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

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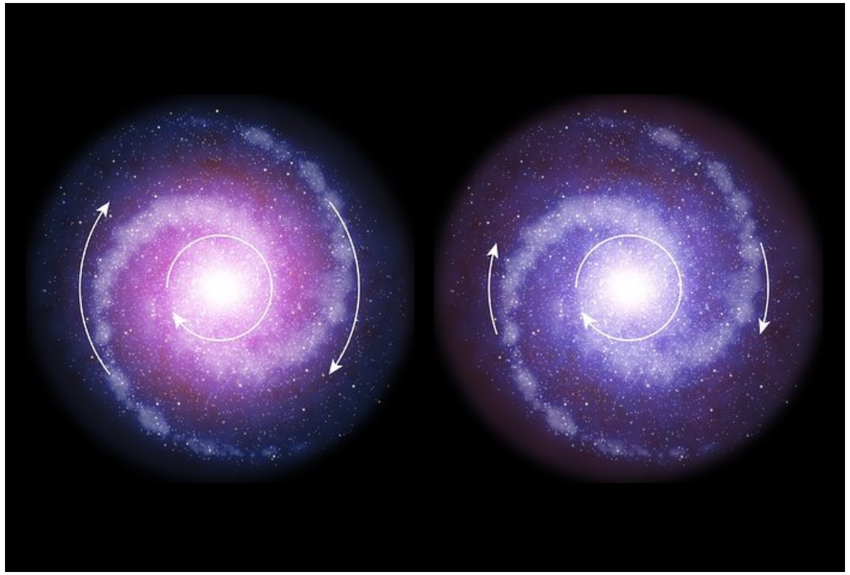
Introduction

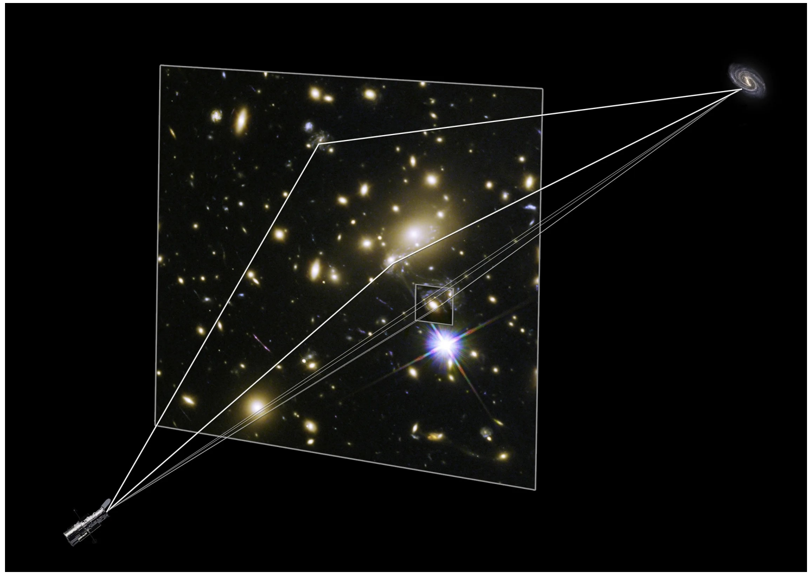
Dark matter: evidence from gravitational effects



