Baryogenesis from Right-Handed Neutrino Oscillations

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Contents

GeV-scale right-handed (RH) neutrinos ν_R

- **Why are such particles interesting?**
  - Neutrino masses by seesaw mechanism
  - Baryon asymmetry of the universe by oscillation mechanism
  - Direct tests by (near) future experiments

Neutrino mass by seesaw mechanism

Two right-handed neutrinos ν_R

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

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**

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

    $\rightarrow$ explain neutrino oscillations

  - **Heavy neutral leptons N** $(N \simeq \nu_R)$
    - Mass M_M
    - Mixing $\Theta = M_D/M_M$

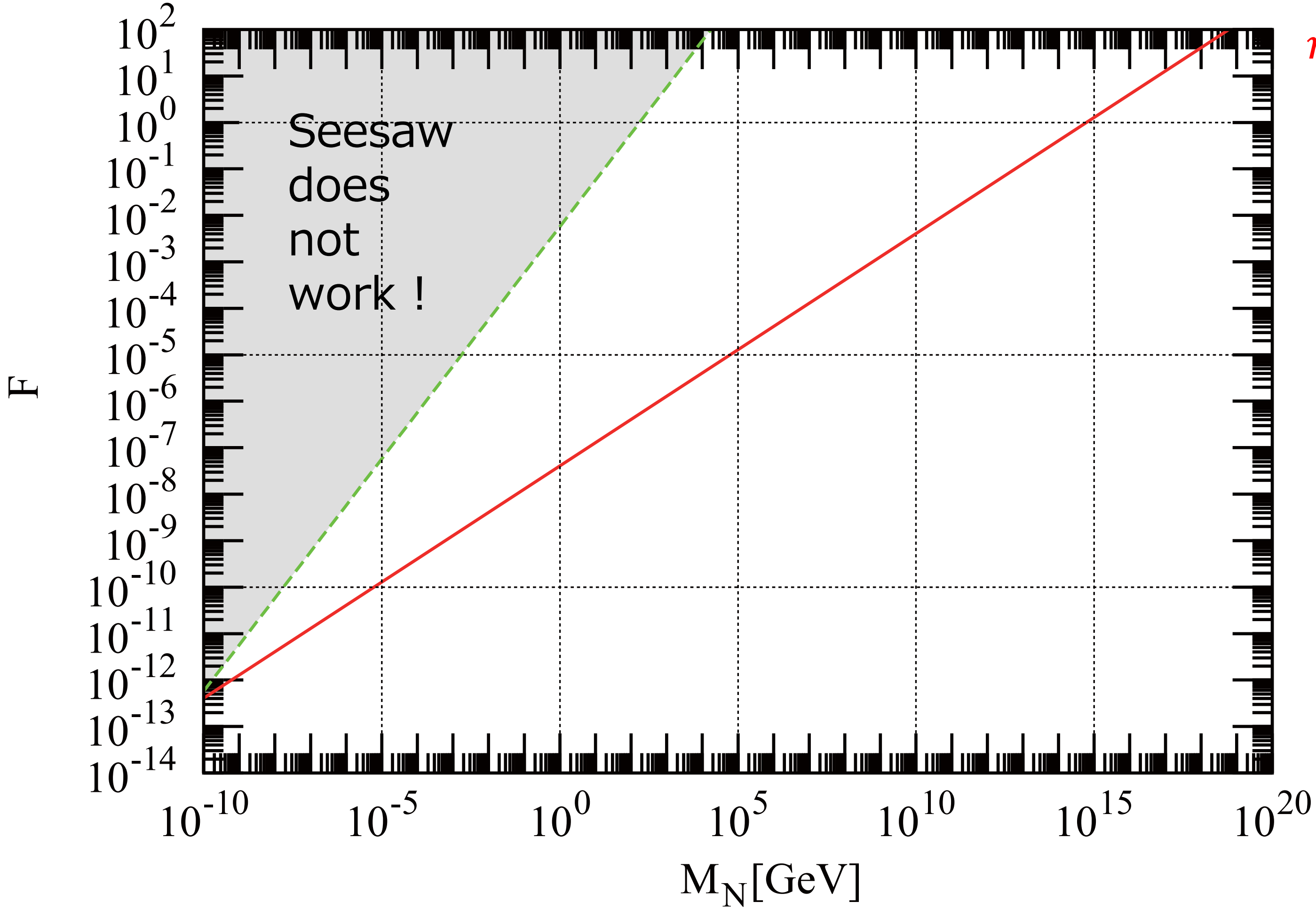
Neutrino mixing

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

Yukawa coupling and Majorana mass

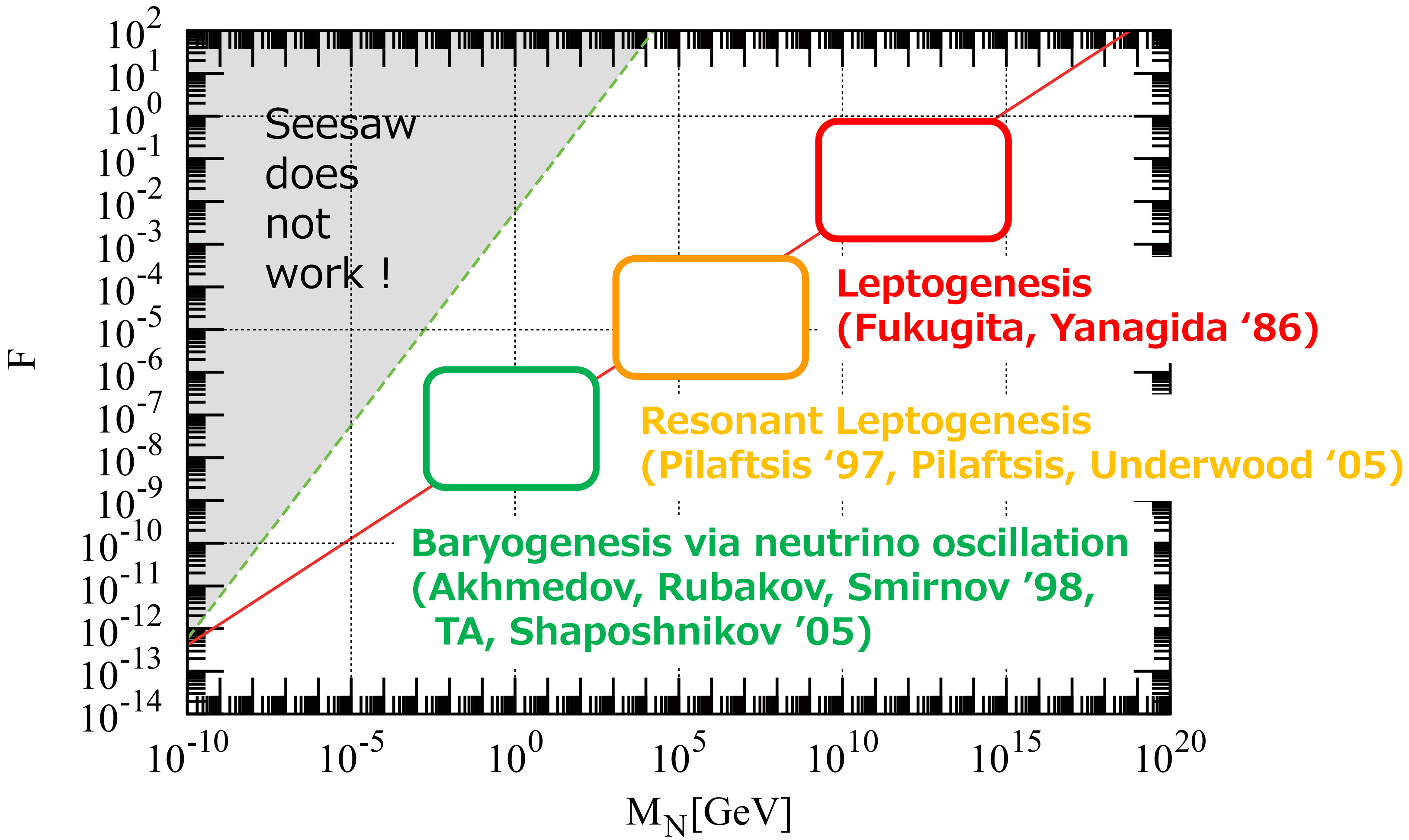
$$m_\nu = \frac{M_D}{M_M} \times M_D = \frac{F^2 \langle \Phi \rangle^2}{M_N} \quad \Longrightarrow \quad F = \frac{\sqrt{m_\nu M_N}}{\langle \Phi \rangle}$$

