Dark Matter Production and Evolution from Primordial Black Holes in the Early Universe (In-progress)

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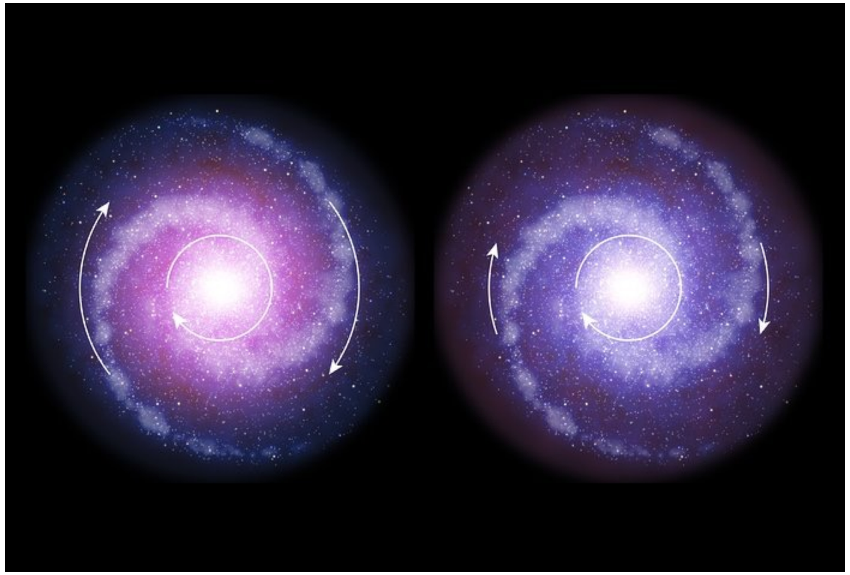
September 9th, 2024 @ Weihai

Introduction

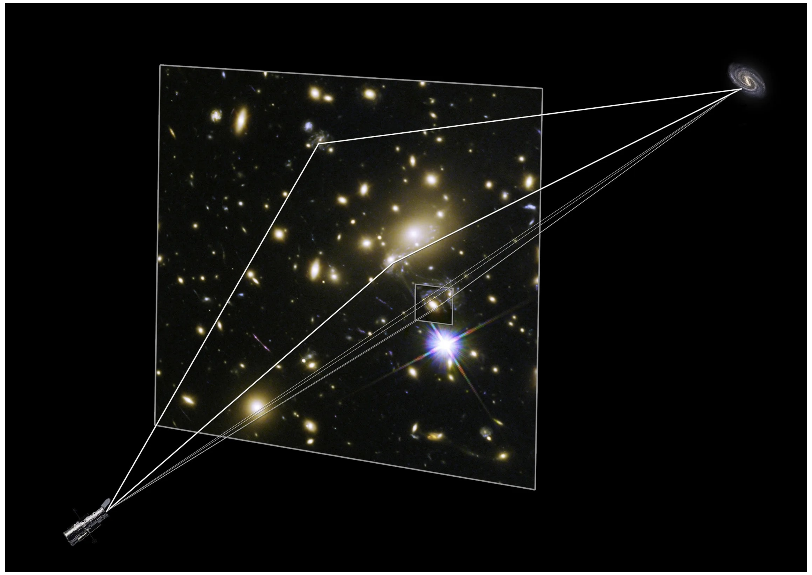
Dark matter: evidences from gravitational effects



