How slowly do PBHs evaporate?

The effect of Memory Burden on the evaporation of Primordial Black Holes

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Overview

1. Why are Primordial Black Holes relevant?
2. What if Black Holes are condensates?
3. What happens if BHs take longer to evaporate?

Why are Primordial Black Holes relevant?

Primordial Black Holes

- Primordial Black Holes are Black Holes forming soon after the Big Bang
- Several different methods of their formation have been studied
  - **e.g.** Primordial overdensities
- They have been studied extensively in the past 50 years despite the fact that there is no evidence for them

Primordial Black Holes

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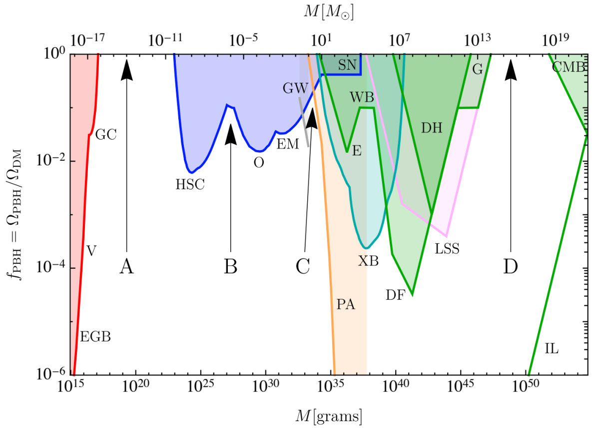
They can be much smaller than astrophysical Black Holes, making their evaporation more relevant.

Their presence and evaporation could affect different epochs of the Universe's history.
e.g. CMB, BBN

They could constitute part/all of the Dark Matter in the Universe.

Bounds on PBH mass as a fraction of Dark Matter



Constraints on $f(M)$ for a monochromatic mass function, from evaporations (red), lensing (blue), gravitational waves (GW) (gray), dynamical effects (green), accretion (light blue), CMB distortions (orange) and large-scale structure (purple), from (Carr, Kühnel 2020).

Hawking evaporation of Black Holes

- A Black Hole can lose mass and emit particles based on its temperature
- The emission spectrum depends on the initial Primordial Black Hole mass spectrum
- The particles emitted by Primordial Black Holes can affect the outcomes of periods like BBN and the emission of CMB

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$\Longrightarrow$ We can constrain the mass spectrum of Primordial Black Holes

Hawking evaporation of Black Holes

A Black Hole will *fully* evaporate in a lifetime τ_H

Hawking lifetime

$$\tau_H \propto \frac{\hbar M^3}{M_{Pl}^4}$$

Its temperature T_{BH} is given as a function of its mass

Black Hole temperature

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As the Black Hole evaporates, the mass decreases and therefore its temperature increases

What if Black Holes are condensates?

Black Holes as condensates of gravitons

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Black Holes as condensates of gravitons

- Hawking evaporation does not account for the quantum nature of Black Holes
- **BUT** we could think of Black Holes as condensates of N gravitons (Dvali, Gomez 2011)

Occupation number of gravitons

$$N = \frac{M r_g}{\hbar}$$

where M is the mass of the source and r_g is its gravitational radius.

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$\Longrightarrow$ **The Black Hole is fully described by N!**

Memory Burden

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- What do we mean by memory?
    - Physical systems are characterized by a set of degrees of freedom and interactions between them
    - The quantum states of the system can be labeled by their occupation numbers

$$\left|n_1, \ldots, n_K\right\rangle$$

    - We can refer to the information stored in this sequence as a **memory pattern**

Memory Burden: A Prototype Model

Prototype Model

k-**memory modes** $\hat{n}_k$ $a_k, a_k^\dagger$	$+$	**master mode** $\hat{n}_0$ $a_0, a_0^\dagger$

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Free Gravitons		**Constituent Gravitons**

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Attractive interaction characterized by $\alpha \propto \frac{1}{N}$

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Attractive interaction characterized by $\alpha \propto \frac{1}{N}$

$$\hat{H} = \epsilon_0 \hat{n}_0 + \left(1 - \frac{\hat{n}_0}{N_c}\right) \sum_{k=1}^{K} \epsilon_k \hat{n}_k$$

