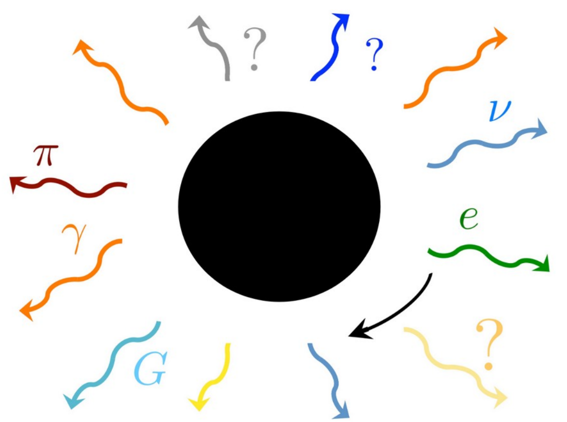
Primordial Black Holes



as probes of New Physics

Marco Calzà.

University of Trento.

In collaboration with Joao G. Rosa, John March-Russell, Filipe Serrano.

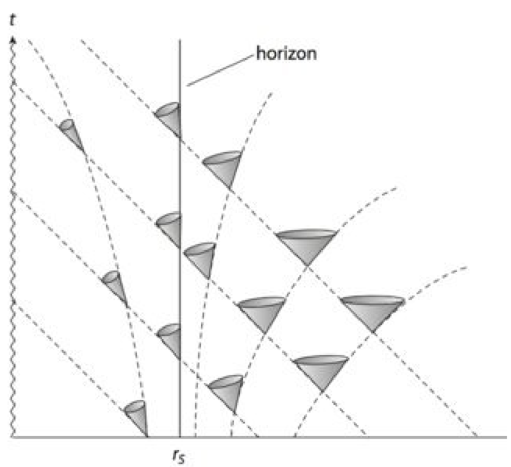
PRIMORDIAL BLACK HOLES

as probes of NEW PHYSICS

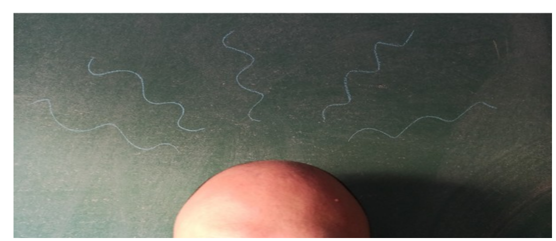
Primordial BH

- PBHs are BHs formed in the **early Universe**
- Through the gravitational collapse of **overdensities** in the **cosmic plasma**
- **Masses** can be several orders of magnitude **below** the **solar mass**

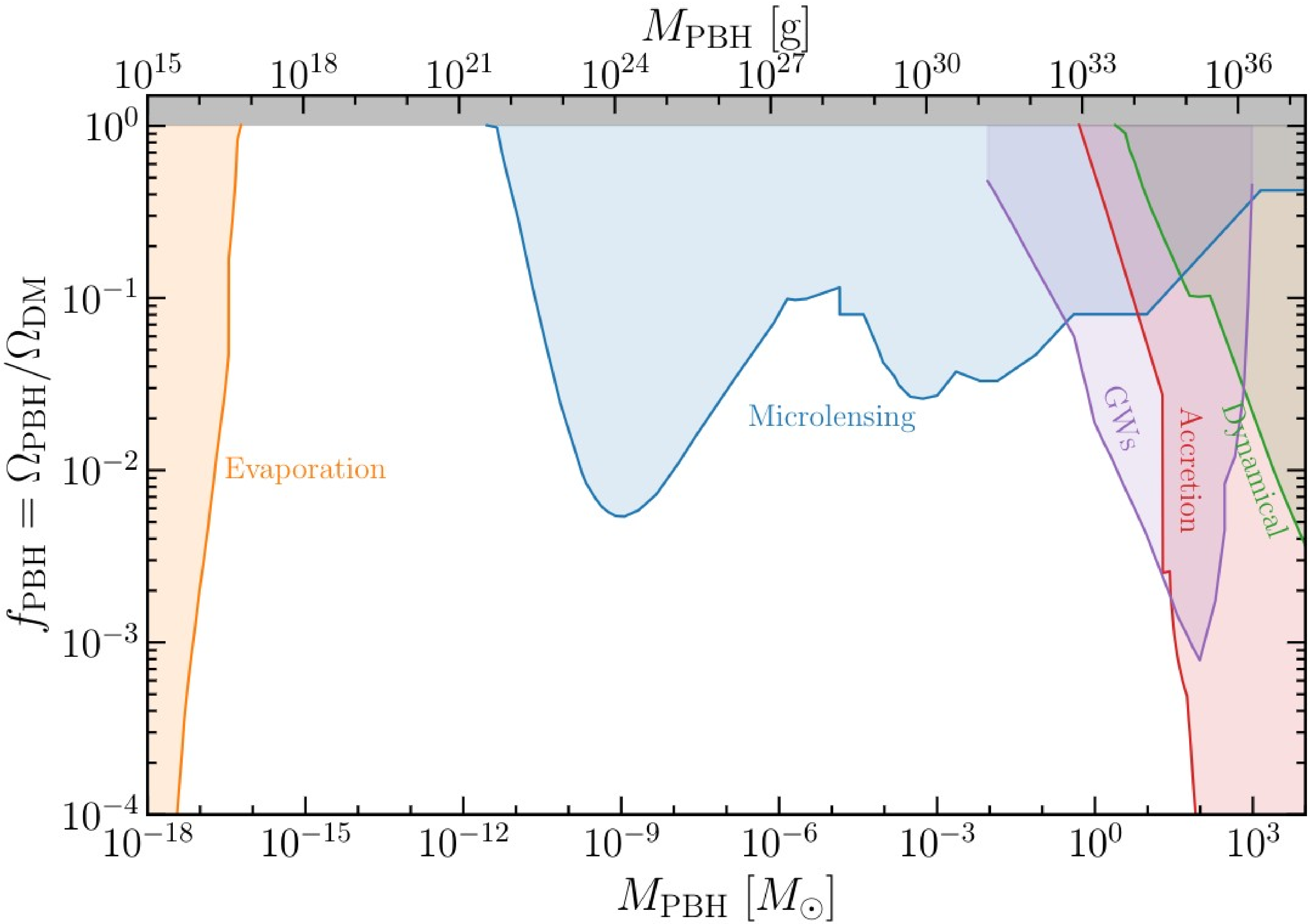
So what? Why?



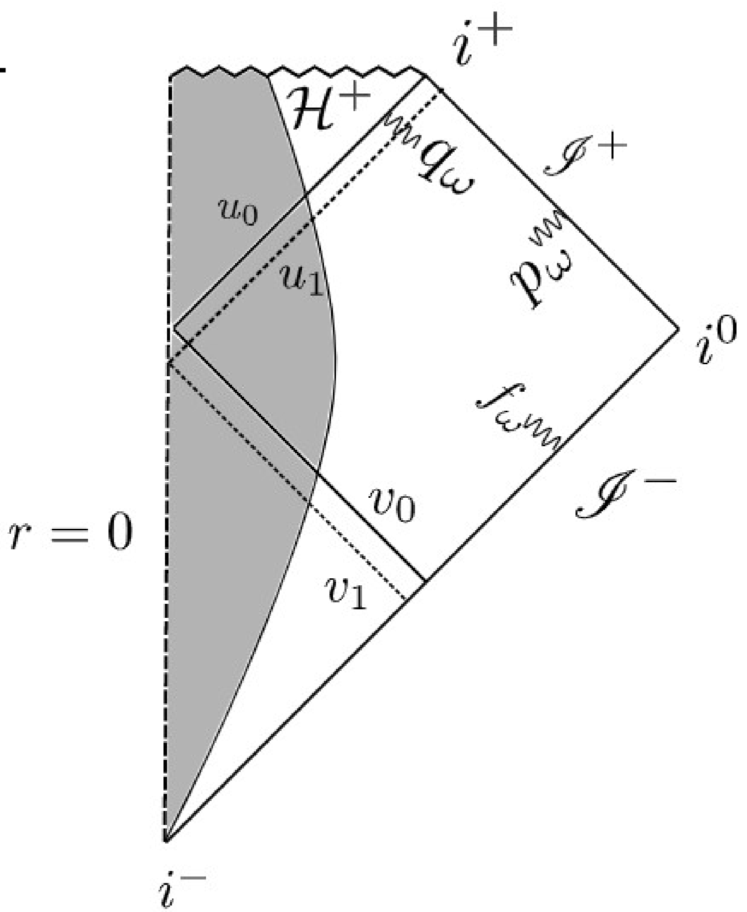
$$M,\ a = J/M^2,\ \cancel{Q}$$



Primordial Black Holes



Hawking evaporation



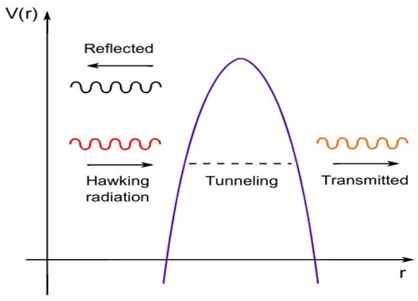
S-T before/after formation of an horizon

[Hawking 1975]

$$T_H = \frac{\kappa}{2\pi} \sim 10\, MeV \left(\frac{10^{12}\, kg}{M} \right)$$

Emission of particles

$$\frac{dN_s}{dt\, d\omega} = \frac{1}{2\pi} \sum_{l,m} \frac{\Gamma_{s,l,m}(\omega)}{e^{2\pi(\omega - m\Omega)/\kappa} \pm 1}$$



Hawking evaporation

[Page 70’s, Chambers, Hiscock & Taylor (1997)]

