Testability of Heavy Neutral Leptons as Origin of the Baryon Asymmetry of the Universe

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2015 DESY Theory workshop on "Physics at the LHC and beyond", October 1st @ DESY Hamburg, Germany

Neutrino Masses from Seesaw Mechanism

Introducing right-handed neutrinos

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\nu_{RI}} i\partial_\mu \gamma^\mu \nu_{RI} - F_{\alpha I} \overline{L_\alpha} \widetilde{\Phi} \nu_{RI} - \frac{M_M}{2} \overline{\nu_{RI}{}^c} \nu_{RI} + h.c.$$

$$|(M_D)_{\alpha I}| \equiv |\langle \Phi \rangle F_{\alpha I}| \ll (M_M)_I$$

$$\hat{M} = \begin{pmatrix} 0 & M_D \\ M_D^T & M_M \end{pmatrix} \xrightarrow[\textit{diagonalization}]{} \begin{pmatrix} M_\nu & 0 \\ 0 & M_N \end{pmatrix}$$

- Mass matrix for the mass eigenstates

$$\begin{cases} M_\nu = -M_D M_M^{-1} M_D^T \\ \quad\;\; = -\langle \Phi \rangle^2 F M_M^{-1} F^T \\ M_N \simeq M_M \end{cases}$$

In order to explain two observed neutrino mass differences at least two right-handed neutrinos are required.

- Neutrino Mixing

$$\begin{cases} \nu_{L\alpha} = U_{\alpha i} \nu_i + \Theta_{\alpha I} N_I^c \\ \nu_{RI} \simeq N_I \end{cases}$$

$$\Theta_{\alpha I} = \langle \Phi \rangle F_{\alpha I} / (M_N)_I \ll 1$$

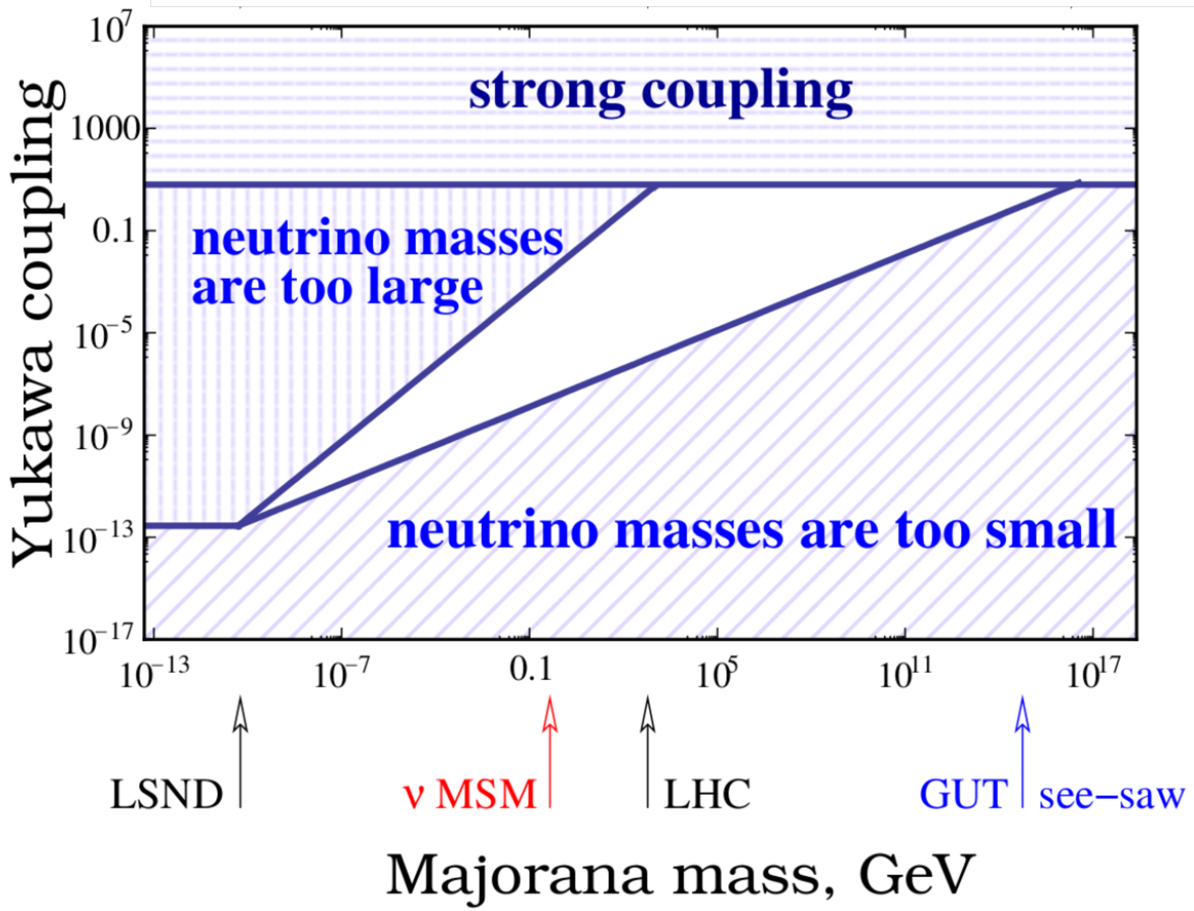
ν_i : Active neutrino

N_I : **Heavy neutral lepton**

Neutrino Masses from Seesaw Mechanism

$$M_\nu = -M_D\, M_M^{-1}\, M_D^T$$
$$= -\langle\Phi\rangle^2 F\, M_M^{-1}\, F^T$$

