ニュートリノを伴わない二重ベータ崩壊と軽い右巻きニュートリノ

田中和樹（新潟大学）

共同研究者

淺賀岳彦（新潟大学）
石田裕之（富山県立大学）

参考文献

Phys.Rev.D103 (2021) 015014 + PTEP 2021 ptab046 + arXiv:2101.12498

Flavor Physics Workshop 2022 @ 伊豆 静岡県　2022年11月9日

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4. $0\nu\beta\beta$ decay in the seesaw mechanism
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1. Introduction

Puzzles of neutrinos in SM

✓ Neutrino masses (oscillation experiments)
✓ Dirac type or Majorana type ?
✓ Right-handed neutrino …?

Oscillation experiment data [NuFIT 5.1('21)]

l : index of lightest active neutrino

Neutrino mass hierarchy	$\Delta m_{21}^2/10^{-5}\mathrm{eV}^2$	$\Delta m_{3l}^2/10^{-3}\mathrm{eV}^2$
NH $(m_1 < m_2 < m_3)$	$7.42^{+0.21}_{-0.20}$	$2.510^{+0.027}_{-0.027}$
IH $(m_3 < m_1 < m_2)$	$7.42^{+0.21}_{-0.20}$	$-2.490^{+0.026}_{-0.028}$

Mass scale $\mathcal{O}(10^{-11})\mathrm{GeV}$

- At least two generations of neutrinos are massive
- Smallness of neutrino masses

$$m_\nu \sim \mathcal{O}(10^{-11})\mathrm{GeV} \ll m_e \sim 10^{-4}\mathrm{GeV}$$

m_ν : active neutrino mass
m_e : electron mass

Beyond SM physics is needed to explain these discrepancies

2. Minimal Seesaw mechanism (SM + 2RHν)

ν_{RI} : right-handed neutrino $F_{\alpha I}$: Yukawa coupling

L_α : SM lepton doublet Φ : SM Higgs doublet M_I : Majorana mass of right-handed neutrino

Lagrangian

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

Seesaw mechanism works!

Assumption for Dirac mass [P. Minkowski ('77)]

& Majorana mass $M_D \,(\equiv \langle\Phi\rangle F) \ll M_I$ $\Rightarrow$ $|m_\nu| = \left|\frac{M_D^2}{M_I}\right| \ll |M_D|$

Prediction

- All mass eigenstates become Majorana particles.
- Natural explanation of smallness of m_ν.
- Beyond SM interaction could occur.

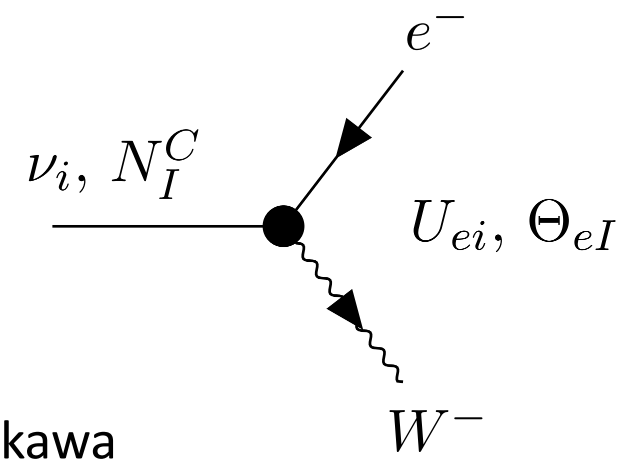
Weak interaction of neutrino

[Pontecorvo('58)] [Maki, Nakagawa, Sakata ('62)]

All mass eigenstates have the weak interaction.

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

$U_{\alpha i}$: Mixing element of active ν (PMNS matrix)
$\Theta_{\alpha I}$: Mixing element of RHν



- Mixing element of RHν

$$\Theta_{\alpha I} = \frac{F_{\alpha I}\langle\Phi\rangle}{M_I}$$

Determined by Yukawa coupling & mass of RHνs

Yukawa coupling

[Casas, Ibarra('01)]

