PRIMORDIAL BLACK HOLES AS A PROBE TO BEYOND STANDARD MODEL PHYSICS

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28th workshop "What comes beyond the Standard Model?"

Content

- Black hole vs Primordial Black Hole
- Early Matter Domination
- PBH Mass Distribution
- Various Components of the Universe
- Role of PBH
- Entropy Release

Content

- Dark Matter from PBH
- Memory Burdened PBH

Black hole vs Primordial Black Hole

- Formation Mechanism:
  Normal black holes: Form from the gravitational collapse of massive stars (supernovae) or by mergers of compact objects.

  Primordial black holes: Hypothetically formed from high-density fluctuations in the very early universe (within fractions of a second after the Big Bang).

Black hole vs Primordial Black Hole

- Formation time:
  Normal black holes: Form much later in cosmic history – millions to billions of years after the Big Bang.

  Primordial black holes: Could form during the radiation-dominated era, much earlier than stars or galaxies.

Black hole vs Primordial Black Hole

- Possible Mass Range:
  Normal black holes: Typically a few solar masses (stellar) to billions of solar masses (supermassive).

  Primordial black holes: Could span a huge mass range – from as tiny as ~10^{-1}g to thousands or millions of solar masses, depending on early-universe conditions.

Black hole vs Primordial Black Hole

- Observable Environment:
  Normal black holes: Usually found in stellar environments, galaxies, and active galactic nuclei — associated with visible astrophysical processes like accretion disks, X-ray emission, or gravitational wave mergers.

  Primordial black holes: Might exist in intergalactic space with no stellar environment — their presence is inferred indirectly, e.g., via gravitational lensing, cosmic microwave background constraints, or gravitational wave signals.

Black hole vs Primordial Black Hole

- Cosmological Implications:
  Normal black holes: Important for galaxy evolution, star formation feedback, and gravitational wave astrophysics.

  Primordial black holes: Hypothetical candidates for dark matter, seeds for supermassive black holes, and probes of early-universe physics (e.g., inflation, phase transitions).

Early Matter Domination

- A phase before Big Bang Nucleosynthesis (BBN) where the universe's expansion is temporarily dominated by non-relativistic matter (instead of the usual radiation domination).

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- A phase before Big Bang Nucleosynthesis (BBN) where the universe's expansion is temporarily dominated by non-relativistic matter (instead of the usual radiation domination).
- Occurs after inflation but before standard radiation domination fully takes over.

Early Matter Domination

How Can EMD Be Achieved?

- Massive Long-Lived Particles: EMD can happen if a heavy field or particle (e.g., moduli, scalar condensate, heavy relic) dominates the energy density because it redshifts more slowly than radiation.

Early Matter Domination

Example Mechanisms:

- Oscillating scalar fields (like moduli from string theory) behave like pressureless matter.
- Decay of a massive unstable particle can delay reheating and prolong matter domination.

Early Matter Domination

Why Does EMD Matter for PBHs?

- In matter domination, density perturbations grow linearly with the scale factor instead of remaining constant (as in radiation domination). This boosts the probability of PBH formation.

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- Radiation pressure resists collapse – but in an EMD phase, the lack of significant pressure allows overdense regions to collapse more easily into PBHs.

- Even small primordial fluctuations can produce a sizable PBH population if EMD persists long enough.

Early Matter Domination

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- EMD phases are generic in many beyond-the-Standard-Model (BSM) scenarios, linking PBHs to new physics (e.g., moduli, inflaton remnants).

PBH Mass Distribution

- Monochromatic Mass Distribution
  1. All PBHs have mass $M = M_0$,
  2. The mass function: $\psi(M) = f_{PBH}\delta(M - M_0)$,
  3. Simplifies abundance calculations.
  4. Allows direct comparison with observational constraints at fixed mass M_0.

PBH Mass Distribution

- Non Monochromatic Mass Distribution
  1. PBHs span a continuous range of masses,
  2. Typical forms include log-normal distribution, power law distribution,
  3. Reflects more realistic formation scenarios.
  4. Constraints depend on the integrated contribution across the mass range.
  5. Enables richer phenomenology for observational signatures.

Various Components of the Universe

- Key Cosmological Components:
The energy content of the Universe can be broadly categorized into:
    1. Radiation (relativistic particles, e.g., photons, neutrinos)
    2. Matter (non-relativistic, e.g., baryons, dark matter)
    3. Vacuum Energy (cosmological constant, dark energy, false vacuum)

Various Components of the Universe

Stage	Dominant Component	EoS w	$\rho(a)$ Scaling
Radiation-Dominated (RD)	Relativistic particles	$w = \frac{1}{3}$	$\rho_R \propto a^{-4}$
Matter-Dominated (MD)	Non-relativistic matter	$w = 0$	$\rho_M \propto a^{-3}$
Vacuum-Dominated (VD)	Cosmological constant / false vacuum	$w = -1$	$\rho_\Lambda = \text{const}$

Various Components of the Universe

- Key Equations:

RD: $\rho_R = \frac{\pi^2}{30} g_* T^4$ and $\mathscr{P}_{\mathrm{R}} = \frac{1}{3}\rho_{\mathrm{R}}$

MD: $\rho_M = nm$ and $\mathscr{P}_{\mathrm{M}} = 0$

VD: $\rho_\Lambda = \mathrm{const}.$ and $\mathscr{P}_\Lambda = -\rho_\Lambda$

Role of PBH

- Entropy production:
  PBHs evaporate via Hawking radiation:

$$T_{BH} = \frac{1}{8\pi G M} = \frac{1}{8\pi}\frac{M_{Pl}^2}{M}$$

Role of PBH

- Evaporation injects energy into the surrounding plasma:

  1. Reheats the universe if PBHs dominate the energy density temporarily

  2. Increases total entropy.

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- Entropy density injection:

$$s = \frac{2\pi^2}{45} g_* T^3$$

Role of PBH

- PBHs can produce stable dark matter particles (e.g., WIMPs, gravitinos, axions) during evaporation($m_\chi < T_{BH}$)

- Dark Matter Yield: $Y_\chi = \frac{n_\chi}{s} \approx \frac{3}{4}\frac{T_{evap}}{m_\chi}Br(\chi)$

