Closing in on primordial black holes

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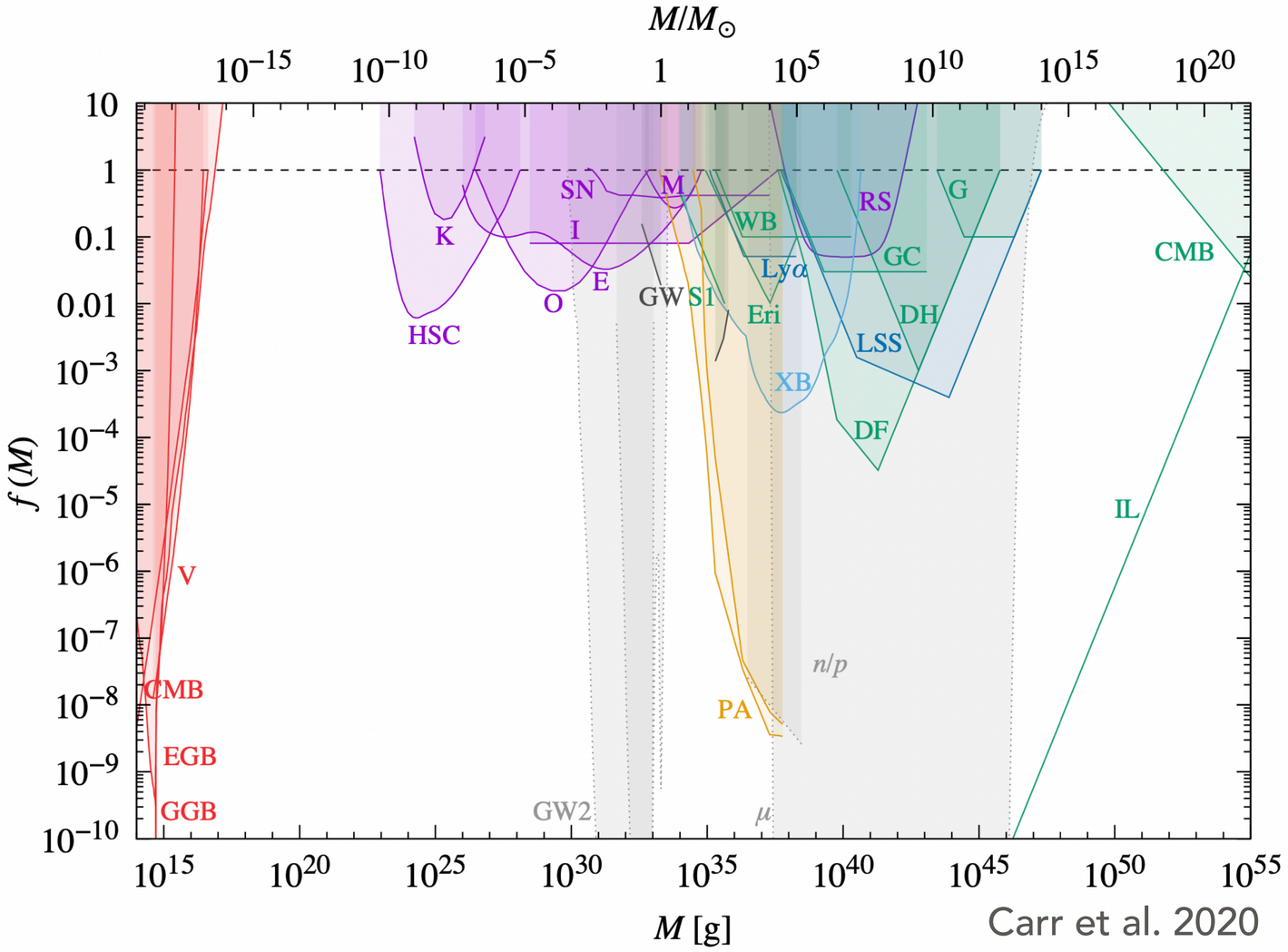
Based on arXiv entries: 1706.10288, 1811.11158, 2008.03289, 2207.07576, 2304.01997

Paris 2023

Where are we with observational constraints?

Overview



Bounds available at https://github.com/bradkav/PBHbounds

Carr et al. 2020

See also Green & Kavanagh 2020

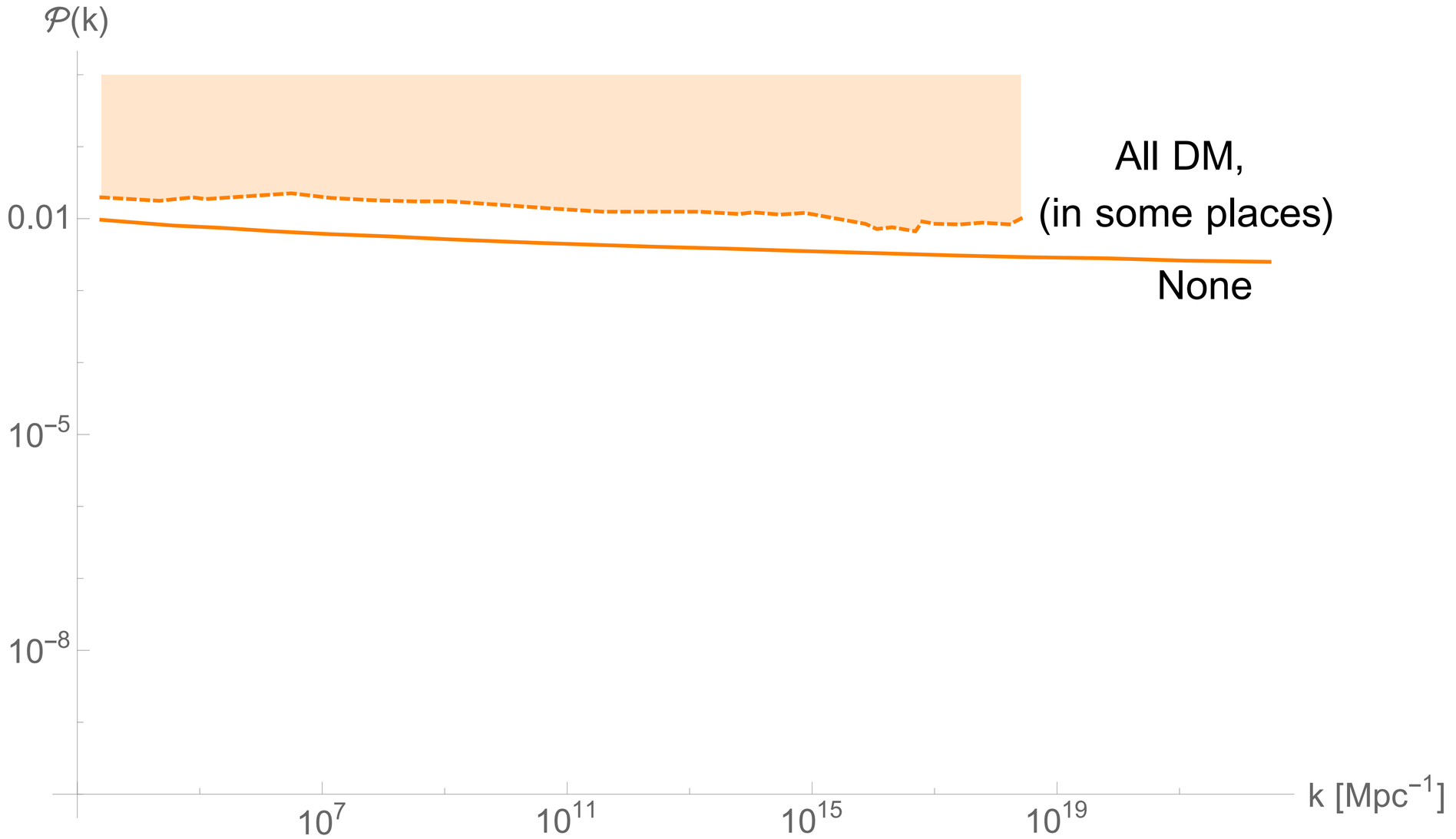
Possibility to make up all of the dark matter

Even if only a small fraction, very prescriptive for early universe theories

1. **How do we produce them?**
2. **Effect of production mechanism on observational constraints?**
3. **If they don’t make up all of the DM, what about a combined scenario?**

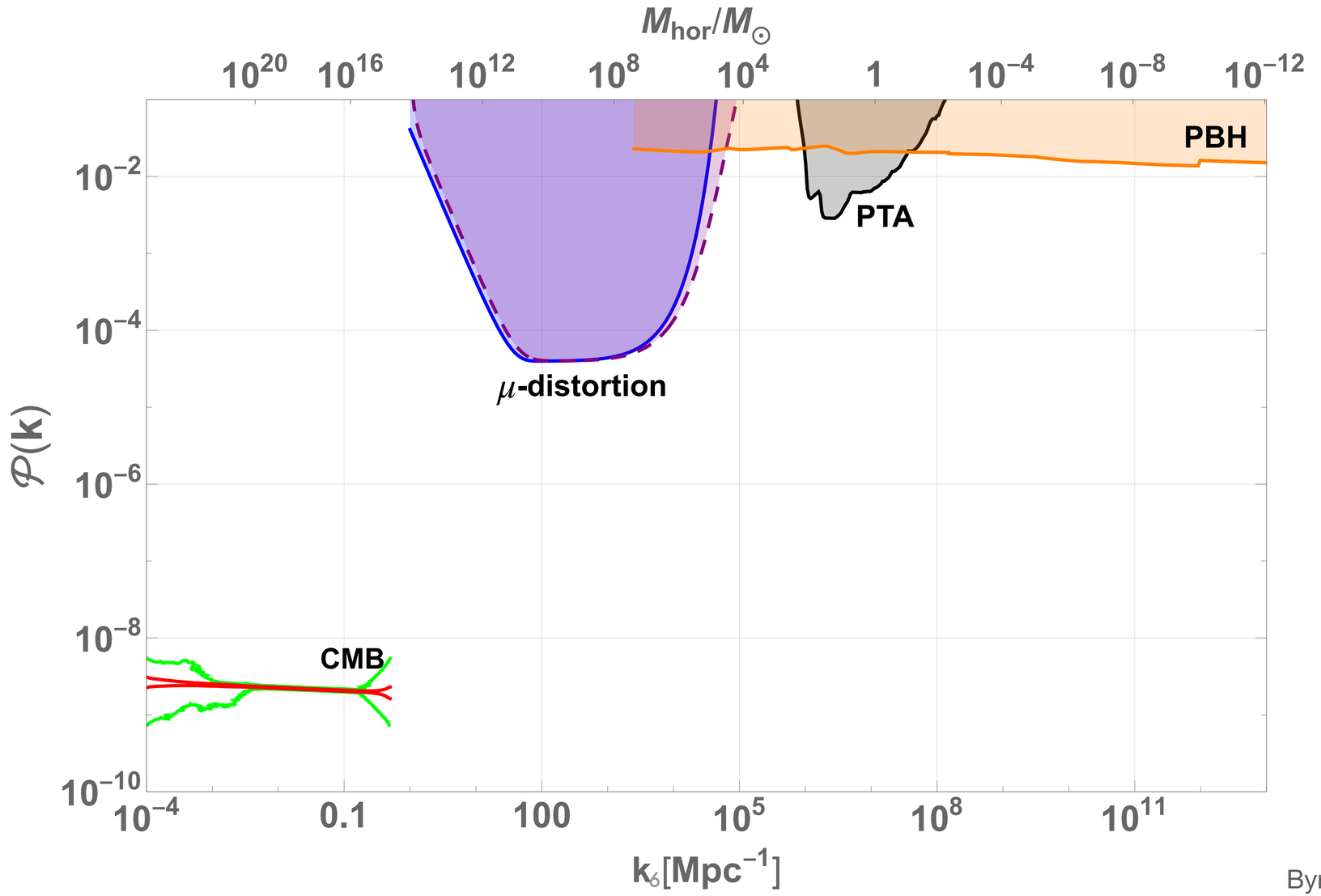
What do we need in order to produce them? (inflationary origin)

