Primordial Black Holes as Cosmic Expansion Accelerators

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GeomGravX 2026
Tartu, Estonia

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Framework: Swiss Cheese cosmology + Regular (repulsive) BHs

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- **Enormous mass range**: from Planck mass ($\sim 10^{-5}$ g) to stellar mass and beyond
- Hawking's discovery of black hole evaporation was directly motivated by PBHs [1974]
- Ultra-light PBHs ($m < 10^9$ g): evaporate before BBN
- Asteroid-mass PBHs ($m \sim 10^{17}$–10^{22} g): viable dark matter

PBH Formation Mechanisms

- Collapse of enhanced primordial perturbations [Garcia-Bellido et al. 1996; Yokoyama 1997; Musco et al. 2021]

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- **Quantum gravity / modified gravity processes** [Papanikolaou 2023; Shafiee & Bahrampour 2023]

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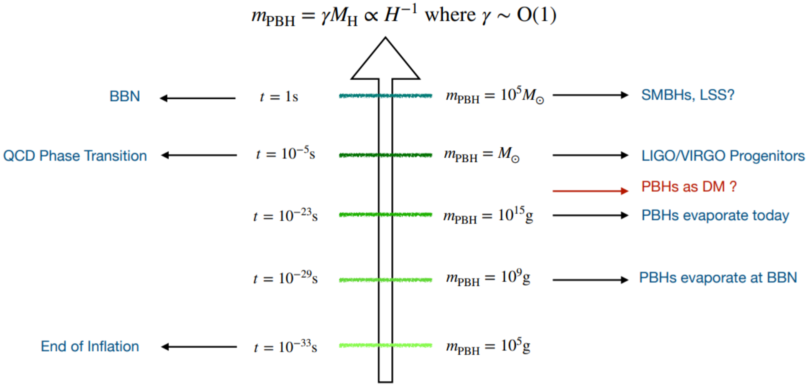
⇒ A **BH-dominated early Universe** before BBN is physically motivated [Nagatani 1999; Conzinu & Marozzi 2023]

PBH Mass Spectrum



See for reviews in [Carr et al.- 2020, Sasaki et al - 2018, Clesse et al. - 2017]

Why PBHs? A Multi-Messenger Object

Established roles:

- Dark matter [Carr & Kühnel 2020]
- Structure formation [Meszaros 1975]
- LIGO/Virgo merger events [Sasaki et al. 2016]
- Reheating [Lennon et al. 2018]
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This work adds:

- ⋆ Inflation *(no inflaton needed)*
- ⋆ Graceful exit & reheating
- ⋆ Early dark energy
- ⋆ Hubble tension resolution

Key requirement:
PBHs must be **repulsive**

Singular vs Regular Black Holes

Singular PBHs (standard):

- Schwarzschild or Kerr metric
- Central curvature singularity
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Physical motivation

Regular BHs arise naturally from quantum gravity: loop quantum gravity, asymptotic safety, non-commutative geometry, higher-dimensional models. . .

[Cadoni & Sanna 2023; Bonanno et al. 2024; Bambi (ed.) 2023]

Four Repulsive Spacetimes

In this work we consider:

- **Hayward** [Hayward 2006]: regular, quantum-gravity inspired, inner de Sitter core
- **Bardeen** [Bardeen 1968]: regular, QG-inspired / non-linear electrodynamics
- **Dymnikova** [Dymnikova 1992]: regular, exact GR solution with NLE source

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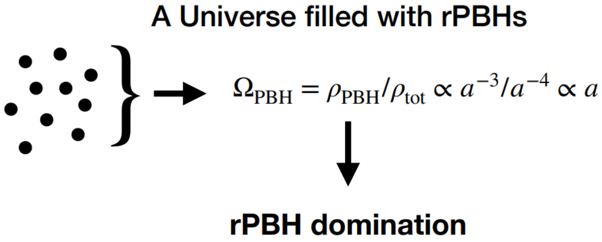

The Swiss Cheese Idea

- Introduced by [Einstein & Strauss 1945]
- Embed spherical BH solutions (“holes”) in an FLRW Universe (“cheese”)
- Matching via Darmois–Israel junction conditions on Σ
- Locally valid: each excised region matched independently
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Why is this valid in the early Universe?

