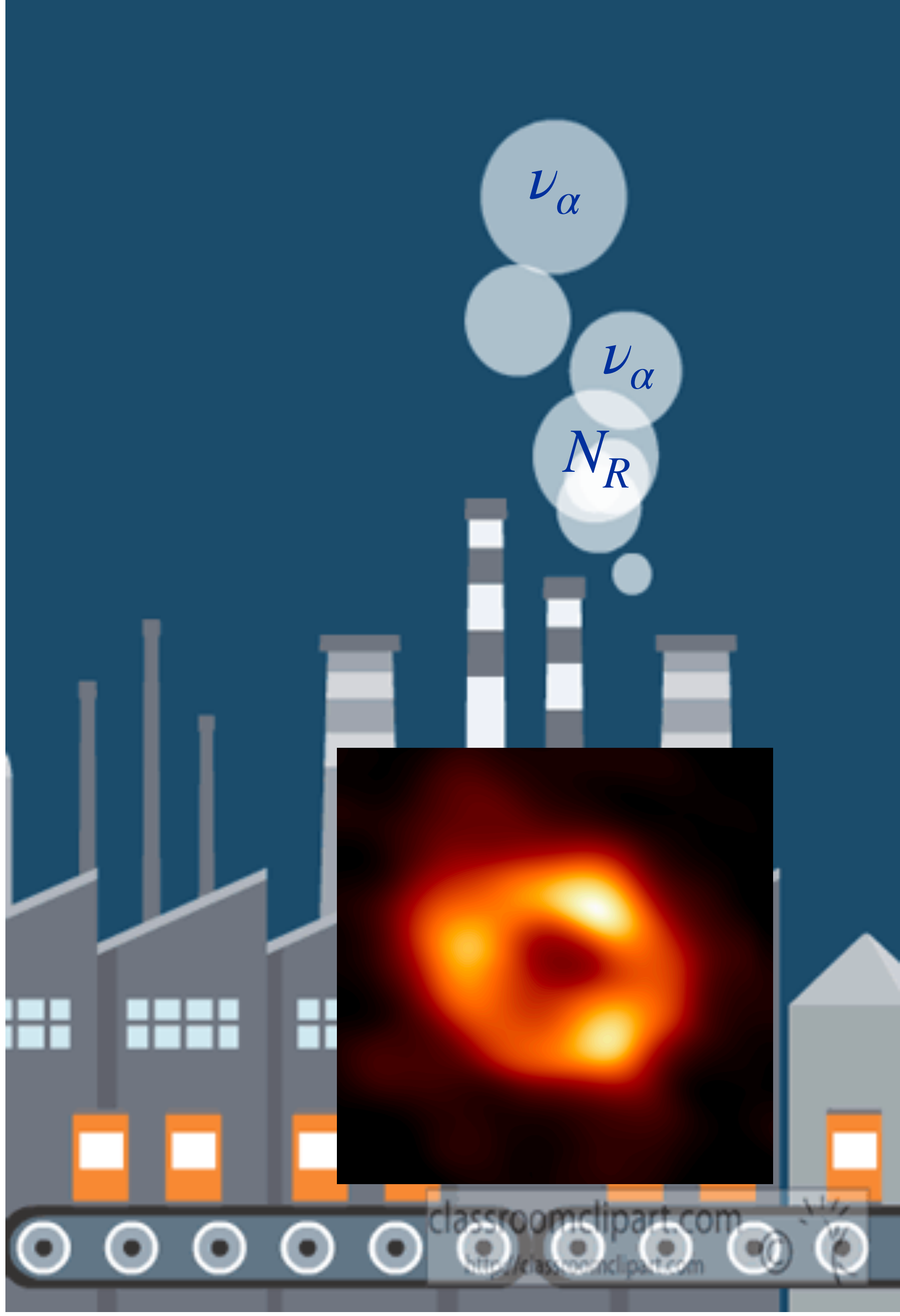
Primordial Black Holes as Particle Factories and Implications for the Early Universe

Yuber F. Perez-Gonzalez

Particle and Astroparticle Theory Seminar
Max-Planck-Institute für Kernphysik
June 26th, 2023



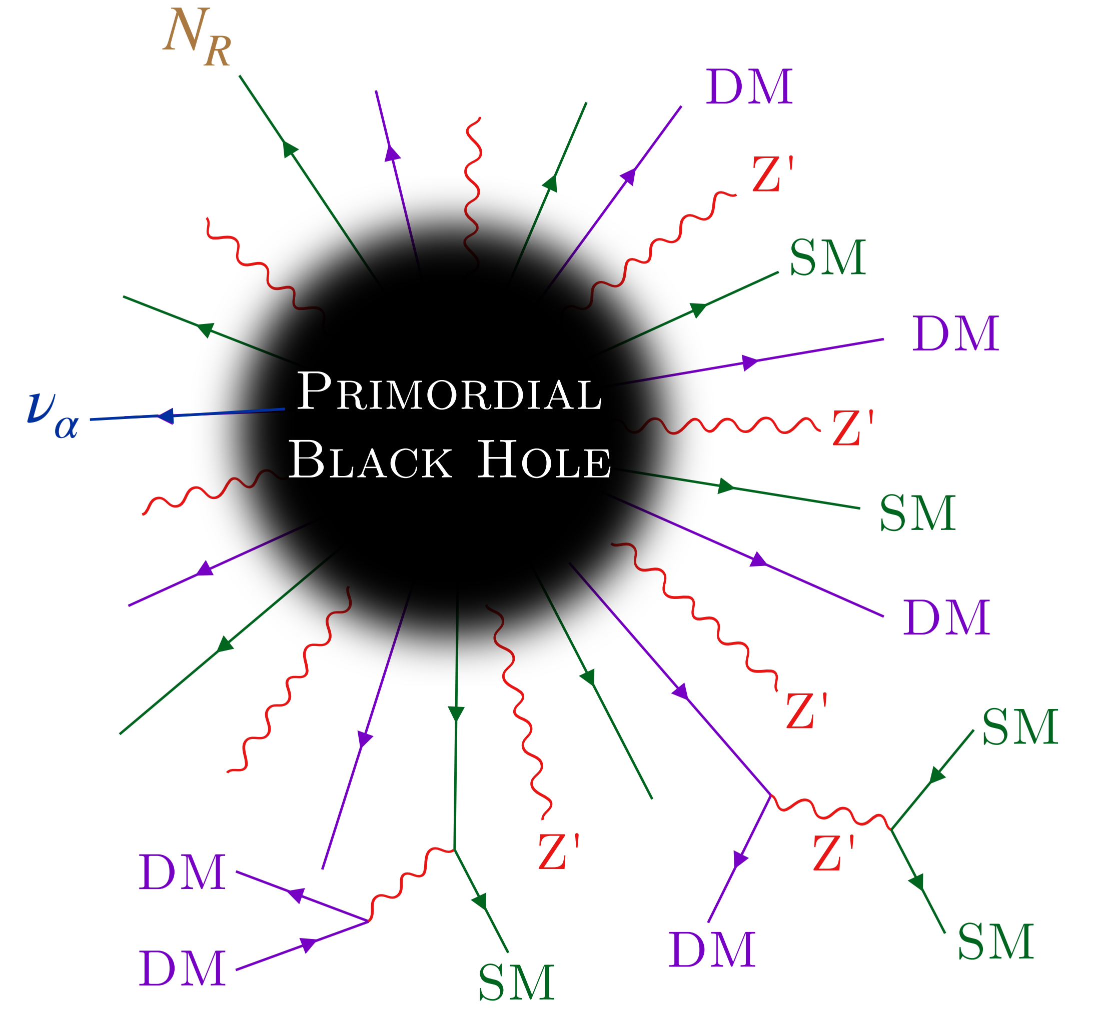
EHT Collaboration

Durham University

IP3

What's the impact of having evaporating Primordial Black Holes in the Early Universe?

- *Introduction:*
  - PBHs — Formation/Evaporation

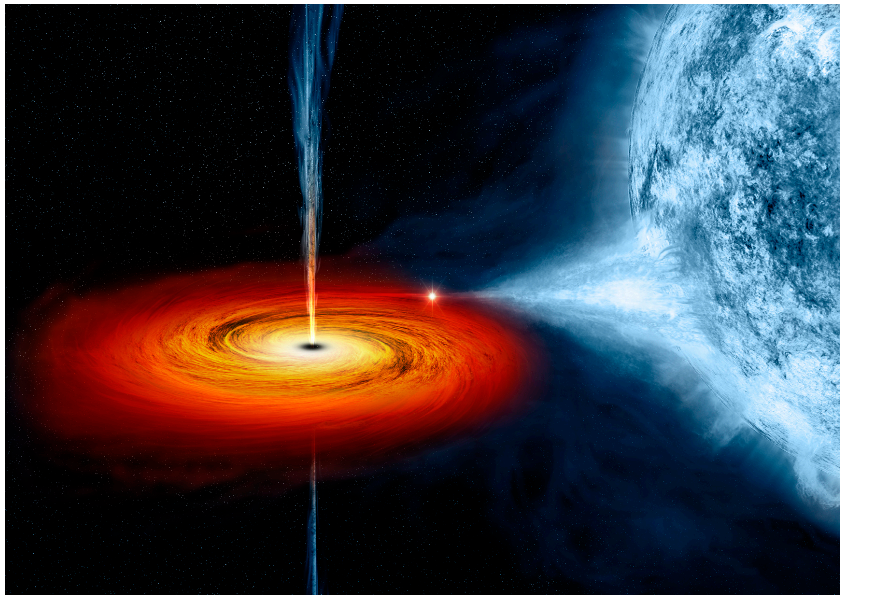


- First Act: Neutrinos and Leptogenesis

- Second Act: Dark Matter

- Third Act: High energy Neutrinos and evaporating PBHs

Primordial Black Holes (PBH)



Astrophysical Black Holes

$M \gtrsim 3M_\odot$

Formation

Lighter Black Holes → Large densities

$r_S = 2GM$

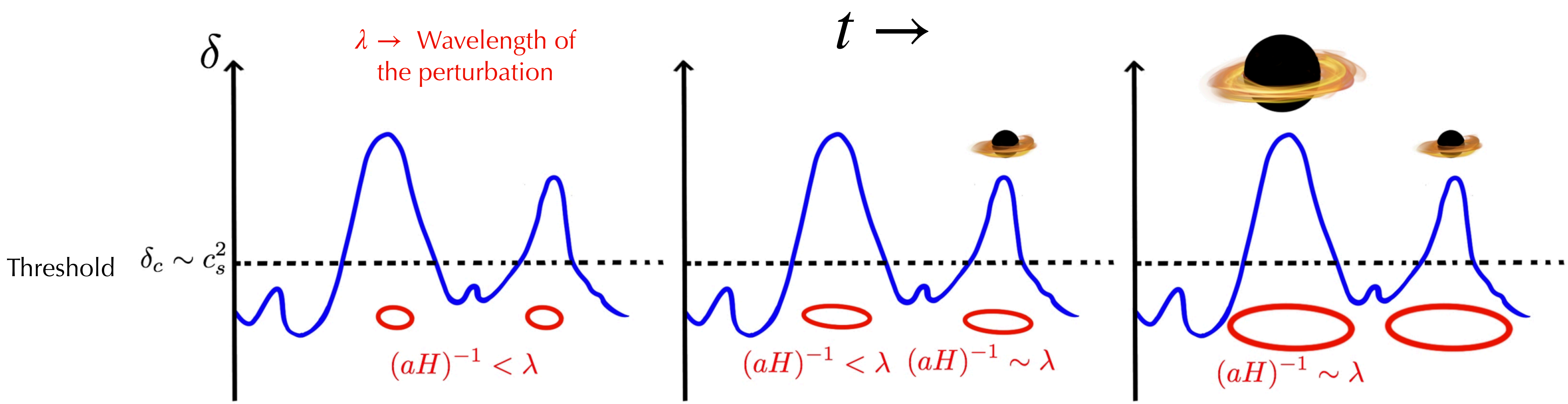
$$M_i \sim \frac{t}{G} \sim 10^{15} \left(\frac{t}{10^{-23}\ \mathrm{s}} \right)\ \mathrm{g}$$

Formation

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

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

- Bubble collisions
- Pressure reduction
- Collapse of density fluctuations



Taken from Villanueva-Domingo, Mena, Palomares-Ruiz 2103.12087

Fraction of the total energy in PBH

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

Assume a monochromatic mass distribution

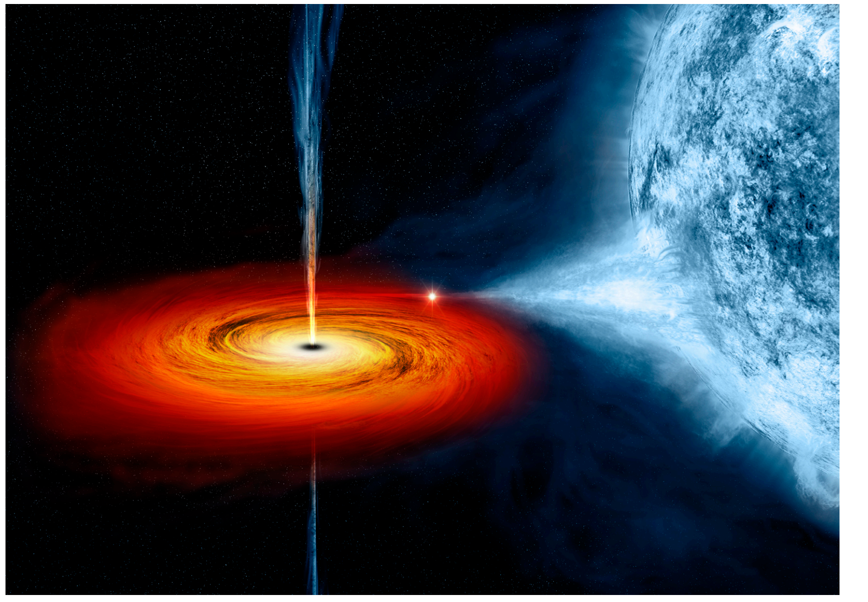
All PBHs with the same mass

$M_{\mathrm{BH},i}$, β

PBH form when the density perturbation enters the Hubble horizon

Carr et al. 2002.12778

Primordial Black Holes (PBH)



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Assume a monochromatic mass distribution

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

Evaporation

Quantum effects are important

$$r_S \sim \lambda_C$$

$$r_S \sim 0.015\ \mathrm{fm} \left(\frac{M}{10^{13}\ \mathrm{g}} \right)$$

Black Holes evaporate by thermal emission

Hawking, 1975

All degrees of freedom!

Evaporation — Schwarzschild BHs

Described by $M_{\rm BH}$

Hawking Instantaneous Spectrum

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

Absorption probability

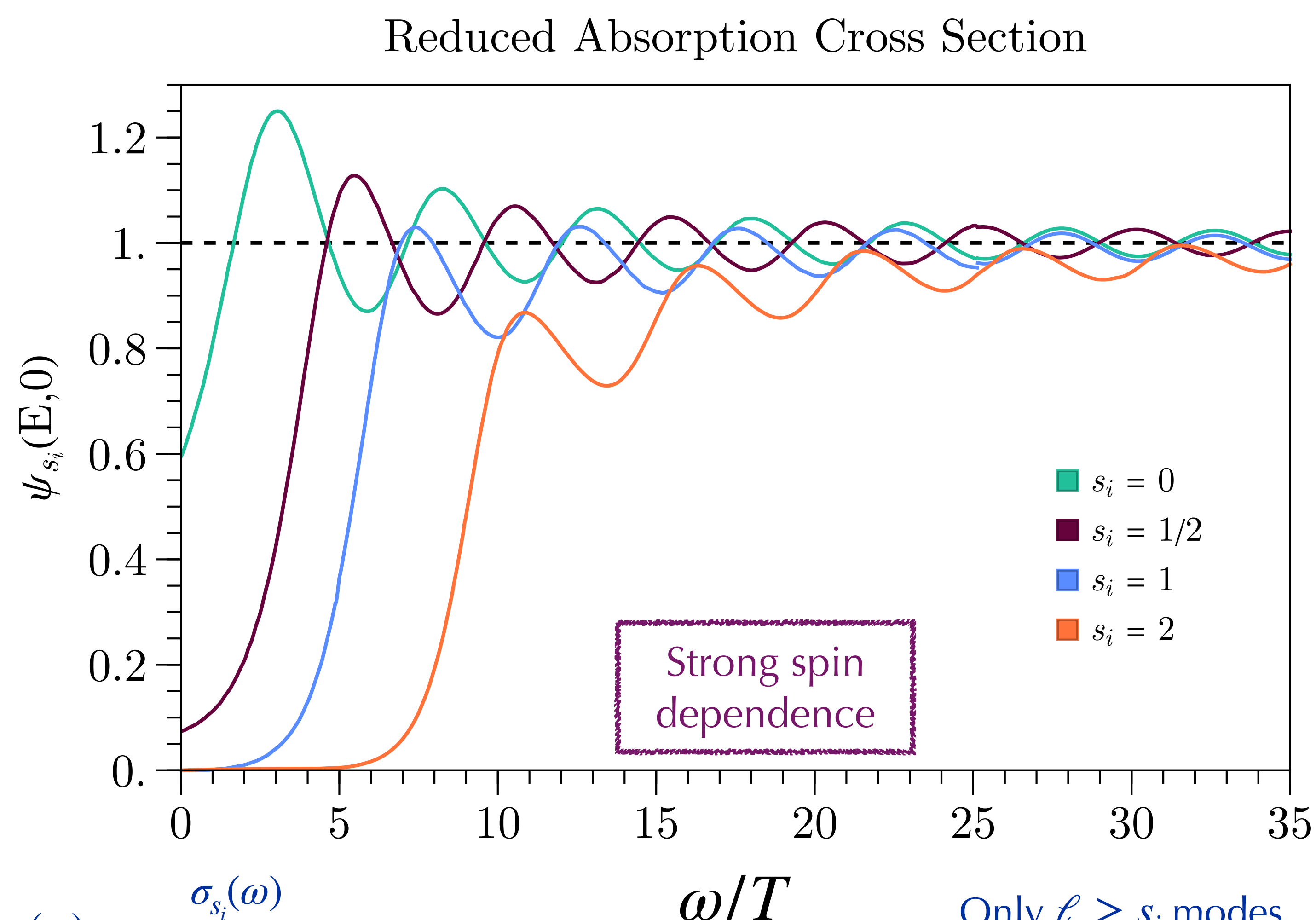
$${}_{s_i}\Gamma(M,\omega,\mu_i) = \frac{1}{\pi}\sigma_{s_i}(M,\omega,\mu_i)\,\omega^2$$

BH Temperature

$$T = \frac{\hbar c^3}{8\pi G M k}$$

$$\sim 1\ \text{GeV}\left(\frac{10^{13}\ \text{g}}{M}\right)$$

*Hic depositum est, quod mortale fuit Isaaci Newtoni



$$\psi_{s_i}(\omega) \equiv \frac{\sigma_{s_i}(\omega)}{27\pi G^2 M_{\rm BH}^2}$$

Only $\ell \geq s_i$ modes

Evaporation — Kerr BHs

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

Axisymmetric case

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

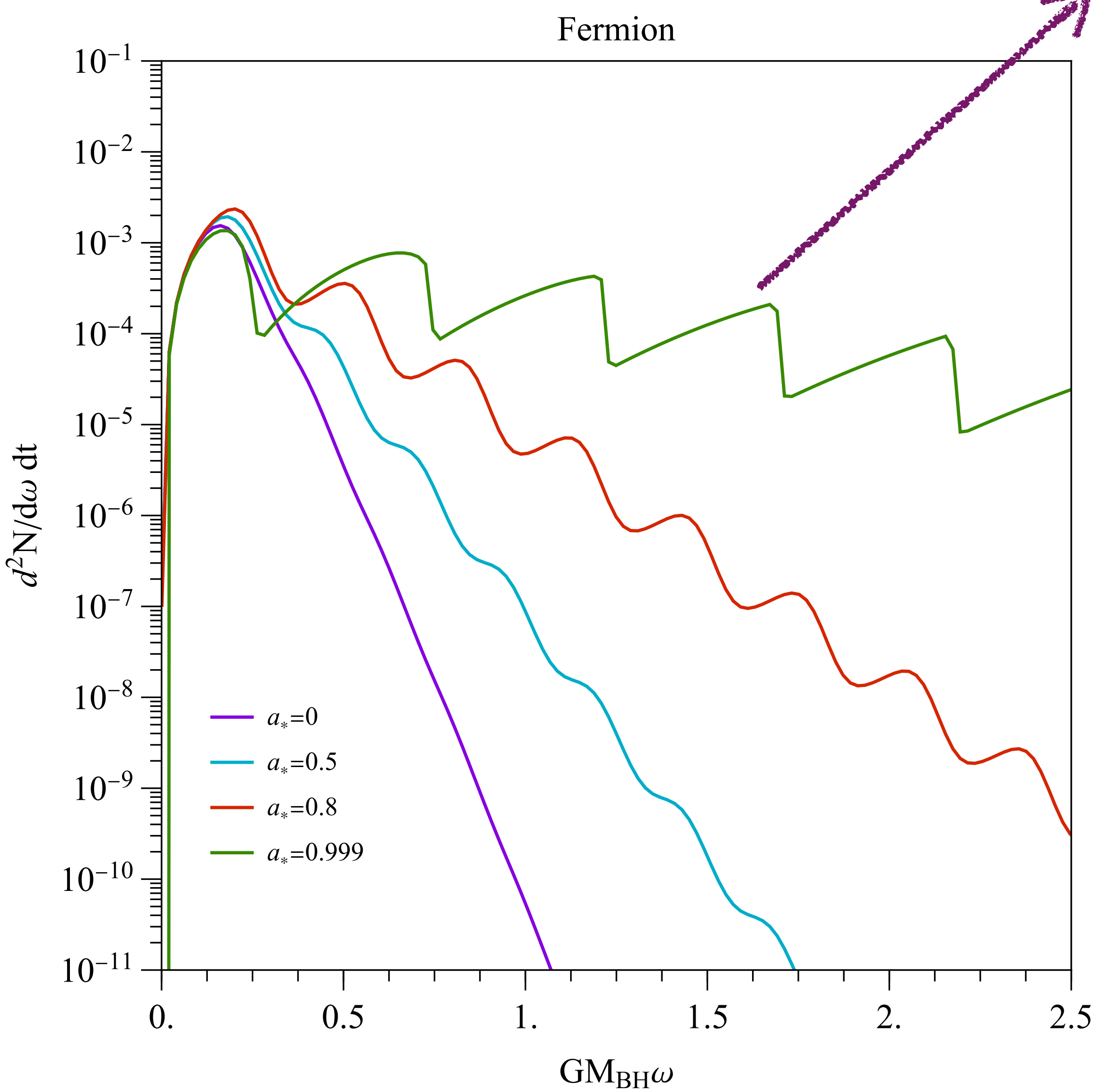
$\varpi_m = \omega - m\Omega$

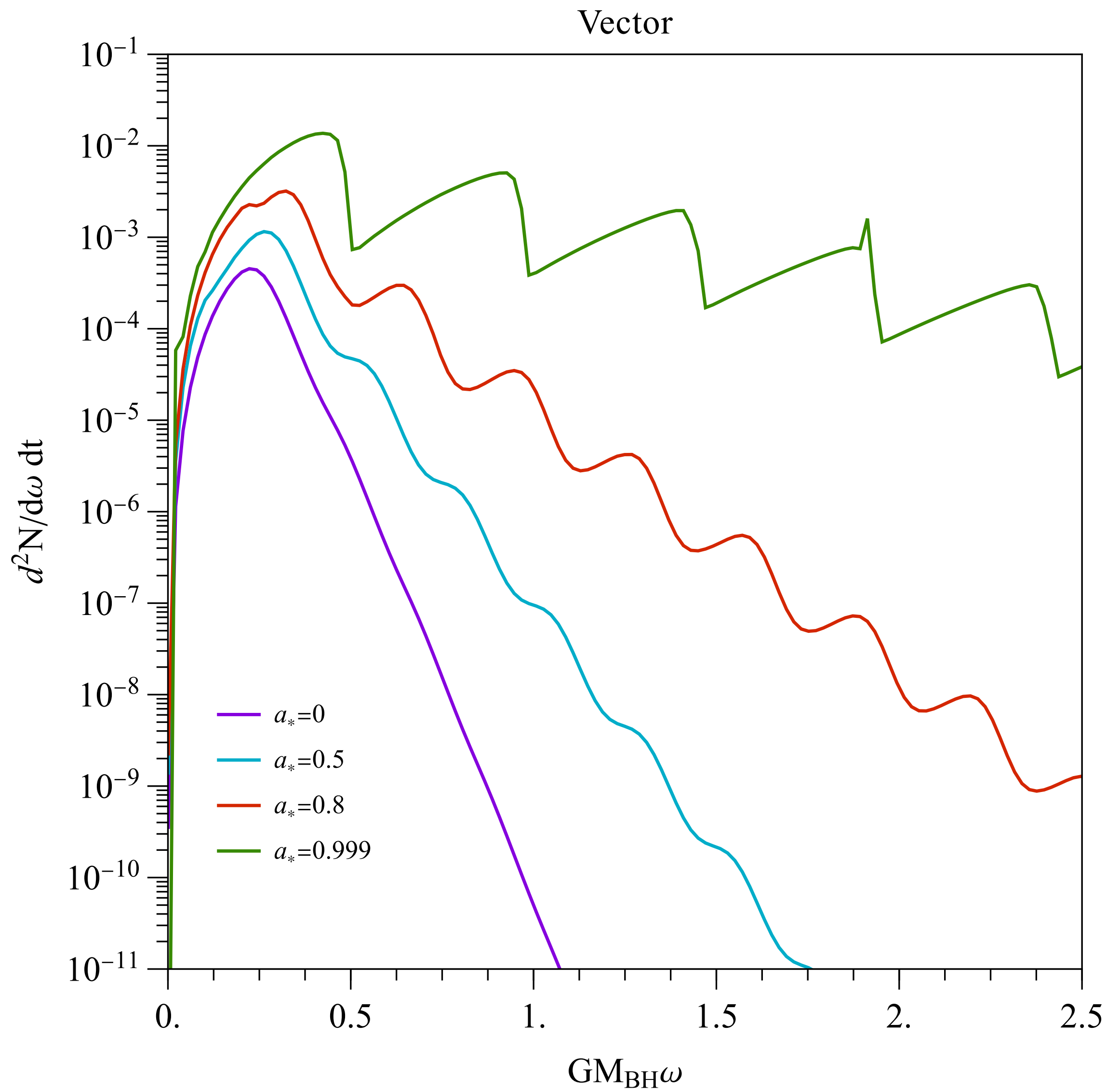
Explicit dependence on m
$\Omega \to$ angular velocity

