Physics of the neutrino masses

Takehiko Asaka (Niigata Univ.)

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Neutrino properties

- Mixing angles and mass squared differences are measured very precisely

$\sin^2\theta_{12} = 0.308^{+0.013}_{-0.012}$ $\Delta m^2_{21} = (7.49^{+0.19}_{-0.17})\times 10^{-5}\ \mathrm{eV}^2$ (NH case)

$\sin^2\theta_{23} = 0.440^{+0.023}_{-0.019}$ $\Delta m^2_{31} = (2.526^{+0.029}_{-0.037})\times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{13} = 0.02163^{+0.00074}_{-0.00074}$

Gonzalez-Garcia, Maltoni and Schwetz (ν-fit, August '16)

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

Physics of neutrino masses

- These unknown properties are important

  - To identify new physics beyond the Standard Model
    - Models of neutrino masses
      - New paritcles ? New interactions ?

  - To understand other questions in the Standard Model
    - Origin of matter of our universe
      - Baryon asymmetry of the Universe
      - Cosmic dark matter
      - …

In this talk

- We discuss physics of right-handed neutrino (ν_R)
  - ν_R and neutrino masses – seesaw mechanism –
  - ν_R and baryon asymmetry of the universe (BAU)
  - ν_R and experimental test of model
  - ν_R and neutrinoless double beta decay

ν_R and neutrino masses
-- seesaw mechanism --

Extension by right-handed neutrinos ν_R

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

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

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

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

Light active neutrinos ν

$$M_\nu = -\frac{M_D^T}{M_M}\times M_D \quad \Leftarrow \text{tiny neutrino masses !}$$

$\rightarrow$ explain neutrino oscillations

Heavy neutral leptons N $(N \simeq \nu_R)$

- Mass M_M
- Mixing $\Theta = M_D/M_M$

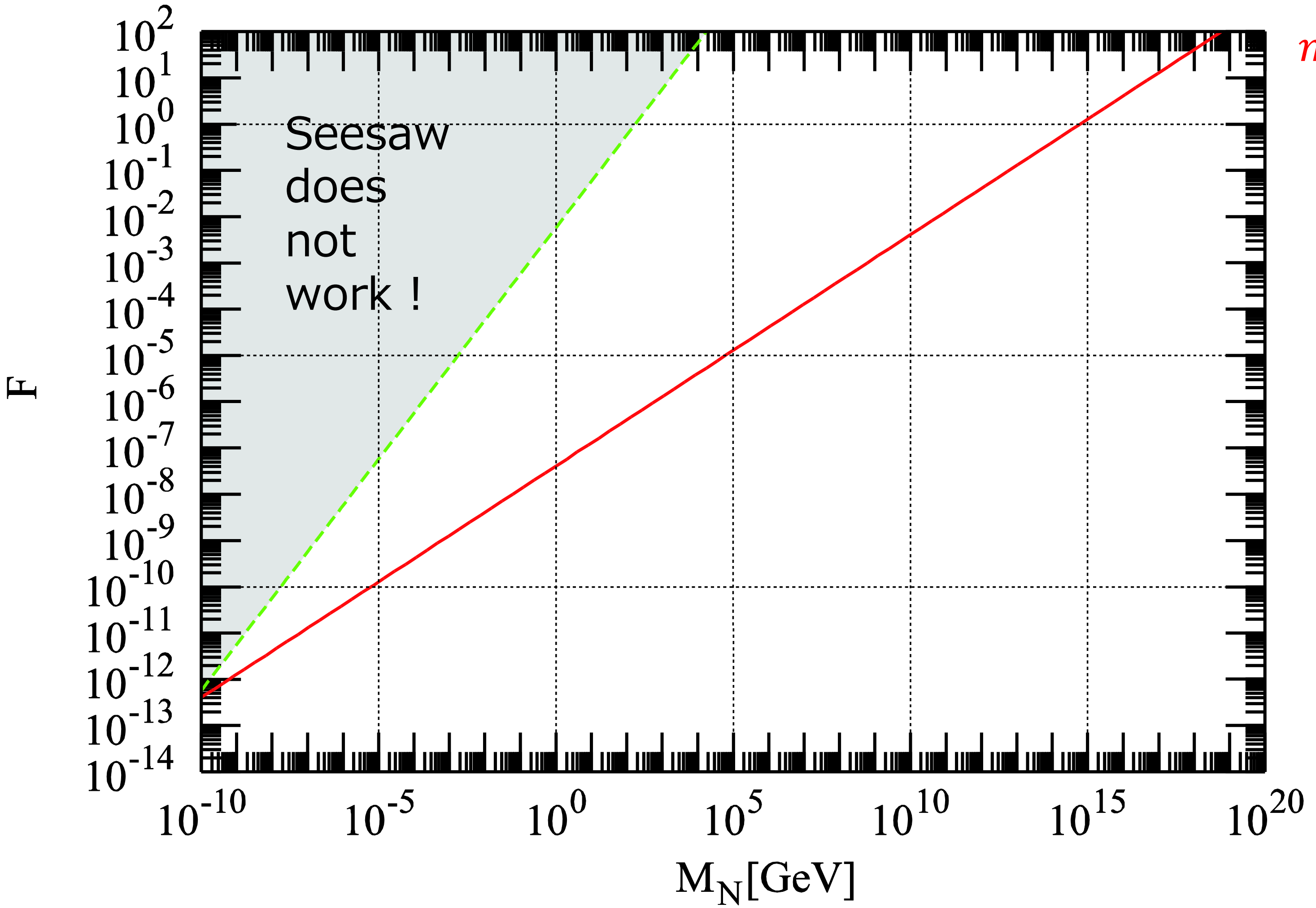
Neutrino mixing

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

Yukawa coupling and Majorana mass

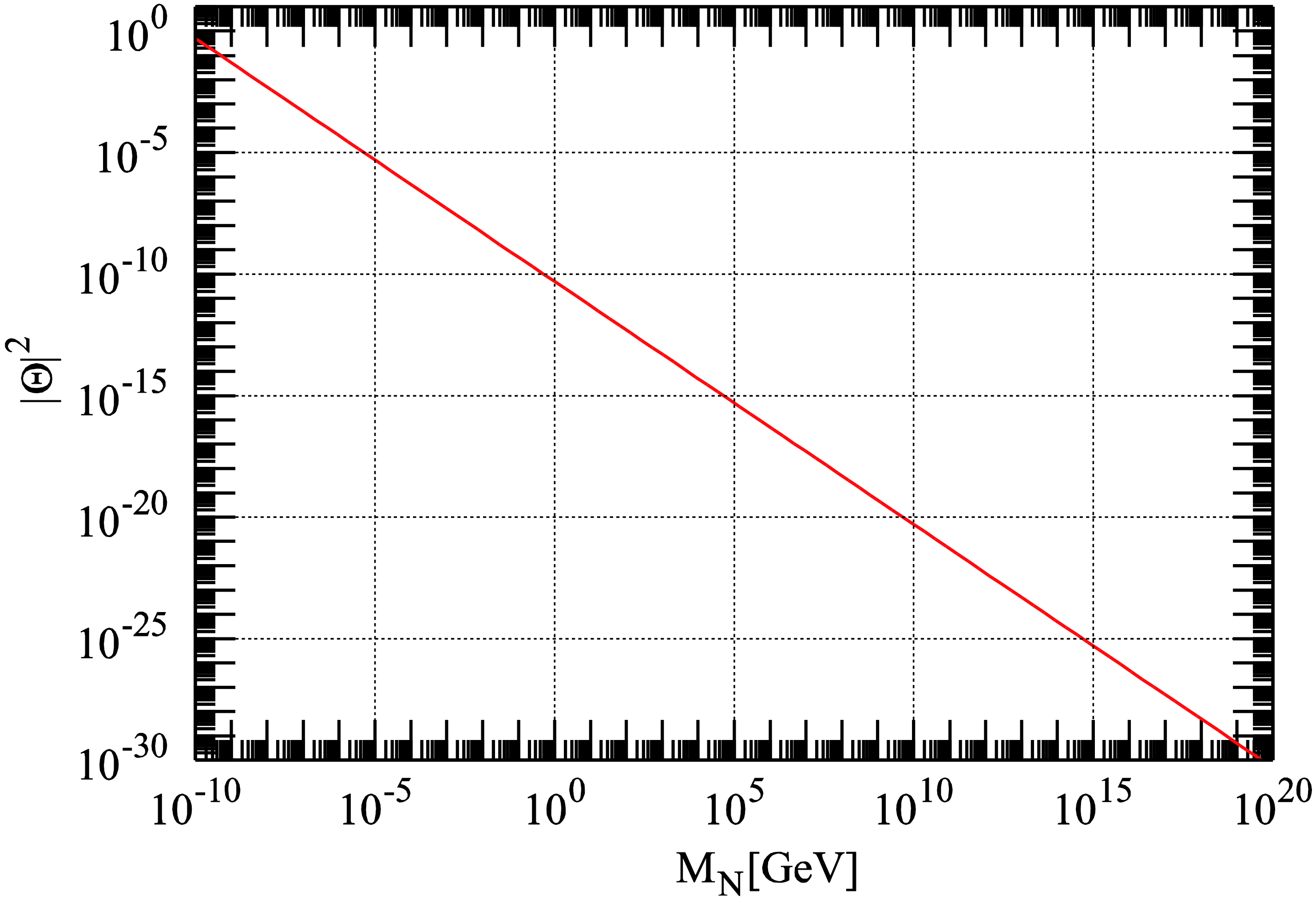
$$m_\nu = \frac{M_D}{M_M} \times M_D = \frac{F^2 \langle \Phi \rangle^2}{M_N} \quad \Longrightarrow \quad F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle}$$

$m_\nu = 5\times10^{-11}$ GeV



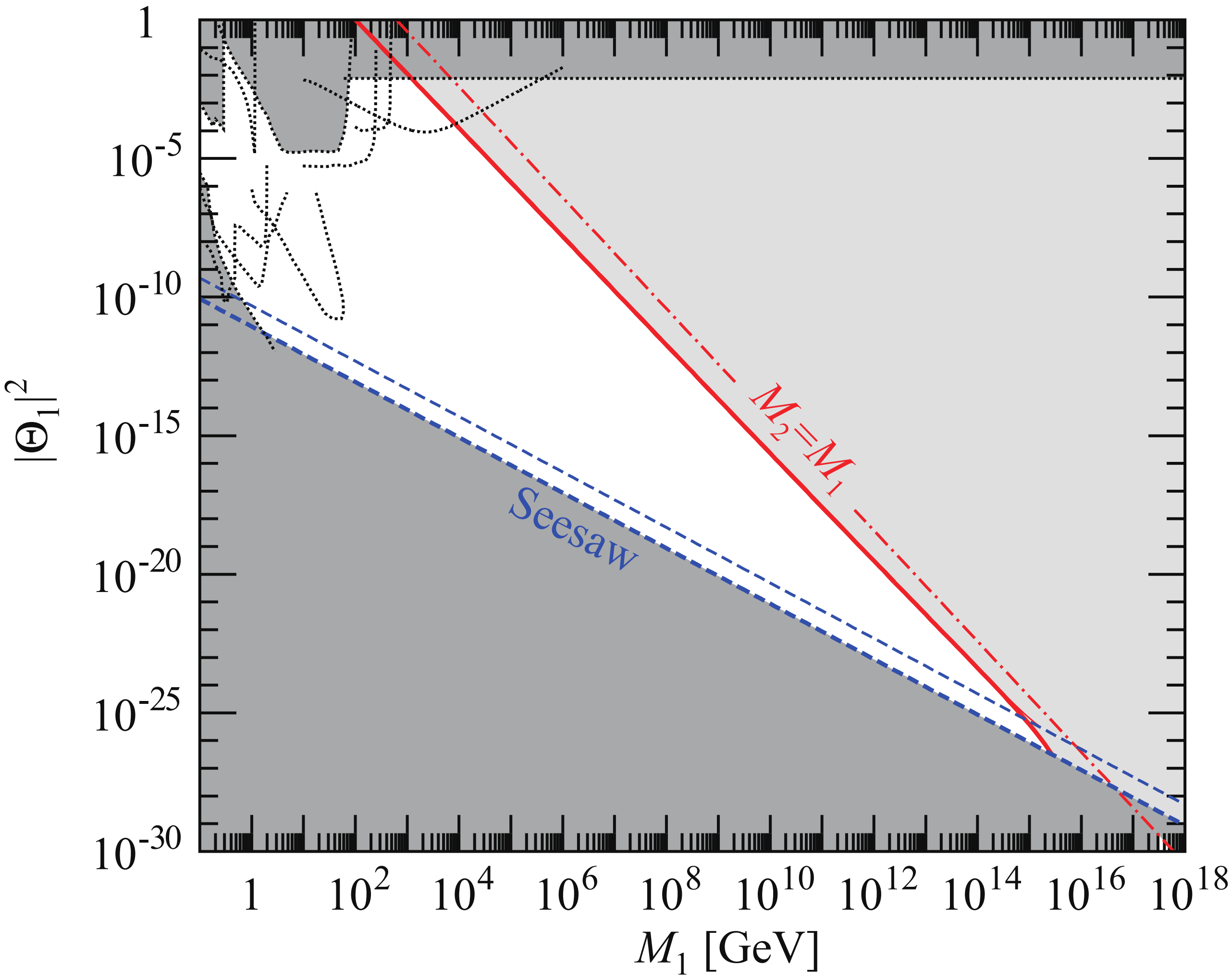
Mixing and mass of heavy neutral lepton

$$|\Theta|^2 = \frac{M_D^2}{M_N^2} = \frac{m_\nu}{M_N} \qquad m_\nu = 5\times10^{-11}\ \text{GeV}$$



Range of parameter space

TA, Tsuyuki '15



Bound from seesaw mechanism

- Mixings of HNL must be sufficiently large to explain masses of active neutrinos !