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



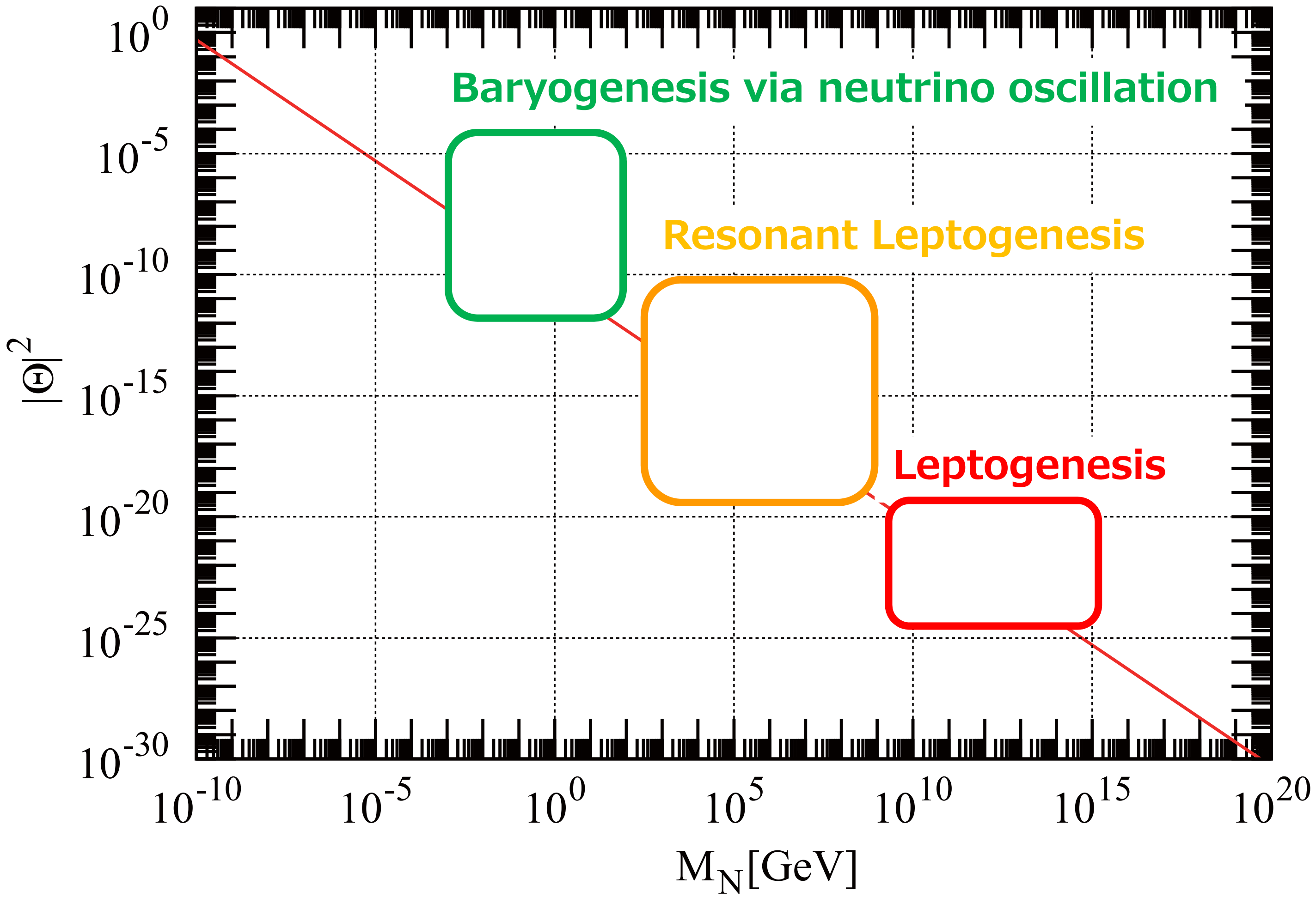
Yukawa coupling and Majorana mass

Explain baryon asymmetry of the universe too!



Mixing and mass of heavy neutrino

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



Baryogenesis by right-handed neutrinos

Baryogenesis conditions

Sakharov (1967)

Can GeV-scale RH neutrinos satisfy baryogenesis conditions?

(1) B and L violations

- (B+L) violation due to sphaleron for $T > 100$ GeV

(2) C and CP violations

- 1 CP phase in quark sector
- 3 CP phases in lepton sector for two RH neutrinos

(3) Out of equilibrium

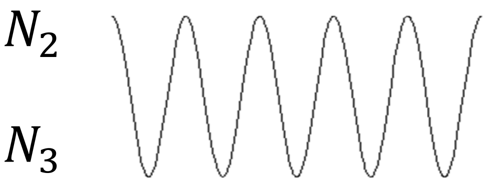
- No 1st order EW phase transition as in the SM
- RH neutrinos can be out of equilibrium, if Yukawa couplings are small enough

Baryogenesis via neutrino oscillation

- **Oscillation of RH neutrinos can be a source of BAU**

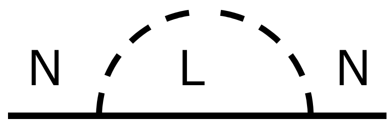
  Akhmedov, Rubakov, Smirnov ('98) / TA, Shaposhnikov ('05)

