レプトン数の破れから探る宇宙バリオン数生成機構の解明

淺賀 岳彦 (新潟大学)

新学術領域
「宇宙の歴史をひもとく地下素粒子原子核研究」
2015年領域研究会 @神戸大学百年記念館
（2015/05/15~17）

Motivation

Origin of neutrino masses

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

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

- Important questions:
  - ***What is the origin of neutrino masses?***
  - ***What are the implications to other physics?***
  - ***How do we test it experimentally?***

RH Neutrinos ν_R and Seesaw Mechanism

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

Minkowski ’77
Yanagida ’79
Gell-Mann, Ramond, Slansky ‘79
Glashow ‘79

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

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

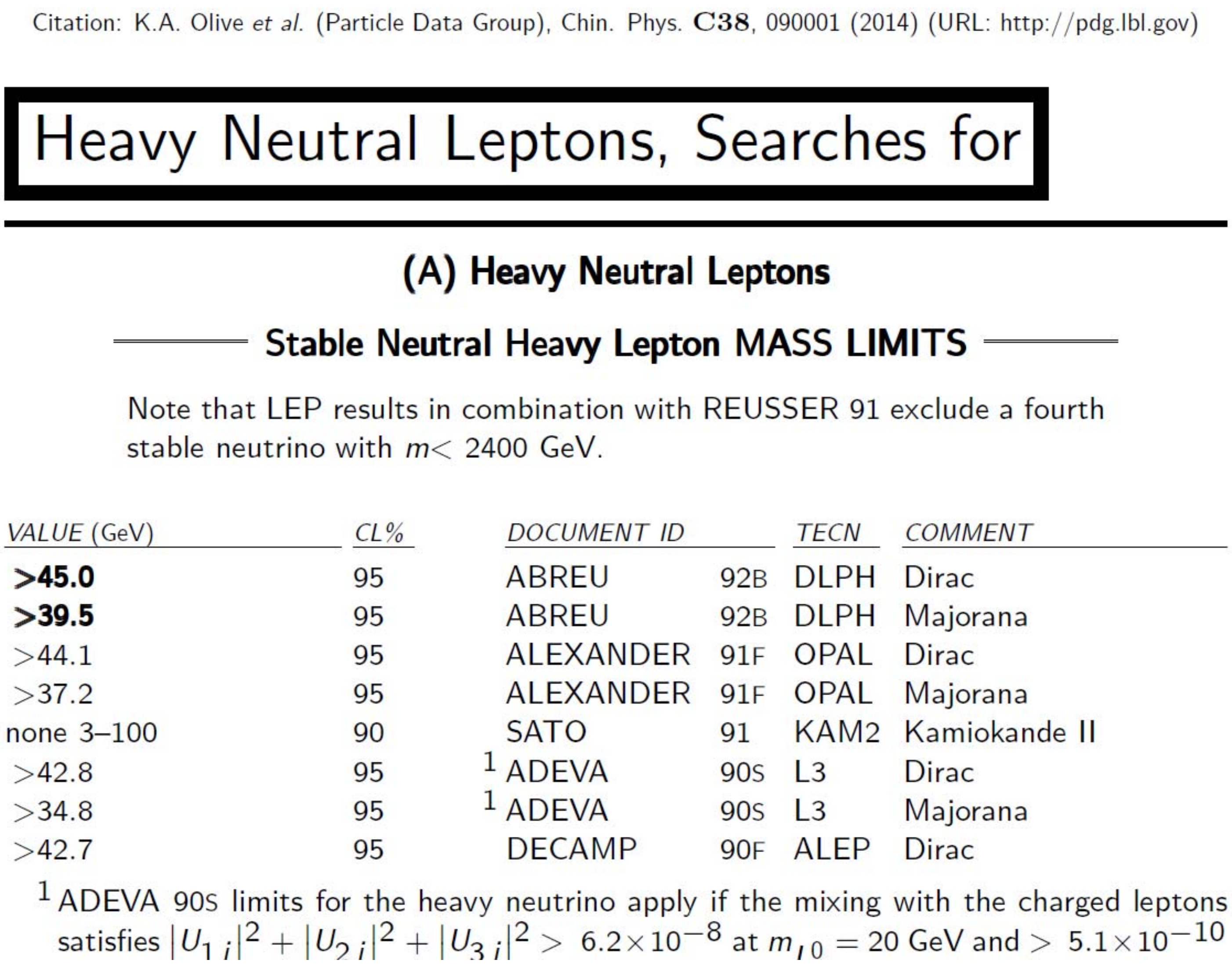
$$M_\nu = -M_D^T\frac{1}{M_M}M_D$$

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

- **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 $\nu_L = U\,\nu + \Theta\,N^c$

Review of Particle Physics



Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

Heavy Neutral Leptons, Searches for

(A) Heavy Neutral Leptons

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m <$ 2400 GeV.

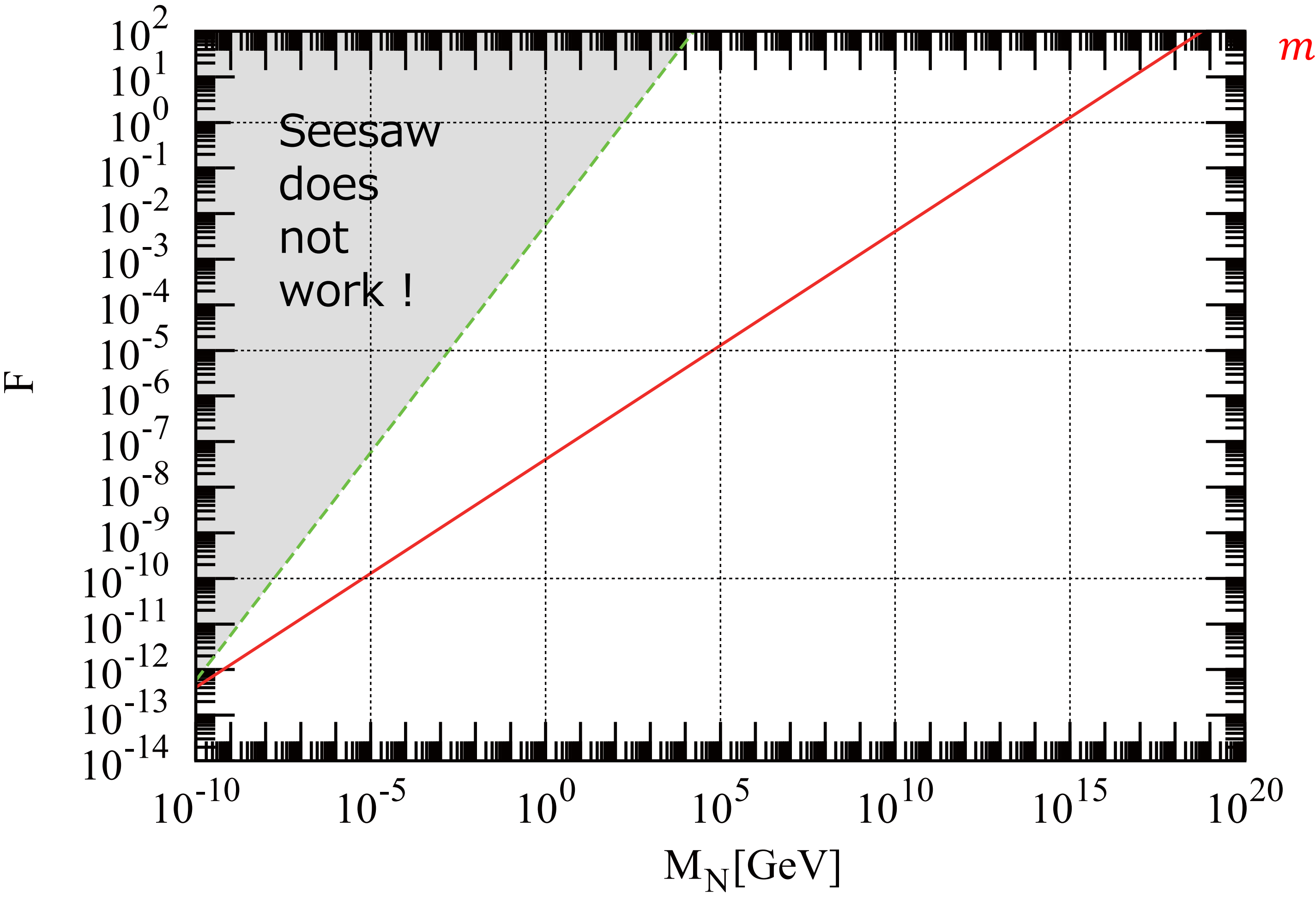
VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
>44.1	95	ALEXANDER	91F	OPAL	Dirac
>37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
>42.8	95	[1] ADEVA	90S	L3	Dirac
>34.8	95	[1] ADEVA	90S	L3	Majorana
>42.7	95	DECAMP	90F	ALEP	Dirac

