Dark matter and dark radiation from primordial black holes

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[2012.09867] in collaboration with I. Masina & G. Orlando
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Introduction

Warm Dark Matter constraints

Dark radiation constraints

Conclusion

Introduction: The missing Dark Matter

Dark matter candidates

- **Massive neutrinos**
- **Weakly Interacting Massive Particles (WIMPs)**
  In particular, many particle physics models provide WIMP candidates!
- **Other particles/fields:** warm dark matter, axions, dark fluids, ...
  Exotic and non-baryonic particles
- **(Primordial) Black Holes**
  Not possible with stellar or supermassive black holes
- **Modified Gravitation Laws**
  MOND, TeVeS, Scalar-tensor theories, ...

In this scenario: light PBHs provide WDM through evaporation.

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 ($M_{\rm PBH} < 10^9\,$g)

Formation

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

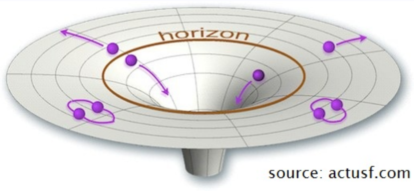
$$M_{\rm PBH}(t_0) \sim M_{\rm P} \times \frac{t_0}{t_{\rm P}} \sim 10^{38}\,{\rm g} \times \left(\frac{t_0}{1\,{\rm s}}\right) \tag{1}$$

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.

Introduction: Hawking radiation



"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:

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

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

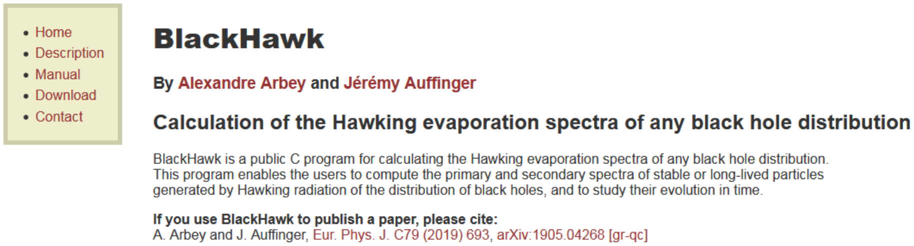
Stacked spectrum

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

Introduction: BlackHawk

`BlackHawk v1.2` [INCOMING IMPORTANT UPDATE]

- 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
- Contact

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]

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WDM constraints: hypotheses

Primordial black holes
PBHs with $M_{\rm BH} < 10^9\,$g evaporated before BBN.

Warm dark matter
There exists a dark sector with at least one "light" particle ($m_{\rm WDM} \sim$ MeV) of spin $s = \{0, 1, 2, 1/2, 3/2\}$ with no interaction with the SM other than gravitational.

Domination
The Universe is dominated by radiation (RD) or by PBHs (BHD; full matter domination). We define the critical value:

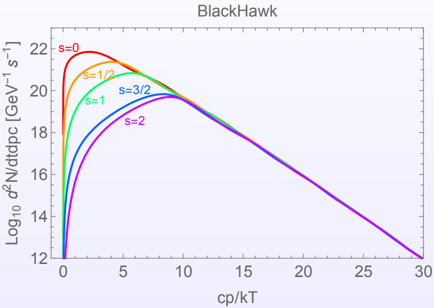
$$\bar{\beta} = \left(\frac{3f(M_{\rm BH})}{\gamma}\right)^{1/2} M_{\rm BH}^{-1} \tag{5}$$

as the maximum β to keep radiation domination, with β the fraction of the Universe collapsed into PBHs at PBH formation.

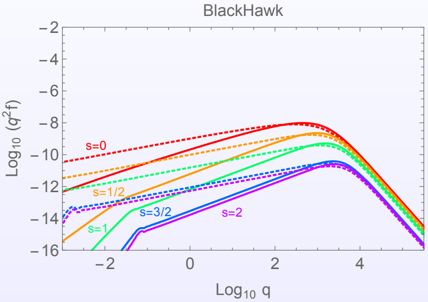
Constraints?
Warm dark matter is constrained by structure formation; linked to the the transfer function of the psd. Once the PBH initial density is fixed, the WDM mass is deduced from its abundance today.

