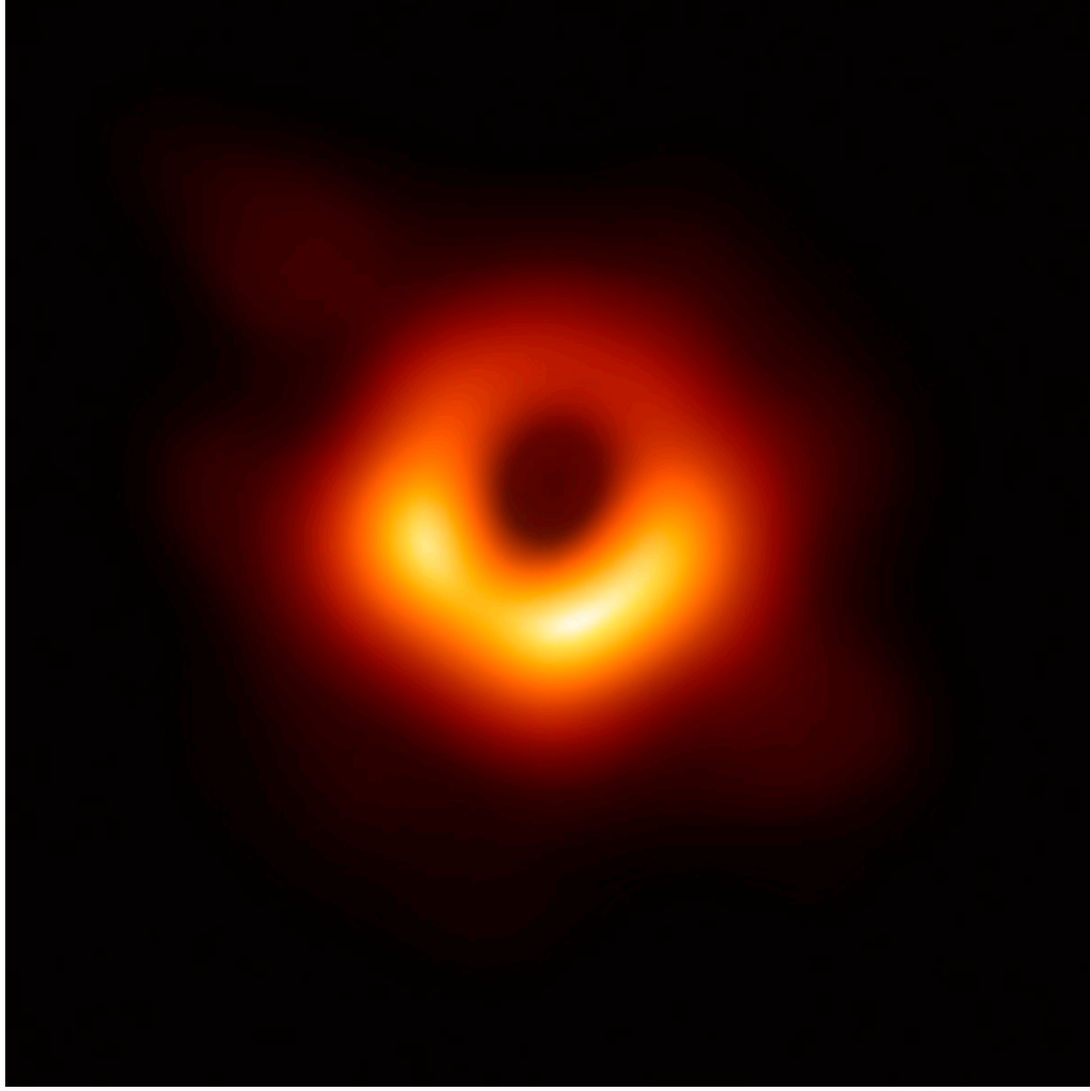
Neutrinos and Primordial Black Holes: An opera in two acts

Yuber F. Perez-Gonzalez



EHT Collaboration

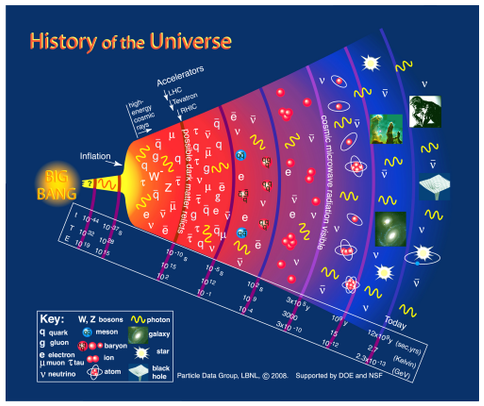
Brookhaven National Laboratory
High Energy Theory Seminar
March 11th, 2021

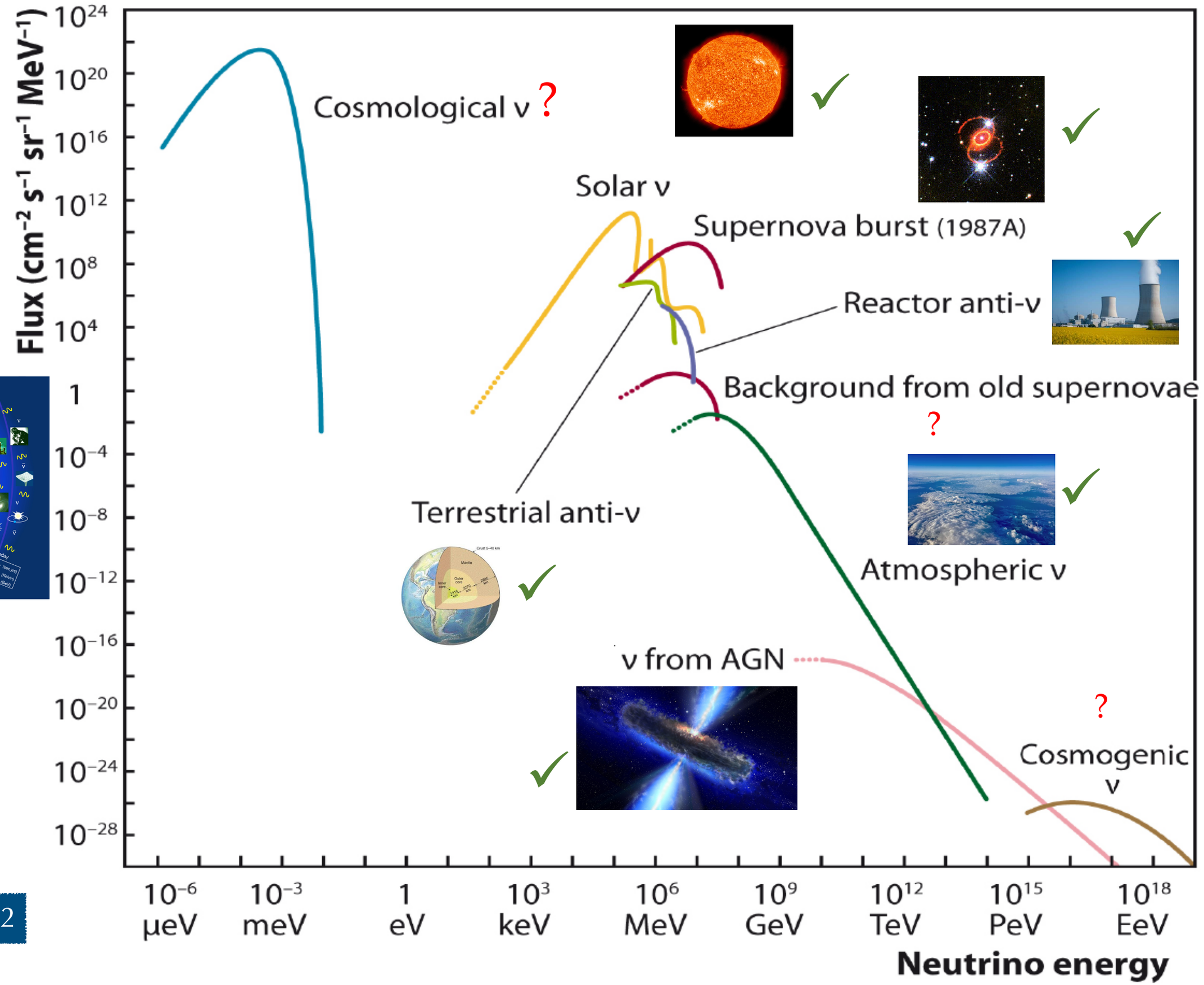
Fermilab

COFI
COLEGIO DE FISICA FUNDAMENTAL E INTERDISCIPLINARIA DE LAS AMERICAS

NORTHWESTERN UNIVERSITY
QUAECUMQUE SUNT VERA
ὁ λόγος καὶ πλήρης ἀλη- Χάριτος θείας
1851

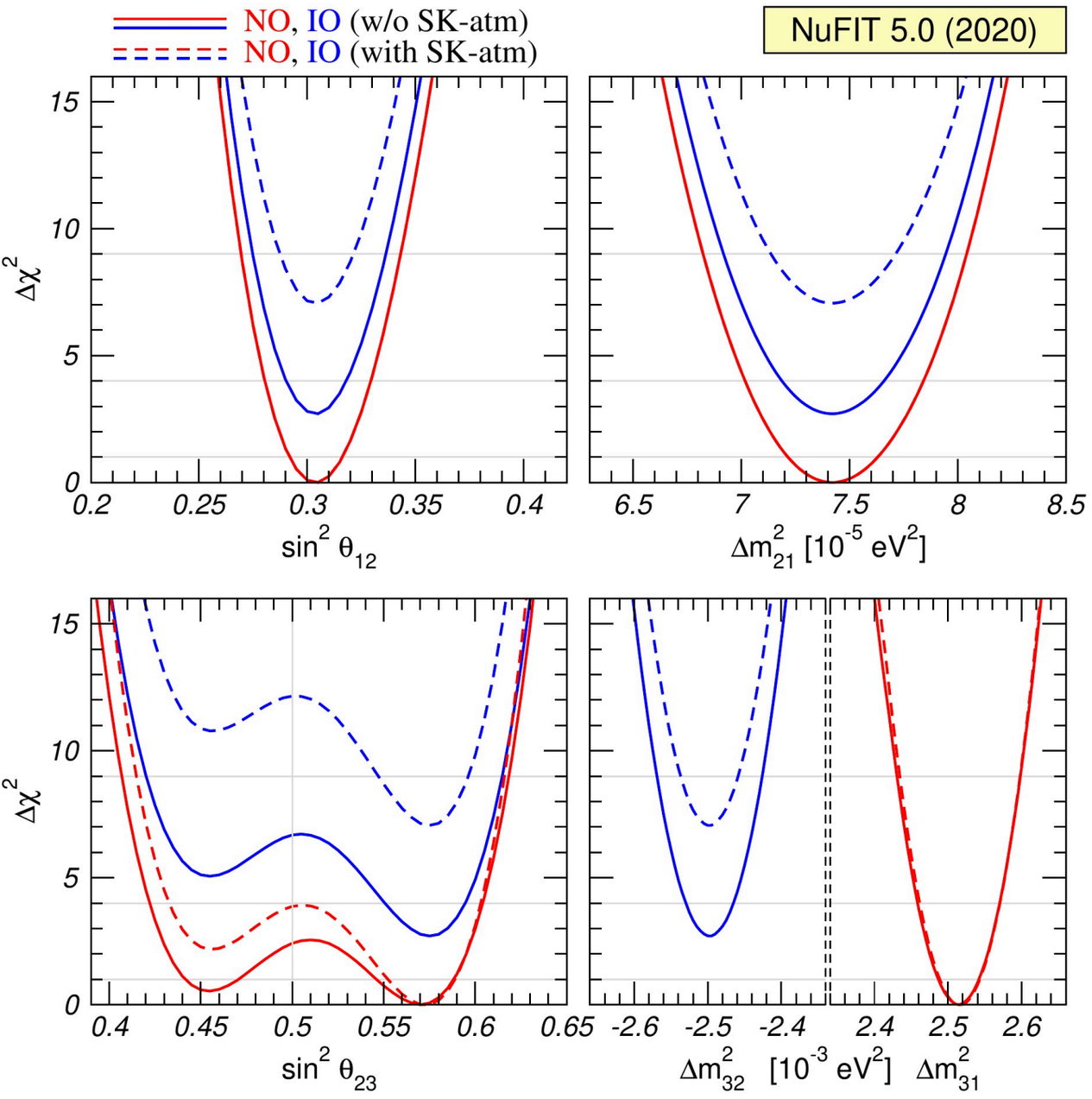
Overture





Katz et.al., 2012

What do we know about neutrino masses and mixing?



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} \, |\nu_i\rangle$$

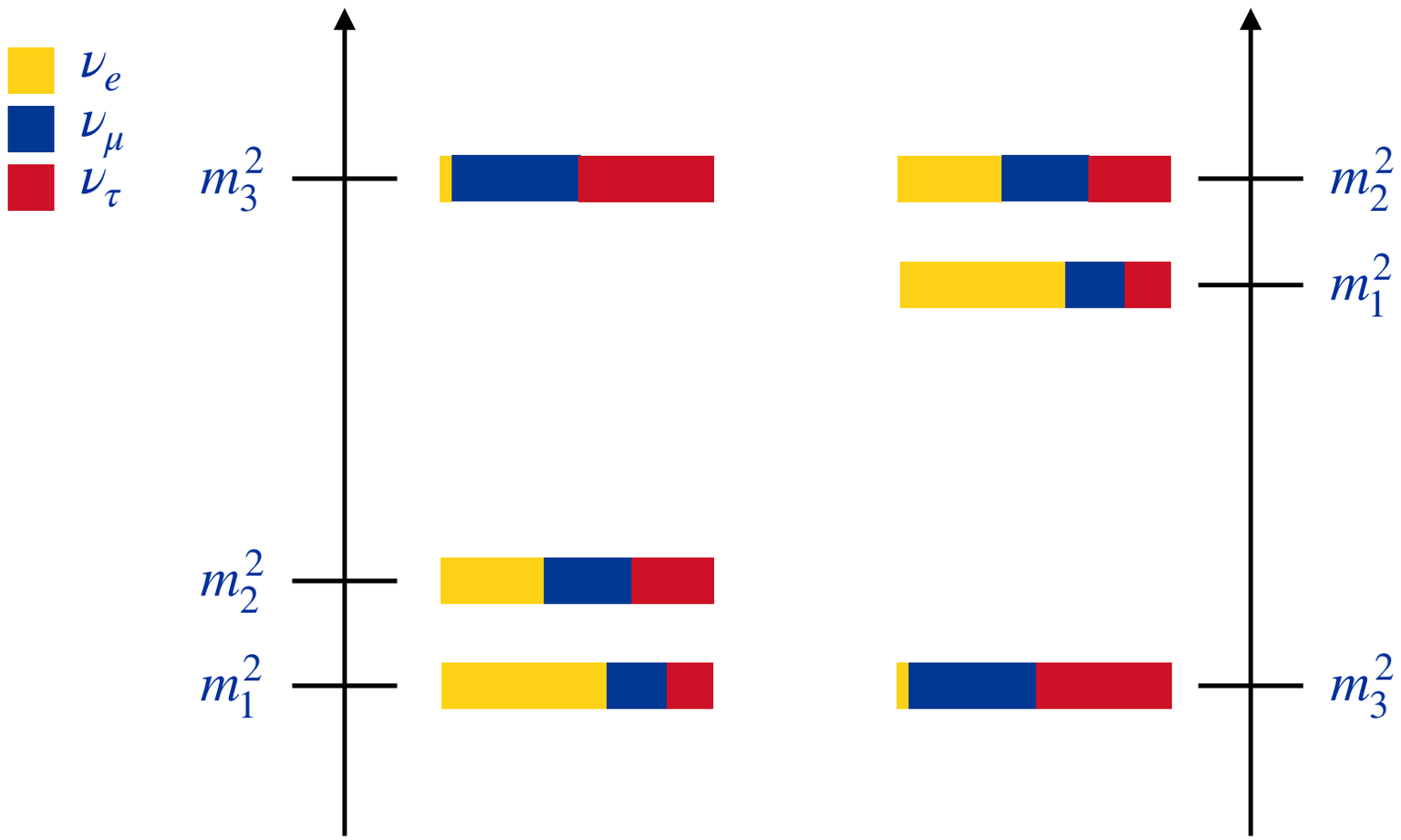
$$P_{\alpha\beta} = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{(m_k^2 - m_j^2)L}{2E}\right)$$

- 3 mixing angles
- 2 non-zero quadratic mass differences

NuFit
JHEP 09 (2020) 178

What do not we know about neutrino masses and mixing?

$|\nu_a\rangle = \tilde{U}_{\alpha a}|\nu_\alpha\rangle$



Normal Ordering

Inverted Ordering

T2K —> NO
NOvA —> NO
T2K + NOvA —> IO

Kelly, Machado, Parke, YFPG, and Funchal
2007.08526

Denton, Gehrlein, Pestes
PRL 126 (2021) 5, 051801

Chatterjee, Palazzo
PRL 126 (2021) 5, 051802

- CP phase - CP violation
- Absolute mass values
- Dirac vs Majorana nature

Dirac vs Majorana

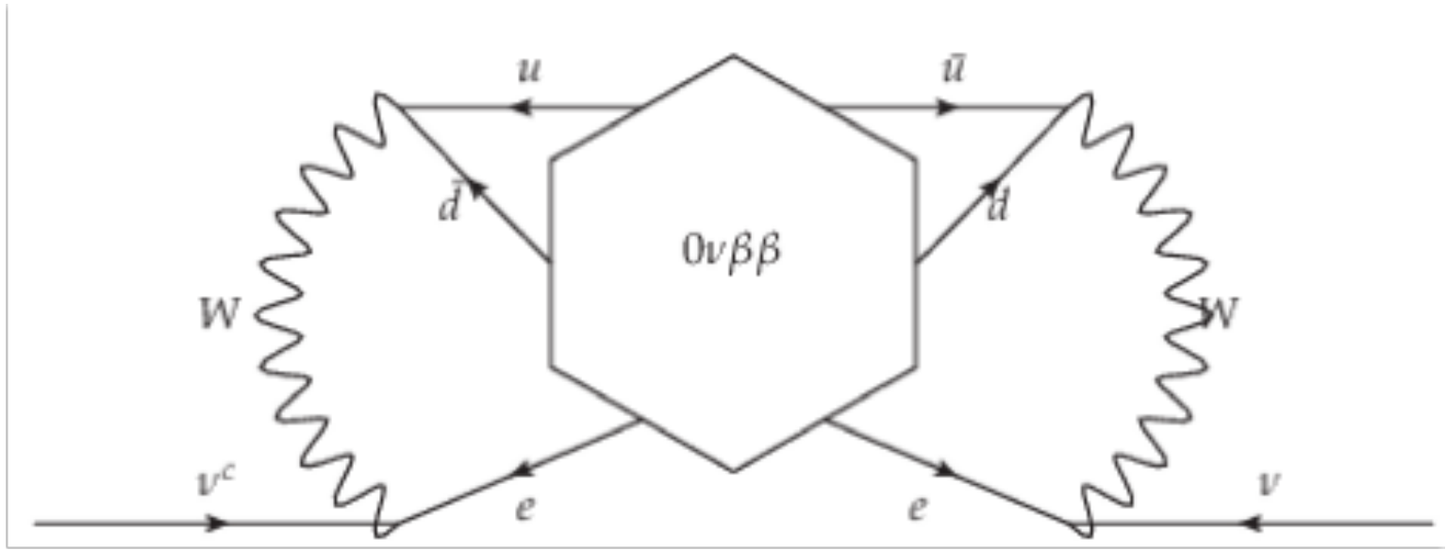
- Neutrino-less double beta decay

Schechter Valle, 1982

$\tau_{1/2} > 10^{27} - 10^{28}$ y

$m_{\beta\beta} < \sim 20$ meV

nEXO, KamLAND2-Zen, Cupid..



