Superradiance and Hawking evaporation in the string axiverse

University of Lisbon
Presented by
Filipe Serrano
Collaboration with Dr. João Rosa and PhD student Marco Calzá

December 19, 2022

String Axiverse

- In string theory, there are a lot of massless fields which are zero modes of p-forms from Kaluza-Klein compactifications of extra dimensions (100-1000 fields).

String Axiverse

- In string theory, there are a lot of massless fields which are zero modes of p-forms from Kaluza-Klein compactifications of extra dimensions (100-1000 fields).
- These massless scalar fields acquire a mass from anomalous $U(1)$ symmetries which are broken via non-perturbative effects (SUSY breaking, internal symmetries)

String Axiverse

- In string theory, there are a lot of massless fields which are zero modes of p-forms from Kaluza-Klein compactifications of extra dimensions (100-1000 fields).
- These massless scalar fields acquire a mass from anomalous $U(1)$ symmetries which are broken via non-perturbative effects (SUSY breaking, internal symmetries)
- There are a lot of **Axion-Like-Particles (ALPs)** - String Axiverse

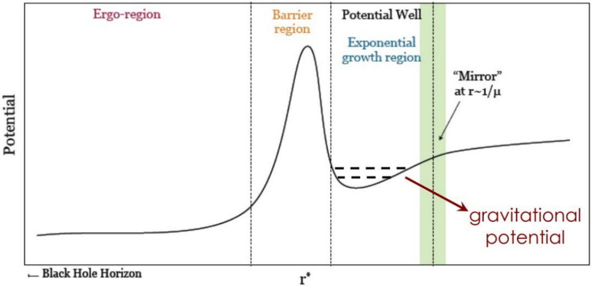
String Axiverse

- In string theory, there are a lot of massless fields which are zero modes of p-forms from Kaluza-Klein compactifications of extra dimensions (100-1000 fields).
- These massless scalar fields acquire a mass from anomalous $U(1)$ symmetries which are broken via non-perturbative effects (SUSY breaking, internal symmetries)
- There are a lot of **Axion-Like-Particles (ALPs)** - String Axiverse
- We considered an axiverse with 1 "heavy" ALP and an arbitrarily large number of "light" ALP species.

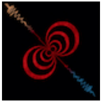
Superradiance (SR)

- It is a scattering process which occurs when a wave interacts with the rotating object while

$$\omega < m\Omega_H \tag{1}$$



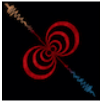
[Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell (2009)]



Superradiance (SR)

- We focused on the primary mode $(n = 2, l = 1, m = 1)$.

$$\Gamma \approx \frac{1}{24} \left(\tilde{a} - 4\alpha_\mu\right) \alpha_\mu^8 \mu \tag{2}$$



- We focused on the primary mode $(n = 2, l = 1, m = 1)$.

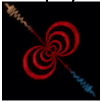
$$\Gamma \approx \frac{1}{24}\left(\tilde{a} - 4\alpha_\mu\right)\alpha_\mu^8 \mu \tag{2}$$

- The equations of motion for M, $\tilde{a} = J/M^2$ and N are

$$\frac{dM_{\text{sup}}}{dt} = -\mu \frac{dN}{dt} \tag{3}$$

$$\frac{dJ_{\text{sup}}}{dt} = -\frac{dN}{dt} \Leftrightarrow \frac{d\tilde{a}}{dt} = -\frac{dN}{dt}\frac{1}{M^2}(1 - 2\tilde{a}\alpha_\mu) \tag{4}$$

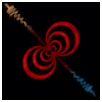
$$\frac{dN}{dt} = \Gamma(M, \tilde{a}, \mu)N \quad , \quad \Gamma(M, \tilde{a}, \mu) = 2\omega_I \tag{5}$$



Hawking Evaporation (HE)

- Black Holes radiate thermal energy at late times,

$$\langle N_s \rangle = \sum_{l,m} \frac{Z^s_{l,m}}{e^{\frac{2\pi\omega}{\kappa}} - (-1)^{2s}} \tag{6}$$



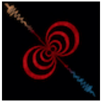
Hawking Evaporation (HE)

- Black Holes radiate thermal energy at late times,

$$\langle N_s \rangle = \sum_{l,m} \frac{Z^s_{l,m}}{e^{\frac{2\pi\omega}{\kappa}} - (-1)^{2s}} \tag{6}$$

- The Black Hole depletes mass and angular momentum depending on the flux of particles being emitted,

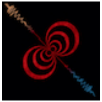
$$\begin{aligned} \frac{dM}{dt} &= -\frac{1}{M^2} f(\tilde{a}, M) \\ \frac{d\tilde{a}}{dt} &= \frac{\tilde{a}}{M^3} \left(-g(\tilde{a}, M) + 2f(\tilde{a}, M)\right) \end{aligned} \tag{7}$$



