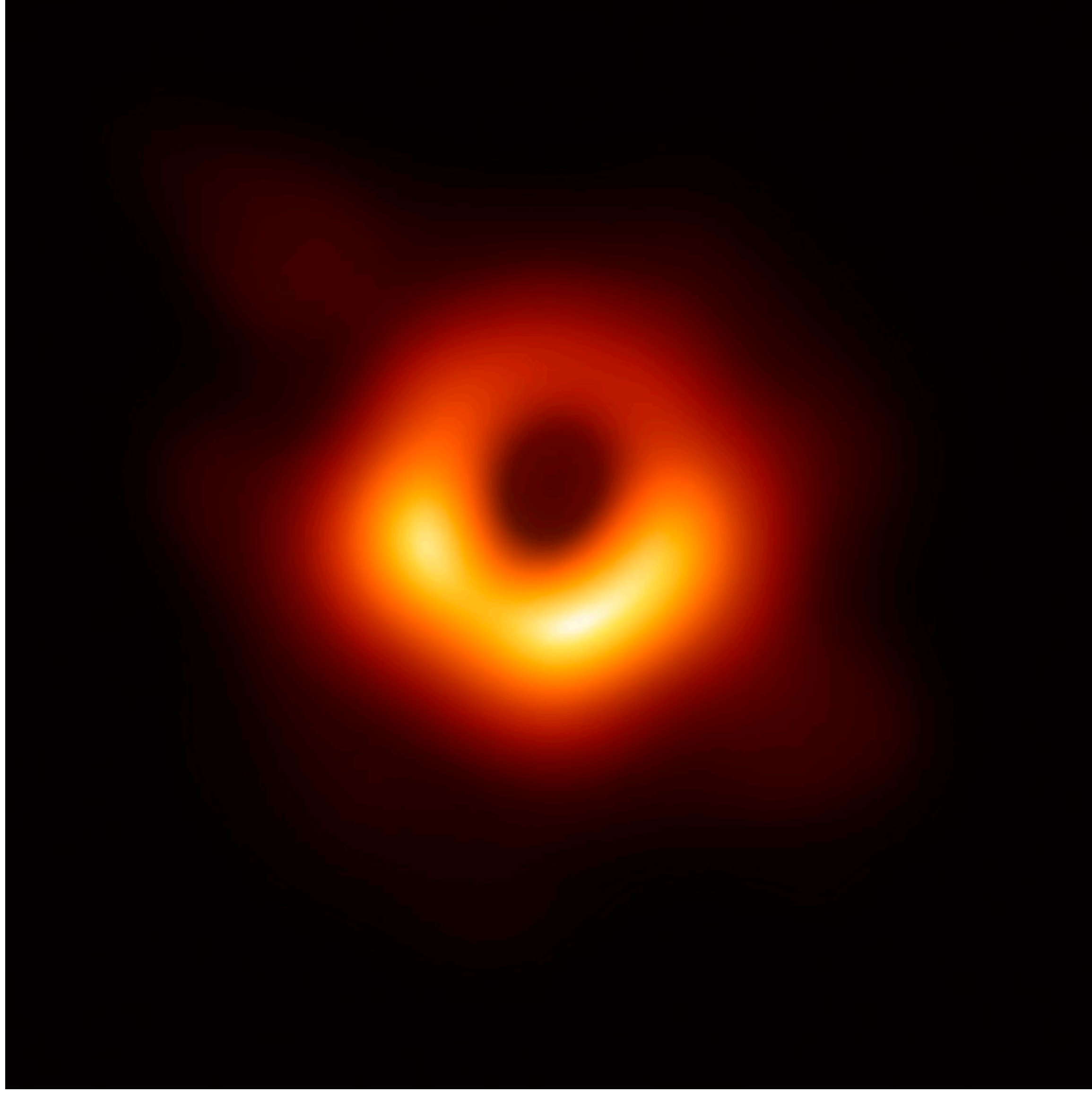
FERMILAB-SLIDES-19-063-T

Dirac and Majorana neutrino signatures of Primordial Black Holes



EHT Collaboration

Yuber F. Perez-Gonzalez

In collaboration with Cecilia Lunardini

arXiv: 1910.XXXXX

Neutrino Platform Week 2019: Hot Topics in Neutrino Physics

CERN, October 11th, 2019

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Are there other mechanisms for neutrino emission?

Primordial Black Holes (PBH)

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Astrophysical Black Holes $M \gtrsim 1.4 M_\odot$

Primordial Black Holes (PBH)

Astrophysical Black Holes

$M \gtrsim 1.4 M_\odot$

"Smaller" Black Holes

Larger densities

$r_S = 2GM$

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

Primordial Black Holes

Carr et al, 0912.5297

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$r_S = 2GM$

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Primordial Black Holes

Formation

- Bubble collisions
- Pressure reduction
- Collapse of density fluctuations

Quantum effects are important

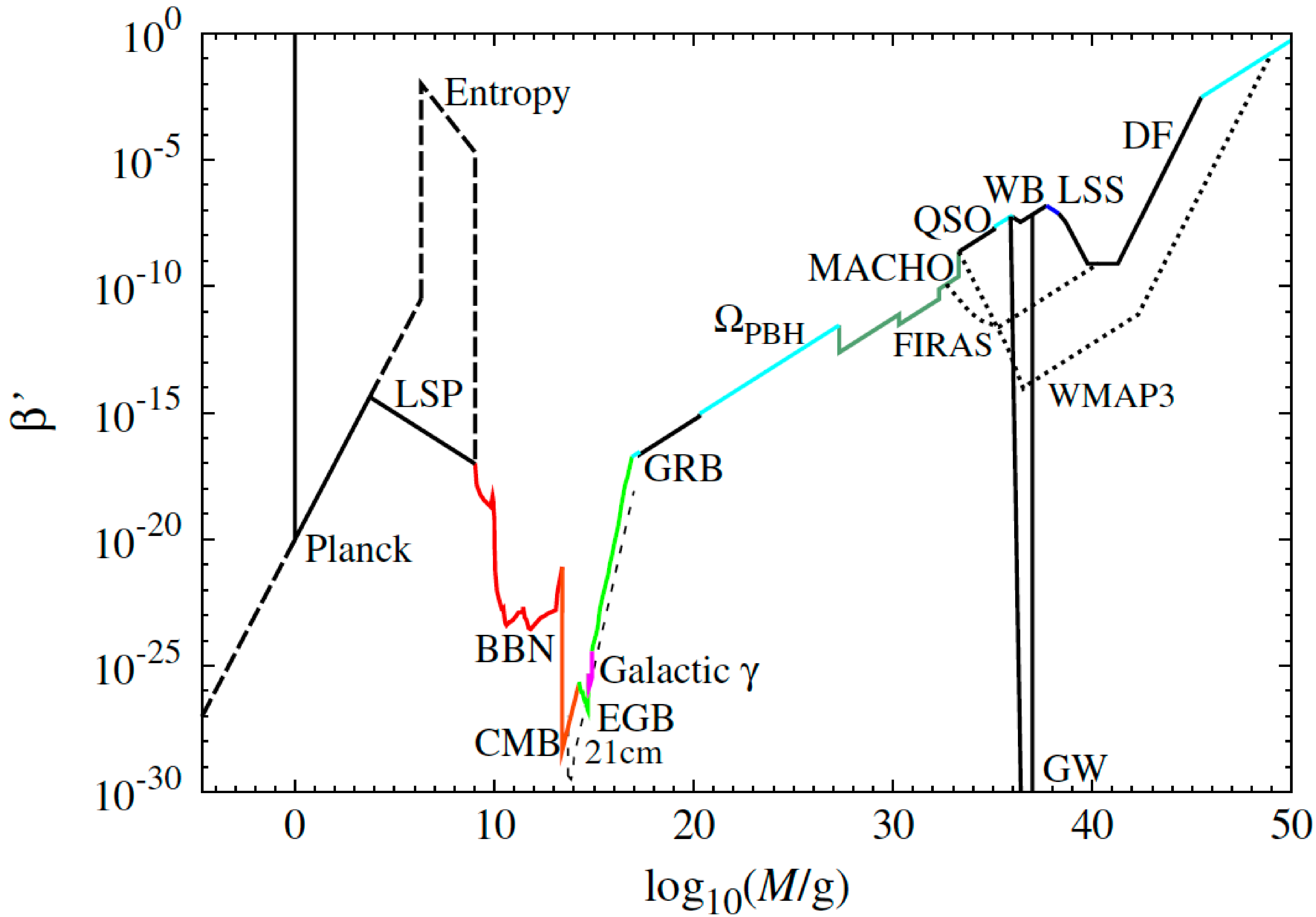
$r_S \sim \lambda_C$

Black Holes evaporate by thermal emission

Hawking, 1975

Carr et al, 0912.5297

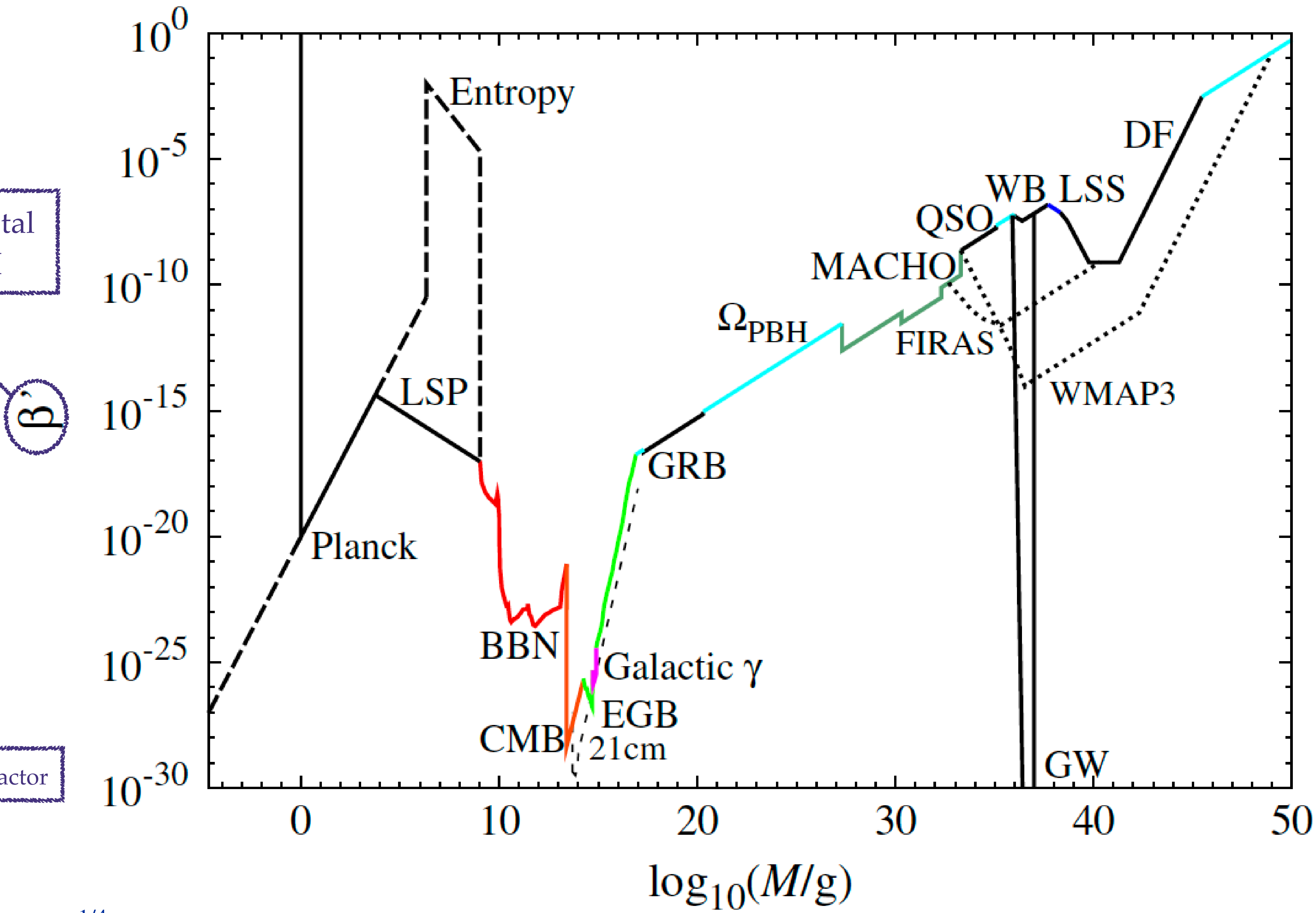
Primordial Black Holes (PBH)



Carr et al. 0912.5297

Primordial Black Holes (PBH)

Fraction of the total energy in PBH



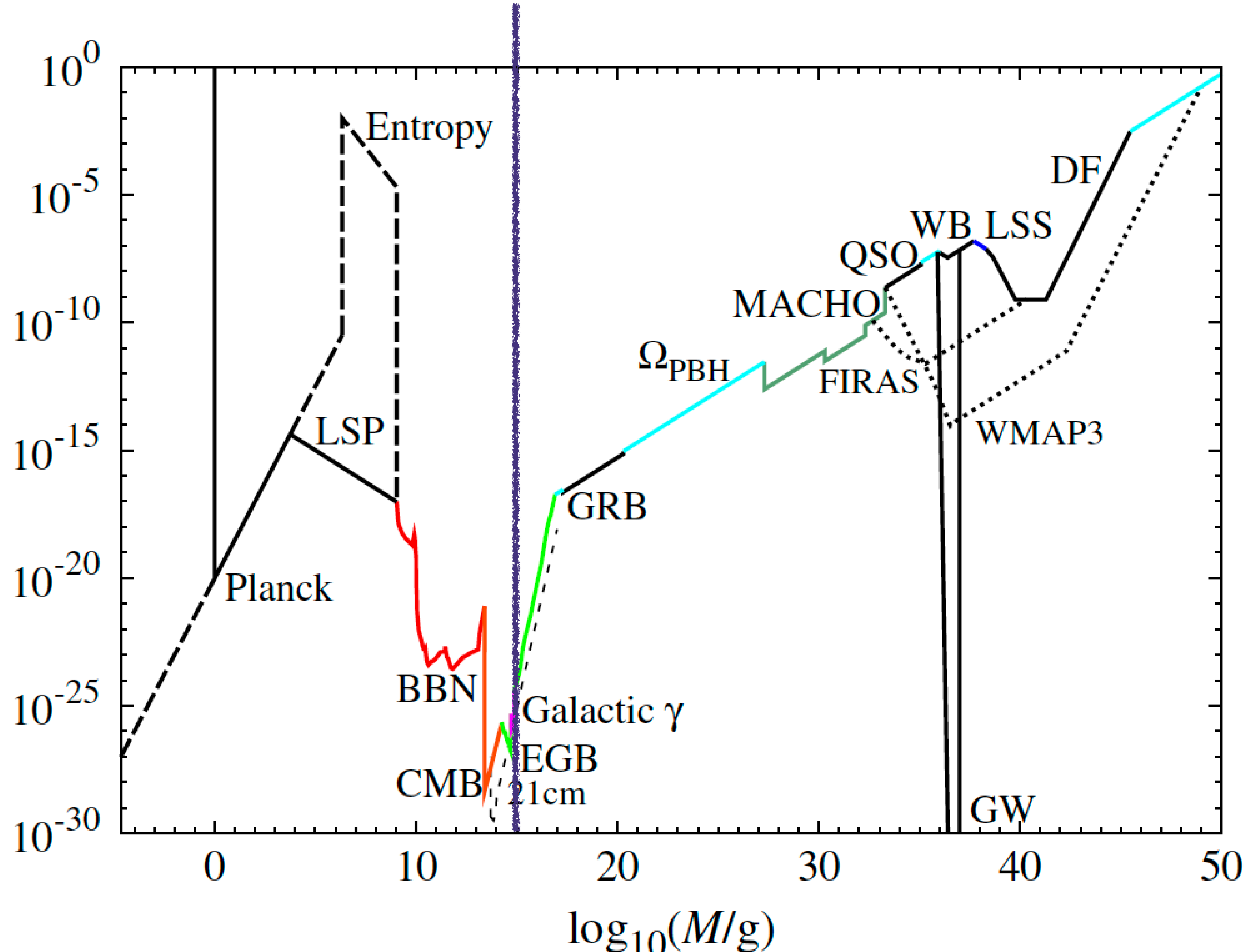
Carr et al. 0912.5297

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

Gravitational collapse factor

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

Primordial Black Holes (PBH)



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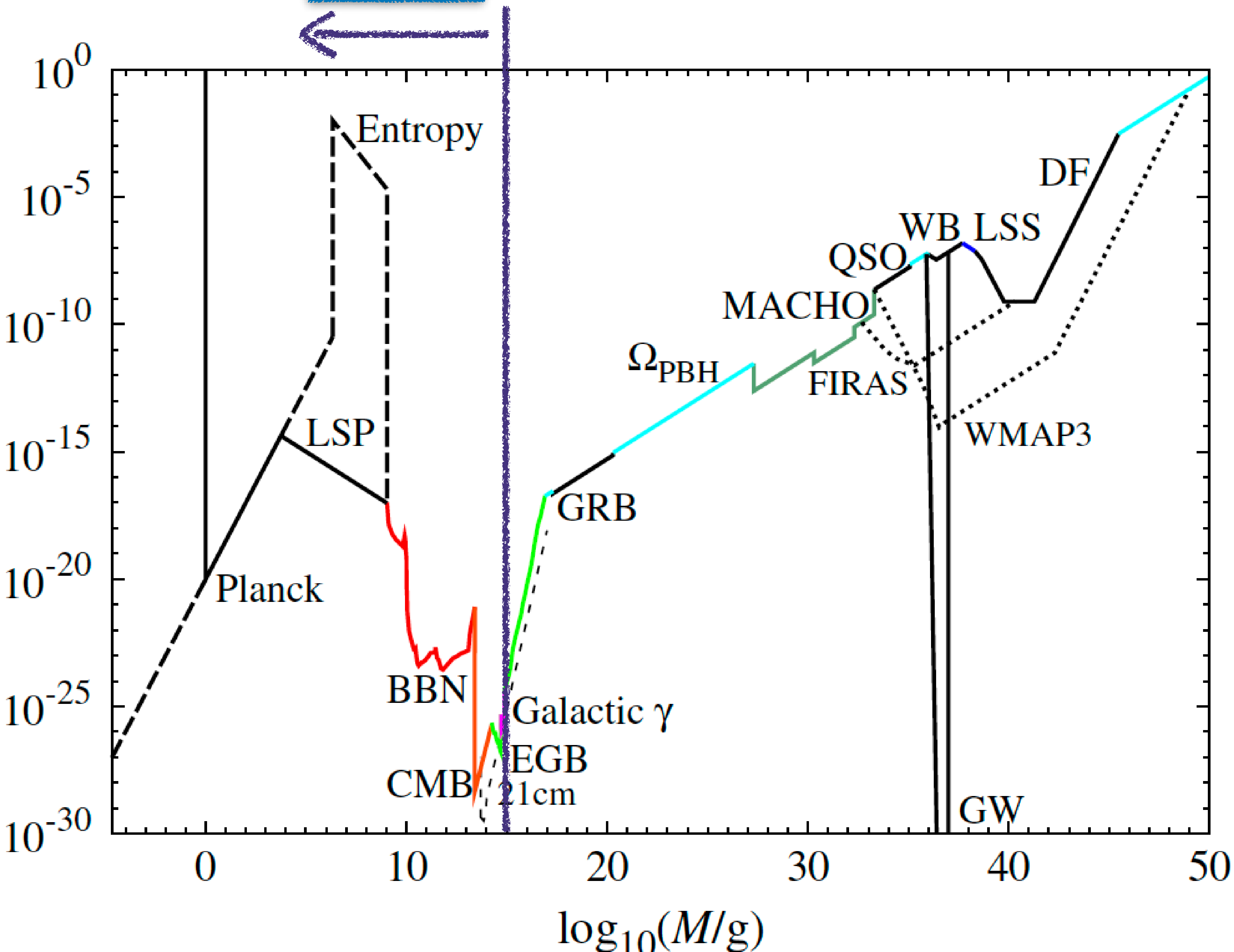
Primordial Black Holes (PBH)

Evaporated



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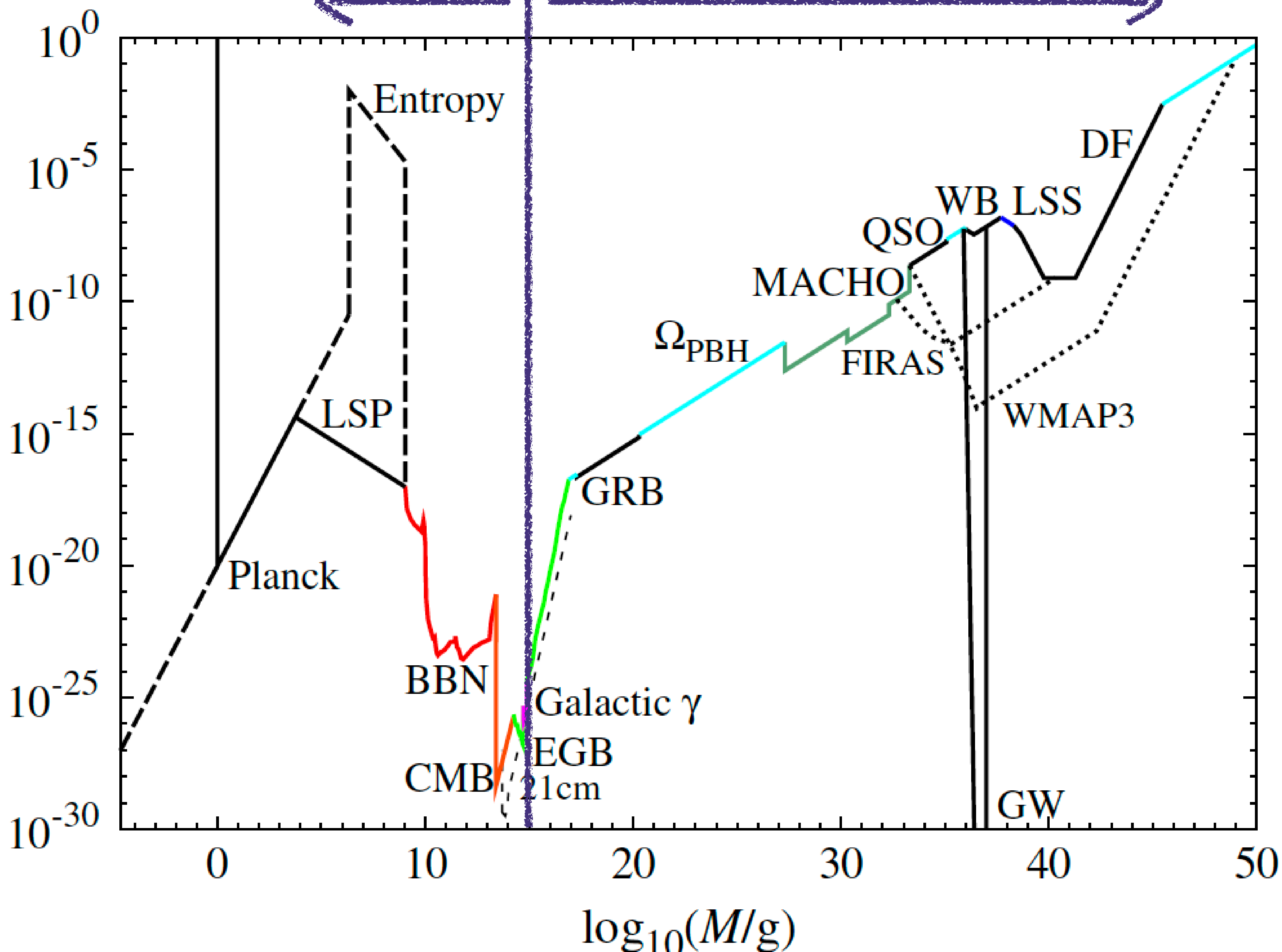
Primordial Black Holes (PBH)

Evaporated

(Part of) Dark Matter?