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

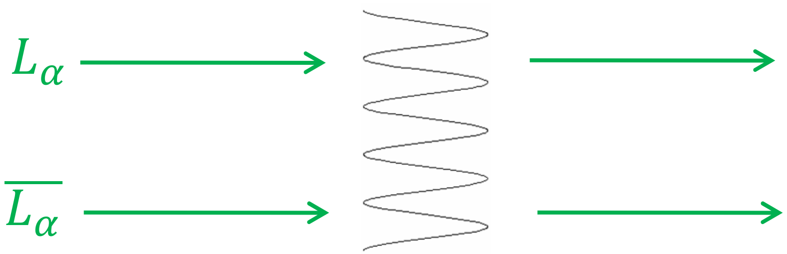


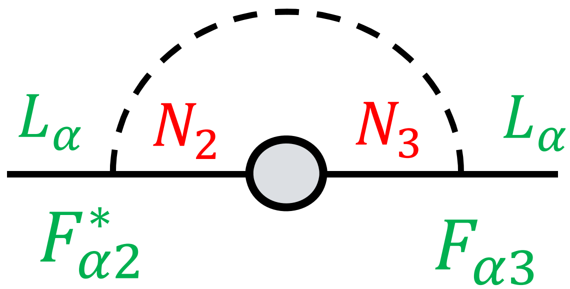
$$V_N = \frac{T^2}{8\,k} F^\dagger F$$

Medium effects

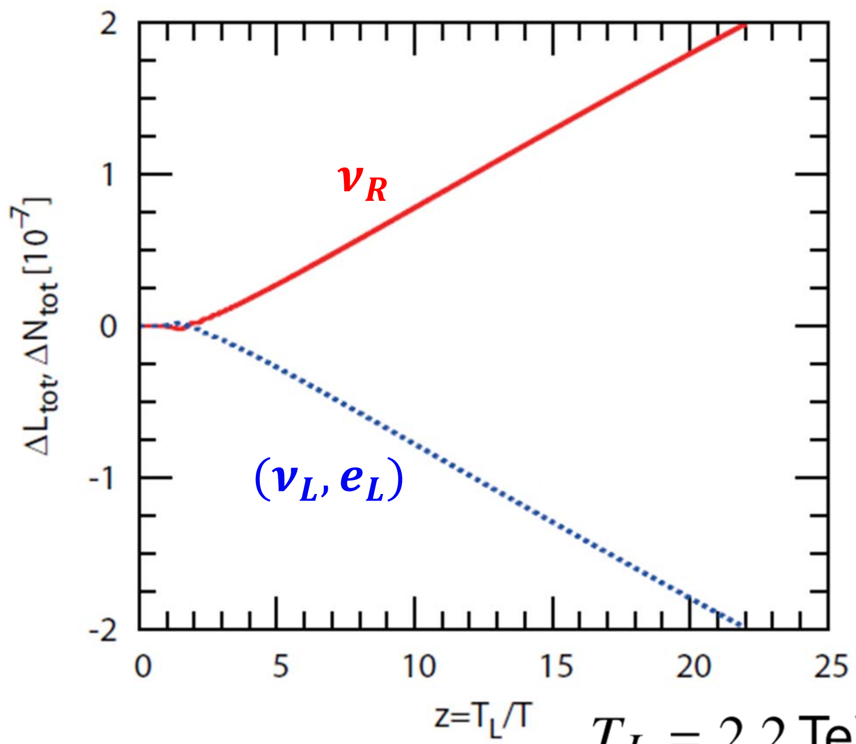


  - Asymmetries are generated since evolution rates of L_α and $\overline{L_\alpha}$ are different due to CPV





Evolution of total 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 $\delta = 3\pi/2$.

Sphaleron converts ΔL partially into baryon asymmetry

[Kuzmin, Rubakov, Shaposhnikov '85]

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

$$\Updownarrow$$

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

[Planck '15]

