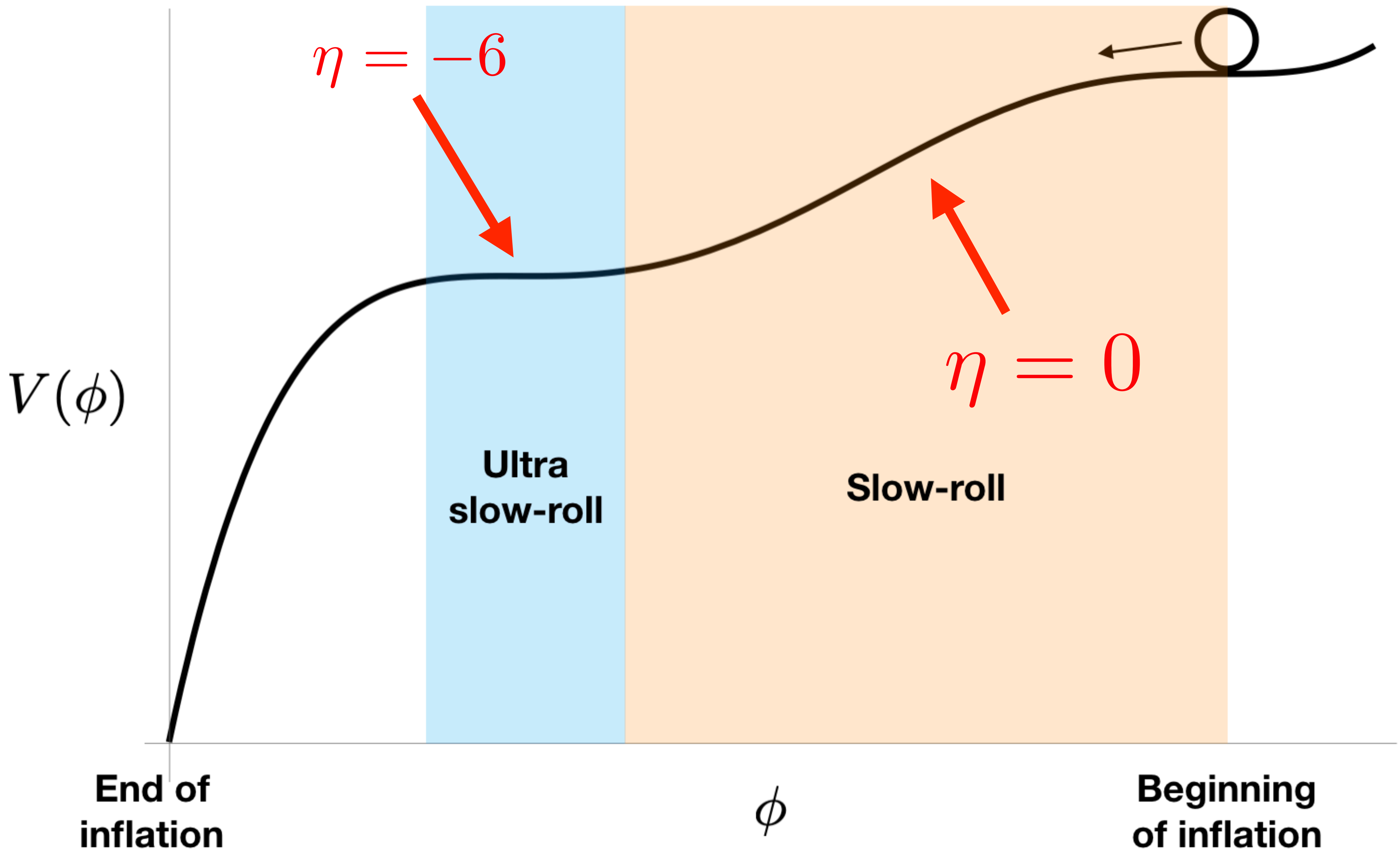
$$\eta = \frac{\dot{\epsilon}}{\epsilon H}$$

Usually for slow-roll approximation we drop this term, which is only valid for ϵ constant and η~0

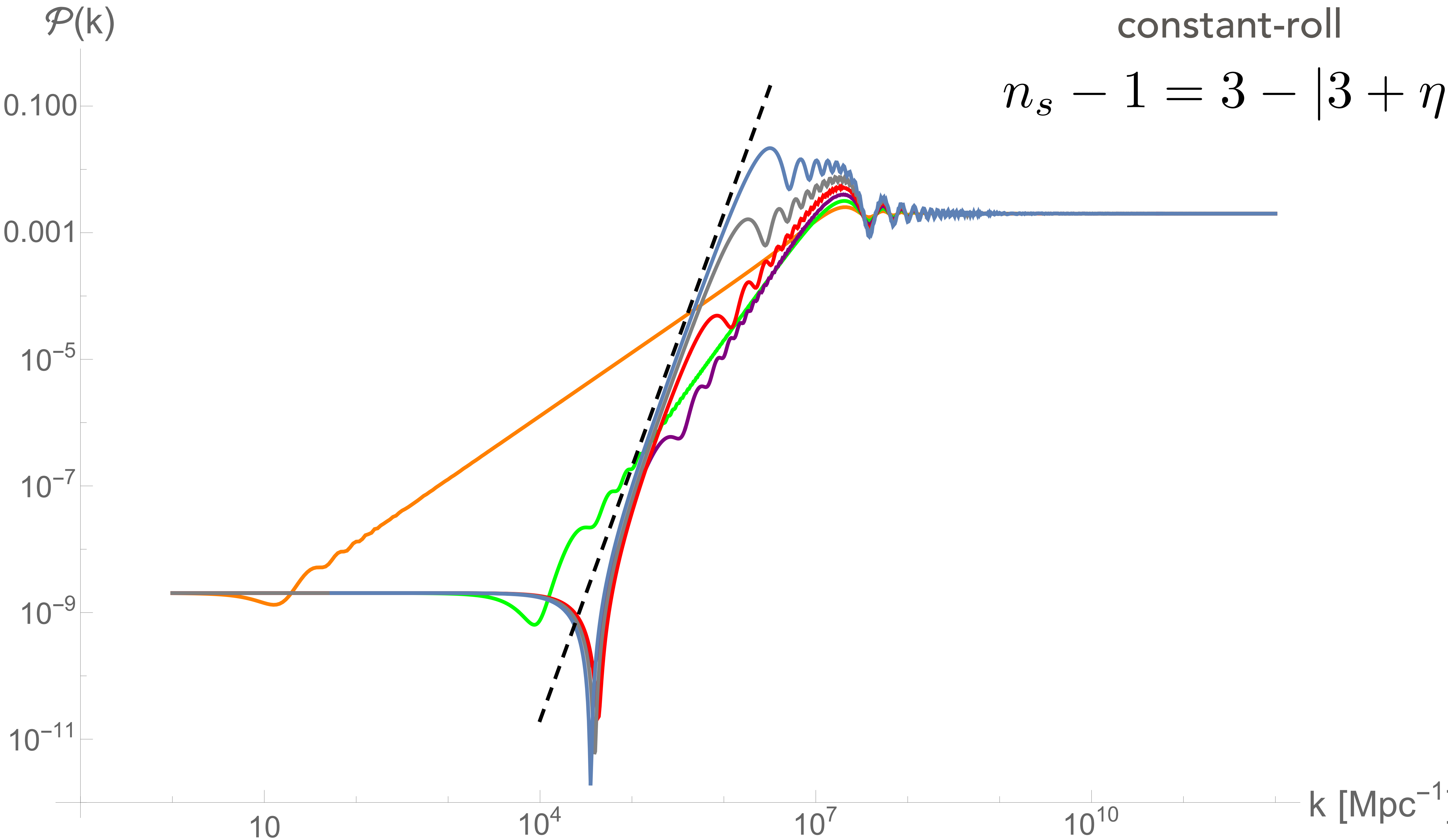
If power spectrum grows, potential gets really flat, so in the limit that it gets totally flat, we drop this term and η~-6