⇨ Correlation between Majorana mass and neutrino Yukawa coupling

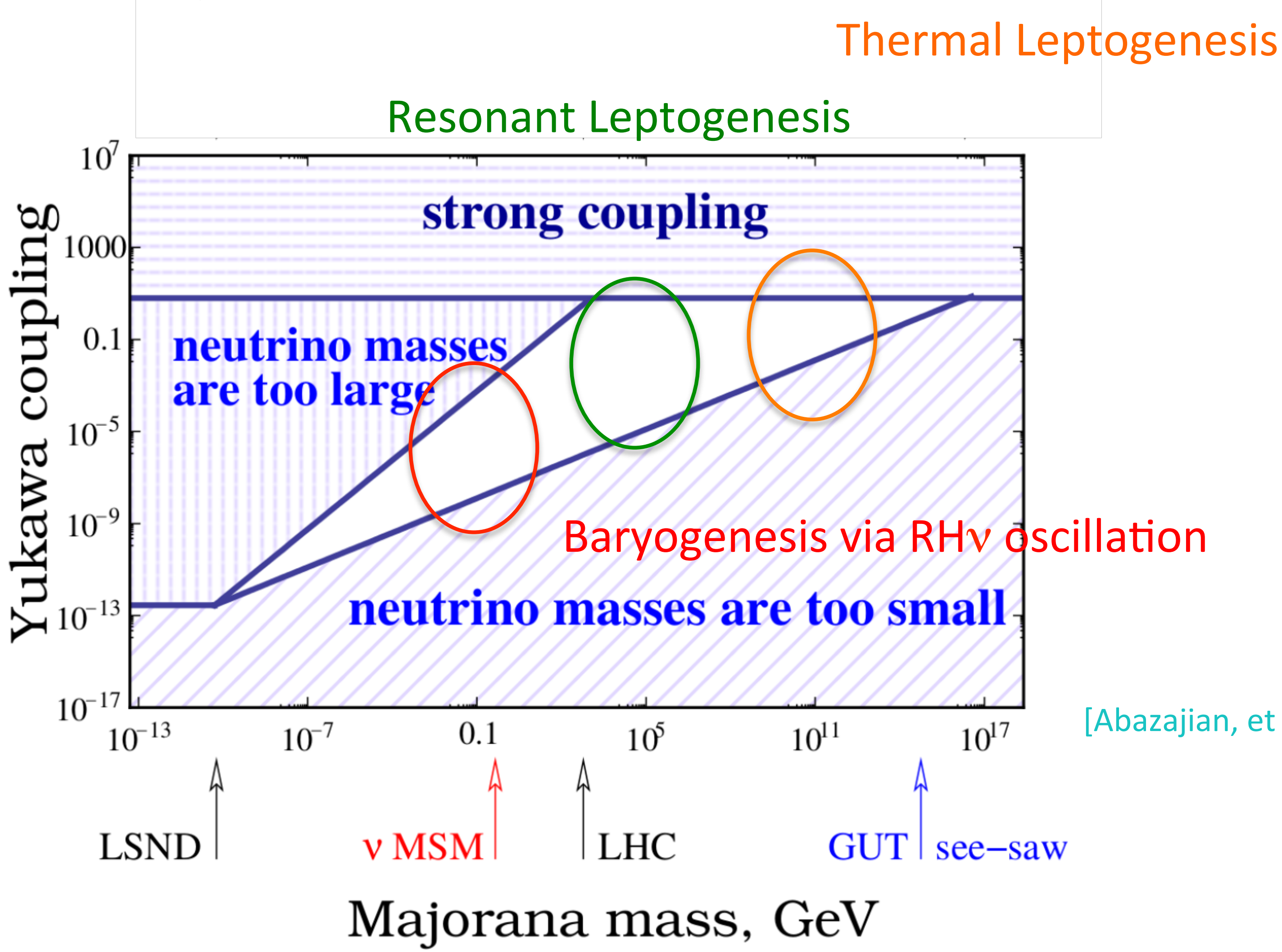


[Abazajian, et al. ('12)]

Baryon Asymmetry of the Universe (BAU)

Right-handed neutrinos can also explain the BAU

- For **CP-violation** minimal number of right-handed neutrinos is two.
- **Out-of-equilibrium** processes must occur



