真の強さを学ぶ。
新潟大學
NIIGATA UNIVERSITY

Origin of neutrino masses and its experimental tests

Takehiko Asaka (Niigata Univ.)

The Future is Flavourful
(2024/06/04-06 @NYCU, Taipei)

Neutrino oscillations

- Three neutrino flavors

$$\nu_e \quad \nu_\mu \quad \nu_\tau$$

Cf. Three charged leptons

$$e \quad \mu \quad \tau$$

- Neutrino oscillations
  - Quantum phenomena where neutrino can change its flavor in propagation
  - Flavor transition probability

$$\boxed{P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)}$$

(simple two-flavor case)

  - Precisely measured by using solar, atmospheric, reactor, accelerator neutrinos

Neutrino properties

- Mixing angles and mass squared differences are measured very precisely

$$\Delta m_{21}^2 = (7.41^{+0.21}_{-0.20})\times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m_{31}^2 = (2.505^{+0.024}_{-0.026})\times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2\theta_{12} = 0.307^{+0.012}_{-0.011}$$

$$\sin^2\theta_{23} = 0.454^{+0.019}_{-0.016}$$

$$\sin^2\theta_{13} = 0.02224^{+0.00056}_{-0.00047}$$

(NH case)

(NuFIT 5.3 (2024), www.nu-fit.org)

- Unknown properties
  - Absolute masses of neutrinos ($m_{\nu\,\mathrm{lightest}}$? Mass ordering ?)
  - CP violations (Dirac phase ? Majorana phase(s) ?)
  - Dirac or Majorana fermions

We do not know how neutrinos obtain masses.

Important Questions

Origin of neutrino masses

- What mechanism ?
- New particle(s) ?
- New interaction(s) ?
- $\cdots$

Implications to other physics

- Baryogenesis ?
- Dark matter ?
- Planck scale physics ?
- $\cdots$

$$\nu$$

Experimental tests

- Search @LHC, Belle-II, $\cdots$
- LNV, LFV
- CPV
- Cosmology (γ, GW, $\cdots$)
- $\cdots$

Further,$\cdots$

- New powerful ν source ?
- New experiment method ?
- Applications to other science ?
- $\cdots$

Contents

- Origin of neutrino masses
  - Standard Model with right-handed neutrinos and the seesaw mechanism

- Cosmological implication of the seesaw mechanism
  - Baryon Asymmetry of the Universe

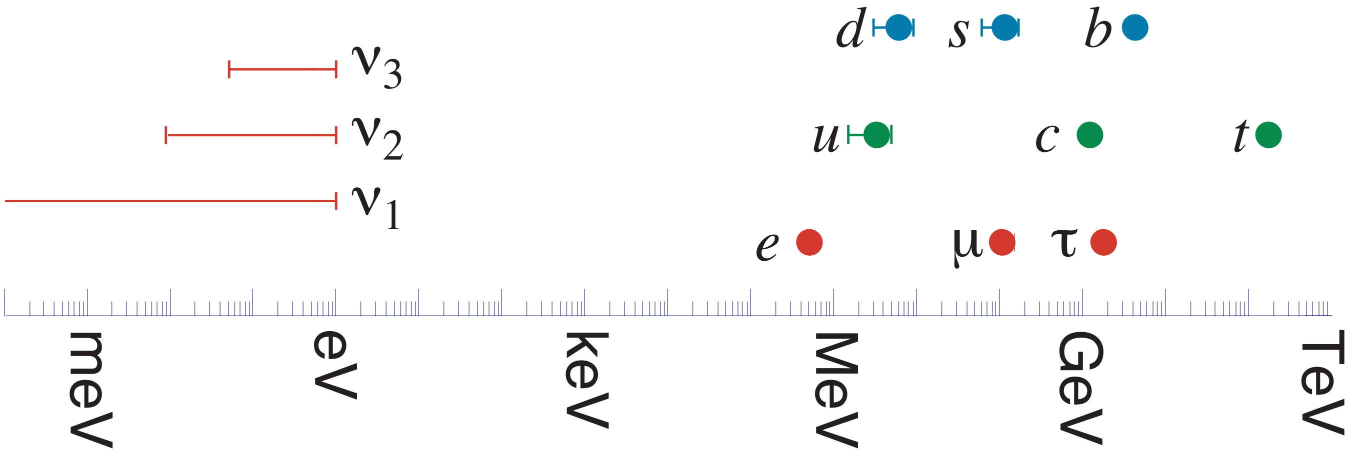
- Experimental tests of seesaw mechanism
  - Neutrinoless Double Beta Decays

- Summary

Origin of Neutrino Masses

Origin of neutrino masses

- Why neutrino masses are so small ?



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

In the SM

- Masses and mixings are originated in Yukawa interaction terms

$$\mathcal{L} = -F_\psi \overline{\Psi}_L \, \Phi \, \Psi_R + h.c \quad \Longrightarrow \quad m_\Psi = F_\psi \, \langle \Phi \rangle$$

- Neutrino masses might be generated in mechanism different from other quarks and leptons

Standard Model

Higgs Boson	Quarks and Leptons		Gauge Bosons
	(left-handed)	(right-handed)	
h	$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$	$u_R \quad c_R \quad t_R$ $d_R \quad s_R \quad b_R$	g Z^0
	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$e_R \quad \mu_R \quad \tau_R$	$W^\pm$ γ

Three right-handed neutrinos

Higgs Boson	Quarks and Leptons (left-handed)	Quarks and Leptons (right-handed)	Gauge Bosons
h	$\begin{pmatrix} u \\ d \end{pmatrix}_L \begin{pmatrix} c \\ s \end{pmatrix}_L \begin{pmatrix} t \\ b \end{pmatrix}_L$	$u_R \quad c_R \quad t_R$ $d_R \quad s_R \quad b_R$	g Z^0
	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$	$e_R \quad \mu_R \quad \tau_R$ $\nu_{R1} \quad \nu_{R2} \quad \nu_{R3}$	$W^\pm$ γ

Why ν_R ?

- Chiral structure of fermions in the SM

- Mass hierarchical patterns of fermion masses
  - neutrino masses << masses of quarks and leptons

    $(m_{atm} \simeq 50\,\mathrm{meV} \ll m_e \simeq 0.5\,\mathrm{MeV})$

- Interesting phenomena by right-handed neutrinos
  - Baryogenesis
    - Leptogenesis / Mechanism by oscillations
  - Dark matter
    - ~10 keV mass right-handed neutrino is a candidate of WDM
      (it may be irrelevant in the seesaw mechanism)
  - etc.

Extension by right-handed neutrinos (ν_R)

- Seesaw mechanism

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

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

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

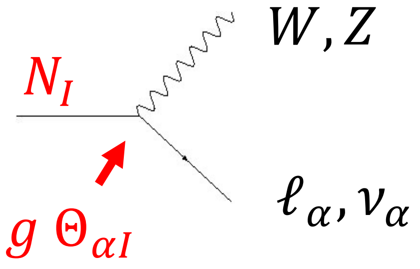
$$M_D \ll M_M$$

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

Smallness of M_ν is naturally explained

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

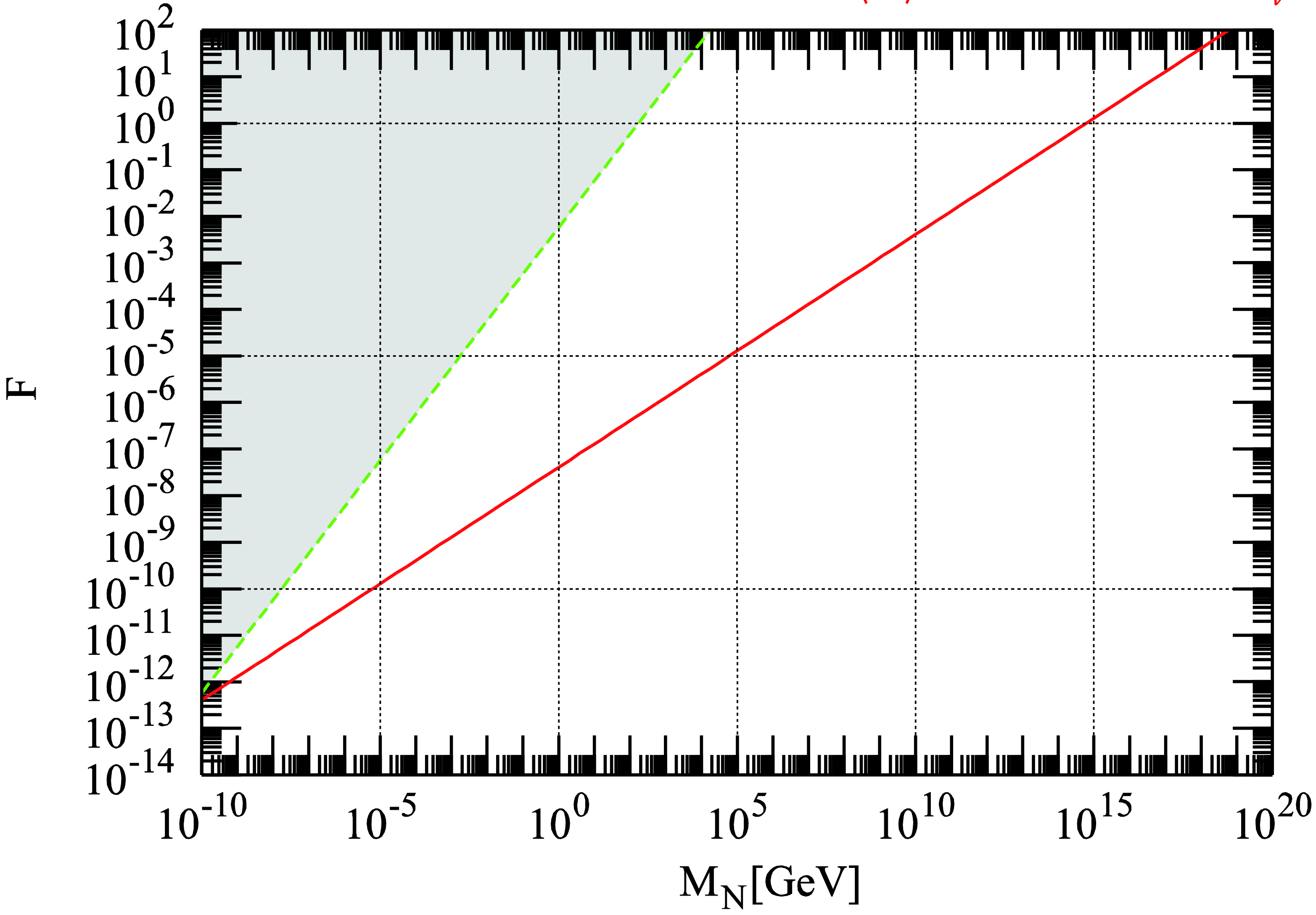
- Mixing in weak interaction
  - $\nu_L = U\,\nu + \Theta\,N^c$



