UNIVERSIDADE D COIMBRA

CFisUC

FCT Fundação para a Ciência e a Tecnologia

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

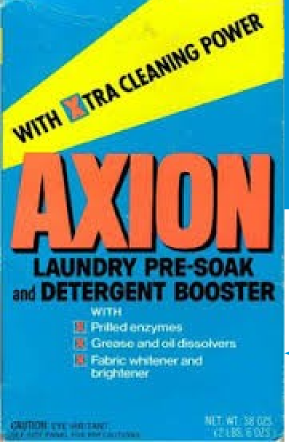
Marco Calzà, John March-Russell, and João G. Rosa.

PASCOS 2022, Heidelberg.

26/07/2022

The goal

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



The String Axiverse

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

String theory: E↓→ SM + $\mathcal{G}$ → 10D (4 s-t + 6 compactified)

Compactified extra dimensions are the key concept for the Axiverse!

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

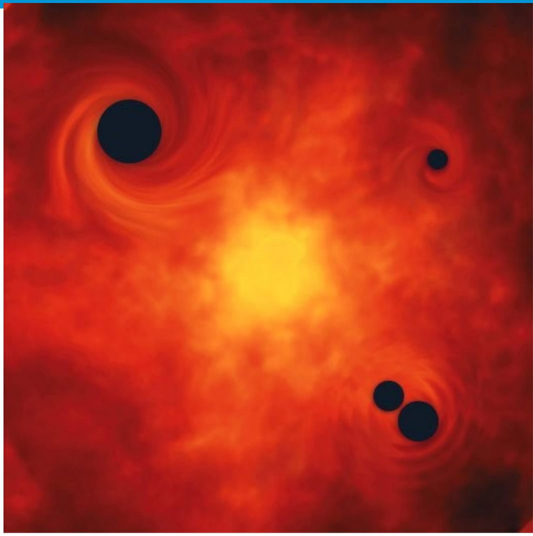
$$C^2 = S^2 \,,\; S^1 \times S^1 \,,\; \ldots$$

Sphere (S^2) — Torus ($S^1 \times S^1$)

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

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**

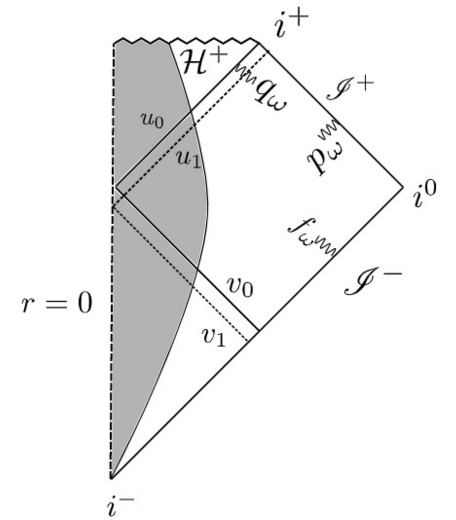


M ~ 10^{12} kg evaporates enough to show changes in a_* in presence of many scalars. (T > few MeV)

Radiation **D**ominated **E**ra → **small** spin (percent level).

