Primordial Black Holes and their relics

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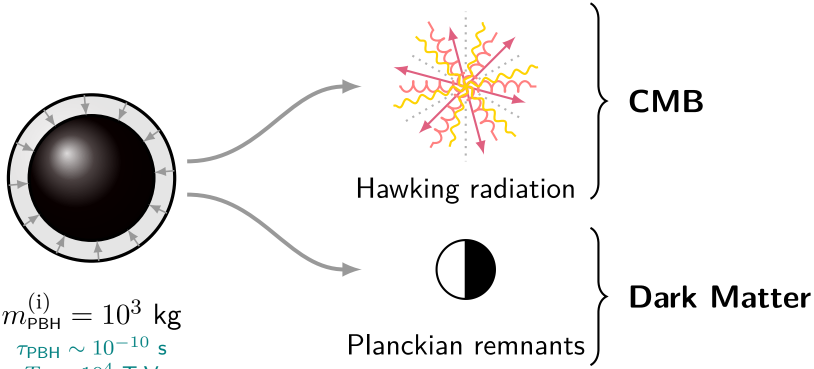
Statement

Give me an early universe and inject any fraction of PBHs of mass $m_{\text{PBH}}^{(\text{i})} = 10^3$ kg. The result will systematically yield a universe where the **dark matter** is solely composed of Planckian remnants, and Hawking evaporation entirely **reheats** the Universe.



$m_{\text{PBH}}^{(\text{i})} = 10^3$ kg

$\tau_{\text{PBH}} \sim 10^{-10}$ s

$T_{\text{H}} \sim 10^4$ TeV

$r_{\text{s}} \sim 10^{-24}$ m

Table of contents

Framework

Cosmological framework

- FLRW + early inflationary phase.

- Dynamics :

$$H^2 \simeq H_0^2 \left(\Omega_{\rm r}\, e^{-4N} + \Omega_{\rm m}\, e^{-3N} + \Omega_\Lambda \right) \ .$$

  $\Omega_A = \rho_A/\rho_{\textsf{crit}}$ and $A \in \{$rad, mat, DM, PBH, $\Lambda, \dots\}$

- Initial mass $m^{(\rm i)}_{\textsf{PBH}} \sim$ Hubble mass at $t_{\textsf{formation}}$:

$$m^{(\rm i)}_{\textsf{PBH}} \approx m^{(\rm i)}_{\rm H} \sim \frac{1}{H} \sim t$$

  monochromatic mass distribution

(loop) Quantum black holes

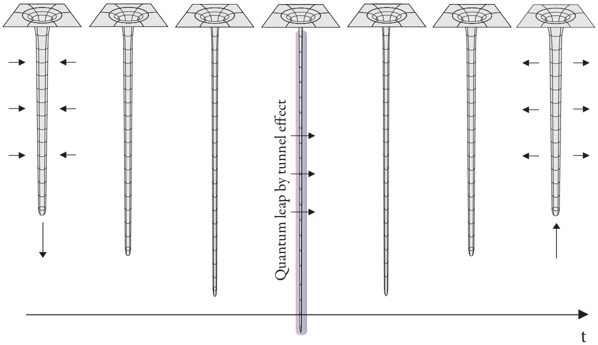
- Quantization of the area operator in LQG leads to discrete spectra :

$$A = 8\pi\ell_P^2\gamma\sqrt{j(j+1)}\,.$$

- The Friedmann-Lemaître equation is quantum-corrected :

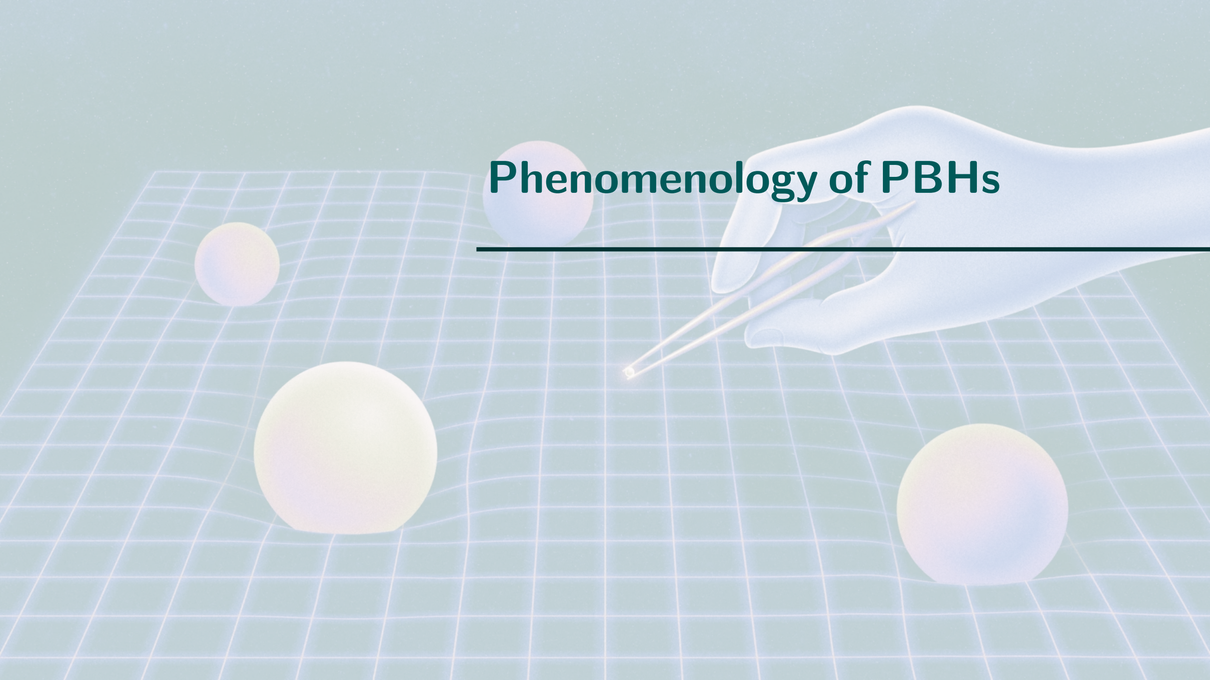
$$H^2 = \frac{8\pi G}{3}\rho\left(1-\frac{\rho}{\rho_{\max}}\right)\,.$$

