The case for, and against, solar mass primordial black holes as dark matter

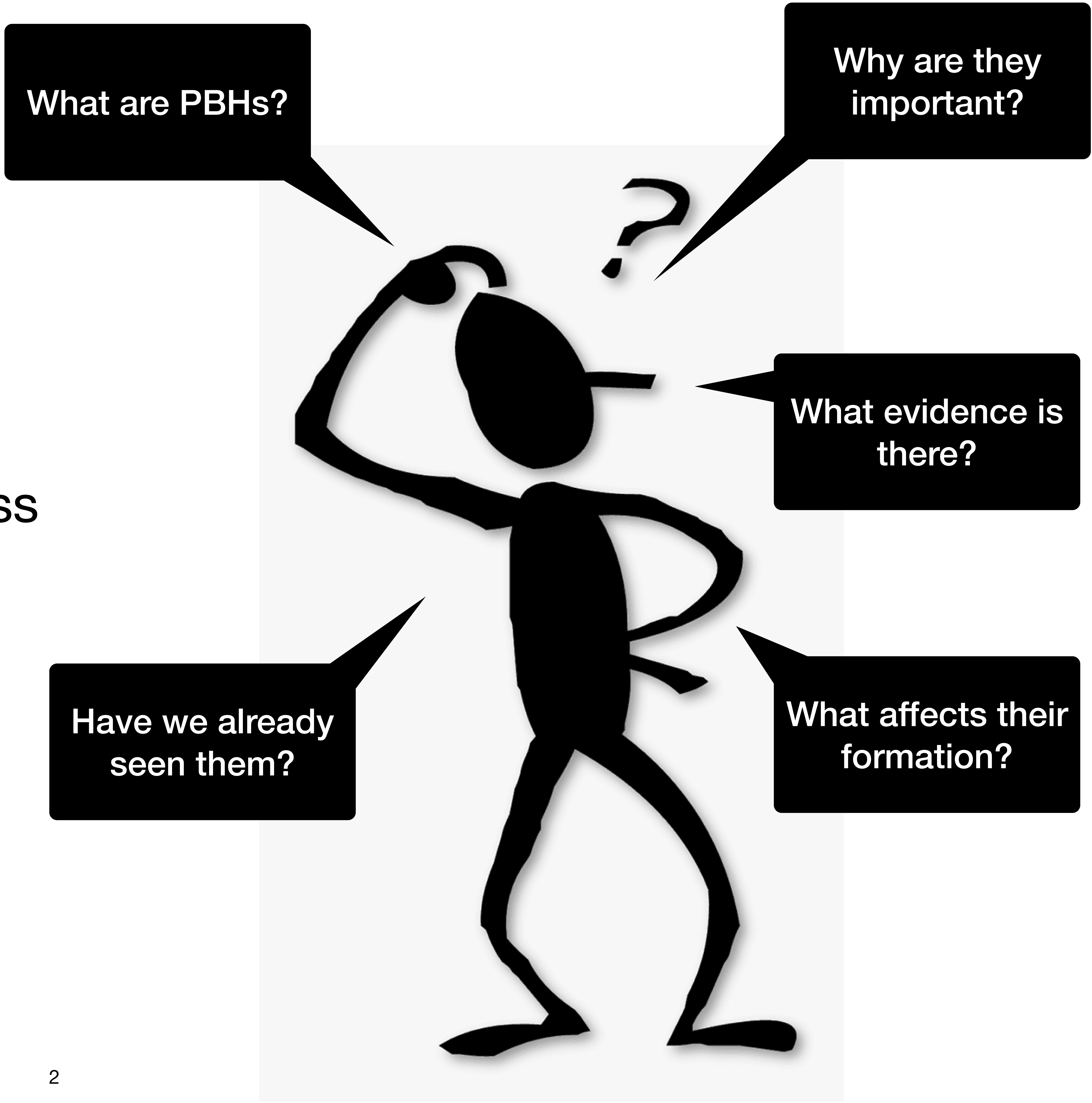
Rencontres de Blois

What does AI think a PBH looks like?

Sam Young, University of Leiden, 18.05.2023

Talk Overview

1. Introduction to dark matter and primordial black holes (PBHs)
2. Evidence for and against solar mass PBHs
3. The formation of solar mass PBHs
4. Summary

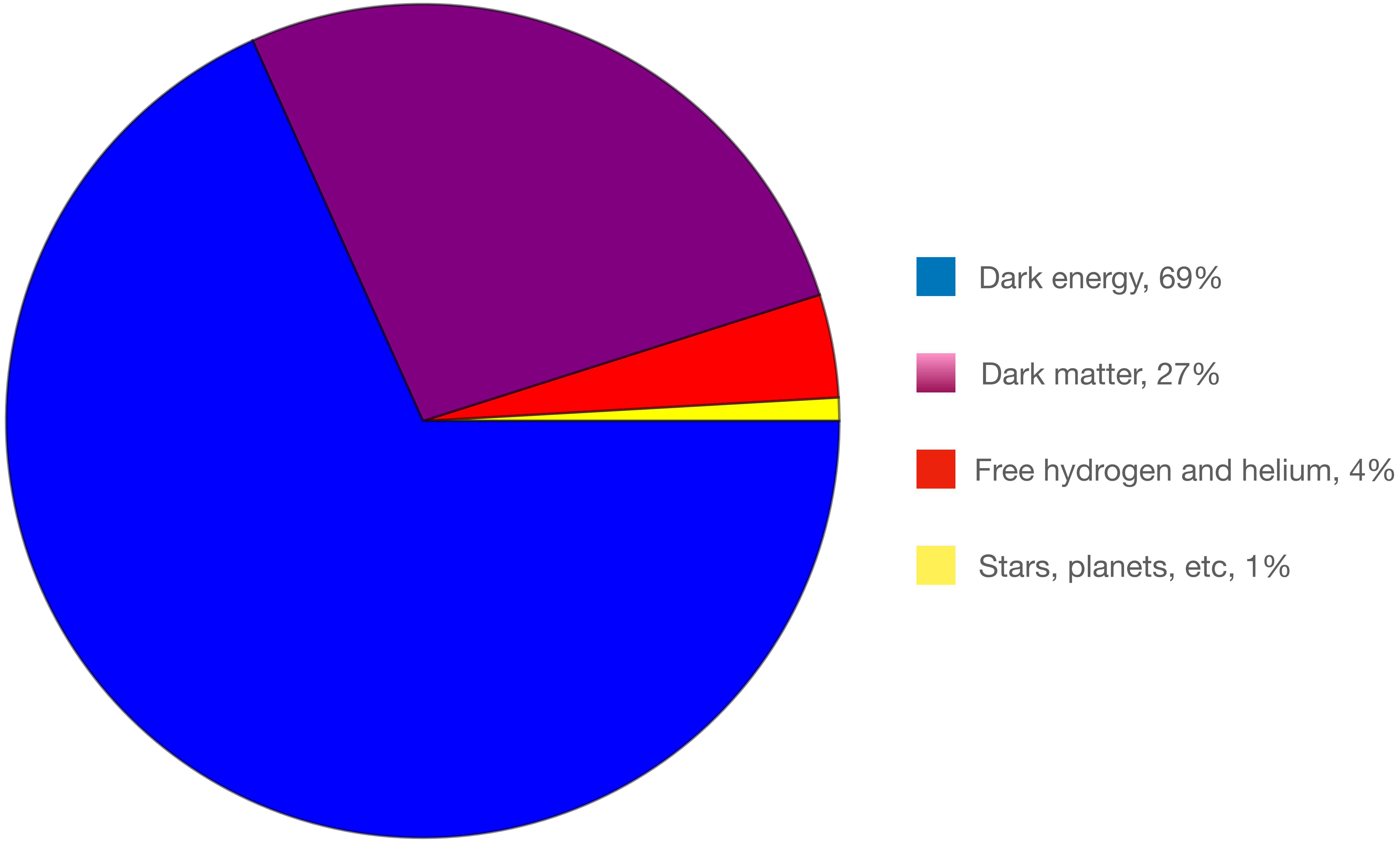


1. Introduction to dark matter and primordial black holes

What are primordial black holes?
What is dark matter?

What is the Universe made of?

What is dark matter?



Could dark matter be made of black holes?

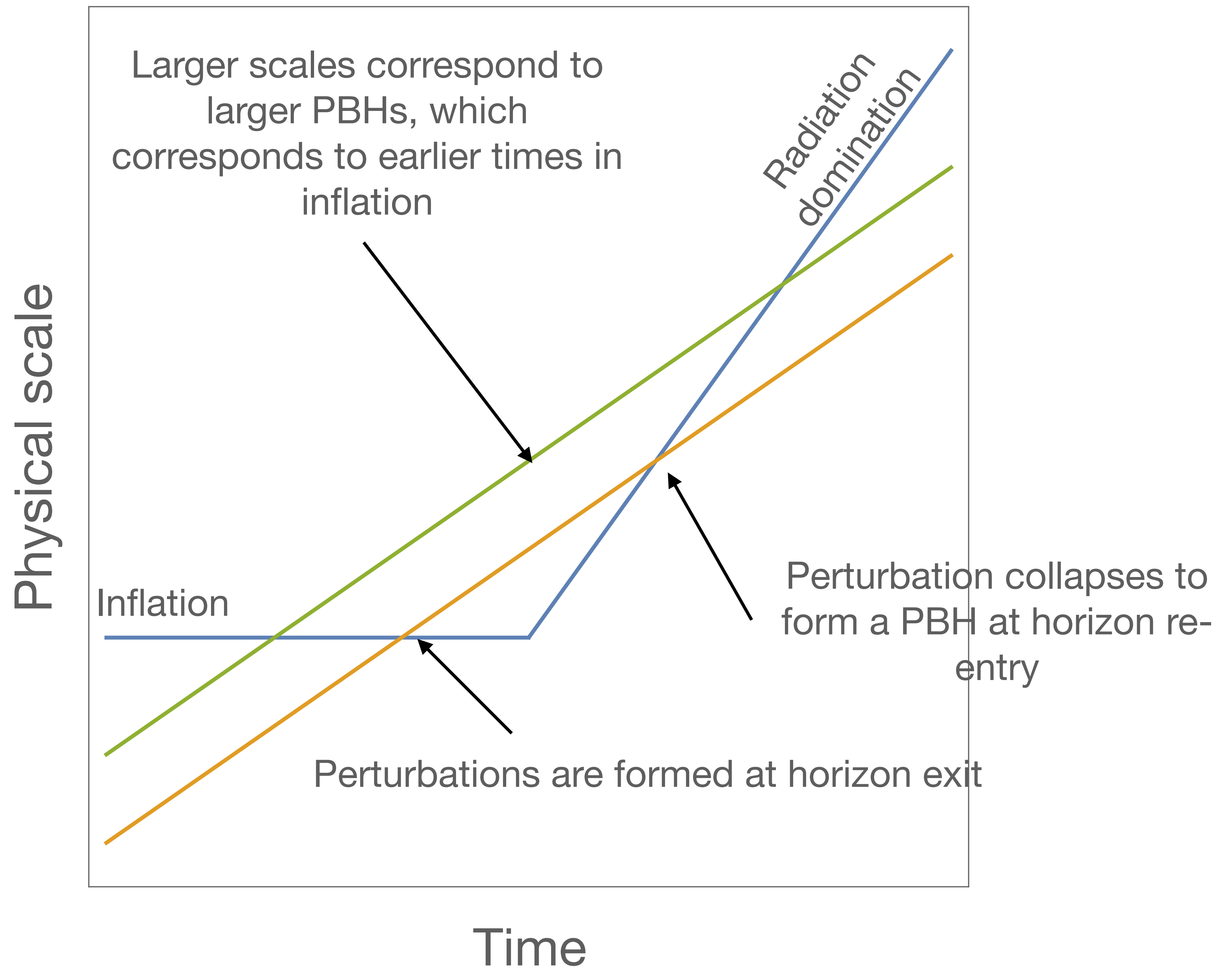
What if dark matter is not a particle at all?

