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Lepton Flavour Violation and DM constraints in a radiative seesaw model

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O. Seto, T.S., and T. Tsuyuki, 2211.10059 (to be published in PRD)

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Physics Beyond the Standard Model

The Standard Model is a successful model 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

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- Baryogenesis? ← **Leptogenesis**
- What is the Dark Matter?
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A radiative seesaw model

(KNT model)

The SM should be extended at some energy scale

KNT model

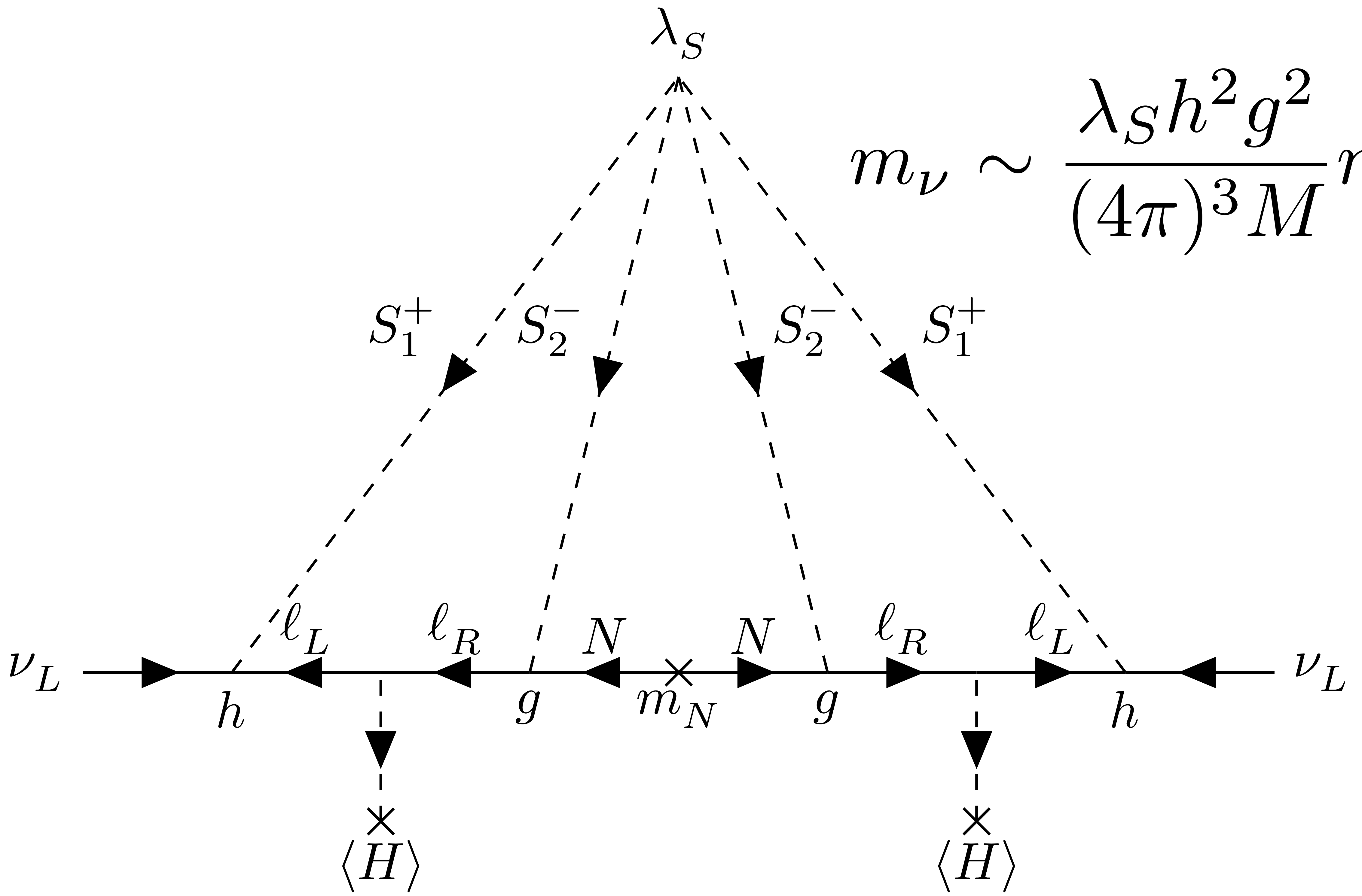
KNT model is a radiative seesaw model

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
- N_1 is a 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