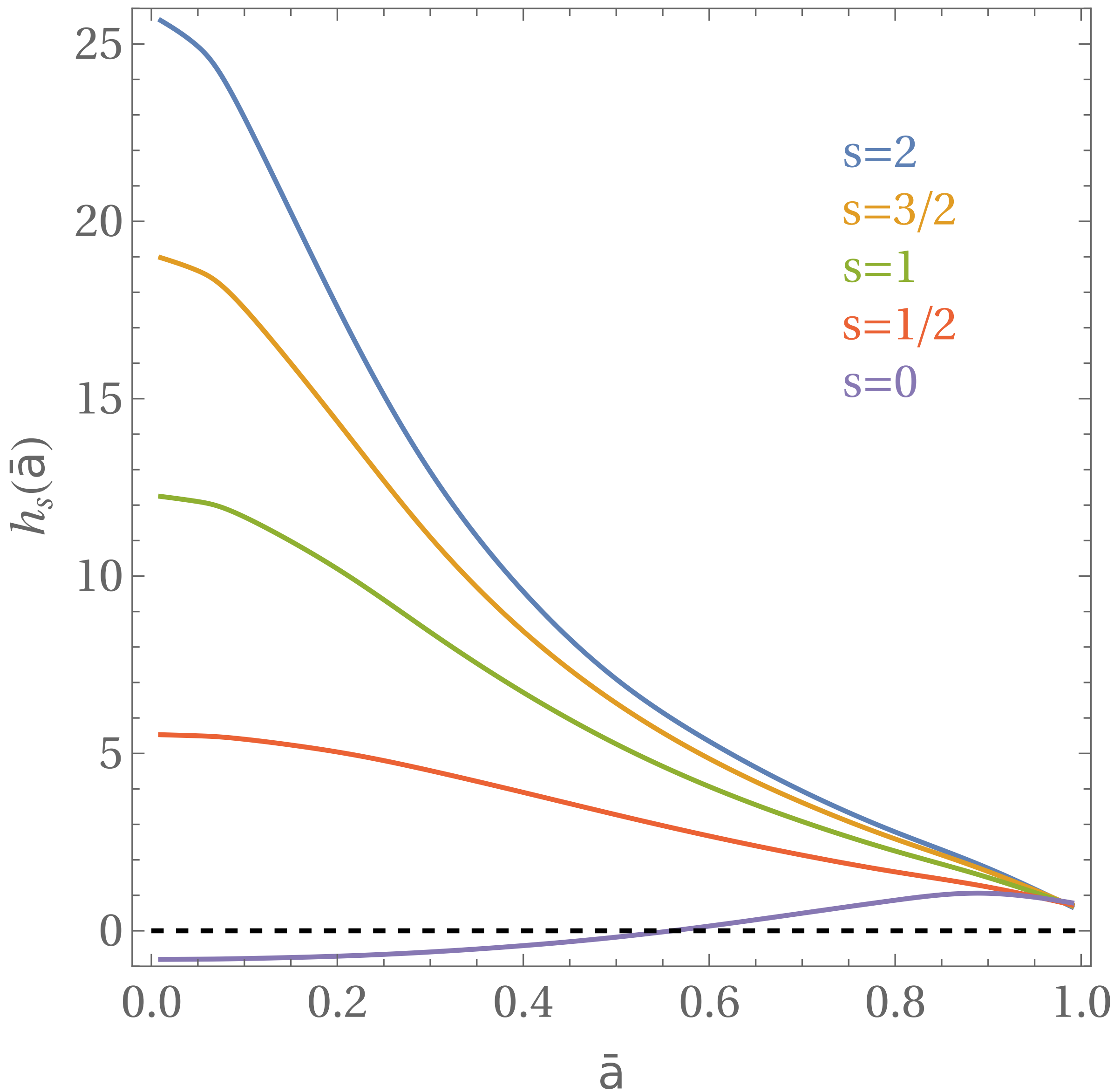
$$\frac{dM}{dt} = -F \frac{M_P^4}{M^2} \qquad \frac{dJ}{dt} = -G \frac{M_P^4}{M^3} J$$

$$\begin{pmatrix} \mathcal{F} \\ \mathcal{G} \end{pmatrix} = \sum_{i,l,m} \frac{1}{2\pi} \int_0^\infty d\bar{\omega} \frac{\Gamma^s_{lm}}{e^{\varpi/T_H} \pm 1} \begin{pmatrix} \bar{\omega} \\ m\tilde{a}^{-1} \end{pmatrix}$$

$$\varpi = \omega - m\Omega_H \qquad \bar{\omega} = \omega M/M_P^2$$

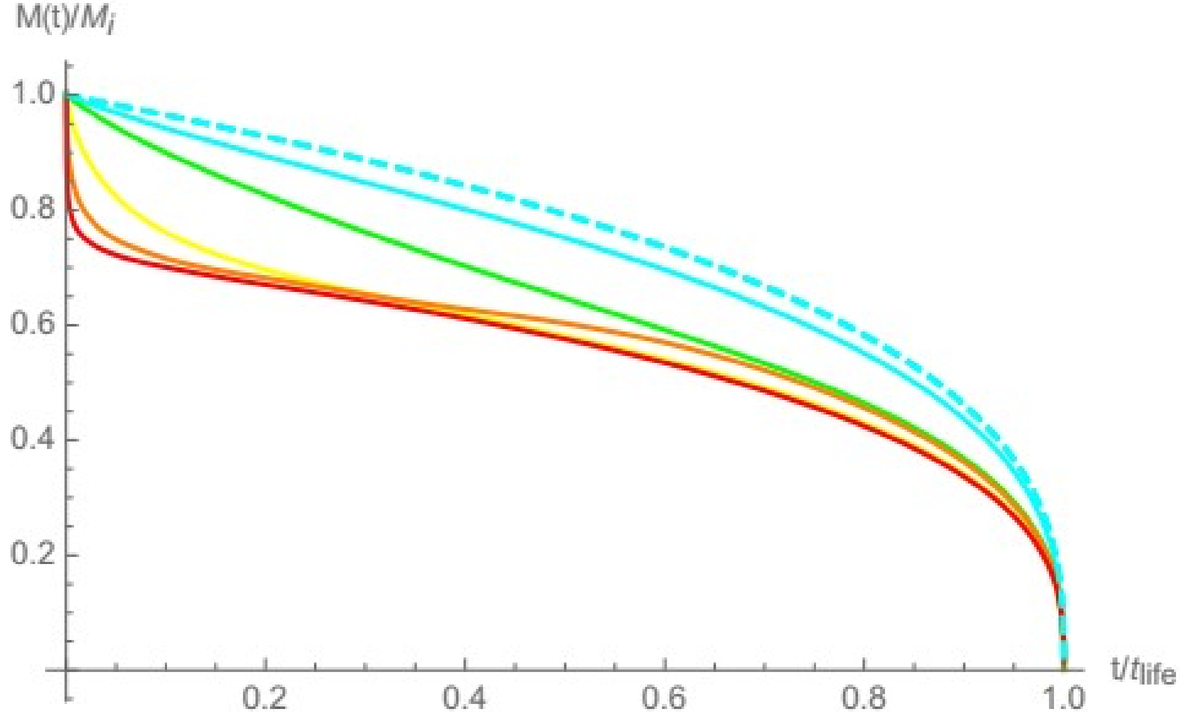
$$\frac{d \log \tilde{a}}{d \log M} = \frac{\mathcal{G}}{\mathcal{F}} - 2 \equiv \mathcal{H}(\tilde{a})$$