- What we know about cold dark matter (its well named):
  - Its cold: $v << c$
  - Its dark: no (or weakly) interacts with electromagnetism. This also means dark matter forms potential wells earlier than baryonic matter*, which later falls into these wells to form galaxies
  - Its matter: it appears to gravitate like matter
- An abundance of black holes would tick all the boxes
- But where would these BHs come from?
  - Forming a BH requires extremely high densities — the cores of dying stars
  - There is another place (time) with high enough density: the early universe

What are PBHs?

Black holes formed in the early universe

- First proposed in the late '60s (Novikov and Zel'dovic) and early 70s (Hawking and Carr)
- Since '70s, many formation mechanisms have been proposed
    - Cosmic string loops
    - Bubble collisions
    - Phase transitions
    - Collapse of primordial perturbations
- PBHs form (roughly) at horizon entry if overdensity is large enough, above some threshold value $\delta_c \sim 0.5$
    - Approximately with the horizon mass
- Larger mass PBHs form at later times from larger scale perturbations
- They can form with almost any mass*
- PBHs are **rare** in the early universe
    - Because its the amount of matter deep in the radiation dominated era



*Hawking was initially looking for an excuse to consider low mass black holes, which would emit more Hawking radiation

Why are PBHs interesting?

Why do I study them?

- PBHs are a unique probe of the small-scale early universe (see next slide)
  - Its hopeless to try and look at e.g. the Solar System and try to work out what was there 13.7 billion years ago
- We may have seen them already: LIGO/Virgo black holes, MaCHOs, GRBs, SMBHs…
- Their presence may explain a lot of unresolved problems in cosmology
  - Nature of dark matter, the early formation of SMBHs, missing satellites, reheating, baryogenesis…
    - (some are more "speculative" than others…)
  - And my personal favourite: Planet 9
  - (Or maybe not…)

Cosmic conundra explained by primordial black holes, 1906.08217 Carr, Clesse, Garcia-Bellido, Kuhnel

My favourite plot:
What if planet 9 is a primordial black hole?

Scholtz&Unwin (arXiv:1909.11090)

SUPPLEMENTARY MATERIAL

A. SIZE OF THE PBH

The Schwarzschild radius of a black hole is given by

$$r_{\rm BH} = \frac{2GM_{\rm BH}}{c^2} \simeq 4.5{\rm cm}\left(\frac{M_{\rm BH}}{5M_\oplus}\right) . \qquad (15)$$

In Figure 1 we provide an exact scale image of a $5M_\oplus$ PBH. The associated DM halo however extends to the stripping radius $r_{t,\odot} \sim 8$AU, this would imply a DM halo which extends roughly the distance from Earth to Saturn (both in real life and relative to the image).

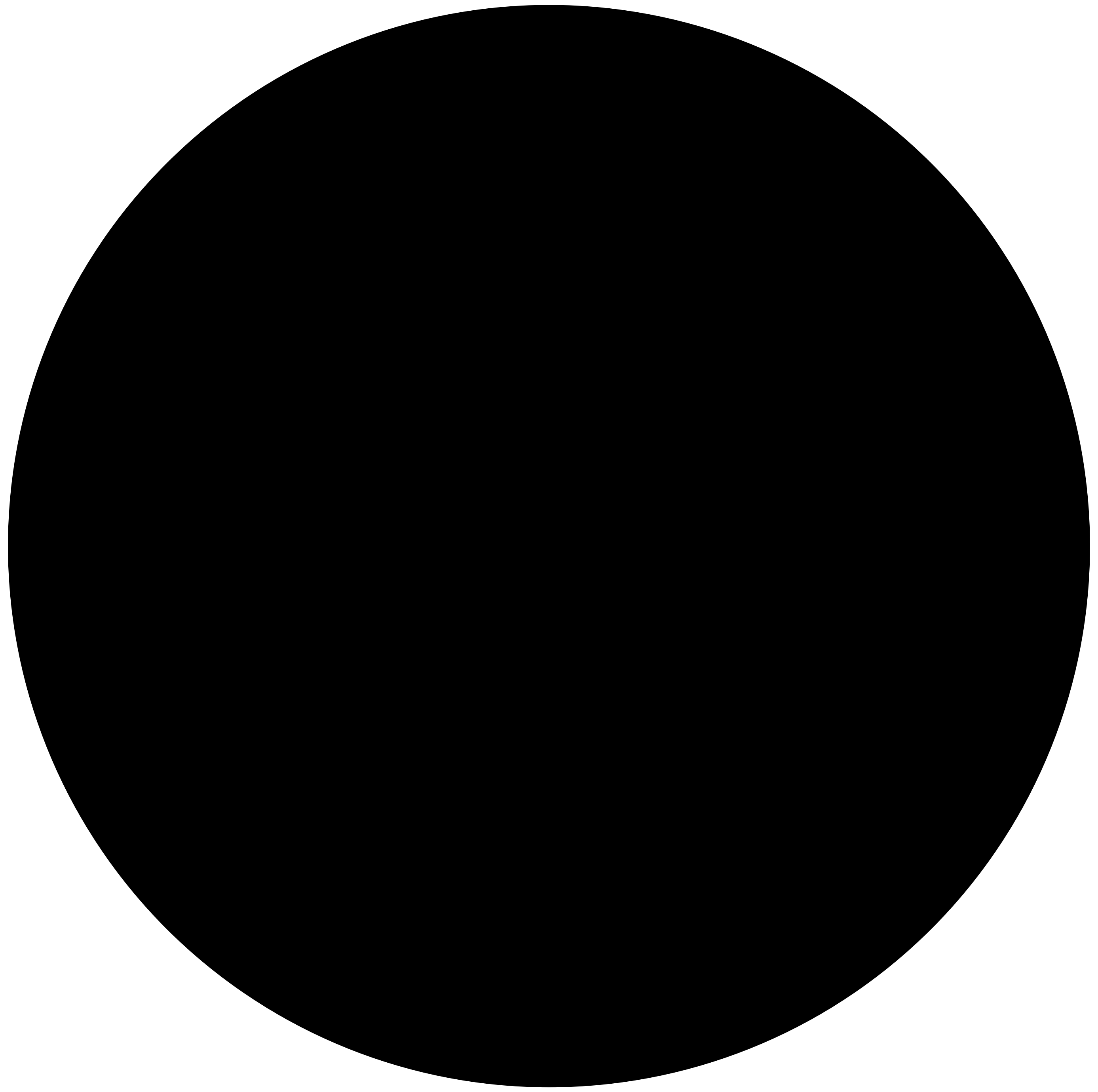


FIG. 1. Exact scale (1:1) illustration of a $5M_\oplus$ PBH. Note that a $10M_\oplus$ PBH is roughly the size of a ten pin bowling ball.