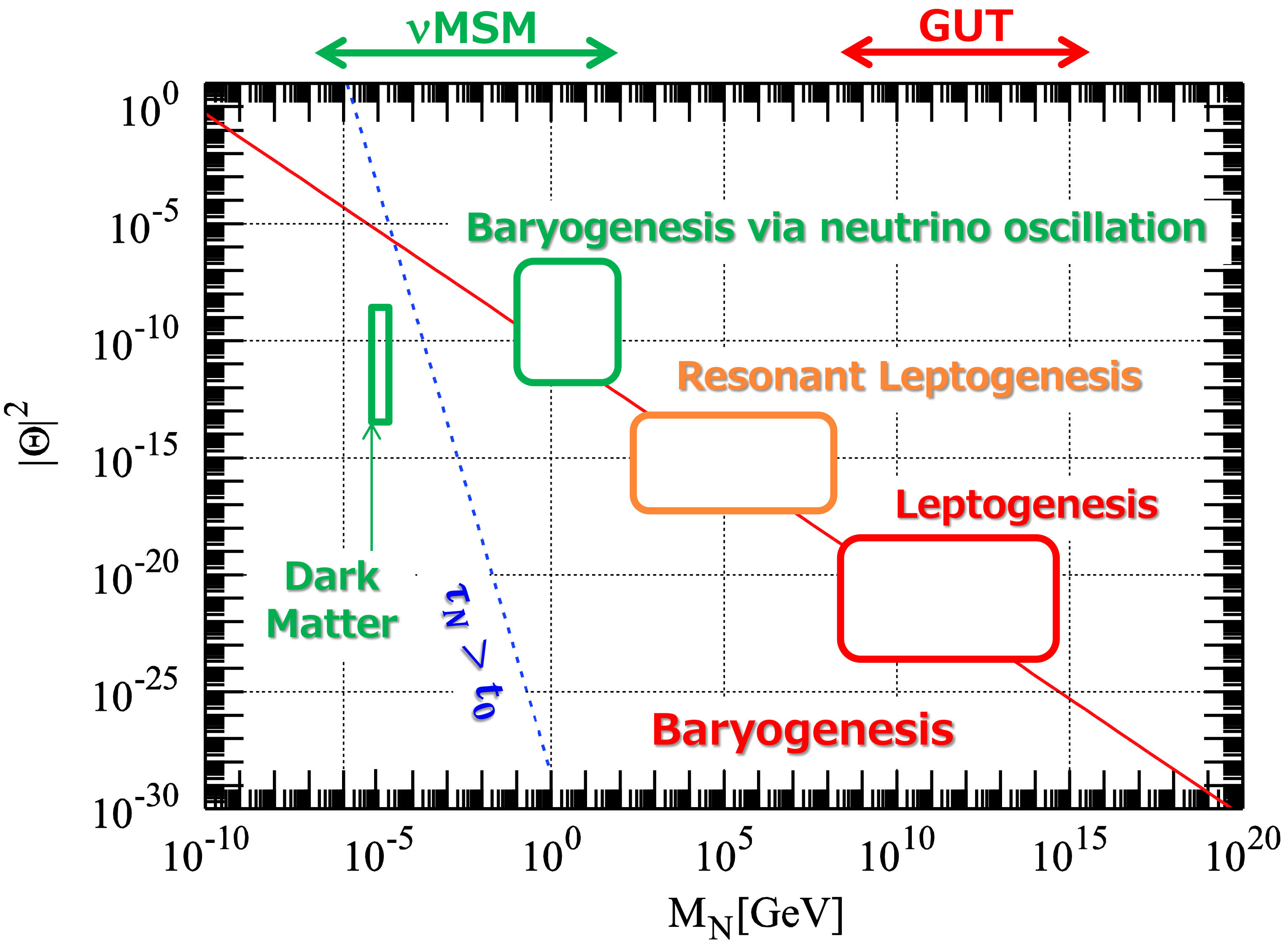
Scale of seesaw (mass of HNL)

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

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



Various Physics of HNL



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

Cosmological implication of the seesaw mechanism

-Baryon Asymmetry of the Universe

Baryons vs antibaryons

Baryon

proton $(B = +1)$
neutron $(B = +1)$

Antibaryon

antiproton $(B = -1)$
antineutron $(B = -1)$

- We observe baryons mostly, not antibaryons
  - Existence of antiproton
    - In cosmic rays, $p + p \to p + p + p + \bar{p}$
    - At colliders, $p + \bar{p} \to X$

- Asymmetry in numbers of baryons and antibaryons
  - HOW LARGE ?

Baryon Asymmetry of the Universe (BAU)

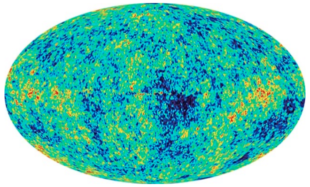
- Observational value

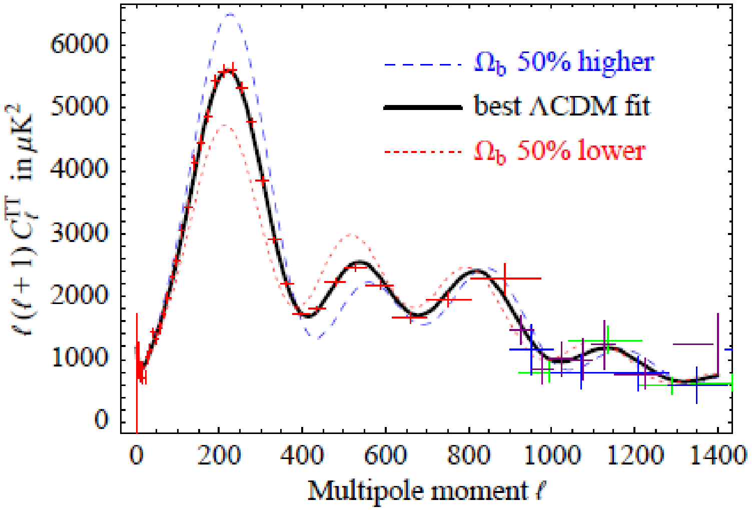
Planck 2018 [1807.06209]

$$\boxed{Y_B = \frac{n_B}{s} = (0.872 \pm 0.004)\times 10^{-10}}$$

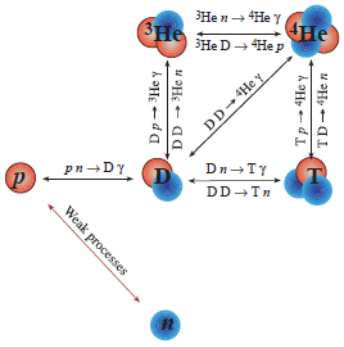
n_B : baryon number density, s : entropy density

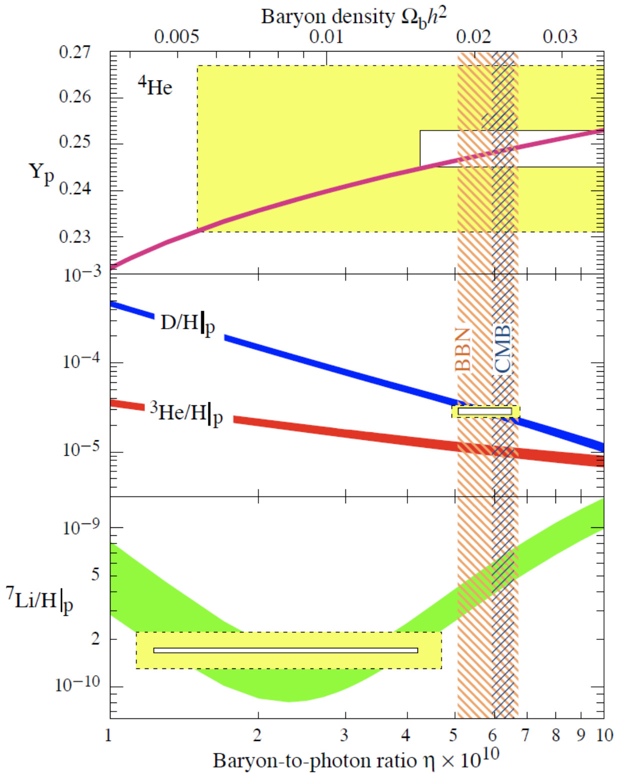
CMBR





BBN





[Strumia 06]

[PDG]

Baryogenesis

- Inflation sets baryon number $B = 0$ and non-zero B must be generated after the inflation
  → Baryogenesis

- Conditions for baryogenesis: Sakharov (1967)

  (1) Baryon number B is violated

  (2) C and CP symmetries are violated

  (3) Out of thermal equilibrium

- We need physics beyond the Standard Model to satisfy all these conditions.

Baryogenesis conditions in the SM

- B and L violation
  - B and L violations in anomalous EW “sphaleron” which is in thermal equilibrium for T>100GeV

- CP violation
  - 1 CP phase in the quark-mixing (CKM) matrix

  → too small

$$\mathrm{CPV} \propto J_{CP}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)/T_{EW}^{12} \sim 10^{-19}$$

- Out of equilibrium
  - Strong 1st order phase transition if $m_H < 72$ GeV

    but $m_H = 125.25$ GeV

  → not satisfied

[Kajantie, Laine, Rummukainen, Shaposhnikov]

→ We have to go beyond the MSM !!

Baryogenesis conditions and ν_R

- B and L violations
  - EW sphaleron : B and L are violated but (B-L) invariant

$$B_f = \frac{8N_F + 4}{22N_F + 13}(B-L)_i = 0.35\,(B-L)_i$$

[Khlebnikov, Shaposhnikov ‘88, Harvey, Turner ‘90]

  - L violation due to Majorana masses

- C and CP violations
  - 1 CP phase in quark sector
  - 6 CP phases in lepton sector (three ν_R case)
    - Rich CP violation

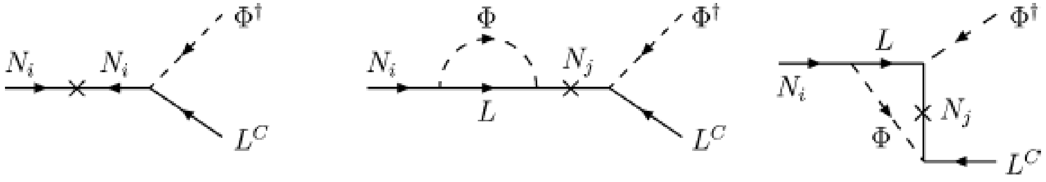
- Out of equilibrium (⇦ depends on scenarios)
  - Out of equilibrium decay
  - Departure from thermal bath
  - ⋯

→ **Three conditions can be satisfied !!**

Leptogenesis

[Fukugita, Yanagida '86]

- Decays of right-handed neutrinos can be a source of BAU
    - CPV in decay



$$\varepsilon_1 = \frac{\Gamma(N_1 \to L + \Phi^\dagger) - \Gamma(N_1 \to \bar{L} + \Phi)}{\Gamma(N_1 \to L + \Phi^\dagger) + \Gamma(N_1 \to \bar{L} + \Phi)}$$

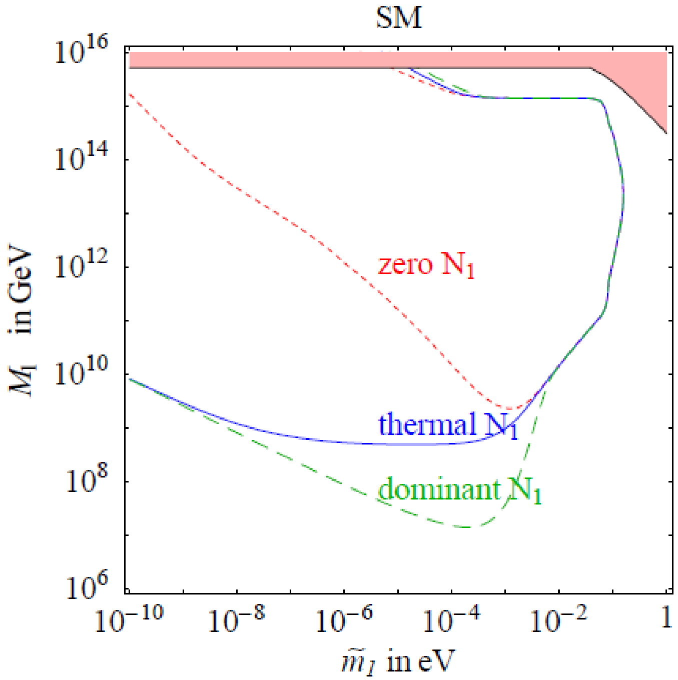
-
    - L can be converted into B by sphaleron

$$\frac{n_B}{s} \propto \varepsilon_1 \ \propto M_1$$

$$M_{N1} > O(10^9)\ \text{GeV}$$

→ Experimental test is impossible

[Giudice et al '03]



Resonant leptogenesis

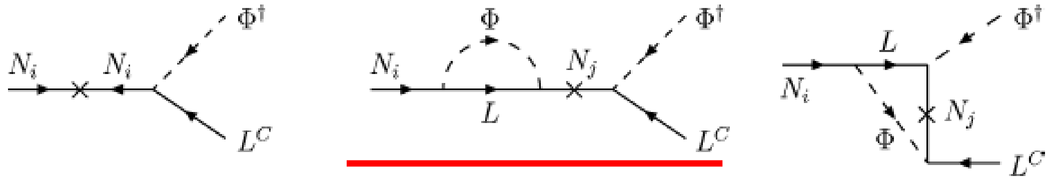
Pilaftsis ’97
Pilaftsis, Underwood ’04

- Resonant production of lepton asymmetry occurs if right-handed neutrinos are quasi-degenerate

$$\varepsilon_1 = \frac{\Gamma(N_1 \to L_L + \overline{\Phi}) - \Gamma(N_1 \to \overline{L_L} + \Phi)}{\Gamma(N_1 \to L_L + \overline{\Phi}) + \Gamma(N_1 \to \overline{L_L} + \Phi)}$$

$\Delta M \ll M_N$

$$\Delta M = M_2 - M_1$$
$$M_N = (M_2 + M_1)/2$$



$$\varepsilon_1 \propto \frac{M_N^2}{\Delta M^2} \qquad (\text{for } \Delta M^2 > O(M_N \Gamma_N))$$

huge enhancement

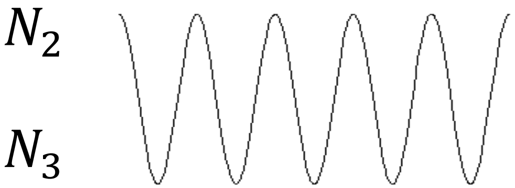
$\Longrightarrow$ Leptogenesis is possible even for $M_1 \ll 10^9$ GeV