All or nothing



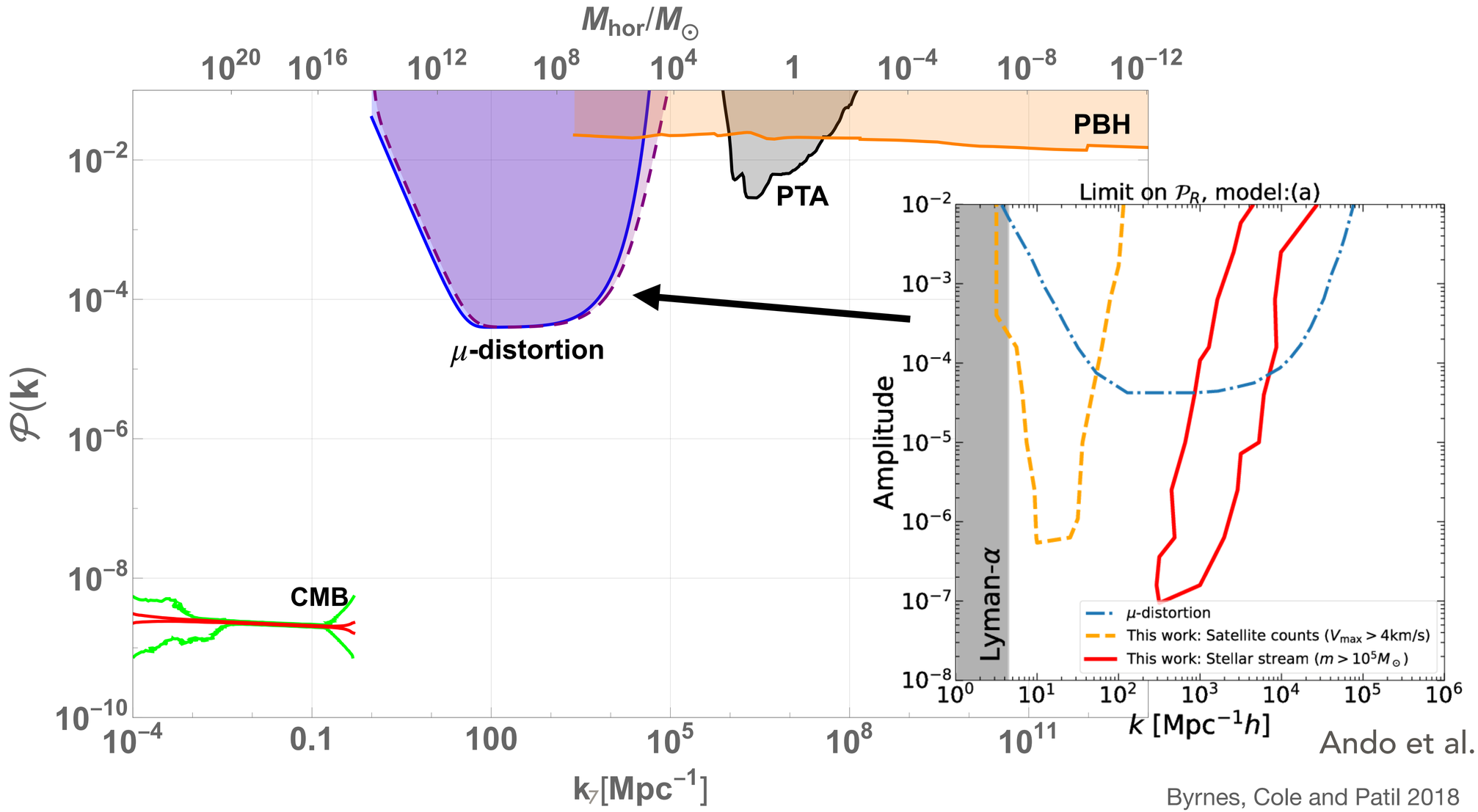
Adapted from Cole, Byrnes 2017

Current constraints on primordial power spectrum



Byrnes, Cole and Patil 2018

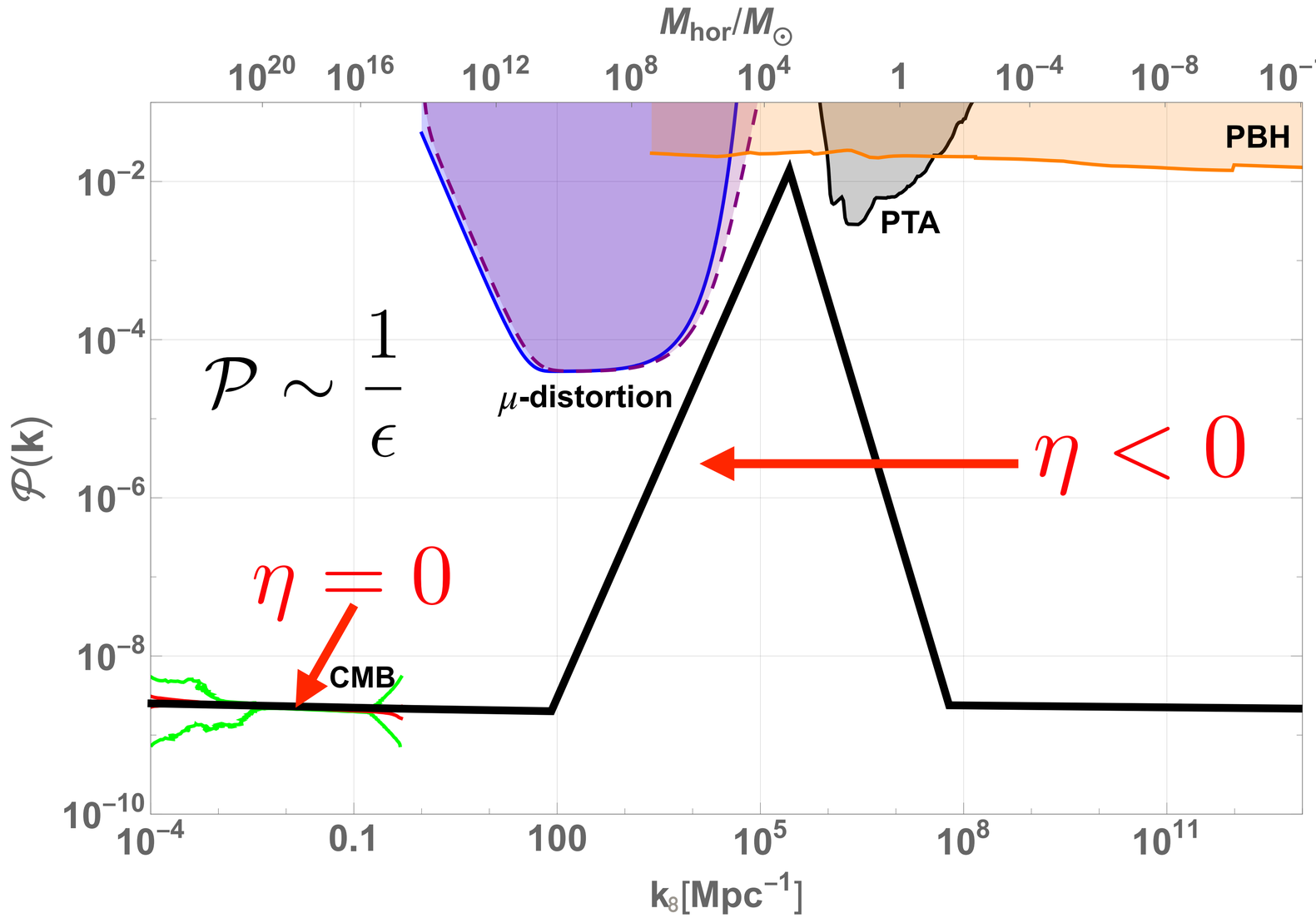
Current constraints on primordial power spectrum



Ando et al. 22

Byrnes, Cole and Patil 2018

Feature needs to fit in between small-scale constraints on the power spectrum

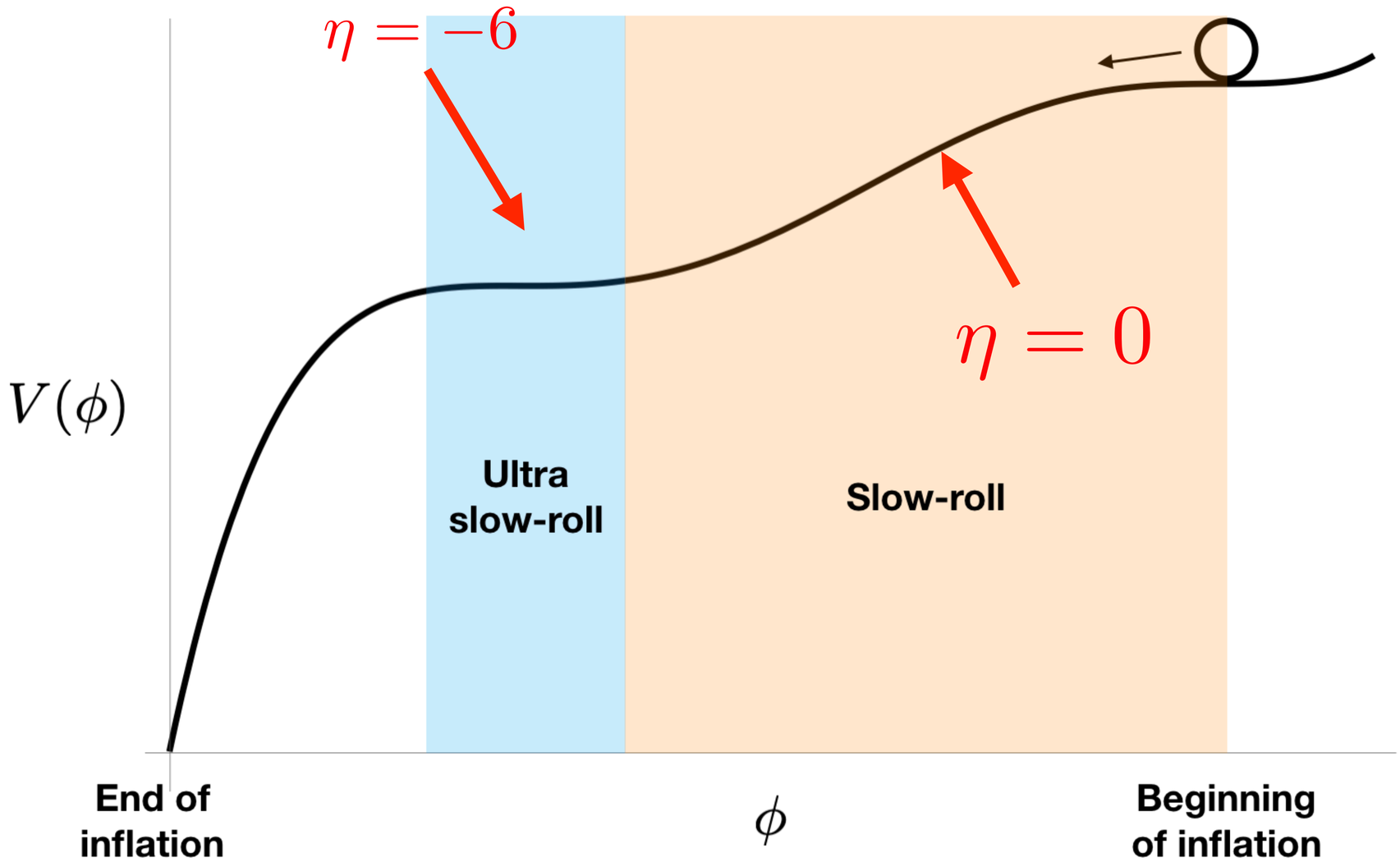


$$\epsilon = -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}^2}{2H^2 M_{\rm pl}^2}$$

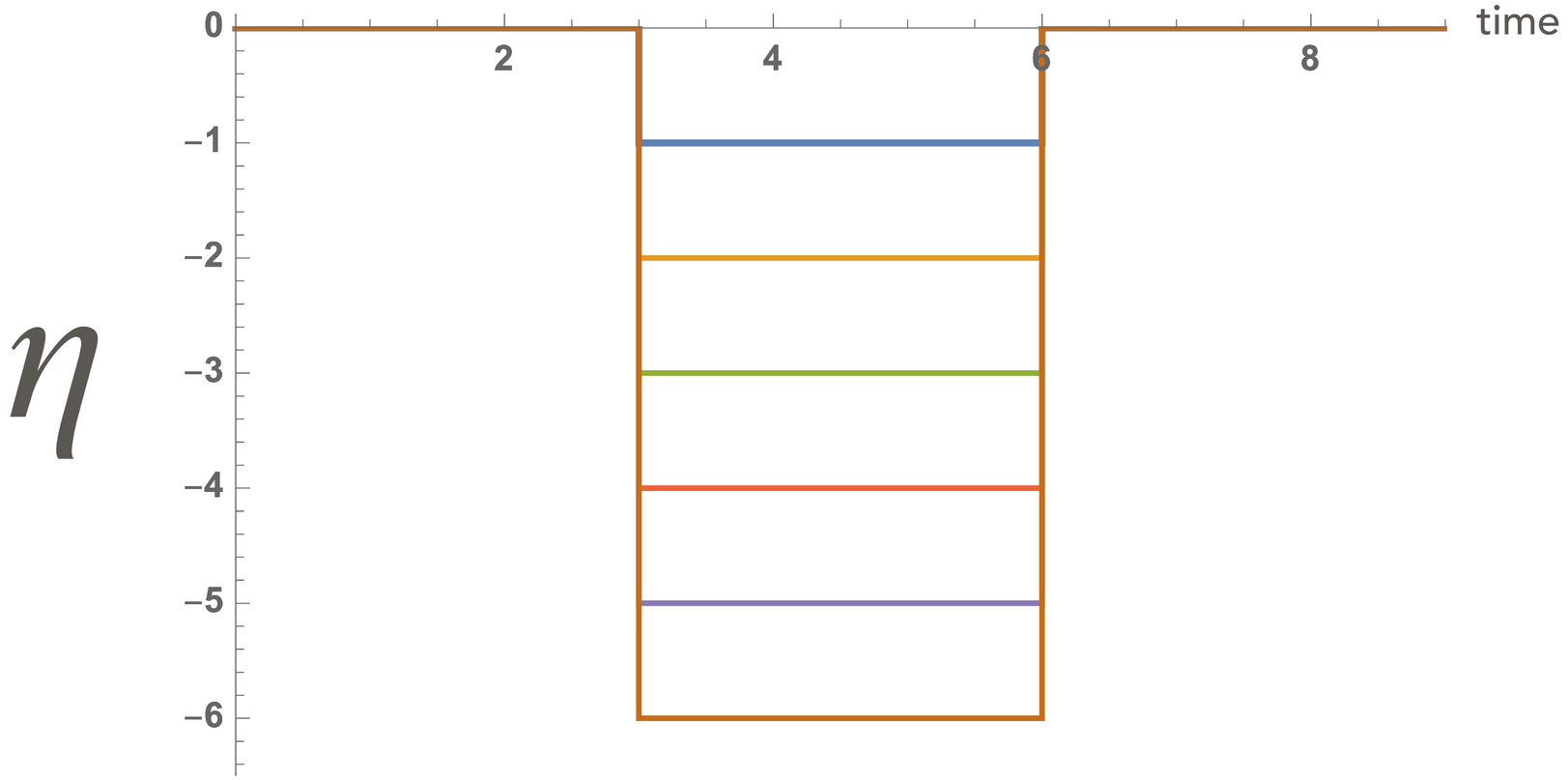
$$\eta = \frac{\dot{\epsilon}}{\epsilon H}$$

