Primordial black hole superradiance and evaporation in the string axiverse

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In the string axiverse scenario, light primordial black holes may spin up due to the Hawking emission of a large number of light (sub-MeV) axions. We show that this may trigger superradiant instabilities associated with a heavier axion during the black holes' evolution, and study the coupled dynamics of superradiance and evaporation. We find, in particular, that the present black hole mass-spin distribution should follow the superradiance threshold condition for black hole masses below the value at which the superradiant cloud forms, for a given heavy axion mass. Furthermore, we show that the decay of the heavy axions within the superradiant cloud into photon pairs may lead to a distinctive line in the black hole's emission spectrum, superimposed on its electromagnetic Hawking emission.

Black holes

Black Holes (BHs) are fascinating objects predicted by Einstein's theory of general relativity as solutions to its famous field equations. They describe regions of space-time hidden behind an **event horizon**, from which not even light can escape, and enclosing a mysterious curvature singularity.
They are thought to form in the gravitational **collapse of stars** heavier than the Sun at the end of their lifetime and most galaxies seem to harbour supermassive black holes with millions or even billions of solar masses. The first image of the shadow cast by the supermassive BH M87* was recently obtained with the Event Horizon Telescope, and the gravitational waves emitted by several merging BH binaries have now been detected with the LIGO and Virgo interferometers.
Large **density fluctuations** in the **early Universe** may also have collapsed into much **lighter** black holes called **Primordial BHs** (PBHs) that could make up a fraction of the dark matter in the Universe.

Hawking evaporation and BH evolution

Hawking radiation is a quasi-thermal radiation emitted by a BH due to relativistic quantum effects. The **Hawking temperature** is inversly proportional to the BH mass and reads

$$T_H \sim \kappa/2\pi \simeq 1\,\mathrm{GeV}\left(10^{10}\,\mathrm{kg}/M\right),$$

Where $\kappa = r_+\sqrt{1-a_*^2}/2$ is the surface gravity and r_+ is the radial distance where the event horizon is located.
Hawking evaporation generically **spins down** a BH. An **exception** is the emission of light **scalar particles**, as first pointed in [1], since these are the only type of particle that can be emitted in the monopole $(l=0)$ mode. Scalar emission may therefore reduce a BH's mass without reducing its angular momentum, therefore increasing its dimensionless spin parameter $a^* = J/M^2$.
The **Page formalism** [2] tracks the evolution of a BH mass and spin, removing the dependence on the BH mass, using the functions

