On Baryogenesis via Neutrino Oscillation in the νMSM

Hiroyuki Ishida (NCTS)

@NCTS Annual Theory Meeting 2017: Particles, Cosmology and Strings

2017/12/06

Collaboration with : Takehiko Asaka (Niigata)
Shintaro Eijima (EPFL→Leiden)
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Based on : PRD 96, 1704.02692 [hep-ph]

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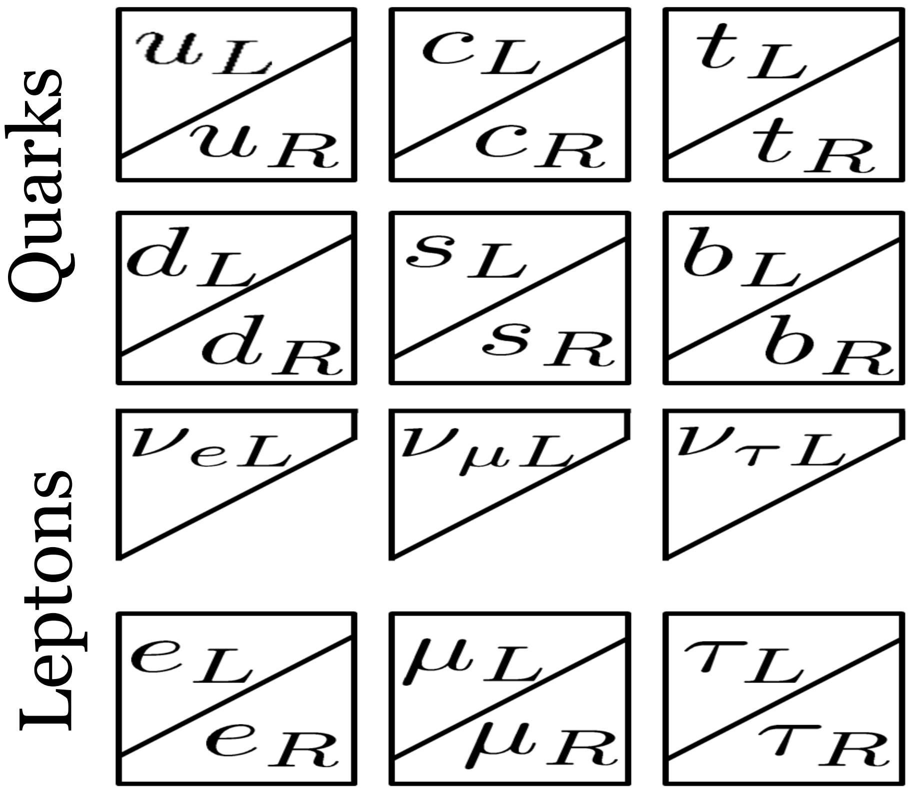
Introduction

- Missing matter field in the SM



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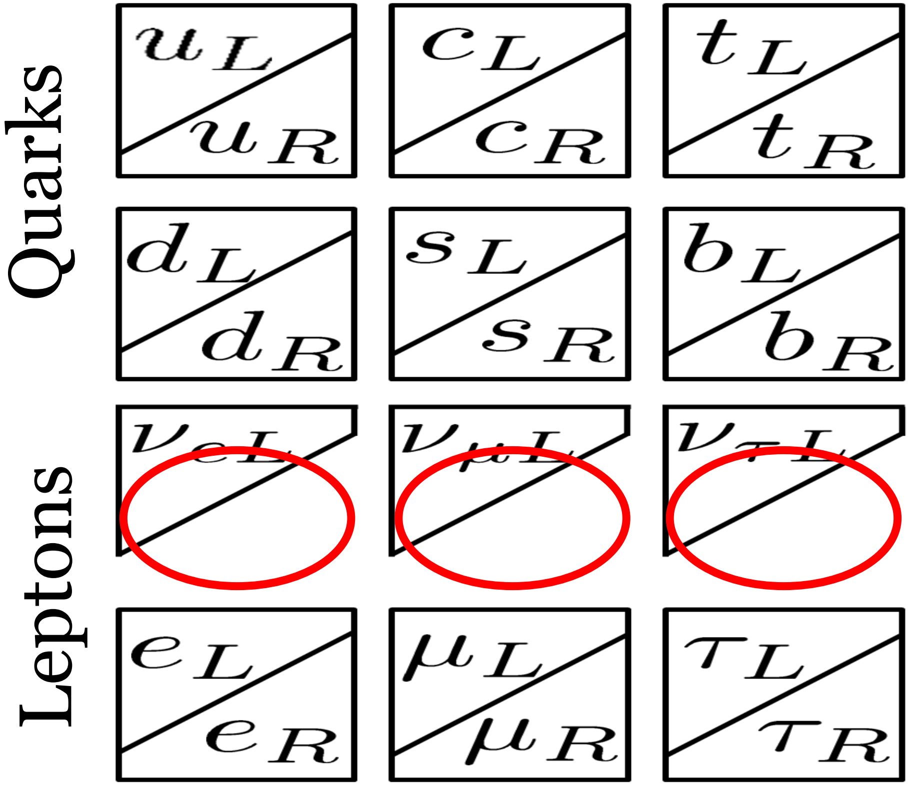

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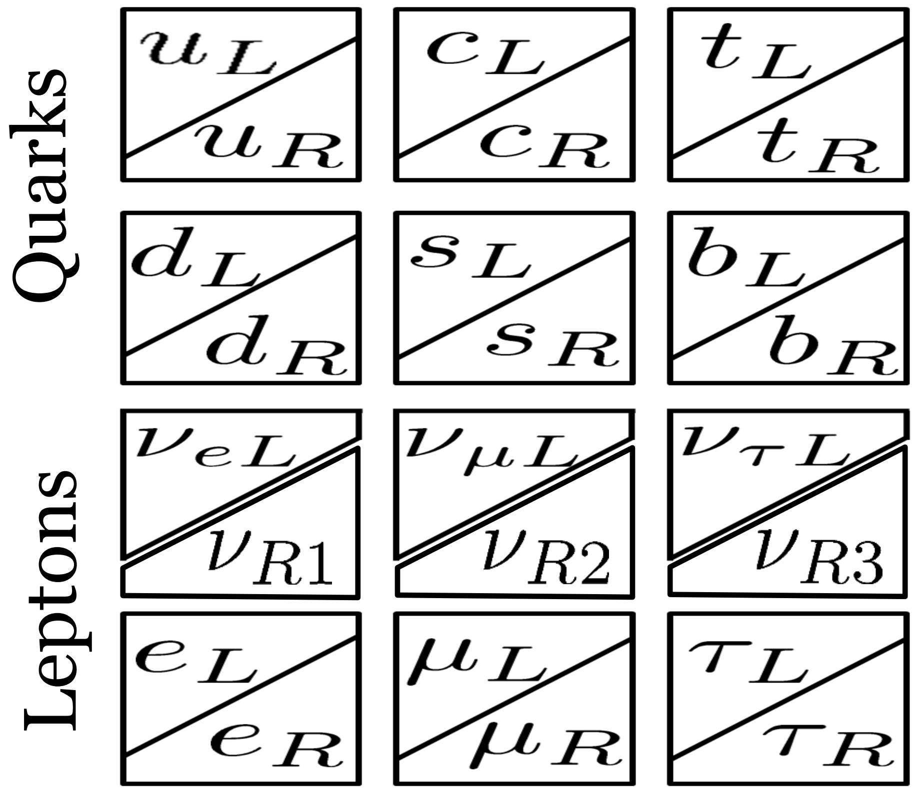

Adding RH neutrinos looks natural!

Introduction

- After adding RHνs,

$$\mathcal{L}_{\nu mass} = F_{\alpha I}\bar{L}_\alpha H \nu_{RI} + \text{h.c.} + \frac{M_M}{2}\overline{\nu_{RI}^c}\nu_{RI}$$

Neutrinos can obtain masses!

-Dirac masses : $M_D \equiv F_{\alpha I}\langle H \rangle$ -Majorana masses : M_M

- Observed tiny ν masses can explain by type-I seesaw

[Minkowski (1977);Yanagida(1979);Gell-Mann,Ramond,Slansky (1979); Glashow (1980);Mohapatra,Senjanovic(1980)]

$$\hat{M} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \xrightarrow[M_D \ll M_M]{\text{diagonalization}} \begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix}$$

where $M_\nu \simeq -M_D M_M^{-1} M_D^T$

How heavy RHν is needed?

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$$\frac{F^2 \langle H \rangle^2}{M_M} \simeq 0.1 \text{ eV}$$

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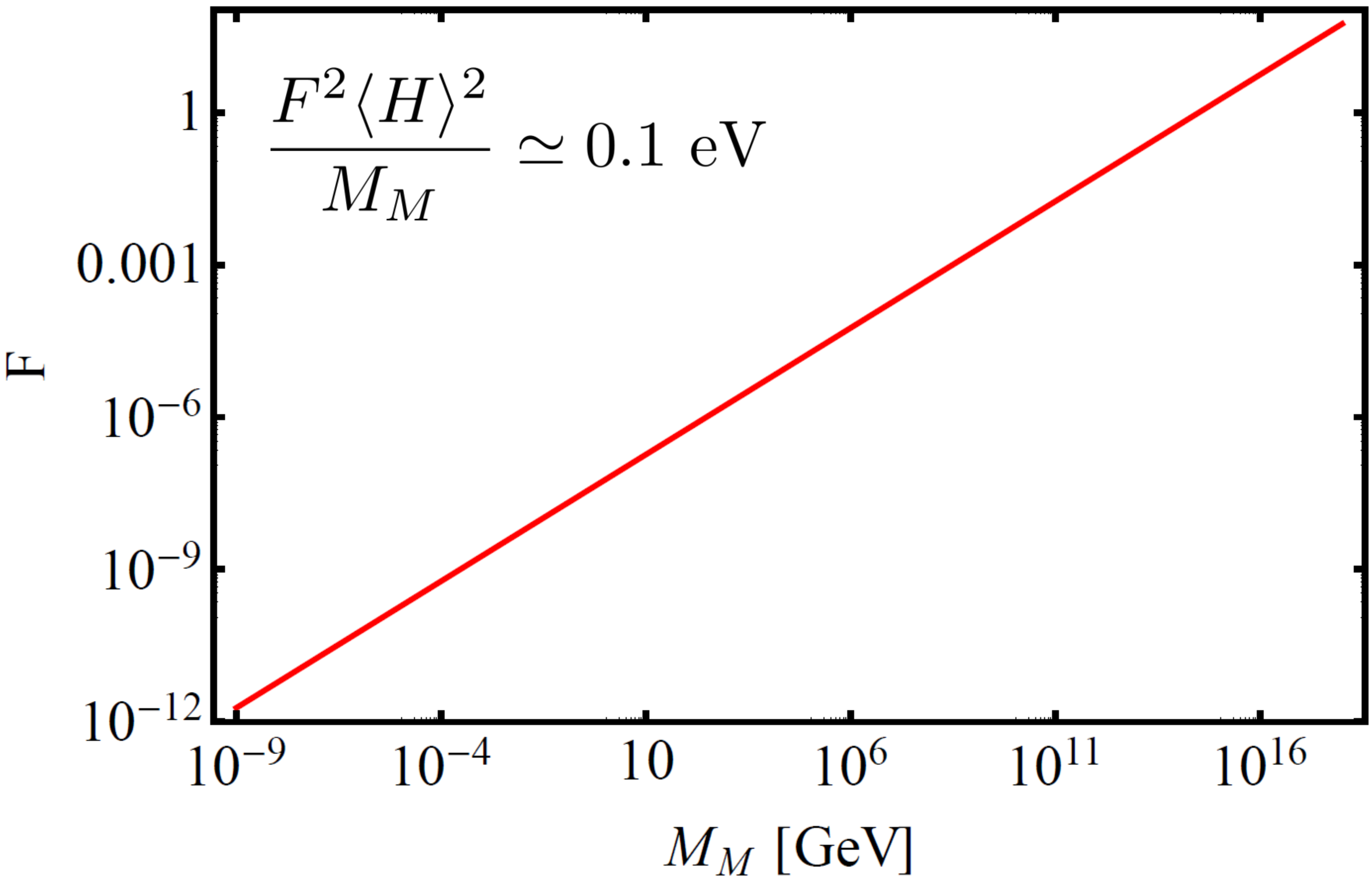

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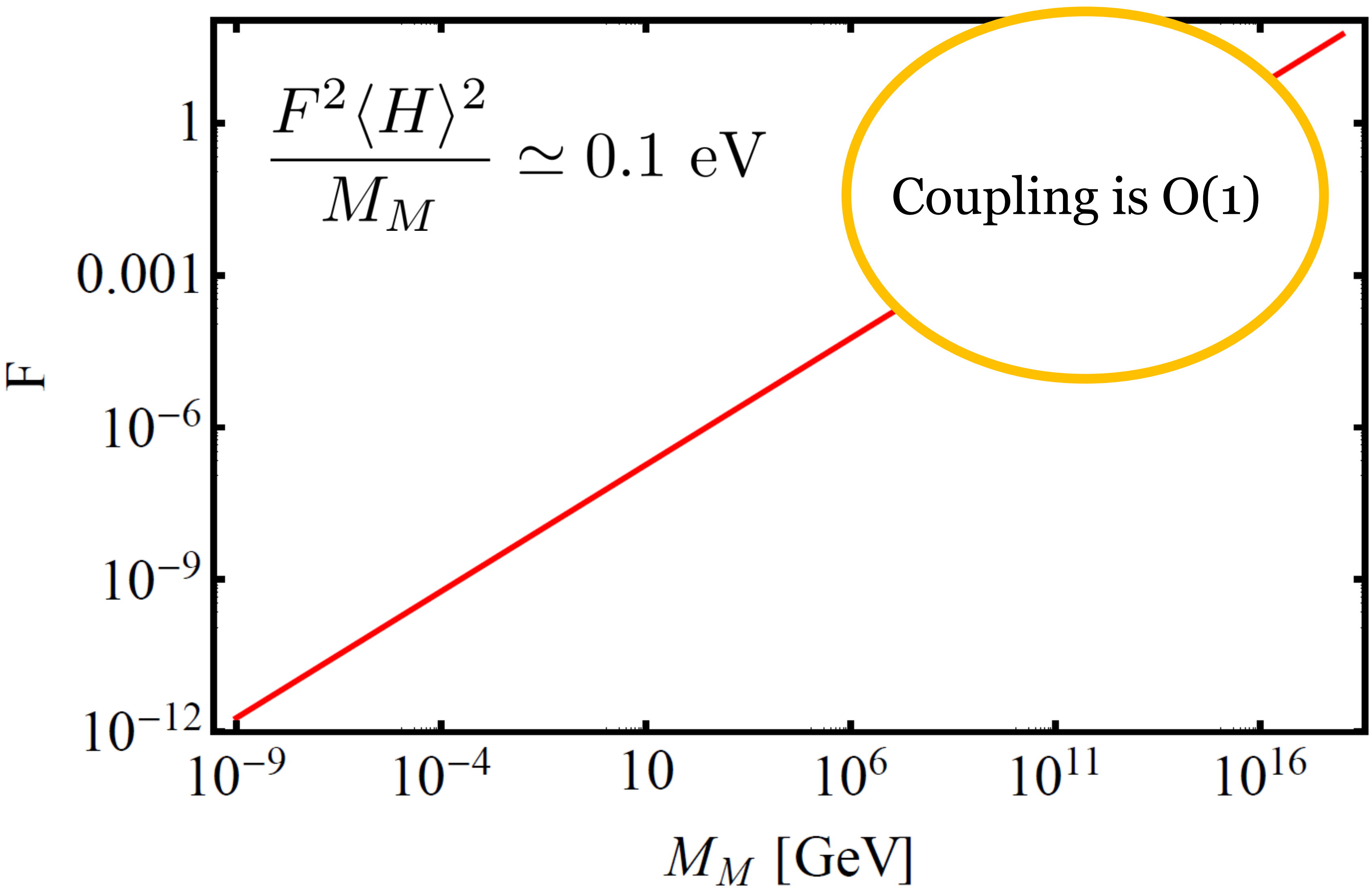

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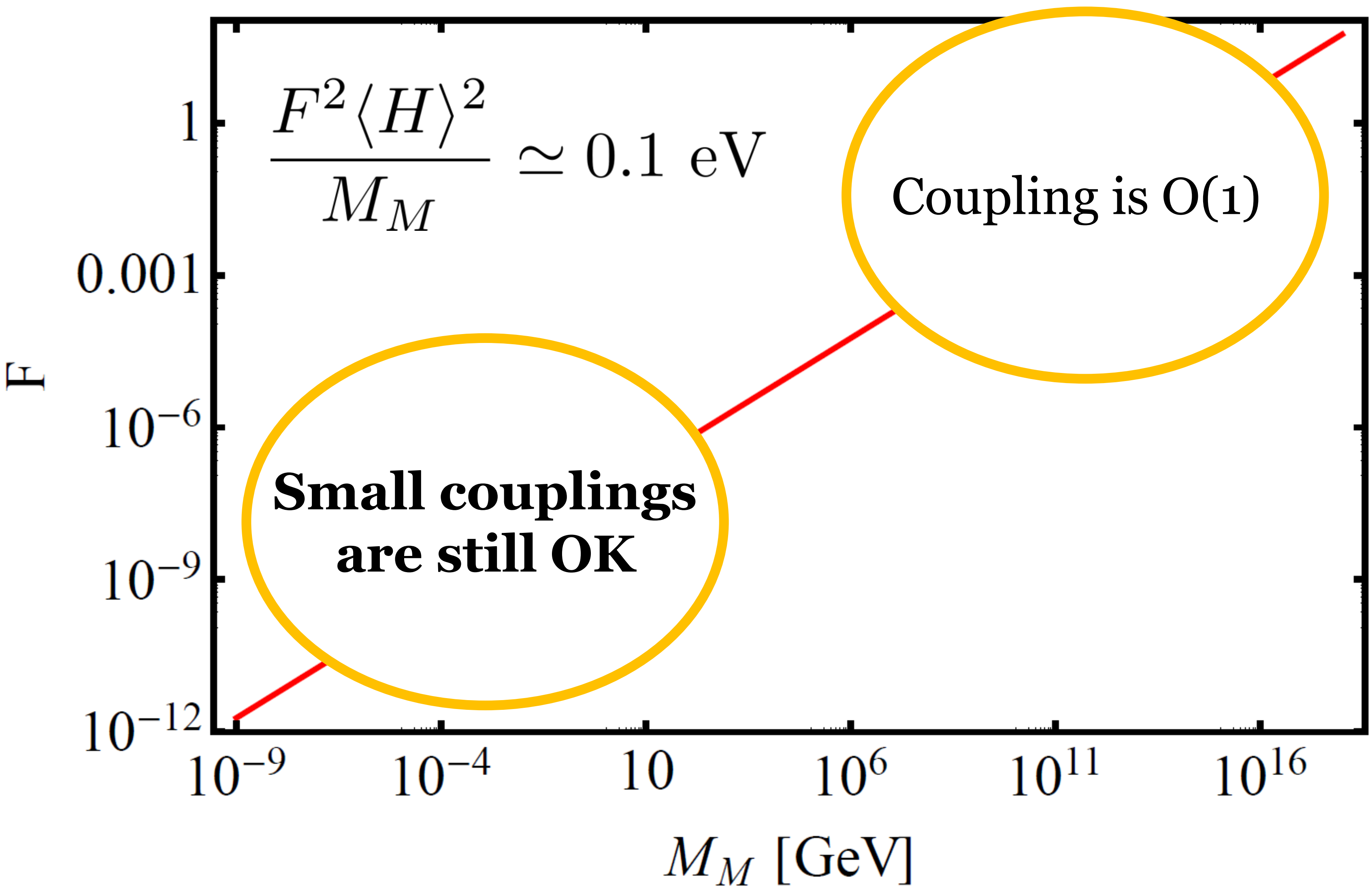