Byrnes, Cole and Patil 2018

Ultra-slow-roll to produce a feature

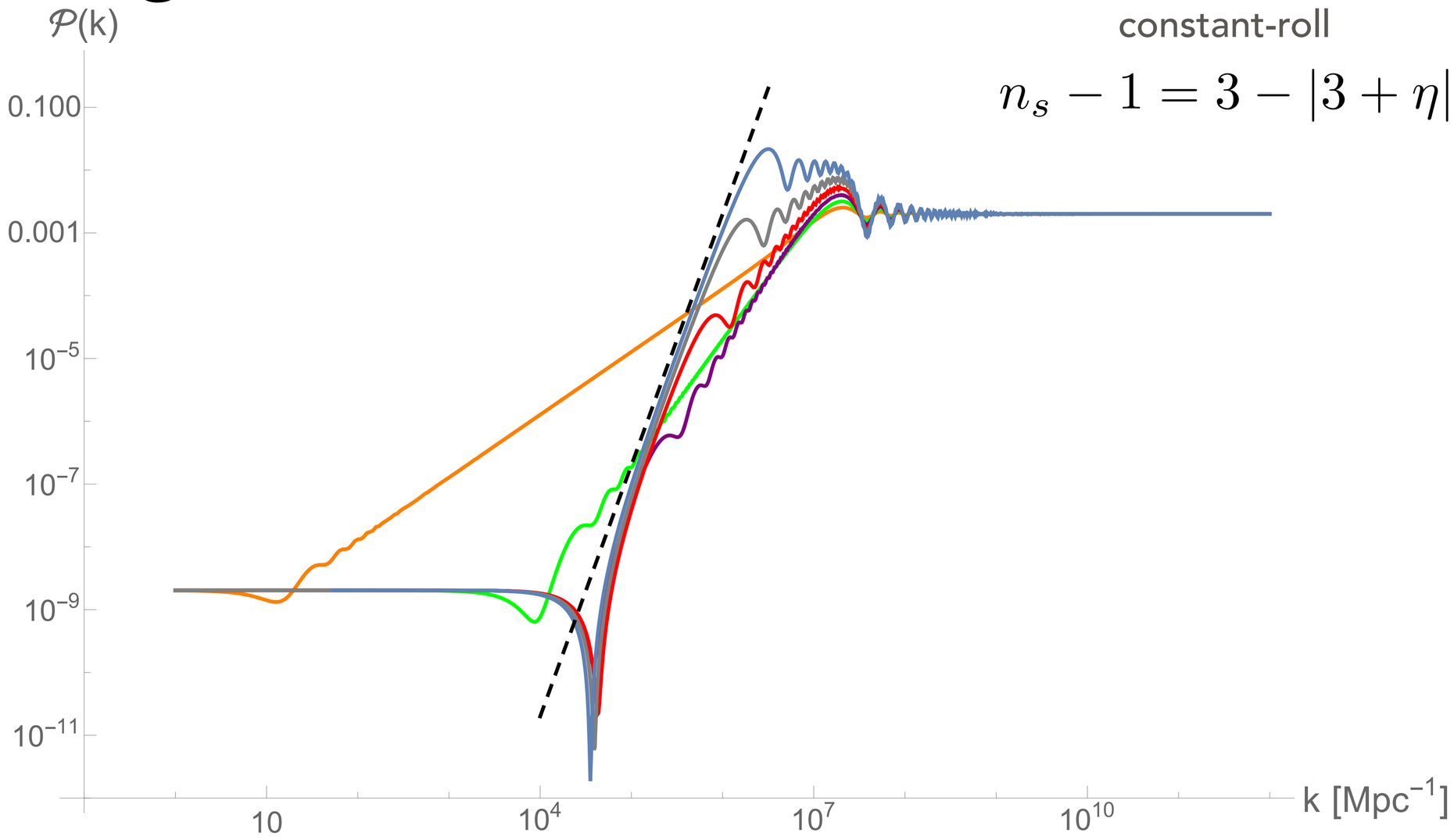


Explore the slope with analytical matching calculations



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

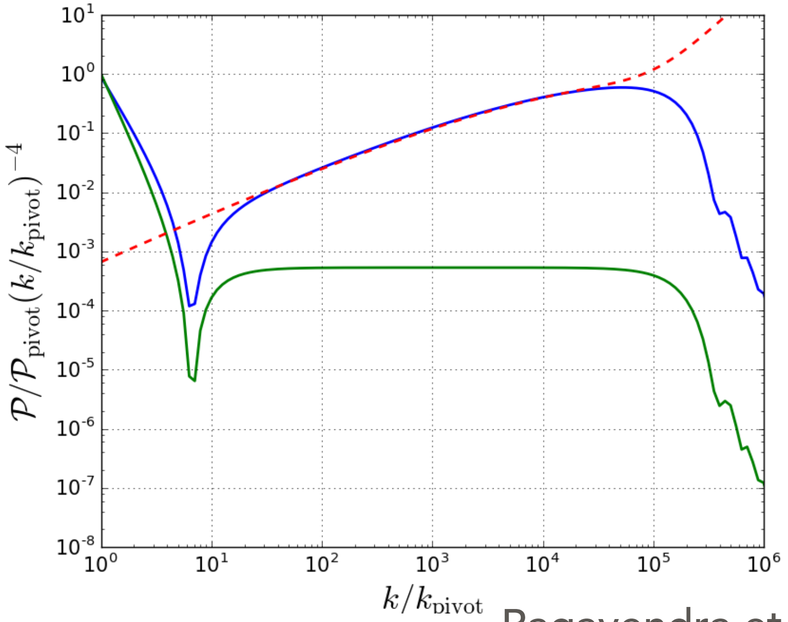
General shape of the power spectrum has a steepest growth limit



