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Low-scale leptogenesis and dark matter in a three-loop radiative seesaw model

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O. Seto, T.S., and T. Tsuyuki, Phys. Rev. D108, 055002 (2023) [arXiv:2211.10059]

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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**
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A radiative seesaw model (KNT model)

The SM should be extended at some energy scale

KNT model

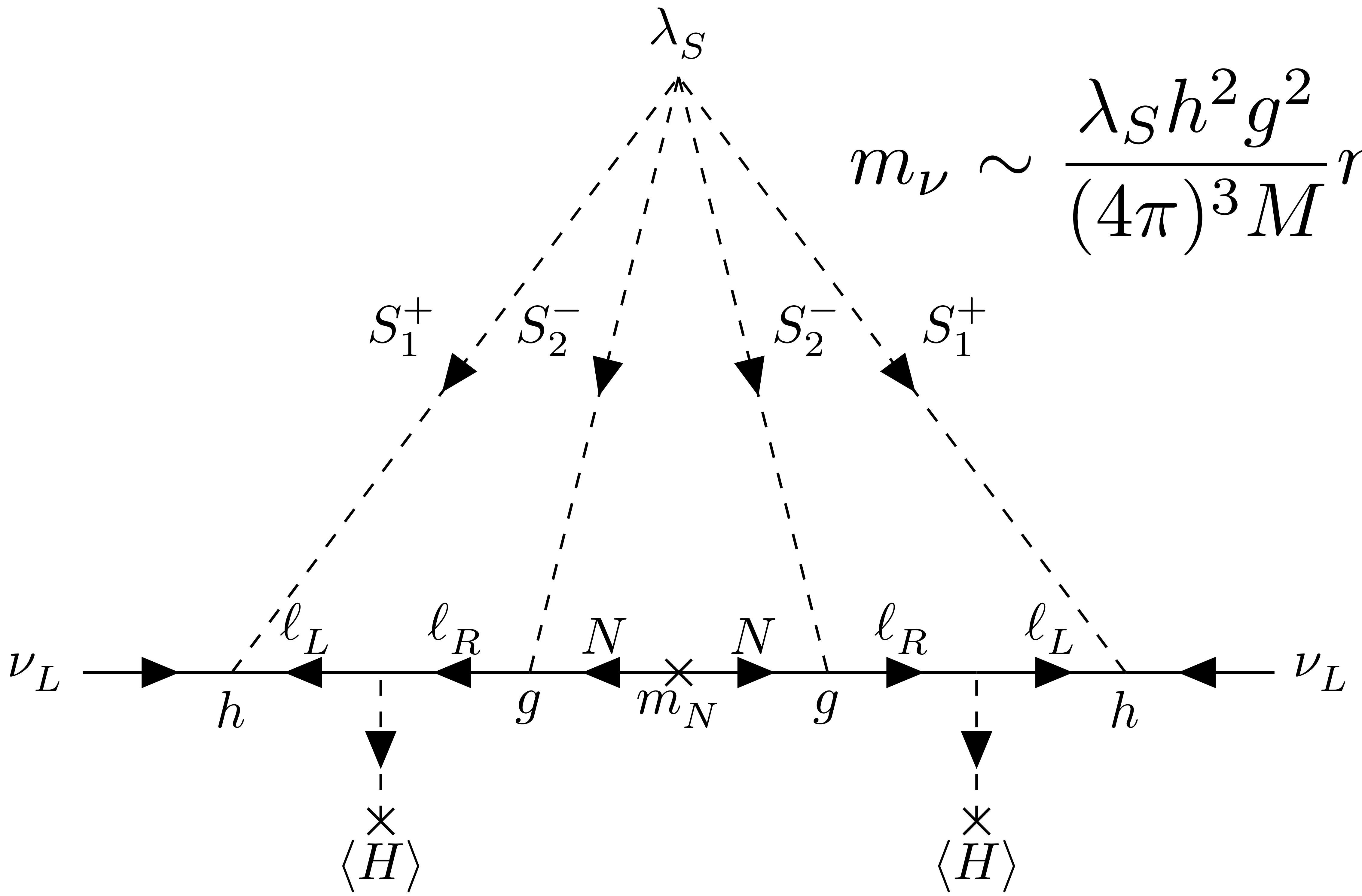
KNT model is a radiative seesaw model

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

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

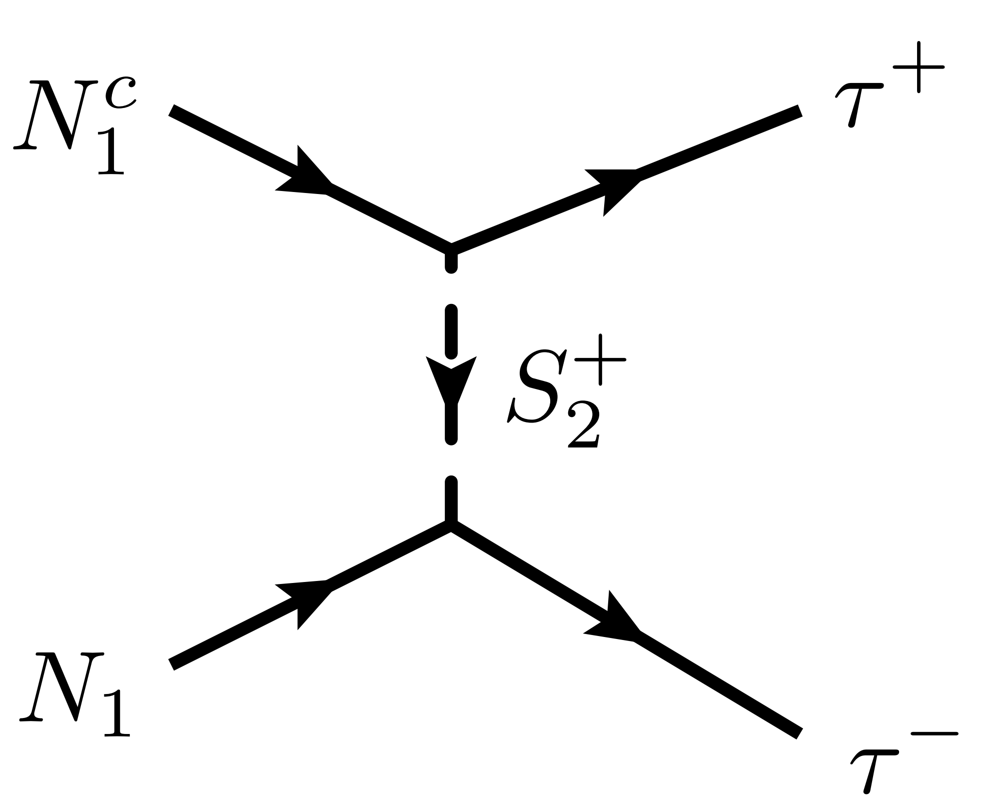
O. Seto, T.S. and T. Tsuyuki, arXiv:2202.00931

