Dark radiation constraints on light primordial black holes

Jérémy Auffinger
j.auffinger@ipnl.in2p3.fr

IP2I & UCBL

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in collaboration with A. Arbey, P. Sandick, B. Shams Es Haghi & K. Sinha

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Introduction

Hawking radiation

Dark radiation constraints

Conclusion

Introduction: Primordial Black Holes

Motivations

- existence of BHs confirmed by X-ray and GW signals and shadow reconstruction
- hints of BHs too light/heavy for stellar origin (see in particular GW190521)
- unknown origin of the (seeds of the) supermassive BHs
- no constraints on light PBHs ($M_{\rm PBH} < 10^9\,{\rm g}$)

Formation

Formation at the end of inflation when overdensities re-enter the Hubble horizon:

$$M_{\rm PBH}(t_0) \sim M_{\rm P} \times \frac{t_0}{t_{\rm P}} \sim 10^{38}\,{\rm g} \times \left(\frac{t_0}{1\,{\rm s}}\right) \quad (1)$$

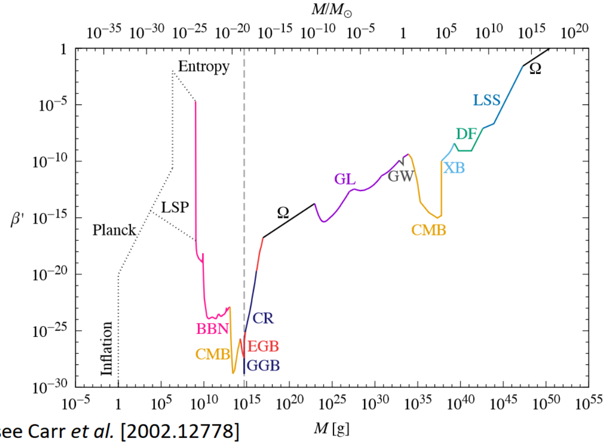
Possible formation of BHs with smaller masses due to incomplete collapse or to other formation channels (1st-order phase transitions, cosmic strings/domain walls collapse, ...).

Spin distribution

Low or high initial spin depending on radiation/matter domination at time of formation and the merging history (M. M. Flores & A. Kusenko [2106.03237]).

Introduction: Light PBHs constraints

PBHs are unconstrained below $M \sim 10^9$ g

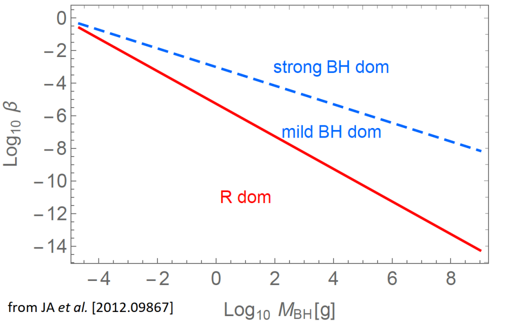


see Carr *et al.* [2002.12778]

Light PBHs may be constrained by the measurement of the stochastic gravitational wave background (see particularly [2105.06816] and references therein).

Introduction: PBHs dominate the universe?

Energy density domination as a function of PBH mass



solid red: maximum β for radiation domination until PBH evaporation.

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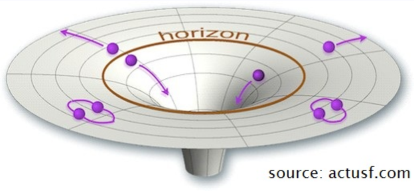
Hawking radiation: Fundamental equations (1)



"Thermal" emission of particles with temperature

$$T(M, a^*) = \frac{r_+ - M}{2\pi(r_+^2 + (a^* M)^2)} \xrightarrow[a^* = 0]{\text{Schwarzschild}} \frac{1}{8\pi M} \qquad (2)$$

Rate for particle i

$$Q_i = \frac{\mathrm{d}^2 N_i}{\mathrm{d}t\mathrm{d}E} = \frac{1}{2\pi} \sum_{\mathrm{dof.}} \frac{\Gamma_i(M, E, a^*)}{e^{E'/T(M,a^*)} \pm 1} \qquad (3)$$

Γ_i: greybody factor (particle spin dependence); E': energy corrected for horizon rotation; $\pm$: fermions/bosons resp.