$$F = \frac{i}{\langle\Phi\rangle} U D_\nu^{1/2} \Omega D_N^{1/2}$$

NH case

$$D_\nu = \mathrm{diag}\,(0, m_2, m_3)$$
$$D_N = \mathrm{diag}\,(M_1, M_2)$$

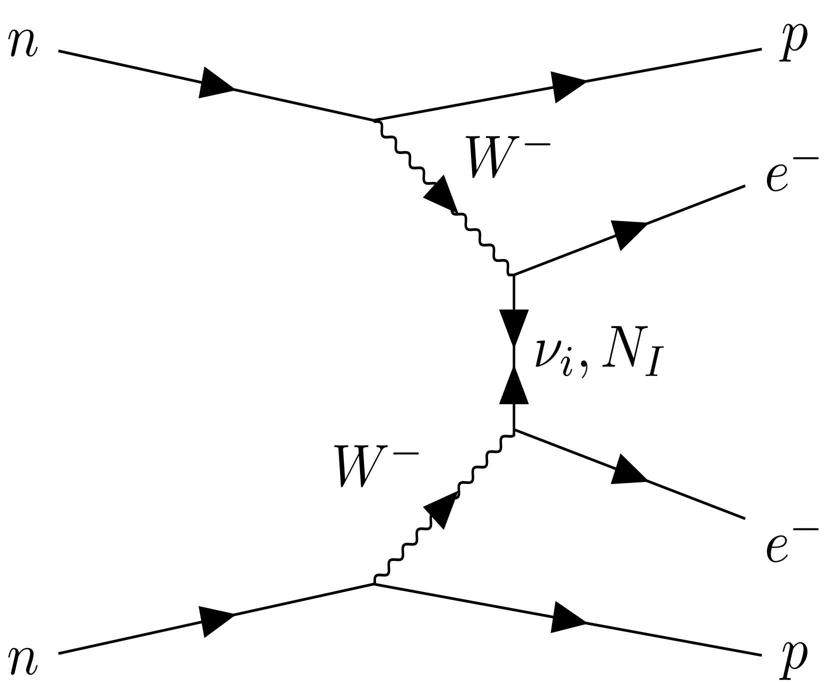
ω : Complex parameter

$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix}$$

$\xi = \pm 1$

3. $0\nu\beta\beta$ decay

What is $0\nu\beta\beta$ decay?



- The decay process violates the lepton number two units.

$$(Z, A) \to (Z+2, A) + 2e^-$$

- One possibility is massive Majorana neutrino mediation.

→It is possible to verify the Majorana nature of the neutrino predicted in seesaw mechanism.

Half-life time of $0\nu\beta\beta$ decay

$$\tau_{1/2}^{-1} = G\,|\mathcal{M}|^2\,|m_{\text{eff}}|^2$$

[Faessler, Gonzalez, Kovalenko, Simkovic('14)]

Current limits on $0\nu\beta\beta$ decay

Half-life time of $0\nu\beta\beta$ decay

$$\tau_{1/2}^{-1} = G\,|\mathcal{M}|^2\,|m_{\text{eff}}|^2$$

[Faessler, Gonzalez, Kovalenko, Simkovic(‘14)]

Active ν’s contribution

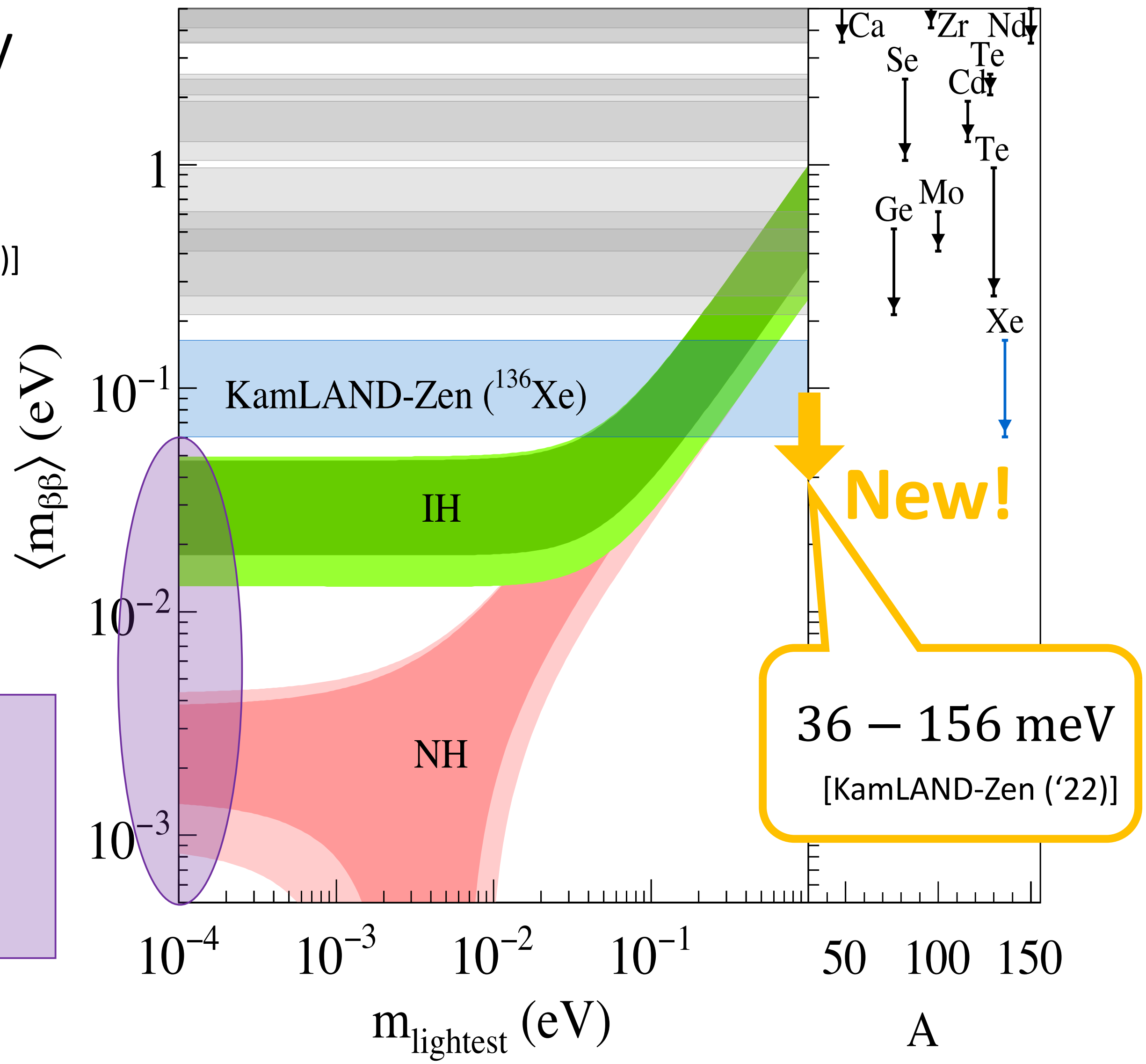
$$m_{\text{eff}}^{\nu} = \sum_i U_{ei}^2 m_i$$

