# Resonant leptogenesis at TeV-scale and neutrinoless double beta decay

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# Outline

1. Introduction
2. Model
3. Numerical result
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5. Summary

# Introduction

## Introduction

- The SM cannot explain the origin of neutrino masses and Baryon asymmetry of the Universe (BAU).

$$Y_B \equiv \frac{n_B}{s} = (8.677 \pm 0.054) \times 10^{-11}$$ [Planck 2016]

- We want to understand these problems by TeV-scale physics.

- Leptogenesis(LG) is the scenario which can resolve the problem of neutrino masses and BAU.

M.Fukugita and T.Yanagida Pays.Lett. **B174** (1986) 45

- But the canonical leptogenesis requires heavy right-handed neutrinos( $M_1 \gtrsim \mathcal{O}(10^9)$ GeV ).

S. Davidson and A. Ibarra, Phys. Lett. **B535**, 25 (2002).

- If right-handed neutrinos are quasi-degenerate, they generate lepton number resonantly (Resonant Leptogenesis, RLG).

A.Pilaftsis and T. E. J. Underwood, Null. Pays. **B 692** (2004) 303

- We focus on right-handed neutrinos which have TeV-scale masses.

- At TeV-scale, the flavor effect is essential.

➡ the CP violation of low energy neutrino physics are involved with high energy physics that is yield of BAU through RLG.

# Model

# Model

- **SM + right-handed neutrinos**

$$\mathcal{L} = \mathcal{L}_{SM} + i\overline{\nu_{RI}}\partial_\mu \gamma^\mu \nu_{RI} - \left( F_{\alpha I}\overline{\ell_\alpha}\Phi\nu_{RI} + \frac{M_{MIJ}}{2}\nu^c_{RI}\nu_{RJ} + h.c. \right)$$

$\nu_{RI} \quad (I = 1, 2, 3)$

$$\ell_\alpha = \begin{pmatrix} \nu_{L\alpha} \\ e_{L\alpha} \end{pmatrix} \quad (\alpha = e, \mu, \tau)$$

$$\Phi = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$$

$M_M = diag(M_1, M_2, M_3)$ : Majorana masses

$D_\nu = diag(m_1, m_2, m_3)$ : active $\nu$ masses

**$\nu$ Yukawa coupling constant**

$$F = \frac{i}{\langle \phi^0 \rangle} U_{PMNS} D_\nu^{\frac{1}{2}} \Omega M_M^{\frac{1}{2}}$$

**: Casas-Ibarra parameterization**

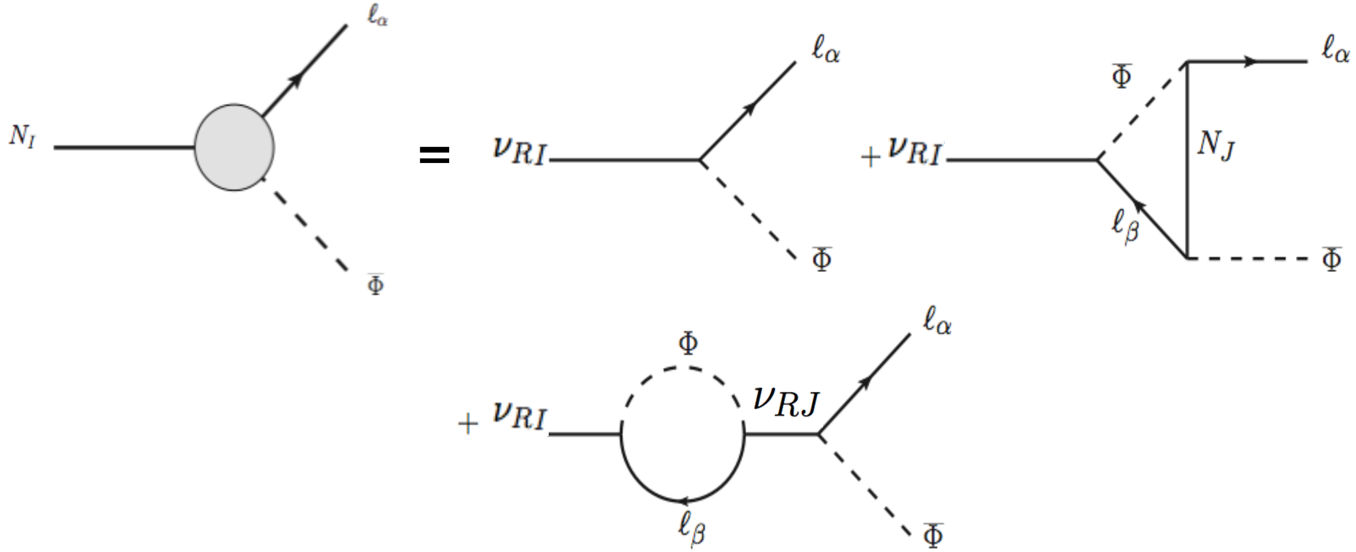
$(\Omega^{\mathrm{T}}\Omega = \mathbf{1})$ [Casas,Ibarra '01]

