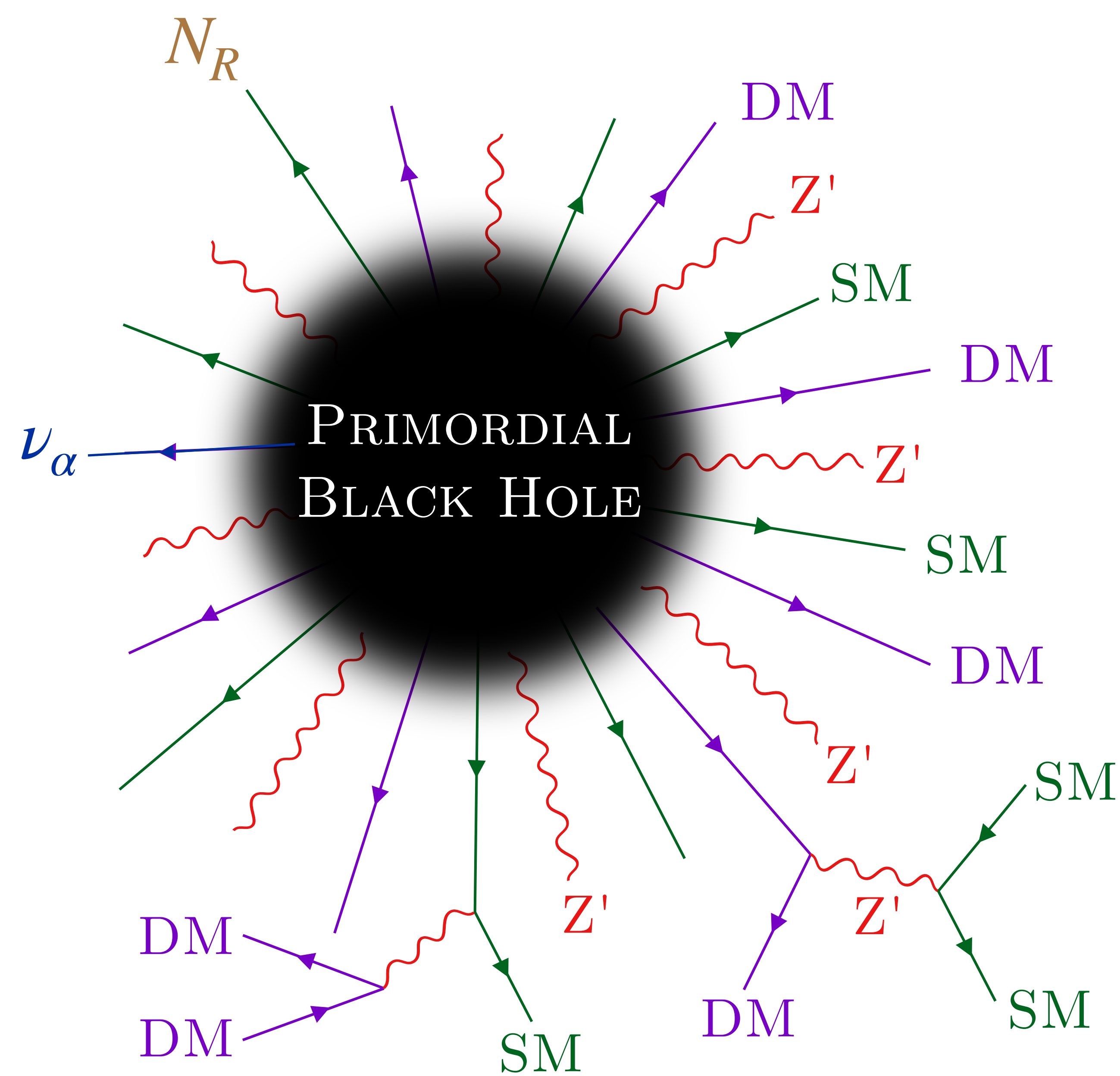
Angular momentum of evaporating primordial black holes through a neutrino lens



Yuber F. Perez-Gonzalez

Based on arXiv: 2307.14408

YOUNGST@RS MITP,
November 6th, 2023

Durham University

IP3

yuber.f.perez-gonzalez@durham.ac.uk

PBH Formation

Lighter Black Holes

$$r_S = 2GM$$

Carr et al. 2002.12778

PBH Formation

Lighter Black Holes → Large densities

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$$M_{\rm BH,i} \sim \frac{t}{G} \sim 10^{15}\ {\rm g} \left(\frac{t}{10^{-23}\ {\rm s}}\right)$$

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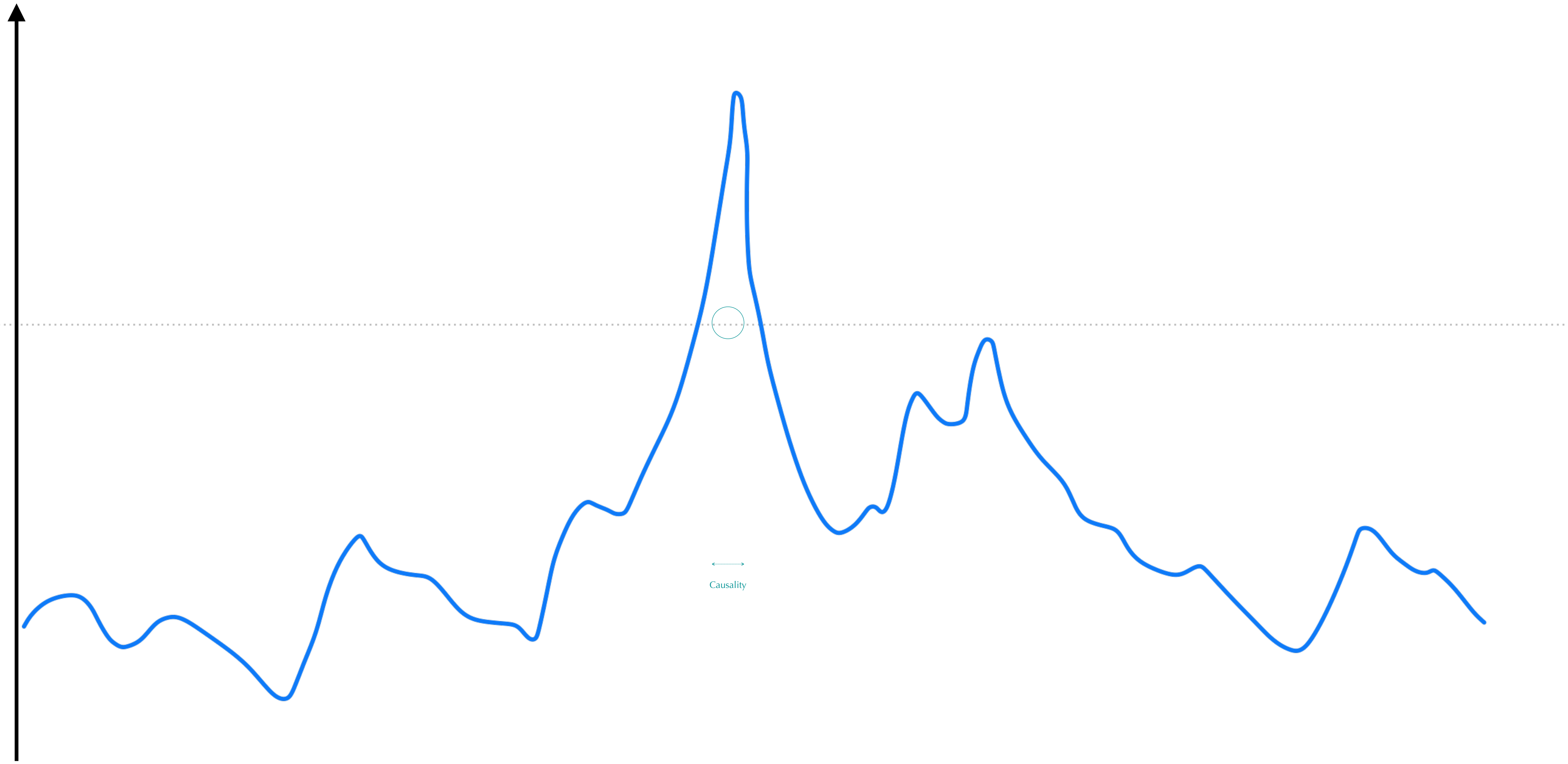
- Bubble collisions
- Pressure reduction
- Collapse of density fluctuations

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}}$$

$$\delta_{\rm th} \sim c_s^2$$



Inspired on Villanueva-Domingo, Mena, Palomares-Ruiz 2103.12087

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Fraction of the total energy in PBH

$$\beta = \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{tot}}}$$

$$M_{\mathrm{BH,i}} \propto \underbrace{\frac{4\pi}{3}\rho\frac{1}{H^3}}_{\text{Mass contained in the horizon}}$$

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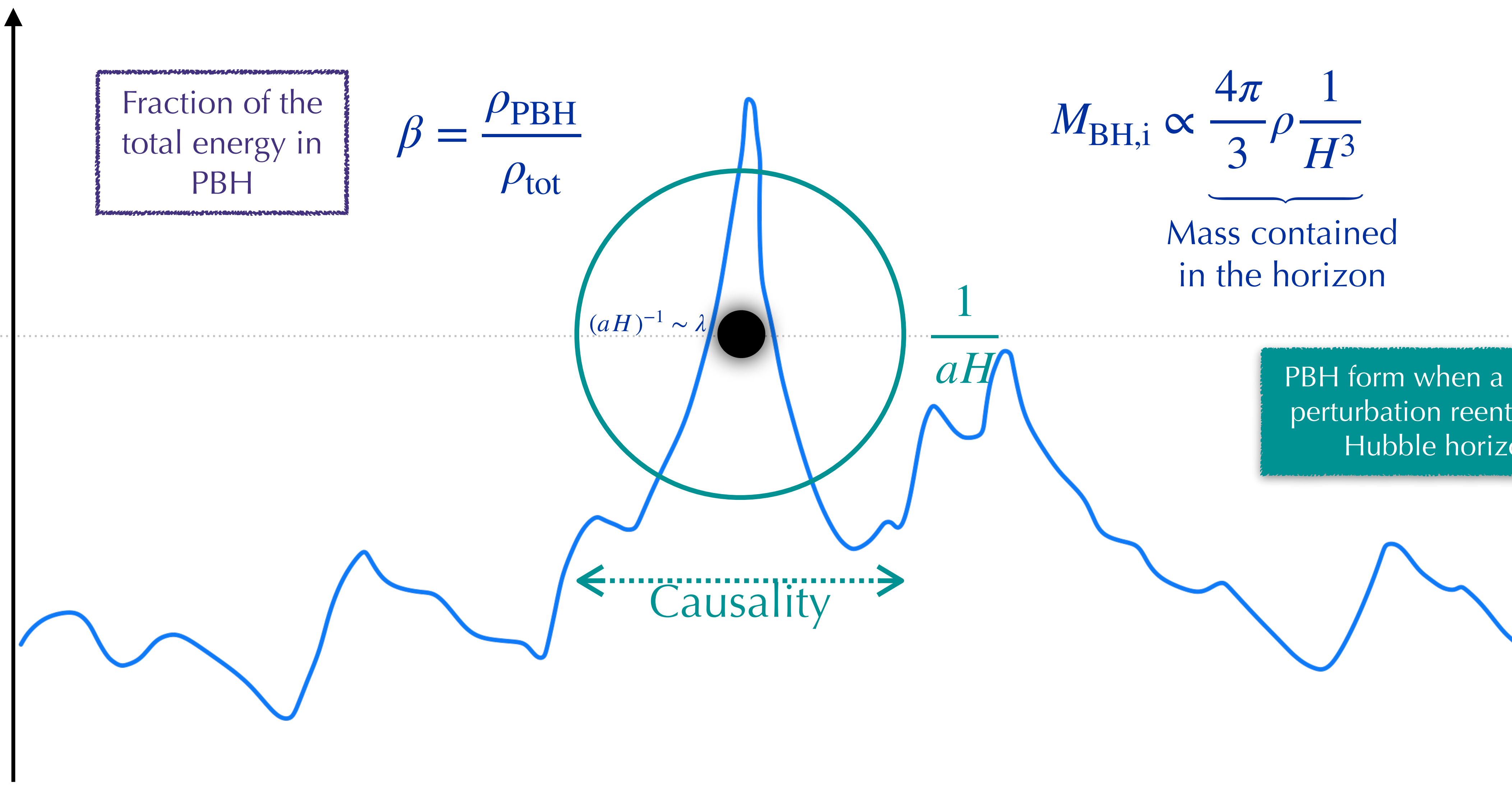

PBH form when a density perturbation reenters the Hubble horizon

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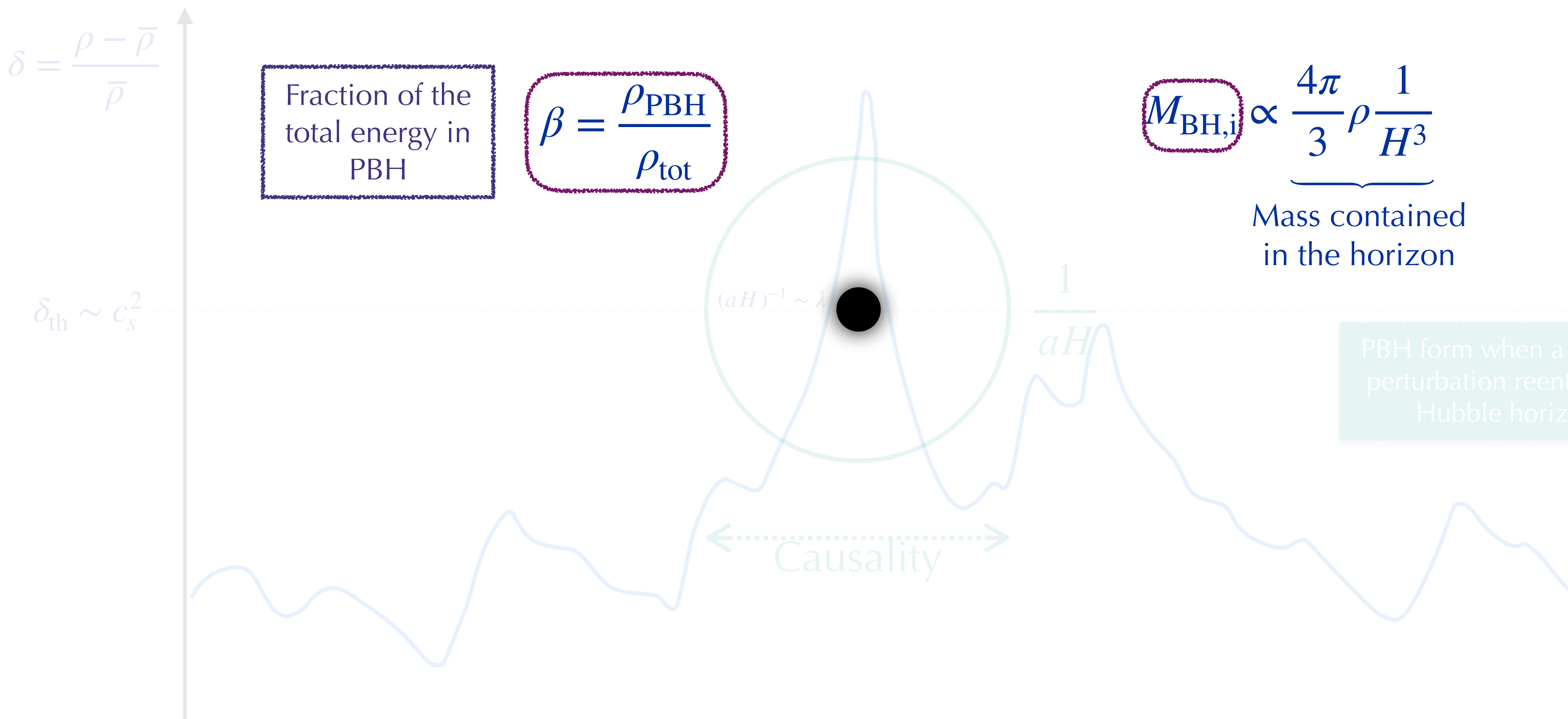


PBH form when a density perturbation reenters the Hubble horizon

Inspired on Villanueva-Domingo, Mena, Palomares-Ruiz 2103.12087

Assume a monochromatic mass distribution

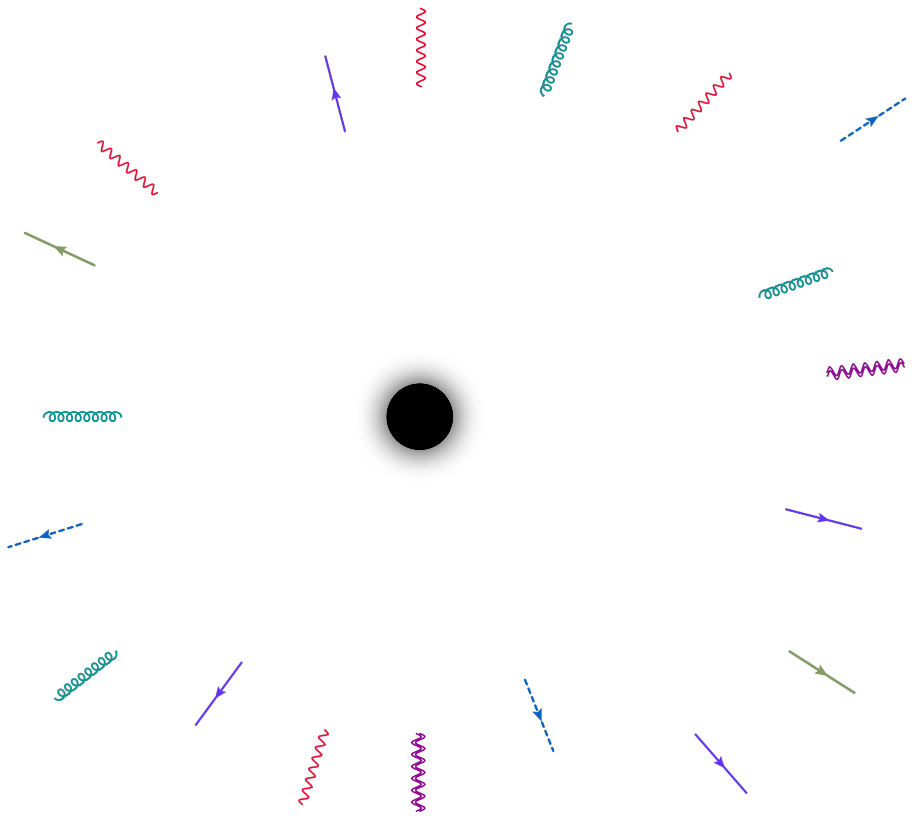
$M_{\mathrm{BH},i}\,,\ \beta$

All PBHs with the same mass

Carr et al. 2002.12778

Evaporation — Schwarzschild BHs

Described by $M_{\rm BH}$

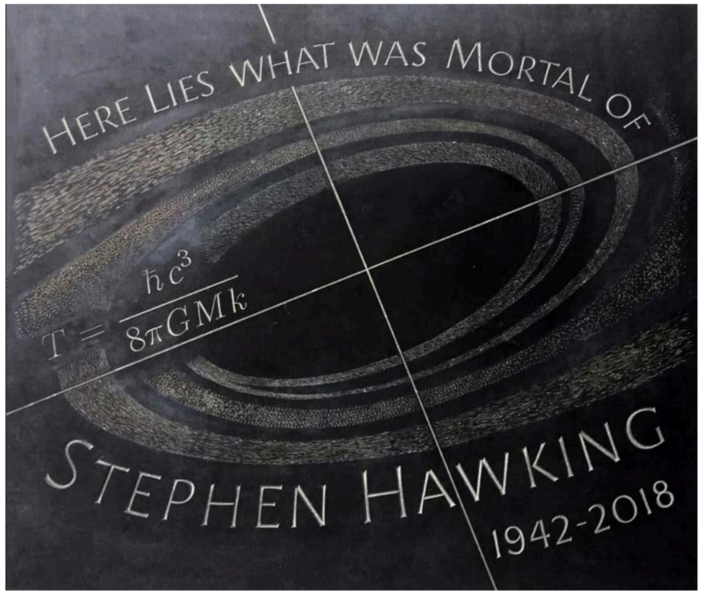


$$\frac{d^2N_i}{d\omega\, dt} = \frac{g_i}{2\pi^2}\frac{{}_{s_i}\Gamma(M,\omega,\mu_i)}{\exp[\omega/T]-(-1)^{2s_i}}$$

Hawking Instantaneous Spectrum

BH Temperature

$$T = \frac{\hbar c^3}{8\pi G M k} \sim 1\ \text{GeV}\left(\frac{10^{13}\ \text{g}}{M}\right)$$



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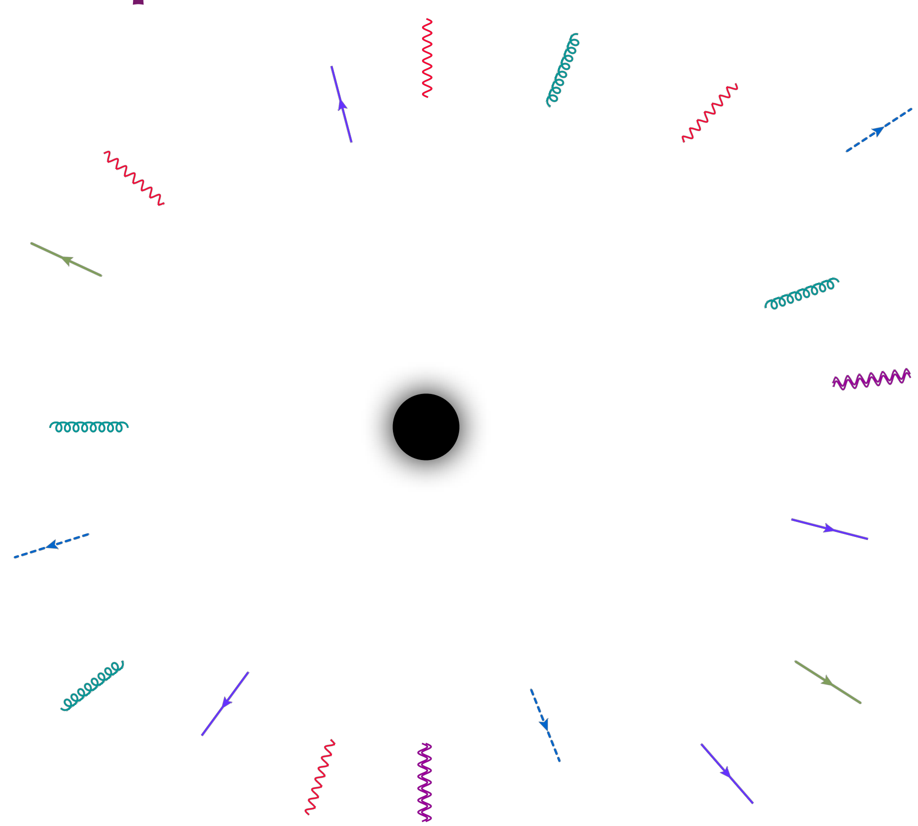

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Hawking Instantaneous Spectrum

Absorption probability

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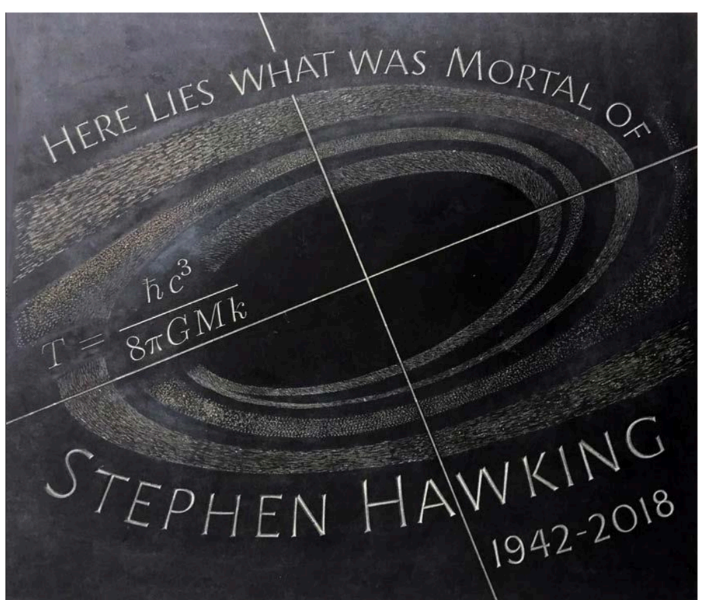
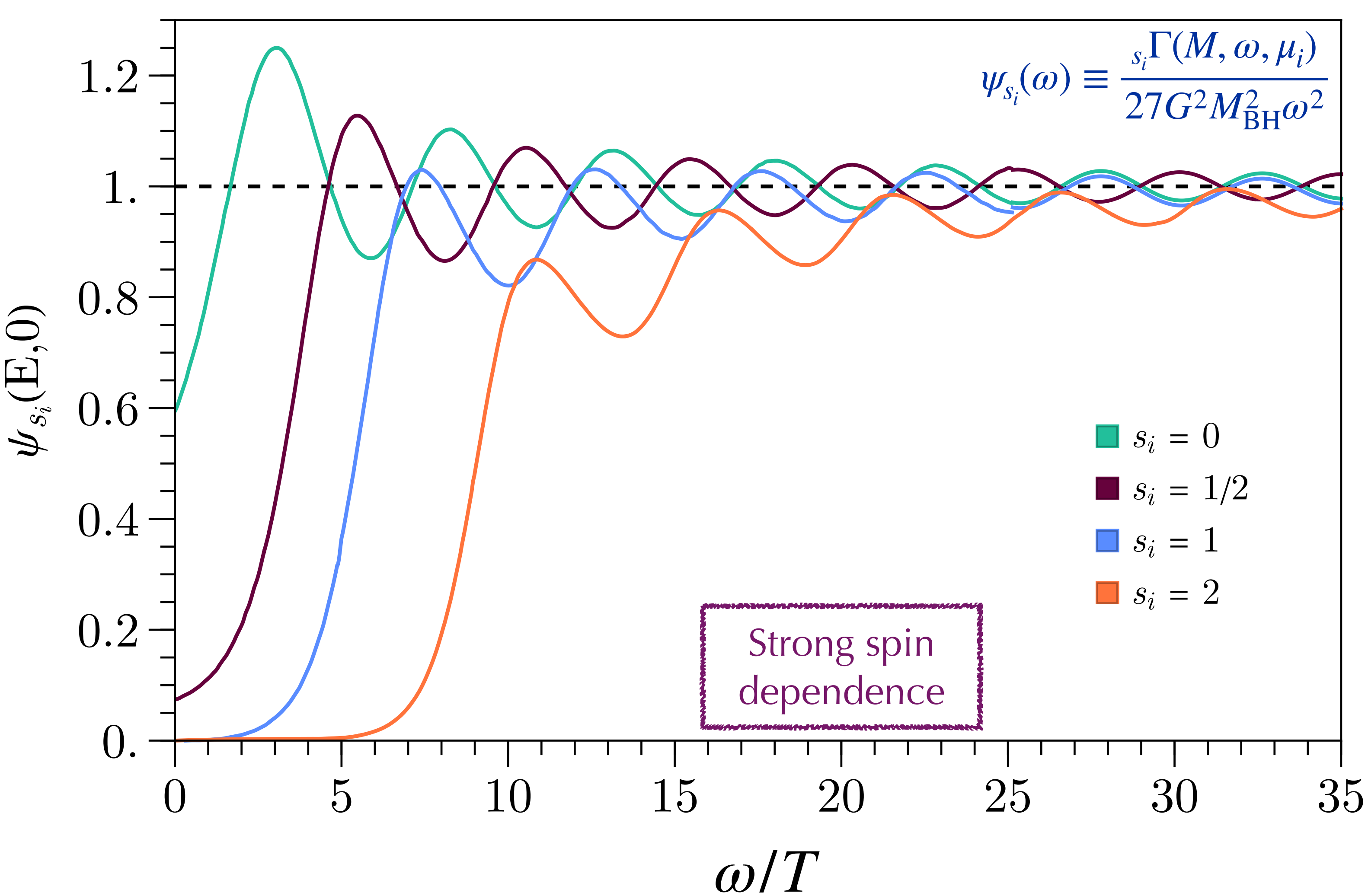
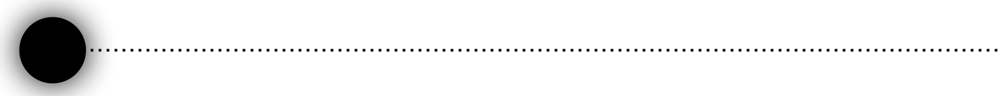




Only $\ell \geq s_i$ modes

Neutrino Emission for Schwarzschild BHs

Neutrinos are massive



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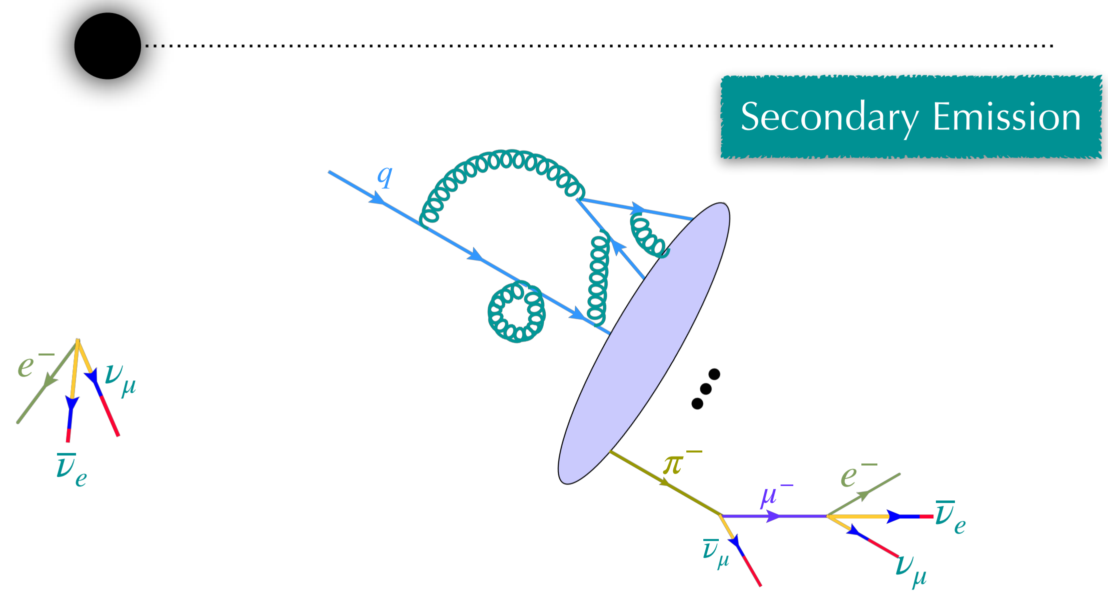
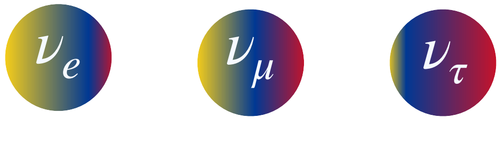


Weak interactions

Gauge interactions

Flavor eigenstate



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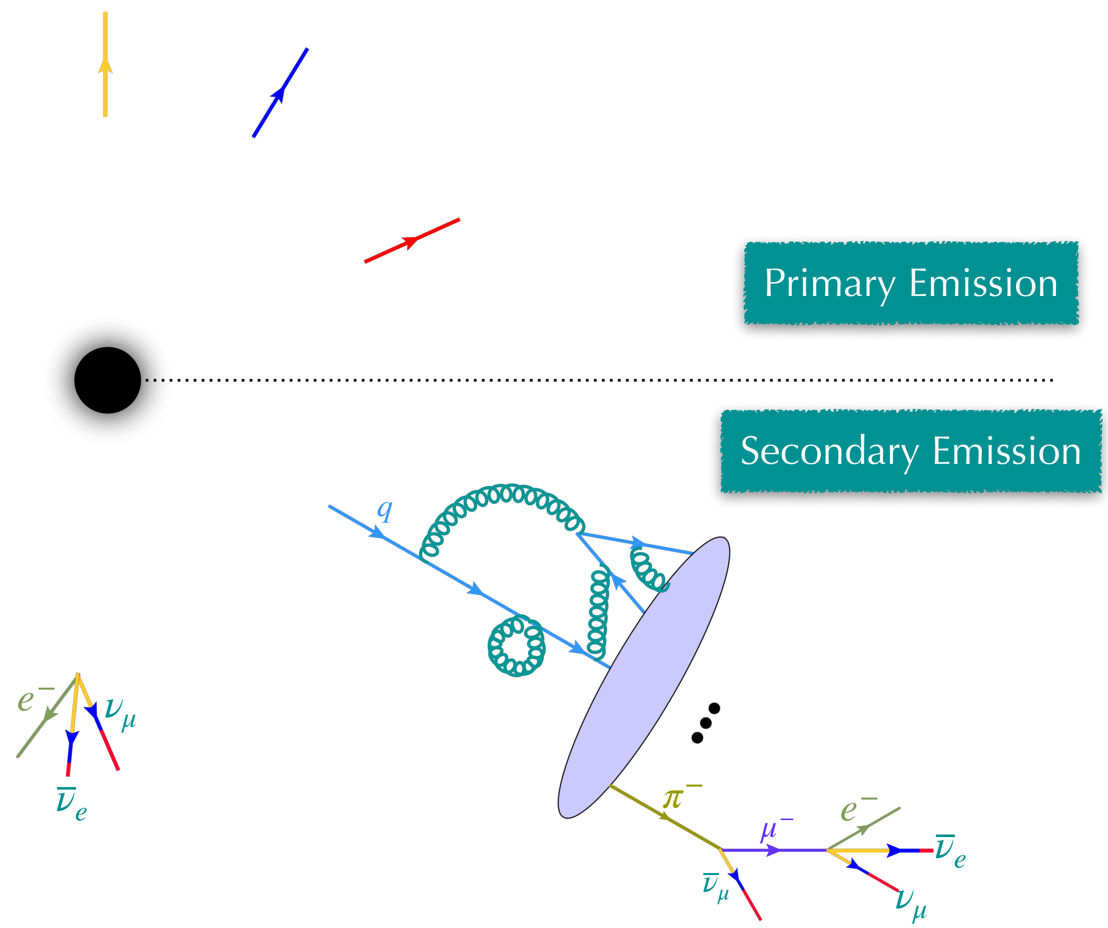

Weak interactions

Gauge interactions

Flavor eigenstate

ν_e ν_μ ν_τ

Hawking Effect

Particle definition in a curved spacetime is observer dependent

Mass eigenstate

ν_1 ν_2 ν_3

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Neutrino Emission for Schwarzschild BHs

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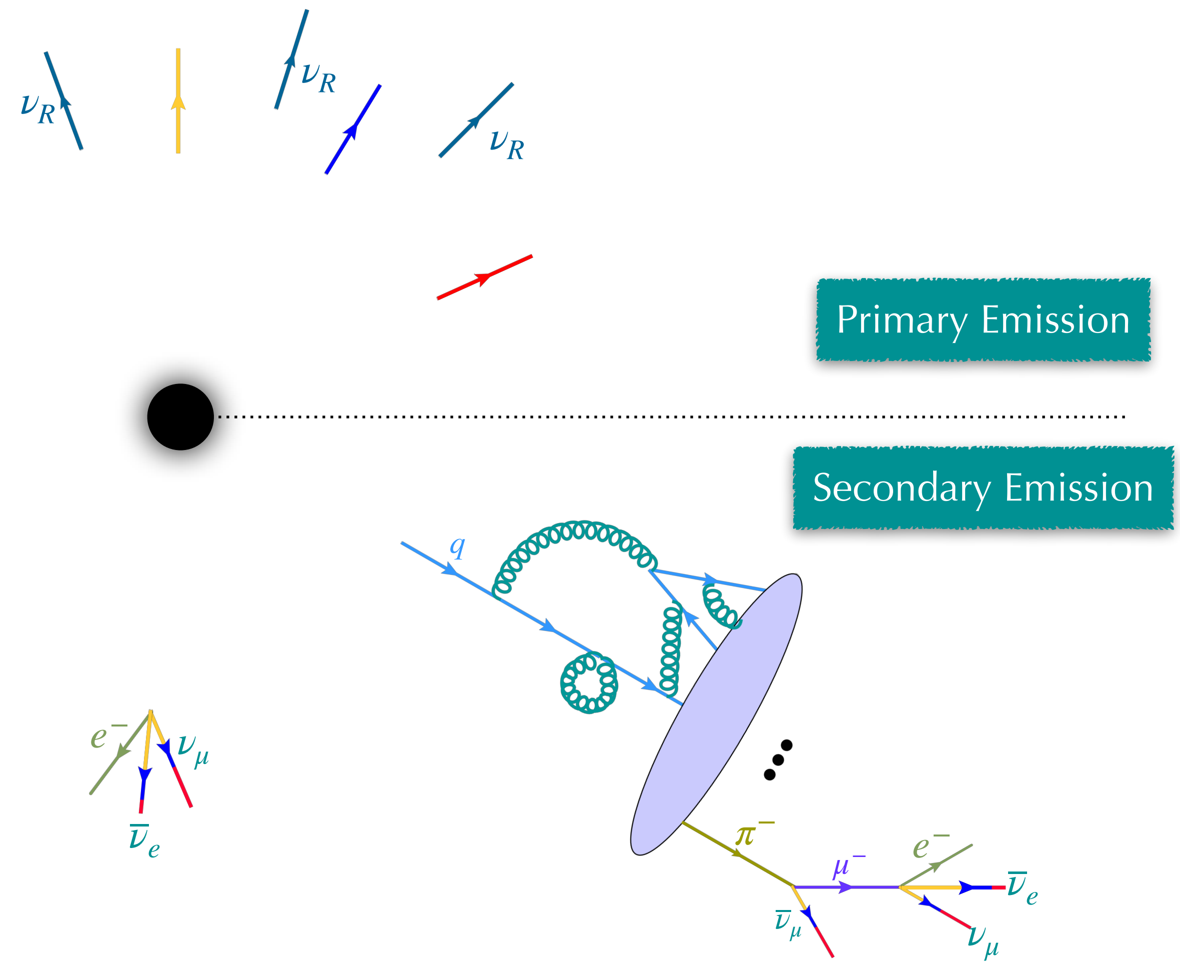
Dirac vs Majorana?