Galaxy rotation curves

Gravitational

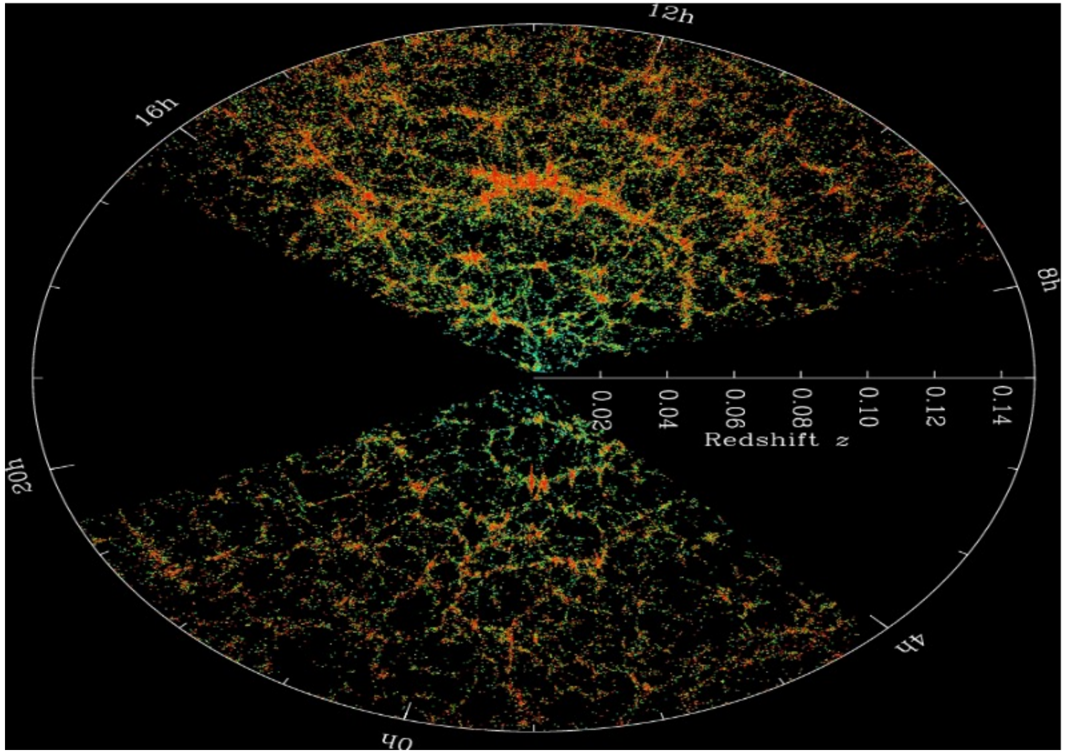
Credit: ESO/L. Calçada



Gravitational lensing

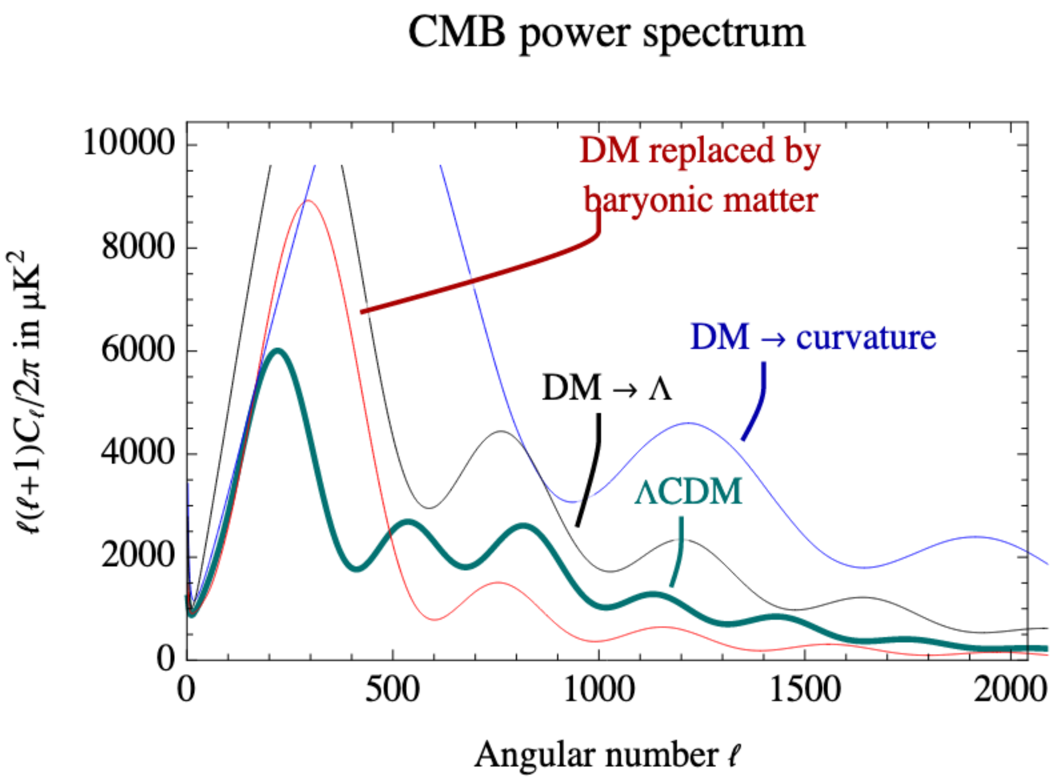
NASA & ESA

Dark matter: evidences from gravitational effects



Large-scale structure

Gravitational



CMB acoustic peaks

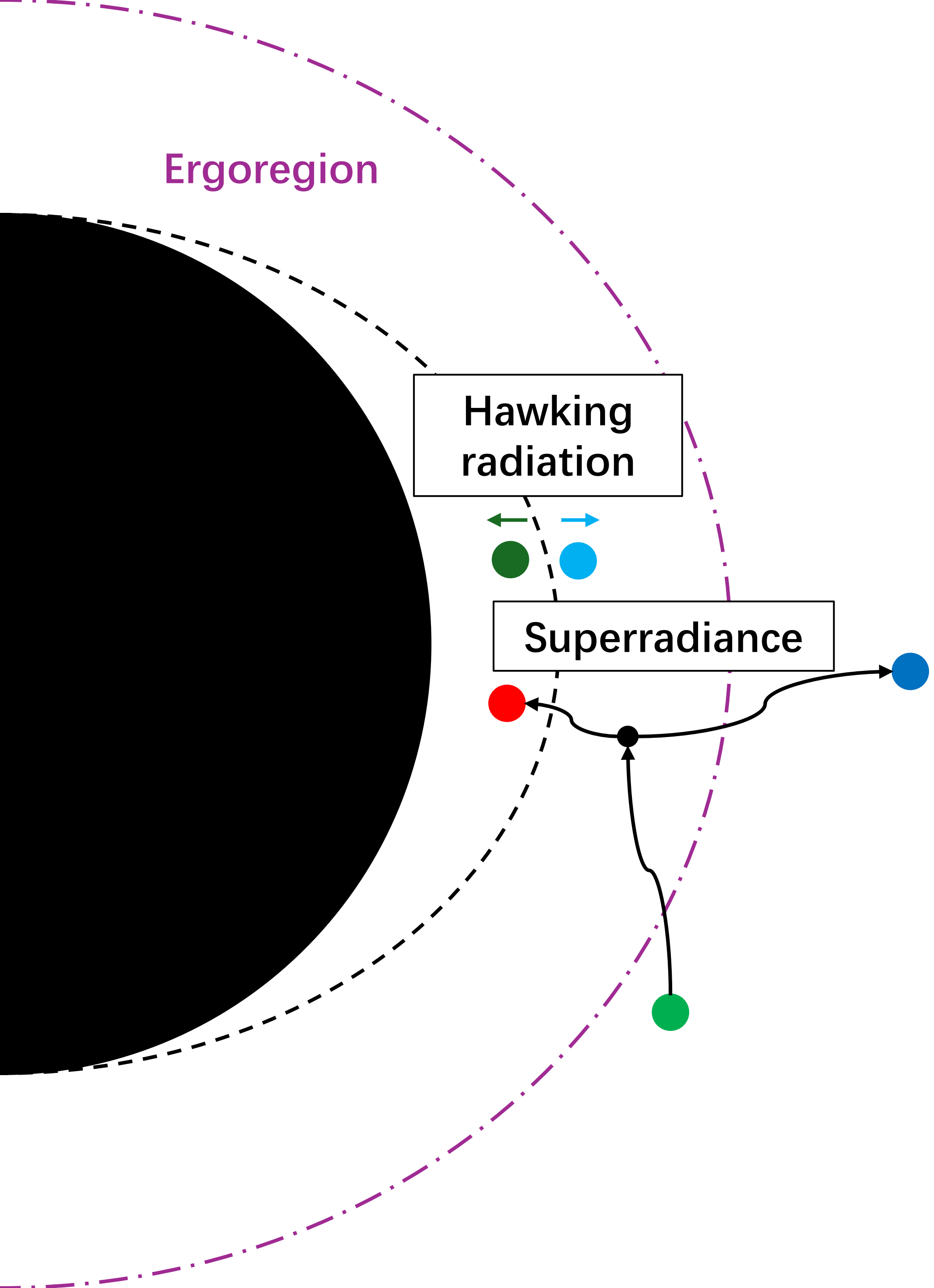
Gravitational

(Cirelli, Strumia and Zupan, 2024)