$$U_{PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta_{cp}} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta_{cp}} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta_{cp}} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta_{cp}} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta_{cp}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

$$\begin{cases} s_{ij} = \sin\theta_{ij} \\ c_{ij} = \cos\theta_{ij} \end{cases}$$ **: mixing angle** **Dirac phase** **Majorana phase**

# Leptogenesis

M.Fukugita and T.Yanagida Pays.Lett. **B174** (1986) 45




## CP violating parameter

$$\varepsilon_1 \equiv \frac{\Gamma\left(\nu_{R1} \to \ell_1 + \overline{\Phi}\right) - \Gamma\left(\nu_{R1} \to \bar{\ell}_1 + \Phi\right)}{\Gamma\left(\nu_{R1} \to \ell_1 + \overline{\Phi}\right) + \Gamma\left(\nu_{R1} \to \bar{\ell}_1 + \Phi\right)}$$

$$= \frac{1}{8\pi} \sum_{J\neq 1} \frac{\mathrm{Im}[(F^\dagger F)_{1J}^{2}]}{(F^\dagger F)_{11}} \left[ I\left(\frac{M_J^2}{M_1^2}\right) + J\left(\frac{M_J^2}{M_1^2}\right)\right] \propto M_1$$

$$I(x) = x^{\frac{1}{2}} \left\{ 1 + (1+x)\log\left(\frac{x}{1+x}\right)\right\}$$

