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Primordial Black Hole Relics as Dark Matter Candidate

Amirah Aljazaeri

Working with: **Christian Byrnes**

To be presented at:
XIV NExT PhD Workshop: the shape of new physics to come.
17 July 2024

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Contents

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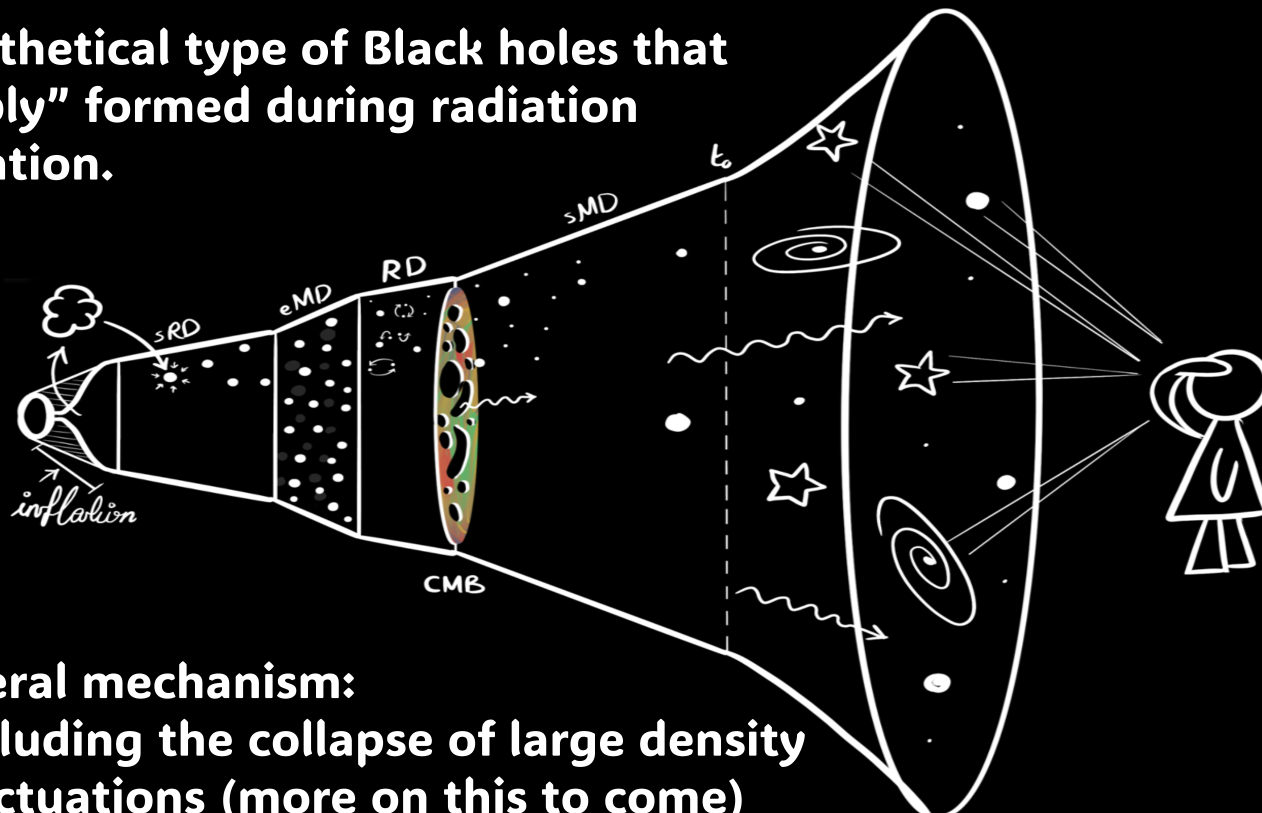
What is a PBH ?

- A hypothetical type of Black holes that "Possibly" formed during radiation domination.



- By several mechanism:
  - Including the collapse of large density fluctuations (more on this to come)

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- There are a few types of black holes, but why PBHs? (motivations)
  - They need no new particles neither a new physics to be the DM.
  - Their potential formation time makes them an excellent DM candidate.
  - They could be a significant fraction of dark matter.
  - They also offer insights into the early universe.

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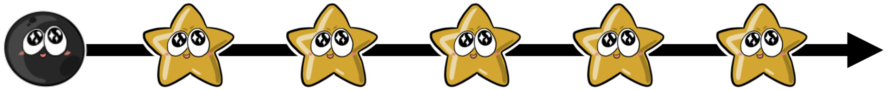

PBHs Formation

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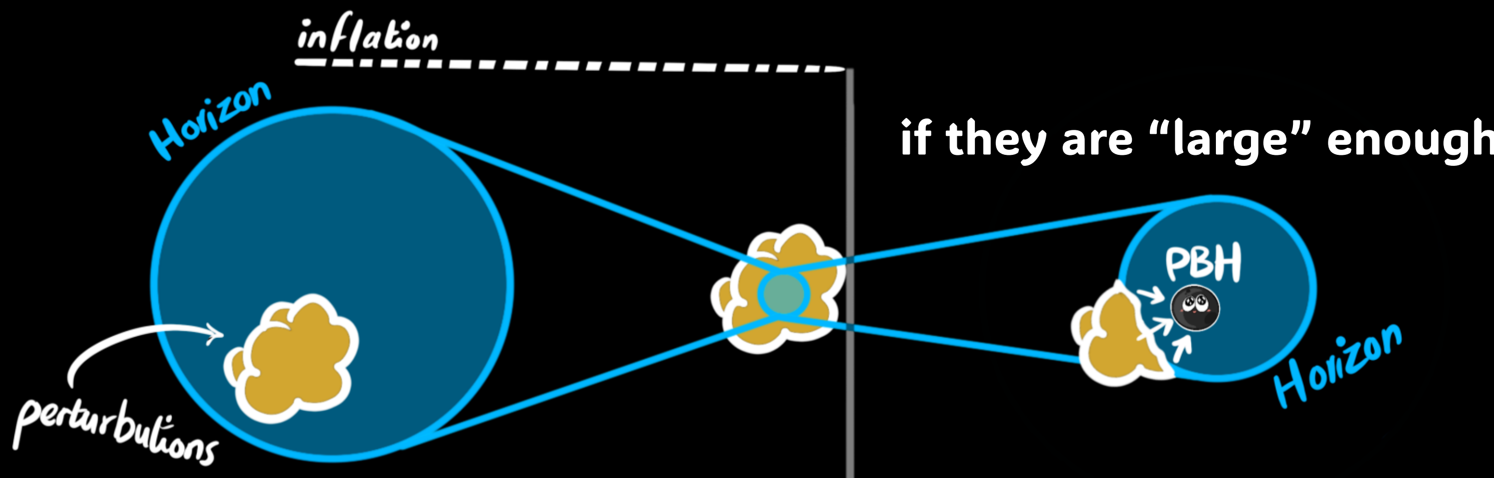