Galaxy rotation curves

Gravitational

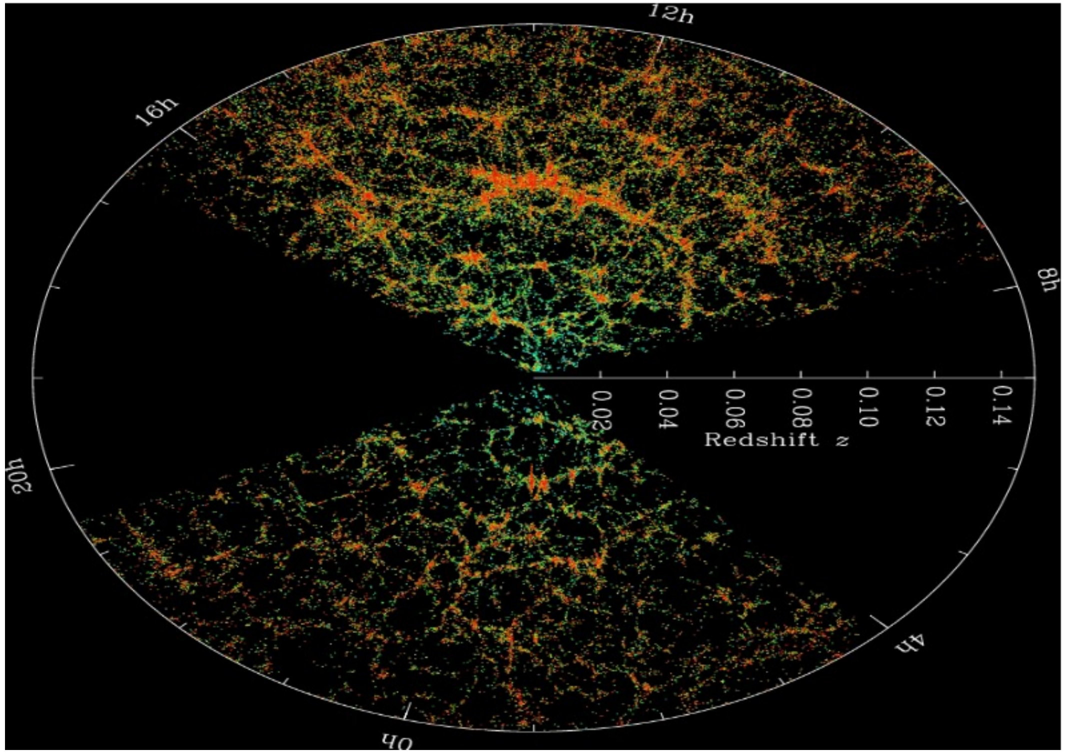
Credit: ESO/L. Calçada



Gravitational lensing

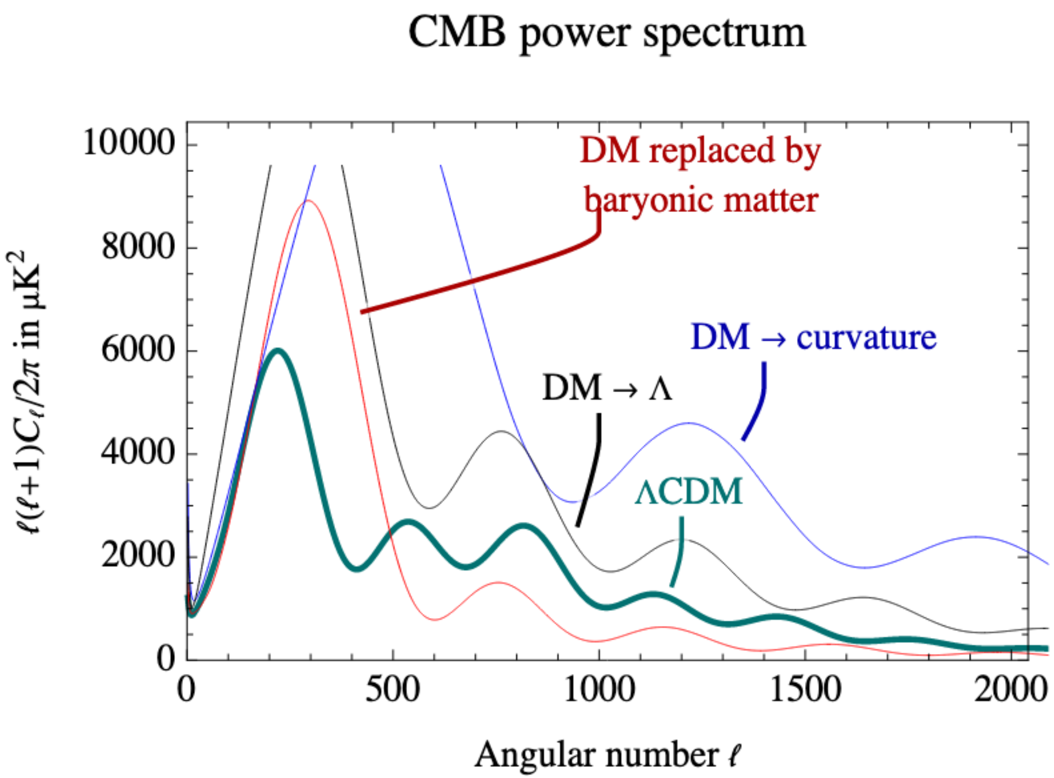
NASA & ESA

Dark matter: evidence from gravitational effects



Large-scale structure

Gravitational



CMB acoustic peaks

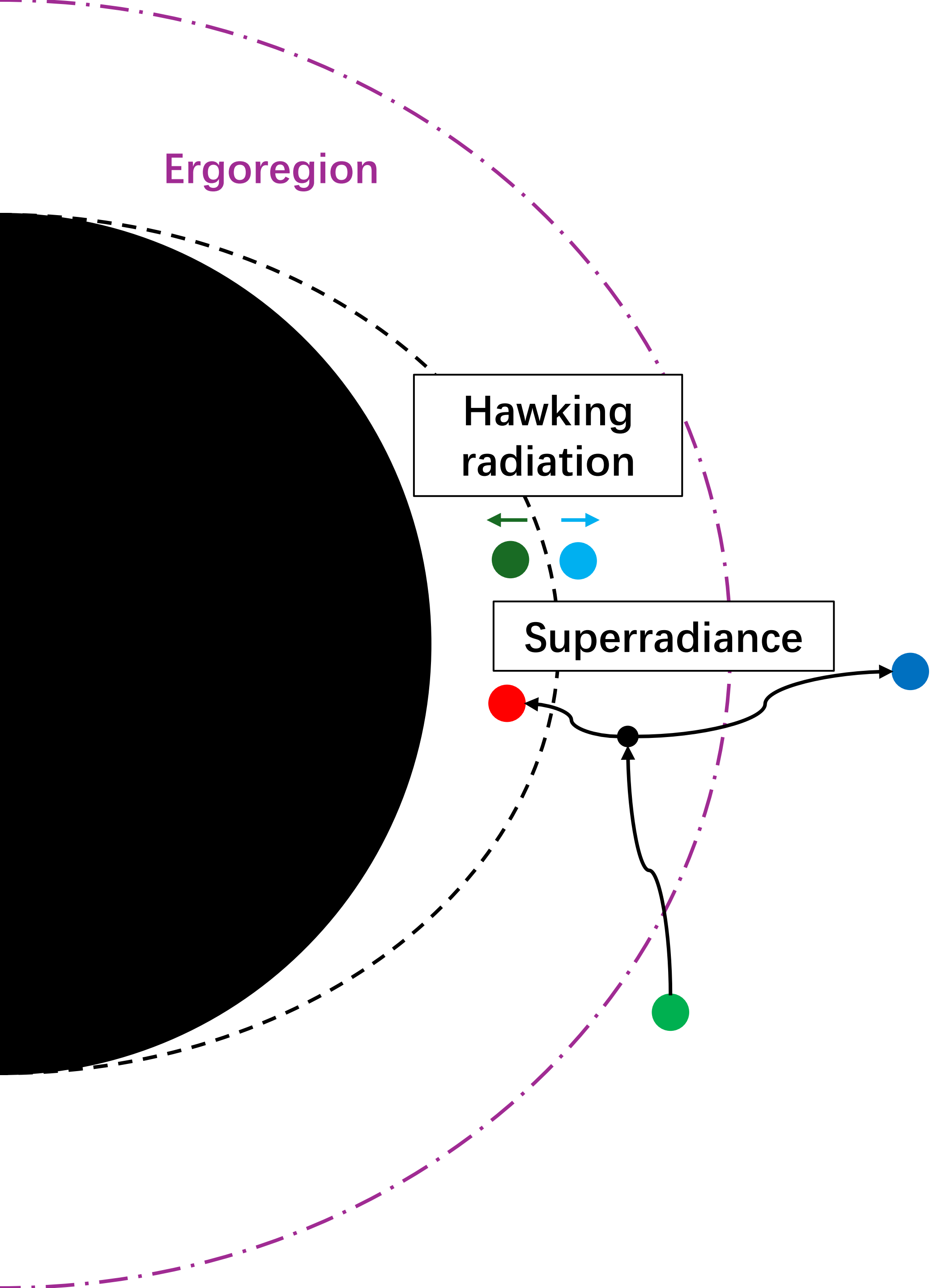
Gravitational

(Cirelli, Strumia and Zupan, 2024)

Motivation for phenomenology

Gravitational evidence → Gravitational-only interaction between DM and SM particles → Gravitational genesis mechanisms

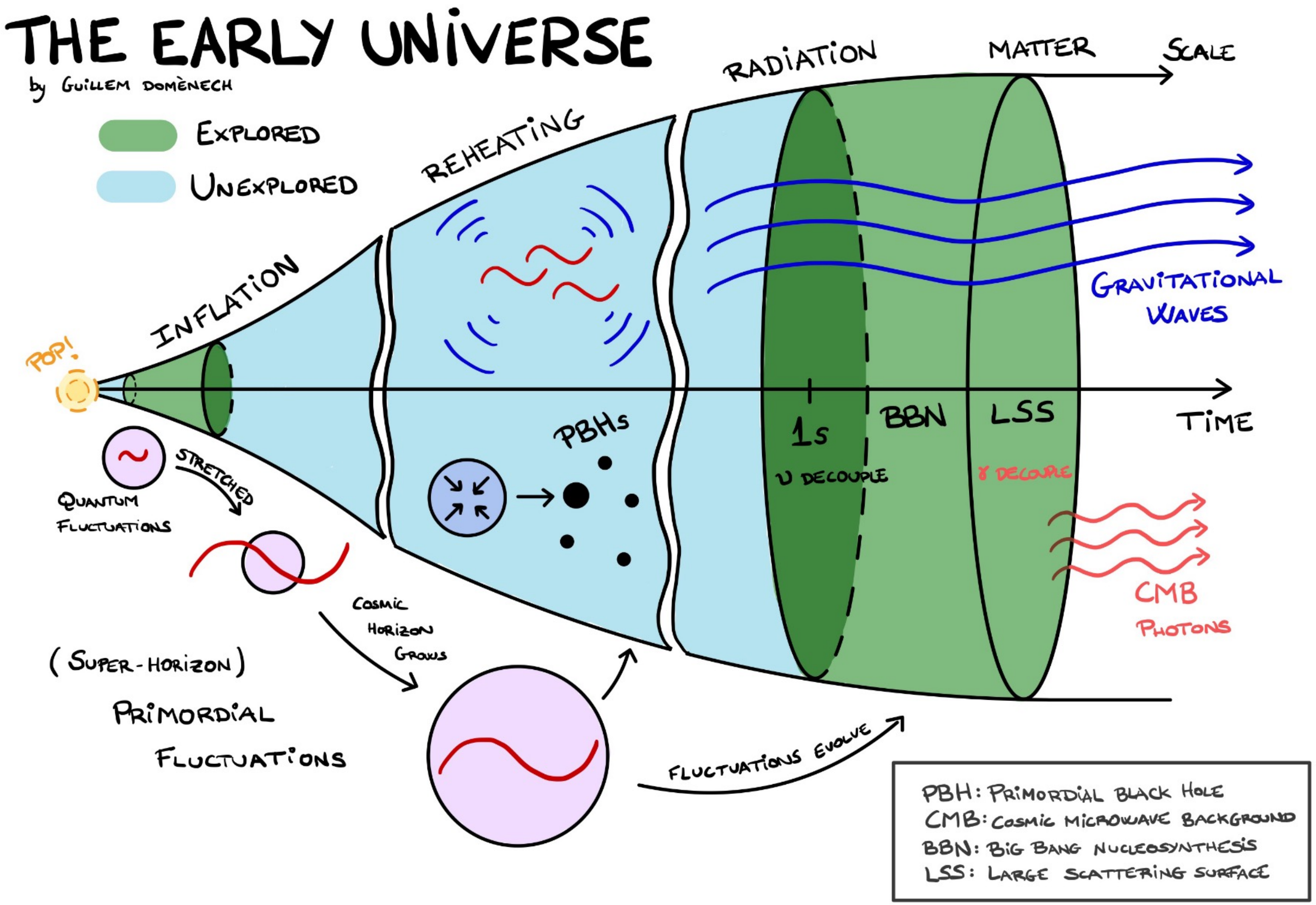
Settings & Preliminary Results



Two mechanisms for gravitational DM genesis, both from black holes

- Hawking radiation
  - Particle creation at the BH horizon
  - Efficiently generates all particles with $\mu \lesssim T_{\mathrm{BH}}$
- Superradiance
  - Requires ergoregion & superradiance condition
  - Leads to a population of superradiant particles in the ergoregion, which forms a superradiant cloud
  - Efficiently generates particles satisfying superradiance condition for mass coupling $M\mu/{M_{\mathrm{Planck}}}^2 \sim O(0.1)$

