Quasi-extremal primordial black holes are a viable dark matter candidate

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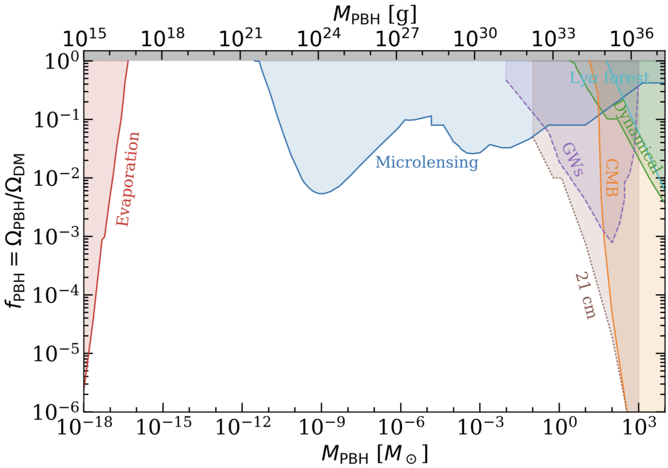
Based on
de Freitas Pacheco, Kiritsis, Lucca and Silk
[arXiv:2301.13215]

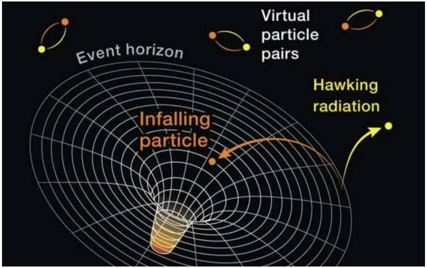
Overview



Adapted from Villanueva-Domingo et al. 2021

In a nutshell

- Consider the production of a particle pairs near the BH horizon
- One particle (with “negative” energy) might fall into the BH while the other (with “positive” energy) can escape the gravitational pull
- Far away from the BH, it looks like the BH is radiating particles
- Since energy is conserved, it will cost some energy to the BH to “emit” that particle, which translates in mass loss
- The more the BH emits particles the more it loses mass and shrinks
  $\rightarrow$ It evaporates!



Adapted from `www.secretsofuniverse.in`

Main consequences

- The emitted radiation is thermal $\rightarrow T \propto 1/M$
- The mass loss rate is found to be $\dot{M} \propto -1/M^2$
  $\rightarrow$ the lighter the BH, the faster it loses its mass and evaporates
- The lifetime of the BH reads

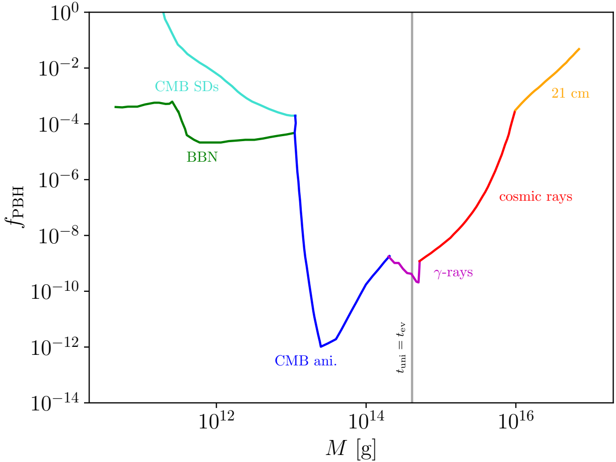
$$t_{\rm ev} \simeq t_{\rm uni} \left(\frac{M}{5.2 \times 10^{14} \text{ g}} \right)^3$$

  $\rightarrow$ PBHs with $M \lesssim 5 \times 10^{14}$ g have completely evaporated by now
- Relevance of PBHs goes beyond their ability to explain DM
  $\rightarrow$ Important to consider PBHs over the full mass spectrum
- Most of the energy injection at $t \simeq t_{\rm ev}$ (analogy to DM decay)
  $\rightarrow$ Correlation between injection time and PBH mass
  $\rightarrow$ Complementarity between different probes becomes fundamental

