since 1887

Neutrino and Leptogenesis

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O. Seto, T.S., and T. Tsuyuki, 2211.10059 (v2 will soon appear)

19. Jul. 2023 Neutrino Workshop at IFIRSE 2023@Quy nhon in Vietnam

Introduction

Physics Beyond the Standard Model

The Standard Model is <u>a successful model</u> for the elementary particle physics

All the particles contained in the SM have been discovered.

But there are a few problems which the SM cannot solve

- What is the origin of tiny neutrino masses?
- Baryogenesis?
- What is the Dark Matter?
- Inflation?
- Charge Quantization?
- …

The SM should be extended at some energy scale

Physics Beyond the Standard Model

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Leptogenesis

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- …

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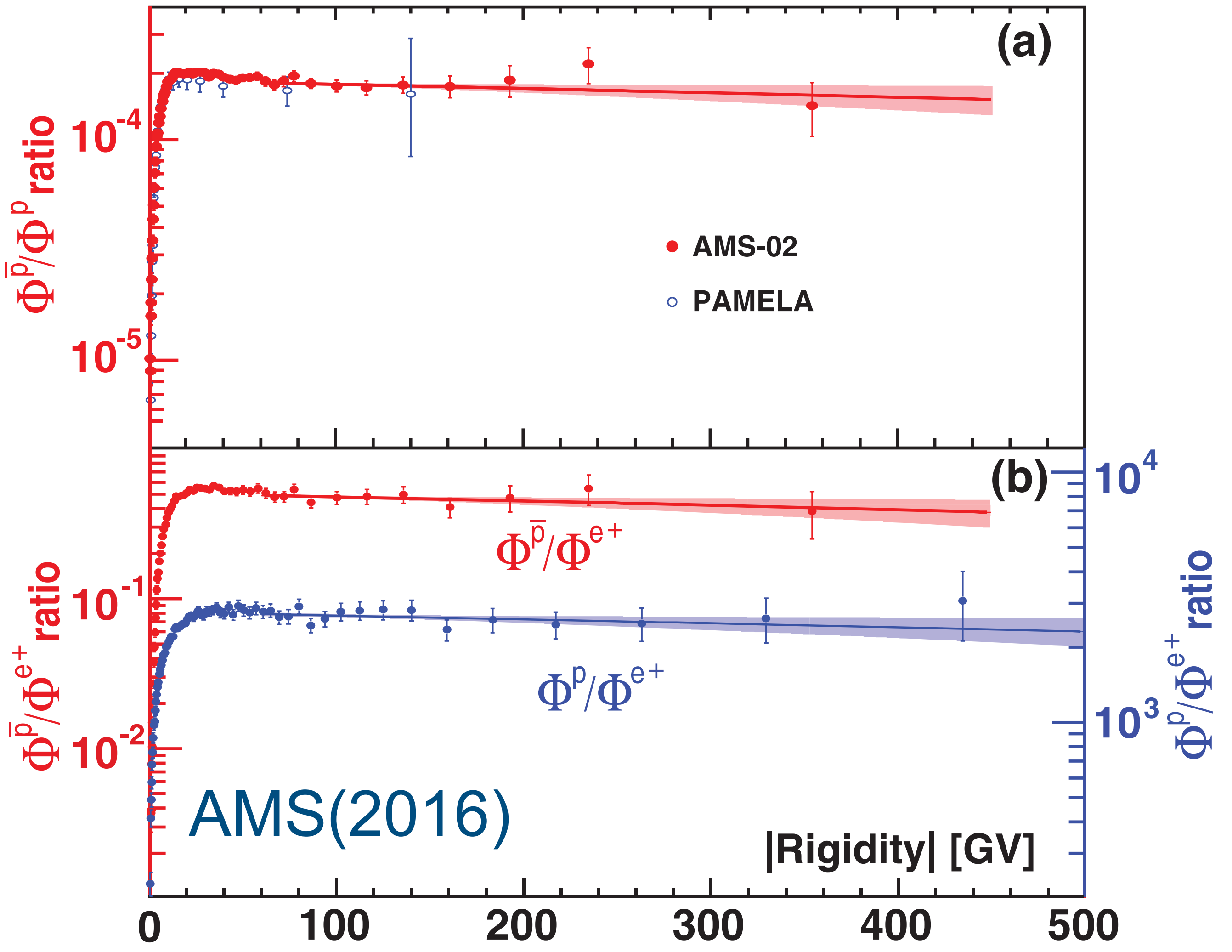
Baryon asymmetry of the Universe

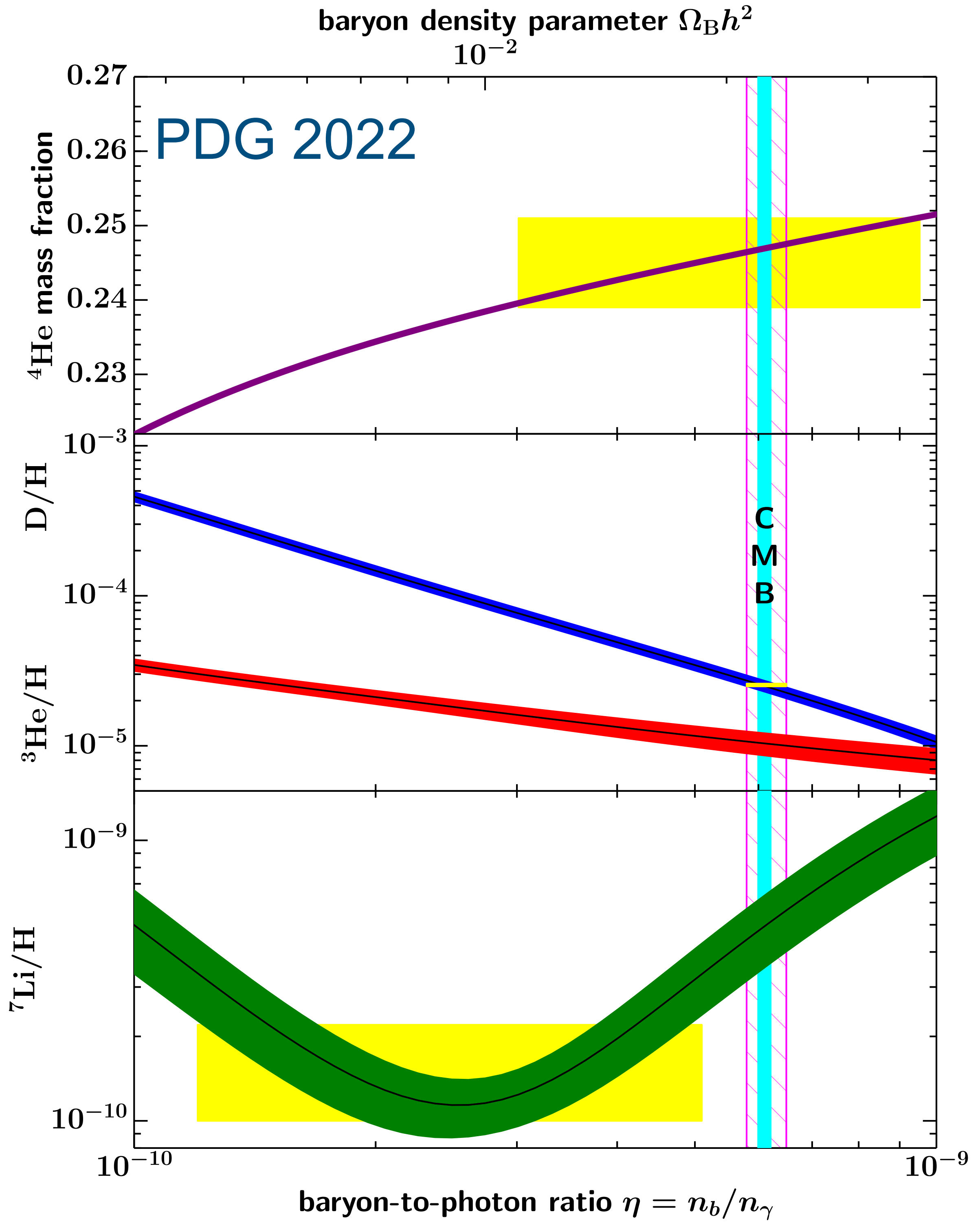
We are surrounded by matter, not anti-matter

- Earth, Sun, Solar system, …
- Cosmic ray from our galaxy

$$\frac{\text{anti-proton}}{\text{proton}} \sim 10^{-4}$$



consistent with secondary prodcution $p+p \to p+p+p+\bar{p}$



Cosmological observation

- Power spectrum of CMB
- Abundance of light elements

$$\eta_B = \frac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6.14(19) \times 10^{-10}$$

Baryogenesis and Sakharov's condidtions

In the Inflation era, primordial baryon number is diluted by reheating of Universe

➡ **Baryogenesis should occur after reheating (inflation)!**

In order to realise it, the Sakharov's conditions should be satisfied.

