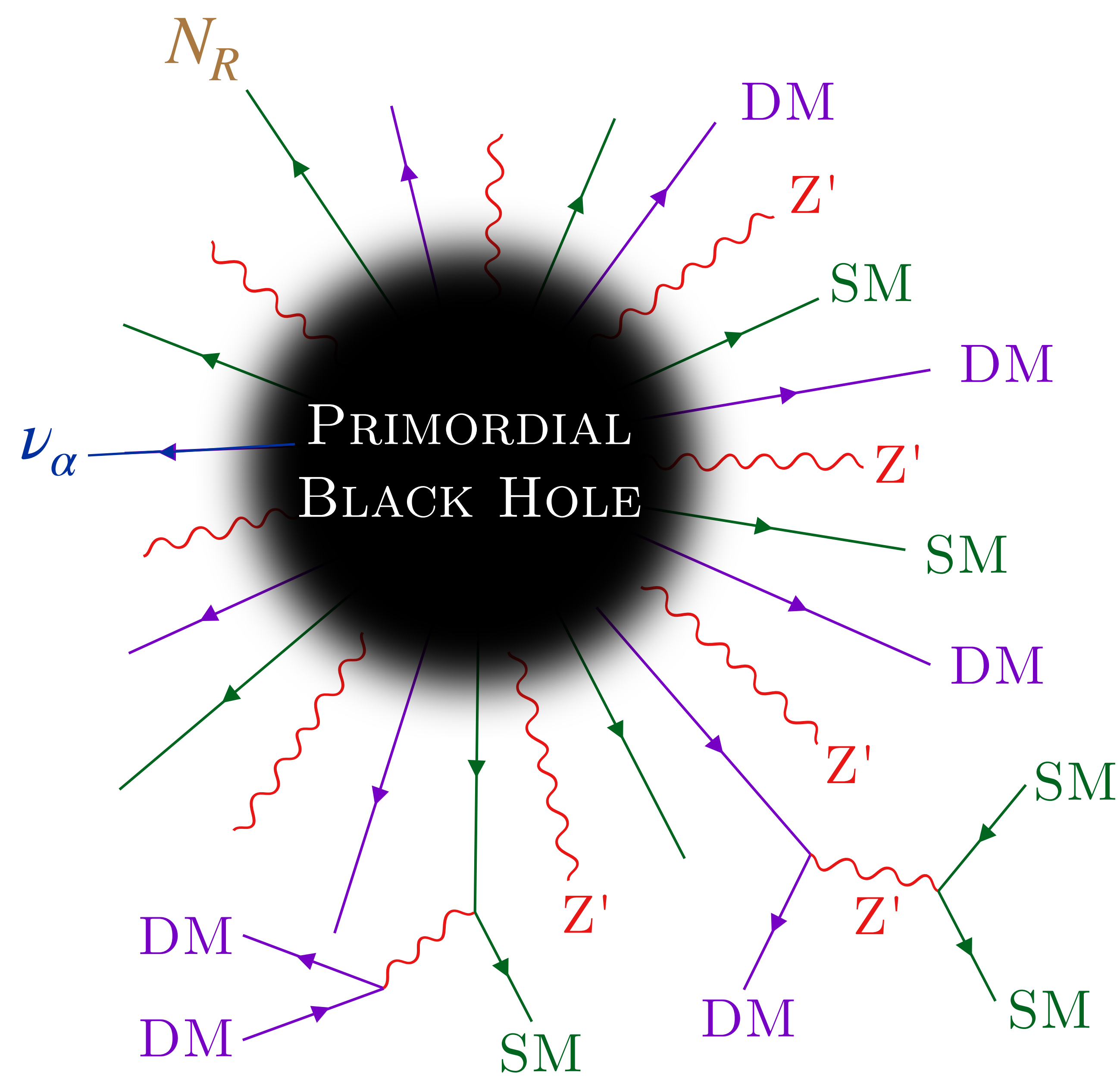
Primordial Black Holes as Particle Factories: Producing Invisibles from Invisibles



Yuber F. Perez-Gonzalez

Invisibles'23 Workshop,
August 31st, 2023

Durham University

IP3

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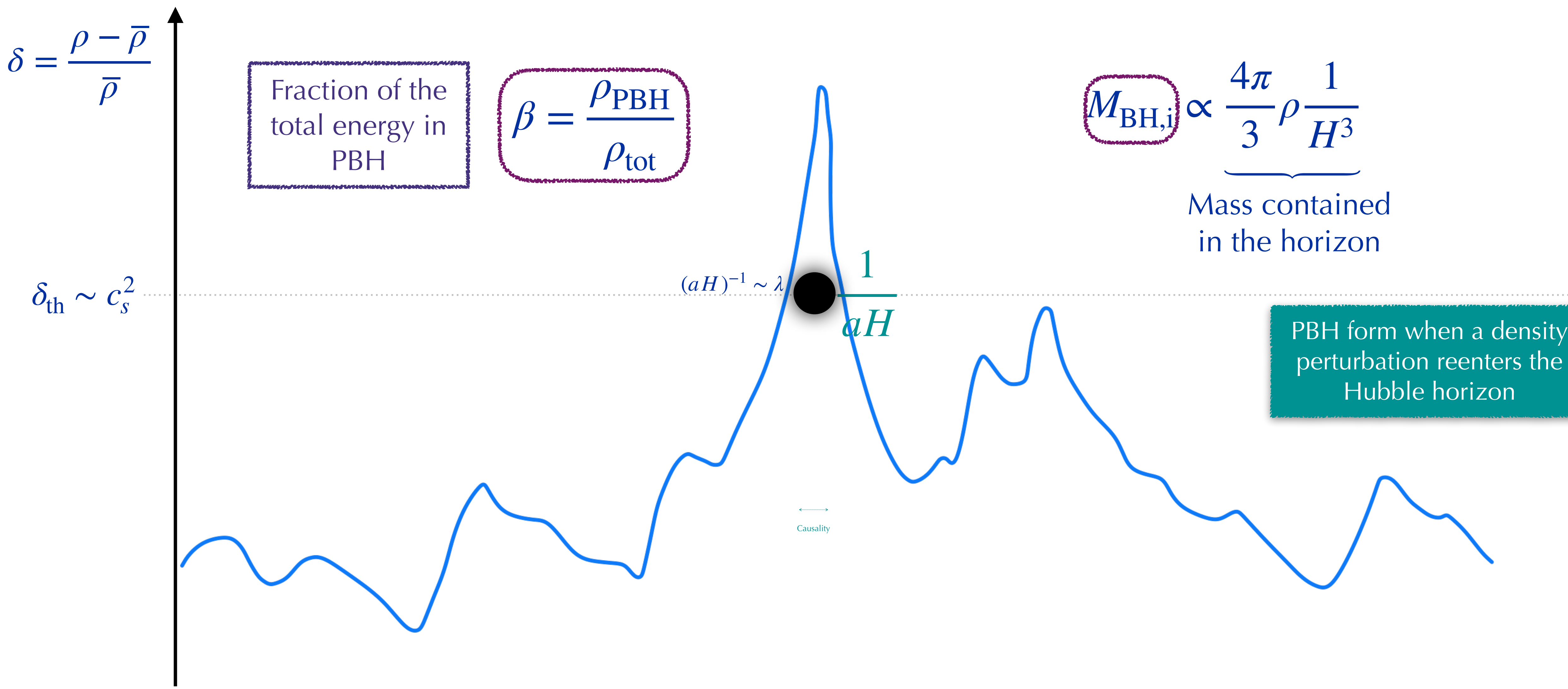
PBH Formation