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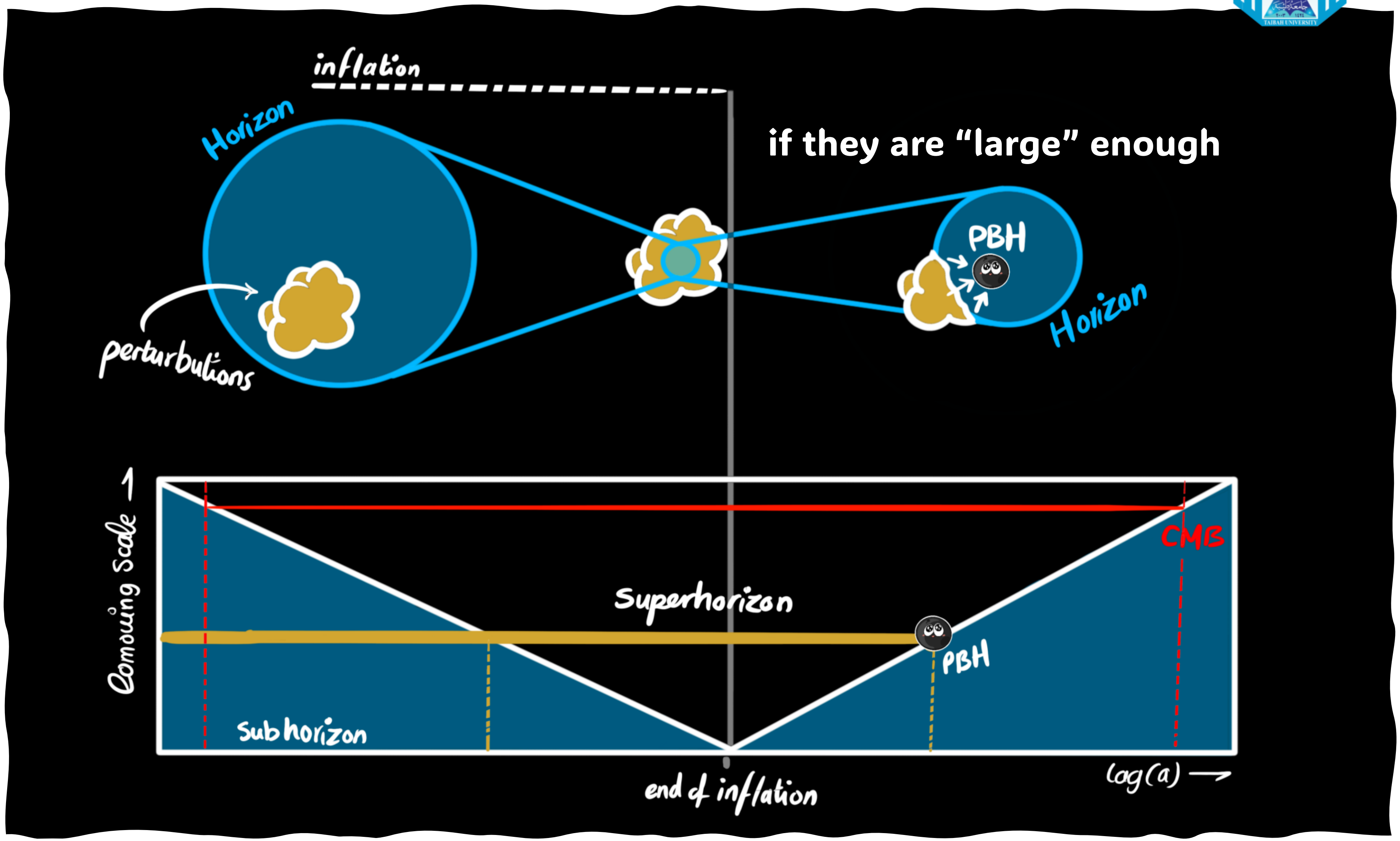
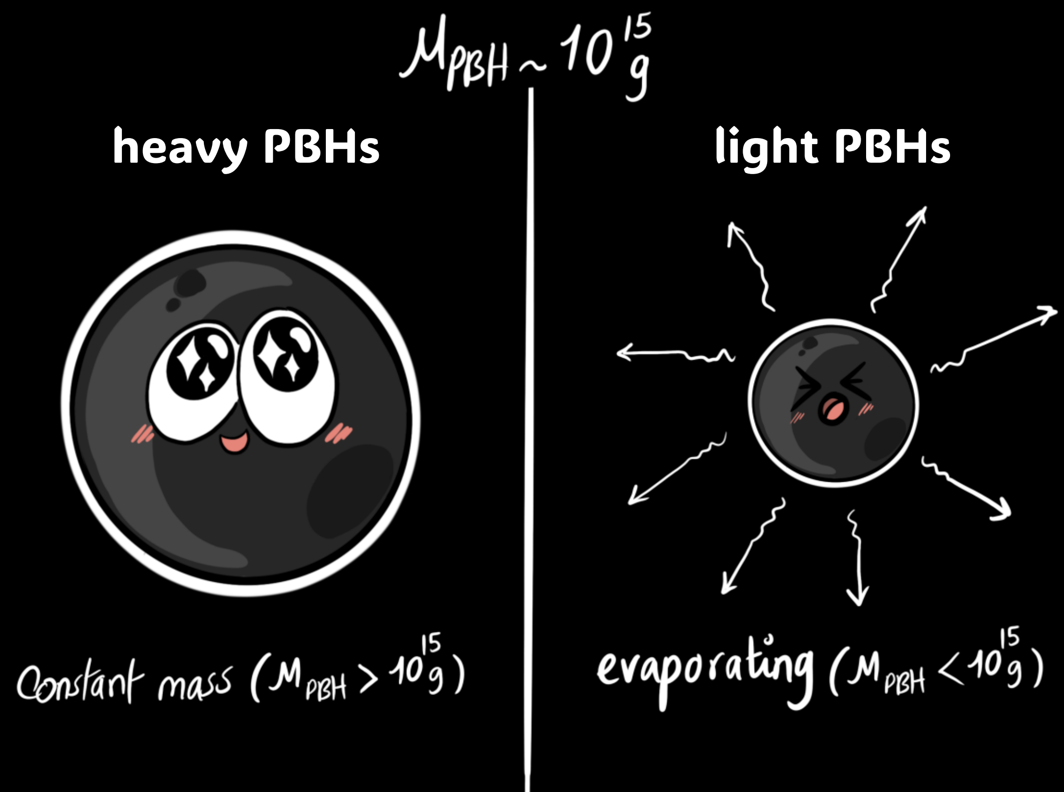
PBHs Formation

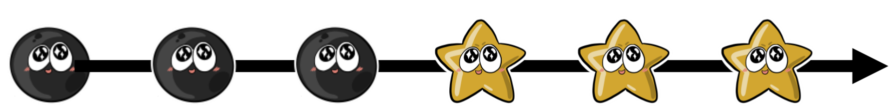


PBH lifetime and evaporation

- The potential formation time of PBHs allows their initial masses to range from about (1 g < MPBH < many solar masses)



- The evaporation time is a function of MPBH.



PBH lifetime and evaporation

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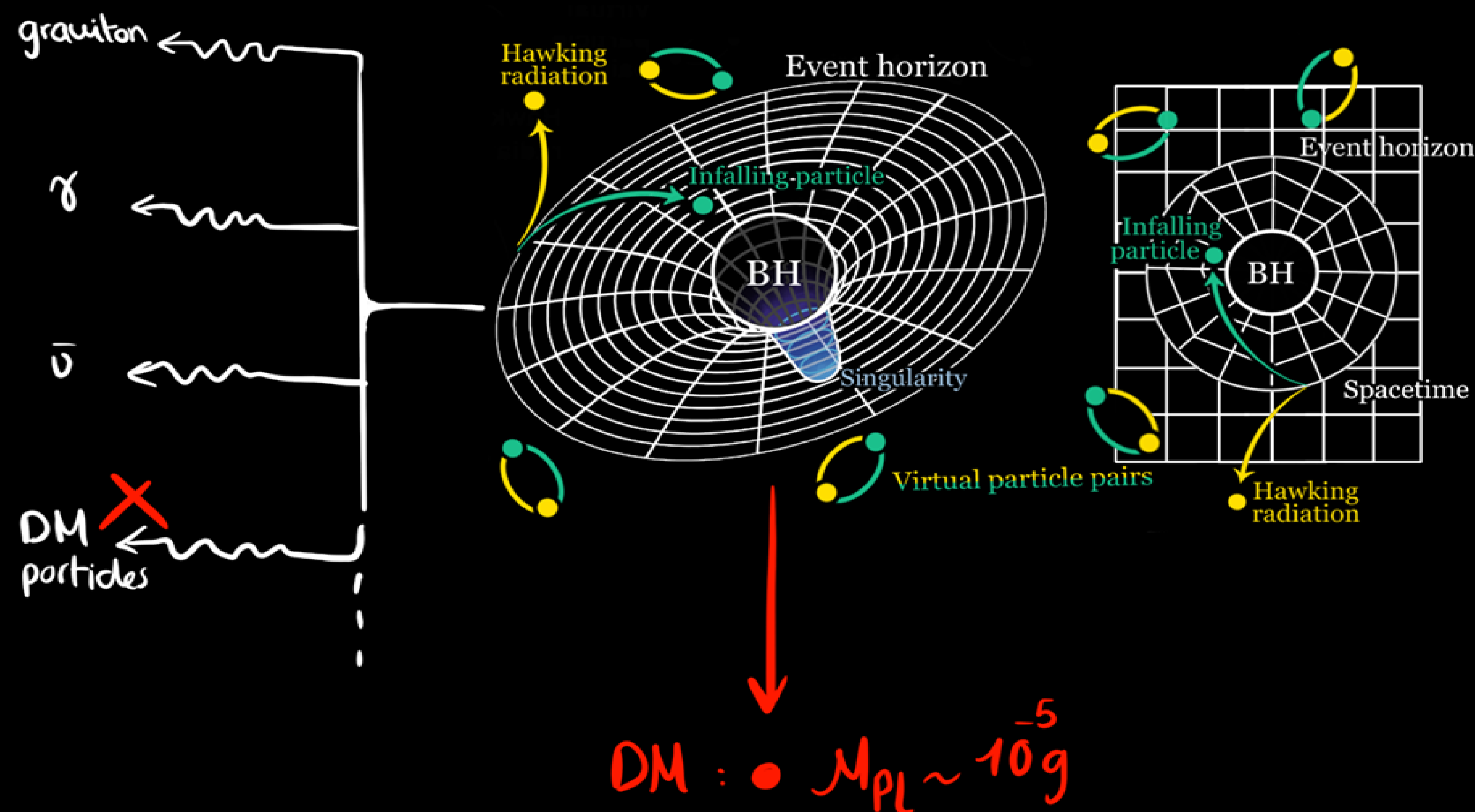

- **Ultra-light PBH could in principle experience Hawking evaporation perhaps into Planck mass relic.**