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 $g_{1i} < 1$

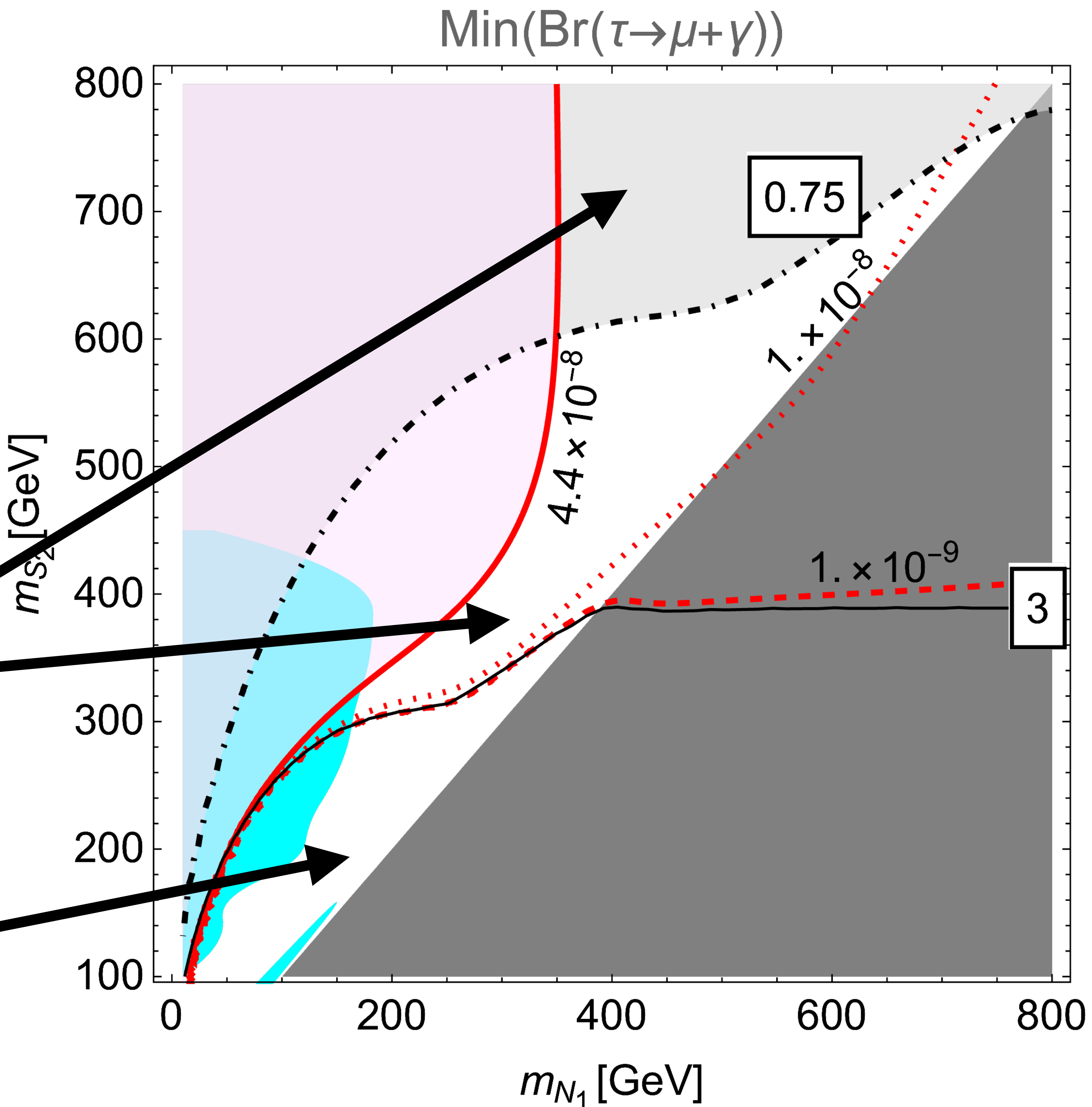
To avoid too large B($\mu \to e\gamma$), $g_{1e}^* g_{1\mu} \simeq 0$ is required