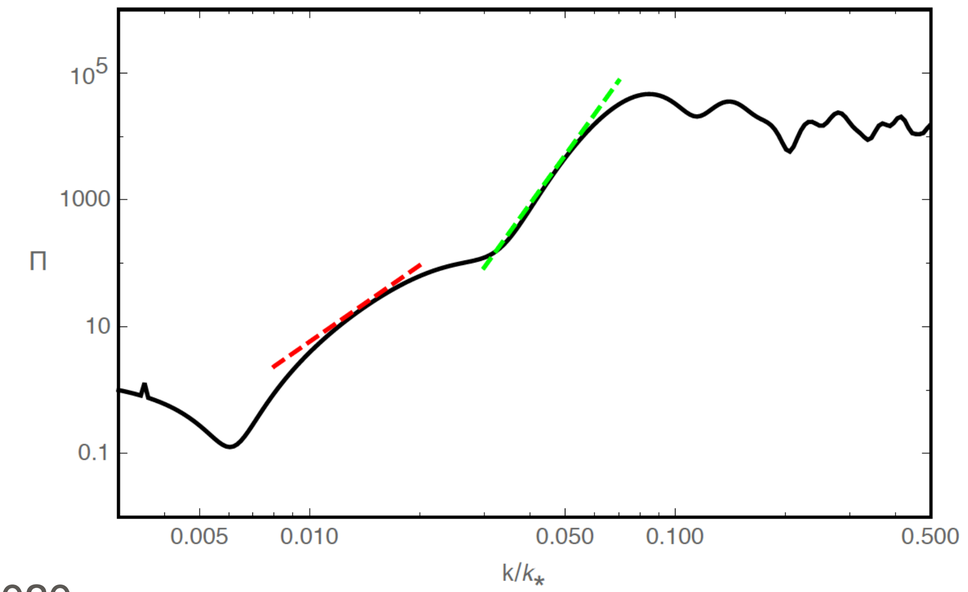
Byrnes, Cole, Patil 2018

Or can we go steeper…

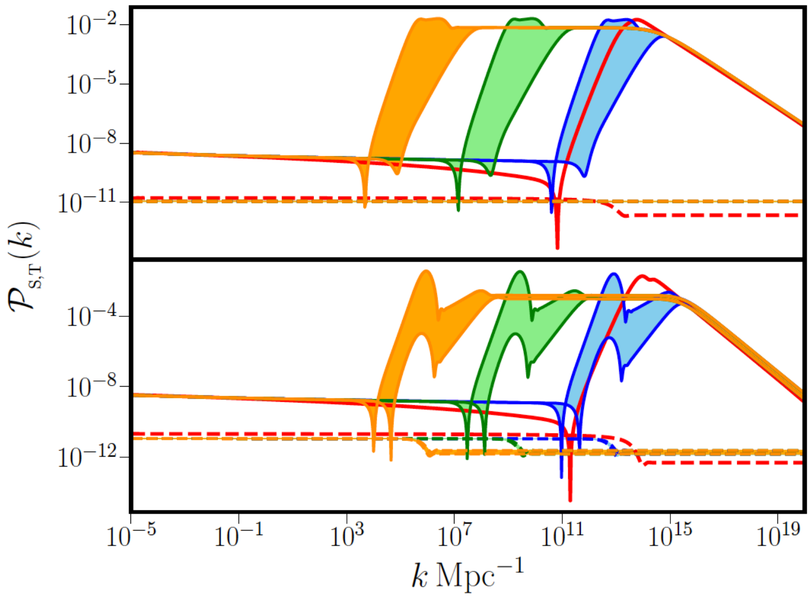
Carrilho et al. 2019

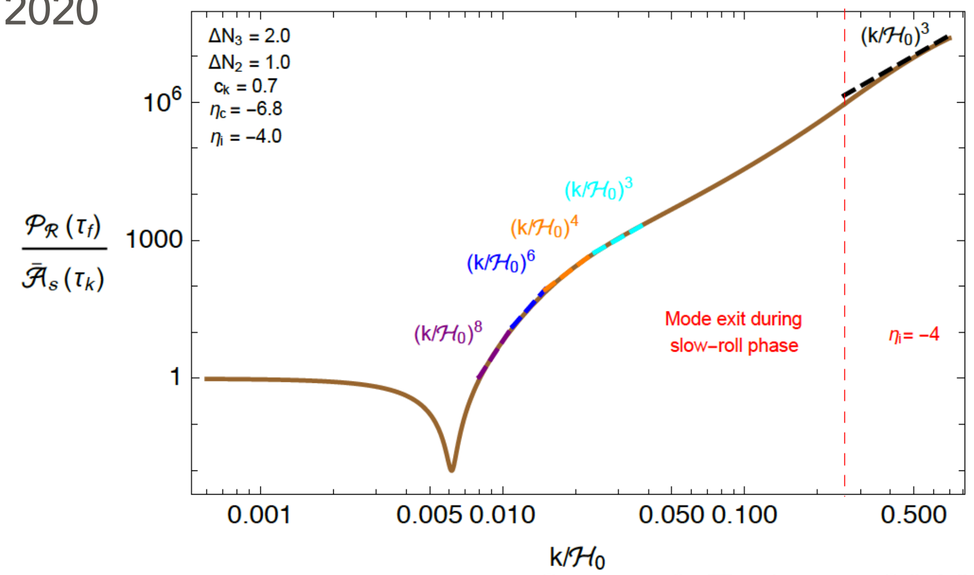


Tasinato 2021



Ragavendra et al 2020

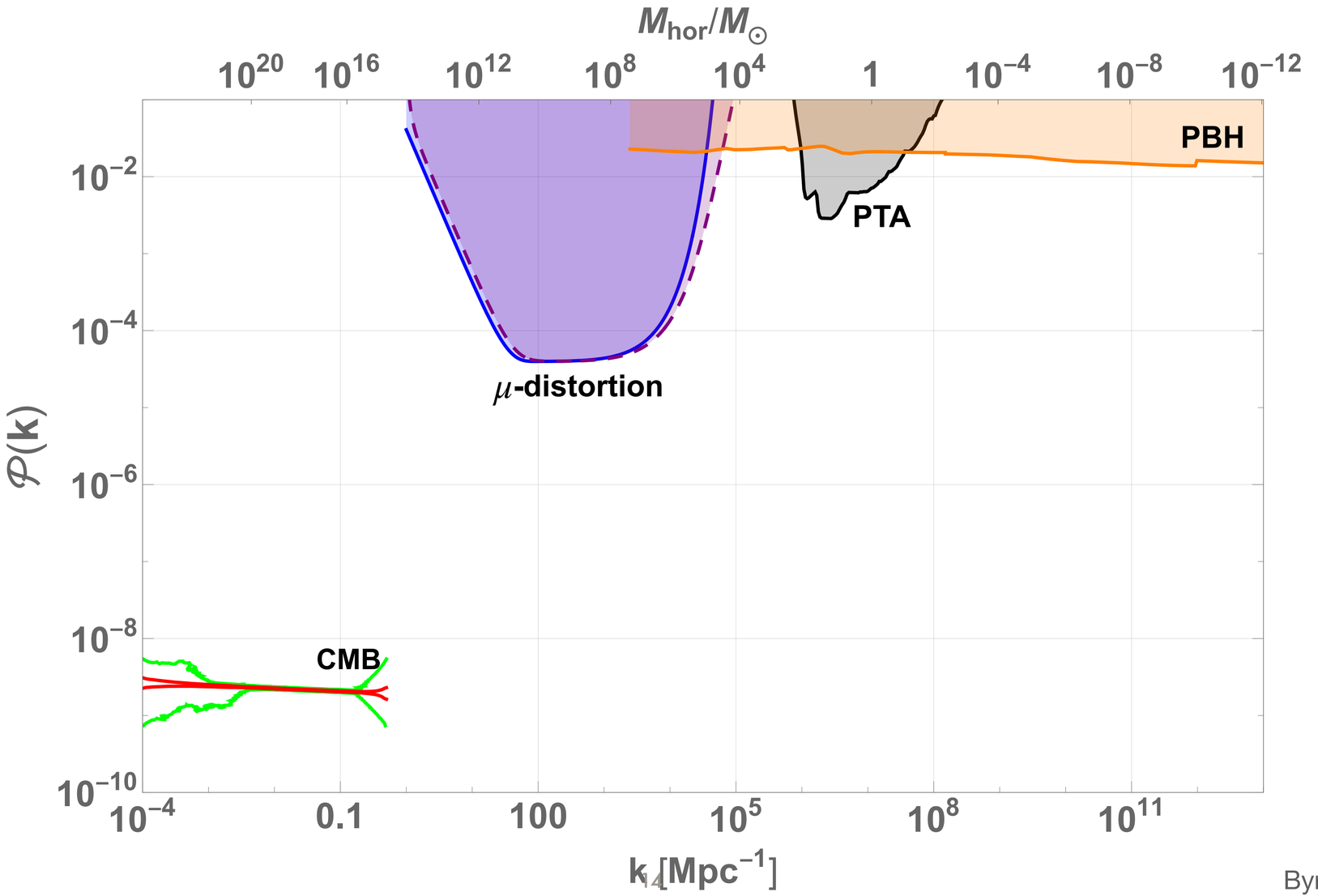




Oszoy & Tasinato 2019

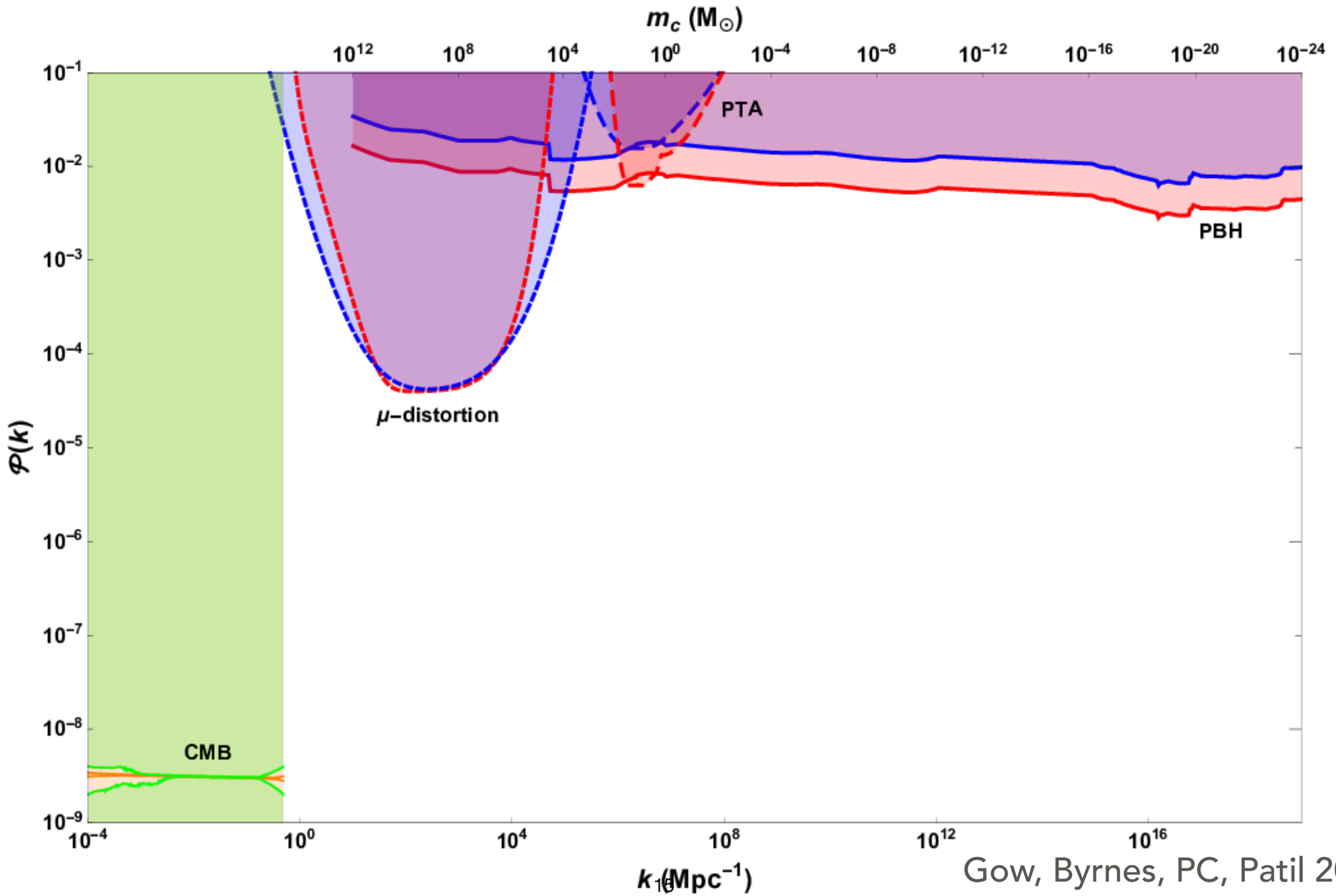
What’s the effect on observational constraints?

Current (2018) constraints on primordial power spectrum



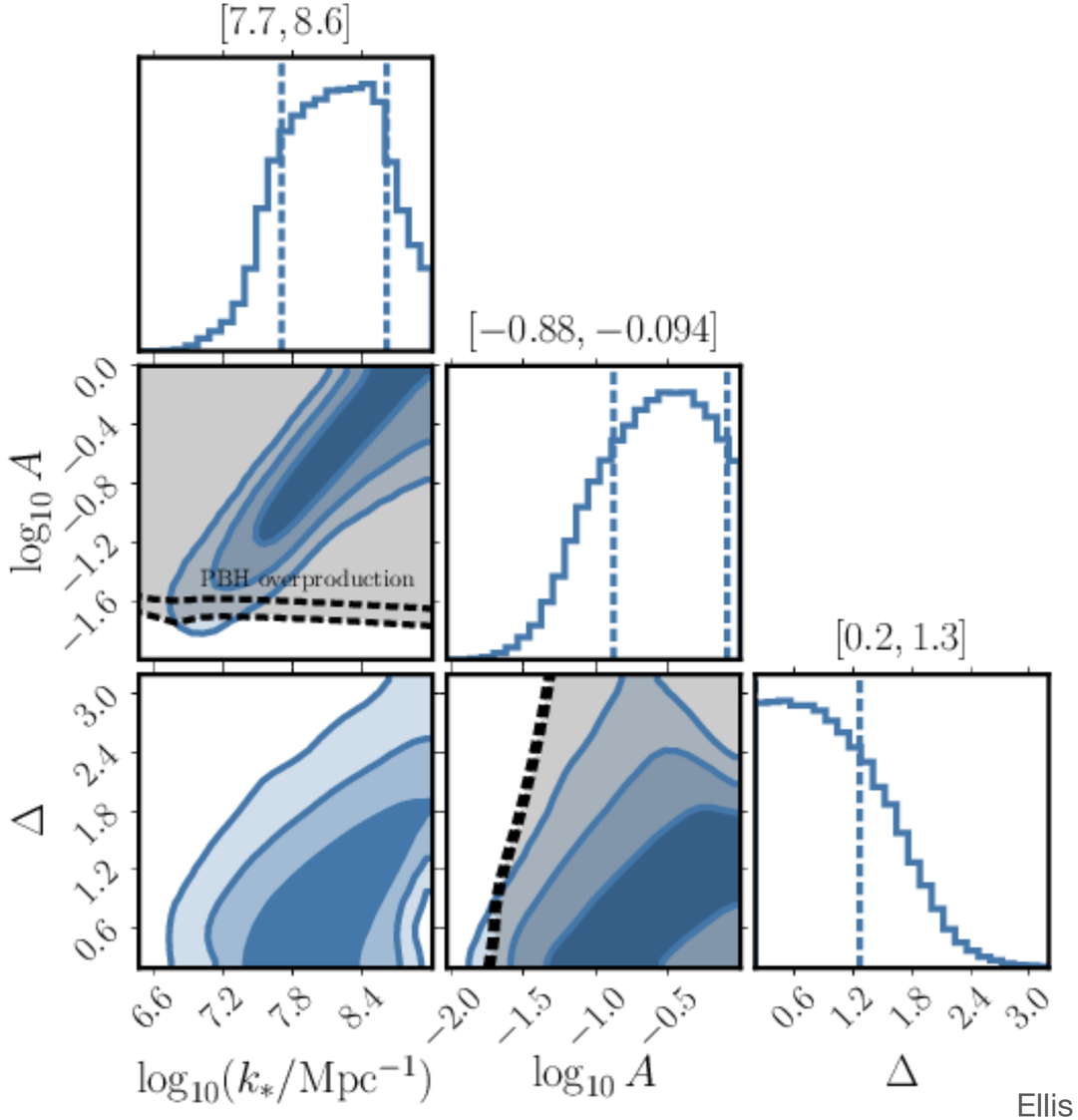
Byrnes, Cole and Patil 2018

Current (2020) constraints on the power spectrum



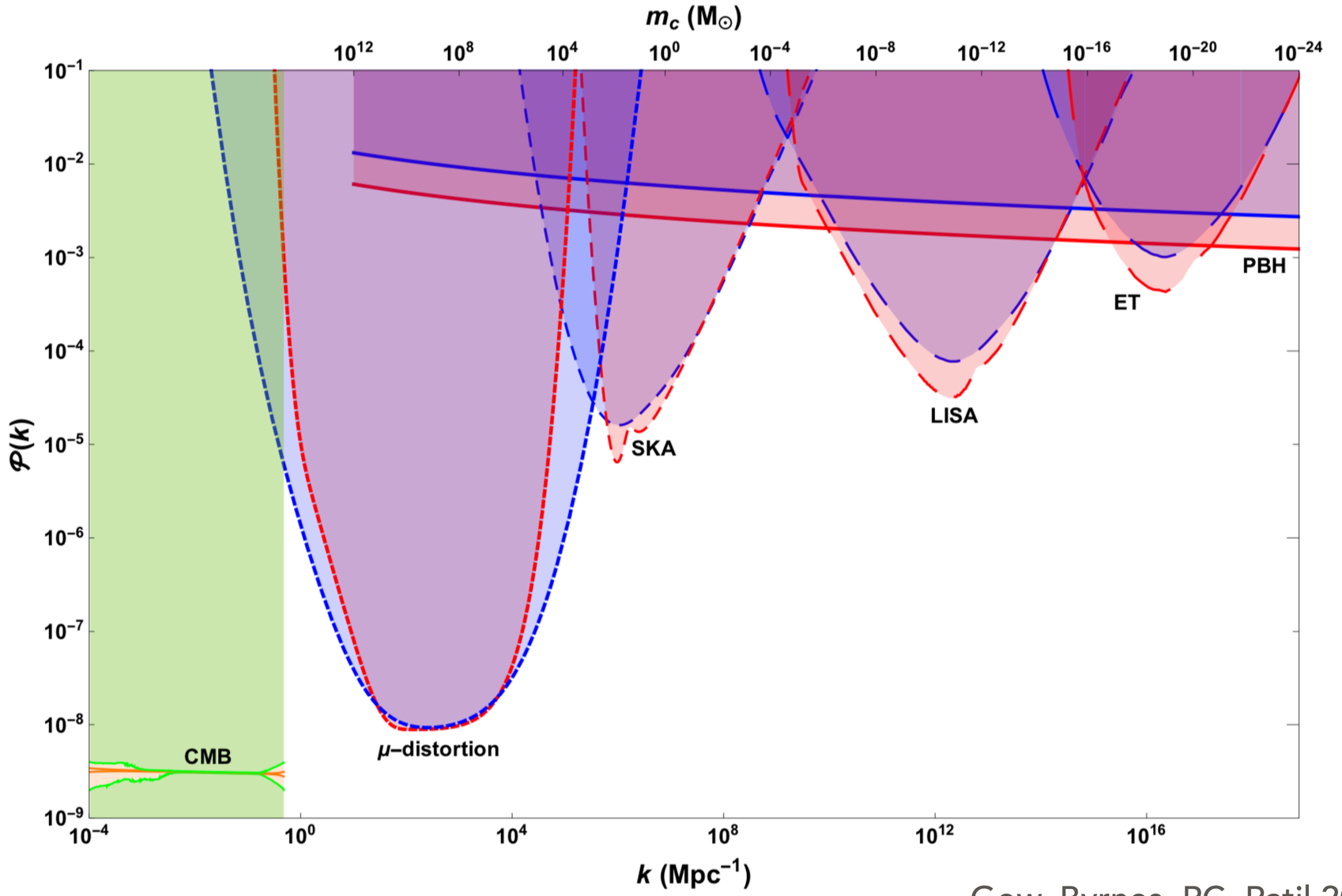
Gow, Byrnes, PC, Patil 2020

NANOGrav results update (2023)