BH Temperature

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

Enhanced emission of $l = m$ modes





Evaporation

$\widetilde{M}_{\rm BH}^{\rm max}(\xi) \equiv M_{\rm BH}(\xi)/M_{\rm BH}^{\rm in}$

$a_{\star,\,\rm in} \to 1$

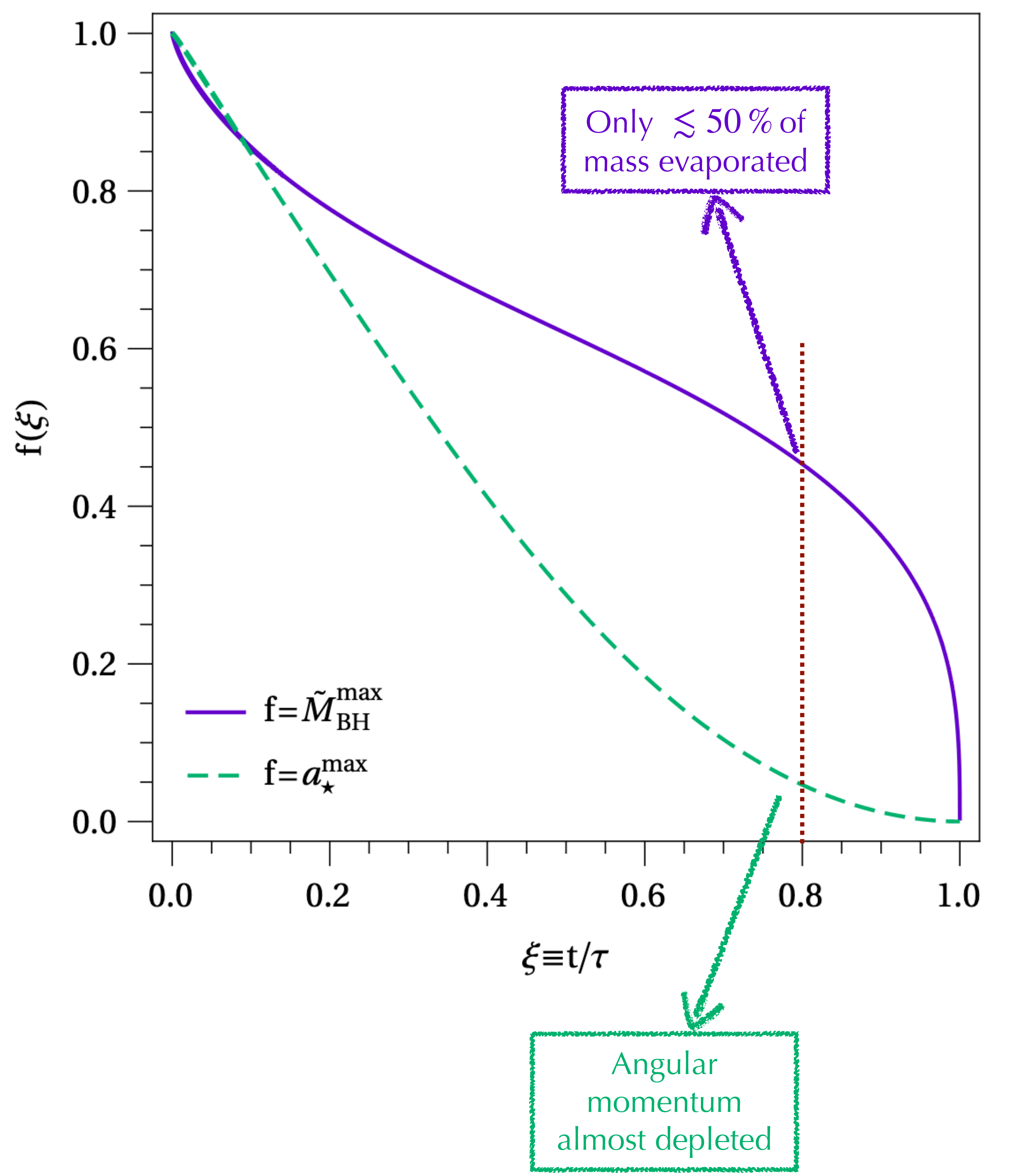
BHs lose mass over time

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

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

Angular momentum depleted faster than mass

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



Evaporation

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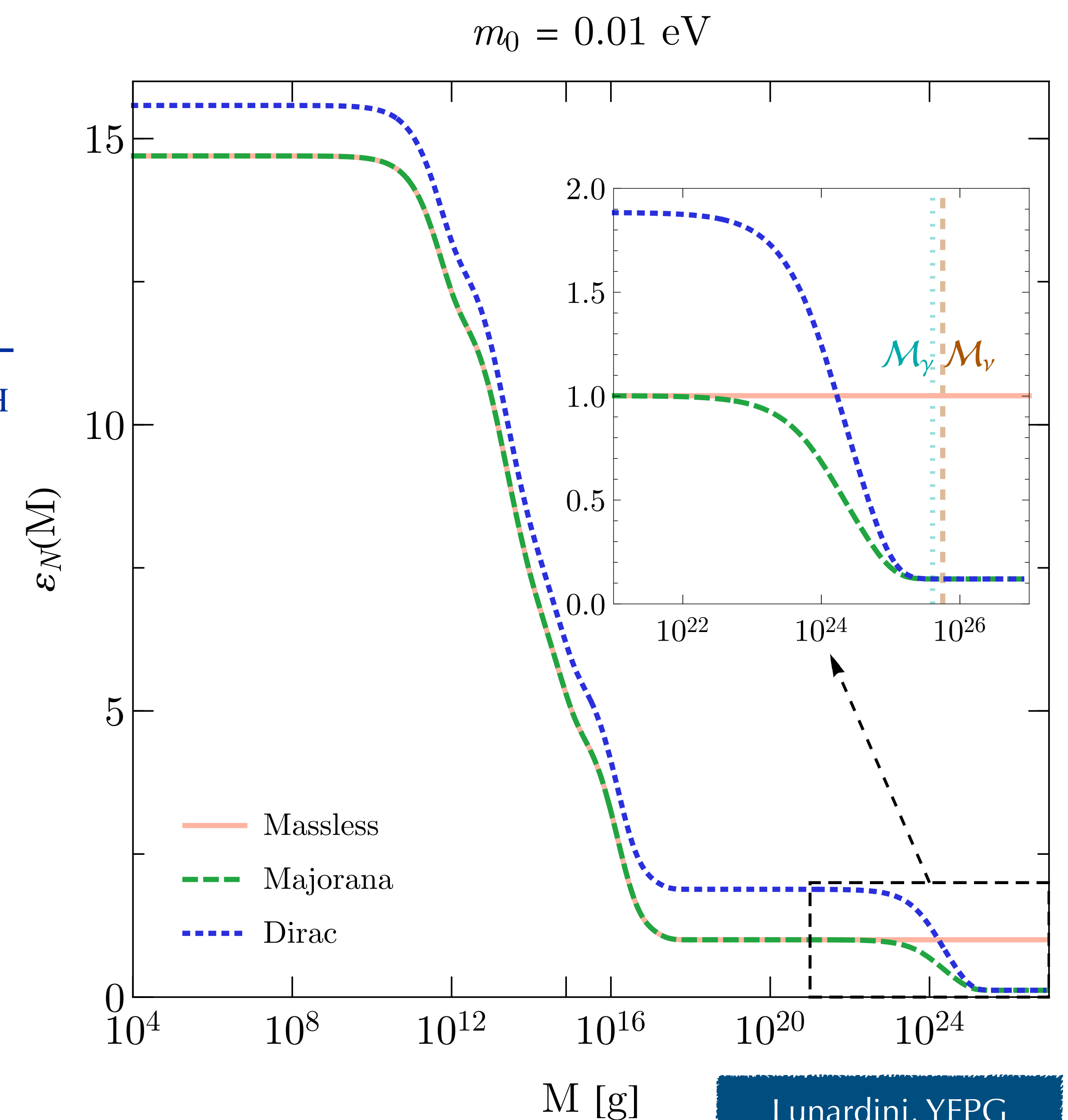
Depends on the set of ***all*** existing dofs

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

J. MacGibbon, 1991

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



Lunardini, YFPG JCAP08(2020)014

BH lifetime for a Schwarzschild BH

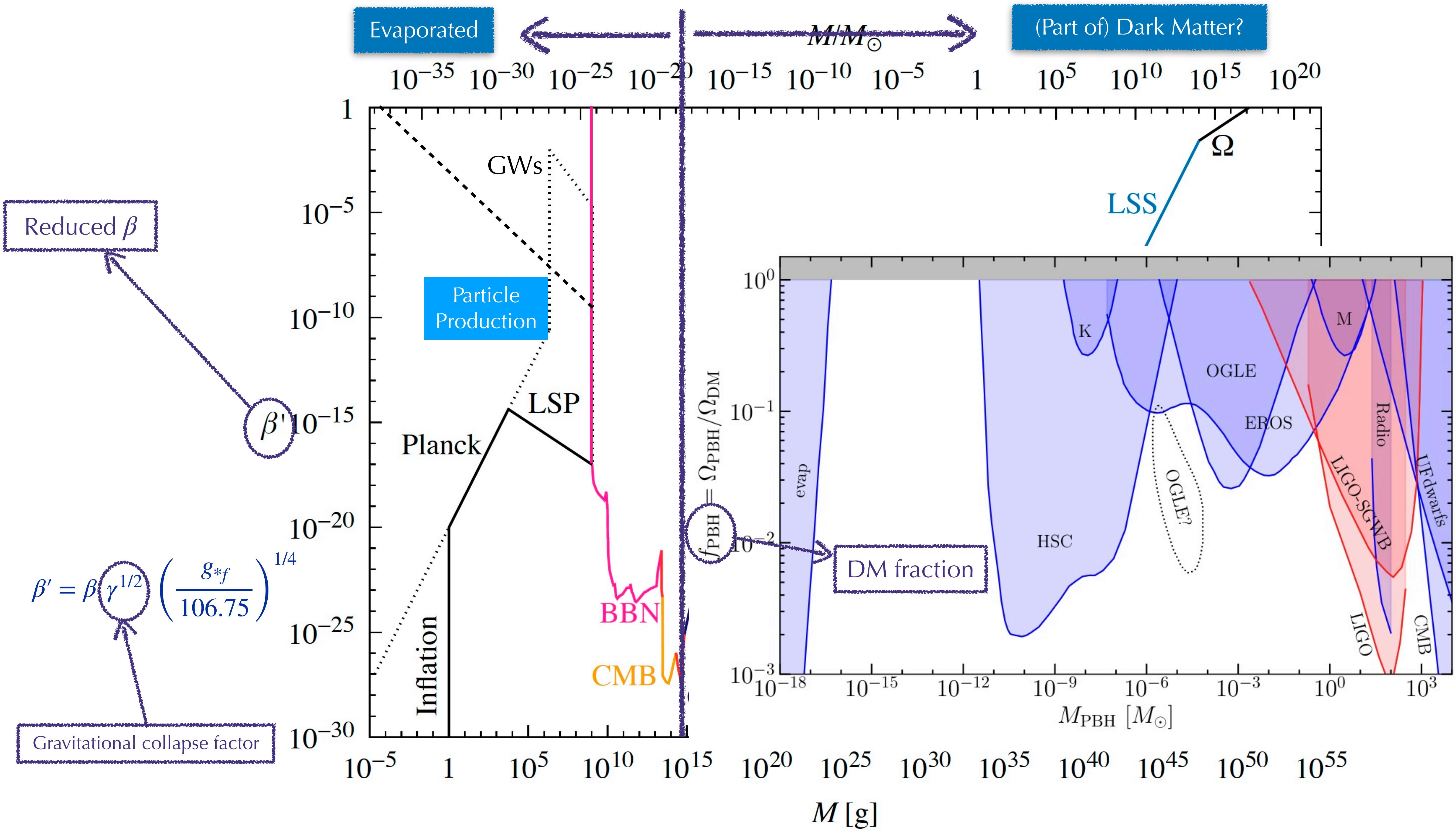
$$\tau = \frac{1}{M_{\rm P}^4}\int_{M_{\rm P}}^{M_{\rm i}}\frac{M^2 dM}{\varepsilon(M)}$$

Planck mass

BH with $M_{\rm i} = M_\odot$:

$\tau \sim 10^{67}$ years

$\sim 10^{57}$ * age of the Universe

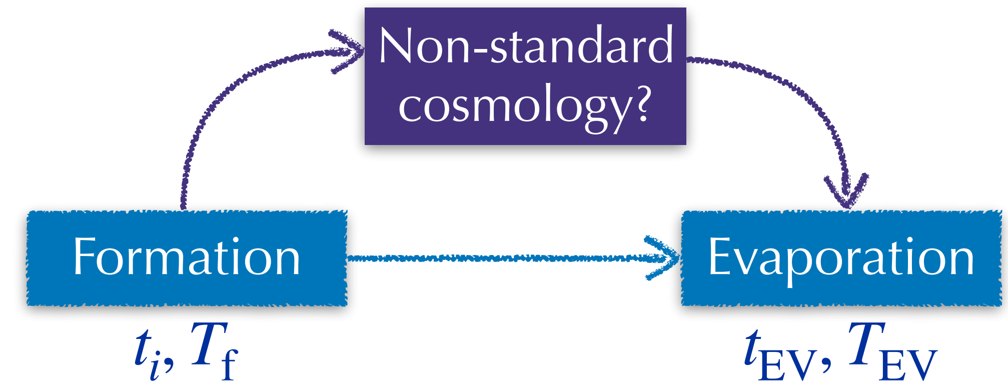


We focus on the region $M_{{\rm BH},i} \leq 10^9$ g

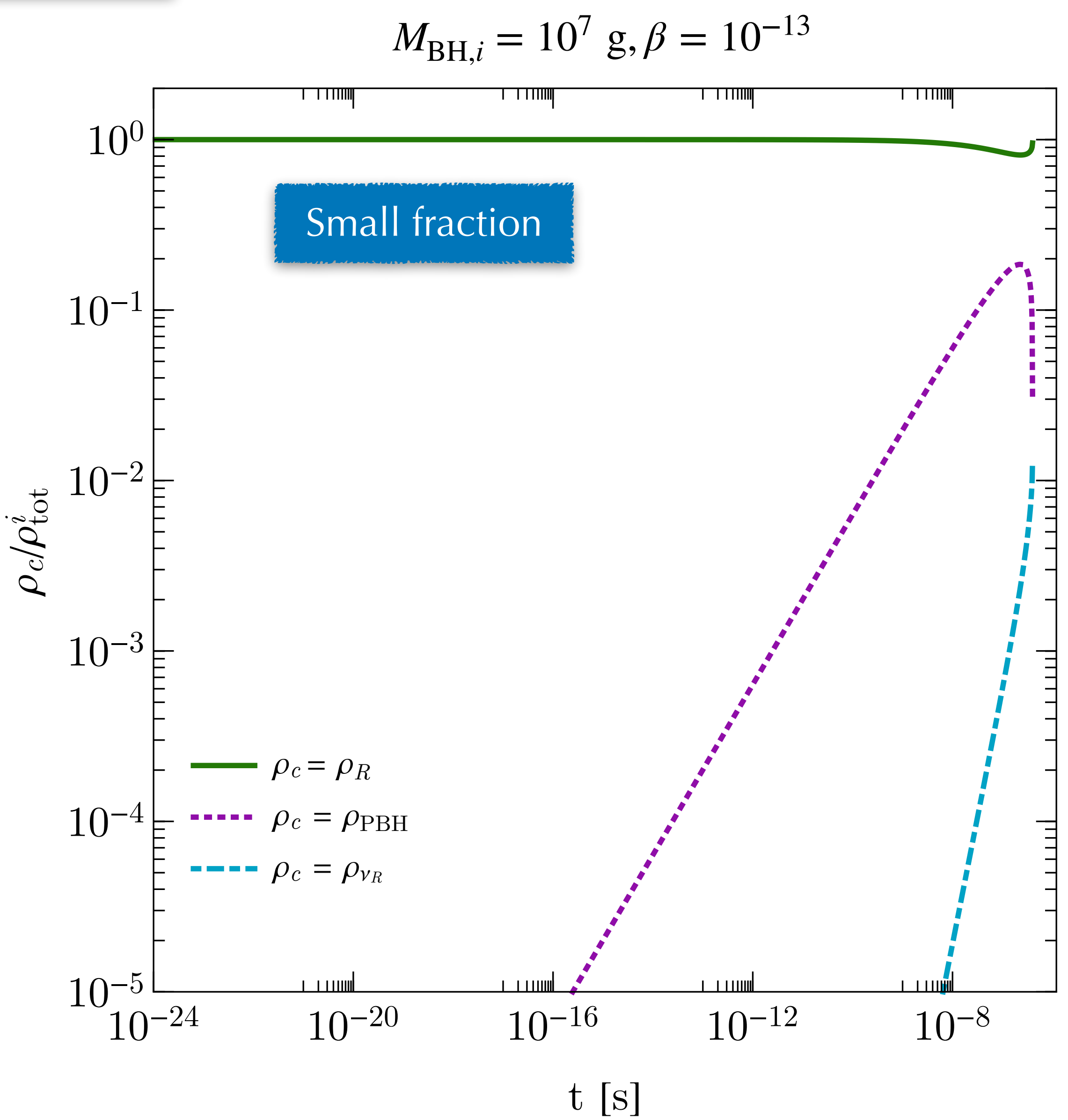
Carr et al. 2002.12778
Domènech et al. 2012.08151

