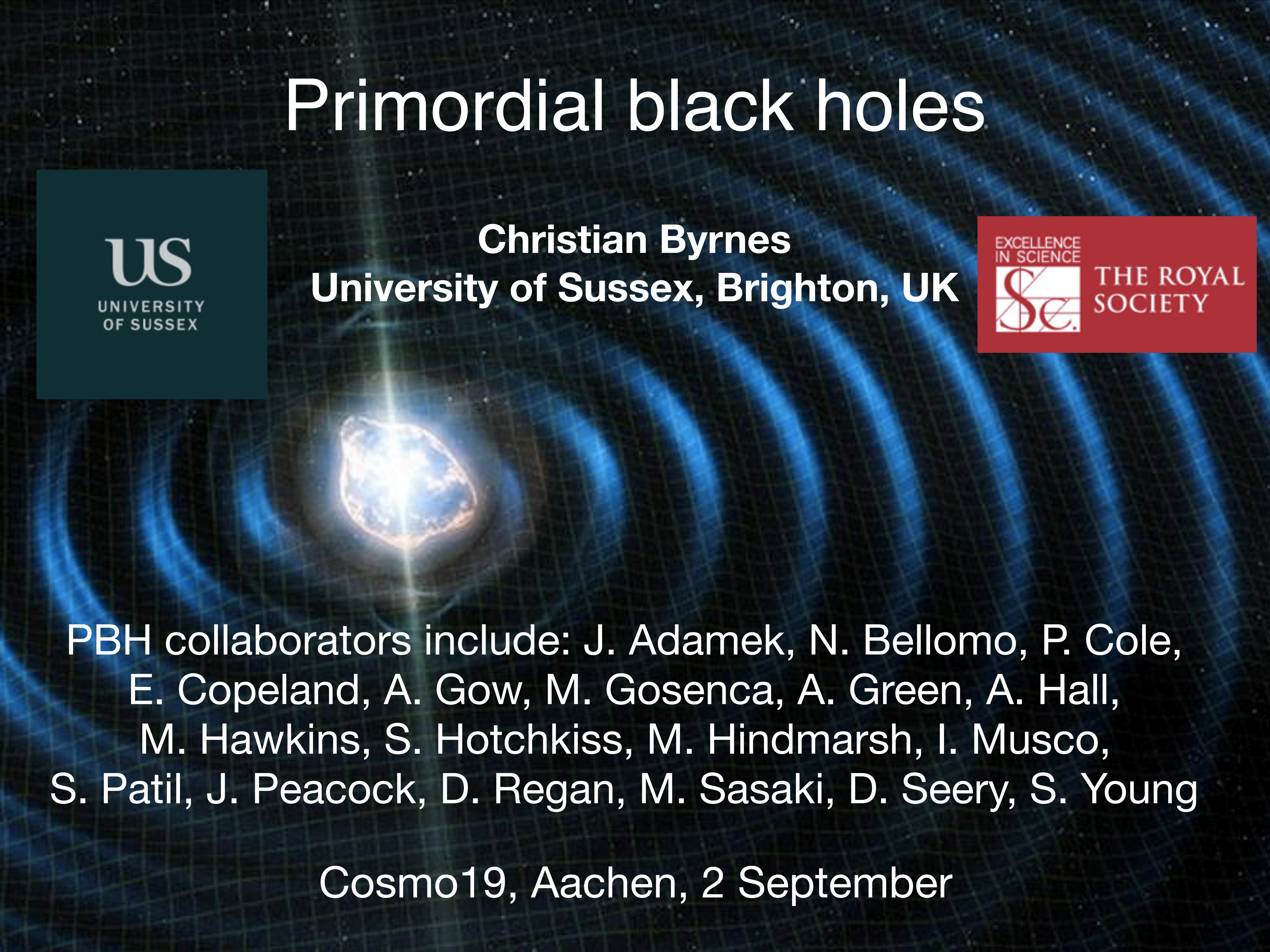

# Primordial black holes

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PBH collaborators include: J. Adamek, N. Bellomo, P. Cole, E. Copeland, A. Gow, M. Gosenca, A. Green, A. Hall, M. Hawkins, S. Hotchkiss, M. Hindmarsh, I. Musco, S. Patil, J. Peacock, D. Regan, M. Sasaki, D. Seery, S. Young

Cosmo19, Aachen, 2 September

# Primordial Black holes (PBHs)

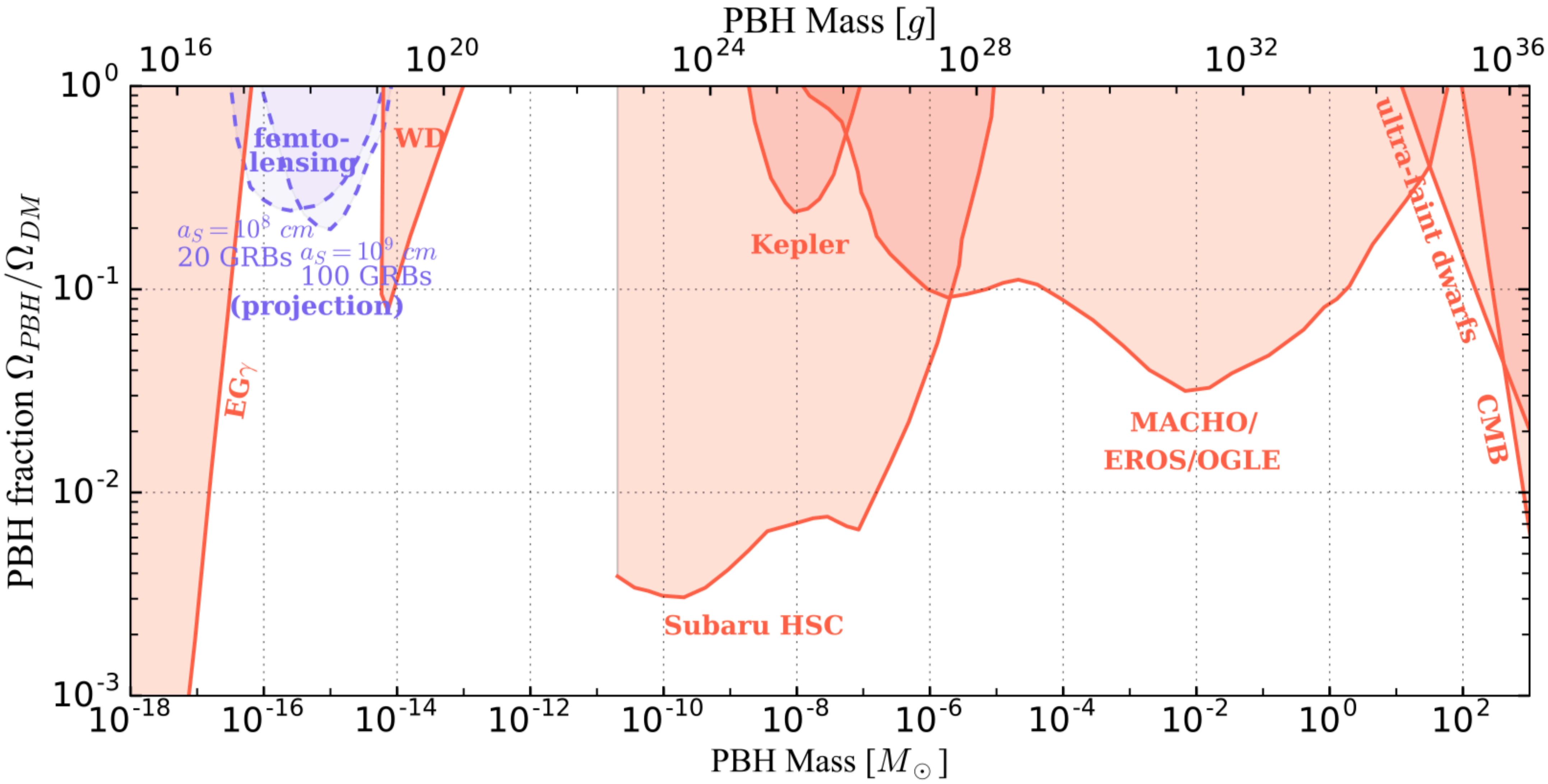
- Are not stellar remnants
- Naturally have all the properties required of dark matter
- Lots of interesting phenomenology: they could change early astrophysics, seed supermassive black holes, generate Hawking radiation…
- Require special initial conditions to form
- They might not exist, but are useful anyway

*Zel’dovich and Novikov 1967; Hawking 1974; Carr and Hawking 1974*

# Contents

- Are PBHs the dark matter?
- Observational hints and constraints
- How can a PBH be distinguished from a stellar remnant?
- How can they form?
- The small scale perturbations
- Future directions

# Constraints on PBHs as DM



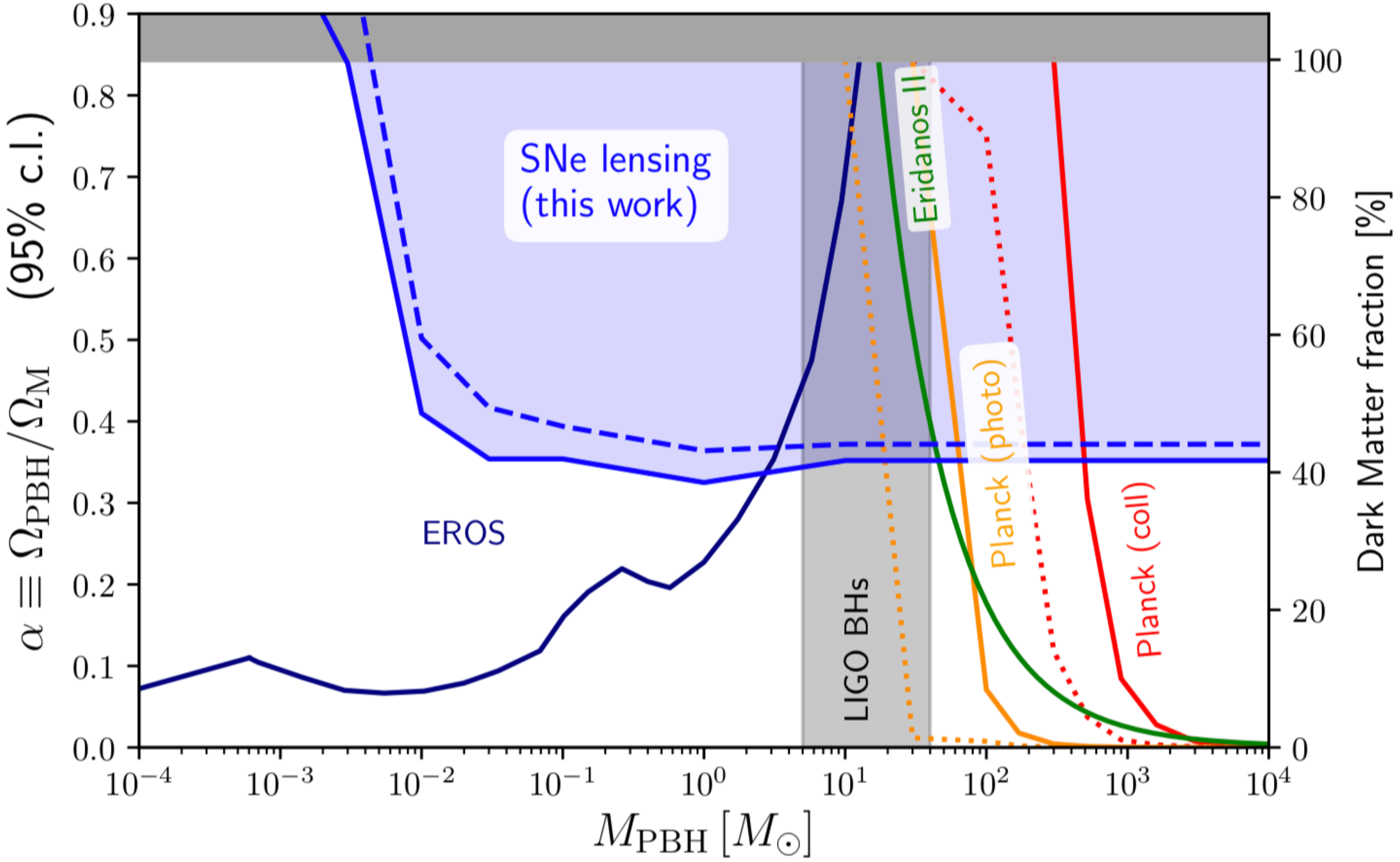
*Katz et al 2018 "Femtolensing revisited"; see also Sasaki et al 2017 Review +++*

The constraints have changed and in several cases weakened upon reanalyses
Lots of people have worked on the constraints

# Constraints on PBHs as DM

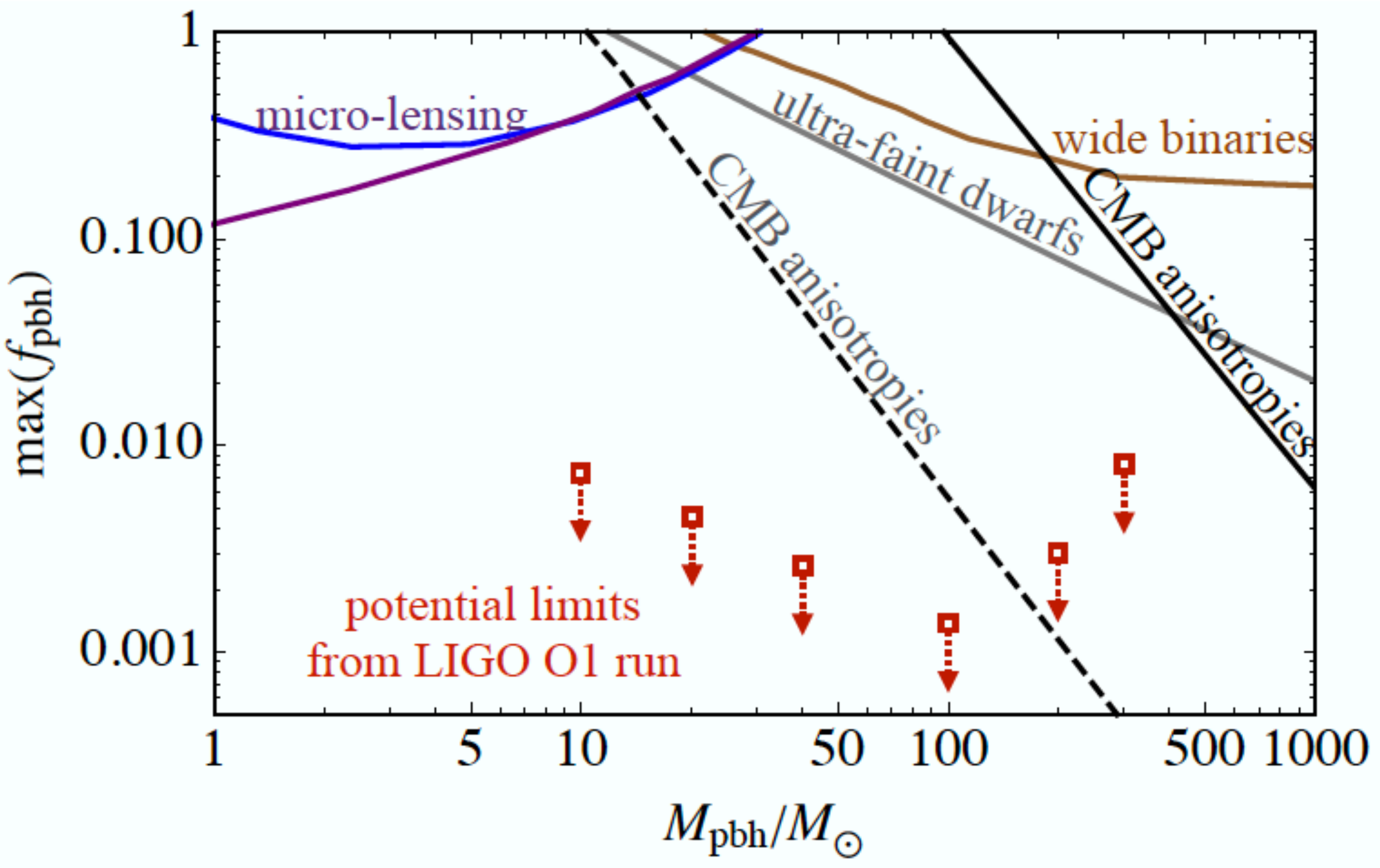
- There is evidence that PBHs cannot form all of the dark matter except in (most of) a mass range $10^{-15}$-$10^{-11}$ $M_{sun}$
- Although “light”, this is the heaviest DM candidate by about 20 orders of magnitude
- Previous microlensing constraints had suggested this was already ruled out, but these neglected finite source and light wavelength effects. *Niikura et al 2018*
- Exception: BHs could leave Planck mass relics when decaying, these are a potentially untestable “nightmare” DM scenario. *MacGibbon 1987*
- Constraints normally assume an (unrealistic) monochromatic mass spectrum. Critical collapse creates a spread of masses. *Yokoyama ’98, Nieyemeyer & Jedamzik ’98*
- The constraints often tighten for broad mass spectra, except in some cases with multiple peaks tuned to “fit in the observational gaps”, e.g. *Bellomo et al 2018*