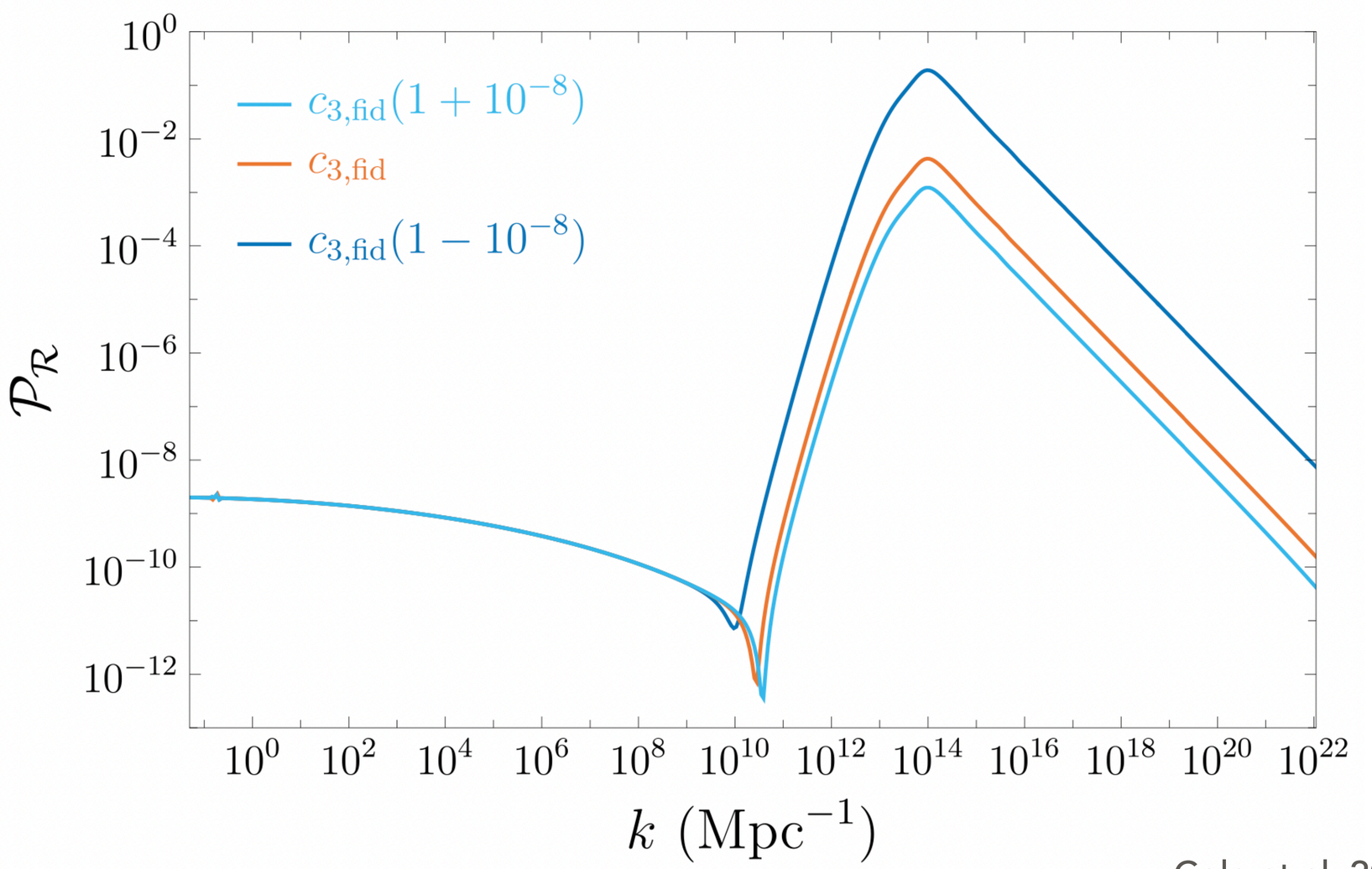
Ellis et al. 2023

Future constraints (202…) will rule out almost PBHs entirely (if they formed from large over densities in early universe)



Gow, Byrnes, PC, Patil 2020

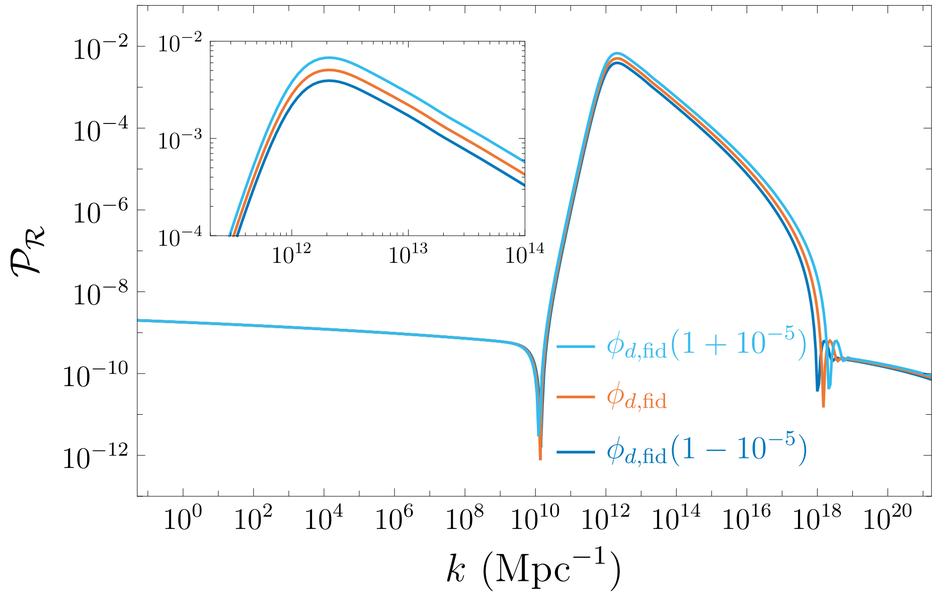
Is there a fine-tuning problem?

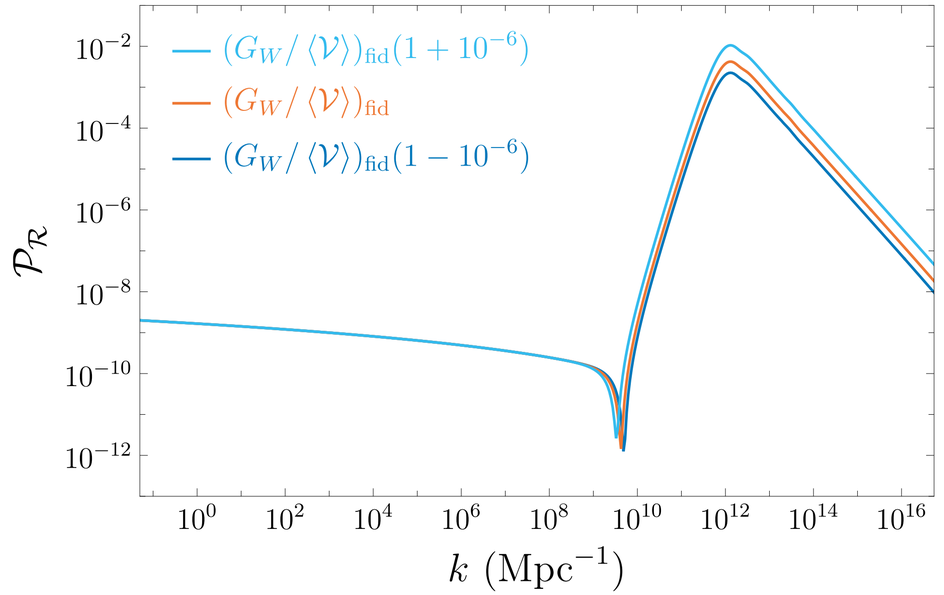


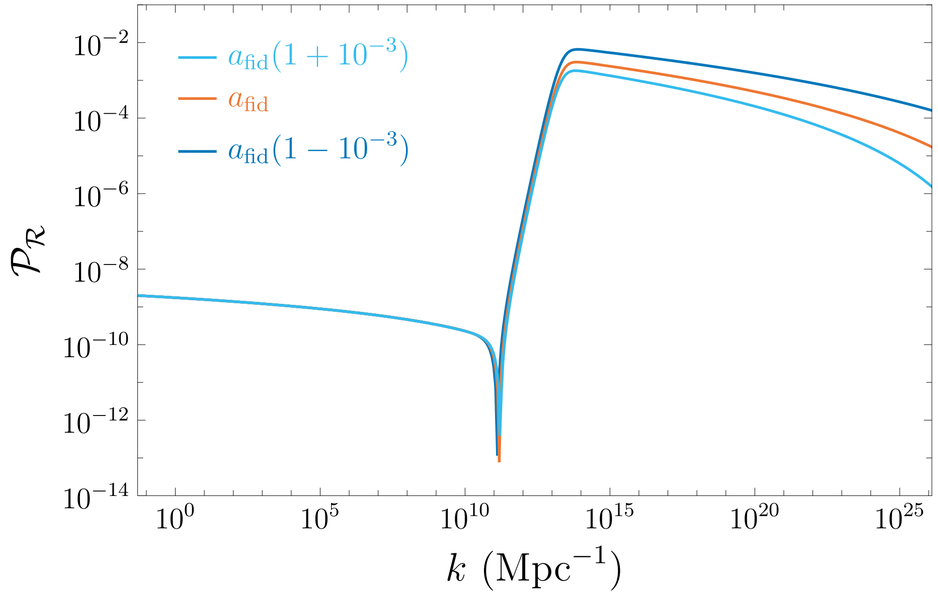
Cole et al. 2023

See e.g. Hertzberg & Yamada 2019

Is there a fine-tuning problem?

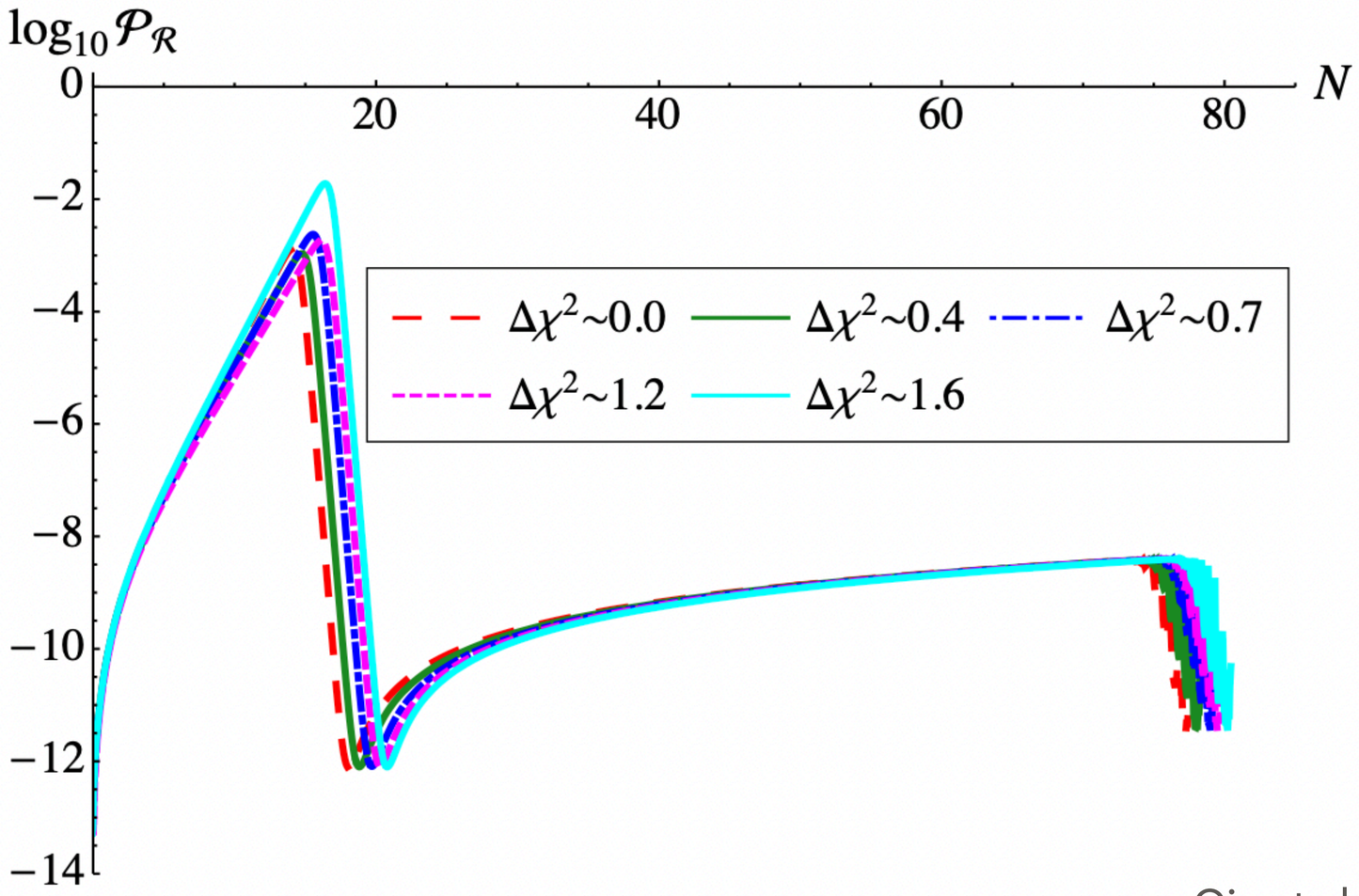






Cole et al. 2023
See e.g. Mishra et al. 2020
Germani & Prokopec 2017
Cicoli et al. 2018