Lighter Black Holes → Large densities

$$r_S = 2GM$$

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

- Bubble collisions
- Pressure reduction
- Collapse of density fluctuations



Fraction of the total energy in PBH

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

$$M_{\mathrm{BH,i}} \propto \frac{4\pi}{3}\rho\frac{1}{H^3}$$

Mass contained in the horizon

PBH form when a density perturbation reenters the Hubble horizon

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

Assume a monochromatic mass distribution

$M_{\mathrm{BH},i}$, β

All PBHs with the same mass

Carr et al. 2002.12778

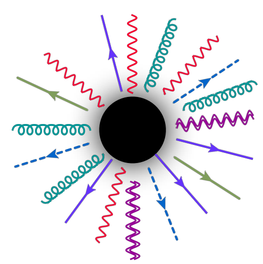
Evaporation — Schwarzschild BHs

Described by $M_{\rm BH}$

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

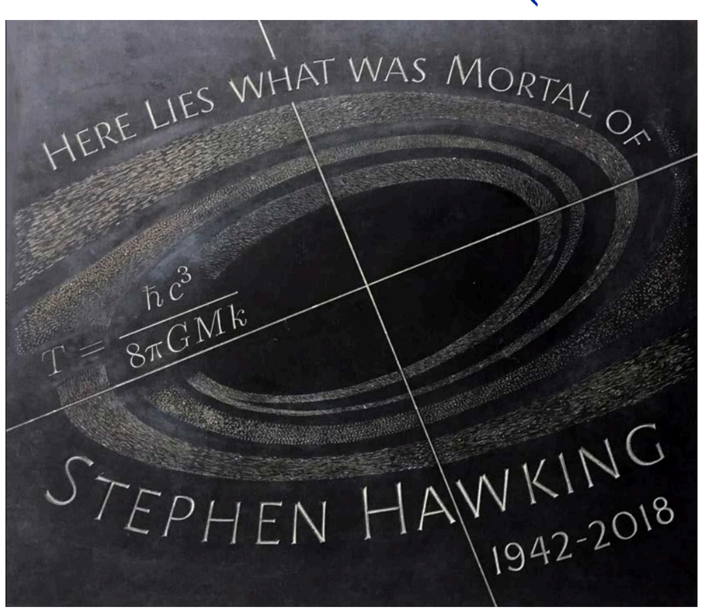
Hawking Instantaneous Spectrum

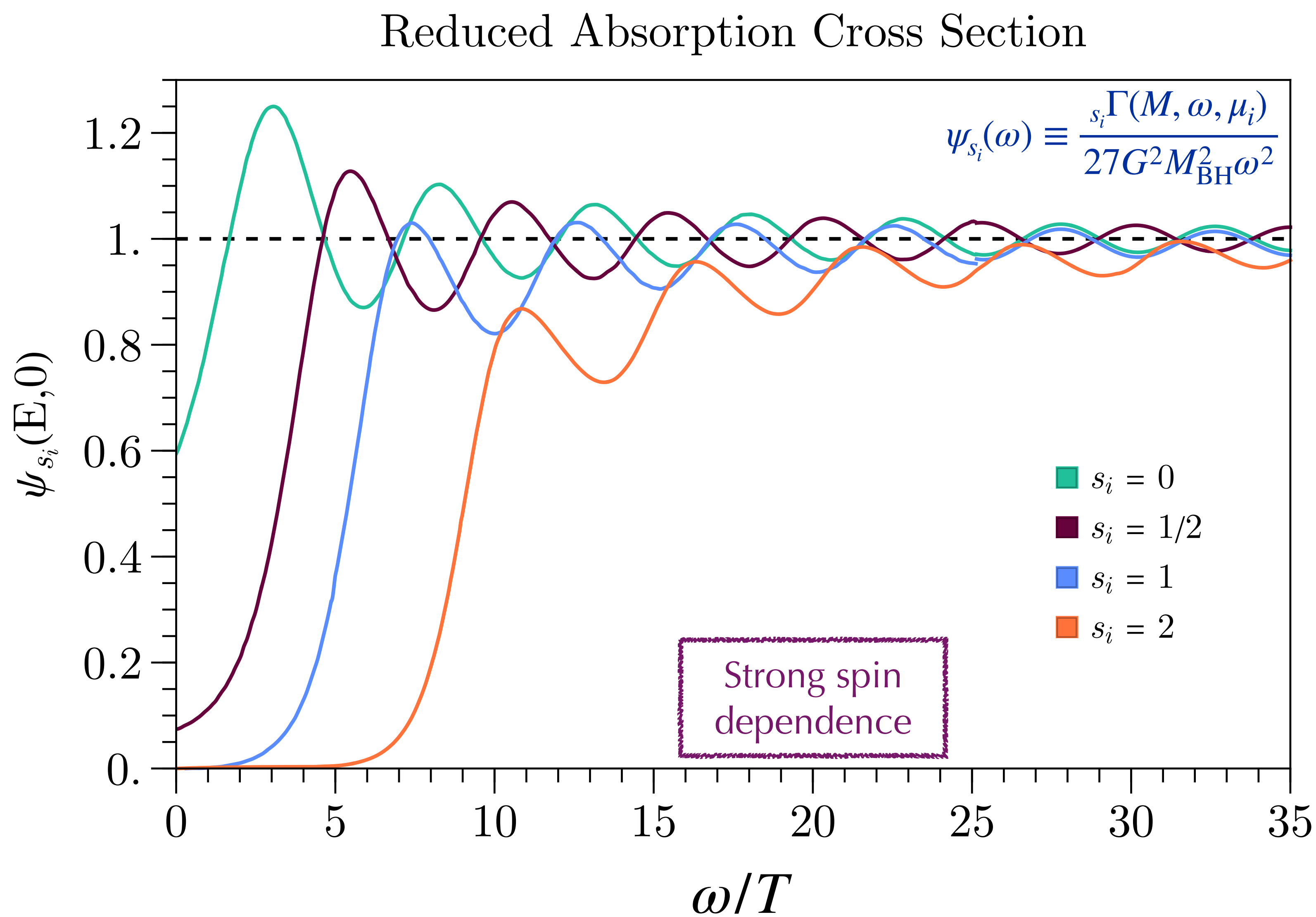
Absorption probability



BH Temperature

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



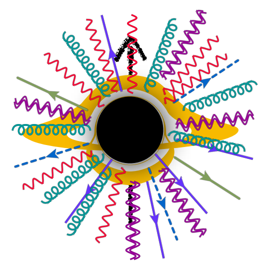


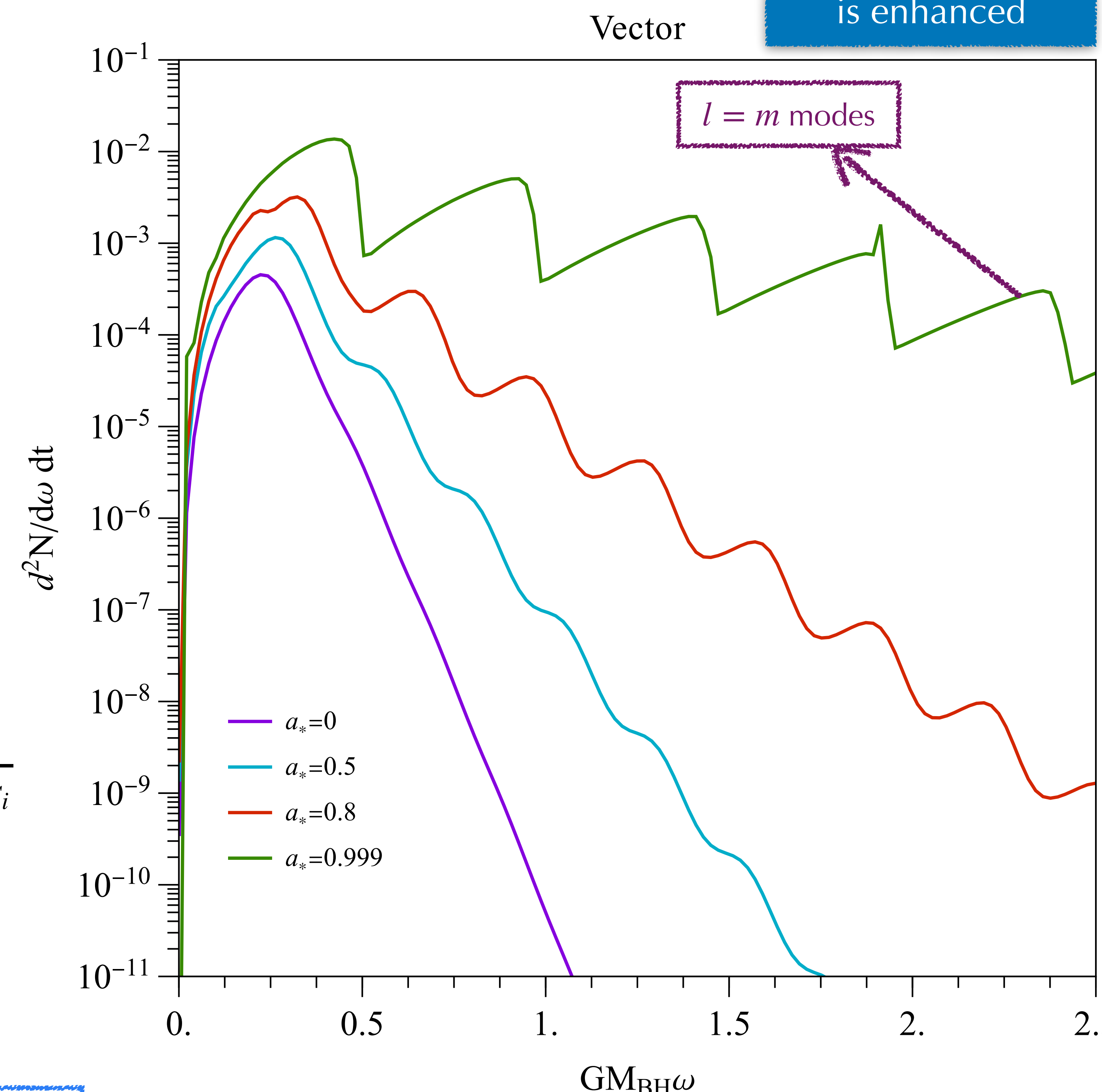
Only $\ell \geq s_i$ modes

Evaporation — Kerr BHs

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

Emission of Corrotating modes is enhanced





BH "wants" to shed off its angular momentum

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

BH Temperature

$$\varpi_m = \omega - m\Omega$$

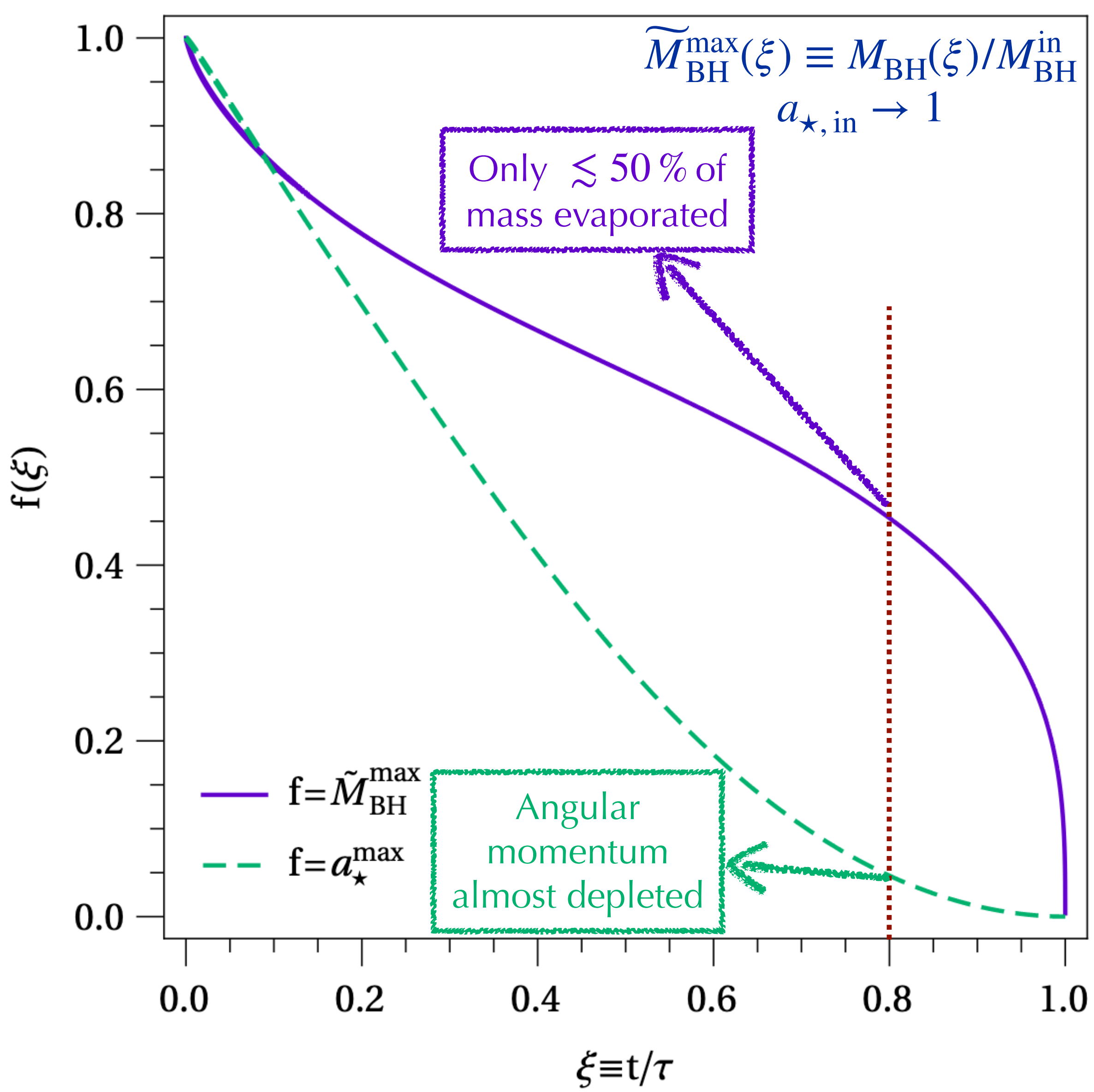
$$T = \frac{1}{4\pi G M} \frac{\sqrt{1 - a_\star^2}}{1 + \sqrt{1 - a_\star^2}}$$

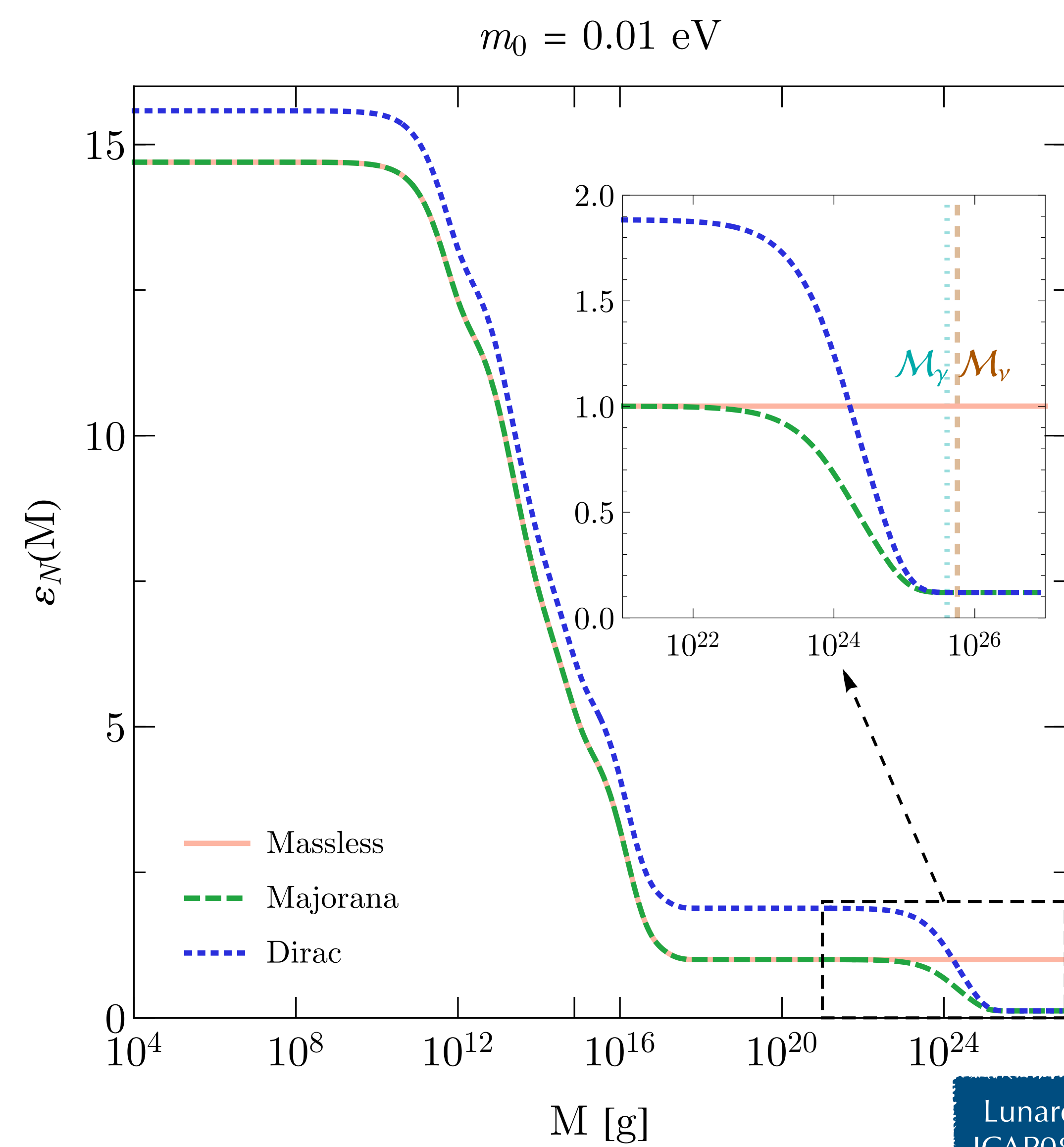
Explicit dependence on m
$\Omega \rightarrow$ angular velocity

Time Evolution

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

$$\frac{da_\star}{dt} = -a_\star[\gamma(M_{\rm BH}, a_\star) - 2\varepsilon(M_{\rm BH}, a_\star)]\frac{M_P^4}{M_{\rm BH}^3}$$





Lunardini, YFPG JCAP08(2020)014

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

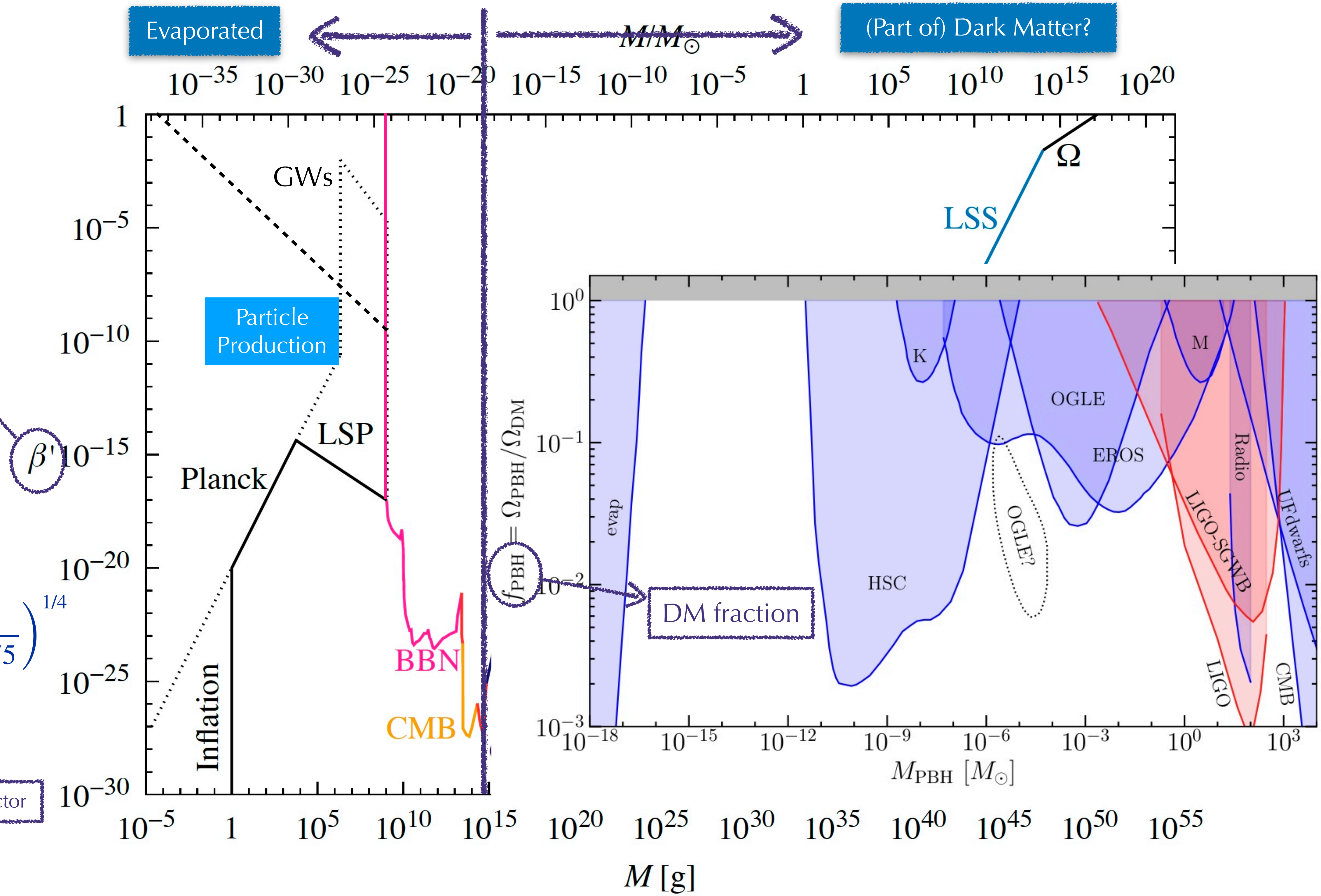
$$\varepsilon = \sum_{i={\rm all},l,m} \int_0^\infty \frac{d^2\mathcal{N}_{ilm}}{d\omega dt}\,\omega d\omega$$

