Lepton number violations in the seesaw mechanism

Takehiko Asaka (Niigata University)

松江素粒子物理学研究会
（2016/03/25~27）

In collaboration with

Hiroyuki Ishida (Shimane University)
Shintaro Eijima (EPFL)
Takanao Tsuyuki (Niigata University)

Contents of my talk

- Introduction
  - Motivations for the seesaw mechanism

- Lepton number violations in the seesaw mechanism
  - $0\nu\beta\beta$ decay (neutrinoless double beta decay)
  - $\mathrm{i}0\nu\beta\beta$ decay (inverse neutrinoless double beta decay)

- Summary

Introduction

Origin of neutrino masses

- Neutrino mass scales
  - Atmospheric: $\Delta m^2_{\rm atm} \simeq 2.4 \times 10^{-3} {\rm eV}^2$
  - Solar : $\Delta m^2_{\rm sol} \simeq 7.5 \times 10^{-5} {\rm eV}^2$

$\Rightarrow$ **Clear signal for new physics beyond the SM !**

- In this talk, we consider

the canonical seesaw mechanism
by right-handed neutrinos !

$$\nu_R$$

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

Why the seesaw mechanism ?

- ⋯, because

attractive !

Why the seesaw mechanism ?

- Chiral structure of fermions in the SM

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

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

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

SM with right-handed neutrinos

$$\delta L = i\overline{\nu_R}\partial_\mu\gamma^\mu\nu_R - F\,\overline{L}\,\nu_R\Phi - \frac{M_M}{2}\overline{\nu_R}\nu_R^c + \text{h.c.}$$

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

- Seesaw mechanism ($M_D = F\langle\Phi\rangle \ll M_M$)

$$-L = \frac{1}{2}(\overline{\nu_L}, \overline{\nu_R^c})\begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c = \frac{1}{2}(\overline{\nu}, \overline{N^c})\begin{pmatrix} M_\nu & 0 \\ 0 & M_M \end{pmatrix}\begin{pmatrix} \nu^c \\ N \end{pmatrix} + h.c.$$

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

$$U^T M_\nu U = diag(m_1, m_2, m_3)$$

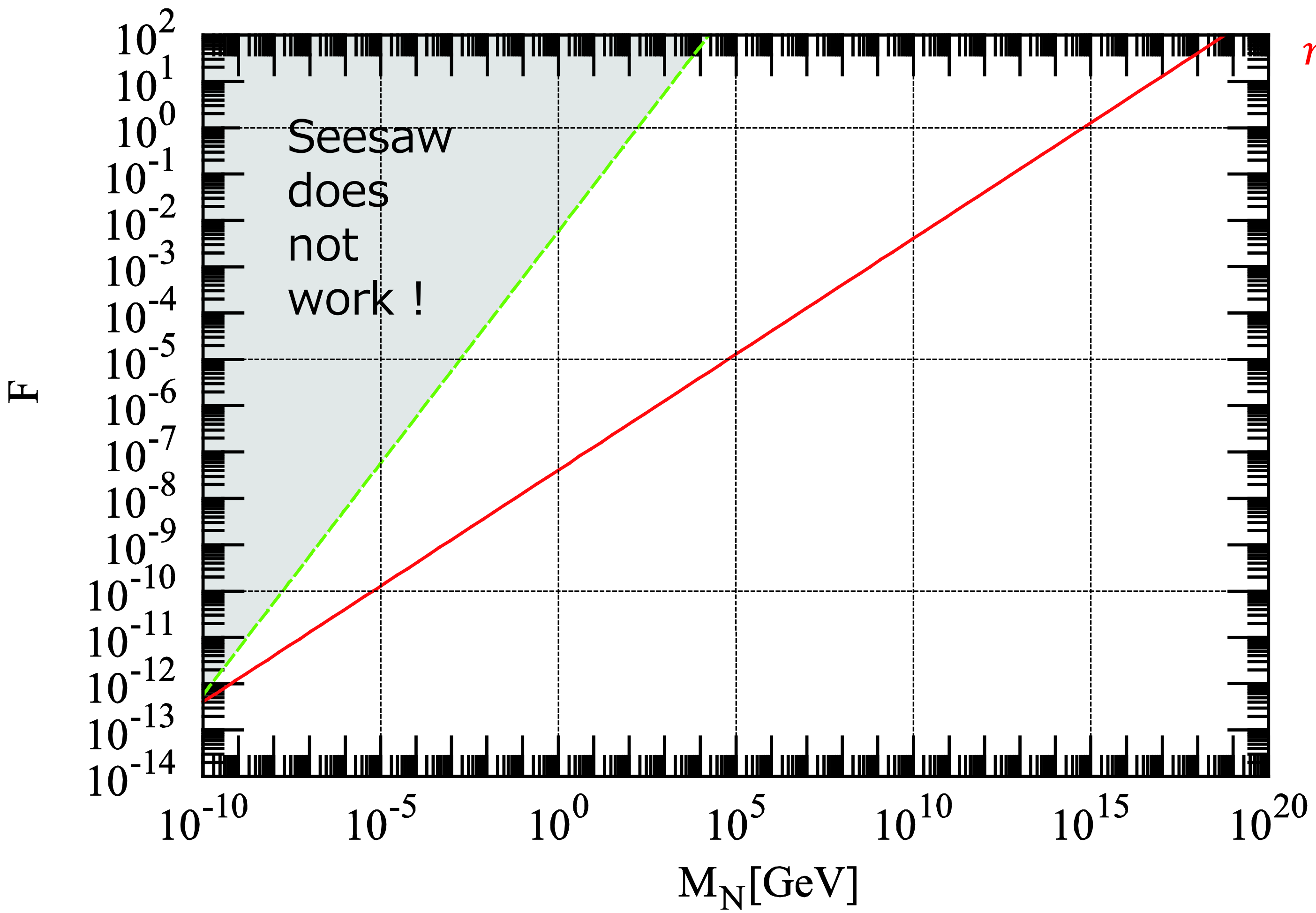
- **Light active neutrinos ν**
  - → explain neutrino oscillations
- **Heavy neutral leptons N** ($N \simeq \nu_R$)
  - Mass M_M
  - Mixing $\Theta = M_D / M_M$