Multi-field inflation



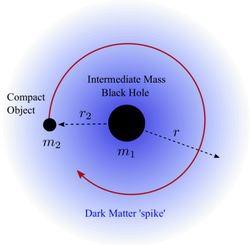
Qin et al. 2023

See also e.g. Fumagalli et al. 2023, Palma et al. 2020

Non-inflationary mechanisms may circumvent some/all of these constraints

Ideas on how to look for a combined scenario…

PBHs + DM must form a spike



- Environmental effects can cause inspiral to either speed up or slow down with respect to vacuum case
- A dephasing to accumulate, which alters the gravitational waveform from the binary's inspiral

$$\dot{r} = \dot{r}_{\rm GW} + \dot{r}_{\rm env}$$

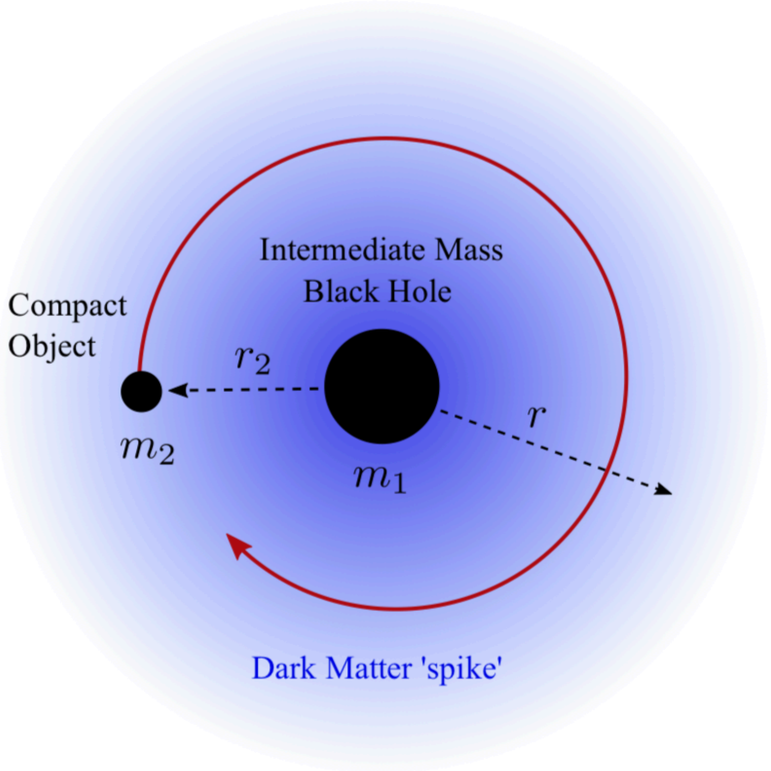
$$\Phi(f) = \int_f^{f_{\rm ISCO}} \frac{{\rm d}t}{{\rm d}f'} f' \, {\rm d}f'$$

$$f(t) = \frac{1}{\pi}\sqrt{\frac{GM}{r(t)^3}}$$

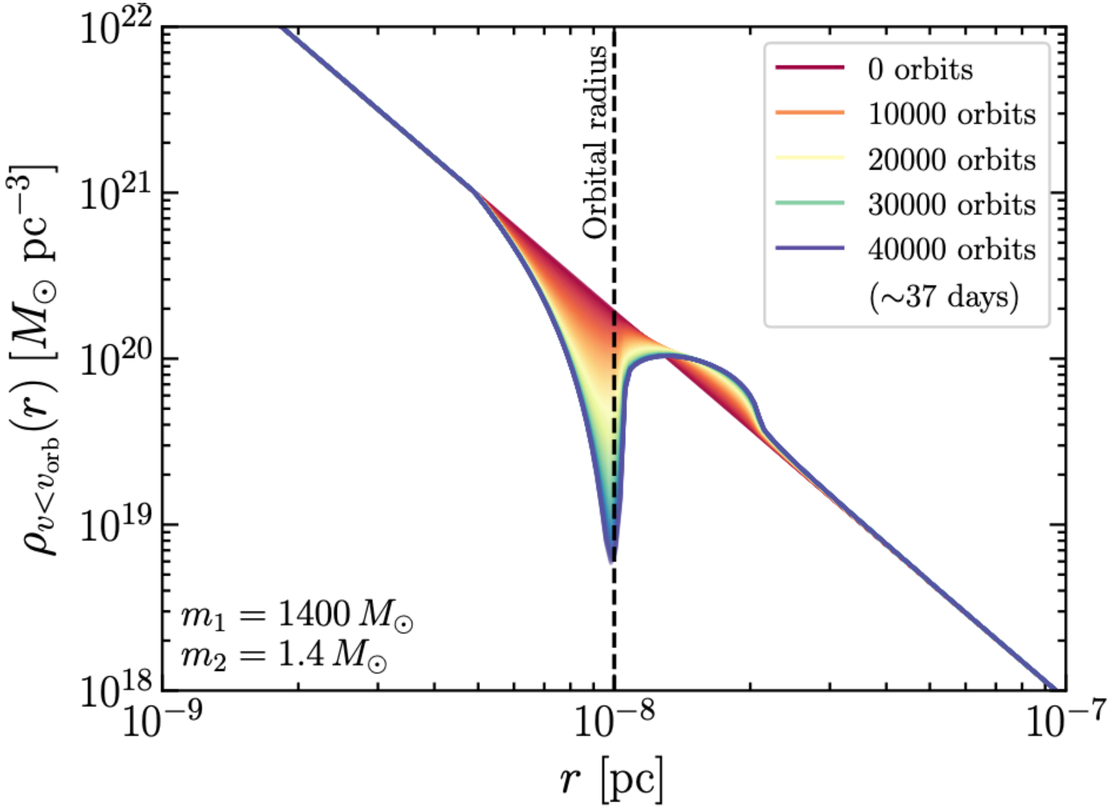
$$h_0(f) = \frac{1}{2}\frac{4\pi^{2/3} G_N^{5/3} \mathcal{M}^{5/3} f^{2/3}}{c^4}\sqrt{\frac{2\pi}{\ddot{\Phi}}}$$

PBHs + DM must form a spike

$$\dot{r}_{\rm DF} = -\frac{8\pi\, G_N^{1/2}\, m_2\, \log\Lambda r_2^{5/2}\, \rho_{\rm DM}(r_2,t)\, \xi(r_2,t)}{\sqrt{M} m_1}$$

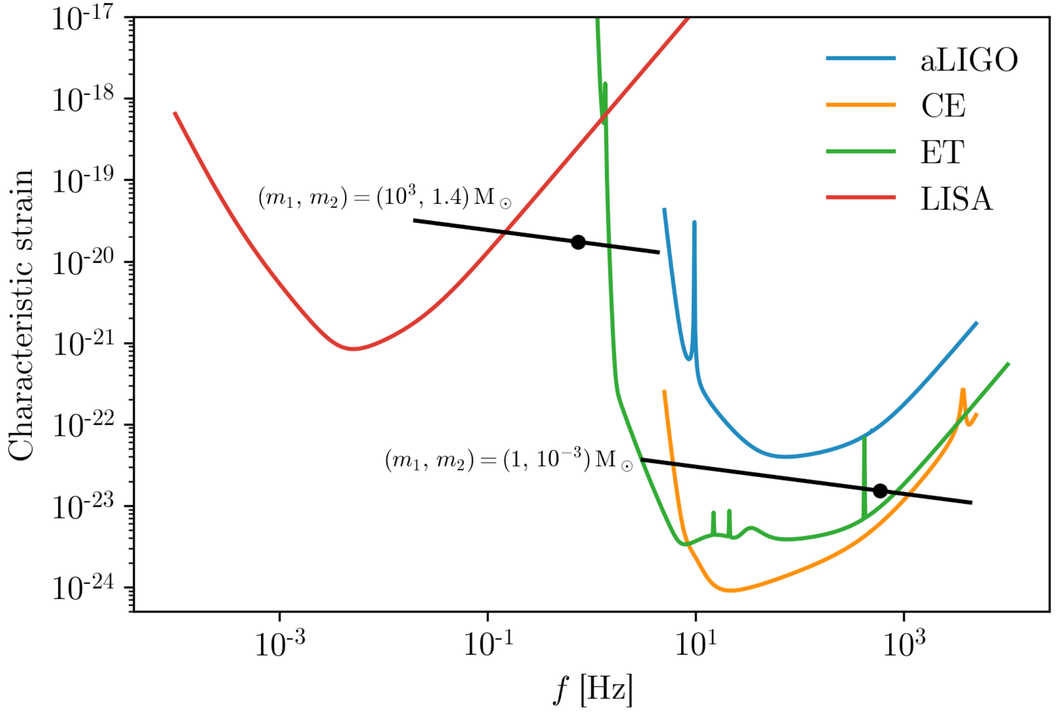


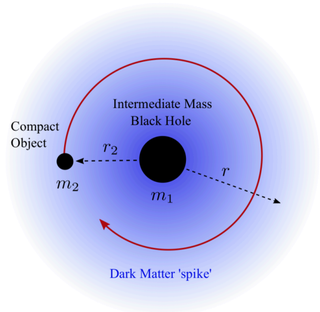
HaloFeedback



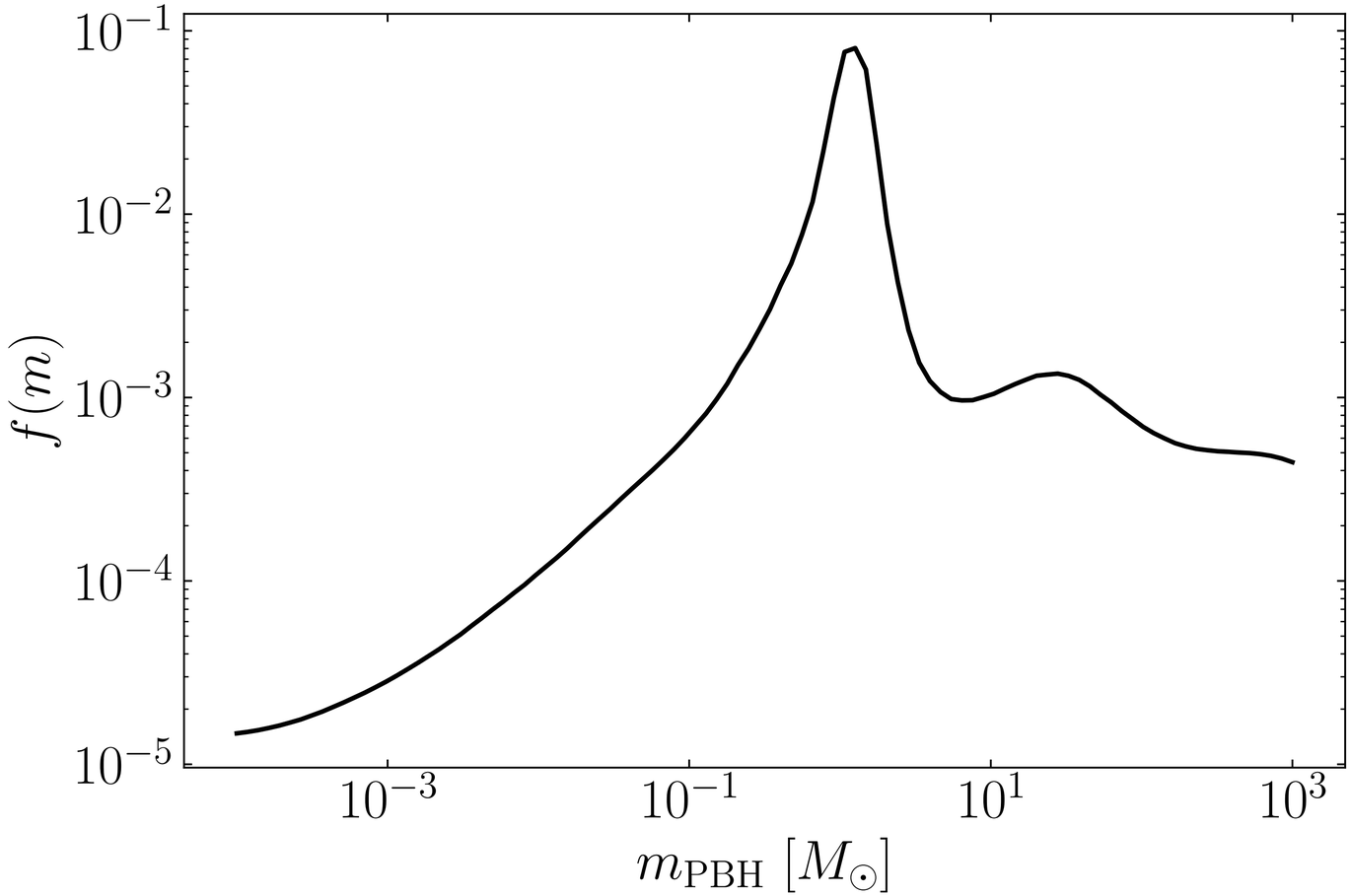
Kavanagh, Nichols, Bertone, Gaggero 2020