$$\rightarrow -\frac{\ddot{\phi}}{\dot{\phi}H} = \epsilon - \frac{\eta}{2} = 3$$

The inflationary potential



Steepest growth

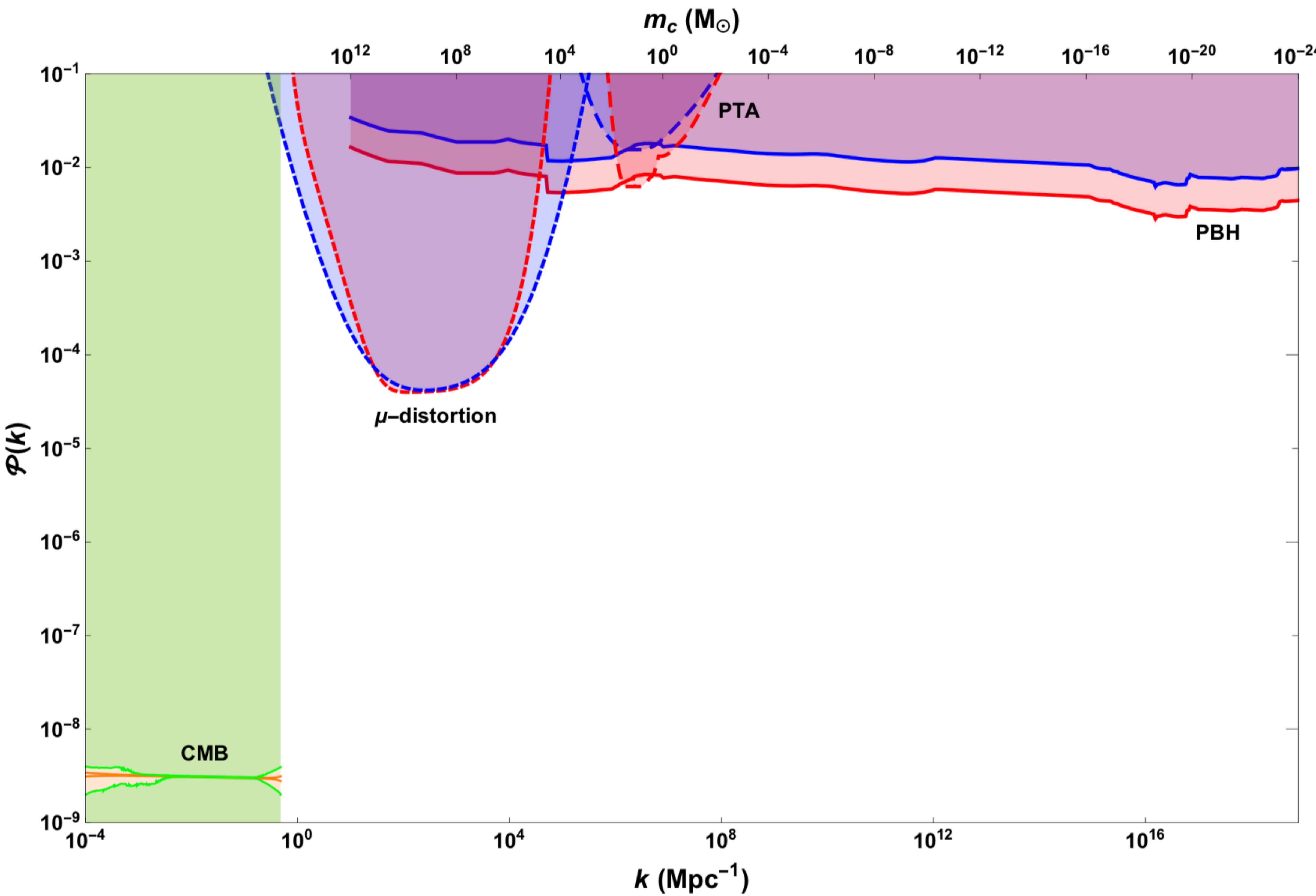


constant-roll

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

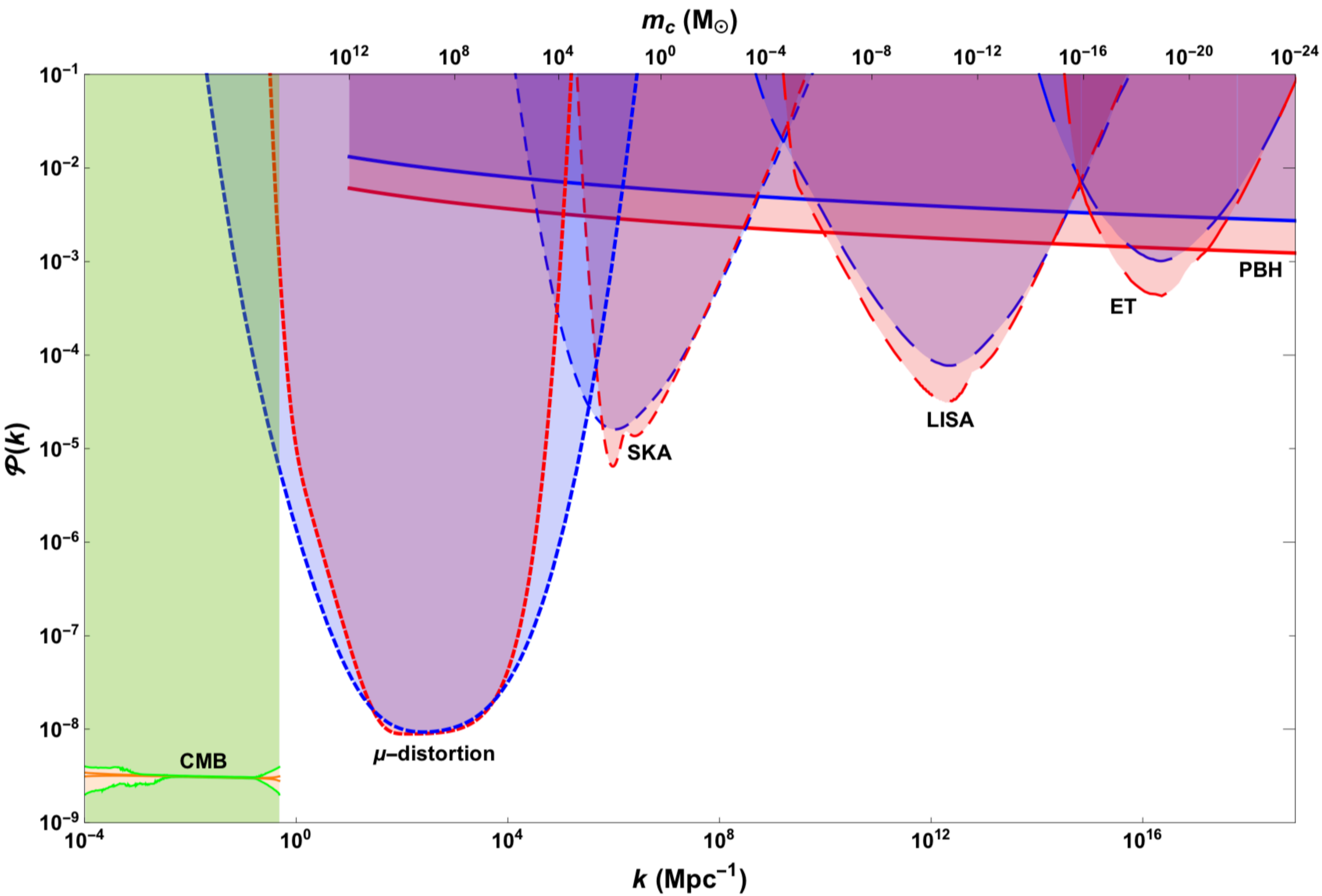
Byrnes, PC, Patil 2018

Consequences for current constraints



Gow, Byrnes, PC, Patil 2020

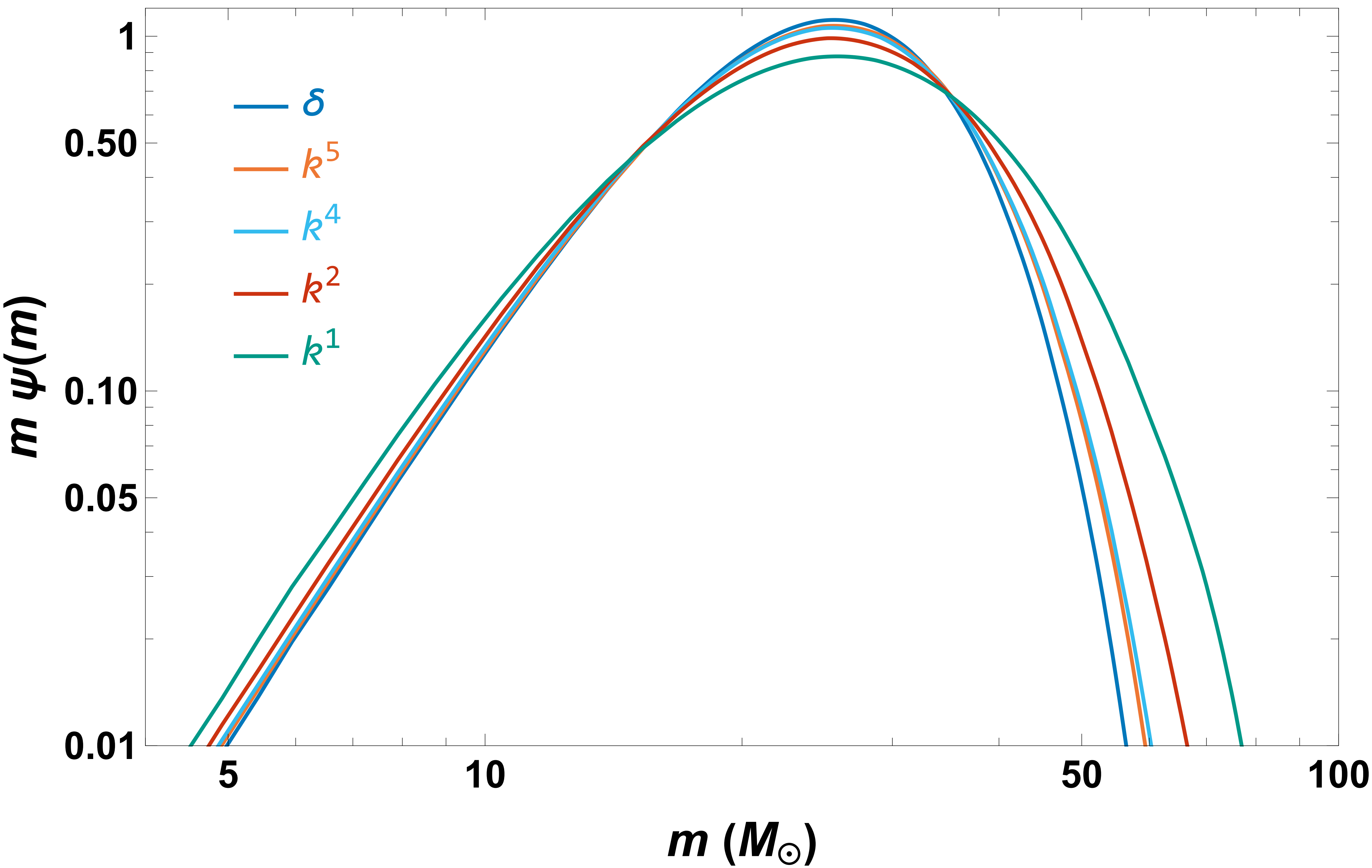
Consequences for future constraints



Gow, Byrnes, PC, Patil 2020

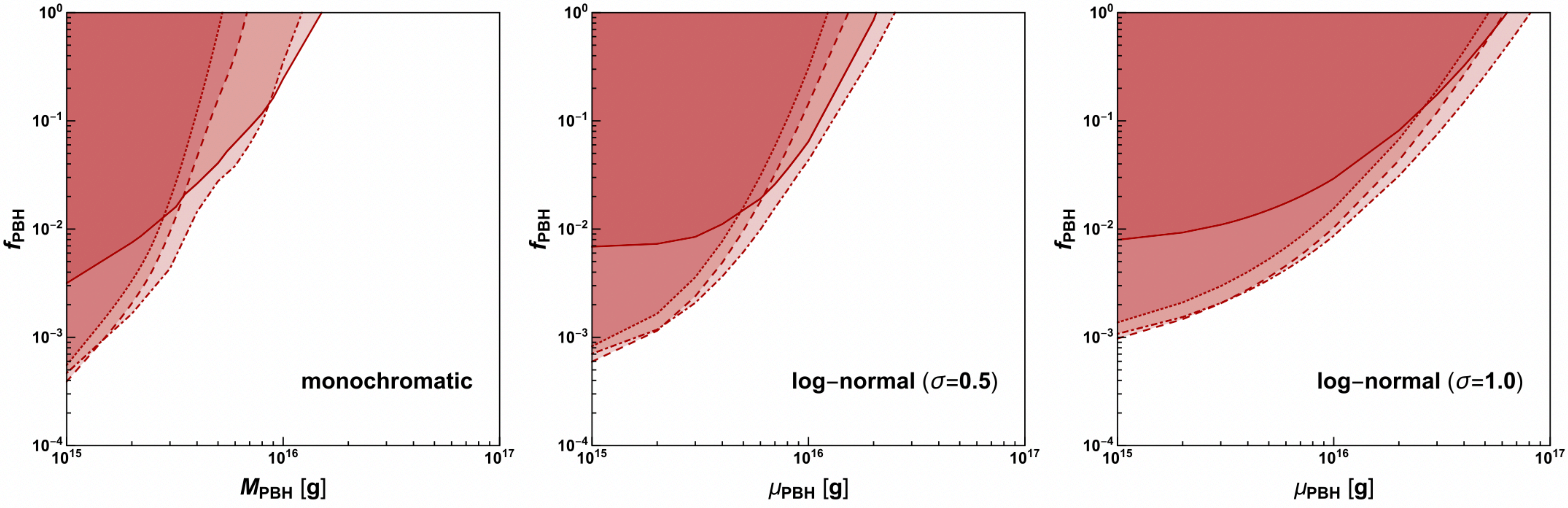
Mass function

Always produce a spread of masses



Neutrino signature from their evaporation

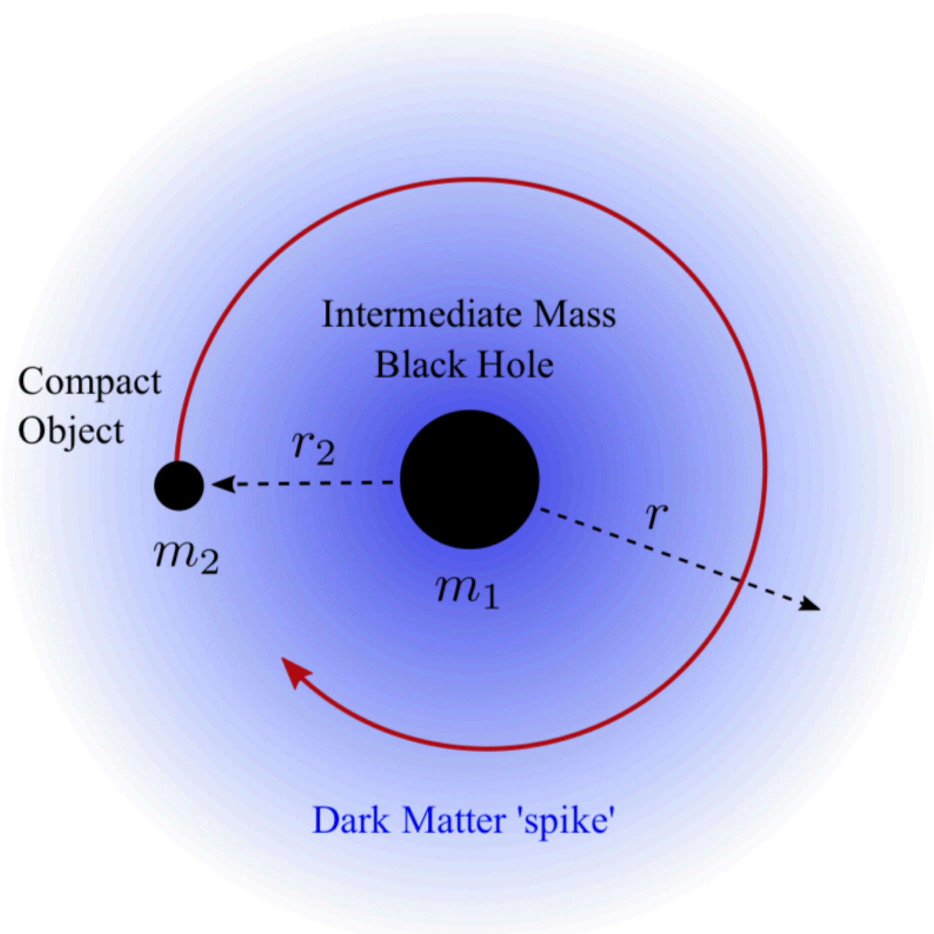
DSNB searches at Super-Kamiokande



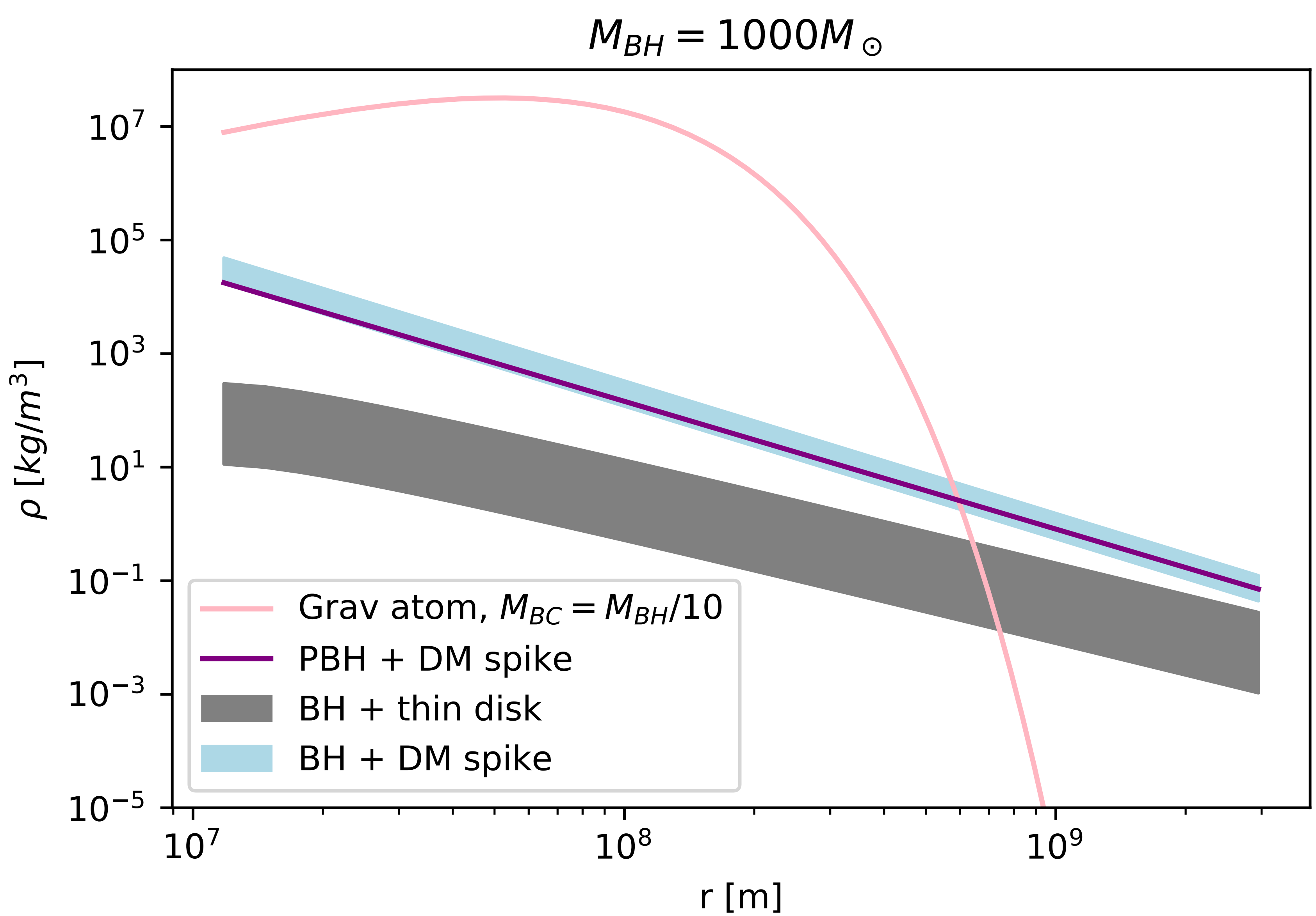
Dasgupta et al. 2020

Dark dresses

Searching for dark matter clouds around binary black holes with gravitational waves… could very dense clouds produce a neutrino signature if the dark matter is annihilating?



Kavanagh et al. 2019



Cole, Coogan, Bertone, Tomaselli in prep.

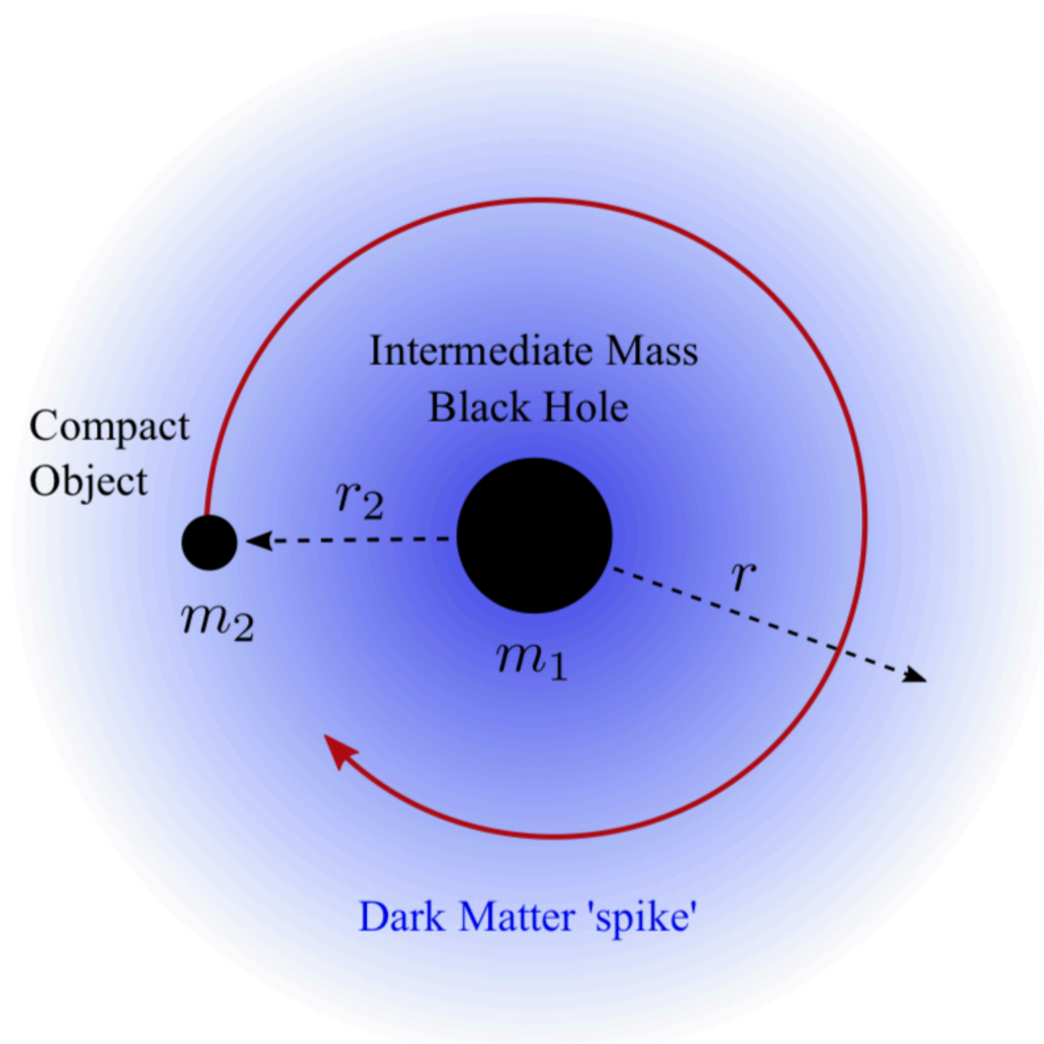
Summary

- Producing even just one primordial black hole is difficult
- However, finding even just one would be a paradigm shift for early universe theories
- Finding more would be a paradigm shift for dark matter
- Need to be sure whether they're there or not, and neutrinos (among other things) are excellent probes of hard-to-reach parameter space

What about direct detection?

Problem: primordial black holes are very difficult to distinguish from astrophysical ones

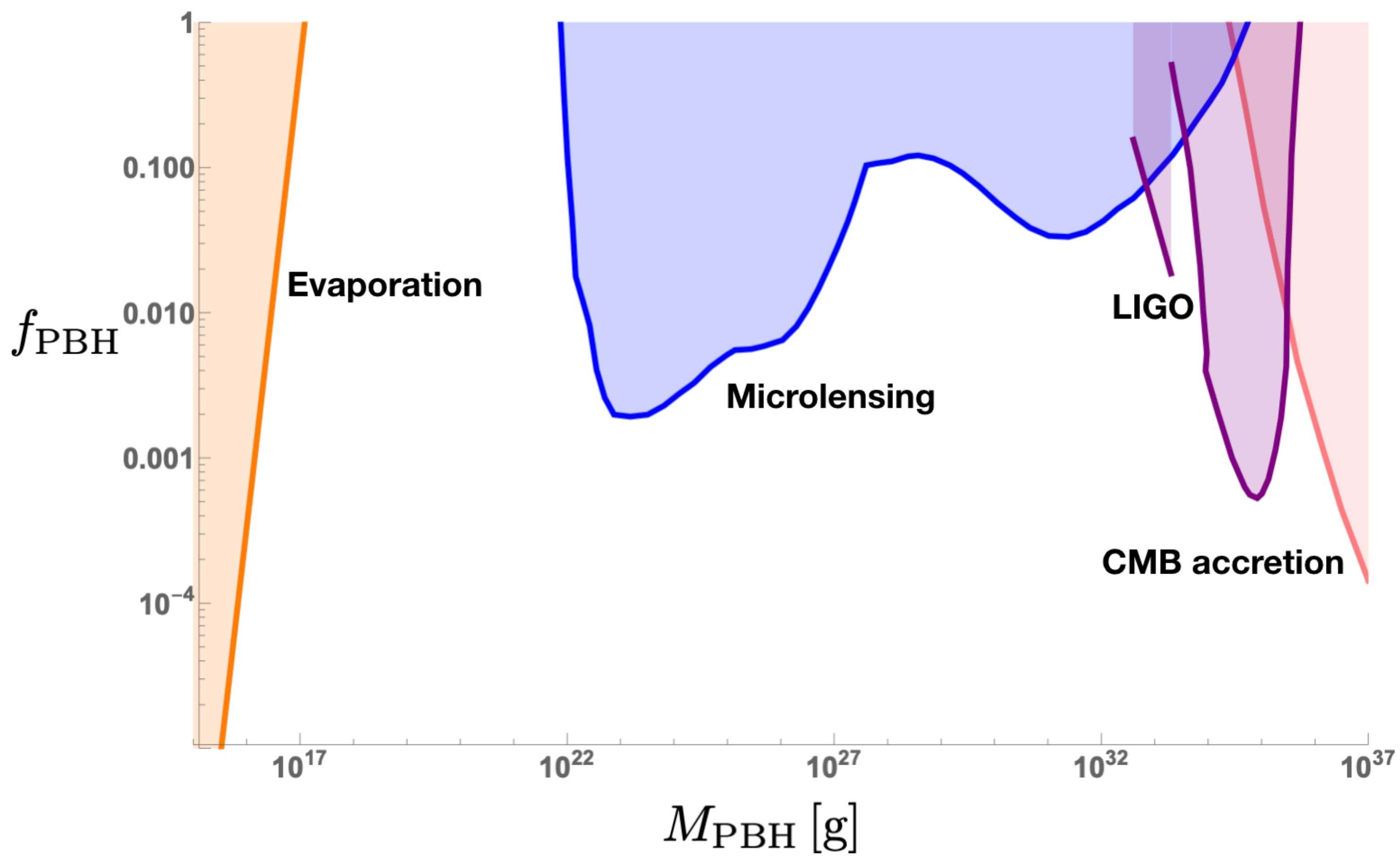
Unless… the black holes are embedded in dark matter clouds



What about direct detection?

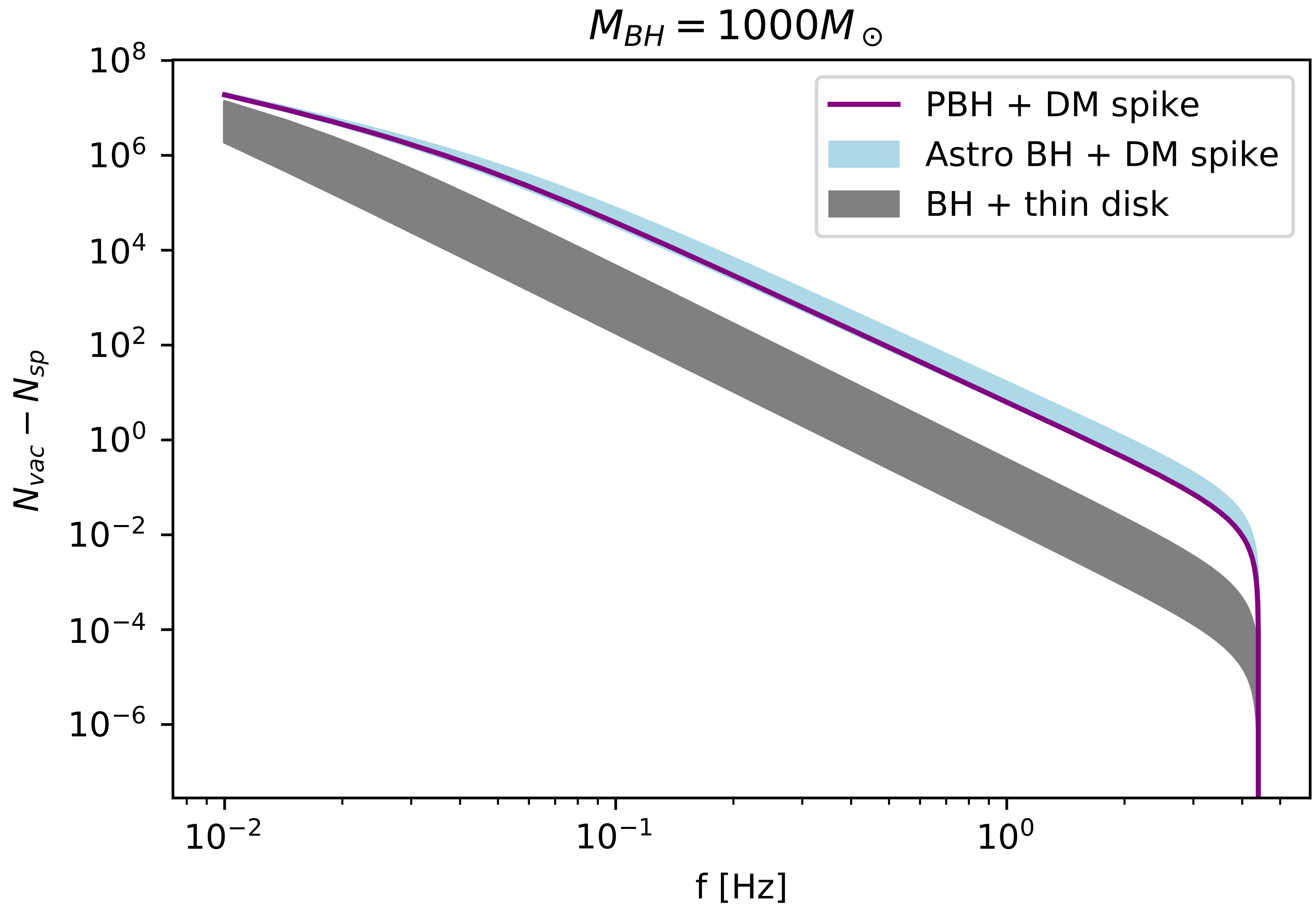
Problem: primordial black holes are very difficult to distinguish from astrophysical ones

If they're less than a solar mass, probably primordial, but with GWs, what can we say?