mixing in CC current $\nu_L = U\,\nu + \Theta\,N^c$

Yukawa Coupling and Mass of HNL

$$F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle}$$

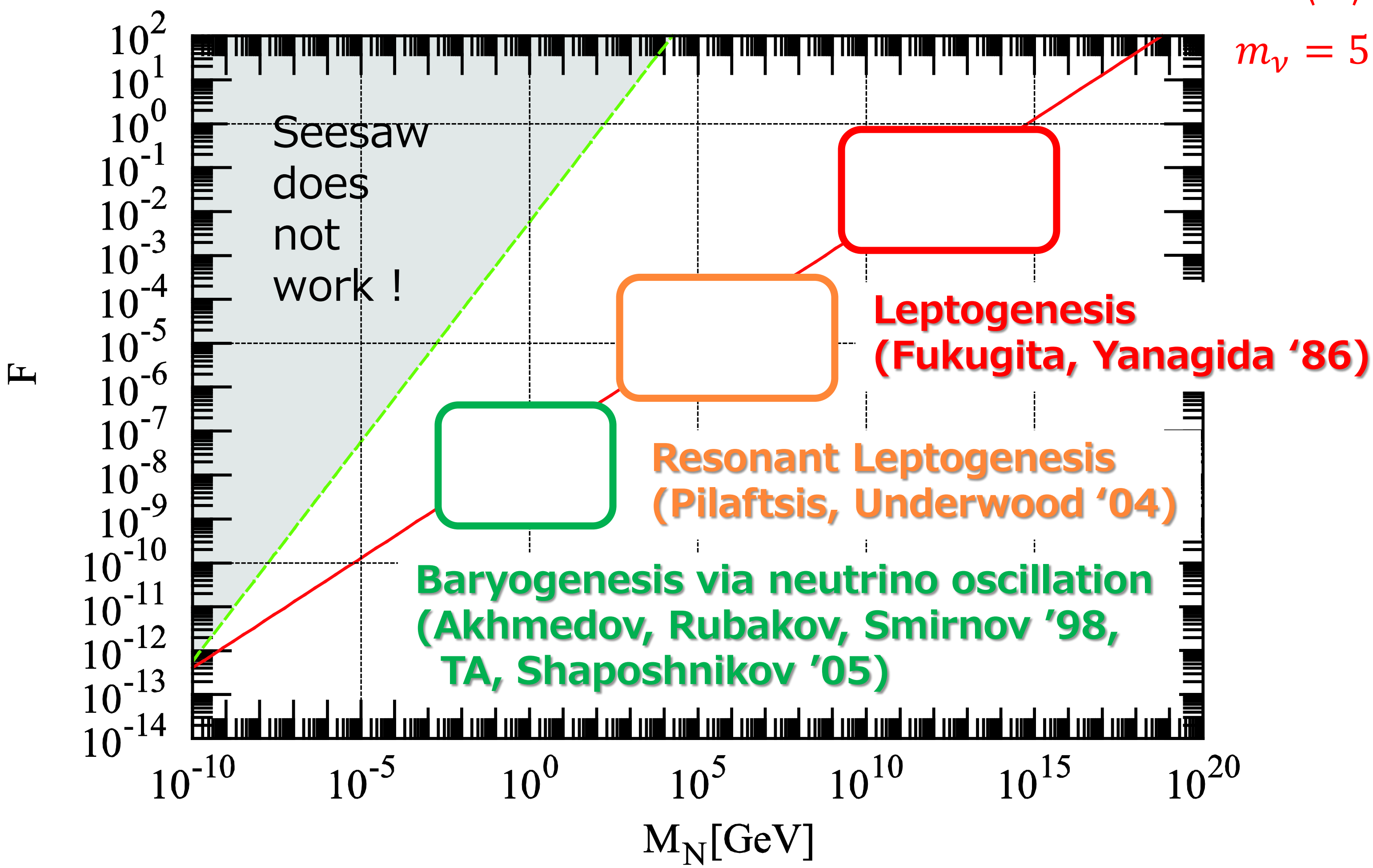
$m_\nu = 5 \times 10^{-11}$ GeV



Yukawa Coupling and Mass of HNL

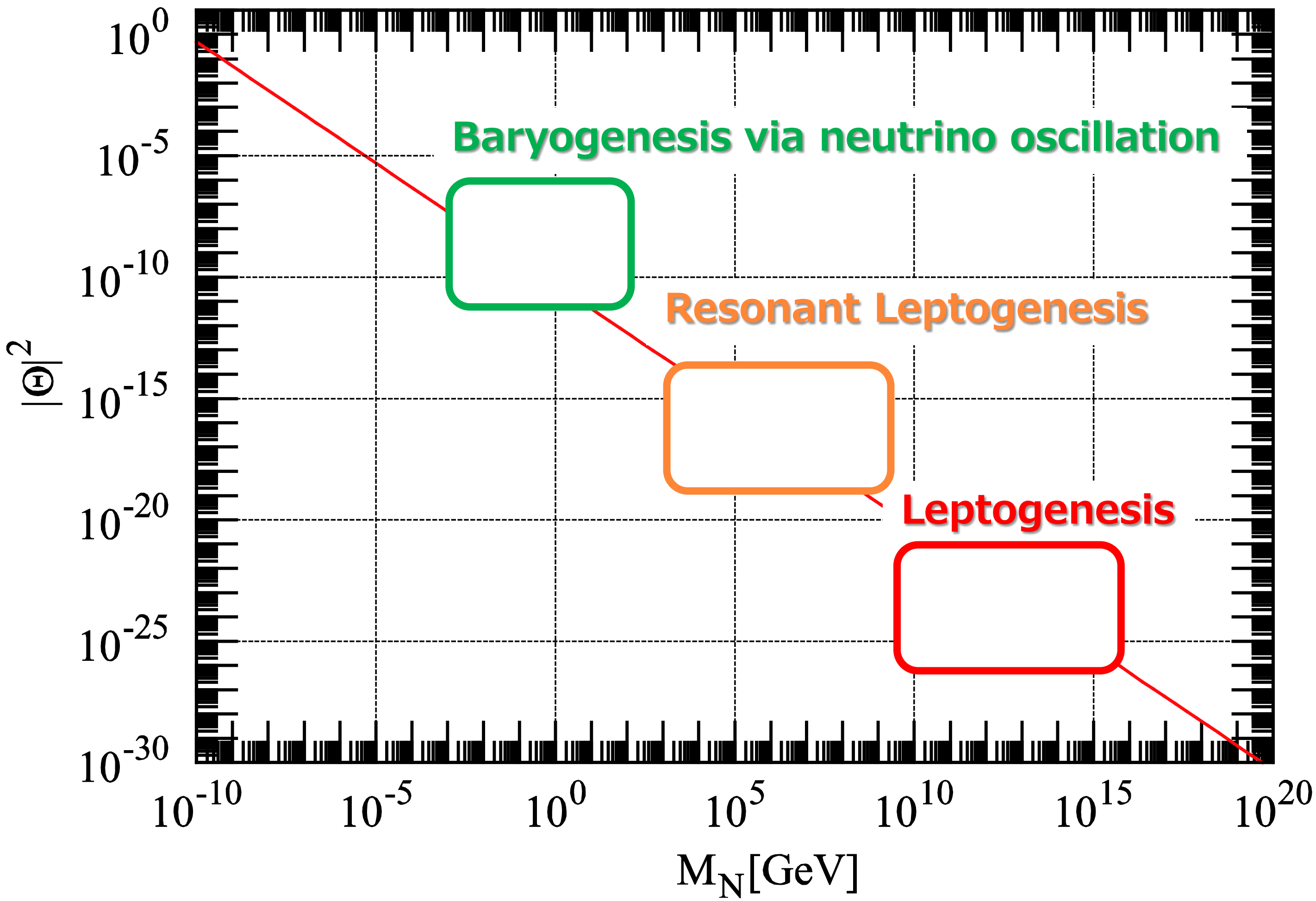
$$F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle}$$

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



Mixing and Mass of HNL

$$|\Theta|^2 = \frac{M_D^2}{M_N^2} = \frac{m_\nu}{M_N} \qquad m_\nu = 5 \times 10^{-11}\ \mathrm{GeV}$$



Motivation of this talk

- How to test the seesaw mechanism?