# Constraints on the LIGO mass range



*Zumalacárregui and Seljak 2018*

# The PBH merger rate places the tightest constraint



*Haimoud et al 2017*

- Caveats:

1. Assumes a monochromatic mass spectrum. Extended by *Chen & Huang '18, Raidal et al '18* ++
2. Assumes PBHs are randomly placed initially, true if Gaussian initial conditions. Clustering does not help *Bringmann et al '18*
3. Assumes BH binaries are not disrupted. Recently tested to z~1000 by simulations (*Raidal et al '18)* and even disrupted PBHs can merge *Vaskonen & Veermäe '19*
4. Neglects halo formation around the BHs. Not a huge effect overall *Kavanagh, Gaggero & Bertone '18*

# Hints for PBHs

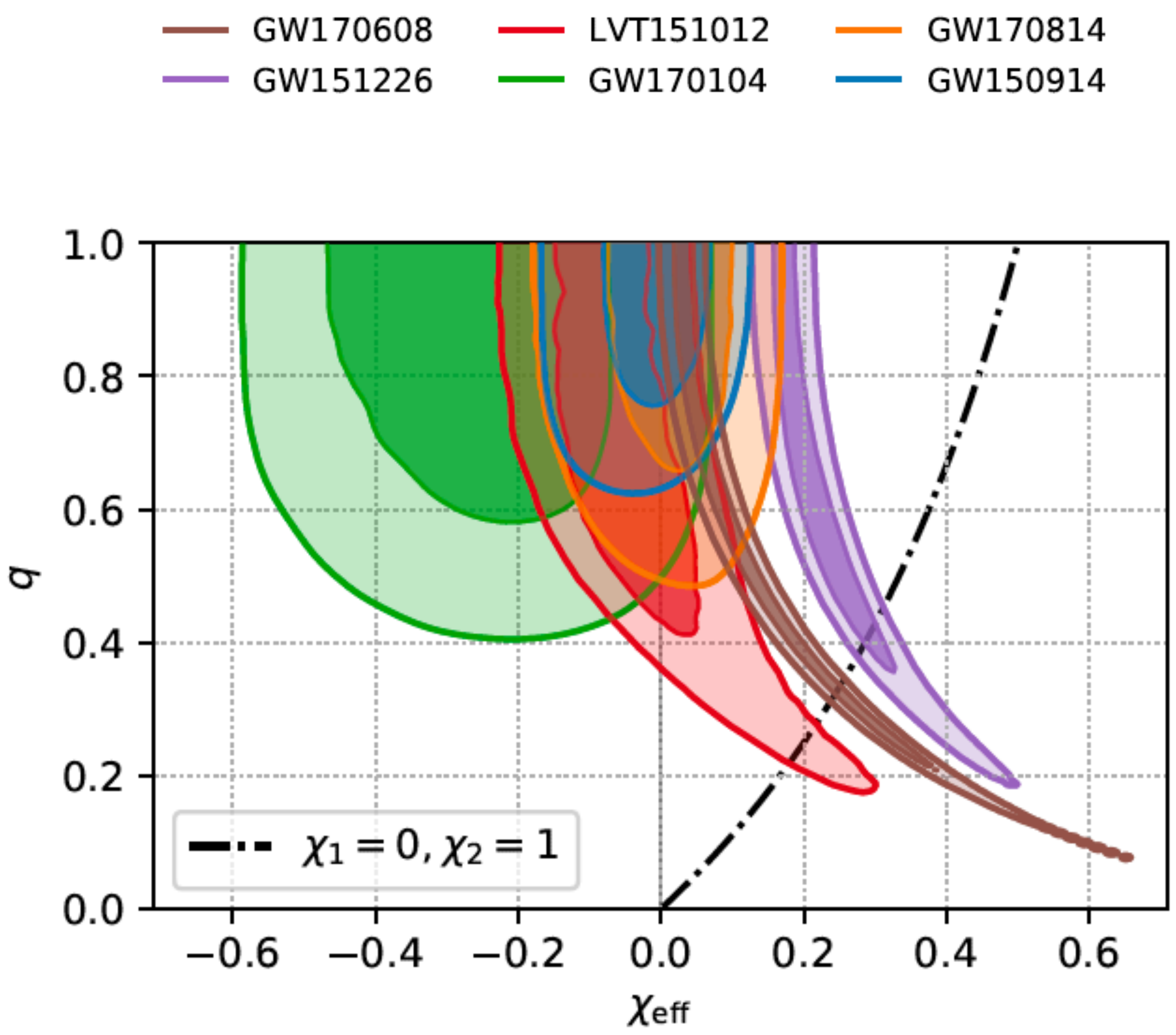
- PBHs might not exist, but there are some hints
  *Clesse & Garcia-Bellido 2017*

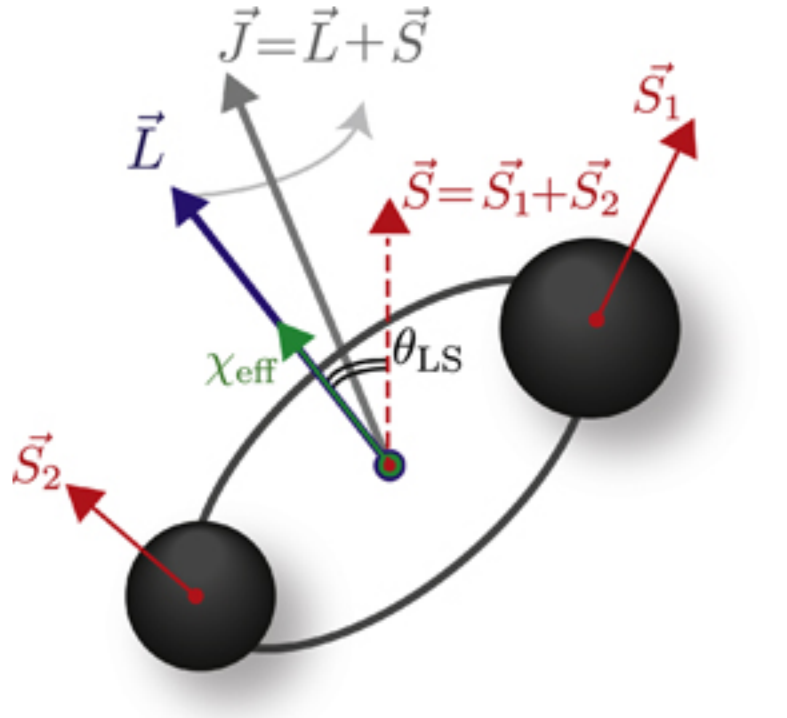
- The “unexpected” masses and low spins of those LIGO/Virgo detected created an explosion of interest.
  *“Did LIGO detect dark matter” Bird et al;*
  *see also Clesse & Garcia-Bellido; Sasaki et al; all 2016*

- The existence of supermassive black holes in almost all galaxies, with unknown formation process. However, creating a heavy PBH seed requires non-Gaussian initial conditions to evade CMB mu-distortion constraints. *Carr, Nakama & Silk 2017*

- Correlation between the cosmic infrared background and unresolved cosmic X-ray background. *Kashlinsky et al Astro2020 white paper*

# Black hole spin





$$\chi_{\rm eff} = \frac{c}{G(m_1 + m_2)} \left( \frac{\vec{S}_1}{m_1} + \frac{\vec{S}_2}{m_2} \right) \cdot \vec{L}$$

$$a_* = \frac{c\,|\,\vec{S}\,|}{Gm^2} \leq 1$$

Negligible spin is expected for PBHs formed during radiation domination. Unlike astrophysical BHs, PBHs do not undergo much collapse before formation. See the talk by de Luca. *Chiba & Yokoyama 2017; Belczynski et al. 2017; Mirbabyi et al 2019; De Luca et al 2019; Fernandez & Profumo 2019*

# What if one PBH was detected?

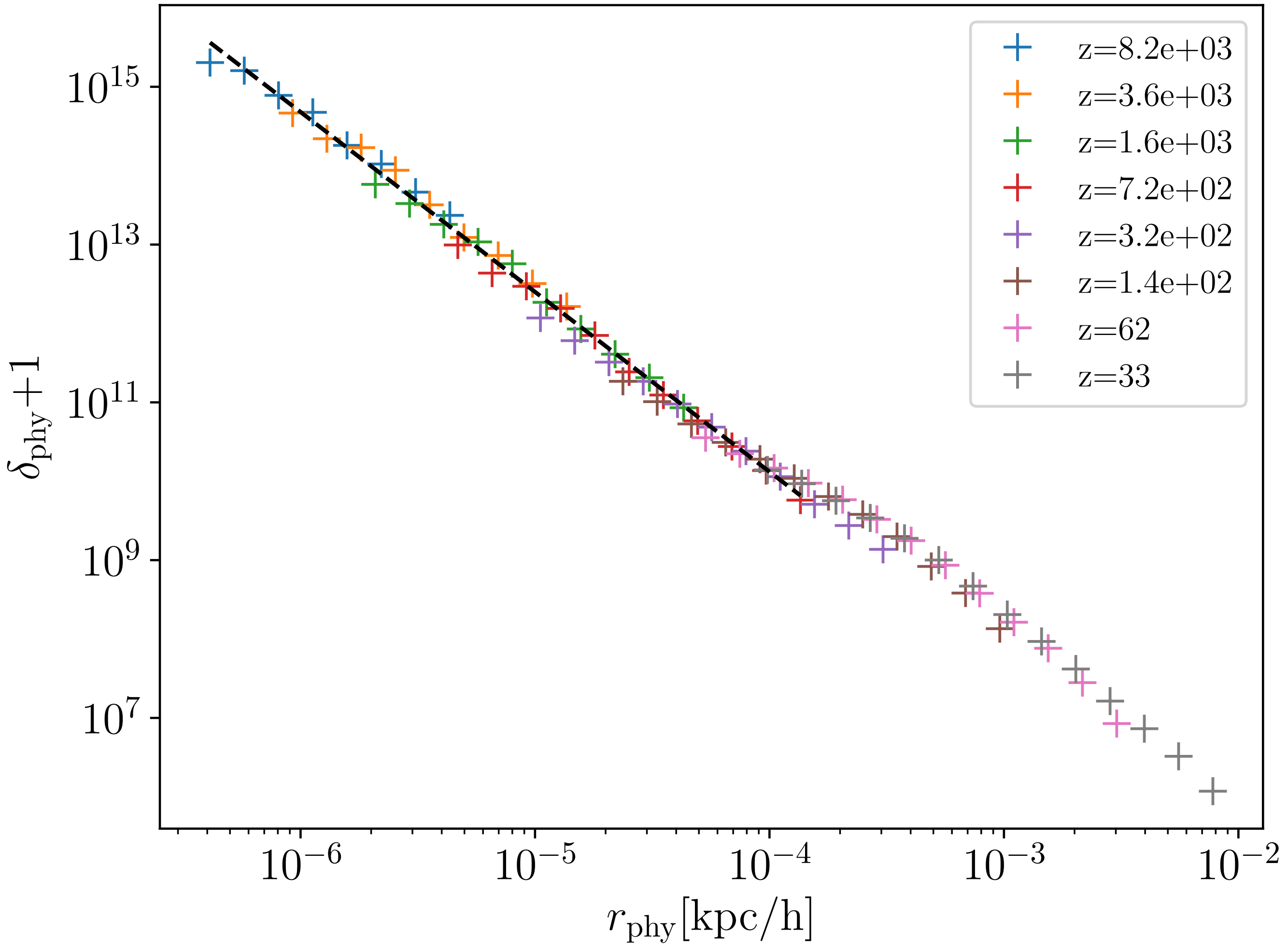
- We would know what some of the DM was (and what some of it is not)
- It would be the oldest relic detected, predating the primordial element abundance generated by BBN
- Other potential relics include: gravitational waves, topological defects such as cosmic strings, CMB spectral distortions, ultracompact minihalos
- Requires non-trivial inflationary dynamics, perhaps with an early-matter-dominated phase and/or topological defects. *PBH review article: Green 2015*

# WIMPs and PBHs are incompatible

- Assuming WIMPs have the standard, velocity independent cross section which gets the right abundance, and $M_{PBH} > 10^{-6}\ M_{sun}$. And annihilation channel into gamma rays.
- If $f_{PBH} < 1$, then another DM component is inevitable
- Steep and high density profiles form around PBHs (density~ $r^{-9/4}$). WIMPs would rapidly annihilate in them.
- In contrast to ultracompact minihalos without a PBH seed. *Gosenca et al '17, Delos et al '17*

- See talk by Derek Inman on 3D simulations with PBHs + lighter DM

- A detection of WIMPs or PBHs may effectively rule out the existence of the other



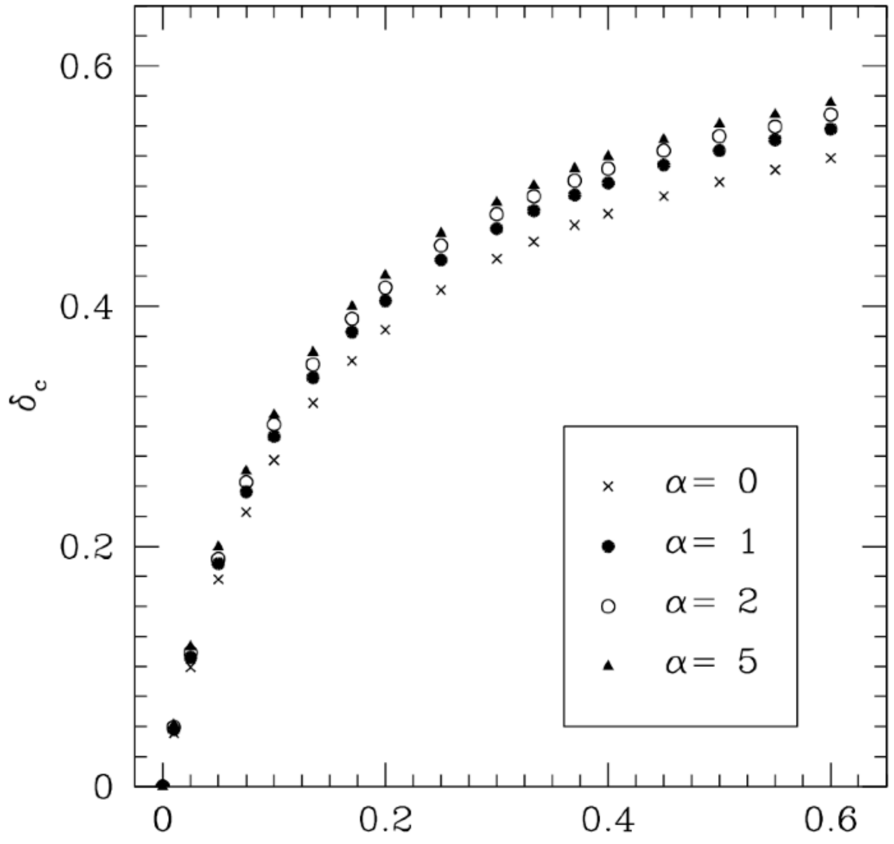
*Adamek, CB, Gosenca & Hotchkiss 2019;*

*Lacki & Beacom 2010; Eroshenko 2016; Boucenna, Kühnel, Ohlsson & Visinelli 2017; Bertone et al 2019*

# PBH formation

1. They form from large amplitude density perturbations shortly after horizon entry
2. Causality prevents collapse while the perturbations are super-horizon
3. Approximate 1-to-1 relation exists between horizon entry time, horizon length and PBH mass