- Approximately homogeneous PBH distribution for small a [Desjacques & Riotto 2018; Ali-Haïmoud 2018; De Luca et al. 2022]
- Stability concerns [Krasinski 2011] are irrelevant: we model an eMD era, not present-day voids

Two Metrics, One Hypersurface

FLRW metric in spherical coordinates:

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2\,d\Omega^2\right)$$

Static–spherically symmetric metric:

$$ds^2 = -F(R)\,dT^2 + \frac{dR^2}{F(R)} + R^2\,d\Omega^2$$

The matching is performed on a spherical hypersurface Σ with fixed comoving radius r_Σ (Schücking radius) in the FLRW frame, corresponding to $R(t) = a(t)\,r_\Sigma$ in the black hole frame.

Darmois–Israel Junction Conditions

Two requirements [Darmois 1927; Eisenhart 1949]:

1. Continuity of the **induced metric** on Σ:

$$-1 = F(R)\left(\frac{dT}{dt}\right)^2 + F(R)^{-1}\left(\frac{dR}{dt}\right)^2$$

2. Continuity of the **extrinsic curvature**:

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Schwarzschild check: $F = 1 - 2G_N m/R, \;\; \rho_M = 3m/(4\pi R^3)$

$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G_N}{3}\rho_M - \frac{k}{a^2}, \qquad \frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}\rho_M \;\Rightarrow$$ **dust Universe** ✓

Matching with the Hayward PBH

- The Hayward metric [Hayward 2006]:

$$F(R) = 1 - \frac{2G_N M(R)}{R}, \; M(R) = \frac{m\,R^3}{R^3 + 2G_N m\,L^2} \approx \begin{cases} m & (R \gg G_N^{1/3} m^{1/3} L^{2/3}) \\ \dfrac{R^3}{2G_N L^2} & (R \ll G_N^{1/3} m^{1/3} L^{2/3}) \end{cases}$$

- For $m > \frac{3\sqrt{3}L}{4G_N}$: outer horizon at $R \simeq 2G_N m$, inner horizon at $R \simeq L$

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- For $m > \frac{3\sqrt{3}L}{4G_N}$: outer horizon at $R \simeq 2G_N m$, inner horizon at $R \simeq L$
- Swiss Cheese matching gives the **modified cosmic expansion equations**:

$$H^2 = \frac{\dot{a}^2}{a^2} = \frac{2G_N m}{R^3 + 2G_N m L^2} - \frac{k}{a^2}\,,$$

$$\frac{\ddot{a}}{a} = \frac{G_N m\,(4G_N L^2 m - R^3)}{(2G_N L^2 m + R^3)^2}$$

Early PBH-Induced Acceleration

Expressing in terms of energy density $\rho = 3m/(4\pi R^3)$:

$$H^2 = \frac{8\pi G_N}{3}\left(\rho^{-1} + \frac{8\pi G_N L^2}{3}\right)^{-1}$$

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The sign of $\ddot{a}$ is determined by $16 G_N L^2 \pi \rho - 3$:

$$\begin{cases} \rho > \rho_c = \dfrac{3}{16\pi G_N L^2} & \Rightarrow \quad \ddot{a} > 0 \quad (\textbf{Acceleration}) \\ \rho < \rho_c = \dfrac{3}{16\pi G_N L^2} & \Rightarrow \quad \ddot{a} < 0 \quad (\text{Deceleration}) \end{cases}$$

The de Sitter Limit

High-density limit $\rho \gg \rho_c$:

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- Hubble scale $H = L^{-1}$ set by the **quantum gravity length** L
- No inflaton, no potential — geometry of regular BHs does the work
- Expansion is **non-singular**: $H \to L^{-1}$ as $\rho \to \infty$ (not ∞!)
- Exit from inflation: **natural and automatic** as ρ dilutes below ρ_c — no fine-tuning

End of Inflation

- **Geometric exit**: inflation ends at $\rho_e \simeq G_N^{-1} L^{-2}$; after inflation:

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- **Evaporation exit**: if PBHs evaporate before the geometric exit, then $H^2 \propto a^{-4}$ (radiation domination).
- **Key result** (valid for all four regular spacetimes):

$$\rho_c \; > \; \rho_{\rm evap} \quad \text{always}$$

Inflation terminates via geometry *first*; evaporation then drives **reheating**.