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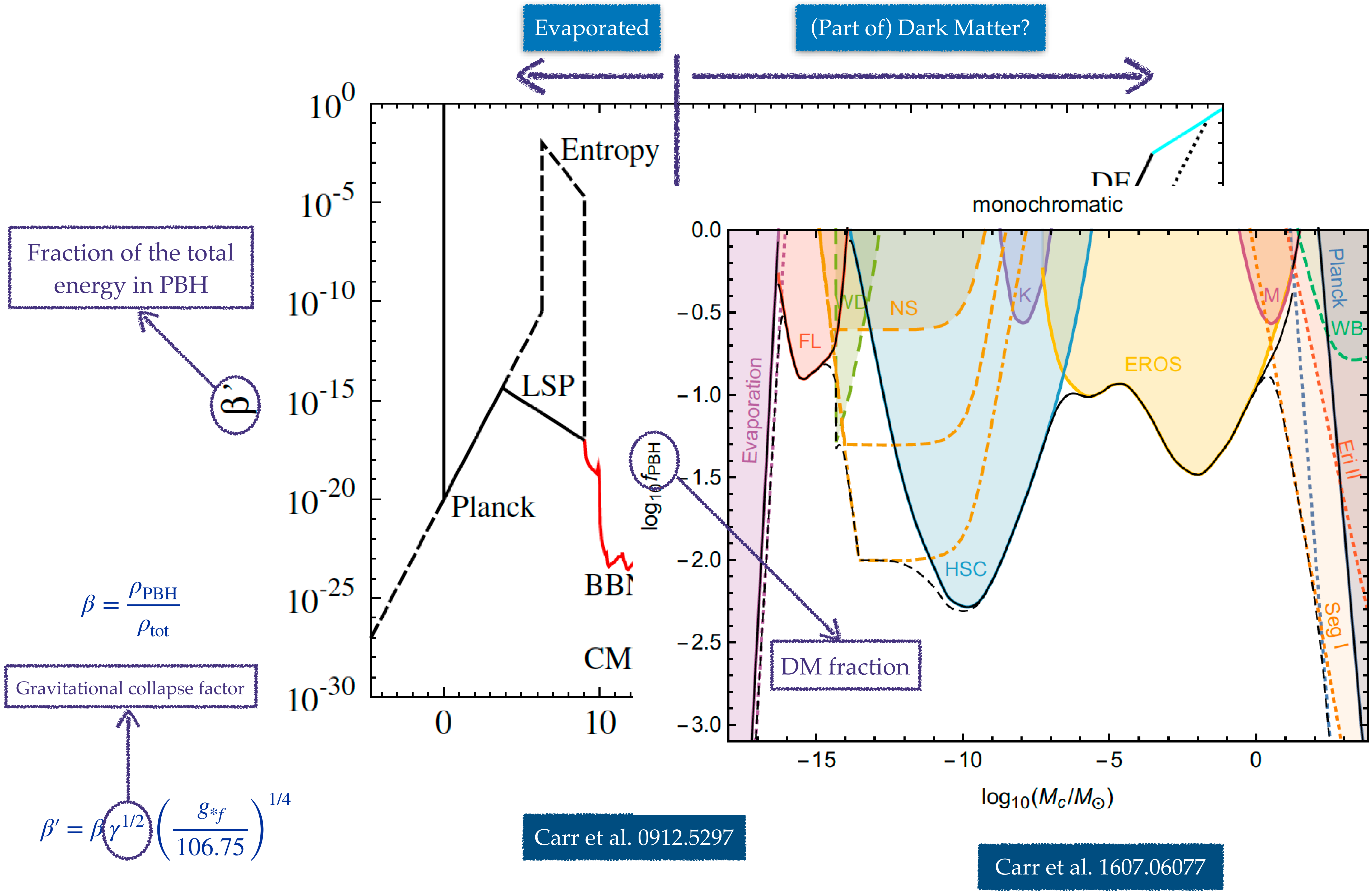

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Neutrino emission in the SM

B. Carr, 1976

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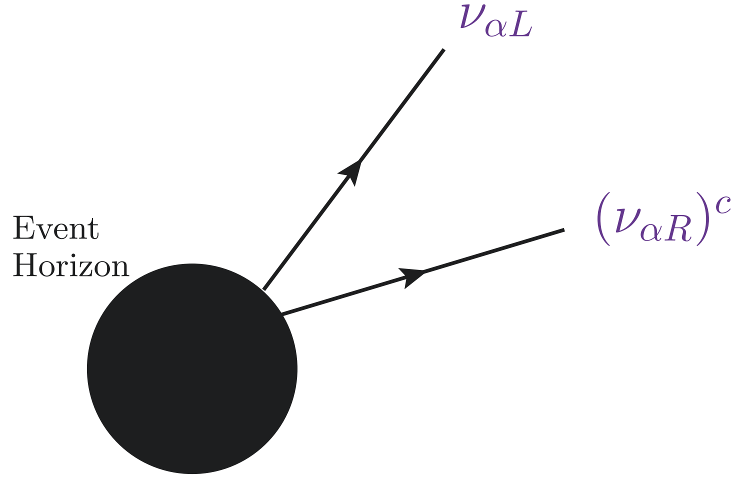
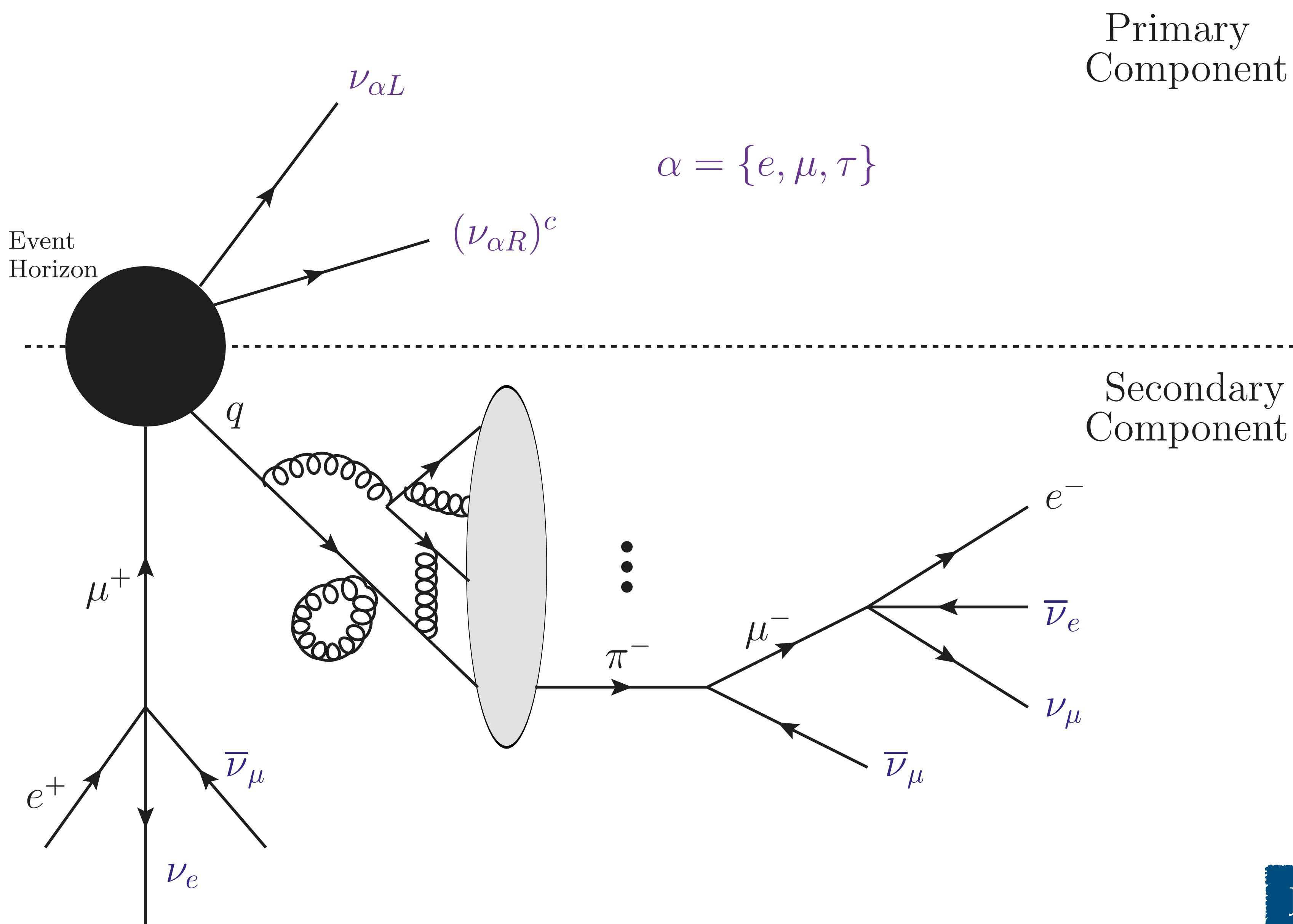


$\alpha = \{e, \mu, \tau\}$

Primary
Component

Neutrino emission in the SM

B. Carr, 1976

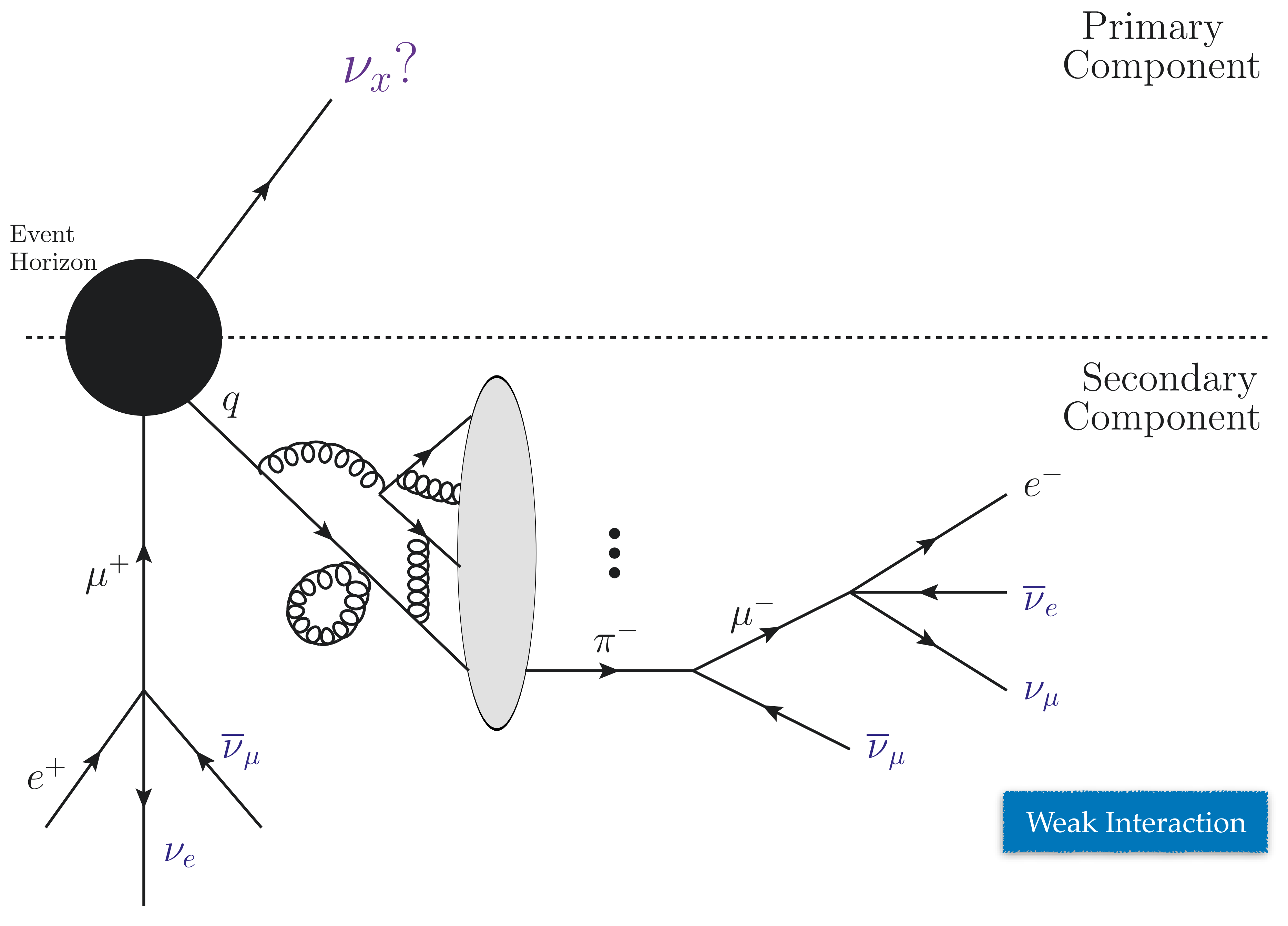


J. MacGibbon, 1991
F. Halzen,9502268
Bugaev, 0005295

Constraints on the diffuse neutrino flux

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

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Weak interactions

$$n \to p^+ + e^- + \overline{\nu_e}$$

Interaction mediated by a gauge boson

Associated production of a charged lepton

Flavor eigenstate

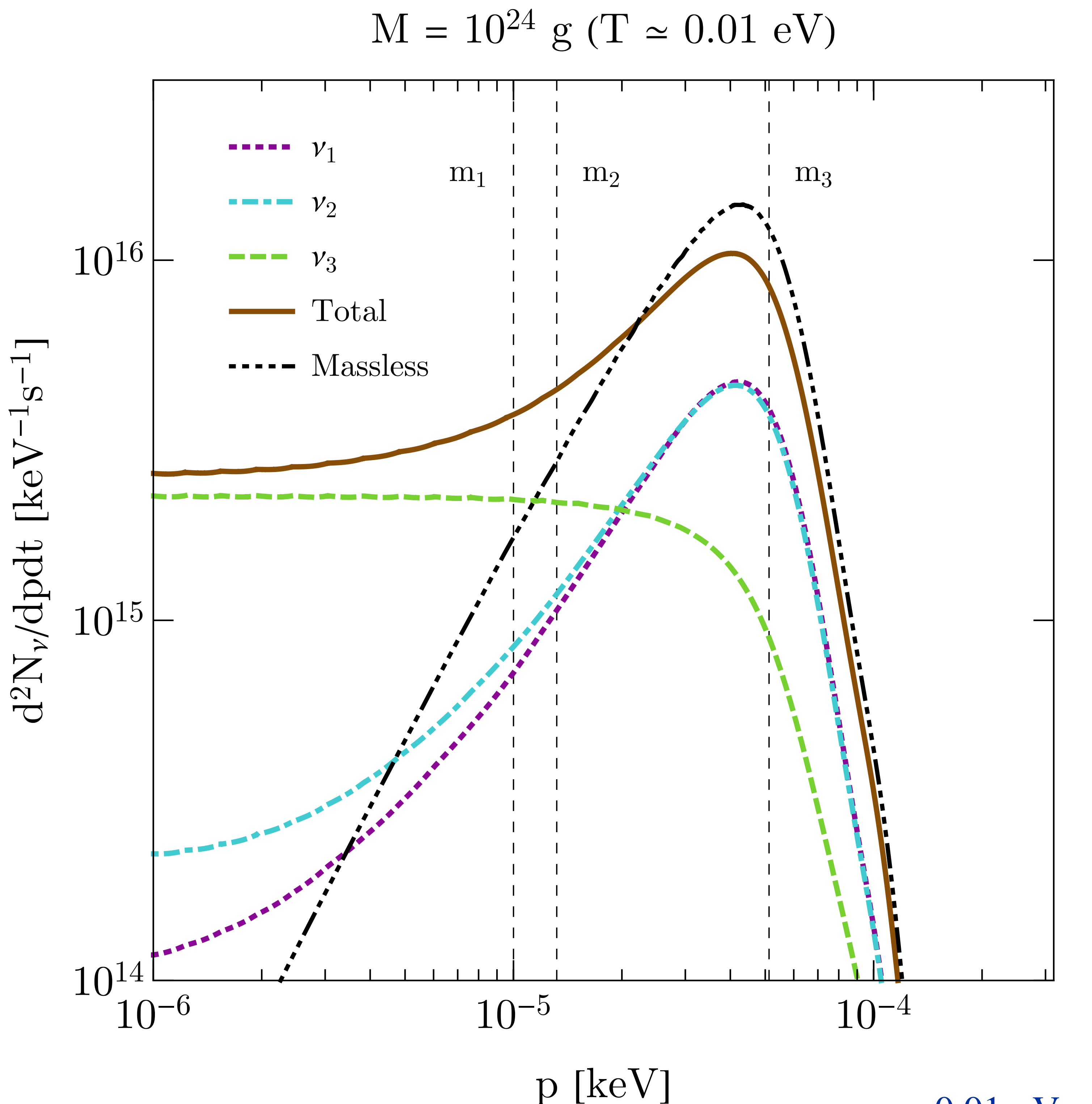
Hawking Effect

What is the state of the emitted neutrino?

Weak interactions	Hawking Effect
$n \to p^+ + e^- + \overline{\nu_e}$	$\langle 0_- \vert b_i^\dagger b_i \vert 0_- \rangle = \Gamma_{ln} \left[\exp\left(E_a / T_{\rm BH} + 1 \right) \right]^{-1}$
Interaction mediated by a gauge boson	Particle definition in a curved spacetime is observer dependent
Associated production of a charged lepton	No associated production of a charged lepton
Flavor eigenstate	***Mass eigenstate***

Neutrino instantaneous spectrum

$$\frac{d^2N_\nu}{dp\,dt} = \sum_{a=1,2,3} \frac{g_a^N}{2\pi^2} \frac{\sigma_{\rm abs}^\nu(M,p,m_a)\,p^2}{\exp[E_a(p)/T]+1}$$



$m_0 = 0.01$ eV

Neutrino instantaneous spectrum

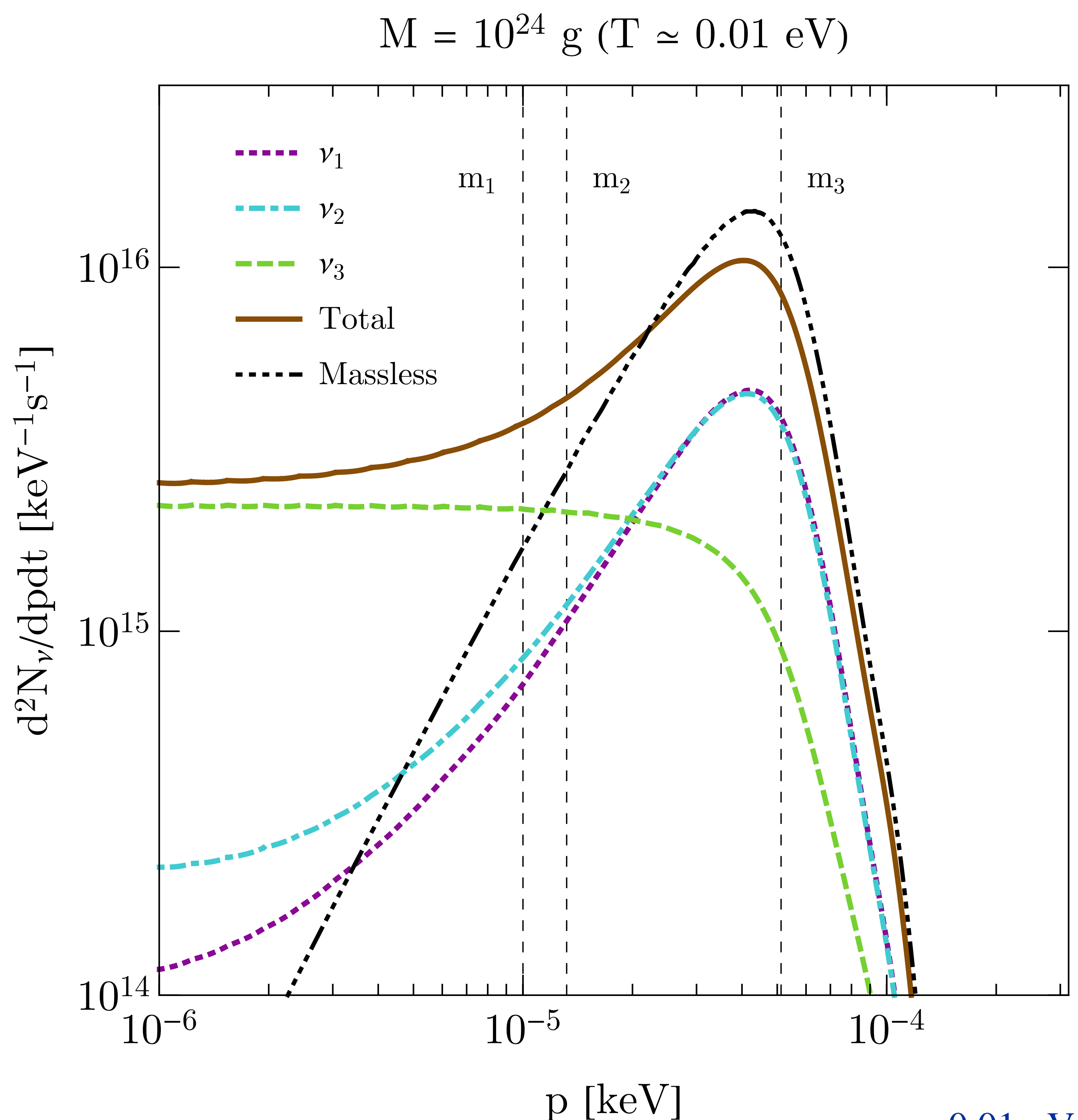
Degrees of freedom

Absorption cross section

$$\frac{d^2N_\nu}{dp\,dt} = \sum_{a=1,2,3} \frac{g_a^N}{2\pi^2} \frac{\sigma_{\rm abs}^\nu(M,p,m_a)\,p^2}{\exp[E_a(p)/T]+1}$$

