Vanishing neutrinoless double beta decay in the seesaw mechanism

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References： 2009.****

Introduction

Neutrino physics: exciting and mysterious

Oscillation experiments: mixing angles
mass squared differences
(Dirac CP phase)

Opened questions: absolute masses
mass hierarchy
Majorana CP phases

Anyway, massive neutrinos have to be achieved somehow

Right-handed neutrinos

Introduction

After having right-handed neutrinos, $(I=1,2)$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\,\overline{\nu_{RI}}\gamma^\mu\partial_\mu\nu_{RI} - \left(F_{\alpha I}\,\overline{\ell_\alpha}\,\Phi\,\nu_{RI} + \frac{M_I}{2}\,\overline{\nu^c_{RI}}\,\nu_{RI} + h.c.\right)$$

Once you impose $M_D \equiv F_{\alpha I}\langle\Phi\rangle \ll M_I$ at any scale of M_I

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

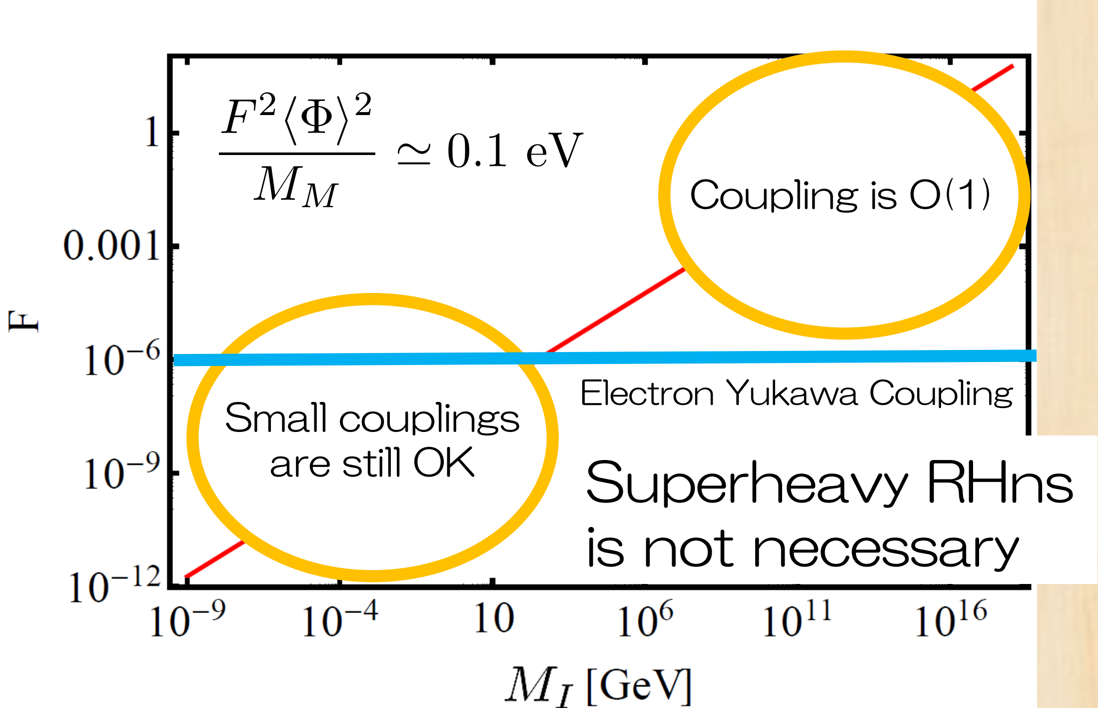
$\sim \mathcal{O}(10^{15\text{-}16})$ GeV of M_I

Assumption: $M_I \lesssim \Lambda_{\rm EW} \sim \mathcal{O}(10^2)$ GeV

Phenomenologically interesting!