Dark dresses

Which leads to an accumulated dephasing in the gravitational wave form (i.e. how many fewer cycles the inspiral lasts than the equivalent system in vacuum)

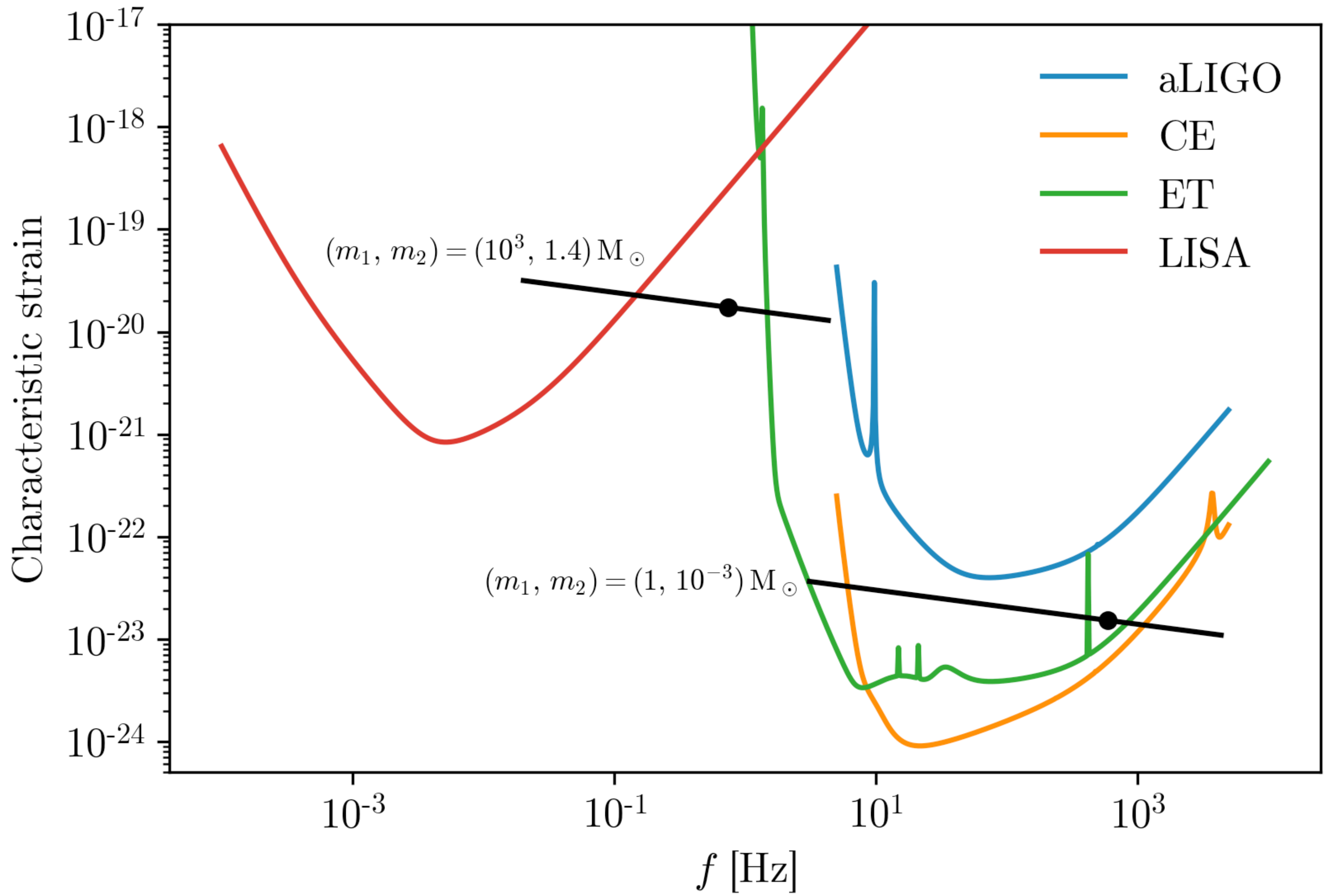


It might look indistinguishable, but in fact… it's not!

Cole, Coogan, Bertone, Tomaselli in prep.

Dark dresses

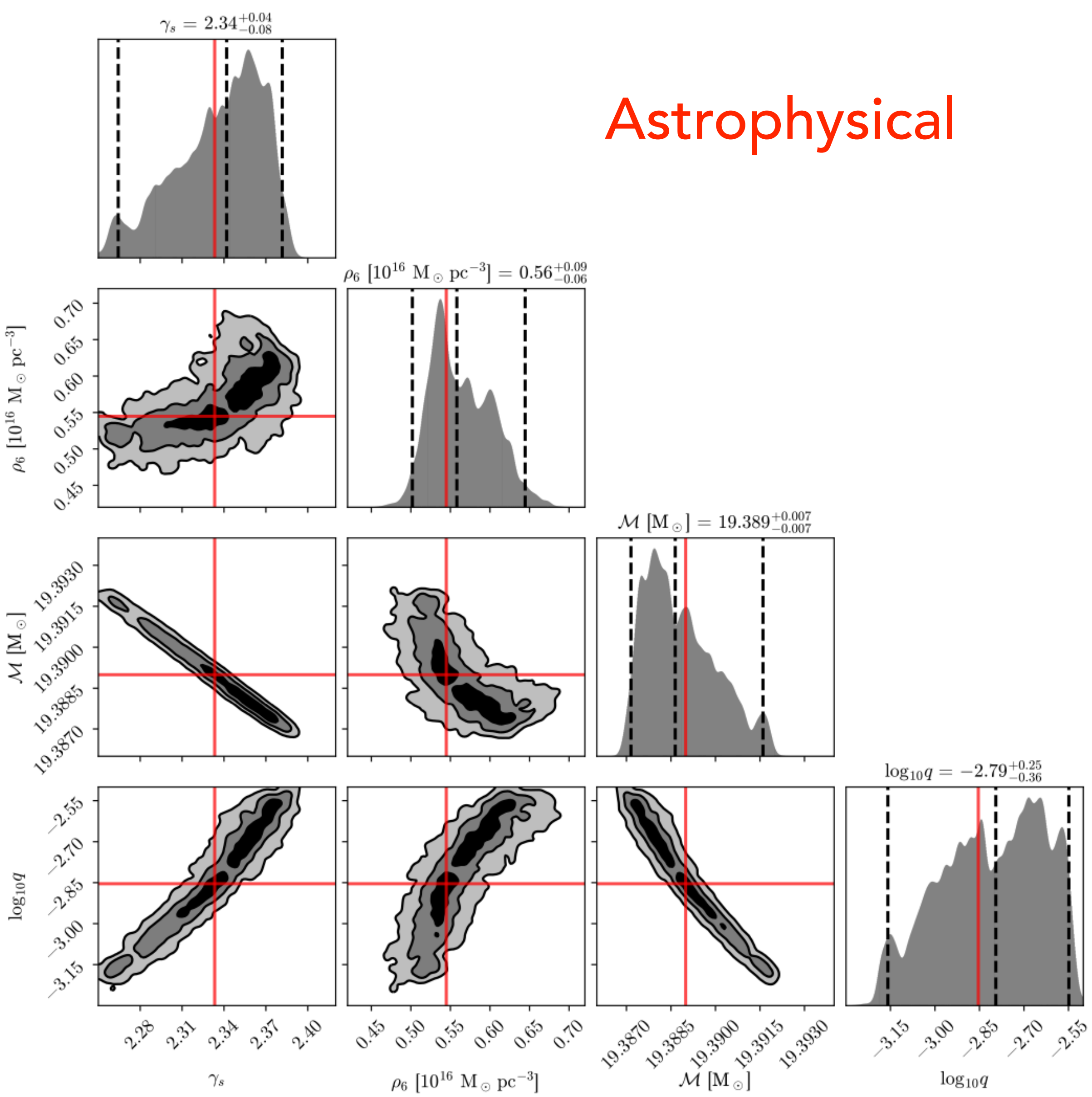
Key is that we need to see enough cycles to observe the accumulated difference from vacuum

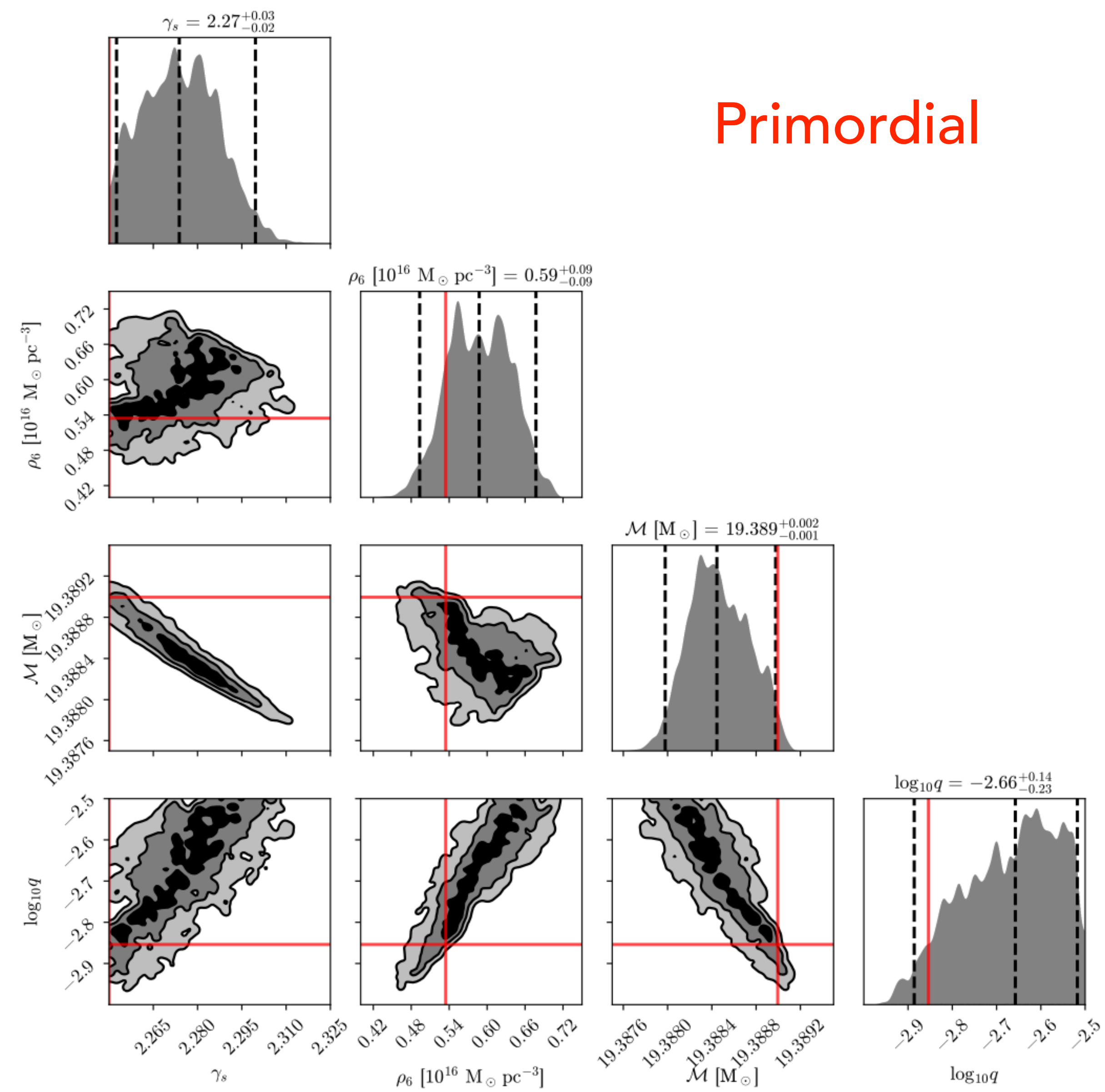


Courtesy of Adam Coogan

With LISA (IMRIs)

We can reconstruct the parameters of the dressed systems, and we're at risk of missing the signals if we use vacuum templates

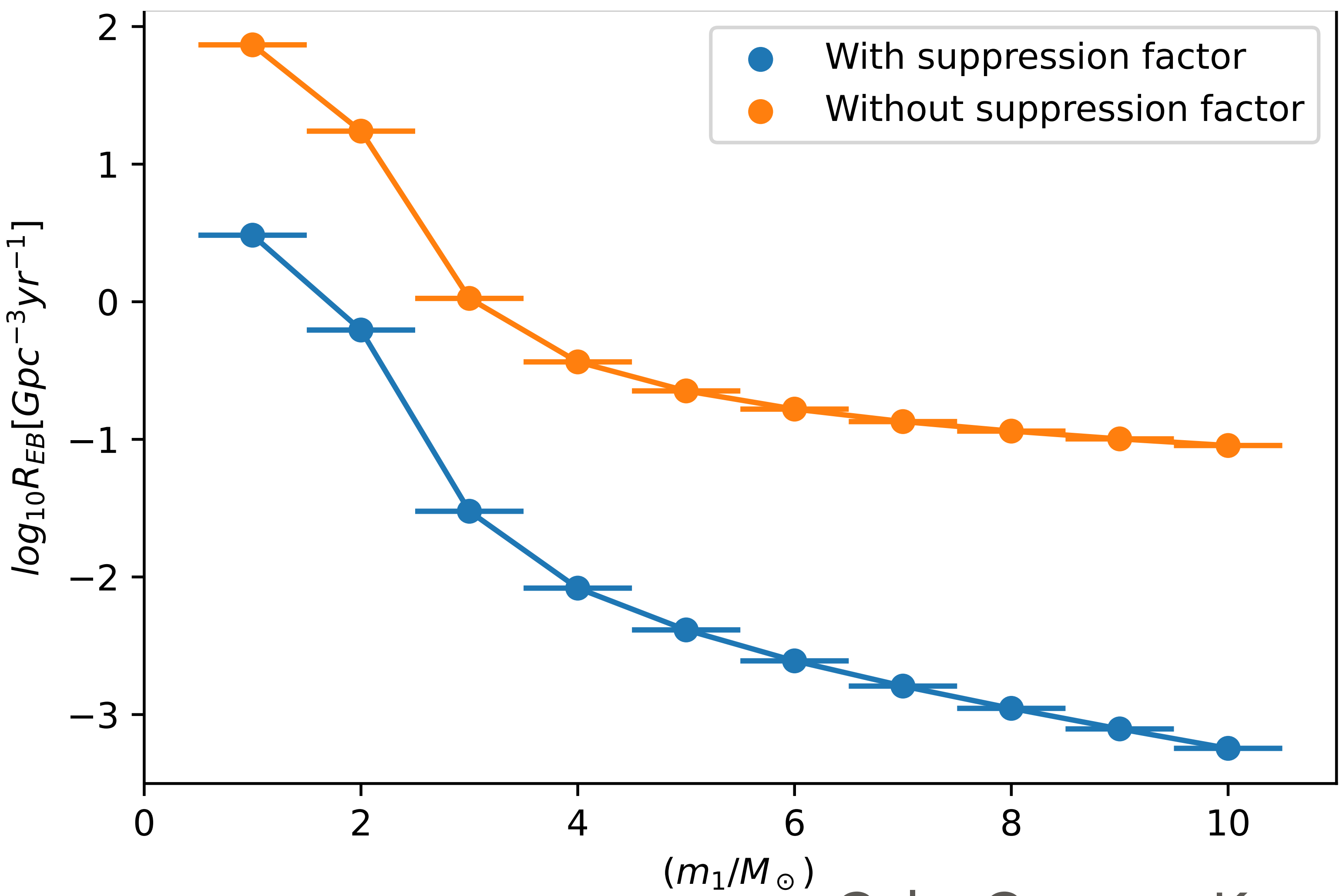




Coogan et al. 2021

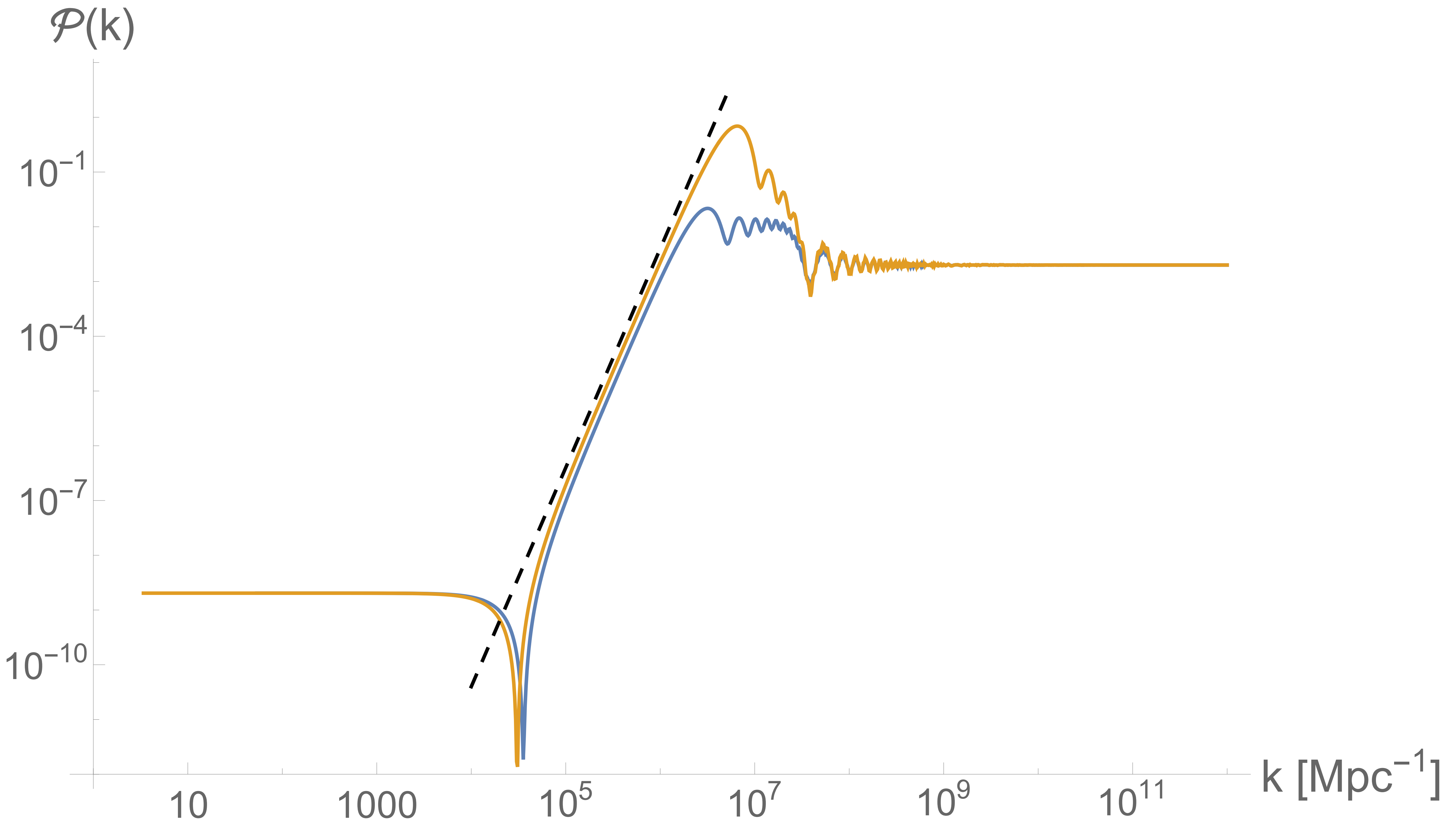
With ET and CE (PBHs)

Expect up to a few per year with ET and CE sensitivity, based on realistic initial conditions.
Tentative conclusion: we will miss these systems if we use vacuum templates, and these systems by definition can't be in vacuum



Cole, Coogan, Kavanagh, Bertone in prep.