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$+$

master mode $\hat{n}_0$ $a_0, a_0^\dagger$ **Constituent Gravitons**

Attractive interaction characterized by $\alpha \propto \frac{1}{N}$

Energy gaps of k-modes are lowered as soon as we occupy the master mode:

$$\varepsilon_k = \left(1 - \frac{n_0}{N_C}\right) \epsilon_k$$

Once $n_0 = N_C$, **all the memory modes are effectively gapless**

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$a_k, a_k^\dagger$ $\quad\quad$ $a_0, a_0^\dagger$

Free Gravitons $\quad\quad$ **Constituent Gravitons**

Let's say each of the memory modes can have at most an occupation number of d, then we have $(d+1)^K$ distinct states with the same energy

Entropy: $S = K \ln(d+1)$

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So the gapless memory modes can contribute to the microscopic entropy!

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Bekenstein-Hawking Entropy: $S = 4\pi G_N M^2$

For the BH mass to decrease, we need to off-load some of these gapless modes!

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$+$ **2nd mode** m_0

$b_0, b_0^\dagger$

which can exchange occupation number with n_0

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which can exchange occupation number with n_0

$$\hat{H} = \epsilon_0 \hat{n}_0 + \epsilon_0 \hat{m}_0 + \left(1 - \frac{\hat{n}_0}{N_c}\right) \sum_{k=1}^{K} \epsilon_k \hat{n}_k + C_0 \left(\hat{a}_0^\dagger \hat{b}_0 + \hat{b}_0^\dagger \hat{a}_0\right)$$

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$$|\mathrm{in}_1\rangle = |\underbrace{N_c}_{n_0}, \underbrace{0}_{m_0}, n_1, \ldots, n_K\rangle$$

The system can avoid the memory burden by exchanging n_0 and m_0 modes

$$|\mathrm{out}_1\rangle = |\underbrace{N_c - \Delta N_c}_{n_0}, \underbrace{\Delta N_c}_{m_0}, n_1, \ldots, n_K\rangle$$

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Free Gravitons — **Constituent Gravitons**

+ **2nd set memory modes $\hat{n}_{k'}$** $a_{k'}, a_{k'}^\dagger$

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$$| \text{ in } \rangle = | \underbrace{N_c}_{n_0}, \underbrace{0}_{m_0}, n_1, \ldots n_K, \underbrace{0}_{n'_1}, \ldots, \underbrace{0}_{n'_{K'}} \rangle$$

The system can avoid memory burden by evolving from k-modes to k'-modes

$$| \text{ out } \rangle = | \underbrace{N_c - \Delta N_c}_{n_0}, \underbrace{\Delta N_c}_{m_0}, \underbrace{0}_{n_1}, \cdots \underbrace{0}_{n_K}, n'_1, \ldots, n'_{K'} \rangle$$

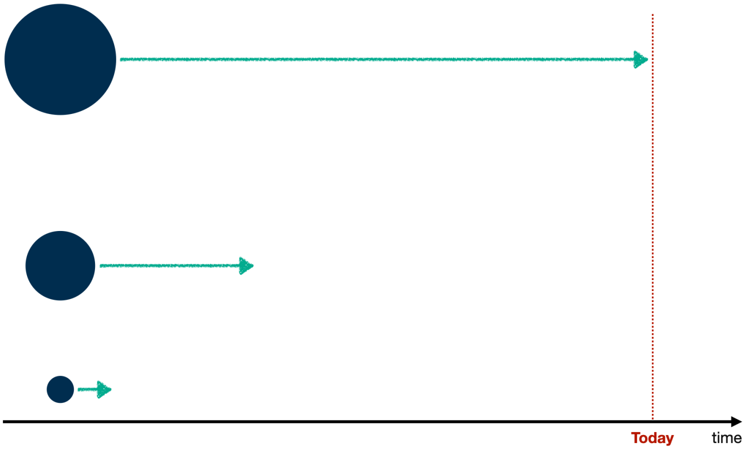
Memory Burden: The Big Picture

- Black holes have a high capacity for memory storage and thus suffer the effect of memory burden
- In order to decay (evaporate), they must off-load the memory pattern from one set of modes to another
- This process will slow down the decay (evaporation) of the Black Hole
  - In fact, we can roughly estimate that it should slow down the evaporation by two powers of the entropy

$$\tau_H \to \tau_{MB} > \tau_H S^2 \approx \frac{M^5}{M_{Pl}^6}$$

What happens if Black Holes take longer to evaporate?

