Primordial Black Holes and their relics

LQG relics: **26/05**.28953

+ upcoming work on generic stabilization

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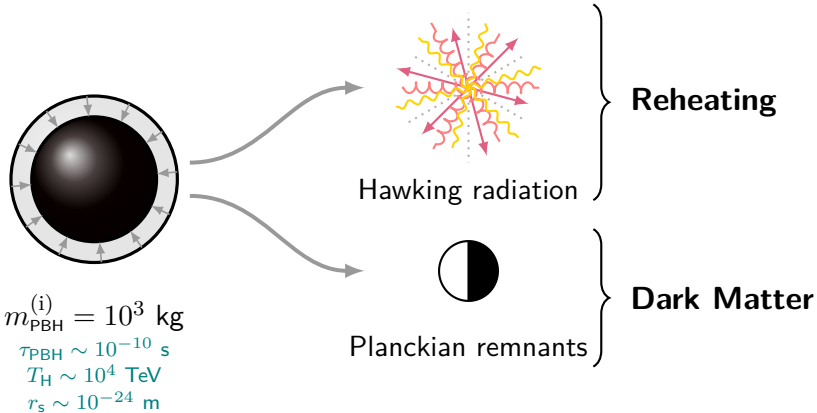
Statement

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



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Framework

Cosmological framework & Relic mass spectrum

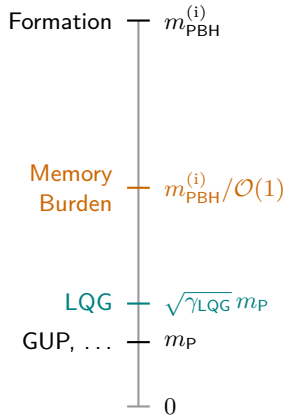
- FLRW + early inflationary phase.
- Standard dynamics :

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

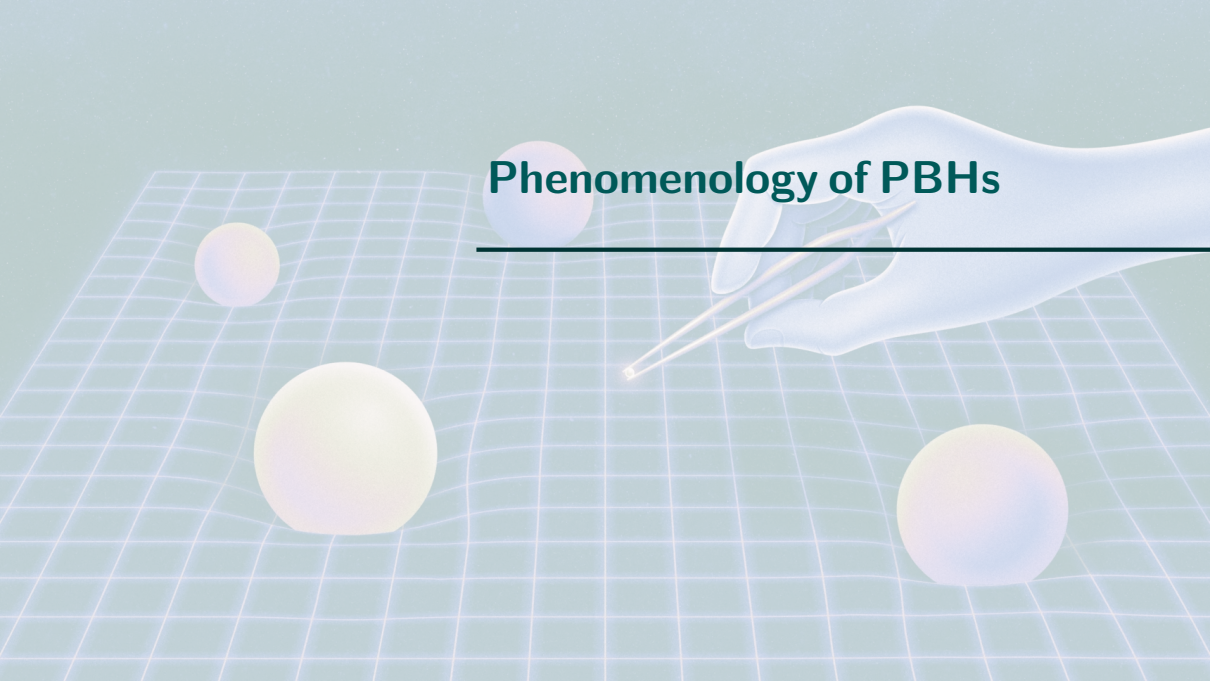
- Initial PBH mass $\sim$ Hubble mass :