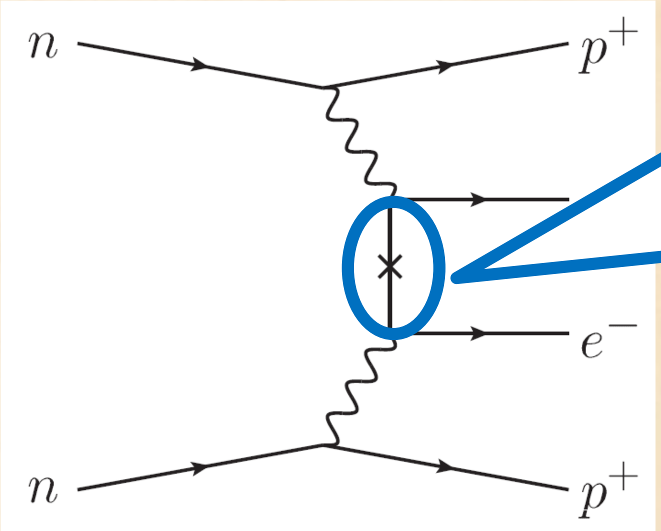
$$\nu_{L\alpha} = U_{\alpha i}\nu_i + \Theta_{\alpha I}N_I^c \quad (\Theta_{\alpha I} \equiv M_D/M_I)$$

active neutrino heavy neutral lepton



Introduction

Neutrinoless double beta decay: hunting Majorana nature



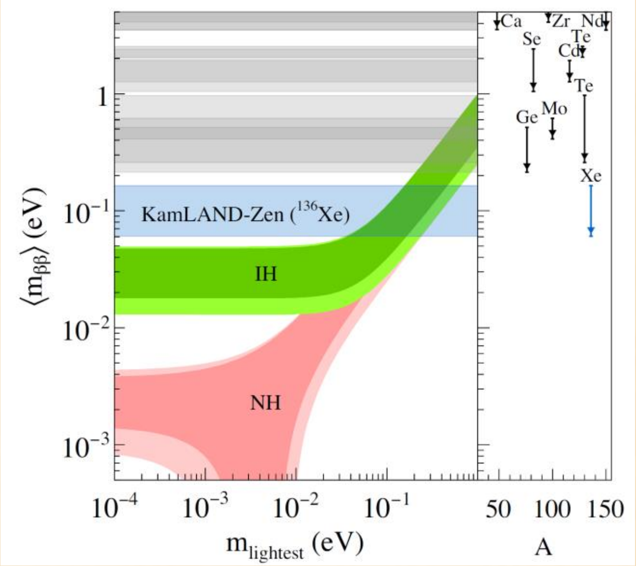
ν_L

ν_L

mass eigenstates

$$\nu_{L\alpha} = U_{\alpha i}\,\nu_i + \Theta_{\alpha I} N_I^c$$

Both of them can contribute



[KamLAND-Zen PRL 117 (2016)]

Effective mass: characterize the decay

$$m_{\text{eff}} = \sum_i m_i U_{ei}^2 + \sum_I f_\beta(M_I) M_I \Theta_{eI}^2 \quad \text{with} \quad f_\beta(M_N) = \frac{\langle p^2\rangle}{\langle p^2\rangle + M_N^2} \quad \left(\sqrt{\langle p^2\rangle} = 200\ \text{MeV}\right)$$

If $M_I \ll \sqrt{\langle p^2\rangle}$, $m_{\text{eff}} = 0$ from seesaw relation $\begin{pmatrix} 0 & M_D \\ M_D^T & M_I \end{pmatrix}$

Question

What happens if…

1. RHνs have hierarchical mass structure

2. one of RHνs significantly contributes to the decay

Namely, we require

$M_1 < \sqrt{\langle p^2 \rangle} \ll M_2$ or, more generally, $\sqrt{\langle p^2 \rangle} \lesssim M_1 \ll M_2$

case A case B

How much effects on $m_{\text{eff}} = \sum_i m_i U_{ei}^2 + \sum_I f_\beta(M_I) M_I \Theta_{eI}^2$?

As a first step, we can simplify

$$m_{\text{eff}} = \sum_i m_i U_{ei}^2 + f_\beta(M_1) M_1 \Theta_{e1}^2 \qquad (f_\beta(M_2) = 0)$$

※show our results for the NH case

Analyses

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

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

$$D_\nu^{\frac{1}{2}} = \mathrm{diag}\,(0\,, \sqrt{m_2}\,, \sqrt{m_3}) \qquad D_N^{\frac{1}{2}} = \mathrm{diag}\left(\sqrt{M_2}\,, \sqrt{M_3}\right)$$

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

$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix} \quad (\omega = \omega_r + i\omega_i\,, \xi = \pm 1\,)$$