Collapse threshold

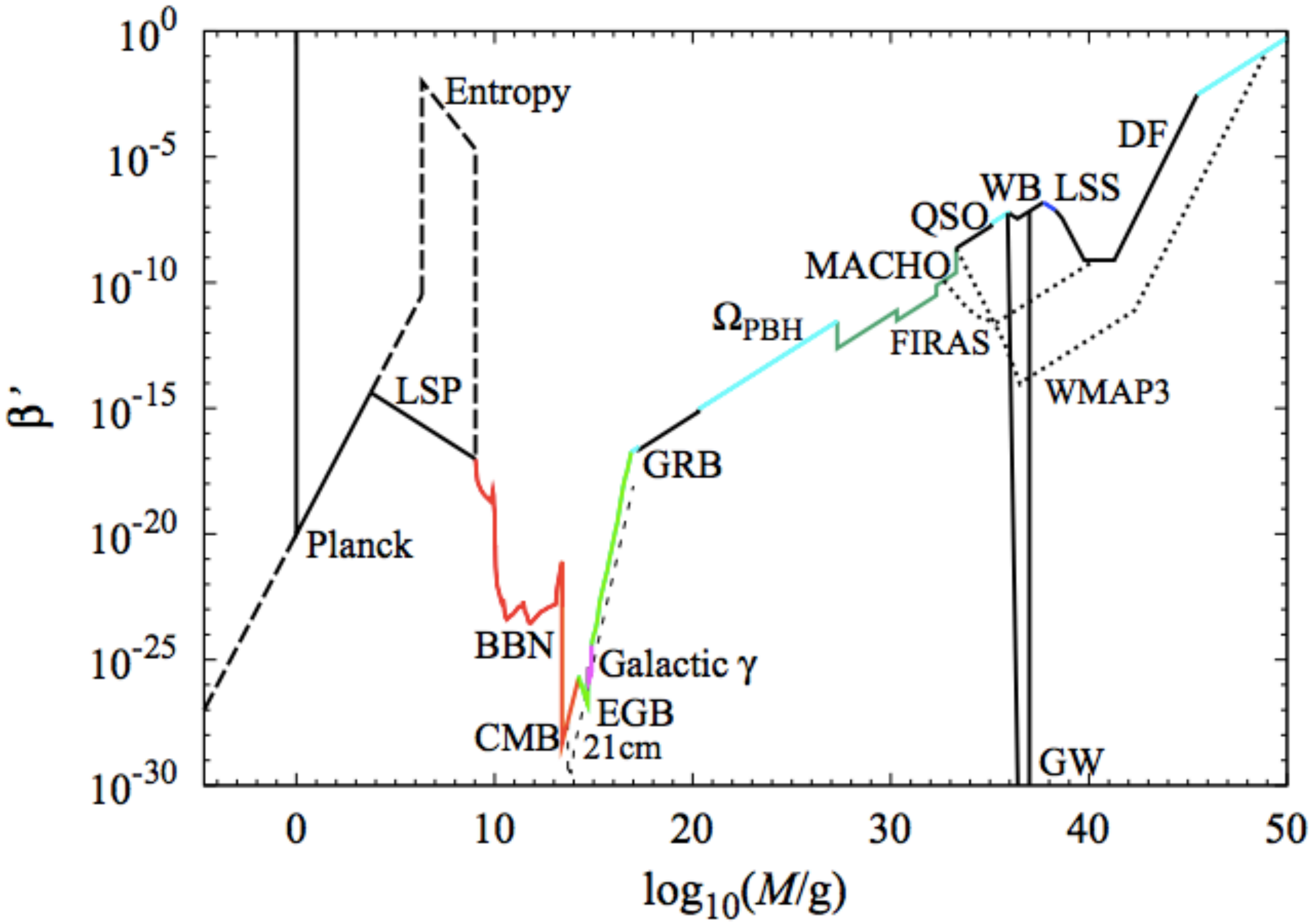


equation of state

*Musco and Miller 2013*

# The PBH fraction at formation is tiny

$$\beta' = e^{-\frac{\delta_c^2}{2\mathscr{P}_\delta}}$$



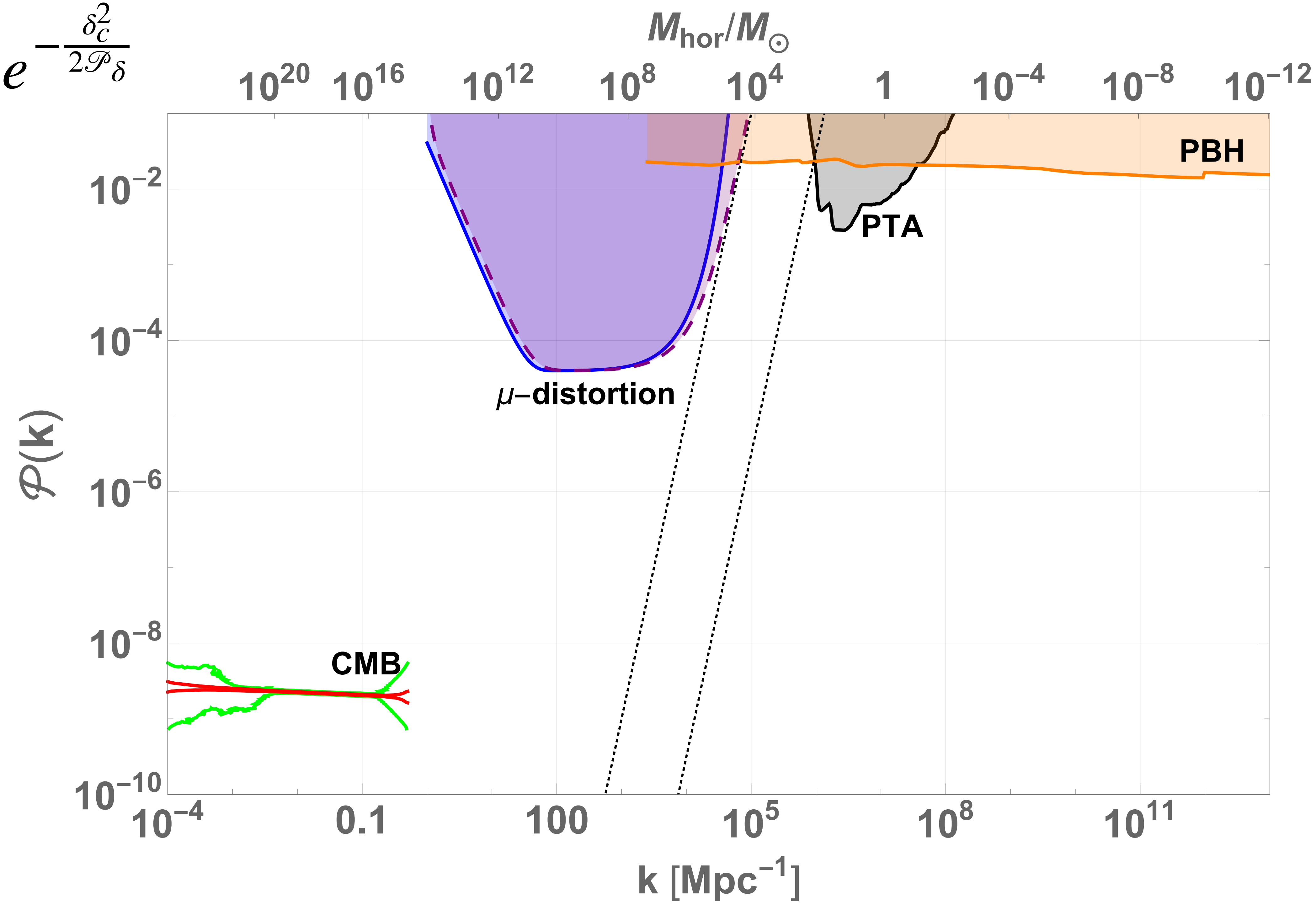
*Carr et al 2009*

$\rho_{PBH} \propto a^{-3}$ $\rho_{rad} \propto a^{-4}$

$\Omega_{PBH}$ grows like the scale factor from formation until radiation-matter equality

# Power spectrum constraints

$$\beta' = e^{-\frac{\delta_c^2}{2\mathscr{P}_\delta}}$$



*CB, Cole & Patil `18; See also Inomata and Nakama `18*

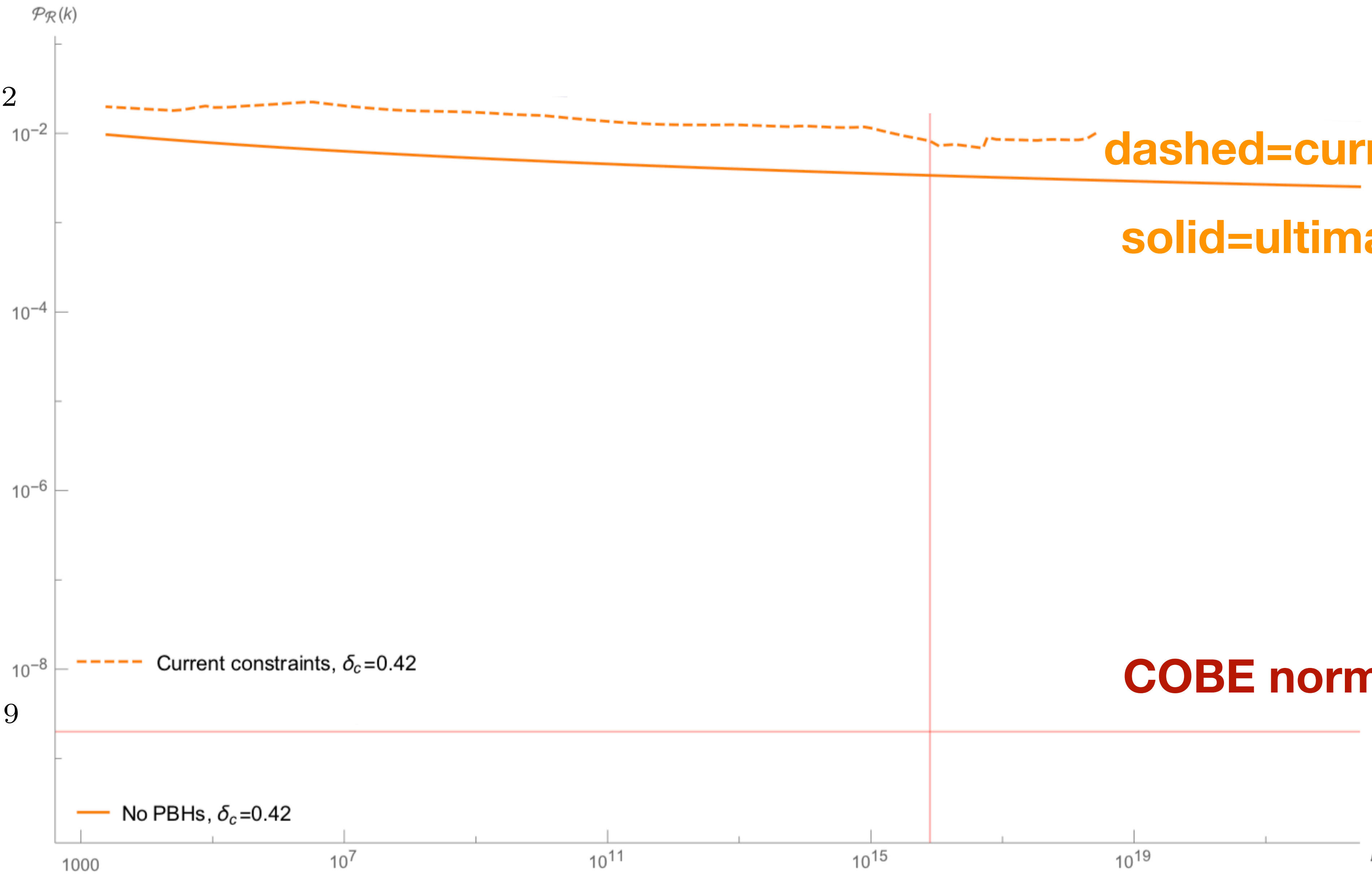
# Small scale perturbations

- We have precision measurements from the CMB and large scale structure on scales > 1 Mpc (which are “linear” today)
- These probe about 2 decades in length scales, but inflation must have lasted much longer
- Radiation pressure/non-linearities erases the memory of smaller scale perturbations, unless there is a relic
- The large scales are well fit by a simple power-law spectrum
- The small scale perturbations could contain lots of new information

# PBH formation comments

- The formation rate is exponentially sensitive to the amplitude of the power spectrum, and the collapse threshold
- Inflationary models posit an inflection point (ultra-slow-roll inflation) or other feature (*see talks by Pattison and Jain later today).*
- The power spectrum can't grow faster than about k4 (in canonical single-field inflation), impacts the constraints. *Byrnes, Cole & Patil '18; Carrilho, Malik & Mulryne '19*
- PBHs are very rare - very sensitive to non-Gaussianity
- The formation criteria depends on the density profile. Many spherically symmetric simulations exist, e.g. *Niemeyer & Jedamjik, Musco & Miller, Harada ++, Nakama ++…*
- Extensive recent analytic work has been done to relate the power spectrum to PBH formation rate at, but (at least) an order unity uncertainty remains (= tens of orders of magnitude in terms of the formation rate). *Germani & Musco '17, Yoo et al '17, Kawasaki & Nakatsuka '19, de Luca et al '19, Young et al '19, Young '19, Kalaja et al '19*

# Ultimate constraints from PBHs



$\mathcal{P}_\zeta = 2 \times 10^{-2}$

$\mathcal{P}_\zeta = 2 \times 10^{-9}$

**dashed=current constraint**

**solid=ultimate constraint**

**COBE normalisation**

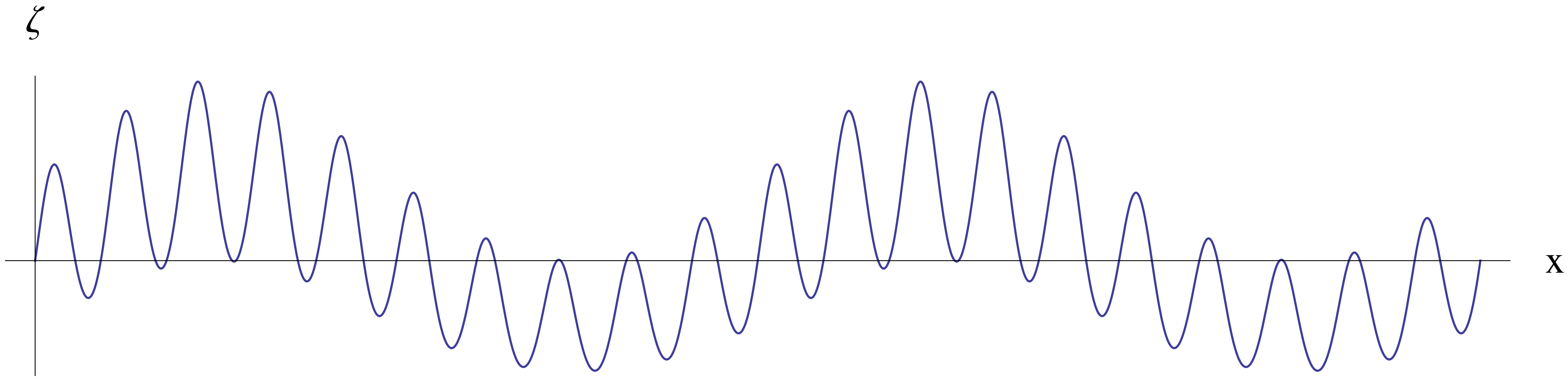
$k[\mathrm{Mpc}^{-1}]$

**$10^{16}$/Mpc**

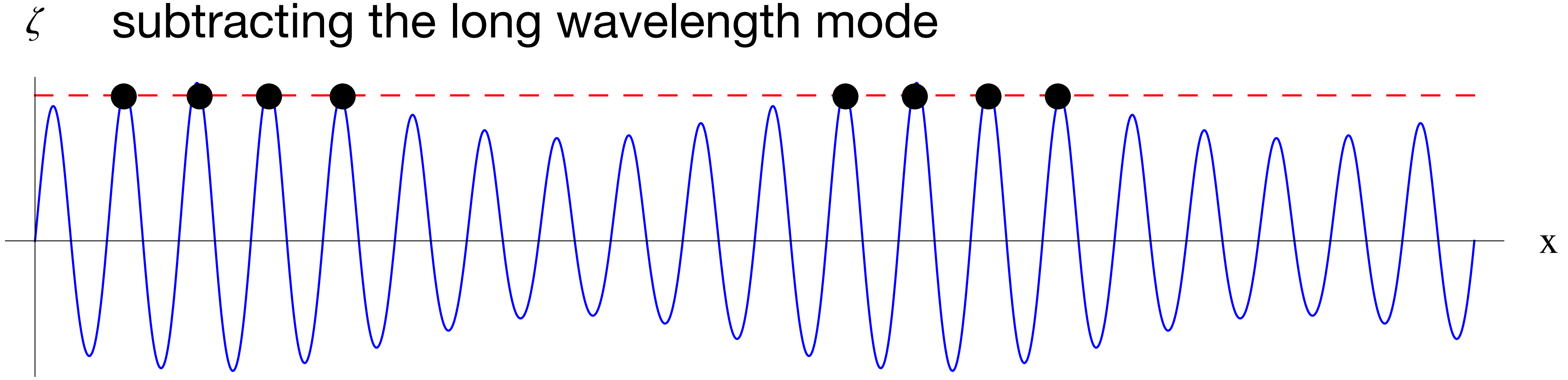
$$\beta' = e^{-\frac{\delta_c^2}{2\mathscr{P}_\delta}}$$