$$m_{\rm PBH}^{(\rm i)} \approx \frac{1}{H_{\rm form}} \sim t_{\rm form}$$

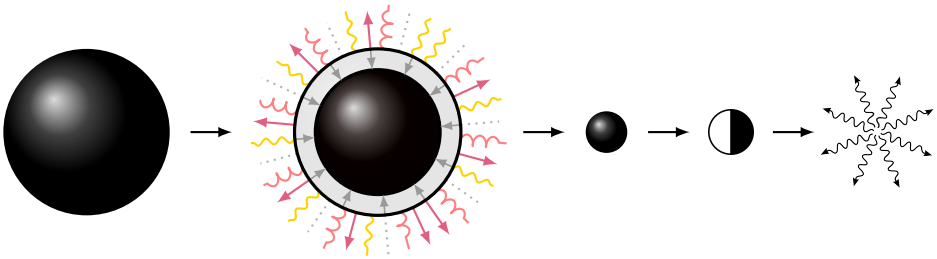
(Monochromatic mass distribution)



Phenomenology of PBHs



Phenomenology of PBHs



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

$m_{\mathrm{PBH}}^{(\mathrm{i})}$ N_{i} N_{b} N_{r}

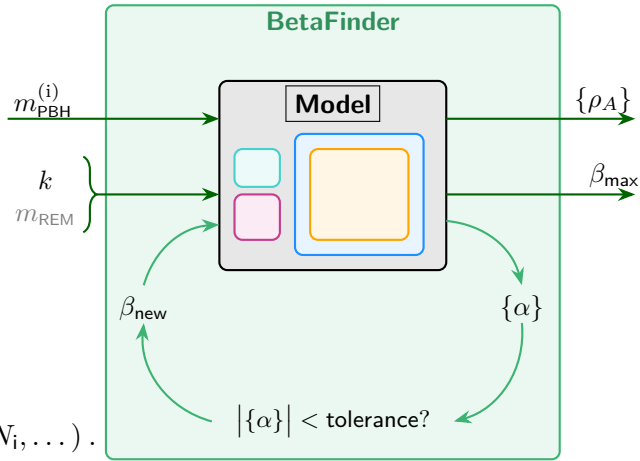
Phase P0 | Phase P1 | Phase P2 | Phase P3

pre-formation | era with PBHs | era with remnants | era without remnants

Implementation

Implementation

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



Initial conditions :

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

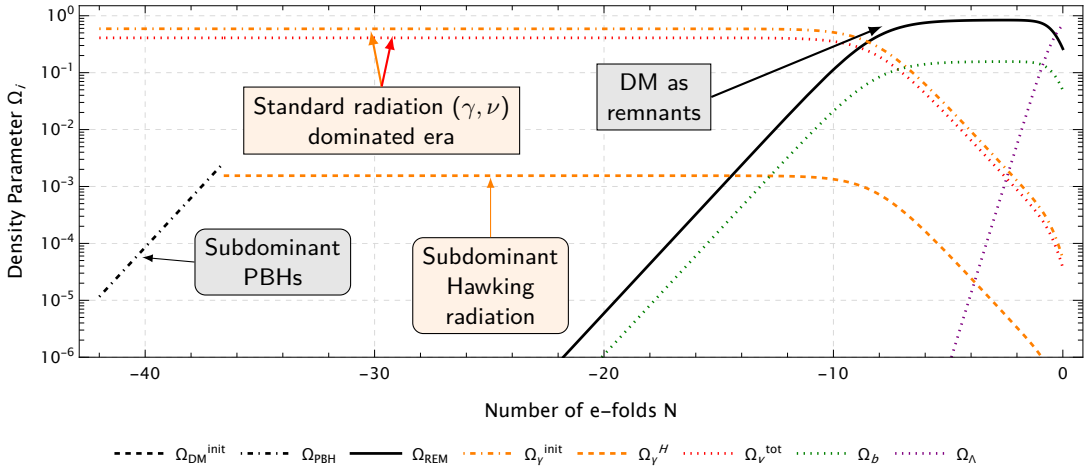
so that :