- Measure energy and angle distributions of heavy neutrino decay

Balantekin, De Gouvêa, Kayser, 2018

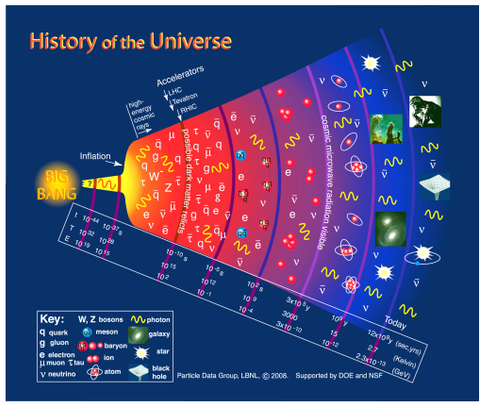
- Detect non-relativistic neutrinos $\nu_a + n \to p^+ + e^-$

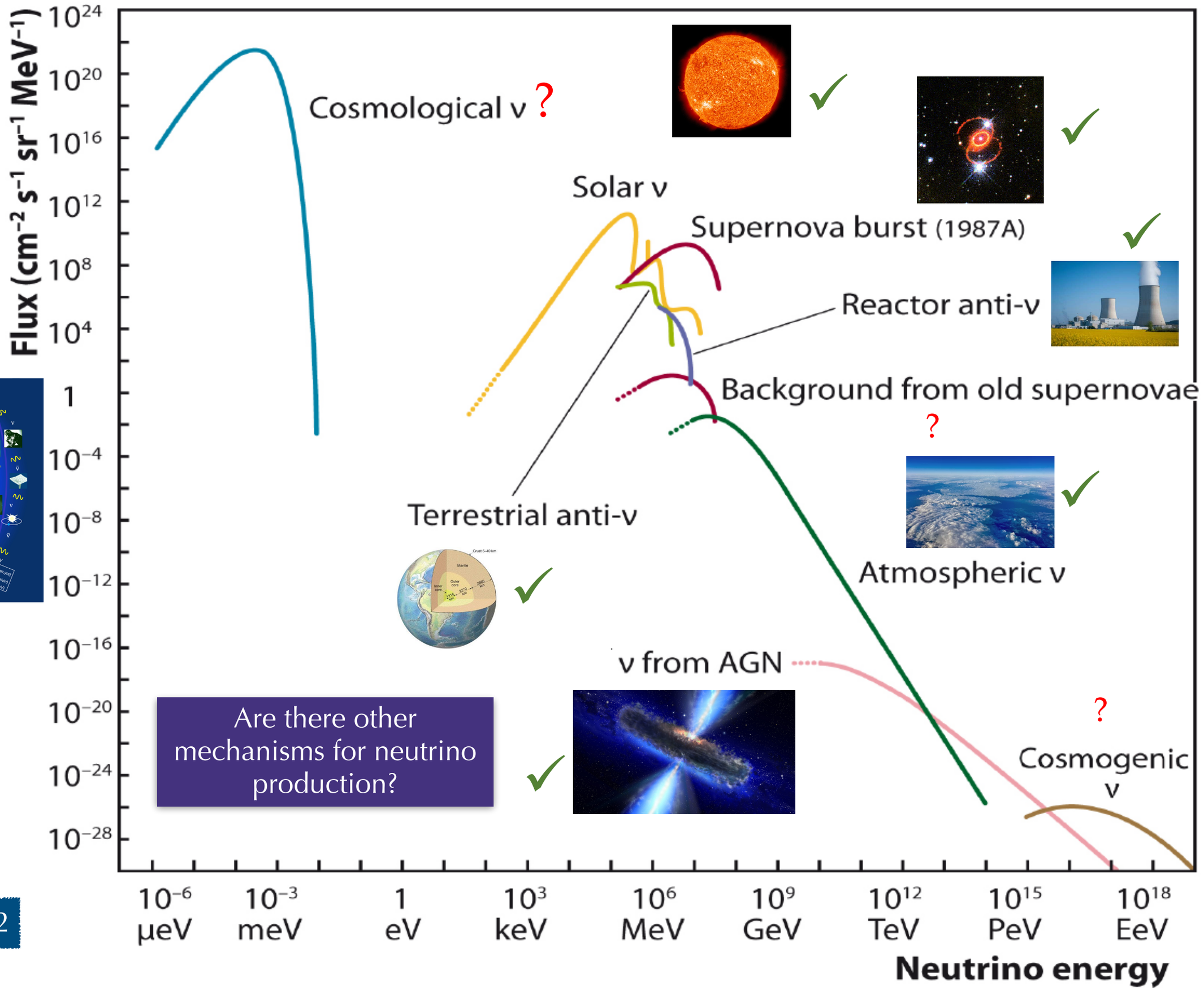
Duda and Gelmini, 2001
Long et.al. 2014

$$\Gamma^{\rm M}_{{\rm C}\nu{\rm B}} = 2\Gamma^{\rm D}_{{\rm C}\nu{\rm B}}$$

- BSM can hinder the neutrino nature

Arteaga, Bertuzzo, YFPG, Funchal, 2017



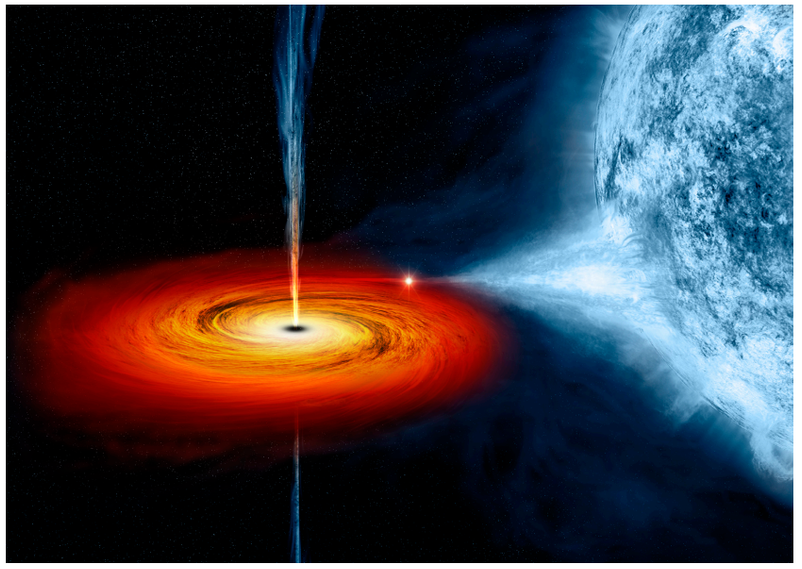


Katz et.al., 2012

Primordial Black Holes (PBH)

Astrophysical Black Holes

$$M \gtrsim 3M_\odot$$



Lighter Black Holes → Large densities

$$r_S = 2GM$$

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

Primordial Black Holes

Formation

- Bubble collisions
- Pressure reduction
- Collapse of density fluctuations

Carr et al, 0912.5297

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

BH evaporation

BHs lose mass over time

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

Depends on the set of possible particles to be emitted

J. MacGibbon, 1991

$$\approx -5.34\times 10^{25}\left(\frac{1\ \text{g}}{M}\right)^2 \varepsilon_N(M)\ \text{gs}^{-1}$$

$\varepsilon_N(M)$: Evaporation function

BH Temperature

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

BH lifetime

$$\frac{\tau}{1\ \text{s}} = \int_{M_{\rm Pl}}^{M_{\rm i}} \frac{M^2 dM}{5.34\times 10^{25}\varepsilon_N(M)}$$

$M_{\rm Pl}$: Planck mass

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

$$\tau \approx 2\times 10^{67}\ \text{years}$$

$$\approx 1.5\times 10^{57} * \text{age of the Universe}$$

Evaporated

$M/M_\odot$

(Part of) Dark Matter?

Fraction of the total energy in PBH

β'

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

Gravitational collapse factor

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

$f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$

DM fraction

LSS

Ω

Planck

LSP

BBN

CMB

Inflation

evap

K

M

OGLE

EROS

OGLE?

HSC

Radio

LIGO-SGWB

UFdwarfs

LIGO

CMB

$M_{\rm PBH}\ [M_\odot]$

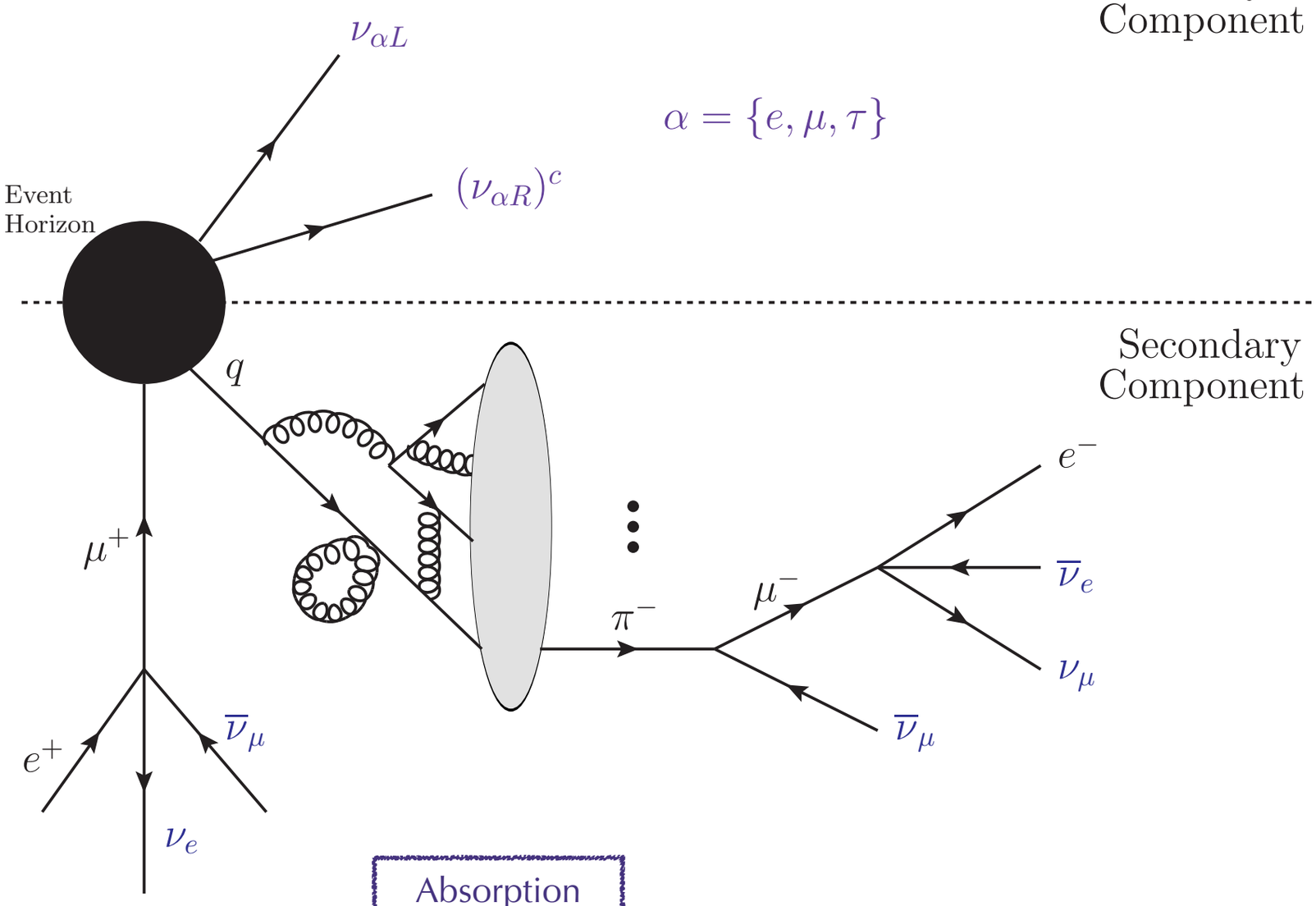
M [g]

Carr et al. 2002.12778

B. Kavanagh
10.5281/zenodo.3538999

Neutrino emission in the SM

B. Carr, 1976



Degrees of freedom

Absorption cross section

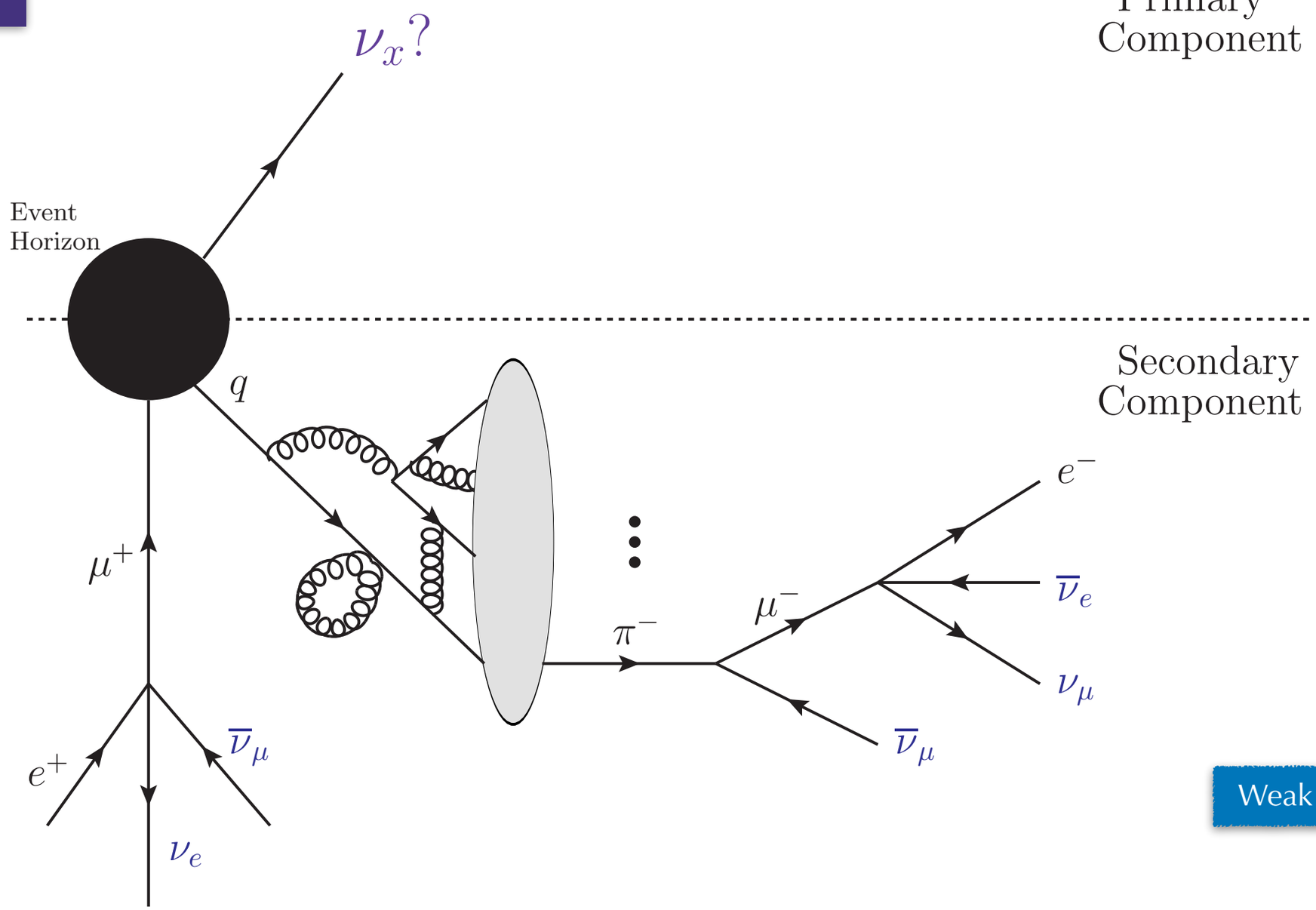
$$\frac{d^2N_\nu}{dp\,dt} = \sum_{a=1,2,3} \frac{g_a^N}{2\pi^2} \frac{\sigma^\nu_{\rm abs}(M,p,m_a)\,p^2}{\exp[E_a(p)/T]+1} \frac{p}{E_a(p)}$$

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

C. Lunardini and YFPG
1910.07864

What is the state of the emitted neutrino?