Combined scenario with future ground-based detectors





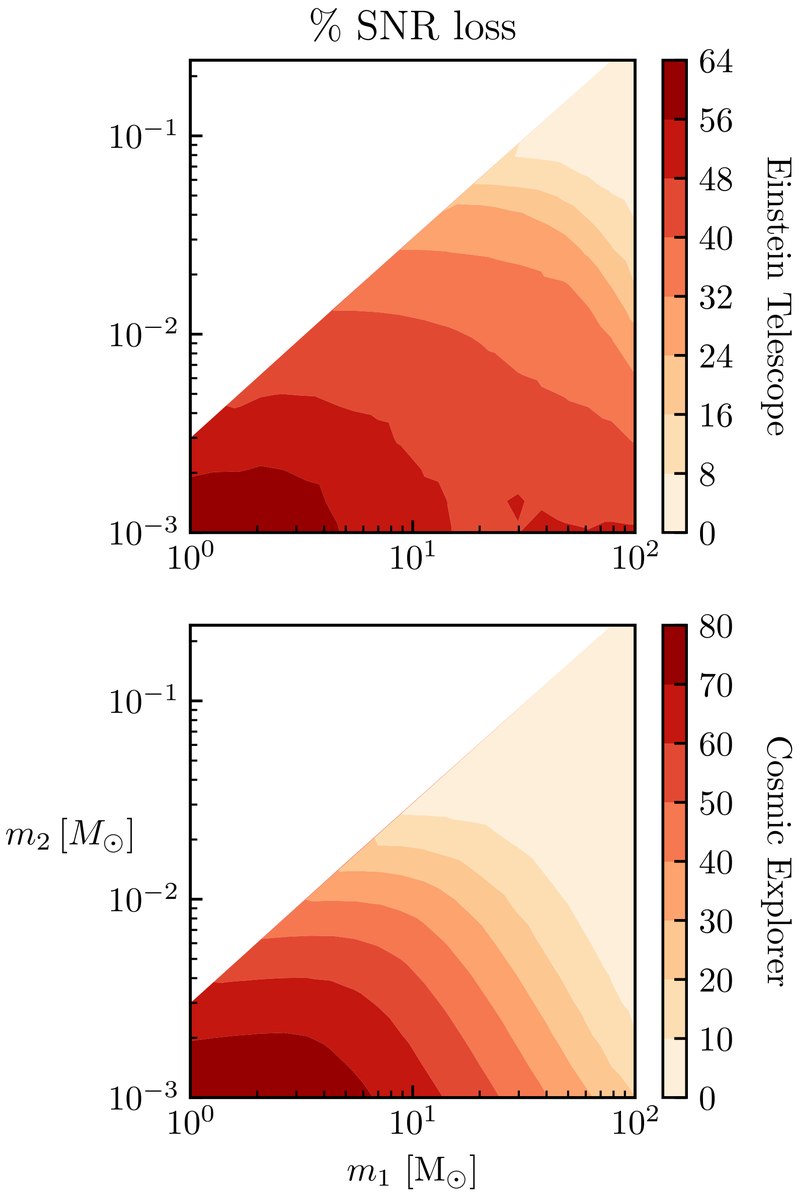
IMRI PBHs must have a dark matter spike

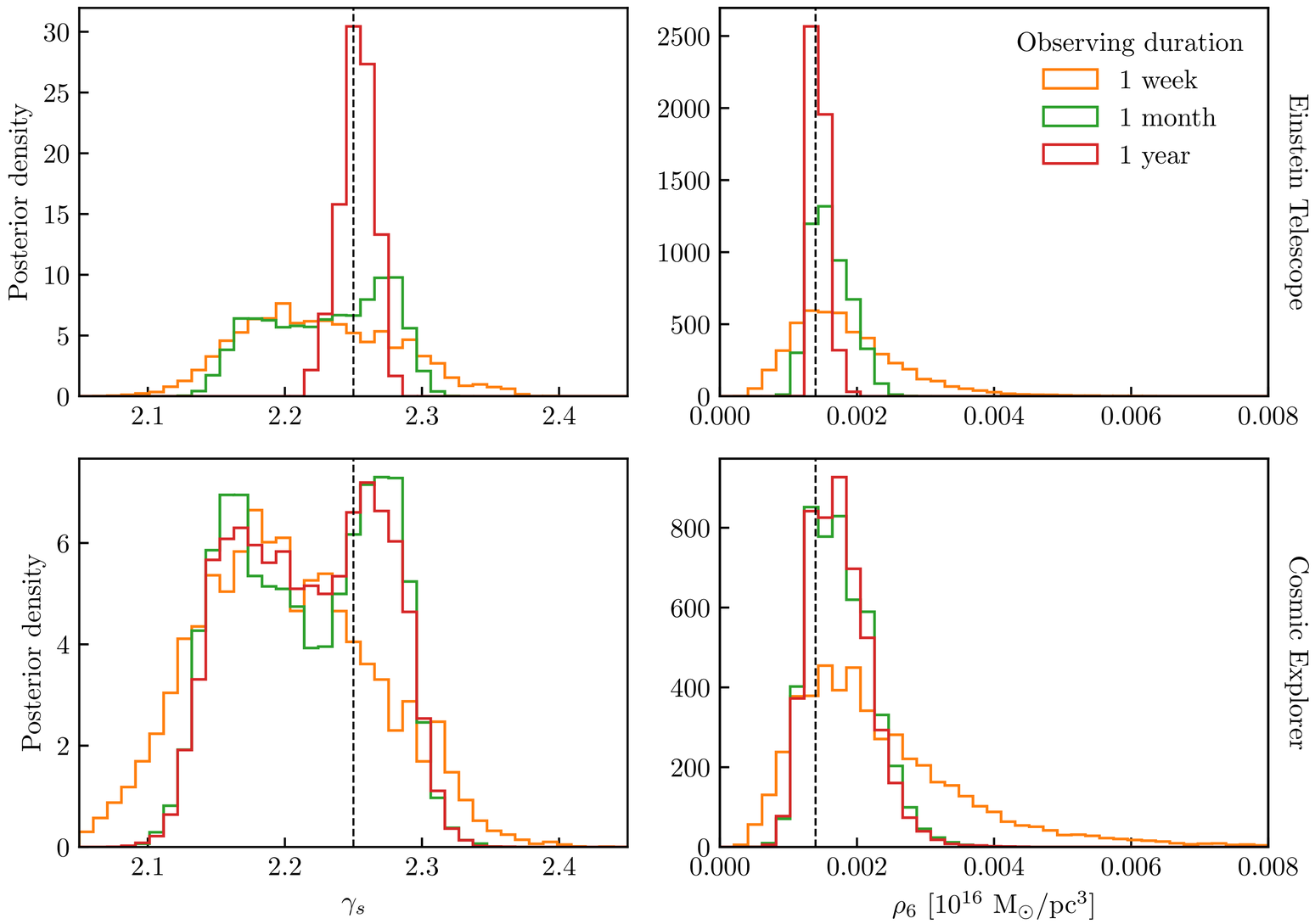


Cole, Coogan, Kavanagh, Bertone 2022

Chance of detecting both with future ground-based GW detectors

1 week signals should be enough



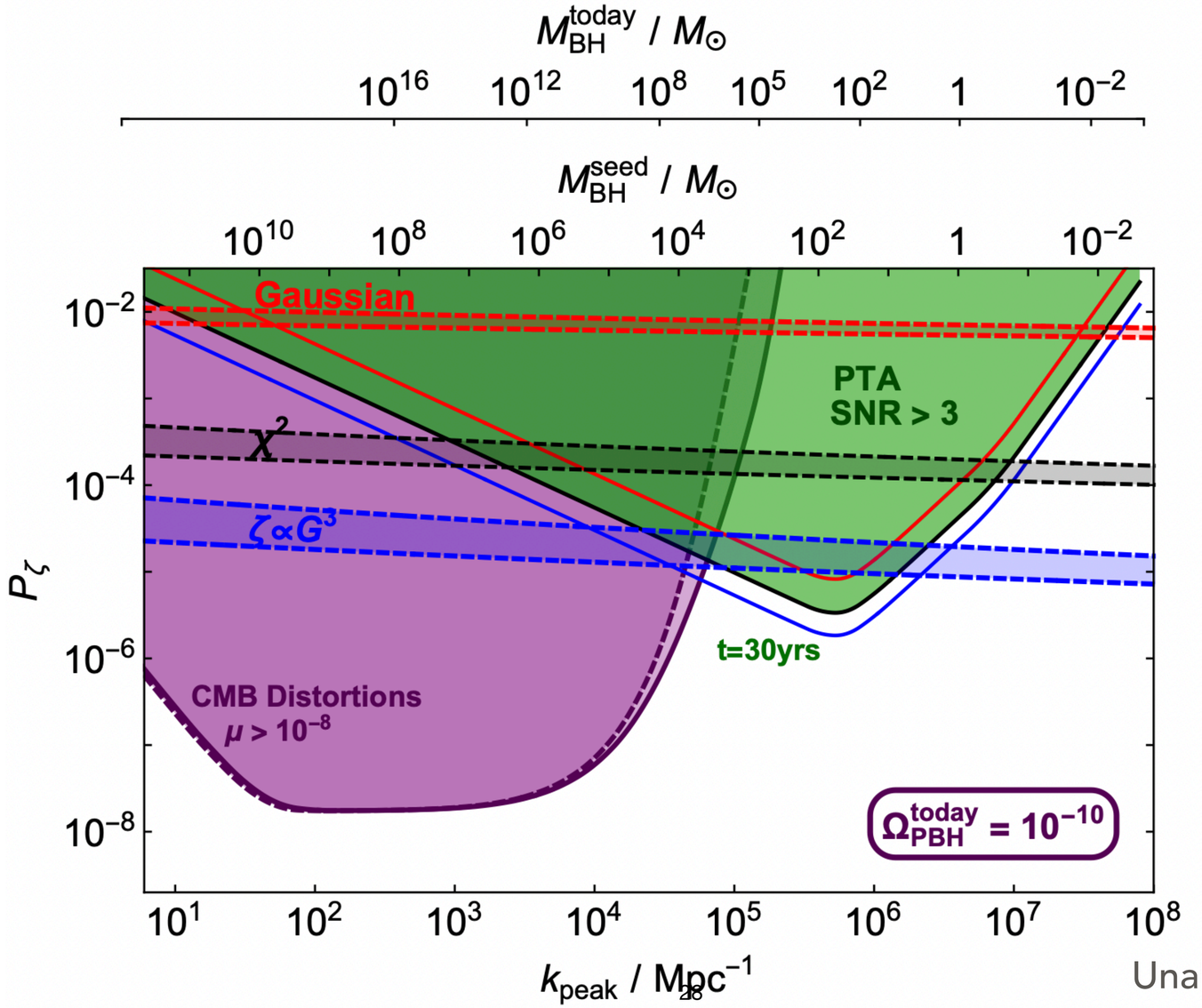


Cole, Coogan, Kavanagh, Bertone 2022

Conclusions

- PBHs are still viable (even as all DM on asteroid range) from an observational standpoint
- However, they are hard to produce in a generic way and we need to consider both parts of the pipeline at the same time
- This is so that we respect both direct and indirect constraints
- Given how much information they would provide, worth checking every part of still-viable parameter space
- Gravitational wave observations across a really wide range of frequencies will provide maybe the clearest picture

Non-Gaussianity and accretion can help a little but won't survive next-generation constraints



Unal et al. 2021

Potentials

- Mishra et al.
- Germani et al.
- Hertzberg et al.
- Cicoli et al.