Lepton number violation

$$\delta L = i\overline{\nu_R}\partial_\mu \gamma^\mu \nu_R - F\,\overline{L}\,\nu_R \Phi - \frac{M_M}{2}\overline{\nu_R}\nu_R^c + \text{h.c.}$$

- Majorana masses break lepton number by two units

  ⮡ clear signals for beyond the Standard Model

- $0\nu\beta\beta$ decay (neutrinoless double beta decay)
- $i0\nu\beta\beta$ decay (inverse neutrinoless double beta decay)

$0\nu\beta\beta$ decay

neutrinoless double beta decay

Neutrinoless double beta ($0\nu\beta\beta$) decay

W.H. Furry 1939

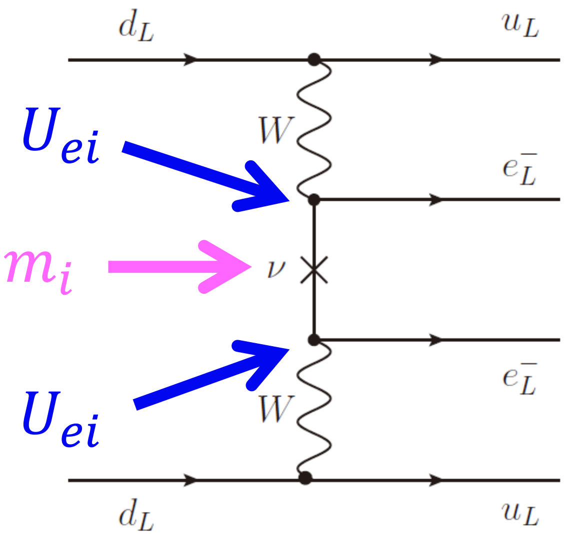
- Neutrinoless double beta ($0\nu\beta\beta$) decay

