Signatures of Loop Quantum Gravity in Primordial Black Hole cosmologies

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LISA Madrid

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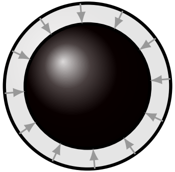
Statement

Give me an early universe and inject any fraction of PBHs of mass $m_{\mathsf{PBH}}^{(\mathrm{i})} = 10^3$ kg.



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

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

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

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

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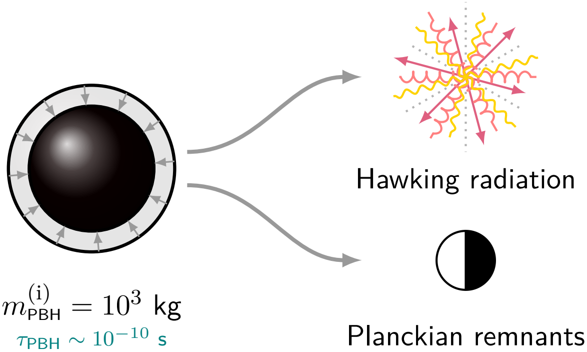

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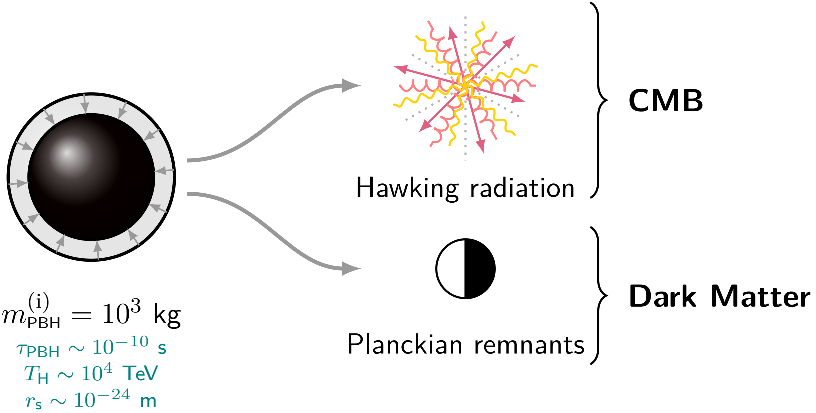
Statement

Give me an early universe and inject any fraction of PBHs of mass $m_{\mathrm{PBH}}^{(\mathrm{i})} = 10^3$ kg. The result will systematically yield a universe where the **dark matter** is entirely made of Planckian remnants, and the entire **radiation** content originates from Hawking evaporation.



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Framework

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- Dynamics :

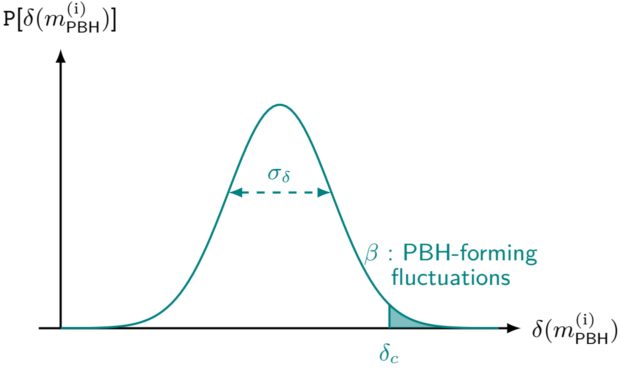
$$H^2 \simeq H_0^2 \left(\Omega_{\rm r}\, e^{-4N} + \Omega_{\rm m}\, e^{-3N} + \Omega_\Lambda\right) \ .$$

Primordial Black Holes (PBHs)

Primordial black holes (PBHs) : form from the collapse of large over-densities upon horizon re-entry.

- Form after the end of inflation.
- Initial mass $m_{\text{PBH}}^{(\text{i})} \sim$ Hubble mass at $t_{\text{formation}}$:

$$m_{\text{PBH}}^{(\text{i})} \approx m_{\text{H}}^{(\text{i})} \sim \frac{1}{H} \sim t$$



Quantum Black Holes

Semi-classical black holes

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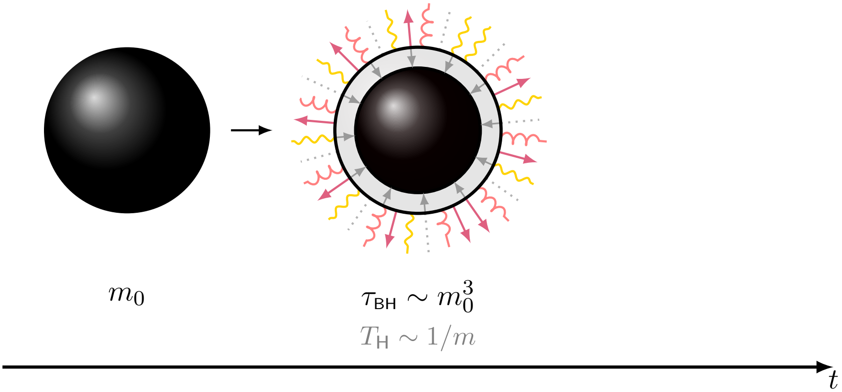

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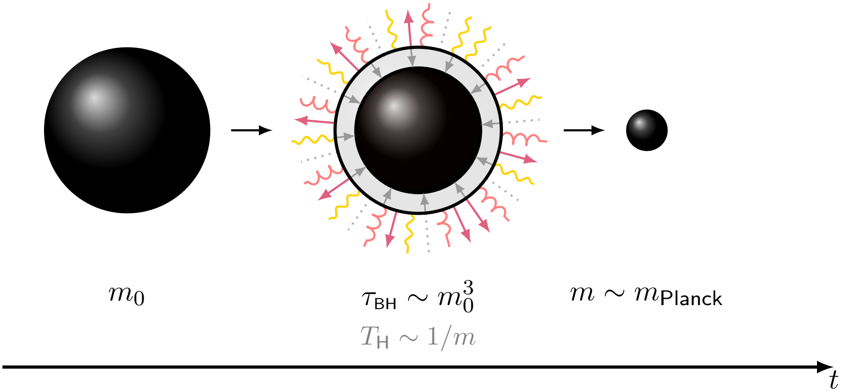

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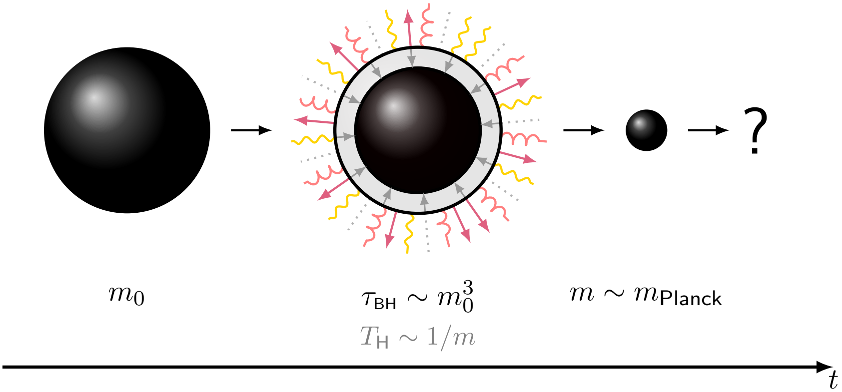

(loop) Quantum black holes

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

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

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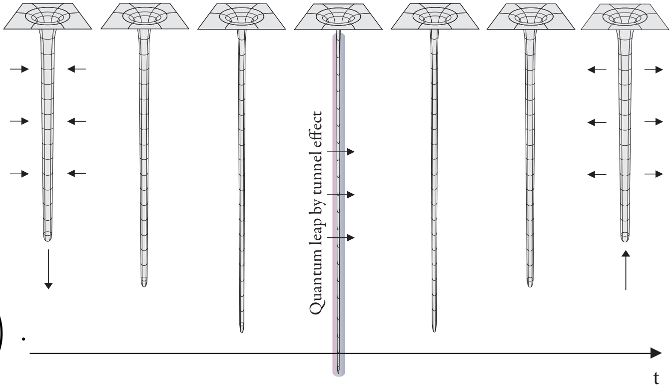
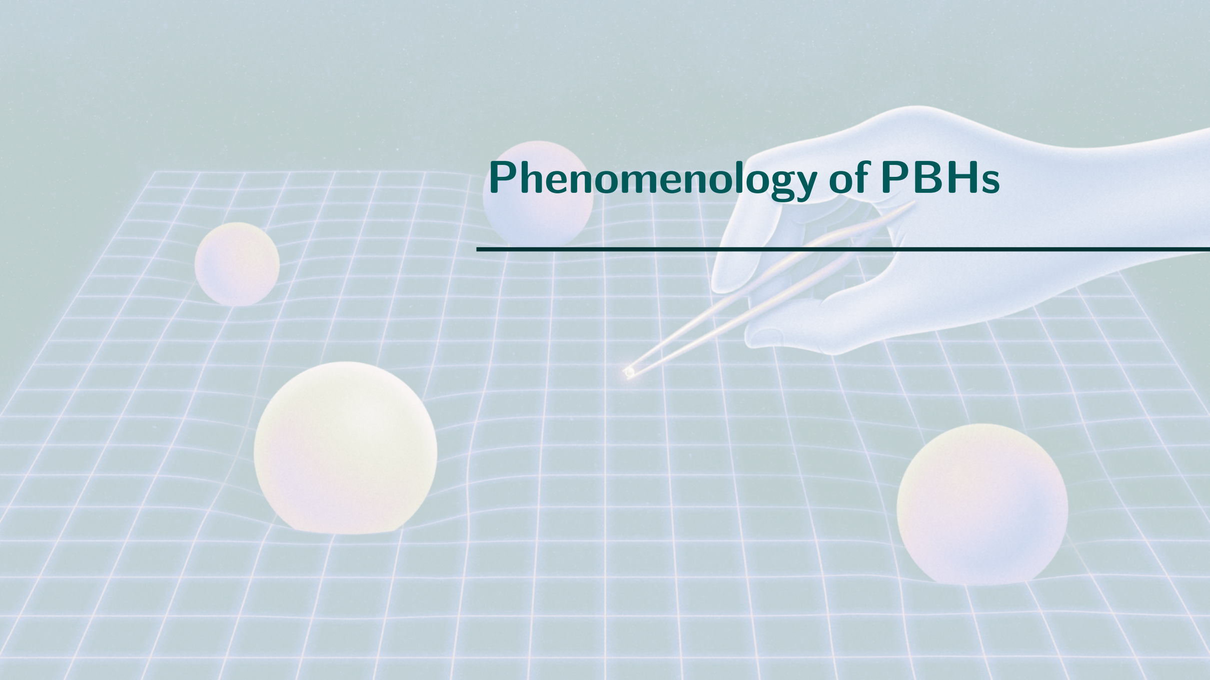
- Cartoon picture of the quantum-corrected geometry : [Rovelli, Vidotto, ...]