Weak interactions

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

Interaction mediated by a gauge boson

Associated with a charged lepton

Flavor eigenstate



Hawking Effect

$$\langle 0_{-} | b_i^{\dagger} b_i | 0_{-} \rangle = \Gamma_{lm} \left[\exp\left(E_a / T_{\rm BH} + 1 \right) \right]^{-1}$$

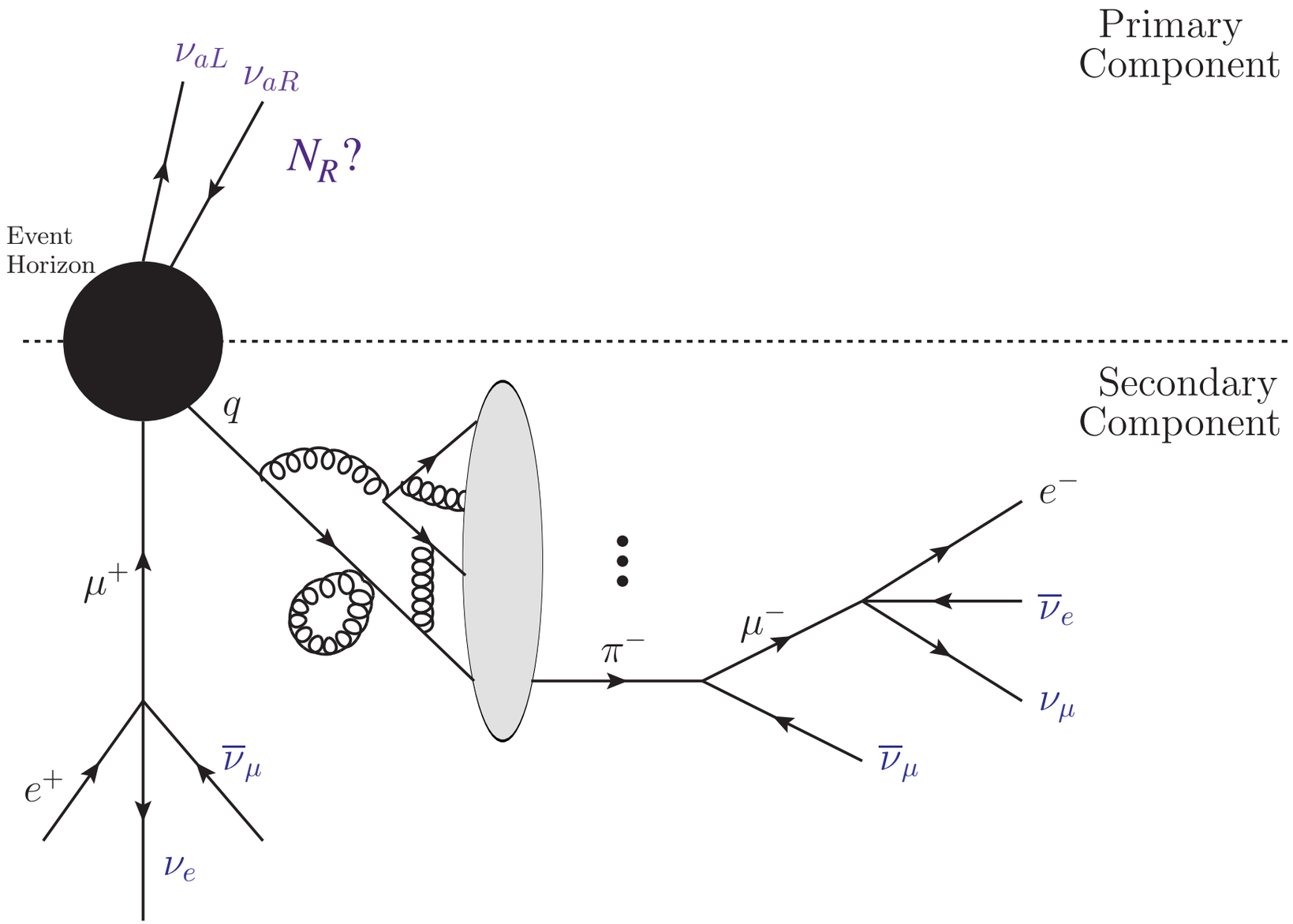
Particle definition in a curved spacetime is observer dependent

Particles with well-defined kinematical properties

Mass eigenstate



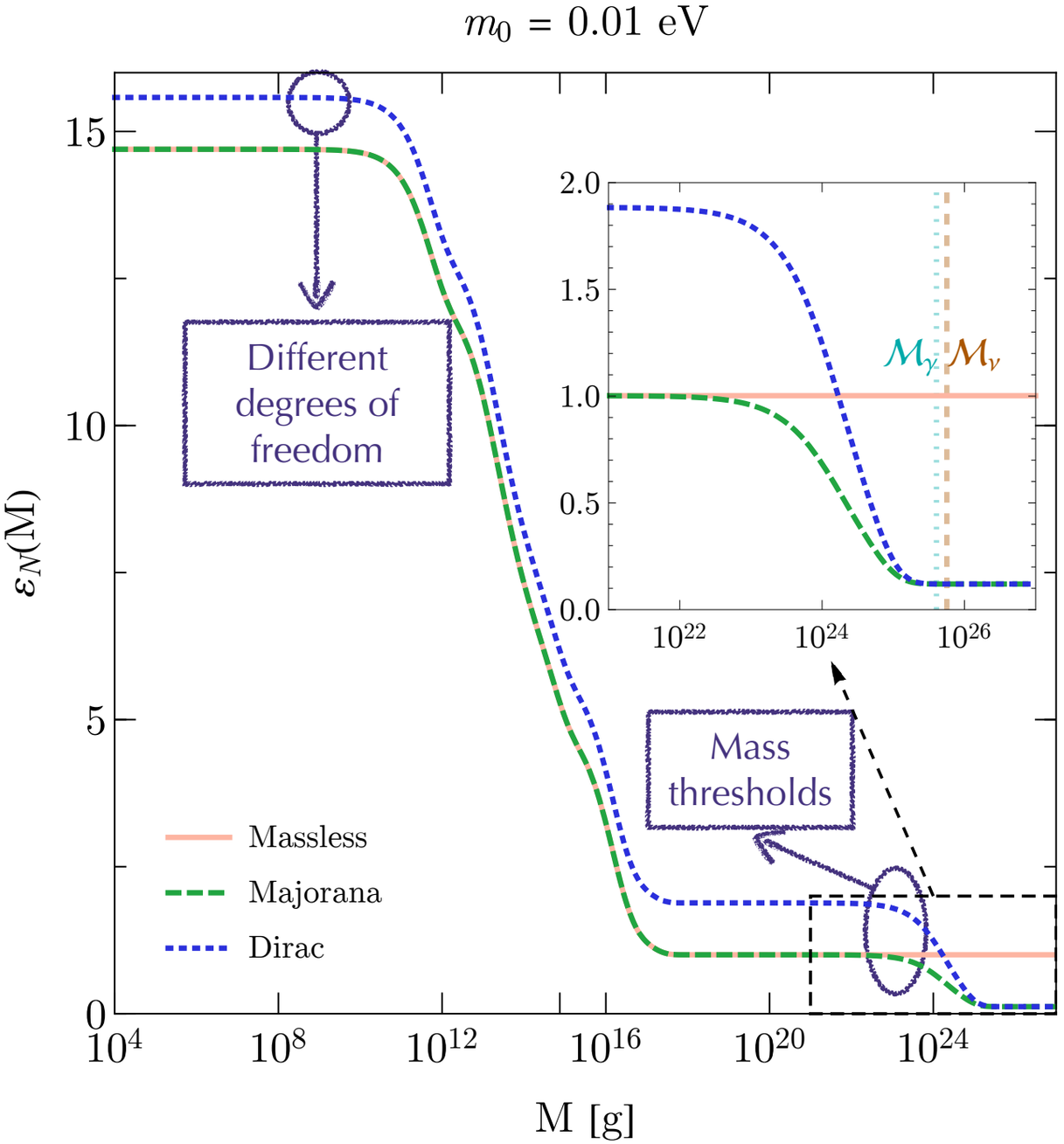
Dirac vs Majorana



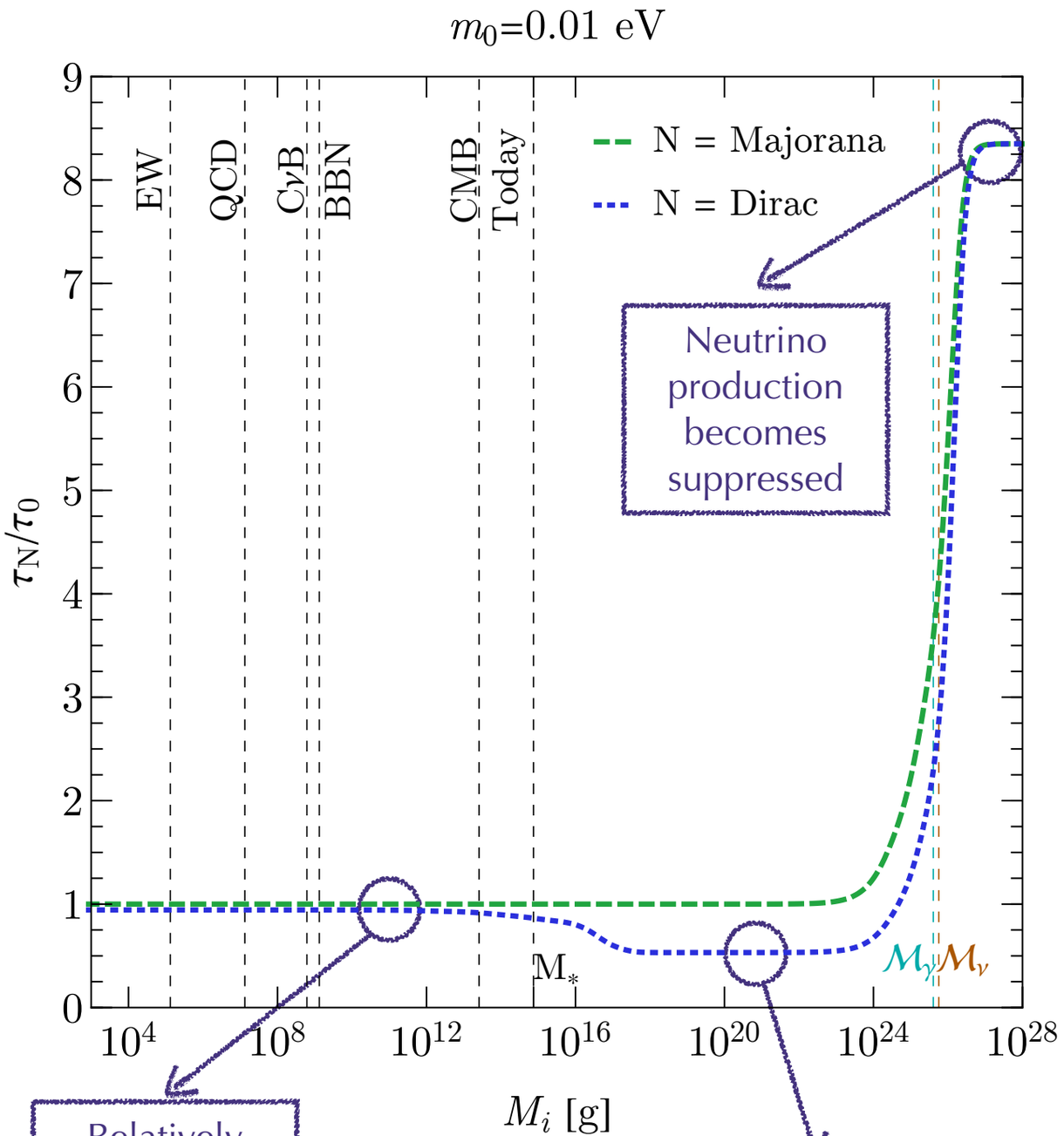
Dirac neutrinos

Majorana neutrinos

BH evaporation



$\mathscr{M}_{\gamma,\nu}$ → Thermal equilibrium with the CMB, CνB



Dirac vs Majorana

Dirac neutrinos

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

Unruh, 1976

No helicity suppression

Production of light RH neutrinos!

Cecilia Lunardini, YFPG
JCAP08(2020)014

First Act

Majorana neutrinos

Heavy RH neutrinos

PBH-induced Leptogenesis

Yamada and Iso, 1610.02586
Morrison et al,1812.10606
Baldes et al, 2004.14773
Hooper and Krnjaic, 2010.01134

YFPG and Jessica Turner,
2010.03565

Second Act

First Act:

Dirac Neutrinos

Cecilia Lunardini, YFPG
JCAP08(2020)014
arXiv:1912:07864

Constraints in the Dirac neutrino case

Let us consider the minimal extension

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

ν_R

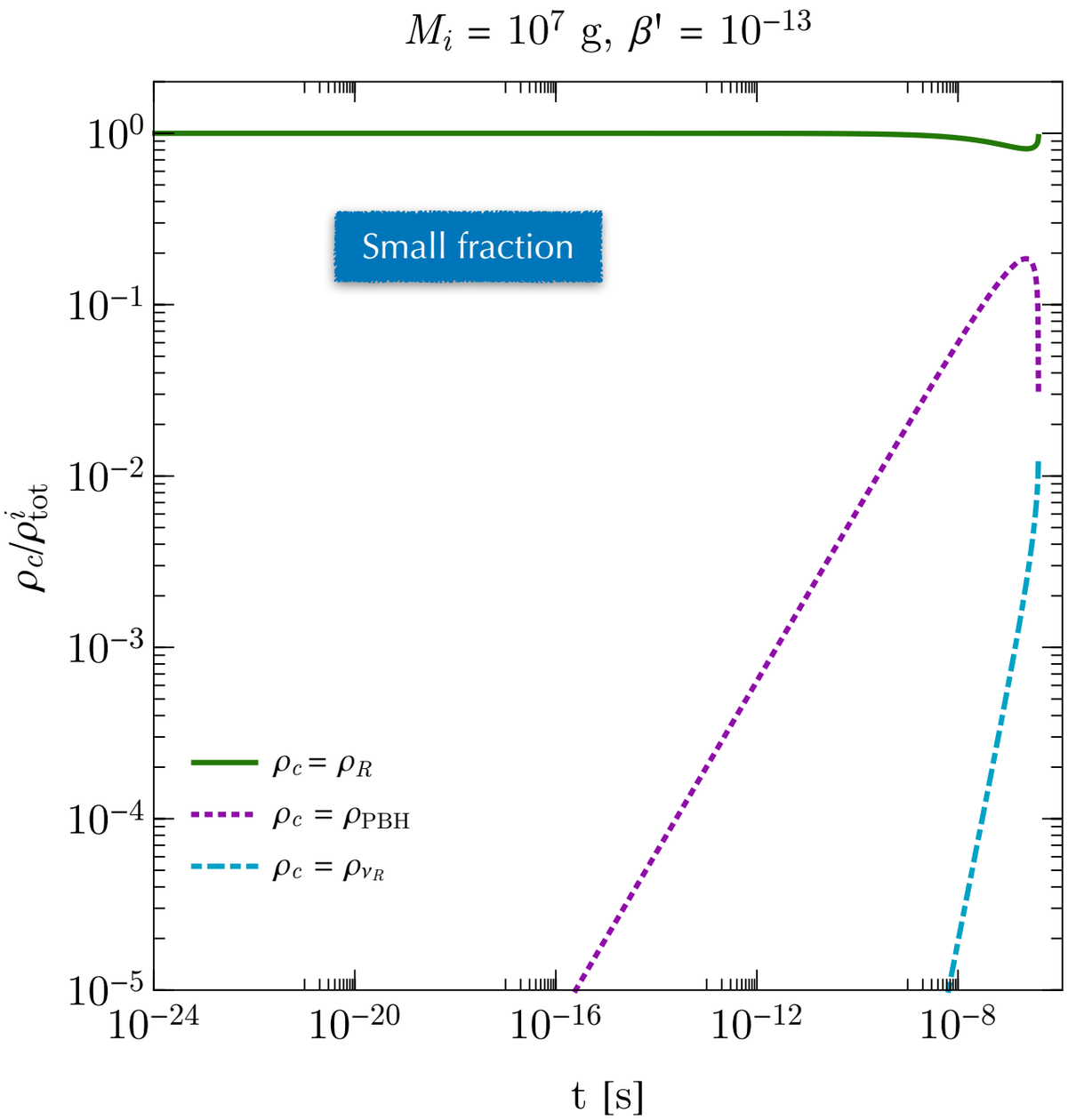
- Not produced thermally — Antonelli et al, 1981
- Do not thermalize — Chen et al, 1509.00481

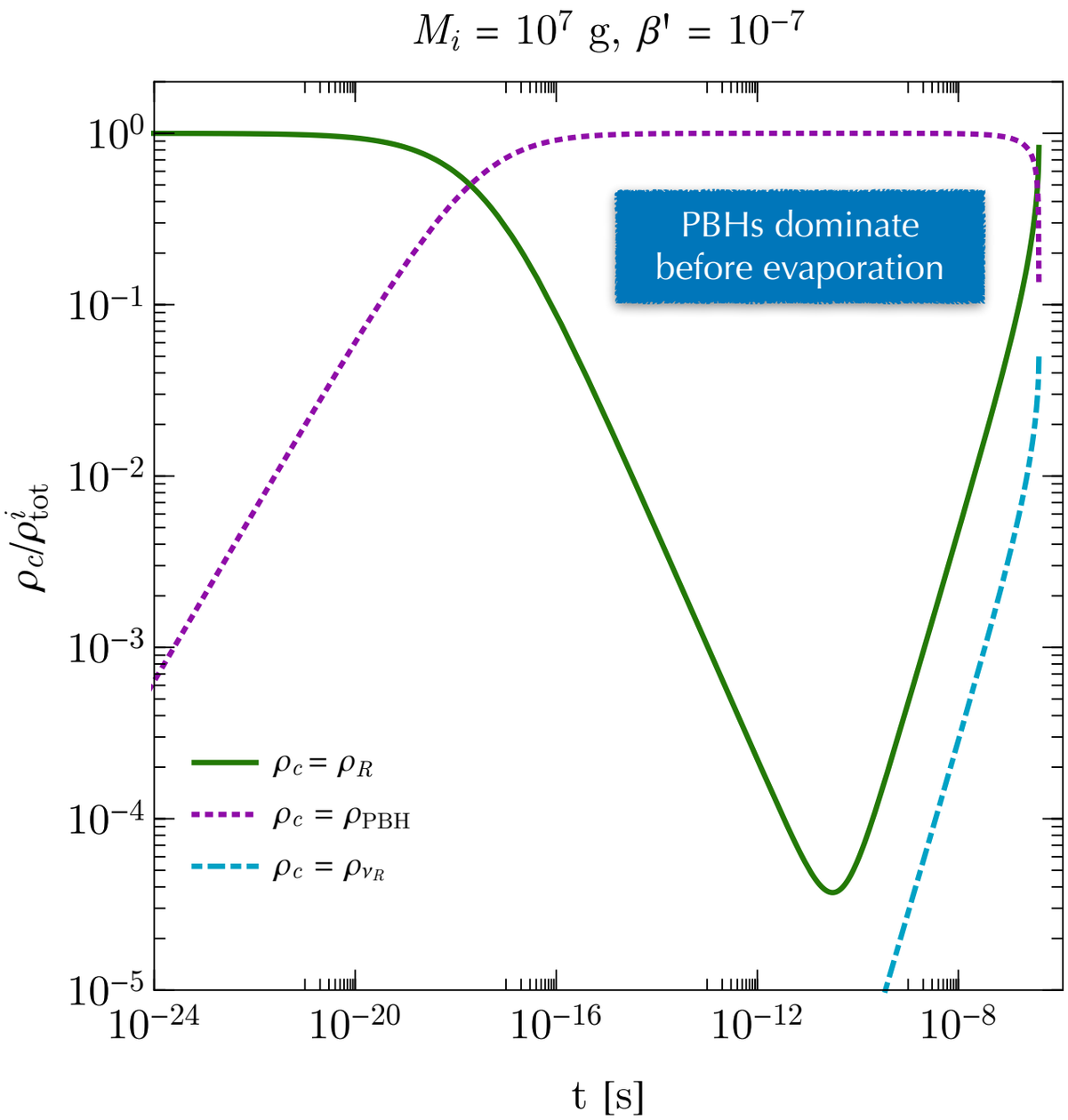
Friedmann-Boltzmann Equations

Non-standard cosmology?