Now, $m_{\text{lightest}} = 0$

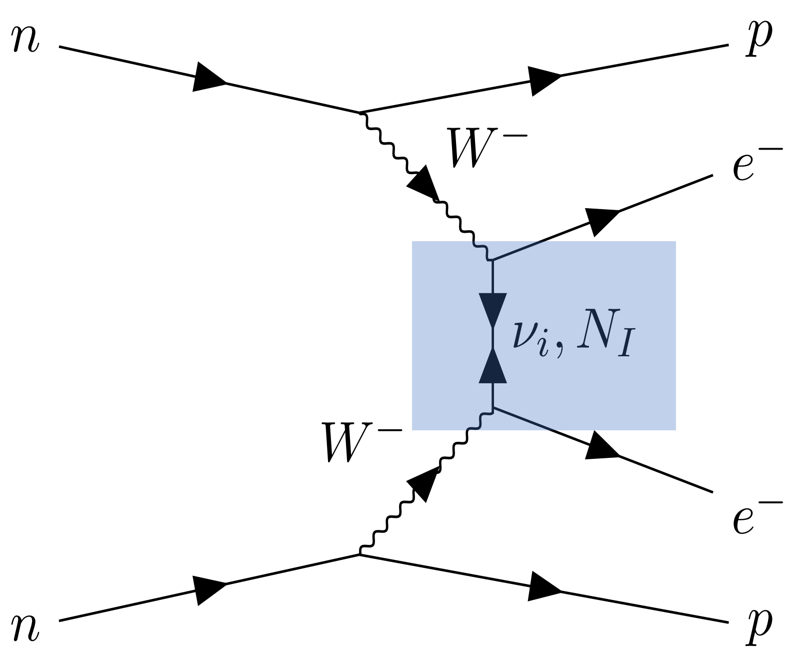
Predicted region

$$|m_{\text{eff}}^{\nu}| = \begin{cases} 1.45 - 3.68 \text{ meV (NH)} \\ 18.6 - 48.4 \text{ meV (IH)} \end{cases}$$

KamLAND-Zen (‘16)



4. $0\nu\beta\beta$ decay in the seesaw mechanism



Effective mass

$$m_{\text{eff}} = m_{\text{eff}}^{\nu} + m_{\text{eff}}^{N}$$

Active ν's contribution $\quad m_{\text{eff}}^{\nu} = \sum_i U_{ei}^2 m_i$

RHν's contribution $\quad m_{\text{eff}}^{N} = \sum_I \Theta_{eI}^2 M_I f_\beta(M_I)$

Suppression factor by the propagator

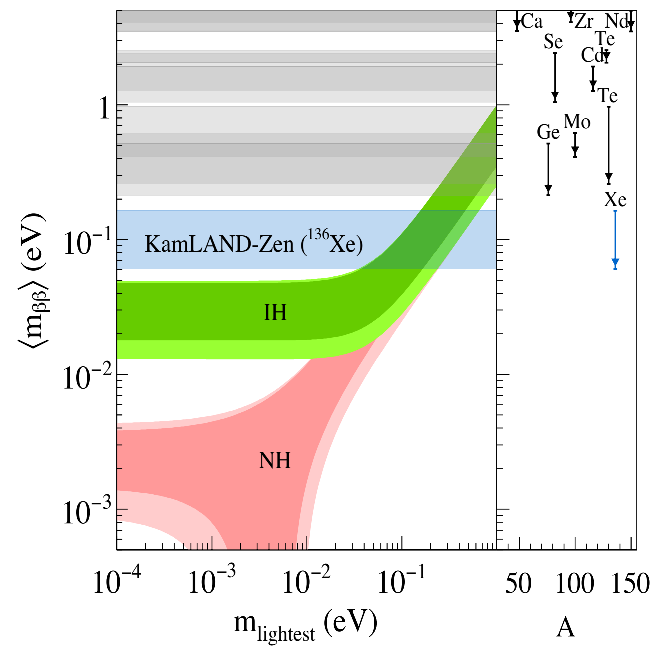
[Faessler, Gonzalez, Kovalenko, Simkovic('14)] [Barea, Kotila, Iachello('15)]

$$\boxed{f_\beta(M_I) = \frac{\Lambda_\beta^2}{\Lambda_\beta^2 + M_I^2}}$$

When $M_I \ll \Lambda_\beta$,
RHν could contribution enough !!