BH Temperature

$$T = \frac{1}{8\pi GM} \approx 1.06 \left(\frac{10^{13}\ \mathrm{g}}{M}\right)\ \mathrm{GeV}$$



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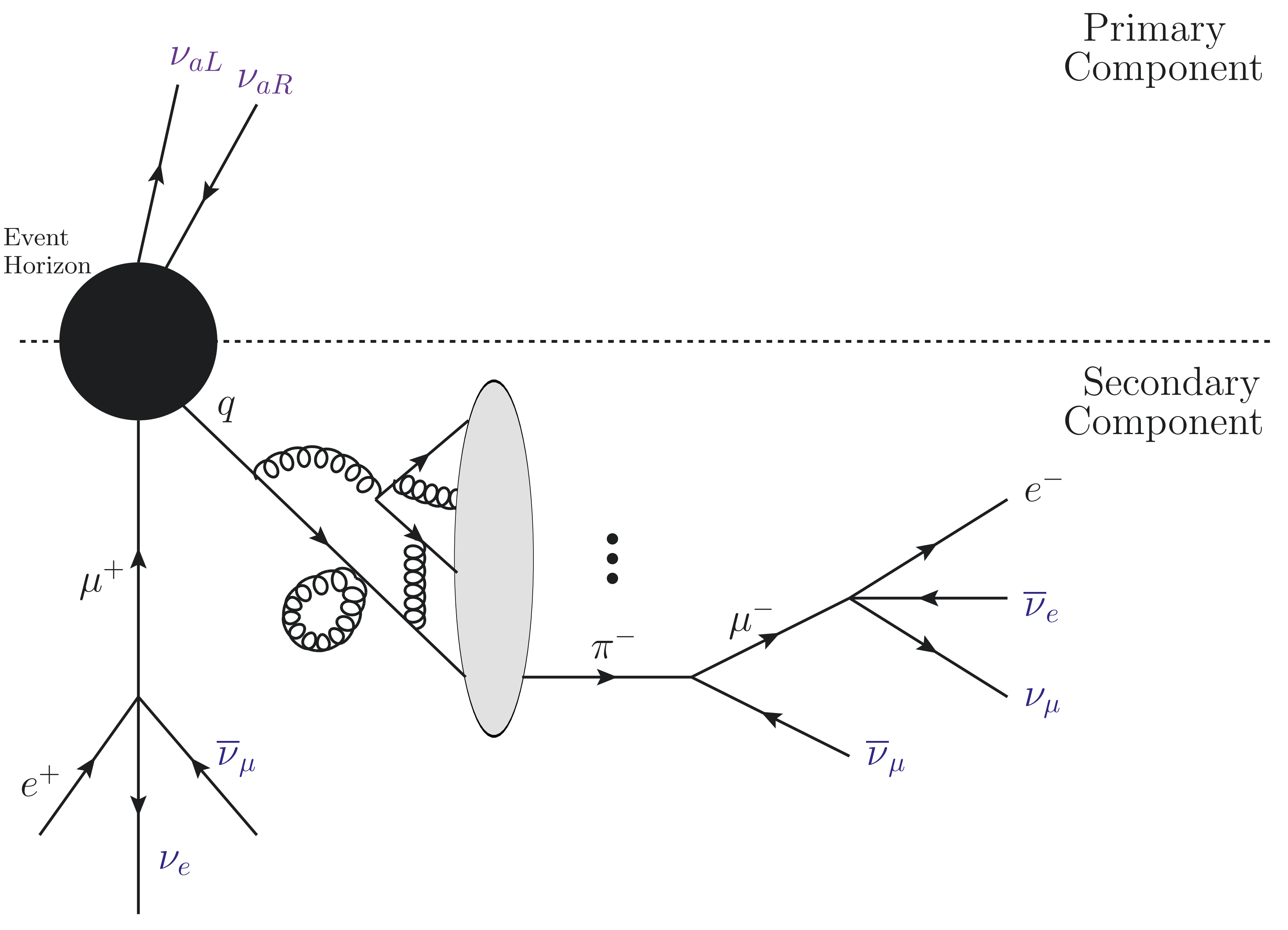
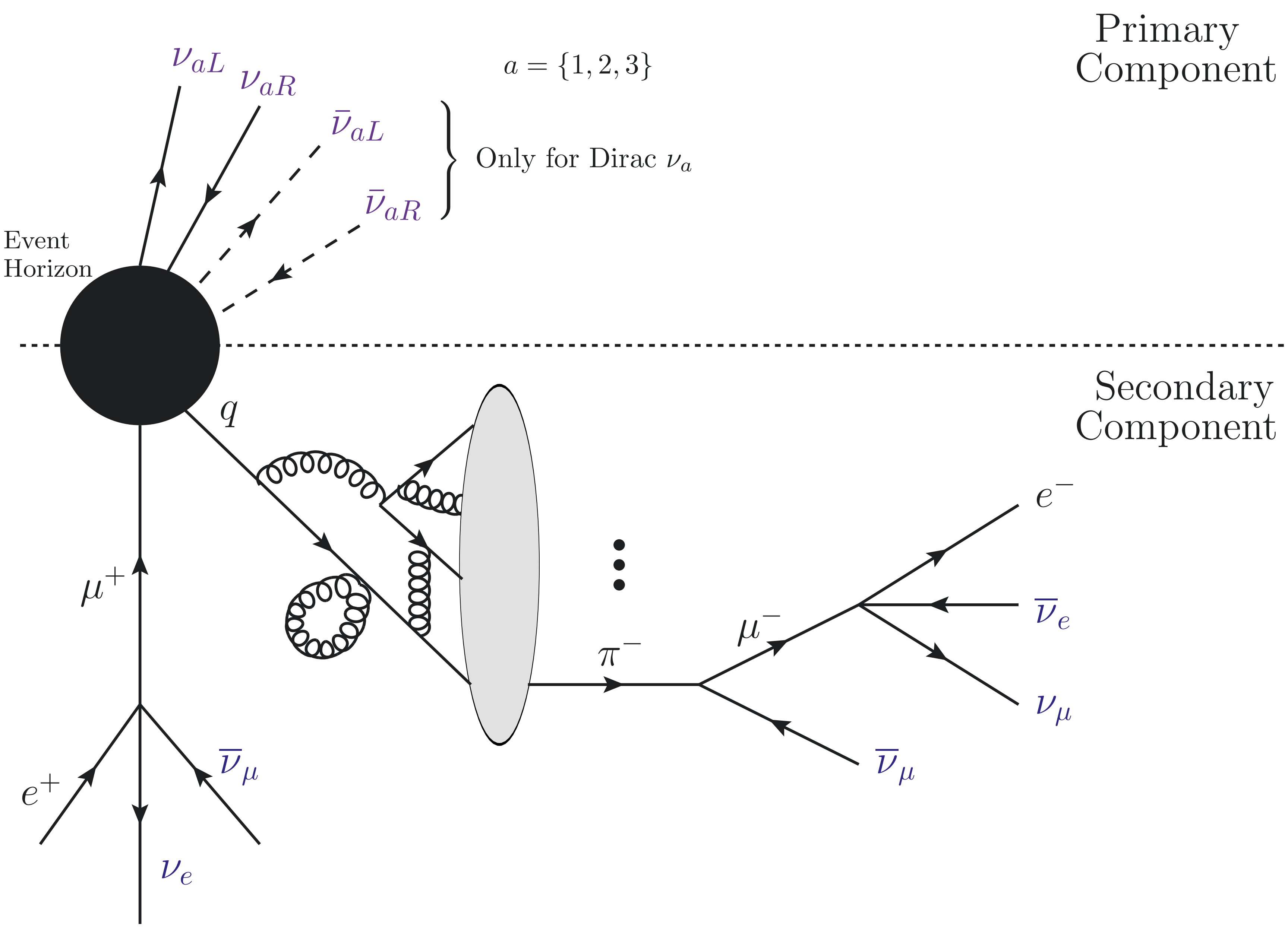
Dirac vs Majorana

Dirac vs Majorana



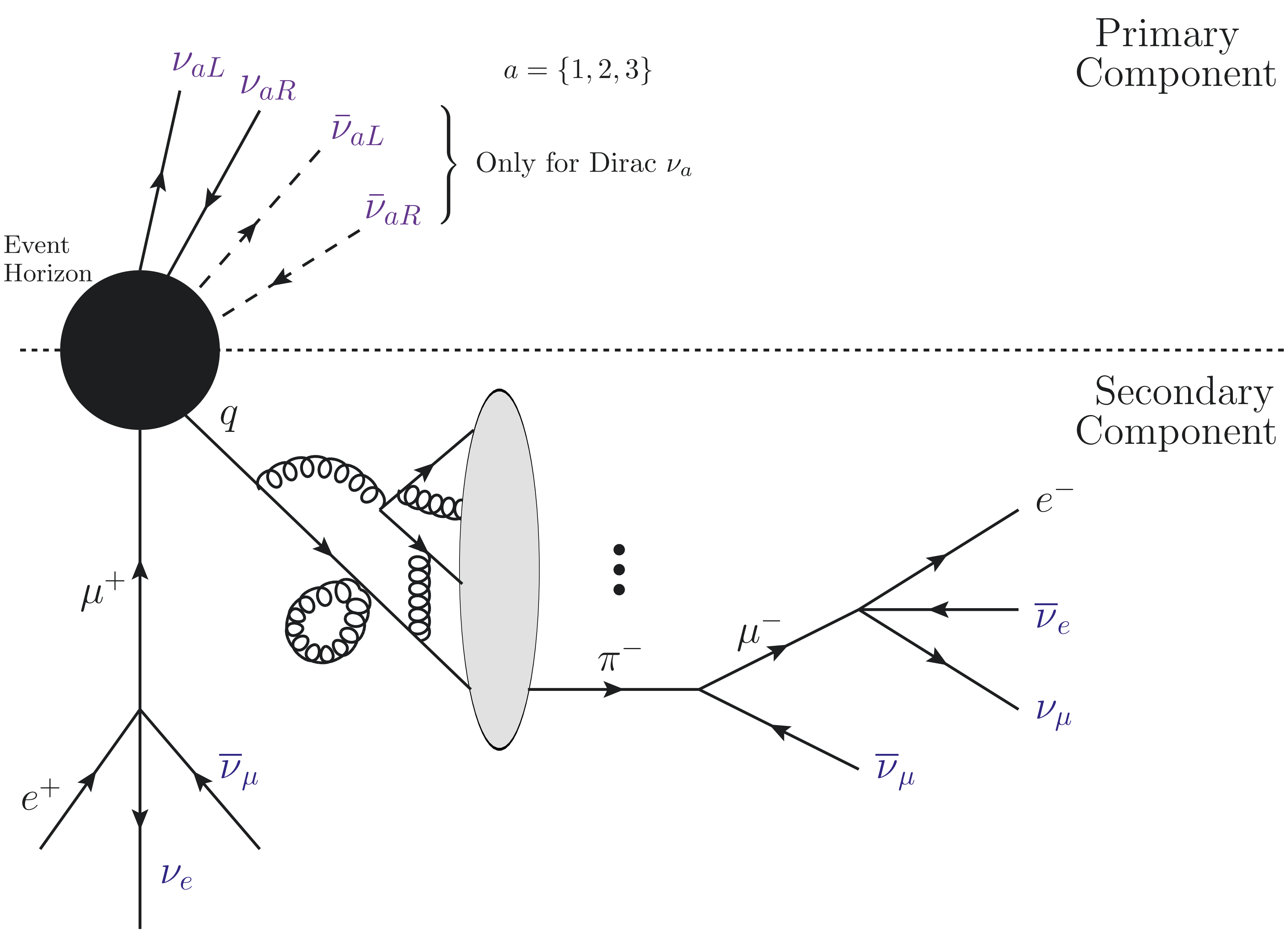
Majorana neutrinos

Dirac vs Majorana



Dirac neutrinos

Dirac vs Majorana



Dirac neutrinos

Phenomenological consequences?

Dirac vs Majorana

Dirac neutrinos

Majorana neutrinos

Dirac vs Majorana

Dirac neutrinos

Majorana neutrinos

Heavy RH neutrinos

↓

PBH-driven Leptogenesis

Yamada and Iso, 1610.02586
Morrison et al,1812.10606

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Cecilia Lunardini, YFPG and Jessica Turner, in preparation

Dirac vs Majorana

Dirac neutrinos

Absorption cross section independent of the helicity

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

Unruh, 1976

No helicity suppression

Majorana neutrinos

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Production of RH neutrinos!

Majorana neutrinos

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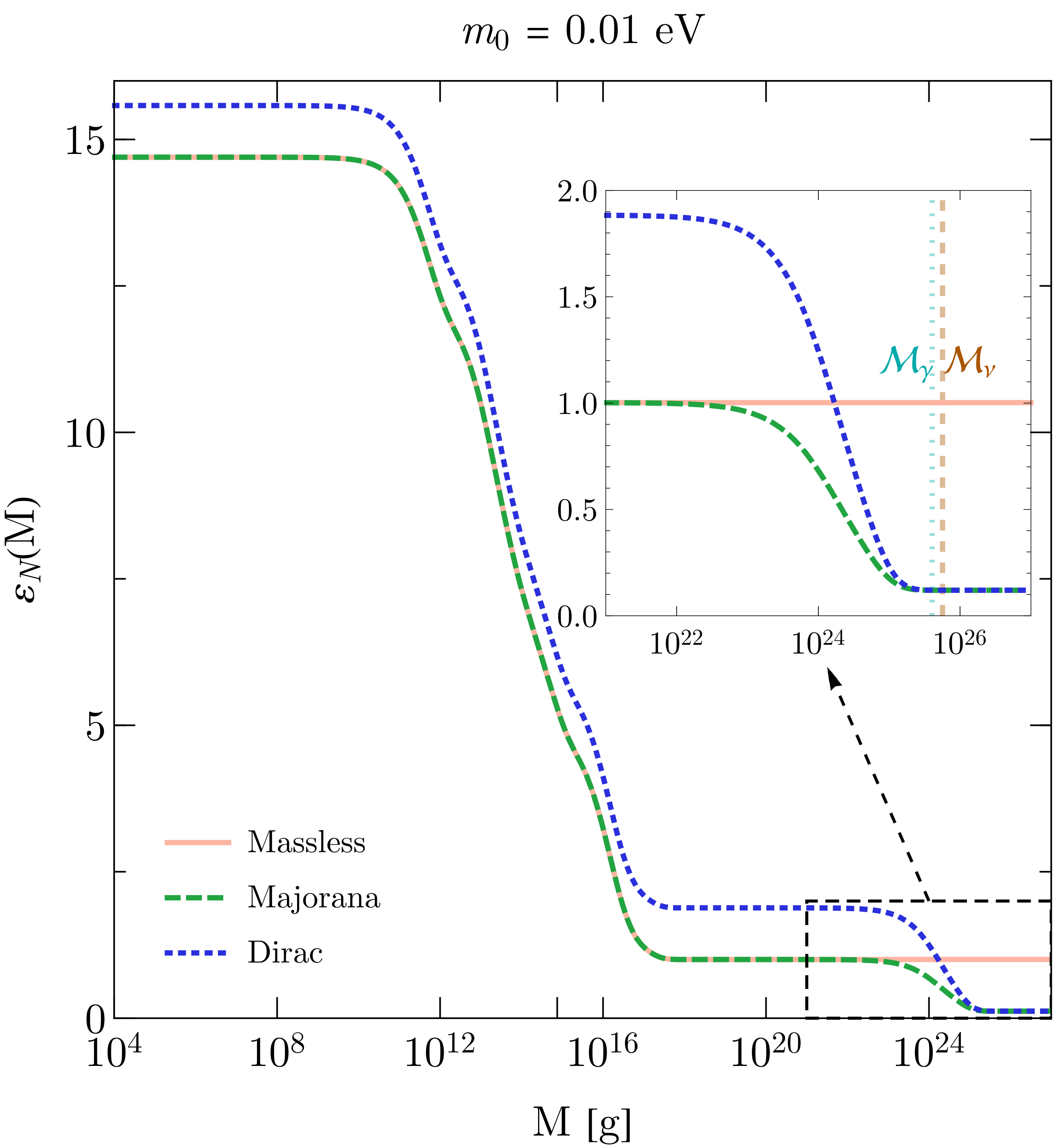
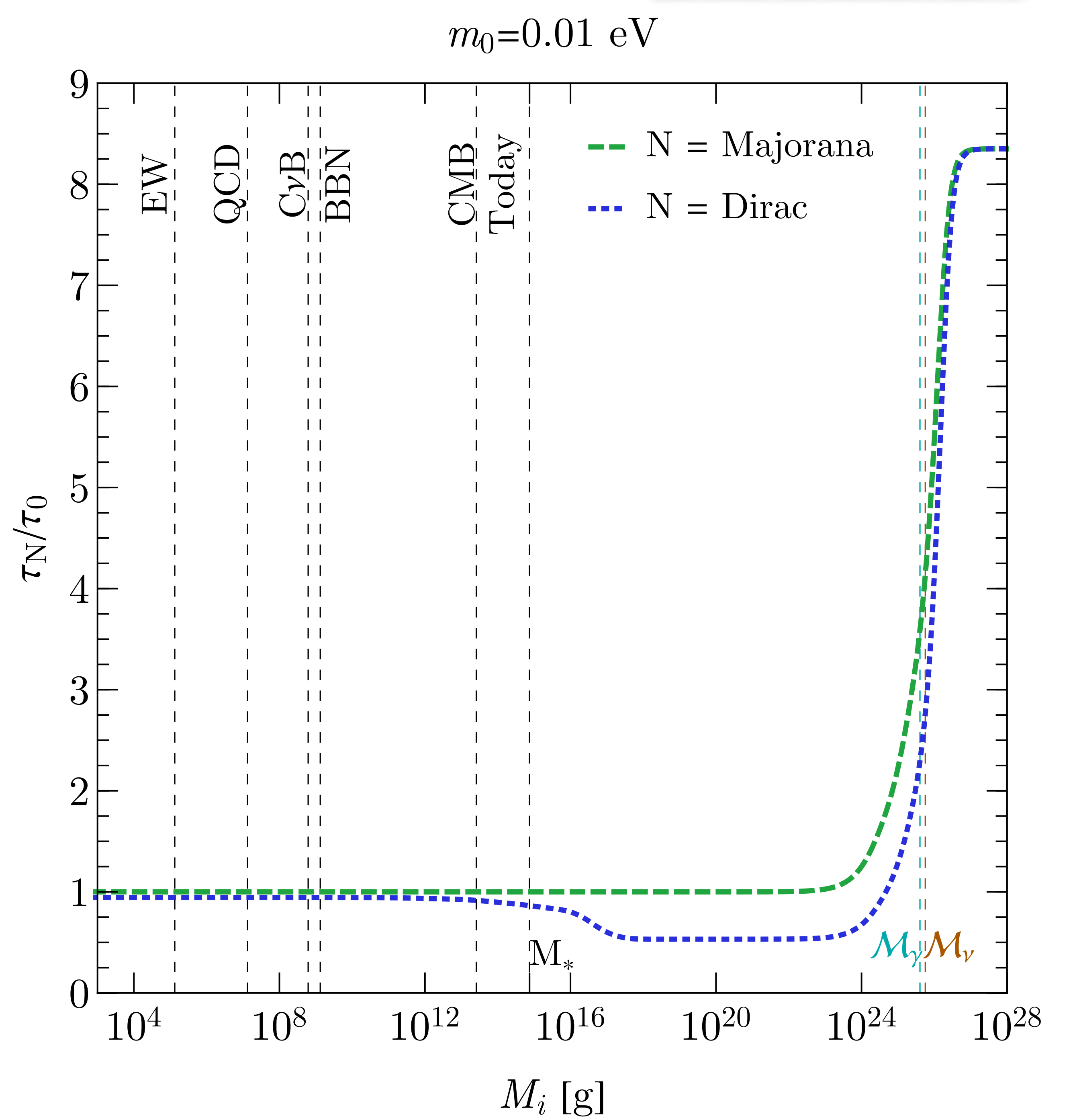
PBH evaporation