PBHs are formed → PBHs evaporate

t_i, T_f $\quad$ t_{EV}, T_{EV}





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

Constraints in the Dirac neutrino case

Let us consider the minimal extension

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

ν_R

- Not produced thermally — Antonelli et al, 1981
- Do not thermalize — Chen et al, 1509.00481

Friedmann-Boltzmann Equations

Non-standard cosmology?

PBHs are formed → PBHs evaporate → Matter-radiation equality

t_i, T_f $\quad$ t_{EV}, T_{EV} $\quad$ t_{EQ}, T_{EQ}

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

Hooper et al, 1905.01301

Evaporated

(Part of) Dark Matter?

Fraction of the total energy in PBH

β'

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

Gravitational collapse factor

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

Entropy

LSP

Planck

BBN

CMB

GRB

$\Omega_{\rm PBH}$

MACHO

QSO

WB LSS

DF

FIRAS

WMAP3

Galactic γ

EGB

21cm

GW

10^{0}

10^{-5}

10^{-10}

10^{-15}

10^{-20}

10^{-25}

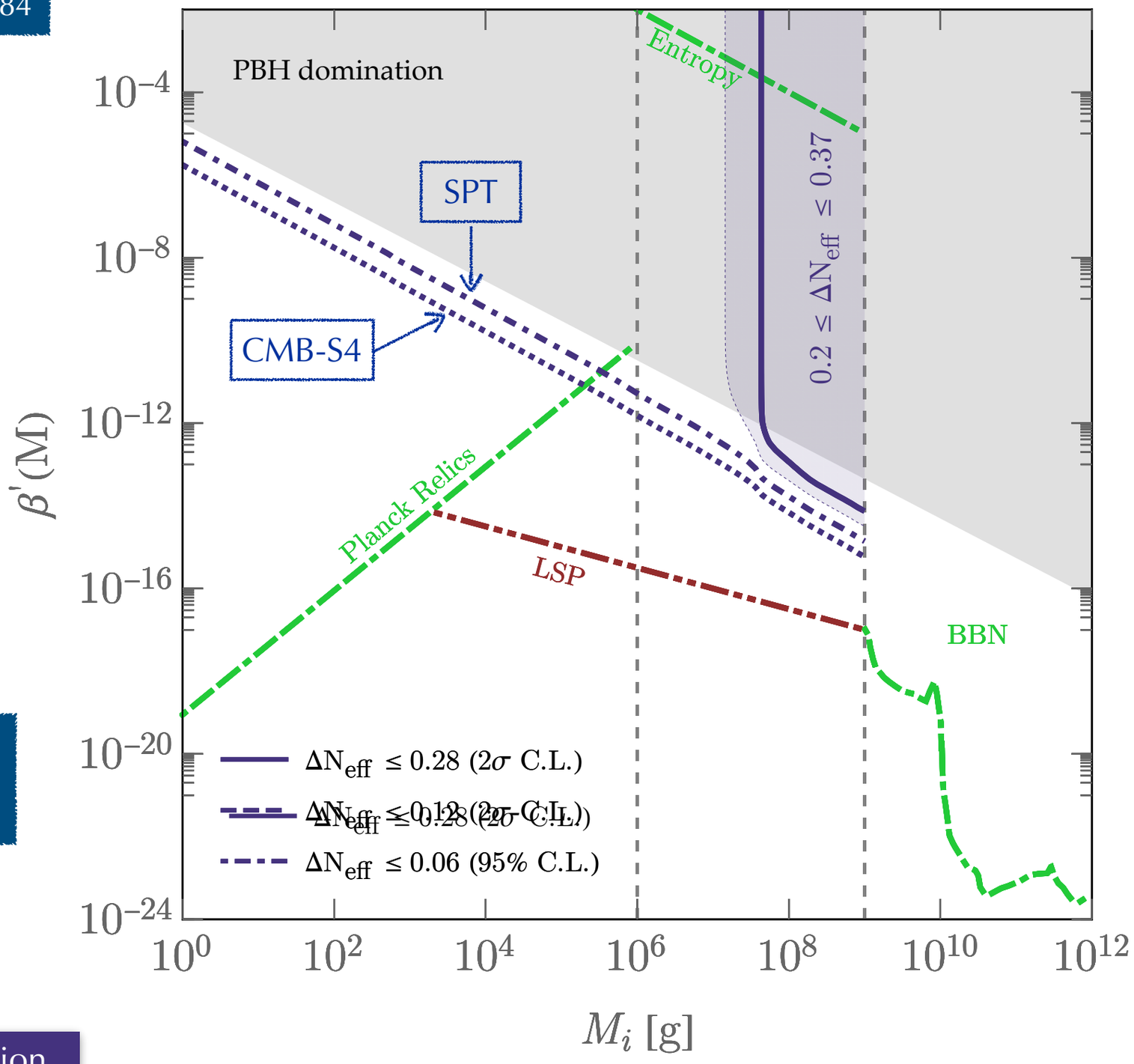
10^{-30}

0 10 20 30 40 50

$\log_{10}(M/\mathrm{g})$

Carr et al. 0912.5297

Green and Liddle, 9903484



Zel'dovich et al, 1977

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

Carr et al, 0912.5297

Alleviate the H_0 tension

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

Constraints in the Dirac neutrino case

Let us consider the minimal extension

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

ν_R

- Not produced thermally — Antonelli et al, 1981
- Do not thermalize — Chen et al, 1509.00481

Friedmann-Boltzmann Equations

Non-standard cosmology?

PBHs are formed → PBHs evaporate → Matter-radiation equality → Today

t_i, T_f | t_{EV}, T_{EV} | t_{EQ}, T_{EQ} | t_0

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

Hooper et al, 1905.01301

Diffuse neutrino flux from PBHs

Could we measure these neutrinos?

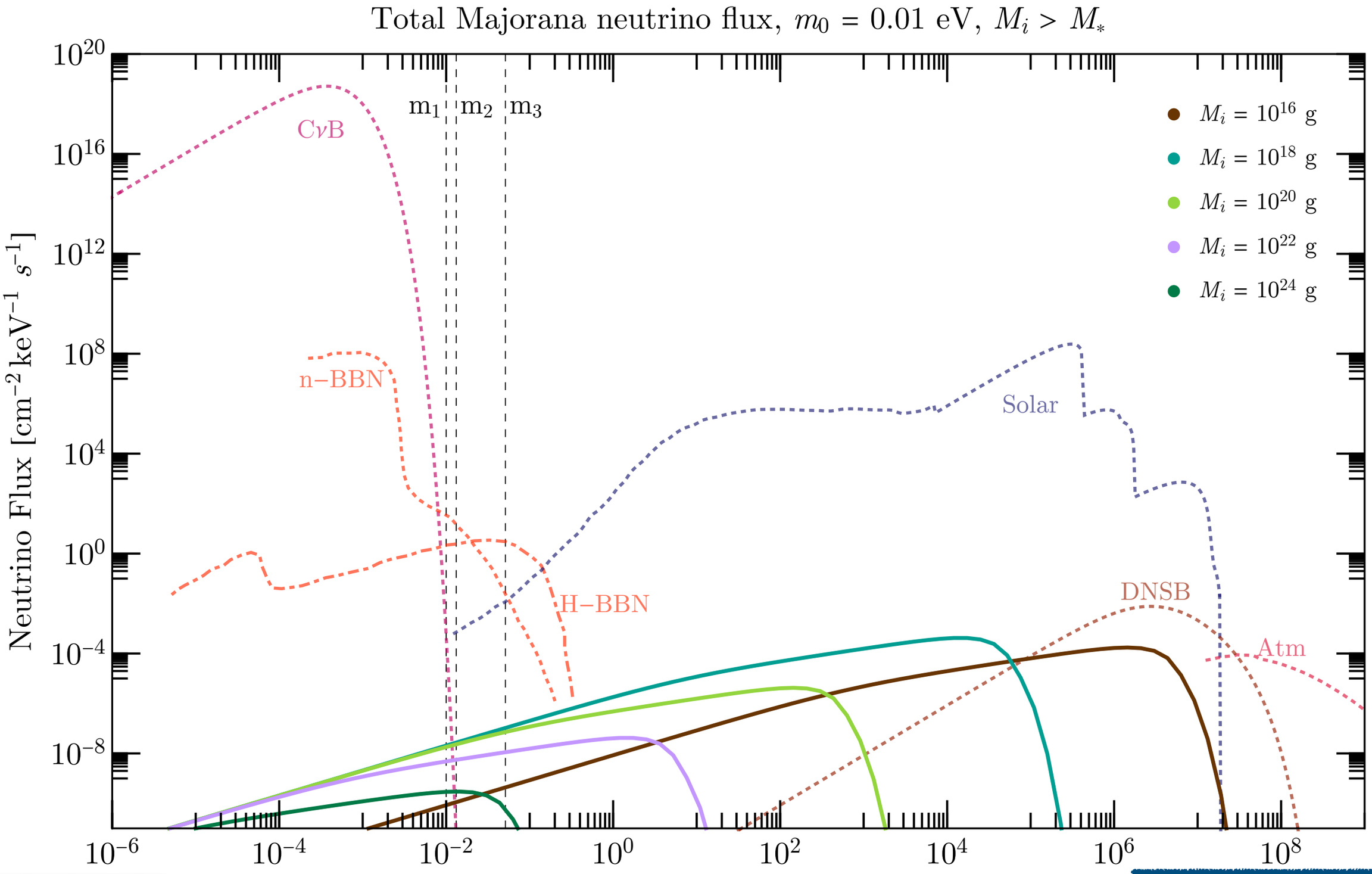
$$\frac{d\Phi^{\nu}_{\rm PBH}}{dp_0} = \int_{t_i}^{\min(t_0,\tau)} dt \frac{d\Omega}{4\pi} \frac{a_0}{a_t} \left(\frac{a_i}{a_0}\right)^3 \frac{\rho^i_{\rm PBH}}{M_i} \frac{d^2N_\nu}{dp\,dt}(M(t), p_0\,a_0/a_t)$$

- $\rho^i_{\rm PBH}/M_i$: PBH initial number
- a_i/a_0: Comoving number density
- $p_0\,a_0/a_t$: Momentum redshift

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

- $z_{\rm EQ}$: Matter-radiation redshift

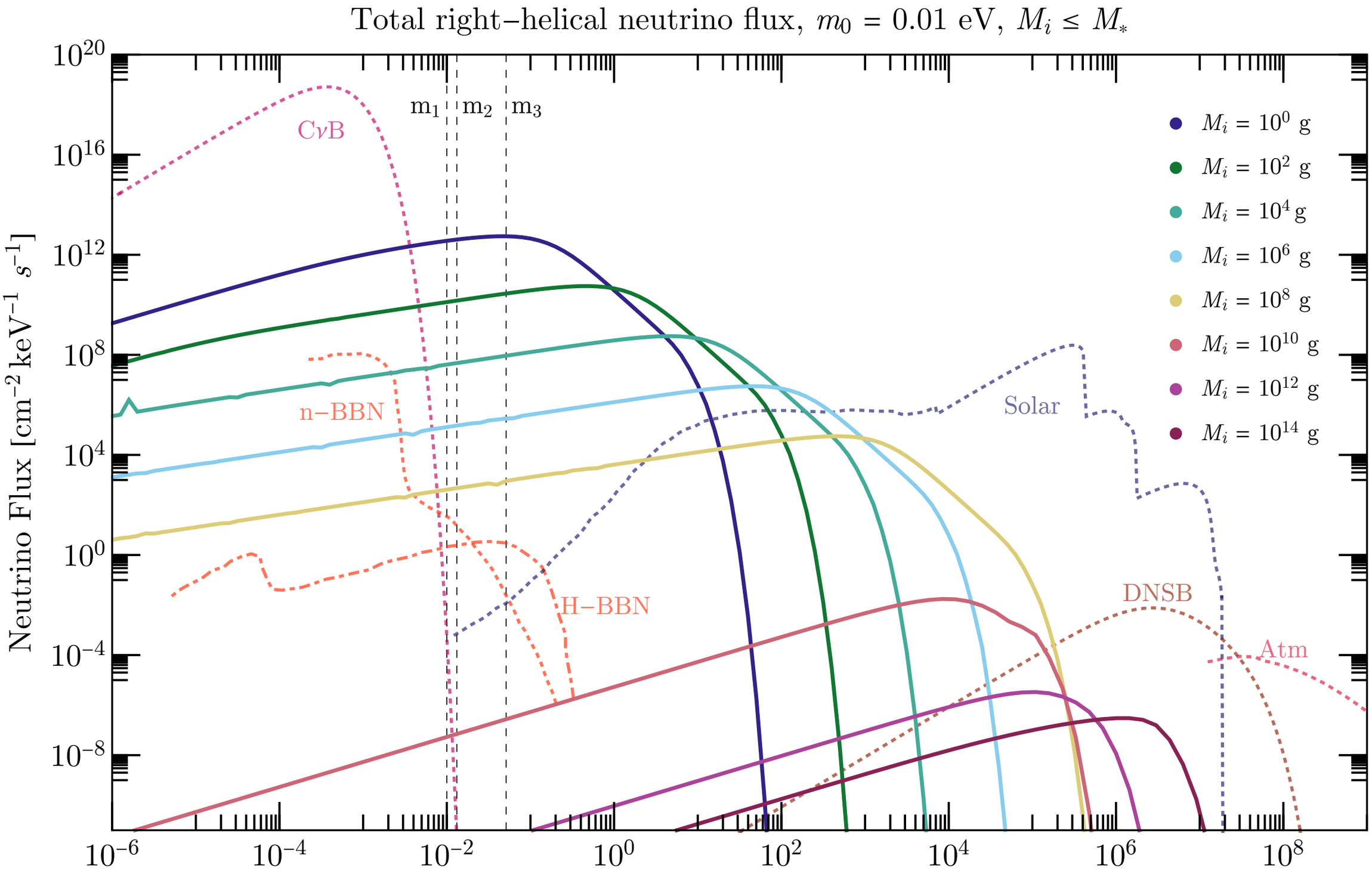
Diffuse flux from non-evaporating PBHs



Extremely suppressed flux

Diffuse flux including the galactic component arXiv: 1912.01014

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?

Helicity suppression

$m_0 = 0.01$ eV

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



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?