$M_1, M_2 \gg \Lambda_\beta$ $\quad f_\beta(M_1) = 0 \quad f_\beta(M_2) = 0$

$$m_{\rm eff}^N = 0 \;\Rightarrow\; m_{\rm eff} = \sum_i U_{ei}^2 m_i$$



$M_1, M_2 \ll \Lambda_\beta$ $\quad f_\beta(M_1) = 1 \quad f_\beta(M_2) = 1$

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix}_{ee} = \left[\begin{pmatrix} U & \Theta \\ -\Theta^\dagger U & 1 \end{pmatrix}\begin{pmatrix} M_\nu^d & 0 \\ 0 & M_I \end{pmatrix}\begin{pmatrix} U^T & -U^T\Theta^* \\ \Theta^T & 1 \end{pmatrix}\right]_{ee}$$

$$= \sum_i U_{ei}^2 m_i + \sum_I \Theta_{eI}^2 M_I$$

[T.Asaka, S.Eijima, H.Ishida ('11)]

$$m_{\rm eff} = \sum_i U_{ei}^2 m_i + \sum_I \Theta_{eI}^2 M_I = 0$$

$$\tau_{1/2}^{-1} = G\,|\mathcal{M}|^2\,|m_{\rm eff}|^2$$

$\Rightarrow$ the decay will never happen

Cancellation by RHν

NH case

Mass assumption $M_1 < \Lambda_\beta \ll M_2$

Suppression factor

$f_\beta(M_1) = 1 - \delta_f^2 \quad f_\beta(M_2) = 0$

The effective mass can be expressed by using Casas-Ibarra parametrization.

$$\begin{aligned} m_{\text{eff}} &= \sum_i U_{ei}^2 m_i + \sum_I \Theta_{eI}^2 M_I f_\beta(M_I) \\ &= [1 - f_\beta(M_1)] \left[U_{e2} m_2^{1/2} \cos\omega + U_{e3} m_3^{1/2} \sin\omega \right]^2 + [1 - f_\beta(M_2)] \left[U_{e2} m_2^{1/2} \sin\omega - U_{e3} m_3^{1/2} \cos\omega \right]^2 \\ &= \left(U_{e2} m_2^{1/2} \sin\omega - U_{e3} m_3^{1/2} \cos\omega \right)^2 + \left(U_{e2} m_2^{1/2} \cos\omega + U_{e3} m_3^{1/2} \sin\omega \right)^2 \times \delta_f^2 \end{aligned}$$

$= 0$

Solve $\Rightarrow$

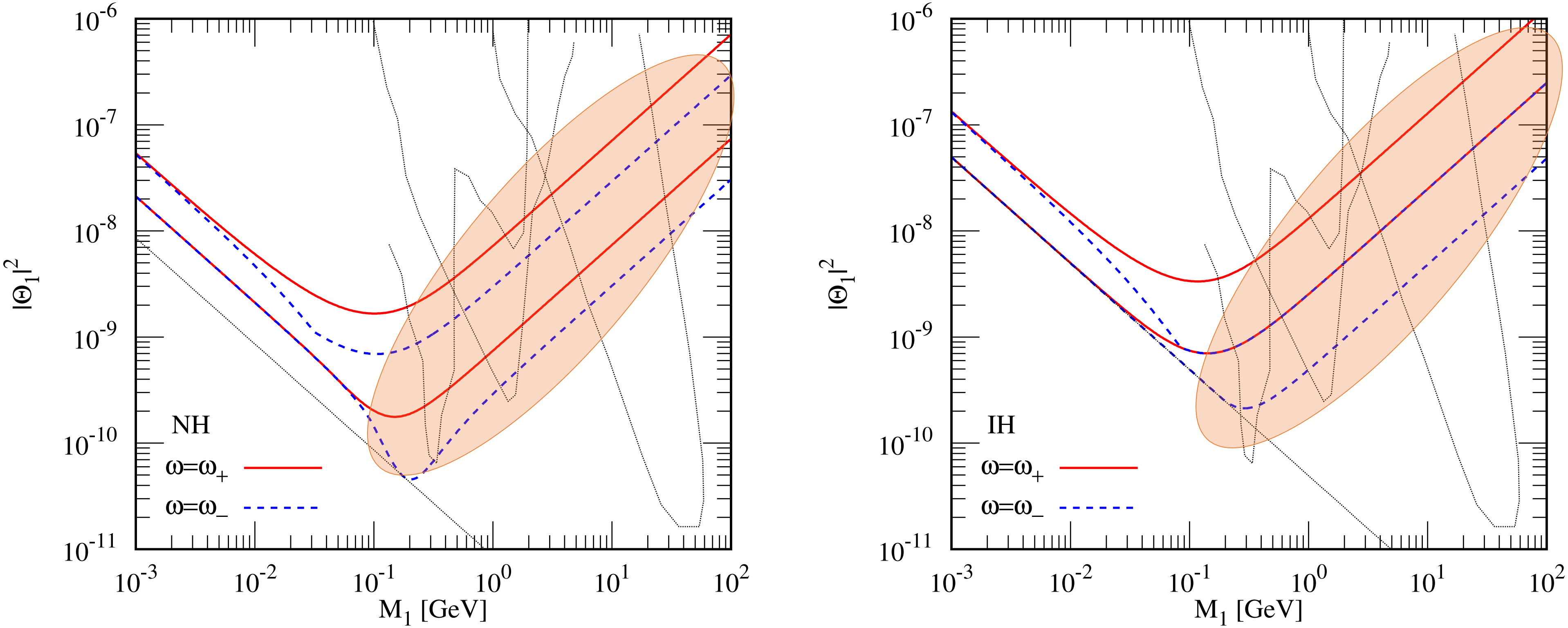
$$\boxed{\tan\omega = \frac{A \pm i\delta_f}{1 \mp i\delta_f A} \equiv \tan\omega_\pm \qquad A = \frac{U_{e3} m_3^{1/2}}{U_{e2} m_2^{1/2}}}$$

$0\nu\beta\beta$ decay is suppressed by the RHν!!