Genesis of DM from PBHs

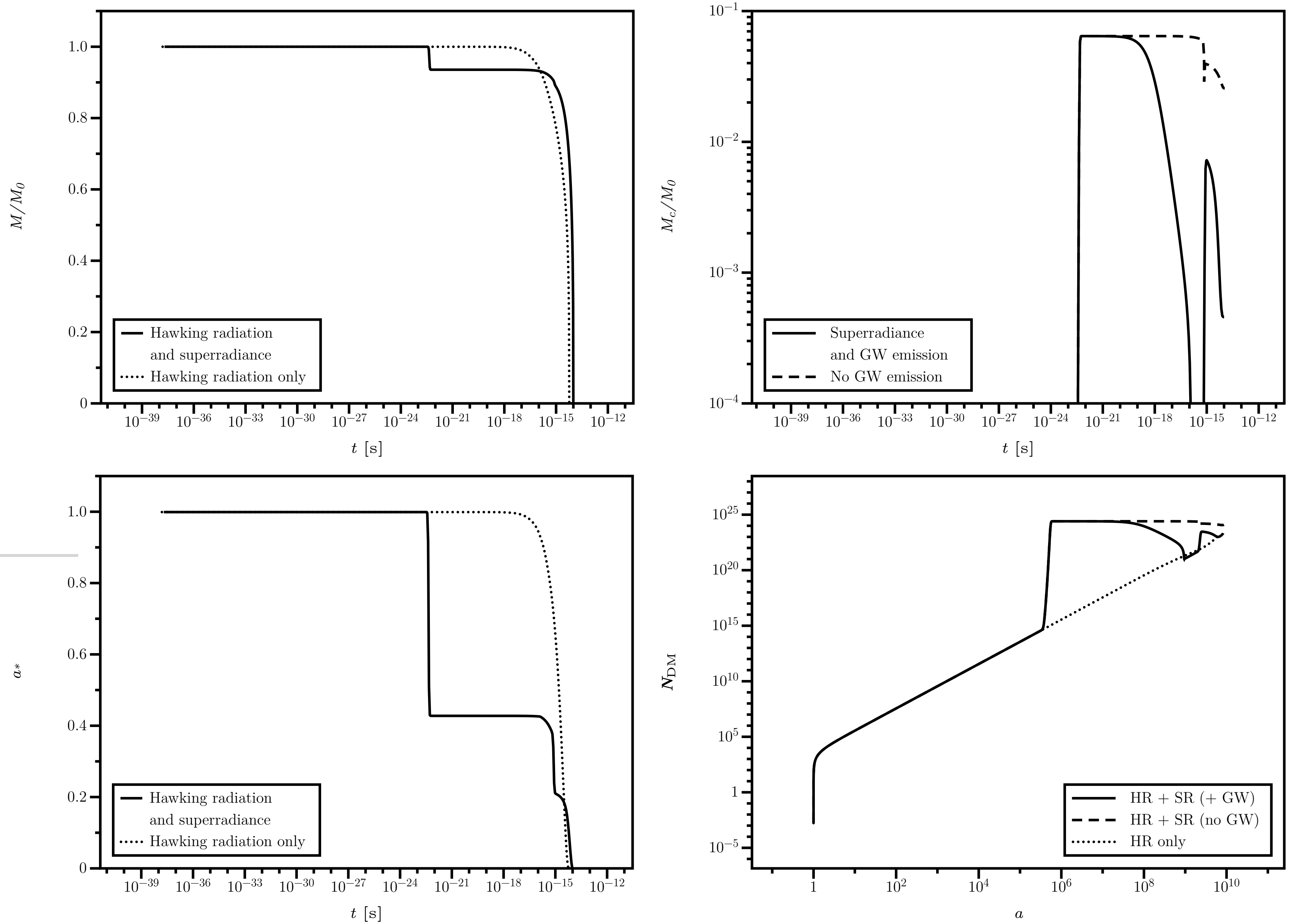


(Domènech, 2023)