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

Cosmologies obtained

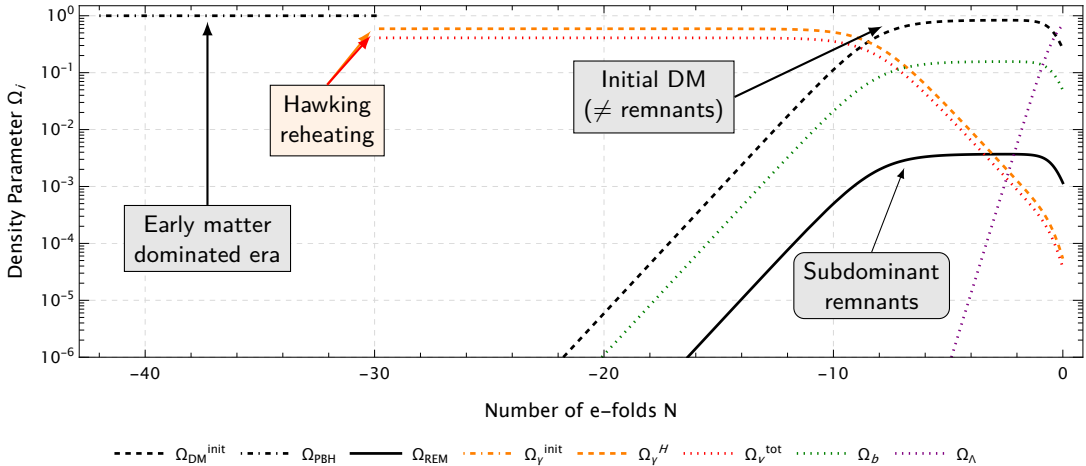
Cosmologies obtained : $m_{\mathrm{PBH}}^{(\mathrm{i})} = 10^2$ kg

$\beta \approx 6 \cdot 10^{-14}$ 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 ($\implies$ EMD era)
  Example : $m_{\text{PBH}}^{(\text{i})} = 10^{4}$ kg.