*Cole & CB ‘17*

# Isocurvature constraints



subtracting the long wavelength mode

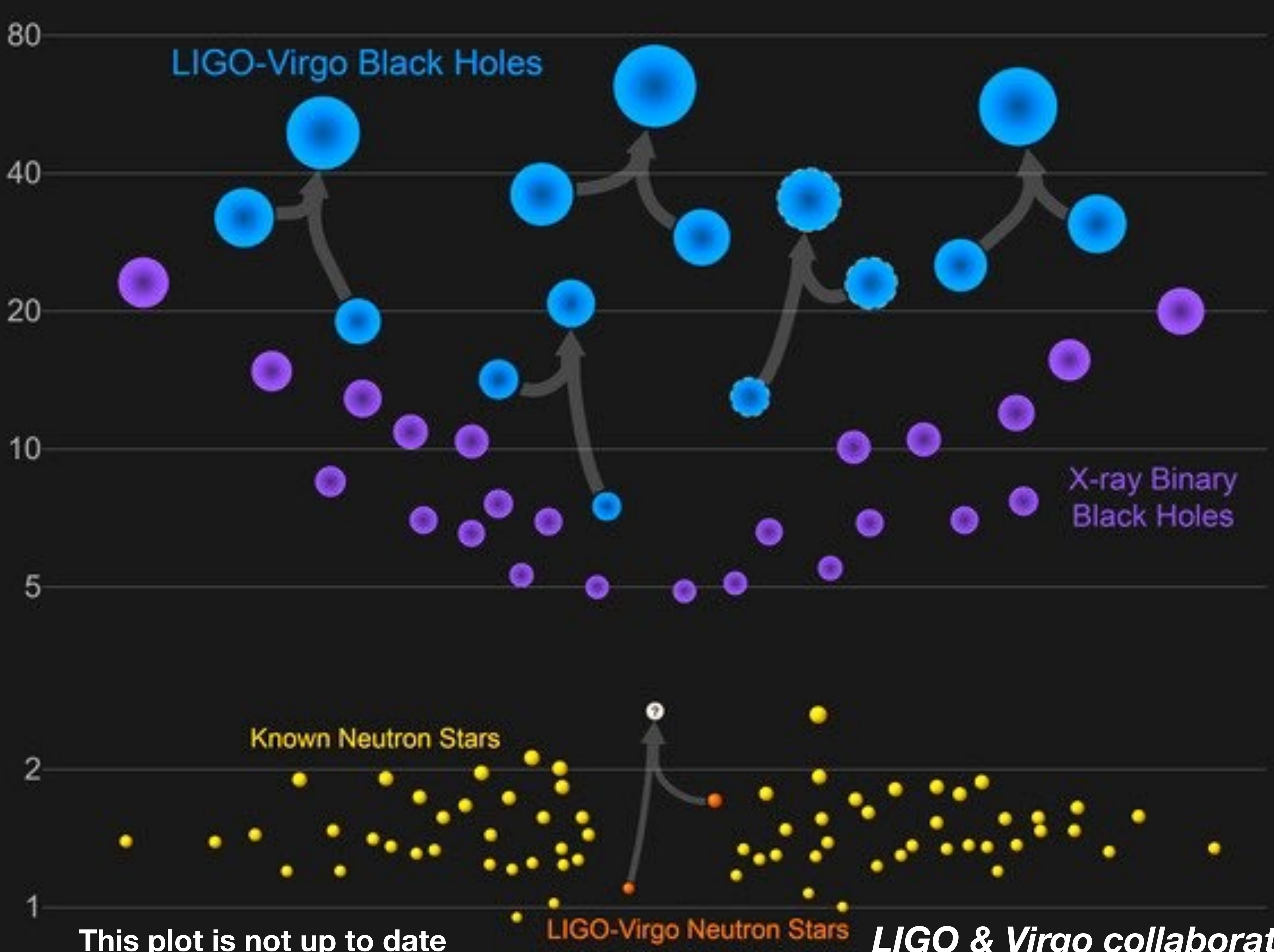


Mode coupling between CMB and PBH forming scales is ruled out, since that would generate a huge DM isocurvature perturbation - *Tada & Yokoyama 2015, Young & CB 2015*

# Black holes have no hair

- Hence, a BH does not “remember” how it formed
- We can only measure the mass and spin
- Fortunately, stellar remnant black holes cannot form with any possible mass
- There is expected to be a lower bound around 5 $M_{sun}$, and no compact objects (including neutron stars) below the Chandrasekhar mass, about 1 $M_{sun}$
- A black hole merger at sufficiently high redshift would have to be primordial in origin. *Koushiappas & Loeb 2017*

# Masses in the Stellar Graveyard

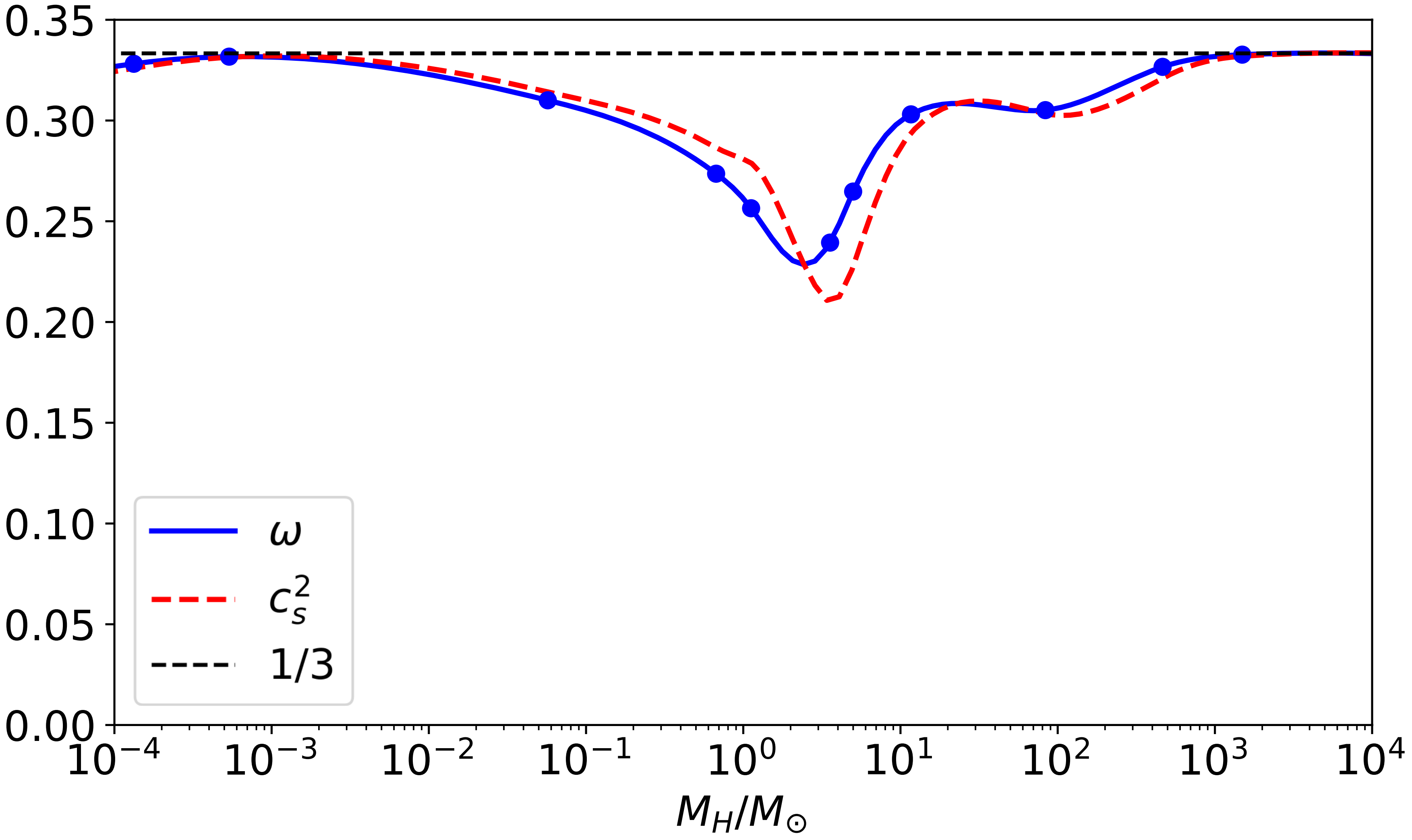


This plot is not up to date

*LIGO & Virgo collaboration*

# The QCD transition

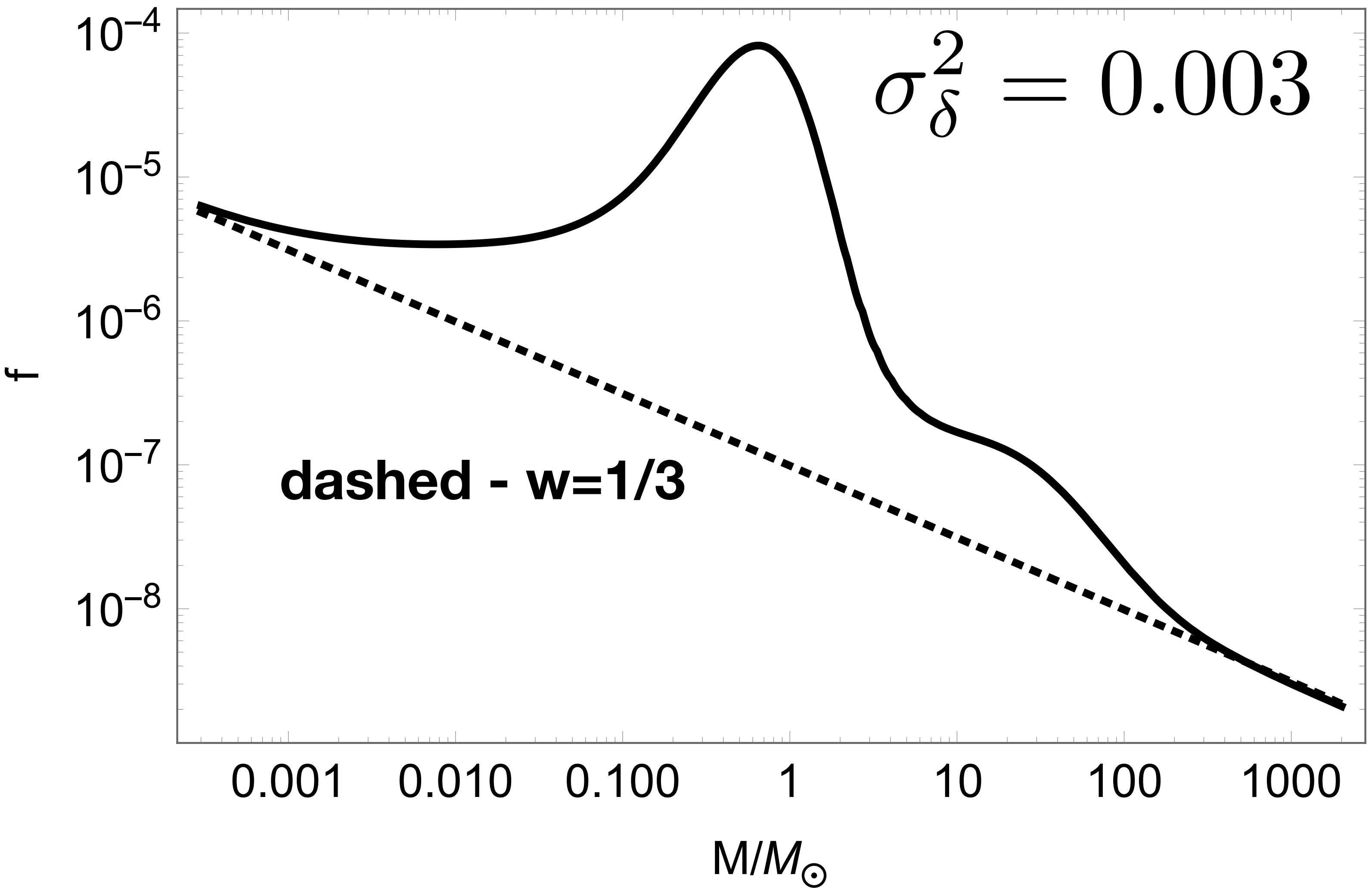
As the Universe cools below 1 GeV (t~$10^{-6}$ s), strong interactions confine quarks into hadrons and the equation-of-state parameter w decreases. *Crawford & Schramm `82, Jedamzik `98*



*CB, Hindmarsh, Young & Hawkins 2018 using Borsanyi et al 2016*

# The resultant PBH mass function

$$f(M) \propto M^{-1/2} e^{-\frac{\delta_c^2}{2\sigma_\delta^2}}$$



The QCD phase transition took place during the time when LIGO mass PBHs would have formed. It boosts the formation rate of solar mass PBHs by 2 orders of magnitude
No detection yet: *LIGO & Virgo collaboration 2019, Magee et al 2019*

# Looking forwards

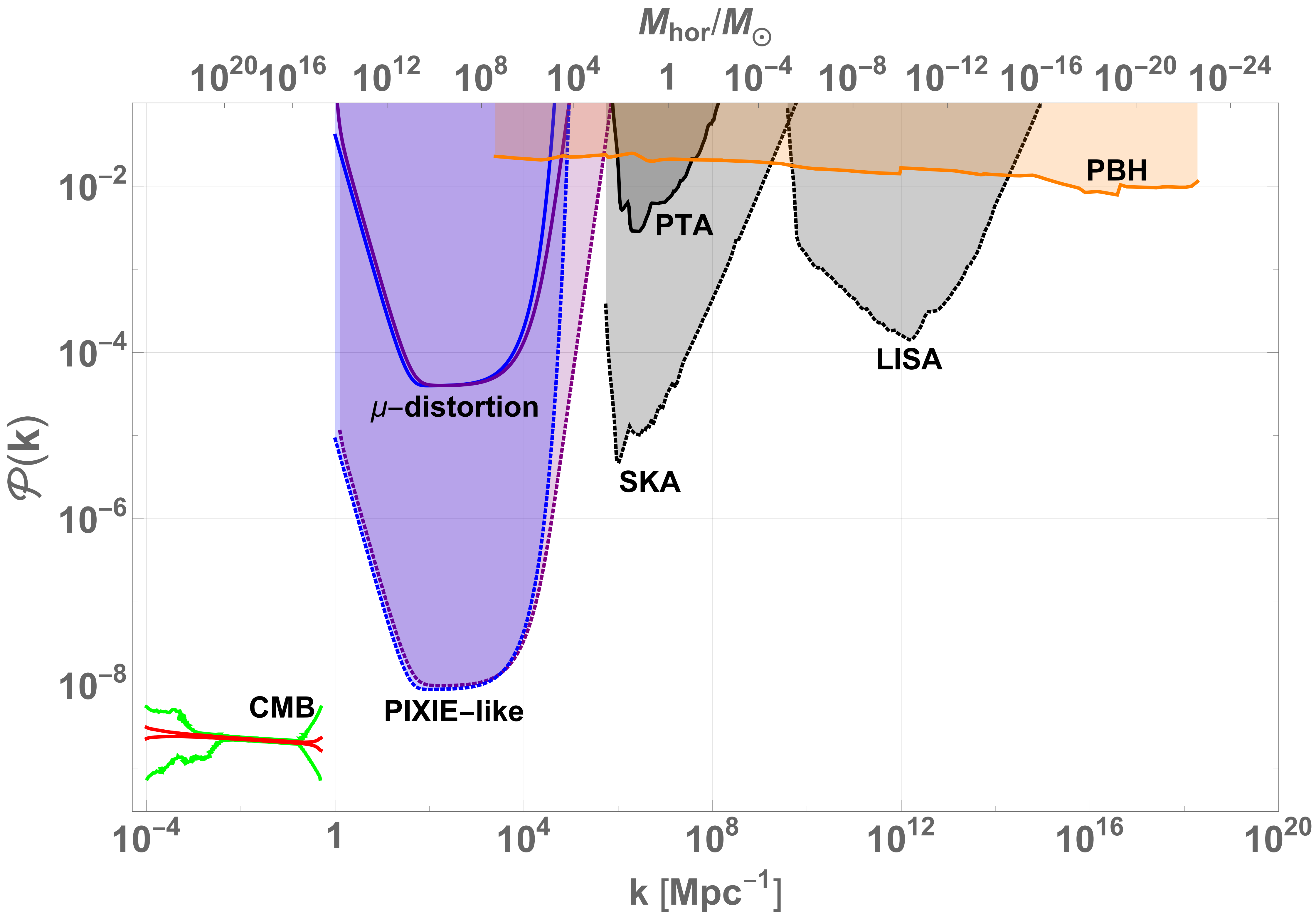
- LIGO/Virgo already have far more than the 10 analysed events, potentially including a BHNS merger and one in the upper mass gap (Tanja Hinterer's talk next)