Weak interactions	Hawking Effect
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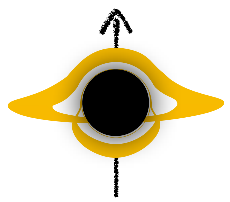
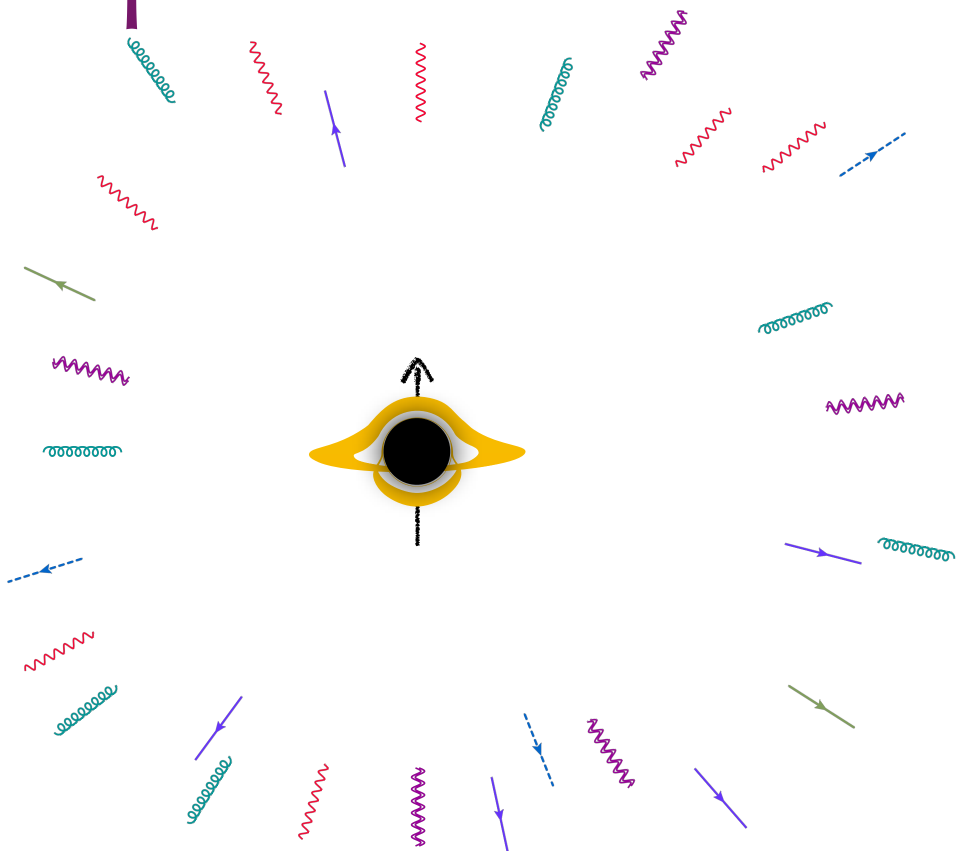


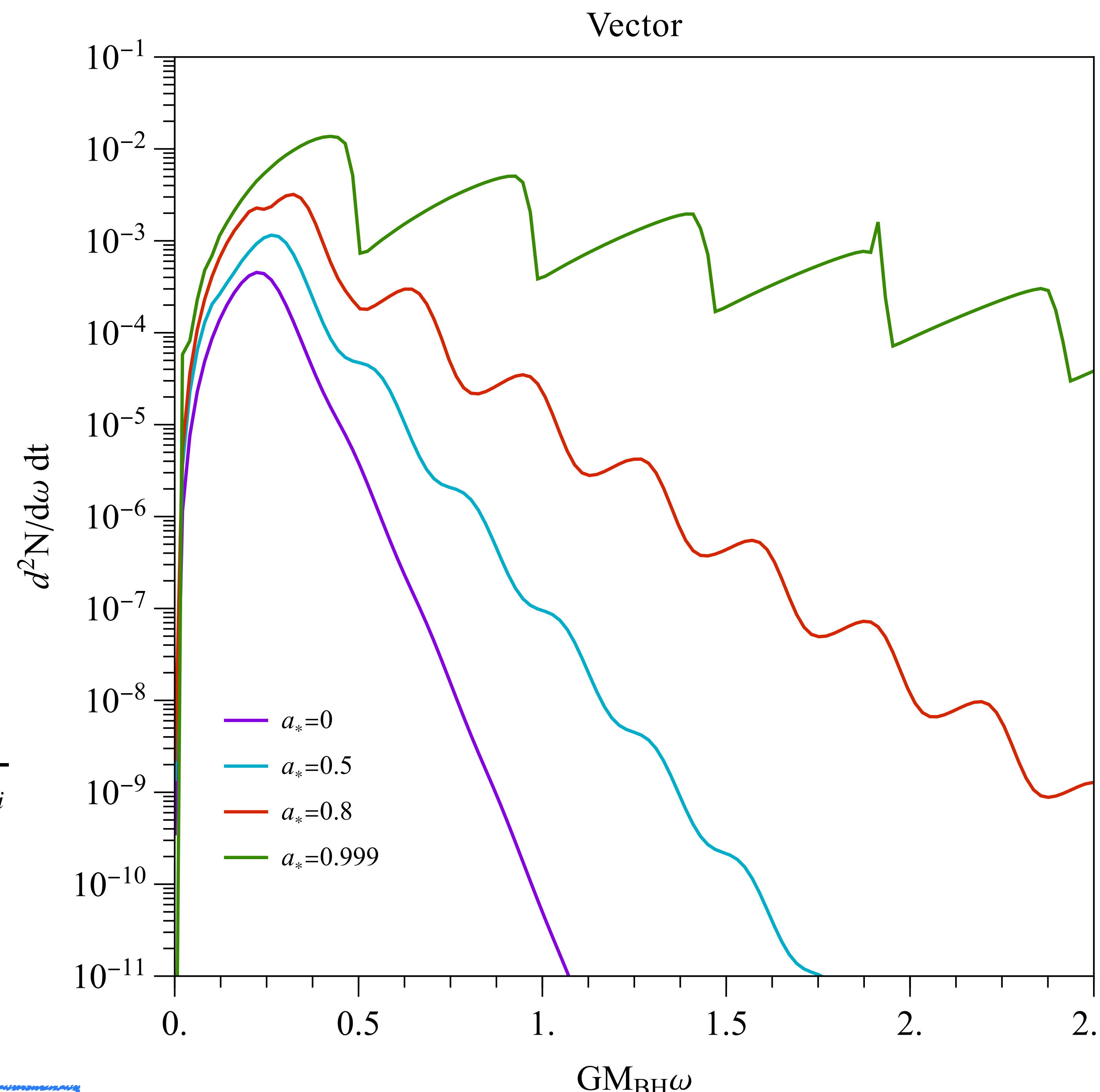
Evaporation — Kerr BHs

Described by $M_{\rm BH}, a_\star = JM_p^2/M_{\rm BH}^2 \in [0,1)$



BH "wants" to shed off its angular momentum

$$\frac{d^2N_i}{d\omega\, dt} = \frac{g_i}{2\pi} \sum_{l=s_i} \sum_{m=-l}^{l} \frac{{}_{s_i}\Gamma_{lm}}{\exp(\varpi_m/T_{\rm BH}) - (-1)^{2s_i}}$$



BH Temperature

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Explicit dependence on m
$\Omega \rightarrow$ angular velocity

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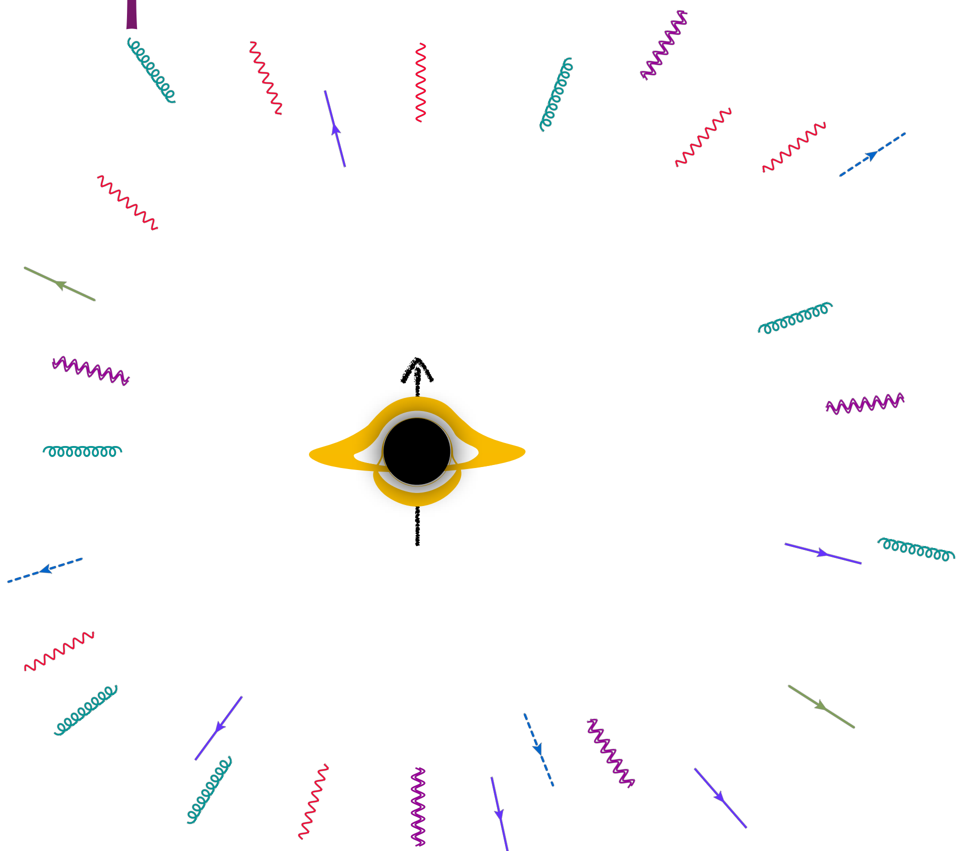

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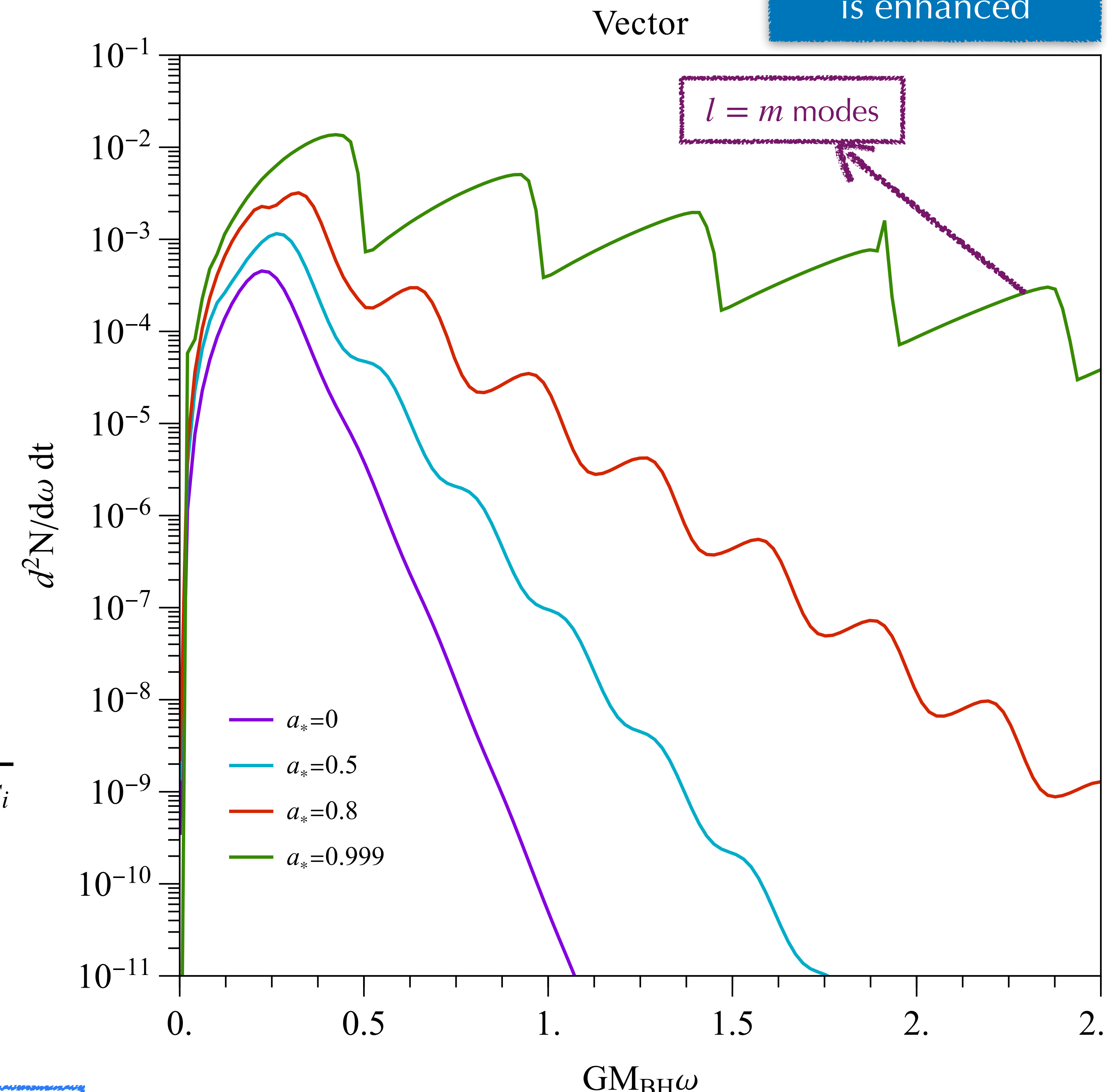
Emission of Corrotating modes is enhanced



Time Evolution

$$\frac{dM_{\rm BH}}{dt} = -\underbrace{\varepsilon(M_{\rm BH}, a_\star)}_{\text{Evaporation function}} \frac{M_P^4}{M_{\rm BH}^2}$$

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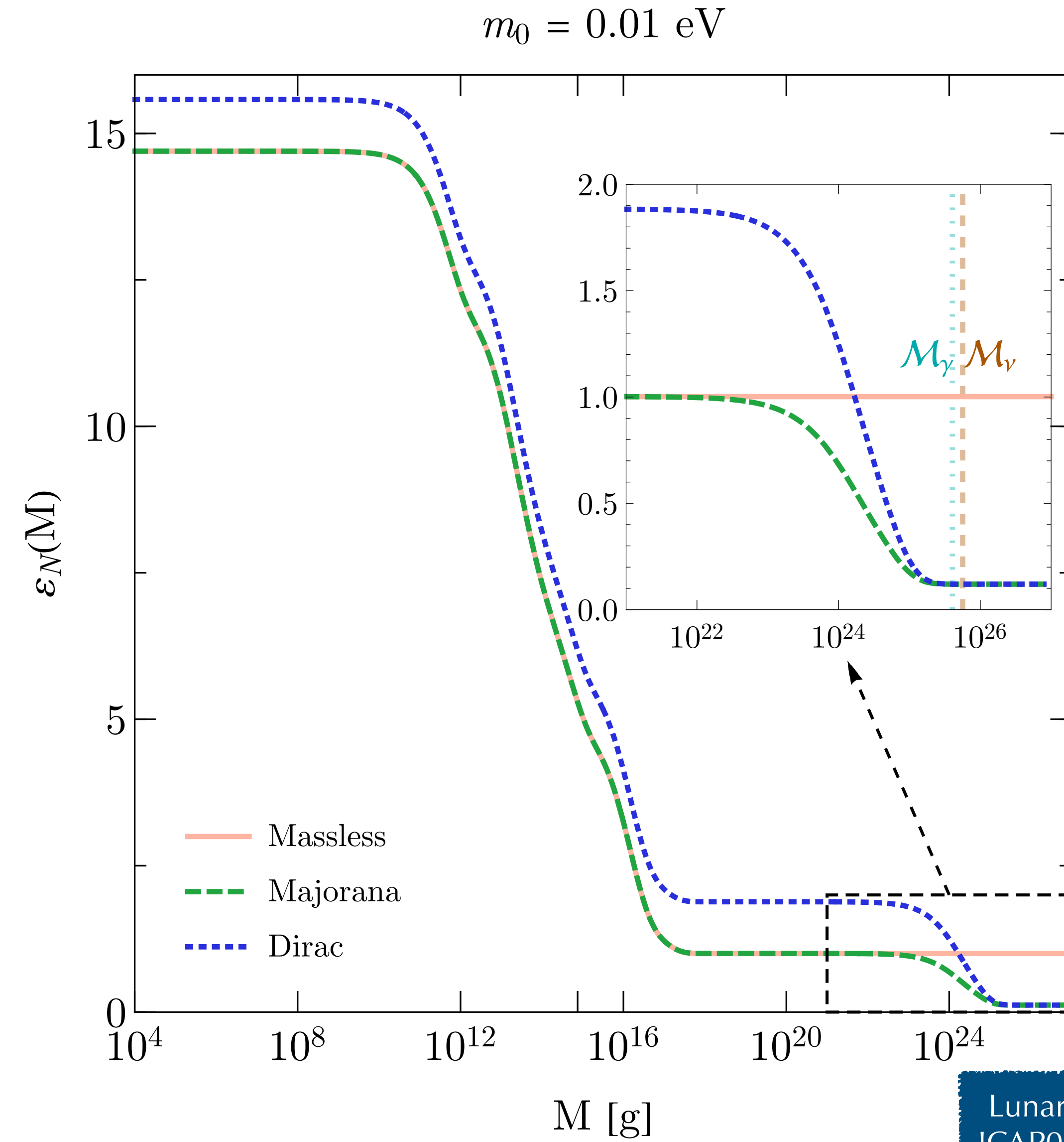

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Depends on the set of ***all*** existing dofs

$$\varepsilon = \sum_{i=\text{all},l,m} \int_0^\infty \frac{d^2\mathcal{N}_{ilm}}{d\omega dt}\,\omega d\omega$$

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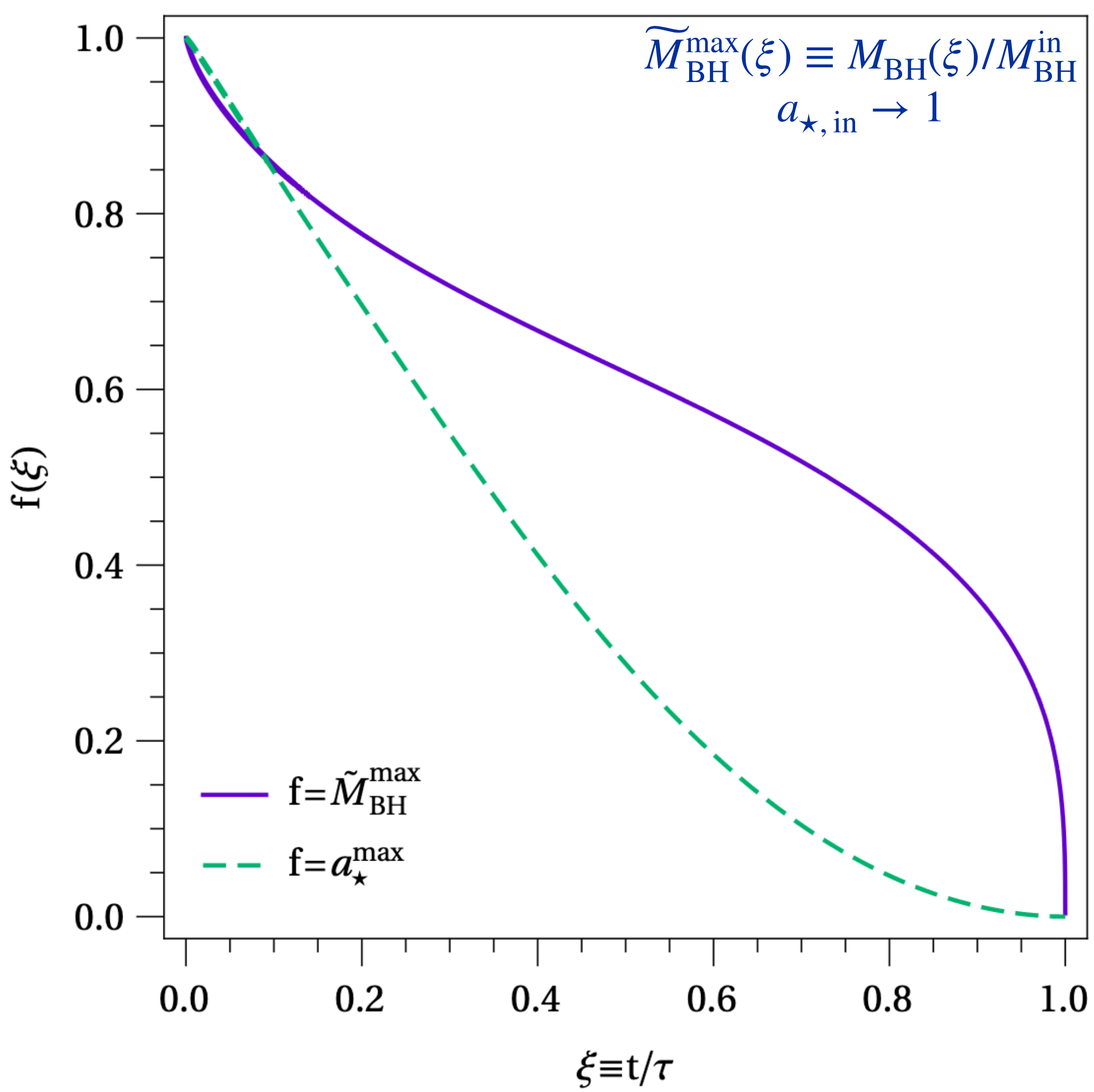

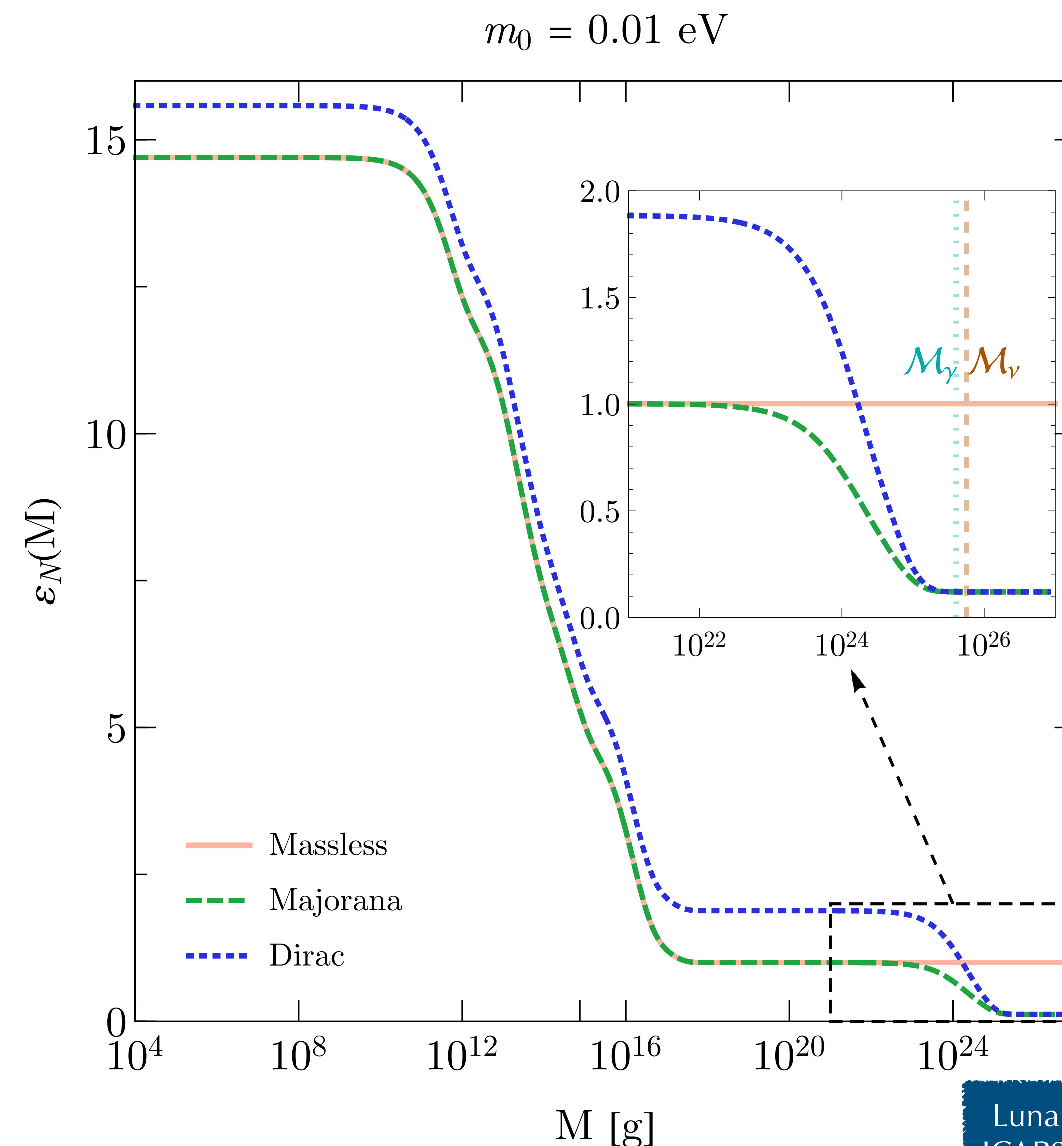

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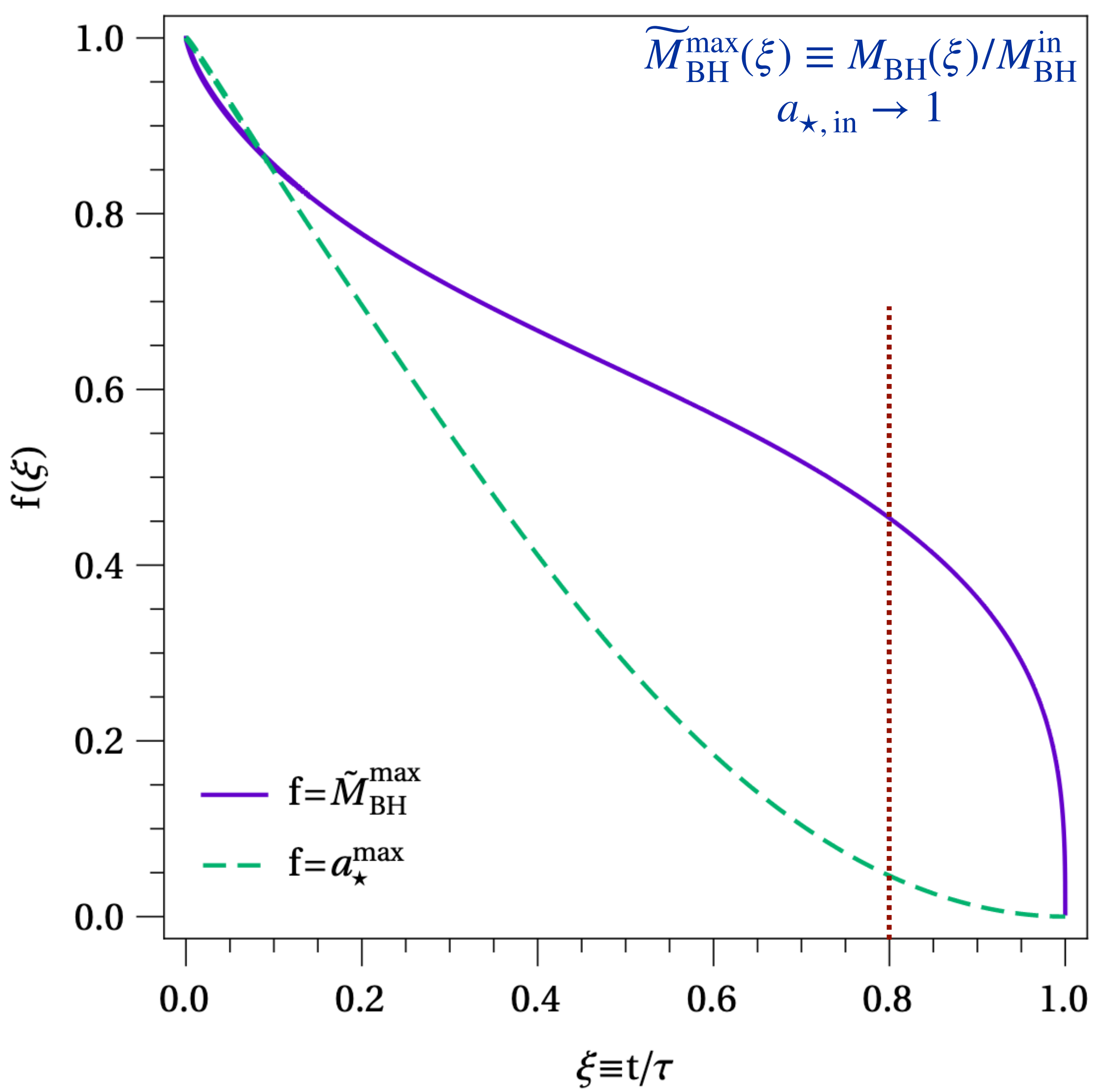

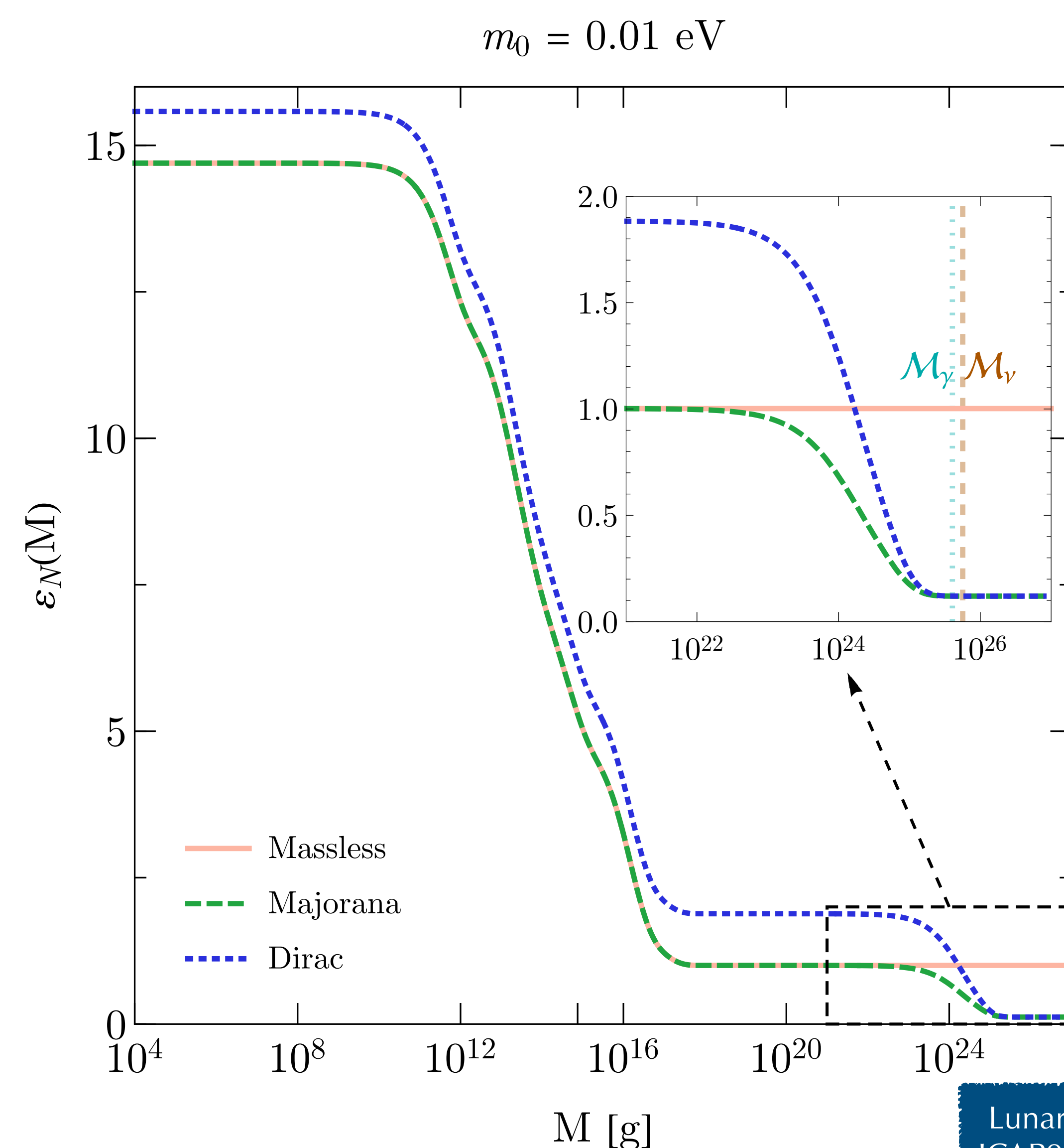

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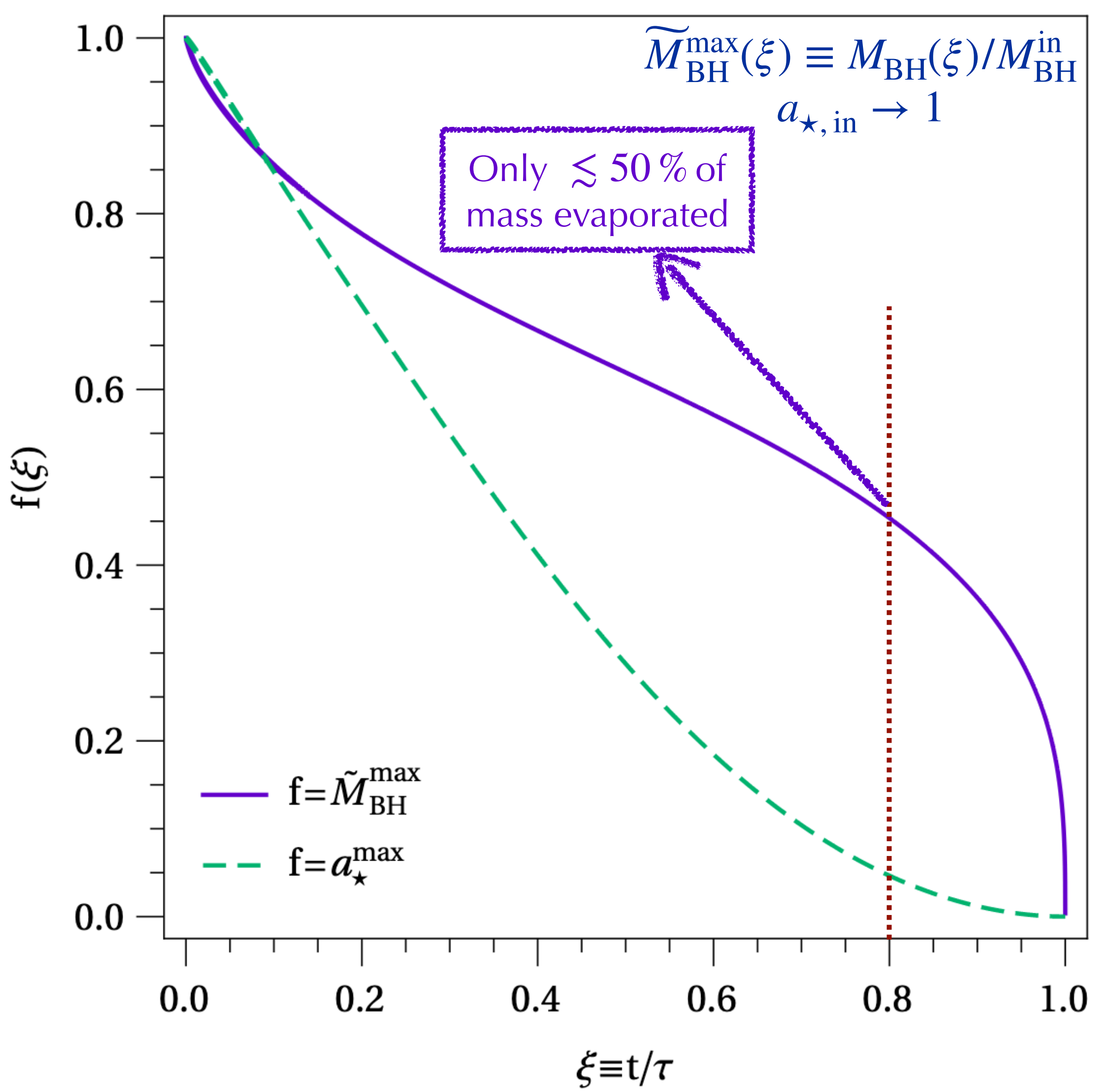

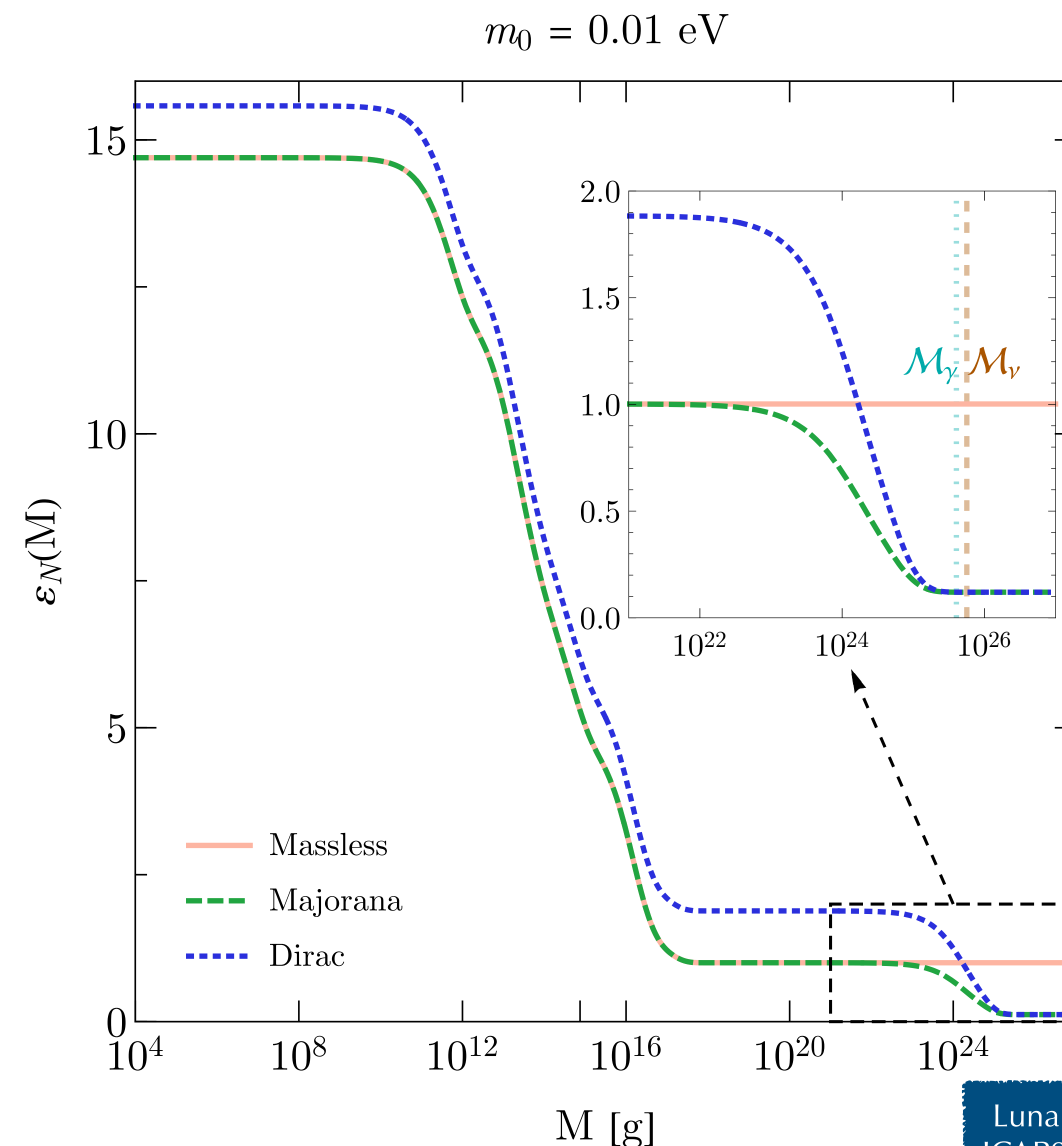

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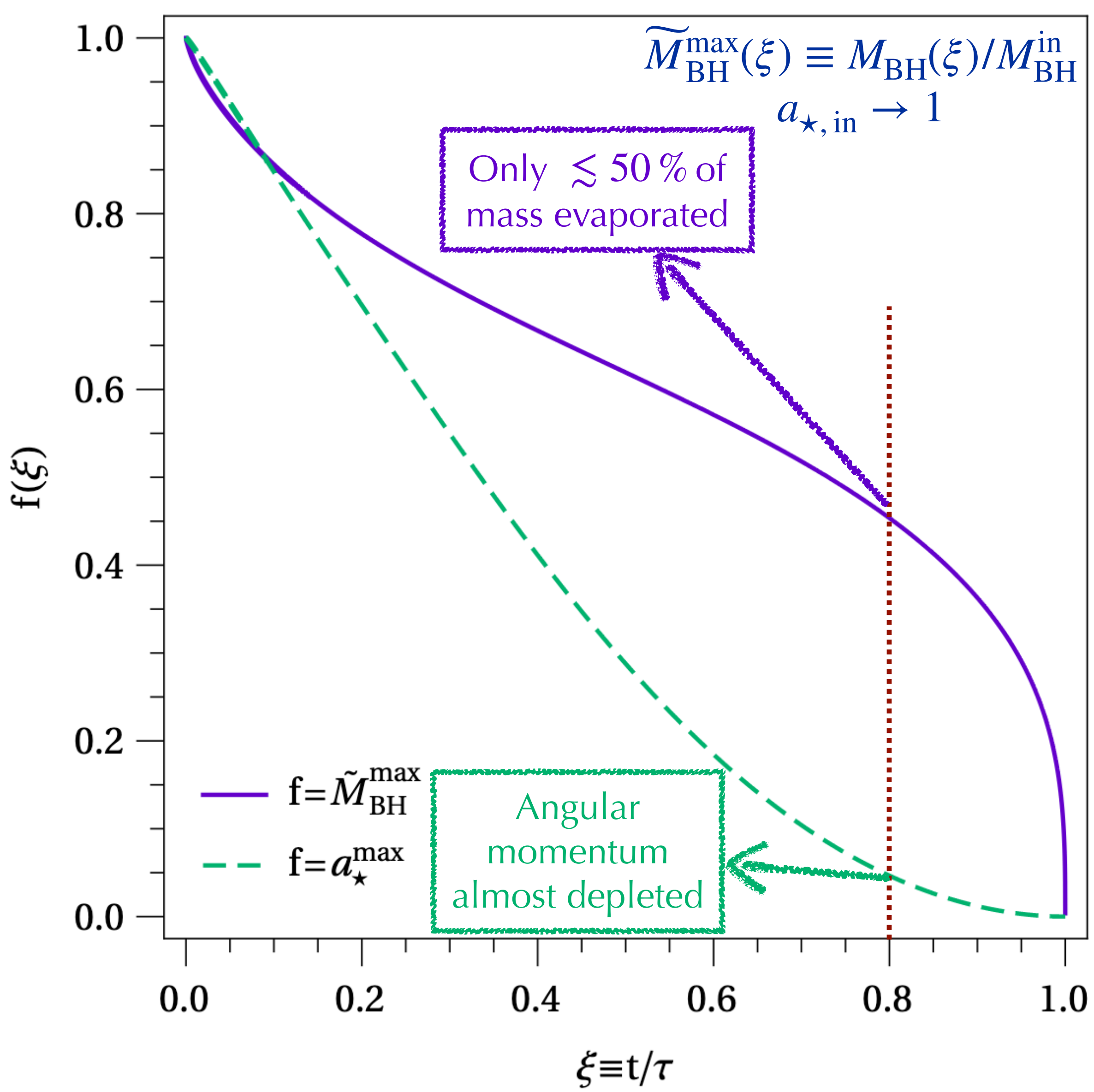