- Baryon number is violated
- Both C and CP are violated
- Out of thermal equilibrium

In early Universe

In a seesaw model (SM+RHN), these conditions can be satisfied as

- Sphaleron ➡ Baryon number violation
- Heavy RHN decay in early Universe ➡ C and CP violation&out of equilibrium

M.Fukugita, T.Yanagida, PLB174,45

(Canonical) Leptogenesis

Leptogenesis

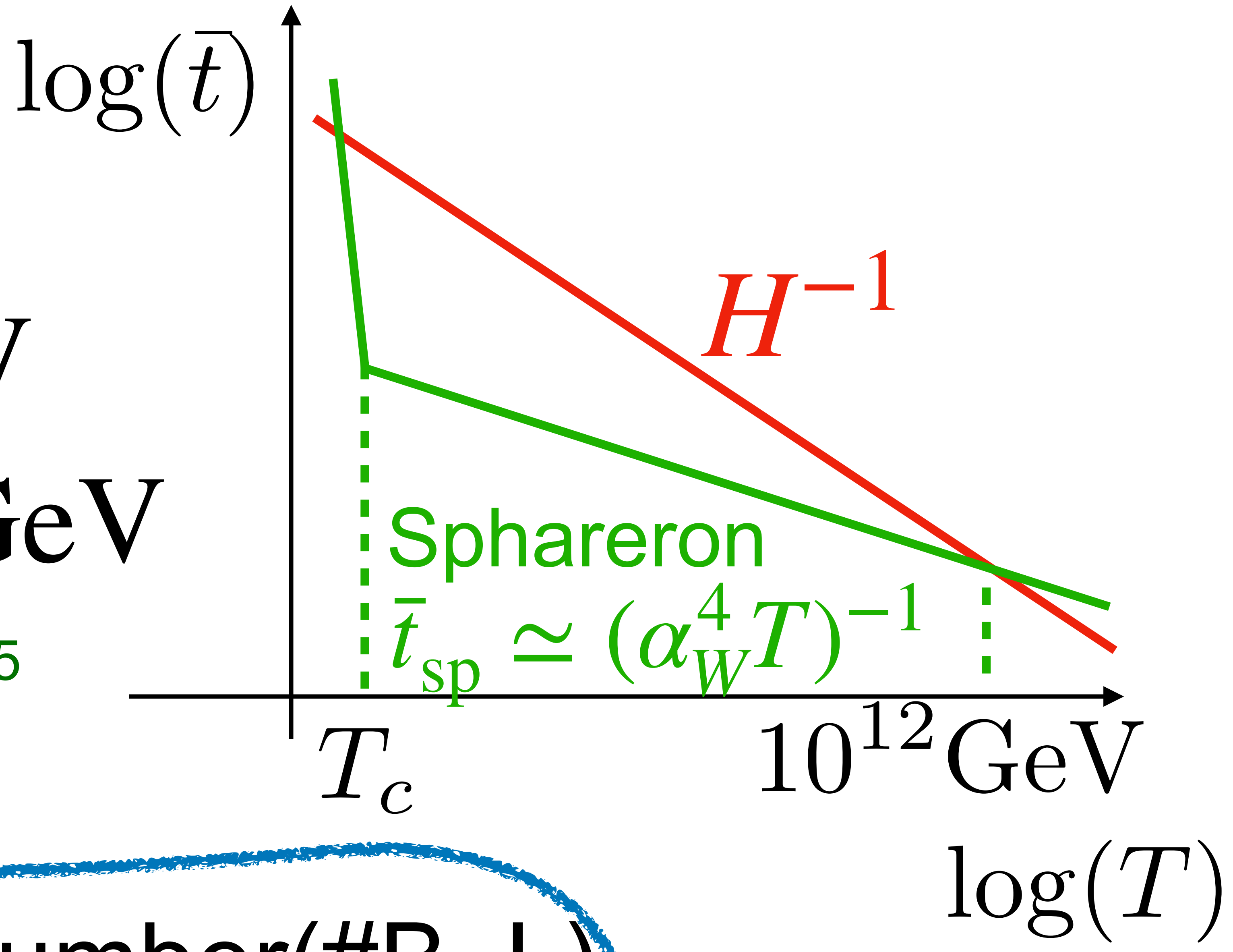
Leptogenesis

Spharelon

An unstable static solution to EOM in the SU(2) gauge theory.

Spharelon leads to the effective operator $O_{B+L} = \Pi_i (q_{Li} q_{Li} q_{Li} \ell_{Li})$

B+L is violated due to the vacuum structure,
while B–L is conserved

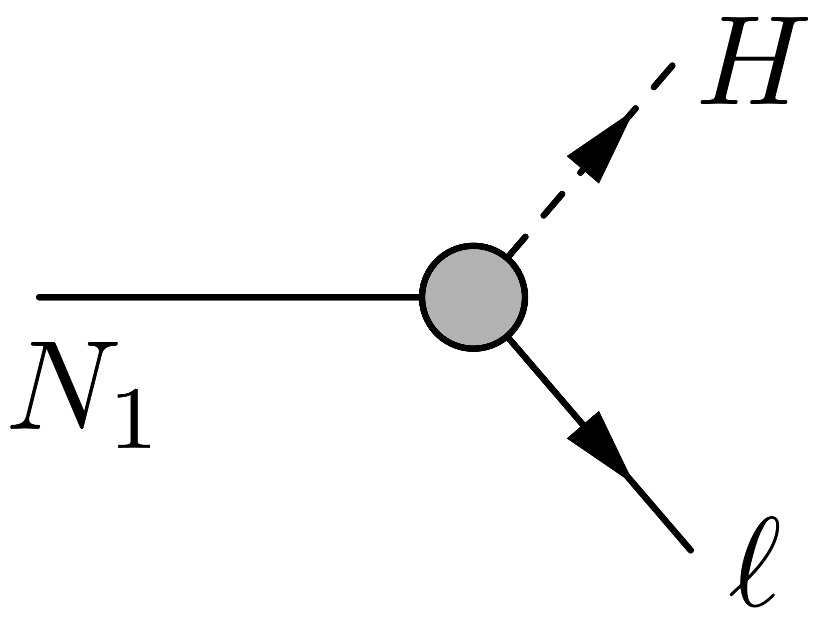


The Spharelon is in the thermal bath at $T_* \leq T \leq 10^{12}$GeV

$T_c = (159 \pm 1)$GeV and $T_* = (131.7 \pm 2.3)$GeV

M. D'Onofrio, K. Rummukainen, A. Tranberg, 1404.3565

Heavy neutrino decay



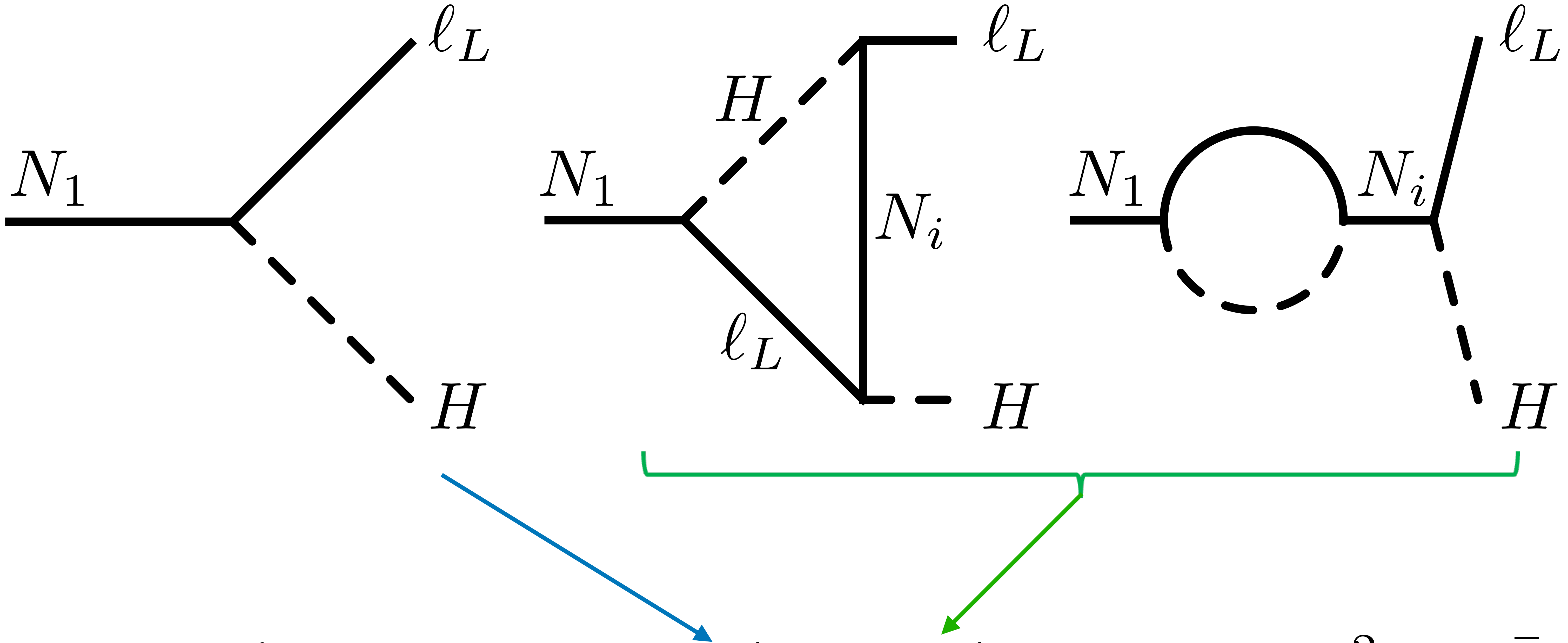
CP violating decay can produce Lepton number(#B–L)

RNH is a Majorana particle → $N_1 = N_1^c$

#B

If CP is violated, $\Gamma(N_1 \to \ell_L + H) \neq \Gamma(N_1 \to \ell^c + H^*)$

CP violation in RHN decay



$N_1 \to \ell_L H \qquad \mathcal{M} = c_0 \mathcal{A}_0 + c_1 \mathcal{A}_1 \qquad |\mathcal{A}_i|^2 = |\bar{\mathcal{A}}_i|^2 \quad \mathcal{A}_0 \mathcal{A}_1^* = \bar{\mathcal{A}}_0 \bar{\mathcal{A}}_1^*$

$N_1 \to \ell_L^c H^* \qquad \bar{\mathcal{M}} = c_0^* \bar{\mathcal{A}}_0 + c_1^* \bar{\mathcal{A}}_1$

$$\epsilon_1 = \frac{\Gamma(N_1 \to \ell_L H) - \Gamma(N_1 \to \ell_L^c H^*)}{\Gamma(N_1 \to \ell_L H) + \Gamma(N_1 \to \ell_L^c H^*)} = -2\frac{\mathrm{Im}(c_0^* c_1)}{|c_0|^2} \frac{\int \mathrm{Im}(\mathcal{A}_0^* \mathcal{A}_1) dQ}{\int |\mathcal{A}_0|^2 dQ}$$