We consider PBHs with ⋯

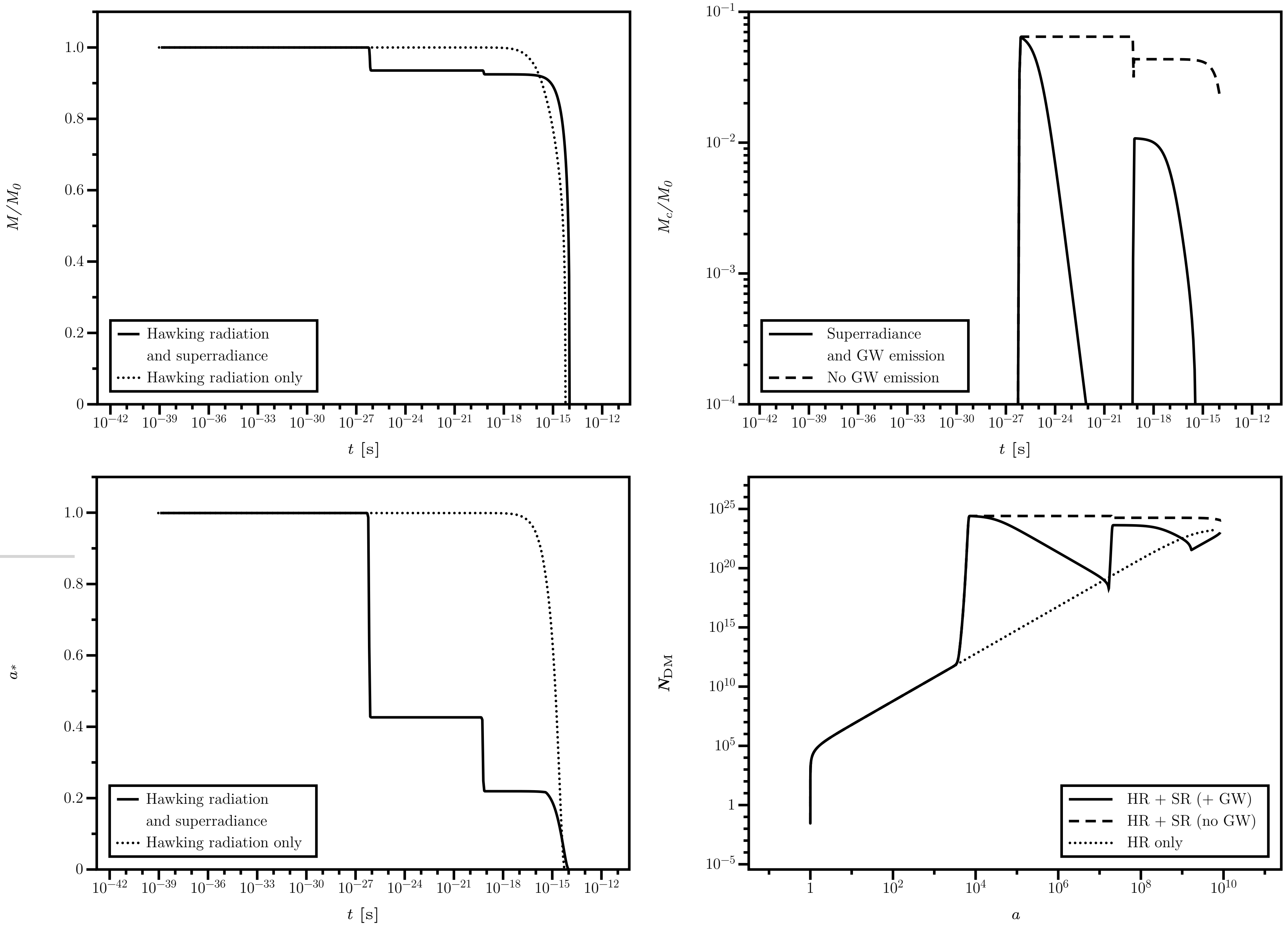
- Initial mass
  - $M_0 \lesssim 10^9\mathrm{g}$ to avoid spoiling BBN
  - $M_0 \gtrsim 0.1\ \mathrm{g}$ from inflation scale, $H_\mathrm{I} \lesssim 10^{14}\mathrm{GeV}$
- Initial abundance
  - $\beta \lesssim 1.1\times 10^{-6}\left(\frac{M_0}{10^4\mathrm{g}}\right)^{-17/24}$ from GWs during BBN, $\Omega_{\mathrm{GW,BBN}} \lesssim 0.05$
  - $\beta \gtrsim 6.4\times 10^{-10}\left(\frac{M_0}{10^4\mathrm{g}}\right)^{-1}$ to allow the early matter-dominated era to exist
- Initial spin satisfying superradiance condition

Scalar DM



M/M_0
t [s]
Hawking radiation
and superradiance
Hawking radiation only
M_c/M_0
Superradiance
and GW emission
No GW emission
a_*
N_DM
a
HR + SR (+ GW)
HR + SR (no GW)
HR only