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

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

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

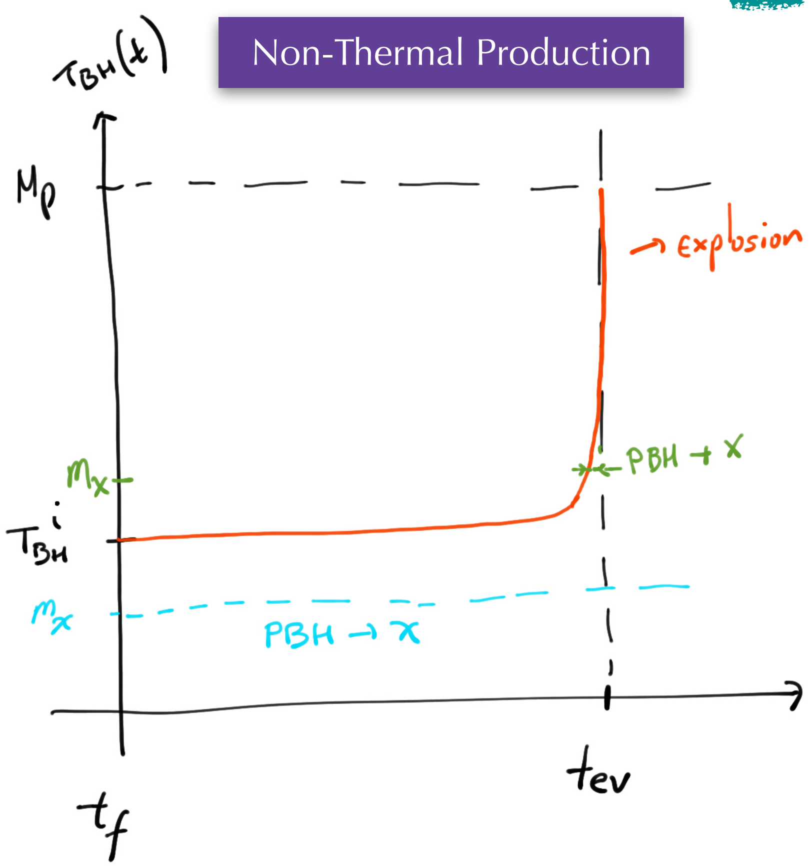
Gravitational collapse factor

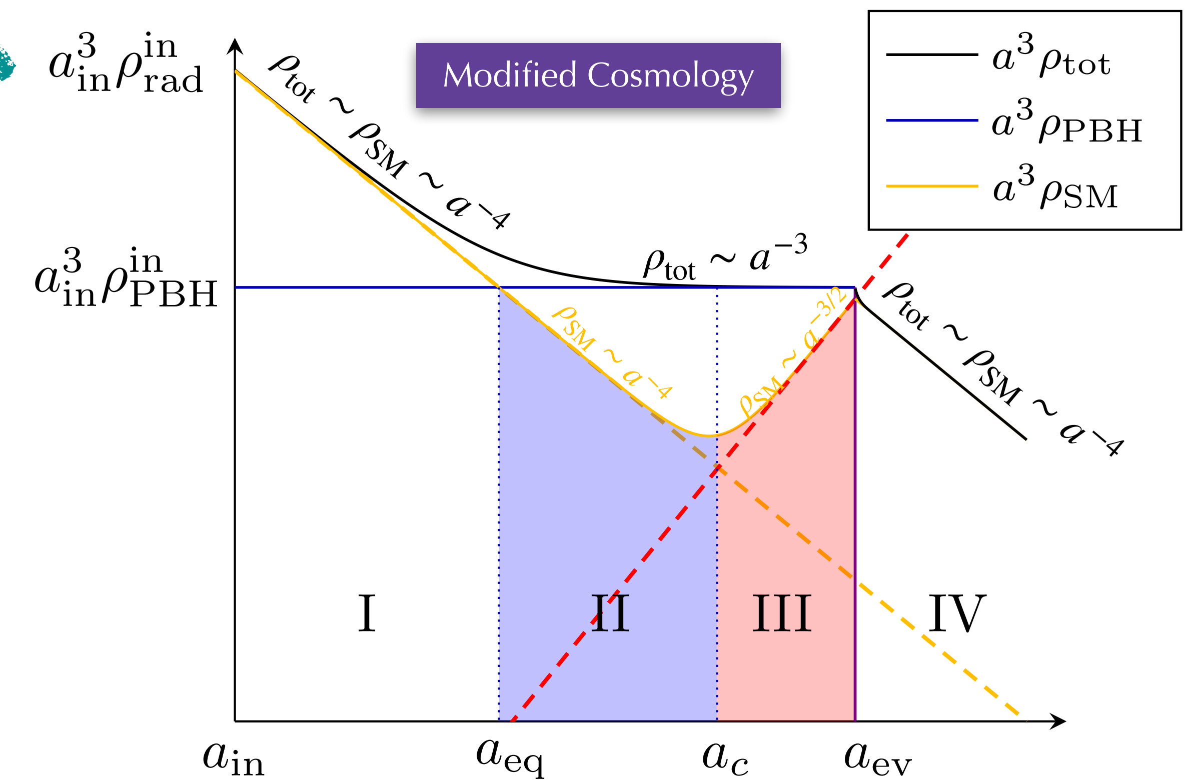
We focus on the region $M_{{\rm BH},i} \leq 10^9$ g

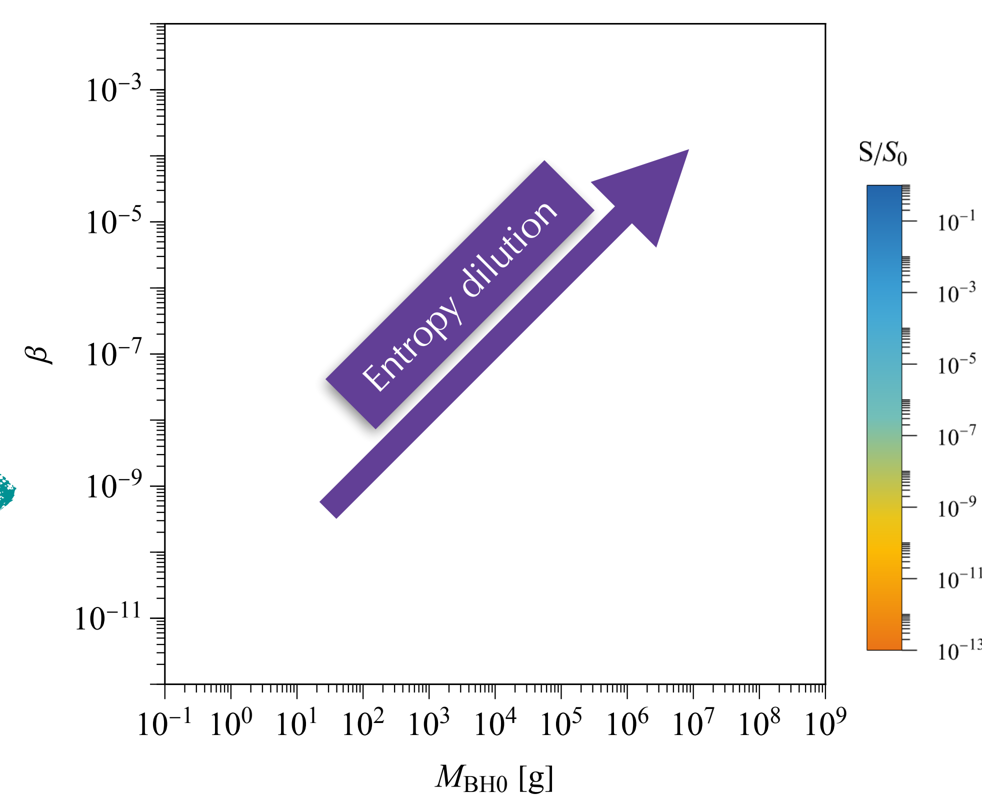
Carr et al. 2002.12778
Domènech et al. 2012.08151

B. Kavanagh
10.5281/zenodo.3538999

Effects on Particle Production







Effects on Particle Production

Baryon Asymmetry

- Modifying Baryogenesis scenarios
- Leptogenesis scenarios
- Producing a local asymmetry at PBH formation
- Connections with PBH-DM

Baumann, Steinhadt, Turok, 0703250
Yamada and Iso, 1610.02586
Fujita et al, 1401.1909
Morrison et al,1812.10606
García-Bellido, Carr, Clesse, 1904.11482
Hooper and Krnjaic, 2010.01134
YFPG and Turner: 2010.03565
Bernal, Fong, YFPG, Turner 2203.08823
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DM production (Besides PBH-DM)

- Purely Gravitationally interacting DM
- Modify Freeze-In/Freeze-out mechanisms
- Axions, ALPs…
- Superradiant enhancement

Fujita et al, 1401.1909
Morrison et al,1812.10606
Baldes et al, 2004.14773
Masina, 2004.04740, 2103.13825
Cheek, Heurtier, YFPG, Turner
2107.00013, 2107.00016, 2212.03878
Bernal, YFPG, Xu, 2205.11522
.
.
.

Dark Radiation

- Production of hot gravitons
- Testable from future measurements on $\Delta N_{\rm eff}$?

Hooper, Krnjaic, McDermott, 1905.01301
Lunardini, YFPG, 1910.07864
Masina, 2004.04740, 2103.13825
Cheek, Heurtier, YFPG, Turner, 2207.09462
.
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Evaporating PBHs

- See Hawking radiation!
- Test PBH properties
- Test BSM?

Baker, Thamm 2105.10506, 2210.02805
Capanema et al, 2110.05637
Calzà, Rosa, 2210.06500
YFPG, 2307.14408
.
.

Neutrinos and Leptogenesis

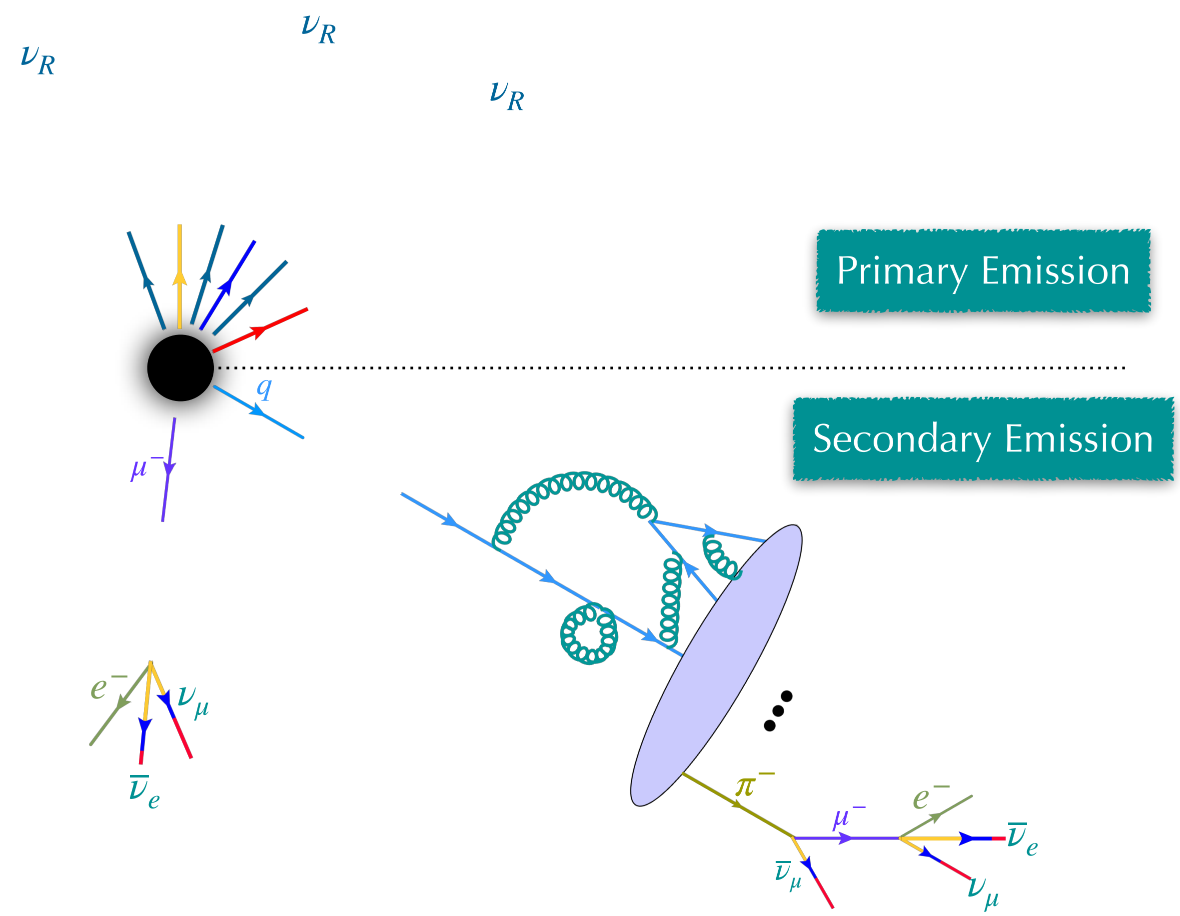
Based on:
Bernal, Fong, YFPG, Turner 2203.08823

Neutrino Emission for Schwarzschild BHs

Neutrinos are massive

↓

Dirac vs Majorana?



Weak interactions	Hawking Effect
Gauge interactions	Particle definition in a curved spacetime is observer dependent
Flavor eigenstate	***Mass*** eigenstate
ν_e ν_μ ν_τ	ν_1 ν_2 ν_3

Lunardini, YFPG
JCAP08(2020)014

Dirac neutrinos

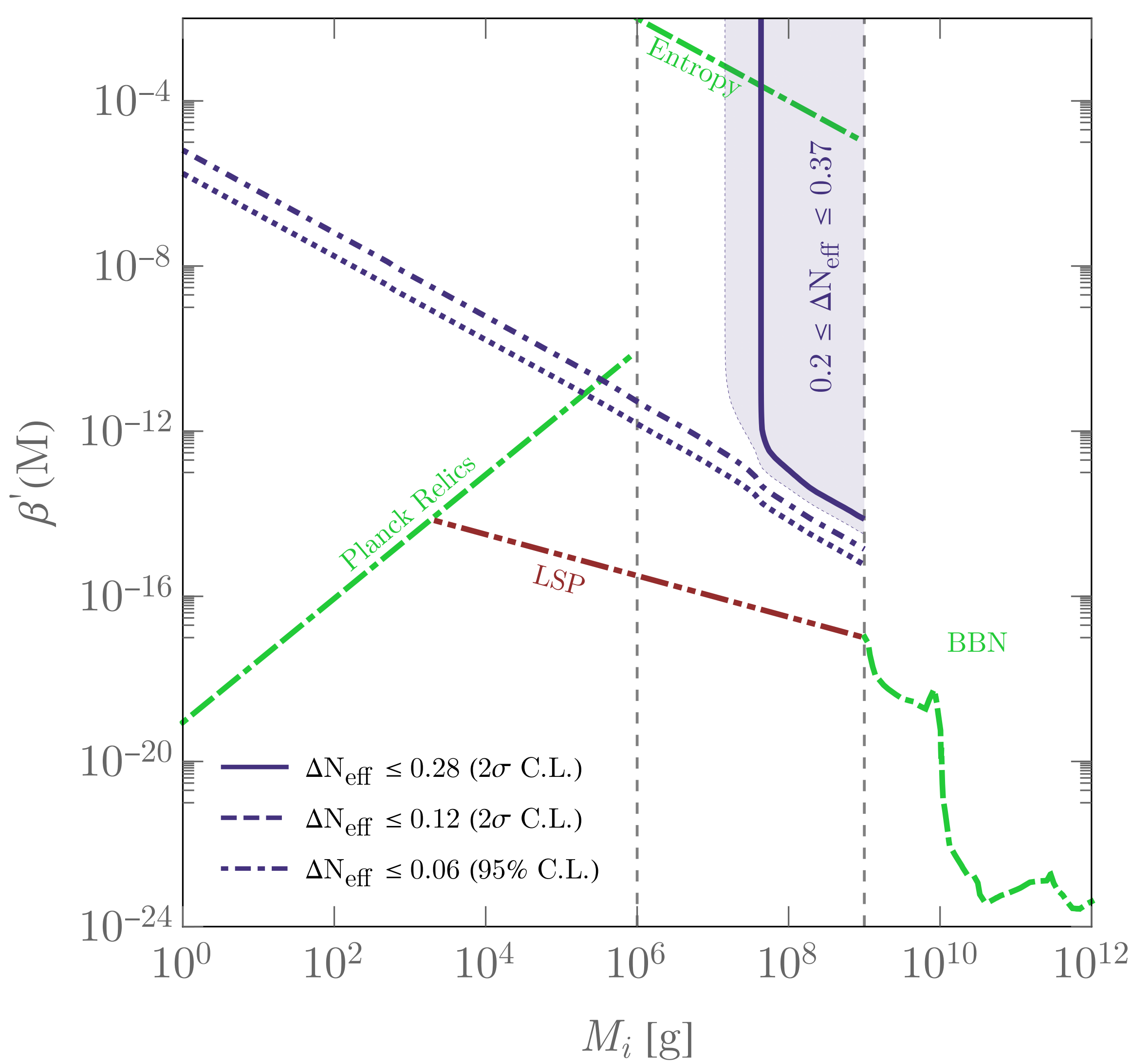
VS

Majorana neutrinos

$$\sigma^{\nu}_{\rm abs}(+1/2) = \sigma^{\nu}_{\rm abs}(-1/2)$$

No helicity suppression

Unruh, 1976



Production of light RH neutrinos $\to \Delta N_{\rm eff}$

Cecilia Lunardini, YFPG
JCAP08(2020)014

Heavy RH neutrinos

PBH-induced Leptogenesis

Baumann, Steinhadt, Turok, 0703250
Fujita et al, 1401.1909
Morrison et al,1812.10606
Hooper and Krnjaic, 2010.01134
.
.
.