- Cartoon picture of the quantum-corrected geometry : [Rovelli, Vidotto, . . .]

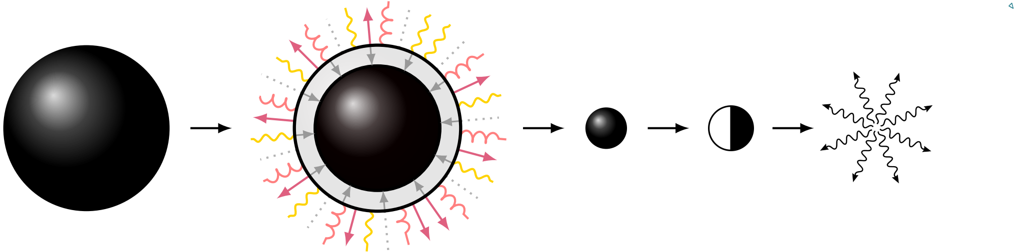


→ **Planckian relics** as DM candidates

Phenomenology of PBHs

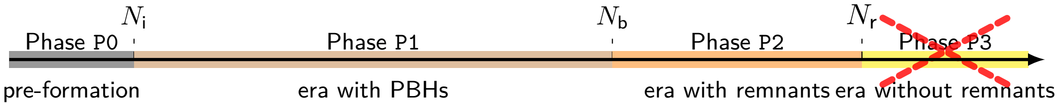


Phenomenology of PBHs



$\beta \equiv \rho_{\mathrm{PBH}}/\rho_{\mathrm{tot}}$ at formation $\quad \tau_{\mathrm{PBH}} \sim \left(m_{\mathrm{PBH}}^{(\mathrm{i})}\right)^3 \quad m_{\mathrm{REM}} \sim m_{\mathrm{P}} \quad \tau_{\mathrm{REM}} \sim \left(m_{\mathrm{PBH}}^{(\mathrm{i})}\right)^{3+k}$

$m_{\mathrm{PBH}}^{(\mathrm{i})}$



Implementation

Implementation

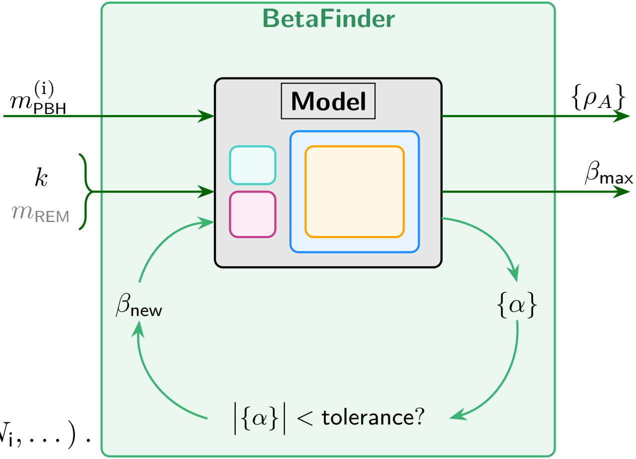
- Initial **mass** $m_{\mathsf{PBH}}^{(\mathrm{i})} \in [10^{-3}, 10^{12}]$ kg evaporated by today.
- Initial **abundance** $\beta \in [0, 1]$.
- The remnant **stability** parameter $k \in [1, \infty)$.

