Neutrinoless Double Beta Decay in the seesaw mechanism

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研究会「ニュートリノを伴わない二重ベータ崩壊とその周辺」
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Based on collaboration with
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Introduction

Neutrino properties

- What are known now ?
  - Mixing angles and mass squared differences are measured very precisely by various oscillation experiments

$$\sin^2\theta_{12} = 0.304^{+0.012}_{-0.012}$$

$$\sin^2\theta_{23} = 0.573^{+0.016}_{-0.020}$$

$$\sin^2\theta_{13} = 0.02219^{+0.00062}_{-0.00063}$$

$$\Delta m^2_{21} = (7.42^{+0.21}_{-0.20})\times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{32} = (2.517^{+0.026}_{-0.028})\times 10^{-3}\ \mathrm{eV}^2$$

for NH case

NuFIT 5.0 (2020)

- What are unknown now ?
  - Absolute masses ? (Mass ordering ? Lightest neutrino mass ?)
  - Dirac or Majorana fermions ?
  - CP violations ? (Dirac phase ? Majorana phase(s) ?)

We do NOT know the mechanism generating neutrino masses !!

Origin of neutrino masses

- Chiral structure of fermions in the SM

left-handed

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$$

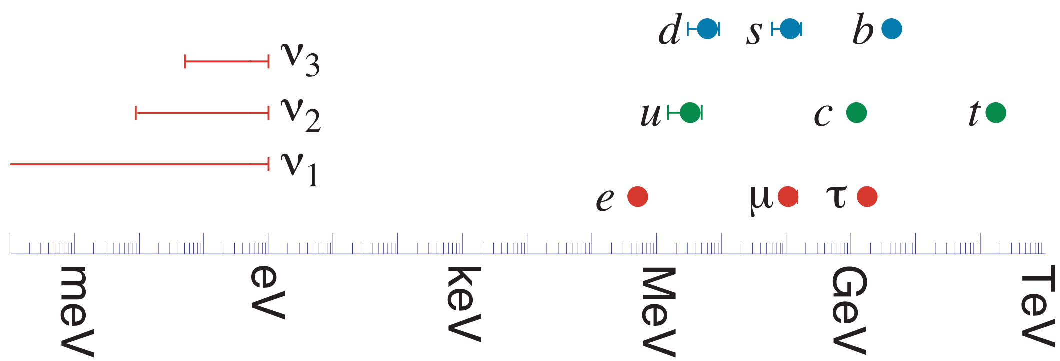
right-handed

$$\begin{matrix} u_R & c_R & t_R \\ d_R & s_R & b_R \end{matrix}$$

$$\begin{matrix} e_R & \mu_R & \tau_R \end{matrix}$$

Why neutrinos are only left-handed ?

- Mass spectrum of fermions in the SM



arXiv:1205.2671v1 [hep-ex] 11 May 2012

Why neutrinos are are so light ?

Right-handed neutrinos

$$\nu_R$$

Extension by right-handed neutrinos (ν_R)

- Seesaw mechanism

Minkowski '77, Yanagida '79, Gell-Mann, Ramond, Slansky '79
Glashow '79

$$\boxed{\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{\nu_R}\partial_\mu\gamma^\mu\nu_R - \left(F\bar{L}\nu_R\Phi + \frac{M_M}{2}\overline{\nu_R^c}\nu_R + h.c.\right)}$$

$$\mathcal{L} \supset \frac{1}{2}\left(\overline{\nu_L}, \overline{\nu_R^c}\right)\begin{pmatrix} 0 & M_D \\ M_D & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c. = \frac{1}{2}\left(\bar{\nu}, \overline{N^c}\right)\begin{pmatrix} M_\nu & 0 \\ 0 & M_N \end{pmatrix}\begin{pmatrix} \nu^c \\ N \end{pmatrix} + \mathrm{h.c.}$$

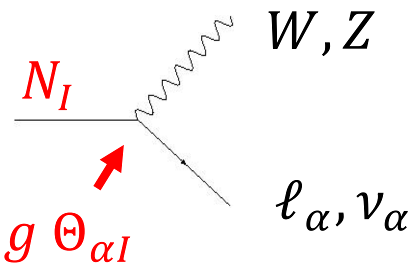
$$M_D \ll M_M$$

- Light active neutrinos ν
  - Mass $M_\nu = -M_D^T \dfrac{1}{M_M} M_D \quad (M_\nu \ll M_D)$

Smallness of M_ν is naturally explained

- Heavy neutral leptons (HNLs) N
  - Mass $M_N = M_M$ and mixing $\Theta = M_D / M_M$

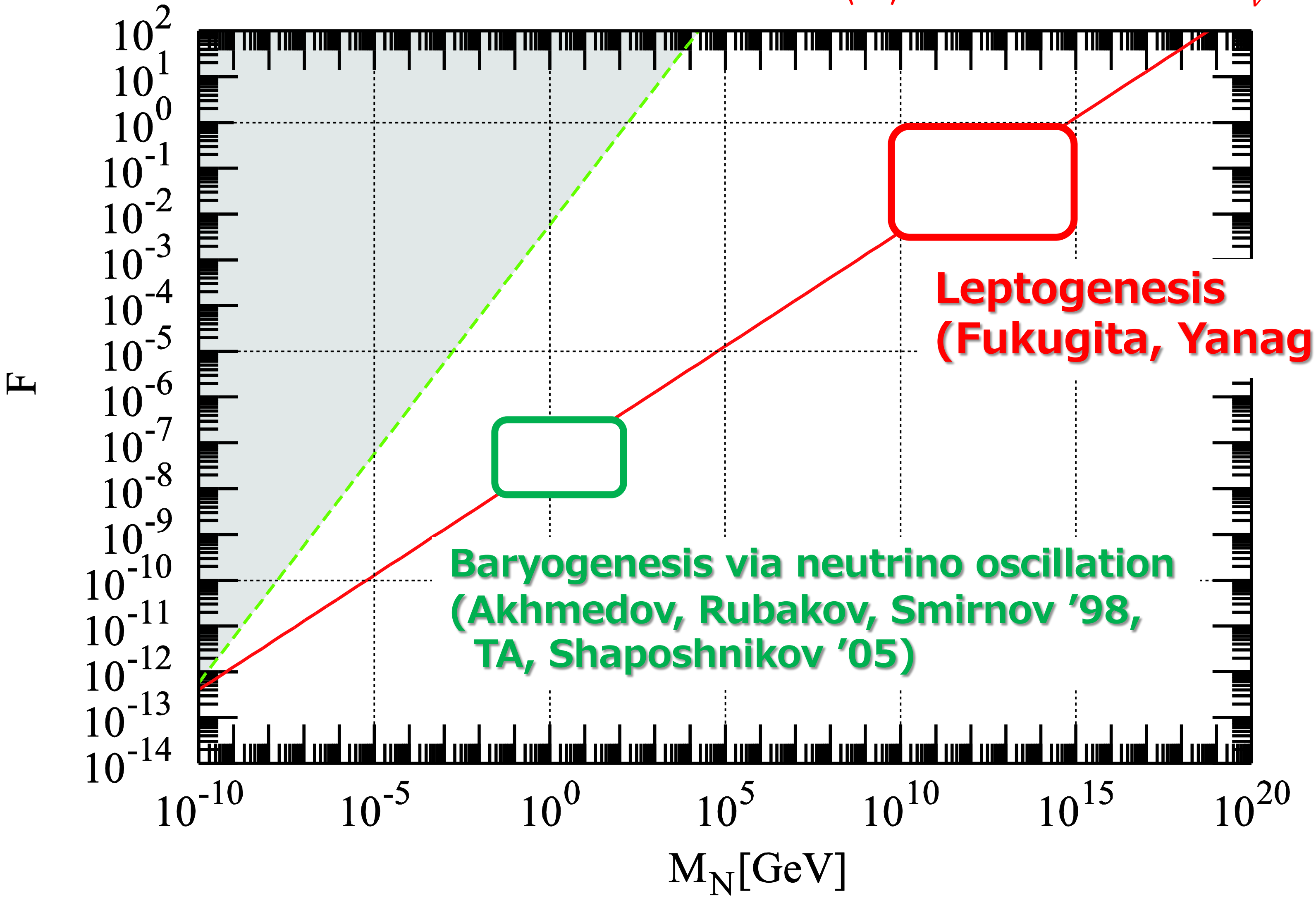
- Mixing in weak interaction
  - $\nu_L = U\,\nu + \Theta\, N^c$



Scale of seesaw (mass of HNL)

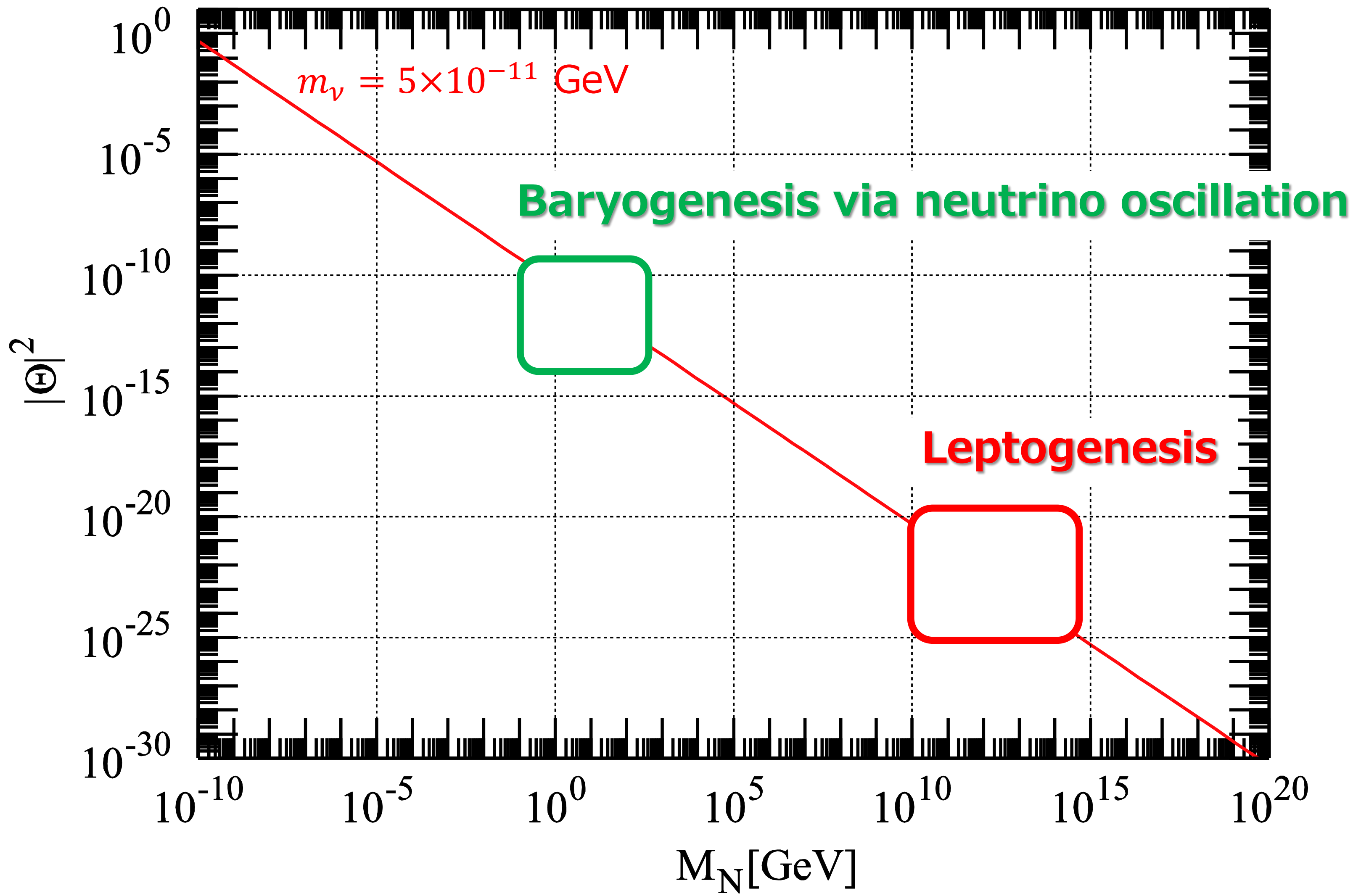
$$M_\nu = -M_D^T \frac{1}{M_M} M_D \Rightarrow F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle}$$