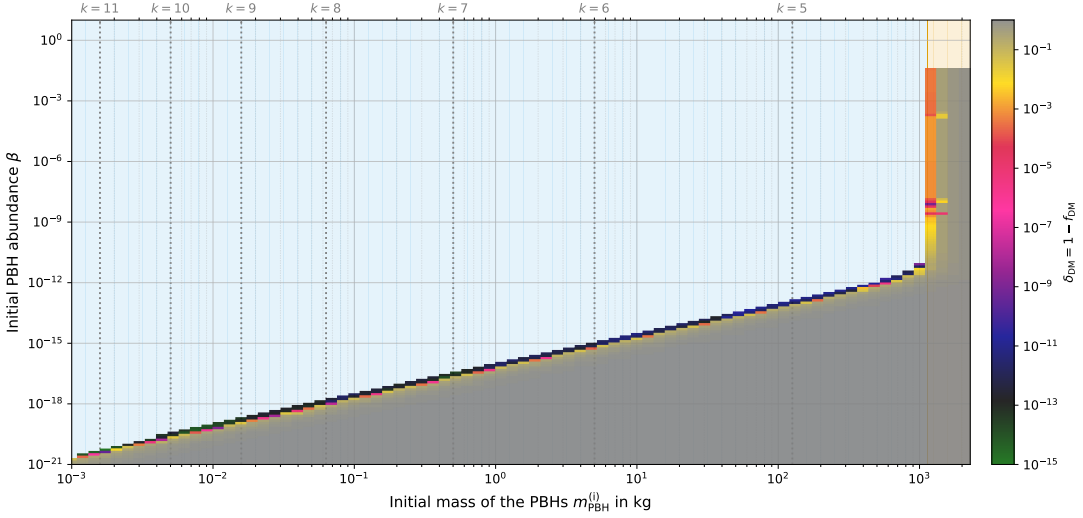
DM Saturation

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

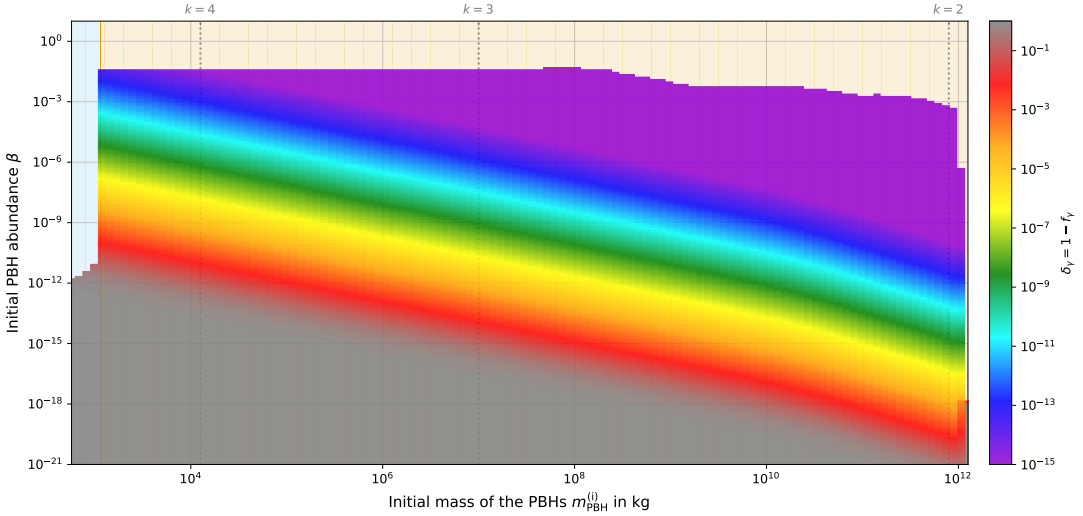
Radiation Saturation

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

Cosmological constraints : regime I



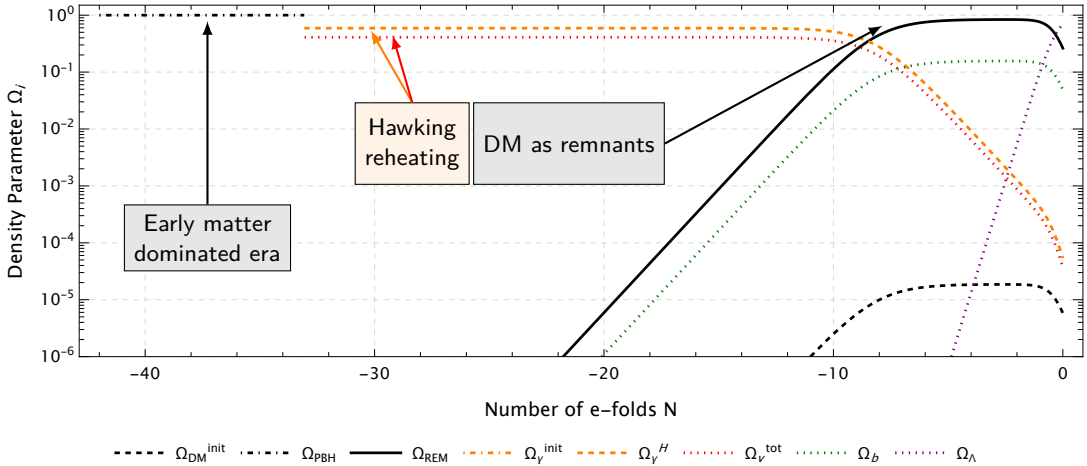
Cosmological constraints : regime II



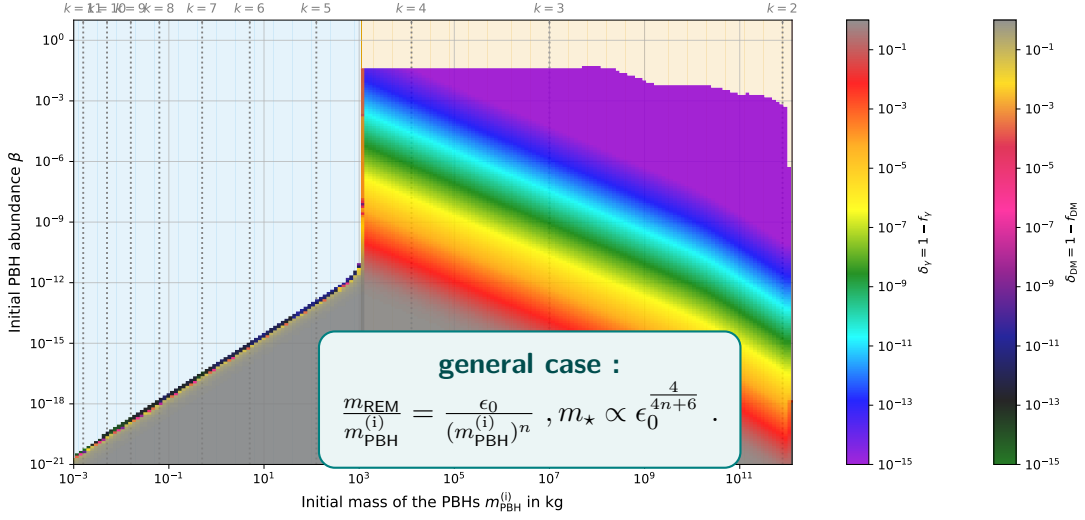
What about the interface between the two regimes,
around $m_{\mathrm{PBH}}^{(\mathrm{i})} \approx 10^3$ kg ?

Cosmologies constraints : the sweet spot