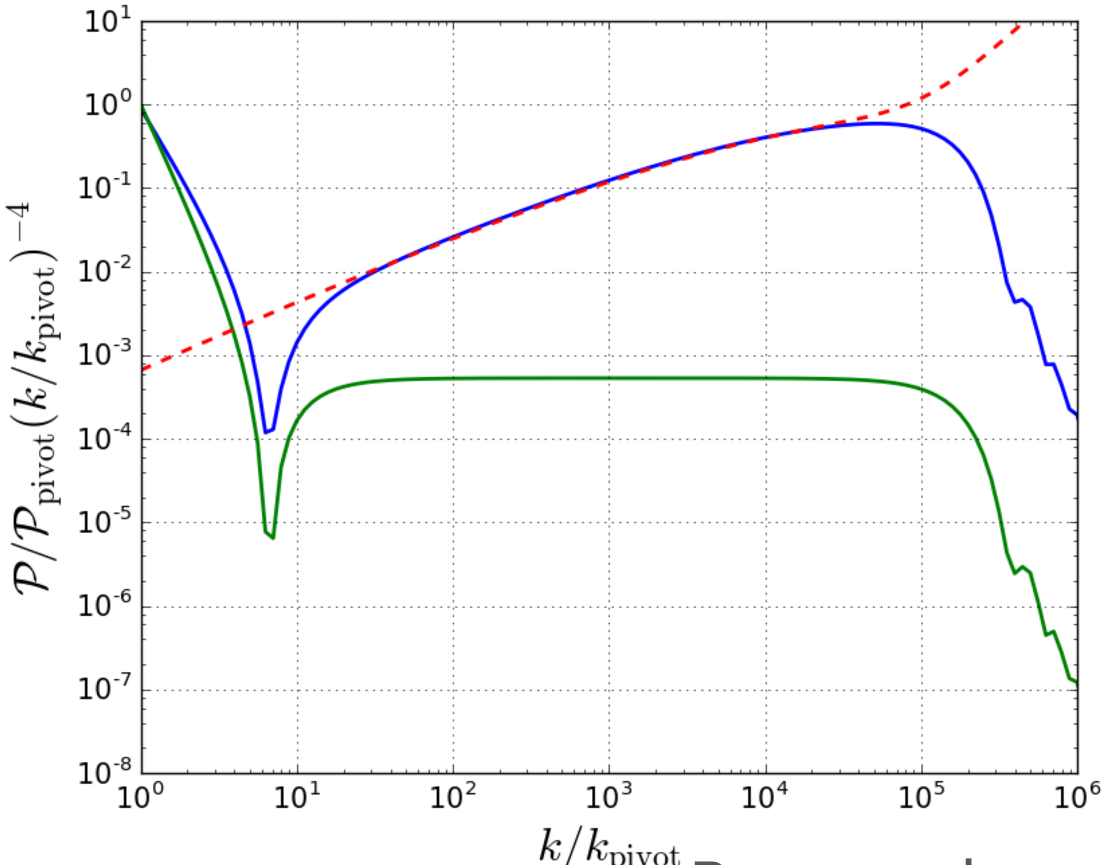
Rolling up hill



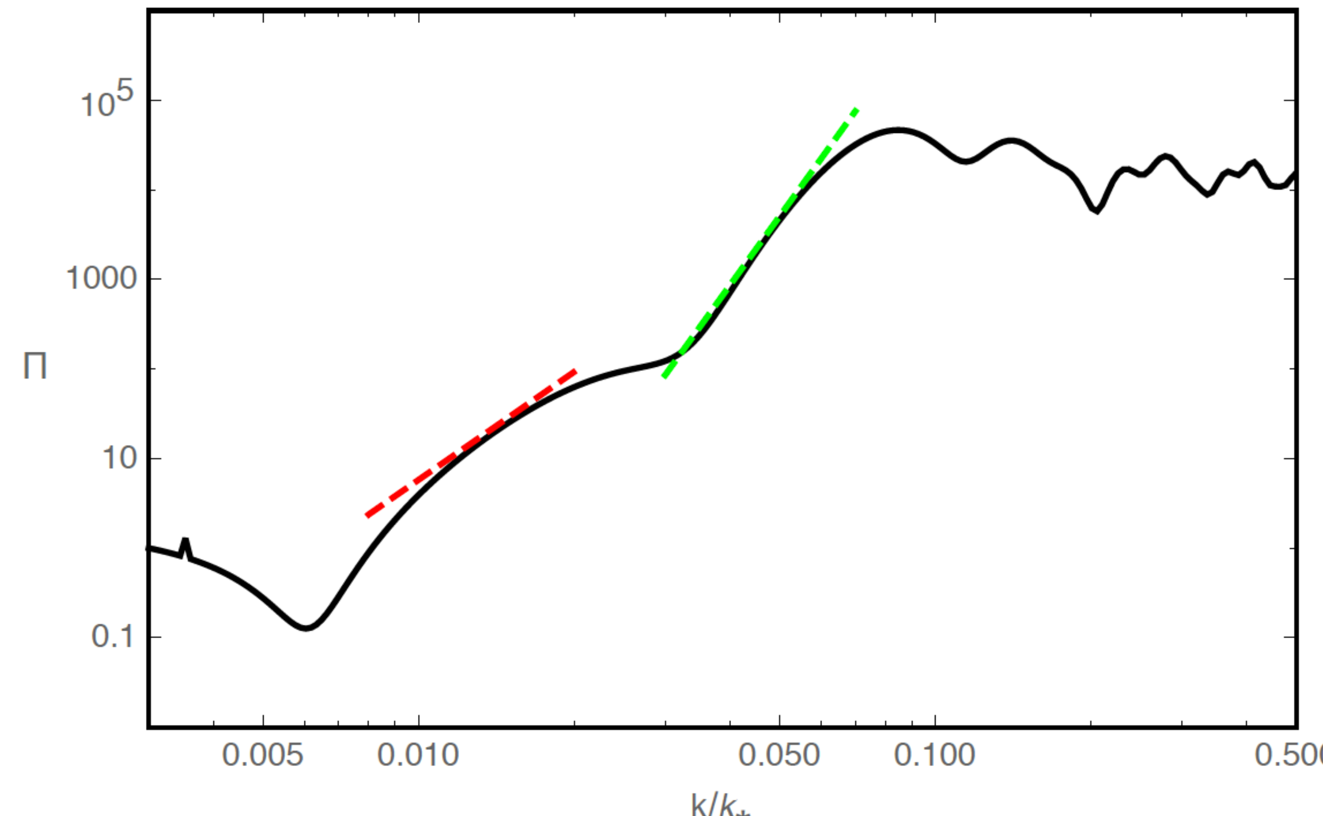
Byrnes, PC, Patil 2018

Or can we go steeper…

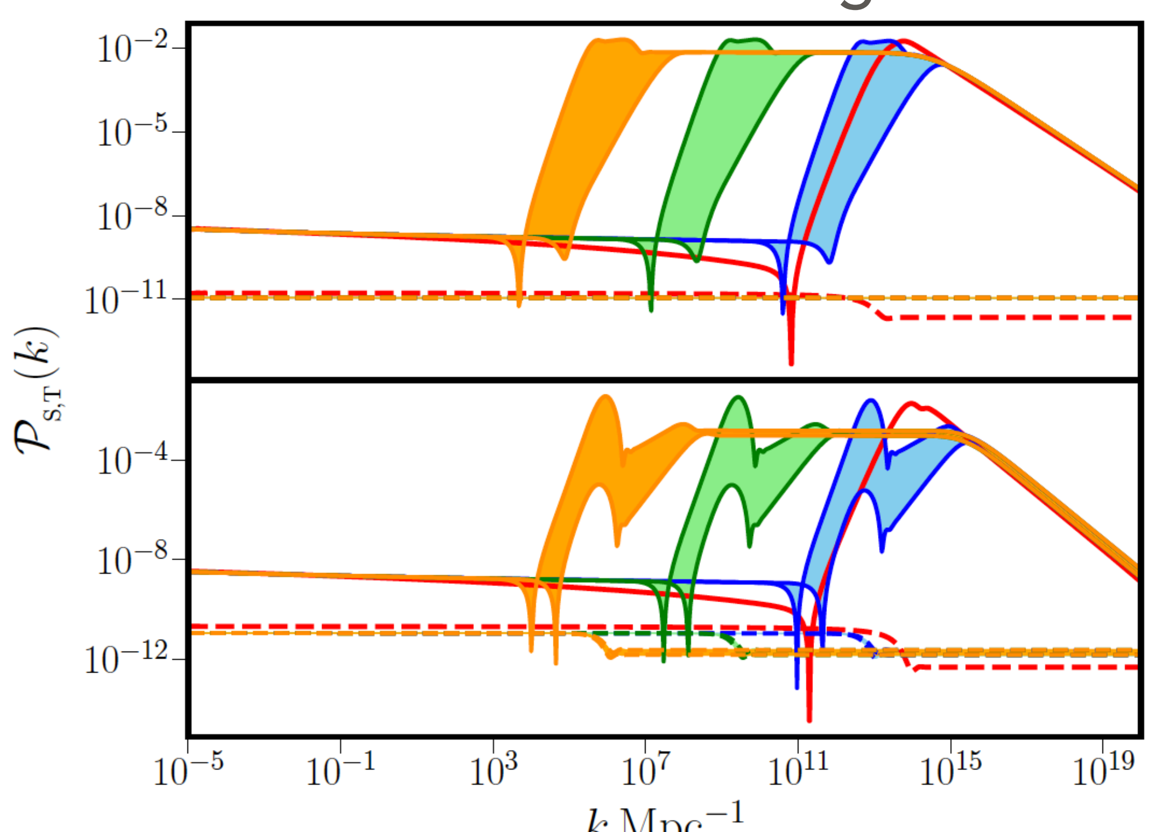
Carrilho et al. 2019

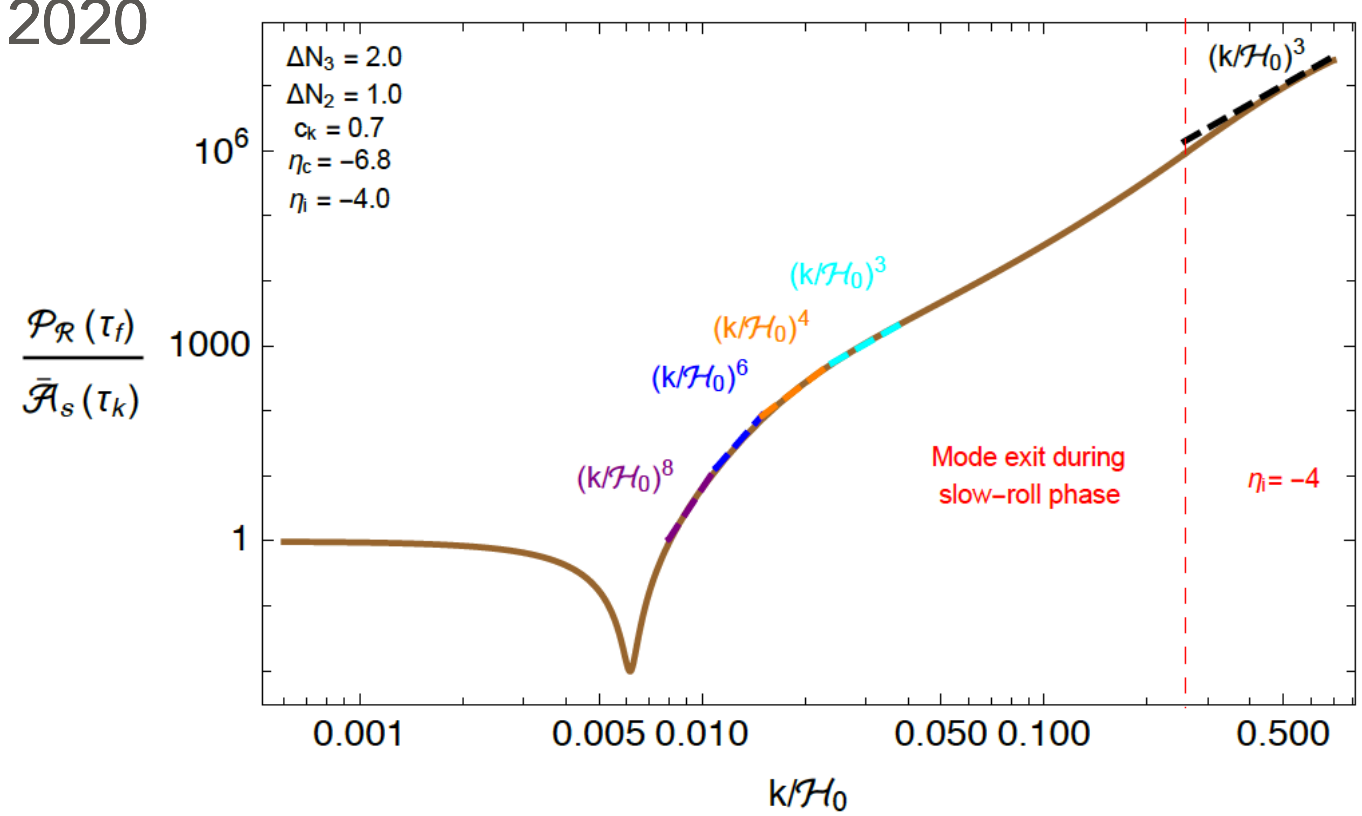


Tasinato 2021



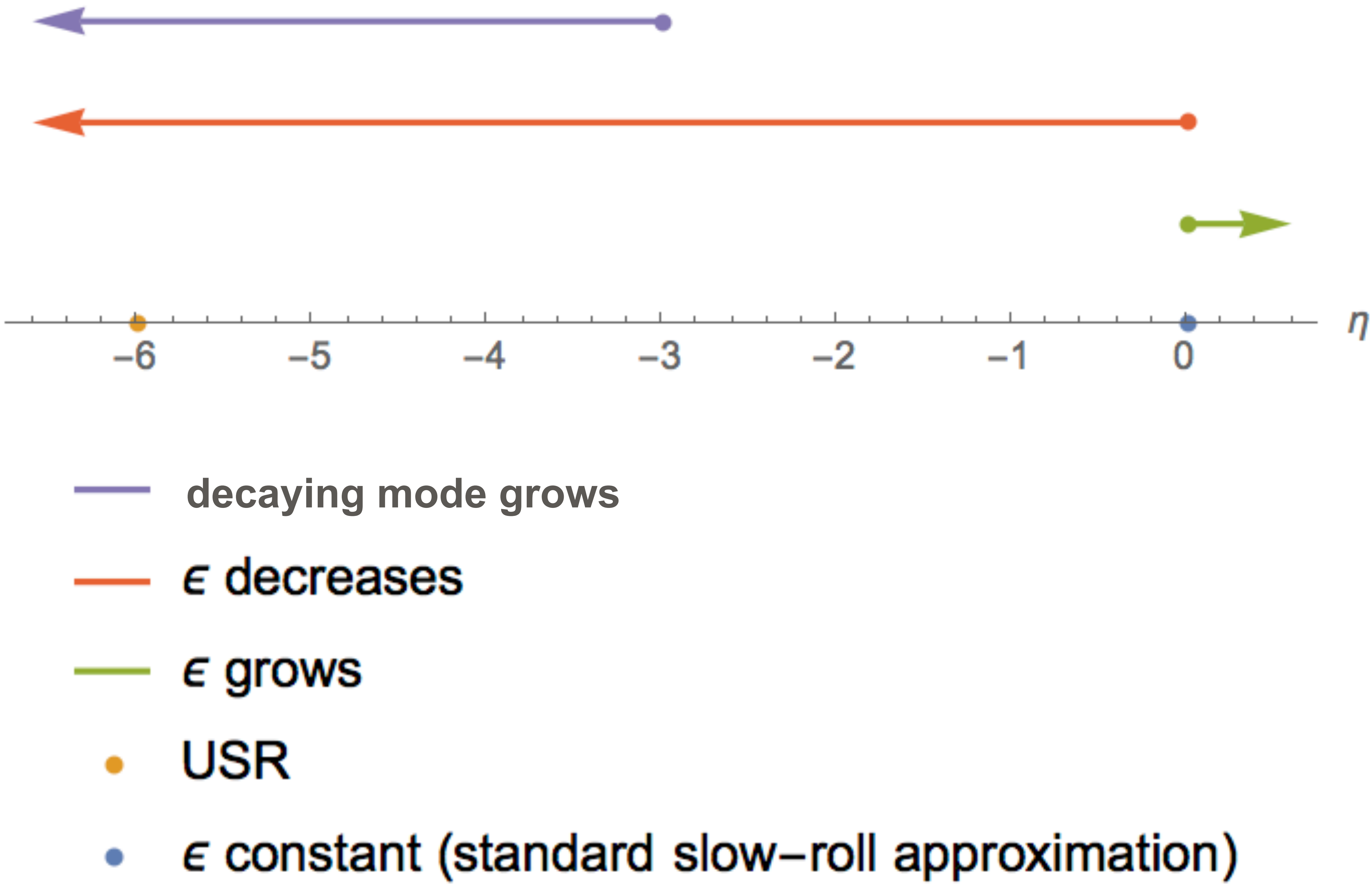
Ragavendra et al 2020





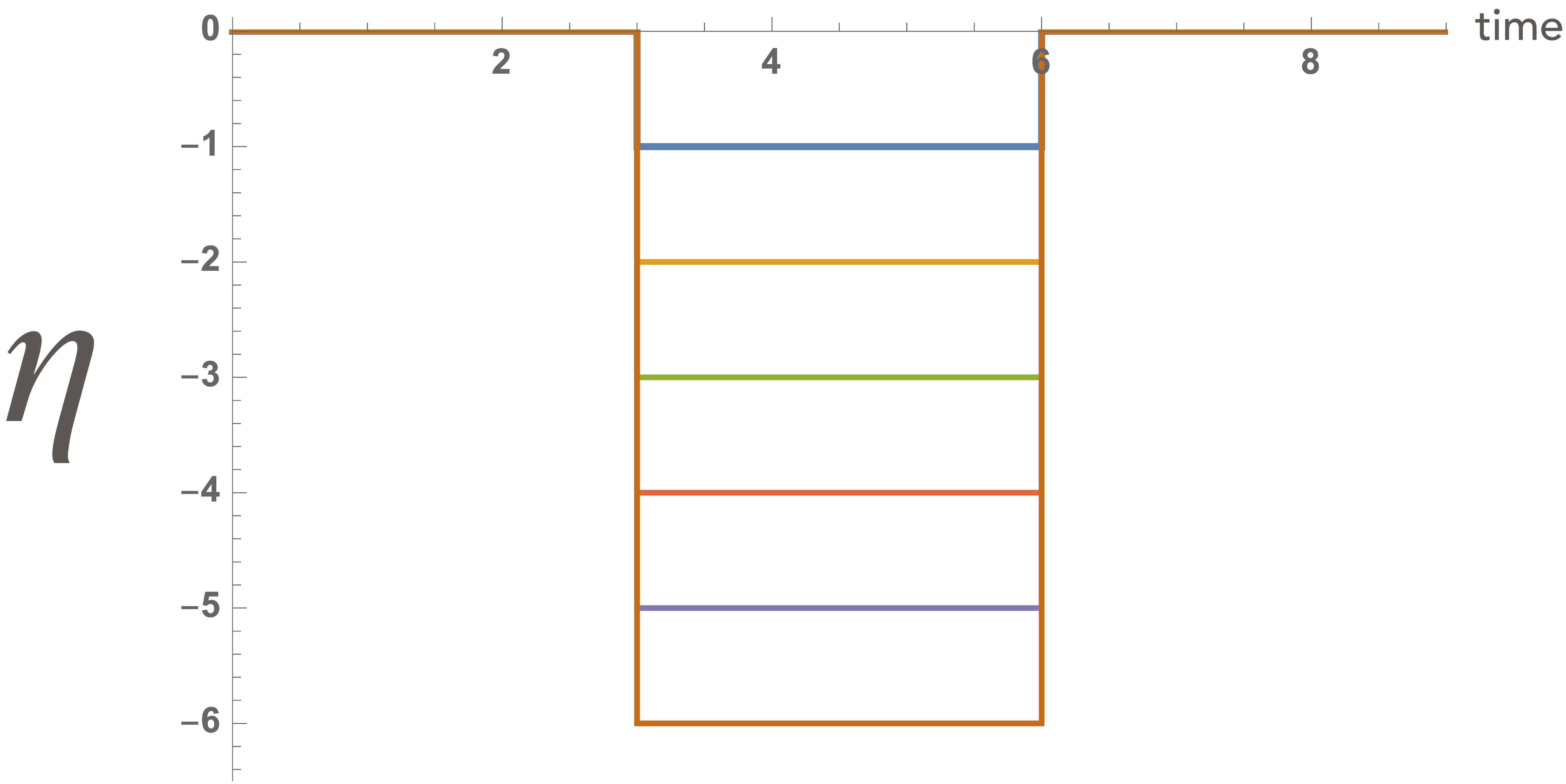
Oszoy & Tasinato 2019

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



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

Superhorizon growth