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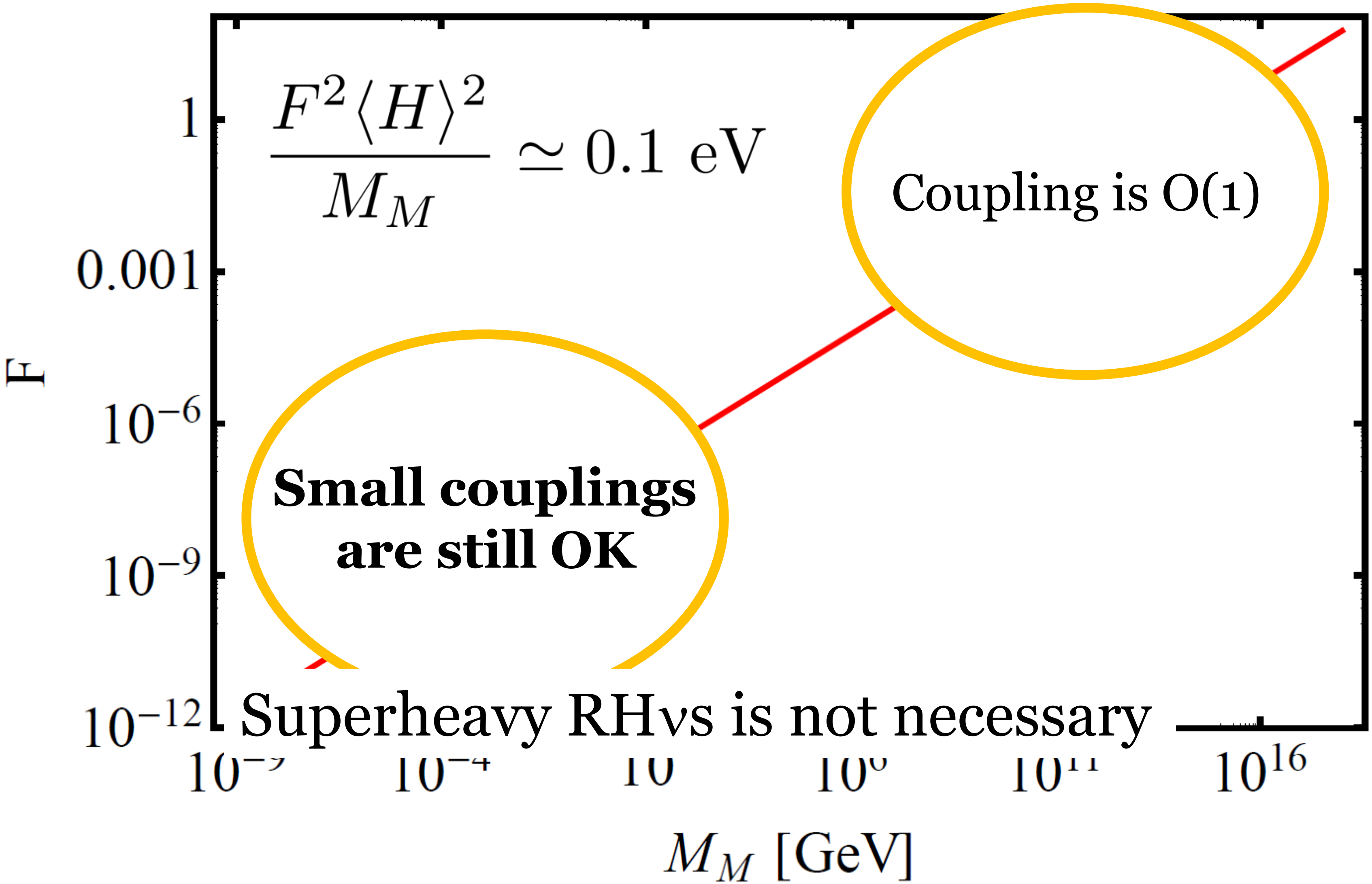

The Neutrino Minimal Standard Model (The νMSM)

The νMSM [Asaka, Blanchet, and Shaposhnikov (2005)] [Asaka and Shaposhnikov (2005)]

- Most economical extension of the SM : SM+3 RHνs

$$\mathcal{L}_N = i\bar{\nu}_{RI}\partial\!\!\!/\nu_{RI} - F_{\alpha I}\bar{L}_\alpha H\nu_{RI} - \frac{M_M}{2}\overline{\nu^c_{RI}}\nu_{RI} + \text{h.c.}$$

- Key assumption

$$M_D \equiv F_{\alpha I}\langle H\rangle \ll M_M \lesssim \Lambda_{\text{EW}}$$

- Typical magnitude of Yukawa couplings

$$M_\nu = -M_D M_M^{-1} M_D^T \to 0.1\ \text{eV}\left(\frac{F}{10^{-7}}\right)^2\left(\frac{1\ \text{GeV}}{M_M}\right)$$

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Direct testability!

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- Physical states of neutrinos

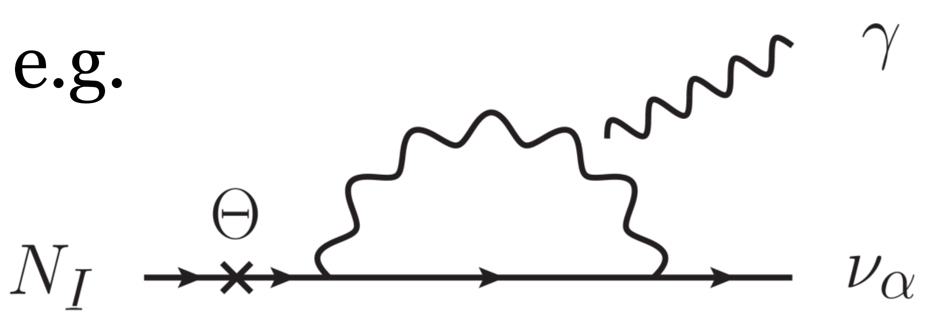
  *active neutrinos : $\nu_i = U^\dagger_{\rm MNS}\nu_{L\alpha} - U^\dagger_{\rm MNS}\Theta\nu^C_{RI}$

  *heavy neutral leptons : $N^C_I = \nu^C_{RI} + \Theta^\dagger\nu_{L\alpha}$

- Important parameter : $\Theta \equiv M_D/M_M$

  RHν can have gauge interaction through this mixing

  e.g.



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  ⟹ right-handed neutrinos

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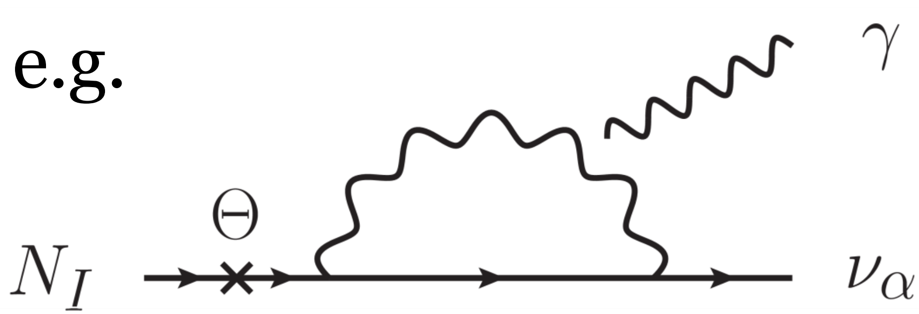

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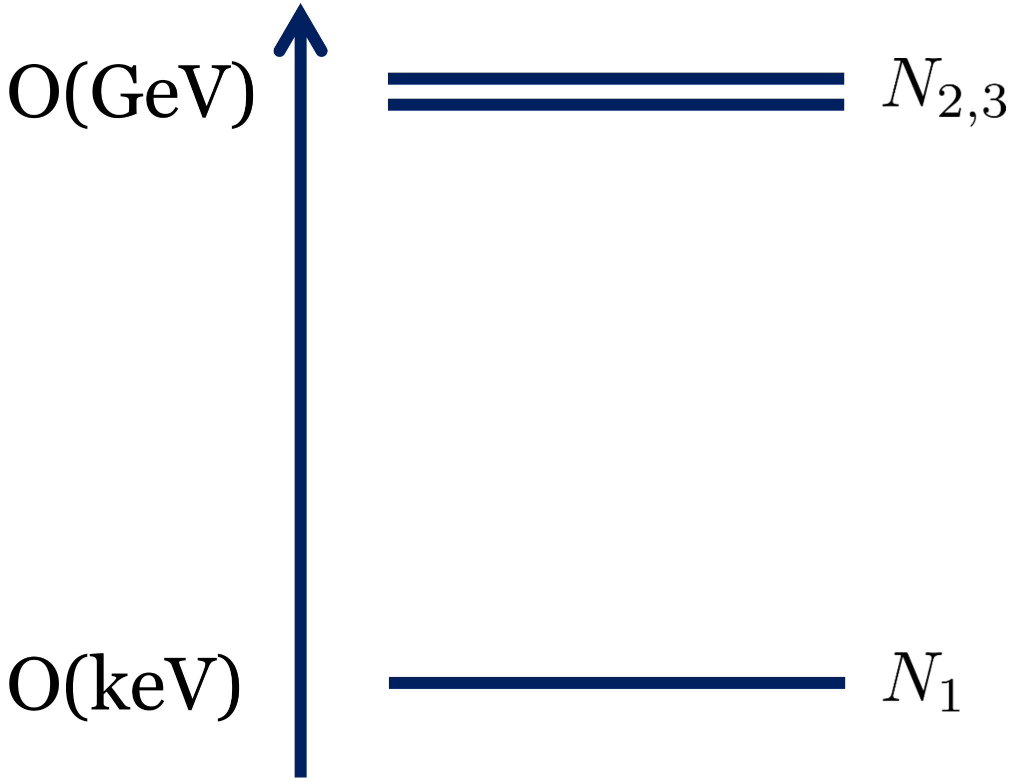

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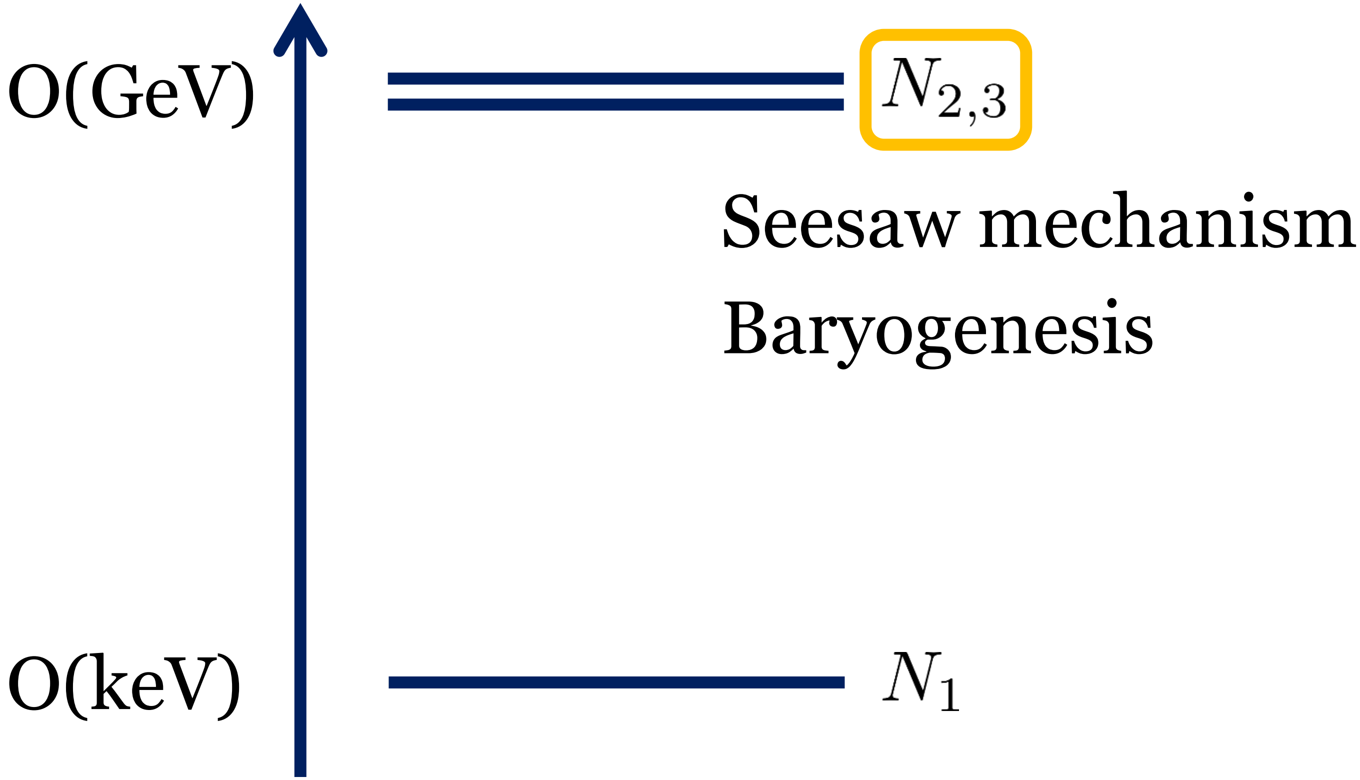

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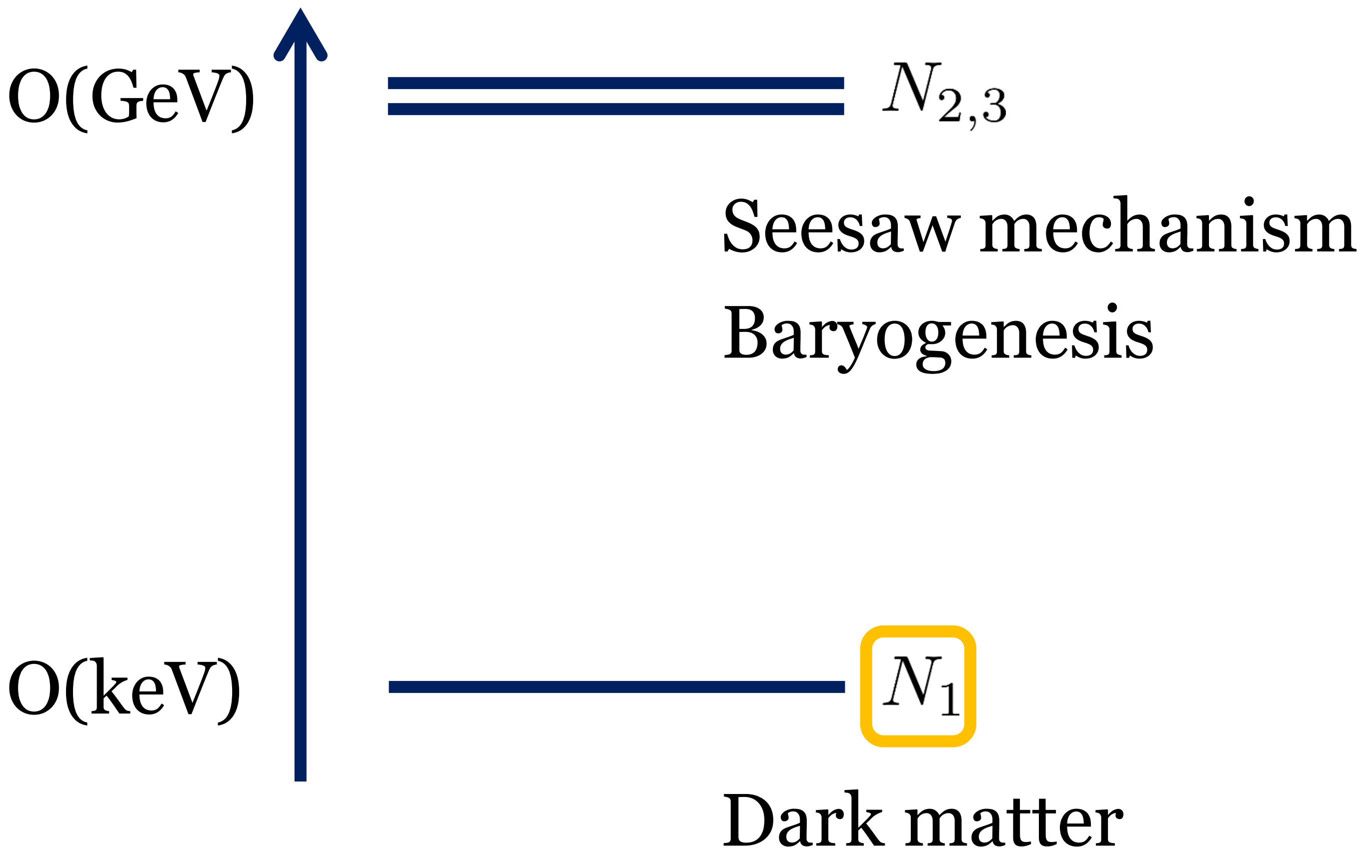

