

## Constraining primordial black holes as dark matter with BlackHawk

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Introduction  
○○○○

Hawking radiation  
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BlackHawk content  
○○○○○

BlackHawk scope and applications  
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Conclusion  
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## Introduction

## Hawking radiation

## BlackHawk content

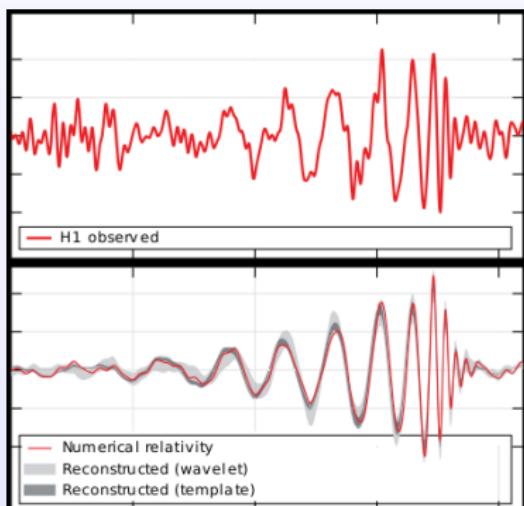
## BlackHawk scope and applications

## Conclusion

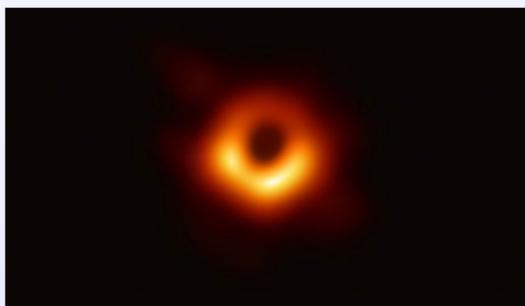
## BlackHawk development context

### Why Primordial Black Holes?

- non-conclusive search for particle DM  
→ PBHs could represent some fraction (or all) of the DM!
- first observations of BHs (mergers and shadow)



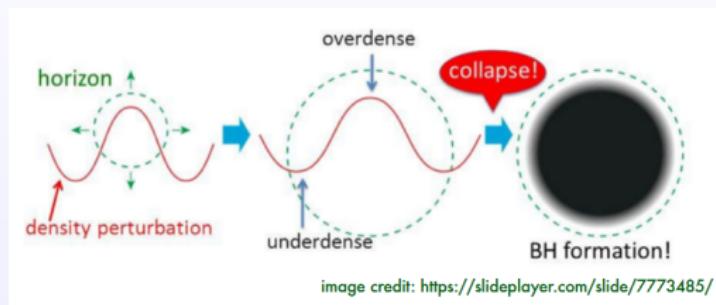
GW150914 - LIGO (2015)



M87 - EHT (2020)

## BlackHawk development context

### PBH formation



$$M \sim 10^{15} \text{ g} \times \left( \frac{t_{\text{form}}}{10^{-23} \text{ s}} \right)$$