Role of PBH

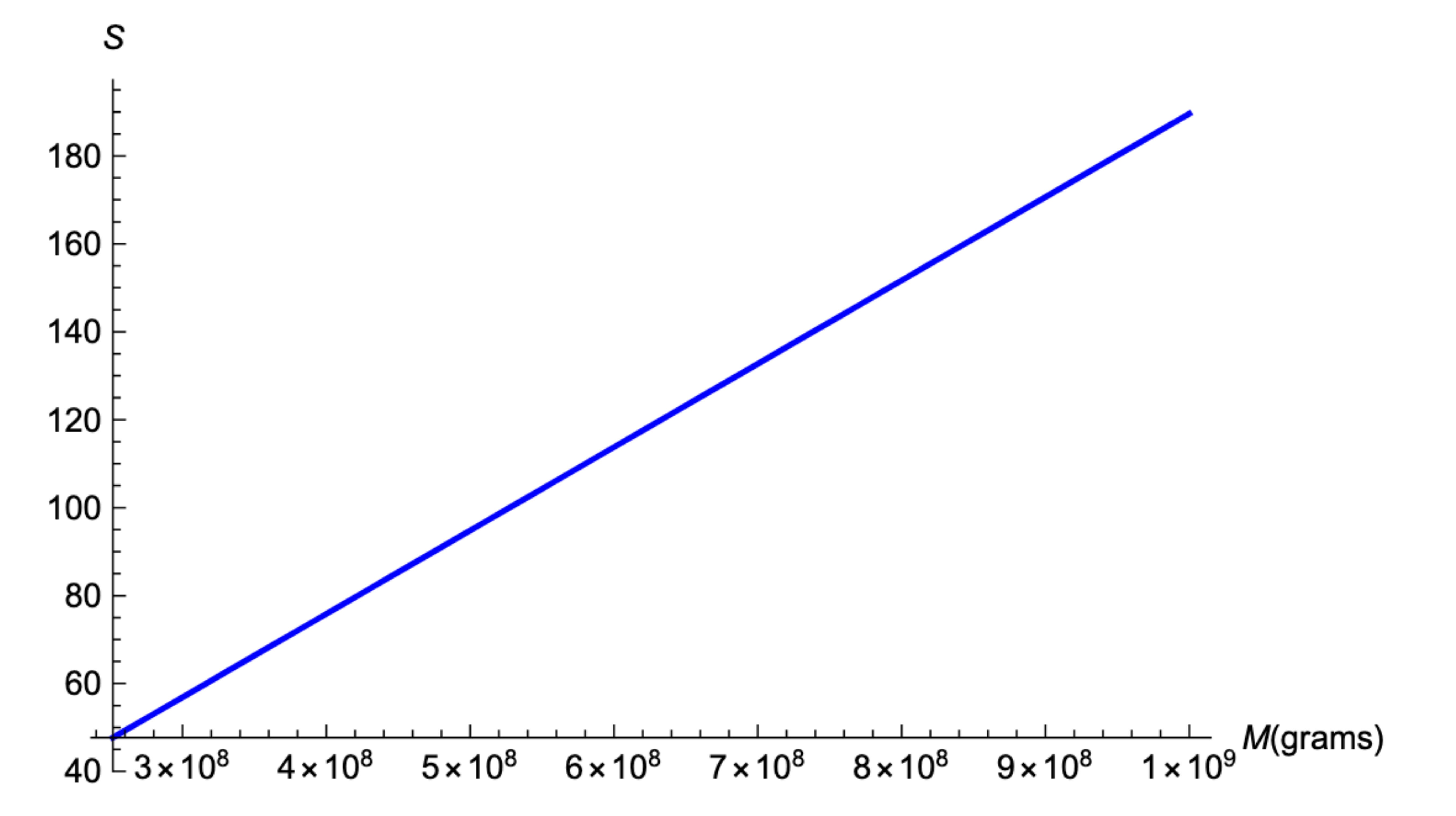
- Modification of Hubble parameters:

$$H(a) = \sqrt{\frac{\rho_R(a) + \rho_{PBH}(a)}{3M_{Pl}^2}}$$

Entropy Release

- Light PBH ($M_{BH} < 10^9$ g) can dominate the early universe and evaporate resulting in the release of entropy.
- For a monochromatic mass distribution and assuming instant decay approximation, the net release in entropy is shown:

Entropy Release



Entropy release as a function of PBH initial mass. (Chaudhuri and Dolgov, JETP 133 (2021) 5, 552-566)

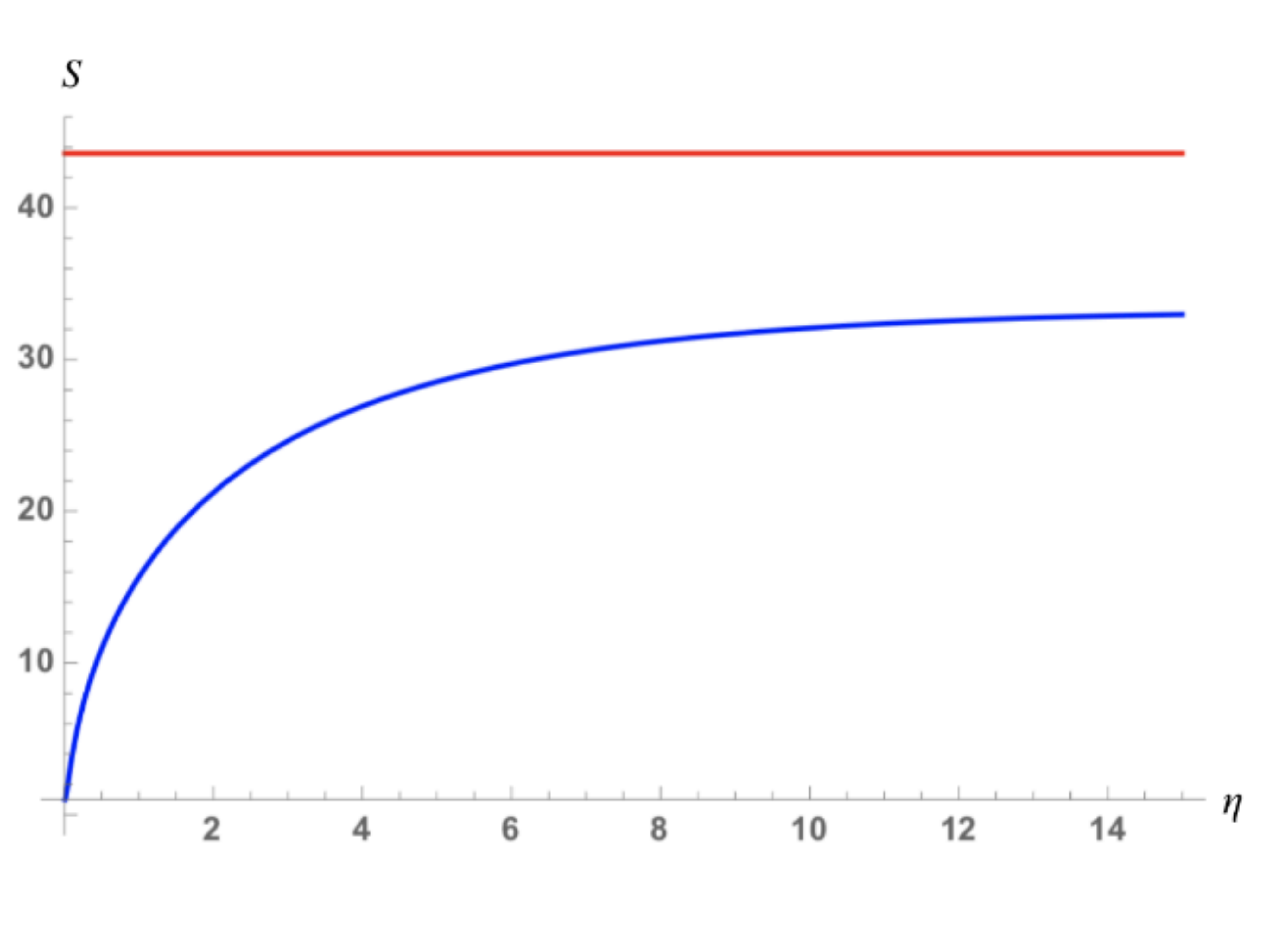
Entropy Release

- For Non-Monochromatic distribution:

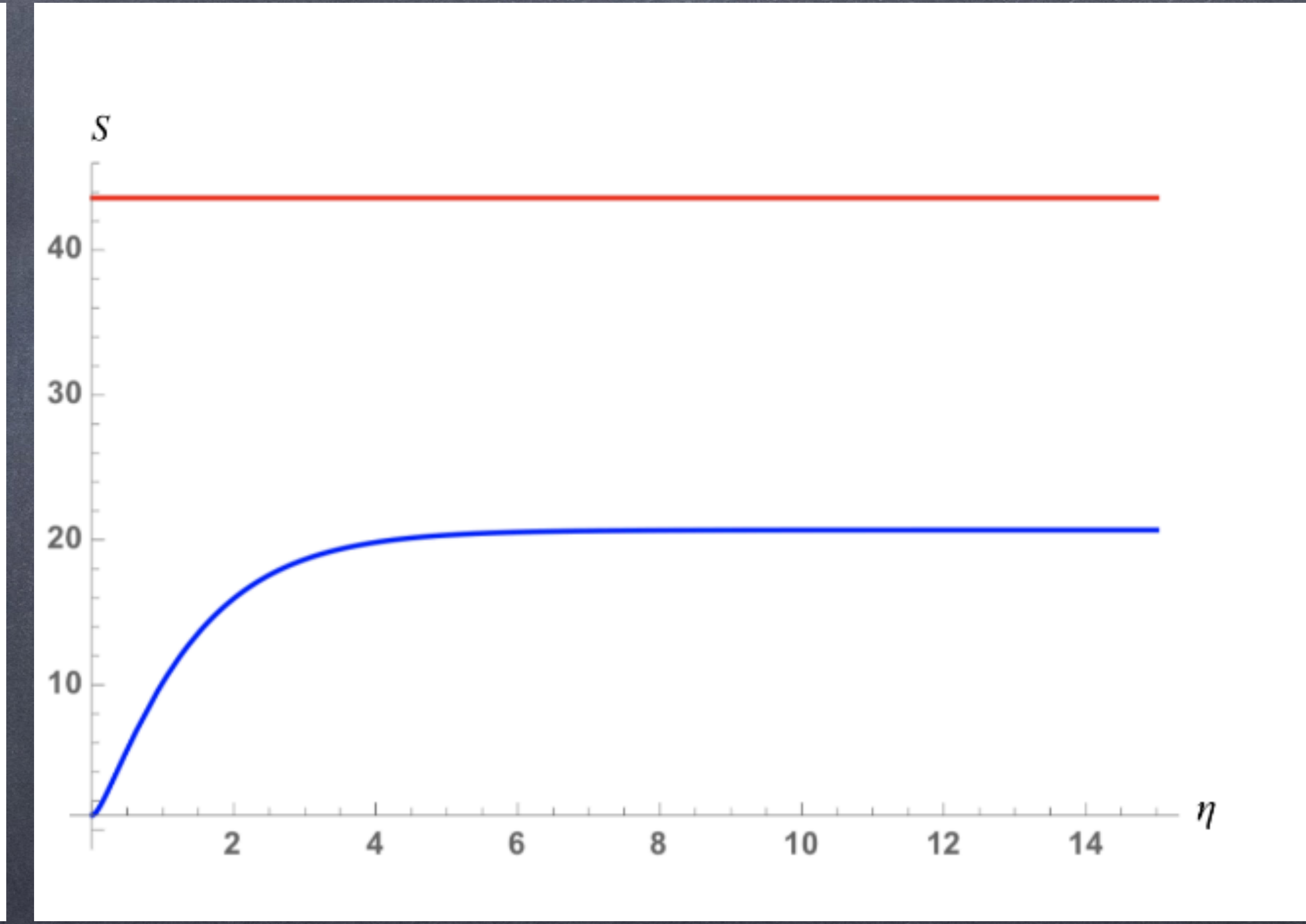
a. $F_1(x) = \beta/(x_{max} - x_{min})$

b. $F_2(x) = \dfrac{\beta}{N} a^2 b^2 (1/a - 1/x)^2 (1/x - 1/b)^2 .$

Entropy Release



Distribution a.



Distribution b.

Ingredients of DM Production from PBH distribution

- Important Parameter:

  1. PBH initial mass (M_{BH}^{in})
  2. Dark Matter mass (m_{DM})
  3. $\beta = \dfrac{\rho_{PBH}^{ini}}{\rho_{PBH}^{ini} + \rho_{rad}^{ini}}$

$$\frac{d\rho_{BH}}{dt} + 3H\rho_{BH} = \frac{\rho_{BH}}{M}\frac{dM}{dt},$$

$$\frac{d\rho_R}{dt} + 4H\rho_R = -\frac{\varepsilon_{SM}(M)}{\varepsilon(M)}\frac{1}{M}\frac{dM}{dt}\rho_{BH}$$

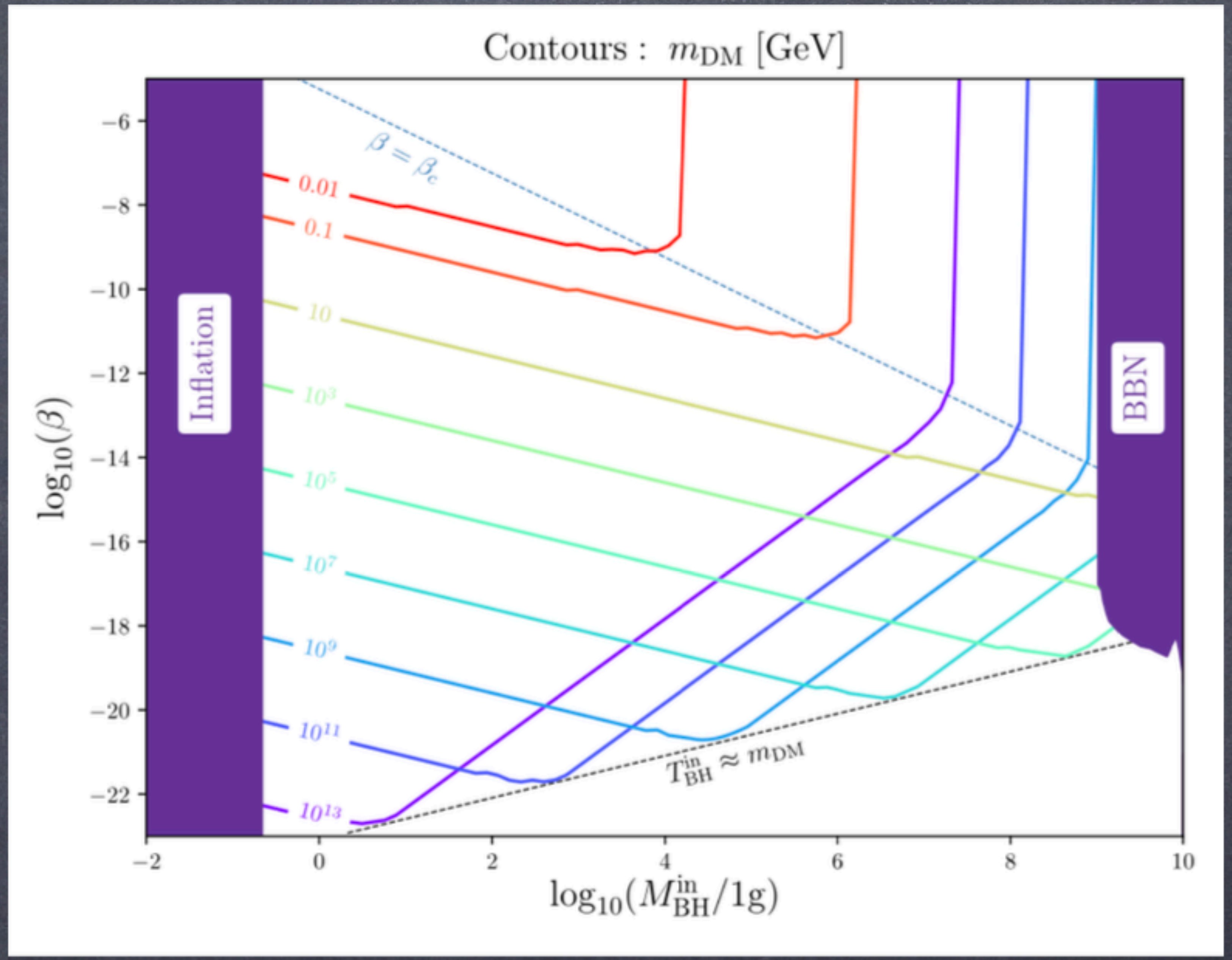
$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = \frac{\rho_{BH}}{M_{BH}}\frac{dN_{DM}}{dt}$$

