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Primordial Black Holes in a Thermal Bath: Cosmological Implications

(Based on arXiv: XX11.XXXX)

In collaboration with Yann Mambrini and Rajesh Karmakar.

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Outline of the talk

Motivation:

Observational difficulty in the early Universe: reason for considering PBH

Goal:

- Brief overview of PBH evaporation
- BH absorption → High-frequency absorption cross-section; → low-frequency absorption cross-section
- Impact of thermal absorption on the PBH evolution
- Improved predictions for the DM from PBHs → Evaporating PBHs; → Stable PBHs as Dark Matter

Conclusions

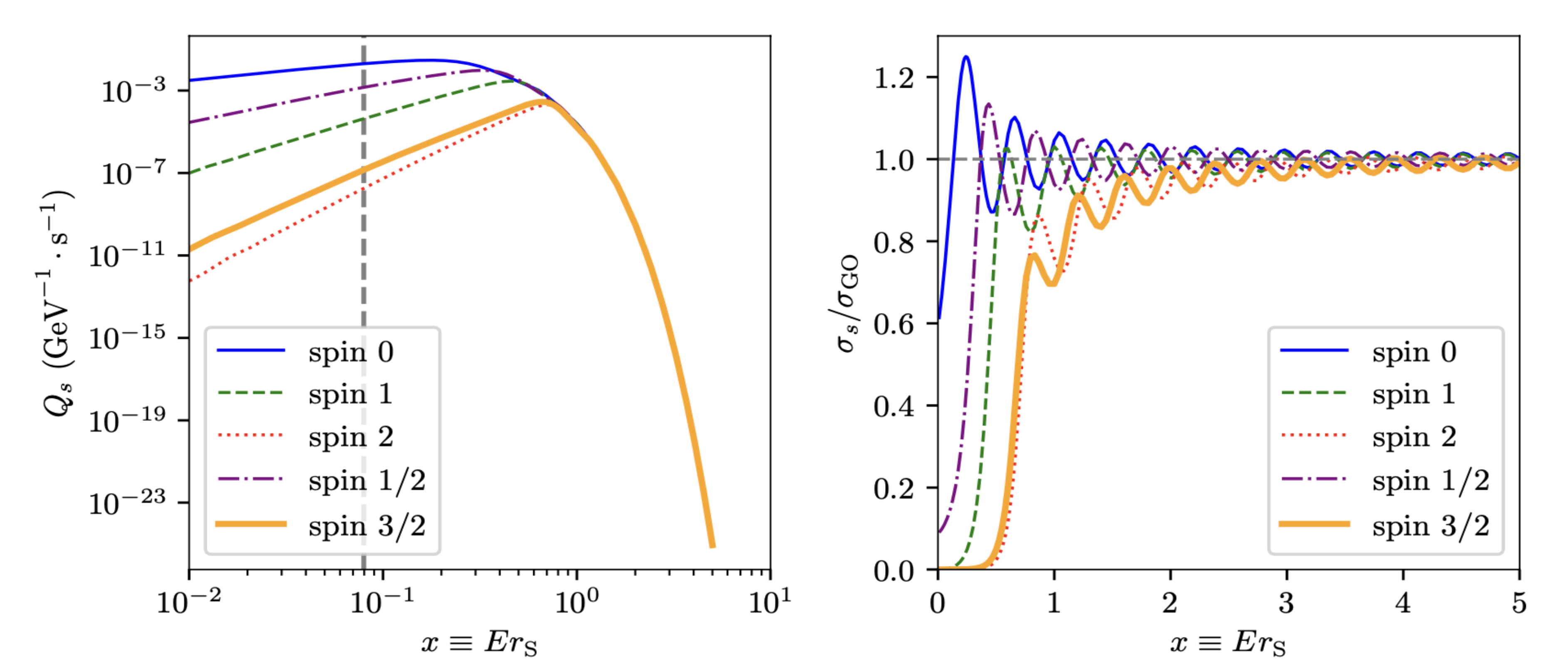
Why Primordial Black Holes?