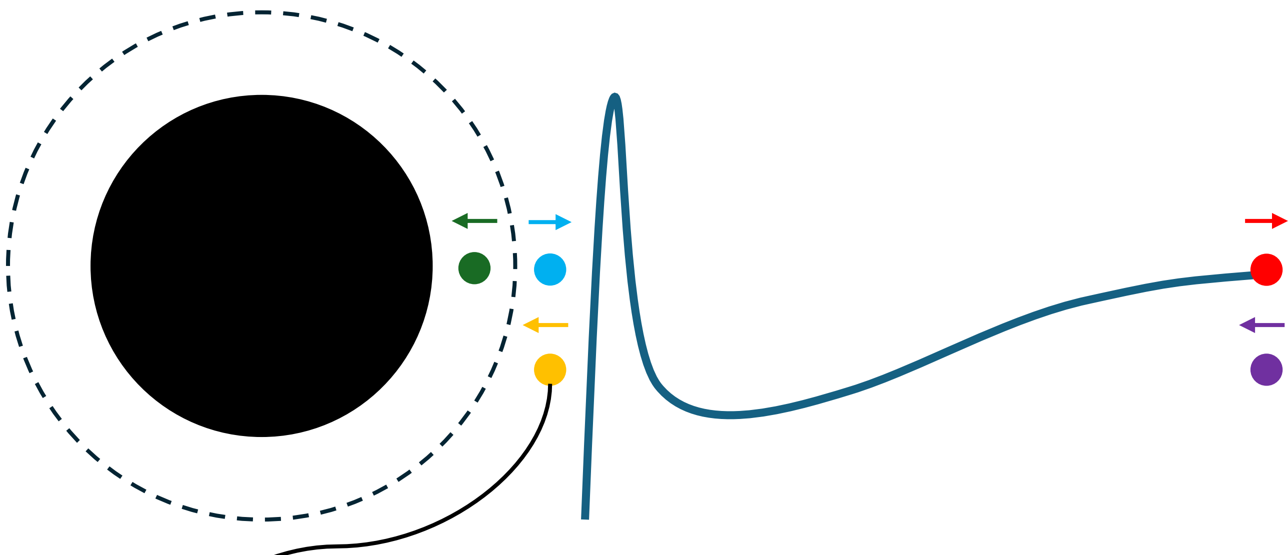
Vector DM



M/M_0
t [s]
Hawking radiation and superradiance
Hawking radiation only
M_c/M_0
Superradiance and GW emission
No GW emission
a_*
$N_{\rm DM}$
a
HR + SR (+ GW)
HR + SR (no GW)
HR only

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

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

Absorption probability for particle-BH scattering

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

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

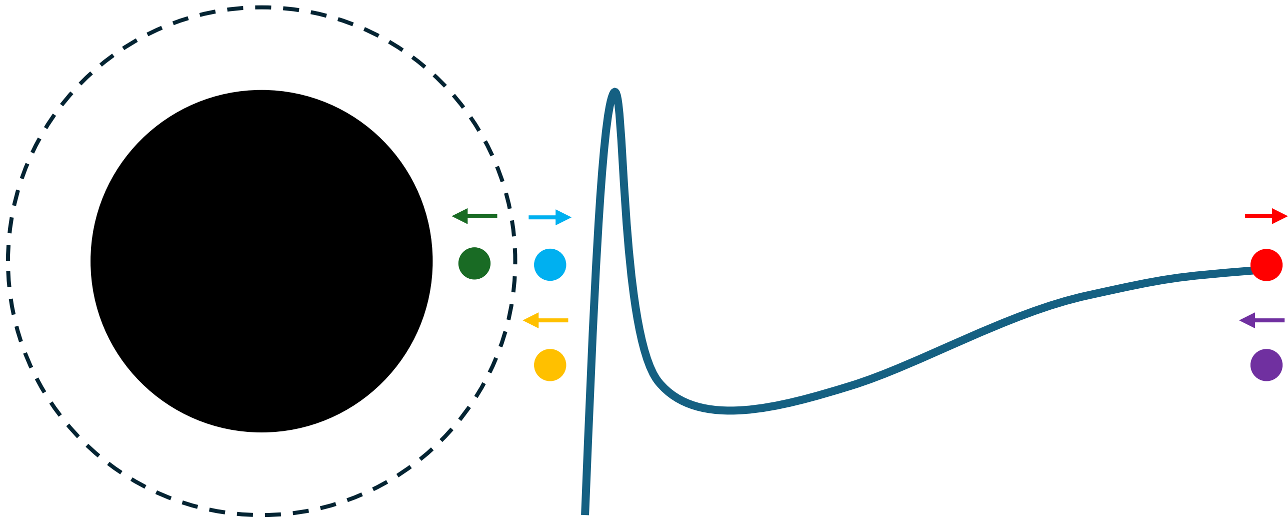
Hawking radiation

- 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

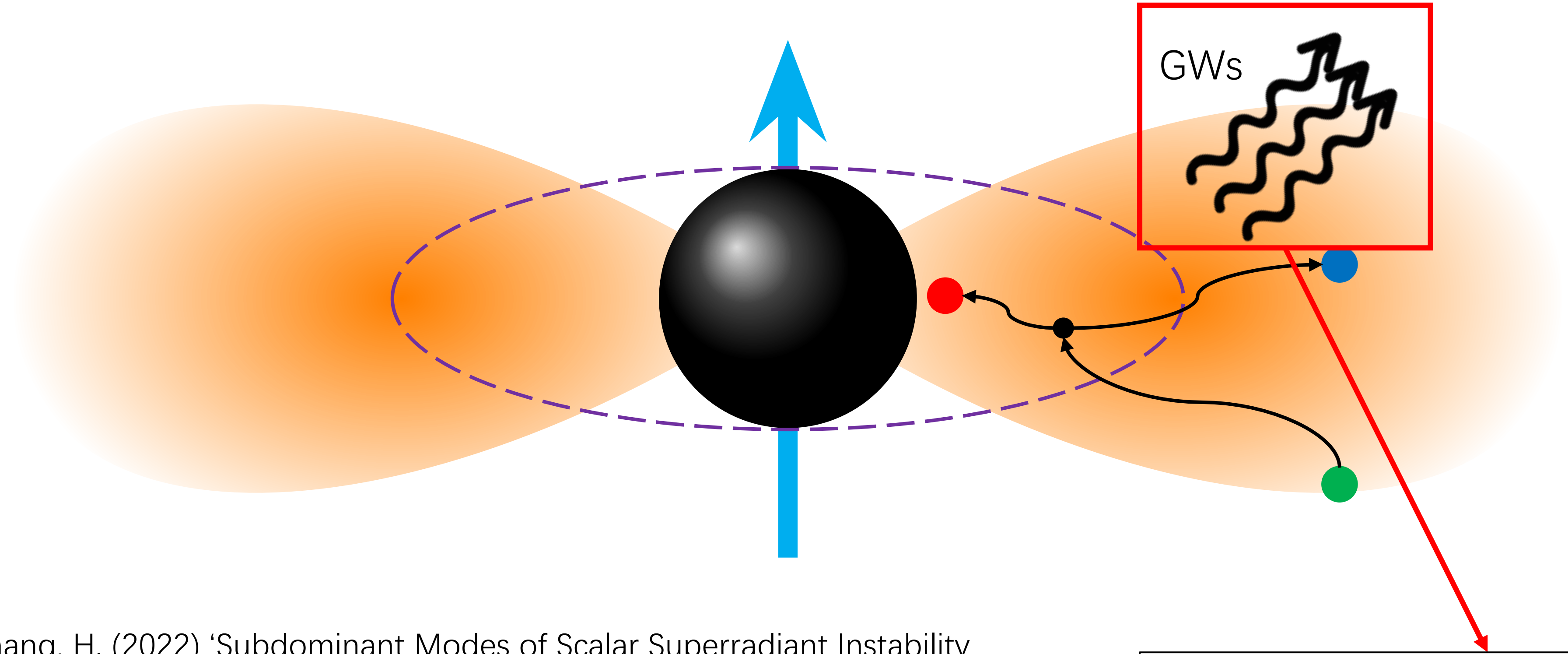
$$g(M, a_*) \equiv -\frac{M}{a_*} \frac{\mathrm{d}J}{\mathrm{d}t}$$
$$= -\frac{M}{a_*} \int_0^{+\infty} \sum_i g_i \sum_{l,m} \frac{\mathrm{d}^2 N_{i,lm}}{\mathrm{d}E\, \mathrm{d}t}$$



