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Physics Beyond with the Quantum and Gravity

IV Flag Meeting, Marco Calzà

06/10/2022

Beyond what?

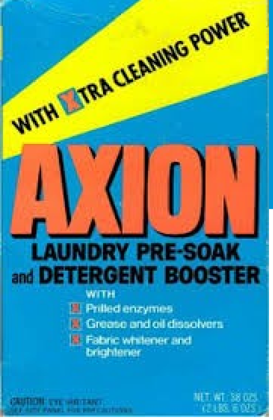
BSM

A new way to probe the total number of ALPs with $m <$ few MeV through the spin distribution of PBHs that are evaporating today!

Detection & M, a* estimation

BGR

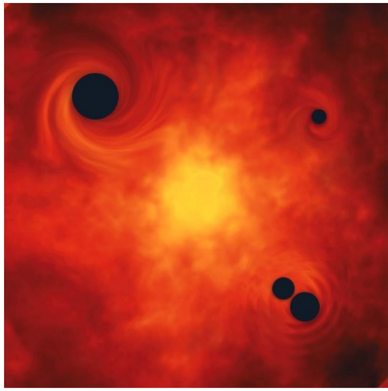
A way to probe the beyond the horizon structure through the dynamics of evaporation (M, a, T) of BHs!



The String Axiverse & PBHs

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

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

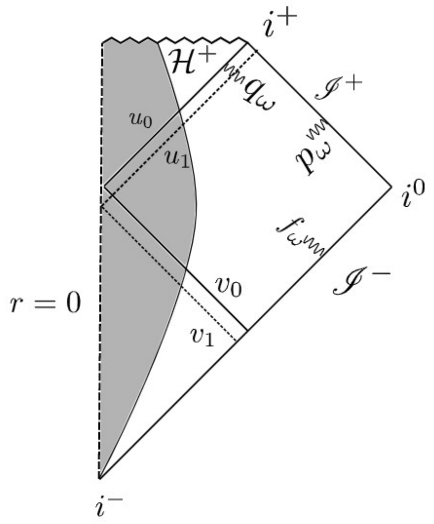


- PBHs are BHs formed in the **early Universe**
- Gravitational collapse of **cosmic plasma over-densities**
- **M** can be several orders of magnitude **below** $M_\odot$

M ~ 10^{12} kg evaporates enough to show changes in a_* in presence of many scalars. (T > few MeV)

RDE → $a_* \sim 0.01$ EMDE → $a_* \sim 0.99$

BH evaporation

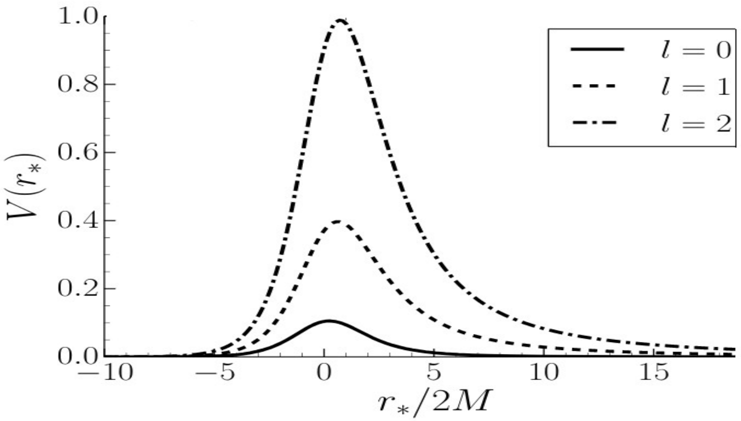


Spacetime before and after the formation of an horizon

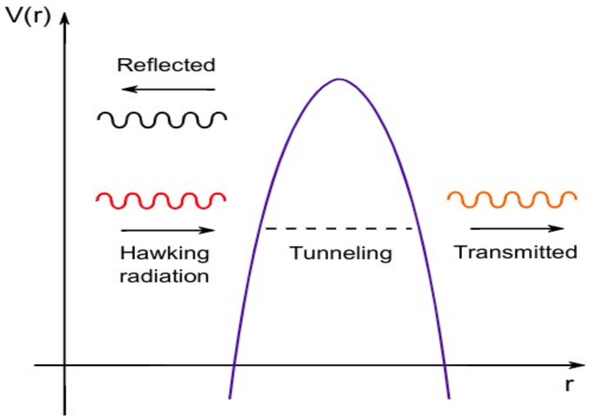
(Hawking 1975)

In a (1+1)D s-t: $n_\omega = \dfrac{1}{\left(e^{\frac{2\omega\pi}{\kappa}} - 1\right)}$, $T_H = \dfrac{\kappa}{2\pi}$

In a 4D s-t: $\nabla^\mu \nabla_\mu \Phi = 0 \;\Rightarrow\; \cdots \;\Rightarrow\; \left(\dfrac{d^2}{dx^2} + \omega^2 - V(r)\right)\psi(r) = 0$



BH geometry acts as a **potential barrier** that **filters Hawking radiation.**



$n_\omega = \dfrac{\Gamma(\omega)}{\left(e^{\frac{\omega}{T_H}} - 1\right)}$, $T_H = \dfrac{\kappa}{2\pi}$

BH evaporation

Radial Teukolsky Equation:

$$\Delta^{-s}\frac{d}{dr}\left(\Delta^{s+1}\frac{dR}{dr}\right)+\left(\frac{K^2-2is(r-M)K}{\Delta}+4is\omega r-\lambda\right)R=0 \longrightarrow \Gamma^{s}_{l,m}(\omega)$$

∀ ∃ field & mode:

$$n^{s}_{l,m}(\omega)=\frac{\Gamma^{s}_{l,m}(\omega)}{\left(e^{\frac{2k\pi}{\kappa}}-1\right)} \qquad \kappa=\frac{\sqrt{1-a_*^2}}{2}r_+ \qquad k=\omega-m\Omega_H$$

Page ('74 -'76)
Hiskock et al ('98)

Mass & angular momentum:

$$\begin{pmatrix}f_s\\ g_s\end{pmatrix}=\frac{1}{2\pi}\sum_{p,l,m}\int_0^\infty\frac{\Gamma^{s}_{l,m}(\omega)}{\left(e^{\frac{2k\pi}{\kappa}}\pm1\right)}\begin{pmatrix}x\\ m\,a_*^{-1}\end{pmatrix}dx \qquad x=\omega M$$

$$\frac{dz}{dy}=\frac{1}{h}=\frac{f}{g-2f} \qquad \frac{d\tau}{dy}=\frac{e^{3z}}{g-2f} \qquad \frac{d a_*}{dt}=\frac{-a_* h f}{M^3}$$

$$y=-\ln[a_*] \qquad z=-\ln[M/M_i] \qquad \tau=-M_i^3 t$$

BH evaporation

A BH is **not** evaporating through **only one field**!!!

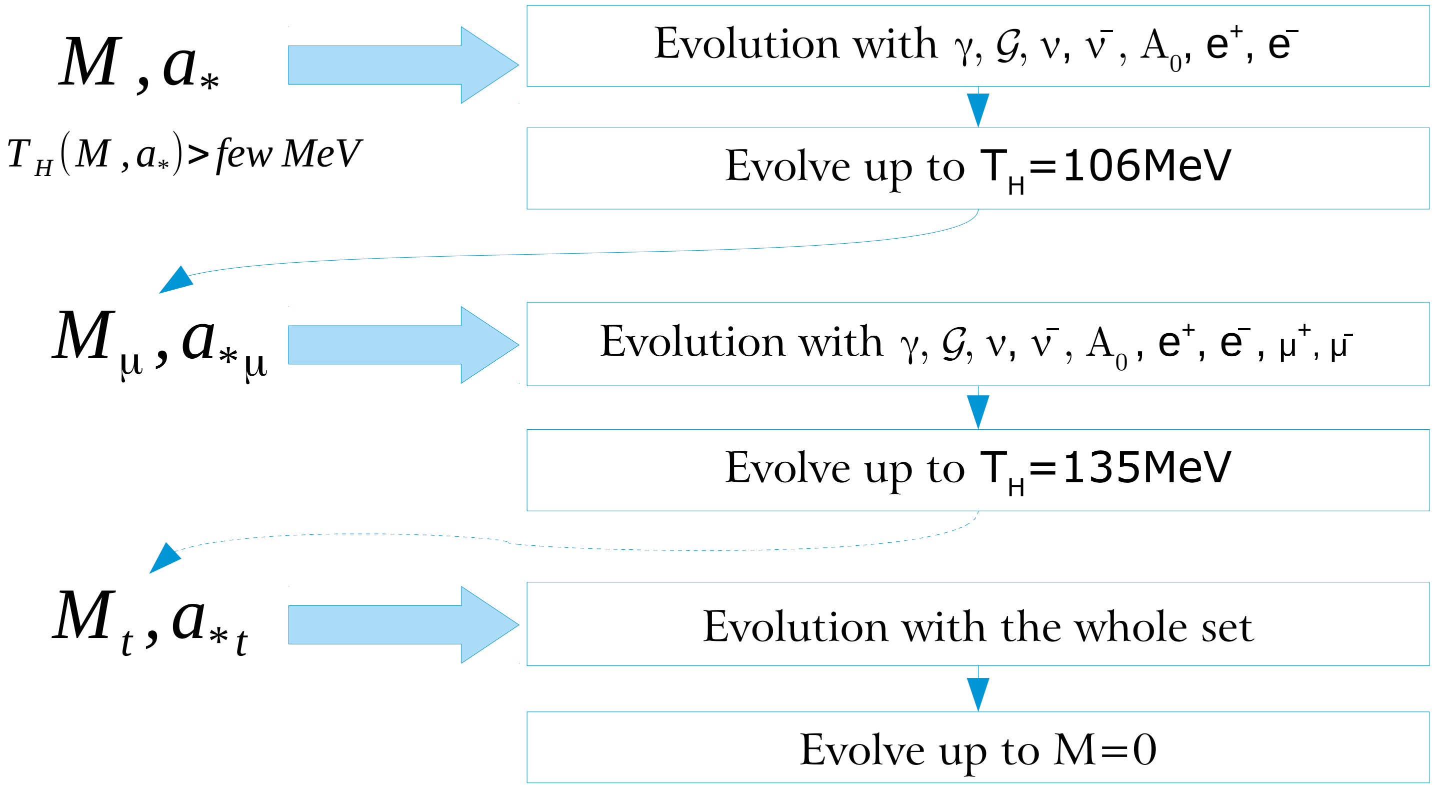
$$\left.\begin{aligned} f_{tot} &= n_0\ f_0 + n_{1/2}\ f_{1/2} + n_1\ f_1 + n_{3/2}\ f_{3/2} + n_2\ f_2 \\ g_{tot} &= n_0\ g_0 + n_{1/2}\ g_{1/2} + n_1\ g_1 + n_{3/2}\ g_{3/2} + n_2\ g_2 \end{aligned}\right\} \longrightarrow h_{tot}$$

Evaporating BH: **M↓** & **T_H↑** → emitted particle **set changes**!!!

Particles emission with **m > T_H** is exponentially **suppressed**

Approximation: particles are considered **massless** for **m < T_H** and are **otherwise absent** from the emission spectrum.

