ALPs Production from Light Primordial Black Holes: The Role of Superradiance

Marco Manno, NEHOP Talk - 21/05/2025

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Based on: Manno M. and Montanino D., 2501.14589

What are Primordial Black Holes?

- **Various** formation scenarios for PBHs have been proposed, but here we remain agnostic.
- They are sensitive to **early universe** physics and can also have an impact on it.
- They could explain lot of unresolved **conundra** (see 1906.08217)
- Here we focus on **Light** PBHs:

$$10\,\mathrm{g} \lesssim M_{\mathrm{PBH}} \lesssim 10^9\,\mathrm{g}$$

Hawking Temperature of Kerr Black Holes

$$T_{\rm BH} = \frac{1}{4\pi G M_{\rm BH}} \frac{\sqrt{1-a_\star^2}}{1+\sqrt{1-a_\star^2}}$$

Spectra of Emitted Particles

$$\frac{d^2\mathcal{N}_i}{dEdt} = \sum_\mu \frac{\Gamma^\mu_{s_i}(M_{\rm BH}, a_\star, E)/2\pi}{\exp\left[(E-\mu\Omega)/T_{\rm BH}\right] - (-1)^{2s_i}}\,,$$

with $\Gamma^\mu_{s_i}(M_{\rm BH}, a_\star, E) = \sum_l \sigma^{l\mu}_{s_i}(M_{\rm BH}, a_\star, E)(E^2 - m_i^2)/\pi$.

Hawking Radiation

The evaporation process leads to a reduction in the BH's mass and spin:

$$\frac{dM_{\rm BH}}{dt} = -\varepsilon(M_{\rm BH}, a_\star)\frac{M_{\rm pl}^4}{M_{\rm BH}^2}\,,$$

$$\frac{da_\star}{dt} = -a_\star[\gamma(M_{\rm BH}, a_\star) - 2\varepsilon(M_{\rm BH}, a_\star)]\frac{M_{\rm pl}^4}{M_{\rm BH}^3}\,,$$

where

$$\varepsilon(M_{\rm BH}, a_\star) = \sum_i \varepsilon_i(M_{\rm BH}, a_\star) = \sum_i \frac{1}{2\pi}\int_{\zeta_i}^{\infty}\sum_\mu \frac{\xi\Gamma^\mu_{s_i}(M_{\rm BH}, a_\star, \xi)}{e^{\xi'} - (-1)^{2s_i}}d\xi\,,$$

$$\gamma(M_{\rm BH}, a_\star) = \sum_i \gamma_i(M_{\rm BH}, a_\star) = \sum_i \frac{4}{a_\star}\int_{\zeta_i}^{\infty}\sum_\mu \frac{\mu\Gamma^\mu_{s_i}(M_{\rm BH}, a_\star, \xi)}{e^{\xi'} - (-1)^{2s_i}}d\xi\,,$$

$$\xi' = \frac{\xi - \mu\Omega(a_\star)M_{\rm BH}/M_{\rm pl}^2}{2}\left(1 + \frac{1}{\sqrt{1-a_\star^2}}\right)\,.$$

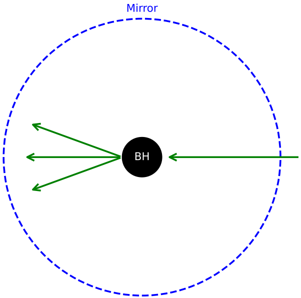
Superradiance, Ref: 2205.11522, 2306.09430

Superradiance is a mechanism of radiation amplification.

Superradiance occurs if the following condition is satisfied:

$$\omega < \mu\Omega \, .$$

In this case, the radiation is repeatedly amplified, leading to a condition of **instability**.



