Primordial Black Holes and the Early Universe

TeVPA 2024, 29th of August 2024

Jessica Turner, IPPP, Durham University

Chicago 2024

Chicago 2024

Primordial Black Holes: What? How? Why?

Hawking & Carr (1974)

- Primordial black holes (PBHs) are black holes that formed in the early Universe due to large density perturbations [inflation, phase transitions, QCD phase transition…]

- PBHs can take a huge range in masses from $(10^{-5} - 10^{37})\, g$

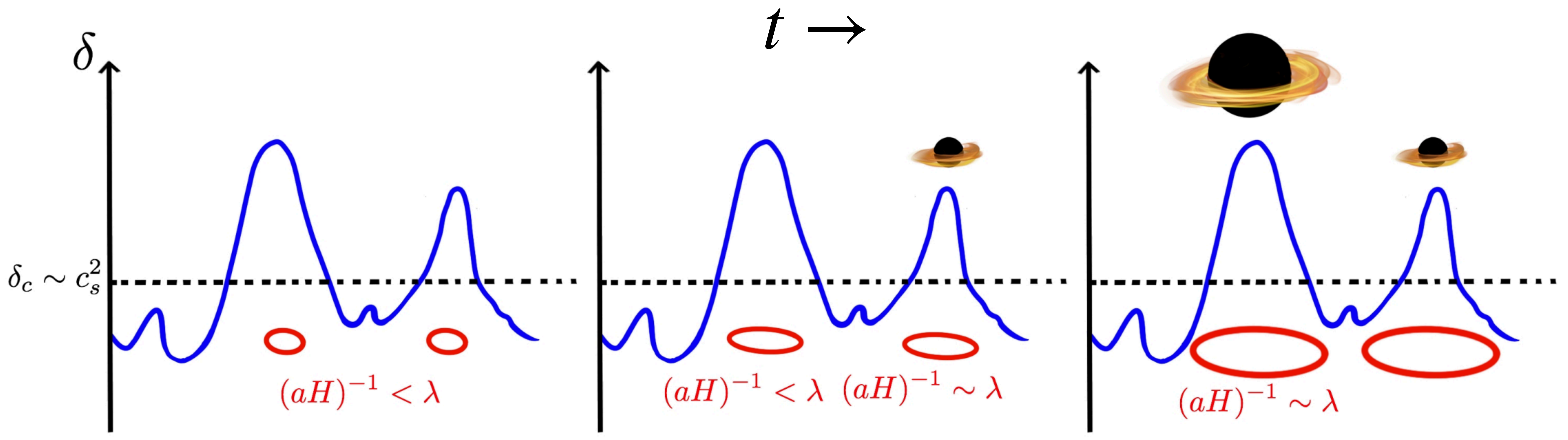

Image credit: Villanueva-Domingo, Mena, Palomares-Ruiz. 2103.12087

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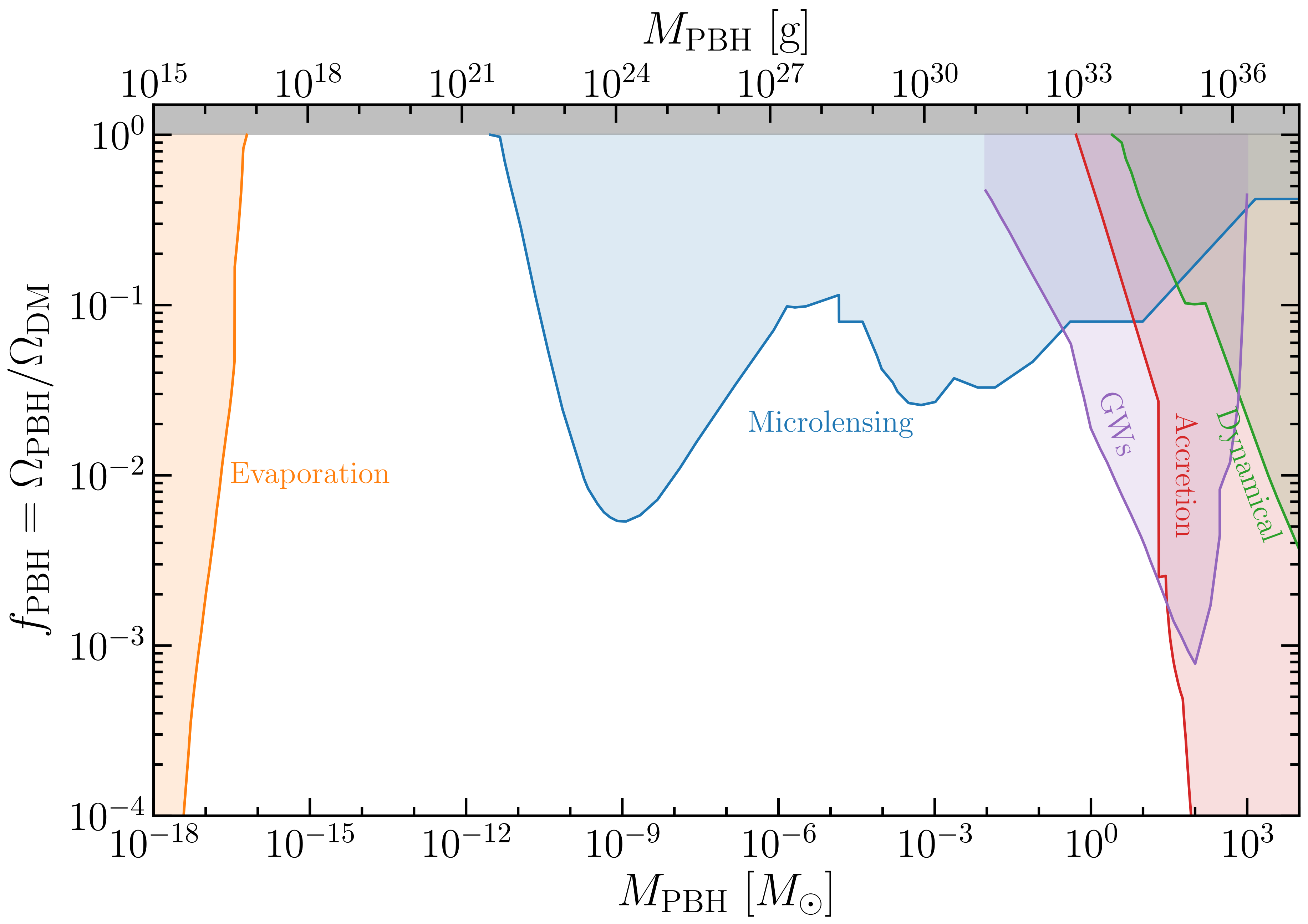

Green & Kavanagh, (2007.10722)

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- Some may be mergers of PBH binaries

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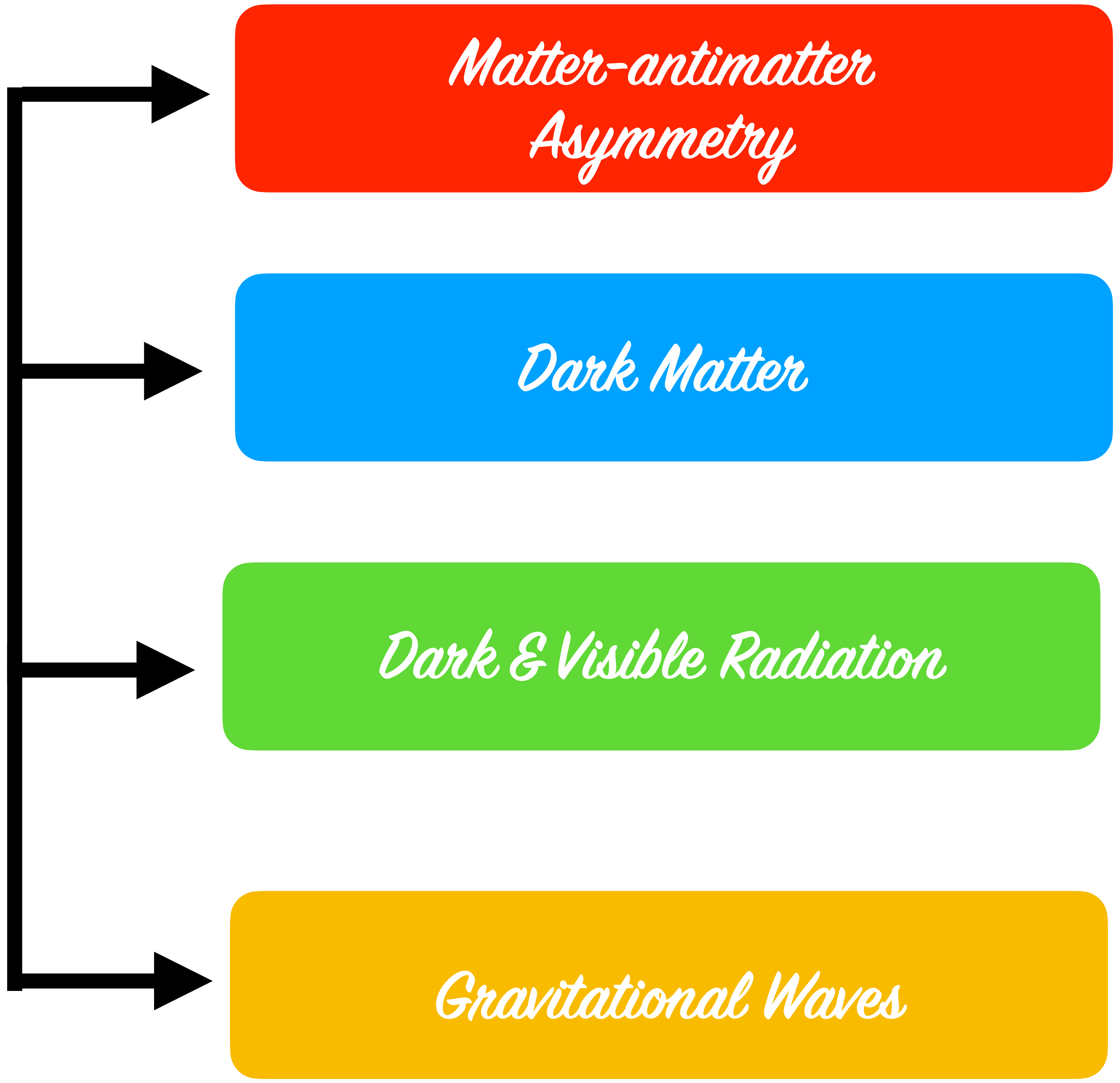
- If PBHs exist, what would their impact on cosmological observables be?



Primordial Black Hole Evaporation

- Schwarzschild radius of a black hole: $r_S \sim 0.015\ \text{fm} \left(\frac{M_{\text{BH}}}{10^{13}\ \text{g}} \right)$
- BH evaporate & lose mass via Hawking radiation: $T_{\text{BH}} \sim 1\ \text{GeV} \left(\frac{10^{13}\ \text{g}}{M_{\text{BH}}} \right)$

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- Observable particle from Hawking evaporation have approximately blackbody spectra

$$\frac{d^2N_i}{dp\,dt} = \frac{g_i}{2\pi^2}\frac{\sigma_{s_i}(M,p,\mu_i)}{\exp[E_a(p)/T] - (-1)^{2s_i}}\frac{p^3}{E_a(p)}$$

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Geometric optics limit

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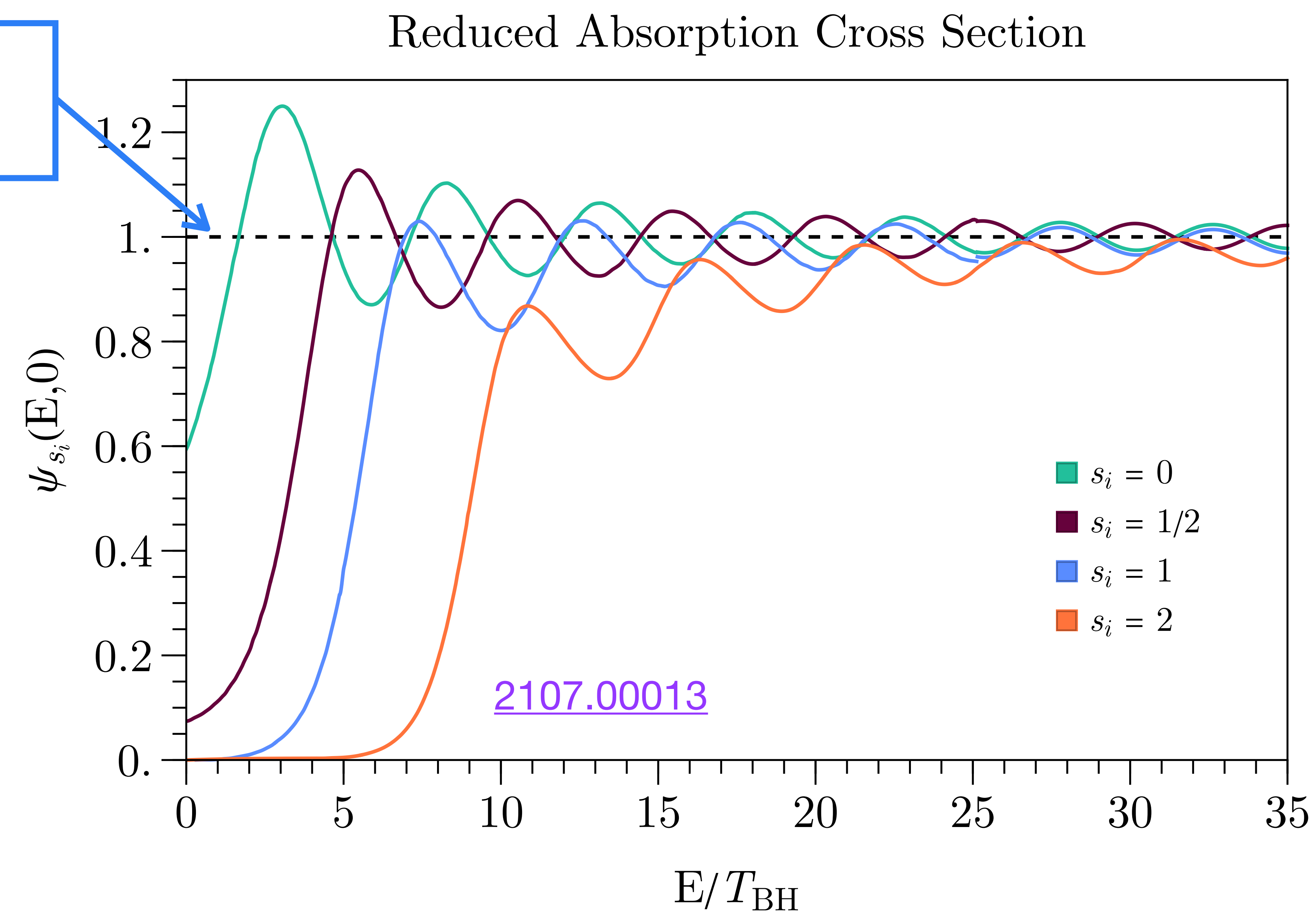

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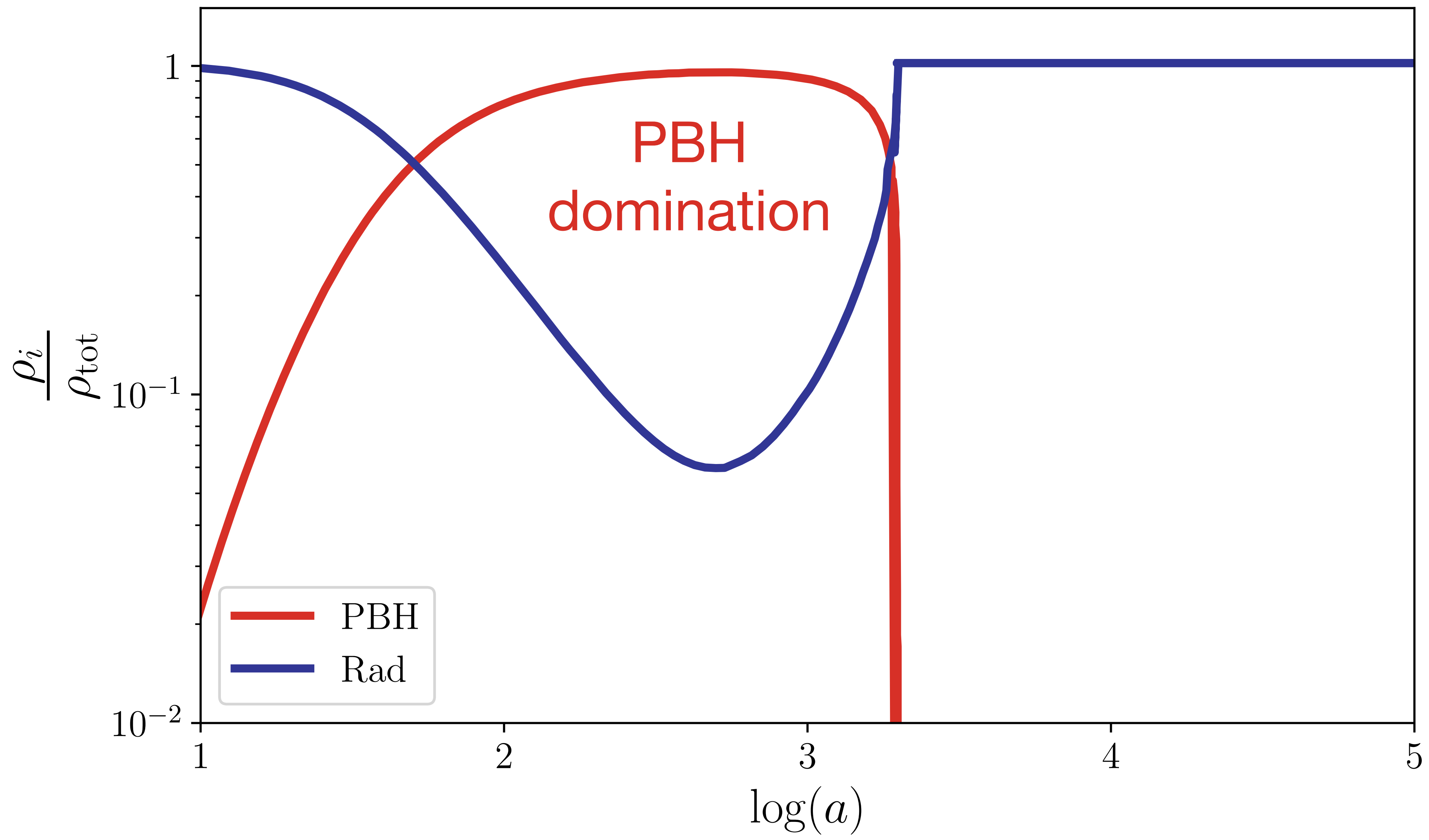

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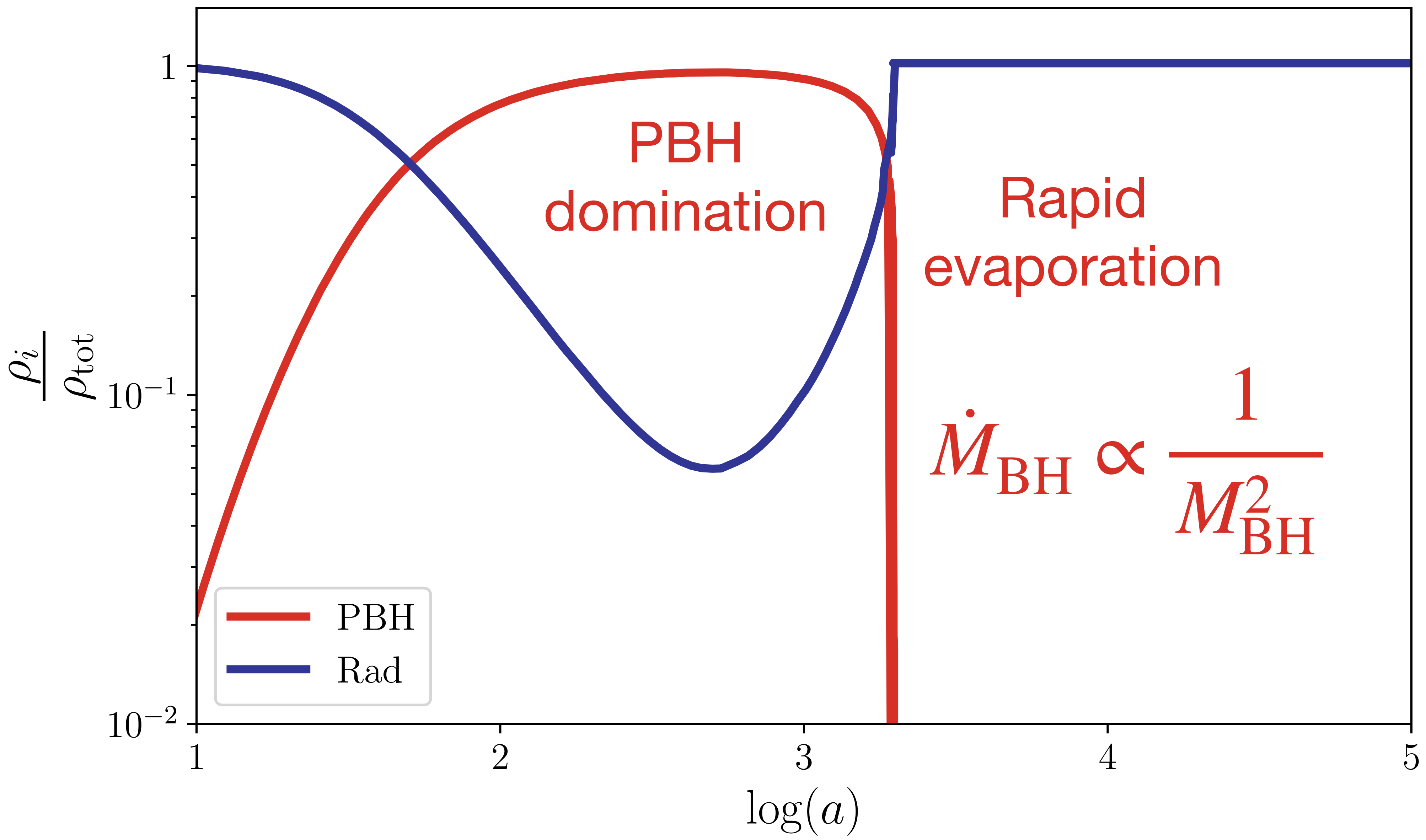
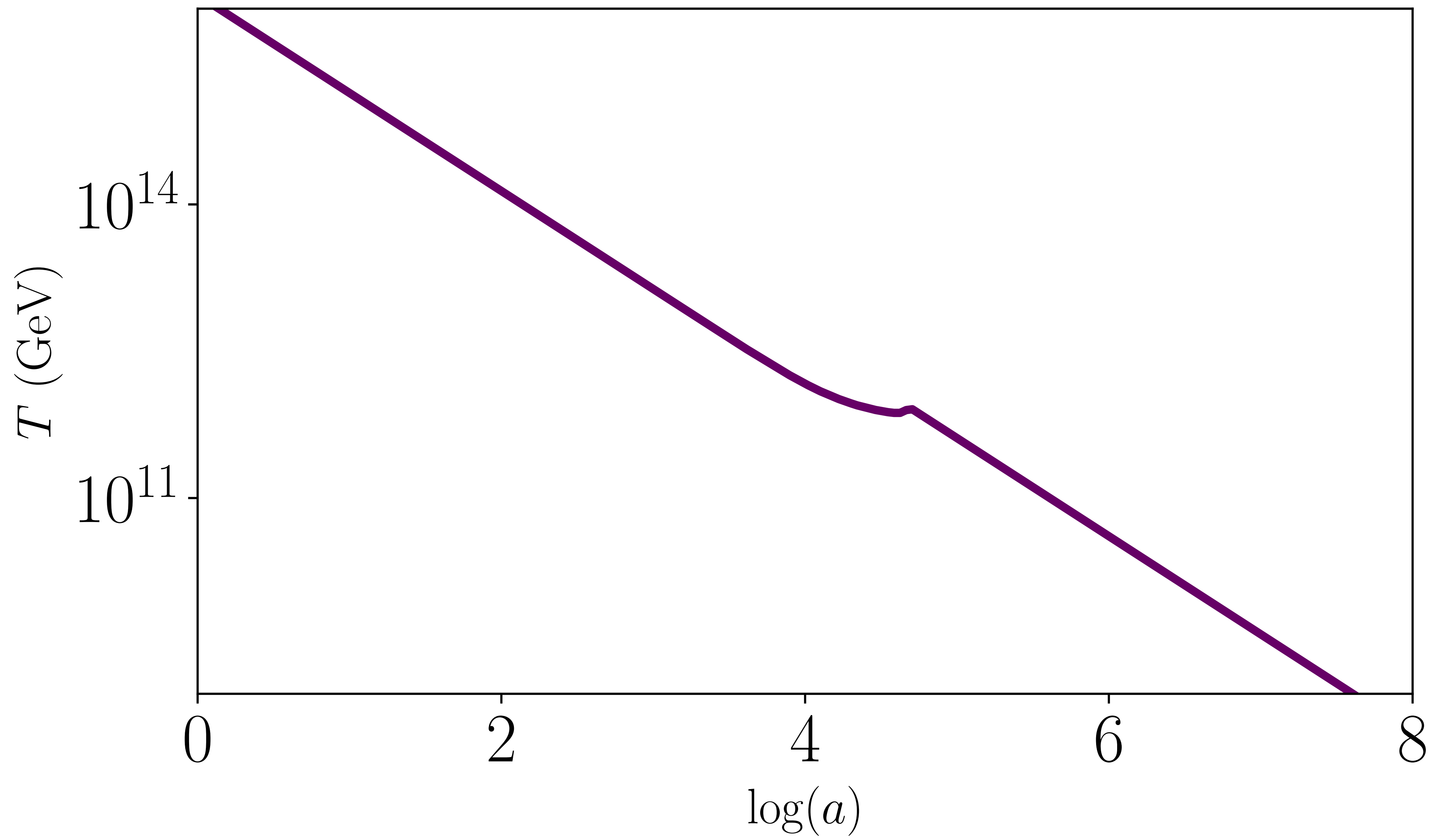
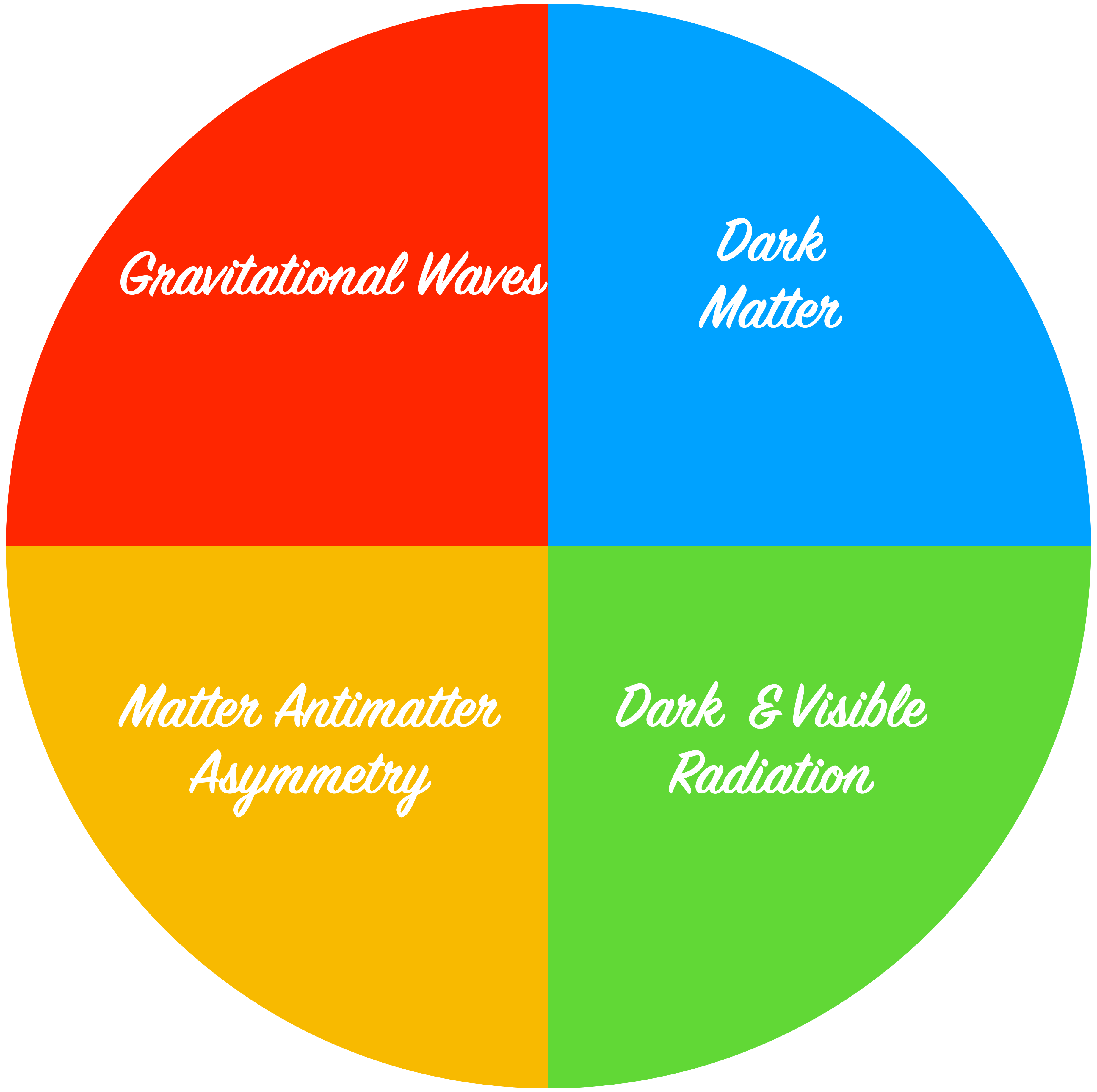
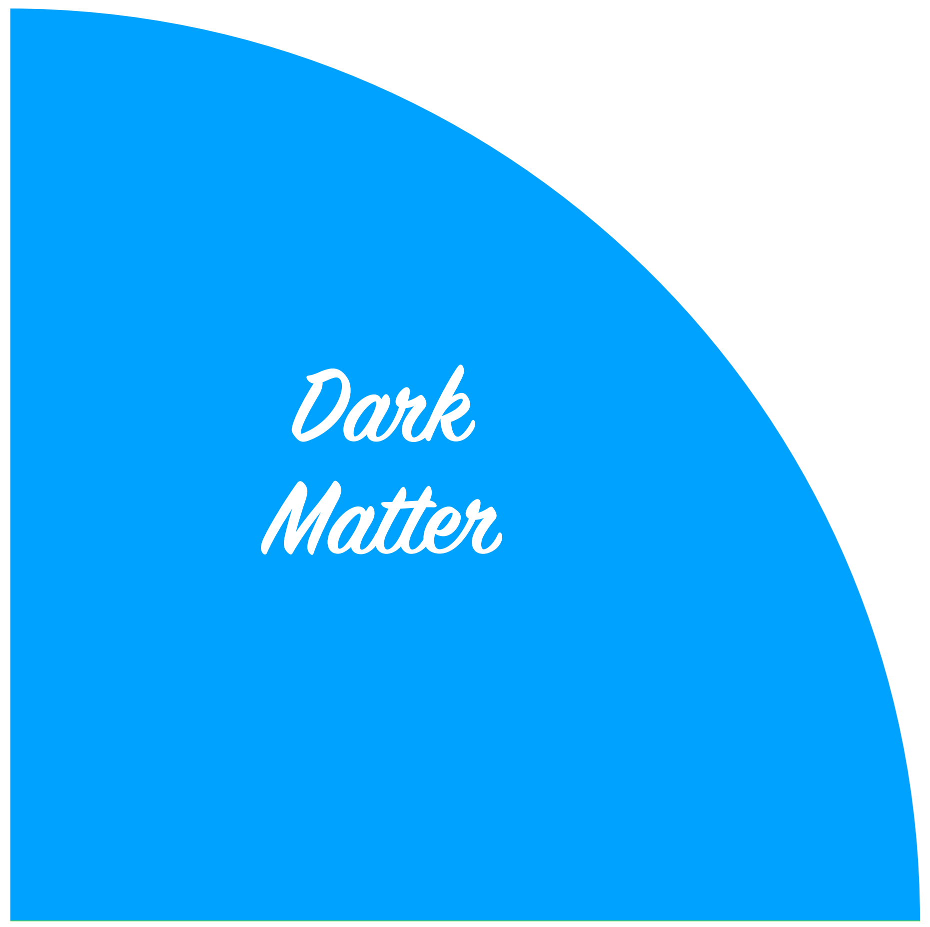
*Assuming monochromatic mass spectrum

- PBHs evaporation is rapid $\Longrightarrow$ reheat the Universe via large **entropy dumps**






Gravitational Waves
Dark Matter
Matter Antimatter Asymmetry
Dark & Visible Radiation


Dark
Matter

Gravitationally Interacting Dark Matter

- Consider feebly interacting DM/purely gravitationally interacting DM & population of PBHs (monochromatic mass spectrum)

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Fujita, Kawasaki, Harigaya & Matsuda (1401.1909)
Lennon, March-Russell, Petrossian-Byrne & Tillim (1712.07664)
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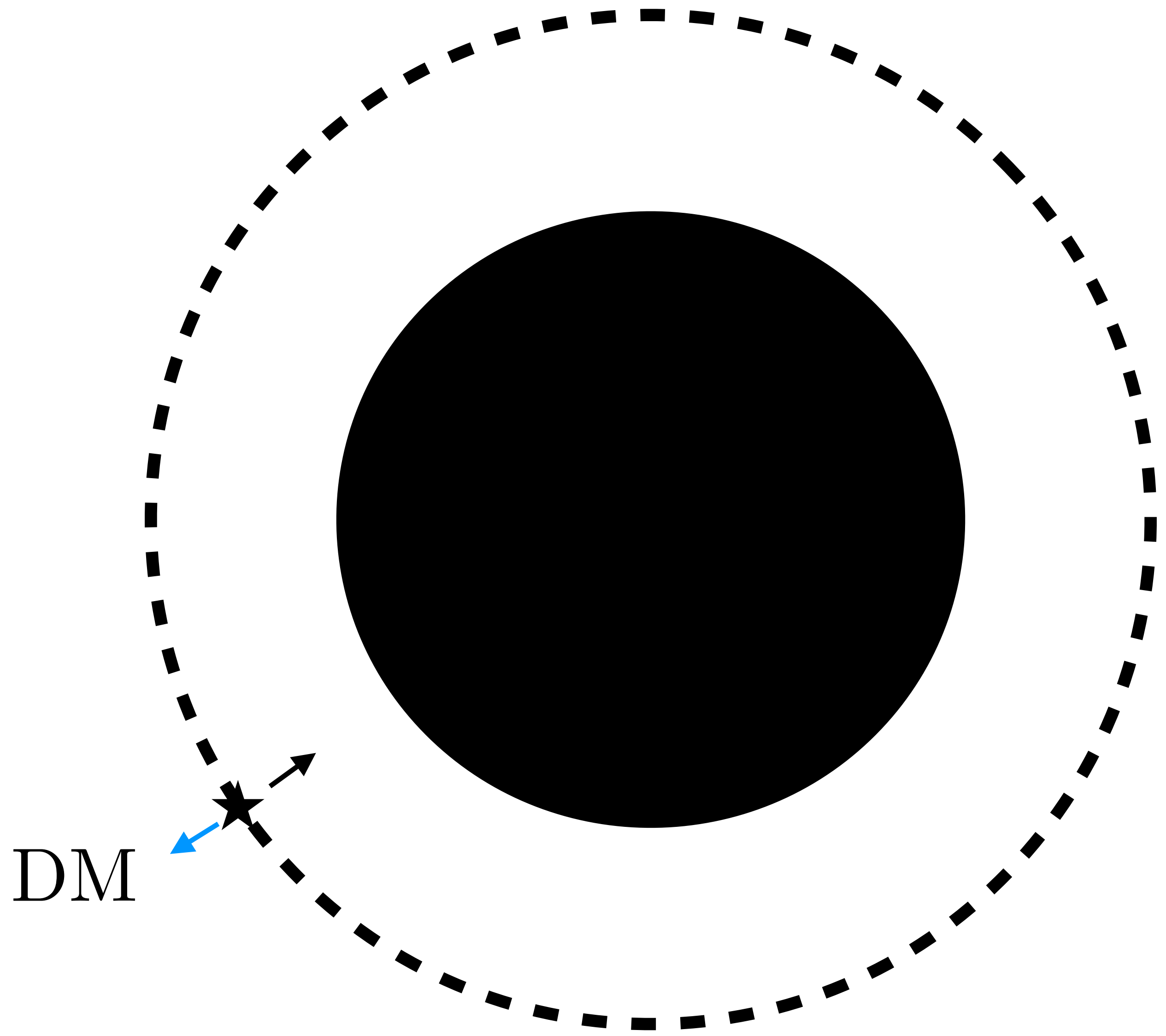