Motivation for Phenomenology

Gravitational evidences → Gravitational interaction between DM and SM particles → Gravitational genesis mechanisms

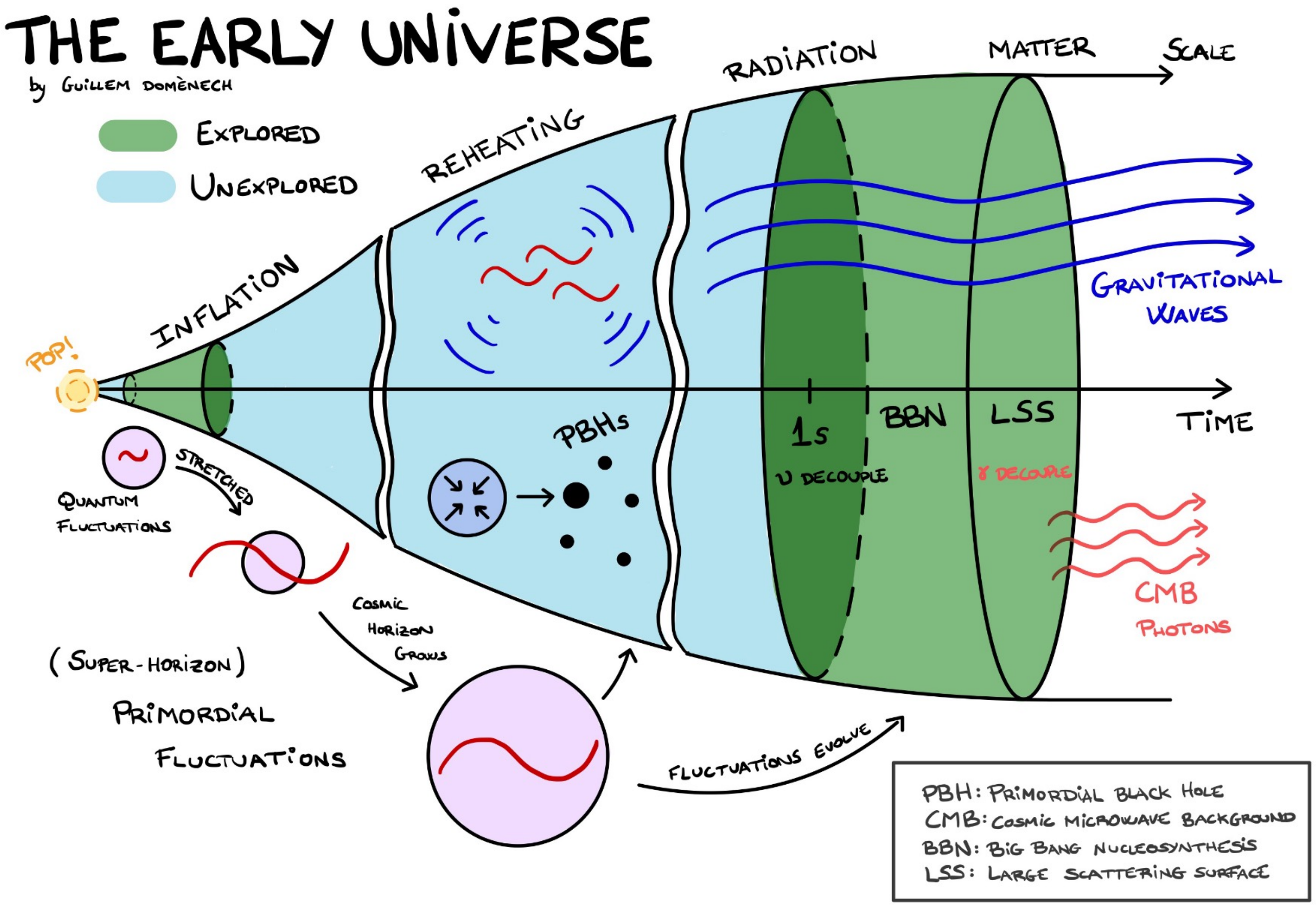
Settings & Preliminary Results



Two mechanisms for gravitational DM genesis, both from black holes

- Hawking radiation
  - Particle creation at the BH horizon
  - Effectively generates all particles with $\mu \lesssim T_{\mathrm{BH}}$
- Superradiance
  - Requires the ergoregion
  - Population of superradiant particles in the BH ergoregion, forming a superradiant cloud
  - Effectively generates particles for mass coupling $M\mu/{M_{\mathrm{Planck}}}^2 \sim O(0.1)$

Genesis of DM from PBHs



(Domènech, 2023)