WDM constraints: Schwarzschild PBHs

DM Hawking radiation spectra [BlackHawk]



Instantaneous spectrum

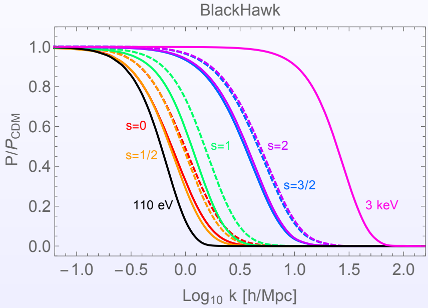


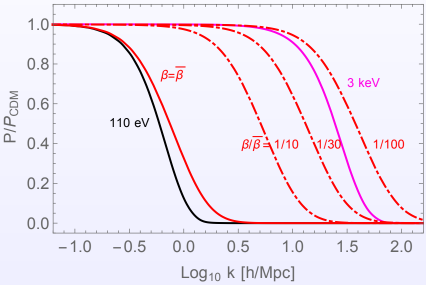
Stacked spectrum (psd) (solid: RD with $\beta = \bar{\beta}$, dotted: full BHD)

p: momentum, T: BH initial temperature, q: adimensioned momentum, f: phase space distribution (psd); plots for 1 additional degree of freedom.

WDM constraints: Transfer function and DM mass

Transfer functions [CLASS]





solid: RD ($\beta = \bar{\beta}$); dashed: full BHD

RD only, spin $s = 0$ different β

Constraints

Lower "thermal DM" limit: $m_{\rm DM} \simeq 3\,\mathrm{keV} \implies \beta/\bar{\beta} \lesssim 1/100$. Full BHD is excluded.
Constraints for all spins:

$$\beta/\bar{\beta} \lesssim (0.013, 0.015, 0.029, 0.15, 0.16) \quad \text{for } s = \{0, 1/2, 1, 3/2, 2\} \tag{6}$$

WDM constraints: DM mass

Abundance of DM today

$$\Omega_{\mathrm{DM}} = \frac{m_{\mathrm{DM}}}{\rho_{\mathrm{c}}} (T_{\mathrm{DM}}(t_0))^3 \int \mathrm{d}q \, 4\pi \, q^2 \, g_{\mathrm{DM}} f_{\mathrm{DM}}(q) \tag{7}$$

where g_{DM} is the number of WDM dof.
Higher WDM spin $\implies$ weaker Hawking radiation $\implies$ higher WDM mass.

DM mass

	$s = 0$	$s = 1/2$	$s = 1$	$s = 3/2$	$s = 2$
$m_{\mathrm{BHD}}/\mathrm{MeV}$	0.112	0.155	0.344	2.28	2.59
$m_{\mathrm{RD}}/\mathrm{MeV}$	0.084	0.116	0.259	1.71	1.94

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DR constraints: hypotheses

Primordial black holes

Spinning PBHs with $M_{\rm BH} < 10^9\,$g evaporated before BBN.

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?

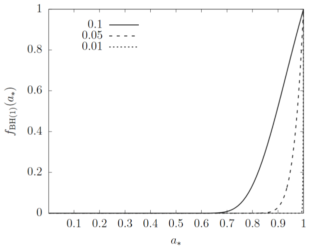
Graviton emission from PBHs contributes to the number of effective neutrinos dofs $N_{\rm eff}$ (CMB and BBN constraints):

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

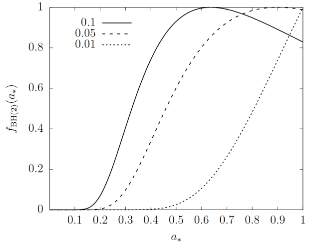
DR constraints: PBH spin distributions

Early Matter Dominated Era (EMDE) [1707.03595]

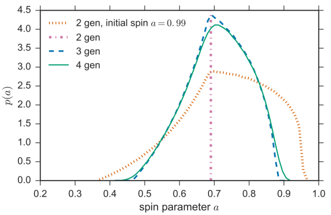
1st order effect



2nd order effect



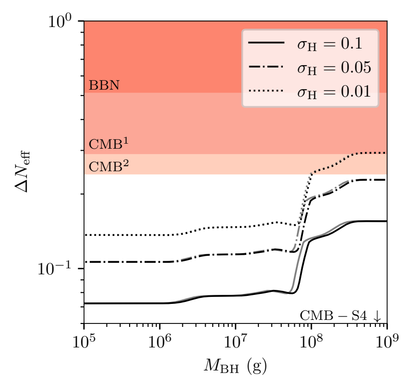
Early mergers [1703.06869]