Second Act:

Majorana Neutrinos

YFPG and Jessica Turner
2010.03565

Leptogenesis in a nutshell

Not fulfilled in the SM

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:

$$\mathscr{L}_Y = -\, Y_\nu^{ab} \overline{L_L^a} \tilde{H} N_{Rb} + \frac{1}{2} \overline{N^c} M_N N$$

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

Complex orthogonal matrix

Neutrino oscillation mixing

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

18 dim parameter space

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

$LH \leftrightarrow \overline{L}H$

Fukugida, Yanagida, '86

Casas, Ibarra, 2001

Leptogenesis in a nutshell

Thermal leptogenesis:

At $T \sim M_N$ RH neutrinos are created

$N \to LH$

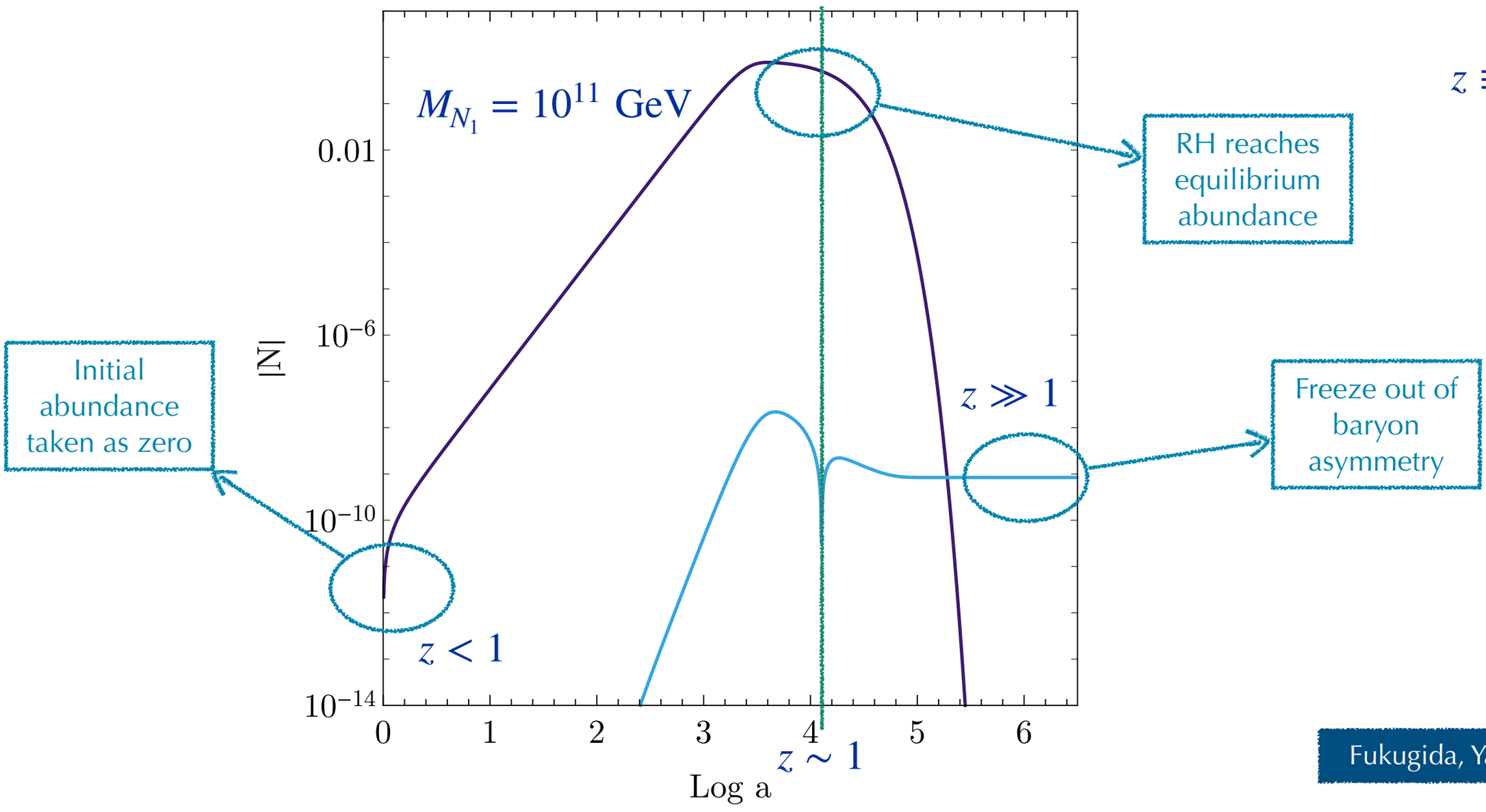
$N \to \overline{L}H$

$LH \to N$

Lepton asymmetry is created

Sphaleron processes

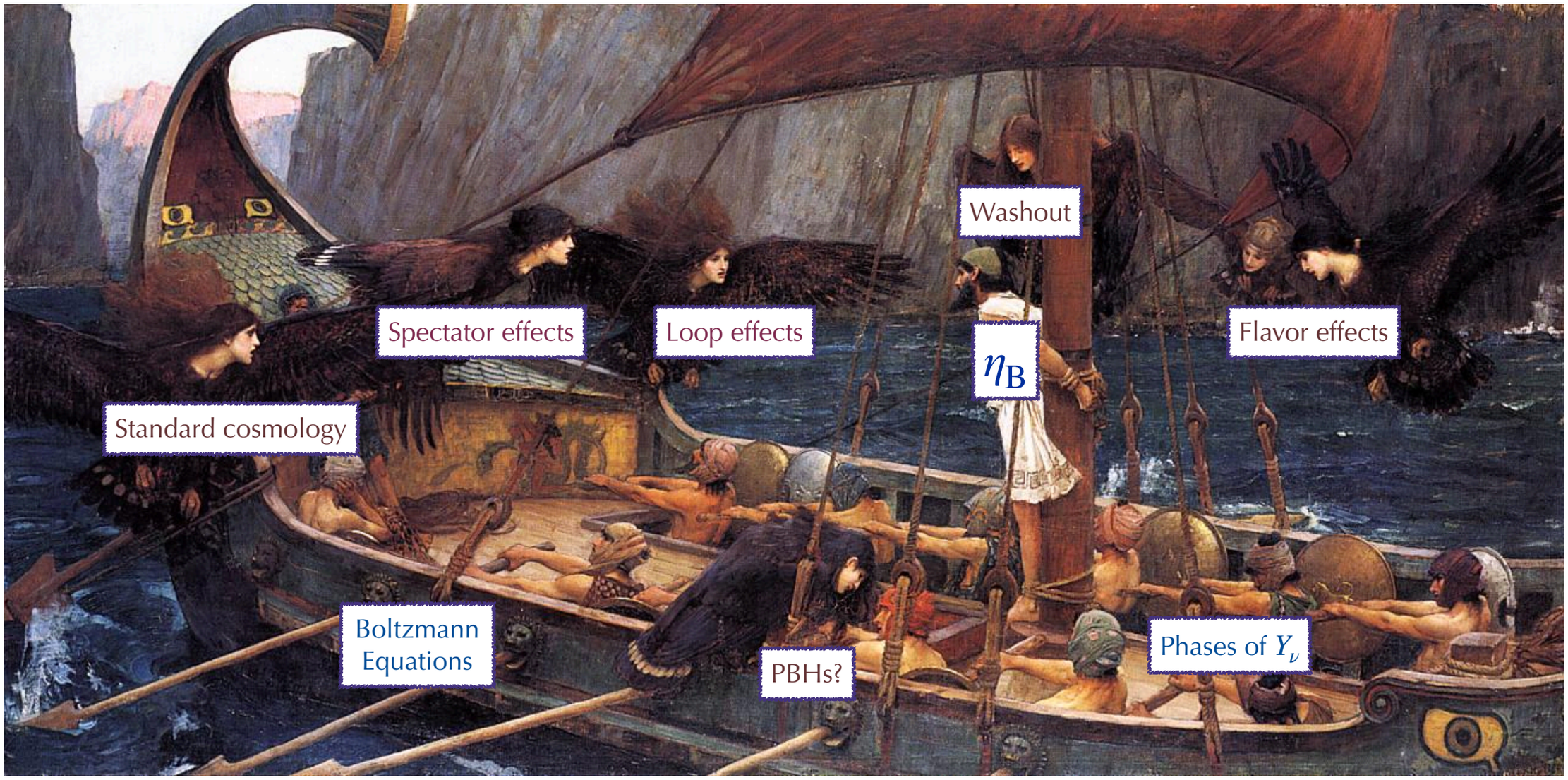
Baryon asymmetry



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

Fukugida, Yanagida, '86

Universal LeptogeneSiS Equation Solver (ULYSSES)

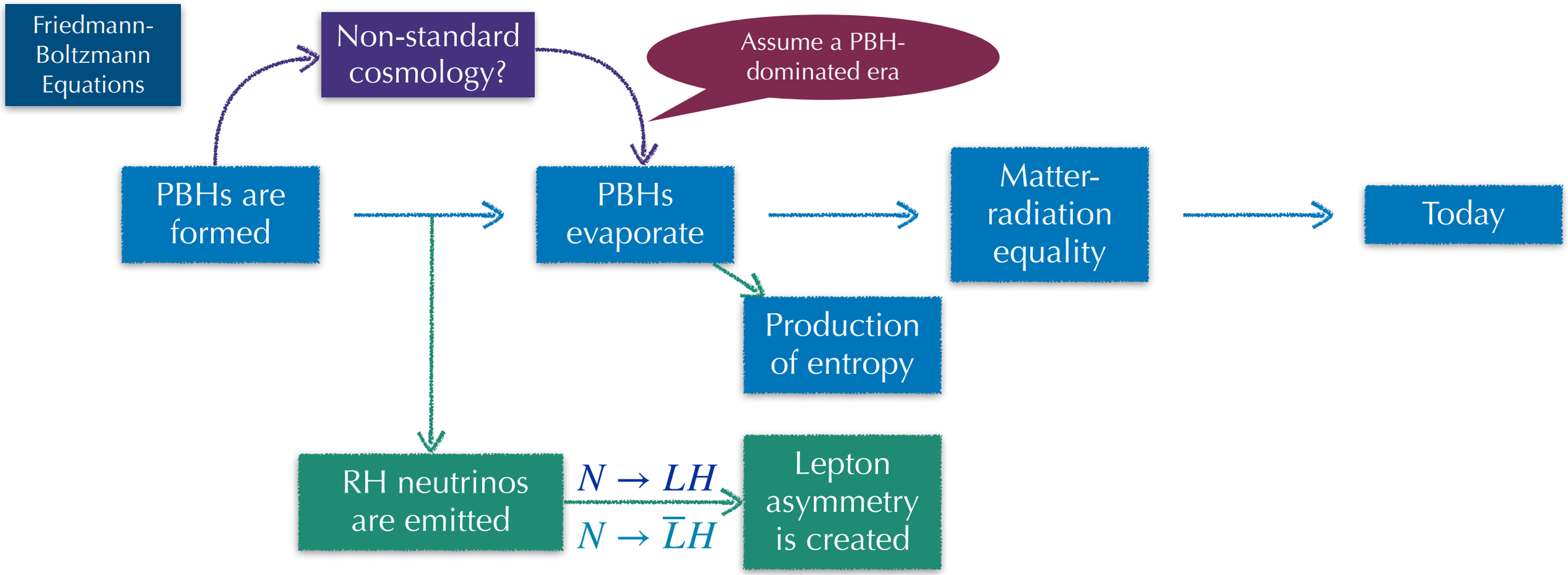


A Granelli, K Moffat, YFPG, H Schulz and Jessica Turner, arXiv: 2007.09150

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

PBH-driven Leptogenesis

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



Boltzmann Equations

Thermal contribution

$$aH\frac{dn_{N_1}^{\rm TH}}{da} = -(n_{N_1}^{\rm TH} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T}$$

$$aH\frac{dn_{N_1}^{\rm BH}}{da} = -n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH} + n_{\rm BH}\Gamma_{\rm BH\to N_1}$$

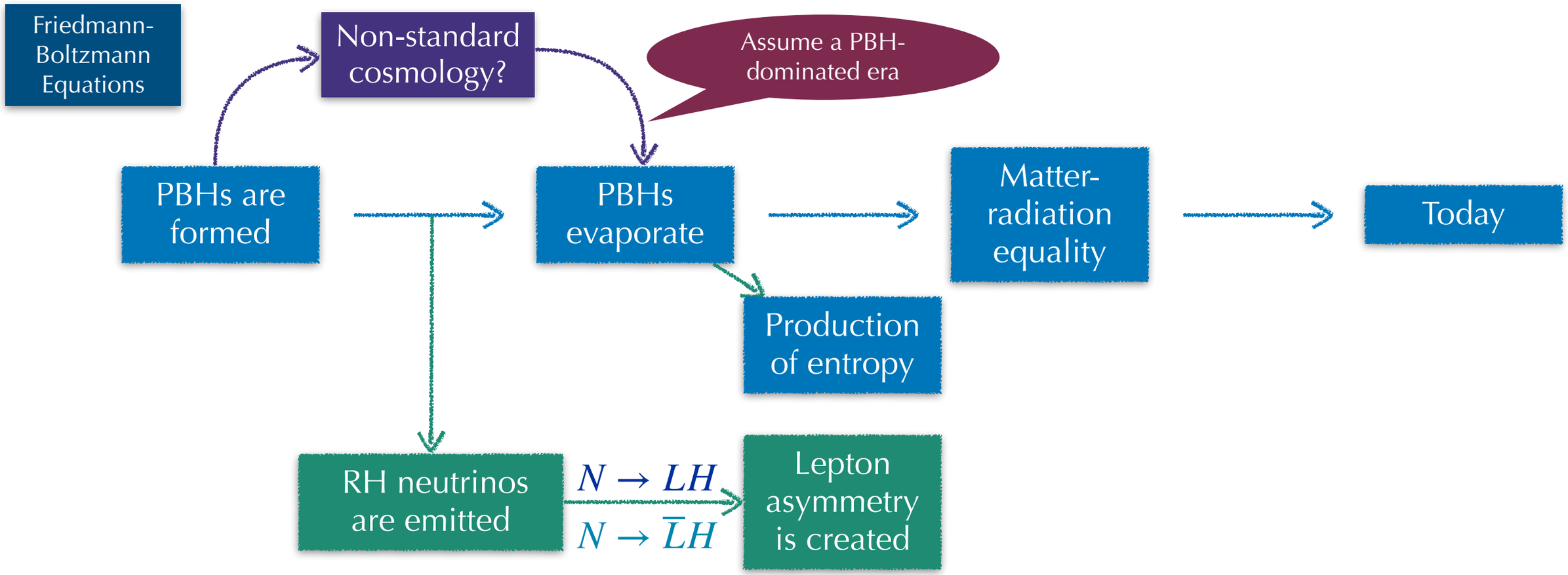
From the evaporation

Thermally averaged RH neutrino decay

$$aH\frac{dn_{\alpha\beta}^{\rm B-L}}{da} = \epsilon_{\alpha\beta}^{(1)}\left[(n_{N_1} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T} + n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH}\right] + \mathscr{W}_{\alpha\beta}$$

α, β → Flavor indexes

PBH-driven Leptogenesis



Three scenarios

A. PBH evaporate before RH are thermally produced
B. Evaporation happens during thermal leptogenesis
C. PBH create a RH density after the thermal case

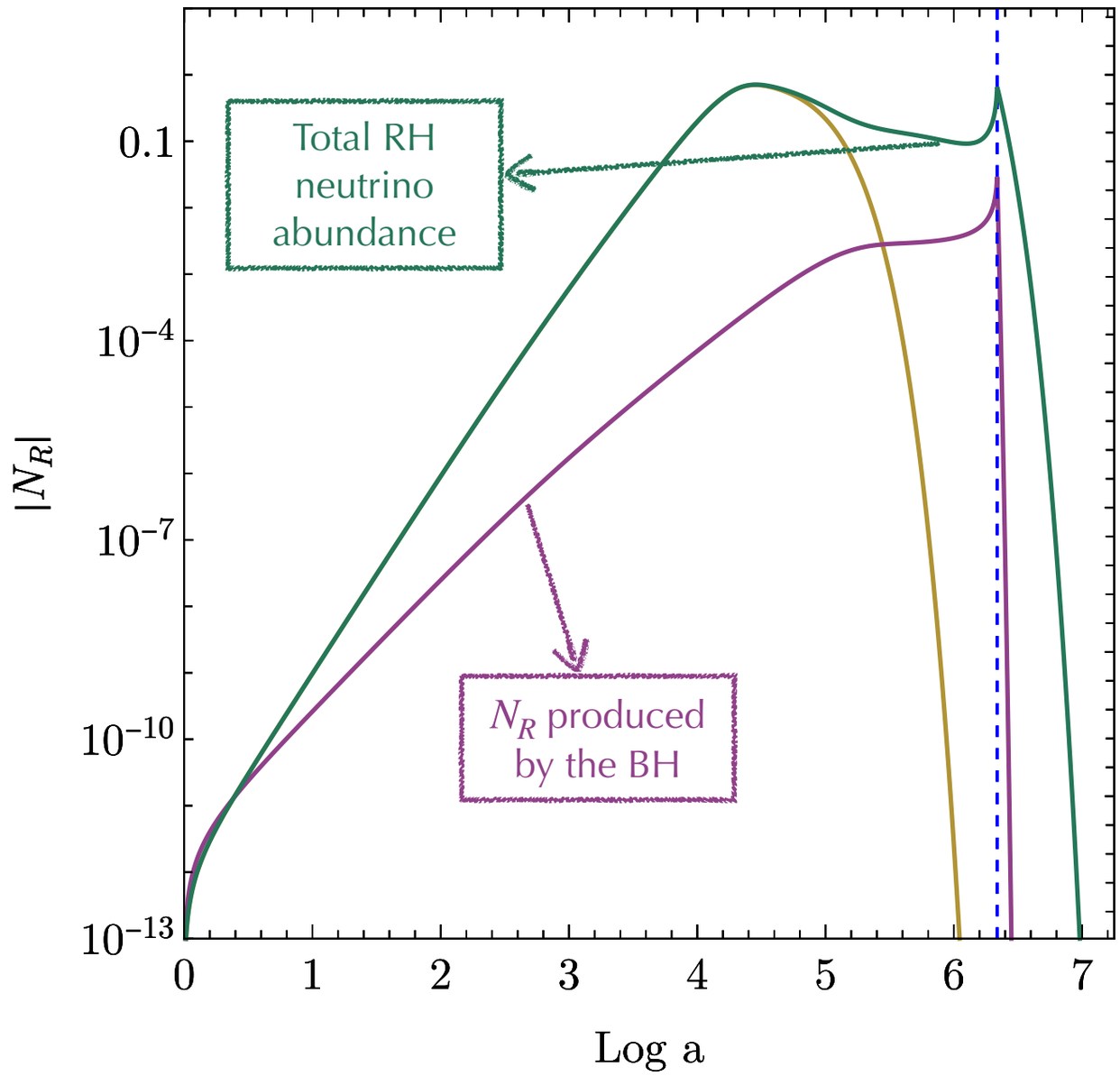
A. PBH evaporate before RH are thermally produced
B. Evaporation happens during thermal leptogenesis

