Primordial black holes and warm dark matter constraints

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Pheno 2021: Phenomenology 2021 Symposium, University of Pittsburgh – May 26th, 2021

Introduction

Hawking radiation

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

Formation

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

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

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.

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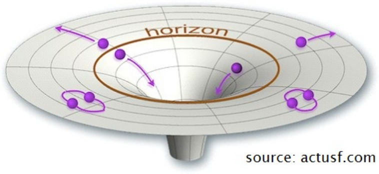
Hawking radiation: equations



"Thermal" emission of particles with temperature:

$$T(M, a^*) = \frac{\kappa}{2\pi} \xrightarrow[a^* = 0]{\text{Schwarzschild}} \frac{1}{8\pi M} \xrightarrow[a^* = 1]{\text{Kerr extremal}} 0 \tag{2}$$

where κ is the surface gravity (metric influence) and rate for particle i:

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

Γ_i is the greybody factor (particle spin dependence)
E' is the energy corrected for horizon rotation
$\pm$ stands for fermions/bosons

Hawking radiation: equations

Evolution parameters

$$f(M,a^*) \equiv -M^2\frac{\mathrm{d}M}{\mathrm{d}t} = M^2\int_0^{+\infty}\sum_{\mathrm{dof.}}\frac{E}{2\pi}\frac{\Gamma(E,M,a^*)}{e^{E'/T}\pm 1}\mathrm{d}E \quad (4a)$$

$$g(M,a^*) \equiv -\frac{M}{a^*}\frac{\mathrm{d}J}{\mathrm{d}t} = \frac{M}{a^*}\int_0^{+\infty}\sum_{\mathrm{dof.}}\frac{m}{2\pi}\frac{\Gamma(E,M,a^*)}{e^{E'/T}\pm 1}\mathrm{d}E \quad (4b)$$

Evolution equations

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{f(M,a^*)}{M^2} \quad \text{and} \quad \frac{\mathrm{d}a^*}{\mathrm{d}t} = \frac{a^*(2f(M,a^*) - g(M,a^*))}{M^3} \quad (5)$$

Stacked spectrum

$$F_i(p(t_{\mathrm{ev}}),t_{\mathrm{ev}}) = \int_{t_{\mathrm{f}}}^{t_{\mathrm{ev}}}\frac{\mathrm{d}^2N_i}{\mathrm{d}t\,\mathrm{d}p(t)}\left(p(t_{\mathrm{ev}})\frac{a(t_{\mathrm{ev}})}{a(t)}, T_{\mathrm{BH}}(t)\right)\frac{a(t_{\mathrm{ev}})}{a(t)}\,\mathrm{d}t \quad (6)$$

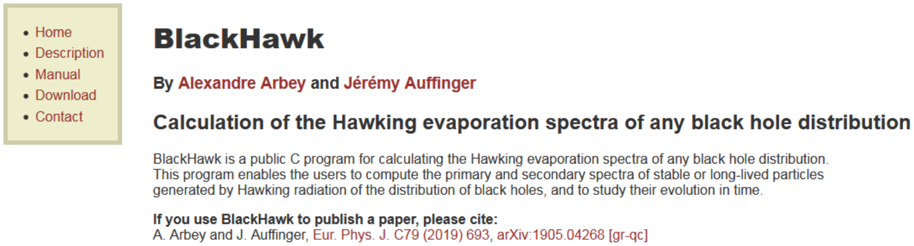
Addition of a dark sector

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

Hawking radiation: 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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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:

$$\bar{\beta} = \left(\frac{3f(M_{\rm BH})}{\gamma}\right)^{1/2} M_{\rm BH}^{-1} \tag{7}$$

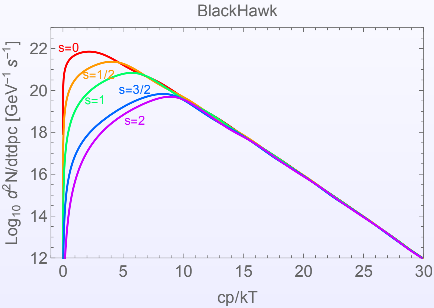
as the maximum β to keep radiation domination, with β the fraction of the Universe collapsed into PBHs at PBH formation.

Constraints?