Initial conditions :

$$\rho_A(N_{\mathsf{i}}^-) = \alpha_A\, \rho_A^{\mathsf{obs}}\, e^{-3(1+\omega_A)N_{\mathsf{i}}} \ ,$$

so that :

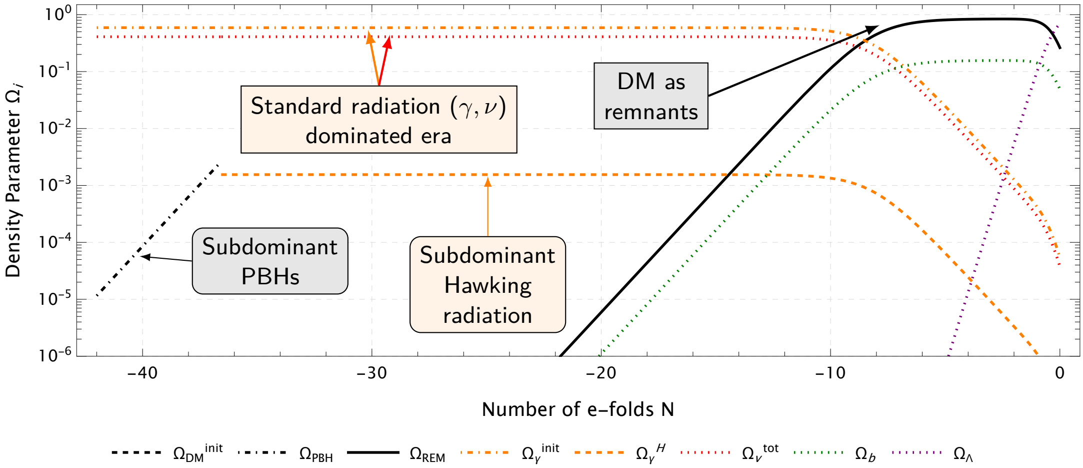
$$\rho_A^{\mathsf{model}}\Big|_0 = \rho_A^{\mathsf{obs}} \implies \alpha_A = \alpha_A(\beta, N_{\mathsf{i}}, \dots)\ .$$



Cosmologies obtained

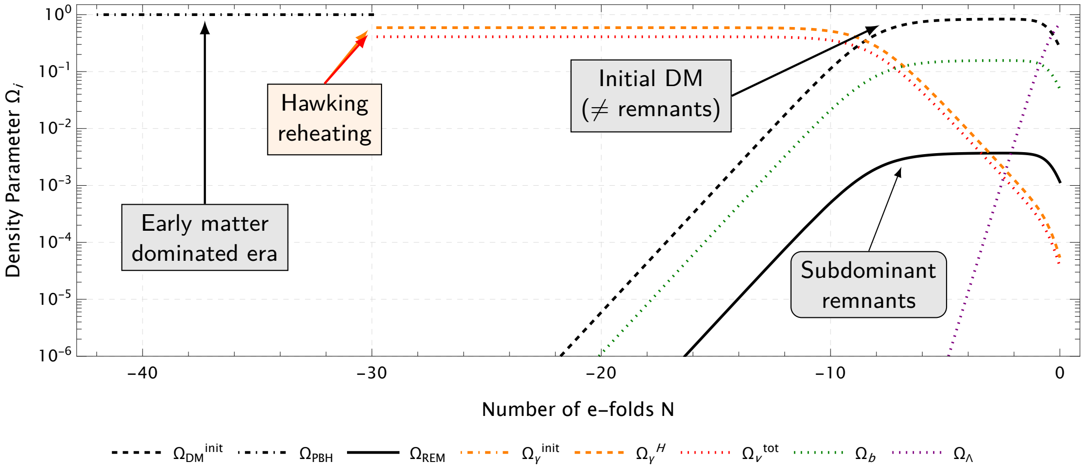
Cosmologies obtained : $m^{(\mathrm{i})}_{\mathrm{PBH}} = 10^2$ kg

$\beta \approx 6 \cdot 10^{-14}$ and $k \geq 4$ gives **100% DM = remnant**.



Cosmologies obtained : $m_{\mathrm{PBH}}^{(\mathrm{i})} = 10^4$ kg

$\beta \approx 4 \cdot 10^{-2}$ and $k \geq 3$ gives **100% rad = Hawking**.



Cosmologies obtained

Depending on the initial mass $m_{\text{PBH}}^{(\text{i})}$ of the PBHs, **two regimes** of cosmologies emerge.

- **Regime I** : $m_{\text{PBH}}^{(\text{i})} \in [10^{-3}, 10^{3}]$ kg
  Dark matter made entirely of remnants.
  Example : $m_{\text{PBH}}^{(\text{i})} = 10^{2}$ kg.

- **Regime II** : $m_{\text{PBH}}^{(\text{i})} \in [10^{3}, 10^{12}]$ kg
  Reheating through Hawking radiation
  ($\Longrightarrow$ EMD era)
  Example : $m_{\text{PBH}}^{(\text{i})} = 10^{4}$ kg.

