Superradiant dark matter production from primordial black holes

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Based on arXiv:2504.18935

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Qingdao

Outline

1. Motivation

Gravitational DM production

2. DM from PBHs

Hawking radiation & Superradiance

3. The missing physics

GW emission & multi-mode dynamics

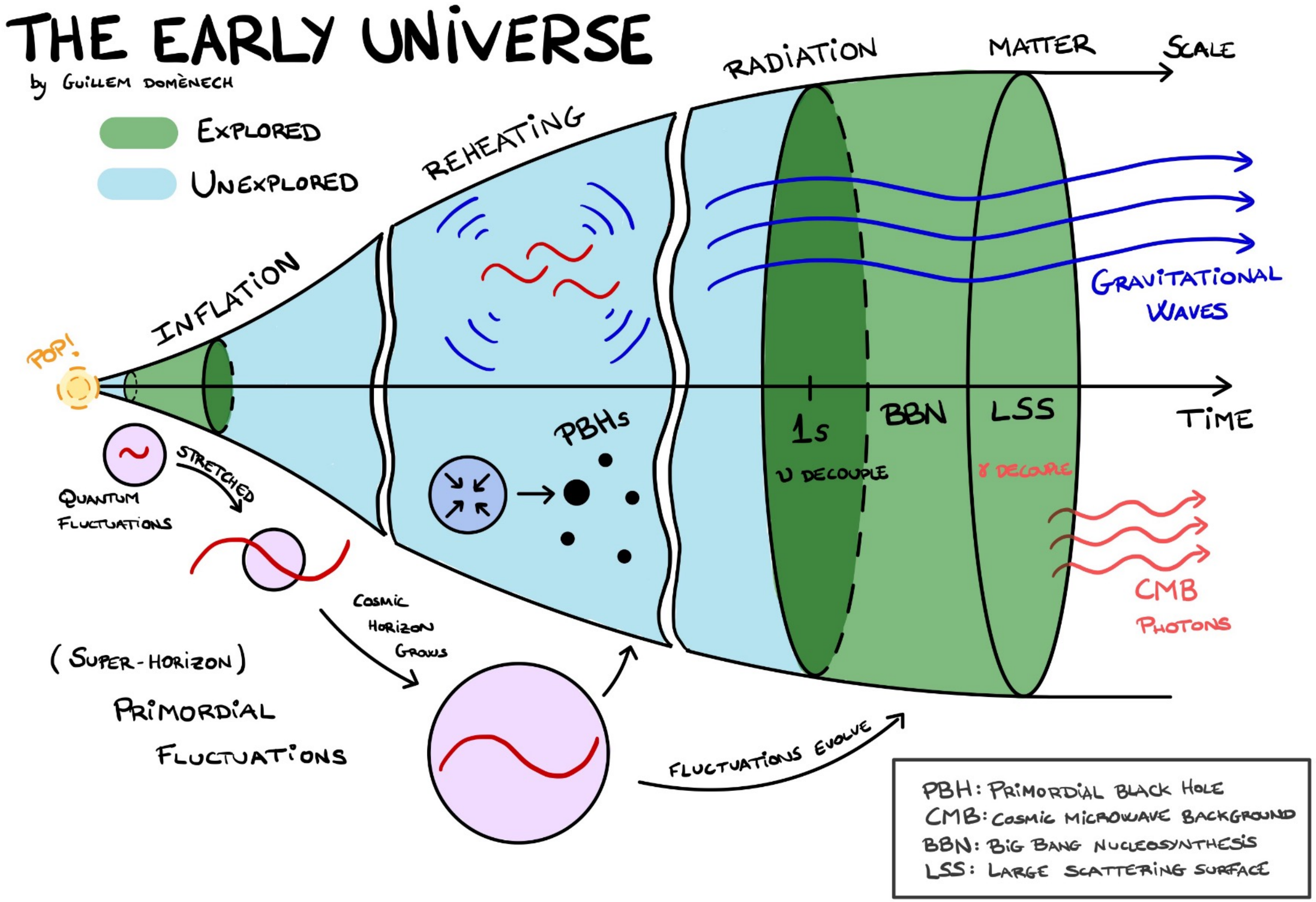
4. Revised dynamics

Evolution & parameter space

5. Conclusion

Take-aways

1. Motivation



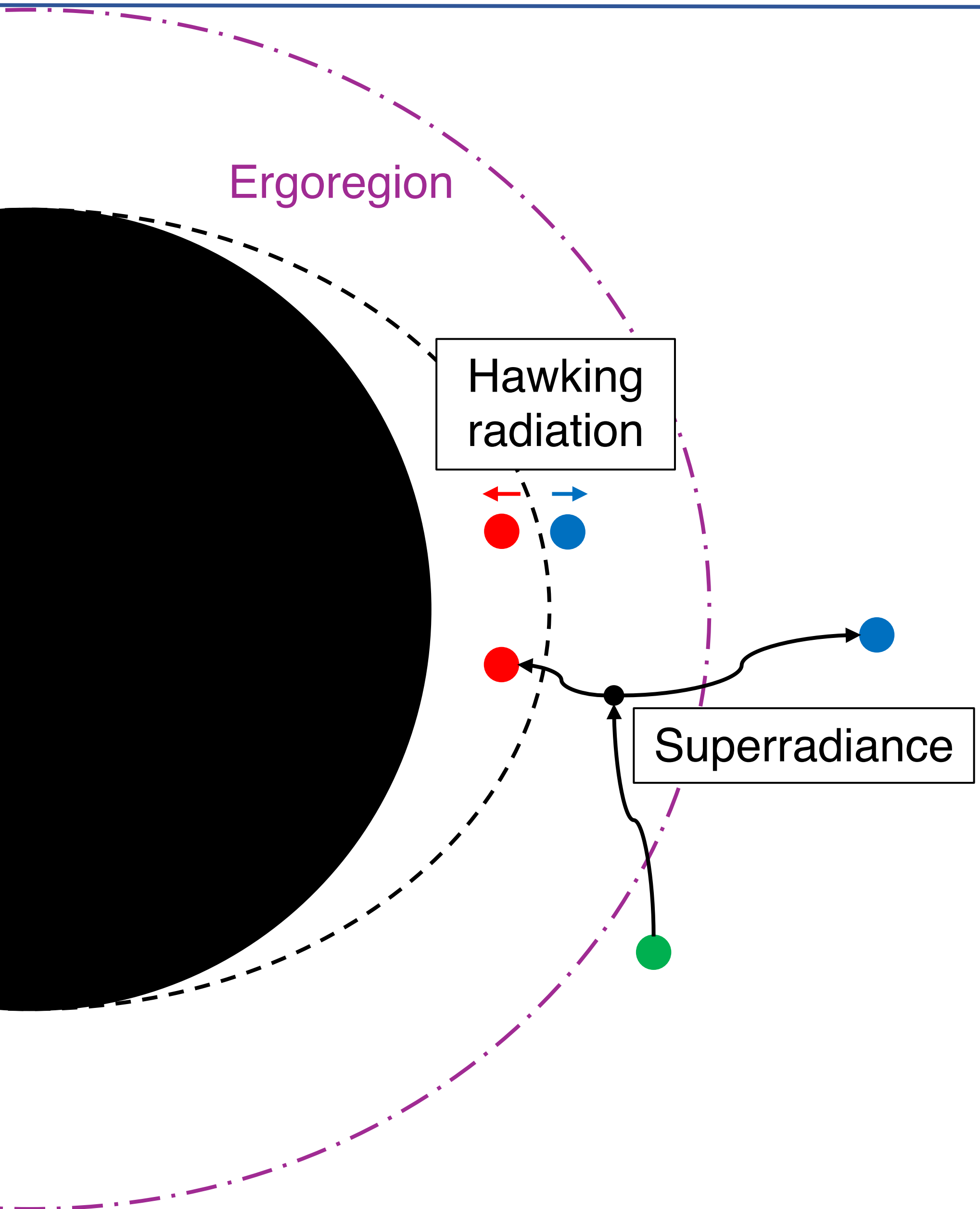
- DM may couple only through gravity.
- Can gravity alone yield today's relic density?