$m_\nu = 5\times 10^{-11}$ GeV



Mass and mixing of HNL

$$|\Theta|^2 = \frac{M_D^2}{M_N^2} = \frac{m_\nu}{M_N}$$

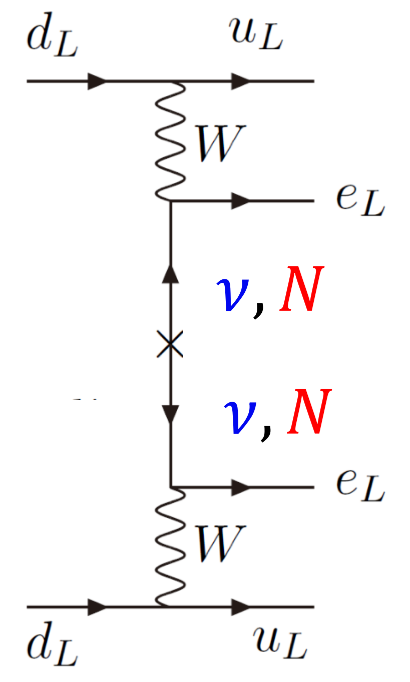


Consequences of seesaw mechanism

- Active neutrinos and HNLs are both Majorana fermions
- Lepton number is violated at Lagrangian level

  - Crucial for explaining the baryon asymmetry of the Univ.
    - Leptogenesis
    - Baryogenesis via neutrino oscillation

  - Lead to non-SM LNV processes
    - Meson decays ($B^- \to N\,\mu^- \to \pi^+\ \mu^-\,\mu^-$)
    - $pp \to \ell^+ N \to \ell^+\ \ell^+ j\, j$
    - $e^- e^- \to W^- W^-$
    - $\cdots$
    - Neutrinoless Double Beta Decay (NDBD)



Contents

Today, we discuss

Neutrinoless Double Beta Decay (NDBD) in seesaw mechanism

- Part 1: NDBD in high-scale seesaw
  - NDBD in modular flavor symmetry

    ref. TA, Yongtae Heo, Takahiro Yoshida (arXiv:2009.12120)
- Part 2: NDBD in low-scale seesaw
  - What if NDBD is unseen ?
  - What if NDBD is observed ?

    ref. TA, Hiroyuki Ishida, Kazuki Tanaka (arXiv:2012.12564, 2012.13527, 2101.12498)
- Summary

Part 1:
NDBD in high-scale seesaw

Effective mass in NDBD decay

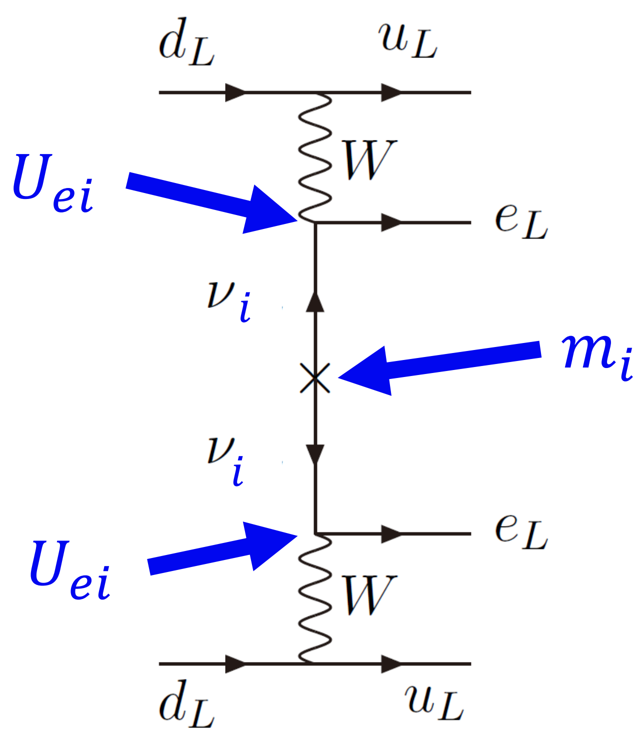
- $0\nu\beta\beta$ decay rate

$$\boxed{\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}|\mathcal{M}^{0\nu}|^2\,|m_{\rm eff}|^2}$$

$G^{0\nu}$: Phase space factor

$\mathcal{M}^{0\nu}$: Nuclear matrix element (NME)

$m_{\rm eff}$: Effective mass



- Effective mass

$$\boxed{m_{\rm eff} = \sum_i U_{ei}^2\, m_i}$$

m_i : active neutrino masses

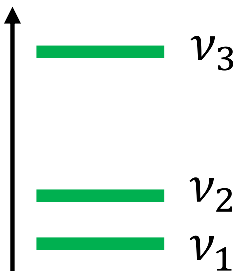
U_{ei} : PMNS neutrino mixing element

Masses and mixings of active neutrinos

- Active neutrino masses (m_1, m_2, m_3)

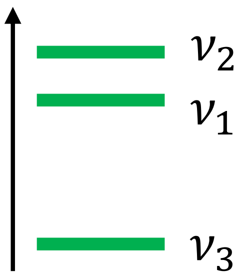
Normal Hierarchy (NH)

$m_3 > m_2 > m_1$



Inverted Hierarchy (IH)

$m_2 > m_1 > m_3$



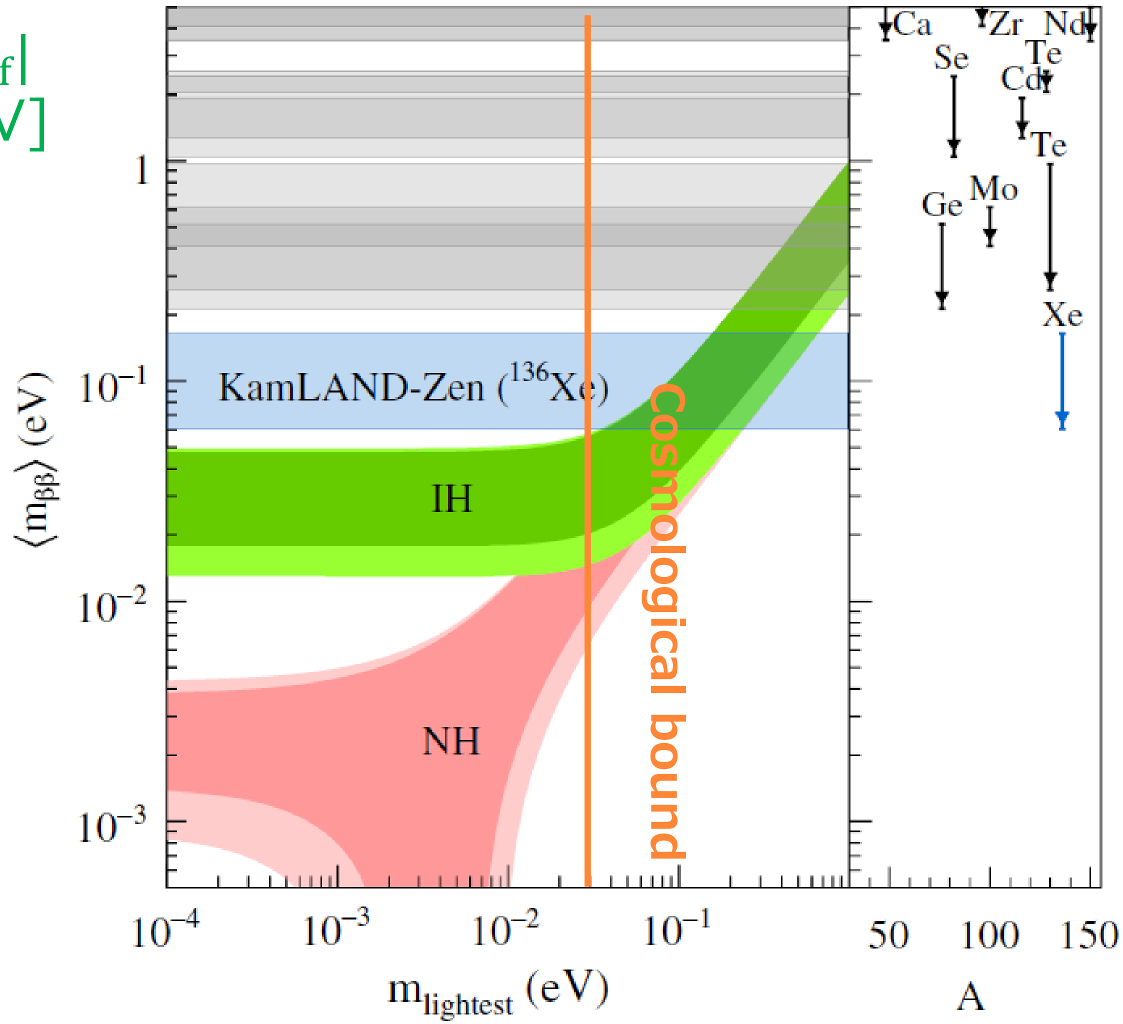
- PMNS mixing matrix $(\theta_{ij}, \delta, \alpha_{21}, \alpha_{31})$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

$$\boxed{m_{\mathrm{eff}} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{12}} + m_3 s_{13}^2 e^{i(\alpha_{31} - 2\delta)}}$$

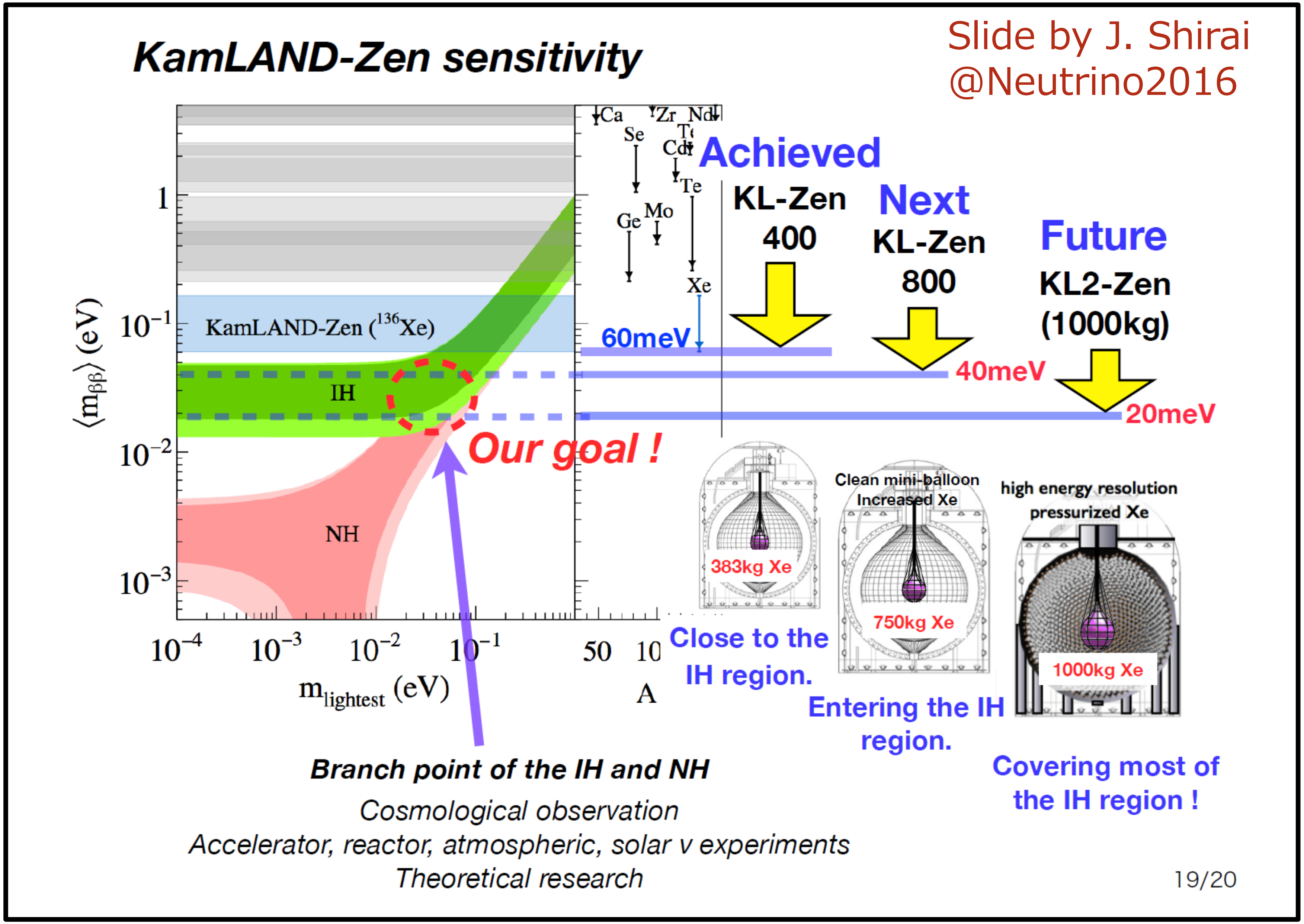
Current status

$|m_{\rm eff}|$
[meV]