We consider PBHs with ⋯

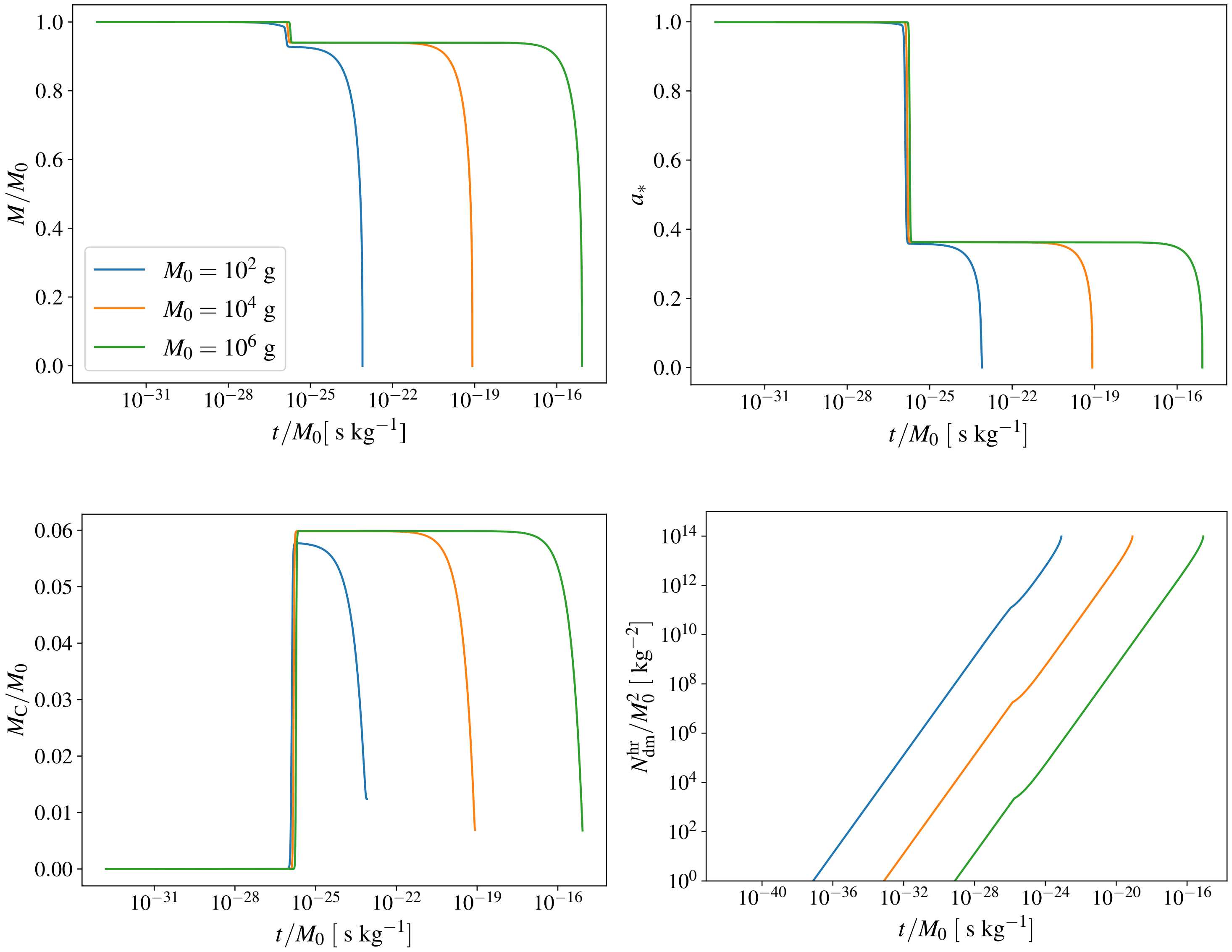
- Initial mass
  - $M_0 \lesssim 10^9\text{g}$ for not to spoil BBN
  - $M_0 \gtrsim 0.1$ g from inflation scale, $H_\text{I} \lesssim 10^{14}\text{GeV}$
- Initial abundance
  - $\beta \lesssim 1.1\times10^{-6}\left(\frac{M_0}{10^4\text{g}}\right)^{-17/24}$ from GWs during BBN, $\Omega_{\text{GW,BBN}} \lesssim 0.05$
  - $\beta \gtrsim 6.4\times10^{-10}\left(\frac{M_0}{10^4\text{g}}\right)^{-1}$ for the early matter-dominated era to exist
- Initial spin satisfying superradiance condition

Single-PBH evolution: Scalar DM particle

$$\frac{dN_{\rm sr}}{dt} = \Gamma_{\rm sr} N_{\rm sr} - \frac{P_{\rm GW}}{\mu},$$
$$\frac{dM}{dt} = -\frac{f(M,a_*)}{M^2} - \mu\Gamma_{\rm sr} N_{\rm sr},$$
$$\frac{{\rm d}a_*}{{\rm d}t} = -a_* \frac{g(M,a_*) - 2f(M,a_*)}{M^3} - \frac{m}{M^2}\Gamma_{\rm sr} N_{\rm sr}.$$

Superradiance
- $\sim$6% BH mass loss
- BH spins down to ~ 0.4
- BH mass $\rightarrow$ superradiant cloud $\rightarrow$ dissipated by GW

Hawking radiation
- Particle production rate is slightly changed when superradiance occurs



