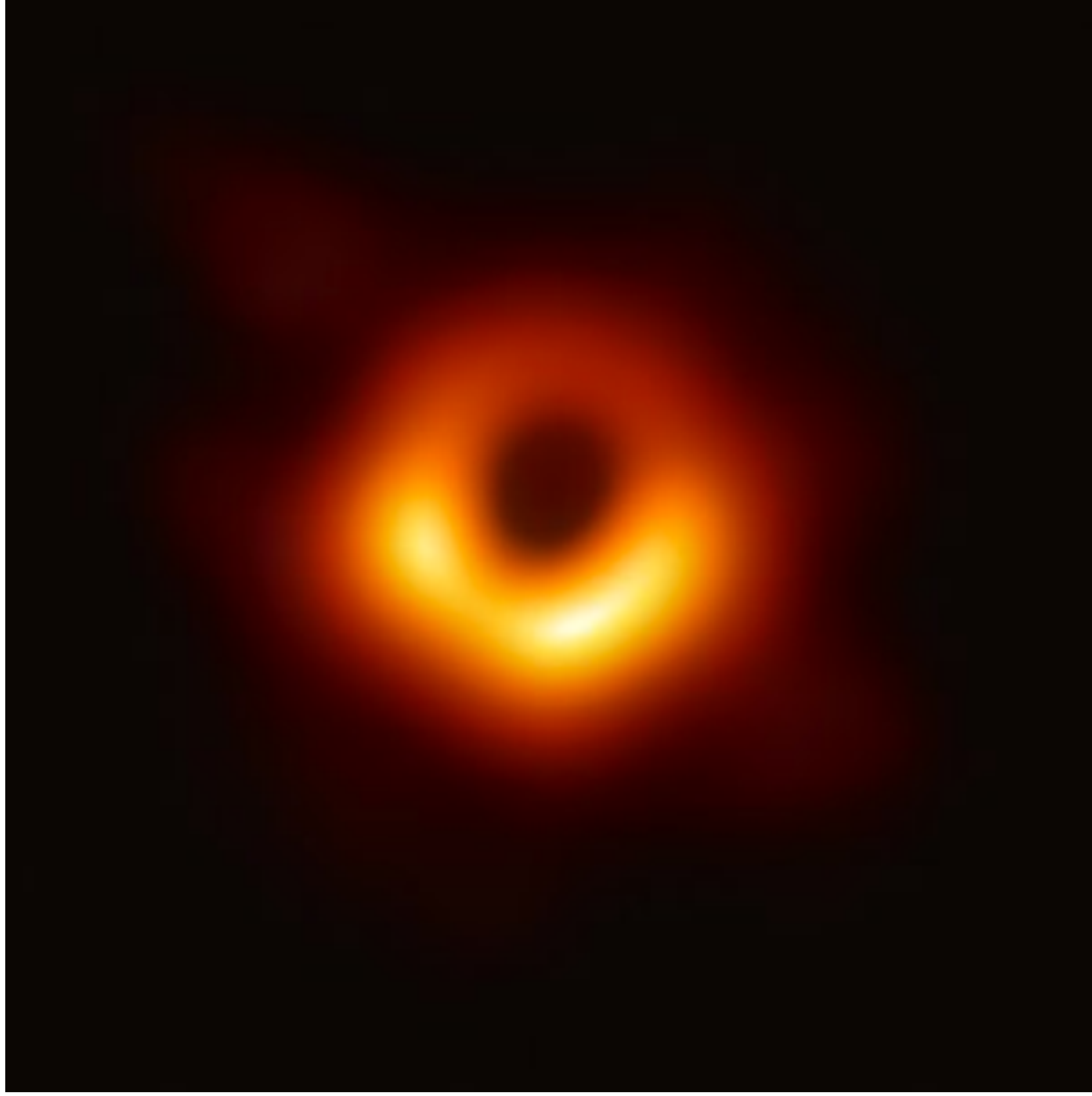
On massive neutrino emission from primordial black holes via Hawking radiation

Yuber F. Perez-Gonzalez



EHT Collaboration

N3AS virtual seminar

August 11, 2020

Fermilab

COFI
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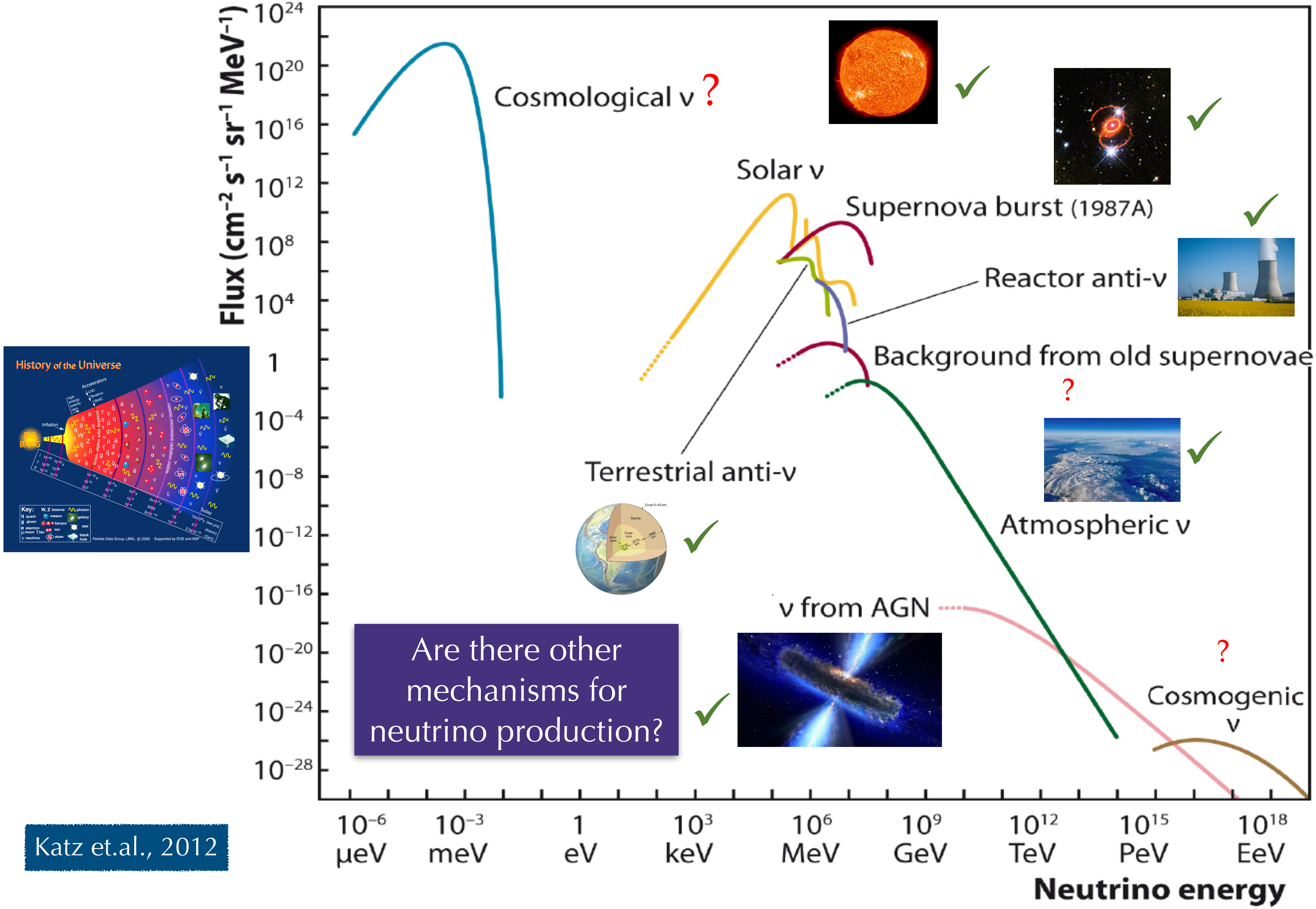
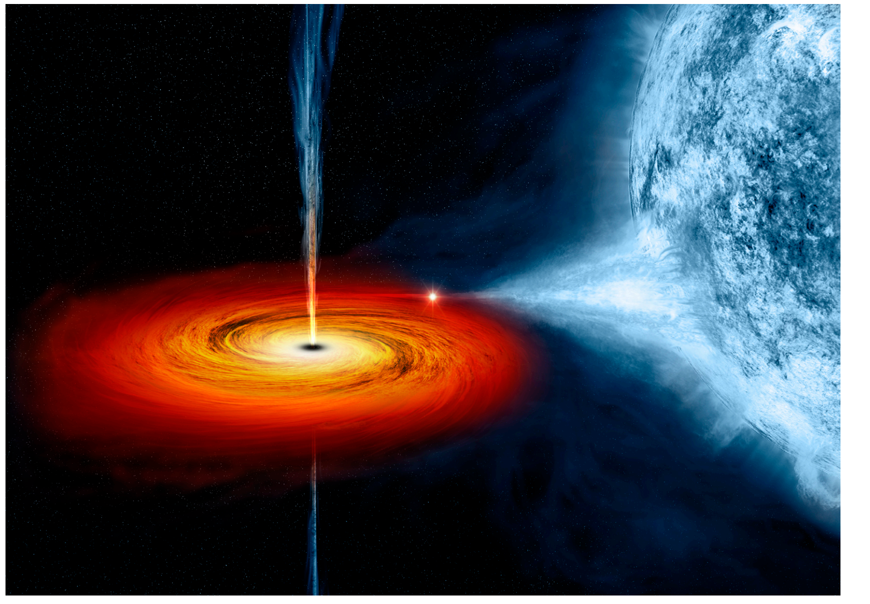
Northwestern



Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν ?
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
?
Terrestrial anti-ν
Atmospheric ν
ν from AGN
?
Cosmogenic ν
Are there other mechanisms for neutrino production?
History of the Universe
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy
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

Quantum effects are important

$r_S \sim \lambda_C$

Black Holes evaporate by thermal emission

Hawking, 1975

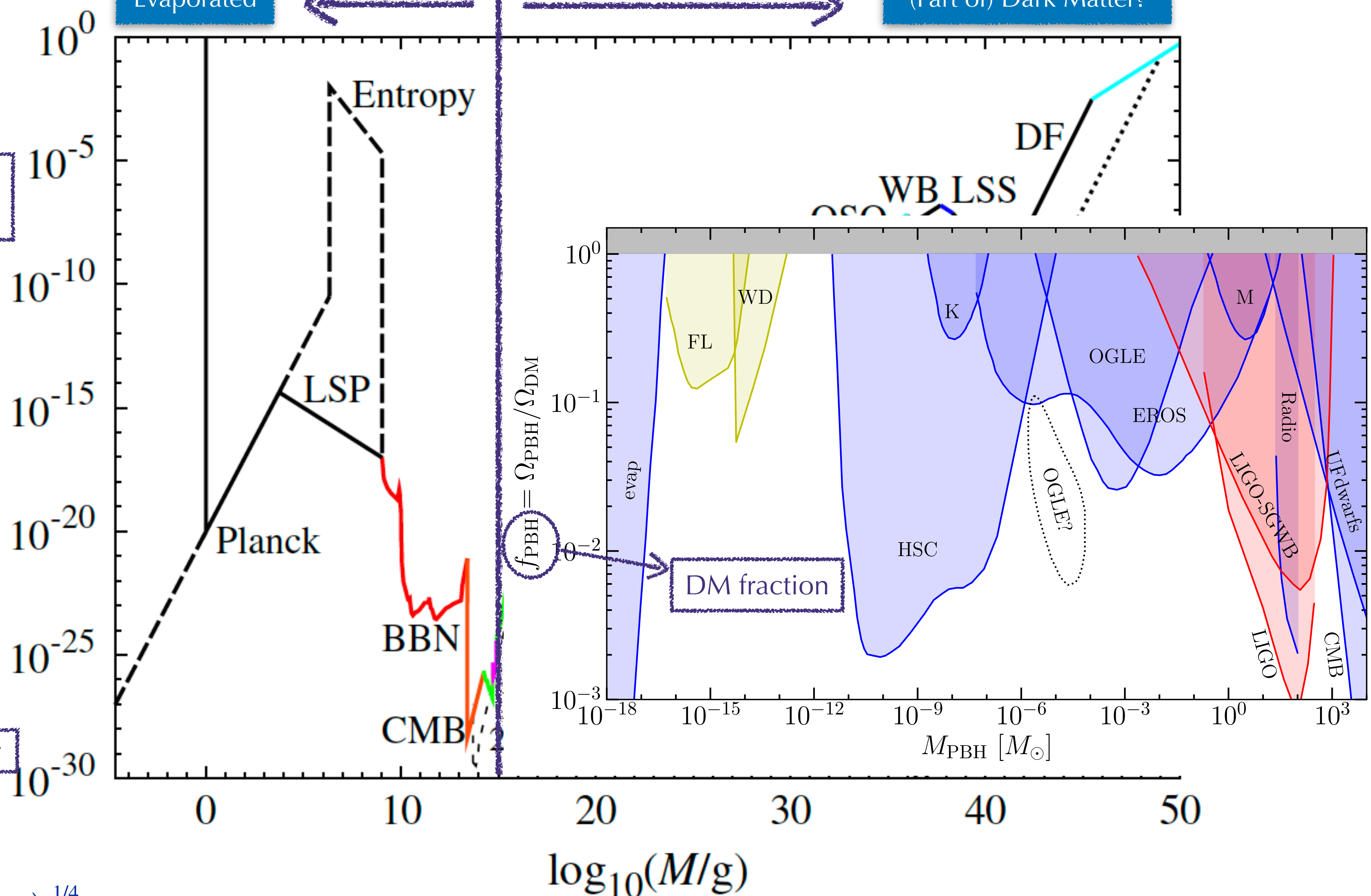
Carr et al, 2002.12778

Primordial Black Holes (PBH)

Evaporated

(Part of) Dark Matter?

Fraction of the total energy in PBH



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

Gravitational collapse factor

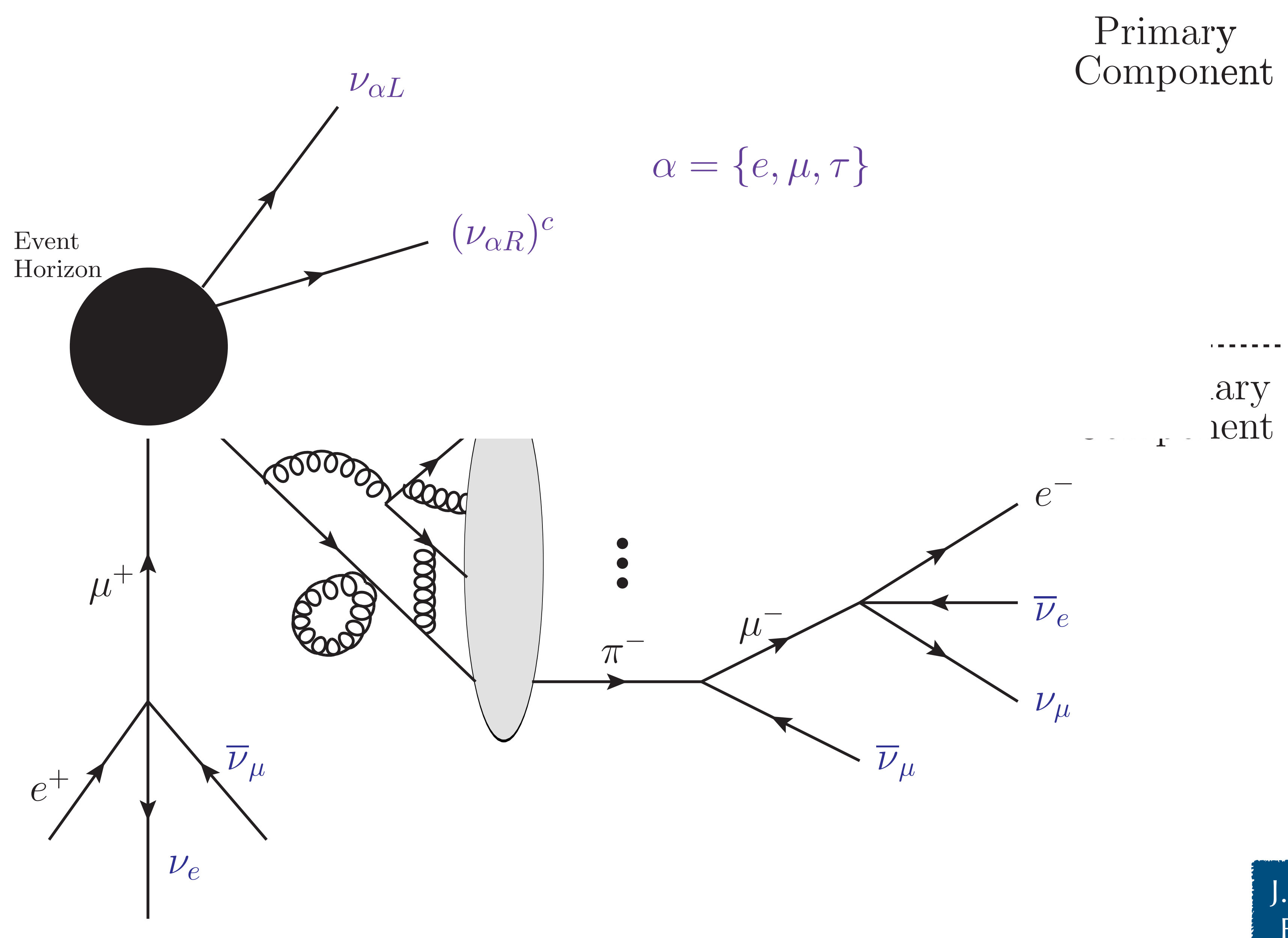
$$\beta' = \beta \gamma^{1/2} \left(\frac{g_{*f}}{106.75} \right)^{1/4}$$