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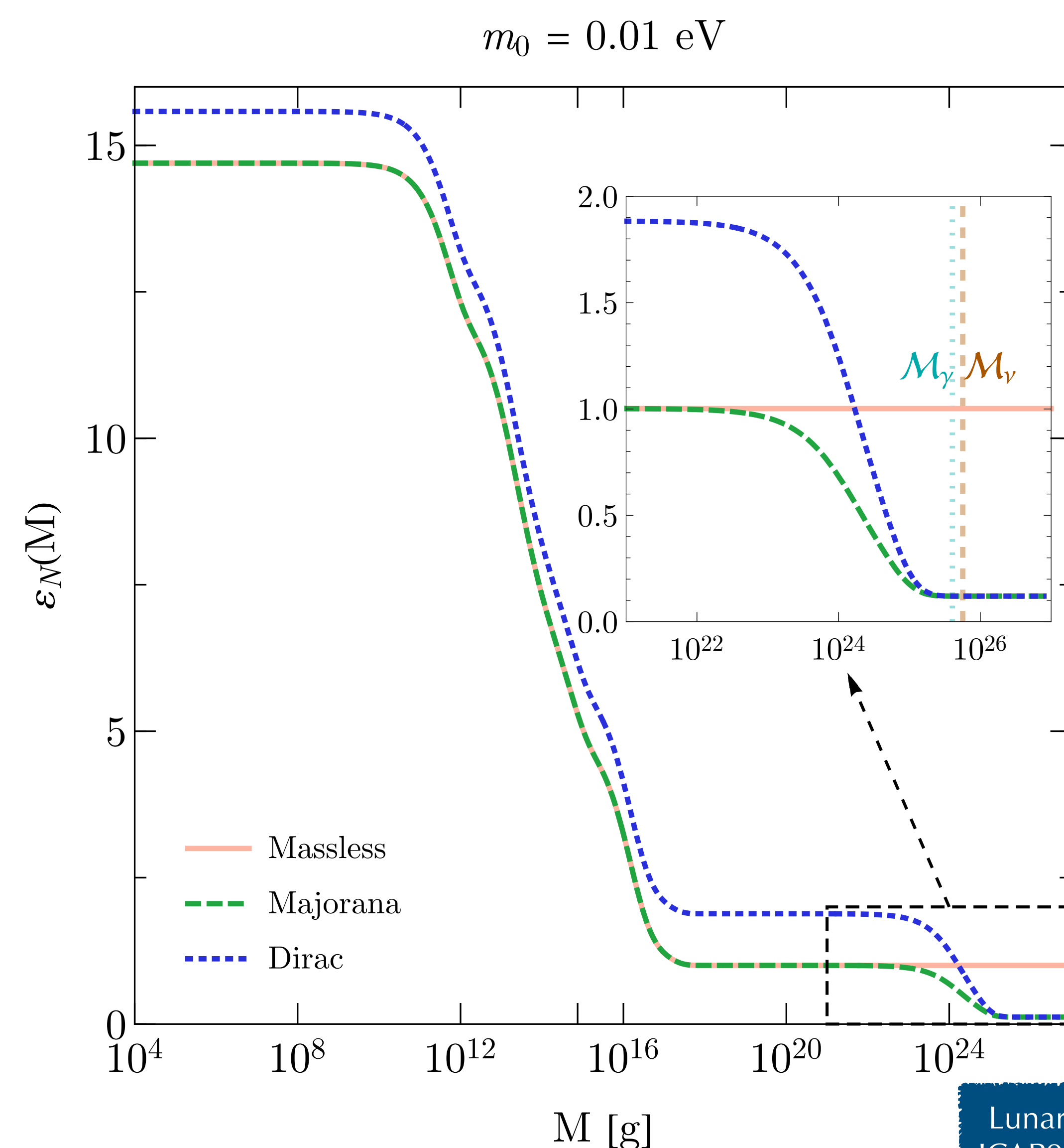

Lunardini, YFPG JCAP08(2020)014

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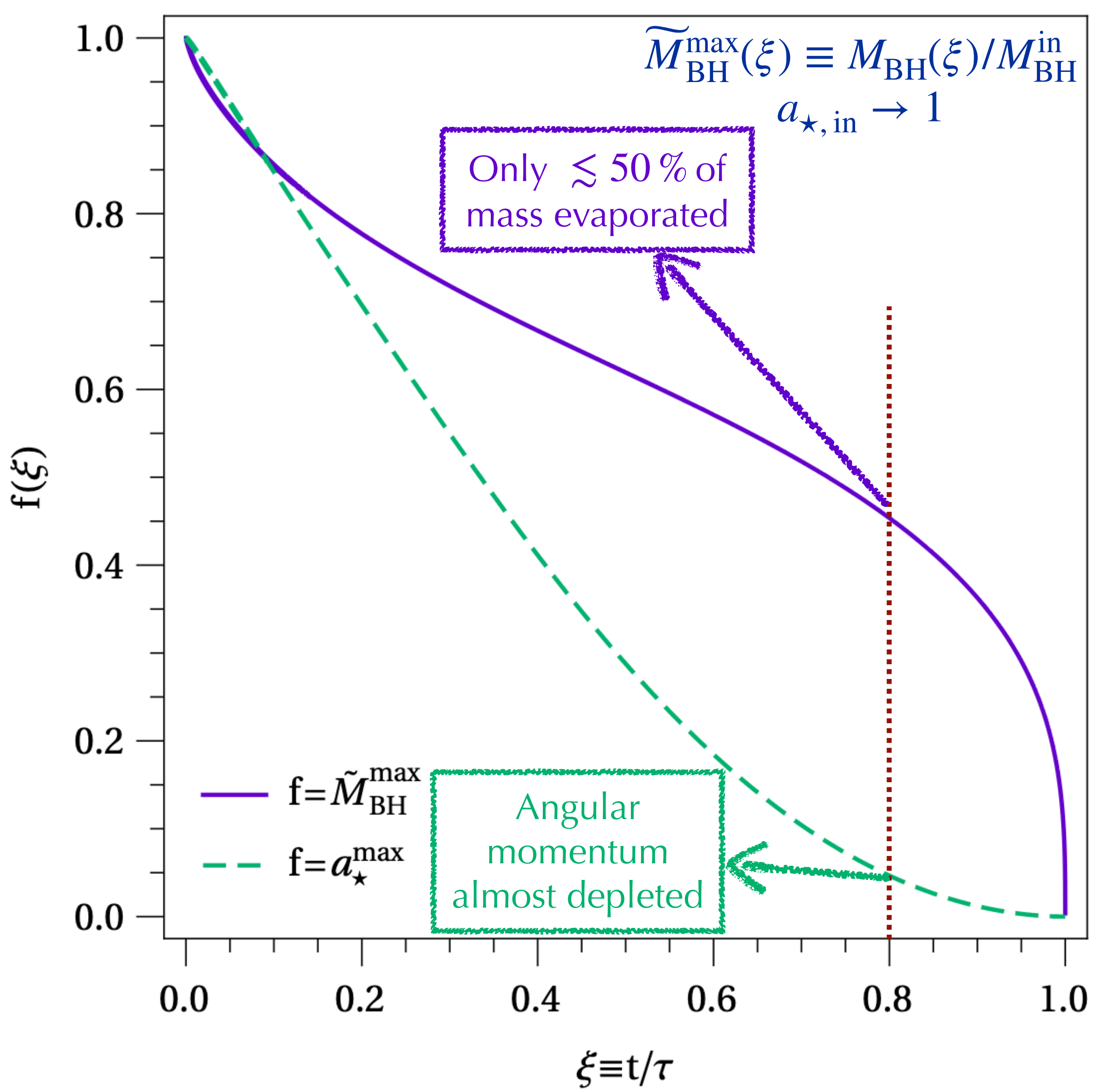

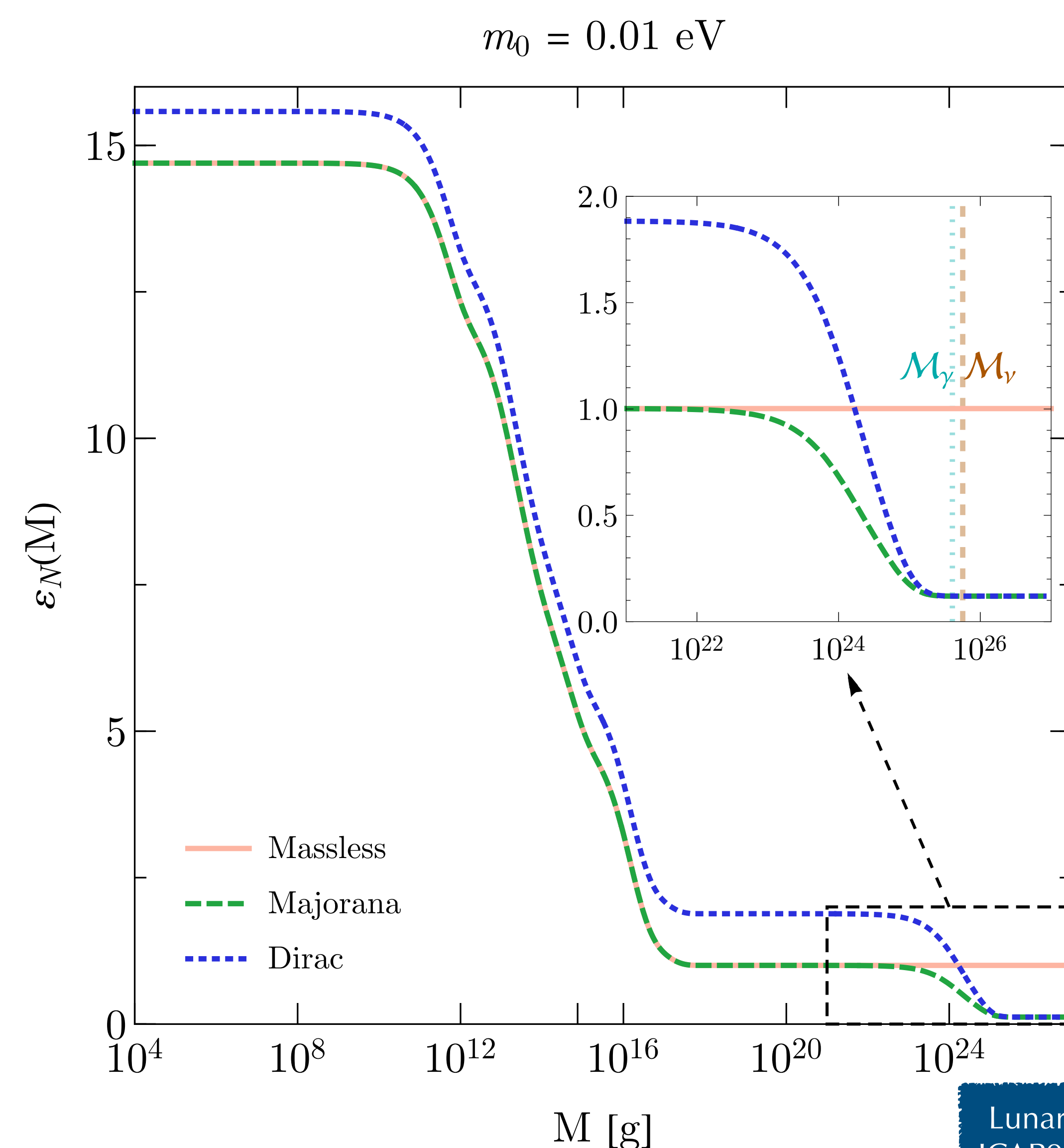

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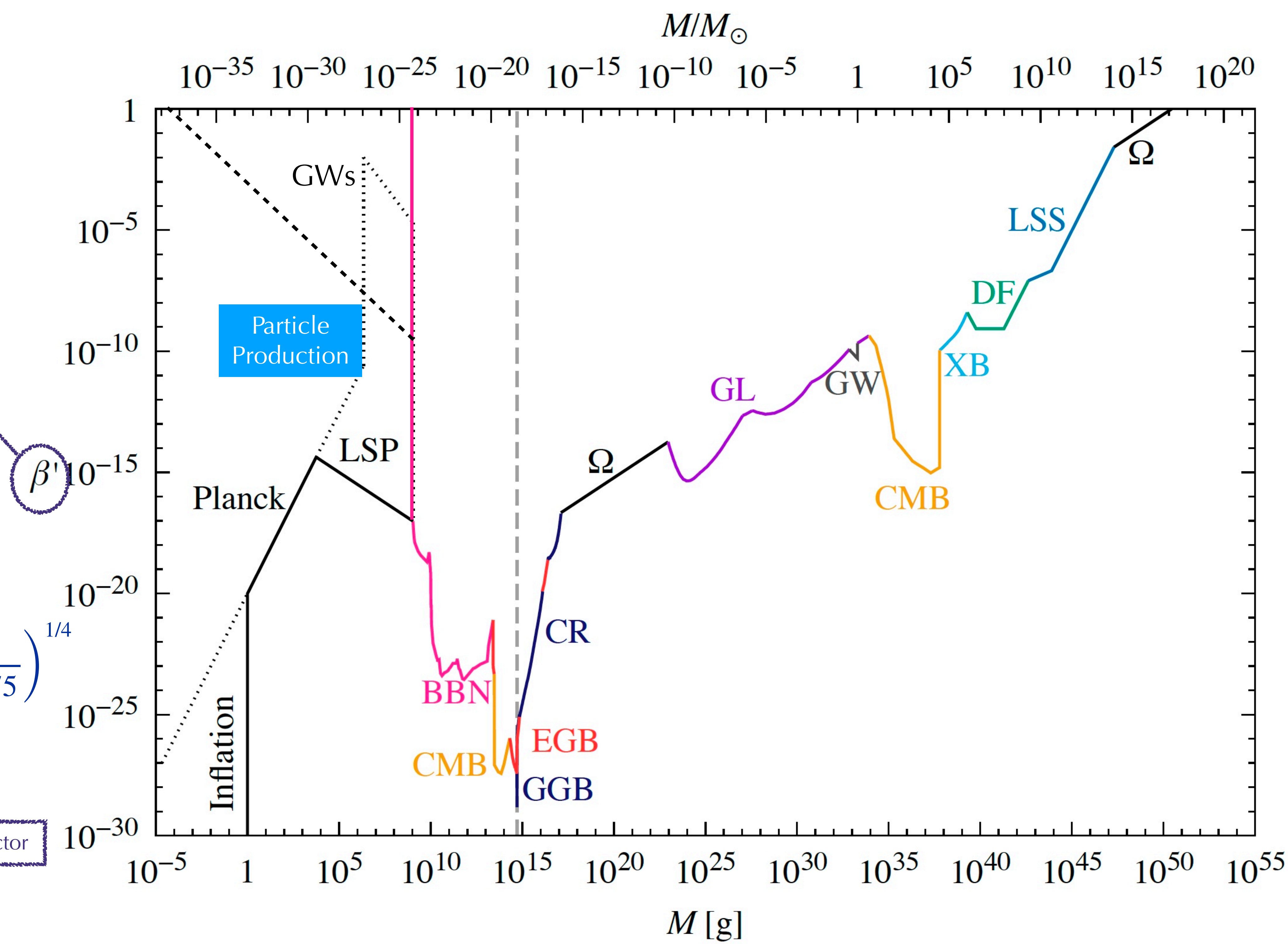
Angular momentum depleted faster than mass*

If there are some PBH still around they ***might*** have a small angular momentum

*Assuming the SM

Reduced β



$$\beta' = \beta\,\gamma^{1/2}\left(\frac{g_{*f}}{106.75}\right)^{1/4}$$

Gravitational collapse factor

Carr et al. 2002.12778
Domènech et al. 2012.08151

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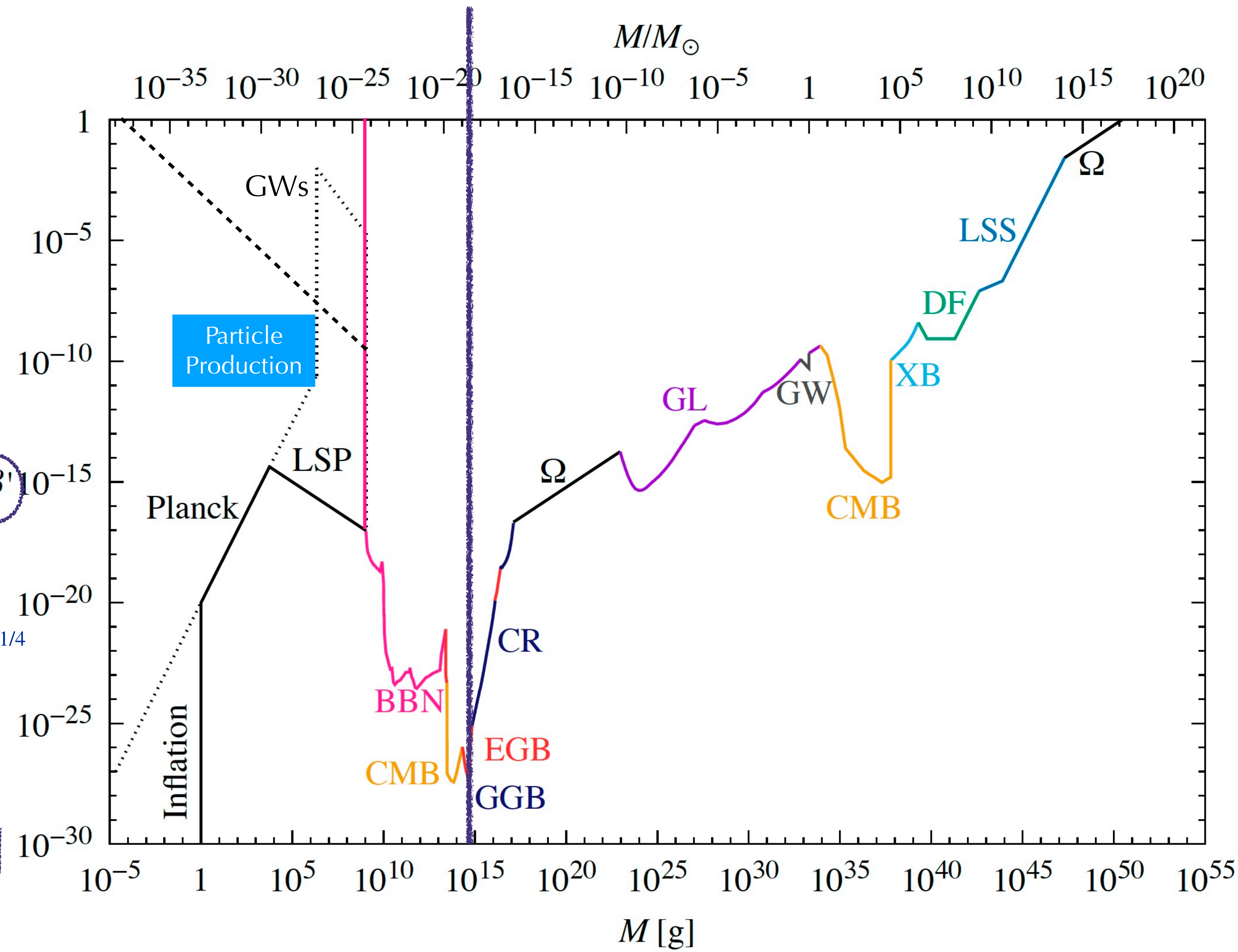

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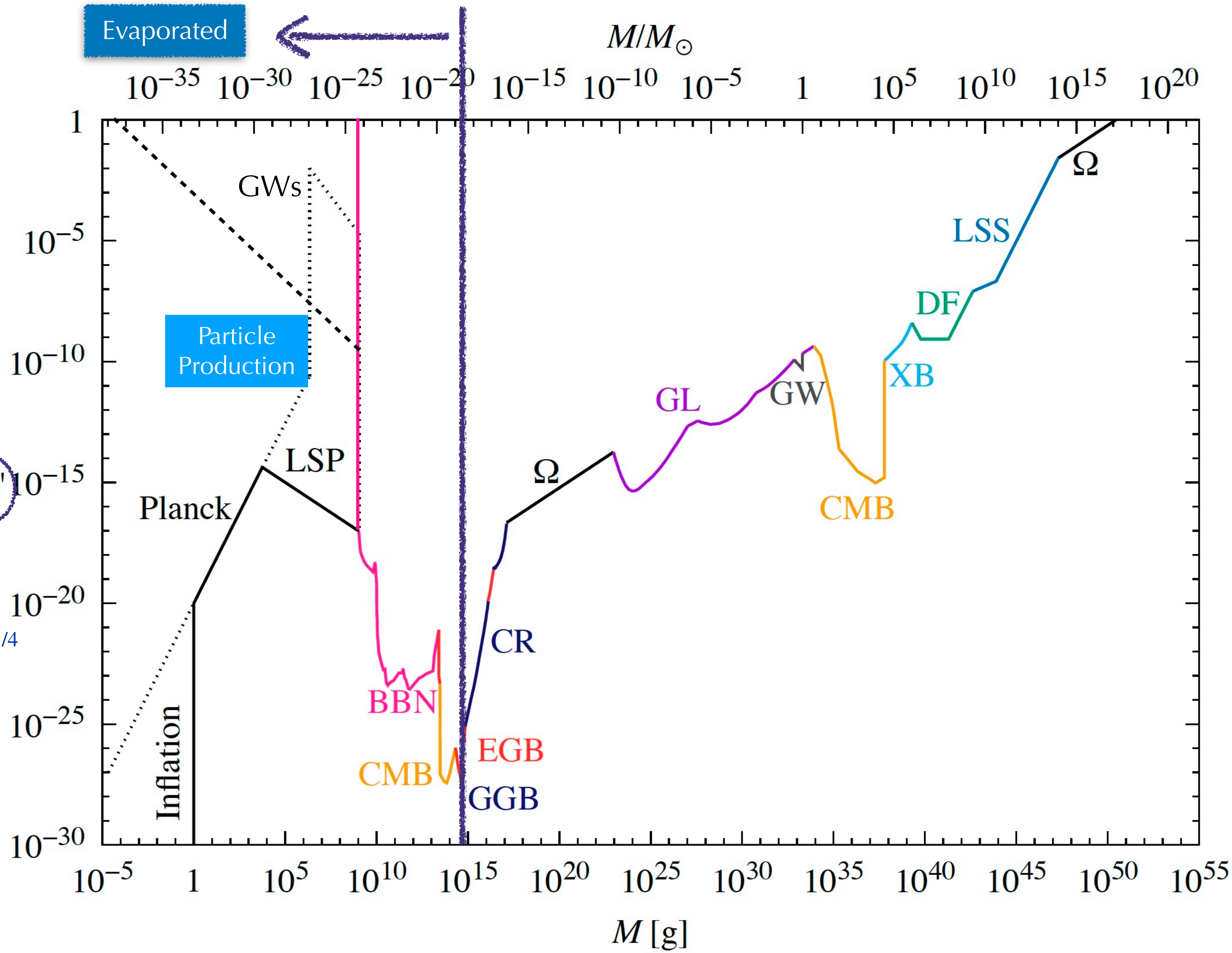

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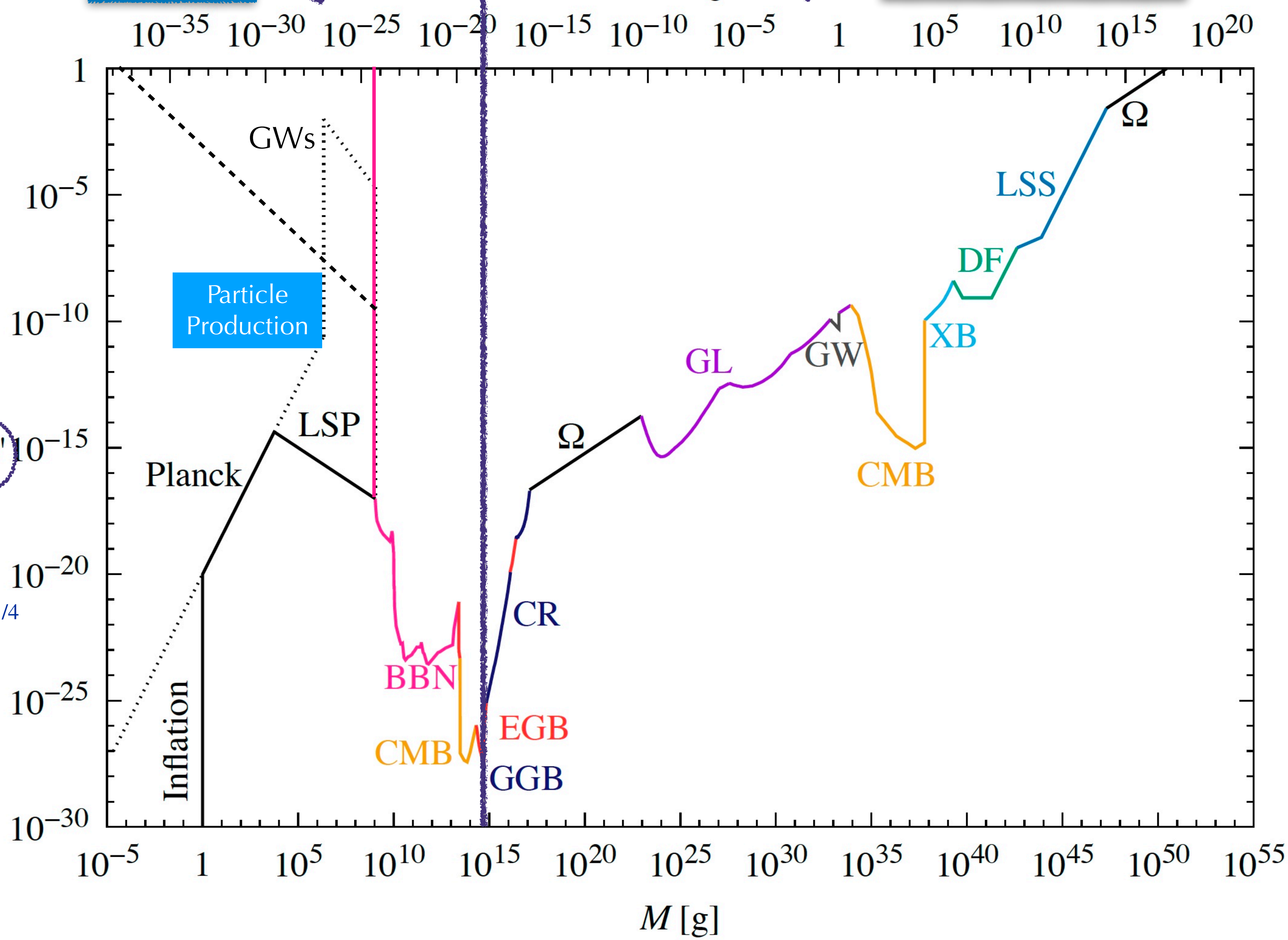
Evaporated

(Part of) Dark Matter?

Reduced β



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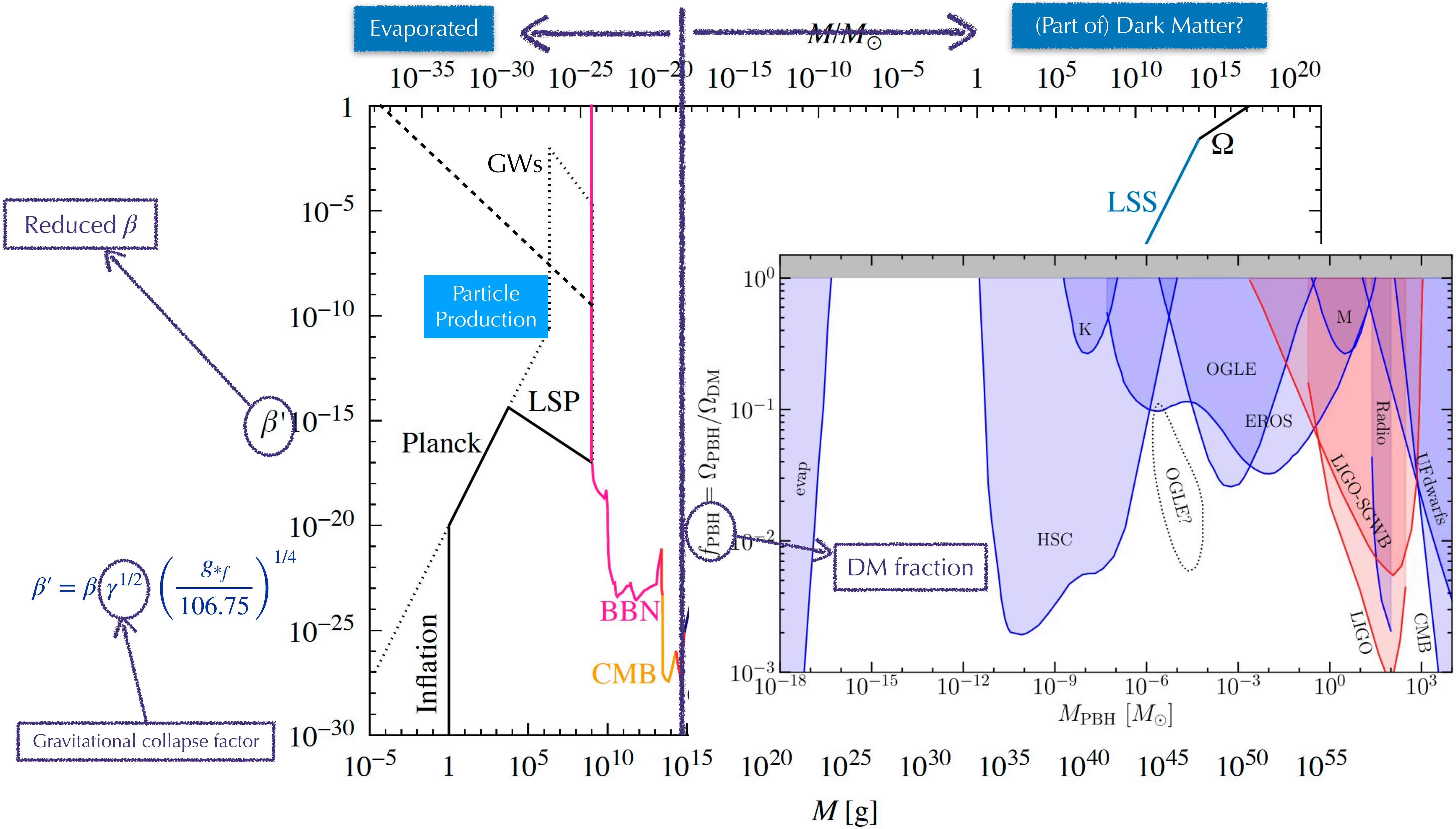

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B. Kavanagh
10.5281/zenodo.3538999

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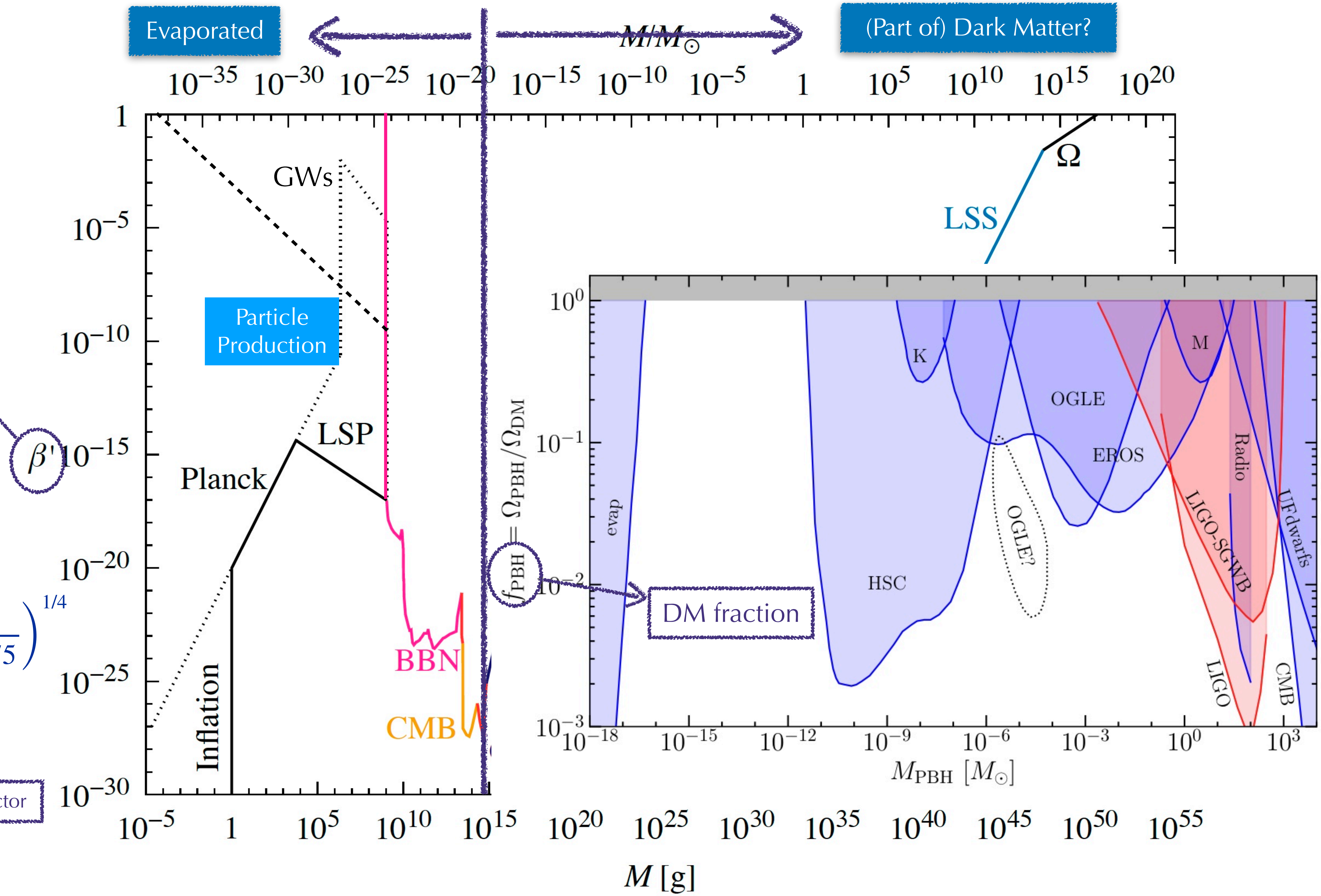

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Gravitational collapse factor

We focus on PBHs evaporating today $M_{\mathrm{BH},i} \sim 10^{15}$ g

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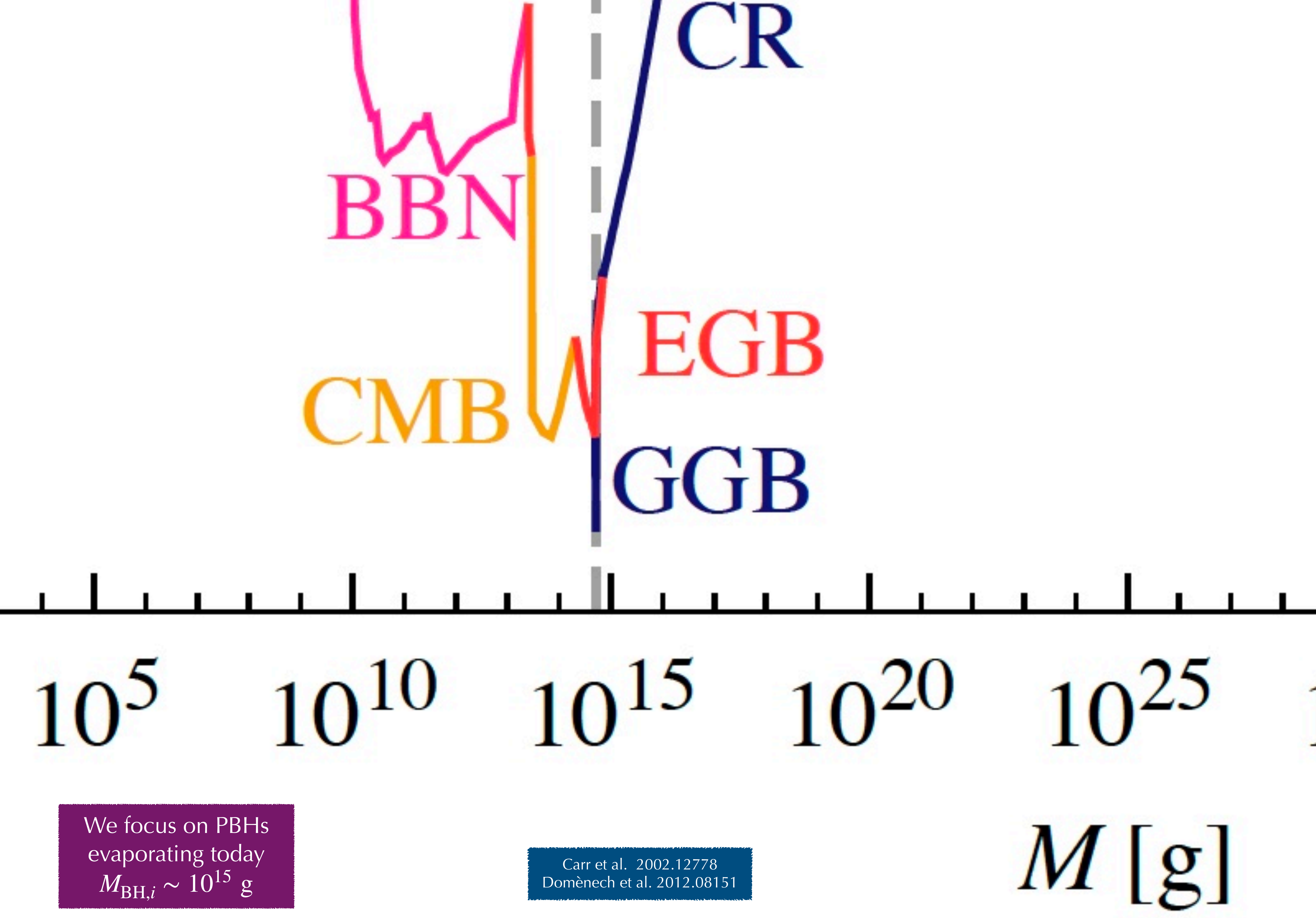

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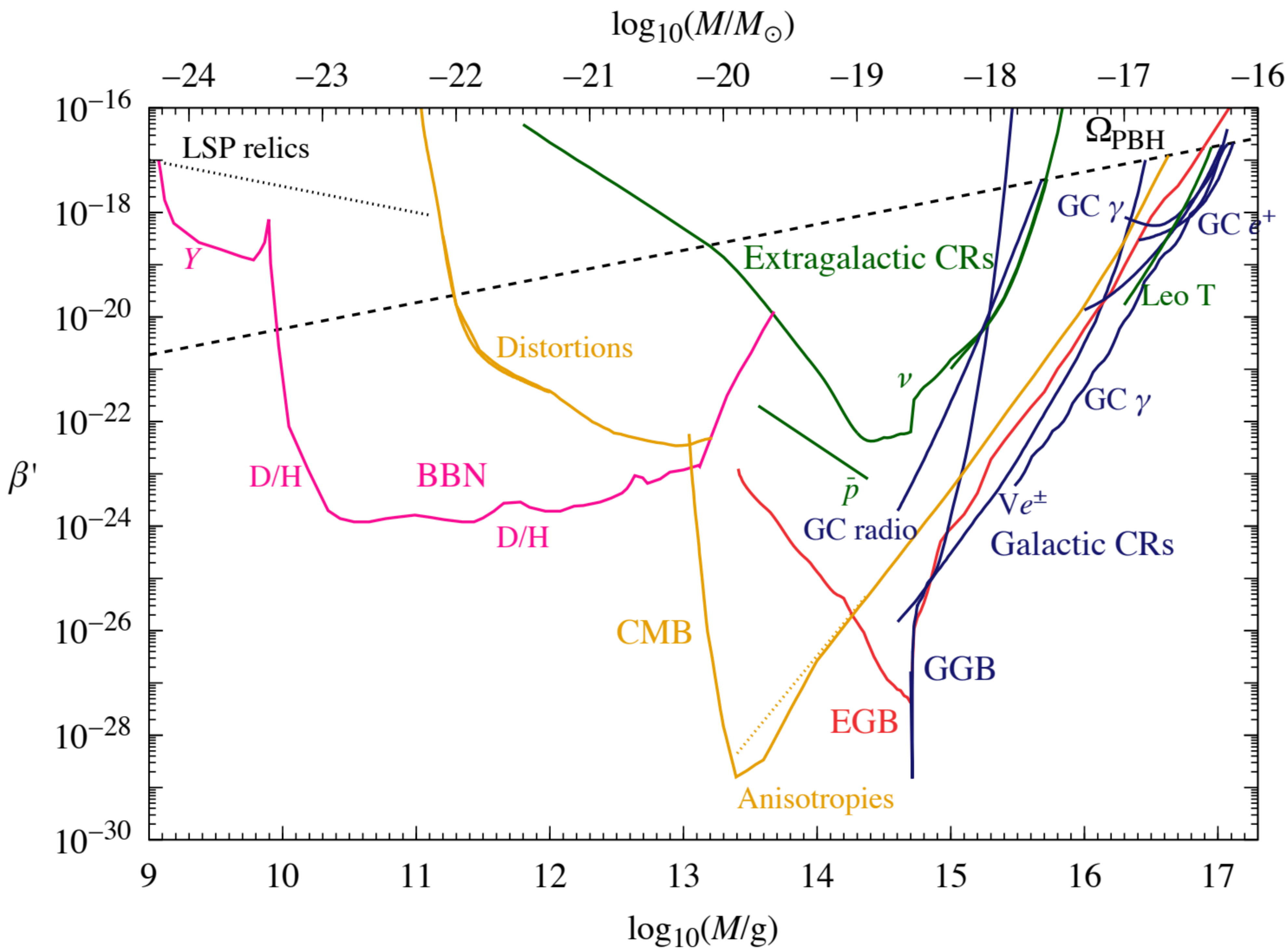