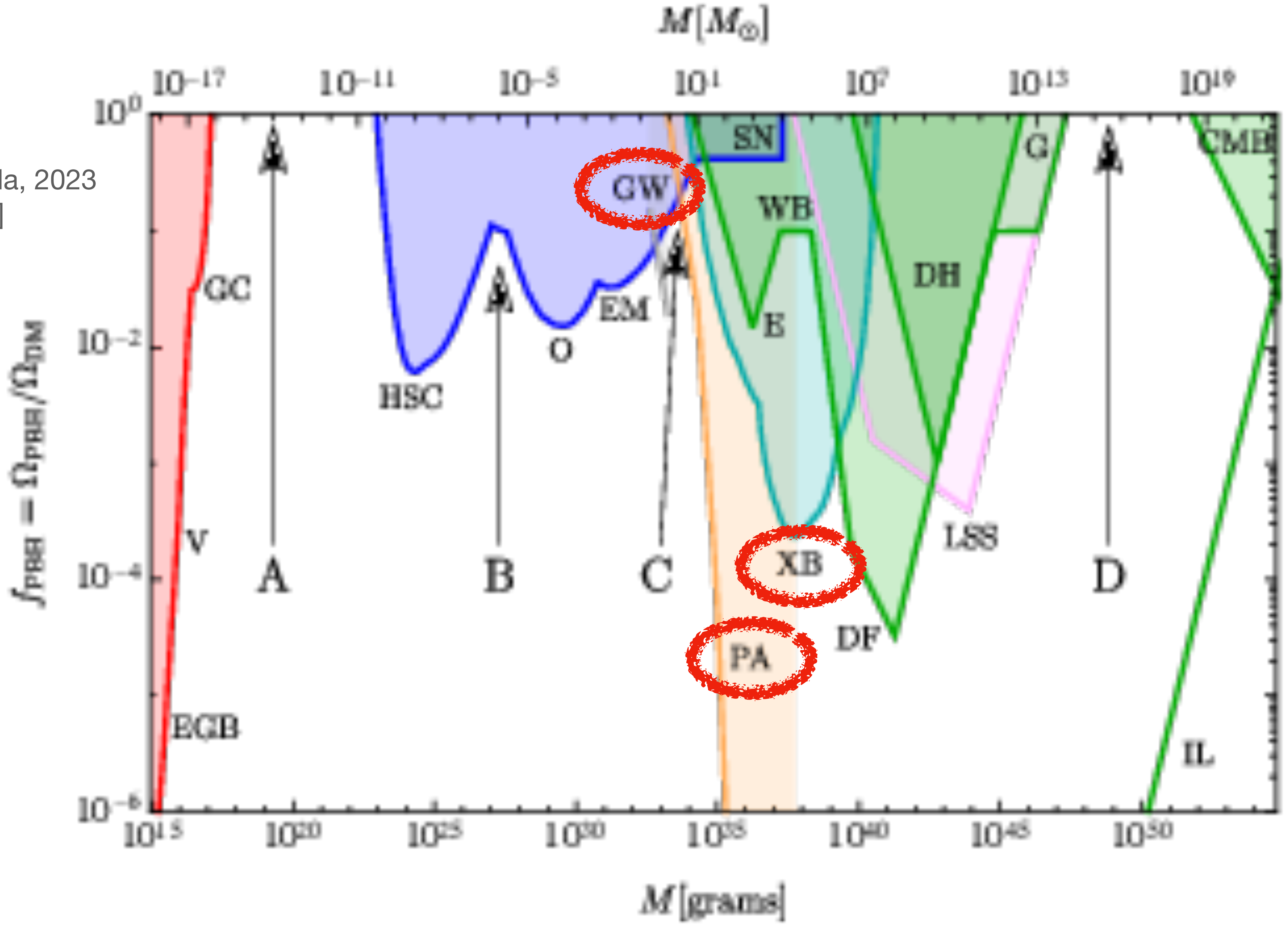
2. Evidence for and against solar mass PBHs

Do we have any evidence for their existence?
Have we seen anything that might rule them out?

Evidence against PBHs

Bad news first: constraints on the abundance

Escriva, Kuhnel, Tada, 2023 [2211.05767]



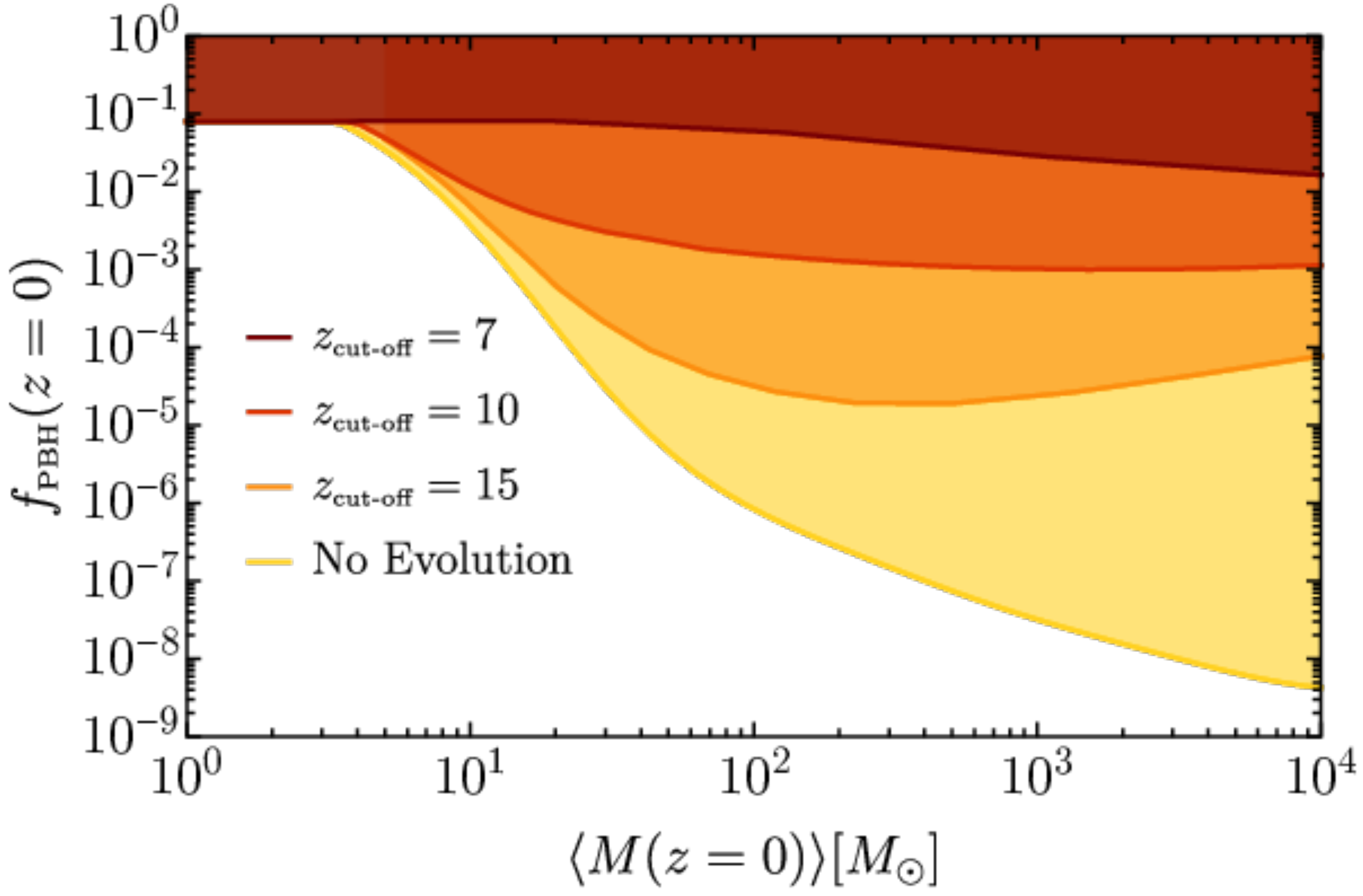
Methods to constrain the PBH abundance

Big Bang nucleosynthesis and Lithium-7 abundance, entropy in the CMB, CMB spectral distortions, CMB anisotropies, extragalactic γ-ray background, galactic γ-ray background, galactic positrons and antiprotons, extragalactic antiprotons, annihilation-line radiation, emission of other particles, deionisation and the 21cm signal, γ-ray bursts and photosphere effects, high energy cosmic ray showers, PBH explosions, Higgs instability, Planck mass relics, Femto- and picolensing, microlensing of stars, microlensing of supernovae, micro- and millilensing of quasars, microlensing of Mira variables, pulsars and fast radio bursts, collisions, disruption of neutron stars and white dwarves, disruption of wide binaries, disruption of globular clusters and dwarf galaxies, disc heating, tidal streams, dynamical friction, intergalactic PBHs, tidal distortion of galaxies, Lyman-α systems, galaxies and clusters, first baryonic clouds, PBH clusters, accretion and X-rays, gravitational wave background, LIGO/Virgo observations of merging black holes, second order tensor perturbations/induced GW background…

Evidence against PBHs

Caveats on the constraints

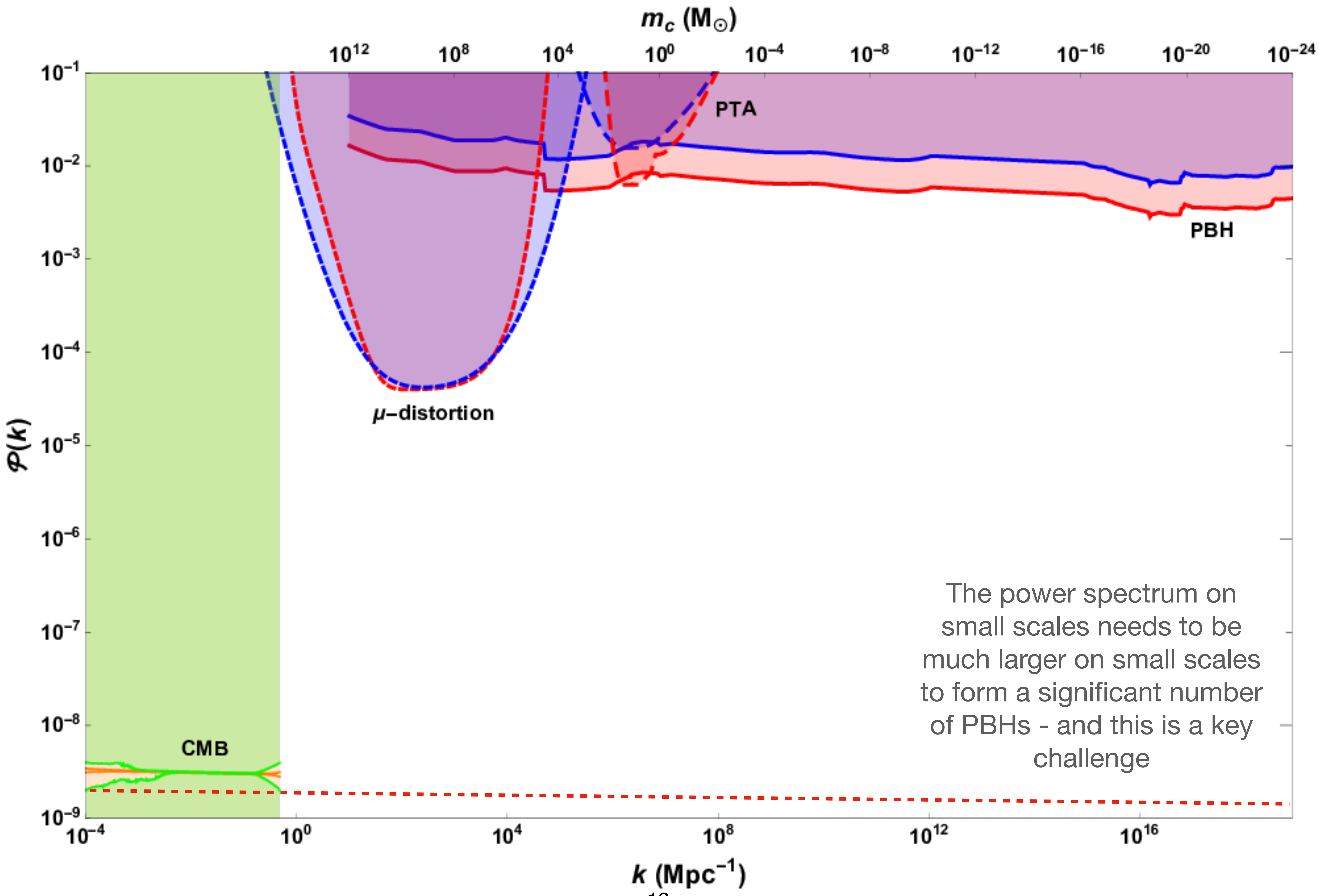
- Constraints typically assume a monochromatic mass function and no clustering
- Uncertainties in how PBHs accrete lead to large uncertainties in the constraints
  - e.g. accretion can be cut off as PBHs fall into potential wells
  - Constraints can weaken by orders of magnitude
- GW constraints assume binary PBHs forms in the early universe, and then merge ~13.7 Gyr later
  - And that NOTHING ELSE happens to it between those times