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

  - LNV ($\Delta L = +2$) process mediated by Majorana massive neutrinos

  - Rate of $0\nu\beta\beta$ decay

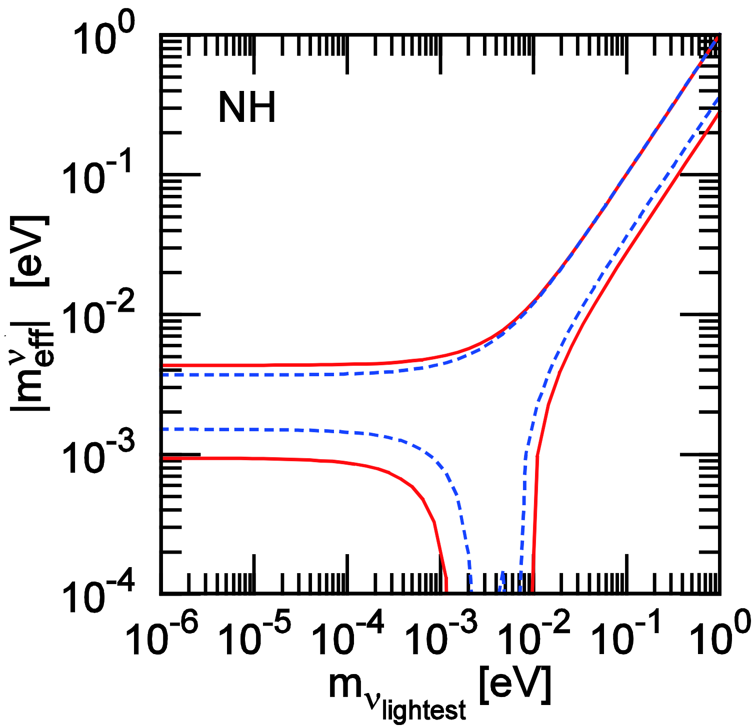
    $\Gamma \propto |m_{\rm eff}|^2$

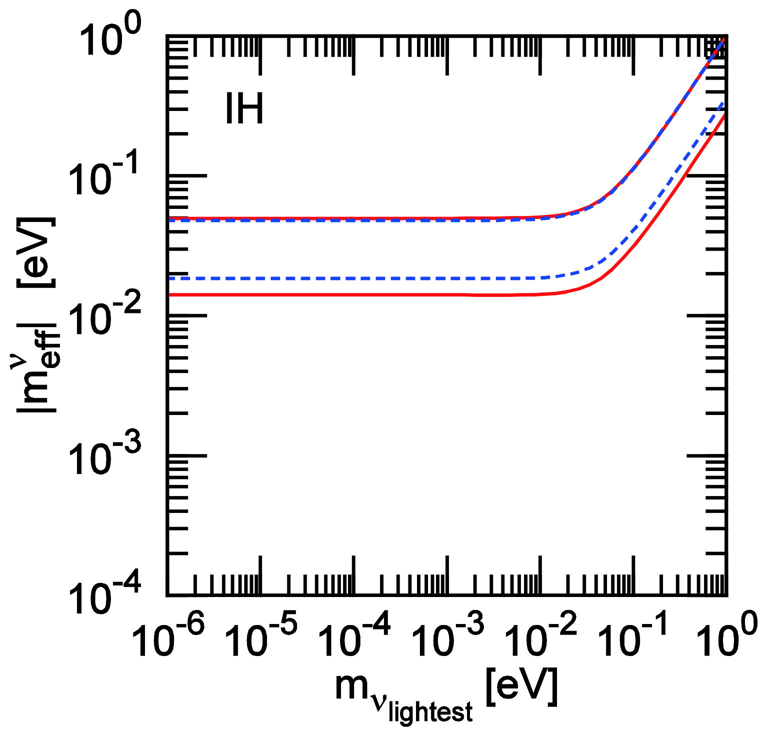


Effective neutrino mass

$$m_{\rm eff}^{\nu} = \sum_{i=1,2,3} m_i \, U_{ei}^2$$

$0\nu\beta\beta$ decay





$m_{\text{eff}} \lesssim (0.185 - 0.276)$ eV

KamLAND-Zen 1211.3863 ^{136}Xe

$m_{\text{eff}} \lesssim (0.213 - 0.308)$ eV

GERDA 1307.4720 ^{76}Ge

→ $m_{\text{eff}} \sim 0.02$ eV in 5yrs (KamLAND-Zen)

Very interesting !!

Planck 2015

$\Sigma\, m_i < 0.23$ eV

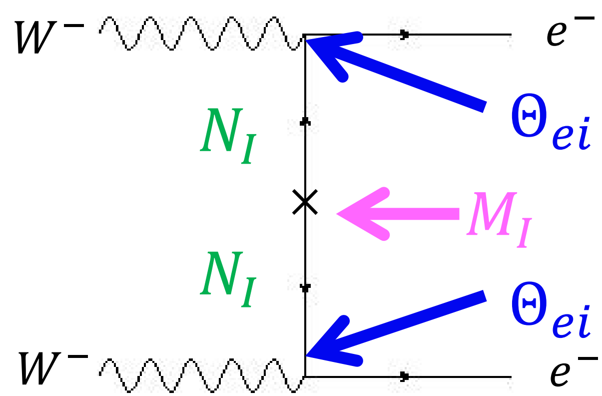
$m_{\nu\text{lighest}} < 0.07\ (0.06)$ eV