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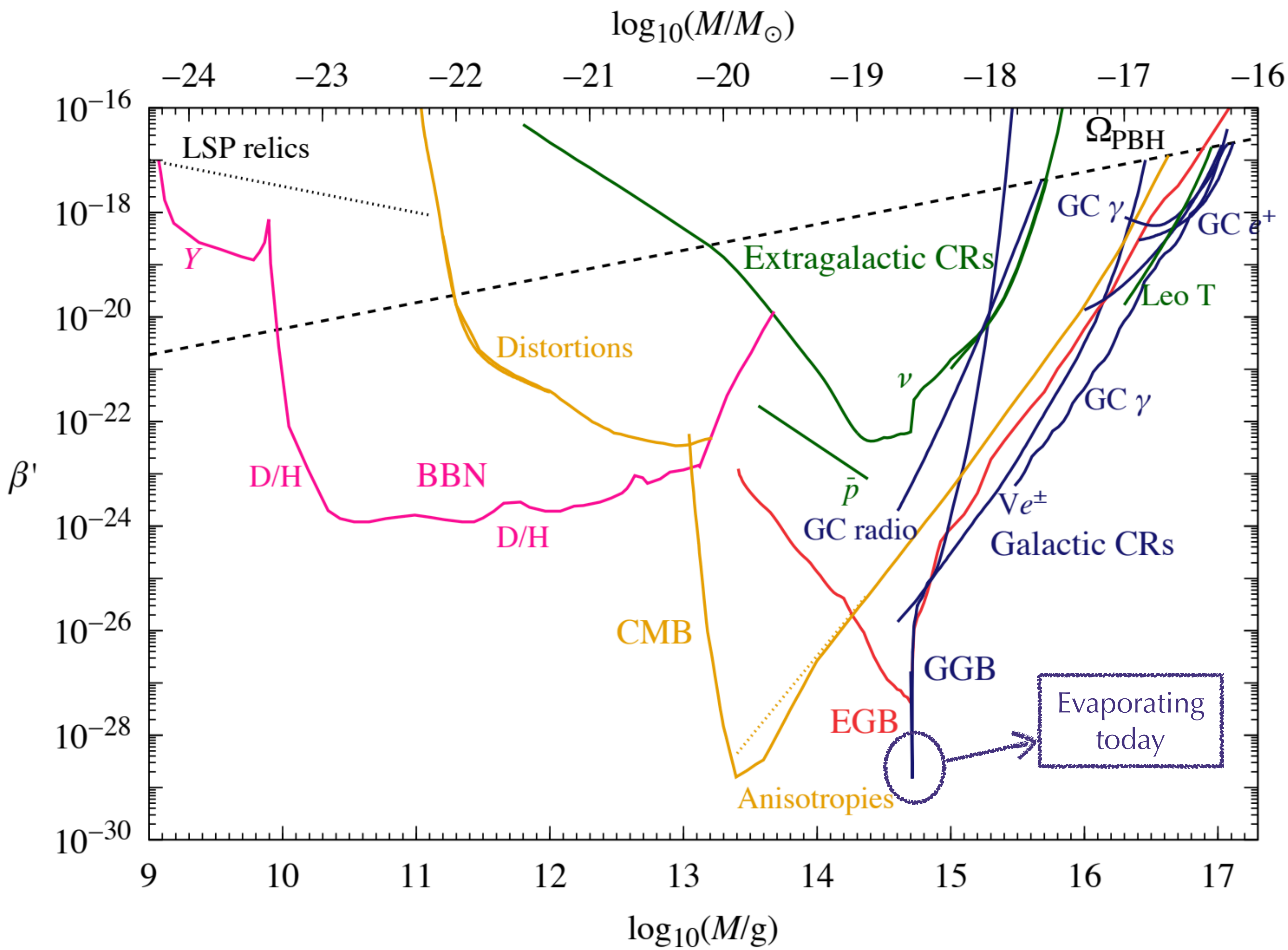

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$M_{\mathrm{BH},i} \sim 10^{15}$ g

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Evaporating PBHs (EPBH)

- Perhaps some PBHs are evaporating today

$$M_{\rm BH,i} \sim 10^{15}\ \mathrm{g}$$

$$\beta' \lesssim 10^{-29}$$

$$n_{\rm PBH} \approx 0.35\ \mathrm{pc}^{-3} \left(\frac{\beta'}{10^{-29}}\right)\left(\frac{10^{15}\ \mathrm{g}}{M_{\rm in}}\right)^{\frac{3}{2}}$$

Evaporating PBHs (EPBH)

- Perhaps some PBHs are evaporating today

$M_{\rm BH,i} \sim 10^{15}$ g

Evaporating today

$\beta' \lesssim 10^{-29}$

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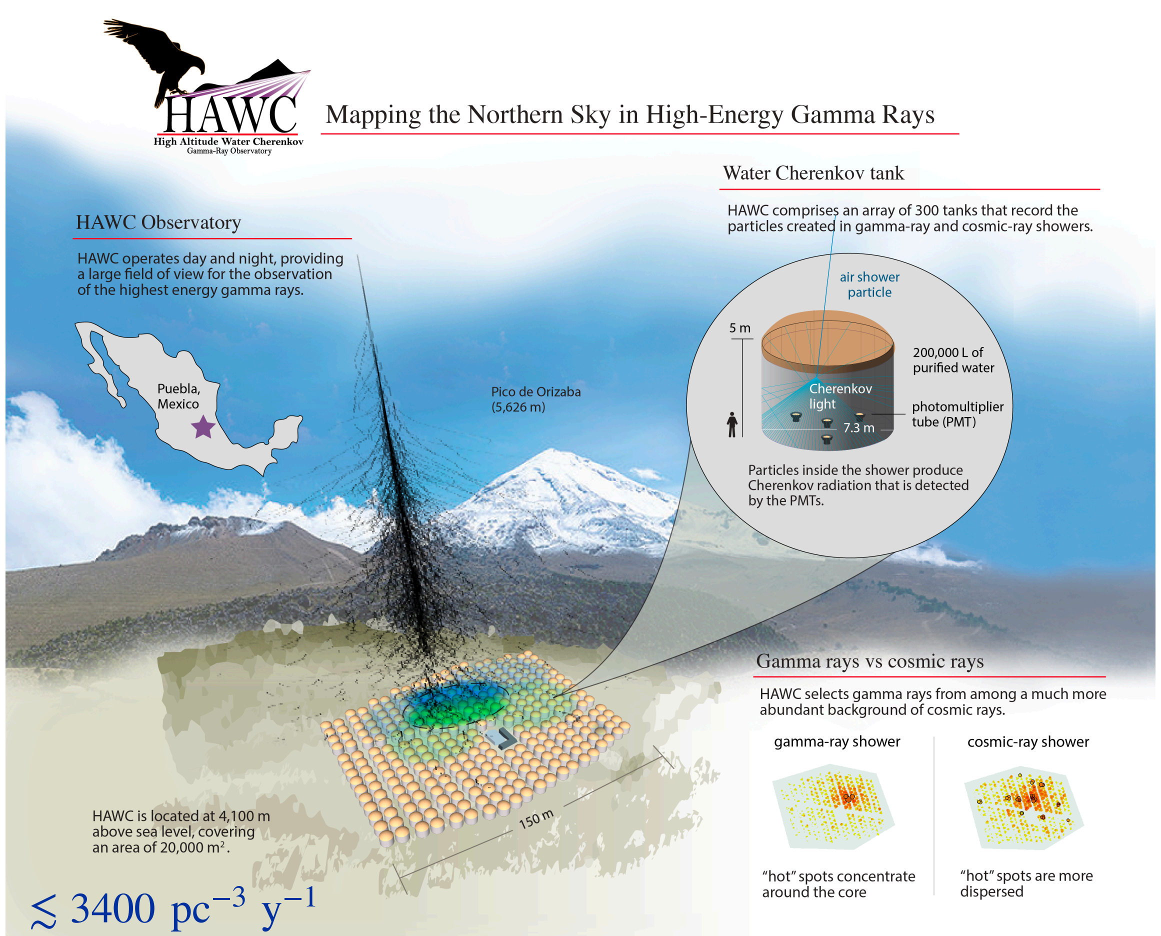
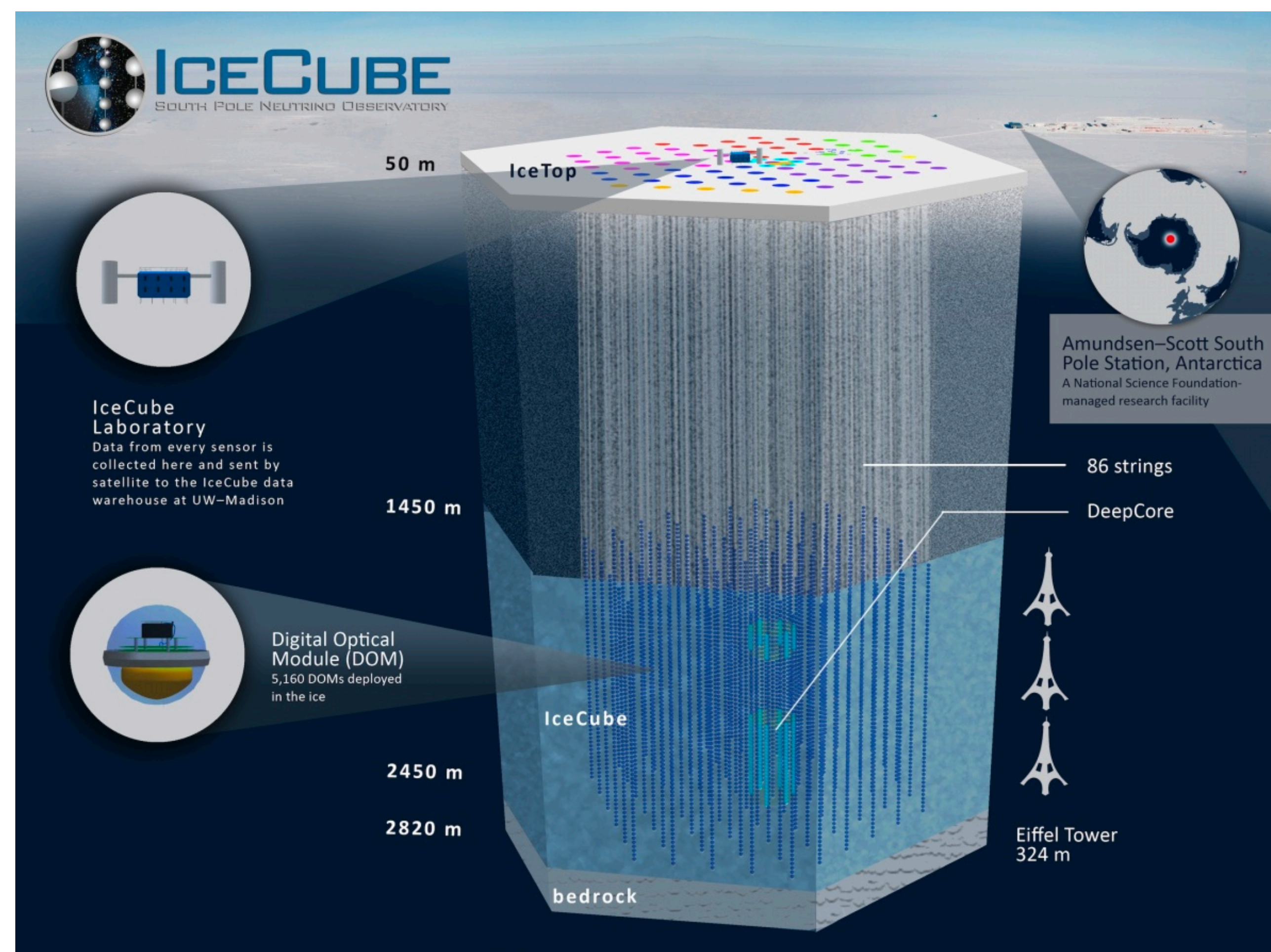
- If this occurs close to Earth, we could see γ, ν's, $e^{\pm}$



$\lesssim 3400\ {\rm pc}^{-3}\ {\rm y}^{-1}$



Evaporating PBHs (EPBH)

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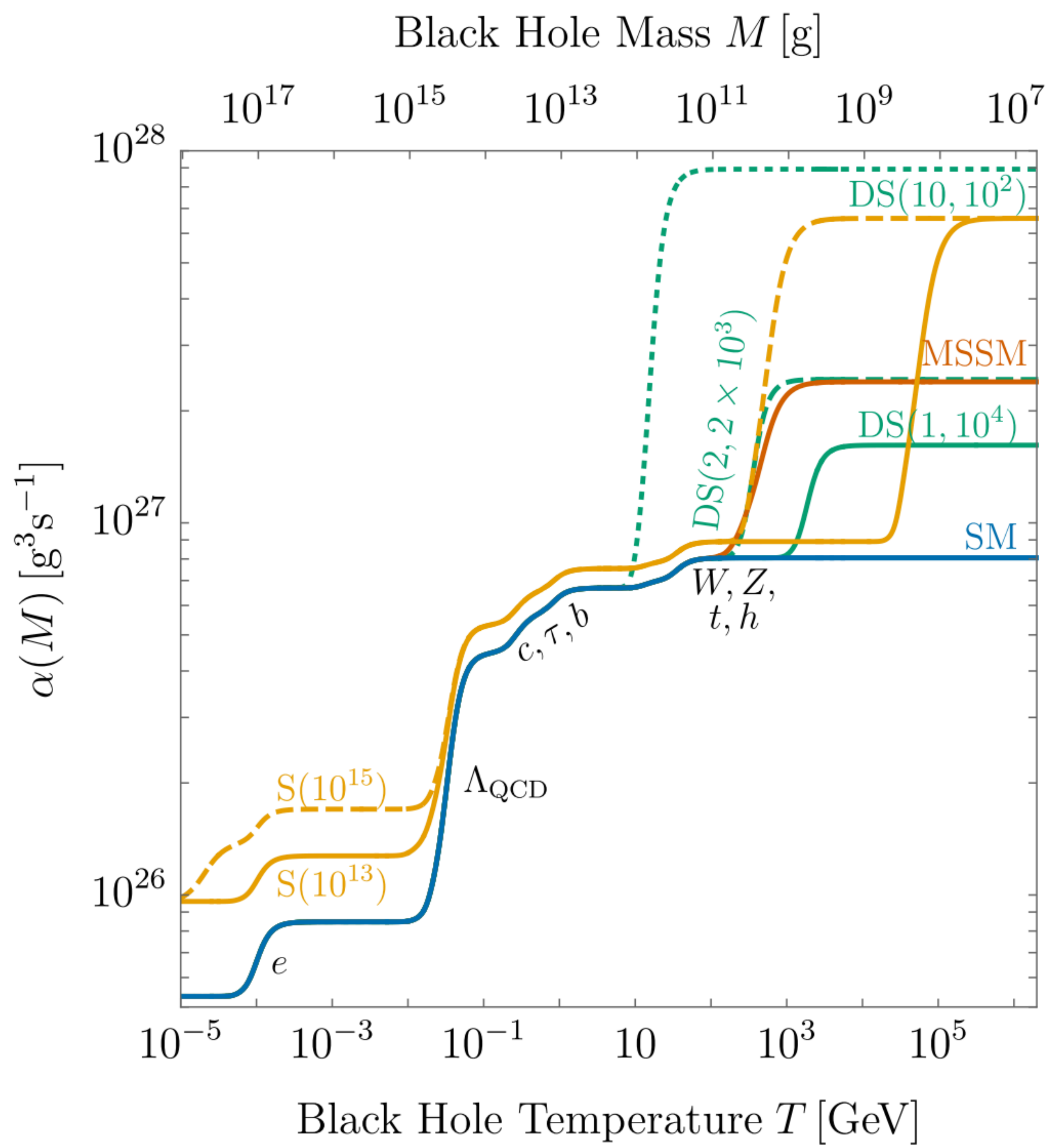
- Test BSM??

Baker, Thamm 2105.10506, 2210.02805



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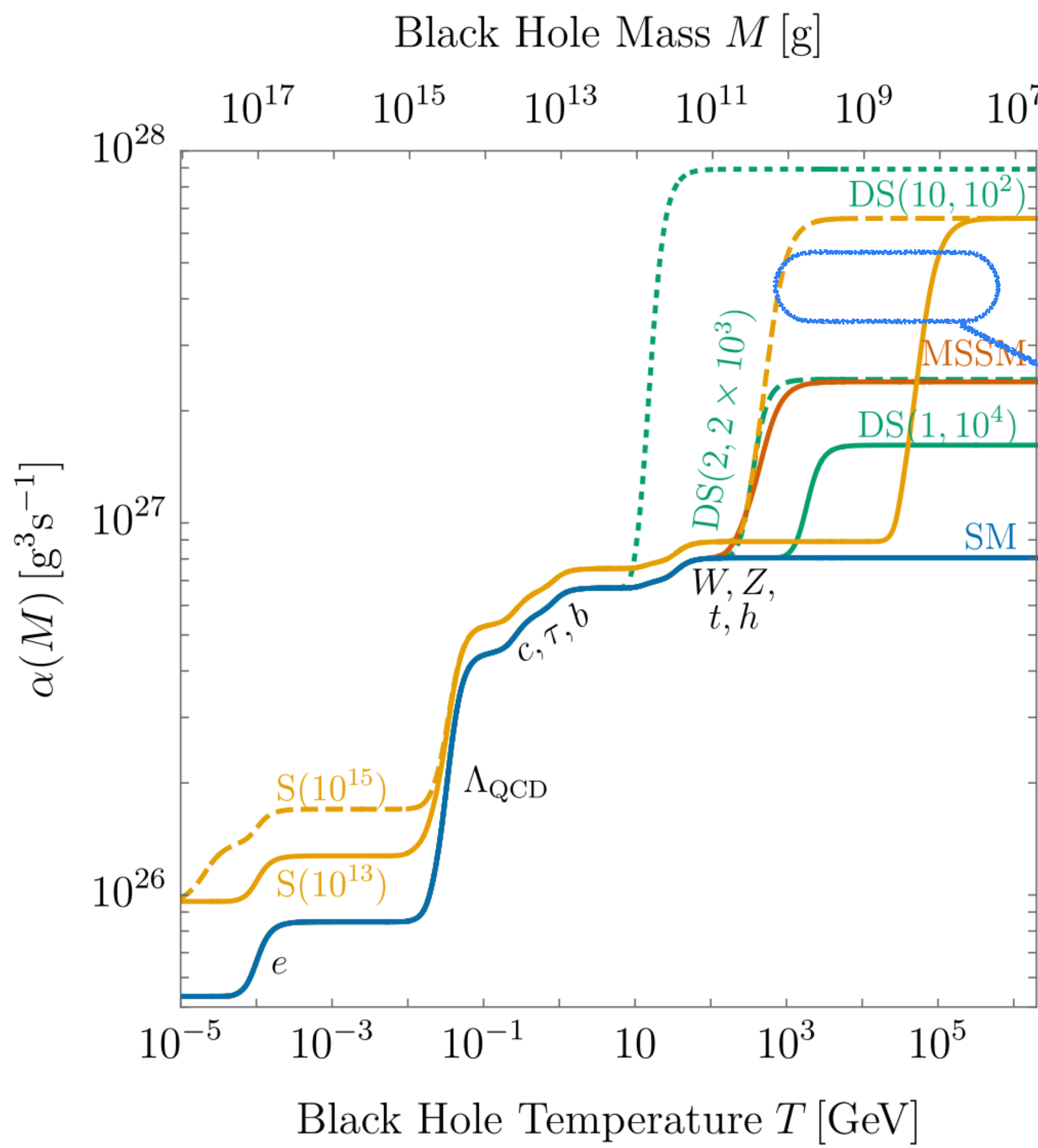

Different models at Higher Scales

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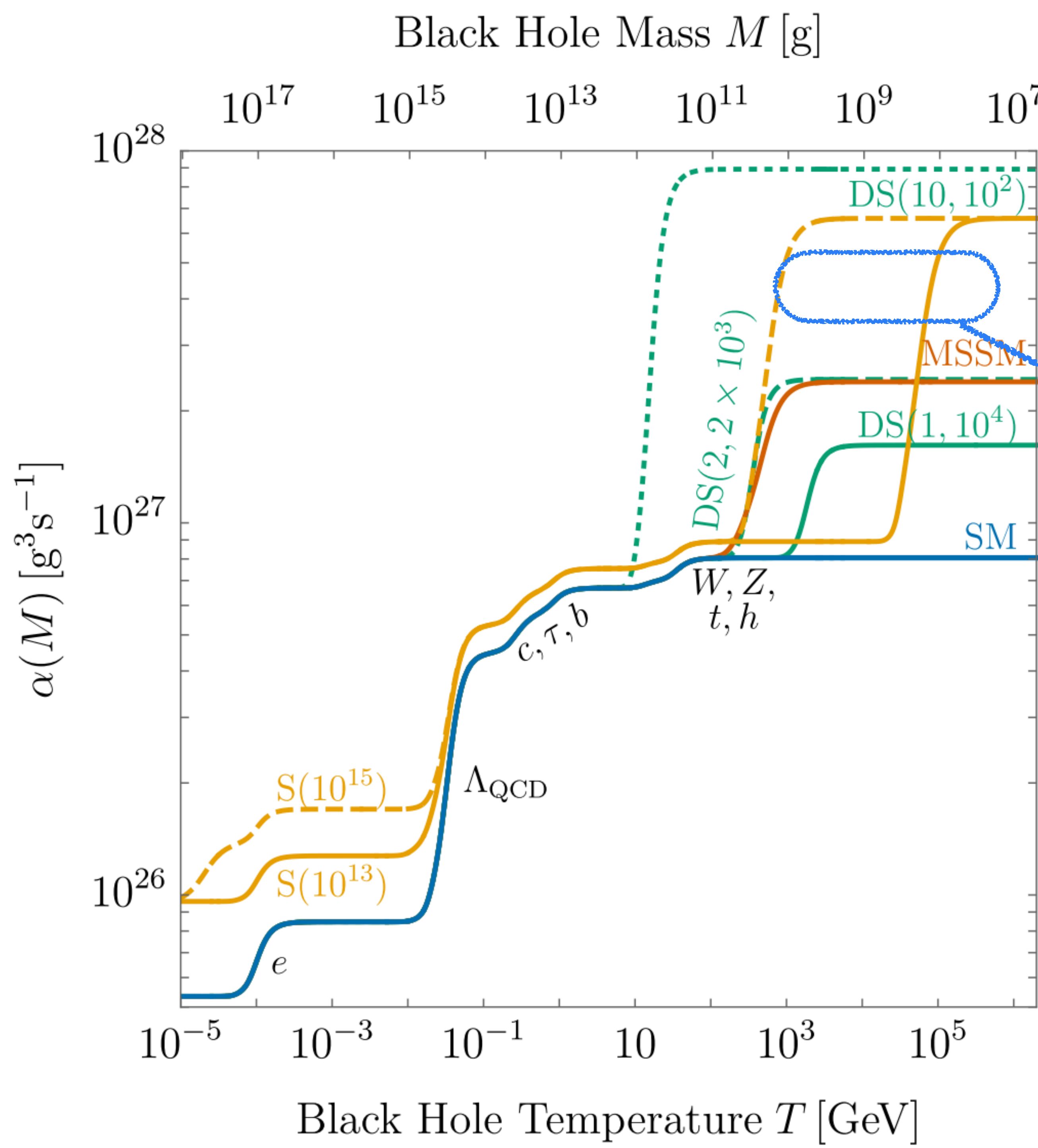
Baker, Thamm 2105.10506, 2210.02805



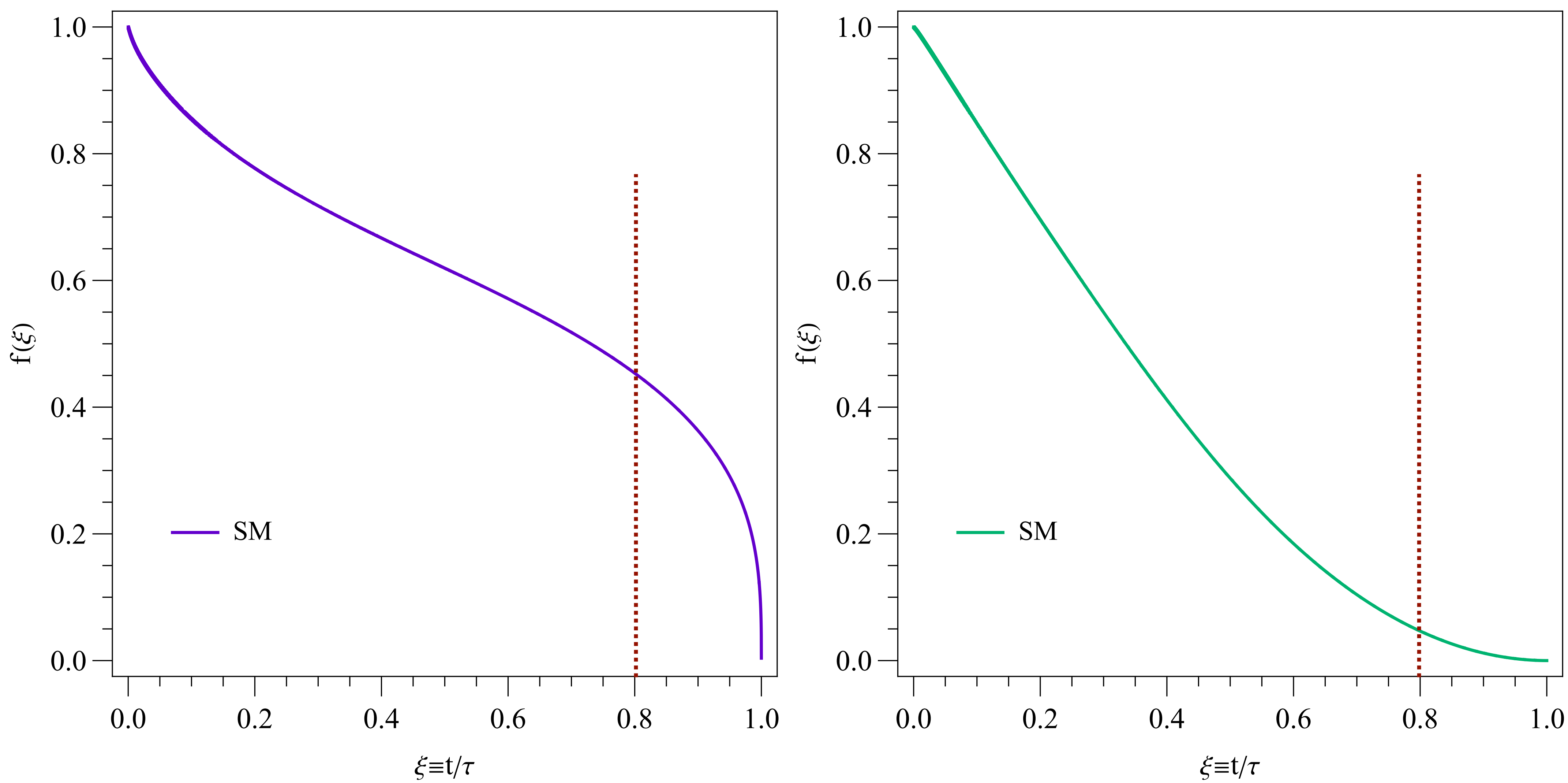
Different models at Higher Scales

Photon spectrum could tell us whether these dofs exist in nature

Anything to learn looking at neutrinos?

Kerr EPBHs

How could a PBH retain its spin until today?



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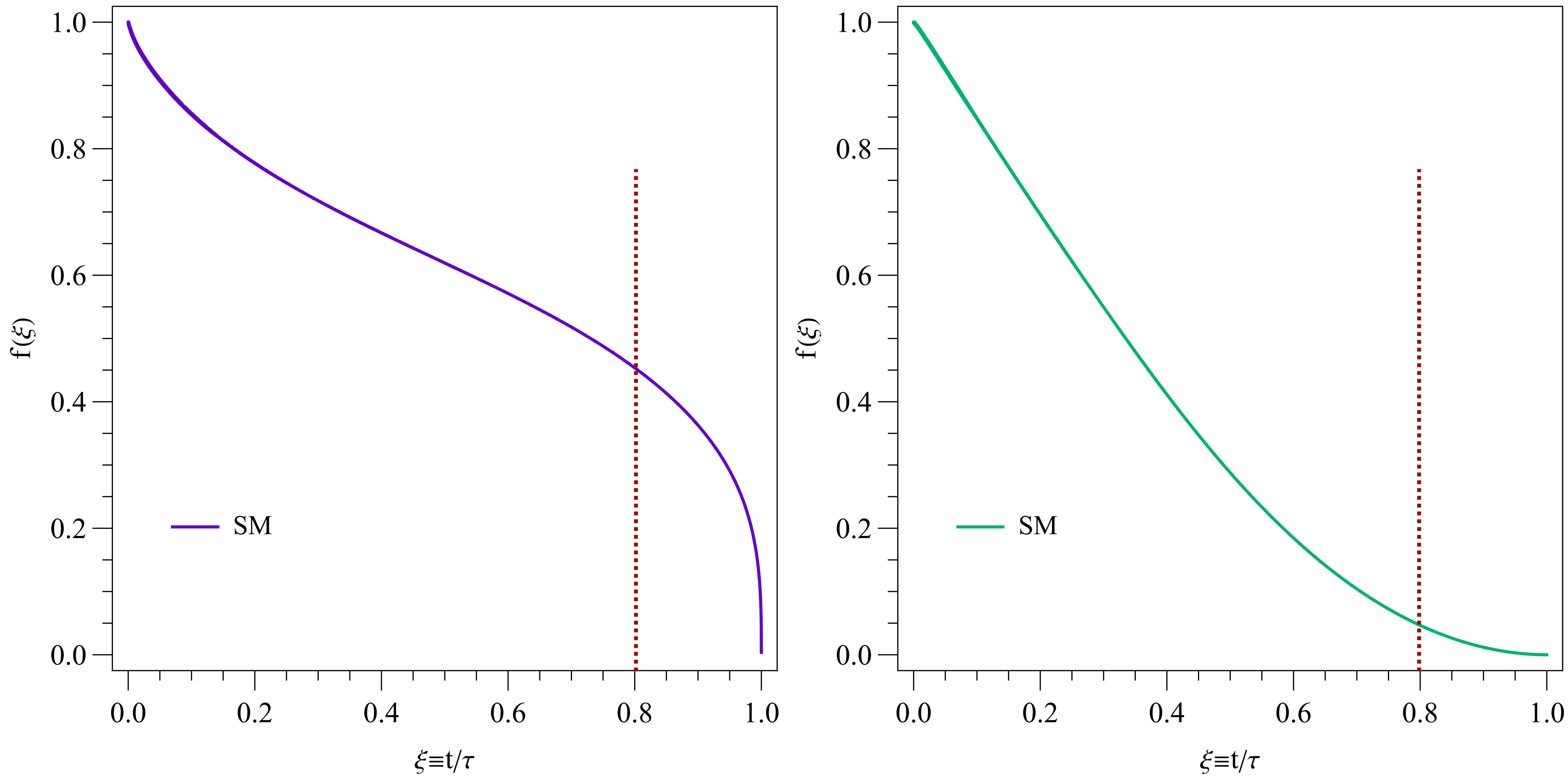
String Axiverse

Arvanitaki, et al, 0905.4720

Scalars only reduce the PBH mass



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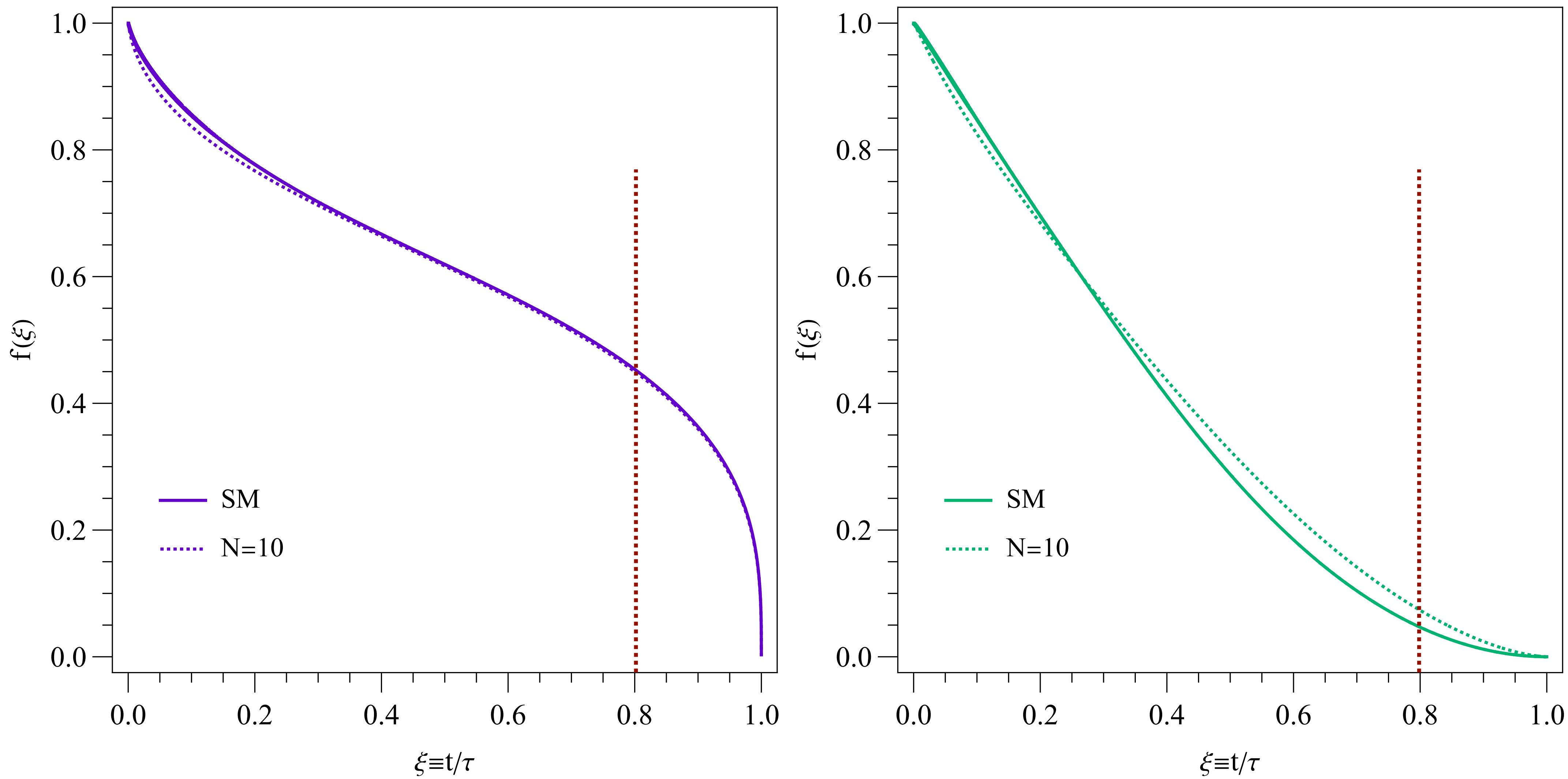

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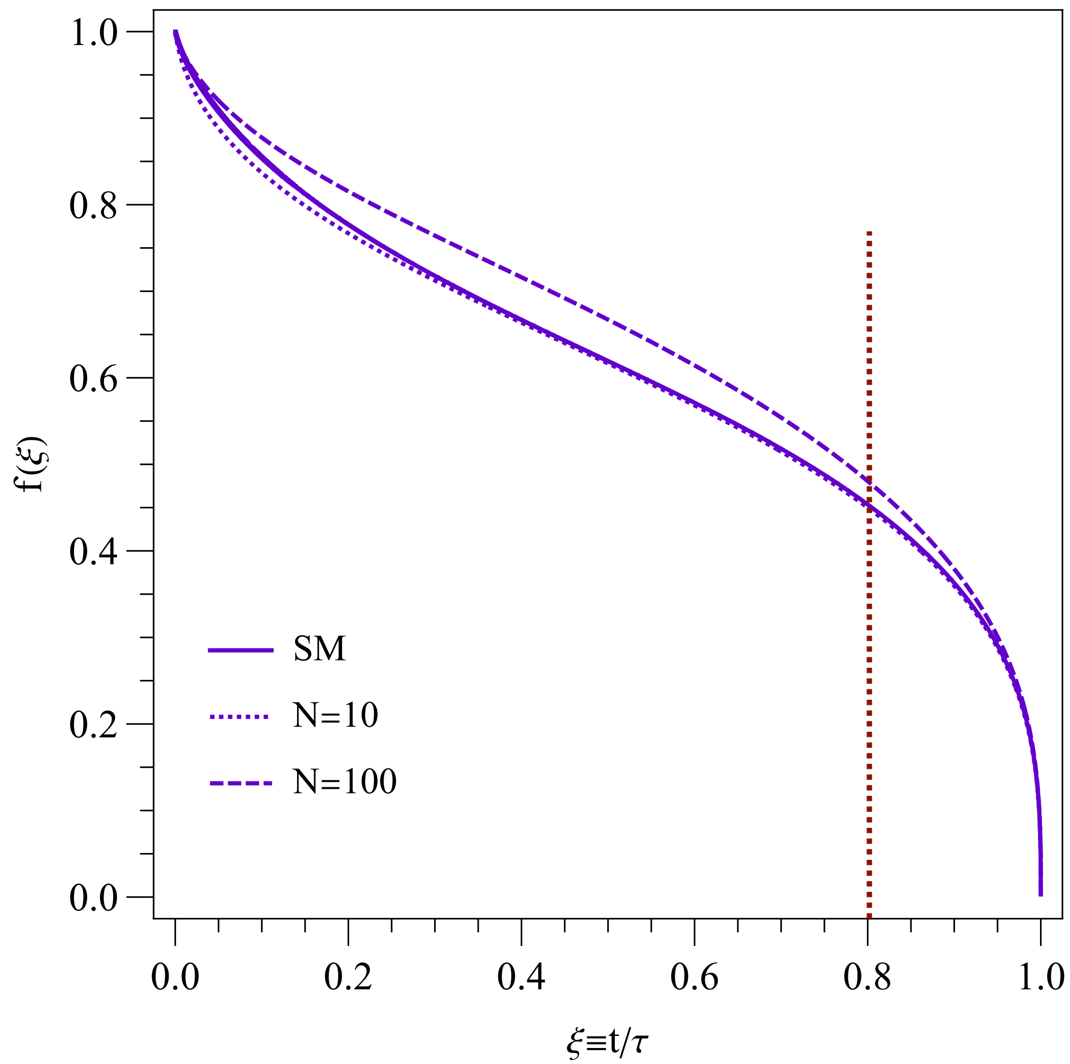