Stacked spectrum

$$F_i(p(t_{\mathrm{ev}}), t_{\mathrm{ev}}) = \int_{t_{\mathrm{f}}}^{t_{\mathrm{ev}}} \frac{\mathrm{d}^2 N_i}{\mathrm{d}t\,\mathrm{d}p(t)} \left(p(t_{\mathrm{ev}}) \frac{a(t_{\mathrm{ev}})}{a(t)}, T_{\mathrm{BH}}(t) \right) \frac{a(t_{\mathrm{ev}})}{a(t)} \,\mathrm{d}t \qquad (4)$$

Hawking radiation: Fundamental equations (2)

Evolution parameters

$$f(M, a^*) \equiv -M^2 \frac{\mathrm{d}M}{\mathrm{d}t} = M^2 \int_0^{+\infty} \sum_i \sum_{\text{dof.}} \frac{E}{2\pi} \frac{\Gamma_i(E, M, a^*)}{e^{E'/T} \pm 1} \mathrm{d}E \tag{5a}$$

$$g(M, a^*) \equiv -\frac{M}{a^*} \frac{\mathrm{d}J}{\mathrm{d}t} = \frac{M}{a^*} \int_0^{+\infty} \sum_i \sum_{\text{dof.}} \frac{m}{2\pi} \frac{\Gamma_i(E, M, a^*)}{e^{E'/T} \pm 1} \mathrm{d}E \tag{5b}$$

Evolution equations

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{f(M, a^*)}{M^2} \quad \text{and} \quad \frac{\mathrm{d}a^*}{\mathrm{d}t} = \frac{a^*(2f(M, a^*) - g(M, a^*))}{M^3} \tag{6}$$

Addition of a dark sector

SM + graviton $\Longrightarrow$ slightly faster evaporation, with an increase of the graviton emission for increasing BH angular momentum

Hawking radiation: BlackHawk

`BlackHawk v1.2` [INCOMING IMPORTANT UPDATE: `v2.0`]

- is open-source
- is written in `C`
- can be run on Linux, MacOS and Windows (using Cygwin)
- can be downloaded at `https://blackhawk.hepforge.org`

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- Description
- Manual
- Download
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BlackHawk

By Alexandre Arbey and Jérémy Auffinger

Calculation of the Hawking evaporation spectra of any black hole distribution

BlackHawk is a public C program for calculating the Hawking evaporation spectra of any black hole distribution. This program enables the users to compute the primary and secondary spectra of stable or long-lived particles generated by Hawking radiation of the distribution of black holes, and to study their evolution in time.

If you use BlackHawk to publish a paper, please cite:
A. Arbey and J. Auffinger, Eur. Phys. J. C79 (2019) 693, arXiv:1905.04268 [gr-qc]

DR constraints: Hypotheses

Primordial black holes

Spinning PBHs with $M_{\rm BH} < 10^9$ g evaporated before BBN. PBHs dominate the universe (β big enough) and their evaporation is the sole source of reheating:

$$\rho_{\rm PBH}(t_{\rm evap}) - \rho_{\rm DR}(t_{\rm evap}) = \rho_{\rm SM}(t_{\rm evap}) = \frac{\pi^2}{30} g_*(T_{\rm RH}) T_{\rm RH}^4 \tag{7}$$

Dark radiation

The dark radiation particle is the massless graviton of spin 2.

Precision aspects

HR computed with `BlackHawk`; reheating dofs using tables from `SuperIso Relic`; reheating time.