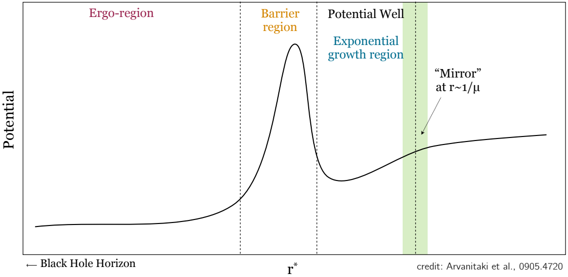
Superradiance

The system composed of a black hole and a massive bosonic field is called a **gravitational atom**. The boson is trapped in hydrogen-like bound states:

$$E_n = \omega_n \simeq m_S - \frac{\alpha^2 m_S}{2n^2} \ ,$$

with

$$\alpha = \frac{r_s}{2\lambda_c} = G M_{\rm BH} m_S \simeq 0.38 \left(\frac{M_{\rm BH}}{10^7 g}\right)\left(\frac{m_S}{10^7 \rm GeV}\right) \ .$$



credit: Arvanitaki et al., 0905.4720

Growth rate for the dominant unstable mode ($n = 2$, $l = \mu = 1$):

$$\Gamma_{sr}(M_{\rm BH}, a_\star) = \frac{m_S}{24}\left(\frac{m_S M_{\rm BH}}{8\pi M_{pl}^2}\right)^8 (a_\star - 2m_S r_+) \ ,$$

and the equations, considering only superradiance, become:

$$\begin{aligned} \frac{d\mathcal{N}_S}{dt} &= \Gamma_{sr}(M_{\rm BH}, a_\star)\mathcal{N}_S \ , \\ \frac{dM_{\rm BH}}{dt} &= -m_S\frac{d\mathcal{N}_S}{dt} \ , \\ \frac{da_\star}{dt} &= -\frac{1}{GM_{\rm BH}^2}\left(\sqrt{2} - 2\alpha a_\star\right)\frac{d\mathcal{N}_S}{dt} \ , \end{aligned}$$

in which $\mathcal{N}_S$ is the number of scalar particles gravitationally bounded to a PBH.

Superradiance

- Numerical simulations indicate that for $a_\star \simeq 1$, the instability is **largest** when:

$$\alpha \sim 0.42$$

- Generally, it's **very efficient** when:

$$\alpha \sim \mathcal{O}(0.1)$$

- In the mass range considered:

$$10\,\mathrm{g} \lesssim M_{\mathrm{BH}} \lesssim 10^9\,\mathrm{g}$$

- The scalar particle mass range should be:

$$10^5\,\mathrm{GeV} \lesssim m_S \lesssim 10^{13}\,\mathrm{GeV}$$

Non standard particles

Axion like particles (ALPs)

- ALPs are hypothetical, light particles predicted by various extensions of the Standard Model.
- Their properties determine whether they behave as dark matter or radiation.
- Here ALPs are assumed to be light enough to remain relativistic $\rightarrow$ **dark radiation**

Moduli

- Scalar fields ($m_\Phi \gtrsim 30$TeV) predicted by *string theory*, arising from the complex Calabi-Yau geometry.
  The *decay rate* of moduli Φ is:

$$\Gamma_\Phi = \tau_\Phi^{-1} = \frac{1}{4\pi} \frac{m_\Phi^3}{(M_{pl}/k)^2}$$

ALPs from Moduli decay

ALPs are produced by processes $\Phi \rightarrow aa$, with a rate:

$$\Gamma_{\Phi \rightarrow aa} = B_a \Gamma_\Phi \ .$$

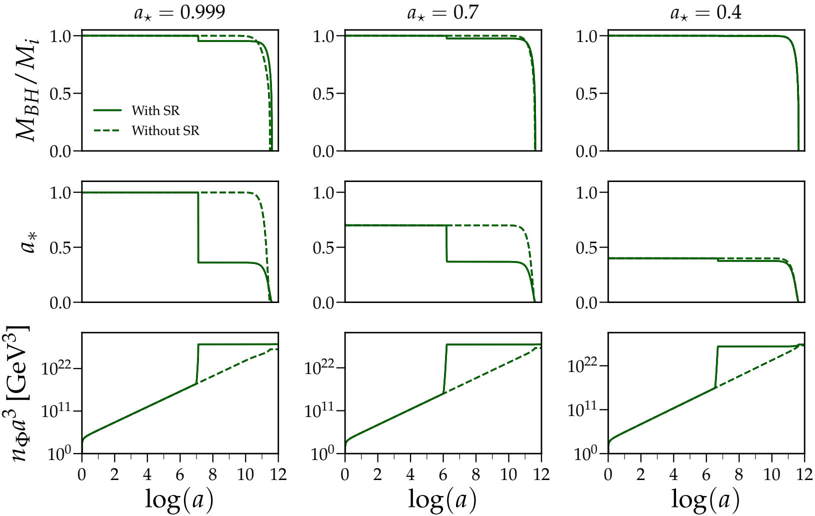
- The equation for the conservation of the total number of moduli is:

$$\dot{n}_\Phi + 3Hn_\Phi = -\Gamma_\Phi n_\Phi \ .$$

- The equations that describe the energy density evolution of ALPs and SM particles are:

$$\dot{\rho}_a + 4H\rho_a = \Gamma_\Phi B_a m_\Phi n_\Phi(t) \ ,$$
$$\dot{\rho}_{SM} + 4H\rho_{SM} = \Gamma_\Phi (1 - B_a) m_\Phi n_\Phi(t) \ .$$

Superradiant production of moduli, FRISBHEE



Values are: $M = 2.6 \times 10^6 g$, $m_\Phi = 10^7 GeV$, $\Omega_{\rm PBH,i} = 10^{-15}$.

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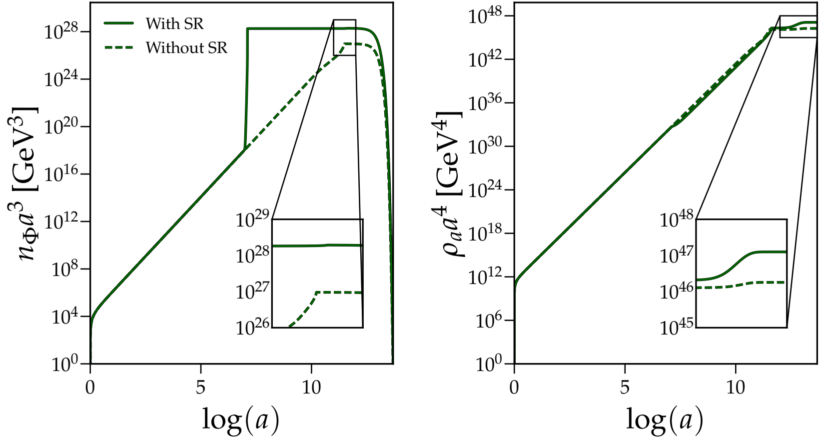
Moduli decay into ALPs

Moduli decay in ALPs, contributing to the **Cosmological Axion Background (CAB)**.



Values are: $M = 2.6 \times 10^6 g$, $m_\Phi = 10^7 GeV$, $\Omega_{\rm PBH,i} = 10^{-15}$, $B_a = 0.1$.

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Contribution of ALPs to ΔN_{eff}

- $\boldsymbol{N}_{\text{eff}}$ quantifies the total **relativistic energy density** in the early universe beyond photons.

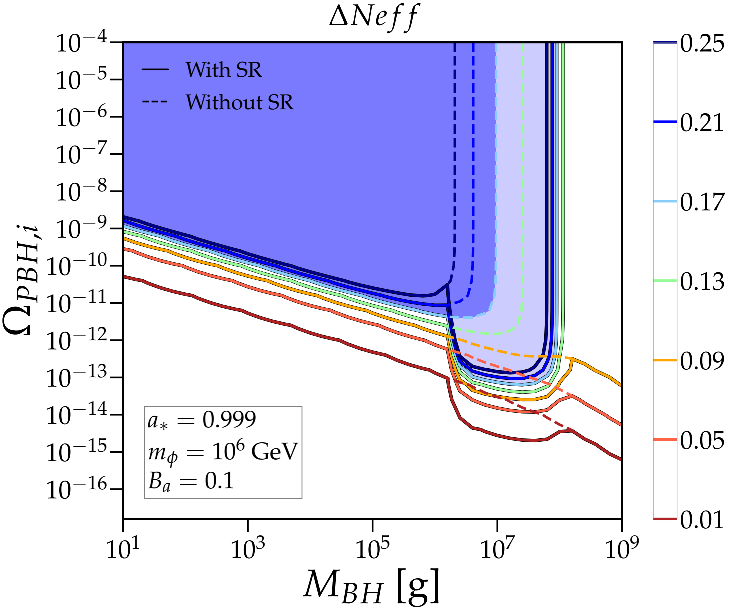
- In the Standard Model, $\boldsymbol{N_{\text{eff}}^{\text{SM}} = 3.043}$ due to the presence of three neutrino species.