Escriva, Kuhnel, Tada, 2023
[2211.05767]

"Not just nails in a coffin"

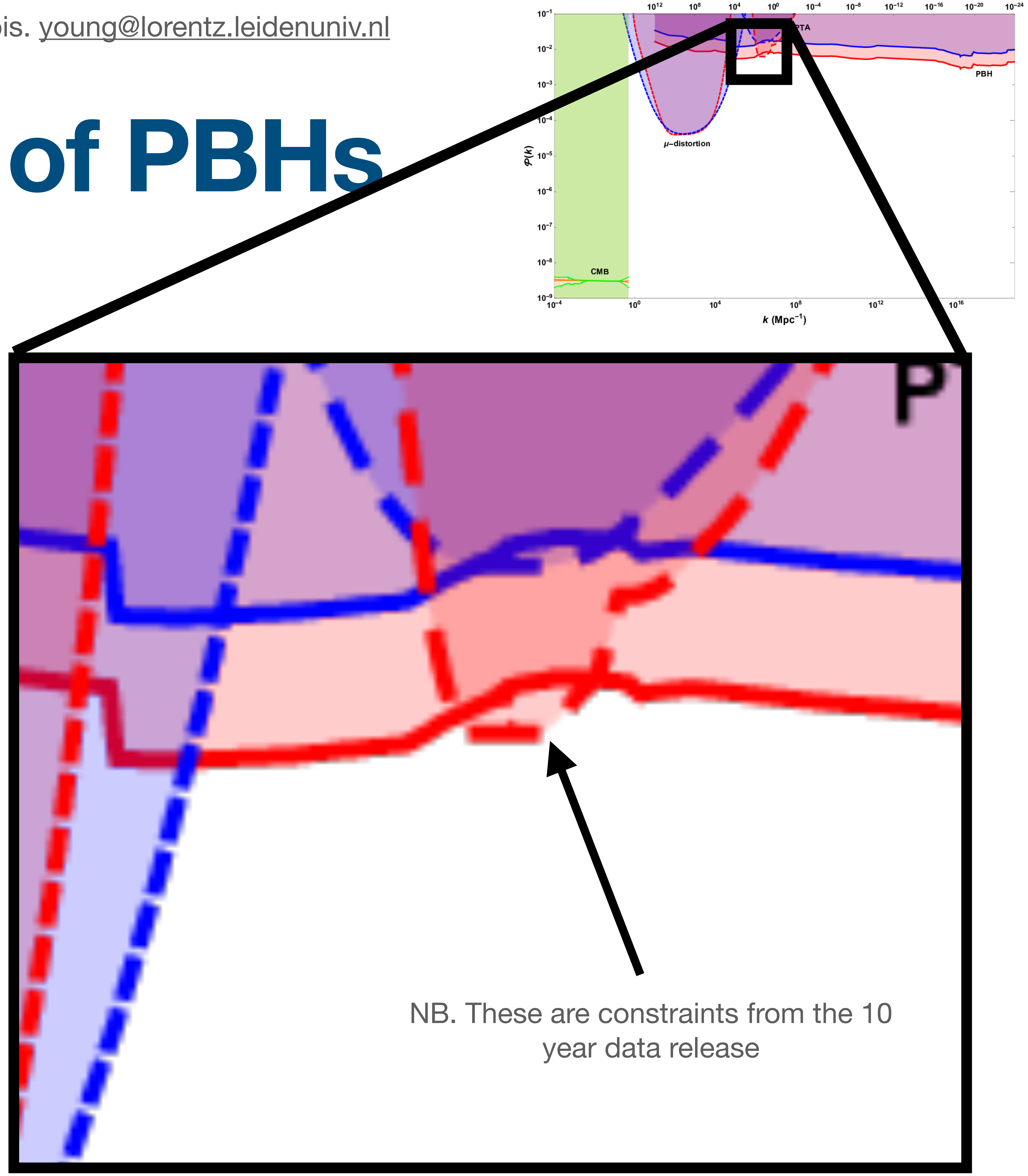
The constraints on the PBH abundance tell us a lot about the early universe



The power spectrum on small scales needs to be much larger on small scales to form a significant number of PBHs - and this is a key challenge

Hints for the existence of PBHs

NANOGrav 12.5 year results

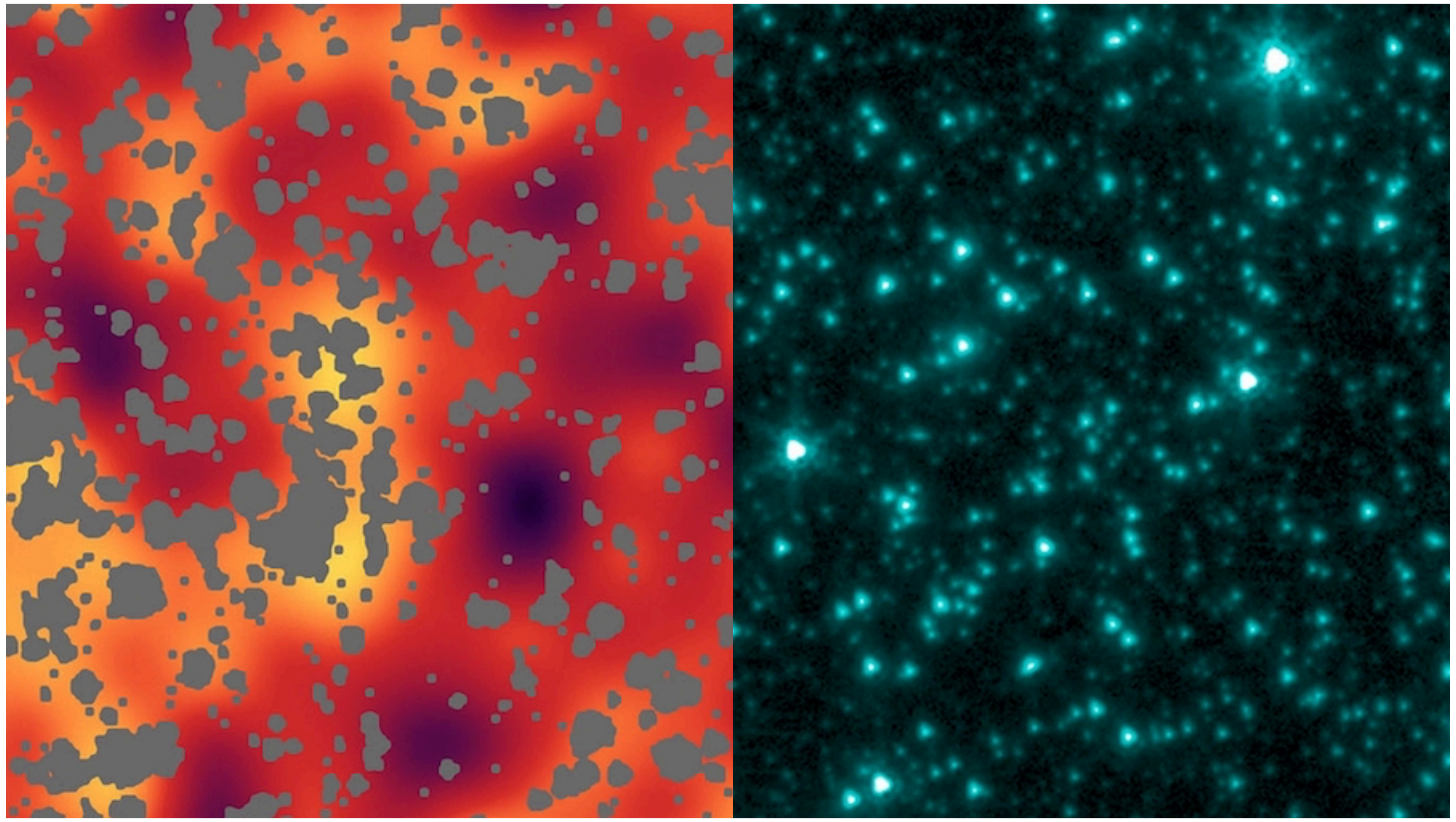


- The North American Nanohertz Observatory for Gravitational Waves (NANOGrav) uses pulsar-timing arrays to search for a stochastic background of gravitational waves
- In 2020, a tentative detection of a GW signal was reported
  - Z. Arzoumanian et al. (NANOGrav), 2020
- Several claims that this may evidence for the existence of PBHs
  - e.g. De Luca et al 2020, Kohri & Tread 2021, Zhao & Wang 2022