Note that $M_1 \gtrsim 10^2$ GeV in this case
in order to convert lepton asymmetry into baryon asymmetry
by EW sphaleron process ($T \gtrsim 10^2$ GeV)

Baryogenesis via Neutrino Oscillation

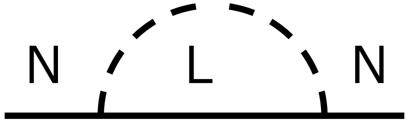
Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)
Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)
…

- Oscillation starts at $\boldsymbol{T_{osc}} \sim (\boldsymbol{M_0}\ \boldsymbol{M_N}\ \boldsymbol{\Delta M})^{1/3}$

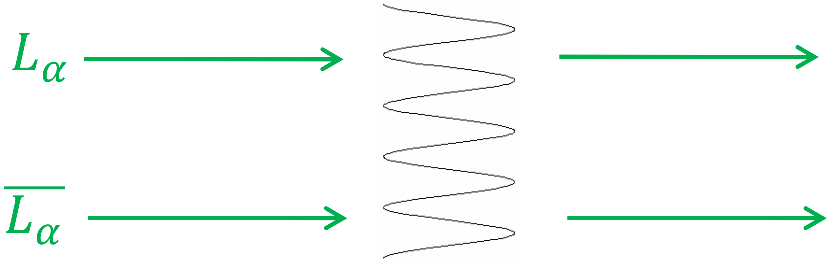


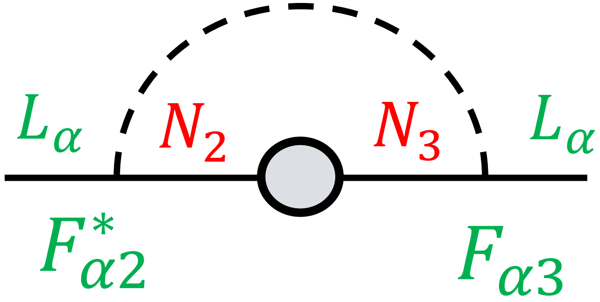
$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects



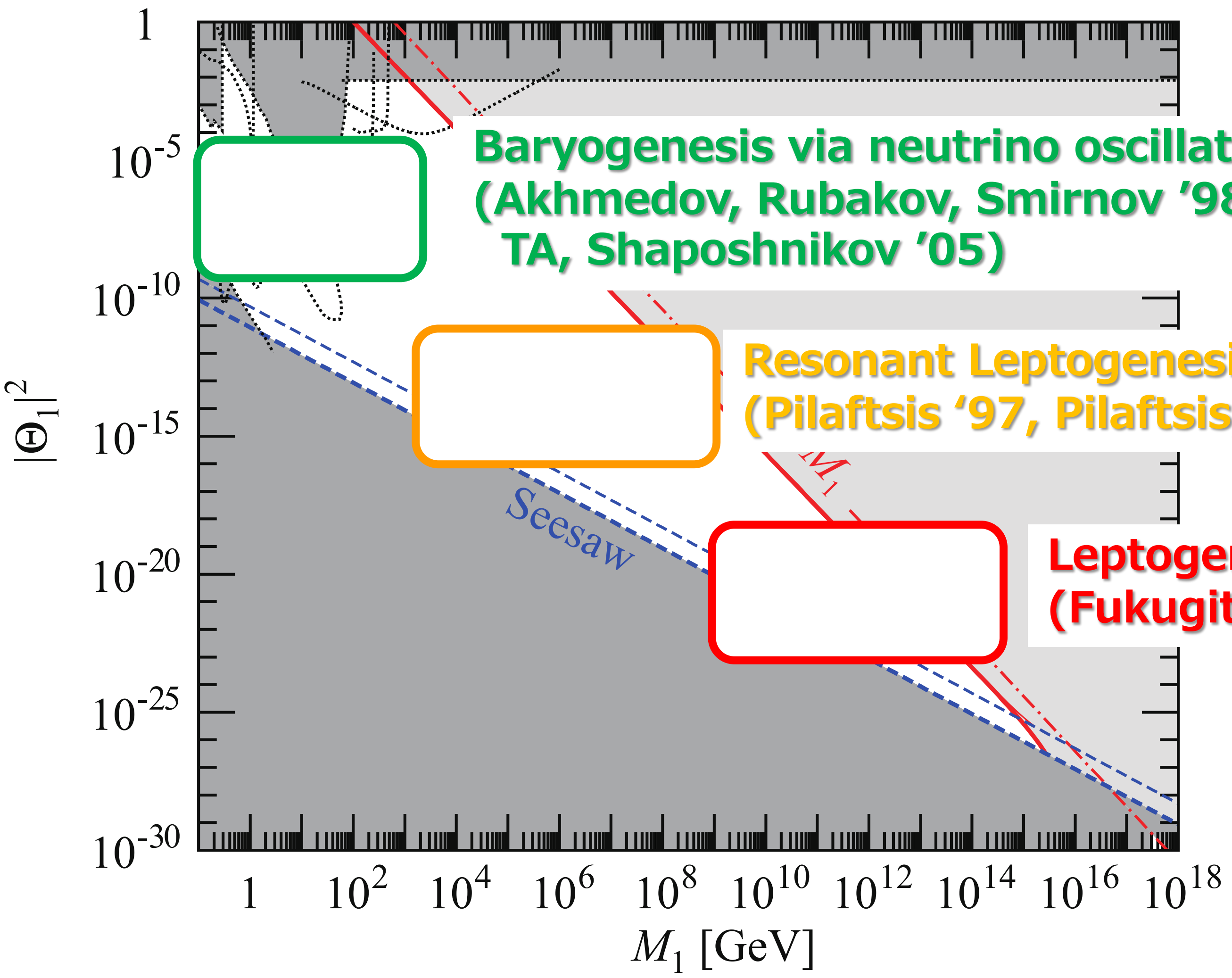
- Asymmetries are generated since evolution rates of L_α and $\overline{L_\alpha}$ are different due to CPV





Baryogenesis region

TA, Tsuyuki '15



Baryogenesis via neutrino oscillation (Akhmedov, Rubakov, Smirnov '98, TA, Shaposhnikov '05)

Resonant Leptogenesis (Pilaftsis '97, Pilaftsis, Underwood '05)

Leptogenesis (Fukugita, Yanagida '86)

BAU and CPV in neutrino sector

- Neutrino Yukawa couplings

$$M_\nu = -M_D^T\, M_{N,\mathrm{diag}}^{-1}\, M_D$$

Casas, Ibarra ('01)

$$F = \frac{i}{\langle \Phi \rangle}\, U\, M_{\nu,\mathrm{diag}}^{1/2}\, \Omega\, M_{N,\mathrm{diag}}^{1/2}$$

In mixing matrix U
of active neutrinos

Dirac phase δ

Majorana phase(s) η (η')

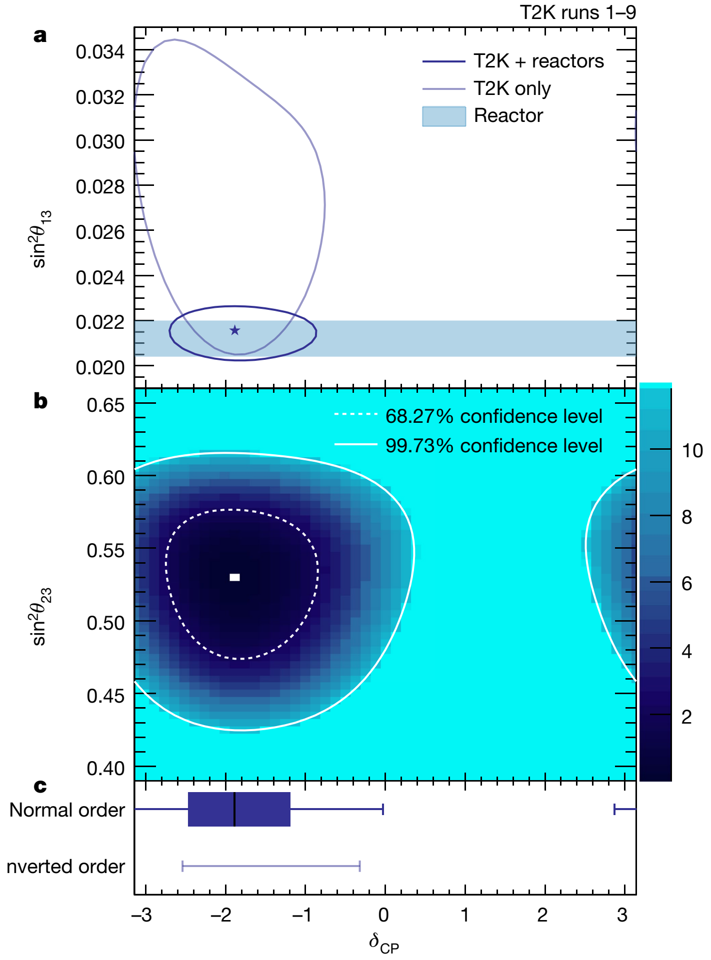
In mixing matrix U
of RH neutrinos

Phase(s) for ν_R

These phases are essential for BAU !

BAU and CPV in neutrino sector

- T2K and NOvA indicate CPV in neutrino sector



T2K Collaboration
Nature 580, 339 (2020)

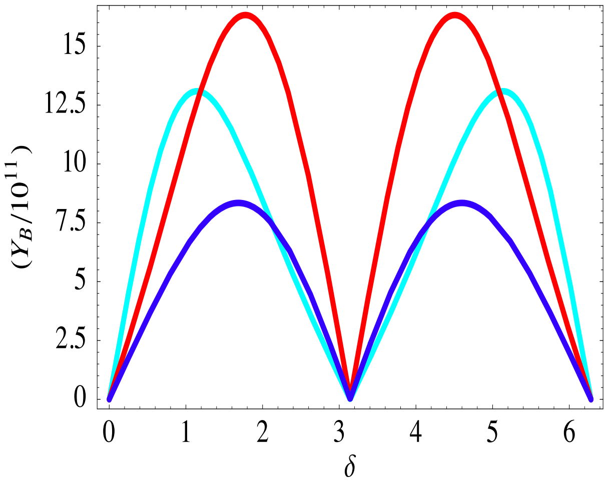
Non-zero Dirac phase

$$\delta \sim -\frac{\pi}{2} \left(or \ \frac{3\pi}{2} \right)$$

Important step to understand baryogenesis by RH neutrinos !