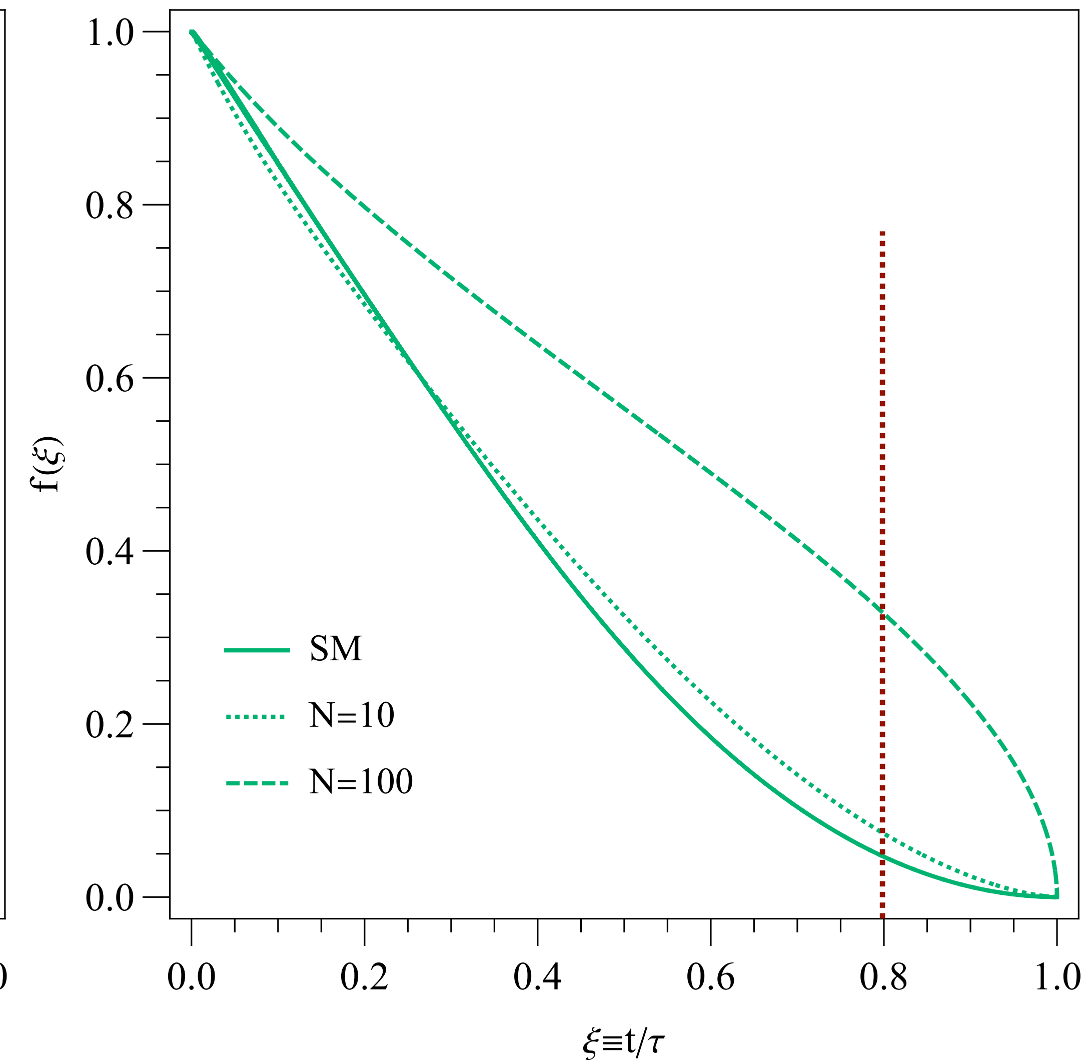

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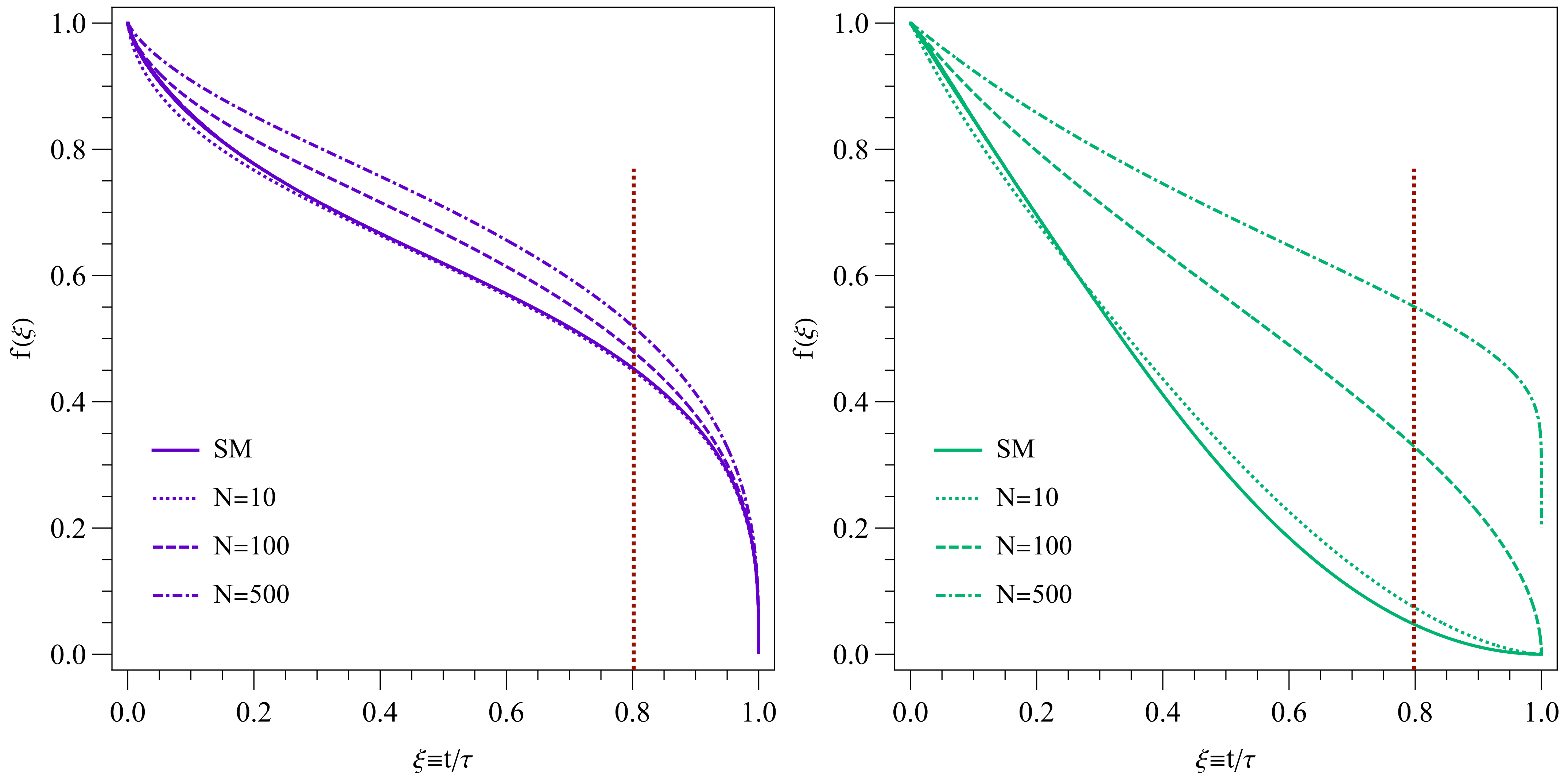

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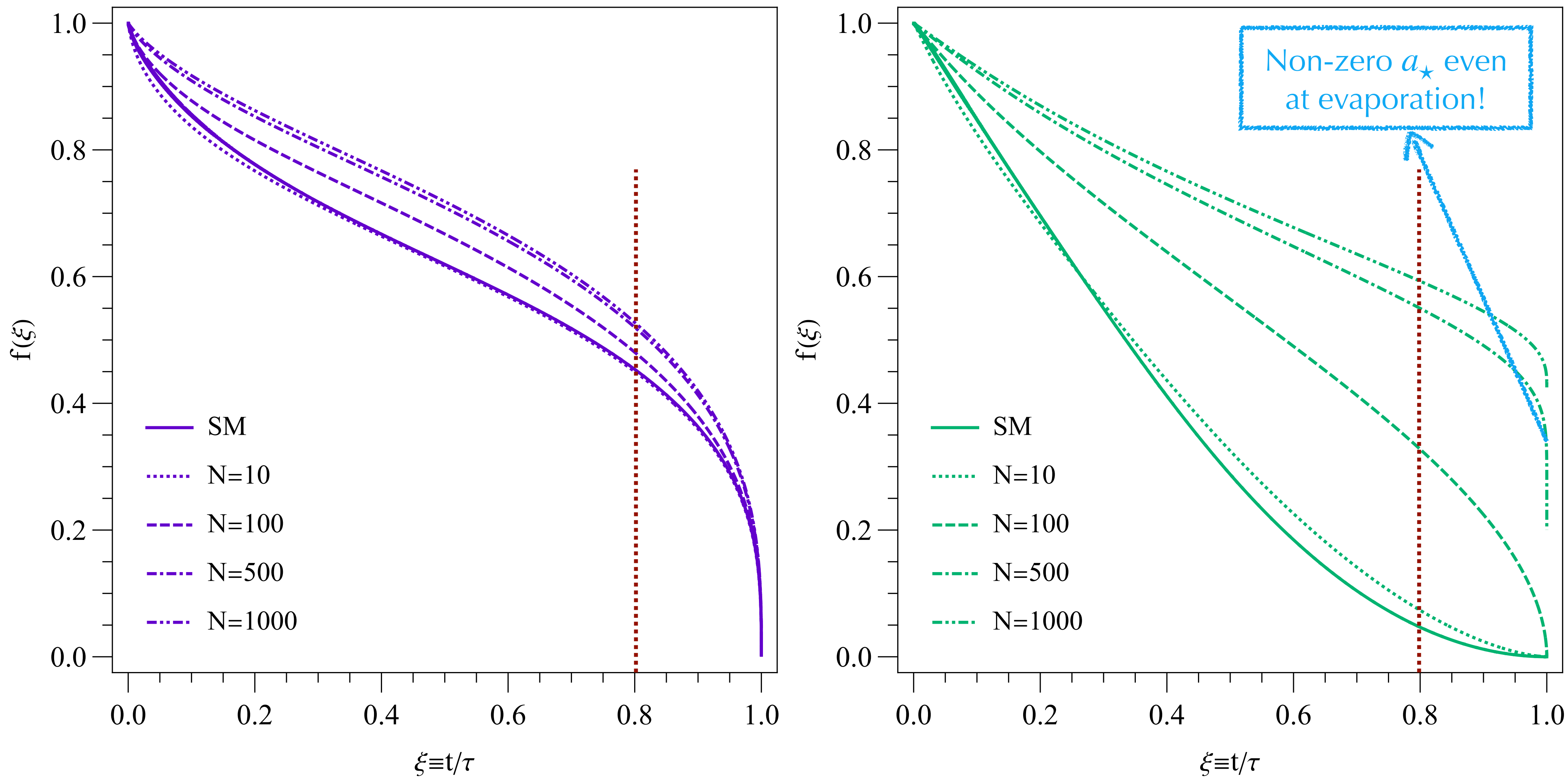

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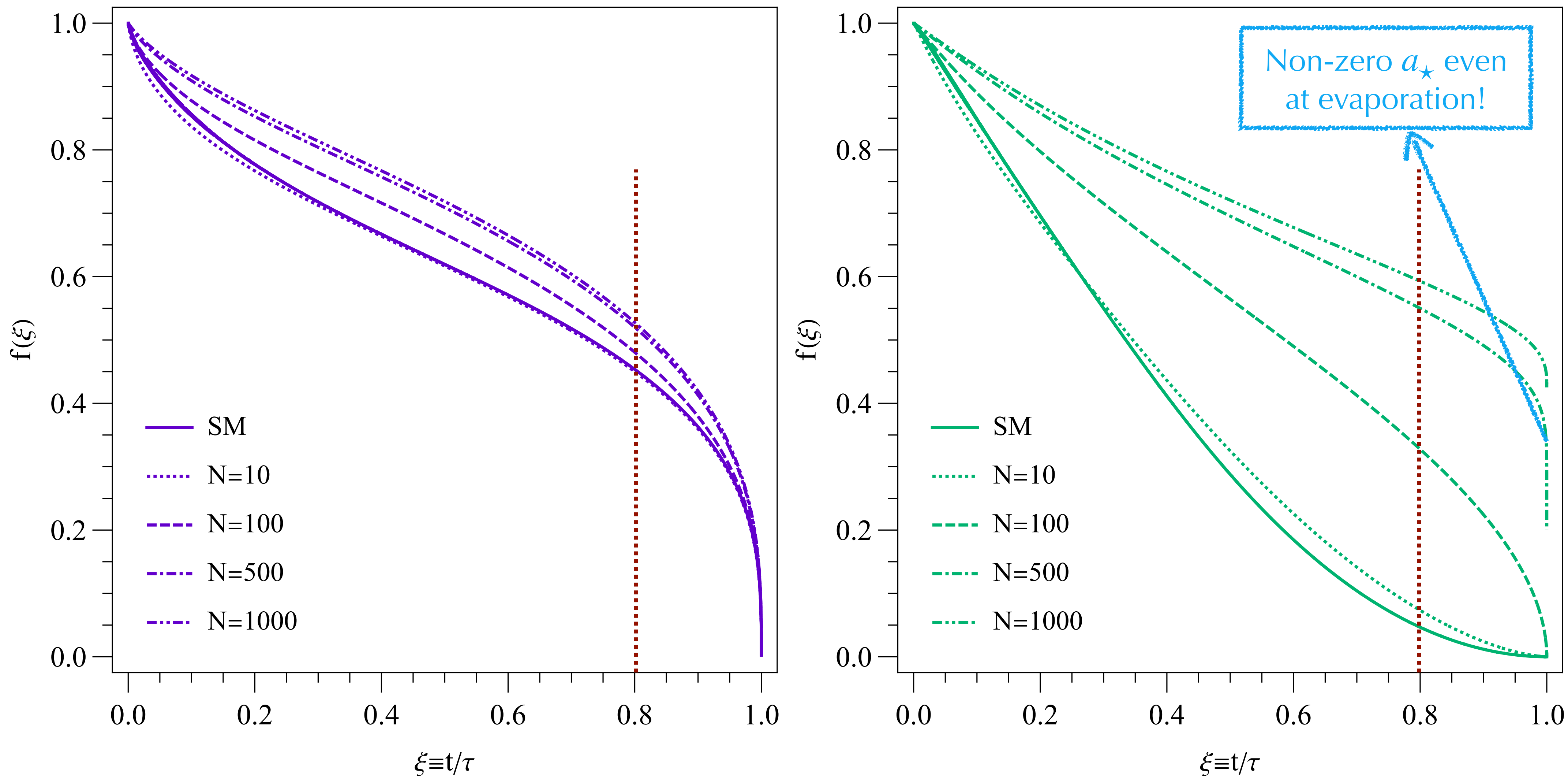

✤ How to measure the spin at the start of the burst?

Capanema et al, 2110.05637
Calzà, Rosa, 2210.06500

Photons dominate the measurement

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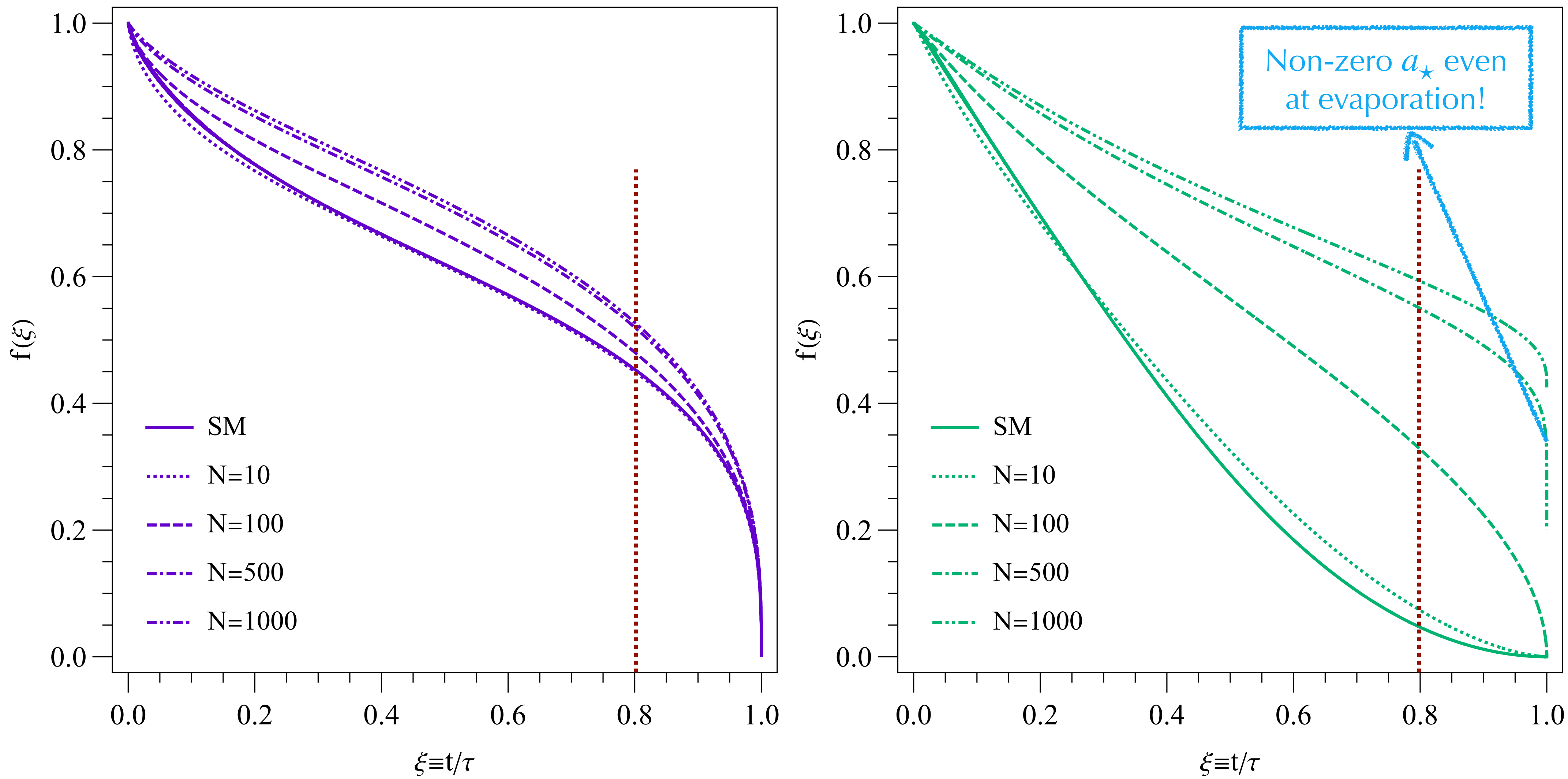

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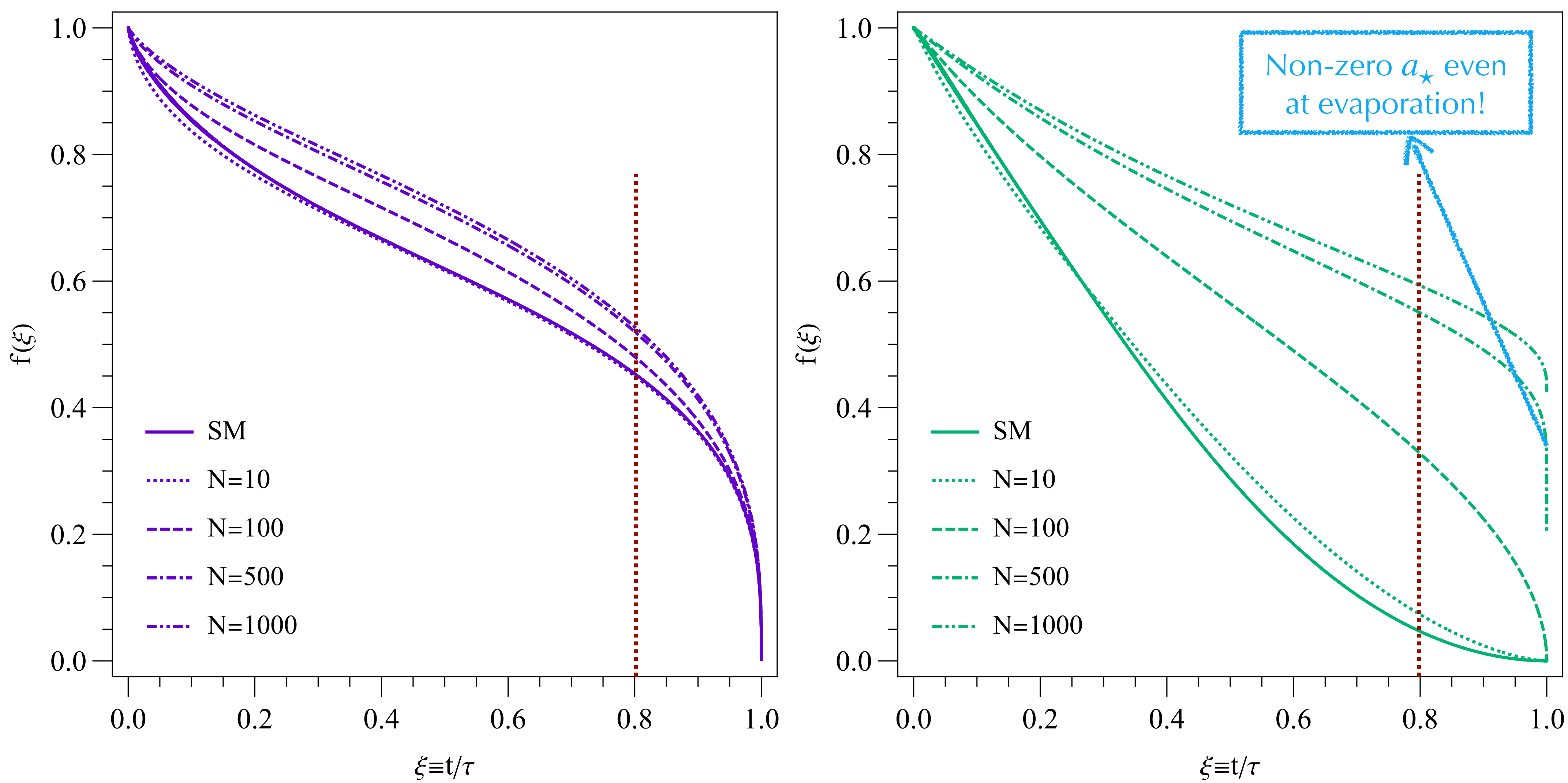

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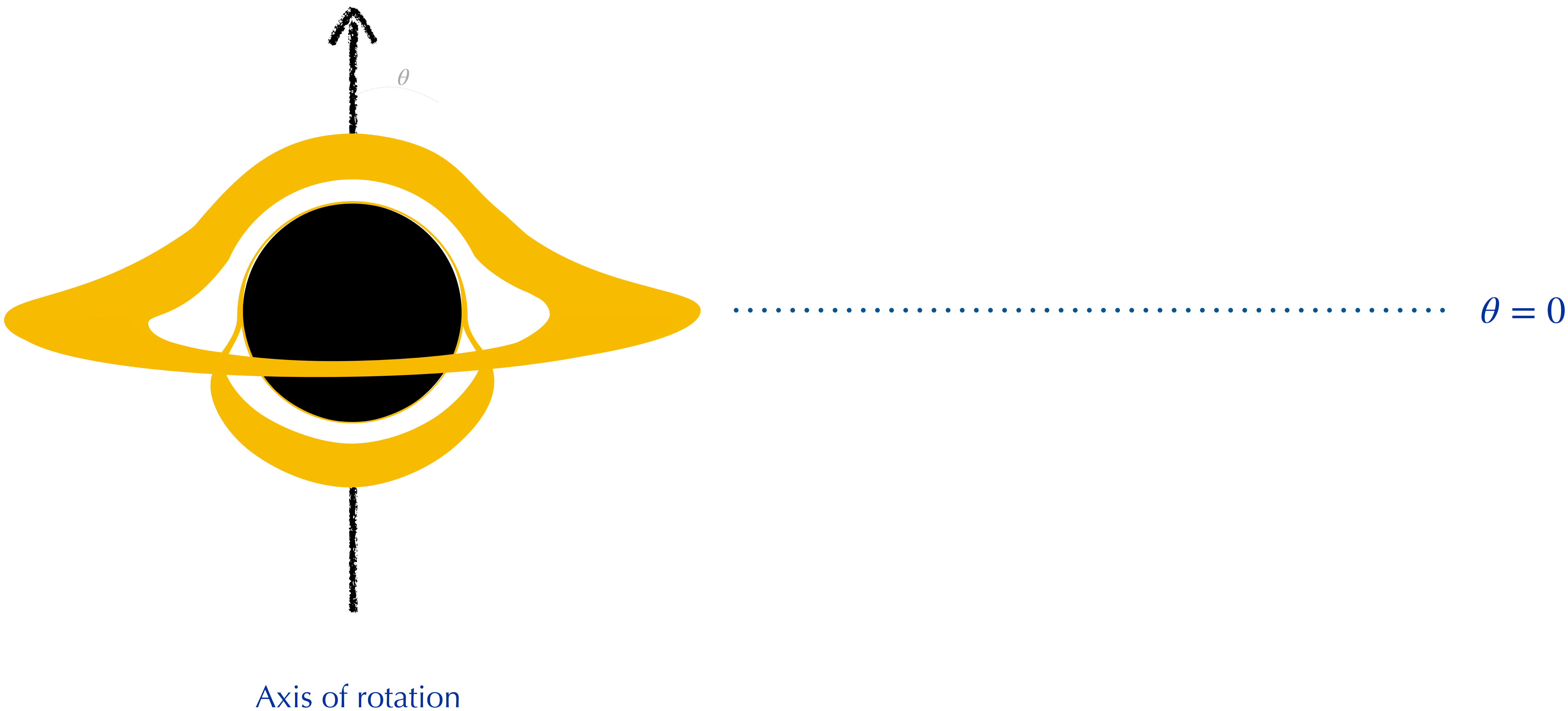
Parity Violation!!

How does it manifest in Hawking evaporation?

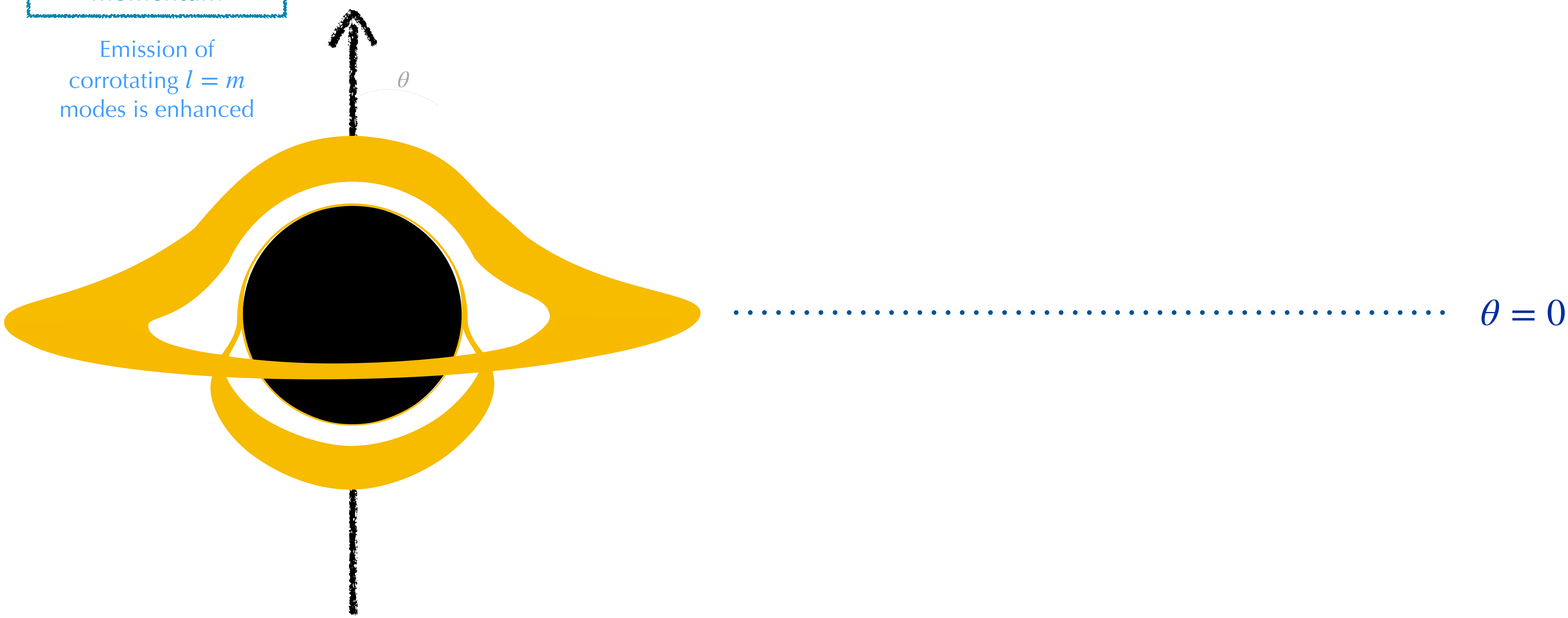
Neutrino Emission Asymmetry



Neutrino Emission Asymmetry

BH "wants" to shed off its angular momentum

Emission of corrotating $l = m$ modes is enhanced



Axis of rotation

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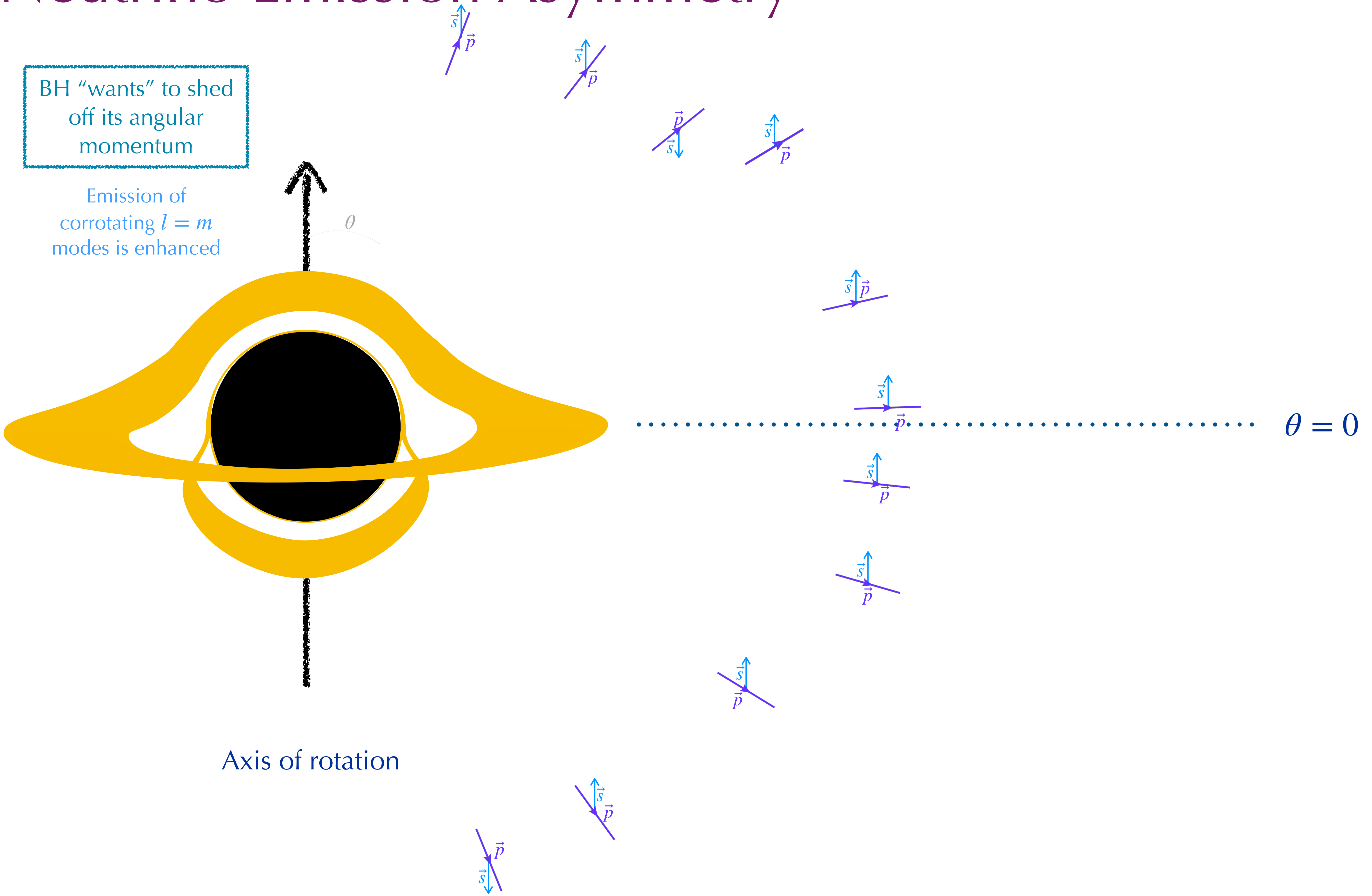

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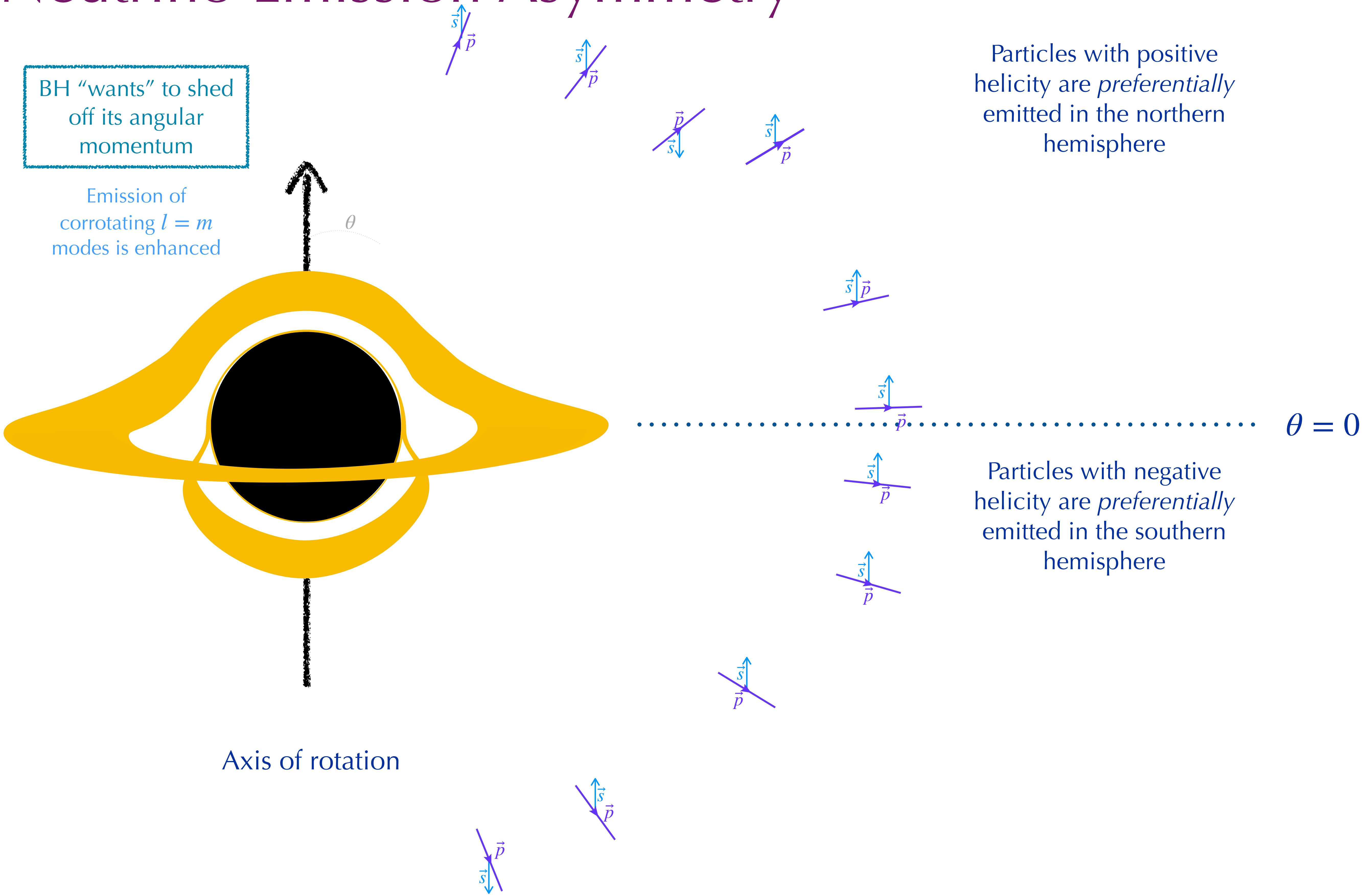

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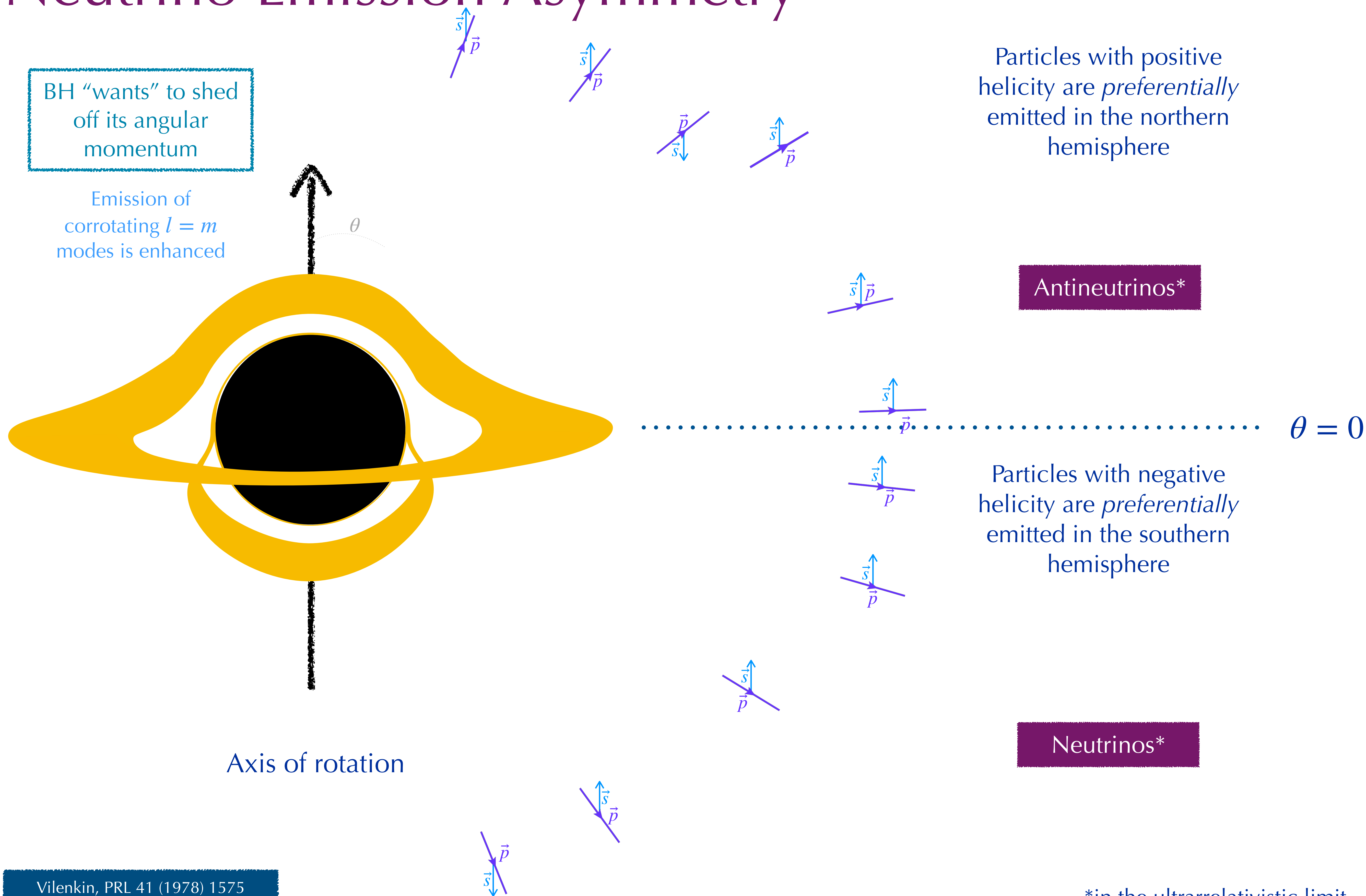

Axis of rotation

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

Antineutrinos*

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

Neutrinos*

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

*in the ultrarrelativistic limit

Neutrino Emission Asymmetry

$\theta \to$ polar angle

BH "wants" to shed off its angular momentum

$$\mathscr{A} \equiv N_\nu - N_{\bar{\nu}}$$

$$\frac{d^3\mathscr{A}}{d\omega dt d\Omega} = \frac{1}{4\pi} \sum_{l=1/2} \sum_{m=-l}^{l} \frac{{}_s\Gamma_{lm}}{\exp(\varpi/T)+1} \left\{ {}_{-\frac{1}{2}}S_{lm}(\theta)^{\,2} - {}_{+\frac{1}{2}}S_{lm}(\theta)^{\,2} \right\}$$