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

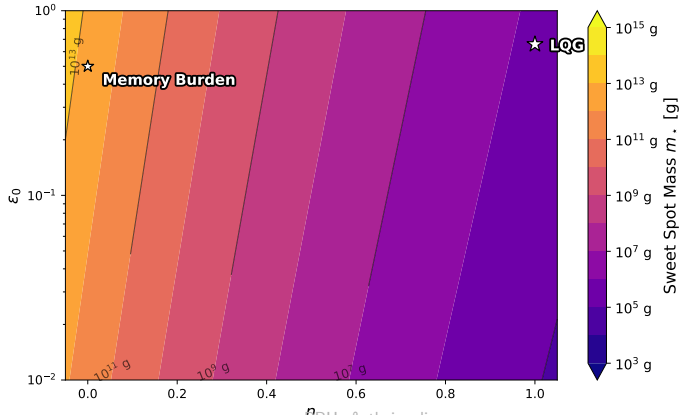


Cosmological constraints : the interface



Other stabilization mechanisms : sweetspot ?

$$\frac{m_{\text{REM}}}{m_{\text{PBH}}^{(\text{i})}} = \frac{\epsilon_0}{(m_{\text{PBH}}^{(\text{i})})^n} \ , \quad m_\star \approx \left[\frac{1}{6\pi\, 10^4} \frac{1}{\rho_\gamma^{\text{obs}}} \left(\frac{\epsilon_0}{R_{\text{obs}}} \right)^4 \right]^{\frac{1}{4n+6}} \ , \qquad R_{\text{obs}} = \frac{\rho_{\text{DM}}^{\text{obs}}}{\rho_\gamma^{\text{obs}}} \ .$$