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2\times10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1\times10^{-10}$

Yukawa Coupling and Mass of HNL

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

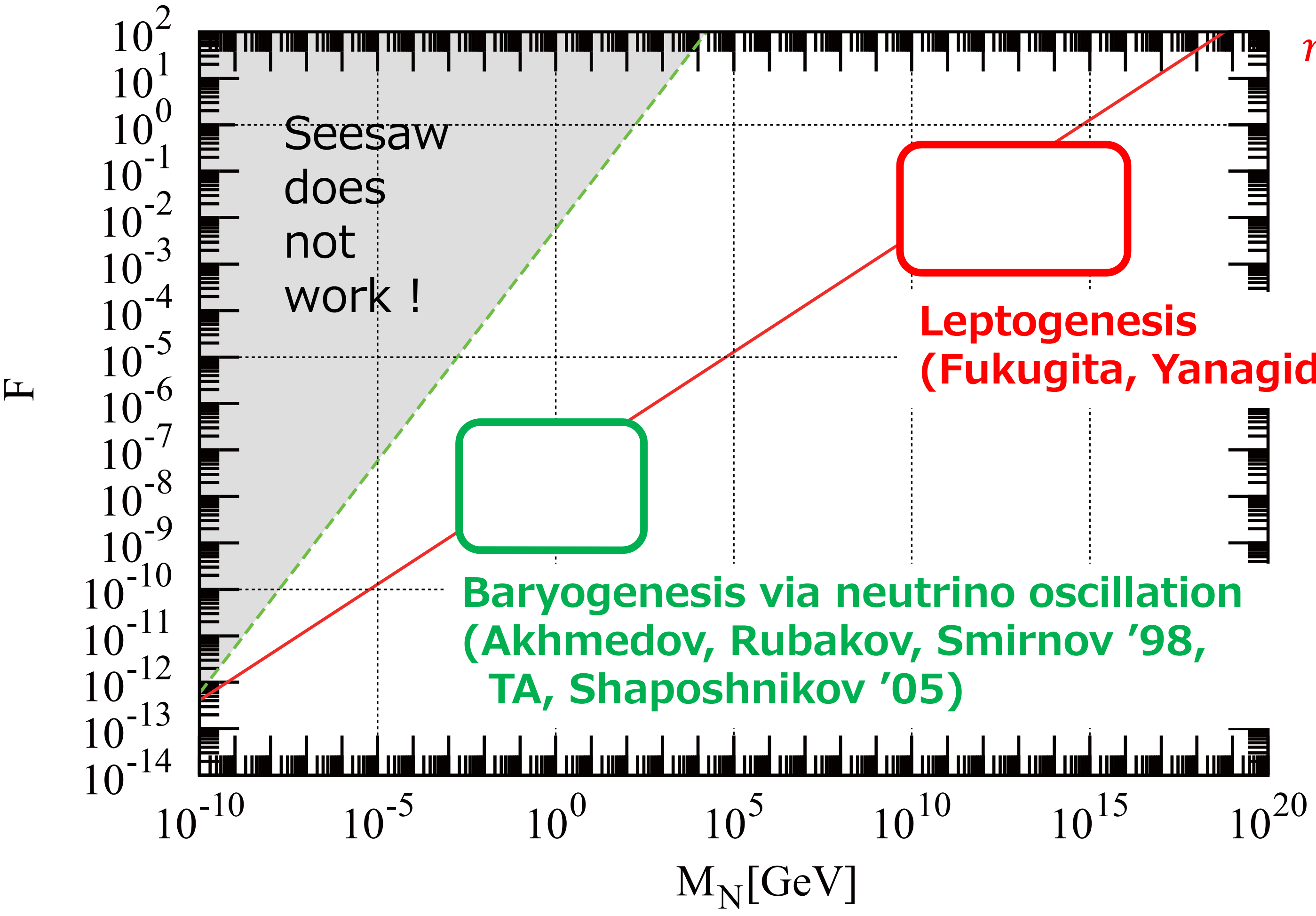
$m_\nu = 5 \times 10^{-11}$ GeV



Yukawa Coupling and Mass of HNL

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

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



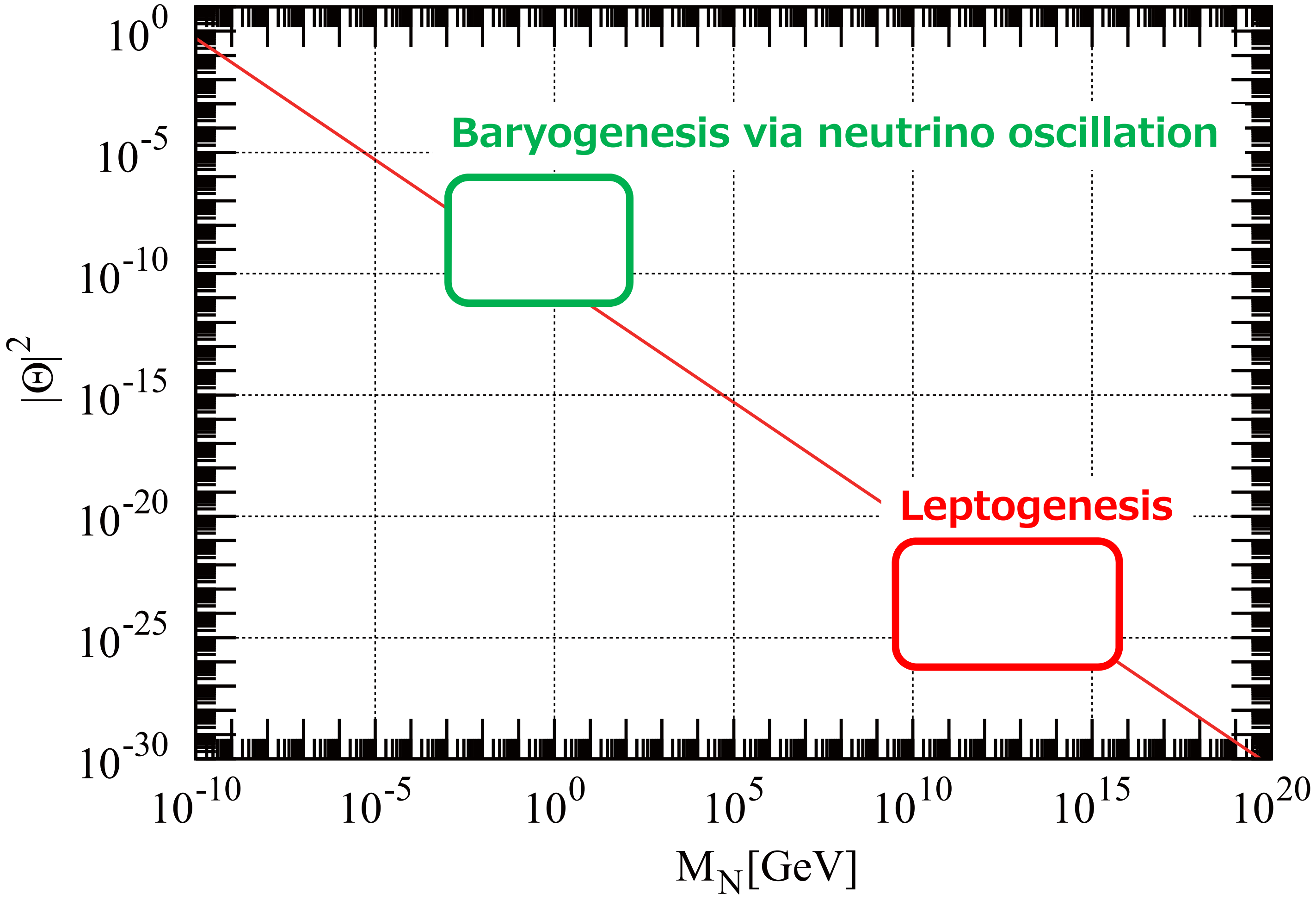
Seesaw does not work !