Early **M**atter **D**ominated **E**ra → Nearly **extremal**

BH evaporation

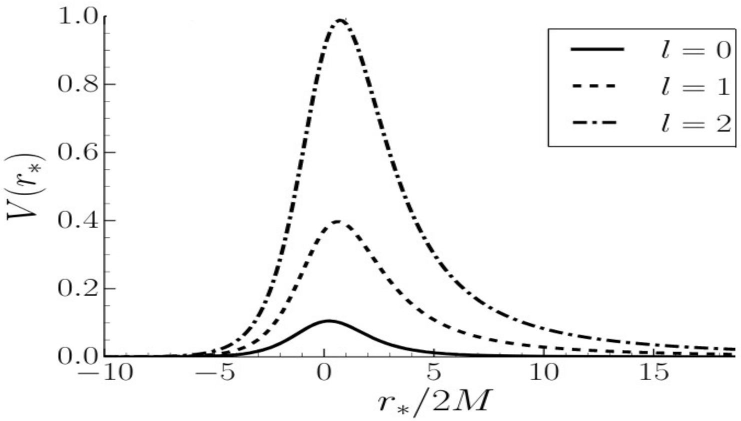


Spacetime before and after the formation of an horizon

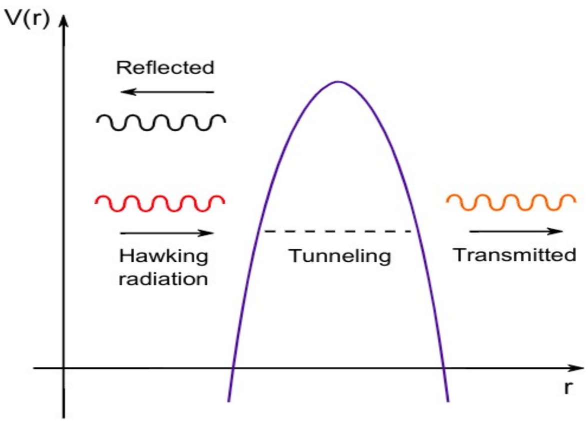
(Hawking 1975)

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

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

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

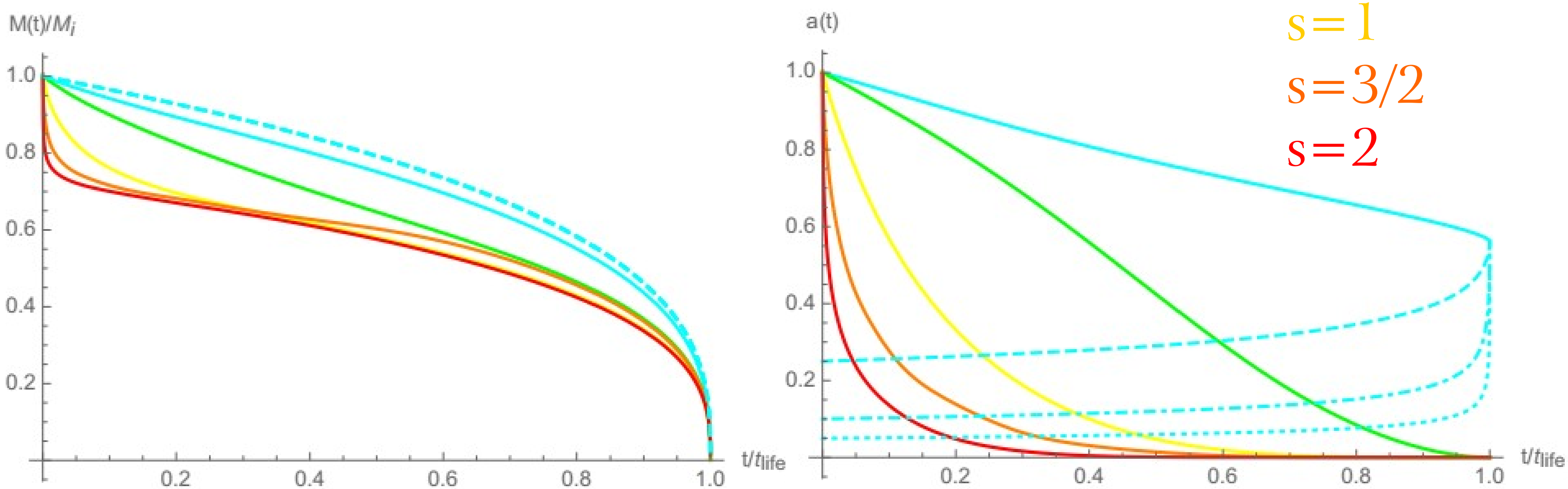
BH evaporation

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

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

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

s=0
s=1/2
s=1
s=3/2
s=2



$a_{*i}=0.99$ — $a_{*i}=0.25$ — $a_{*i}=0.1$ — $a_{*i}=0.05$

BH evaporation

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

$$f_{tot} = n_0\, f_0 + n_{1/2}\, f_{1/2} + n_1\, f_1 + n_{3/2}\, f_{3/2} + n_2\, f_2$$

$$g_{tot} = n_0\, g_0 + n_{1/2}\, g_{1/2} + n_1\, g_1 + n_{3/2}\, g_{3/2} + n_2\, g_2$$