BH lifetime and number of particles emitted

$$\tau_{\mathrm{BH}} = \frac{1}{3} \left(\frac{27}{4} \frac{106.75 + 2 + g_{\mathrm{dm}}}{30720\pi} \right)^{-1} M_0^3$$
$$\approx 2 \times 10^{-19}\ \mathrm{s} \left(\frac{M_0}{1\ \mathrm{kg}} \right)^3$$
$$N_{\mathrm{dm,S}}^{\mathrm{hr}} \approx 8.95 \times 10^{13} \left(\frac{M_0}{1\ \mathrm{kg}} \right)^2$$

Superradiance



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

Decreases the mass of the 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.

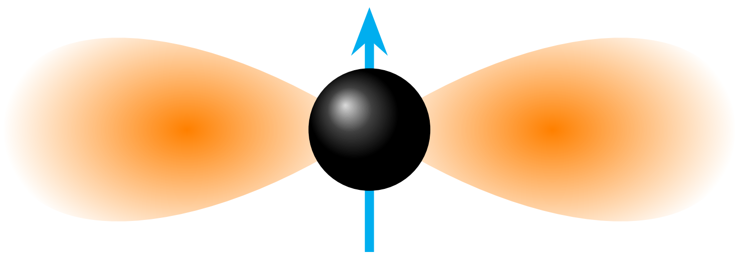
for detailed discussions.

Superradiance

Dominant scalar mode

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

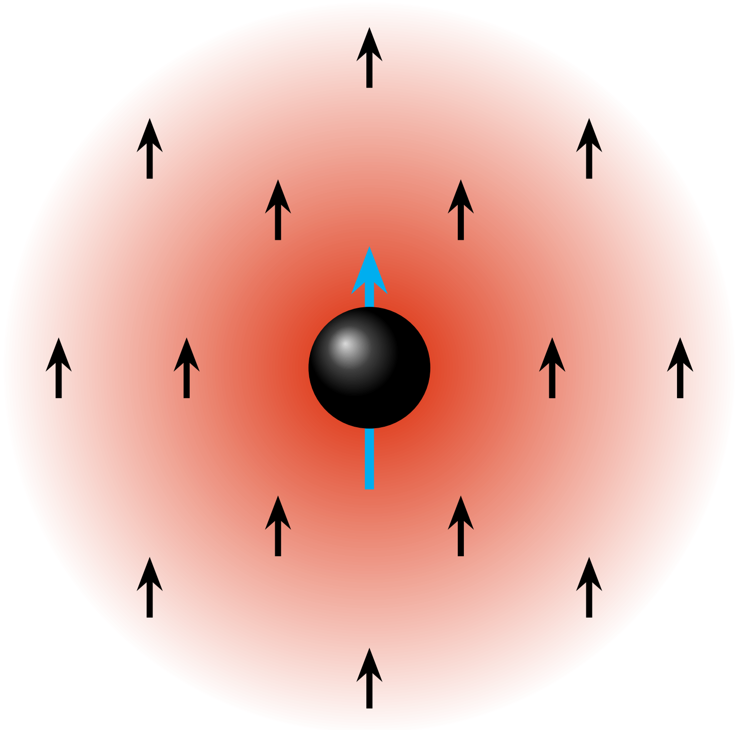
$$\tau_{\mathrm{S}}^{\mathrm{sr}} \approx 5.94 \times 10^{-26}\ \mathrm{s}\left(\frac{M}{1\ \mathrm{kg}}\right)\left(\frac{0.1}{M\mu_S}\right)^9 \frac{1}{a_*}$$