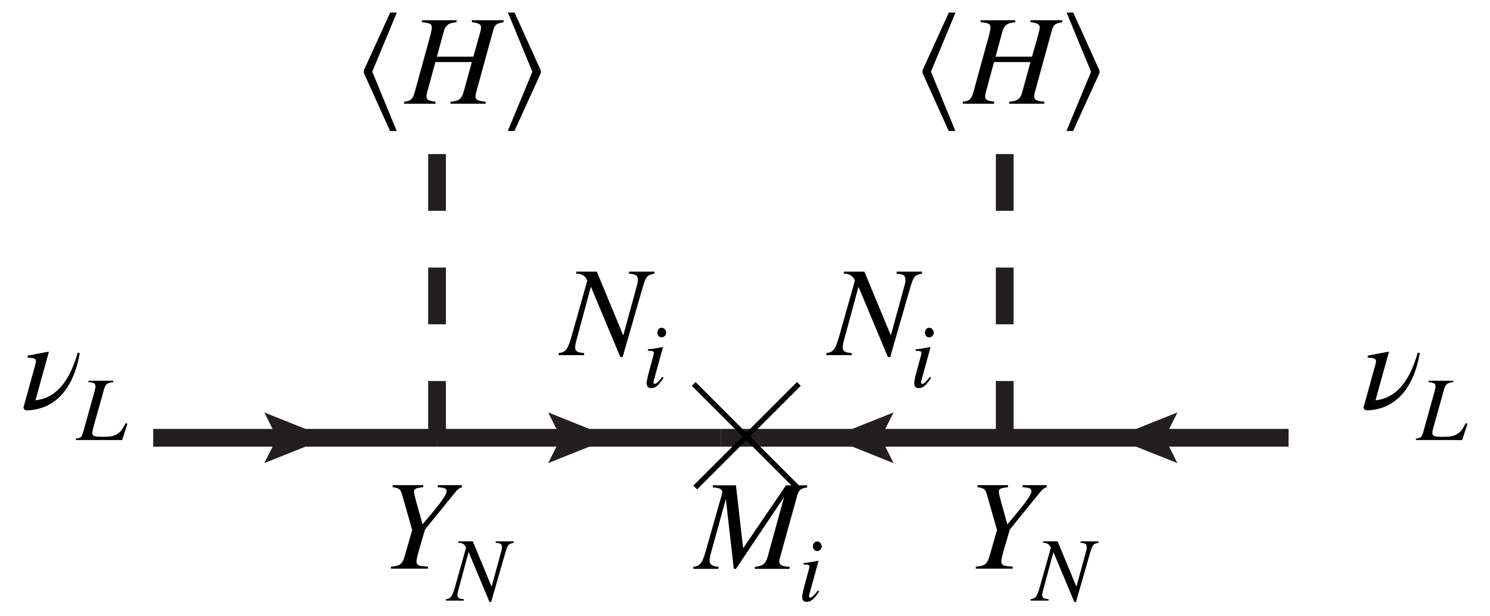
Davidson-Ibarra bound

For $M_1 \ll M_{2,3}$,

$$\epsilon_1 \simeq \frac{3M_1}{16\pi}\sum_i \frac{\mathrm{Im}\left((Y_N Y_N^\dagger)_{1j} M_j^{-1} (Y_N Y_N^\dagger)_{1j}\right)}{(Y_N Y_N^\dagger)_{11}} + \mathcal{O}(M_j^2/M_1^2)$$

In the seesaw model, the neutrino mass matrix is given by

$$m_\nu = \frac{v^2}{2} Y_N^T M^{-1} Y_N$$



$$\Rightarrow \quad Y_N = \frac{\sqrt{2}}{v}\sqrt{\hat{M}}R\sqrt{\hat{m}}U^\dagger$$

J.A. Casas and A. Ibarra, NPB618, 171

$\hat{M} = \mathrm{diag}(M_1, M_2, M_3)$

$\hat{m} = \mathrm{diag}(m_1, m_2, m_3)$

U: PMNS matrix

$RR^T = I$

$$\Rightarrow \quad \epsilon_1 = \frac{3M_1}{8\pi v^2}\frac{\sum_i \mathrm{Im}(m_i R_{1i}^2)}{\sum_i m_i |R_{1i}^2|} \leq \frac{3M}{8\pi v^2}\frac{|\Delta m_{\mathrm{atm}}^2|}{m_1 + m_3} \simeq 10^{-6}\left(\frac{M_1}{10^{10}\mathrm{GeV}}\right)$$

Independent of U !

Large CP violation requires heavy RHN

S. Davidson, A. Ibarra, PLB535, 25

Boltzmann equation

The Boltzmann equation is used for quantitative estimation of the produced #B-L

Decay Scattering

$$z = \frac{M_1}{T}$$

$$zH\frac{dN_N}{dz} = -(\Gamma_D + \Gamma_S)(N_N - N_N^{\rm eq})$$

e.g. Inverse decay

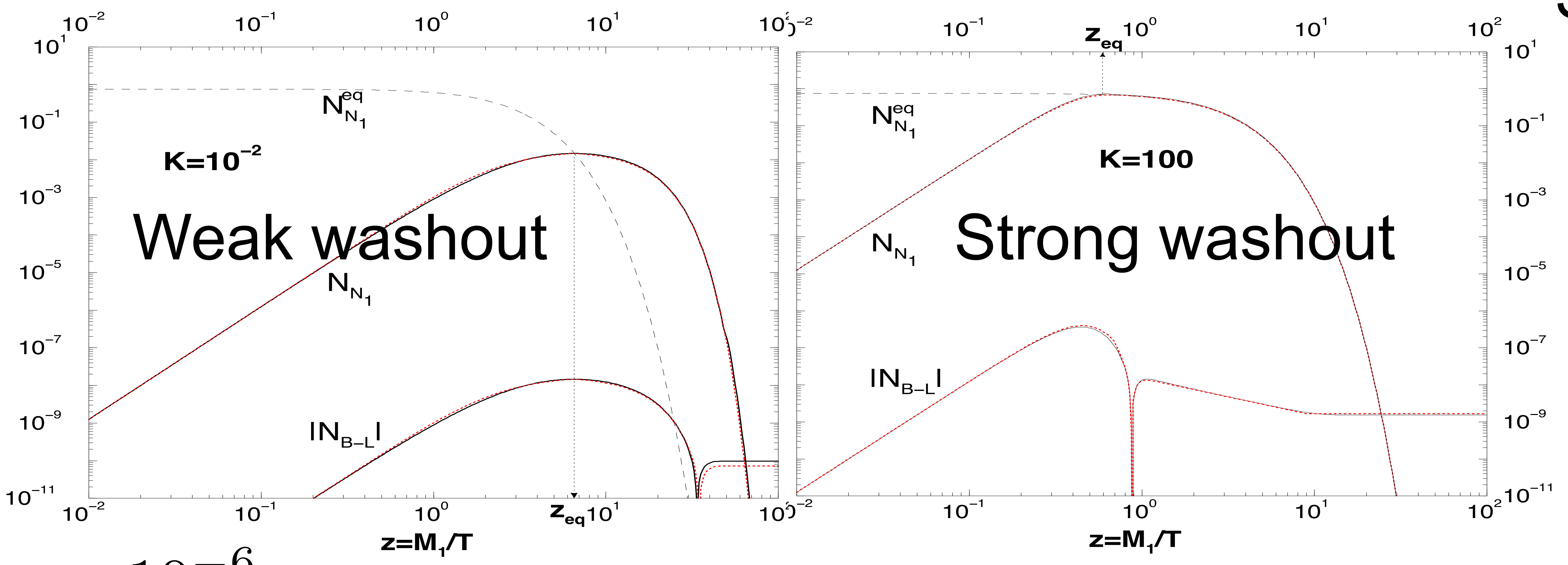
$$zH\frac{dN_{B-L}}{dz} = -\epsilon_1\Gamma_D(N_N - N_N^{\rm eq}) - \Gamma_W N_{B-L}$$

Asymmetry pruduction Washout

Strength of the washout:

$$K = \frac{\Gamma_D(z=\infty)}{H(z=1)} \simeq \frac{\tilde{m}_1}{10^{-3}\mathrm{eV}}$$