- A novel and promising candidate for cold dark matter
- There are several mechanisms, including inflation, that can generate PBH abundantly.
- Non-baryonic, non-relativistic and nearly collisionless.
- Ultralight PBH can be responsible for the production of DM as well as SM particles.
- Several gravitational wave sources associated with PBHs give rise to the detection possibilities of the Early Universe.
- The detection of gravitational waves (GWs) by LIGO hints at the potential presence of PBHs.

PBH formation during early Universe : Possibilities

- Inflation origin
- Preheating after inflation
- Collapse of domain walls
- Collapse of cosmic strings
- Electroweak phase transition, first-order phase transition

Energy spectrum



Left: Energy spectrum of the emitting particles. Right: absorption cross-section in high energy limit

$$Q_s(E, M_\mathrm{BH}) \equiv \frac{\mathrm{d}^2 N_s}{\mathrm{d}t\mathrm{d}E} = \frac{\Gamma_s}{e^{E/T_\mathrm{BH}} - (-1)^{2s}}$$

$$\sigma_s \equiv \frac{\pi \Gamma_s}{E^2}\,, \quad \sigma_\mathrm{GO} \equiv \frac{27}{4}\pi r_\mathrm{S}^2$$

A. Cheek, L. Heurtier, Y. F. Perez-Gonzalez and J. Turner, Phys. Rev. D 105 (2022).
A. Arbey and J. Auffinger, Eur. Phys. J. C 79, 693 (2019).

Primordial Black Hole evaporation

- The rate of change of the BH mass : $$\frac{dM_{\rm BH}}{dt} = -\sum_j \int_0^\infty E_j \frac{\partial^2 N_j}{\partial p\,\partial t}\,dp = -\epsilon(M_{\rm BH})\,\frac{M_P^4}{M_{\rm BH}^2}$$

- The mass-dependent evaporation function. $\epsilon(M_{\rm BH})$: $$\epsilon(M_{\rm BH}) = \sum g_j\,\epsilon_j(z_j)$$

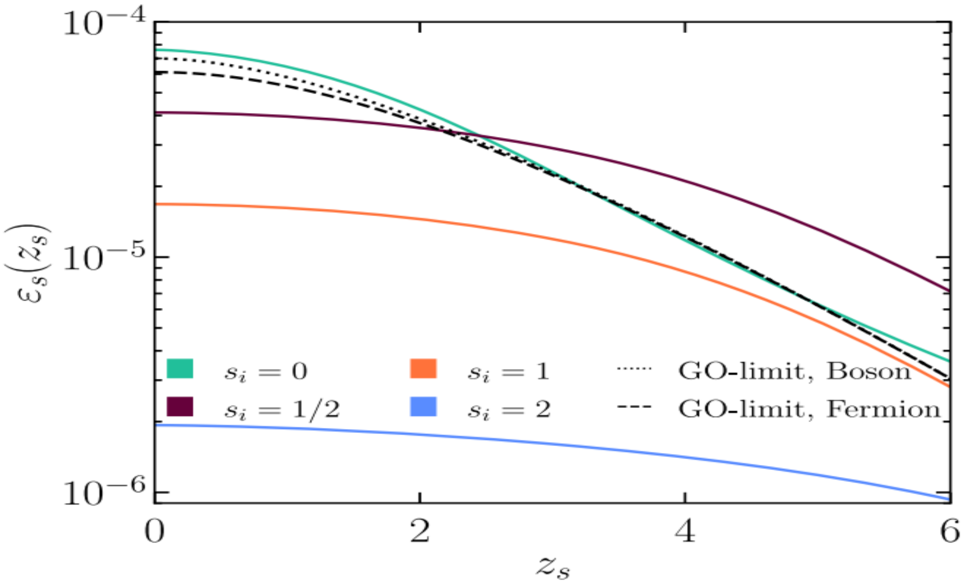
$$E_j = \sqrt{m_j^2 + p^2}\,, \quad z_j = m_j/T_{\rm BH}$$