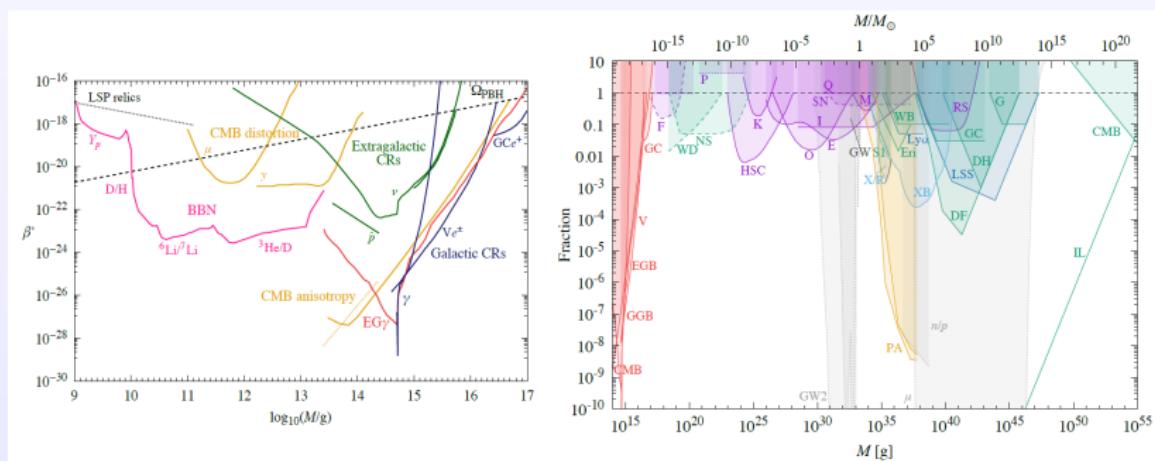
### Motivations

- open windows for DM:  $10^{17} - 10^{22}$  g et  $\mathcal{O}(10) \times M_\odot$
- unusual mergers (mass, spin) at LIGO/VIRGO
- development of gravitational wave astronomy  $\implies$  access to GW signature of PBH formation

## BlackHawk development context

### Primordial Black Holes constraints

- dynamical constraints (disruption of stars, shape of dwarf galaxies, ...)
- lensing constraints (microlensing, femtolensing, ...)
- cosmological constraints (effect of accretion on the CMB, ...)
- **Hawking radiation constraints (gamma rays, effect on BBN, ...)**



PBH constraints (Carr *et al.* 2020 [arXiv:2002.12778])

## BlackHawk development context

### What about the Black Hole nature?

- nature of the horizon?
- nature of the singularity?
- (extended-)GR metric around a BH?
- thermodynamics and information?
- (BSM) “spectrum of Nature”?

### Hawking radiation

→ Hawking radiation gives access to all of those aspects, and can be used to constrain the abundance of BHs in the remaining open windows for them to represent all of DM.

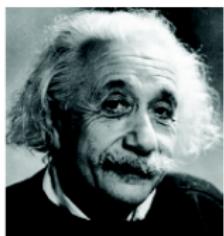
## Phenomenology



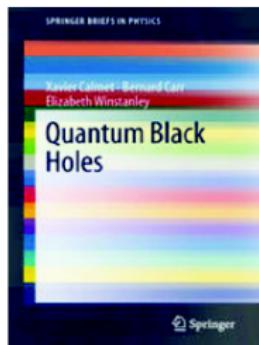
Quantum Mechanics



Thermodynamics

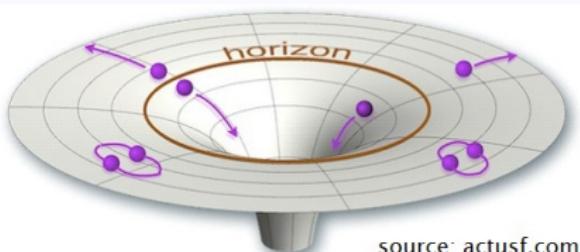


General Relativity



## Basic formulas

### Hawking “master” formula



Emission rate for particle  $i$ :

$$Q_i \equiv \frac{d^2 N_i}{dt dE} = \frac{1}{2\pi} \sum_{l,m} \frac{\Gamma_{s_i}^{l,m,dof}(E, M, \mu_i, \dots)}{e^{E'/T} - (-1)^{2s_i}}$$

$s_i$ : spin,  $E$ : energy,  $M$ : BH mass,

$\mu_i$ : particle rest mass

### “Greybody” factors $\Gamma$

Computed thanks to the equations of motion of particles in the BH metric. E.g. for spherically symmetric and static BHs:  $ds^2 = -G(r)dt^2 + F(r)^{-1}dr^2 + H(r)d\Omega^2$

### Hawking Temperature

$T$  is also metric dependent:  $T = \frac{\kappa}{2\pi} \Rightarrow \begin{cases} T_{\text{sph}} = \frac{1}{4\pi} \sqrt{\frac{FG'^2}{G}} \\ T_K = \frac{1}{2\pi} \left( \frac{r_+ - M}{r_+^2 + a^*{}^2 M^2} \right)^{\text{hor}} \end{cases}$

## BH evolution

Page coefficients (e.g.: Kerr,  $a^* \equiv J/M^2 \in [0, 1[)$ )