Leptogenesis (Fukugita, Yanagida ‘86)

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

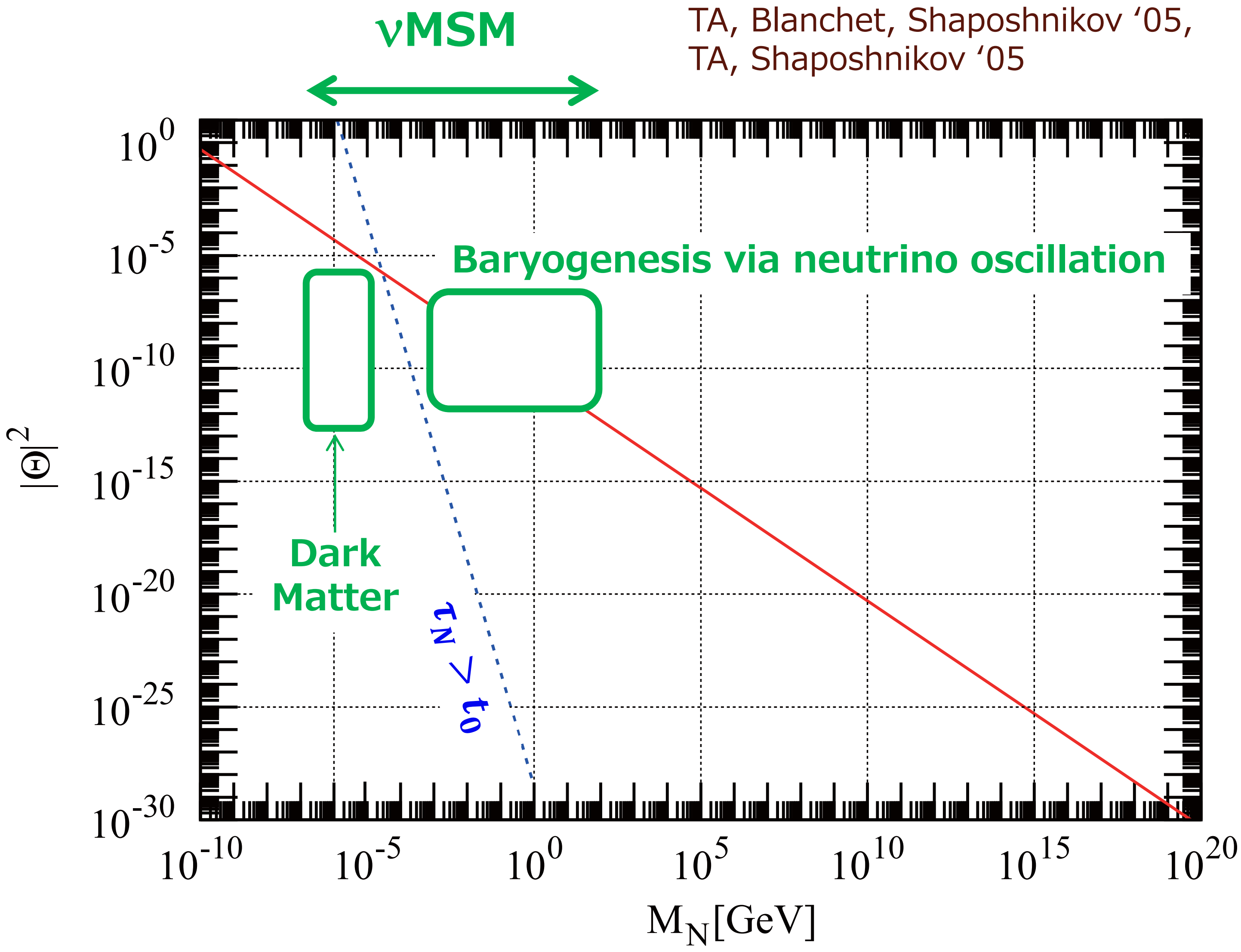
Mixing and Mass of HNL

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



Various Physics of HNLs

TA, Blanchet, Shaposhnikov '05,
TA, Shaposhnikov '05



Target

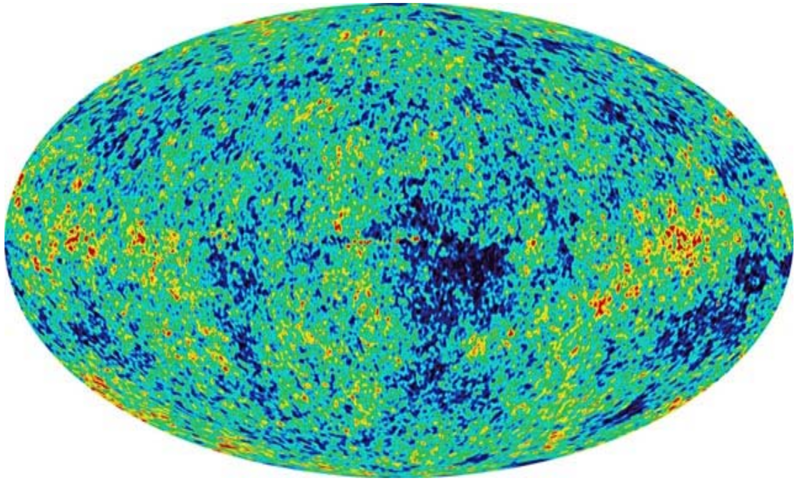
Baryon asymmetry of the universe (BAU)

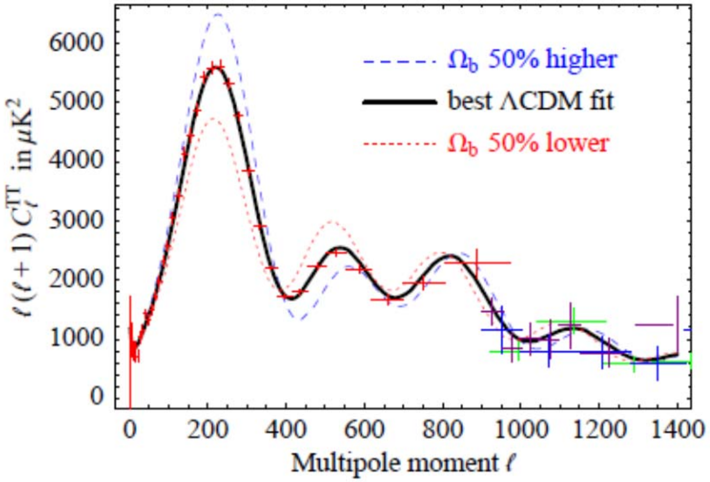
Baryon Number B = (# of baryons) − (# of antibaryons)

$$\boxed{\frac{n_B}{s} = (8.676 \pm 0.054) \times 10^{-11}}$$

Planck 2015
[arXiv:1502.01589]

n_B : Baryon number density
s : Entropy density





[Strumia 06]