KamLAND-Zen PRL117, 082503 ('16)

Future prospects

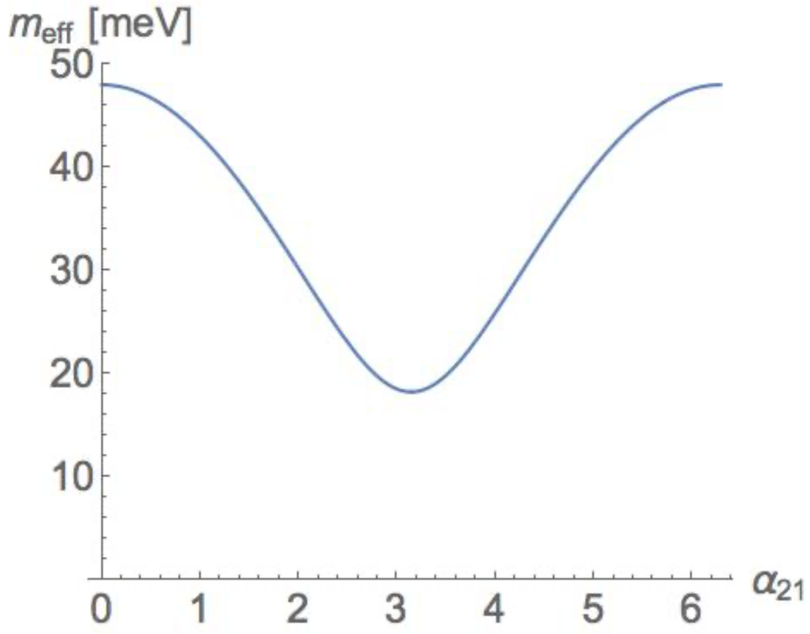


0νββ decay and Majorana phase

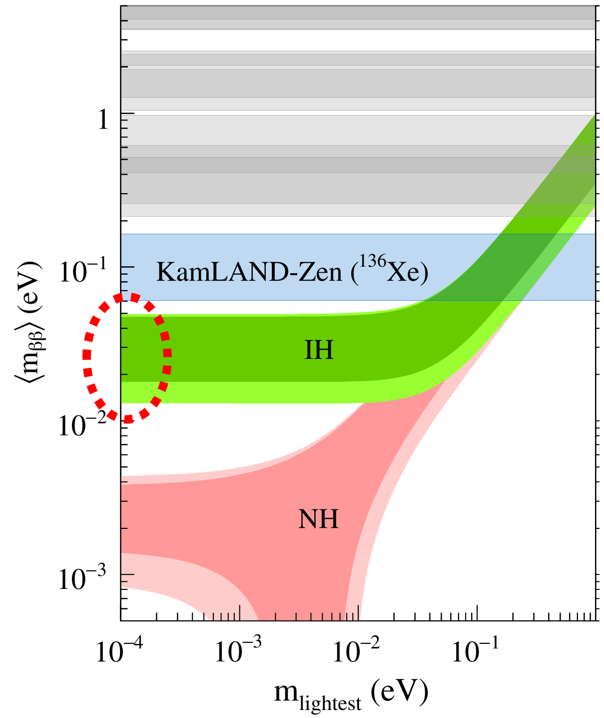
- IH case with $\boldsymbol{m_2 > m_1 \gg m_3}$

$$m_{\rm eff} \simeq c_{13}^2\,[m_1^2 c_{12}^4 + m_2^2 s_{12}^4 + 2\cos(\alpha_{21}) m_1 m_2 c_{12}^2 s_{12}^2]^{1/2}$$

$|m_{\rm eff}|$ [meV]



Majorana phase α_{21}



Mass ordering, lightest neutrino mass and CPV phases are crucial for estimation of effective mass !

Flavor Symmetry

- Horizontal symmetry between generations of matter fields can relate elements of Yukawa coupling matrix !

Flavor Symmetry $\qquad \nu_e \quad \nu_\mu \quad \nu_\tau$ $\Longleftrightarrow$

  - So far, various flavor symmetries have been discussed !

- Discrete flavor symmetries
  - Flavor mixing can be understood in connection with geometry
  - Especially, typical mixing pattern of neutrinos can be explained by S4, A4, ⋯ discrete symmetries !

See reviews:
Altarelli, Feruglio ('10), King, Luhn ('13), Tanimoto ('15), Petcov ('17)

Origin of Discrete Flavor Symmetry

[Feruglio 1706.08749]

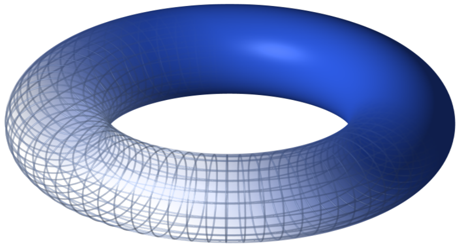
- Ferglio
  - Modular Symmetry in torus compactification is an origin of discrete flavor symmetry.
  - Modular Symmetry controls the superpotential leading to the desired mass hierarchies and mixing angles of quarks and leptons

Kobayashi, Tanaka, Tatsuishi 1803.10391
Penedo, Petcov 1806.11040
Criado, Feruglio 1807.01125
Kobayashi, Omoto, Shimizu, Tanimoto, Tatsuishi 1808.03012
Novichkov, Penedo, Petcov, Titov 1811.04933, 1812.02158
Anda, King, Perdomo 1812.05620
Okada, Tanimoto 1812.09677
Kobayashi, Shimizu, Takagi, Tanimoto, Tatsuishi, Uchida 1812.11072
Novichkov, Petcov, Tanimoto 1812.11289
…

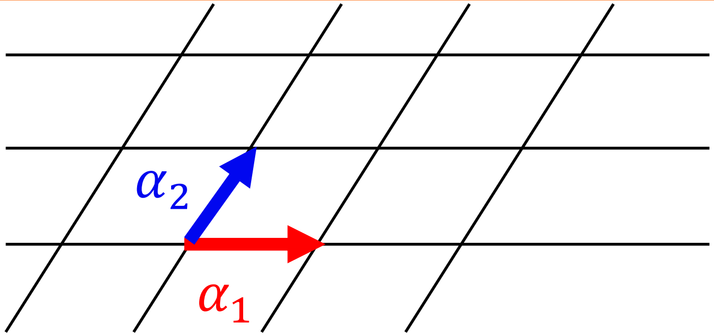
Modular Symmetry

Torus compactification

- Torus $\mathbb{C}/\Lambda$



https://commons.wikimedia.org/



$$\alpha_1 = 2\pi R$$
$$\alpha_2 = 2\pi R\ \tau$$

- Transformations of basis vectors

$$\begin{pmatrix} \alpha_2' \\ \alpha_1' \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} \alpha_2 \\ \alpha_1 \end{pmatrix}, \quad \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL(2,\mathbb{Z}),$$

$$SL(2,\mathbb{Z}) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \middle| a,b,c,d \in \mathbb{Z}, ad-bc=1 \right\}$$

$$\tau \to \tau' = \gamma\tau = \frac{a\tau+b}{c\tau+d},$$

- Modular Symmetry $\bar{\Gamma}$

$$\bar{\Gamma} = \frac{SL(2,Z)}{\{\mathrm{I},-\mathrm{I}\}} = PSL(2,Z)$$

Modular symmetry

- Modular group is generated by two elements

$$S : \tau \to -1/\tau \qquad S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$T : \tau \to \tau + 1 \qquad T = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$$

$S^2 = 1$ and $(ST)^3 = 1$

- Finite quotient subgroup by imposing $T^N = 1$

$$\Gamma_N = \{S, T \mid S^2 = \mathbf{1},\ (ST)^3 = \mathbf{1},\ T^N = \mathbf{1}\}$$

  - Finite non-Abelian discrete group

$$\Gamma_2 \simeq S_3\,,\quad \Gamma_3 \simeq A_4\,,\quad \Gamma_4 \simeq S_4\,,\quad \Gamma_5 \simeq A_5\,, \cdots$$

These symmetries can play a role of discrete flavor symmetry !

Chiral matter multiplet

- Modular transformation $\tau \to \tau' = \gamma\tau = \dfrac{a\tau + b}{c\tau + d},$

$$\hat{\Phi} \to \hat{\Phi}' = (c\tau + d)^{-k_\Phi} \rho_\Phi(\gamma)\, \hat{\Phi}$$

$$\begin{cases} -k_\Phi & : \text{modular weight} \\ \rho_\Phi & : \text{representation matrix} \end{cases}$$

- Superpotential
  - Modular invariant terms are obtained by matter multiplets as well as the modular forms.
    - Modular forms: holomorphic functions of the modulus τ

$$Y(\tau) \to (c\tau + d)^{k_Y} \rho_Y(\gamma) Y(\tau)$$

  - Modular symmetry restricts the interaction terms in the superpotential, i.e., Yukawa coupling constants !
    - Successful descriptions of masses and mixings of fermions

Active research topic !!

Model with modular A4 symmetry

TA, Y. Heo, T. Yoshida arXiv:2009.12120

	$\hat{L}$	$\hat{E}^c_1, \hat{E}^c_2, \hat{E}^c_3$	$\hat{N}^c$	$\hat{H}_u$	$\hat{H}_d$	$\hat{S}$	Y^{A_4}
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$
A_4	$\mathbf{3}$	$\mathbf{1}, \mathbf{1}'', \mathbf{1}'$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{3}$
M.W.	-1	-1	-1	-1	-1	-1	$+2$
R	$-$	$-$	$-$	$+$	$+$	$+$	$+$

- Introduce a singlet multiplet $\hat{S}$

$$\hat{S} = \begin{pmatrix} \hat{S}_1 \\ \hat{S}_2 \\ \hat{S}_3 \end{pmatrix}$$

  - Origins of mu-term and Majorana masses

$$W = k\,(\hat{S} Y^{A_4} \hat{H}_u \hat{H}_d)_{\mathbf{1}} + h_1 \left((\hat{S} Y^{A_4})_{\mathbf{1}} \hat{N}^c \hat{N}^c\right)_{\mathbf{1}} + h_2 \left((\hat{S} Y^{A_4})_{\mathbf{1}'} \hat{N}^c \hat{N}^c\right)_{\mathbf{1}} + h_3 \left((\hat{S} Y^{A_4})_{\mathbf{1}''} \hat{N}^c \hat{N}^c\right)_{\mathbf{1}} + h_4 \left((\hat{S} Y^{A_4})_{\mathbf{3s}} \hat{N}^c \hat{N}^c\right)_{\mathbf{1}} + h_5 \left((\hat{S} Y^{A_4})_{\mathbf{3a}} \hat{N}^c N^c\right)_{\mathbf{1}} .$$