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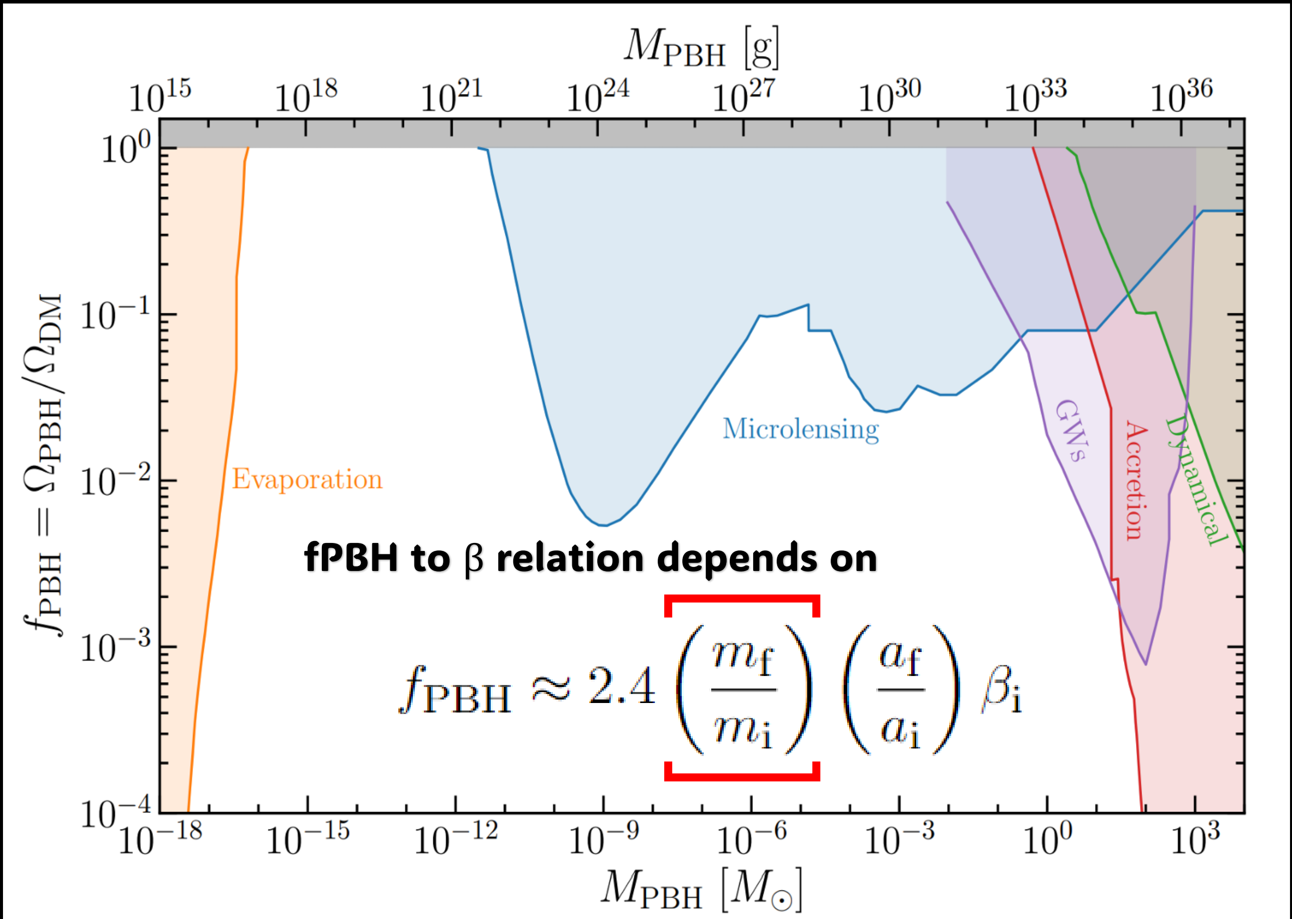
Constraints on..

The fraction of DM as PBHs: f_{PBH}



- **If a PBH vanished (m_f = 0), which motivate the need for relics.**
- **It is well constrained, leaving a small open window.**
- **What is β ?**

Green, Anne M., and Bradley J. Kavanagh. Nuclear and Particle Physics 48.4 (2021): 043001.

The abundance of PBHs : β

$$\beta = \frac{\rho_{\rm PBH}}{\rho_{\rm tot}}\bigg|_{\rm form} = \frac{\rho^{\rm i}_{\rm PBH}}{\rho_r} = \frac{\rho^{\rm eq}_{\rm PBH}}{\rho^{\rm eq}_{\rm tot}}\left(\frac{a_{\rm i}}{a_{\rm eq}}\right) \approx f_{\rm PBH,0}\left(\frac{a_{\rm i}}{a_{\rm eq}}\right)$$

Describes the total energy density at formation that would have fallen into PBHs.

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- **No PBH yet has been detected.**

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Constraints on..

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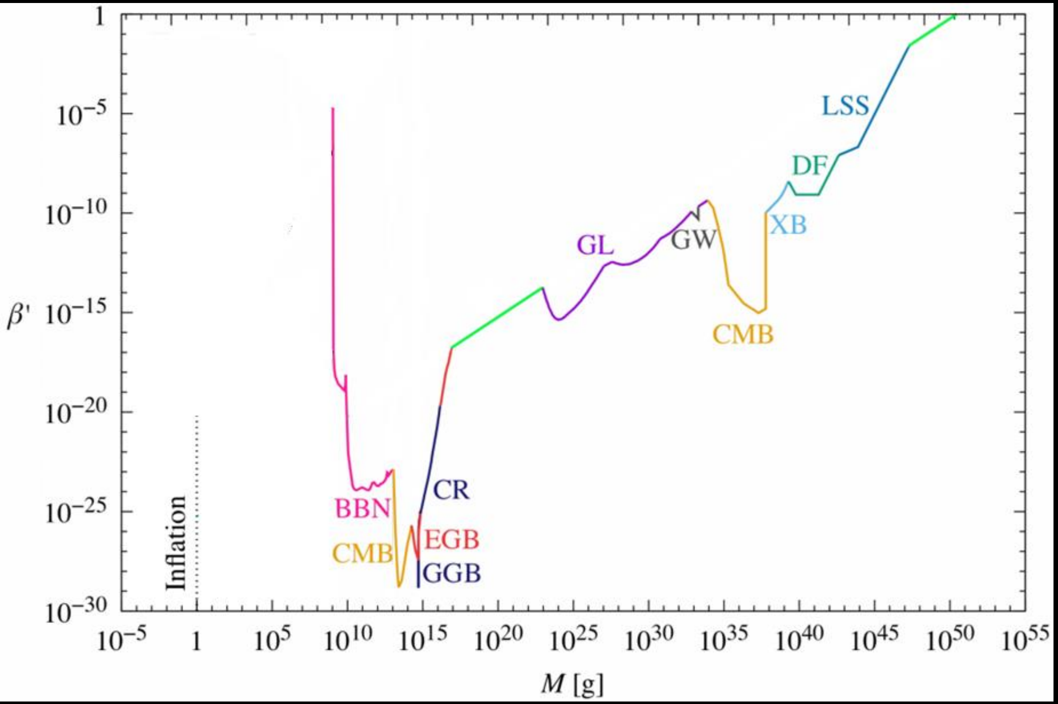
Describes the total energy density at formation that would have fallen into PBHs.

- **No PBH yet has been detected.**
- **light PBHs is constrained by the effects of their Hawking radiation on today's observations.**
- **heavy PBHs can be typically seen through their lensing, dynamic and gravitational effects on other astrophysical objects and processes**



Carr, Bernard, et al. "Constraints on primordial black holes." Reports on Progress in Physics .116902 :(2021)84.11

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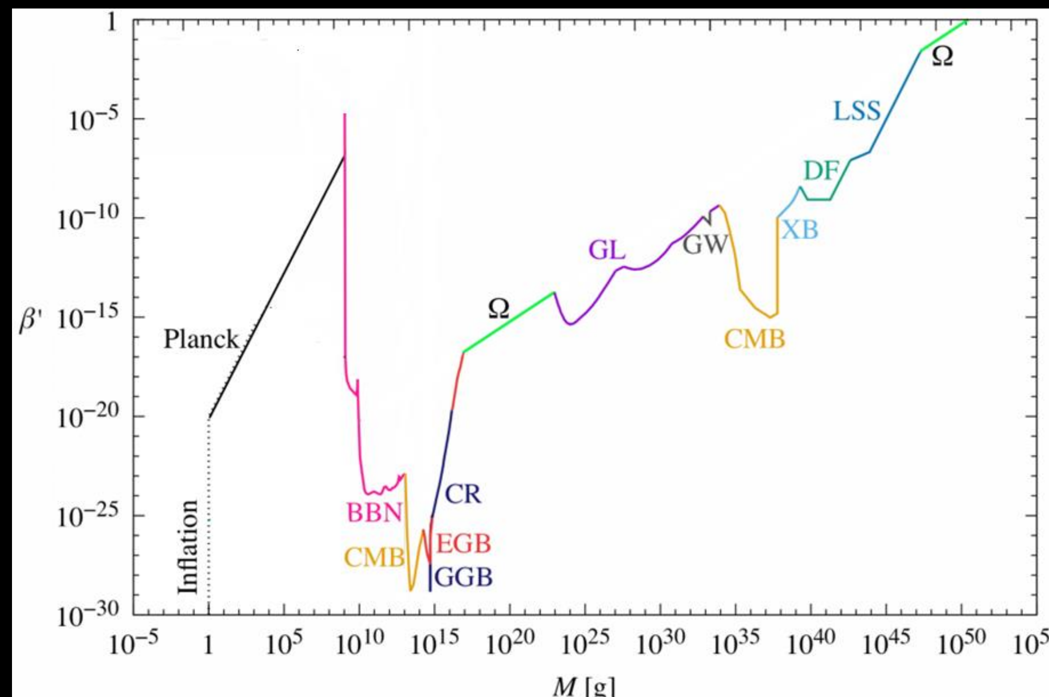