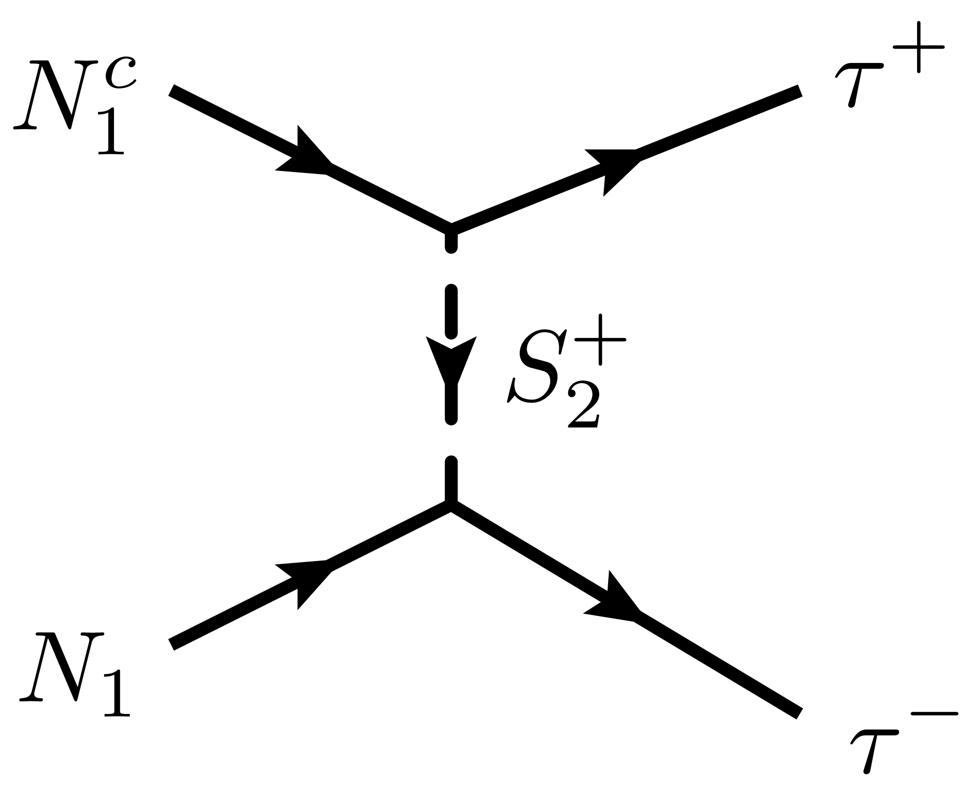
$$M < \mathcal{O}(100\ \mathrm{TeV})$$

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

DM and LFV

O. Seto, TS, T. Tsuyuki, PRD105, 095018(2022)

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



$x_f \sim 1/20$

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

Let us consider a constraint $|g_{1i}| < 1$

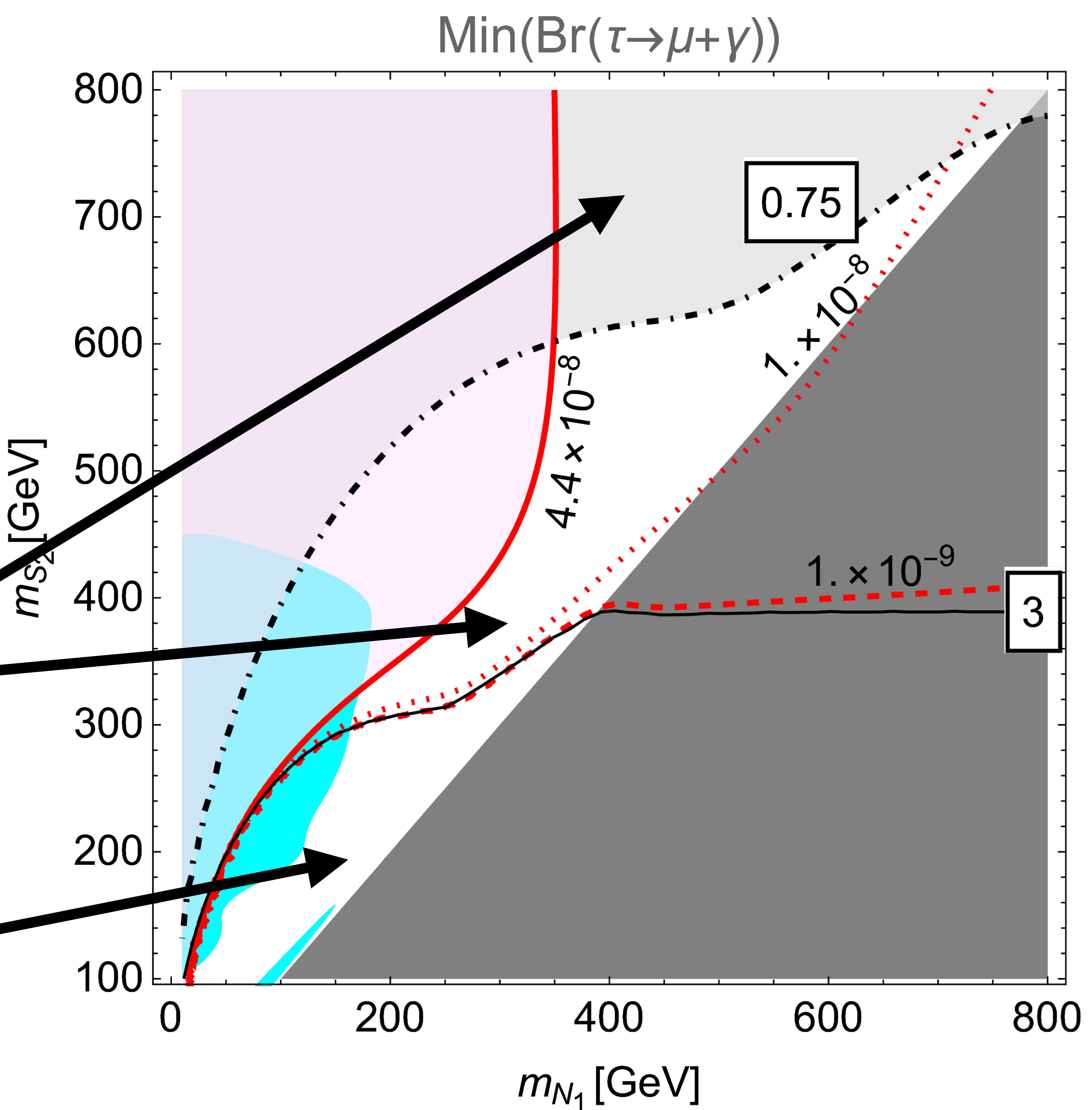
To avoid too large B($\mu \to e\gamma$), $g_{1e}^* g_{1\mu} \simeq 0$ is required