Observational signatures

Observational signatures : Overview

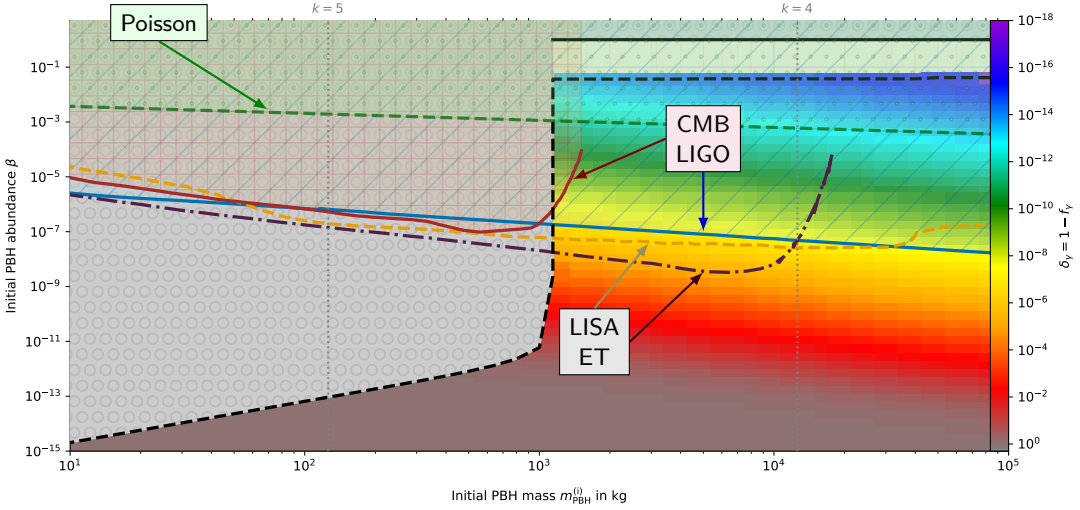
1. **Scalar-Induced Gravitational Waves** : large primordial scalar perturbations.

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 : the Poltergeist mechanism



Constraints from temperature (regime II)

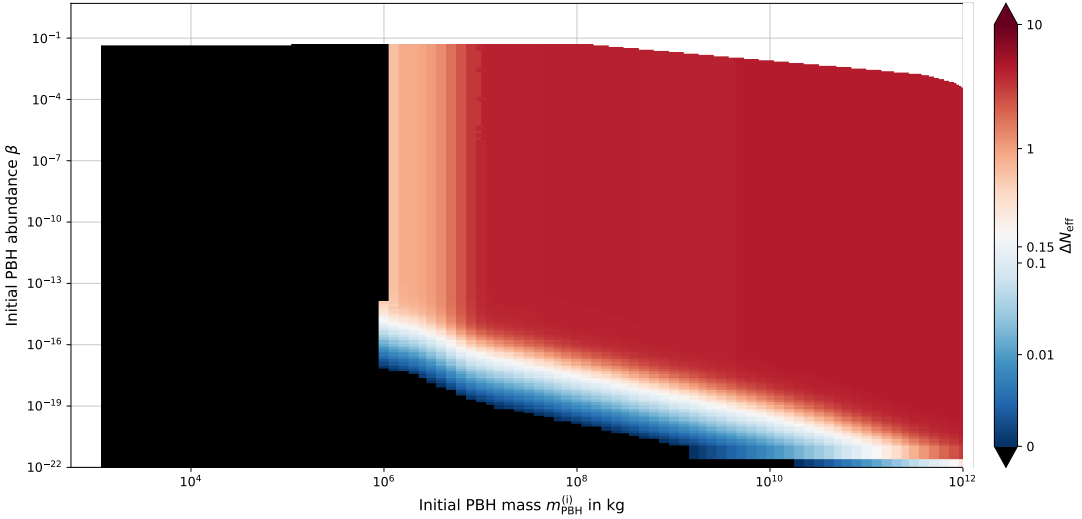
1. $\Delta N_{\rm eff}$:
   Thermalizing neutrinos requires :