SM + RH neutrinos

Depends on the set of possible particles to be emitted





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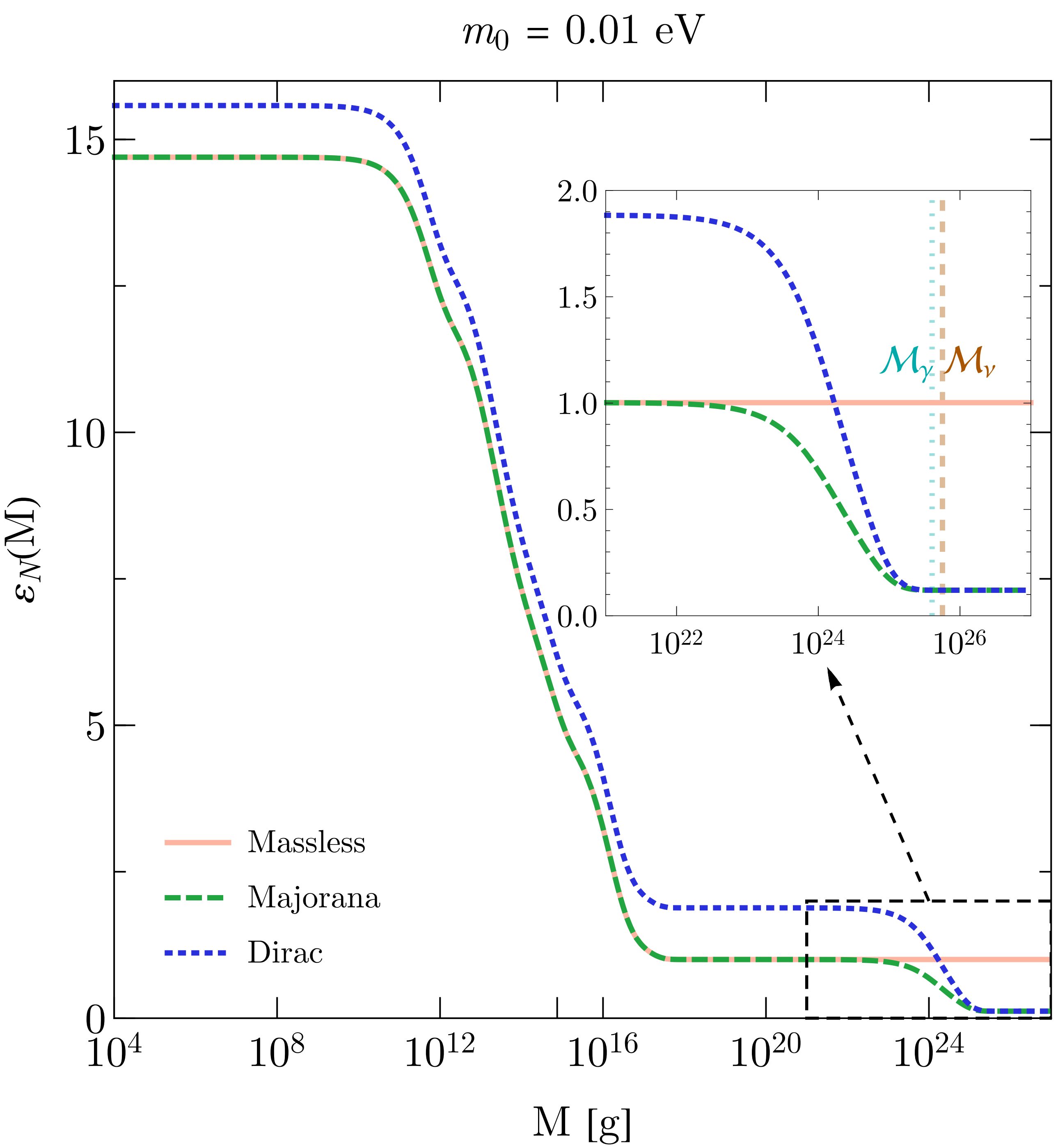

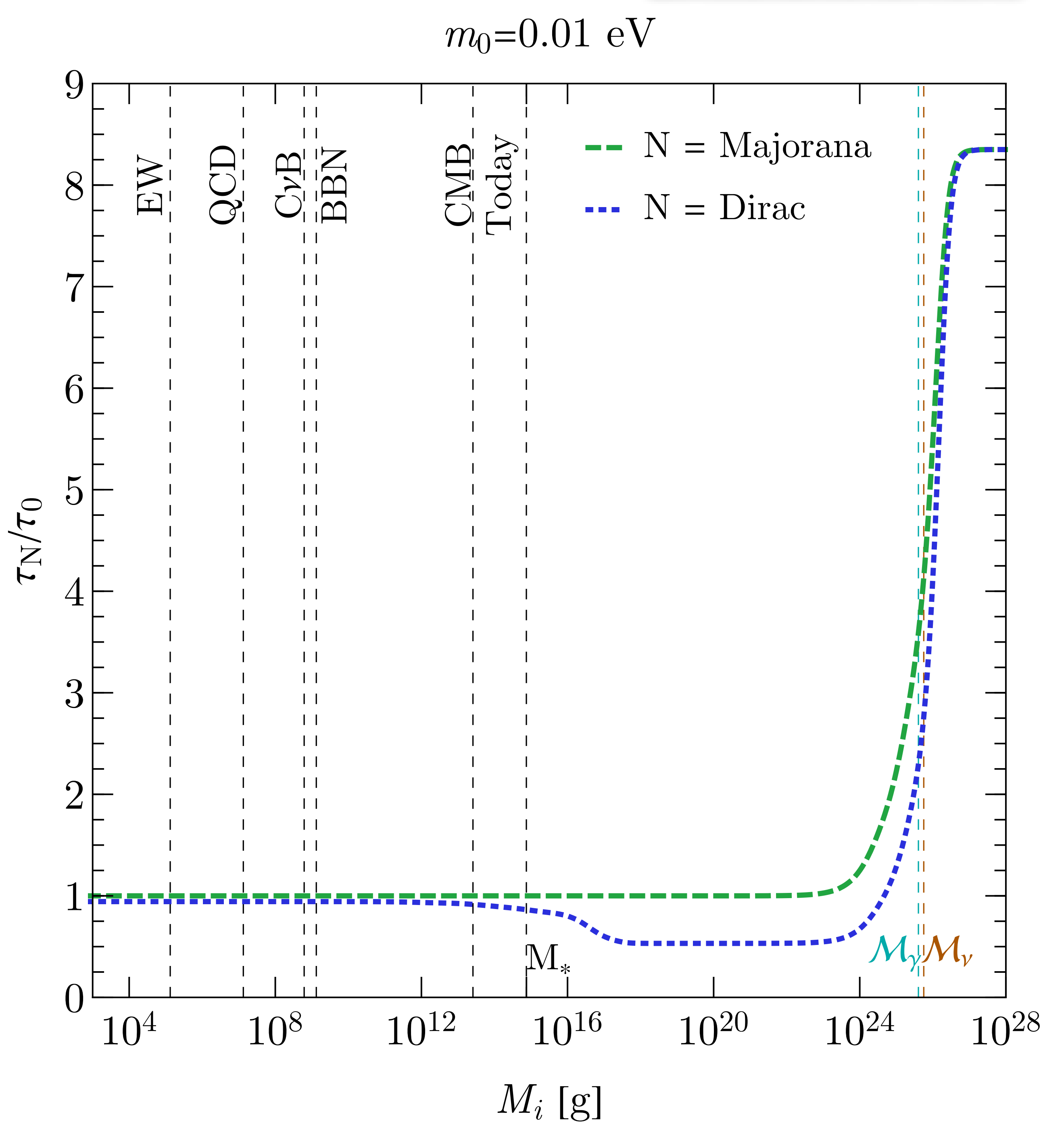

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Evaporation function

PBH evaporation

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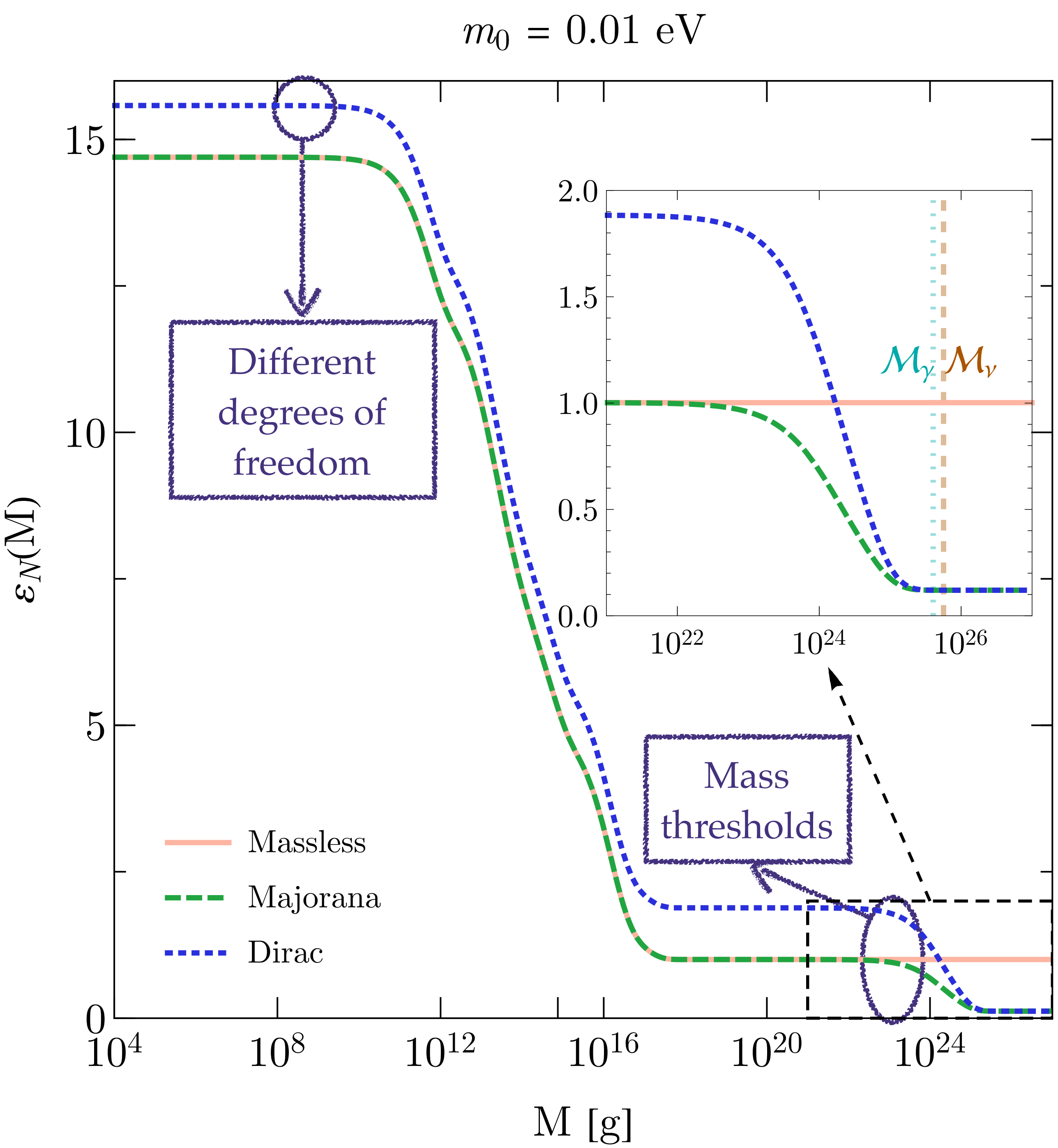

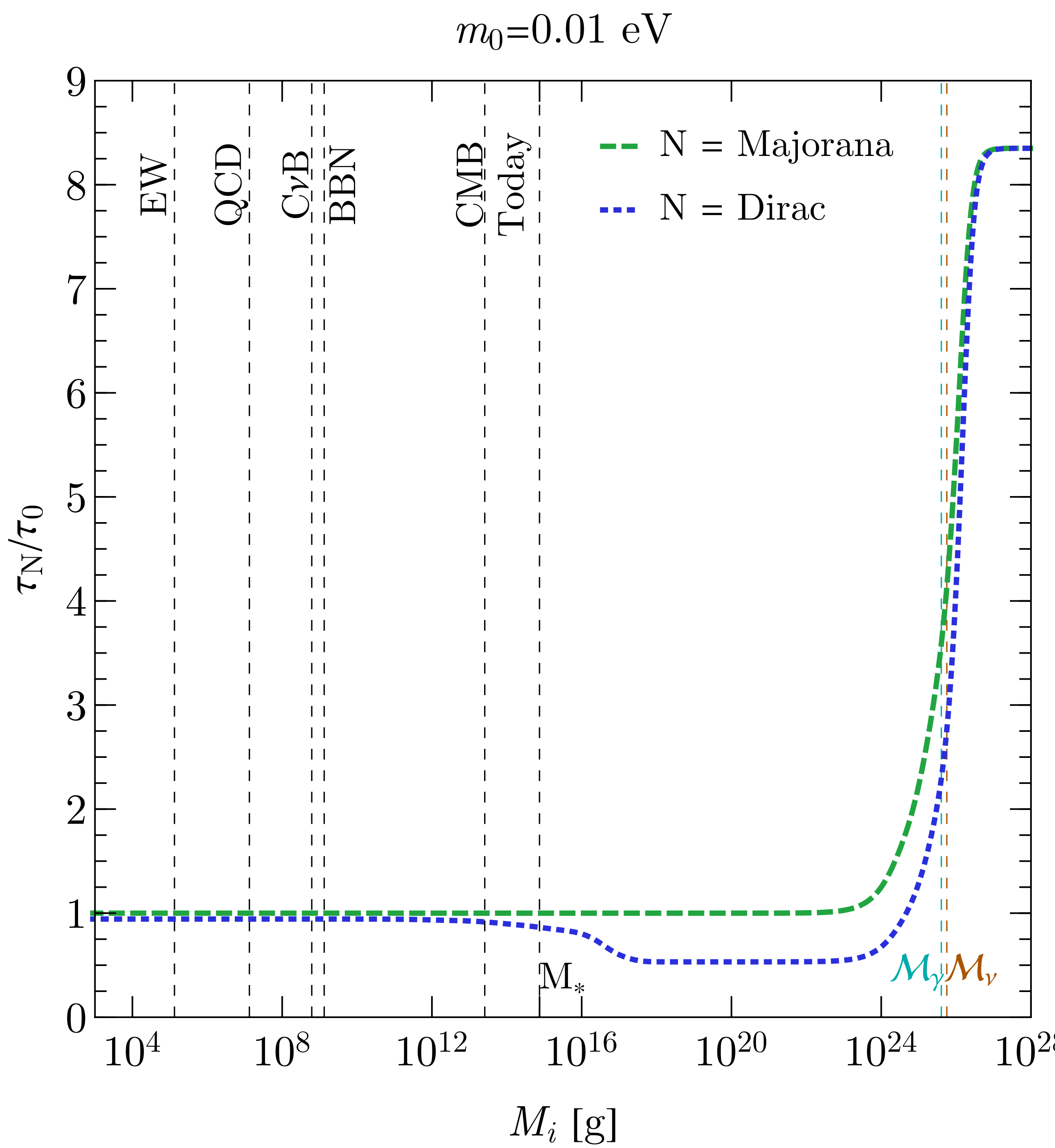

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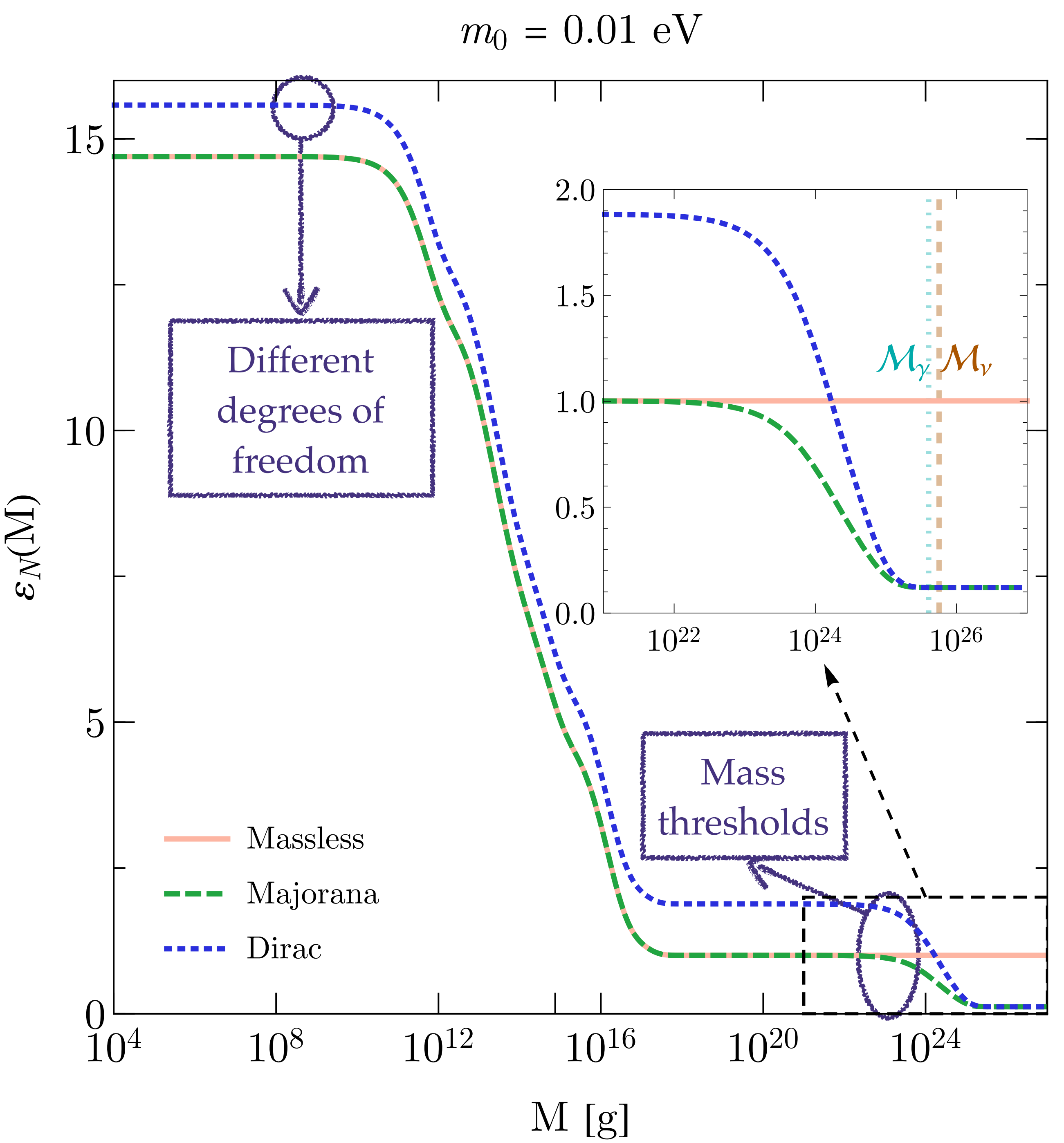

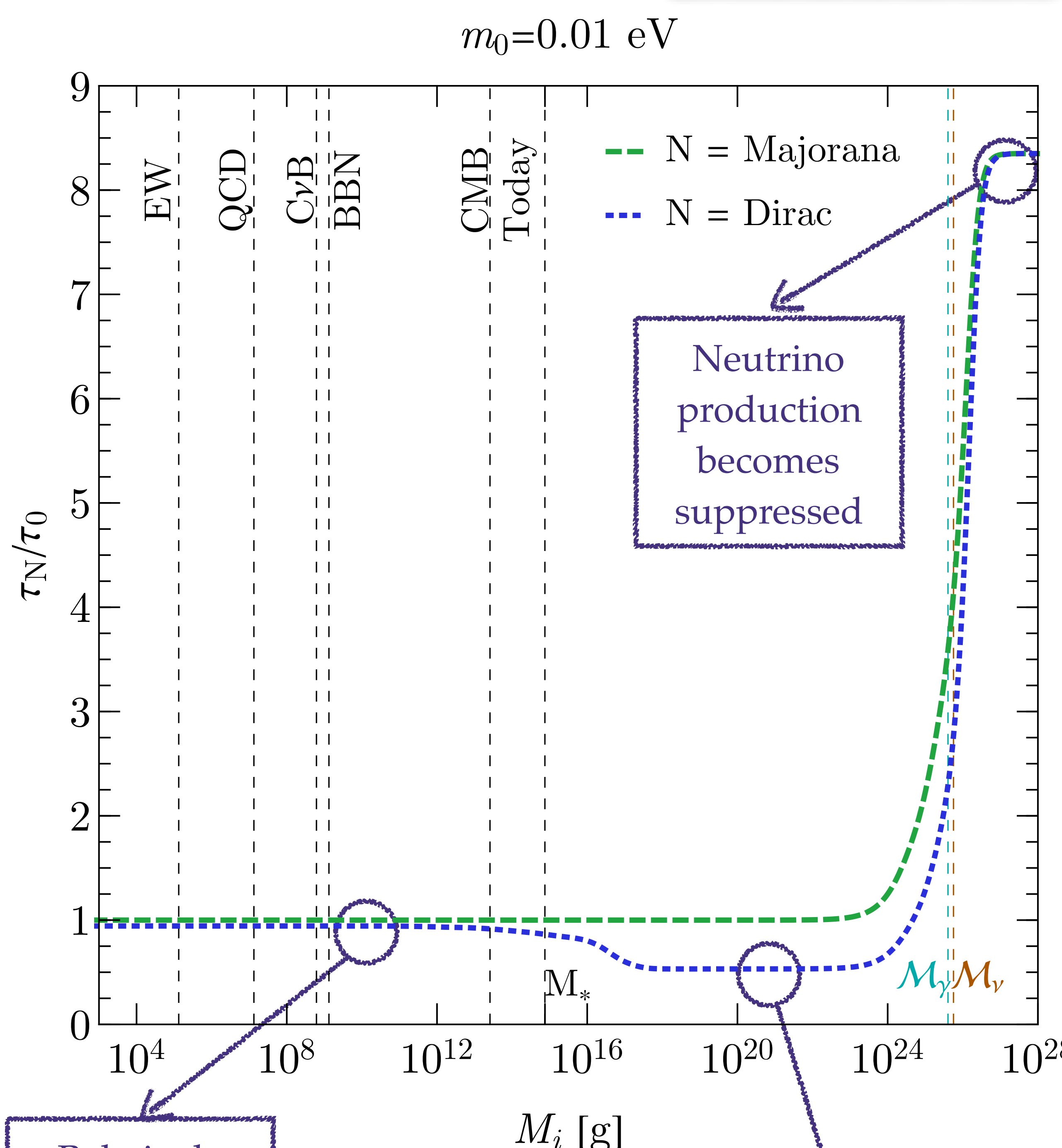

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Evaporation function

Constraints in the Dirac neutrino case

Constraints in the Dirac neutrino case

Let us consider the minimal extension

$$\mathscr{L}_Y = -\, Y_\nu^{ab} \overline{L_L^a} \widetilde{H}\, \nu_{bR}$$

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ν_R → Not produced thermally — Antonelli et al, 1981

ν_R → Do not thermalize — Chen et al, 1509.00481

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PBHs are formed

t_i, T_f

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PBHs are formed → PBHs evaporate

t_i, T_f — $t_\mathrm{EV}, T_\mathrm{EV}$

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Friedmann-Boltzmann Equations