Conditions for baryogenesis

- **Sakharov (1967)**

(1) Baryon number B is violated

(2) C and CP symmetries are violated

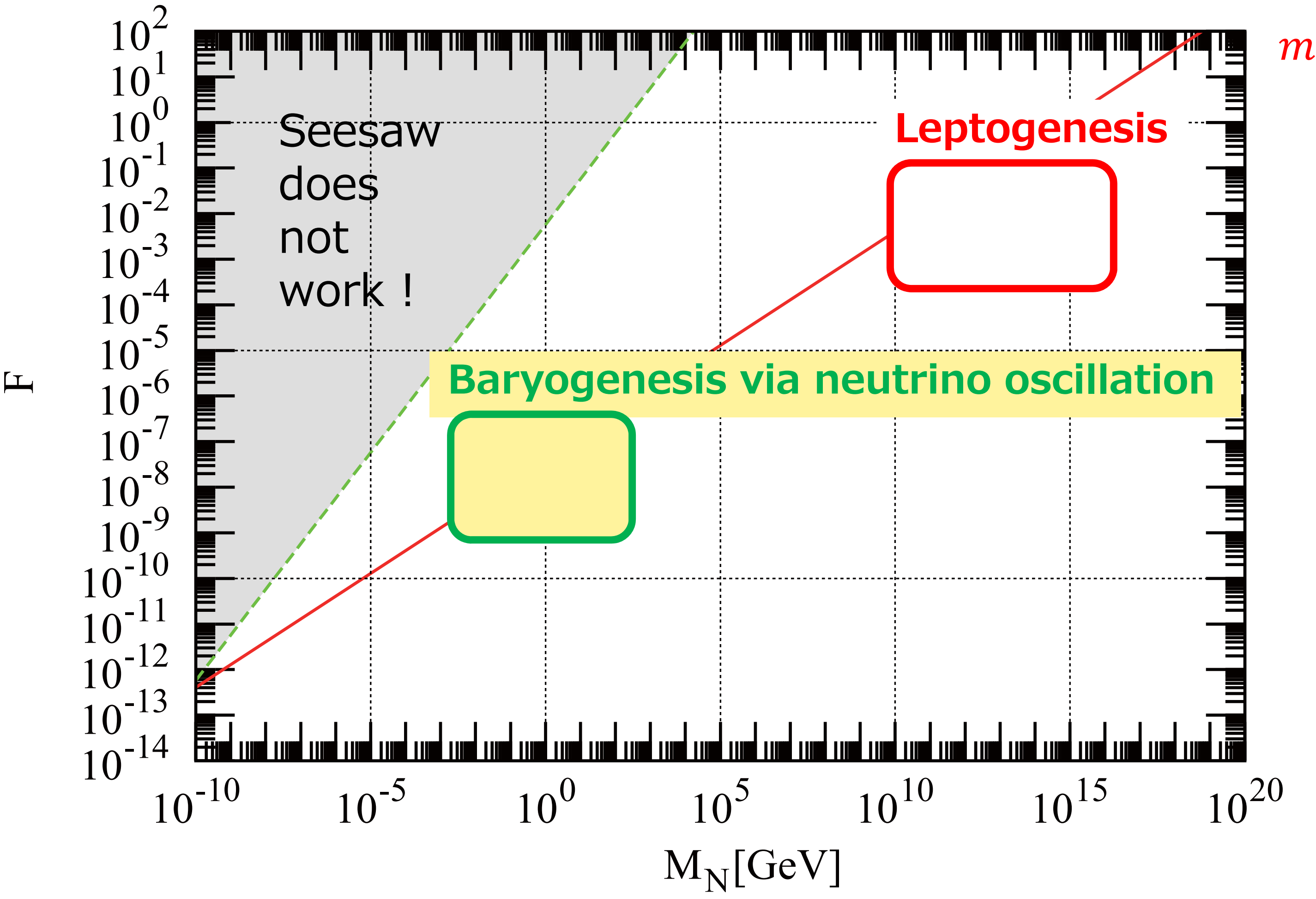
(3) Out of thermal equilibrium

"According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot Universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions."

Yukawa Coupling of HNL

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

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



Baryogenesis conditions

- **B and L violations**
  - (B+L) violation due to sphaleron
  - L violation due to Majorana masses

    Majorana masses < 100 GeV

    → negligible for T>100 GeV

- **C and CP violations**
  - 1 CP phase in quark sector
  - 6 CP phases in lepton sector

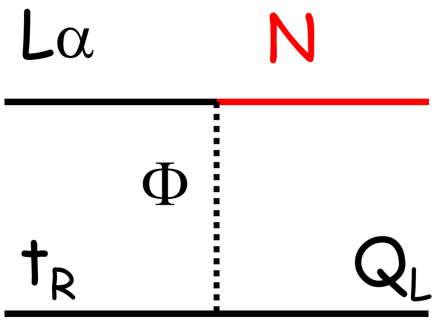
Baryogenesis conditions

- **Out of equilibrium**
  - No 1st order EW phase transition as in the SM
  - Heavy neutral leptons can be out of equilibrium, if Yukawa couplings are small enough
    - To ensure this condition up to T～100GeV

➡ $F < 2 \times 10^{-7}$

➡ $M_N < 17$ GeV

[TA, Shaposhnikov '05]



The model with HNLs with MN<100 GeV can realize all three conditions for baryogenesis

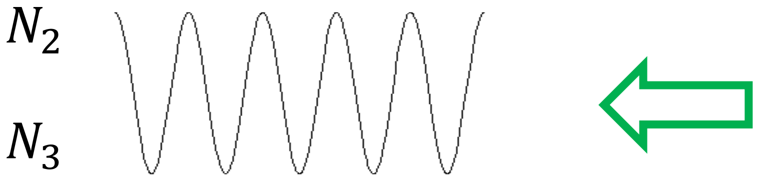
Baryogenesis via Neutrino Oscillation

- Oscillation of HNLs can be a source of BAU

  Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)

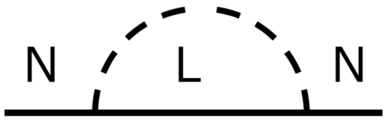
  Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
  TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
  Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)

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

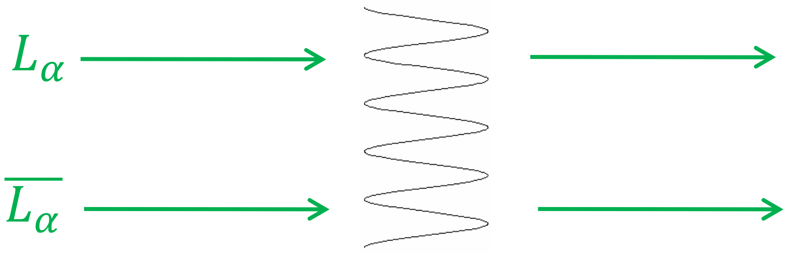


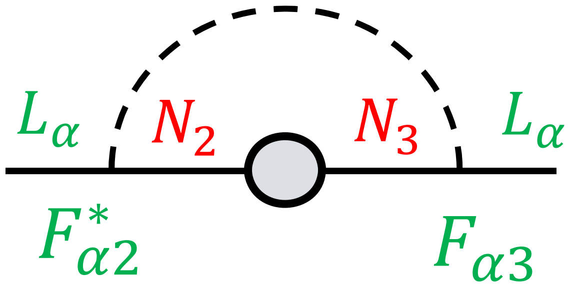
$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects



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





Evolution of Each Asymmetry

Active Sector

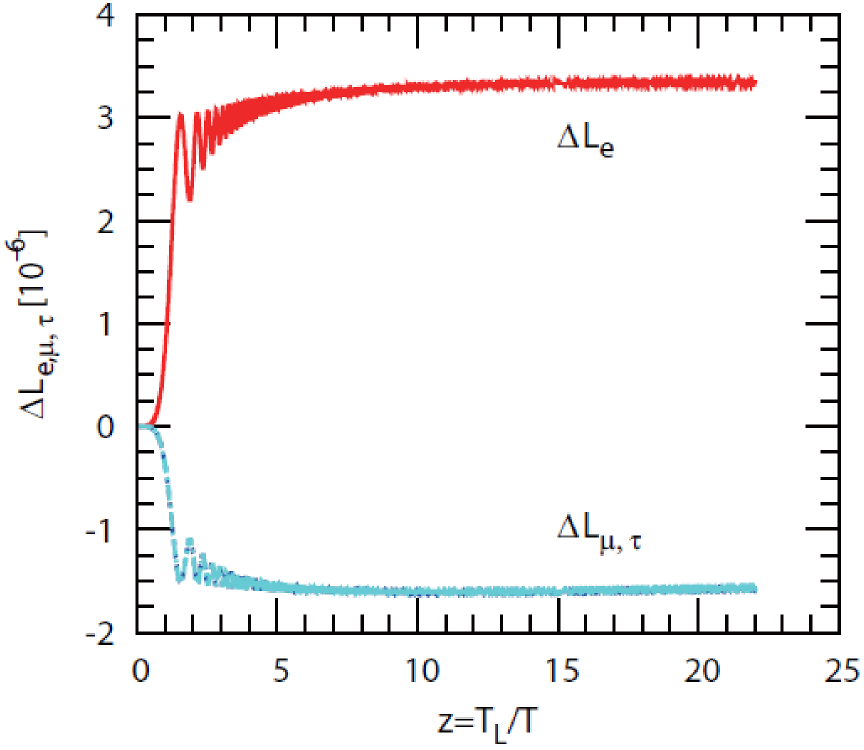


Figure 5: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Sterile Sector

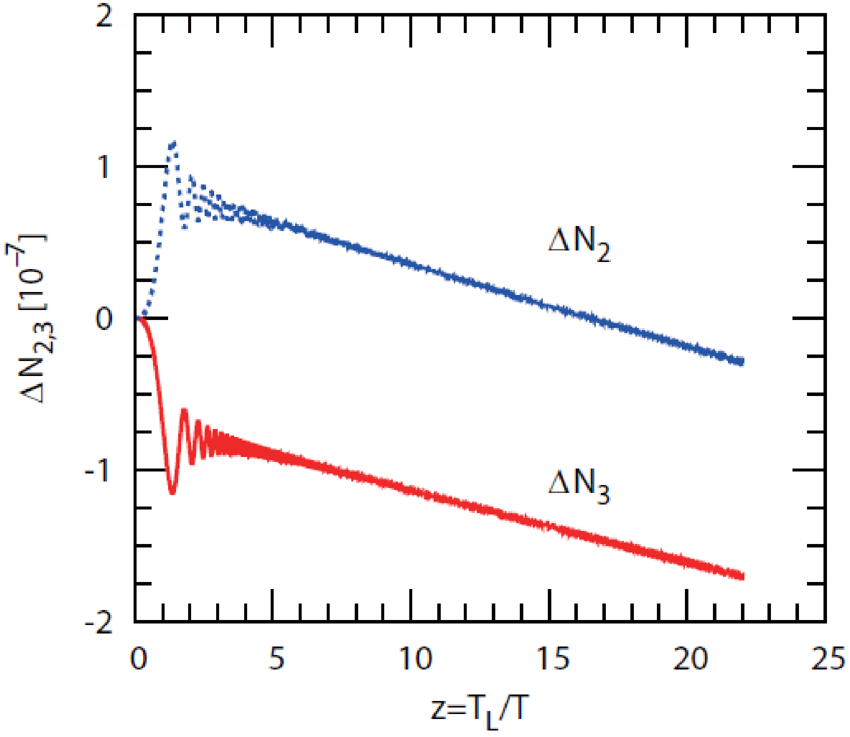
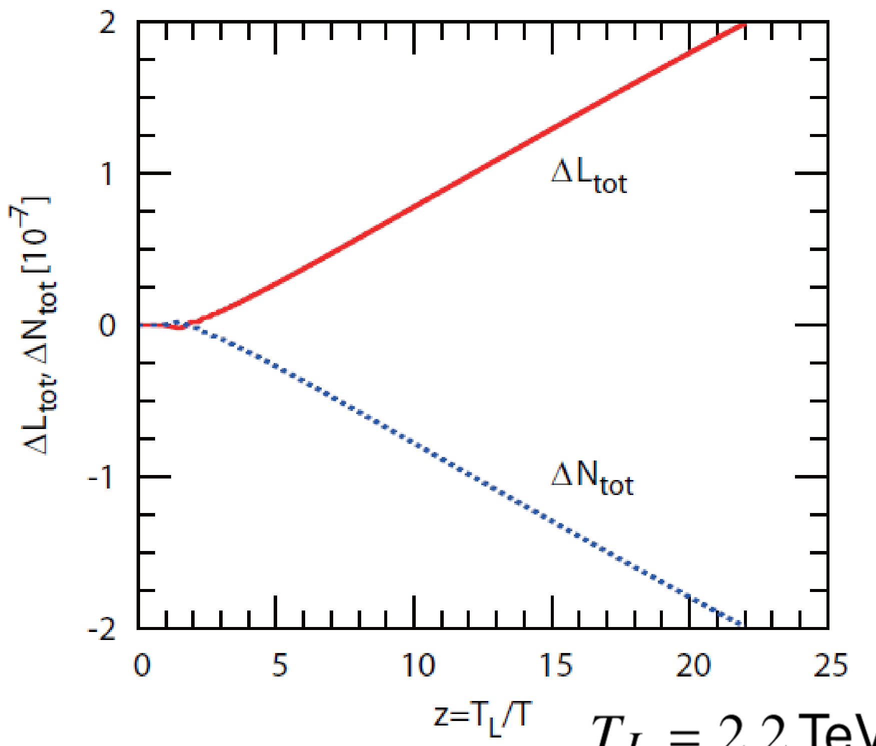


Figure 6: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

$T_{osc} = 2.2$ TeV

Evolution of Asymmetries



T_L = 2.2 TeV

Figure 7: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Shaleron converts ΔL partially into baryon asymmetry

[Kuzmin, Rubakov, Shaposhnikov]

$$B = -\frac{28}{79}\Delta L_{tot} \neq 0$$

$$\frac{n_B}{s} = -2.5\times 10^{-4}\Delta L_{tot}(T_W)$$

⇕

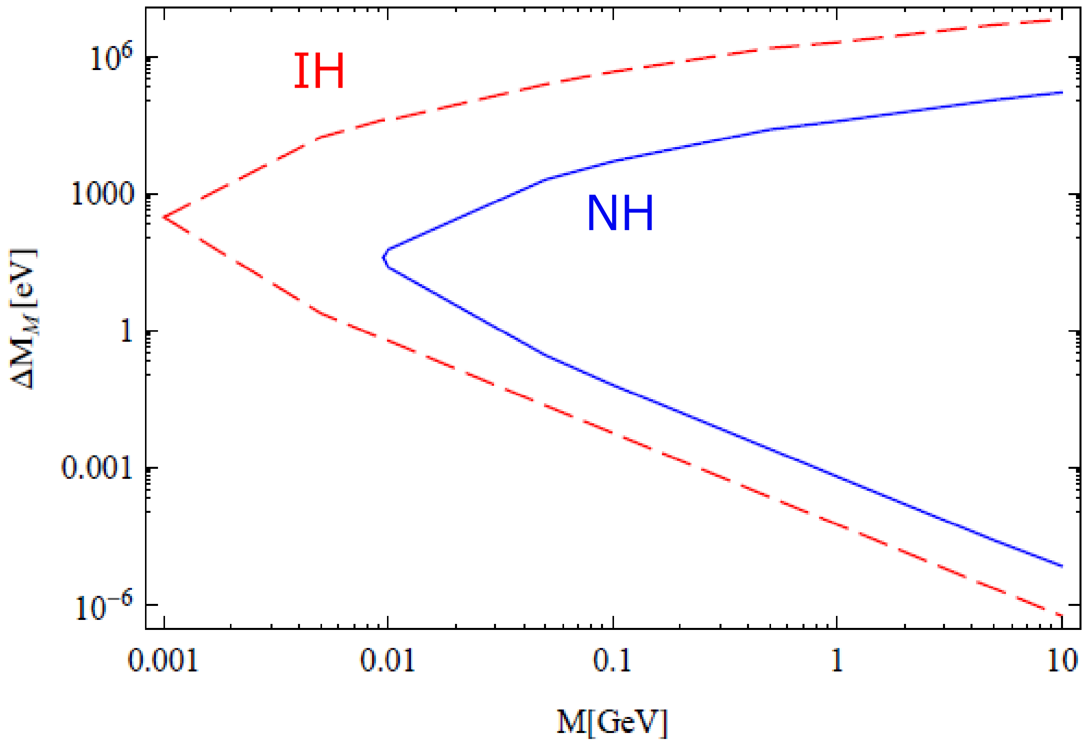
$$\frac{n_B}{s} = (8.579 \pm 0.109)\times 10^{-11}$$

[Planck 2013]