- LISA and future ground based detectors will be sensitive to very high redshift mergers + better probe of the spins, mass ratio, etc

- Theoretical analysis of the formation criteria has greatly improved in recent years, but 3D simulations of PBH formation are still required (especially during early matter domination)

- See talks by Racco, Franciolini, Inomata, Terada and Dvorkin

# Future constraints



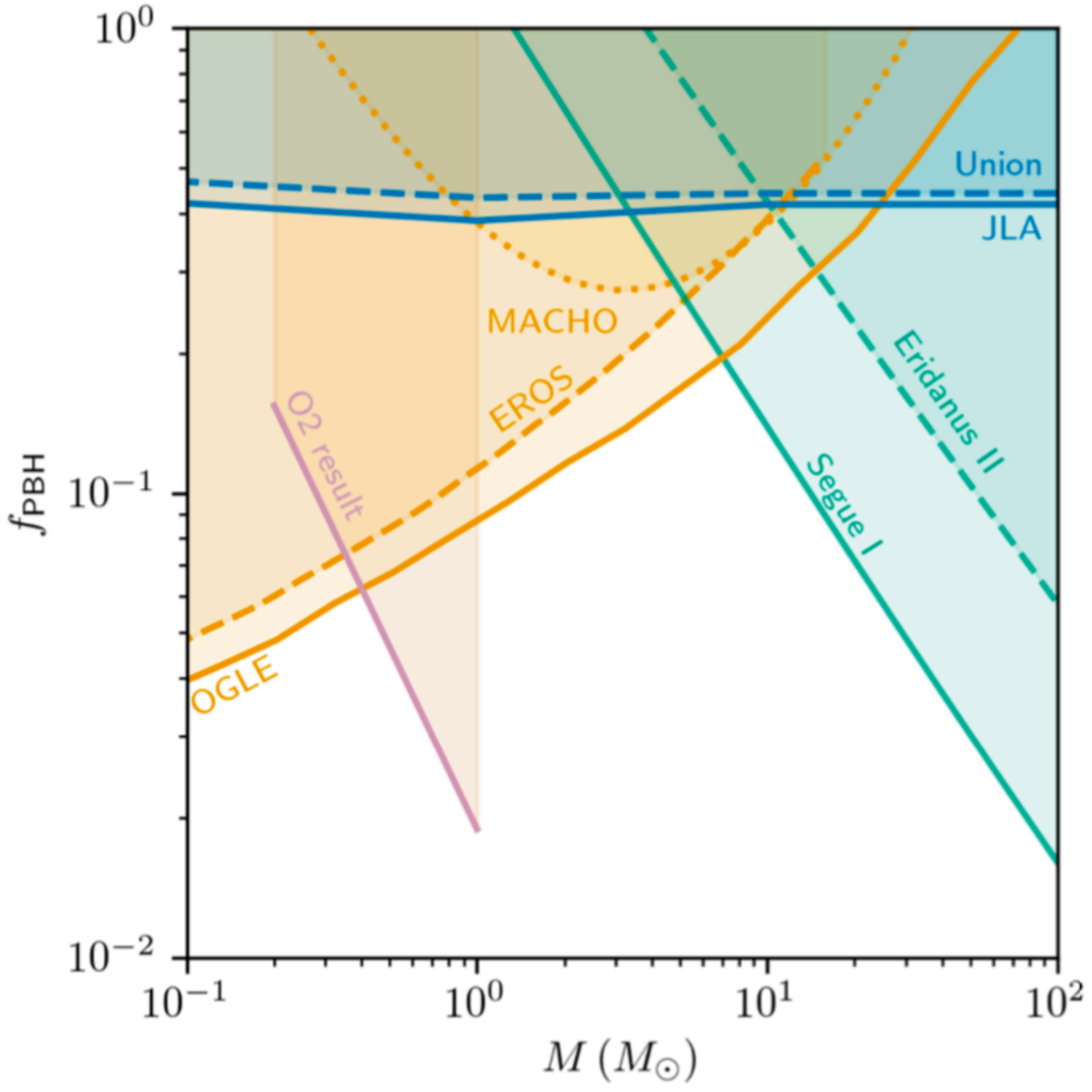
*CB, Cole & Patil 2018*

# Summary

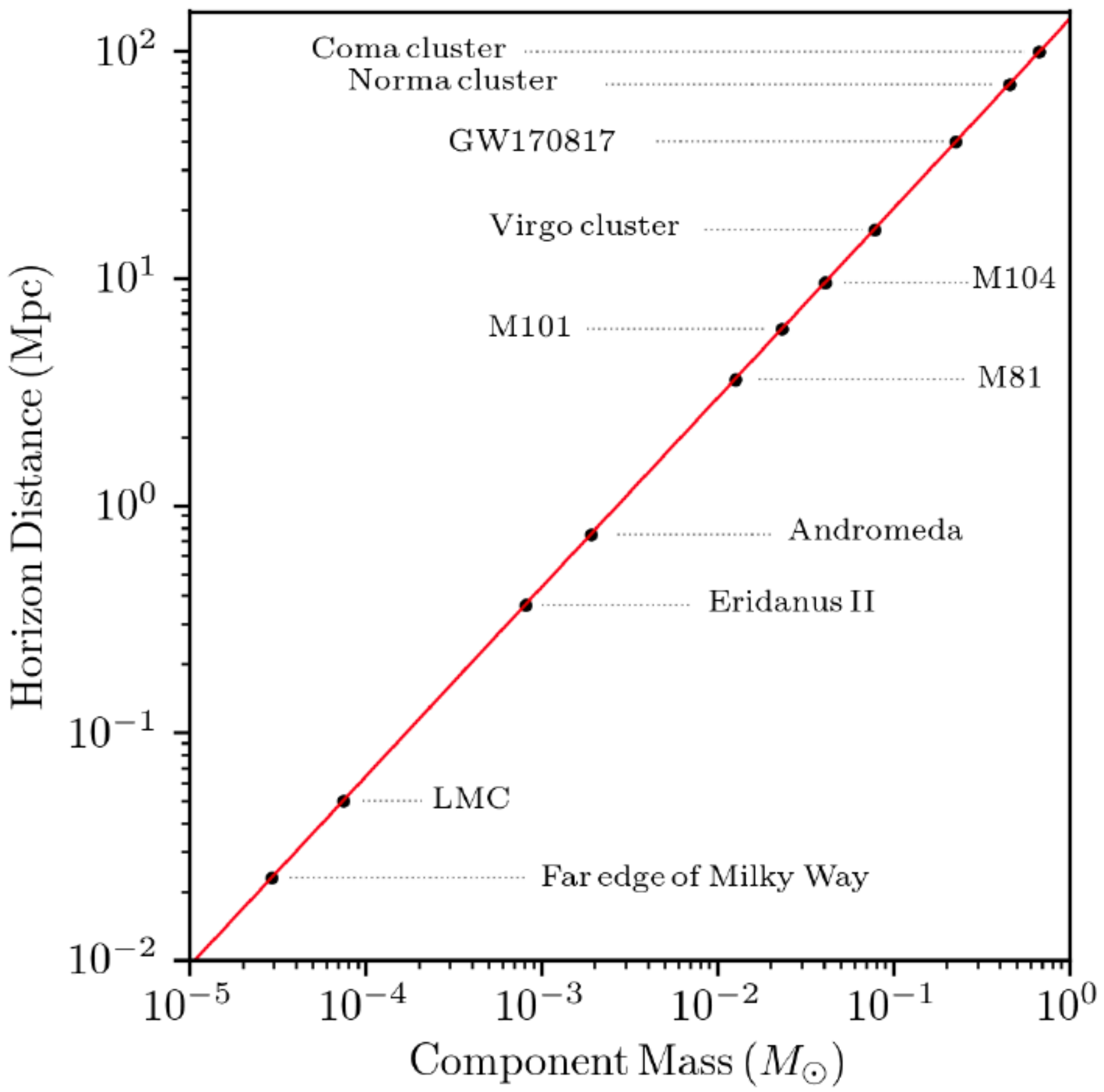
- Interest in PBHs has exploded since the first GW detection
- PBHs are used to probe the initial conditions and constituents of the Universe
- PBHs in the LIGO/Virgo mass range cannot be more than ~1-10% of the DM
- Asteroid mass PBHs could be all the DM, and LISA can test this scenario
- The detection of one PBH would be huge, and several “smoking gun” scenarios exist
- Even without a detection, PBHs constrain a greater range of scales than any other probe

# Sub-solar mass GW searches

GW searches have been made, with no detections so far
These are below the Chandrasekhar mass, hence potential proof of a primordial origin



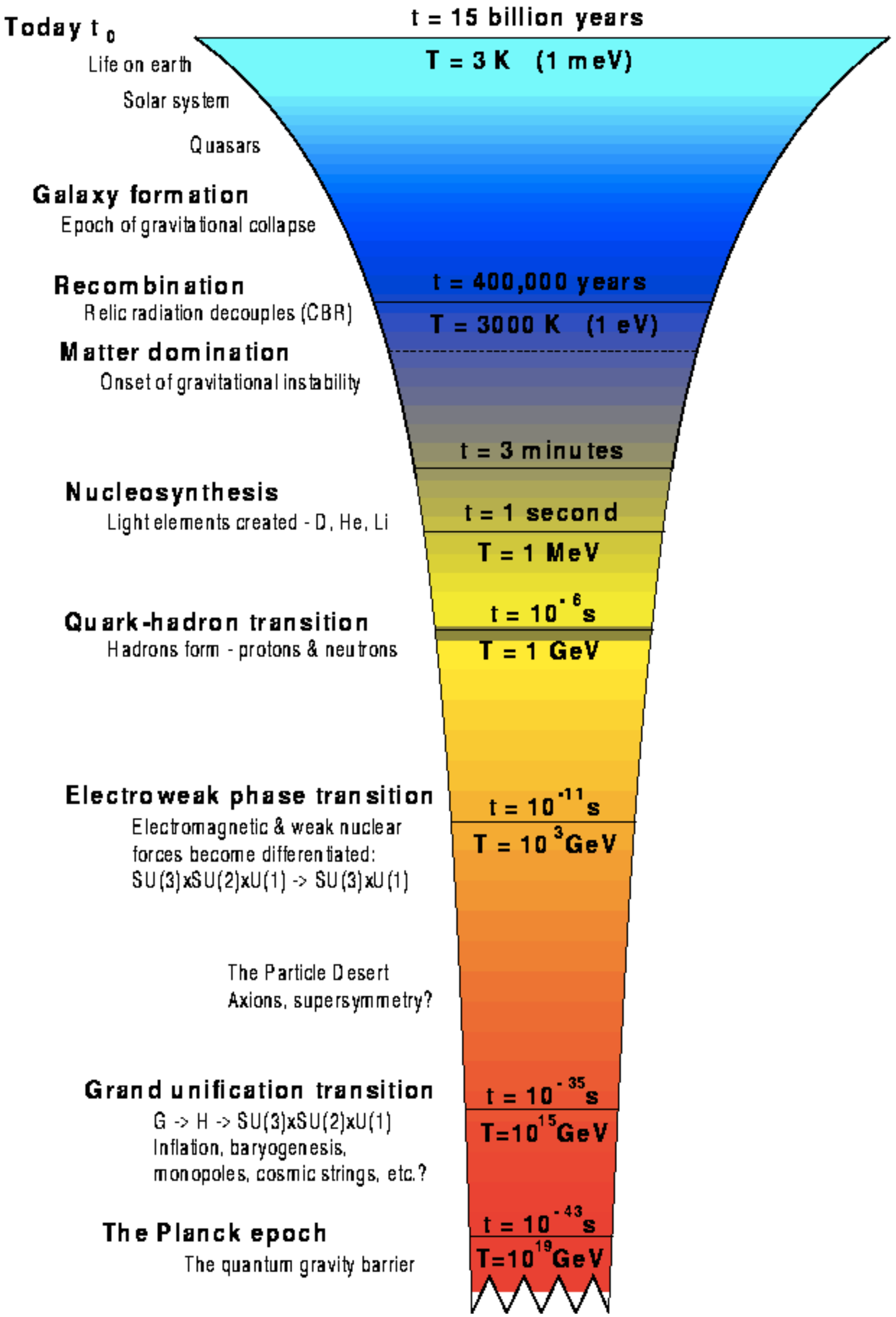
*LIGO & Virgo collaboration 2019*



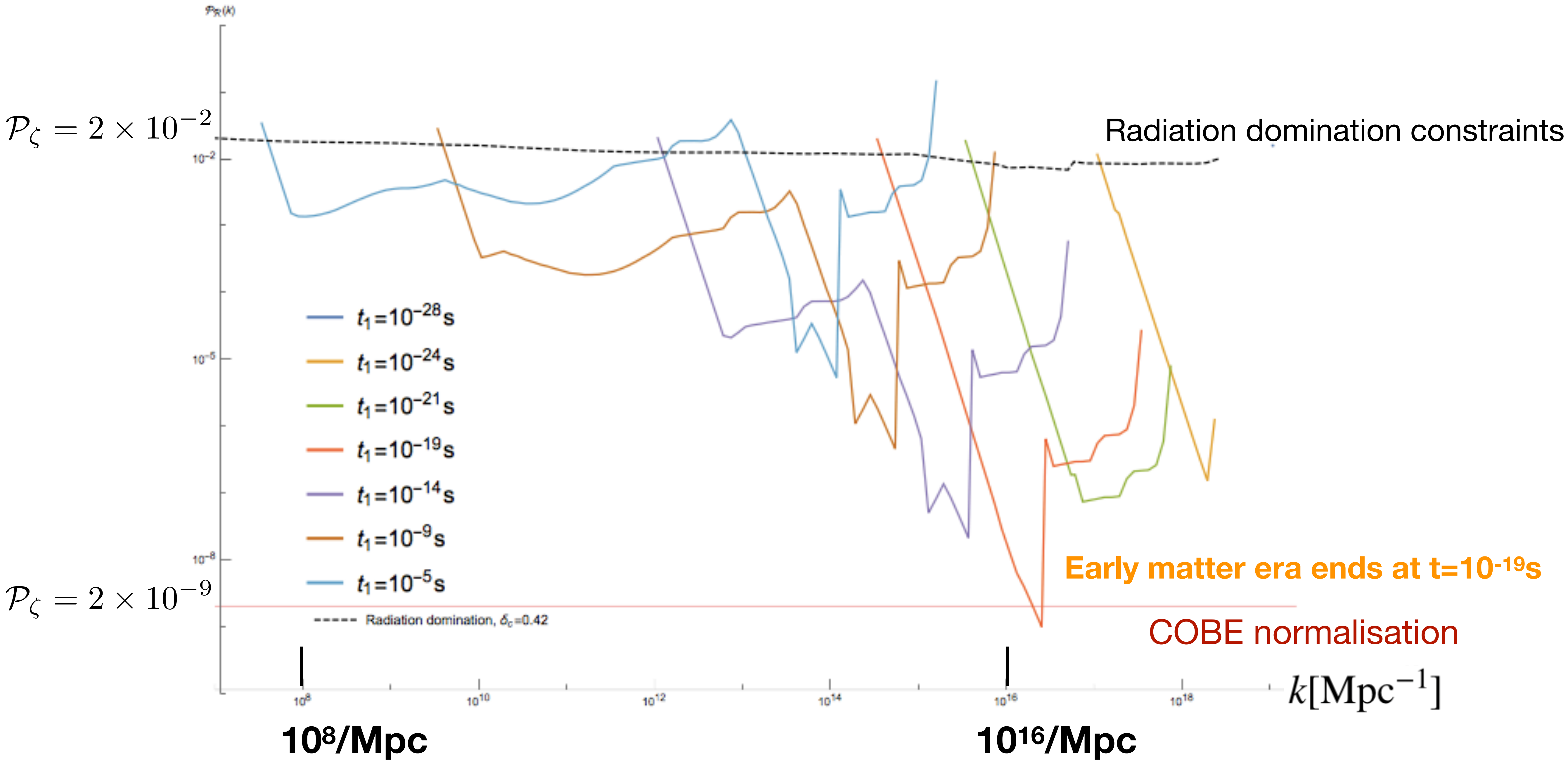
*Magee et al 2018*

# A cosmological coincidence

- The QCD transition occurs during the time when LIGO mass PBHs formed.
- The horizon mass has grown by about 50 orders of magnitude since the end of inflation.
- QCD transition: $t \sim 10^{-6}$ s, $T \sim 200$ MeV, $M \sim 1\,M_\odot$, $k \sim 10^7\ \mathrm{Mpc}^{-1}$