- Answer — Yes, via PBHs!
  - Hawking radiation
  - Superradiant instabilities

- We consider early-universe PBHs that evaporate before BBN: $M_{\rm ini} \lesssim 10^9$ g

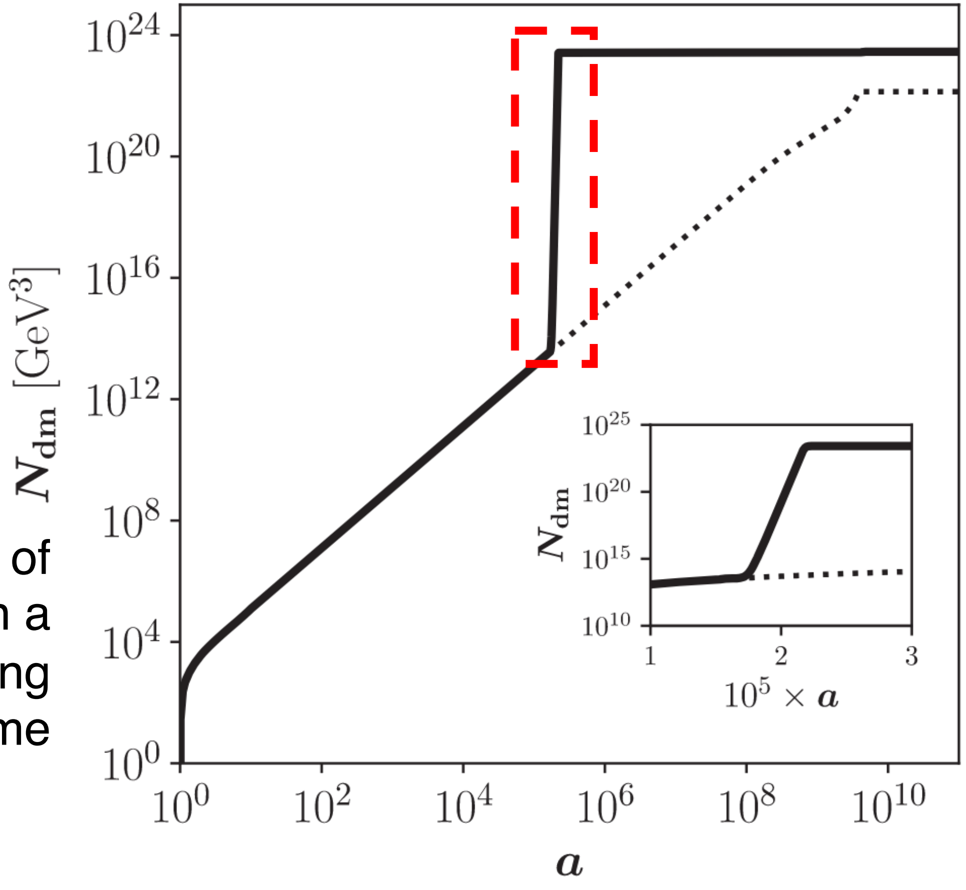
Domènech (2023)
arXiv:2307.06964

2. DM from PBHs: Hawking radiation & superradiance



- Hawking radiation
  - Efficiently generates all particles with mass $\lesssim T_{\mathrm{BH}}$
- Superradiance
  - Extraction of mass and angular momentum from Kerr BH
    - Requires enough BH spin (decay when not enough)
  - Population of superradiant particles (with mass μ)
    - Forms a "superradiant cloud"
  - Mass coupling $M\mu/{M_{\mathrm{Planck}}}^2 \sim O(0.1)$

3. Previous investigation



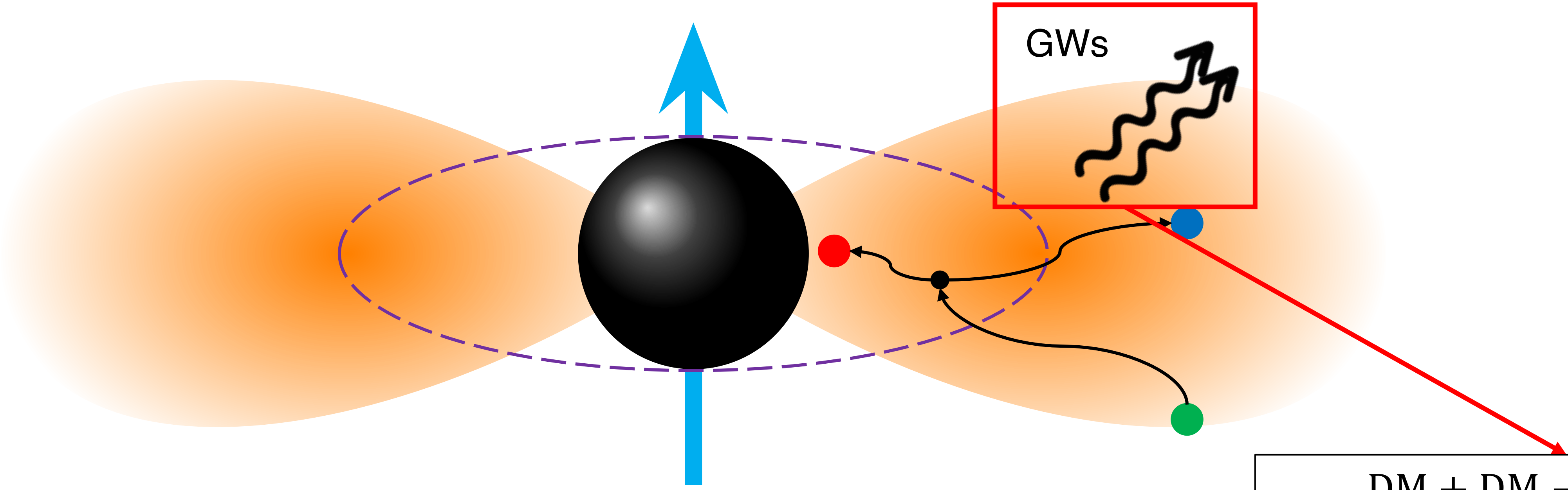
Number of DM in a comoving volume

Scale factor

- DM **enhanced** by superradiance
  - Hawking radiation alone: $\mathcal{N}_{\rm DM} \sim 10^{21}$
  - Superradiance: $\mathcal{N}_{\rm DM} \sim 10^{23}$
- Settings of Bernal et al.:
  - Scalar DM particle
  - A single superradiant mode
  - No evolution after growth
- This picture is **incomplete**:
  - Missing GW emission
  - Missing multi-mode dynamics