Detailed interplay with Thermal Leptogenesis

YFPG and Turner,
PRD 104(2021) 103021
Bernal, Fong, YFPG, Turner
2203.08823

High Scale Leptogenesis

RH reaches equilibrium abundance

$M_N \gtrsim 10^{12}$ GeV

RH neutrinos are produced

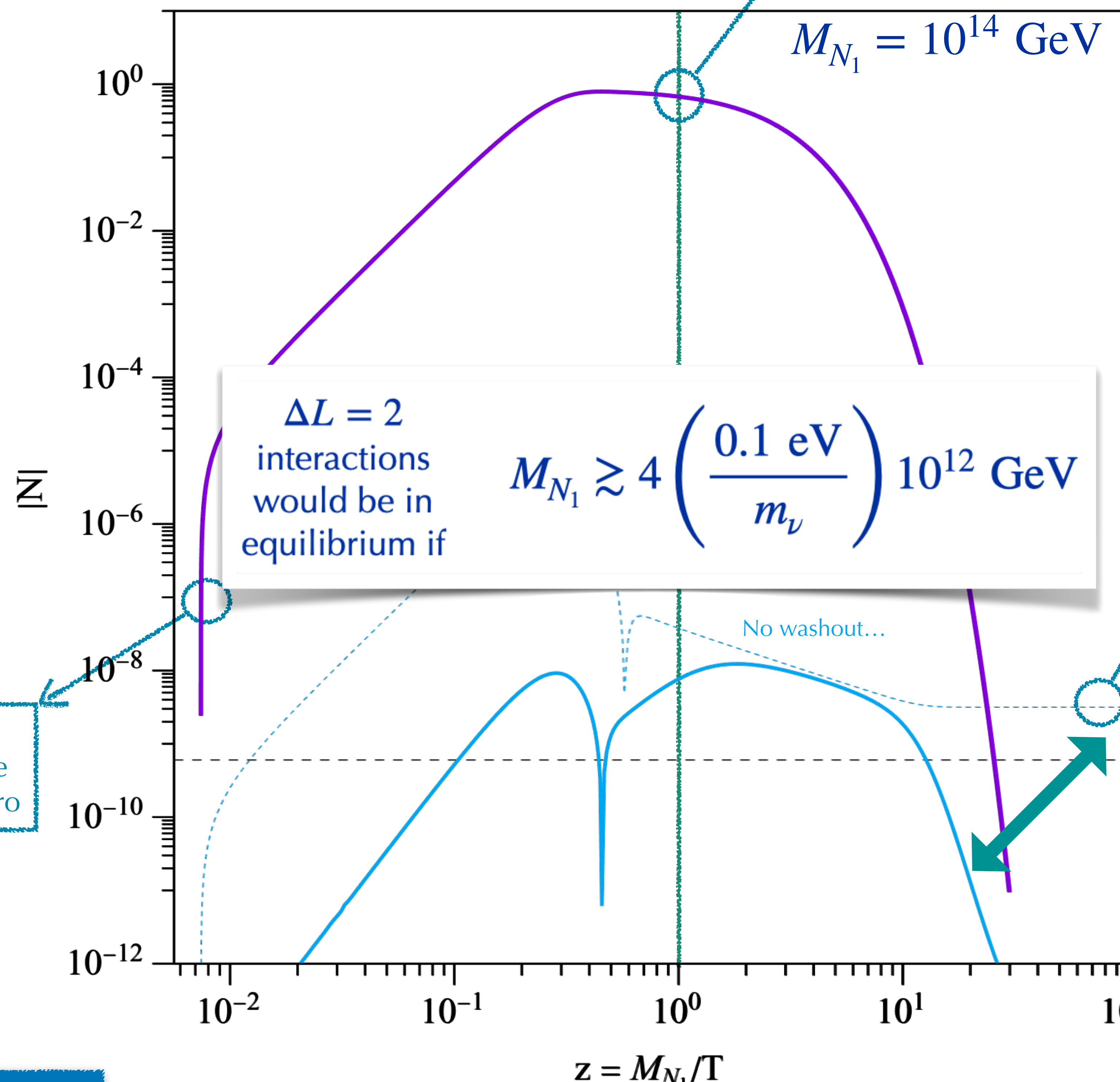
$N \to \bar{L}H$

$N \to LH$

Lepton asymmetry is created

Sphaleron processes

Baryon asymmetry



Initial abundance taken as zero

Freeze out of baryon asymmetry

Strong Washout from $\Delta L = 2$ processes

$\bar{\ell} H^\dagger \leftrightarrow \ell H$

$\ell \ell \to H^\dagger H^\dagger$

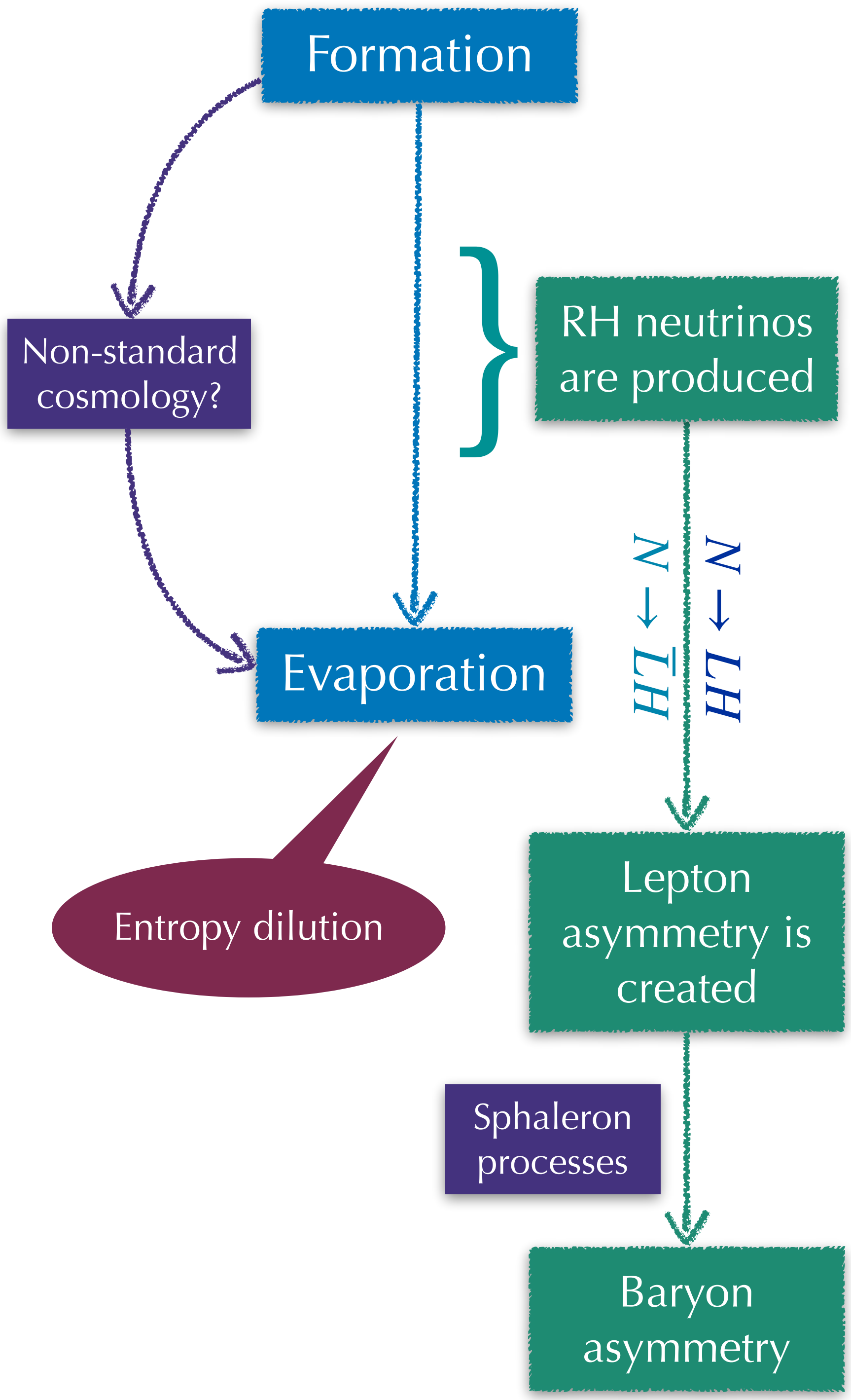
How to save HSL? → Produce RHNs after washout process have frozen out?

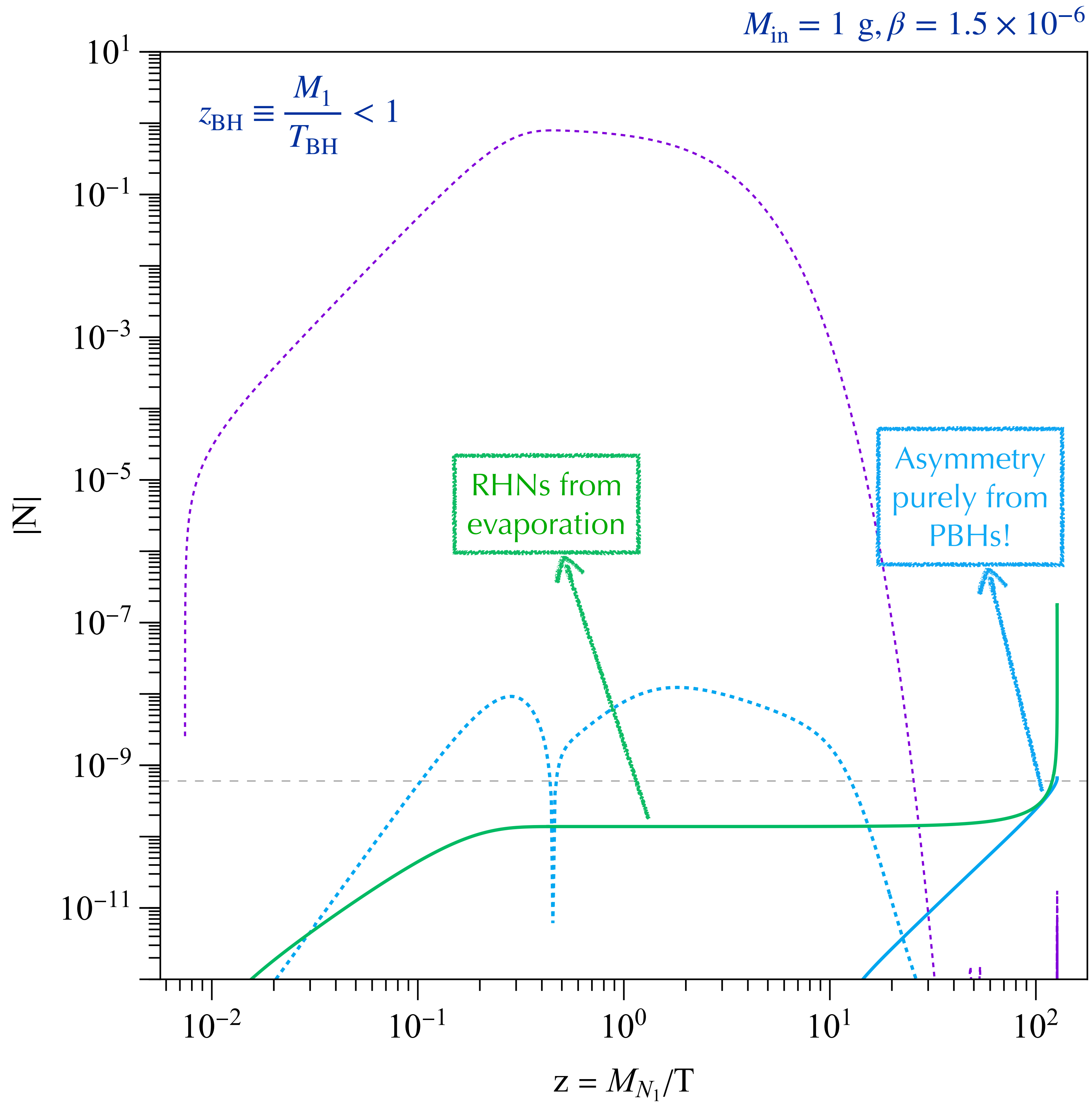
PBHs!