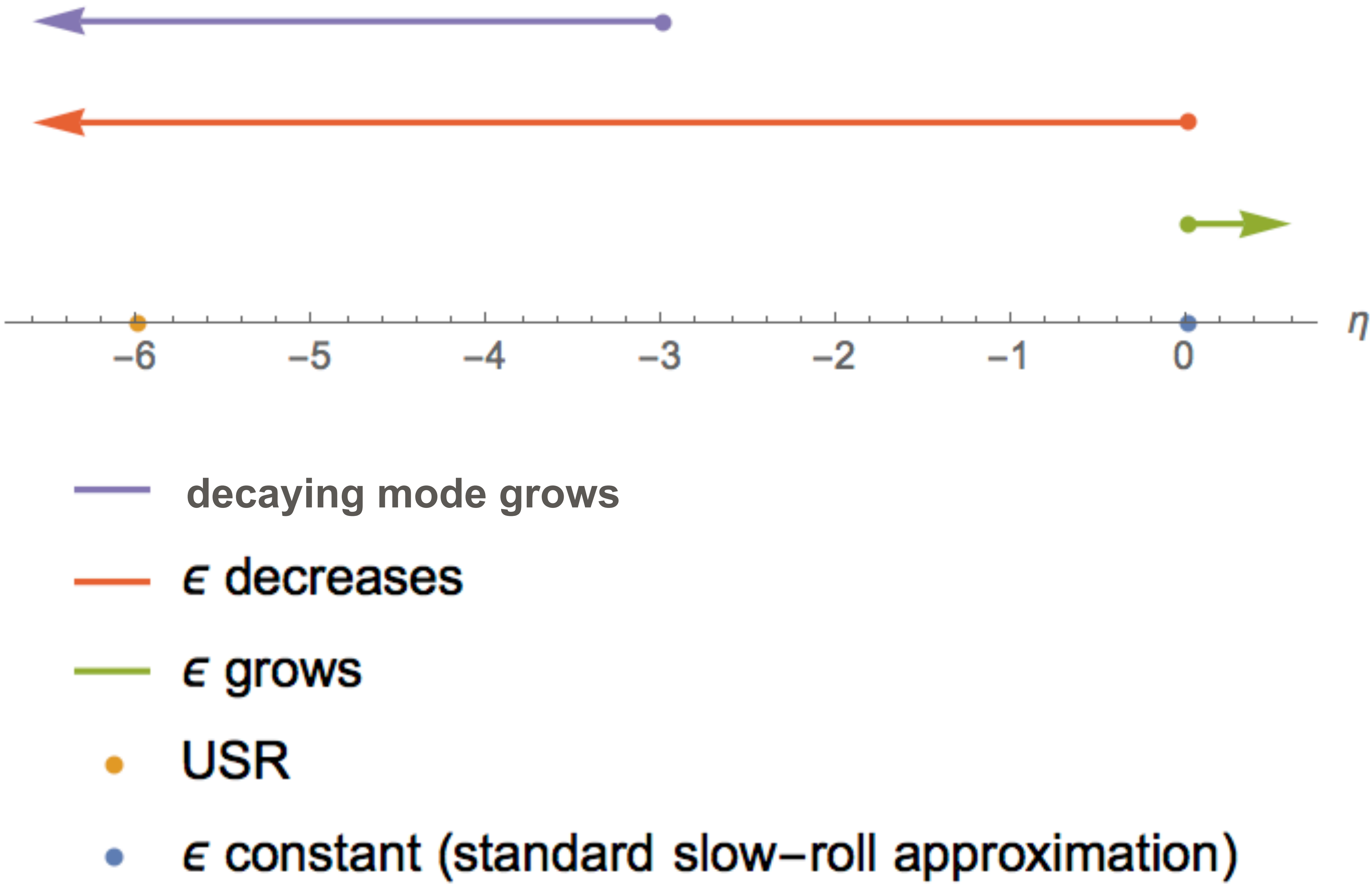
In the slow-roll approximation, everything freezes out after horizon exit. Beyond slow-roll, super horizon growth is possible

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

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

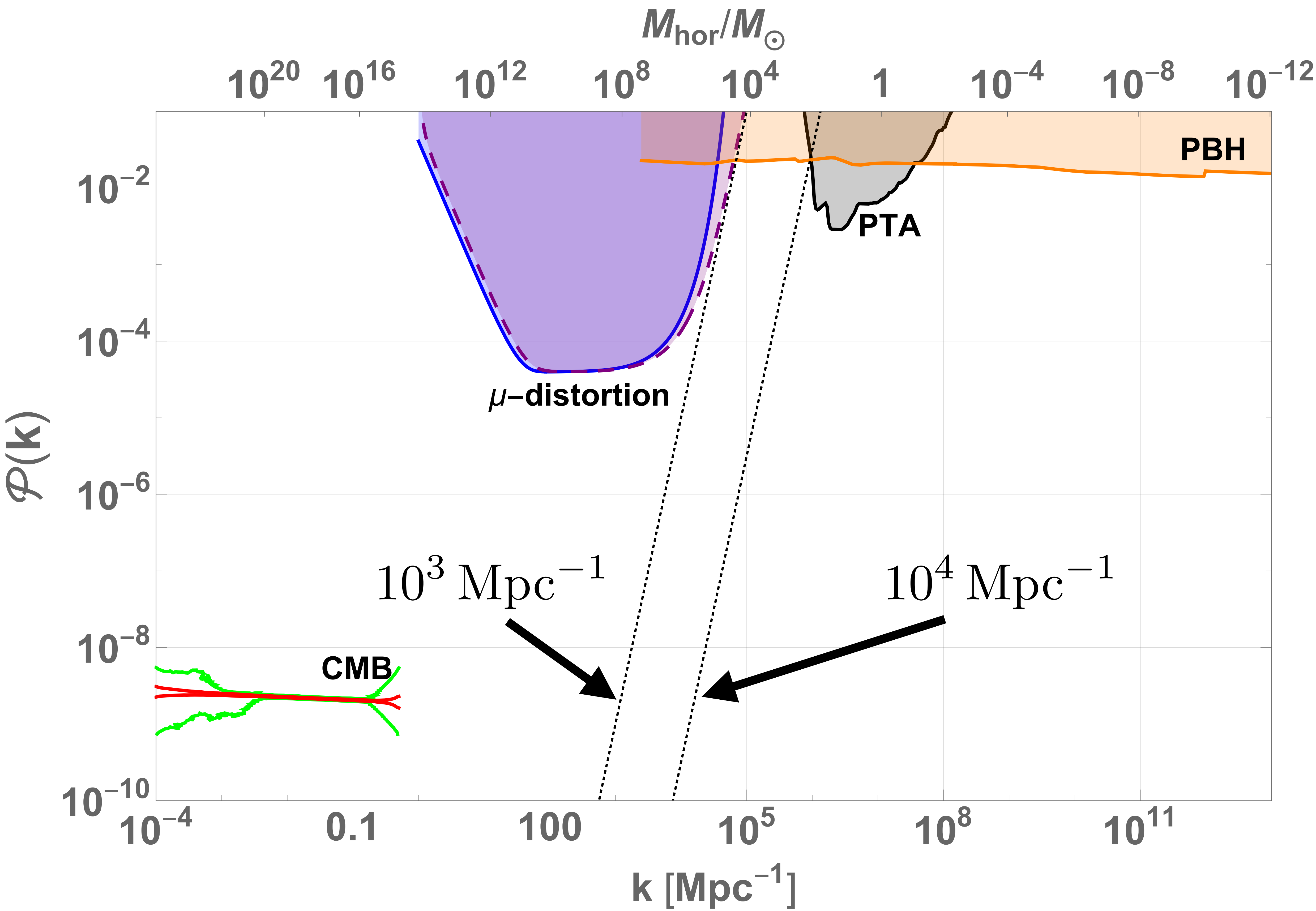
this is because the previously decaying mode starts to grow

SR/BSR/USR

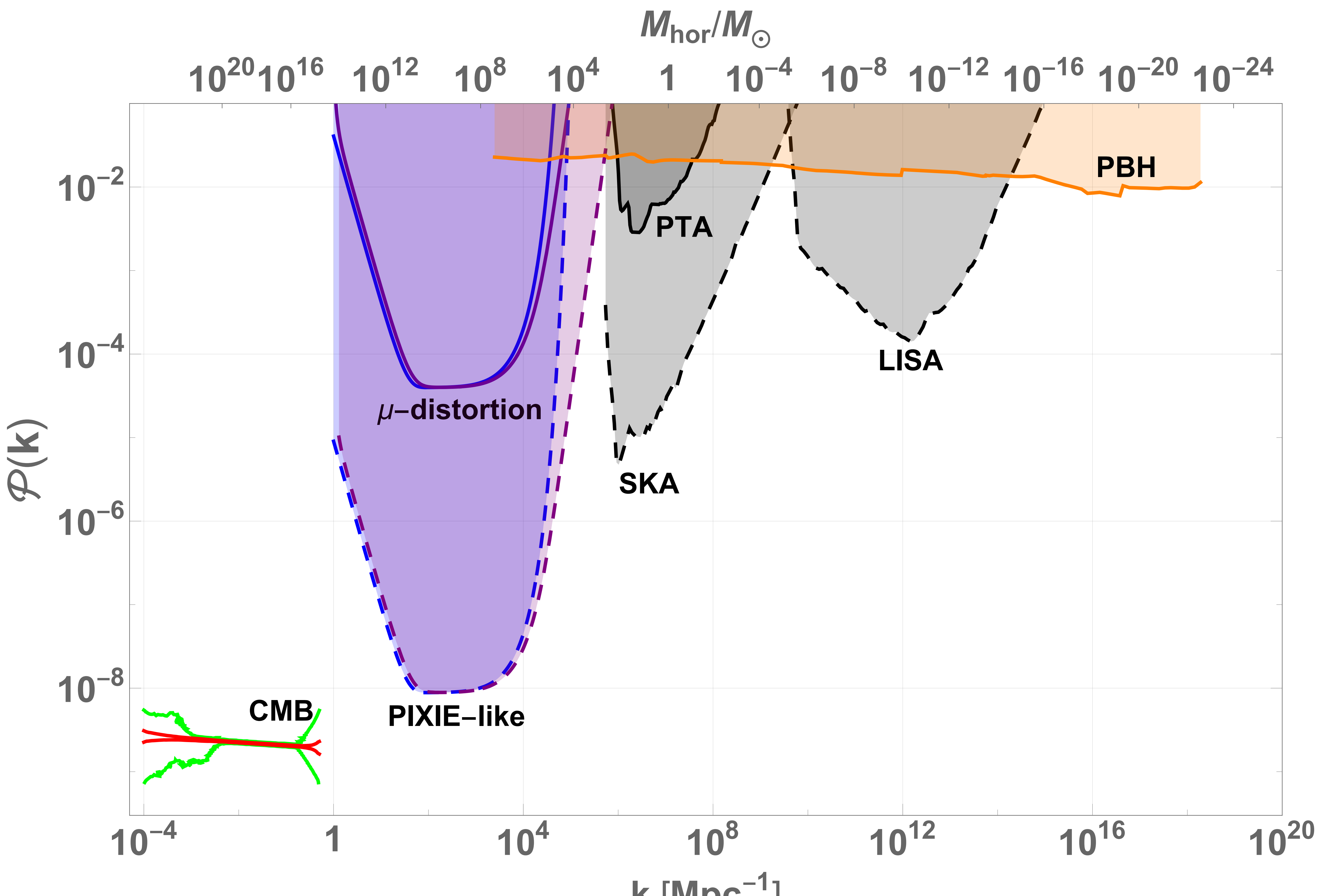


−6
−5
−4
−3
−2
−1
0
η
decaying mode grows
ϵ decreases
ϵ grows
USR
ϵ constant (standard slow−roll approximation)