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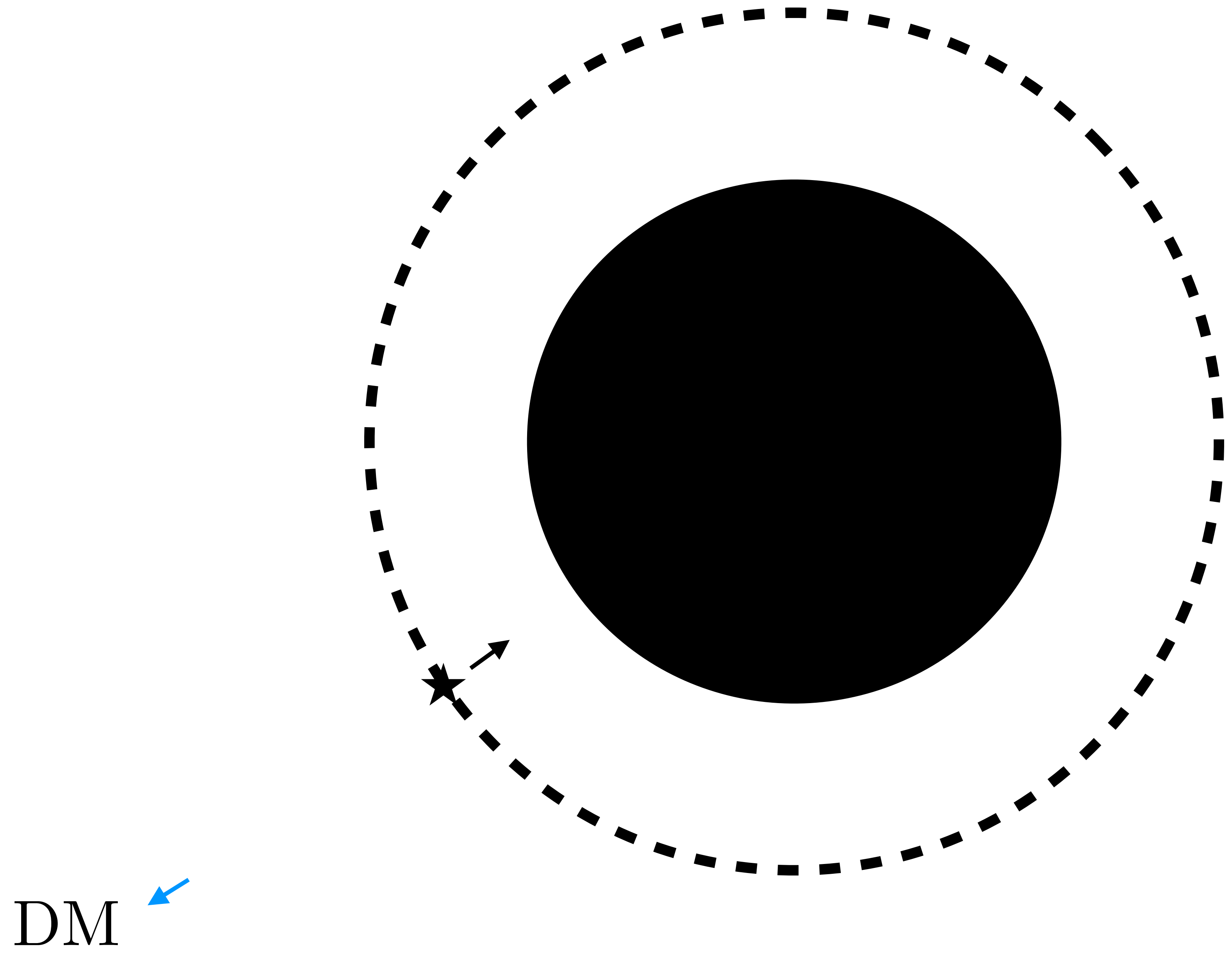

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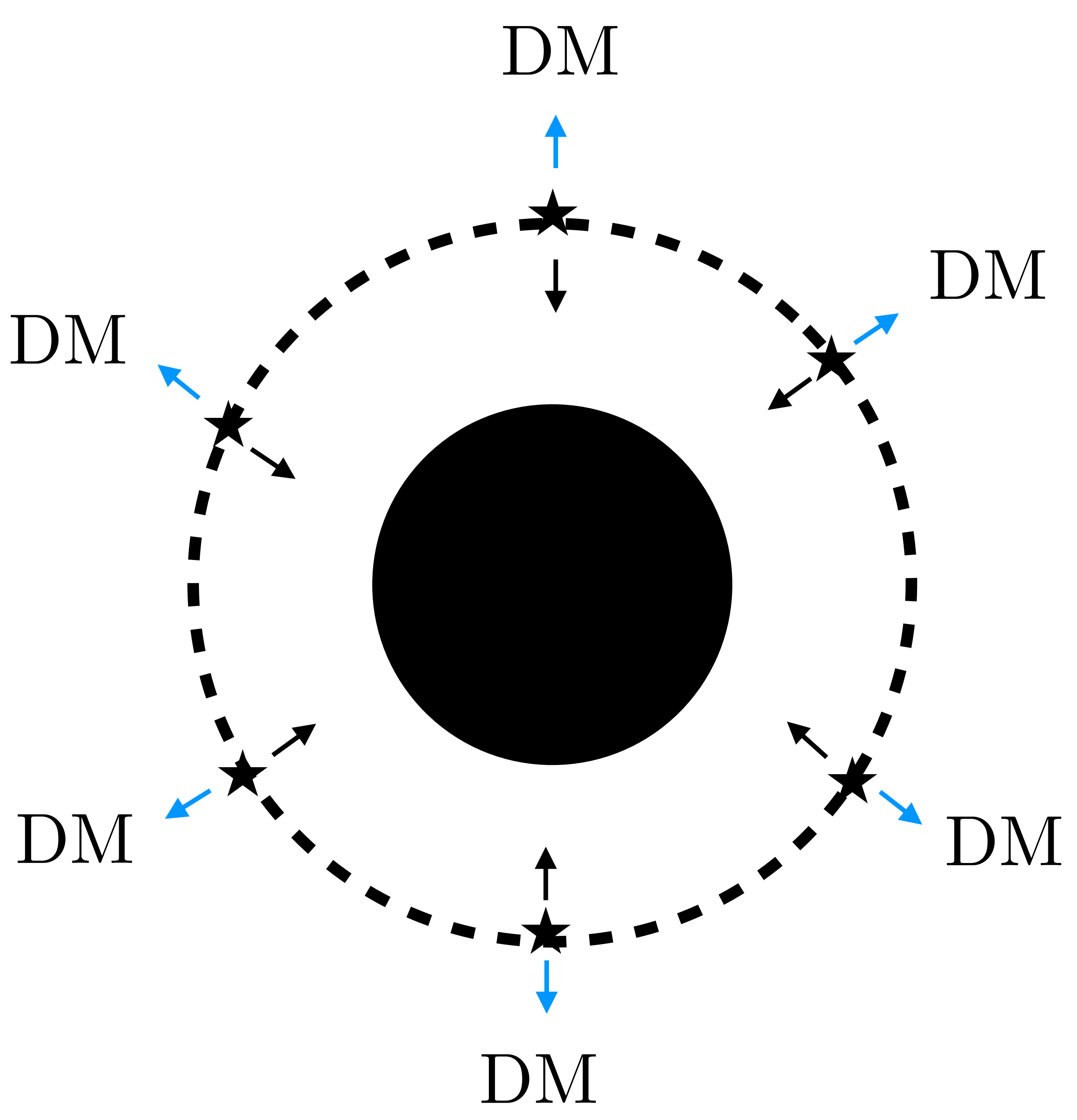

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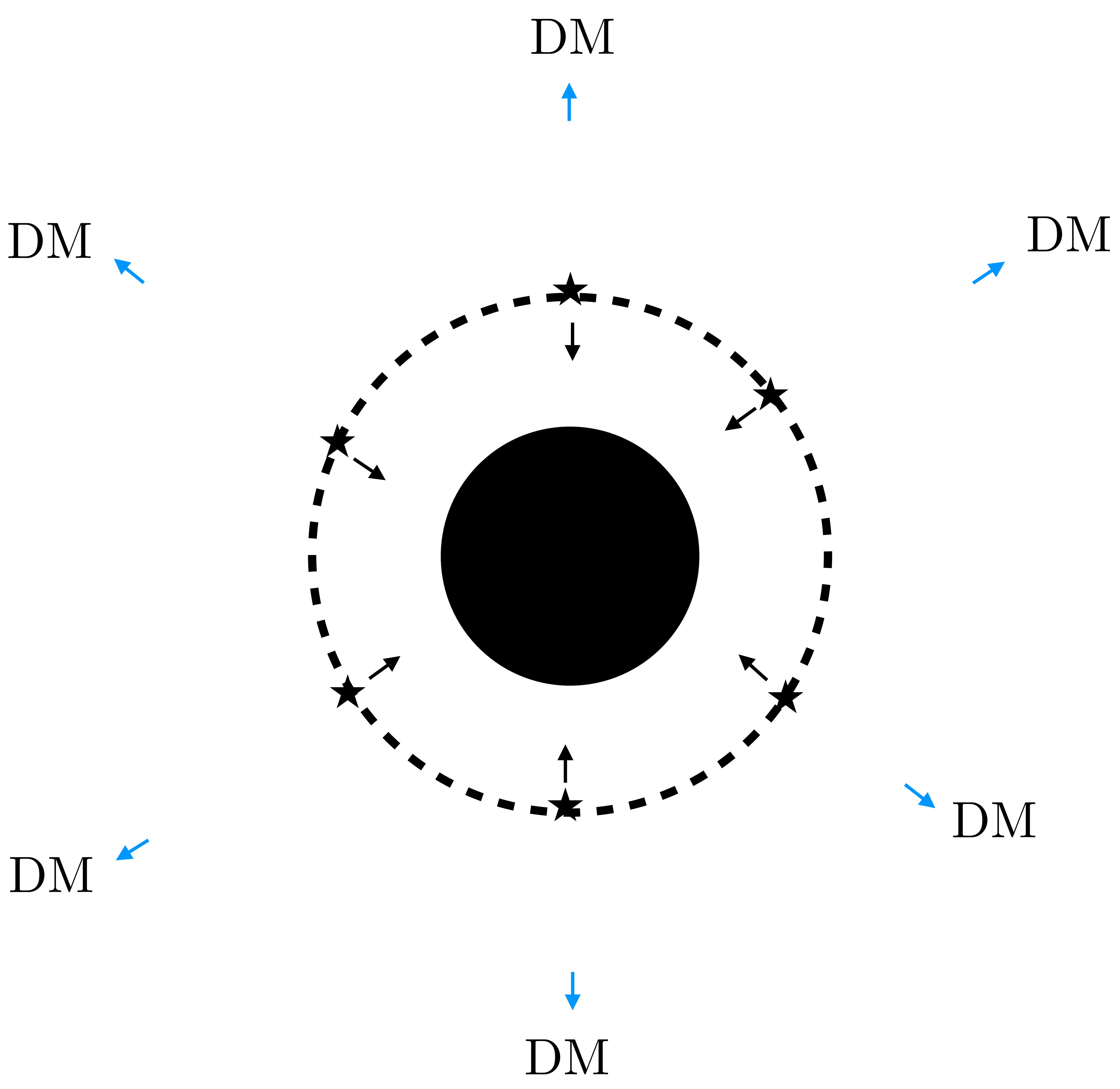

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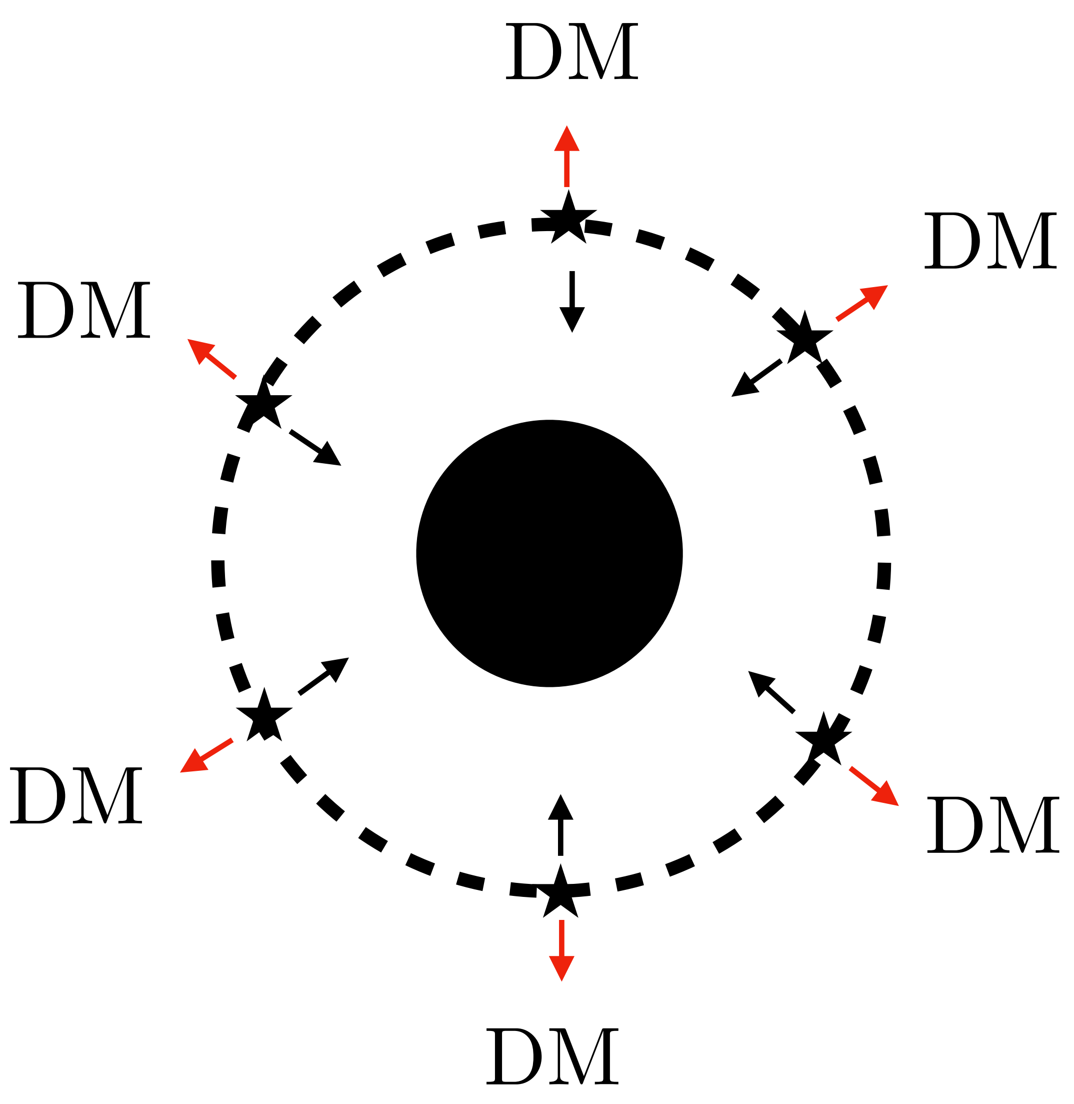

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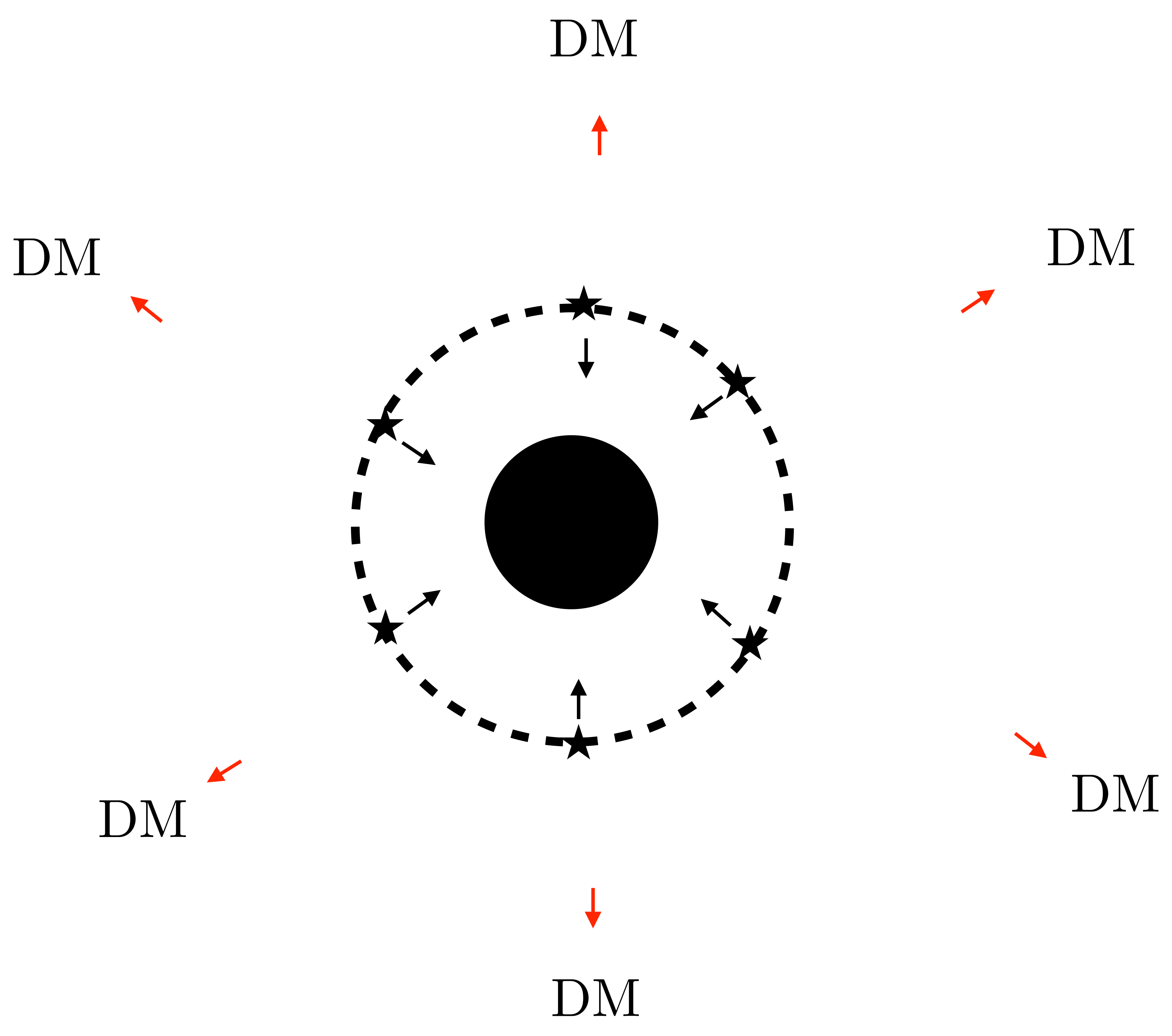

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DM can be boosted

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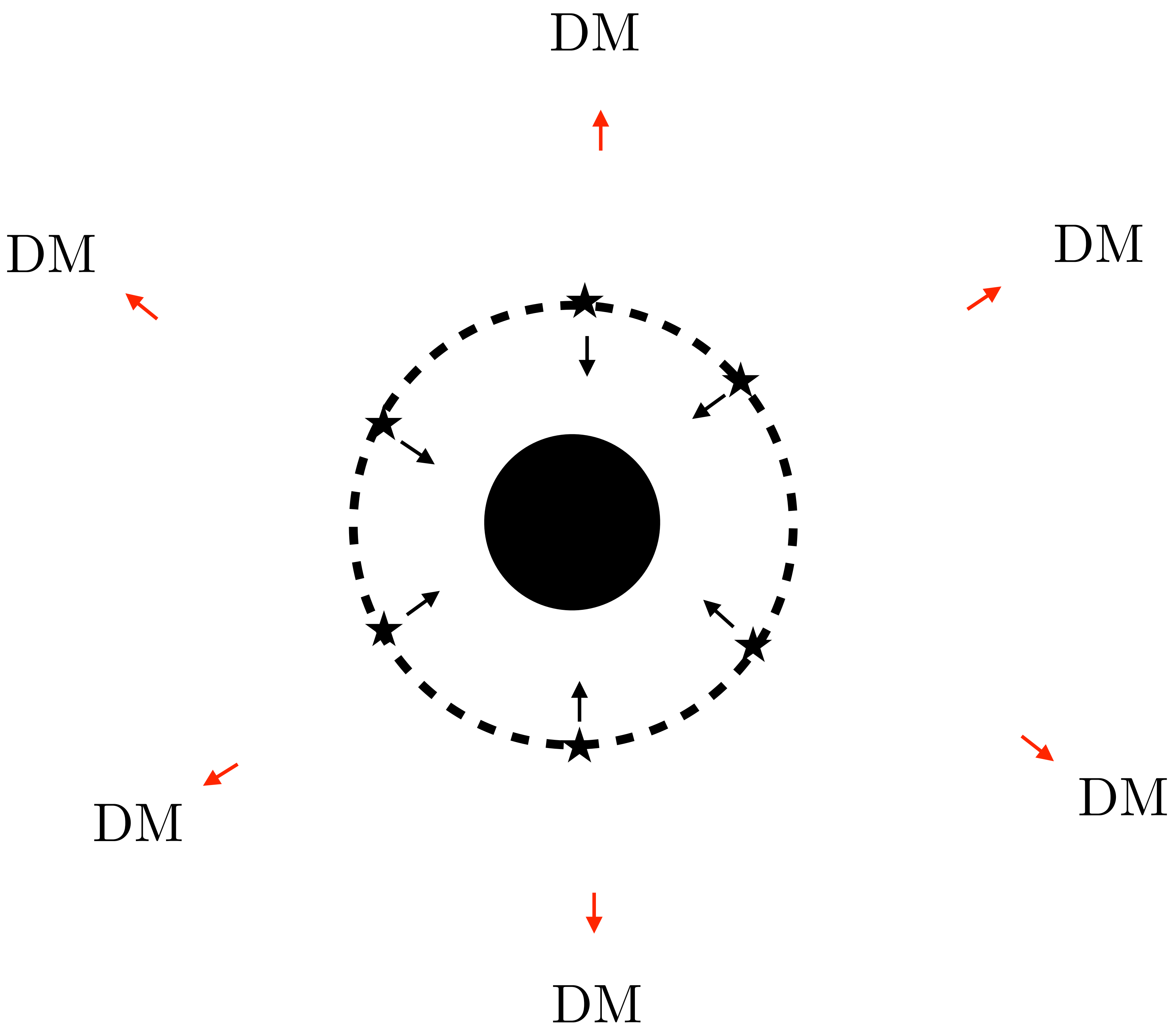
$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = n_{\rm PBH}\,\Gamma_{\rm BH\to DM}$$

DM produced from PBH Hawking radiation



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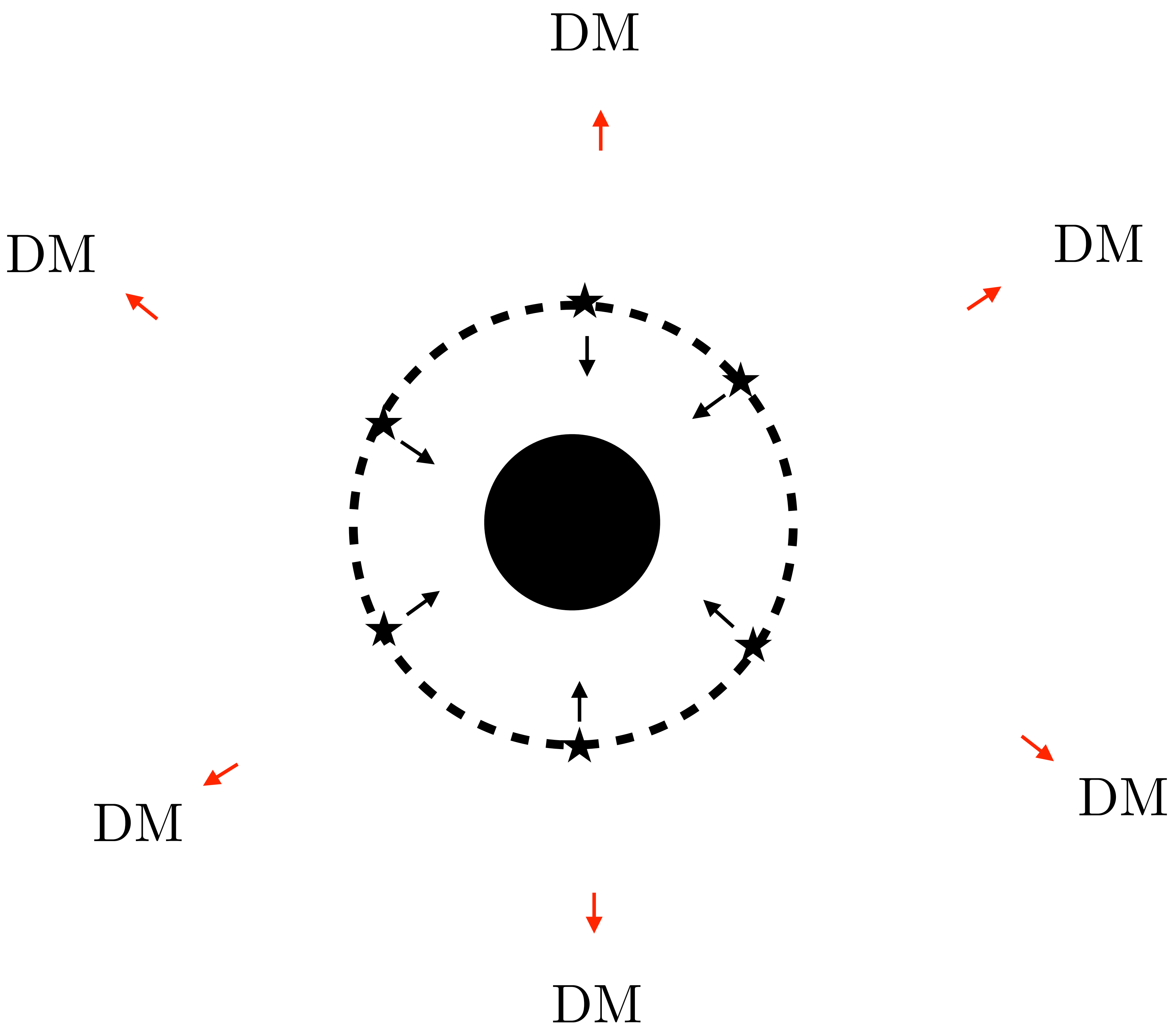

$$\dot{n}_{\mathrm{DM}} + 3Hn_{\mathrm{DM}} = n_{\mathrm{PBH}}\Gamma_{\mathrm{BH}\to\mathrm{DM}}$$

$$\dot{\rho}_{\mathrm{SM}} + 4H\rho_{\mathrm{SM}} = -\frac{1}{M_{\mathrm{BH}}}\dot{M}_{\mathrm{BH}}\Big|_{\mathrm{SM}}\rho_{\mathrm{PBH}}$$

SM d.o.f from PBH Hawking radiation

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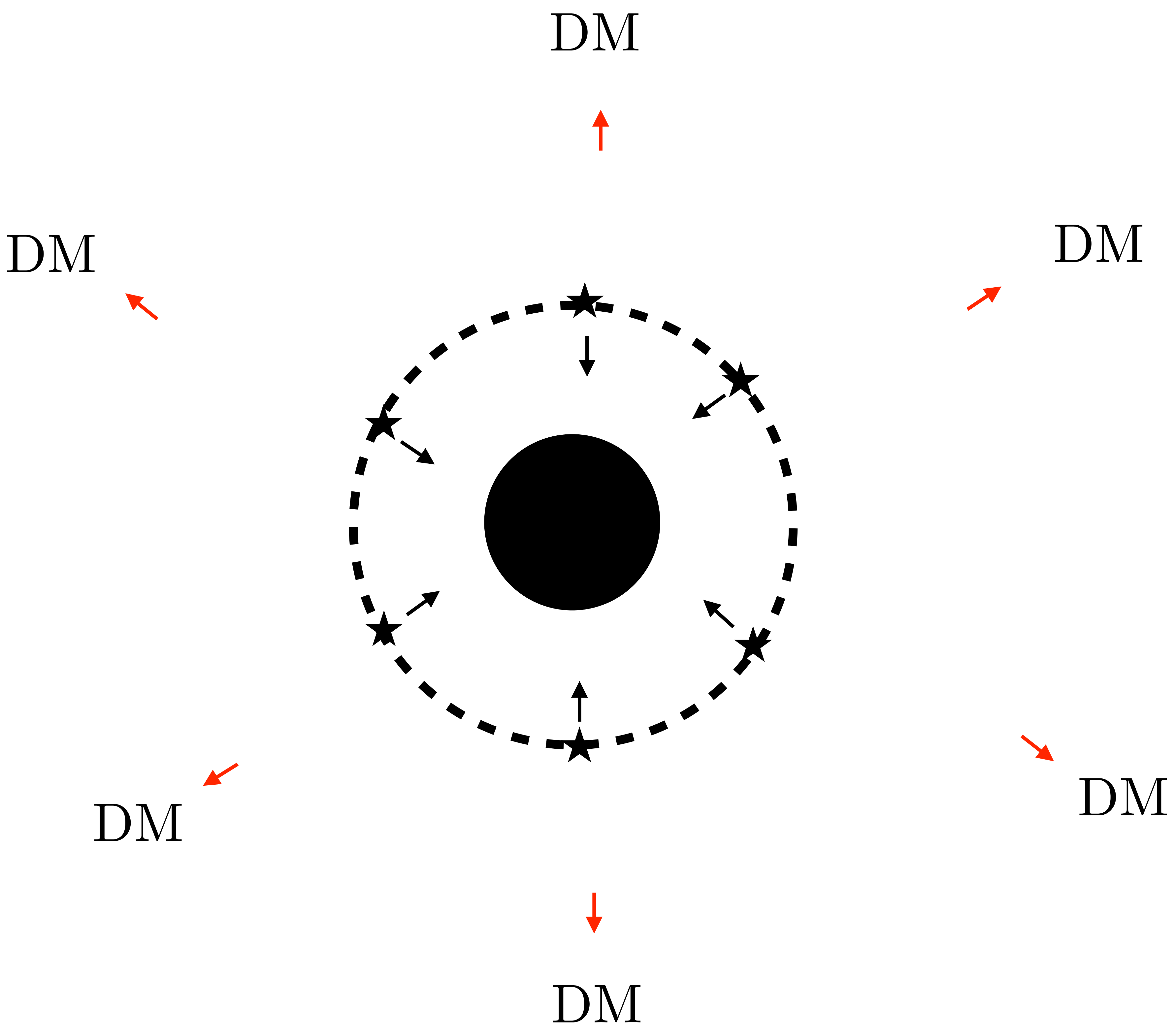

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Mass loss rate $\propto 1/M_{\mathrm{BH}}^2$
Contains greybody factor

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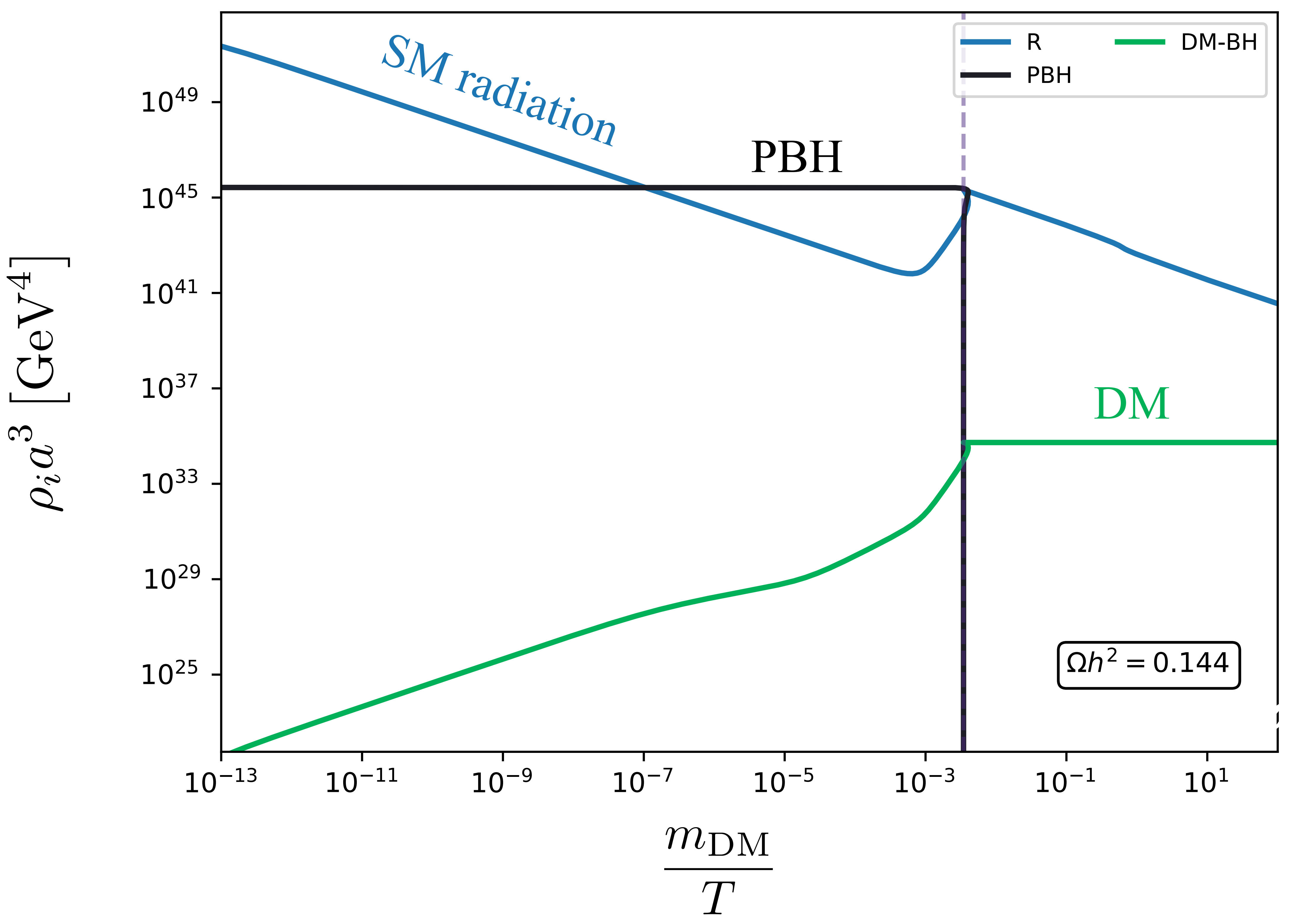
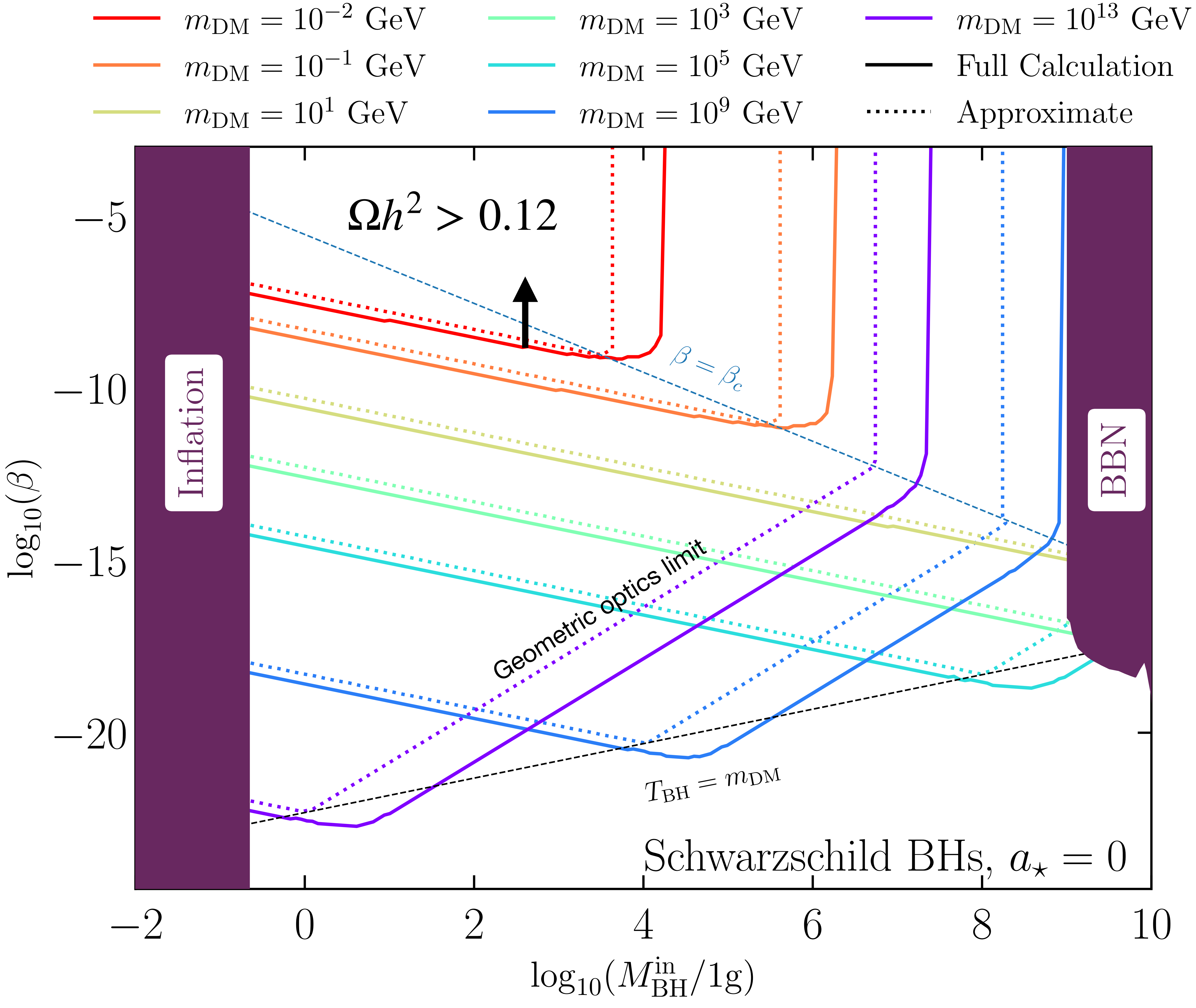