Bernal et al. (2022)
10.1103/PhysRevD.106.015020

3.1. The first missing physics: GW emission

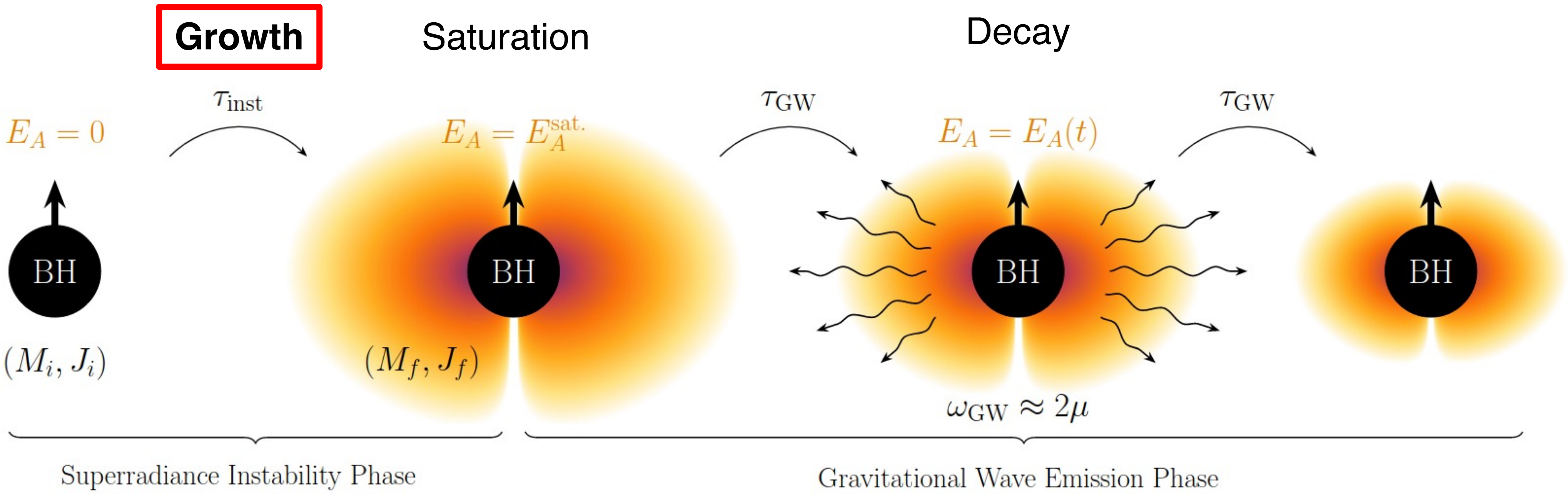


$\mathrm{DM} + \mathrm{DM} \longrightarrow \mathrm{Graviton}$

Decreases the mass of the superradiant cloud

Detailed discussions:
Guo, Y.-D. et al. (2023)
10.1103/PhysRevD.107.075009
Guo, Y.-D. et al. (2024)
10.1103/PhysRevD.110.083029