Carr, Bernard, et al. "Constraints on primordial black holes." Reports on Progress in Physics .116902 :(2021)84.11

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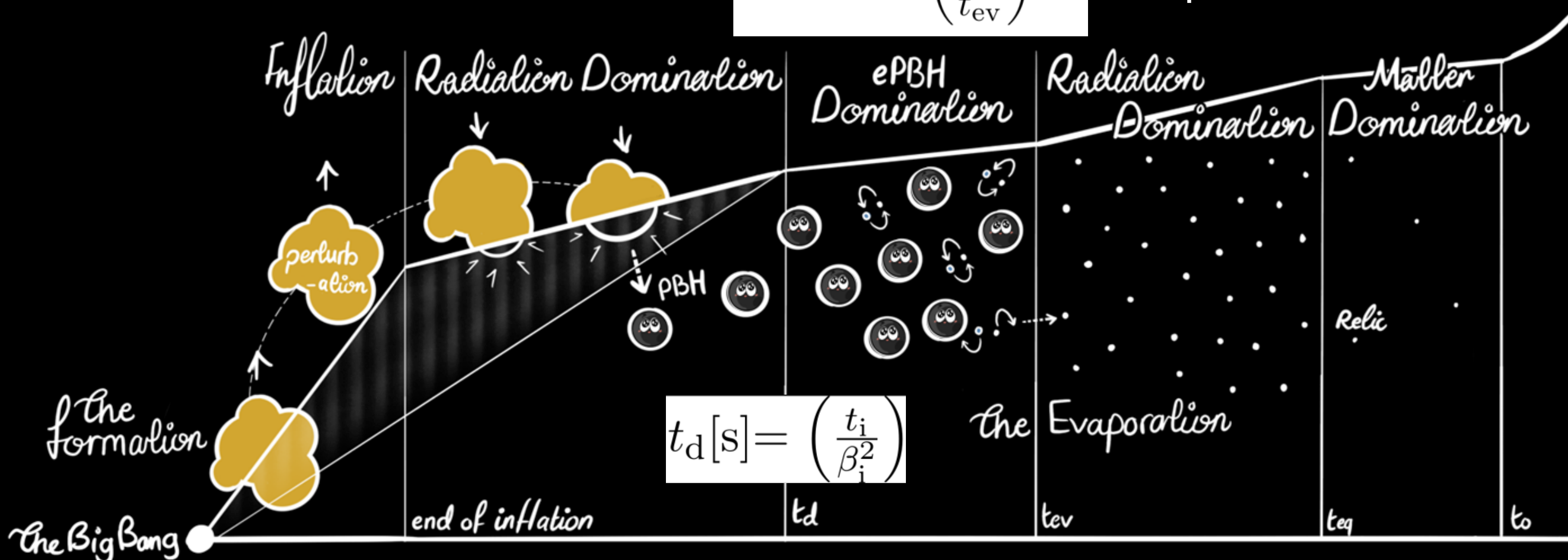
PBH domination era.

- One can assume that universe formerly experienced an early matter-dominated epoch in which PBHs predominated after the standard RD.
- This is not a constraint on β but rather a limit.
- Why such an era is interesting?

E.g.
Papanikolaou, T., Vennin, V., & Langlois, D. (2021). Gravitational waves from a universe filled with primordial black holes. 2021(03), 053

$$\beta_{\rm i} > \beta_{\rm cri} = \left(\frac{t_{\rm i}}{t_{\rm ev}}\right)^{1/2}$$ → β = 1



$$t_{\rm d}[{\rm s}] = \left(\frac{t_{\rm i}}{\beta_{\rm i}^{2}}\right)$$

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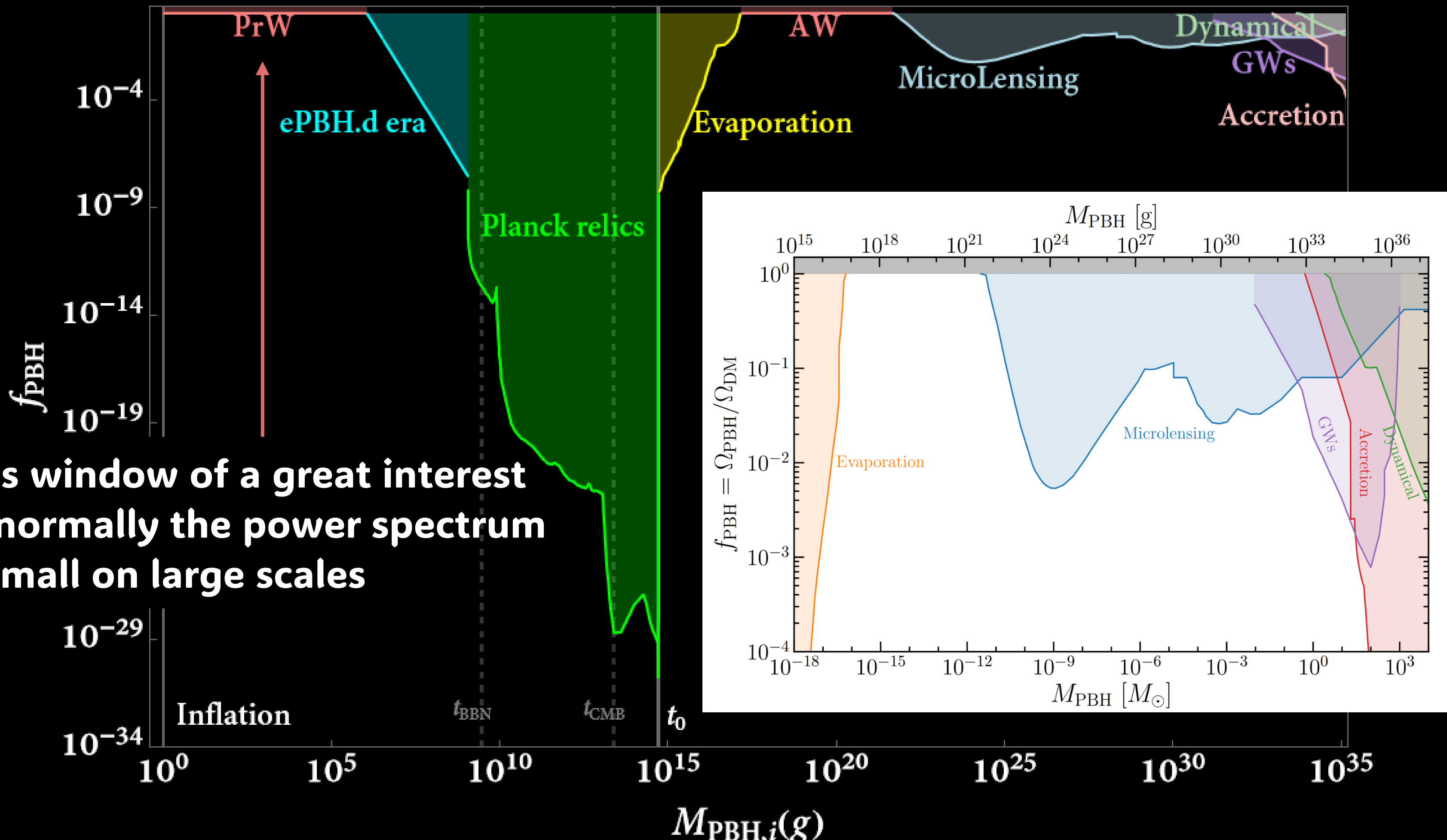
Master Plot

The fraction of DM as PBHs: f_{PBH}



This window of a great interest as normally the power spectrum is small on large scales