Set up of our description



M, a_*

$T_H(M, a_*) > few\ MeV$

Evolution with $\gamma, \mathcal{G}, \nu, \bar{\nu}, A_0, e^+, e^-$

Evolve up to T_H=106MeV

$M_\mu, a_{*\mu}$

Evolution with $\gamma, \mathcal{G}, \nu, \bar{\nu}, A_0, e^+, e^-, \mu^+, \mu^-$

Evolve up to T_H=135MeV

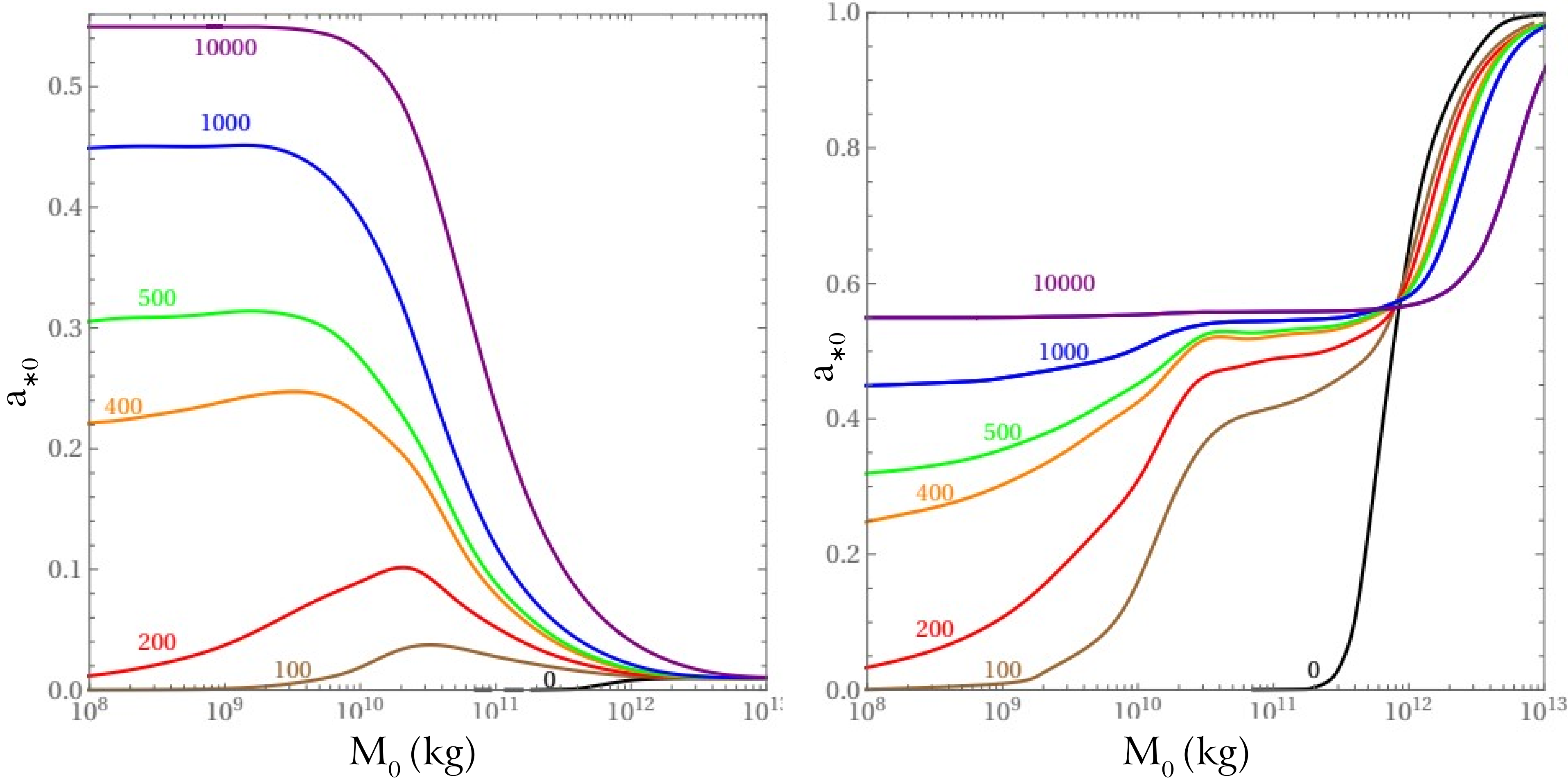
M_t, a_{*t}

Evolution with the whole set

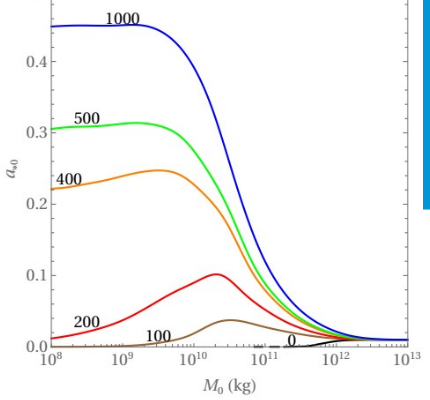
Evolve up to M=0

String Axiverse → N_a scalars field in addition to the SM particles and the graviton.

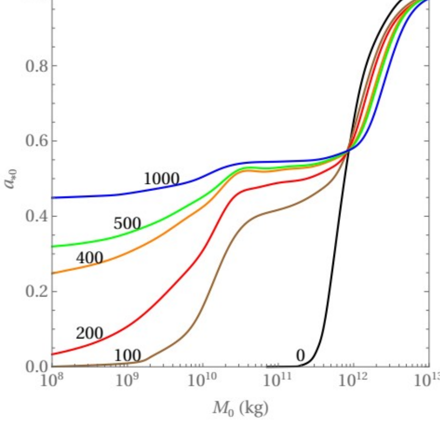
Axiverse fingerprint in PBHs evaporation



Present PBH spin, a_{*0}, as a function of their present mass, M_0, for an initial population with spin $a_* = 0.01, 0.99$ and varying mass. Curves labeled by number of light ALPs.



Why is this so interesting?



ALPs → **cosmological** and **astrophysical effects** → **signatures** of **individual** axions (mass ranges), **not** of the **whole** ‘string **axiverse**’.

The **PBH spin distribution** from **evaporation** process in the presence of **many light scalar** fields **cannot**, to our knowledge, be **mimicked** by other processes → **unique signature** of an **underlying theory** with a large number of light scalars.

Hot Dark Radiation

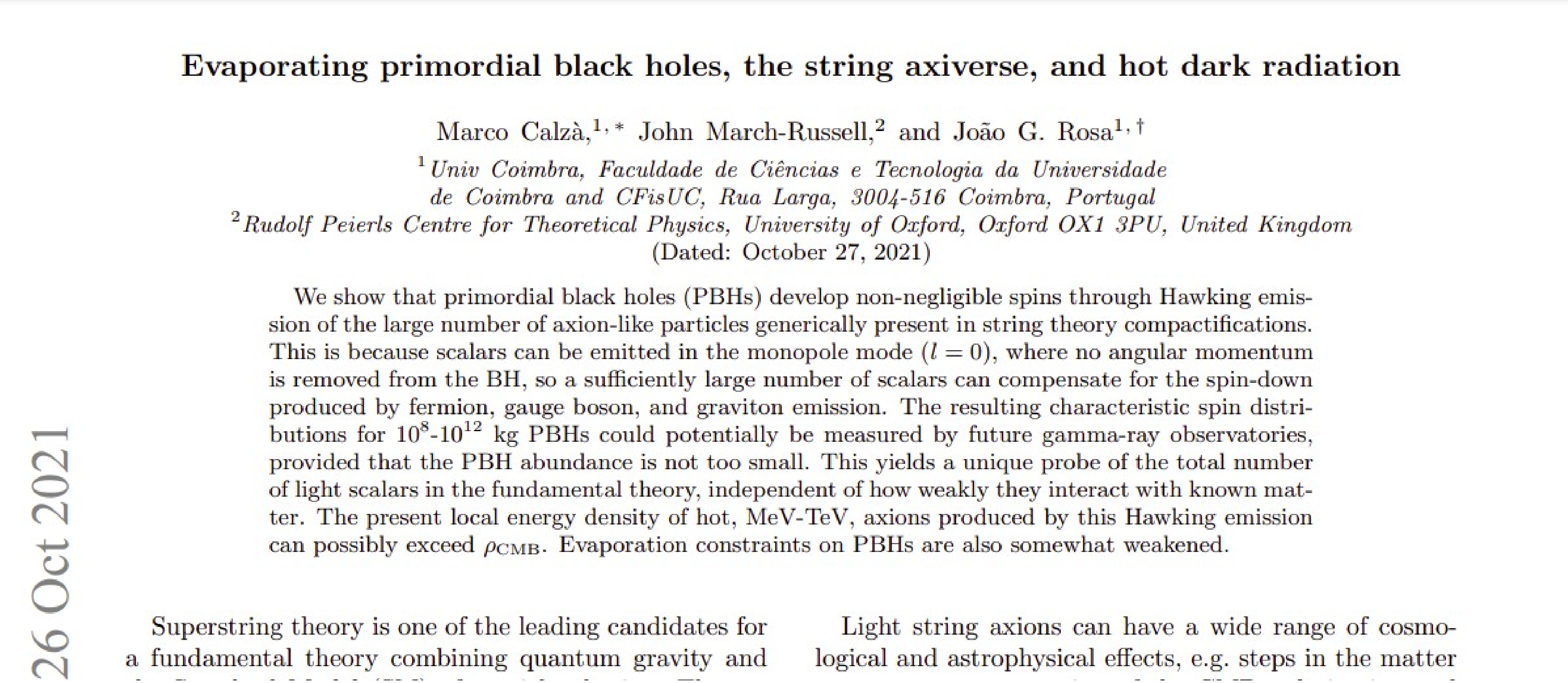
Integrated flux of ALPs from a single PBH in the relevant PBH spin range

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

- ➔ 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.

References



Evaporating primordial black holes, the string axiverse, and hot dark radiation

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(Dated: October 27, 2021)

We show that primordial black holes (PBHs) develop non-negligible spins through Hawking emission of the large number of axion-like particles generically present in string theory compactifications. This is because scalars can be emitted in the monopole mode ($l = 0$), where no angular momentum is removed from the BH, so a sufficiently large number of scalars can compensate for the spin-down produced by fermion, gauge boson, and graviton emission. The resulting characteristic spin distributions for 10^8-10^{12} kg PBHs could potentially be measured by future gamma-ray observatories, provided that the PBH abundance is not too small. This yields a unique probe of the total number of light scalars in the fundamental theory, independent of how weakly they interact with known matter. The present local energy density of hot, MeV-TeV, axions produced by this Hawking emission can possibly exceed $\rho_{\rm CMB}$. Evaporation constraints on PBHs are also somewhat weakened.

26 Oct 2021

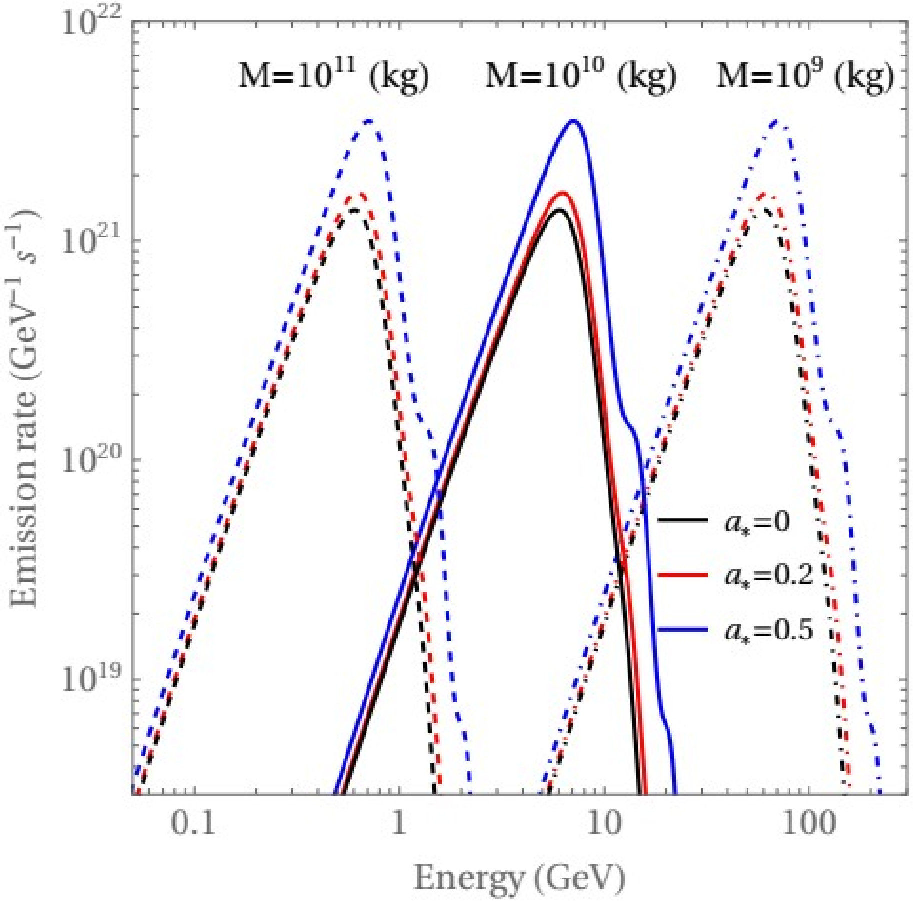
Superstring theory is one of the leading candidates for a fundamental theory combining quantum gravity and