- Evaporation function for massless particles

$$\epsilon_j(0) = \frac{27}{4}\,\frac{\xi\,\pi\,g_j}{480}$$

and total evaporation function

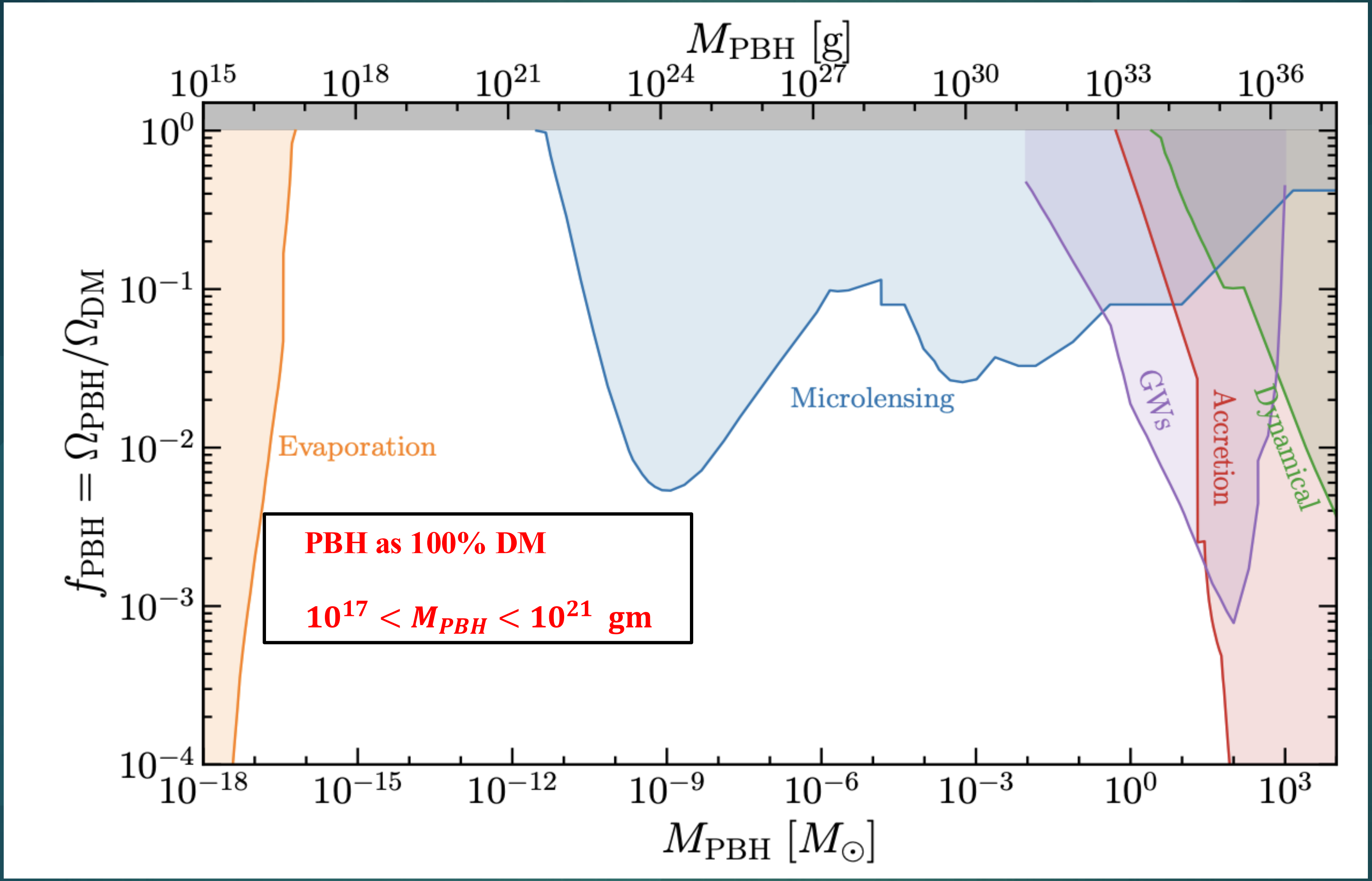
$$\epsilon = \frac{27}{4}\,\frac{g_*(T_{\rm BH})\pi}{480}$$



Compare the evaporation function with the function to the to the geometric optics limit

A. Cheek, L. Heurtier, Y. F. Perez-Gonzalez and J. Turner, Phys. Rev. D 105 (2022).
A. Arbey and J. Auffinger, Eur. Phys. J. C 79, 693 (2019).