- Bound on the mixing of the lightest HNL N_1

TA, Tsuyuki '15

$$\boxed{|\Theta_1|^2 \geq \frac{m_l}{M_1}}$$

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

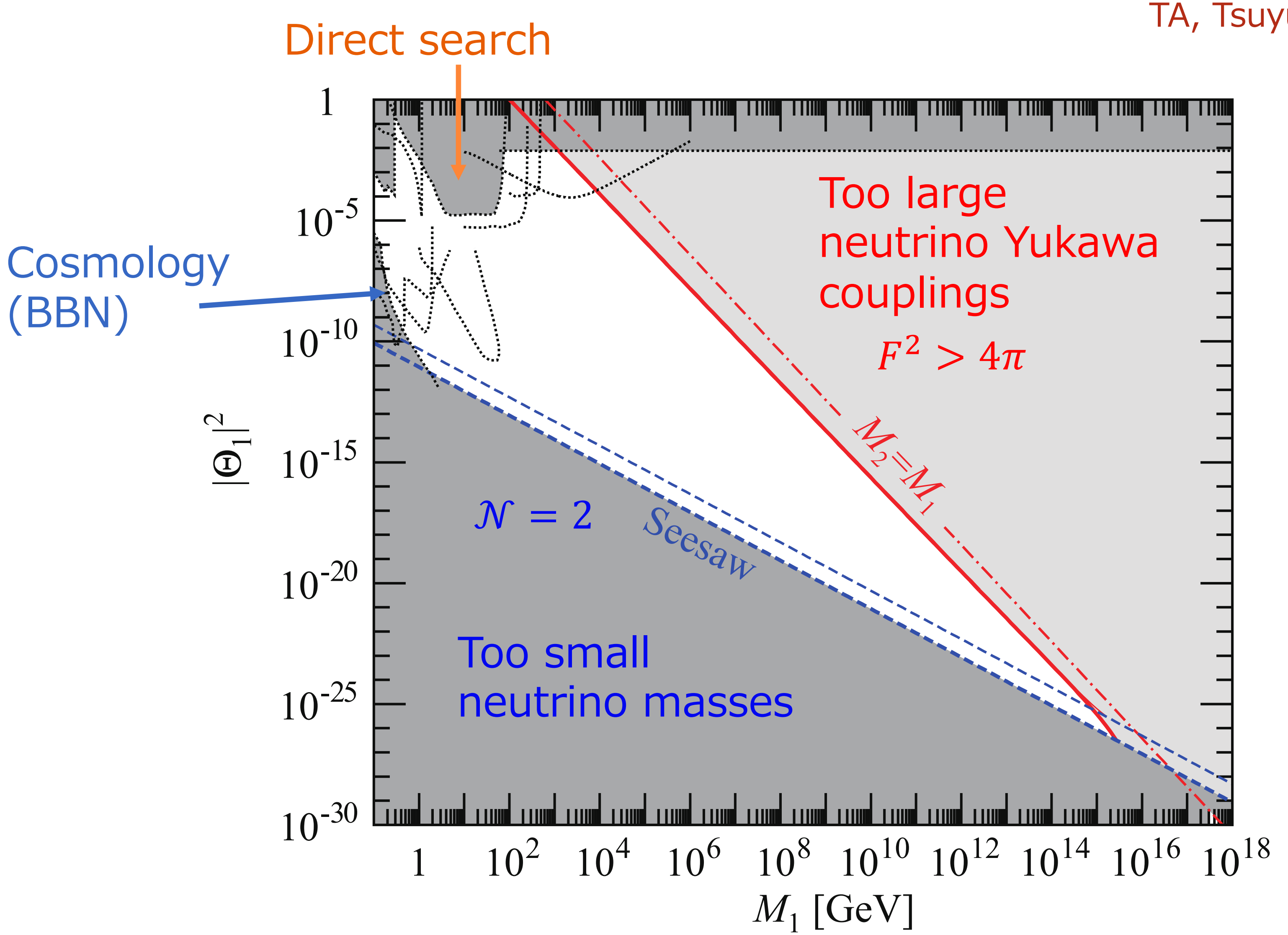
$$m_l = \begin{cases} m_1\ (m_3) \text{ in the NH (IH) for 3RHN } (\mathcal{N}=3) \\ m_2\ (m_1) \text{ in the NH (IH) for 2RHN } (\mathcal{N}=2) \end{cases}$$

NOTE: $|\Theta_1|^2$ can be zero for $\mathcal{N}=3$

(No lower bound for $\mathcal{N}>3$)

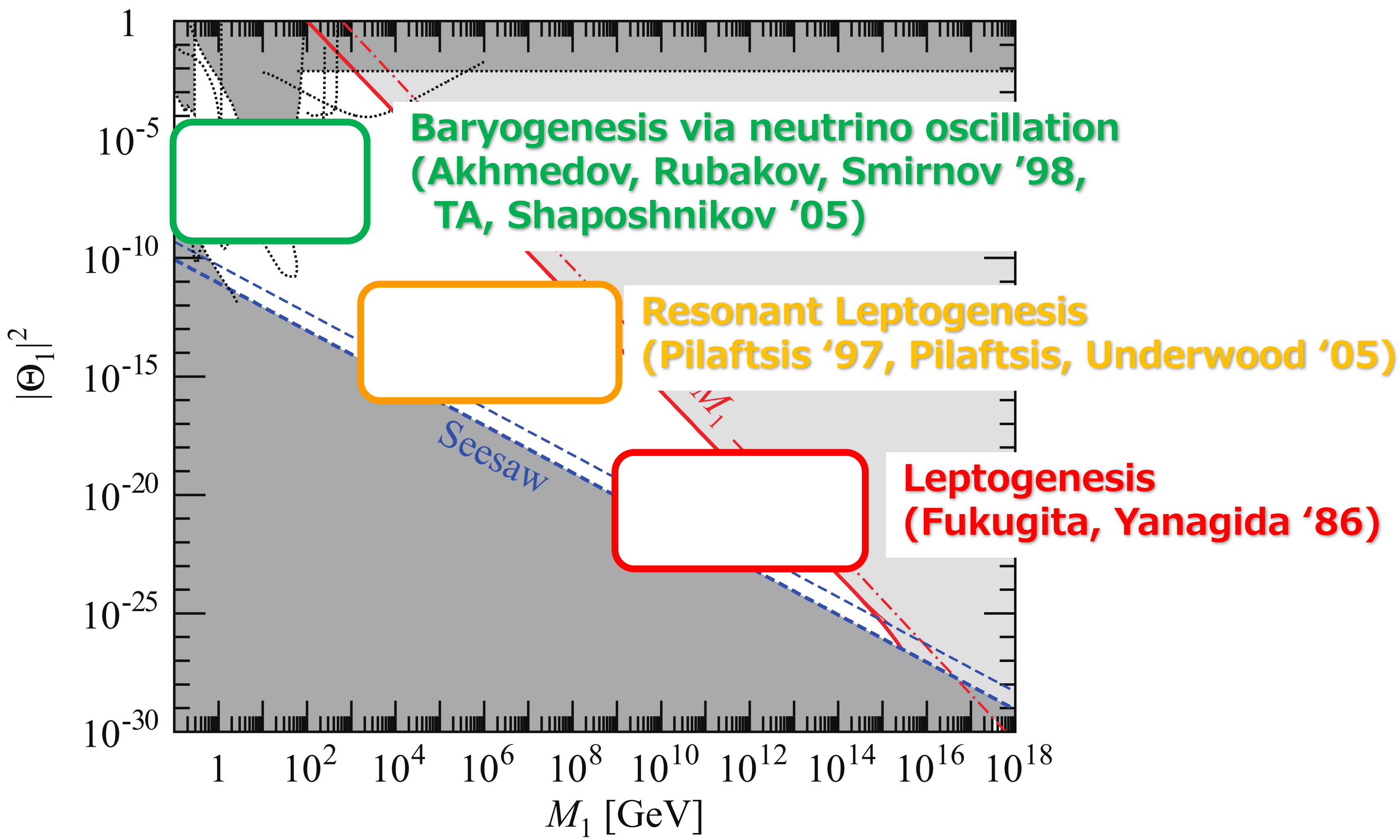
Range of parameter space

TA, Tsuyuki '15



Baryogenesis regions

TA, Tsuyuki '15



ν_R and baryon asymmetry of the universe (BAU)

Baryon asymmetry of the universe (BAU)

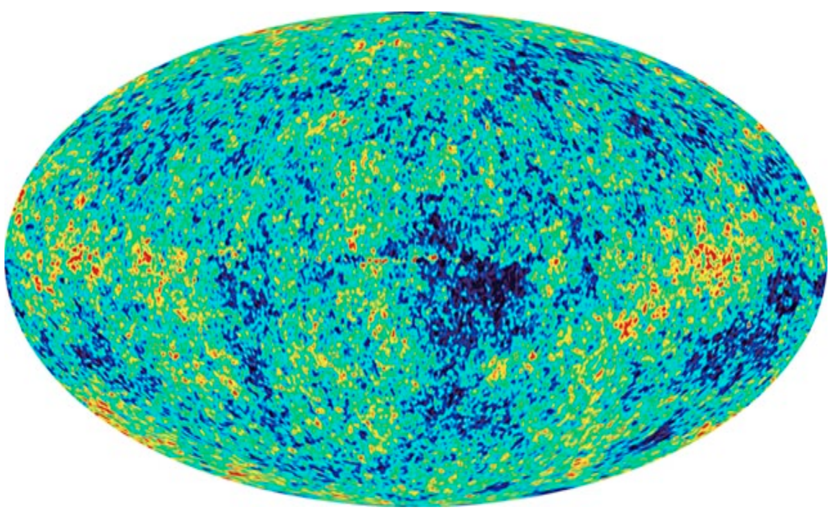
Baryon Number B = (# of baryons) − (# of antibaryons)

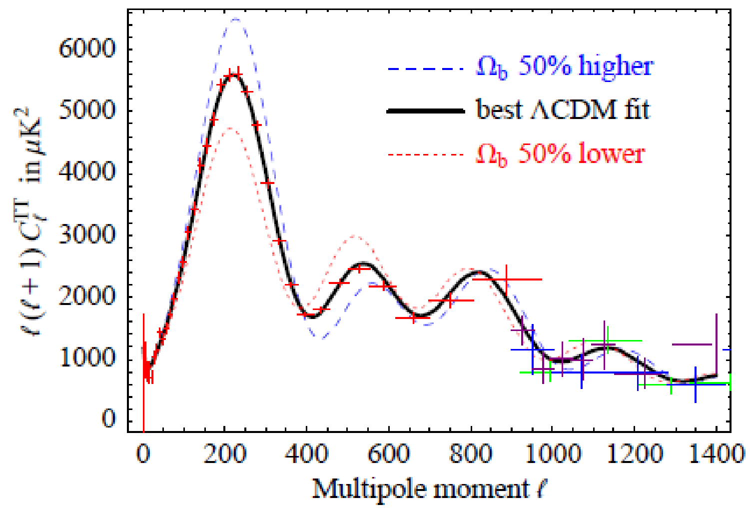
$$\frac{n_B}{s} = (8.676 \pm 0.054) \times 10^{-11}$$

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."

Baryogenesis Conditions in the SM

- B+L violations
  - Sphaleron for T>100GeV
- C and CP violations
  - 1 CP phase in the quark-mixing (CKM) matrix

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

→ too small

- Out of equilibrium
  - Strong 1st order phase transition if $m_H < 72$ GeV, but $m_H = 125$ GeV

→ not satisfied

[Kajantie, Laine, Rummukainen, Shaposhnikov]

New physics is needed !

Baryogenesis conditions and ν_R

- By introducing ν_R three conditions can be satisfied

- The way to generate BAU is different depending on the scale of Majorana mass

  - Leptogenesis

  - Resonant leptogenesis

  - Baryogenesis via neutrino oscillations

Leptogenesis

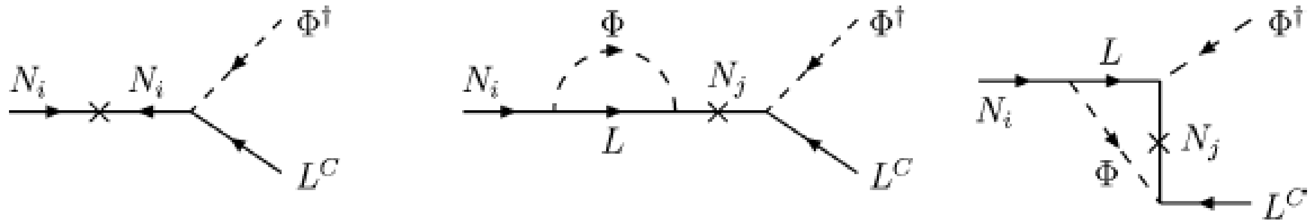
[Fukugita, Yanagida '86]

- ν_R (N) can into LH leptons and also their anti-particles

$$N_1 \to L_L + \overline{\Phi}$$
$$N_1 \to \overline{L_L} + \Phi$$

- When CP is violated in neutrino sector,

$$\varepsilon_1 = \frac{\Gamma(N_1 \to L_L + \overline{\Phi}) - \Gamma(N_1 \to \overline{L_L} + \Phi)}{\Gamma(N_1 \to L_L + \overline{\Phi}) + \Gamma(N_1 \to \overline{L_L} + \Phi)} \neq \mathbf{0}\ !$$



$\Longrightarrow$ generate asymmetry ΔL_L between $\#L_L$ and $\#\overline{L_L}$

- Asymmetry in L_L is partially converted into baryon asymmetry by EW sphaleron process ($T \gtrsim 10^2$ GeV)

$$\Delta L_L \implies B$$

Leptogenesis

[Fukugita, Yanagida '86]

- Yield of BAU

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

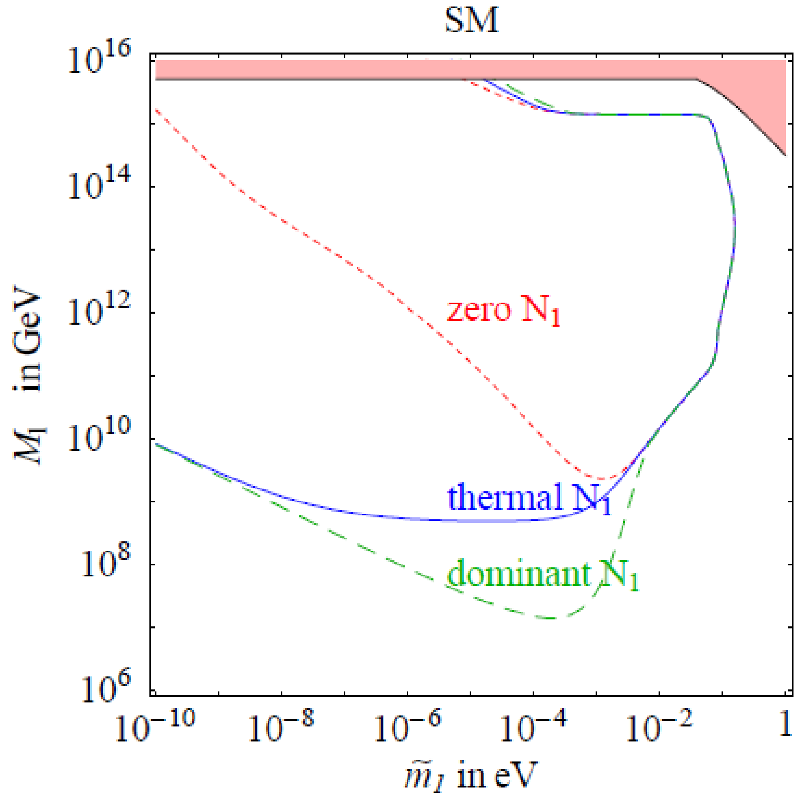
$$\frac{n_B}{s} \propto \varepsilon_1 \propto M_1 \quad \longleftarrow \quad M_1 \ll M_{2,3,\ldots}$$