Hawking spectra obtained using `BlackHawk`

https://link.springer.com/article/10.1140/epjc/s10052-021-09702-8

Single-PBH evolution: Vector DM particle

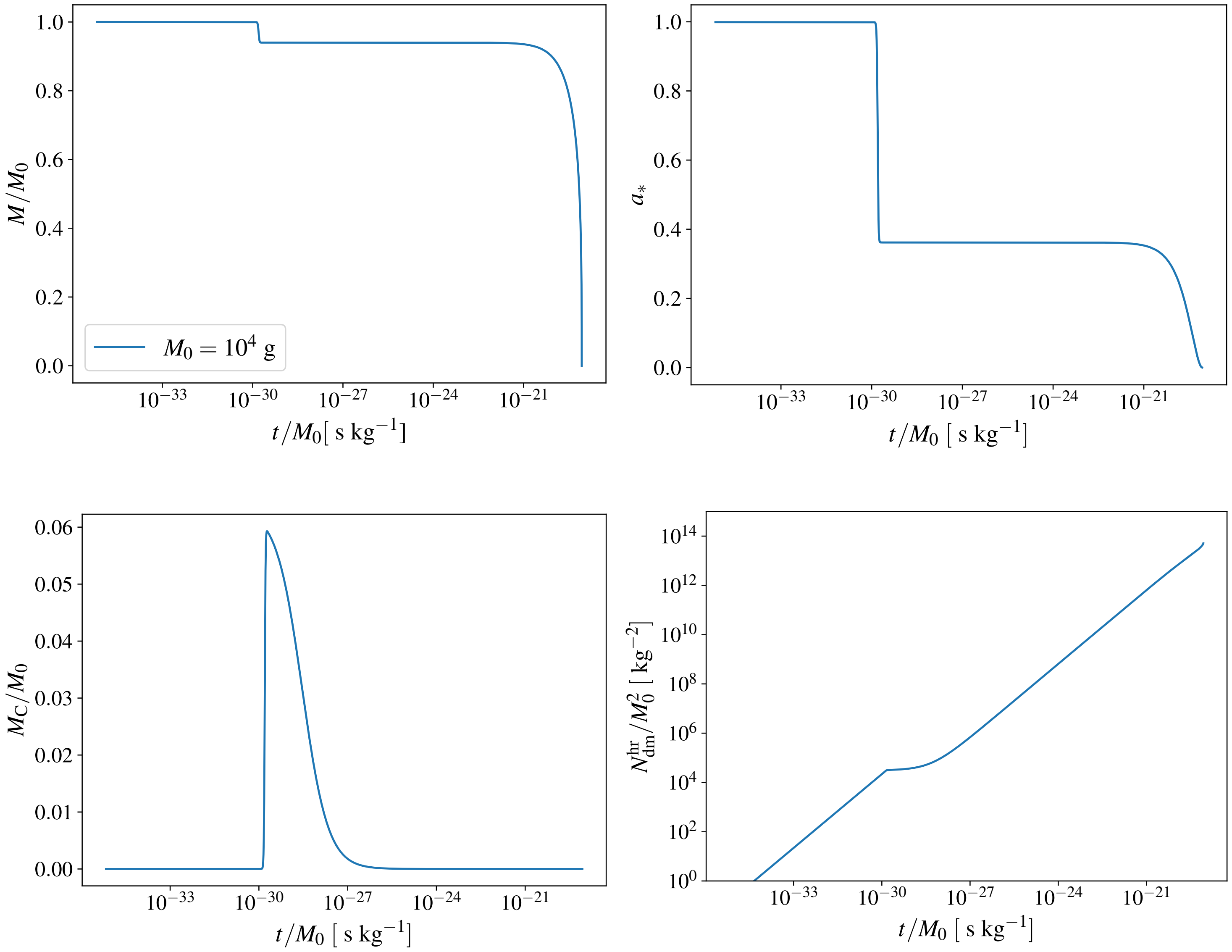
$$\frac{dN_{\rm sr}}{dt} = \Gamma_{\rm sr} N_{\rm sr} - \frac{P_{\rm GW}}{\mu},$$
$$\frac{dM}{dt} = -\frac{f\left(M, a_*\right)}{M^2} - \mu \Gamma_{\rm sr} N_{\rm sr},$$
$$\frac{\mathrm{d}a_*}{\mathrm{d}t} = -a_* \frac{g\left(M, a_*\right) - 2f\left(M, a_*\right)}{M^3} - \frac{m}{M^2}\Gamma_{\rm sr} N_{\rm sr}.$$

Superradiance

- Similar BH mass and spin losses
- Superradiant cloud is completely depleted

Hawking radiation

- Particle production rate is slightly changed when superradiance occurs
- DM particle number is like the scalar case



Hawking spectra obtained using `BlackHawk`
https://link.springer.com/article/10.1140/epjc/s10052-021-09702-8

Mechanisms

Hawking radiation

- Horizon temperature
- Schwarzschild: $T_{\mathrm{BH}} = 1/(8\pi M_{\mathrm{BH}})$
- Kerr: $T_{\mathrm{BH}} = \sqrt{1 - a_*^2}/(4\pi r_+)$

Production rate

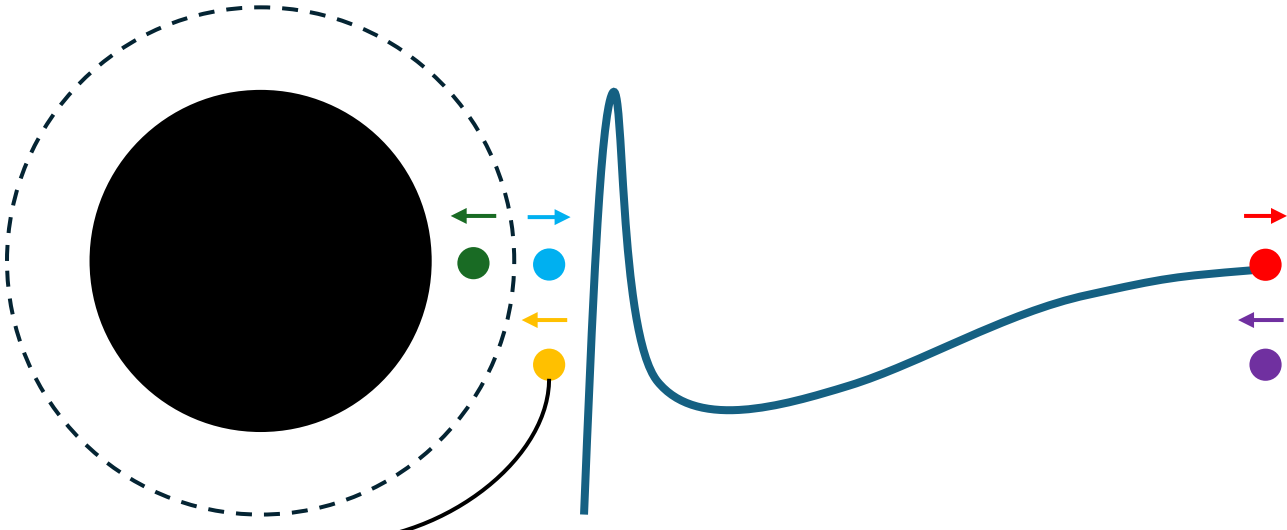
- Schwarzschild:

$$\frac{\mathrm{d}^2 N_i}{\mathrm{d}E\,\mathrm{d}t} = \frac{g_i}{2\pi} \frac{\Gamma_{s_i}(M_{\mathrm{BH}}, E)}{\exp(E/T_{\mathrm{BH}}) - (-1)^{2s_i}}$$