3.1. The first missing physics: GW emission

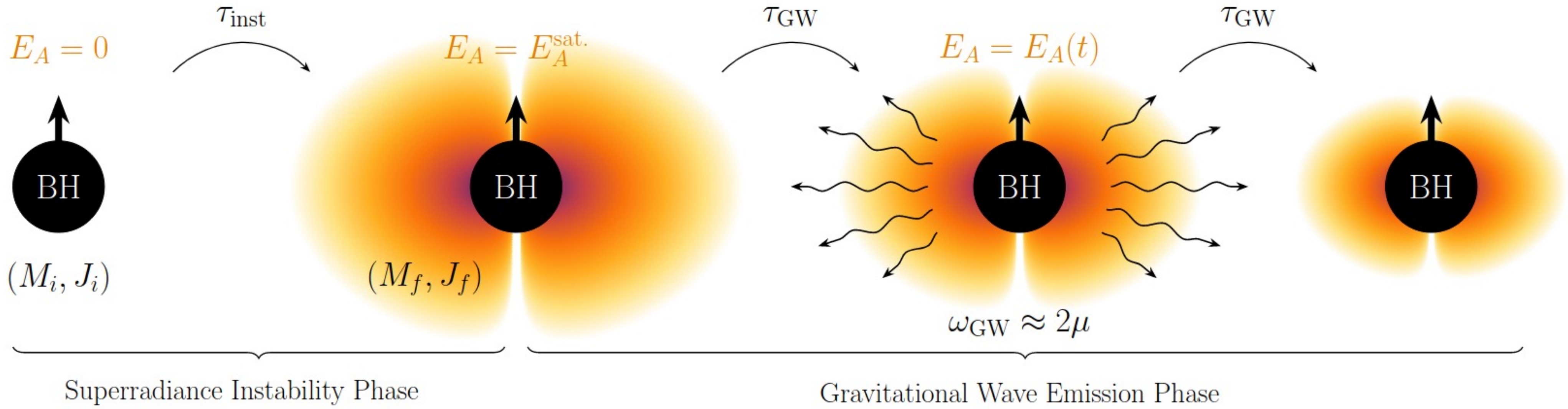


Evolution of superradiance: **Growth** → Saturation → Decay

Figure from
Siemonsen, N., & East, W. E. (2020)
PRD, 101(2), 024019

3.1. The first missing physics: GW emission

Growth **Saturation** Decay



Evolution of superradiance: Growth → **Saturation** → Decay

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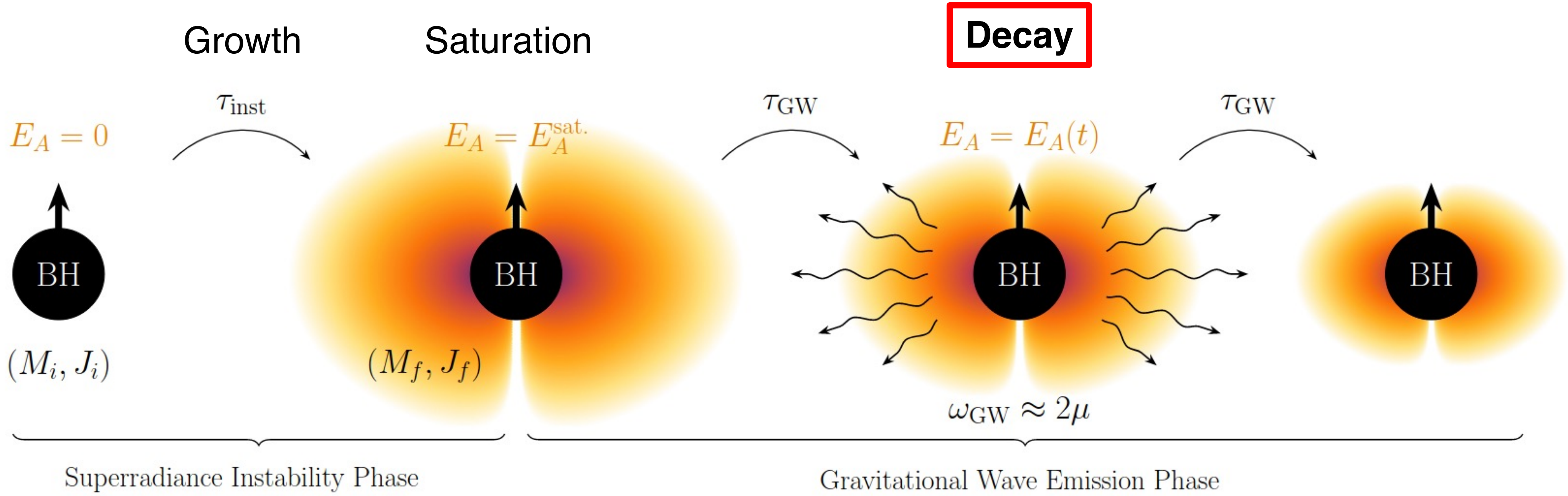

Evolution of superradiance: Growth → Saturation → **Decay**

Figure from
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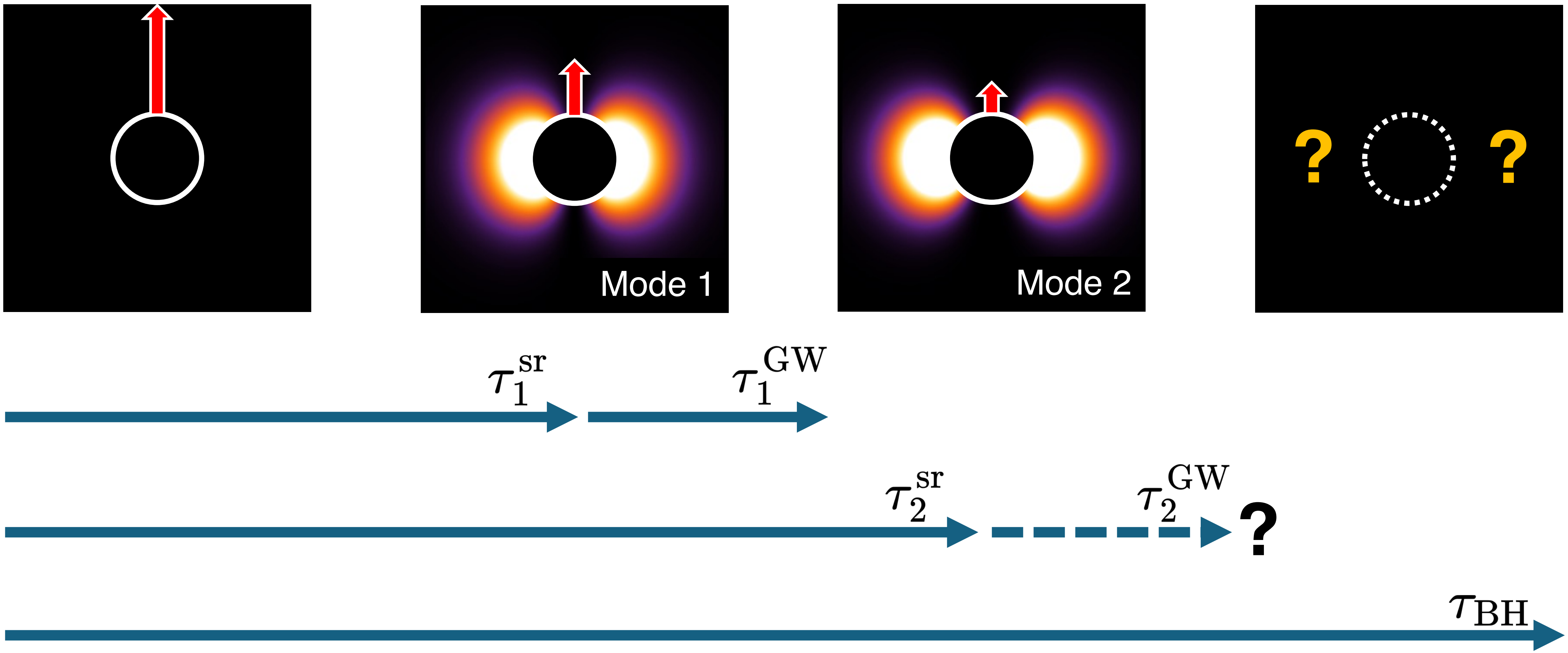
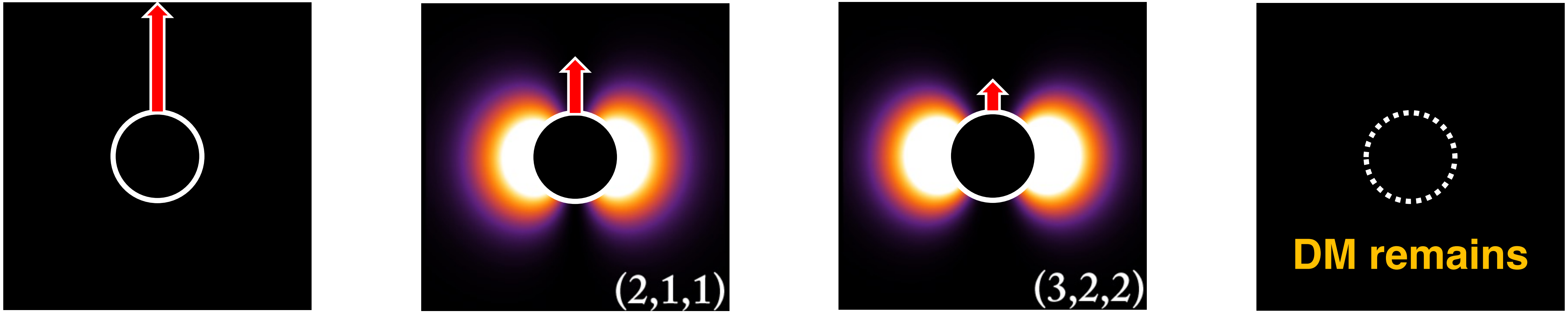
3.2. The second missing physics: Multi-mode dynamics