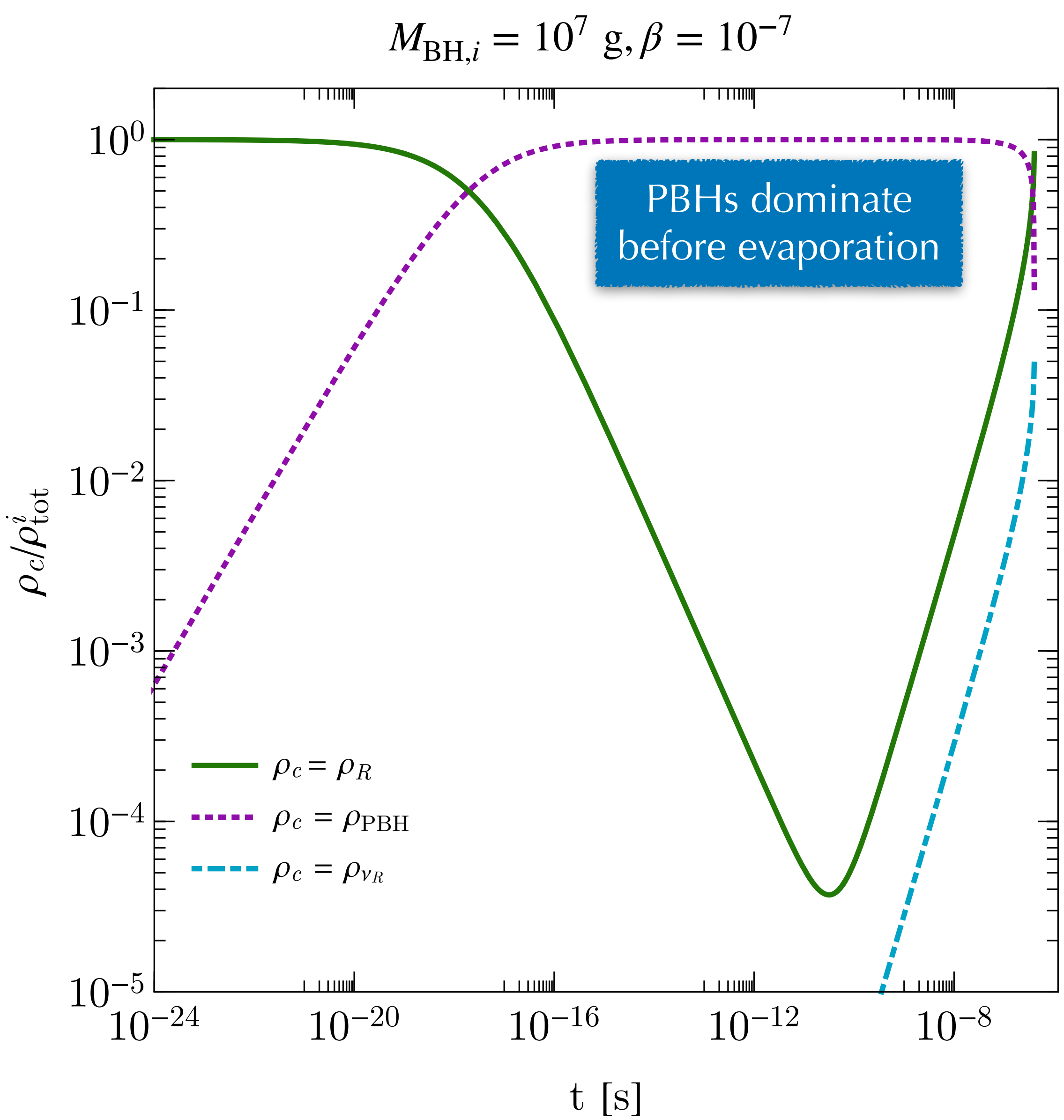
B. Kavanagh
10.5281/zenodo.3538999

PBHs: Rise and Fall



PBHs behave (almost) as matter





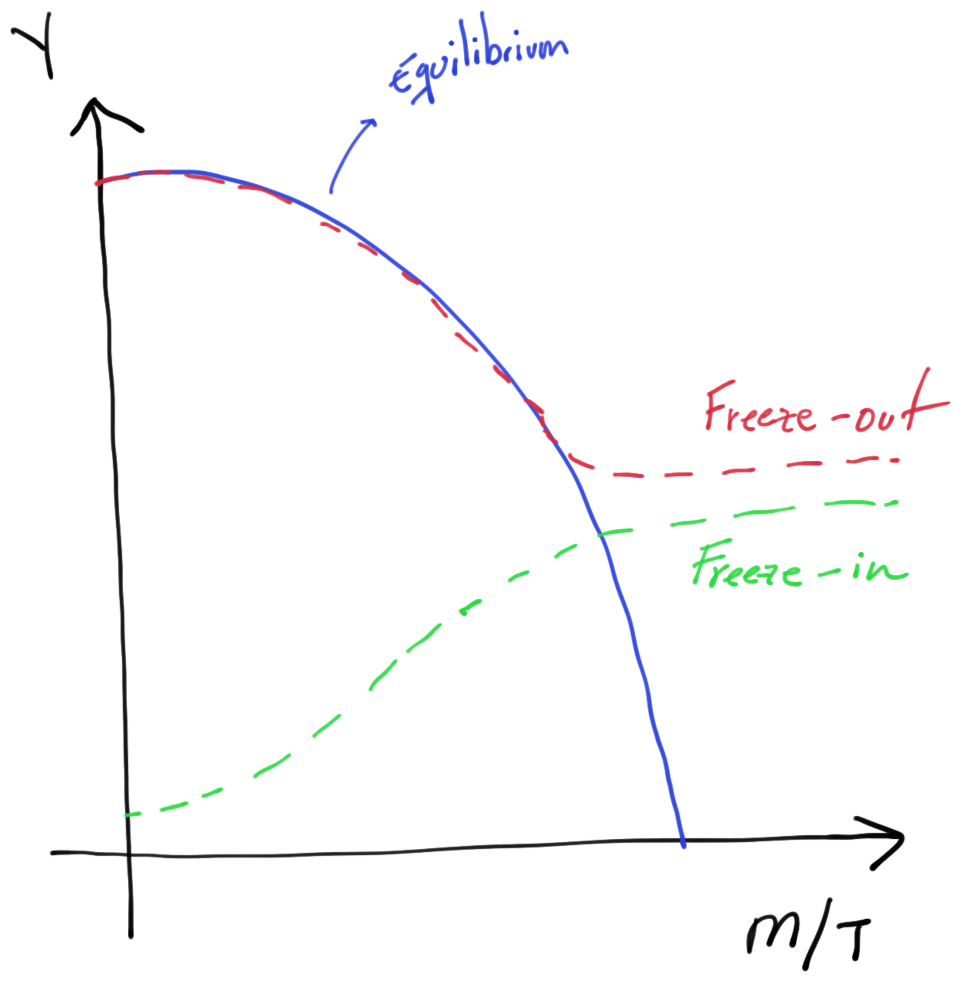
Initial fraction

$$\beta \gtrsim 2.5 \times 10^{-14} \left(\frac{g_*(T_f)}{106.75}\right)^{-\frac{1}{4}} \left(\frac{M_i}{10^8\ \text{g}}\right)^{-1} \left(\frac{\varepsilon_D(M_i)}{15.35}\right)^{\frac{1}{2}}$$

Hooper et al, 1905.01301

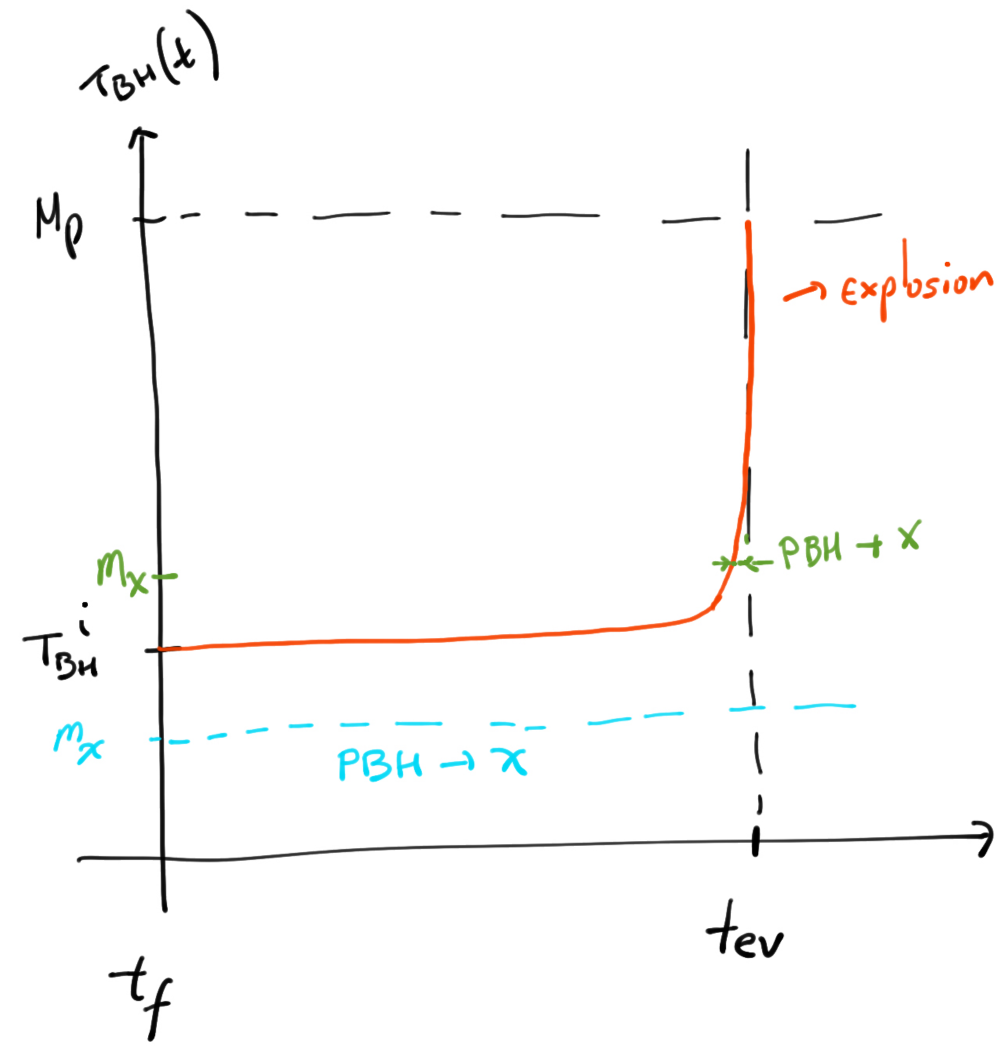
Why is interesting the particle production via evaporation?

(Thermal) Particle decoupling



Abundances depend on masses and interactions

Hawking Evaporation

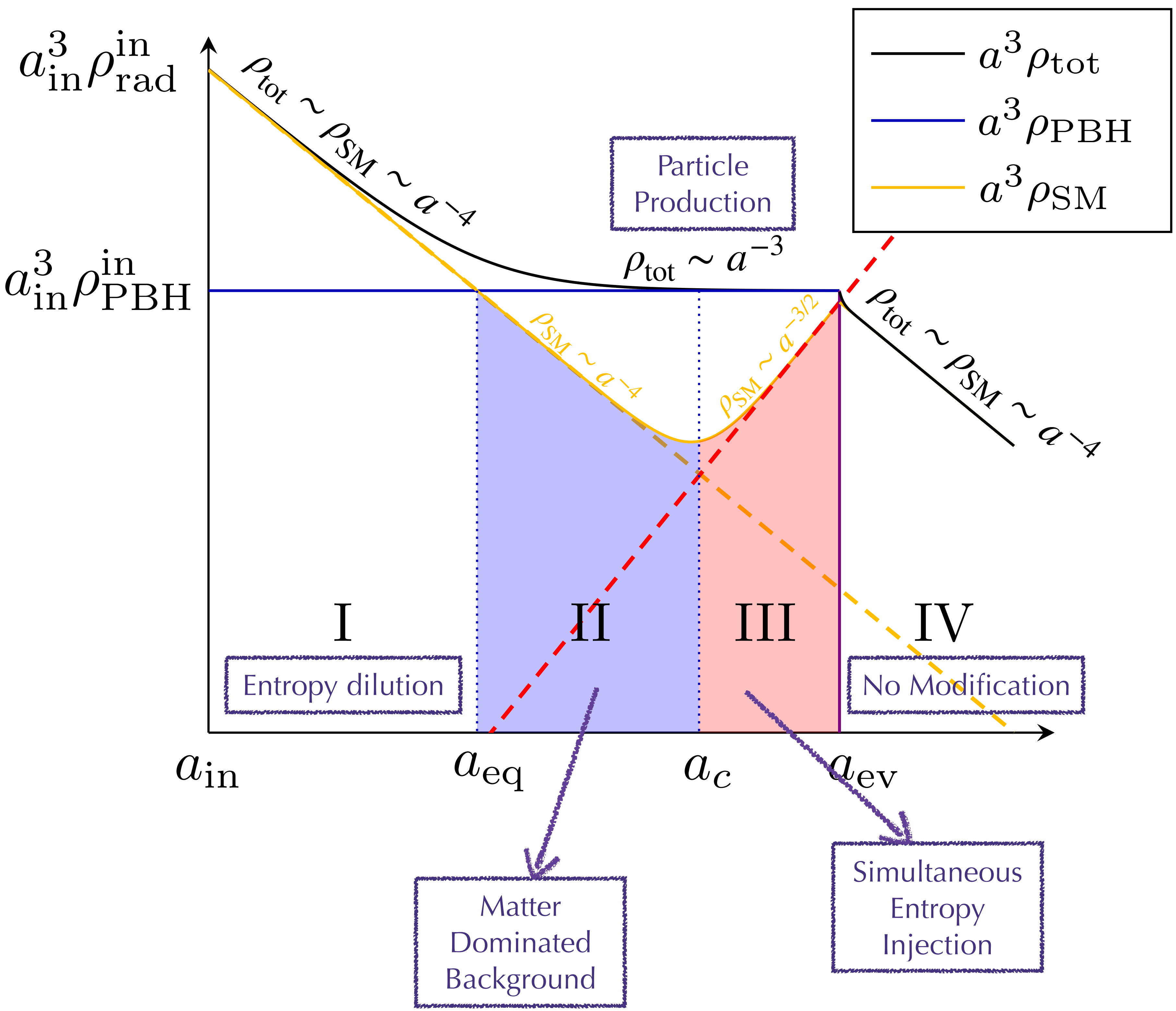


Abundances depend on masses and PBH parameters

Interplay??

- ❖ Modified Cosmology
- ❖ Particle production
- ❖ Entropy dilution

Why is interesting the particle production via evaporation?



In a PBH dominated Early Universe

Why is interesting the particle production via evaporation?

DM production
(Besides PBH-DM)

- Purely Gravitationally interacting DM
- Modify Freeze-In/Freeze-out mechanisms

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
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.
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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
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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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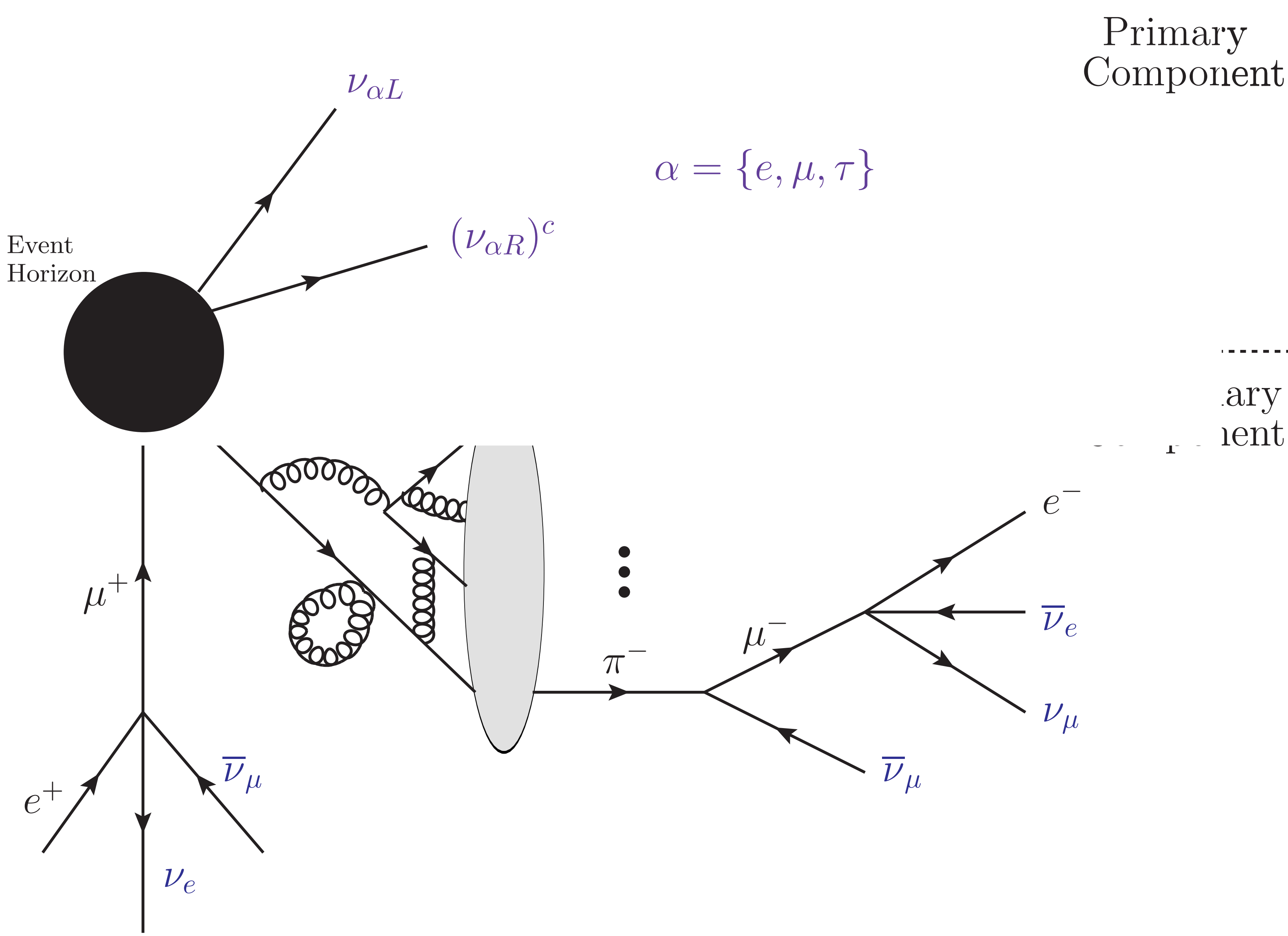
First Act
Neutrinos and Leptogenesis

Based on:
YFPG and Turner: 2010.03565
Bernal, Fong, YFPG, Turner 2203.08823

What about neutrino emission?

In the SM…



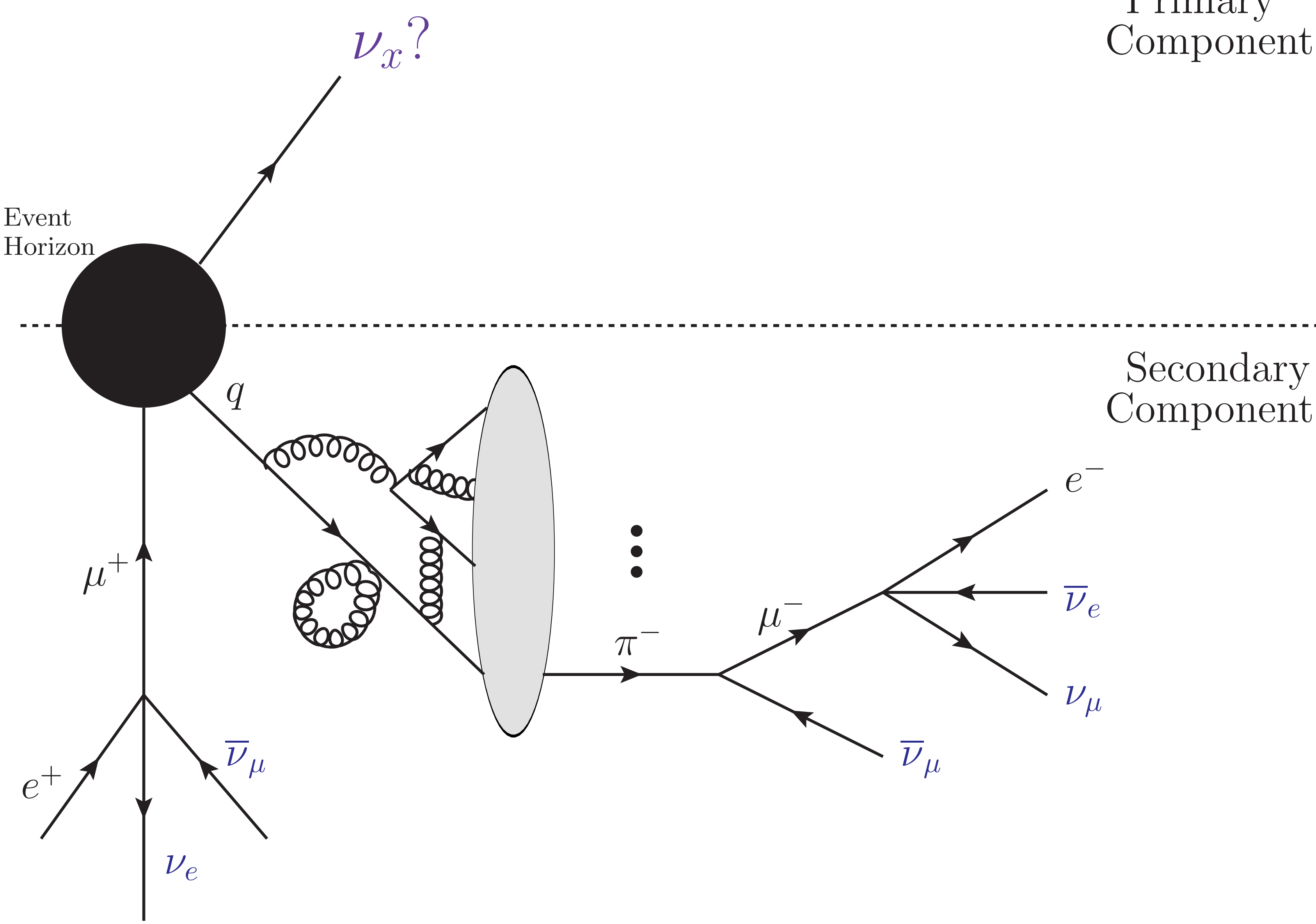
Constraints on the diffuse neutrino flux

B. Carr, 1976

J. MacGibbon, 1991
F. Halzen,9502268
Bugaev, 0005295

What is the state of the emitted neutrino?

Neutrinos are massive

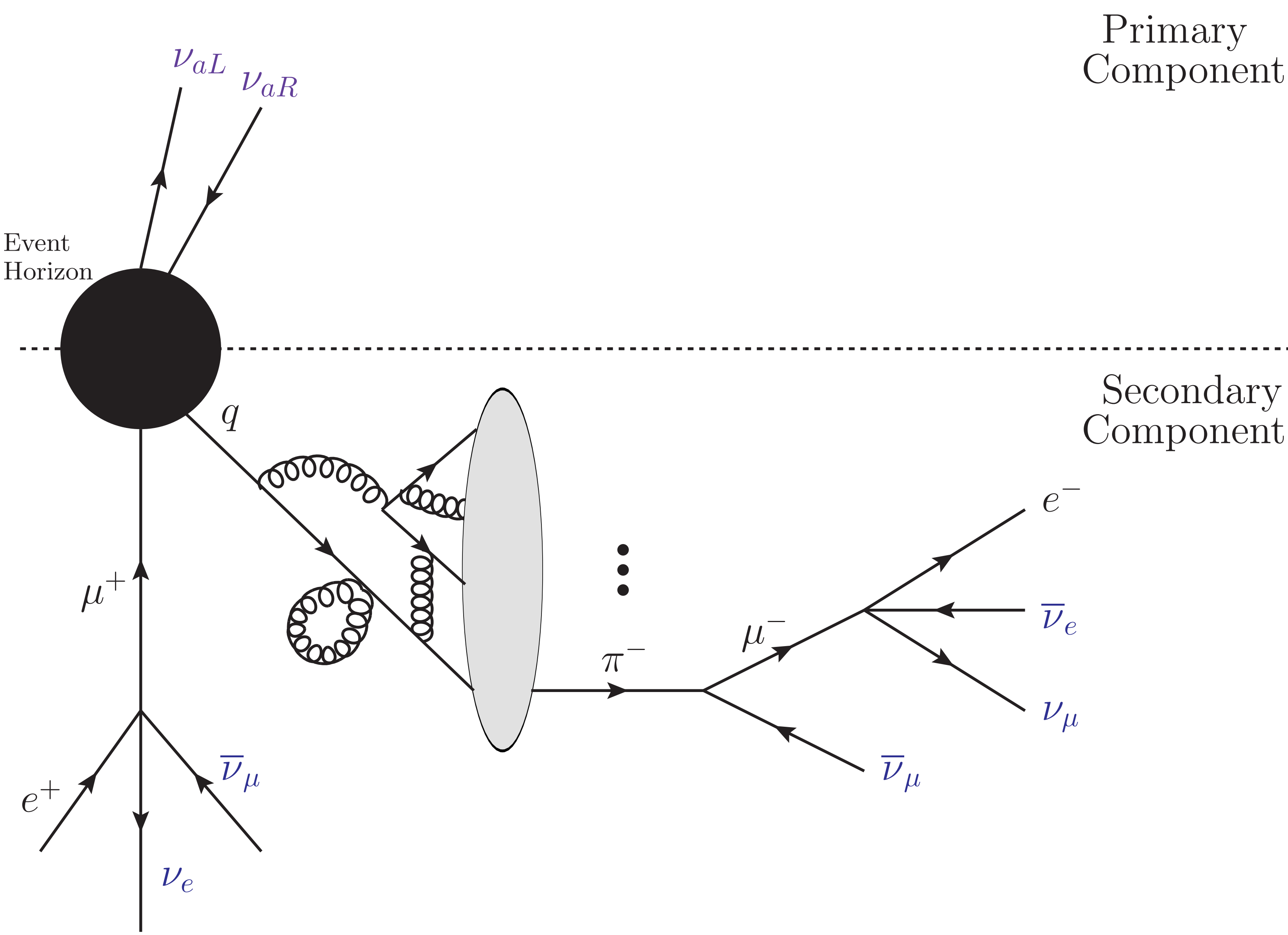


Weak Interaction

What is the state of the emitted neutrino?