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*simple production mechanism (Dodelson-Widrow)

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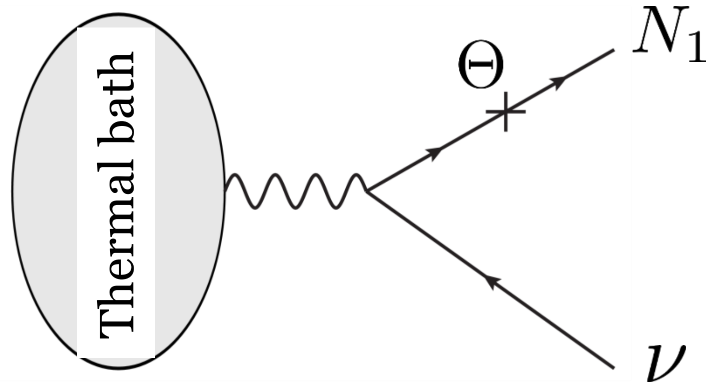

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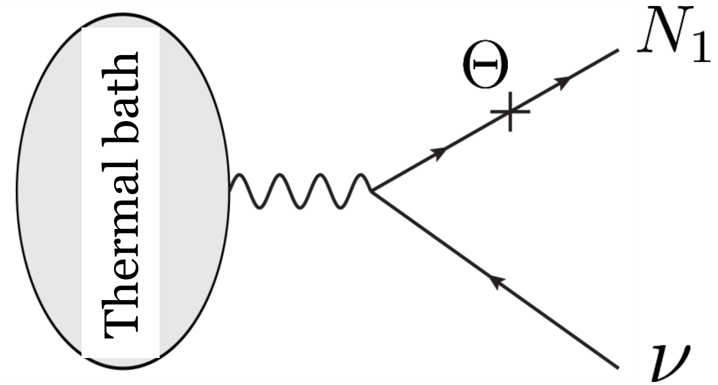

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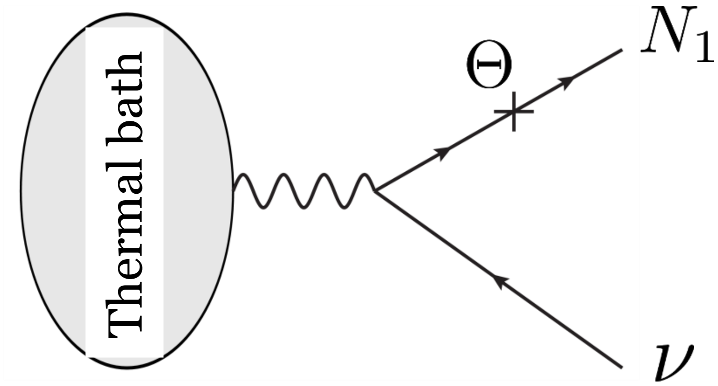

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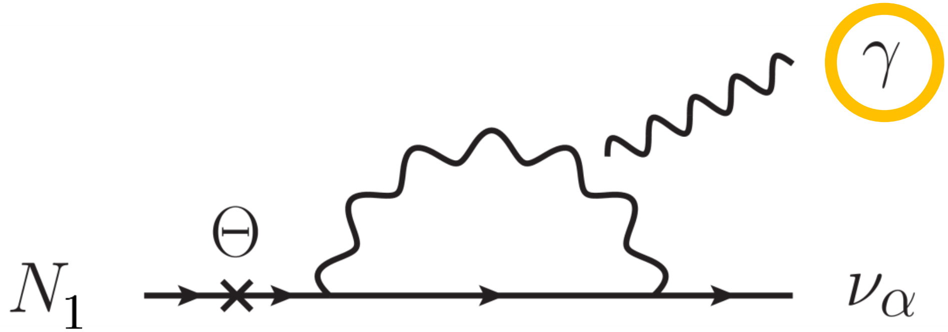

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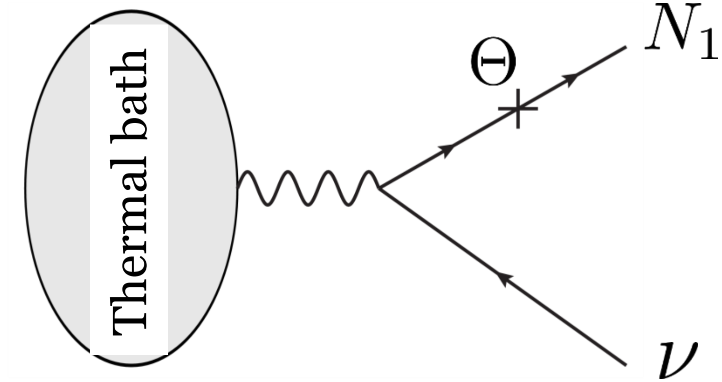

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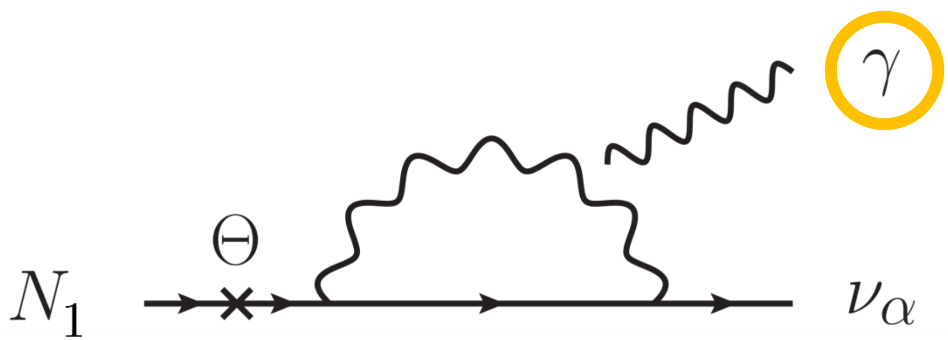

X-ray observatory

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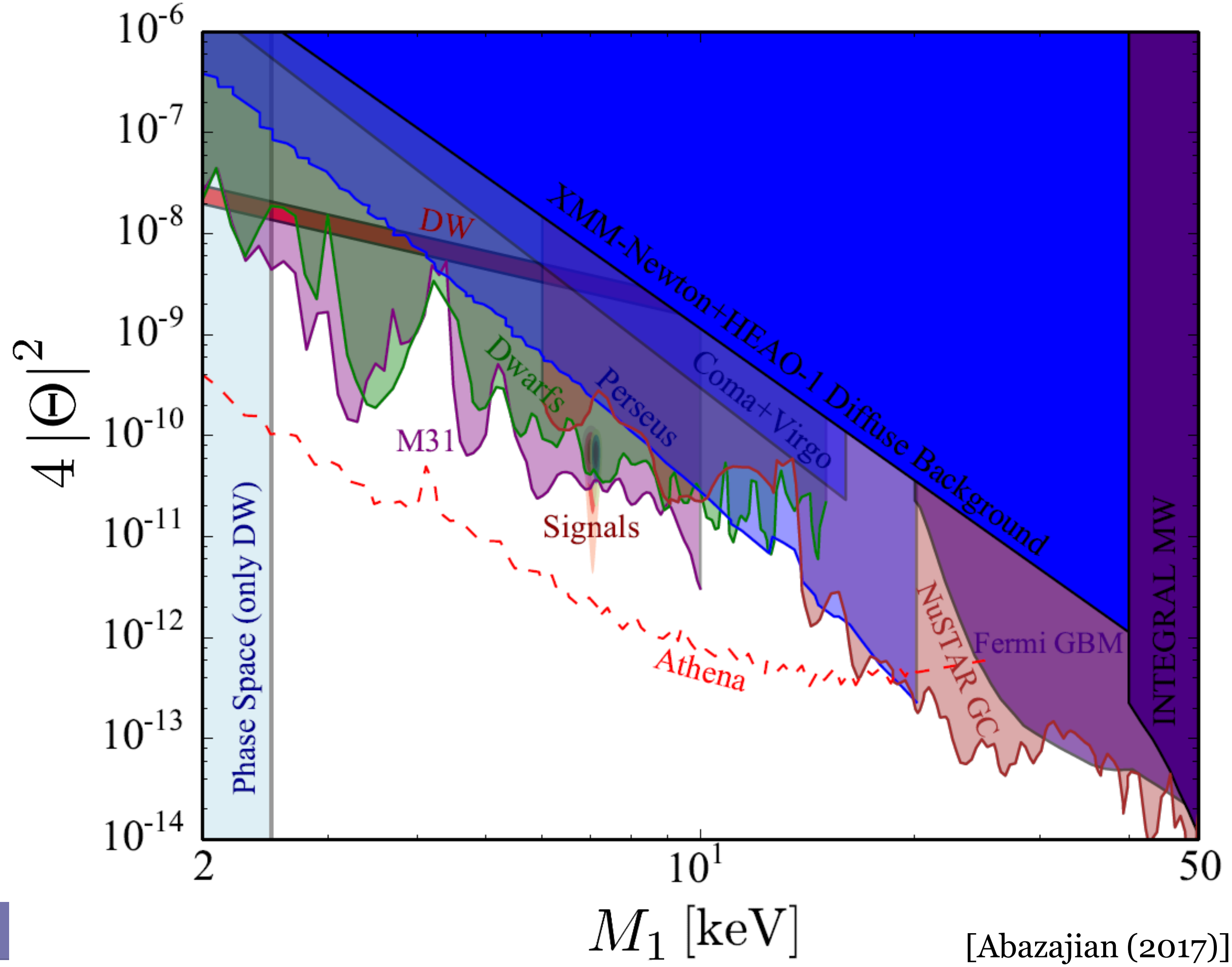

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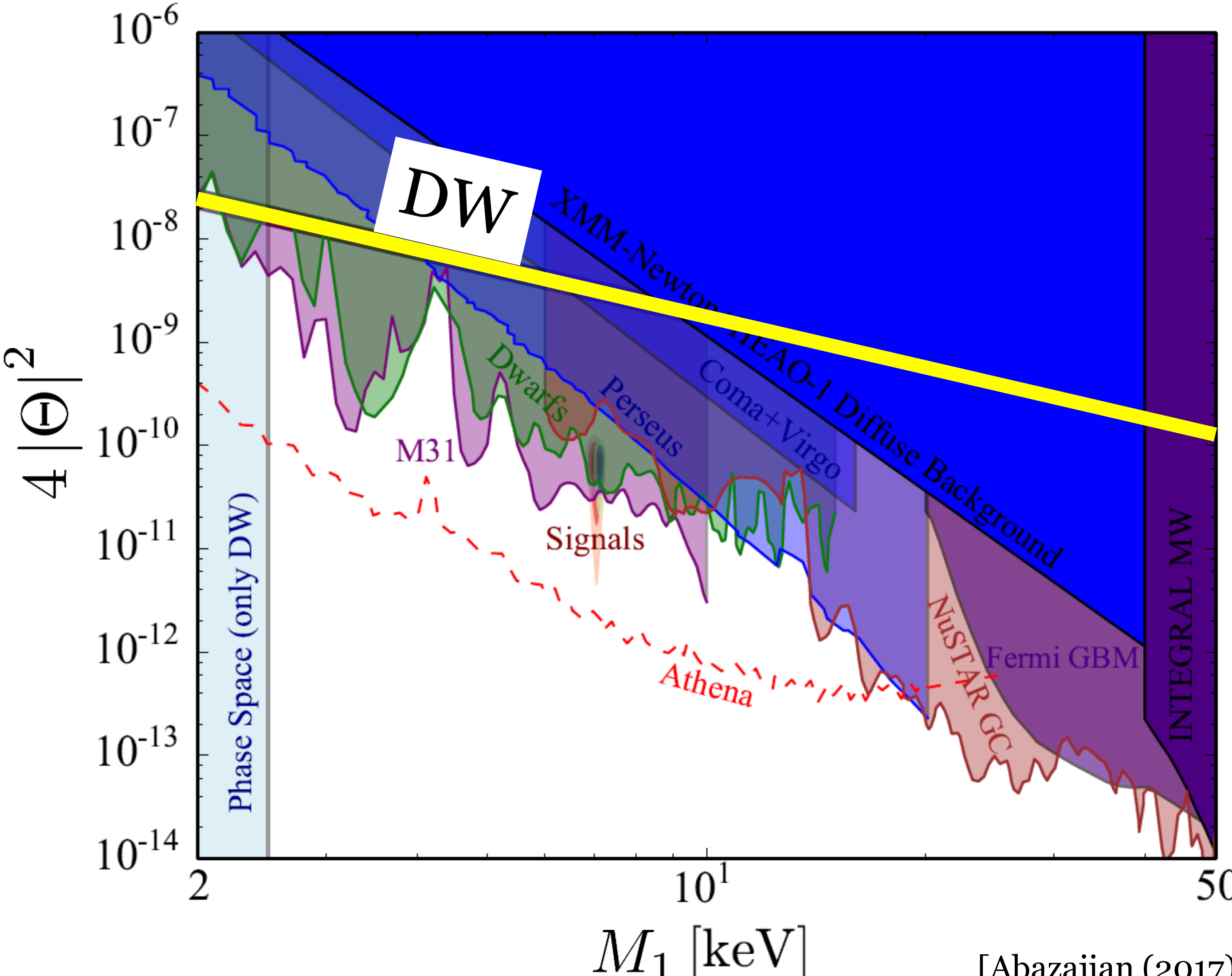

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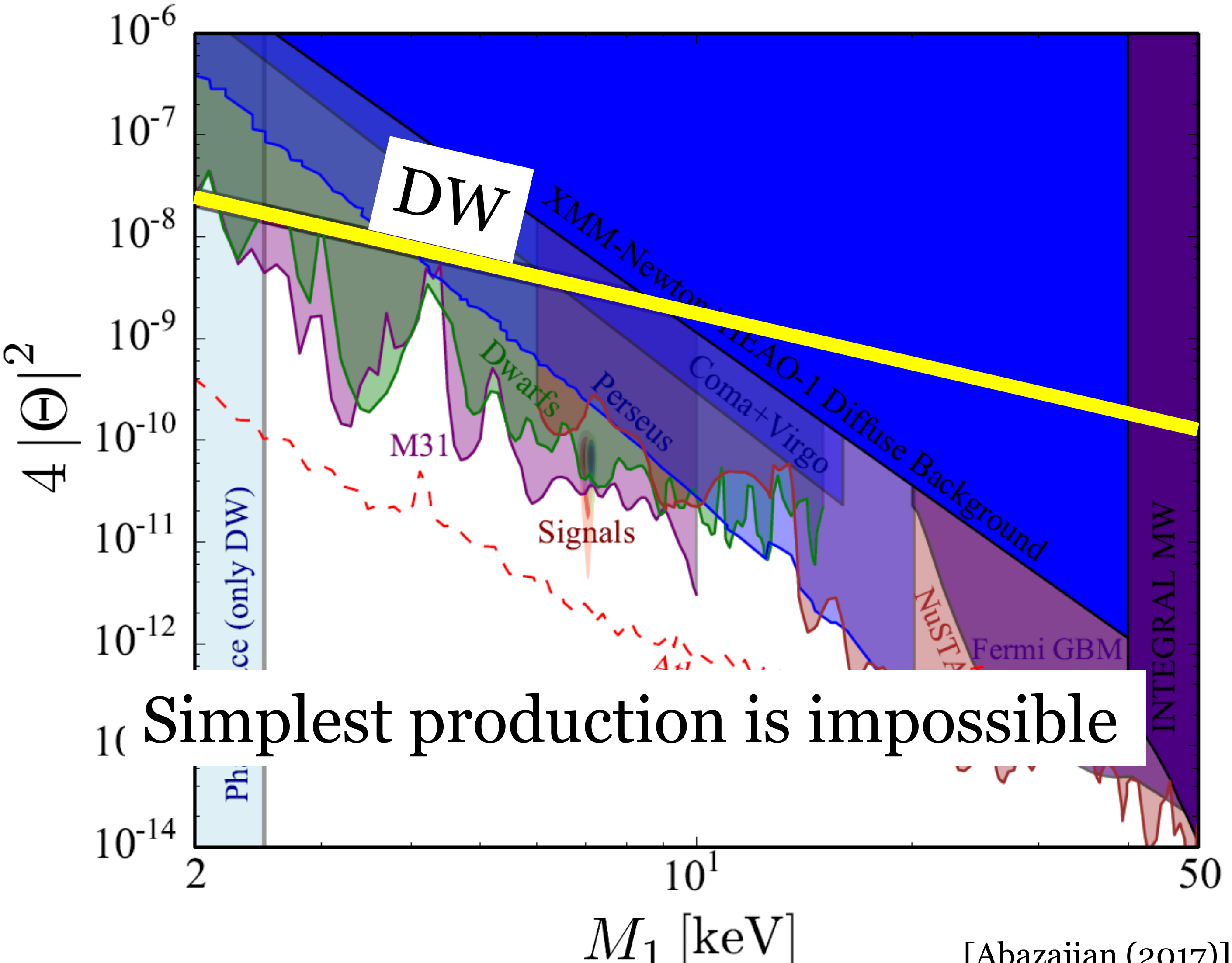

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  Roughly speaking,

$$F_{\alpha 1}^2 \sim 10^{-24} \left(\frac{\Theta^2}{10^{-8}} \right) \left(\frac{1\ \mathrm{keV}}{M_1} \right)^2$$

We need really tiny Yukawa coupling for the DM

➡ Decouple from seesaw relation $\frac{F_{\alpha 1}^2 \langle H \rangle^2}{1\ \mathrm{keV}} \sim 10^{-5}\ \mathrm{eV}$

➡ Consider separately from $N_{2,3}$

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In this talk, I just focus on physics of N_1

Higher dimensional operator for initial conditions of physics in the νMSM

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So far…

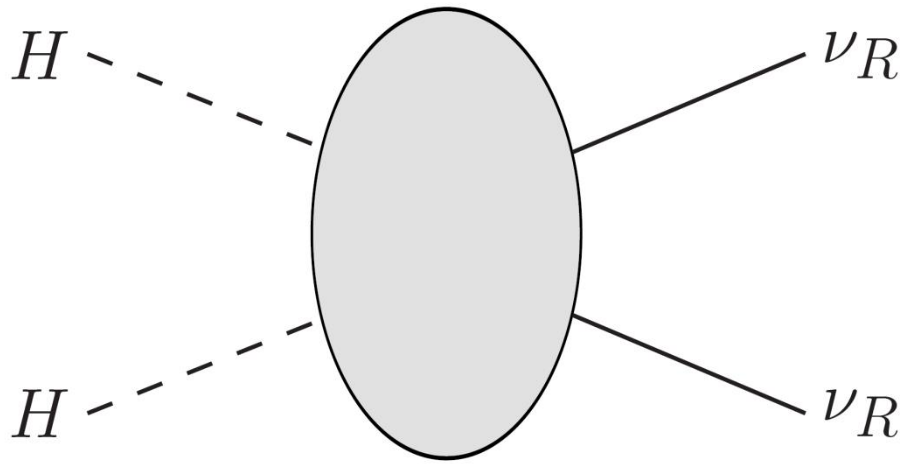
In the analysis of the BAU and the DM,

no initial RHν is assumed.