More than 3 g_{1i} are needed

More than 2 g_{1i} are needed

$\tau \to \mu\gamma$ or $\tau \to e\gamma$ can be significantly enhanced

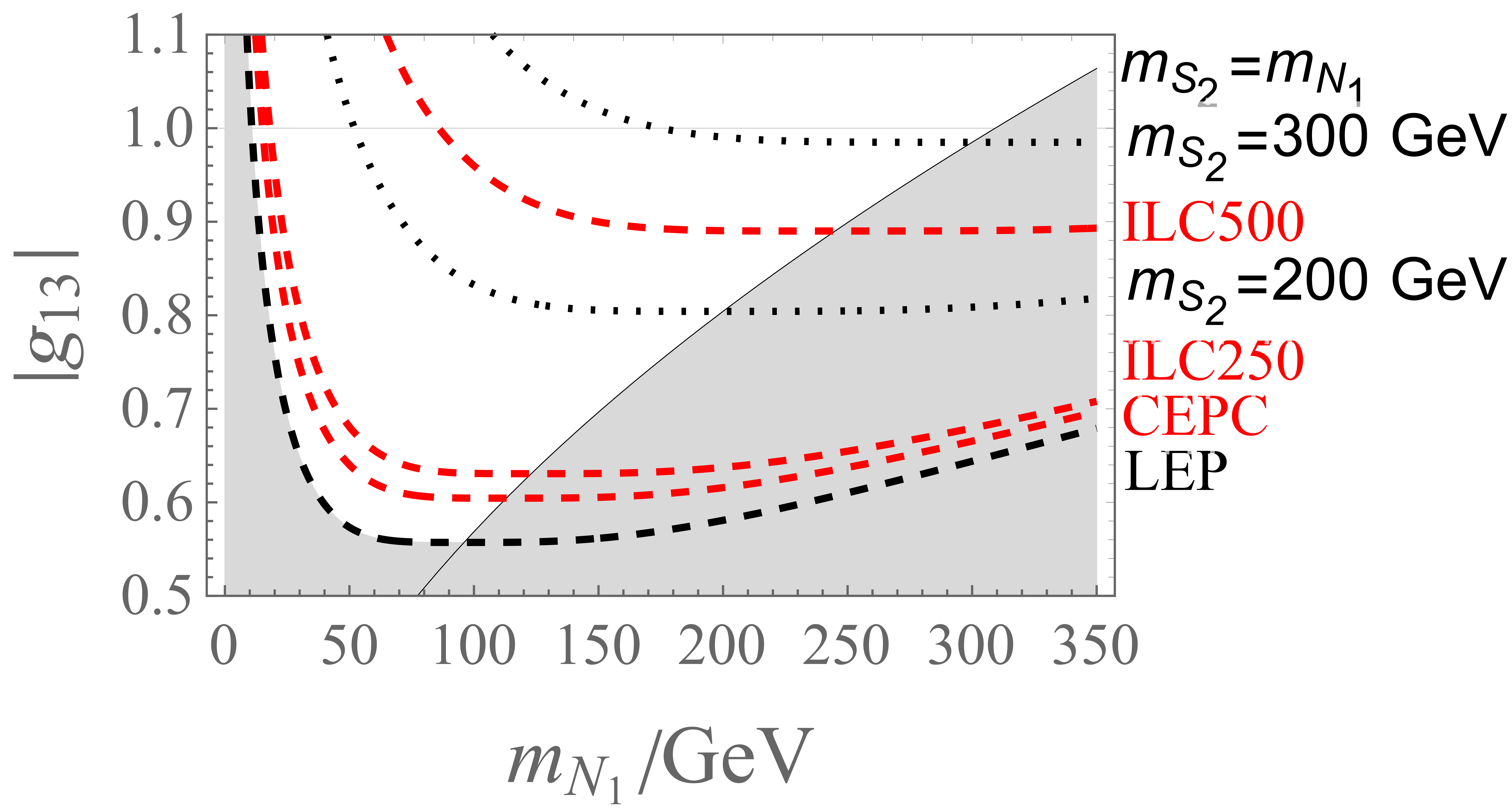
One g_{1i} is enough



DM in the KNT

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

In the case with $g_{1e} = g_{1\mu} = 0$



The scenario can be explored by future lepton collider experiments.

Leptogenesis in the KNT model

How about the Baryogenesis in the KNT model?

Possibility of the thermal leptogenesis

The Lepton asymmetry is produced by N_2 decay: $N_2 \to S_2^- + e_{Ri}^+ \overset{\cancel{CP}}{\longleftrightarrow} N_2 \to S_2^+ + e_{Ri}^-$

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

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

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

M. D'Onofrio, K. Rummukainen, A. Tranberg, PRL113,141602(2014)

We should check whether the sceario can produce enough baryon asymmetry

If not, what kind of model extension is necessary?

Some issues in the scenario

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

  Sphaleron should decoupled before $S_2^{\pm}$ decay is completed $\quad \hookrightarrow N_1 + e_{Rj}^{\mp}$

  $\boxed{m_{S_2} \text{ cannot be much larger than } T_*}$

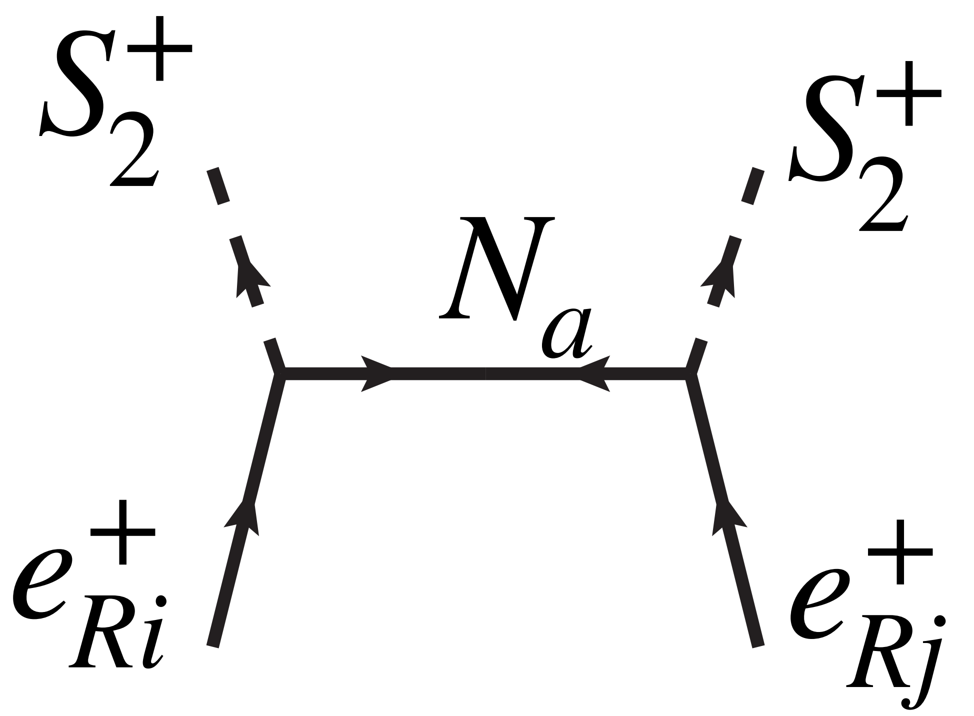
- $|g_{2i}| \simeq \mathcal{O}(10^{-6})$ is required for $N_{N_2} \neq N_{N_2}^{\rm eq}$ at $T \sim M_2$

  N_2 cannot contribute to M_ν

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

$$zH\frac{N_{N_2}}{dz} = -(\Gamma_D + \Gamma_S)(N_{N_2} - N_{N_2}^{\rm eq})$$

$$zH\frac{N_{N_{B-L}}}{dz} = -\epsilon_2\Gamma_D(N_{N_2} - N_{N_2}^{\rm eq}) - \Gamma_W N_{B-L}$$



Inverse decay & Scattering

Nuetrino mass matrix with $g_{2i} \ll 1$

N_2 cannot play a role in 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 $f_a = (M_a^2/m_{S_2}^2, m_{S_1}^2/m_{S_2}^2) \lesssim 1$

Only N_3 contributes to m_ν ⟵ $f_1 \ll f_3$

A simple example:

To avoid $\tau \to \mu\gamma$

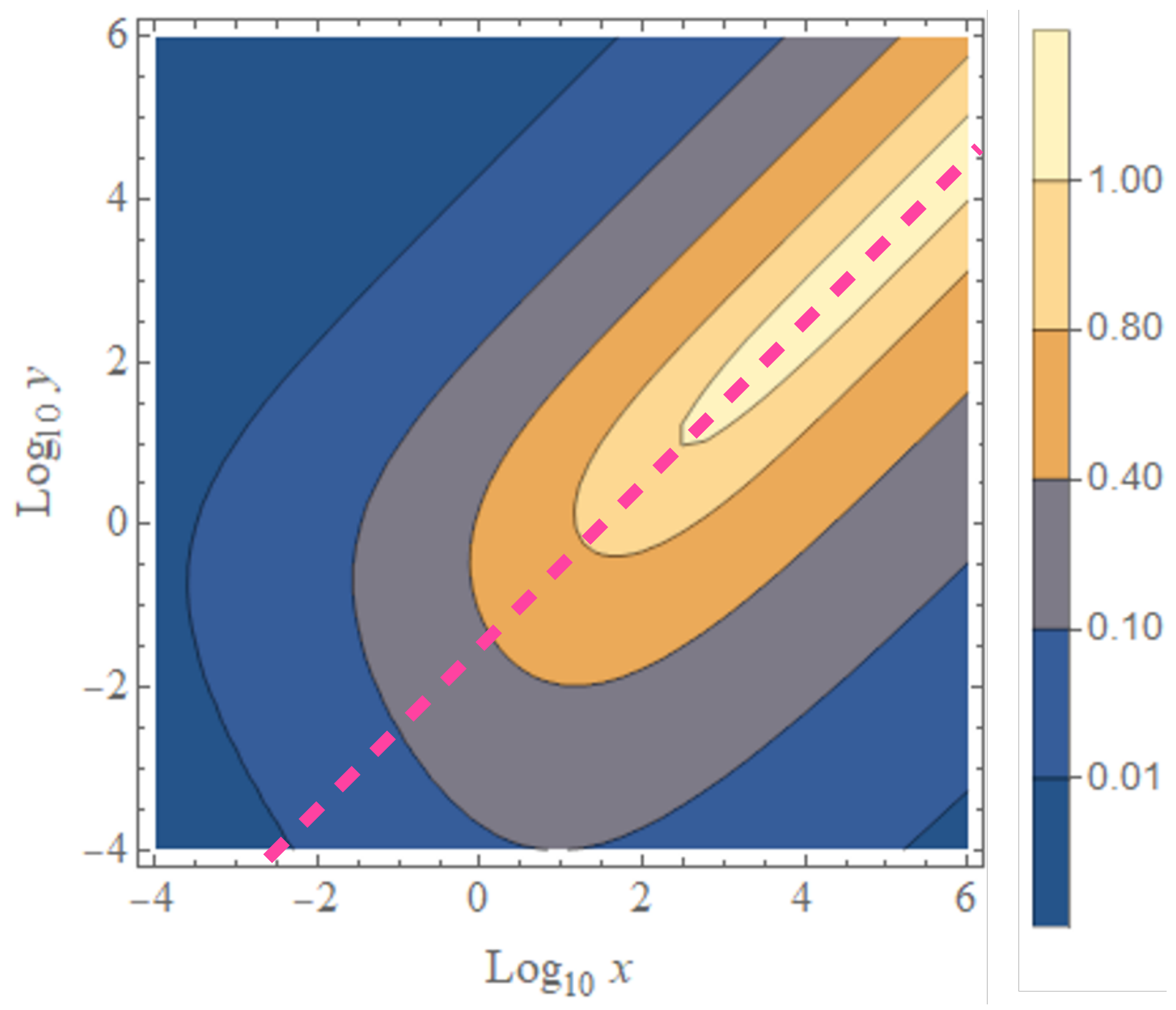
$$g = \begin{pmatrix} 0 & 0 & g_{13} \\ 0 & g_{32} & g_{33} \end{pmatrix}$$

DM

ν-osc

Negligible contribution to M_ν

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



O. Seto, TS, T. Tsuyuki, PRD105, 095018(2022)

We can reproduce an appropriate m_ν

Four generations RHN

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

m_ν ➡ 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!