Weak interactions	Hawking Effect
$n \to p^+ + e^- + \overline{\nu_e}$	$\langle 0_- \vert b_i^\dagger b_i \vert 0_- \rangle = \Gamma_{lm} \left[\exp\left(E_a / T_{\rm BH} + 1 \right) \right]^{-1}$
Interaction mediated by a gauge boson	Particle definition in a curved spacetime is observer dependent
Associated with a charged lepton	Particles with well-defined kinematical properties
Flavor eigenstate	***Mass*** eigenstate
ν_e ν_μ ν_τ	ν_1 ν_2 ν_3

Dirac vs Majorana



Majorana neutrinos

Phenomenological consequences?

Dirac neutrinos

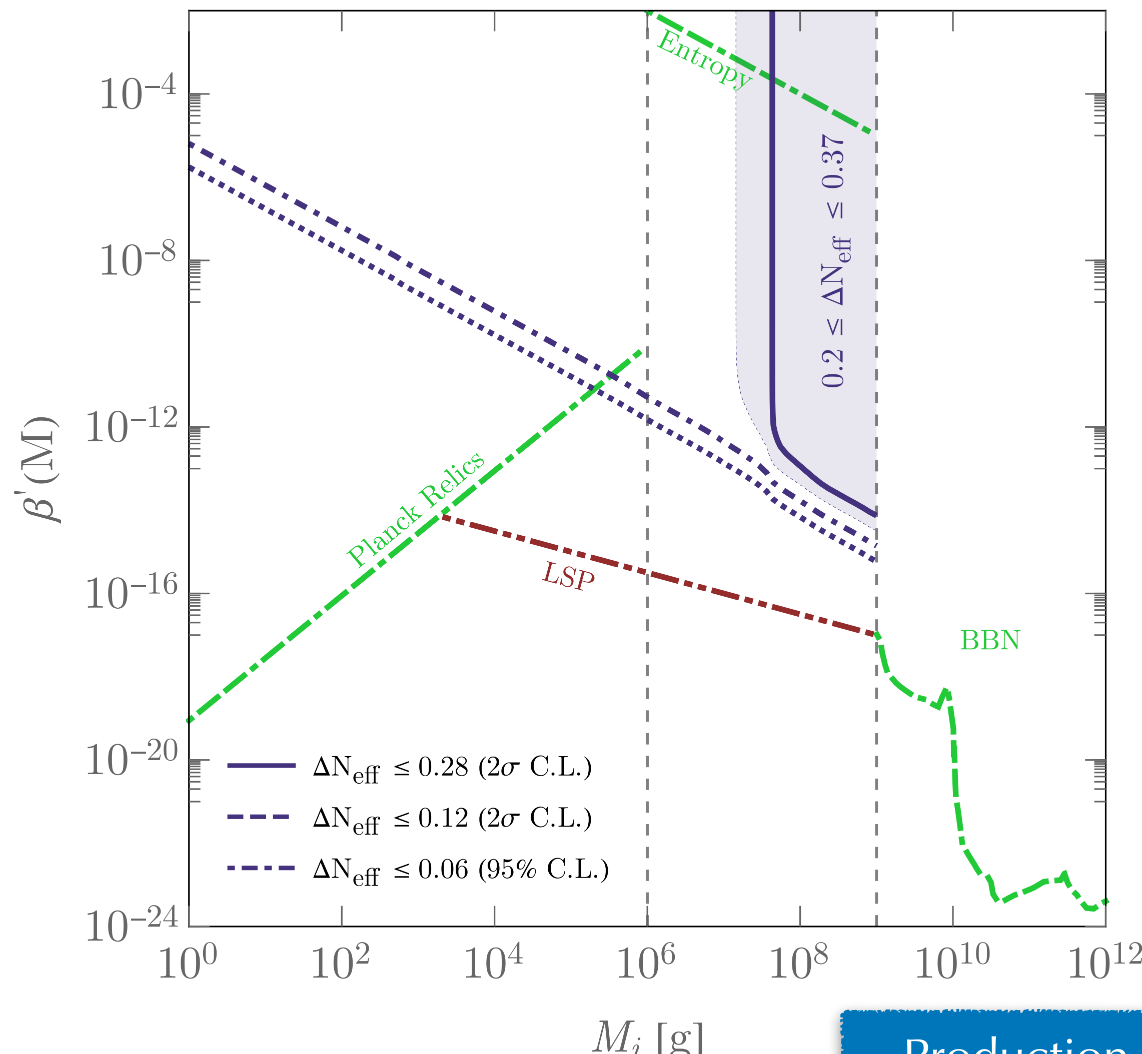
VS

Majorana neutrinos

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

Unruh, 1976

No helicity suppression



Cecilia Lunardini, YFPG
JCAP08(2020)014

Production of light RH neutrinos!

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
.
.
.

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

Thermal Leptogenesis in a nutshell

Baryon asymmetry

$$\eta_{\rm CMB} = (6.23 \pm 0.17) \times 10^{-10}$$

$$\eta_{\rm BBN} = (6.08 \pm 0.06) \times 10^{-10}$$

Sakharov Conditions

- Baryon and Lepton number violation
- CP violation
- Departure from thermal equilibrium

Type I seesaw:

$$-\mathscr{L} \supset \frac{1}{2} M_{N_i} \overline{N_i^c} N_i + \overline{\ell}_\alpha H^* Y_{\alpha i} N_i + \mathrm{H.c.}$$

$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_N} \sim \mathscr{O}(0.1\ \mathrm{eV})$$

$$Y_\nu = \frac{1}{v} U_{\rm PMNS} \sqrt{m_\nu} R^T M_N^T$$

Casas, Ibarra, 2001

Boltzmann Equations

$$\frac{dn_{N_i}}{dz} = D_i (n_{N_i} - n_{N_i}^{\rm eq})$$

$$\frac{dn_{\rm B-L}}{dz} = \sum_i \epsilon_i D_i (n_{N_i} - n_{N_i}^{\rm eq}) - \mathscr{W}_i n_{\rm B-L}$$

Washout

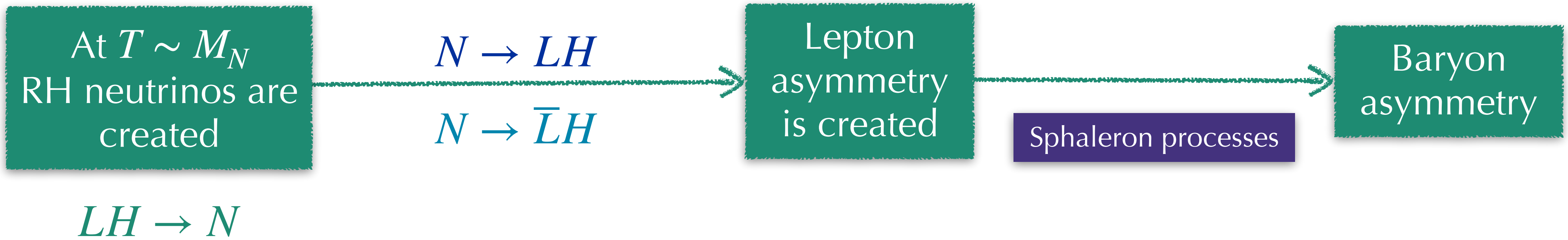
$$LH \leftrightarrow \overline{L}H$$

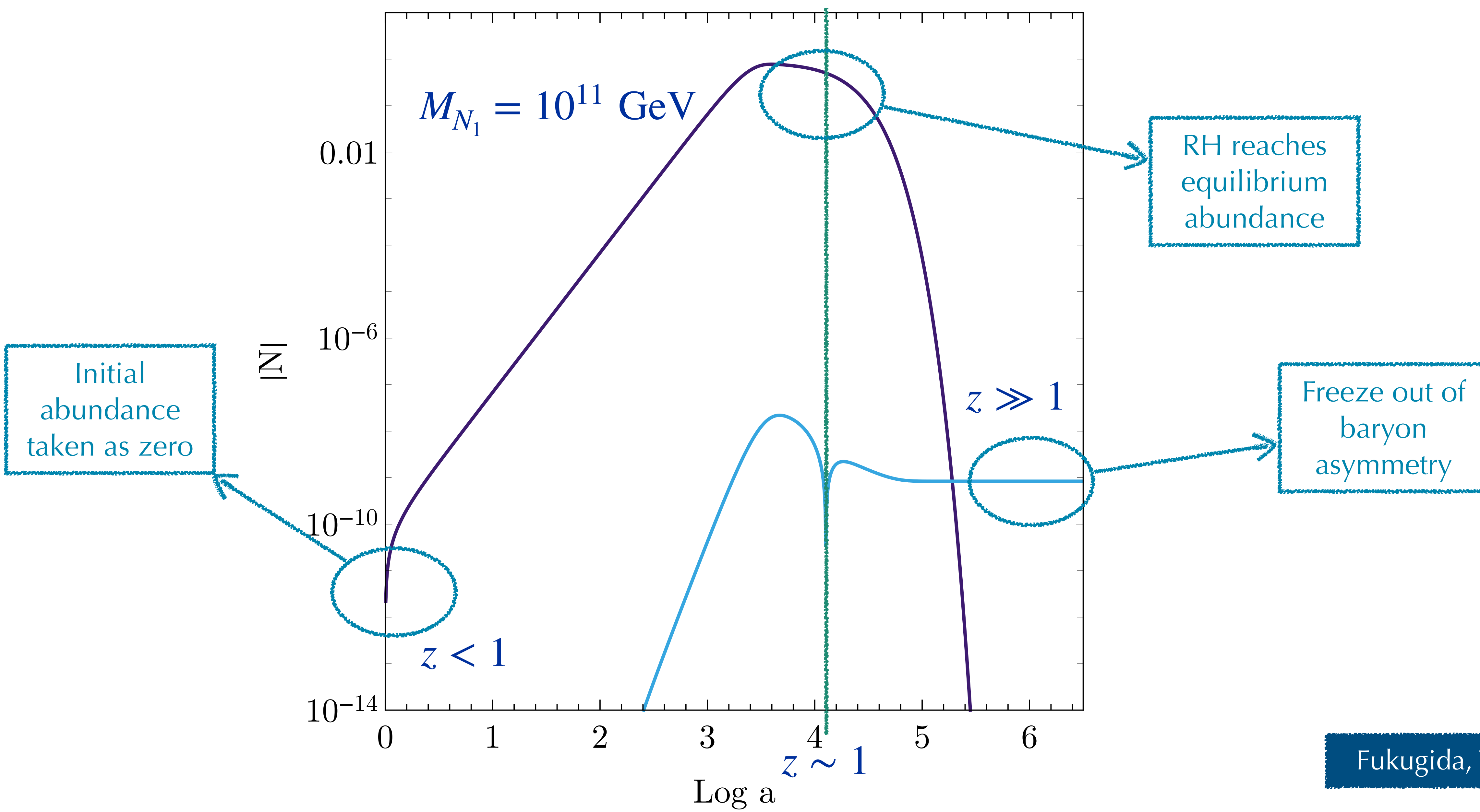
$$\Delta L = 2$$

Fukugida, Yanagida, '86

Thermal Leptogenesis in a nutshell

$z \equiv \frac{M_{N_1}}{T}$





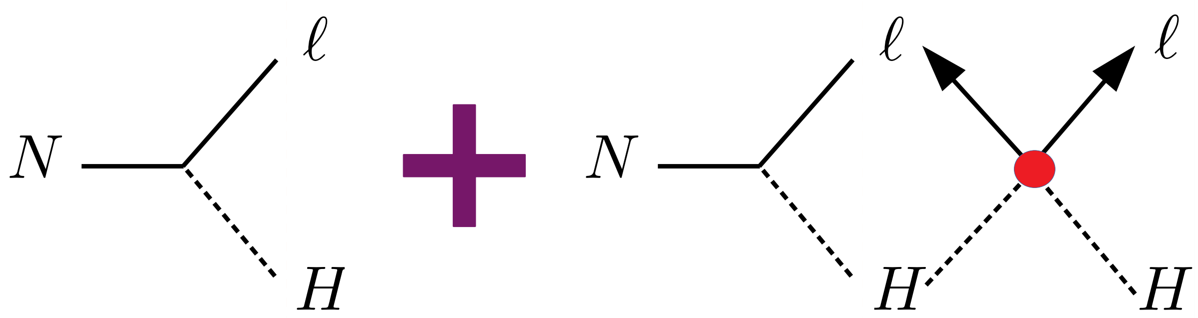
Fukugida, Yanagida, '86

High Scale Leptogenesis

$M_N \gtrsim 10^{12}$ GeV

$M_{N_1} < M_{N_2} < M_{N_3}$

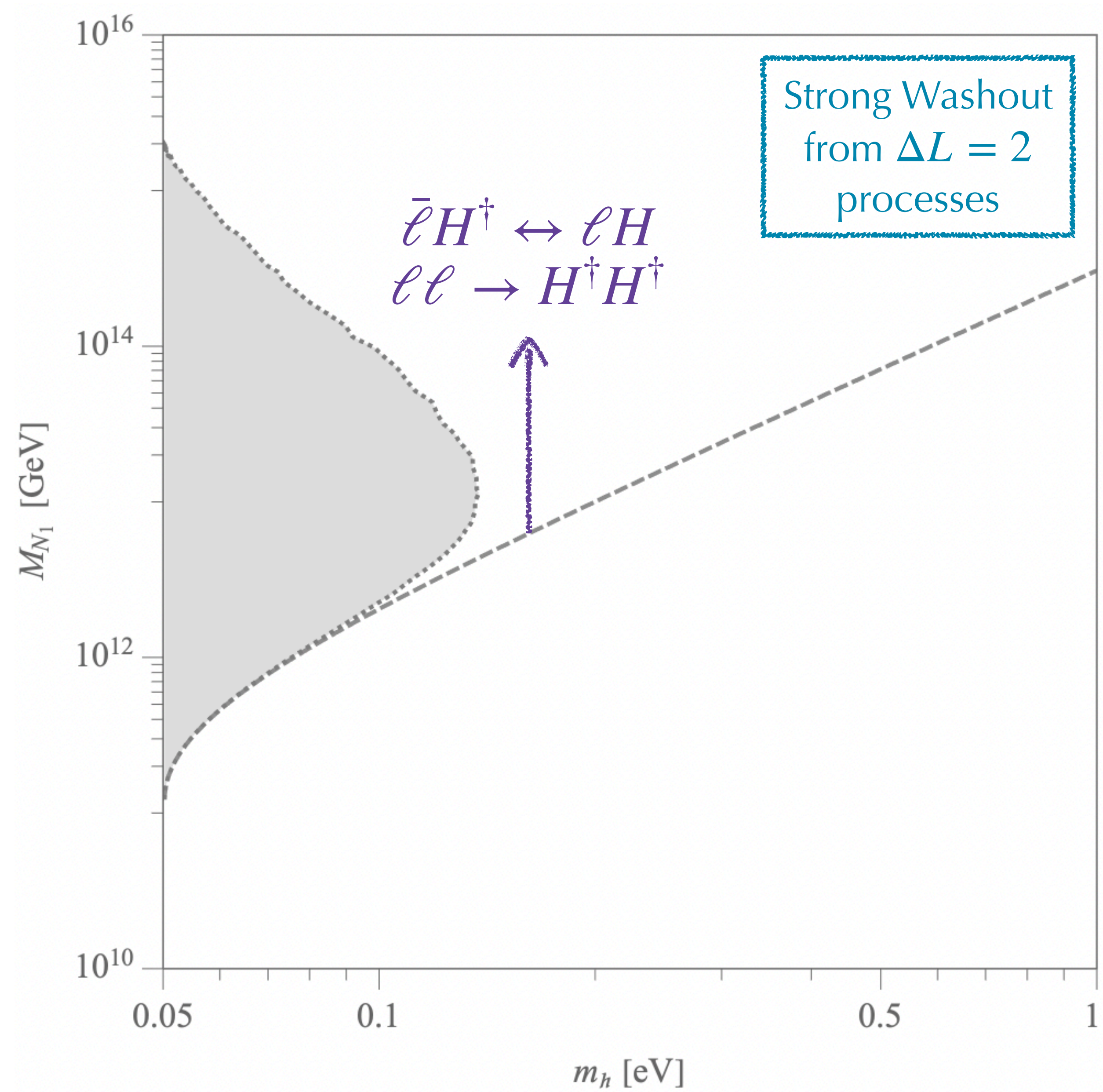
CP violation from interference



$$\frac{\epsilon}{M_N} \propto \frac{m_\nu}{v^2} \propto \sqrt{\sigma_{\Delta L=2}}$$

$\Delta L = 2$ interactions would be in equilibrium if

$$M_{N_1} \gtrsim 4 \left(\frac{\mathbf{0.1\ eV}}{m_\nu} \right) \mathbf{10^{12}\ GeV}$$



m_h = Heaviest neutrino mass

Maximizing over Yukawa parameters

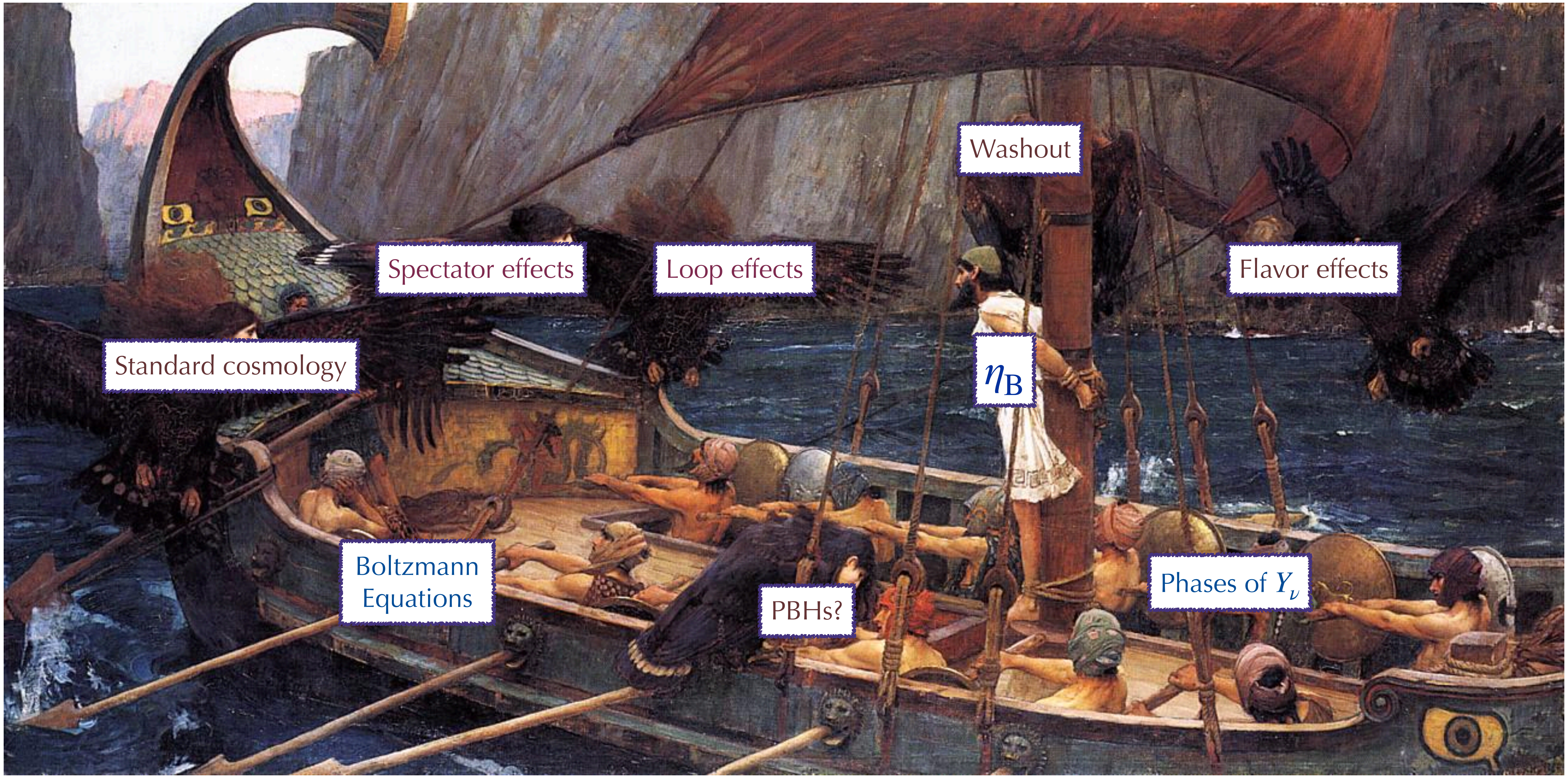
How to save HSL? → Produce RHNs after washout process have frozen out?

PBHs!

Giudice *et al.*, 2004
Buchmuller *et al.*, 2005

Intermezzo.