Lower bound on Majorana mass in order to explain the observed BAU

$$M_1 > O(10^9)\ \text{GeV}$$

→ impossible to test directly such a heavy particle by experiments

[Giudice et al '03]



Resonant leptogenesis

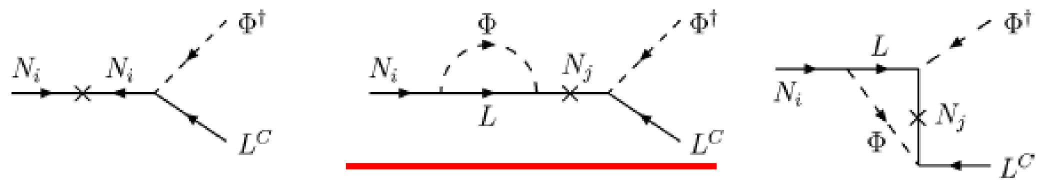
Pilaftsis '97
Pilaftsis, Underwood '04

- 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

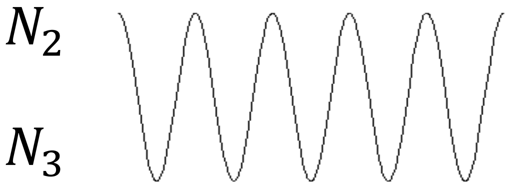
$\Longrightarrow$ Leptogenesis is possible even for $M_1 \ll 10^9$ GeV

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

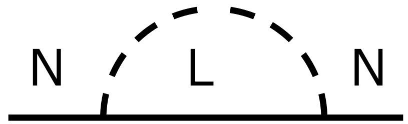
Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)
Shaposhnikov ('08), Canetti, Shaposhnikov ('10)
TA, Ishida ('10), Canetti, Drewes, Shaposhnikov ('12), TA, Eijima, Ishida ('12)
Canetti, Drewes, Shaposhnikov ('12), Canetti, Drewes, Frossard, Shaposhnikov ('12)
...

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

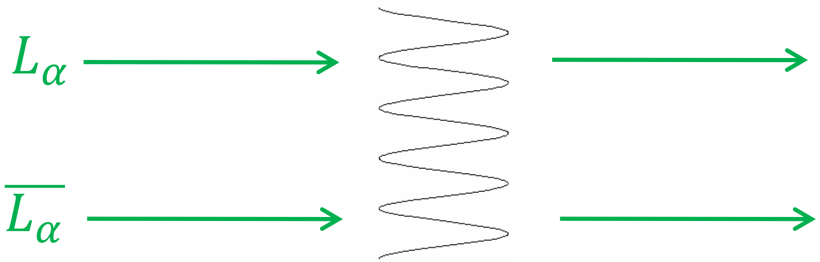


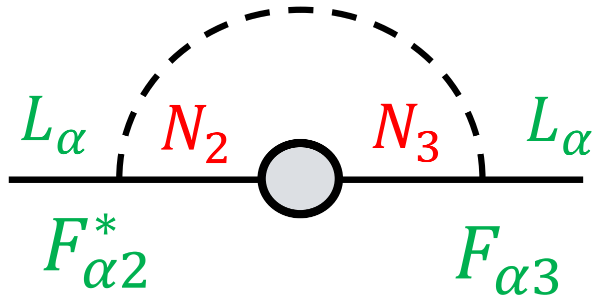
$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects



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

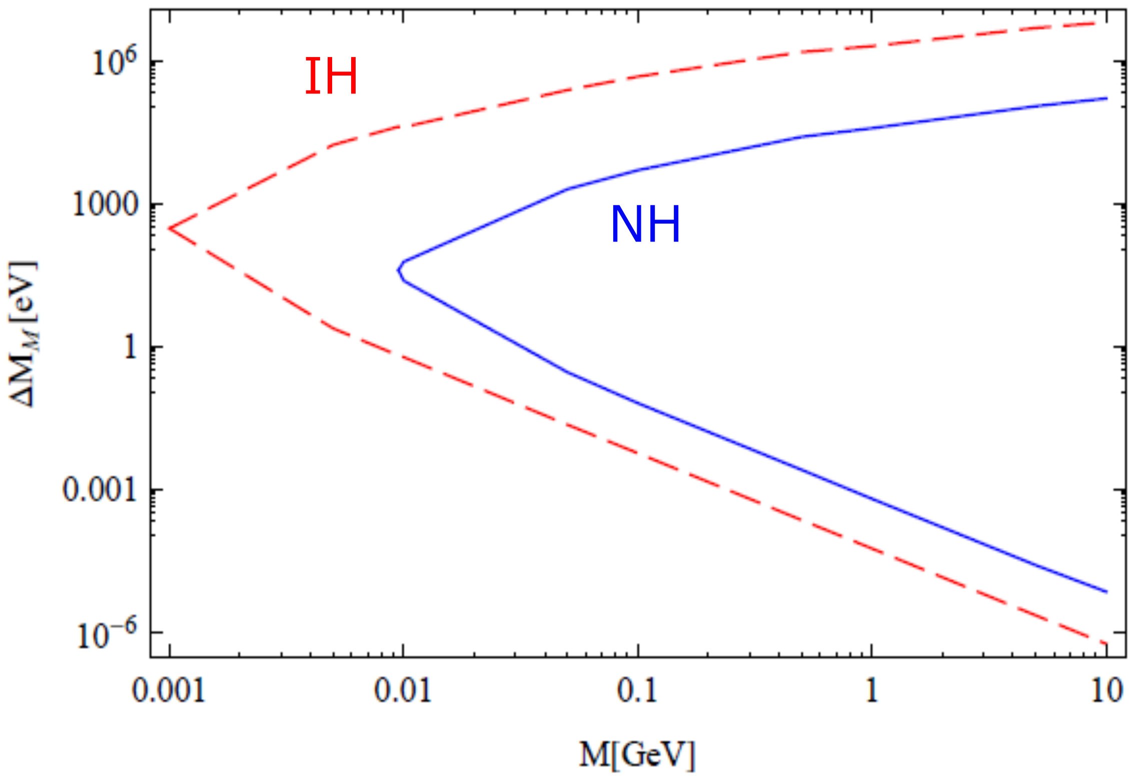




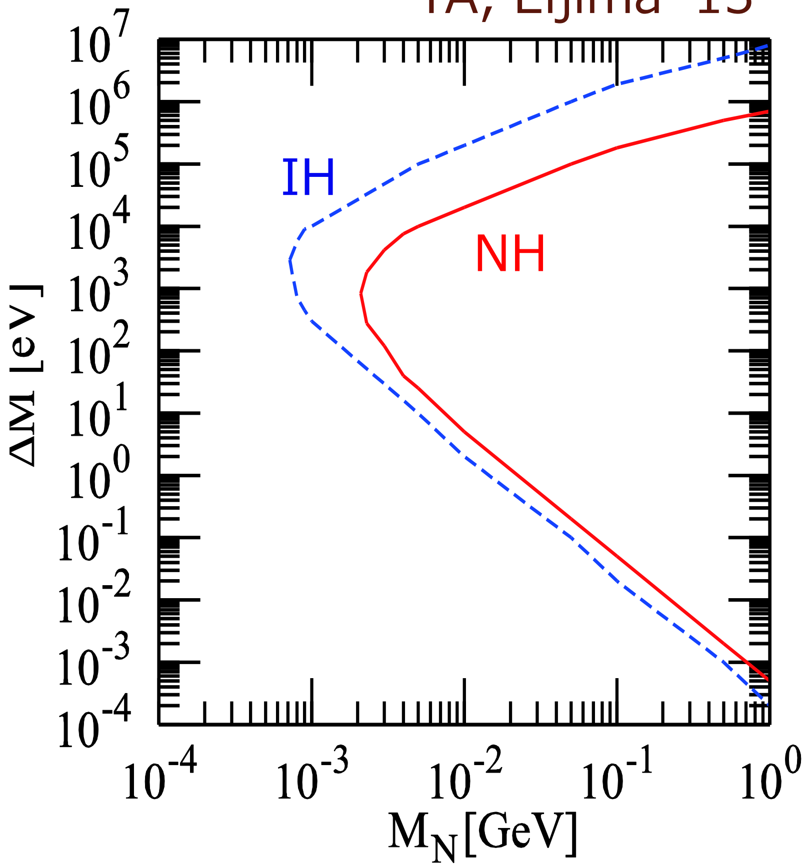
Baryogenesis Region

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

Canetti, Shaposhnikov '10



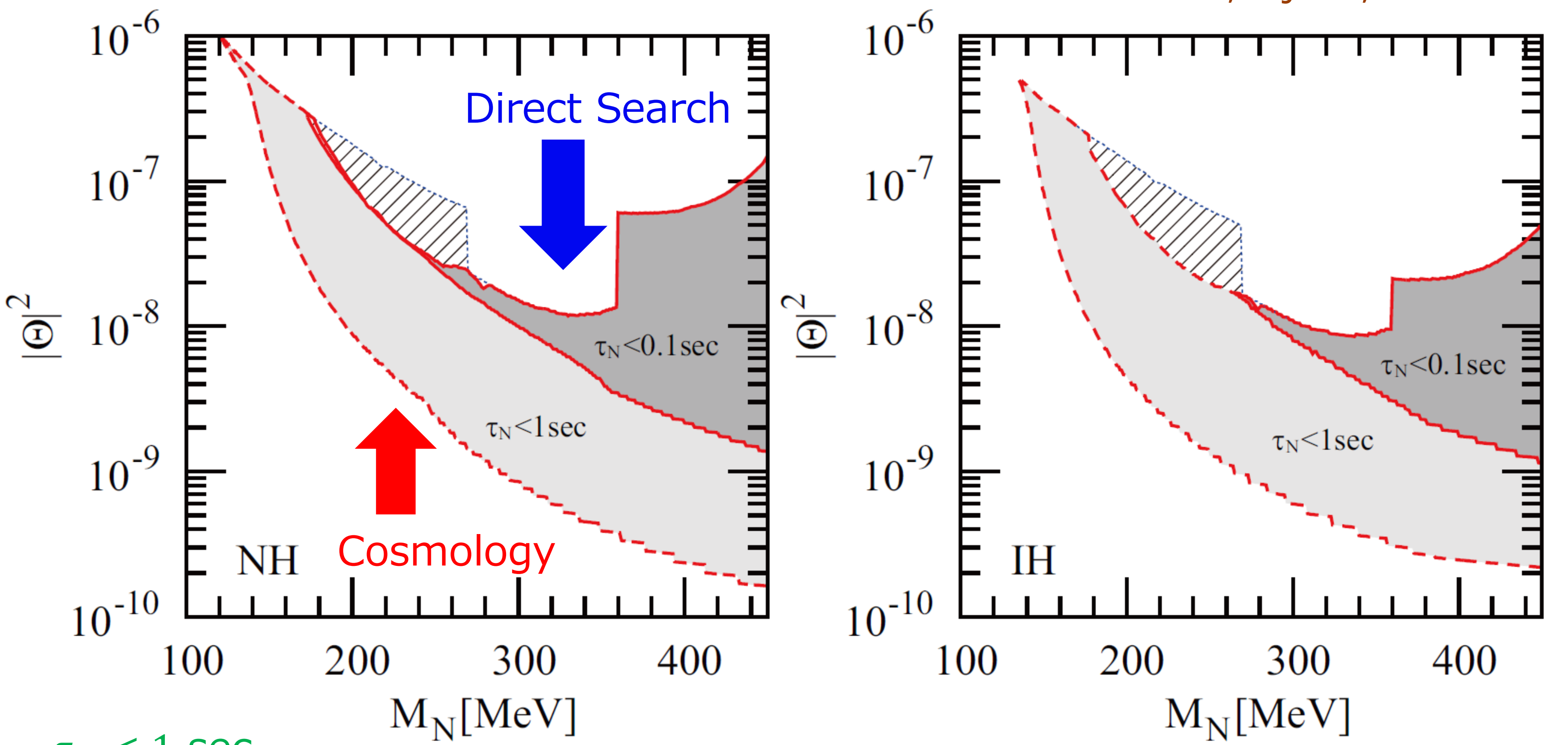
TA, Eijima '13



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

Constraints on HNL

TA, Eijima, Takeda '14

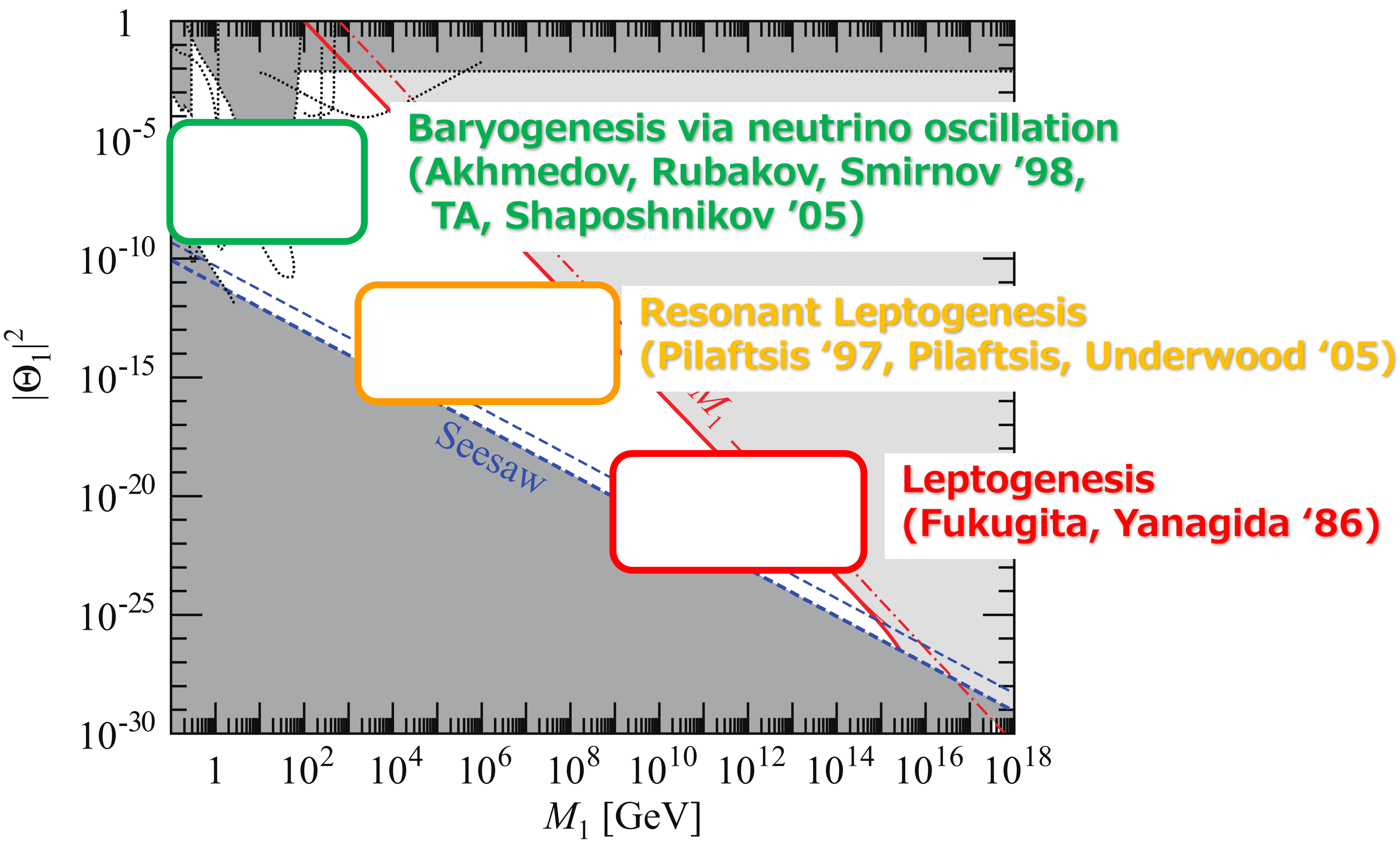


$\tau_N < 1$ sec

$M_N > 122$ MeV (NH) $M_N > 136$ MeV (IH)

Baryogenesis regions

TA, Tsuyuki '15



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

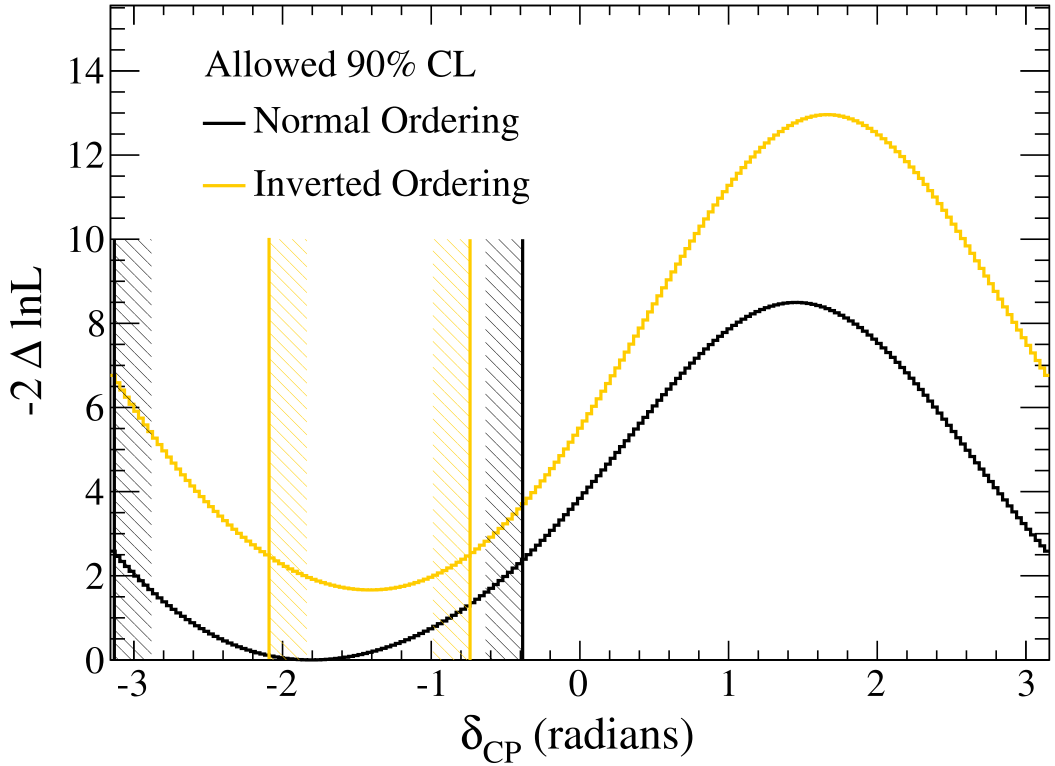
Phase(s) for ν_R

These phases are essential for BAU !

BAU and CPV in neutrino sector

- T2K and NOvA indicate CPV in neutrino sector

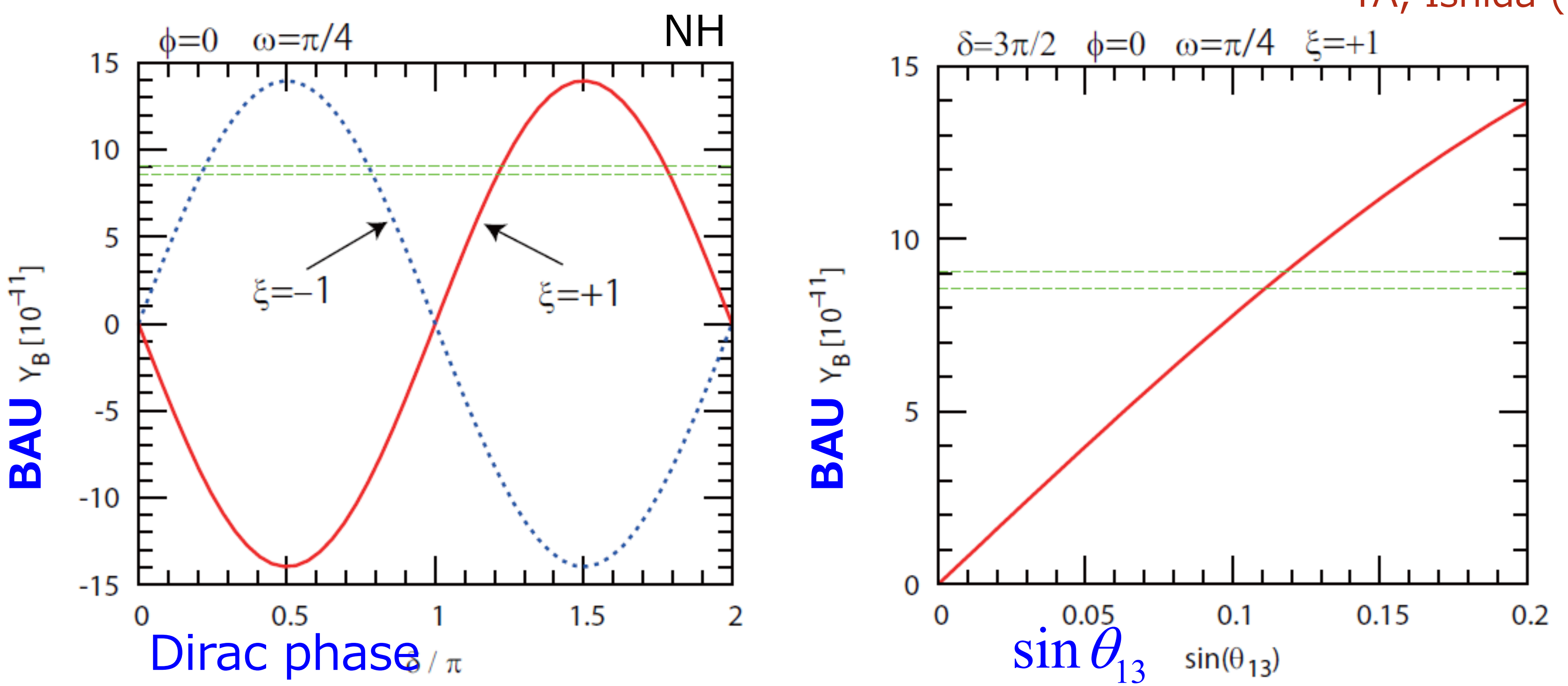
T2K, PRL 118, 151801 ('17)



Important step to understand baryogenesis by RH neutrinos !

Dirac phase δ and baryogenesis via oscillation

TA, Ishida ('10)

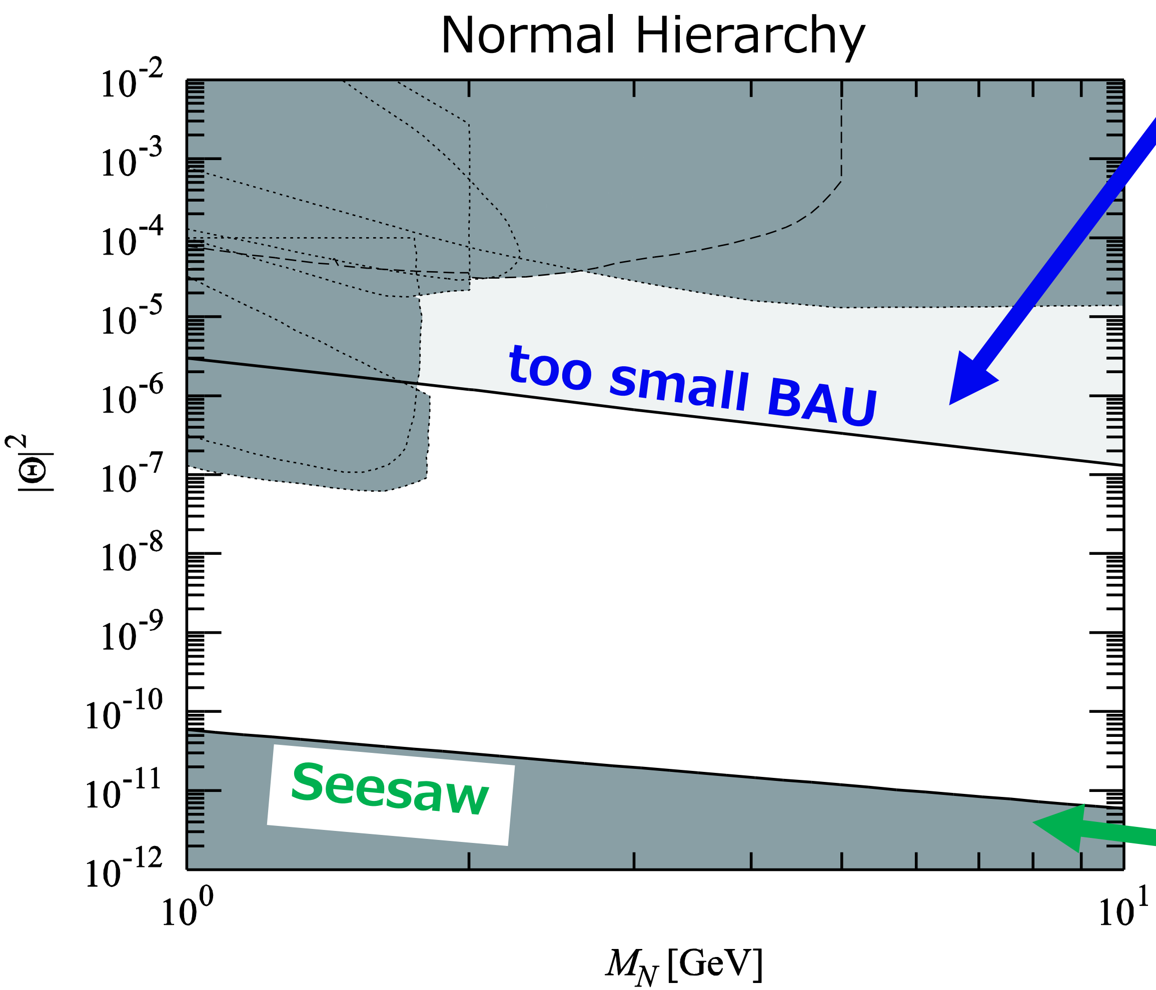


$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\phi} & \\ & & 1 \end{pmatrix}$$

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

ν_R and experimental test of model

Baryogenesis region



Bound from BAU

to avoid strong washout

Canetti, Shaposhnikov '10 [arXiv:1006.0133]

Drewes, Garbrecht, Gueter, Klaric '16 [arXiv:1609.09069]

TA, Eijima, Ishida, Minogawa, Yoshii '17 [to appear]

