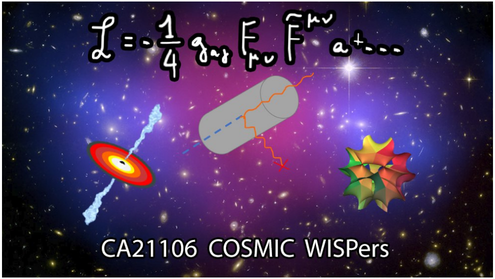
ALPs Production from Light Primordial Black Holes: The Role of Superradiance

Marco Manno, Wispers Talk - 19/03/2025



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

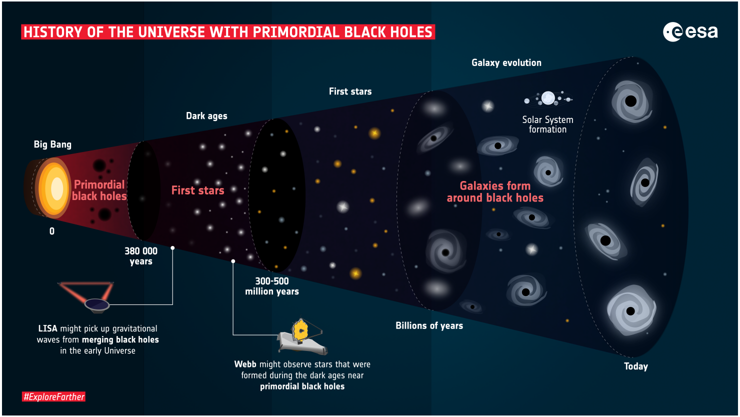
What are Primordial Black Holes?

- Primordial black holes (PBHs) have been proposed to form by **density fluctuations** during post inflationary eras.
- Unlike stellar-collapse black holes, PBHs could have formed much earlier in cosmic history.
- A key feature is their wide range of possible masses.
- In this context, Light Primordial Black Holes (LPBs) are defined as PBHs with masses in the range $10g \lesssim M \lesssim 10^9 g$.

When they formed?

$$M \sim 10^6 \left(\frac{t_f}{10^{-32} s} \right) g \qquad \rightarrow \qquad 10g \leq M \leq 10^9 g$$

$$10^{-37} s \leq t_f \leq 10^{-29} s$$



Why are PBHs important?

- **Wide range of masses:** Play roles in cosmology and astrophysics
- **Dark Matter candidates:** PBHs have been proposed as DM candidates
- **Window into the early universe:** PBHs are sensistive to processes in this period
- **LIGO-Virgo observations:** BHs mergers could have primordial origin
- **Cosmic conundra:** Thermal history and PBHs could explain lot of unresolved conundra (galaxies at high redshifts, some microlensing events, . . .)
- **Cosmological consequences:** Matter and energy density injection

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**

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

PBHs mechanisms

Hawking radiation

- PBHs emit radiation known as Hawking Radiation.
- Causes black hole to lose mass and spin, leading to evaporation.
- Produces SM particles and (possibly) BSM particles.

Superradiance

- Amplification of wave modes scattering off a rotating black hole.
- Occurs when wave frequency is less than black hole's event horizon angular velocity.
- Waves grow exponentially, extracting energy from the black hole.

Hawking Temperature of Kerr Black Holes

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

Spectrum 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 $\Gamma^\mu_{s_i}(M_{\rm BH}, a_\star, E) = \sum_l \sigma^{l\mu}_{s_i}(M_{\rm BH}, a_\star, E)(E^2 - m_i^2)/\pi$.
Greybody factor: deviation of the emission-spectrum of a black hole from a pure black-body spectrum.

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

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

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

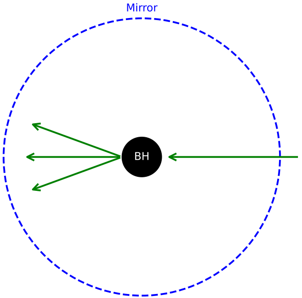
$$\xi' = \frac{\xi - \mu\Omega(a_\star)M_{\rm BH}/M_{\rm pl}^2}{2}\left(1 + \frac{1}{\sqrt{1 - a_\star^2}}\right)\,.$$

Superradiance

Strictly connected to Hawking radiation is the process of **superradiance**, which 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**.