BAU and Dirac Phase

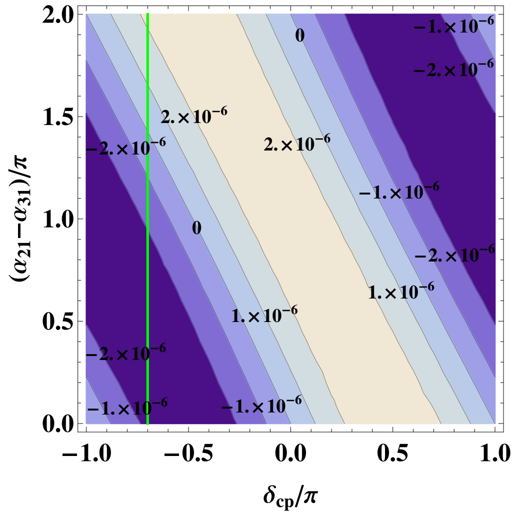
- Canonical leptogensis



Hierarchical RHN with $M_1 = 5{\times}10^{11}$GeV

Pascoli, Petcov, Riotto '07

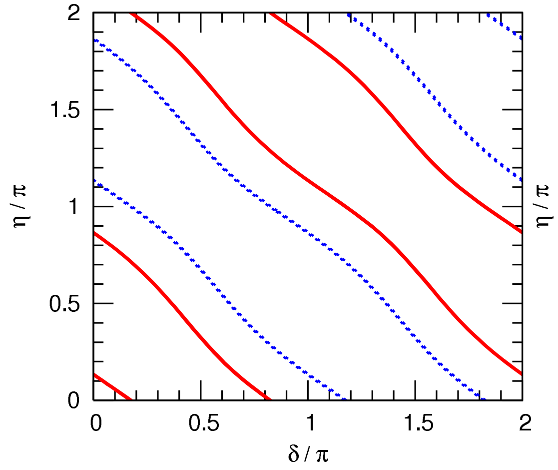
- Resonant leptogensis



Degenerate RHNs with $M_1 = 10^3$ GeV

TA, Yoshida '18

- Baryogenesis via neutrino oscillation



Degenerate RHNs with $M_1 = 5$ GeV

TA, Ishida '10

Experimental Test of the seesaw mechanism

Consequences of seesaw mechanism

- Important consequence of the seesaw mechanism

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

- ◘ Lepton number is violated at Lagrangian level

	Φ	$L = (\nu, e)^T$	ν_R
L	0	+1	+1

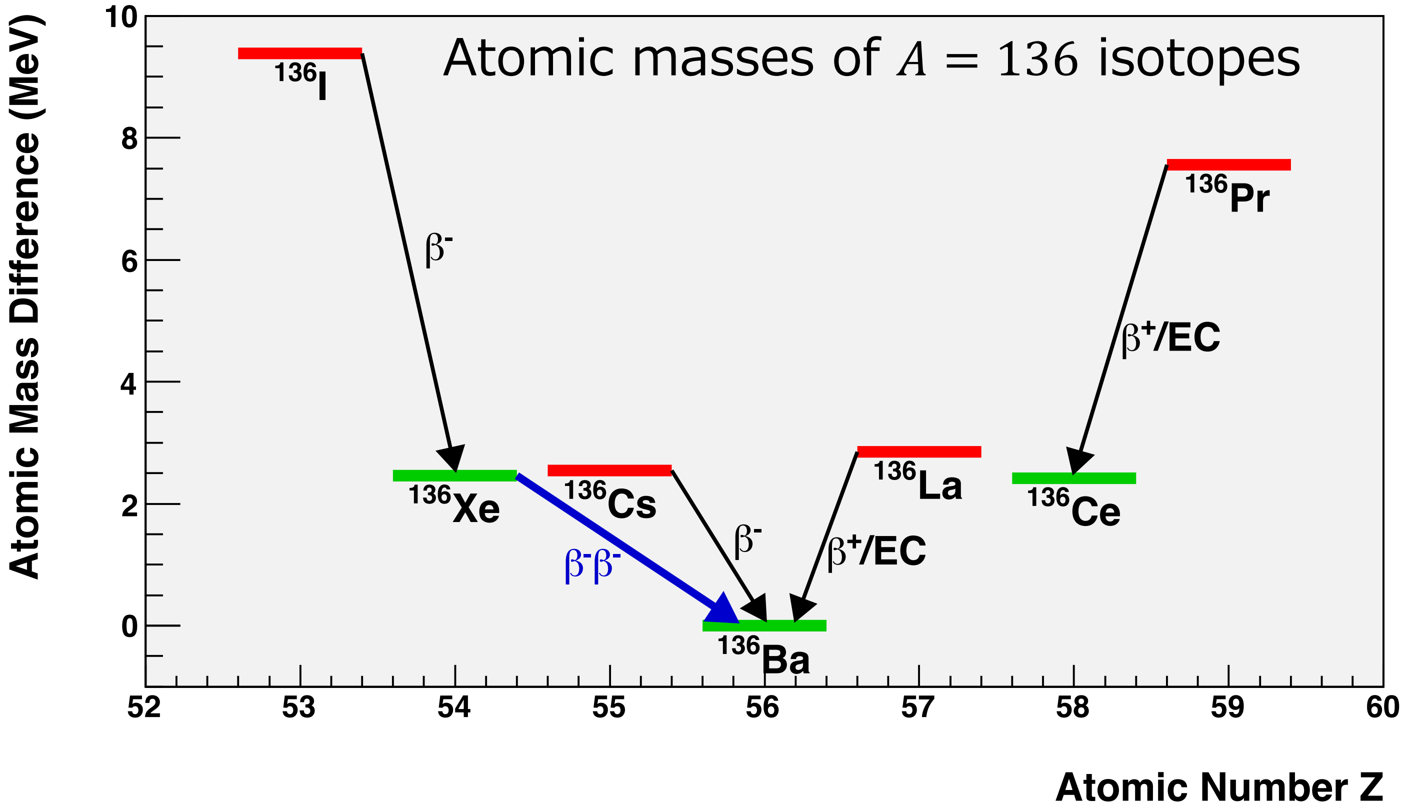
- ◘ Active neutrinos and HNLs are both Majorana fermions

⇨ Non-SM Lepton Number Violating (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)**

Beta decays

- Beta decays
  - β^- mode: (A, Z) → (A, Z+1) + e^- + $\bar{\nu}_e$
  - β^+ mode: (A, Z) → (A, Z−1) + e^+ + ν_e



J.J. Gomez-Cadenas, J. Martin-Albo, M. Mezzetto, F. Monrabal and M. Sorel, (2012) arXiv:1109.5515 [hep-ex]

Double beta decay (2νββ decay)

- 2νββ decay

$$\boxed{A(Z,N) \rightarrow A(Z\pm 2, N\mp 2) \ + \ 2\,e^{\mp} + 2\bar{\nu}_e(2\nu_e)}$$

  - Second order of weak interaction
    → Very long lifetime

Isotope	$T_{1/2}^{2\nu}$ (year)	Experiments
^{48}Ca	$(4.4^{+0.6}_{-0.5}) \times 10^{19}$	Irvine TPC [28], TGV [29], NEMO3 [30]
^{76}Ge	$(1.5 \pm 0.1) \times 10^{21}$	PNL-USC-ITEP-YPI [31], IGEX [32], H-M [33]
^{82}Se	$(0.92 \pm 0.07) \times 10^{20}$	NEMO3 [34], Irvine TPC [35], NEMO2 [36]
^{96}Zr	$(2.3 \pm 0.2) \times 10^{19}$	NEMO2 [37], NEMO3 [38]
^{100}Mo	$(7.1 \pm 0.4) \times 10^{18}$	NEMO3 [34], NEMO-2 [39], Irvine TPC [40]
^{116}Cd	$(2.8 \pm 0.2) \times 10^{19}$	NEMO3 [30], ELEGANT [41], Solotvina [42], NEMO2 [43]
^{130}Te	$(6.8^{+1.2}_{-1.1}) \times 10^{20}$	CUORICINO [44], NEMO3 [45]
^{136}Xe	$(2.11 \pm 0.21) \times 10^{21}$	EXO-200 [24]
^{150}Nd	$(8.2 \pm 0.9) \times 10^{18}$	Irvine TPC [40], NEMO3 [46]

J.J. Gomez-Cadenas, J. Martin-Albo, M. Mezzetto, F. Monrabal and M. Sorel, (2012)
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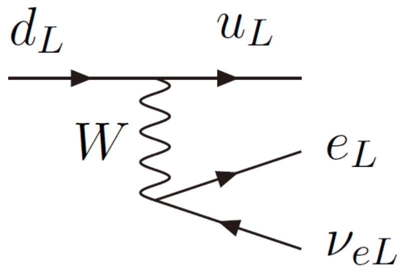
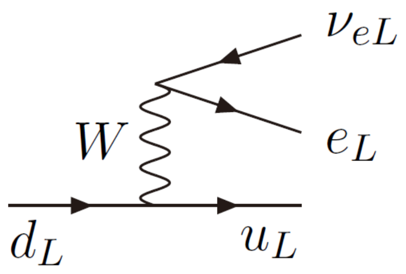
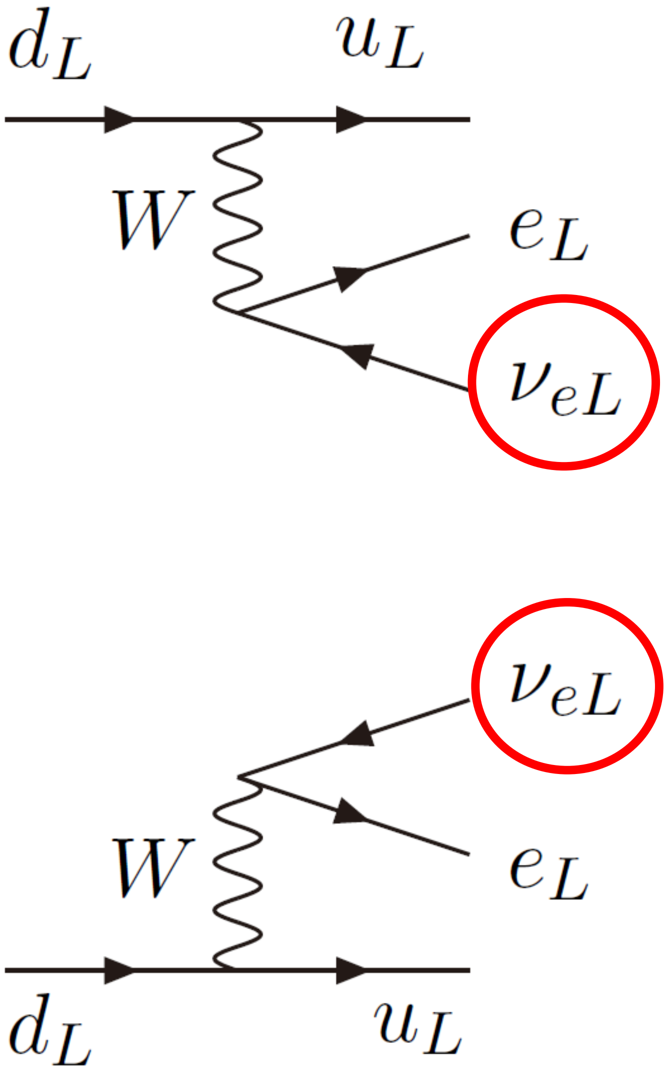
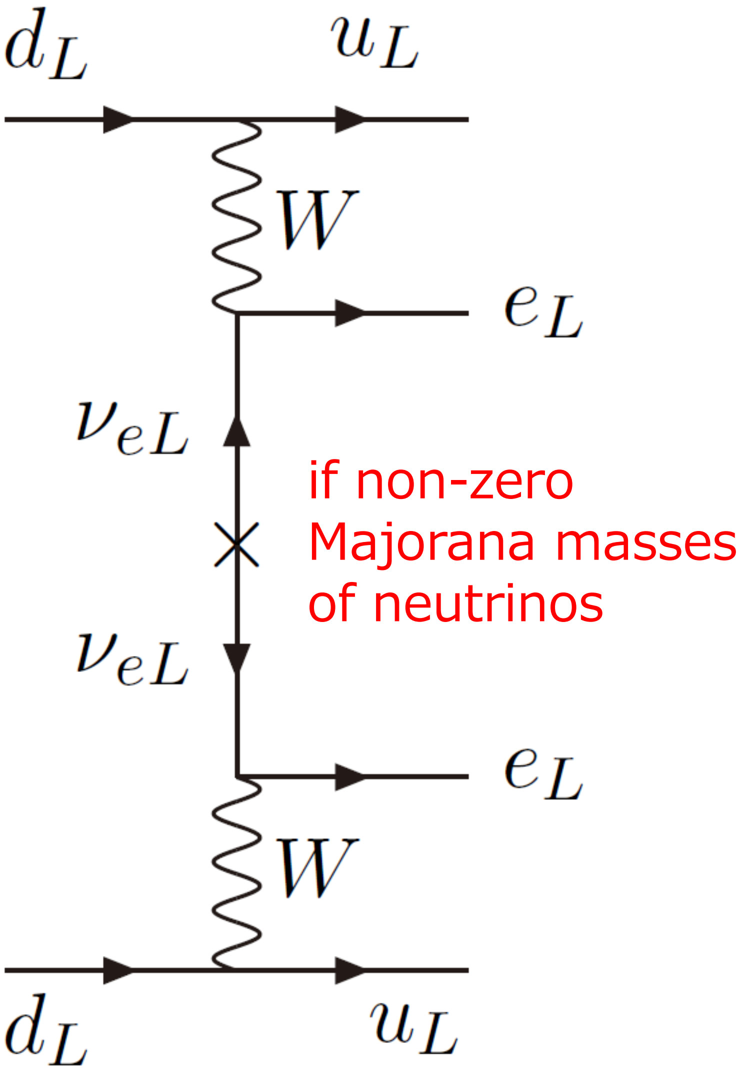




2νββ decay



0νββ decay



if non-zero Majorana masses of neutrinos

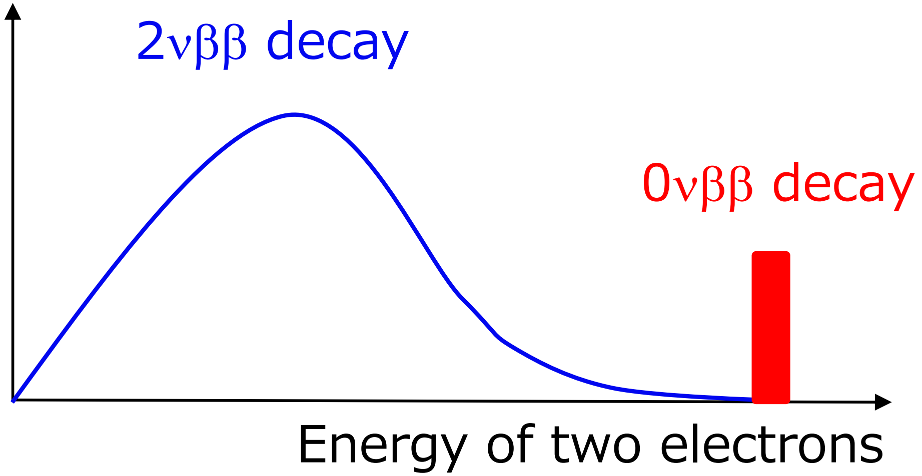
Neutrinoless double beta decay (NDBD)