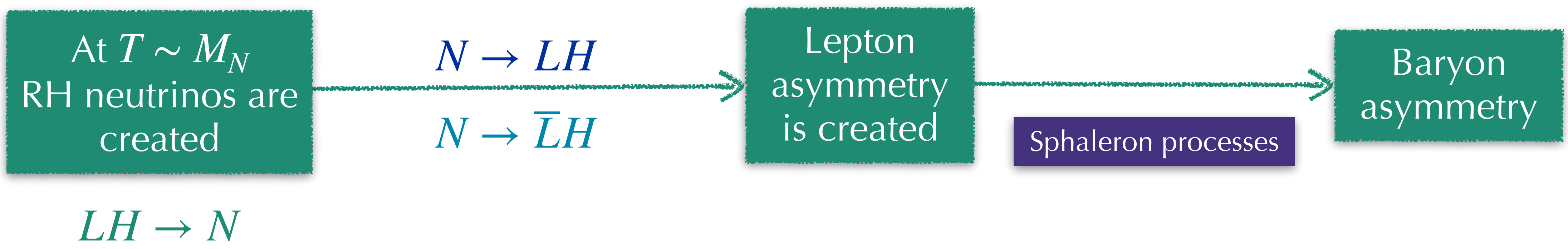
Universal LeptogeneSiS Equation Solver (ULYSSES)

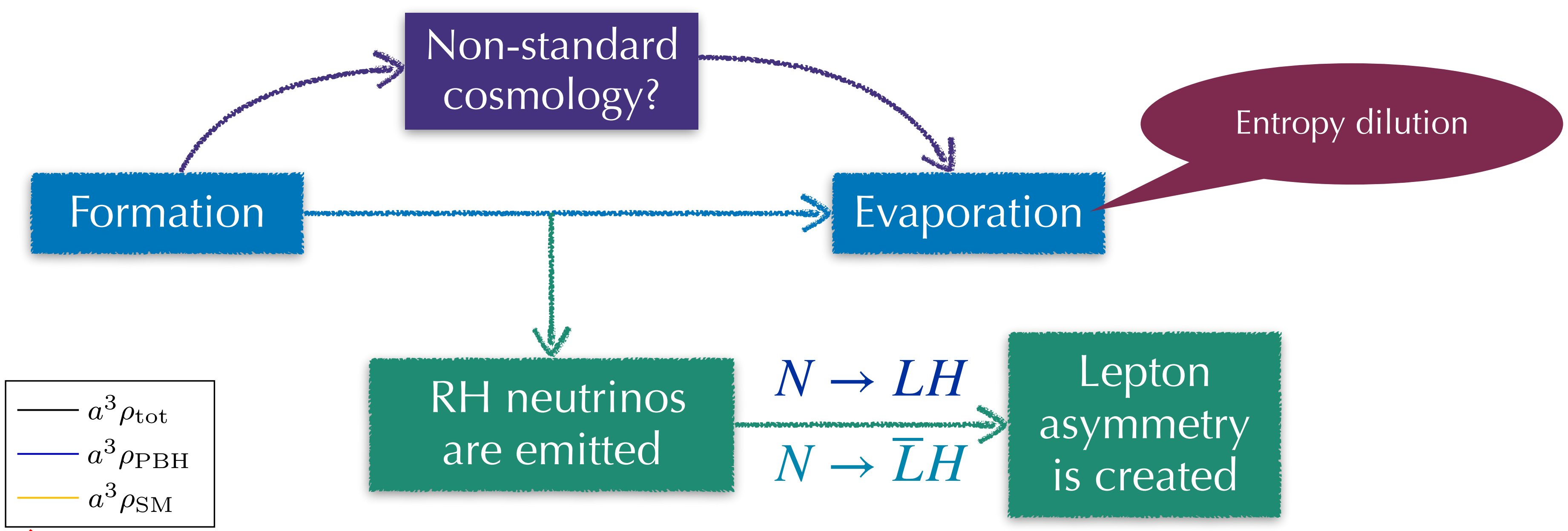


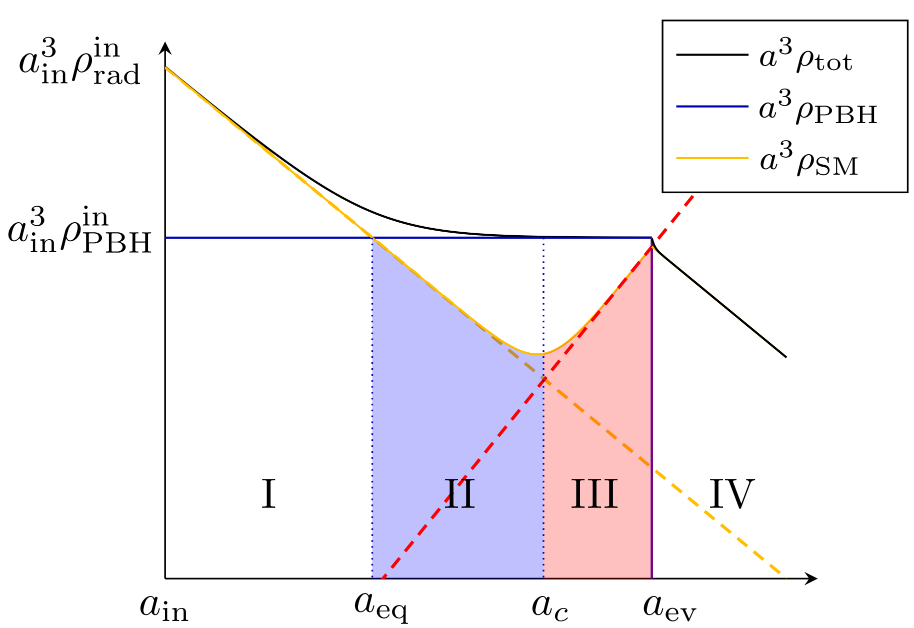
A Granelli, K Moffat, YFPG,
H Schulz and J Turner,
arXiv: 2007.09150
arXiv:2301.05722

- Leptogenesis via decays and resonant leptogenesis
- ARS Leptogenesis
- Easy parallelization
- Rapid evaluation
- Multidimensional scan of the parameter space

PBH + Leptogenesis







$$z_{\rm BH} \equiv \frac{M_{N_1}}{T_{\rm BH}}$$

PBH + Leptogenesis

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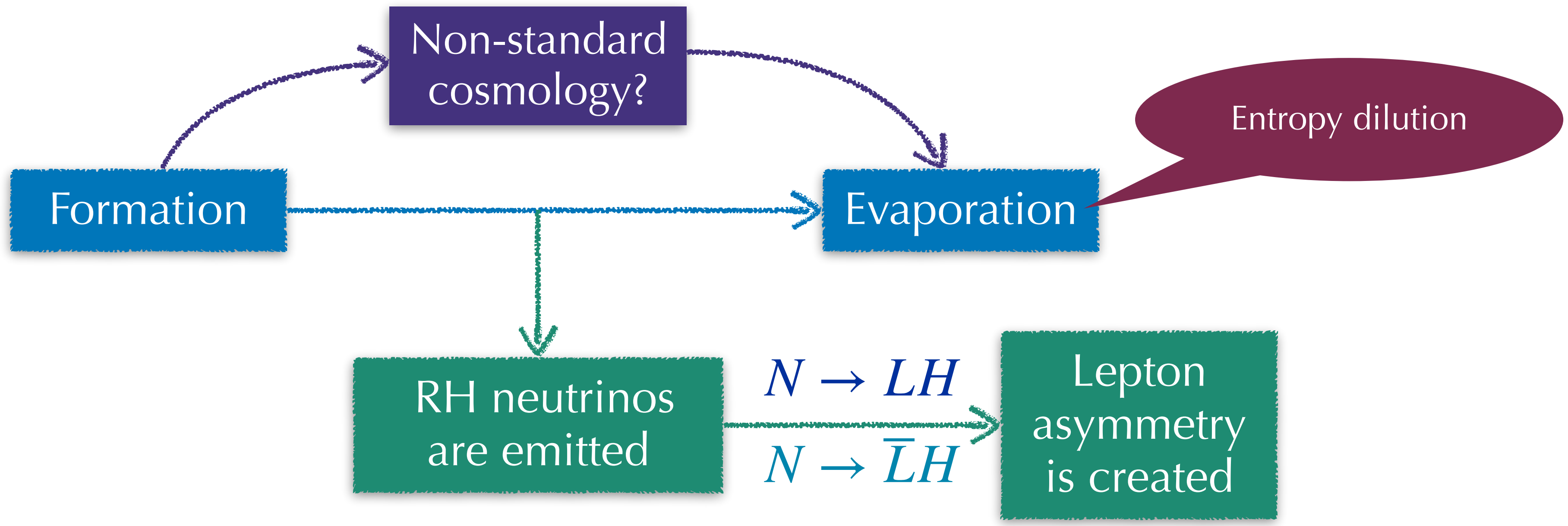
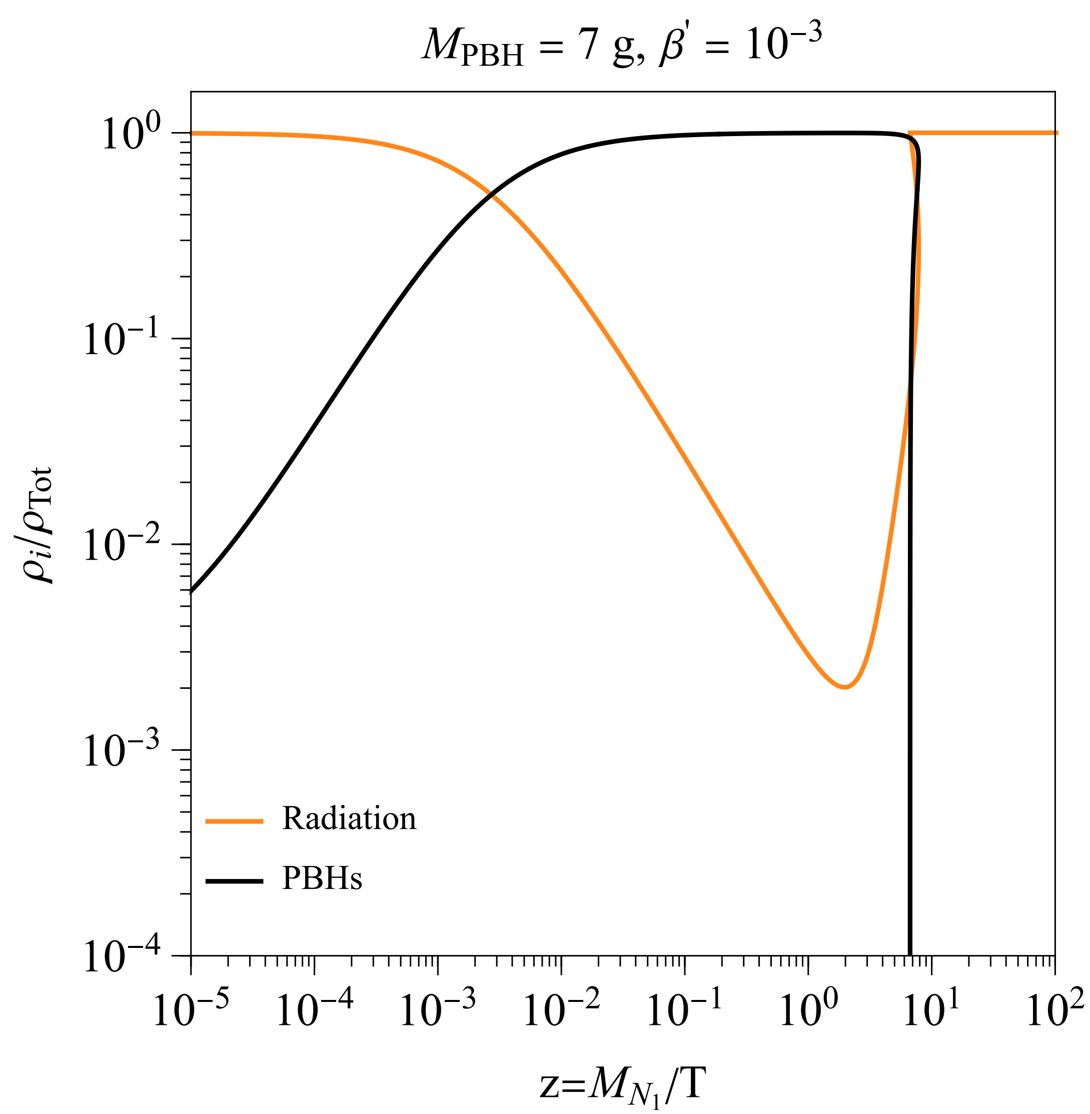
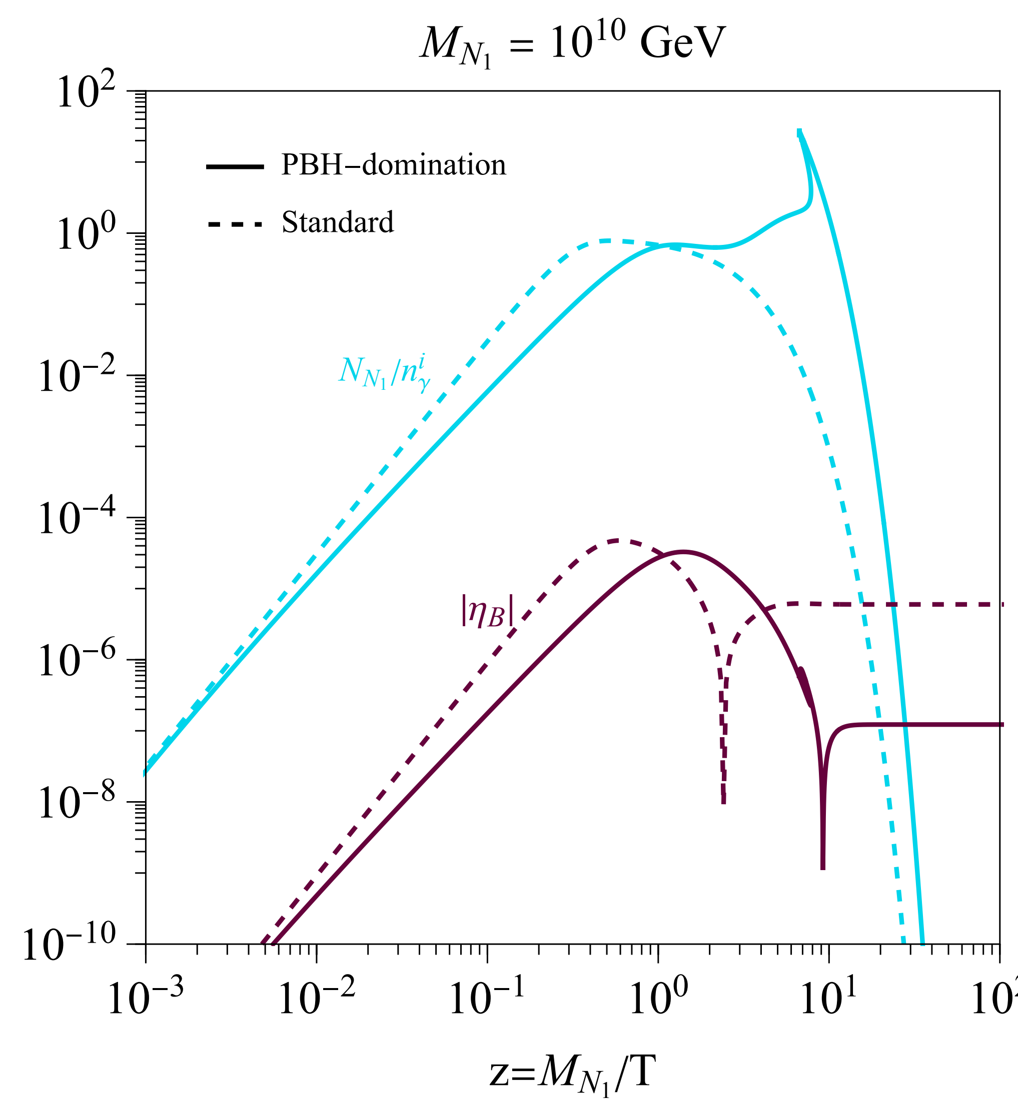


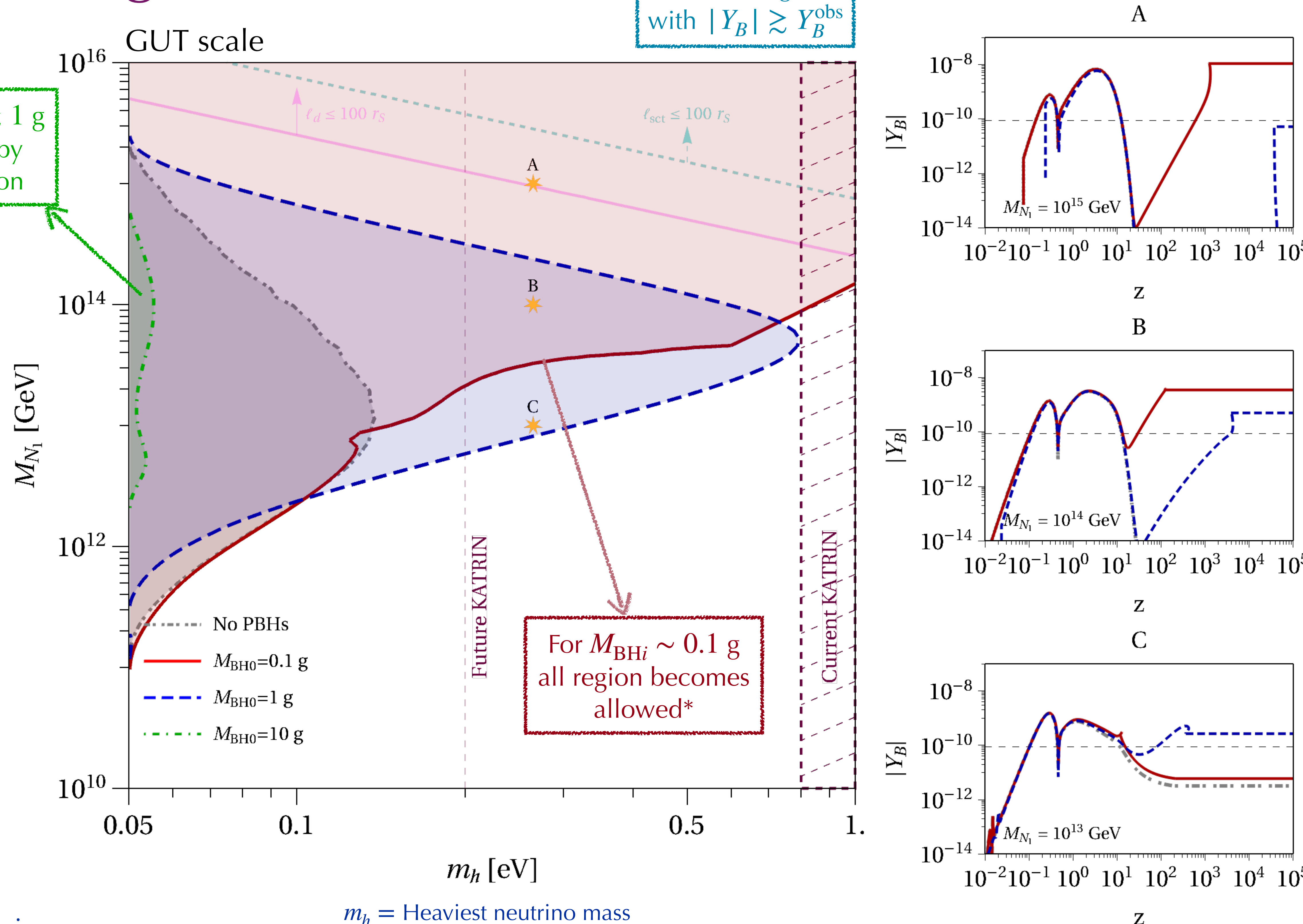




Rescuing HSL

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

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

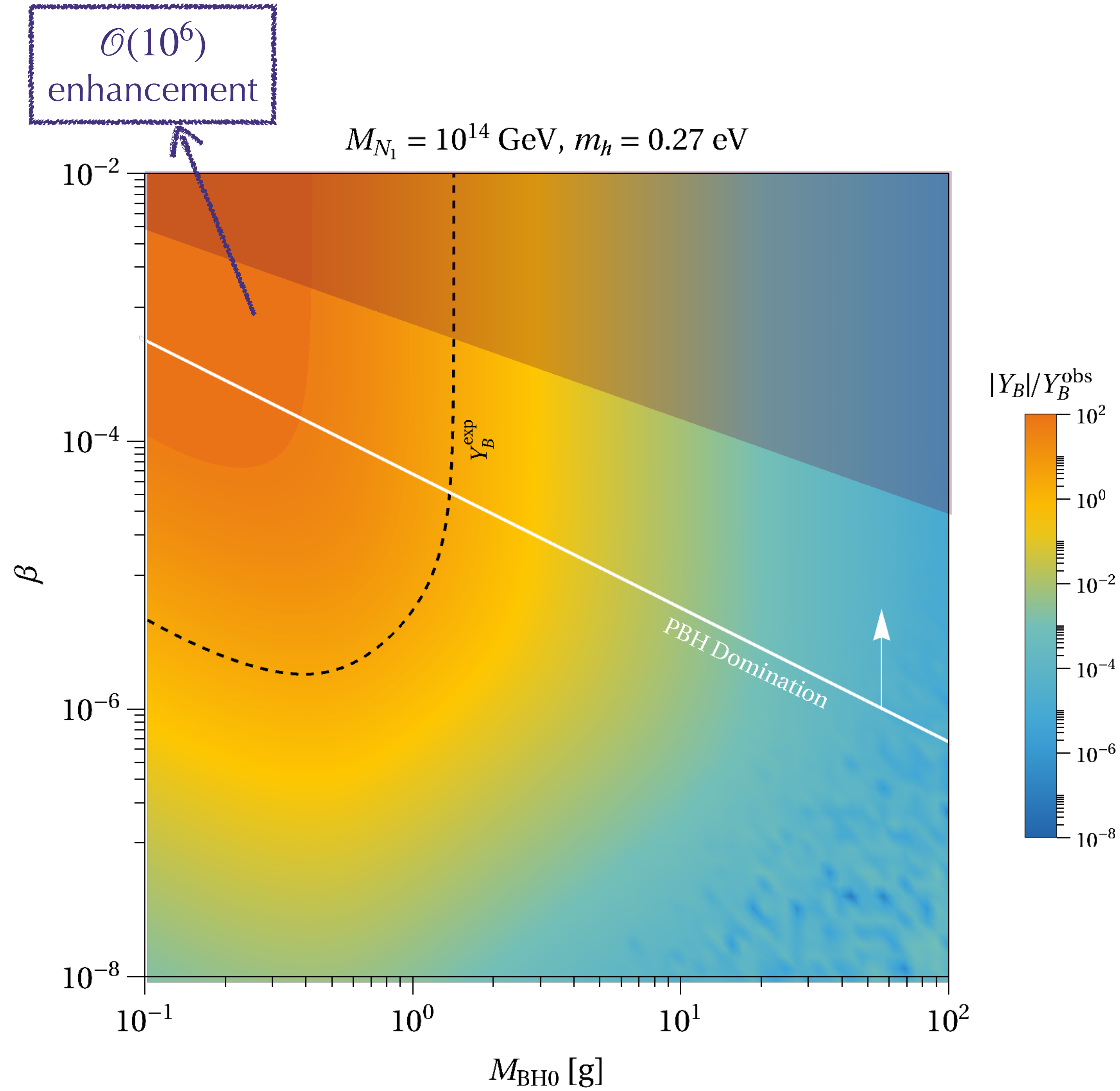


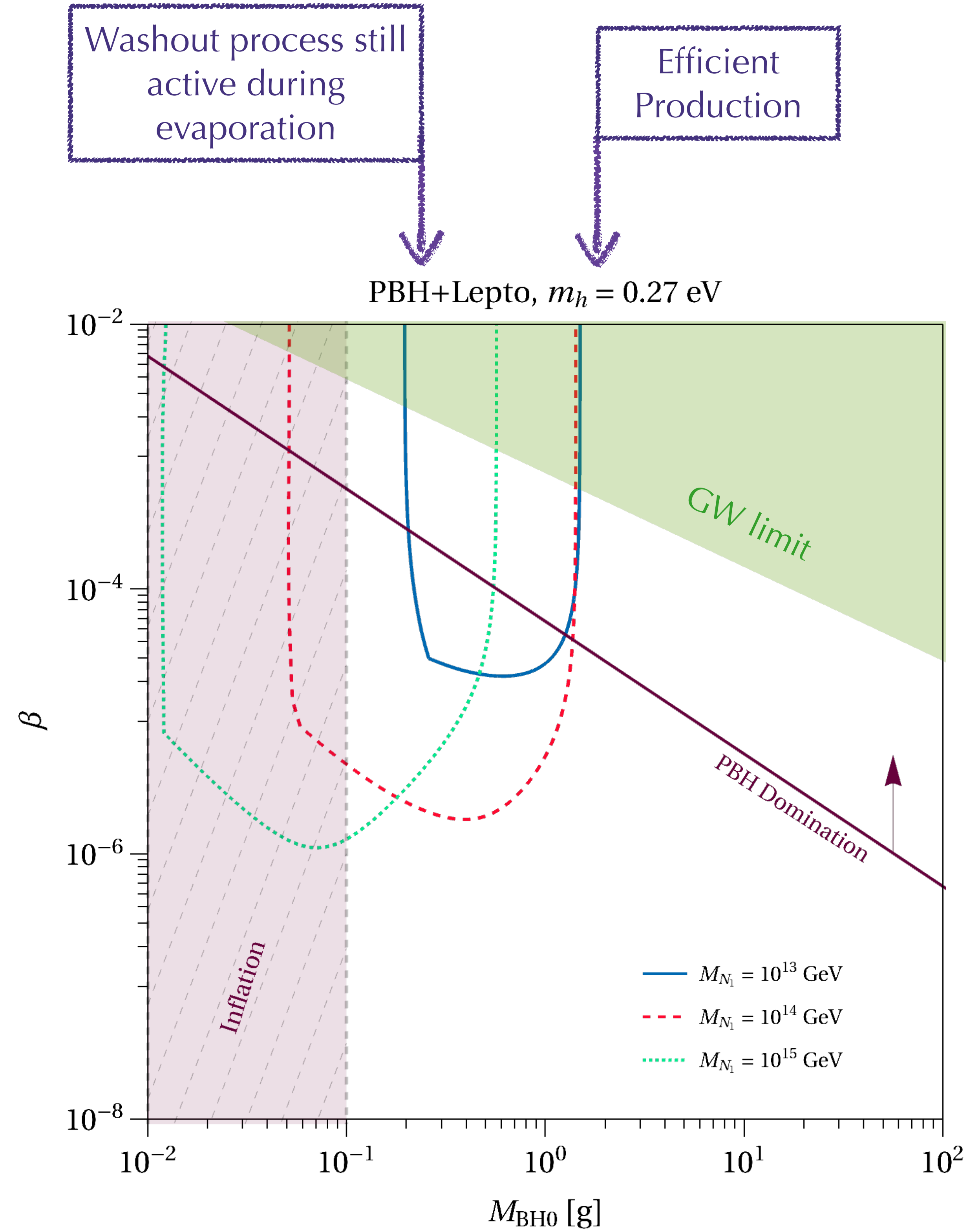
m_h = Heaviest neutrino mass

Maximizing over Yukawa parameters

*Up to perturbativity

Rescuing HSL





Mass Distributions

Monochromatic approximation *too* approximated?