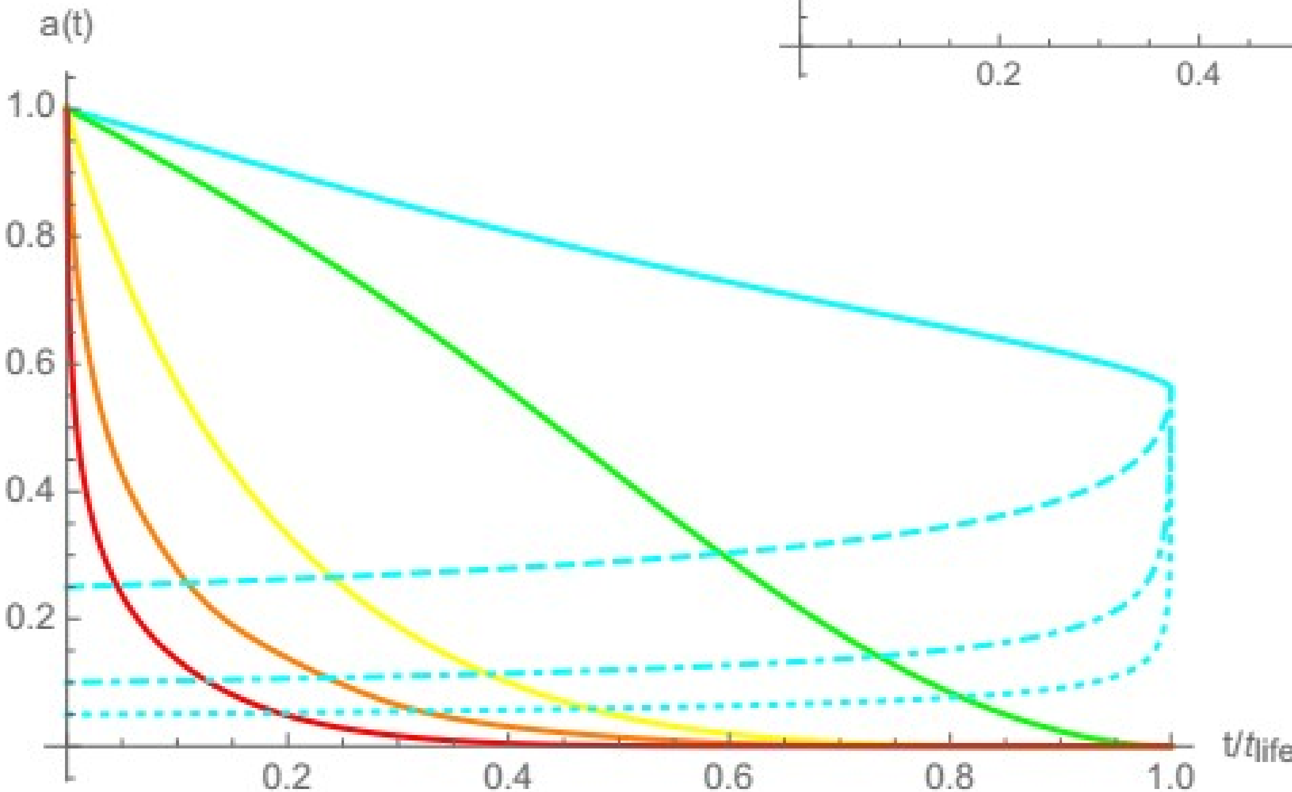
Hawking evaporation



Hawking evaporation

$\boldsymbol{M}\downarrow$ & $\boldsymbol{T_H}\uparrow$





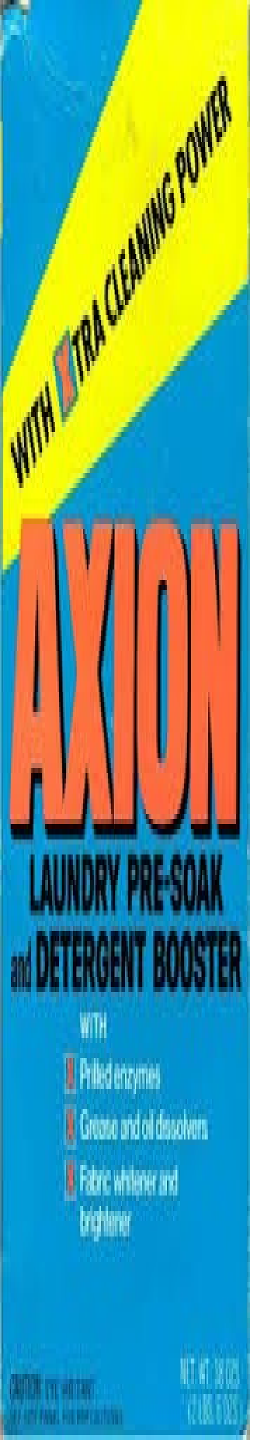
s=0

s=1/2

s=1

s=3/2

s=2



The String Axiverse

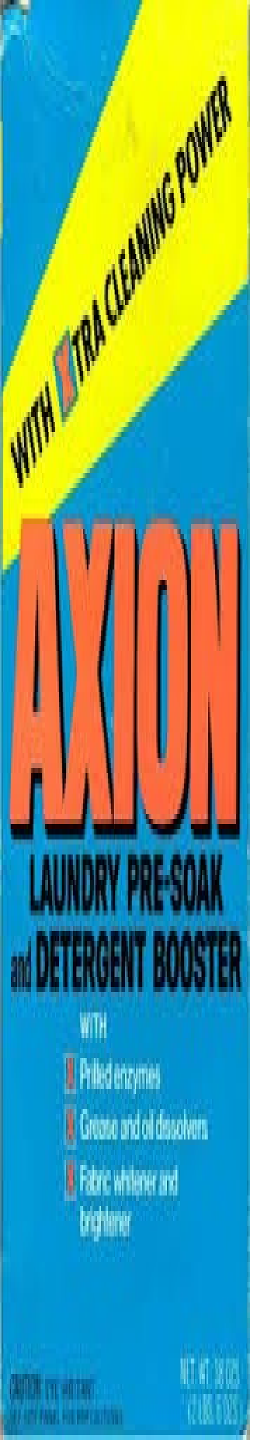
[Arvanitaki et al. (2010)]

- Scalar field with a shift symmetry in 4D
- No mass terms by perturbative effects
- Mass is generated by non-perturbative effects

(Assuming one QCD axion)

String theory: $E\downarrow \rightarrow SM + G$ 10D (4 s-t + 6 compactified)

Compactified extra dimensions is the key ingredient!

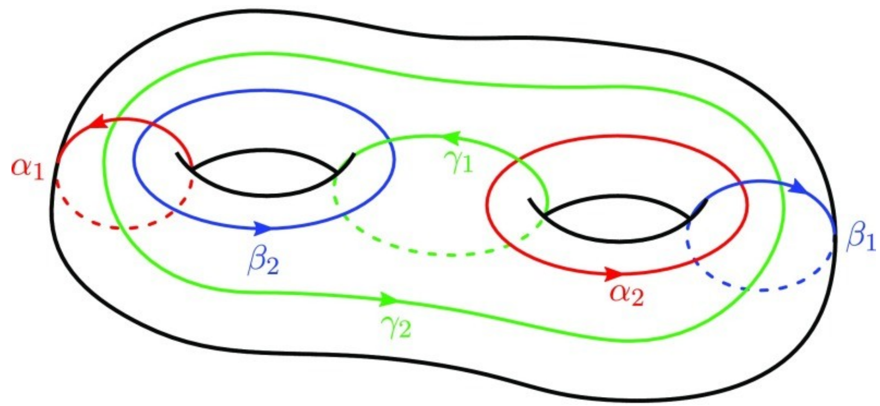


The String Axiverse

In the extra-D there are new states, called p-form.

Basically, tensor fields in the extra-D

Neaveu-Schwarz & Ramond-Ramond fields



$$a(x) = \frac{1}{A_{C^n}} \int_{C^n} B_n$$

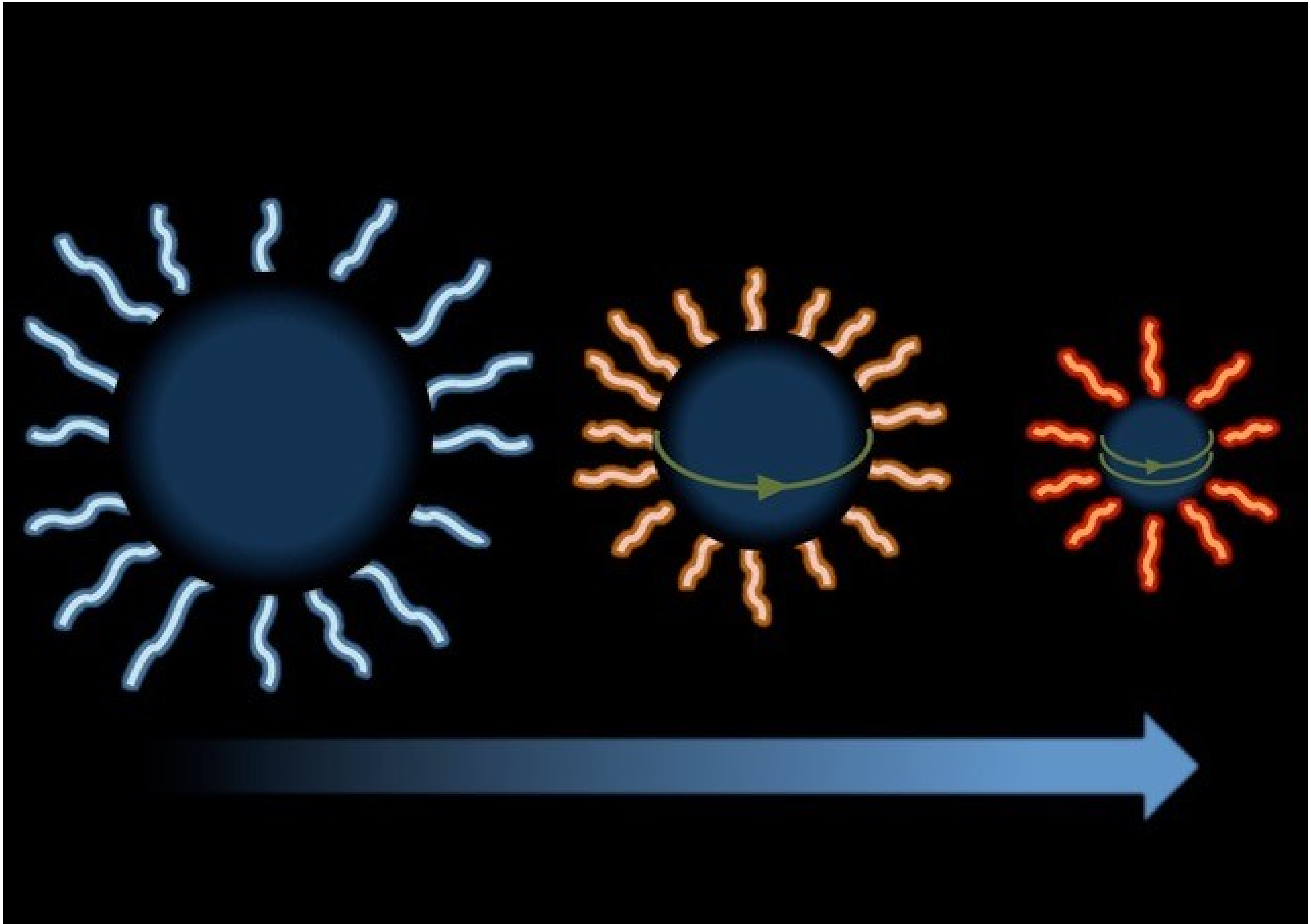
$$C^2 = S^2 \; , \; S^1 \times S^1 \; , \; \ldots$$

Sphere

Torus

6 extra-D + many ways to compactify = ($N_a \sim [100\text{-}10^5]$)

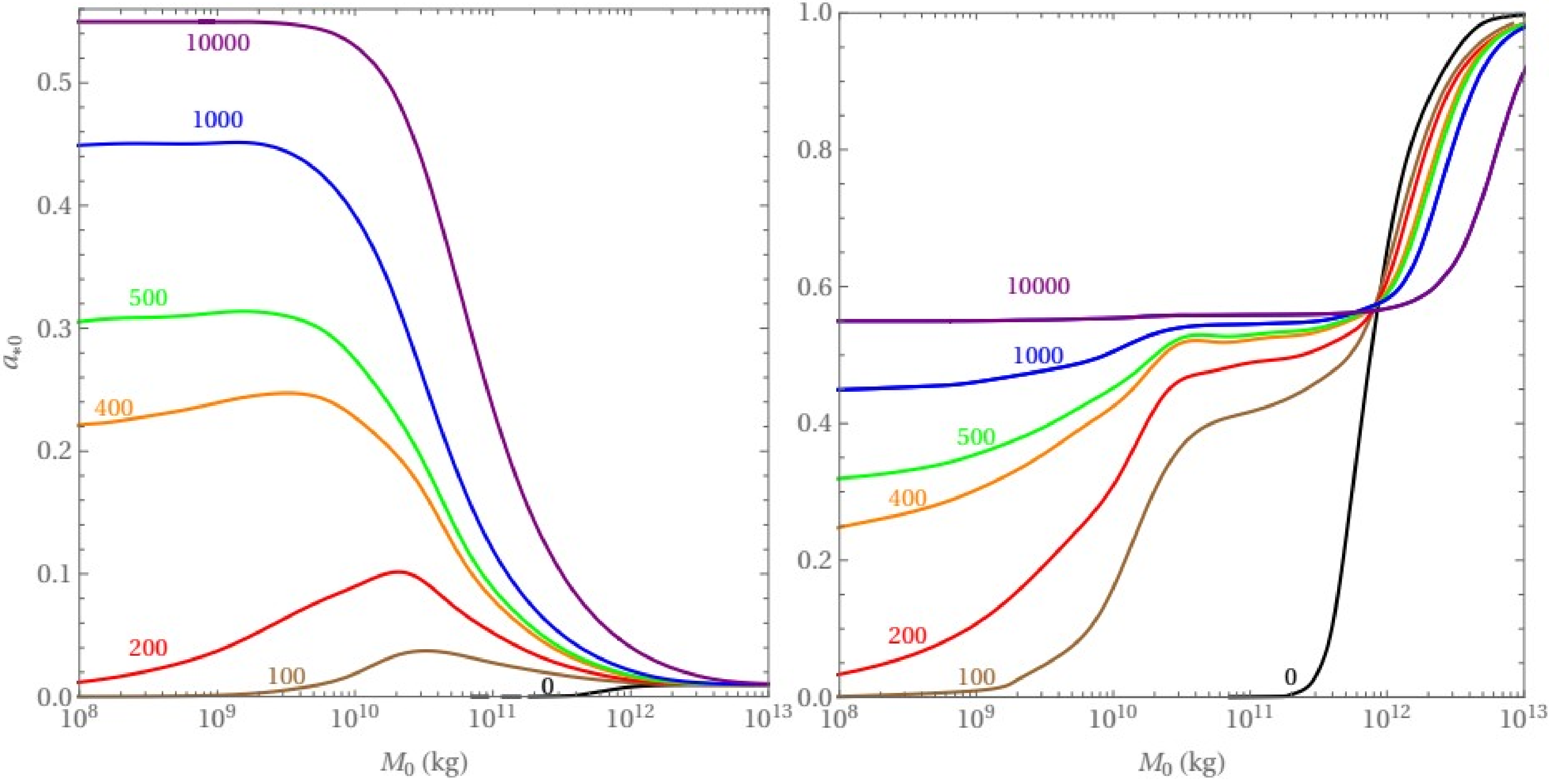
Axiverse + PBHs Evaporation



Axiverse fingerprint in PBH evaporation

SM particles + graviton + N axions

[1]