3.2. The second missing physics: Multi-mode dynamics

- Example: Scalar superradiance



$$\tau_{211}^{\rm sr} \approx 5.94 \times 10^{-26}\ {\rm s} \left(\frac{M}{1\ {\rm kg}}\right)\left(\frac{0.1}{M\mu}\right)^{9} \frac{1}{a_*}$$

$$\tau_{211}^{\rm GW} \approx 1.0 \times 10^{-19}\ {\rm s} \left(\frac{M}{1\ {\rm kg}}\right)\left(\frac{0.1}{M\mu}\right)^{15} \frac{1}{a_*}$$

$$\tau_{322}^{\rm sr} \approx 1.37 \times 10^{-18}\ {\rm s} \left(\frac{M}{1\ {\rm kg}}\right)\left(\frac{0.1}{M\mu}\right)^{13} \frac{1}{a_*}$$

$$\tau_{322}^{\rm GW} \approx 1.8 \times 10^{-10}\ {\rm s} \left(\frac{M}{1\ {\rm kg}}\right)\left(\frac{0.1}{M\mu}\right)^{19} \frac{1}{a_*}$$

$$\tau_{\rm BH} \approx 2.3 \times 10^{-19}\ {\rm s} \left(\frac{M_{\rm ini}}{1\ {\rm kg}}\right)^{3}$$

Previous dynamics

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N^{sr}: **Occupation number**

$$\frac{\mathrm{d}N^{\mathrm{sr}}}{\mathrm{d}t} = \Gamma^{\mathrm{sr}} N^{\mathrm{sr}}$$

Γ^{sr}: **Superradiance rate**

Growth for $\Gamma > 0$

Decay for $\Gamma < 0$

Previous dynamics

$N^{\rm sr}$: Occupation number

$$\frac{\mathrm{d}N^{\rm sr}}{\mathrm{d}t} = \Gamma^{\rm sr} N^{\rm sr}$$

$\Gamma^{\rm sr}$: Superradiance rate

Growth for $\Gamma > 0$

Decay for $\Gamma < 0$

f: Page factor of mass loss

PBH mass

$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{f\left(M, a_*\right)}{M^2} - \mu \Gamma^{\rm sr} N^{\rm sr}$$

A superradiant particle takes mass of μ

Previous dynamics

$N^{\rm sr}$: Occupation number

$$\frac{\mathrm{d}N^{\rm sr}}{\mathrm{d}t}=\Gamma^{\rm sr}N^{\rm sr}$$

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Growth for $\Gamma>0$

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PBH mass

$$\frac{\mathrm{d}M}{\mathrm{d}t}=-\frac{f\left(M,a_*\right)}{M^2}-\mu\Gamma^{\rm sr}N^{\rm sr}$$

A superradiant particle takes mass of μ

g: Page factor of angular momentum loss

PBH spin

$$\frac{\mathrm{d}a_*}{\mathrm{d}t}=-a_*\frac{g\left(M,a_*\right)-2f\left(M,a_*\right)}{M^3}-\frac{m}{M^2}\Gamma^{\rm sr}N^{\rm sr}+\frac{2a_*}{M}\mu\Gamma^{\rm sr}N^{\rm sr}$$

A superradiant particle takes angular momentum of m

4. Revised dynamics

N_i^{sr}: Occupation number of mode i

$$\frac{\mathrm{d}N_i^{\mathrm{sr}}}{\mathrm{d}t} = \Gamma_i^{\mathrm{sr}} N_i^{\mathrm{sr}} - \frac{P_i^{\mathrm{GW}}}{\mu}$$

PBH mass

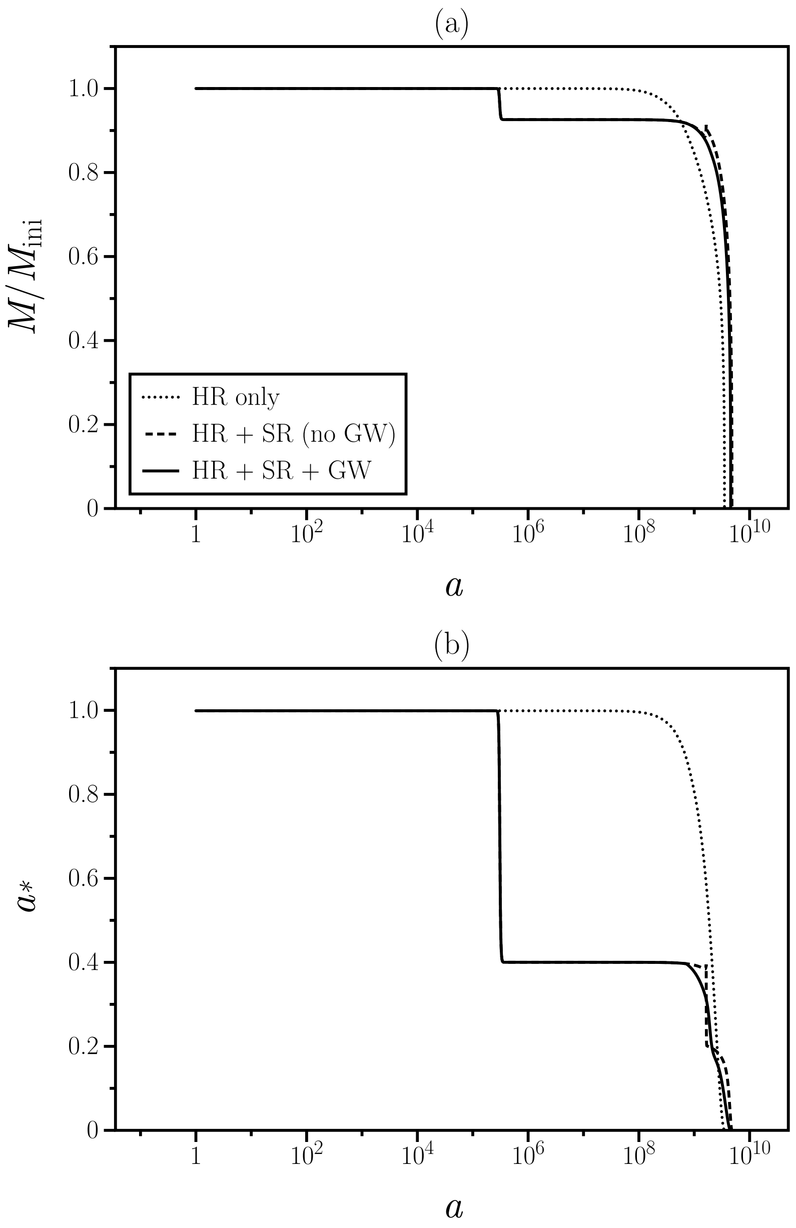
$$\frac{\mathrm{d}M}{\mathrm{d}t} = -\frac{f\left(M, a_*\right)}{M^2} - \sum_i \mu \Gamma_i^{\mathrm{sr}} N_i^{\mathrm{sr}}$$

PBH spin

$$\frac{\mathrm{d}a_*}{\mathrm{d}t} = -a_* \frac{g\left(M, a_*\right) - 2f\left(M, a_*\right)}{M^3} - \sum_i \frac{m}{M^2} \Gamma_i^{\mathrm{sr}} N_i^{\mathrm{sr}} + \frac{2a_*}{M} \sum_i \mu \Gamma_i^{\mathrm{sr}} N_i^{\mathrm{sr}}$$