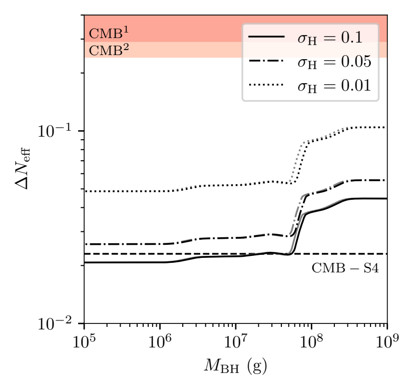
DR constraints: EMDE

Present and future CMB and BBN constraints

1st order effect



2nd order effect

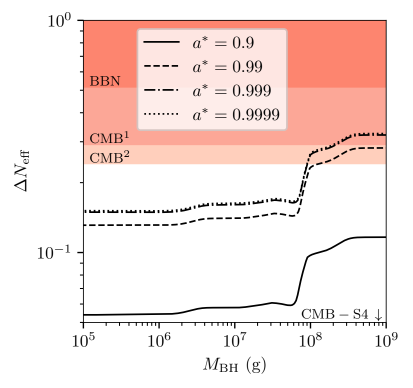


$\sigma_{\rm H}$: width of the density perturbation spectrum.

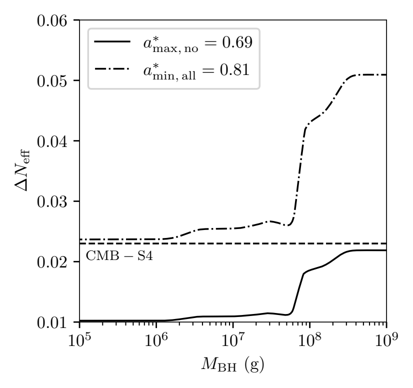
CMB^1: TT+low E, CMB^2: TT,TE,EE+low E, BBN: computed with `AlterBBN`

DR constraints: high spins & CMB-S4 prospects

High spins constraints



CMB-S4 prospects



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Some literature

- WDM constraints and PBHs: Fujita *et al.* [1401.1909], Lennon *et al.* [1712.07664], Masina [2004.04740], Baldes *et al.* [2004.14773], Gondolo *et al.* [2009.02424], JA, I. Masina & G. Orlando [2012.09867], Masina [2103.13825]
- 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]

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)

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

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

Time at formation (RD)

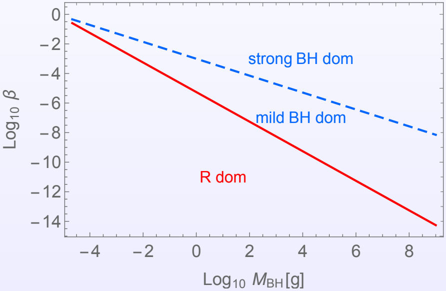
$$t_{\mathrm{f}} = \frac{M_{\mathrm{BH}}}{\gamma} = 10^{-23} \left(\frac{M_{\mathrm{PBH}}}{10^{15}\,\mathrm{g}}\right) \mathrm{s} \tag{10}$$

Density at formation

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

ρ_{BH}: PBH energy density, n_{PBH}: PBH number density

Energy density domination as a function of PBH mass



solid red: $\beta = \bar{\beta}$

Hawking radiation equations

Evolution parameters

$$f(M,a^*) \equiv -M^2\frac{\mathrm{d}M}{\mathrm{d}t} = M^2\int_0^{+\infty}\sum_{\mathrm{dof.}}\frac{E}{2\pi}\frac{\Gamma(E,M,a^*)}{e^{E'/T}\pm 1}\mathrm{d}E \tag{12a}$$

$$g(M,a^*) \equiv -\frac{M}{a^*}\frac{\mathrm{d}J}{\mathrm{d}t} = \frac{M}{a^*}\int_0^{+\infty}\sum_{\mathrm{dof.}}\frac{m}{2\pi}\frac{\Gamma(E,M,a^*)}{e^{E'/T}\pm 1}\mathrm{d}E \tag{12b}$$