Hot Dark Radiation

Integrated flux of ALPs from a single PBH in the relevant PBH spin range

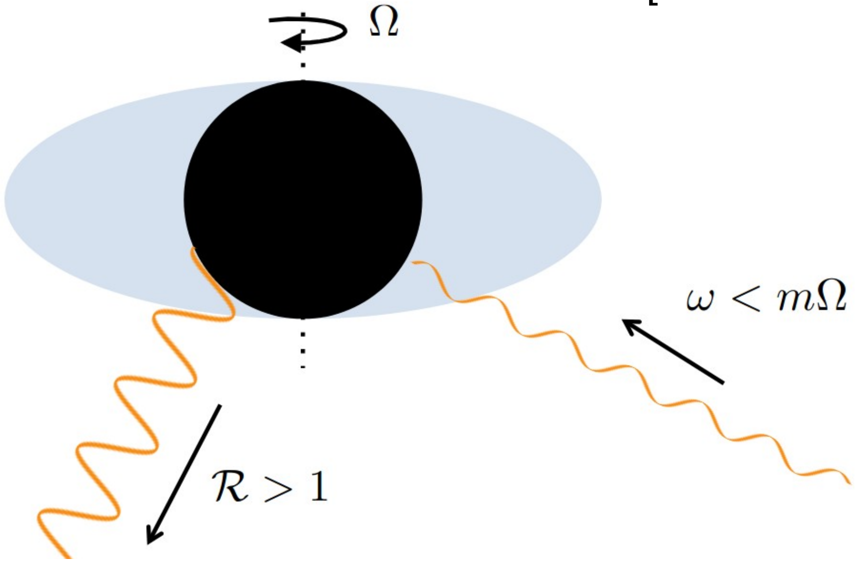
$$\sim 3\times 10^{22} N_a \left(10^{10}/M\right) s^{-1}$$

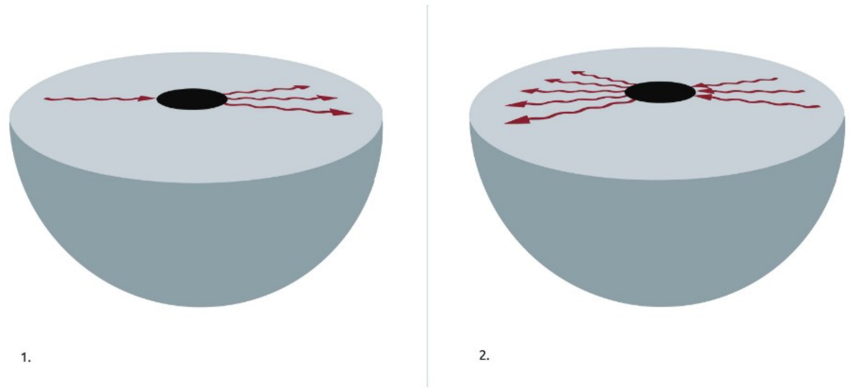
- Reasonable N_a → Hawking luminosity is ALPs dominated
- Hot (10^{10} kg → $T_H \sim 1$ GeV)
- Dark to the SM
- Not red-shifted (It is now evaporating)
- Usual constraints (BBN, CMB…) do not apply → potentially the present ALPs hot 'dark-radiation' $\rho > \rho_{CMB}$.

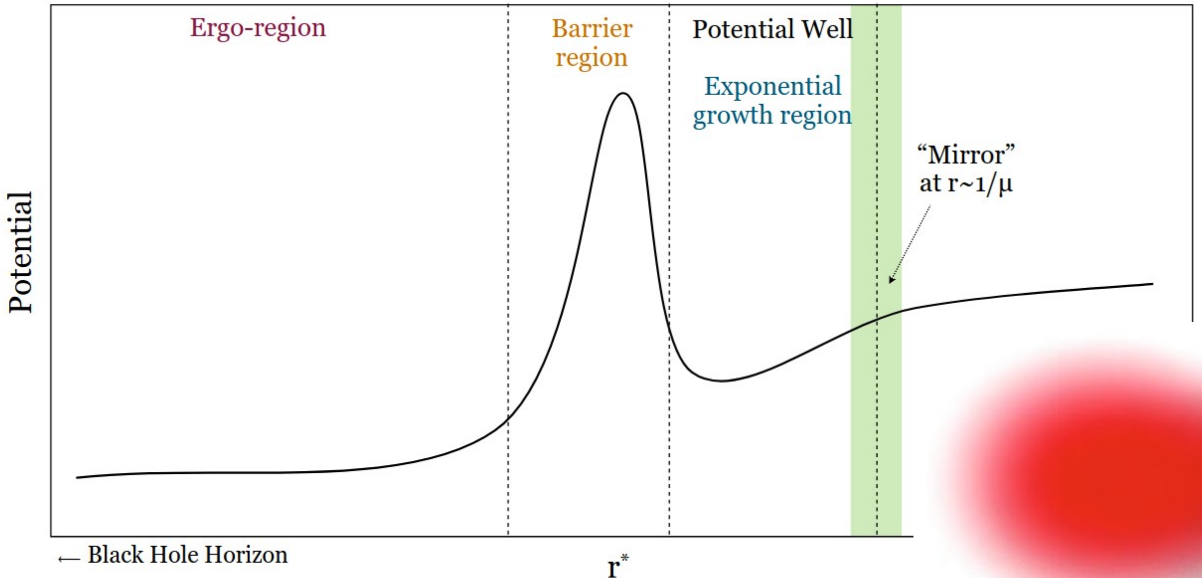
Detection of background energetic dark axions is a striking signal for both axiverse physics and the existence of Hawking evaporating PBHs.

BHs Superradiance

[Zeldovich (1966)]

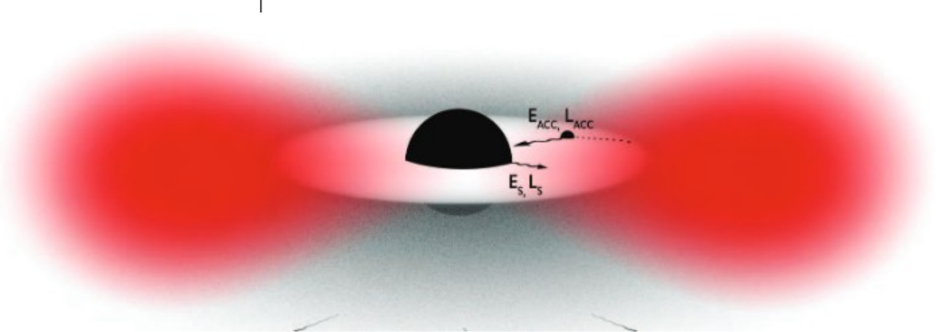




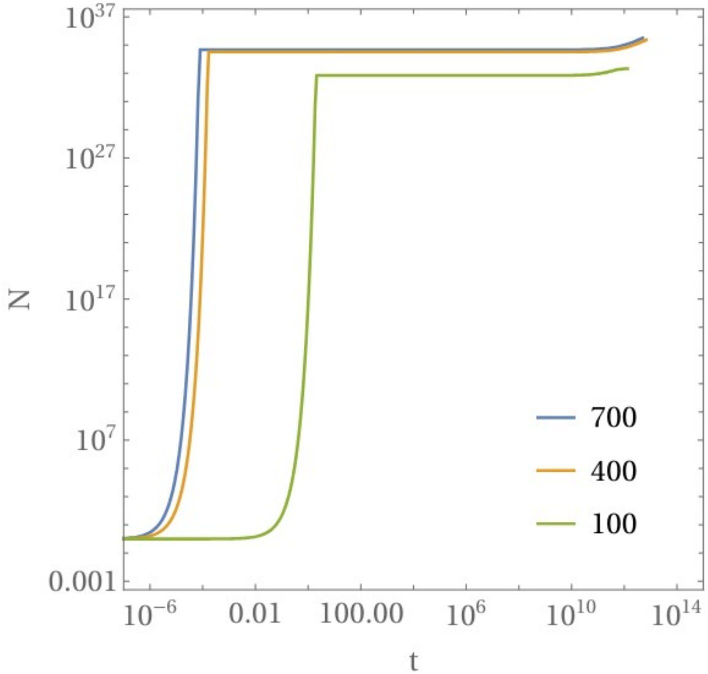


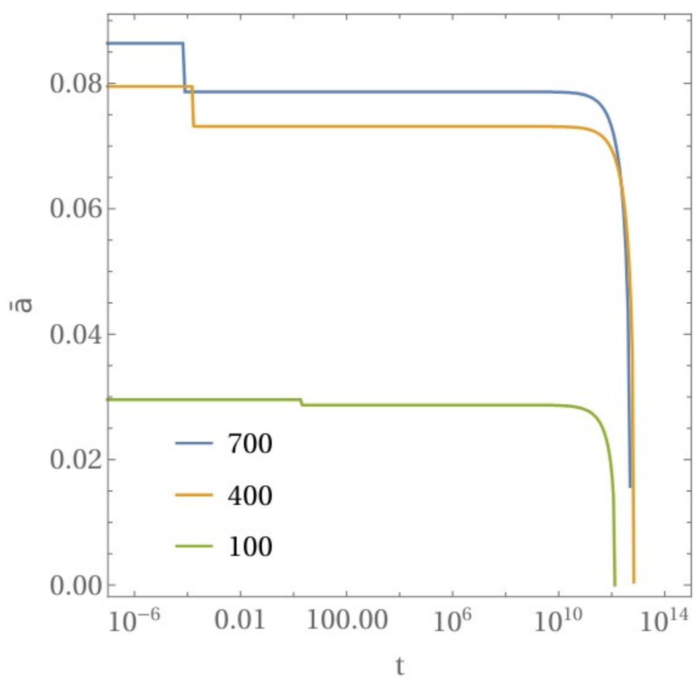
[Arvanitaki et al. (2009)]