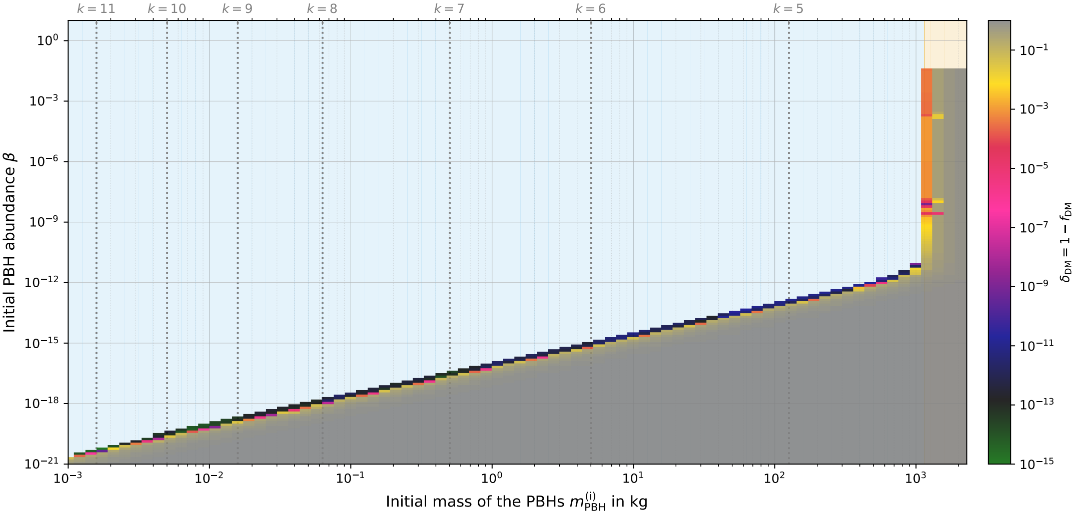
DM Saturation

$$f_{\text{DM}} = \frac{\rho_{\text{REM}}}{\rho_{\text{DM,tot}}} \, , \quad \delta_{\text{DM}} = 1 - f_{\text{DM}} \, .$$

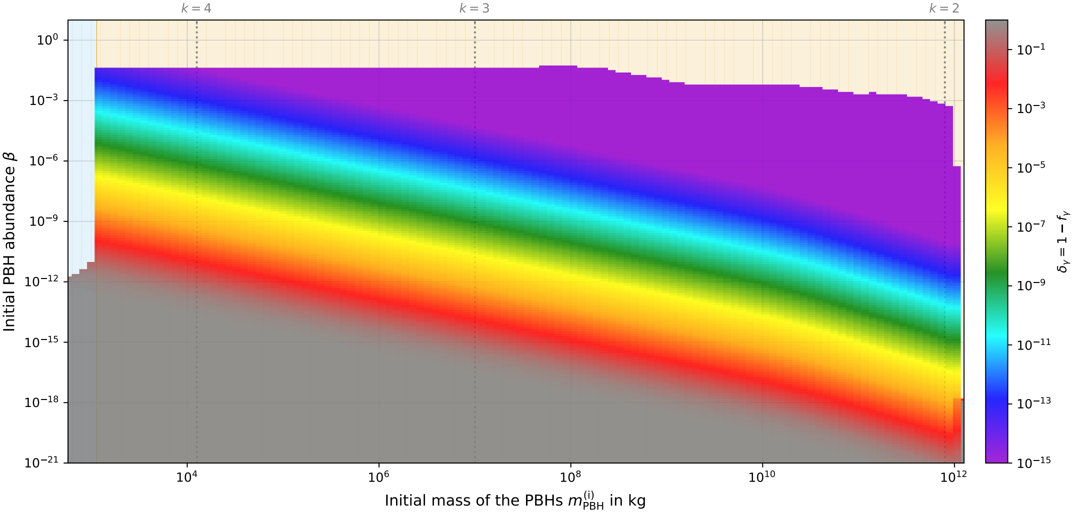
Radiation Saturation

$$f_{\gamma} = \frac{\rho_{\gamma}^{\text{H}}}{\rho_{\gamma,\text{tot}}} \, , \quad \delta_{\gamma} = 1 - f_{\gamma} \, .$$

Cosmological constraints : regime I



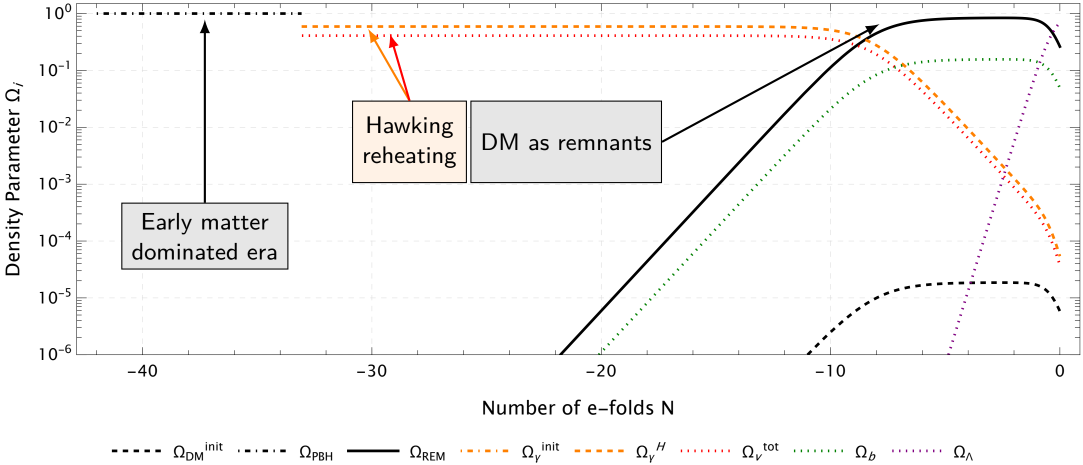
Cosmological constraints : regime II



What about the interface between the two regimes,
around $m_{\text{PBH}}^{(\mathrm{i})} \approx 10^3$ kg ?