Evolution equations

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{f(M,a^*)}{M^2} \quad \text{and} \quad \frac{\mathrm{d}a^*}{\mathrm{d}t} = \frac{a^*(2f(M,a^*)-g(M,a^*))}{M^3} \tag{13}$$

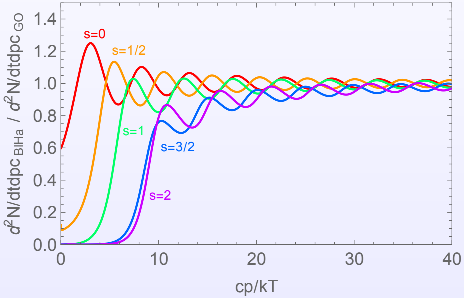
Stacked spectrum

$$F_i(p(t_{\mathrm{ev}}),t_{\mathrm{ev}}) = \int_{t_{\mathrm{f}}}^{t_{\mathrm{ev}}}\frac{\mathrm{d}^2N_i}{\mathrm{d}t\,\mathrm{d}p(t)}\left(p(t_{\mathrm{ev}})\frac{a(t_{\mathrm{ev}})}{a(t)},\,T_{\mathrm{BH}}(t)\right)\frac{a(t_{\mathrm{ev}})}{a(t)}\,\mathrm{d}t \tag{14}$$

Addition of a dark sector

SM + (W)DM particle (+ graviton) $\Longrightarrow$ faster evaporation

Hawking radiation cross section for all spins



(Schwarzschild BHs only)

WDM constraints: phase space distribution

Stacked redshifted spectrum

$$F(p(t_{\rm ev}), t_{\rm ev}) = \int_{t_{\rm f}}^{t_{\rm ev}} \mathrm{d}t \, \frac{\mathrm{d}^2 N}{\mathrm{d}t\,\mathrm{d}p(t)} \left(p(t_{\rm ev}) \frac{a(t_{\rm ev})}{a(t)}, T_{\rm BH}(t) \right) \frac{a(t_{\rm ev})}{a(t)} \tag{15}$$

Radiation/BH domination

$$\text{R:} \quad \frac{a(t_{\rm ev})}{a(t)} = \left(\frac{t_{\rm ev}}{t}\right)^{1/2} \qquad \text{BH:} \quad \frac{a(t_{\rm ev})}{a(t)} = \left(\frac{t_{\rm ev}}{t}\right)^{2/3} \tag{16}$$

$a(t)$: scale factor

Phase space distribution

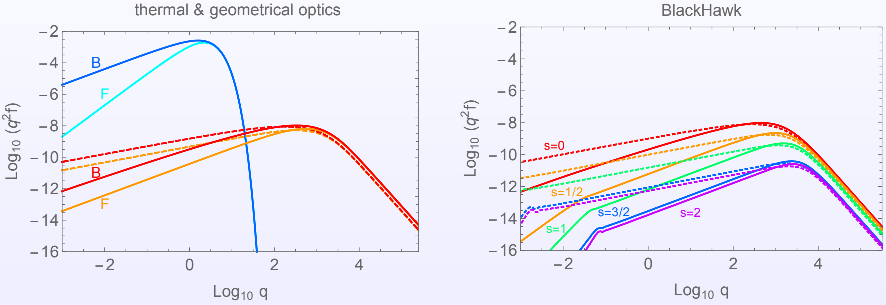
$$f_{\rm DM}(p(t_{\rm ev}), t_{\rm ev}) = A_{\rm R,BH} \frac{\tilde{F}(x(t_{\rm ev}))}{x(t_{\rm ev})^2} \tag{17}$$

where $x(t_{\rm ev}) \equiv p(t_{\rm ev})/T_{\rm BH}$ and $\tilde{F} \equiv T_{\rm BH}^3 F$ and $[M_{\rm P} = 1]$

$$A_{\rm R} = \beta 3(8\pi)^2(4\pi)\gamma^{1/2}(3f(M_{\rm BH}))^{3/2} M_{\rm BH}^{-1} \qquad A_{\rm BH} = 3(8\pi)^2(4\pi)(3f(M_{\rm BH}))^2 M_{\rm BH}^{-2} \tag{18}$$