$$\Gamma_S \sim \Gamma_{211}$$

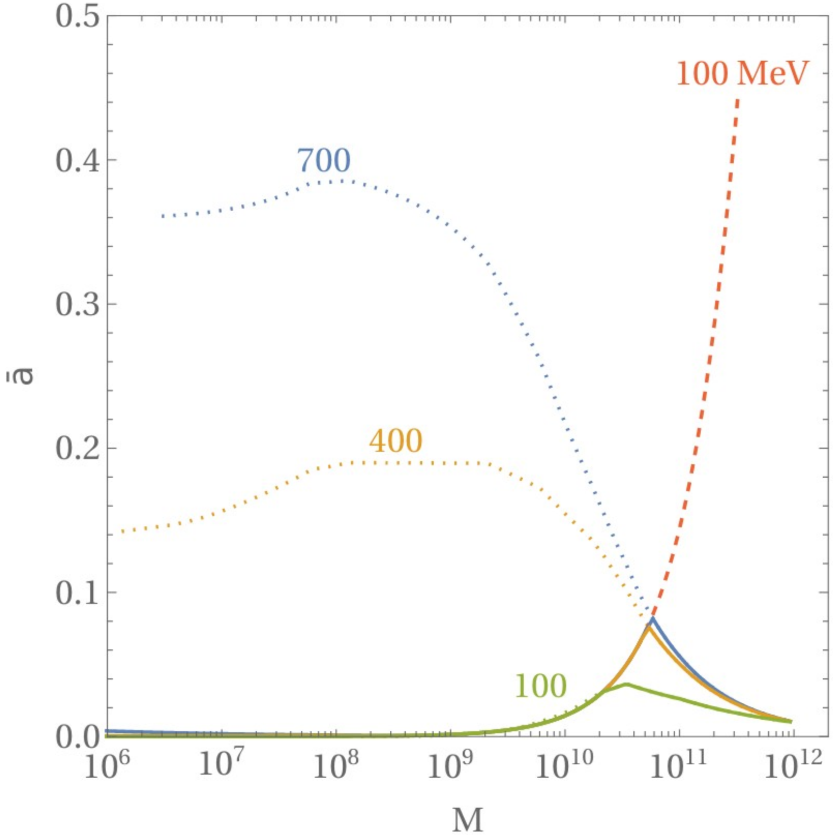


Superradiance + ALPs





[2]



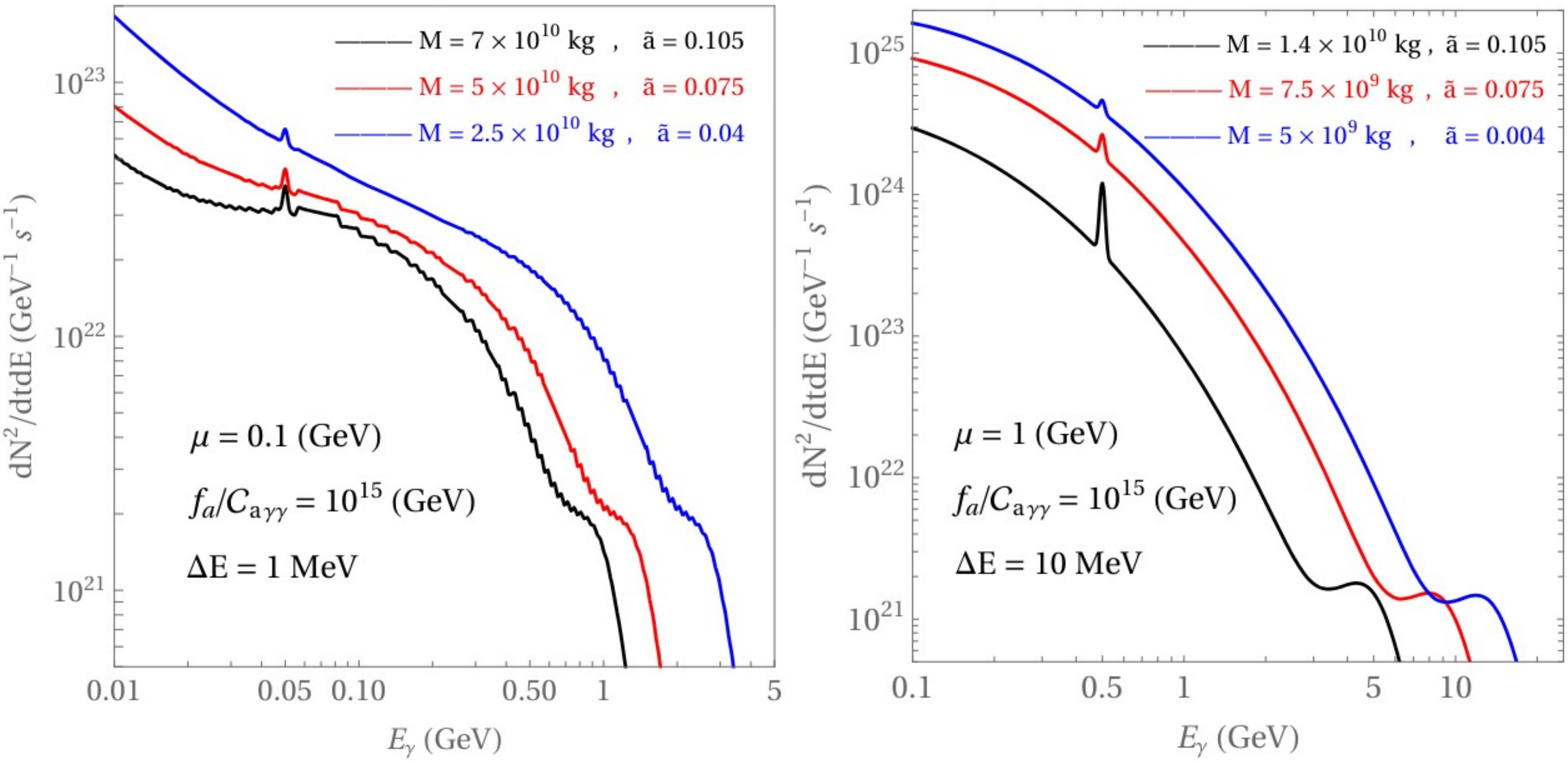
$$\frac{dN}{dt} = \Gamma_s(M, \tilde{a}, \mu) N$$

$$\frac{dM}{dt} = -\mathcal{F}(\tilde{a}) \frac{M_P^4}{M^2} - \mu \Gamma_s N$$

$$\frac{d\tilde{a}}{dt} = \tilde{a} \frac{M_P^4}{M^3} (-\mathcal{G}(\tilde{a}) + 2\mathcal{F}(\tilde{a})) - \frac{M_P^2}{M^2} \Gamma_s N$$

Superradiance + ALPs

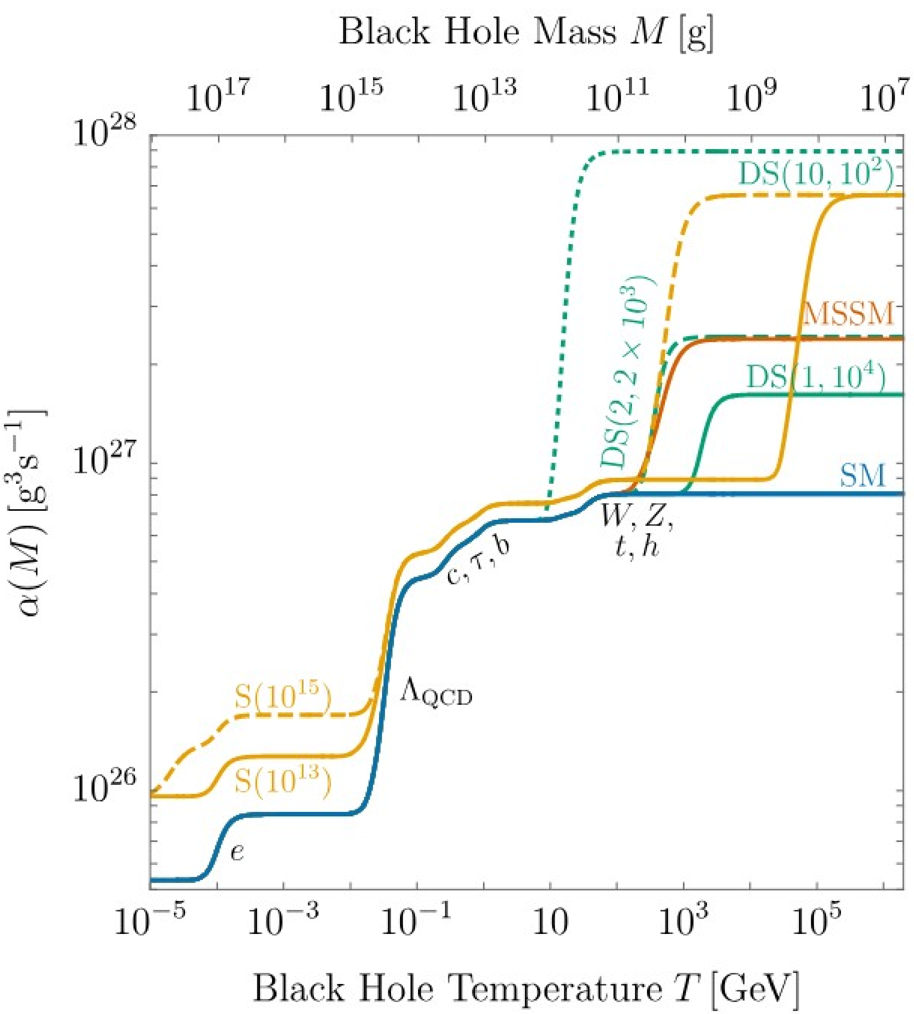
[2]