Depletion functions

- For a massive particle of spin s,

$$\begin{pmatrix} f_s \\ g_s \end{pmatrix} = -\frac{1}{2\pi}\Theta(T-\mu)\sum_{l,m}\int_0^{\infty}\frac{Z^s_{l,m}(\alpha_\omega,\tilde{a})d\alpha_\omega}{e^{\frac{2\pi(\omega-m\Omega)}{\kappa}}-(-1)^{2s}}\begin{pmatrix} \alpha_\omega \\ m/\tilde{a} \end{pmatrix} \tag{8}$$

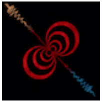


Depletion functions

- For a massive particle of spin s,

$$\begin{pmatrix} f_s \\ g_s \end{pmatrix} = -\frac{1}{2\pi}\Theta(T-\mu)\sum_{l,m}\int_0^{\infty}\frac{Z^s_{l,m}(\alpha_\omega,\tilde{a})d\alpha_\omega}{e^{\frac{2\pi(\omega-m\Omega)}{\kappa}}-(-1)^{2s}}\begin{pmatrix} \alpha_\omega \\ m/\tilde{a} \end{pmatrix} \tag{8}$$

- In order to maximize the effects of Hawking evaporation, we considered Black Holes which are evaporating today - **Primodial Black Holes**.



Depletion functions

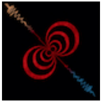
- For a massive particle of spin s,

$$\begin{pmatrix} f_s \\ g_s \end{pmatrix} = -\frac{1}{2\pi}\Theta(T-\mu)\sum_{l,m}\int_0^\infty \frac{Z^s_{l,m}(\alpha_\omega,\tilde{a})d\alpha_\omega}{e^{\frac{2\pi(\omega-m\Omega)}{\kappa}}-(-1)^{2s}}\begin{pmatrix} \alpha_\omega \\ m/\tilde{a} \end{pmatrix} \quad (8)$$

- In order to maximize the effects of Hawking evaporation, we considered Black Holes which are evaporating today - **Primodial Black Holes**.

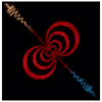
-

$$M_0 = 10^{12}\ \text{kg} \quad \tilde{a}_0 = 0.01 \quad (9)$$



Gameplan

- Compute the purely evaporating system.



Gameplan

- Compute the purely evaporating system.
- Compute the intersection between the superradiant threshold and the "Regge" trajectory of the purely evaporating system.

Gameplan

- Compute the purely evaporating system.
- Compute the intersection between the superradiant threshold and the "Regge" trajectory of the purely evaporating system.
- Solve the new system of equations,

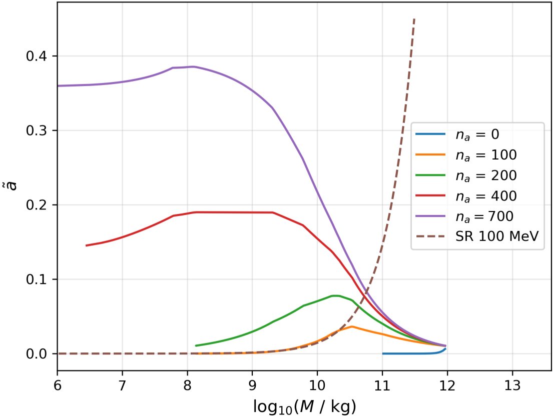
$$\frac{dM}{dt} = -\frac{f(\tilde{a})}{M^2} - \mu\Gamma N \tag{10}$$

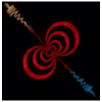
$$\frac{d\tilde{a}}{dt} = \frac{\tilde{a}}{M^3}(-g(\tilde{a}) + 2f(\tilde{a})) - \frac{\Gamma N}{M^2} \tag{11}$$

$$\frac{dN}{dt} = \Gamma N \tag{12}$$

with initial conditions,

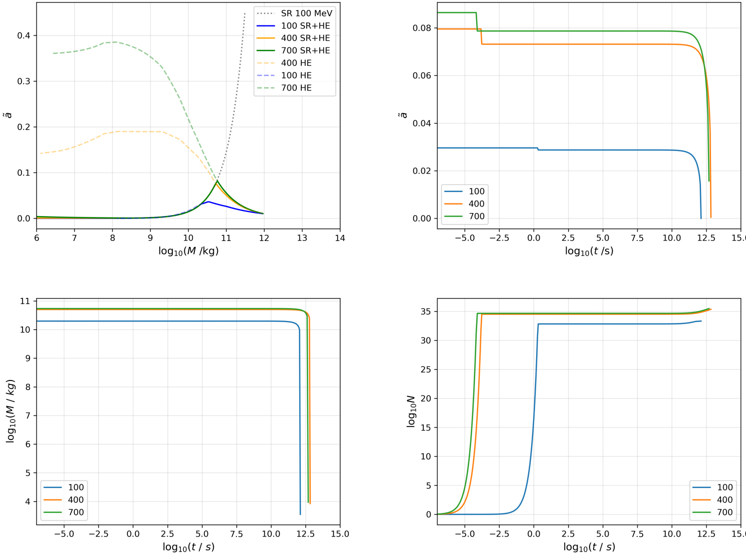
$$M_0 = M_t \text{ kg} \quad \tilde{a}_0 = \tilde{a}_t \quad N_0 = 1$$