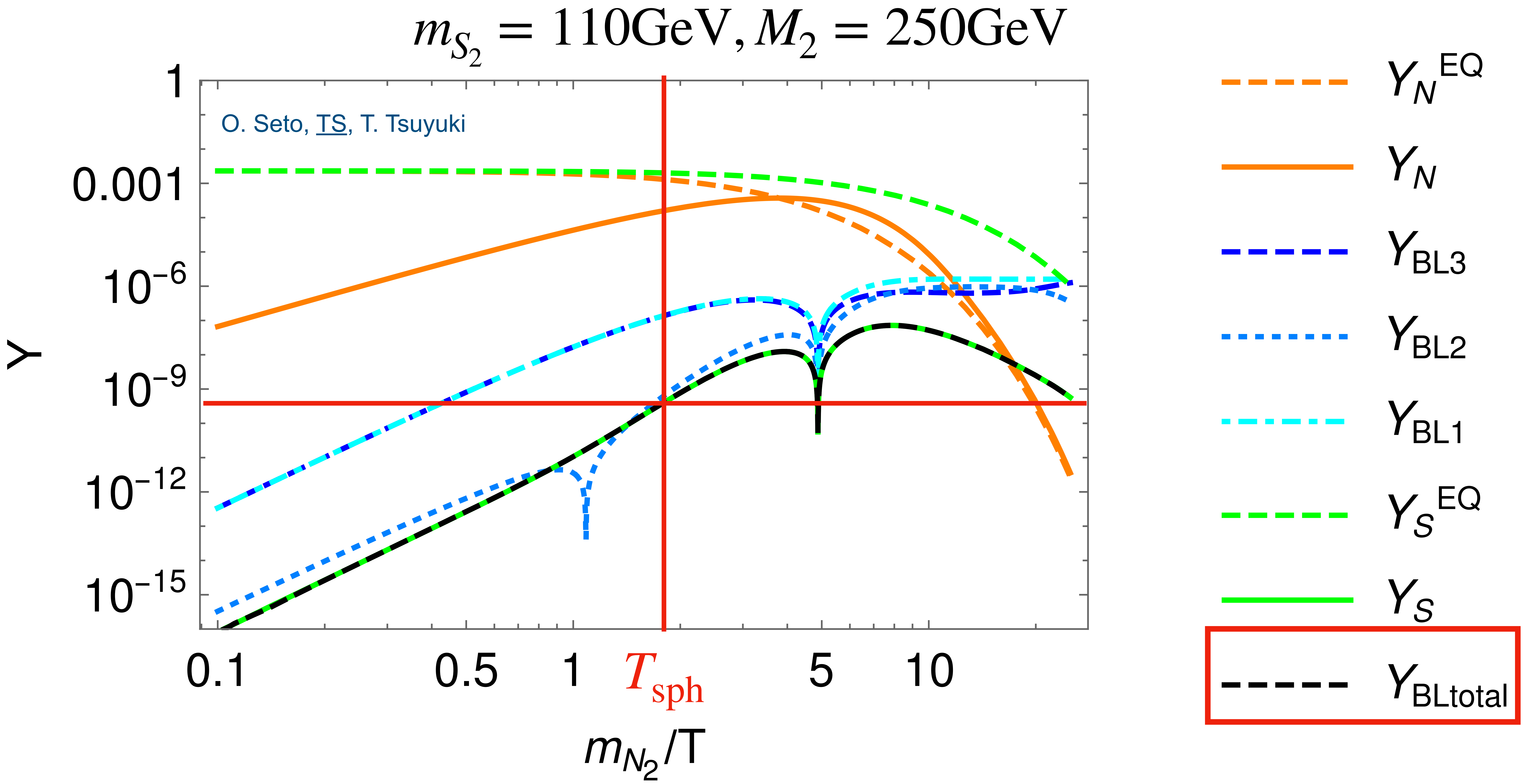
A benchmark example

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

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}
$\arg(g_{21})$	$\pi/4$

Evolutions of Y_{B-L}

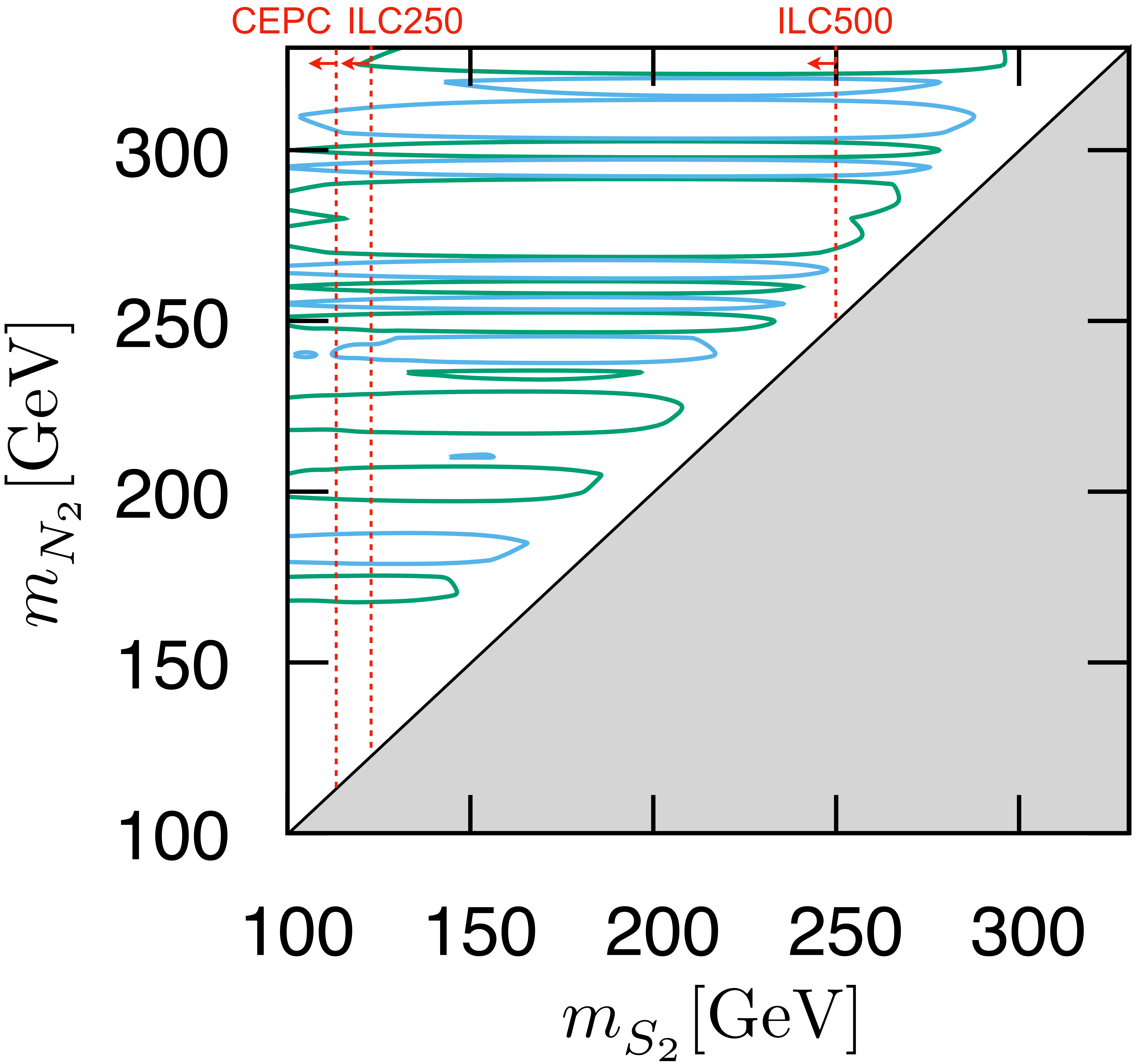
O. Seto, T.S., and T. Tsuyuki, 2211.10059v2



Before N_2 decay is frozen, #B is frozen by sphaleron decoupling. ➡ **NEW SCENARIO!**

Scanning of m_{S_2} and M_2

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



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

- 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 preferred by both DM and Leptogenesis
  - A good benchmark for complementarity of ν, cosmology, flavour and collider.
  - We propose a new scenario for a leptogenesis at $T \sim 100$GeV
- Constructing a UV picture of the model will be future work.

Backup

An idea of thermal Leptogenesis

Spharelon

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

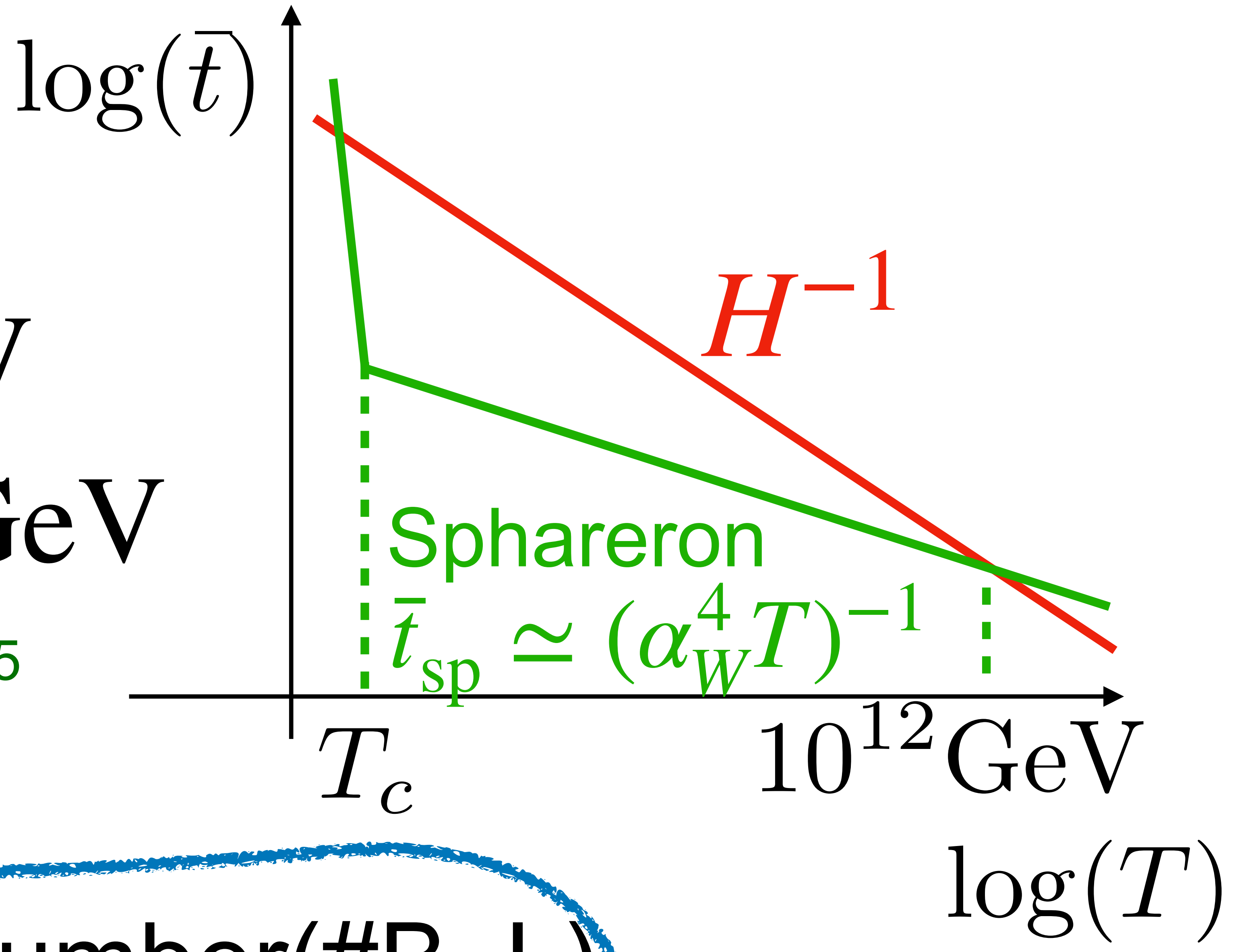
Spharelon leads to the effective operator $O_{B+L} = \Pi_i (q_{Li} q_{Li} q_{Li} \ell_{Li})$