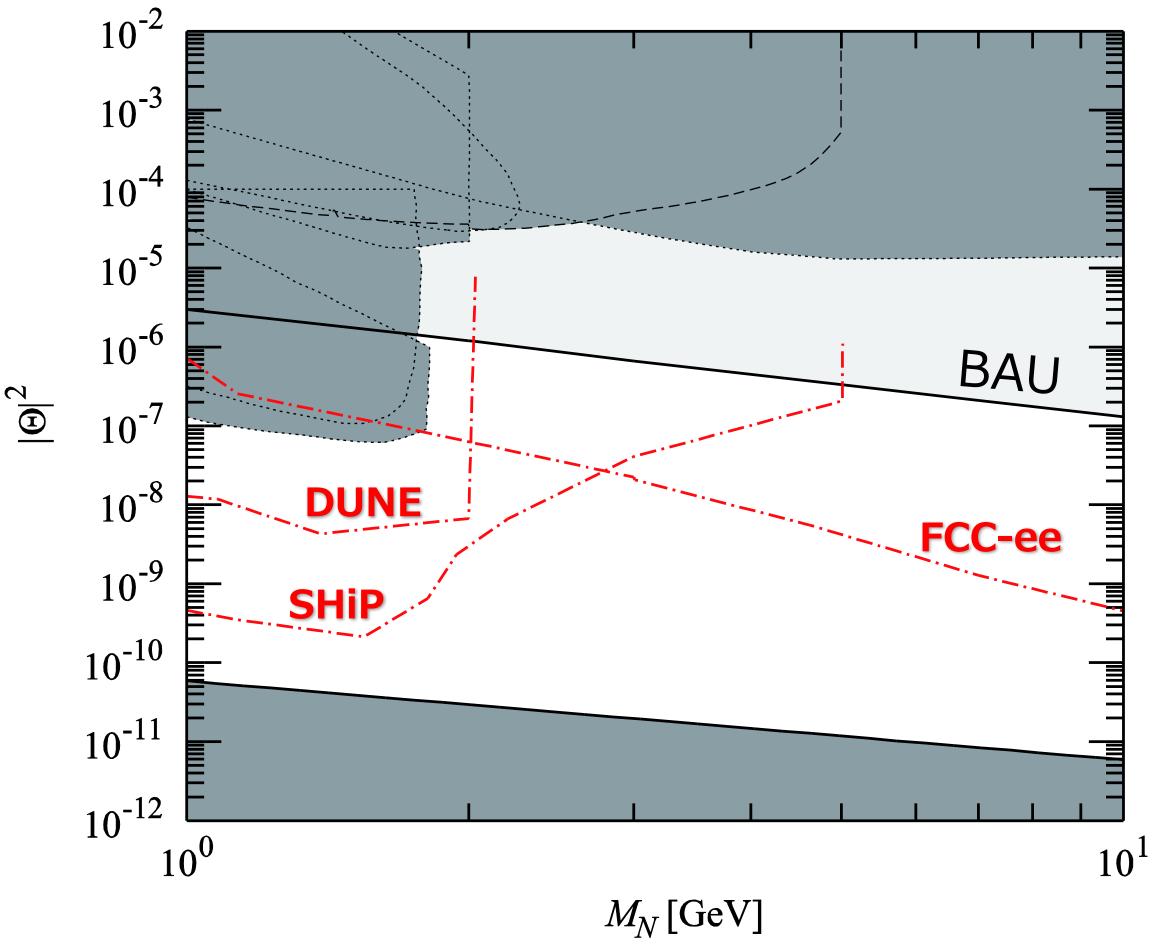
Bound from Seesaw

to explain neutrino masses

$$|\Theta|^2 > \frac{\Sigma m_i}{2\, M_N}$$

Sensitivities by future searches

Normal Hierarchy



Sensitivity for $|\Theta_\mu|^2$

- **LBNE (DUNE)**
  N decay inside near detector
  Adams et al '13 [arXiv:1307.7335]

- **SHiP**
  beam dump exp.
  Anelli et al '13 [arXiv:1504.04956]

- **FCC-ee at Z-pole**
  displaced vertex of N decay
  Blondel, Graverini, Serra, Shaposhnikov
  (FCC-ee study team) '14
  [arXiv:1411.5230]

From experimental study of ν_R together with BAU,
we may know parameters of the model !

Model with two right-handed neutrinos

- **Model parameters**

Casas, Ibarra (01)

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

masses of ν_i

m_1, m_2, m_3

Mass ordering

mixings of ν_i

$\theta_{23}, \theta_{12}, \theta_{13}$

Dirac phase

δ

Majorana phase

η

masses of ν_R

$M_N, \Delta M$

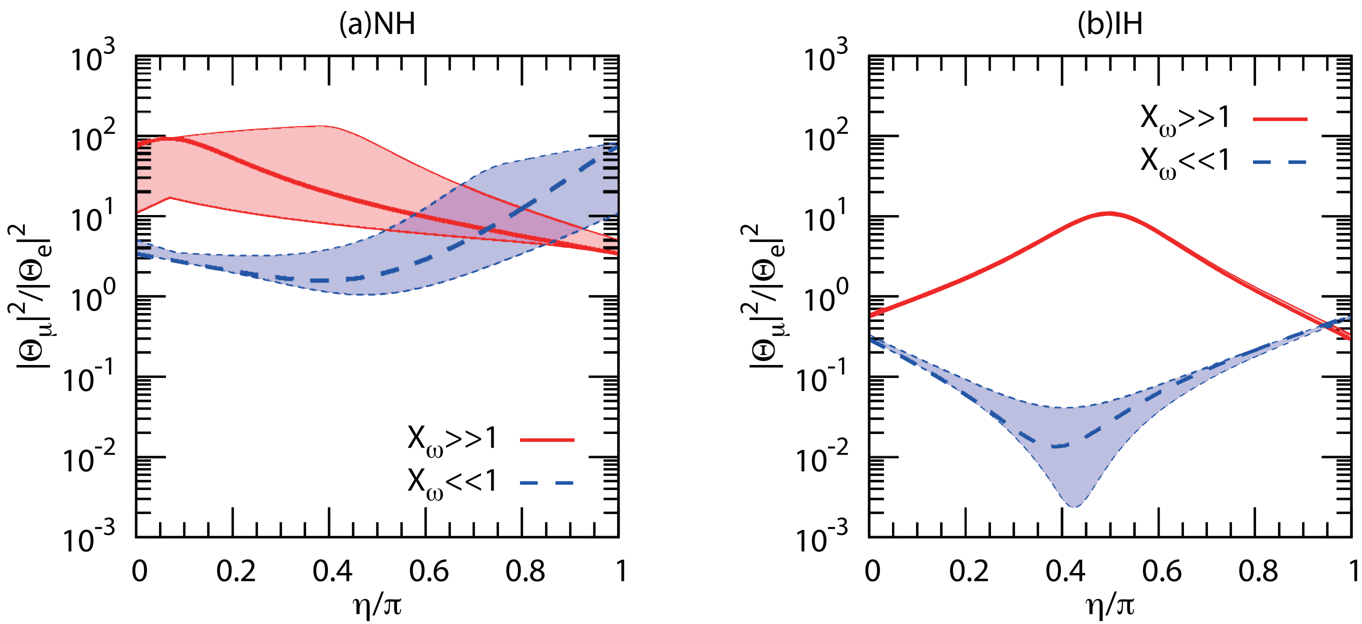
$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \sin\omega & \cos\omega \end{pmatrix}$$

Reω, $X_\omega = e^{\mathrm{Im}\omega}$

How do we determine these unknown parameters ?

Search experiments

- Consider ν_R would be discovered with large mixing $\boldsymbol{\Theta}$
  - Degenerate mass M_N can be measured
    - NOTE: BAU requires $\Delta M \ll M_N$
  - Mixing can be measured → $X_\omega \gg 1$ or $X_\omega \ll 1$ can be measured
    - $|\Theta|^2 = \sum_{\alpha=e,\mu,\tau} |\Theta_{\alpha I}|^2 = \frac{\Sigma m_i}{2\, M_N}(X_\omega^2 + X_\omega^{-2})$
  - $|\Theta|_e^2$, $|\Theta|_\mu^2$, and $|\Theta|_\tau^2$ depend on Majorana phase η and X_ω



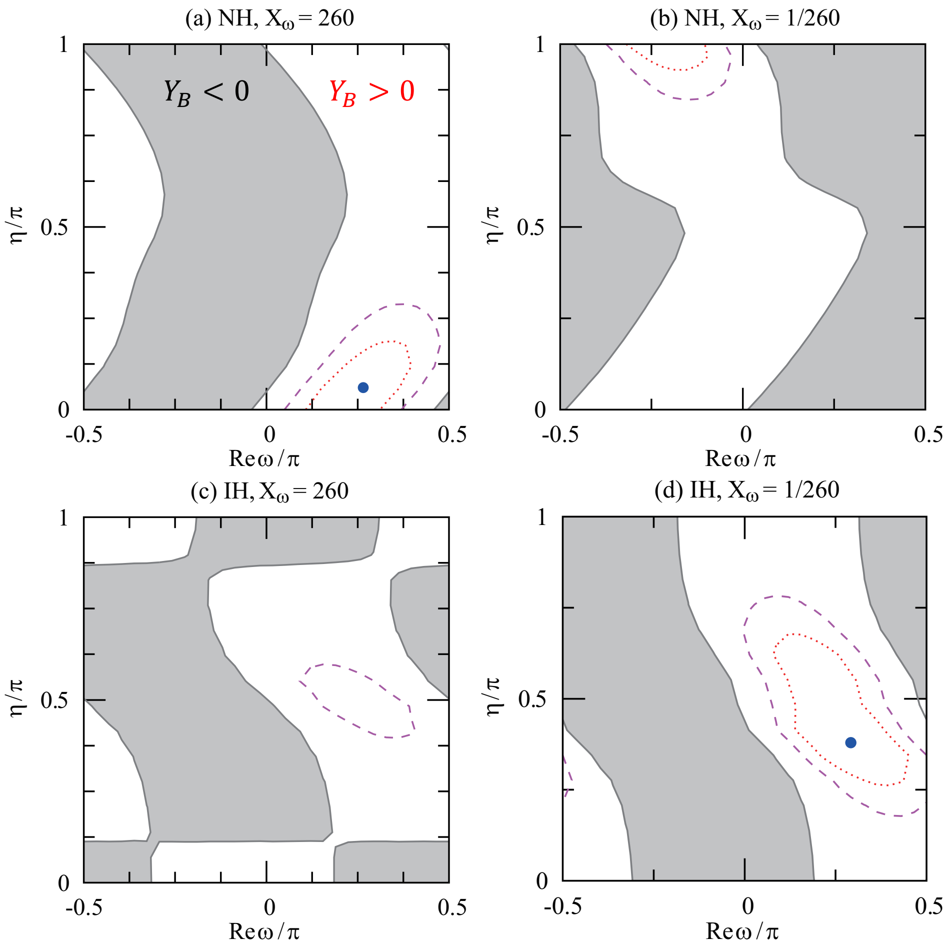
The ratio $|\Theta_\mu|^2/|\Theta_e|^2$ may determine η

We may also learn whether $X_\omega \gg 1$ or $X_\omega \ll 1$

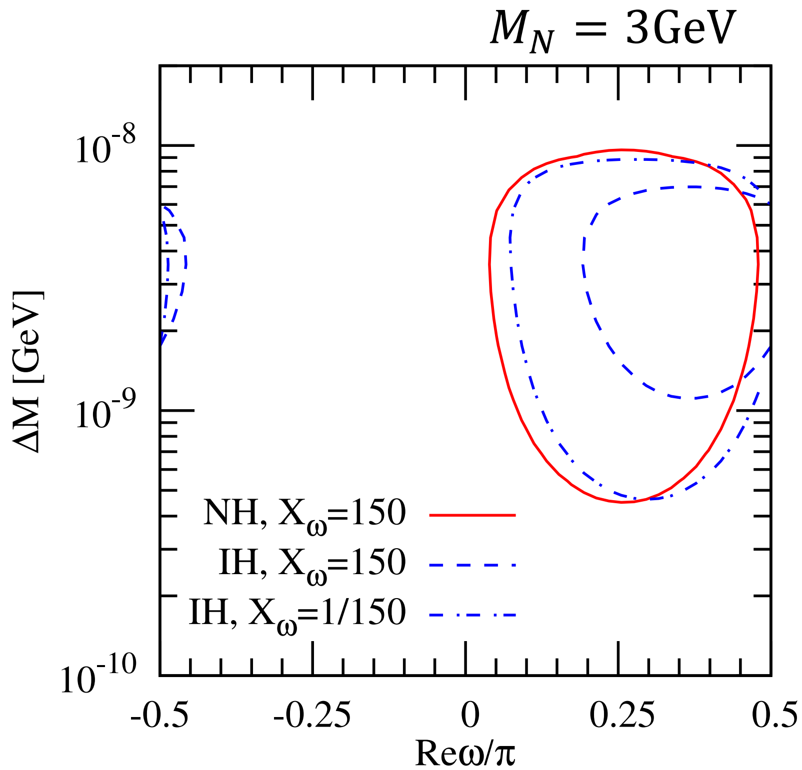
Baryon asymmetry

- Reω and ΔM are difficult to be probed by search experiments, since $|\Theta_{\alpha I}|$ are insensitive in large mixing region
- BAU is crucial to determine them

Majorana phase η



Mixing angle Reω between two RH neutrinos



BAU (sign and magnitude) can indicate the region of

Reω and ΔM

Model with two right-handed neutrinos

- **Model parameters**

Casas, Ibarra (01)

$$F = U_{\rm PMNS}\, M_\nu^{1/2}\, \Omega\, M_M^{1/2}$$

masses of ν_i

m_1, m_2, m_3

Mass ordering

mixings of ν_i

$\theta_{23}, \theta_{12}, \theta_{13}$

Dirac phase

δ

Majorana phase

η

masses of ν_R

M_N, ΔM

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

$\mathrm{Re}\,\omega$, $X_\omega = e^{\mathrm{Im}\,\omega}$

Oscillation experiments

Search experiments

Baryon asymmetry

ν_R and neutrinoless double beta decay

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

W.H. Furry 1939

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

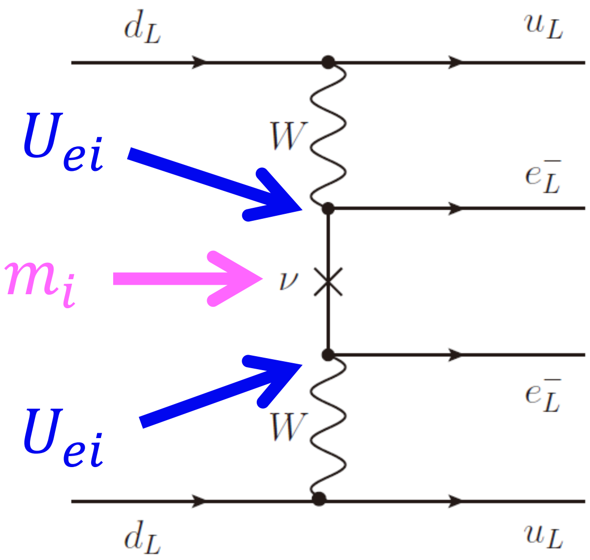
  $$(Z, A) \to (Z+2, A) + 2e^-$$

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

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

$$T_{1/2}^{-1} = A \frac{m_p^2}{\langle p^2 \rangle^2} \left| m_{\rm eff} \right|^2$$

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



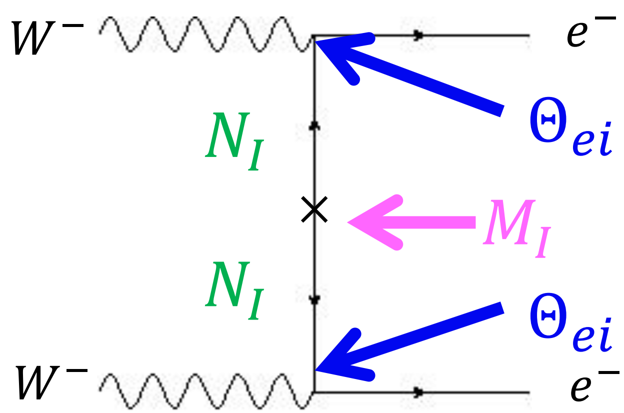
Faessler, Gonzalez, Kovalenko, Simkovic '14