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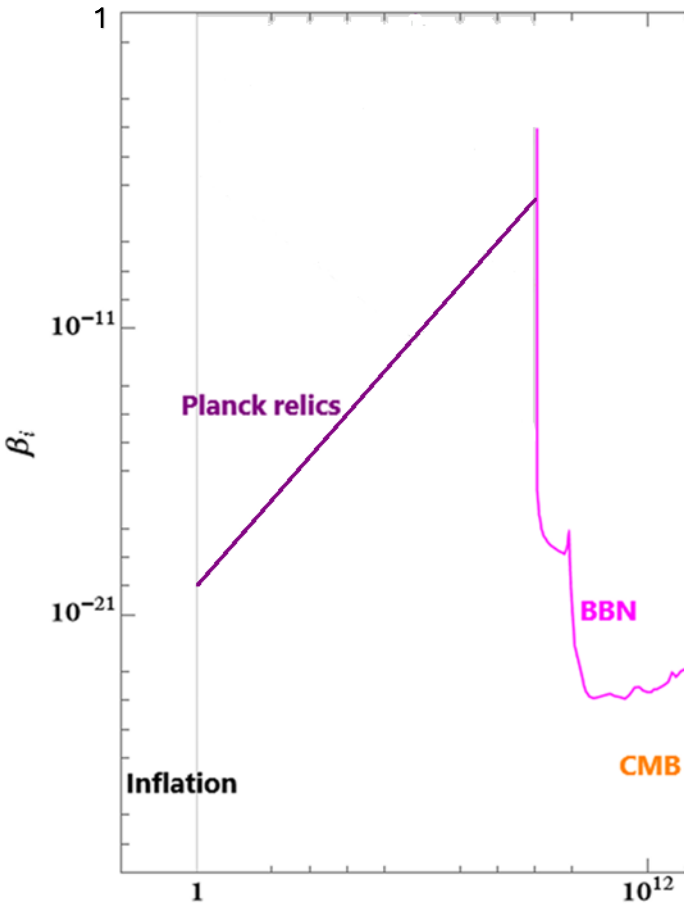
1
10^{-11}
10^{-21}
β_i
Planck relics
BBN
CMB
Inflation
1
10^{12}

Stochastic Gravitational waves from PBH

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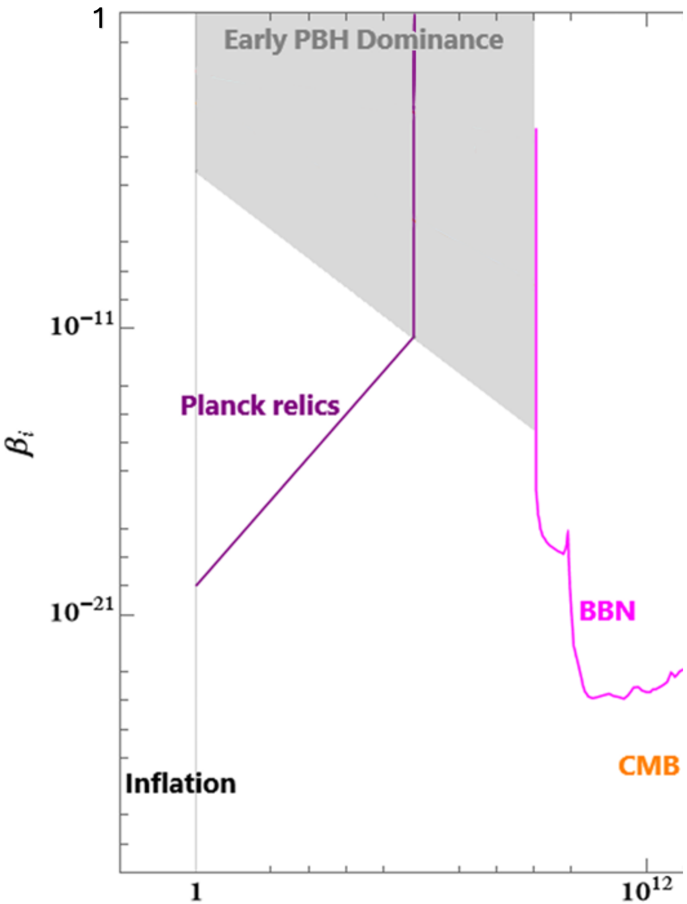

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Stochastic Gravitational waves from PBH

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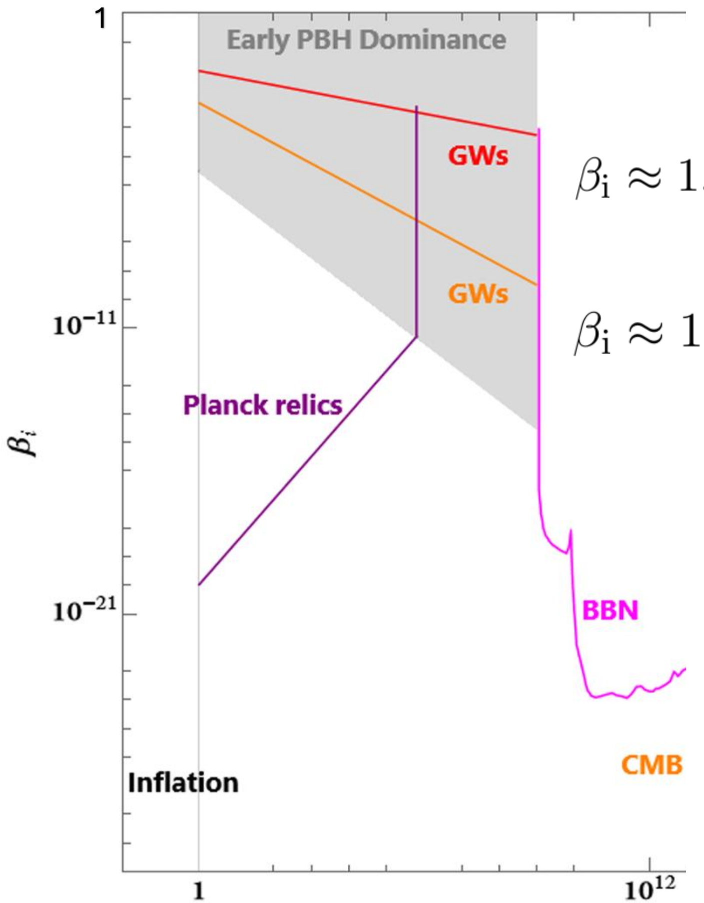

$$\beta_{\rm i} \approx 1.4 \times 10^{-4} \left(\frac{M_{\rm PBH,i}}{10^9 {\rm g}}\right)^{-1/4}$$

arXiv:2010.11573v3
Papanikolaou, Vincent Vennin... (2021)

$$\beta_{\rm i} \approx 1.1 \times 10^{-6} \left(\frac{M_{\rm PBH,i}}{10^4 {\rm g}}\right)^{-17/24}$$

arXiv:2012.08151v2
Domenech, Sasaki... (2021)

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We talked about..

- DM might not be a new particle. Moreover, if it is BHs, it has to be primordial.
- PBH evaporating into Planck mass relics:
  - Opens a unique window that explains all DM.
  - Tightens the observational constraints on β for light masses, which applies into f_{PBH}.
  - most importantly: it provides a meaningful interpretation of fPBH at small scales.
- Having an early PBH domination era set an additional constraint on f_{PBH} from accounting for all the DM today.
- Further discussion: Stochastic gravitational waves are the key probe when explaining how the PBH relics have formed.

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Thank you

Diffuse emission from black hole remnants

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[1] *Dept. of Physics & Astronomy, Western University, N6A 3K7, London ON, Canada*
[2] *Dept. of Philosophy and Rotman Institute, Western University, N6A 3K7, London ON, Canada*
[3] *Aix Marseille University, Université de Toulon, CNRS, CPT, 13288 Marseille, France*
[4] *Perimeter Institute, 31 Caroline Street North, N2L 2Y5 Waterloo ON, Canada*

(Dated: May 5, 2023)

At the end of its evaporation, a black hole may leave a remnant where a large amount of information is stored. We argue that the existence of an area gap as predicted by Loop Quantum Gravity removes a main objection to this scenario. Remnants should radiate in the low-frequency spectrum. We model this emission and derive properties of the diffuse radiation emitted by a population of such objects. We show that the frequency and energy density of this radiation, which are measurable in principle, suffice to estimate the mass of the parent holes and the remnant density, if the age of the population is known.

Kazemian, S., Pascual, M., Rovelli, C., & Vidotto, F. (2023). Diffuse emission from black hole remnants. *Classical and Quantum Gravity*, *40*(8), 087001.