- Kerr:

The Greybody factor

$$\frac{\mathrm{d}^2 N_{i,lm}}{\mathrm{d}E\,\mathrm{d}t} = \frac{\Gamma_{s_i}^{lm}(M_{\mathrm{BH}}, E, a_*)}{\exp[(E - m\Omega_{\mathrm{H}})/T_{\mathrm{BH}}] - (-1)^{2s_i}}$$



Absorption probability for particle-BH scattering

$$\Gamma = \sigma p^2/\pi$$

Absorption cross section $\sigma \approx 27\pi G^2 M^2$ for Schwarzschild BH and massless particles with high energy (The geometrical-optics limit)

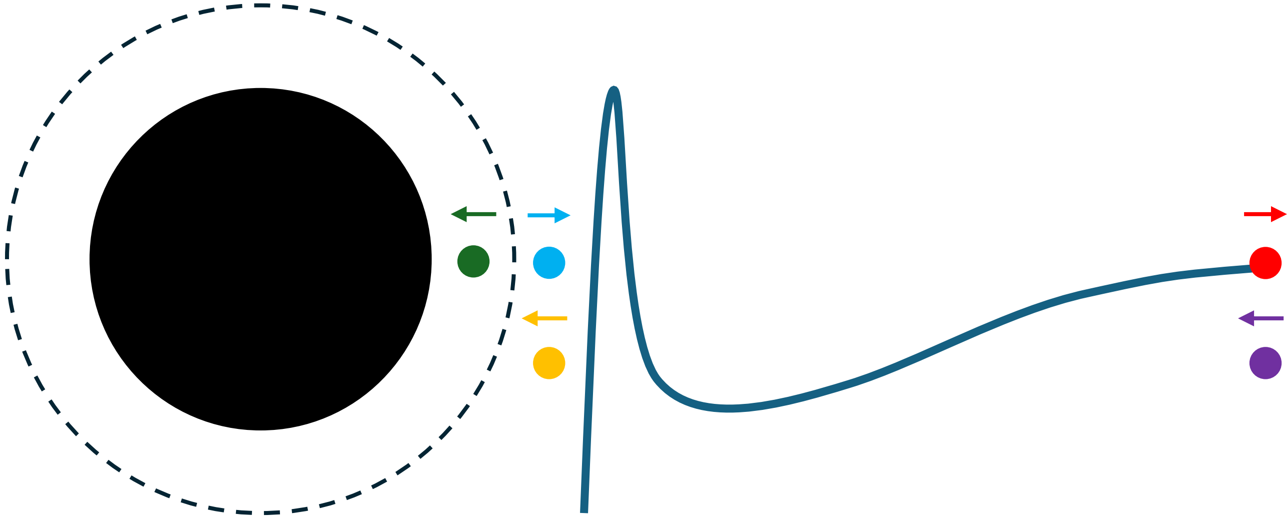
Hawking radiation

- Energy loss rate

$$f(M,a_*) \equiv -M^2 \frac{\mathrm{d}M}{\mathrm{d}t} = M^2 \int_0^{+\infty} E \sum_i \frac{\mathrm{d}^2 N_i}{\mathrm{d}E\,\mathrm{d}t}\,\mathrm{d}E$$

- Angular momentum loss rate

$$g(M,a_*) \equiv -\frac{M}{a_*}\frac{\mathrm{d}J}{\mathrm{d}t} = -\frac{M}{a_*}\int_0^{+\infty} \sum_i g_i \sum_{l,m} \frac{\mathrm{d}^2 N_{i,lm}}{\mathrm{d}E\,\mathrm{d}t}$$