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

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

active neutrinos **heavy neutral leptons**

- HNLs may give a significant contribution to m_{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

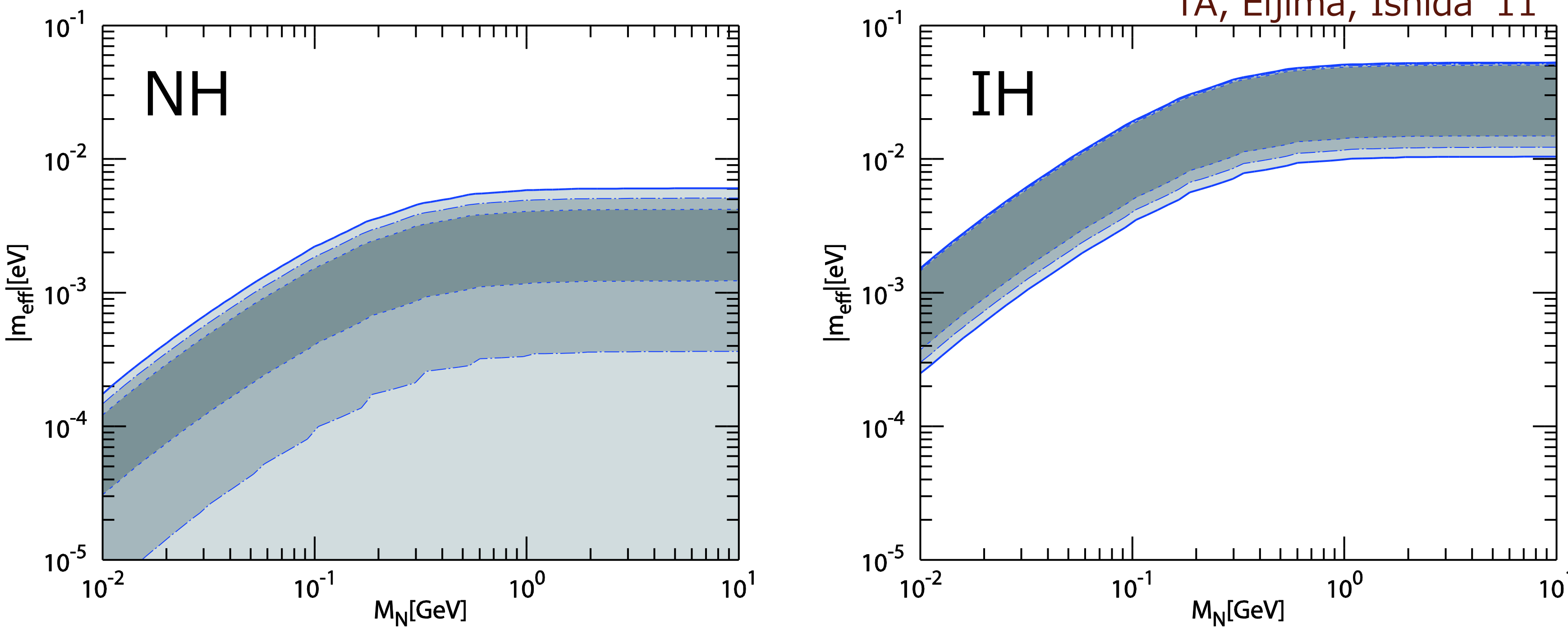
$0\nu\beta\beta$ decay in the seesaw

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

$$m_{\rm eff} = \sum_i m_i U_{ei}^2 + \sum_I f_\beta(M_I) M_I\, \Theta_{eI}^2 = \mathrm{m}_{\rm eff}^{\nu}[\,1\, - f_\beta(M_N)]$$

  - 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

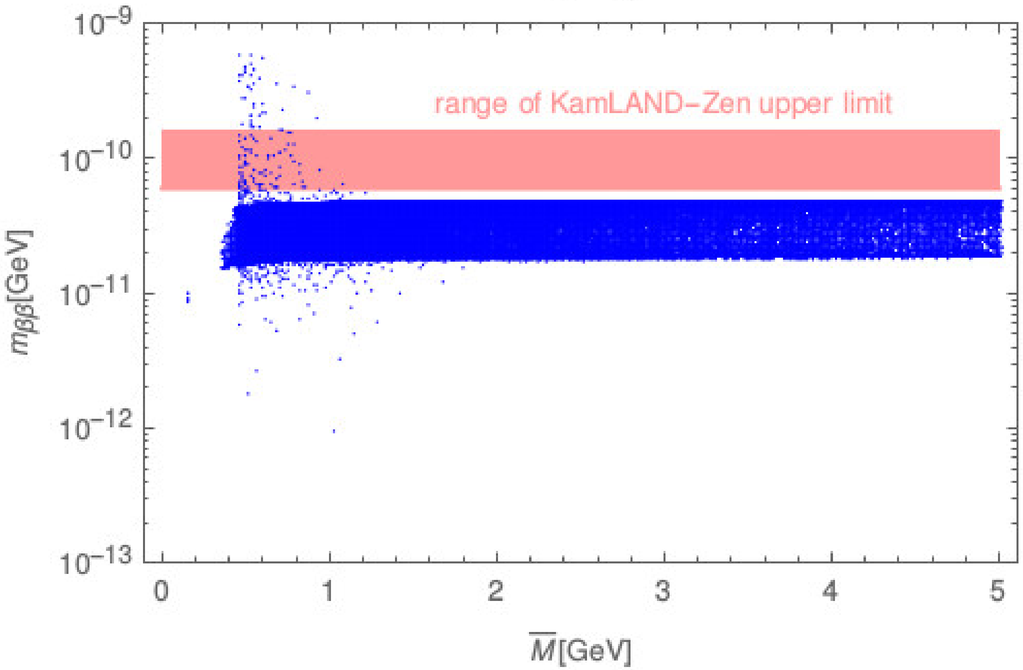
TA, Eijima, Ishida '11



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

- Recently, it has been pointed out that $\nu_R{}'s$ give a significant, additive contribution to effective mass for IH and $M_N\sim500$ MeV when ΔM is relatively large

Drewes, Eijima ('16), TA, Eijima, Ishida ('16),
Hernandez, Kekic, Lopez-Pavon, Racker, Salvado ('16)



Drewes, Eijima ('16)

It is an interesting signal of $\nu_R{}'s$ for the seesaw mechanism and baryogenesis via neutrino oscillation !

Summary

- Right-handed neutrinos are well-motivated physics beyond the Standard Model

- They can explain neutrino masses through the seesaw mechanism and baryon asymmetry of the universe (BAU) (via leptogenesis, neutrino oscillation, ⋯) at the same time.

- Experimental tests of such right-handed neutrinos are important to understand the origin of neutrino masses and BAU

Backup

Evolution of Each Asymmetry

Active Sector

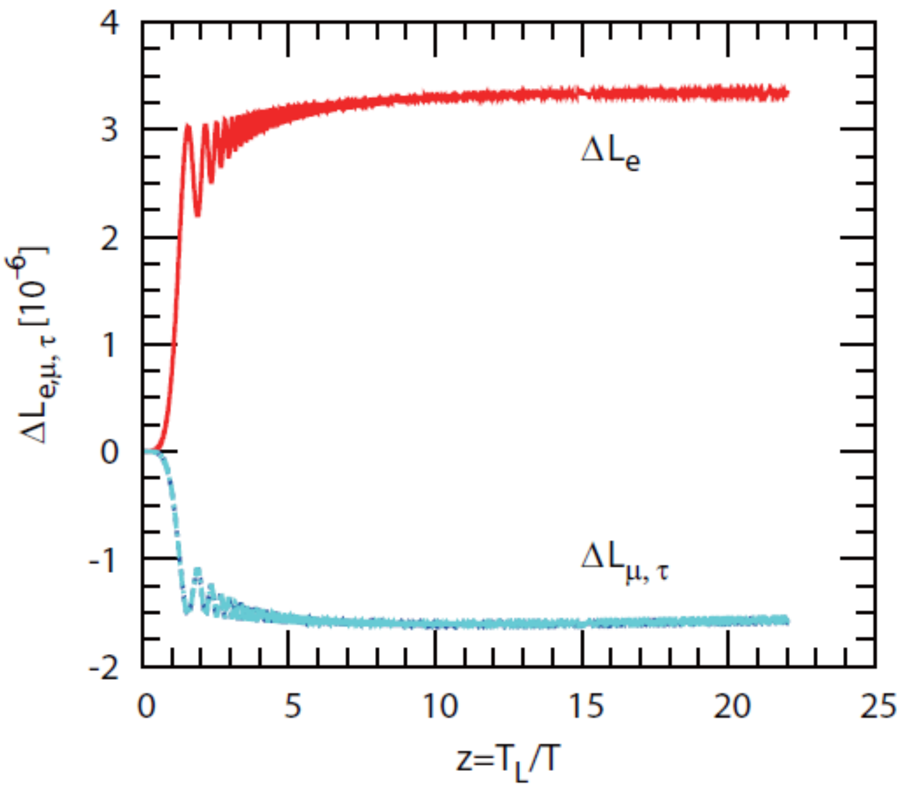


Figure 5: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

Sterile Sector

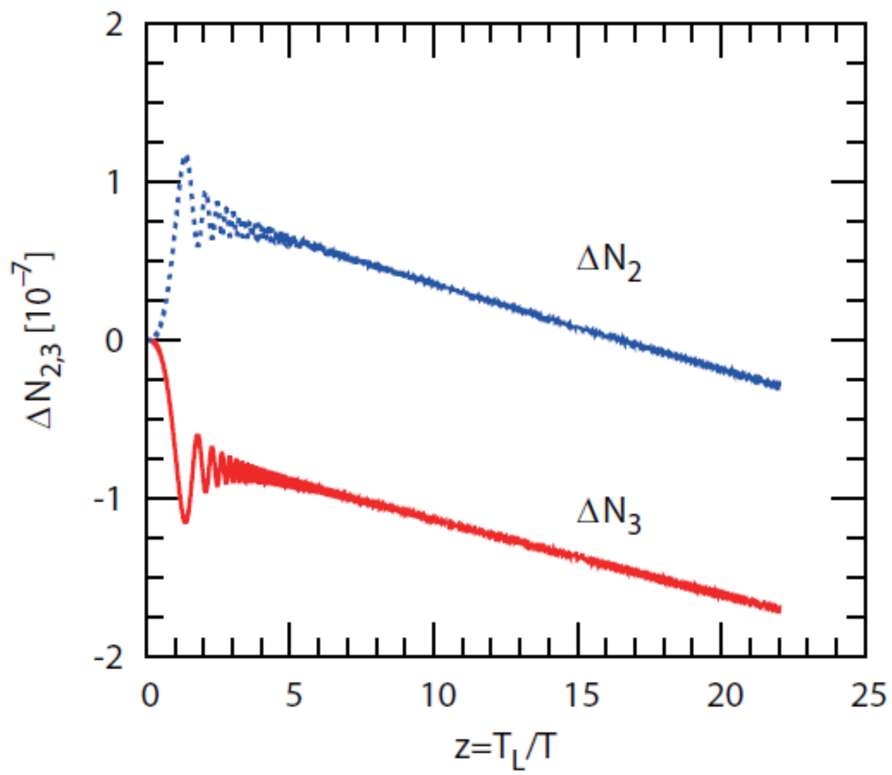
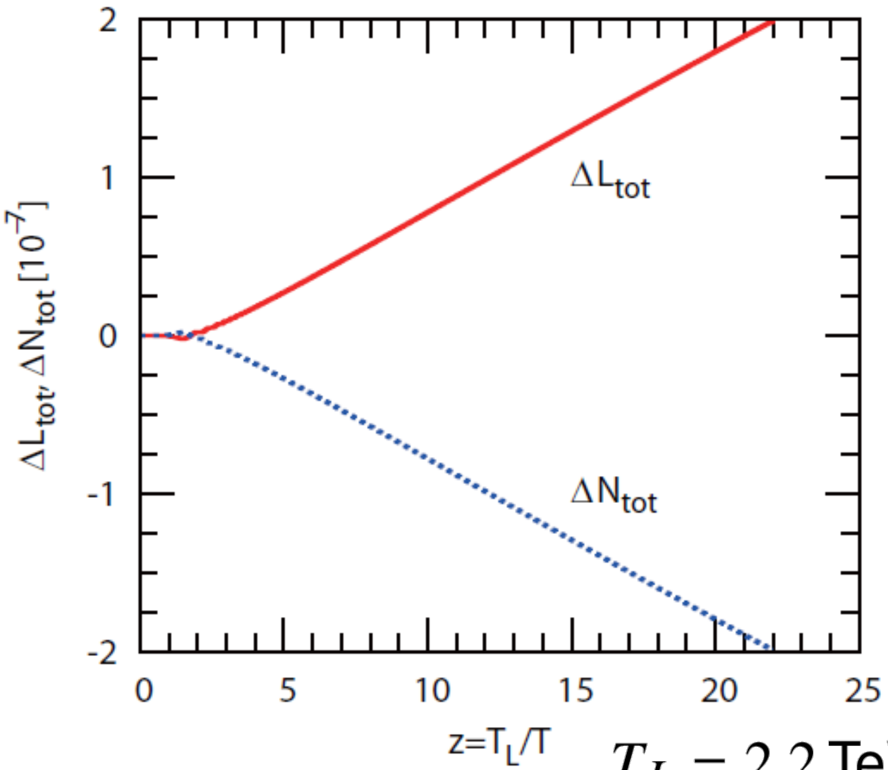


Figure 6: Evolution of asymmetries in terms of $z = T_L/T$. Here we take $M_3 = 3$ GeV, $\Delta M_{32}^2/M_3^2 = 10^{-8}$, $\xi = +1$, $\sin\theta_{13} = 0.2$, $\phi = 0$, $\omega = \pi/4$ and $\delta = 3\pi/2$.