${}_{\pm\frac{1}{2}}S_{lm}(\theta) \to$ solutions of angular equation

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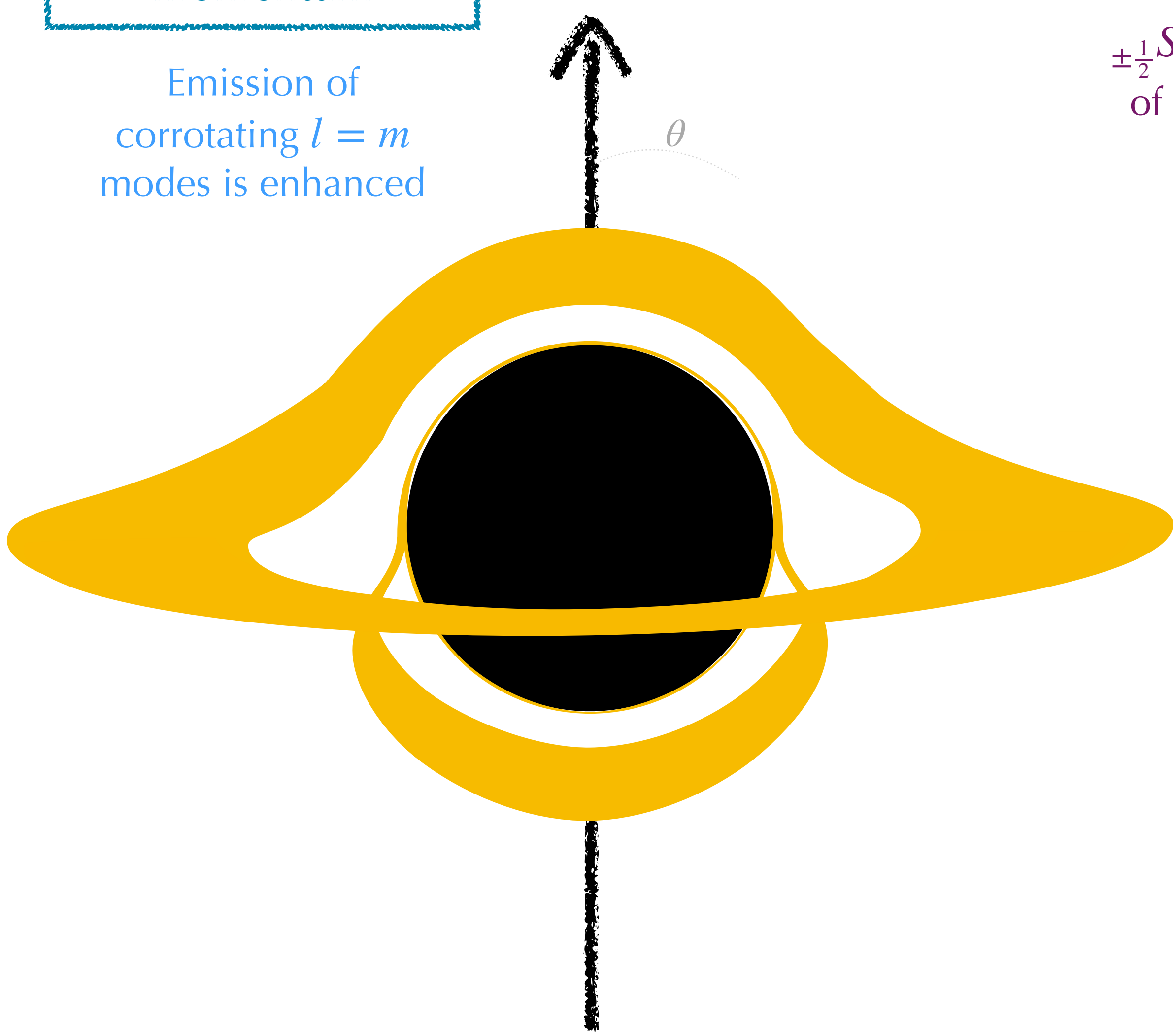

Axis of rotation

YFPG 2307.14408

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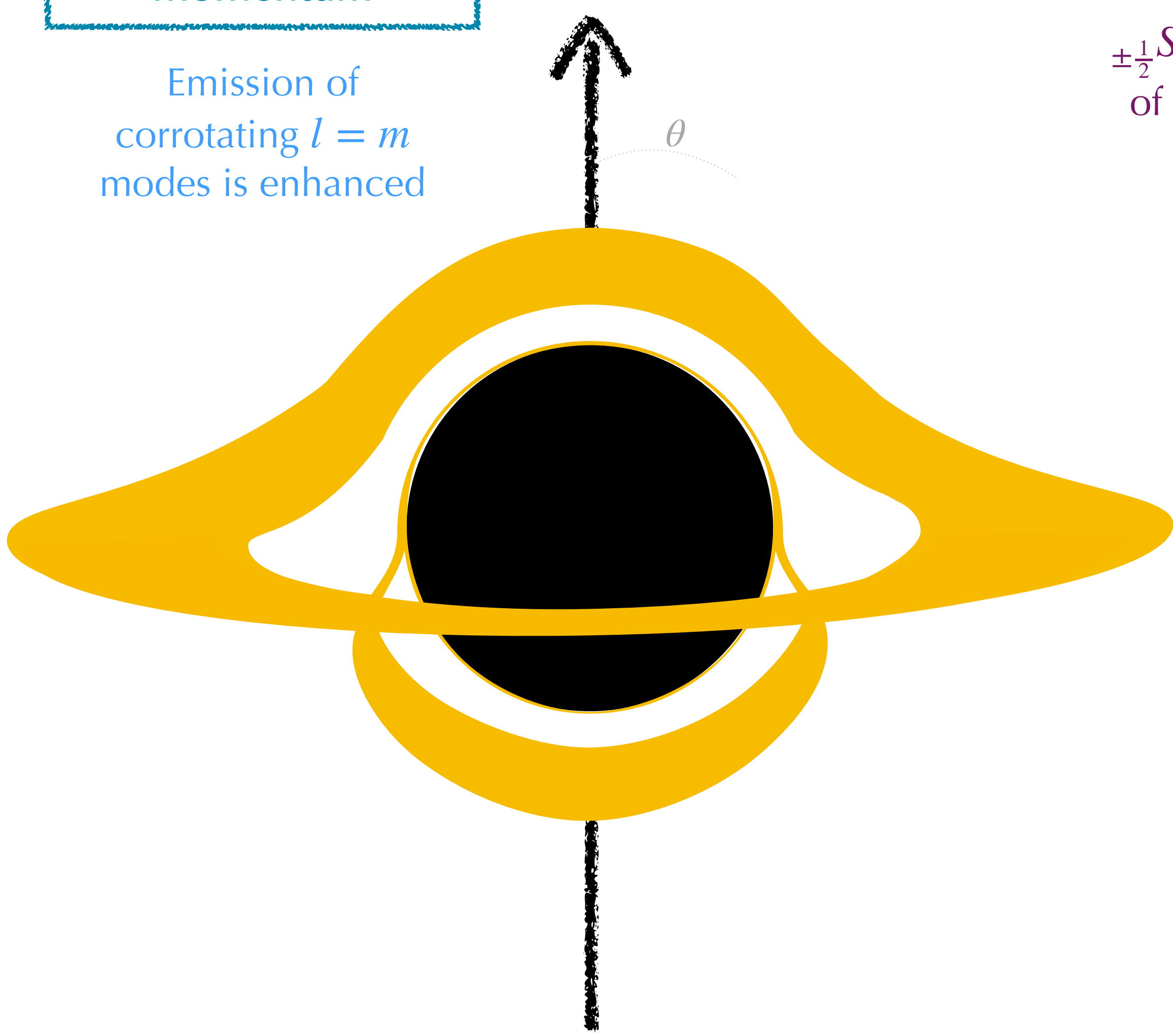

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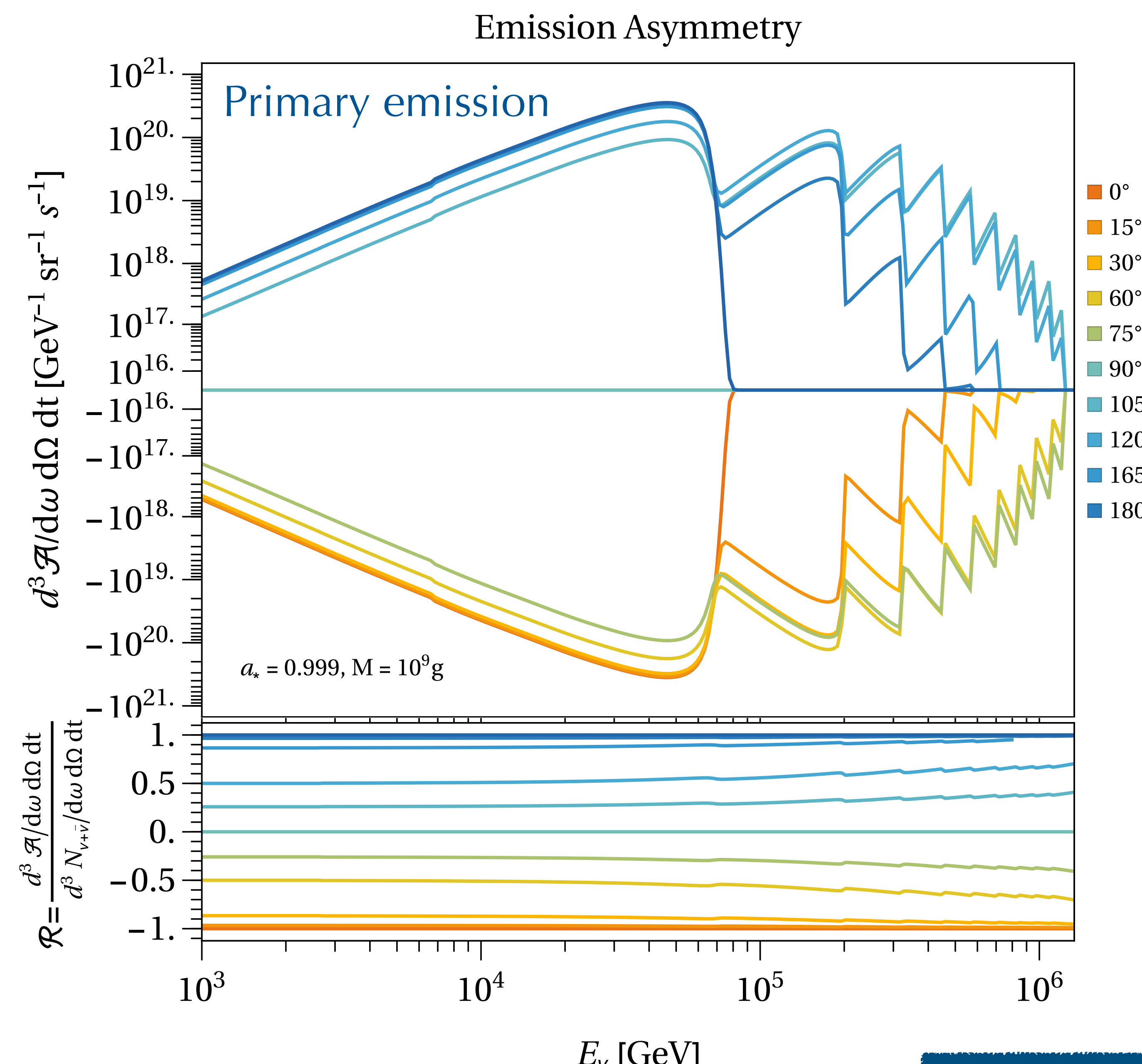

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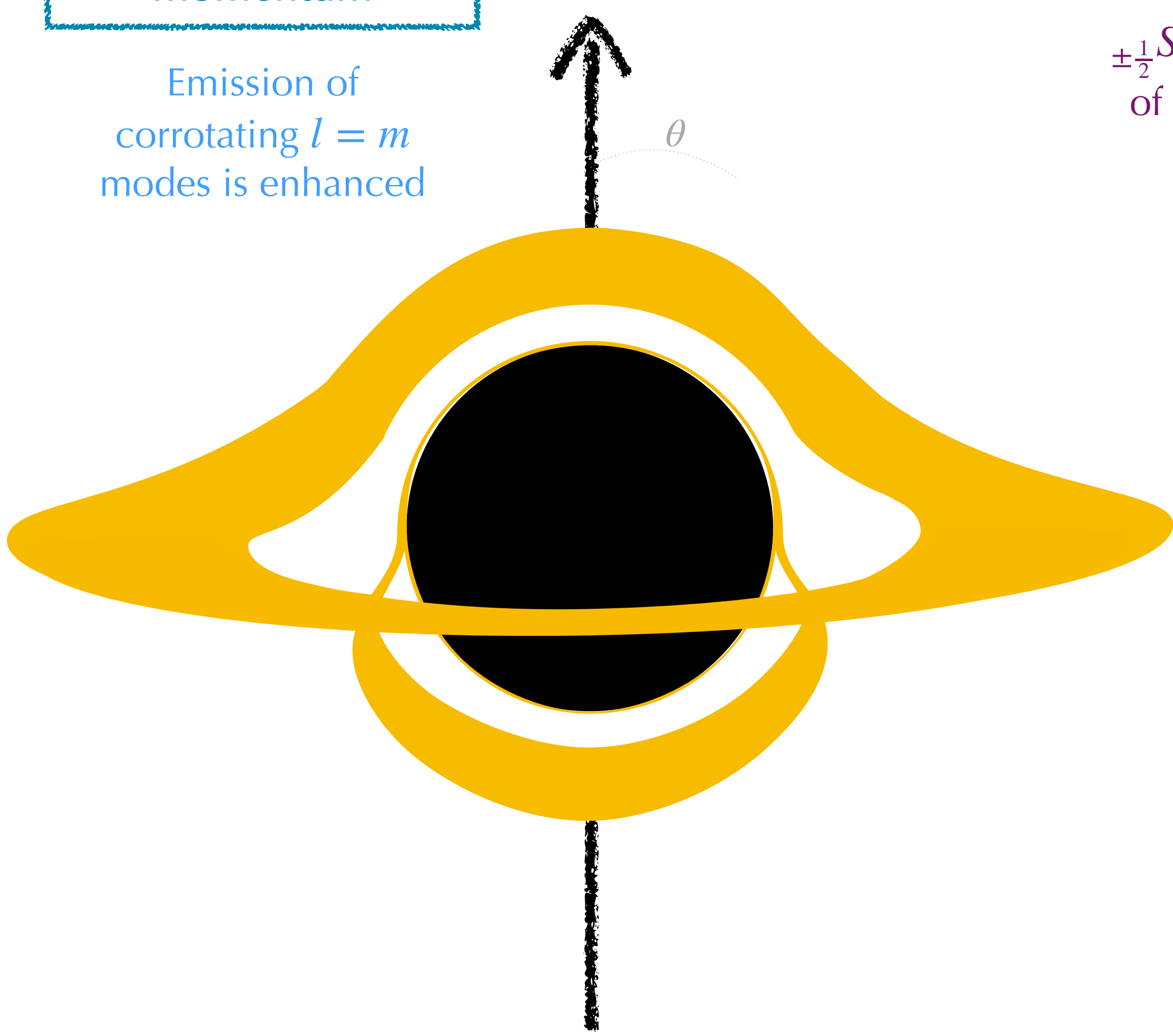

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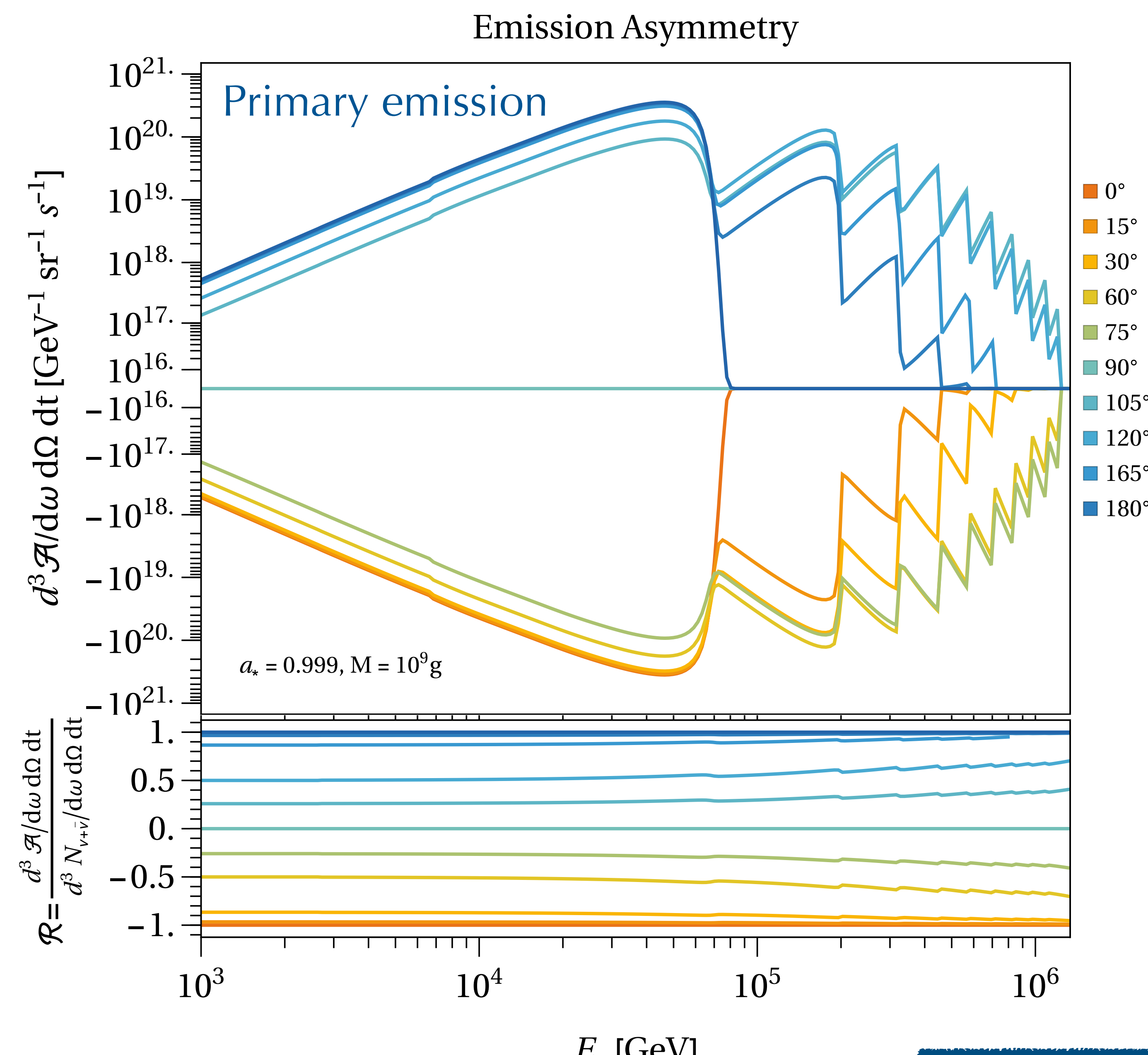


YFPG 2307.14408

Could neutrinos tell us the spin of a PBH?

Photons?

$\boxed{\text{BH “wants” to shed off its angular momentum}}$

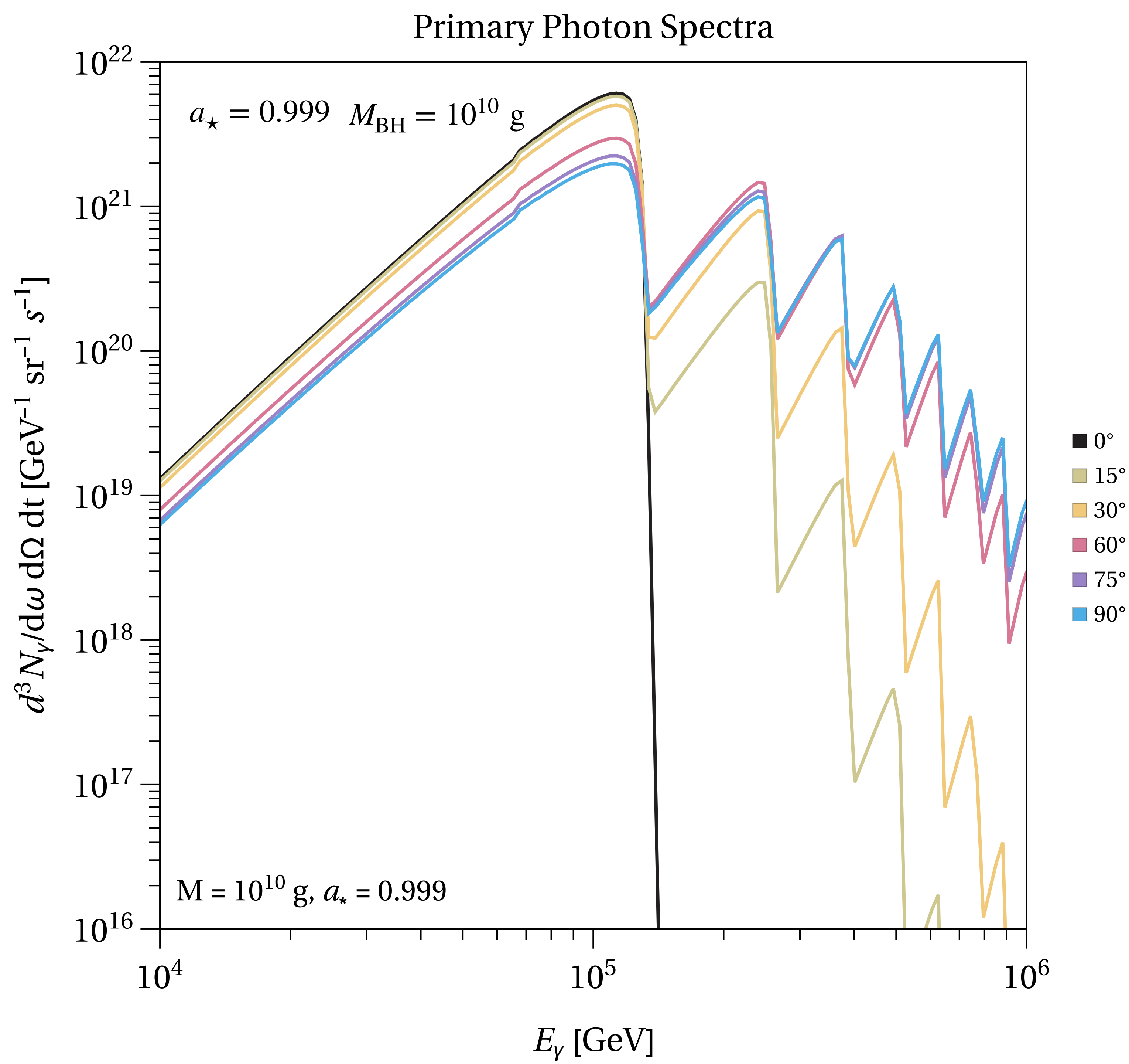
Emission of corrotating $l = m$ modes is enhanced

Photons?

BH "wants" to shed off its angular momentum → Emission of higher spin particles is enhanced

Emission of corrotating $l = m$ modes is enhanced

Also dependent on the polar angle



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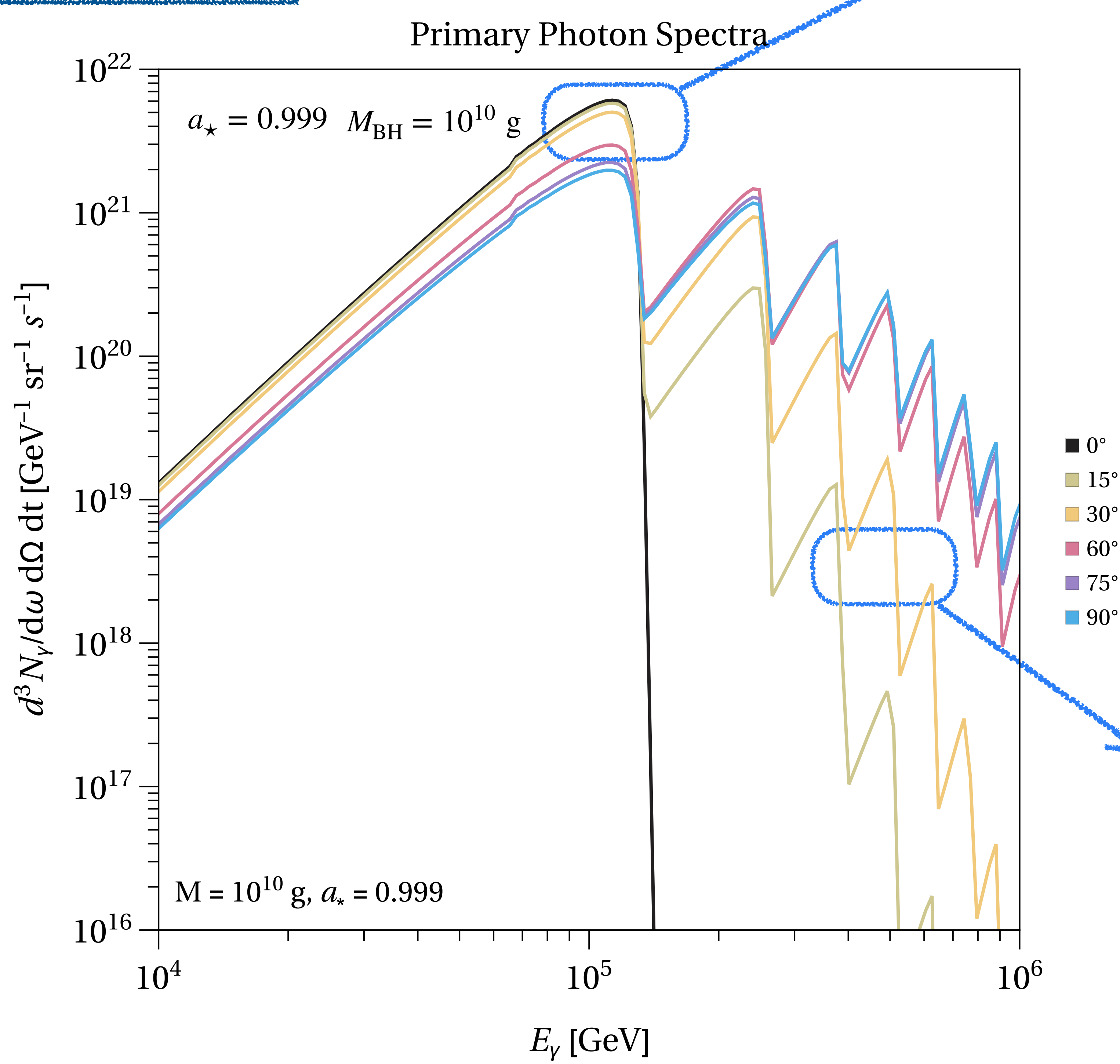

In the poles only $l = 1$ contribute

Modes start to contribute for larger θ

Photons?

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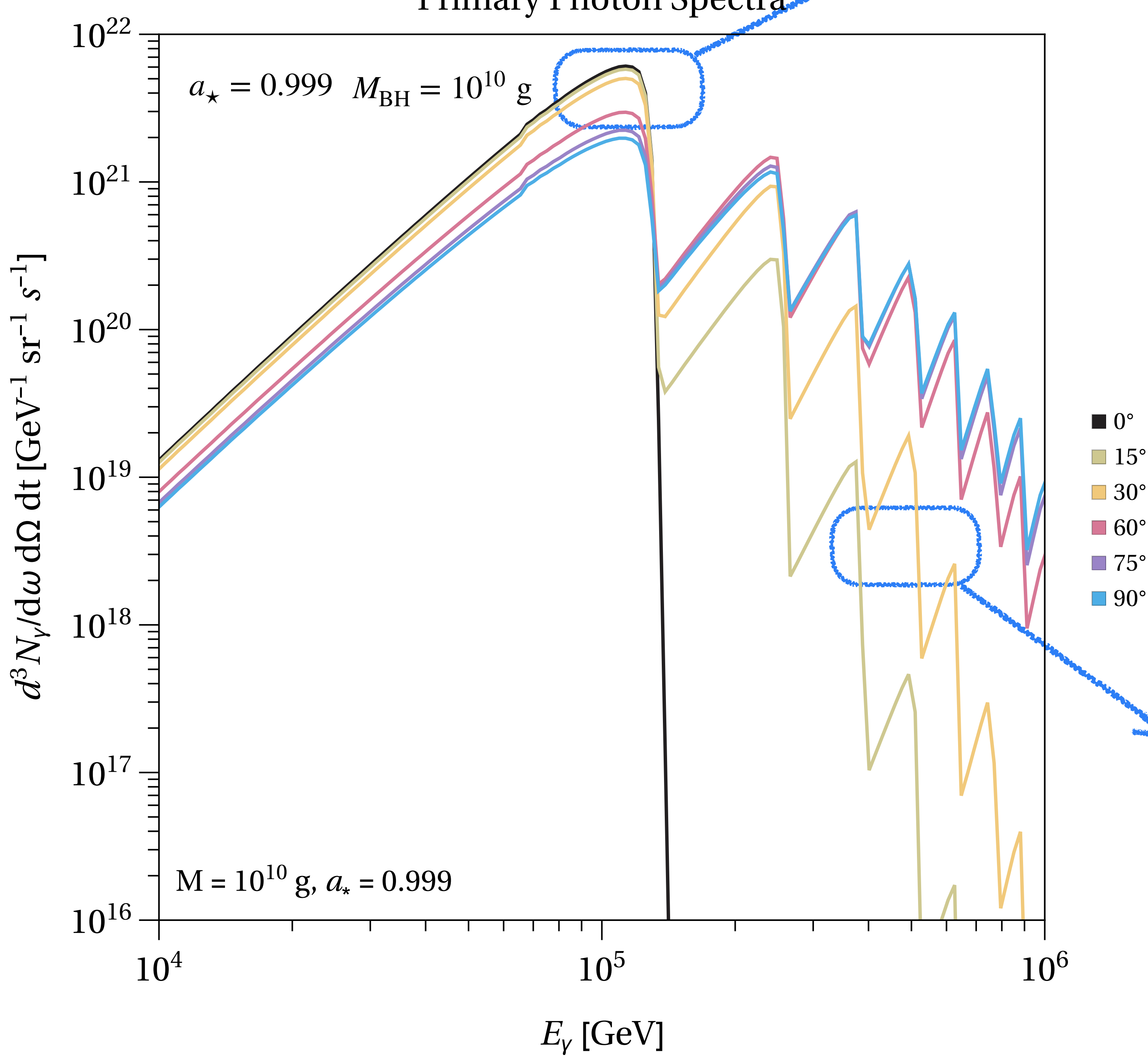
Also dependent on the polar angle

Symmetric under $\theta \to \pi - \theta$

We can't tell which is the EPBH hemisphere facing Earth



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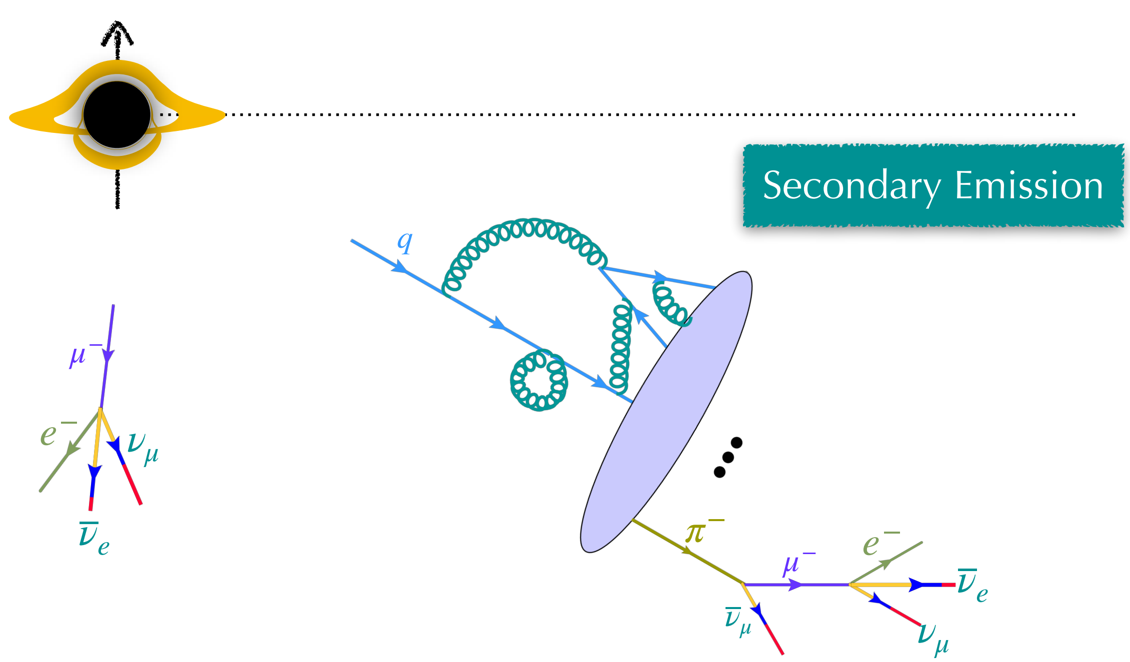
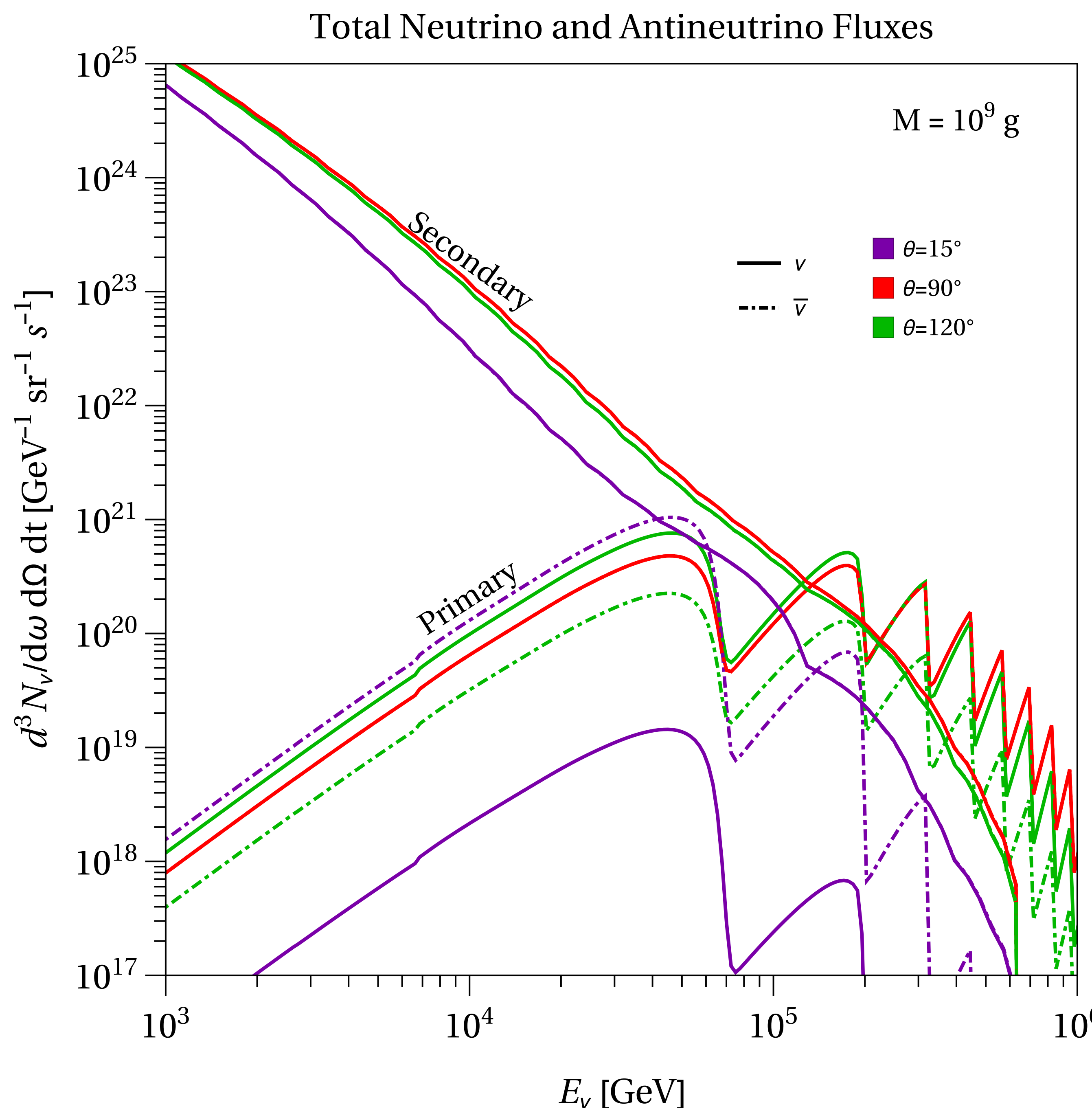
Secondaries?

$$\frac{d^3N^{\rm sec}_{\nu(\gamma)}}{d\omega dt d\Omega} = \int_0^\infty d\omega' \int d\Omega' \sum_i \frac{d^3N_i}{d\omega' dt d\Omega'} \frac{d^2 n_{i\to\nu(\gamma)}}{d\omega d\Omega}$$

$\frac{d^2 n_{i\to\nu(\gamma)}}{d\omega d\Omega}$ → energy and angular distribution of neutrinos/photons → Pythia





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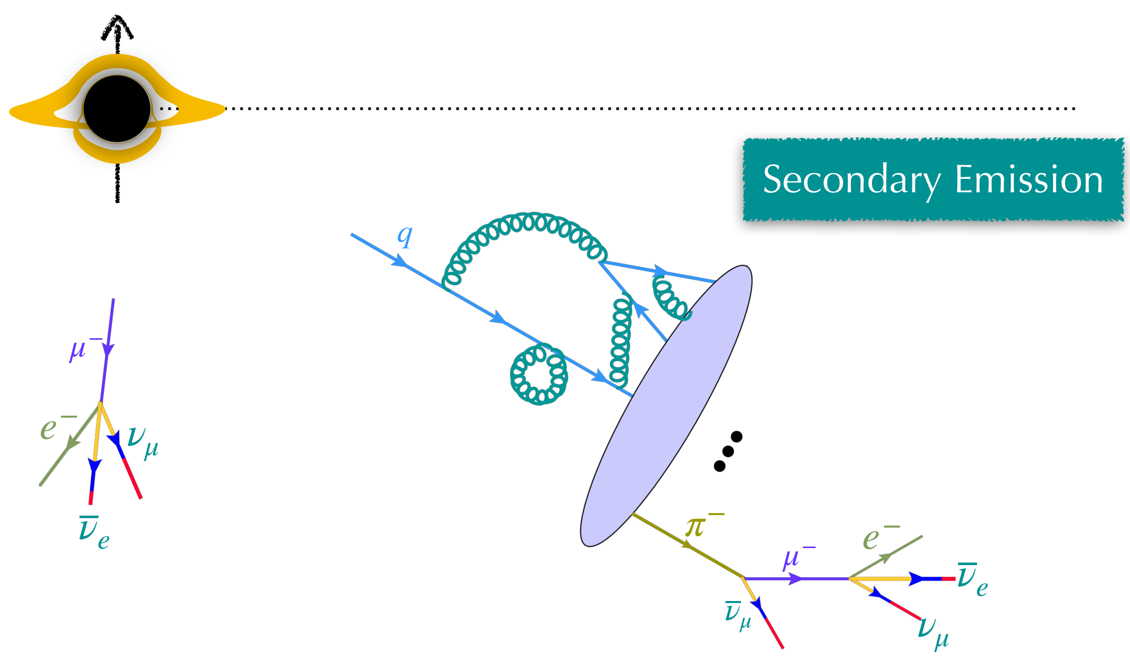
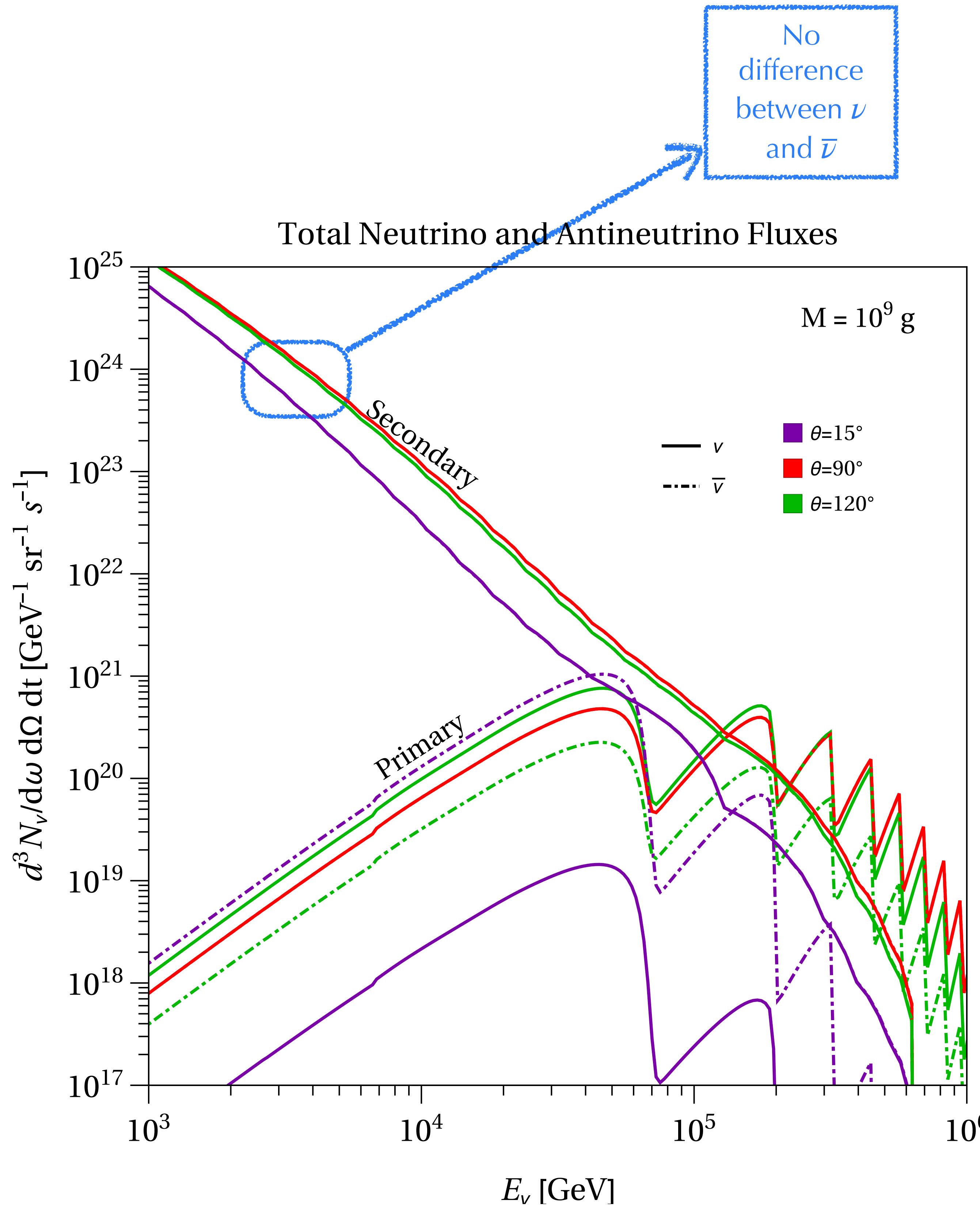
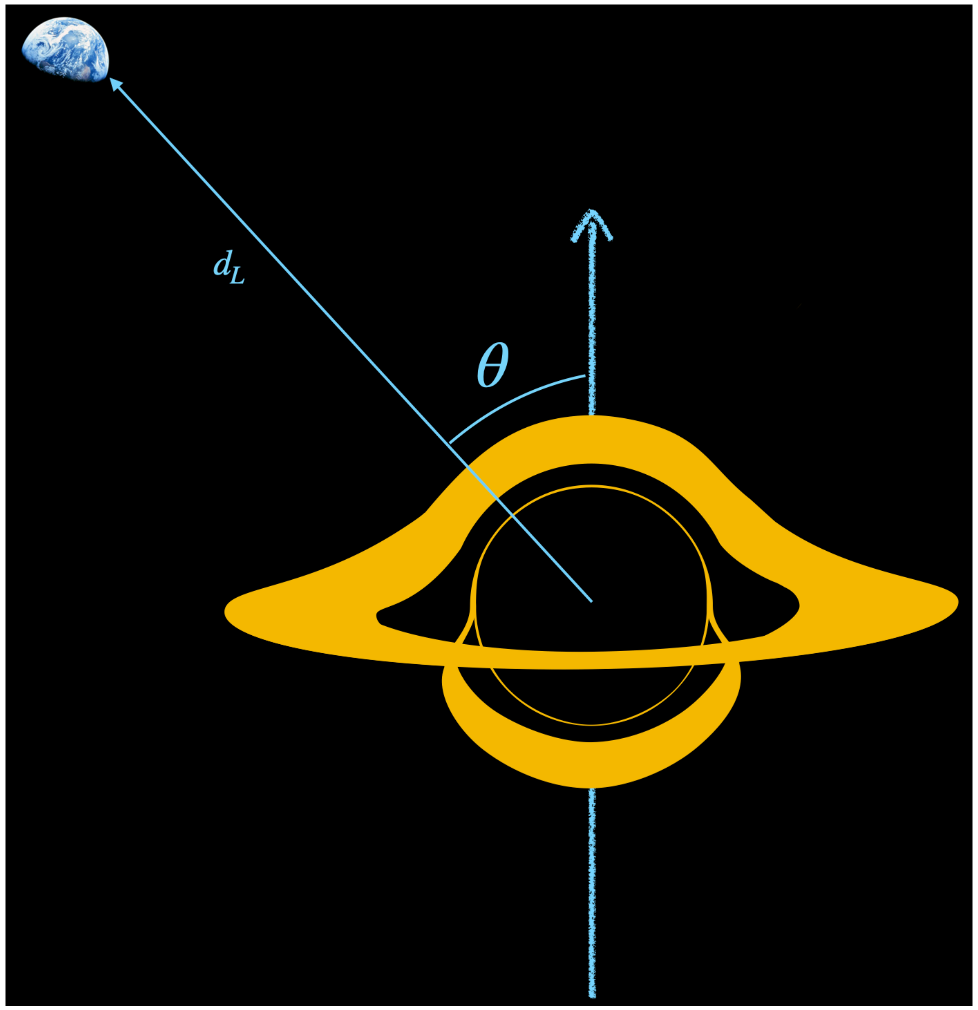