- Planck results: $N_{\text{eff}} = 2.99 \pm 0.17$
- Any **additional radiation** — such as a population of relativistic **axion-like particles (ALPs)** — contributes to $\boldsymbol{\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}}$.

- This contribution can be quantified after redshifting the ALP energy density to the decay epoch:

$$\Delta N_{\text{eff}} = 7.446 \times \frac{g_\rho(T_d)}{g_\rho(T_0)} \left(\frac{g_S(T_0)}{g_S(T_d)}\right)^{4/3} \frac{\rho_a(T_d)}{\rho_{\text{SM}}(T_d)}.$$

$\Delta N_{\rm eff}$ with moduli, $m_\Phi = 10^6 GeV$



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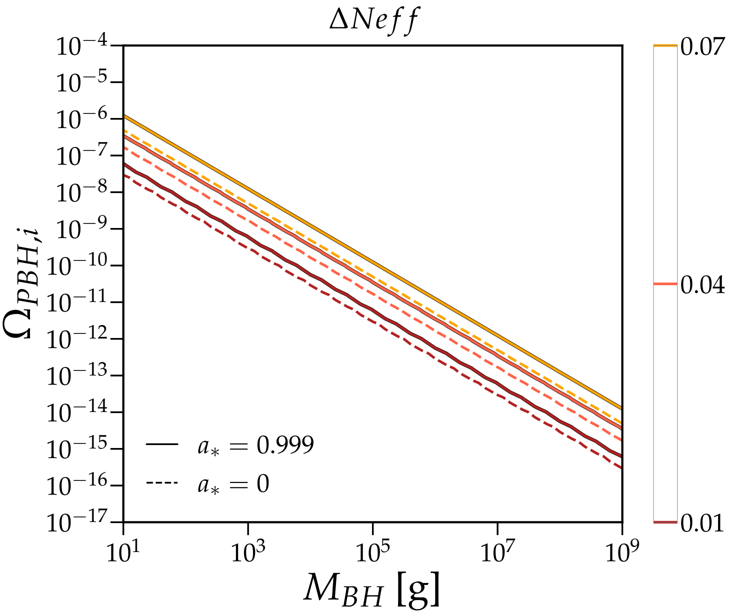
$\Delta N_{\rm eff}$ without moduli



Conclusions

We summarize the findings on ALPs production from LPBHs:

- PBHs are crucial in cosmology as they can significantly **influence** the particle and radiation content of the early universe.
- In the presence of **heavy particles** such as moduli, the interplay of Hawking radiation and Superradiance in LPBHs is crucial.
- The decay of moduli leads to the production of **ALPs**, which can be quantified through $\Delta N_{\mathbf{eff}}$.

Thank you for your attention!

Questions?