  - Realistic masses and mixings of neutrinos

$$\langle \hat{S} \rangle = \begin{pmatrix} S_1 \\ S_2 \\ 0 \end{pmatrix}$$

Superpotential

$$W = k\,(\hat{S} Y^{A_4} \hat{H}_u \hat{H}_d)_{\mathbf{1}}$$
$$+ f_1\,(\hat{L} Y^{A_4})_{\mathbf{1}}\, \hat{E}_1^c\, H_d + f_2\,(\hat{L} Y^{A_4})_{\mathbf{1}'}\, \hat{E}_2^c\, H_d + f_3\,(\hat{L} Y^{A_4})_{\mathbf{1}''}\, \hat{E}_3^c\, H_d$$
$$+ g_1\left((\hat{L} Y^{A_4})_{\mathbf{3s}}\, \hat{N}^c\, \hat{H}_u\right)_{\mathbf{1}} + g_2\left((\hat{L} Y^{A_4})_{\mathbf{3a}})_{\mathbf{1}}\, \hat{N}^c\, \hat{H}_u\right)_{\mathbf{1}}$$
$$+ h_1\left((\hat{S} Y^{A_4})_{\mathbf{1}} \hat{N}^c\, \hat{N}^c\right)_{\mathbf{1}} + h_2\left((\hat{S} Y^{A_4})_{\mathbf{1}'} \hat{N}^c\, \hat{N}^c\right)_{\mathbf{1}} + h_3\left((\hat{S} Y^{A_4})_{\mathbf{1}''} \hat{N}^c\, \hat{N}^c\right)_{\mathbf{1}}$$
$$+ h_4\left((\hat{S} Y^{A_4})_{\mathbf{3s}} \hat{N}^c\, \hat{N}^c\right)_{\mathbf{1}} + h_5\left((\hat{S} Y^{A_4})_{\mathbf{3a}} \hat{N}^c\, N^c\right)_{\mathbf{1}}.$$

$$Y^{A_4} = \begin{pmatrix} 1 + 12q + 36q^2 + 12q^3 + \cdots \\ -6q^{\frac{1}{3}}(1 + 7q + 8q^2 + \cdots) \\ -18q^{\frac{2}{3}}(1 + 2q + 5q^2 + \cdots) \end{pmatrix} \to \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad \mathrm{Im}\tau \gg 1$$

$$\langle \hat{H}_d \rangle \quad \langle \hat{H}_u \rangle \quad \langle \hat{S} \rangle = \begin{pmatrix} S_1 \\ S_2 \\ 0 \end{pmatrix}$$

$\Downarrow$

Mass matrices of leptons

Mass matrices

$$M_E = \langle \hat{H}_d \rangle P_{ijk} \begin{pmatrix} f_1 & 0 & 0 \\ 0 & f_2 & 0 \\ 0 & 0 & f_3 \end{pmatrix}$$

$$P_{ijk} \quad (\hat{E}^c_1, \hat{E}^c_2, \hat{E}^c_3) \Updownarrow (e^c, \mu^c, \tau^c)$$

$$M_D = \langle \hat{H}_u \rangle P^T_{ijk} \begin{pmatrix} 2g_1 & 0 & 0 \\ 0 & 0 & -g_1 + g_2 \\ 0 & -g_1 - g_2 & 0 \end{pmatrix}$$

Here we take

$$P_{ijk} = \mathrm{diag}(1,1,1)$$

$$M_M = \begin{pmatrix} (h_1 + 4h_4)S_1 & 0 & (h_2 + h_4 + h_5)S_2 \\ 0 & (h_2 - 2h_4 - 2h_5)S_2 & (h_1 - 2h_4)S_1 \\ (h_2 + h_4 + h_5)S_2 & (h_1 - 2h_4)S_1 & 0 \end{pmatrix}$$

Neutrino mass matrix of active neutrinos

$$M_\nu = -M_D^T \frac{1}{M_M} M_D$$

Seesaw mass matrix of active neutrinos

$$M_\nu = -M_D^T M_M^{-1} M_D = \Lambda \begin{pmatrix} 1 & b_2 b_3 & b_3 \\ b_2 b_3 & b_1 b_2 & b_1 \\ b_3 & b_1 & b_3^2 \end{pmatrix}$$

$$\Lambda = -\frac{4 g_1^2 (h_1 - 2h_4)^2 \langle \hat{H}_u \rangle^2 S_1^2}{(h_1 - 2h_4)^2 (h_1 + 4h_4) S_1^3 + (h_2 + h_4 + h_5)^2 (h_2 - 2h_4 - 2h_5) S_2^3}$$

$$b_1 = \frac{(g_1^2 - g_2^2)(h_1 + 4h_4)}{4 g_1^2 (h_1 - 2h_4)},$$

$$b_2 = -\frac{(g_1 + g_2)(h_2 - 2h_4 - 2h_5) S_2}{(g_1 - g_2)(h_1 - 2h_4) S_1},$$

$$b_3 = \frac{(g_1 - g_2)(h_2 + h_4 + h_5) S_2}{2 g_1 (h_1 - 2h_4) S_1}.$$

Seesaw mass matrix of active neutrinos

$$M_\nu = -M_D^T M_M^{-1} M_D = \Lambda \begin{pmatrix} 1 & b_2 b_3 & b_3 \\ b_2 b_3 & b_1 b_2 & b_1 \\ b_3 & b_1 & b_3^2 \end{pmatrix}$$

- Described by four parameters

$$\underbrace{\Lambda,}_{\text{Overall scale of neutrino masses}} \quad \underbrace{b_1, \quad b_2, \quad b_3}_{\text{Mass ratios and mixing angles of neutrinos}}$$

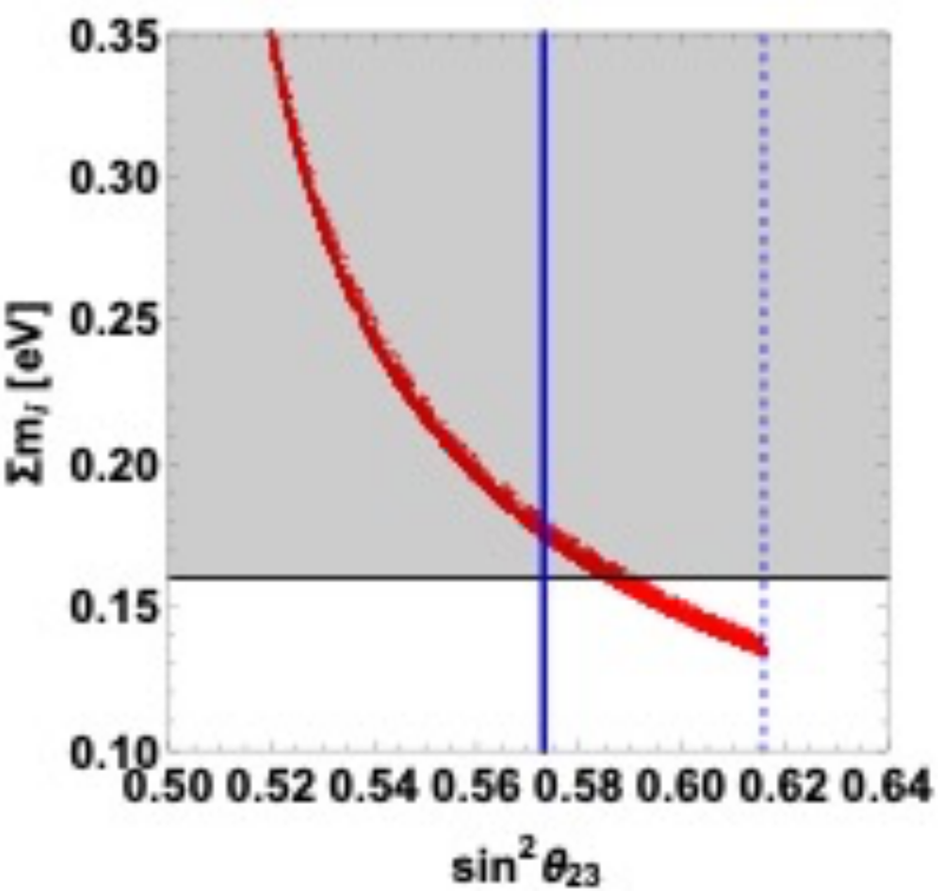
Overall scale of neutrino masses

Mass ratios and mixing angles of neutrinos

- Find parameter range which is consistent with the neutrino oscillation data (3 mixing angles, 2 mass squared differences)

Prediction: neutrino masses

- Only **normal hierarchy** fits the neutrino data
- Sum of neutrino masses



Good target for cosmological obs.

$$\boxed{\sum m_i \geq 0.13 \text{ eV}}$$

- Cosmological bound

$$\sum_{i=1}^{3} m_i \leq 0.160 \text{ eV}$$ [Planck 2018]

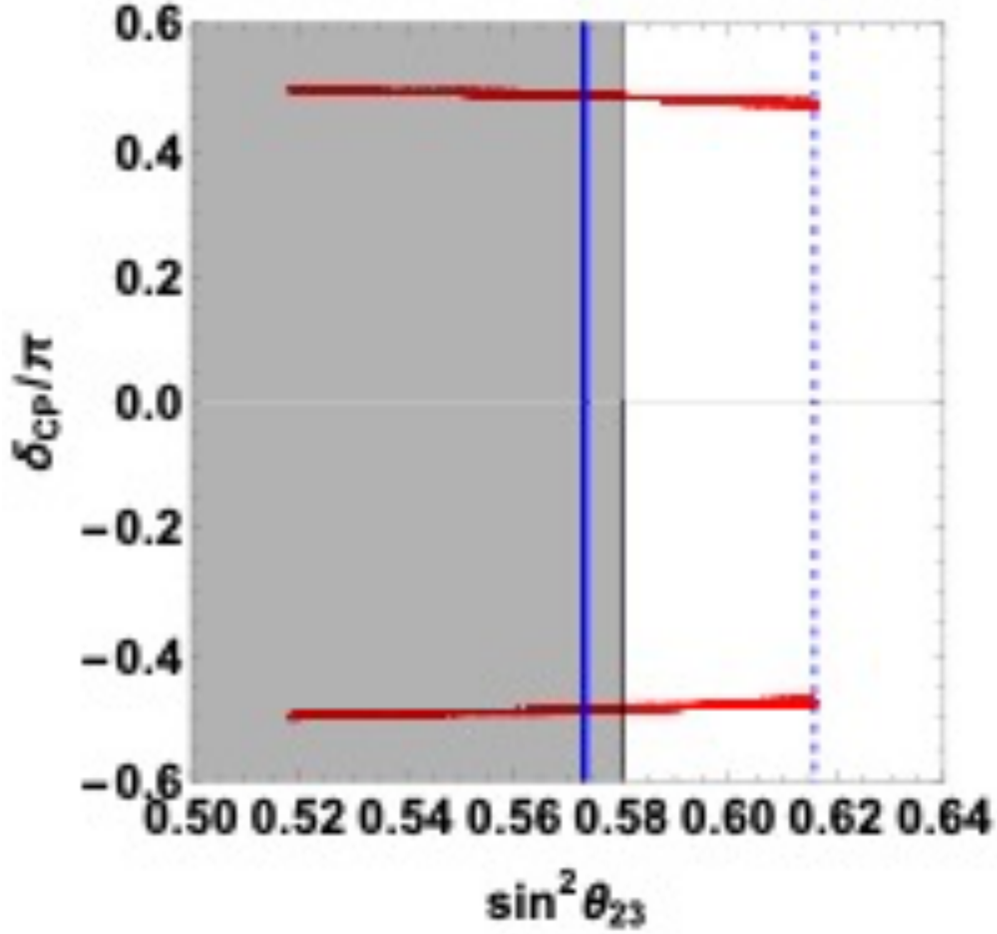
$$\Downarrow$$

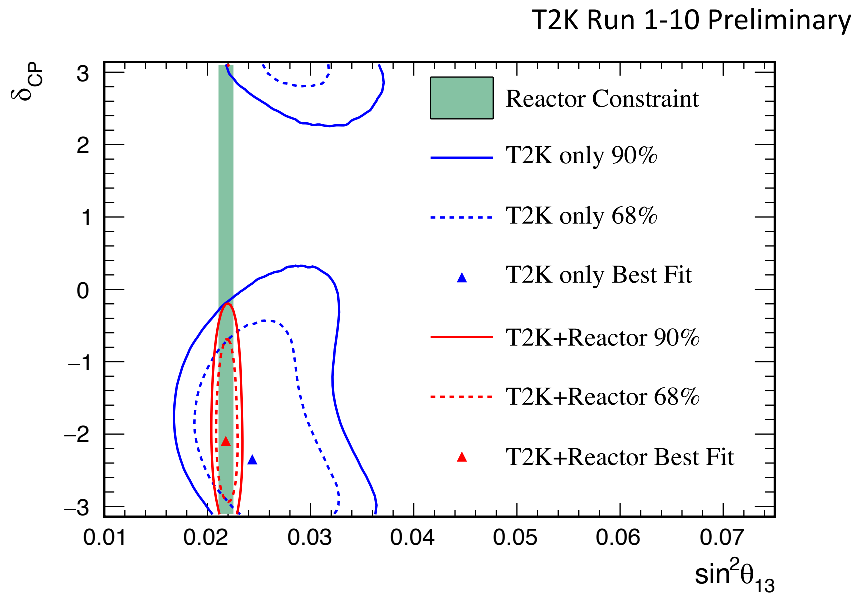
$$\boxed{\sin^2\theta_{23} \geq 0.58}$$

Good target for LBL neutrino exp.