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

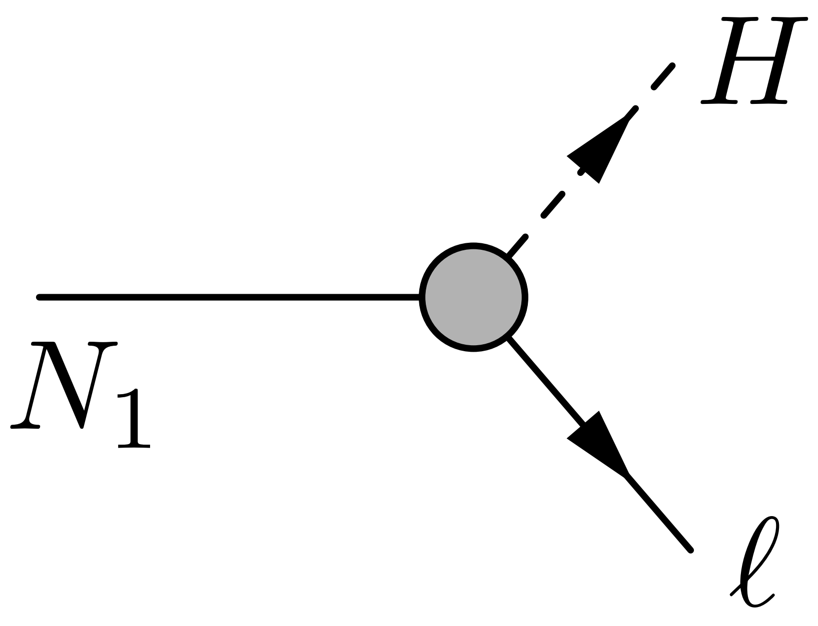
The Spharelon is in the thermal bath at $T_* \leq T \leq 10^{12}\mathrm{GeV}$

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

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



Heavy neutrino decay



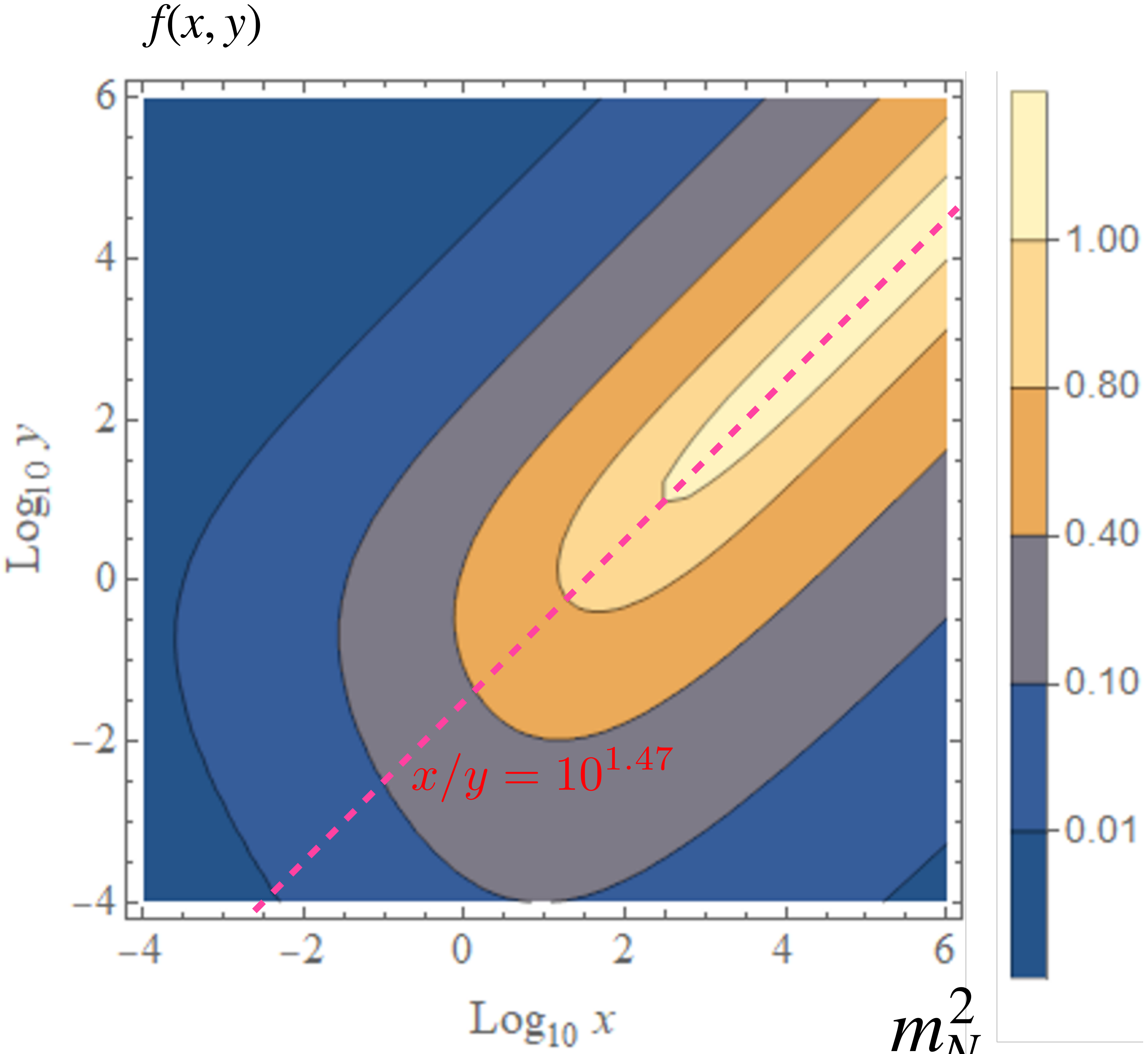
CP violating decay can produce Lepton number(#B–L)