$T_{osc} = 2.2$ 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]

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

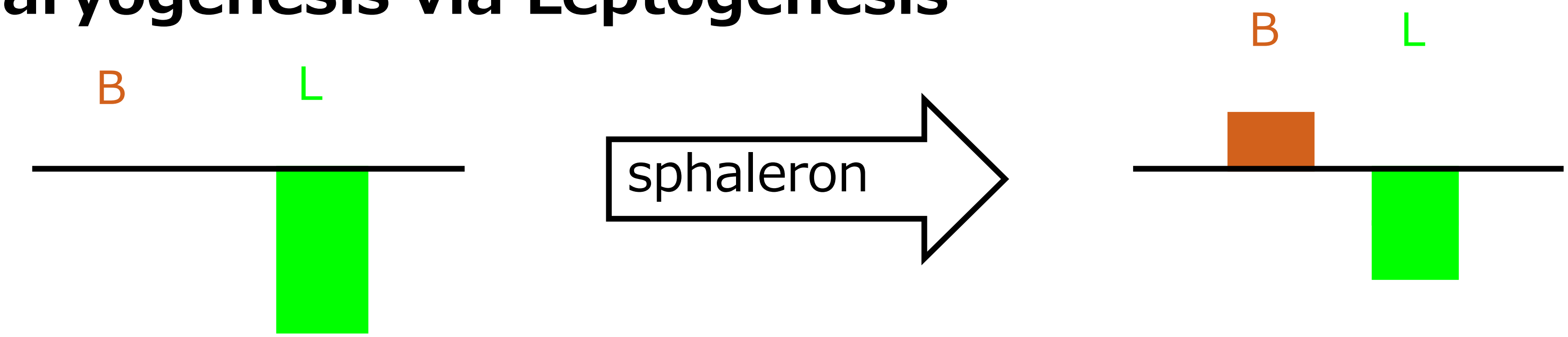
$$\frac{n_B}{s} = -2.5\times10^{-4}\,\Delta L_{tot}(T_W)$$

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

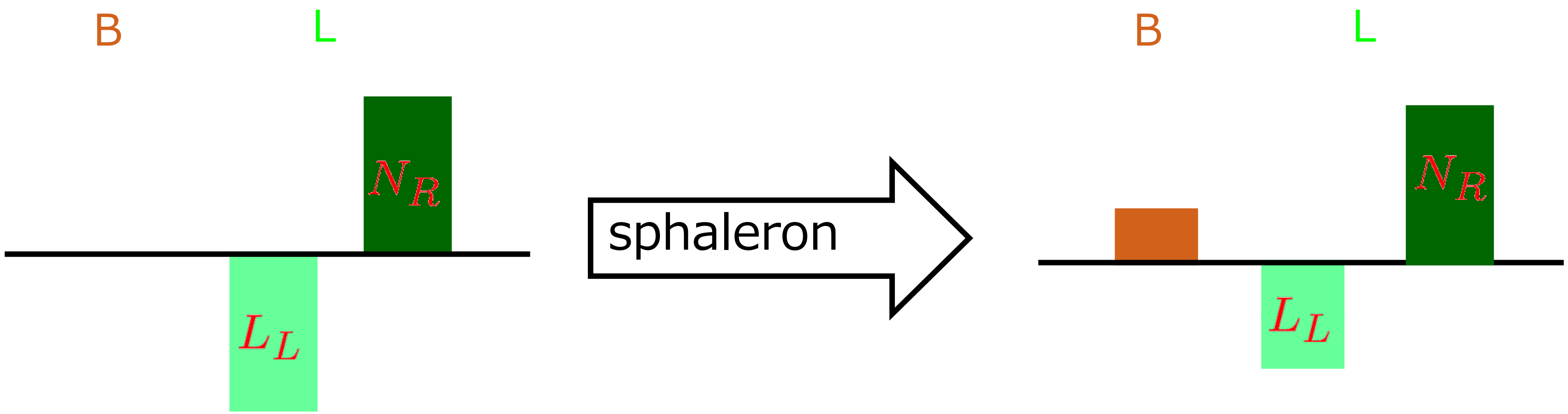
[Planck 2013]

Key Point

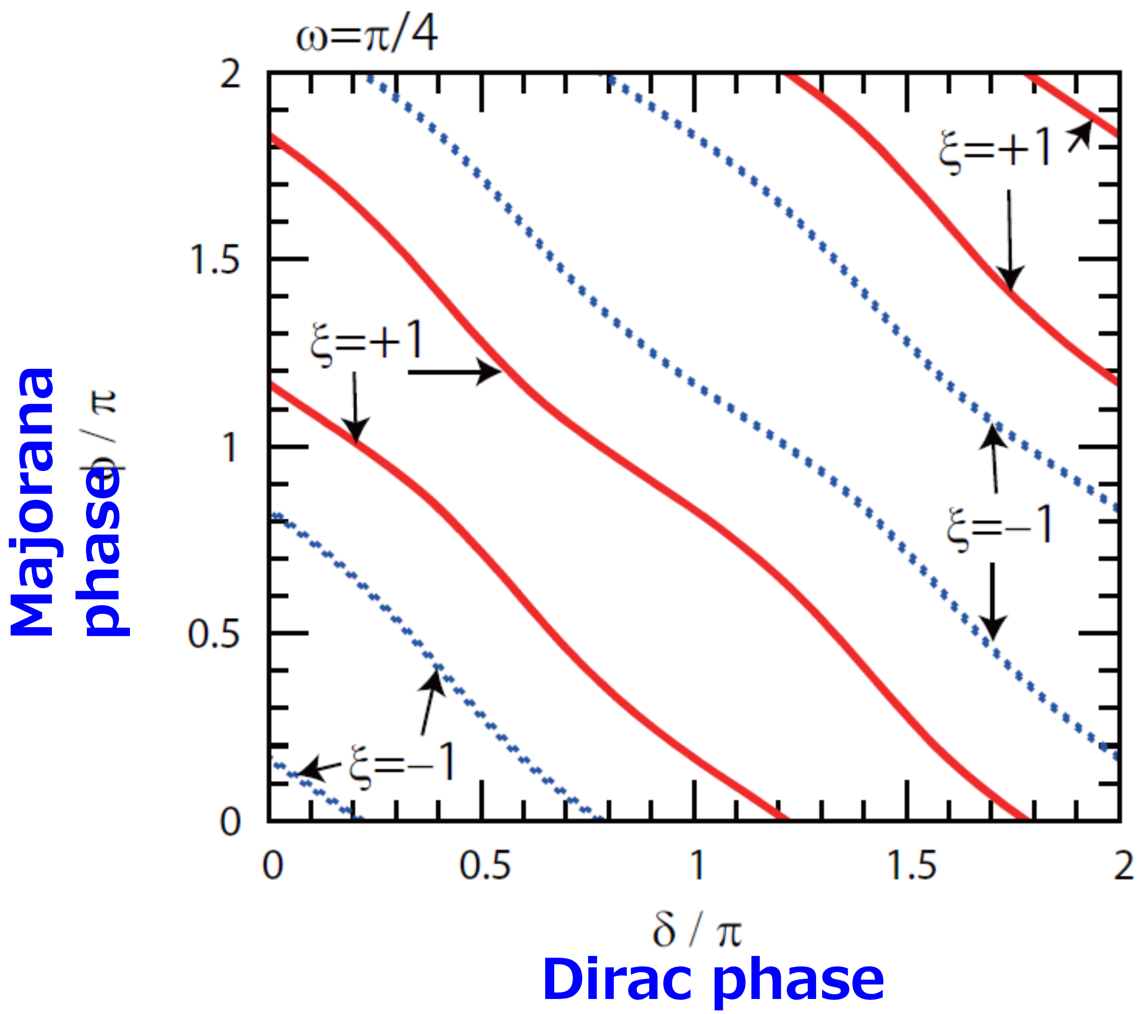
Baryogenesis via Leptogenesis



Baryogenesis via Neutrino Oscillation



Regions accounting for BAU



$$\left.\frac{n_B}{s}\right|_{\rm obs} = (8.81 \pm 0.23) \times 10^{-11}$$

Inputs:

$$M_3 = 3\text{GeV}$$

$$M_2^2 = M_3^2\ (1 - 10^{-8})$$

$$\sin\theta_{13} = 0.2$$

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

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

- Seesaw relation plays an important role !

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

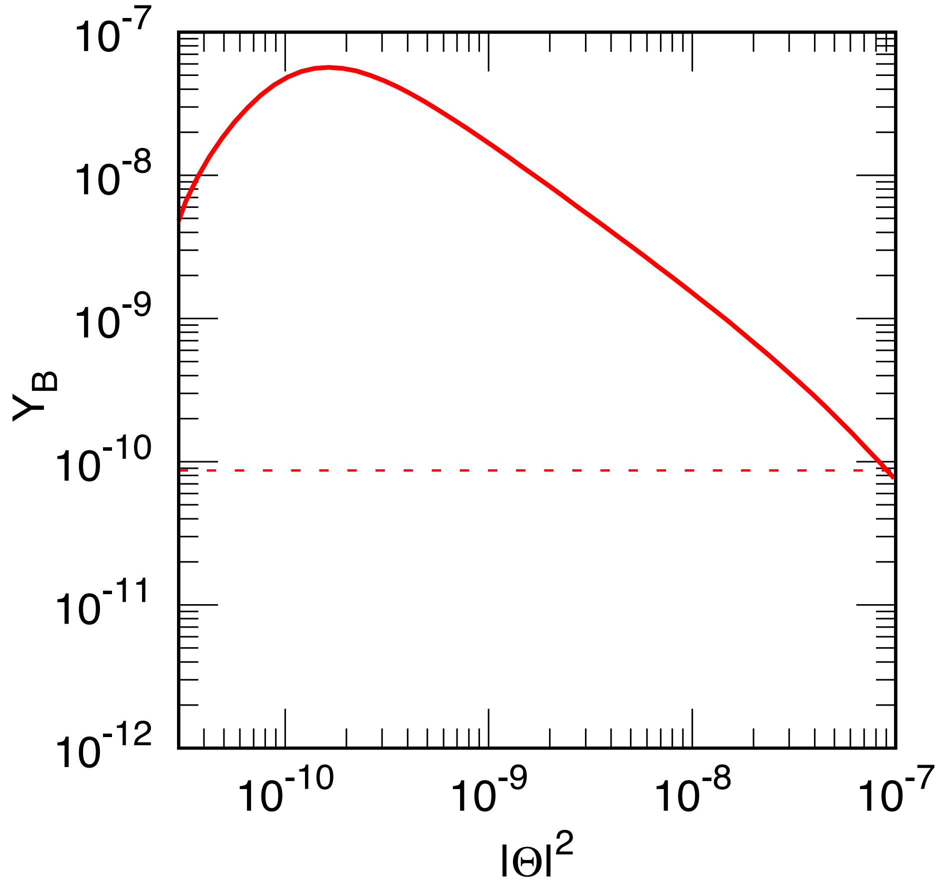
- When all HNLs are light $M_I \ll \sqrt{\langle p^2 \rangle} \sim 0.1$ GeV (i.e. $f_\beta = 1$),

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

  - This shows $0\nu\beta\beta$ decay does not occur even if neutrinos are Majorana fermions.
  - In this case, there is no bound on the mixing from $0\nu\beta\beta$ decay

Upper bound on mixing from BAU

- Large mixing region
  - good for search of HNLs
  - bad for strong washout of BAU

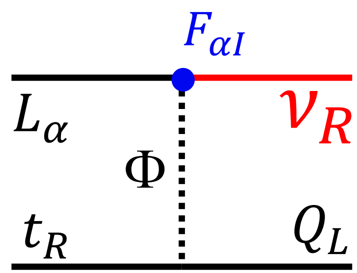


TA, Eijima, Ishida, Minogawa, Yoshii ’17 [to appear]

- Large mixing means ⋯

$$\Theta_{\alpha I} = \frac{[M_D]_{\alpha I}}{M_I} = \frac{F_{\alpha I}\langle\Phi\rangle}{M_I}$$

→ large Yukawa couplings



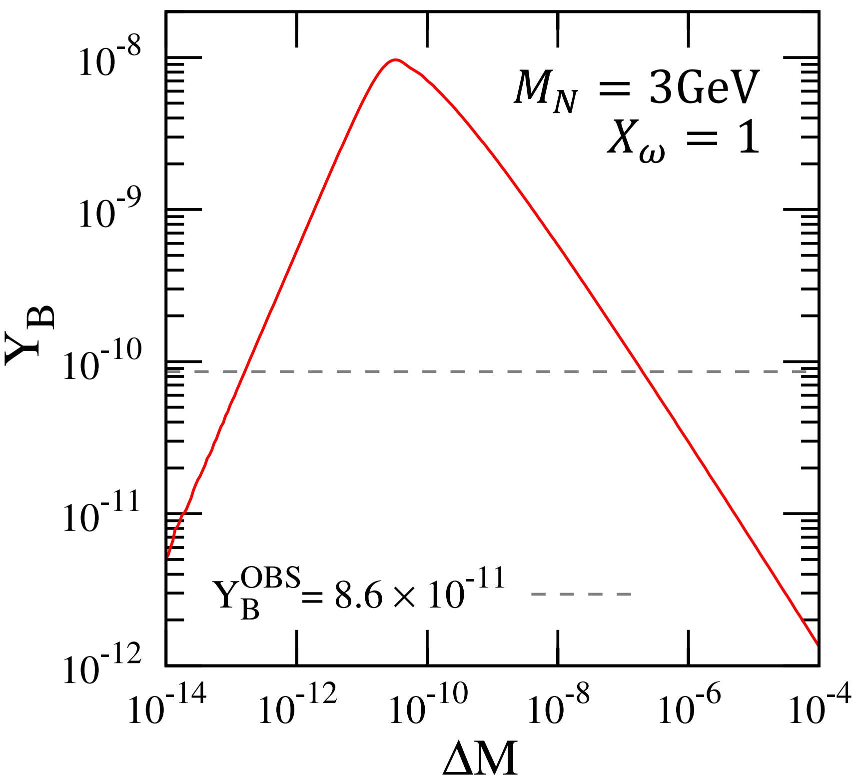
→ thermalization of ν_R

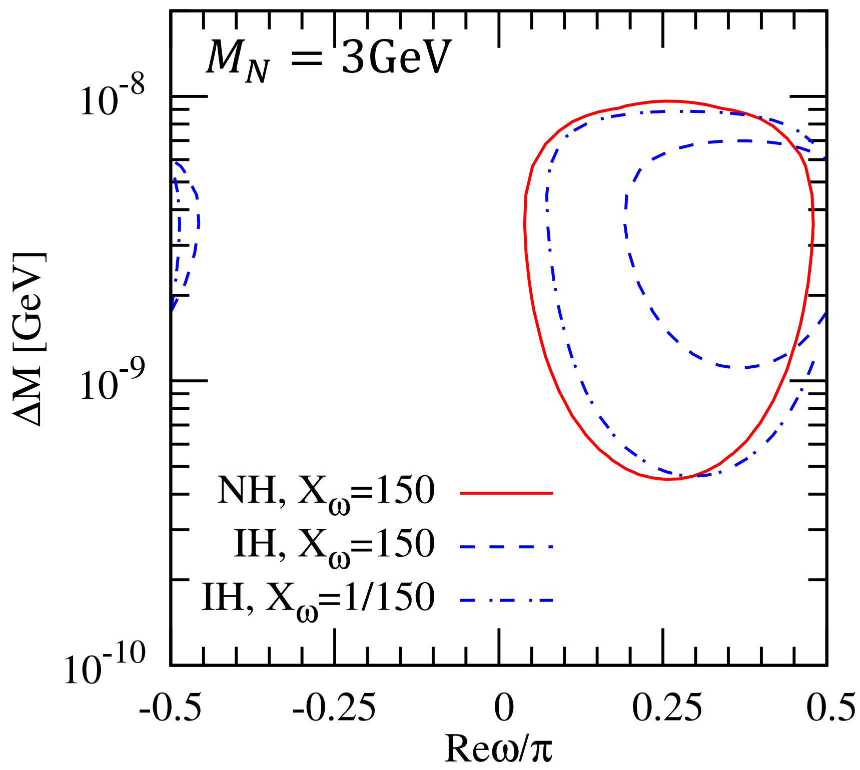
→ strong washout of BAU

Mass difference of ν_R

- ΔM is important parameter for baryogenesis
  - CP asymmetry
  - Oscillation temperature