Consequences of evaporation slow down



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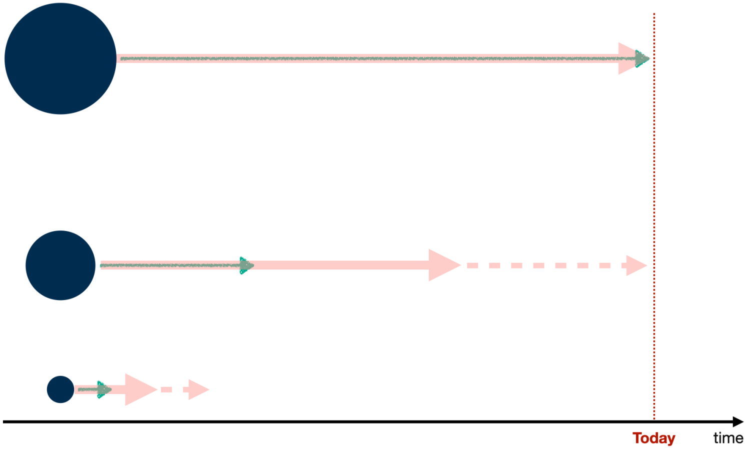
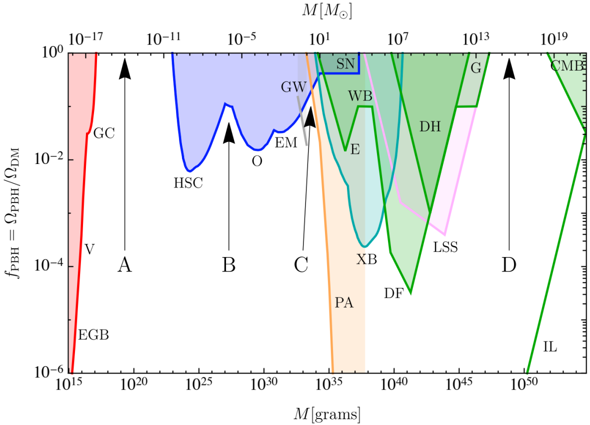
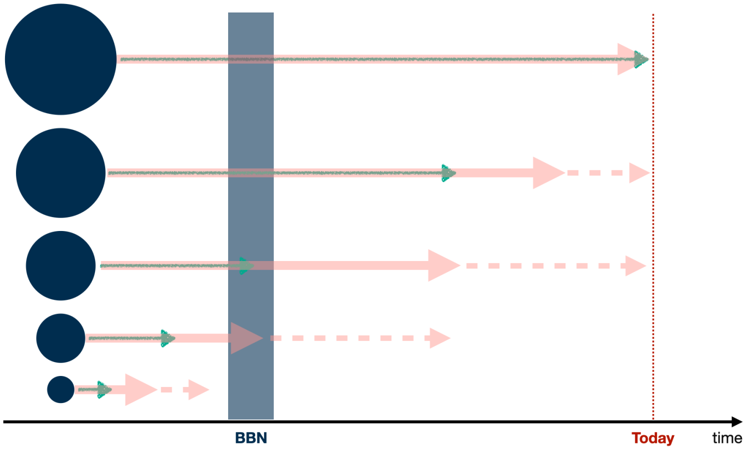


Consequences of slow down: CMB bound



Consequences of slow down: BBN bound



Consequences of evaporation slow down: Summary

- If evaporation of PBHs is slowed down, this changes the evolution of the their mass spectrum throughout the history of the universe
  - This includes the mass distribution of PBHs during periods such as Big Bang Nucleosynthesis
  - The mass distribution of PBHs that would still be around today is extended
- The bounds on which PBH masses could contribute to the Dark Matter in the Universe are relaxed

To be continued...

- How do the evaporation bounds of the PBH mass distribution change with memory burden?
- How can the masses of PBHs around during BBN change in order to reevaluate this bound?
- How does this affect the possibility of PBHs constituting Dark Matter?
- Could the new bounds have a potentially observable signature?

Thank you for listening!