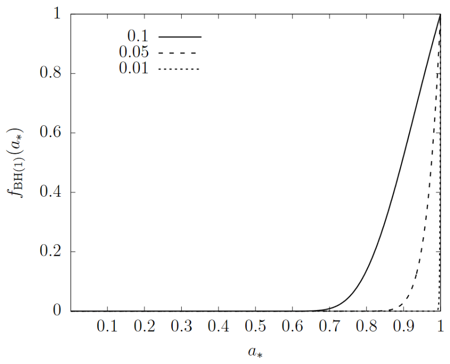
Constraints?

Graviton emission from PBHs contributes to the number of effective neutrinos dofs $N_{\rm eff}$ (CMB and BBN constraints):

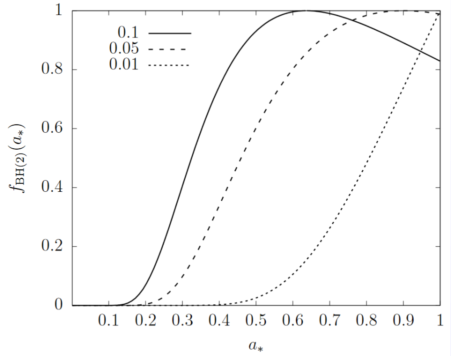
$$\Delta N_{\rm eff} = \frac{\rho_{\rm DR}(t_{\rm EQ})}{\rho_{\rm R}(t_{\rm EQ})} \left[N_\nu + \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \right] \tag{8}$$

DR constraints: PBH spin distributions (1)

Early Matter Dominated Era (EMDE) [1707.03595]



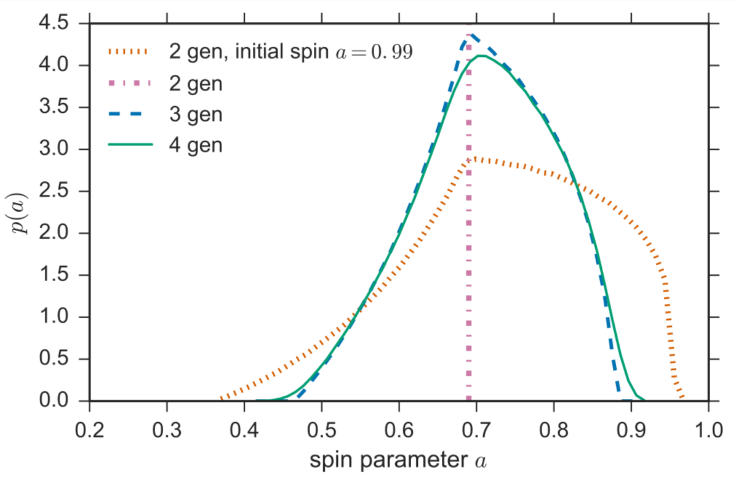
1st order effect: non-sphericity of the collapsing matter shell



2nd order effect: non-homogeneity of the collapsing matter shell

DR constraints: PBH spin distributions (2)

Early mergers [1703.06869] (see also [2103.0400])