Resulting constraints

1) BBN ($z \sim \mathcal{O}(10^6 - 10^3)$, $M \sim \mathcal{O}(10^{10} - 10^{13}$ g)):
   - Energy injections can alter expansion history or destroy elements
2) CMB spectral distortions ($z \sim \mathcal{O}(10^6 - 10^3)$, $M \sim \mathcal{O}(10^{11} - 10^{13}$ g)):
   - Energy injections distort the CMB energy spectrum
3) CMB anisotropies ($z \sim \mathcal{O}(10^3 - 10^1)$, $M \sim \mathcal{O}(10^{13} - 10^{16}$ g)):
   - Energy injections during the dark ages partially re-ionize the universe and change the visibility function
4) 21 cm lines ($z \sim \mathcal{O}(30 - 10)$, $M \sim \mathcal{O}(10^{16} - 10^{17}$ g)):
   - Energy injections impact T_b and hence transition probability
5) Cosmic and γ-ray background ($z \sim \mathcal{O}$(few), $M \sim \mathcal{O}(10^{14} - 10^{16}$ g)):
   - You do not want the PBHs to produce more $e^{\pm}$ and γs than you see

Resulting constraints



Adapted from de Freitas Pacheco et al. 2023

Caveat

- This is all true as long as the PBHs are Schwarzschild BHs
  $\rightarrow$ But what if the PBHs had charge Q or angular momentum J?
- In standard picture no reason to expect their existence, but alternatives can be formulated (example below)
- BHs with $Q/M = 1$ or $a/M = 1$ are referred to as extremal and quasi-extremal if $Q/M \rightarrow 1$ or $a/M \rightarrow 1$
- In general, the degree of quasi-extremality can be captured by the parameter ϵ

$$\epsilon^2 = 1 - \frac{Q^2}{M^2} \quad \text{or} \quad \epsilon^2 = 1 - \frac{a^2}{M^2} \tag{1}$$

  (which would also include e.g., higher dim. BHs)
- $\epsilon = 1 \rightarrow$ Schwarzschild BH, $\epsilon \ll 1 \rightarrow$ quasi-extremal BH (qBH), $\epsilon = 0 \rightarrow$ extremal BH

Caveat

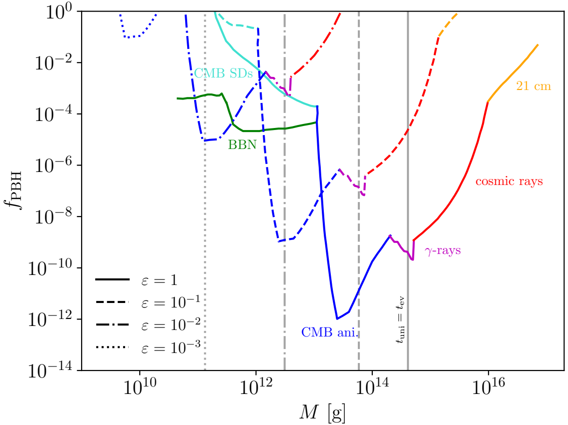
- Naive understanding: for qBHs, the "pull" towards the horizon gets additional components on top of gravity (like e.g., ergosphere)
- If PBHs had $\epsilon \ll 1$, their temperature would become

$$T \simeq \frac{4\epsilon}{8\pi M} \tag{2}$$

$\rightarrow$ qBHs evaporate at lower temperature than BHs with same mass

- For luminosity and lifetime this implies $L \propto \epsilon^4$ and $t_{\rm ev} \propto \epsilon^{-4}$
$\rightarrow$ the energy injection is suppressed and delayed
- All aforementioned constraints (except for BBN) directly depend on
1) L, which determines $f_{\rm PBH}$ limit, and
2) $t_{\rm ev}$, which determines $M_{\rm PBH}$ dependence
$\rightarrow$ Can be simply recast for any value of ϵ

Caveat



$\rightarrow$ Such light PBHs can be the DM!

Adapted from de Freitas Pacheco et al. 2023

Follow-up ideas

[1] The quickest one et al., "*What would it take to form quasi-extremal PBHs?*", (could soon be) in prep.

- Very interesting question with no easy answer (it might indeed be impossible, but it would be nice to know)
- Intersection of cosmology, GR and particle physics

[2] Hopefully not the same one et al., "*What would it take to observe and identify quasi-extremal PBHs?*", (could soon be) in prep.

- More data-focused
- Intersection of cosmological, GW and (gravitational) direct detection probes

Have a look at Bai & Orlofsky 2019, Lehmann et al. 2019 and de Freitas Pacheco et al. 2023 to get a feeling for the tasks

Conclusions

- Constraints on Hawking evaporation place tight bounds on the PBH abundance at masses between $10^{10} - 10^{18}$ g
- Assuming PBHs to be quasi-extremal significantly weakens them
- qPBHs with $\epsilon \lesssim 10^{-3}$ can be the DM even for PBH masses as low as 10^{11} g and below
- The questions of formation and observability remain open and deserve further study