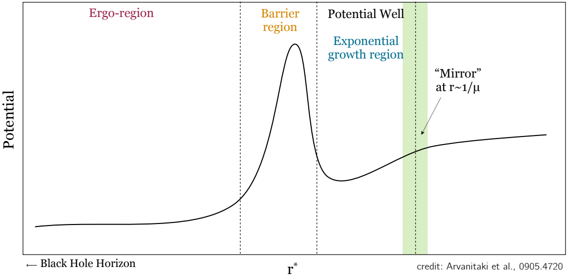
Superradiance

The system composed of a black hole and a massive bosonic field is called a **gravitational atom**. The boson can be 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

Superradiance

The growth rate can be approximated as:

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

and the equations, considering only superradiance, become:

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

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

In this work, as a product of the Hawking evaporation, we also considered:

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 ($m_\Phi \gtrsim 30\text{TeV}$) 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 $\Phi \to aa$, with a rate:

$$\Gamma_{\Phi \to aa} = B_a \Gamma_\Phi \ ,$$

where B_a is the branching ratio, which quantifies how many moduli decay in ALPs.

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

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

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

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

Complete scenario

Taking into account all the previous equations:

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

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

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

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

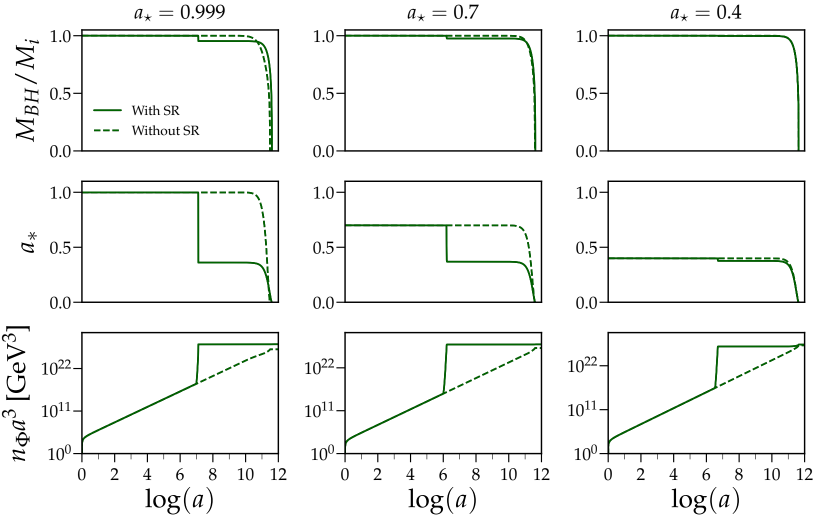
$$\dot{\rho}_{\mathrm{BH}} + 3H\rho_{\mathrm{BH}} = \frac{1}{M}\dot{M}_{\mathrm{BH}}\rho_{\mathrm{BH}} \ ,$$

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

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

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

Superradiant production of moduli



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

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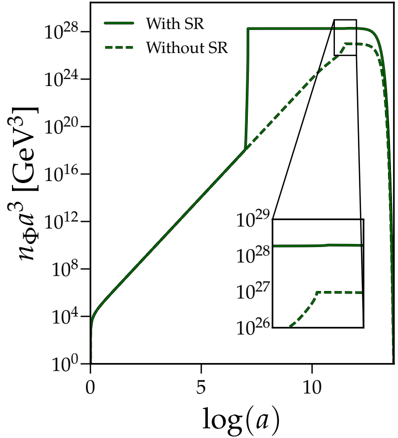
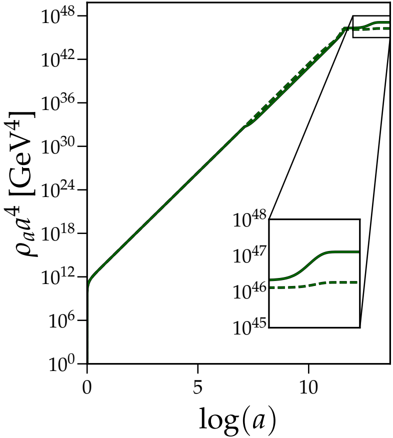
Moduli decay in ALPs, contributing to the **Cosmological Axion Background (CAB)**.





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

Effective Number of Neutrinos, $N_{\rm eff}$

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

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

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

Extra Effective Number, $\Delta N_{\rm eff}$

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

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

The extra contribution $\Delta N_{\rm eff}$ can be expressed as:

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

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

Redshift

SM radiation:

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

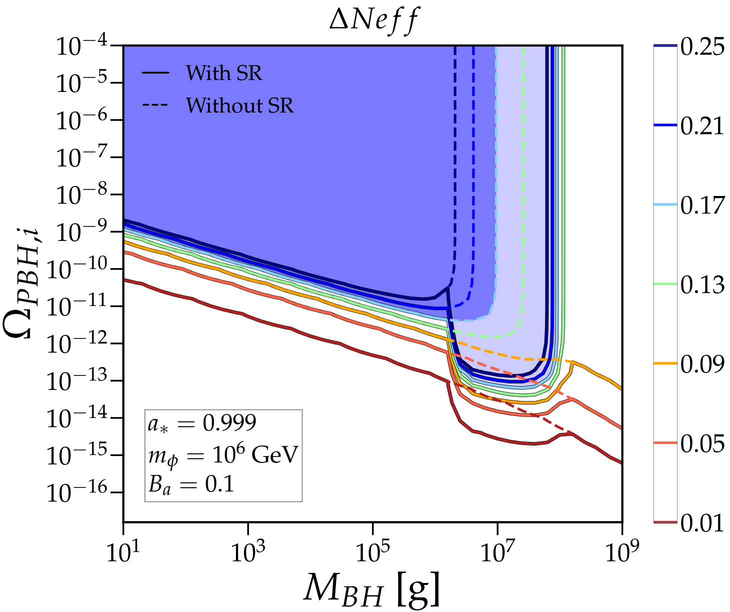
Dark radiation:

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

Extra effective number:

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

ΔN_{eff} with moduli, $m_\Phi = 10^6 GeV$



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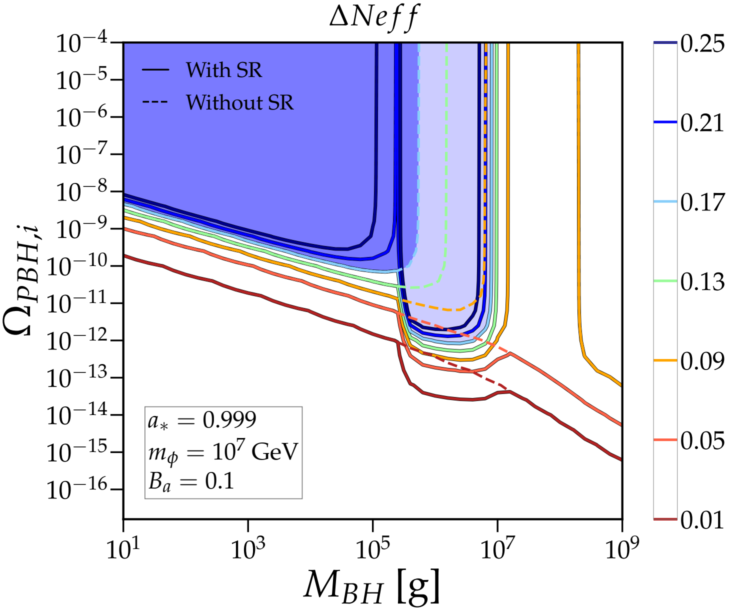
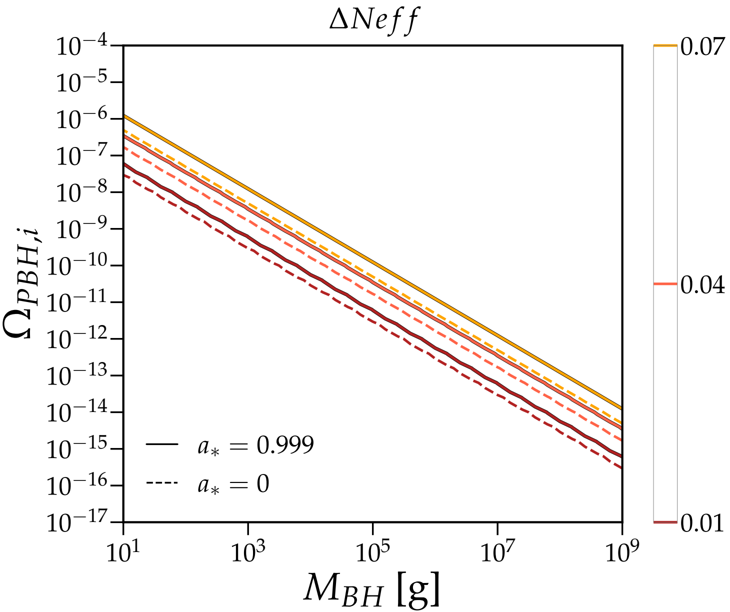
ΔN_{eff} with moduli, $m_\Phi = 10^7 GeV$



ΔN_{eff} without moduli



Conclusions

- **Importance of PBHs:** Primordial Black Holes (PBHs) are crucial in cosmology as they can significantly influence the particle and radiation content of the early universe.
- **Superradiance and Hawking Radiation:** The interplay between superradiance and Hawking radiation is fundamental, especially if heavy particles such as moduli exist. This interaction can lead to the production of exotic particles like ALPs.
- **Cosmological Implications:** ALPs produced in this context can act as *dark radiation*.
  Their presence can be quantified through the extra effective number of neutrinos, ΔN_{eff}.

Thank you for your attention!

Questions?

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