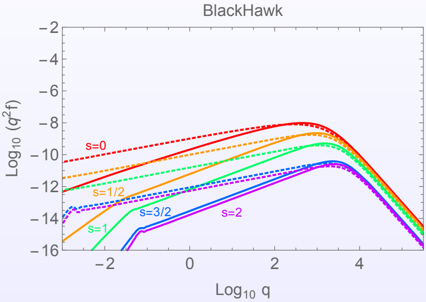
Warm dark matter is constrained by structure formation; linked to the the transfer function of the psd. Once the PBH initial density is fixed, the WDM mass is deduced from its abundance today.

WDM constraints: Schwarzschild PBHs

DM Hawking radiation spectra [BlackHawk]



Instantaneous spectrum

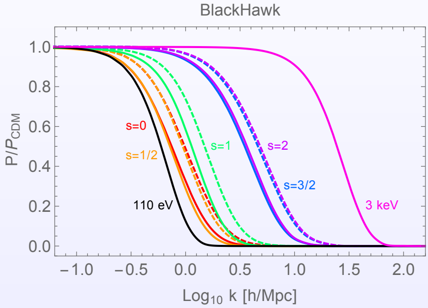


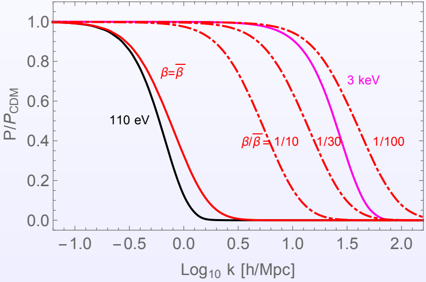
Stacked spectrum (psd) (solid: RD with $\beta = \bar{\beta}$, dotted: full BHD)

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

$$\beta/\bar{\beta} \lesssim (0.013, 0.015, 0.029, 0.15, 0.16) \quad \text{for } s = \{0, 1/2, 1, 3/2, 2\} \tag{8}$$

WDM constraints: DM mass

Abundance of DM today

$$\Omega_{\rm DM} = \frac{m_{\rm DM}}{\rho_{\rm c}} (T_{\rm DM}(t_0))^3 \int {\rm d}q \, (4\pi q^2) \, g_{\rm DM} f_{\rm DM}(q) \tag{9}$$

where $g_{\rm DM}$ is the number of WDM dof.

Effect of WDM spin

Higher WDM spin $\Longrightarrow$ weaker Hawking radiation
$\Longrightarrow$ higher WDM mass
$\Longrightarrow$ weaker β constraints

DM mass

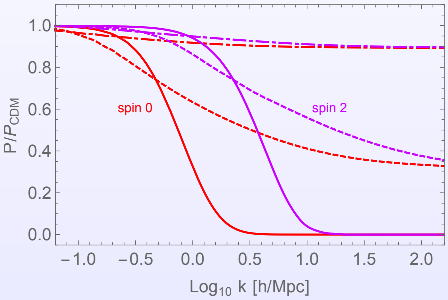
	$s=0$	$s=1/2$	$s=1$	$s=3/2$	$s=2$
$\bar{m}_{\rm BHD}/{\rm MeV}$	0.112	0.155	0.344	2.28	2.59
$\bar{m}_{\rm RD}/{\rm MeV}$	0.084	0.116	0.259	1.71	1.94

WDM constraints: mixed CDM/WDM models

Hypothesis

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

Transfer functions



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

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

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

WDM constraints: spinning PBHs

$\longrightarrow$ 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

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Some literature

- older papers about WDM constraints and PBHs: Fujita *et al.* [1401.1909], Lennon *et al.* [1712.07664], Masina [2004.04740], Baldes *et al.* [2004.14773]
- this work: JA, I. Masina & G. Orlando [2012.09867]
- extension to Kerr PBHs: Masina [2103.13825]

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)

$$M_{\rm BH} = \gamma \frac{4\pi}{3} \rho_{\rm R}(t_{\rm f}) (2t_{\rm f})^3 = \gamma \frac{4\pi}{3} \rho_{\rm R}(t_{\rm f}) (H(t_{\rm f}))^{-3} = \frac{\gamma}{2H(t_{\rm f})} \gtrsim \frac{\gamma}{3}\,\text{g} \tag{10}$$

$\rho_{\rm R}$: 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)

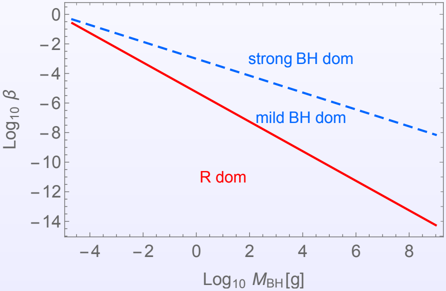
$$t_{\rm f} = \frac{M_{\rm BH}}{\gamma} \tag{11}$$