Cosmologies constraints : the sweet spot

$\beta \approx 2 \cdot 10^{-4}$ and $k \geq 3$ gives $\delta_\gamma \approx 10^{-11}$ and $\delta_{\text{DM}} \approx 10^{-5}$.



Observational signatures

Observational signatures : Overview

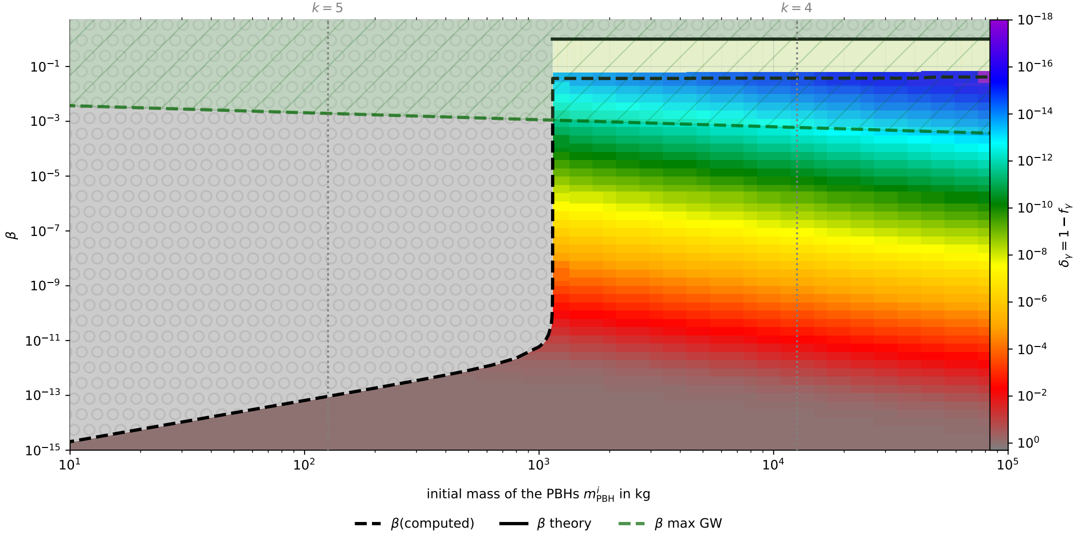
1. **Scalar-Induced Gravitational Waves** : large primordial scalar perturbations.

2. **Poisson fluctuations** : if EMD era.
   [Papanikolaou, Vennin, Langlois ; 21]

3. **The Poltergeist mechanism** : if monochromatic mass spectrum.
   [Bhaumik, Ghoshal, Jain, Lewicki ; 22]

4. **Dark radiation** : from (i) non-thermalized neutrinos (ii) Hawking gravitons.

Observational signatures : Poisson fluctuations



Observational signatures : the Poltergeist mechanism

Monochromatic mass distribution → almost instantaneous transition from the EMD era to a RD era.

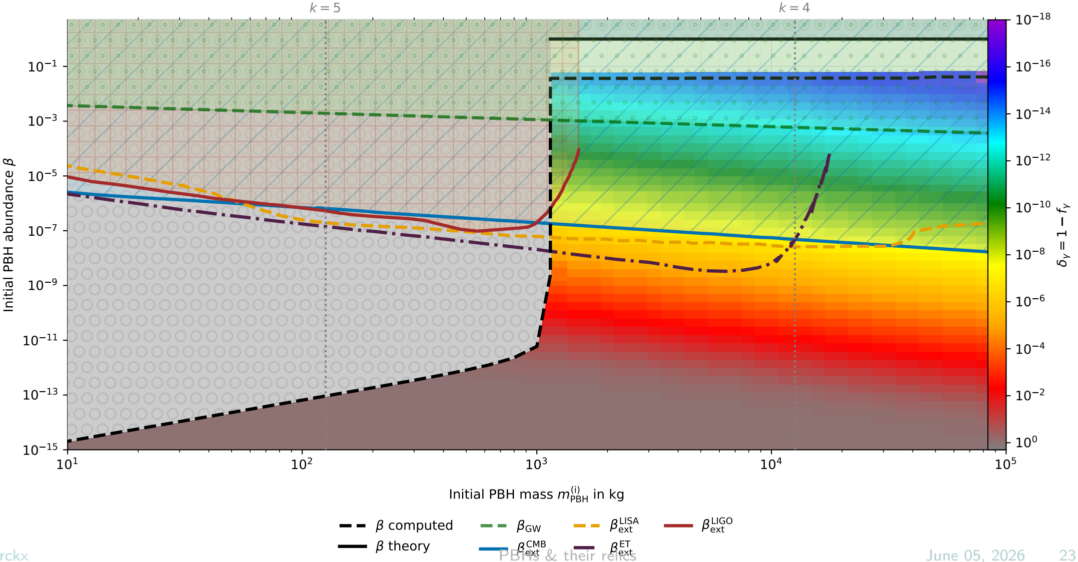
This sudden transition heavily amplifies the SIGW spectrum (**Poltergeist mechanism**).