Phenomenology of PBHs



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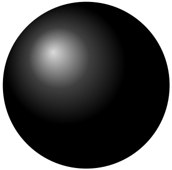
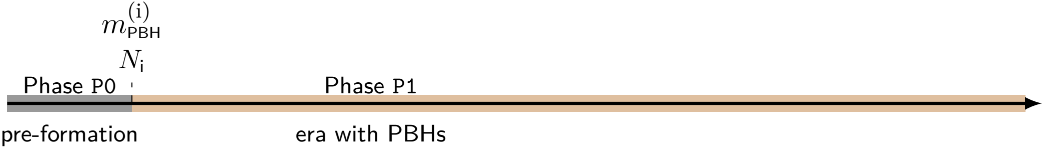


$\beta \equiv \rho_{\text{PBH}}/\rho_{\text{tot}}$ at formation



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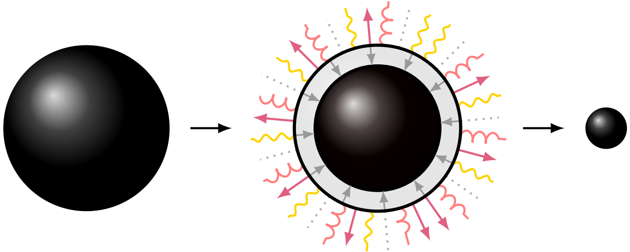

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$\tau_{\mathsf{PBH}} \sim {m_{\mathsf{PBH}}^{(\mathrm{i})}}^{3}$

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

N_{i}

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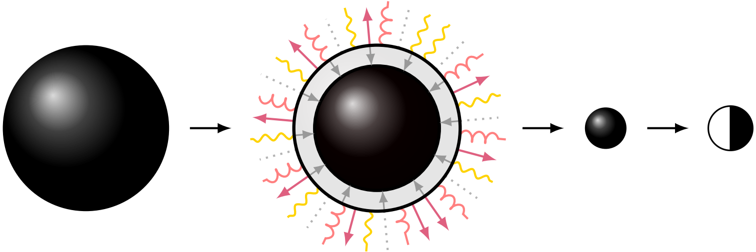

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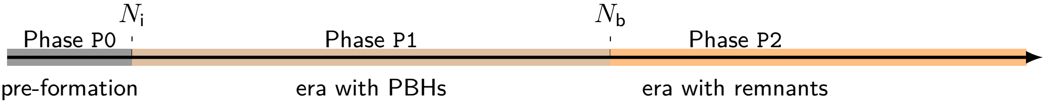
$m_{\mathsf{REM}} \sim m_{\mathsf{P}}$



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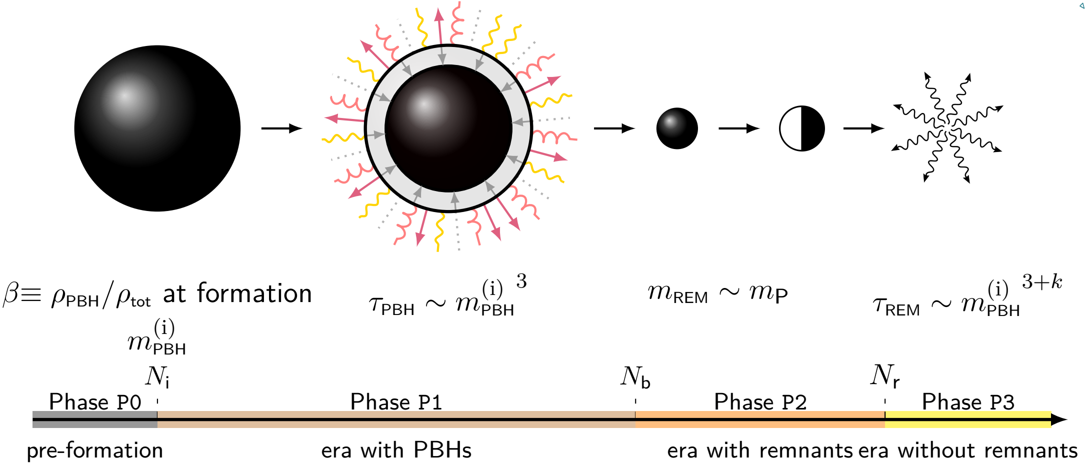

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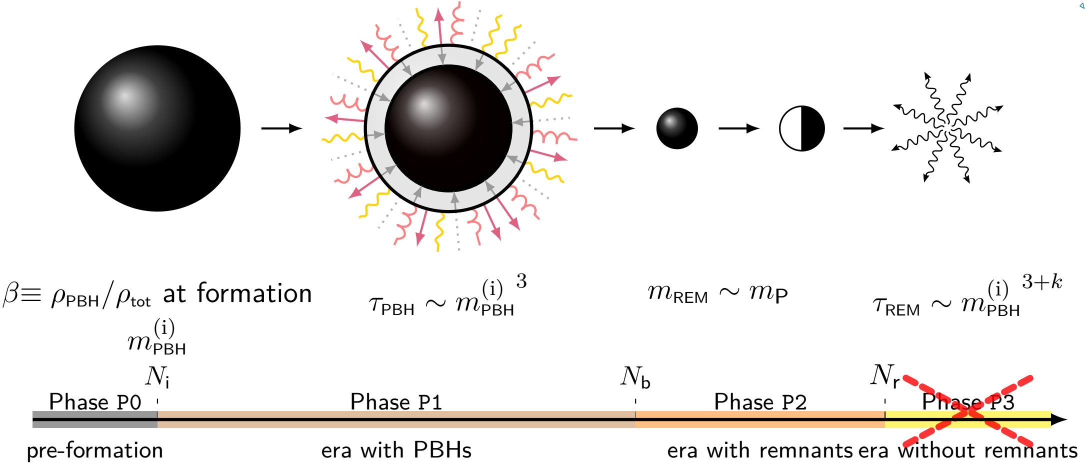

Implementation

Implementation : analytical part

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

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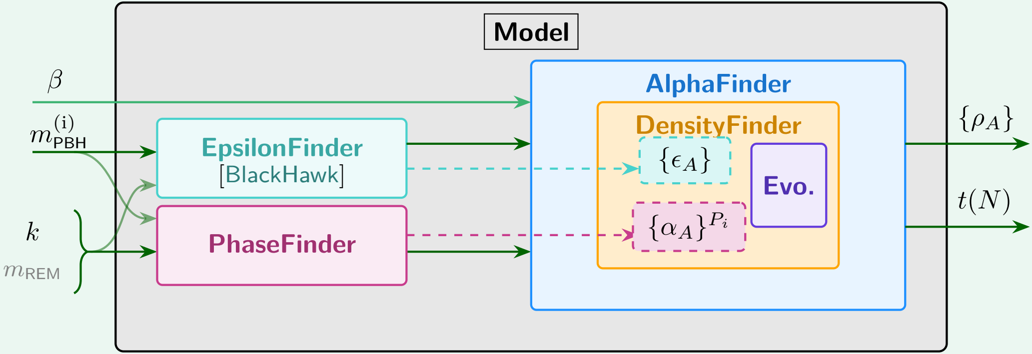
Initial conditions parameterized by α_A :

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

so that :

$$\rho_A^{\mathsf{model}}\Big|_{\mathsf{today}} = \rho_A^{\mathsf{obs}} \quad \Longrightarrow \quad \alpha_A = \alpha_A(\beta, N_{\mathsf{i}}, \dots) \ .$$

Implementation : numerical part



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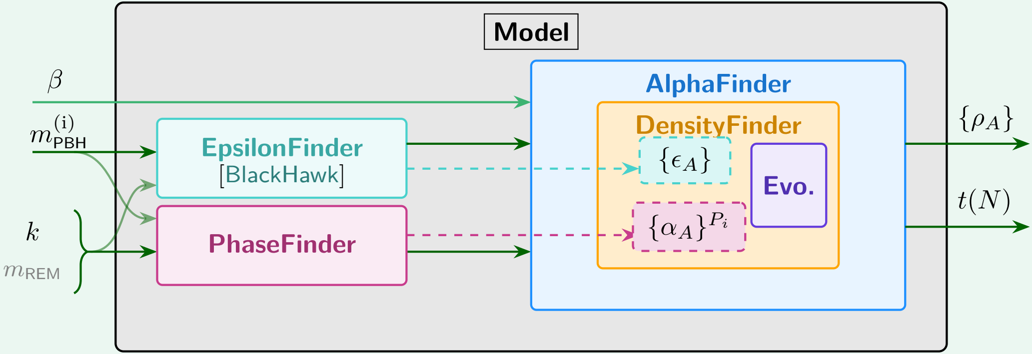

Inputs :

- β : initial abundance of PBHs
- $m_{\text{PBH}}^{(\text{i})}$: initial mass of PBHs
- k : parametrization of the lifetime of remnants
- m_{REM} : mass of the remnant

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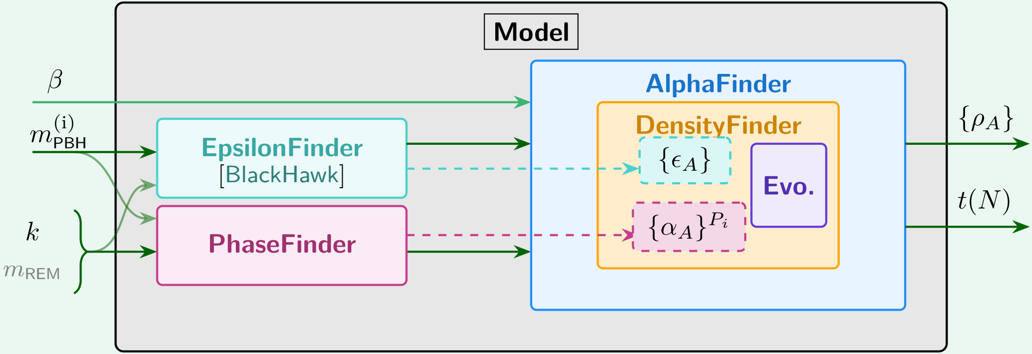

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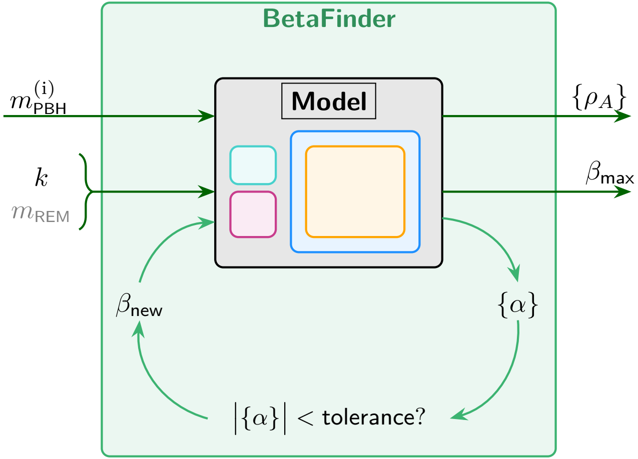
Outputs :

- $\{\rho_A\}$: density of each species
- $t(N)$: cosmic time as a function of the scale factor

Implementation : numerical part



Cosmologies obtained

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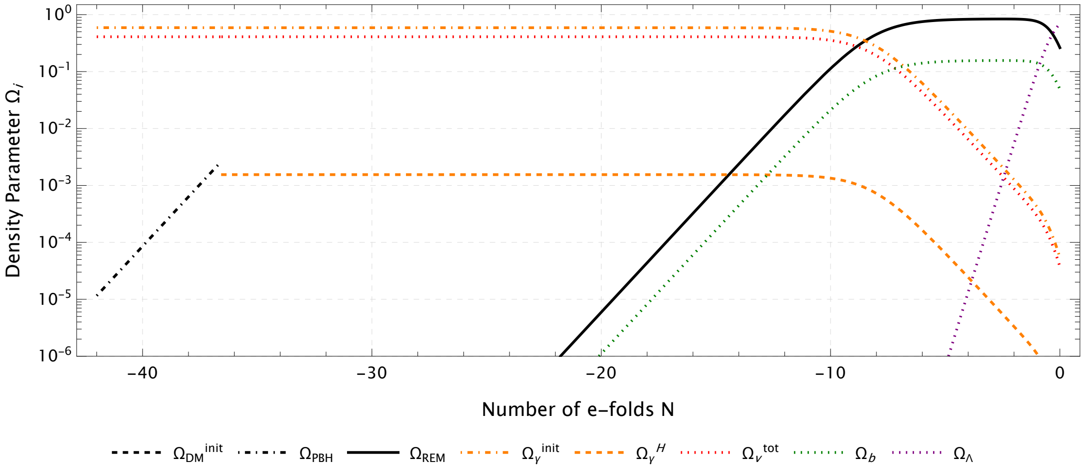
$\beta \approx 6 \cdot 10^{-14}$ and $k \geq 4$ gives **100% DM = remnant**.