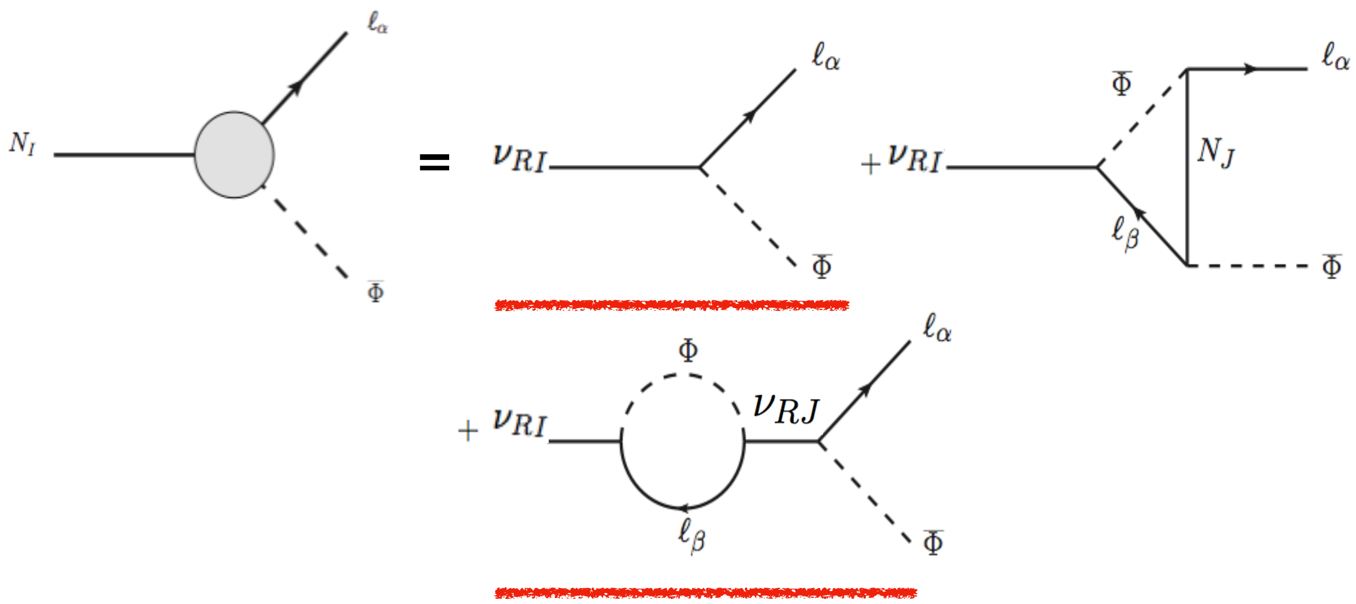
$$J(x) = \frac{x^{\frac{1}{2}}}{1-x}$$

$$\begin{cases} I(x) \to -\frac{1}{2\sqrt{x}} \\ J(x) \to -\frac{1}{\sqrt{x}} \end{cases} \quad (x \gg 1)$$

$$(M_1 \ll M_2, M_3)$$

➡ **Need heavy right-handed neutrinos** $(\mathcal{O}(10^9)\ \mathrm{GeV})$

# Resonant LG + flavor effect




## CP violating parameter

$$\varepsilon_{\alpha I} \equiv \frac{\Gamma\left(\nu_{RI} \to \ell_\alpha + \overline{\Phi}\right) - \Gamma\left(\nu_{RI} \to \overline{\ell_\alpha} + \Phi\right)}{\Gamma\left(\nu_{RI} \to \ell_I + \overline{\Phi}\right) + \Gamma\left(\nu_{RI} \to \overline{\ell_I} + \Phi\right)}$$

$$= \frac{1}{8\pi} \frac{\mathrm{Im}[F^*_{\alpha I} F_{\alpha J} (F^\dagger F)_{IJ}]}{(F^\dagger F)_{II}} \frac{M_I M_J (M_I^2 - M_J^2)}{(M_I^2 - M_J^2)^2 + A^2}$$

(J ≠ I)

regulator : $A = M_I \Gamma_I + M_J \Gamma_J$

M. Garny, A. Kartavtsev and A. Hohenegger, Annals Phys. 328 (2013) 26
S. Iso, K. Shimada, and M. Yamanaka, JHEP. 04, 062, (2014).

$$|\varepsilon_{\alpha I}|_{max} = \frac{1}{8\pi} \frac{\mathrm{Im}[F^*_{\alpha I} F_{\alpha J} (F^\dagger F)_{IJ}]}{(F^\dagger F)_{II}} \frac{M_I M_J}{2|A|}$$

for $(M_I^2 - M_J^2)^2 = (M_N \Delta M)^2 = A^2$

$M_N$ : average value of $M_I$ and $M_J$
$\Delta M$ : difference between $M_I$ and $M_J$

# Numerical result

# Parameters

## Assumptions

- two RH $\nu$ are responsible to the LG and also seesaw mechanism.
- The lightest mass of active $\nu$ is taken to be zero.
- $\omega_{IJ}$ is real(CP-violation occurs only in the active $\nu$ sector).

$$\Omega = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\omega_{23} & \sin\omega_{23} \\ 0 & -\sin\omega_{23} & \cos\omega_{23} \end{pmatrix} \quad \text{(for NH)} \qquad \begin{pmatrix} \cos\omega_{12} & \sin\omega_{12} & 0 \\ -\sin\omega_{12} & \cos\omega_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{(for IH)}$$

- Input parameters: $\theta_{ij}$, $\Delta m^2_{ij}$ (central values) [NuFIT(2018)]

- We estimate maximum value of yield of baryon asymmetry.
In other words, $\Delta M$ is minimized.