RNH is a Majorana particle $\longrightarrow$ $N_1 = N_1^c$

#B

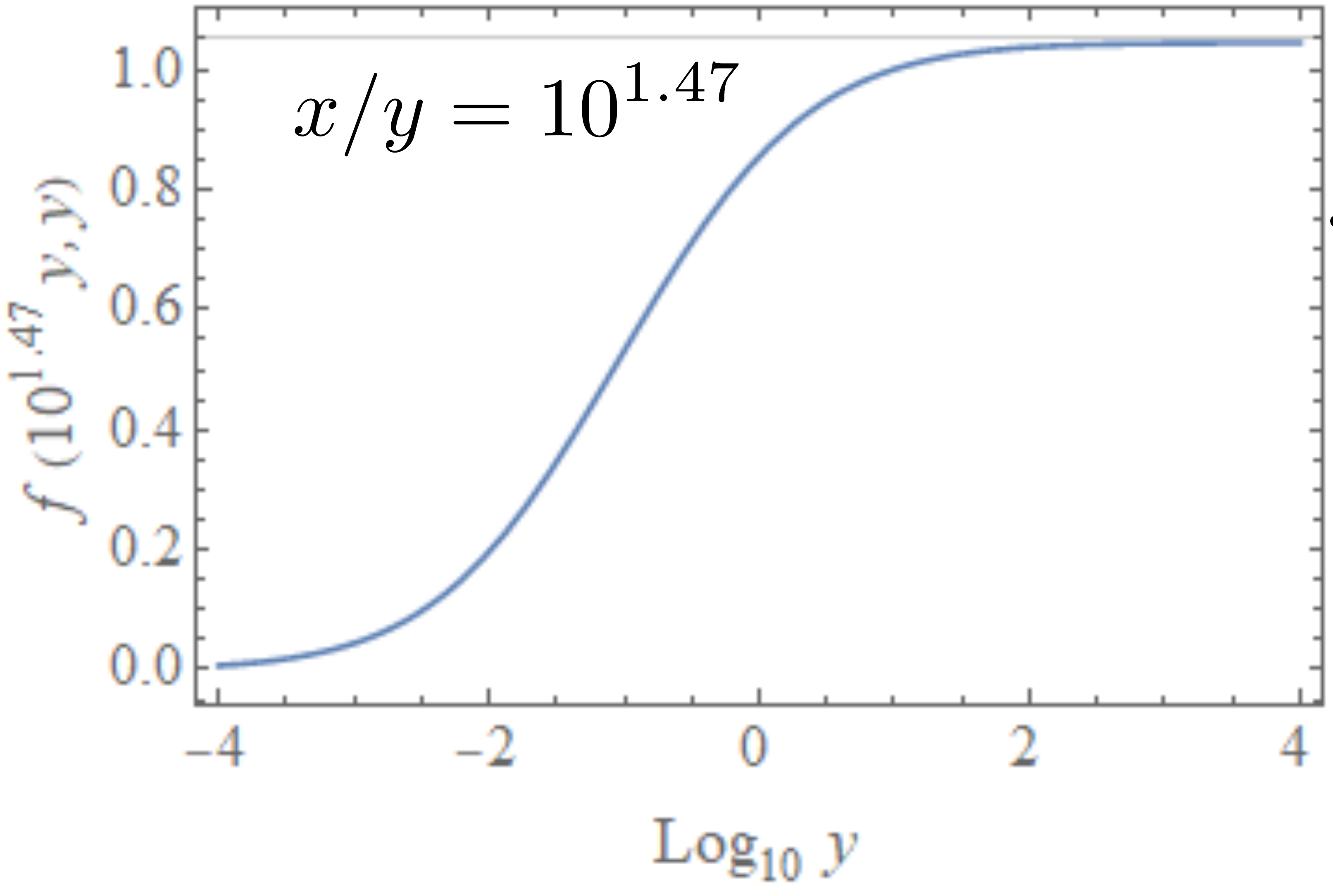
If CP is violated, $\Gamma(N_1 \to \ell_L + H) \neq \Gamma(N_1 \to \ell^c + H^*)$

Loop functions



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

$$M_\nu \sim \frac{\lambda_S h^2 g^2}{(4\pi)^3 m_{S_1}} m_\ell^2 f(x, y)$$



Upper limit
$f(x, y) < 1.05$

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

$$x_I = \frac{m_{N_I}^2}{m_{S_2}^2}, \quad y = \frac{m_{S_1}^2}{m_{S_2}^2}$$

The function $f(x, y)$ is maximized when $m_{S_1}^2 \simeq 30 m_{N_i}^2$ and these mass are larger than $m_{S_2}^2$

Upper limit on m_{S_1}

Similar size

Neutrino data

$$\left\{\begin{aligned}
(M_\nu)_{\mu\mu} &= \frac{\lambda_S m_\tau^2 h_{23}^2}{4(4\pi)^3 m_{S_1}} \sum_I g_{I3}^2 f(x_I, y) \\
(M_\nu)_{\mu\tau} &= \frac{\lambda_S m_\mu m_\tau h_{23}^2}{4(4\pi)^3 m_{S_1}} \sum_I g_{I2} g_{I3} f(x_I, y) \\
(M_\nu)_{\tau\tau} &= \frac{\lambda_S m_\mu^2 h_{23}^2}{4(4\pi)^3 m_{S_1}} \boxed{\sum_I g_{I2}^2 f(x_I, y)}
\end{aligned}\right.$$

$$\rightarrow \left|\sum_I g_{I2}^2 f(x_I, y)\right| \le \sum_I f(x_I, y) < 1.05 n_{\text{eff}}$$

n_{eff} is the number of the N_i with $f(x_I, y) \sim 1.05$ and $g_{I2} \sim 1$

$(M_\nu)_{\tau\tau}$ gets <u>the strongest suppression</u> by m_μ^2

Large couplings are required

We get the upper limit on m_{S_1}

$$m_{S_1} < 7.39 \times 10^4 \text{ GeV} \left(\frac{0.02 \text{ eV}}{|(M_\nu)_{\tau\tau}|}\right) |h_{23}|^2 n_{\text{eff}}$$

How is the LFV constraint?