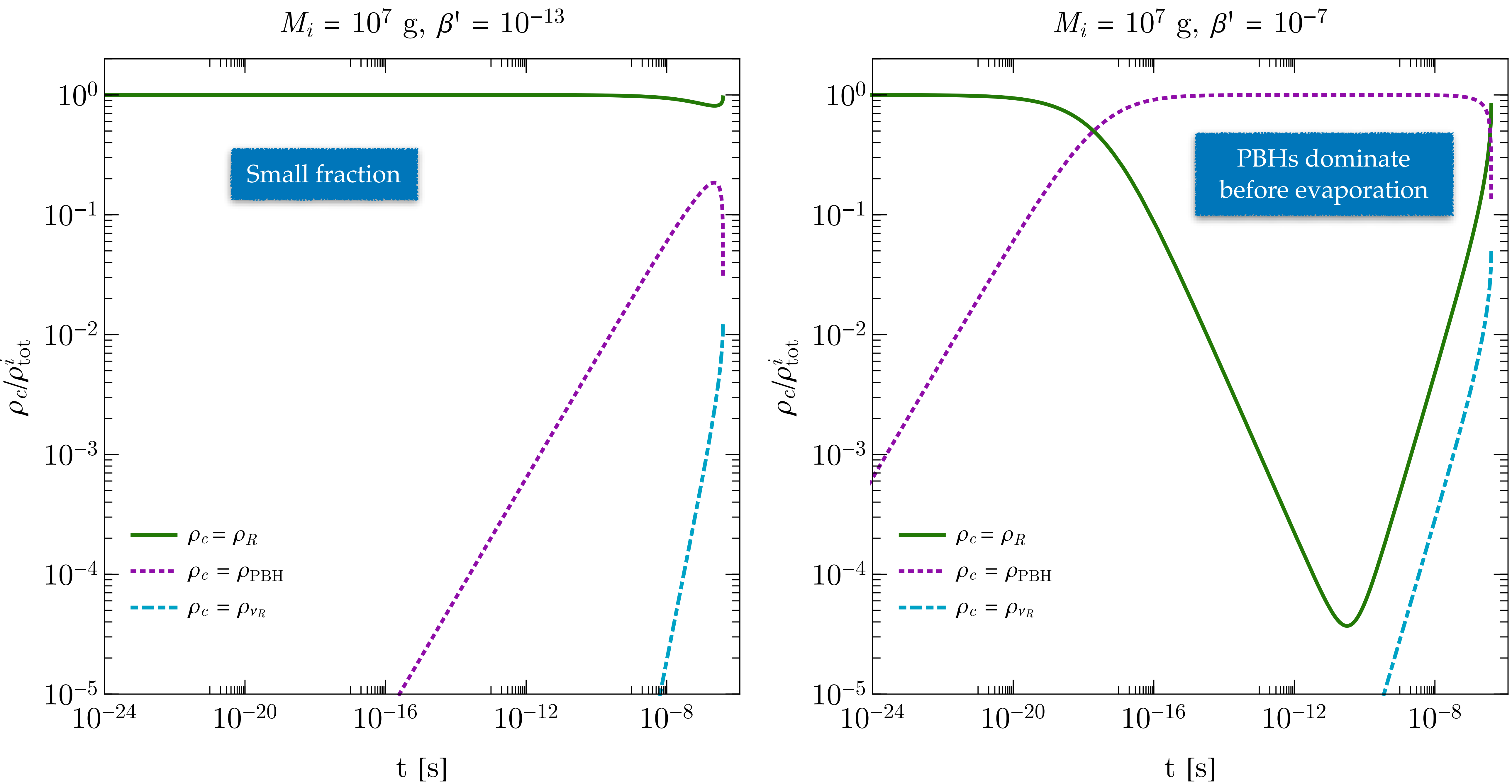
Non-standard cosmology?

PBHs are formed → PBHs evaporate

t_i, T_f

t_{EV}, T_{EV}

Constraints in the Dirac neutrino case



Initial fraction

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

Hooper et al, 1905.01301

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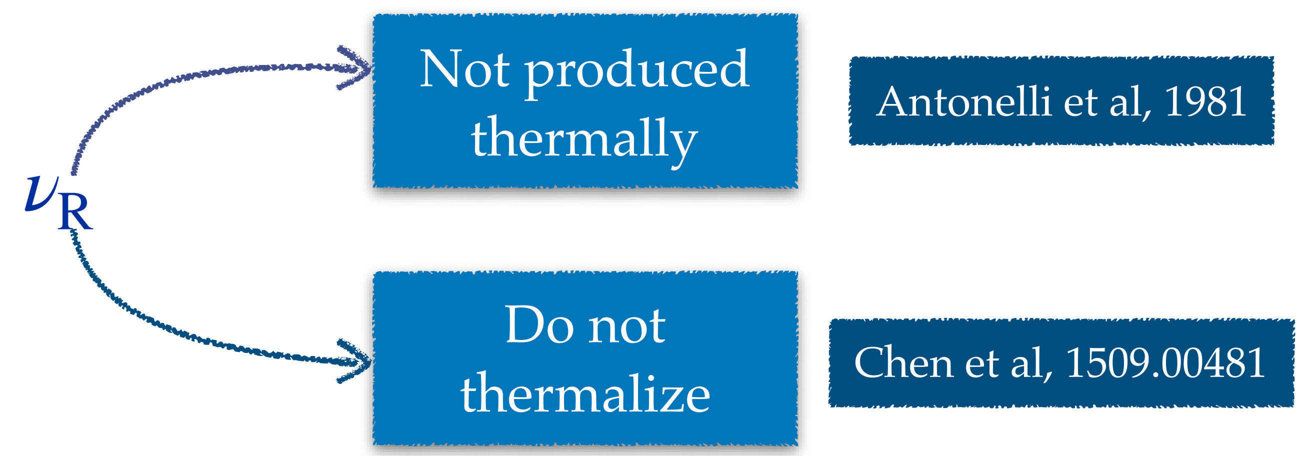

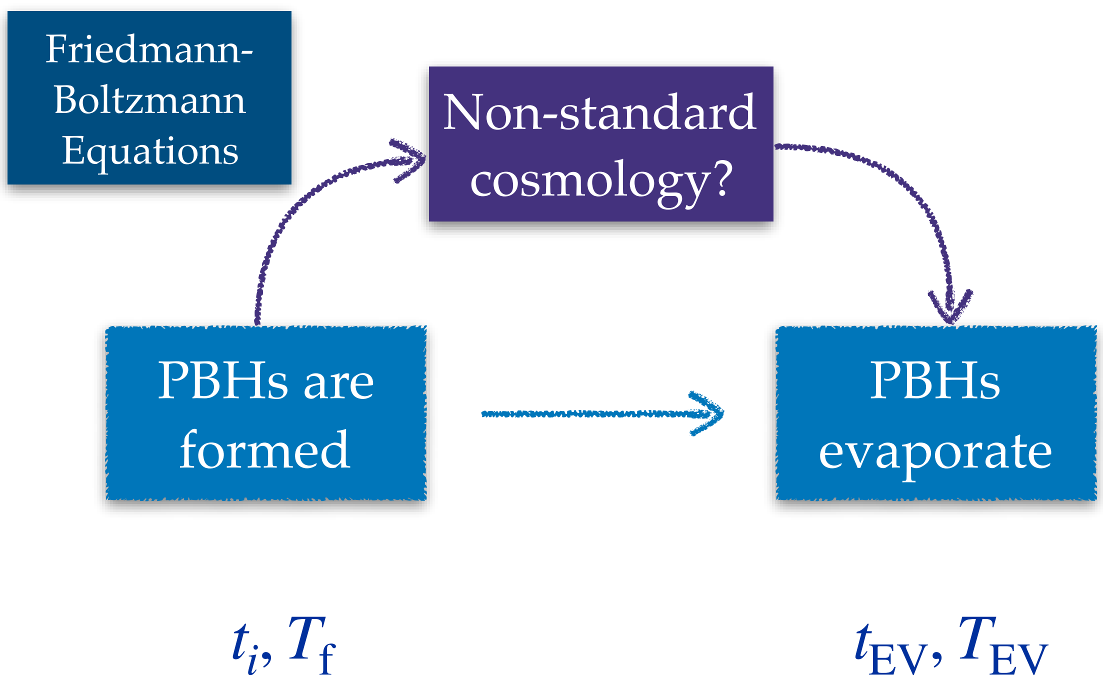

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Friedmann-Boltzmann Equations

Non-standard cosmology?

PBHs are formed → PBHs evaporate → Matter-radiation equality

t_i, T_f

t_{EV}, T_{EV}

t_{EQ}, T_{EQ}

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PBHs are formed → Non-standard cosmology? → PBHs evaporate → Matter-radiation equality

t_i, T_f — t_{EV}, T_{EV} — t_{EQ}, T_{EQ}

$$\Delta N_{\rm eff} = \left\{ \frac{8}{7}\left(\frac{4}{11}\right)^{-\frac{4}{3}} + N_{\rm eff}^{\rm SM} \right\} \frac{\rho_{\nu_R}(T_{EV})}{\rho_R(T_{EV})} \left(\frac{g_*(T_{EV})}{g_*(T_{EQ})}\right) \left(\frac{g_{*S}(T_{EQ})}{g_{*S}(T_{EV})}\right)^{\frac{4}{3}}$$

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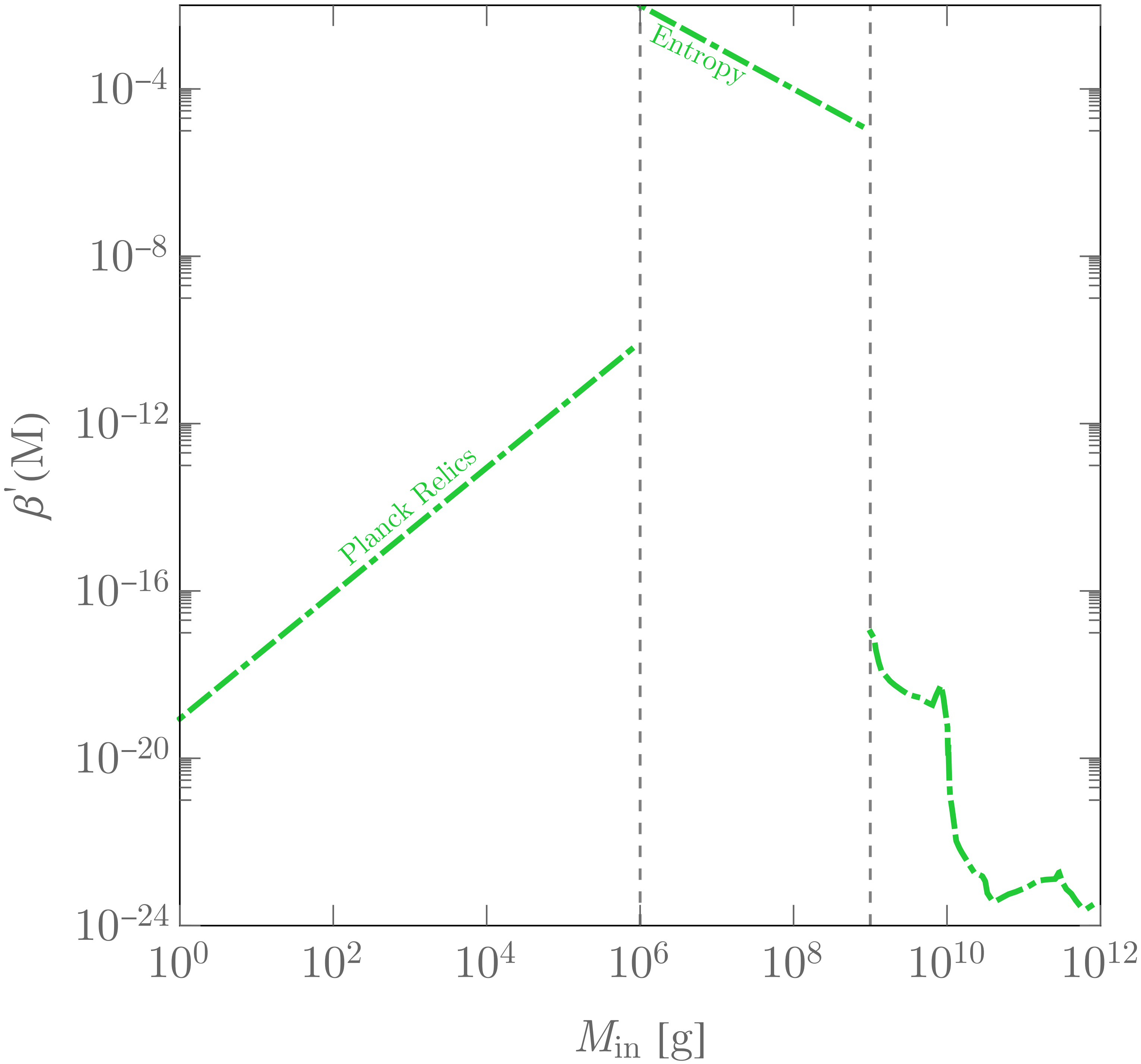

Zel'dovich et al, 1977

MacGibbon, 1987
Barrow et al, 1992
Carr et al, 1994

Carr et al, 0912.5297

What happens when $M \to M_{Pl}$?

Constraints in the Dirac neutrino case

Green and Liddle, 9903484

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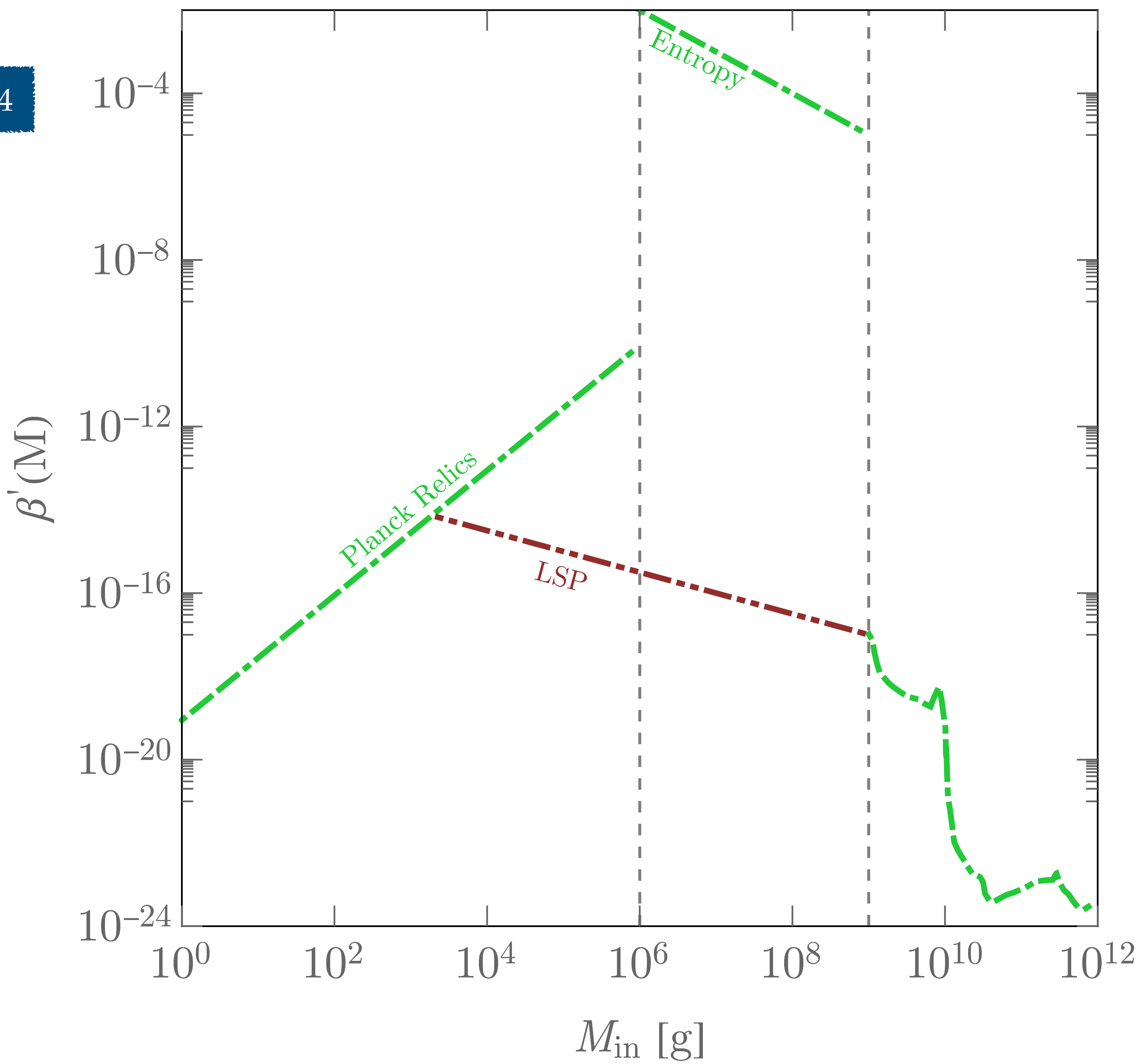

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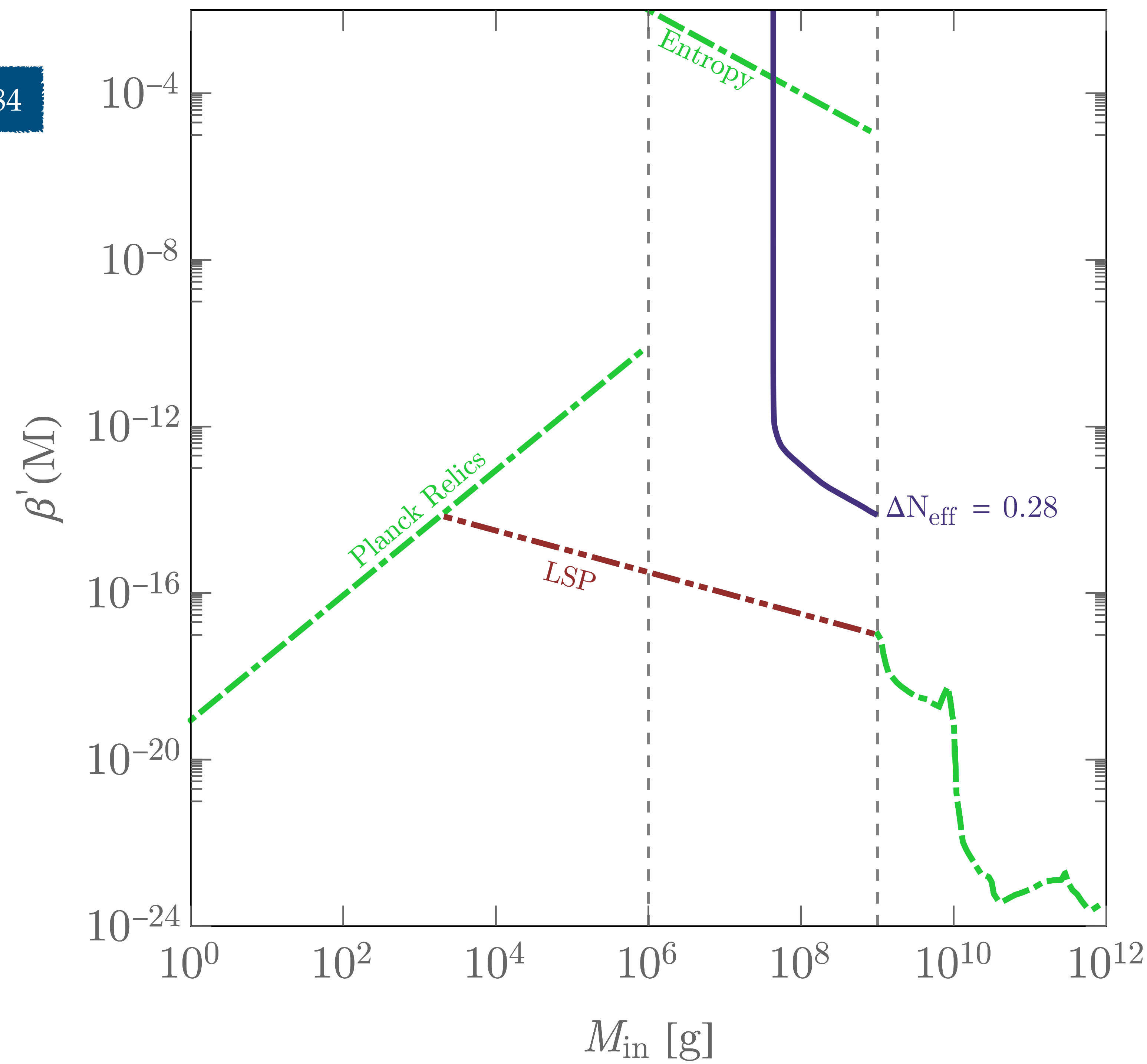