$$\beta_c = \gamma^{-\frac{1}{2}}\left(\frac{\mathcal{G}g_{\star,H}(T_{BH})}{10640\pi}\right)^{\frac{1}{2}}\frac{M_{Pl}}{M},$$

- Constrains from BBN, Inflation and GW Observations

Relic Contours: Single PBH Distribution

DM of mass range $(1 - 10^9)$GeV produced from an evaporating monochromatic PBH distribution cannot satisfy DM relic in the PBH dominated region of parameter space due to the BBN bounds

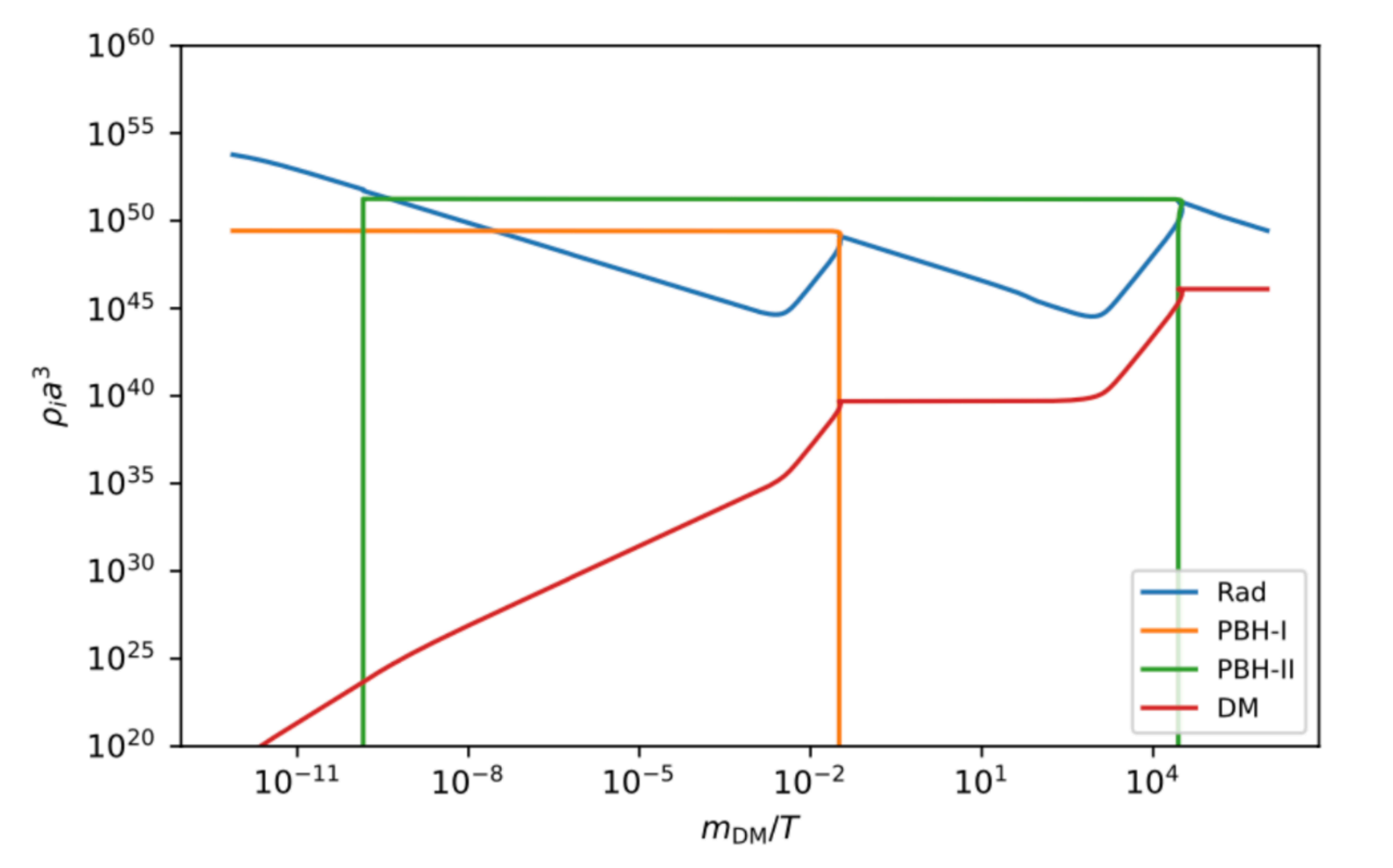


PHYS. REV. D 105, 015023 (2022)

2PBH Scenario: Formalism

- Temporally separated formation of two monochromatic PBH distributions.
- $T_1 > T_2$ and hence, $M_{BH1}^{in} < M_{BH2}^{in}$
- The one-PBH case is compared to the second PBH of the two-PBH scenario.
- $\beta_1 = \dfrac{\rho_{BH1}(T_1)}{\rho_{BH1}(T_1) + \rho_{Rad}(T_1)}\ ,\ \beta_2 = \dfrac{\rho_{BH1}(T_2) + \rho_{BH2}(T_2)}{\rho_{BH1}(T_2) + \rho_{BH2}(T_2) + \rho_{Rad}(T_2)}$