PBH as DM- Current constraints



Current constraints on the monochromatic PBH

Marc Oncins, arXiv:2205.14722

PBH absorption: High-frequency absorption cross section

- Condition: Thermal wavelength is smaller than the BH size → $\omega \gg 1/r_s$

- Schwarzschild space-time line element : $$ds^2 = -\left(1 - \frac{2GM_{\rm BH}}{r}\right) dt^2 + \left(1 - \frac{2GM_{\rm BH}}{r}\right)^{-1} dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2.$$

- Radial geodesic equation for Schwarzschild spacetime: $\dot{r}^2 + V_{eff}(r) = 0$
  → $$V_{eff}(r) = \left(1 - \frac{2GM_{\rm BH}}{r}\right)\frac{\mathcal{L}}{r^2} - \mathcal{E}^2$$

- Capture cross-section: $\sigma_{hf} = \pi b_c^2 \longrightarrow \mathcal{L}/\mathcal{E}$

- The critical impact parameter corresponds to unstable circular orbit → $V_{eff}(r)|_{r=r_c} = 0, \quad \frac{dV_{eff}(r)}{dr}\Big|_{r=r_c} = 0$
  → $b_c = 3\sqrt{3}\,GM_{\rm BH}$

- High-Frequency Absorption Cross Section → $$\sigma_{\rm hf} = 27\pi G^2 M_{\rm BH}^2 = \frac{27}{64\pi}\frac{M_{\rm BH}^2}{M_P^4}$$

C. L. Benone, E. S. de Oliveira, S. R. Dolan, and L. C. B. Crispino, Phys. Rev. D 89, 104053 (2014).

PBH absorption: Low-frequency absorption cross section

- Condition: Thermal wavelength is larger than the BH size ➡ $\omega \ll 1/r_h$
- The absorption cross-section is suppressed and depends on → spin of the incoming particle; → frequency of the incoming particle
- In the low-frequency limit ➡

$$\sigma_{\rm lf} \sim \begin{cases} 16\pi G^2 M_{\rm BH}^2, & s = 0, \\ 2\pi G^2 M_{\rm BH}^2, & s = 1/2, \\ \frac{64\pi}{3} G^4 M_{\rm BH}^4 \omega^2, & s = 1. \end{cases}$$

- Comments: $\omega \to 0$ limit, the spin ½ particles and spin 0 particles have a higher absorption probability. spin-1 particles (e.g., photons), the absorption cross section becomes negligibly small

D. N. Page, Phys. Rev. D 13, 198 (1976)
R. Brito, V. Cardoso, and P. Pani, Lect. Notes Phys.906, pp.1 (2015)

Impact of thermal absorption on PBH evolution

- PBHs form during a RD era as a result of the gravitational collapse of density fluctuations

$$M_{\rm in} = \gamma \rho_{\rm R}(t_{\rm in}) \frac{4}{3}\pi \frac{1}{H_{\rm in}^3} = 4\pi\gamma \frac{M_{\rm p}^2}{H_{\rm in}}$$

Collapse efficiency

- Thermal wavelength at the time of formation: $\lambda_{\rm in} = \frac{2\pi}{T_{\rm in}} = \sqrt{\frac{\pi}{\gamma}} \left(\frac{\pi^2 g_*(T)}{90}\right)^{\frac{1}{4}} \left(\frac{M_{\rm in}}{M_{\rm p}}\right)^{\frac{1}{2}} \frac{1}{M_{\rm p}}$

- Imposing condition for the high-frequency limit $r_s > \lambda_{\rm in}$:

$$\gamma > 16\pi^4 \left(\frac{g_*(T)}{90}\right)^{\frac{1}{2}} \left(\frac{M_{\rm p}}{M_{\rm in}}\right) \sim 7.12 \times 10^{-3} \left(\frac{1\,{\rm g}}{M_{\rm in}}\right)$$