$$\tilde{m}_1 = \frac{(Y_N Y_N^\dagger)_{11}}{M_1}\langle H\rangle^2$$



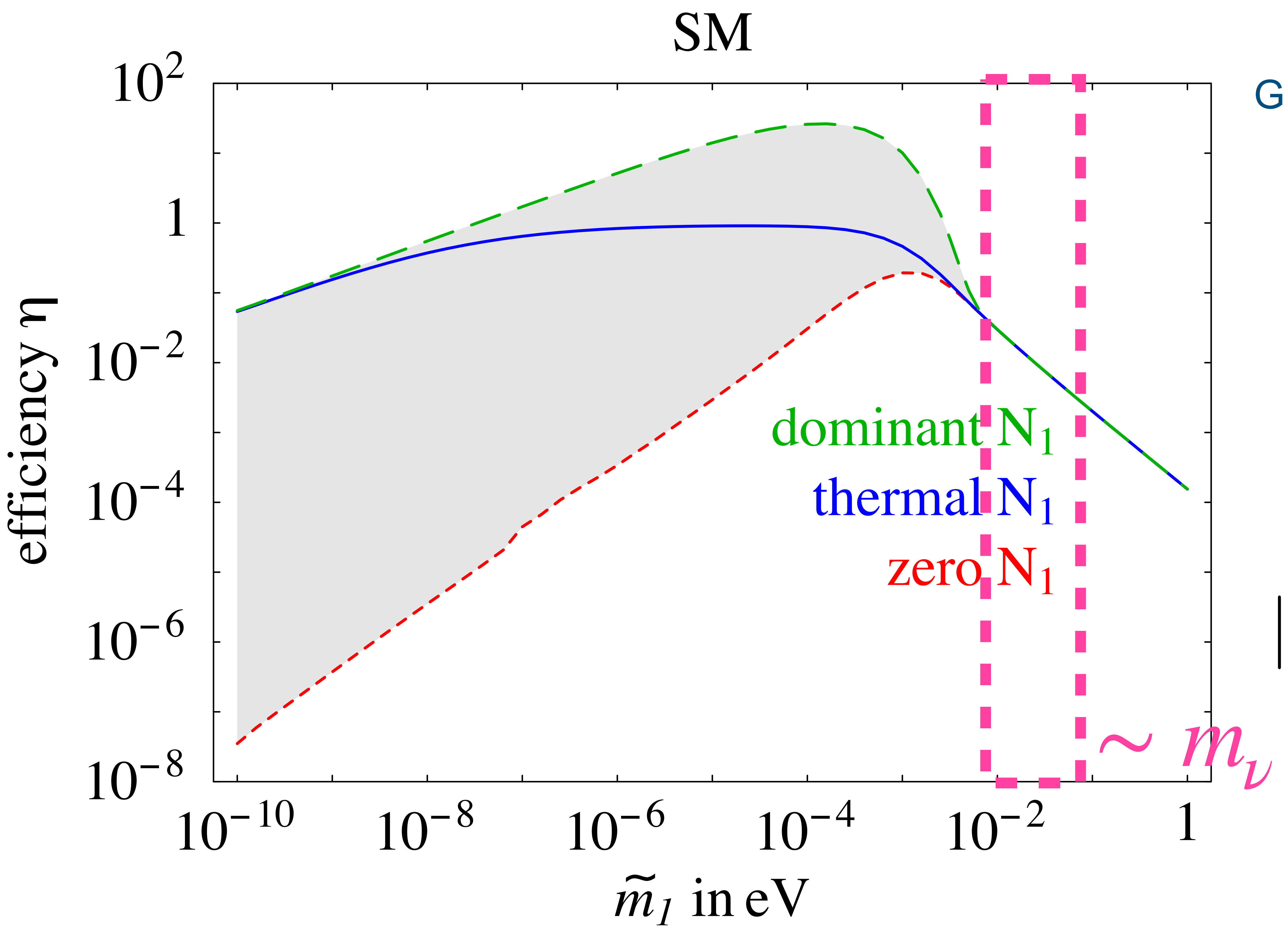
$\epsilon_1 = 10^{-6}$

W. Buchmüller,P. Di Bari, and M. Plümacher, hep-ph/0401240

Lower bound on RHN mass

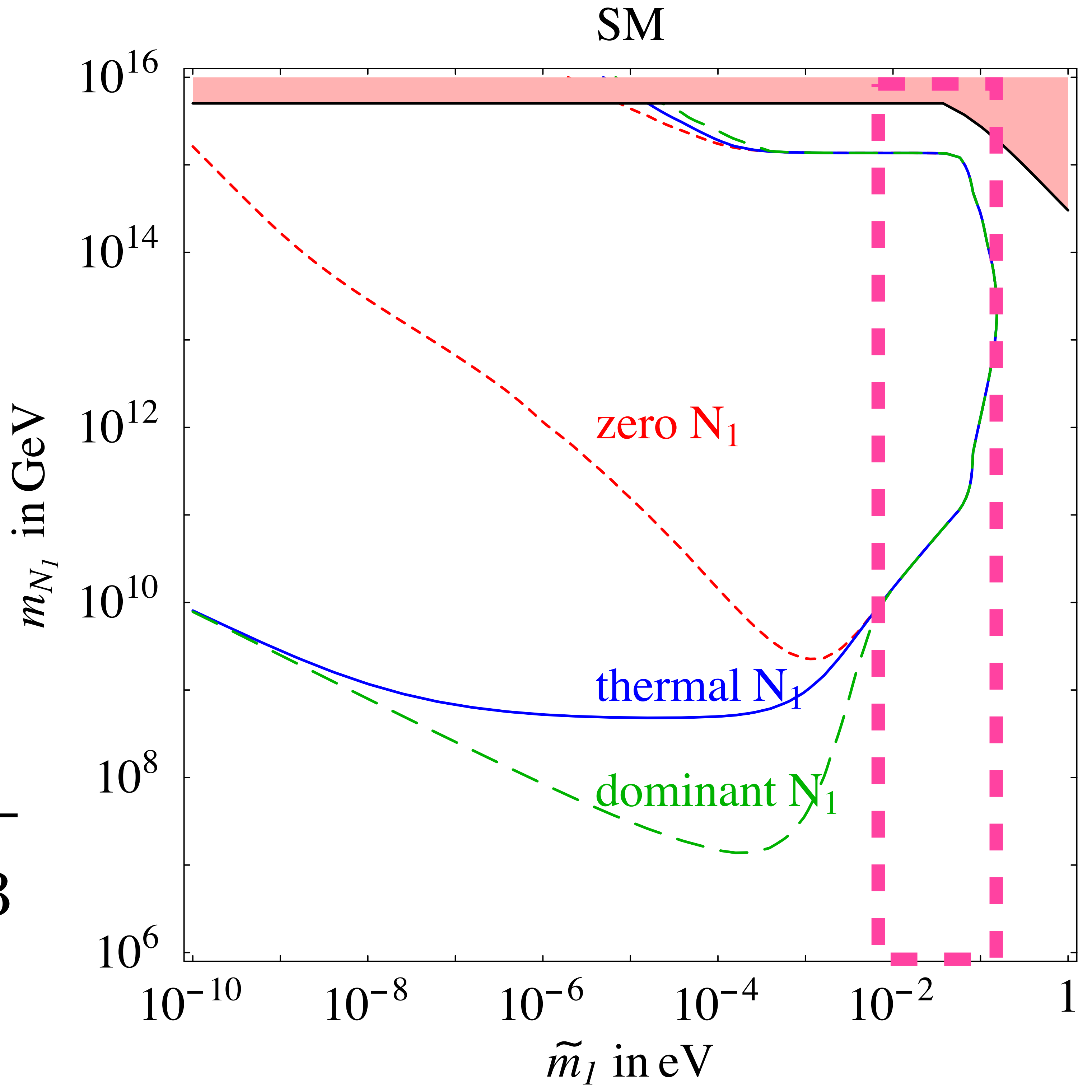
After combining all ingredients, the Baryon asymmetry is estimated as

$$\eta_B = \frac{n_B}{s} \simeq -1.38 \times 10^{-3} \epsilon_1 \eta$$ Efficiency factor



G. F. Guidce et al., hep-ph/0310123

$$|\epsilon_1| \leq \frac{3M_1}{8\pi v^2}\frac{|\Delta m^2_{\rm atm}|}{m_1 + m_3}$$



$M_1 \geq 10^{8-10}$GeV is necessary

It's very high scale.

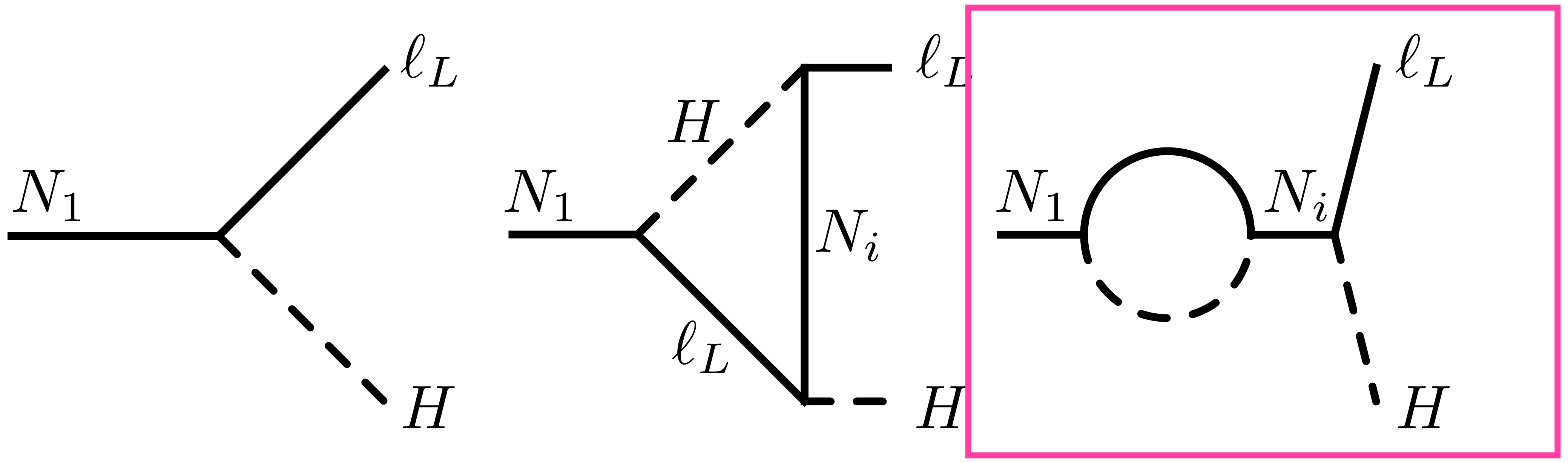
Examples of Low scale Leptogenesis

Can we consider a Leptogenesis scenario with much lighter RHN?

How to go beyond the Davidson-Ibarra bound?

Resonant Leptogenesis

L. Covi, E. Roulet, F. Vissani, PLB384, 169; A. Pilaftsis, T.E.J. Underwood, NPB692,303;…



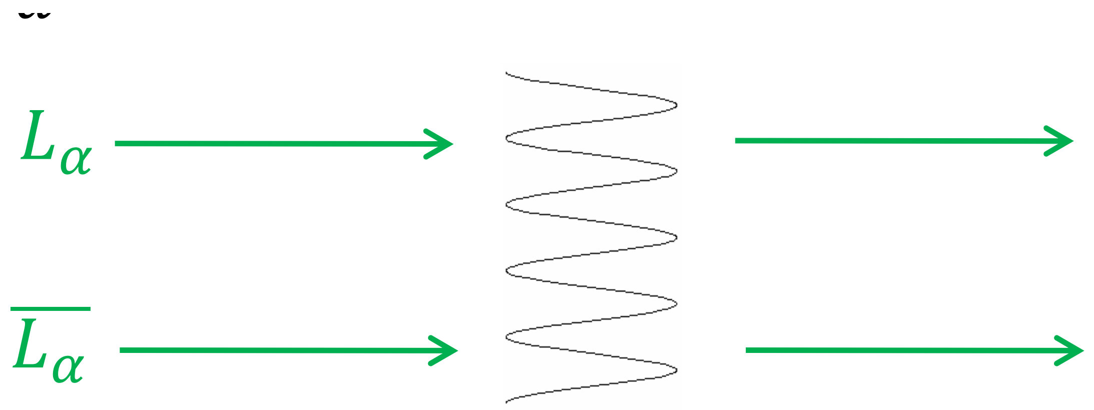
$$\epsilon_1 \propto \frac{(M_1^2 - M_j^2) M_1 \Gamma_j}{(M_1^2 - M_j^2)^2 + M_1^2 \Gamma_j^2}$$

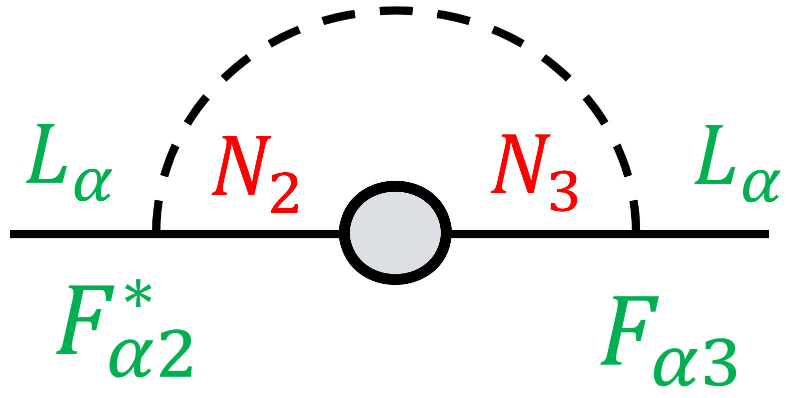
CPV can be maximized to be O(1) when $M_j - M_1 \simeq \frac{1}{2}\Gamma_1 = \frac{M_1}{16\pi}(Y_N Y_N^\dagger)_{11} \ll M_1$