Hints for the existence of PBHs

Correlations in the CIB and CXB

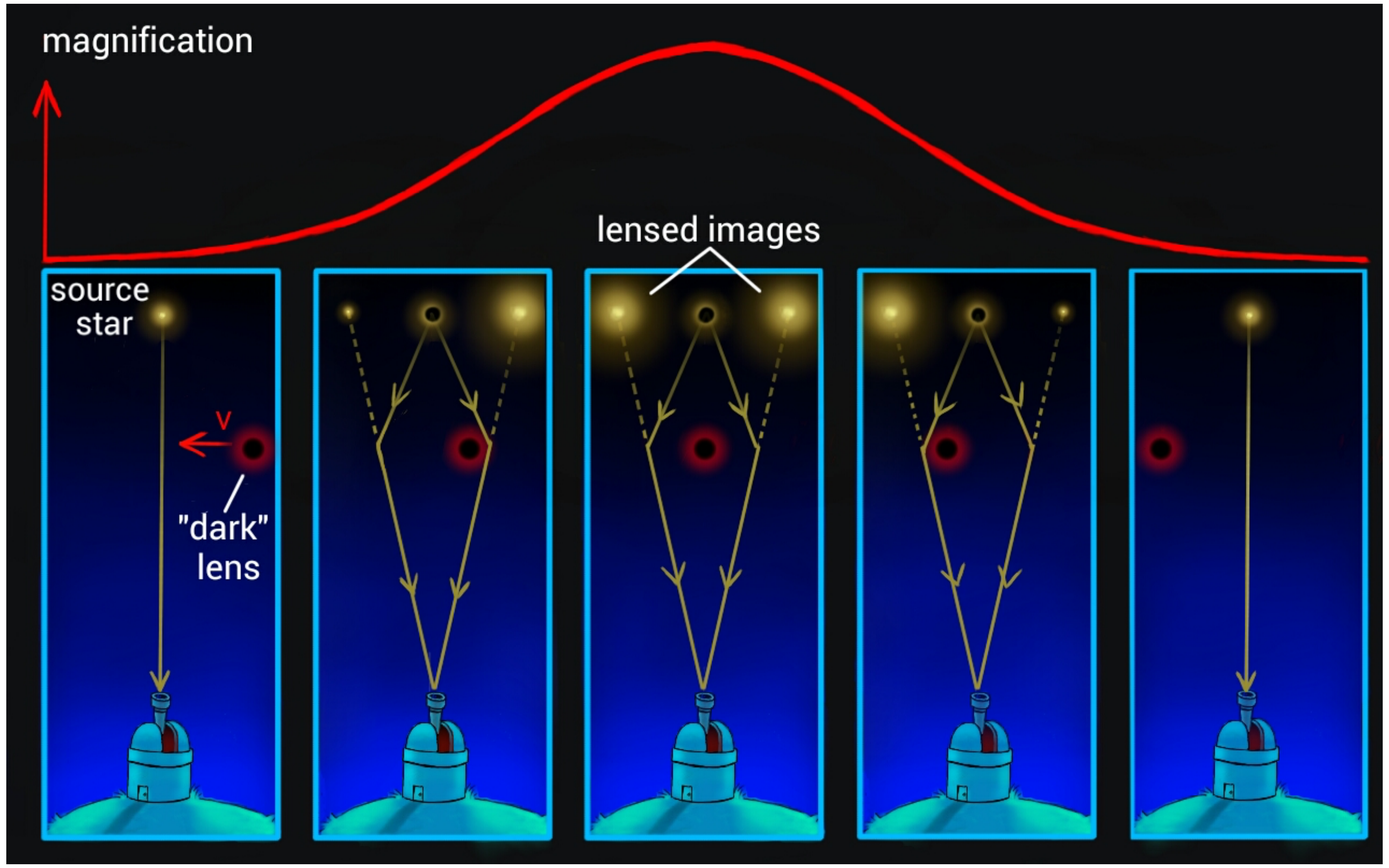
- Early structures too small to be observed contribute to the CIB
  - e.g Spitzer-IRAC
  - An excess of power on small scales is observed
- The CXB is believed to originate from accretion onto black holes
- A strong cross-correlation is observed between the CXB and CIB
  - Cappelluti et al 2017, Kashlinsky 2016
- What if a population of solar mass PBHs exists?
- Poisson fluctuations in the PBH number density would explain the excess power and the cross correlation



Hints for the existence of PBHs

Observation of MaCHOs

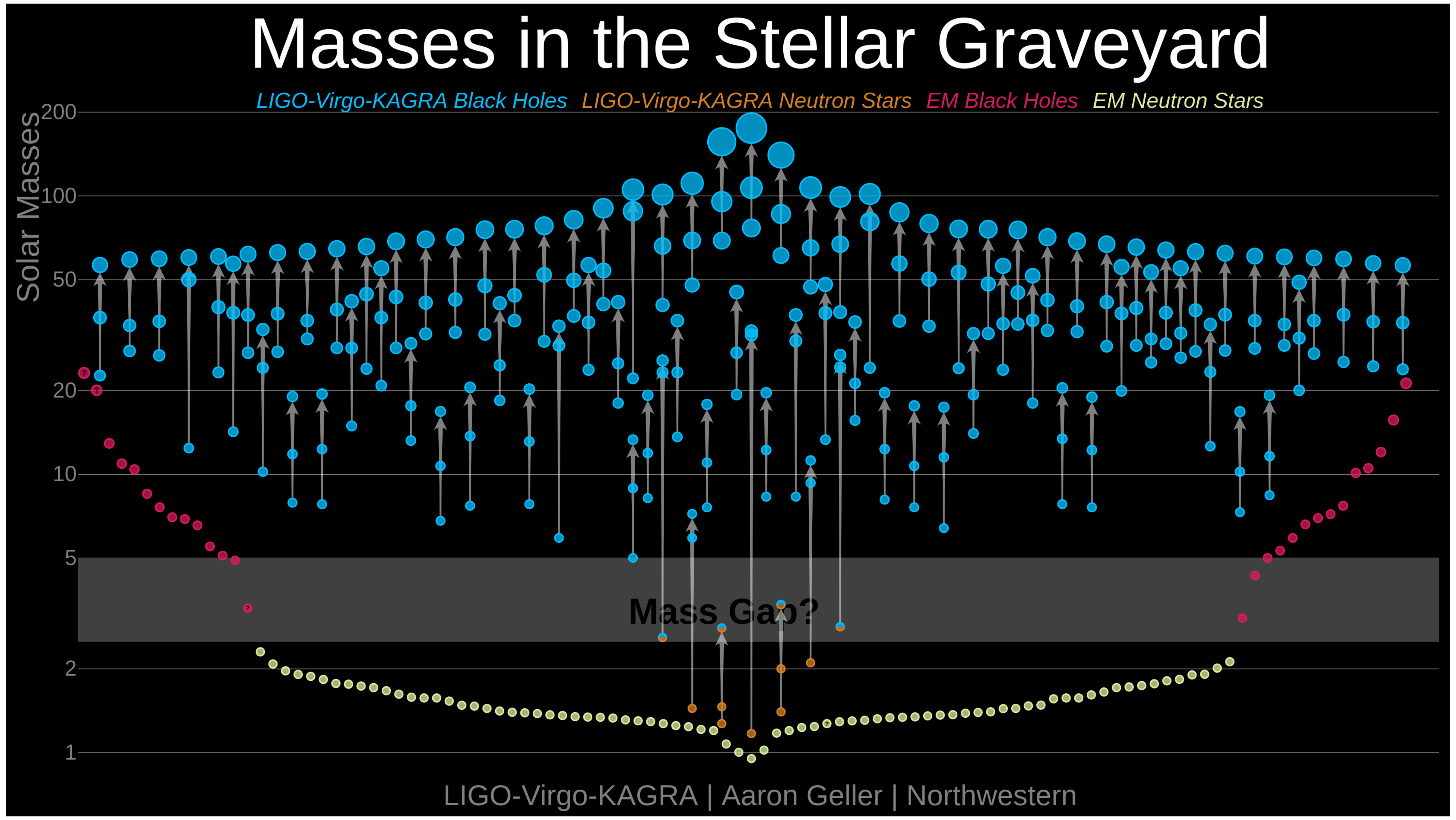
- In the 1990's, the MaCHO collaboration searched for dark matter around the Milky Way using gravitational microlensing
- The results suggest the existence of "dark gravitational lenses" with mass $m \sim 0.5 M_\odot$
  - e.g. Alcock et al, 2001
- It was concluded that they couldn't make up more than 40% of dark matter
- Results can depend upon PBH clustering, galactic profile, etc



Hints for the existence of PBHs

Did LIGO detect dark matter?

- LIGO first observed GWs from merging BHs in 2015
  - LIGO/Virgo (arXiv:1602.03837)
- Challenging to explain these observations with astrophysical BHs — could these be PBHs?
- Binary formation in galactic haloes
  - Bird et al (arXiv:1603.00464), Clesse & Garcia-Bellido (arXiv:1603.05234)
- Binary formation in the early universe
  - Sasaki et al (arXiv:1603.08338), Ali-Haimoud et al (arXiv:1709.06576), Radial et al (arXiv:1707.01480)
  - More on this later
- If dark matter is made of PBHs, merger rate is expected to be higher than observed
- Conclusion: also challenging to explain with PBHs
- Why would PBHs form with this mass range?