This amplifies the characteristic double-peak structure :

1. Primordial fluctuations.
2. Poisson fluctuations.

Constraints have been derived in [Bhaumik, Ghoshal, Jain, Lewicki ; 22], and are reproduced hereafter.

Observational signatures : the Poltergeist mechanism



Constraints from temperature (regime II)

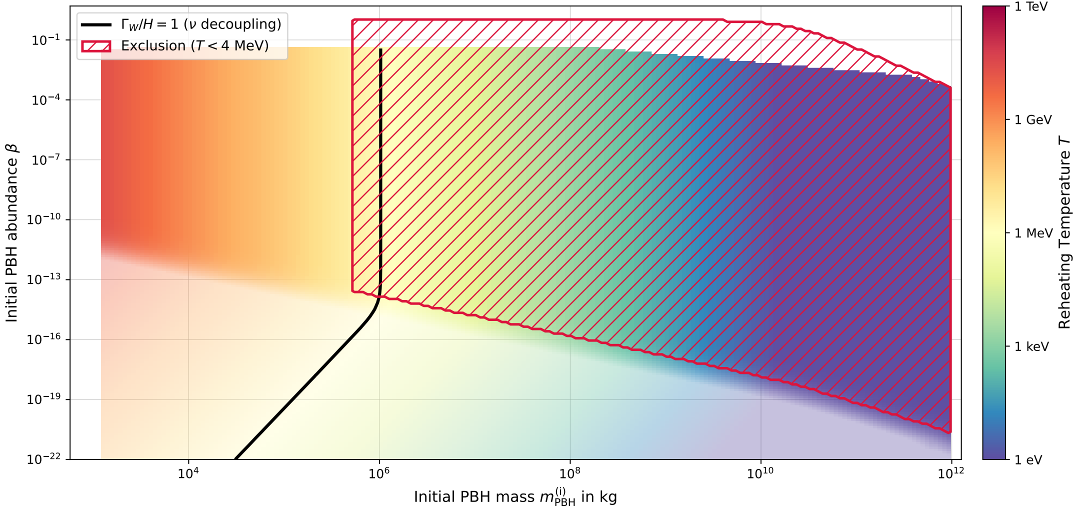
1. Reheating :
   At N_b, injected energy $\rho^{\rm H}_{\rm rad} = \rho^{\rm H}_\gamma + \rho^{\rm H}_\nu$. [Hannestad,04]

$$T(\rho^{\rm H}_{\rm rad}, g_*) \gtrsim T^{\sf min}_{\rm reheat} \approx 4 \text{ MeV} \ .$$

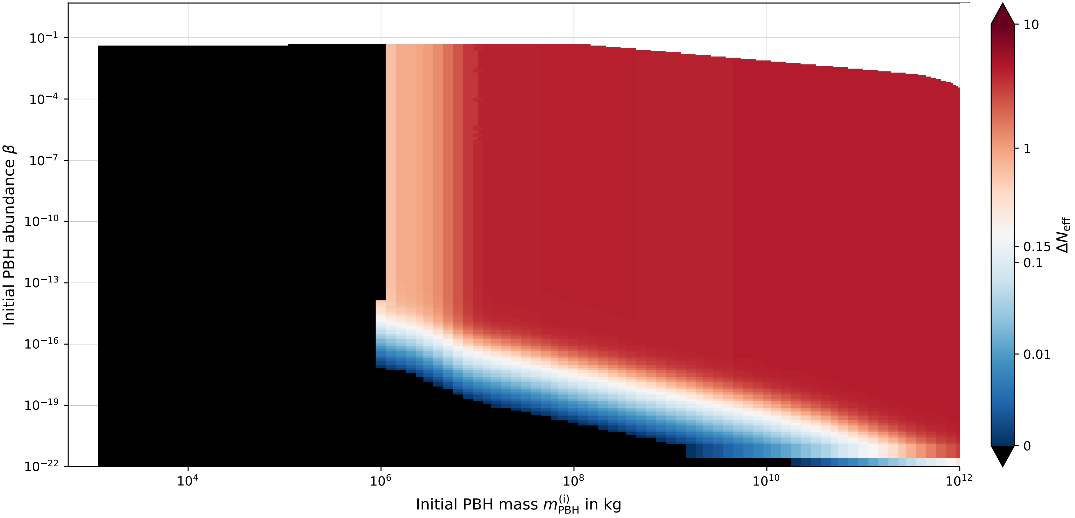
2. $\Delta N_{\rm eff}$:
   Thermalizing neutrinos requires :

$$\frac{\Gamma_W}{H} \gtrsim 1 \ .$$

Temperature : Hawking reheating



Temperature : $\Delta N_{\rm eff}$



Summary and outlook

Summary

Main results

Light PBHs evaporating into stable Planckian remnants offer an alternative DM candidate and reheating mechanism.