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

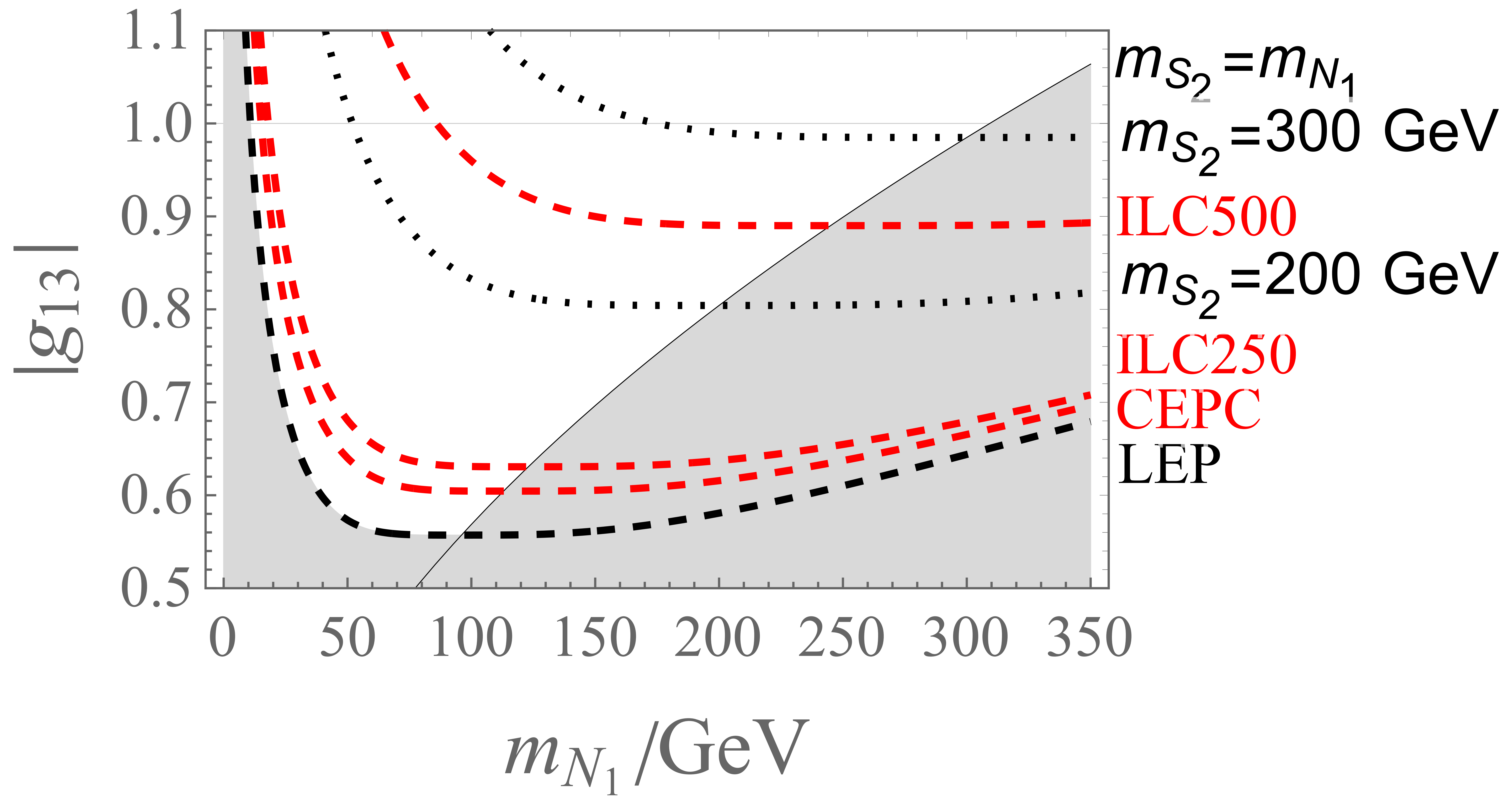
One g_{1i} is enough



DM in the KNT

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

In the case with $g_{1e} = g_{1\mu} = 0$ Relevant parameters: g_{13} , m_{N_1}, m_{S_2}



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: $N_2 \to S_2^- + e_{Ri}^+ \overset{\not{CP}}{\longleftrightarrow} N_2 \to S_2^+ + e_{Ri}^-$

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

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 $N_2 \to S_2^\mp + e_{Ri}^\pm$, $\hookrightarrow N_1 + e_{Rj}^\mp$

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

  m_{S_2} cannot be much larger than T_*

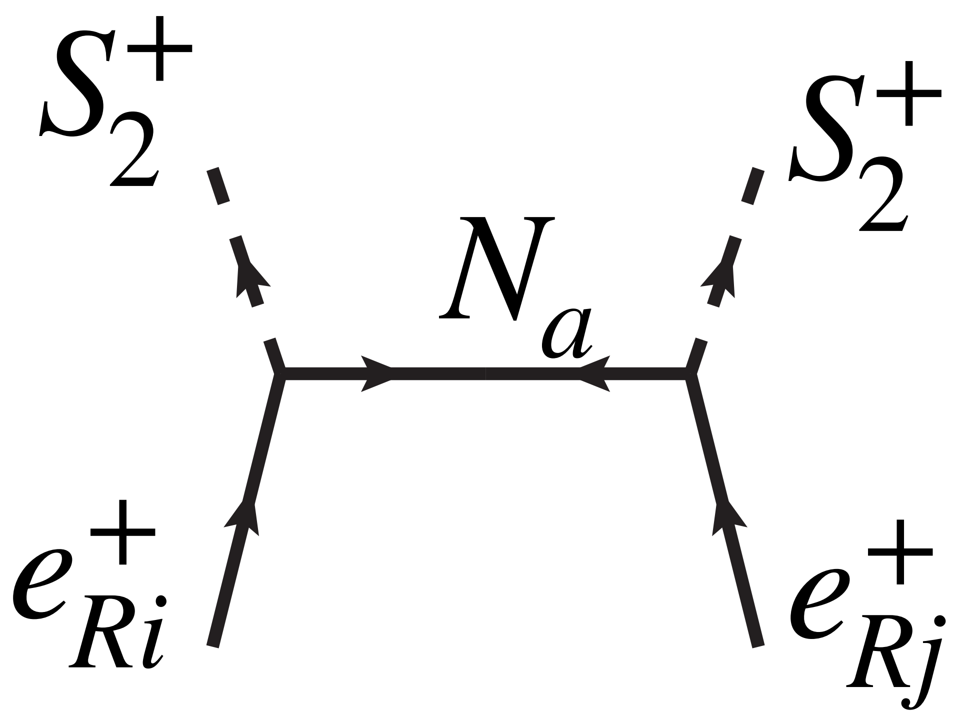
- $g_{2i} \simeq \mathcal{O}(10^{-7\sim 8})$ is required for $N_{N_2} \neq N_{N_2}^{\rm eq}$ at $T \sim M_2$