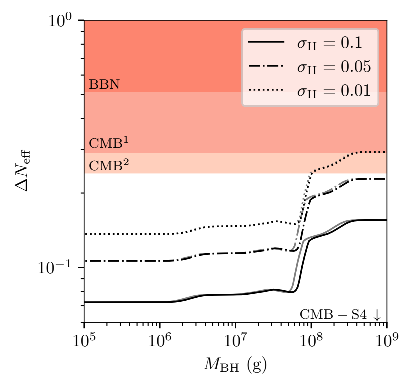


Same asymptotic distribution ($a^* \simeq 0.7$) starting from any initial spin

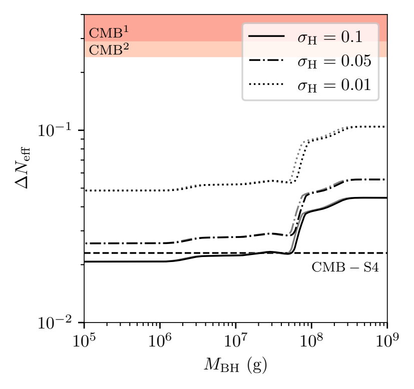
DR constraints: EMDE

Present and future CMB and BBN constraints

1st order effect



2nd order effect



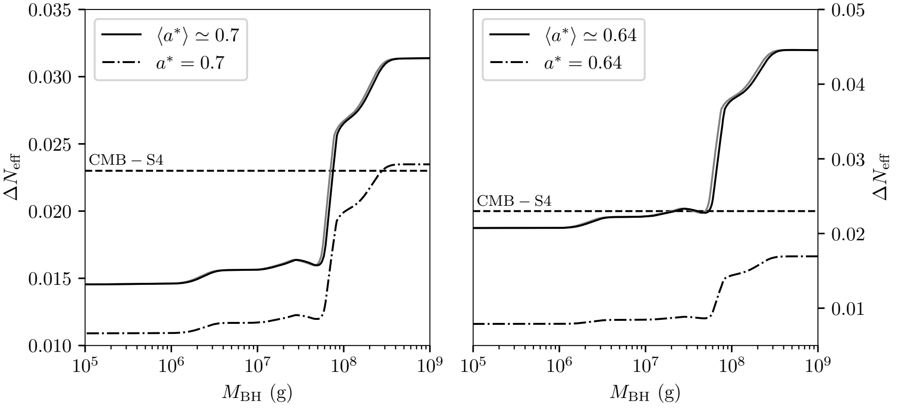
$\sigma_{\rm H}$: width of the density perturbation spectrum

CMB[1]: TT+low E, CMB[2]: TT,TE,EE+low E, BBN: computed with `AlterBBN`

DR constraints: Comparison between averaged and full spin distribution

Early mergers

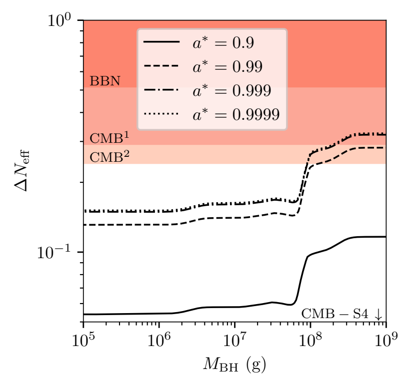
EMDE, 2nd order effect, $\sigma_{\rm H} = 0.1$



grey: $t_{\rm RH}$ is the last PBH evaporation time (heaviest); black: $t_{\rm RH}$ is the averaged evaporation time wighted by the spin distribution

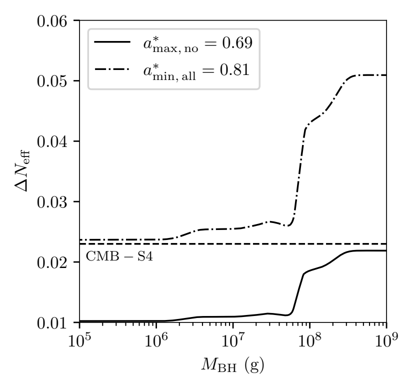
DR constraints: High spins & CMB-S4 prospects

High spins constraints



PBHs with $a^* \gtrsim 0.99$ and $M \gtrsim 10^8$ g are already excluded by CMB measurements

CMB-S4 prospects



PBHs with $a^* \gtrsim 0.81$ are probed by CMB S-4 on the full mass range; PBHs with $a^* \lesssim 0.69$ are not probed at all by CMB S-4

Conclusion

Takeaway conclusion:

"Graviton radiation by spinning light primordial black holes will be probed by CMB stage-4 experiments with conclusive results."

Some literature

- DR constraints and PBHs: Lennon *et al.* [1712.07664], Hooper *et al.* [1905.01301], Hooper *et al.* [2004.00618], Masina [2004.04740], Baldes *et al.* [2004.14773], Keith *et al.* [2006.03608], Masina [2103.13825], A. Arbey, JA, P. Sandick, B. Shams Es Haghi & K. Sinha [2104.04051], Domènech *et al.* [2105.06816].