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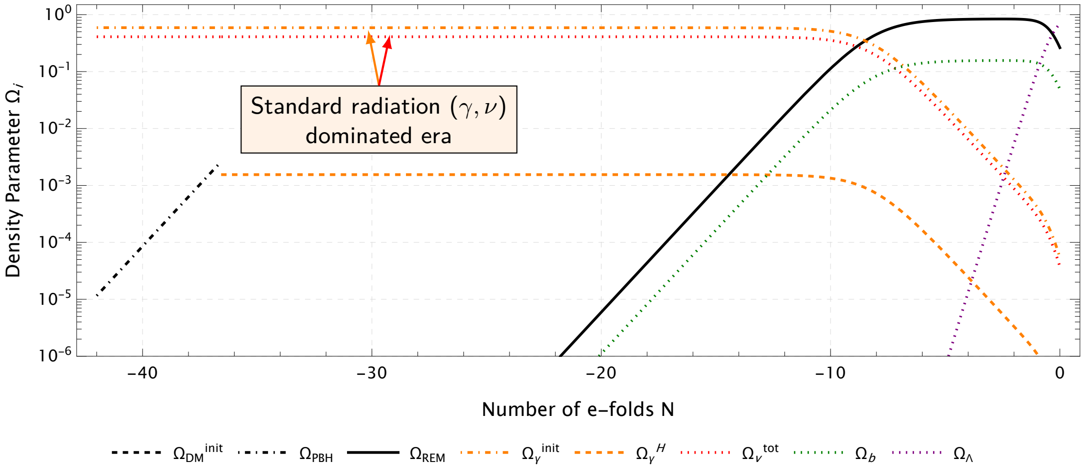

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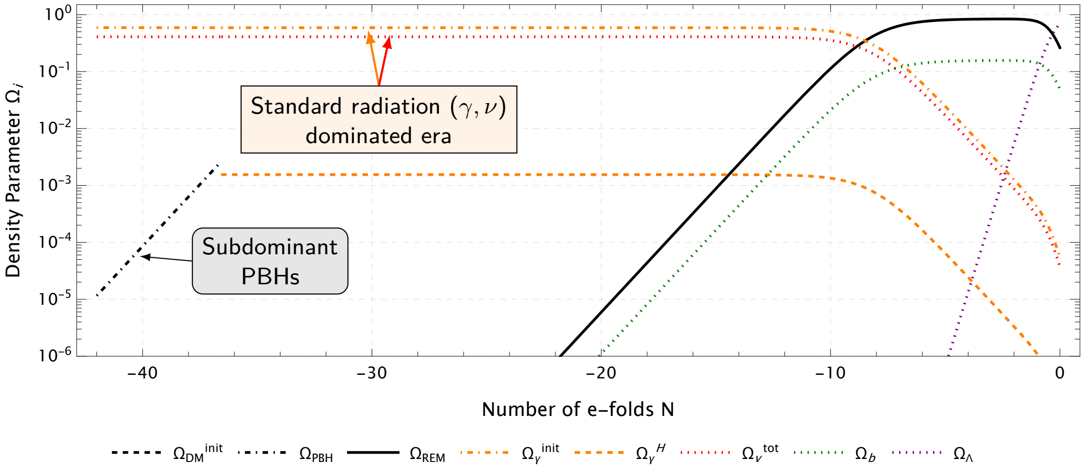

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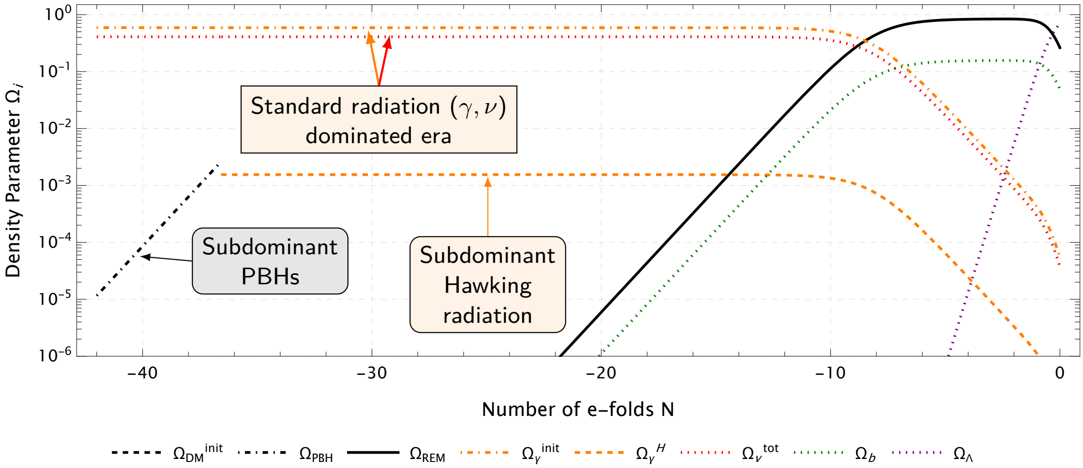

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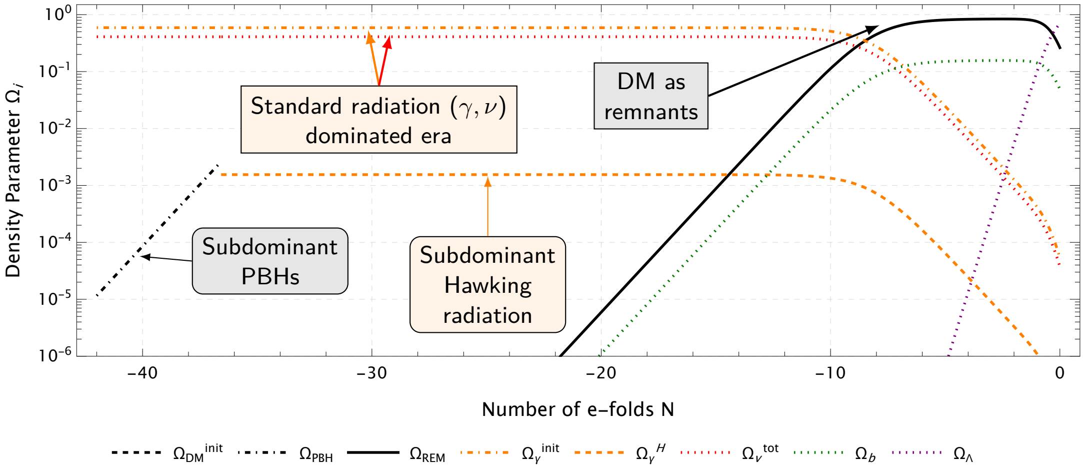

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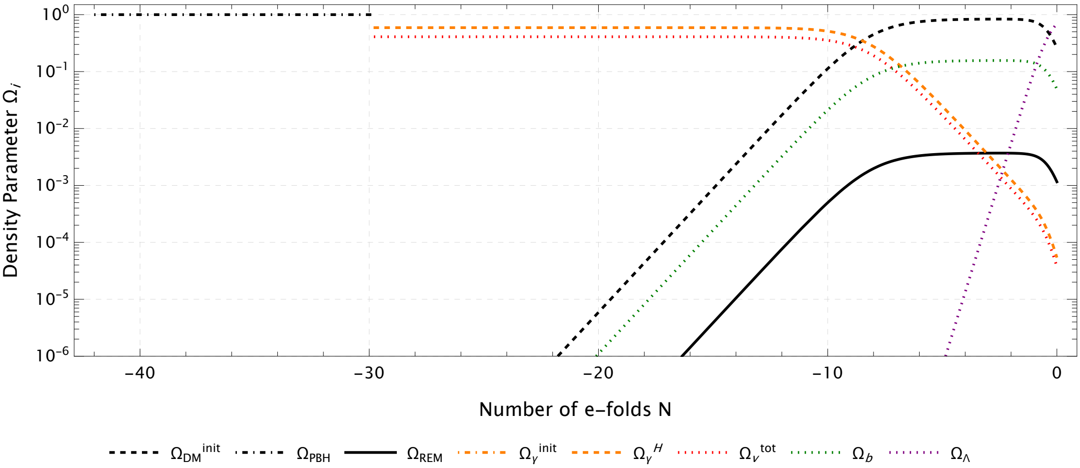

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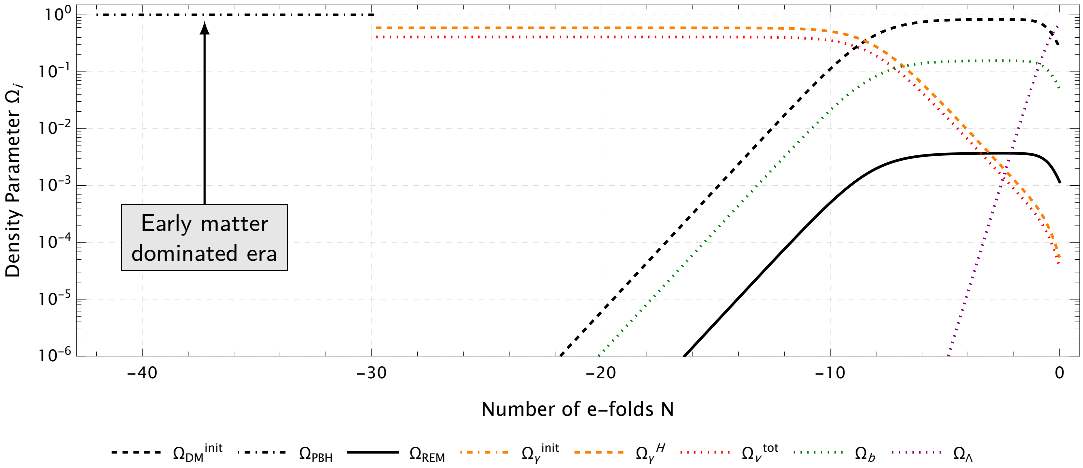

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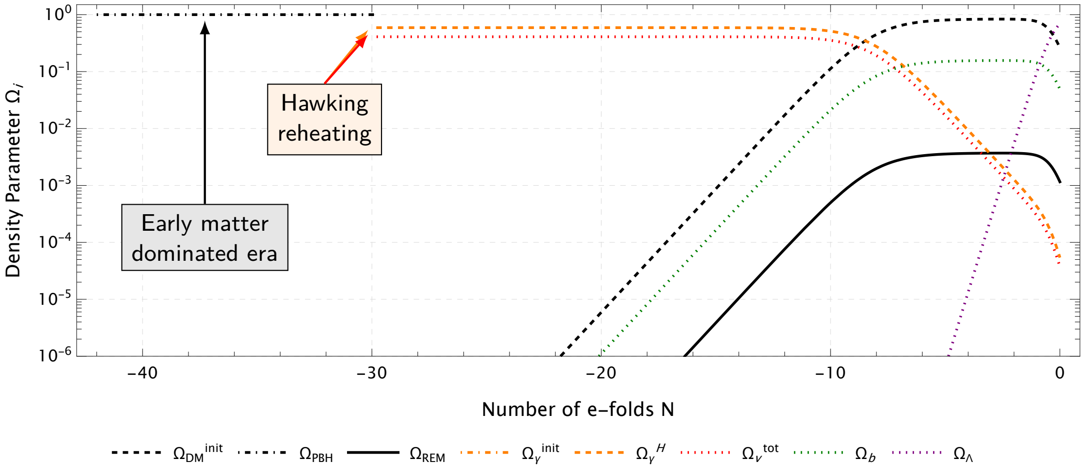

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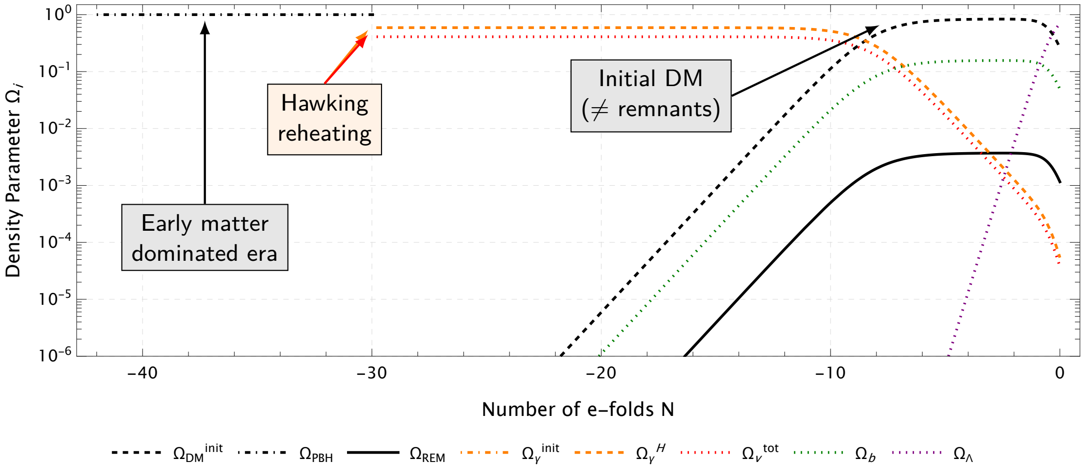

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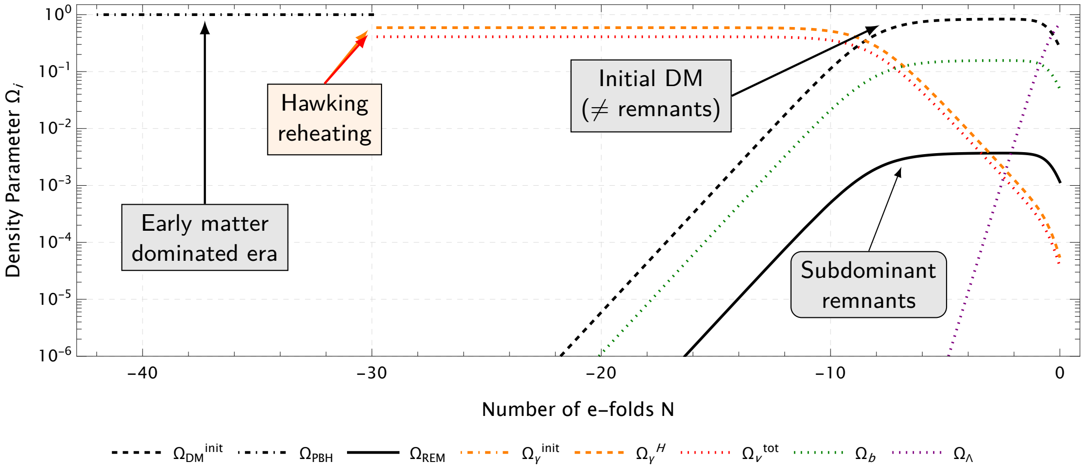

Cosmologies obtained

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

DM Saturation

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

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  Example : $m_{\text{PBH}}^{(\text{i})} = 10^{2}$ kg.