Carr et al. 2002.12778

B. Kavanagh 10.5281/zenodo.3538999

Neutrino emission in the SM

B. Carr, 1976

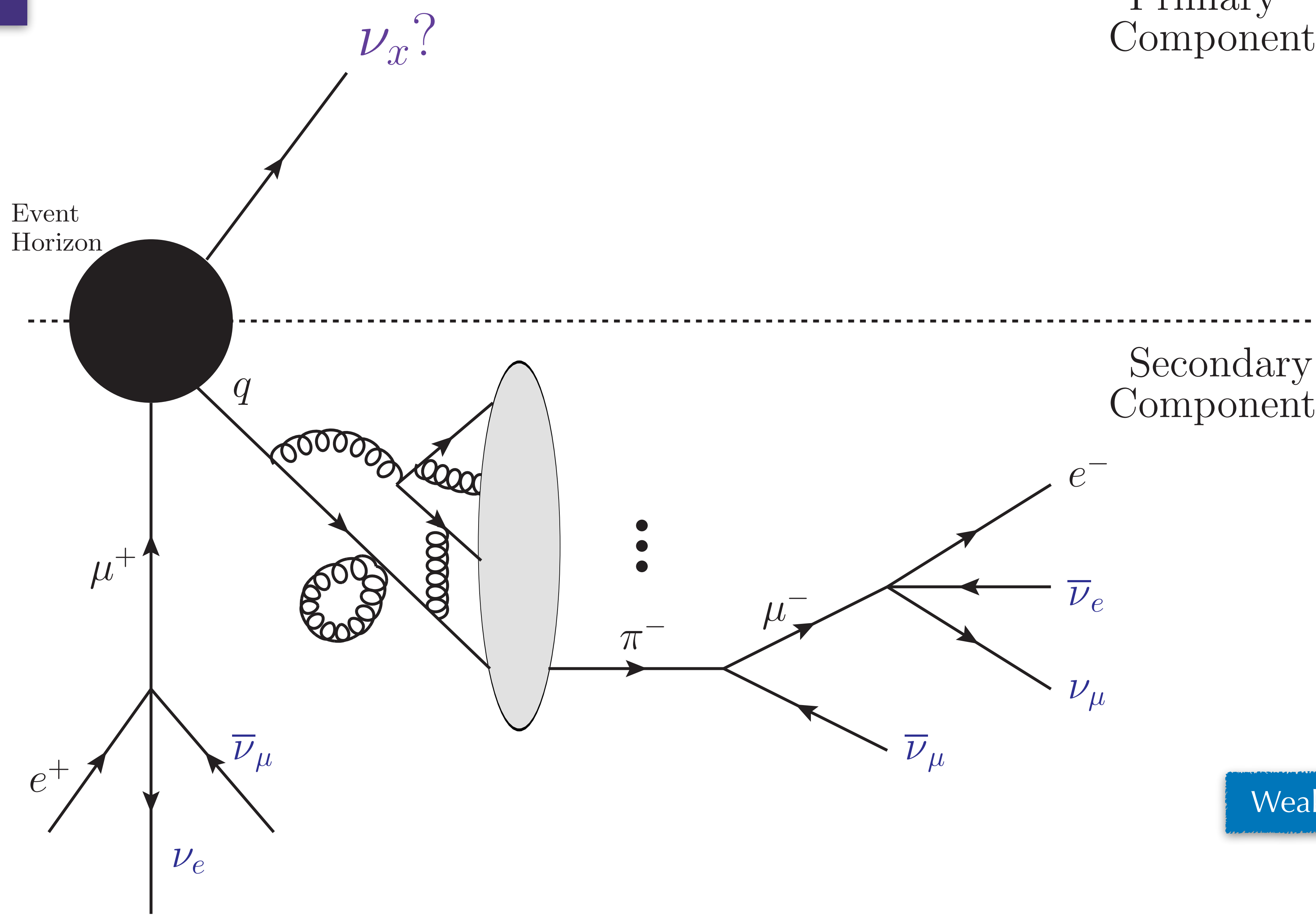


J. MacGibbon, 1991
F. Halzen,9502268
Bugaev, 0005295

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

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

Interaction mediated by
a gauge boson

Associated with a
charged lepton

Flavor eigenstate

ν_e ν_μ ν_τ

Hawking Effect

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

Particle definition in a curved
spacetime is observer dependent

No associated
production of a charged
lepton

Mass eigenstate

ν_1 ν_2 ν_3

Neutrino instantaneous spectrum

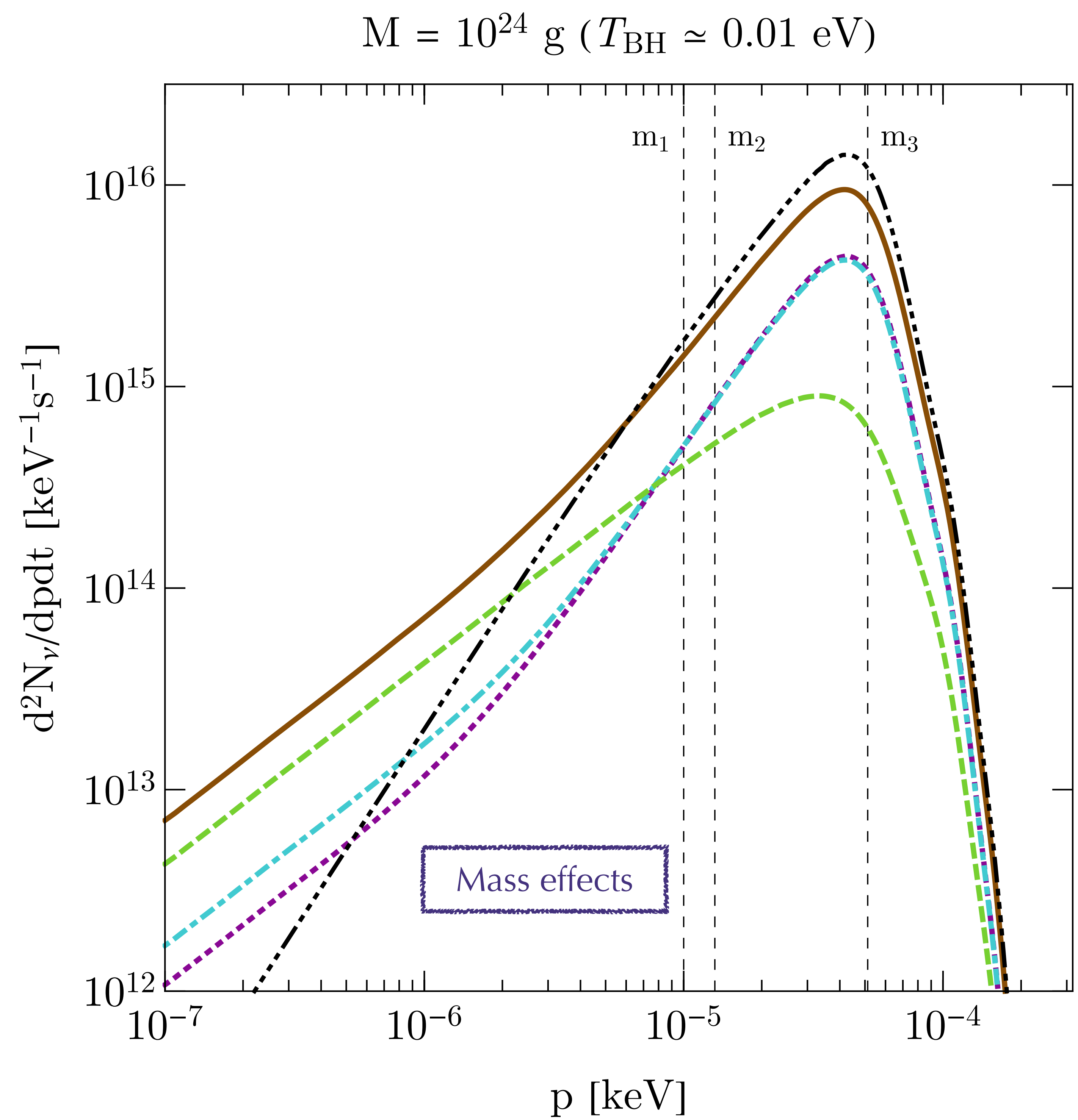
Degrees of freedom