N_1 contribution

$$\Theta_{e1}^2\, M_1\, f_\beta(M_1) = -\left(U_{e2}m_2^{1/2}\cos\omega + U_{e3}m_3^{1/2}\sin\omega\right)^2 (1-\delta_f^2)$$

Analyses

Effective mass

$$m_{\text{eff}} = \left(U_{e2} m_2^{1/2} \sin\omega - U_{e3} m_3^{1/2} \cos\omega\right)^2 + \left(U_{e2} m_2^{1/2} \cos\omega + U_{e3} m_3^{1/2} \sin\omega\right)^2 \times \delta_f^2$$

If $\delta_f = 0$

case A

$$m_{\text{eff}} = \left(U_{e2} m_2^{1/2} \sin\omega - U_{e3} m_3^{1/2} \cos\omega\right)^2 \Rightarrow \tan\omega = \frac{U_{e3} m_3^{1/2}}{U_{e2} m_2^{1/2}}$$

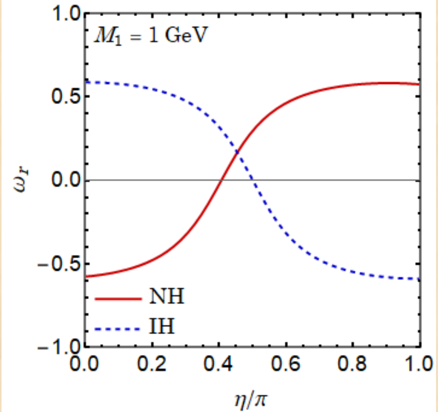
case B

consistent by taking $\delta_f = 0$

$$\tan\omega = \frac{A \pm i\delta_f}{1 \mp i\delta_f A} \equiv \tan\omega_\pm$$ where $$A \equiv \frac{U_{e3} m_3^{1/2}}{U_{e2} m_2^{1/2}}$$

Especially,

$$\tan 2\omega_r = \frac{2\mathrm{Re}A}{1 - |A|^2}$$ (independent of M_1)

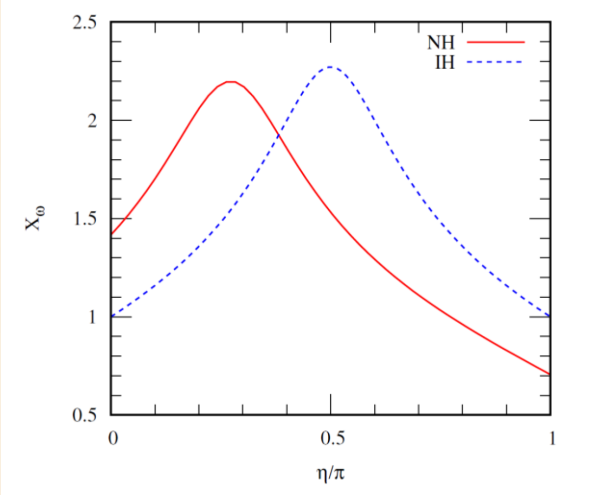


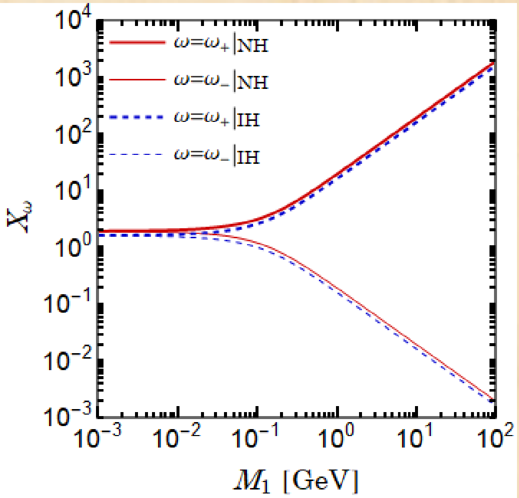
Analyses

Constraints on ω_i

$$(\exp[\omega_i])^2 = X_\omega^2 = \frac{1 \pm \delta_f}{1 \mp \delta_f}\sqrt{\frac{1+|A|^2+2\mathrm{Im}A}{1+|A|^2-2\mathrm{Im}A}}$$