- How long? ⟶ $\frac{M_{\rm BH}^2}{M_{\rm in}} \frac{\gamma}{16\pi^4 M_{\rm p}} \left(\frac{90}{g_*(T)}\right)^{1/2} = \frac{t_{\rm hl}}{t_{\rm in}}.$

- Evolution of the PBH mass: $\frac{dM}{dt} = -\epsilon \frac{M_{\rm p}^4}{M_{\rm in}^2} + \rho_R \left[\sigma_{\rm hf}\,\Theta(t_{\rm hl} - t) + \sigma_{\rm lf}\,\Theta(t - t_{\rm hl})\right]$

M. R. Haque, R. Karmakar, and Y. Mambrini, arXiv:XX11.XXXX

Mass evolution of PBHs

- PBH evolution after formation, ignoring the Hawking evaporation term

$$\frac{dM_{\rm BH}}{dt} = \frac{27}{16\pi^2}\rho_R\frac{M_{\rm BH}^2}{M_{\rm p}^4}$$

$$\frac{1}{M_{\rm in}} - \frac{1}{M_{\rm BH}} = \frac{81}{64\pi^2 M_{\rm p}^2}\left(\frac{1}{t_{\rm in}} - \frac{1}{t}\right)$$

- In the case where BH mass diverges, i.e, $M_{\rm BH} \to \infty$

$$t = \left(\frac{1}{t_{\rm in}} - \frac{64\pi^2 M_{\rm p}^2}{81 M_{\rm in}}\right)^{-1}$$

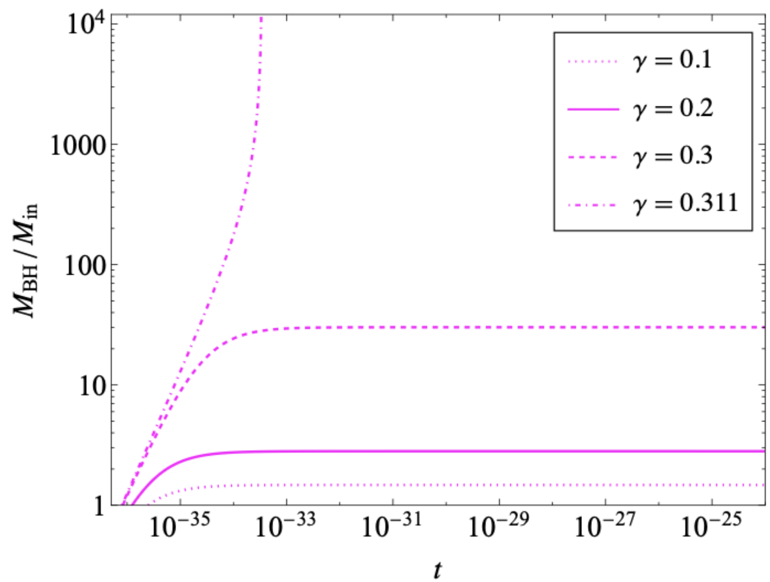
$$t_{\rm in} = \frac{M_{\rm in}}{8\pi\gamma M_{\rm p}^2}$$

- There is always a critical value present

$$\gamma_c = \frac{8\pi}{81} \approx 0.31.$$

- Amount of growth in mass:

$$M_{\rm BH} = M_{\rm in}\left(1 - \frac{\gamma}{\gamma_c}\right)^{-1}$$



M. R. Haque, R. Karmakar, and Y. Mambrini, arXiv:XX11.XXXX

Improved restrictions on PBH parameters

- Maximum allowed mass in case of PBH domination scenario calculated, setting $\tau_{\rm ev} \sim 1$ sec

$$M_{\rm in} < 1.62 \times 10^9\,{\rm g} \longrightarrow M_{\rm in} < (5.76 \times 10^8,\, 5.38 \times 10^7)\,{\rm g} \ \text{ for } \ \gamma = (0.2,\, 0.3)$$

- Minimum PBH mass required for the BHs to remain stable until today is calculated, setting PBH lifetime to the age of the universe

$$M_{\rm in} > 1.2 \times 10^{15}\,{\rm g} \longrightarrow M_{\rm in} > (4.4 \times 10^{14},\, 4.1 \times 10^{13})\,{\rm g} \text{ for } \gamma = (0.2,\, 0.3)$$