Prediction: Dirac CPV phase

- Clear predictions on CPV phases



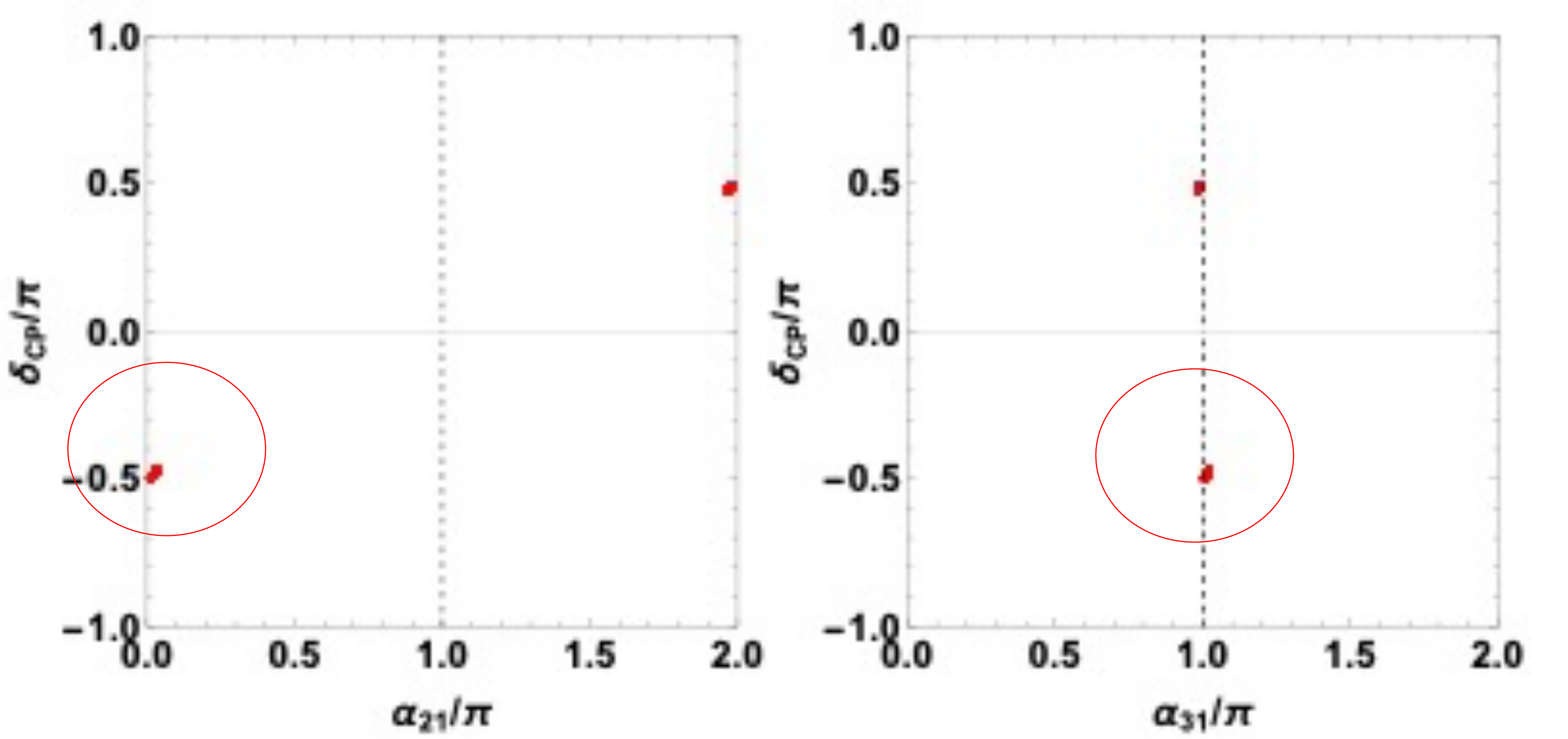


T2K @Neutrino 2020
Slide by P. Dunne

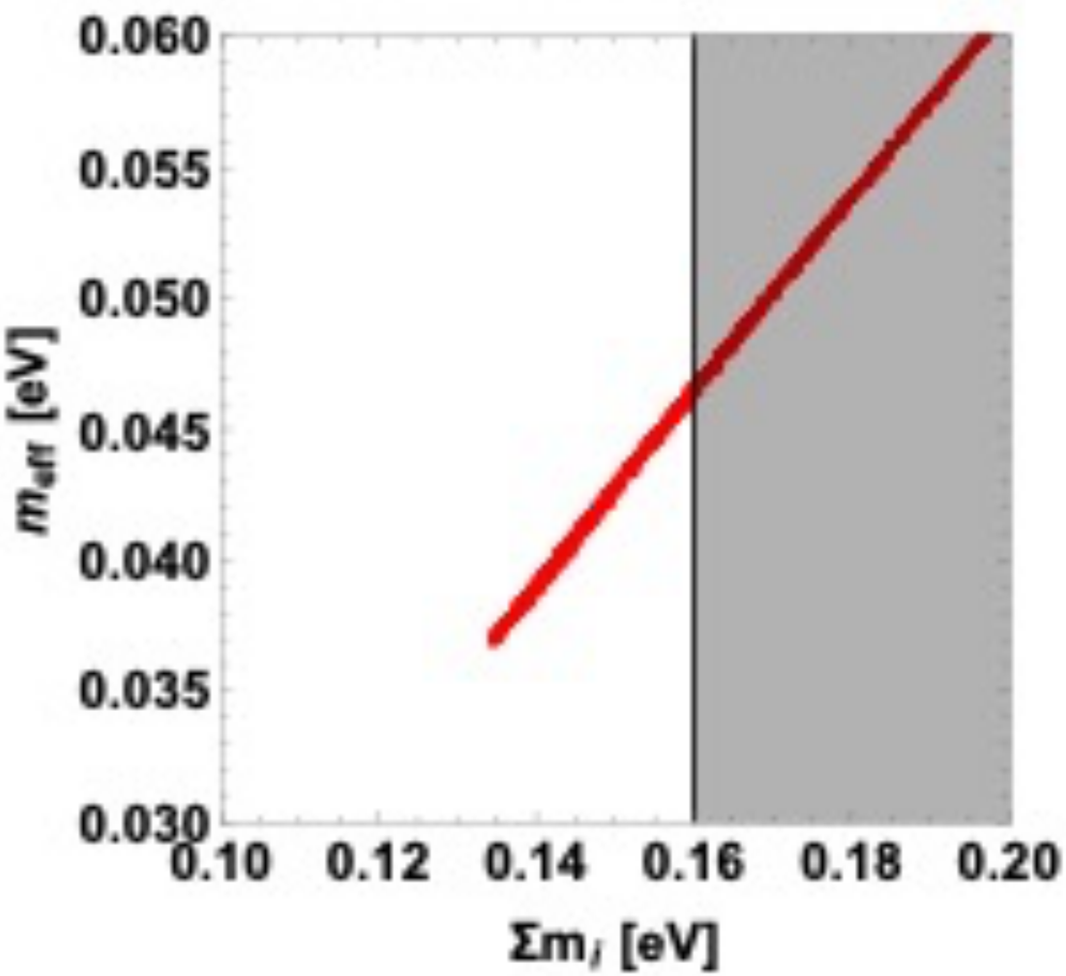
$$\delta_{CP} \approx -0.5\pi, \qquad +0.5\pi$$

Prediction: Majorana CPV phases

- Clear predictions on CPV phases

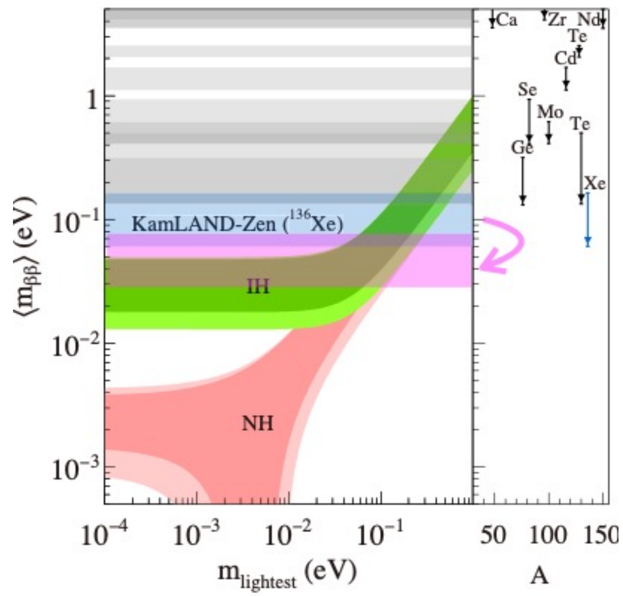


Neutrinoless double beta decay



$$0.037\ \mathrm{eV} \le m_{\mathrm{eff}} \le 0.047\ \mathrm{eV}$$

KamLAND-Zen 800 @TAUP2020
Slide by Y. Gando



Good target for
KamLAND-Zen 800

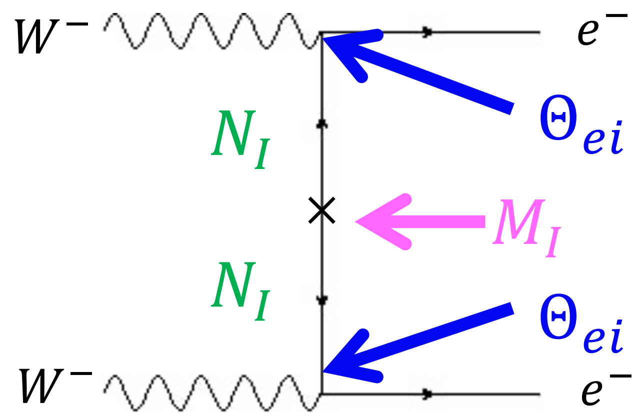
Part 2:
NDBD in low-scale seesaw

NDBD decay in low-scale seesaw

- Both active neutrinos and HNLs contribute to NDBD

$$\mathcal{M}^{\rm tot} = \mathcal{M}^{\nu} \sum_i m_i U_{ei}^2 + \sum_I \mathcal{M}^N(M_I)\, M_I\, \Theta_{eI}^2$$

$$= \mathcal{M}^{\nu} \underbrace{\left[\sum_i m_i U_{ei}^2 + \sum_I \frac{\mathcal{M}^N(M_I)}{\mathcal{M}^{\nu}}\, M_I\, \Theta_{eI}^2 \right]}_{\text{Effective mass } m_{\rm eff}}$$



- Suppression Factor

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

$$\Lambda_\beta = \sqrt{\langle \vec{p}_F^{\,2} \rangle} \sim 200 \text{ MeV}$$

$$\mathcal{M}^{\nu} \supset \frac{1}{p^2 - m_i^2} \simeq \frac{1}{-\langle \vec{p}_F^{\,2} \rangle}$$

$$\mathcal{M}^{N} \supset \frac{1}{p^2 - M_I^2} \simeq \frac{1}{-(\langle \vec{p}_F^{\,2} \rangle + M_I^2)}$$

Faessler, Gonzalez, Kovalenko, Simkovic '14
Barea, Kotila, Iachello '15

Effective mass in low-scale seesaw

- Effective mass

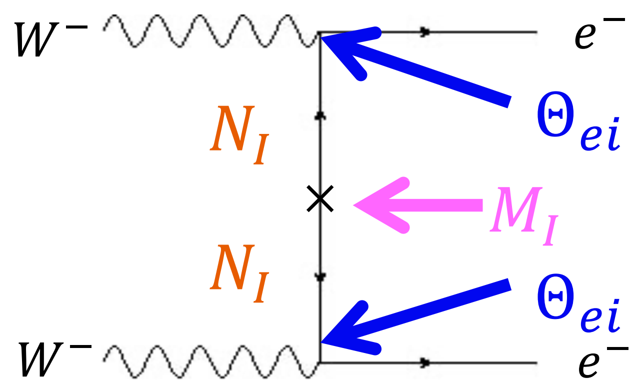
$$m_{\text{eff}} = \underbrace{\sum_{i=1,2,3} m_i\, U_{ei}^2}_{\text{active neutrinos } \nu_i} + \underbrace{\sum_I f_\beta(M_I)\, M_I\, \Theta_{eI}^2}_{\text{HNLs } N_I}$$

$$m_{\text{eff}}^{\nu} \qquad m_{\text{eff}}^{N}$$

$$\begin{cases} f_\beta(M_I) = \dfrac{\Lambda_\beta^2}{\Lambda_\beta^2 + M_I^2} \\ \Lambda_\beta \sim 200\ \text{MeV} \end{cases}$$

- N_{I} may give a significant contribution to m_{eff} !