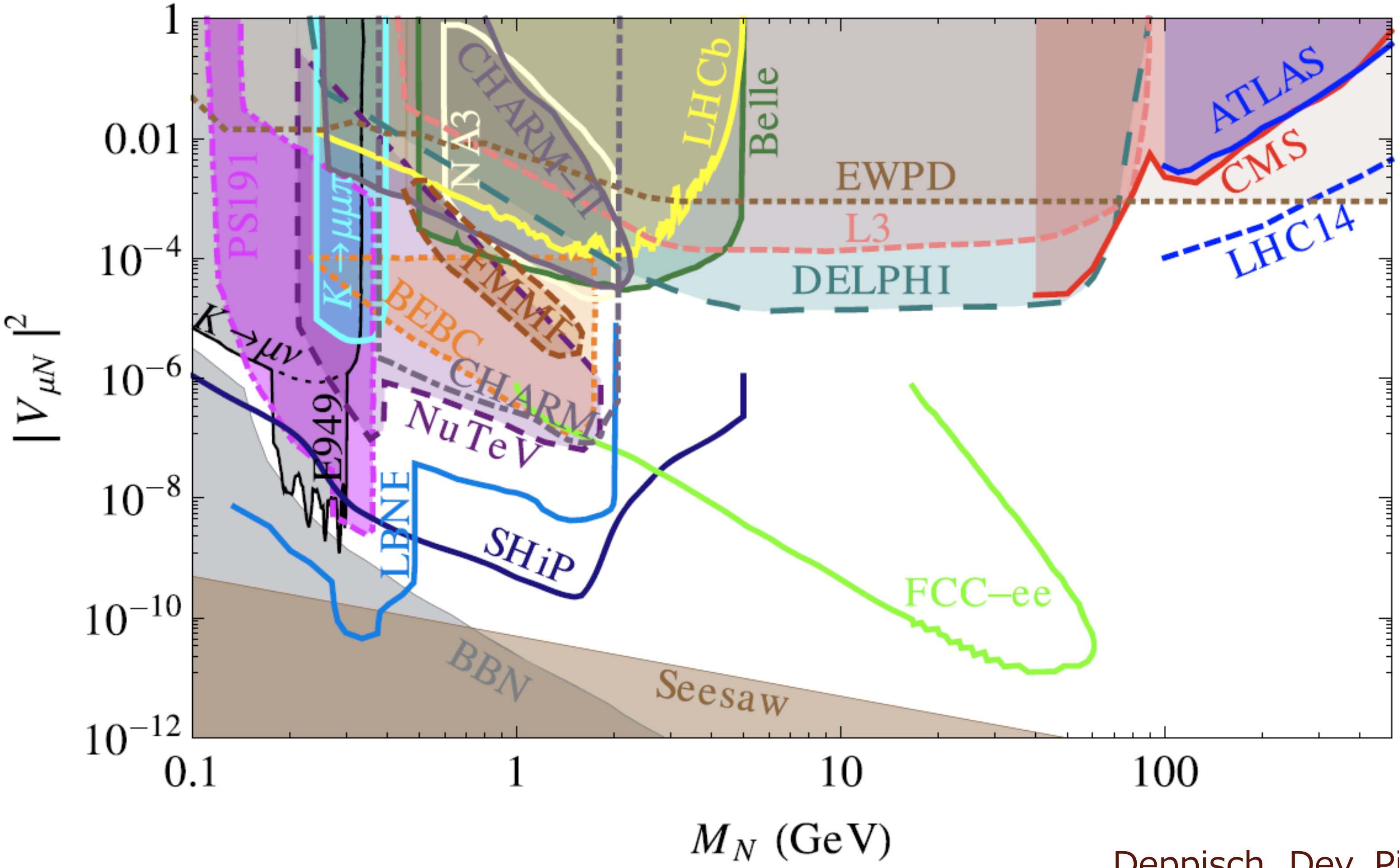
$$T_{osc} \simeq (M_0\ M_N\ \Delta M)^{1/3}$$





Limits on HNL

- Limits on the mixing $\Theta_{\mu I}$



Deppisch, Dev, Pilaftsis '15
[arXiv:1502.06541]

BBN Constraint on Lifetime

- Long-lived $N_{2,3}$ may spoil the success of BBN
  - Speed up the expansion of the universe
    - $\rho_{\rm tot} = \rho_{\rm MSM} + \rho_{N_{2,3}} \Rightarrow \; H^2 = \frac{\rho_{\rm tot}}{3\, M_P^2}$
    - p-n conv. decouples earlier ⟹ overproduction of ${}^4\mathrm{He}$

      $n + \nu \;\leftrightarrow\; p + e^-, \ldots$
  - Distortion of spectrum of active neutrinos
    - $N_{2,3} \;\rightarrow \nu\, \bar{\nu}\, \nu,\;\; e^+\, e^-\, \nu, \ldots$
    - Additional neutrinos may not be thermalized

  ⇒ Upper bound on lifetime

- Dolgov, Hansen, Rafflet, Semikoz ('00)
  - One family case:

$$\tau_N < 0.1\,\mathrm{sec}\;\;\mathrm{for}\; M_N > m_\pi$$

NH Case

[TA, Ishida '10]

$$\delta_\nu = \frac{1}{2}\sin\theta_{12}\sin 2\theta_{13}[\cos^2\theta_{13}(3+\cos 4\theta_{23}) - 4\sin^2\theta_{13}]\,\sin(\delta+\eta) + \cos\theta_{12}\sin 4\theta_{23}\cos^3\theta_{13}\sin\eta + \mathcal{O}(r_{\rm m})\,.$$

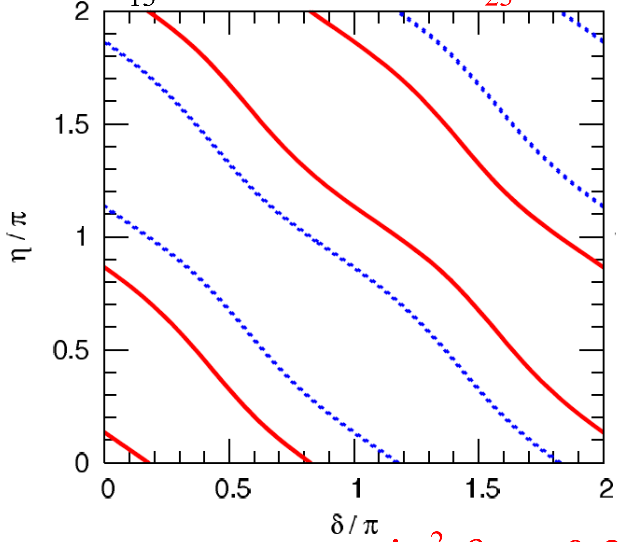
$$r_m = m_{sol} / m_{atm} = 0.18$$

- When θ23 = π/4 (maximal)
  - $\mathrm{BAU} \propto \sin(\delta+\eta)$
- When θ13 = 0
  - $\mathrm{BAU} \propto \sin\eta$
- When θ23 = π/4 and θ13 = 0
  - $\delta_\nu = 0$

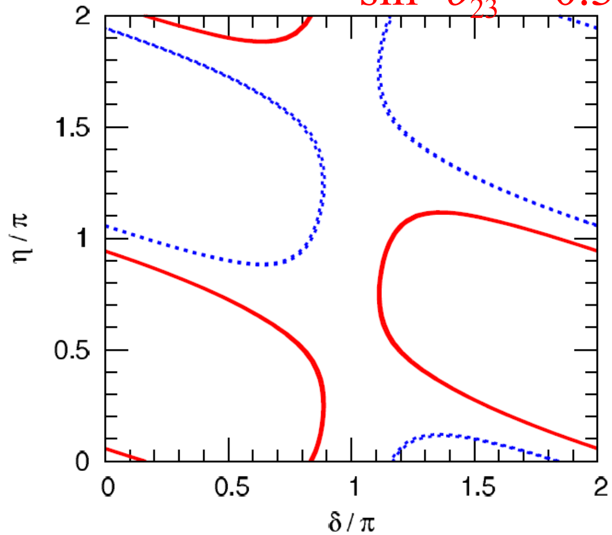
    No BAU is generated !

$M_3 = 5\mathrm{GeV}, \Delta M_{32}^2 / M_3^2 = 10^{-8}$

$\sin^2\theta_{13} = 0.053$ $\sin^2\theta_{23} = 0.5$

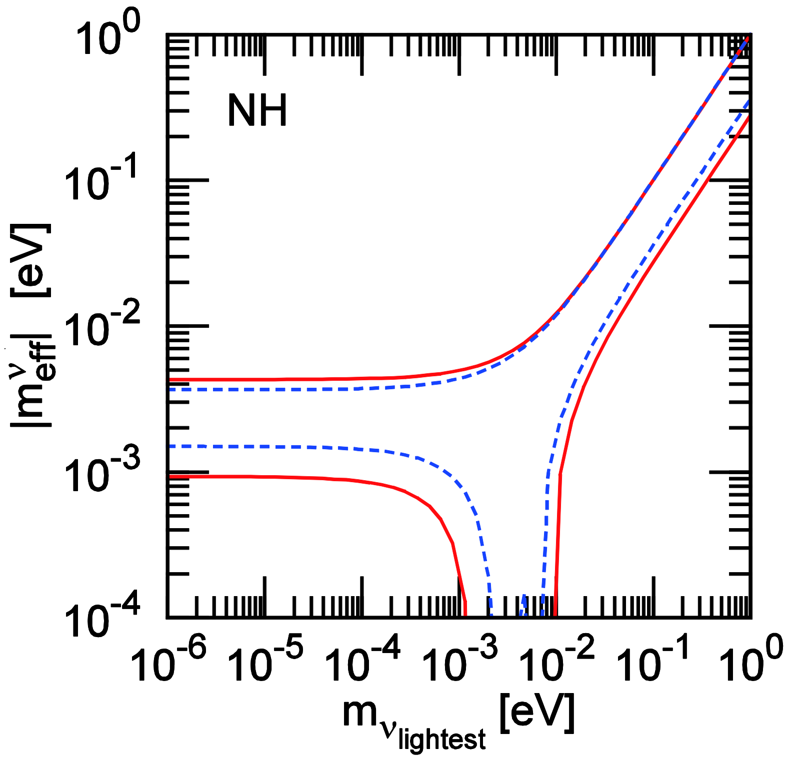


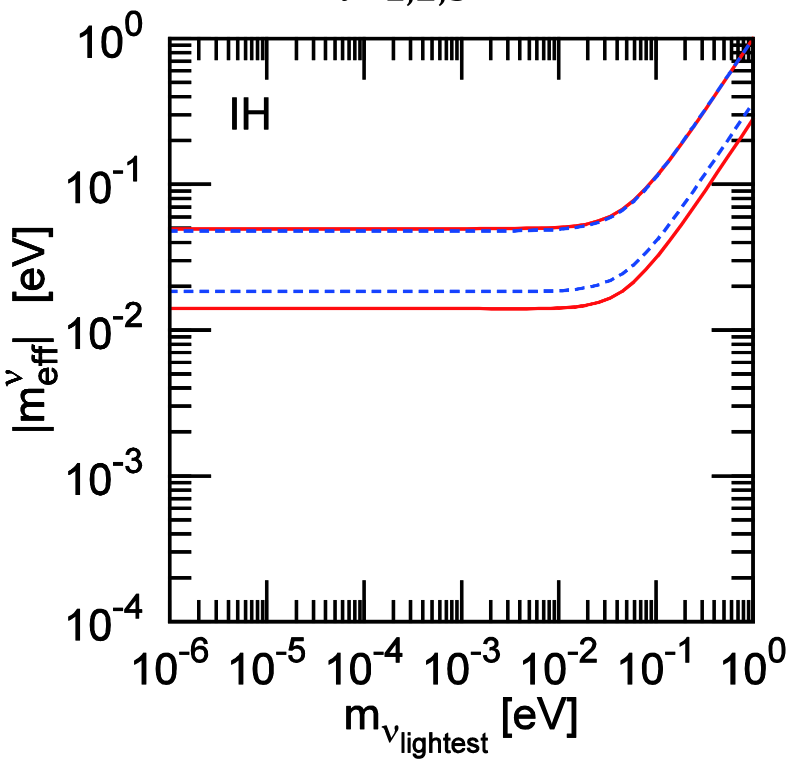
$\sin^2\theta_{23} = 0.36$



$0\nu\beta\beta$ decay

- Contribution from active neutrinos $m_{\rm eff}^{\nu} = \sum_{i=1,2,3} m_i\, U_{ei}^2$





Planck 2015

$\Sigma\, m_i < 0.23$ eV

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

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

KamLAND-Zen 1211.3863 ^{136}Xe

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

GERDA 1307.4720 ^{76}Ge

LNV in the seesaw

- Other LNV processes induced by Majorana HNL in the seesaw mechanism
  - $pp \to \ell^+ N \to \ell^+ \ \ell^+ j\, j$ @LHC
  - $B^+ \to \ell^+ N \to \ell^+ \ \ell^+ \pi^-$ @SuperKEKB
  - $K^+ \to \ell^+ N \to \ell^+ \ \ell^+ \pi^-$ @J-PARC
  - $e^- e^- \to W^- W^-$ @ILC, FCC-ee
  - $\cdots$