- 0νββ decay

Furry, Phys. Rev. 56, 1184 ('39)

$$\boxed{A(Z,N) \rightarrow A(Z\pm 2, N \mp 2) \ + \ 2\,e^{\mp}}$$

  - Clear experimental signature



  - Lepton number violation ($\Delta L = \pm 2$)
    - new physics beyond the Standard Model

Effective mass in NDBD decay

- Decay rate

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

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

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

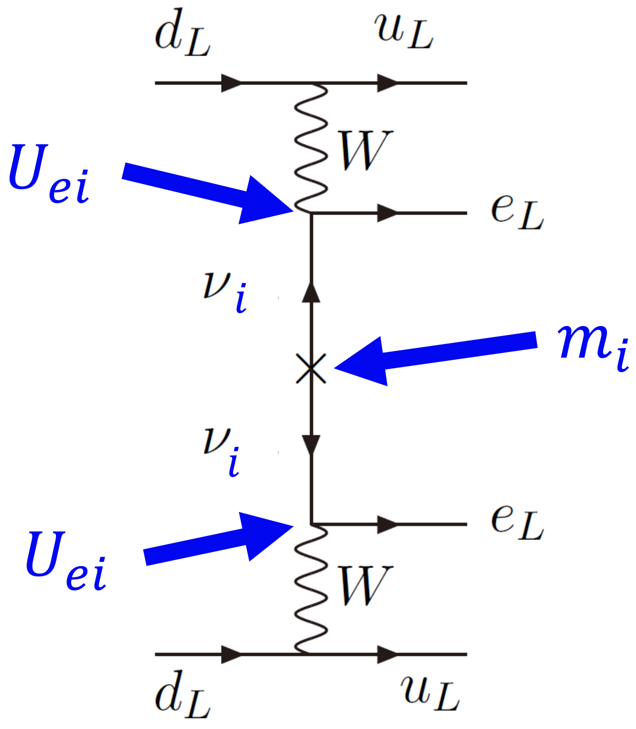
$m_{\rm eff}$: Effective mass

- Effective mass from active neutrinos

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

m_i : active neutrino masses

U_{ei} : PMNS neutrino mixing elements

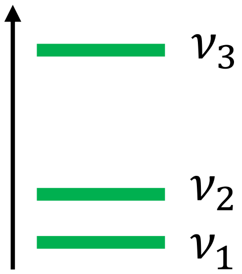


Masses and mixings of active neutrinos

- Active neutrino masses (m_1, m_2, m_3)

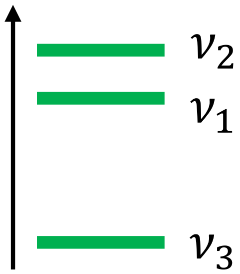
Normal Hierarchy (NH)

$m_3 > m_2 > m_1$



Inverted Hierarchy (IH)

$m_2 > m_1 > m_3$



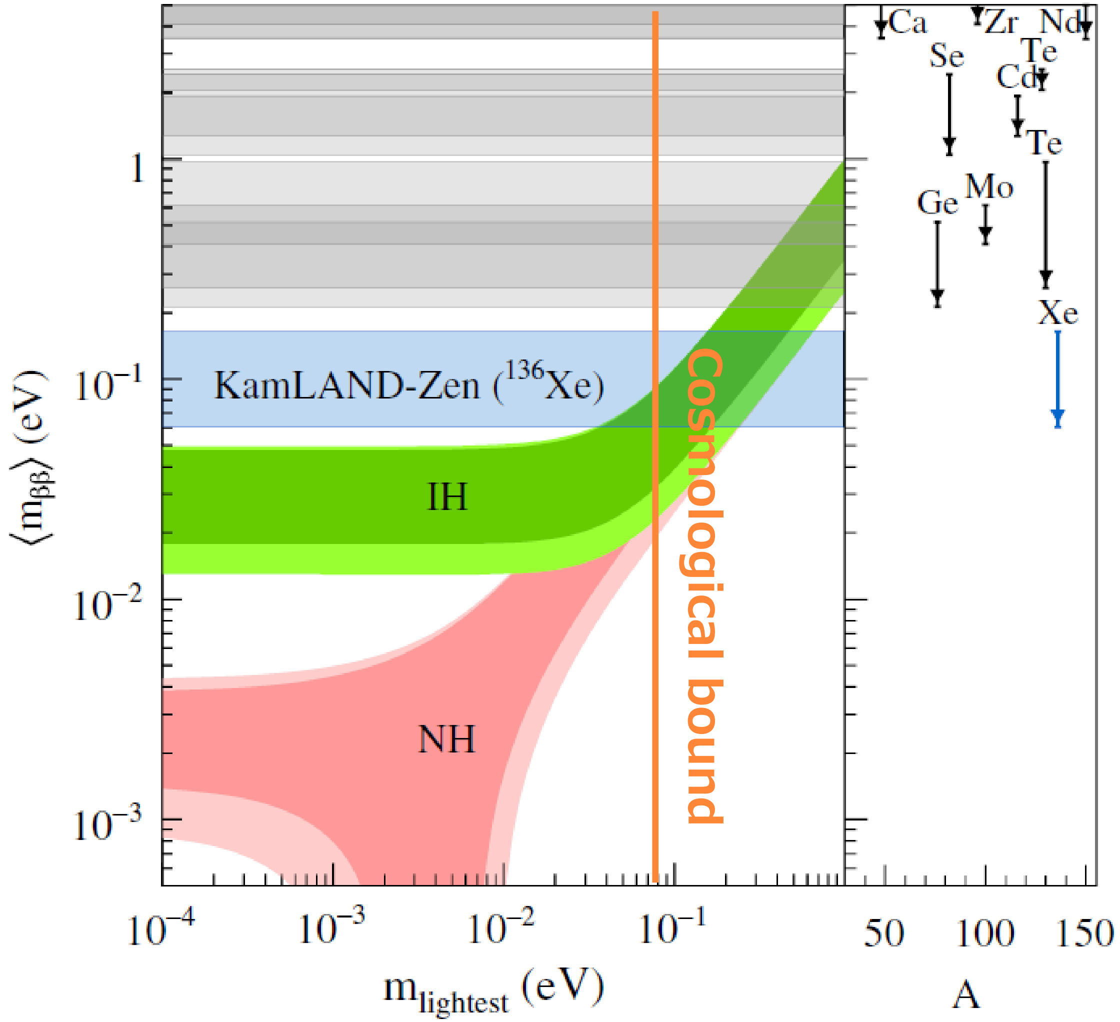
- PMNS mixing matrix $(\theta_{ij}, \delta, \alpha_{21}, \alpha_{31})$

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

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

Current status

$|m_{\mathrm{eff}}|$ [eV]



KamLAND-Zen PRL117, 082503 (‘16)

Predicted range of $|m_{\mathrm{eff}}^{\nu}|$
(for $m_{\mathrm{lightest}} = 0$)

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

KamLAND-Zen

$$|m_{\mathrm{eff}}| < (36 - 156)\mathrm{meV}$$

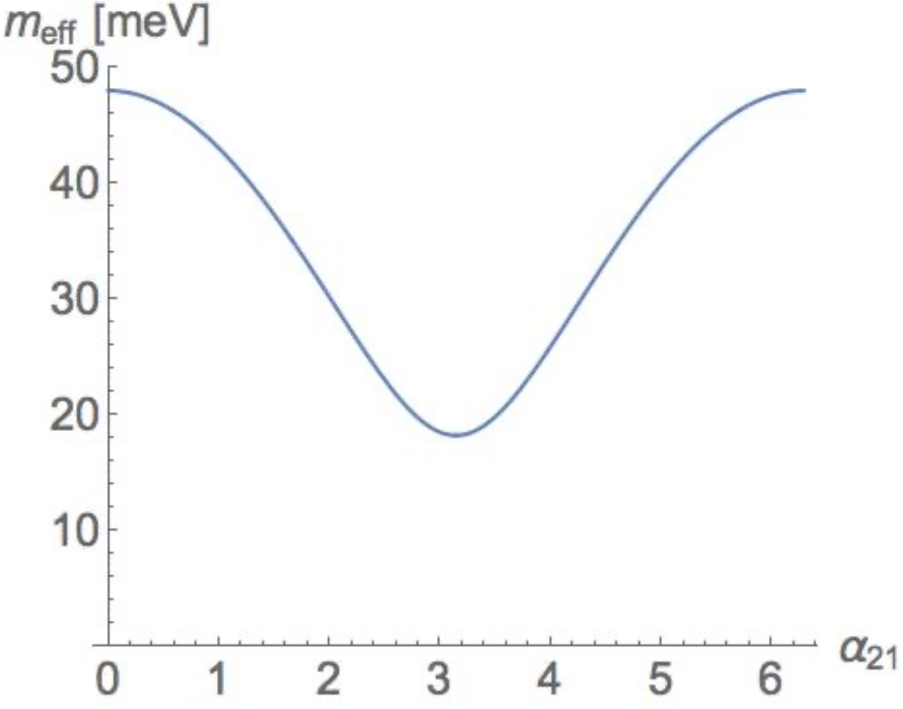
arXiv:2203.02139

0νββ decay and Majorana phase

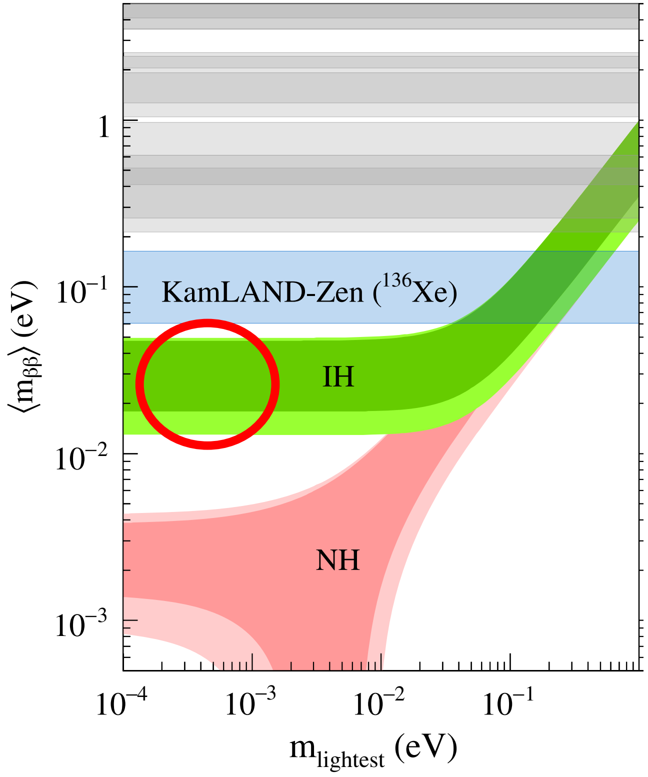
- IH case with $\boldsymbol{m_2 > m_1 \gg m_3}$