# Early matter domination dramatically tightens constraints



$\mathcal{P}_\zeta = 2\times10^{-2}$

Radiation domination constraints

**Early matter era ends at t=$10^{-19}$s**

$\mathcal{P}_\zeta = 2\times10^{-9}$

COBE normalisation

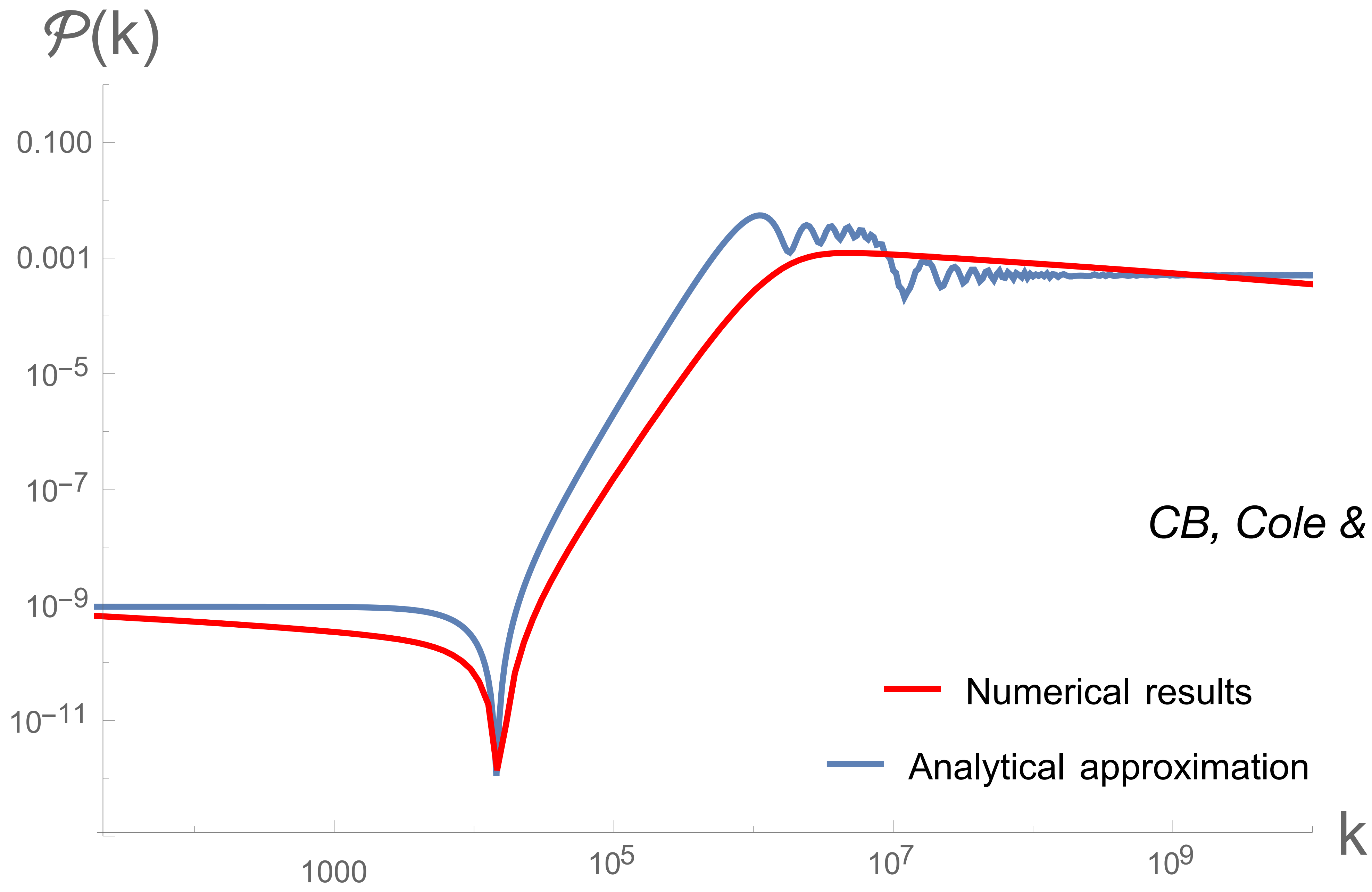
$k[\mathrm{Mpc}^{-1}]$

**$10^{8}$/Mpc**

**$10^{16}$/Mpc**

*Cole & CB '17*

# “Realistic” model with a smooth potential

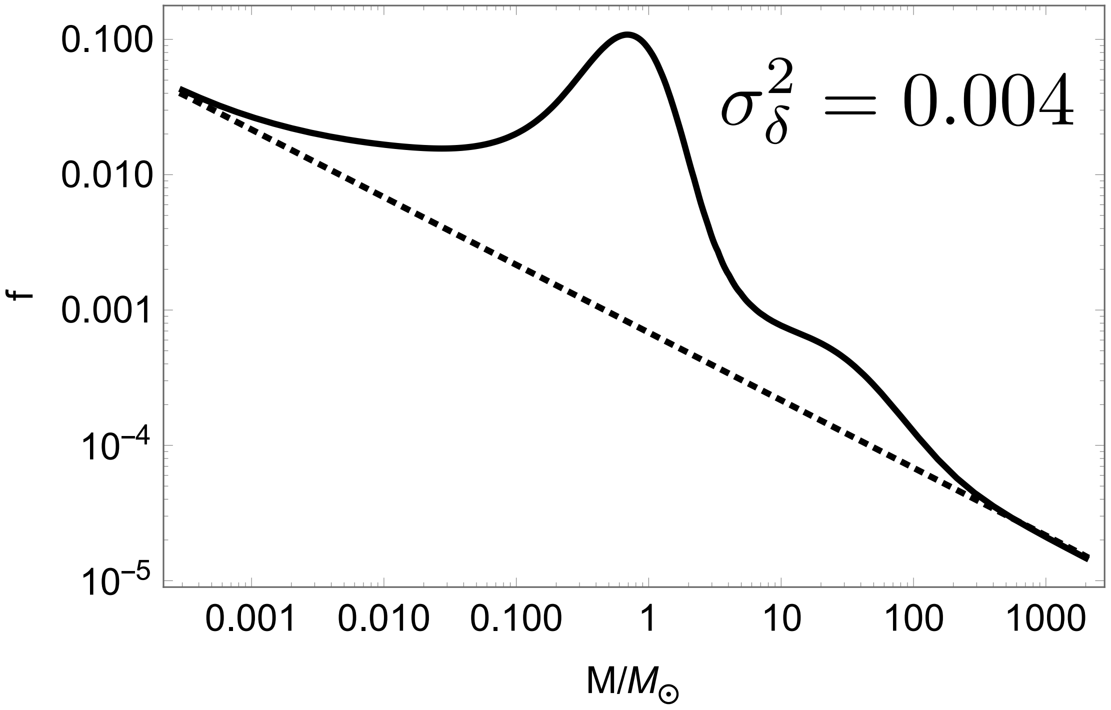


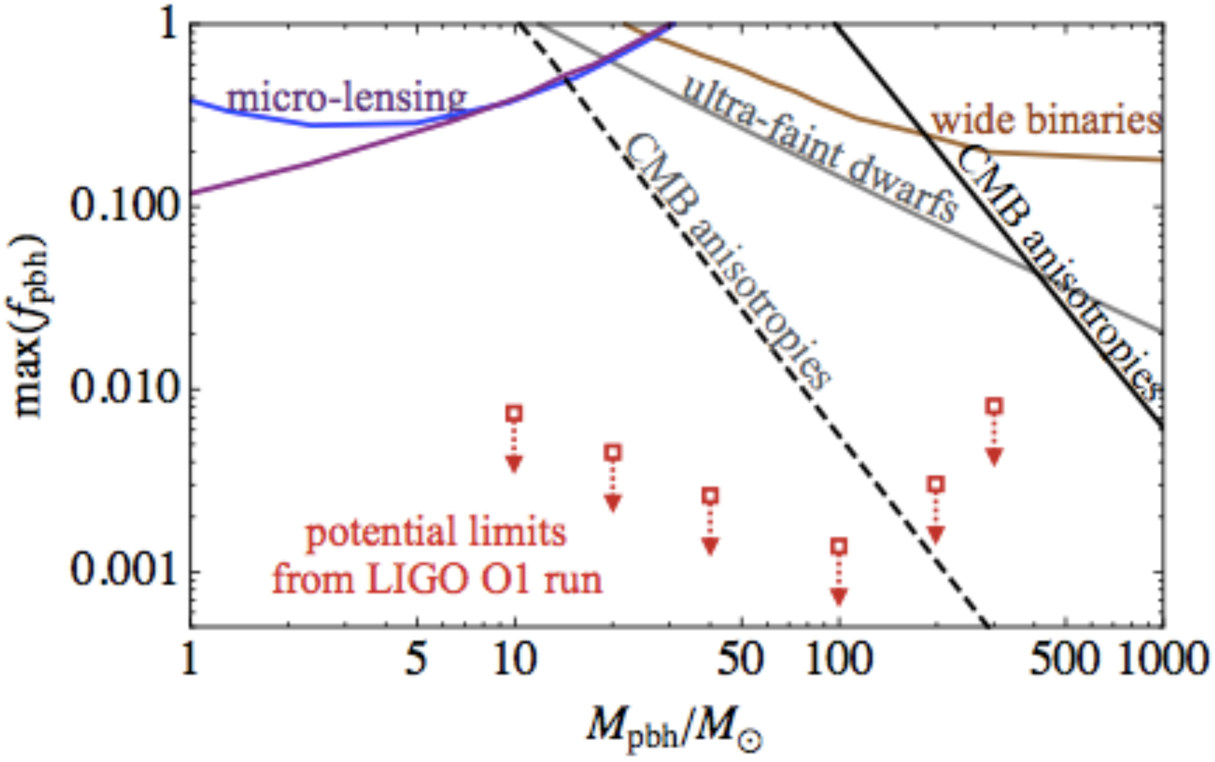
*CB, Cole & Patil 2018*

The red line is a full result from a smooth potential (*Germani & Prokopec* `17), while the red line is based on a piecewise analytic calculation.
Calculated using CPPTransport created by *David Seery 2016*

# The resultant PBH mass function

$$f(M) = \frac{1}{\Omega_{\mathrm{CDM}}} \frac{\mathrm{d}\Omega_{\mathrm{PBH}}}{\mathrm{d}\ln M_{\mathrm{H}}}$$





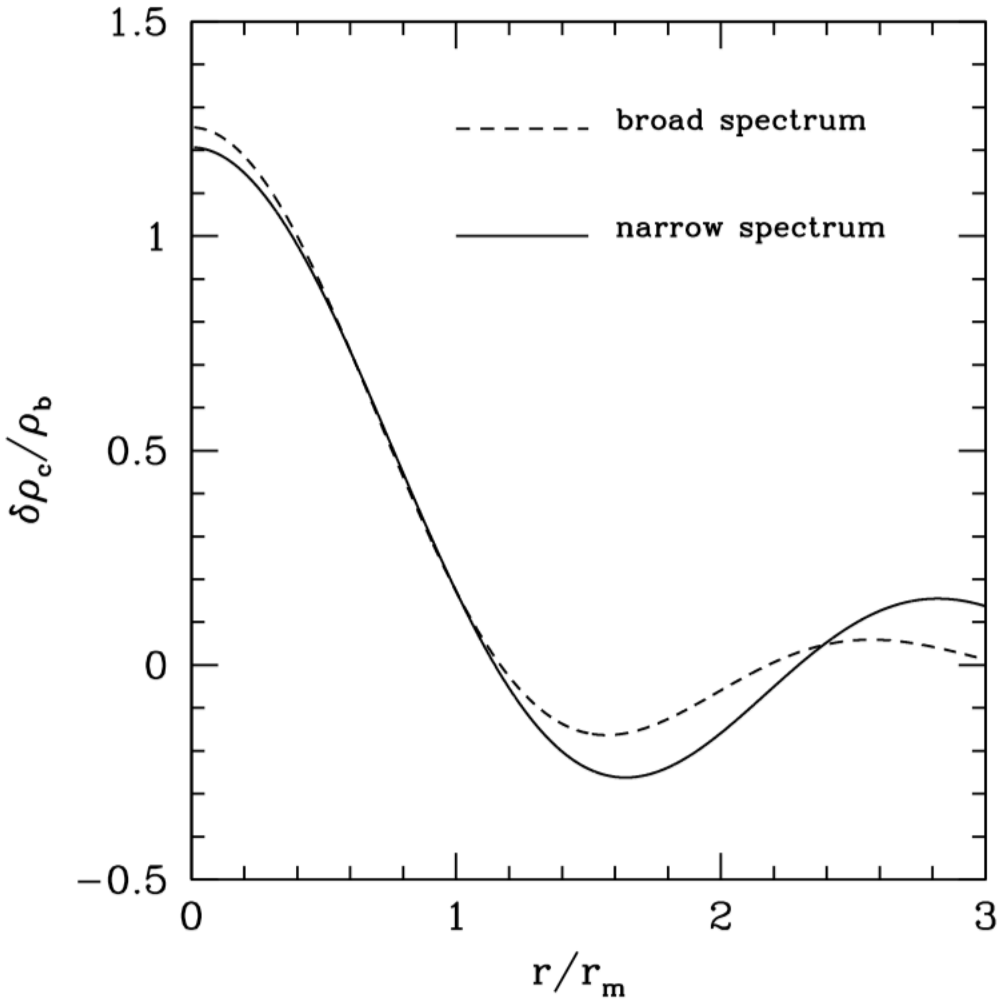
*CB, Hindmarsh, Young & Hawkins 2018*

*Haimoud et al 2017*

For the left plot, approx 10% of DM is made up of ~ solar mass PBHs and 0.1% lies in the LIGO mass range - enough to get the merger rate LIGO detects
*Sasaki et al + Haimoud et al + Chen & Huang + Raidal et al + many more*

# The density profiles are related to the power spectrum shape

Due to the 2-point correlation function which tells you the density near peaks and shows that spherical symmetry is a good approximation
(*BBKS 1986* classic paper, non-spherical effects *Kühnel & Sandstad 2016*)
The density profile does not change strongly assuming a smooth peak in the primordial power spectrum, independently of the width