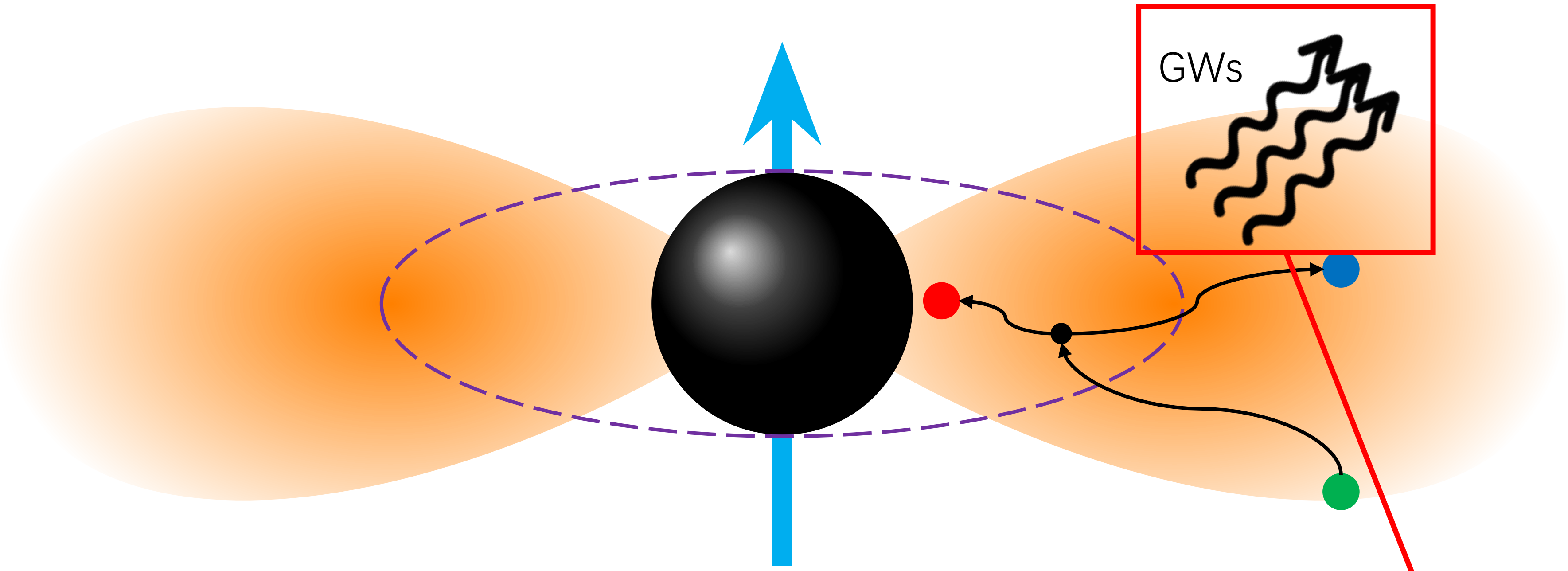


BH lifetime and number of particles emitted

$$\tau_{\mathrm{BH}} = \frac{1}{3}\left(\frac{27}{4}\,\frac{106.75+2+g_{\mathrm{dm}}}{30720\pi}\right)^{-1} M_0^3 \approx 2\times 10^{-19}\ \mathrm{s}\left(\frac{M_0}{1\ \mathrm{kg}}\right)^3$$

$$N^{\mathrm{hr}}_{\mathrm{dm,S}} \approx 8.95\times 10^{13}\left(\frac{M_0}{1\ \mathrm{kg}}\right)^2$$

Superradiance



$\mathrm{DM} + \mathrm{DM} \longrightarrow \mathrm{Graviton}$

Decrease superradiant cloud

See

Guo, Y., Bao, S. and Zhang, H. (2022) 'Subdominant Modes of Scalar Superradiant Instability and Gravitational Wave Beats'. Available at: https://doi.org/10.1103/PhysRevD.107.075009.

&

Guo, Y.-D. *et al.* (2024) 'The evolution and detection of vector superradiant instabilities'. Available at: https://doi.org/10.48550/arXiv.2407.00767.

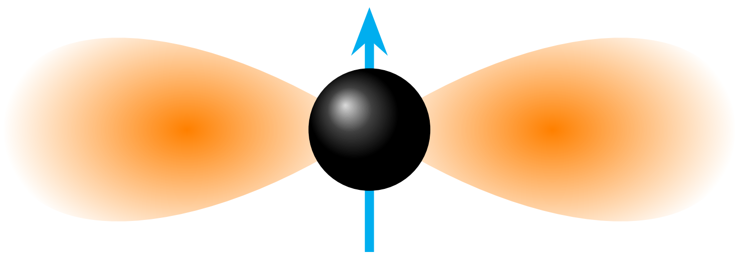
for detailed discussions.

Superradiance

Dominant scalar mode

$$\Gamma_{\rm S}^{\rm sr} = \frac{1}{24}(a_* - 2r_+\mu_{\rm S})(M\mu_{\rm S})^9$$

$$\tau_{\rm S}^{\rm sr} \approx 5.94 \times 10^{-26}\ {\rm s}\left(\frac{M}{1\ {\rm kg}}\right)\left(\frac{0.1}{M\mu_S}\right)^9 \frac{1}{a_*}$$

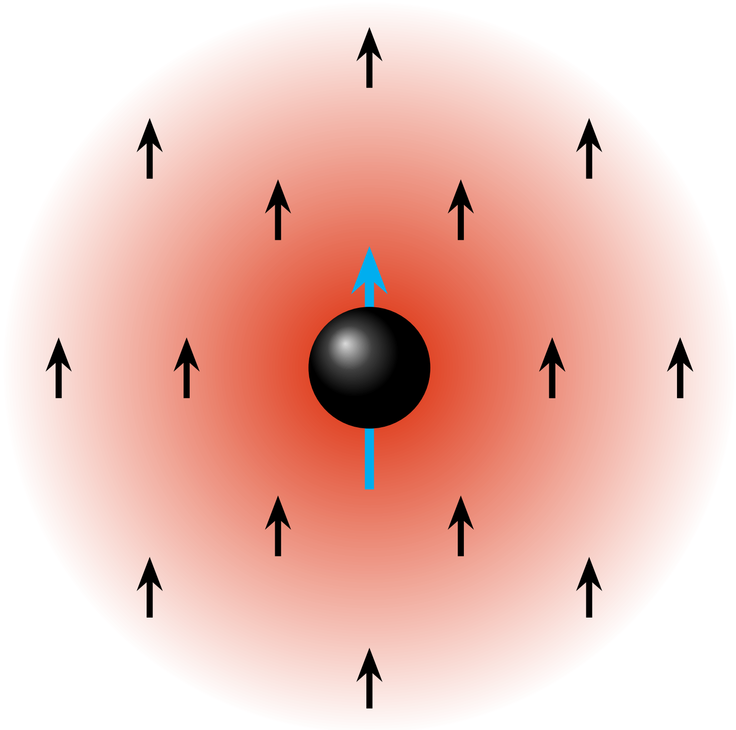


Dominant vector mode

$$\Gamma_{\rm V}^{\rm sr} = 4(a_* - 2r_+\mu_{\rm V})(M\mu_{\rm V})^7$$

$$\tau_{\rm V}^{\rm sv} \approx 6.19 \times 10^{-30}\ {\rm s}\left(\frac{M}{1\ {\rm kg}}\right)\left(\frac{0.1}{M\mu_{\rm V}}\right)^7 \frac{1}{a_*}$$

$$N_{\rm max}^{\rm sr} \approx 2.11 \times 10^{15}\left(\frac{M}{1\ {\rm kg}}\right)^2\left(a_{*0} - 0.4\frac{M\mu}{0.1}\right)$$