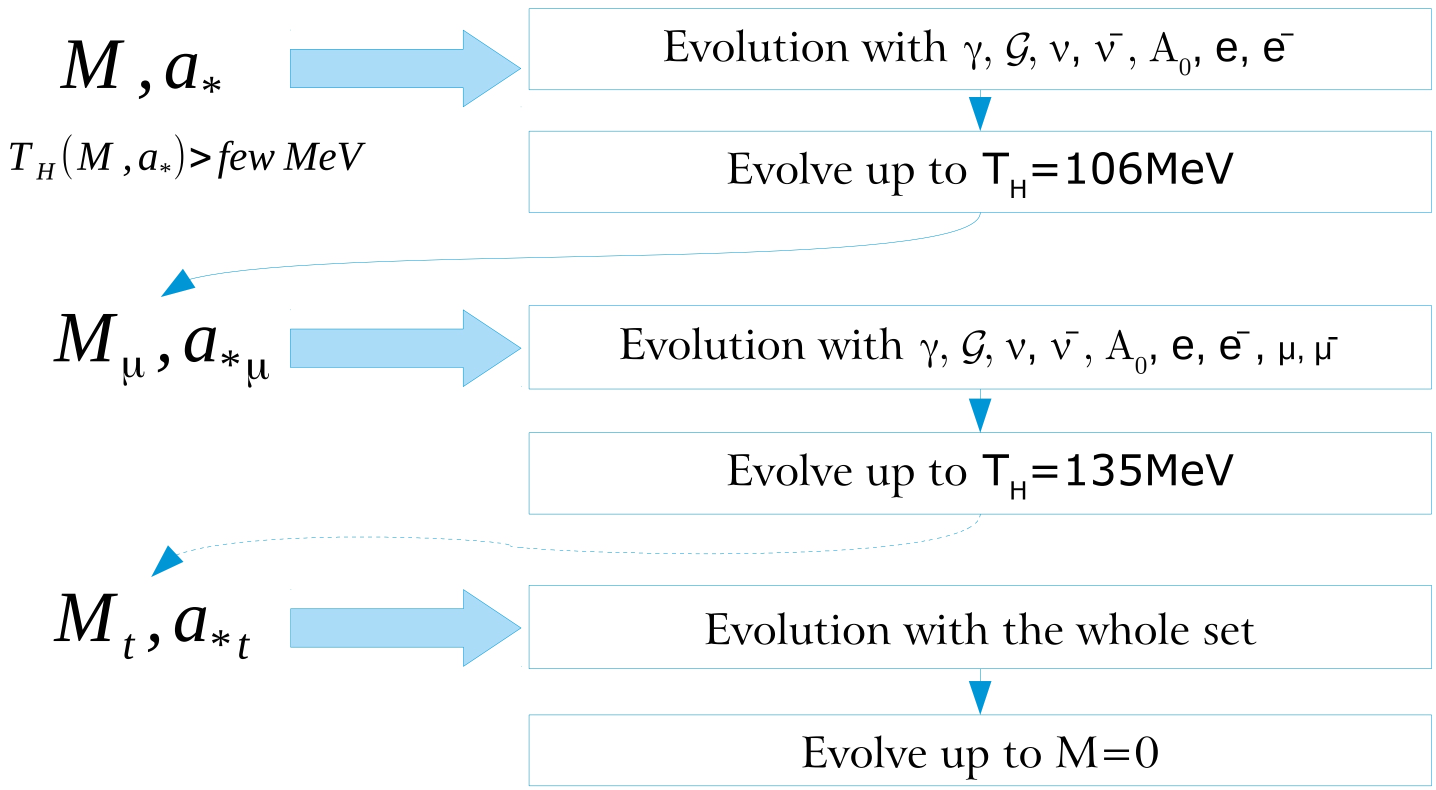
$\rightarrow h_{tot}$

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

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