- Modification on the critical value of β and reheating temperature:

$$\beta_{\rm c}^{\rm T} \sim \xi(\gamma)^{-1}\beta_{\rm c}, \qquad T_{\rm RH}^{\rm T} \sim \xi(\gamma)^{-3/2}\,T_{\rm RH}$$

$$\xi(\gamma) = (1 - \tfrac{\gamma}{\gamma_{\rm c}})^{-1}$$

- Remarks: Inclusion of absorption leads to inclusion of absorption leads to an O(1) correction for $\gamma = 0.2$ and O(2) correction for $\gamma = 0.3$.

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Impact on the DM parameter-space from PBH evaporation

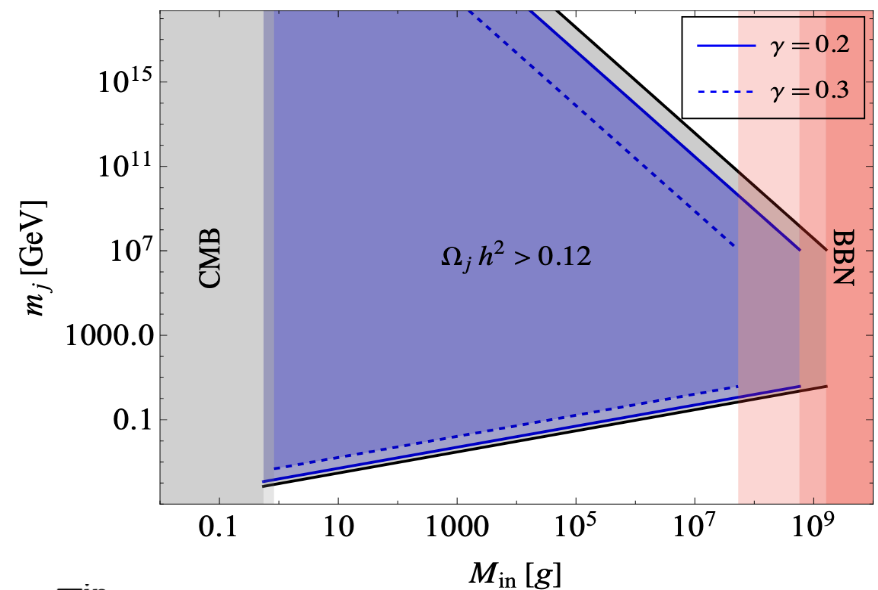
❖ Present-day DM relic abundance →

$$\Omega_j h^2 = 1.6 \times 10^8 \, \frac{g_0}{g_{\rm RH}} \, \frac{N_j \times n_{\rm BH}(t_{\rm ev})}{T_{\rm RH}^3} \, \frac{m_j}{\rm GeV}$$

$$\mathcal{N}_i = \frac{15\, C\, \zeta(3)}{g_\star(T_{\rm BH})\, \pi^4} \begin{cases} \left(\frac{\xi(\gamma)\, M_{\rm in}}{M_{\rm P}}\right)^2 , & m_j < T_{\rm BH,\,T}^{\rm in} \, , \\ \left(\frac{M_P}{m_j}\right)^2 , & m_j > T_{\rm BH,\,T}^{\rm in} \, , \end{cases}$$

❖ Final DM relic density today

$$\frac{\Omega_j h^2}{0.12} = \begin{cases} \sqrt{\frac{1.14\times 10^8}{\xi(\gamma)\, M_{\rm in}}} \left(\frac{m_j}{\rm GeV}\right) , & m_j < T_{\rm BH,\,T}^{\rm in} \, , \\ \left(\frac{10^8 {\rm g}}{\xi(\gamma)\, M_{\rm in}}\right)^{\frac{5}{2}} \left(\frac{1.2\times 10^{10}\,{\rm GeV}}{m_j}\right) , & m_j > T_{\rm BH,\,T}^{\rm in} \end{cases}$$