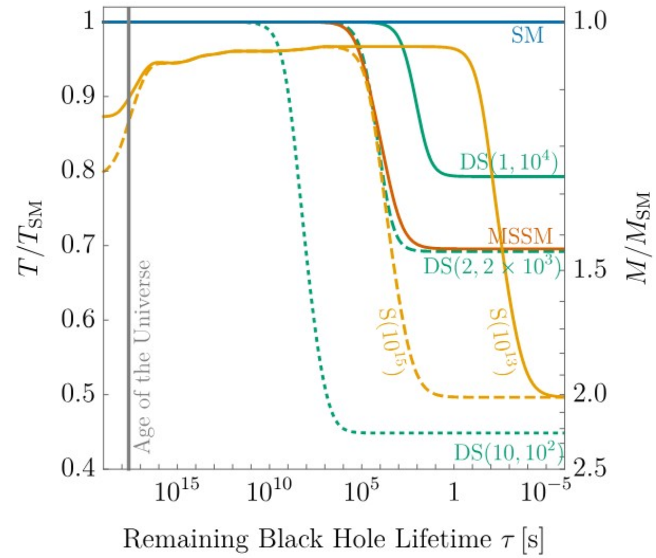


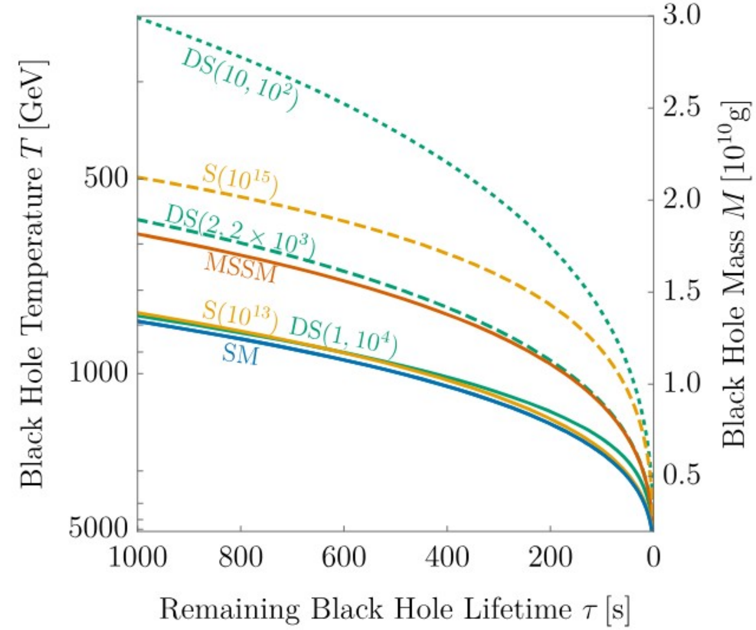
High Energy BSM

[Baker & Thamm (2022-23)]

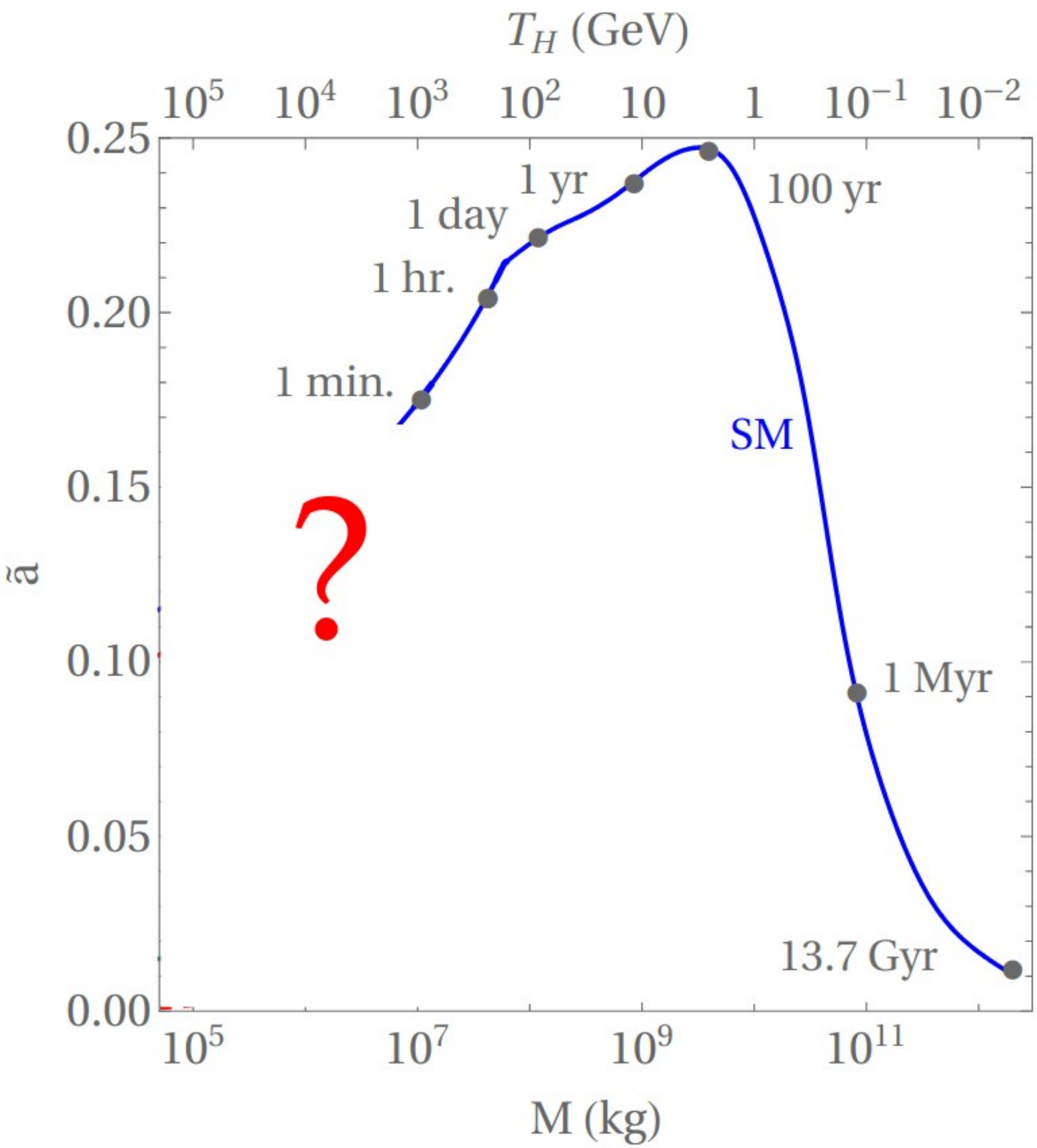
$$T_H = \frac{\kappa}{2\pi} \sim 10\,MeV\left(\frac{10^{12}\,kg}{M}\right)$$





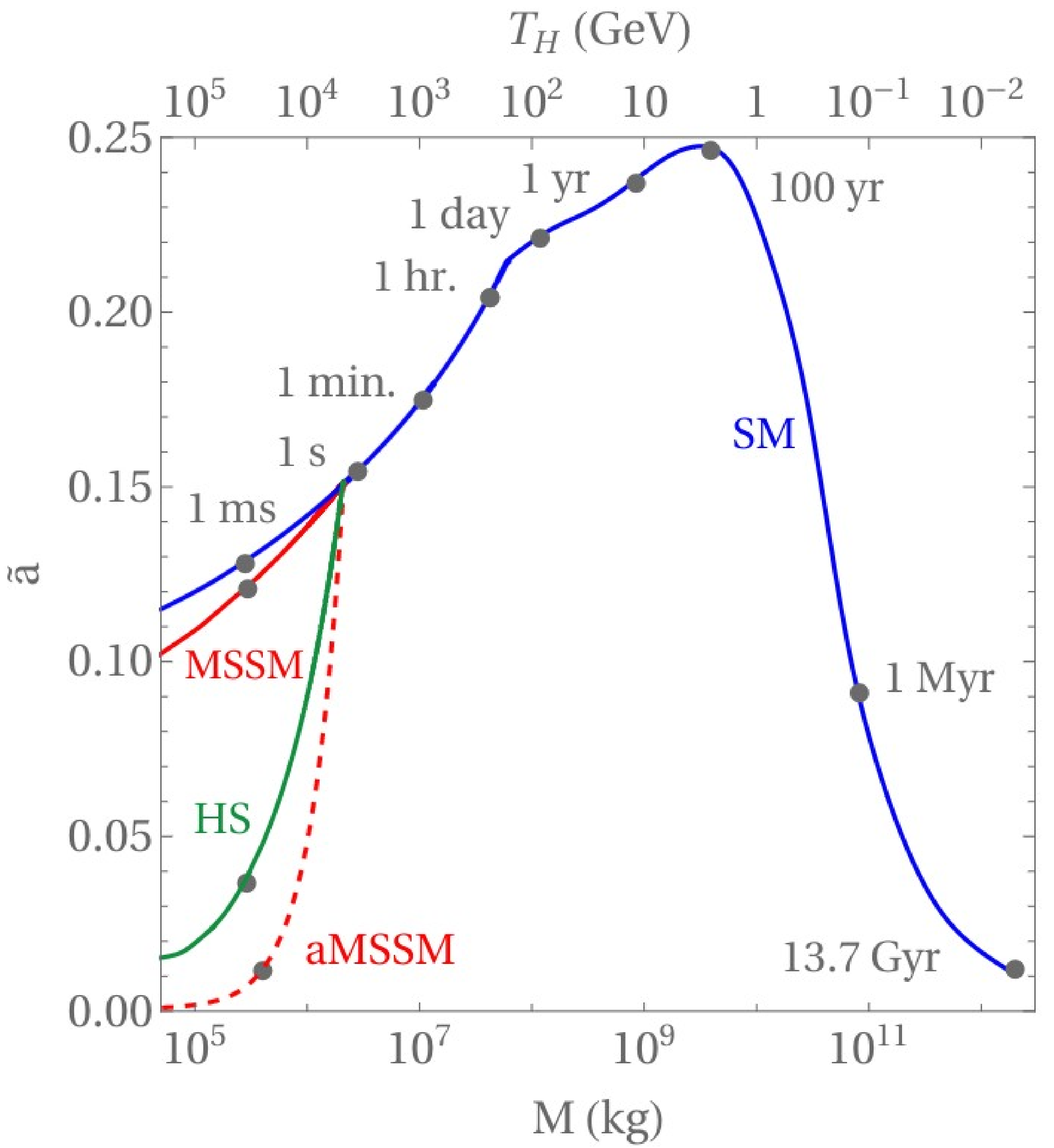


High Energy BSM



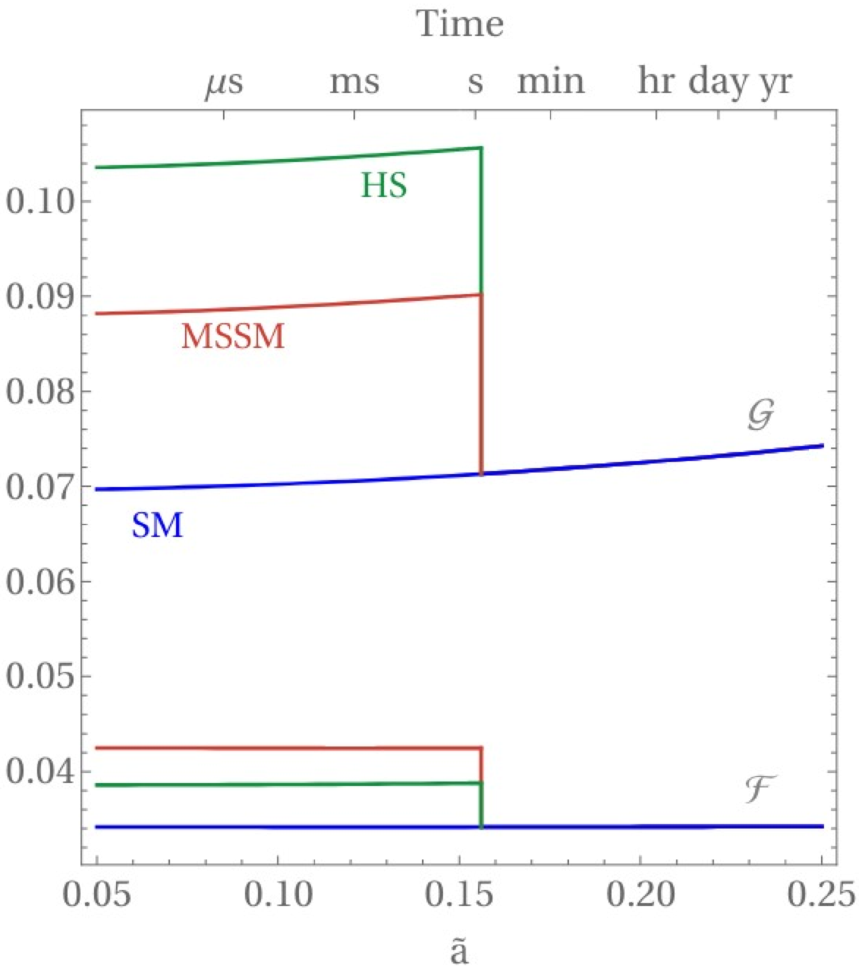
High Energy BSM

[3]