Higher dimensional operator effect

- RHνs could be produced via…

$$\mathcal{L}_{\rm HD} = \frac{A_{IJ}}{\Lambda} H^\dagger H \overline{\nu^c_{RI}} \nu_{RJ} + \text{h.c.}$$



Produced amount of RHνs

$$\left[\rho_N^I\right]_{IJ} = \# \times \frac{M_P T_R}{\Lambda^2} \left[A^\dagger A\right]_{IJ}$$

$$\xrightarrow{\Lambda \to M_P} \# \times \frac{T_R}{M_P} \left[A^\dagger A\right]_{IJ}$$

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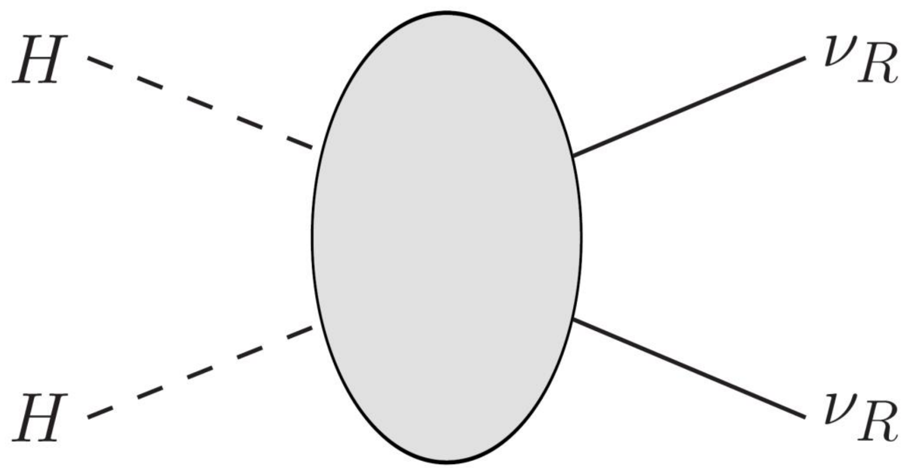

Previous work ： [Bezrukov, Gorbunov, and Shaposhnikov (2009)]

Higgs-driven inflation are low energy phenomena, having nothing to do with inflation. We study then a modification of the νMSM, adding to its Lagrangian higher dimensional operators suppressed by the Planck scale. The role of these operators in Higgs-driven inflation is clarified. We find that these operators do not contribute to the production of *Warm Dark Matter* (WDM) and to baryogenesis. We also demonstrate that the sterile neutrino with

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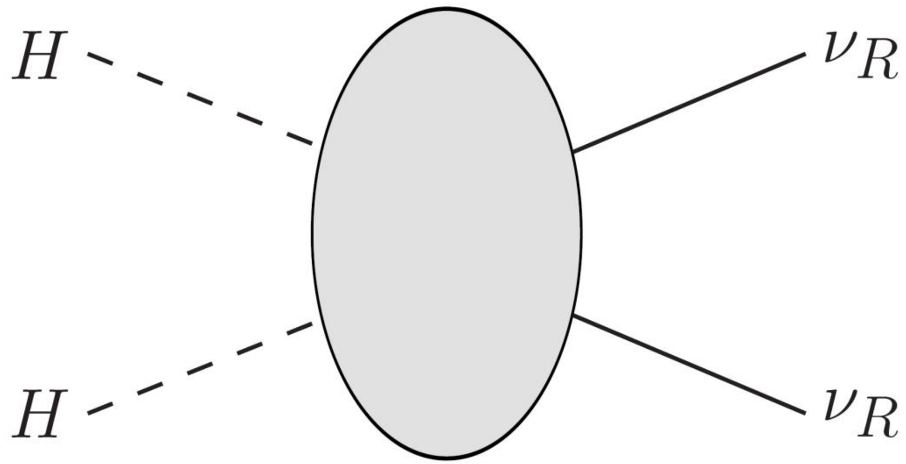

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Higher dimensional operator effect

- Reason of previous conclusions

Produced amount of right-handed neutrino

$$\left[\rho_N^I\right]_{IJ} = \# \times \frac{T_R}{M_P}\left[A^\dagger A\right]_{IJ}$$

Reheating is governed by Higgs boson decay

$$T_R \simeq (3-15)\times 10^{13}\ \mathrm{GeV}$$

$$\frac{T_R}{M_P} \sim 10^{-5}$$ suppressed enough!!

Here, we just blind ourselves to the reheating

Higher dimensional operator effect

- Effect on (constraint from) DM production

If

$$\sum_\alpha |\Theta_{\alpha 1}|^2 \ll 8 \times 10^{-8} \left(\frac{M_1}{1\ \mathrm{keV}} \right)^{-2}$$

DW mechanism does not work at all

Production via HD operators becomes more important!!

Higher dimensional operator effect

- Effect on (constraint from) DM production

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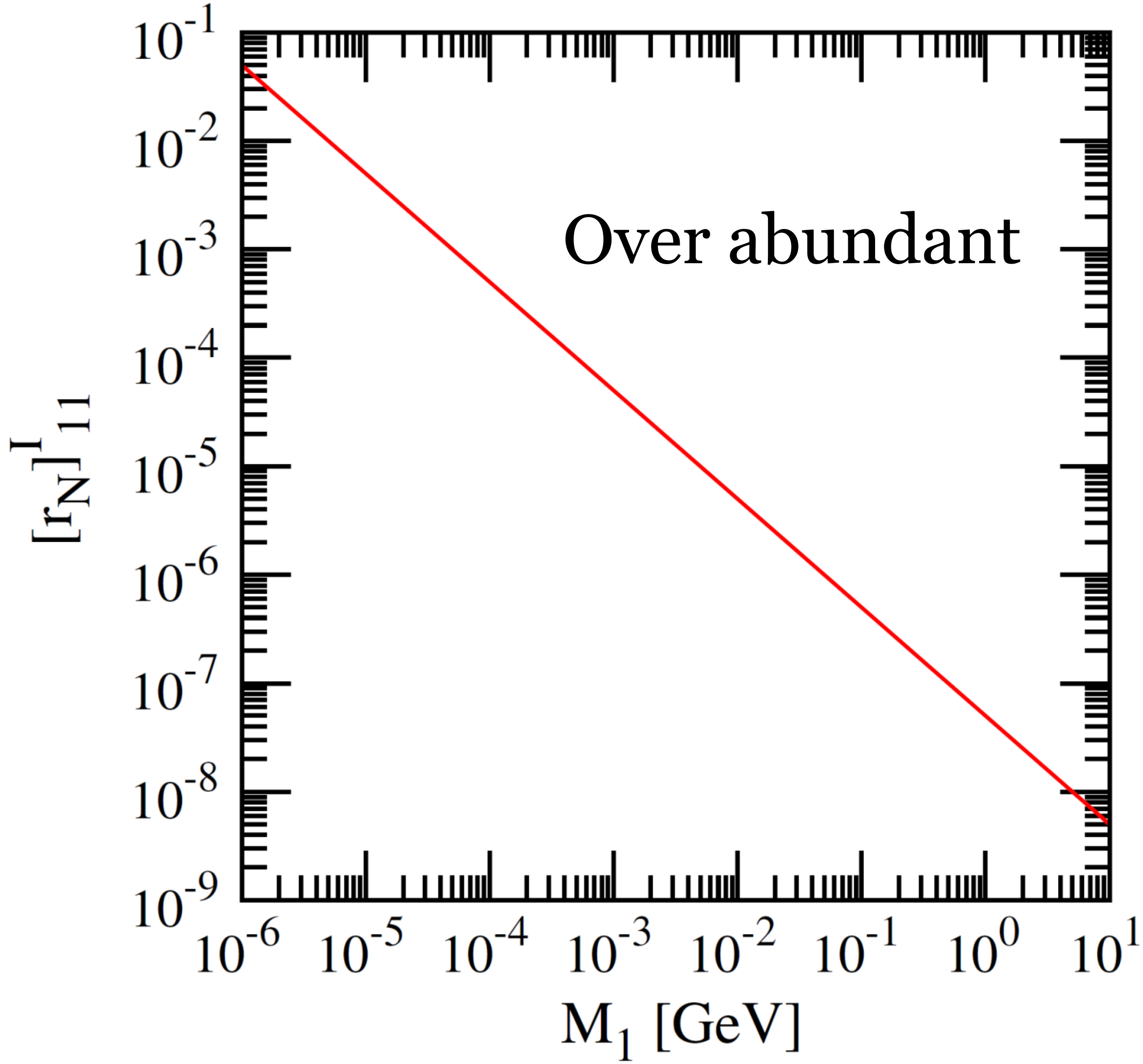

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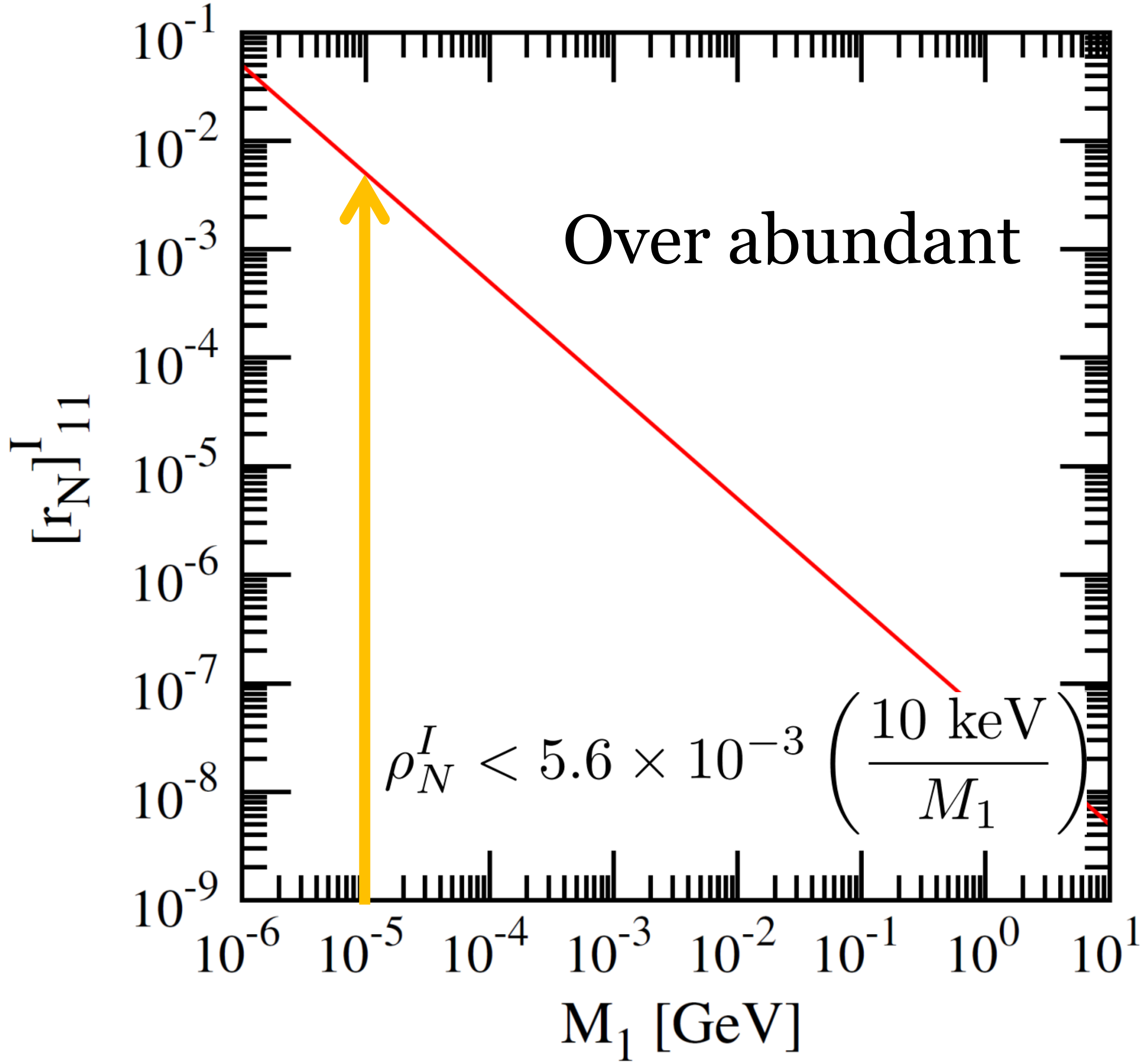

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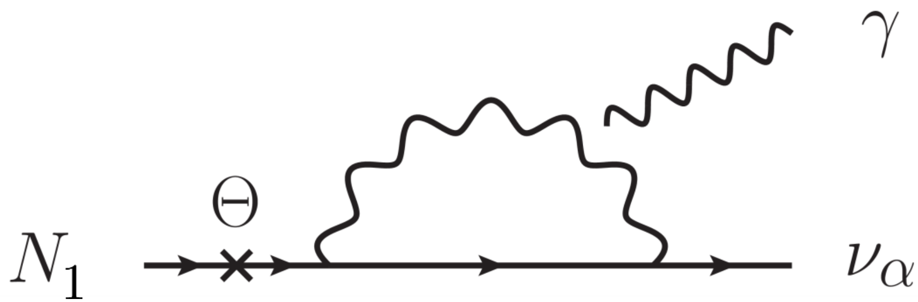
- When $T_R = 10^{13}$ GeV , $A = \mathcal{O}(1)$

$$M_{N_1} \simeq 5 \text{ GeV}$$



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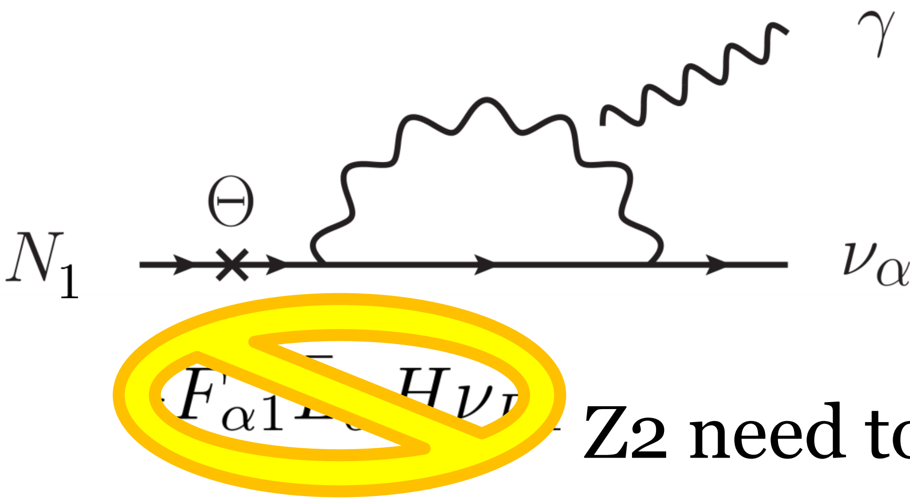

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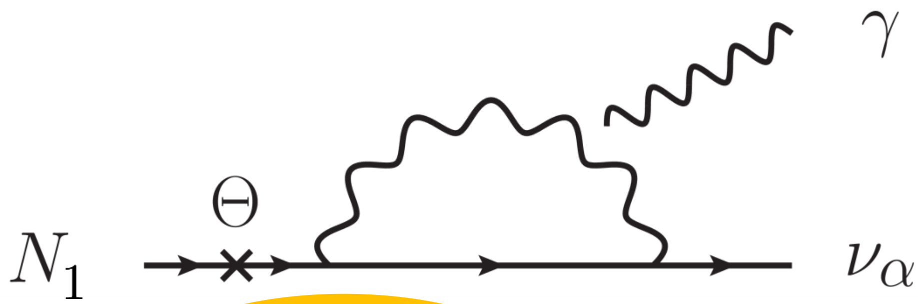

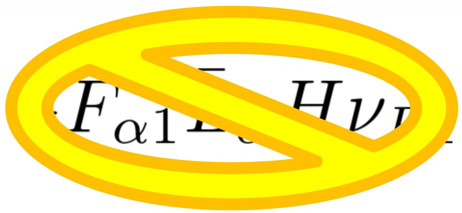

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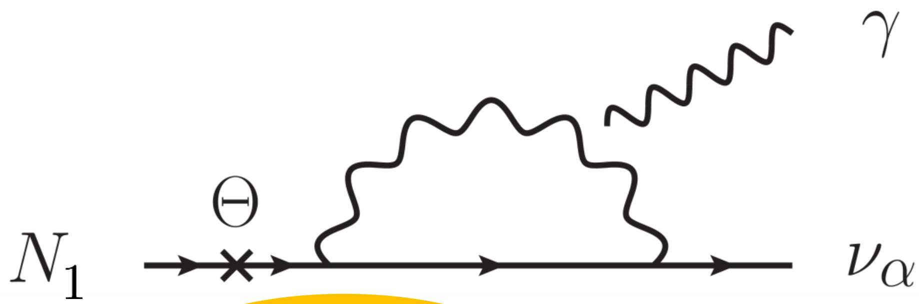

$F_{\alpha 1}\bar{L}_\alpha H\nu_R$ Z2 need to be imposed

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This DM production becomes important!