Cheek, Heurtier, Perez-Gonzalez & JT (2107.00013)

Gravitationally Interacting Dark Matter

$$\beta \equiv \frac{\rho^{\rm in}_{\rm PBH}}{\rho^{\rm in}}$$



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Dashed from Gondolo, Sandick, Shams Es Haghi 2009.02424

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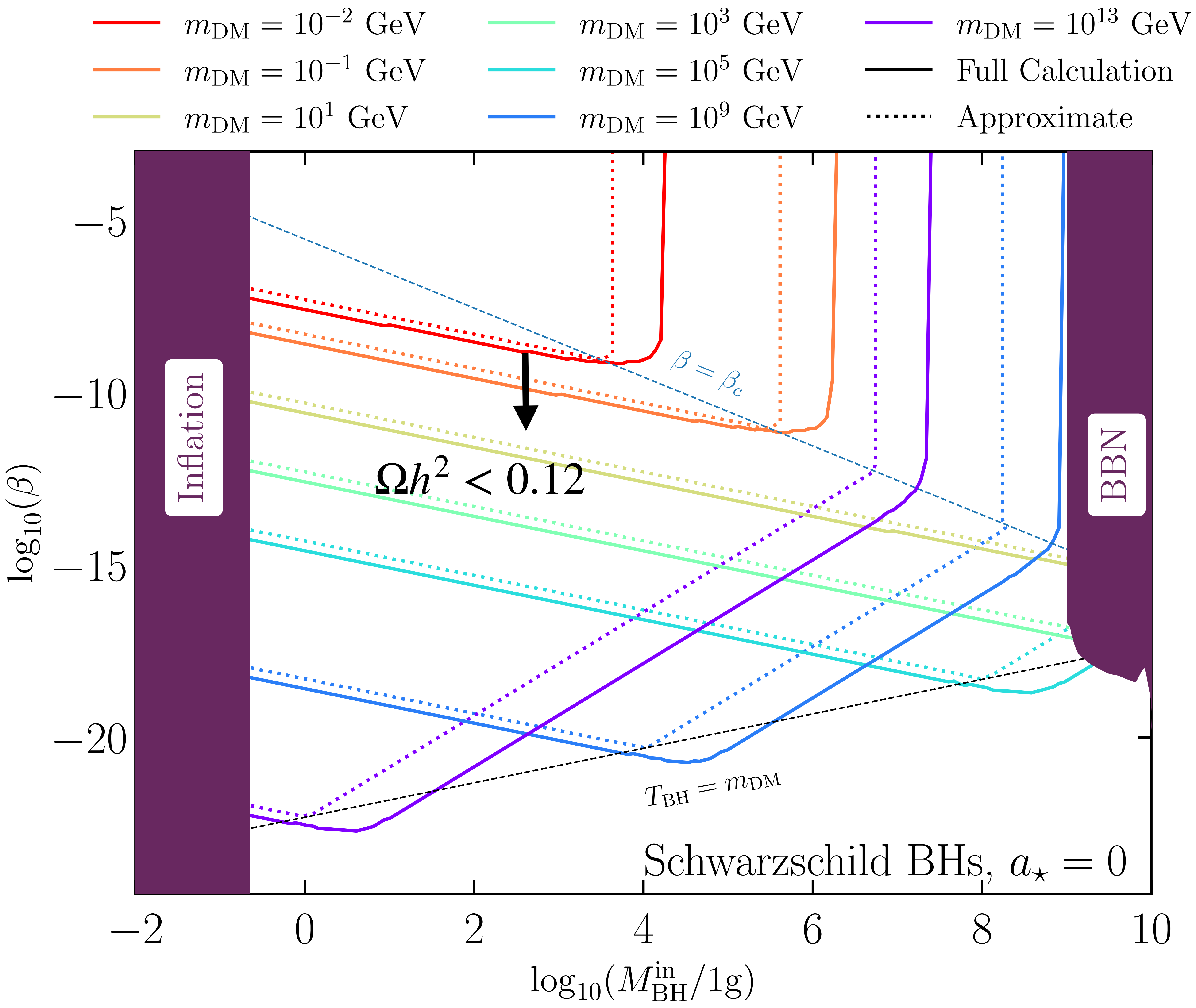

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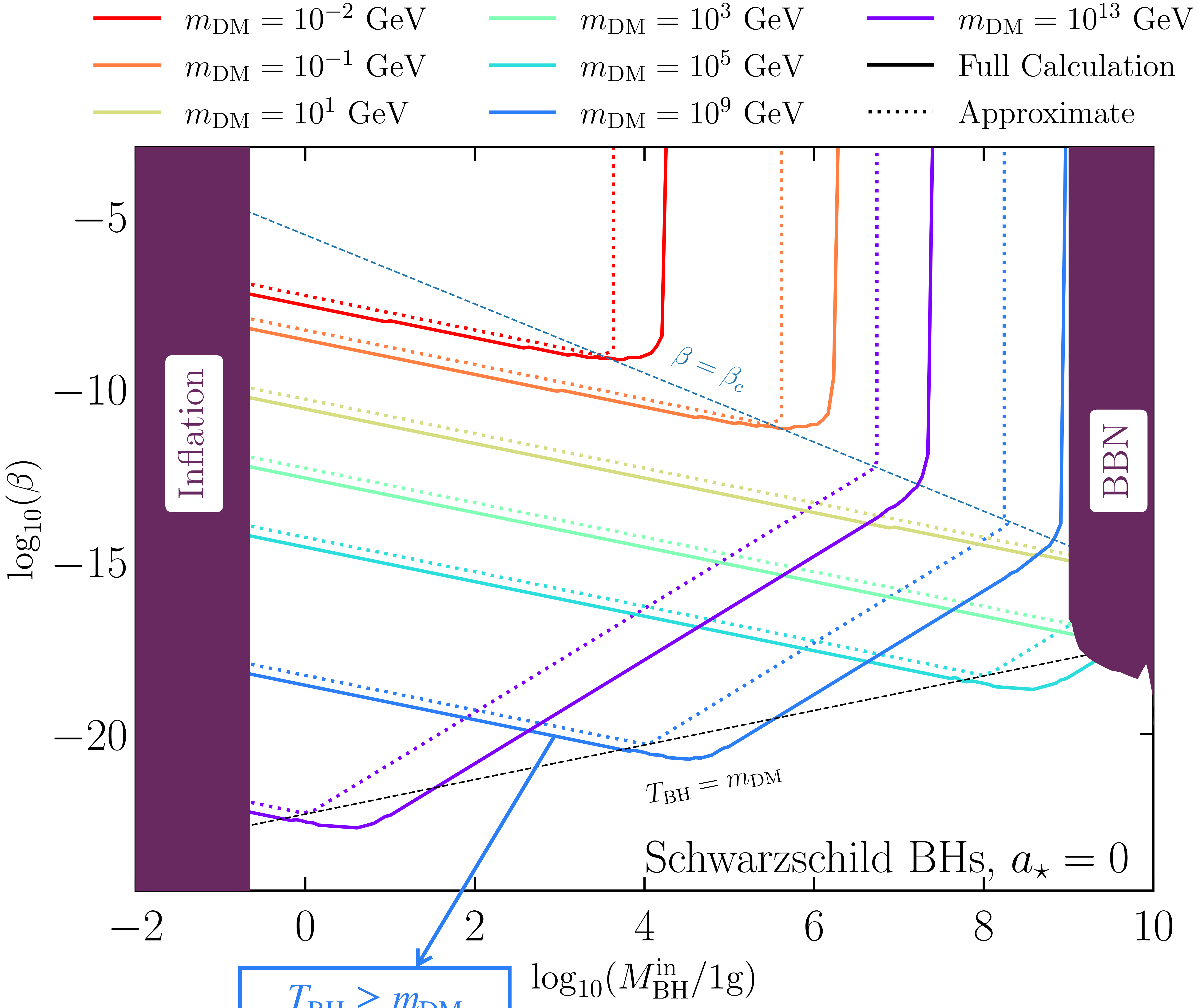

$T_{BH} \geq m_{DM}$
Overproduction of DM

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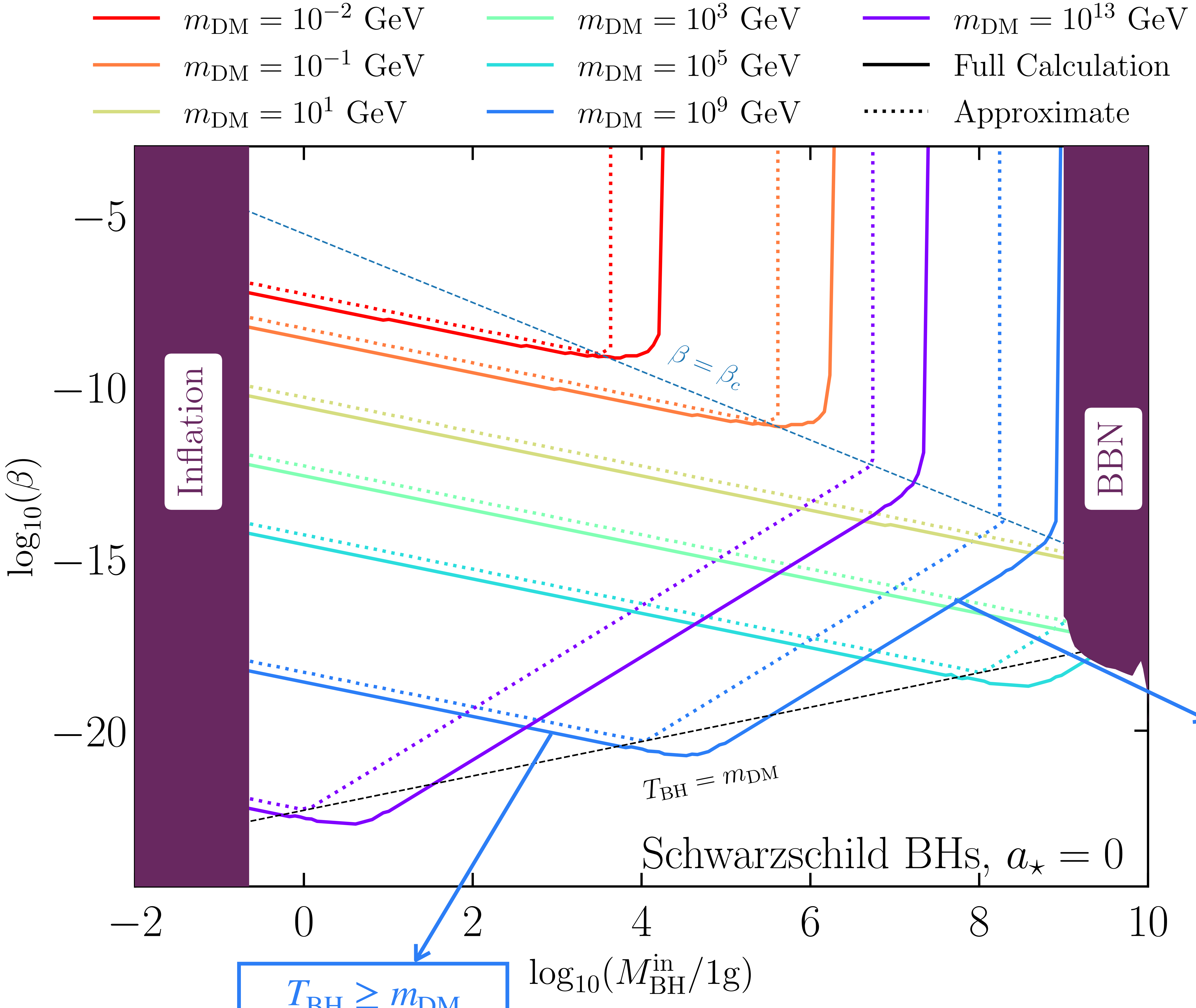

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$T_{BH} < m_{DM}$
Heavier PBHs not hot enough to produce DM

$T_{BH} \geq m_{DM}$
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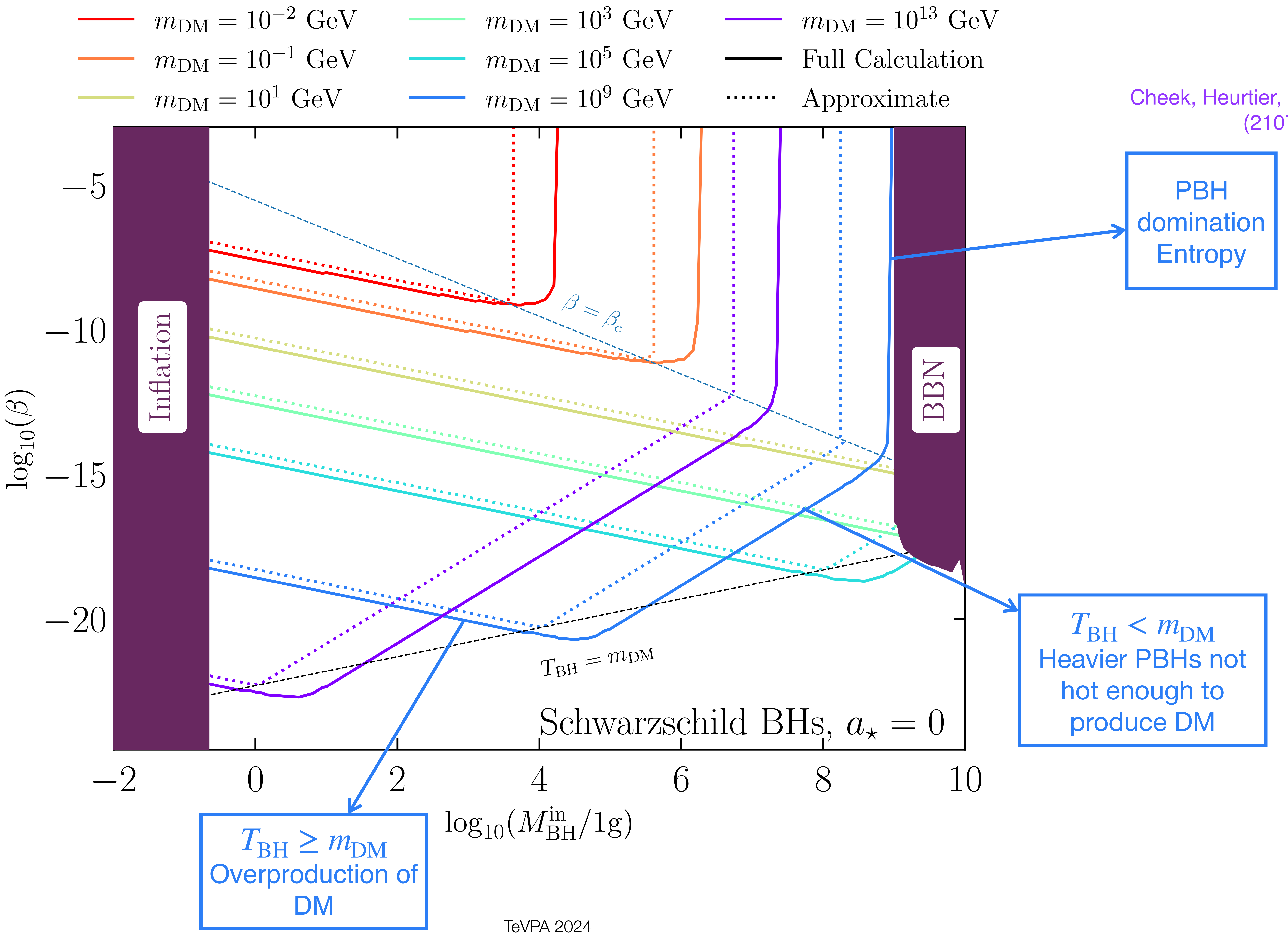

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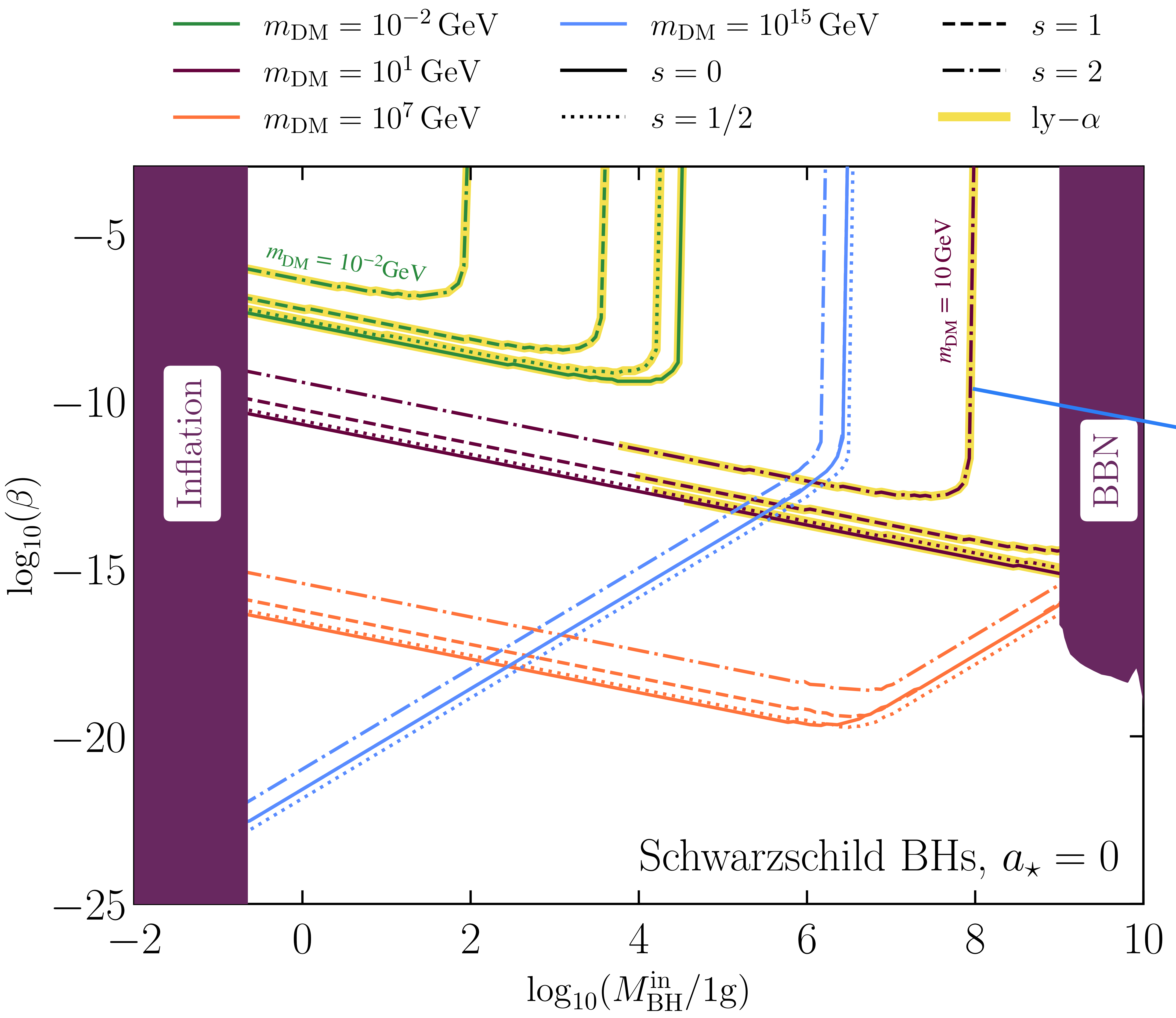

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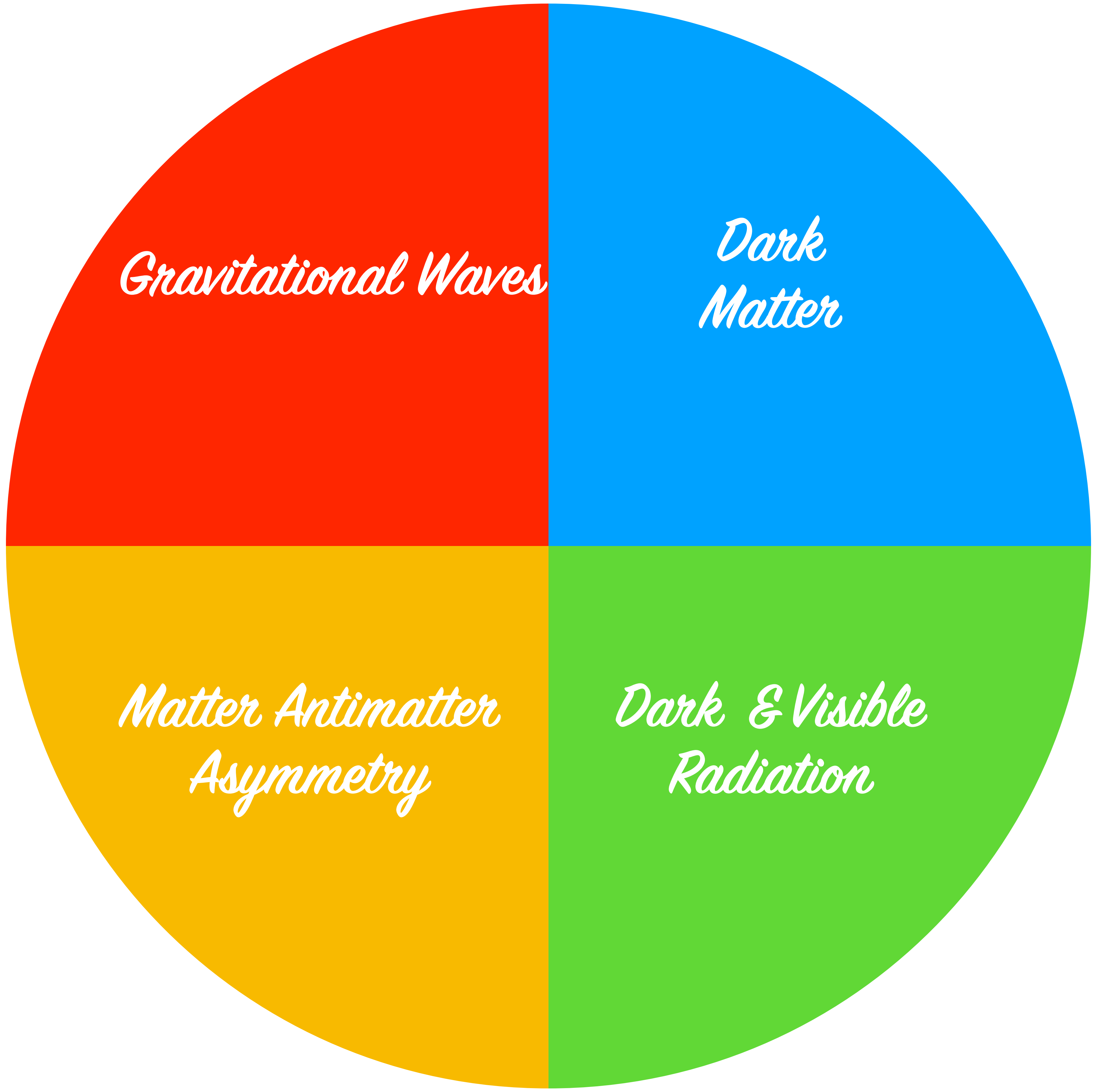
"Light" DM can be boosted when $T_{\rm BH} \gg m_{\rm DM}$ & warm DM constraints apply

Dashed from Gondolo, Sandick, Shams Es Haghi 2009.02424

See also Baldes, Decant, Hooper & Lopez-Honorez (2004.14773)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Dark
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Primordial Black Holes & Dark Radiation

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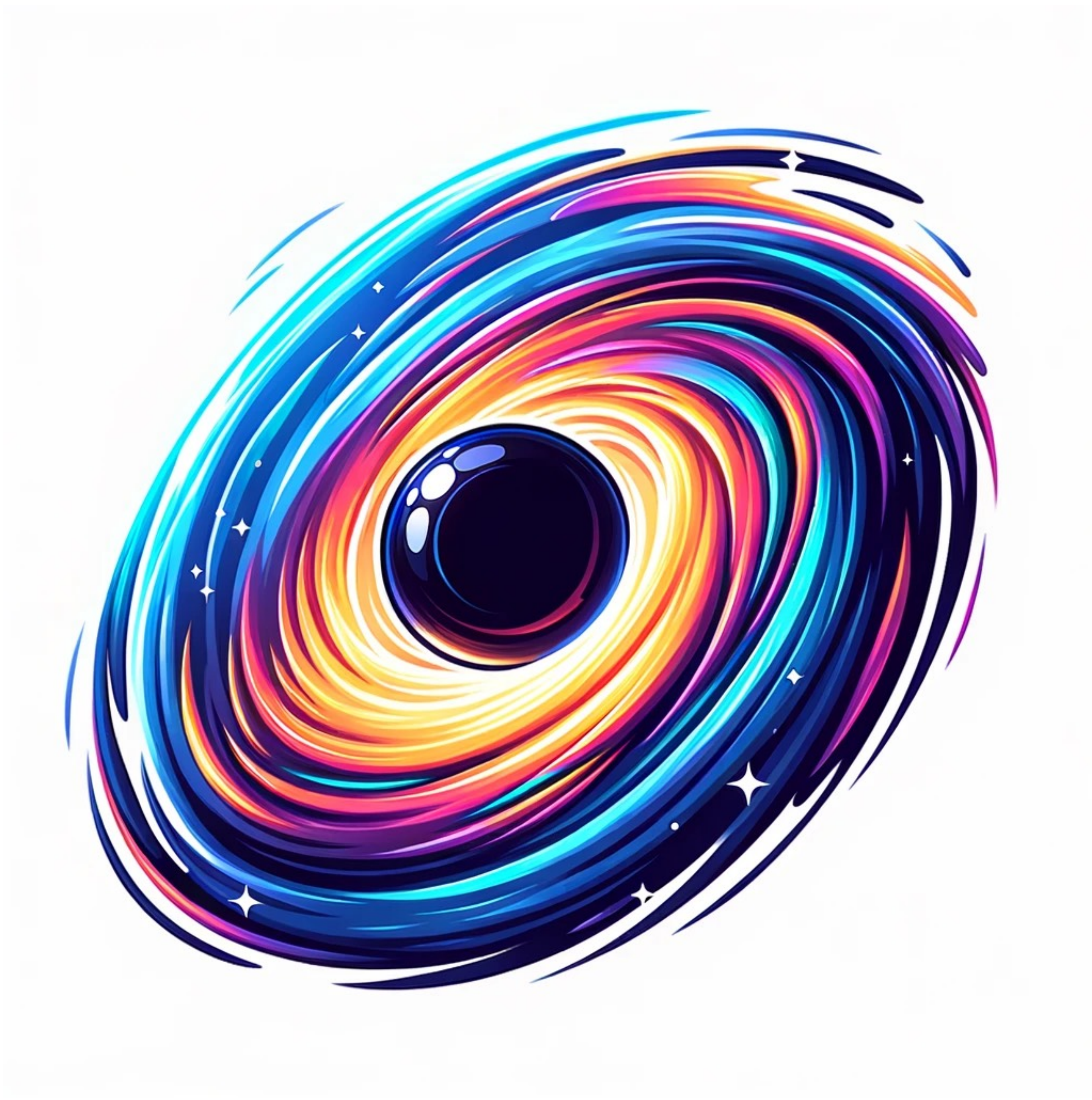

$$a_\star = \frac{J M_{\rm Pl}^2}{M_{\rm BH}^2}$$

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Primordial Black Holes & Dark Radiation

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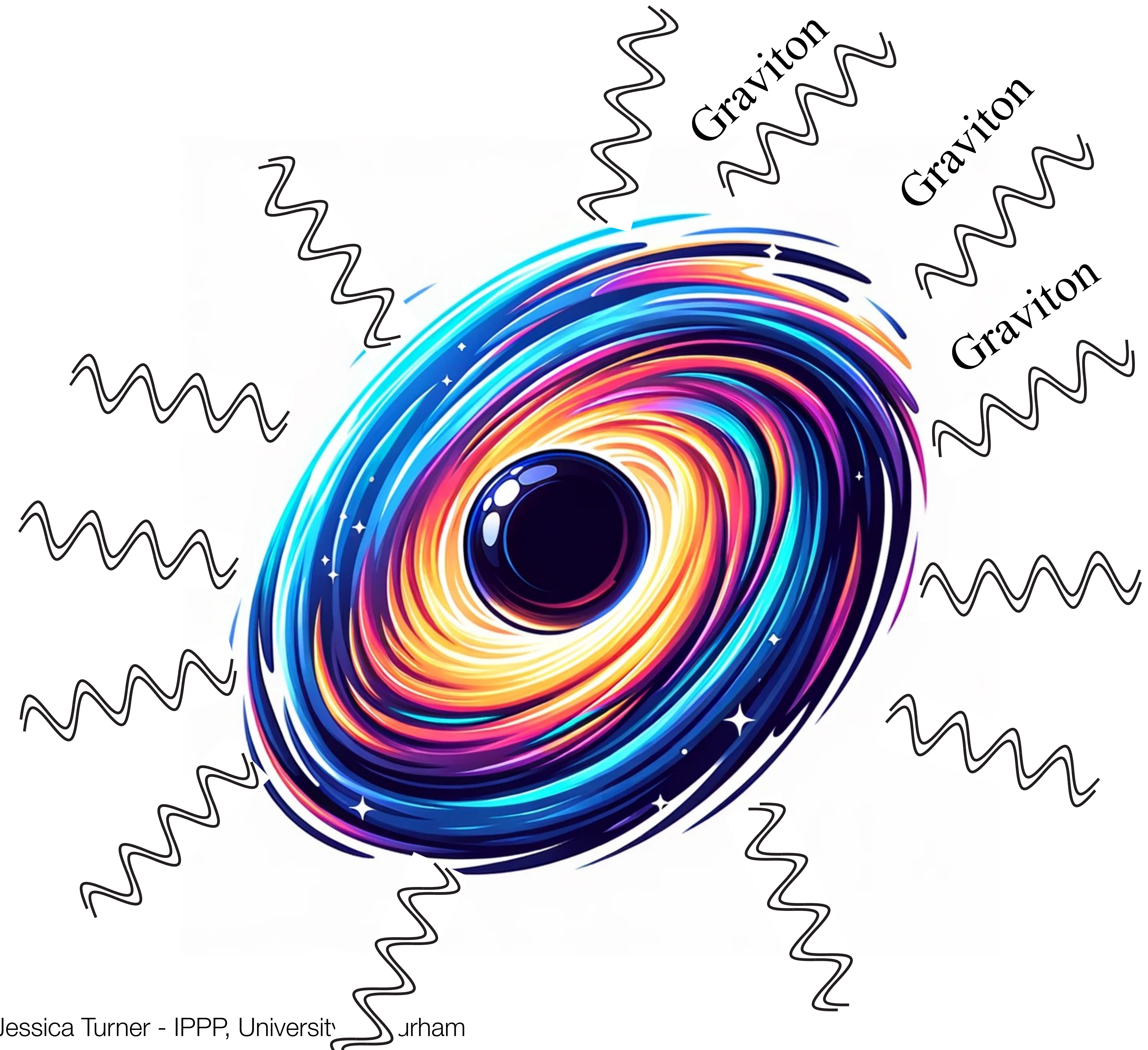

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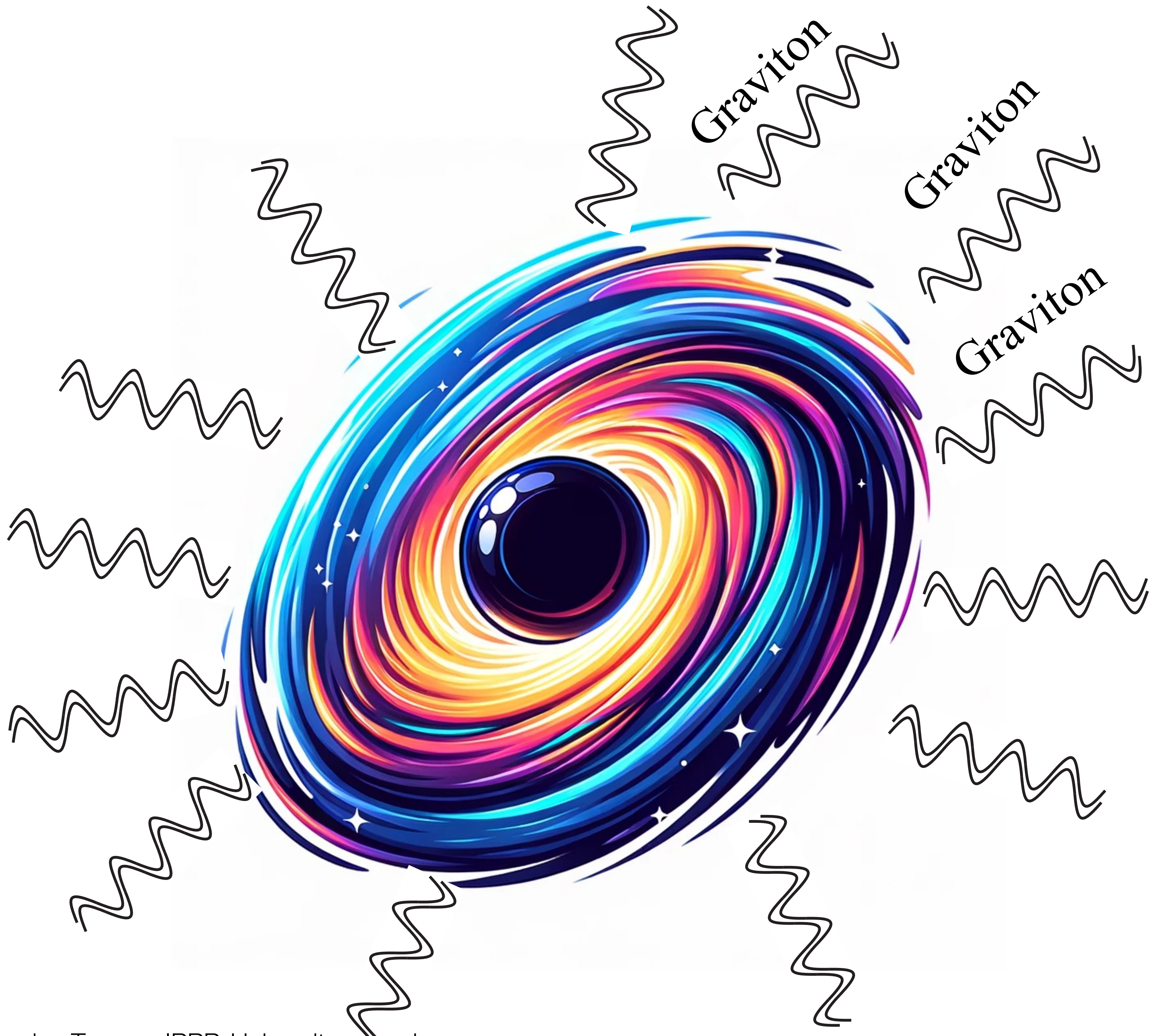