Determining the angular momentum

Previous works ignored the dependence on θ

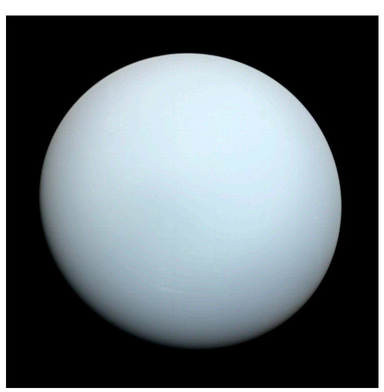
Neutrino - antineutrino events will depend on θ



$$N_X(\theta) = \frac{1}{d_L^2}\int_{\omega_{\min}}^{\omega_{\max}}\int_0^{\tau} dt\,\frac{d^3N_X}{d\omega dt d\Omega}\,A_{\rm eff}(\omega,\zeta)\,d\omega$$

$$X = \nu_\mu, \overline{\nu_\mu}, \gamma$$

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



Uranus - Sun

YFPG 2307.14408

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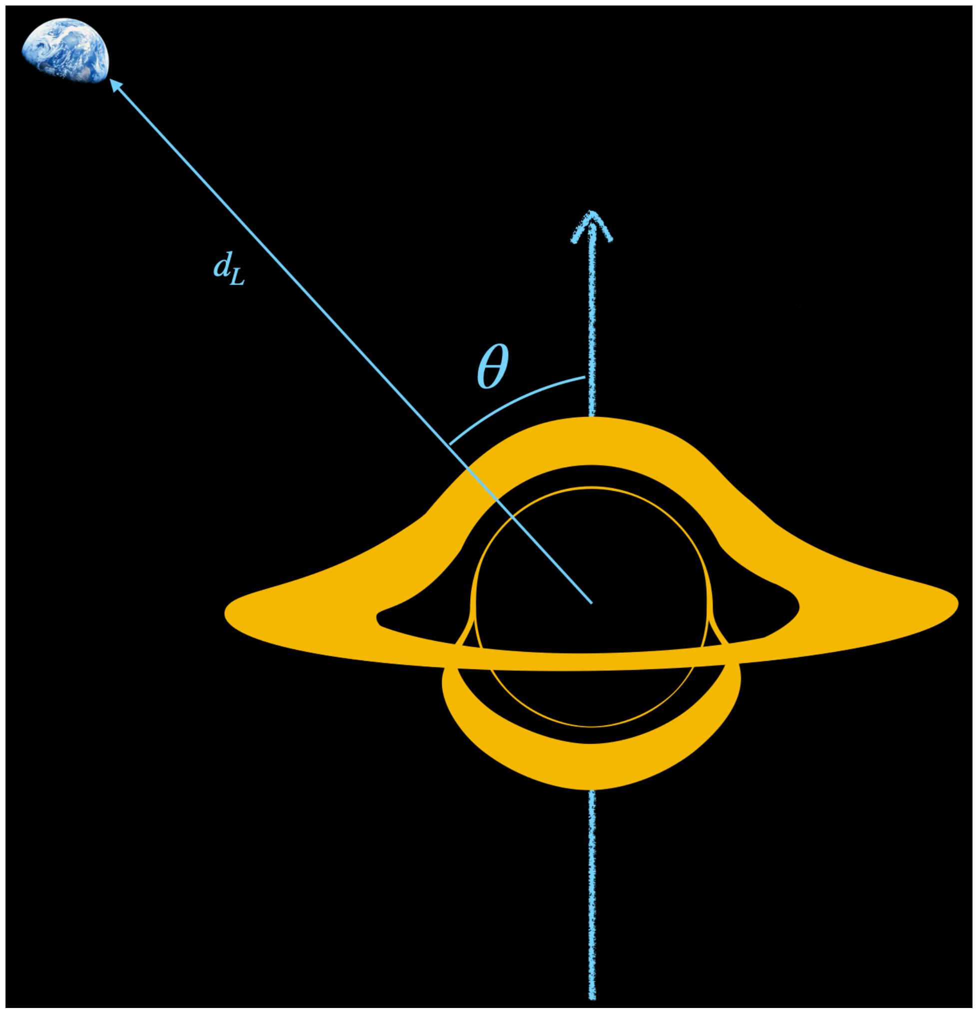

IceCube/HAWK effective area

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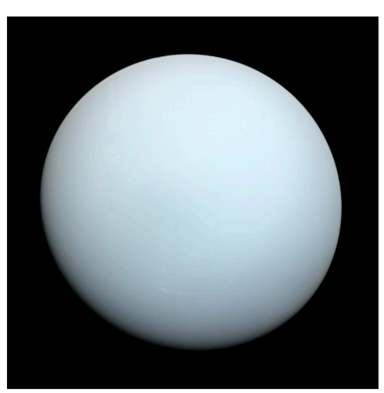

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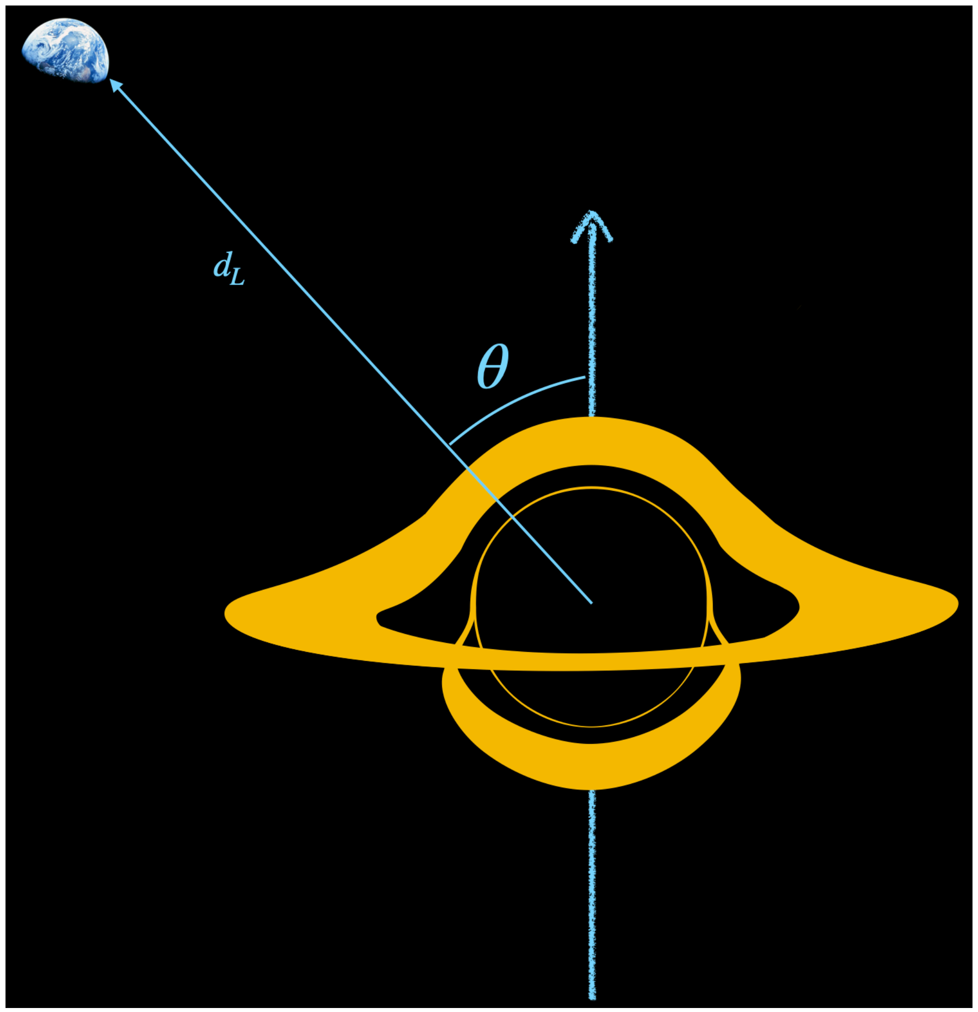

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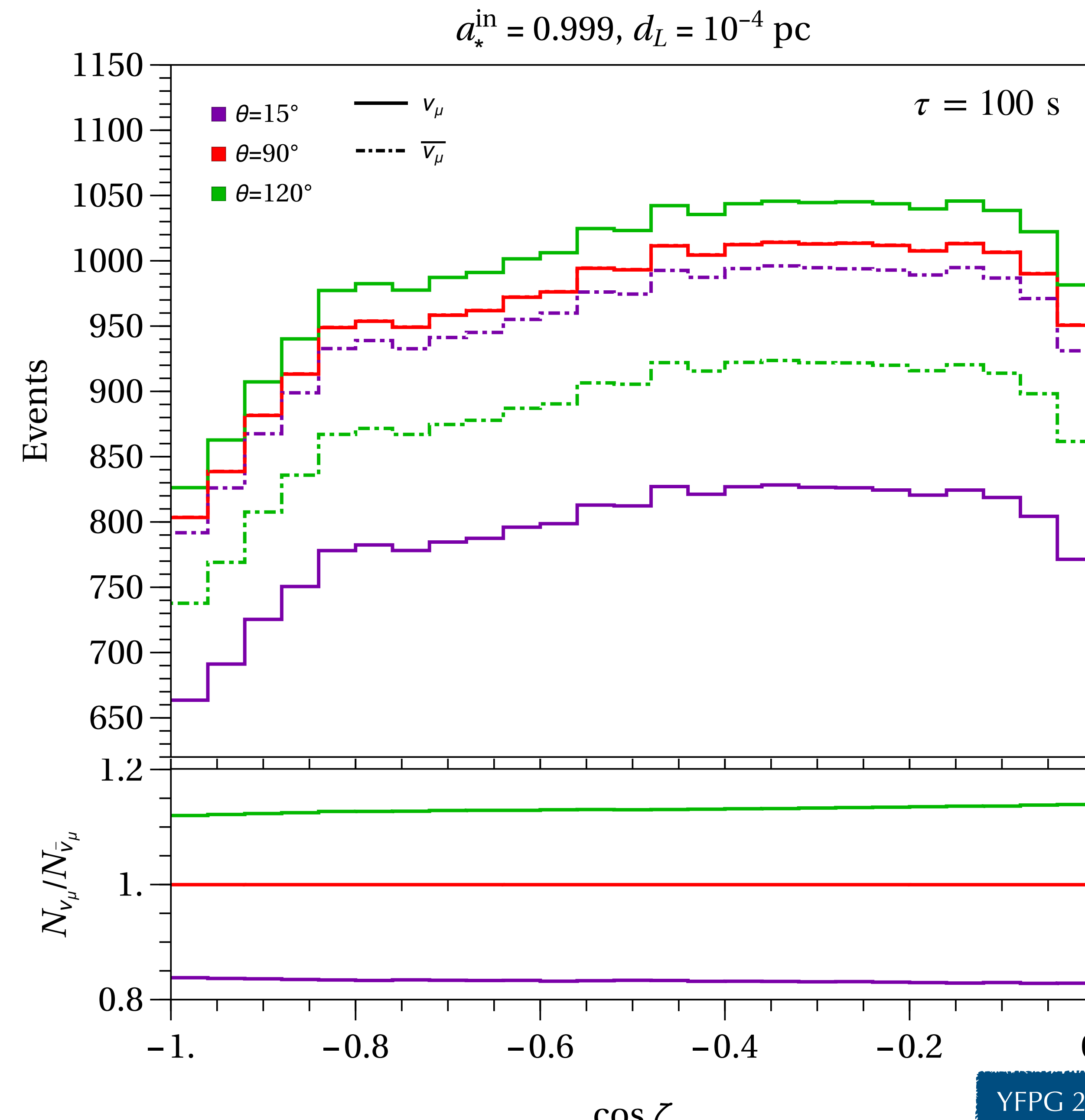

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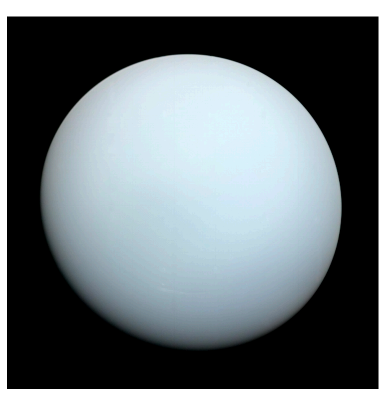

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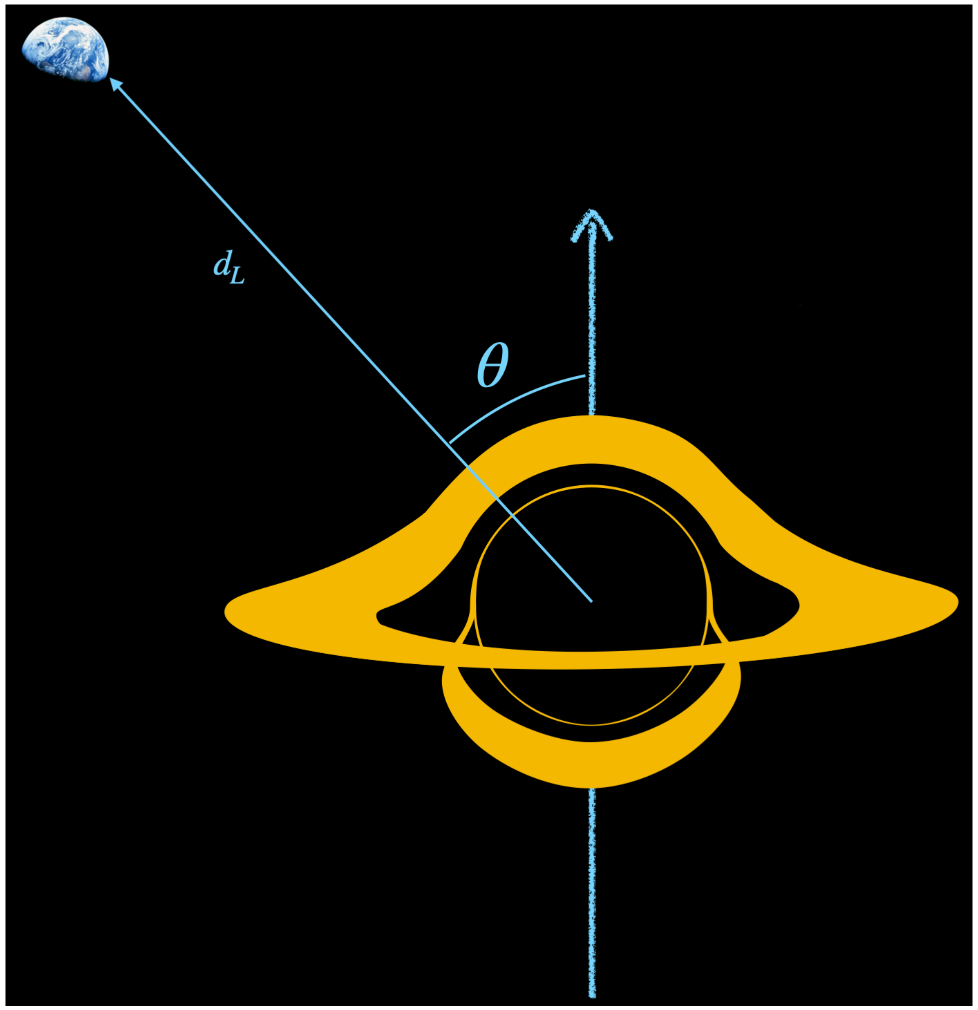
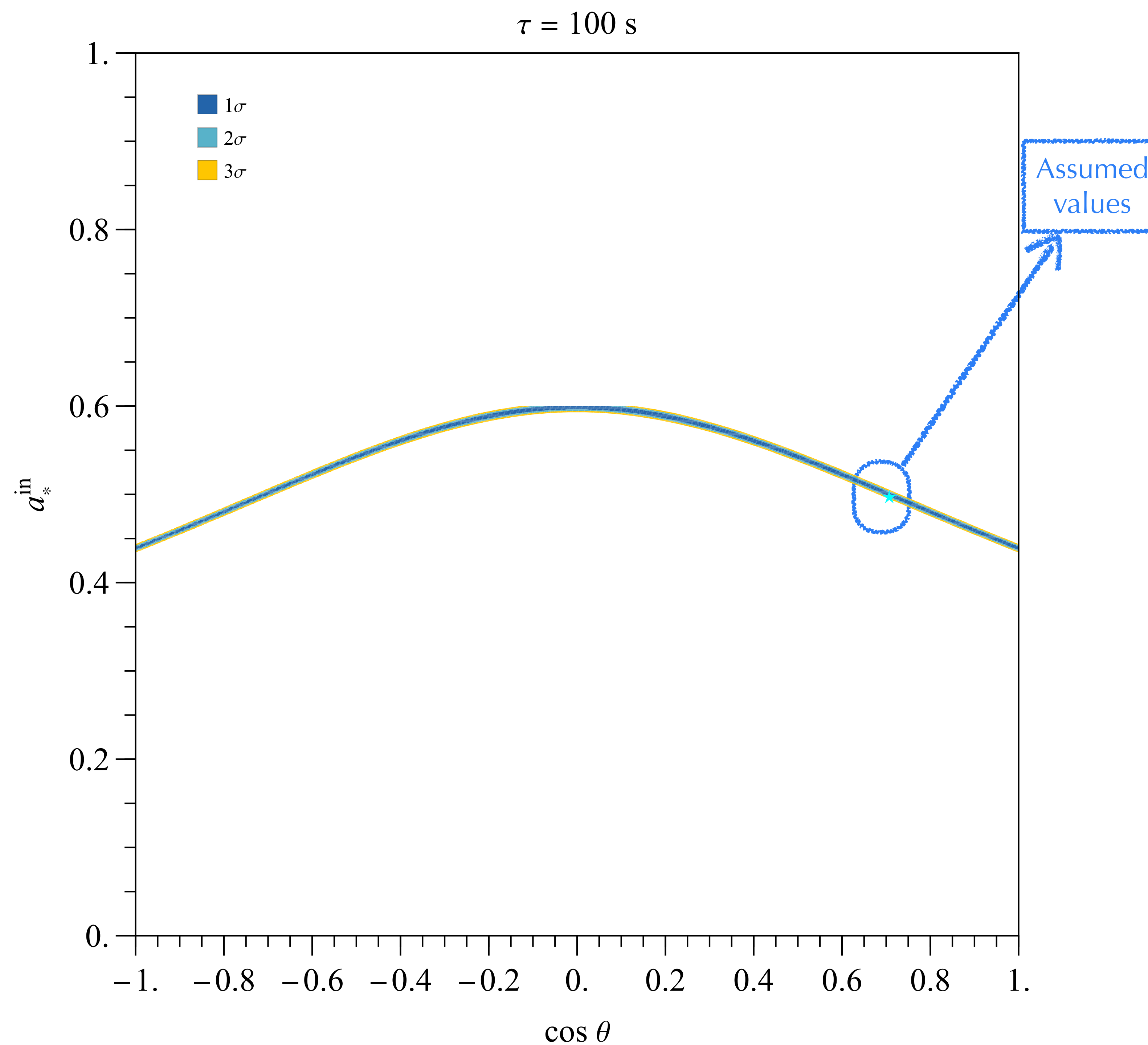
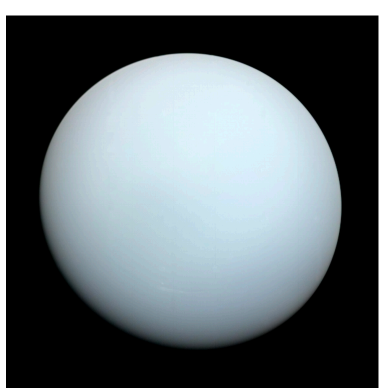


Assume: $a_\star = 0.5$, $\theta = 45^\circ$, $\zeta = -18^\circ$

Best case scenario



$d_L = 10^{-4}$ pc ≈



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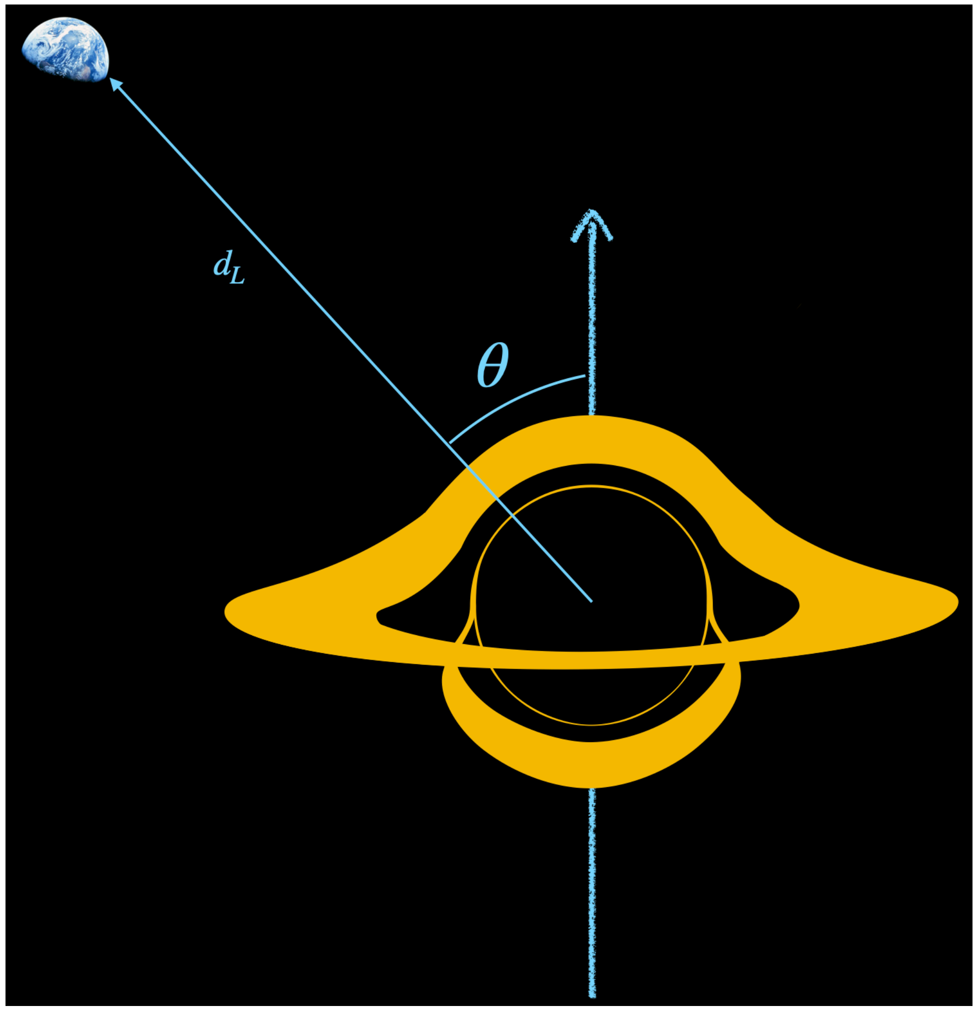

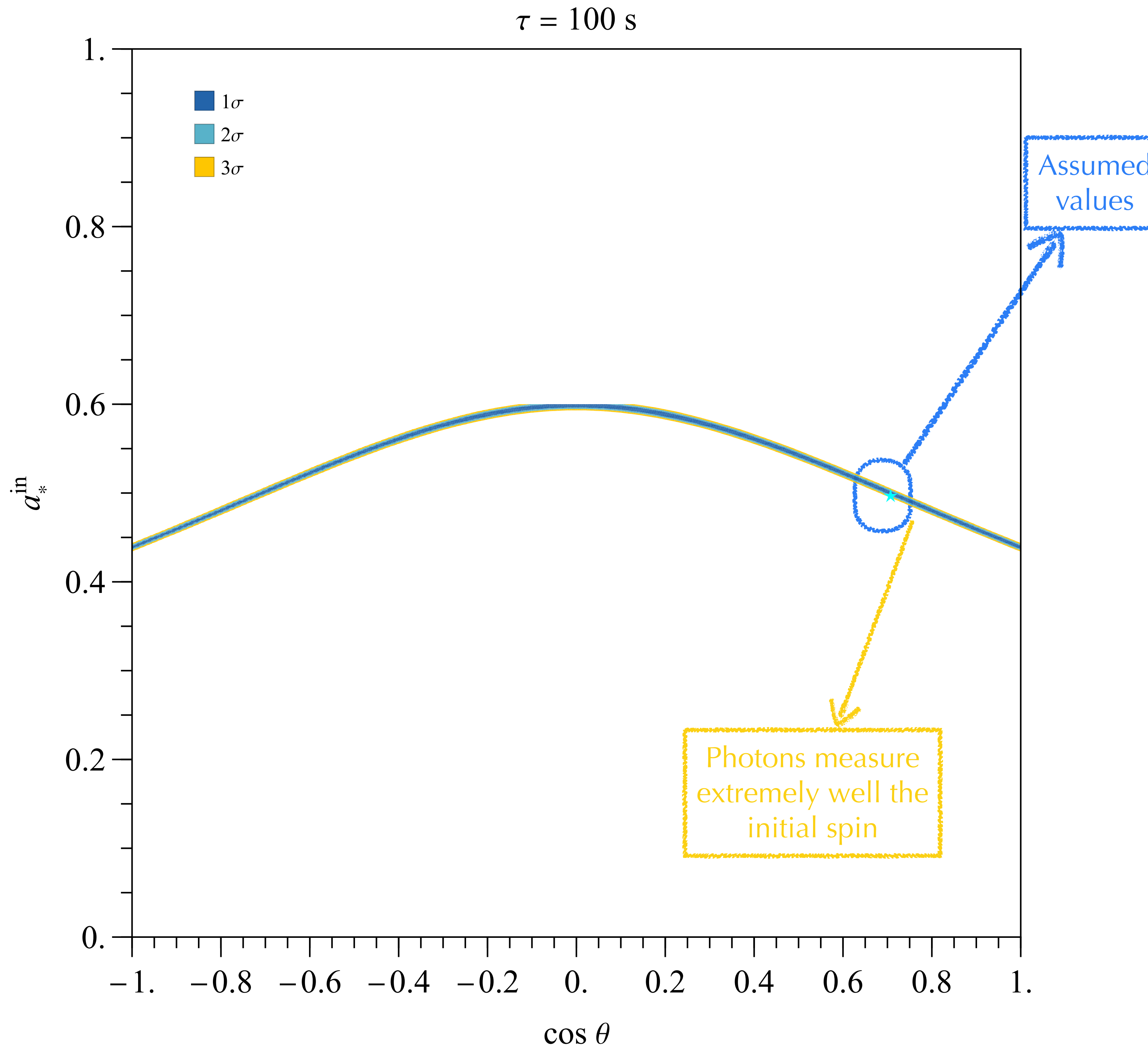

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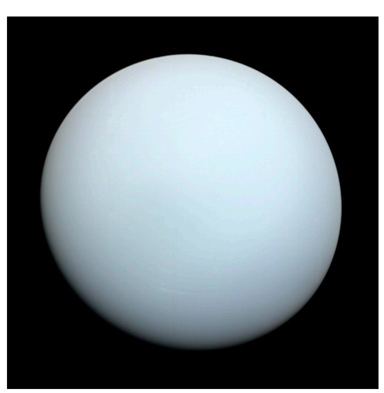

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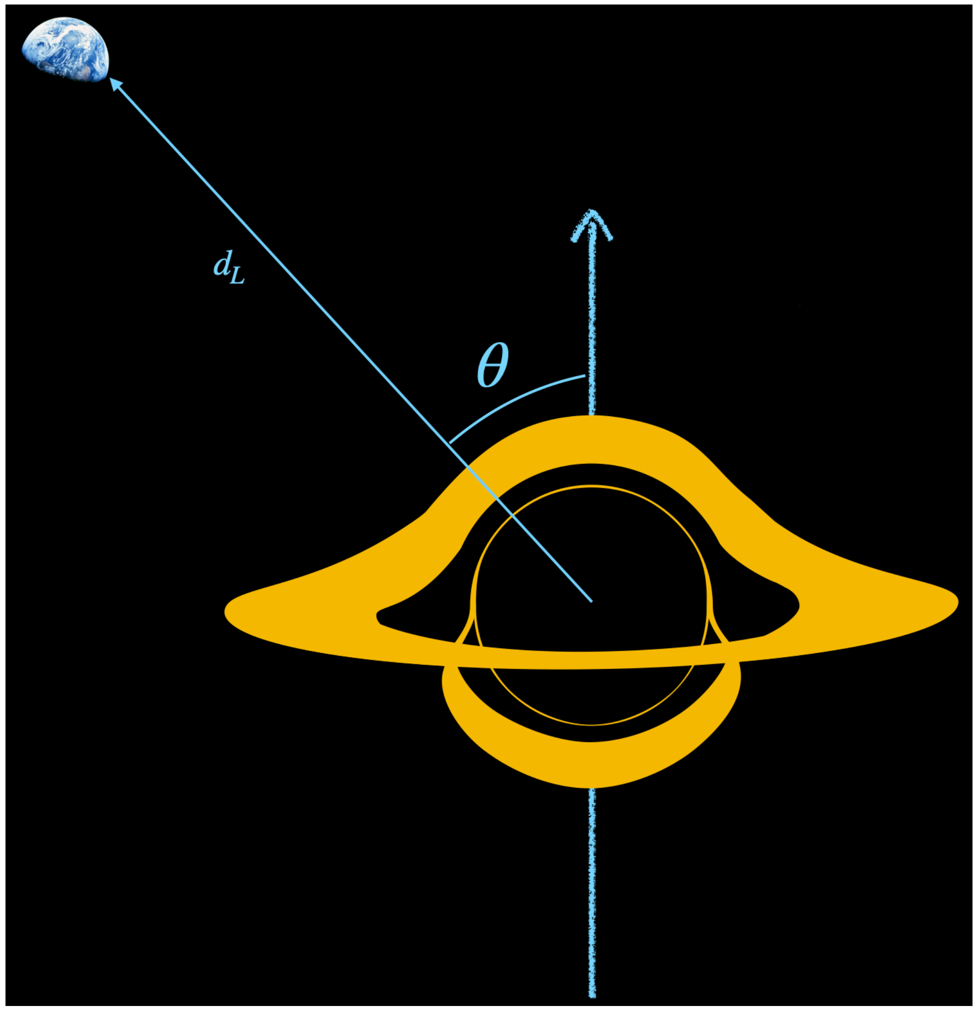

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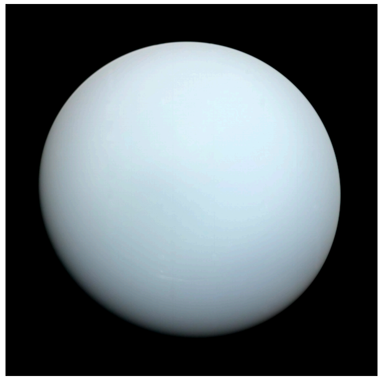
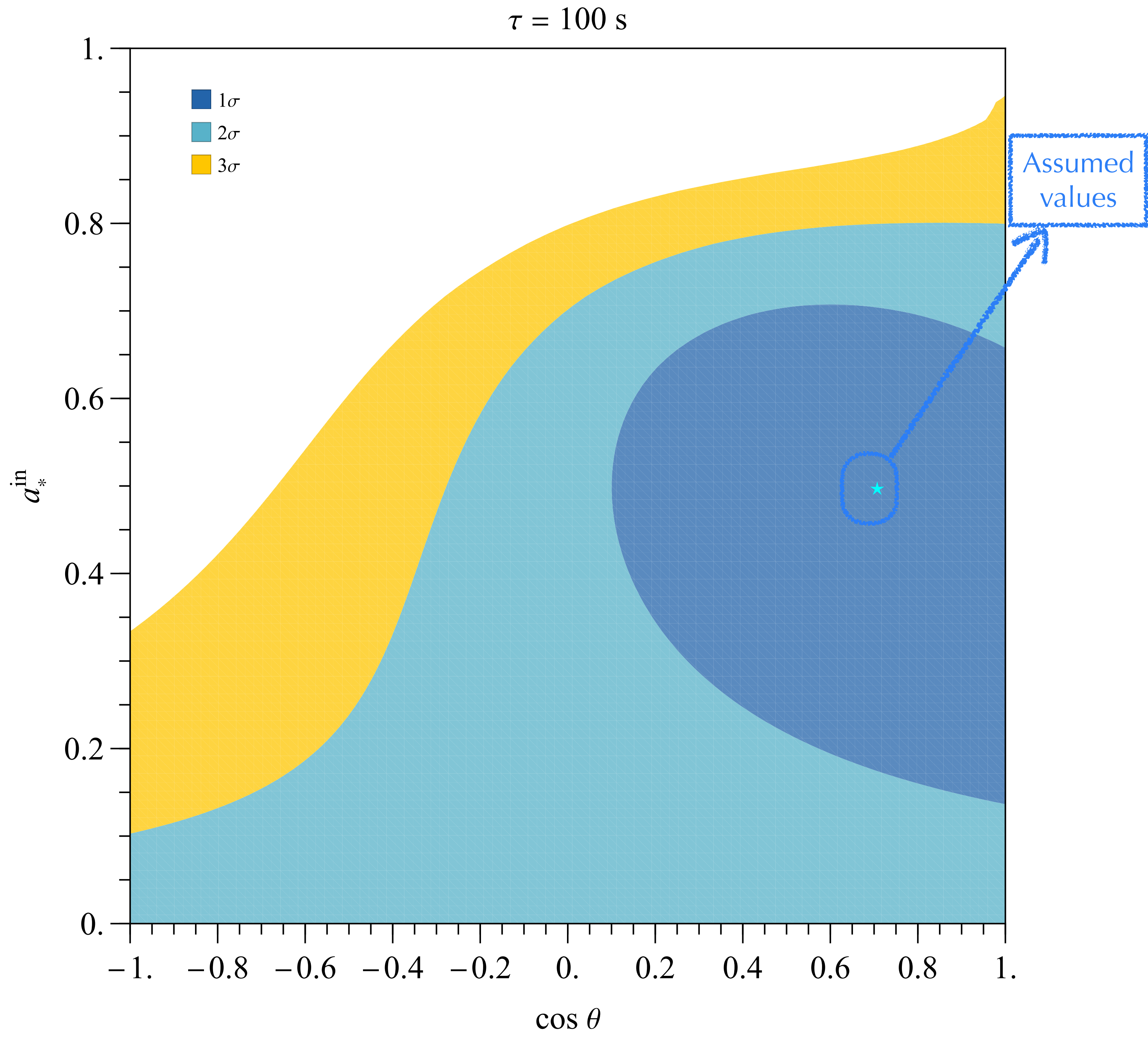


Uranus - Sun

Assume: $a_\star = 0.5,\ \theta = 45^\circ,\ \zeta = -18^\circ$

Best case scenario



YFPG 2307.14408

Determining the angular momentum

Previous works ignored the dependence on θ

Neutrino - antineutrino events will depend on θ

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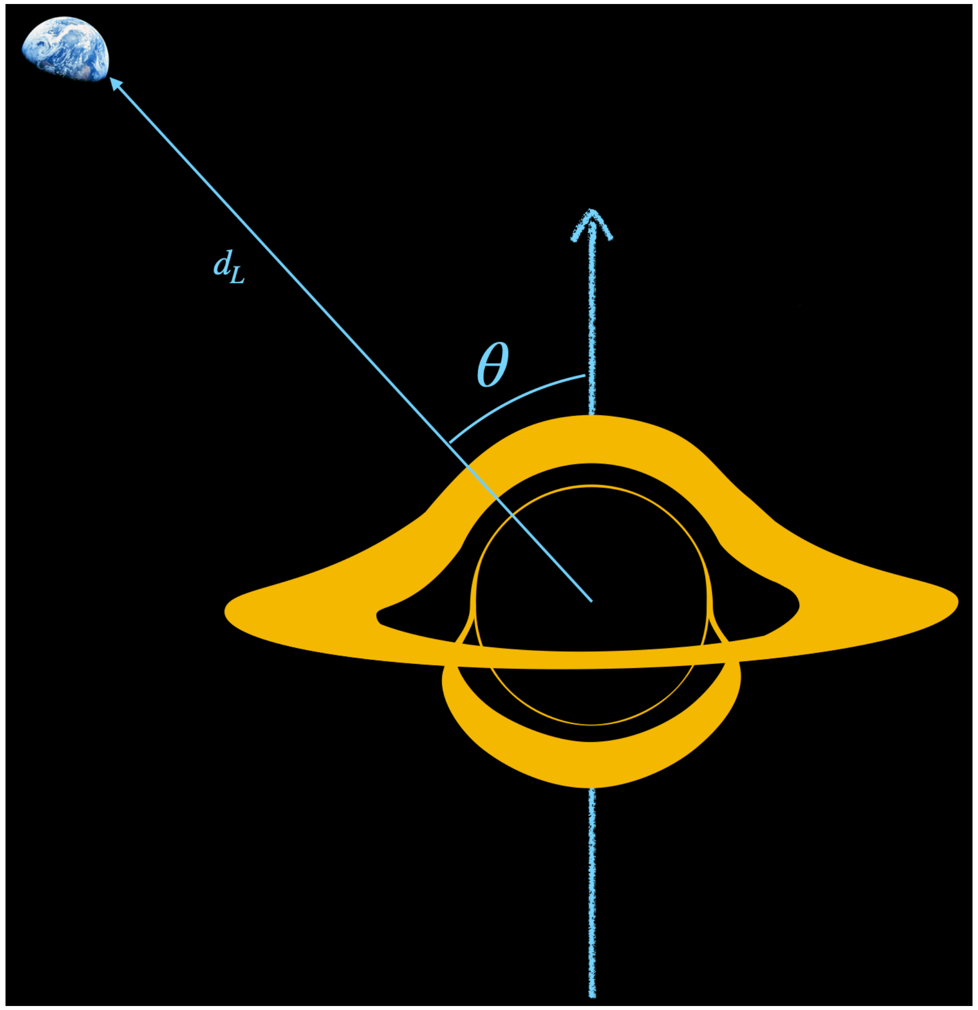