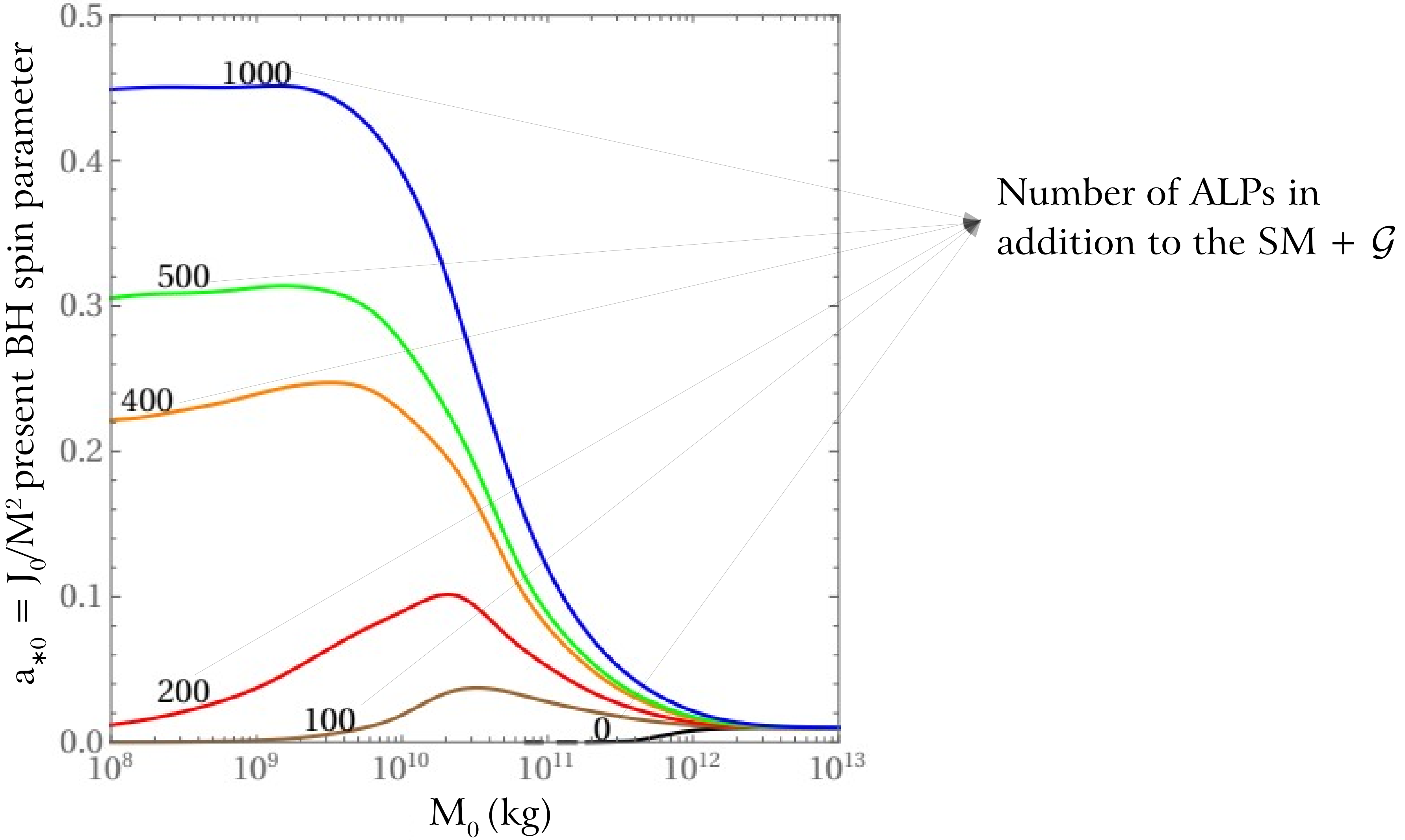
Approximation: particles are considered **massless** for **m < T_H** and are **otherwise absent** from the emission spectrum.