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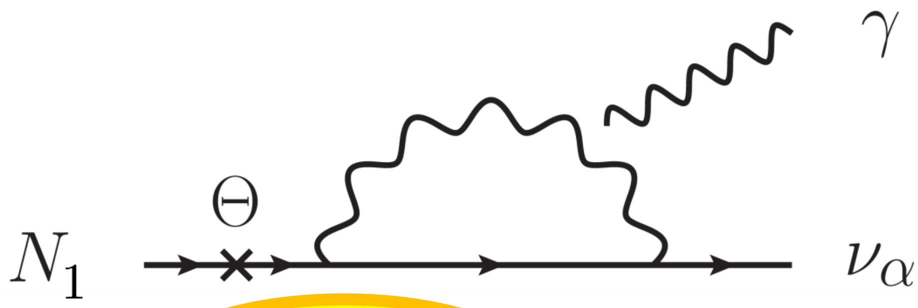

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Test might become difficult…

Higher dimensional operator effect

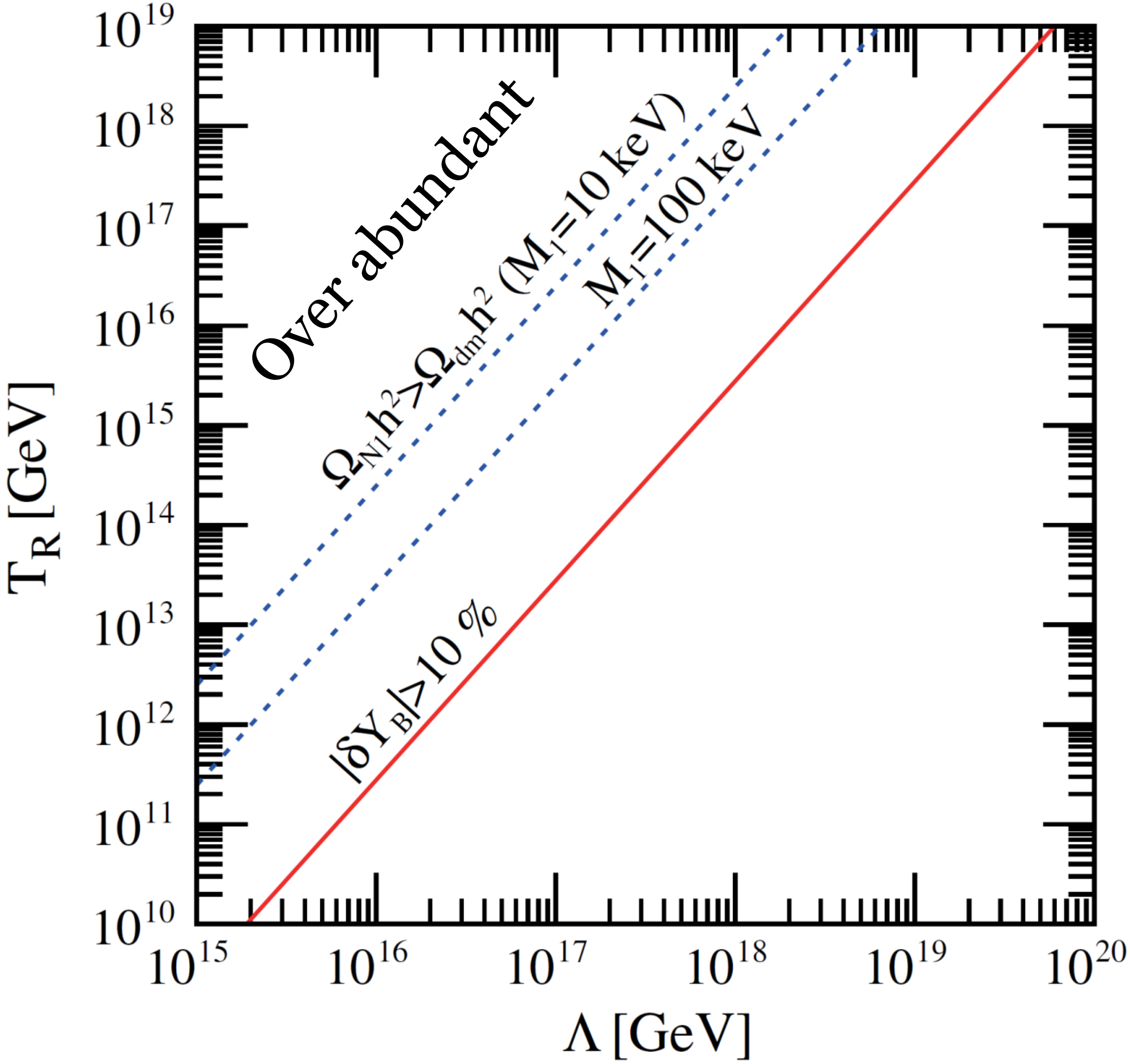
- Predicted reheating temperature

Coupling constant is assumed to be universal $A_{IJ} = 1$

Higher dimensional operator effect

- Predicted reheating temperature

Coupl ... al $A_{IJ} = 1$



Higher dimensional operator effect

- Implication to DM physics

Resonant production with lepton asymmetry

[Shi and Fuller (1999)]

Higher dimensional operator effect

- Implication to DM physics

Resonant production with lepton asymmetry

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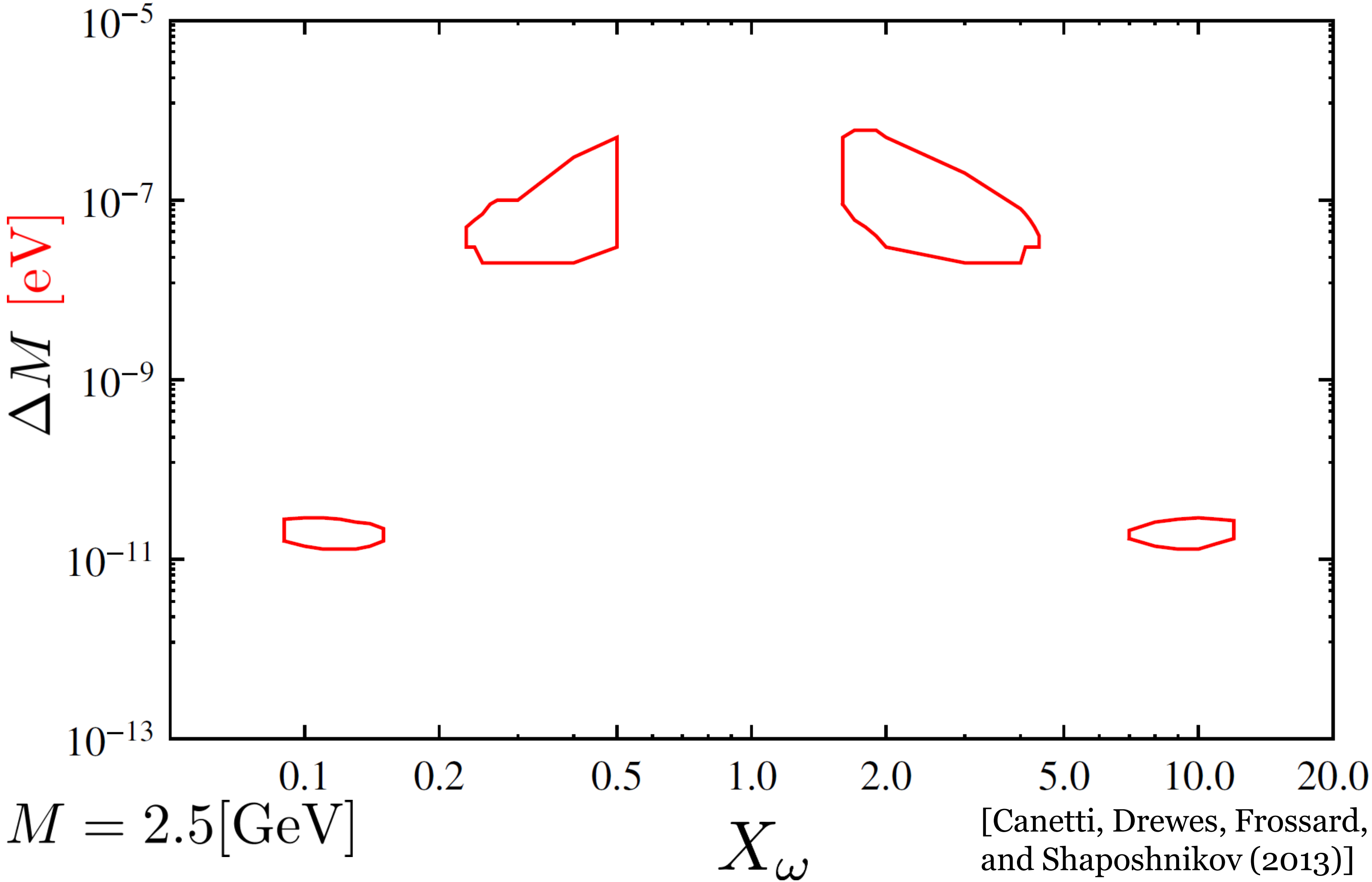

$M = 2.5[\mathrm{GeV}]$

[Canetti, Drewes, Frossard, and Shaposhnikov (2013)]

Higher dimensional operator effect

- Implication to DM physics

Resonant production with lepton asymmetry

[Shi and Fuller (1999)]

Higher-dimensional operator could give significant effects on baryogenesis

↳ Parameter space could be changed enough!

↳ DM production need to be reevaluated!

Conclusions

Conclusions

- The νMSM

  SM+3RHνs with masses below than EW scale

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DM

Seesaw&baryogenesis

Testability

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- The νMSM

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DM Seesaw&baryogenesis Testability

Simple production conflict with observation…

Conclusions

- The νMSM

  SM+3RHνs with masses below than EW scale

  DM   Seesaw&baryogenesis   Testability

  Simple production conflict with observation…

- Impact of higher-dimensional operator on DM

  HD operators could help to produce DM abundance

  BAU could also be improved

- When $\Lambda \gg T_R$, HD effects become negligible

THANK YOU FOR YOUR ATTENTION!

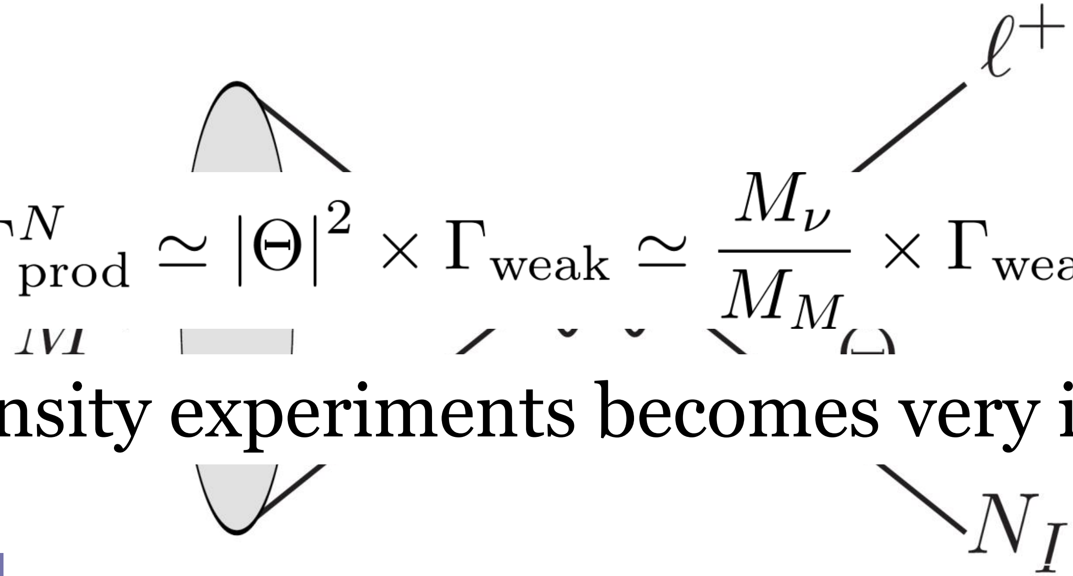
Introduction

- Testability of RHνs

Center mass energy of LHC: 10^4 GeV

Direct production is impossible when $M_M \sim 10^{15}$ GeV

If $M_M < M_{\rm meson}$

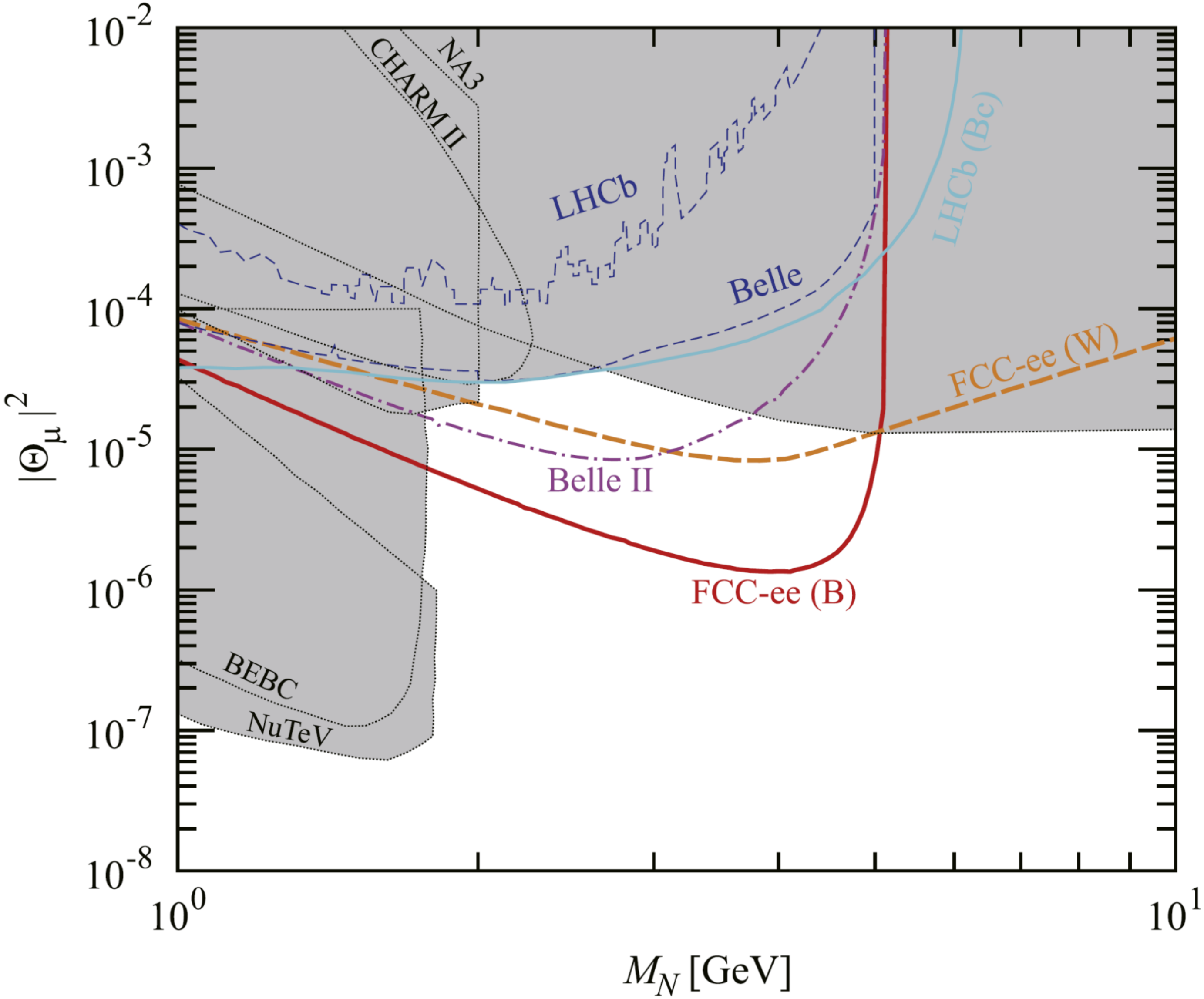


$$\Gamma^N_{\rm prod} \simeq |\Theta|^2 \times \Gamma_{\rm weak} \simeq \frac{M_\nu}{M_M} \times \Gamma_{\rm weak}$$

High intensity experiments becomes very important!!

Introduction

- Testability of RHνs [Asaka and HI (2016)]



Generic form of Yukawa coupling [Casas, Ibarra(2001)]

- When 2RHν explain the tiny ν masses by seesaw

$$F_{\alpha I} = \frac{i}{\langle H \rangle} U D_\nu^{\frac{1}{2}} \Omega D_N^{\frac{1}{2}}$$

$(M_N = 3 \text{ GeV})$

* $D_N^{\frac{1}{2}} = \mathrm{diag}\left(\sqrt{M_2}, \sqrt{M_3}\right) \equiv \left(\sqrt{M_N - \Delta M/2}, \sqrt{M_N + \Delta M/2}\right)$

* $D_\nu^{\frac{1}{2}} = \mathrm{diag}\,(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})$

* $U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{13}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\eta} & \\ & & 1 \end{pmatrix}$

* $\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix}$ for N.H. $\Omega = \begin{pmatrix} \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix}$ for I.H.

ω is arbitrary complex $\xi = \pm 1$

Generic form of Yukawa coupling [Casas, Ibarra(2001)]

• Feature of matrix Ω

$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \cos\mathrm{Re}\omega & -\sin\mathrm{Re}\omega \\ 0 & \xi\sin\mathrm{Re}\omega & \xi\cos\mathrm{Re}\omega \end{pmatrix} \begin{pmatrix} 0 & 0 \\ \cosh\mathrm{Im}\omega & -i\sinh\mathrm{Im}\omega \\ i\sinh\mathrm{Im}\omega & \cosh\mathrm{Im}\omega \end{pmatrix}$$

Imaginary part can determine the magnitude of Yukawa coupling

Because, $\sinh\mathrm{Im}\omega = \frac{1}{2}\left(\exp\left[\mathrm{Im}\omega\right] - \exp\left[-\mathrm{Im}\omega\right]\right)$

$$\cosh\mathrm{Im}\omega = \frac{1}{2}\left(\exp\left[\mathrm{Im}\omega\right] + \exp\left[-\mathrm{Im}\omega\right]\right)$$

Hereafter, $\exp[\mathrm{Im}\omega] \equiv X_\omega$

The νMSM [Asaka, Blanchet, and Shaposhnikov (2005)] [Asaka and Shaposhnikov (2005)]

- Baryogenesis via neutrino oscillation

Sakharov's criteria

Sakharov's criteria	
Baryon number violation	B+L violation by anomaly $(T \gtrsim 100\mathrm{GeV})$ [Kuzmin, Rubakov and Shaposhnikov (1969)]
C and CP violation	Complex phase in the CKM matrix as well as in the PMNS matrix. [Maki, Nakagawa and Sakata (1962) ; Pontecorvo (1967)]
Departure from thermal equilibrium	RHνs are departure from thermal equilibrium from the beginning

$$F \sim 4 \times 10^{-8} \left(\frac{M_N}{\mathrm{GeV}}\right)^{1/2} \left(\frac{\sqrt{\Delta m^2_{\mathrm{atm}}}}{2.5 \times 10^{-3}\mathrm{eV}}\right)^{1/4}$$

All of the criteria can be satisfied in the νMSM!