Light string axions can have a wide range of cosmological and astrophysical effects, e.g. steps in the matter

Detectability

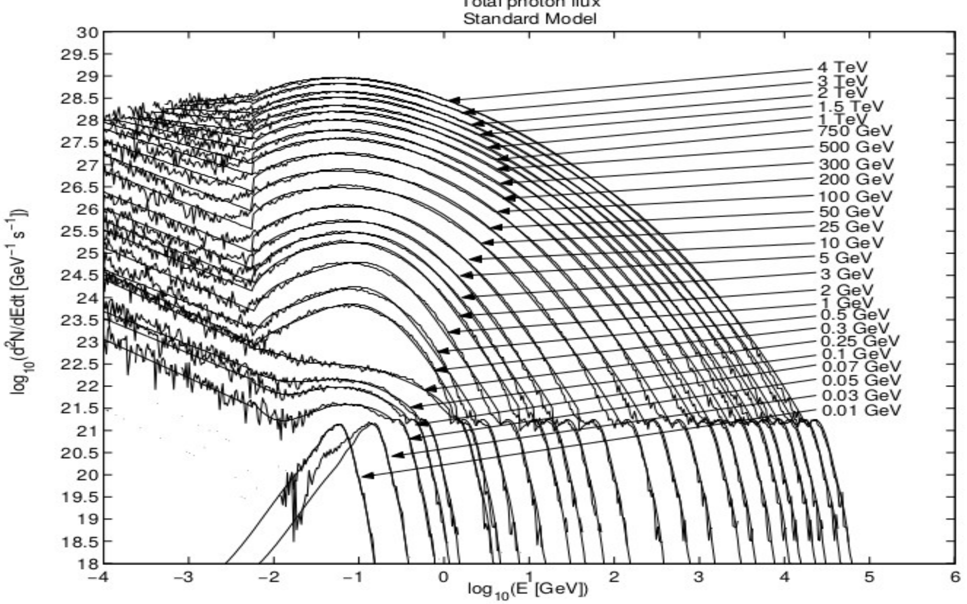
PBH primary photon emission rate:

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



- Peak position → M_0
- Peak hight → a_{*0}
- Measure PBH spins $a_{*0} > 0.1$ with at least a ~10% precision measurement (distance parallax)
- The time evolution of T_H is faster in the presence of many ALPs, than in the Na = 0 case.
- Similar effect for spin-1/2 → nontrivial dependence on the PBH mass and spin of the whole spectrum (next slides).

Detectability



- 2^{ry} flux dominates for PBHs ∈ [10^9-10^{11}] kg.

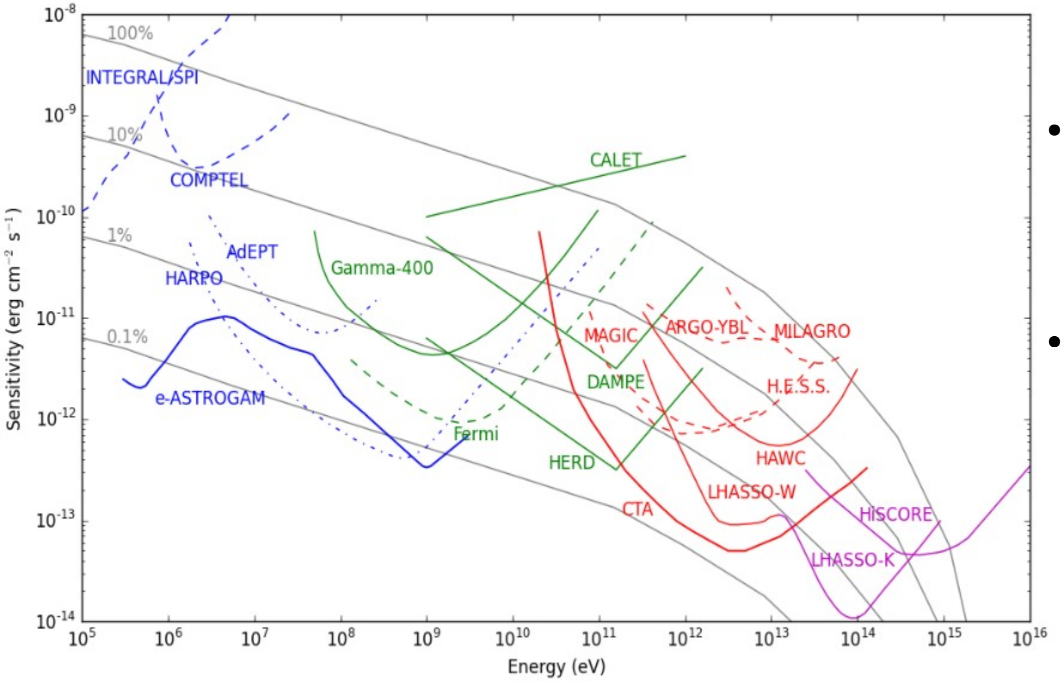
  J. H. MacGibbon et al (2015)

- 10^{10} kg PBHs γ-emission (1^{ry} & 2^{ry}) up to ~ 200 AU may be detectable!

  M. Ackermann et al.
  [Fermi-LAT] (2018)

- Present M_0 PBHs mean distance $d \sim 40\,AU\,(M_0/10^{10}\,kg)^{1/3}(10^{-7}/f_0)^{1/3}$, $\rho_{PBHs}=f_0\rho_{DM}$, $f_0\sim 10^{-7}$

PBHs present fraction f_0 of the local dark matter density

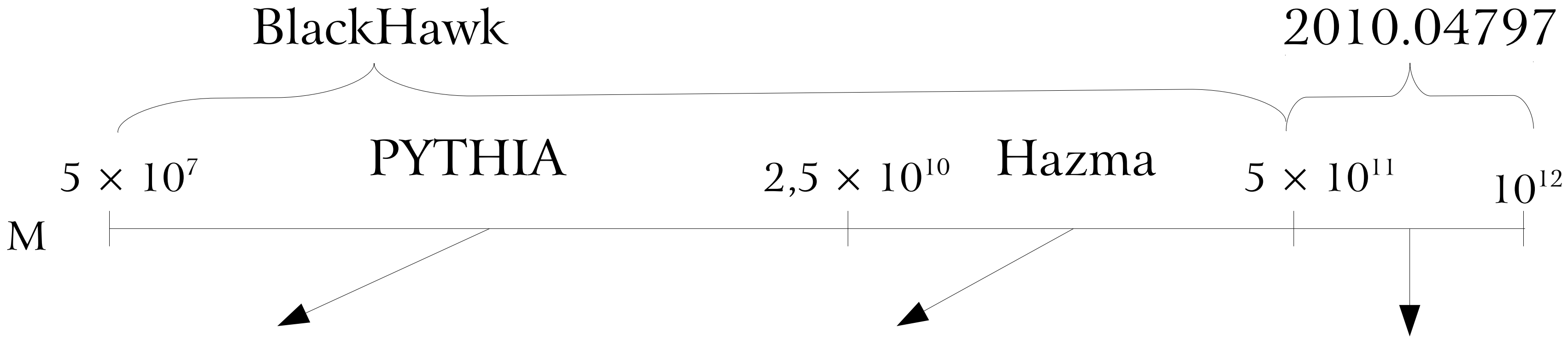


- Planned γ-ray observatories: HARPO, e-ASTROGAM in the energy range of 0.1-1GeV [J. Knödlseder (2016)].

- Improvement of a few orders of magnitude required if $f_0 << 10^{-7}$, or for an accurate determination of the PBH mass and spin.

Distant independent meaurment of M and a*

$M \in [10^{12}, 5 \times 10^{7}]$ kg and $a^* \in [0, 0.5]$ ⇨ $T \in [10$ MeV, 200 GeV$]$.