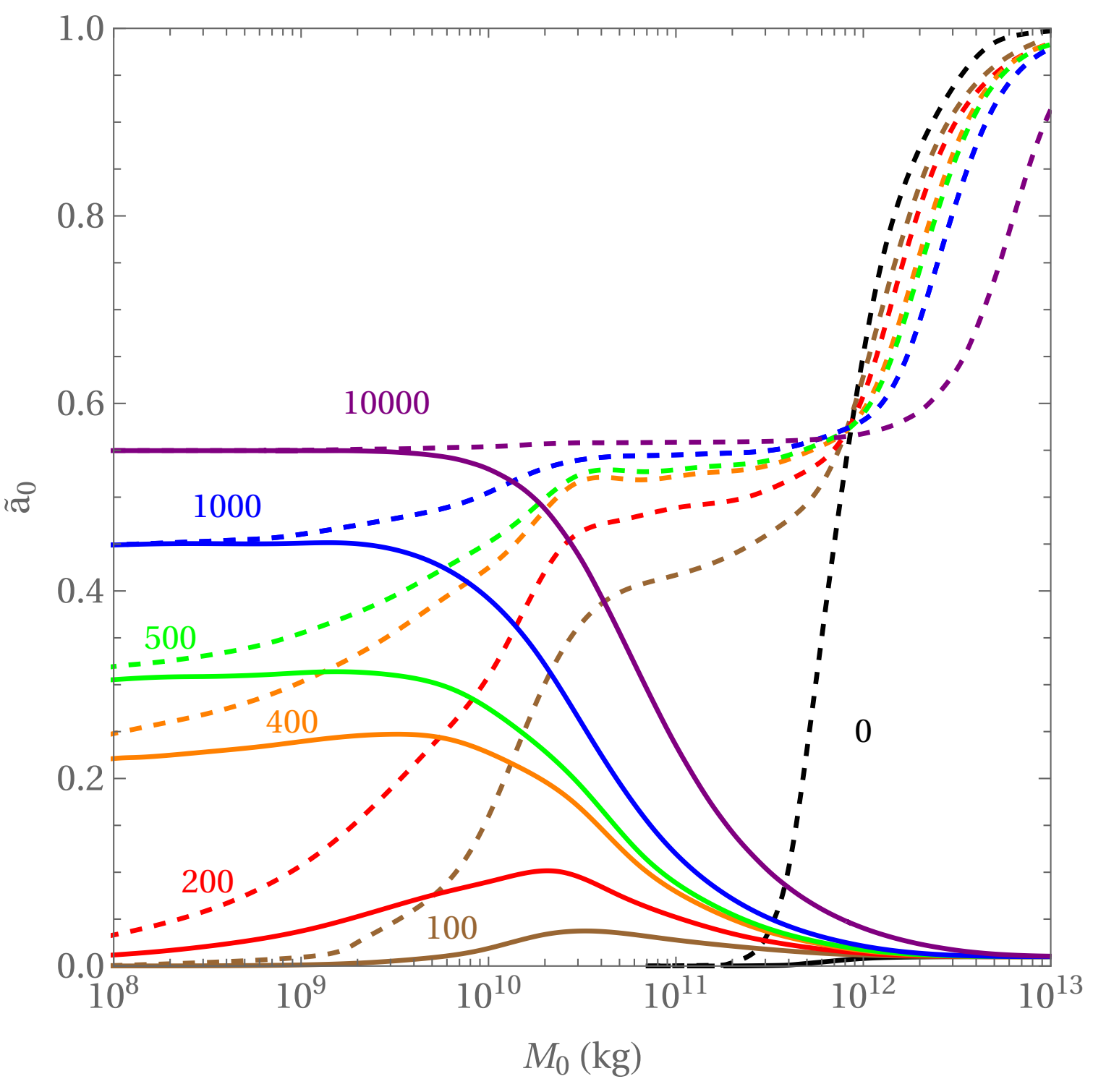
$$\begin{pmatrix} f_s \\ g_s \end{pmatrix} = \begin{pmatrix} M^2\, dM/dt \\ -M/a^*\, dJ/dt \end{pmatrix} = \frac{1}{2\pi}\sum_{p,l,m}\int_0^\infty \frac{\Gamma^s_{l,m}(\omega)}{\left(e^{2\pi k/\kappa}\pm 1\right)}\begin{pmatrix} x \\ m a_*^{-1} \end{pmatrix} dx$$

where $x=\omega M$, $k=\omega - m\Omega_H$, with Ω angular velocity of the event horizon. The upper (lower) component corresponds to fermion (boson) fields. The so called **grey-body factors** $\Gamma = 1-\left|Z_{out}/Z_{\mathrm{in}}\right|^2$, where Z_{in} and Z_{out} denote the amplitudes of the ingoing and outgoing wave modes, can be computed by solving the massless radial **Teukolsky equation** imposing ingoing boundary conditions at the horizon [3].

Axion-like particle and PBHs evolution

The **axion** is a **pseudo-scalar** particle predicted by the Peccei-Quinn model to explain why Quantum Chromodynamics is invariant under CP. As a weakly interacting and long-lived particle, the axion is a natural dark matter candidate.
A fairly generic prediction of **string theory** (with six compact extra-dimensions) is the existence of a large number (10^2-10^5) of light or even **ultra-light** pseudoscalar particles in the effective four-dimensional theory with masses generated solely by non-perturbative effects. [4]. These are called **Axion-Like Particles** (ALPs).

We include in our numerical calculation an **arbitrary number**, N_a , of **scalars** which we assume to have **masses below** the initial $\mathbf{T_H}$, which is around the 10 MeV scale for PBHs with a **lifetime** comparable to the age of the **Universe**. These are emitted alongside photons, gravitons, neutrinos and electrons/positrons from the start of our calculation. As a PBH evaporates, its T_H increases, and we eventually include muons, taus and QCD degrees of freedom in the evolution at the corresponding mass thresholds (i.e. when $T_H > m$).
Our results [5] shows that the present mass-spin distribution of PBHs is sensitive to the presence of light ALPs.