The νMSM [Asaka, Blanchet, and Shaposhnikov (2005)] [Asaka and Shaposhnikov (2005)]

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[Akhemedov, Rubakov, and Smirnov ('98)]
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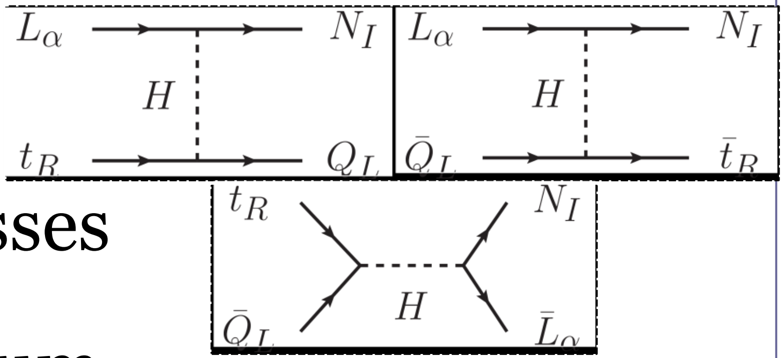


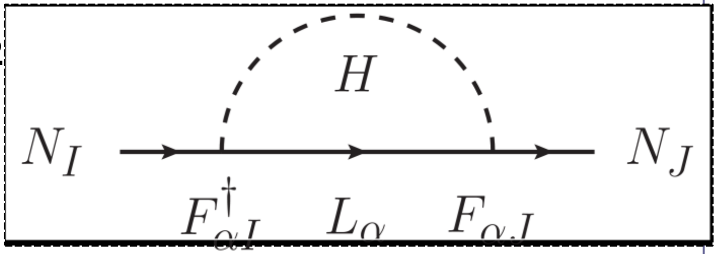
Initial condition : No RHν

Produced by scattering processes

Depart from thermal equilibrium

RHνs start to oscillate at T_L @F^2

$$V_N = \frac{T}{8}\left[F^\dagger F\right]_{IJ}$$



Typical temperature to oscillate

$$T_L = 320\ \mathrm{GeV}\left(\frac{M_N}{3\ \mathrm{GeV}}\right)^{2/3}\left(\frac{\Delta M^2/M_N^2}{10^{-10}}\right)^{1/3}$$

The νMSM [Asaka, Blanchet, and Shaposhnikov (2005)] [Asaka and Shaposhnikov (2005)]

- Baryogenesis via neutrino oscillation

[Akhemedov, Rubakov, and Smirnov ('98)]
[Asaka and Shaposhnikov (2005)]

Through oscillation, CPV occurs via Yukawa couplings

$$A_{32}^{\alpha} = \mathrm{Im}\left[F_{\alpha I}\left[F^{\dagger}F\right]_{IJ}F^{\dagger}_{\alpha J}\right] \neq 0\,.$$

Asymmetries are stored in each active flavor

however, $\Sigma_{\alpha} A_{32}^{\alpha} = 0$

No net asymmetry in the end @F^4 order

Asymmetry is produced @F^6 order effects

The νMSM [Asaka, Blanchet, and Shaposhnikov (2005)] [Asaka and Shaposhnikov (2005)]

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Important fact : total lepton number is conserved

⇒ Lepton number separation

$$\Delta L_{\rm tot} = \sum_\alpha \Delta L_\alpha + \sum_I \Delta N_I = 0\,,$$

$$\sum_\alpha \Delta L_\alpha = -\sum_I \Delta N_I \neq 0\,.$$

$\Delta N_I \neq 0$

$\Delta L_\alpha \neq 0$

Baryon number is produced through sphaleron

$$\Delta B = -\frac{28}{79} \sum_\alpha \Delta L_\alpha$$

[Khlebnikov; Shaposhnikov(1988)]
[Harvey; Turner(1990)]

The νMSM

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$$\Leftrightarrow$$

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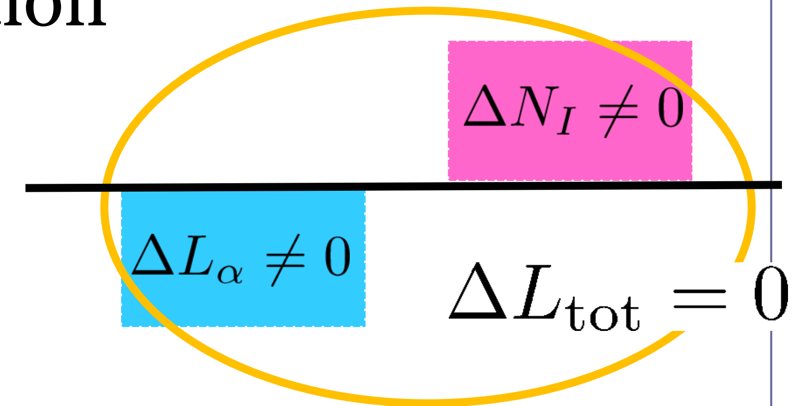

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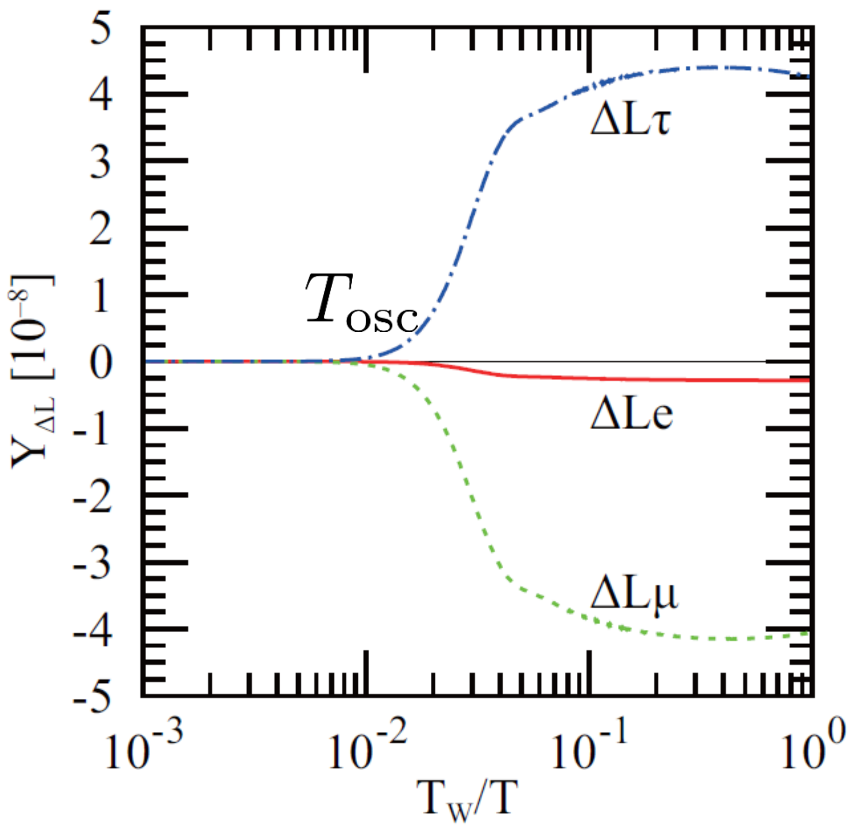
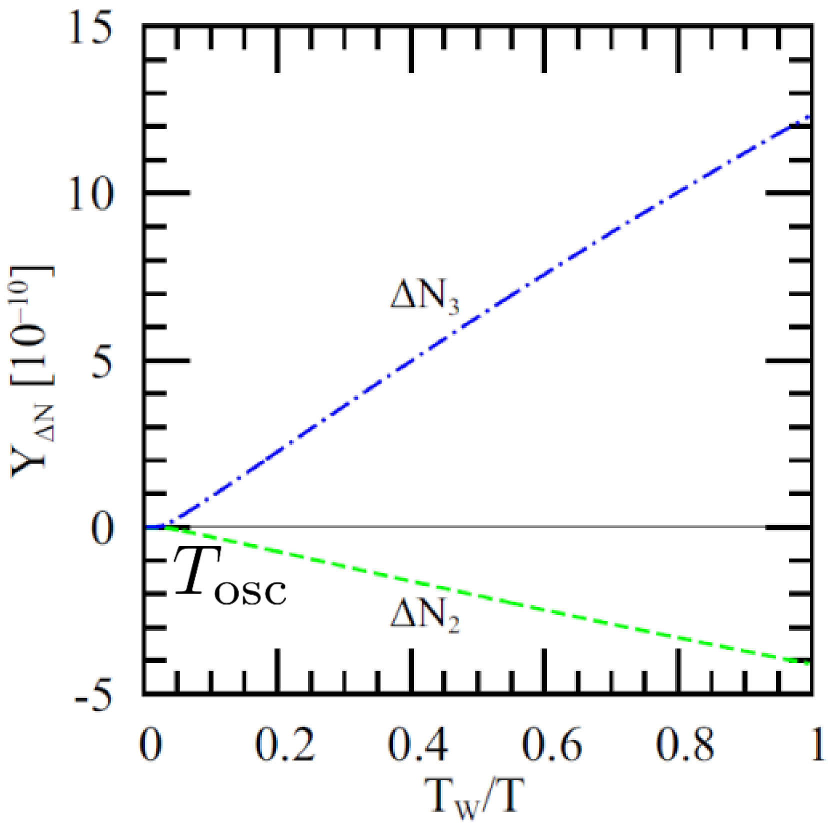
Evolution of asymmetries(Each flavor)





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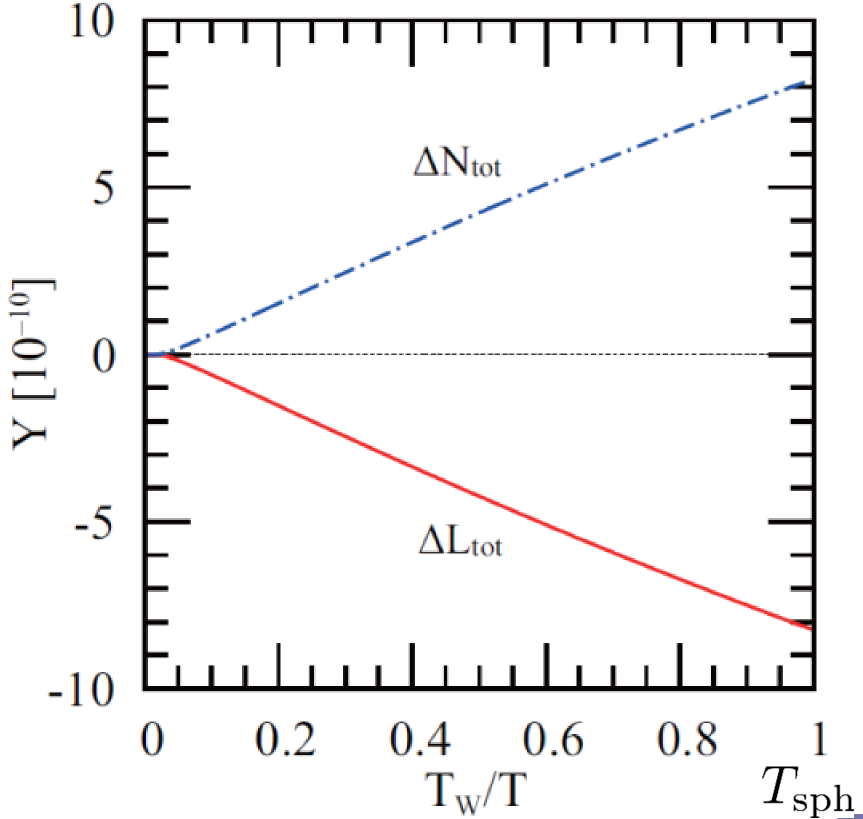
Evolution of asymmetries(Total)



The νMSM [Asaka, Blanchet, and Shaposhnikov (2005)] [Asaka and Shaposhnikov (2005)]

- Kinetic equations point of view [Asaka, Eijima, and HI (2012)]

$$\frac{d\rho_N(k_N)}{dt} = -i\left[H_N^0 + V_N\,, \rho_N\right] - \frac{1}{2}\left\{\Gamma_N^d\,, \rho_N\right\} - \frac{1}{2}\left\{\Gamma_N^p\,, \mathbf{1} - \rho_N\right\} \left(\rho_N = \begin{pmatrix} [\rho_N]_{22} & [\rho_N]_{23} \\ [\rho_N]_{32} & [\rho_N]_{33} \end{pmatrix}\right)$$

Usual initial condition : $\rho_N^I = 0$

Question : Is there really NO other source than the scatterings?

Previous work : [Bezrukov, Gorbunov, and Shaposhnikov

Higgs-driven inflation are low energy phenomena, having nothing to do with inflation. We study then a modification of the νMSM, adding to its Lagrangian higher dimensional operators suppressed by the Planck scale. The role of these operators in Higgs-driven inflation is clarified. We find that these operators do not contribute to the production of *Warm Dark Matter* (WDM) and to baryogenesis. We also demonstrate that the sterile neutrino with

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IS IT REALLY TRUE?

Higher dimensional operator effect

- Effects on the baryogenesis

$$\delta Y_B \equiv \frac{Y_B\big|_{[\rho_N]^I{}_J \neq 0} - Y_B\big|_{[\rho_N]^I{}_J = 0}}{Y_B\big|_{[\rho_N]^I{}_J = 0}}$$

- Oscillation temperature

$$T_L = 320\ \text{GeV} \left(\frac{M_N}{3\ \text{GeV}}\right)^{2/3} \left(\frac{\Delta M^2/M_N^2}{10^{-10}}\right)^{1/3}$$

- ΔM ↑ -Oscillation temperature ↑

$T_L \simeq T_{\text{sph}}$ is given $\Delta M \simeq 10^{-10}\ \text{GeV}$

Higher dimensional operator effect

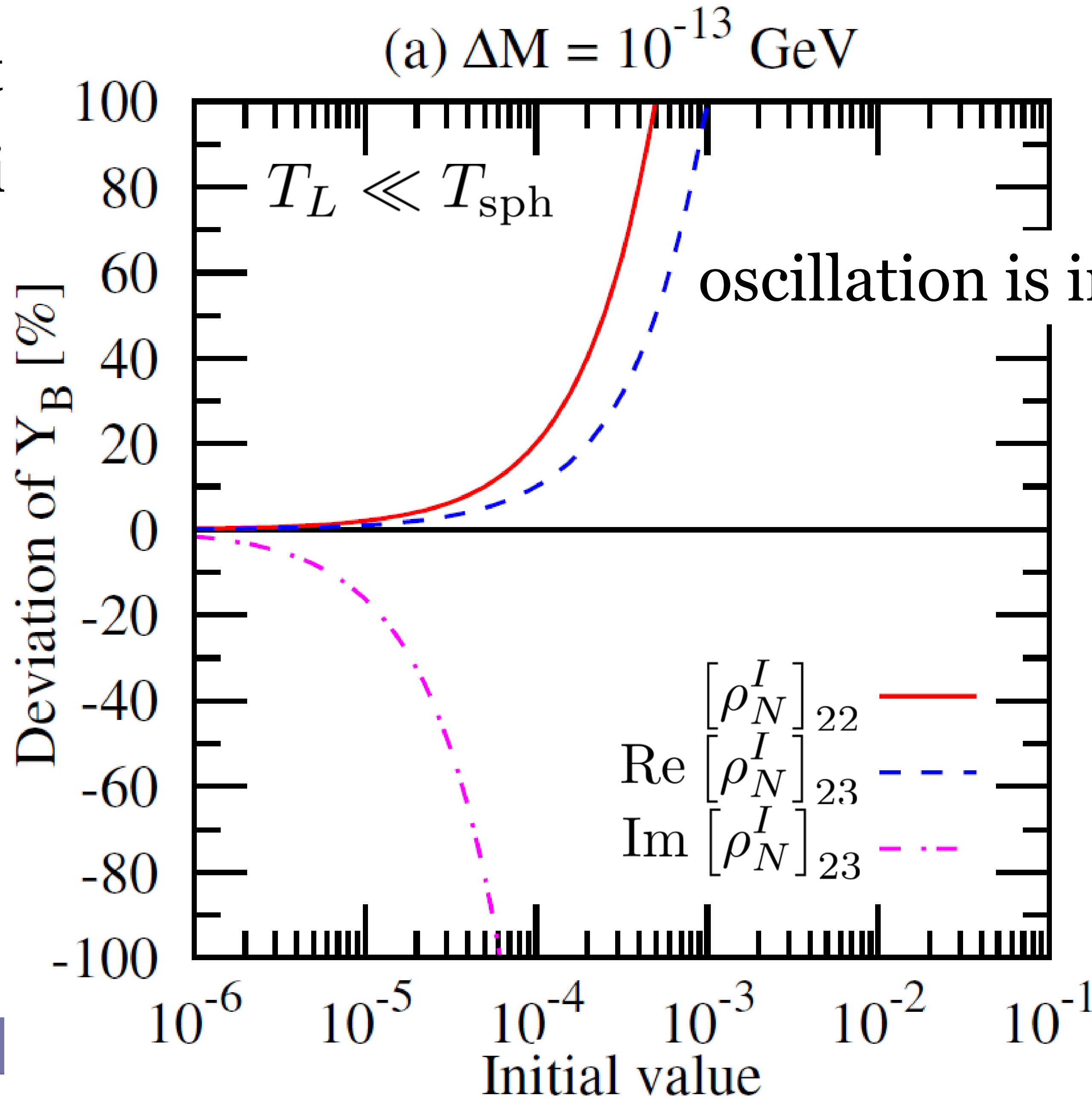
- Effects on the baryogenesis

We fix $X_\omega = 1$ (washout effect does not work)

Higher dimensional operator effect

- Effect

We fi ... k)