Consequences for observational constraints



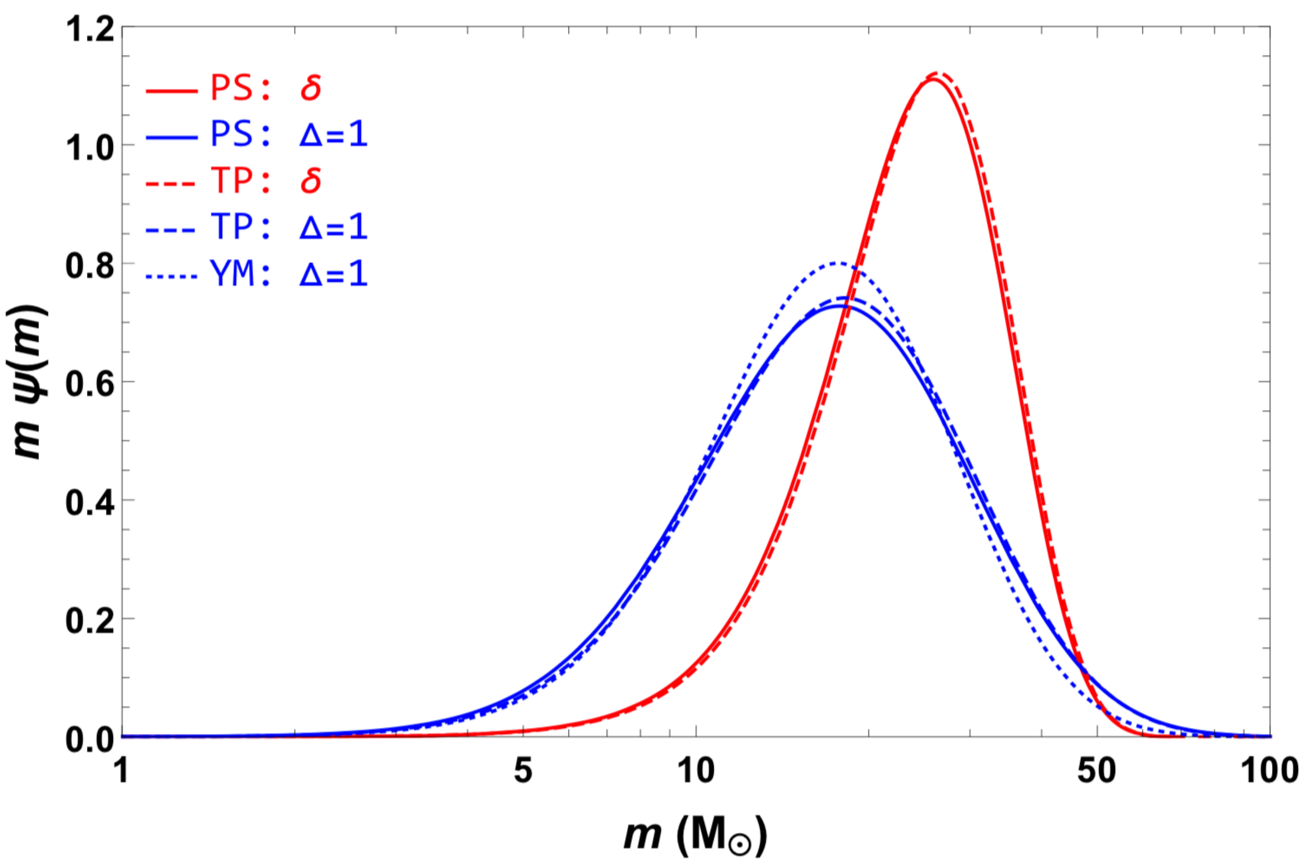
Future forecasts

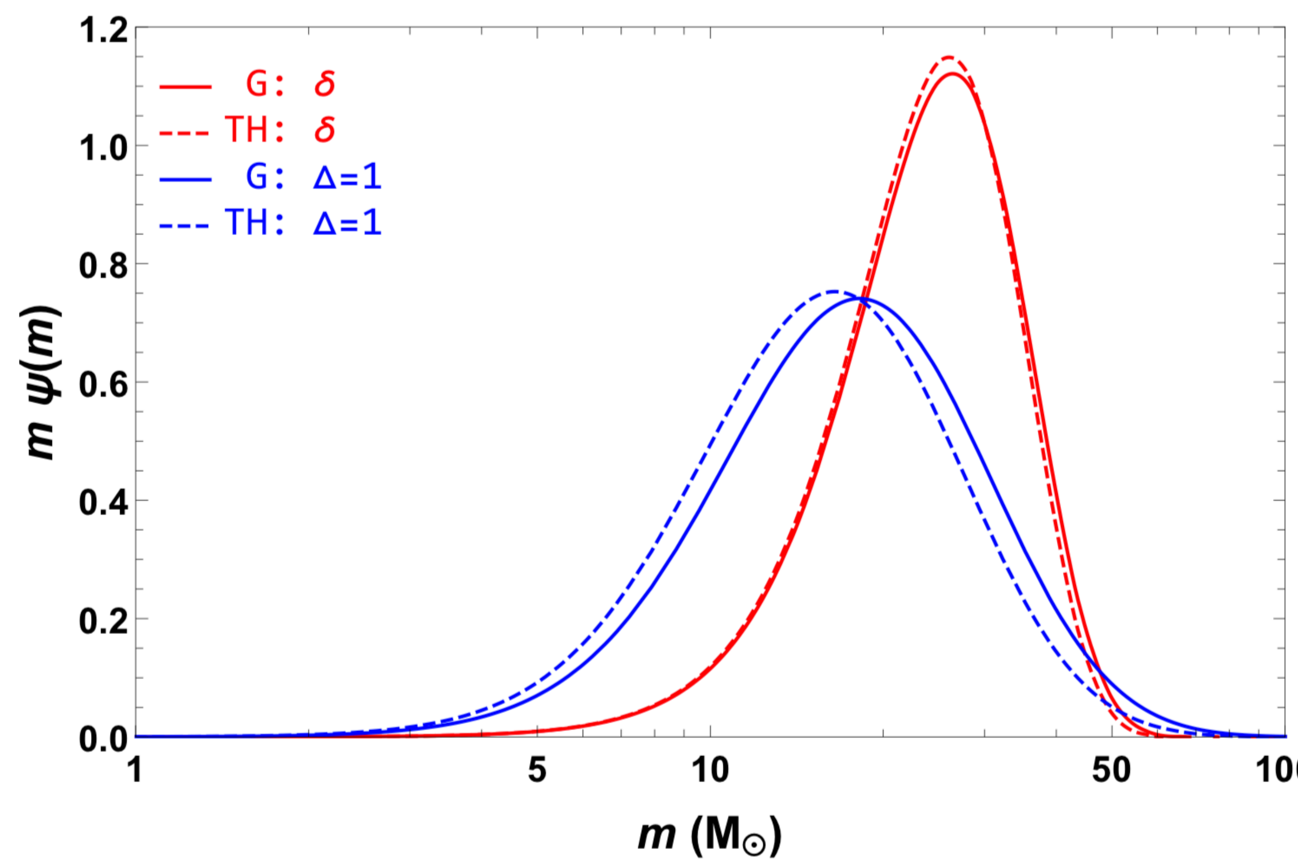


Byrnes, PC, Patil 2018

Consistency is key

Press-Schechter or Peaks Theory + window function



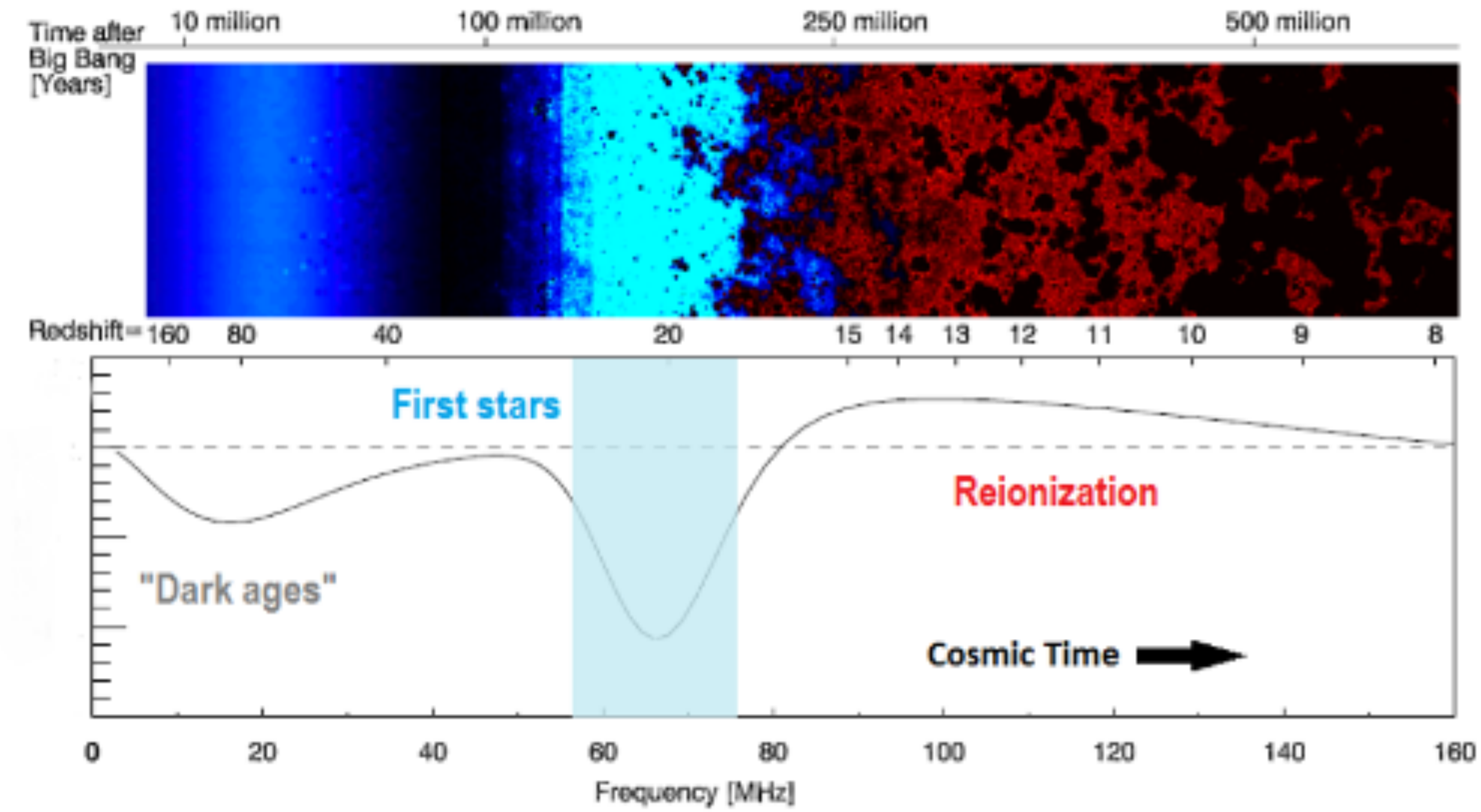


Fix the window function,
change the method

Fix the method,
change the window function

Gow, Byrnes, PC, Young 2020

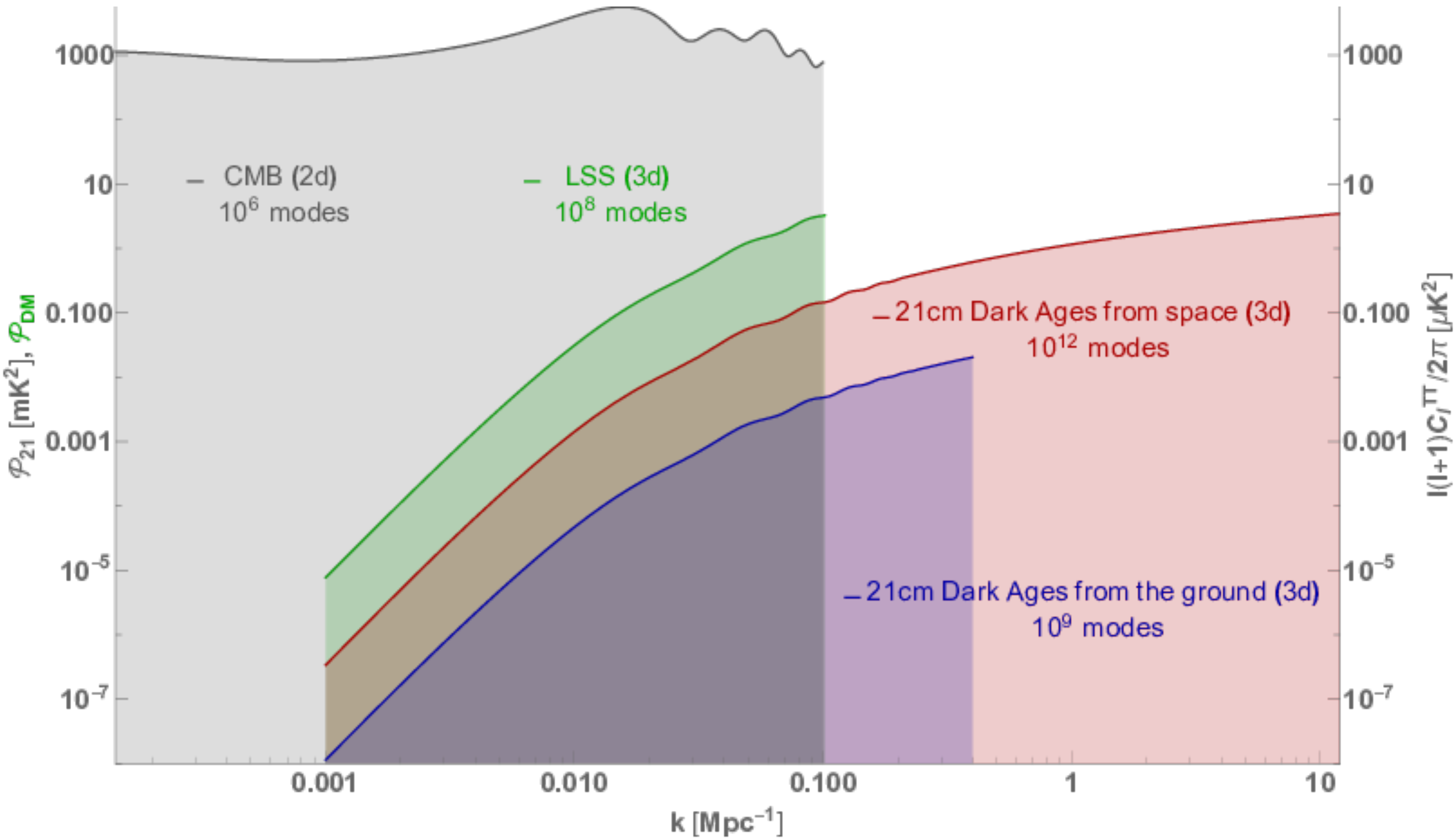
21cm power spectrum as a probe of primordial fluctuations



Pritchard, Loeb 2012
Loeb, Munoz 2018

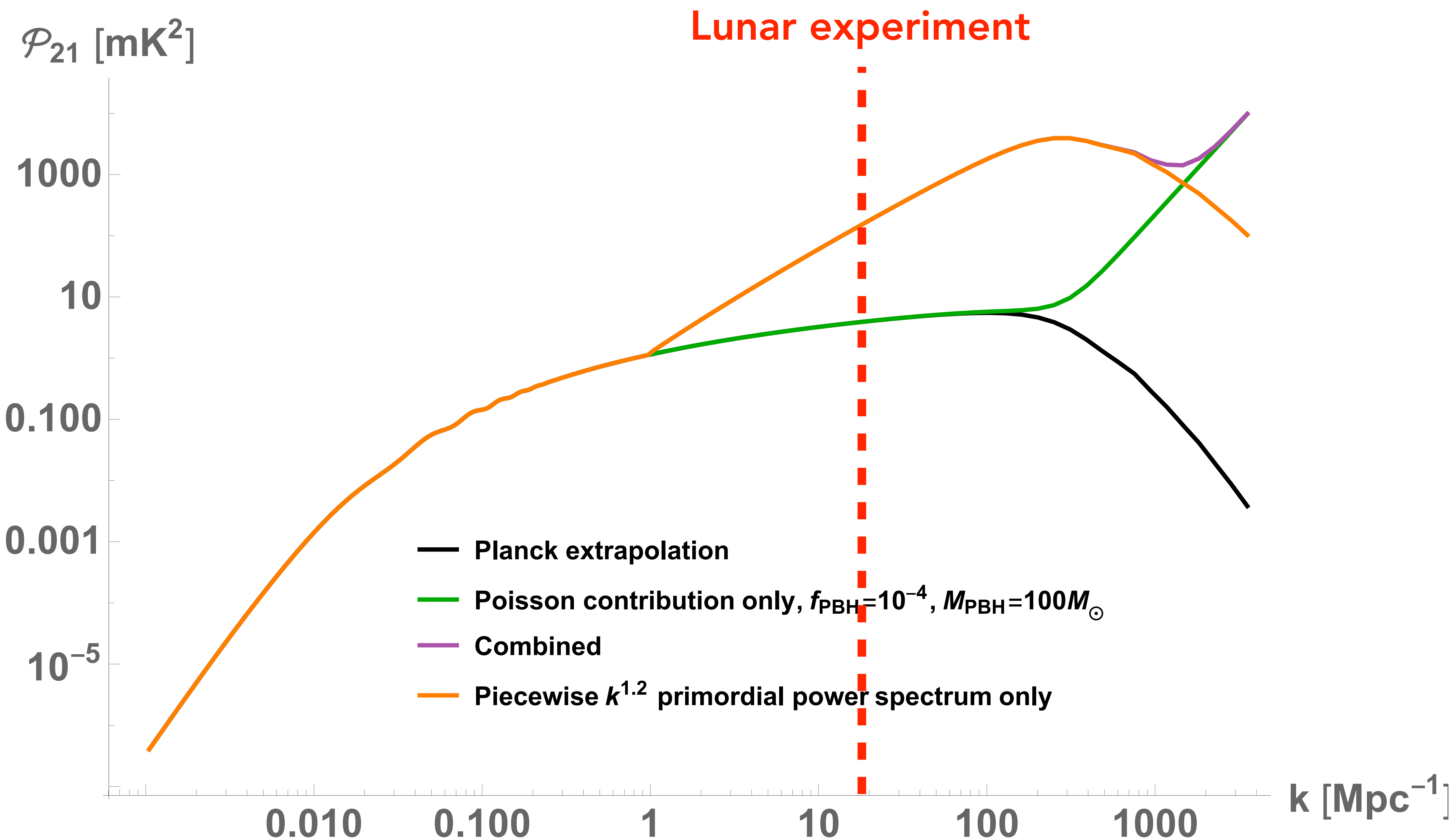
- Distribution of hydrogen inferred from 21cm signal with radio interferometer observations
- Tracer for the underlying dark matter distribution as physics still linear in the Dark Ages
- Tracer for the primordial fluctuations
- Probe for small-scale power and/or PBHs

21cm observations



PC, Silk 2019

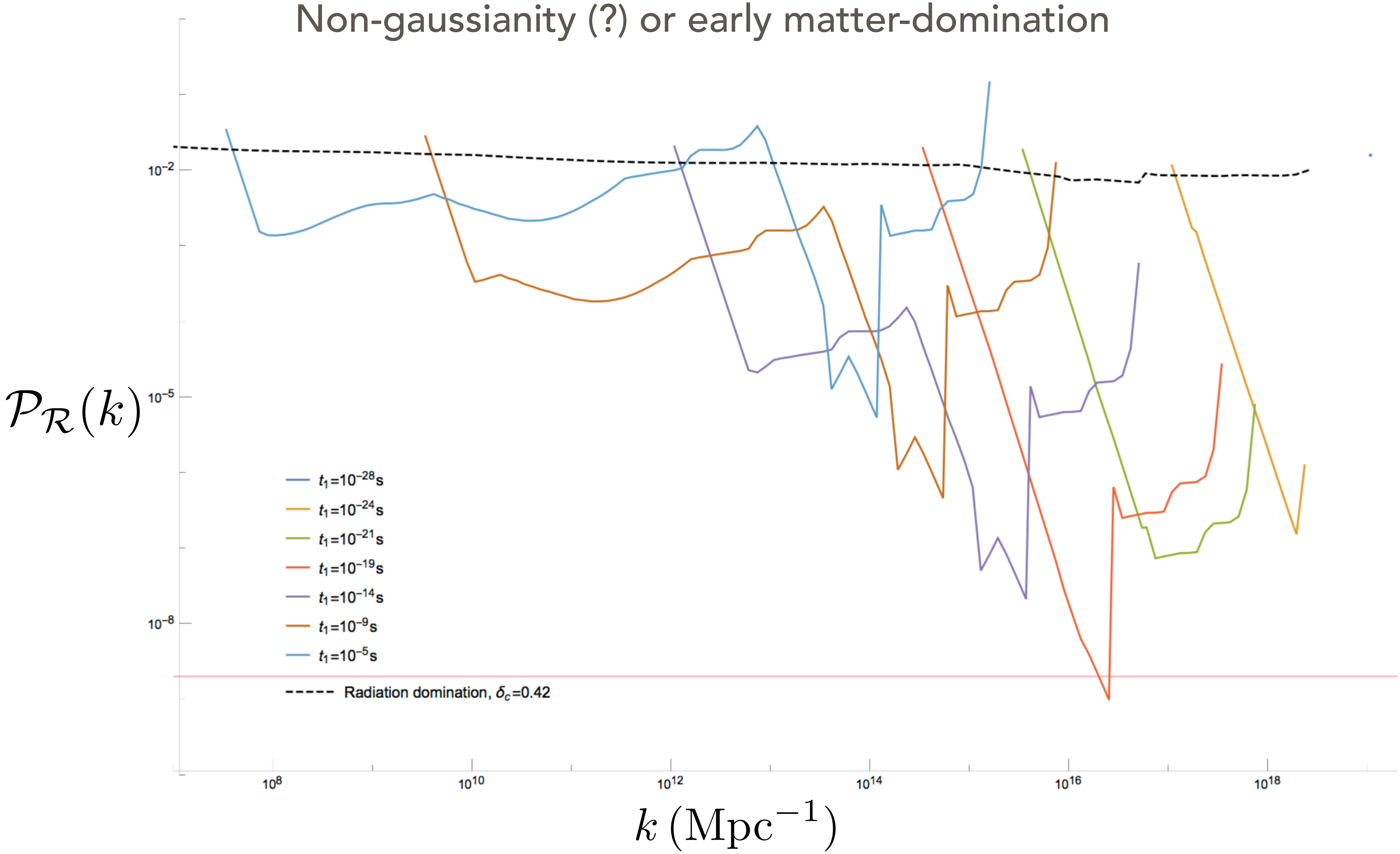
21cm observations



PC, Silk 2019

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

Non-gaussianity (?) or early matter-domination

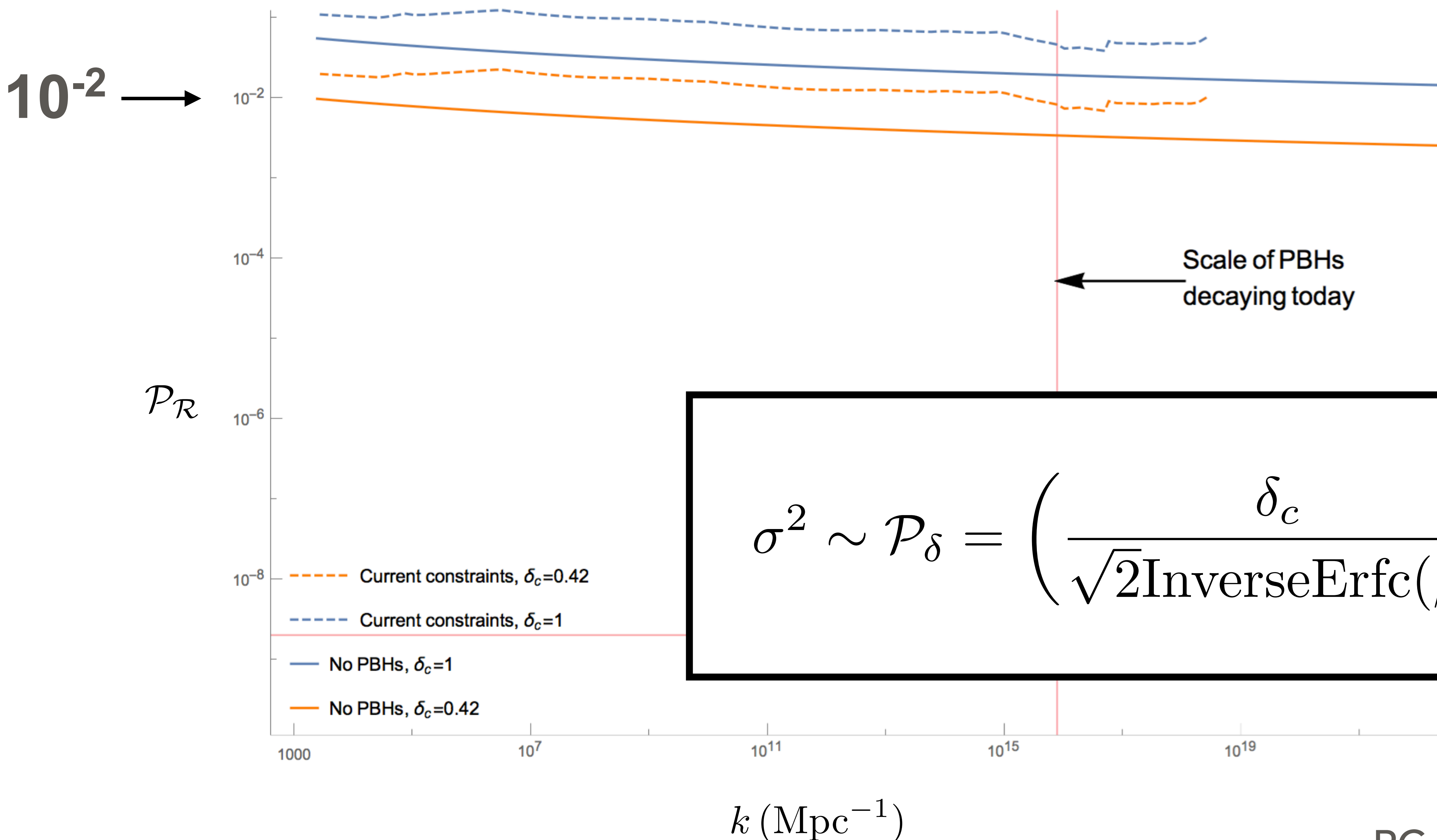


PC, Byrnes 2017

see also Carr, Tenkanen and Vaskonen 2017

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.