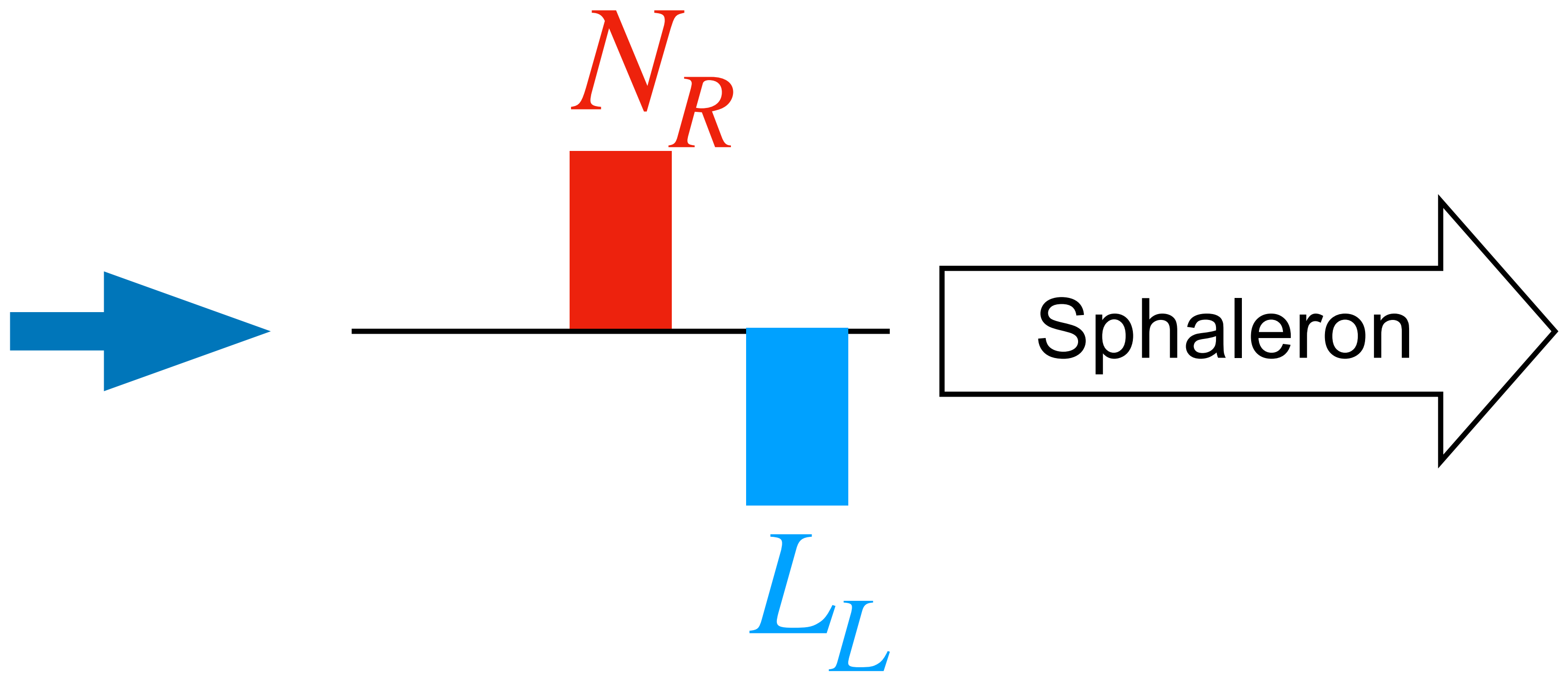
e.g. For $M_1 \sim \mathrm{TeV}$, $M_2 - M_1 \sim \mathrm{keV}$

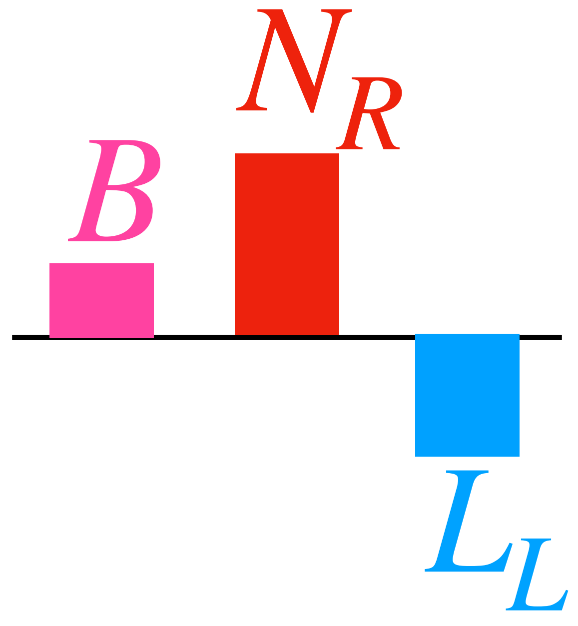
Baryogenesis via neutrino oscillation

E.K. Akhmedov, V.A. Rubakov, A.Y. Smirnov, PRL81, 1359 ; T. Asaka, M. Shaposhnikov, PLB620, 17





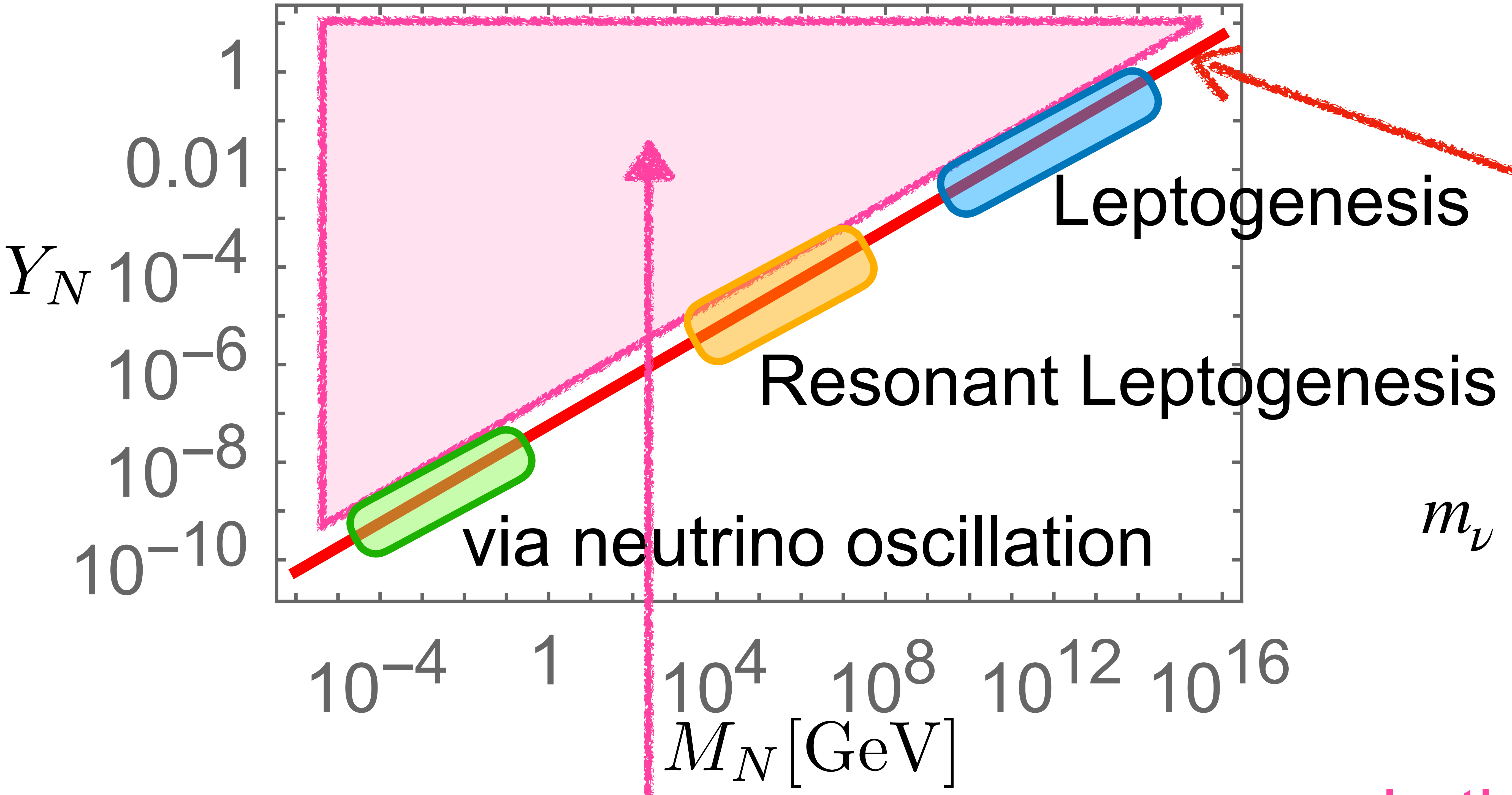




From Asaka san's slide

Enhancement of CPV by large YN

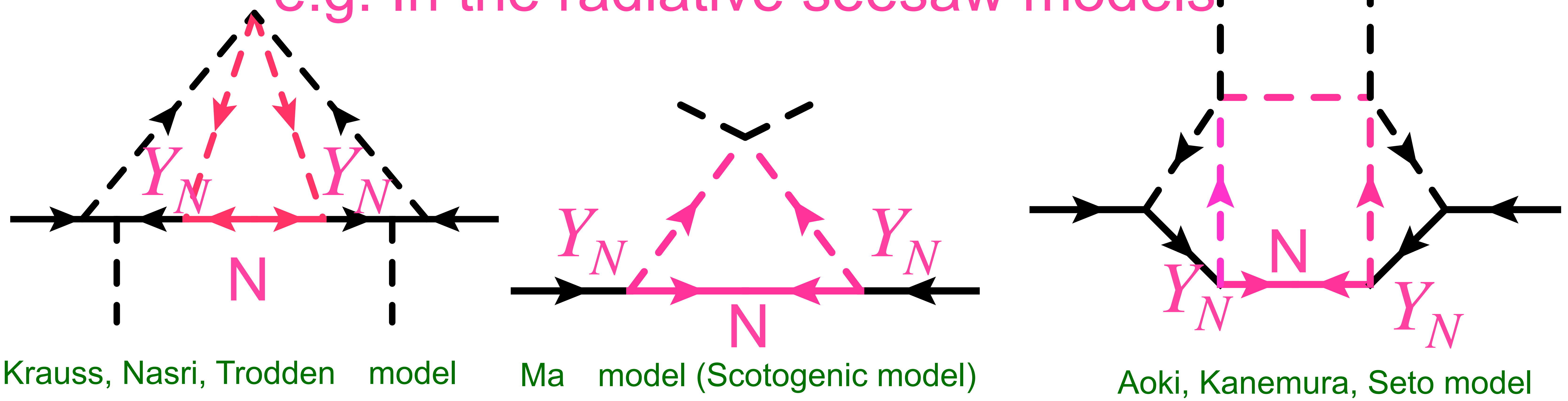
Another way to violate the Davidson-Ibarra bound is breaking the seesaw relation



$$m_\nu = \frac{v^2}{2} Y_N^T M^{-1} Y_N \quad \Rightarrow \quad Y_N \sim \frac{1}{v}\sqrt{m_\nu M}$$