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

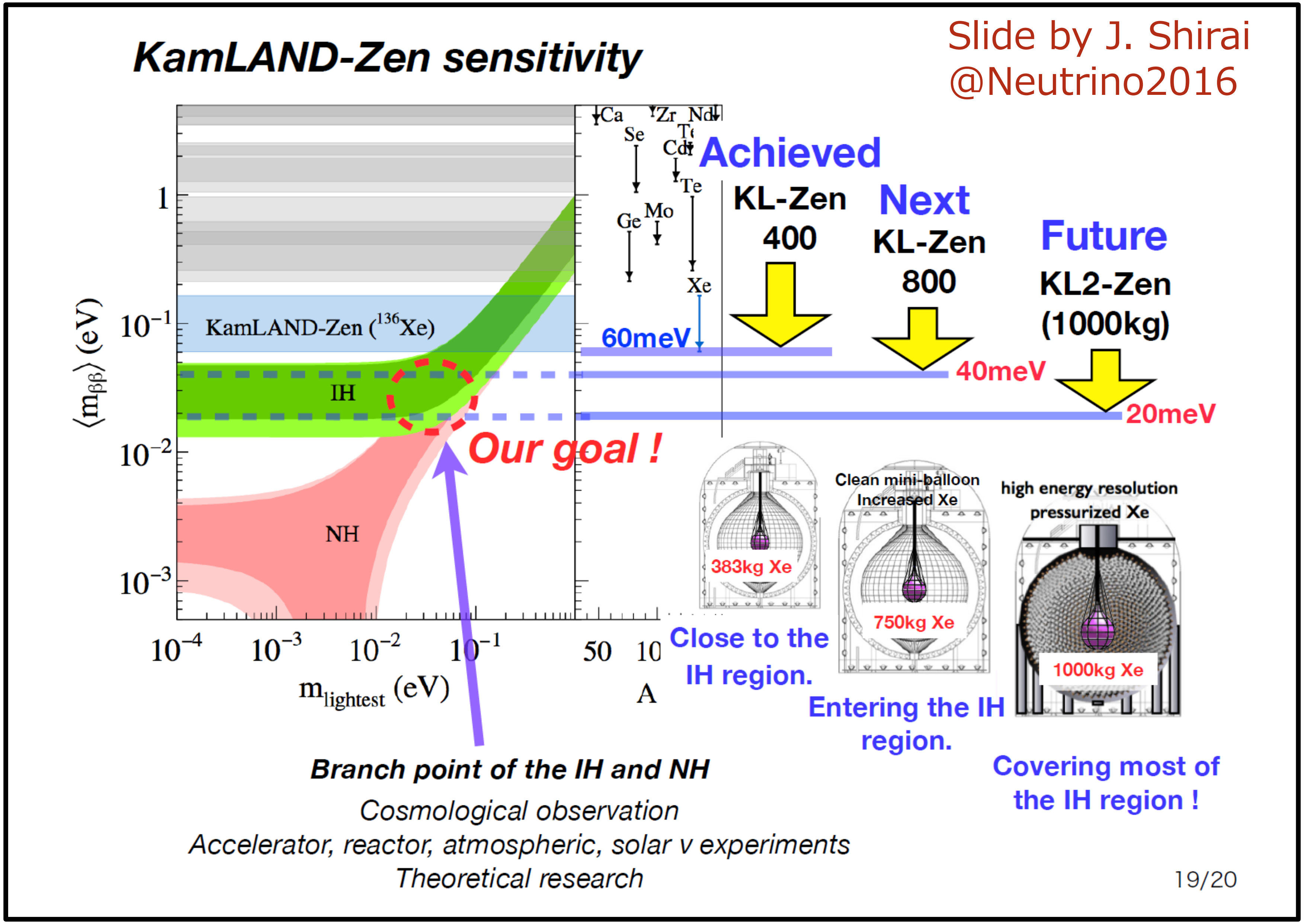
$m_{\rm eff}$ [meV]



Majorana phase α_{21}



Future prospects



KamLAND-Zen sensitivity

Slide by J. Shirai
@Neutrino2016

Achieved
KL-Zen 400

Next
KL-Zen 800

Future
KL2-Zen (1000kg)

Our goal !

Close to the IH region.

Entering the IH region.

Covering most of the IH region !

Branch point of the IH and NH

Cosmological observation
Accelerator, reactor, atmospheric, solar ν experiments
Theoretical research

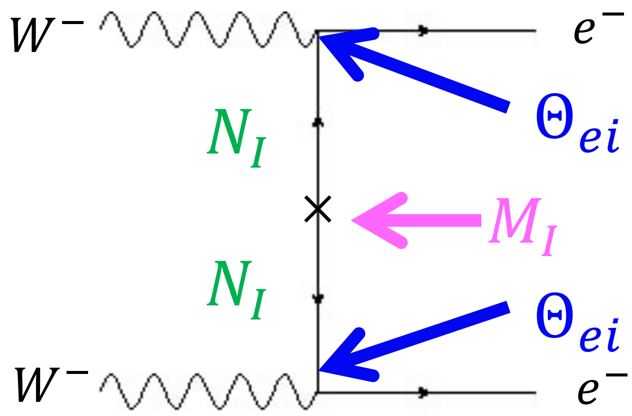
Neutrinoless double beta decays in the low-scale seesaw mechanism

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

$$m_{\text{eff}} = \underline{\sum_{i=1,2,3} m_i\, U_{ei}^2} \quad + \quad \underline{\underline{\sum_I f_\beta(M_I)\, M_I\ \Theta_{eI}^2}}$$

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

active neutrinos ν_{i}

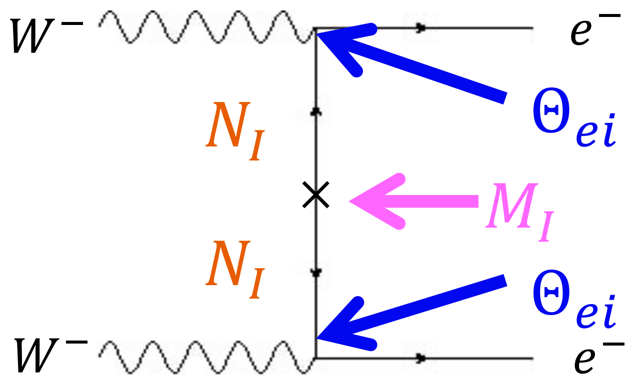
m_{eff}^{ν}

HNLs N_{I}

m_{eff}^{N}

- 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 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 ?
  - Masses and mixings of HNLs

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

$$m_{\mathrm{eff}} = m^{\nu}_{\mathrm{eff}} + \underset{\overset{\Uparrow}{N_1}}{f_\beta(M_1)\, M_1 \Theta^2_{e1}} + \underset{\overset{\Uparrow}{N_2}}{f_\beta(M_2)\, M_2 \Theta^2_{e2}}$$

What if NDBD will not be observed ?

HNL may hide NDBD ($M_1 \ll M_2$)

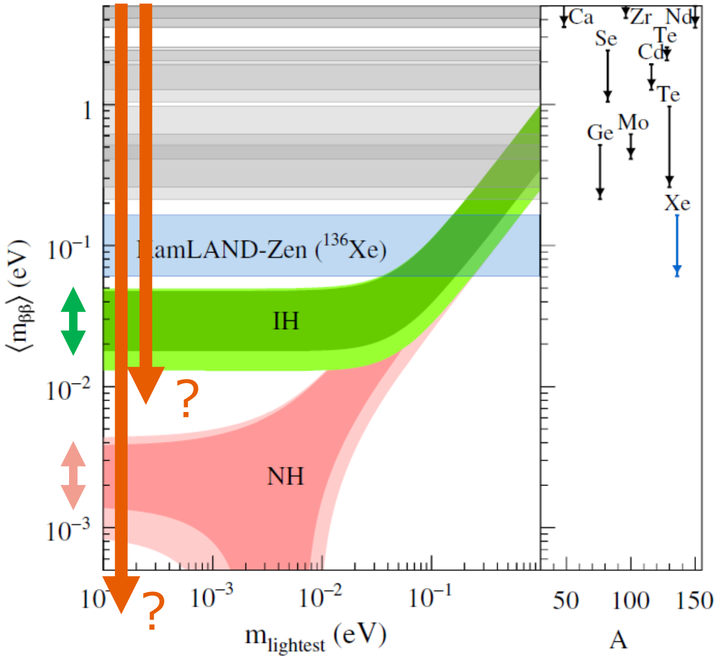
- Effective mass

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

  - $m_{\rm lightest} = 0$ 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)

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

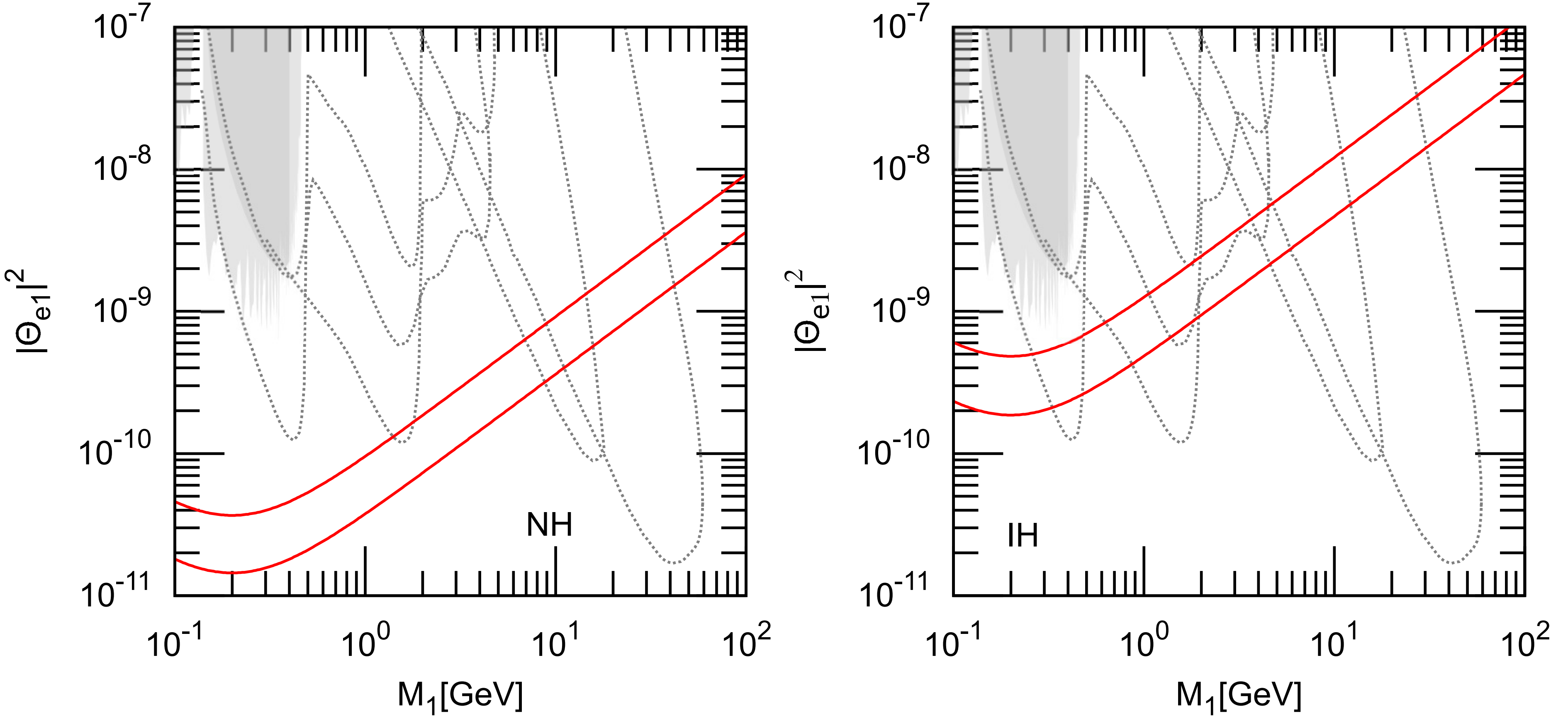
$\Longrightarrow$ NDBD is hidden by HNL contribution

What's happen ?

Consequence 1

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

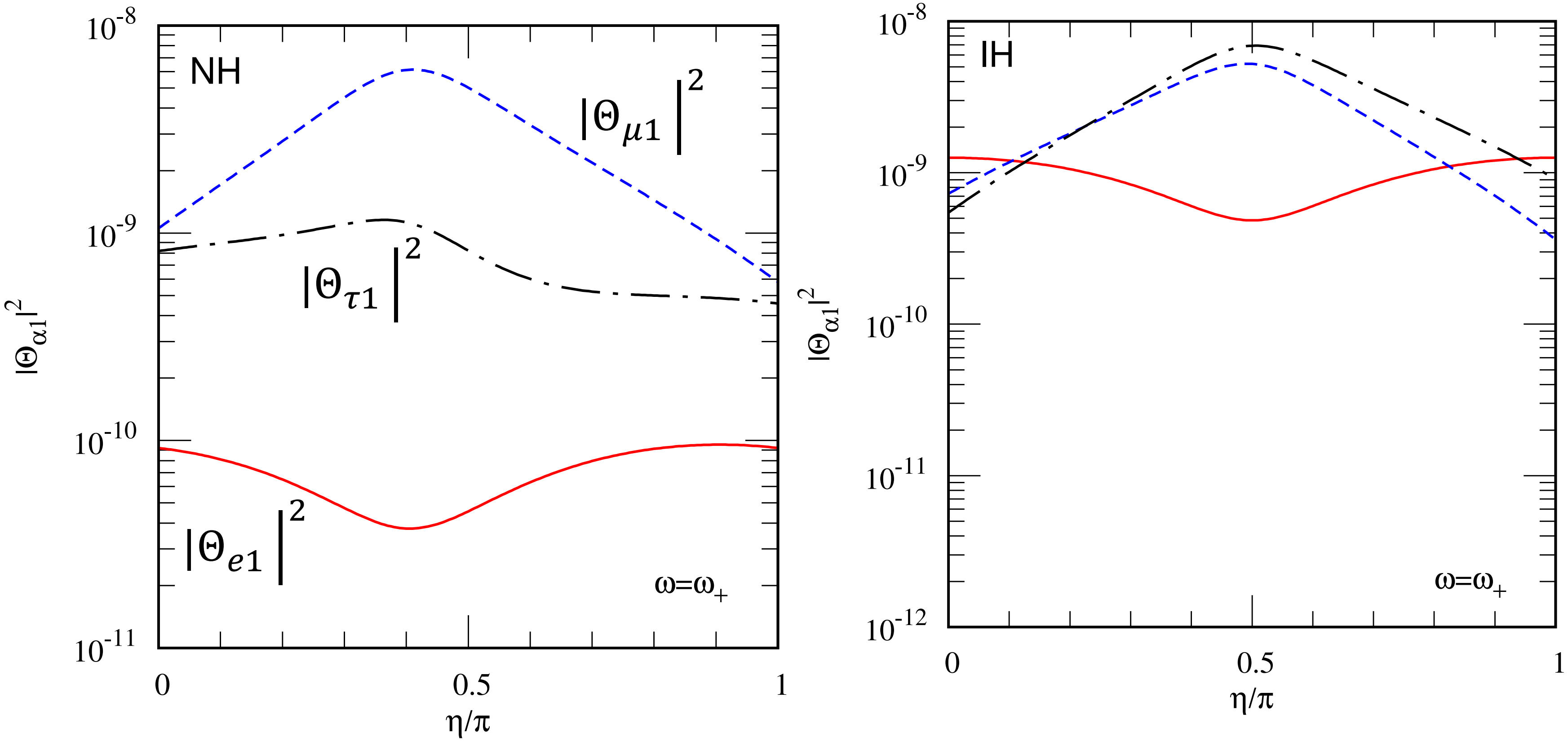
$$|\Theta_{e1}|^2 = \frac{|m_{\rm eff}^{\nu}|}{M_1 f_\beta(M_1)}$$