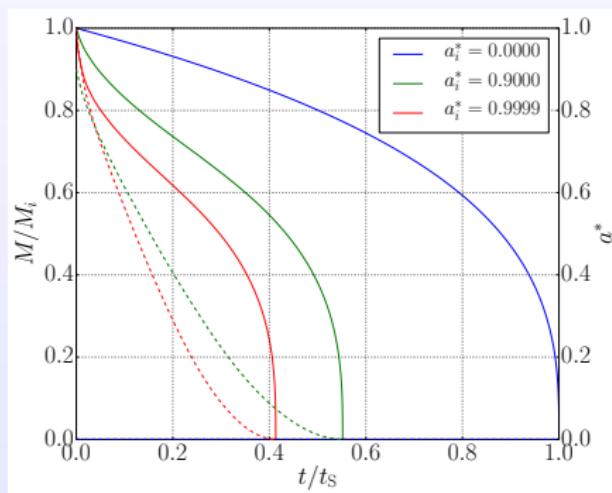
$$\begin{cases} f \equiv -M^2 \frac{dM}{dt} = M^2 \int_0^{+\infty} \sum_{i,l,m,dof} \frac{E}{2\pi} \frac{\Gamma_{s_i}^{l,m}}{e^{E'/T} - (-1)^{2s_i}} dE \\ g \equiv -\frac{M}{a^*} \frac{dJ}{dt} = \frac{M}{a^*} \int_0^{+\infty} \sum_{i,l,m,dof} \frac{m}{2\pi} \frac{\Gamma_{s_i}^{l,m}}{e^{E'/T} - (-1)^{2s_i}} dE \end{cases} \implies \begin{cases} \frac{dM}{dt} = -\frac{f}{M^2} \\ \frac{da^*}{dt} = \frac{a^*(2f - g)}{M^3} \end{cases}$$

Example from [arXiv:1906.04196]

Co-evolution of  $M$  and  $a^*$ : BHs rapidly lose their mass and angular momentum.

$$T \propto M^{-1} \implies T \nearrow$$

**DARWIN**



## “Greybody” factors computation

### General scheme

$$\left\{ \begin{array}{l} \text{Eq. motion} \\ \text{metric} \end{array} \right. \xrightarrow{\substack{\text{separation} \\ \text{simplification}}} \quad \text{Wave eq.:} \quad \frac{d^2 Z}{dr^{*2}} + (E^2 - V(r^*))Z = 0 \quad \xrightarrow{\substack{\text{numerical} \\ \text{resolution}}} \quad \text{Transm. coeff.:} \quad \Gamma \quad \Gamma$$

Example in spherical symmetry [arXiv:2101.02951, arXiv:2107.03293]

$$V_0(r^*) = \nu_0 \frac{G}{H} + \frac{\partial_*^2 \sqrt{H}}{\sqrt{H}}$$

$$V_1(r^*) = \nu_1 \frac{G}{H}$$

$$V_2(r^*) = \nu_2 \frac{G}{H} + \frac{(\partial_* H)^2}{2H^2} - \frac{\partial_*^2 \sqrt{H}}{\sqrt{H}}$$

$$V_{1/2}(r^*) = \nu_{1/2} \frac{G}{H} \pm \sqrt{\nu_{1/2}} \partial_* \left( \sqrt{\frac{G}{H}} \right)$$



## BlackHawk

**BlackHawk [arXiv:1905.04268,arXiv:2108.02737]**

Public and free code accessible at <https://blackhawk.hepforge.org/>

- Home
- Description
- Manual
- Download
- Contact

## BlackHawk

By **Alexandre Arbey and Jérémie 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. C* 79 (2019) 693, arXiv:1905.04268 [gr-qc]

## Any distribution of BHs

### BH nature

Hawking radiation available for Schwarzschild, Kerr (parameter  $a^*$ ), Reissner-Nordström (parameter  $Q^*$ ), higher-dimensional and polymerized (LQG) BHs.

### BH distributions

Several realistic extended distributions  $n(M, \dots)$  for both mass and secondary parameter are implemented:

- Dirac (= monochromatic)
- log-normal
- power-law
- uniform
- ...

→ Users can provide their own BH distribution.