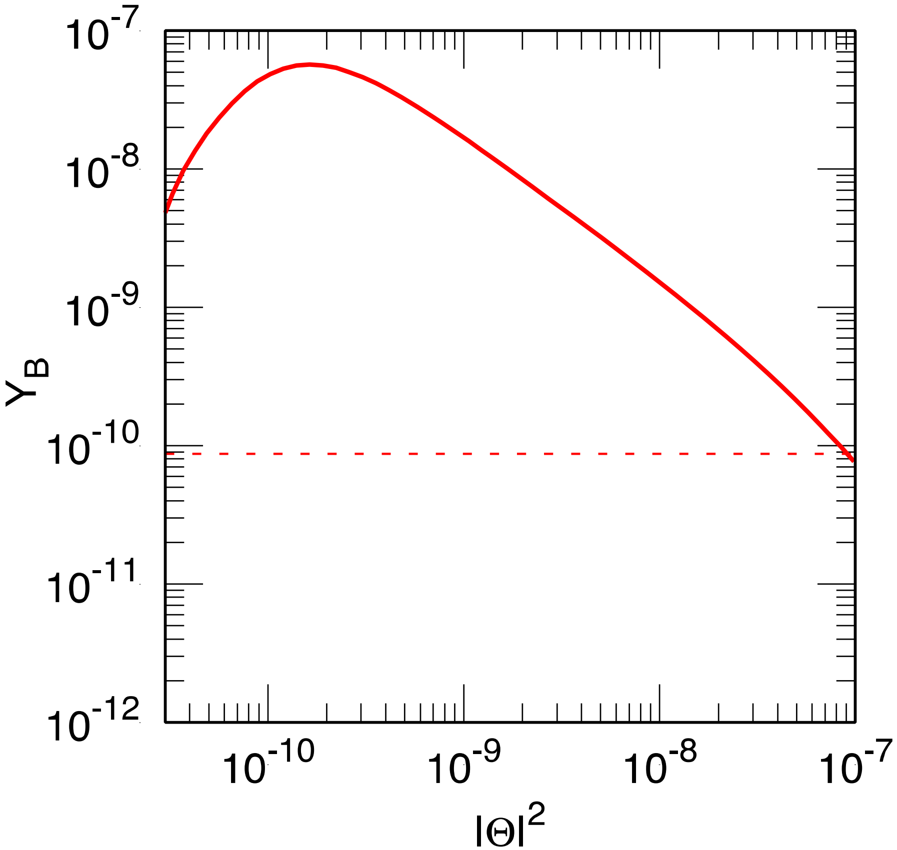
Separation of asymmetries between (ν_L, e_L) and ν_R

See, however, the recent discussions:

Hambye, Teresi '16, '17, Ghiglieri, Laine '17,
Eijima, Shaposhnikov '17

Upper bound on mixing from BAU

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

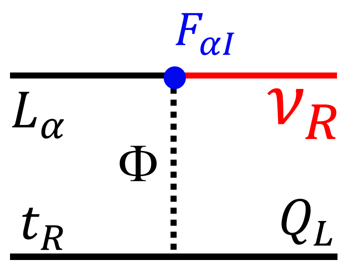


TA, Eijima, Ishida, Minogawa, Yoshii '17 [to appear]