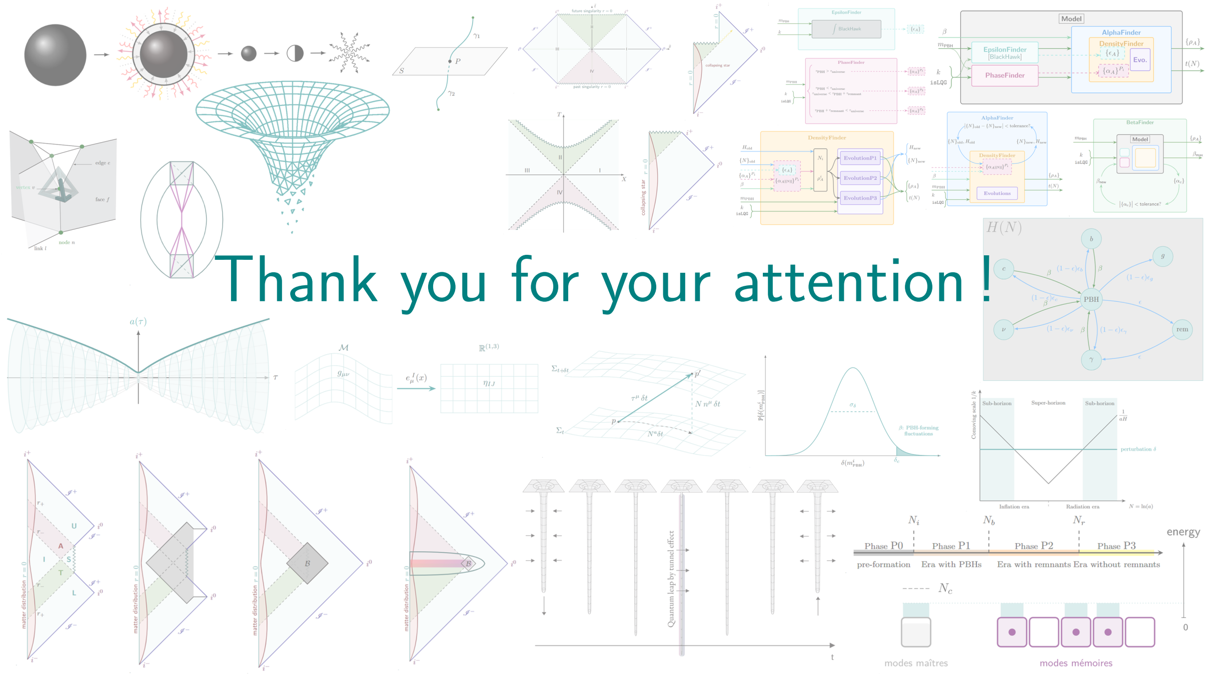
1. **Regime I ($m_{\text{PBH}}^{(\text{i})} \leq 10^3$ kg)** : remnants can account for 100% of DM ($f_{\text{DM}} \approx 1$), requiring $k \geq 4$.
2. **Regime II (10^3 kg $\leq m_{\text{PBH}}^{(\text{i})}$)** : PBHs induce an EMD era ($f_\gamma \approx 1$).

$\rightarrow$ At $m_{\text{PBH}}^{(\text{i})} \approx 10^3$ kg, PBHs simultaneously generate the entire DM abundance and the background radiation content, without requiring strict fine-tuning for the initial fraction β.

Outlook

- Extended mass functions : model dependent signatures.
- Finer thermal history : treatment of non-thermalized species, baryogenesis, ...
- Other stability mechanisms : e.g. memory burden effect, ...
- Explore bouncing cosmologies.
- Formation mechanisms for 10^3 kg PBHs.
- ...

Thank you for your attention !



Backup slides

Loop Quantum gravity

1. **Hilbert space** $\mathcal{H}$:

$$\mathcal{H}_\Gamma = \mathrm{L}_2\left[\frac{\mathrm{SU}(2)^L}{\mathrm{SU}(2)^N}\right] \ni \psi$$

2. **Operator algebra** $\mathcal{A}$:

$$[L^i{}_a, L^j{}_b] = i\ell_{\mathrm{Planck}}\delta_{ab}\epsilon^{ij}{}_k L^k{}_a$$

3. **Transition amplitudes** W :

$$W(\psi) = \sum_\sigma \prod_f d_{j_f} \prod_v W_v$$

$$W_v = \left(P_{\mathrm{SL}(2,\mathbb{C})} \circ Y_\gamma \psi_v\right)(\mathbf{1})$$

LQG : Classical theory

1. **Variables** :
   tetrad $e^I{}_\mu$ (such that $g_{\mu\nu}(x) = e^I{}_\mu(x) e^J{}_\nu(x) \eta_{IJ}$) and spin connection $\omega^{IJ}{}_\mu$.
   Gauge group : $\mathcal{G} = \mathrm{Diff}(\mathcal{M}) \times \mathrm{SO}(3,1)_{\mathrm{local}}$