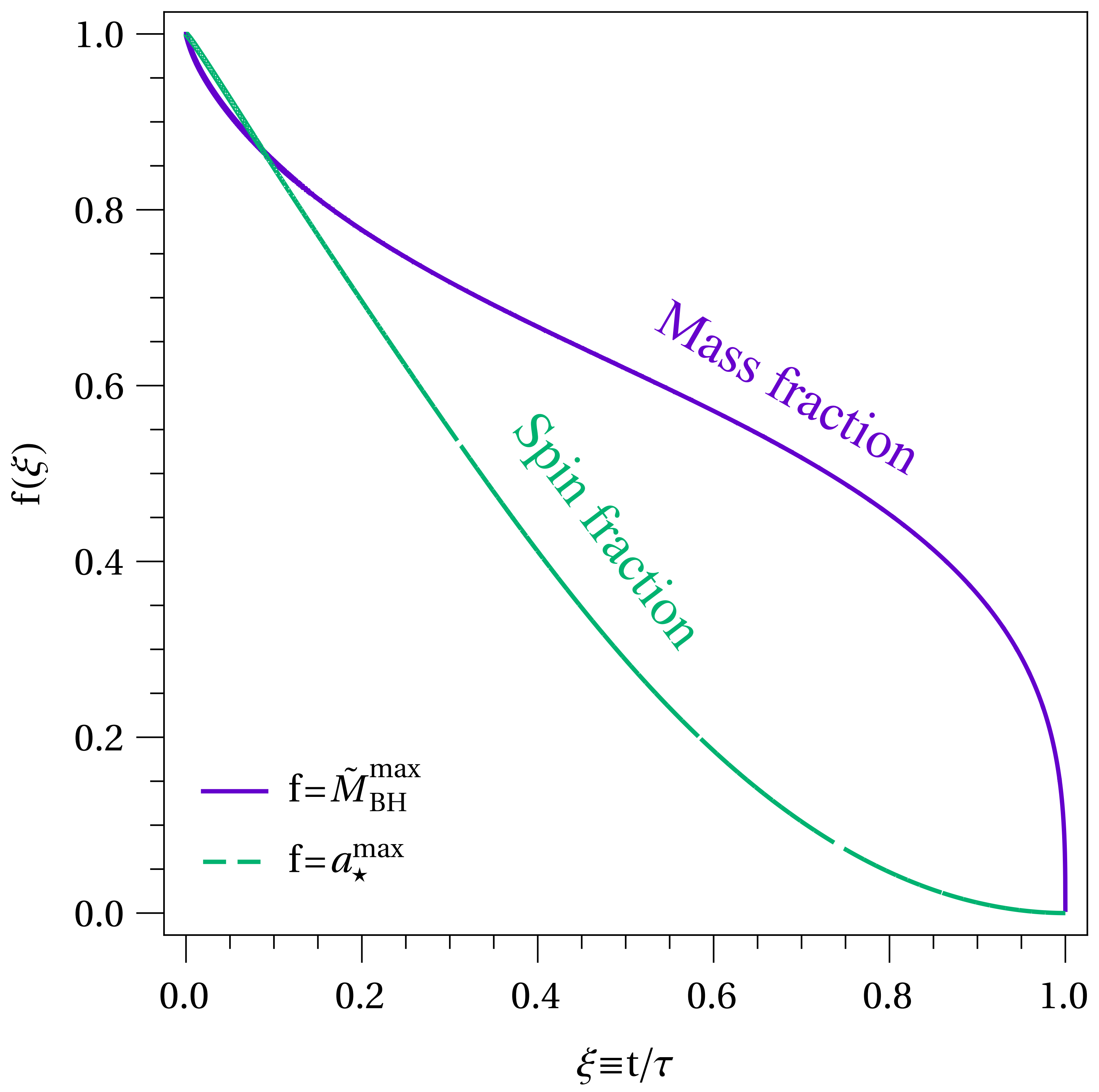

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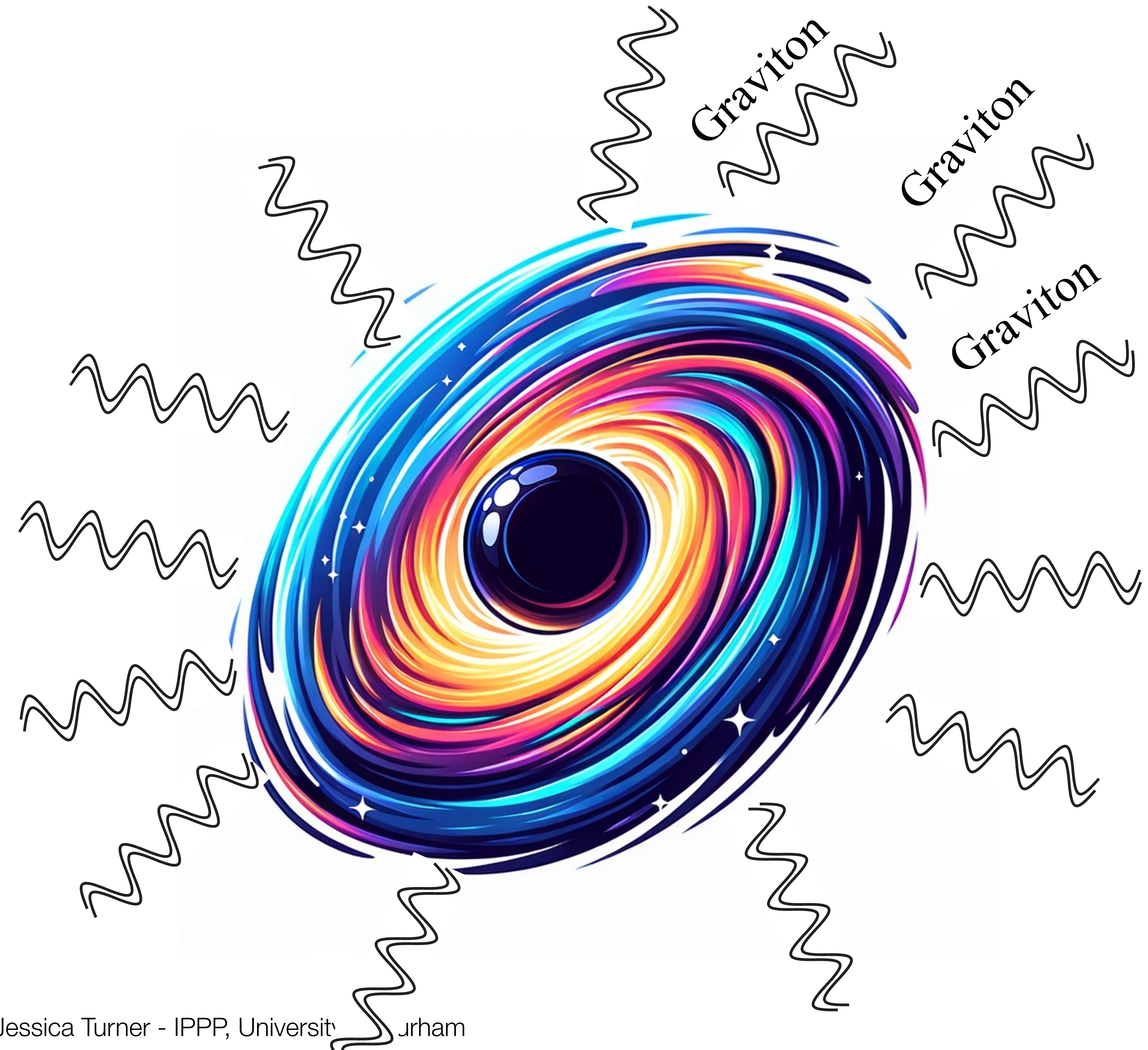
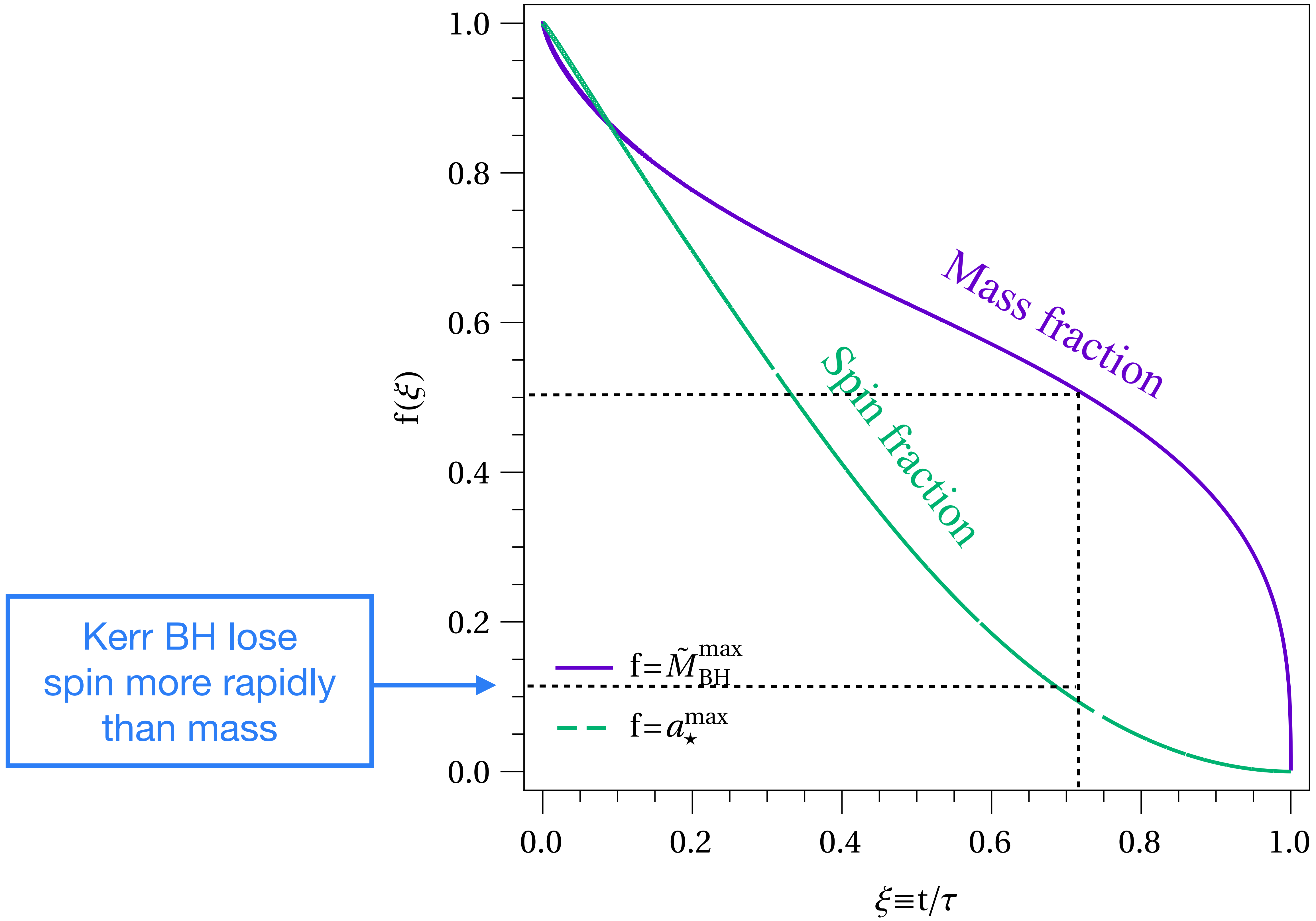
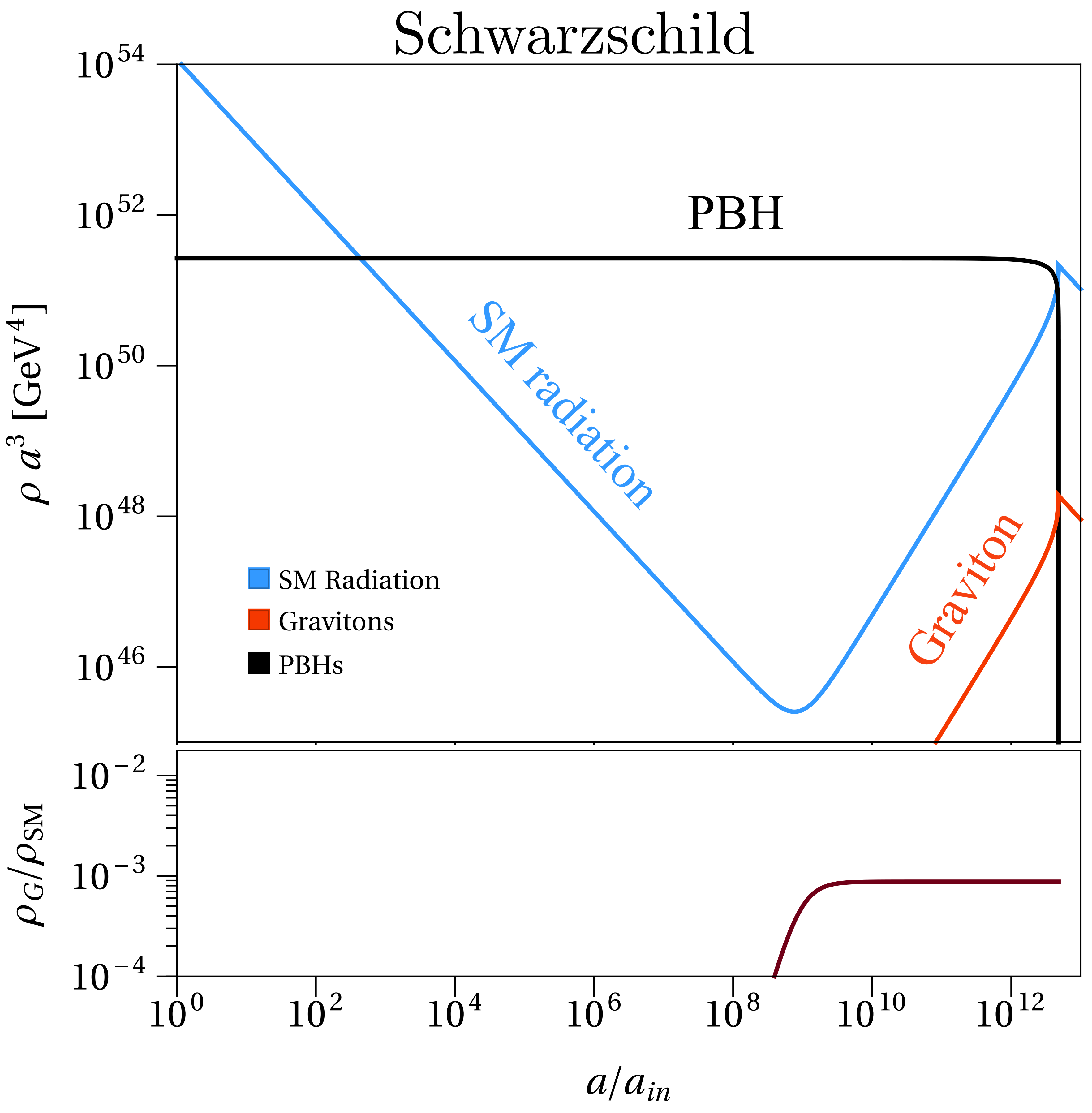


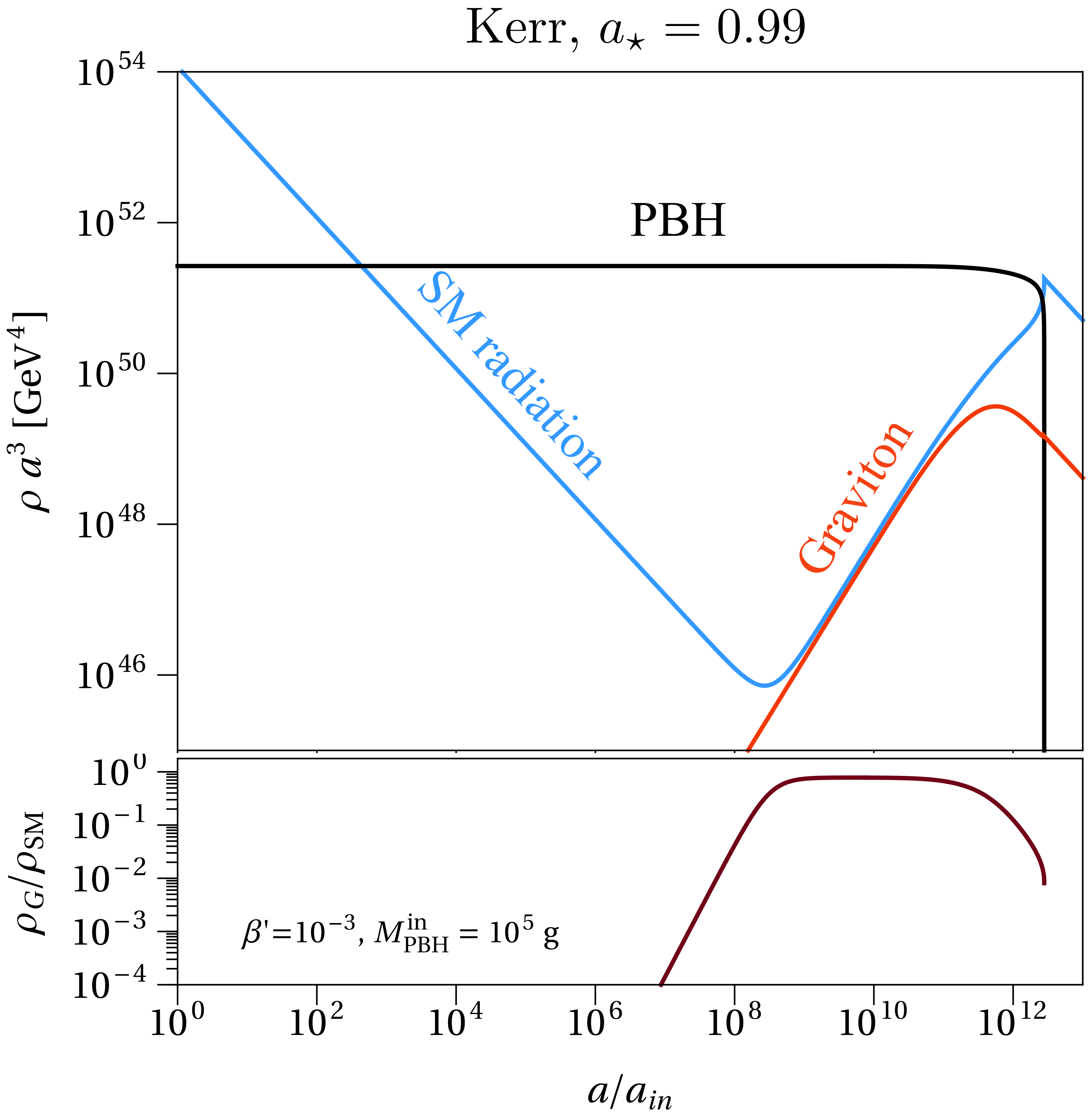


Primordial Black Holes & Dark Radiation

Hooper, Krnjaic & McDermott (1905.01301)
Hooper, Krnjaic, March-Russell, McDermott & Byrne (2004.00618)
Masina (2004.04740) Masina (2103.13825)
Arbey, Auffinget, Sandrick, Es Haghi, Sinha (2104.04051)

- Production of “hot gravitons” from PBHs can contribute to $\Delta N_{\rm eff}$



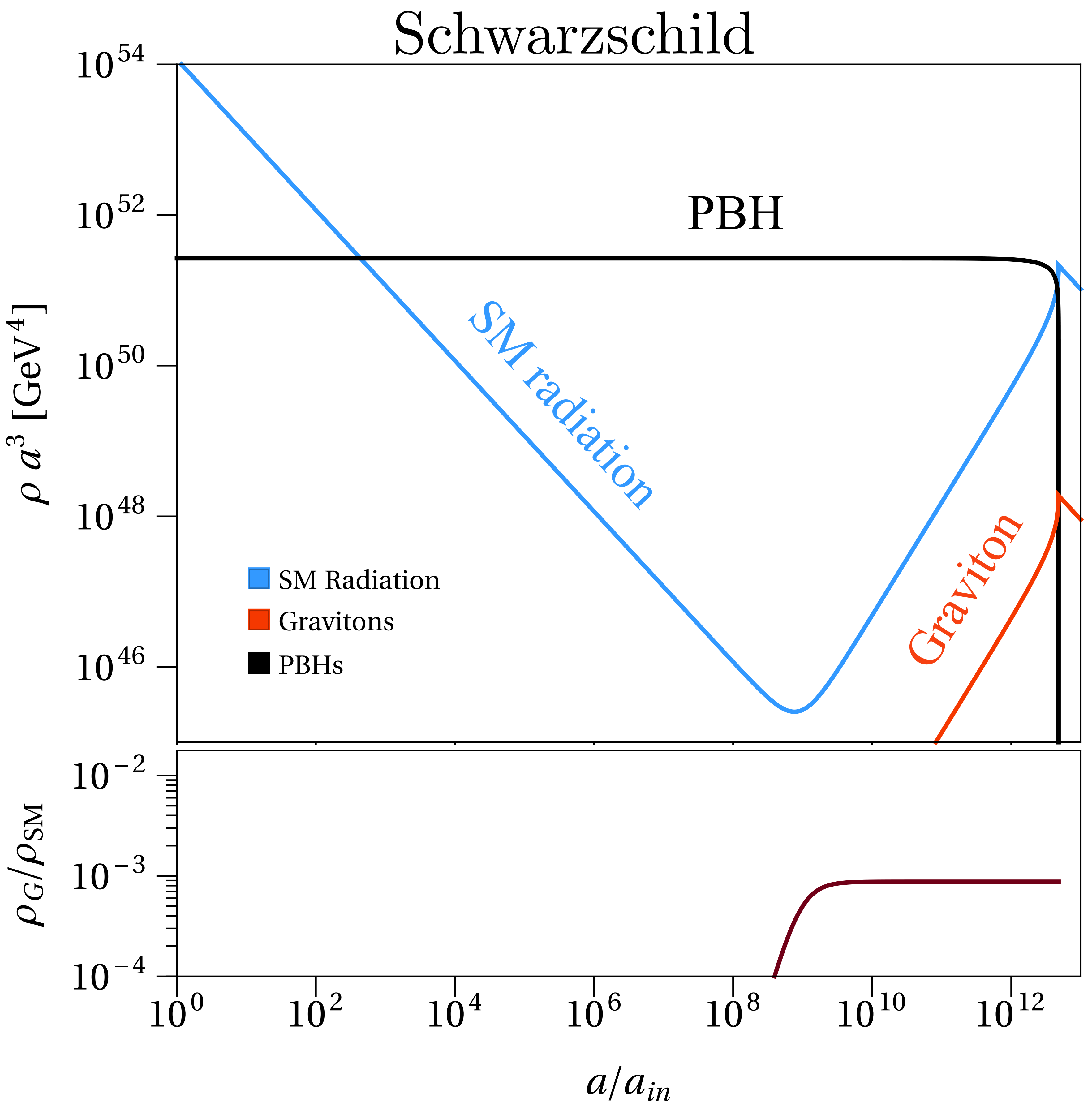


Cheek, Heurtier, Perez-Gonzalez, JT
2207.09462

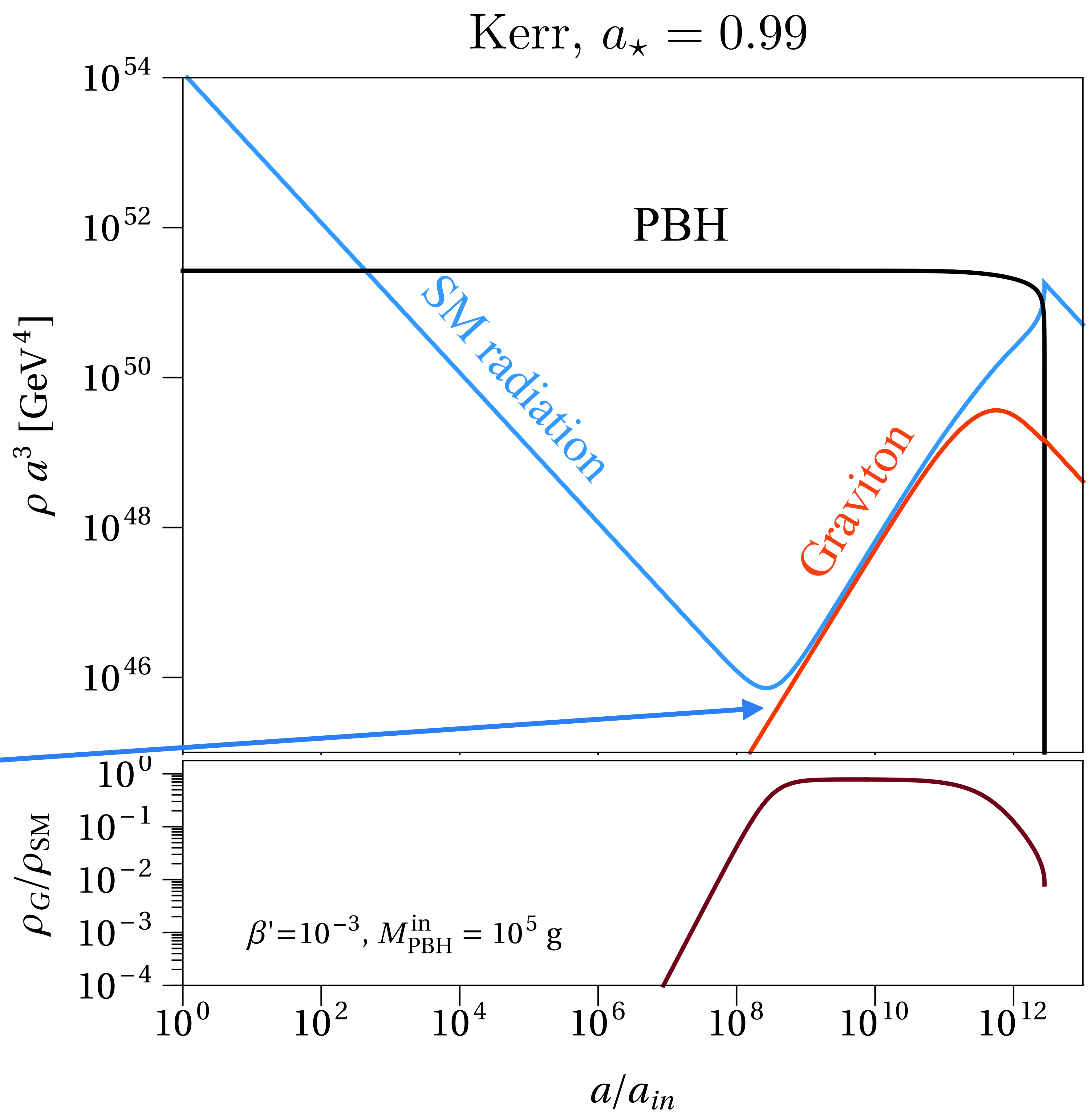
Primordial Black Holes & Dark Radiation

Hooper, Krnjaic & McDermott (1905.01301)
Hooper, Krnjaic, March-Russell, McDermott & Byrne (2004.00618)
Masina (2004.04740) Masina (2103.13825)
Arbey, Auffinget, Sandrick, Es Haghi, Sinha (2104.04051)

- Production of “hot gravitons” from PBHs can contribute to ΔN_{eff}



Graviton production Earlier



Cheek, Heurtier, Perez-Gonzalez, JT
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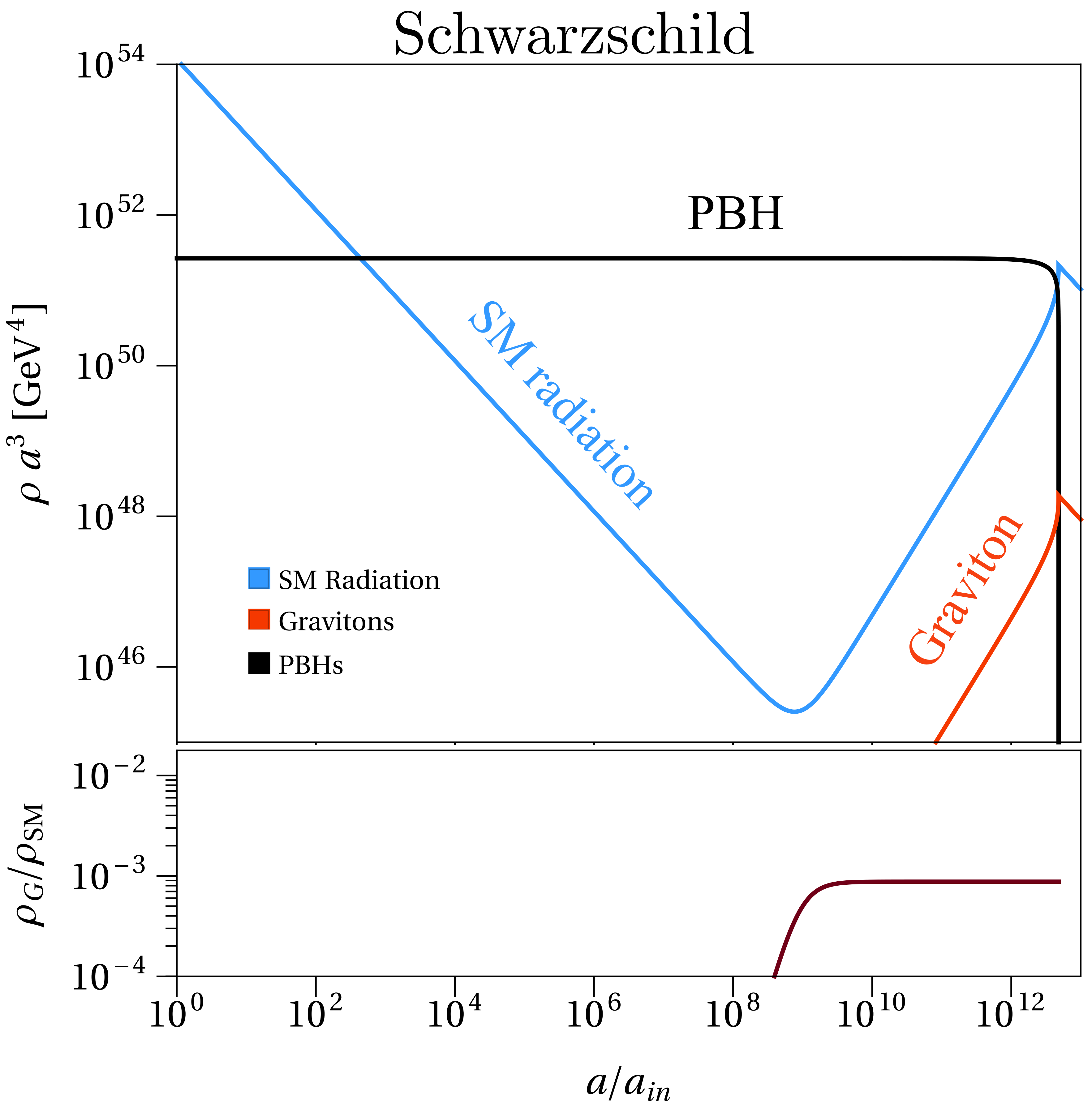

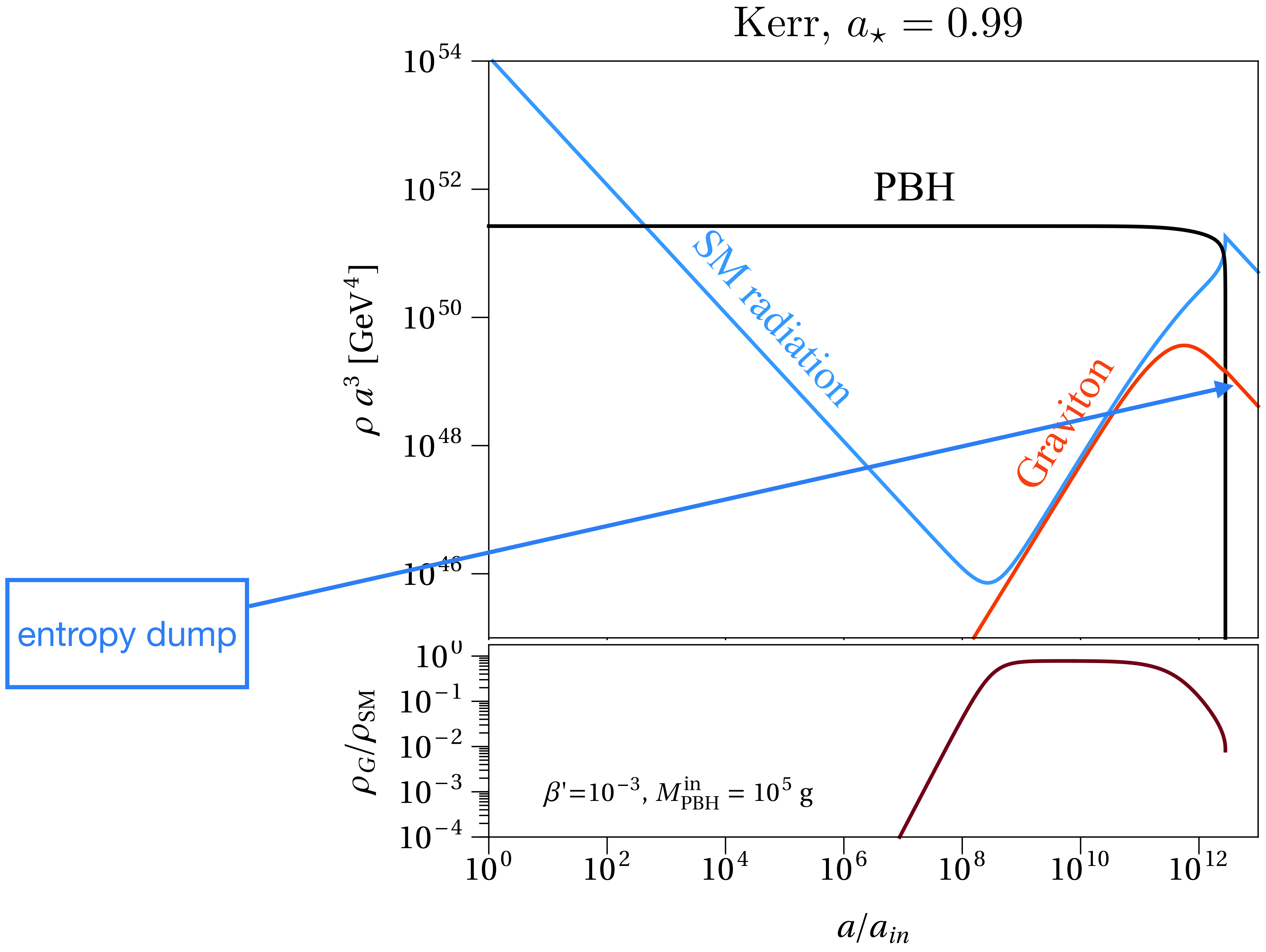

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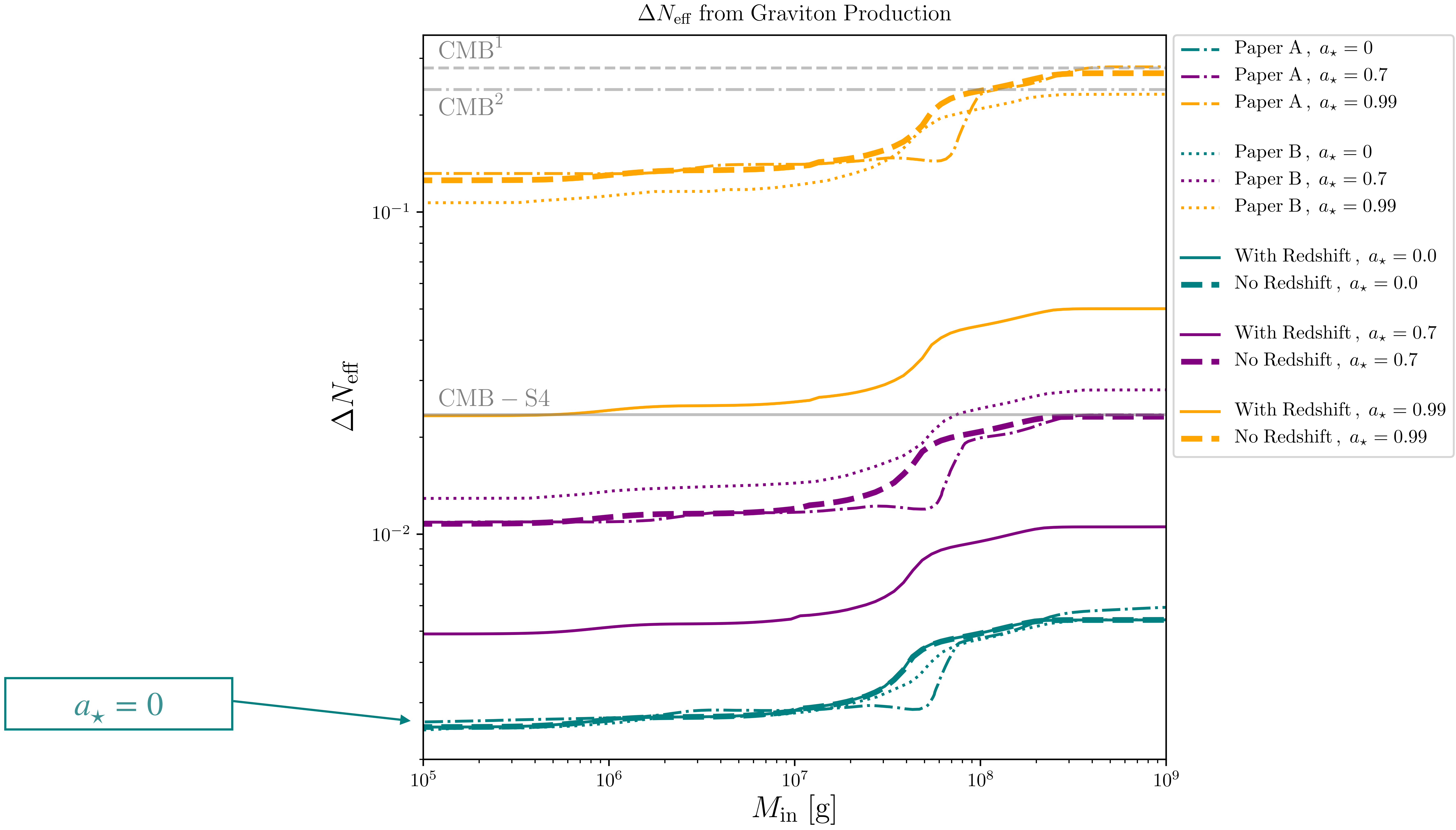