BlackHawk

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PYTHIA

Hazma

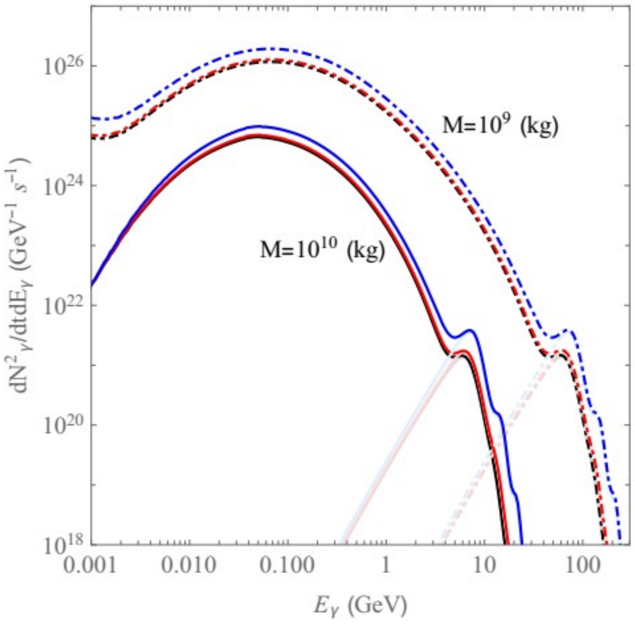
M

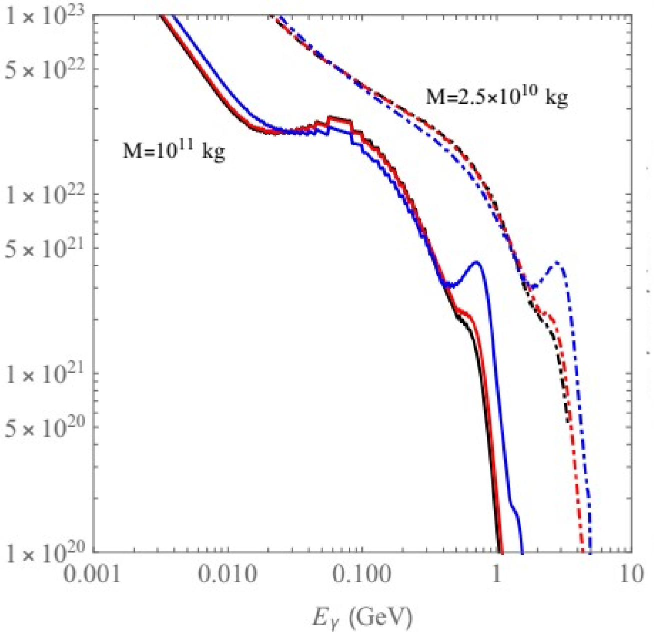
5×10^{7}

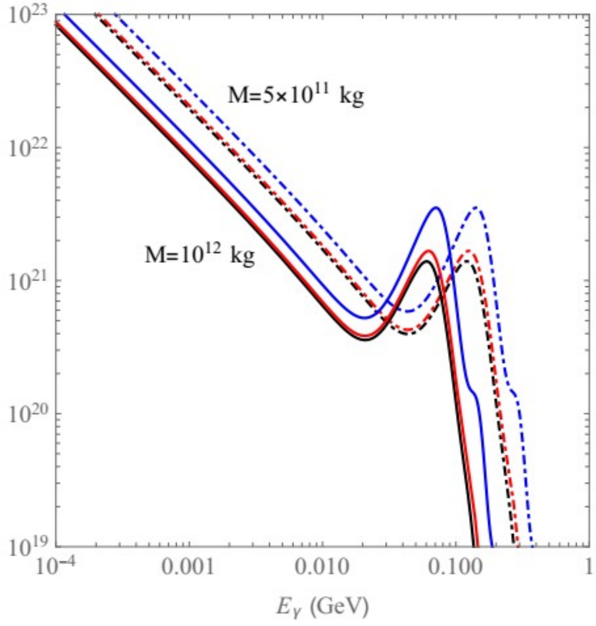
$2{,}5 \times 10^{10}$

5×10^{11}

10^{12}







Distant independent meaurment of M and a*

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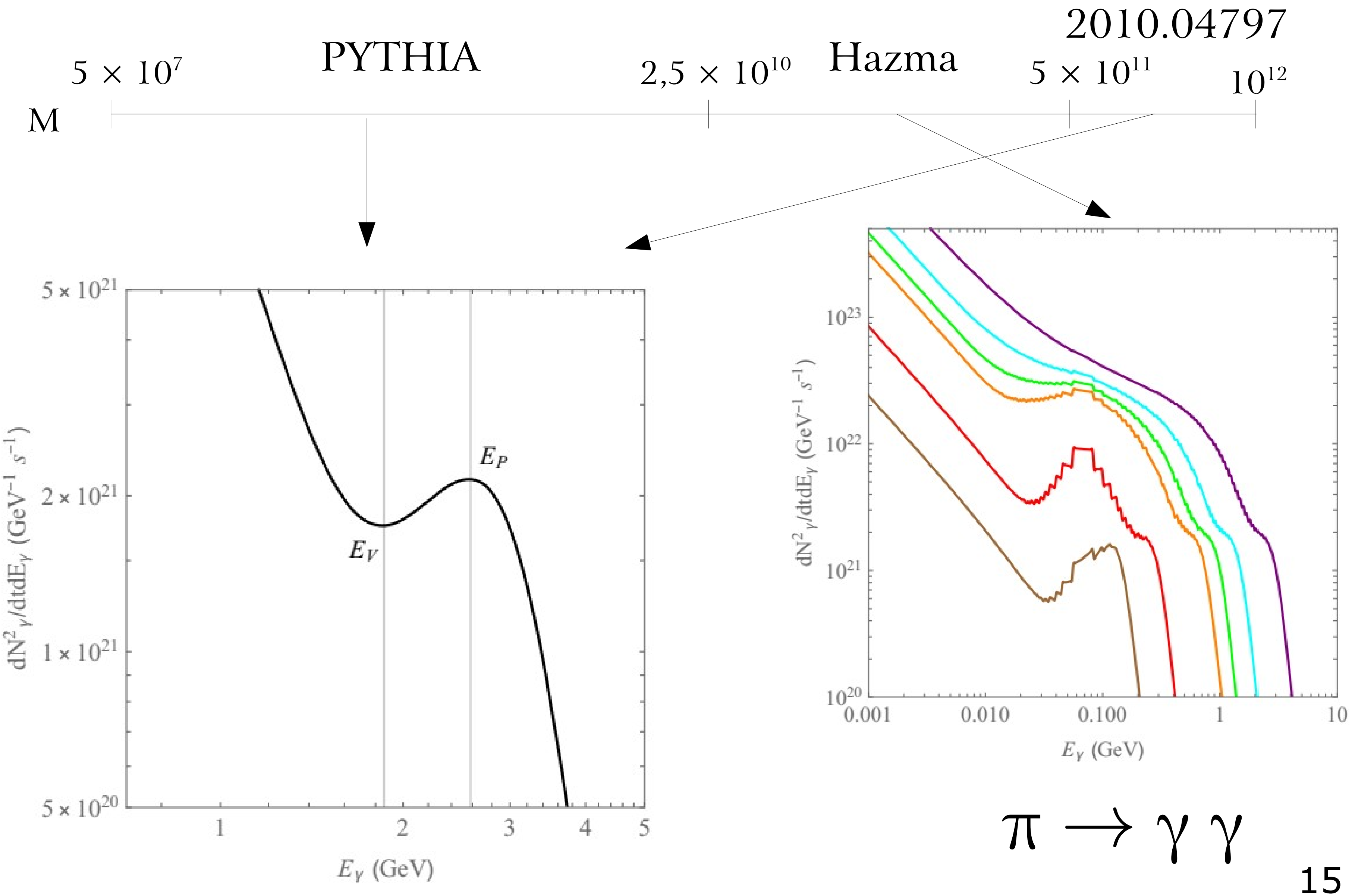

$\pi \rightarrow \gamma\,\gamma$

Distant independent meaurment of M and a*

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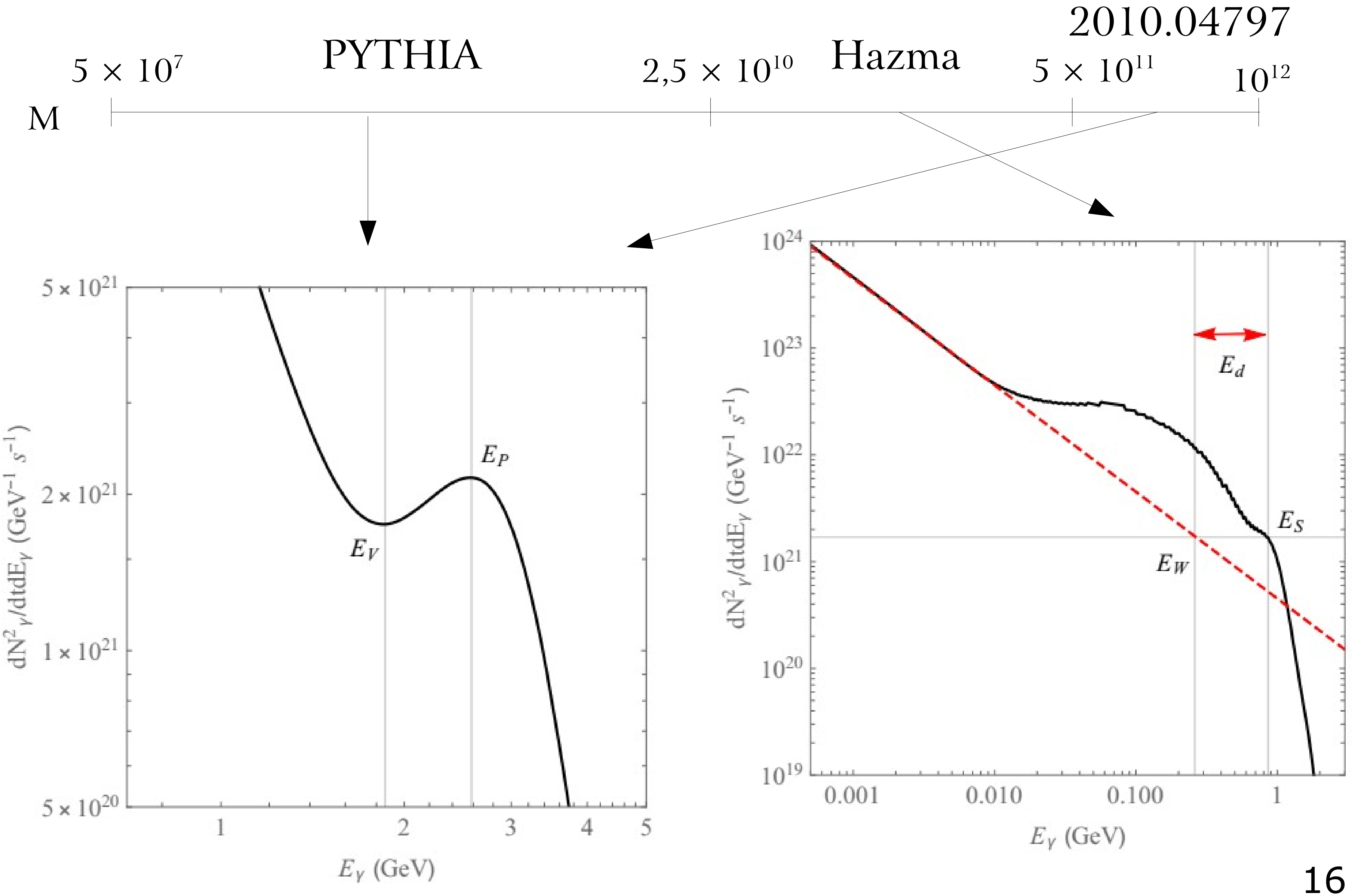

M

5×10^7 PYTHIA $2{,}5 \times 10^{10}$ Hazma 5×10^{11} 10^{12}

Low mass region

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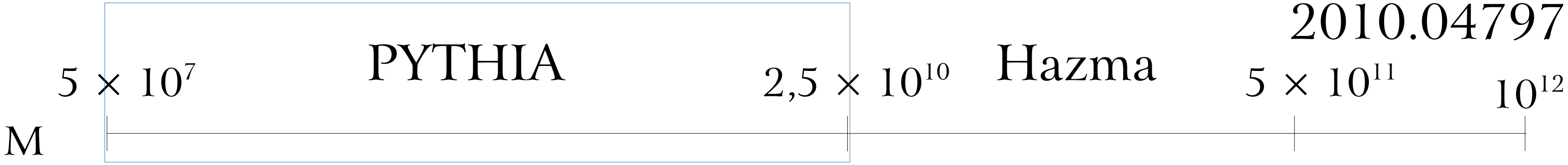
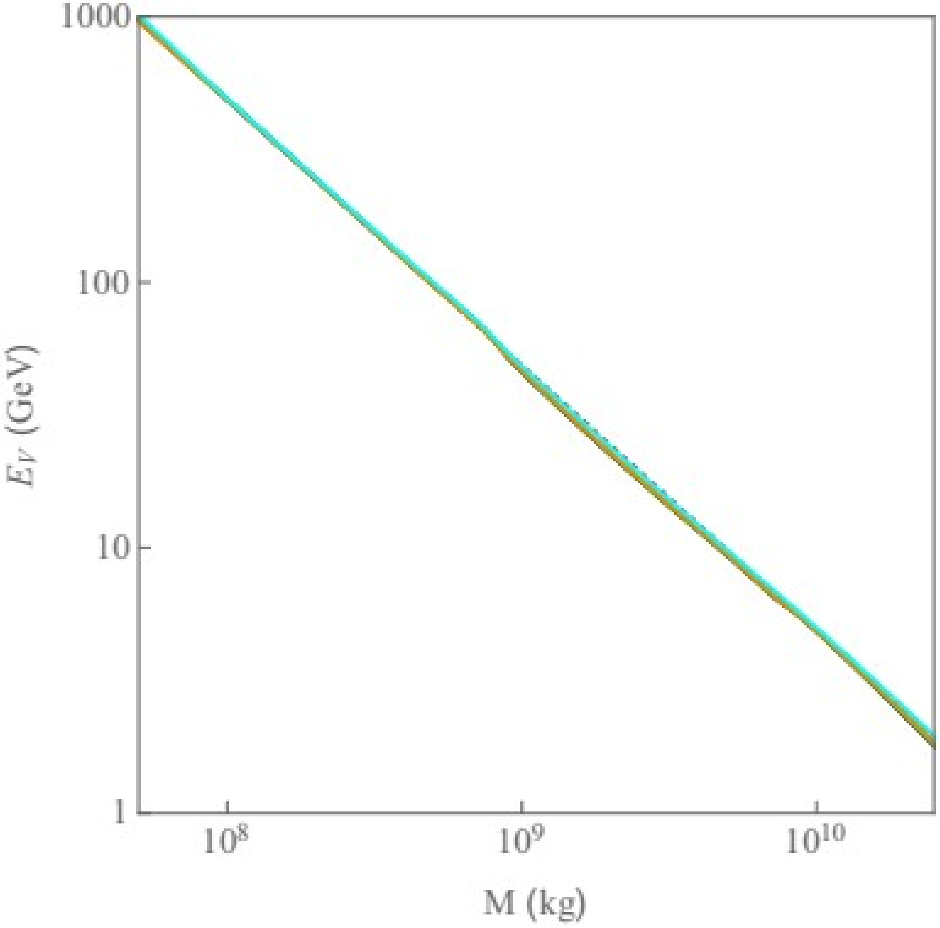
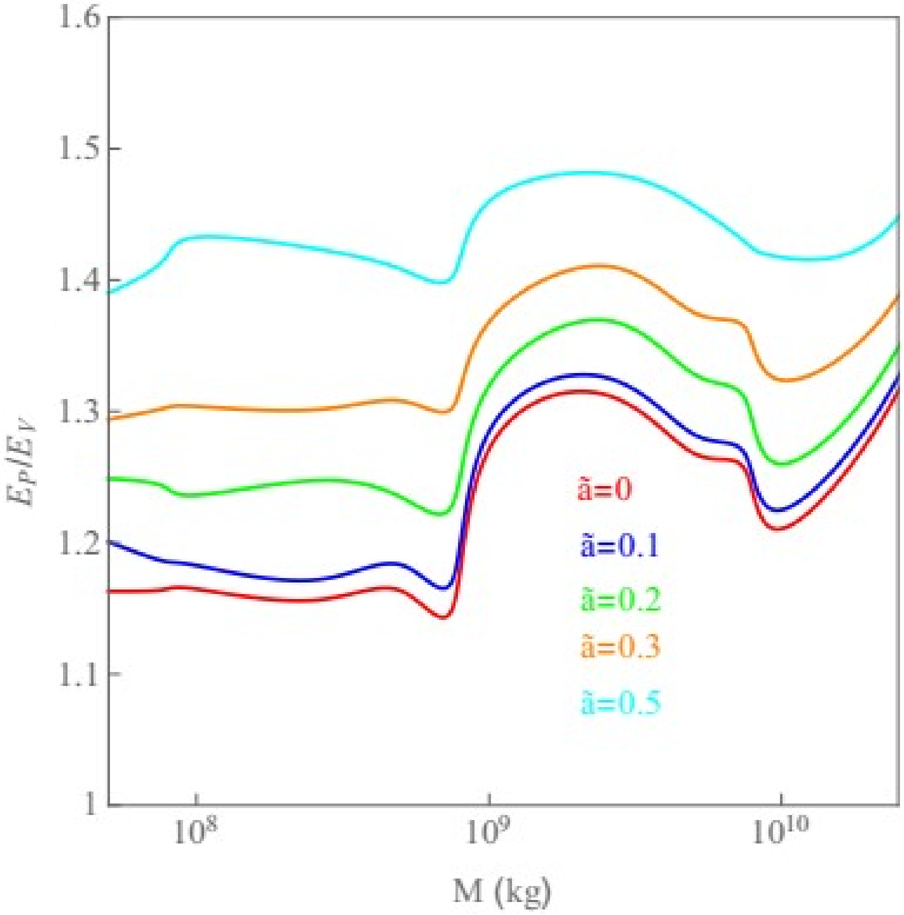
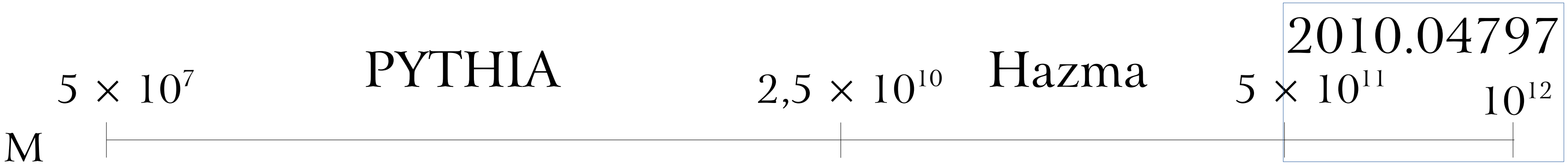