Even if no decay is observed, the information of RHν could be extracted!

Future experiments of direct search of RHνs

$$|\Theta_1|^2 = \sum_{\alpha=e,\mu,\tau} |\Theta_{\alpha 1}|^2$$



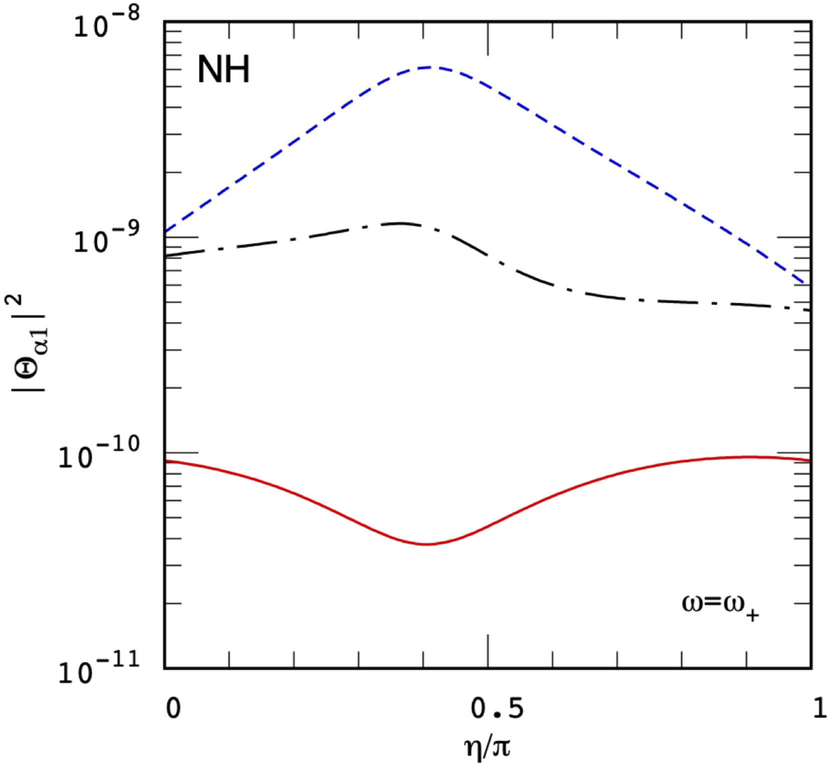
Huge region can be searched on future experiments

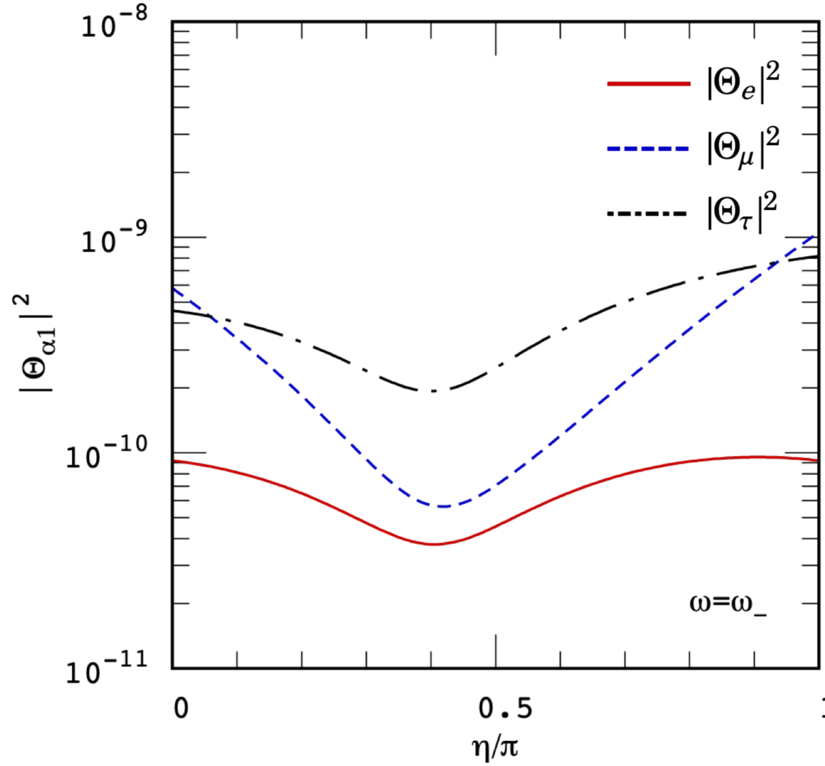
Mixing elements of N_1

$$\Theta_{\alpha I} = \frac{F_{\alpha I}\langle\Phi\rangle}{M_I}$$

RHν suppress the $0\nu\beta\beta$ decay, if

$$\tan\omega = \frac{A \pm i\delta_f}{1 \mp i\delta_f A} \equiv \tan\omega_{\pm}$$