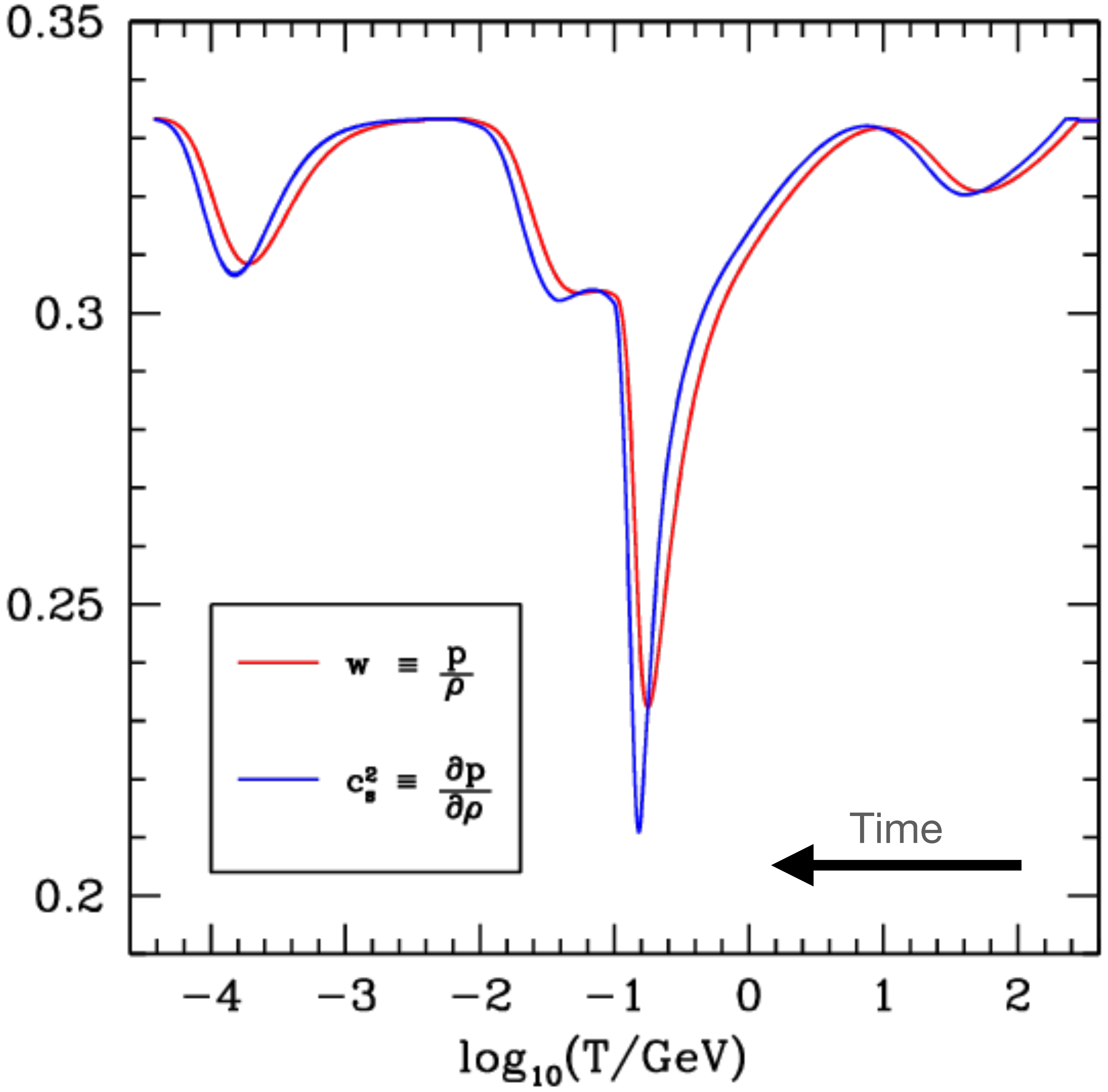


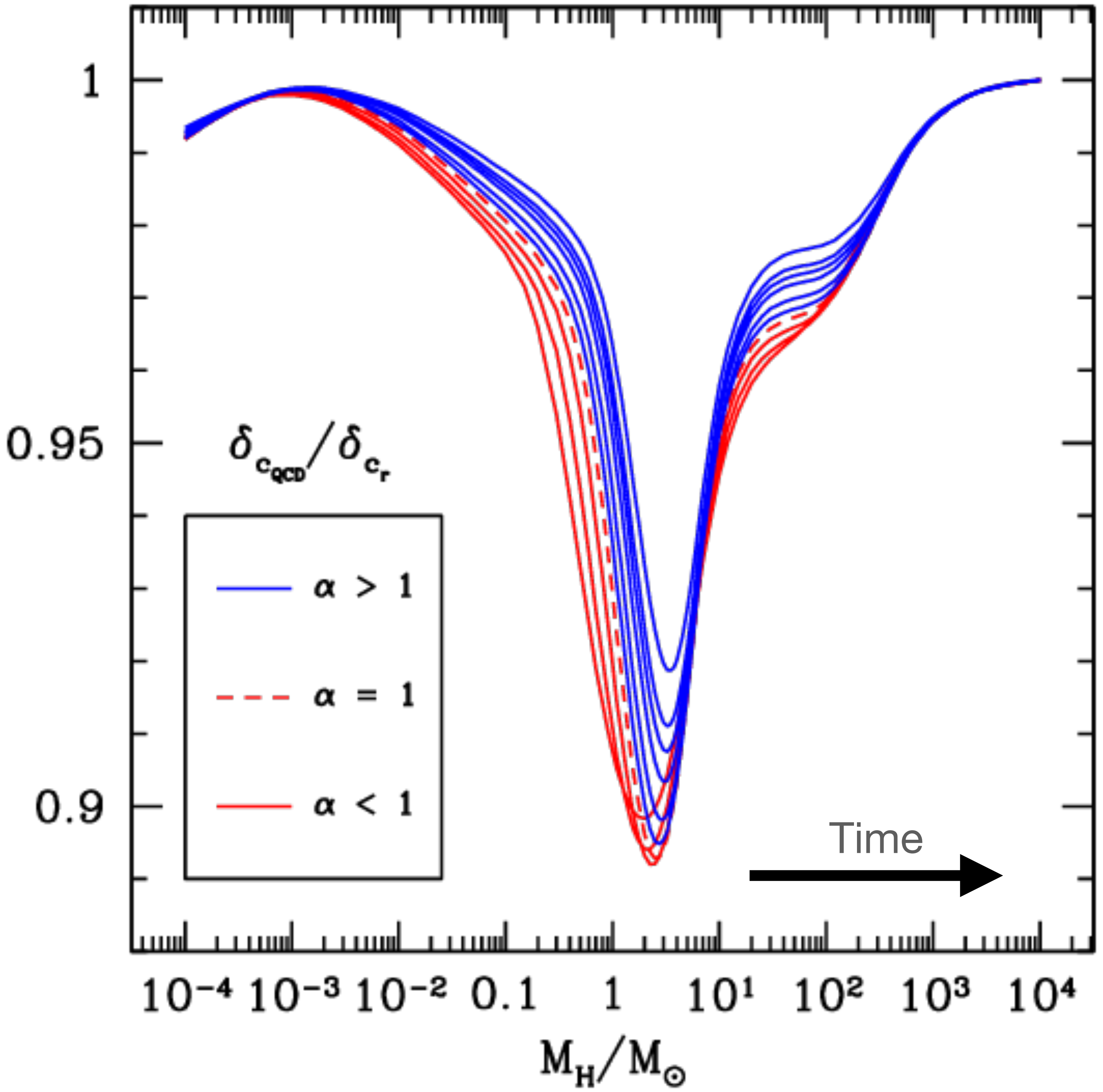
3. The formation of solar mass PBHs

Is there a natural explanation that they form with this mass?
What else is happening at that time?

The QCD phase transition

Musco, Jedamzik, SY, 2023





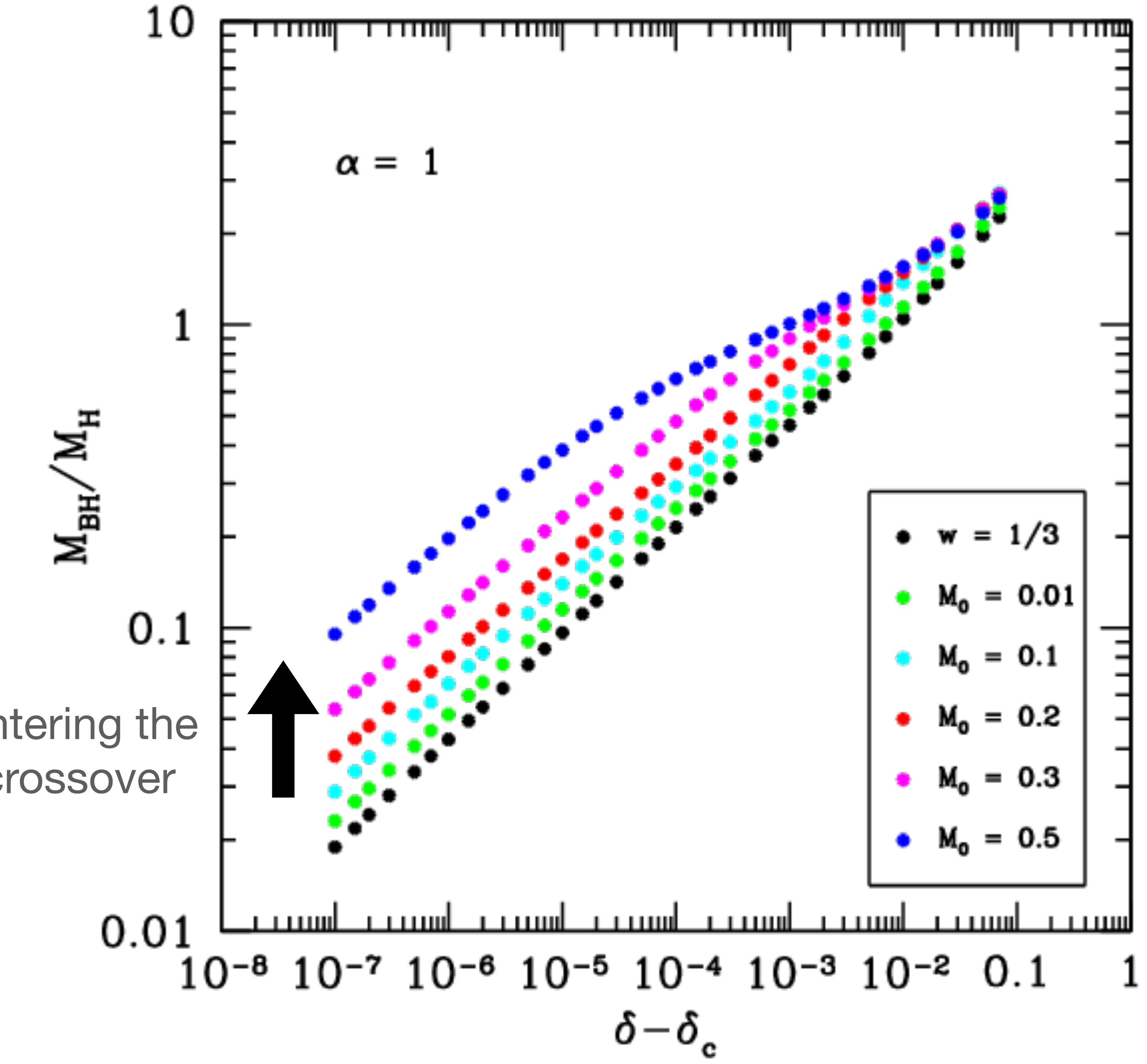
PBH abundance at the time of formation: $\beta \sim \exp\left(-\frac{\delta_c^2}{2\sigma^2}\right)$