Without the seesaw relation, this space can be used

e.g. In the radiative seesaw models



Leptogenesis in the KNT model

O. Seto, T.S., and T. Tsuyuki, 2211.10059 (v2)

KNT model

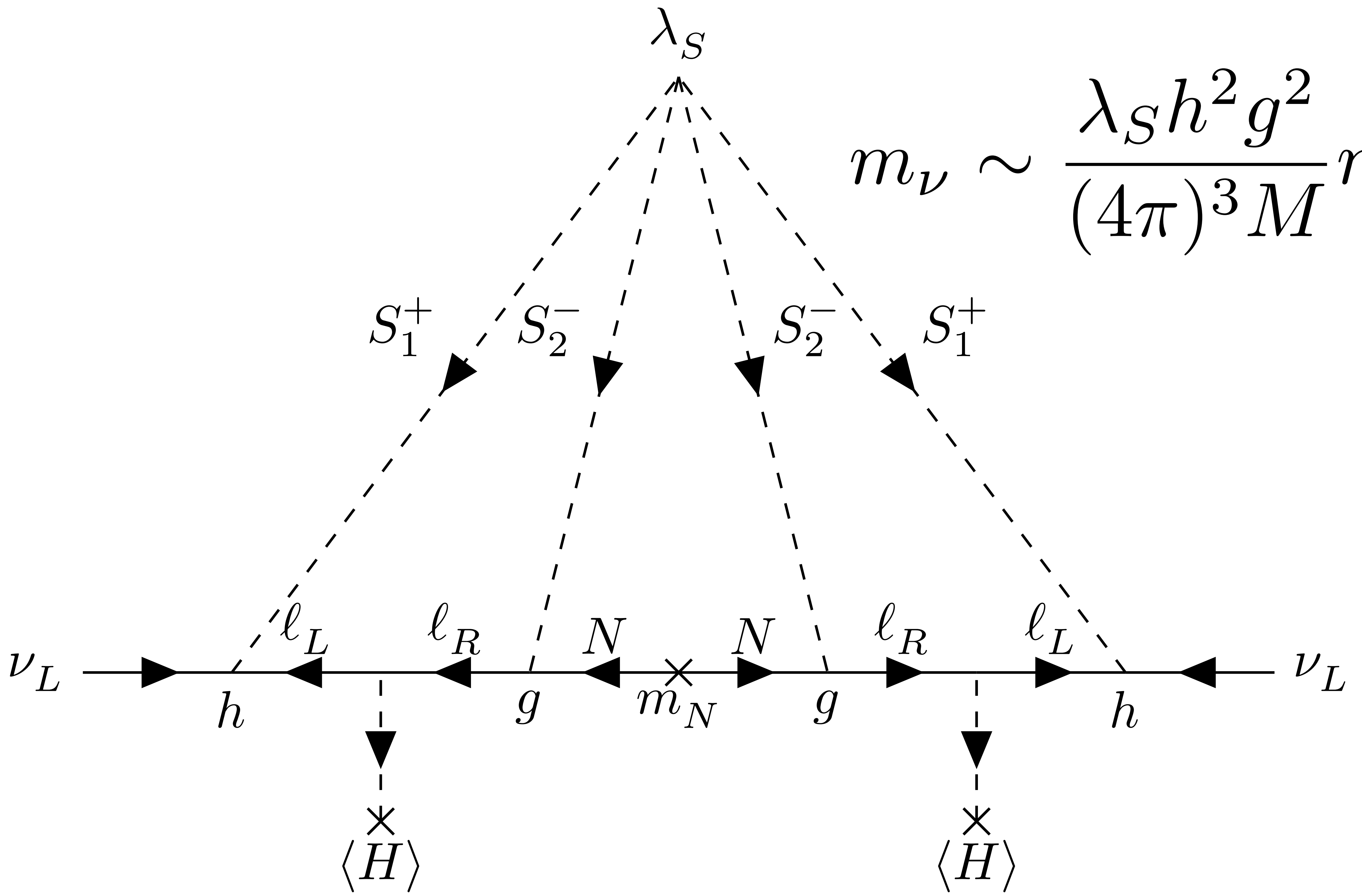
KNT model is a radiative seesaw model

L. Krauss, S. Nasri, and M. Trodden, PRD67, 085002 (2003)

	SU(3)	SU(2)	U(1)	Z_2
N_i	**1**	**1**	0	–
S_1^+	**1**	**1**	1	+
S_2^-	**1**	**1**	–1	–

- Tiny neutrino mass
- Dark matter candidate

m_ν is generated at the three loop level



$$m_\nu \sim \frac{\lambda_S h^2 g^2}{(4\pi)^3 M} m_\ell^2$$

All the dimensionless couplings are less than one

The mass scale M have an upper limit

$M < \mathcal{O}(100\ \mathrm{TeV})$

O. Seto, T.S. and T. Tsuyuki, arXiv:2202.00931

Leptogenesis in the KNT model

In the KNT model, N_1 is a DM candidate

The Lepton asymmetry is produced by N_2 decay: $N_2 \to S_2^- + e_{Ri}^+$ $\overset{\not{CP}}{\longleftrightarrow}$ $N_2 \to S_2^+ + e_{Ri}^-$

The Lepton asymmetry → #B via Sphaleron $Y_B = \frac{n_B}{s} = -\frac{32}{89} Y_{e_R}$

There are three big issues in this scenario

- $Y_{S_2} = -Y_{e_R}$ ➡ The late-time decay of $S_2^\pm$ washes out #L $N_2 \to S_2^\mp + e_{Ri}^\pm$, $\hookrightarrow N_1 + e_{Rj}^\mp$

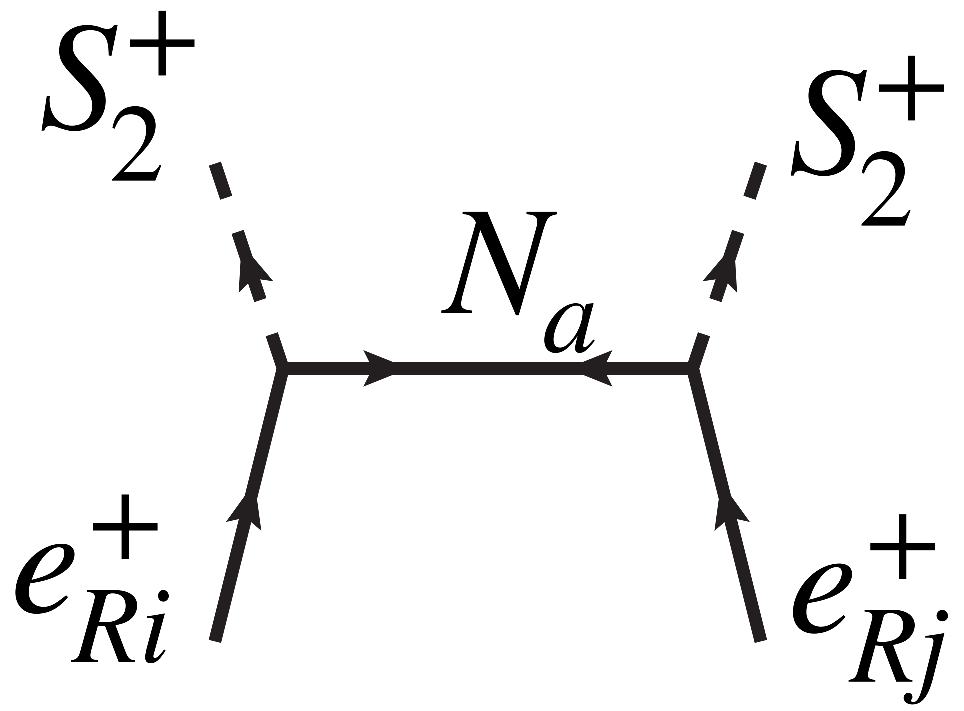
  Sphaleron should decoupled before $S_2^\pm$ decay is completed

  m_{S_2} cannot be much larger than T_*

- $|g_{2i}| \simeq \mathcal{O}(10^{-6})$ is required for $\Gamma_N/H < 1$ at $T \simeq M_2$

  N_2 cannot contribute to M_ν

- Washout by $\Delta L = 2$ scattering is significant



Neutrino mass

N_1 and N_3 contribute to M_ν

$$M_\nu \simeq \frac{\lambda_S}{4(4\pi)^3 m_{S_1}} \begin{pmatrix} 0 & h_{12} & h_{13} \\ -h_{12} & 0 & h_{23} \\ -h_{13} & -h_{23} & 0 \end{pmatrix} \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} g^T \begin{pmatrix} f_1 & 0 \\ 0 & f_3 \end{pmatrix} g \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \begin{pmatrix} 0 & -h_{12} & -h_{13} \\ h_{12} & 0 & -h_{23} \\ h_{13} & h_{23} & 0 \end{pmatrix}$$