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

DM Saturation

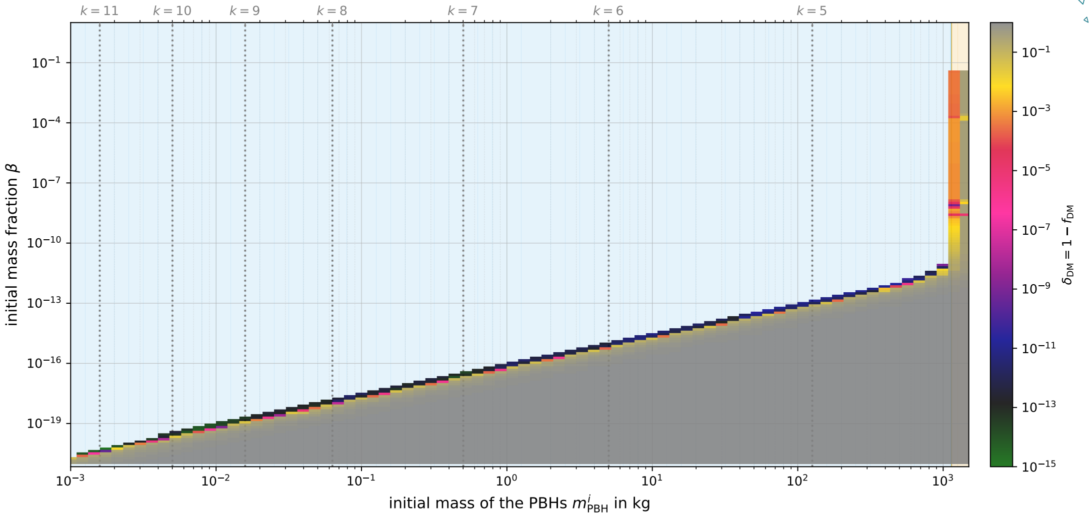
$$f_{\text{DM}} = \frac{\rho_{\text{REM}}}{\rho_{\text{DM,tot}}} \,, \quad \delta_{\text{DM}} = 1 - f_{\text{DM}} \,.$$

Radiation Saturation

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

Cosmological constraints

Cosmological constraints : regime I



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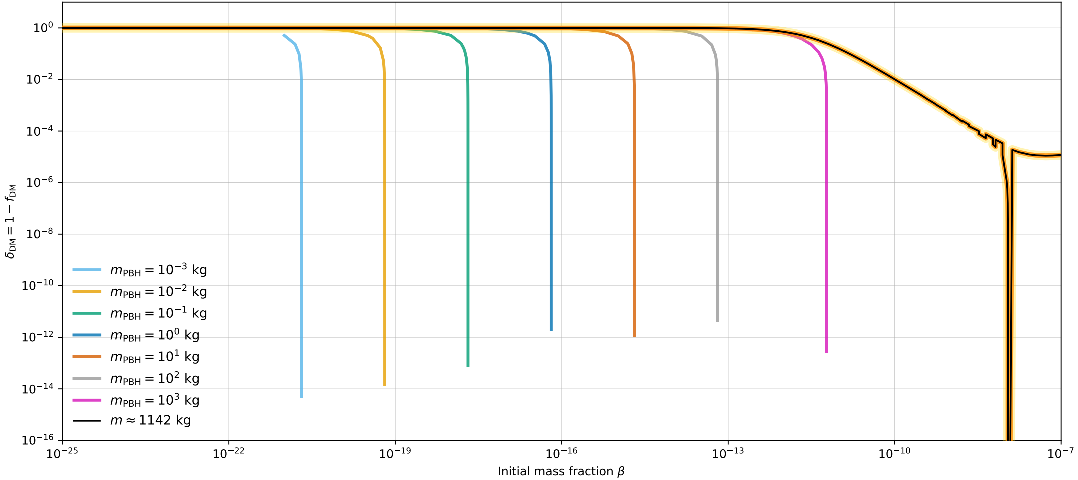
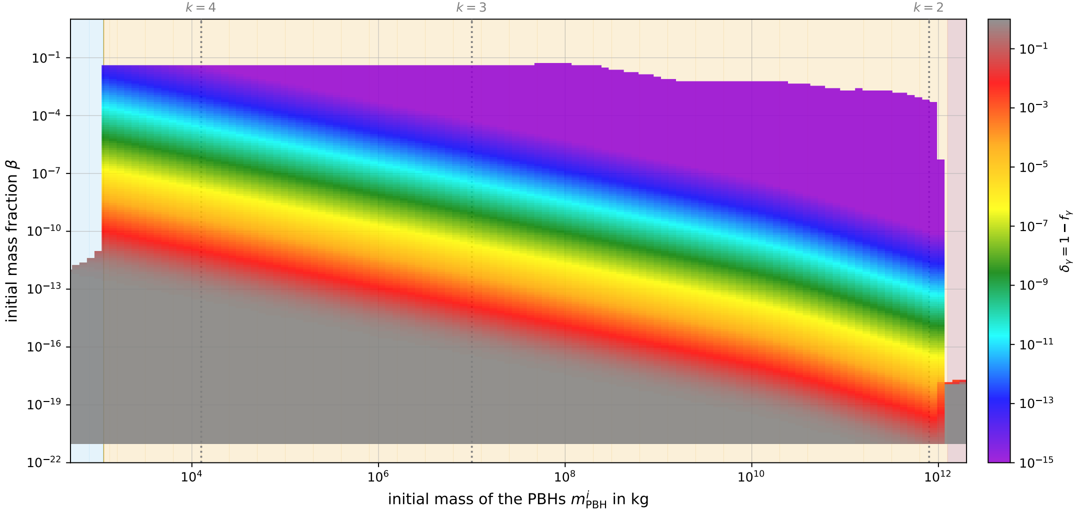


Cosmological constraints : regime II



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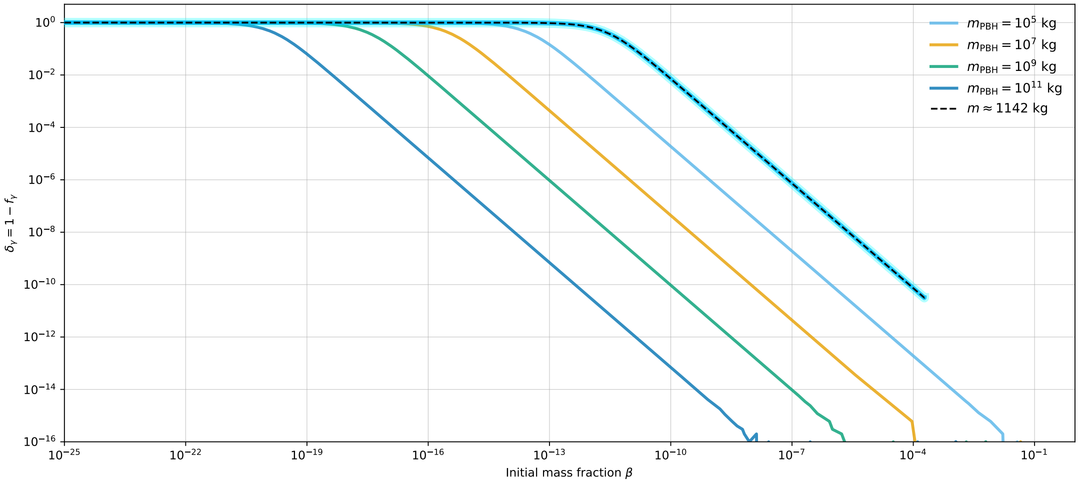
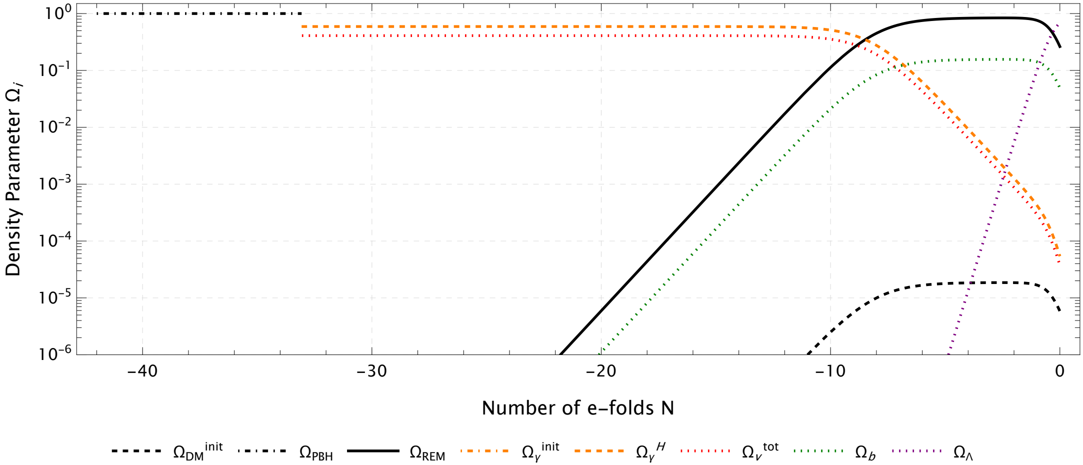


What about the interface between the two regimes,
around $m_{\textsf{PBH}}^{(\mathrm{i})} \approx 10^3$ kg ?

Cosmologies constraints : the sweet spot

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



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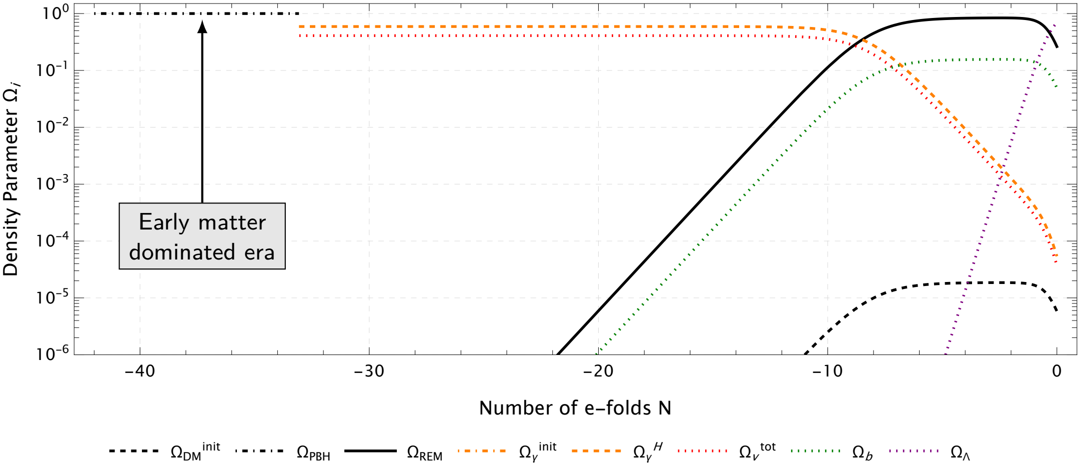

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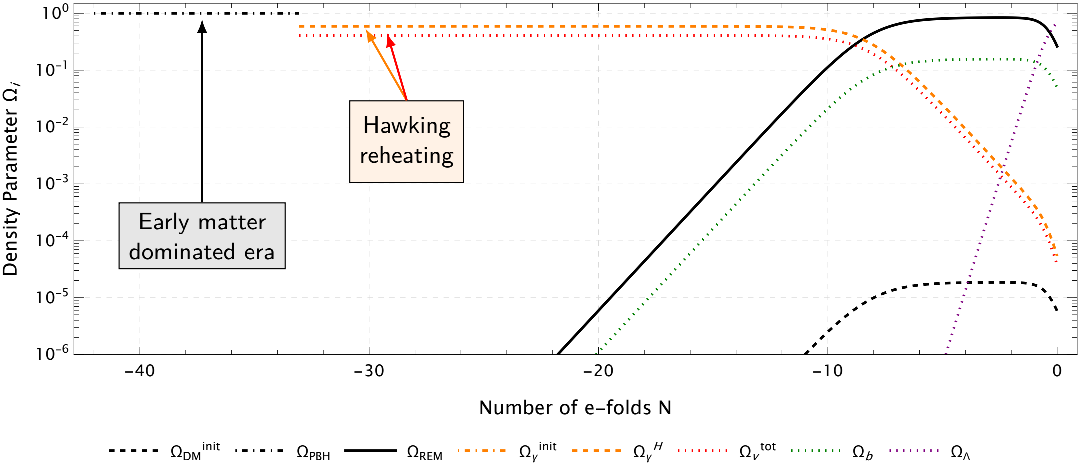