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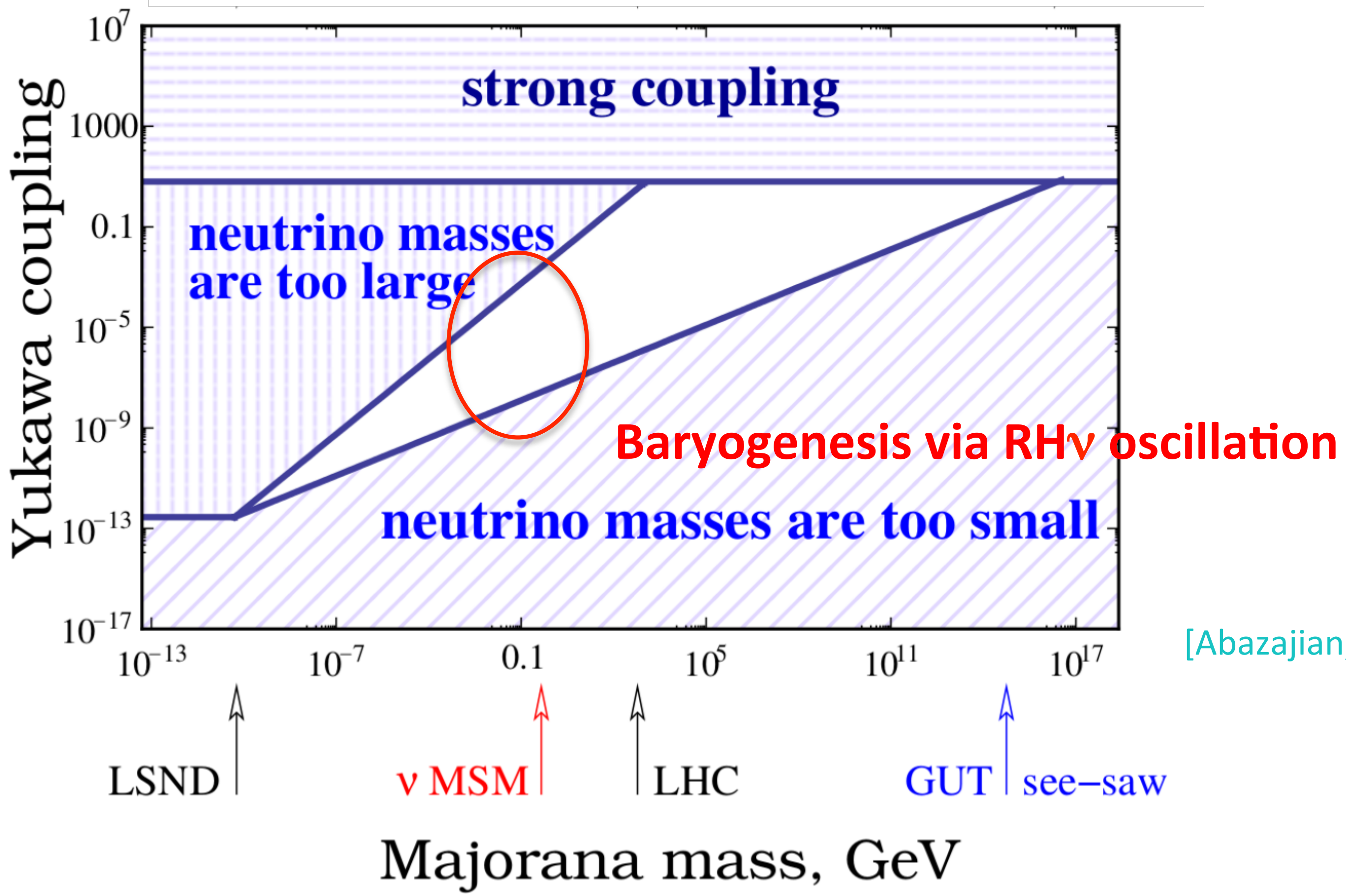

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Baryogenesis via RHν Oscillation

[Akhemedov, Rubakov, Smirnov('98)] [Asaka, Shaposhnikov('05)]

- Minimal case : N_1 and N_2 with $M_{1,2} = \mathcal{O}(1)$ GeV
- Out-of-equilibrium processes by **suppressed neutrino Yukawa couplings**

$F_{1,2} \sim \mathcal{O}(10^{-7})$

Right-handed neutrino sector deviated from equilibrium

⇩ ⇧ Yukawa interaction → $\boldsymbol{\Delta L}$ —Sphaleron process→ $\boldsymbol{\Delta B}$

Left-handed lepton sector in equilibrium

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

[Khlebnikov, Shaposhnikov('88)]

The contribution of mass is suppressed by temperature, $\boldsymbol{T \geq \Lambda_{\rm EW} \simeq 100}\mathrm{GeV}$

→ Decay process is irrelevant.

→ The origin of lepton asymmetry is right-handed neutrino oscillation.

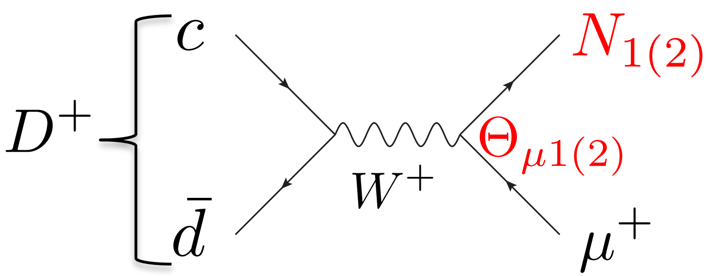
→ **The mechanism requires $N_{1,2}$ are quasi-degenerate.**

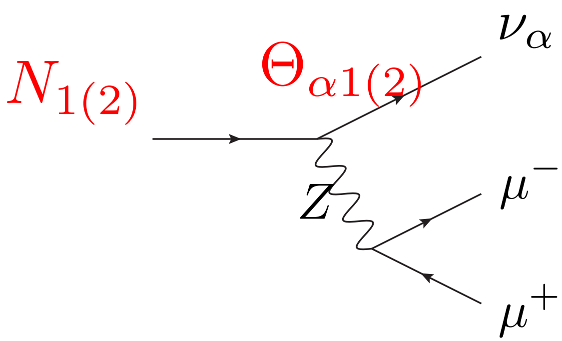
$$\frac{M_2 - M_1}{2} \equiv \Delta M \ll M_N \equiv \frac{M_2 + M_1}{2}$$

Direct Search of Heavy Neutral Leptons

From neutrino mixing $\boldsymbol{\nu_{L\alpha} = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c}$

HNLs have weak interaction.