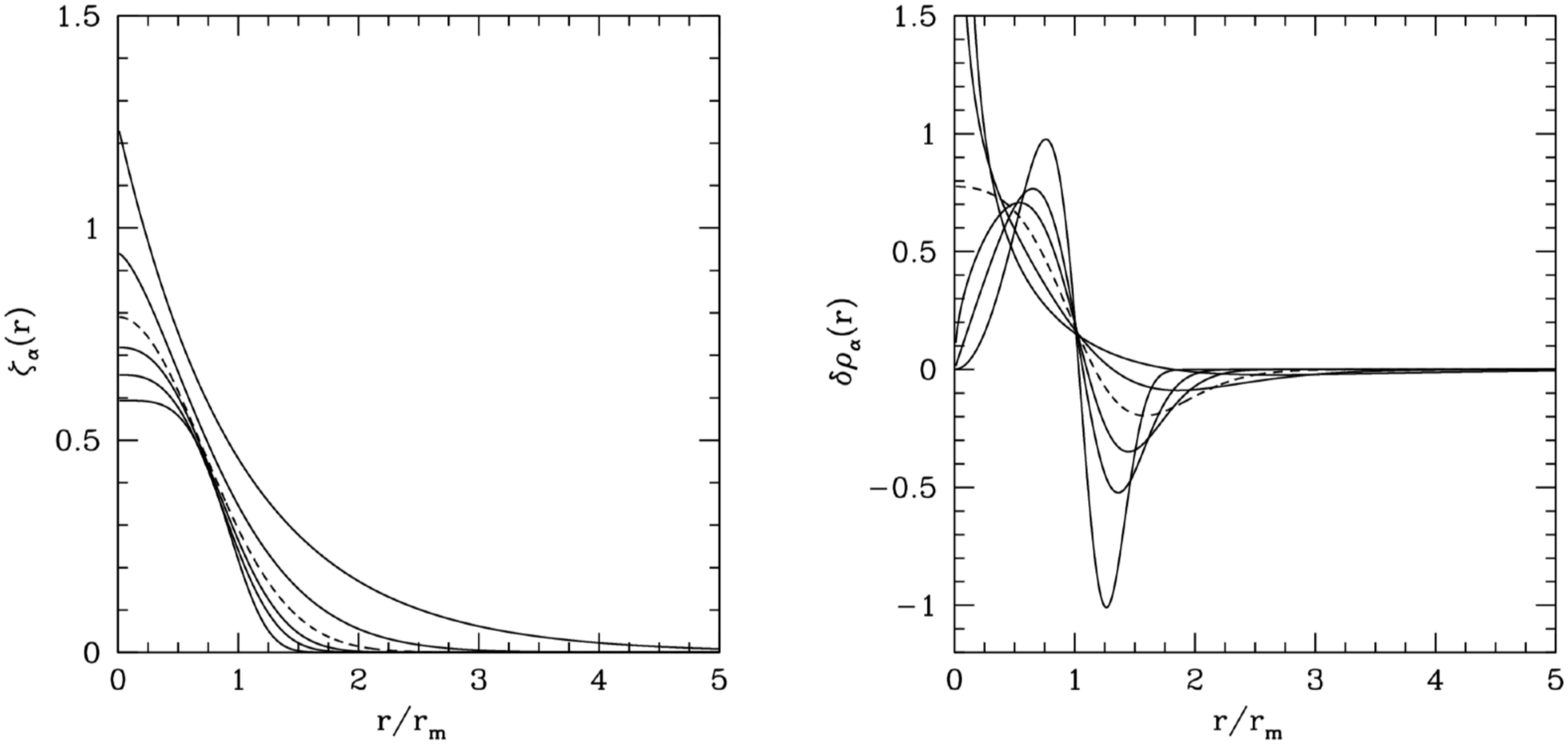
*Germani & Musco 2018*

# The density profiles are related to the power spectrum shape

Curvature perturbation profiles:
$$\zeta_\alpha(r) = \mathcal{A}\exp\left[-\left(\frac{r}{r_m}\right)^{2\alpha}\right]$$

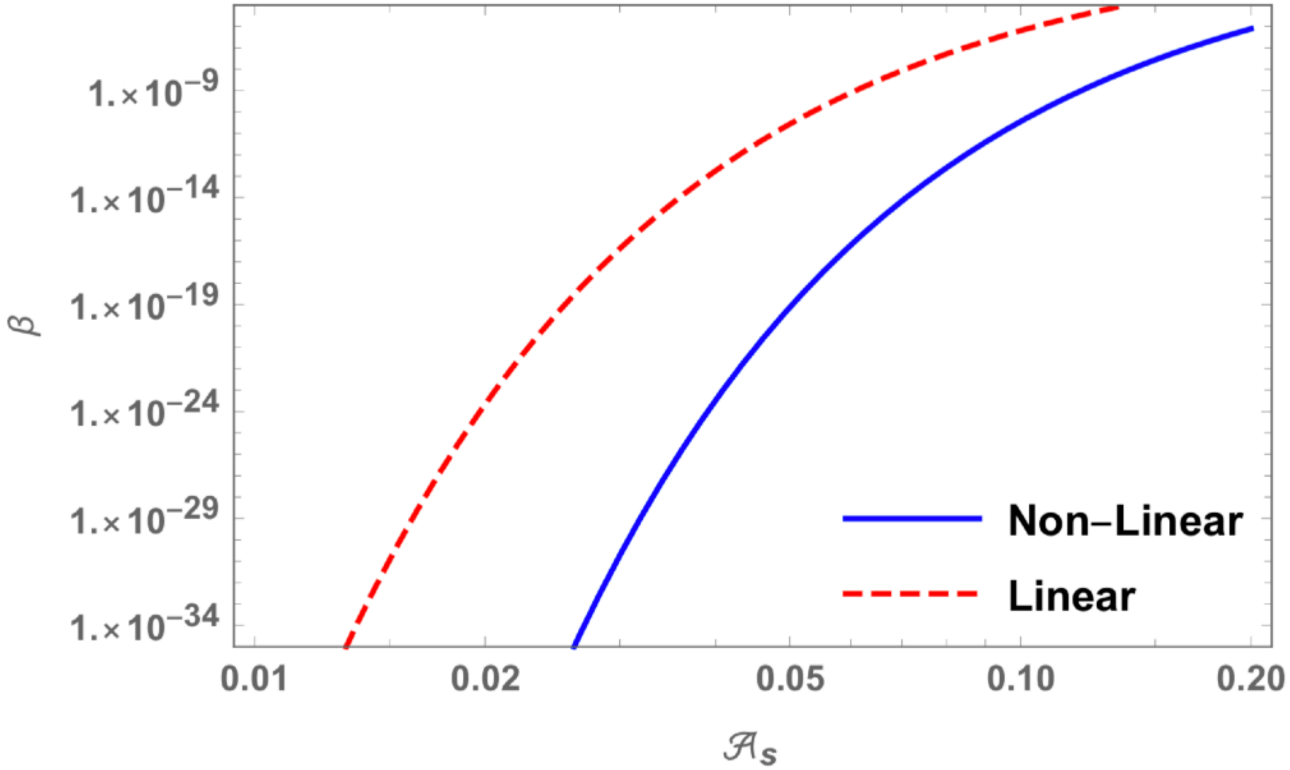
$r_m$ is the scale at which the compaction function is maximised
$$\mathcal{C}(r,t) \equiv 2\frac{M(r,t) - M_b(r,t)}{R(r,t)}$$

Profile dependence: *Musco 2018* (see also *Nakama, Harada, Polnarev & Yokoyama 2014)*



*Young, Musco, CB 2019*

# Power spectrum constraints are weakened by a factor ~ 2



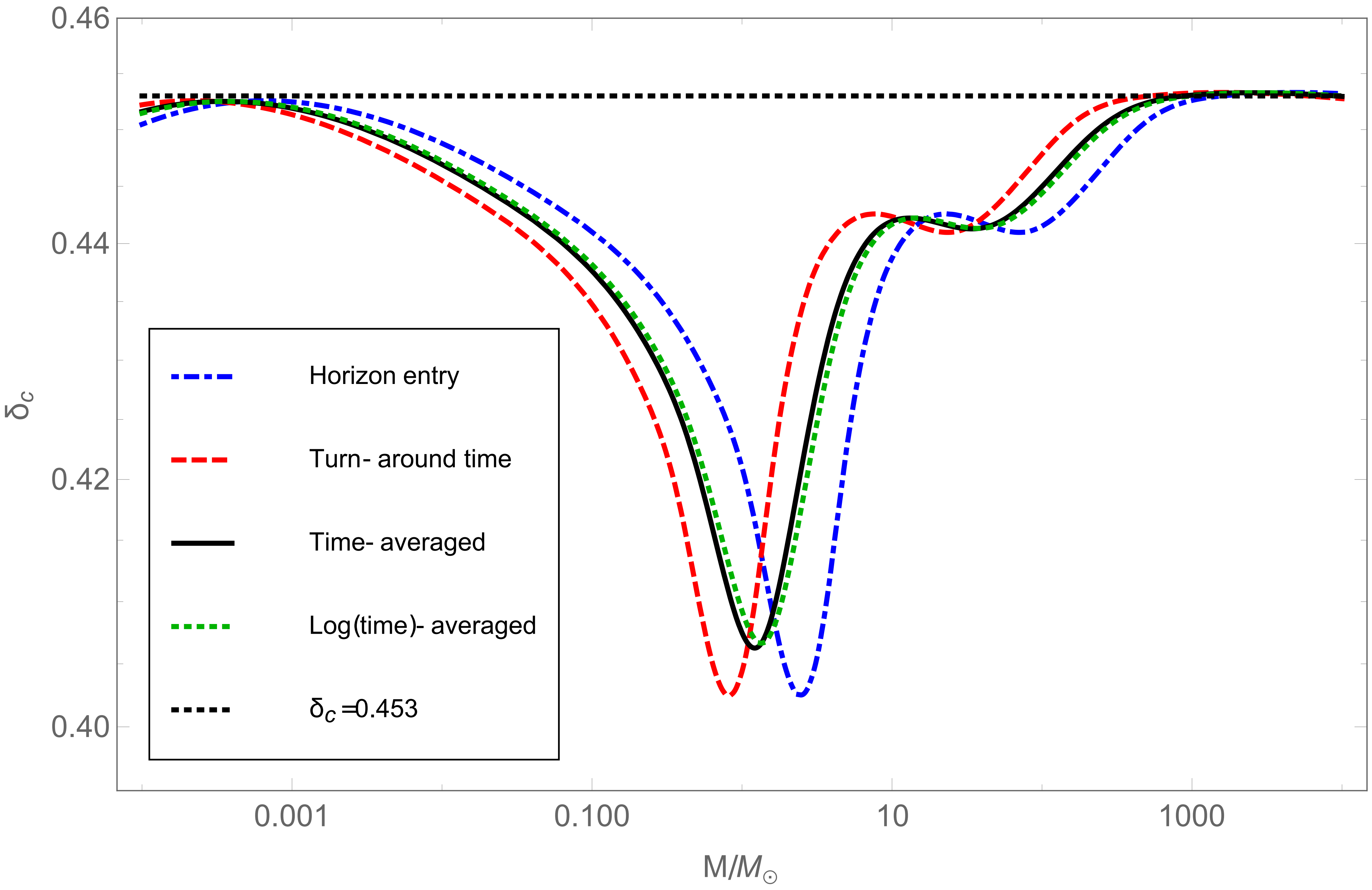
Delta function power spectrum
*Young, Musco, CB `19*

In order to generate the same number of PBHs when taking the non-linear (NL) relation into account, compared to the normal/wrong case that you use the linear relation, the power spectrum amplitude needs to increase by the ratio

$$1.5 \lesssim \frac{\mathscr{A}_{NL}}{\mathscr{A}_L} = \frac{16\left(1-\sqrt{\frac{2-3\delta_c}{2}}\right)^2}{9\delta_c^2} \lesssim 4$$

For the typical value of delta_c~0.55, power spectrum constraints are weakened by a factor of 2

# Collapse threshold vs horizon mass

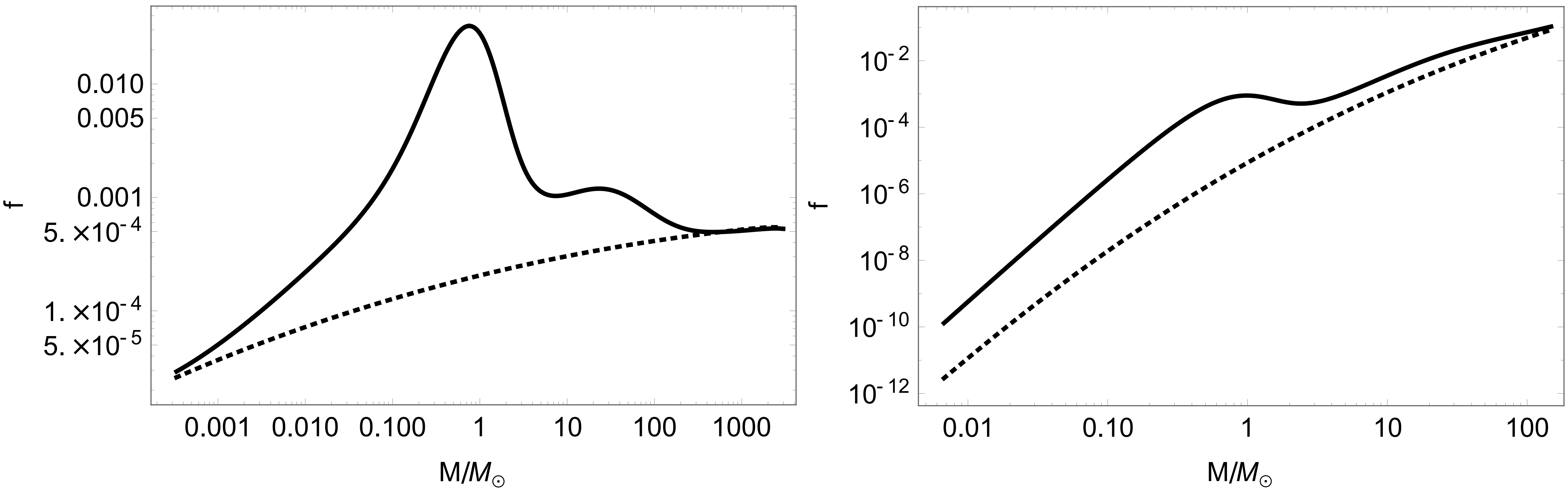


*CB, Hindmarsh, Young & Hawkins 2018*

# Varying the primordial perturbations

If the primordial power spectrum is not scale invariant on the relevant scales then the mass function changes, but a peak remains

$n_s - 1 = -0.05$ $\qquad$ $n_s - 1 = -0.2$



# The PBH merger rate

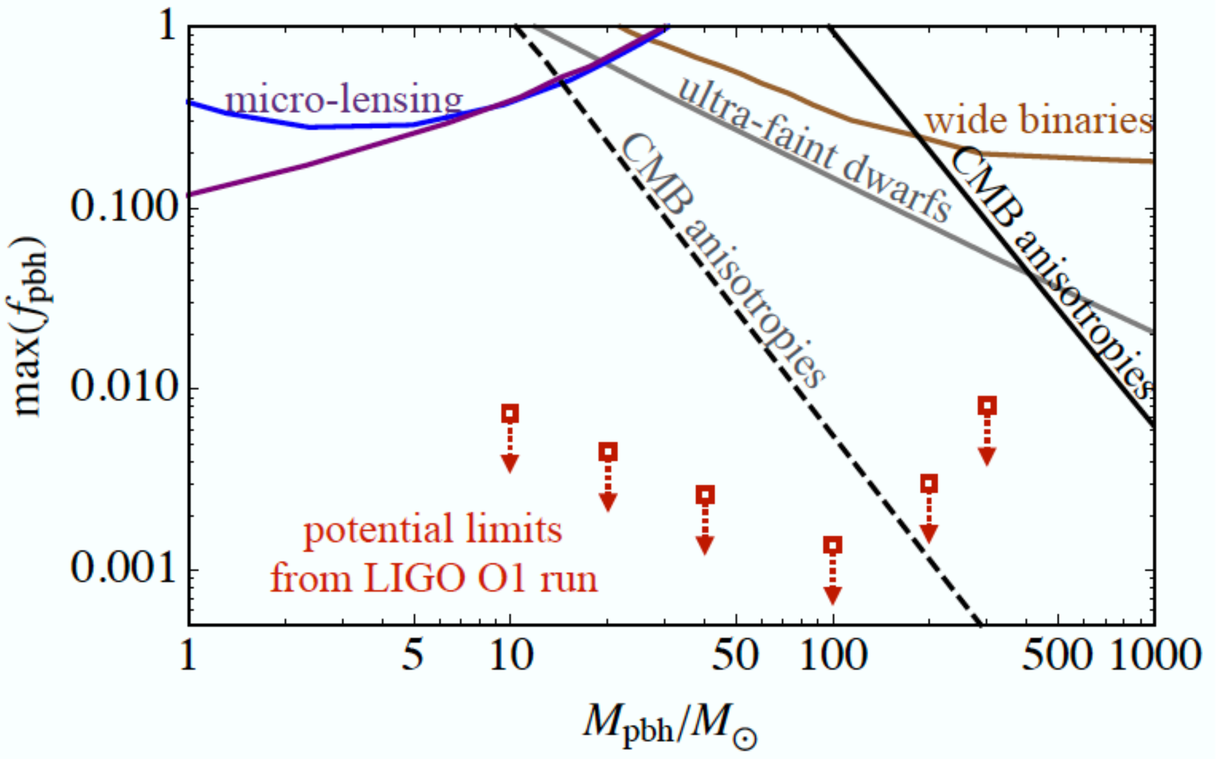


FIG. 7. Potential upper bounds on the fraction of dark matter in PBHs as a function of their mass, derived in this paper (red arrows), and assuming a narrow PBH mass function. These bounds need to be confirmed by numerical simulations. For comparison we also show the microlensing limits from the EROS [21] (*purple*) and MACHO [20] (*blue*) collaborations (see Ref. [74] for caveats and Ref. [32] for a discussion of uncertainties), limits from wide Galactic binaries [22], ultra-faint dwarf galaxies [25], and CMB anisotropies [24].