Fukugida, Yanagida'86,
Giudice *et al.*, 2004
Buchmuller *et al.*, 2005

Bernal, Fong, YFPG, Turner 2203.08823

PBH + Leptogenesis

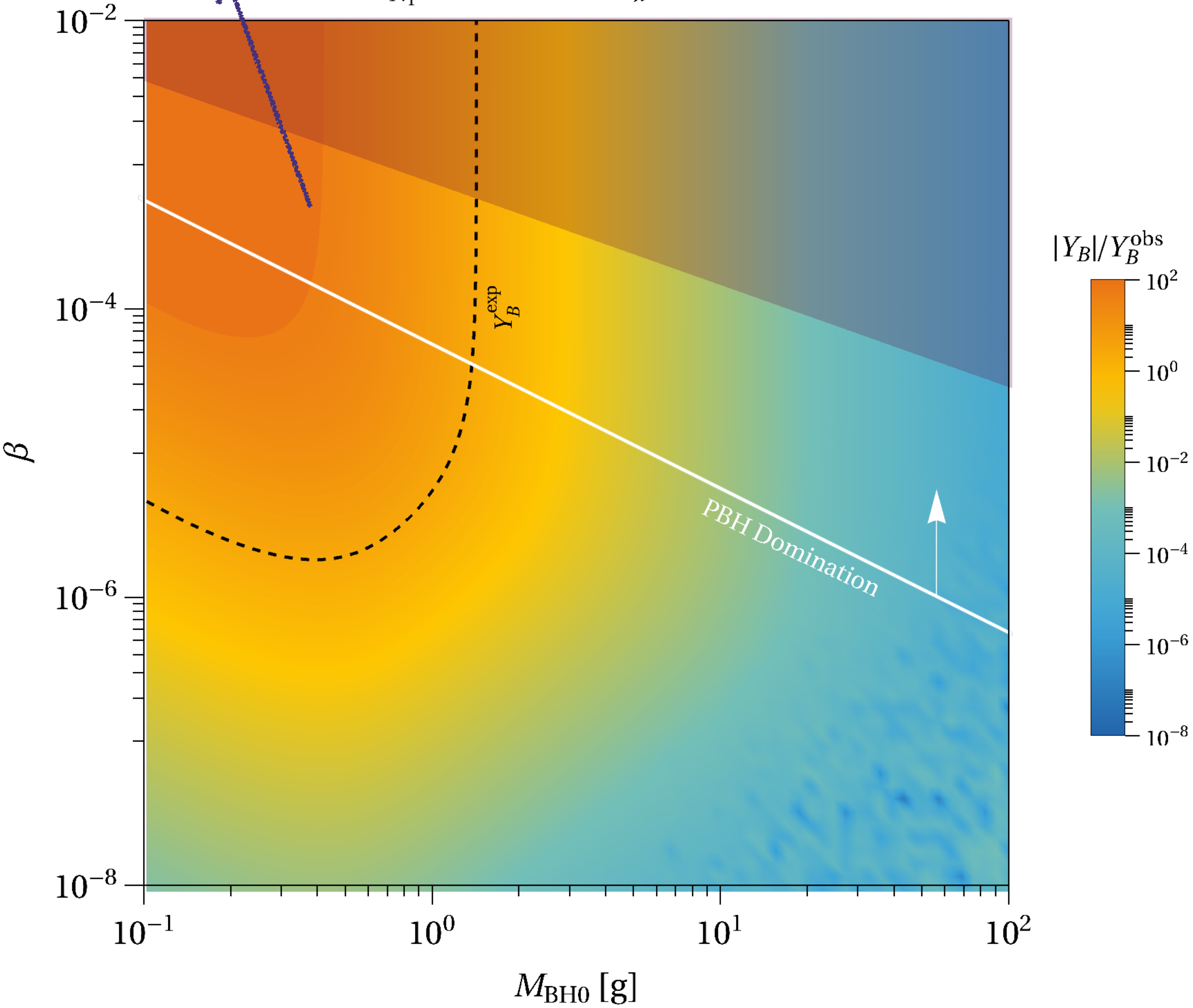




Bernal, Fong, YFPG, Turner 2203.08823

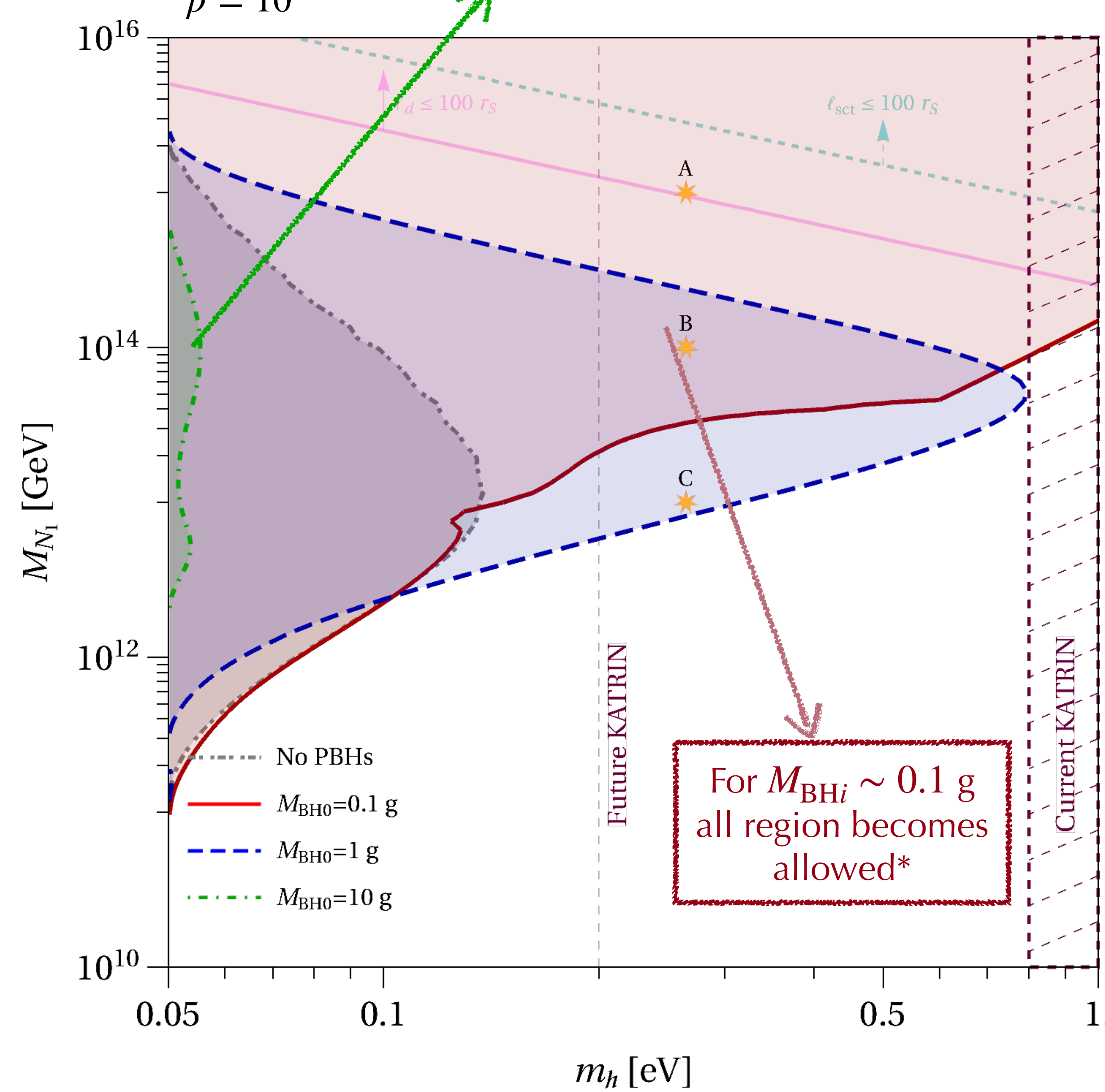
Rescuing HSL

$\mathcal{O}(10^6)$ enhancement



$M_{\mathrm{BH}i} \gtrsim 1$ g Entropy dilution

Colored Regions with $|Y_B| \gtrsim Y_B^{\rm obs}$



For $M_{\mathrm{BH}i} \sim 0.1$ g all region becomes allowed*

m_h = Heaviest neutrino mass

PBHs allow for viable HS leptogenesis for heavier active neutrinos

Maximizing over Yukawa parameters

*Up to perturbativity

Bernal, Fong, YFPG, Turner 2203.08823

Mass Distributions

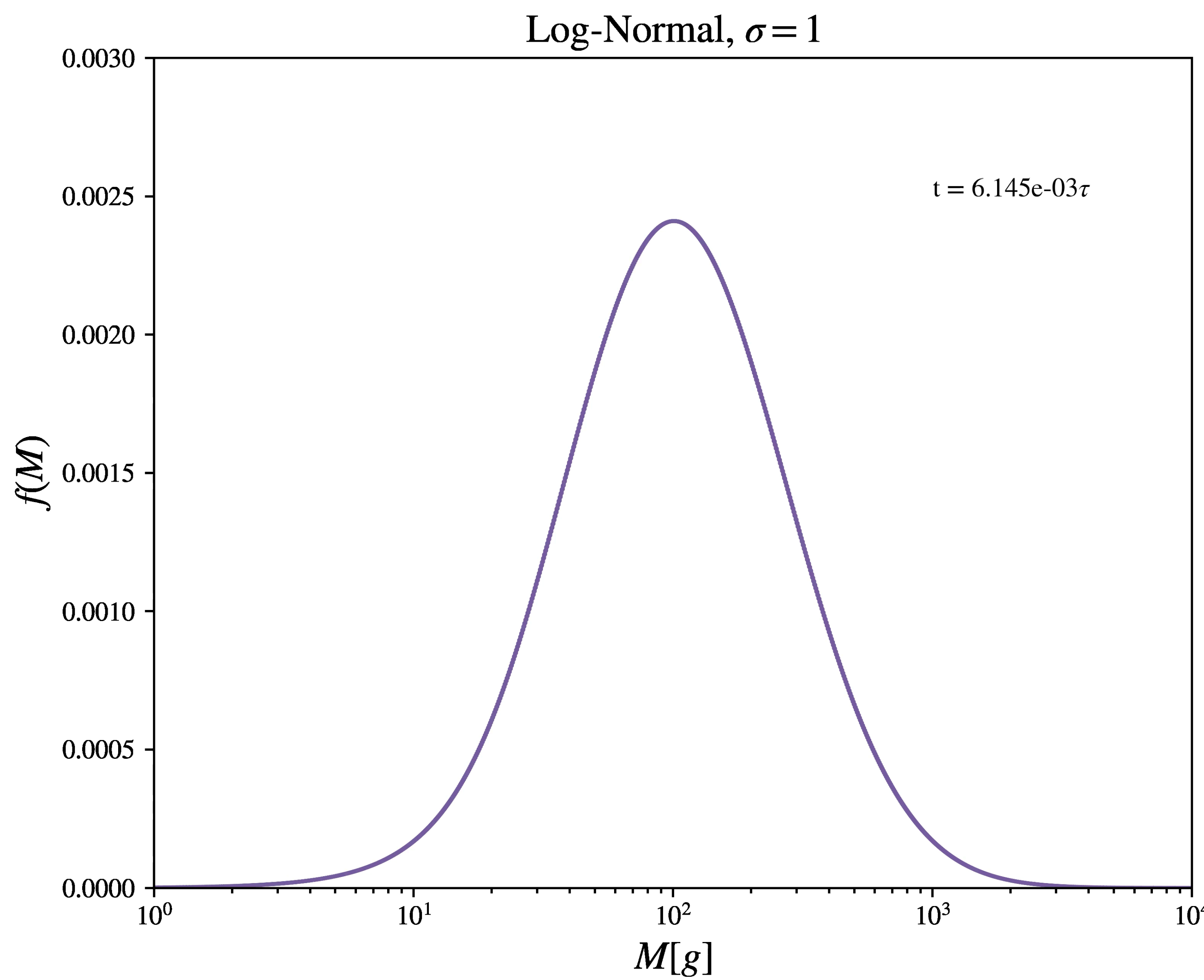
Monochromatic approximation *too* approximated?

$$n_{\rm PBH} = \int dM\, f(M) \qquad f(M) = \frac{n_{\rm BH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$

Log-normal distribution

Dolgov, 93
Green, 2016
Kannike, 2017

Connection with different formation mechanisms?



Having PBHs with different masses could have a distinct impact on the previous results

Mass Distributions

Dolgov, 93
Green, 2016
Kannike, 2017

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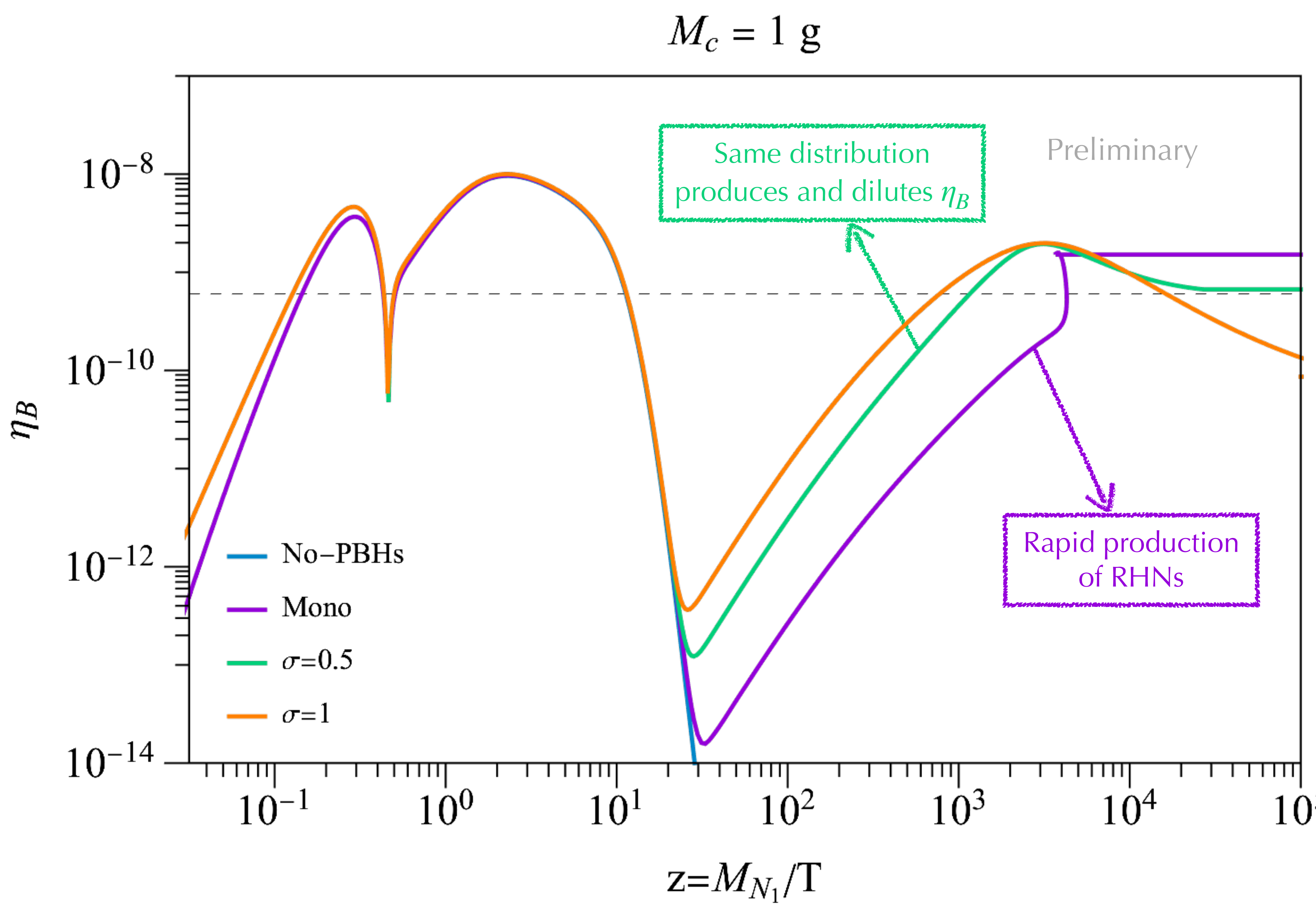
$$n_{\rm PBH} = \int dM\, f(M) \qquad f(M) = \frac{n_{\rm BH}}{\sqrt{2\pi}\sigma M} \exp\left(-\frac{\log^2(M/M_c)}{2\sigma^2}\right)$$



Having PBHs with different masses could have a distinct impact on the previous results

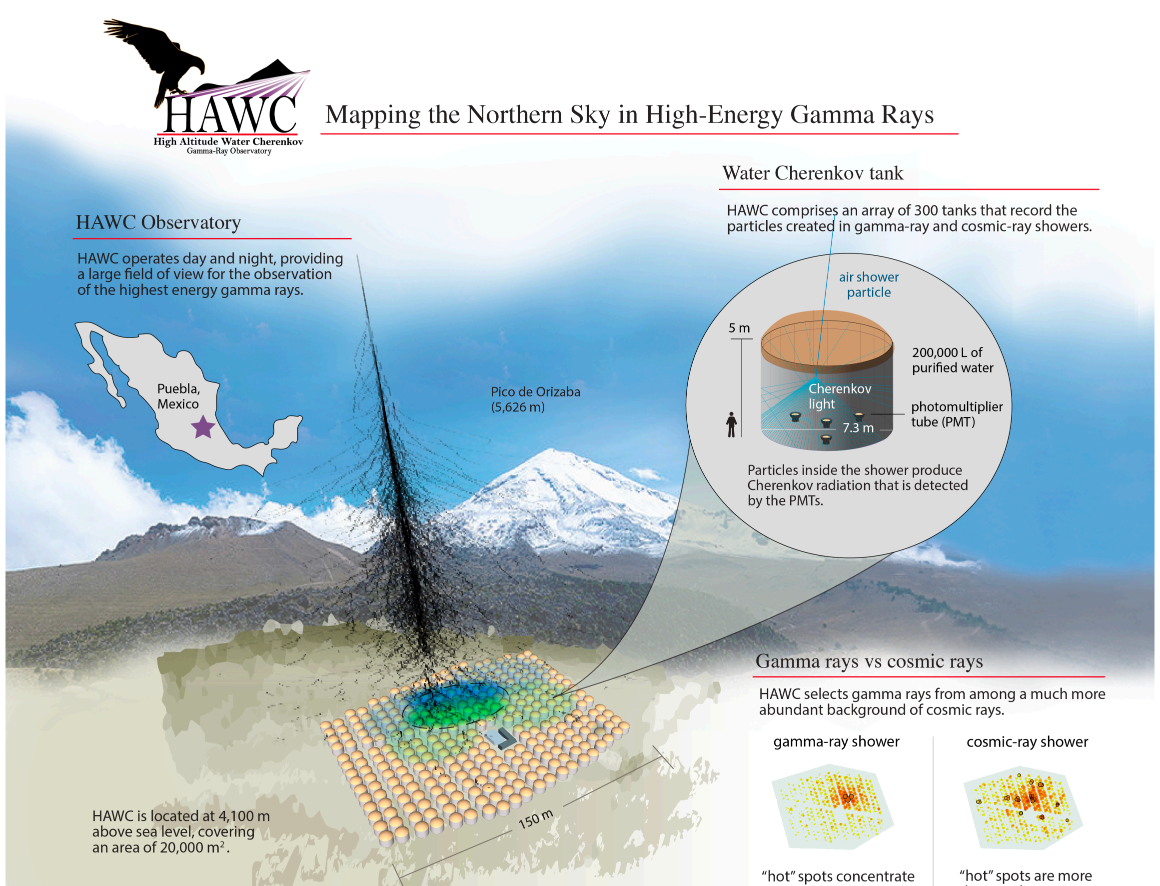
High Energy Neutrinos and Evaporating PBHs