The PBH abundance is extremely sensitive to small changes in δ_c

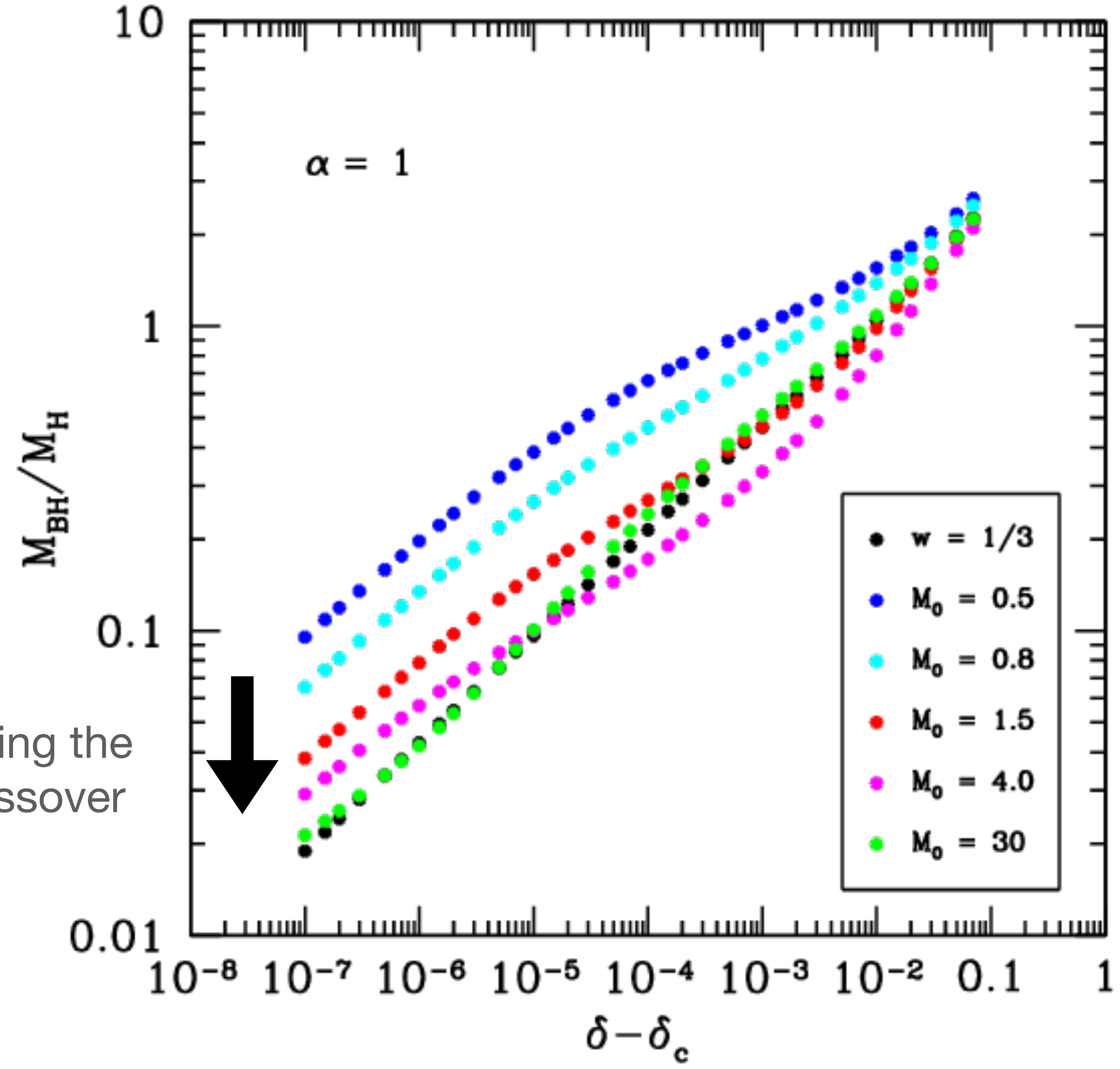
PBH formation during the QCD crossover

Simulations of PBH formation

Musco, Jedamzik, SY, 2023



Entering the crossover



Exiting the crossover

- With peaks theory, we can predict the abundance of perturbations with a given scale and amplitude, given a primordial power spectrum
- Using the simulation results, we can then predict the abundance of PBHs of different masses
- Caveats: we assume a fixed form for the power spectrum, a Gaussian distribution, and that PBHs make up all of DM

Peaks theory and its extensions

SY & Musso (arXiv:2001.06469)

- Peak constraint:

$$n(\bar{C}) \sim \delta_{\mathrm{D}}\left(\frac{\mathrm{d}C}{\mathrm{d}r}\right)\Theta_{\mathrm{H}}\left(\; \frac{\mathrm{d}^2C}{\;}\right)$$ [redacted]

[redacted]rbation
[redacted]tion

- Again calculatin[redacted]

Some maths happens

[redacted] $\sqrt{\;1-\gamma_{0,2}^2}$ [redacted] $\exp\left(-\frac{1+\frac{16\sigma_0^2}{R^4\sigma_2^2}-\frac{8\sigma_0\gamma_{0,2}}{R^2\sigma_2}}{1-\gamma_{0,2}^2}\frac{\nu^2}{2}\right)$

- [redacted]olves the "PBH cloud-in-cloud" problem
- [redacted]cally predicts more PBHs than a PS approach, and a narrower mass function

The complicated maths-y bit I

$$n_{\mathrm{pk}} = \frac{\sigma_2^3 \sigma_{RR}}{\sigma_1^3 \sigma_R} \left| \begin{vmatrix} \zeta_{00} & \frac{\sigma_{1R}}{\sigma_{RR}} \phi_j \\ \frac{\sigma_{1R}}{\sigma_2} \phi_i & \zeta_{ij} \end{vmatrix} \right| \delta_D(\eta_0) \ldots$$ [redacted]

- We have a lot of [redacted]

$\nu = \frac{C}{\ldots}$ [redacted]

[redacted] variant quantities

[redacted] $_{ij} = \zeta_{ij} - \delta_{ij} J_1/3$

Some maths happens

- [redacted] on of ν and J_1

$\eta_0 = $ [redacted] $\zeta_0 - \frac{\ldots}{2} J_1 \sigma_2 \Big)$

The complicated maths-y bit II

$$\nu = \frac{C}{\sigma_0}, \zeta_{00} = -\frac{C''}{\sigma_{RR}},$$

$$\eta^2 = \sum_i \eta_i^2, J_1 = -\mathrm{tr}(\zeta_{ij}), J_2 = \frac{3}{}$$ [redacted]

- To calculate $\mathcal{N}$ [redacted]
  - ν, ζ_{00} [redacted]

Some maths happens

[redacted] $\mathcal{N}(\zeta_{00} | \bar{\nu}, \bar{J}_1)$

$f($ [redacted] $5\Big)\exp\left(\frac{-5J_1^2}{2}\right) + \left(\frac{31J_1^2}{4} + \frac{8}{5}\right)\exp\left(\frac{-5J_1^2}{8}\right)\Big] + \frac{1}{2}(J_1^3 - 3J_1)\left[\mathrm{Erf}\left(\sqrt{\frac{5}{2}}J_1\right) + \mathrm{Erf}\left(\sqrt{\frac{5}{2}}\frac{J_1}{2}\right)\right]$

$\bar{J}_1 \equiv$ [redacted] $(R^2\sigma_2)$

The complicated maths-y bit III

- In the high-peak limit we are interested in, we can [redacted]
- Firstly, $f(J_1) \approx J_1^3$
- Secondly, the PDF of ζ_{00} bec [redacted]
- Typically, $\alpha \approx 1$ exc [redacted]
- Finally, we [redacted]

Some maths happens

[redacted] factor between $\nu = C/\sigma_0$ and $J_1 = -\nabla^2 C/\sigma_2$

- [redacted] extra factor of ν and a change in the exponential term
- E [redacted] less peaks may be predicted dependent on the shape of the power spectrum and the smoothing sca [redacted]

The PBH mass function

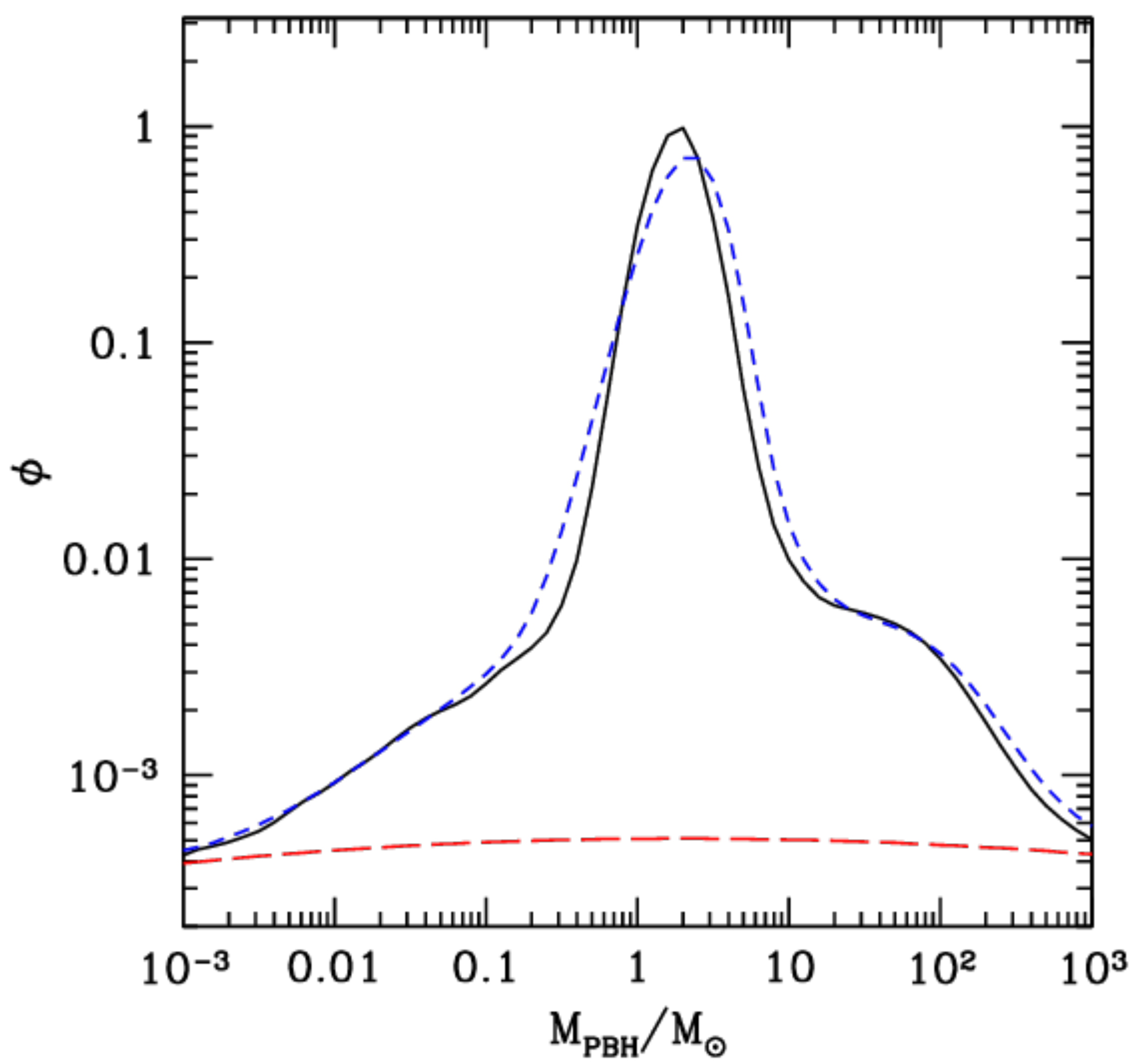
Does the QCD transition remove the required tuning?