WDM constraints: phase space distribution

PSD for thermal DM and for WDM

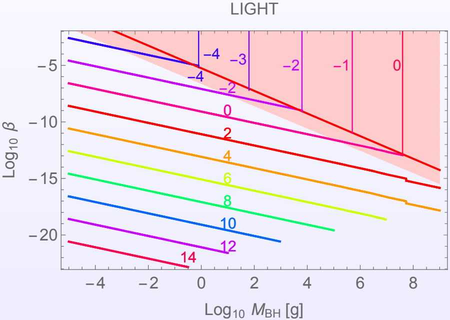


Solid blue: thermal DM; solid red & orange: RD with $\beta = \bar{\beta}$; dashed red & orange: full BHD
B: Boson; F: Fermion

Solid: RD with $\beta = \bar{\beta}$; dashed: full BHD

WDM constraints: β plot

Isocontours of $\log_{10}(m_{\mathrm{WDM}})$ and constraints on β



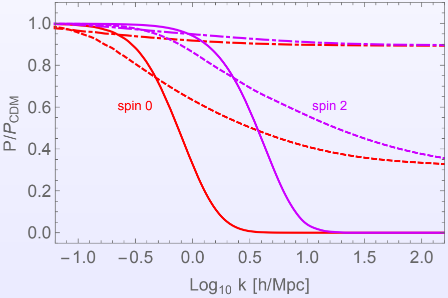
This is the figure for QDM spin $s = 0$ in the geometrical optics approximation. For $s \neq 0$ in the precise Hawking radiation calculations, we calculated that m_{WDM} increases as s increases, thus constraints on β are less stringent.

WDM constraints: mixed CDM/WDM models

Hypothesis

DM is composed of a cold component and a warm component. Let $f_{\mathrm{WDM}} \equiv \Omega_{\mathrm{WDM}}/\Omega_{\mathrm{DM}}$, thus $1 - f_{\mathrm{WDM}} = \Omega_{\mathrm{CDM}}/\Omega_{\mathrm{DM}}$.

Transfer functions



RD only, $\beta/\bar{\beta} = 1$

solid: $f_{\mathrm{WDM}} = 1$; dashed: $f_{\mathrm{WDM}} = 10^{-1}$; dot-dashed: $f_{\mathrm{WDM}} = 10^{-2}$

$\Longrightarrow$ Constraints on β are weaker as the CDM component dominates.

WDM constraints: spinning PBHs

⟶ See the recent paper [2103.13825] by I. Masina

Main changes

- high spin particles Hawking radiation is enhanced as a^* increases
- PBH lifetime is (slightly) smaller as a^* increases

Main conclusions

- even with extremal spin, full PBHs domination is excluded
- dependence of the constraints on a^*: the scenario is even more constrained as a^* increases for high spin particles

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:

$$\rho_{\rm PBH}(\tau) - \rho_{\rm DR}(\tau) = \rho_{\rm SM}(\tau) \equiv \frac{\pi^2}{30} g_*(T_{\rm RH}) T_{\rm RH}^4 \tag{19}$$

The densities evolve through expansion until equality with:

$$\frac{\rho_{\rm DR}(t_{\rm EQ})}{\rho_{\rm R}(t_{\rm EQ})} = \frac{\rho_{\rm DR}(t_{\rm RH})}{\rho_{\rm R}(t_{\rm RH})} \left(\frac{g_*(T_{\rm RH})}{g_*(T_{\rm EQ})}\right) \left(\frac{g_{*,S}(T_{\rm EQ})}{g_{*,S}(T_{\rm RH})}\right)^{4/3} \tag{20}$$

`BlackHawk` computation

$$\rho_{\rm DR/SM}(t_{\rm RH}) = \int_0^1 {\rm d}a^* \, \frac{{\rm d}n}{{\rm d}a^*} \int_0^{t_{\rm RH}} {\rm d}t \int_0^{+\infty} {\rm d}E \, E \, \frac{{\rm d}^2 N_{\rm DR/SM}}{{\rm d}t{\rm d}E}(M, a^*) \tag{21}$$

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:

$$\langle \tau \rangle \equiv \int_0^1 \tau(M, a^*) \frac{{\rm d}n}{{\rm d}a^*} \, {\rm d}a^* \tag{22}$$

DR constraints: comparison between averaged and full spin distribution

Early mergers

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