Absorption cross section

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

BH Temperature

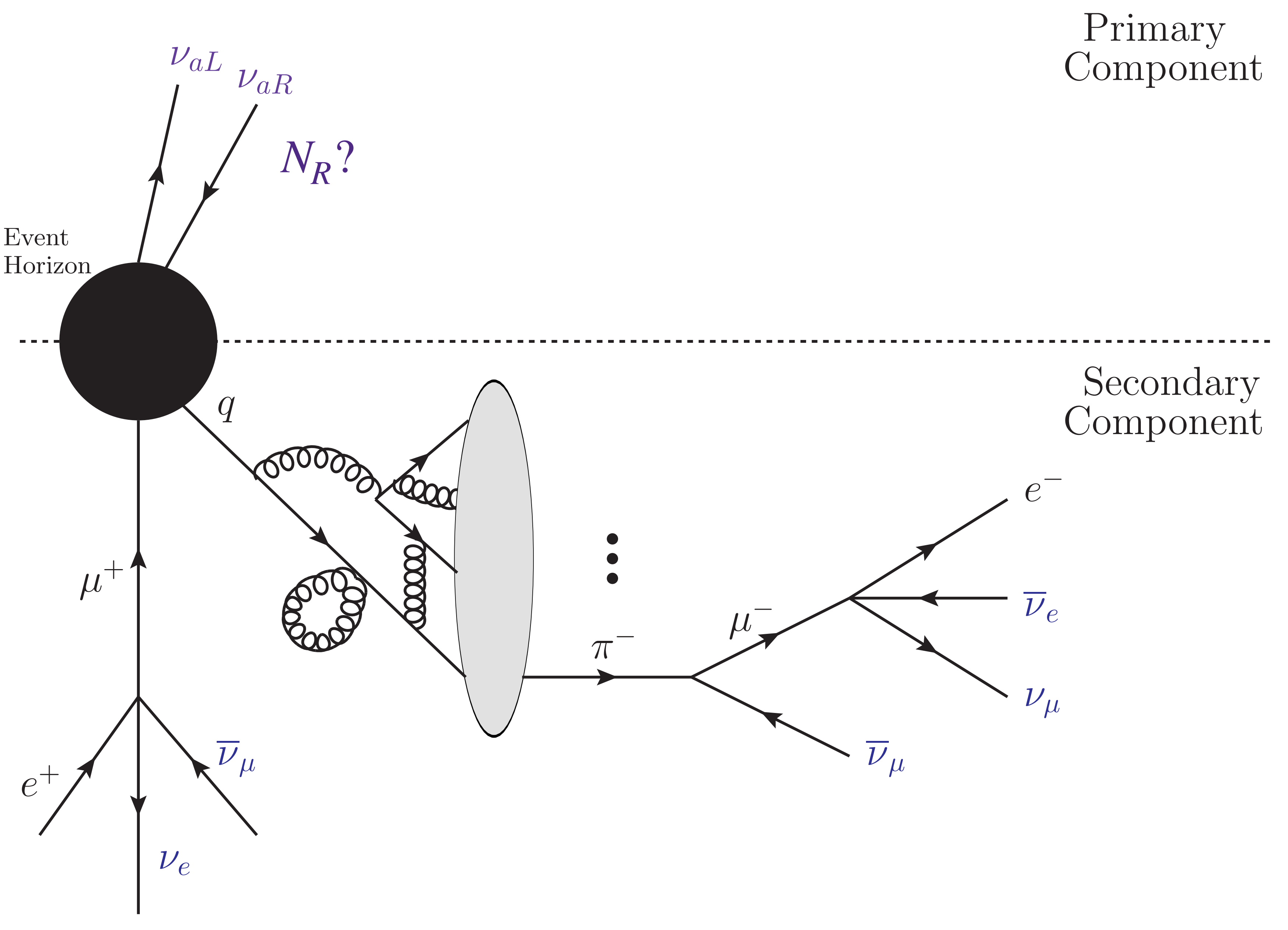
$$T = \frac{1}{8\pi GM} \approx 1.06 \left(\frac{10^{13}\ \text{g}}{M}\right) \text{GeV}$$



$m_0 = 0.01$ eV

Schwarzschild BH

Dirac vs Majorana



Majorana neutrinos

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
arXiv:1912:07864

Majorana neutrinos

Heavy RH neutrinos

↓

PBH-driven Leptogenesis

Yamada and Iso, 1610.02586
Morrison et al,1812.10606
Baldes et al, 2004.14773

Cecilia Lunardini, YFPG
and Jessica Turner,
in preparation

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

PBHs are formed

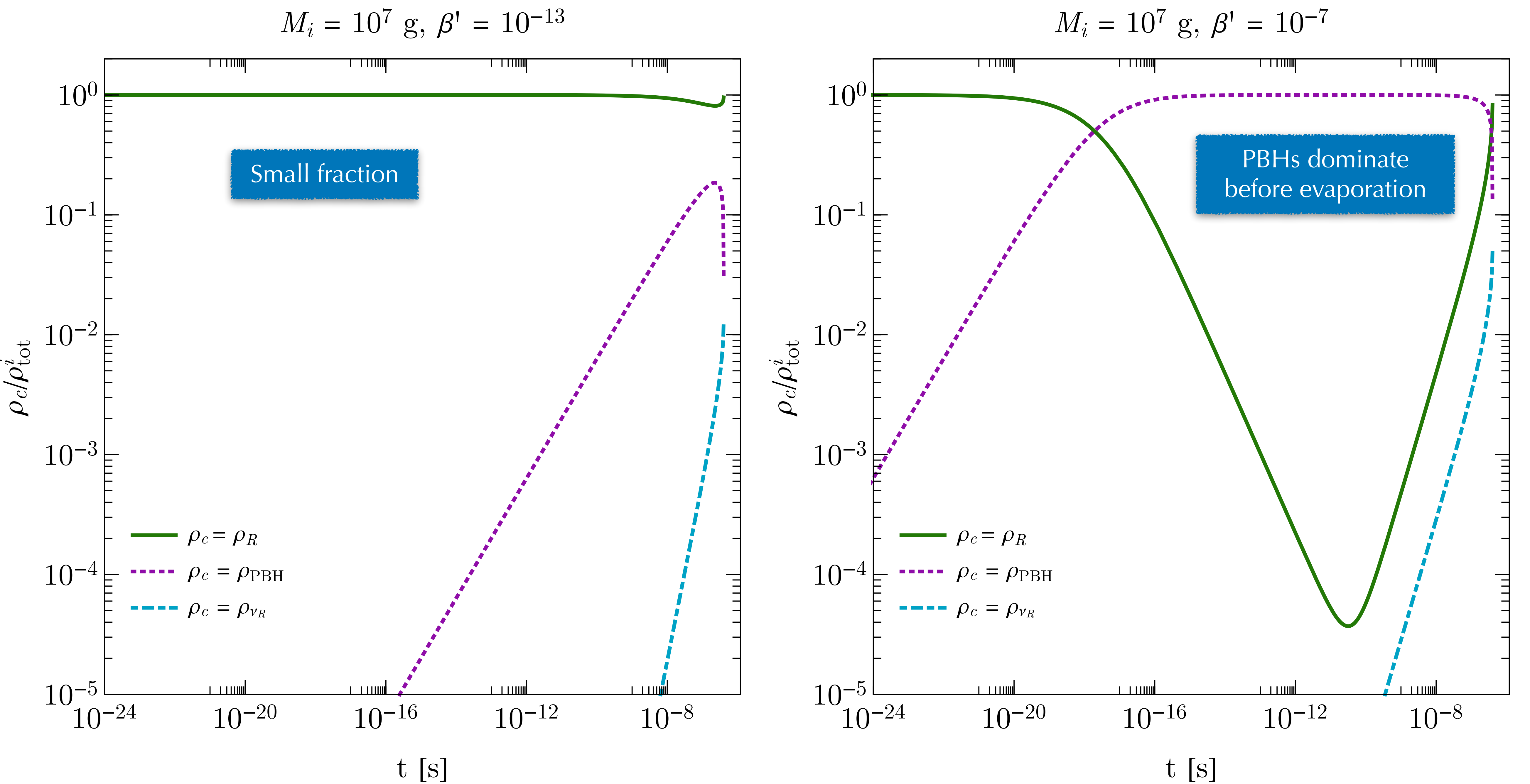
Non-standard cosmology?