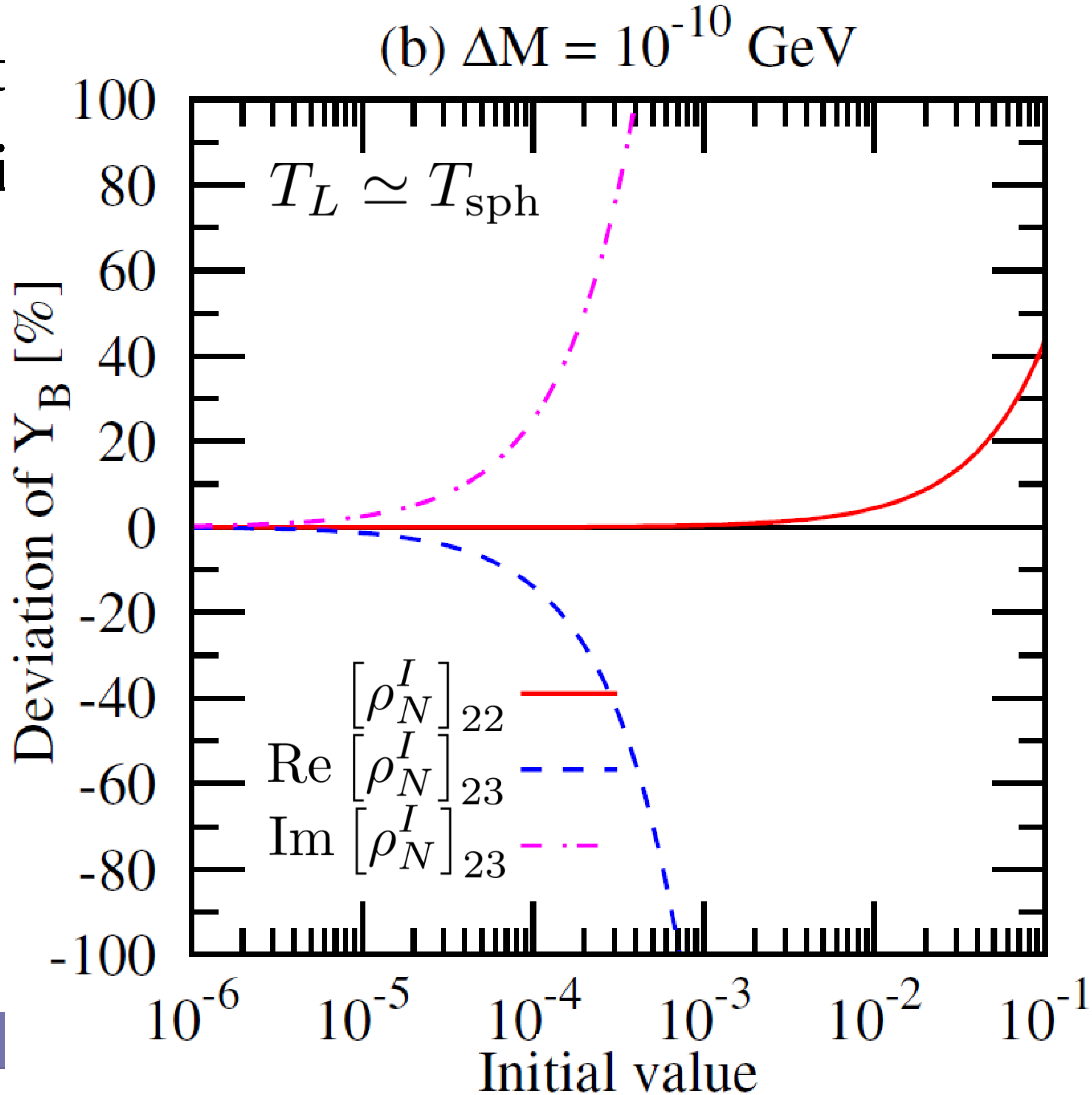


oscillation is ineffective

Higher dimensional operator effect

- Effect

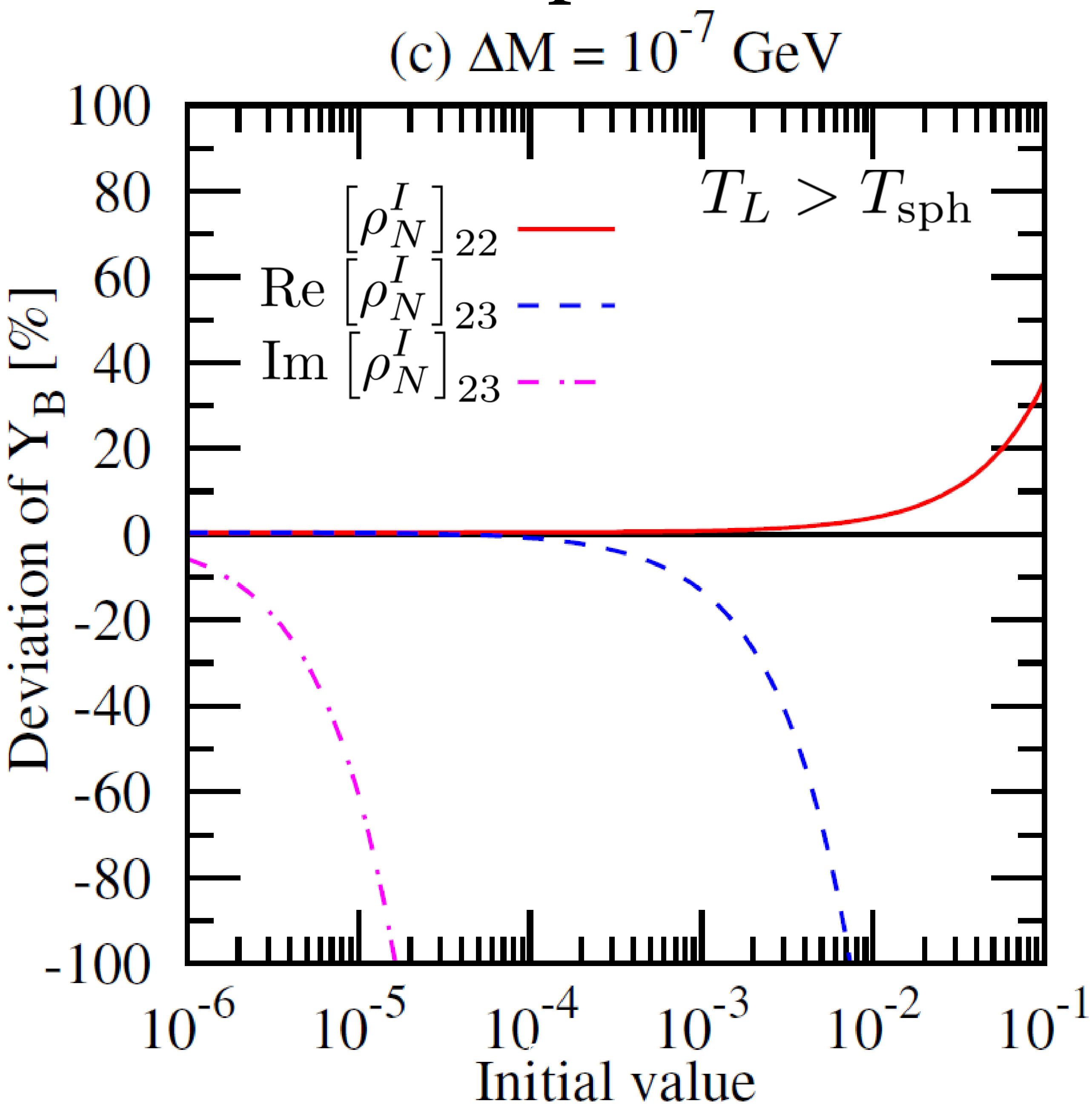
We fi … ·k)



Higher dimensional operator effect

- Effect

We fi ·k)



Higher dimensional operator effect

- Effects on the baryogenesis : summary

  Imaginary part of off-diagonal element is important!

Higher dimensional operator effect

- Effects on the baryogenesis : summary

Imaginary part of off-diagonal element is important!

to create asymmetry

to enhance oscillation

Higher dimensional operator effect

- Effects on the baryogenesis : summary

  Imaginary part of off-diagonal element is important!

  to create asymmetry — to enhance oscillation

- Only if $\Delta M \ll 10^{-10}\ \mathrm{GeV}\ (T_L \ll T_{\mathrm{sph}})$

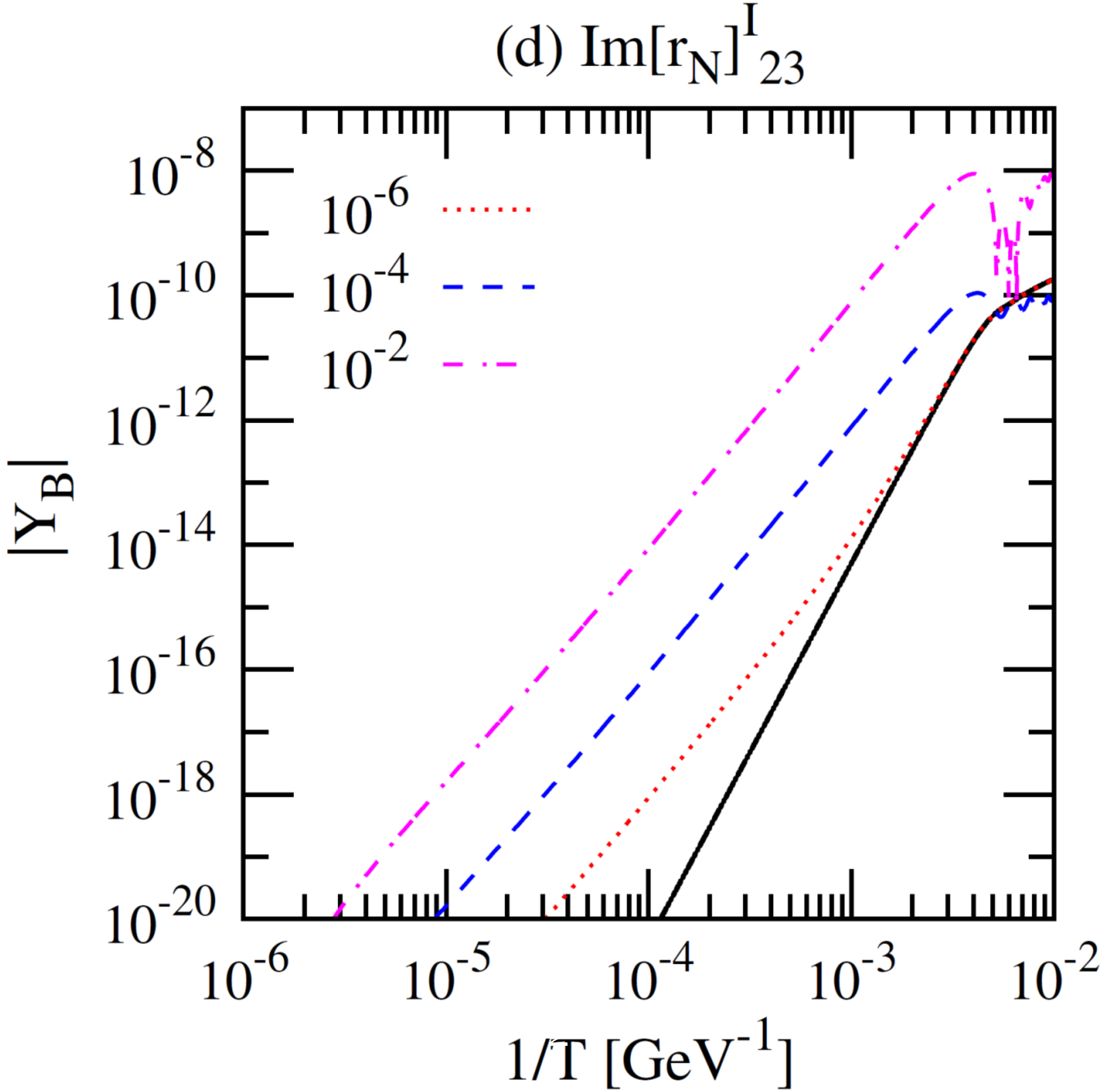
  Diagonal element also becomes significant!

- Even if $\mathrm{Im}\left[\rho_N^I\right]_{23} = 10^{-5}\ (T_R \sim 10^{13}\mathrm{GeV})$

  Y_B can be changed ⇨ New discovery!!

Higher dimensional operator effect

- Detail evolution of Y_B $(\Delta M = 10^{-10}\mathrm{GeV}\,, X_\omega = 1)$



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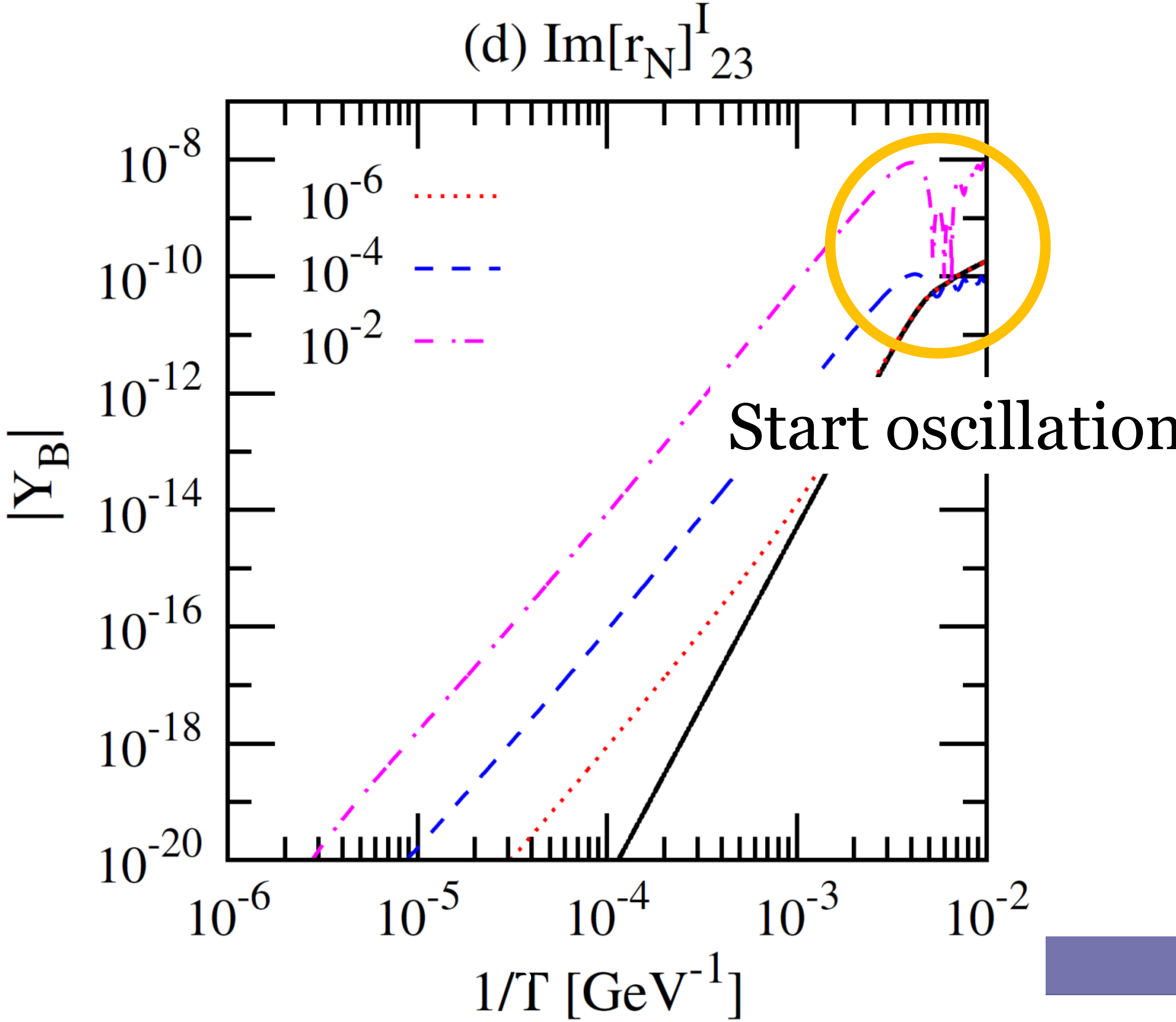