Formalism: Evolution of components of the Universe



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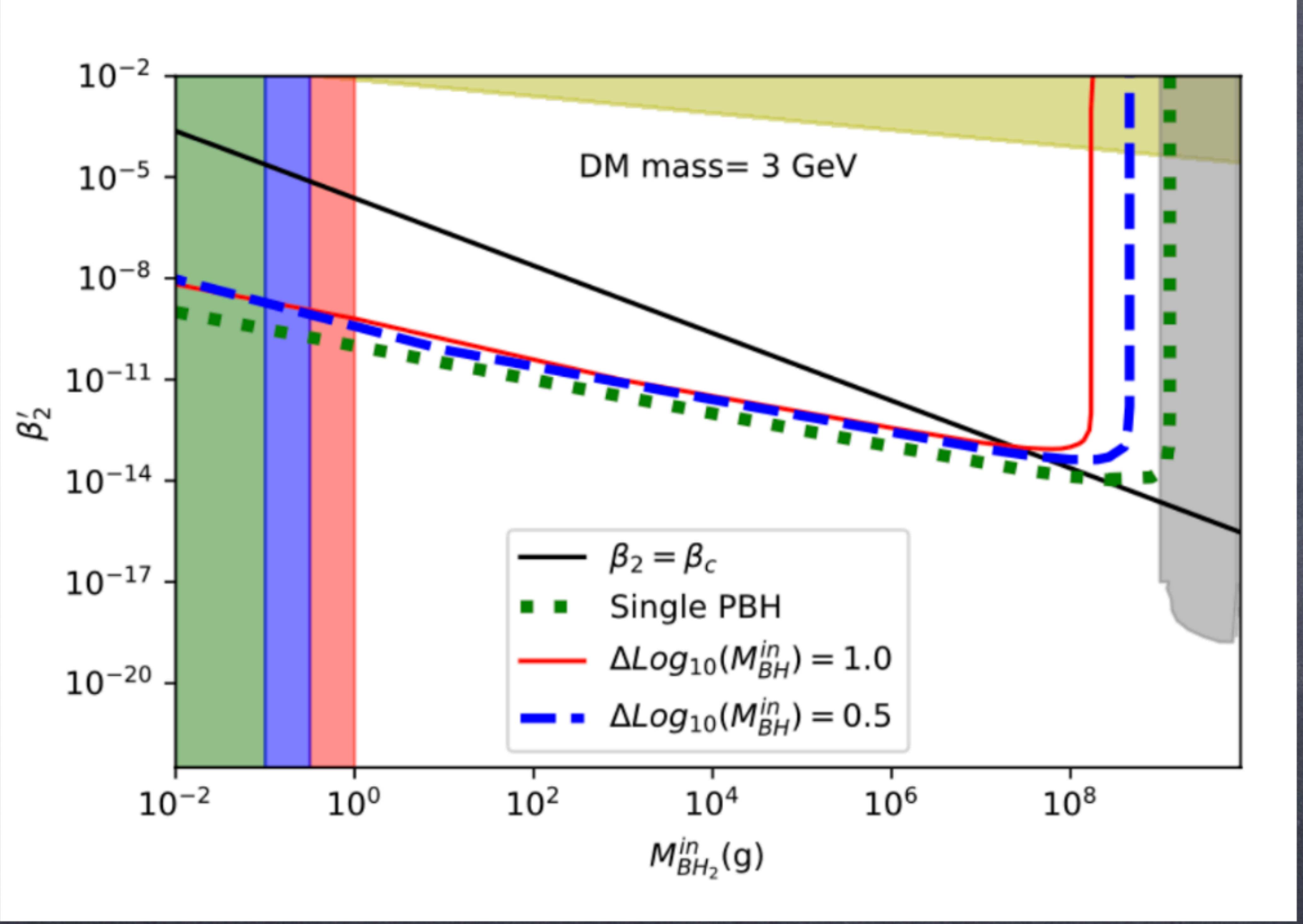