Initial condition for the later development of thermal leptogenesis

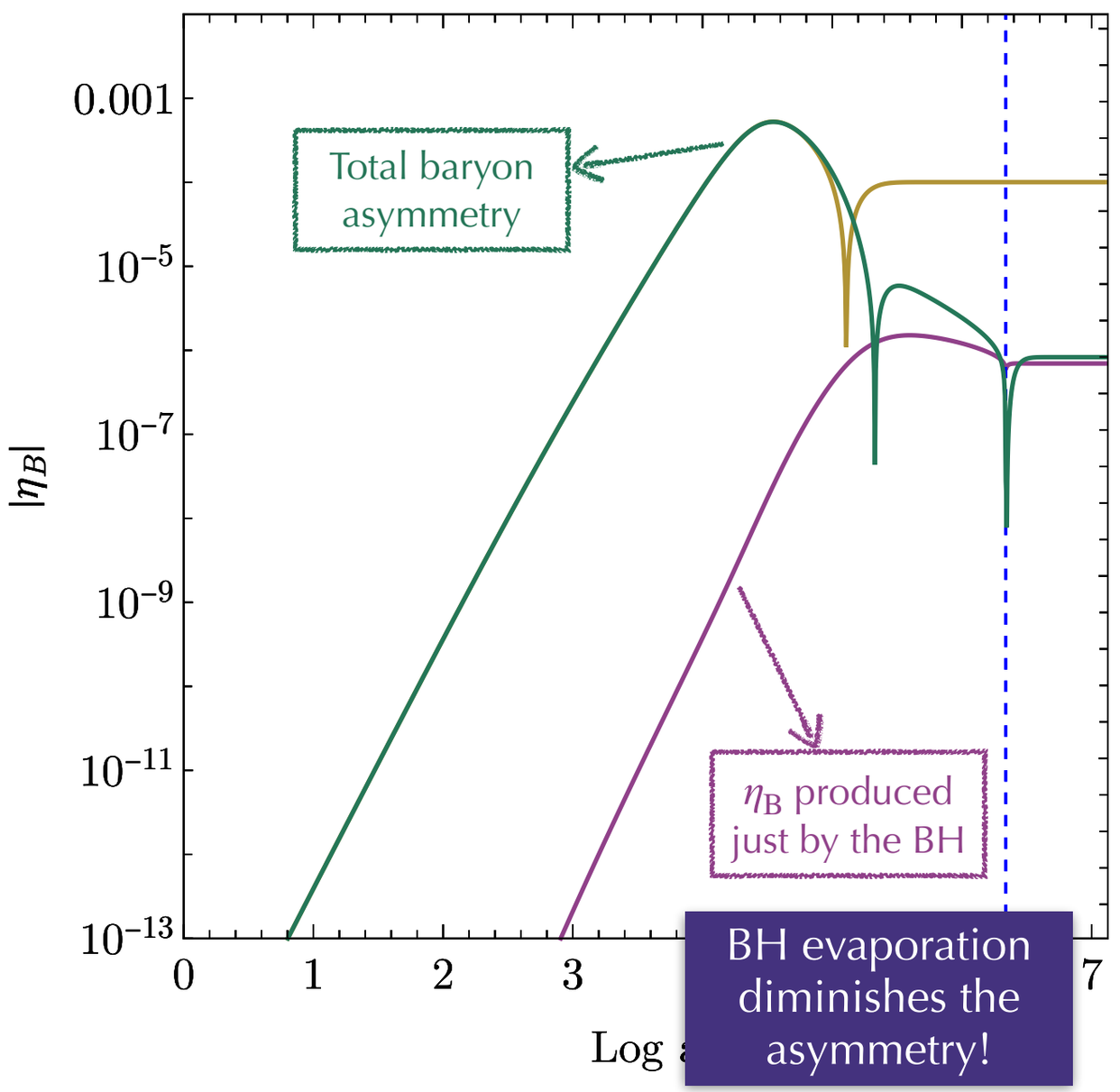
$M_i = 1.7$ g
$\beta'_i = 10^{-3}$

Washout effects are still important

RH neutrino abundance



Final baryon asymmetry



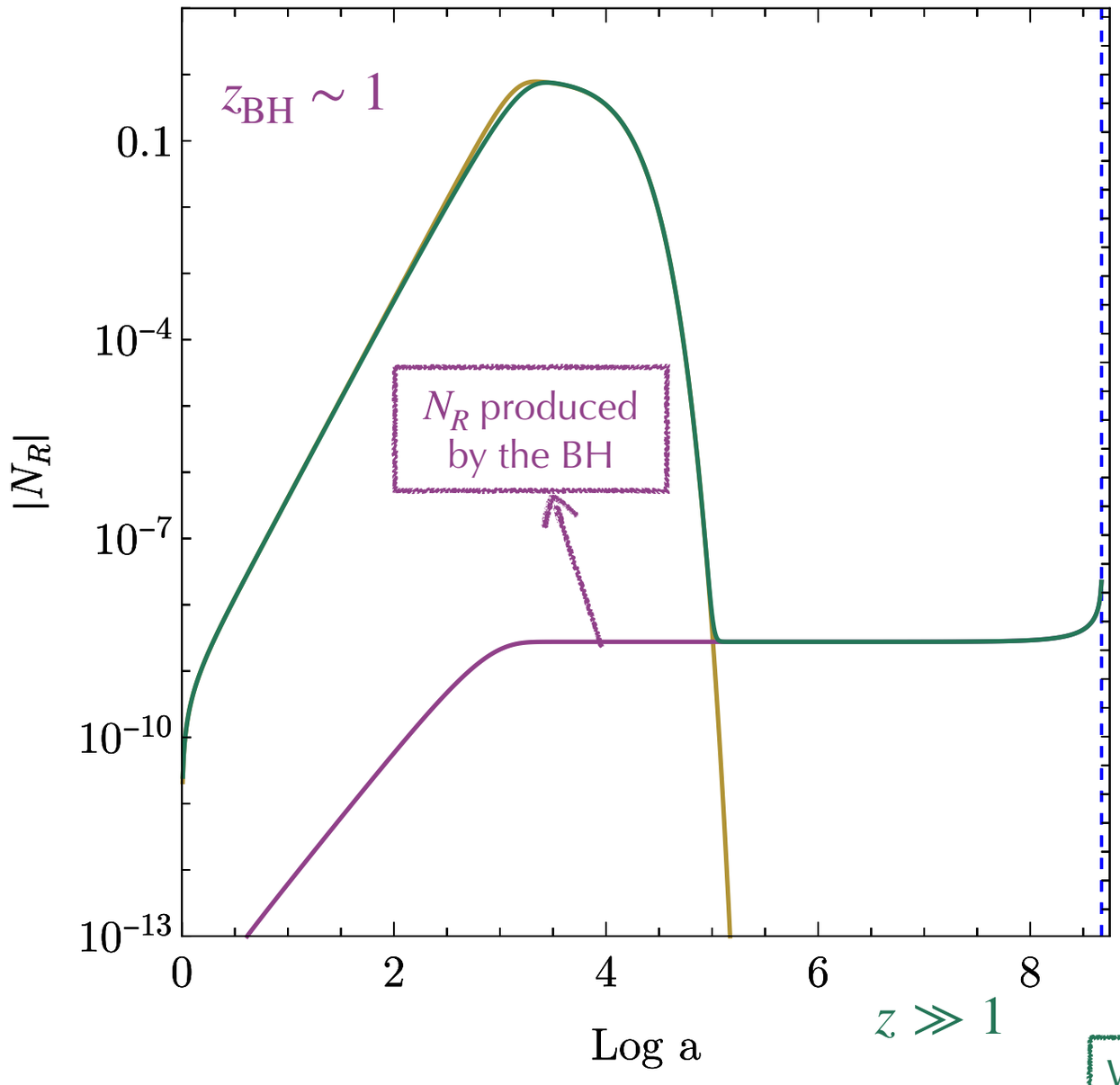
BH evaporation diminishes the asymmetry!

C. PBH create a RH density after the thermal case

How after is "after"?