$0\nu\beta\beta$ decay in the seesaw

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

- HNLs may give a significant contribution to $m_{\rm eff}$!

$$m_{eff}^N = \begin{cases} M_I\, \Theta_{eI}^2 & (M_I^2 \ll \langle p \rangle^2) \\ \dfrac{\langle p \rangle^2}{M_I}\Theta_{eI}^2 & (M_I^2 \gg \langle p \rangle^2) \end{cases}$$



$$f_\beta(M_I) = \frac{\langle p \rangle^2}{\langle p \rangle^2 + M_I^2}$$

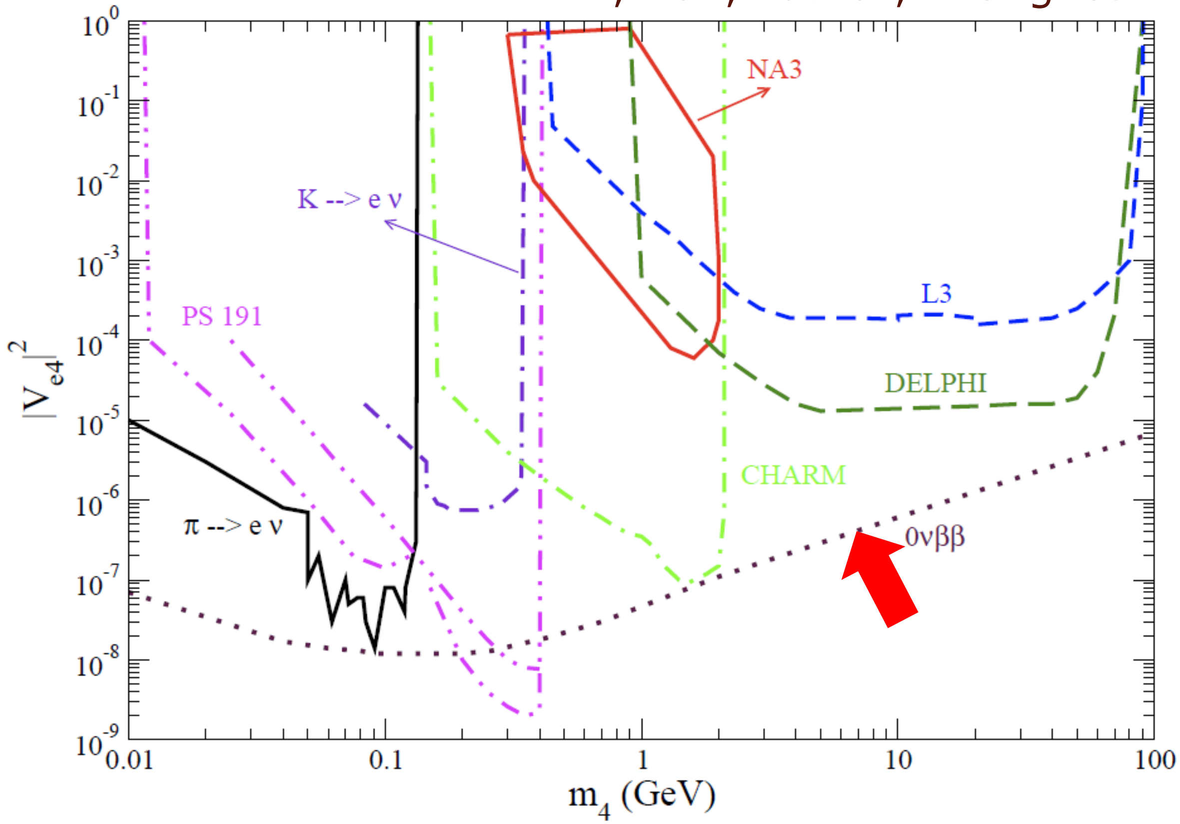
$$\sqrt{\langle p^2 \rangle} \sim 200\ \text{MeV}$$

Faessler, Gonzalez, Kovalenko, Simkovic '14

$0\nu\beta\beta$ decay in the seesaw

- Stringent constraint on the mixing:

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

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

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

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

$0\nu\beta\beta$ decay in the seesaw

- When all HNLs are degenerate $M_I = M_N$,

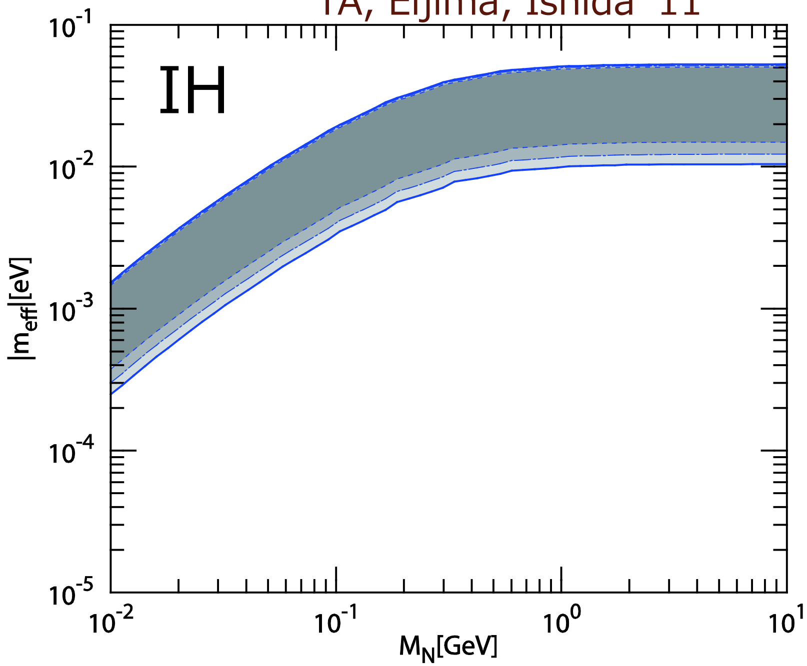
$$m_{\rm eff} = m_{\rm eff}^{\nu} + \sum_I f_\beta(M_I) M_I\, \Theta_{eI}^2 = m_{\rm eff}^{\nu} + f_\beta(M_N) \sum_I M_N\, \Theta_{eI}^2$$