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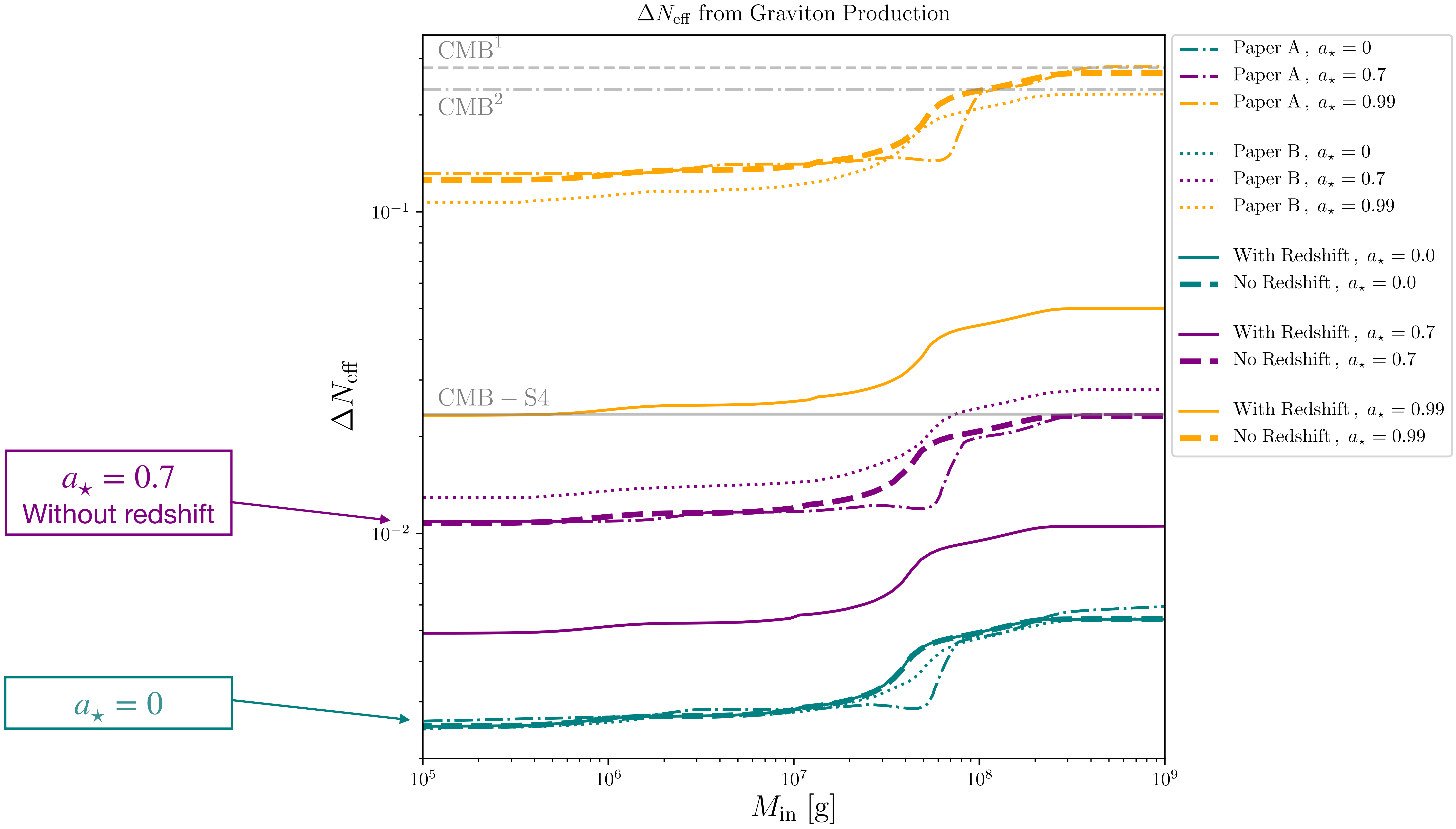

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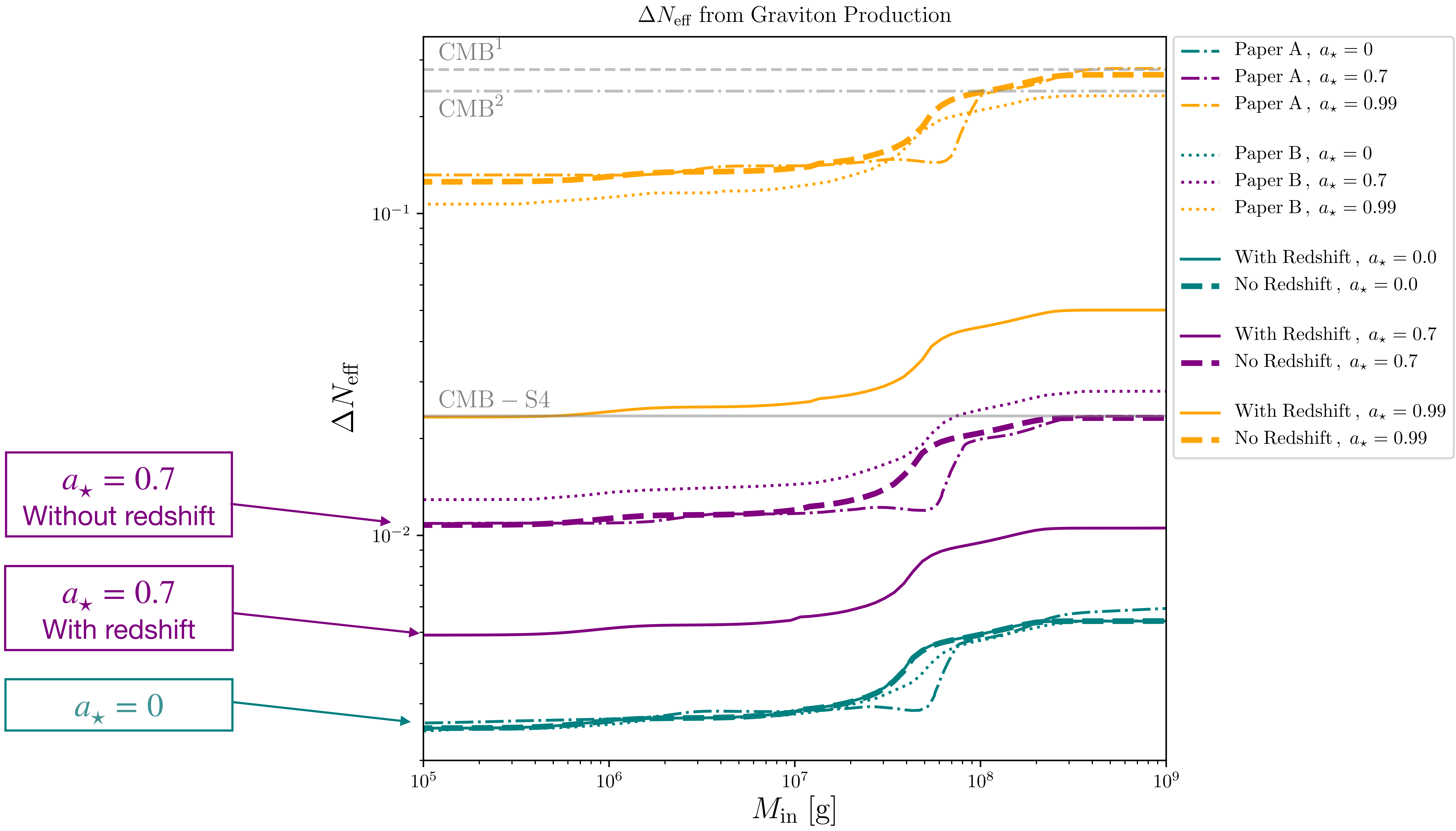
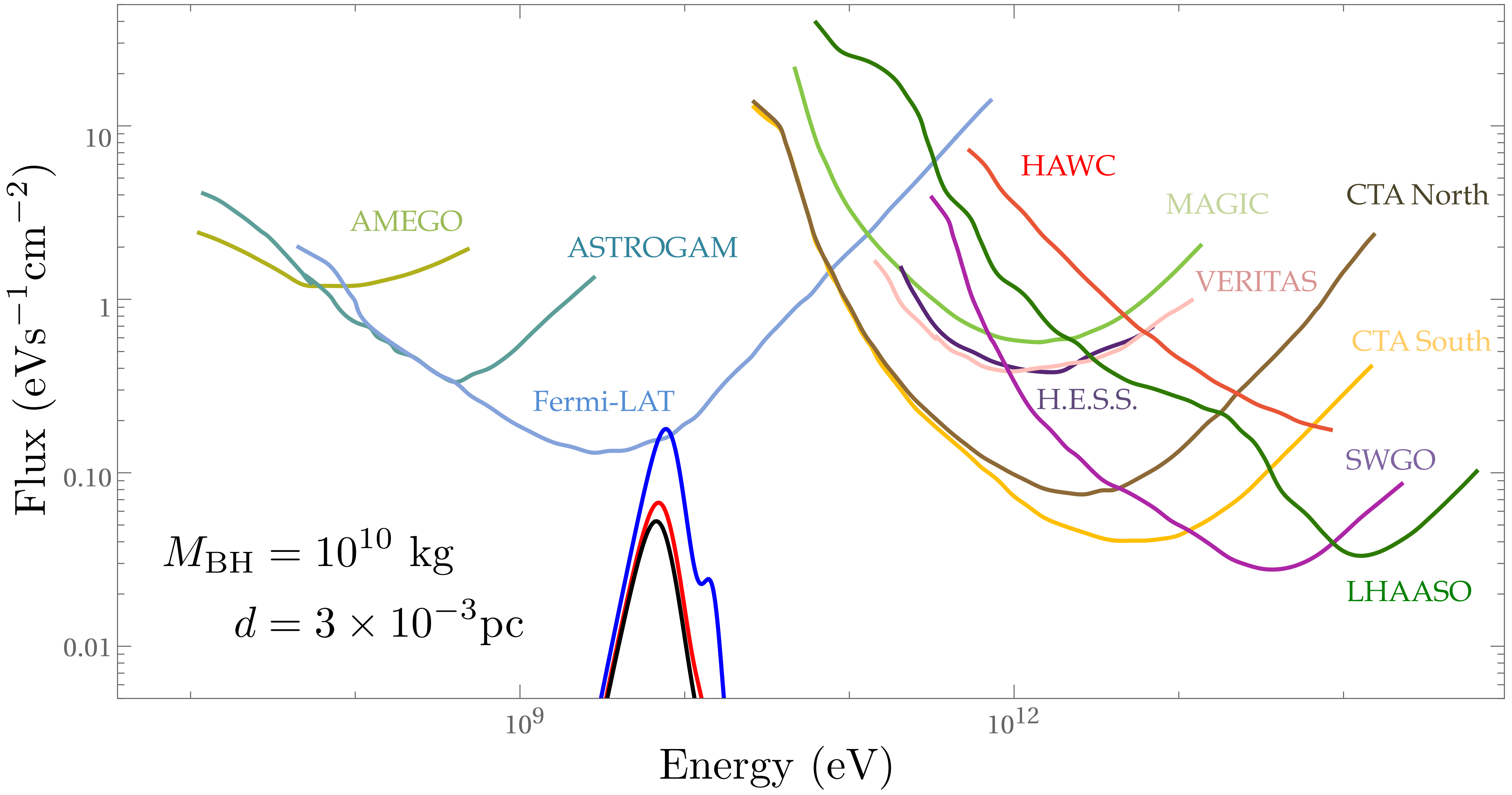
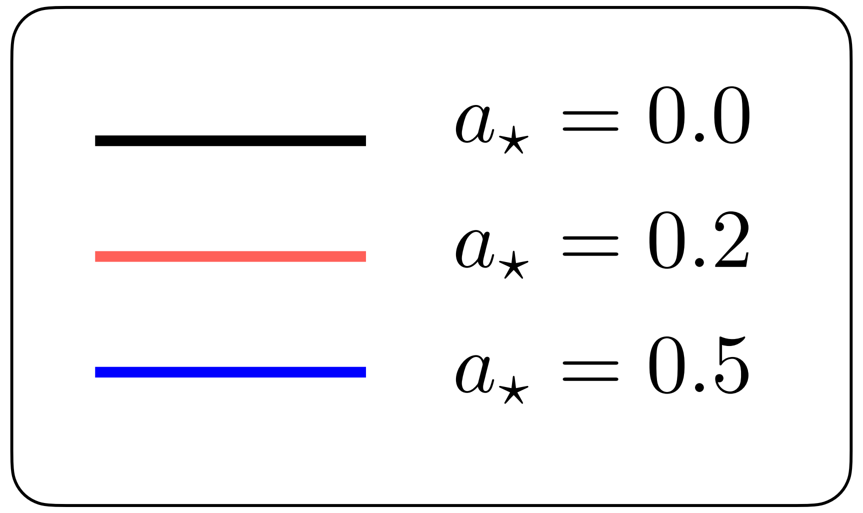


Primordial Black Holes & Visible Radiation

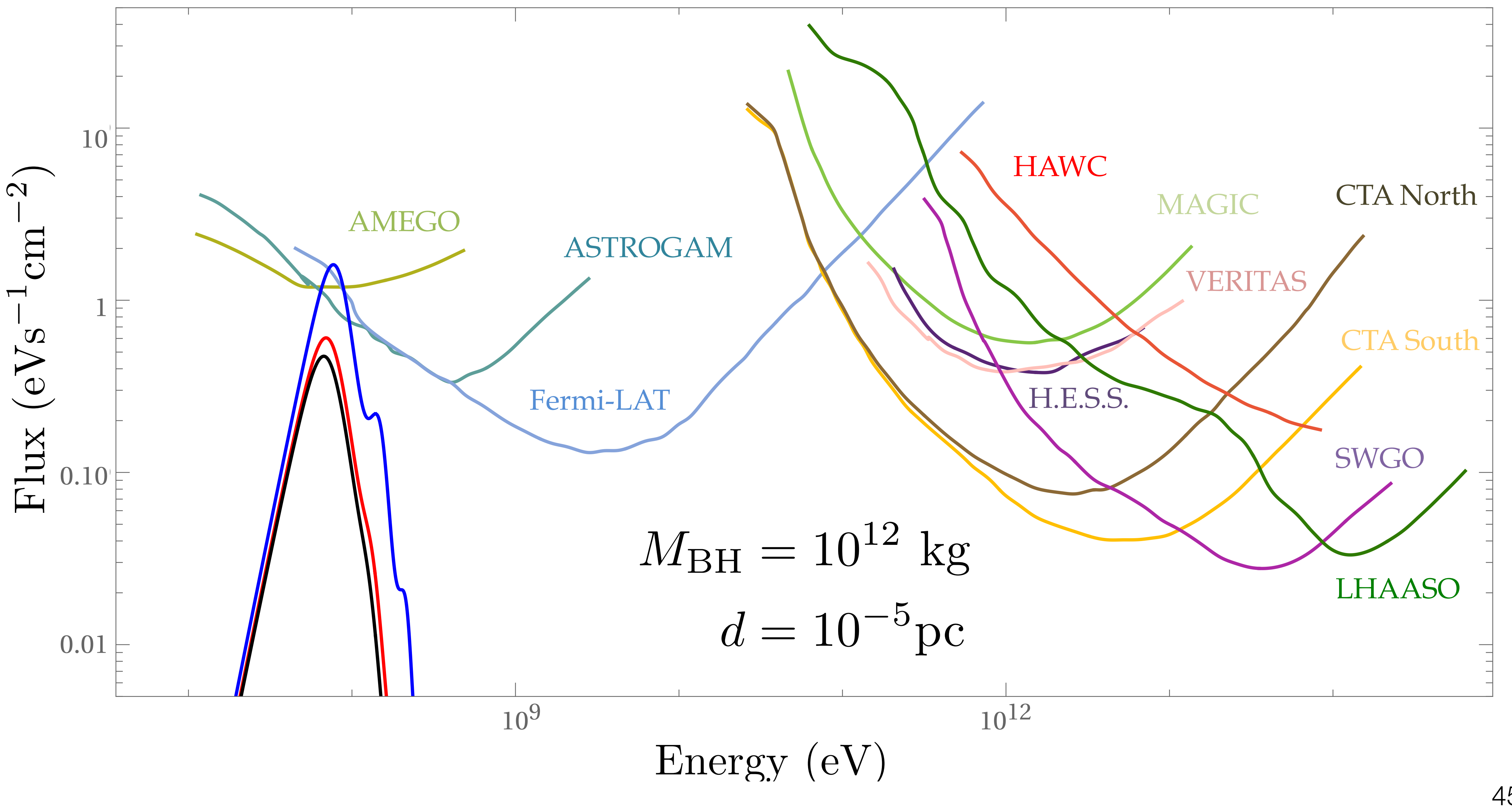
- Consider **currently evaporating Kerr PBH**. Photon emission enhanced for higher $a_\star$

Image credit: Calza & Rosa





Calza & Rosa
2312.09261



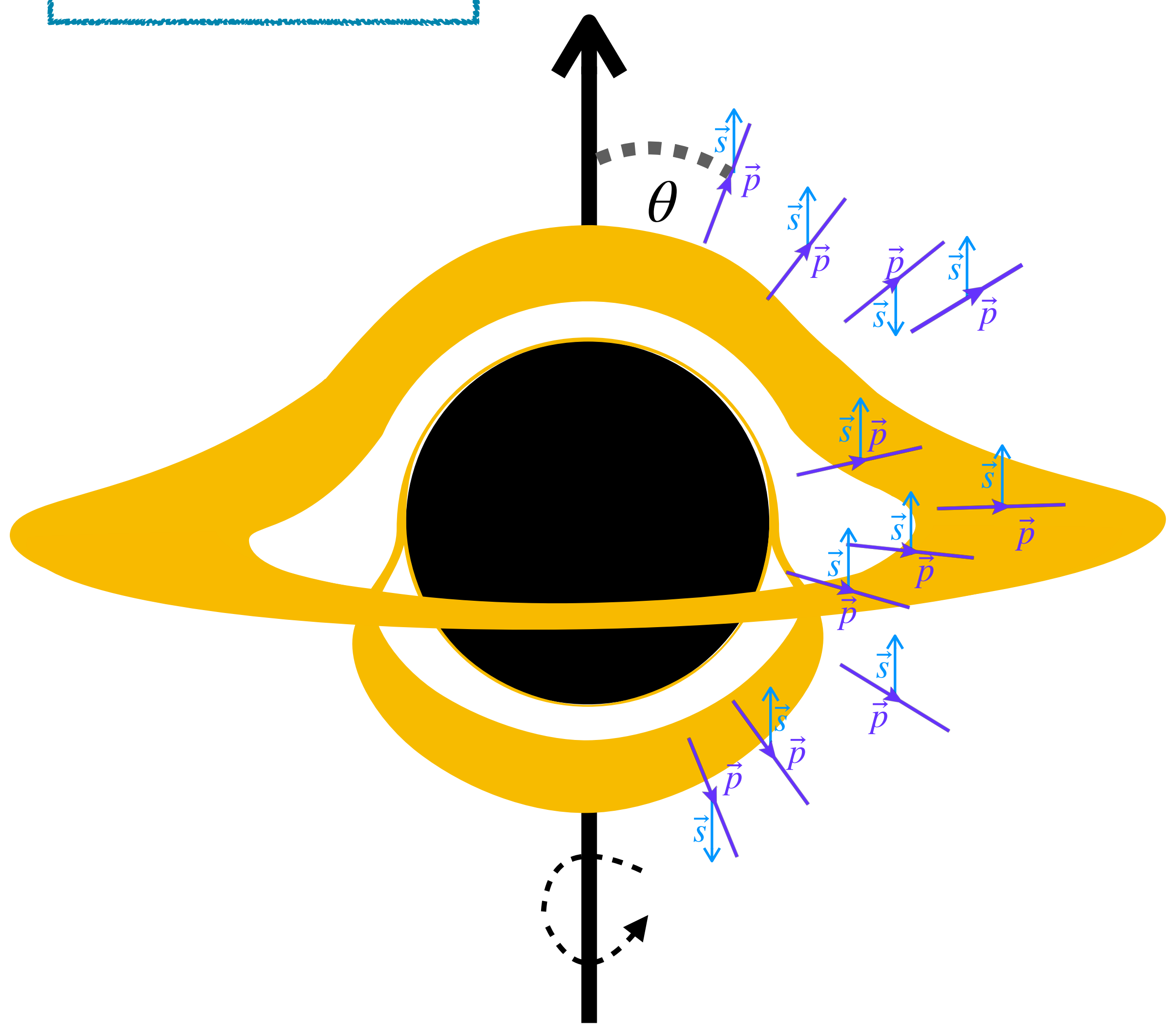
Primordial Black Holes & Visible Radiation

- Kerr PBHs emit neutrinos and antineutrinos asymmetrically

Perez-Gonzalez (2207.09462)

Image Credit: Yuber Perez-Gonzalez

BH “wants” to shed off its angular momentum



Axis of rotation

Particles with positive helicity are *preferentially* emitted in the northern hemisphere

Antineutrinos*

$\theta = 0$

Particles with negative helicity are *preferentially* emitted in the southern hemisphere

Neutrinos*

Vilenkin, PRL 41 (1978) 1575
Leahy, Unruh, PRD 19 (1979) 3509

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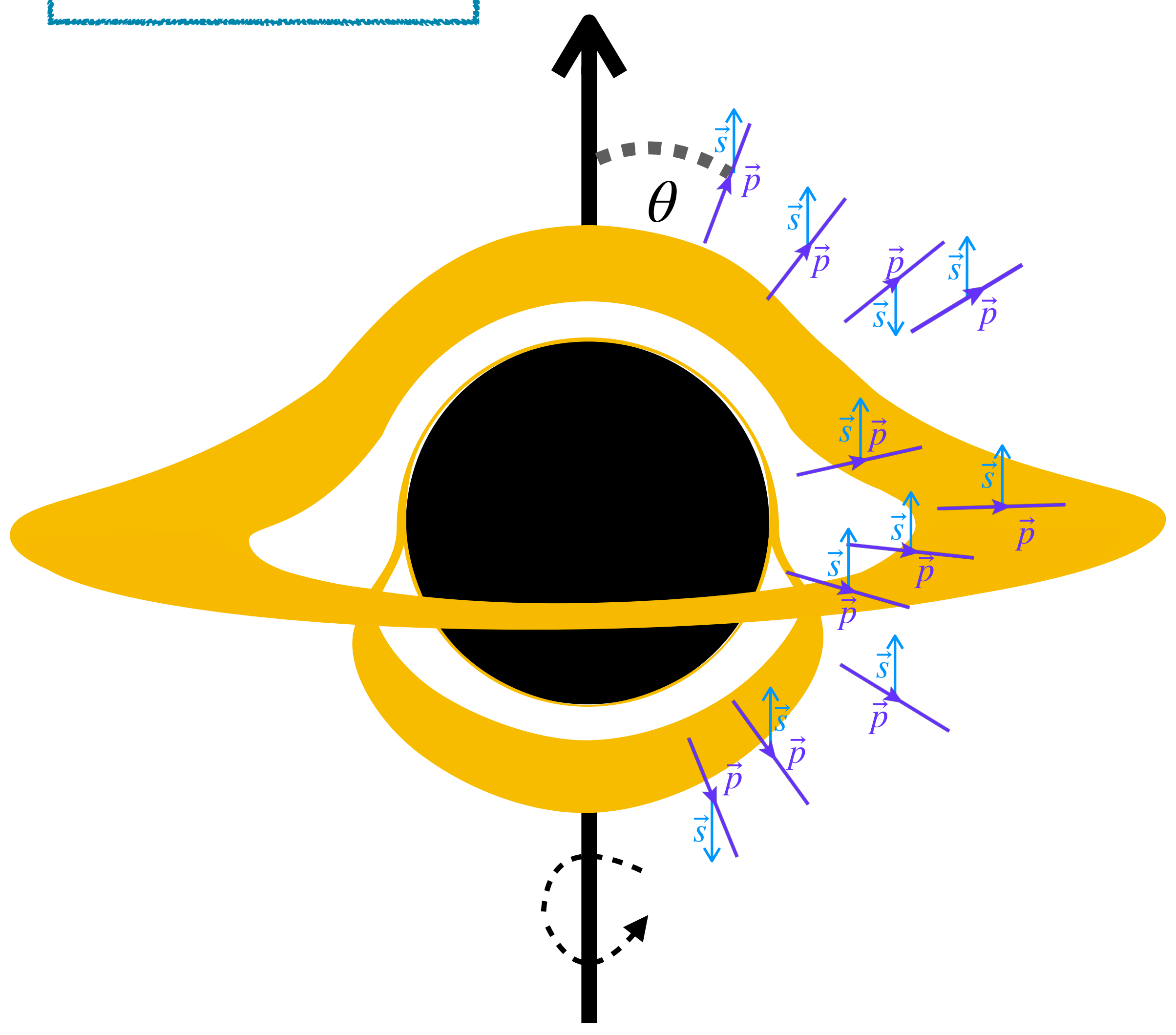

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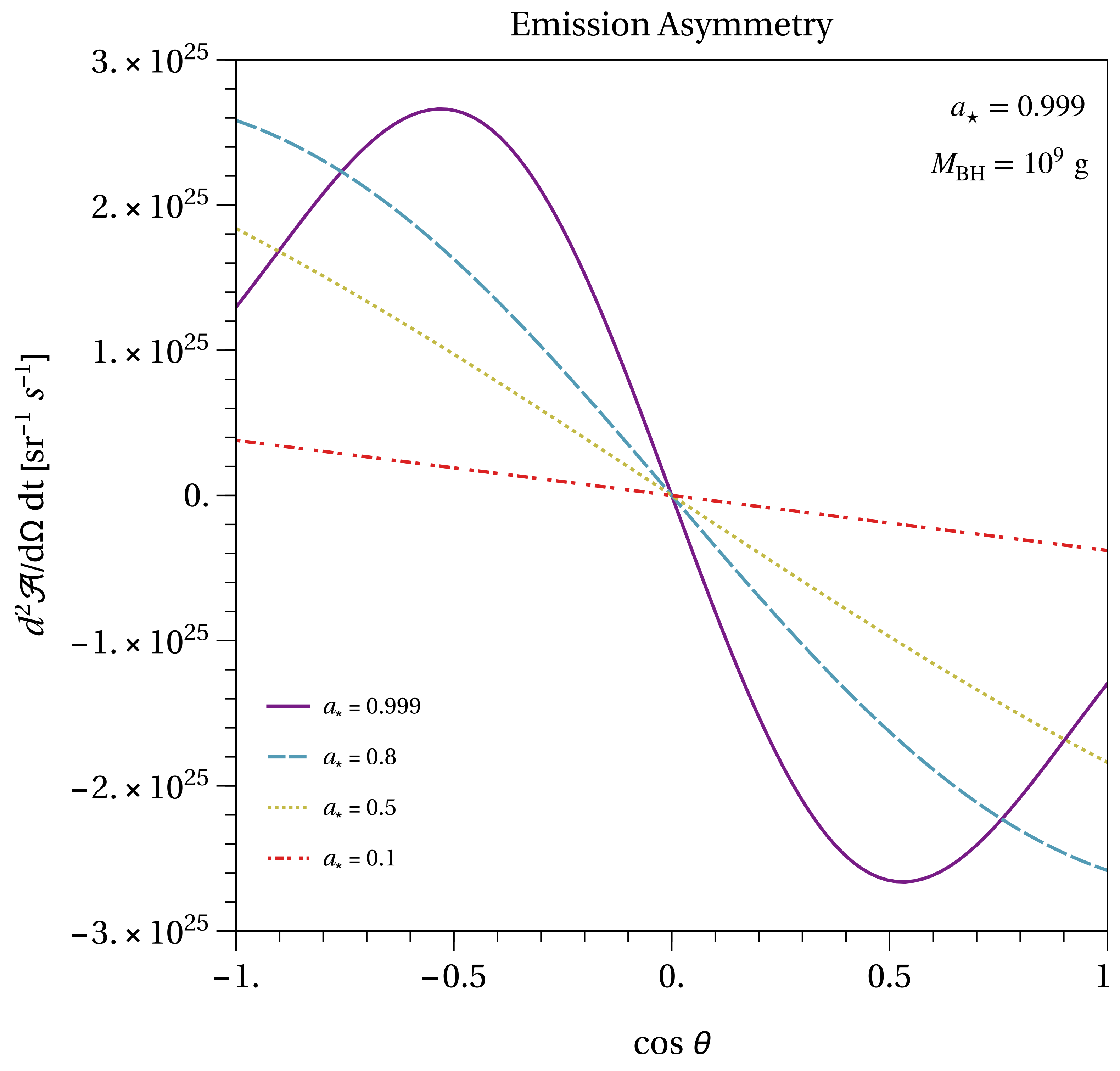

$\nu - \bar{\nu}$ rate

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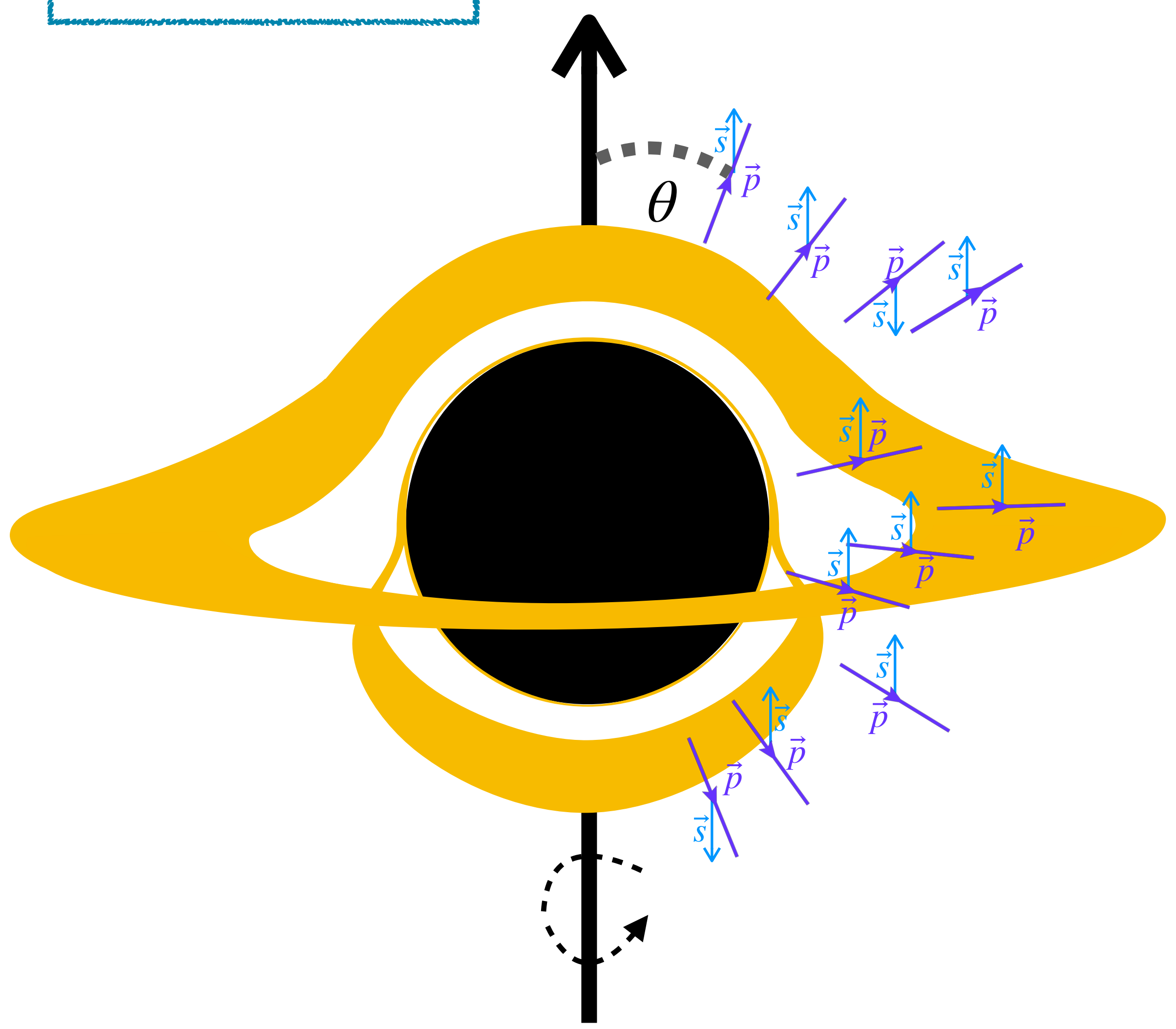

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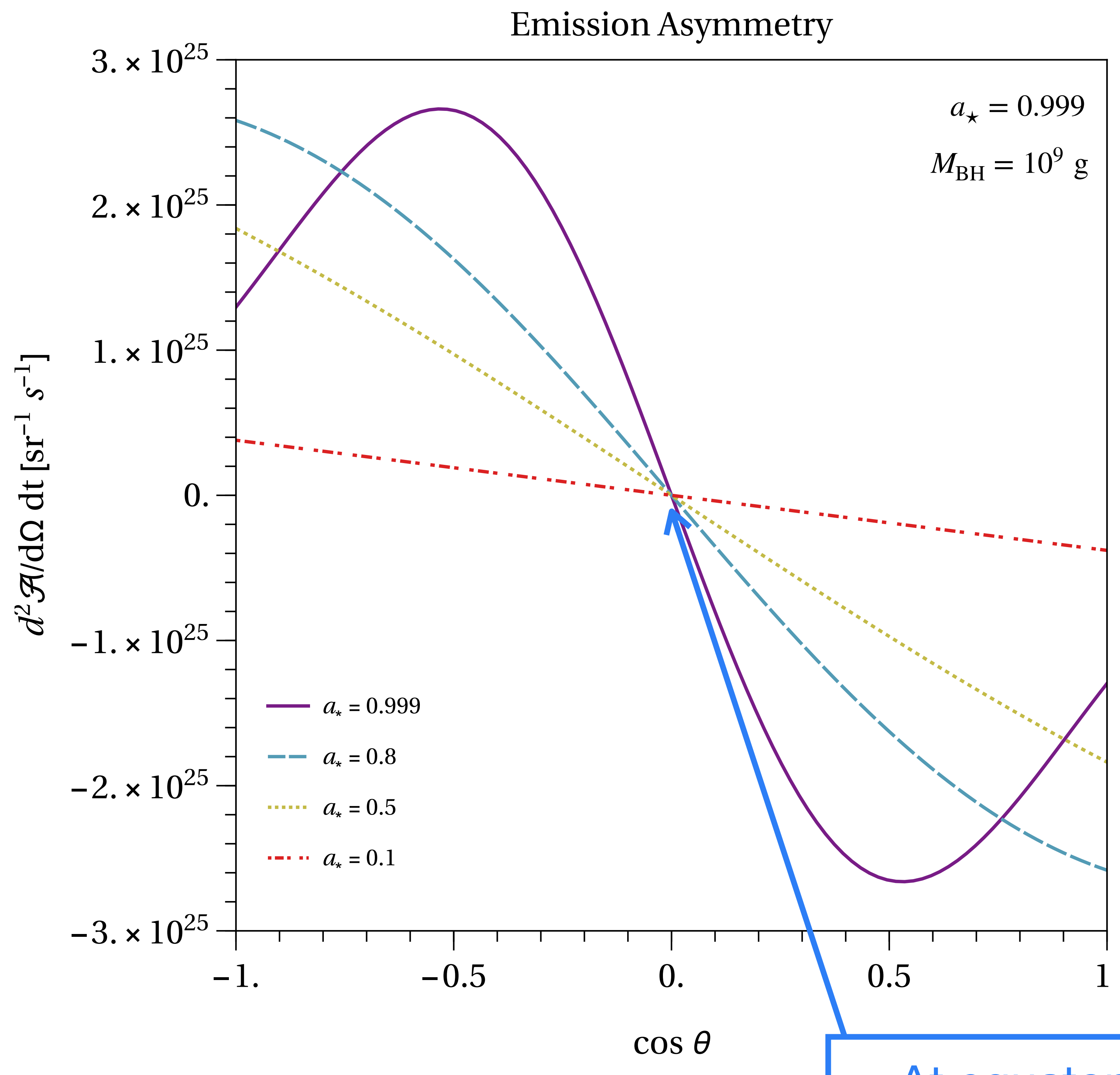