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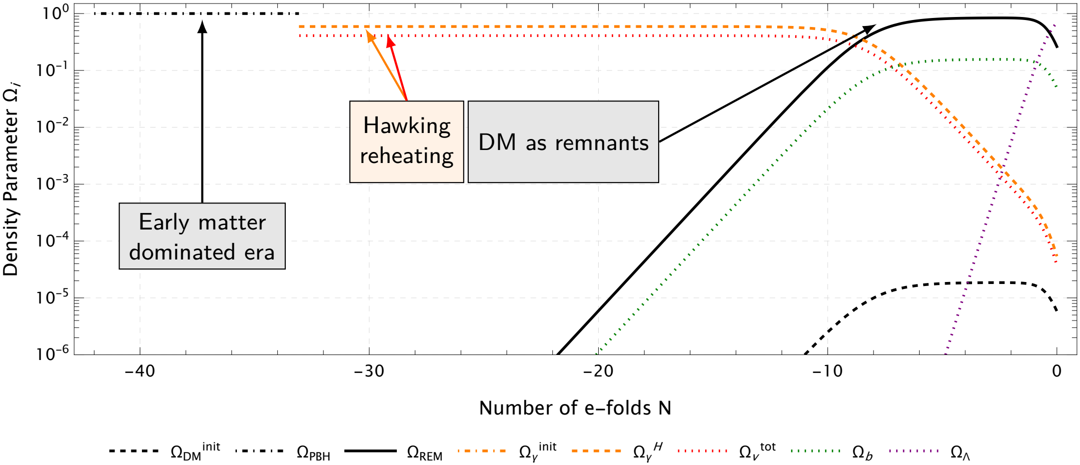

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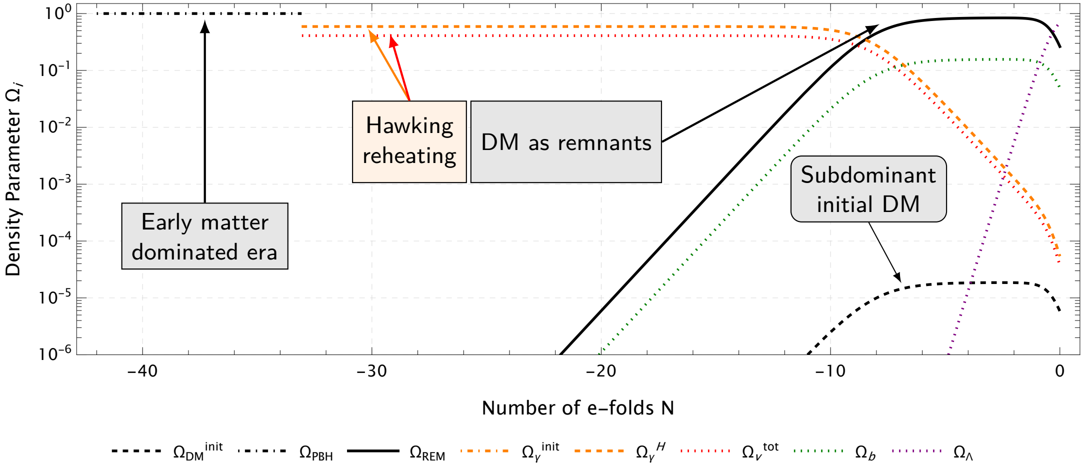

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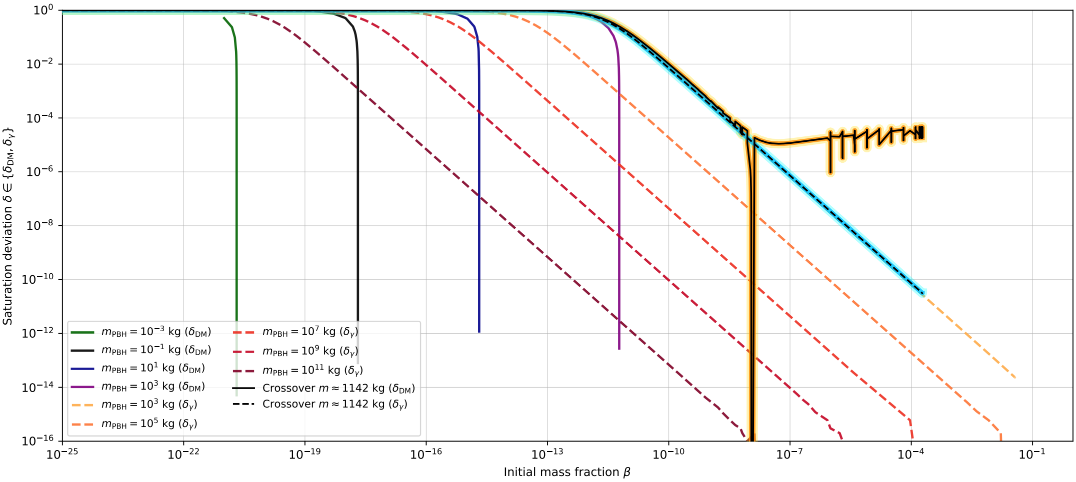


Observational signatures

Observational signatures : Overview

- **Scalar-Induced Gravitational Waves** : large primordial scalar perturbations.
- **Poisson fluctuations** : if EMD.
- **The Poltergeist mechanism** : if monochromatic mass spectrum.
- **Dark radiation** : from (i) non-thermalized neutrinos (ii) Hawking gravitons.

Observational signatures : scalar-induced GWs

Large primordial scalar perturbations $\Longrightarrow$ tensor fluctuations $\mathcal{O}(\delta^2)$.

(LISA not sensitive for small PBHs)

SIGW background = dark radiation, bounded by ΔN_{eff} :

$$\Delta N_{\text{eff}} \approx 8.3 \cdot 10^4 \, \Omega_{\text{GW},0} \ .$$

Using the Press-Schechter formalism to get $\beta = \beta(\sigma)$, the limits on ΔN_{eff} constrain the initial PBH abundance :

- Current bounds ($\Delta N_{\text{eff}} < 0.15$ [Planck, BBN, BAO]) :

$$\beta \lesssim 0.14 \ .$$

- Future sensitivity ($\Delta N_{\text{eff}} < 0.03$ [CMB-S4, LiteBird, ...]) :

$$\beta \lesssim 2 \cdot 10^{-4} \ .$$

Observational signatures : Poisson fluctuations

If PBHs dominate the energy density (EMD era), their discrete distribution generates **Poisson fluctuations**.

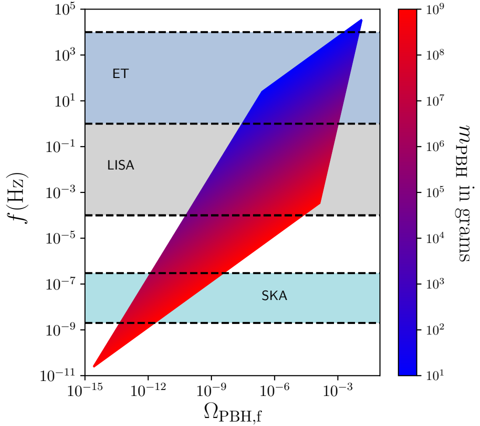
These source a distinct GW background [Papanikolaou, Vennin, Langlois ; 21].

Imposing that

$\Delta N_{\text{eff}} < 0.15 \implies \Omega_{\text{GW},0} \leq 1.8 \cdot 10^{-8}$

constrains β :

$$\beta \lesssim 10^{-3} \ .$$



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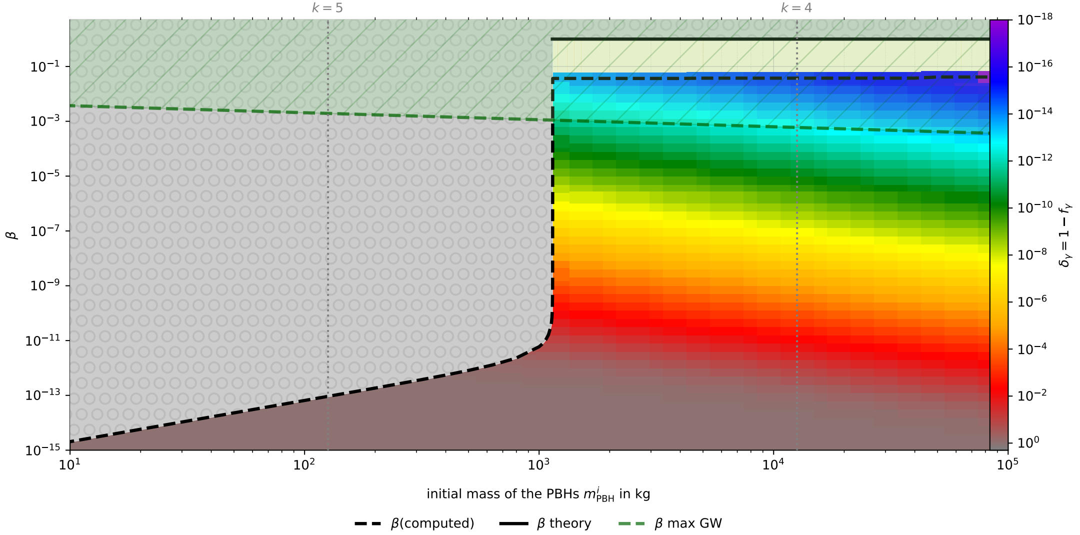


Observational signatures : the Poltergeist mechanism

Monochromatic mass distribution $\rightarrow$ almost instantaneous transition from the EMD era to a RD era.

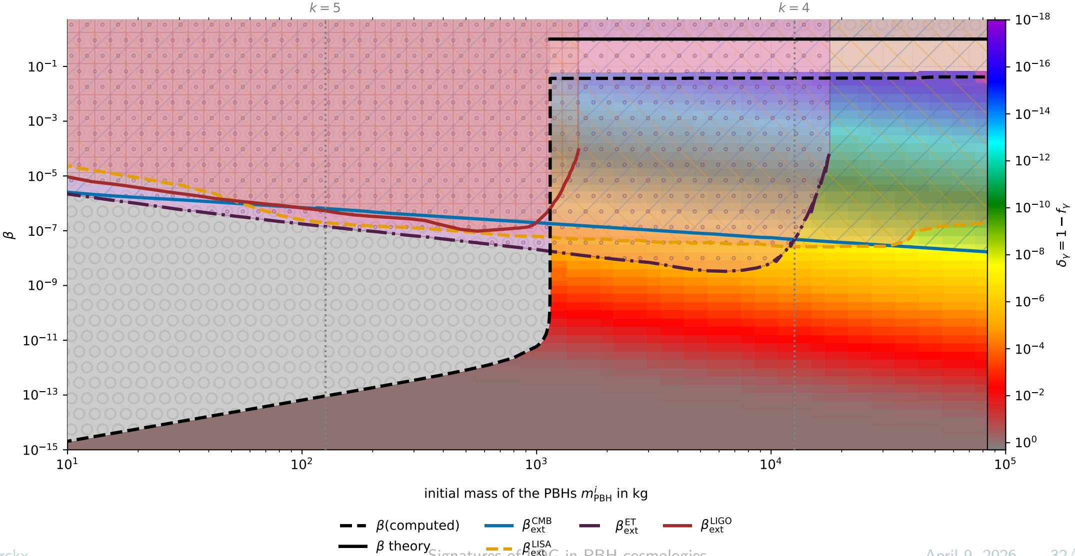
This sudden transition heavily amplifies the SIGW spectrum (**Poltergeist mechanism**).

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



Temperature and reheating

Temperature : basics

Temperature of a relativistic thermal bath follows :

$$\rho_{\rm rad} = \frac{\pi^2}{30} g_*(T) T^4 \ ,$$

where $g_*(T)$ is the temperature-dependent effective number of relativistic degrees of freedom.

Given $\rho_{\rm rad}$, the background temperature T_{bath} is obtained by inverting the above relation.