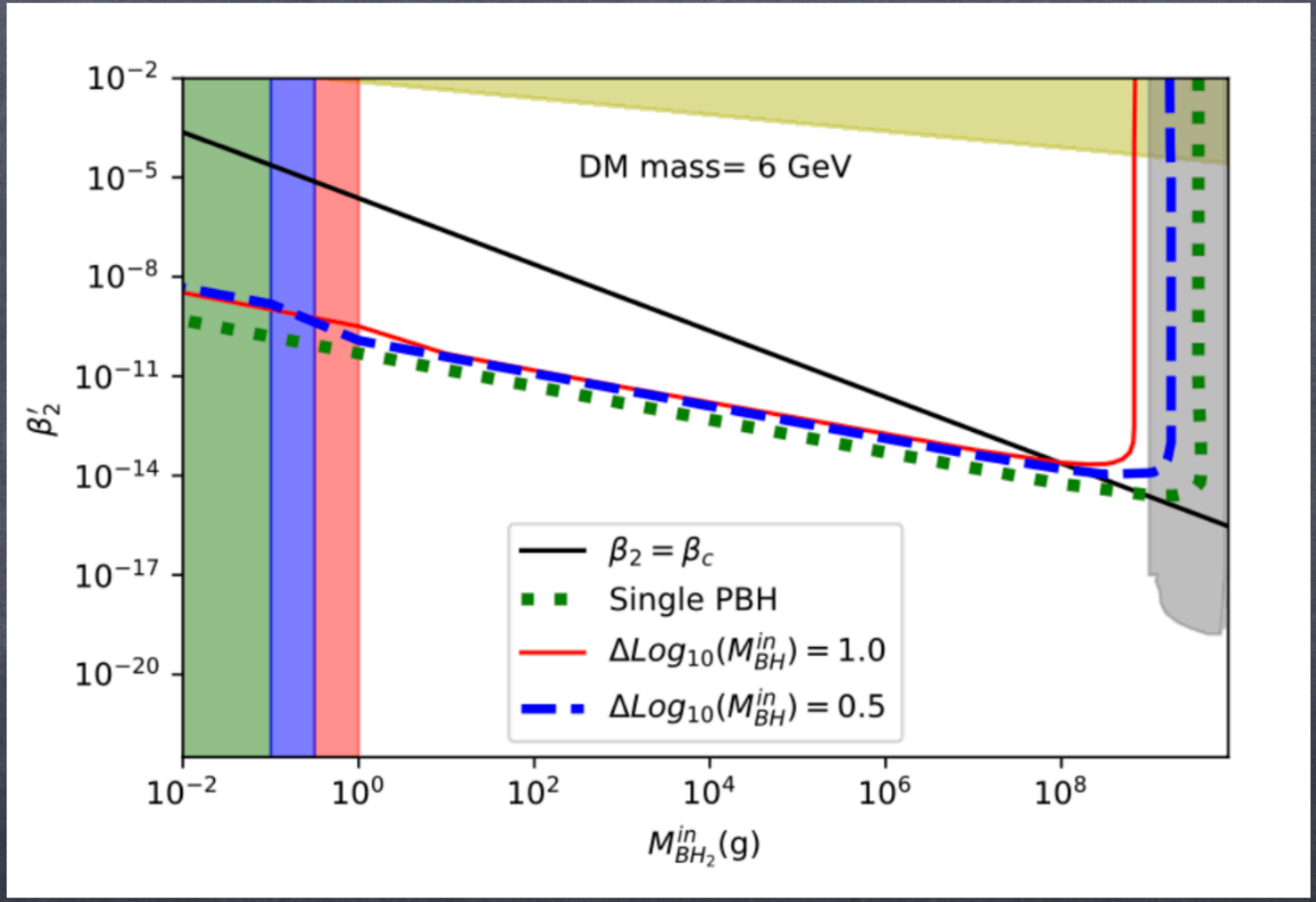

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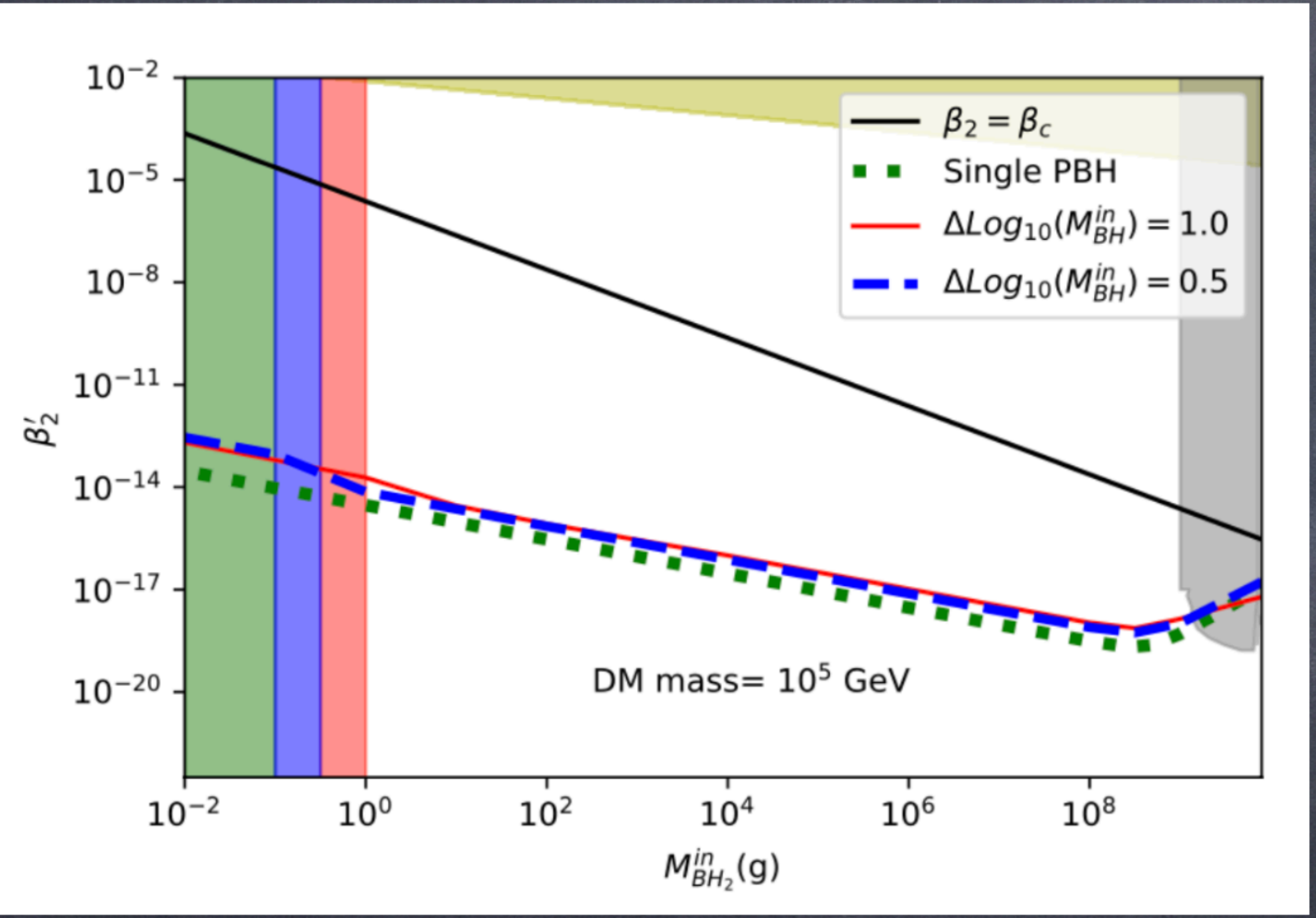