$\nu - \bar{\nu}$ rate

At equator no asymmetry

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Primordial Black Holes & Visible Radiation

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Perez-Gonzalez (2207.09462)

Image Credit: Yuber Perez-Gonzalez

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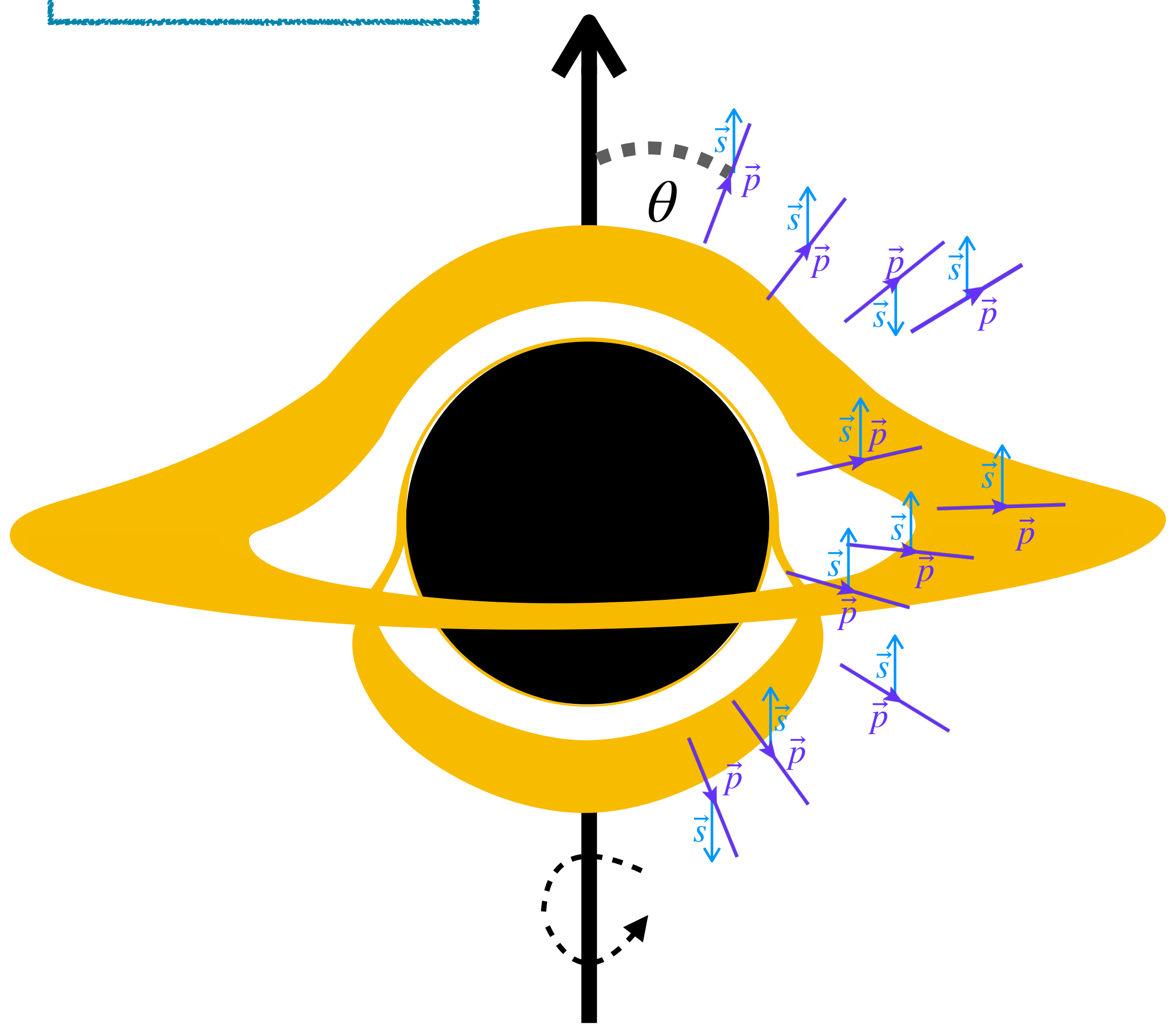

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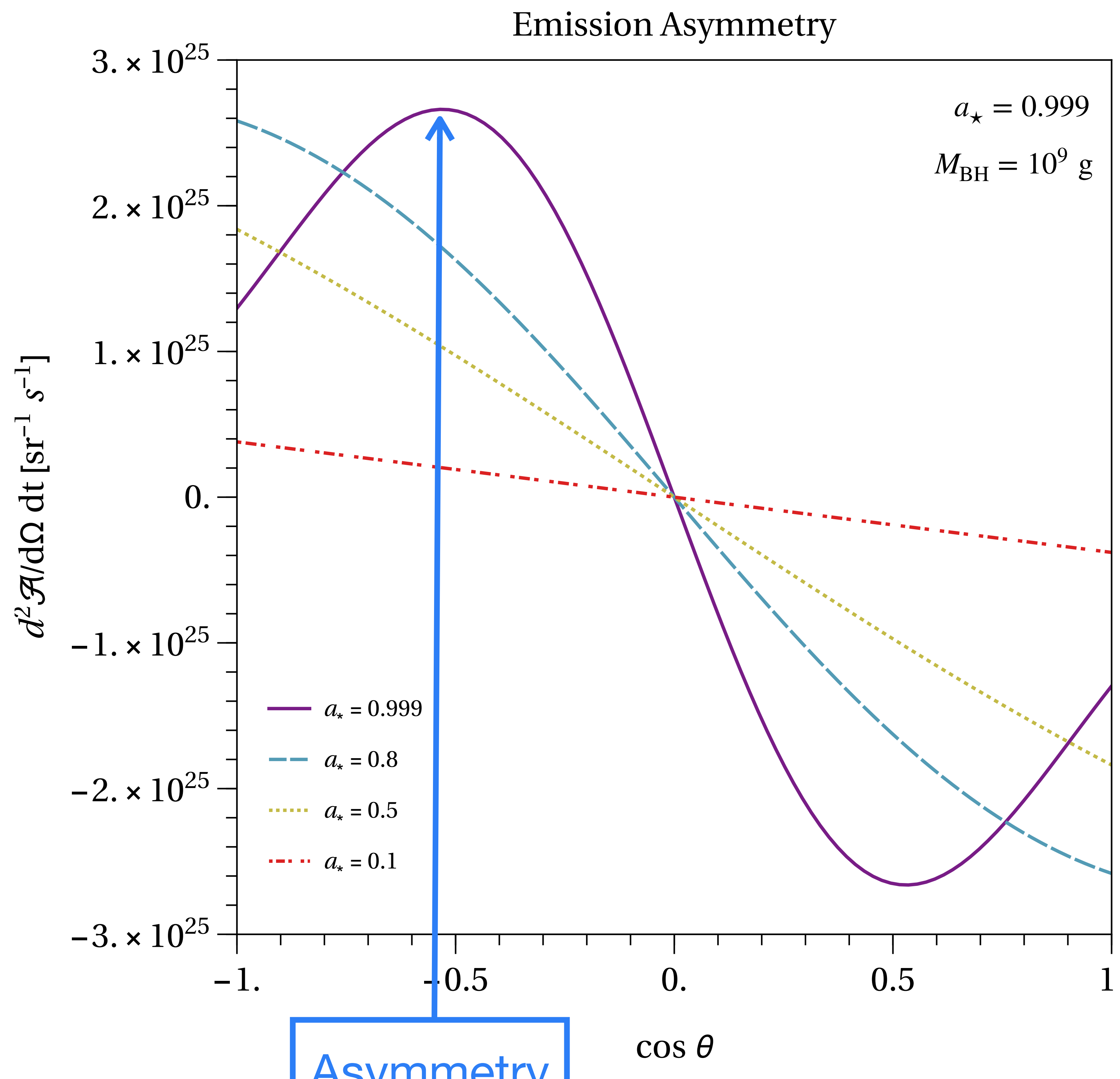

$\nu - \bar{\nu}$ rate

Asymmetry maximised $\sim 60^\circ$

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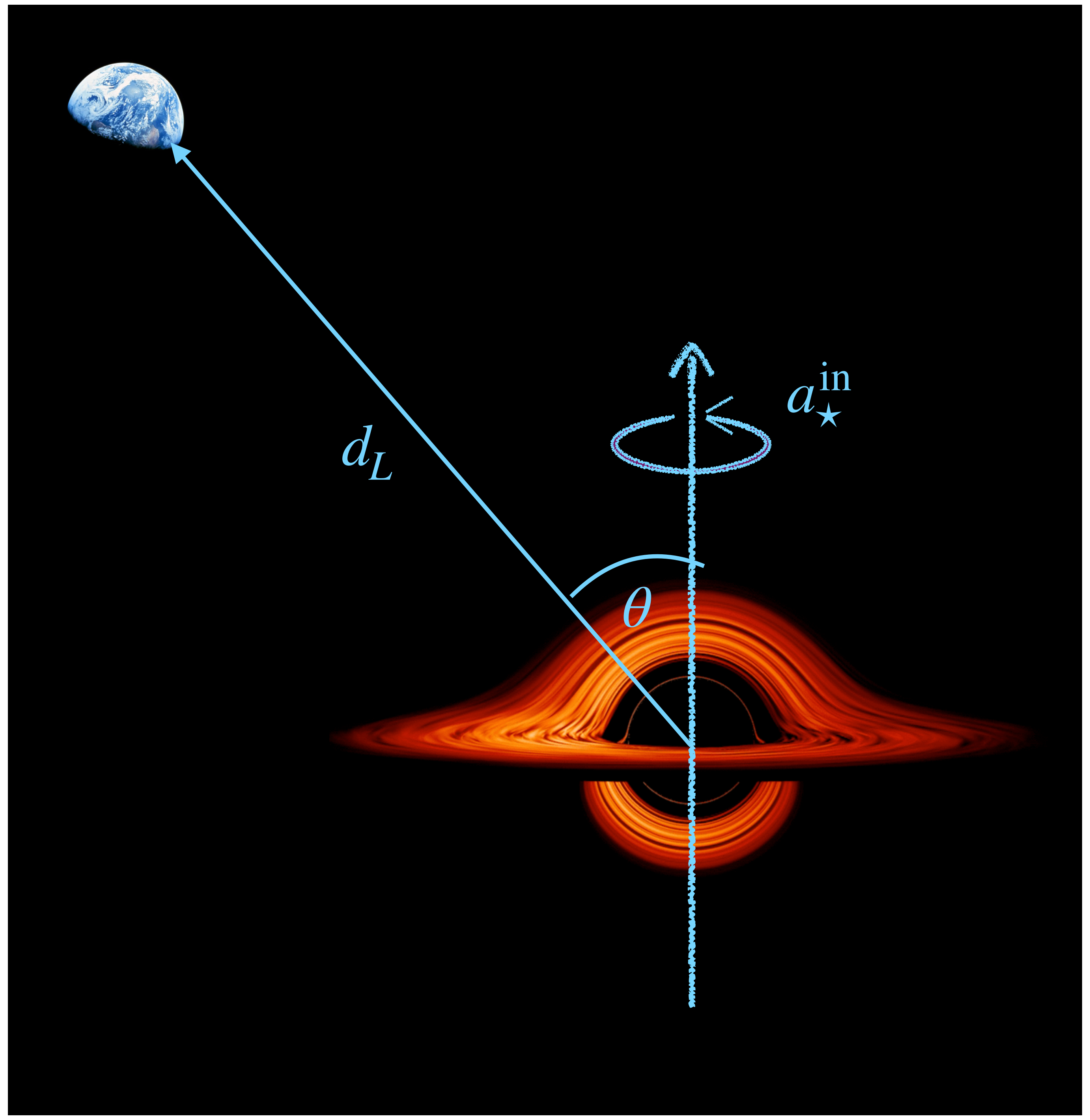
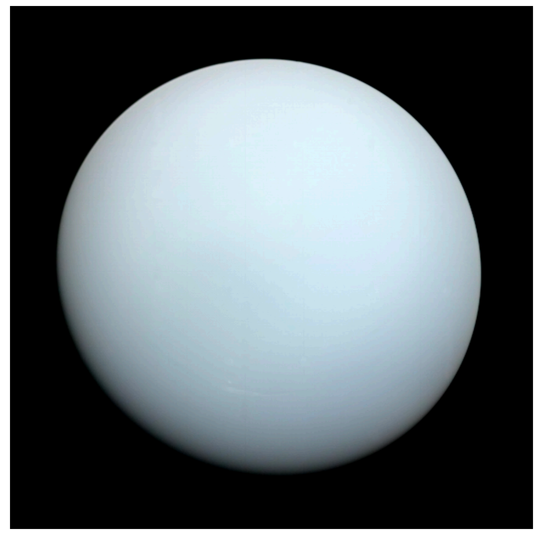
Primordial Black Holes & Visible Radiation

- Consider **currently evaporating, spinning PBH** in our solar system

Animation credits: Yuber Perez-Gonzalez



$d_L = 10^{-4}$ pc $\approx$



Uranus - Sun

Perez-Gonzalez (2207.09462)

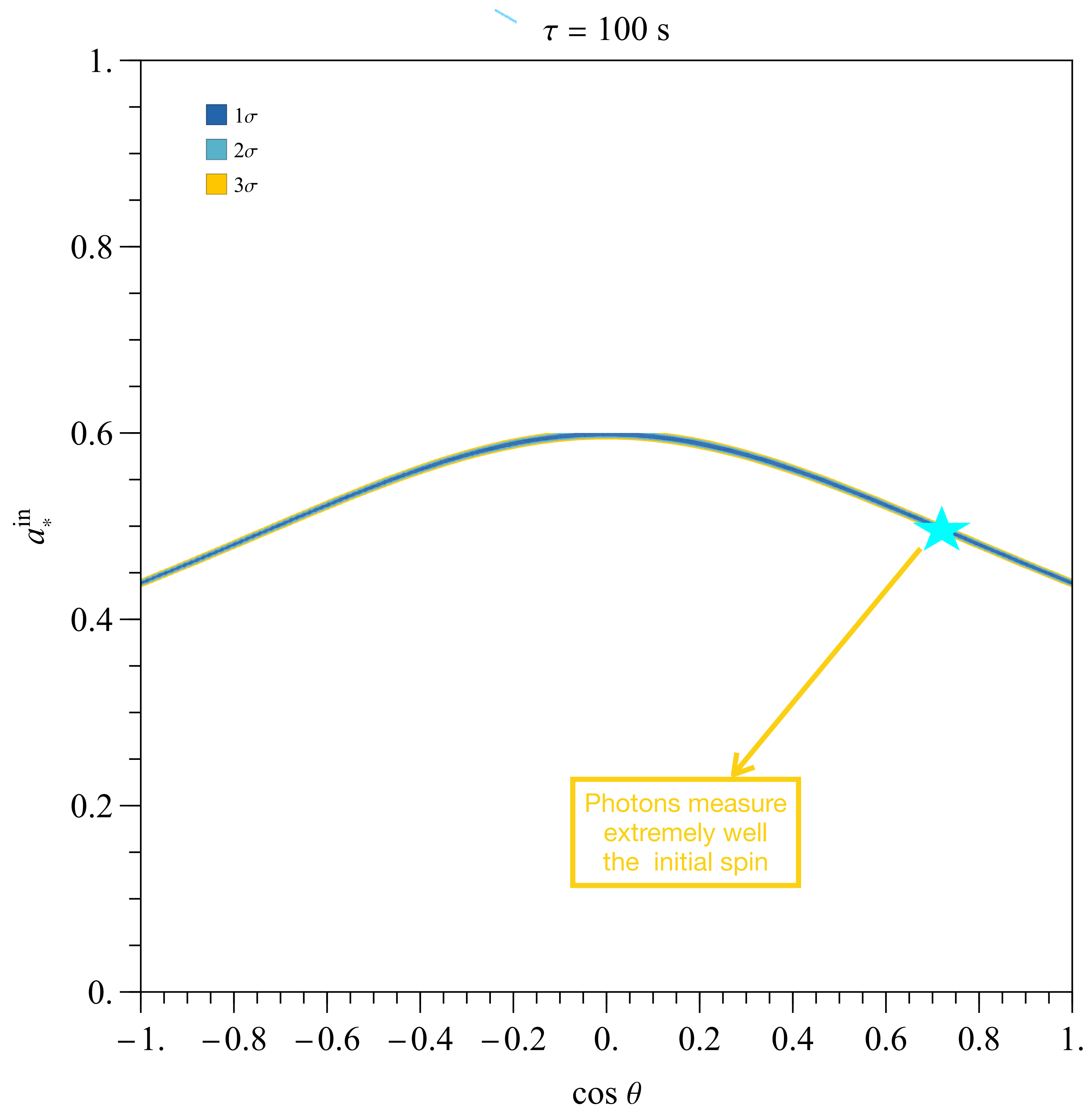
Primordial Black Holes & Visible Radiation

- Consider **currently evaporating, spinning PBH** in our solar system

- TeV scale gamma rays emitted by PBH can be detected by HAWC, degeneracy between θ and $a_\star$

Perez-Gonzalez (2207.09462)

Assume: $a_\star = 0.5,\ \theta = 45°$ ★



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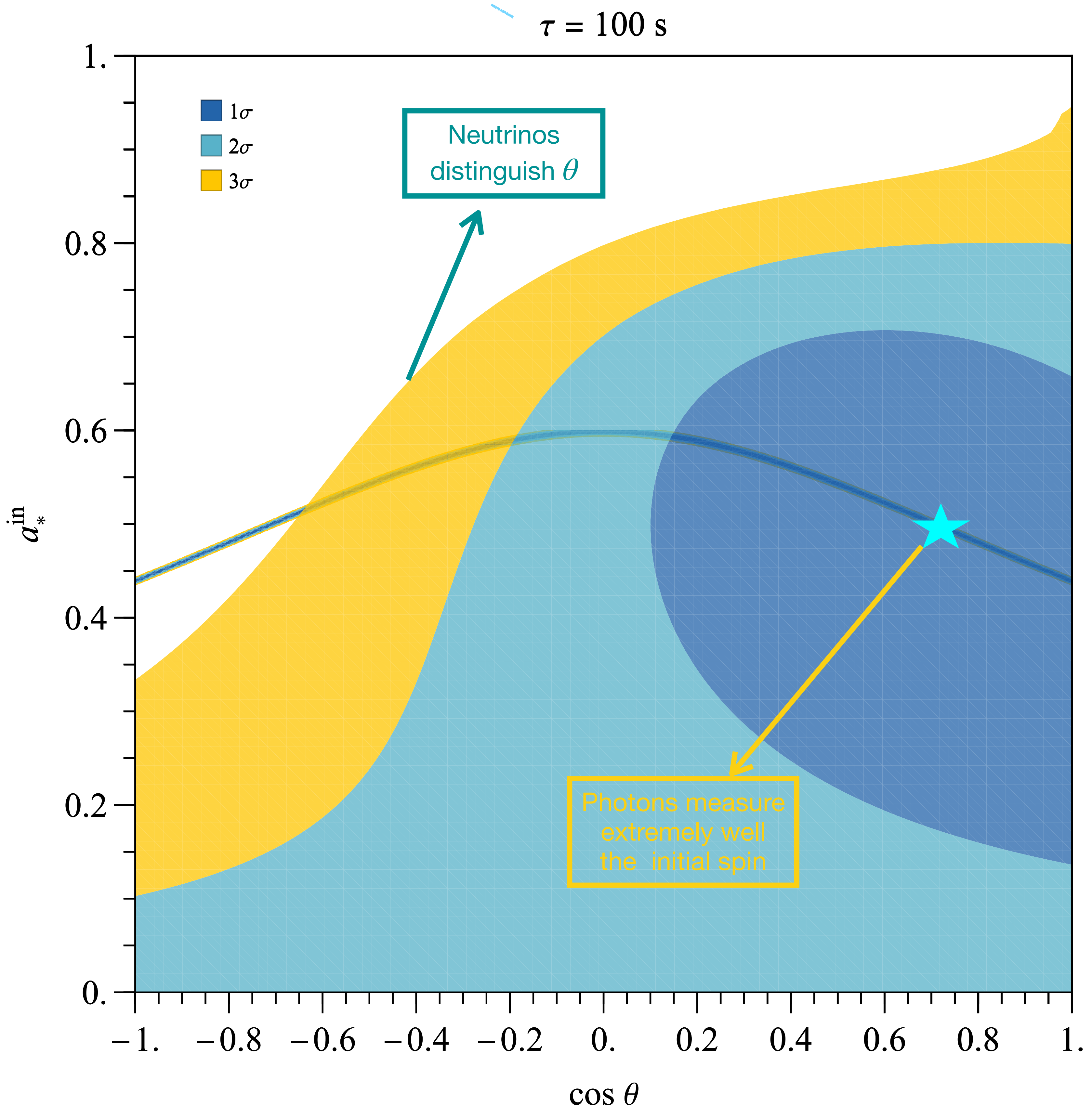

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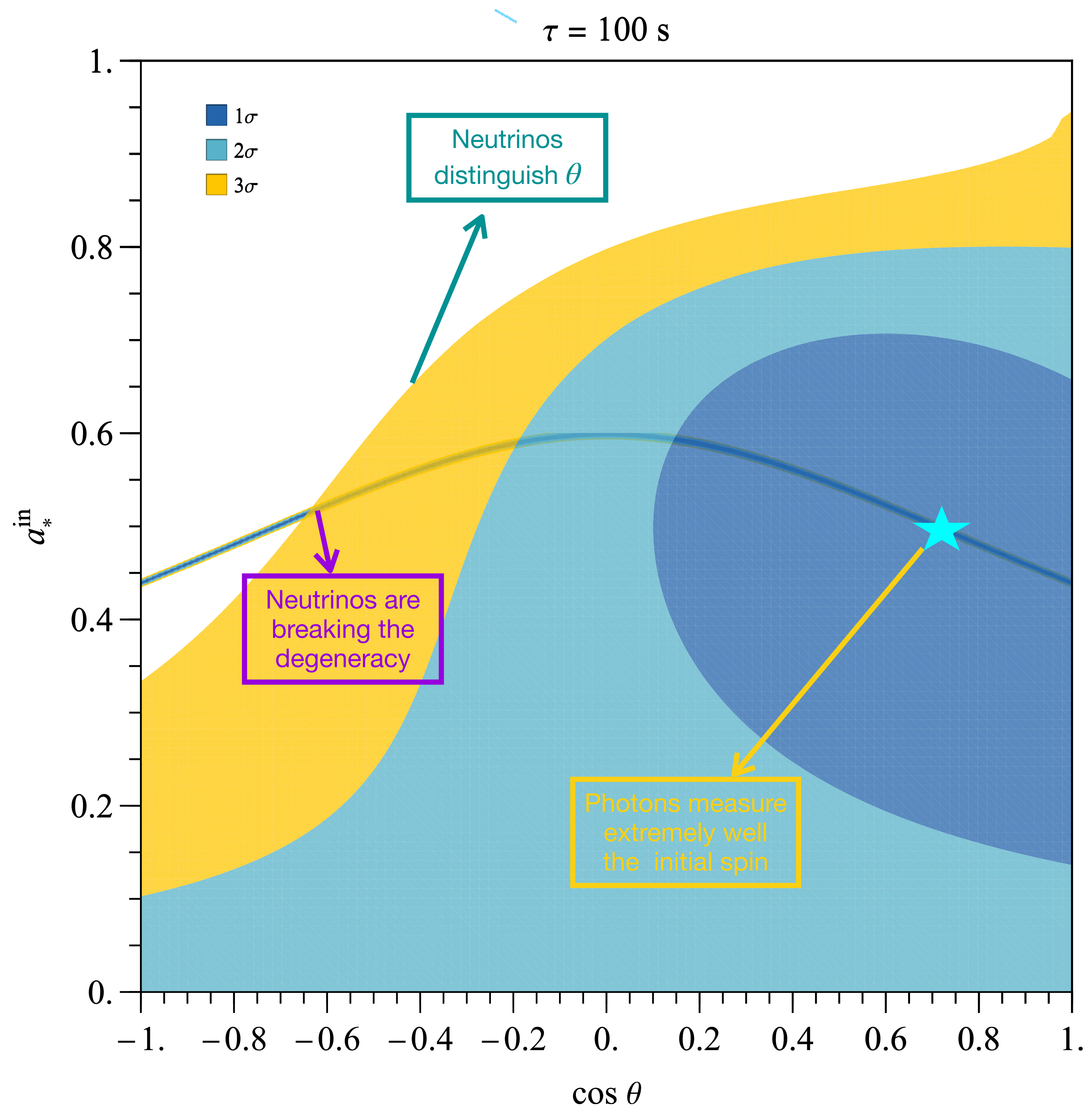

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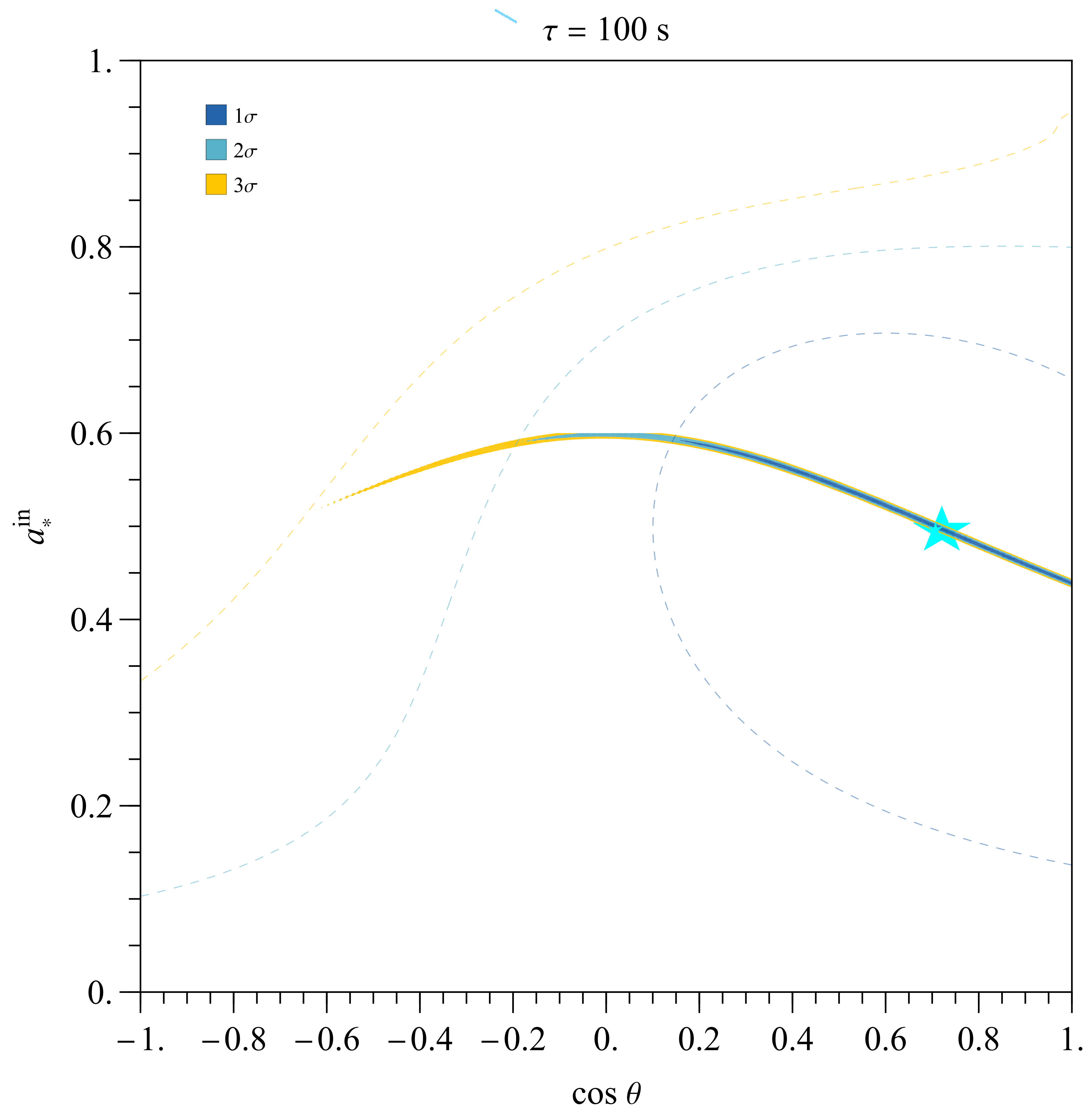
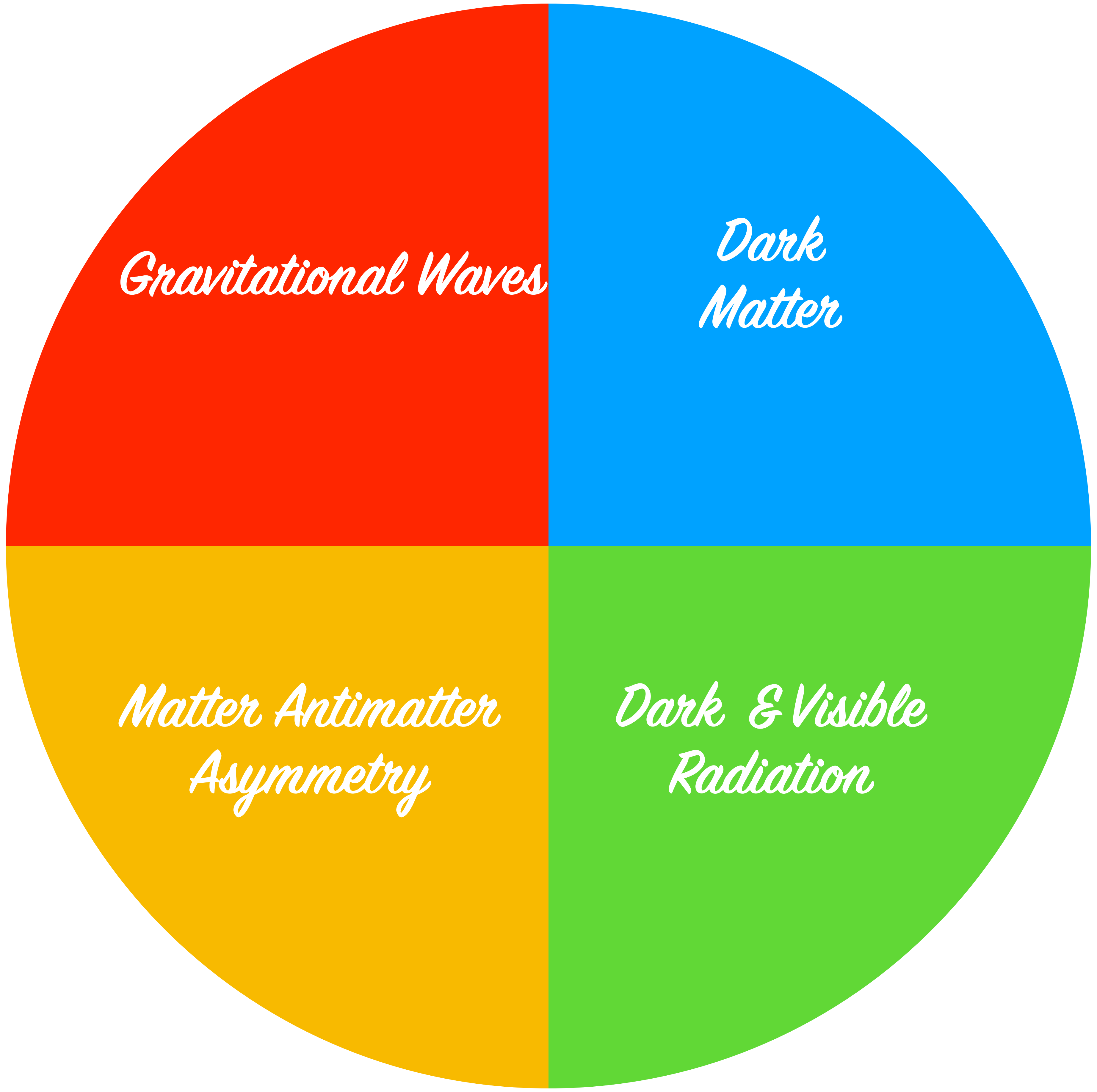
- Measurements of both photon & neutrinos-antineutrino asymmetry allows for $a_\star$ & θ to be determined




Gravitational Waves
Dark
Matter
Matter Antimatter
Asymmetry
Dark & Visible
Radiation

Matter Antimatter Asymmetry

Primordial Black & Matter Antimatter Asymmetry

- **PBHs**: unique particle source, early matter domination, entropy injections. How does this interplay with baryogenesis?