Temperature : PBH in a thermal bath

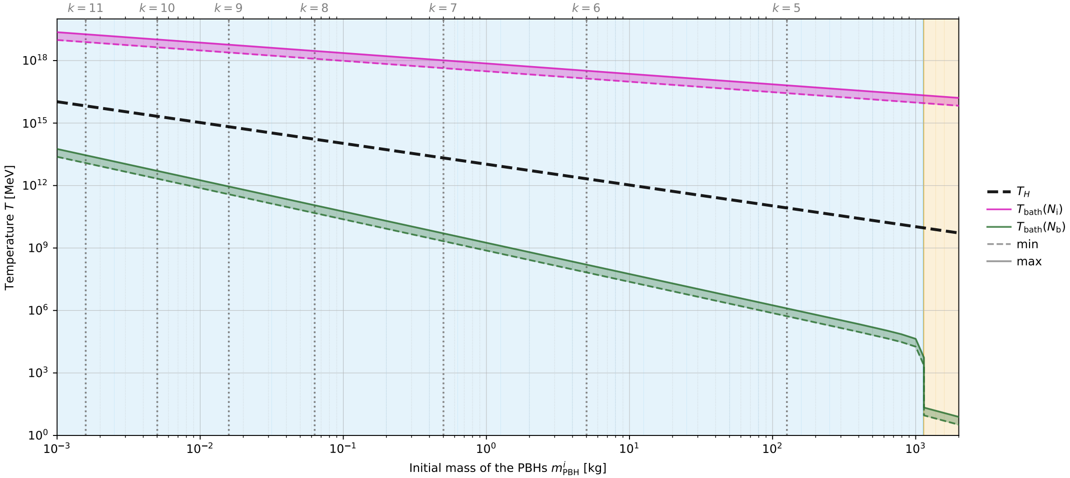
BHs have a negative heat capacity :

$$C = \frac{\partial m}{\partial T} \sim -m^2 < 0$$

BHs cannot be in stable thermal equilibrium with a heat bath at temperature T_{bath}.

1. If $T_H > T_{\text{bath}}$, **emission** dominates. Semi-classical $\dot{m} \sim -m^{-2}$ rate.
2. If $T_H < T_{\text{bath}}$, **absorption** dominates. Classical $\dot{m} \sim m^2 T_{\text{bath}}^4$ rate.
   Enhanced evaporation rate [Kalita,Maity,Chatterjee ;25]

Temperature : PBH in a thermal bath



Temperature : Hawking reheating

In Regime II, evaporation reheats the universe by injecting a radiation density $\rho_{\text{rad}}^{\text{H}} = \rho_{\gamma}^{\text{H}} + \rho_{\nu}^{\text{H}}$ at N_{b}. Assuming instantaneous thermalization,

$$T(\rho_{\text{rad}}^{\text{H}}, g_*) \gtrsim T_{\text{reheat}}^{\text{min}} \ .$$

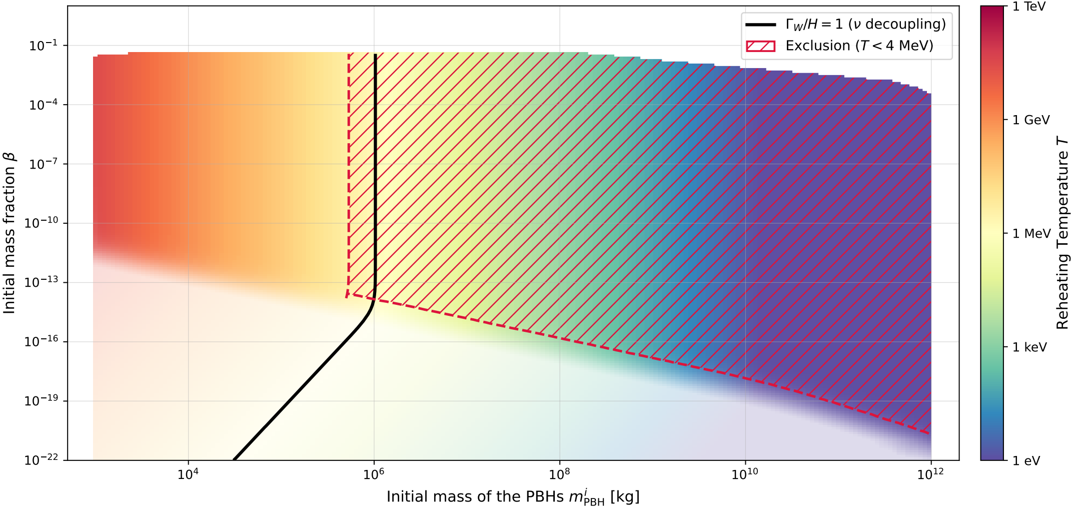
Requiring $T_{\text{reheat}}^{\text{min}} \gtrsim 4$ MeV [Hannestad,04] excludes a region of the $(m_{\text{PBH}}^{(\text{i})}, \beta)$ parameter space.

Thermal equilibrium requires the weak interaction rate to exceed the Hubble expansion :

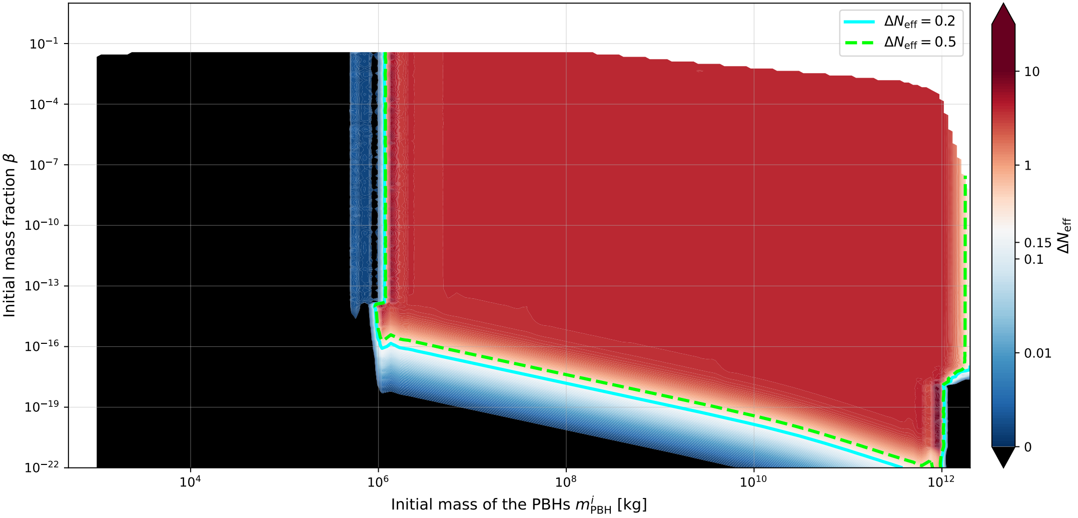
$$\frac{\Gamma_W}{H} \gtrsim 1$$

Once $\Gamma_W/H < 1$, ν decouple $\implies$ source ΔN_{eff}.

Temperature : Hawking reheating



Temperature : ΔN_{eff}



Summary and outlook

Summary

Main results

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

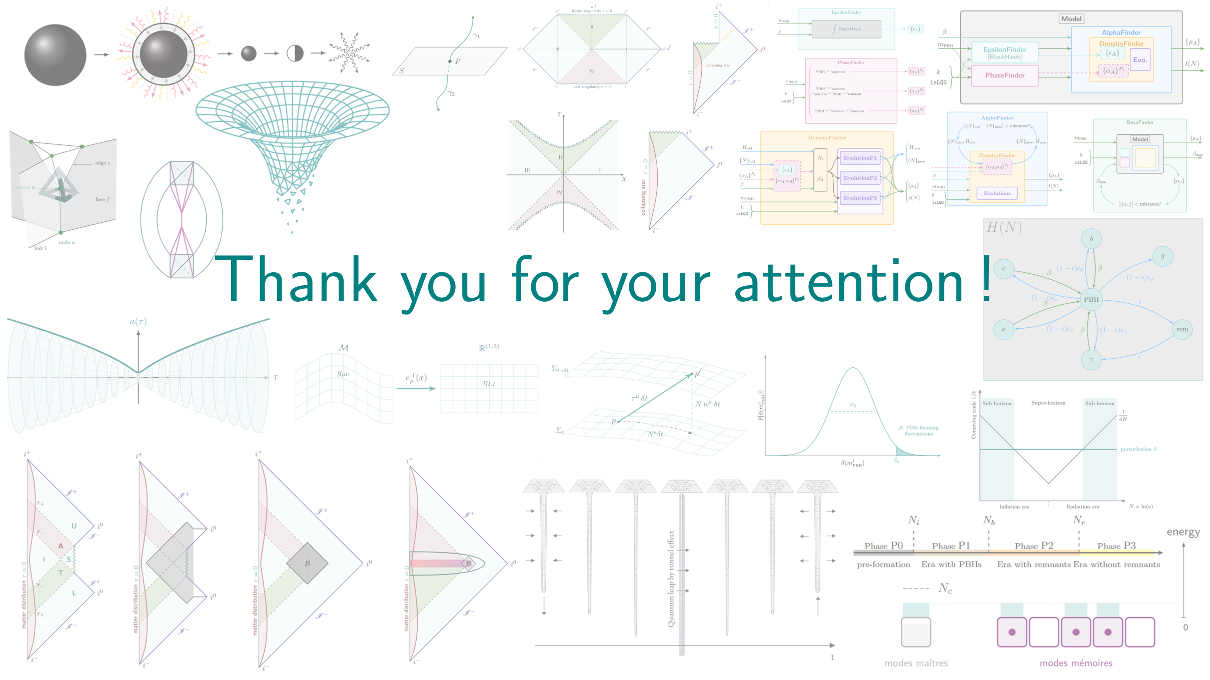
1. **Regime I ($m_{\textsf{PBH}}^{(\mathrm{i})} \leq 10^3$ kg)** : remnants can account for 100% of DM ($f_{\mathrm{DM}} \approx 1$), requiring $k \geq 4$.
2. **Regime II (10^3 kg $\leq m_{\textsf{PBH}}^{(\mathrm{i})}$)** : PBHs induce an EMD era ($f_\gamma \approx 1$).

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

Outlook

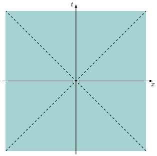
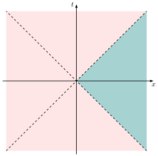
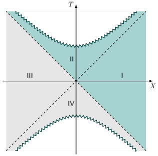
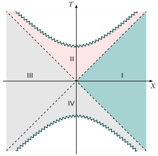
- Extended mass functions : model dependent signatures.
- Finer thermal history : treatment of non-thermalized species, baryogenesis, ...
- Explore bouncing cosmologies.
- Formation mechanisms for 10^3 kg PBHs.
- ...

Thank you for your attention !

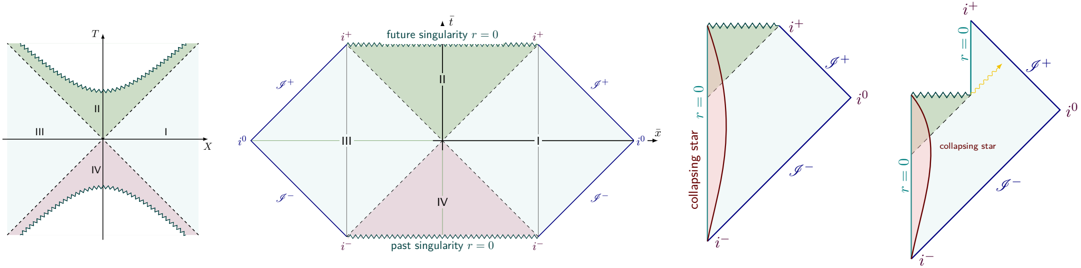


Backup slides

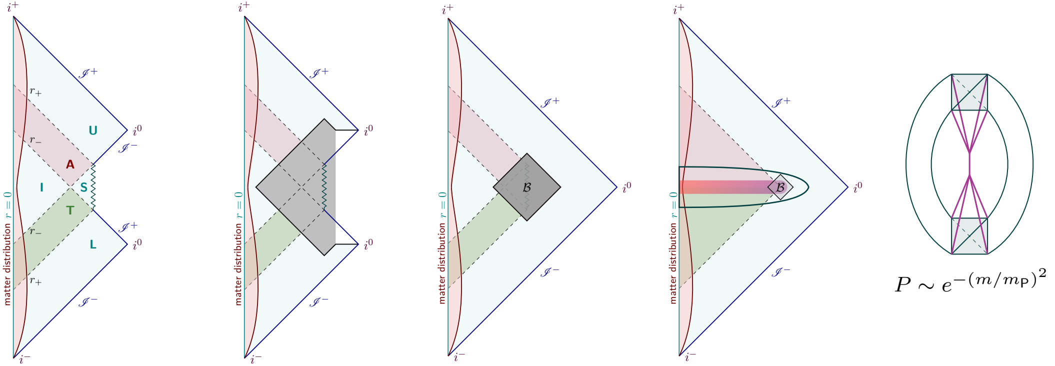
Unruh effect *vs* Hawking radiation

	Unruh effect	Hawking radiation
Framework	QFT in flat spacetime ; uniformly accelerated observer with proper acceleration $\tilde{a}$.	QFT in curved spacetime ; observer near the event horizon with surface gravity κ.
Plane waves related by $\hat{b}_p = \int \mathrm{d}k(\alpha_{pk}\hat{a}_k - \beta_{pk}\hat{a}_k^\dagger)$		
Vacua	Minkowski vacuum $\hat{a}_k \left\|0\right\rangle_M = 0$ *vs* Rindler vacuum $\hat{b}_p \left\|0\right\rangle_R = 0$ avec $\|\alpha_{pk}\|^2 = e^{\frac{2\pi p}{\tilde{a}}} \|\beta_{pk}\|^2$.	Kruskal vacuum $\hat{a}_k \left\|0\right\rangle_K = 0$ *vs* Boulware vacuum $\hat{b}_p \left\|0\right\rangle_B = 0$ avec $\|\alpha_{pk}\|^2 = e^{\frac{2\pi p}{\kappa}} \|\beta_{pk}\|^2$.
Temperatures	$T_U = \dfrac{\tilde{a}}{2\pi}$ (comoving observer).	$T_H = \dfrac{\kappa}{2\pi} = \dfrac{1}{8\pi m}$ (static observer at infinity).
Diagrams	 	 

(loop) Quantum black holes : “old” diagrams



(loop) Quantum black holes : “new” diagrams



$$P \sim e^{-(m/m_{\mathrm{P}})^2}$$

→ Prediction of a Planckian remnant when the black hole evaporates to Planckian mass.