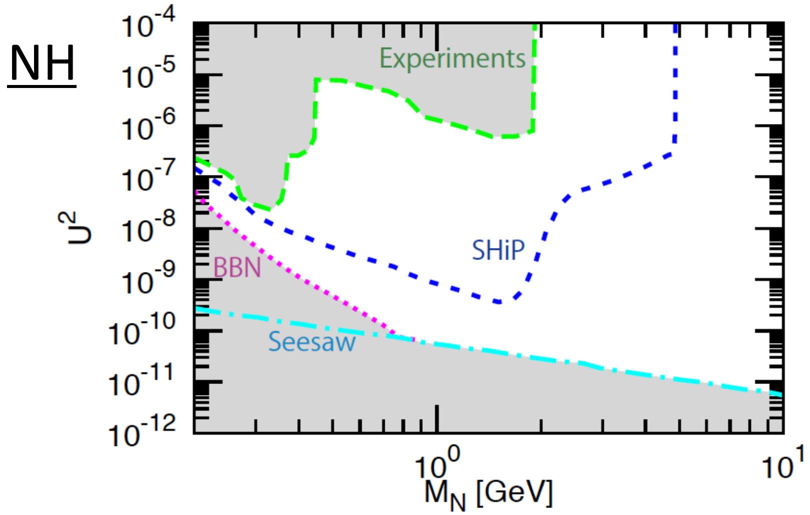


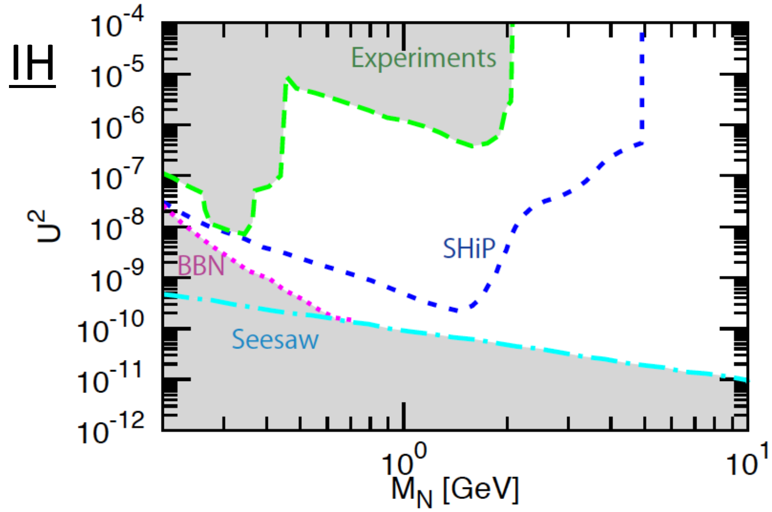


Search for Hidden Particles (SHiP) experiment

– Beam dump experiment at the CERN SPS

$$U^2 \equiv \sum_{\alpha, I} |\Theta_{\alpha I}|^2$$



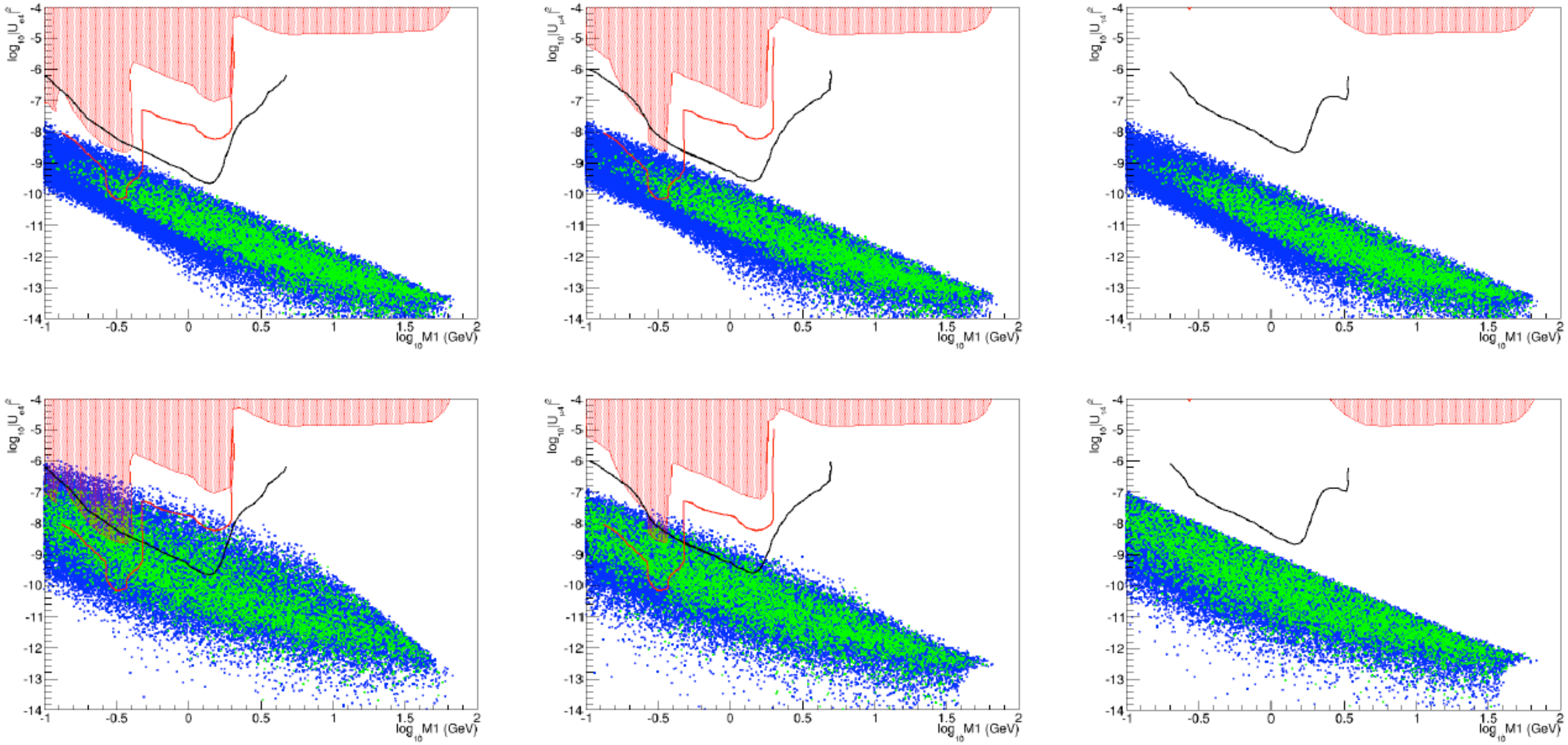


Testability of HNLs as origin of the BAU

In the recent analysis parameter space predicted from the observed BAU is estimated numerically **under assuming a upper bound of Yukawa coupling in order to avoid HNLs go into equilibrium before the sphaleron freeze-out**.

NH

IH



[Hernandez, Kekic, Lopez-Pavon, Racker, Rius ('15)]

⇨ SHiP experiment is accessible **only for IH case**.

Kinetic Equations

- Two 2x2 matrix of density : $\rho_N, \ \rho_{\bar{N}}$
- Three lepton asymmetry : ΔL_α

$$\rho_N = \begin{pmatrix} (\rho_N)_{11} & (\rho_N)_{12} \\ (\rho_N)_{21} & (\rho_N)_{22} \end{pmatrix}$$

$\rho_{N\,IJ}\,(I = J)$: occupation number
$\rho_{N\,IJ}\,(I \neq J)$: correlation between $N_{1,2}$

N Oscillation **Destruction and Production**