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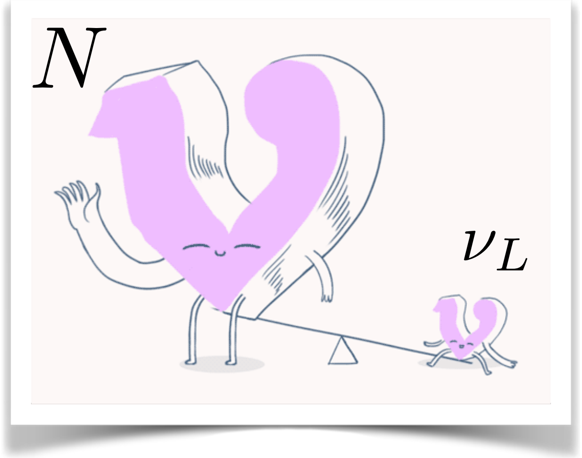

$$\mathcal{L} \supset Y_\nu \bar{L}\tilde{H}N - \frac{1}{2}M_N\overline{N^c}N \implies m_\nu = \frac{Y_\nu^2 v^2}{2M_N} \sim 0.1\text{eV}$$

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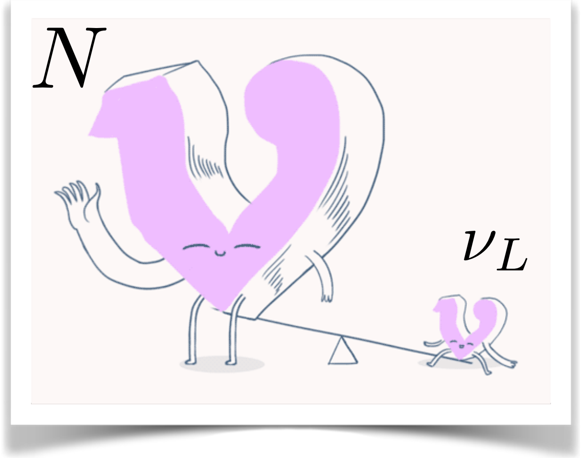

☑ Lepton number violation

☑ C & CP-violation

☑ Departure from thermal equilibrium

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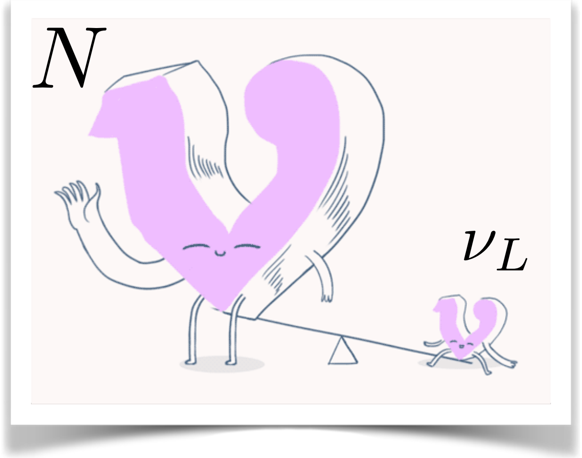

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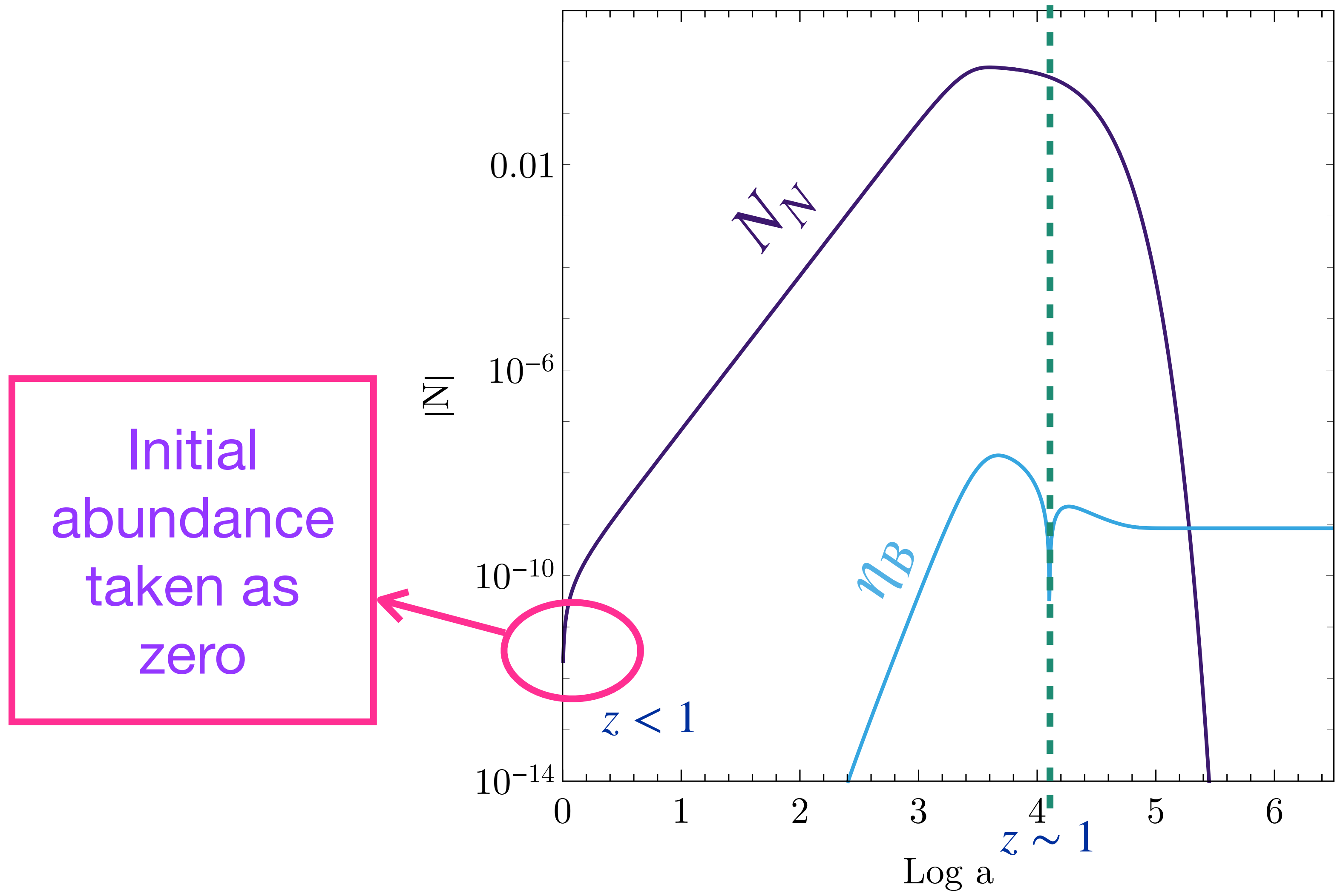

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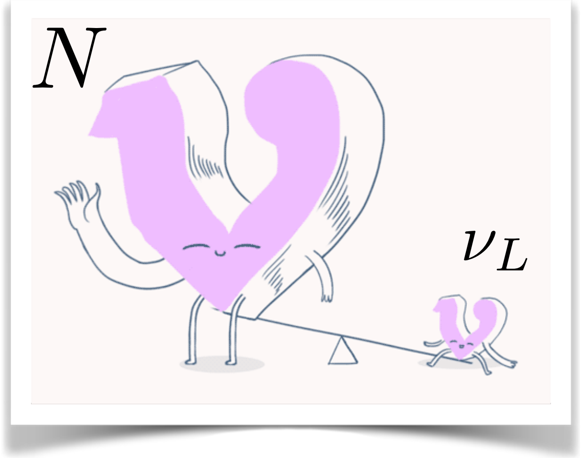

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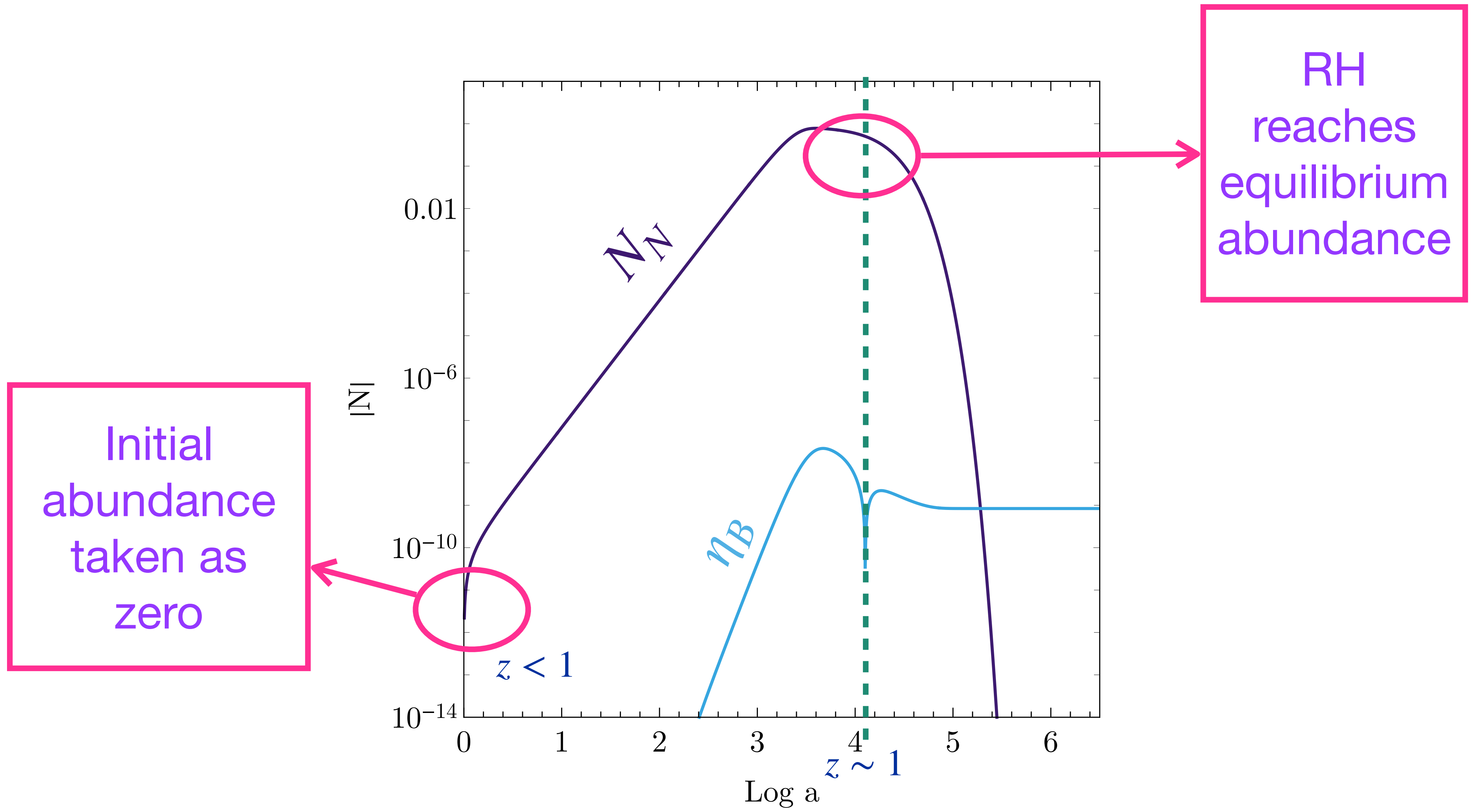

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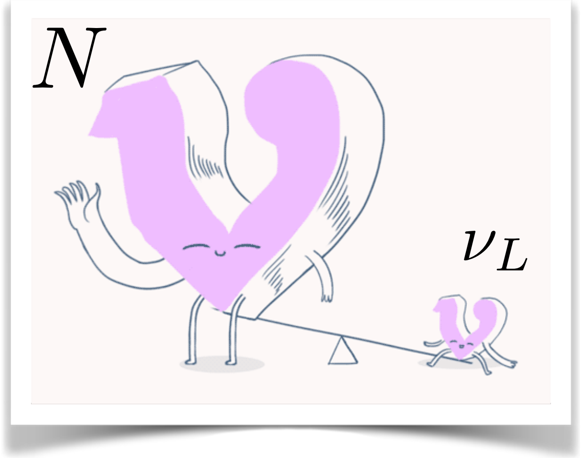

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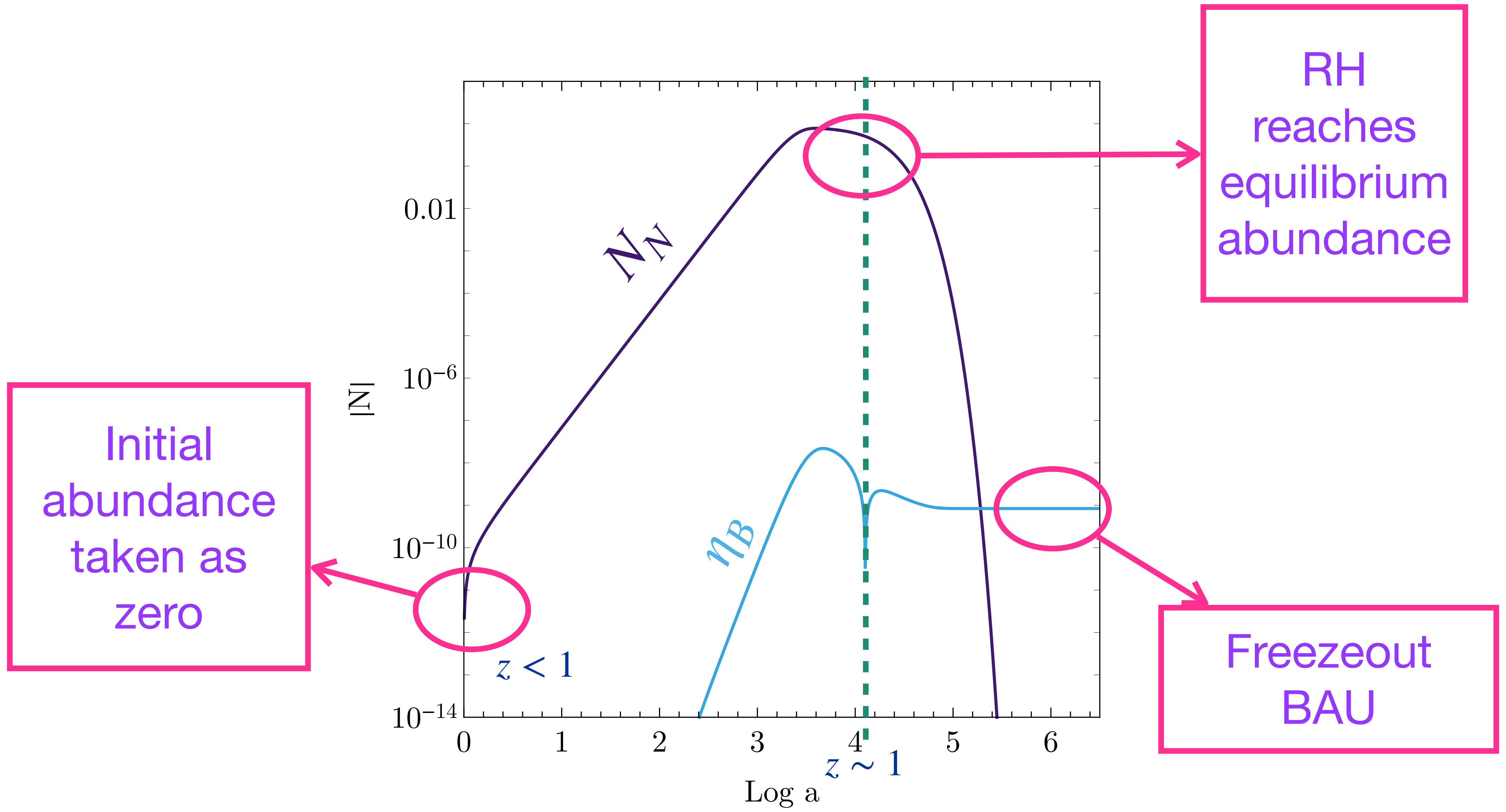

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$$\dot{\rho}_{\mathrm{SM}} + 4H\rho_{\mathrm{SM}} = -\frac{1}{M_{\mathrm{BH}}}\dot{M}_{\mathrm{BH}}\Big|_{\mathrm{SM}}\rho_{\mathrm{PBH}}$$

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

$$aH\frac{dn_{B-L}}{da} = \epsilon_1[(n_N - n_N^{\mathrm{eq}})\Gamma_N^{\mathrm{TH}} + n_N^{\mathrm{BH}}\Gamma_N^{\mathrm{BH}}] - Wn_{B-L}$$

Lepton asymmetry from plasma

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Lepton asymmetry From PBHs

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Washout processes

$$aH\frac{dn_{B-L}}{da} = \epsilon_1[(n_N - n_N^{\rm eq})\Gamma_N^{\rm TH} + n_N^{\rm BH}\Gamma_N^{\rm BH}] - Wn_{B-L}$$

Lepton asymmetry from plasma

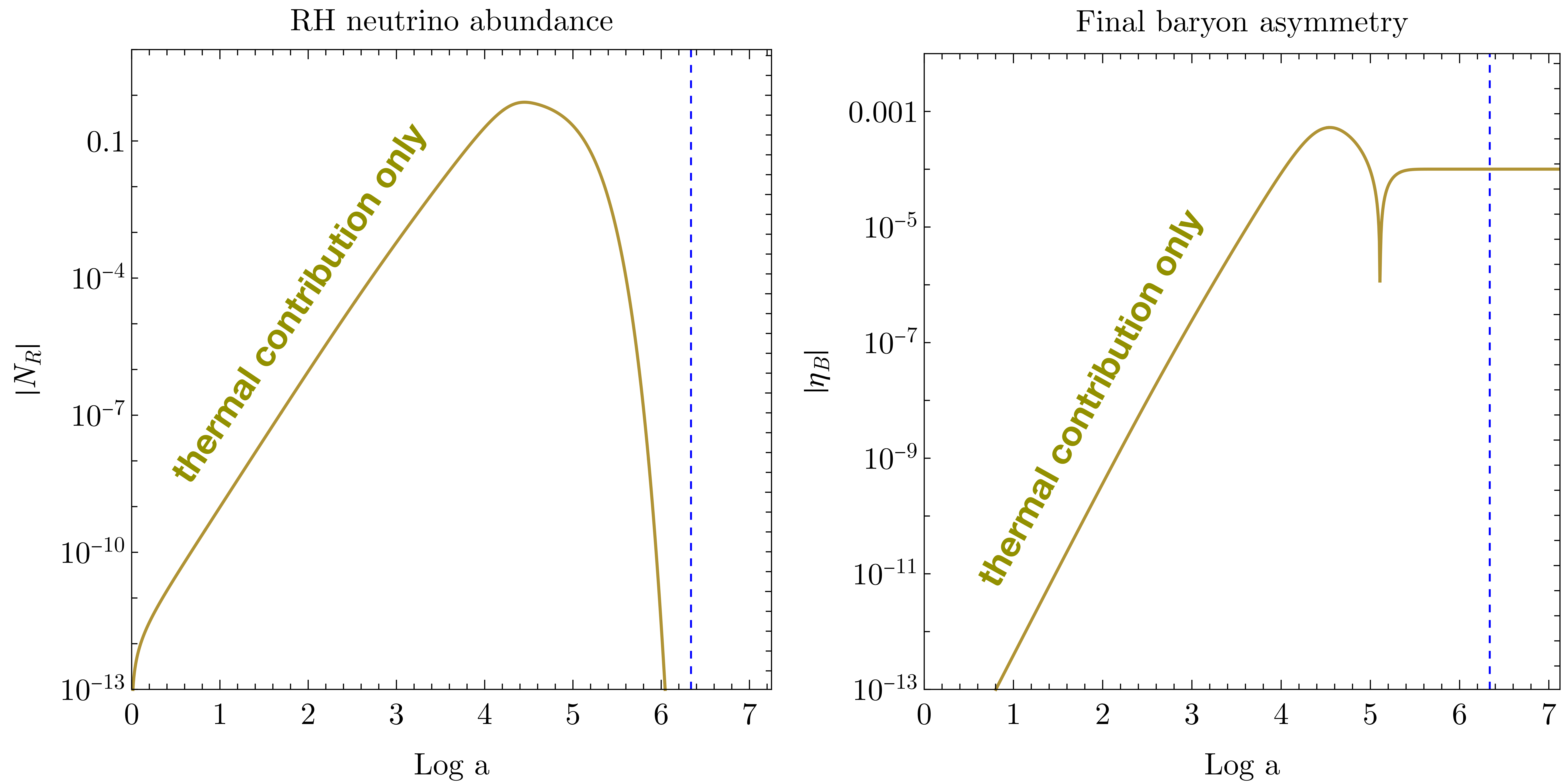
Lepton asymmetry From PBHs

Primordial Black & Matter Antimatter Asymmetry

- Assume monochromatic population of PBHs

Perez-Gonzalez & JT (2010.03565)

$$M_{\rm BH}^{\rm int} = 1.7\ {\rm g} \quad \beta_i = 10^{-3} \quad M_N = 10^{11}{\rm GeV}$$



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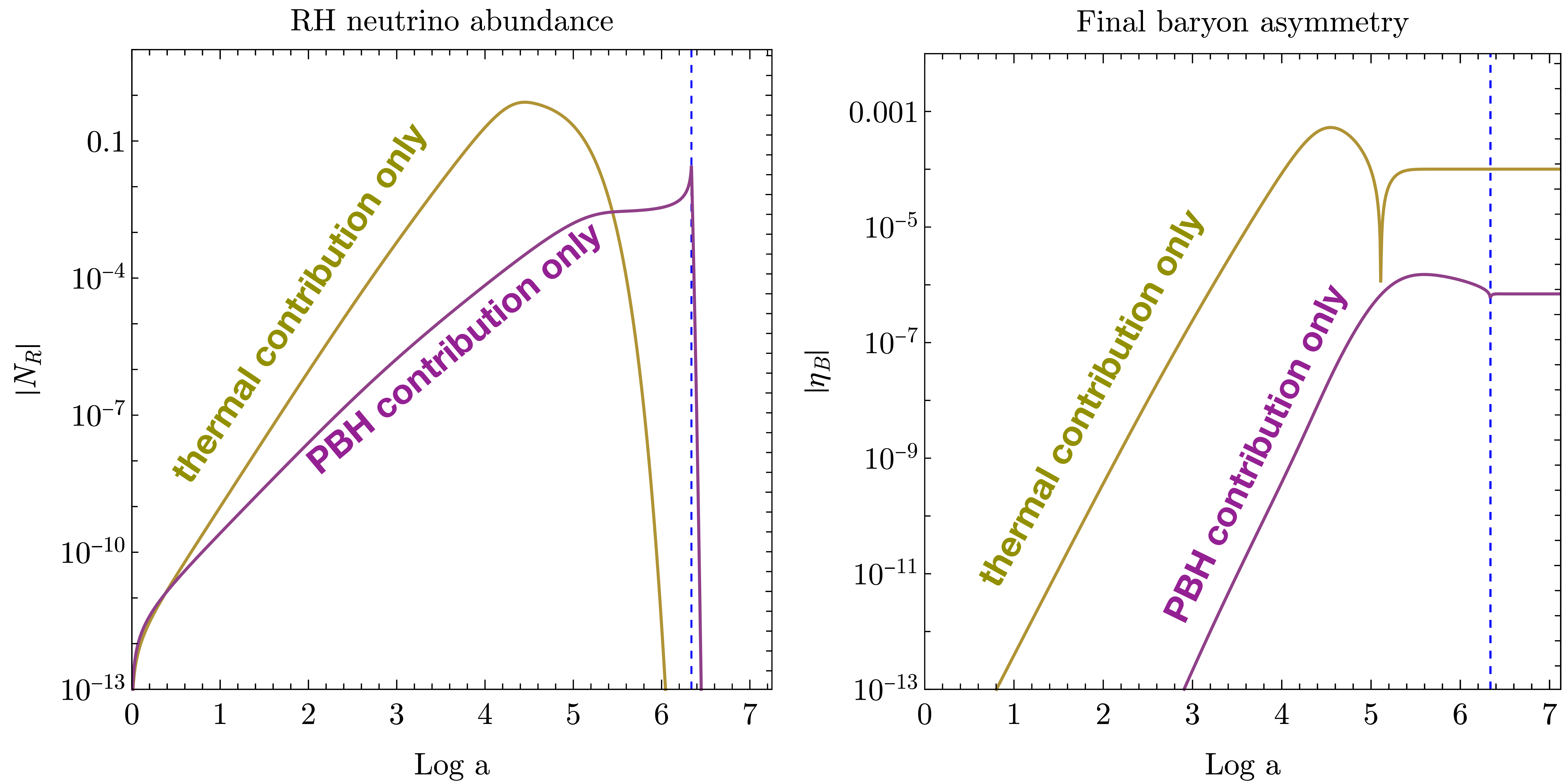

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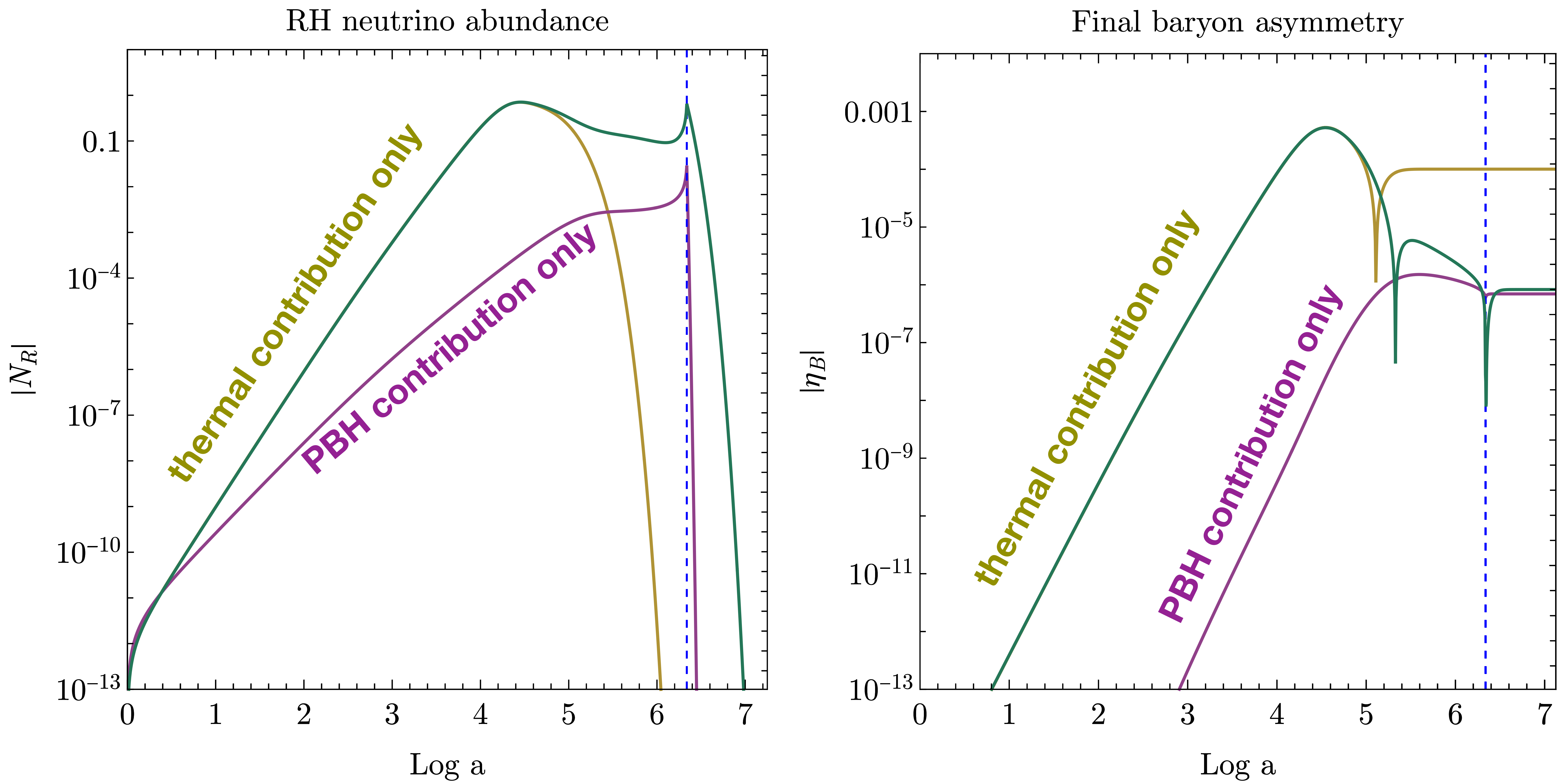

Primordial Black & Matter Antimatter Asymmetry

- Assume slightly heavier monochromatic population of PBHs

Perez-Gonzalez & JT (2010.03565)

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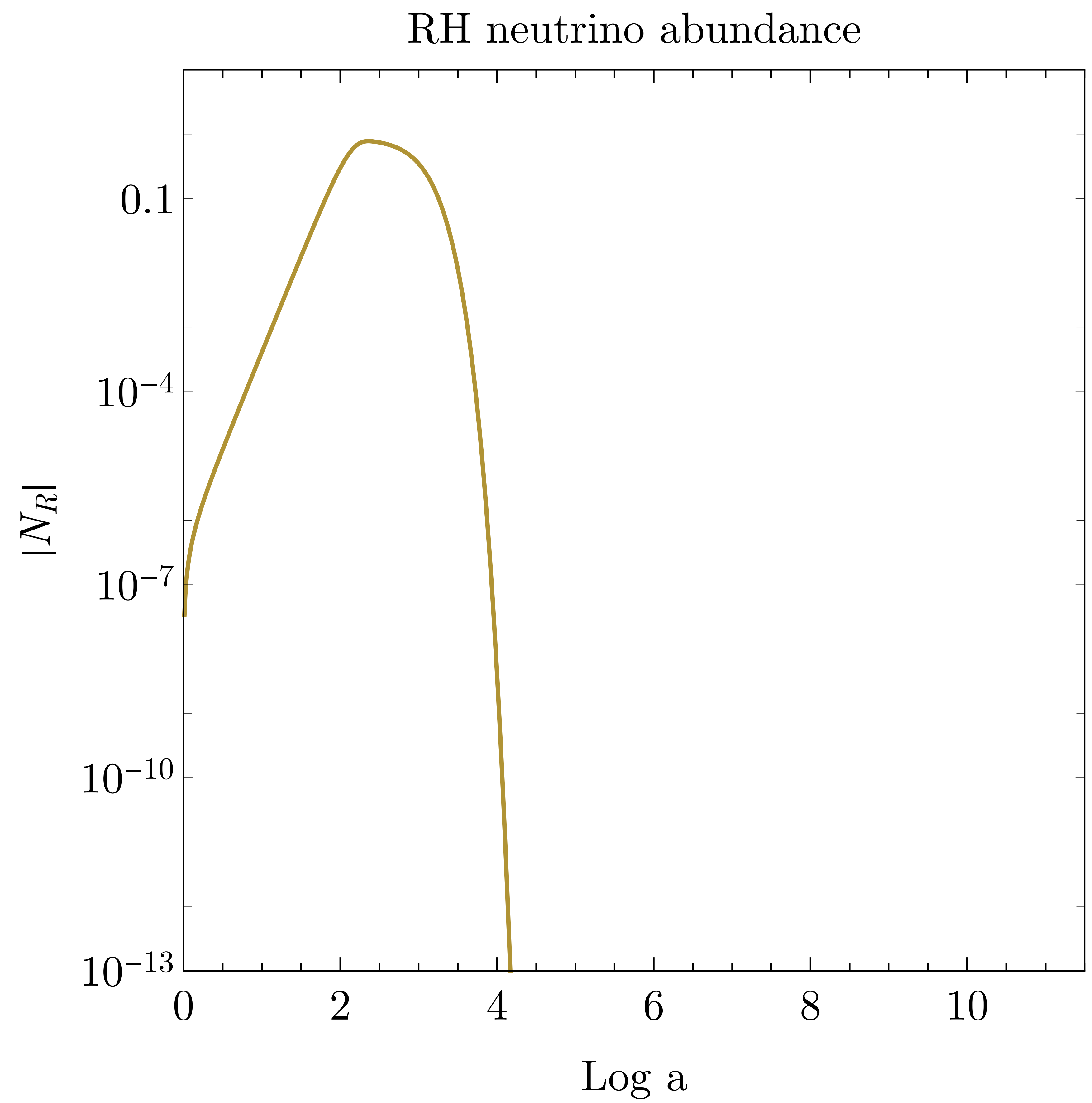

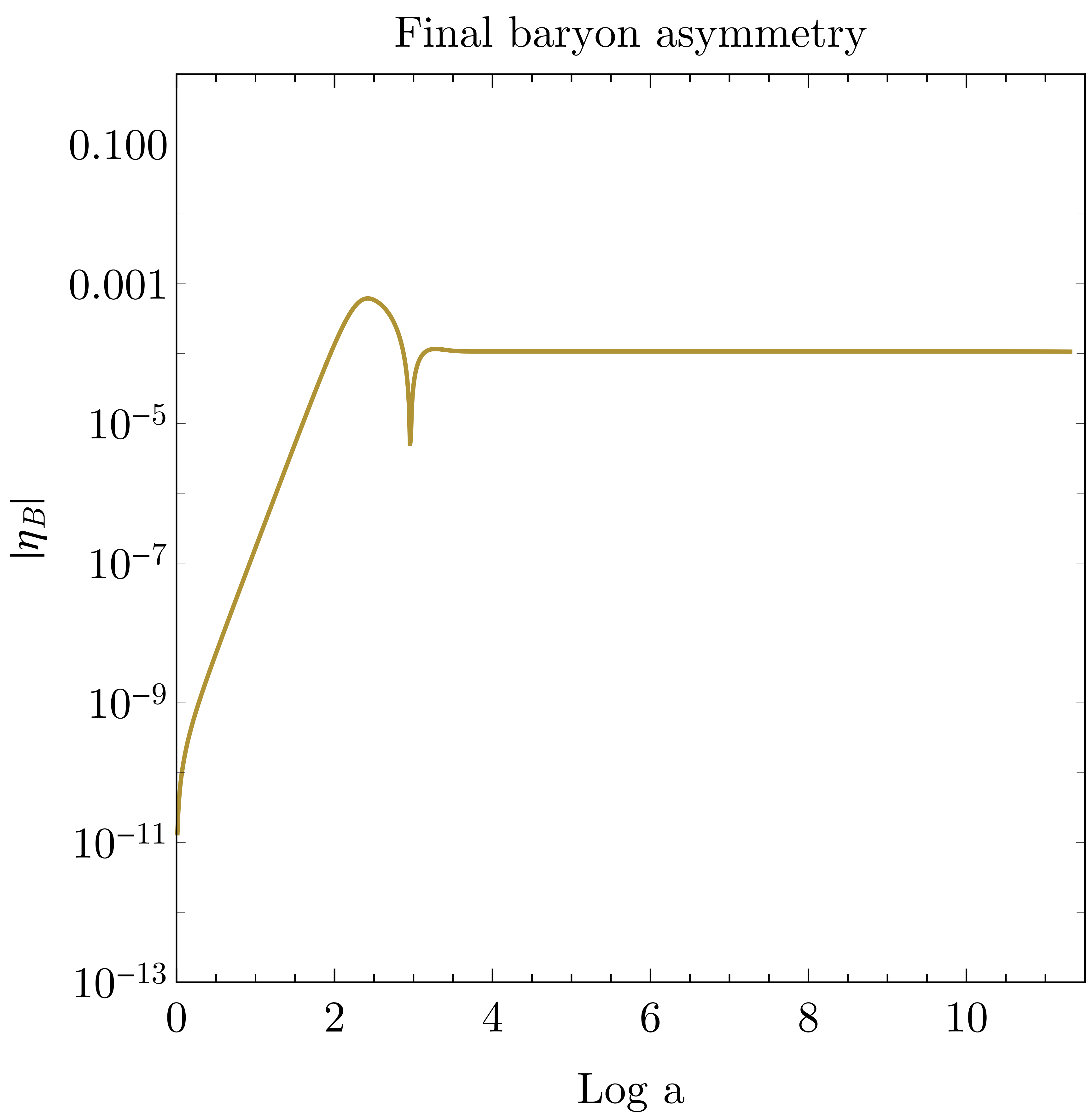

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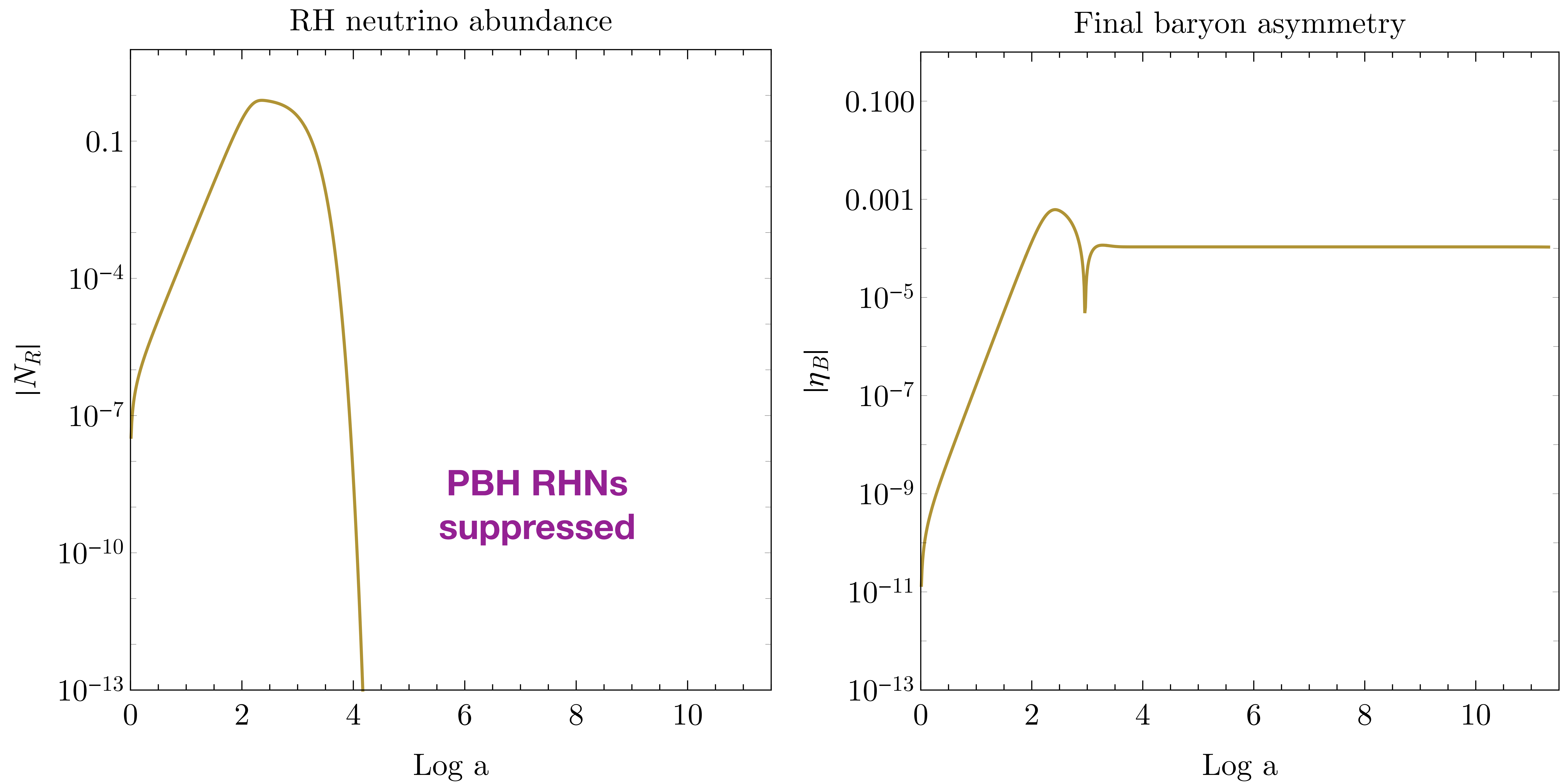