PBH Evaporation and Reheating

Hayward evaporation law [Frolov & Zelnikov 2017]:

$$\frac{dm(t)}{dt} \sim -\frac{n_{\rm p}}{1920\pi}\frac{l_{\rm Pl}^2}{L^2}\frac{1}{G_N^2 m^2} \sim \frac{1}{C^3 G_N^2 m^2}\,, \qquad t_{\rm evap} = \frac{1}{3} C^3 G_N^2 m^3$$

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Consistency with BBN ($t_{\rm BBN} \simeq 1\,\text{min}$):

$$t_{\rm evap} \leq t_{\rm BBN} \;\Rightarrow\; m \leq G_N^{-2/3} C^{-1} (3 t_{\rm BBN})^{1/3} \;\approx\; 5\times 10^8\,\text{g}$$

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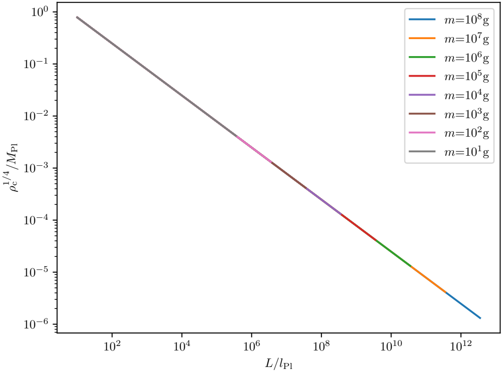
Reheating temperature:

$$T_{\rm reh} = \left(\frac{30}{\pi^2 g_{\rm reh}}\right)^{1/4} L^{-1/2} G_N^{-1/4}$$

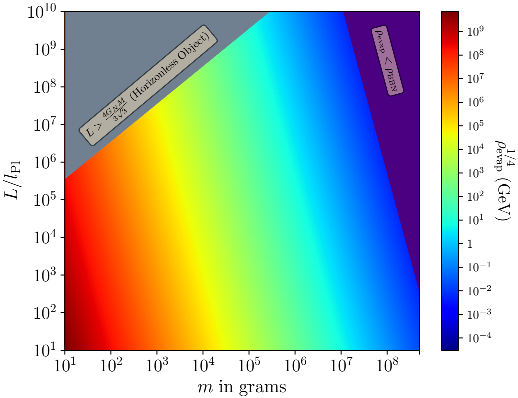
Natural, clean reheating via Hawking radiation — no additional couplings required

Critical Energy Scale



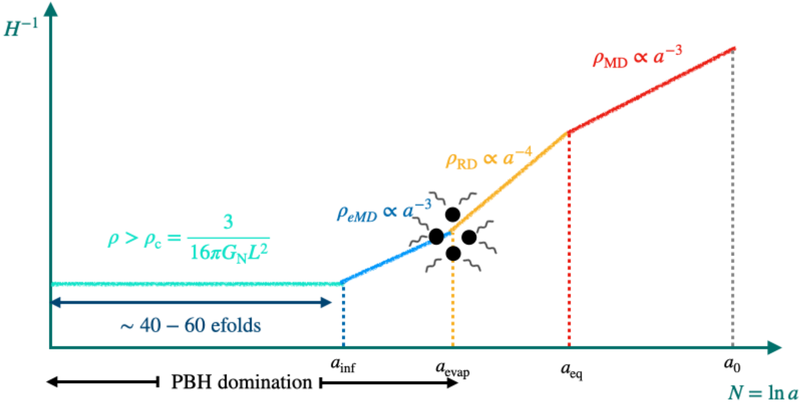
$\rho_c \propto L^{-2}$: larger quantum gravity scale $L \Rightarrow$ lower inflation energy scale.
Constraint $L < 4G_N m/(3\sqrt{3})$ ensures presence of horizons.

Evaporation Energy Scale



$\rho_c > \rho_{\rm evap}$ throughout the entire allowed parameter space. Magenta region ($\rho_{\rm evap} < \rho_{\rm BBN}$) is excluded.

Evolution of the Cosmological Horizon



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- These results are **model-independent**: confirmed for all four repulsive spacetimes (Hayward, Bardeen, Dymnikova, SdS).

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Thank You!

Phys.Lett.B 870 (2025) 139948 | Int.J.Mod.Phys.D 34 (2025) 16, 2544015

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- For $m \sim 10^{12}$ g and $0.107 < \Omega_{\rm PBH}^{\rm eq} < 0.5$, one gets:

$$\Omega_{\rm EDE}(t_{\rm LS}) < 0.015$$

$$0.015 < \Omega_{\rm EDE}(t_{\rm eq}) < 0.107$$

Consistent with CMB [Pettorino et al. 2013] and LSS [Smith et al. 2021] constraints ✓