Dominant vector mode

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

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



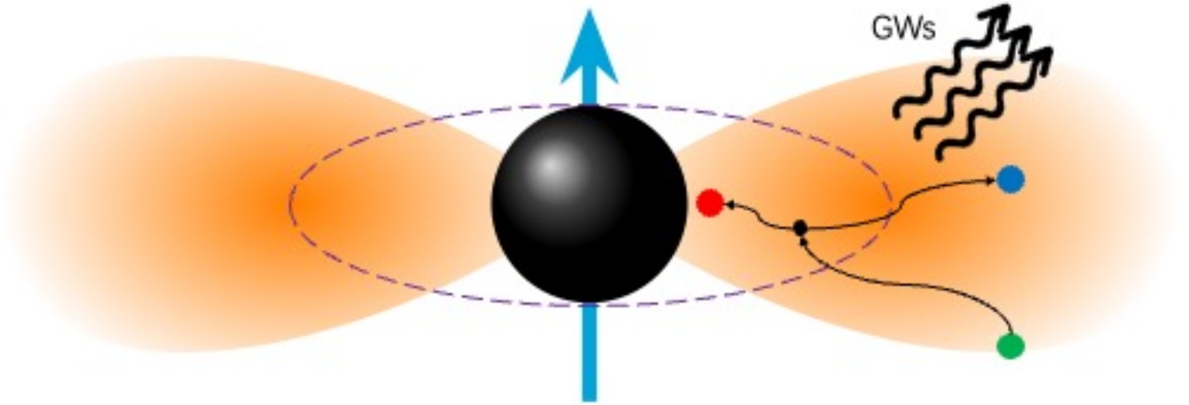
$$N_{\max}^{\mathrm{sr}} \approx 2.11 \times 10^{15}\left(\frac{M}{1\ \mathrm{kg}}\right)^2\left(a_{*0} - 0.4\frac{M\mu}{0.1}\right)$$

GW emission of the cloud

Power

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

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

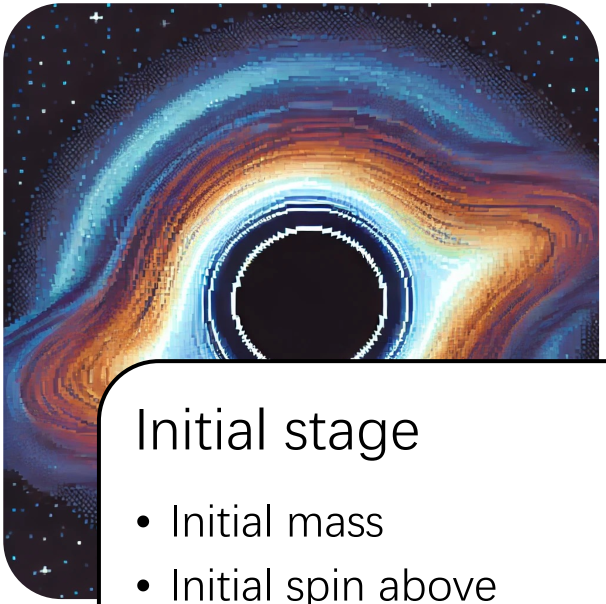


Duration

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

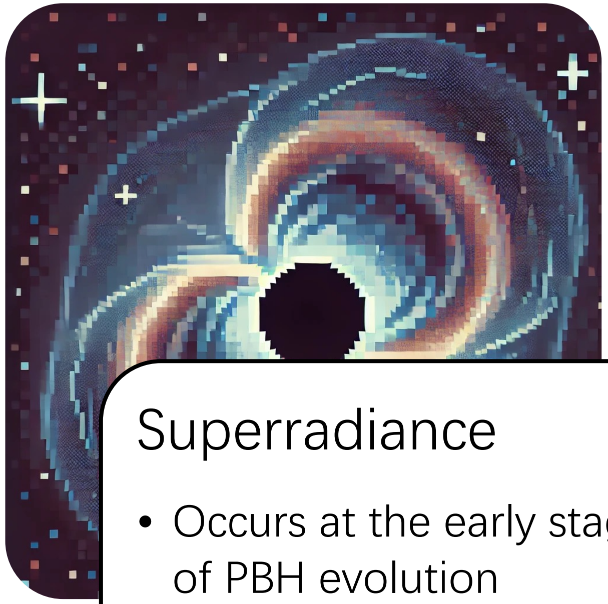
$$\tau_{\rm V}^{\rm GW} \approx 4.34 \times 10^{-27}\,{\rm s}\left(\frac{M}{1\,{\rm kg}}\right)\left(\frac{0.1}{M\mu_S}\right)^{11}\frac{1}{a_*}$$

A sketch of the evolution



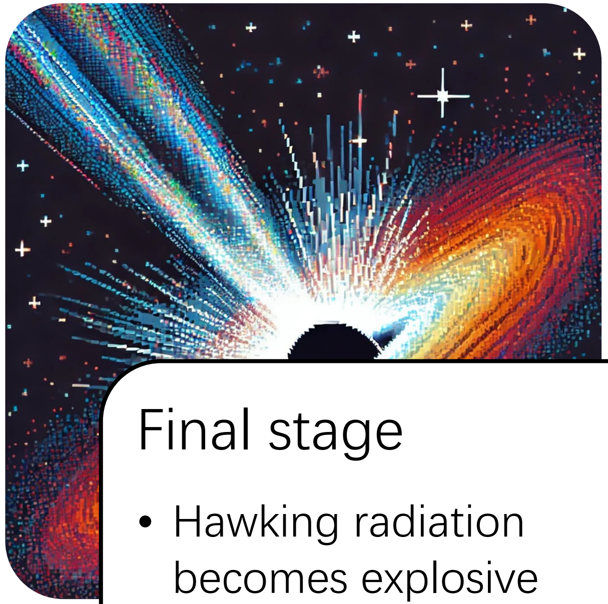
Initial stage

- Initial mass
- Initial spin above superradiance threshold
- Initial abundance



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
- PBH fully evaporates
- Superradiant DM particles in cloud, if any, become free

AI-generated images

THANK YOU!