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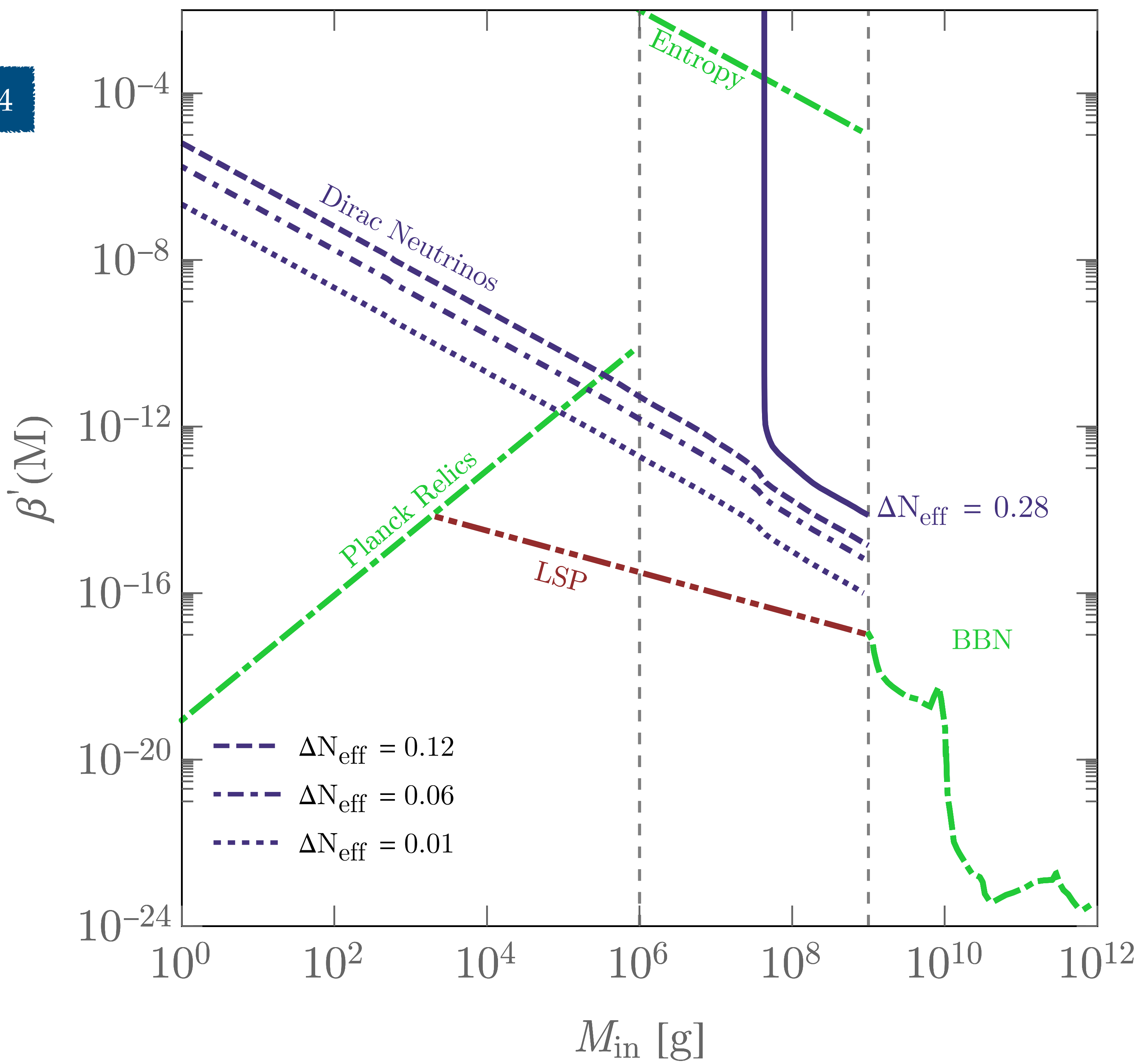

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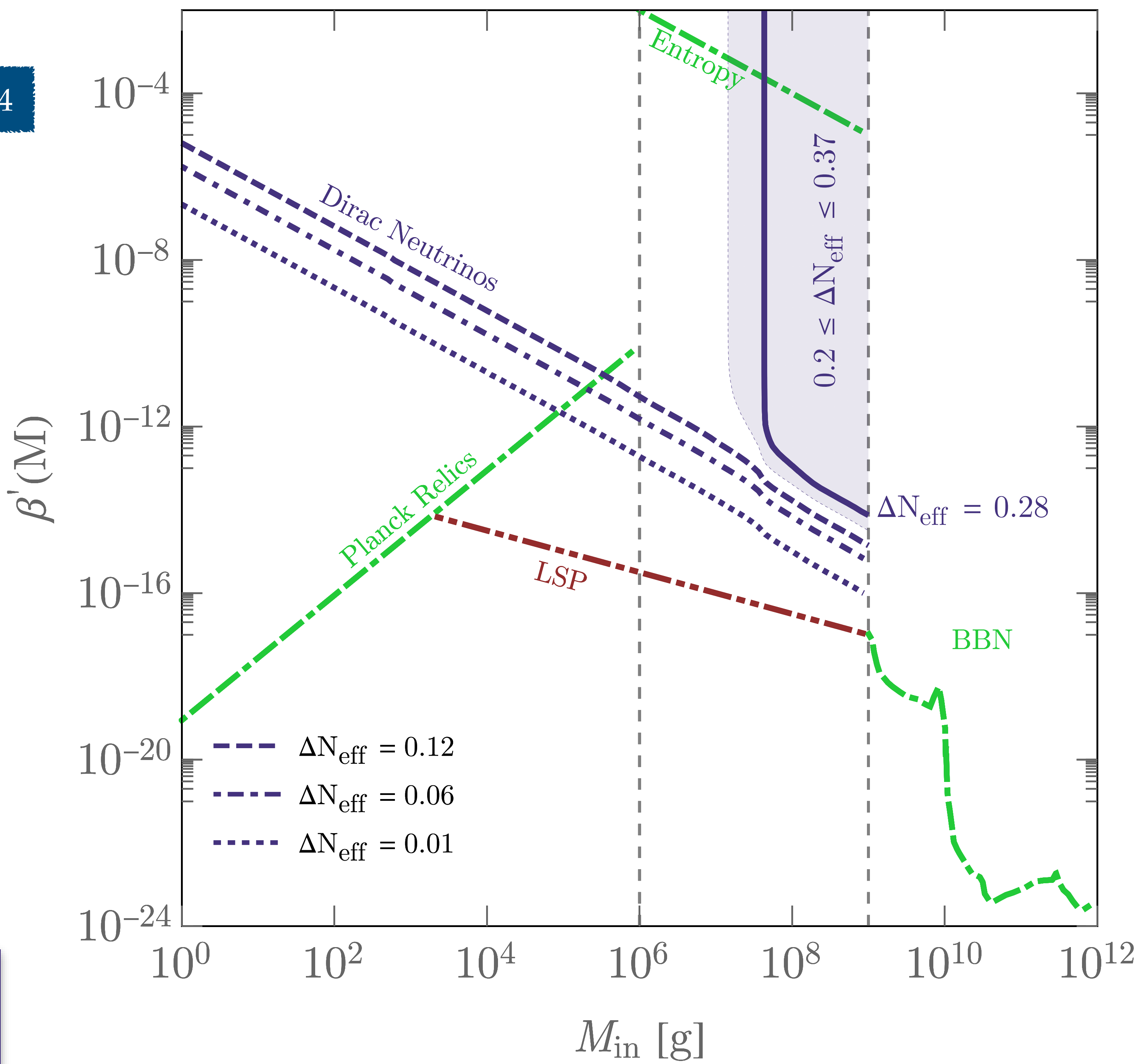

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Carr et al, 0912.5297

Tension between the early and late measurements of the Hubble constant

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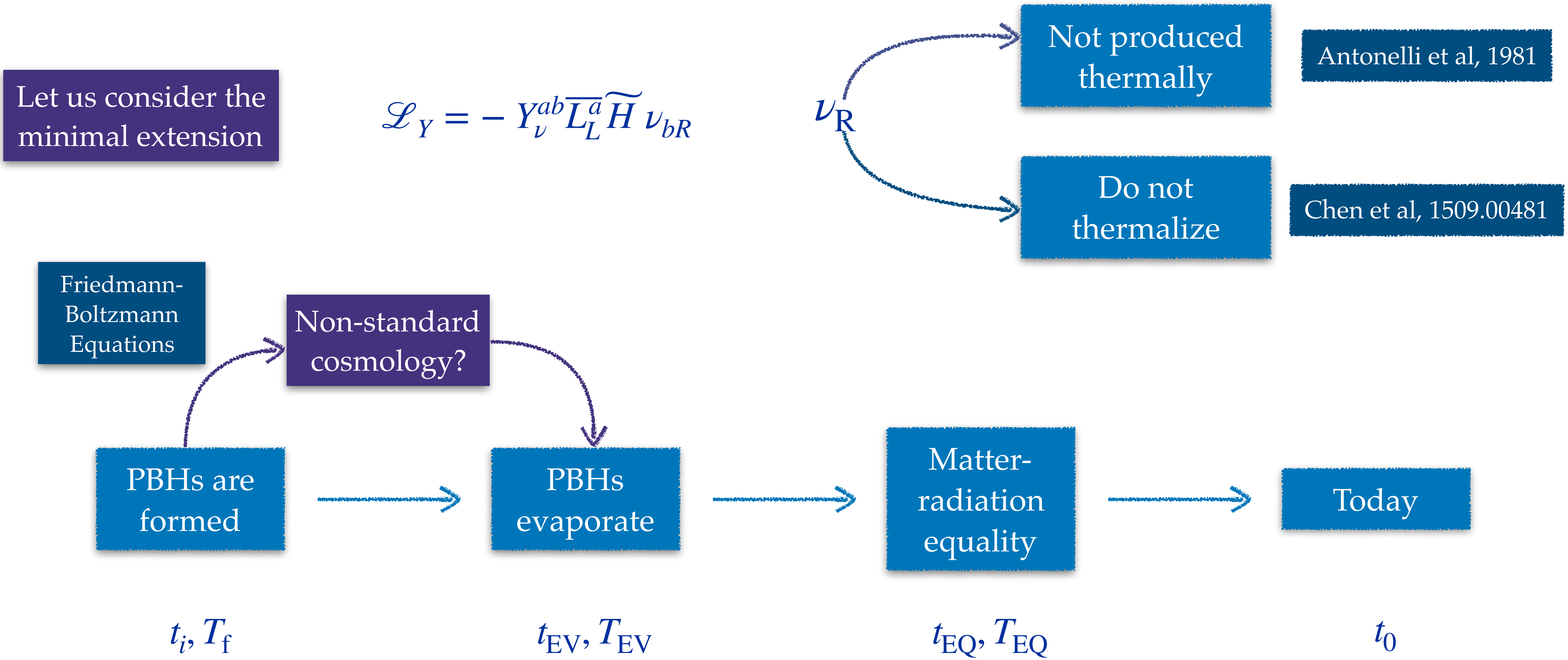

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Hooper et al, 1905.01301

Diffuse neutrino flux from PBHs

Could we measure these neutrinos?

$$\frac{d\Phi^{\nu}_{\rm PBH}}{dp_0} = \int_{t_i}^{\min(t_0,\tau)} dt \frac{d\Omega}{4\pi} \frac{a_0}{a_t} \left(\frac{a_i}{a_0}\right)^3 \frac{\rho^i_{\rm PBH}}{M_i} \frac{d^2N_\nu}{dp\, dt}(M(t),\, p_0\, a_0/a_t)$$

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PBH initial number

Comoving number density

Momentum redshift

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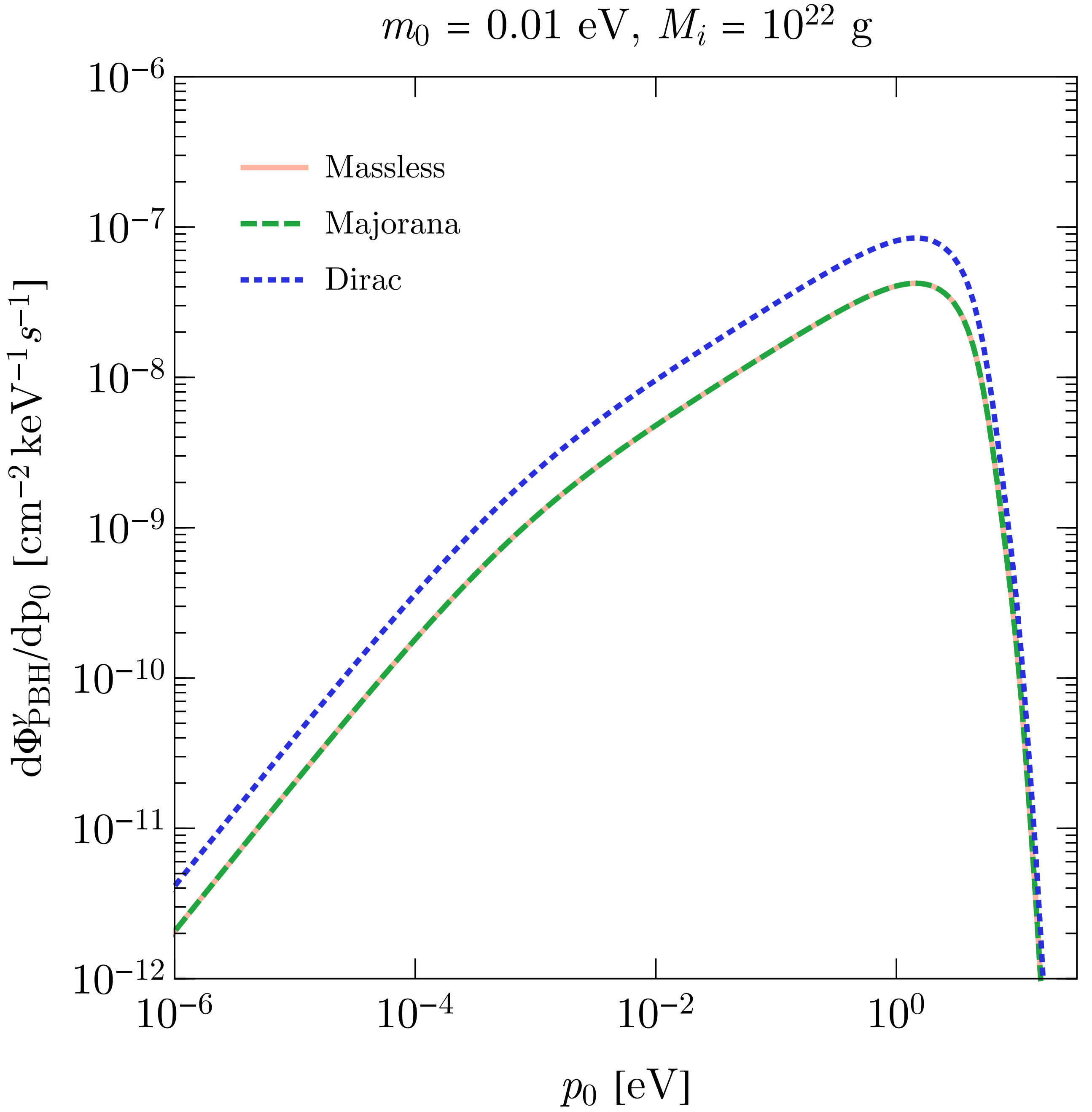
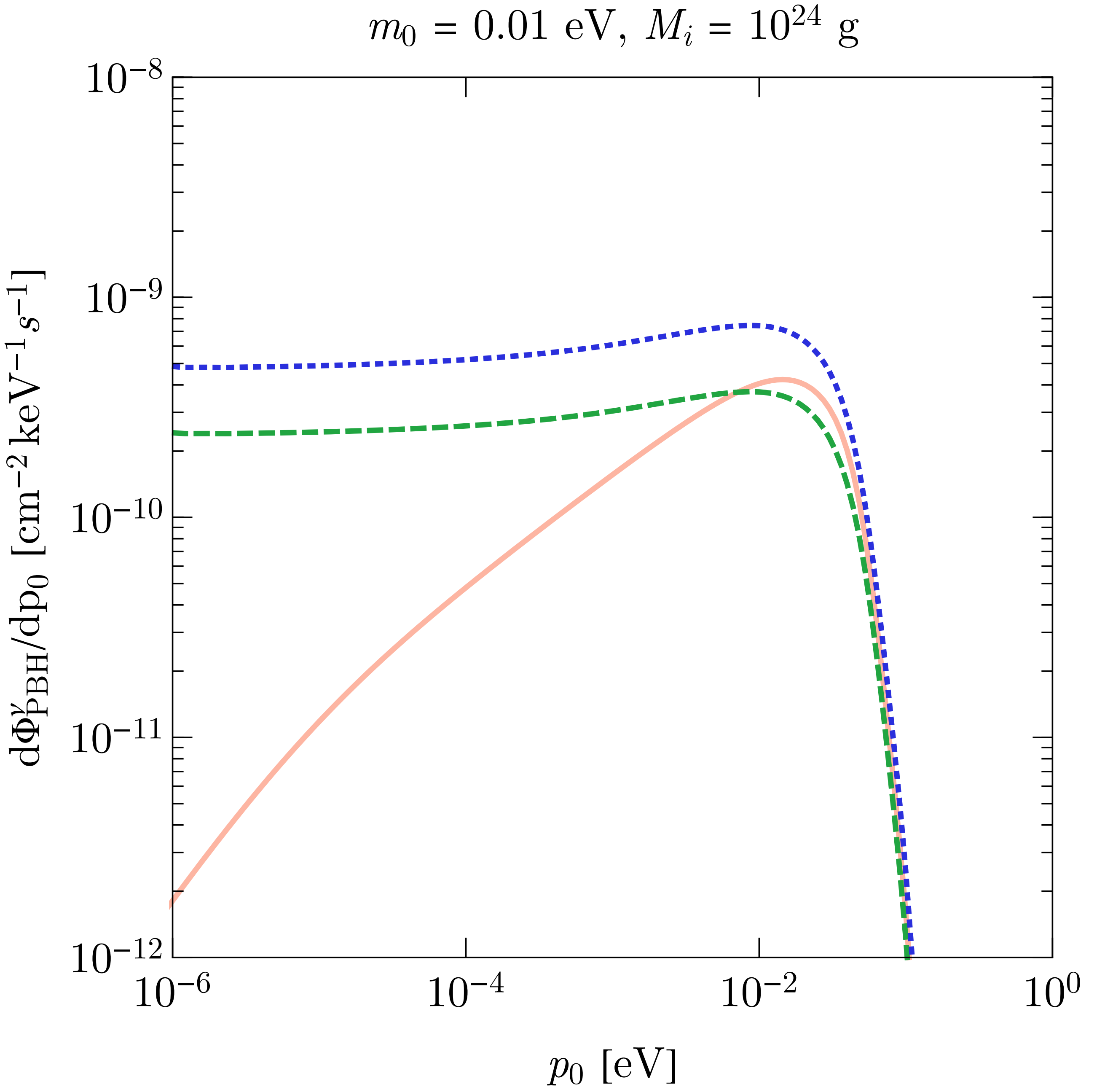
$$\frac{a_i}{a_0} = \left(\frac{a_i}{a_{\rm EV}}\right)\left(\frac{g_{*S}(T_{\rm EV})}{g_{*S}(T_{\rm EQ})}\right)^{\frac{1}{3}}\left(\frac{T_{\rm EV}}{T_{\rm EQ}}\right)\left(1 + z_{\rm EQ}\right)$$