$$\begin{cases} i\dfrac{d\rho_N}{dt} = [H, \rho_N] - \dfrac{i}{2}\{\Gamma_N, \rho_N - \rho^{eq}\} + \dfrac{i}{2}\Delta L_\alpha \tilde{\Gamma}^\alpha_N \ , \\ i\dfrac{d\rho_{\bar{N}}}{dt} = [H^*, \rho_{\bar{N}}] - \dfrac{i}{2}\{\Gamma^*_N, \rho_{\bar{N}} - \rho^{eq}\} - \dfrac{i}{2}\Delta L_\alpha \tilde{\Gamma}^{\alpha *}_N \ , \\ i\dfrac{d\Delta L_\alpha}{dt} = -i\Gamma^\alpha_L \Delta L_\alpha + i\,\mathrm{tr}\left[\tilde{\Gamma}^\alpha_L(\rho_N - \rho^{eq})\right] - i\,\mathrm{tr}\left[\tilde{\Gamma}^{\alpha *}_L(\rho_{\bar{N}} - \rho^{eq})\right] \end{cases}$$

Communication term between LHL sector and N sector

Interactions rates : $\Gamma_N = \sum_\alpha F^*_{\alpha I} F_{\alpha I} R(T, M)_{\alpha\alpha}$

$$R = 0.012\,T$$

$$(\tilde{\Gamma}_L)_{IJ} \simeq (\tilde{\Gamma}^\alpha_N)_{IJ} = F^*_{\alpha I} F_{\alpha I} R(T, M)_{\alpha\alpha}$$

$$\Gamma^\alpha_L = (FF^\dagger)_{\alpha\alpha} R(T, M)_{\alpha\alpha}$$

Effective Hamiltonian : $H \simeq \dfrac{1}{2k}\left[-2M_N \Delta M \sigma_3 + F^\dagger F \dfrac{T^2}{4}\right]$

Strong coupling and large mass difference

$$i\frac{d\Delta L_\alpha}{dt} = -i\Gamma_L^\alpha \Delta L_\alpha + i\mathrm{tr}\left[\tilde{\Gamma}_L^\alpha(\rho_N - \rho^{eq})\right] - i\mathrm{tr}\left[\tilde{\Gamma}_L^{\alpha *}(\rho_{\bar{N}} - \rho^{eq})\right]$$