Depends on the oscillation parameters and Majorana CP phase

Flavour Structure of the KNT

$$\boldsymbol{M_\nu} = \frac{\lambda_S}{4(4\pi)^3 m_{S_1}} \boldsymbol{h} \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \boldsymbol{g}^T \begin{pmatrix} f_1 & 0 & 0 \\ 0 & f_2 & 0 \\ 0 & 0 & f_3 \end{pmatrix} \boldsymbol{g} \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \boldsymbol{h}^T$$

$$\sim \boldsymbol{h} \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \boldsymbol{X} \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \boldsymbol{h}^T$$

In this case, we can use the following relations

Y. Irie, O. Seto, TS, Phys. Lett. B820, 136486(2021)

$$k \equiv \frac{h_{12}}{h_{23}} = \frac{(M_\nu)_{e\mu}(M_\nu)_{\mu\tau} - (M_\nu)_{e\tau}(M_\nu)_{\mu\mu}}{(M_\nu)_{\mu\mu}(M_\nu)_{\tau\tau} - (M_\nu)^2_{\mu\tau}}$$

$$k' \equiv \frac{h_{13}}{h_{23}} = \frac{(M_\nu)_{e\mu}(M_\nu)_{\tau\tau} - (M_\nu)_{e\tau}(M_\nu)_{\mu\tau}}{(M_\nu)_{\mu\mu}(M_\nu)_{\tau\tau} - (M_\nu)^2_{\mu\tau}}$$

Constraints from the LFV

We focus on the $S_1^{\pm}$ contribution

$$\mathrm{Br}(\mu \to e\gamma) \simeq \frac{\alpha^2}{768\pi G_F^2 m_{S_1}^4} |h_{13} h_{23}^*|^2$$

$$m_{S_1} < 7.39 \times 10^4 \text{ Gev} \left(\frac{0.02 \text{ eV}}{|(M_\nu)_{\tau\tau}|} \right) |h_{23}|^2 n_{\text{eff}}$$

$$\mathrm{Br}(\mu \to e\gamma) > 7.45 \times 10^{-16} \frac{|h_{13}|^2}{|h_{23}|^6 n_{\text{eff}}} \left(\frac{(M_\nu)_{\tau\tau}}{0.02 \text{ eV}} \right)$$

For Normal Ordering (NO) $m_1 < m_2 < m_3$

$k' \equiv \frac{h_{13}}{h_{23}} \sim 0.3 < 1$ leads to $h_{13} < h_{23} \leq 1$ $\Rightarrow$ $\mathrm{Br}(\mu \to e\gamma) > 5.0 \times 10^{-18} \left(\frac{|(M_\nu)_{\tau\tau}|}{0.02 \text{ eV}} \right)^4 \left(\frac{n_{\text{eff}}}{2} \right)^{-4} \left(\frac{|k'|}{0.329} \right)^2$

For Inverted Ordering (IO) $m_3 < m_1 < m_2$

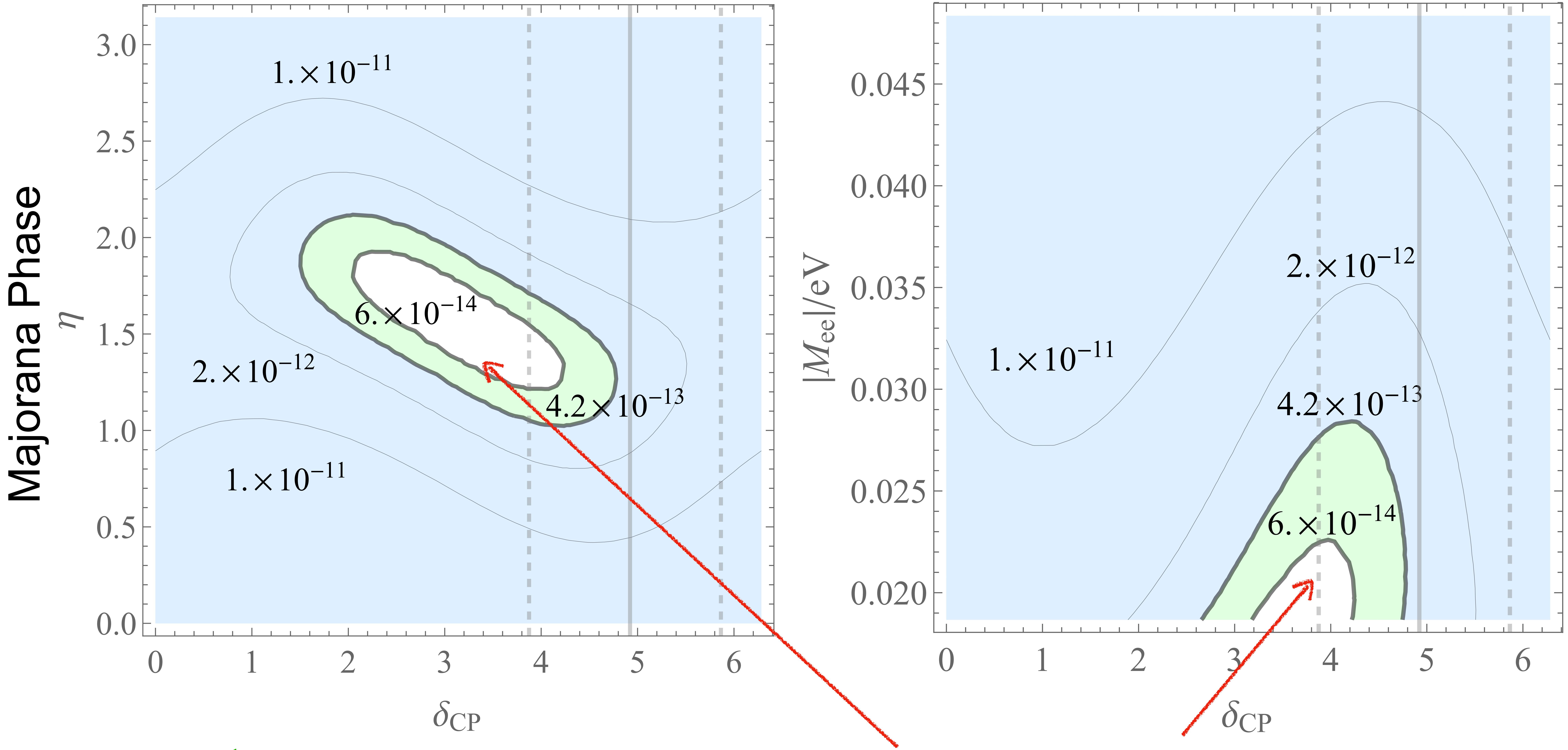
$k' \sim 5 > 1$ leads to $h_{23} < h_{13} \leq 1$ $\Rightarrow$ $\mathrm{Br}(\mu \to e\gamma) > 7.4 \times 10^{-13} \left(\frac{|(M_\nu)_{\tau\tau}|}{0.02 \text{ eV}} \right)^4 \left(\frac{n_{\text{eff}}}{2} \right)^{-4} \left(\frac{|k'|}{5.01} \right)^6$

Significant!

Experimental constraint: $\mathrm{Br}(\mu \to e\gamma) < 4.2 \times 10^{-13}$

The constraints on the model in the IO case

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



$n_{\rm eff} = 1$ case $\quad m_{N_1} \lesssim m_{S_2} \ll m_{N_{2,3}} \simeq m_{S_1}/5.43$

$(M_\nu)_{\tau\tau}$ is very suppressed