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

- This shows $0\nu\beta\beta$ decay does not depend on the mixing of HNL
- 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

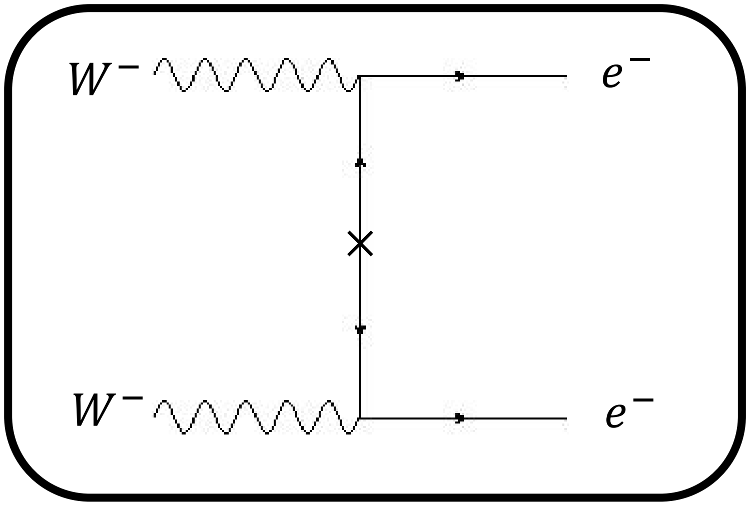


i$0\nu\beta\beta$ decay

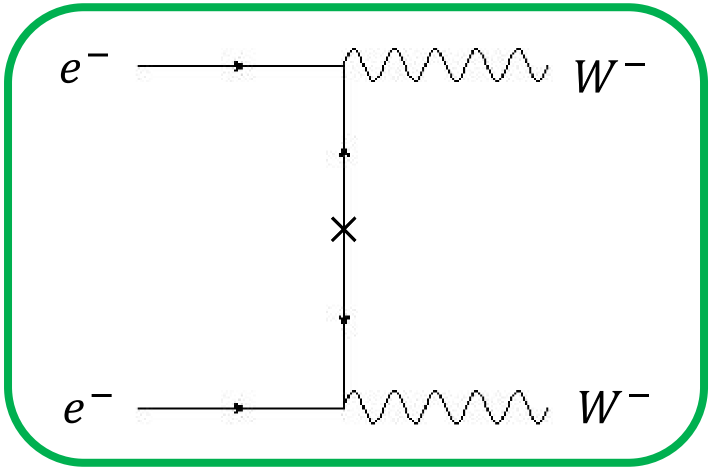
"inverse" neutrinoless double beta decay

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

$0\nu\beta\beta$ decay



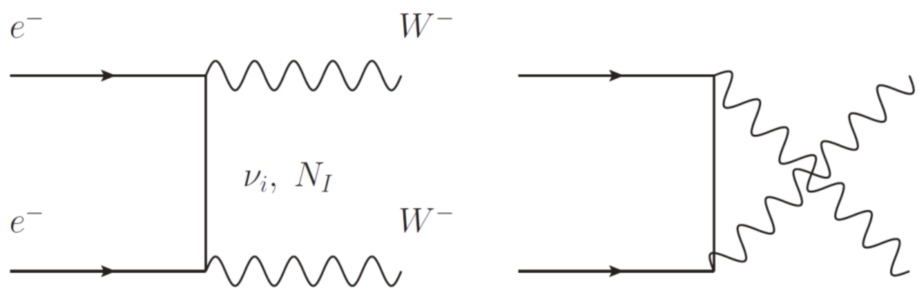
Inverse $0\nu\beta\beta$ decay



Inverse neutrinoless double beta ($i0\nu\beta\beta$) decay

- $e^-e^- \to W^-W^-$ offers test for LNV

[T. G. Rizzo 1982]