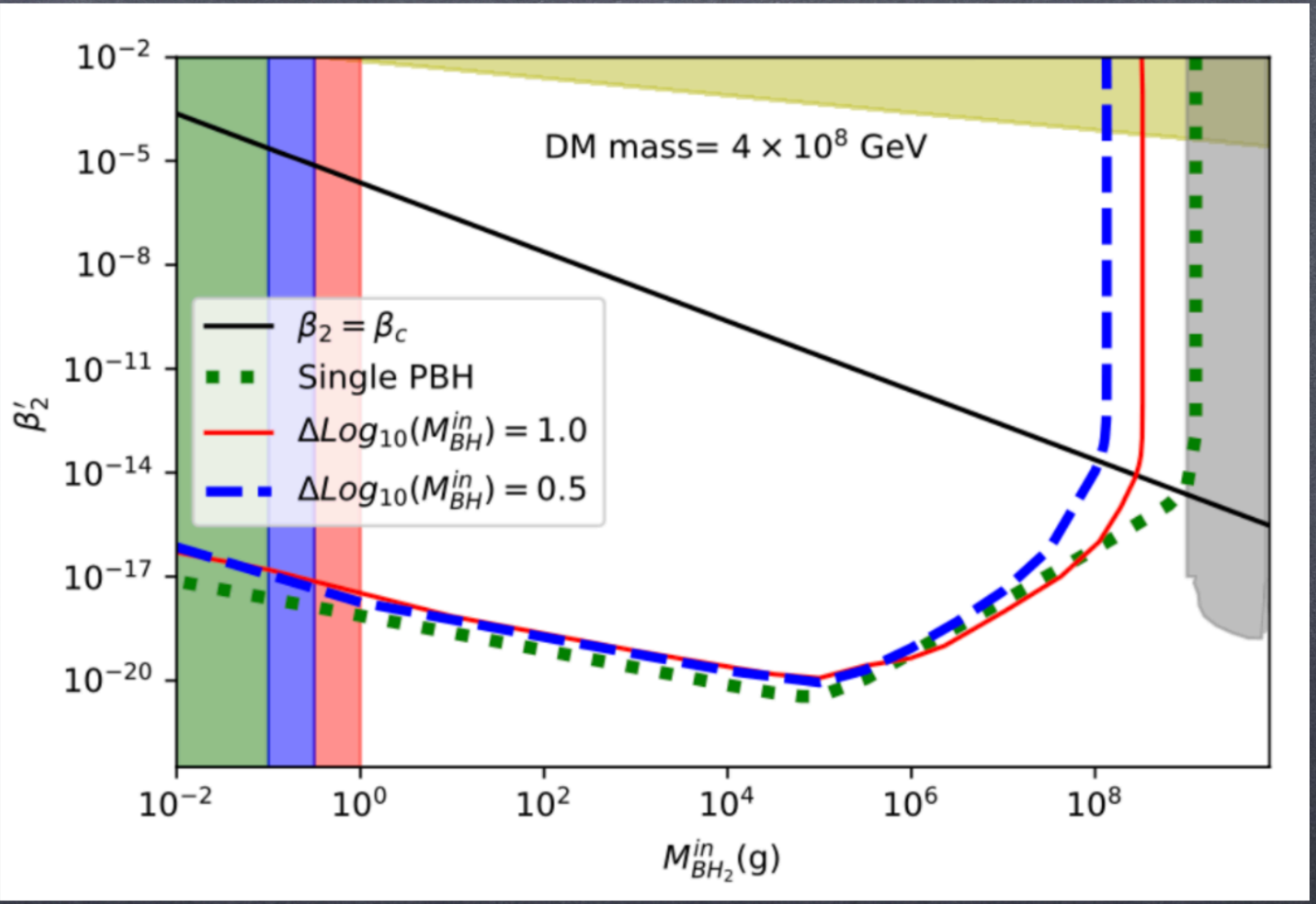

Exact window of relaxation

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- For $\Delta Log_{10}(M_{BH}^{in}) = 1.0$ in grams, the disallowed DM mass is $(7.24 - 8.91 \times 10^7)$ GeV.

- For $\Delta Log_{10}(M_{BH}^{in}) = 0.5$ in grams, the disallowed DM mass is $(5.56 - 2.67 \times 10^7)$ GeV.

(Chaudhuri, Coleppa and Loho
PRD 108 (2023) 3, 035040)