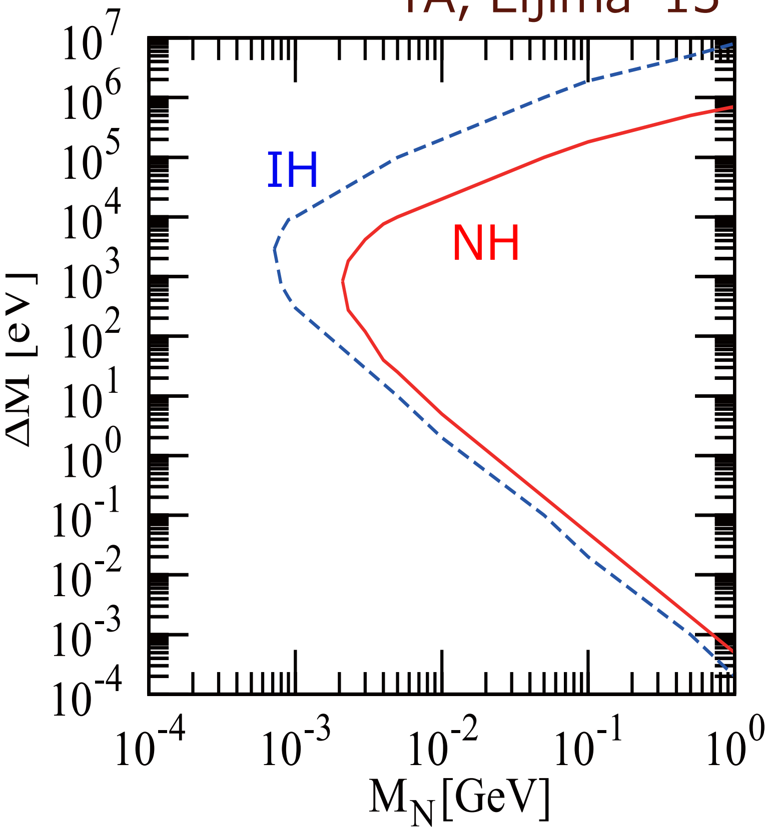
Baryogenesis Region

Region accounting for $\frac{n_B}{s} = (8.55\text{-}9.00) \times 10^{-11}$

Canetti, Shaposhnikov ‘10



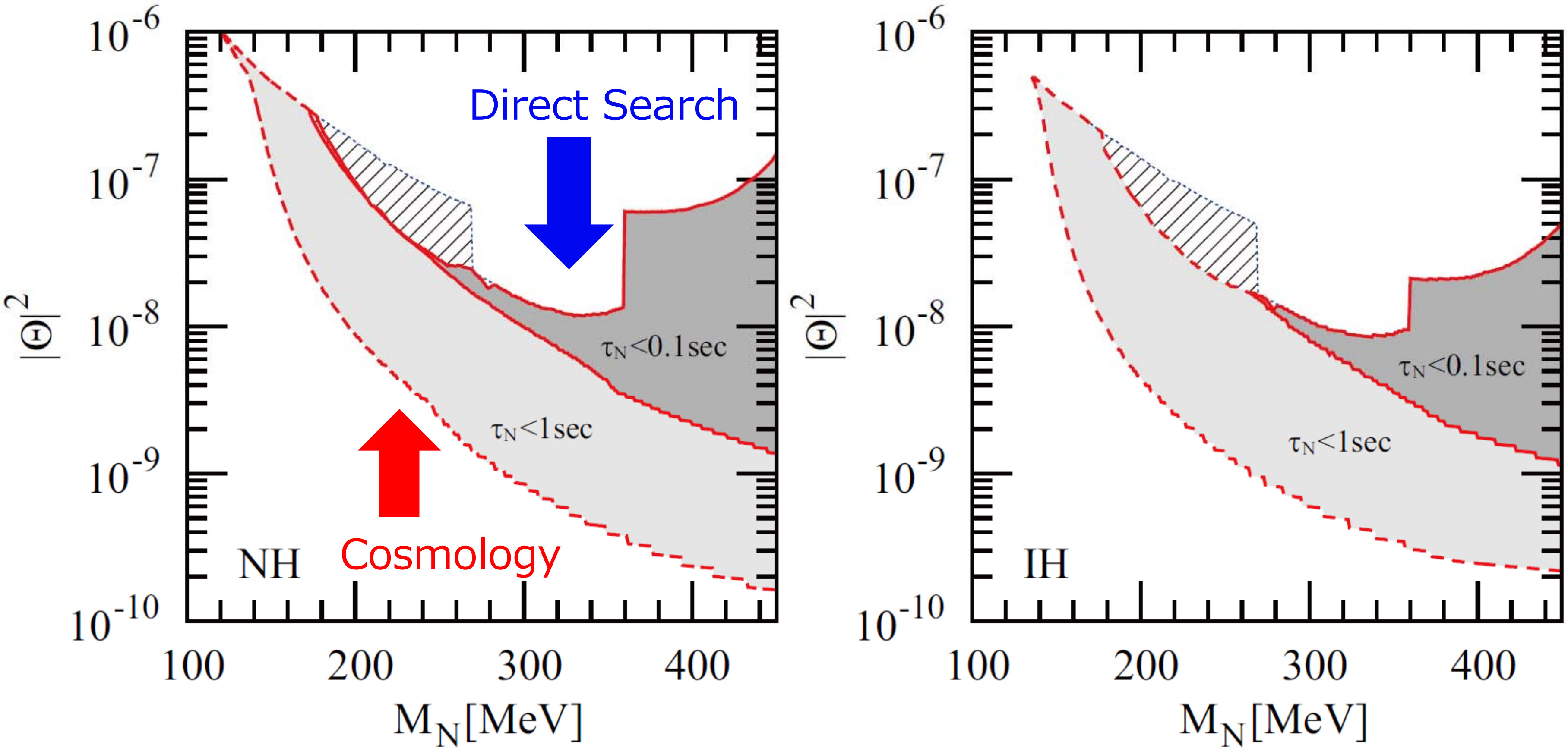
TA, Eijima ‘13



$M_N > 2.1$ MeV (NH) $M_N > 0.7$ MeV (IH)

Constraints on HNLs

TA, Eijima, Takeda ‘14



Task

Research Task

- Target:
  HNLs for seesaw mechanism and baryogenesis
  - Quasi-degenerate with $M_N = O(0.1 - 10^2)$ GeV
  - Mixing elements $\Theta = M_D/M_N$
  - Majorana fermions

  ⇒ induce Lepton Number Violating (LNV) processes

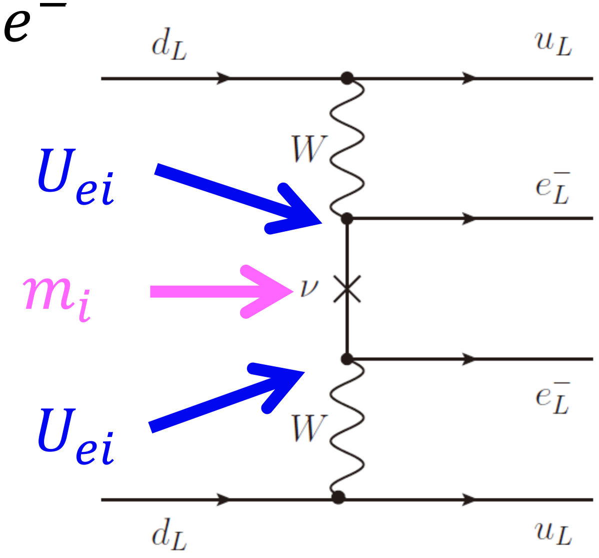
- Task:
  Study various tests for LNV by HNLs !

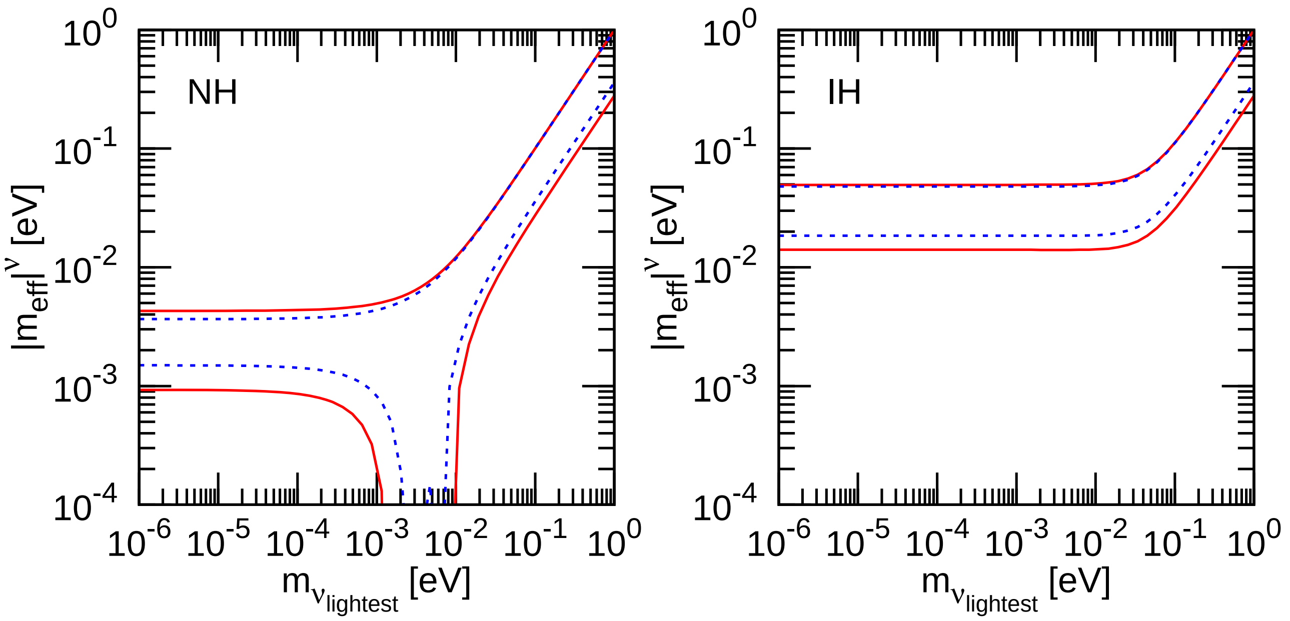
Neutrinoless double beta decay

[W.H. Furry 1939]