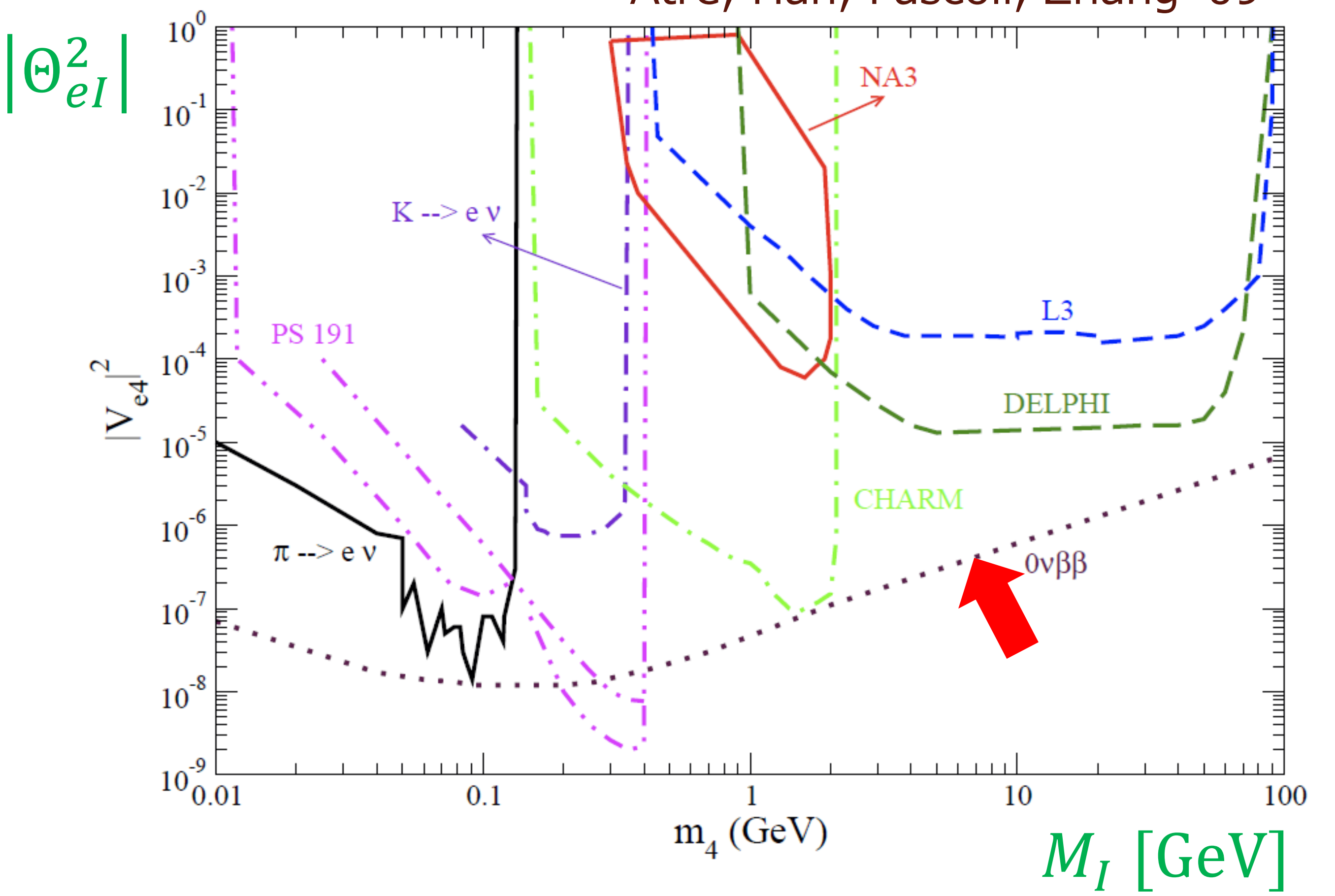
$$m_{\text{eff}}^{N} = \begin{cases} M_I\, \Theta_{eI}^2 & (M_I \ll \Lambda_\beta) \\ \dfrac{\Lambda_\beta{}^2}{M_I^2} M_I \Theta_{eI}^2 & (M_I \gg \Lambda_\beta) \end{cases}$$



NDBD in low-scale seesaw

- Constraint on the mixing $|\Theta_{eI}^2|$

Atre, Han, Pascoli, Zhang '09



This bound cannot be applied to
some cases in the seesaw mechanism !

Seesaw relation between mixings

- Neutrino mass matrix

$$\widehat{M_\nu} = \begin{pmatrix} \mathbf{0} & M_D \\ M_D^T & M_M \end{pmatrix}$$

$$\mathbf{0} = \left[\widehat{M_\nu}\right]_{\alpha\beta} = \left[\widehat{U}\widehat{M_\nu}^{diag}\widehat{U}^T\right]_{\alpha\beta}$$

Seesaw relation

$$0 = \sum_{i=1,2,3} m_i\, U_{\alpha i} U_{\beta i} + \sum_I M_I\, \Theta_{\alpha I}\, \Theta_{\beta I}$$

$\underline{\boldsymbol{\alpha = \beta = e}}$

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

When all HNLs are lighter than Λ_β

- Effective mass

$$m_{\rm eff} = m_{\rm eff}^{\nu} + \sum_I f_\beta(M_I)\, M_I\ \Theta_{eI}^2$$

$$= m_{\rm eff}^{\nu} + \sum_I M_I\ \Theta_{eI}^2$$

$$= 0$$

When $M_I \ll \Lambda_\beta$,
$f_\beta(M_I) = 1$

Seesaw relation

$$0 = m_{\rm eff}^{\nu} + \sum_I M_I\, \Theta_{eI}^2$$

NLDB is hidden by HNLs
even if lepton number is violated in the seesaw mechanism

Cf. We have to include sub-leading corrections
(EW loop corr., sub-leading corr. in seesaw etc.)

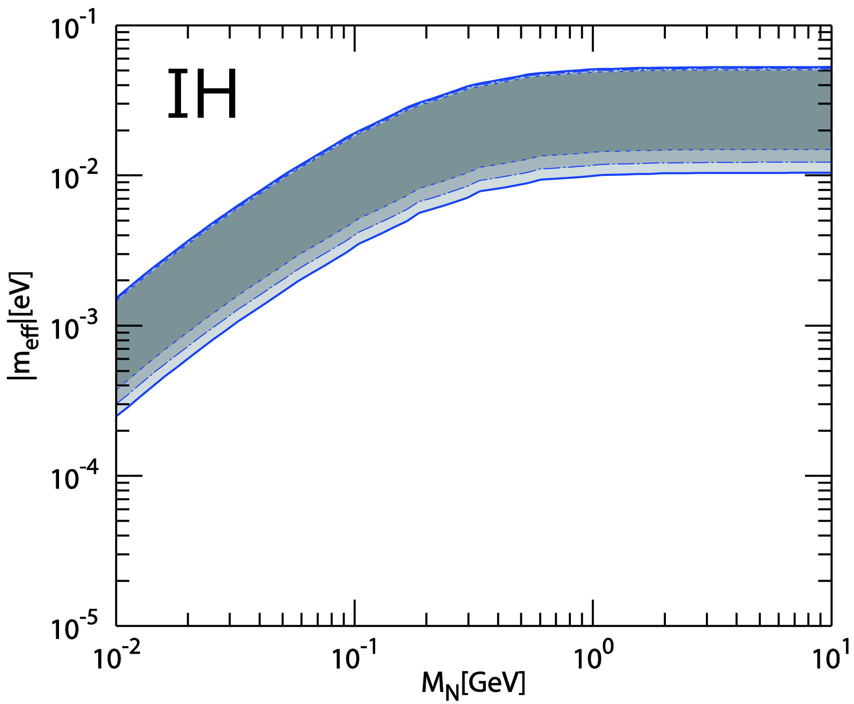
When all HNLs are degenerate

- When all heavy neutrinos are degenerate $M_I = M_N$,

$$m_{\rm eff} = m_{\rm eff}^{\nu} + \sum_I f_\beta(M_I) M_I\, \Theta_{eI}^2 = m_{\rm eff}^{\nu} + f_\beta(M_N) \sum_I M_N\, \Theta_{eI}^2$$

$$= m_{\rm eff}^{\nu}[\,1 - f_\beta(M_N)]$$

TA, Eijima, Ishida '11



- This shows $m_{\rm eff}$ does not depend on the mixing Θ_{eI}
- Degenerate HNLs give always destructive contribution

NDBD and HNLs

- HNLs in the seesaw mechanism may give a significant, constructive or destructive contribution to effective mass depending on masses and mixing elements

- What can we learn about HNLs in the seesaw mechanism by forthcoming NDBD experiments ?
  - What if NDBD is unseen ?
  - What if NDBD is seen ?

- To make a simple discussion, we consider the minimal seesaw model with TWO right-handed neutrinos.

$$m_{\mathrm{eff}} = m_{\mathrm{eff}}^{\nu} + \underbrace{f_\beta(M_1)\, M_1 \Theta_{e1}^2}_{N_1} + \underbrace{f_\beta(M_2)\, M_2 \Theta_{e2}^2}_{N_2}$$

What if NDBD is unseen?