$M_i = 10^2$ g
$\beta'_i = 10^{-3}$

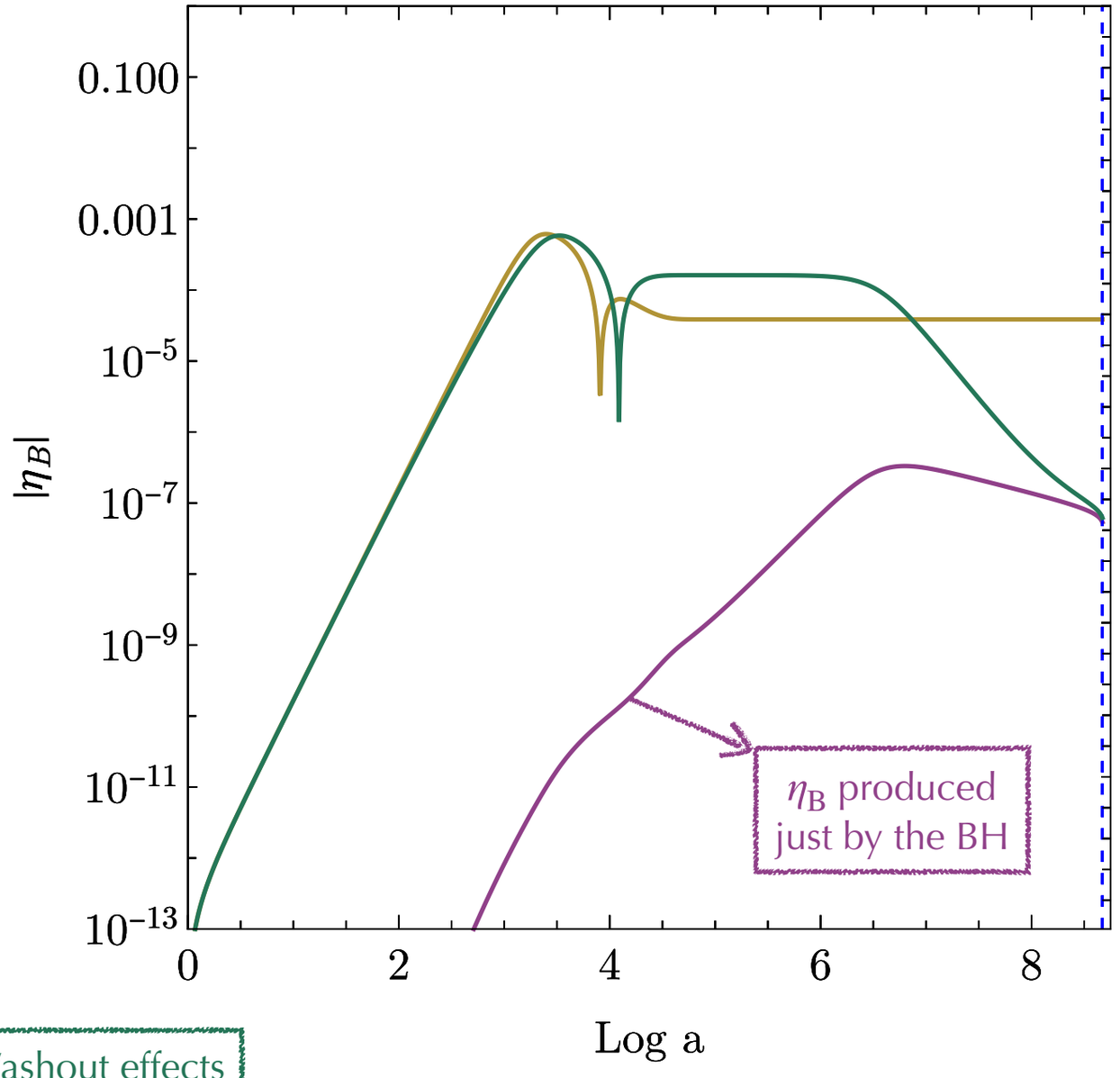
RH neutrino abundance



$z \gg 1$

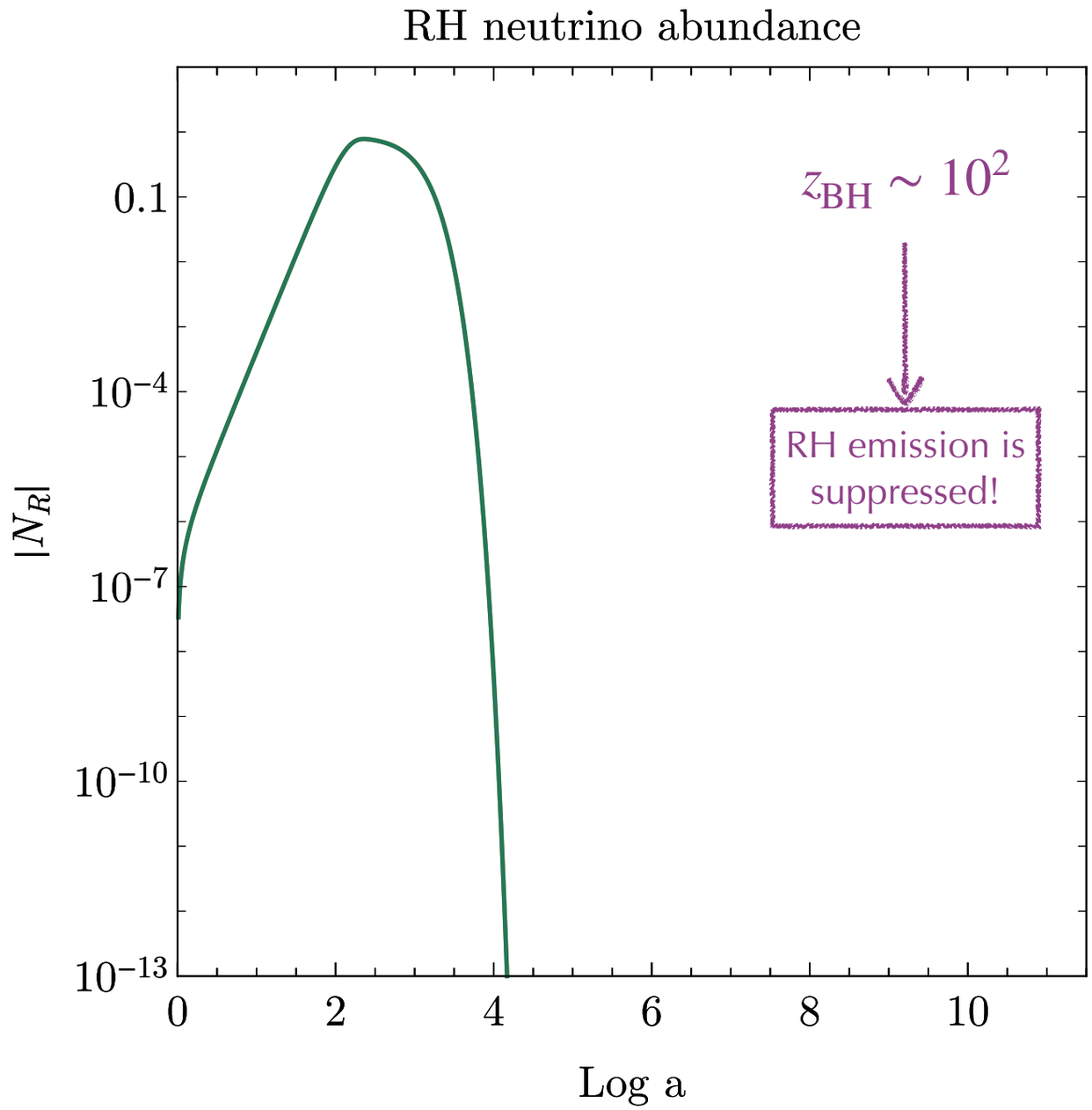
Washout effects freeze out

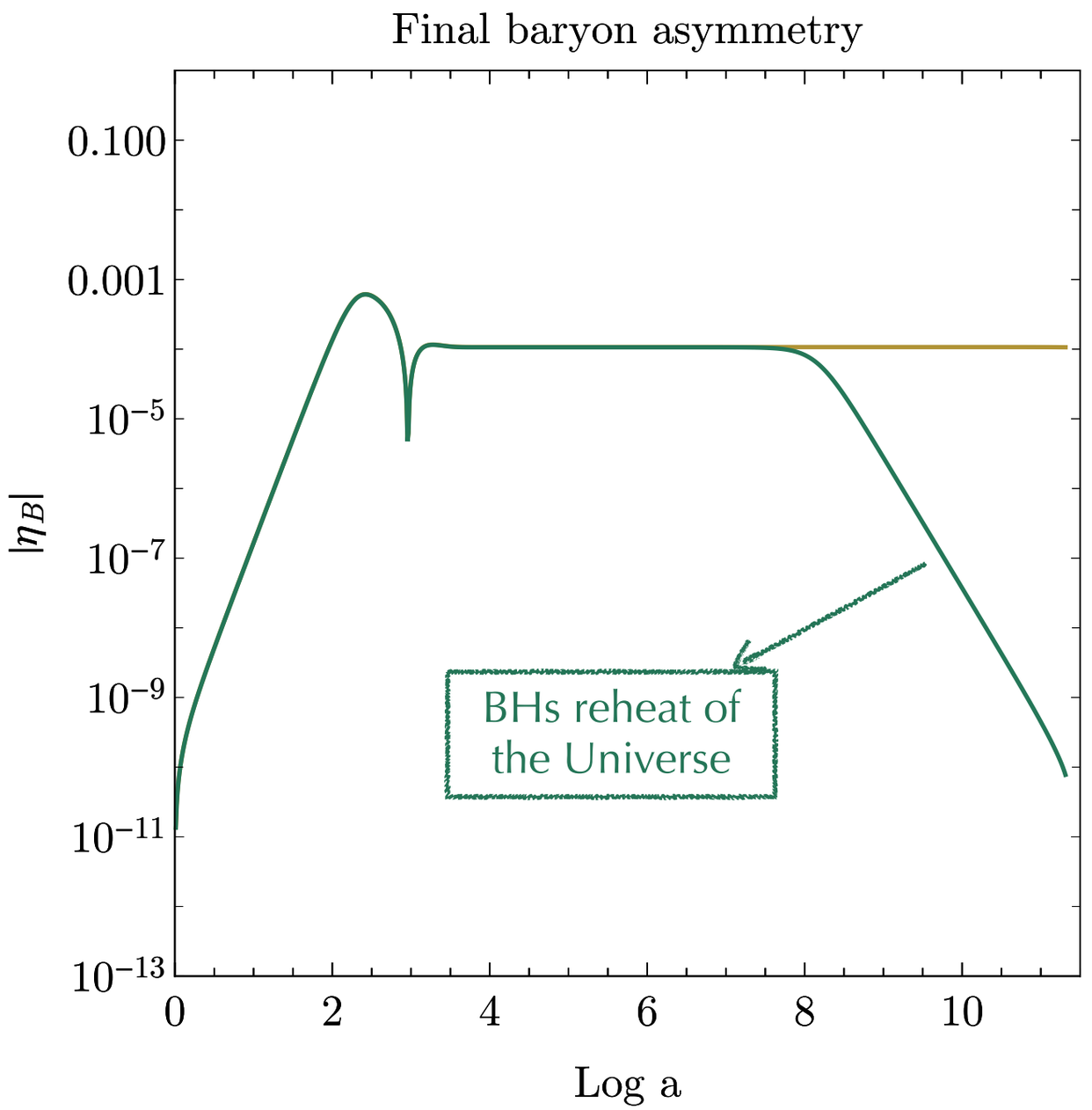
Final baryon asymmetry



C. PBH create a RH density after the thermal case

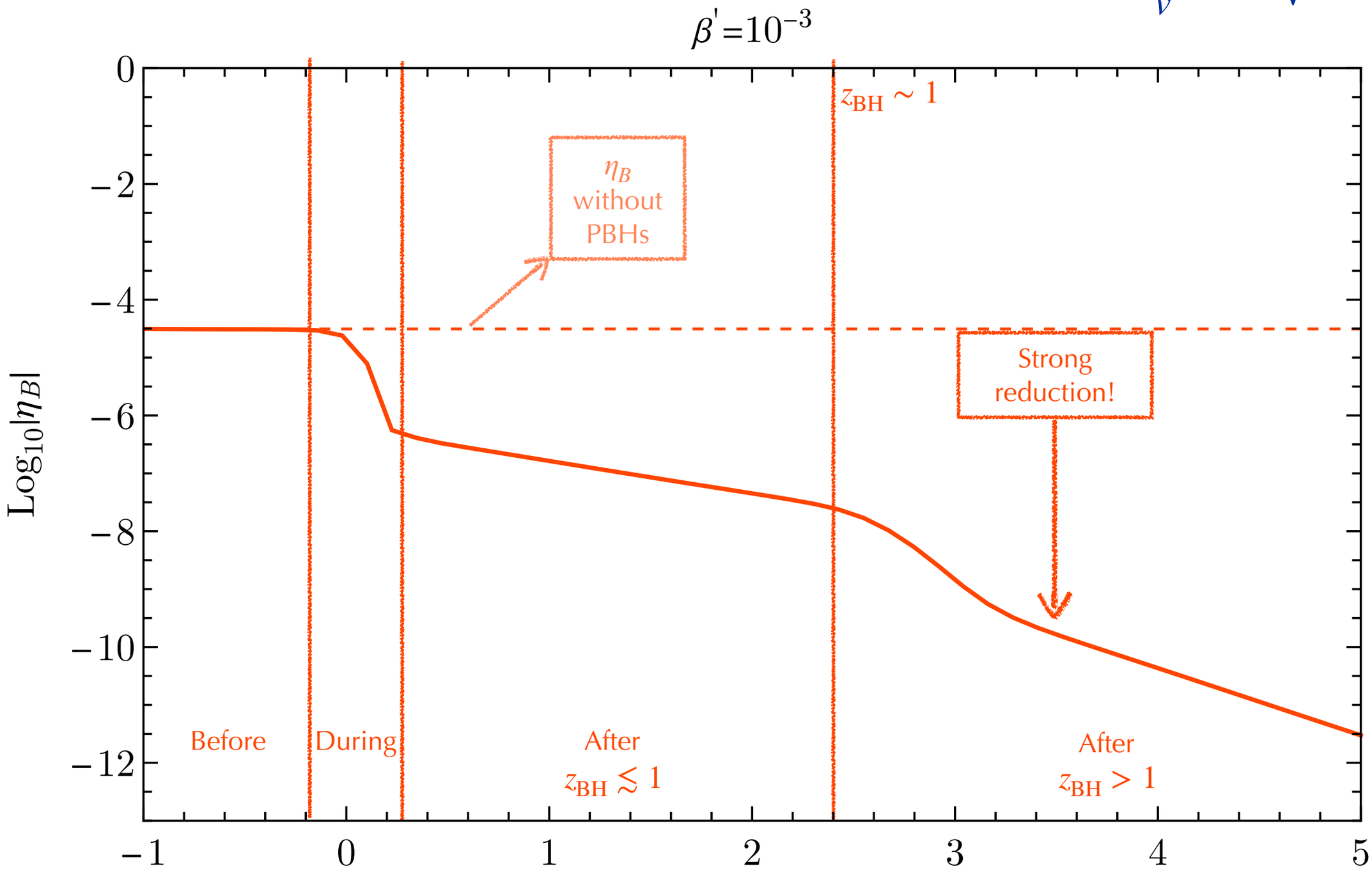
$M_i = 10^4$ g
$\beta'_i = 10^{-3}$





High mass scale Leptogenesis

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



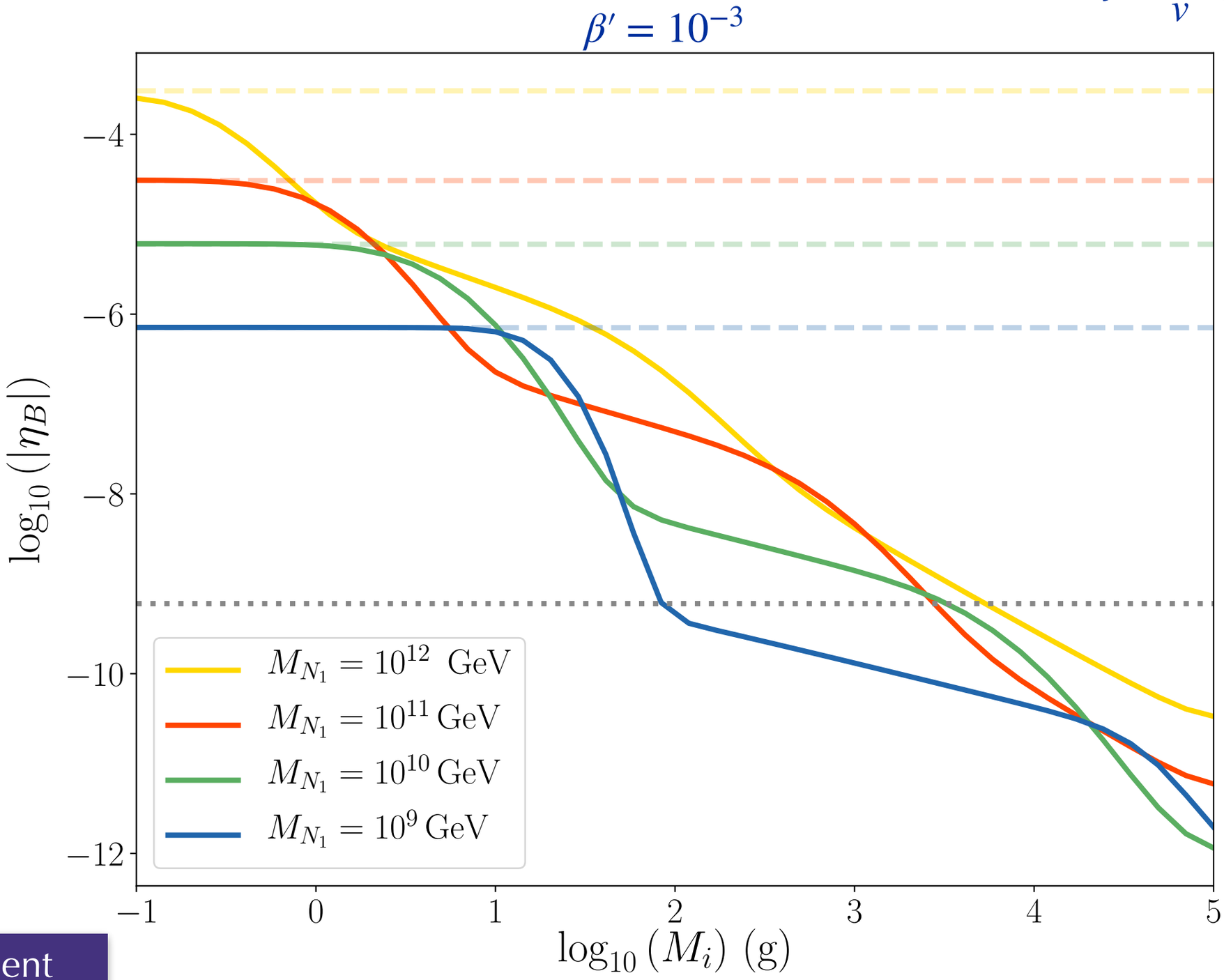
$M_{N_1} = 10^{11}$ GeV

Consider fine-tuned Yukawas

High mass scale Leptogenesis

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

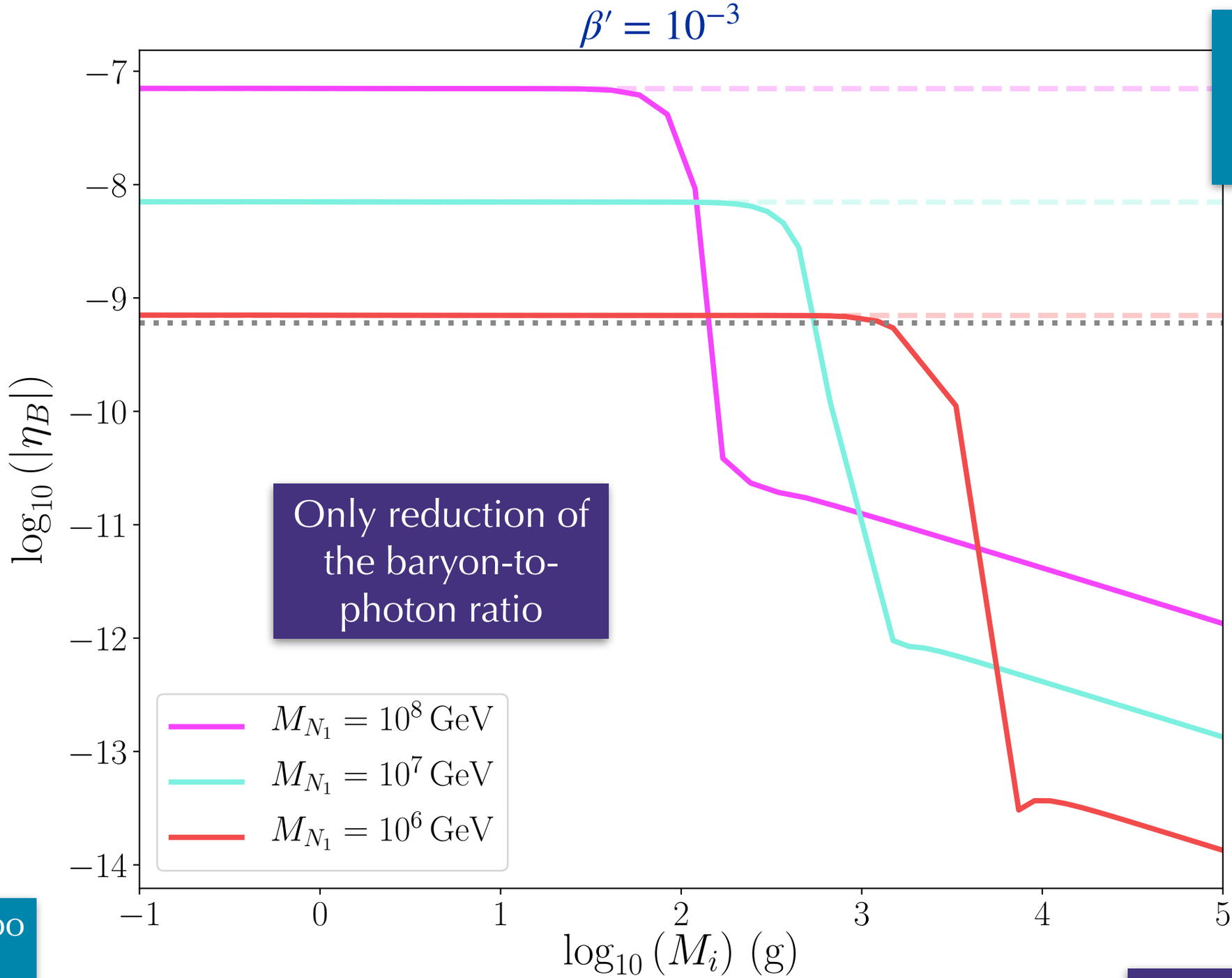
$\epsilon_{\alpha\beta} \propto Y_\nu$



Enhancement depends on the RH neutrino mass

$$M_i \sim \frac{1}{8\pi G M_{N_1}} \sim 105.7 \text{ g} \left(\frac{10^{11} \text{ GeV}}{M_{N_1}} \right)$$

Intermediate mass scale Leptogenesis



Large fine tuning in the Yukawa couplings

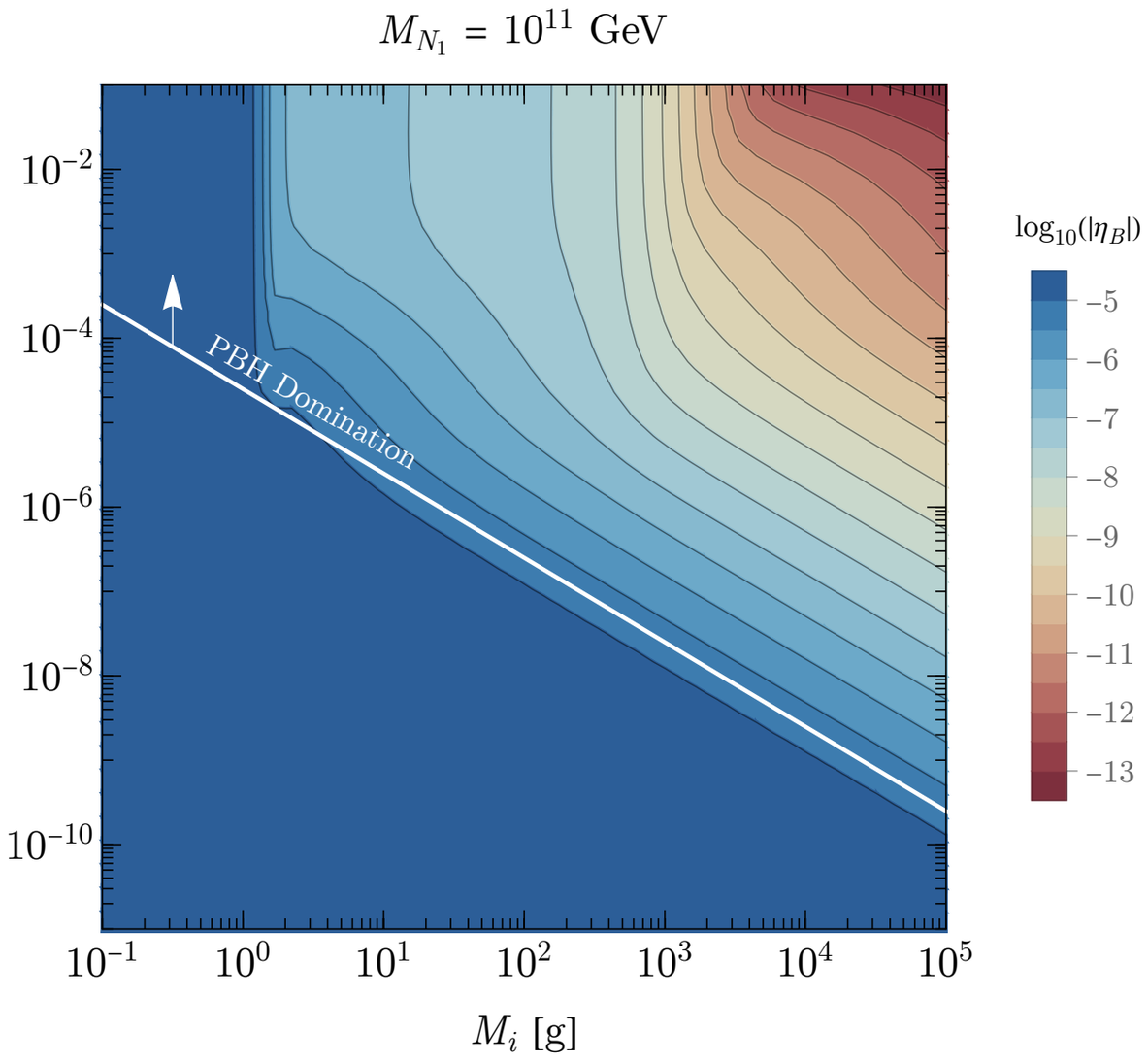
Only reduction of the baryon-to-photon ratio

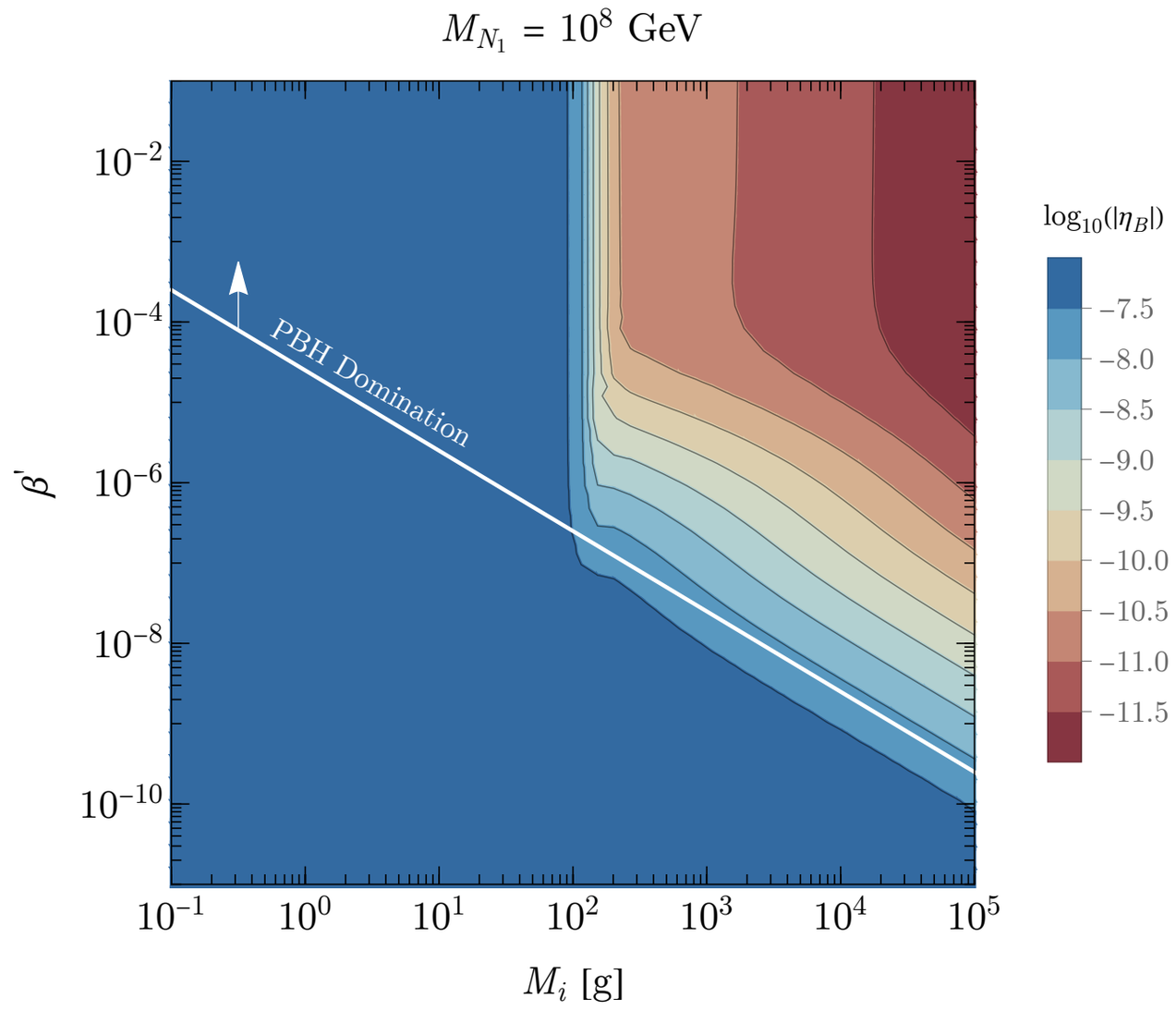
RH masses too small to induce enhancement

Significant Tension!!