- Large mixing means ⋯

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

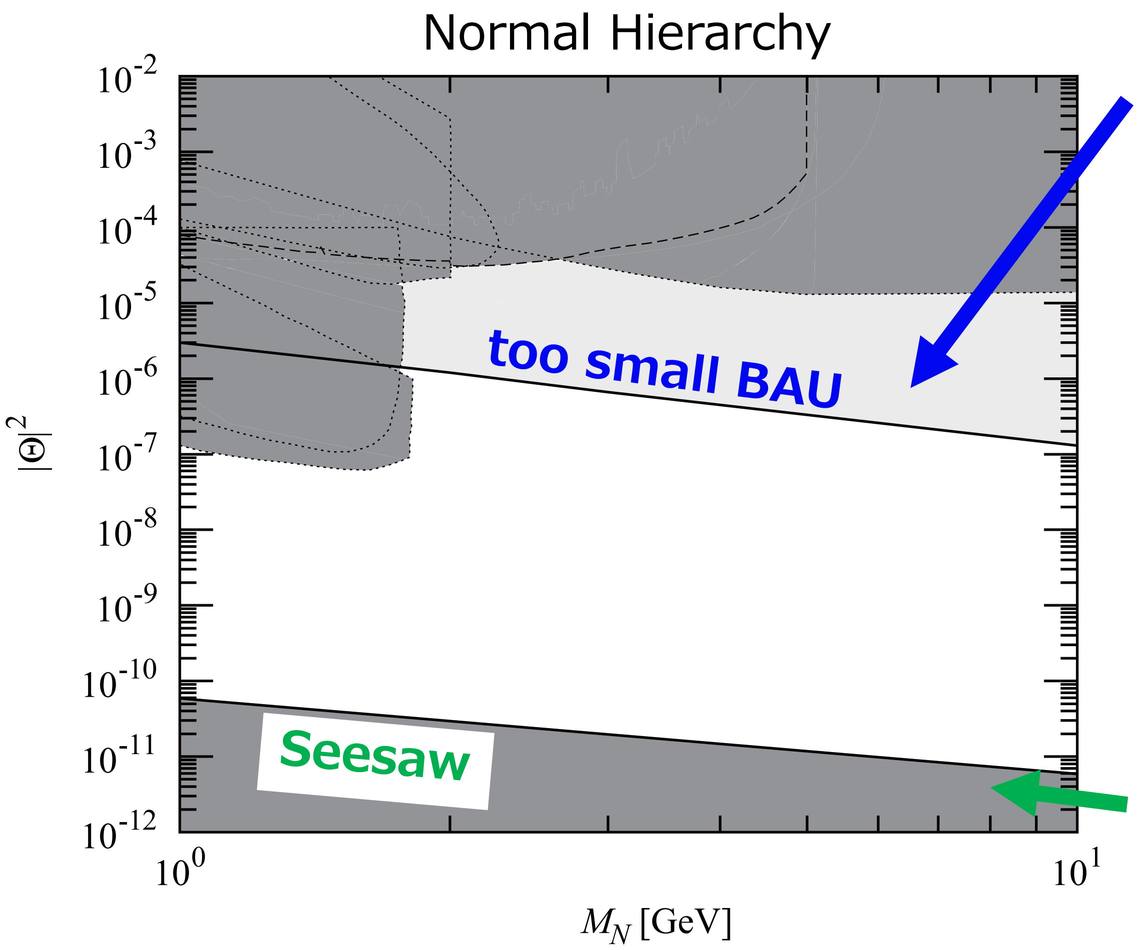
$\rightarrow$ large Yukawa couplings



$\rightarrow$ thermalization of ν_R

$\rightarrow$ strong washout of BAU

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]

See also a poster #16 by Juraj Klaric

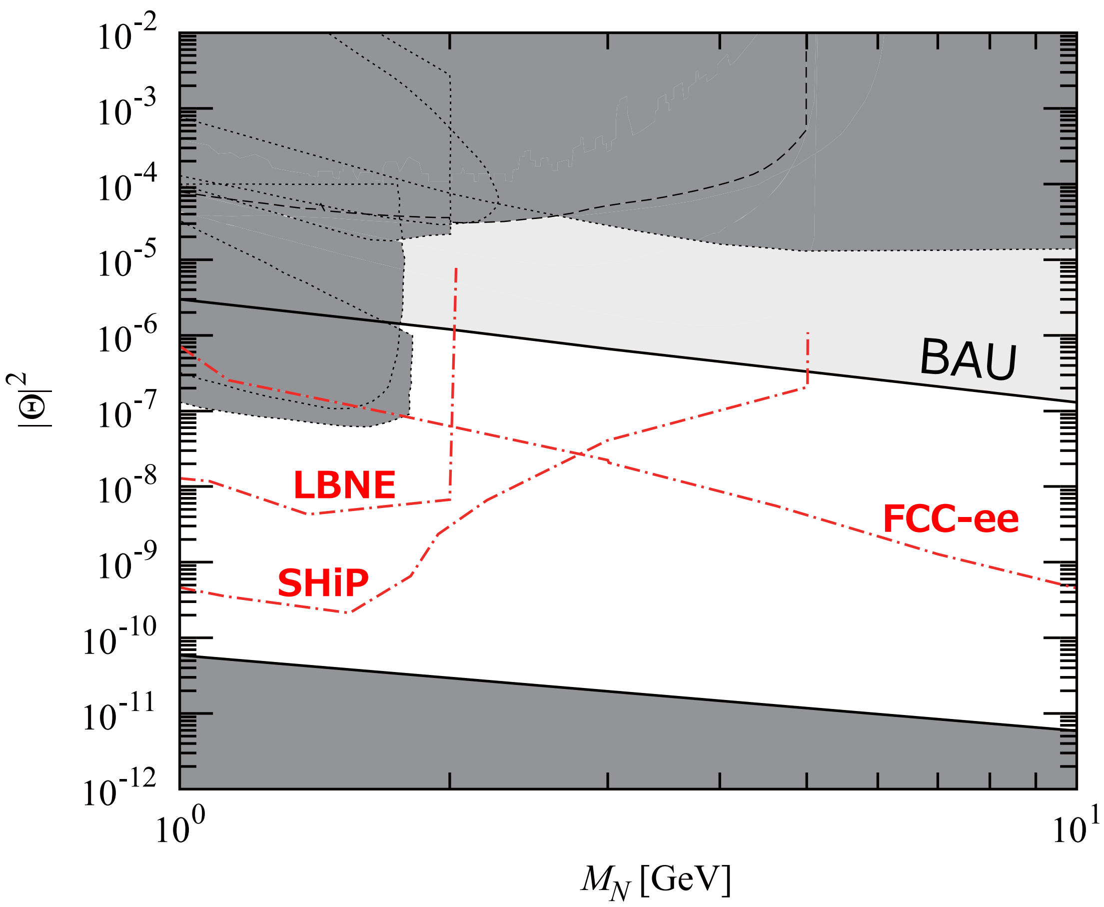
Bound from Seesaw

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]