Implementation - Analytical Part

Initial conditions parameterized by $\alpha_A : \rho_A(N = N_i^-) = \alpha_A \rho_A^{\text{obs}} e^{-3(1+\omega_A)N_i}$.
So that $\rho_A^{\text{model}} = \rho_A^{\text{obs}}$, $\alpha_A = \alpha_A(\beta, N_i, \dots)$.

Phase P1

$$\alpha_b^{\text{P1}} = \frac{1}{1-\beta} \,, \quad \alpha_\gamma^{\text{P1}} = \frac{1}{1-\beta} \,,$$

$$\alpha_c^{\text{P1}} = 1 - \frac{\beta}{1-\beta} \frac{\rho_b^{\text{obs}} + \rho_\gamma^{\text{obs}}(1+C_{\nu\gamma})e^{-N_{\text{i}}}}{\rho_{\text{DM}}^{\text{obs}}} \,.$$

Phase P2

$$\alpha_b^{\text{P2}} = \frac{1}{1-\beta} \,,$$

$$\alpha_c^{\text{P2}} = \frac{1}{1-\beta} + \frac{\beta\epsilon}{(\beta-1)\rho_{\text{DM}}^{\text{obs}}} \frac{e^{N_{\text{i}}}\left(\rho_b^{\text{obs}} + \rho_{\text{DM}}^{\text{obs}}\right) + (1+C_{\nu\gamma})\,\rho_\gamma^{\text{obs}}}{e^{N_{\text{i}}}\,(1-\beta[1-\epsilon]) + e^{N_{\text{b}}}\beta(1+C_{\nu\gamma})(1-\epsilon)\epsilon_\gamma} \,,$$

$$\alpha_\gamma^{\text{P2}} = \frac{e^{N_{\text{i}}}}{(\beta-1)\,\rho_\gamma^{\text{obs}}} \frac{\rho_\gamma^{\text{obs}}\,(1-\beta[1-\epsilon]) - e^{N_{\text{b}}}\beta(1-\epsilon)\epsilon_\gamma\left(\rho_b^{\text{obs}} + \rho_{\text{DM}}^{\text{obs}}\right)}{e^{N_{\text{i}}}\big(-1+\beta[1-\epsilon]\big) - (1+C_{\nu\gamma})e^{N_{\text{b}}}\beta(1-\epsilon)\epsilon_\gamma} \,.$$

Phase P3

$$\alpha_b^{\text{P3}} = \frac{1}{1-\beta} \,, \quad \alpha_c^{\text{P3}} = \frac{1}{1-\beta} \,,$$

$$\alpha_\gamma^{\text{P3}} = \frac{e^{N_{\text{i}}}}{(1-\beta)\rho_\gamma^{\text{obs}}} \frac{(1-\beta)\rho_\gamma^{\text{obs}} - (\rho_b^{\text{obs}} + \rho_{\text{DM}}^{\text{obs}})\beta\left(e^{N_{\text{r}}}\epsilon + e^{N_{\text{b}}}[1-\epsilon]\epsilon_\gamma\right)}{e^{N_{\text{i}}}(1-\beta) + (1+C_{\nu\gamma})\beta\left(e^{N_{\text{r}}}\epsilon + e^{N_{\text{b}}}[1-\epsilon]\epsilon_\gamma\right)} \,.$$

Implementation - maximizing β

$$\alpha_A\left(\beta^{(A)}, m_{\mathsf{PBH}}^{(\mathrm{i})}\right) = 0 \quad \longrightarrow \quad \beta = \beta_A\left(m_{\mathsf{PBH}}^{(\mathrm{i})}\right) \ .$$

For α_c^{P1}, $\alpha_\gamma^{\mathsf{P2}}$ and α_c^{P2}, one gets :

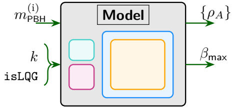
$$\beta_c^{\mathsf{P1}} = \frac{\rho_{\mathsf{DM}}^{\mathsf{obs}}}{\rho_b^{\mathsf{obs}} + \rho_{\mathsf{DM}}^{\mathsf{obs}} + \left(1 + C_{\nu\gamma}\right) e^{N_{\mathsf{i}}} \rho_\gamma^{\mathsf{obs}}} \ , \qquad \beta_\gamma^{\mathsf{P2}} = \frac{\rho_\gamma^{\mathsf{obs}}}{\left(1-\epsilon\right)\left(e^{N_{\mathsf{b}}}\epsilon_\gamma\left[\rho_b^{\mathsf{obs}} + \rho_{\mathsf{DM}}^{\mathsf{obs}}\right] + \rho_\gamma^{\mathsf{obs}}\right)} \ ,$$

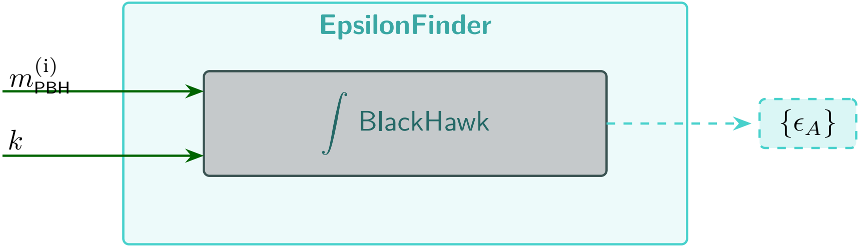
$$\beta_c^{\mathsf{P2}} = \frac{\rho_{\mathsf{DM}}^{\mathsf{obs}}}{\rho_{\mathsf{DM}}^{\mathsf{obs}} + \epsilon\rho_b^{\mathsf{obs}} - \left(1 + C_{\nu\gamma}\right) e^{N_{\mathsf{b}} - N_{\mathsf{i}}} \left(1-\epsilon\right)\epsilon_\gamma \rho_{\mathsf{DM}}^{\mathsf{obs}} + e^{-N_{\mathsf{i}}}\left(1 + C_{\nu\gamma}\right)\epsilon\rho_\gamma^{\mathsf{obs}}} \ .$$

If one let $\alpha_A = \delta_A$ with $\delta_A \ll 1$, one can get $\beta_A(\delta)$:

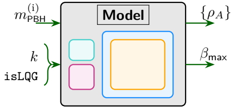
$$\beta_\gamma^{(\delta)} = \frac{\begin{aligned}&-(1+C_{\nu\gamma})e^{N_{\mathsf{b}}}\delta(1-\epsilon)\epsilon_\gamma\rho_\gamma^{\mathsf{obs}} - e^{N_{\mathsf{i}}}\left(e^{N_{\mathsf{b}}}[1-\epsilon]\epsilon_\gamma[\rho_b^{\mathsf{obs}} + \rho_{\mathsf{DM}}^{\mathsf{obs}}] + [1-2\delta]\rho_\gamma^{\mathsf{obs}} - [1-\delta]\epsilon\rho_\gamma^{\mathsf{obs}}\right) \\ &+\sqrt{\begin{aligned}&4e^{N_{\mathsf{i}}}(1-\delta)\delta(1-\epsilon)(e^{N_{\mathsf{i}}} - [1+C_{\nu\gamma}]e^{N_{\mathsf{b}}}\epsilon_\gamma){\rho_\gamma^{\mathsf{obs}}}^2 \\ &+\left(e^{N_{\mathsf{i}}}\left[-\{1-\epsilon\} + \delta\{2-\epsilon\}\right]\rho_\gamma^{\mathsf{obs}} - e^{N_{\mathsf{b}}+N_{\mathsf{i}}}[1-\epsilon]\epsilon_\gamma[\rho_b^{\mathsf{obs}} + \rho_{\mathsf{DM}}^{\mathsf{obs}}] - [1+C_{\nu\gamma}]e^{N_{\mathsf{b}}}\delta[1-\epsilon]\epsilon_\gamma\rho_\gamma^{\mathsf{obs}}\right)^2\end{aligned}}\end{aligned}}{2\delta(1-\epsilon)(e^{N_{\mathsf{i}}} - [1+C_{\nu\gamma}]e^{N_{\mathsf{b}}}\epsilon_\gamma)\rho_\gamma^{\mathsf{obs}}}$$