Based on:
YFPG, 2307.14408

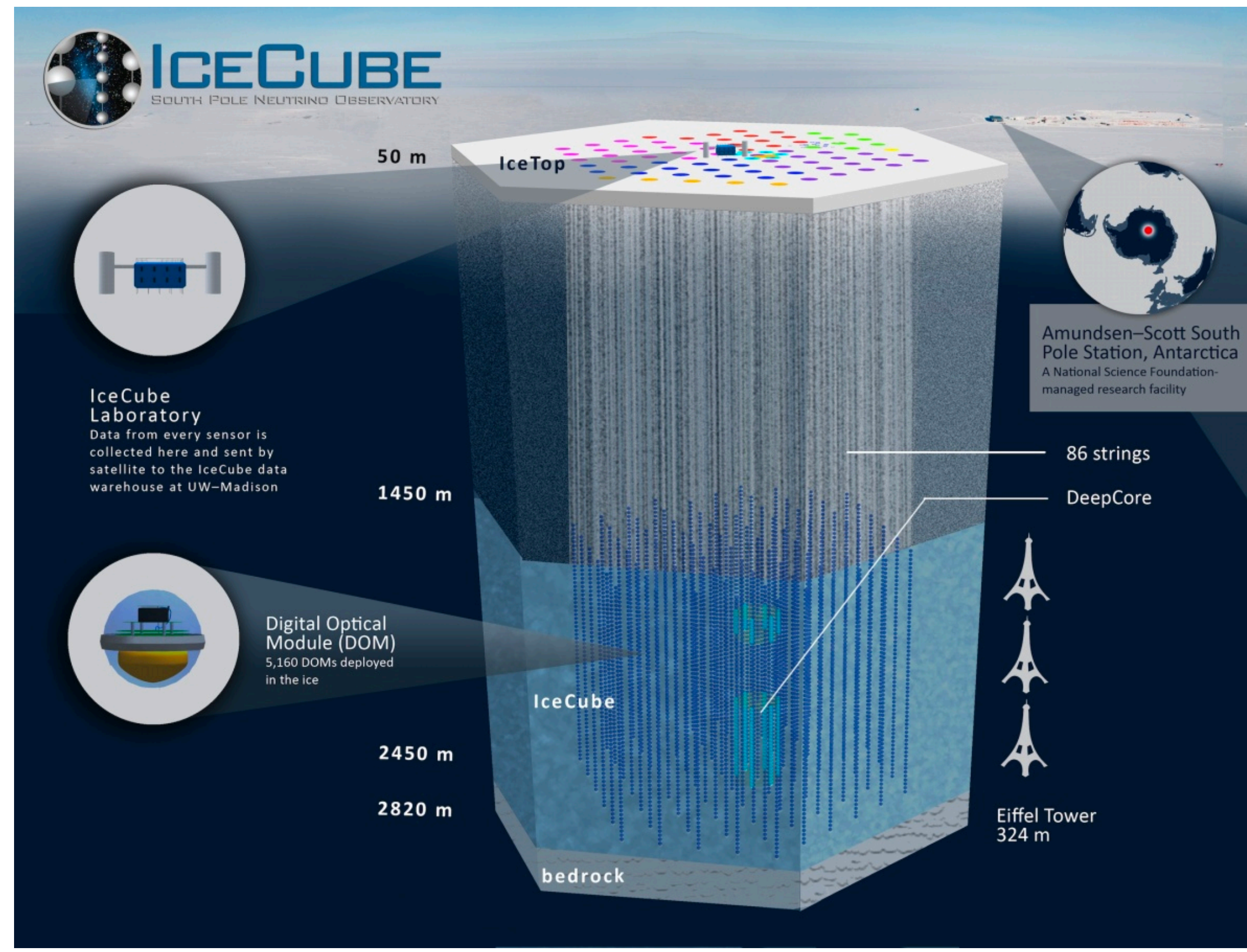
Evaporating PBHs (EPBH)

- Perhaps some PBHs are evaporating today $M_{\rm BH,i} \sim 10^{15}$ g

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



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



- Test BSM??

Baker, Thamm 2105.10506, 2210.02805

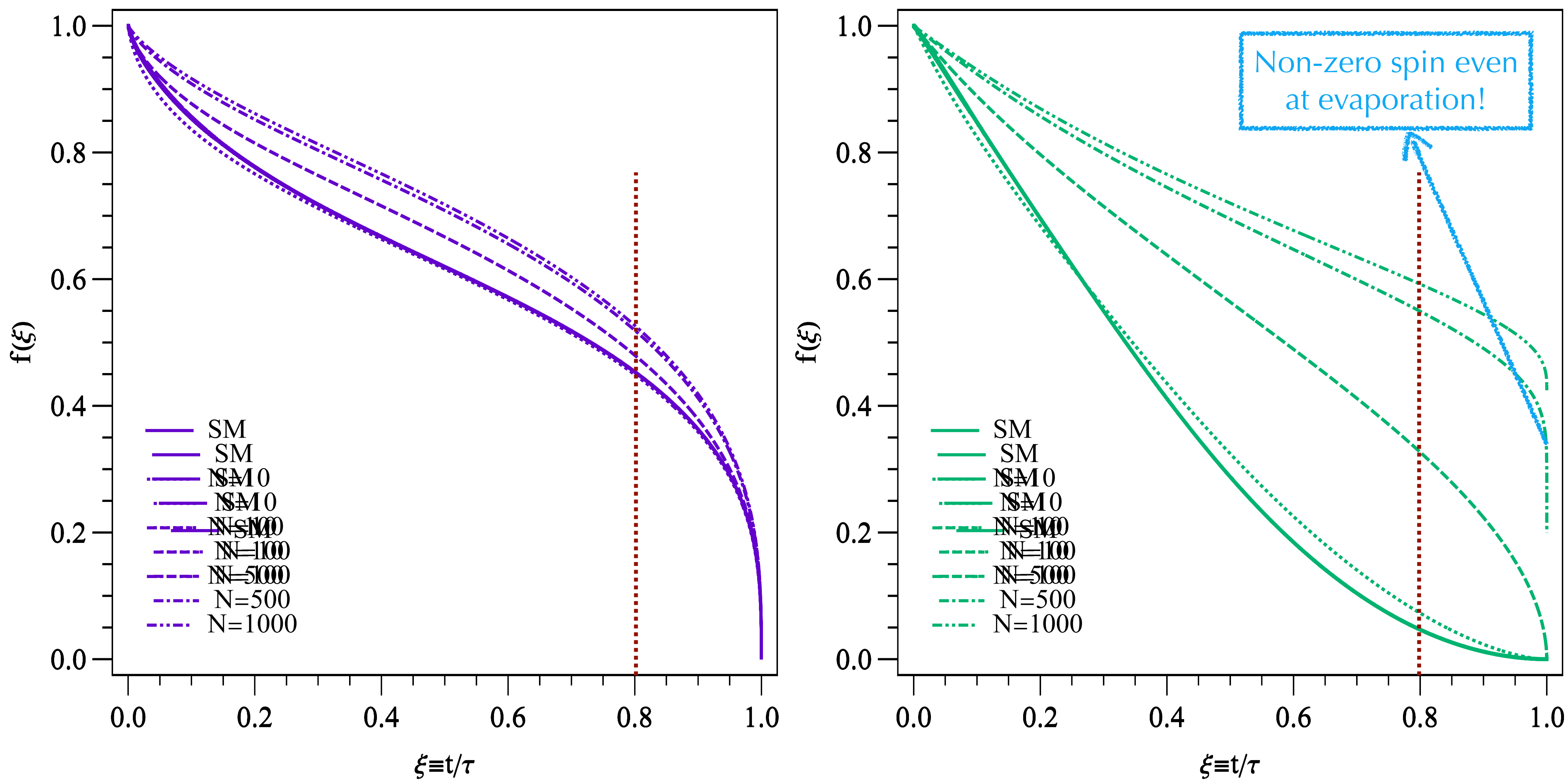
Kerr EPBHs

How could a PBH retain its spin until today?

String Axiverse

Arvanitaki, et al, 0905.4720

Scalars only reduce the PBH mass



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

Capanema et al, 2110.05637
Calzà, Rosa, 2210.06500

Photons dominate the measurement

Anything to learn from neutrinos?

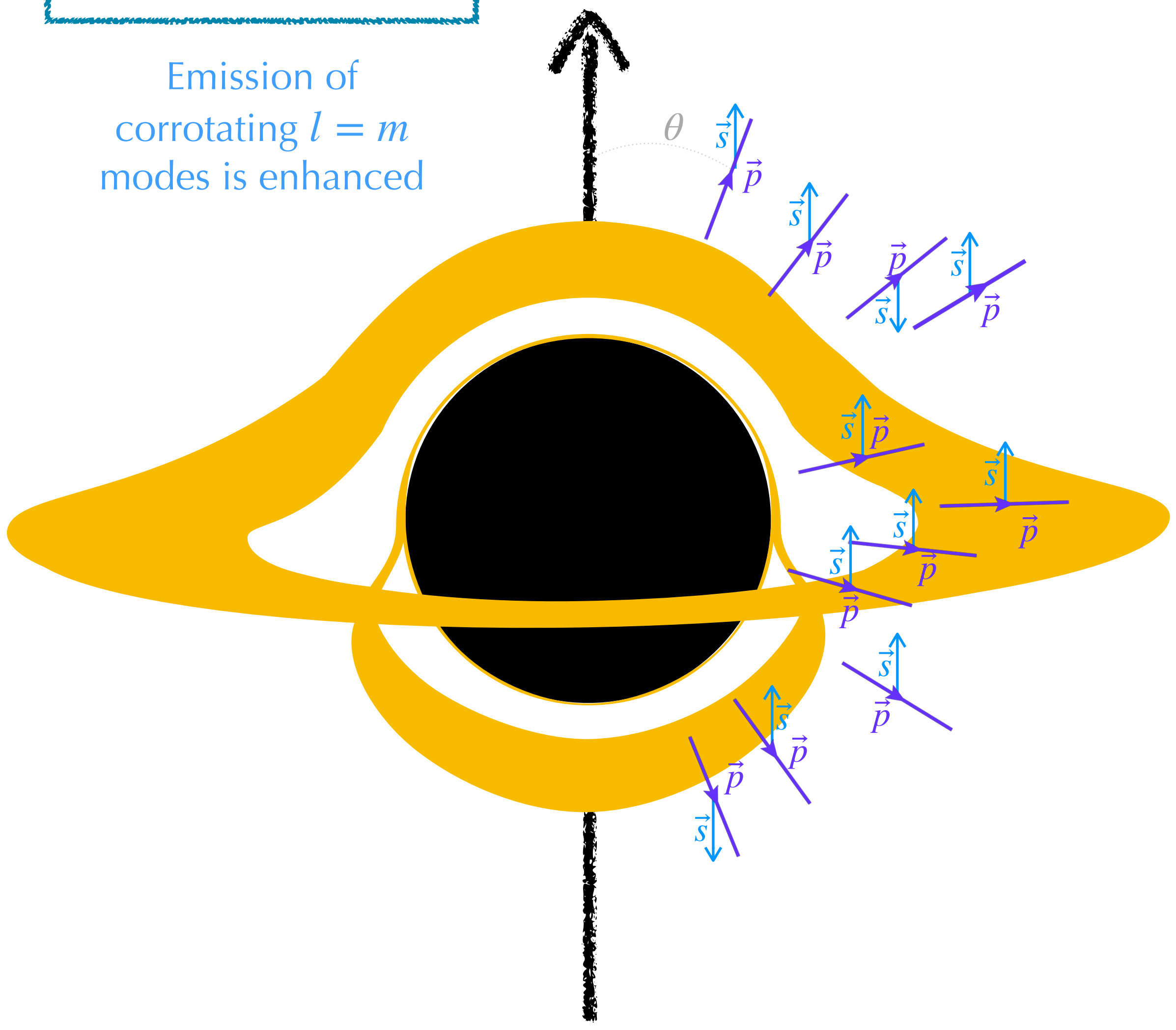
Parity Violation!!

How does it manifest in Hawking evaporation?

Neutrino Emission Asymmetry

BH “wants” to shed off its angular momentum

Emission of corrotating $l = m$ modes is enhanced



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

*in the ultrarrelativistic limit

Neutrino Emission Asymmetry

$\theta \to$ polar angle

BH "wants" to shed off its angular momentum

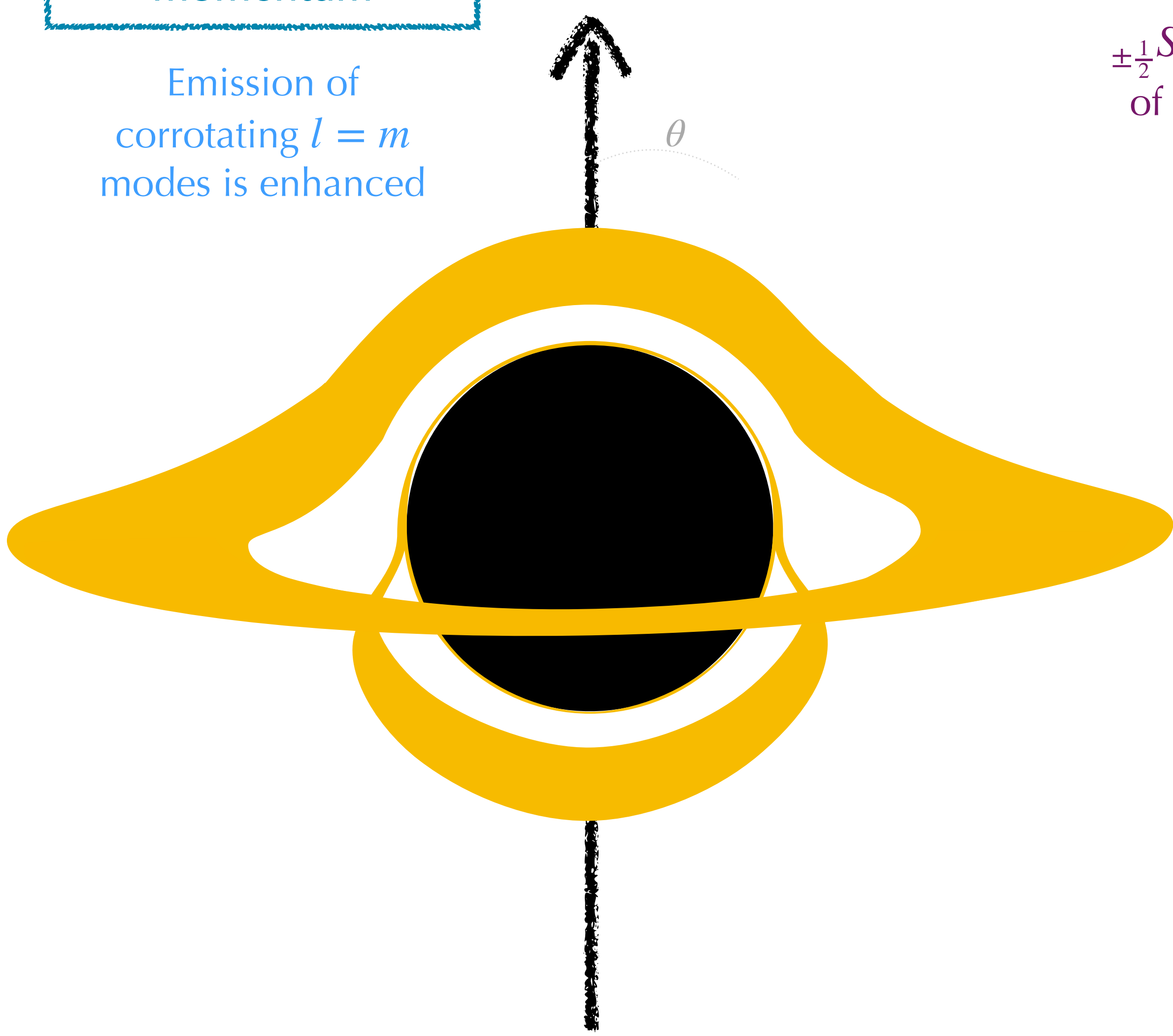
$\mathscr{A} \equiv N_\nu - N_{\bar{\nu}}$