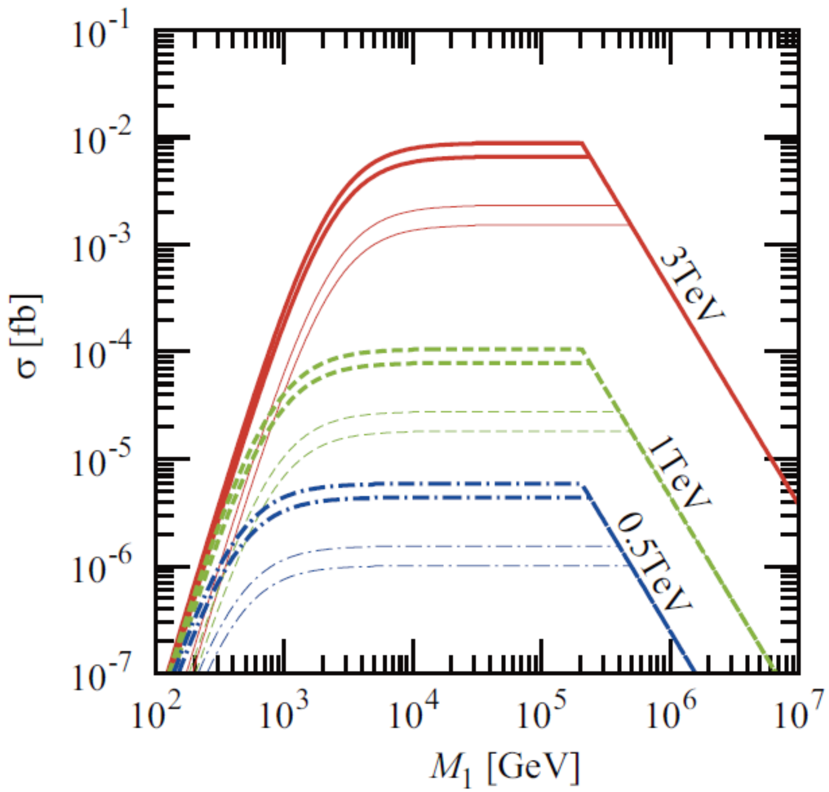
- e^-e^- collision is option of ILC, CLIC
- Advantages over $0\nu\beta\beta$ decay
  - Signal is clean
  - Free from uncertainty in nuclear matrix elements
  - Can occur even if $0\nu\beta\beta$ decay is absent

→ Inverse $0\nu\beta\beta$ decay and $0\nu\beta\beta$ decay are complementary tests for LNV in the seesaw mechanism

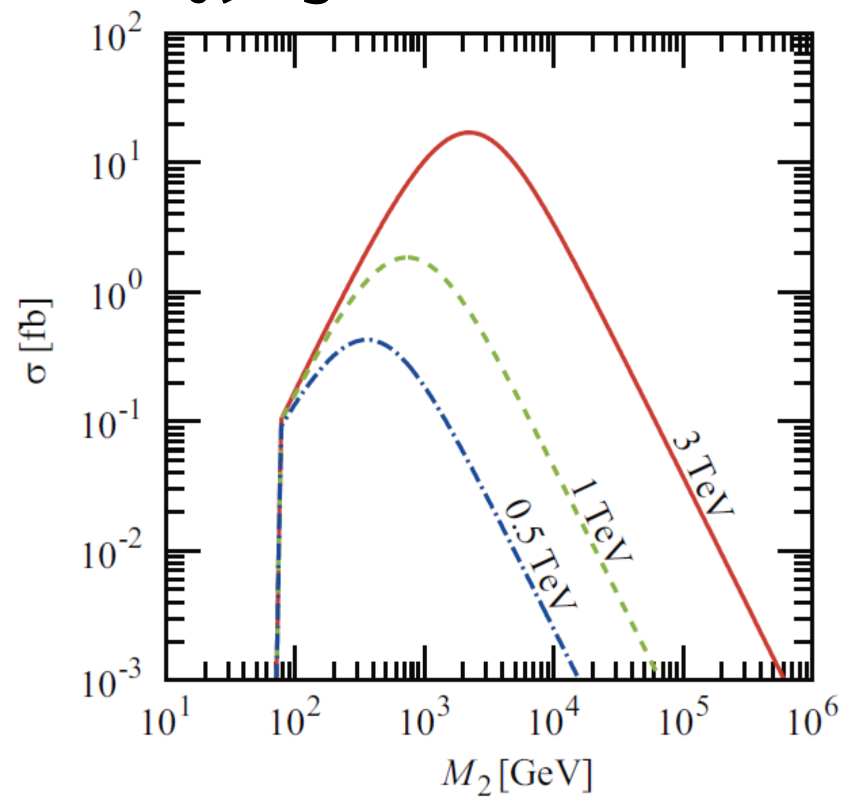
Inverse $0\nu\beta\beta$ decay in the seesaw

- Maximal cross section of $e^- e^- \to W^- W^-$ TA, Tsuyuki '15

$\mathcal{N}=2$



$\mathcal{N}=3$



Inverse $0\nu\beta\beta$ decay in the seesaw

- How obtain large cross section ? --- idea

$0\nu\beta\beta$ decay

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

$$m_{\rm eff} \sim \Theta_{e2}^2 \frac{\langle p^2 \rangle}{M_2} \gg m_{\rm eff}^{\rm OBS}$$

inconsistent !

$$0 \simeq \Theta_{e1}^2 \frac{\langle p^2 \rangle}{M_1} + \Theta_{e2}^2 \frac{\langle p^2 \rangle}{M_2}$$

N_2

$M_2 = 1\mathrm{TeV}$

$|\Theta_{e2}|^2 = 10^{-3}$

Seesaw relation

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

$$M_2 |\Theta_{e2}|^2 \gg |m_{\rm eff}^{\nu}|$$

cannot satisfy!