## Greybody factors

### Computation of the GFs

Mathematica scripts have been used to solve the Teukolsky equations of the propagation of particles for all particle spins (0, 1, 2, 1/2 and 3/2). We solve Schrödinger-like wave equations of the form

$$\frac{d^2 Z}{dr^{*2}} + (\omega^2 - V(r^*))Z = 0 \quad (1)$$

where  $V(r^*)$  is the potential barrier for Hawking radiation (determined by the BH metric) and  $\omega$  is the particle energy. The GFs are defined as the ratio between on-horizon and infinity wave amplitudes

$$\Gamma \equiv \left| \frac{Z_{\text{inf.}}}{Z_{\text{hor.}}} \right|^2 \quad (2)$$

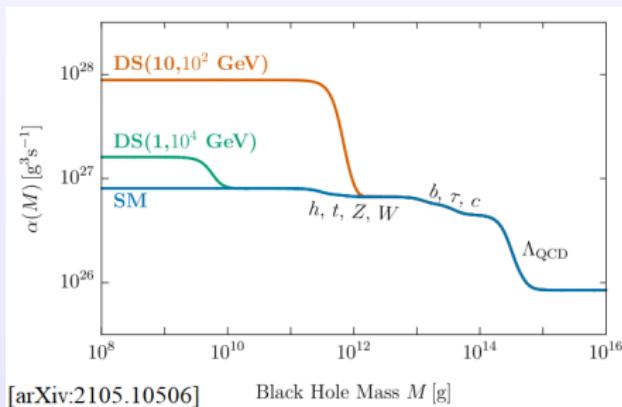
## Evaporation coefficients

### Evaporation equations

Evaporation of BHs results from the emission of particles that carry away energy  $E$  and some secondary parameter  $x$  (spin, charge...). The Page coefficients  $f$  and  $g$  are obtained by integrating over the instantaneous emission rate.

$$f \sim \int \sum_i E \times Q_i \quad \text{and} \quad g \sim \int \sum_i x \times Q_i$$

→ Dofs can embed DM emission! The existence of a dark sector at high energies modifies the evolution of BHs!



# BlackHawk

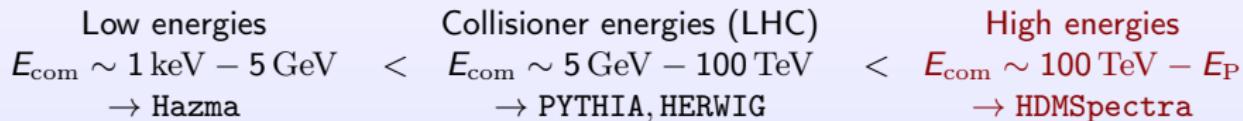
## Secondary spectra

Particle produced by Hawking radiation are not all stable: **hadronization, disintegration, radiation...**

## General scheme



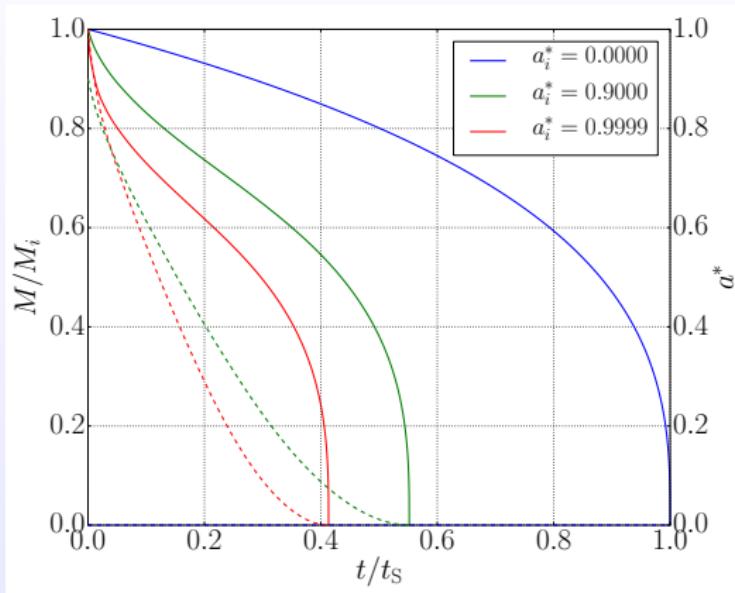
## Interfaces



→ New physics at high energies may alter the secondary spectra!