GW emission of the cloud

Power

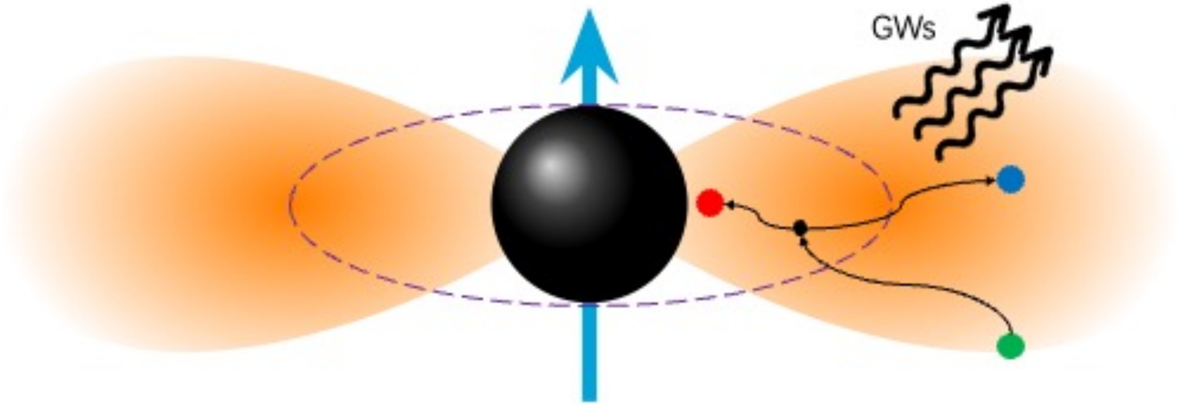
$$P_{\mathrm{S}}^{\mathrm{GW}} \approx \frac{484+9\pi^2}{23040}\left(\frac{M_S}{M}\right)^2 (M\mu_S)^{14}$$

$$P_{\mathrm{V}}^{\mathrm{GW}} \approx 60\left(\frac{M_V}{M}\right)^2 (M\mu_V)^{10}$$

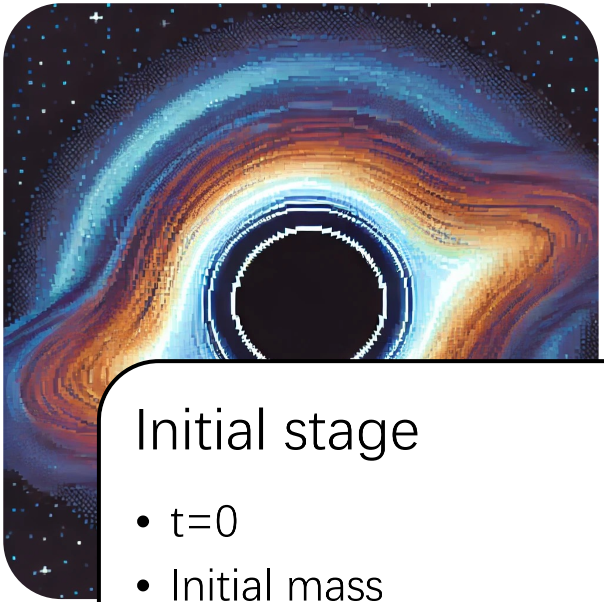
Duration

$$\tau_{\mathrm{S}}^{\mathrm{GW}} \approx 1.03 \times 10^{-19}\,\mathrm{s}\left(\frac{M}{1\,\mathrm{kg}}\right)\left(\frac{0.1}{M\mu_S}\right)^{15}\frac{1}{a_*}$$

$$\tau_{\mathrm{V}}^{\mathrm{GW}} \approx 4.34 \times 10^{-27}\,\mathrm{s}\left(\frac{M}{1\,\mathrm{kg}}\right)\left(\frac{0.1}{M\mu_S}\right)^{11}\frac{1}{a_*}$$

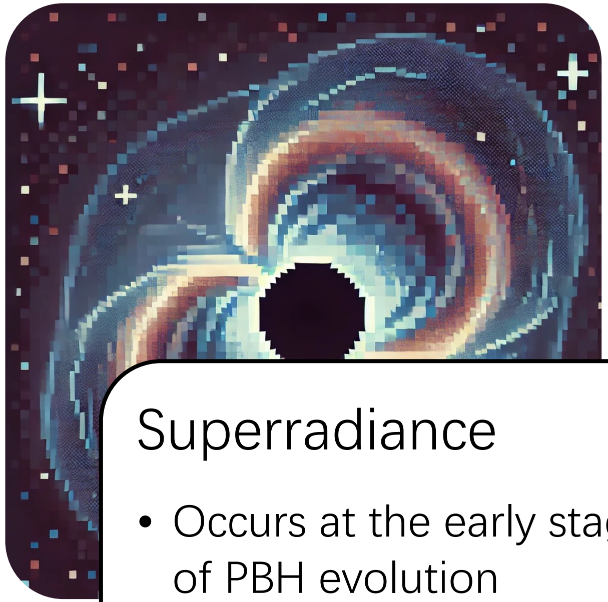


A sketch of the evolution



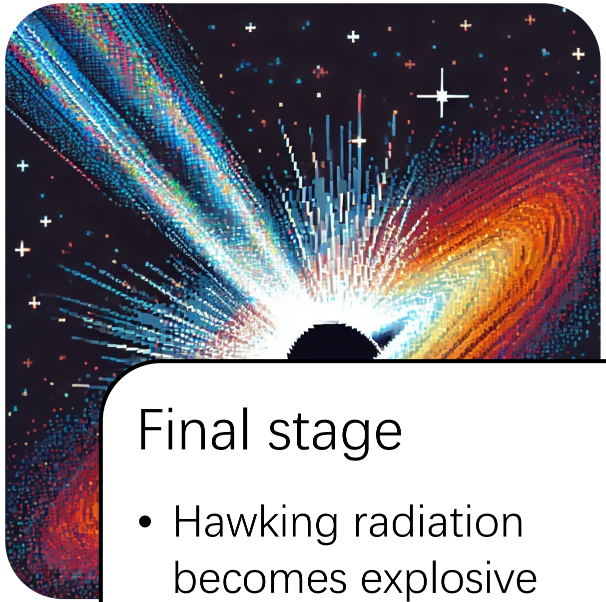
Initial stage

- t=0
- Initial mass
- Initial spin above superradiance threshold



Superradiance

- Occurs at the early stage of PBH evolution
- A maximum DM occupation number is reached
- The cloud is dissipated by GW emission



Final stage

- Hawking radiation becomes explosive
- BH mass decreases very fast
- GW emission of the superradiant cloud becomes negligible

AI-generated images

THANK YOU!