Breakdown of Hawking Evaporation opens new Mass Window for Primordial Black Holes as Dark Matter Candidate

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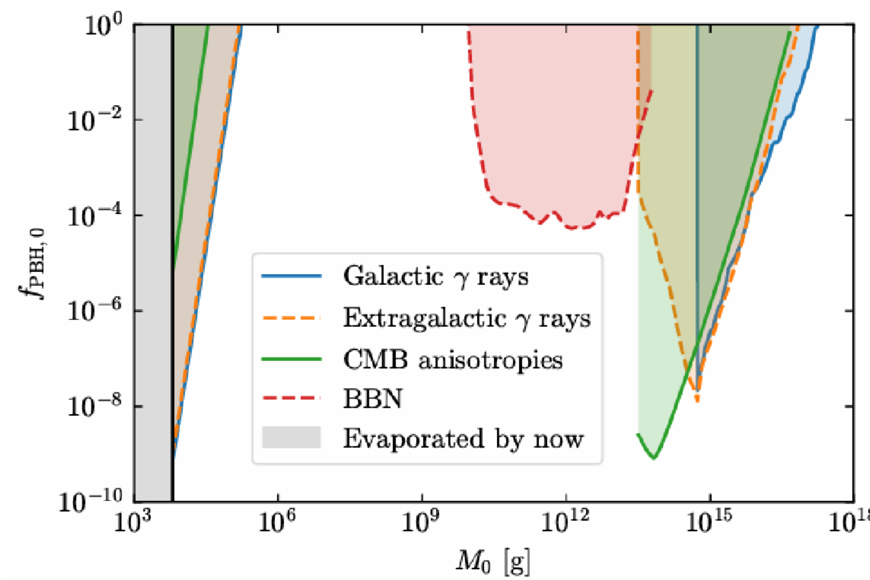
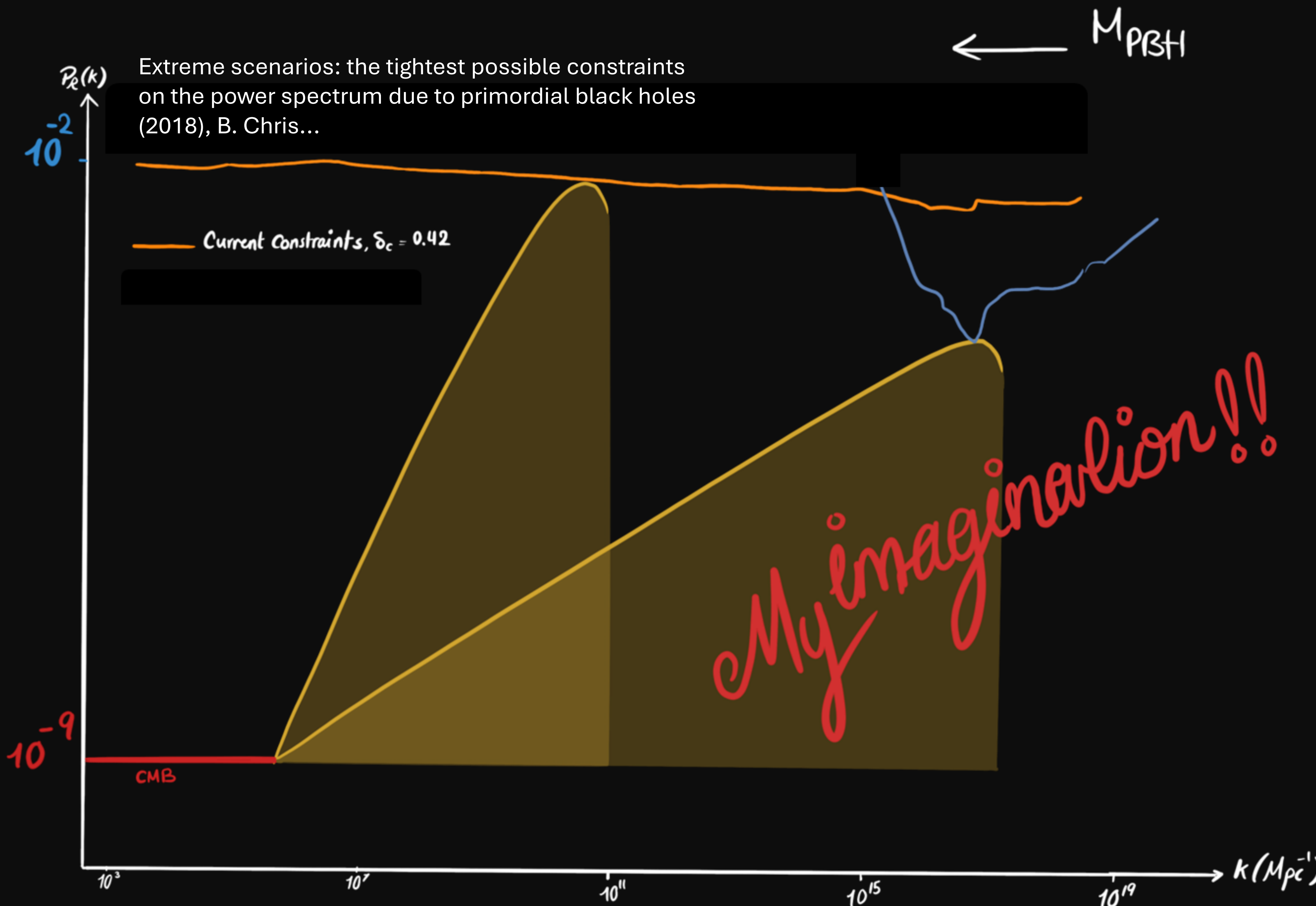
Accepted XXX. Received YYY; in original form ZZZ

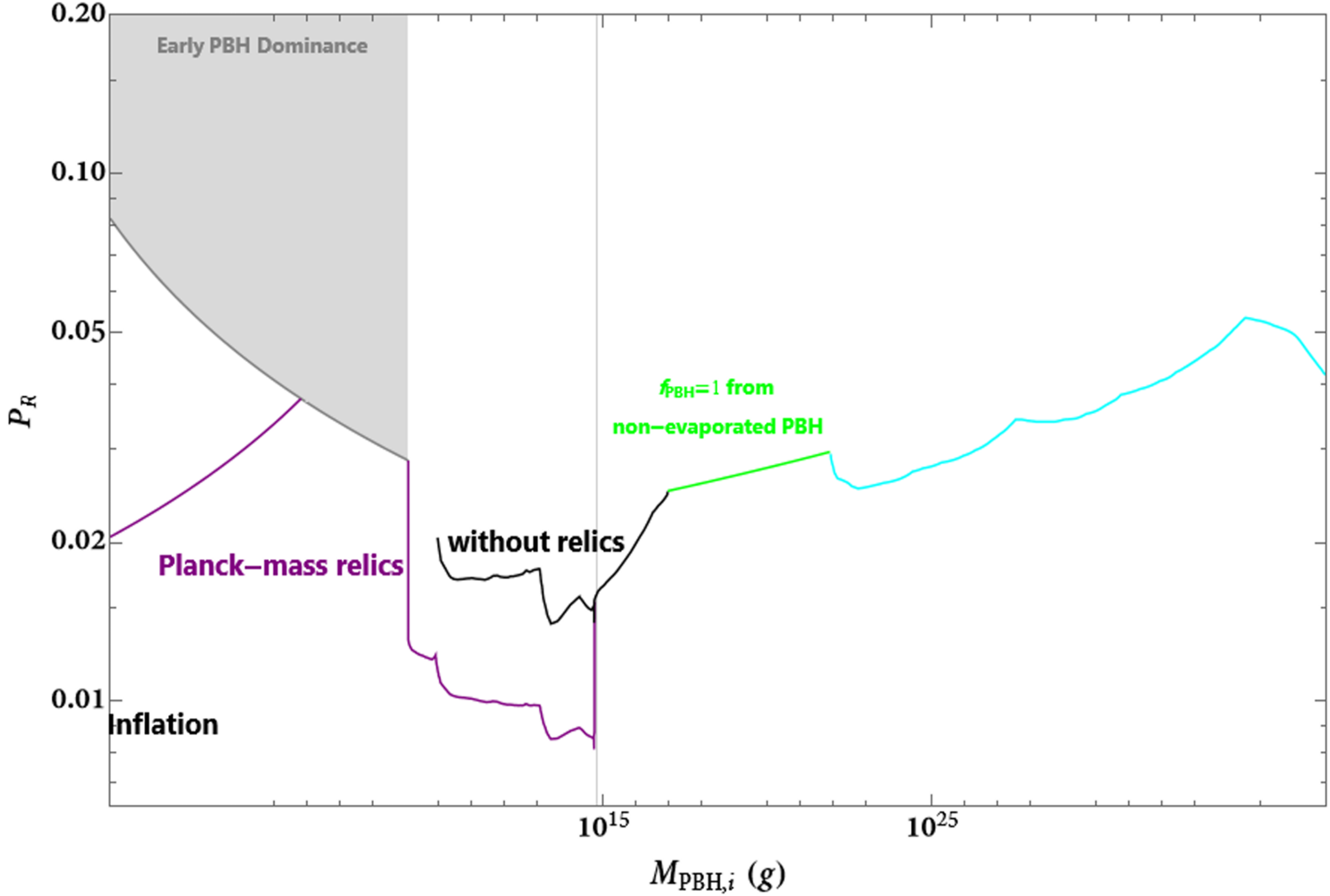
ABSTRACT
The energy injection through Hawking evaporation has been used to put strong constraints on primordial black holes as a dark matter candidate at masses below 10^{17} g. However, Hawking's semiclassical approximation breaks down at latest after half-decay. Beyond this point, the evaporation could be significantly suppressed as was shown in recent work. In this study, we review existing cosmological and astrophysical bounds on primordial black holes taking this effect into account. We show that the constraints disappear completely for a reasonable range of parameters, which opens a new window below 10^{10} g for light primordial black holes as a dark matter candidate.