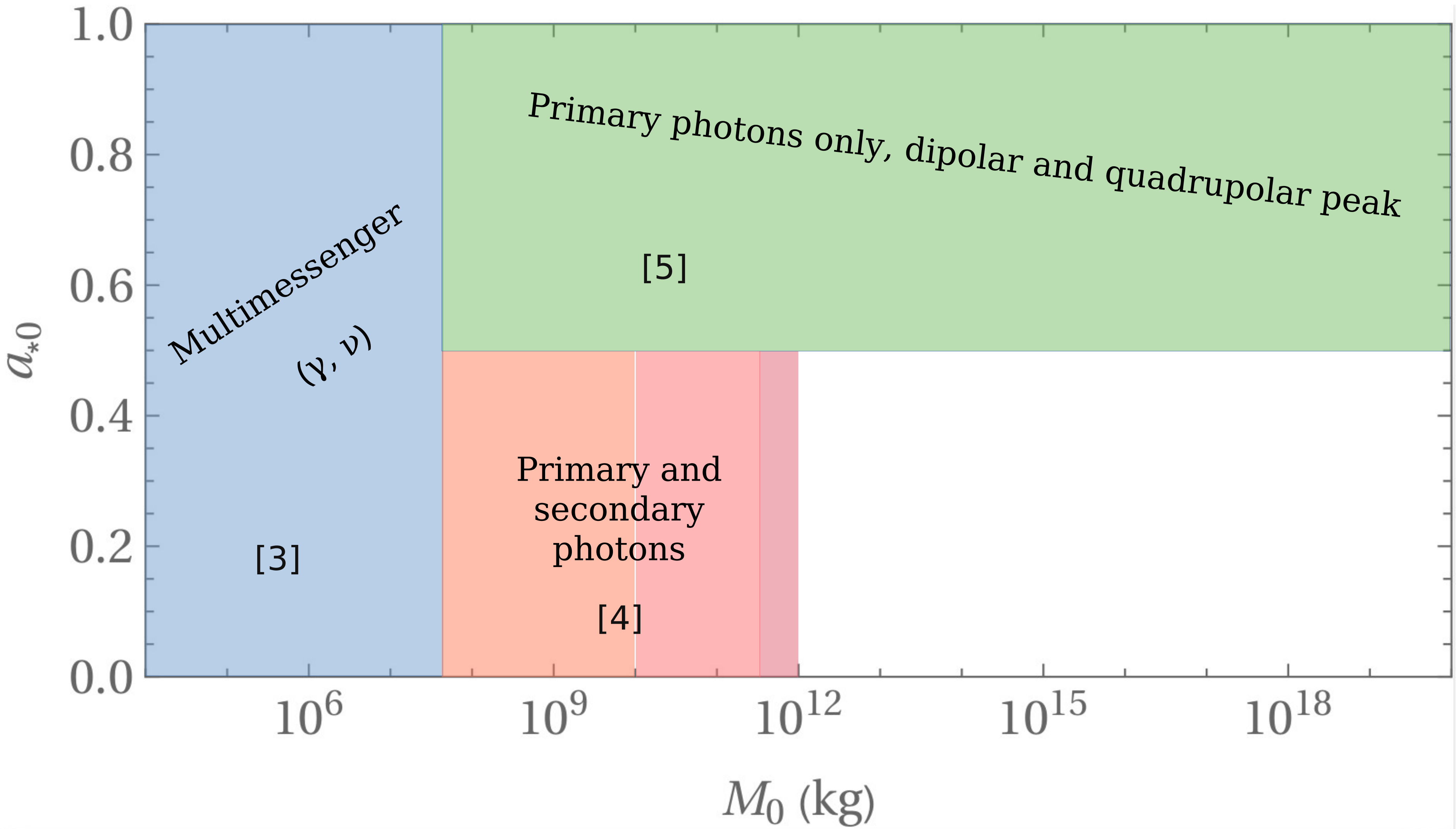
High Energy BSM

[3]

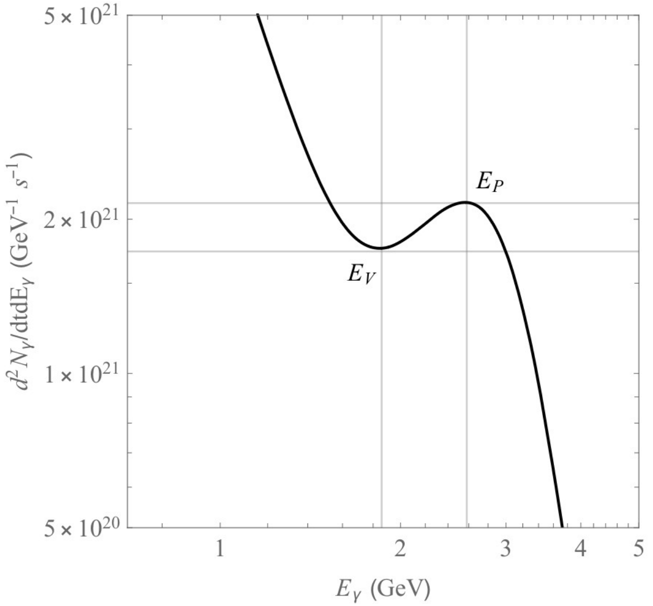


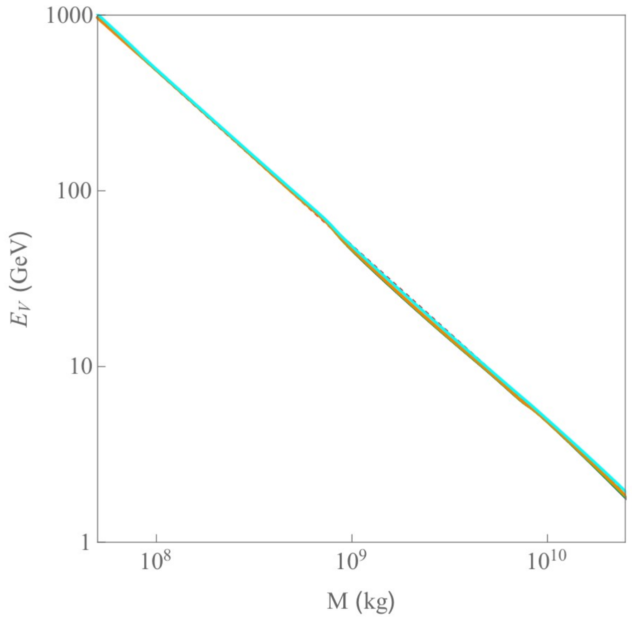
$$\begin{pmatrix} \mathcal{F} \\ \mathcal{F}' \\ \mathcal{G} \\ \mathcal{G}' \end{pmatrix} = \begin{pmatrix} \mathcal{F}_0 & \mathcal{F}_{1/2} & \mathcal{F}_1 & \mathcal{F}_{3/2} \\ \mathcal{F}'_0 & \mathcal{F}'_{1/2} & \mathcal{F}'_1 & \mathcal{F}'_{3/2} \\ \mathcal{G}_0 & \mathcal{G}_{1/2} & \mathcal{G}_1 & \mathcal{G}_{3/2} \\ \mathcal{G}'_0 & \mathcal{G}'_{1/2} & \mathcal{G}'_1 & \mathcal{G}'_{3/2} \end{pmatrix} \begin{pmatrix} n_0 \\ n_{1/2} \\ n_1 \\ n_{3/2} \end{pmatrix}$$