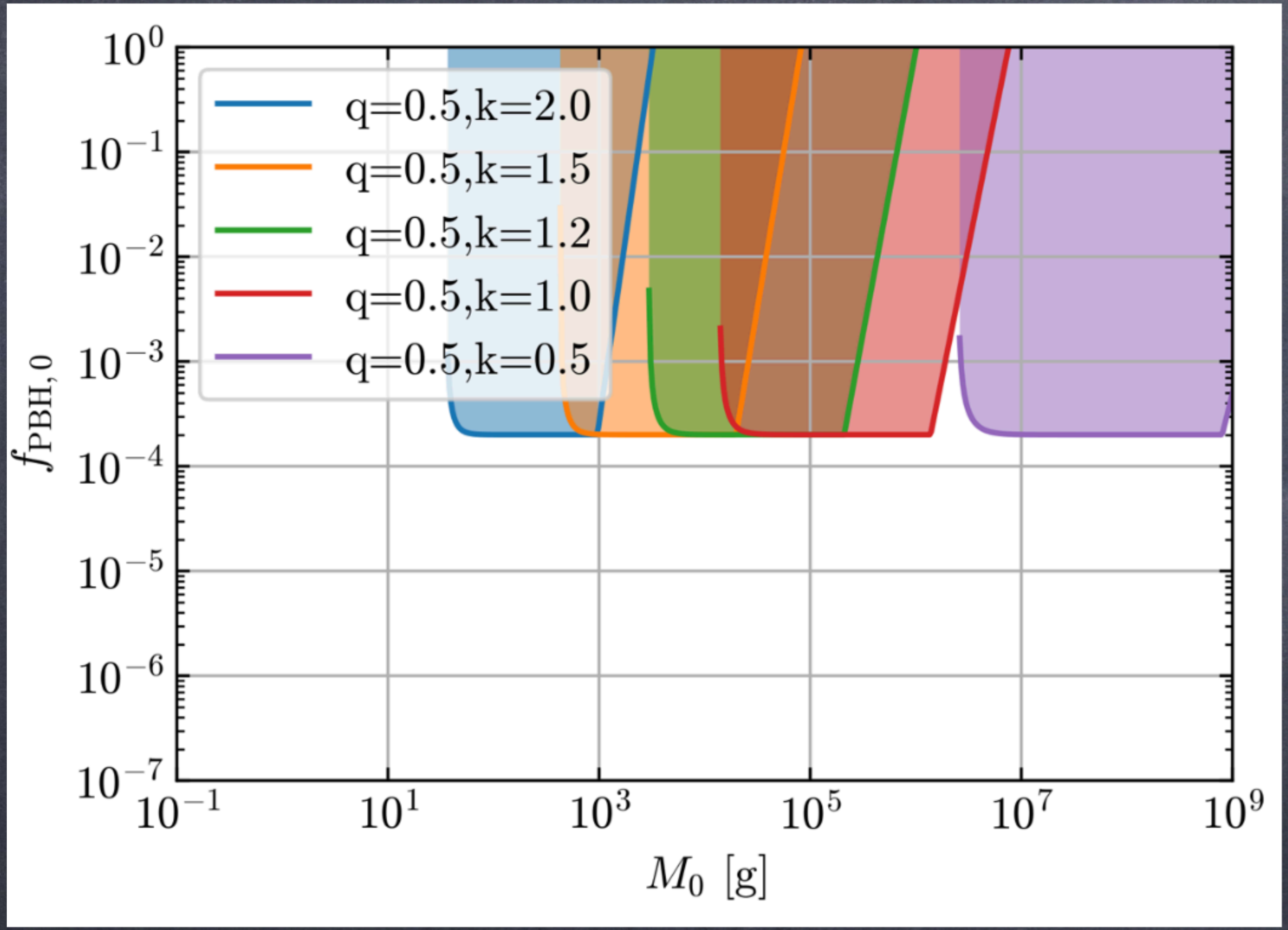
Memory Burdened PBH

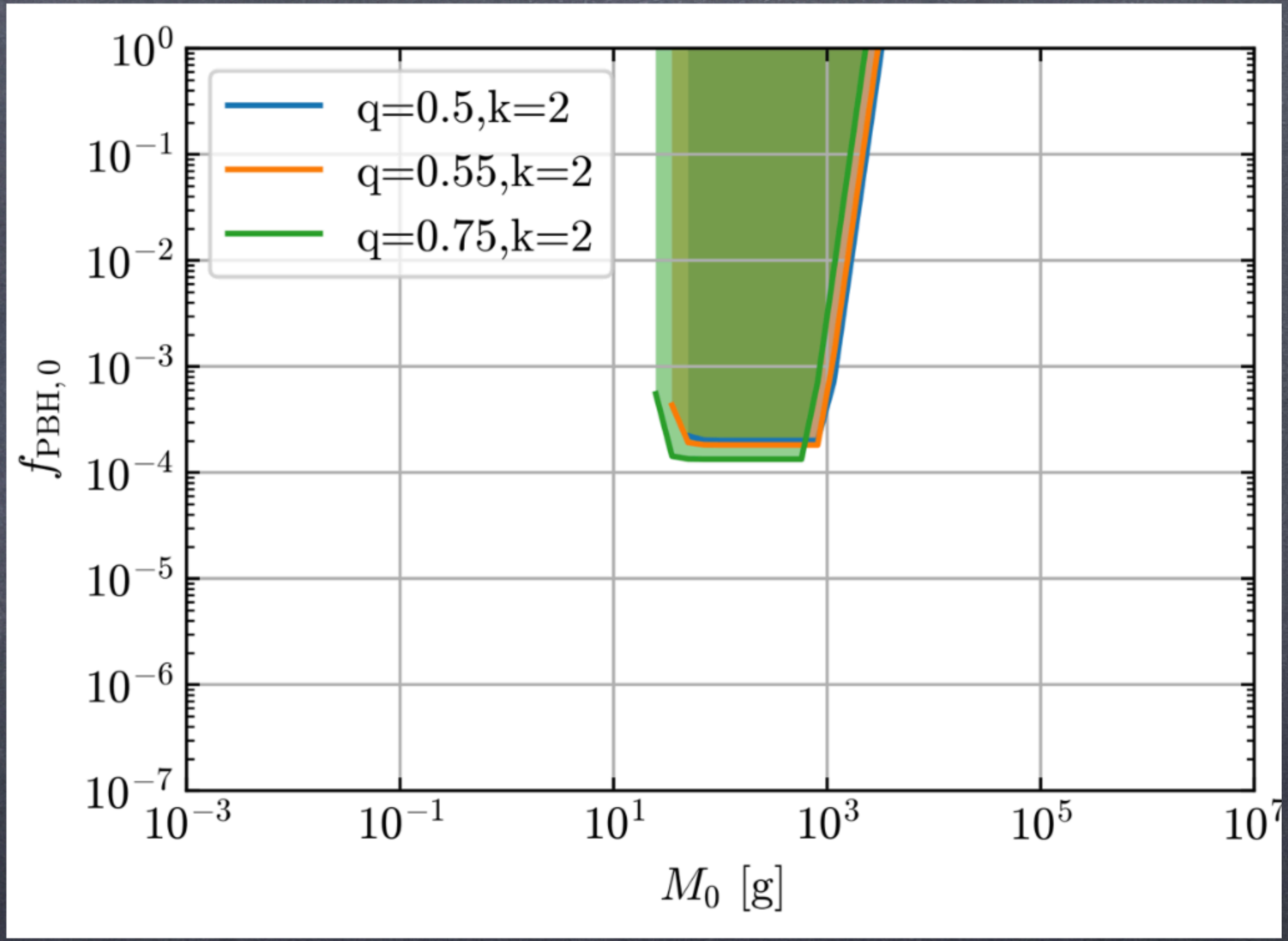
- The evaporation of PBH gets suppressed largely after it has lost half of its mass.
- This is called the memory burden effect (Dvali, PRD 102, 10, 103523 (2022))
- The mass $M_{BH} = qM_{in}$ and $\frac{dM_{BH}}{dt} = -\frac{\epsilon}{S(M_{BH})^k}\frac{M_P^4}{M_{BH}^2}$

Memory Burdened PBH

- The suppression of Hawking evaporation due to the memory burden effect fundamentally reshapes constraints on PBHs, most notably for $M_0 < 10^{10}\,\mathrm{g}$ - assuming it becomes relevant when the black hole has lost half its initial mass.
- Previous work has focused on the question, whether this opens up a new window for PBHs to make up the entire dark matter.
- However, even much lighter PBHs that cannot explain the present dark matter density can be interesting probes of the physics of the early Universe.

Memory Burdened PBH

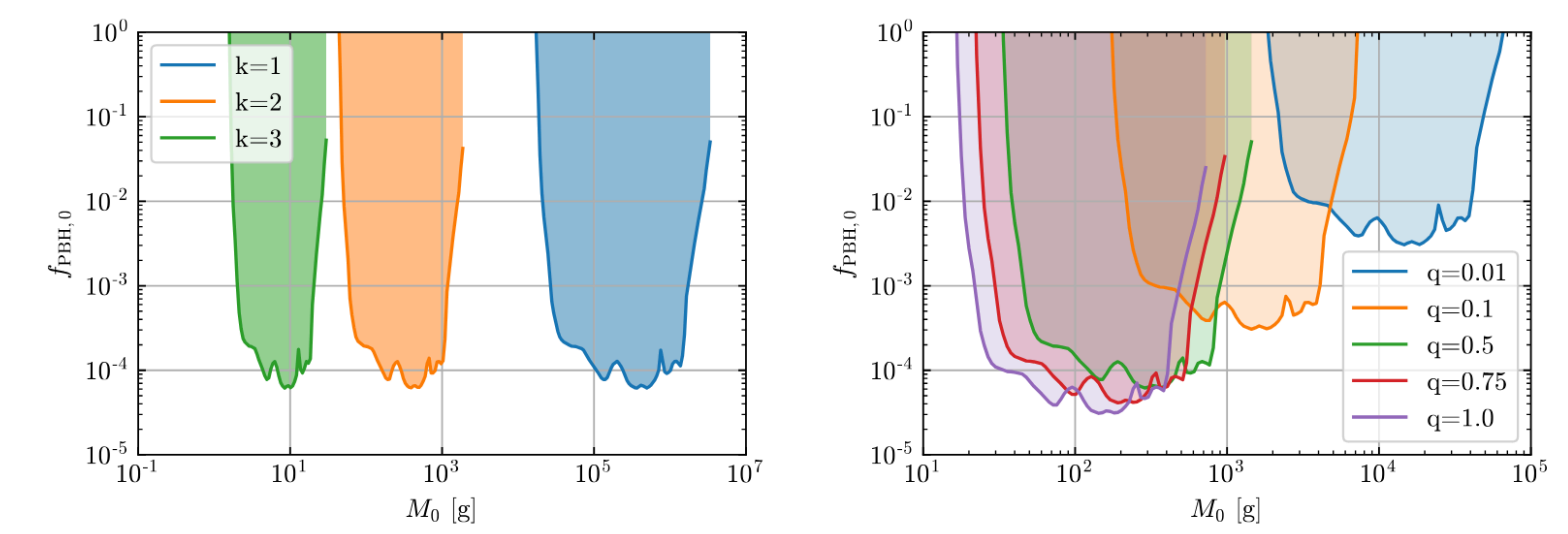




Modified BBN bounds

Chaudhuri, Kohri, Thoss arXiv:2506.20717

Memory Burdened PBH



Bounds on $f_{\mathrm{PBH},0}(M_0)$ from BBN (shaded regions). The left panel displays constraints for q=0.5 and various values of k. The right panel shows bounds for k=2 and various value of q.

Memory Burdened PBH

- The bounds from BBN extend the existing constraints to lighter PBHs that do not survive to the present day - unless they leave behind relics.

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- The bounds from BBN extend the existing constraints to lighter PBHs that do not survive to the present day - unless they leave behind relics.
- While they are thus excluded from making up the present dark matter, light evaporating PBHs have been studied as a mechanism to produce particle DM, to address baryogenesis or as a source of gravitational waves, recently also in the context of the memory burden effect.

Memory Burdened PBH

- For these analyses, our constraints provide important limits for the available parameter space. In particular, for k=1, PBHs have to be lighter than $M_0 = 10^4\,\mathrm{g}$ in order to avoid cosmological constraints and evaporate before the onset of BBN.
- Observational limits on the tensor-to-scalar ratio imply that PBHs, which form from density fluctuations seeded by inflation, have a mass of at least $\sim 1\,\mathrm{g}$.

Memory Burdened PBH

- Together with our results, this imposes a bound of $k \lesssim 3$ in order to have fully evaporating PBHs that are not strongly constrained by BBN, although the precise bound will depend on the value of γ and the accretion of the black hole after horizon formation.

THANK YOU

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Спасибо

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