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



$M_1 = 1\ \mathrm{GeV}$

TA, Ishida, Tanaka arXiv:2012.13186

HNL may hide NDBD ($M_1 \simeq M_2$)

- When all heavy neutrinos are degenerate $M_1 = M_2 = M_N$,

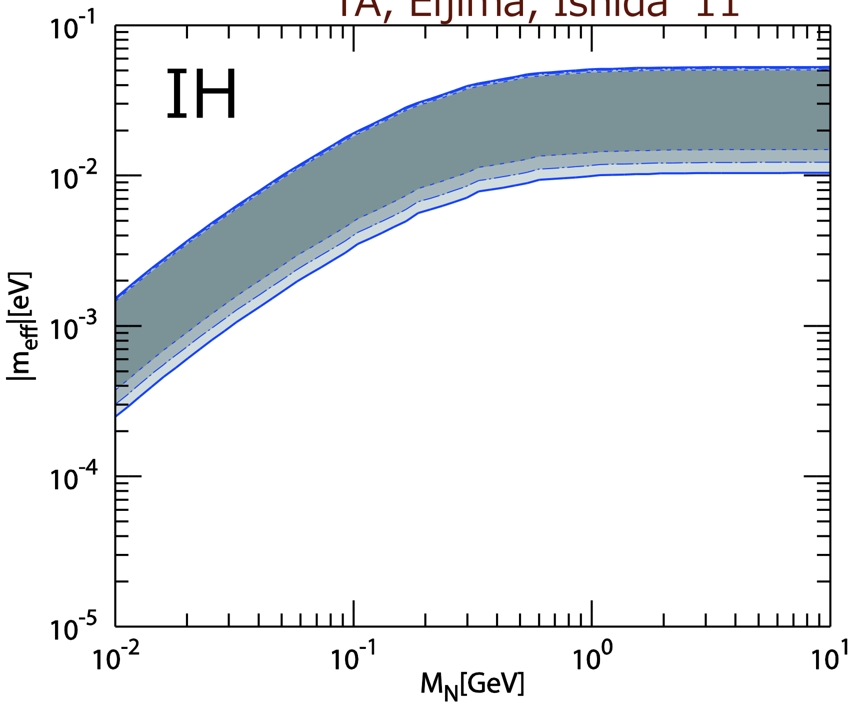
$$m_{\text{eff}} = m_{\text{eff}}^{\nu} + \sum_I f_\beta(M_I) M_I\, \Theta_{eI}^2 = m_{\text{eff}}^{\nu} + f_\beta(M_N) \underline{\sum_I M_N\, \Theta_{eI}^2}$$

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

- ☐ This shows m_{eff} does not depend on the mixing Θ_{eI}
- ☐ Heavy neutrinos give destructive contribution
- ☐ In this case, there is no bound on the mixing from $0\nu\beta\beta$ decay

→ $0\nu\beta\beta$ decay may be absent even if lepton number is violated in the seesaw mechanism

TA, Eijima, Ishida '11



Seesaw relation between mixings

- Neutrino mass matrix

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

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

Seesaw relation

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

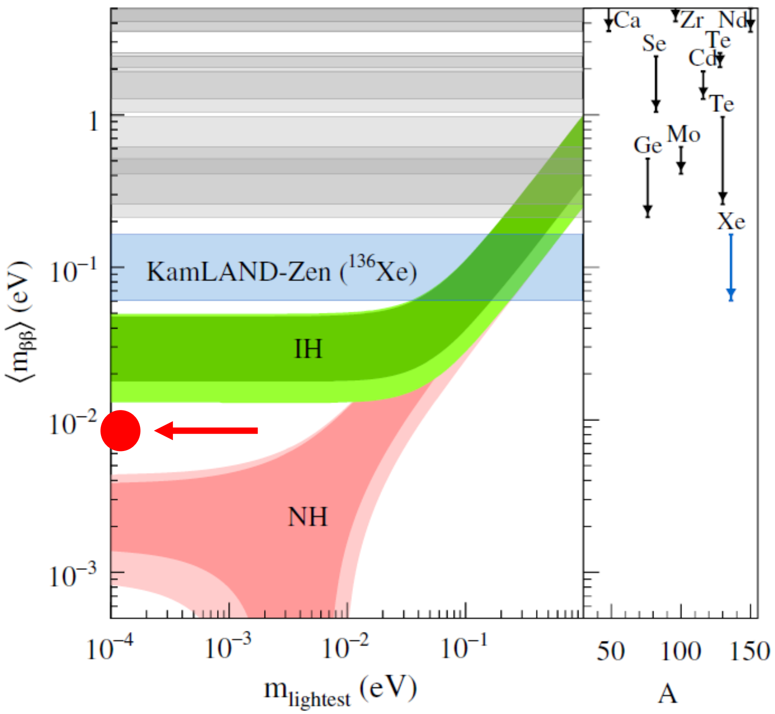
$$\underline{\boldsymbol{\alpha = \beta = e}}$$

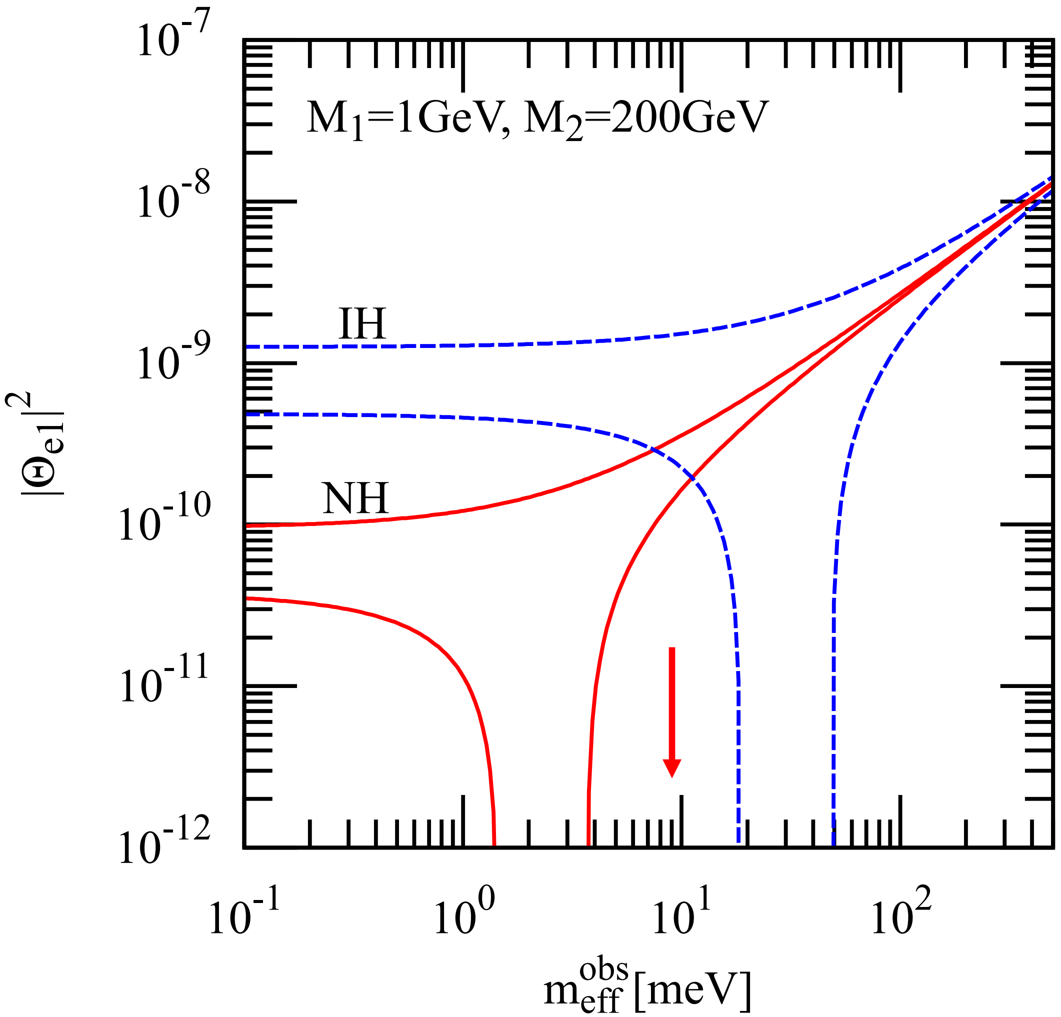
$$0 = \sum_i m_i U_{ei}^2 + \sum_I M_I\, \Theta_{eI}^2 = m_{\mathrm{eff}}^{\nu} + \sum_I M_I\, \Theta_{eI}^2$$

What if NDBD will be observed ?

Consequence (Hierarchical HNLs)

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



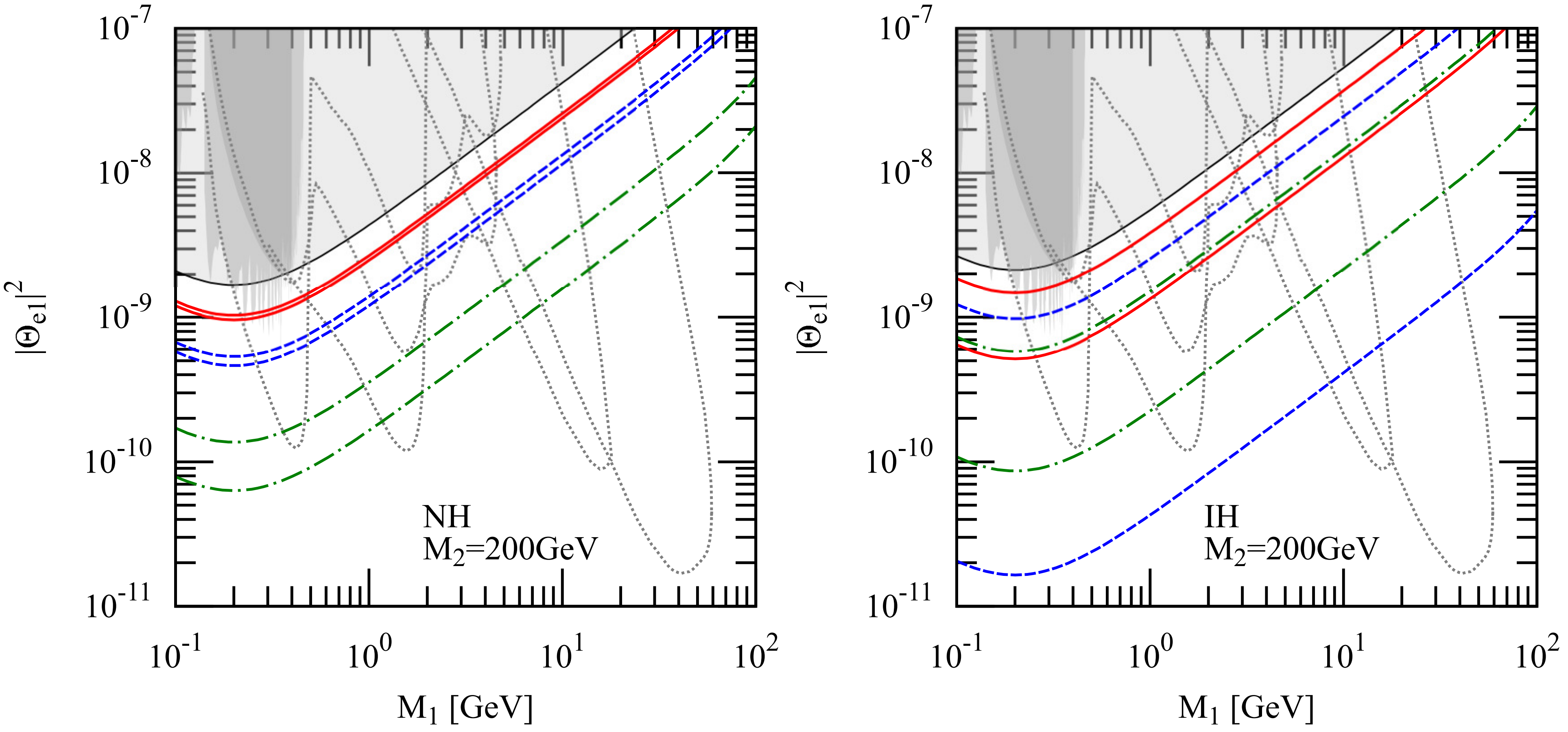


TA, Ishida, Tanaka arXiv:2101.12498

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

NDBD in different nuclei

- Effective mass
  - Active neutrino contribution

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

independent on decay nuclei

  - HNL contribution

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

dependent on decay nuclei !