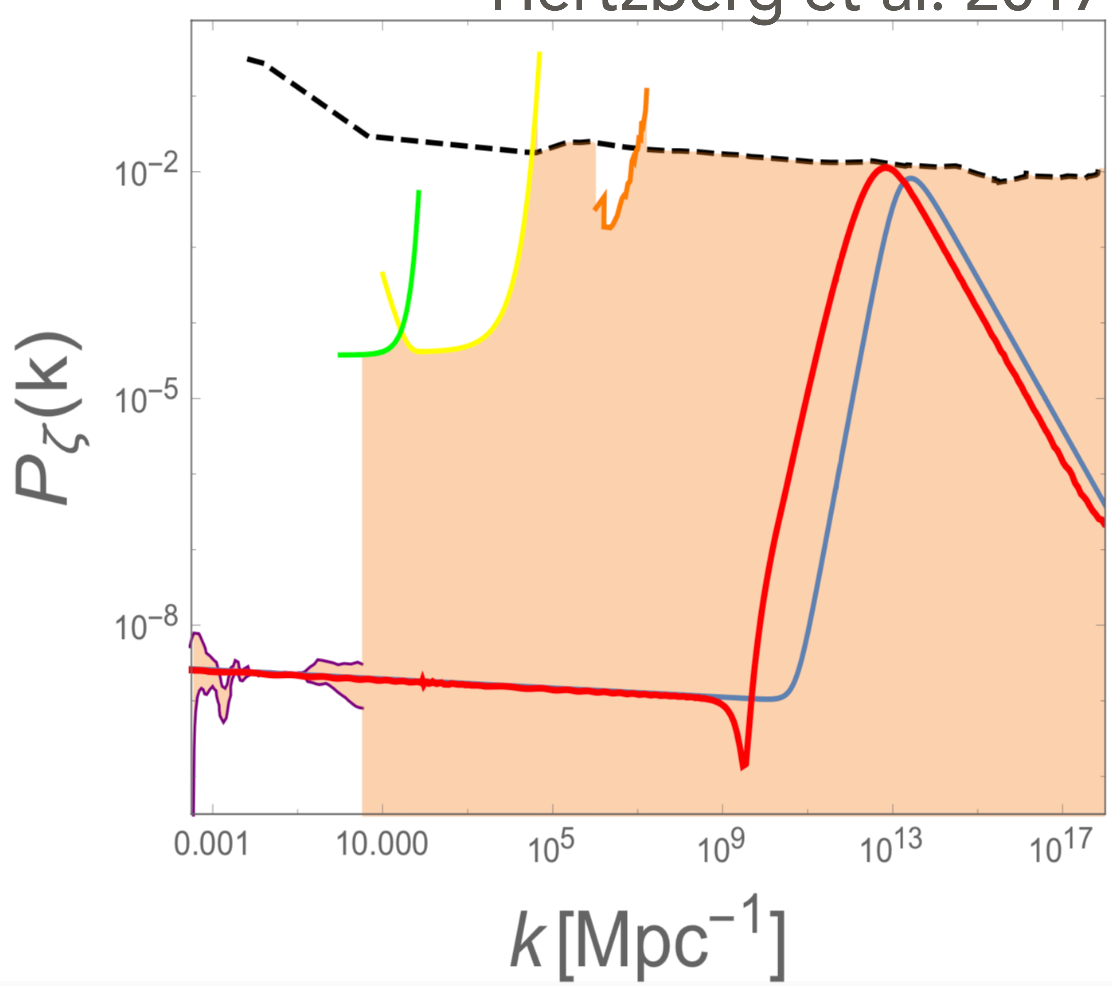
$$\sigma^2 \sim \mathcal{P}_\delta = \left(\frac{\delta_c}{\sqrt{2}\mathrm{InverseErfc}(\beta)}\right)^2$$

PC, Byrnes 2017

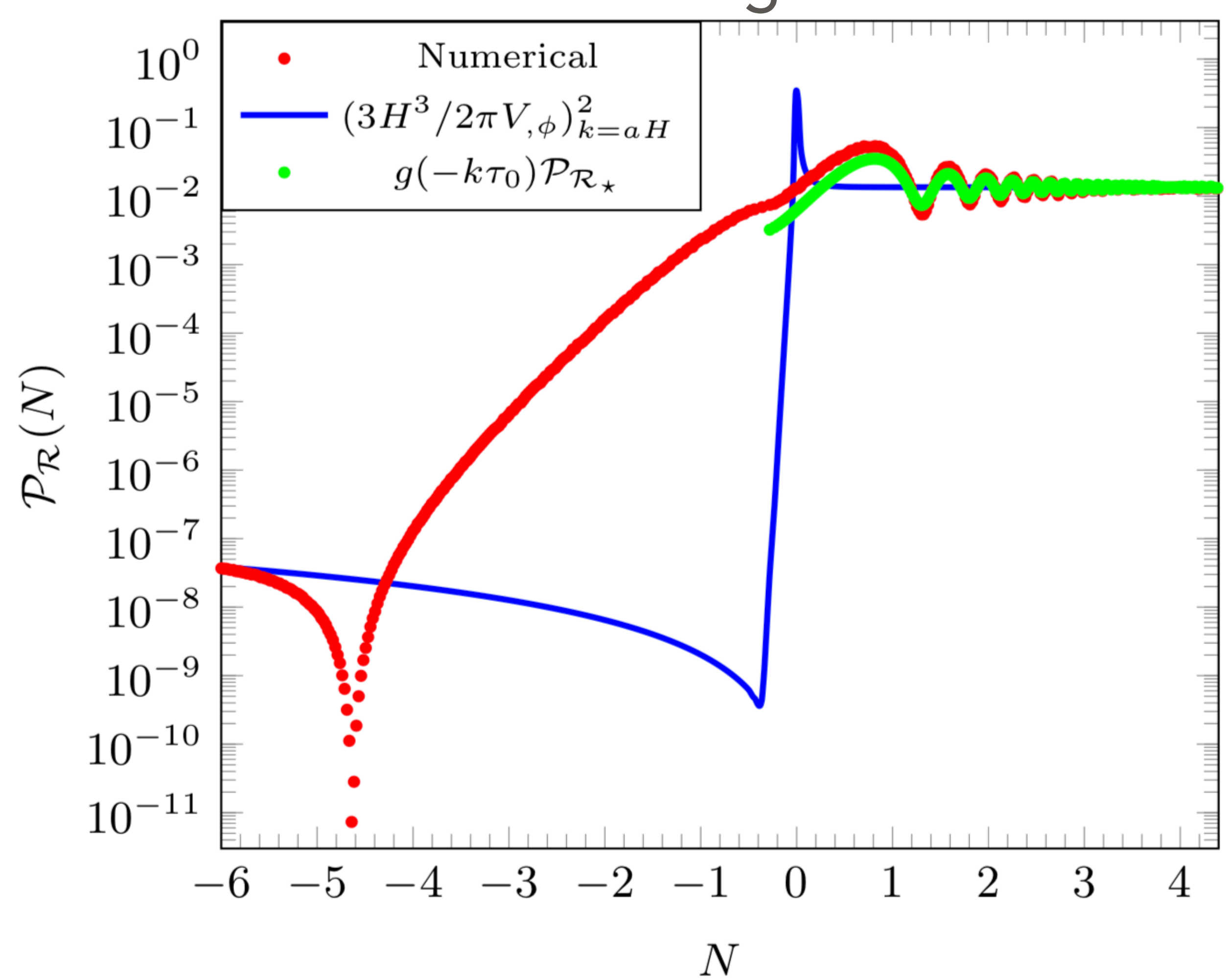
THE DIP

Transient, but always there. Not due to epsilon increasing solely - could something like PIXIE detect it?

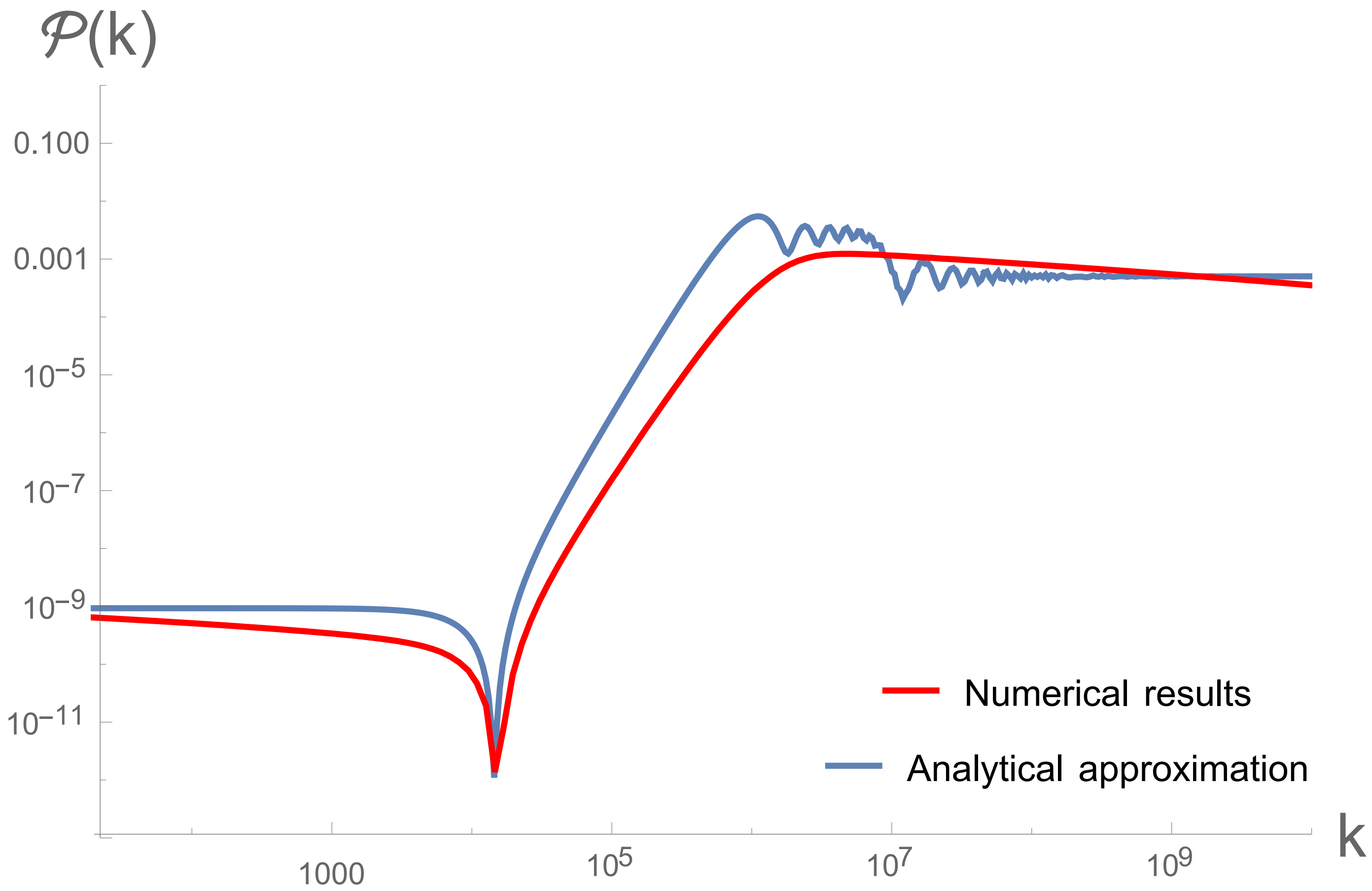
Hertzberg et al. 2017



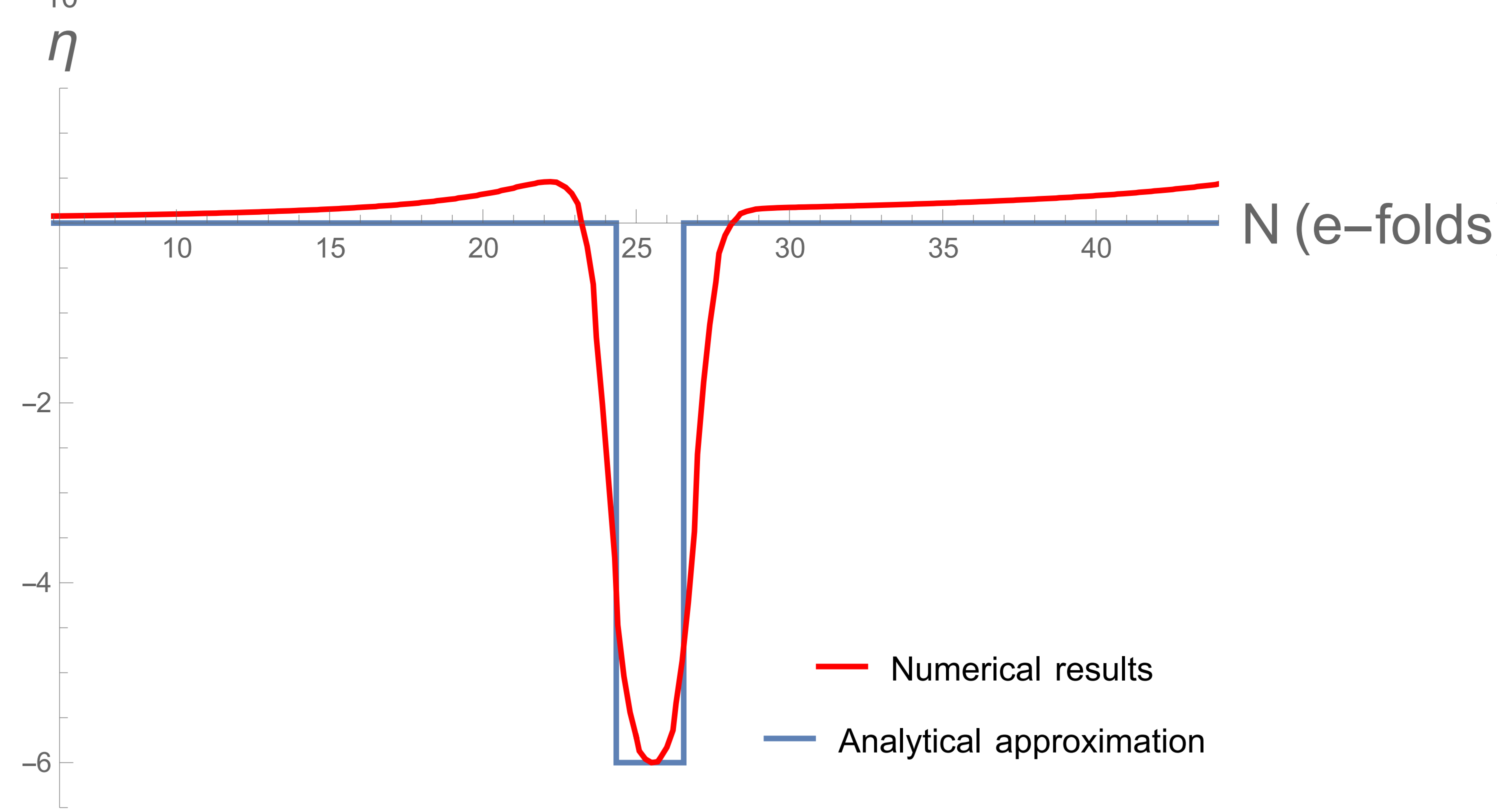
Biagetti et al. 2018



Numerical comparison



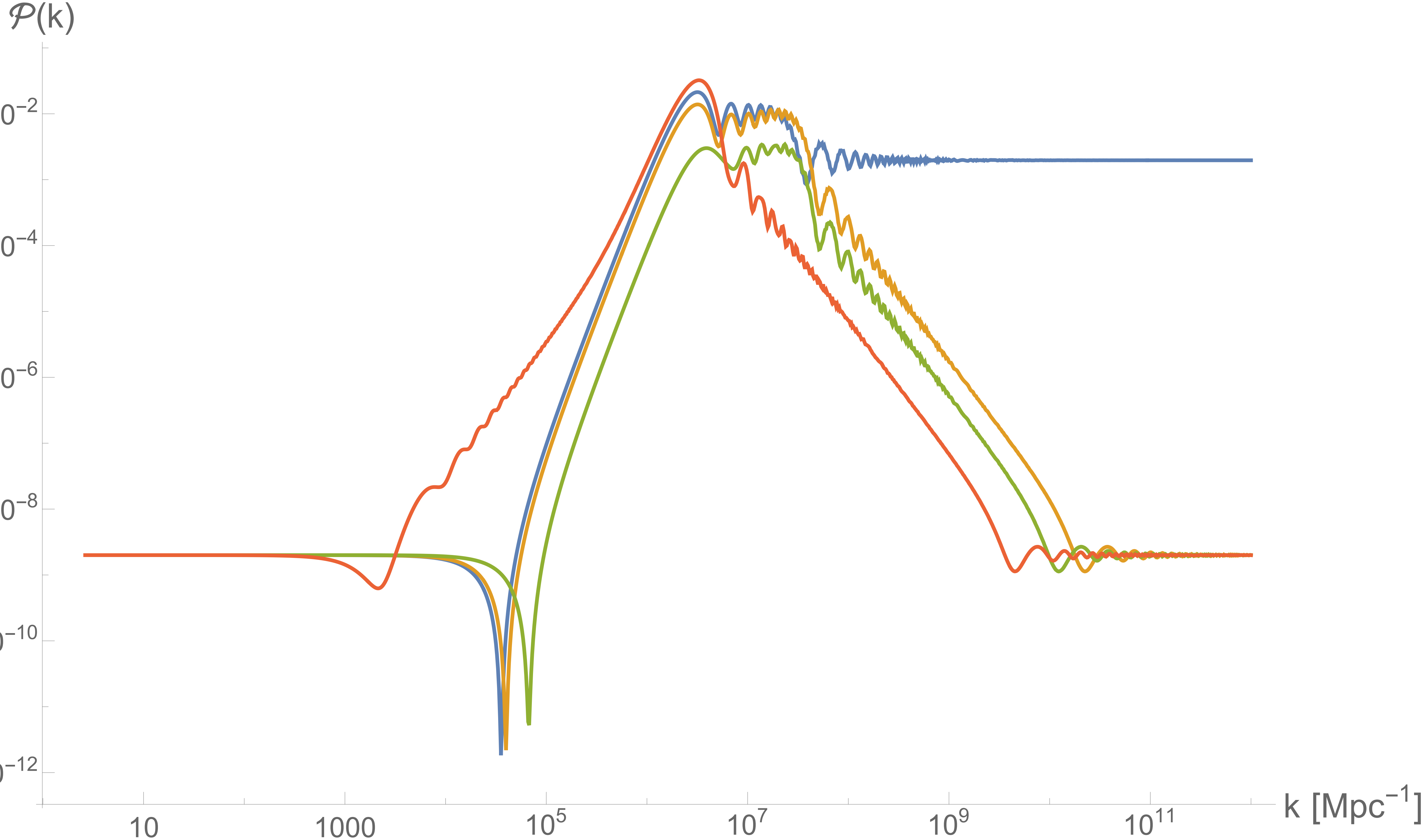
Good approximation of the main features, and dip still there in analytical approximation where epsilon never increases