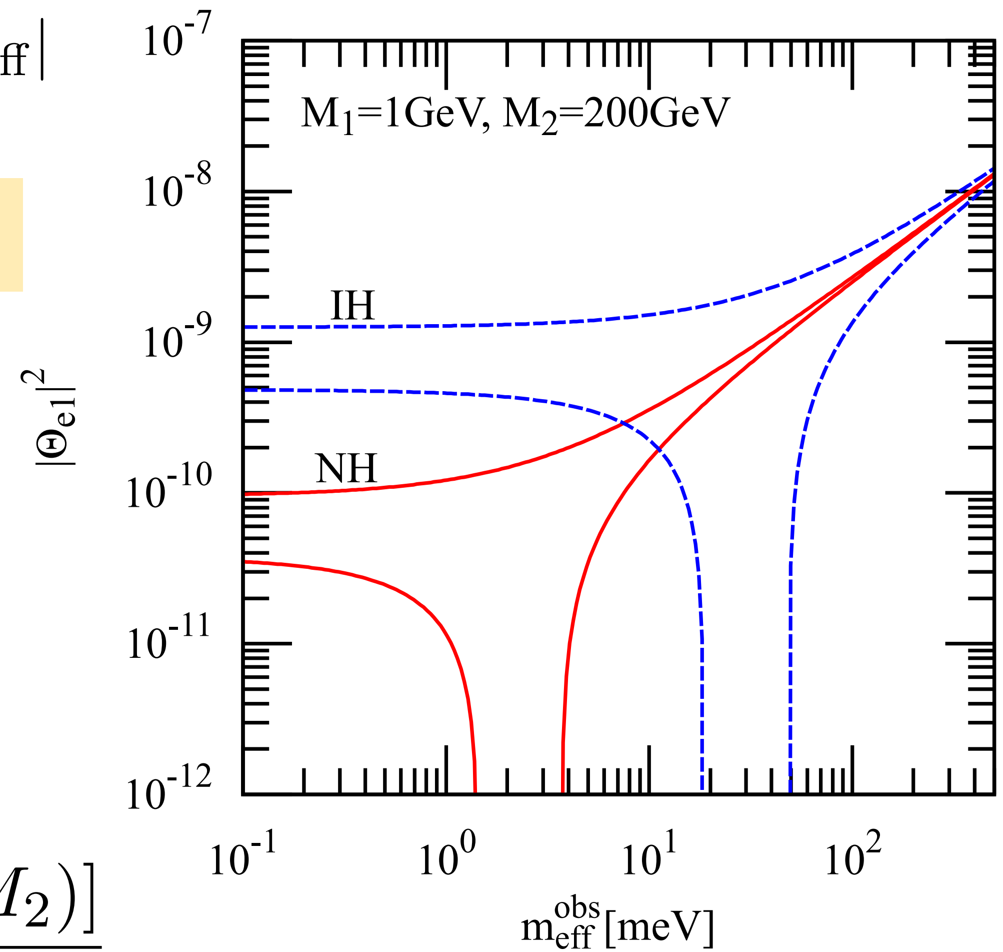


$M_1 = 1\text{GeV}, M_2 = 200\text{GeV}$

Observed case $m_{\rm eff}^{\rm obs} = |m_{\rm eff}|$

Mass assumption $M_1 \neq M_2$

The absolute value of the mixing element is determined by the effective mass of the observed decay.