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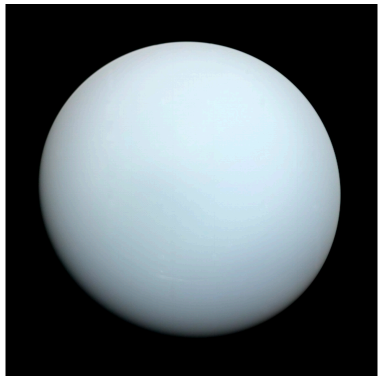

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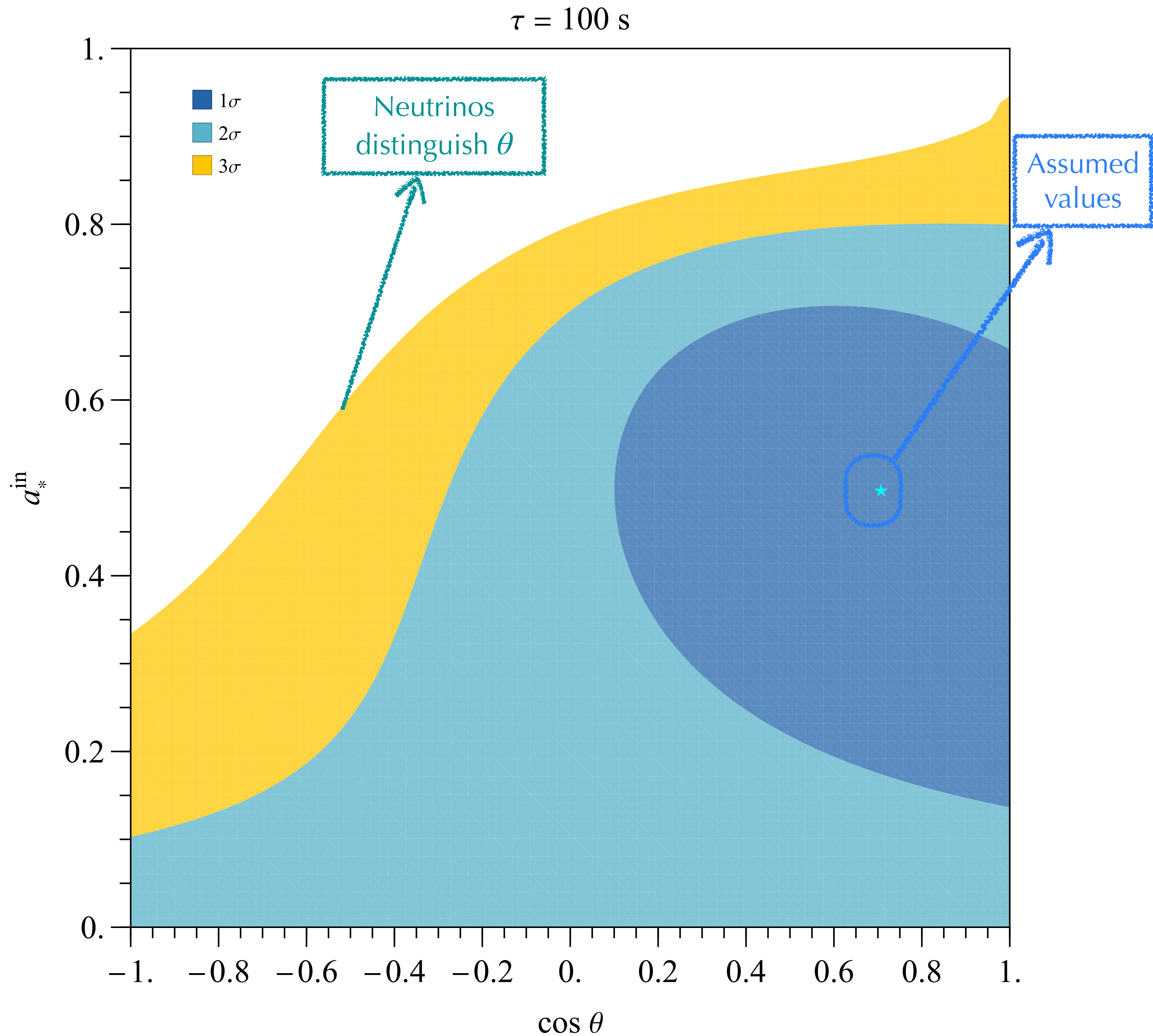

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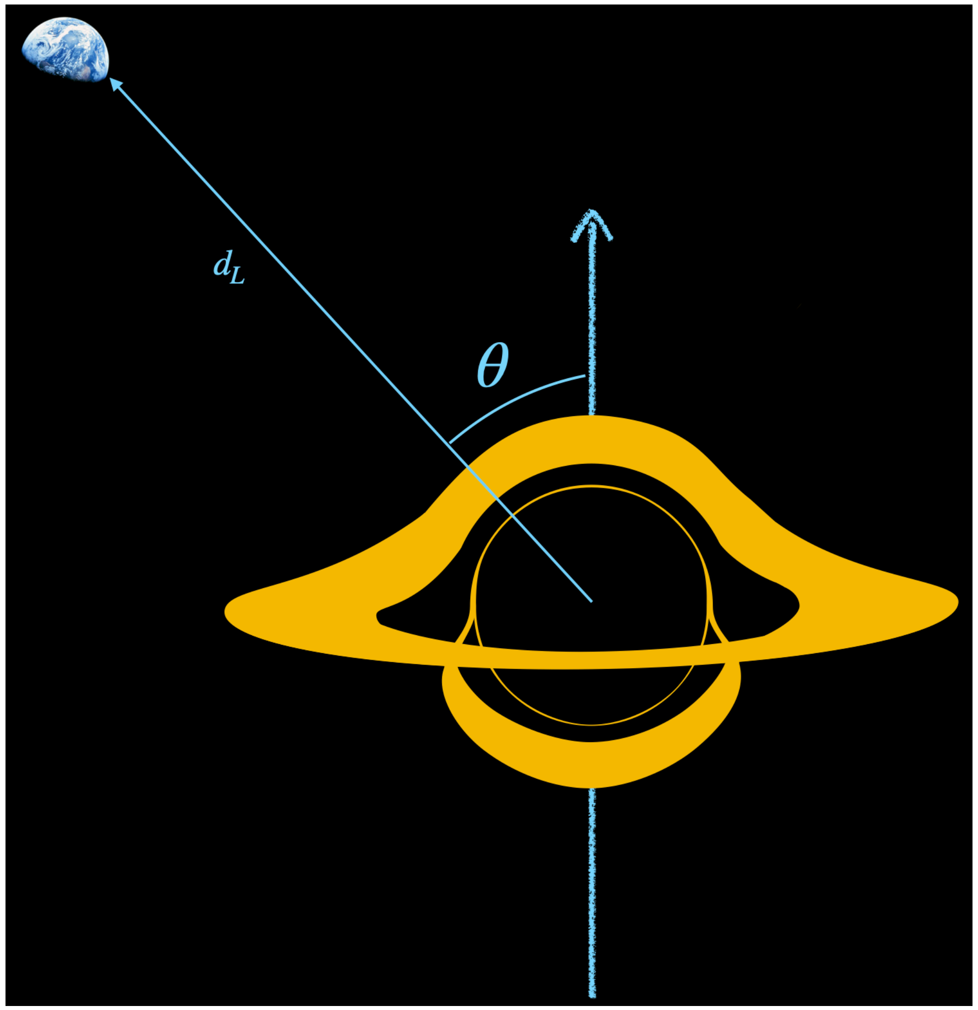

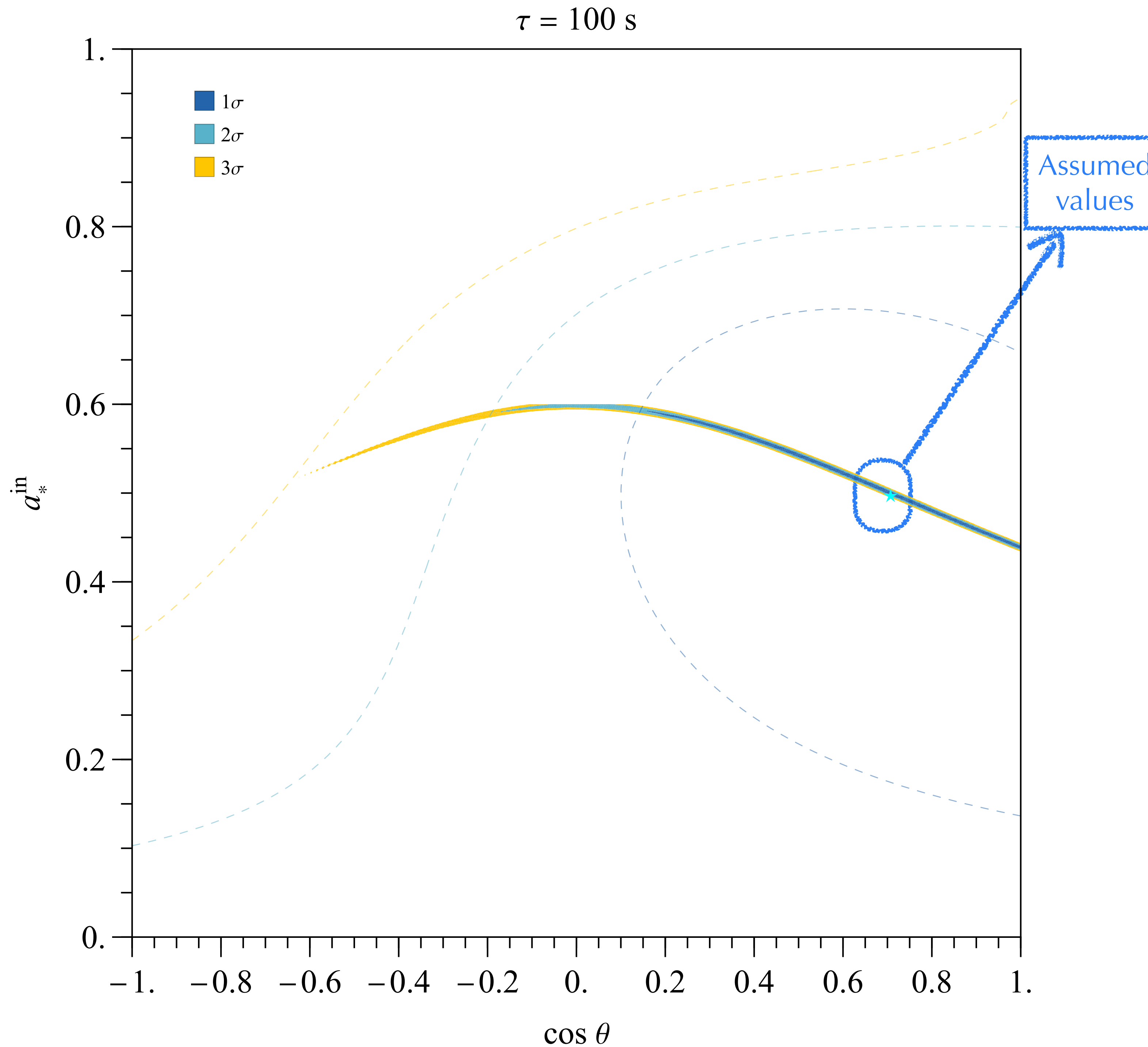

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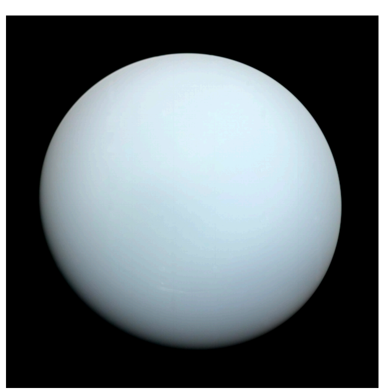

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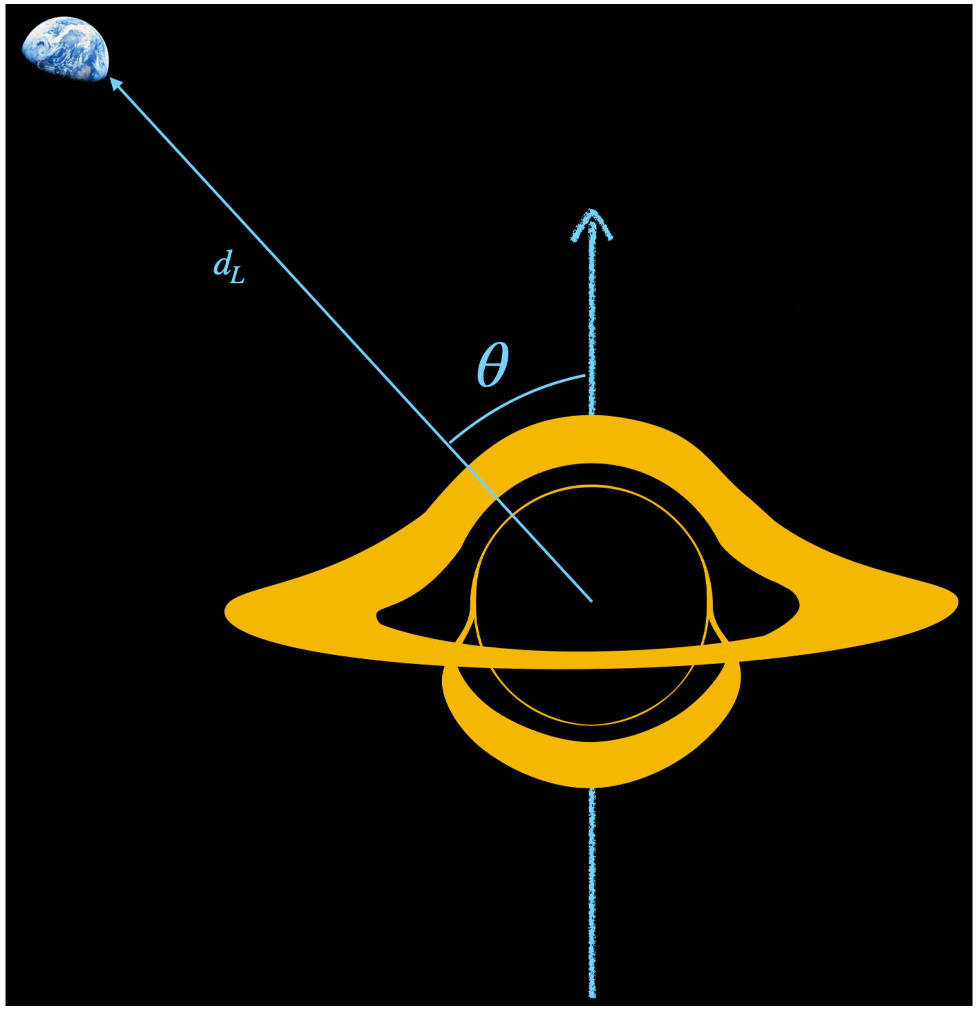

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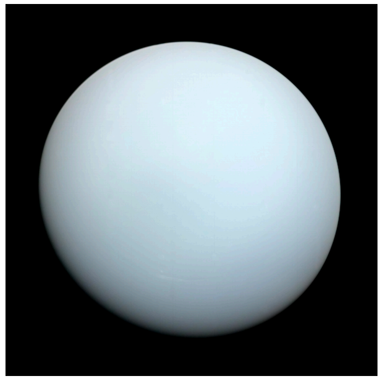

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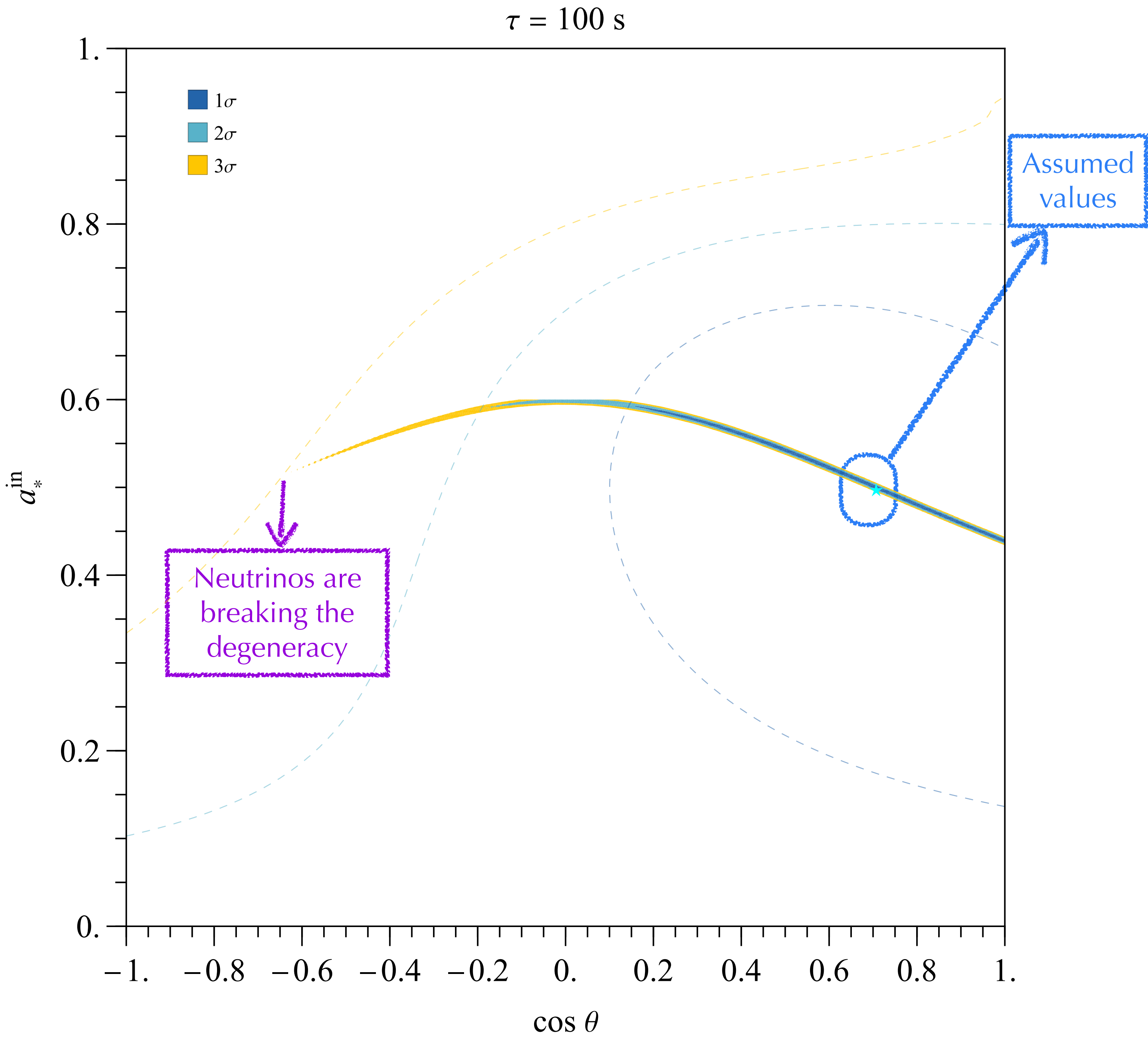

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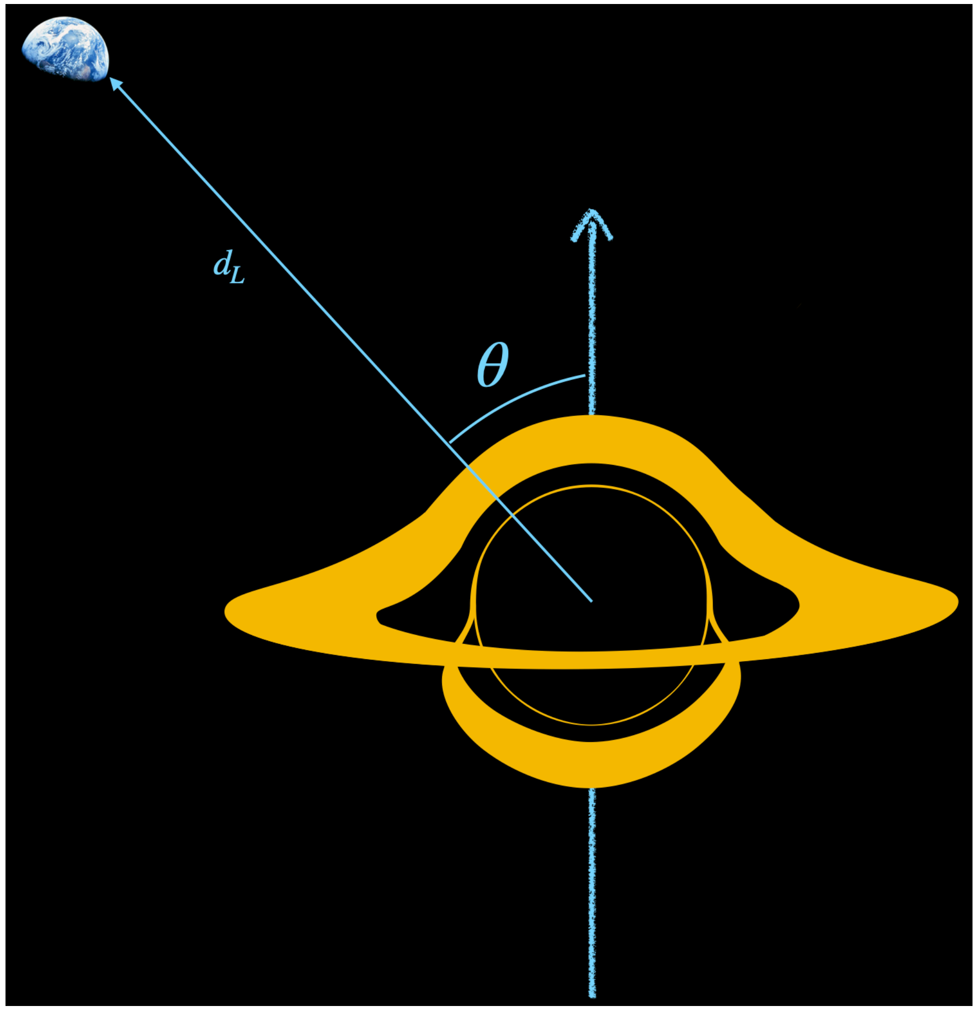

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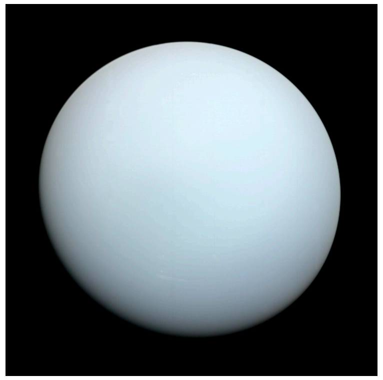

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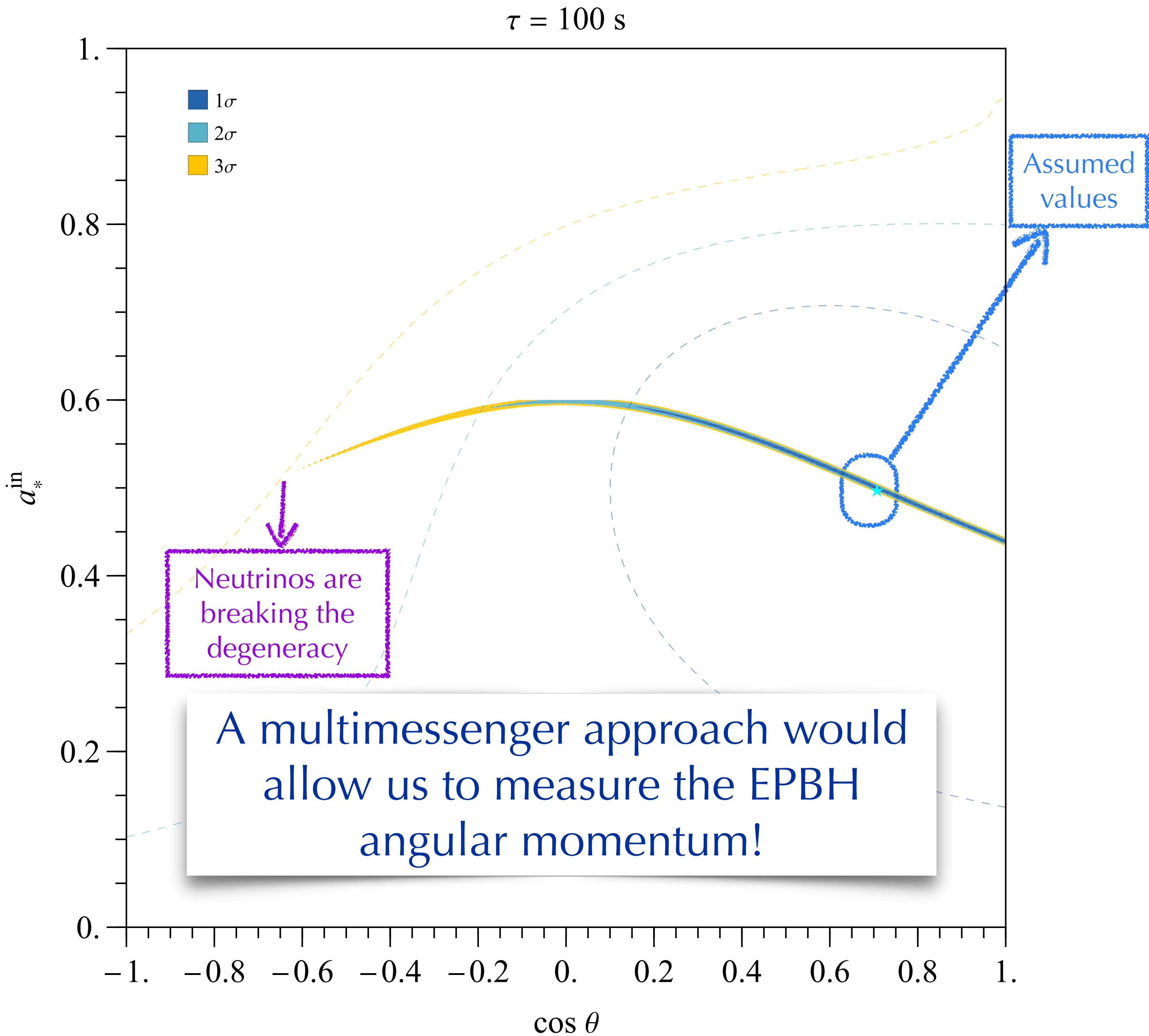

A multimessenger approach would allow us to measure the EPBH angular momentum!

YFPG 2307.14408

Determining the angular momentum

Previous works ignored the dependence on θ

Neutrino - antineutrino events will depend on θ

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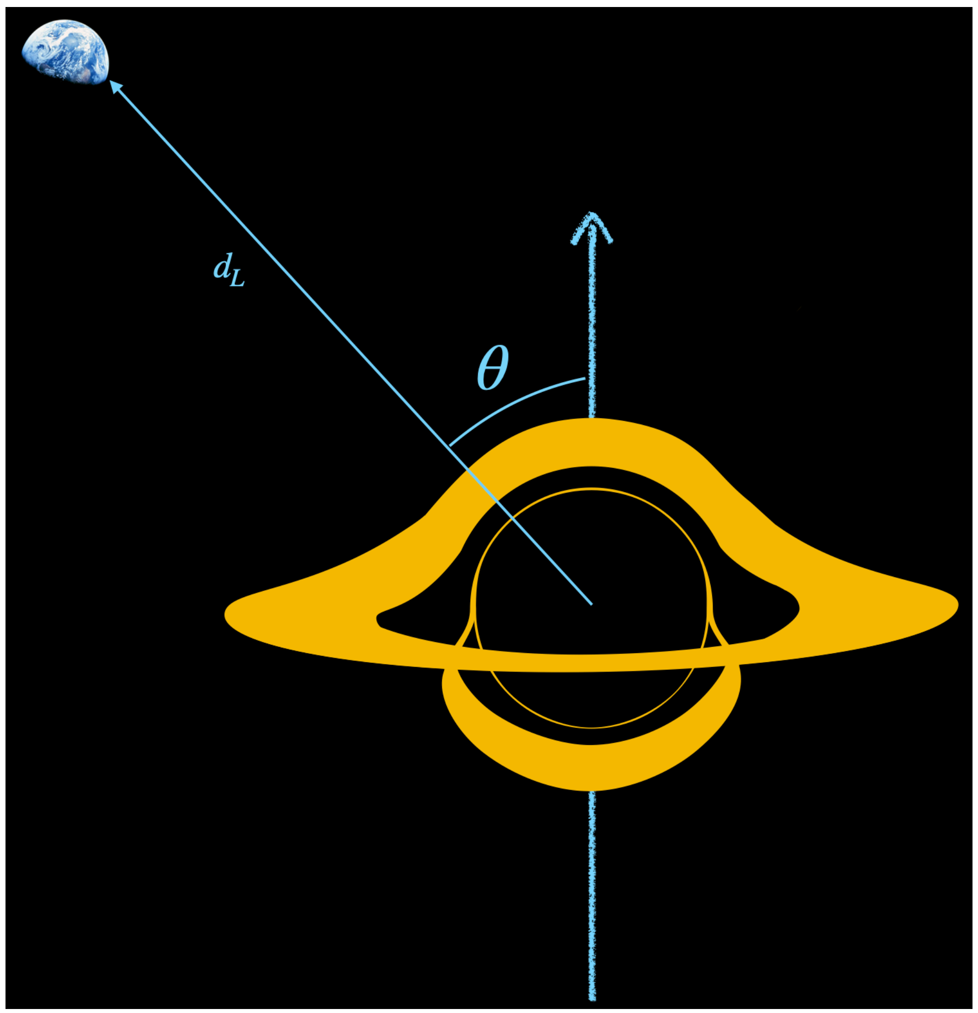
How close?



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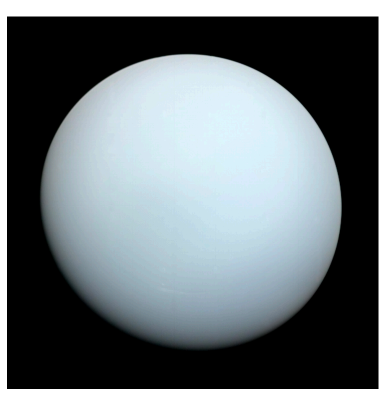

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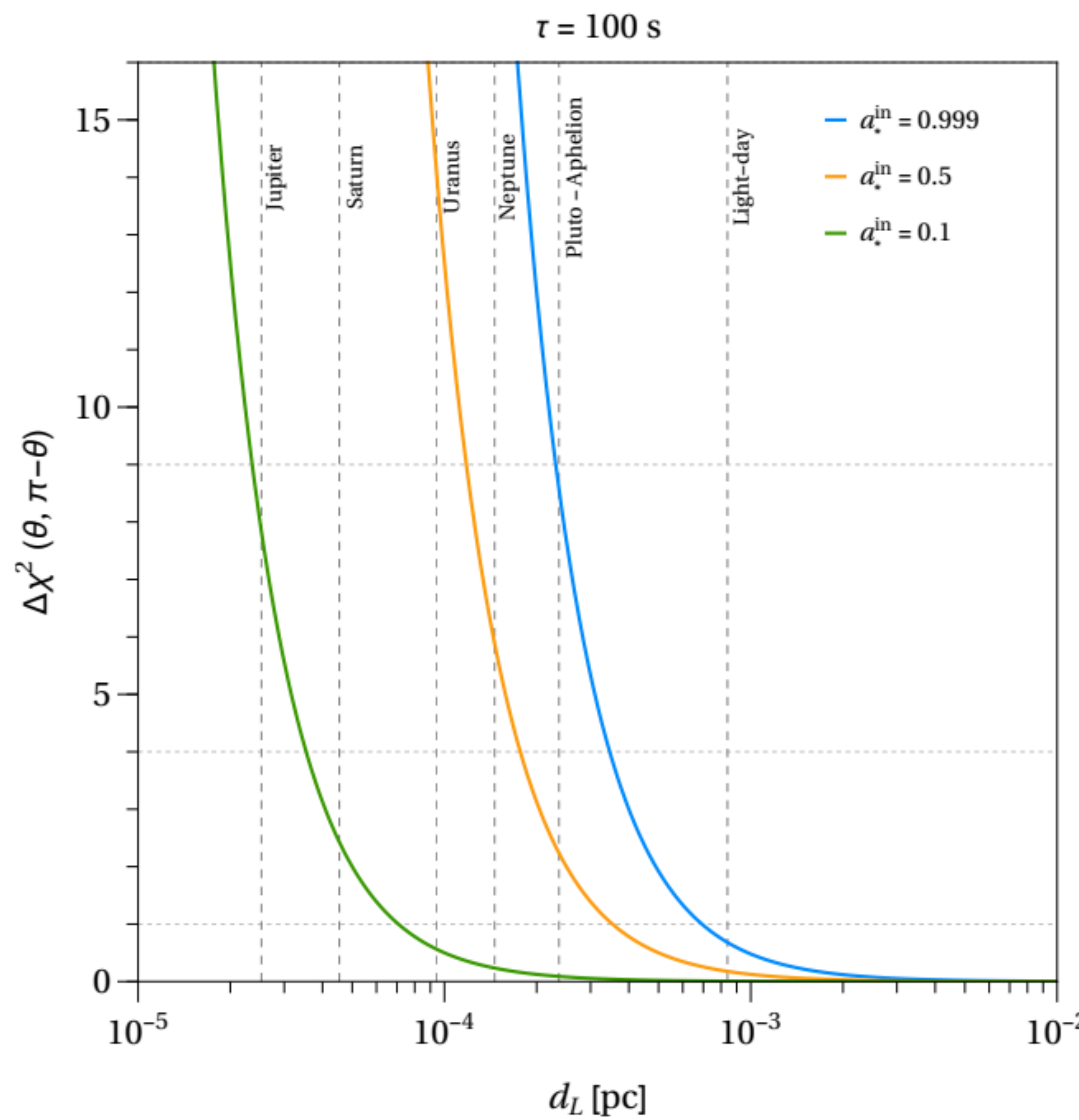

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Summary

- BH evaporation offers a unique mechanism to produce particles beyond colliders!

- Anything else to learn by measuring neutrinos & antineutrinos in neutrino telescopes for an EPBH?

  - Prospects in future observatories? IC Gen2, KM3Net, P-ONE, Trident…

  - Neutrinos as a tool to measure the number of scalars

  - Maybe BSM that only affects neutrinos but not photons?

    De Romeri, YFPG, Tolino, 240X.XXXXX

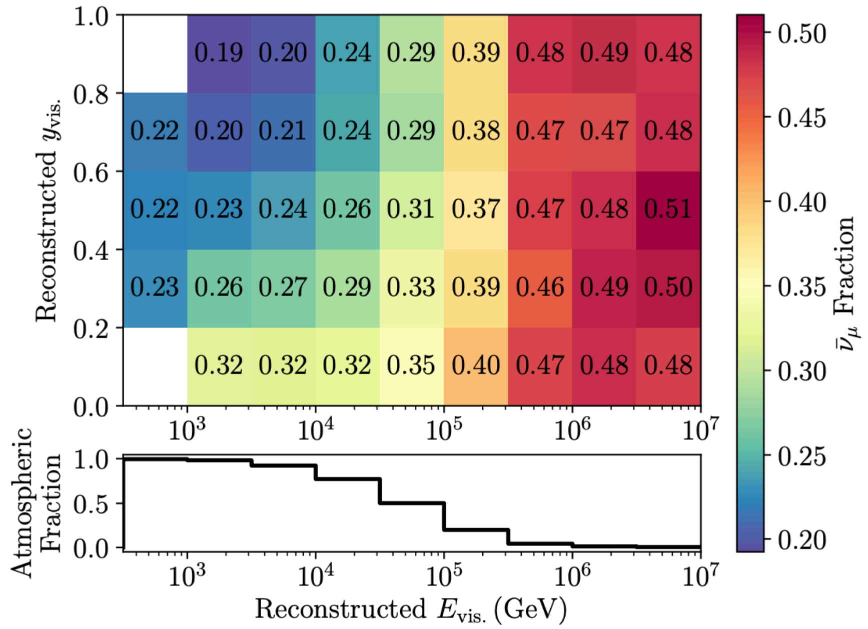
    ➡ *Stay tuned!*

Thank you!

Backup

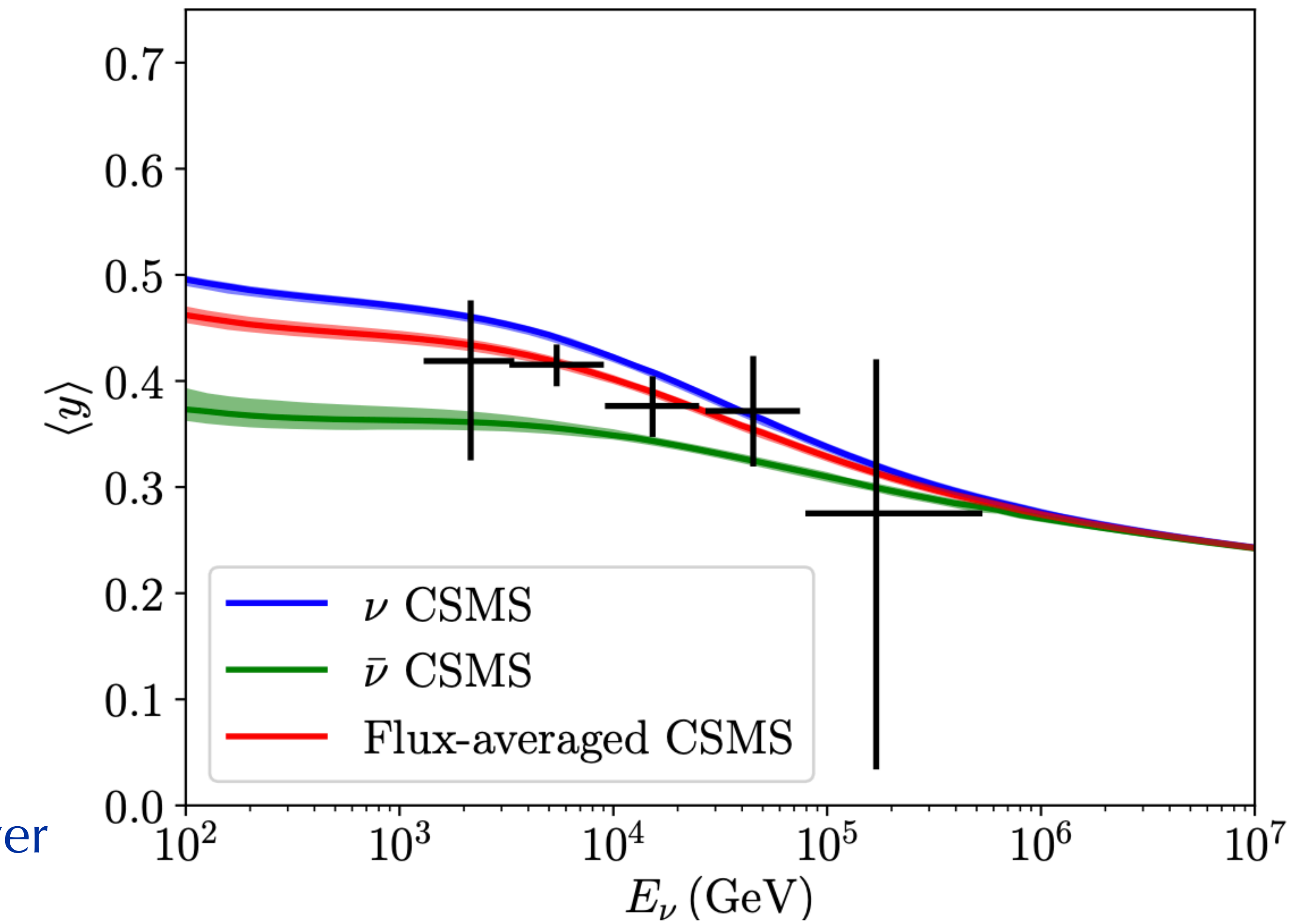
ν vs $\overline{\nu}$ in IceCube

Inelasticity: –the fraction of a neutrino's energy transferred to hadrons



$$y_{\text{vis.}} = \frac{E_{\text{casc.}}}{E_{\text{vis.}}}$$

$$E_{\text{vis.}} = E_{\text{casc.}} + E_{\text{track}}$$



E_{casc} → photons from hadronic shower
E_{track} → Muon track

$$R_{\nu_\mu/\overline{\nu}_\mu} = 0.77^{+0.44}_{-0.25}$$

Atmospheric Neutrinos

IC: 1808.07629