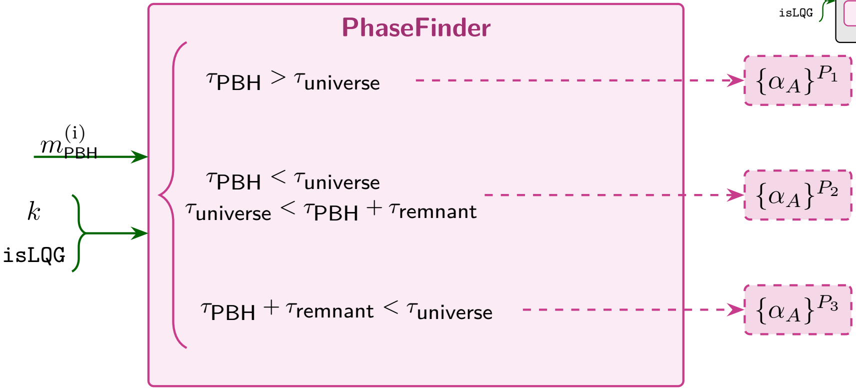
Model description - EpsilonFinder



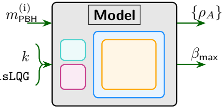


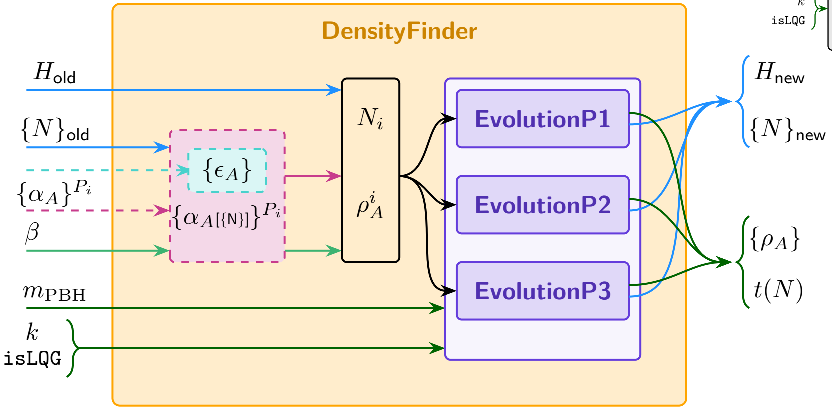
Model description - PhaseFinder



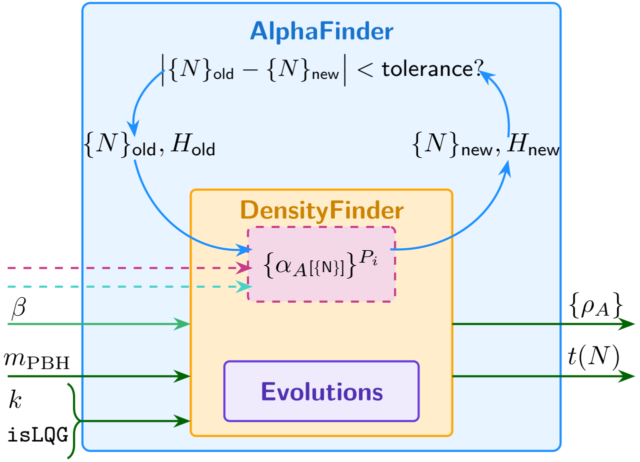


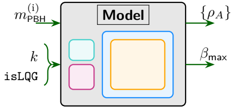
Model description - DensityFinder



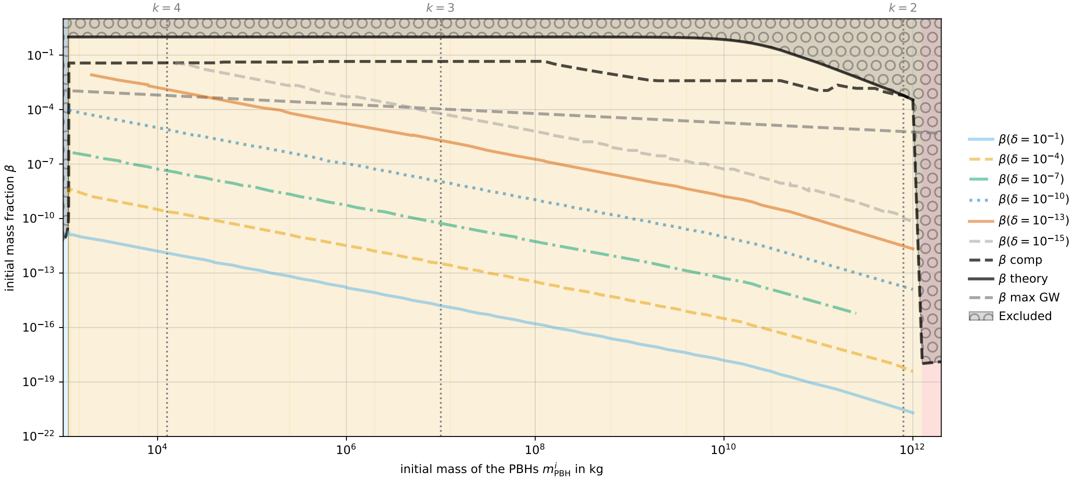


Model description - `AlphaFinder`

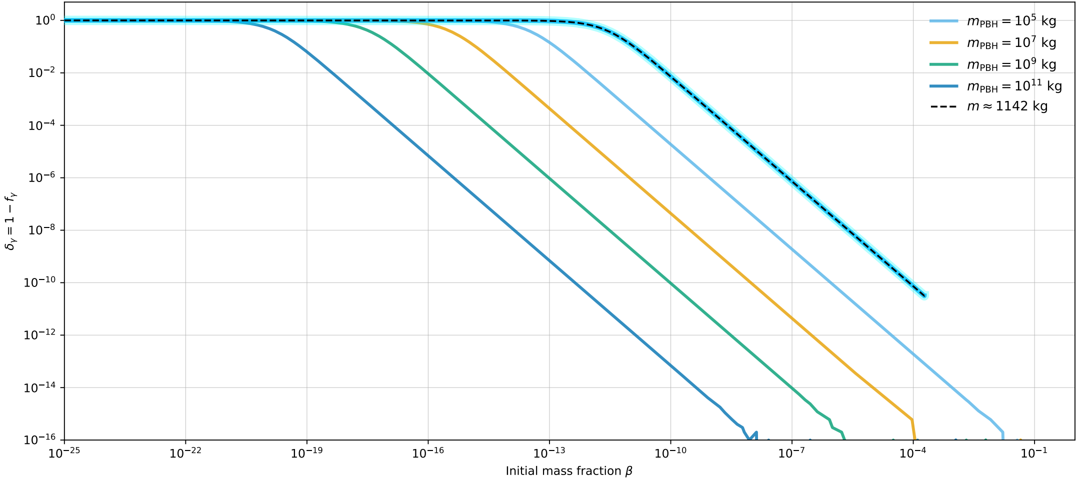




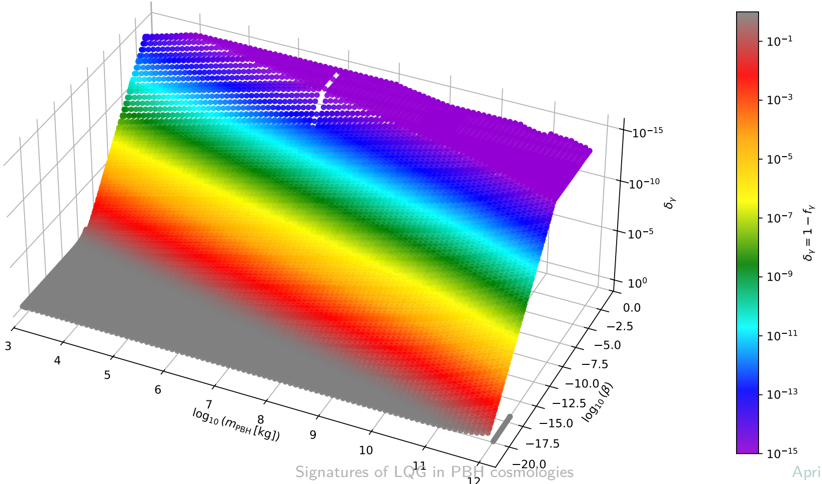
Genericity of β in the regime II



Genericity of β in the regime II



Genericity of β in the regime II



Genericity of β in the regime II

- Ratio of PBH to initial radiation at formation epoch (N_i) :

$$\frac{\rho_{\mathsf{PBH}}(N_\mathsf{i})}{\rho_\gamma^{\mathrm{i}}(N_\mathsf{i})} \approx \frac{\beta}{1-\beta} \quad \Longrightarrow \quad \frac{\rho_{\mathsf{PBH}}(N_\mathsf{b})}{\rho_\gamma^{\mathrm{i}}(N_\mathsf{b})} \approx \frac{\beta}{1-\beta} e^{N_\mathsf{b}-N_\mathsf{i}} .$$

- Hawking injection defines the radiation deficit parameter δ_γ :

$$\frac{\rho_\gamma^{\mathrm{H}}(N_\mathsf{b})}{\rho_\gamma^{\mathrm{i}}(N_\mathsf{b})} = \frac{1-\delta_\gamma}{\delta_\gamma}$$

- Equating $\rho_\gamma^{\mathrm{H}}(N_\mathsf{b}) \approx \rho_{\mathsf{PBH}}(N_\mathsf{b})$ in the saturation limit isolates β :

$$\beta \approx \left(1 + \frac{\delta_\gamma}{1-\delta_\gamma} e^{N_\mathsf{b}-N_\mathsf{i}}\right)^{-1}$$

Consequence : At the background level, the initial fraction β is highly degenerate with the EMD duration $\Delta N = N_\mathsf{b} - N_\mathsf{i}$.

SIGW

Goal : relate β and ΔN_{eff} from scalar-induced GWs.
Press-Schechter formalism for the probability density function :

$$\beta = \mathrm{erfc}\left(\frac{\delta_c}{\sqrt{2}\sigma}\right) \approx \frac{\sqrt{2}\sigma}{\sqrt{\pi}\delta_c} e^{-\frac{\delta_c^2}{2\sigma^2}} \ ,$$

with $\delta_c \approx 0.45$ and $\sigma^2 \approx (2/3)^2 \mathcal{P}_p$ (for $\beta \ll 1$) is the variance of primordial density fluctuations. Inverting the above relation gives $\mathcal{P}_p(\beta)$ the power spectrum of the curvature perturbations, which can be related to the one of the tensor fluctuations h by :

$$\mathcal{P}_h(k, t_k) = \frac{\mathcal{P}_p^2}{16\pi} \frac{9k^2(k^2 - 4k_p^2)^2 |k^2 - 2k_p^2|}{k_p^4 (3k^2 + k_p^2)^2 |k^2 - k_p^2|} \Theta(2k_p - k) \ ,$$

where k_p is the position of the peak. Today's GW spectrum is related to $\mathcal{P}_h(k, t_k)$ by :

$$\Omega_{\text{GW},0} = \frac{a_0 k^2}{a_{\text{eq}} k_{\text{eq}}} T^2(k, t_0) \mathcal{P}_h(k, t_k) \approx \frac{a_{\text{eq}}}{a_0} \mathcal{P}_h(k, t_k) \approx 3.1 \cdot 10^{-4} \mathcal{P}_p^2 \ .$$

SIGW

The relation between N_{eff} and $\Omega_{\text{GW},0}$ is extracted from :

$$\rho_\gamma + \rho_\nu + \rho_{\text{GW}} = \frac{\pi^2}{15} T_\gamma^4 + \frac{7\pi^2}{120} T_\nu^4 N_{\text{eff}} \ ,$$

where $N_{\text{eff}} = 3.046 + \Delta N_{\text{eff}}$.

This gives $\Delta N_{\text{eff}} \approx 8.3 \cdot 10^4 \, \Omega_{\text{GW},0}$. For $\Delta N_{\text{eff}} < 0.15$ [Planck, BBN, BAO], we get $\beta \lesssim 0.14$.

Future measurements [CMBs4, LiteBird, ...] could bring $\Delta N_{\text{eff}} < 0.03 \implies \beta \lesssim 2 \cdot 10^{-4}$.

EMD era : GW plateau constrain

In case of an PBH-dominated era, the **Poisson fluctuations** of the PBH distribution source a GW background. For a monochromatic distribution, the following relation holds [Papanikolaou, Vennon, Langlois ; 21] :

$$\Omega_{\mathrm{GW},0} = \Omega_{\mathrm{rad},0}\mu\left(\kappa - \ln(\beta_{\mathrm{GW}})\right)\beta_{\mathrm{GW}}^{16/3} \ ,$$

where

$$\mu = \frac{1}{16}\left(\frac{45}{2}m_{\mathrm{PBH}}^{(\mathrm{i})}\right)^{4/3}\left(\frac{g_{\mathrm{eff}}}{100}\right)^{-2/3} \ , \quad \kappa = \frac{4}{3\sqrt{5}\pi} + \frac{3}{2}\ln(2) \ .$$

Solving for β_{GW} while imposing $\Omega_{\mathrm{GW},0} \leq 1.8 \cdot 10^{-8}$ gives the following constraint on β :

$$\beta \leq \left(-\frac{3}{16}\frac{\Omega_{\mathrm{rad},0}}{\Omega_{\mathrm{GW},0}}\mu\, W_{(-)}\left[-\frac{16}{3}\frac{\Omega_{\mathrm{GW},0}}{\mu\,\Omega_{\mathrm{rad},0}}e^{-16\kappa/3}\right]\right)^{-3/16}$$

Evaporation density : Independence from β

Objective : Show $\rho_{\rm PBH}(N_{\rm b})$ (and thus final ρ_γ) is independent of initial fraction β.

1. Initial setup (PBH scaling as matter from $N_{\rm i}$) :

$$\rho_{\rm PBH}(N_{\rm b}) \approx \beta \underbrace{3M_{\rm P}^2 H_{\rm i}^2}_{\rho_{\rm tot}(N_{\rm i})} e^{-3(N_{\rm b}-N_{\rm i})}$$

2. Two-phase expansion : $N_{\rm i} \xrightarrow{\text{RD}} N_{\rm dom} \xrightarrow{\text{EMD}} N_{\rm b}$

- **RD ($N_{\rm i} \to N_{\rm dom}$) :** PBH domination condition ($\beta e^{\Delta N} = 1$)

$$e^{-3(N_{\rm dom}-N_{\rm i})} = \beta^3 \quad \Longrightarrow \quad H_{\rm dom}^2 \approx H_{\rm i}^2 \beta^4$$

- **EMD ($N_{\rm dom} \to N_{\rm b}$) :** Matter-like scaling ($H^2 \propto a^{-3}$)

$$e^{-3(N_{\rm b}-N_{\rm dom})} \approx \frac{H_{\rm b}^2}{H_{\rm dom}^2} \approx \frac{H_{\rm b}^2}{H_{\rm i}^2\beta^4}$$

3. Recombination :

$$\rho_{\rm PBH}(N_{\rm b}) \approx \beta(3M_{\rm P}^2 H_{\rm i}^2)\left[\beta^3\left(\frac{H_{\rm b}^2}{H_{\rm i}^2\beta^4}\right)\right] = 3M_{\rm P}^2 H_{\rm b}^2$$

$\Longrightarrow$ **Exact cancellation of β.** Final density strictly fixed by $H_{\rm b}$ (PBH mass).

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

Viability at $m_{\text{PBH}}^{(\text{i})} \approx 10^3\,\text{kg}$

Target regime : $f_{\text{DM}} = 1$ and $f_\gamma = 1$.

1. Mass-excluded

- Wash-in $(m_{\text{PBH}}^{(\text{i})} \leq 1\,\text{kg})$
- Asymmetric $(m_{\text{PBH}}^{(\text{i})} \leq 10^{-3}\,\text{kg})$
- Spontaneous $(m_{\text{PBH}}^{(\text{i})} > 10^{12}\,\text{kg})$

2. Mass-compatible

- **GUT :** Post-EWPT decay.
- **Hot Spot :** Local sphalerons.
- **Shocks :** Mass fits