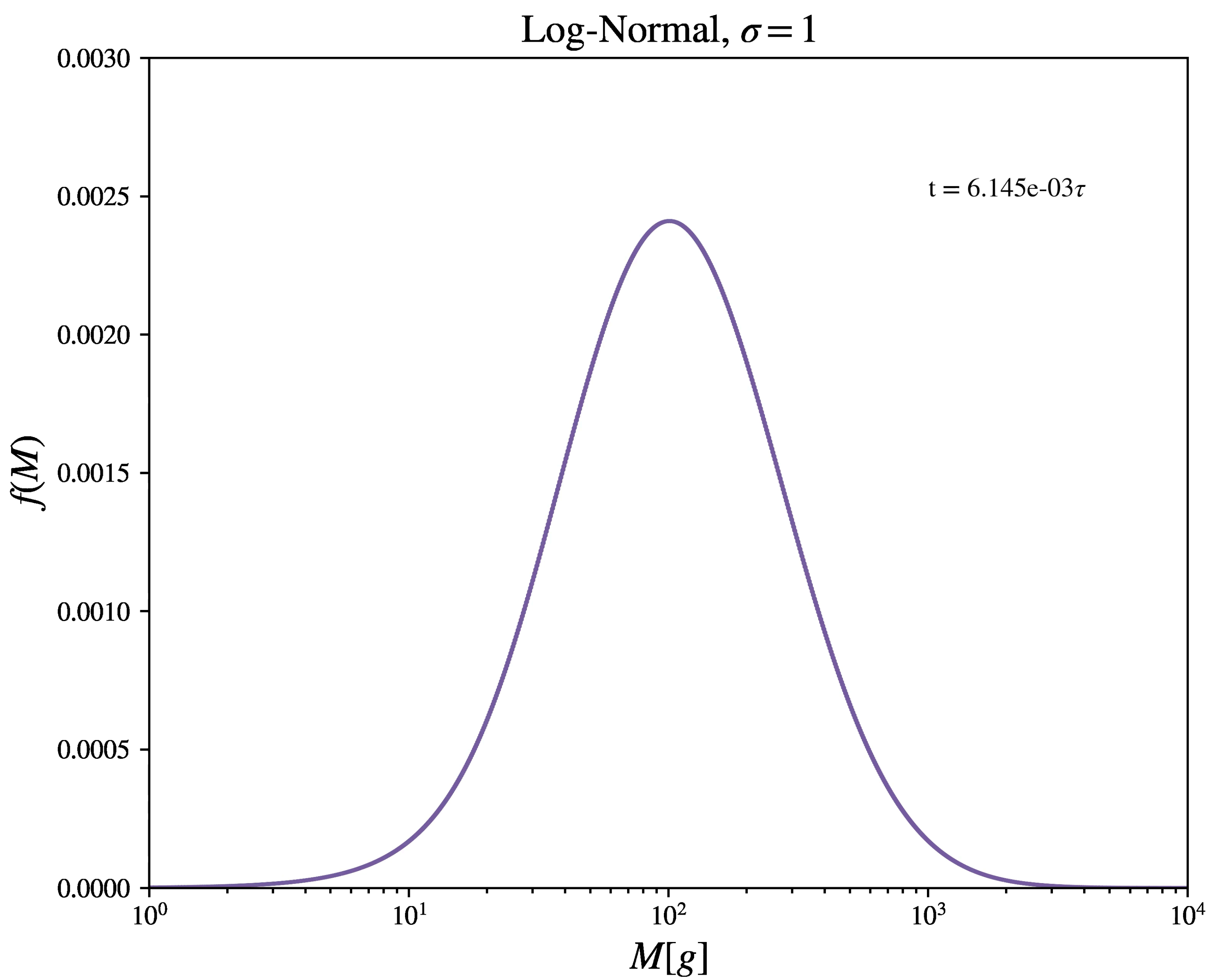
Connection with different formation mechanisms?

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

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

Log-normal distribution

Dolgov, 93
Green, 2016
Kannike, 2017



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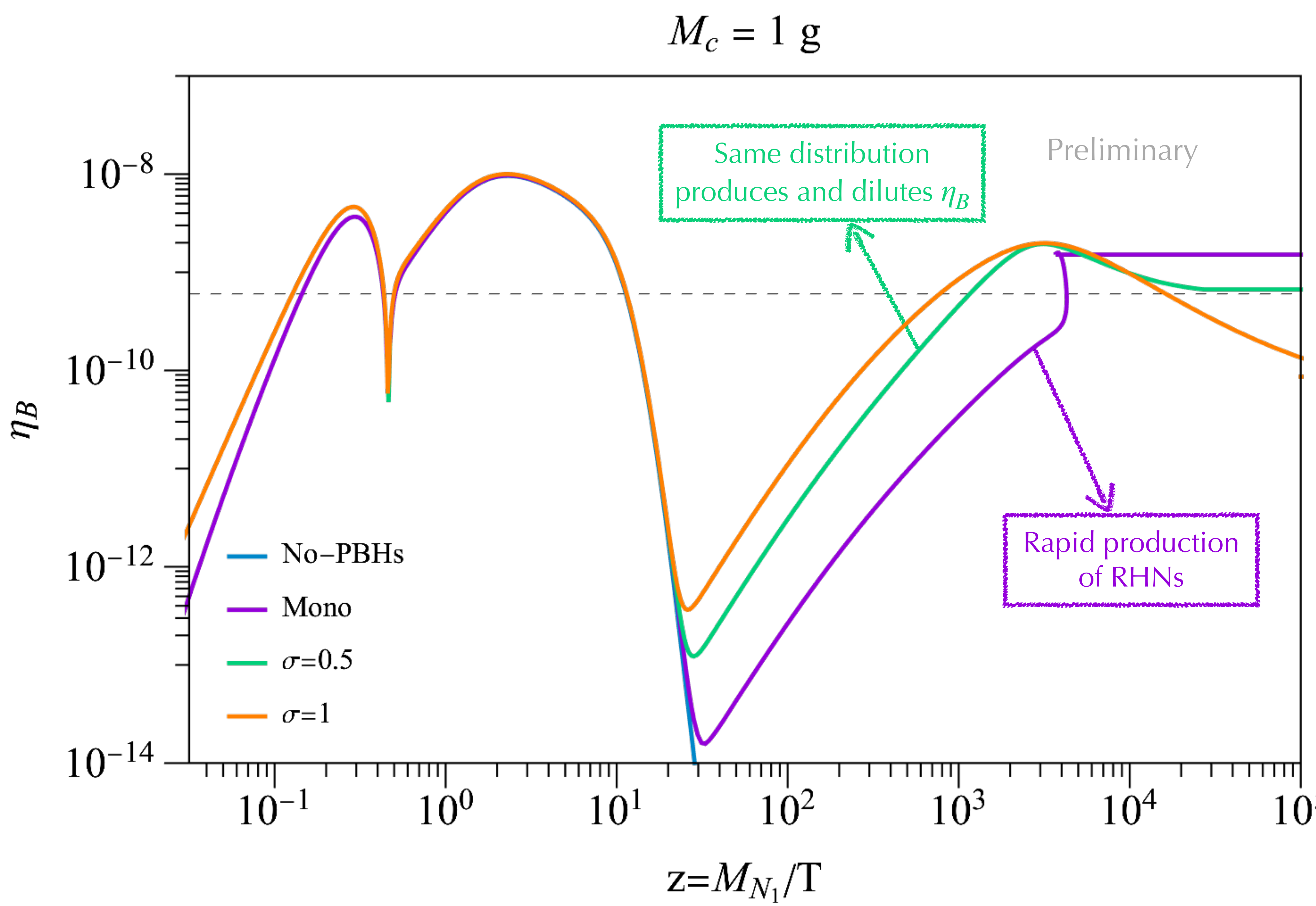

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Morrison et al,1812.10606
García-Bellido, Carr, Clesse, 1904.11482
Hooper and Krnjaic, 2010.01134
.
.
.

Dark Radiation

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

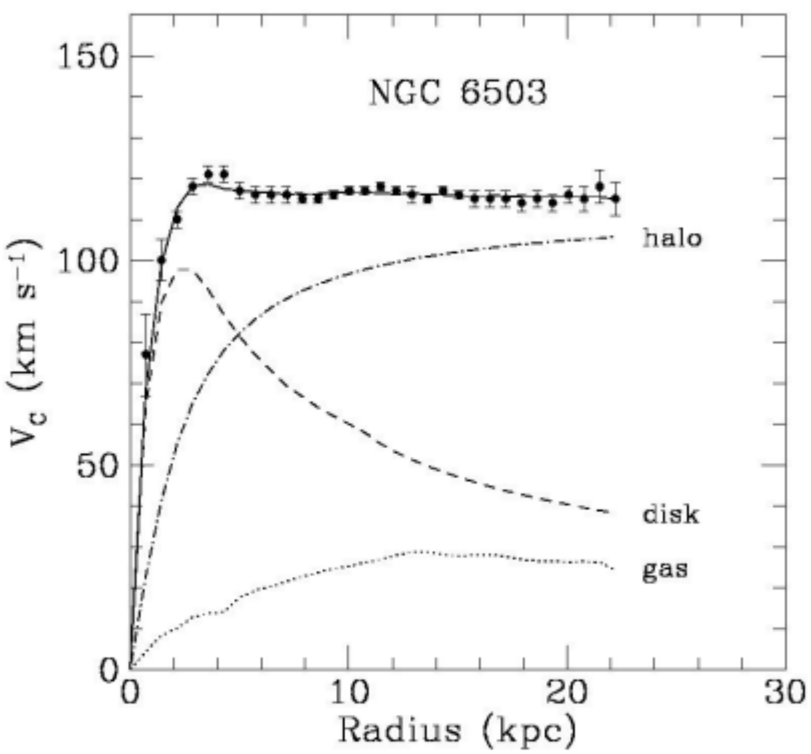
Hooper, Krnjaic, McDermott, 1905.01301
Lunardini, YFPG, 1910.07864
Masina, 2004.04740, 2103.13825
Cheek, Heurtier, YFPG, Turner, 2207.09462
.
.

Second Act
Dark Matter

Based on:
Cheek, Heurtier, YFPG, Turner 2107.00013, 2107.00016, 2212.03878
Cheek, Heurtier, YFPG, Turner, 2207.09462

Only Gravitational Interacting DM

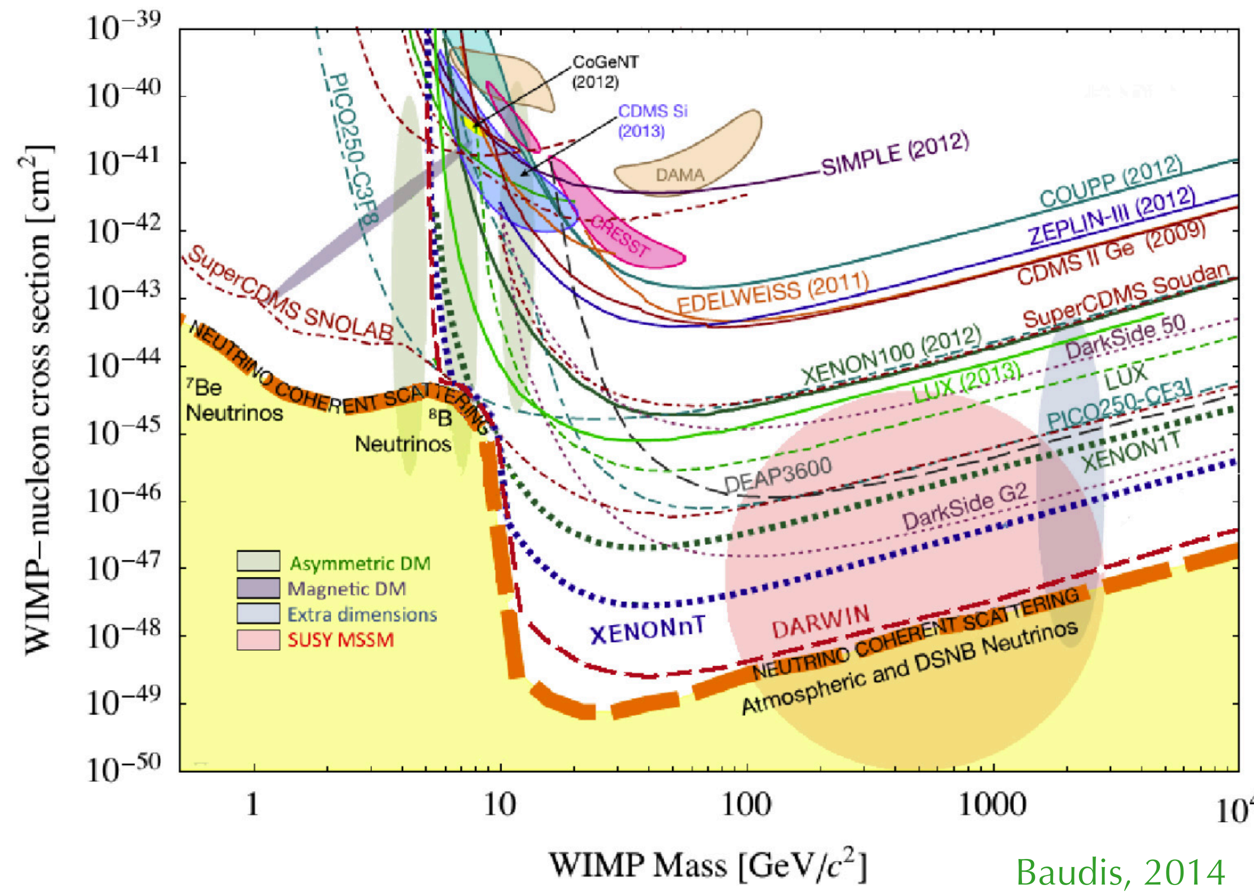
Plenty of evidence pointing to the existence of Dark Matter



Particle DM models **often** rely on BSM interactions to produce the relic abundance

Could the DM only interact gravitationally??

We're searching for it in terrestrial experiments



Baudis, 2014

How to produce it in the Early Universe?

PBHs!

Gondolo *et al.*, 2020
Bernal *et al.*, 2020
Baldes *et al.*, 2020

Only Gravitational Interacting DM

Consider equations for DM number densities

Boltzmann Equations

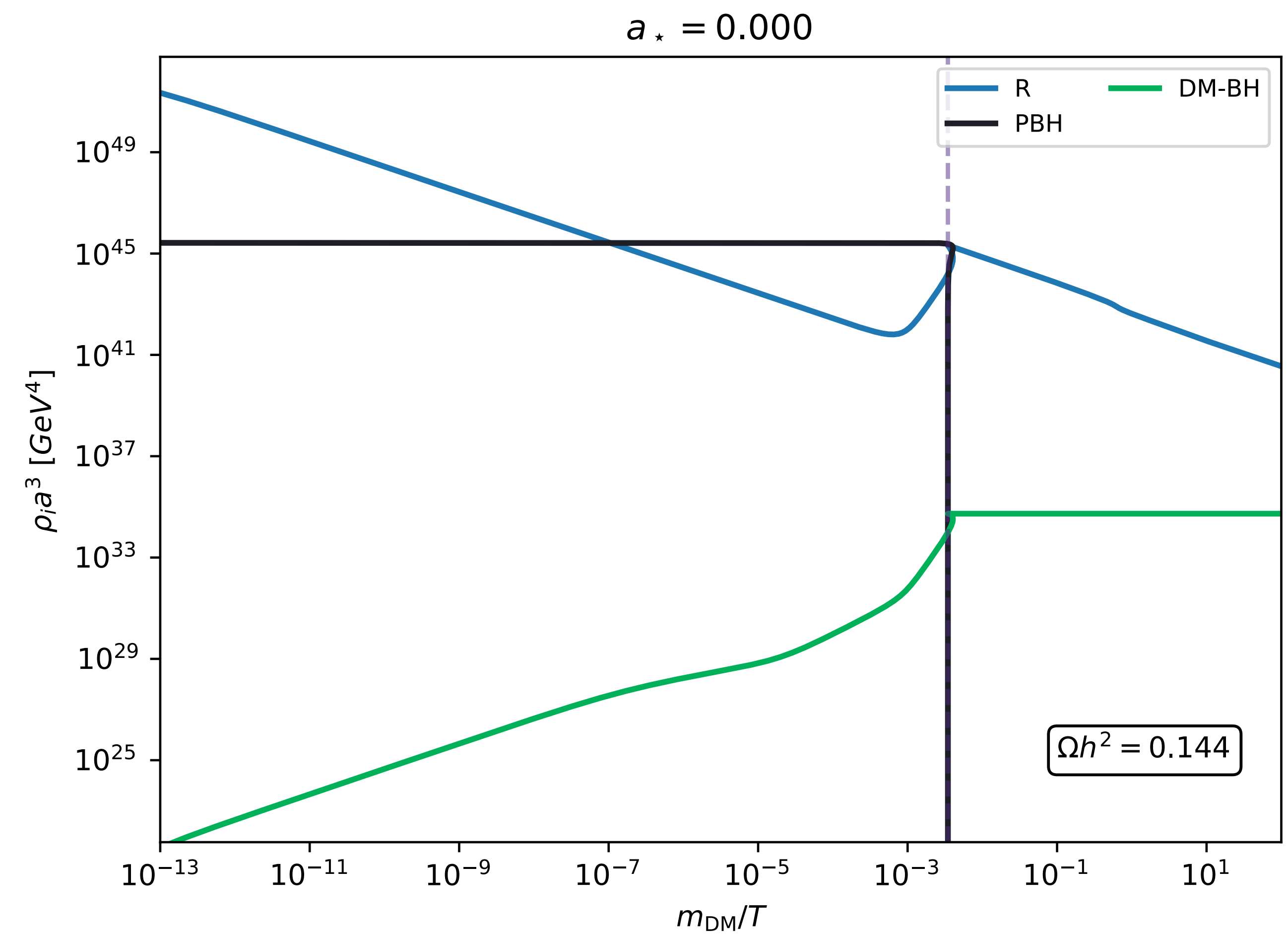
Evaporation

$$\dot{n}_{\rm DM} + 3Hn_{\rm DM} = g_i \int \left.\frac{\partial f_i}{\partial t}\right|_{\rm PBH} \frac{p^2 dp}{2\pi^2}$$

$$= n_{\rm PBH}\,\Gamma_{{\rm BH}\to i}(M_{\rm BH})$$

$$\dot{\rho}_{\rm SM} + 4H\rho_{\rm SM} = -\left.\frac{d\log M}{dt}\right|_{\rm SM} \rho_{\rm PBH}$$

$$\dot{\rho}_{\rm PBH} + 3H\rho_{\rm PBH} = \frac{d\log M_{\rm BH}}{dt}\rho_{\rm PBH}$$



$m_{\rm DM} = 0.1$ GeV

$\beta' = 10^{-7}$

$M_{\rm BH,i} = 10^6$ g

Particle emission rate

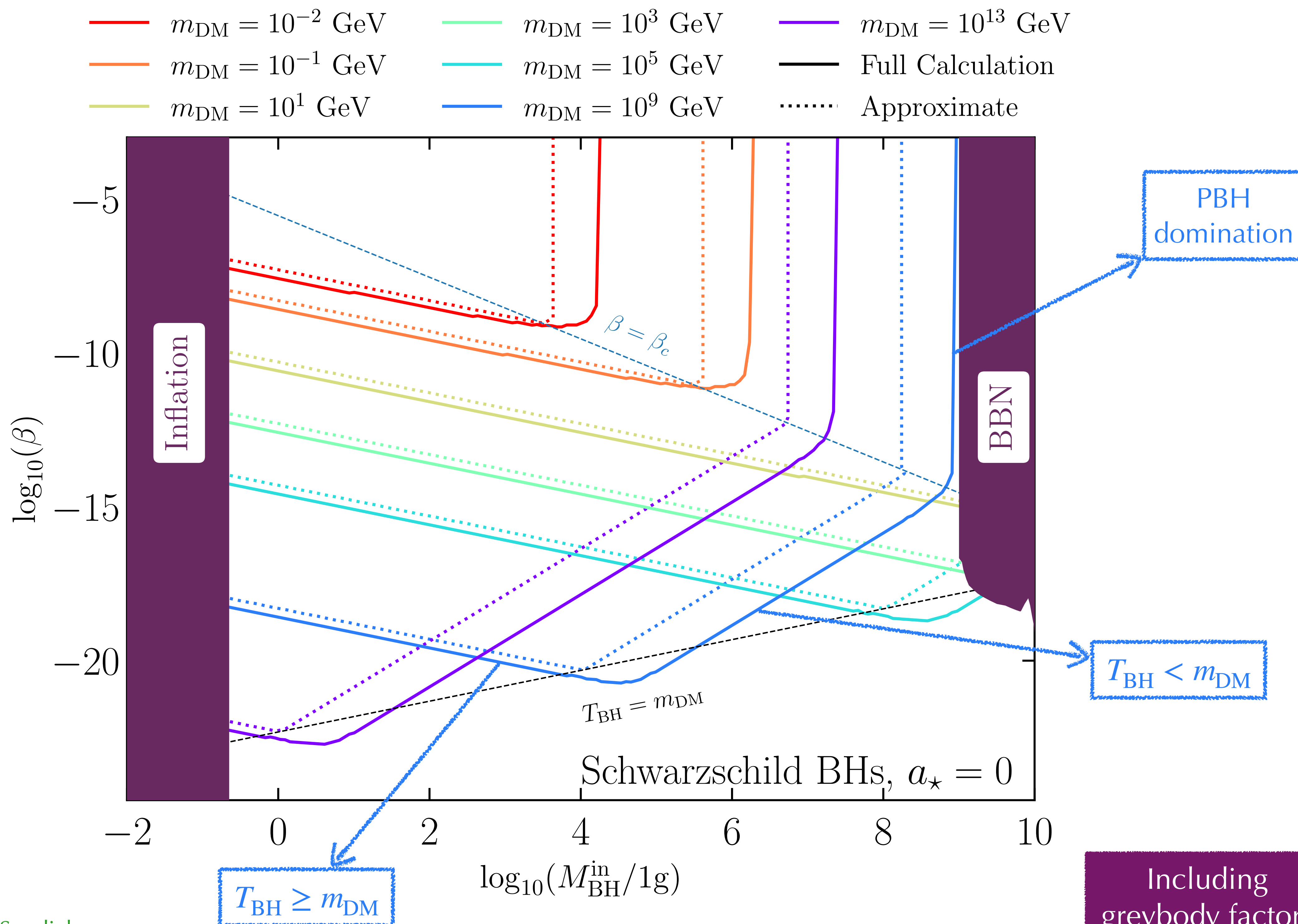
$$\Gamma_{{\rm BH}\to i}(M_{\rm BH}) = \int dp \frac{d^2\mathcal{N}_i}{dp\,dt}$$