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

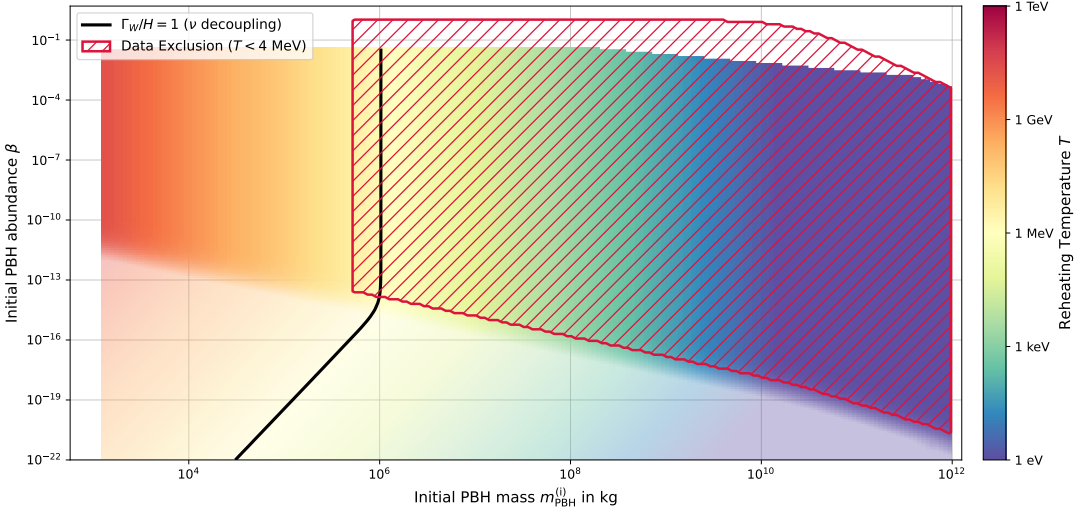
2. Reheating :
   At $N_{\rm b}$, injected energy $\rho^{\rm H}_{\rm rad} = \rho^{\rm H}_{\gamma} + \rho^{\rm H}_{\nu}$. [Hannestad,04]

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

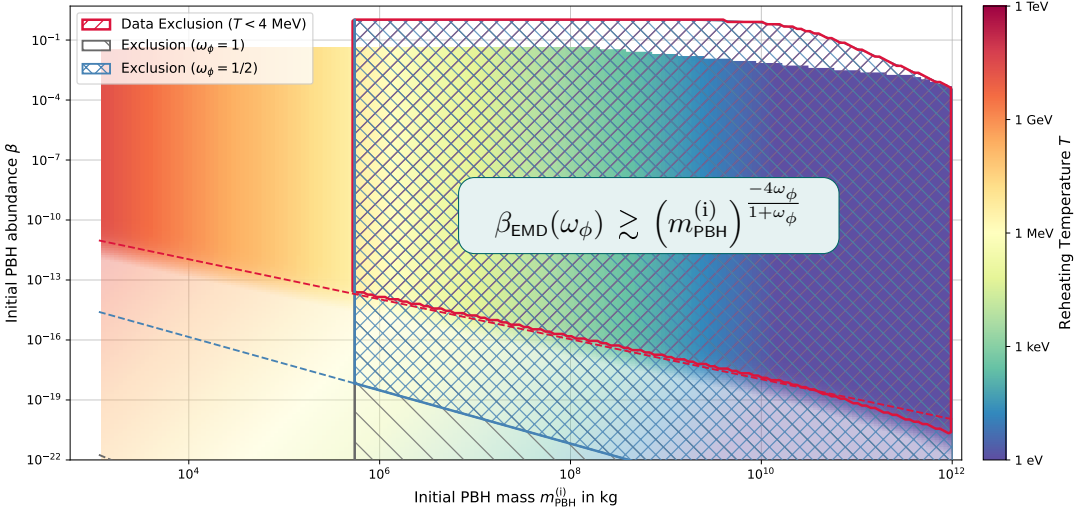
Temperature : ΔN_{eff}



Temperature : Hawking reheating



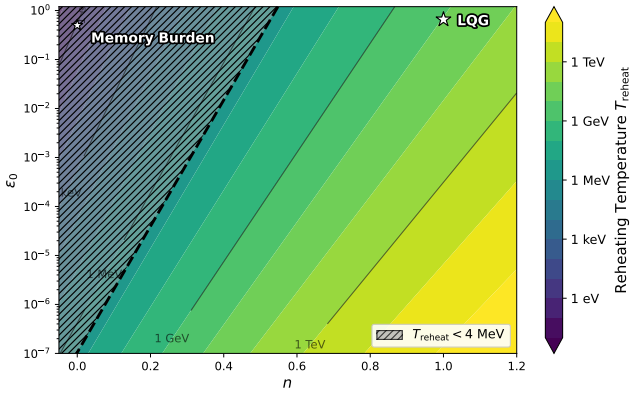
Temperature : Hawking reheating



Other stabilization mechanisms : sweetspot ?