Density at formation

$$\beta \equiv \frac{\rho_{\rm BH}(t_{\rm f})}{\rho_{\rm R}(t_{\rm f})} = M_{\rm BH} \frac{n_{\rm BH}(t_{\rm f})}{\rho_{\rm R}(t_{\rm f})} \tag{12}$$

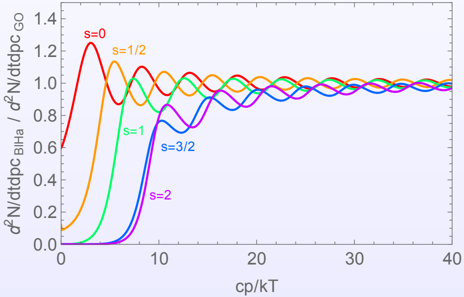
$\rho_{\rm BH}$: PBH energy density, $n_{\rm PBH}$: PBH number density

Energy density domination as a function of PBH mass



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

Hawking radiation cross section for all spins



(Schwarzschild BHs only)

Phase space distribution: definitions & equations

Stacked redshifted spectrum

$$F(p(t_{\rm ev}), t_{\rm ev}) = \int_{t_{\rm f}}^{t_{\rm ev}} {\rm d}t \, \frac{{\rm d}^2 N}{{\rm d}t \, {\rm d}p(t)} \left(p(t_{\rm ev}) \frac{a(t_{\rm ev})}{a(t)}, T_{\rm BH}(t) \right) \frac{a(t_{\rm ev})}{a(t)} \tag{13}$$

Radiation/BH domination

$$\text{R:} \quad \frac{a(t_{\rm ev})}{a(t)} = \left(\frac{t_{\rm ev}}{t}\right)^{1/2} \qquad \text{BH:} \quad \frac{a(t_{\rm ev})}{a(t)} = \left(\frac{t_{\rm ev}}{t}\right)^{2/3} \tag{14}$$

$a(t)$: scale factor

Phase space distribution

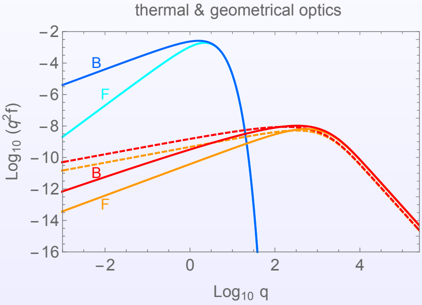
$$f_{\rm DM}(p(t_{\rm ev}), t_{\rm ev}) = A_{\rm R,BH} \frac{\tilde{F}(x(t_{\rm ev}))}{x(t_{\rm ev})^2} \tag{15}$$

where $x(t_{\rm ev}) \equiv p(t_{\rm ev})/T_{\rm BH}$ and $\tilde{F} \equiv T_{\rm BH}^3 F$ and

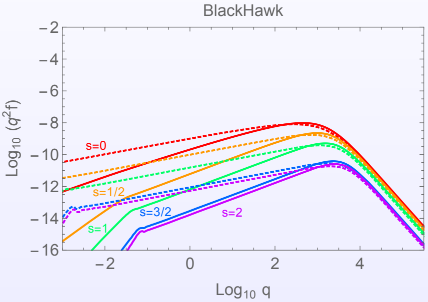
$$A_{\rm R} = \beta 3 (8\pi)^2 (4\pi) \gamma^{1/2} (3 f(M_{\rm BH}))^{3/2} M_{\rm BH}^{-1} \qquad A_{\rm BH} = 3(8\pi)^2 (4\pi)(3 f(M_{\rm BH}))^2 M_{\rm BH}^{-2} \tag{16}$$

Phase space distribution: comparison to thermal DM

PSD for thermal DM and for WDM



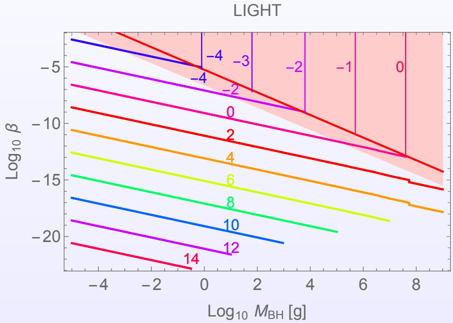
Solid blue: thermal DM; solid red & orange: RD with $\beta = \bar{\beta}$; dashed red & orange: full BHD
B: Boson; F: Fermion



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.