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Backup Slides

Constraints from Cosmological Data

Constraints on the masses of PBHs come mainly from:

- **Primordial Nucleosynthesis (BBN)**

$$M_{\rm PBH} < 10^9 {\rm g}\ .$$

- **Inflation**

$$M_{\rm PBH} > 10\ {\rm g}\ .$$

Furthermore, the are constraints on the initial abundance $\Omega_{PBH,i} = \rho_{\rm PBH,i}/\rho_r$:

- **Influence of Gravitational Waves on BBN**

$$\Omega^{\rm max}_{\rm PBH,i} \simeq 1.1 \times 10^{-6} \left(\frac{M_{\rm PBH}}{10^4 {\rm g}}\right)^{-\frac{17}{24}}\ .$$

Taking into account all the previous equations:

$$\dot{\mathcal{N}}_\Phi = \Gamma_{sr}\mathcal{N}_\Phi \ ,$$

$$\dot{M} = -\varepsilon M_{pl}^4/M^2 - m_\varphi \dot{\mathcal{N}}_\Phi \ ,$$

$$\dot{a}_* = -a_*(\gamma - 2\varepsilon)M_{pl}^4/M^3 - \frac{1}{GM^2}(\sqrt{2} - 2\alpha a_*)\dot{\mathcal{N}}_\Phi \ ,$$

$$\dot{\rho}_\Phi + 3H\rho_\Phi = \Gamma_{sr}\rho_\Phi + \varepsilon_\Phi \frac{M_{\rm pl}^4}{M_{\rm BH}^2} n_{\rm BH} - \Gamma_\Phi \rho_\Phi \ ,$$

$$\dot{\rho}_{\rm BH} + 3H\rho_{\rm BH} = \frac{1}{M}\dot{M}_{\rm BH}\rho_{\rm BH} \ ,$$

$$\dot{\rho}_{SM} + 4H\rho_{SM} = \varepsilon_{SM}\frac{M_{pl}^4}{M^2} n_{\rm BH} + (1 - B_a)\Gamma_\Phi \rho_\Phi \ ,$$

$$\dot{\rho}_a + 4H\rho_a = \varepsilon_a \frac{M_{pl}^4}{M^2} n_{\rm BH} + B_a \Gamma_\Phi \rho_\Phi \ ,$$

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}[\rho_{SM} + \rho_a + \rho_\Phi + \rho_{\rm BH}] \ .$$

Effective Number of Neutrinos, N_{eff}

In standard cosmology, when the photon temperature drops below $T_\gamma \sim 1\,\text{MeV}$, neutrinos decouple from the rest of the radiation, forming a **cosmic neutrino background (CNuB)**. The energy density today can be written as:

$$\rho_{\text{r,std}} = \rho_\gamma \left[1 + N_{\text{eff}} \frac{7}{8} \left(\frac{4}{11} \right)^{\frac{4}{3}} \right]$$

where N_{eff} is the effective number of neutrinos and is equal to 3.043, mainly because neutrinos do not decouple instantaneously.

Extra Effective Number, ΔN_{eff}

Planck satellite measurements indicate $N_{\text{eff}} = 2.99 \pm 0.17$.

- Data allow for the existence of an extra radiation component.
- In our model, this dark radiation component is identified with ALPs.

The extra contribution ΔN_{eff} can be expressed as:

$$\Delta N_{\text{eff}} = \frac{\rho_a(T_0)}{\rho_r(T_0)} \left[N_{\text{eff}} + \frac{8}{7} \left(\frac{11}{4} \right)^{4/3} \right]$$

Next step: *Redshift this expression to the decay time* t_d *(temperature* T_d*).*

SM radiation:

$$\frac{\rho_r(T_0)}{\rho_{\text{SM}}(T_d)} = \frac{g_\rho(T_0)}{g_\rho(T_d)} \left(\frac{T_0}{T_d}\right)^4 = \frac{g_\rho(T_0)}{g_\rho(T_d)} \left(\frac{g_S(T_d)}{g_S(T_0)}\right)^{4/3} \left(\frac{a(T_d)}{a(T_0)}\right)^4 \ .$$

Dark radiation:

$$\frac{\rho_a(T_0)}{\rho_a(T_d)} = \left(\frac{a(T_d)}{a(T_0)}\right)^4 \ .$$

Extra effective number:

$$\Delta N_{\text{eff}} = 7.446 \times \frac{g_\rho(T_d)}{g_\rho(T_0)} \left(\frac{g_S(T_0)}{g_S(T_d)}\right)^{4/3} \frac{\rho_a(T_d)}{\rho_{\text{SM}}(T_d)} \ .$$