Once HNLs equilibrate, the wash-out of asymmetries is determined by the damping term

By using general Yukawa matrix

$$\mathrm{NH},\ M_N = 1\,\mathrm{GeV},\ \Delta M = 10^{-3}\,\mathrm{GeV}$$

$$U^2 = 9\times10^{-8}$$ (in the region covered by SHiP)

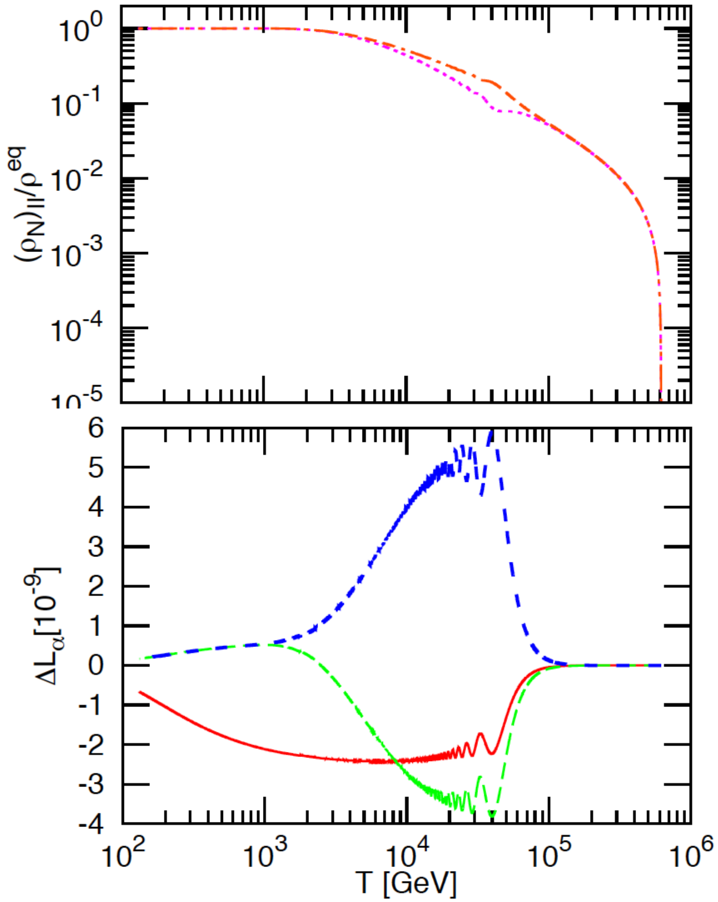
$$\Gamma_L^e = 2\times10^{-16}\ T$$

$$\Gamma_L^\mu = 8\times10^{-15}\ T$$

$$\Gamma_L^\tau = 1\times10^{-14}\ T$$

$$Y_B = 1.2\times10^{-10} > Y_B^{obs} \simeq 9\times10^{-11}$$

Due to the small damping rate sufficient amount of baryon asymmetry can survive even after HNLs are equilibrated.

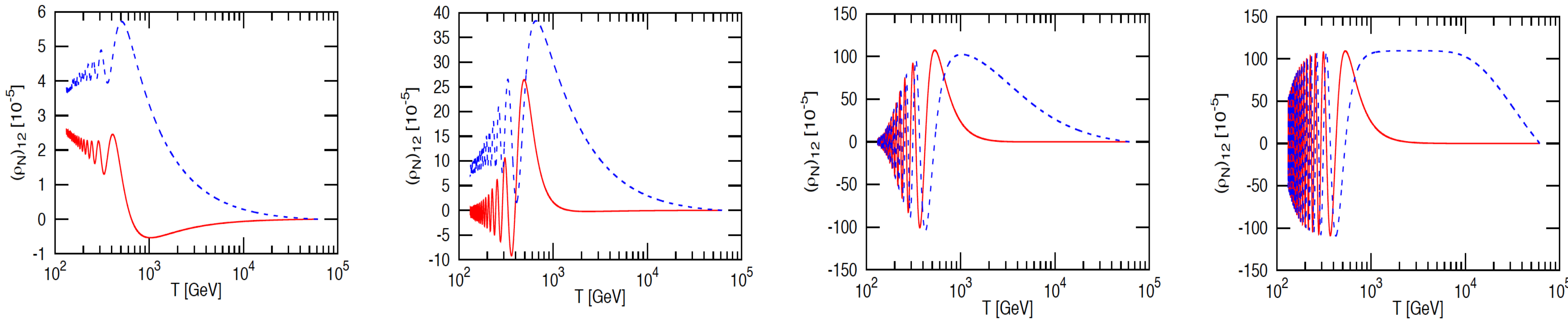


Strong coupling and small mass difference

Equilibration : $\frac{\rho_N}{\rho^{eq}} \to \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

NH, $M_N = 1$ GeV, $\Delta M = 10^{-9}$ GeV

$U^2 = 2.3 \times 10^{-10}$ $U^2 = 2.3 \times 10^{-9}$ $U^2 = 2.3 \times 10^{-8}$ $U^2 = 2.3 \times 10^{-7}$