High mass reagion



M

5×10^7

PYTHIA

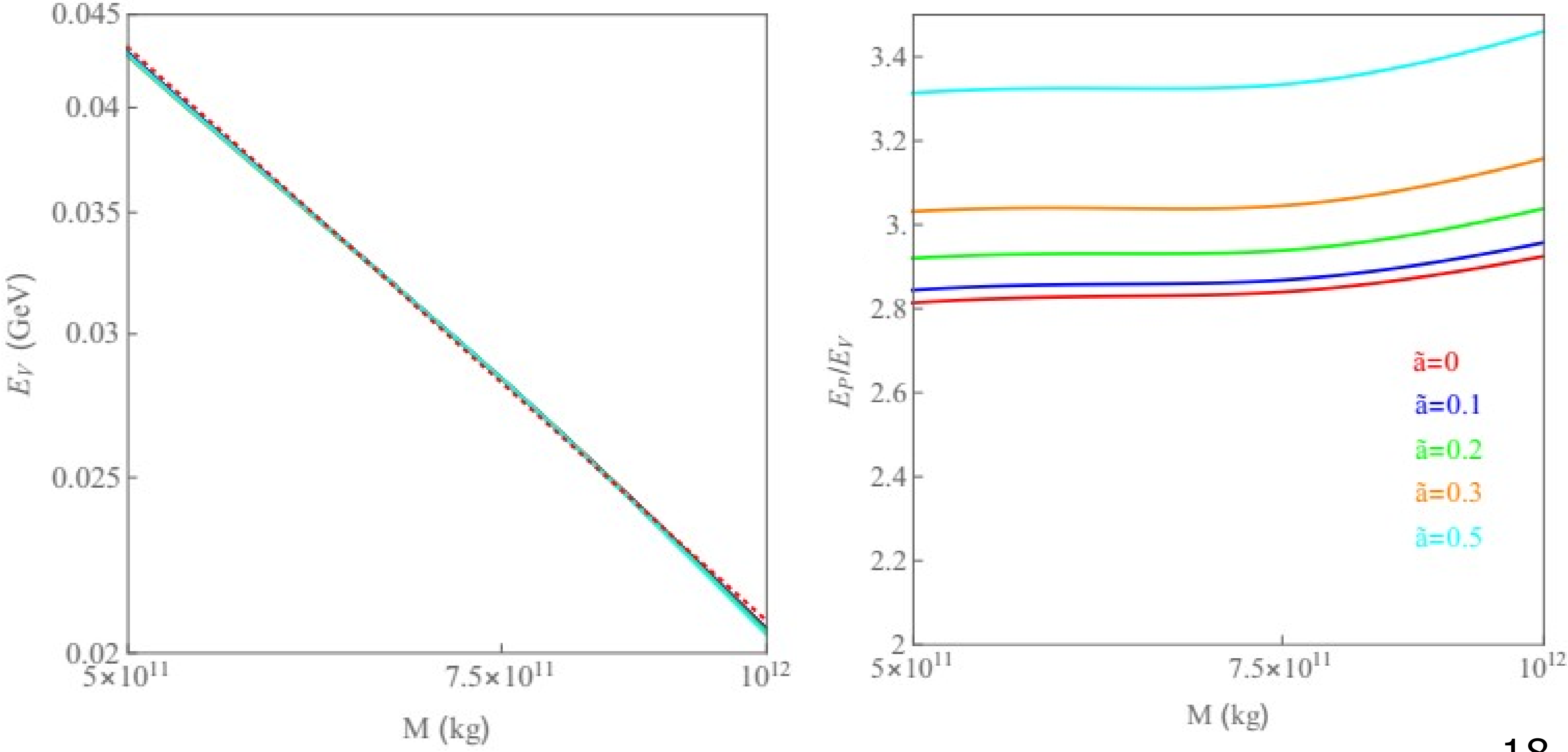
$2{,}5 \times 10^{10}$

Hazma

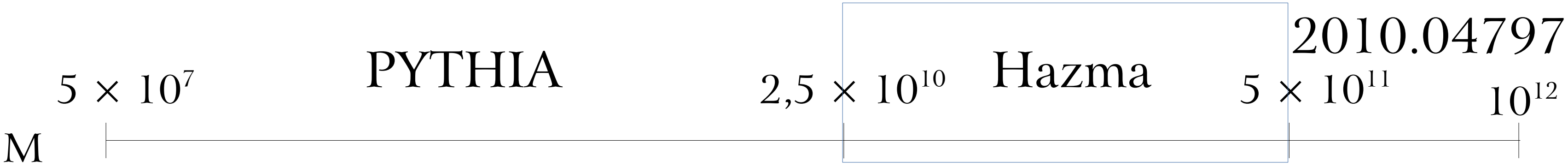
5×10^{11}

2010.04797

10^{12}



Intermediate mass region



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PYTHIA

Hazma

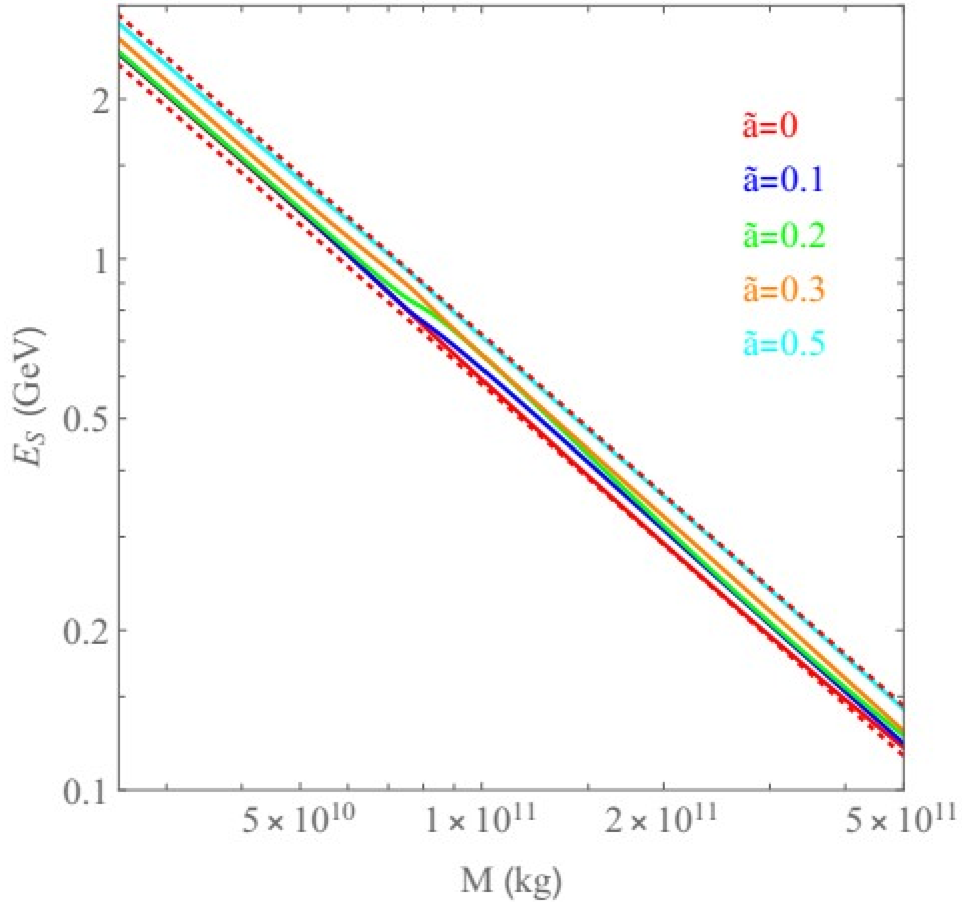
M

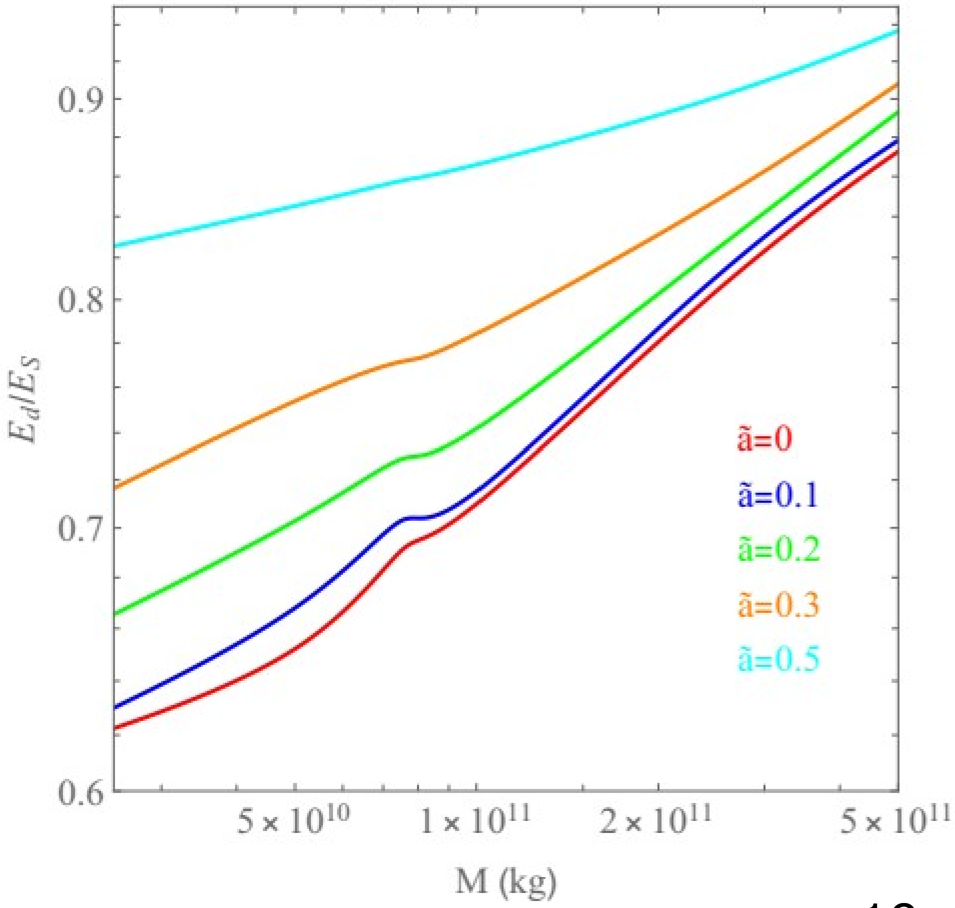
5×10^{7}

$2{,}5 \times 10^{10}$

5×10^{11}

10^{12}





Why is this so interesting?