$$0 \simeq \Theta_{e2}^2 M_2 + \Theta_{e3}^2 M_3$$

N_1

$M_1 \ll M_2$

$|\Theta_{e1}|^2 \ll |\Theta_{e2}|^2$

N_3

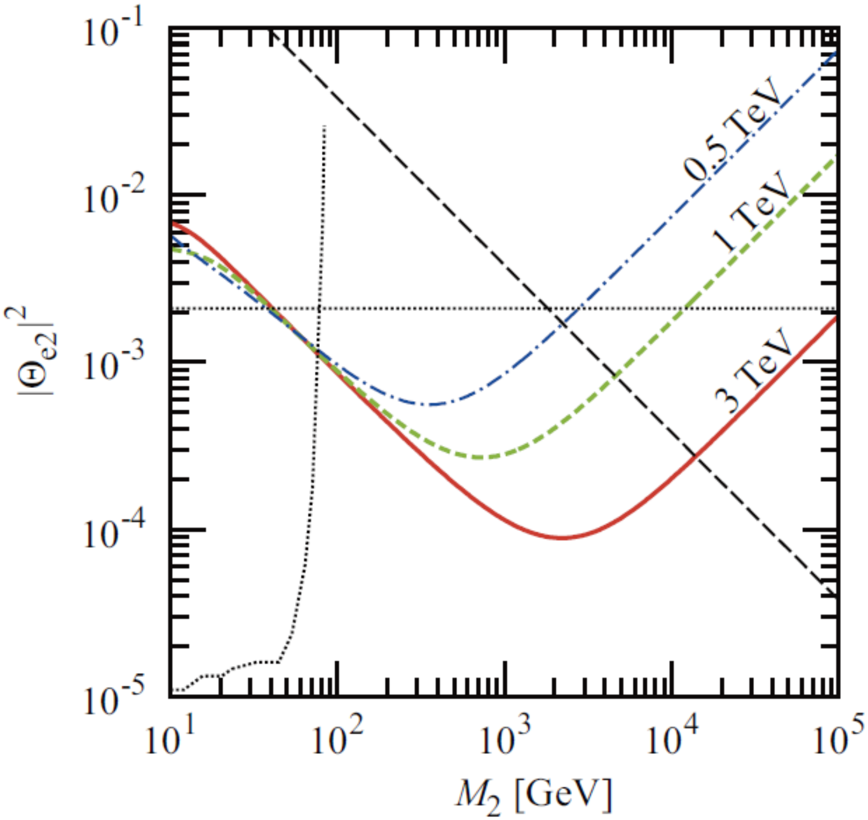
$M_3 \gg M_2$

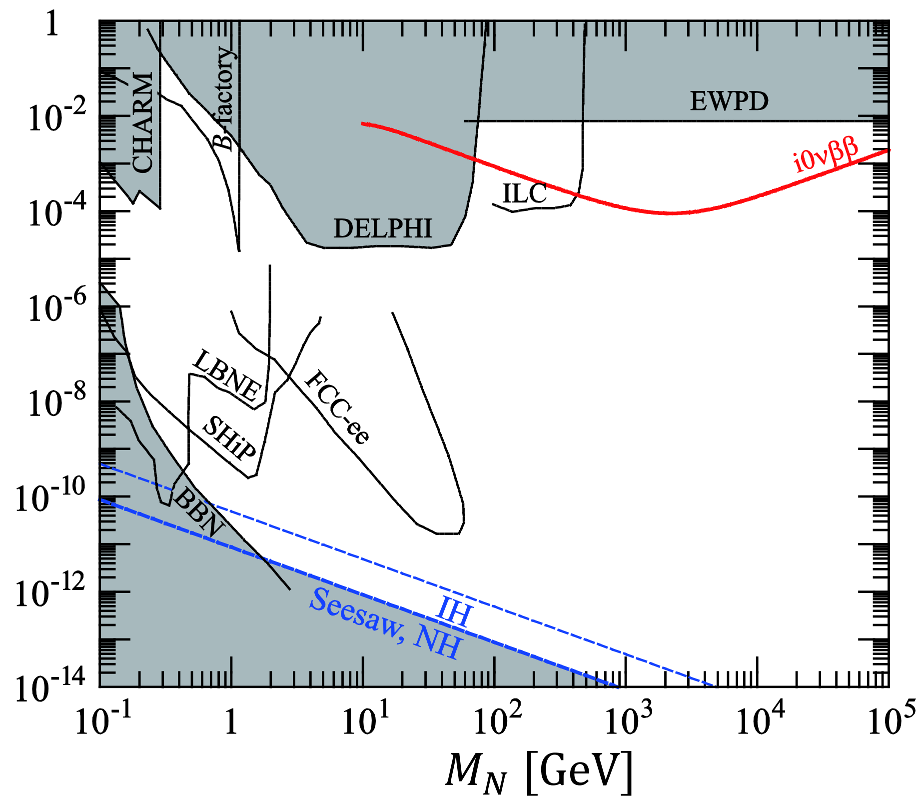
$|\Theta_{e3}|^2 \ll |\Theta_{e2}|^2$

Inverse $0\nu\beta\beta$ decay in the seesaw

- Sensitivity of mixing (@100 fb^{-1})

TA, Tsuyuki '15





The i$0\nu\beta\beta$ decay can probe right-handed neutrino with mass $\gg \sqrt{s}$

Summary

Summary

- The seesaw mechanism by right-handed neutrinos is attractive, not only because it can explain the smallness of neutrino masses, but also because it can explain various physics beyond the Standard Model including baryogenesis, dark matter, ⋯

- The experimental test of the seesaw mechanism is important
  - Direct search of right-handed neutrinos
  - Tests by lepton number violations
  - ⋯

- We have studied the tests by lepton number
  - Neutrinoless double beta decay
  - Inverse neutrinoless double beta decay ($e^- e^- \to W^- W^-$)