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

"Neutrinos" "Antineutrinos"

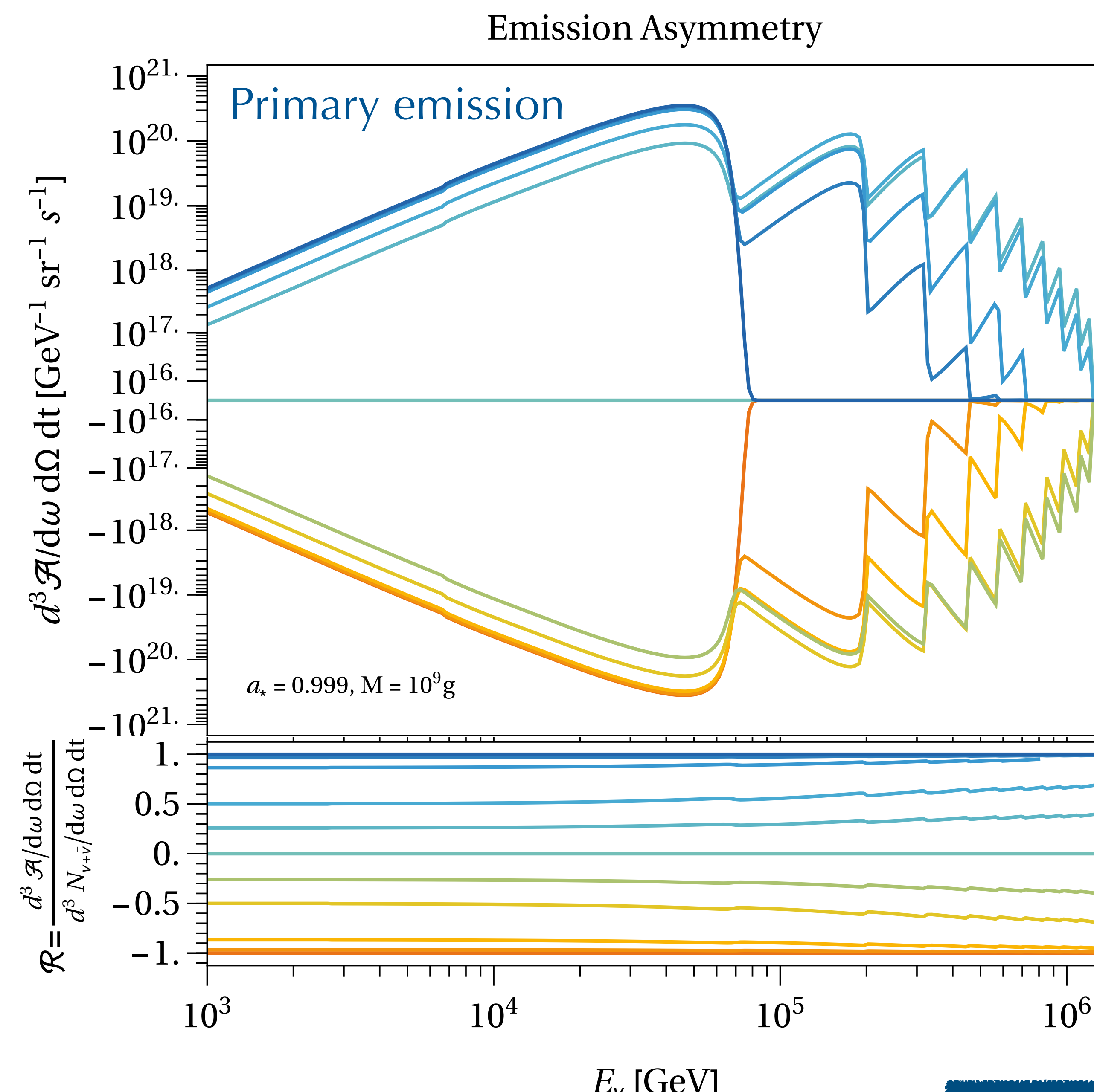
${}_{\pm\frac{1}{2}}S_{lm}(\theta) \to$ solutions of angular equation

Emission of corrotating $l = m$ modes is enhanced



Axis of rotation

Could neutrinos tell us the spin of a PBH?



YFPG 2307.14408

Photons?

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

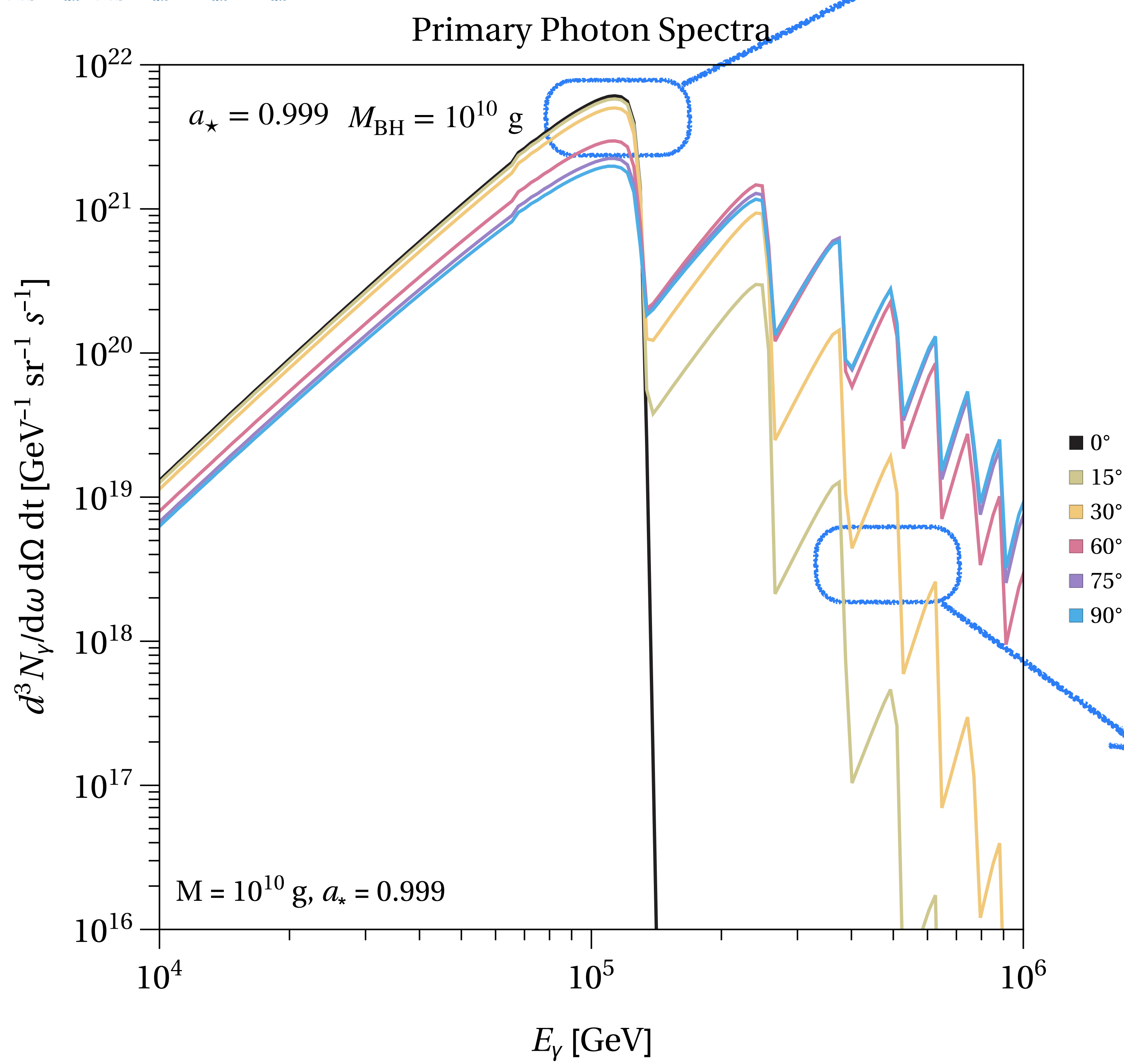
Emission of corrotating $l = m$ modes is enhanced

Also dependent on the polar angle

↓

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

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



In the poles only $l = 1$ contribute

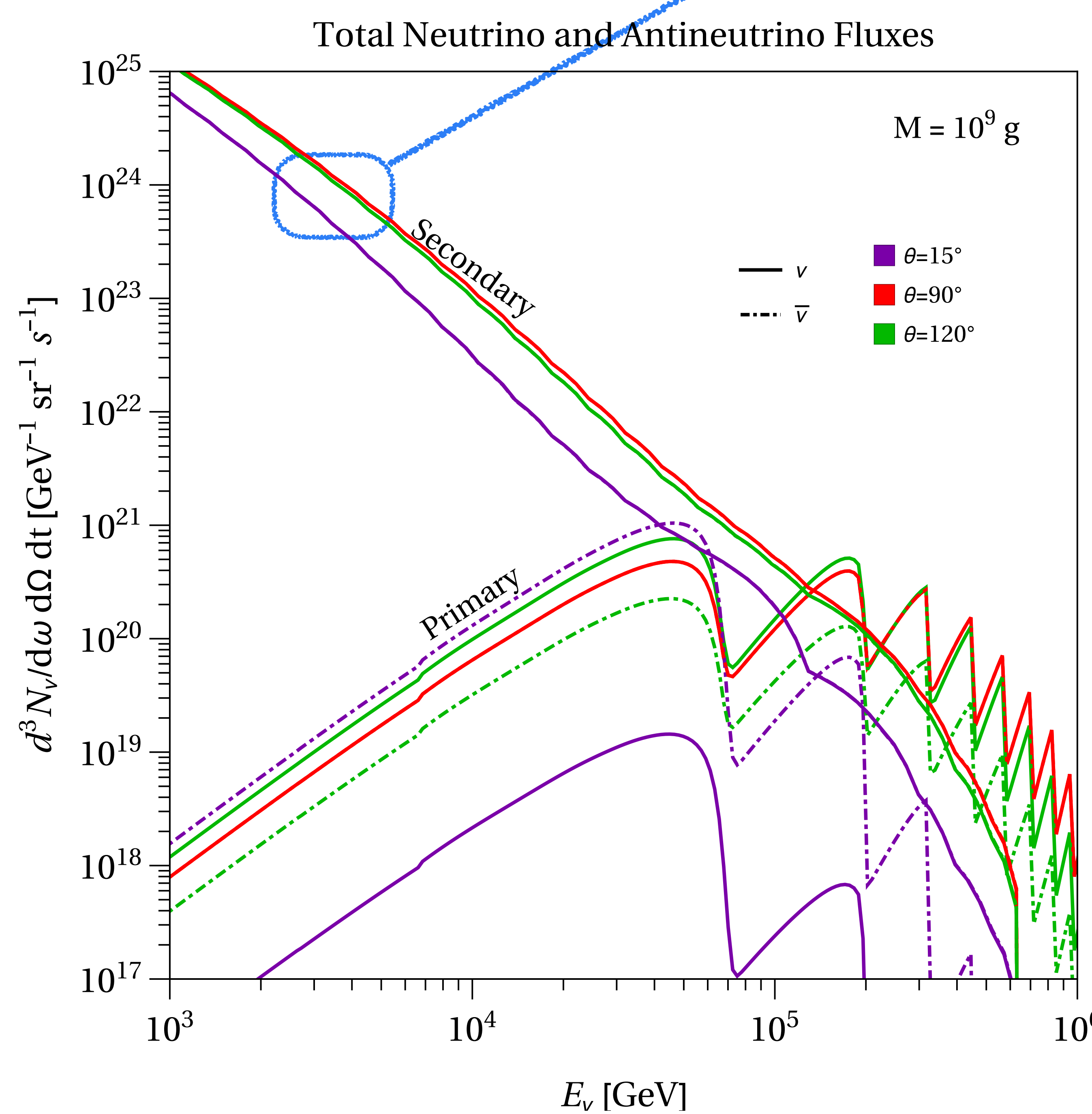
Modes start to contribute for larger θ

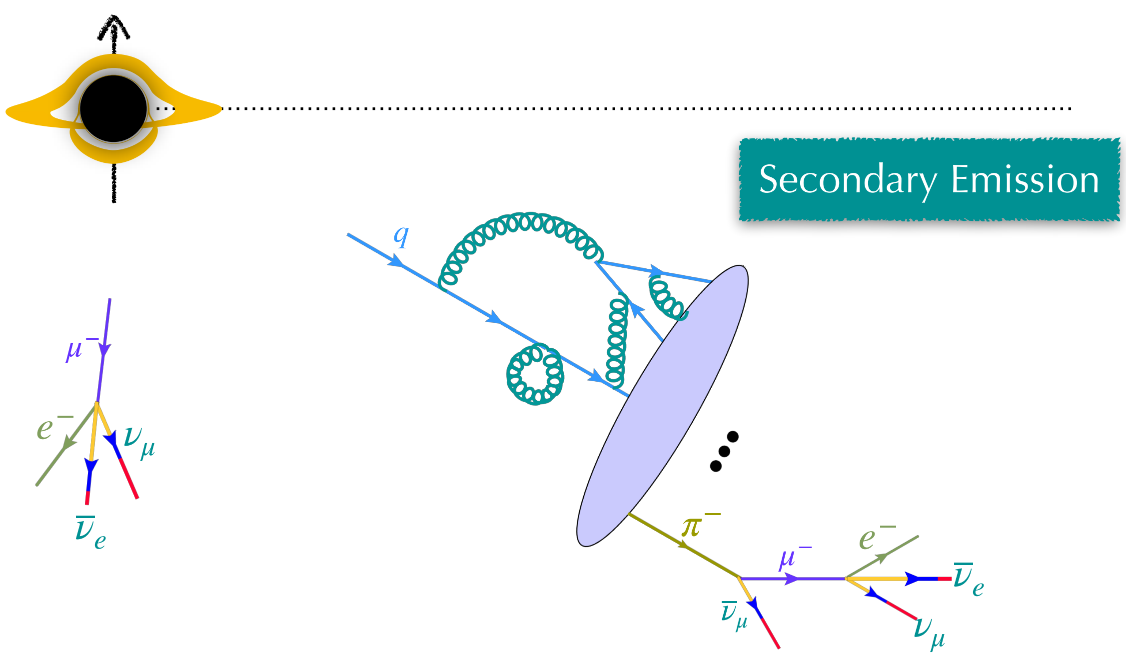
Secondaries?