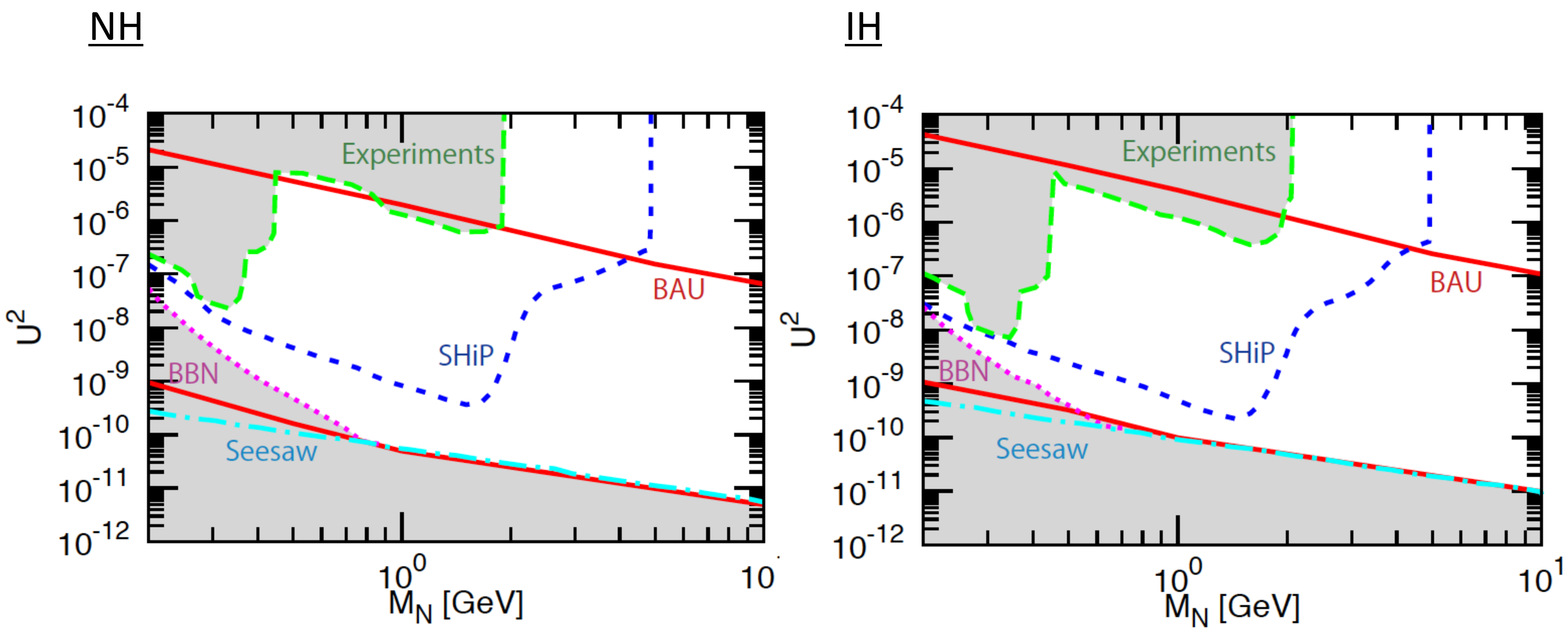


$Y_B = 8.5 \times 10^{-9}$ $Y_B = 2.2 \times 10^{-7}$ $Y_B = 4.3 \times 10^{-8}$ $Y_B = 2.8 \times 10^{-9}$

Strong coupling enhances not only interaction rates but also transition rate between HNLs. The large transition of HNLs keeps them out of equilibrium to lower temperature.

Results

From full scan of parameter space



For both NH and IH cases SHiP experiment would probe HNLs as origins of neutrino masses and BAU.

Summary

- Two right-handed neutrinos can explain the BAU and tiny neutrino masses at the same time.
  Even if the masses of heavy neutral leptons are below electroweak scale, the particles still can be origins of the phenomena beyond the SM. In principle, they are testable by using current experimental technique.

- In the strong coupling case for the baryogenesis, the equilibration of HNLs depends on the mass difference. Moreover, even if HNLs go into equilibrium the observed baryon asymmetry can be generated in some cases due to the small damping rates.

- Numerical calculation in all parameter space shows near future experiment (SHiP) would investigate wide region satisfied from observations of neutrino oscillation and BAU for both hierarchy cases.

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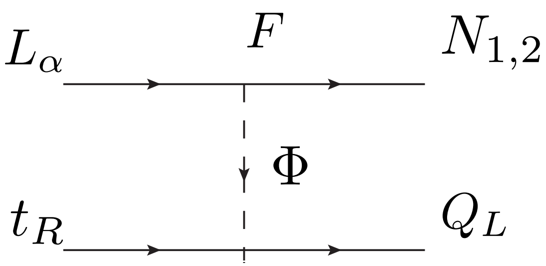
Baryogenesis via RHν Oscillation

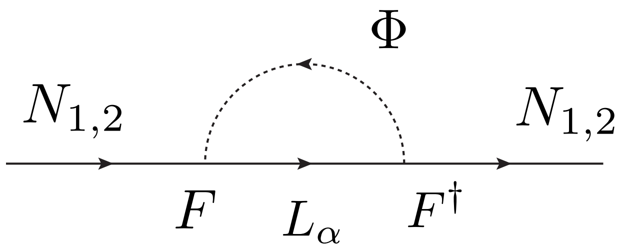
[Akhemedov, Rubakov, Smirnov('98)] [Asaka, Shaposhnikov('05)]