PBHs evaporate

t_i, T_f

$t_\mathrm{EV}, T_\mathrm{EV}$

Constraints in the Dirac neutrino case



Initial fraction

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

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

ν_R → Do not thermalize — Chen et al, 1509.00481

Friedmann-Boltzmann Equations

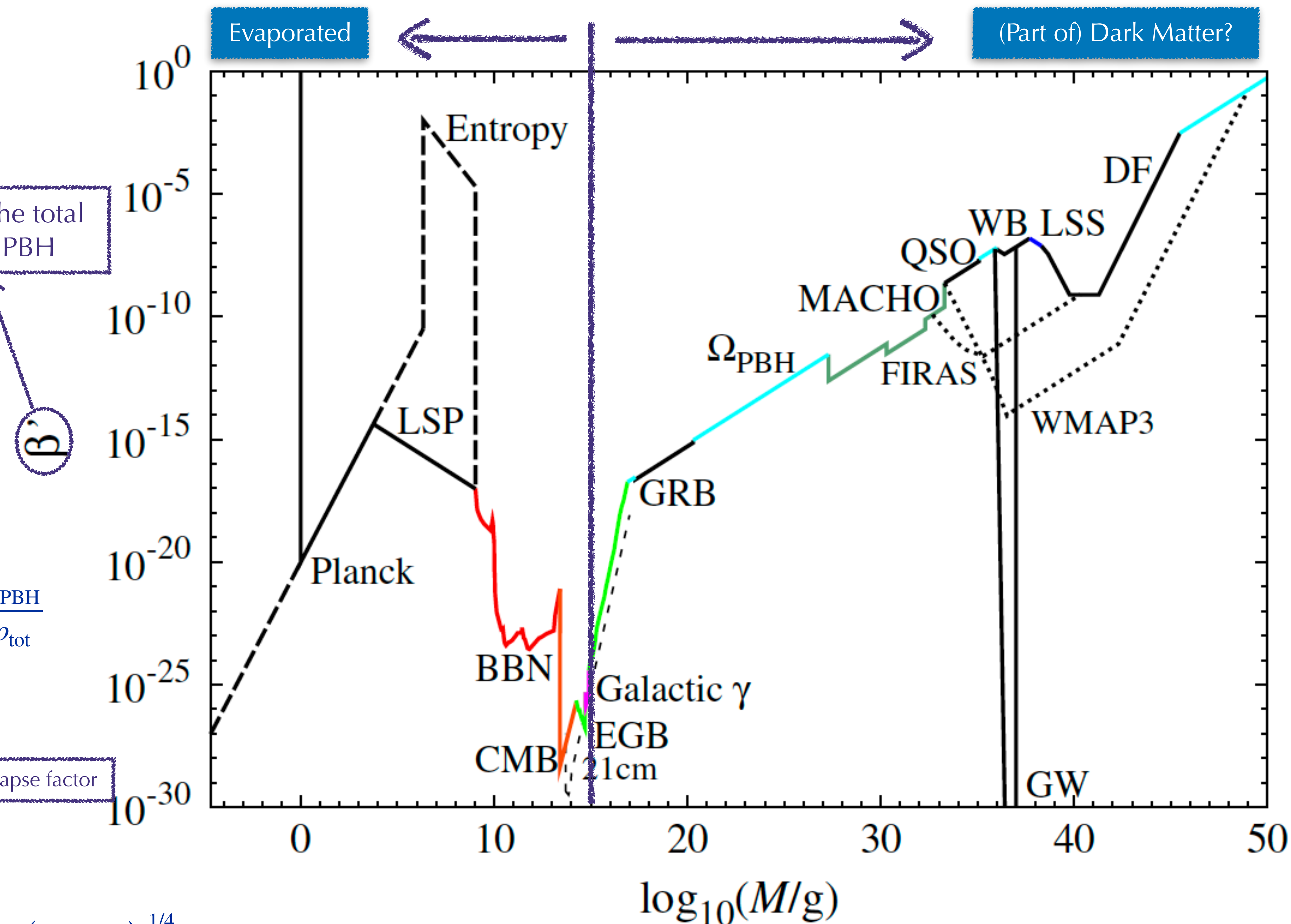
PBHs are formed → Non-standard cosmology? → PBHs evaporate → Matter-radiation equality

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

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

Hooper et al, 1905.01301

Constraints in the Dirac neutrino case



Fraction of the total energy in PBH

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

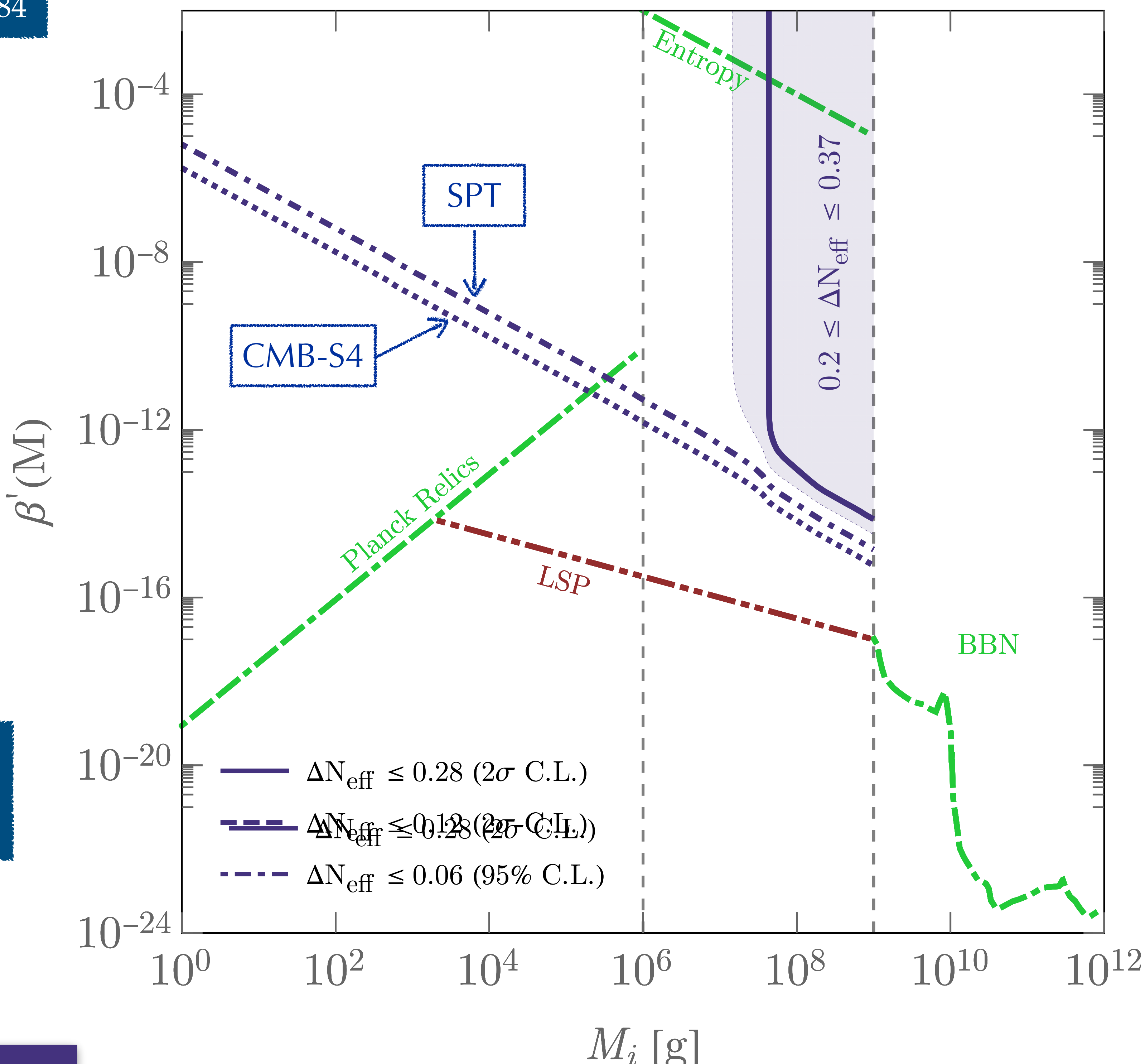
Gravitational collapse factor

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

Carr et al. 0912.5297

Constraints in the Dirac neutrino case

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

ν_R → Do not thermalize — Chen et al, 1509.00481

Friedmann-Boltzmann Equations

Non-standard cosmology?

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

$t_i, T_{\rm f}$ — $t_{\rm EV}, T_{\rm EV}$ — $t_{\rm EQ}, T_{\rm EQ}$ — t_0

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

Hooper et al, 1905.01301

Diffuse neutrino flux from PBHs

Could we measure these neutrinos?