$\delta_f = 0$ $\delta_f \neq 0$



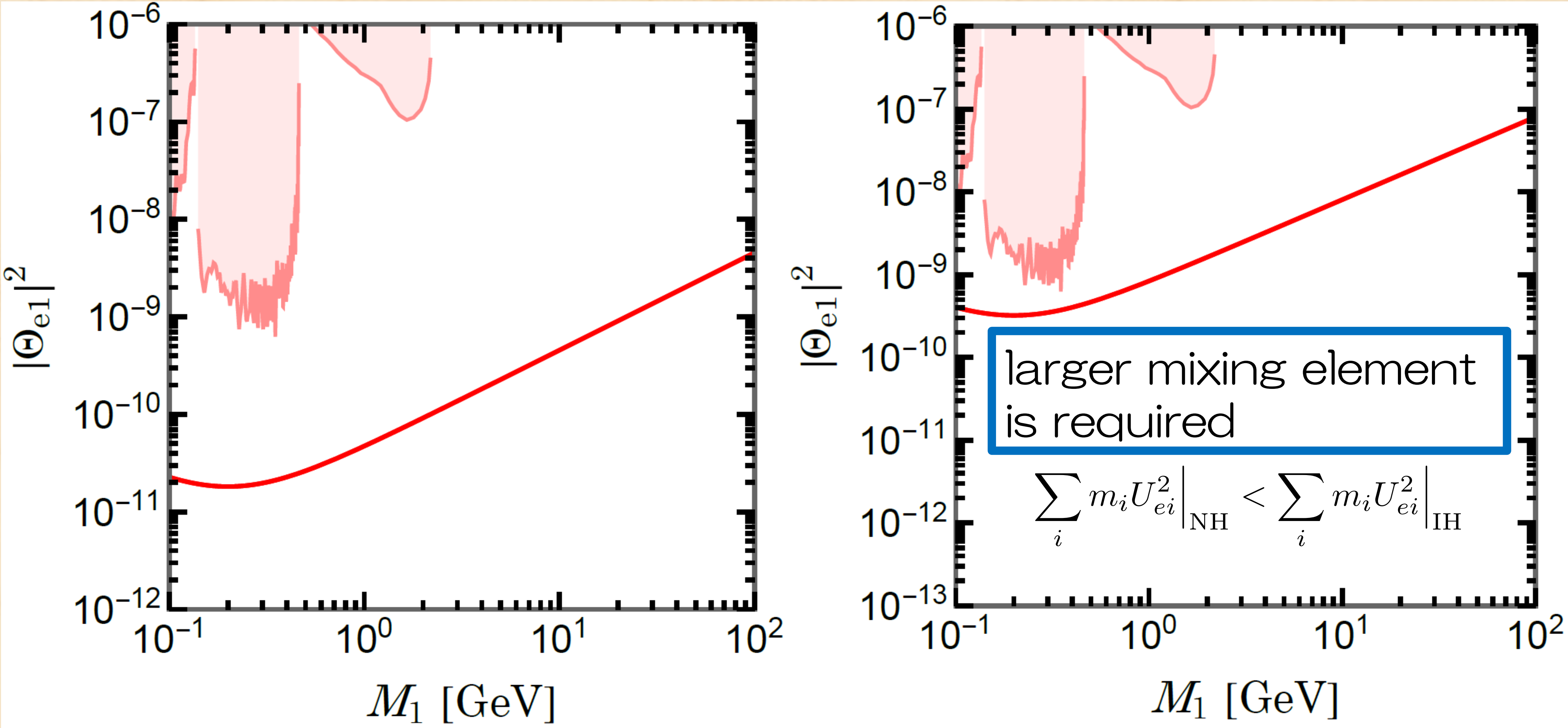


Since $F_{\alpha 1} \propto X_\omega$, heavier RHν needs larger $F_{\alpha 1}$ for larger $\Theta_{\alpha 1}$