Experimental tests of right-handed neutrinos

Properties of right-handed neutrinos

- ν_R with large $|\Theta|$ is a good target for search experiments

- For large $|\Theta|$ region, the possible values of model parameters are limited in order to generate the sufficient baryon asymmetry

- Yield of baryon asymmetry depends on neutrino Yukawa couplings
  - Due to the exchange of asymmetries between LH and RH leptons, BAU depends on PMNS mixing matrix
    → baryon asymmetry couples to CPV at low energies

- 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)

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

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

$M_N, \Delta M$

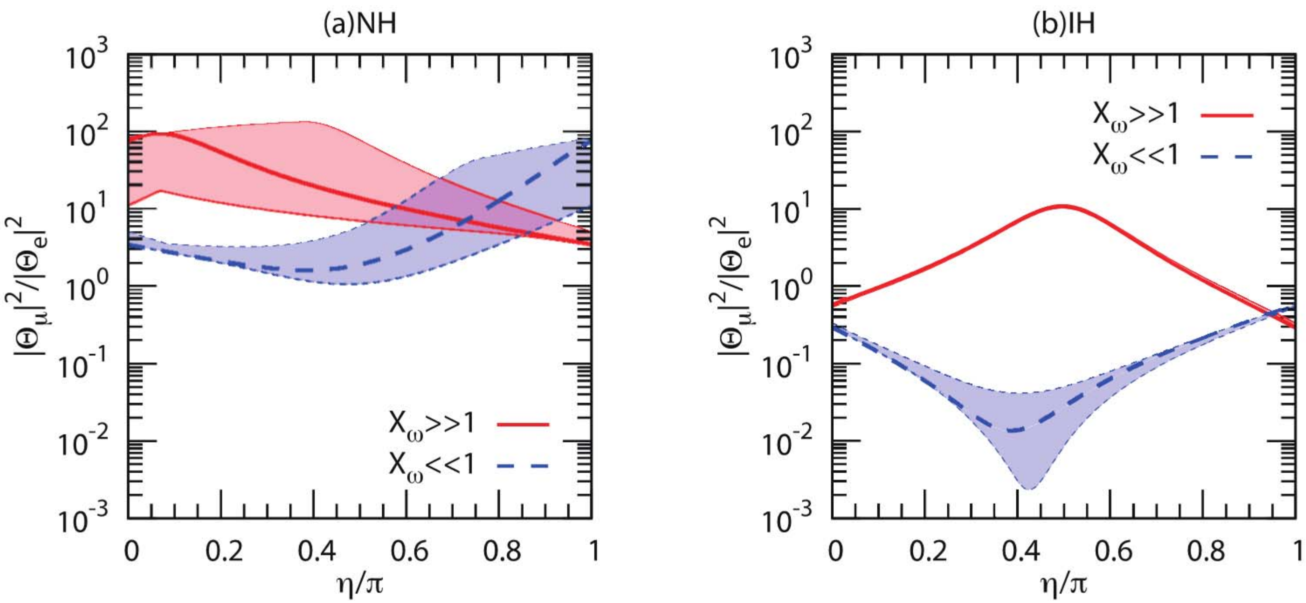
$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \sin\omega & \cos\omega \end{pmatrix}$$

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 $\mathbf{\Theta}$
  - 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