## BlackHawk results: Lifetime and spin evolution of BHs

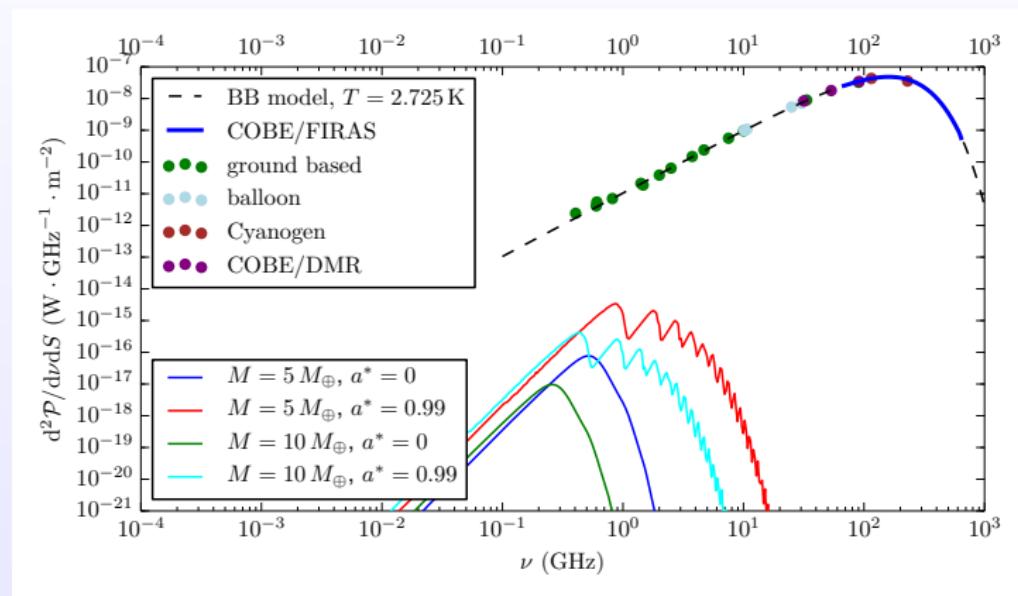
Literature lacked precise results on BH (spin) evolution.



A. Arbey, JA & J. Silk [arXiv:1906.04196]

## BlackHawk results: instantaneous spectra

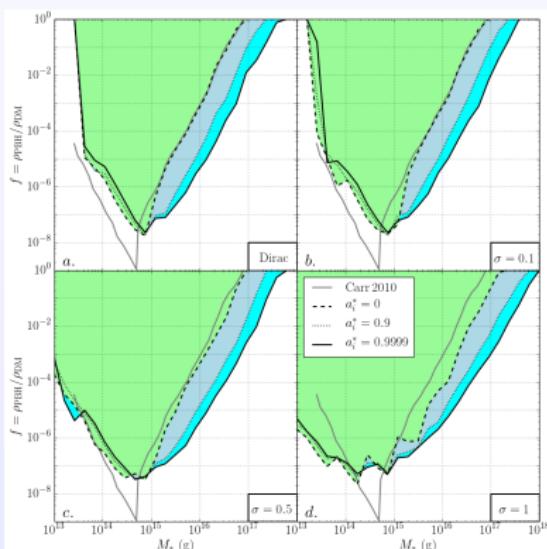
Instantaneous spectra can be used to characterize the emission of a known or putative source, e.g. radio emission by Planet 9 if it were a PBH.