<u>Lepton asymmetry production</u>

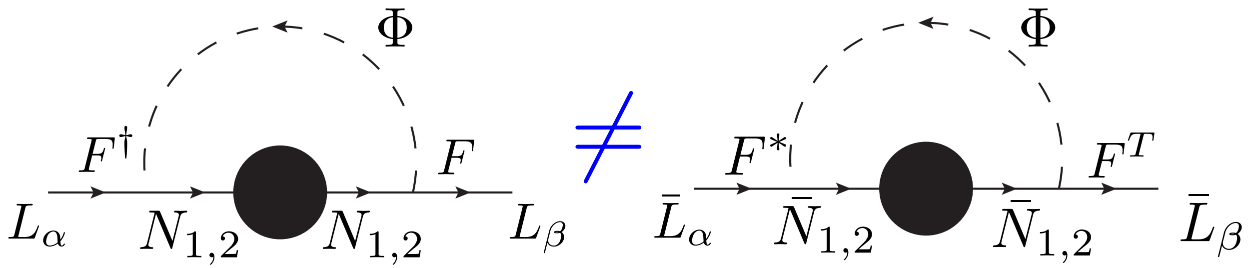
0. Initial condition : $n_N = n_{\bar{N}} = 0\,,\ \Delta L = \Delta B = 0$

1. Production and Oscillation of (F^2)





2. CP violating processes in left-handed sector (F^4)



$\Delta L_e,\ \Delta L_\mu,\ \Delta L_\tau \neq 0$

$\Delta L_{\rm tot} = \sum_\alpha L_\alpha = 0$

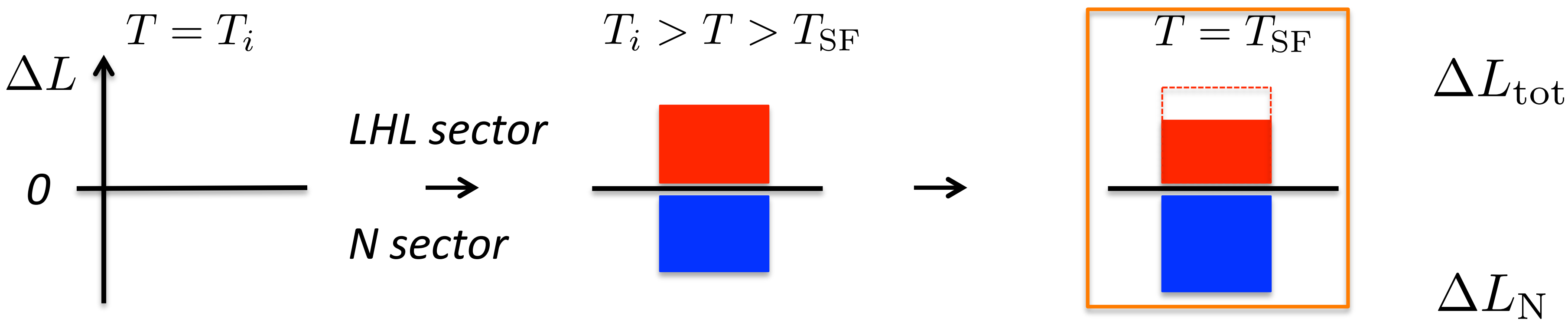
3. $\Delta L_{\rm tot} = \sum_\alpha L_\alpha \neq 0$ in the evolution with hierarchical Yukawa couplings (F^6)

Baryogenesis via RHν Oscillation

[Akhemedov, Rubakov, Smirnov('98)] [Asaka, Shaposhnikov('05)]

The contribution of mass is suppressed by temperature, $\boldsymbol{T \geq \Lambda_{\rm EW} \simeq 100{\rm GeV}}$

→ **Lepton number is conserved in the whole system.**



$\Delta L_{\rm tot}$ is partially converted to baryon asymmetry by sphaleron.

$$\Delta B = -\frac{28}{79}\Delta L_{\rm tot} \quad \text{at} \quad T = T_{\rm SF}$$

[Khlebnikov, Shaposhnikov('88)]

Parameterization of $F_{\alpha I}$ for $N_{1,2}$

From seesaw mass matrix $M_\nu = -\langle\Phi\rangle^2 F\, M_M^{-1}\, F^T$,

$$F = (i/\langle\Phi\rangle) U\, D_\nu^{\frac{1}{2}}\, \Omega\, D_N^{\frac{1}{2}}$$ (3x2 matrix) [Casas, Ibarra ('01)]

- $D_\nu^{\frac{1}{2}} = \mathrm{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3})$
- $D_N^{\frac{1}{2}} = \mathrm{diag}(\sqrt{M_1}, \sqrt{M_2}) = \mathrm{diag}(\sqrt{M_N - \Delta M}, \sqrt{M_N + \Delta M})$
- $$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\eta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
- $$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \end{pmatrix}$$ (*e.g.* NH)

ω :complex parameter $\quad \xi = \pm 1$

For large $\mathrm{Im}\omega$

$$F \propto \exp(\mathrm{Im}\omega) \equiv X_\omega$$

ν osc. is guaranteed as long as this parameterization is relevant.