- $0\nu 2\beta$ decay: $(Z,A) \rightarrow (Z+2,A) + 2e^-$
  - Clear signal of LNV !
  - Effective neutrino mass

$$m_{\text{eff}} = \sum_{i=1,2,3} m_i\, U_{ei}^2 + \ \ldots$$



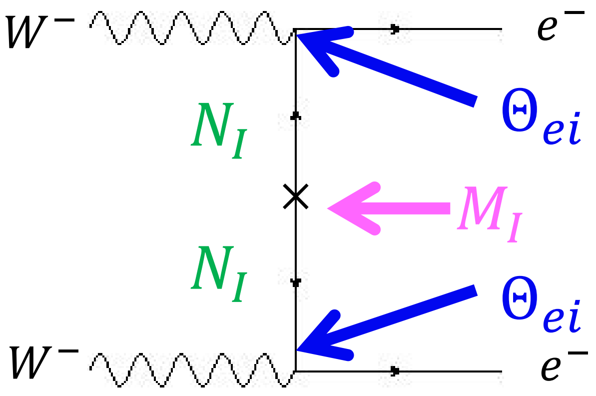


Effective neutrino mass

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

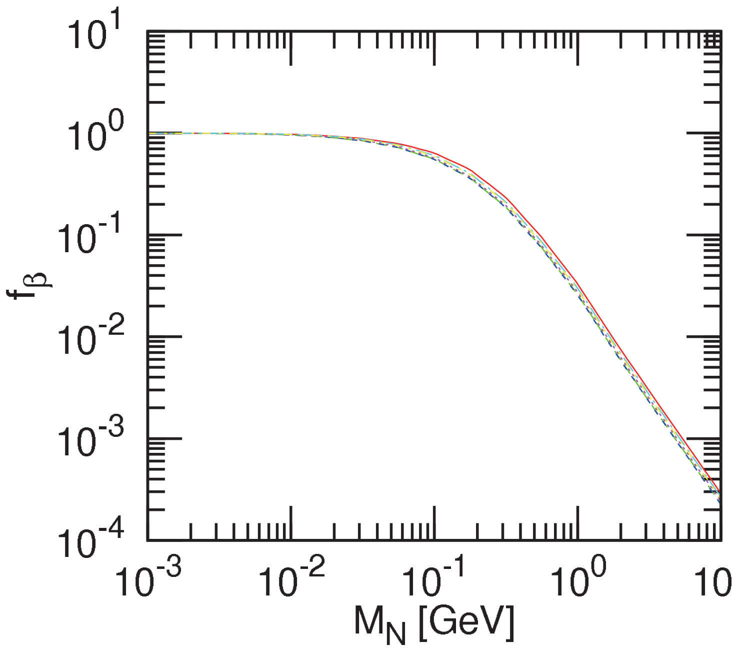
active neutrinos

heavy neutral leptons



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

$$f_\beta(M) = M^{0\nu\beta\beta}(M)/M^{0\nu\beta\beta}(0)$$



[Blennow, Frenandez-Martinez, Pavon, Mnendez ’10]

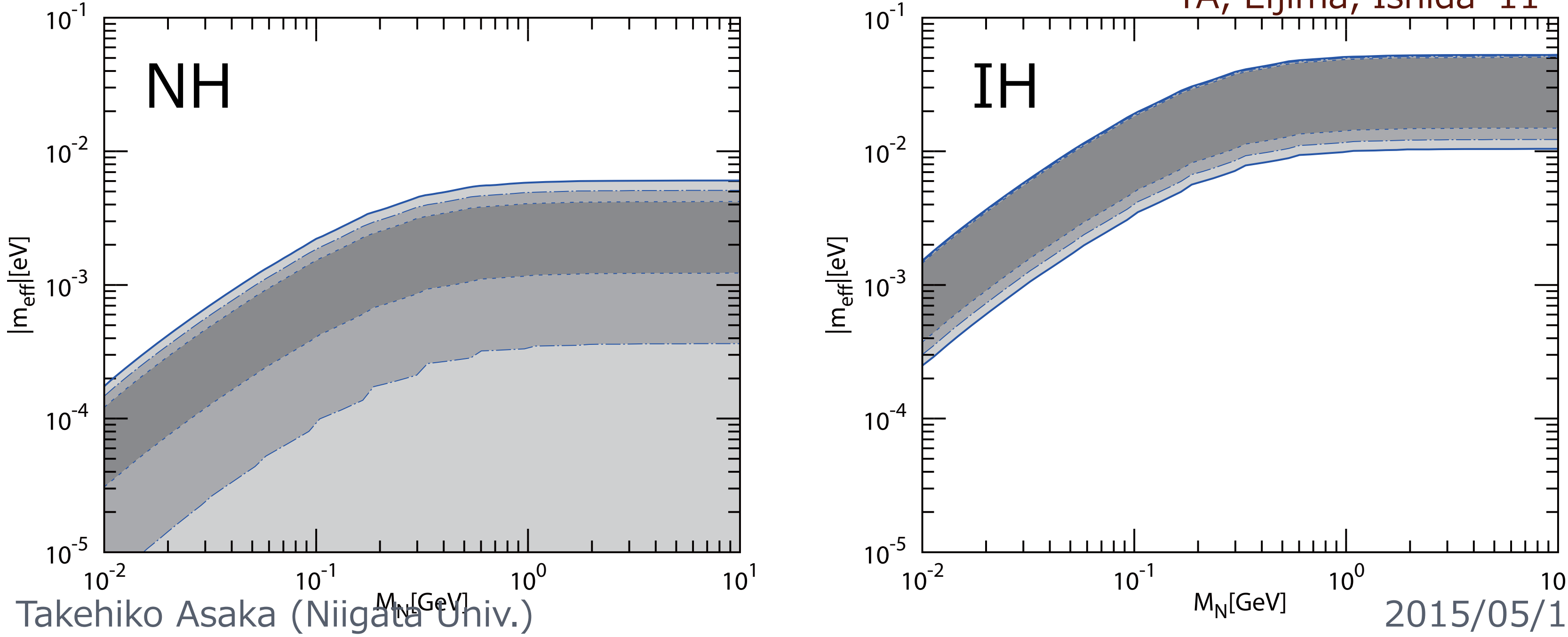
$m_{\rm eff}$ in the νMSM

Bezrukov '05
TA, Eijima, Ishida '11

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

- DM N_1 gives negligible contribution since $\Theta_{\alpha 1}$ is very small
- Lightest ν gives negligible contribution since $m < O(10^{-5})$ eV
- Heavier $N_{2,3}$ give destructive contribution to active ν's one