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

Our code is publicly available in

FRISBHEE

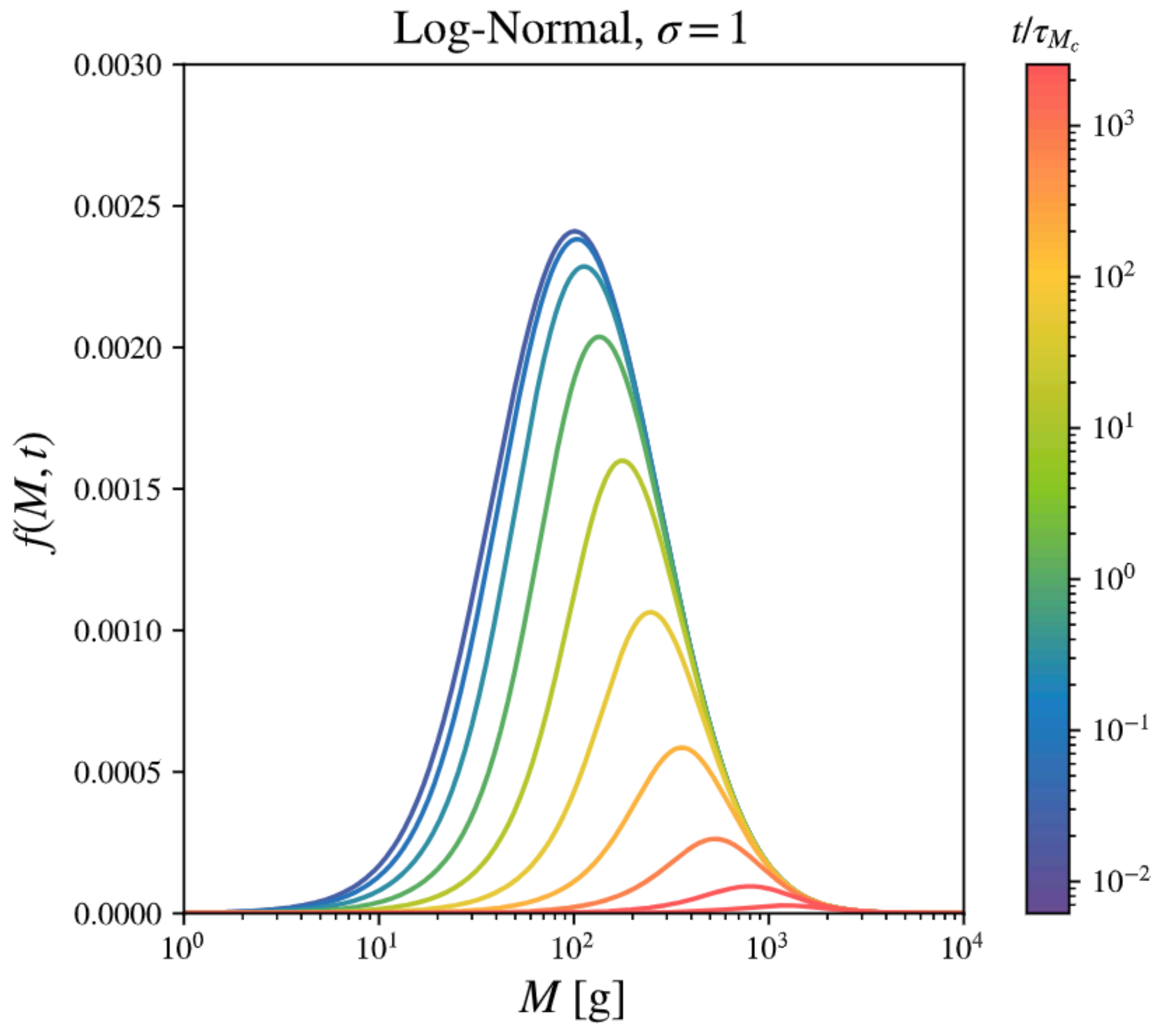
Only Gravitational Interacting DM

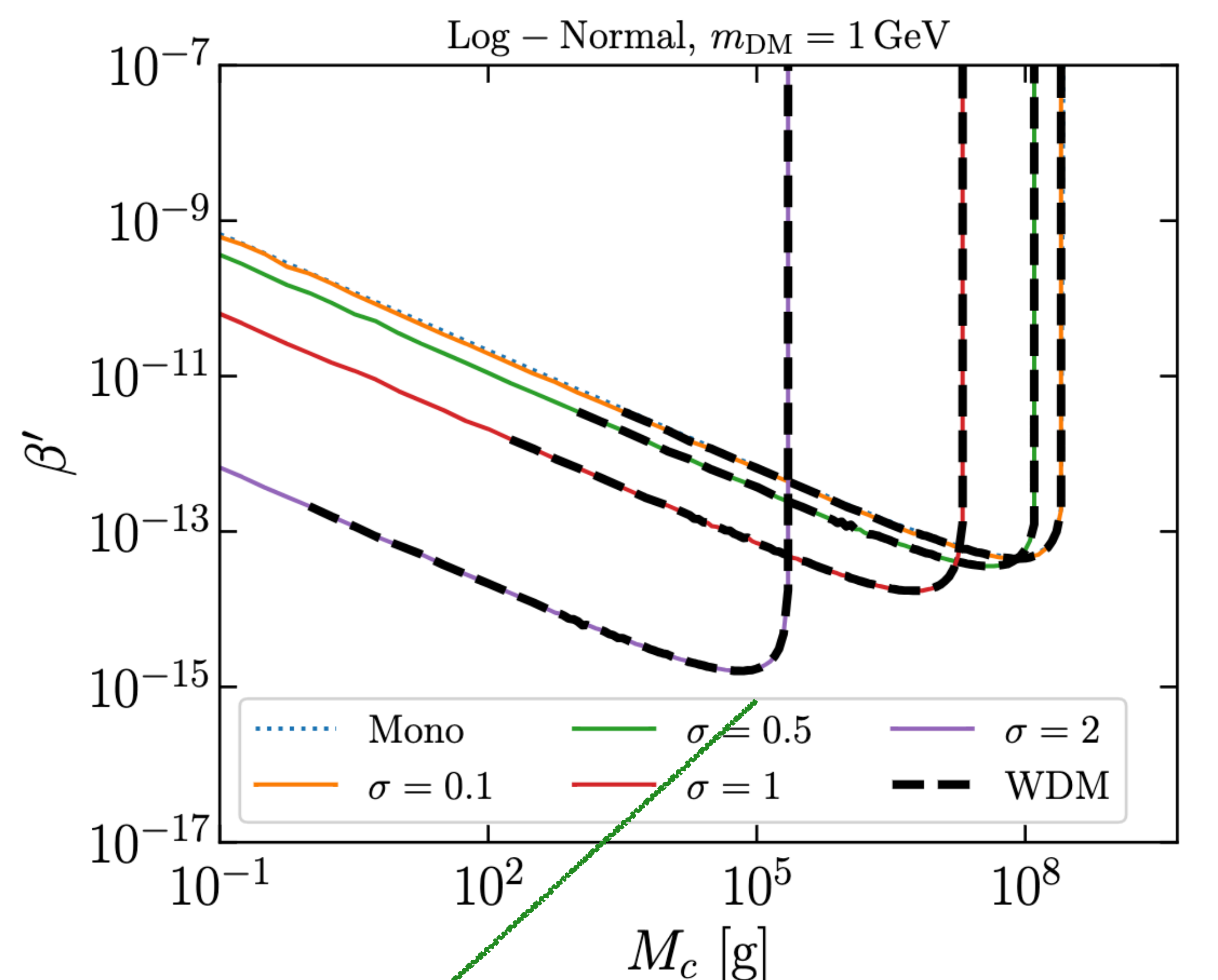


Dashed from Gondolo, Sandick, Shams Es Haghi 2009.02424

Including greybody factors

Mass distributions





$$N_{\rm DM} \propto \begin{cases} \dfrac{M_{\rm BH}^2}{M_p^2} & T_{\rm in} > m_{\rm DM} \\ \dfrac{M_p^2}{m_{\rm DM}^2} & T_{\rm in} < m_{\rm DM} \end{cases}$$

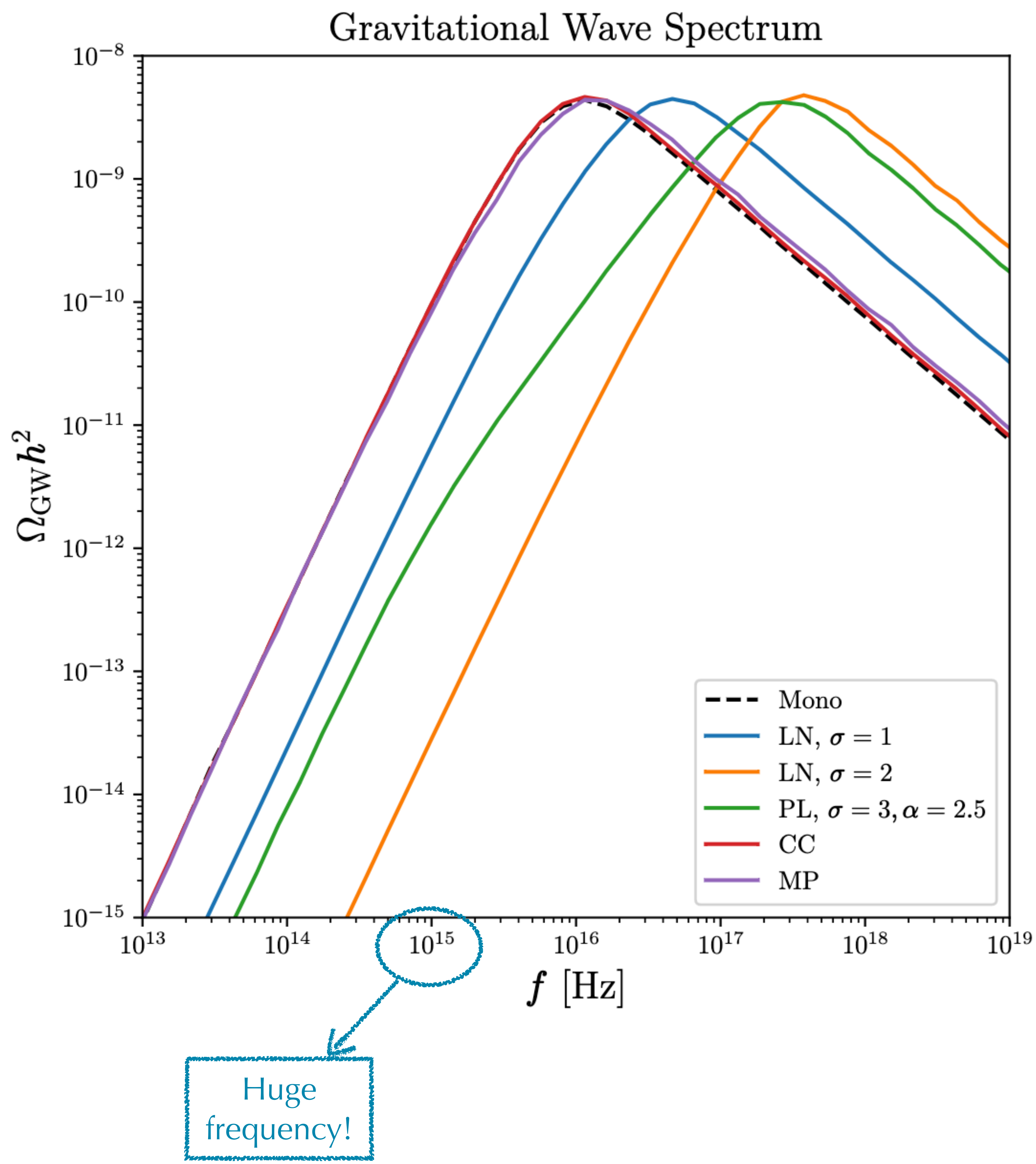
Heavier PBHs produce more light DM

Testing these scenarios?

Gravitational Waves?

How to prove that the early Universe had a PBH-dominated era?

Example: GW produced by the evaporation



Arvanitaki, Geraci, 2013

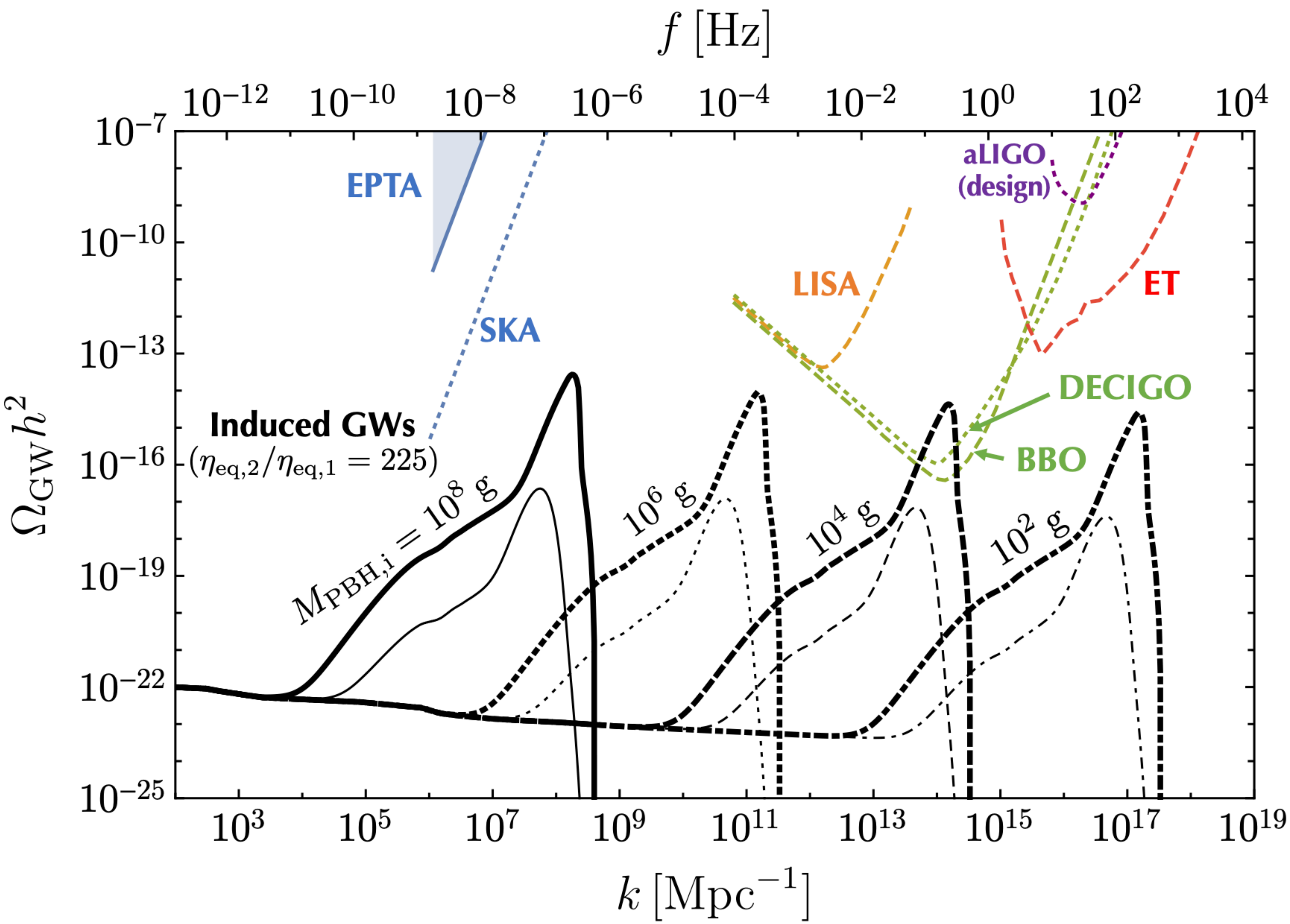
Ito et al, 2020

Chen et al, 2020

Gravitational Waves?

How to prove that the early Universe had a PBH-dominated era?

Poltergeist Mechanism



GWs are induced after the sudden transition from a matter to radiation dominated U

Inomata et al, 2003.10455

See also: 2205.06260

Third Act:
High energy Neutrinos and Evaporating PBHs

Based on:
YFPG, 230X.XXXXX

Evaporating PBHs (EPBH)

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

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

- Test BSM??

Baker, Thamm 2105.10506, 2210.02805

- How to measure PBH properties during evaporation?

Capanema et al, 2110.05637
Calzà, Rosa, 2210.06500

- Kerr EPBHs → Incorrect assumptions on Hawking spectrum

Photons dominate the measurement

Anything to learn from neutrinos?

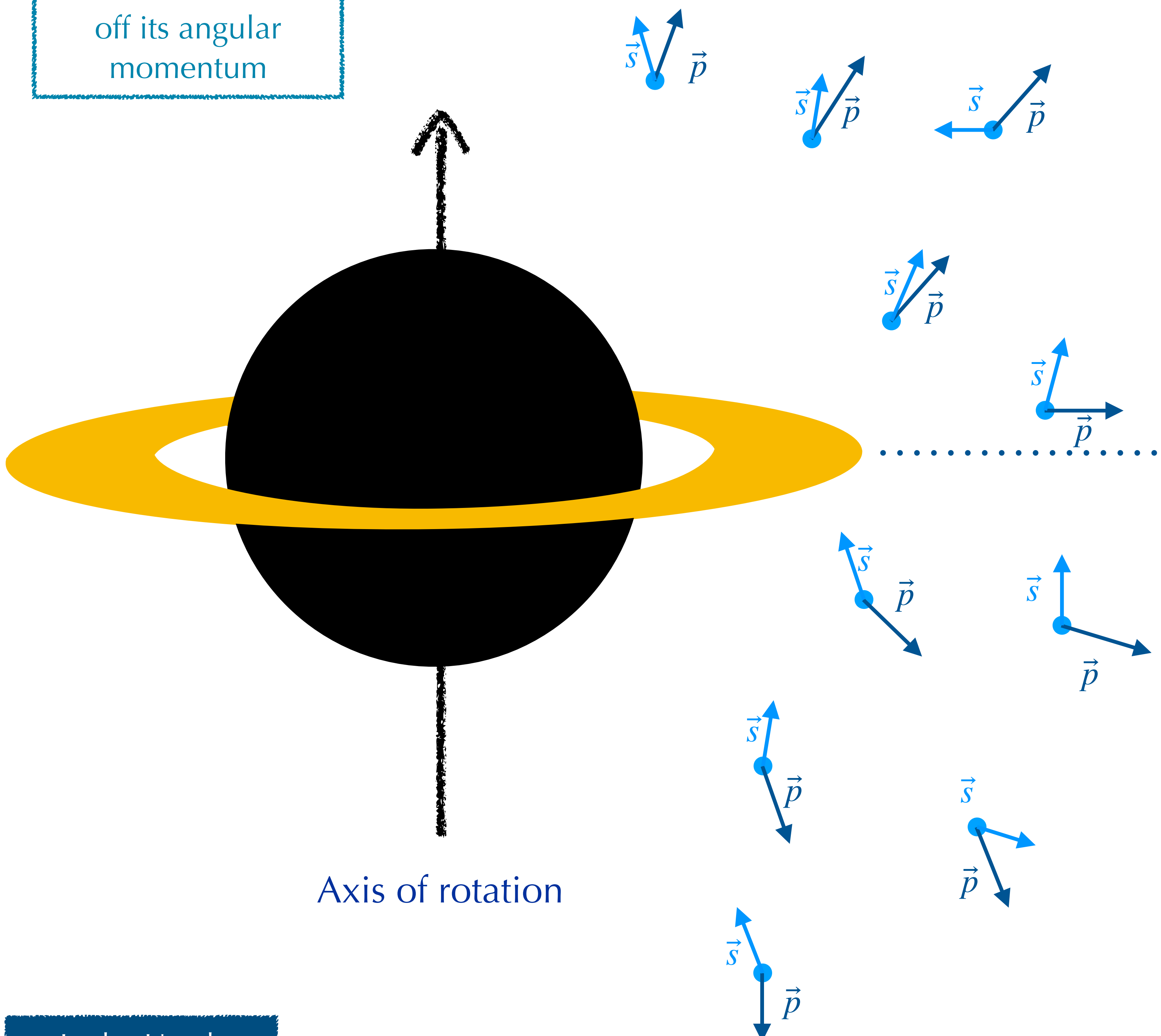
↓

Parity Violation!!

How does this manifest in Hawking evaporation?