  N_2 cannot contribute to M_ν ➡ M_ν generation is governed by other RHNs

- 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:

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

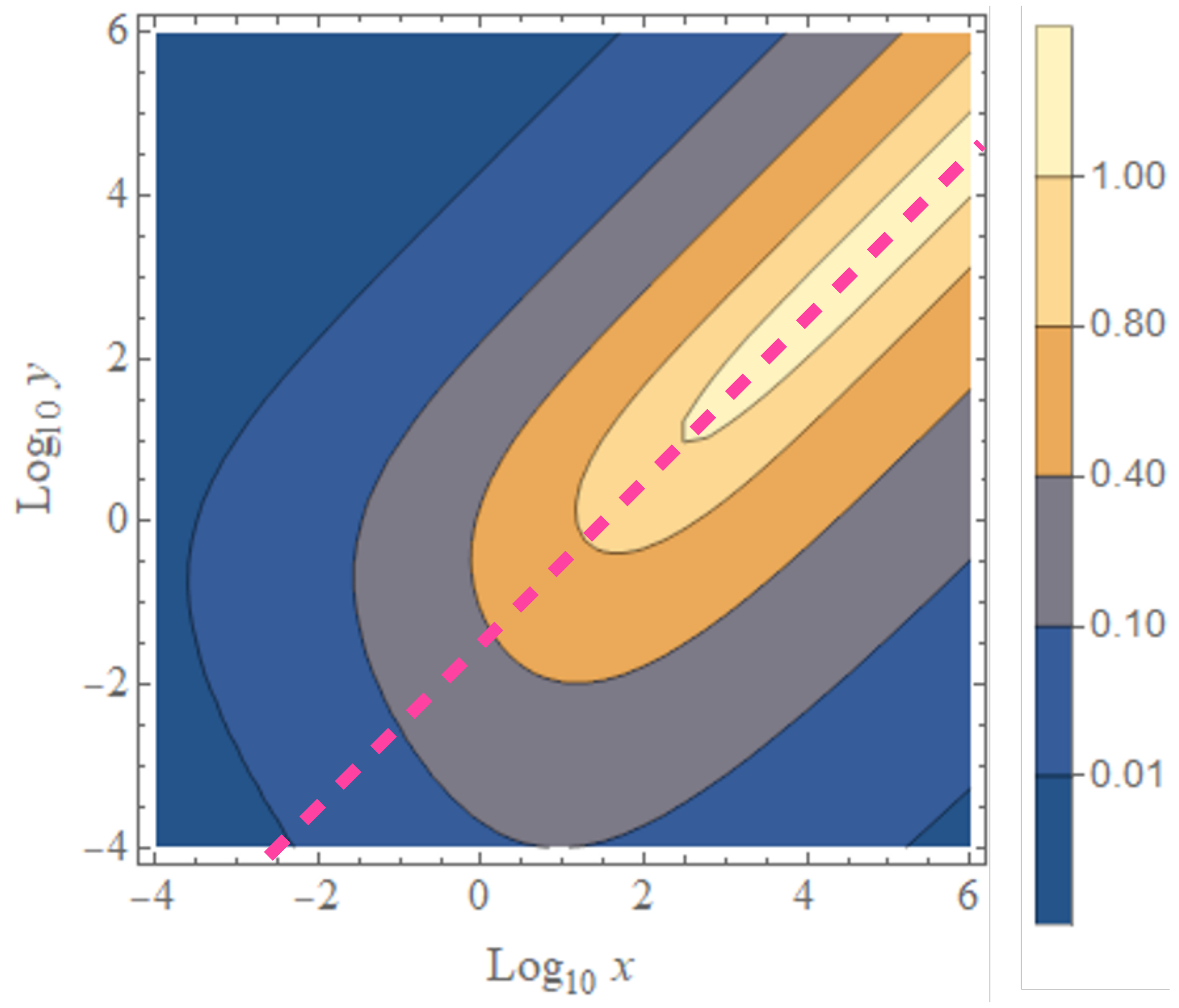
To avoid $\tau \to \mu\gamma$ (the 0 in the (1,2) entry)

DM (g_{13})

ν-osc (g_{32}, g_{33})

Negligible contribution to M_ν (first column of zeros)

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!