Set up of our description



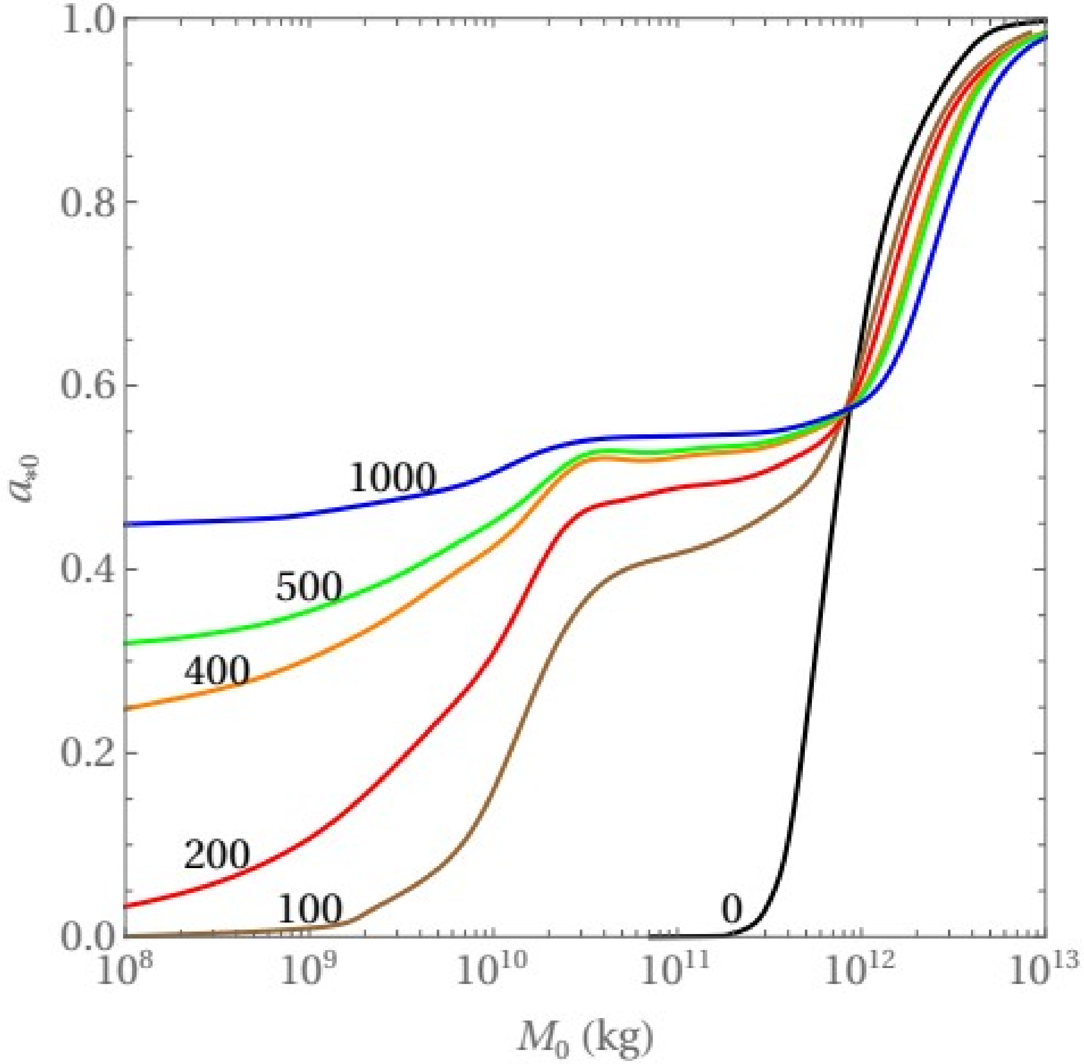
String Axiverse → N_a scalars field in addition to the SM particles and the graviton.

Axiverse fingerprint in PBHs evaporation

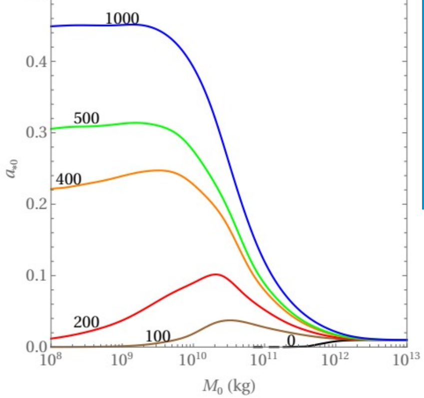


Present PBH spin, a_{*0}, as a function of their present mass, M_0, for an initial population with spin $a_* = 0.01$ and varying mass. Curves labeled by number of light ALPs.

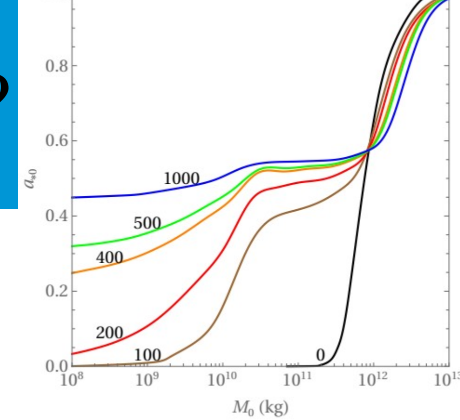
Axiverse fingerprint in PBHs evaporation



Present PBH spin, a_{*0}, as a function of their present mass, M_0, for an initial population with spin $a_* = 0.99$ 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

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

➔ 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

UNIVERSIDADE D COIMBRA

1 2 9 0

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

Marco Calzà,[1,*] John March-Russell,[2] and João G. Rosa[1,†]

[1] *Univ Coimbra, Faculdade de Ciências e Tecnologia da Universidade de Coimbra and CFisUC, Rua Larga, 3004-516 Coimbra, Portugal*

[2] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3PU, United Kingdom*

(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.

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

Thanks for your attention!!!