Loop function $f_a = (M_a^2/m_{S_2}^2, m_{S_1}^2/m_{S_2}^2) \lesssim 1$

A simple example:

$$g = \begin{pmatrix} 0 & 0 & g_{13} \\ 0 & g_{32} & g_{33} \end{pmatrix}$$

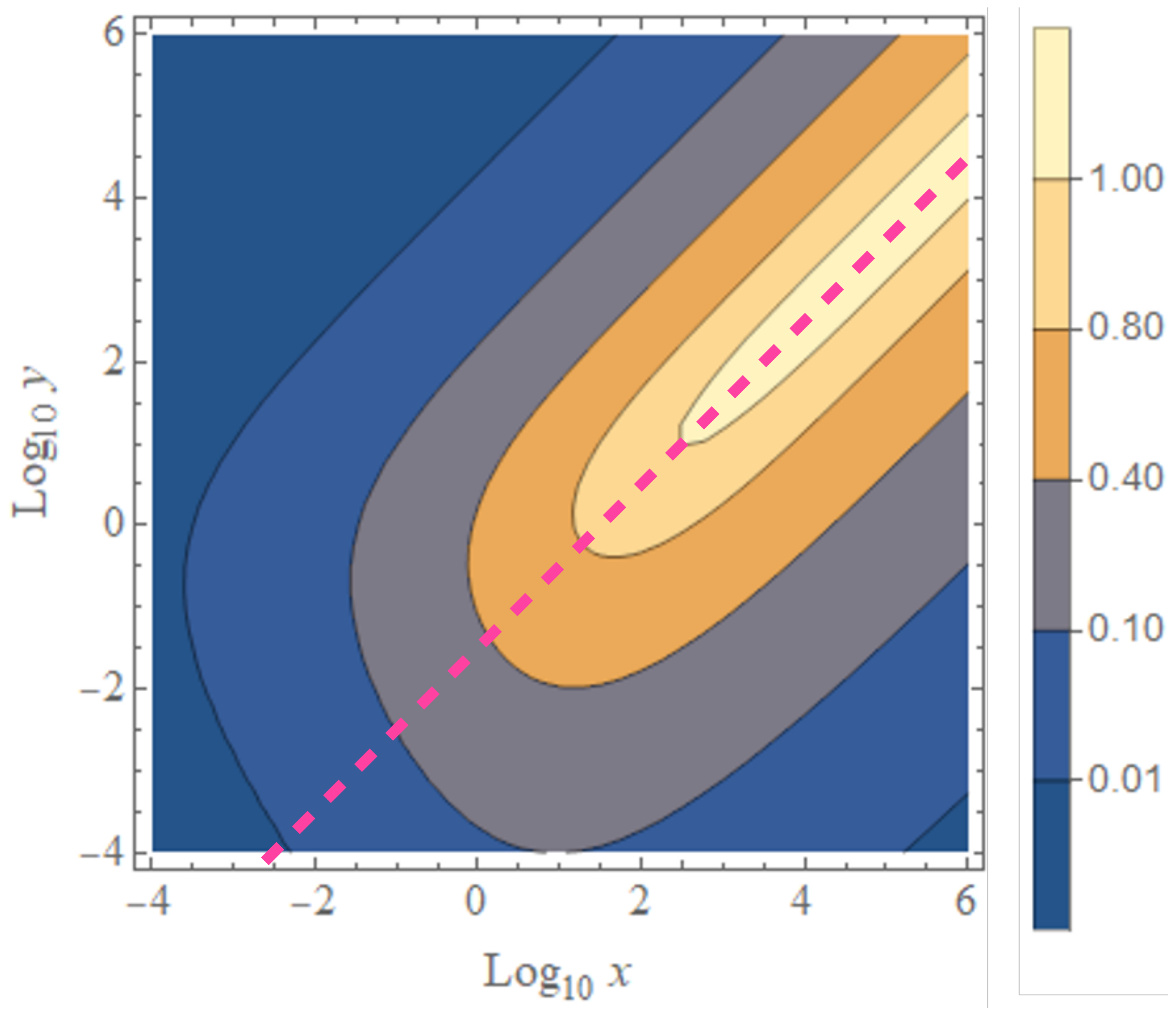
To avoid $\tau \to \mu\gamma$ (the 0 in row 1, column 2)

DM (g_{13})

ν-osc (g_{32}, g_{33})

Negligible contribution to M_ν (first column)

It tends to cause dangerous $\mu \to e\gamma$

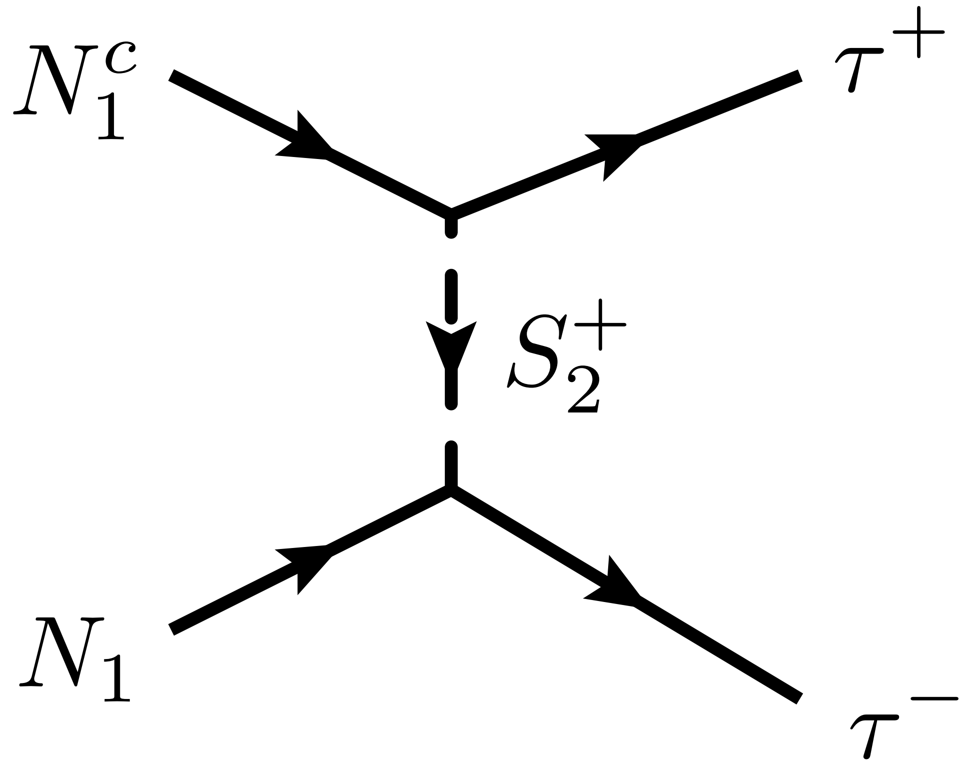


O. Seto, TS, T. Tsuyuki, arXiv:2202.00931

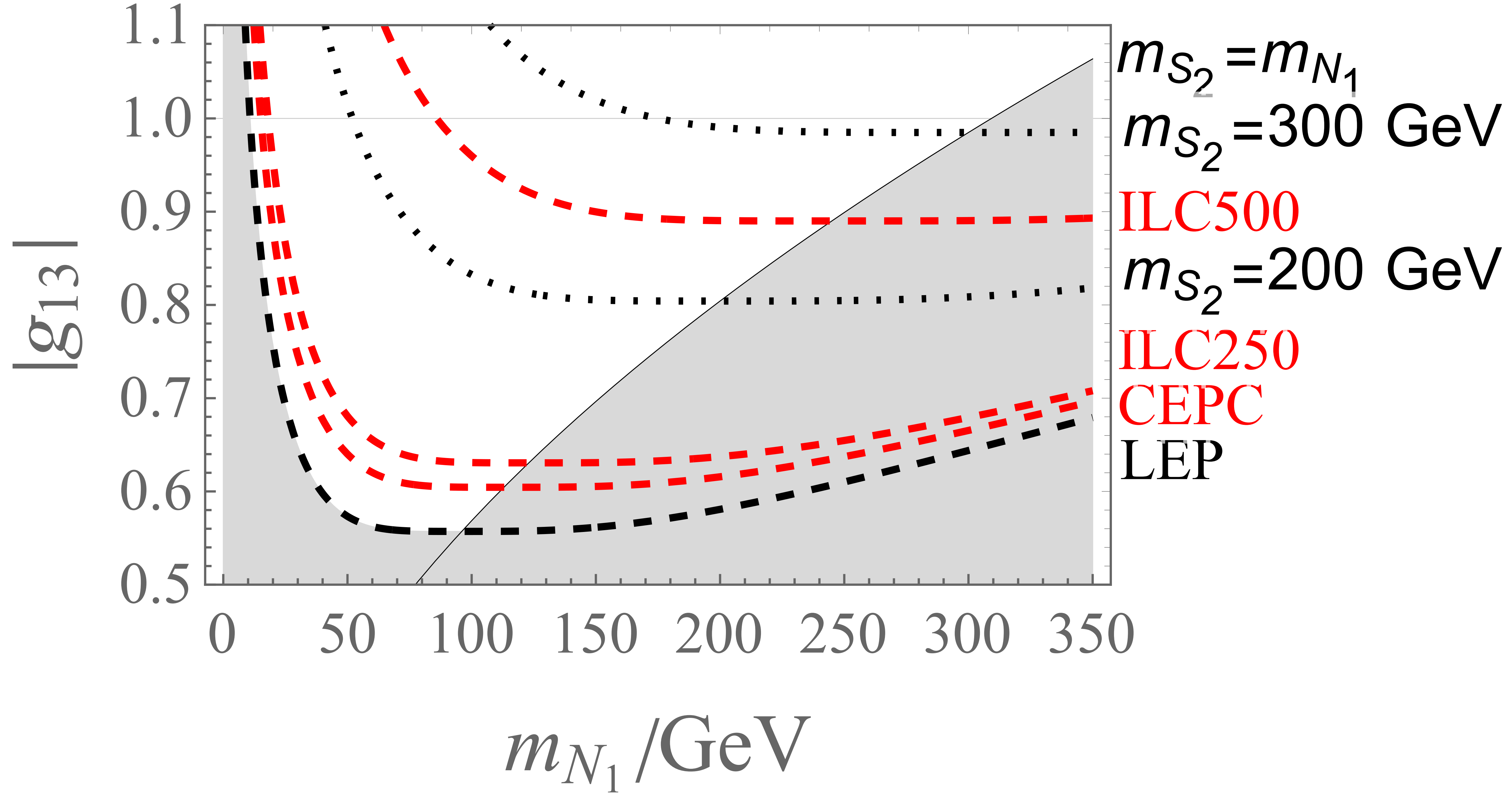
Dark matter in the KNT model

The annihilation of the DM: $\langle \sigma v \rangle \simeq \frac{m_{N_1}^2 (m_{N_1}^4 + m_{S_2}^4)}{8\pi (m_{N_1}^2 + m_{S_2}^2)^4} |g_{1\tau}|^4 \frac{1}{x_f}$

$x_f \sim 1/20$



DM abundance is $\Omega_{N_1} h^2 \simeq 0.12 \frac{2.9 \times 10^{-9}\ \mathrm{GeV}^{-2}}{\langle \sigma v \rangle}$



Light m_{S_2} is prefered!