BH superradiance and the axiverse

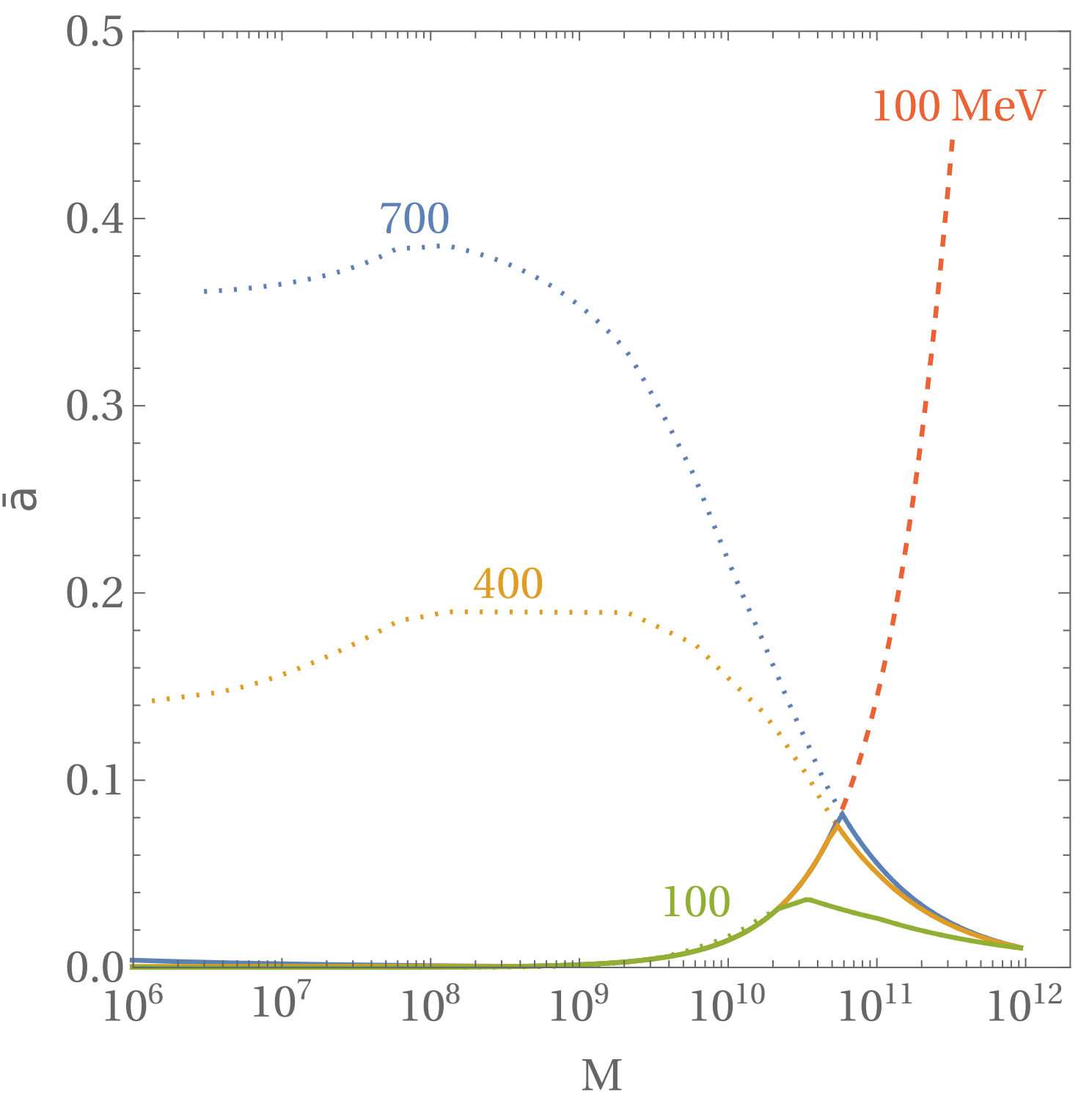
A **scalar relativistic** wave propagating in an **absorbing medium** is described by a damped wave equation:

$$\dot{\phi} + \gamma\phi - \nabla^2 = 0$$

with wave modes of the form $e^{i\omega t + m\varphi}$ in a frame where the medium is at rest. However, if the medium is **rotating** in an inertial frame, the azimuthal coordinate becomes $\omega' = \omega - m\Omega < m\Omega$ and hence the wave frequency is $\varphi' = \varphi + \Omega t$.
This means that the damping term changes sign and the medium **amplifies** rather than absorbs the radiation for low frequencies: $\omega < m\Omega$
A black hole is, by definition, a perfect absorber, so that a spinning black hole can amplify incoming radiation! If we surround the black hole with a **mirror**, multiple amplifications lead to an instability: a **black hole bomb** [6].
This is not science fiction, since Nature provides its own mirror! Massive fields can be trapped in **Hydrogen-like bound states** in the black hole's gravitational potential well. In the **superradiant regime** these are continuously amplified, leading to an **exponentially** fast particle production powered by the black hole's rotation (see e.g. [7] for a review).
Superradiant instabilities can only occur for low mass (bosonic) fields/particles:

$$\mu \lesssim \frac{\hbar c}{G M_{BH}} \sim 10^{10}\left(\frac{M_\odot}{M_{BH}}\right) eV/c^2$$

and the dominant mode is the **2p-state** (*l=m=1*), leading to a dense toroidal-shaped particle cloud around the black hole, powered by its rotation. The instability **spins down** the black hole until the superradiance condition is **saturated** or other effects come into play.



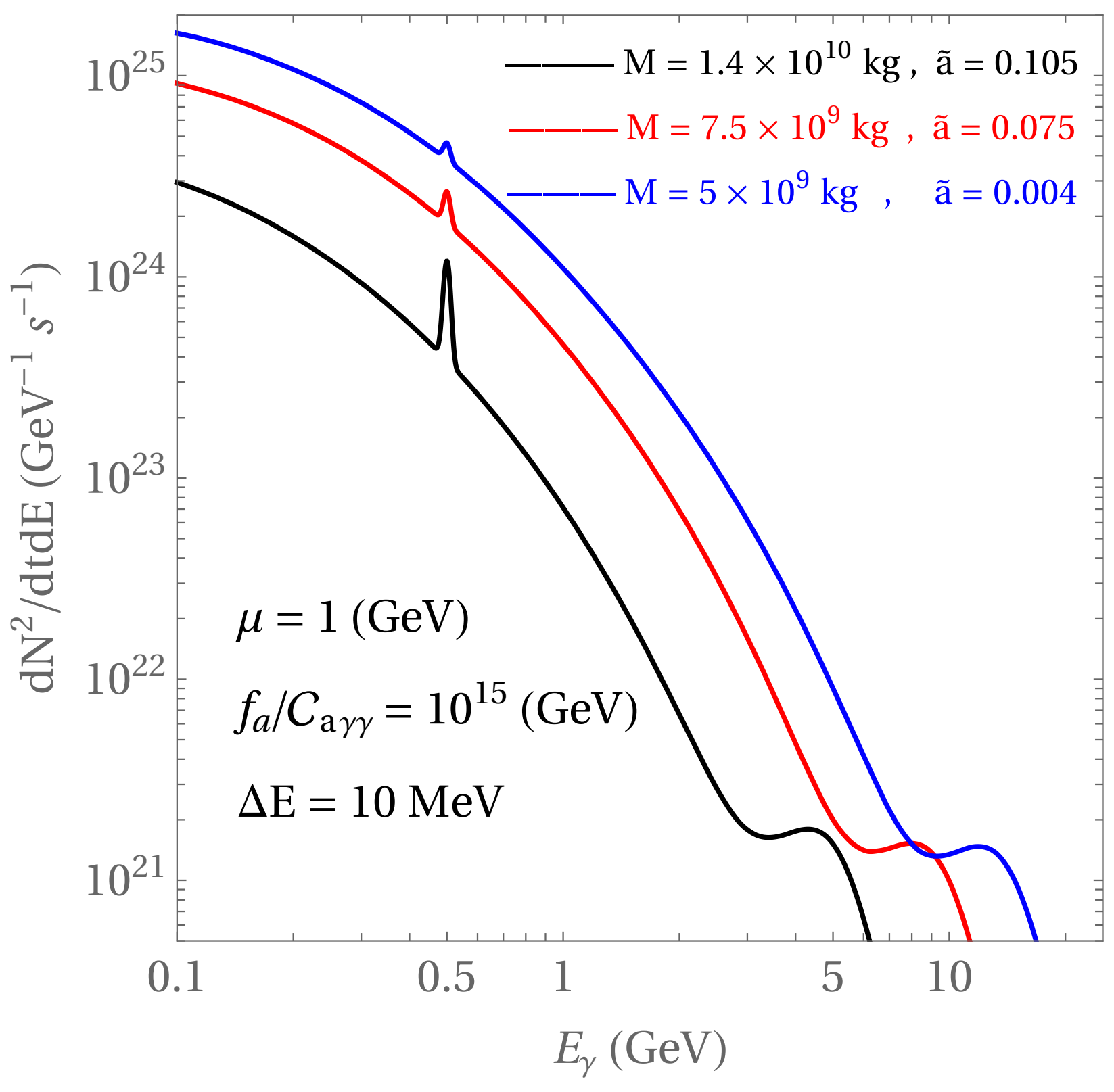
Direct detection of superradiant axion clouds