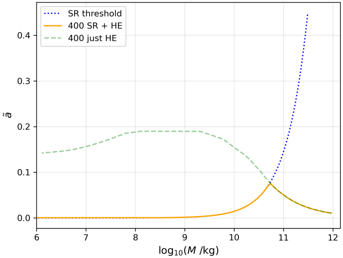


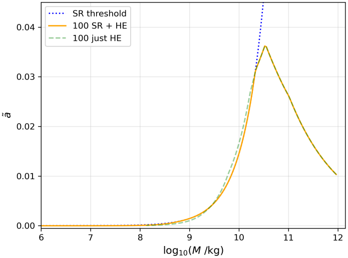
- Depending on the number of light ALP species, we have different trigger conditions.

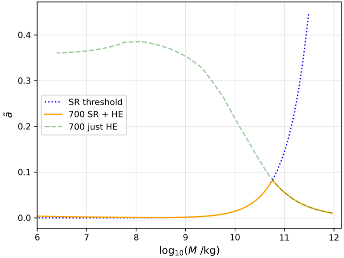
Evolution Results

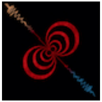


Regge trajectories





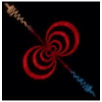




Axion Decay

- Study the photon flux contributions from SR to the HE spectrum,

$$\mathcal{L} = \frac{C\alpha_{\mathrm{EM}}}{4\pi f_a}\theta\epsilon^{abcd}F_{ab}F_{cd} \tag{13}$$



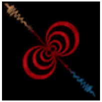
Axion Decay

- Study the photon flux contributions from SR to the HE spectrum,

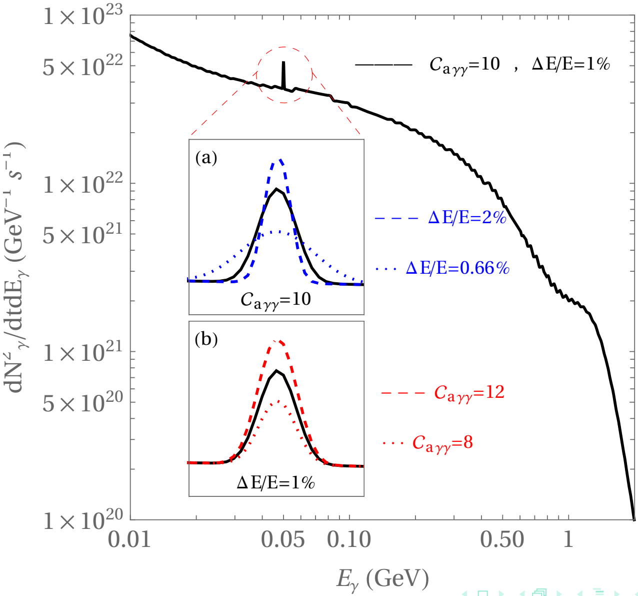
$$\mathcal{L} = \frac{C\alpha_{\text{EM}}}{4\pi f_a}\theta\epsilon^{abcd}F_{ab}F_{cd} \tag{13}$$

- Not considering self interactions imposes an upper limit in the photon flux.

$$\frac{dN}{dtdE} < \frac{\alpha_{\text{EM}}^2}{128\pi^3}\left|C_{\gamma\gamma}\right|^2\frac{100}{\sqrt{3}}\frac{\sqrt{\tilde{a}-4\alpha_\mu}}{\tilde{a}}\frac{E}{\Delta E} \tag{14}$$



Axion Decay Flux



In sum

- A PBH with $M_0 = 10^{12}$ kg and $\tilde{a}_0 = 0.01$ will start evaporating, increasing $\tilde{a}$ due to the high number of light ALP species.
- The number of light ALP species will dictate the black hole state at which the instability occurs.
- There will be a pseudo equilibrium state before the superradiant rate generates heavy ALPs until the the maximum number possible.
- The astrophysical signatures of the String Axiverse can be seen in both the HE spectrum and the Axion decay spectrum.