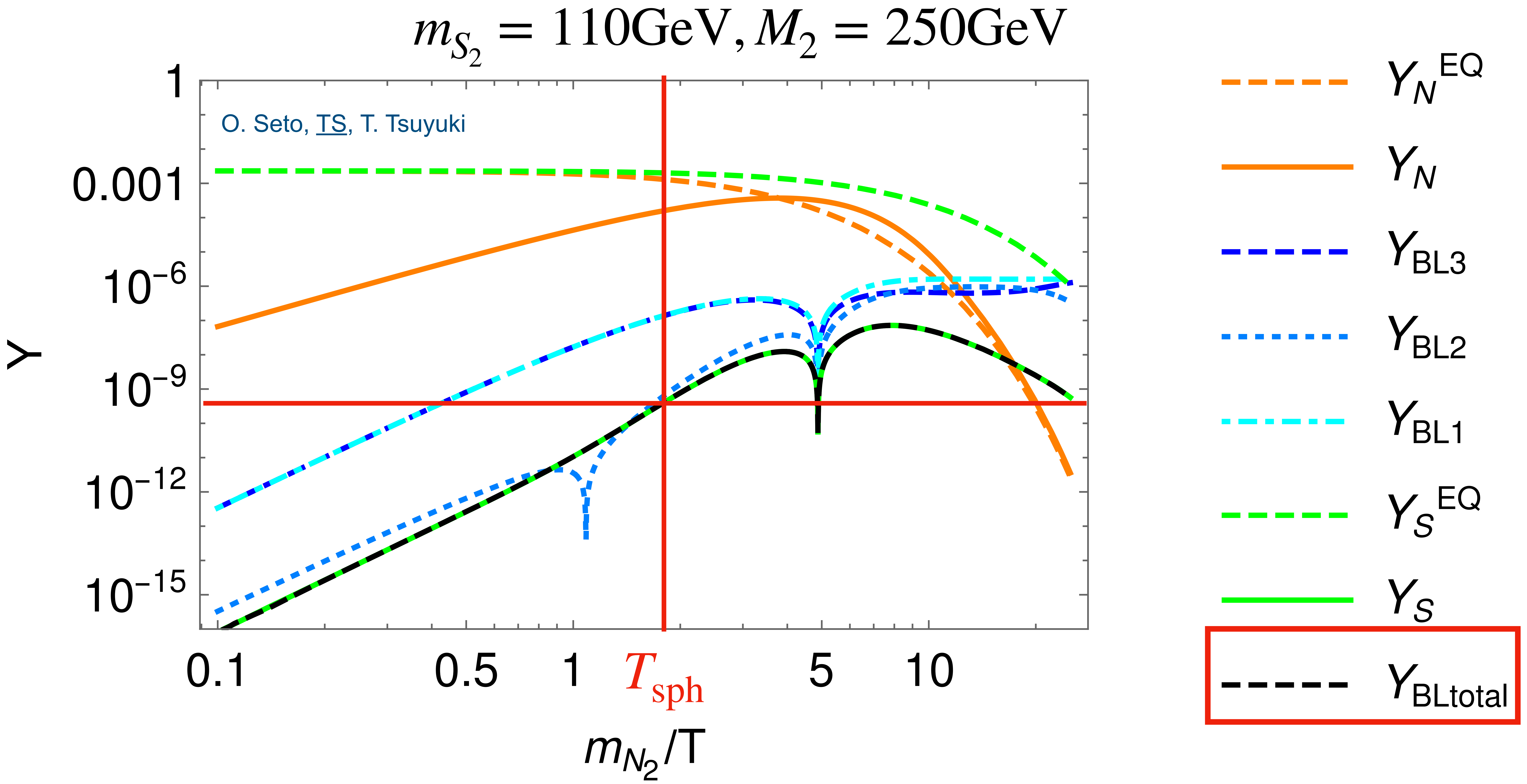
A benchmark example

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

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}

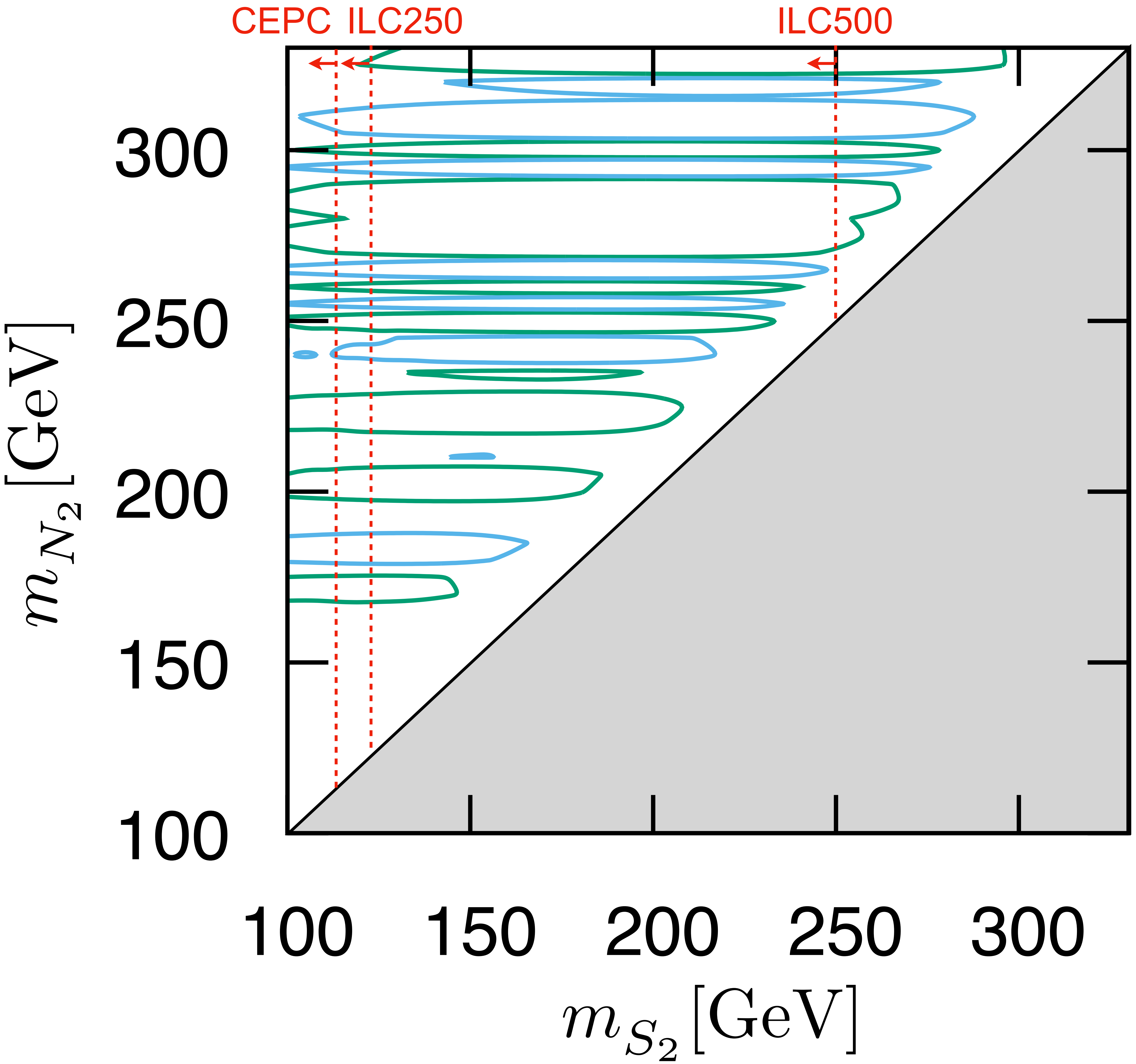
O. Seto, T.S., and T. Tsuyuki, 2211.10059v2



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
  - A good benchmark for complementarity of ν, cosmology, flavour and collider.
  - Three RHN case does not work because of too strong washout by $\Delta L = 2$ scattering processes.
  - A case with the fourth-generation RHNs provides enough large baryon asymmetry!
  - $m_{S_2} = \mathcal{O}(100)\mathrm{GeV}$ is preferred by both DM and Leptogenesis
- We propose a new scenario for a leptogenesis at $T \sim 100$GeV
  - We try to figure out the detail properties of such a scenario.
- Constructing a UV picture of the model will be future work.