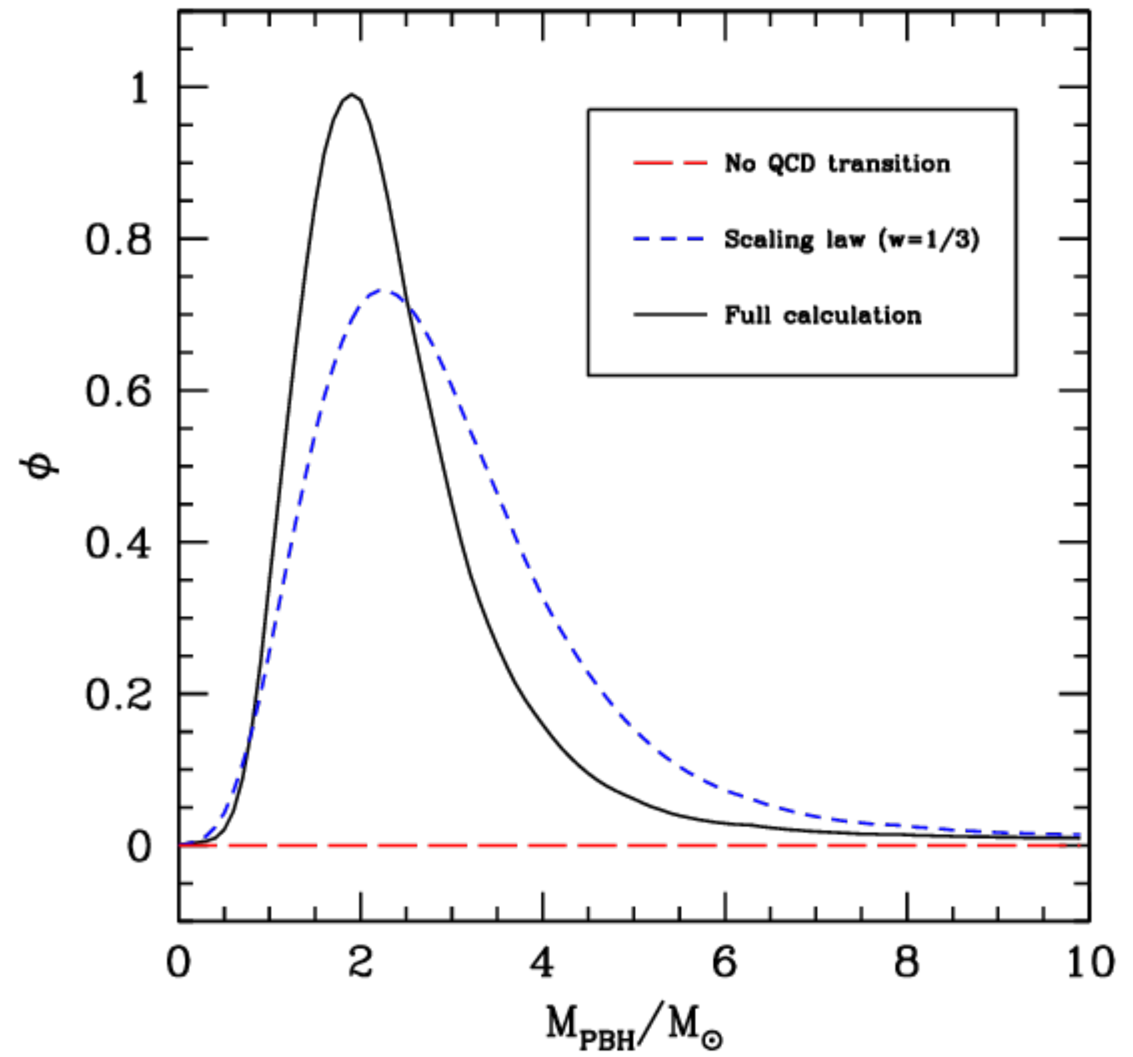
- PBH formation is enhanced by a factor ~1000 during the crossover

NB. This is the spectral index at the PBH scale, but this cannot be true up to CMB scales

- A spectral index $n_s \sim 0.96$ gives a roughly mass-independent mass function
  - (i.e. with the least amount of tuning to get the mass you want)
- The mass function has a sharp peak at $\sim 2M_\odot$
- This could explain the CIB/CXB correlations and MaCHO observations
- …but not the LIGO black holes

A scale invariant power spectrum $n_s = 1$ gives a PBH mass function $\phi \sim m^{-1/2}$



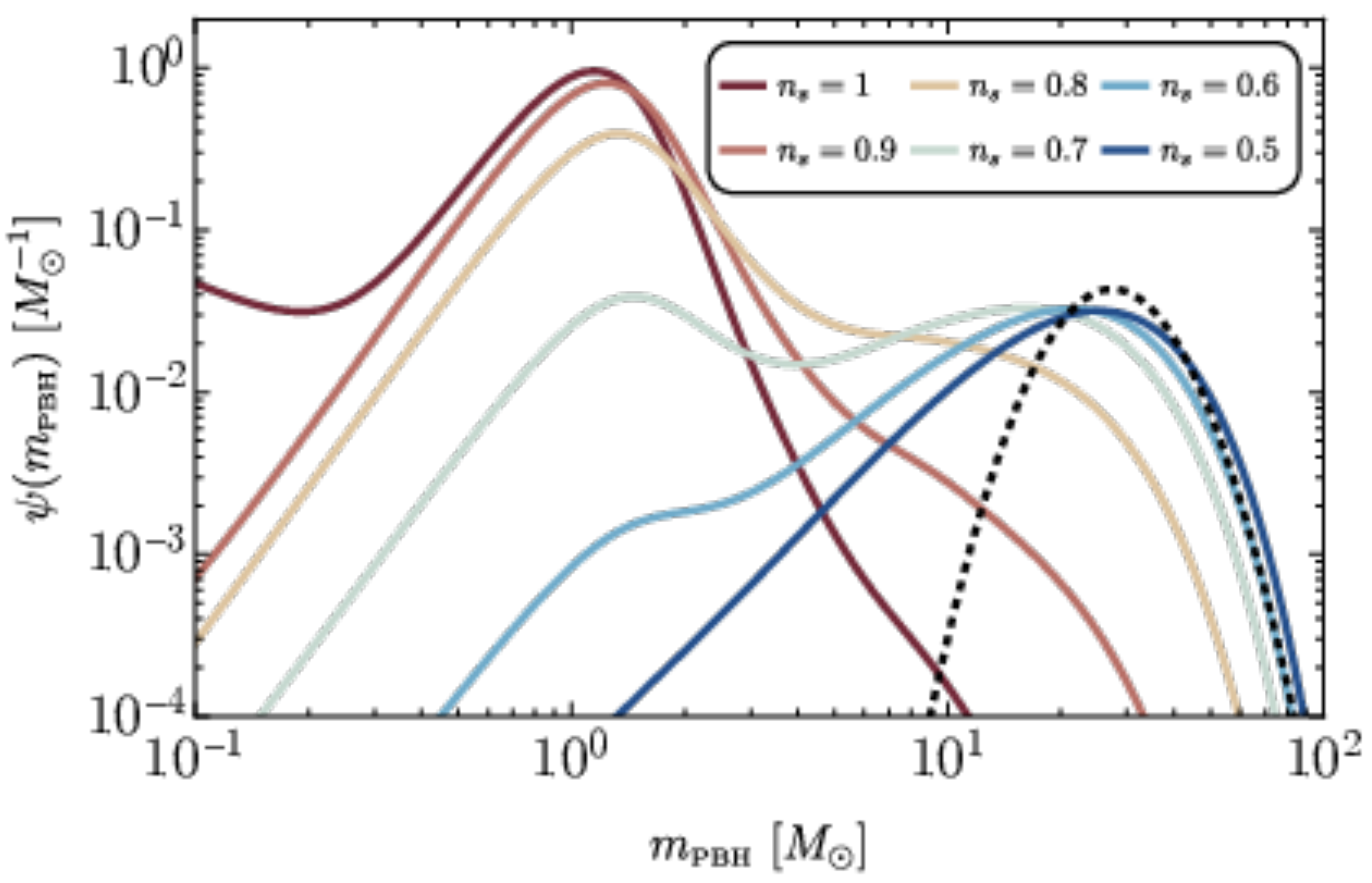


Can the QCD crossover explain the LIGO BHs?

Franciolini, Musco, Pani, Urbano 2022

- If we consider a different power spectrum, you can predict a mass function which fits the LIGO data

- But this reintroduces the tuning required to fix the PBH mass
  - Somewhat removes the motivation to think they formed



Summary


Inflation/ astroparticle physics
Particle physics
Numerical relativity
Theoretical/numeric cosmology/ astrophysics/LSS
Too many fields to list…
Inflation sources cosmological perturbations
Pressure drops during the QCD crossover
Formation of solar mass PBHs?
PBHs make up all, or a fraction, of dark matter?
Observational evidence for/ against PBHs?
Accretion constraints, LIGO merger rate
Key observables for solar mass PBHs
MaCHOs, CIB/ CXB correlations, LIGO BHs, NANOGrav
Early times
Late times