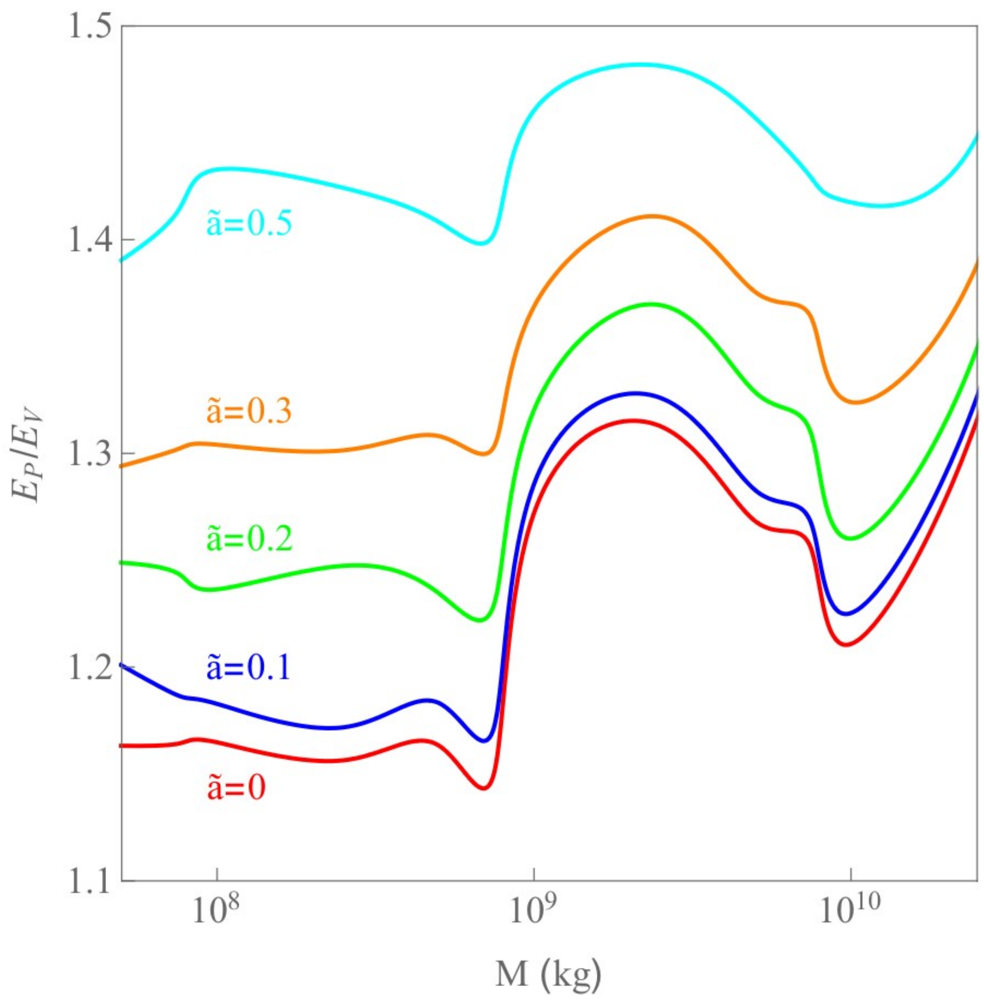
Determining mass and spin of light PBHs



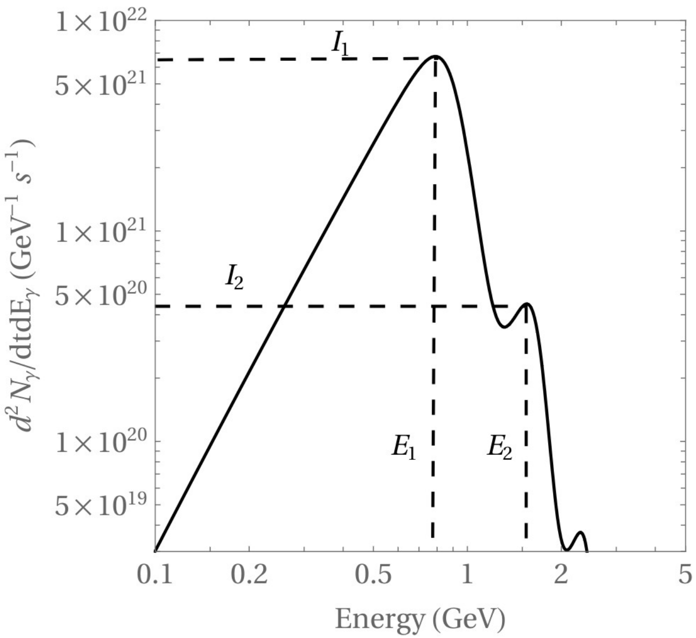
How to infer mass and spin?

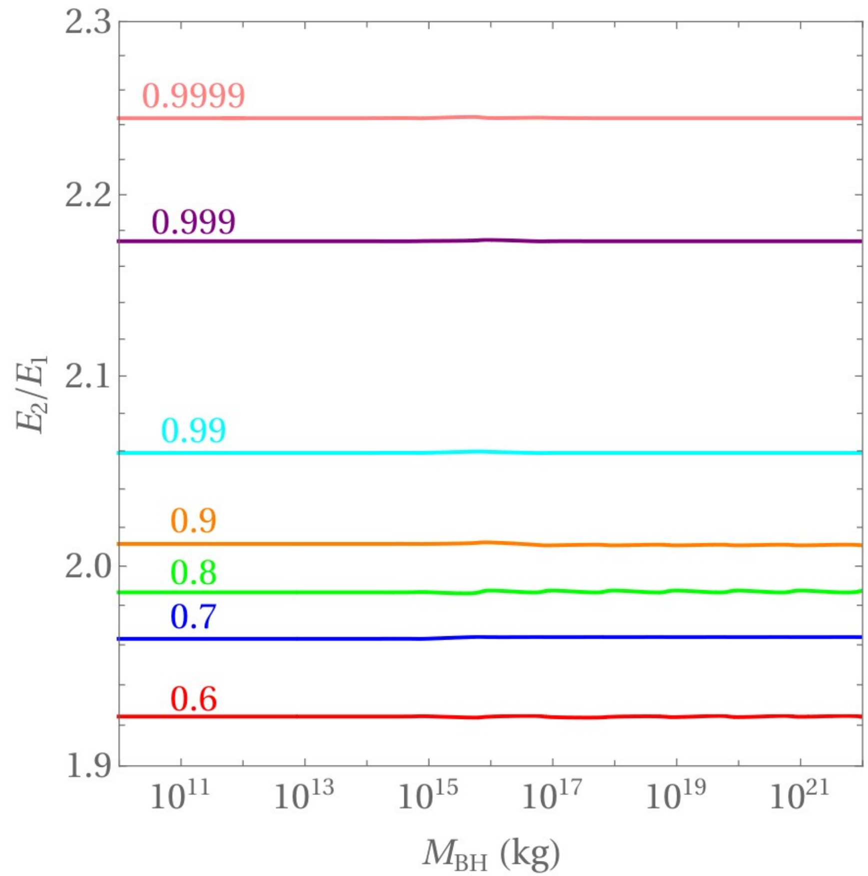


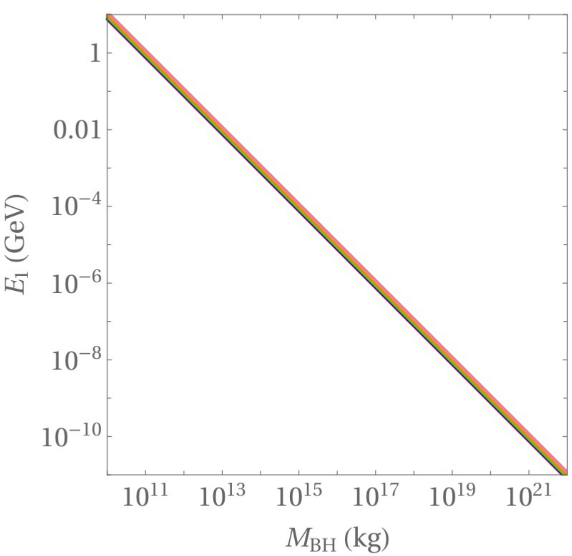


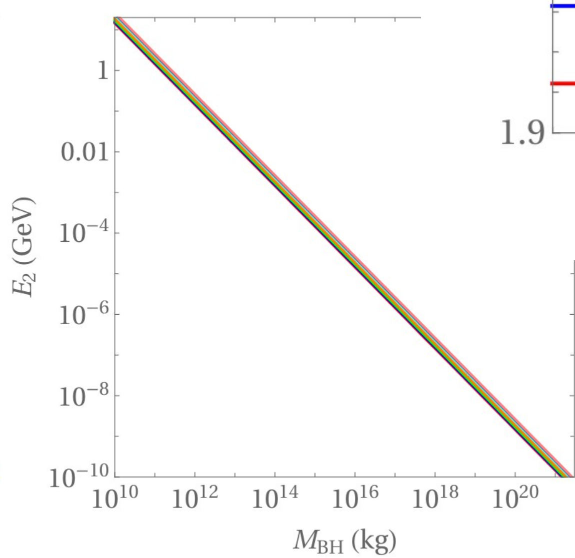


How to infer mass and spin?

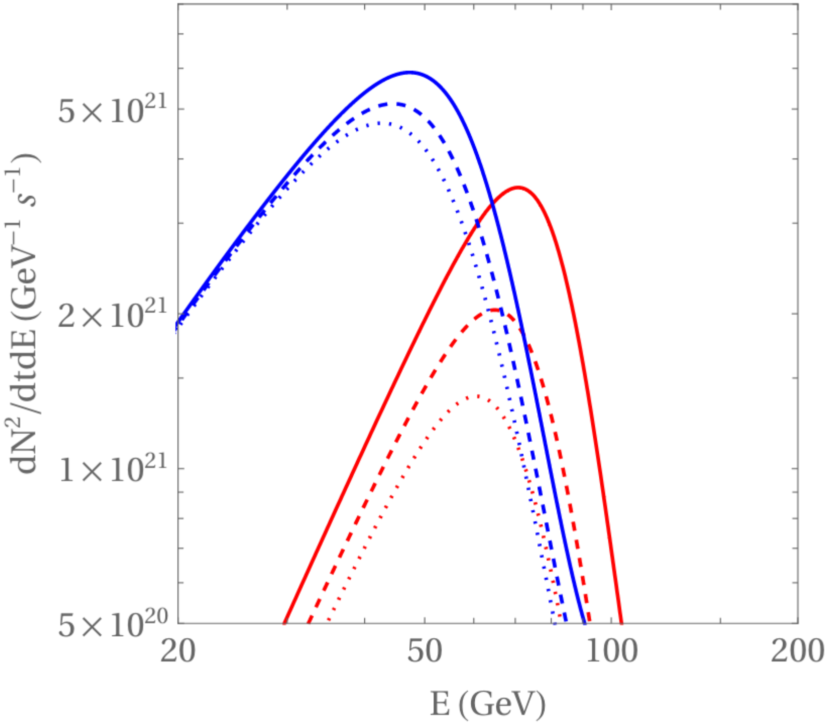








How to infer mass and spin?



Primary photon (red) and single neutrino (blue) Hawking emission spectra for a PBH with $M = 10^9$ kg and $\tilde{a} = 0$ (dotted), $\tilde{a} = 0.2$ (dashed) and $\tilde{a} = 0.5$ (solid).

$$E_{\gamma,\nu} \propto T_H \propto M^{-1}$$

Maximum emission rates $I_{\gamma,\nu}$ independent of the PBH mass.

The ratios between these quantities for ν and γ depend only on ã

$$\frac{E_\nu}{E_\gamma} = 0.705 - \frac{0.559\tilde{a}^2}{1+5.18\tilde{a}}\,, \qquad \frac{I_\nu}{I_\gamma} = 3.423 - \frac{31.05\tilde{a}^2}{1+7.05\tilde{a}}$$

References

[1] M. Calzá, J. March-Russell & J. G. Rosa, PRL 133 (2024) 26, 261003

[2] M. Calzá & J. G. Rosa, JHEP 12 (2022) 090

[3] M. Calzá, J. G. Rosa & F. Serrano, JHEP 05 (2024) 140

[4] M. Calzá, J. G. Rosa, JHEP 08 (2024) 012

[5] M. Calzá, J. G. Rosa, [arXiv:2312.09261] (Accepted in JHEP)


"That's all Folks!"