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

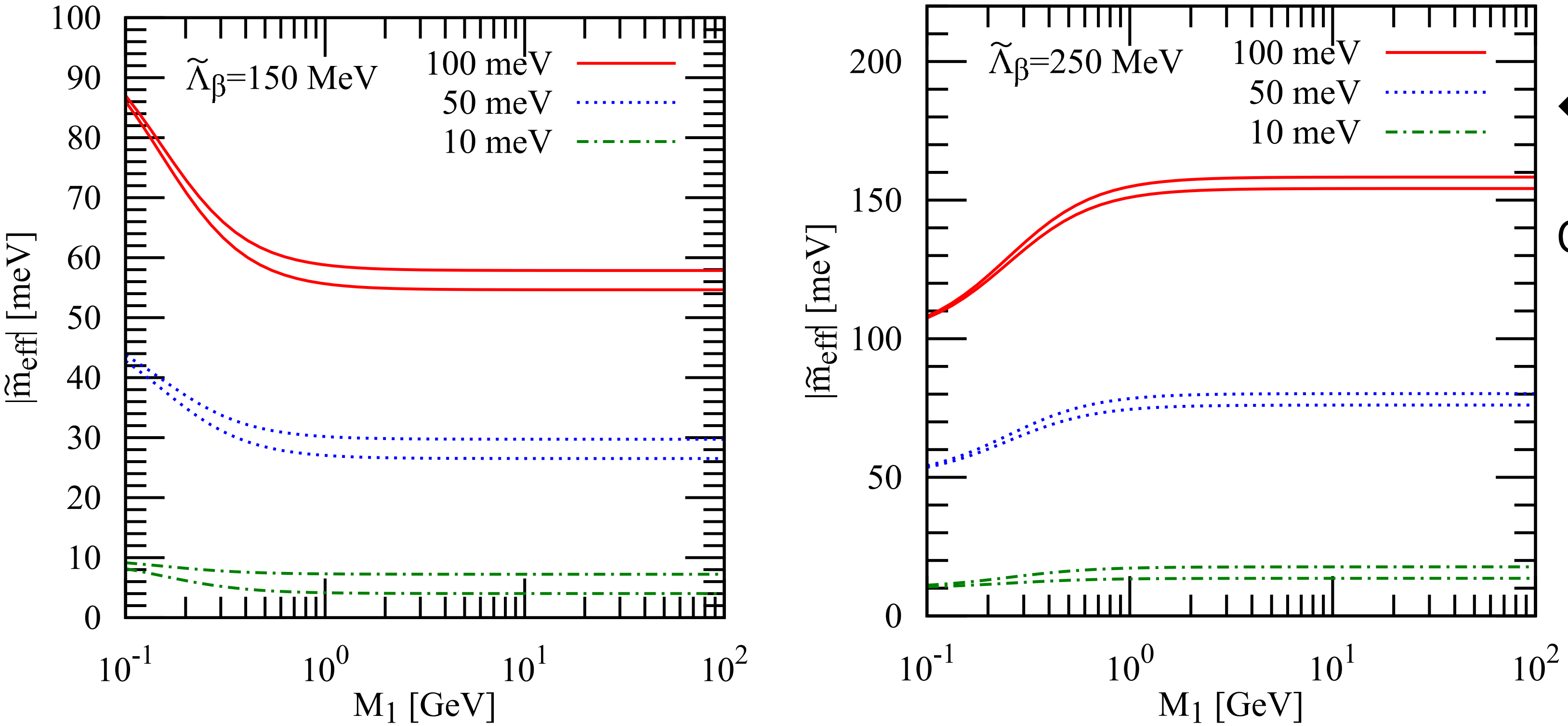
Multiple detection/non-detection by NDBD using different nuclei

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

Impact of different NDBD nuclei

- When NDBD would be observed for the nucleus $\Lambda_\beta = 200$ MeV

$M_2 = 200$ GeV



Observed $m_{\rm eff}$

TA, Ishida, Tanaka arXiv:2101.12498

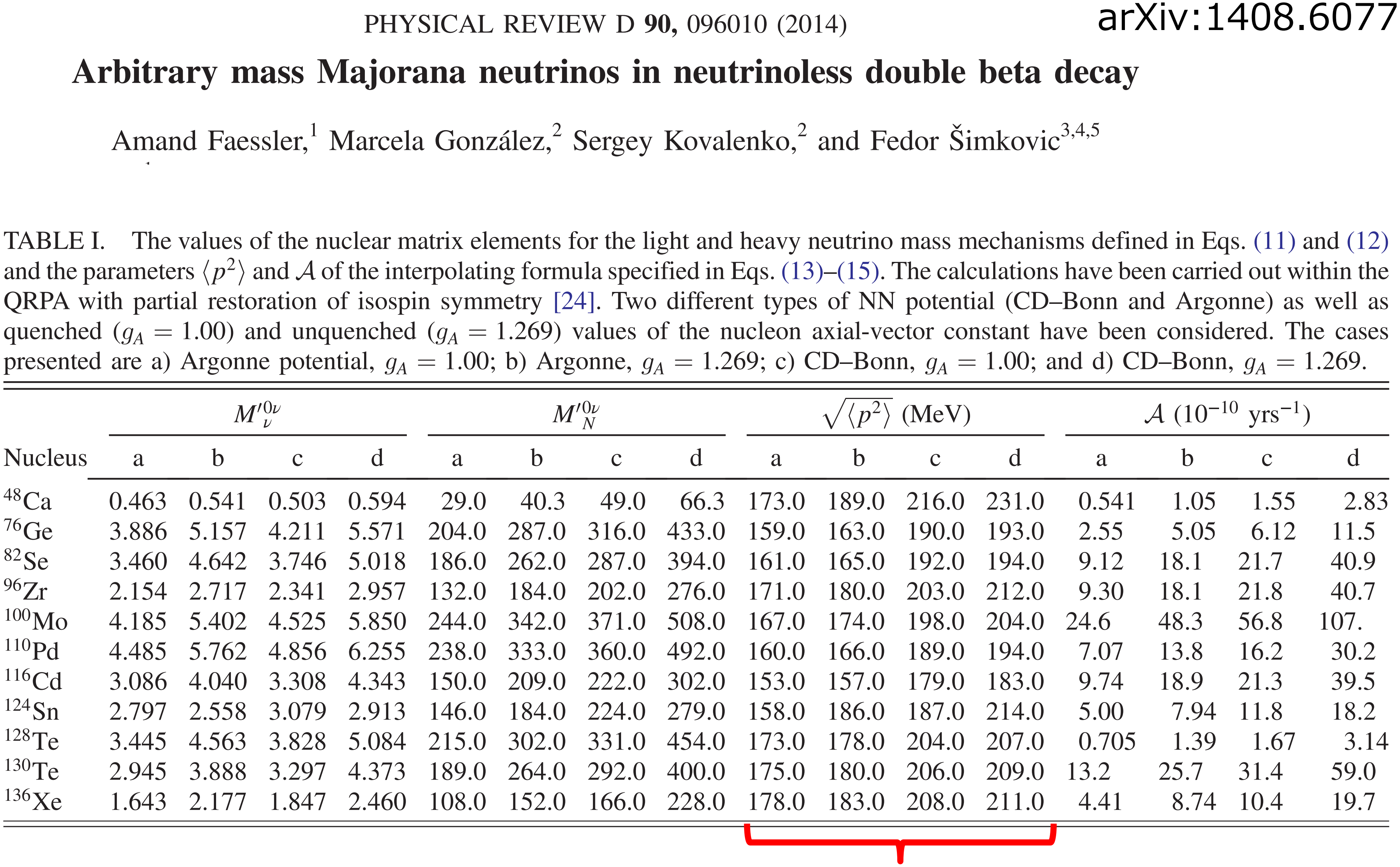
Summary

Summary

- Origin of neutrino masses is important for physics beyond SM
- SM with **RH neutrinos** are attractive scenarios
  - **Seesaw mechanism** for very small neutrino masses
  - RH neutrinos (HNLs)
    - **Baryon Asymmetry of the Universe (BAU)**
    - Various scenarios depending on masses (Leptogenesis, Resonant Leptogenesis, Baryogenesis via oscillations
- **Neutrinoless double beta decays**
  - Light RH neutrinos may give a significant, constructive or destructive contribution
  - Multiple detections/non-detections by NDBD using different nuclei are crucial to reveal the properties of HNLs in the seesaw mechanism

BACKUP

arXiv:1408.6077



PHYSICAL REVIEW D **90,** 096010 (2014)

Arbitrary mass Majorana neutrinos in neutrinoless double beta decay

Amand Faessler,[1] Marcela González,[2] Sergey Kovalenko,[2] and Fedor Šimkovic[3,4,5]

TABLE I. The values of the nuclear matrix elements for the light and heavy neutrino mass mechanisms defined in Eqs. (11) and (12) and the parameters $\langle p^2 \rangle$ and $\mathcal{A}$ of the interpolating formula specified in Eqs. (13)–(15). The calculations have been carried out within the QRPA with partial restoration of isospin symmetry [24]. Two different types of NN potential (CD–Bonn and Argonne) as well as quenched ($g_A = 1.00$) and unquenched ($g_A = 1.269$) values of the nucleon axial-vector constant have been considered. The cases presented are a) Argonne potential, $g_A = 1.00$; b) Argonne, $g_A = 1.269$; c) CD–Bonn, $g_A = 1.00$; and d) CD–Bonn, $g_A = 1.269$.

	$M'^{0\nu}_{\nu}$				$M'^{0\nu}_{N}$				$\sqrt{\langle p^2 \rangle}$ (MeV)				$\mathcal{A}$ (10^{-10} yrs^{-1})			
Nucleus	a	b	c	d	a	b	c	d	a	b	c	d	a	b	c	d
^{48}Ca	0.463	0.541	0.503	0.594	29.0	40.3	49.0	66.3	173.0	189.0	216.0	231.0	0.541	1.05	1.55	2.83
^{76}Ge	3.886	5.157	4.211	5.571	204.0	287.0	316.0	433.0	159.0	163.0	190.0	193.0	2.55	5.05	6.12	11.5
^{82}Se	3.460	4.642	3.746	5.018	186.0	262.0	287.0	394.0	161.0	165.0	192.0	194.0	9.12	18.1	21.7	40.9
^{96}Zr	2.154	2.717	2.341	2.957	132.0	184.0	202.0	276.0	171.0	180.0	203.0	212.0	9.30	18.1	21.8	40.7
^{100}Mo	4.185	5.402	4.525	5.850	244.0	342.0	371.0	508.0	167.0	174.0	198.0	204.0	24.6	48.3	56.8	107.
^{110}Pd	4.485	5.762	4.856	6.255	238.0	333.0	360.0	492.0	160.0	166.0	189.0	194.0	7.07	13.8	16.2	30.2
^{116}Cd	3.086	4.040	3.308	4.343	150.0	209.0	222.0	302.0	153.0	157.0	179.0	183.0	9.74	18.9	21.3	39.5
^{124}Sn	2.797	2.558	3.079	2.913	146.0	184.0	224.0	279.0	158.0	186.0	187.0	214.0	5.00	7.94	11.8	18.2
^{128}Te	3.445	4.563	3.828	5.084	215.0	302.0	331.0	454.0	173.0	178.0	204.0	207.0	0.705	1.39	1.67	3.14
^{130}Te	2.945	3.888	3.297	4.373	189.0	264.0	292.0	400.0	175.0	180.0	206.0	209.0	13.2	25.7	31.4	59.0
^{136}Xe	1.643	2.177	1.847	2.460	108.0	152.0	166.0	228.0	178.0	183.0	208.0	211.0	4.41	8.74	10.4	19.7

Baryogenesis region

Klaric, Shaposhnikov, Timiryasov arXiv:2103.16545