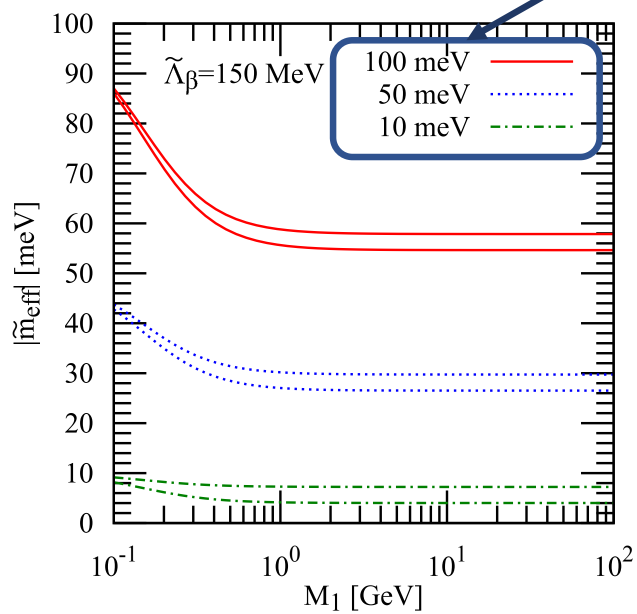


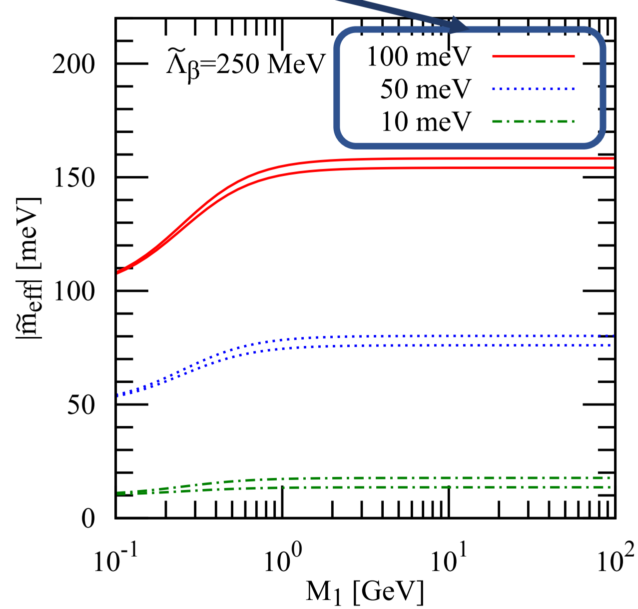
$$\Theta_{e1}^2 = \frac{m_{\rm eff} - m_{\rm eff}^{\nu}\left[1 - f_\beta(M_2)\right]}{M_1\left[f_\beta(M_1) - f_\beta(M_2)\right]}$$

5. Future experiments

Predicted effective mass

$$\tilde{m}_{\text{eff}} = \left[1 - \tilde{f}_\beta(M_2)\right] m^\nu_{\text{eff}} + \left[m_{\text{eff}} - m^\nu_{\text{eff}}\left[1 - f_\beta(M_2)\right]\right] \frac{\tilde{f}_\beta(M_1) - \tilde{f}_\beta(M_2)}{f_\beta(M_1) - f_\beta(M_2)}$$





Effective mass of the decay observed for nuclei with $\Lambda_\beta = 200$ MeV.

Fermi momentum of nuclei

^{76}Ge : 159.0 – 193.0 MeV
^{136}Xe : 178.0 – 211.0 MeV

[Faessler, Gonzalez, Kovalenko, Simkovic('14)]

The effective masses of the decays including RHν's contribution becomes different depending on the decay nuclei.

6. Summary

- We discussed the $0\nu\beta\beta$ decay in the **minimal** seesaw mechanism.
- We comprehensively investigated the contribution of the RHνs to the $0\nu\beta\beta$ decay.
- Especially, when Majorana mass is lighter than the typical Fermi momentum, the decay is strongly suppressed and may no longer occur.
- We showed that the properties of RHν may be characterized by the future decay-observation-experiments.
- We pointed out that multiple experiments using different nuclei are important to understand the properties of RHνs (masses and mixing elements).