➔ EM radiation is the most probable source of information

➔ Knowing the distance of a PBH may be a difficult task

➔ M and a* are known → theoretically have the PBH photon-flux

Compare it with the experimental one → distance

...Next weeks on the Arxiv...

How to go Beyond GR?

$$\nabla^{\mu}\nabla_{\mu}\Phi=0 \quad \Rightarrow \quad \frac{1}{\sqrt{-g}}\partial^{\mu}\left(\sqrt{-g}\,g_{\mu\nu}\partial^{\nu}\right)\Phi=0 \quad \Rightarrow \quad \cdots$$

Take a mertic not vacuum solution of GR

Simpson-Visser:

$$ds^2=-\left(1-\frac{r_S}{\sqrt{\tilde{r}^2+\ell^2}}\right)dt^2+\left(1-\frac{r_S}{\sqrt{\tilde{r}^2+\ell^2}}\right)^{-1}d\tilde{r}^2+\left(\tilde{r}^2+\ell^2\right)\left(d\theta^2\sin^2(\theta)\,d\phi^2\right)$$

Adding rotation

Kerr-black-bounce: $r=\sqrt{\tilde{r}^2+\ell^2}$

$$ds^2=-\left(1-\frac{2Mr^2}{\Sigma}\right)dt^2+\frac{\Sigma}{\delta\Delta}dr^2+\Sigma d\theta^2+\frac{A\sin^2\theta}{\Sigma}d\phi^2-\frac{4Mar\sin^2\theta}{\Sigma}dtd\phi.$$

$$\Sigma=r^2+a^2\cos^2\theta, \qquad \Delta=r^2+a^2-2Mr, \qquad A=(r^2+a^2)^2-\Delta a^2\sin^2\theta, \qquad \delta=1-\frac{\ell^2}{r^2}$$

The Kerr-black-bounce metric

➔ $\ell = 0$ → Kerr metric.

➔ $\ell > r_+$ → A wormhole throat at a larger radial value with respect to the coordinate singularity of the event horizon → WH

➔ $\ell < r_+$ → A wormhole is enclosed in the event horizon → BH

If $0 < \ell < r_-$ Regular BH with event and inner Cauchy horizons.

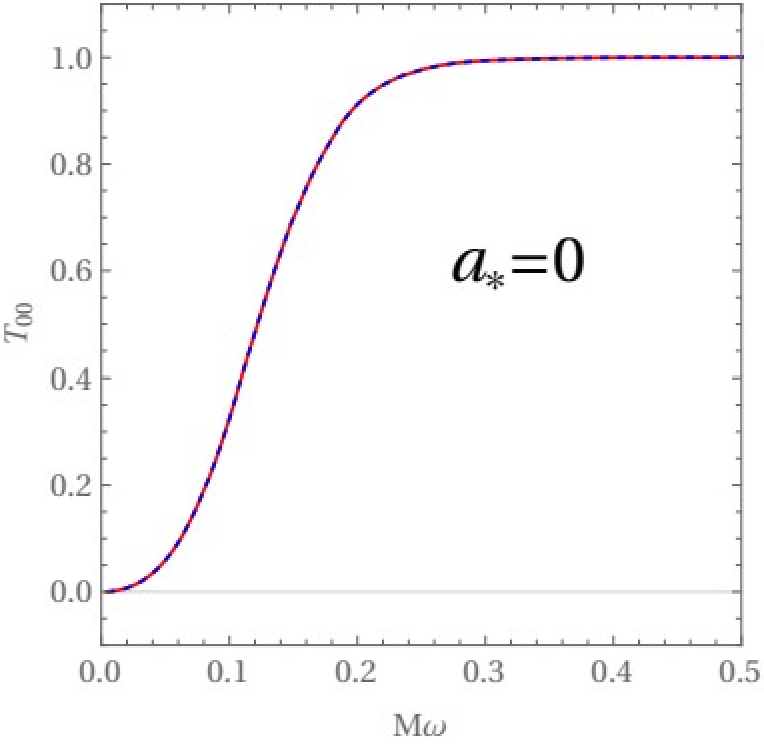
If $r_- < \ell < r_+$ the inner horizon is absent (avoids instabilities and mass inflation problems).

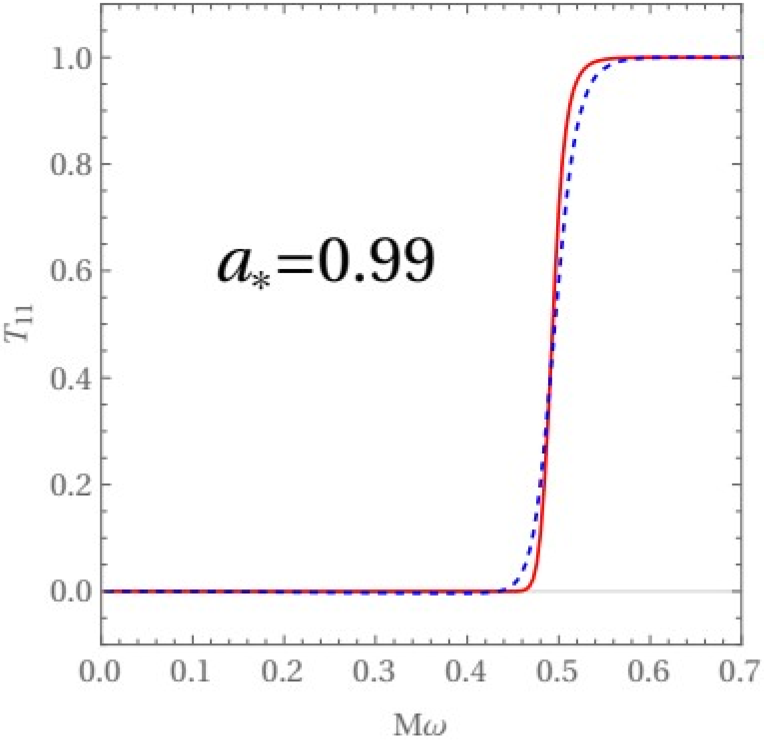
Allows a nearly maximal value of $\boldsymbol{\ell = 0.99}$ for which the Kerr-bb mostly differs from a Kerr BH and still describes a BH.

$$\nabla^{\mu}\nabla_{\mu}\Phi=0 \quad\Rightarrow\quad \frac{1}{\sqrt{-g}}\partial^{\mu}\left(\sqrt{-g}\,g_{\mu\nu}\partial^{\nu}\right)\Phi=0 \quad\Rightarrow\quad \cdots$$

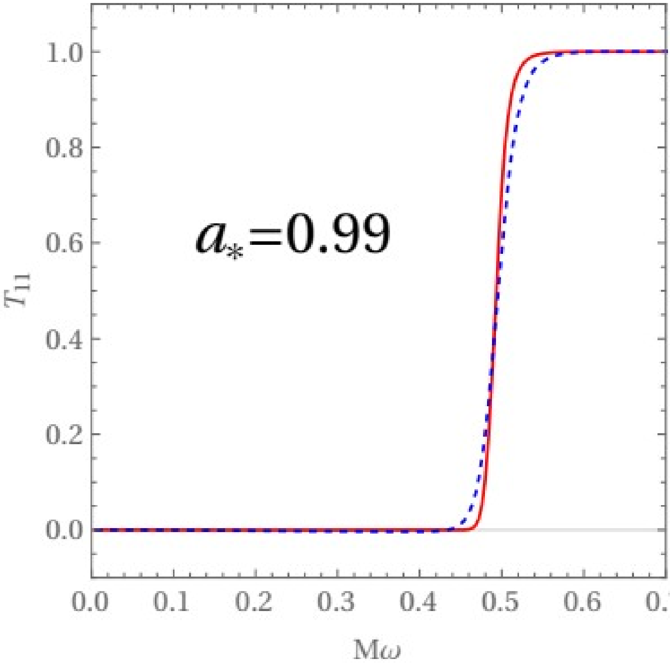
$$\sqrt{\delta}\frac{d}{dr}\left(\sqrt{\delta}\Delta\frac{dR_{lm}}{dr}\right)+\left(\frac{K^2}{\Delta}+2am\omega-a^2\omega^2-A_{lm}\right)R_{lm}=0, \longrightarrow \Gamma^{s}_{l,m}(\omega)$$