HNL may hide NDBD

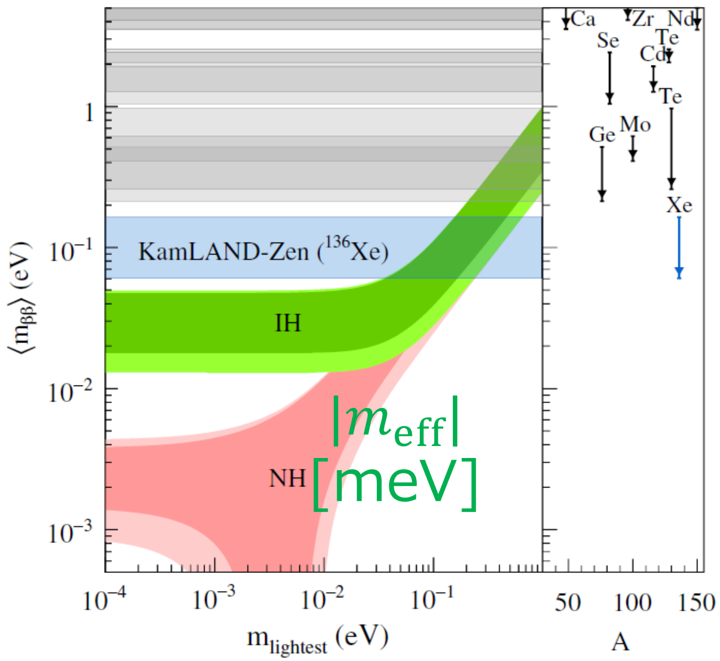
- Effective mass

$$m_{\rm eff} = m_{\rm eff}^{\nu} + f_\beta(M_1)\, M_1 \Theta_{e1}^2 + f_\beta(M_2)\, M_2 \Theta_{e2}^2$$

  - $m_{\rm lightest} = 0$ in the minimal seesaw

$$|m_{\rm eff}^{\nu}| = \begin{cases} 1.5 - 3.7 \text{ meV (NH)} \\ 19 - 48 \text{ meV (IH)} \end{cases}$$

KamLAND-Zen PRL117, 082503 ('16)



- Consider $M_1 \ll M_2$ (N_2 decouple)

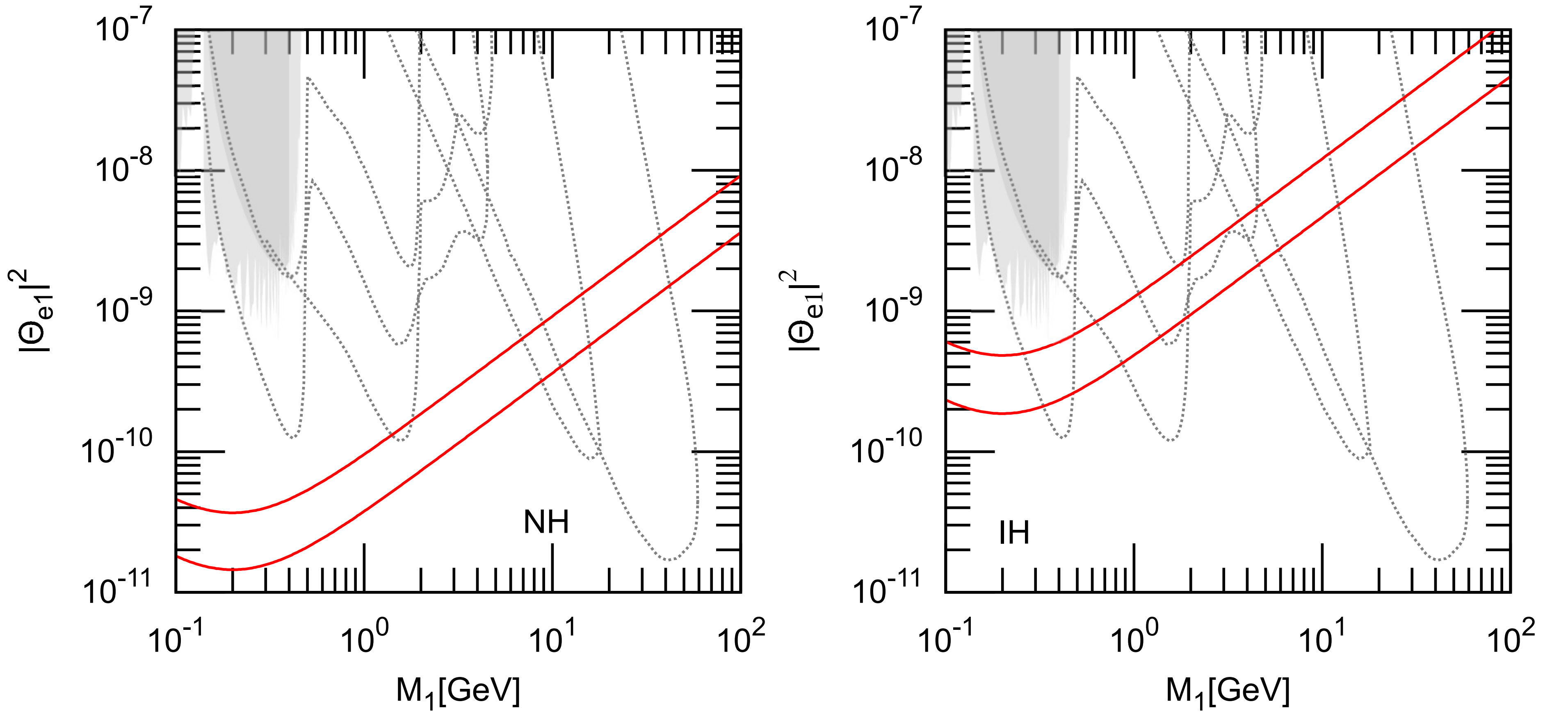
$$\boxed{m_{\rm eff} = m_{\rm eff}^{\nu} + f_\beta(M_1)\, M_1 \Theta_{e1}^2 = 0}$$

$\Longrightarrow$ NDBD is hidden by HNL contribution

What's happen ?

Consequence 1

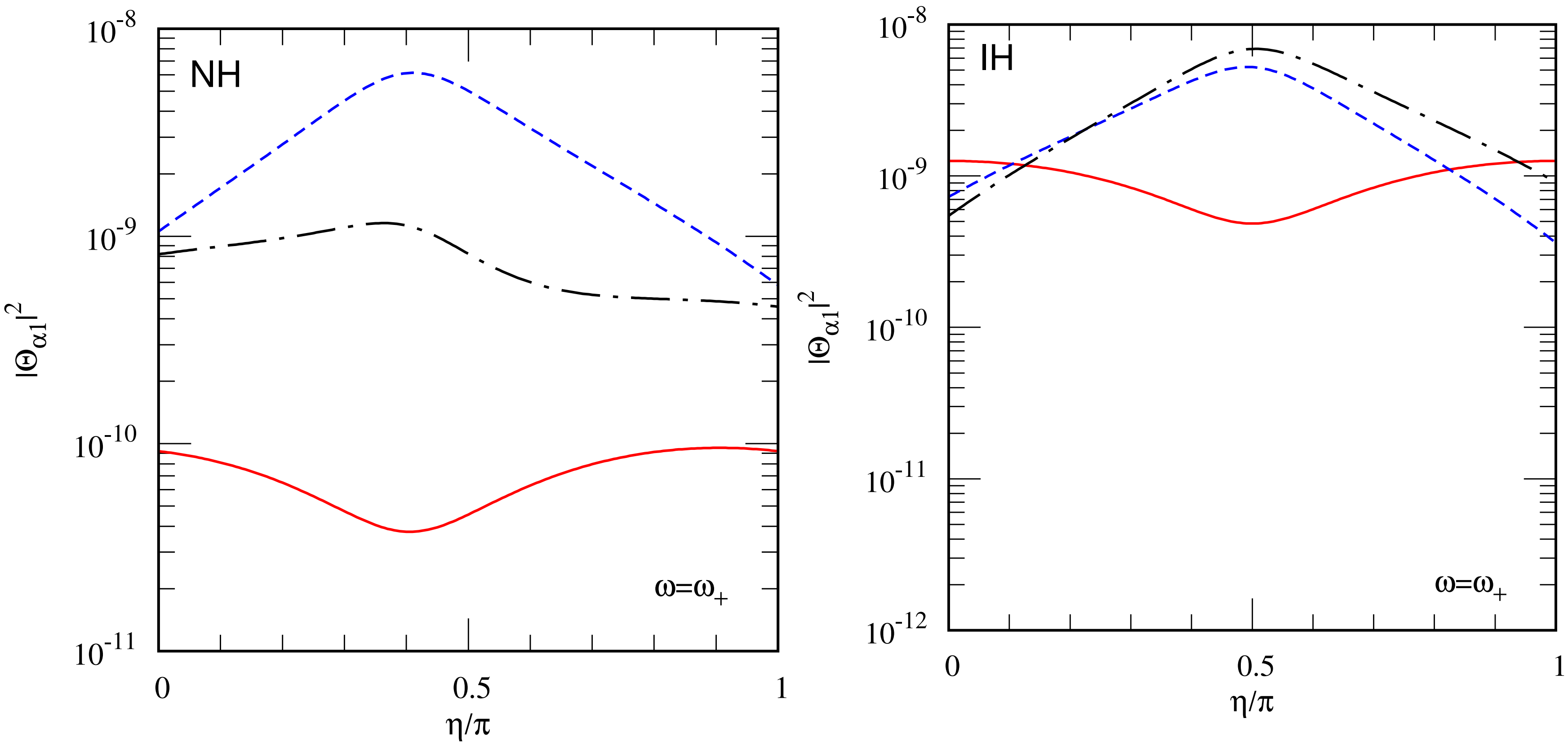
- Range of mixing element $|\Theta_{e1}|^2$ is predicted



TA, Ishida, Tanaka arXiv:2012.13186

Consequence 2

- Flavor structure of mixing elements $(|\Theta_{e1}|^2, |\Theta_{\mu 1}|^2, |\Theta_{\tau 1}|^2)$ depends on mass ordering and Majorana phase



TA, Ishida, Tanaka arXiv:2012.13186

What if NDBD is observed ?

HNL may enhance/suppress NDBD

- Effective mass

$$m_{\rm eff} = m_{\rm eff}^{\nu} + f_\beta(M_1)\, M_1 \Theta_{e1}^2 + f_\beta(M_2)\, M_2 \Theta_{e2}^2$$

Seesaw relation $0 = m_{\rm eff}^{\nu} + M_1 \Theta_{e1}^2 + M_2 \Theta_{e2}^2$

Hierarchical HNLs $M_2 > M_1$

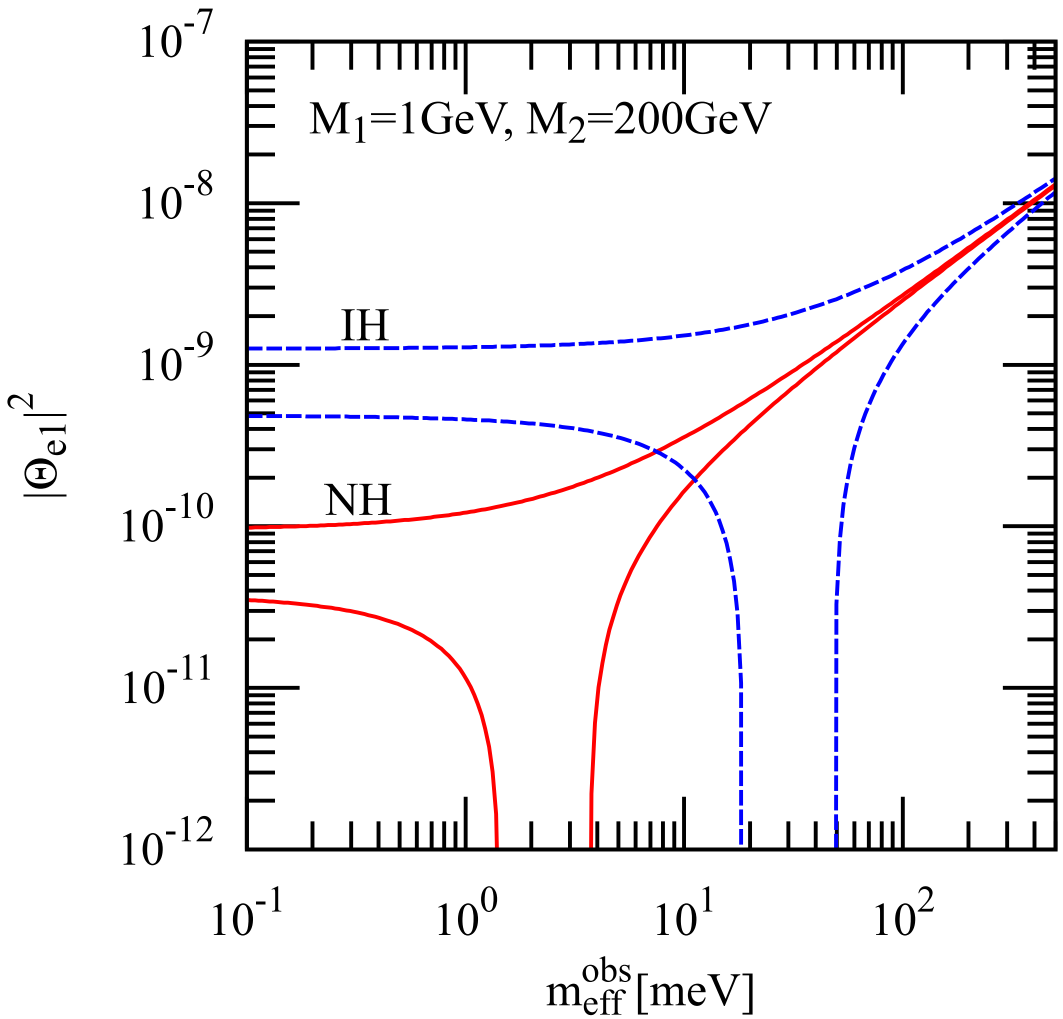
$$\boxed{\Theta_{e1}^2 = \frac{m_{\rm eff} - m_{\rm eff}^{\nu}\,[1 - f_\beta(M_2)]}{M_1\,[f_\beta(M_1) - f_\beta(M_2)]}}$$