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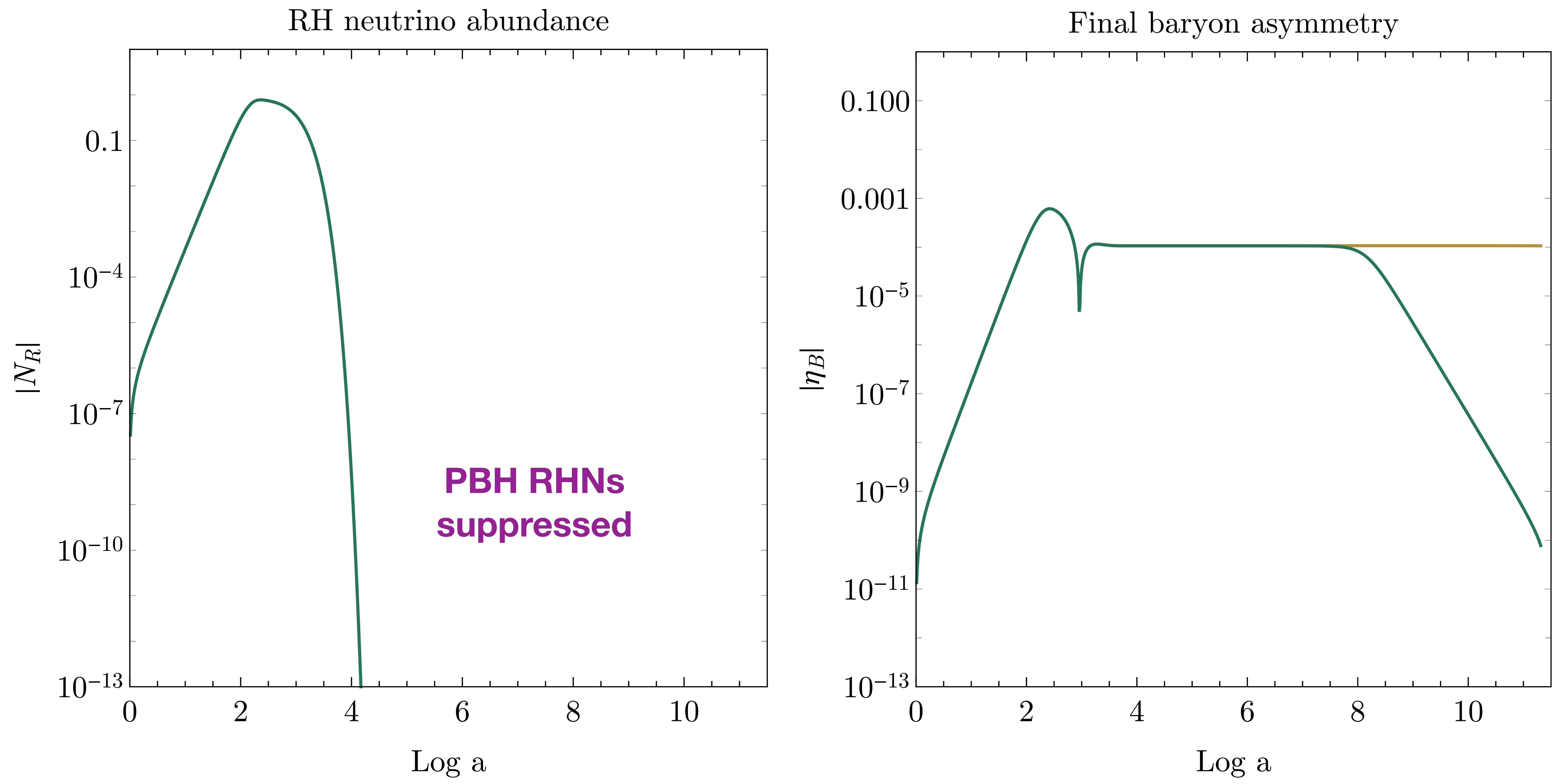
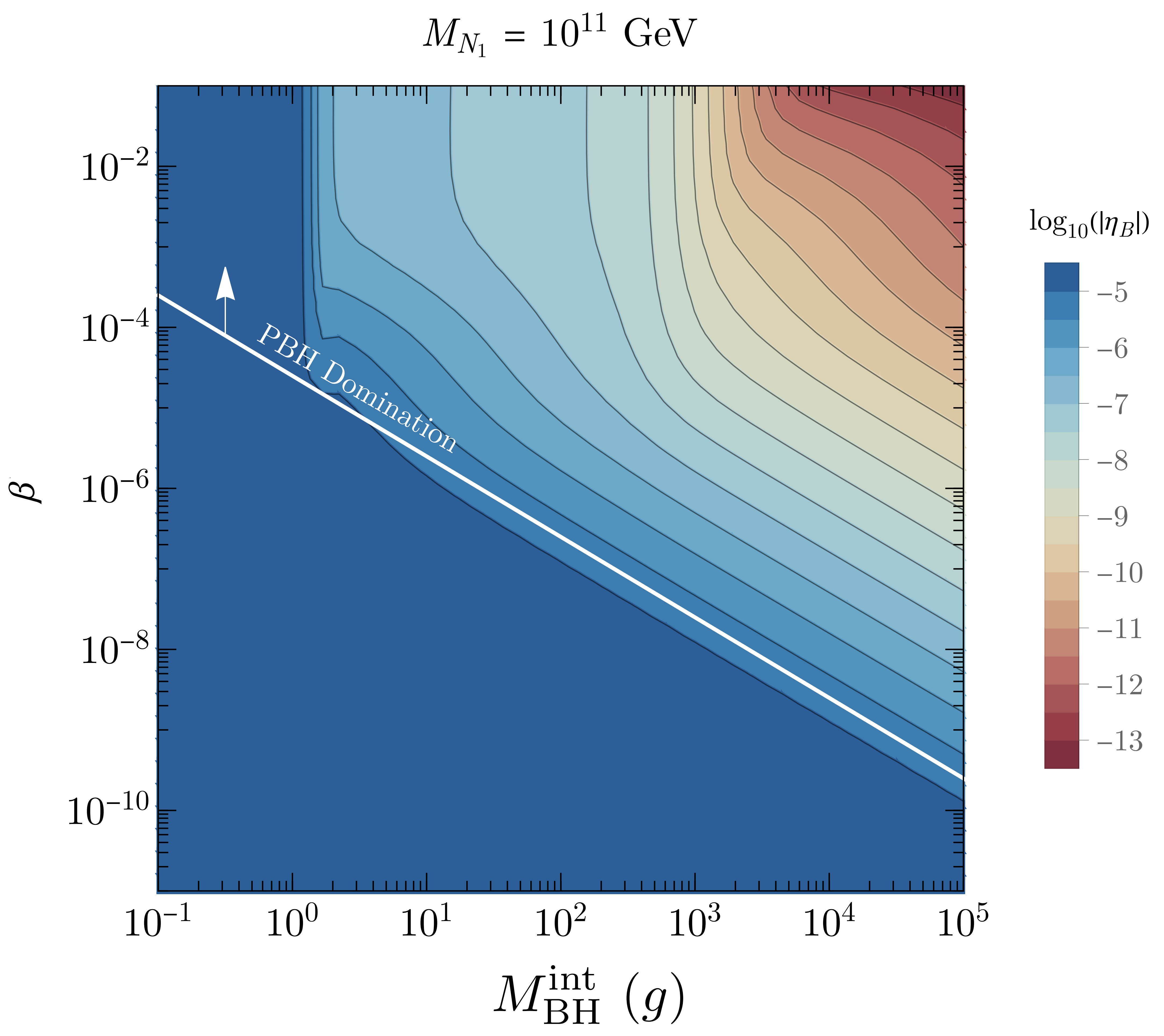
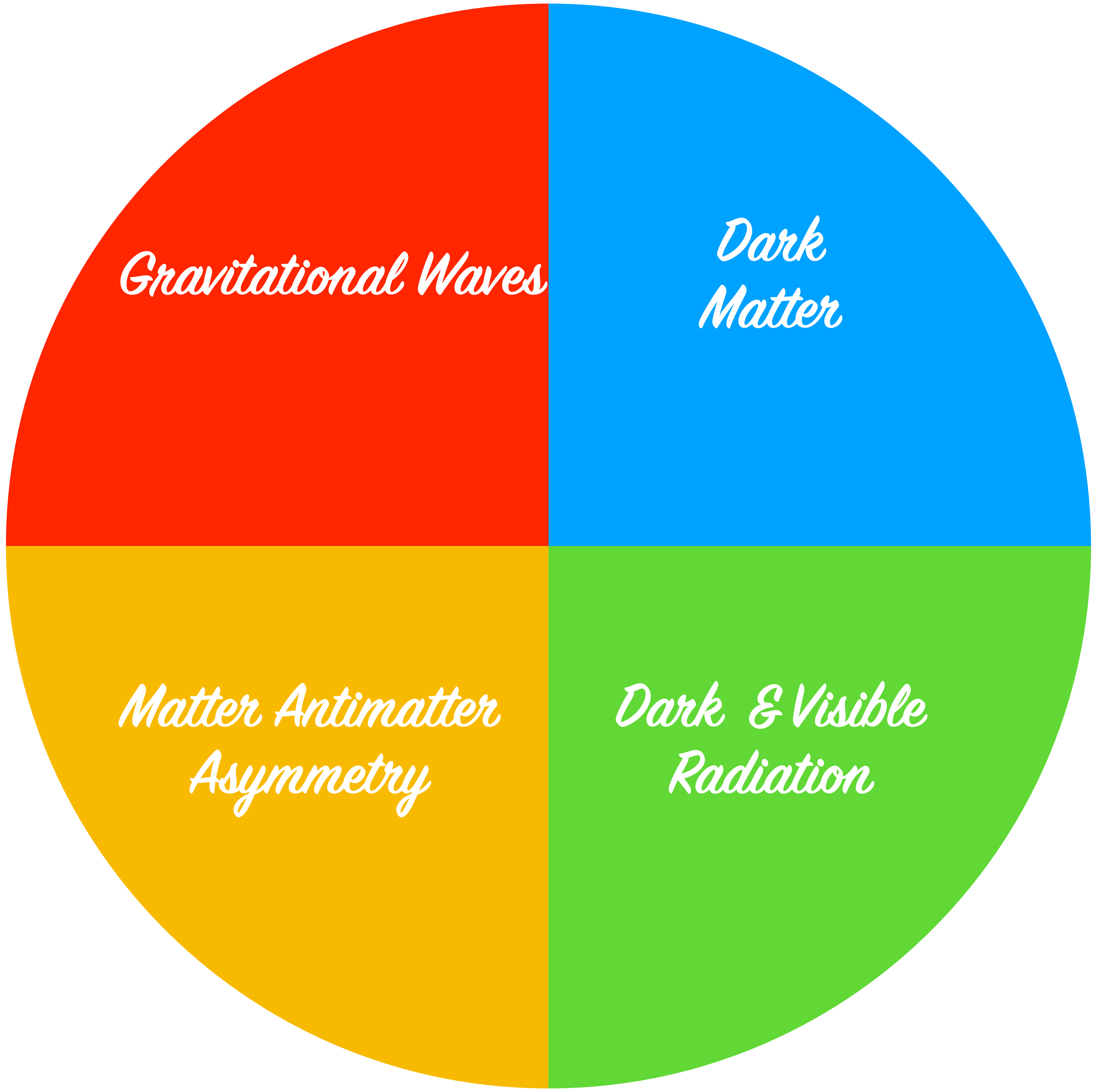


Primordial Black Hole Leptogenesis

Perez-Gonzalez & JT (2010.03565)

- Assume a population of monochromatic PBHs & $10^6 \lesssim M_N\,(\mathrm{GeV}) \lesssim 10^{12}$
- Heavier PBHs ($\gtrsim 1$ kg) produce fewer heavy RHNs but more photons.
- Entropy dump dilutes baryon asymmetry (thermal & PBH-induced)
- Heavy PBHs in the early Universe likely conflict with leptogenesis and most high-scale, early-time baryogenesis models.



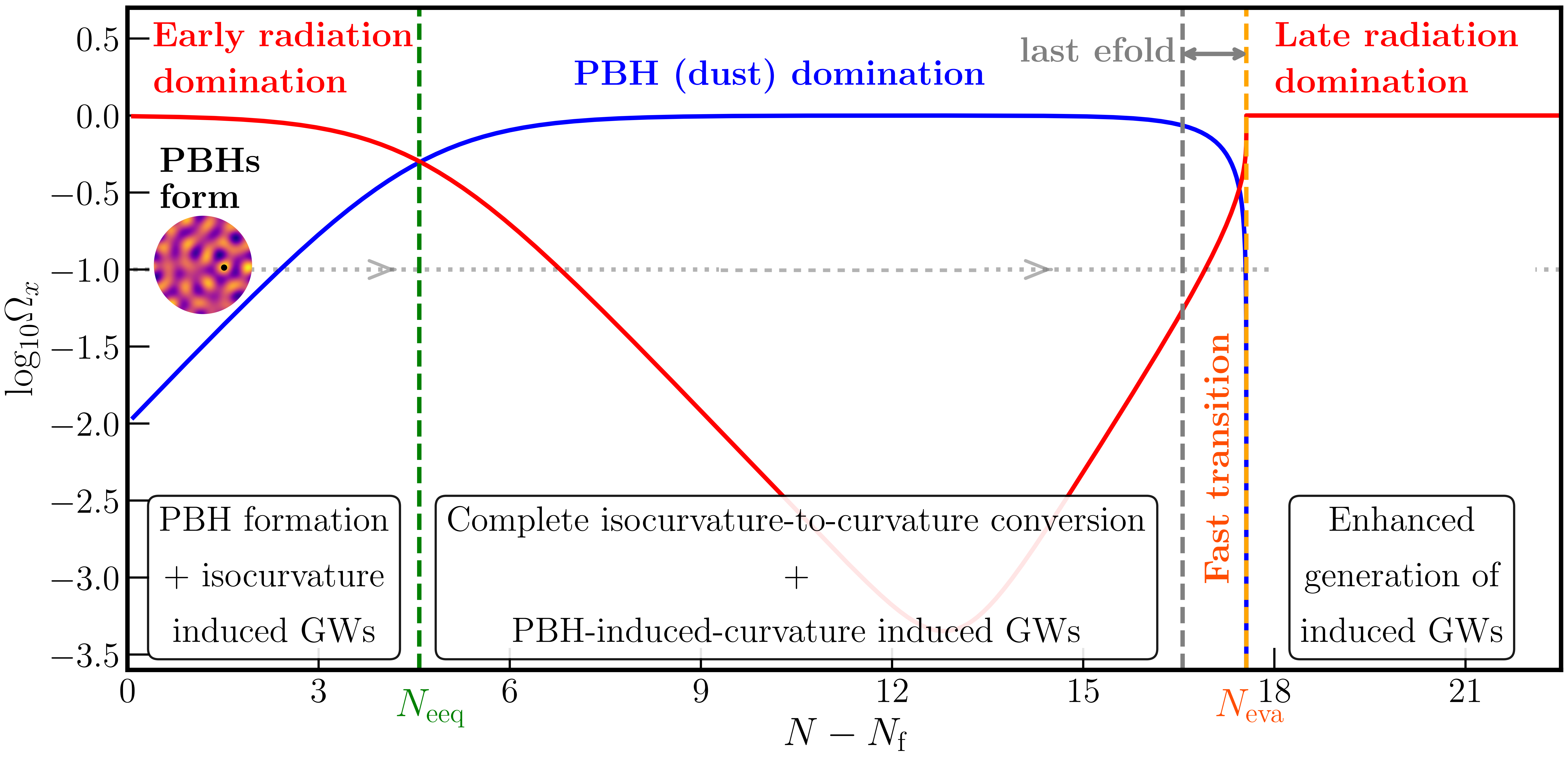

Gravitational Waves
Dark Matter
Matter Antimatter Asymmetry
Dark & Visible Radiation

Gravitational Waves

Primordial Black Holes & Gravitational Waves

Image credit Guillem Domenech: 2402.17388

$$\Omega_x = \frac{\rho_x}{\rho_{tot}}$$



Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)

Langlois, Papanikolaou, Vennin (2003.10455)

Domenech, Lin, Sasaki (2012.08151)

Primordial Black Holes & Gravitational Waves

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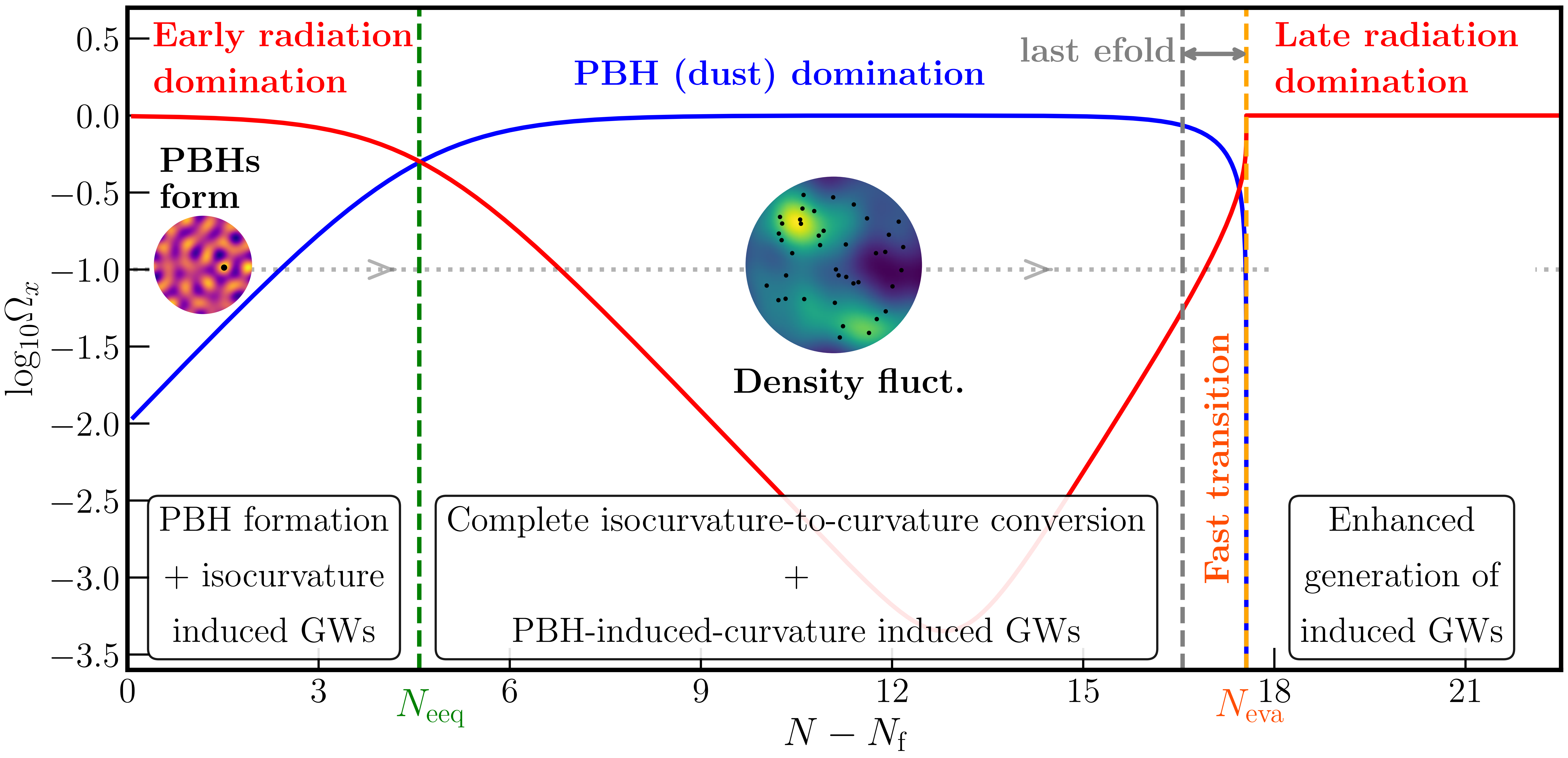

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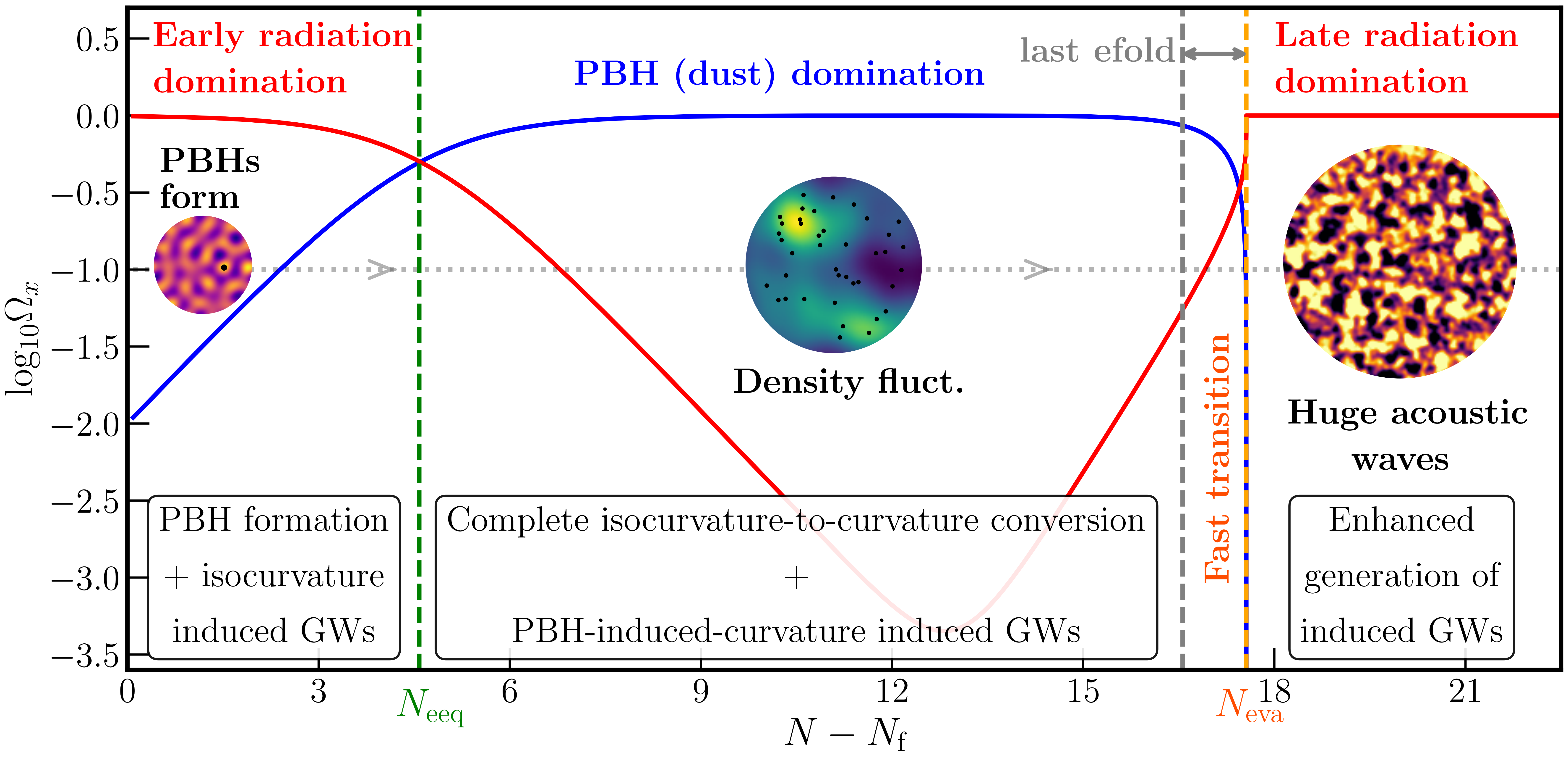

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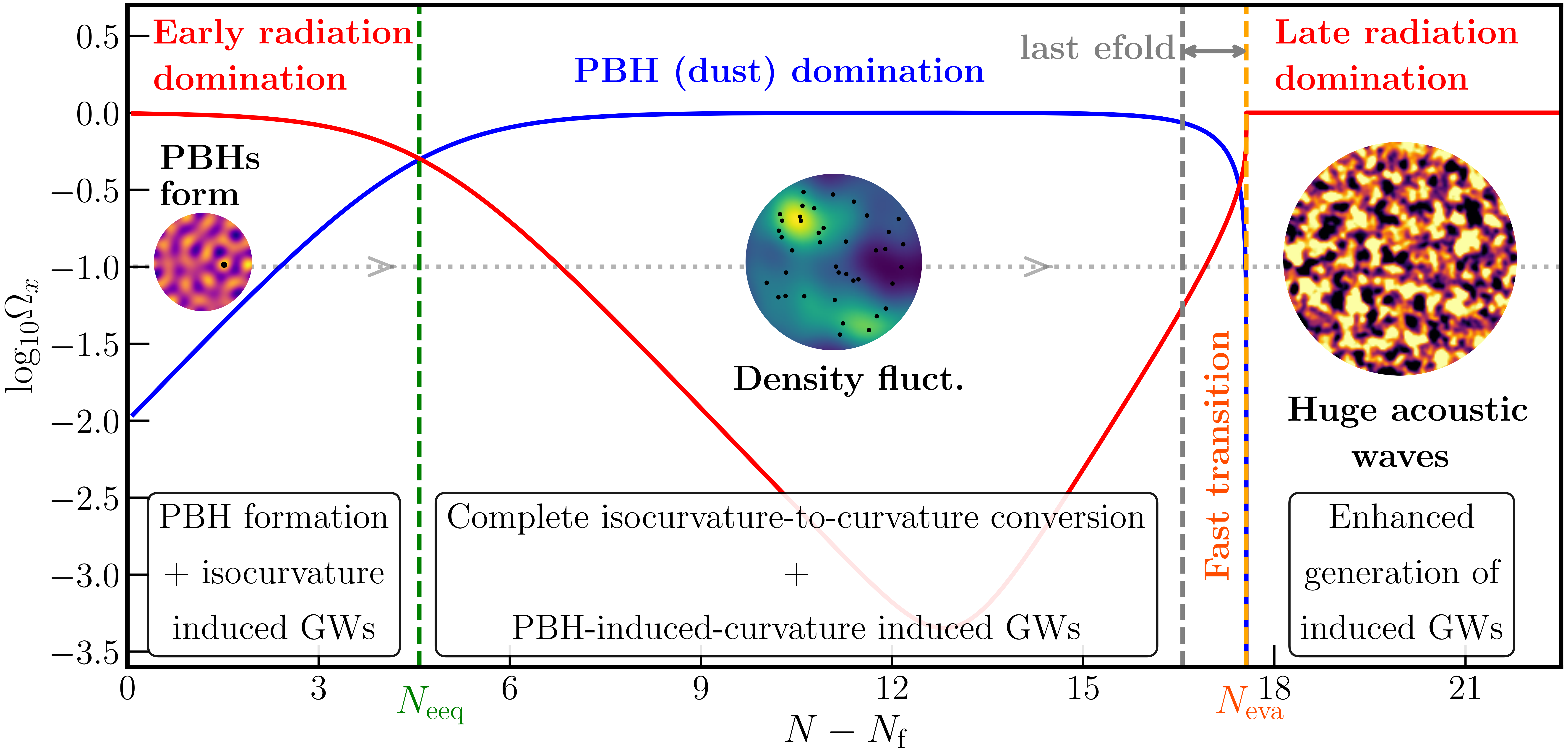

Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)

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Domenech, Lin, Sasaki (2012.08151)

Sudden evaporation of all PBHs, creates large velocity fluctuations in radiation fluid

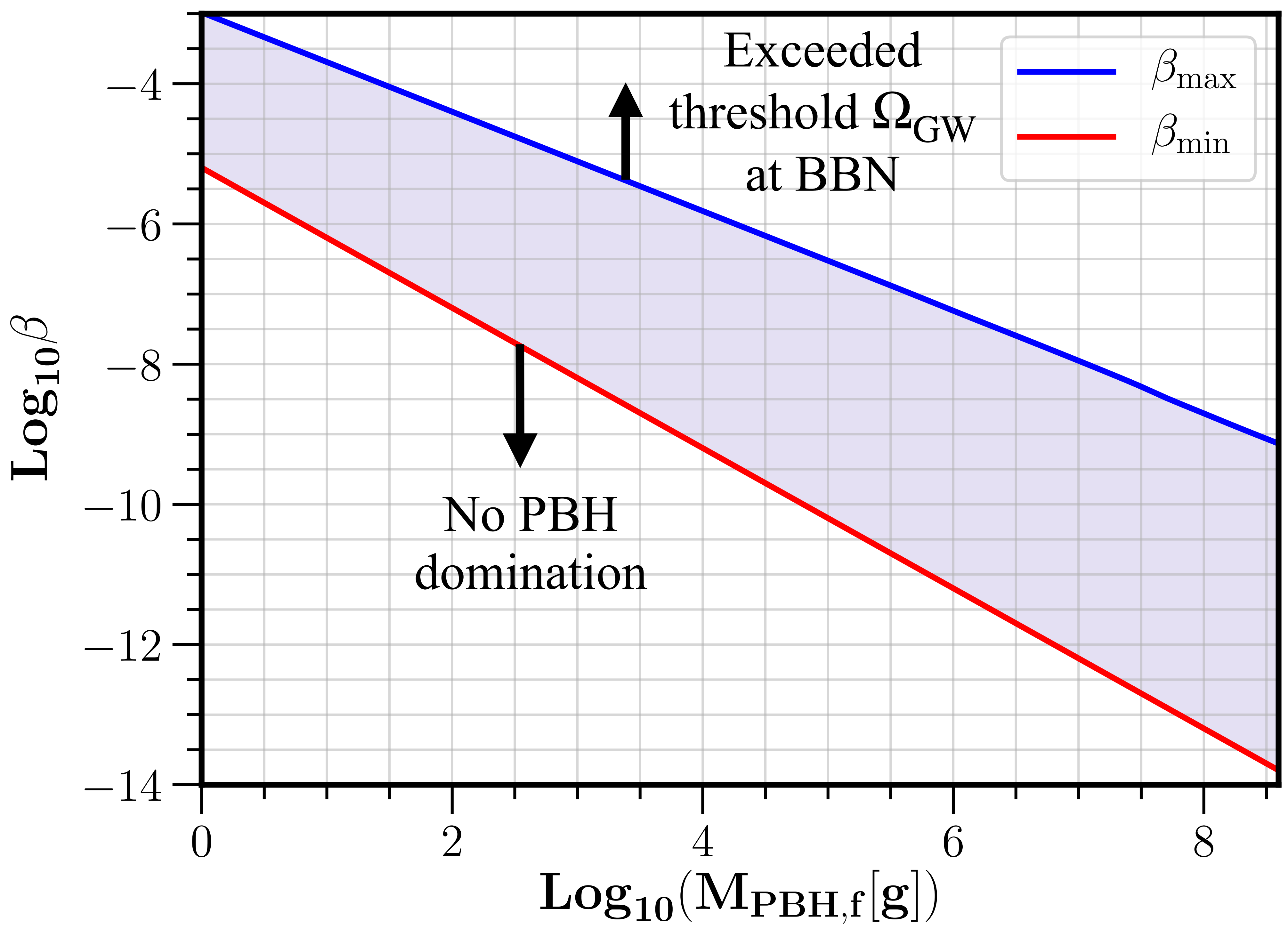
$\Longrightarrow$ large GW signal

$$(\partial_t^2 + 3H\partial_t - \nabla)h_{ij} \sim \widehat{TT}_{ij}^{ab}\partial_a V \partial_b V$$

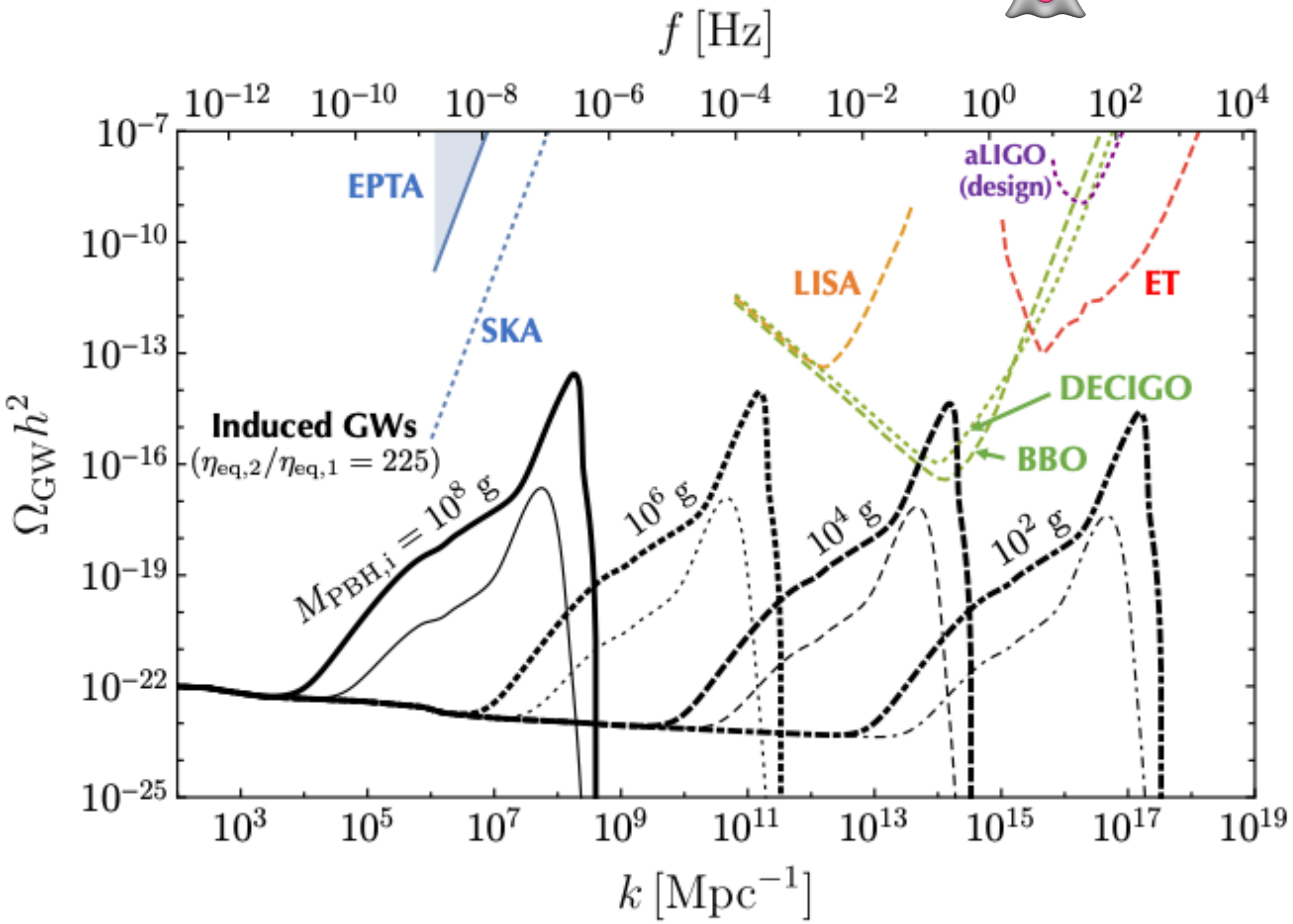
Primordial Black Holes & Gravitational Waves

- Density fluctuation that create PBH give induced GWs see Domenech (2109.01398)

- Effect is largest for PBHs with monochromatic mass spectrum



Domenech, Lin, Sasaki (2012.08151)



Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)

Summary

- PBHs can be a democratic non-thermal source of particle production in the early Universe. PBHs also provide large entropy dumps and early matter domination

- These features mean that PBHs can affect many early Universe phenomena including the production of dark matter, dark radiation and gravitational waves

- Heavy PBHs $\gtrsim$ kg place significant tension on high-scale baryogenesis.

- Detection of induced GWs would be an exciting avenue to reassess our theories of baryogenesis, dark matter and radiation

Thank you for listening