TA, Eijima, Ishida '11



m_{eff} in the νMSM

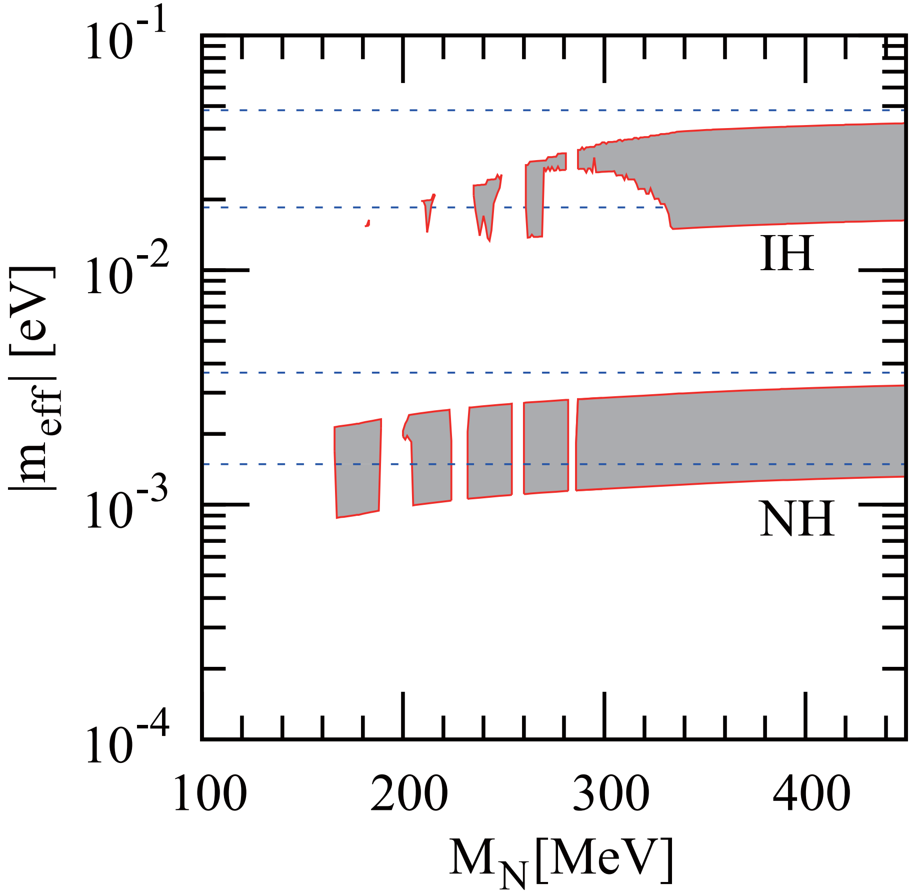
- Constraints from search experiments and cosmology restrict the predicted range of effective neutrino mass

NH

$$m_{\mathrm{eff}} = (0.879 - 3.66)\ \mathrm{meV}$$

IH

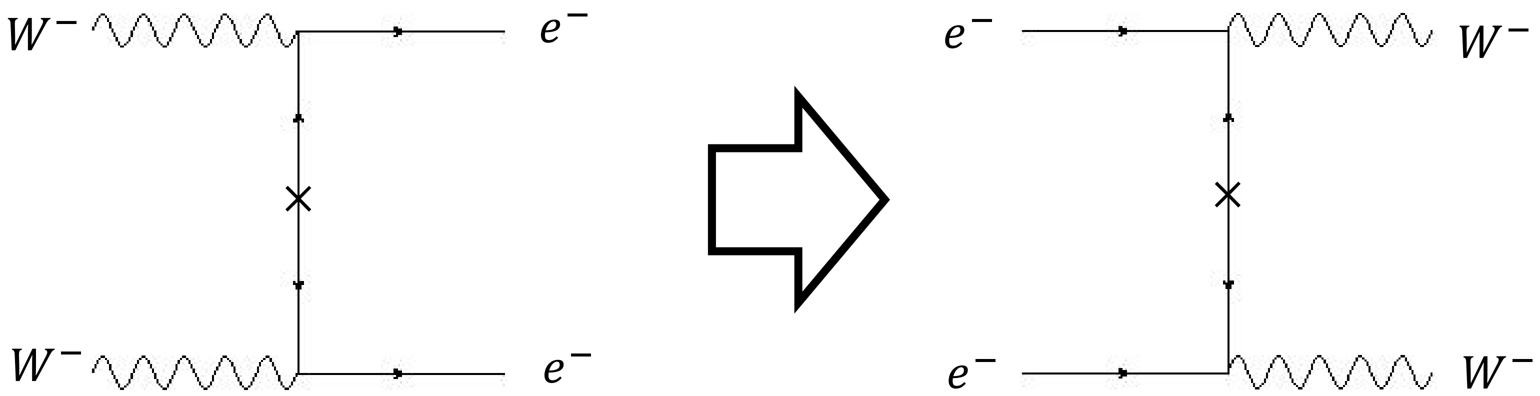
$$m_{\mathrm{eff}} = (13.8 - 47.9)\ \mathrm{meV}$$



TA, Eijima, Ishida
preliminary

Inverse neutrinoless double beta decay

[T. G. Rizzo 1982]

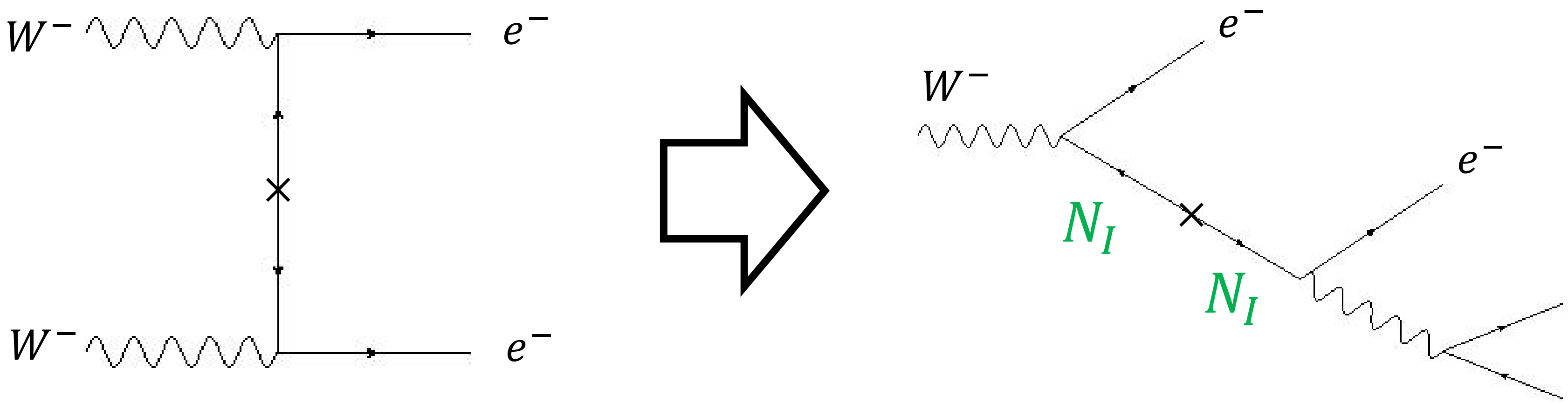


- e^-e^- collision is an option of ILC

  ⇒ test of LNV process: $\boxed{e^- e^- \rightarrow W^- W^-}$

- Tasks
  - Estimate $\sigma(e^-e^- \rightarrow W^-W^-)$ by HNLs for seesaw mechanism and baryogenesis
  - Study correlation between $\sigma(e^-e^- \rightarrow W^-W^-)$ and BAU

LNV decays of HNL



- HNLs can be produced by CC interaction
  ⇒ Tests for LNV decays of HNLs
  - $W^- \to e^- \, N_I \to e^- \, (e^- \, q \, \overline{q'})$ @ LHC, ILC, ⋯
  - $B^- \to e^- \, N_I \to e^- \, (e^- \, \pi^+)$ @ Super-KEKB, LHCb
  - $K^- \to e^- \, N_I \to e^- \, (e^- \, \pi^+)$ @ J-PARC
  - ⋯

Summary

Summary

- Heavy neutral leptons (right-handed neutrinos) below the electroweak scale are well-motivated particles physics beyond the standard Model.
  - Seesaw mechanism for neutrino masses
  - Baryogenesis via neutrino oscillation
  - Dark matter (sterile neutrino dark matter)

- We study various tests for LNV by such heavy neutral leptons
  - Neutrinoless double beta decay
  - Inverse neutrinoless double beta decay ($e^- e^- \to W^- W^-$)
  - LNV decays of HNLs ($W^- \to e^-\ N_I \to e^-\ (e^-\ \pi^+), \cdots$)

⇒ understand the origin of neutrino masses
as well as the origin of matter of our universe!