- **Our revision:**
- **Added GW emission**
- **Added multi-mode dynamics**

4.1. Revised dynamics: Evolution, **scalar** case



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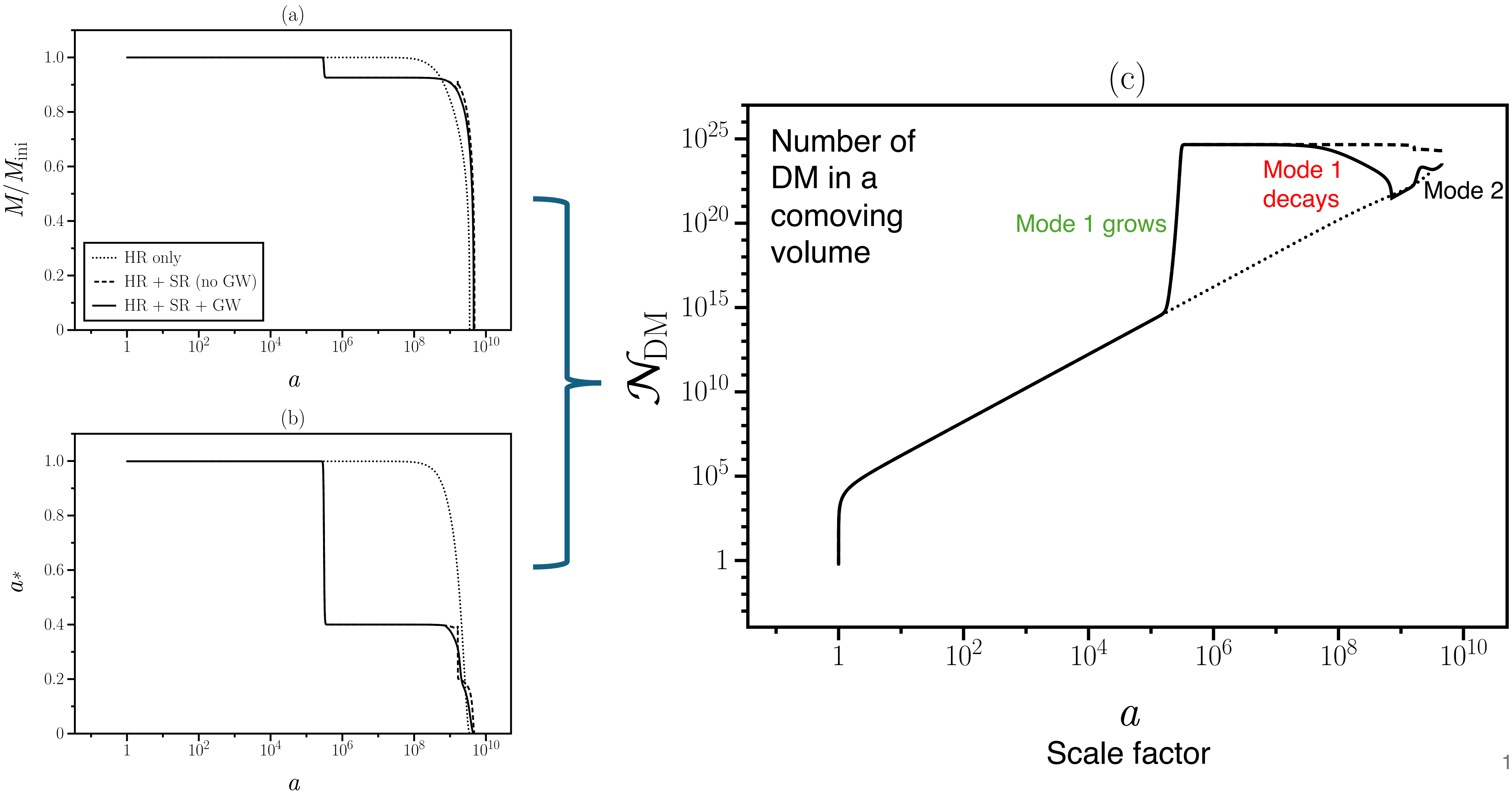