$$\frac{m_{\rm REM}}{m_{\rm PBH}^{(\rm i)}} = \epsilon \equiv \frac{\epsilon_0}{(m_{\rm PBH}^{(\rm i)})^n}$$

Model	ϵ_0	n
LQG	$\sqrt{3\sqrt{3}\gamma}/2 \sim 1$	1
MBe	$1/2,\ 1/3$	0



Summary and outlook

Summary

Main results

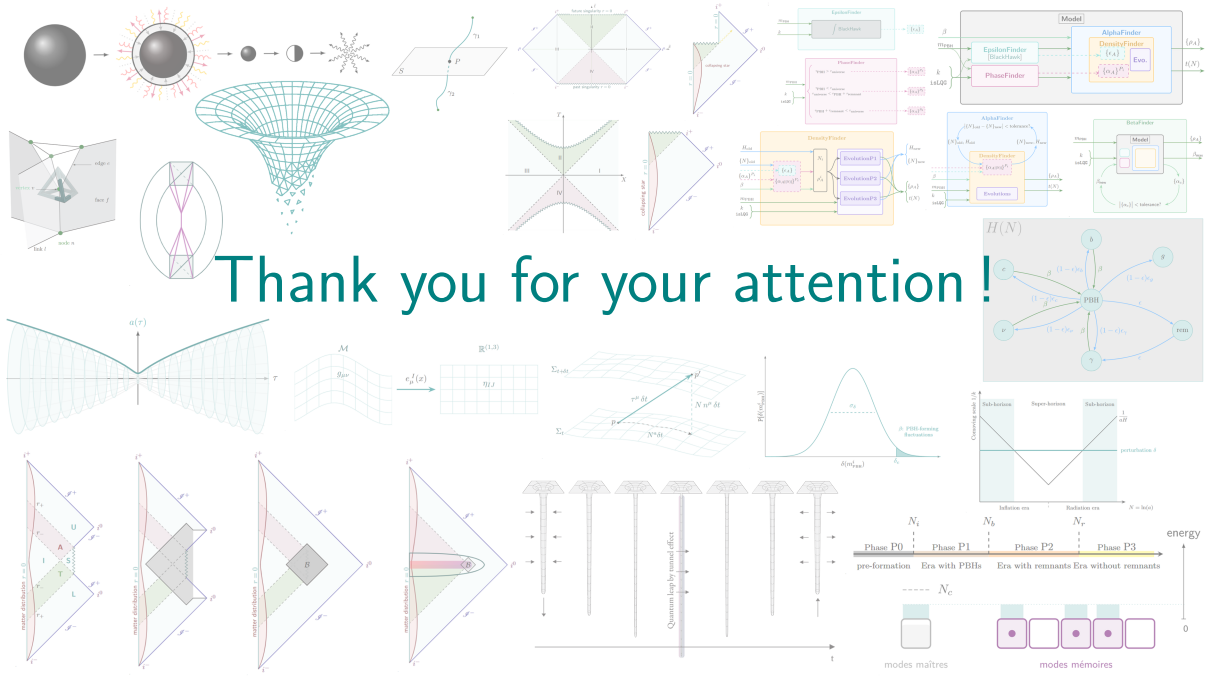
Light PBHs evaporating into stable Planckian remnants offer an alternative DM candidate and reheating mechanism.

1. **Regime I ($m_{\mathrm{PBH}}^{(\mathrm{i})} \leq 10^3$ kg)** : remnants can account for 100% of DM ($f_{\mathrm{DM}} \approx 1$), requiring $k \geq 4$.
2. **Regime II (10^3 kg $\leq m_{\mathrm{PBH}}^{(\mathrm{i})}$)** : 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 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 !
Model
EpsilonFinder
BlackHawk
PhaseFinder
AlphaFinder
DensityFinder
Evo.
BetaFinder
Evolutions
EvolutionP1
EvolutionP2
EvolutionP3
PBH
rem
Sub-horizon
Super-horizon
Sub-horizon
Inflation era
Radiation era
perturbation δ
Phase P0
Phase P1
Phase P2
Phase P3
pre-formation
Era with PBHs
Era with remnants
Era without remnants
energy
modes maîtres
modes mémoires
Quantum leap by tunnel effect