Dependence on β'

How the depletion depends on the initial fraction?





Diminution is a generic and important feature to be taken into account

Gravitational Waves?

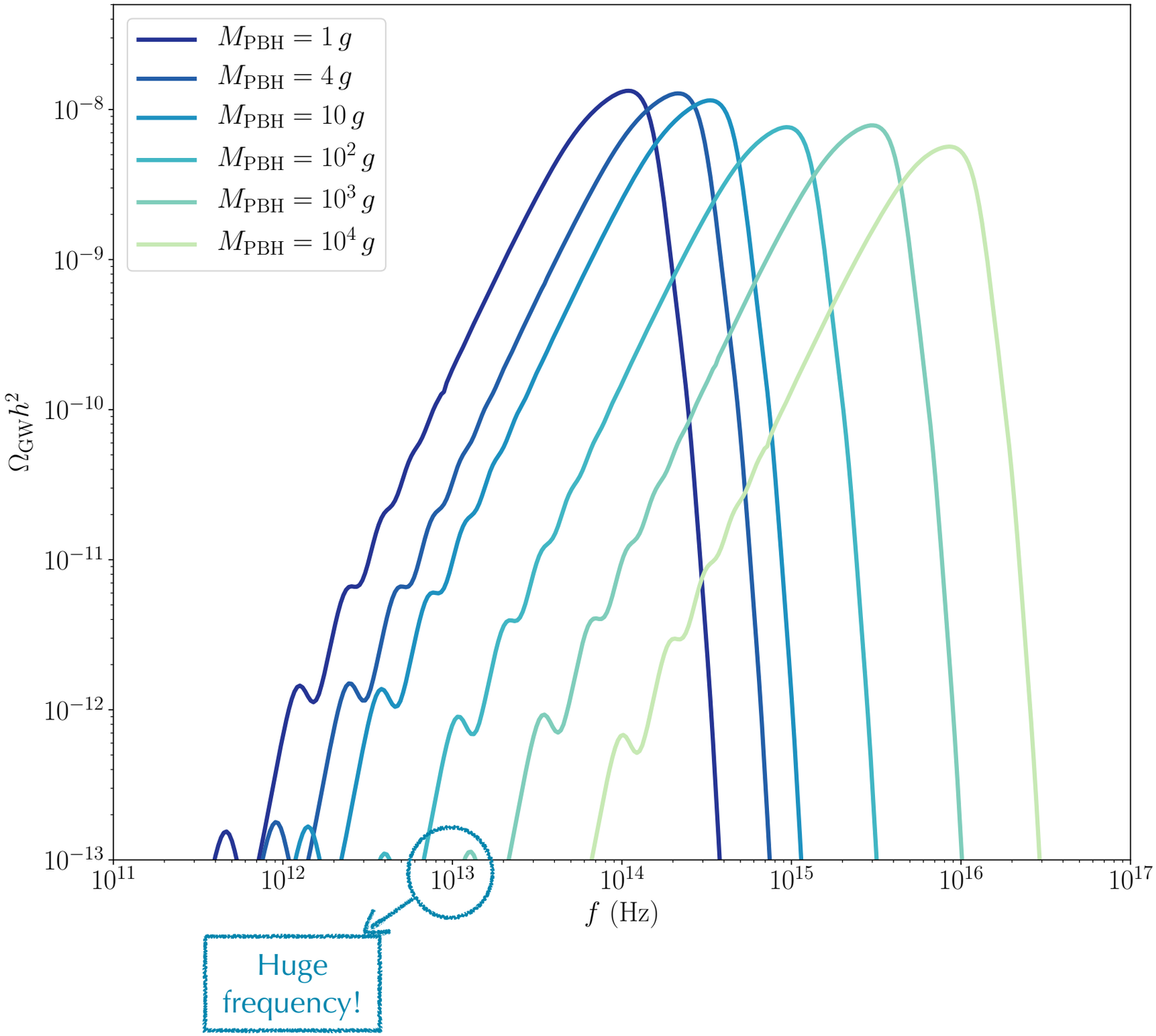
How to prove that the early Universe had a PBH-dominated era?

Example: GW produced by the evaporation

Arvanitaki, Geraci, 2013

Ito et al, 2020

Chen et al, 2020



Coda

- 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
- The diffuse flux of RH neutrinos can be large, but more careful analysis on its possible detection should be performed
- Black hole evaporation diminished the baryon asymmetry in the leptogenesis scenario.
- Falsifiable intermediate scale Leptogenesis if proven a PBH dominated era!
- What about other leptogenesis scenarios? What about other neutrino mass models?
- More phenomena yet to be explored!

Thanks!

Backup

Evaporation function

$$\varepsilon_N(M) = 2f_1 + 4f_{1/2}^1 \left\{ \sum_{\ell=e,\mu,\tau} \exp\left[-\frac{M}{\beta_{1/2} M_\ell}\right] + 3\sum_q \exp\left[-\frac{M}{\beta_{1/2} M_q}\right] \right\}$$

$$+2\,\eta_\nu^N f_{1/2}^0 \sum_{a=1,2,3} \exp\left[-\frac{M}{\beta_{1/2} M_a}\right]$$

$$+16 f_1 \exp\left[-\frac{M}{\beta_1 M_g}\right]$$

$$+3f_1 \left\{ 2\exp\left[-\frac{M}{\beta_1 M_W}\right] + \exp\left[-\frac{M}{\beta_1 M_Z}\right] \right\} + f_0 \exp\left[-\frac{M}{\beta_0 M_H}\right]$$

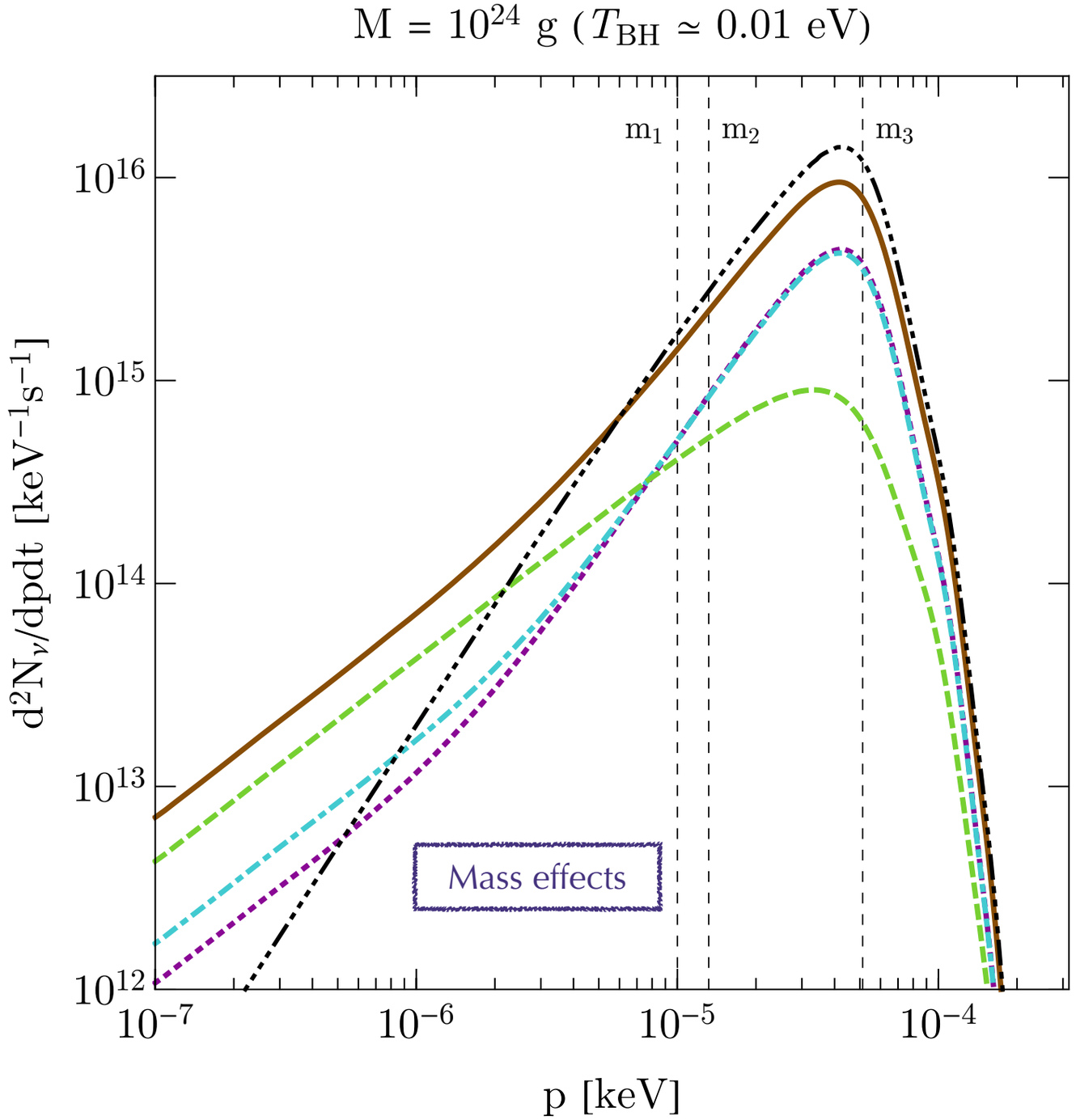
$$\beta_s = \begin{cases} 2.66 & \text{for } s = 0 \\ 4.53 & \text{for } s = \frac{1}{2} \\ 6.04 & \text{for } s = 1 \end{cases} \qquad f_s = \begin{cases} 0.267 & \text{for } s = 0 \\ 0.060 & \text{for } s = 1 \\ 0.007 & \text{for } s = 2 \end{cases} \qquad f_{1/2}^q = \begin{cases} 0.147 & \text{for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

Neutrino instantaneous spectrum

Degrees of freedom

Absorption cross section

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



Schwarzschild BH

$m_0 = 0.01$ eV

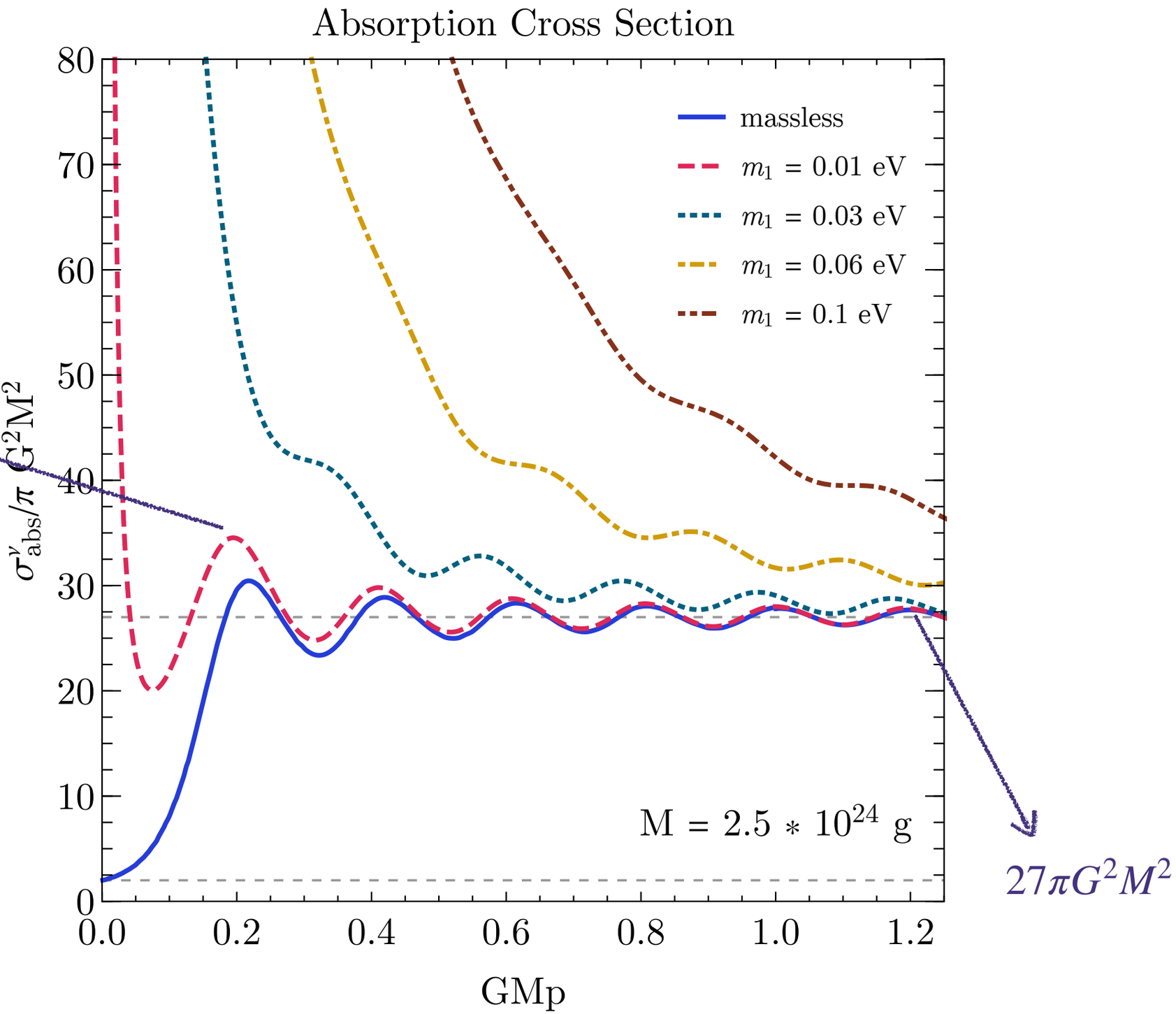
Absorption cross section

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

Contribution of different partial waves

Mass dependent

Emitted particles propagate in the curved spacetime



$27\pi G^2 M^2$

Non-thermalization of RH states

Chen et al, 1509.00481

$$\Gamma_{\rm RH}(T \gtrsim v) \sim |Y_\nu^{ab}|^2 T \longrightarrow T \sim \mathcal{O}(\text{keV})$$

Inconsistent

$$\Gamma_{\rm RH}(T \lesssim v) \sim G_{\rm F}^2 m_\nu^2 T^3 \longrightarrow T \gtrsim \mathcal{O}(10^{12}\ \text{GeV})$$

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

Evolving with the scale factor

$$\varrho_{\rm R} = a^4 \rho_{\rm R}, \qquad \varrho_{\rm BH} = a^3 \rho_{\rm BH}$$

Friedmann and Boltzmann Equations

Evaporation

$$\frac{d\varrho_{\rm BH}}{da} = \frac{1}{M}\frac{dM}{da}\varrho_{\rm BH}$$

$$\frac{d\varrho_{\rm R}}{da} = -\frac{\varepsilon_{\rm SM}(M)}{\varepsilon(M)}\frac{1}{M}\frac{dM}{da}a\varrho_{\rm BH}$$

BR into SM

$$H^2 = \frac{8\pi G}{3}\left(\varrho_{\rm BH}a^{-3} + \varrho_{\rm R}a^{-4}\right)$$

Hubble expansion

Temperature evolution

$$\frac{dT}{da} = -\frac{T}{\Delta}\left\{\frac{1}{a} + \frac{\varepsilon_{\rm SM}(M)}{\varepsilon(M)}\frac{1}{M}\frac{dM}{da}\frac{g_*(T)}{g_{*S}(T)}\frac{a\varrho_{\rm BH}}{4\varrho_{\rm R}}\right\}$$

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

Boltzmann Equations

Thermal contribution

$$aH\frac{dn_{N_1}^{\rm TH}}{da} = -(n_{N_1}^{\rm TH} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T}$$

$$aH\frac{dn_{N_1}^{\rm BH}}{da} = -n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH} + n_{\rm BH}\Gamma_{\rm BH\to N_1}$$

RH neutrinos emitted from the evaporation

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

Thermally averaged RH neutrino decay

$$aH\frac{dn_{\alpha\beta}^{\rm B-L}}{da} = \epsilon_{\alpha\beta}^{(1)}\left[(n_{N_1} - n_{N_1}^{\rm eq})\Gamma_{N_1}^{T} + n_{N_1}^{\rm BH}\Gamma_{N_1}^{\rm BH}\right] + \mathscr{W}_{\alpha\beta}$$

α, β → Flavor indexes

$$\Gamma_{\rm BH\to N_1} \equiv \int_0^\infty \frac{d^2\mathscr{N}_{N_1}}{dp\,dt}dp$$

$$\approx \frac{27T_{\rm BH}}{32\pi^2}\left(-z_{\rm BH}{\rm Li}_2(-e^{-z_{\rm BH}}) - {\rm Li}_3(-e^{-z_{\rm BH}})\right)$$

$$\Gamma_{N_1}^{\rm BH} \equiv \left\langle \frac{M_{N_1}}{E_{N_1}} \right\rangle_{\rm BH} \Gamma_{N_1}^{0} \approx \frac{\mathscr{K}_1(z_{\rm BH})}{\mathscr{K}_2(z_{\rm BH})}\Gamma_{N_1}^{0}$$

Neutrino spectrum

Hawking spectrum

Degrees of freedom

Absorption cross section

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

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

BH Temperature

Absorption cross section

$$\alpha_g^a = GMm_a$$

$$\sigma^\nu_{\rm abs}(M,p,m_a)$$

$\alpha_g^a \gg 1$ → Classical

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

$$\alpha_g^a \sim 1 \longrightarrow M \sim 2.66\times 10^{25}\ {\rm g}\left(\frac{0.01\ {\rm eV}}{m_a}\right)$$