Key words: dark matter – black hole physics – gamma-rays: general





Extreme scenarios: the tightest possible constraints on the power spectrum due to primordial black holes (2018), B. Chris...
M_{PBH}
$P_R(k)$
10^{-2}
10^{-9}
Current Constraints, δ_c = 0.42
[redacted]
CMB
My imagination!!
10^3
10^7
10^{11}
10^{15}
10^{19}
$k\,(Mpc^{-1})$



0.20
0.10
0.05
0.02
0.01
Early PBH Dominance
$f_{PBH}=1$ from
non−evaporated PBH
without relics
Planck−mass relics
Inflation
10^{15}
10^{25}
P_R
$M_{PBH,i}$ (g)

The abundance of PBH at formation:

$$\beta = \frac{\rho_{PBH}}{\rho_{tot}}\Big|_{form} \quad \text{until } t_{eq} \quad \rho_{tot} \propto a^{-4}, \quad \rho_{PBH} \propto a^{-3}$$

$$\Rightarrow \beta_{eq} = \frac{a_{eq}}{a_i}\beta_i = \left(\frac{M_{eq}}{M_i}\right)^{1/2}\beta_i$$

@ t_{eq}: $\frac{\rho_{dm}}{\rho_{tot}} + \frac{\rho_b}{\rho_{tot}} = \frac{1}{2}$

$$\Rightarrow \frac{\rho_{dm}}{\rho_{tot}}\left(1 + \frac{\Omega_b}{\Omega_{DM}}\right) = \frac{1}{2}$$

Then to relat $f_{PBH,0}$ with β_i, we need to find:

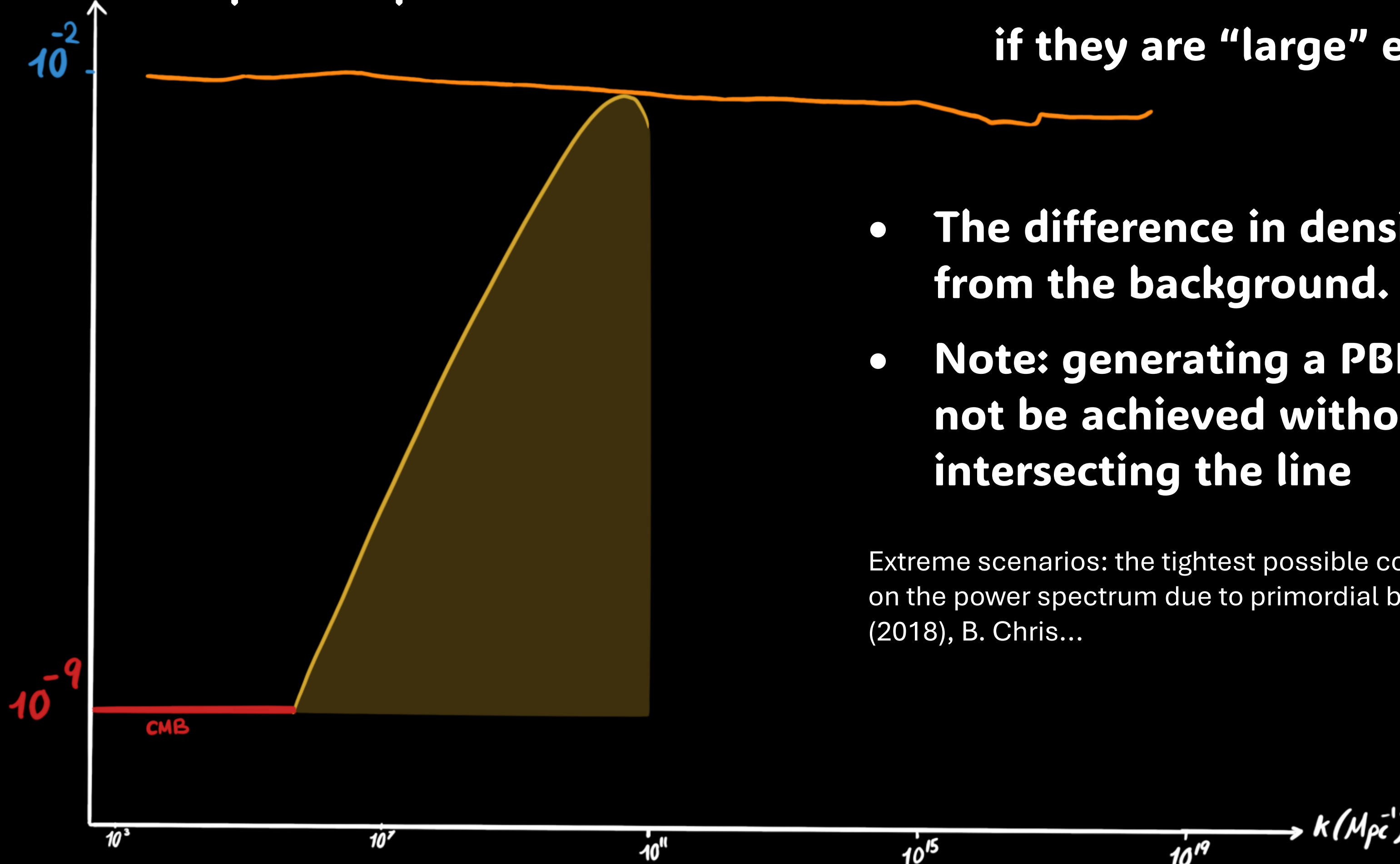
$$\beta_{eq} = \frac{\rho_{PBH}}{\rho_{tot}}\Big|_{eq} = \frac{\rho_{PBH}}{\rho_{dm}} \cdot \frac{\rho_{dm}}{\rho_{tot}}$$

$$= f_{PBH,0} \cdot \left(\frac{1}{2\left(1 + \frac{\Omega_b}{\Omega_{DM}}\right)}\right)$$

$$\Rightarrow \boxed{\frac{f_{PBH,0}}{2\left(1 + \frac{\Omega_b}{\Omega_{DM}}\right)} = \left(\frac{a_{eq}}{a_i}\right)\beta_i \cdot \left(\frac{m_f}{m_i}\right)}$$

The power spectrum

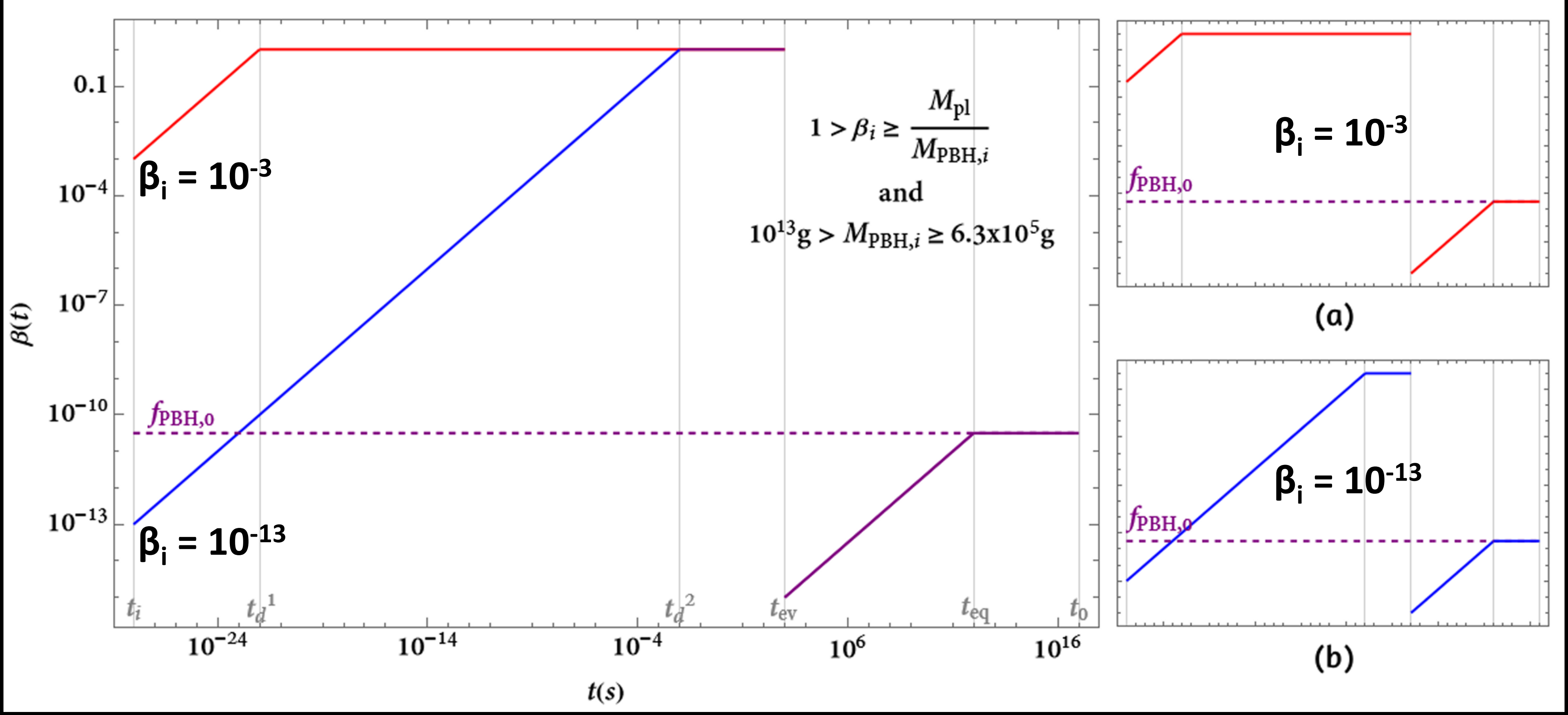
if they are “large” enough



- **The difference in densities from the background.**
- **Note: generating a PBH can not be achieved without intersecting the line**