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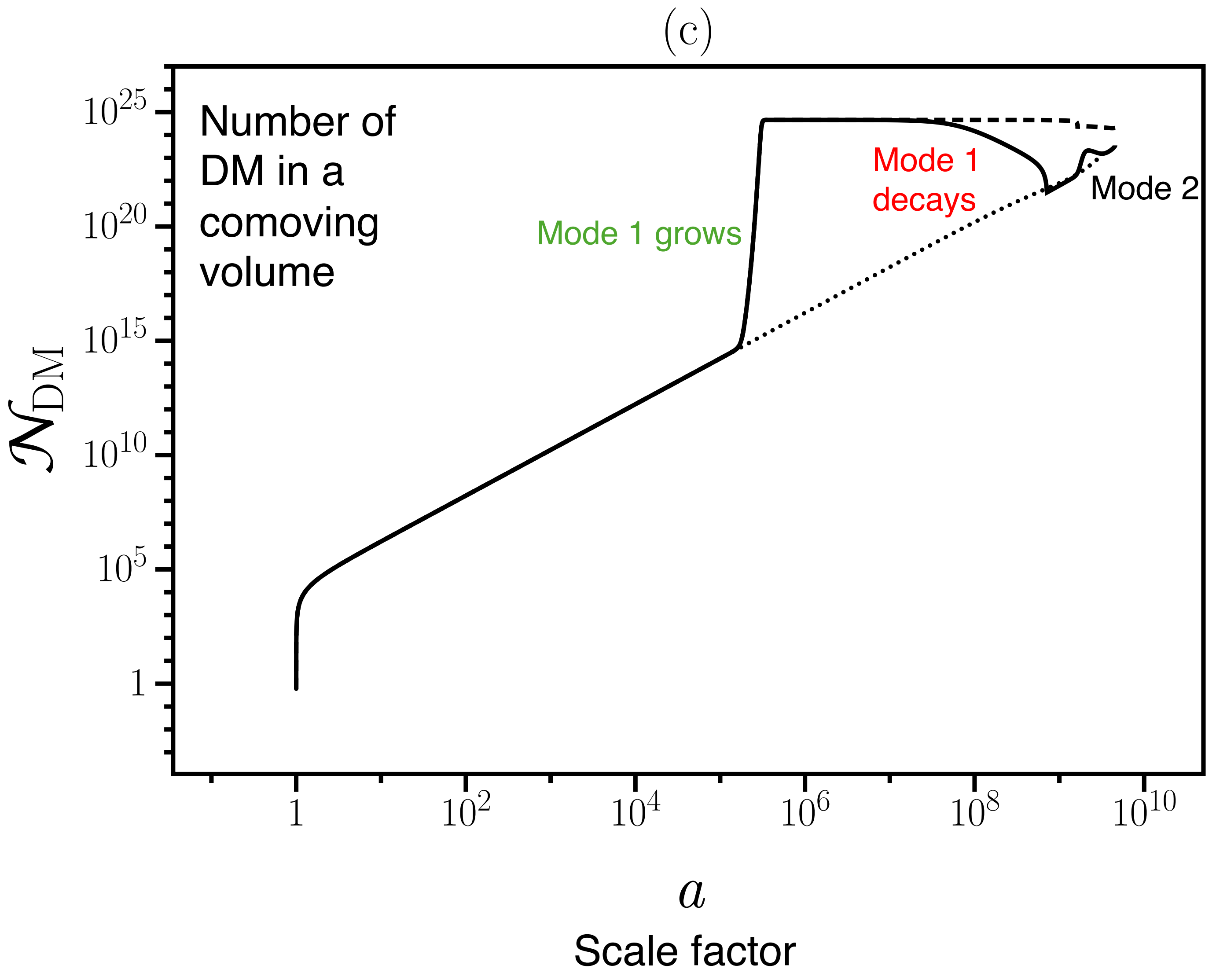
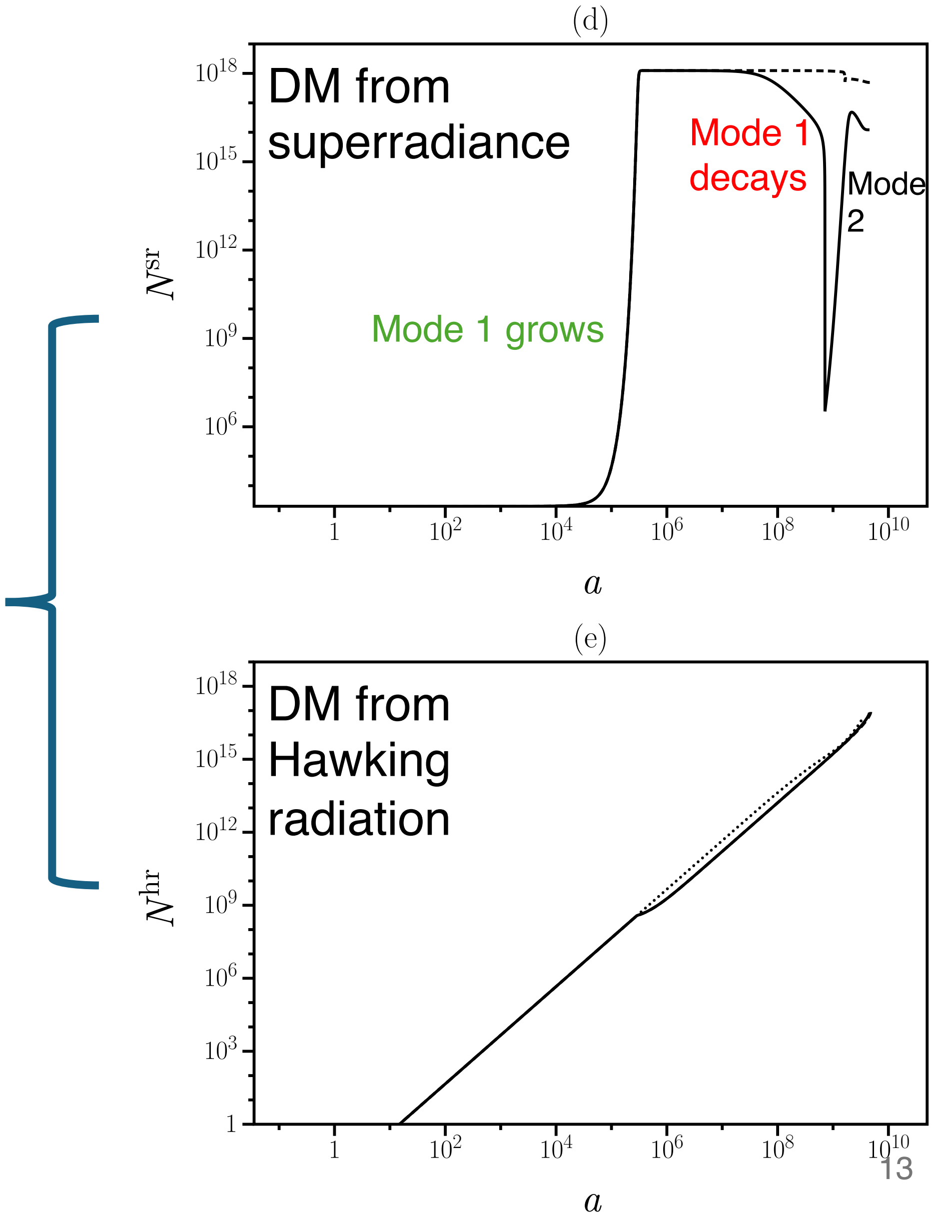
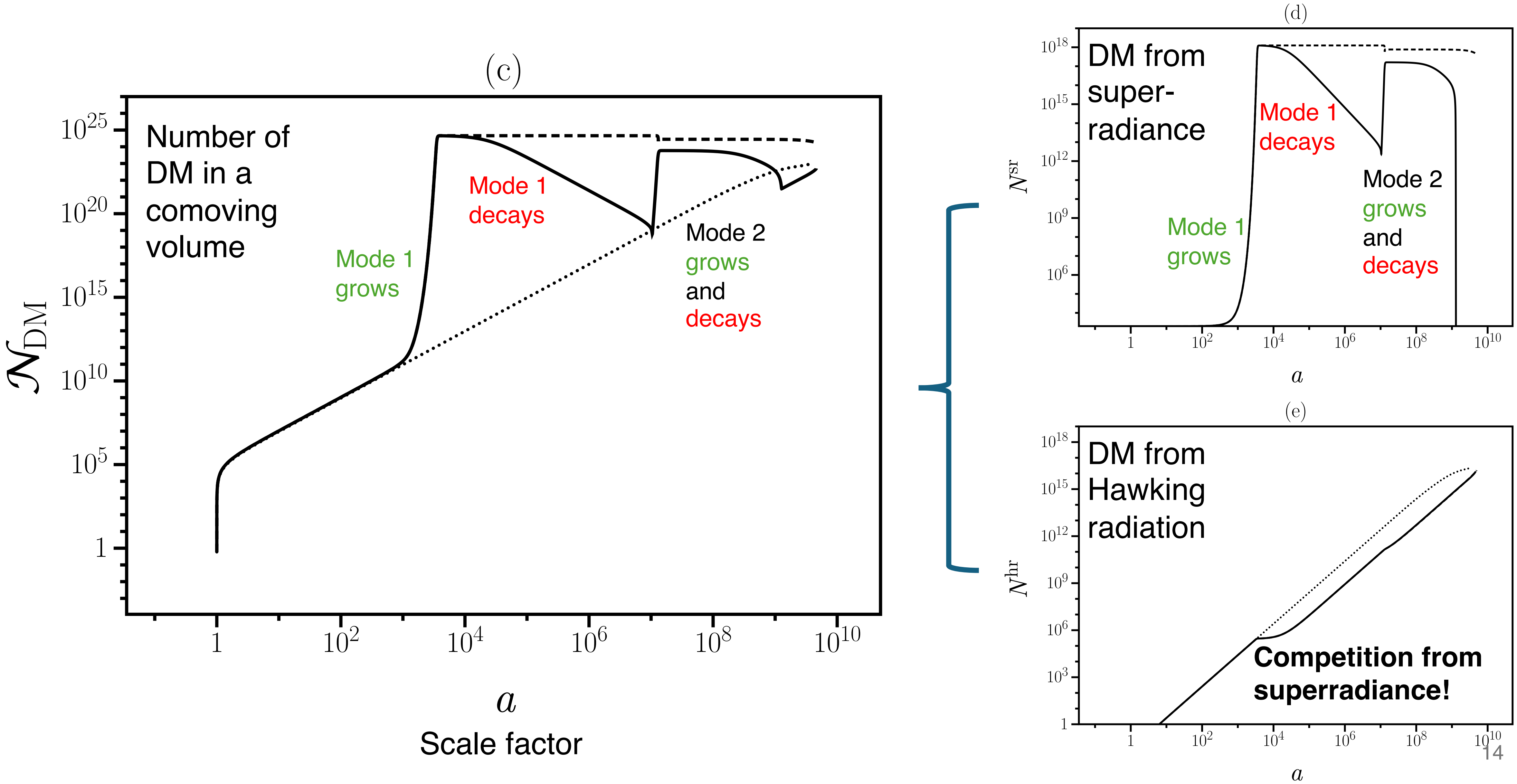