Adapted from A. Arbey & JA [arXiv:2006.02944]

## BlackHawk results: time dependent spectra (1)

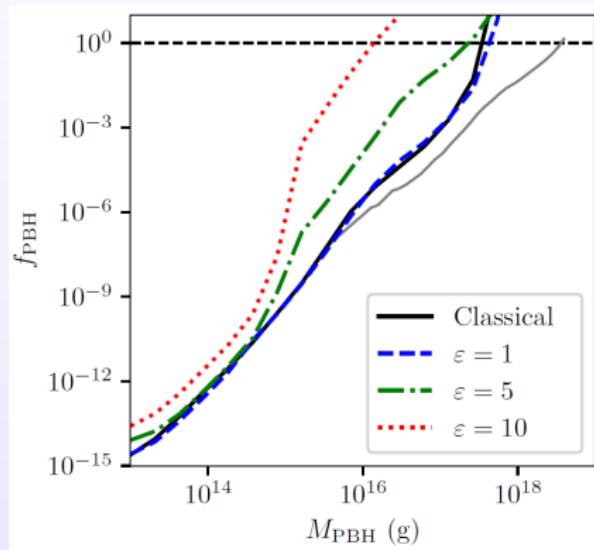
PBHs evaporated or currently evaporating produce time-stacked spectra associated with cosmological constraints, e.g. on the isotropic gamma-ray background. Constraints depend on the spin of BHs and on the width of the mass distribution.



A. Arbey, JA & J. Silk [arXiv:1906.04750]

## BlackHawk results: time dependent spectra (2)

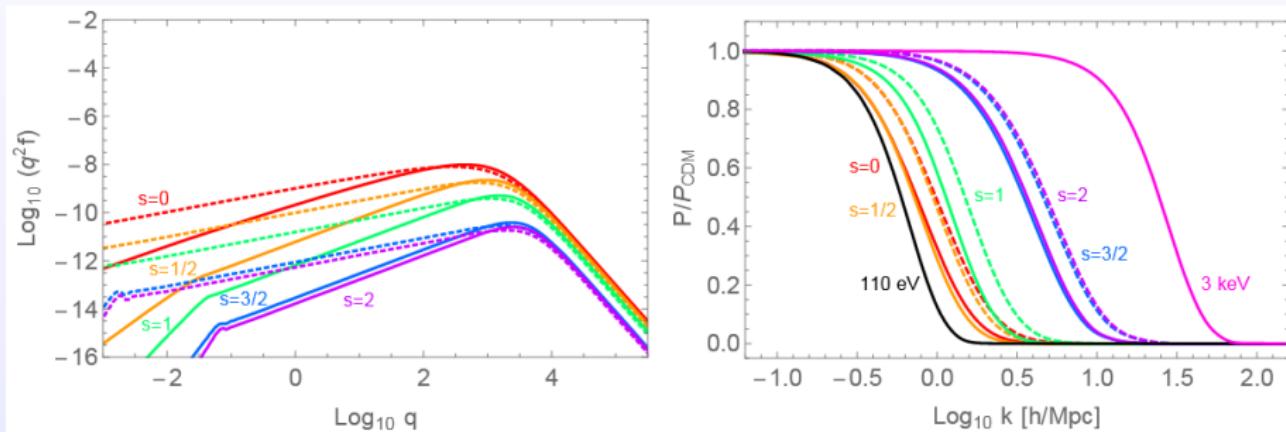
The quantum nature of BHs can modify the spectra and thus the associated constraints.  
 $\varepsilon$ : quantum deformations in LQG polymerization



A. Arbey, JA, M. Geiller, L. R. Etera & F. Sartini [arXiv:2107.03293]

## BlackHawk results: DM emission

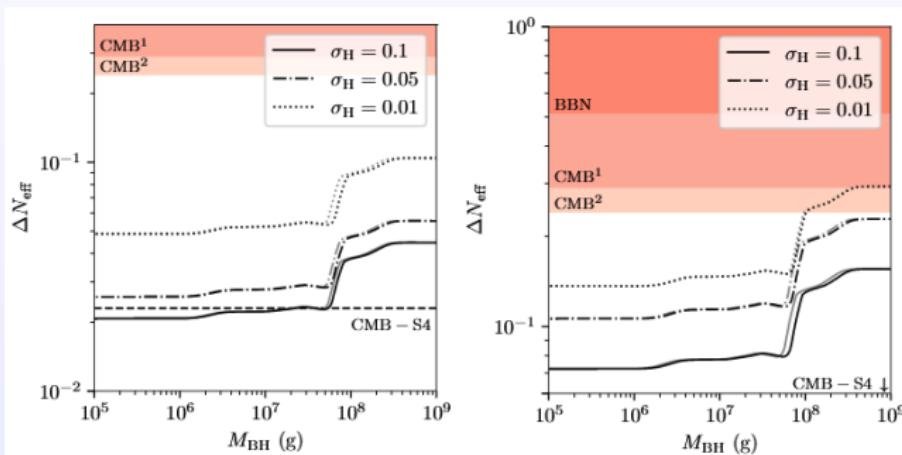
BHs emit any dof and thus any dark sector particle on top of the SM radiation. Constraints can be obtained through an interface with CLASS.