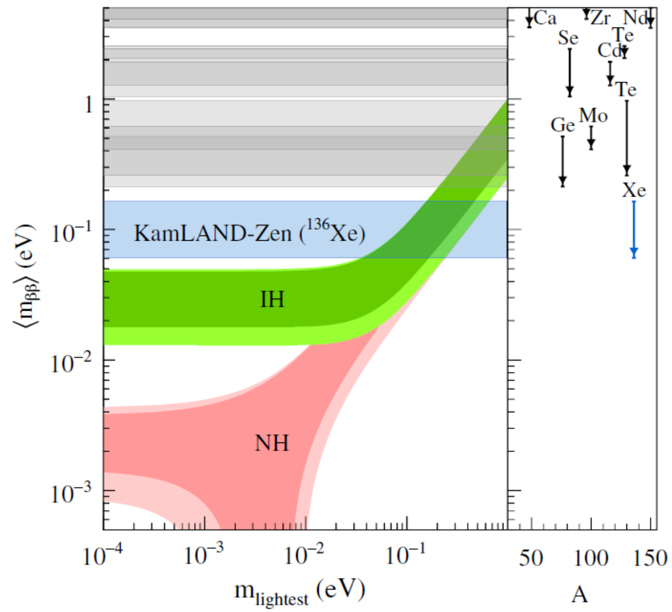
- If NDBD is seen at $|m_{\rm eff}| = m_{\rm eff}^{\rm obs}$,

What's happen ?

Consequence (Hierarchical HNLs)

- Range of mixing element $|\Theta_{e1}|^2$ is predicted depending on $m_{\rm eff}^{\rm obs}$





KamLAND-Zen

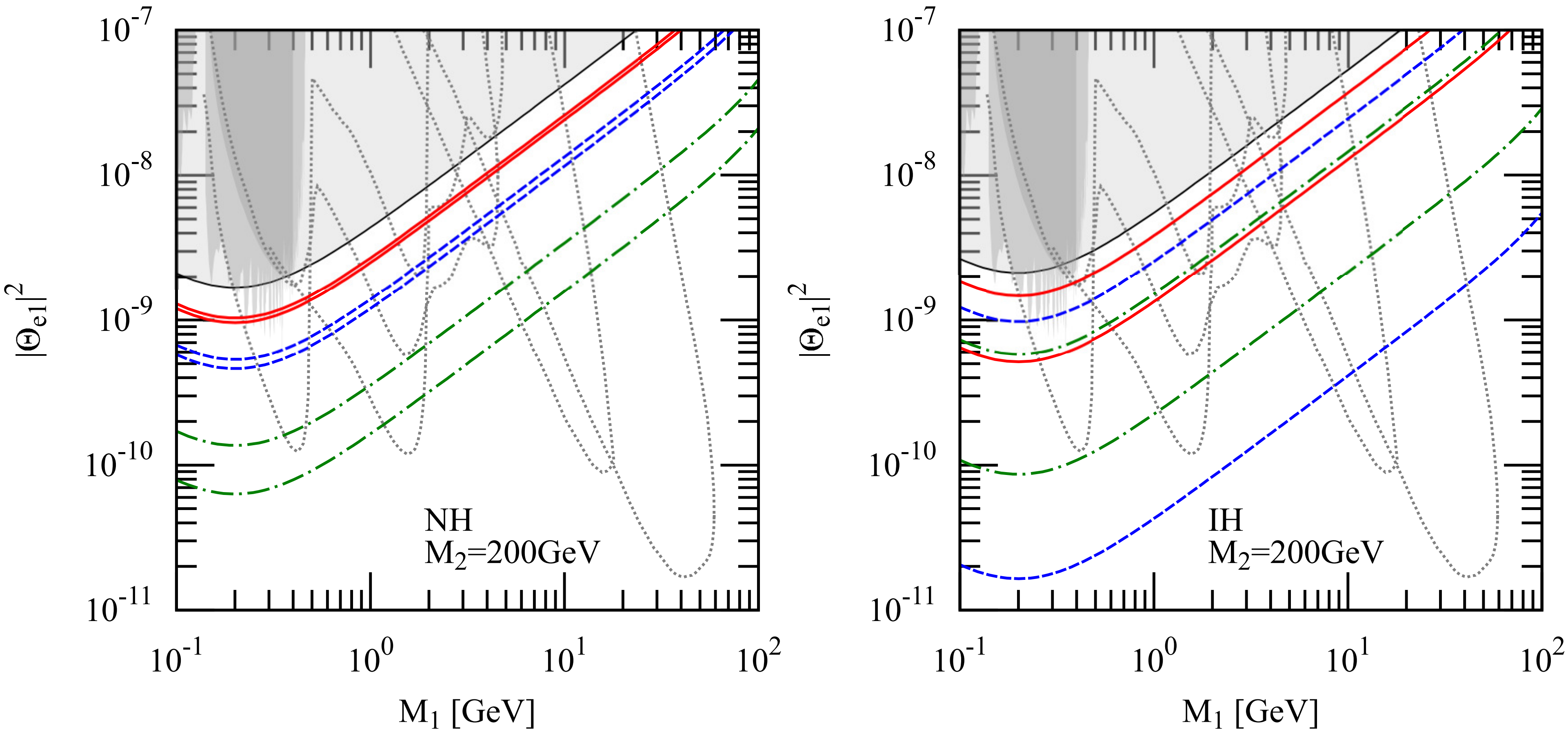
$|m_{\rm eff}| < (61 - 165)\,\mathrm{meV}$

TA, Ishida, Tanaka arXiv:2101.12498

Consequence (Hierarchical HNLs)

- Range of mixing element $|\Theta_{e1}|^2$ is predicted

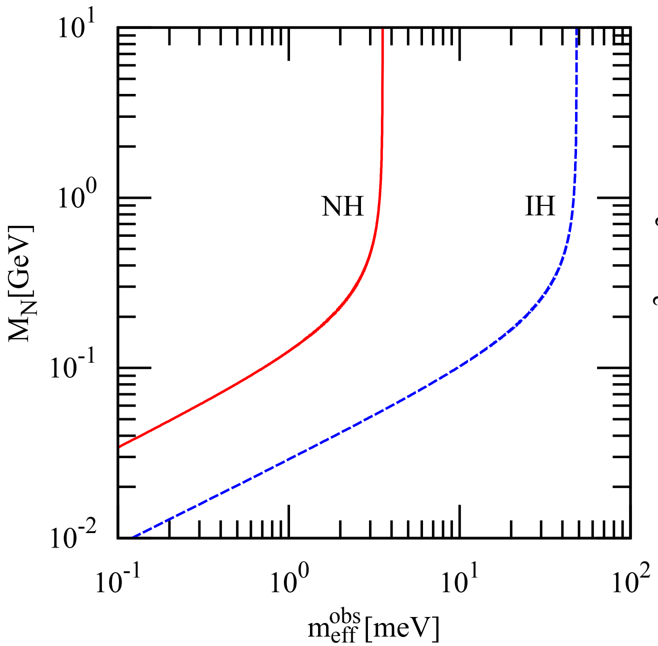
$m_{\rm eff}^{\rm obs}$=100meV (red), 50meV (blue), 10meV (green)

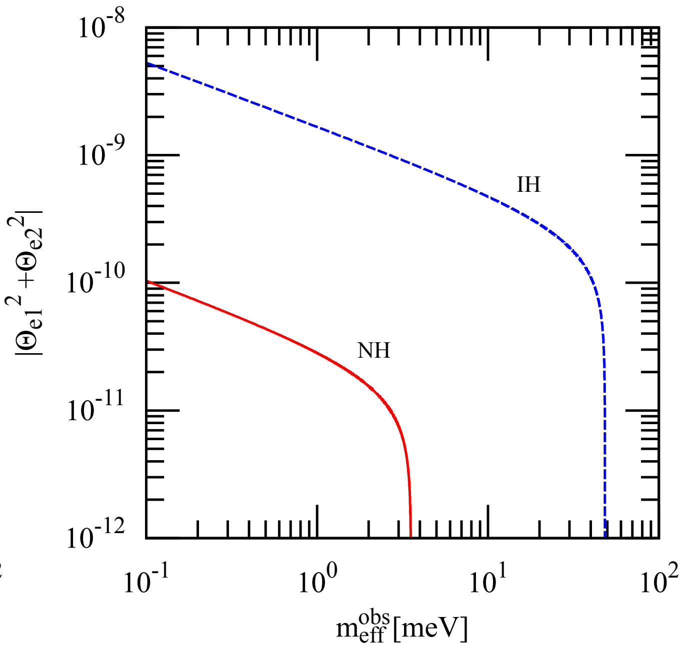


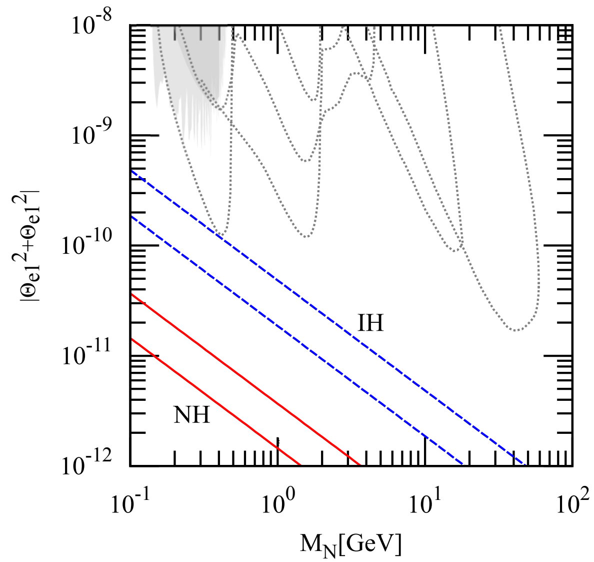
TA, Ishida, Tanaka arXiv:2101.12498

Consequence (Degenerate HNLs)

- Mass and mixing elements are predicted depending on $m_{\rm eff}^{\rm obs}$
  - $m_{\rm eff}^{\rm obs} < |{\rm m}_{\rm eff}^{\nu}|$ in the degenerate HNL case







Direct search for degenerate HNLs is difficult

TA, Ishida, Tanaka arXiv:2101.12498

NDBD in different nuclei

- Effective mass
  - Active neutrino contribution

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

independent on decay nuclei

  - HNL contribution

$$m_{\mathrm{eff}}^{N} = \sum_I f_\beta(M_I)\, M_I\ \Theta_{eI}^2$$

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

dependent on decay nuclei !

Multiple detection/non-detection by NDBD using different nuclei

is crucial to reveal the properties of HNLs in the seesaw mechanism

Summary

Summary

- We have investigated NDBD in the seesaw mechanism
  - Active neutrinos and HNLs are both Majorana fermions
  - NDBD is an important test of the seesaw mechanism, i.e. to reveal the properties of HNLs (right-handed neutrinos)

- Part 1: NDBD in the high-scale seesaw mechanism
  - Active neutrino contribution depends on mass ordering, lightest neutrino mass and CP phases
  - Flavor symmetry (e.g. modular symmetry) can restrict the predicted range of the effective mass, which will be faced with near future experiments
- Part 2: NDBD in the low-scale seesaw mechanism
  - HNLs can give a significant destructive/constructive effect
  - Range of the mixing elements of HNLs can be found, which is a good target for future direct search experiments
  - Mass ordering and CP phases can be studied through the flavor structure of the mixing elements of HNLs