4.1. Revised dynamics: Evolution, **vector** case



4.2. Revised dynamics: Cosmological evolution

- Three components in the early universe: **PBHs, SM particles, DM particles**

$$\rho_{\rm PBH} + \rho_{\rm SM} + \rho_{\rm DM} = \frac{3H^2}{8\pi}$$

4.2. Revised dynamics: Cosmological evolution

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$$\frac{\mathrm{d}\rho_{\rm PBH}}{\mathrm{d}t} + 3H\rho_{\rm PBH} = \frac{\rho_{\rm PBH}}{M}\frac{\mathrm{d}M}{\mathrm{d}t}$$

PBH evolution under mass loss

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PBH evolution under mass loss

$$\frac{{\rm d}\rho_{\rm SM}}{{\rm d}t} + 4H\rho_{\rm SM} = -\frac{\rho_{\rm PBH}}{M}\frac{{\rm d}M}{{\rm d}t}\bigg|_{\rm SM}$$

SM particles from Hawking radiation

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- Three components in the early universe: **PBHs, SM particles, DM particles**

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PBH evolution under mass loss

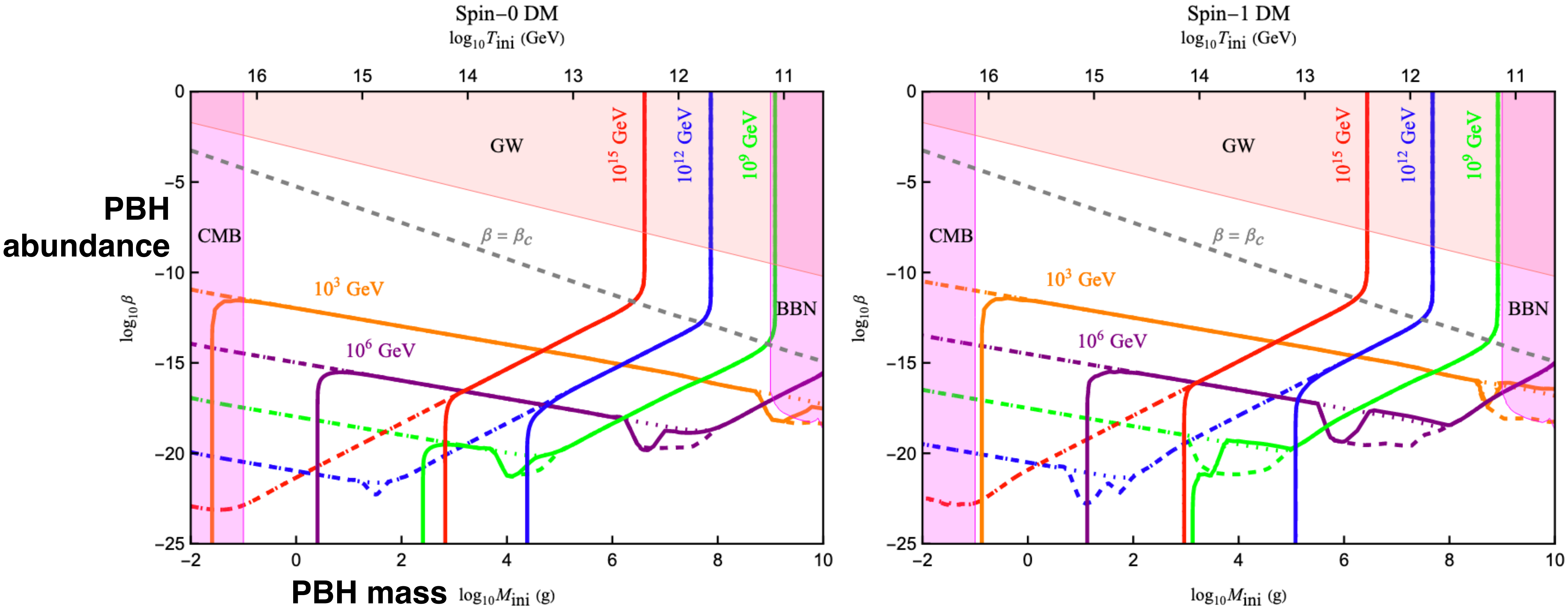
$$\frac{{\rm d}\rho_{\rm SM}}{{\rm d}t} + 4H\rho_{\rm SM} = -\frac{\rho_{\rm PBH}}{M}\frac{{\rm d}M}{{\rm d}t}\bigg|_{\rm SM}$$

SM particles from Hawking radiation

$$\frac{{\rm d}\rho_{\rm DM}}{{\rm d}t} + 3H\rho_{\rm DM} = \frac{\rho_{\rm PBH}}{M}\mu\left(\frac{{\rm d}N^{\rm hr}}{{\rm d}t} + \sum_i \frac{{\rm d}N_i^{\rm sr}}{{\rm d}t}\right)$$

DM particles from Hawking radiation & superradiance

4.2. Revised dynamics: Parameter space



- Solid: Hawking radiation + Superradiance (with GW) + Gravitational UV freeze-in (an independent DM production channel)
- Dashed: Hawking radiation +superradiance (without GW)
- Dotted: Hawking radiation alone

5. Conclusion

- After adding **GW emission** and **multi-mode dynamics** for superradiance:
  - Scalar DM
    - Contribution from superradiance: Can be **moderated**
  - Vector DM
    - Contribution from superradiance: Can be **negative!!!**
  - Parameter space thereby revised

Thank you!