Neutrino Emission Asymmetry

BH "wants" to shed off its angular momentum



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

Antineutrinos*

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

Neutrinos*

Leahy, Unruh
PRD 19(1979)3509

*in the ultrarrelativistic limit

Neutrino Emission Asymmetry

$\theta \to$ polar angle

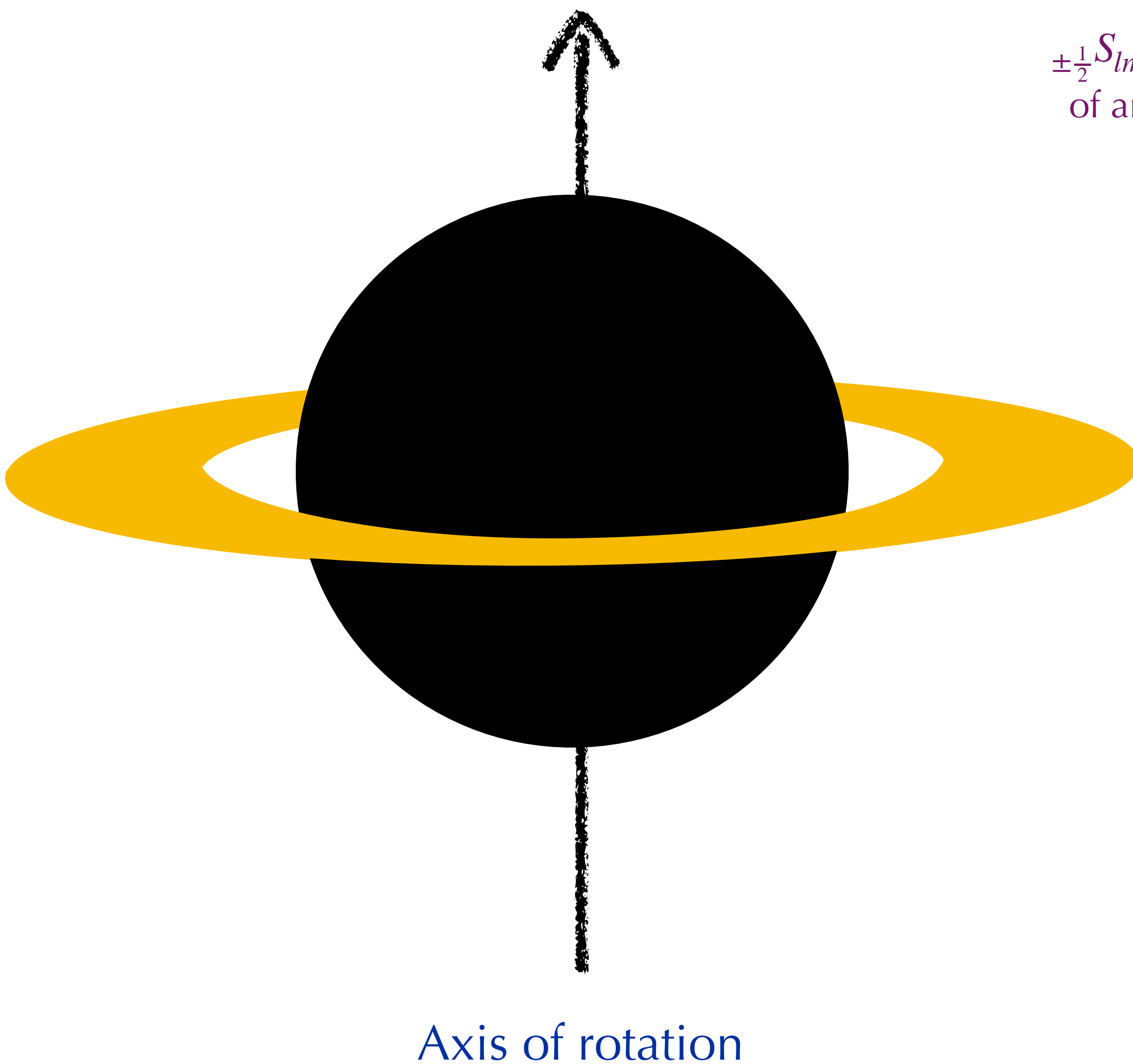
BH "wants" to shed off its angular momentum

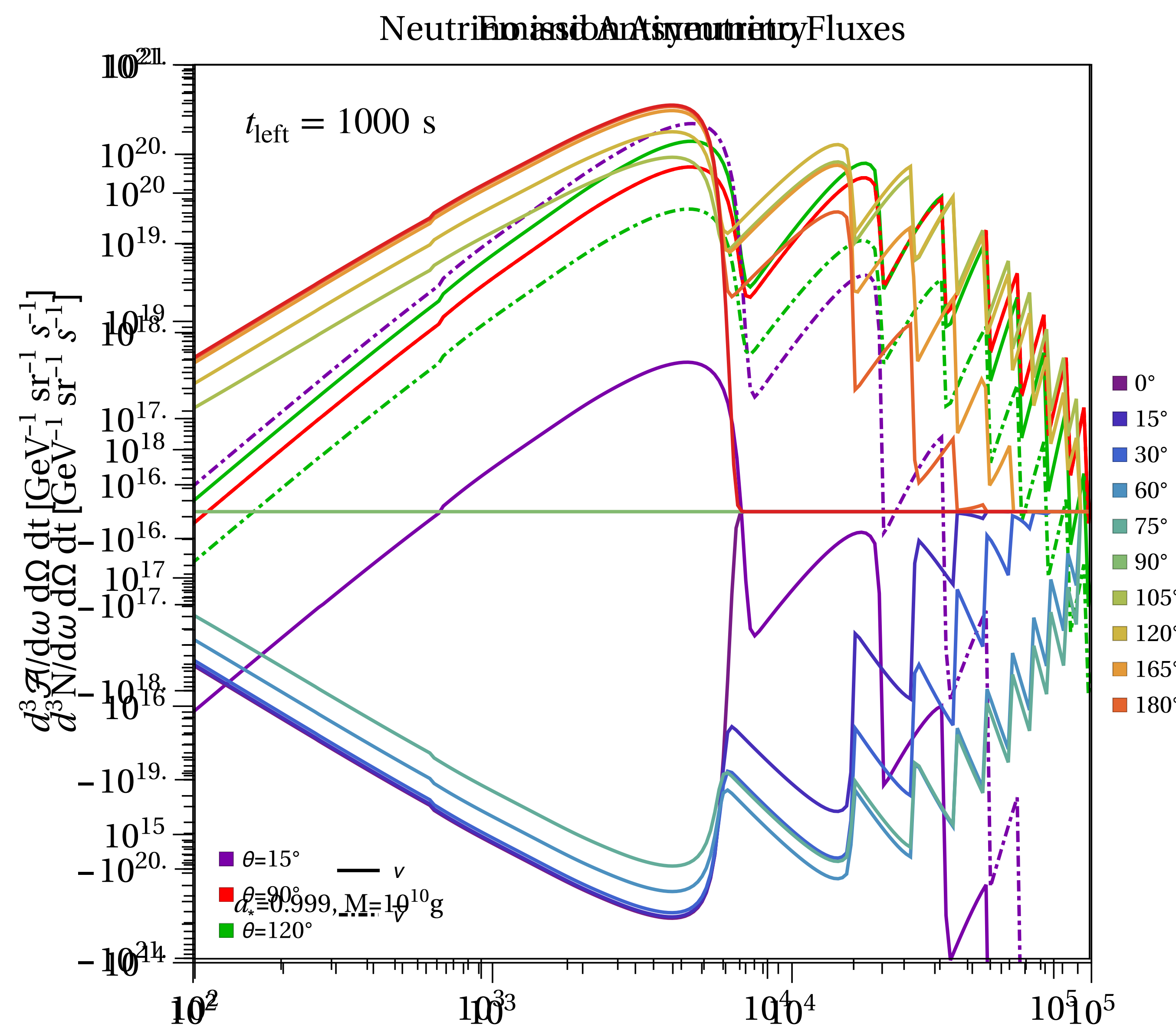
$$\mathscr{A} \equiv N_\nu - N_{\bar{\nu}}$$

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

"Neutrinos" "Antineutrinos"

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



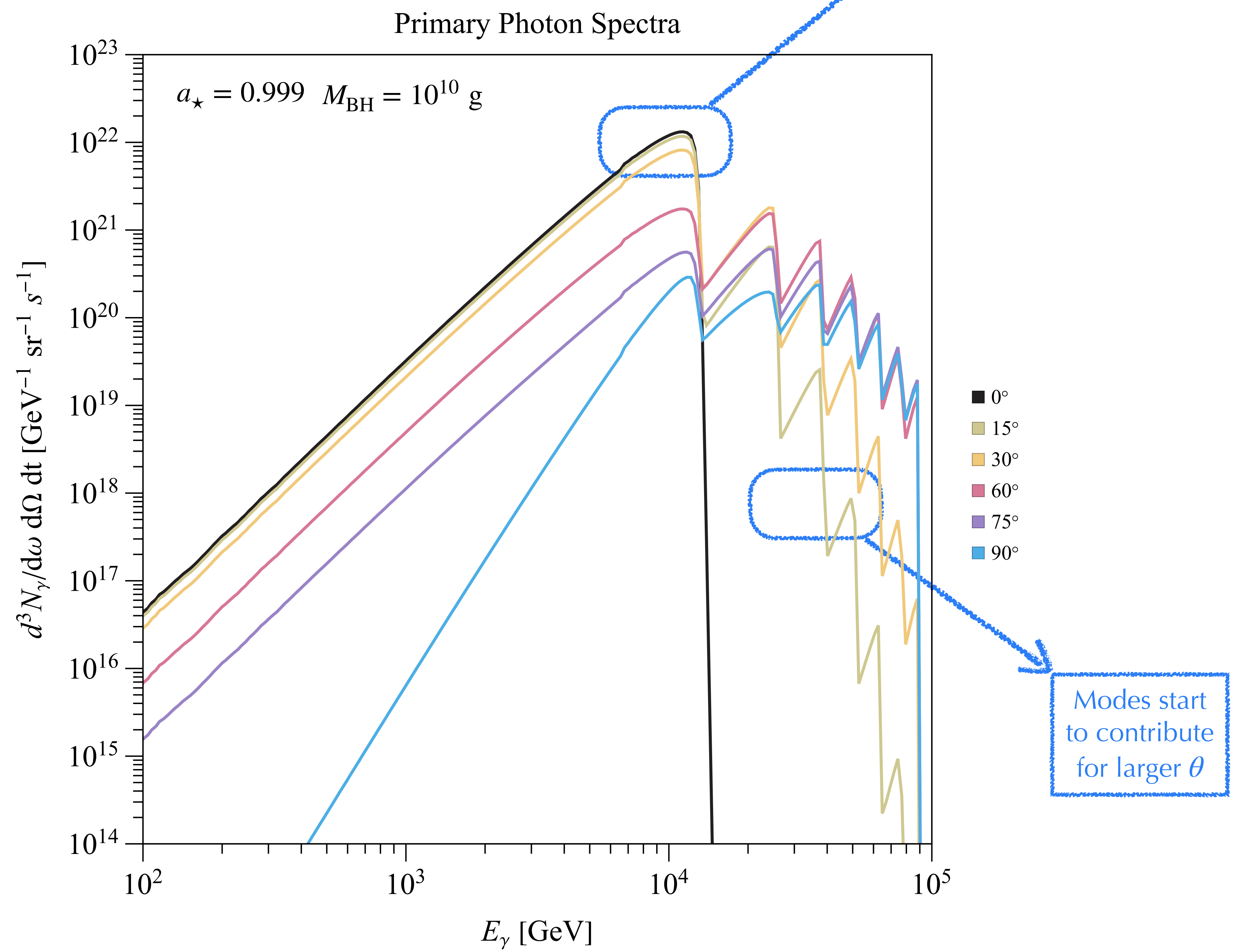


Primary emission

Could neutrinos tell us the spin of a PBH?

Photons?

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



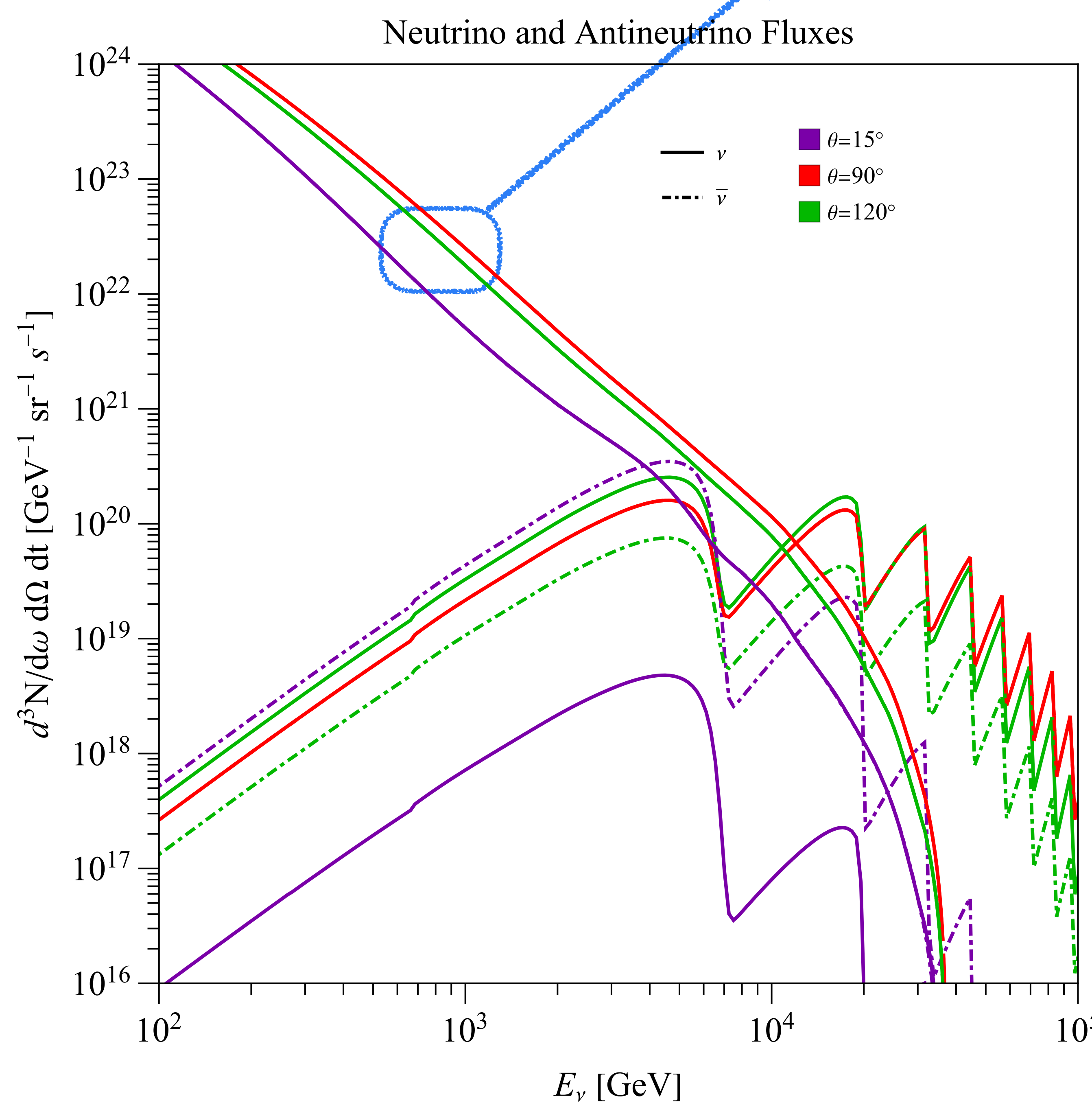
Also dependent on the polar angle

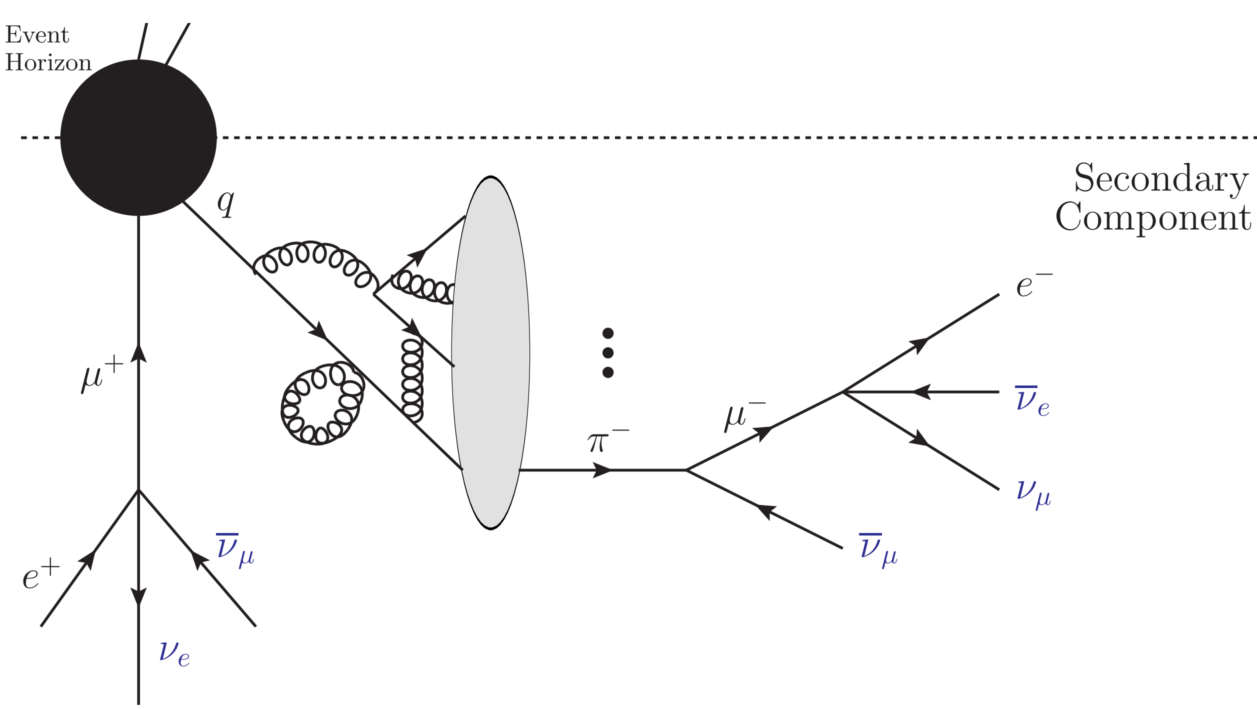
Secondaries?

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

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

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

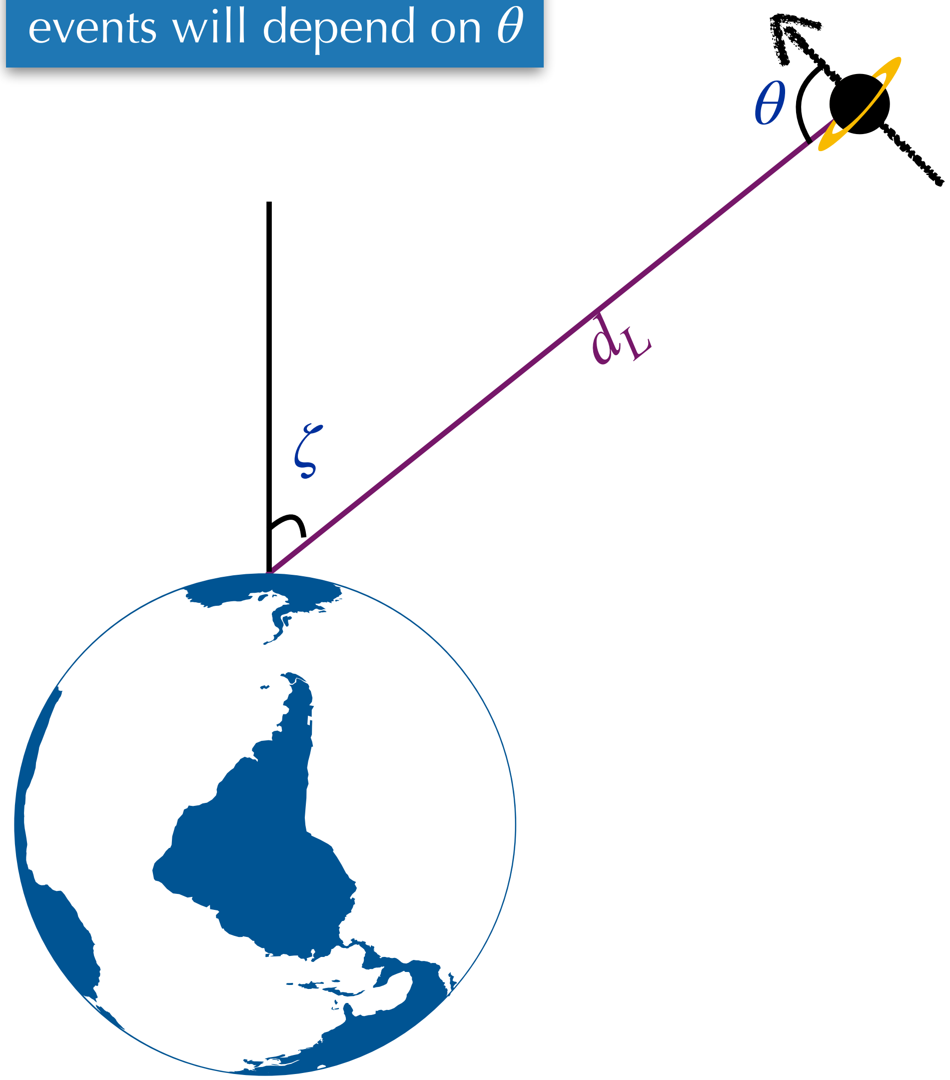




Determining the angular momentum

Previous works ignored the dependence on θ

Neutrino - antineutrino events will depend on θ

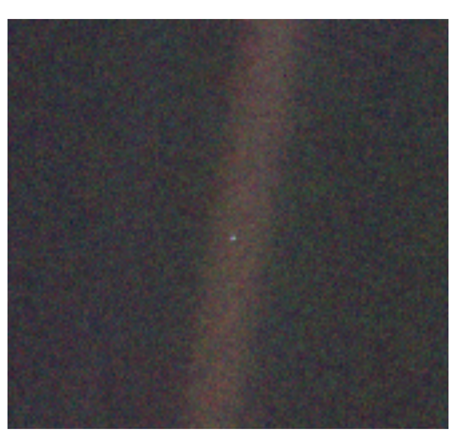


$$N_X(\theta) = \frac{1}{d_L^2} \int_{\omega_{\min}}^{\omega_{\max}} \int_0^{\tau} dt \, \frac{d^3 N_X}{d\omega dt d\Omega} A_{\text{eff}}(\omega, \zeta) d\omega$$

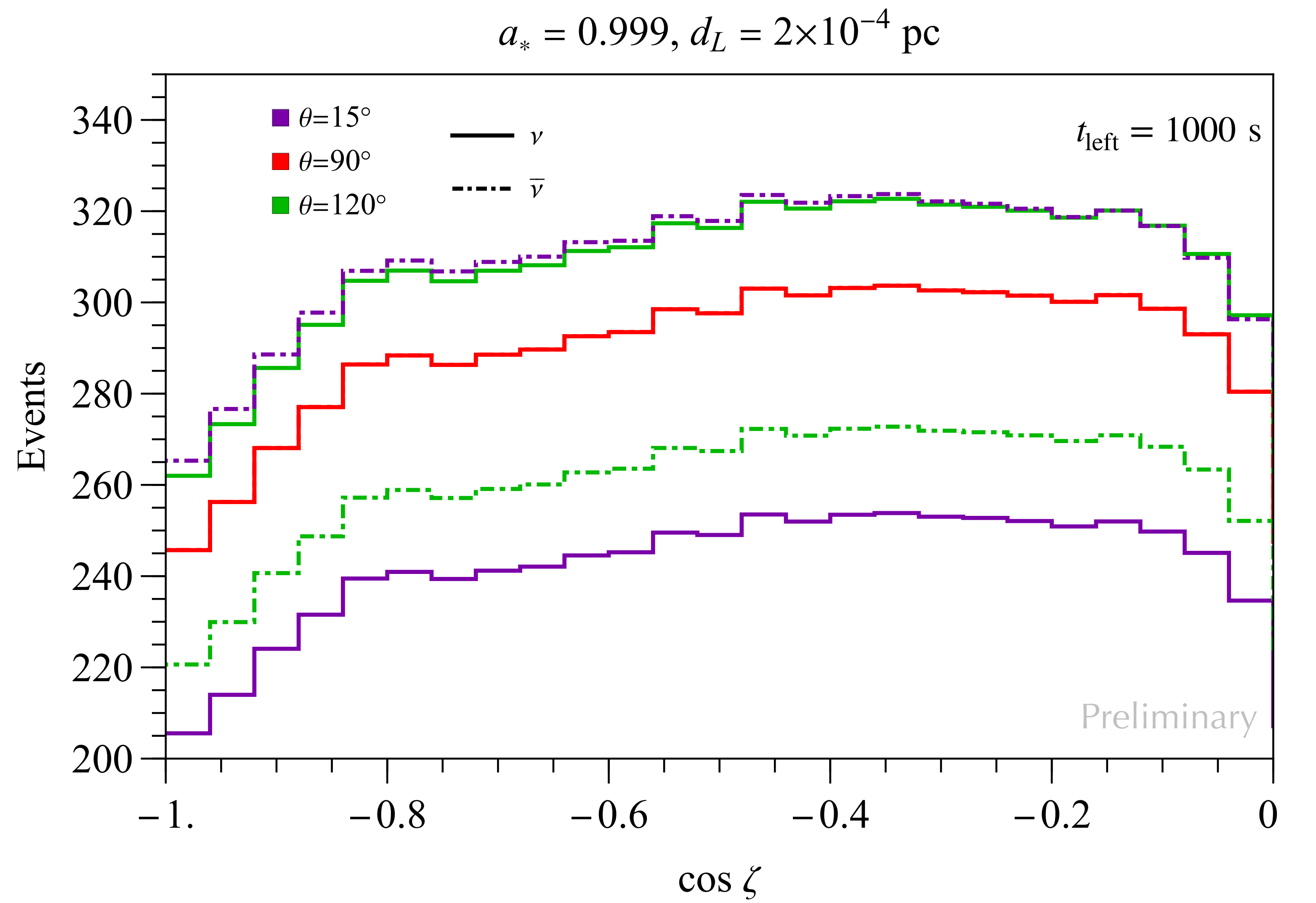
IceCube/HAWK effective area

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

$d_L = 2 \times 10^{-4}$ pc $\approx$



Pale blue dot



Conclusions

- 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
- We explored the effects on leptogenesis assuming the existence of a PBH population
- 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 and EPBH?

Thank you!