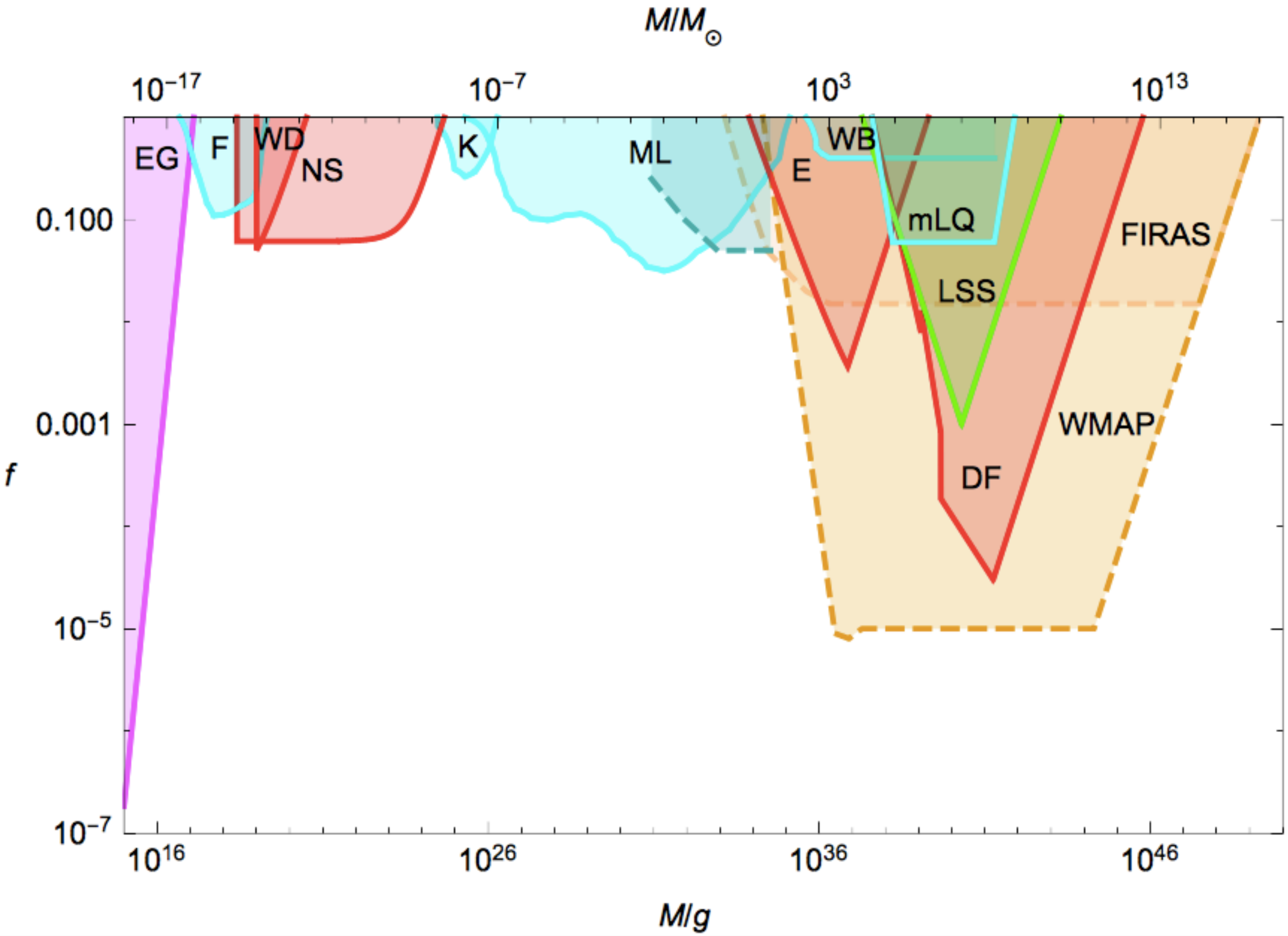
*Haimoud et al 2017*

- Caveats:

1. Assumes a monochromatic mass spectrum
2. Assumes PBHs are randomly placed initially
3. Assumes BH binaries are not disrupted
4. Neglects accretion around the BHs

First cosmological evolution simulations
*Raidal, Spethmann, Vaskonen & Veermäe `18*

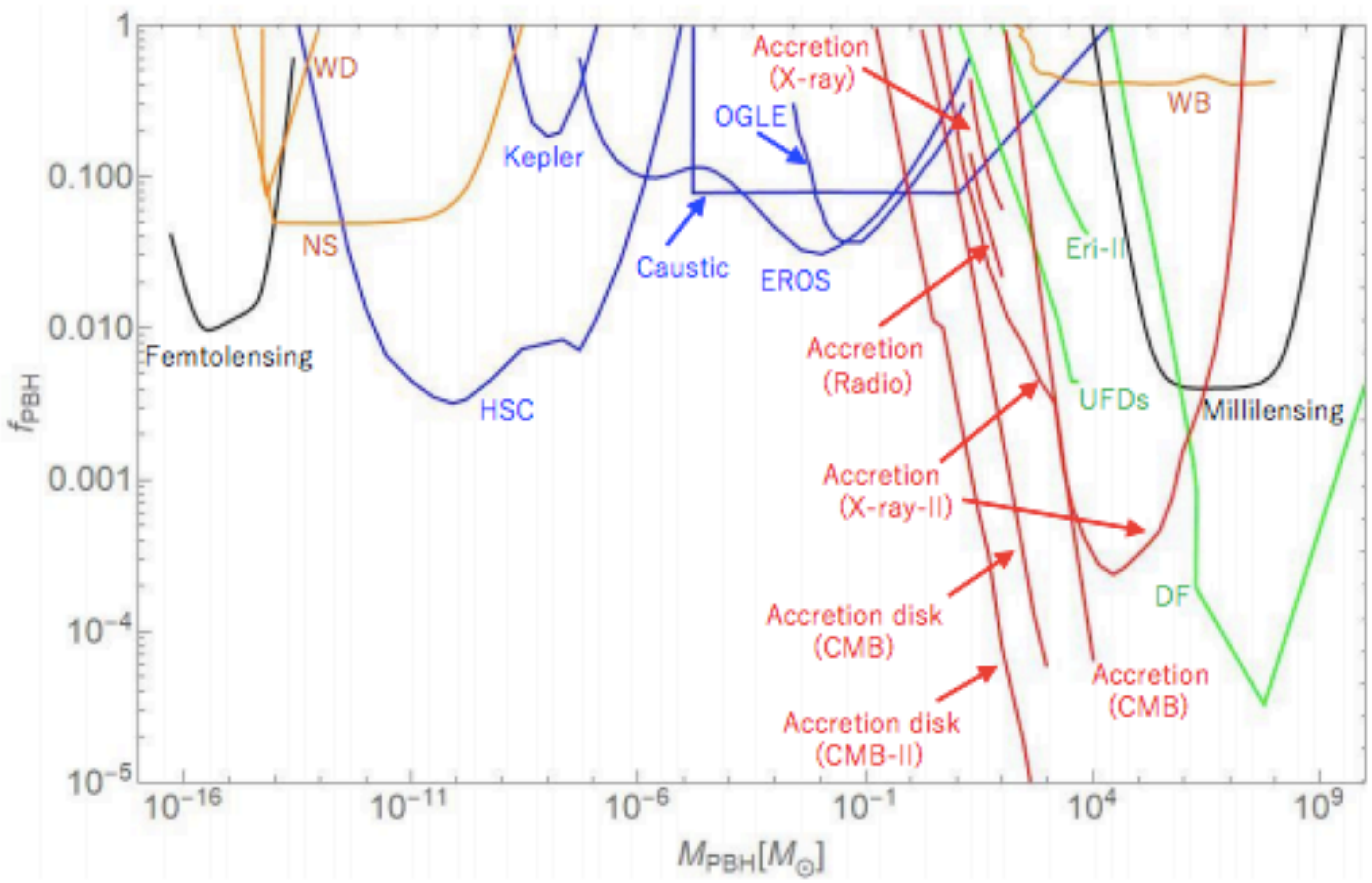
# Allowed fraction of PBHs in DM



*Carr, Kuehnel & Sandstad 2017*

*See also Barack et al 2018; Black holes, gravitational waves and fundamental physics: a roadmap*

# (Disputed) observational constraints



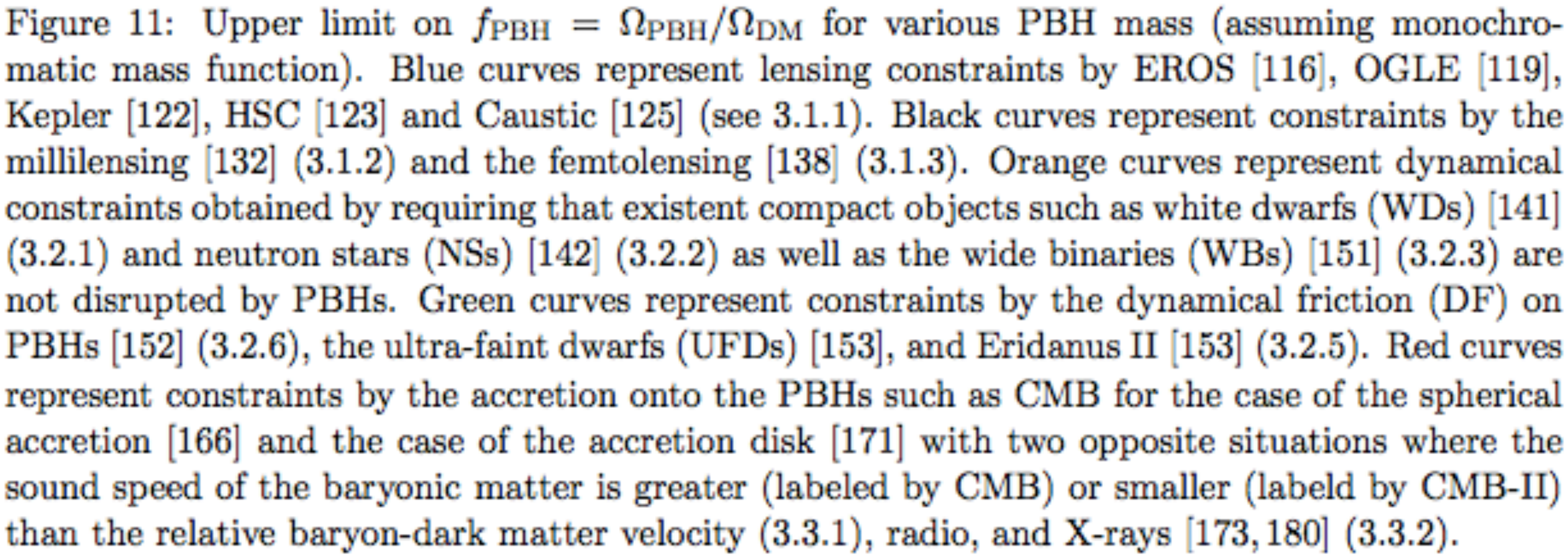
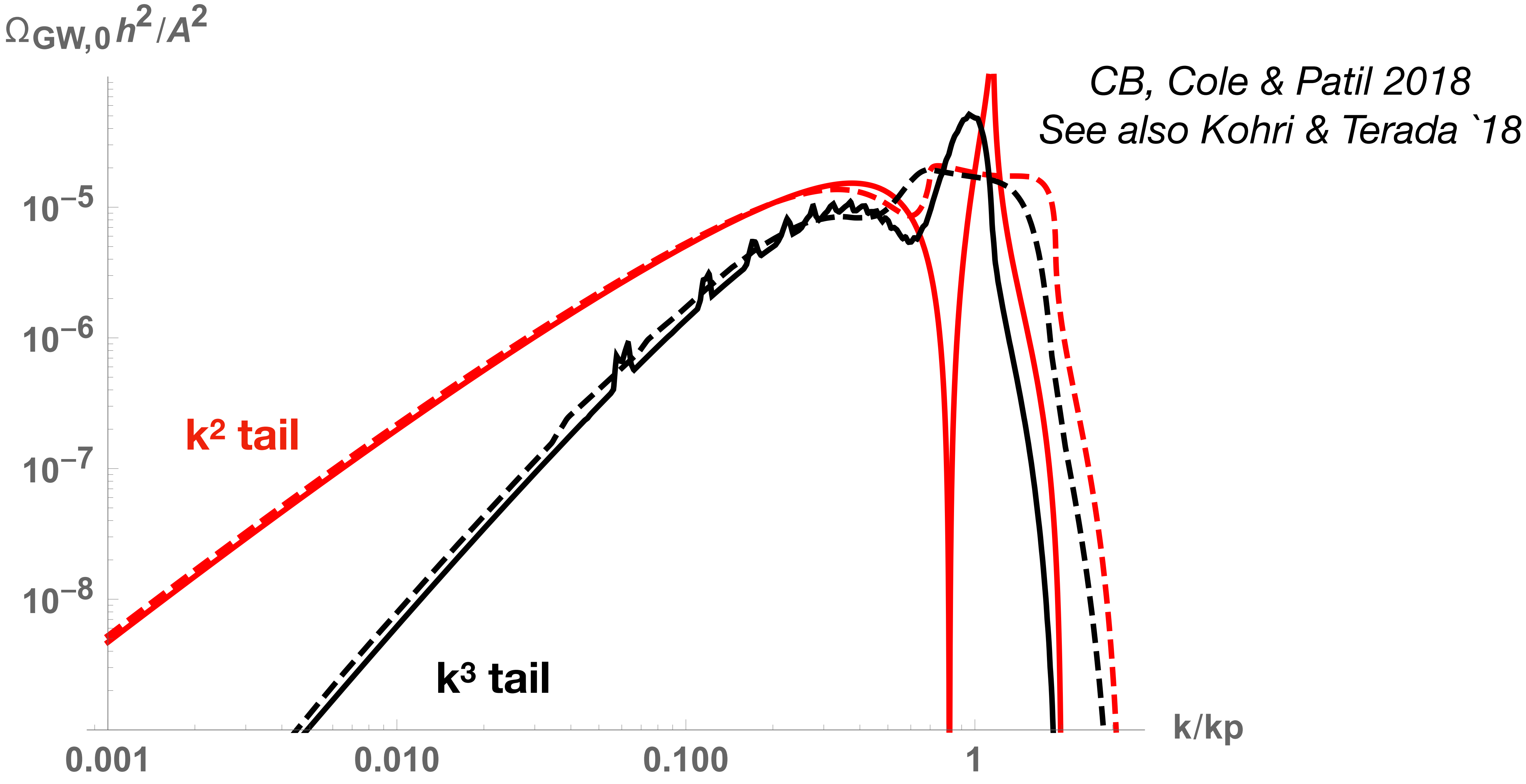


Figure 11: Upper limit on $f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$ for various PBH mass (assuming monochromatic mass function). Blue curves represent lensing constraints by EROS [116], OGLE [119], Kepler [122], HSC [123] and Caustic [125] (see 3.1.1). Black curves represent constraints by the millilensing [132] (3.1.2) and the femtolensing [138] (3.1.3). Orange curves represent dynamical constraints obtained by requiring that existent compact objects such as white dwarfs (WDs) [141] (3.2.1) and neutron stars (NSs) [142] (3.2.2) as well as the wide binaries (WBs) [151] (3.2.3) are not disrupted by PBHs. Green curves represent constraints by the dynamical friction (DF) on PBHs [152] (3.2.6), the ultra-faint dwarfs (UFDs) [153], and Eridanus II [153] (3.2.5). Red curves represent constraints by the accretion onto the PBHs such as CMB for the case of the spherical accretion [166] and the case of the accretion disk [171] with two opposite situations where the sound speed of the baryonic matter is greater (labeled by CMB) or smaller (labeld by CMB-II) than the relative baryon-dark matter velocity (3.3.1), radio, and X-rays [173, 180] (3.3.2).

**Sasaki et al 2017 Review**

# GW spectrum



Red line - delta function scalar power spectrum
Black line - $k^4$ scalar power spectrum with cut off
Surprisingly, the delta function scalar power spectrum has a broader GW spectrum
This is unphysical and a warning against using delta function power spectra