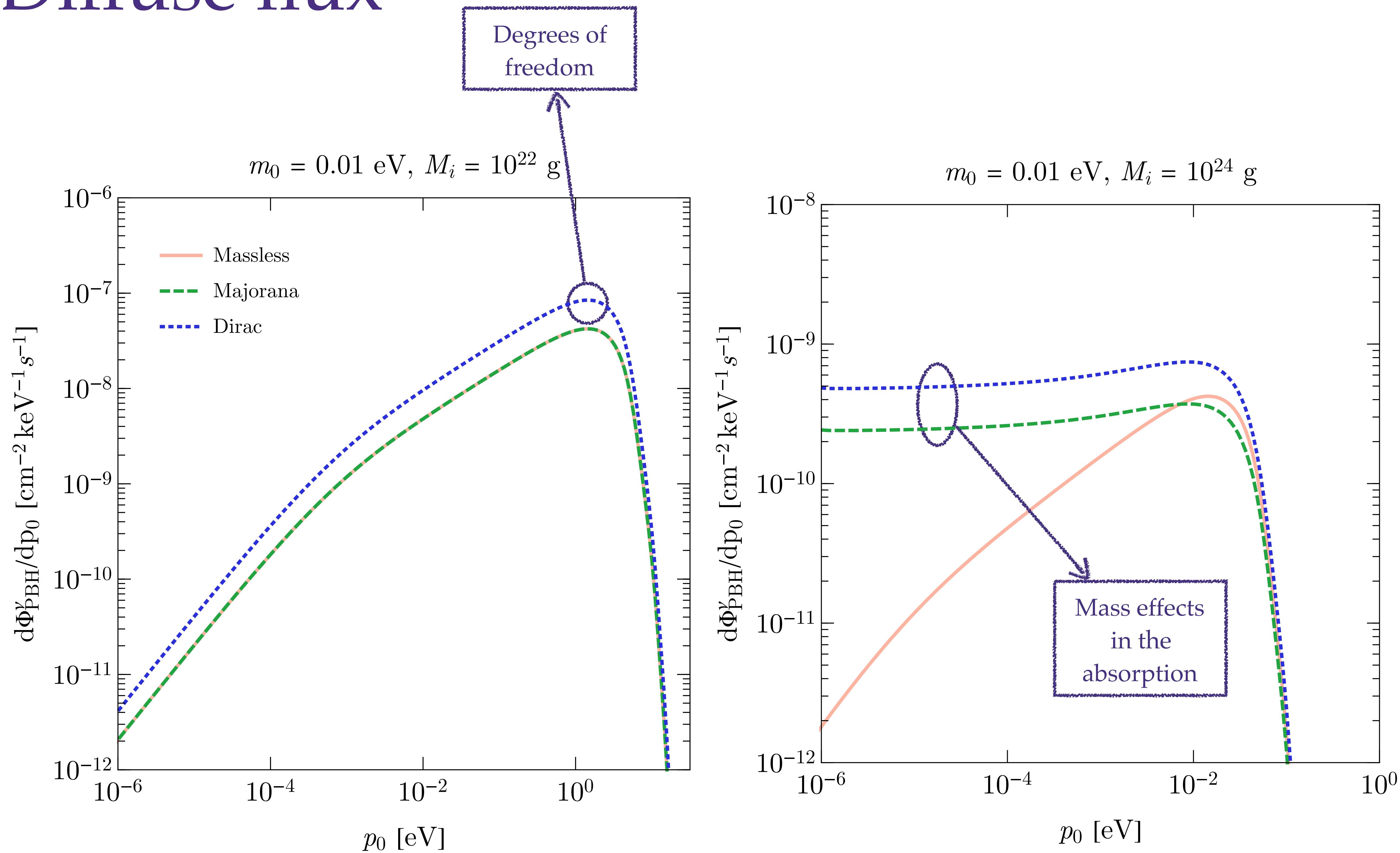
Matter-radiation redshift

Diffuse flux

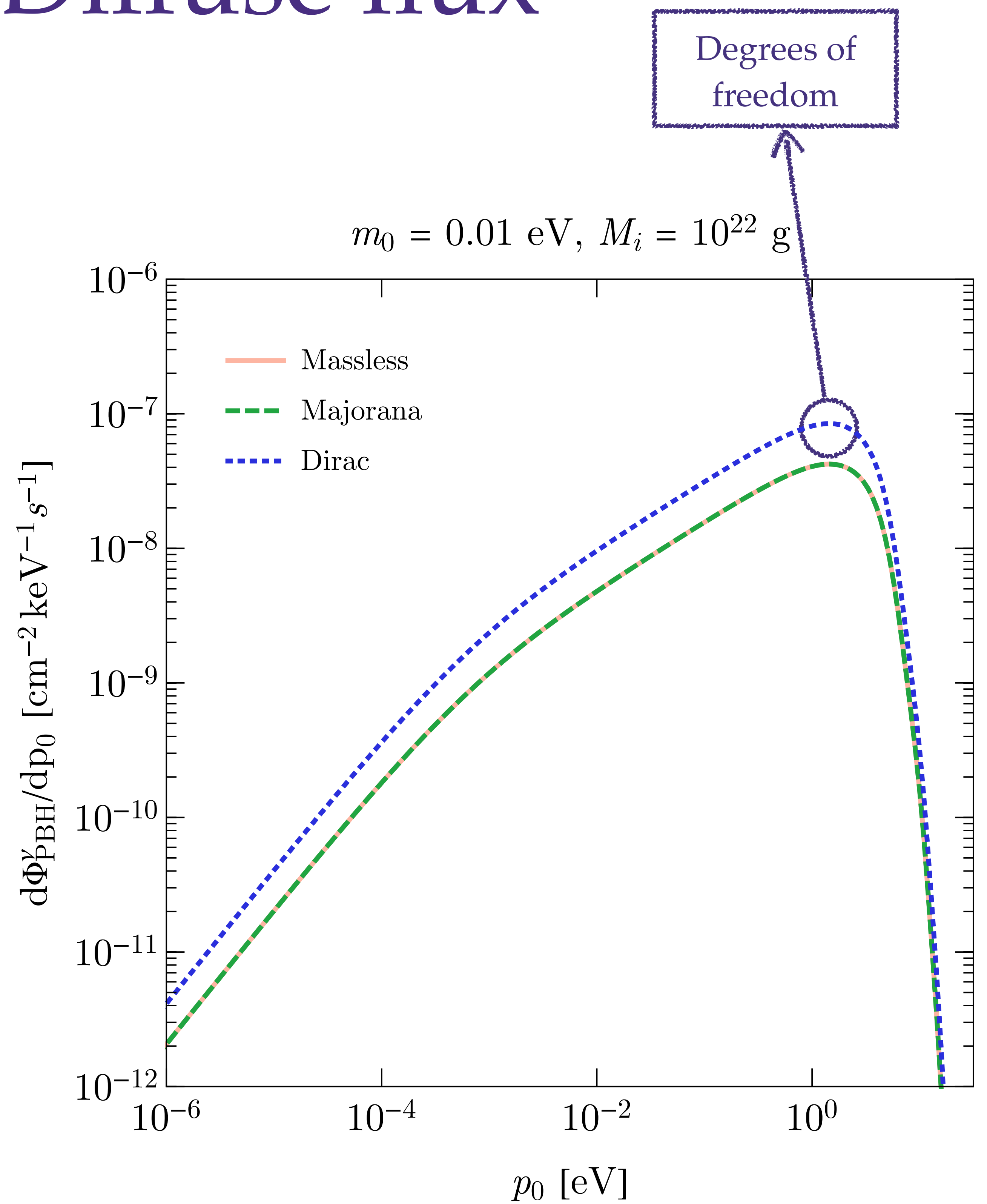


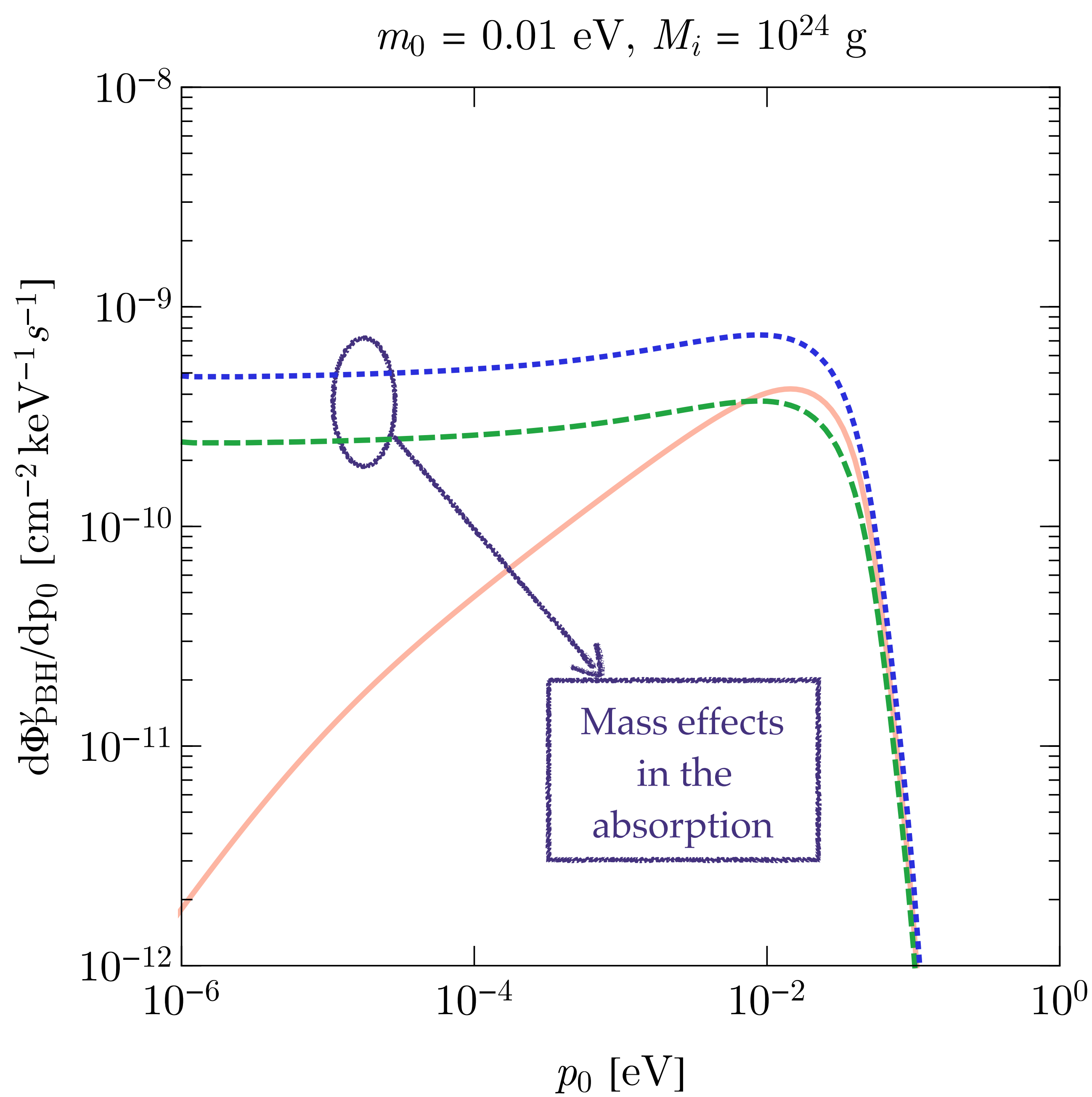


Diffuse flux



Diffuse flux

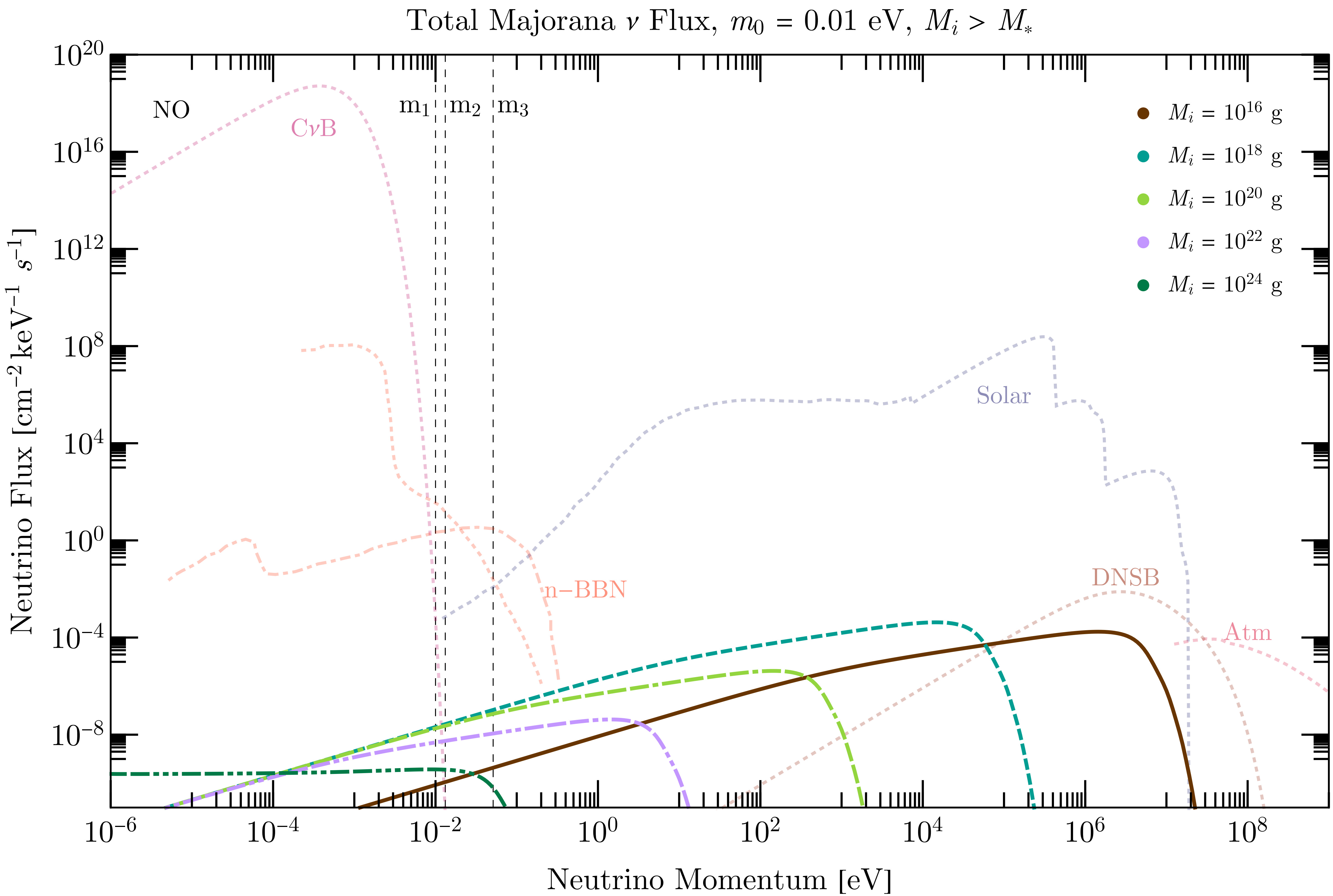




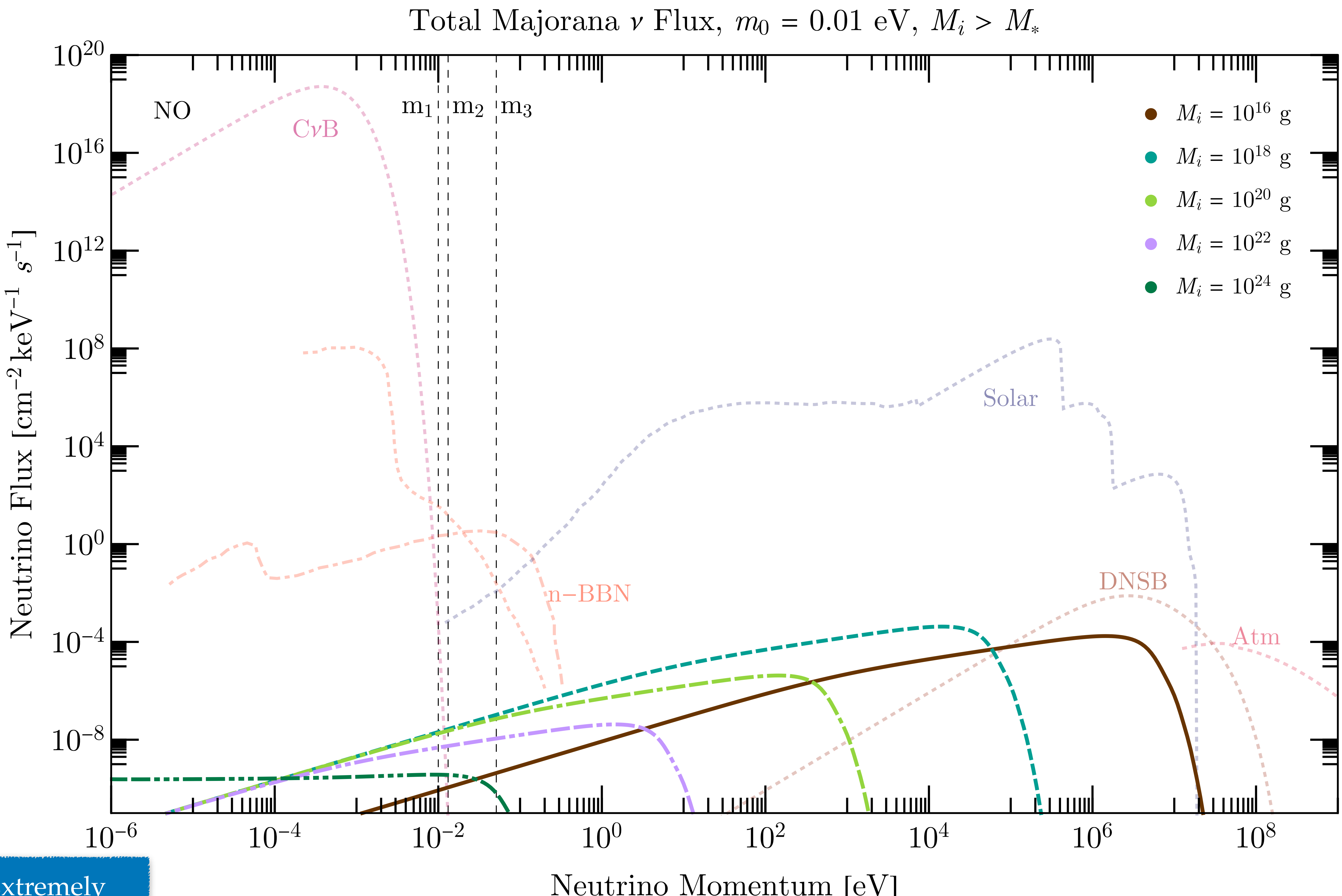
Information on the neutrino mass and nature

Could it be detectable?

Diffuse flux from non-evaporating PBHs

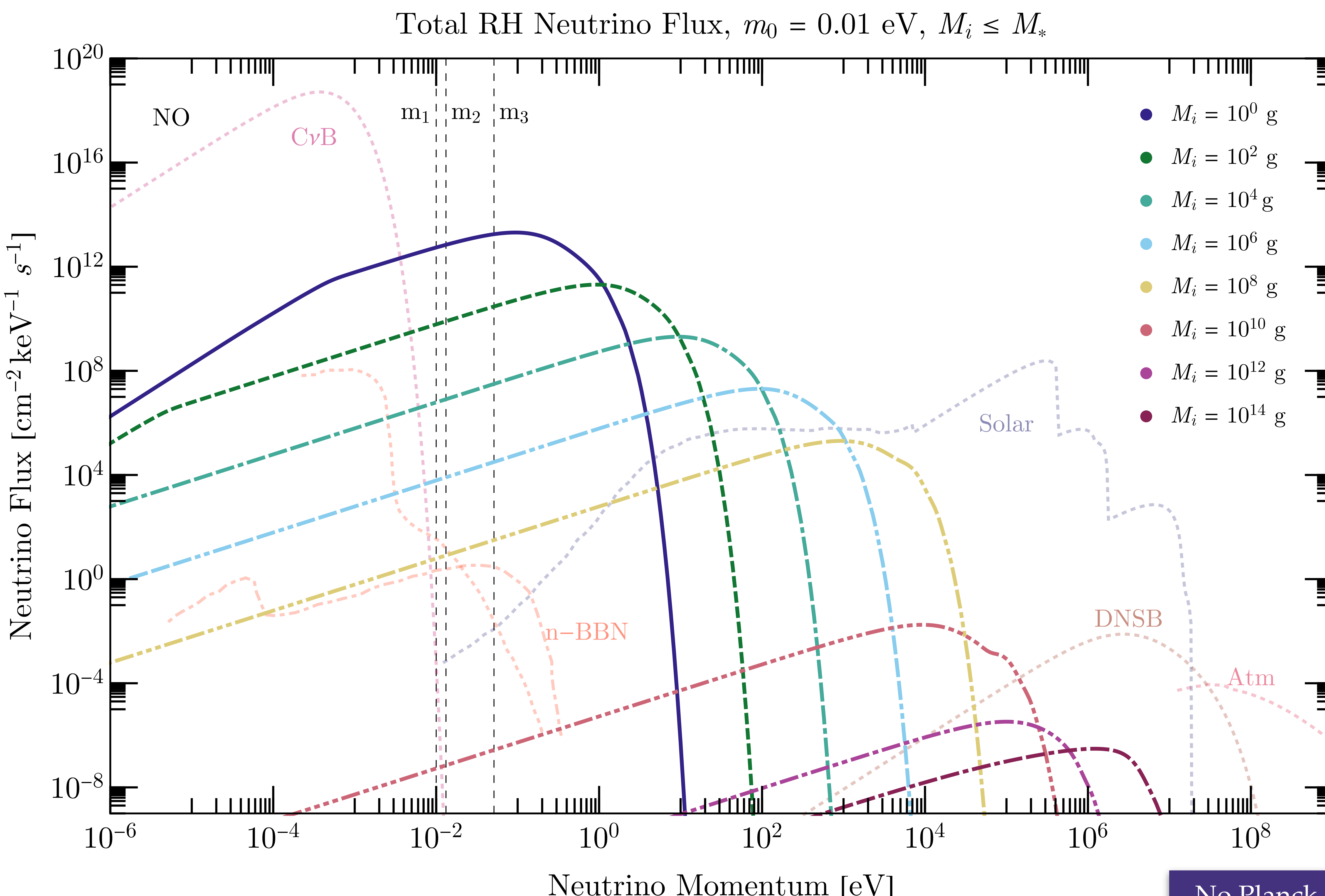


Diffuse flux from non-evaporating PBHs



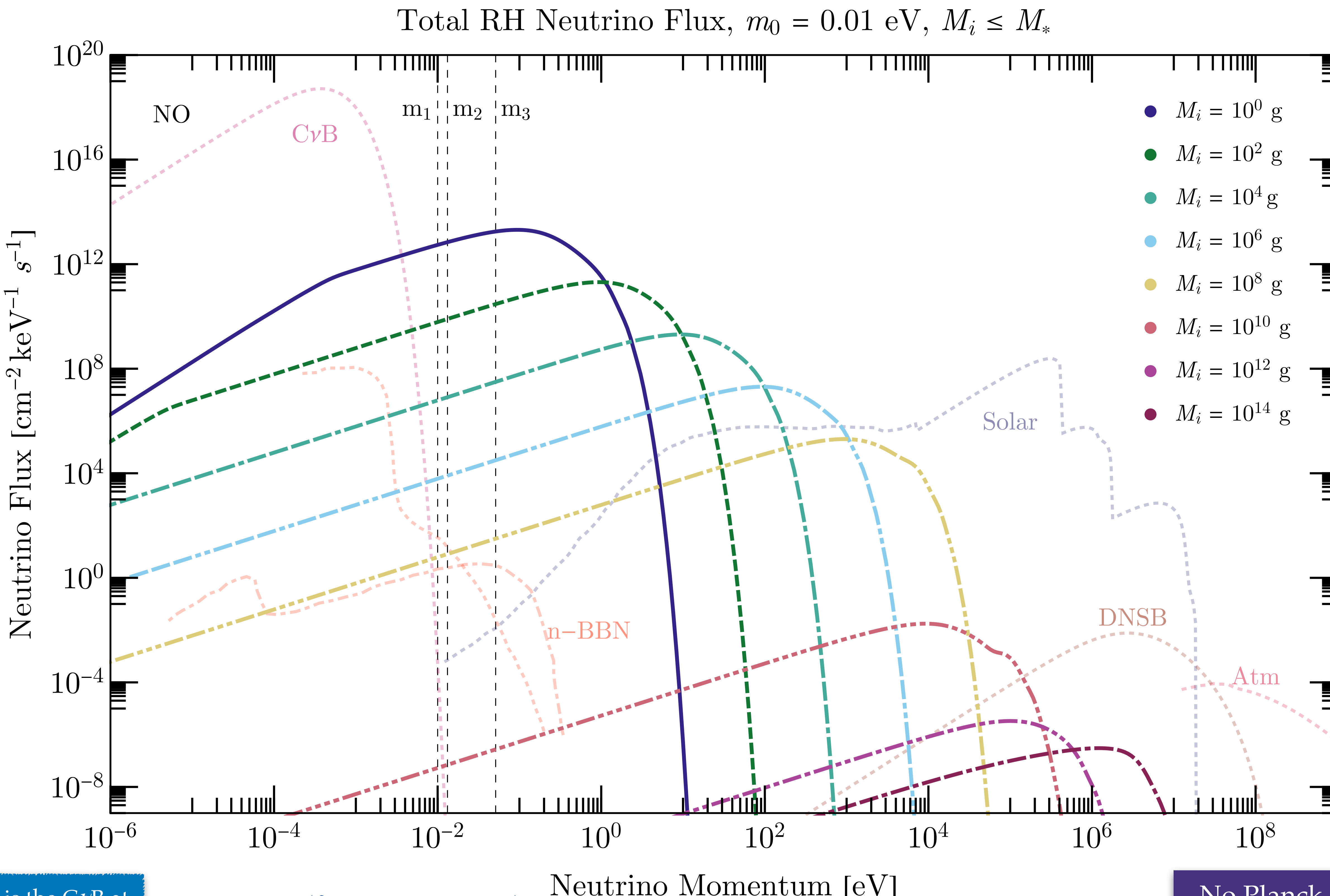
Extremely suppressed flux

Diffuse flux of RH neutrinos from PBHs



No Planck-relic constraint

Diffuse flux of RH neutrinos from PBHs



Why is the CνB at lower momenta?

$E_\nu \sim \mathcal{O}(10^{13})$ GeV $(M/1\text{g})^{-1}$

No Planck-relic constraint

Detection?