Back up

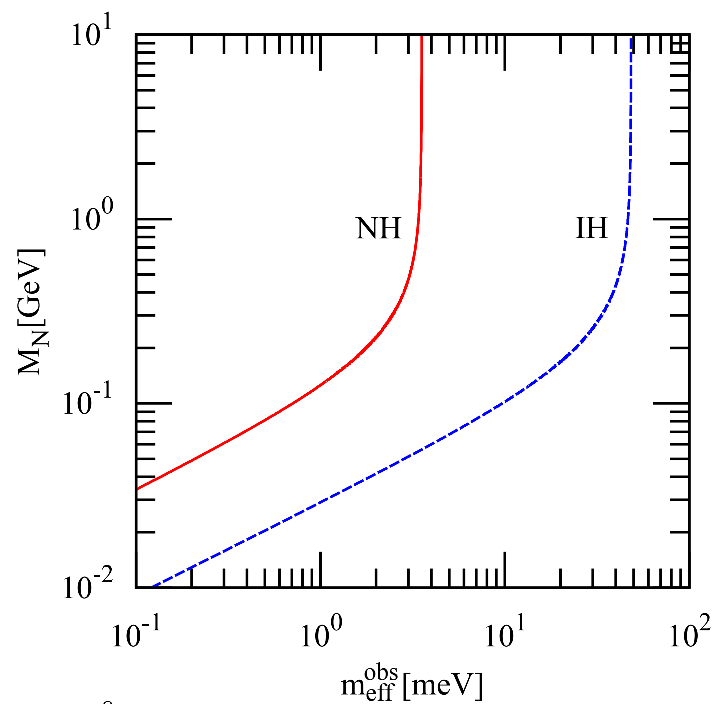
Enhancement by N

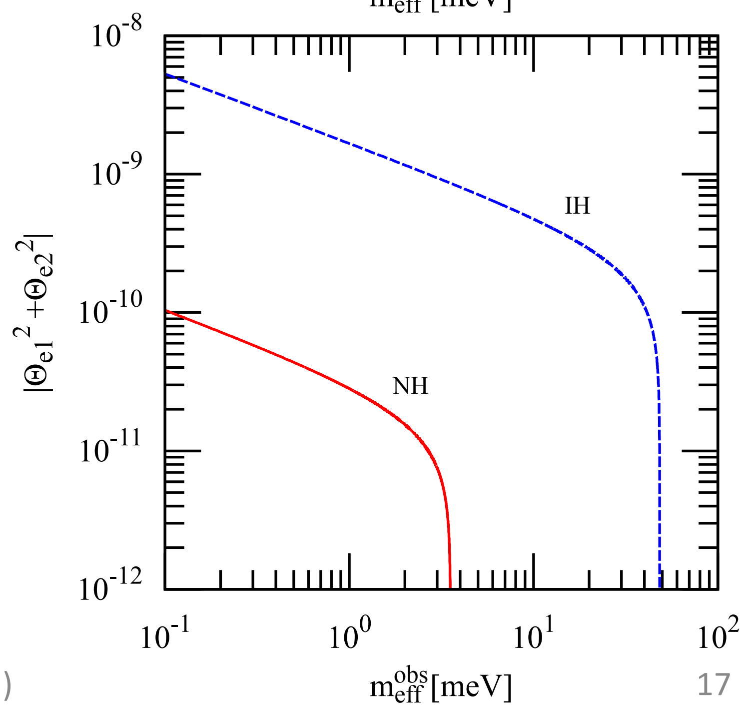
Mass assumption $M_1 = M_2 = M_N$

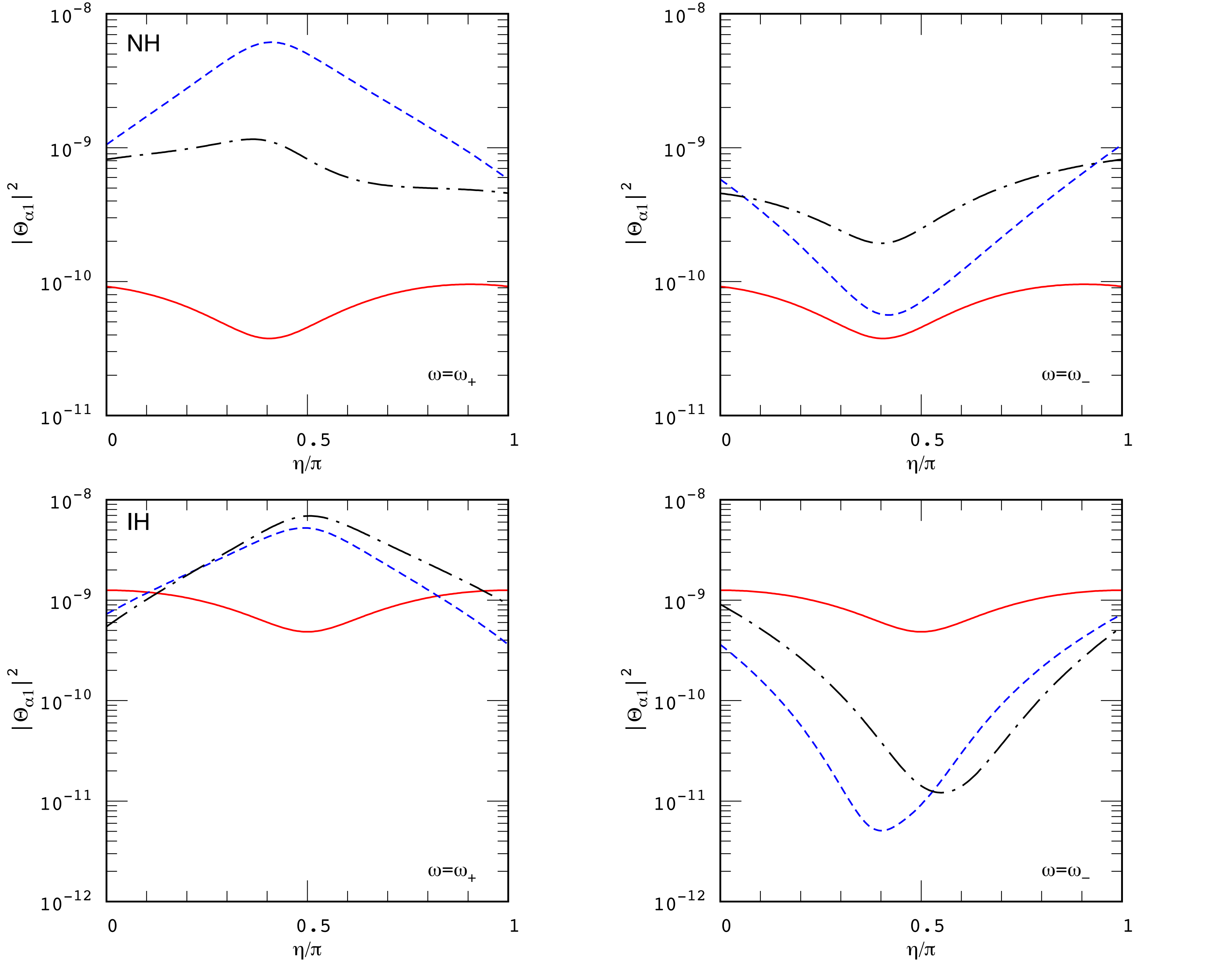
Predictions are obtained regarding the absolute value of the sum of the mixing elements and the mass of the RHν.

$$M_N = \Lambda_\beta \sqrt{\frac{m_{\rm eff}^{\rm obs}}{|m_{\rm eff}^{\nu}| - m_{\rm eff}^{\rm obs}}}$$

$$\left|\Theta_{e1}^2 + \Theta_{e2}^2\right| = \frac{|m_{\rm eff}^{\nu}|}{\Lambda_\beta}\sqrt{\frac{|m_{\rm eff}^{\nu}| - m_{\rm eff}^{\rm obs}}{m_{\rm eff}^{\rm obs}}}$$







NH
IH
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$|\Theta_{\alpha 1}|^2$
$\omega=\omega_+$
$\omega=\omega_-$
0
0.5
1
η/π