Evaporating PBHs may be detected through their Hawking photon emission. The **primary photon spectrum** for can be calculated through

$$\frac{dN}{dt\, dE_\gamma} = \frac{1}{2\pi}\sum_{l,m}\frac{\Gamma^1_{l,m}(\omega)}{\left(e^{2\pi k/\kappa}-1\right)}.$$

The **secondary photons** resulting from fragmentation and decay of primarly emitted **unstable** particles can be numerically accounted (e.g. Using `BlackHawk`).
The formation of **superradiant clouds** may leave a much more direct observational signature, since the produced **axions decay** into photon pairs. In particular, an evaporating PBH surrounded by a heavy axion cloud will emit photons as a result of both Hawking emission and **heavy axion** decay, yielding a unique spectrum.
The heavy axions within the superradiant cloud decay into photon pairs with a rate

$$\Gamma_a = \frac{g^2_{a\gamma\gamma}\mu^3}{64\pi} \quad \text{where} \quad g_{a\gamma\gamma} = \frac{\alpha_{EM}}{2\pi f_a}|\mathcal{C}_{a\gamma\gamma}| \quad \text{is model-dependent.}$$



The corresponding photon emission spectrum is given by

$$\frac{d^2 N_{\gamma,a}}{dt\, dE_\gamma} = 2\Gamma_a \mathcal{N}\,\delta\left(E_\gamma - \mu/2\right)$$
$$= \frac{2\Gamma_a \mathcal{N}}{\sqrt{2\pi}\,\Delta E}\, e^{\frac{(E_\gamma-\mu/2)^2}{2\Delta E^2}}.$$

Where we replaced the monochromatic spectrum by a Gaussian function of width ΔE in order to take into account the effects of a detector's resolution. We then obtain for the maximum photon emission [8].

References

[1] C.M. Chambers, W.A. Hiscock and B. Taylor, Phys.Rev. Lett. 78, 3249 (1997).
[2] D.N. Page, Phys.Rev. D13, 198(1976), D14, 3260(1976).
[3] S.A. Teukolsky, Astrophys. J. 185, 635 (1973).
[4] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper and J. March-Russell, Phys. Rev. D81 (2010), 123530.
[5] M. Calza, J. March-Russel and J. Rosa, arXiv:2110.13602 (2021).
[6] Press W. H. Press and S. A. Teukolsky, Nature 238 (1972) 211–212.
[7] R. Brito, V. Cardoso, P. Pani, Lect. Notes Phys. 971 (2020) [arXiv:1501.06570].
[8] M. Calza, J. Rosa and F. Serrano [arXiv:2306.09430]