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Helicity suppression

$m_0 = 0.01\ \text{eV}$

$$\frac{m_\nu}{E_\nu} \sim 10^{-1} \longrightarrow \boxed{M = 1\ \text{g}}$$

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Akhmedov's talk

PTOLEMY?

$$\nu_a + n \to p^+ + e^-$$

$$\Gamma^{\rm D}_{\rm C\nu B} \sim 40 \ [\text{kg} - \text{year}]^{-1}$$

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Akhmedov's talk

PTOLEMY?

$$\nu_a + n \to p^+ + e^-$$

$$\Gamma^{\rm D}_{\rm C\nu B} \sim 40 \; [\text{kg} - \text{year}]^{-1}$$

$$\Gamma^{\nu}_{\rm PBH} \sim 10^{-2} \; [\text{kg} - \text{year}]^{-1}$$

PBH RH flux is still suppressed

Are there other possible ways to try to detect this RH neutrino flux?

Conclusions

- BHs are sources of neutrinos in mass eigenstates
- The PBH evaporation depends on whether neutrinos are Dirac or Majorana particles
- In the Dirac scenario, there is not a helicity suppression of the emission of right-handed neutrinos
- We derived a constraint on the initial PBH fraction given the measurement of Neff by Planck
- For certain values, it is possible to ease the Hubble measurement tension
- The diffuse flux of RH neutrinos can be large, but more careful analysis on its possible detection should be performed

Thank you!

Backup slides

Evaporation function

$$
\begin{aligned}
\varepsilon_N(M) = 2f_1 + 4f^1_{1/2} &\left\{ \sum_{\ell=e,\mu,\tau} \exp\left[-\frac{M}{\beta_{1/2}M_\ell}\right] + 3\sum_q \exp\left[-\frac{M}{\beta_{1/2}M_q}\right] \right\} \\
&+2\,\eta_\nu^N f^0_{1/2} \sum_{a=1,2,3} \exp\left[-\frac{M}{\beta_{1/2}M_a}\right] \\
&+16 f_1 \exp\left[-\frac{M}{\beta_1 M_g}\right] \\
&+3f_1 \left\{ 2\exp\left[-\frac{M}{\beta_1 M_W}\right] + \exp\left[-\frac{M}{\beta_1 M_Z}\right] \right\} + f_0 \exp\left[-\frac{M}{\beta_0 M_H}\right]
\end{aligned}
$$

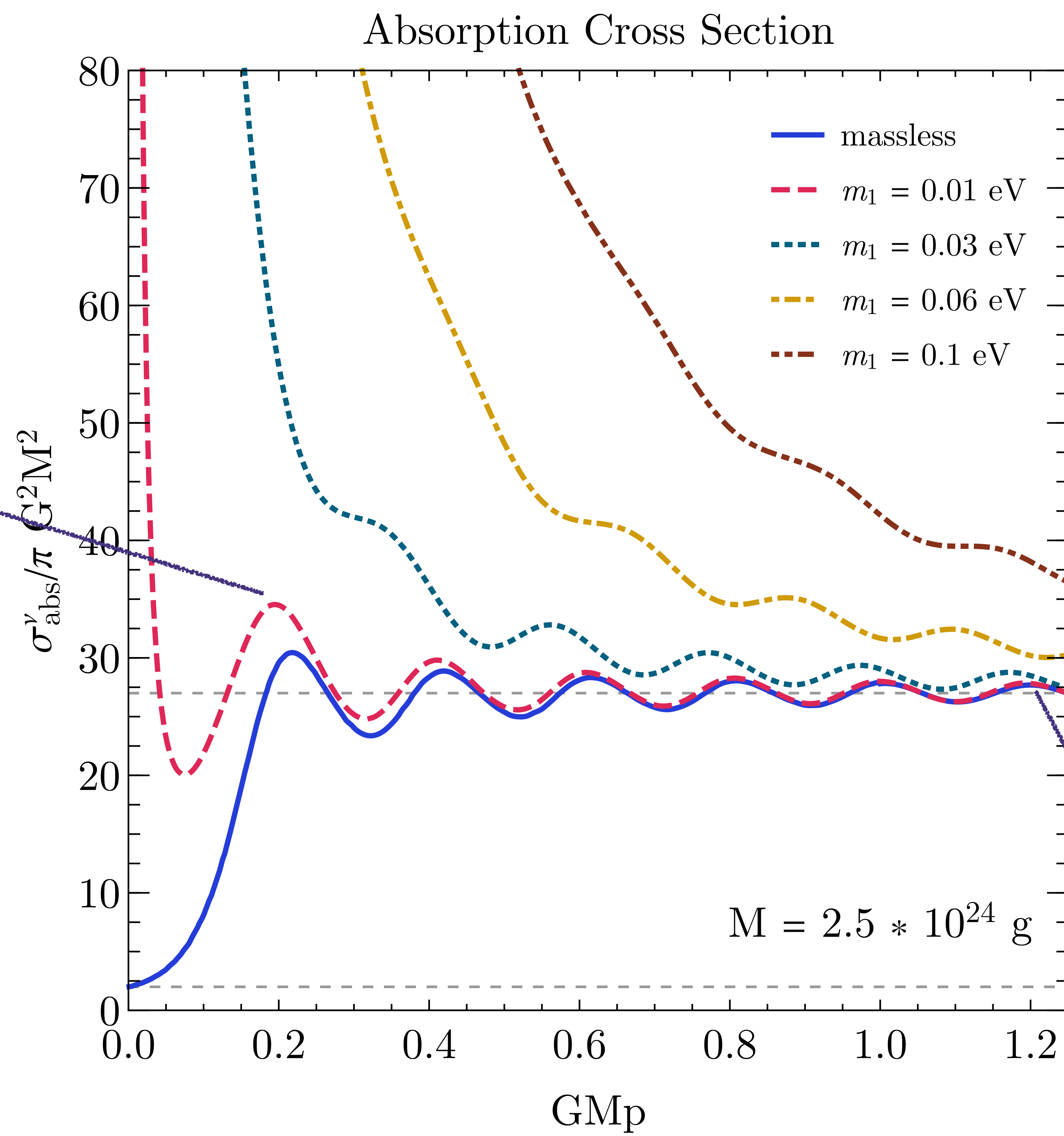
$$
\beta_s = \begin{cases} 2.66 & \textbf{for } s = 0 \\ 4.53 & \textbf{for } s = \frac{1}{2} \\ 6.04 & \textbf{for } s = 1 \end{cases}
\qquad
f_s = \begin{cases} 0.267 & \textbf{for } s = 0 \\ 0.060 & \textbf{for } s = 1 \\ 0.007 & \textbf{for } s = 2 \end{cases}
\qquad
f^q_{1/2} = \begin{cases} 0.147 & \textbf{for } q = 0 \text{ (neutral)} \\ 0.142 & \textbf{for } q = 1 \text{ (charged)} \end{cases}
$$

Absorption cross section

$\sigma^{\nu}_{\text{abs}}(M, p, m_a)$

Contribution of different partial waves

Mass dependent



$27\pi G^2 M^2$

Constraints in the Dirac neutrino case

Let us consider the minimal extension

$$\mathscr{L}_Y = -\, Y_\nu^{ab} \overline{L_L^a} \widetilde{H}\, \nu_{bR}$$

Antonelli et al, 1981

Chen et al, 1509.00481

Do not thermalize ← ν_R → Not produced thermally

Assuming an initial radiation-dominated Universe

Formation Temperature

$$T_f = \left(\frac{45}{16\pi^3 G^3}\right)^{\frac{1}{4}} g_*(T_f)^{-\frac{1}{4}} \gamma^{\frac{1}{2}} M_i^{-\frac{1}{2}}$$

Initial fraction

$$\beta' = \gamma^{\frac{1}{2}} \left(\frac{g_*(T_f)}{106.75}\right)^{-\frac{1}{4}} \frac{\rho^i_{\rm PBH}}{\rho^i_{\rm tot}}$$

Gravitational collapse factor

Monochromatic mass distribution

Constraints in the Dirac neutrino case

Friedmann and Boltzmann Equations

$$\dot{\rho}_{\rm PBH} + 3H\rho_{\rm PBH} = \frac{\dot{M}}{M}\rho_{\rm PBH}$$

Evaporation

$$\dot{\rho}_{\rm R} + 4H\rho_{\rm R} = -\frac{\varepsilon_{\rm SM}(M)}{\varepsilon_{\rm D}(M)}\frac{\dot{M}}{M}\rho_{\rm PBH}$$

BR into SM

$$\dot{\rho}_{\nu_{\rm R}} + 4H\rho_{\nu_{\rm R}} = -\frac{\varepsilon_{\nu_{\rm R}}}{\varepsilon_{\rm D}(M)}\frac{\dot{M}}{M}\rho_{\rm PBH}$$

$$\varepsilon_{\nu_{\rm R}} = 6 * 0.147$$

$$H^2 = \frac{8\pi G}{3}(\rho_{\rm PBH} + \rho_{\rm R} + \rho_{\nu_{\rm R}})$$

Hubble expansion

Temperature evolution

$$\frac{\dot{T}}{T} = -\frac{H}{\Delta} - \frac{1}{\Delta}\frac{\dot{M}}{M}\frac{g_*(T)}{g_{*S}(T)}\frac{\rho_{\rm PBH}}{4(\rho_{\rm R} + \rho_{\nu_{\rm R}})}$$

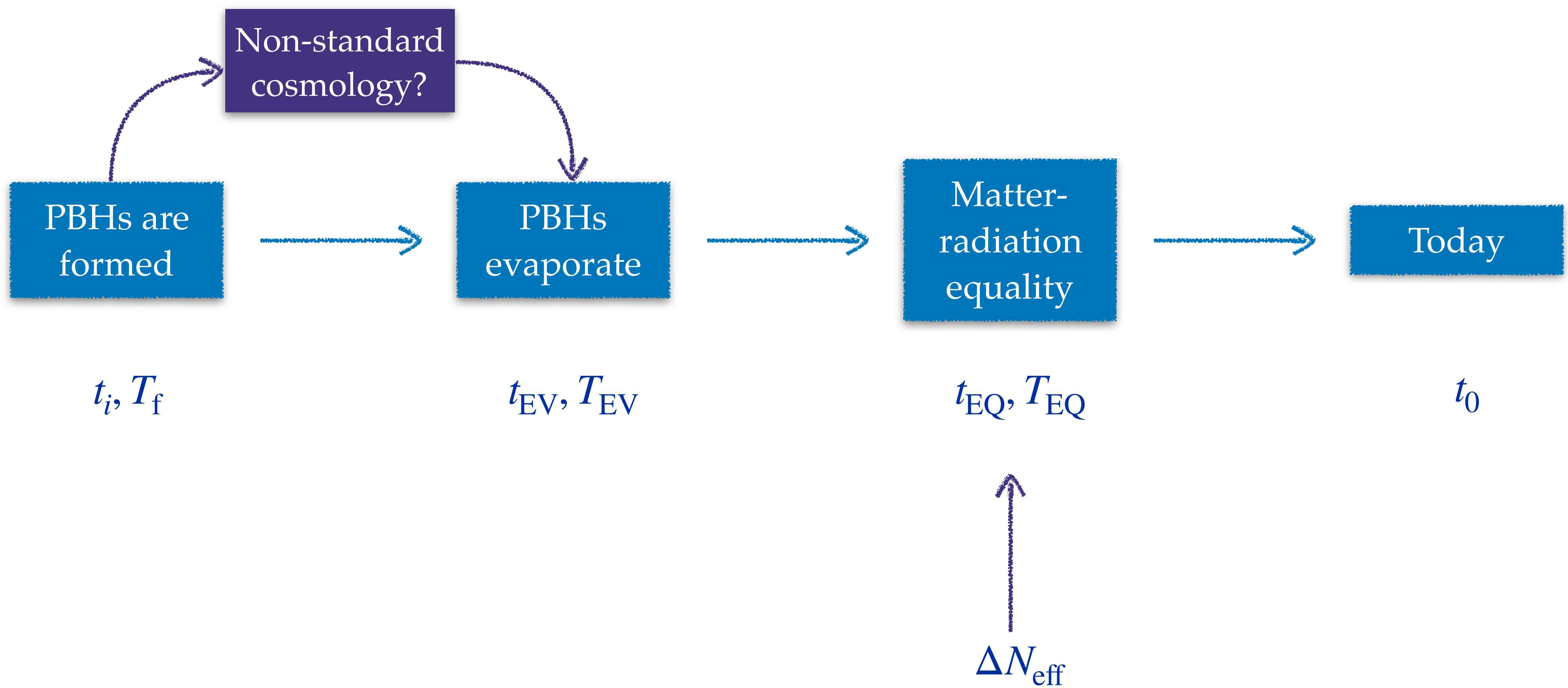
$$\Delta = 1 + \frac{T}{3g_{*S}(T)}\frac{dg_{*S}(T)}{dT}$$

Initial fraction

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

Hooper et al, 1905.01301

Constraints in the Dirac neutrino case



$$\Delta N_\mathrm{eff} = \left\{ \frac{8}{7}\left(\frac{4}{11}\right)^{-\frac{4}{3}} + N_\mathrm{eff}^\mathrm{SM} \right\} \frac{\rho_{\nu_\mathrm{R}}(T_\mathrm{EV})}{\rho_\mathrm{R}(T_\mathrm{EV})} \left(\frac{g_*(T_\mathrm{EV})}{g_*(T_\mathrm{EQ})}\right) \left(\frac{g_{*S}(T_\mathrm{EQ})}{g_{*S}(T_\mathrm{EV})}\right)^{\frac{4}{3}}$$

Hooper et al, 1905.01301

Neutrino spectrum

Hawking spectrum

$$\frac{d^2N_\nu}{dp\,dt} = \sum_{a=1,2,3} \frac{g_a^N}{2\pi^2} \frac{\sigma_{\rm abs}^\nu(M,p,m_a)\,p^2}{\exp[E_a(p)/T_{\rm BH}] + 1}$$

- g_a^N: Degrees of freedom
- $\sigma_{\rm abs}^\nu(M,p,m_a)$: Absorption cross section

$$T_{\rm BH} = \frac{1}{8\pi GM}$$ ← BH Temperature

Absorption cross section

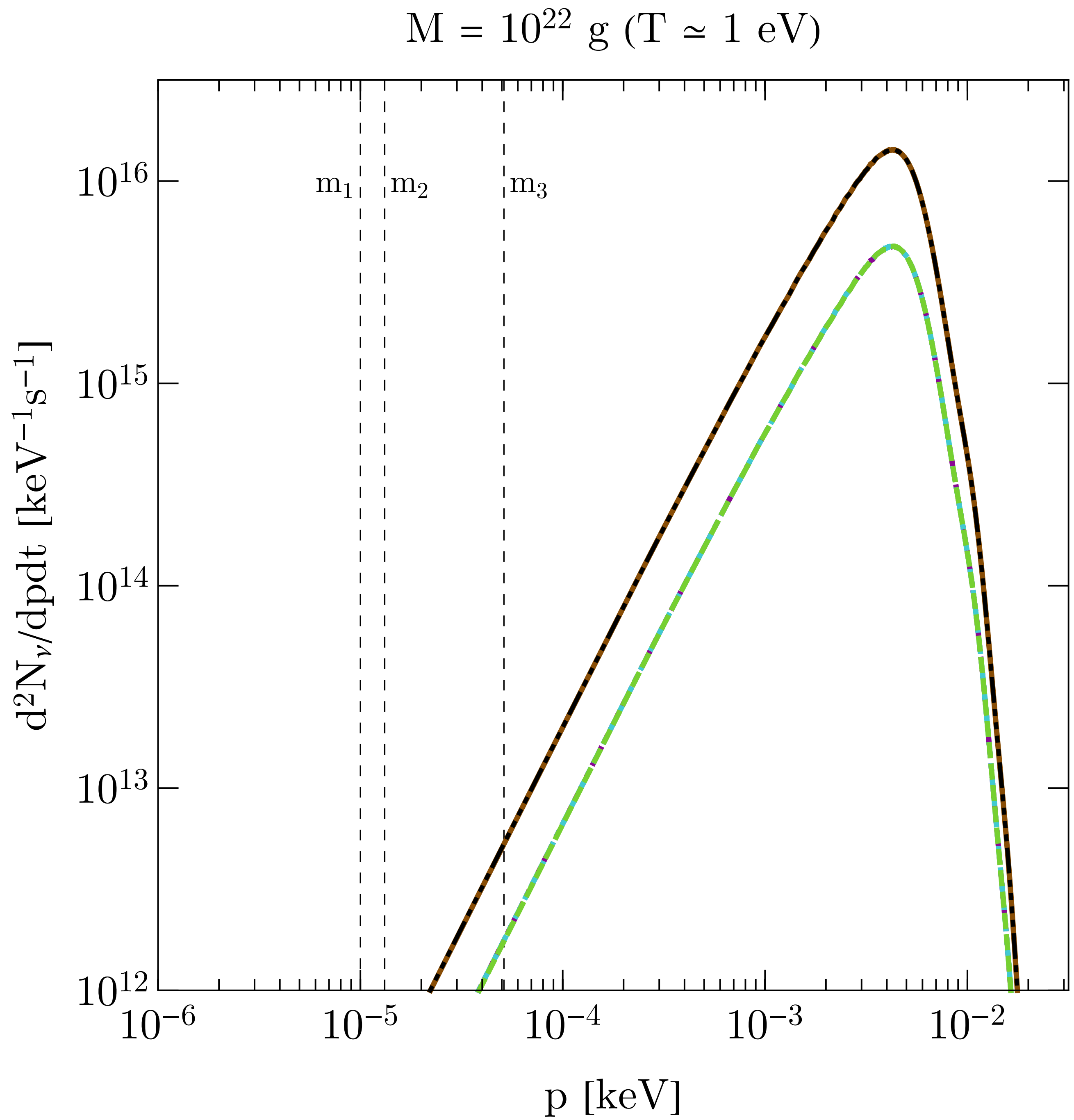
$$\alpha_g^a = GMm_a$$

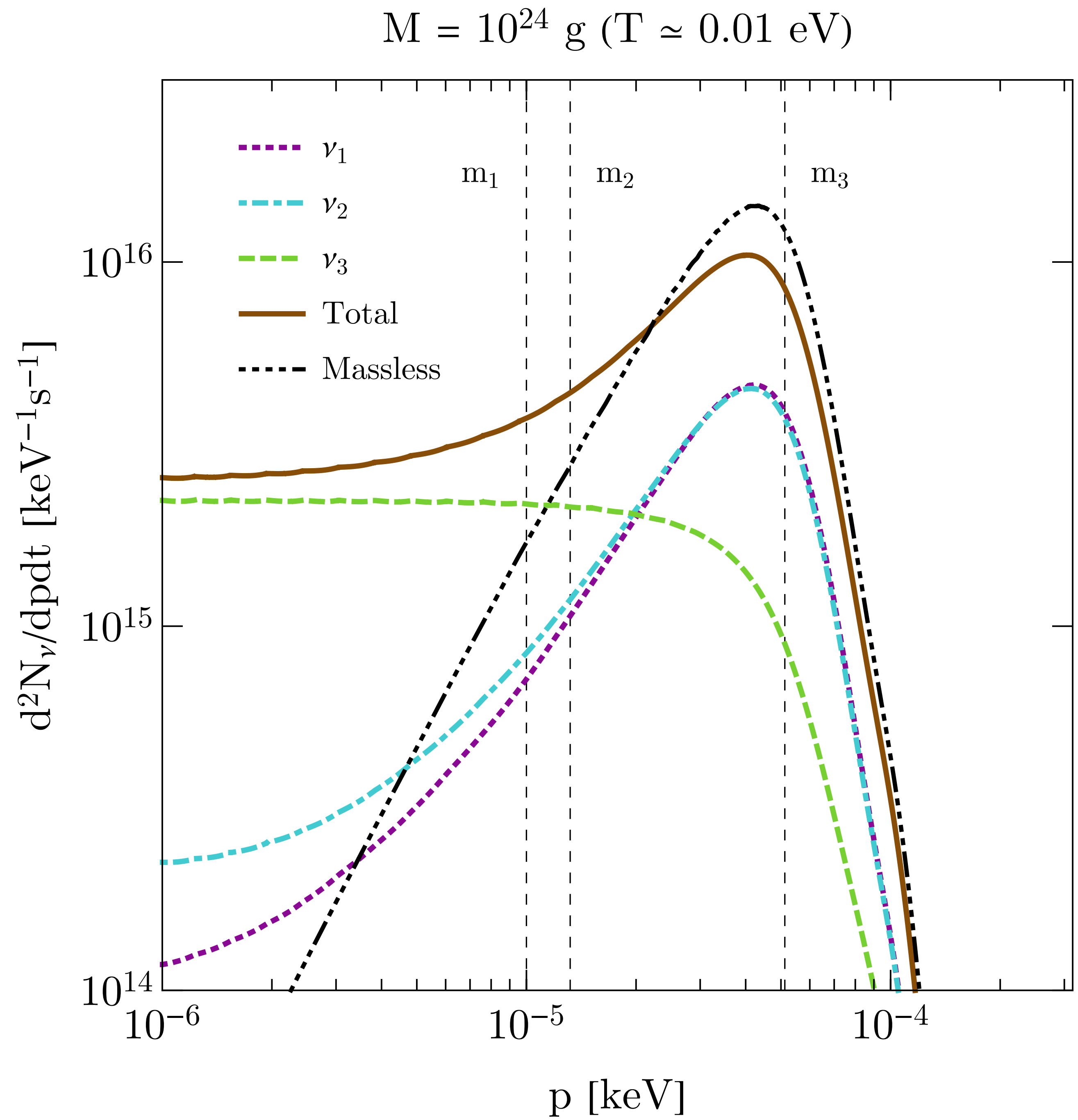
$\sigma_{\rm abs}^\nu(M,p,m_a)$:

- $\alpha_g^a \gg 1$ → Classical
- $\alpha_g^a \sim 1$ → Full mass effects in the absorption

$$\alpha_g^a \sim 1 \longrightarrow M \sim 2.66\times10^{25}\ {\rm g}\left(\frac{0.01\ {\rm eV}}{m_a}\right)$$

Hawking spectrum





$$\dot{M} = -\sum_j \frac{g_j}{2\pi^2} \int dp\, E_j(p) \frac{\sigma_{\rm abs}^{s_j}(M,p)\, p^2}{\exp[E_j(p)/T] - (-1)^{2s_j}}$$