David Seery's CPPTransport for numerical results

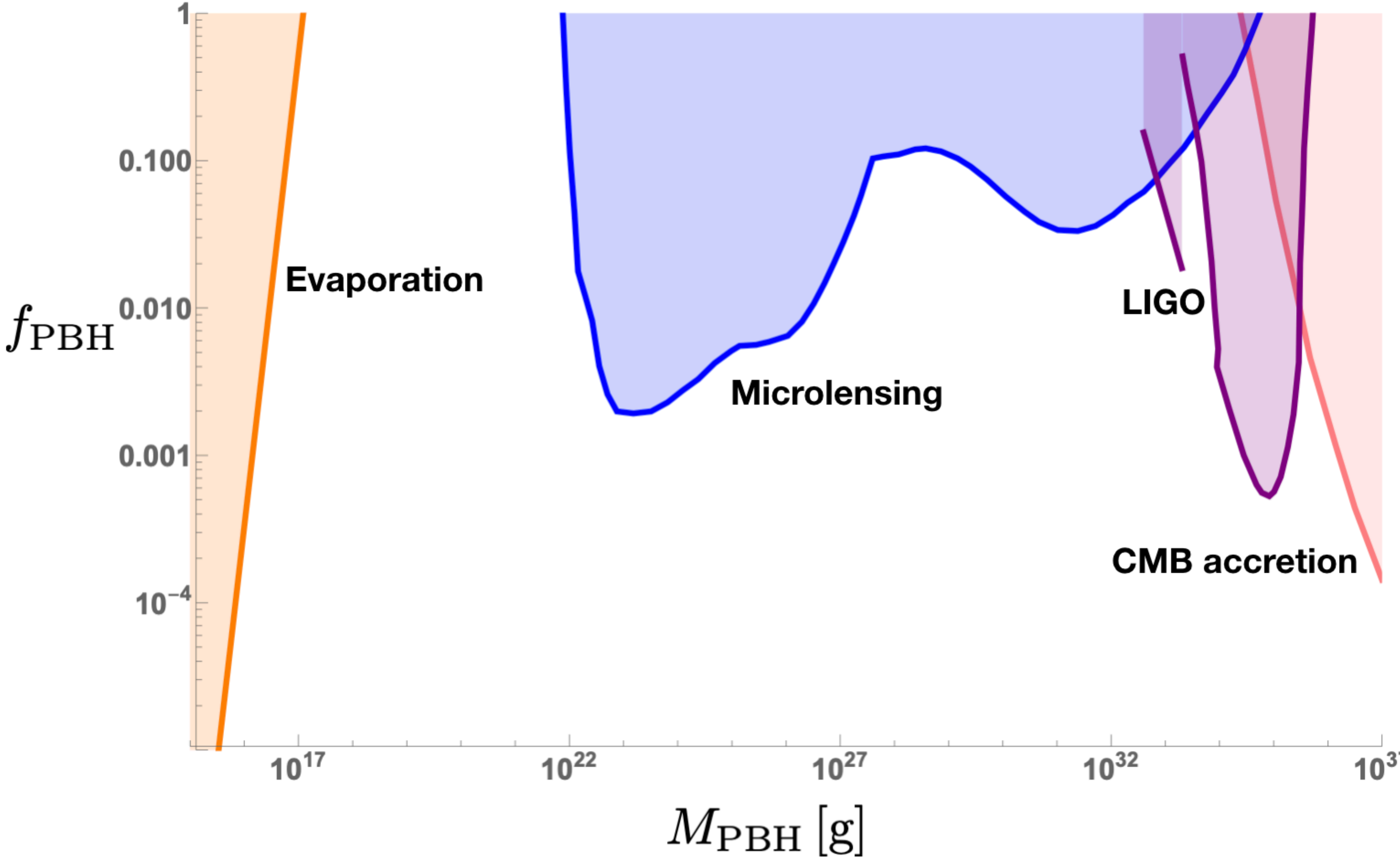
Byrnes, PC, Patil 2018

Multi-matching

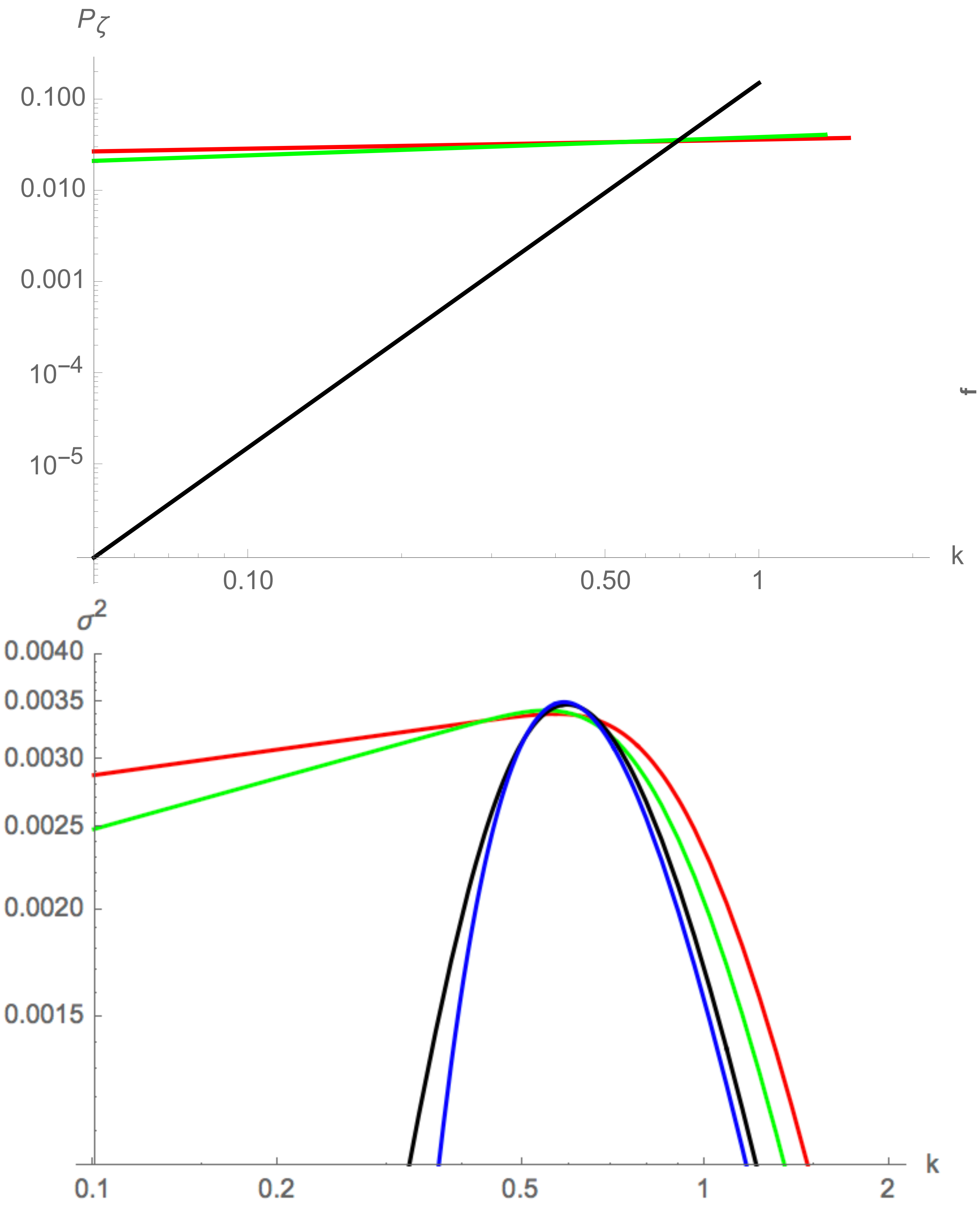


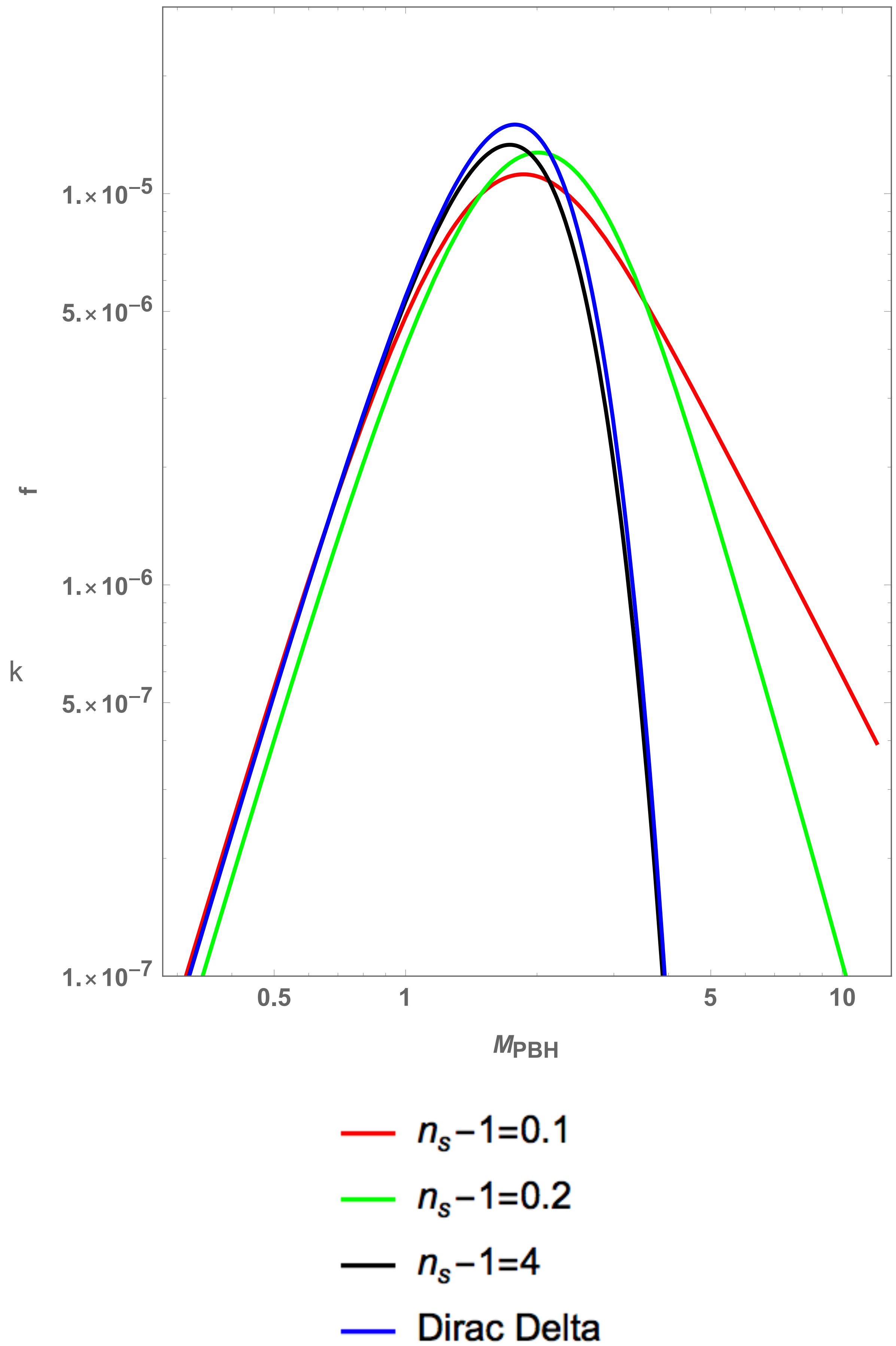
Byrnes, PC, Patil 2018

Why might we want PBHs?

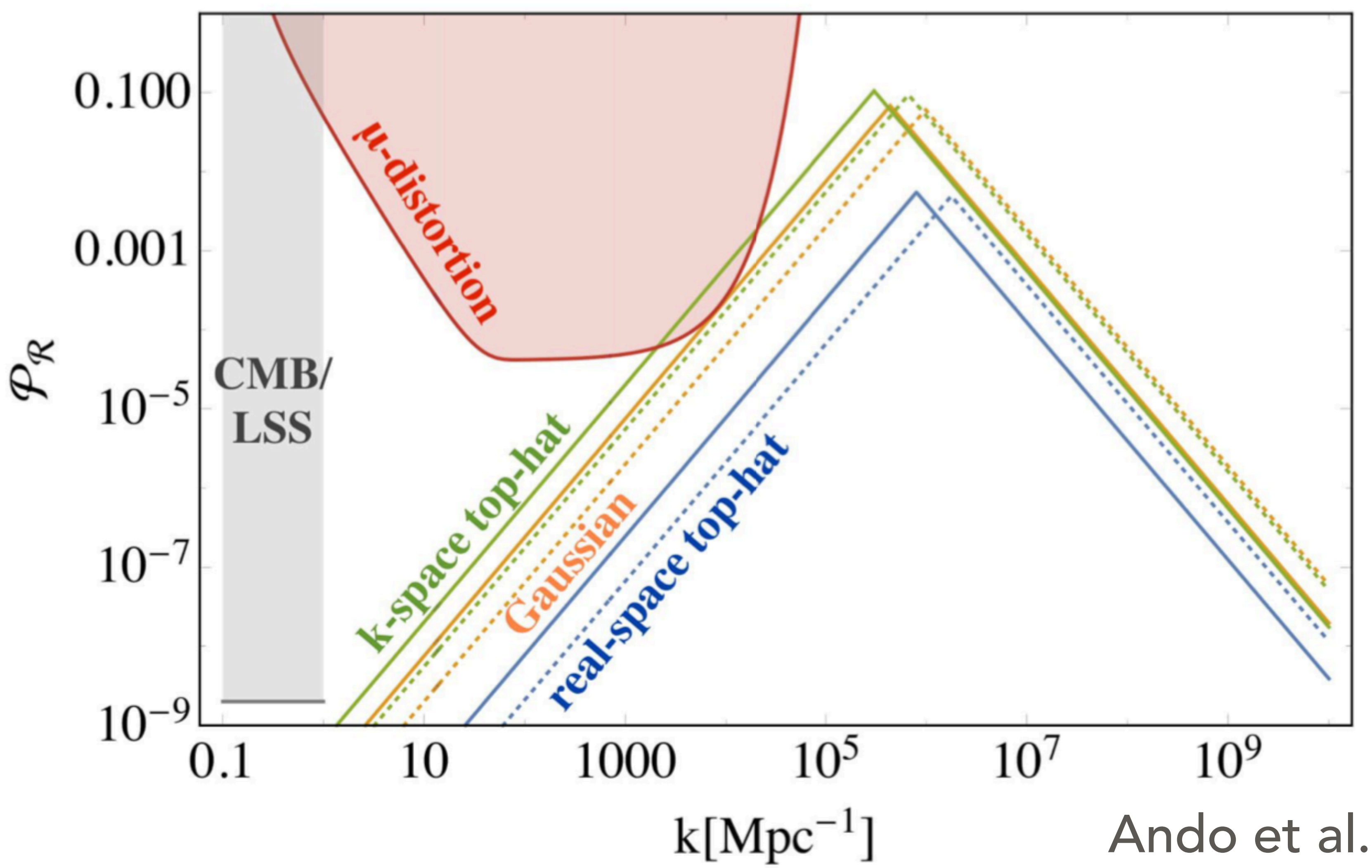


Mass function dependence





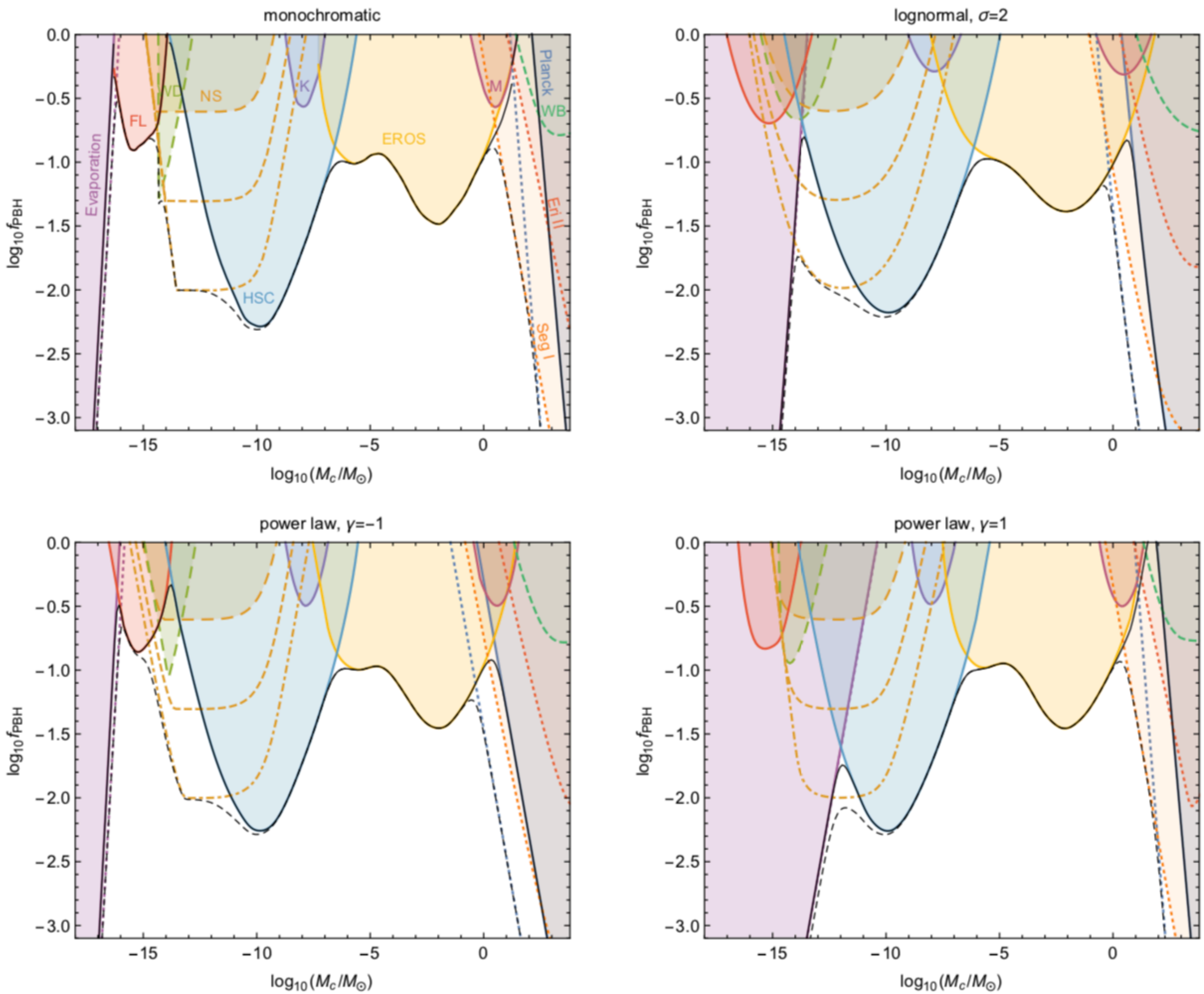
Long list of theoretical uncertainties



Ando et al. 2018

- Window function and method for defining threshold possibly big problems
- We show that provided you use the correct parameters in the method for the window function you smooth with, the uncertainties are <10%.
- Account for the non-linear relationship between density perturbation and curvature perturbation and extended mass functions.

Extended mass functions



Carr et al. 2017

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

Follow the curvature perturbation through different phases of inflation

Instead write the equation of motion in terms of the Mukhanov-Sasaki variable so that we can study the comoving curvature perturbation

$$v_k'' + (k^2 - \frac{z''}{z})v_k = 0 \qquad v_k = z\mathcal{R}, \quad z = \sqrt{2\epsilon}a$$

Assume that ϵ is small

$$v_k'' + (k^2 - \frac{\nu^2 - \frac{1}{4}}{\tau^2})v_k = 0$$

where ν just depends on η and has simple solutions if η is constant