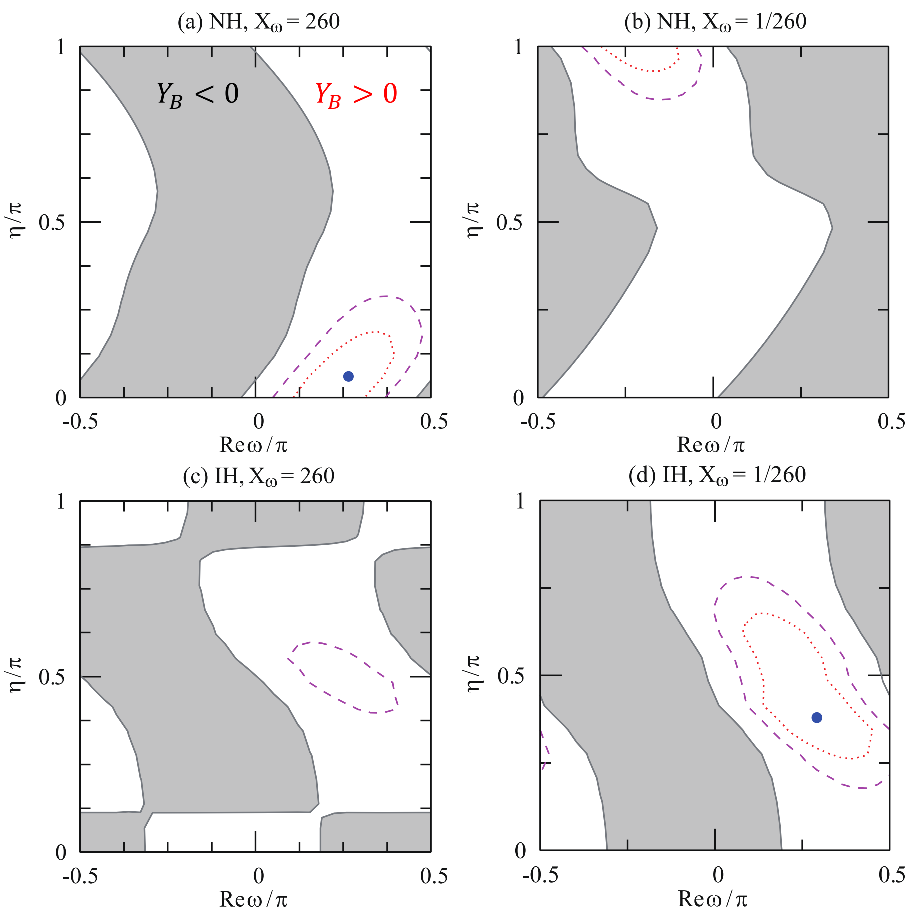
The ratio $|\Theta_\mu|^2/|\Theta_e|^2$ may determine η

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

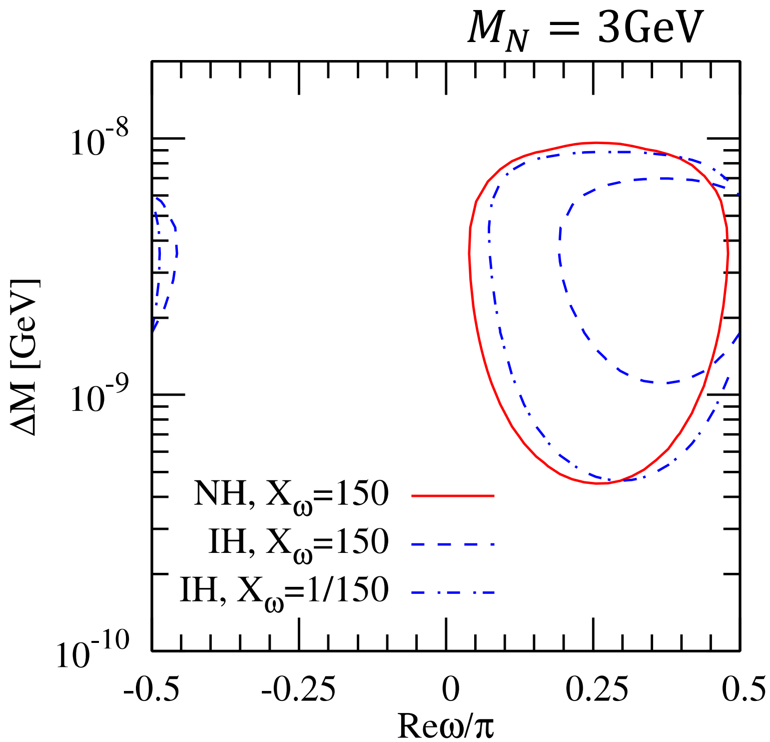
Baryon asymmetry

- $\mathrm{Re}\,\omega$ 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 $\mathrm{Re}\,\omega$ between two RH neutrinos



BAU (sign and magnitude) can indicate the region of $\mathrm{Re}\,\omega$ and ΔM

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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

Summary

- We have considered

  right-handed neutrinos with GeV-scale mass

  - Tiny neutrino masses by seesaw mechanism
  - Baryon asymmetry of the universe by oscillation mechanism
  - Direct tests by future experiments are possible
    - Direst search at SHiP, DUNE, FCC-ee, ⋯
    - Model parameters (masses, couplings, and CPV of right-handed neutrinos) may be studied