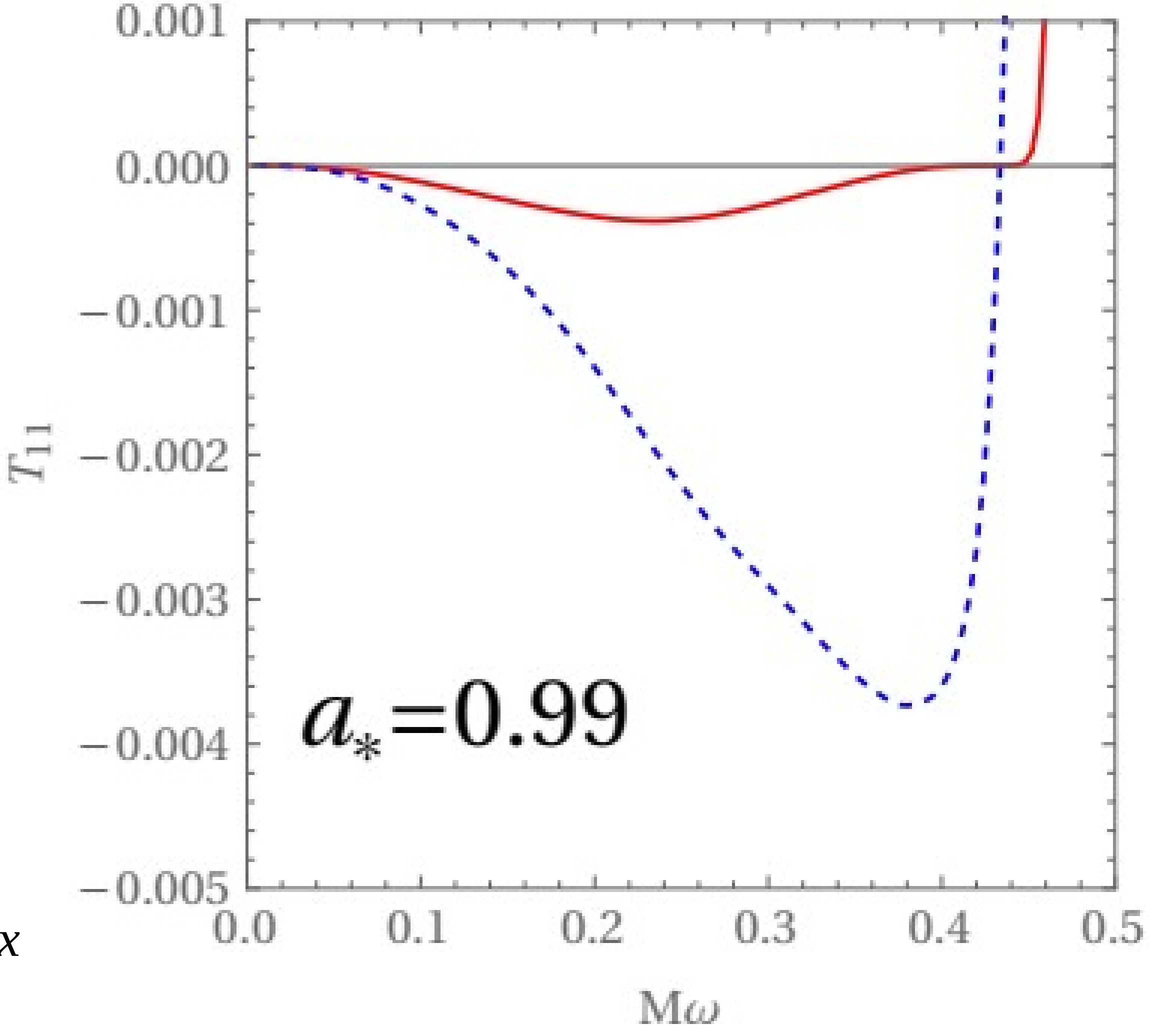
Differences in the GBFs





Differences in the GBFs

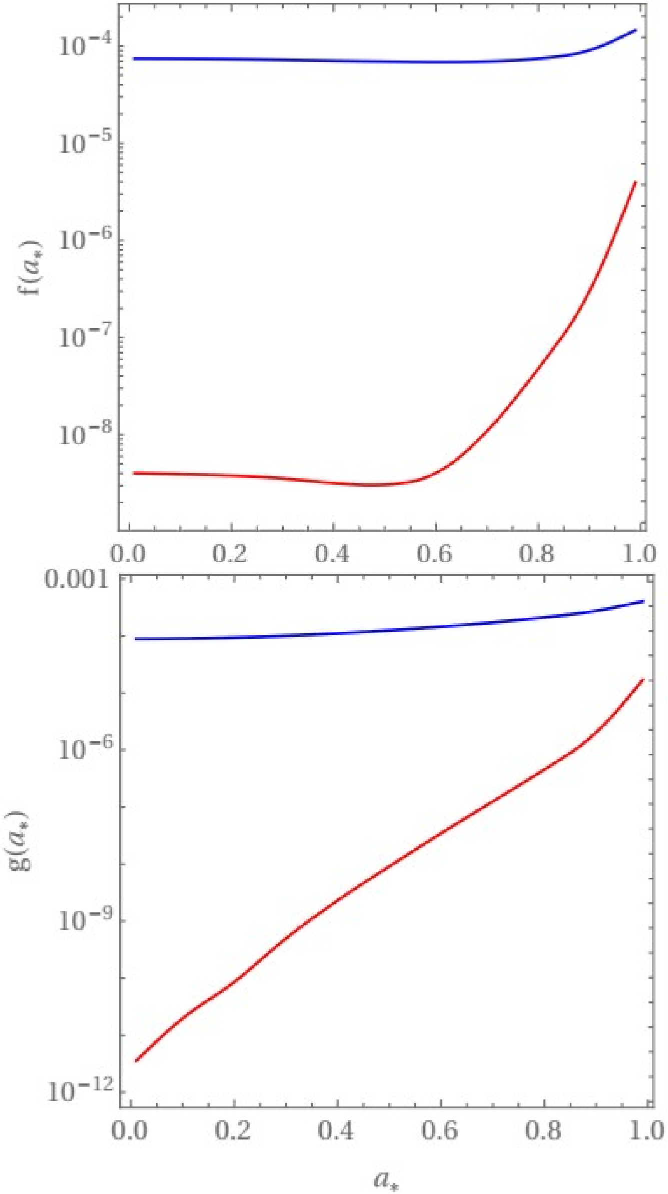




$$\begin{pmatrix} f_0 \\ g_0 \end{pmatrix} = \frac{1}{2\pi} \sum_{p,l,m} \int_0^\infty \frac{\Gamma^0_{l,m}(\omega)}{\left(e^{\frac{2k\pi}{\kappa}} - 1\right)} \begin{pmatrix} x \\ m a_*^{-1} \end{pmatrix} dx$$

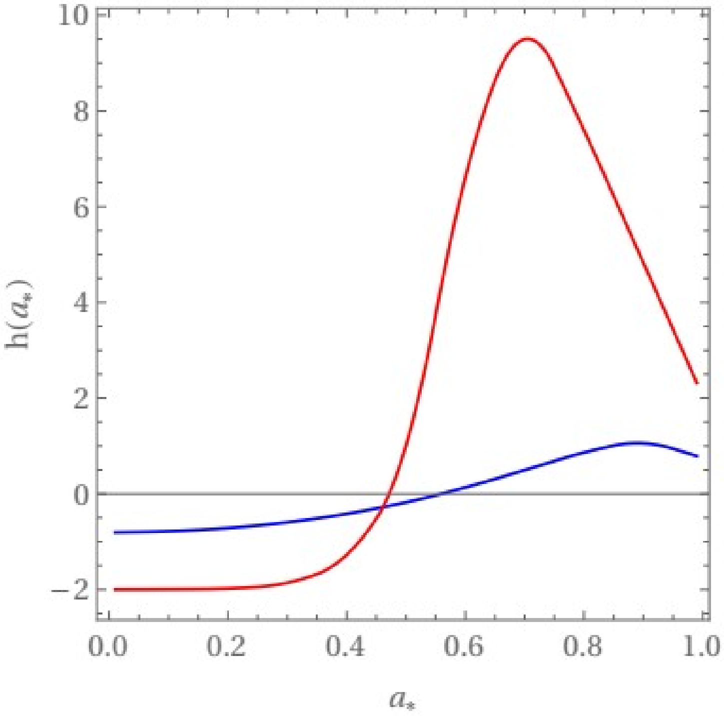
$$x = \omega M$$

Depleting functions

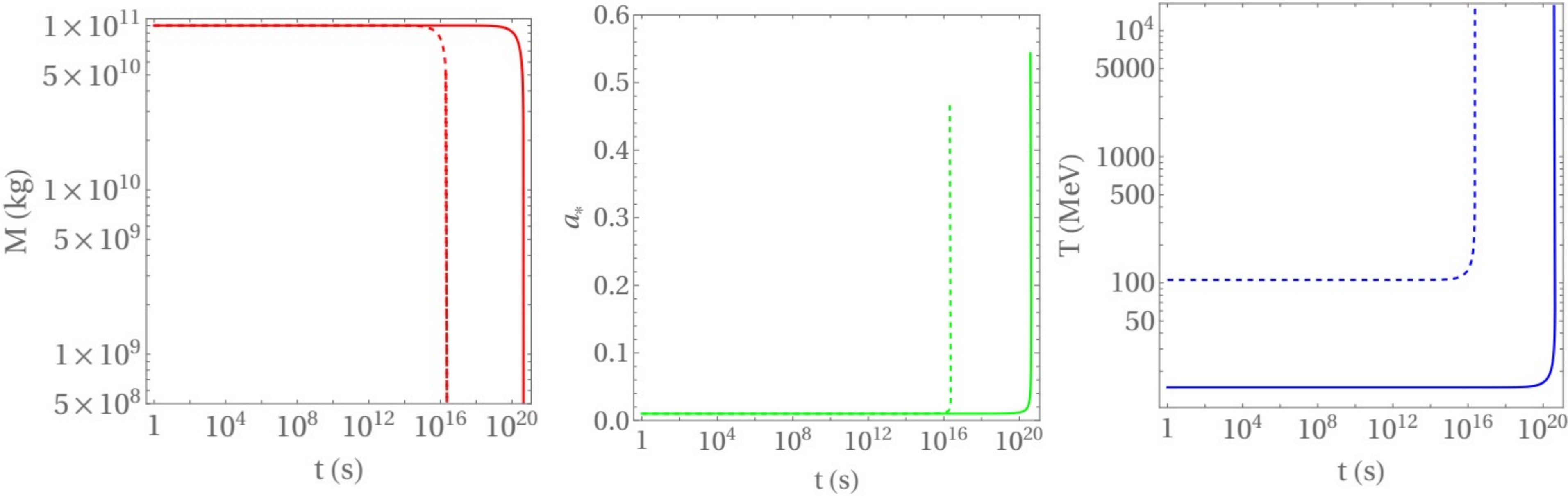


$$\begin{pmatrix} f_0 \\ g_0 \end{pmatrix} = \frac{1}{2\pi} \sum_{p,l,m} \int_0^\infty \frac{\Gamma^0_{l,m}(\omega)}{\left(e^{\frac{2k\pi}{\kappa}} - 1\right)} \begin{pmatrix} x \\ m\, a_*^{-1} \end{pmatrix} dx$$