JA, I. Masina & G. Orlando [arXiv:2012.09867]

## BlackHawk results: DR emission

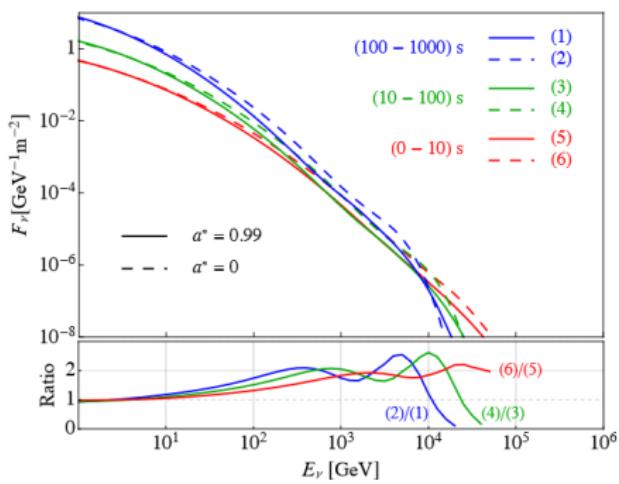
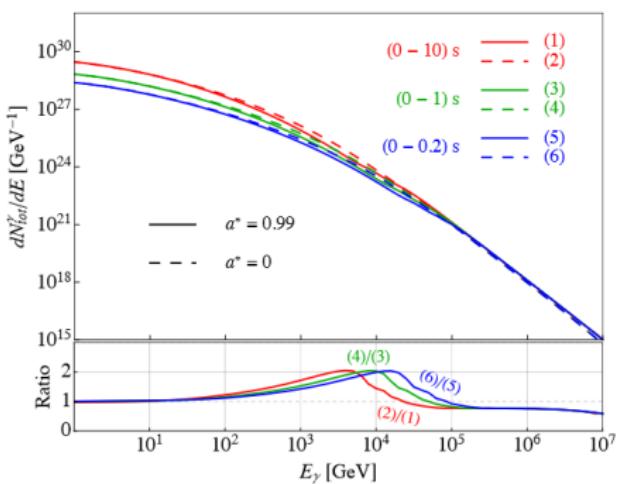
BHs can emit gravitons that behave as dark radiation and are constrained by CMB/BBN experiments.



A. Arbey, JA, P. Sandick, B. Shams Es Haghi & K. Sinha [arXiv:2104.04051]

## BlackHawk results: PBH final burst (not us)

As their mass decreases, PBHs emit more energetic radiation until final burst, accessible to high energy gamma-ray (H.E.S.S., HAWC, Milagro, VERITAS, Fermi-LAT,...) or neutrino (IceCube, ...) detectors. The details of the final burst light curve provides information on BSM physics at  $>$  TeV scale.



A. Capanema, A. F. Esmaeli & A. Esmaili [arXiv:2104.04051]

## Conclusion

### BlackHawk

- is the first **open-source** code for Hawking radiation computation
- computes **instantaneous** and **time dependent** spectra
- computes the radiation of **non standard BHs**
- computes the radiation of **BSM DM/DR dofs**
- is **regularly updated** with new features (accretion? new BH solutions? hadronization at extreme energies?)

### Downloads + list of publications

<https://blackhawk.hepforge.org>

### BlackHawk manual

**BlackHawk: A public code for calculating the Hawking evaporation spectra of any black hole distribution**, Eur. Phys. J. C79 (2019) 693 [arXiv:1905.04268]  
**Beyond the Standard Model with BlackHawk v2.0**, Eur. Phys. J. C81 (2021) 910 [arXiv:2108.02737]