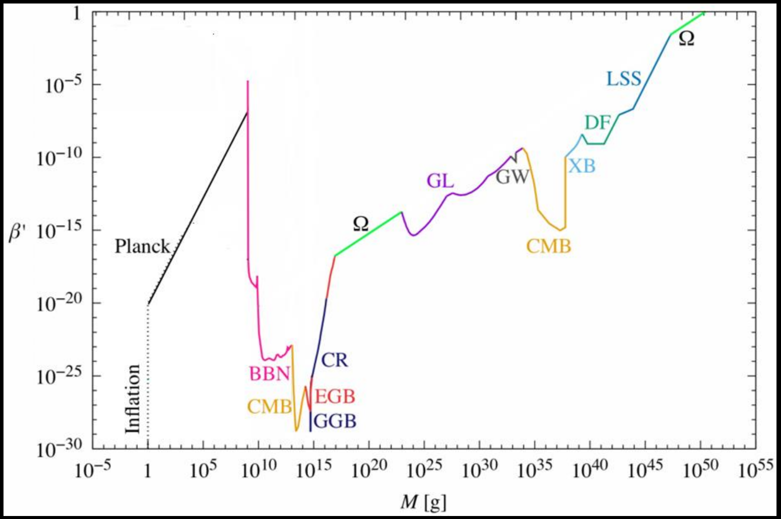
Extreme scenarios: the tightest possible constraints on the power spectrum due to primordial black holes (2018), B. Chris...

The abundance of PBHs as function of time for different β_i and same initial mass



The fraction of DM as PBHs ($f_{\rm PBH}$):

$$f_{\rm PBH} \approx 2.4 \left(\frac{m_{\rm f}}{m_{\rm i}}\right)\left(\frac{a_{\rm f}}{a_{\rm i}}\right)\beta_{\rm i}$$



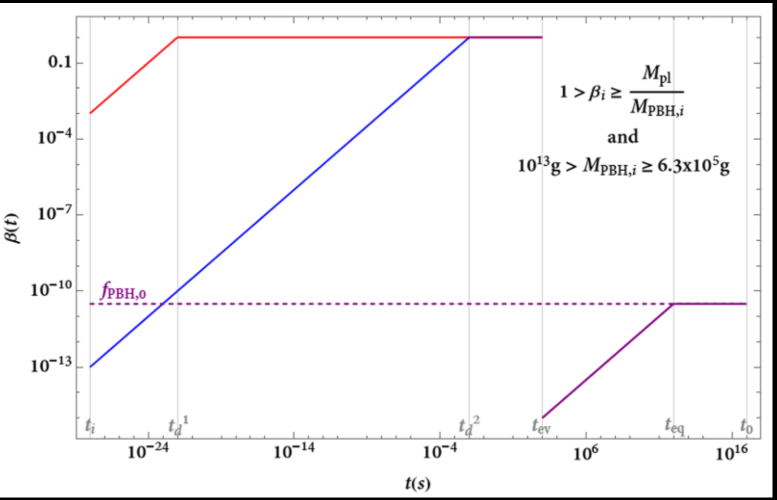
Assuming Mpl relics:

$$f_{\rm PBH,0} \approx 2.4 \left(\frac{M_{\rm pl}}{M_{\rm PBH,i}}\right)\left(\frac{a_{\rm eq}}{a_{\rm i}}\right)\beta_{\rm i}$$

Assuming early PBH domination era:

$$f_{\rm PBH,0} = \left(\frac{M_{\rm pl}}{M_{\rm PBH,i}}\right)\left(\frac{a_{\rm d}}{a_{\rm i}}\right)\left(\frac{a_{\rm eq}}{a_{\rm ev}}\right)\beta_{\rm i}$$
$$= \left(\frac{M_{\rm pl}}{M_{\rm PBH,i}}\right)\left(\frac{a_{\rm eq}}{a_{\rm ev}}\right)$$

$$f_{\rm PBH,0} \approx 10^{14}\left(\frac{M_{\rm PBH,i}}{\rm g}\right)^{-5/2}$$



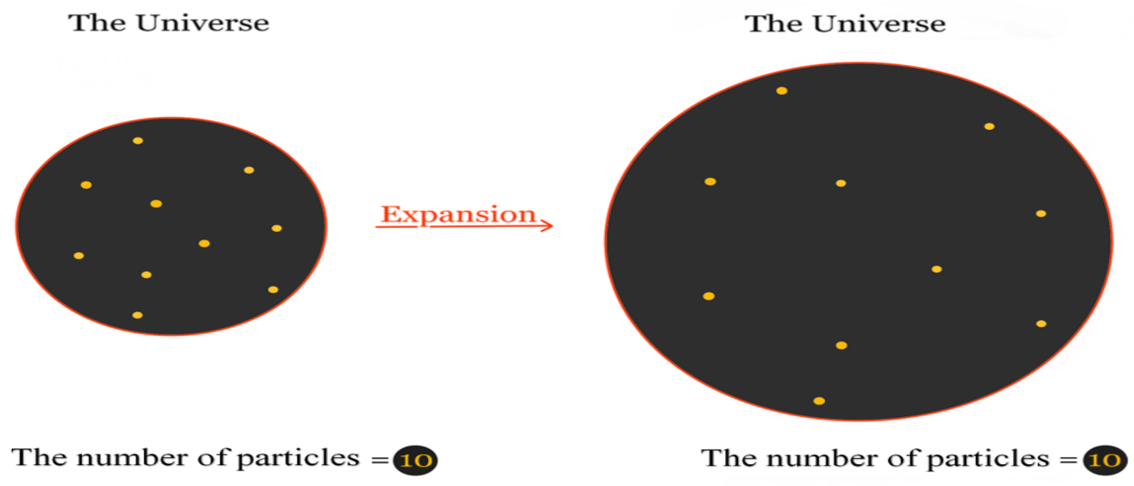


Figure 2.2: The distribution of non-relativistic particles (matter) as the universe expands. We can see that as the universe expands, the number of particles remains the same and the volume becomes larger; therefore, the number density should scale as $n \propto a^{-3}$.

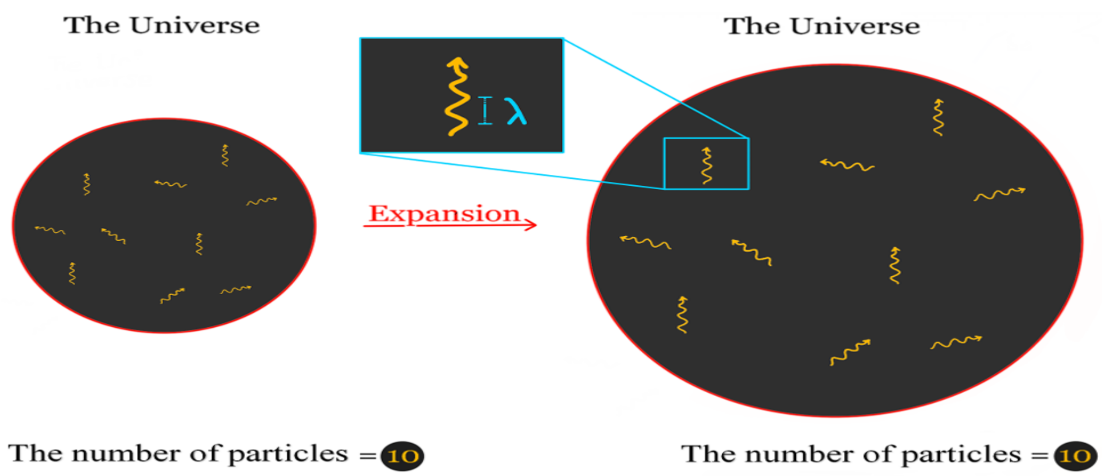


Figure 2.3: The distribution of relativistic particles (radiation) as the universe expands. We can see that as the universe expands, the number of particles remains the same and the volume becomes larger; therefore, the number density should scale as $n \propto a^{-3}$. However, the energy of every individual photon (any massless particle) depends on the wavelength and scales as $E_\gamma \propto \lambda^{-1} \propto a^{-1}$.