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

PBH initial number

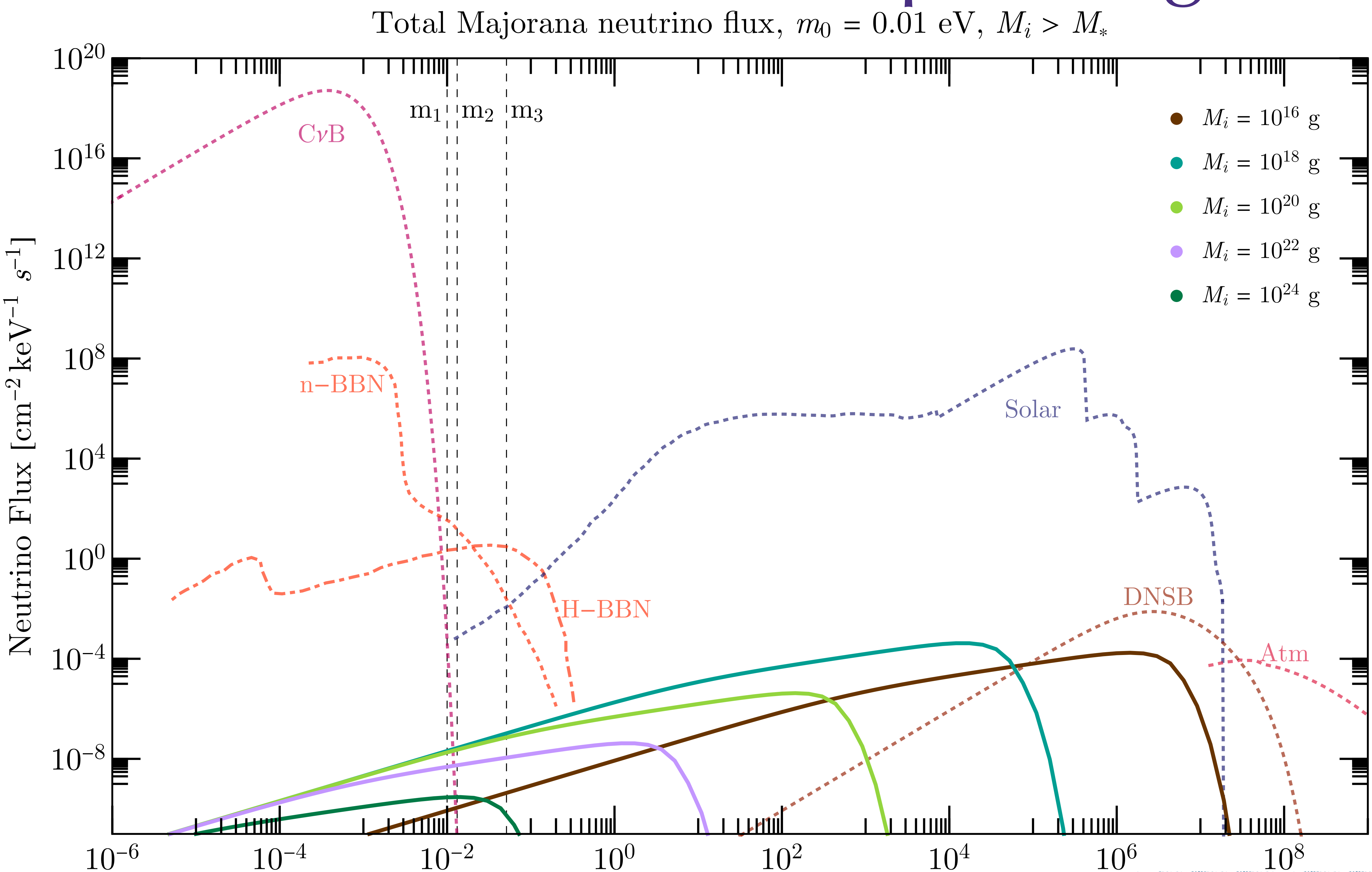
Comoving number density

Momentum redshift

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

Matter-radiation redshift

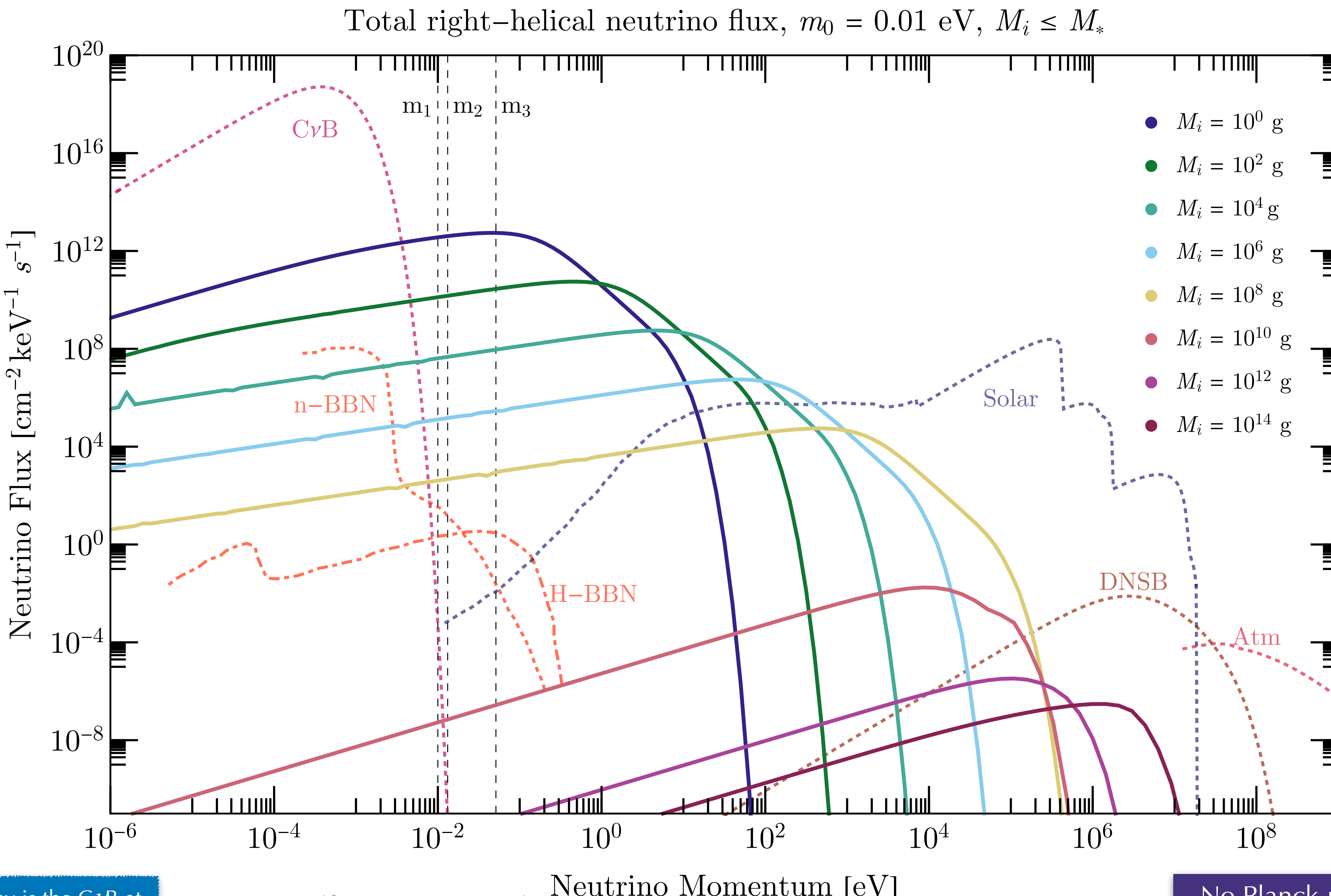
Diffuse flux from non-evaporating PBHs



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

$m_0 = 0.01\ \text{eV}$

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

PTOLEMY?

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

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

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

PBH RH flux is still suppressed

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

Majorana Neutrinos

Preliminary results

Cecilia Lunardini, YFPG
and Jessica Turner

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:

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

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

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

Complex orthogonal matrix (R)

Neutrino oscillation mixing ($U_{\rm PMNS}$)

Boltzmann Equations

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

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

Fukugida, Yanagida, '86

Casas, Ibarra, 2001

Leptogenesis in a nutshell

Thermal leptogenesis:

At $T \sim M_N$ RH neutrinos are created

$LH \rightarrow N$

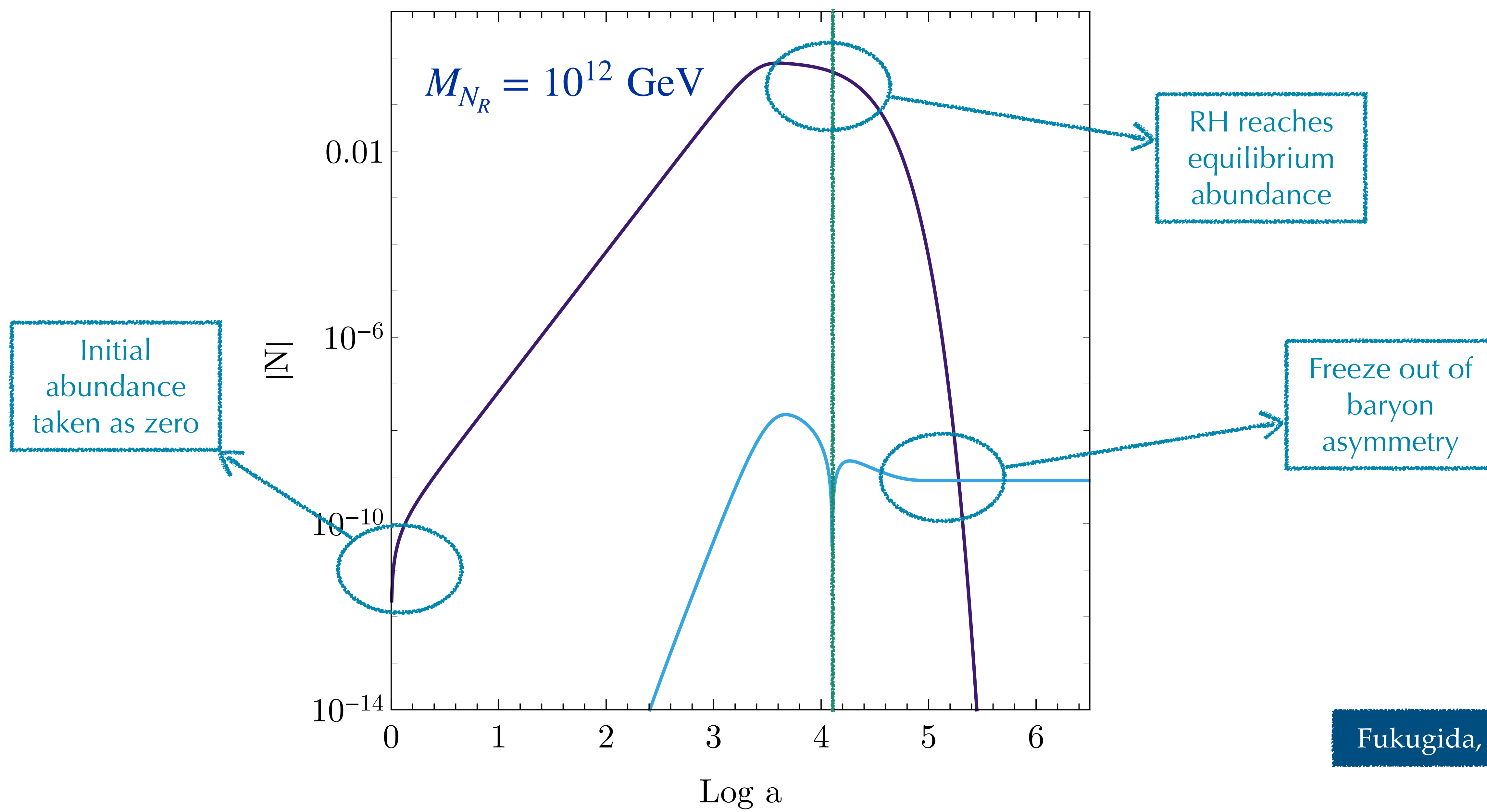
$N \rightarrow LH$

$N \rightarrow \bar{L}H$

Lepton asymmetry is created

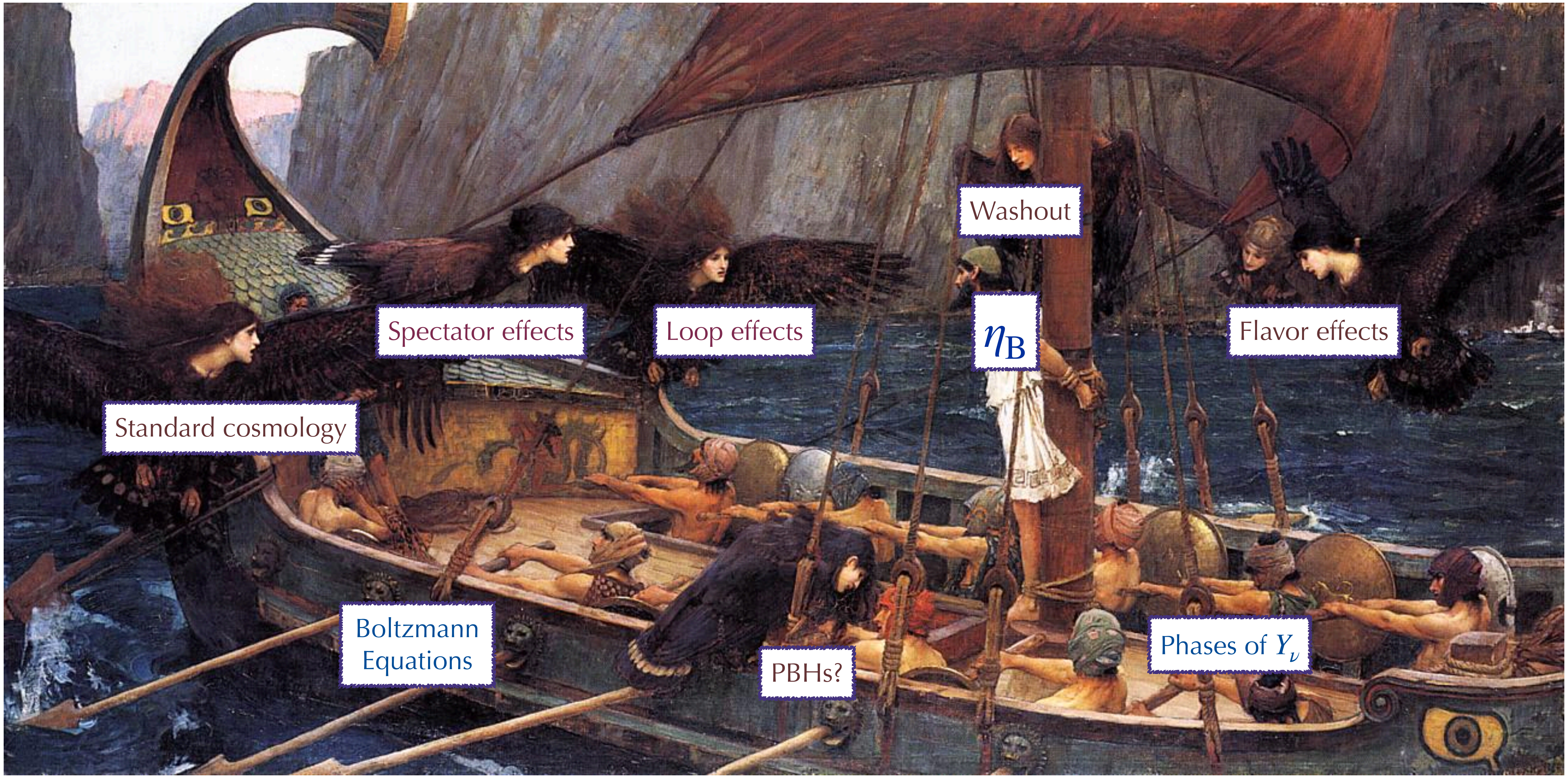
Sphaleron processes

Baryon asymmetry



Fukugida, Yanagida, '86

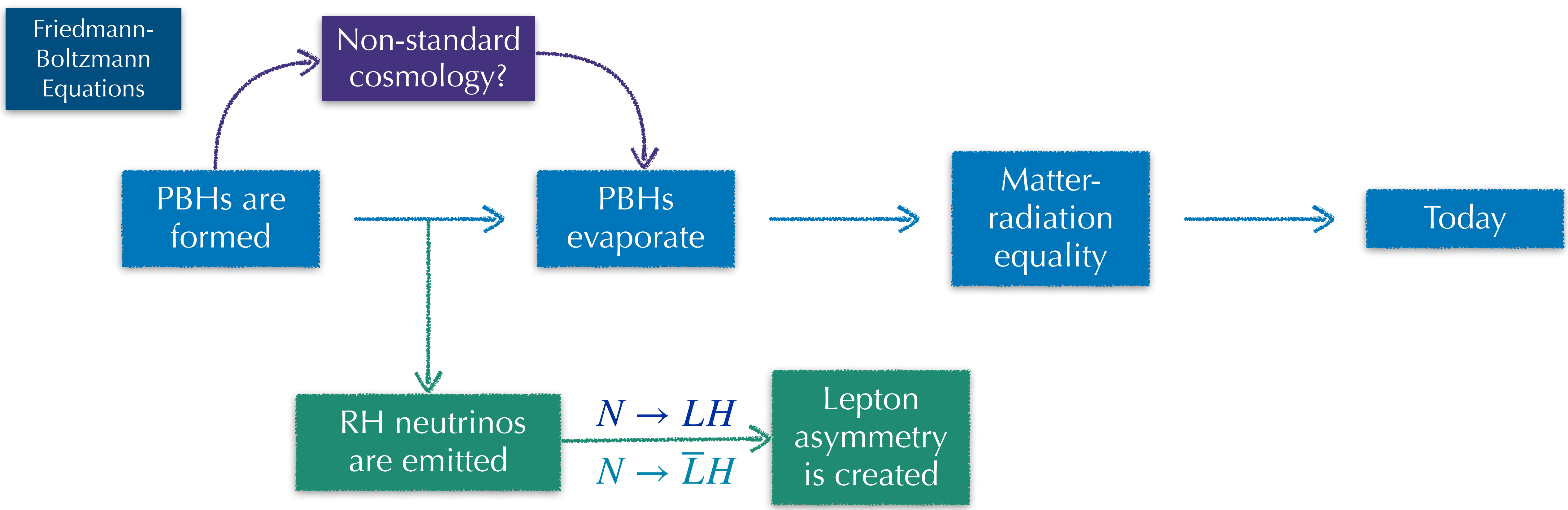
Universal LeptogeneSiS Equation Solver (ULYSSES)