BlackHawk

Download at: `https://blackhawk.hepforge.org`

[IMPORTANT UPDATE INCOMING]

Thank you for your attention!

contact email: j.auffinger@ipnl.in2p3.fr

Backup

Backup

Backup[1]

[1] Backup

Mass at formation (RD)

$$M_{\rm BH} = \gamma \frac{4\pi}{3} \rho_{\rm R}(t_{\rm f})\,(2t_{\rm f})^3 = \gamma \frac{4\pi}{3} \rho_{\rm R}(t_{\rm f})\,(H(t_{\rm f}))^{-3} = \frac{\gamma}{2H(t_{\rm f})} \gtrsim \frac{\gamma}{3}\,{\rm g} \tag{9}$$

$\rho_{\rm R}$: radiation energy density, $t_{\rm f}$: formation time, H: Hubble parameter, γ: fraction of a Hubble shell that collapses into a PBH

Time at formation (RD)

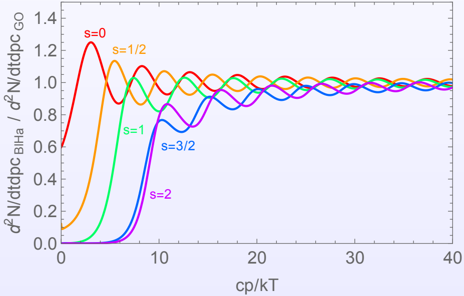
$$t_{\rm f} = \frac{M_{\rm BH}}{\gamma} = 10^{-23} \left(\frac{M_{\rm PBH}}{10^{15}\,{\rm g}} \right) {\rm s} \tag{10}$$

Density at formation

$$\beta \equiv \frac{\rho_{\rm BH}(t_{\rm f})}{\rho_{\rm R}(t_{\rm f})} = M_{\rm BH} \frac{n_{\rm BH}(t_{\rm f})}{\rho_{\rm R}(t_{\rm f})} \tag{11}$$

$\rho_{\rm BH}$: PBH energy density, $n_{\rm PBH}$: PBH number density

Hawking radiation cross section for all spins



(Schwarzschild BHs only)

DR constraints: DR density

Definition

PBHs evaporate in both the full SM and DR; thus the SM density gives the reheating temperature at PBH evaporation:

$$\rho_{\mathrm{PBH}}(\tau) - \rho_{\mathrm{DR}}(\tau) = \rho_{\mathrm{SM}}(\tau) \equiv \frac{\pi^2}{30} g_*(T_{\mathrm{RH}}) T_{\mathrm{RH}}^4 \tag{12}$$

The densities evolve through expansion until equality with:

$$\frac{\rho_{\mathrm{DR}}(t_{\mathrm{EQ}})}{\rho_{\mathrm{R}}(t_{\mathrm{EQ}})} = \frac{\rho_{\mathrm{DR}}(t_{\mathrm{RH}})}{\rho_{\mathrm{R}}(t_{\mathrm{RH}})} \left(\frac{g_*(T_{\mathrm{RH}})}{g_*(T_{\mathrm{EQ}})} \right) \left(\frac{g_{*,S}(T_{\mathrm{EQ}})}{g_{*,S}(T_{\mathrm{RH}})} \right)^{4/3} \tag{13}$$

`BlackHawk` computation

$$\rho_{\mathrm{DR/SM}}(t_{\mathrm{RH}}) = \int_0^1 \mathrm{d}a^* \, \frac{\mathrm{d}n}{\mathrm{d}a^*} \int_0^{t_{\mathrm{RH}}} \mathrm{d}t \int_0^{+\infty} \mathrm{d}E \, E \, \frac{\mathrm{d}^2 N_{\mathrm{DR/SM}}}{\mathrm{d}t \mathrm{d}E}(M, a^*) \tag{14}$$

Reheating time

Reheating time can be defined as time of last PBH evaporation (corresponds to the lowest spin) or more intuitively by the average lifetime:

$$\langle \tau \rangle \equiv \int_0^1 \tau(M, a^*) \frac{\mathrm{d}n}{\mathrm{d}a^*} \, \mathrm{d}a^* \tag{15}$$