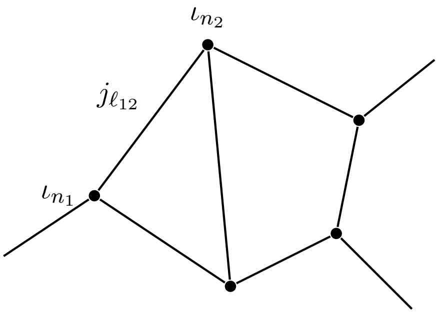
2. **Action** :

$$S[e,\omega] = \int B[e] \wedge F[\omega] \qquad B[e] = \underbrace{\left(* + \frac{1}{\gamma_{\mathsf{LQG}}}\right)(e \wedge e)}_{\text{simplicity constraint}}$$

LQG : Hilbert space

- **Graph** Γ : set of N nodes n connected by L links ℓ.
- **Boundary states** : $\phi_\Gamma(\{g_\ell = \mathcal{P}\exp(\int_\ell \omega)\})$ such that $\phi_\Gamma(\{g_\ell\}) = \phi_\Gamma(\{h_{s(\ell)} g_\ell h^{-1}_{t(\ell)}\}) \forall h_n \in \mathrm{SU}(2)$.
- **Spin network basis** :
  Plancherel decomposition $|\Gamma, j_\ell, \iota_n\rangle$

$$\phi_\Gamma(g_\ell; j_\ell, \iota_n) = \bigotimes_{n\in N} \iota_n \cdot_\Gamma \bigotimes_{\ell\in L} D^{(j_\ell)}(g_\ell)$$



LQG : Transition amplitudes

1. General amplitude :

$$Z[h_{\mathsf{in}}, h_{\mathsf{out}}] = \int_{h_{\mathsf{in}}}^{h_{\mathsf{out}}} [\mathcal{D}g] e^{iS[g]}$$

$$Z_{\mathsf{SF}}[\psi_{\mathsf{in}} \otimes \psi_{\mathsf{out}}] = \sum_{\sigma} \prod_{f} d_{j_f} \prod_{v} \left(P_{\mathrm{SL}(2,\mathbb{C})} \circ Y_\gamma \psi_v \right) \mathbf{(1)}$$

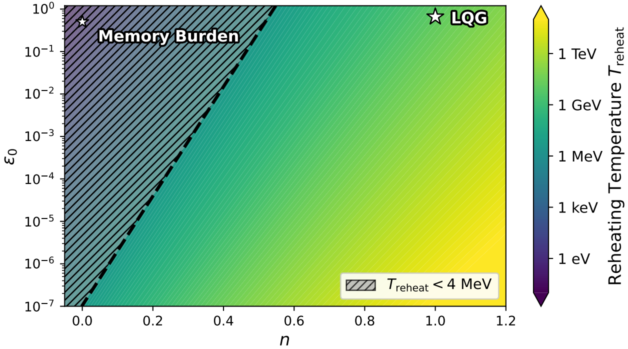
2. One vertex, one group element :

$$W_v(h) = \int_{\mathrm{SL}(2,\mathbb{C})} \mathrm{d}\mu(G) \prod_f \sum_j d_j D^{(j)}_{mn}(h) D^{(\gamma j, j)}_{jm,jn}(G)$$

Other stabilization mechanisms : sweetspot ?

$$\frac{m_{\text{REM}}}{m^{(\text{i})}_{\text{PBH}}} = \epsilon \equiv \epsilon_0 \cdot {m^{(\text{i})}_{\text{PBH}}}^{-n}$$

- LQG : $\epsilon_0 = \sqrt{3\sqrt{3}\gamma/2} \sim 1$ and $n = 1$
- MBe : $\epsilon_0 = 1/2, 1/3$ and $n = 0$



Baryogenesis mechanisms : Schematic overview

- **GUT baryogenesis** [Hooper, Krnjaic ; '20]
  $T_{\text{Hawking}} \nearrow \implies M_{\text{GUT}}$ emission $\xrightarrow{\text{CPV decay}} \Delta B \neq 0$
- **Hot spot leptogenesis** [Gunn et al. ; '24]
  Local T_{H} heats plasma $\implies$ EW restored locally $\implies$ RHN emission
- **Exploding PBH shocks** [Klipfel ; '26]
  Terminal $\dot{M} \to \infty \implies$ Ultrarelativistic shocks $\implies$ Chiral charge
- **Asymmetric evaporation** [Juan et al. ; '25]
  Horizon curvature $\implies$ Chemical potential $\mu \implies$ Biased emission
- **Spontaneous (USR)** [Balaji ; '26]
  Inflaton velocity $\dot{\phi} \implies$ Effective $\mu \implies$ Plasma bias
- **Wash-in leptogenesis** [Schmitz, Xu ; '26]
  Thermal equilibrium $\implies$ Pre-existing charge transfer