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



Three scenarios

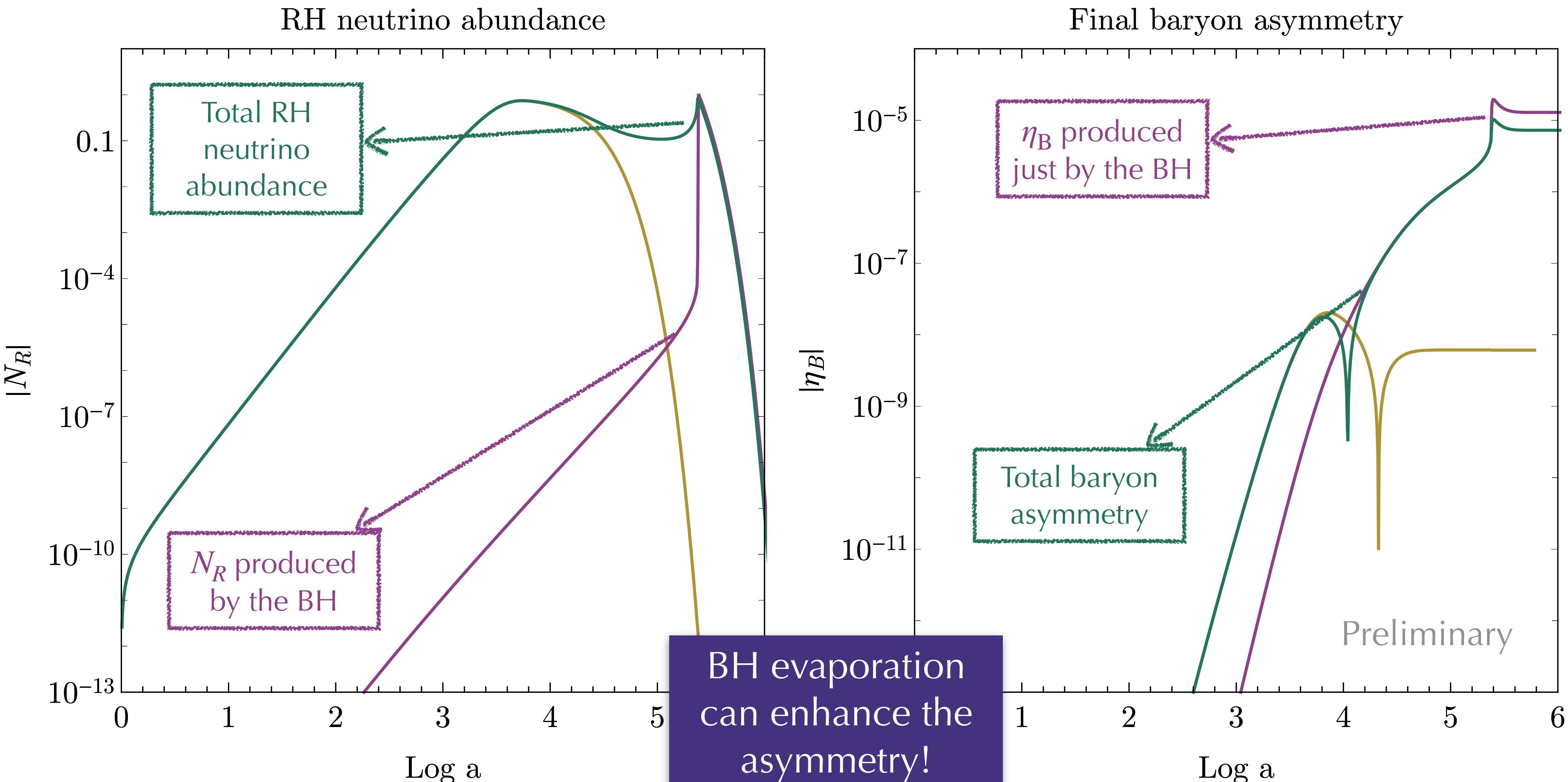
A. PBH evaporate before RH are thermally produced
B. Evaporation happens at more or less at the same time
C. PBH create a RH density when the plasma would not be able to do.

PBH-driven Leptogenesis

A. PBH evaporate before RH are thermally produced
B. Evaporation happens at more or less at the same time

The thermal plasma would equilibrate the over abundance created by the PBHs

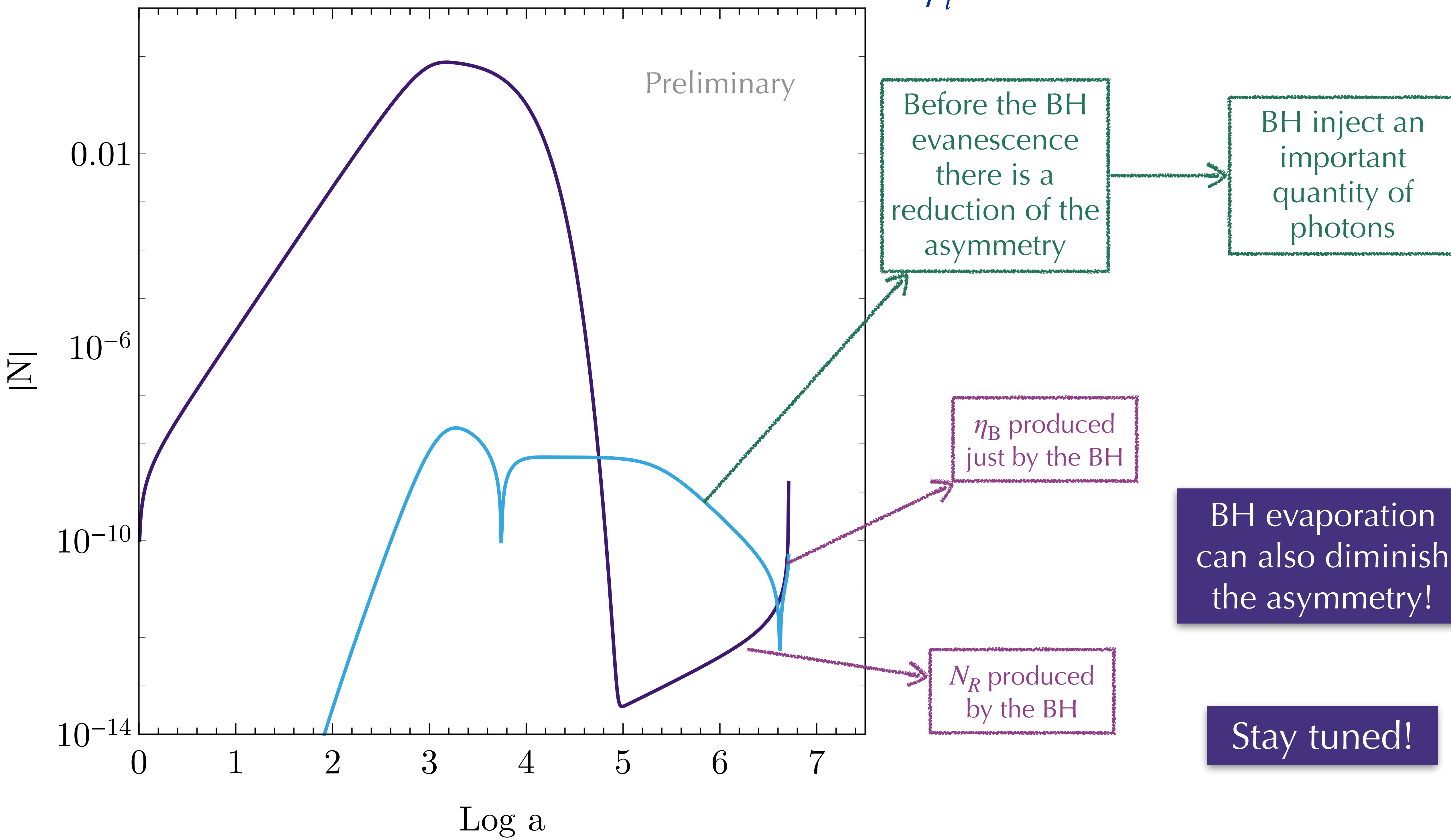
$M_i = 0.3$ g
$\beta'_i = 10^{-3}$



PBH-driven Leptogenesis

C. PBH create a RH density when the plasma would not be able to do.

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



BH evaporation can also diminish the asymmetry!

Stay tuned!

Conclusions

- 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
- Preliminary results show that black hole evaporation can enhance or diminish the baryon asymmetry in the leptogenesis scenario.
- What about spinning black holes?

Thanks!