Higher dimensional operator effect

- Impact of $\mathrm{Im}\left[\rho_N^I\right]_{23}$

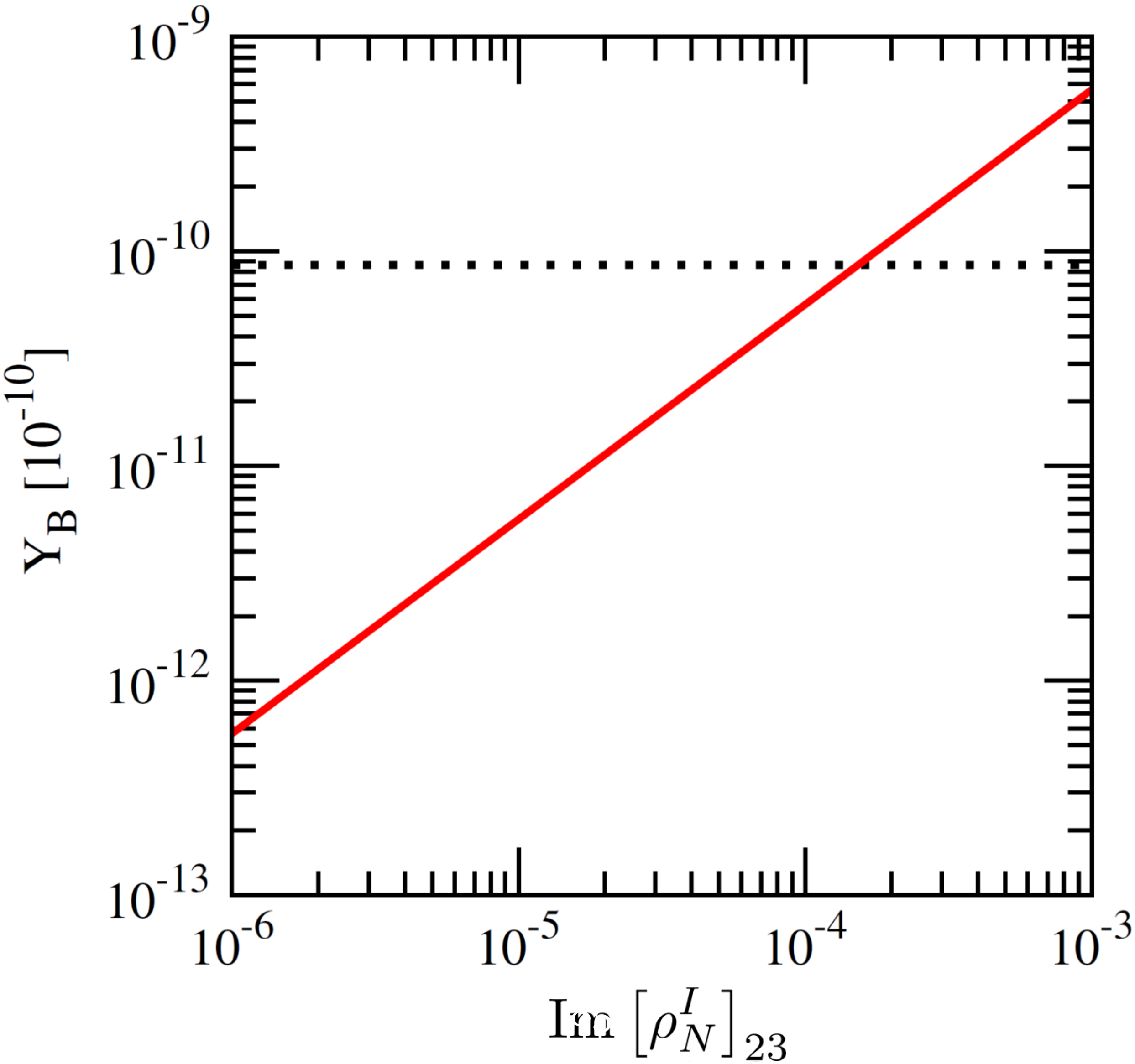
  Off-diagonal element is unique source of CPV

  $$\delta = \eta = \mathrm{Im}\omega = 0$$

Higher dimensional operator effect

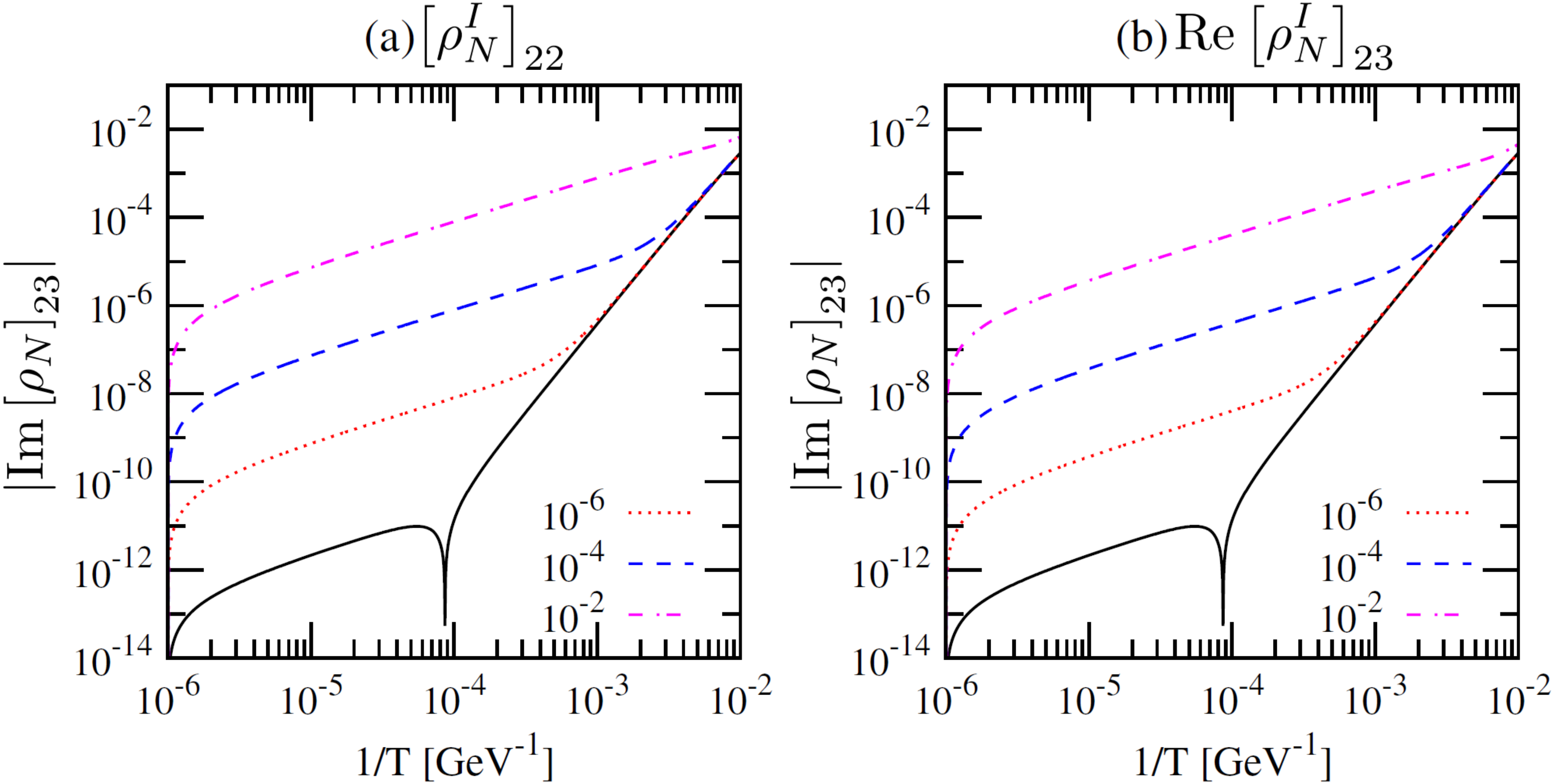
- Impact of $\mathrm{Im}\,[\rho_N^I]_{23}$

Off-d ... PV



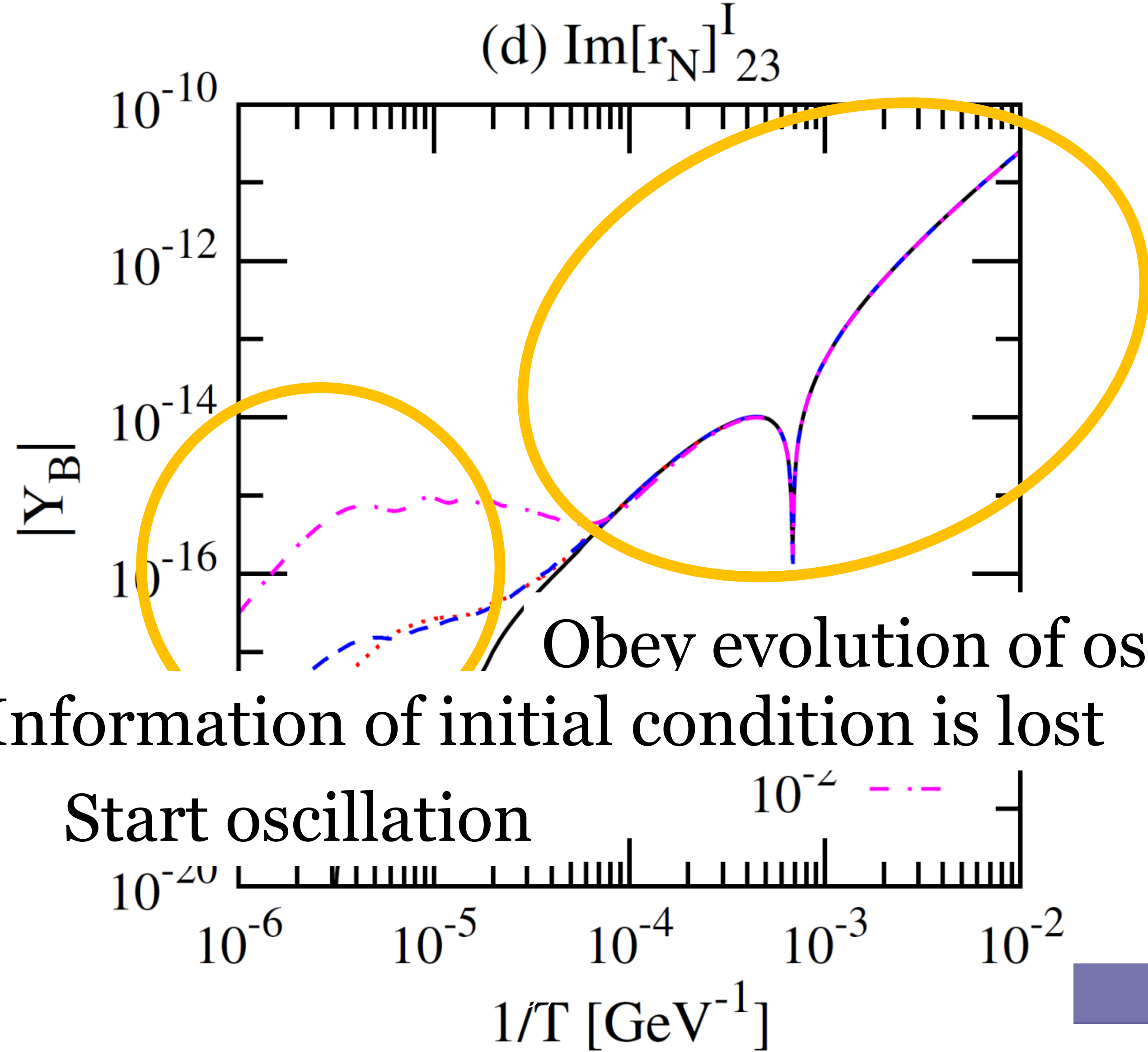
Higher dimensional operator effect

- Detail evolution of $\mathrm{Im}\,[\rho_N]_{23}$



Higher dimensional operator effect

- Detail evolution of Y_B $(\Delta M = 10^{-10}\mathrm{GeV}\,, X_\omega \gg 1)$



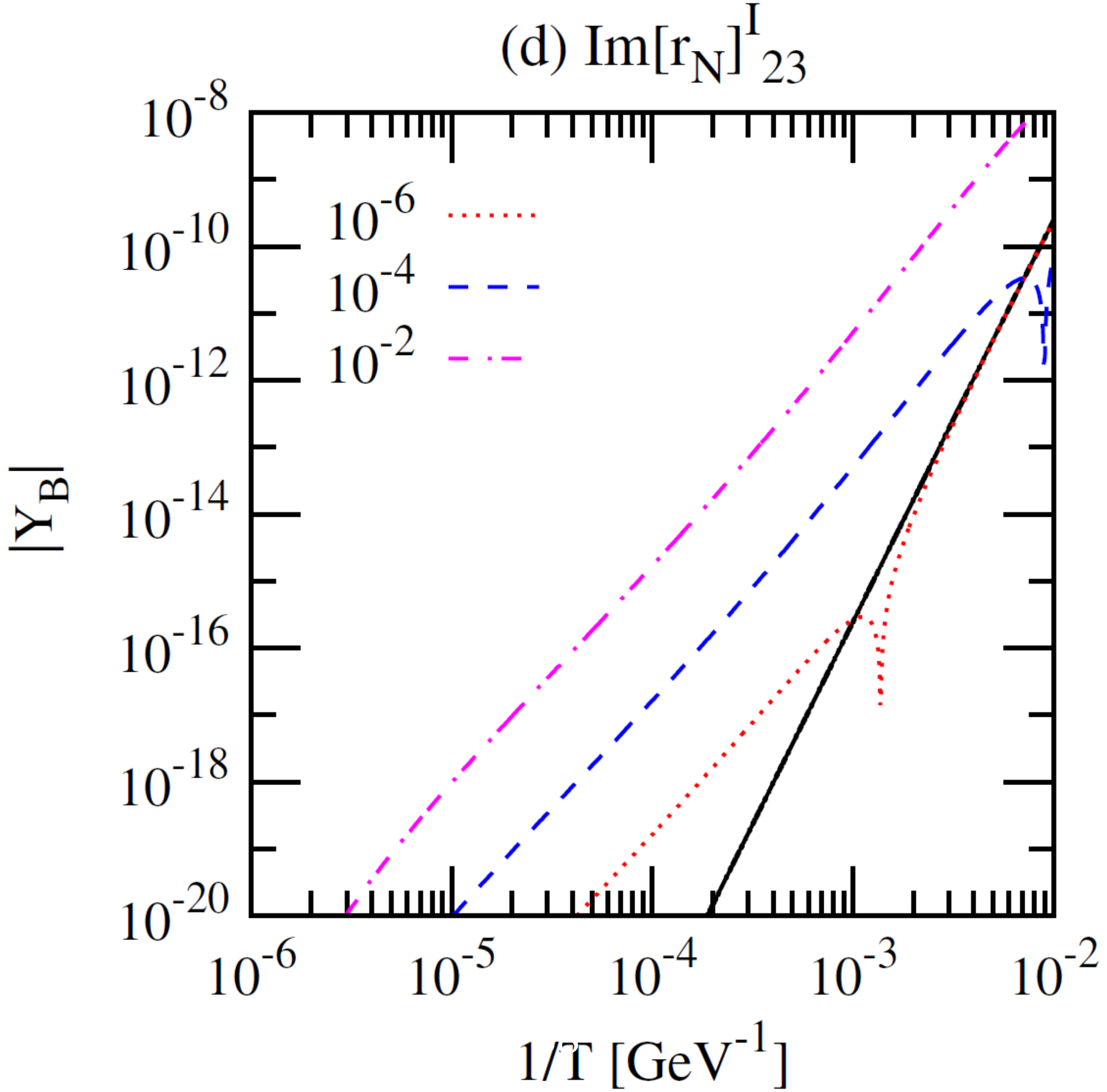
Obey evolution of oscillation

Information of initial condition is lost

Start oscillation

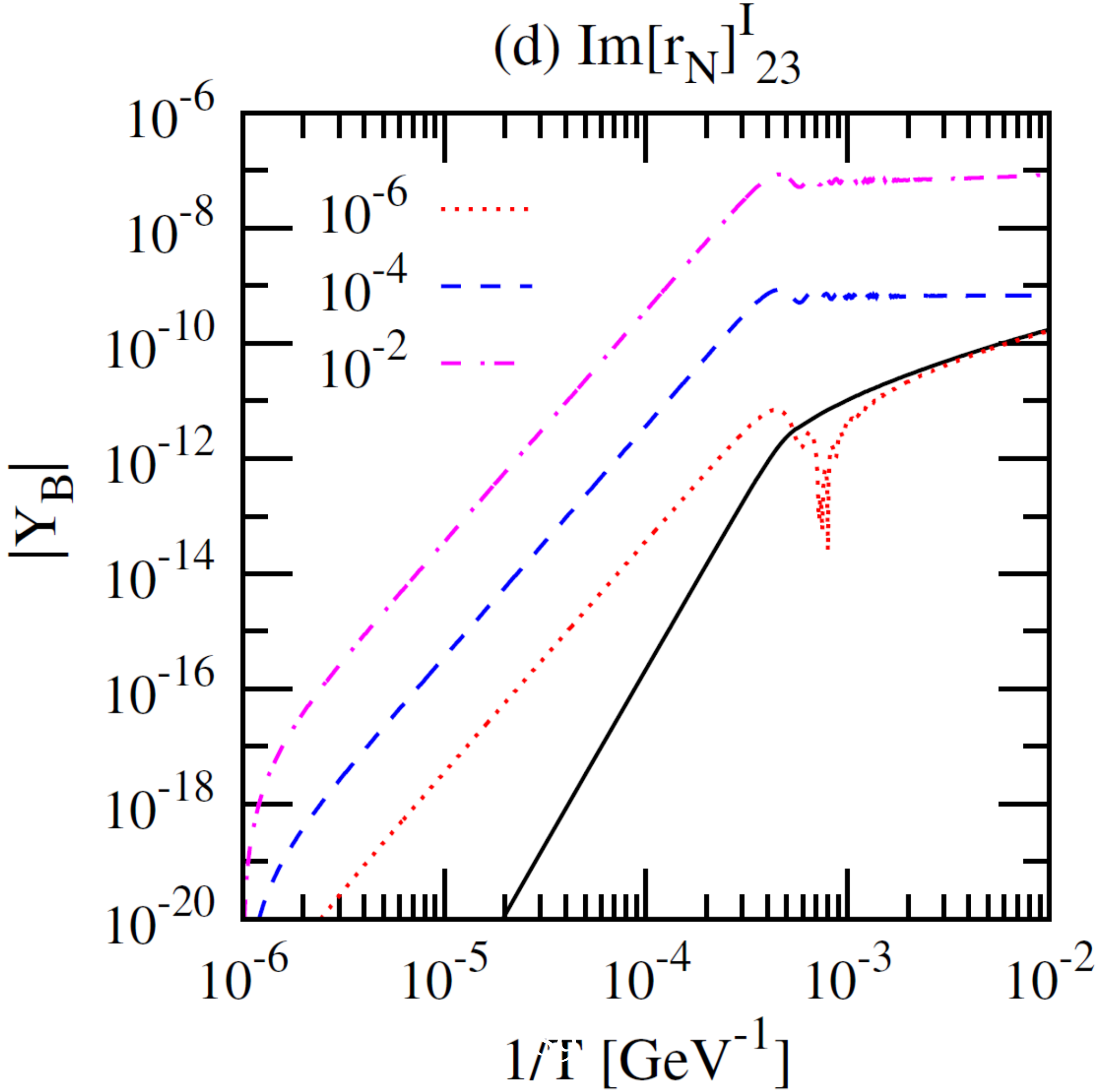
Higher dimensional operator effect

- Detail evolution of Y_B $(\Delta M = 10^{-13}\mathrm{GeV}\,, X_\omega = 1)$



Higher dimensional operator effect

- Detail evolution of Y_B $(\Delta M = 10^{-7}\mathrm{GeV}\,, X_\omega = 1)$



Conclusions

- Future works

  -Including LNV processes [Eijima and Shaposhnikov (2017)] [Chiglieri and Laine (2017)]

  -Including CPV Higgs decay processes [Hambye and Tresi (2017)]

  When Yukawa is big enough $(X_\omega \gg 1)$,
  these effects take place

  -Detail analysis of indirect effect on DM production