$$m_{\rm eff} = \sum_i m_i U_{ei}^2 + f_\beta(M_1) M_1 \Theta_{e1}^2 = 0$$

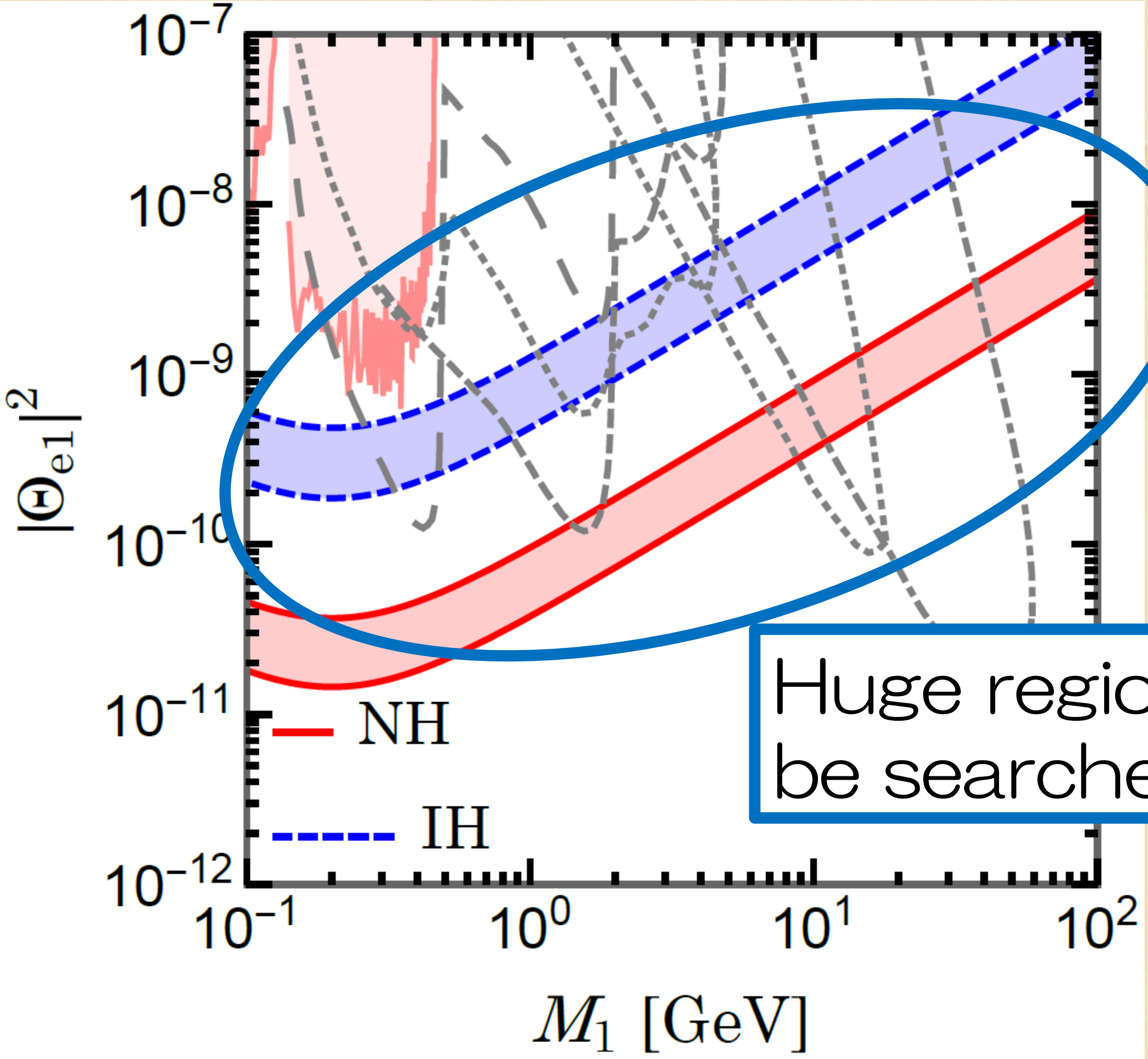
Prediction

Since ω is highly constrained, $(\eta = 0.3\pi)$



Prediction

Comparison with future sensitivity



Huge region can be searched!

Conclusions

Right-handed neutrinos: neutrino masses, baryon asymmetry

Naively, Majorana neutrinos are predicted

Neutrinoless double beta decay (#L)

If right-handed neutrino has significantly light mass
and contributes to the decay,

such contribution would obliterate the decay

Novel feature by our work!

Mixing elements are highly constrained
strongly depending on Majorana phase

Future collider would
determine missing
neutrino properties!

Thank you very much for your attention!