$$\kappa = \sqrt{\frac{r_H^2}{r_H^2 + \ell^2}} \sqrt{1 - a_*^2}/2r_+$$

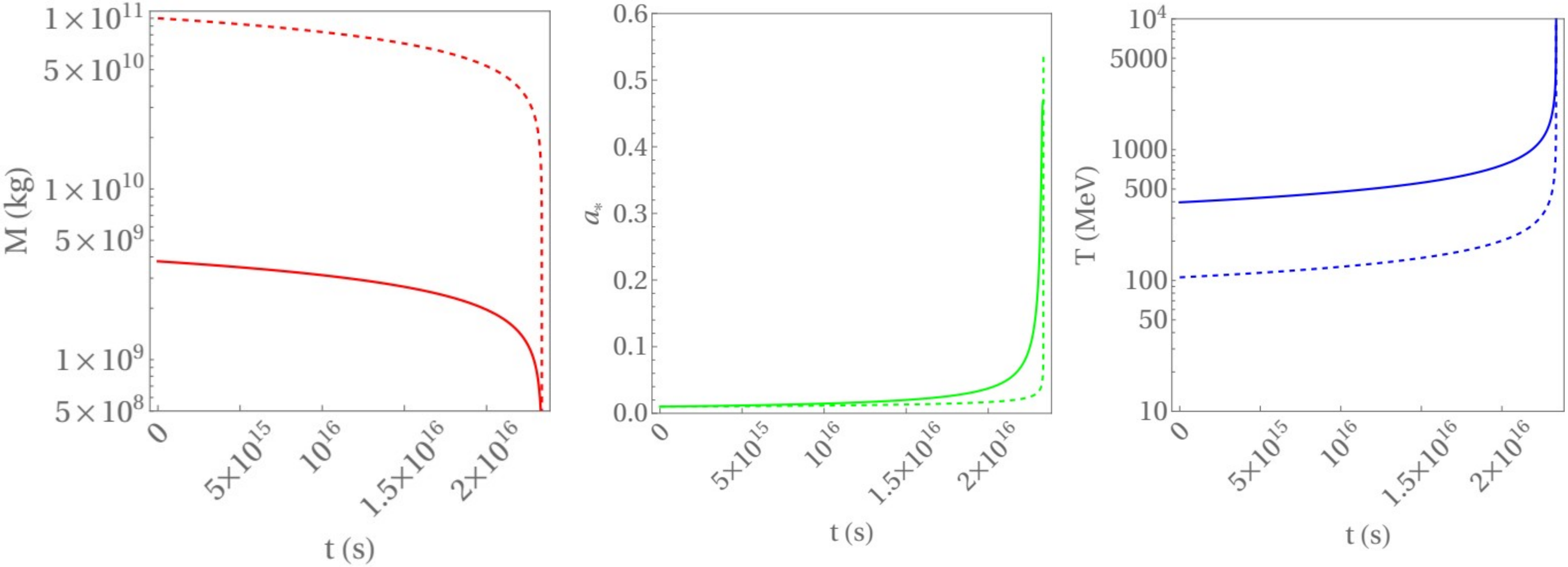


Same M evolutions



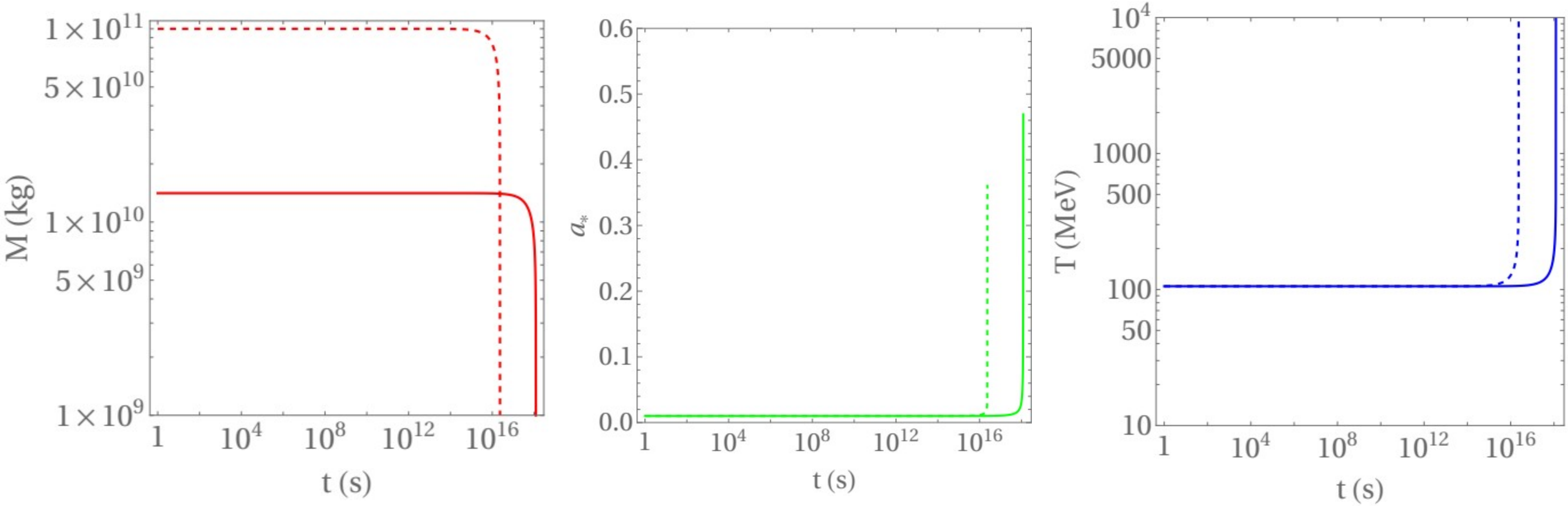
Solid Kerr BH Dashed Kerr-b-b BH

Same life-time evolutions



Solid Kerr BH   Dashed Kerr-b-b BH

Same T evolutions

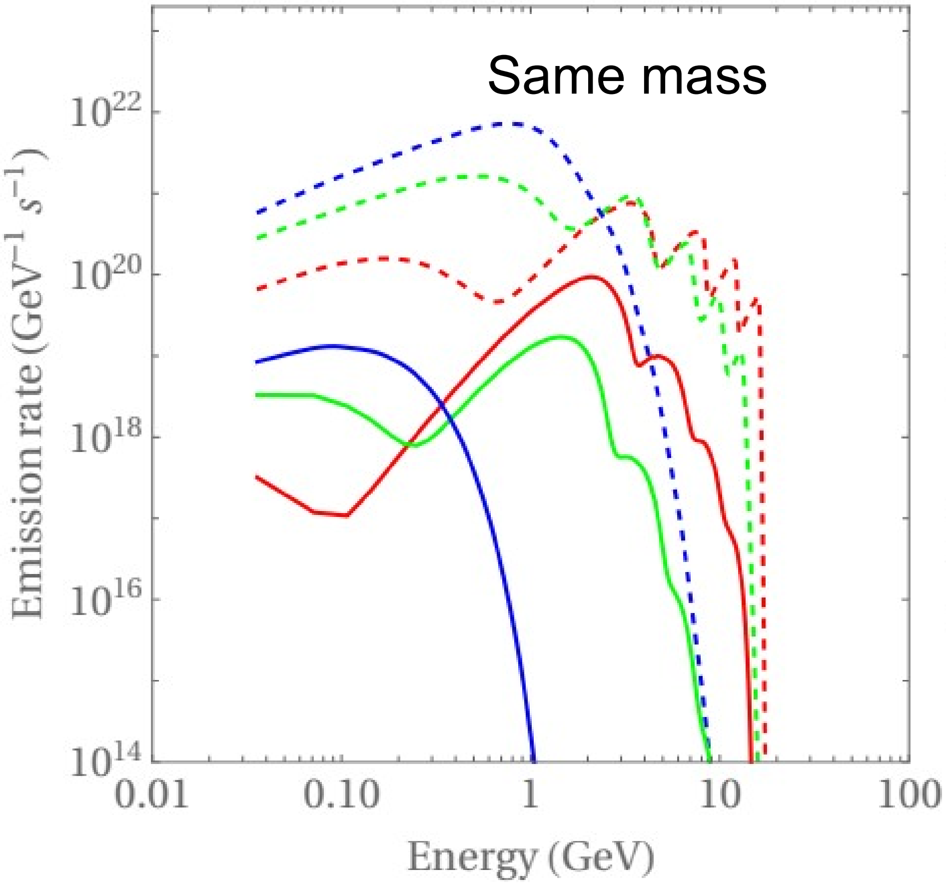


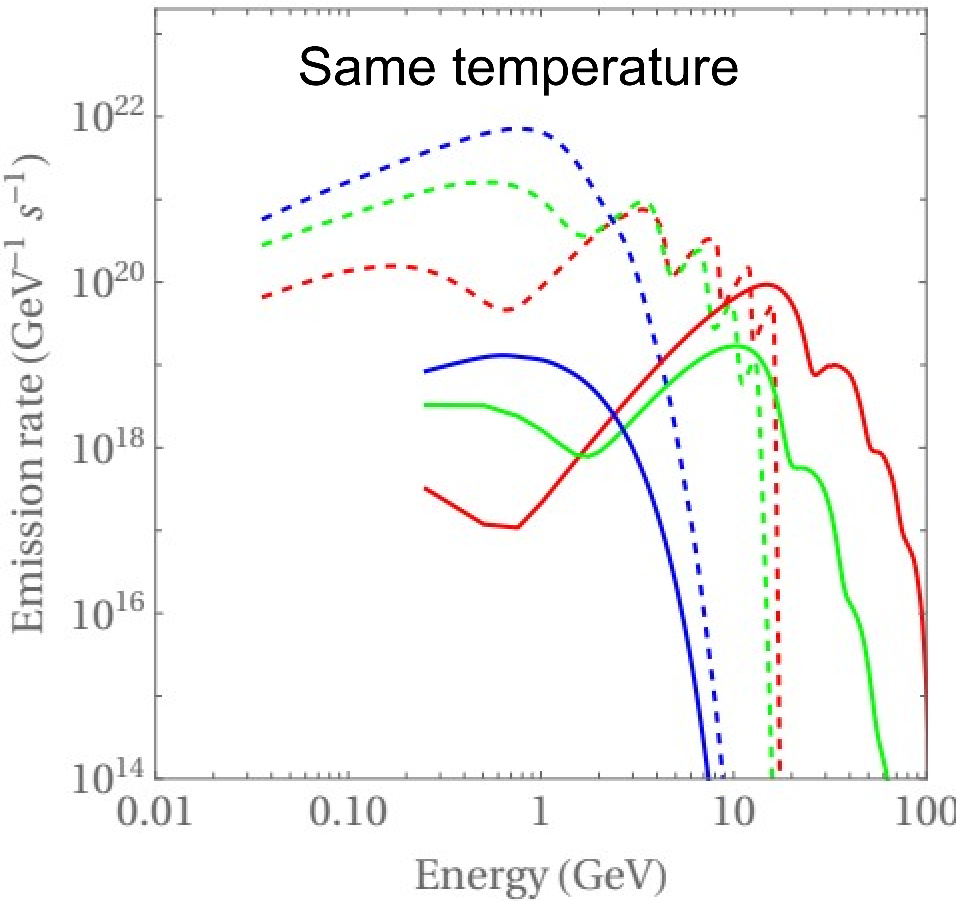
Solid Kerr BH Dashed Kerr-b-b BH

Primary scalar emission

$$\frac{d^2N}{dtdE} = \frac{1}{2\pi}\sum_{l,m}\frac{T_{l,m}(\omega)}{e^{2\pi k/\kappa}-1} \,.$$

$$\kappa = \sqrt{\frac{r_H^2}{r_H^2+\ell^2}}\sqrt{1-a_*^2}/2r_+$$



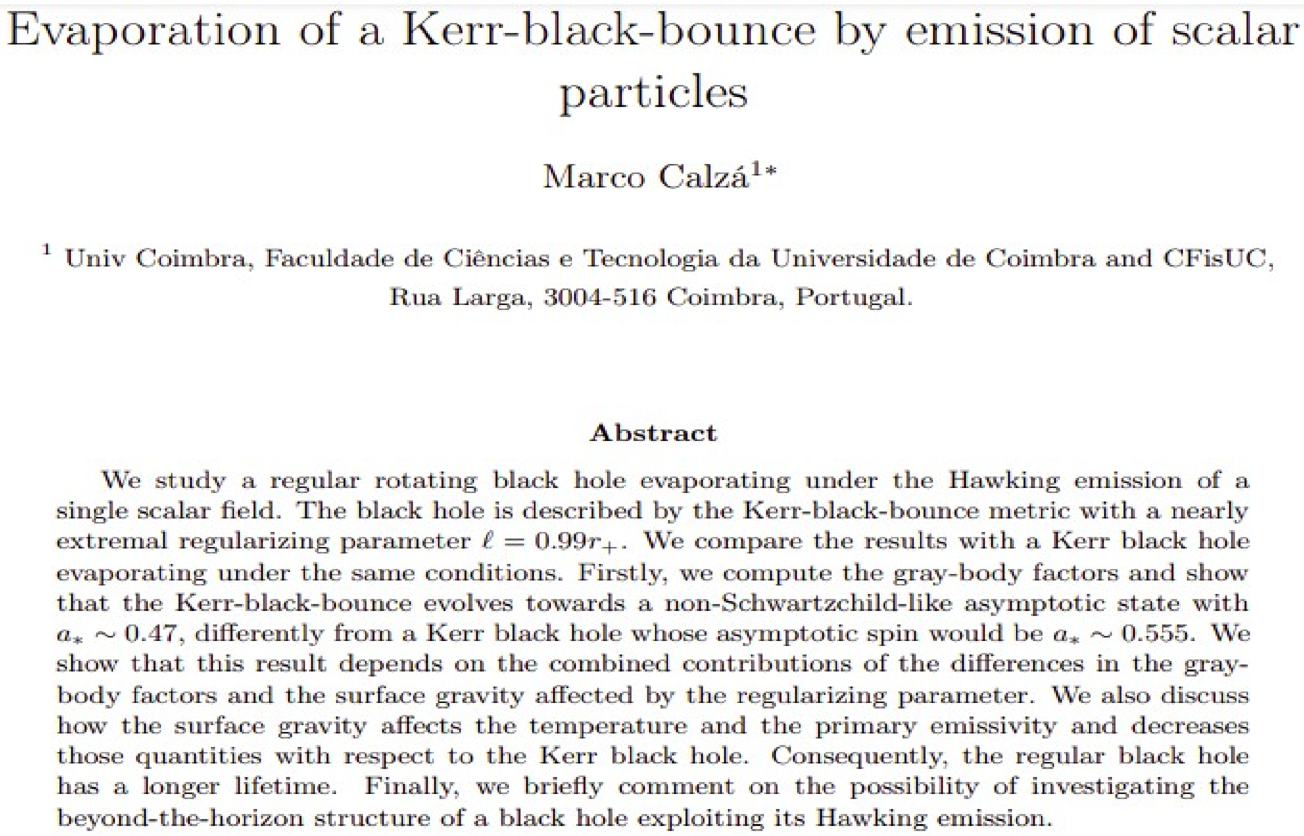


Why is this so interesting?

BH structure → Event Horizon (Bogoliubov transf.) → cause differences in the Hawking emission.

No information is coming from inside the EH but in a certain sense you can look inside with out looking inside!!!

References



Evaporation of a Kerr-black-bounce by emission of scalar particles

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Abstract

We study a regular rotating black hole evaporating under the Hawking emission of a single scalar field. The black hole is described by the Kerr-black-bounce metric with a nearly extremal regularizing parameter $\ell = 0.99r_+$. We compare the results with a Kerr black hole evaporating under the same conditions. Firstly, we compute the gray-body factors and show that the Kerr-black-bounce evolves towards a non-Schwartzchild-like asymptotic state with $a_* \sim 0.47$, differently from a Kerr black hole whose asymptotic spin would be $a_* \sim 0.555$. We show that this result depends on the combined contributions of the differences in the gray-body factors and the surface gravity affected by the regularizing parameter. We also discuss how the surface gravity affects the temperature and the primary emissivity and decreases those quantities with respect to the Kerr black hole. Consequently, the regular black hole has a longer lifetime. Finally, we briefly comment on the possibility of investigating the beyond-the-horizon structure of a black hole exploiting its Hawking emission.

Thanks for your attention!!!