❖ Remarks: For. $\gamma = 0.3$, we found a $\mathcal{O}(1)$ correction for $m_j < T_{\rm BH,\,T}^{\rm in}$ and $\mathcal{O}(4)$ Correction for $m_j > T_{\rm BH,\,T}^{\rm in}$

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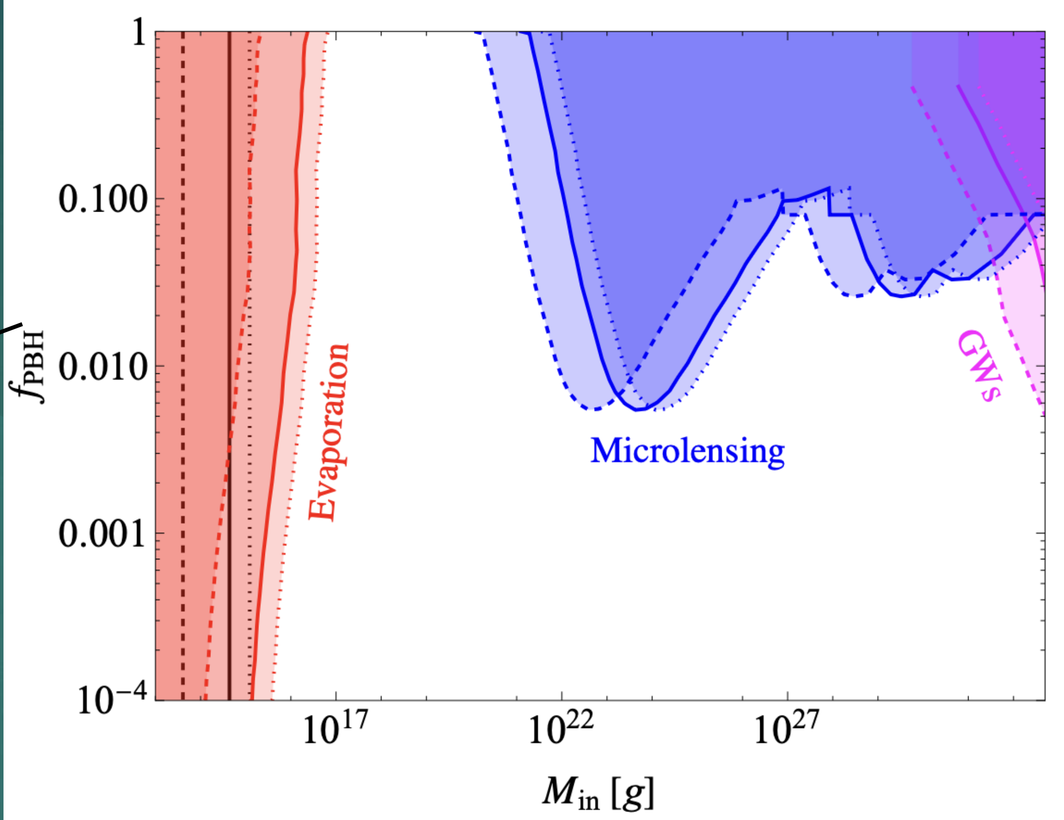
Constraints on the PBH dark matter fraction

$$f_{\rm PBH} = \frac{\Omega_{\rm PBH}}{\Omega_{\rm DM}}$$



- PBHs can be treated entirely as DM → $5 \times 10^{16}\,{\rm g} \lesssim M_{\rm in} \lesssim 5 \times 10^{21}\,{\rm g}$ (standard case)

$\gamma = 0.2,\ 10^{16}\,{\rm g} \lesssim M_{\rm in} \lesssim 10^{21}\,{\rm g}$ $\quad$ $\gamma = 0.3,\ 10^{15}\,{\rm g} \lesssim M_{\rm in} \lesssim 10^{20}\,{\rm g}$

Conclusions

- PBHs can account for dark matter either by surviving as stable relics or via non-thermal dark matter production from evaporation.
- I have shown how the evolution of PBHs in the early universe is changed by the absorption of the surrounding thermal radiation bath.
- Finally, I show that the prediction of dark matter from PBHs is modified when such absorption phenomena are taken into account, which are natural and cannot be ignored.

Thank You