Four generations RHN

g_{32} and g_{33} are large ➡ $\ell_i^\pm \ell_j^\pm \to S_2^\pm S_2^\pm$ ($\ell_{i,j} = \tau$ or μ) is fast

$\Delta_\tau + \Delta_\mu$ is washed out too fast

To produce Δ_e, large g_{31} is necessary,

but the washout also becomes significant and $\mathrm{Br}(\mu \to e\gamma)$ is too large

We need a fourth RHN for successful leptogenesis!

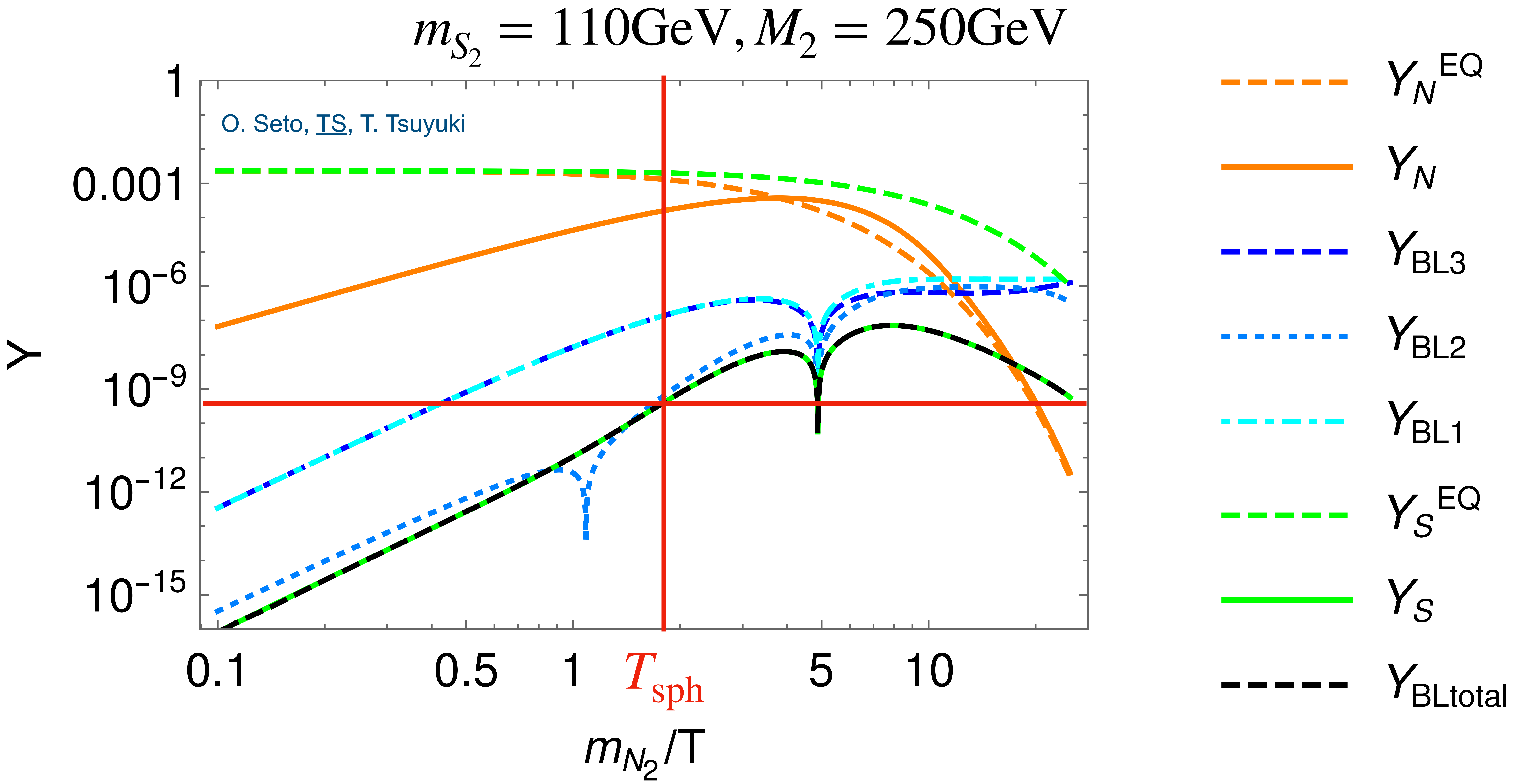
A benchmark example

$$g = \begin{pmatrix} 0 & 0 & g_{13} \\ g_{21} & 0 & 0 \\ 0 & g_{32} & g_{33} \\ g_{41} & 0 & 0 \end{pmatrix}$$

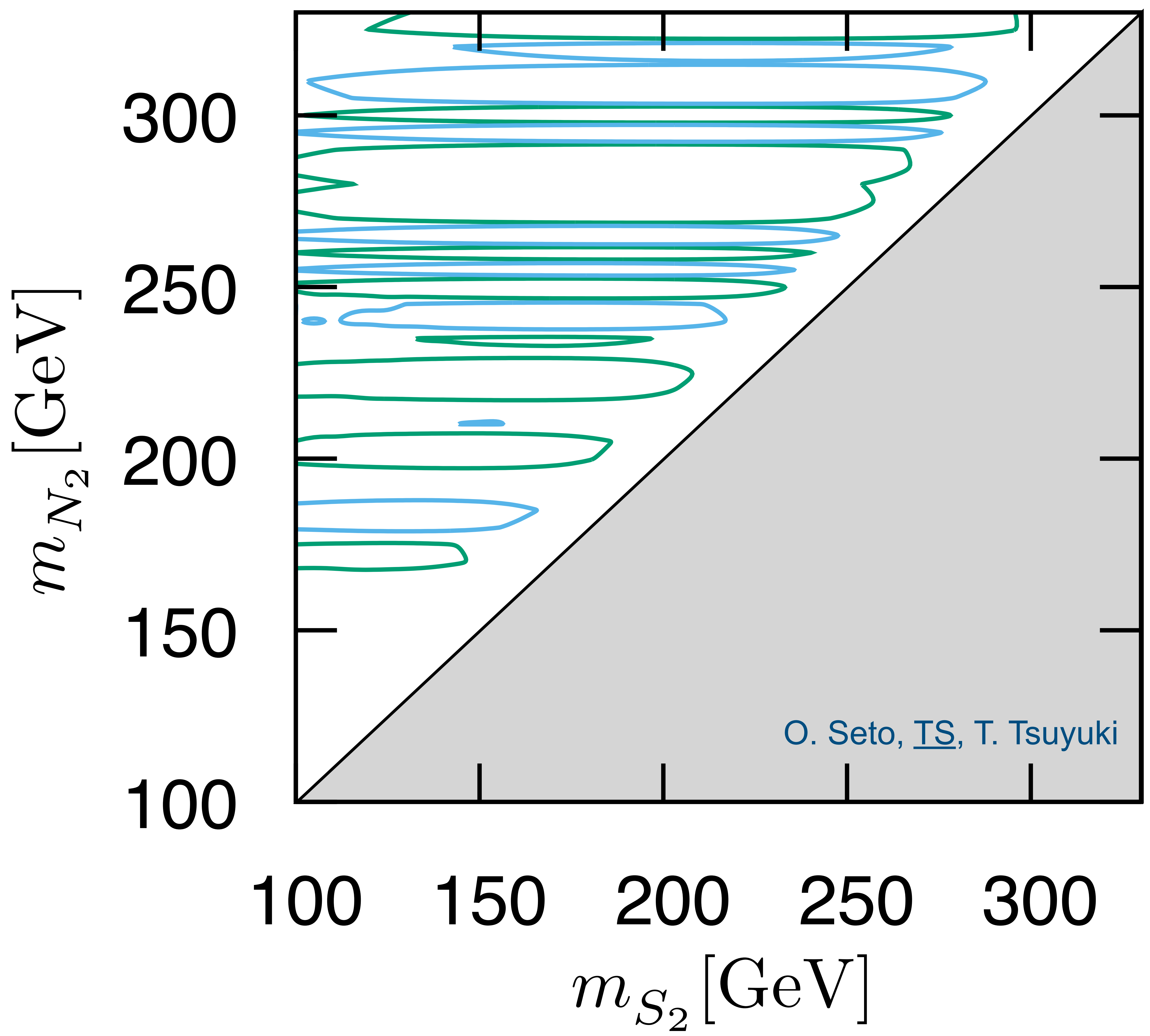
Parameter	Value
m_{S_1}	2.33×10^4 GeV
m_{S_2}	Scanned in $[100, 350]$ GeV
m_{N_1}	Depending on m_{S_2}
m_{N_2}	Scanned in $[100, 500]$ GeV
m_{N_3}	3.67×10^6 GeV
m_{N_4}	1.0×10^8 GeV
λ_S	1.0
(h_{12}, h_{23}, h_{13})	$(0.600e^{-0.0480i},\ 1.0,\ 0.329e^{0.102i})$
$(g_{13}, g_{32}, g_{33}, g_{41})$	$(1.0,\ 1.0,\ -0.053,\ 0.1)$
$\lvert g_{21}\rvert$	Depending on m_{N_2}
$\arg(g_{21})$	$\pi/4$

O. Seto, TS, T. Tsuyuki

Evolutions of Y_{B-L}



Scanning of m_{S_2} and M_2



In the wide range of the mass parameters, enough Y_B can be produced.

$m_{S_2} \sim \mathcal{O}(100)\mathrm{GeV}$ is predicted.

Summary

- Leptogenesis usually requires a very high-scale mass of RHN
- Low-scale leptogenesis is an attractive idea because of its testability.
- We considered a leptogenesis scenario in the KNT model
    - Three RHN case does not work because of too strong washout by $\Delta L = 2$ scattering processes.
    - A case with the fourth-generation RHN provides enough large baryon asymmetry!
    - $m_{S_2} = \mathcal{O}(100)\mathrm{GeV}$ is prefered by both DM and Leptogenesis
    - A good benchmark for complementarity of neutrino, cosmology, and collider.
- Constructing a UV picture of the model will be future work.