No difference between ν and $\overline{\nu}$

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

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

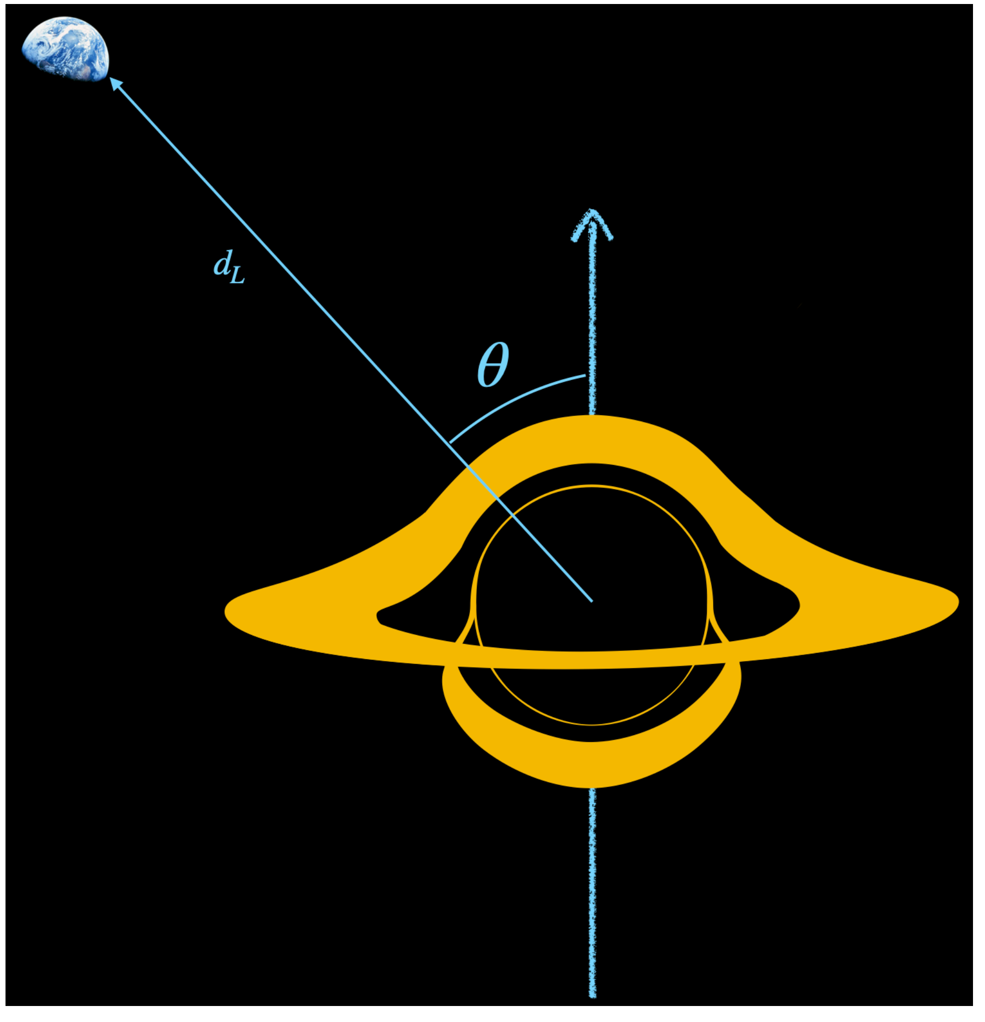




Determining the angular momentum

Previous works ignored the dependence on θ

Neutrino - antineutrino events will depend on θ

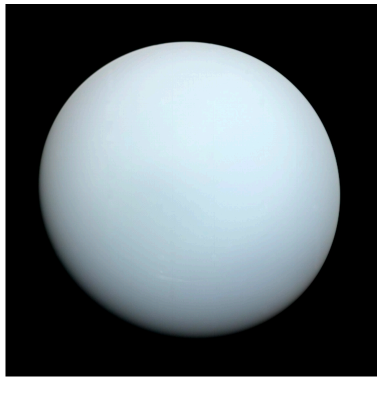


IceCube/HAWK effective area

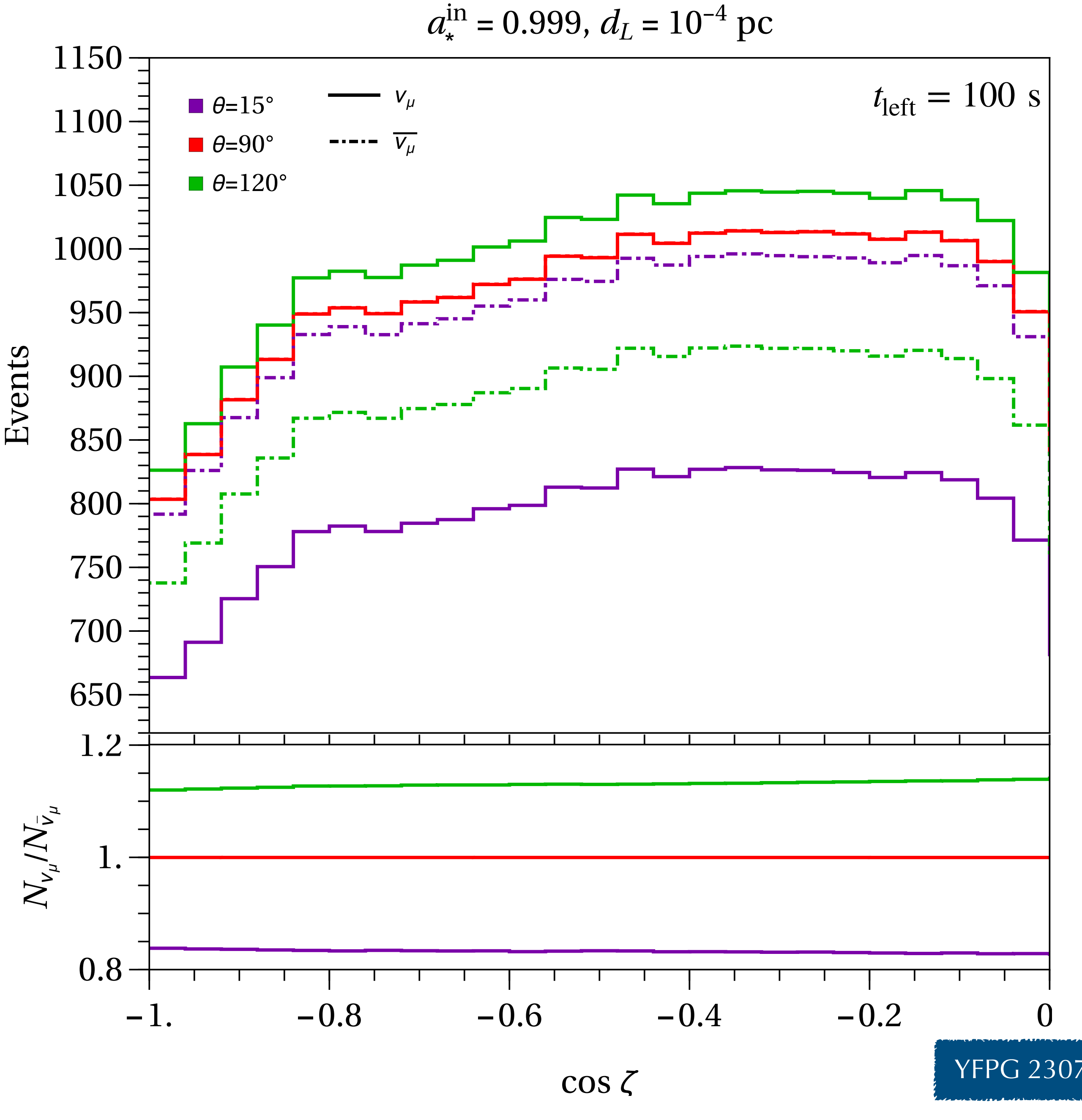
$$N_X(\theta) = \frac{1}{d_L^2}\int_{\omega_{\min}}^{\omega_{\max}}\int_0^{\tau} dt \, \frac{d^3N_X}{d\omega dt d\Omega} A_{\rm eff}(\omega,\zeta) d\omega$$

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

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



Uranus - Sun



YFPG 2307.14408

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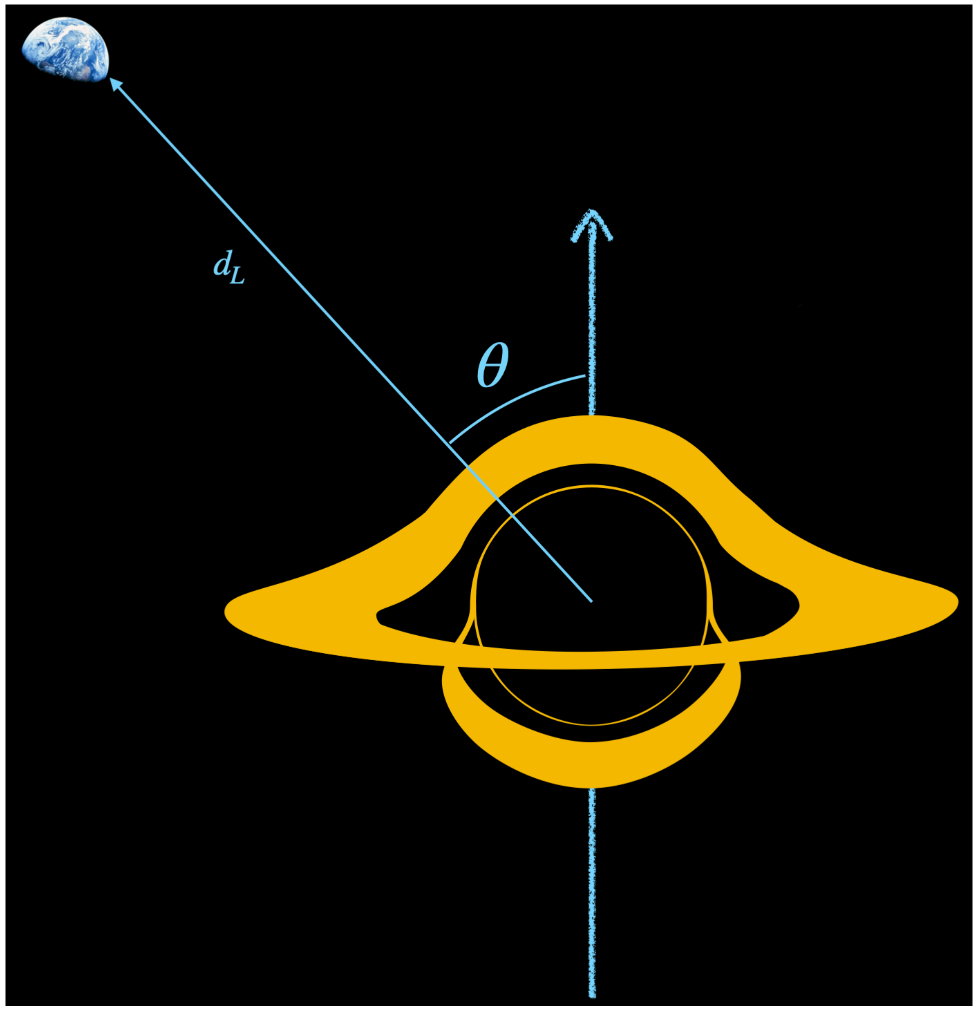
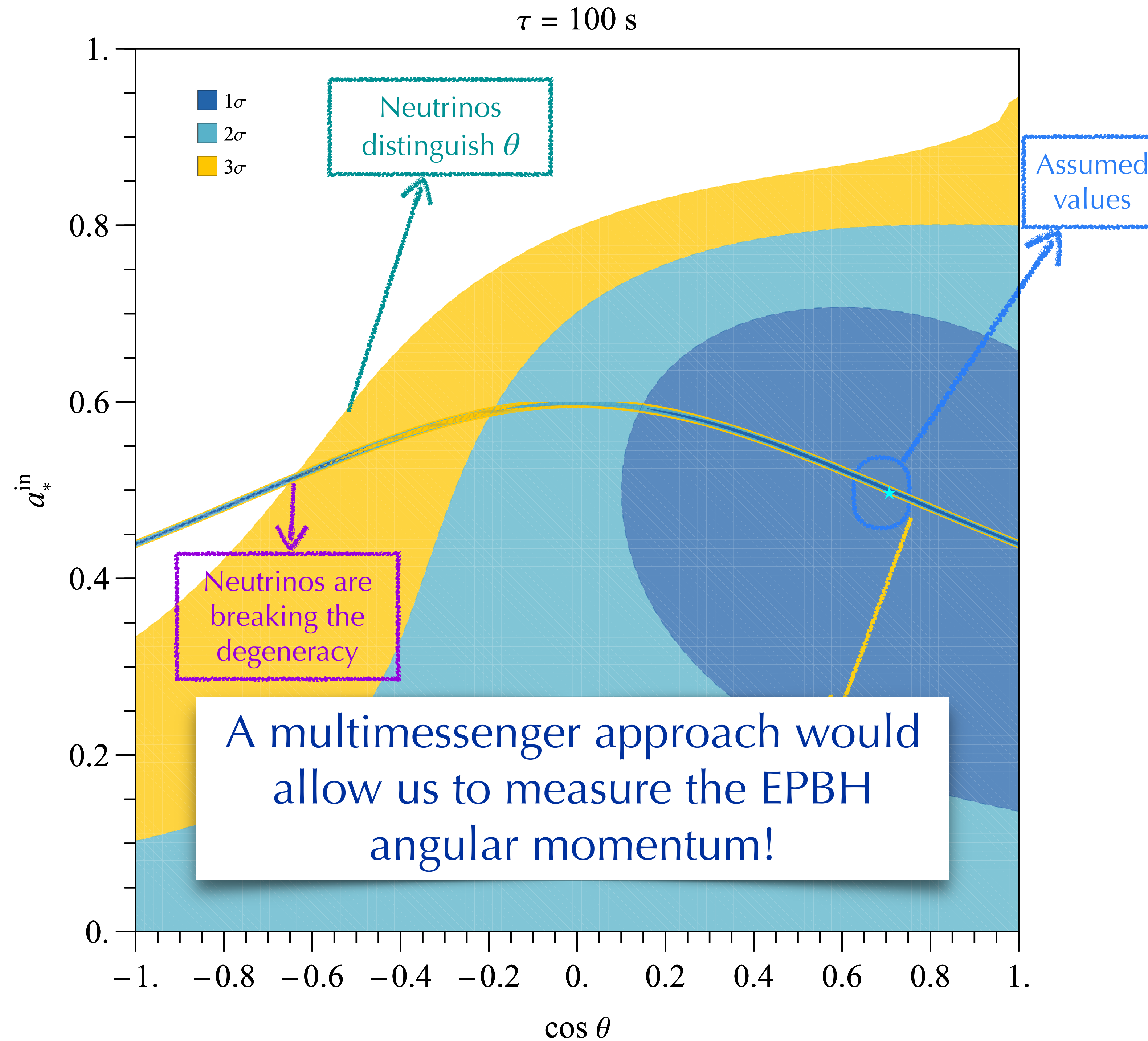


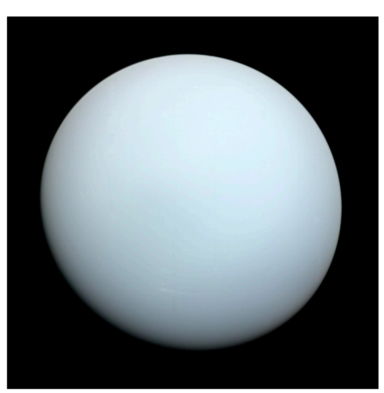
Assume: $a_\star = 0.5,\ \theta = 45^\circ,\ \zeta = -18^\circ$

Best case scenario



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

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



Uranus - Sun

YFPG 2307.14408

Summary

- PBH evaporation offers a unique mechanism to produce particles in the Early Universe
- The effects are threefold:
  - Universal particle emission
  - Modifying the Cosmological Background
  - Entropy dilution
- Future directions:
  - Relating to “more realistic” PBH formation mechanisms (connected to PBH-DM?)
  - Low scale leptogenesis? Sphalerons around PBHs after EWPT?
  - Kerr PBH $\longrightarrow$ Additional interesting properties!
  - Anything else to learn by measuring neutrinos & antineutrinos in IC for an EPBH?

Thank you!


KARL
SCHWARZSCHILD
ALFRED
SCHWARZSCHILD
GEB. 24. OKT. 1914
GEST. 12. MAI 1944
ELSE
SCHWARZSCHILD
GEB. ROSENBACH
GEB. 28. SEPT. 1879
GEST. 29. DEZ. 1950