$$V(\phi) = V_0 \frac{\phi^2}{M^2 + \phi^2} \left[1 - A \exp\left(-\frac{1}{2} \frac{(\phi - \phi_0)^2}{\sigma^2} \right) \right]$$

$$V(\phi) = \frac{\lambda}{12} \phi^2 v^2 \frac{6 - 4a\frac{\phi}{v} + 3\frac{\phi^2}{v^2}}{\left(1 + b\frac{\phi^2}{v^2}\right)^2} \ ,$$

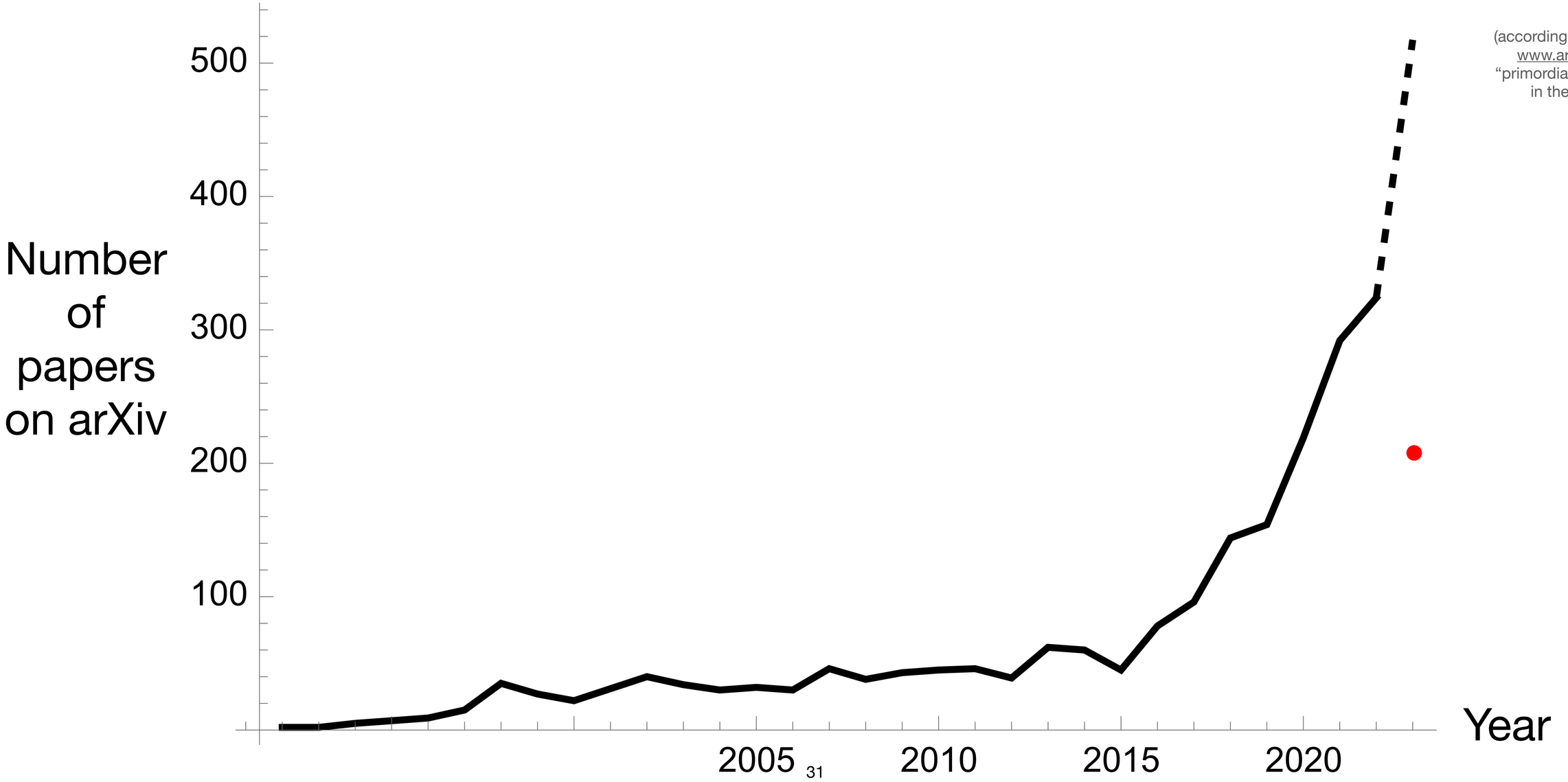
$$U(\phi) = U_0 \left[1 + c_1 \frac{\phi}{\Lambda} + \frac{c_2}{2} \frac{\phi^2}{\Lambda^2} + \frac{c_3}{3!} \frac{\phi^3}{\Lambda^3} + \frac{c_4}{4!} \frac{\phi^4}{\Lambda^4} + \frac{c_5}{5!} \frac{\phi^5}{\Lambda^5} \right]$$

$$V_{\rm inf} = V_0 \left(C_1 + C_2\, e^{-\frac{4}{\sqrt{3}}\hat{\phi}} + C_3\, e^{-\frac{2}{\sqrt{3}}\hat{\phi}} - \ e^{-\frac{1}{\sqrt{3}}\hat{\phi}} + C_4\, e^{\frac{2}{\sqrt{3}}\hat{\phi}} + C_5\, e^{\frac{1}{\sqrt{3}}\hat{\phi}} \right)$$

Open questions about production

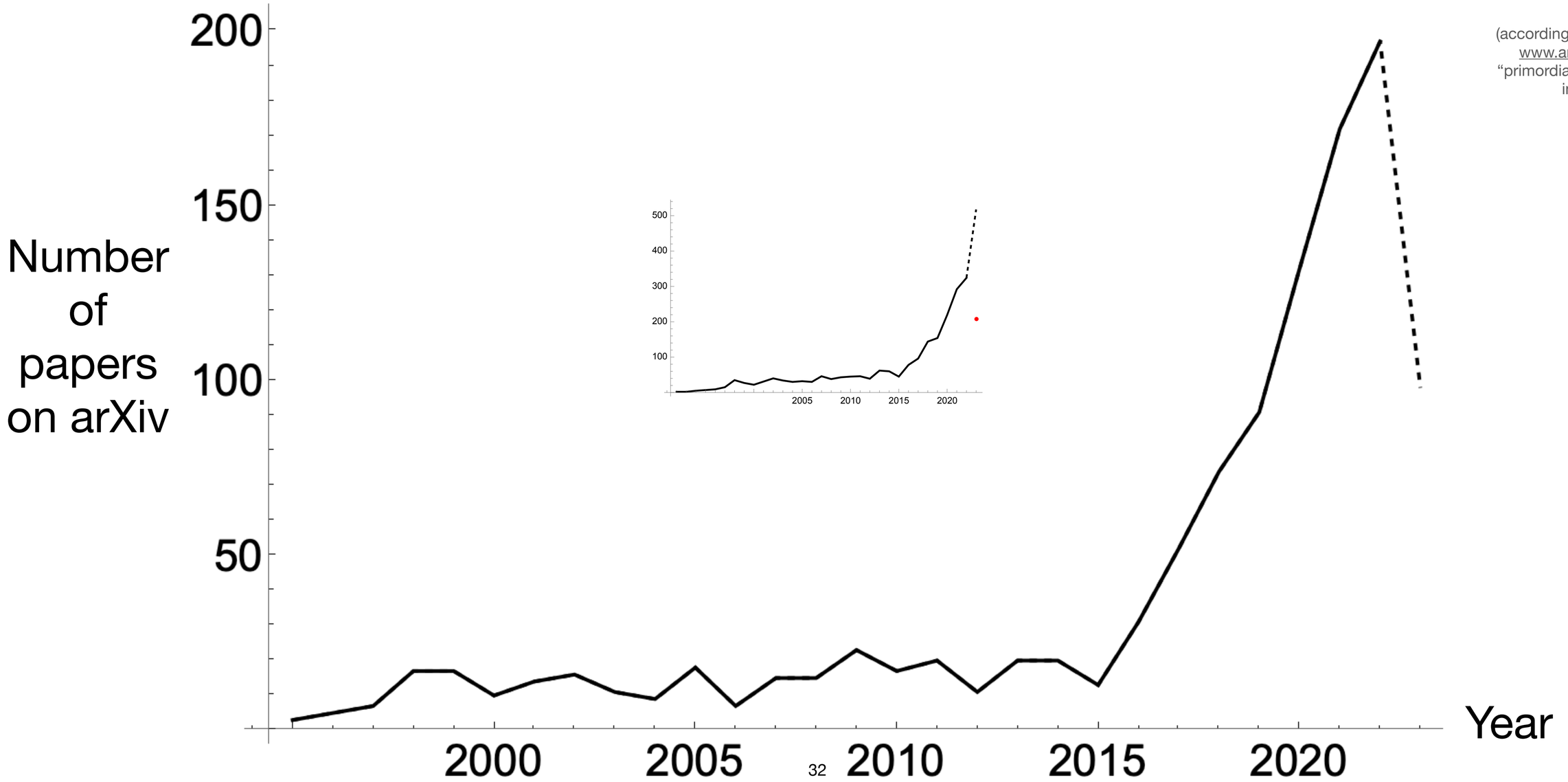
- Single-field vs. multifield inflation?
- Effect of non-gaussianity
- Quantum diffusion
- Totally different production mechanism? E.g. collapse of cosmic strings or topological defects

The rise of the PBH



(according to a search on www.arxiv.org with "primordial black hole(s)" in the abstract)

The rise of the PBH



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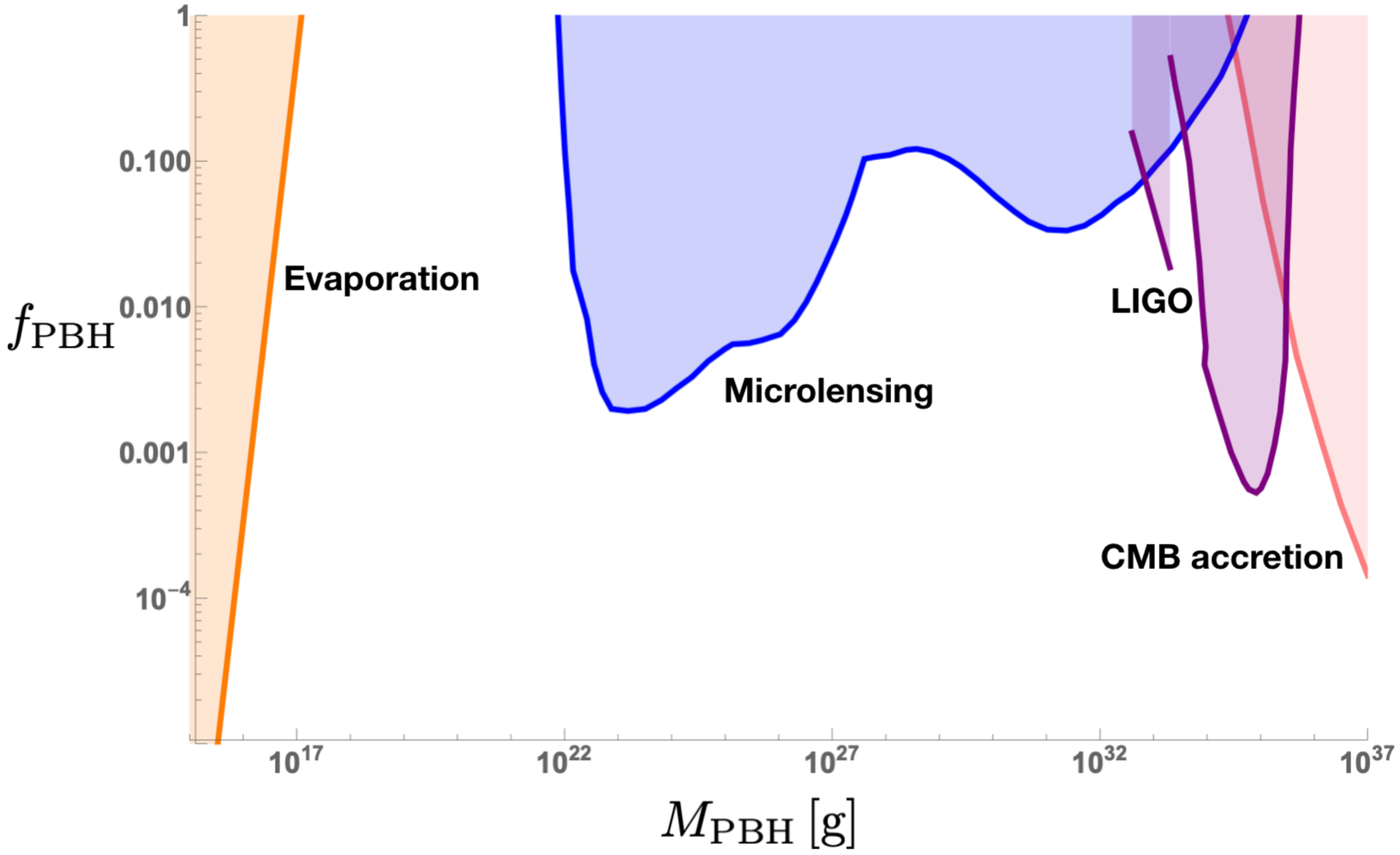

Cole, PhD thesis 2020