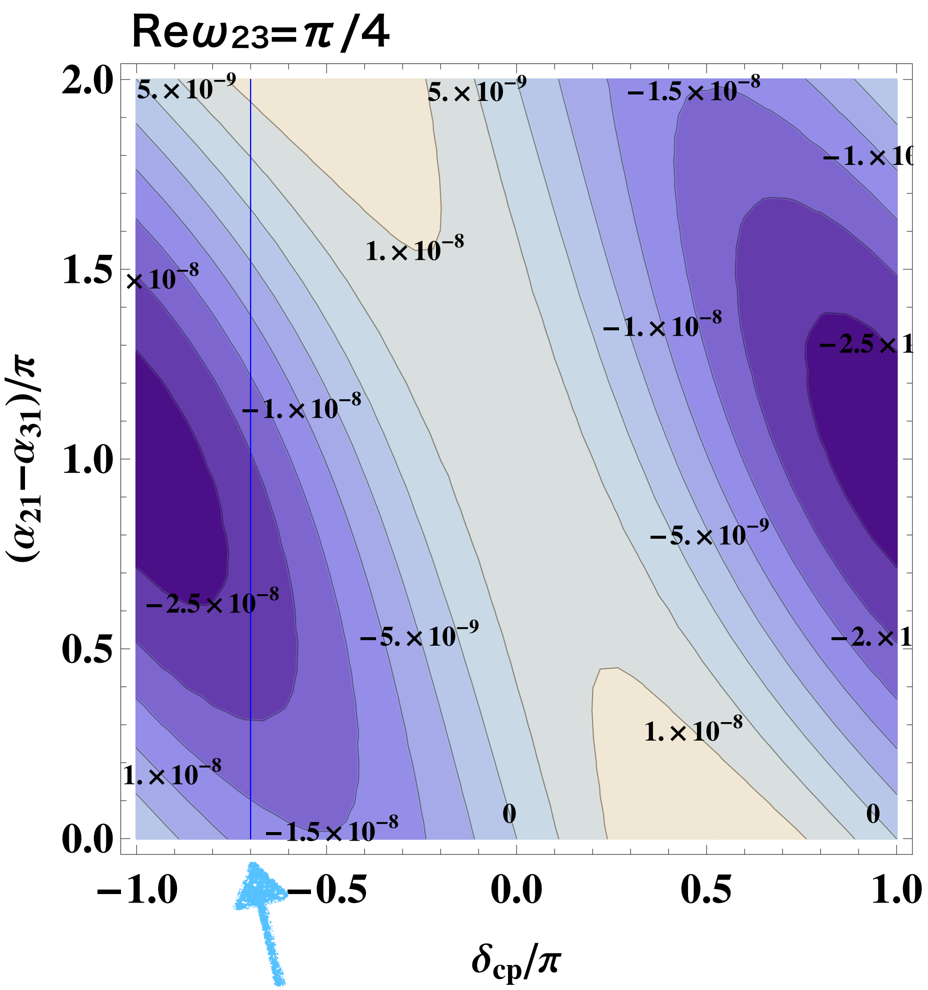
$$M_N = 1 \text{ TeV}$$

$$\Delta M = \frac{M_I \Gamma_I + M_J \Gamma_J}{2 M_N}$$

Parameters
- Active $\nu$ : $\delta_{CP}$, $\alpha_{21}$-$\alpha_{31}$: NH ($\alpha_{21}$: IH)
- Sterile $\nu$ : Re$\omega_{23}$ : NH (Re$\omega_{12}$ : IH)

# $\delta_{cp}$ and Majorana phase

NH case



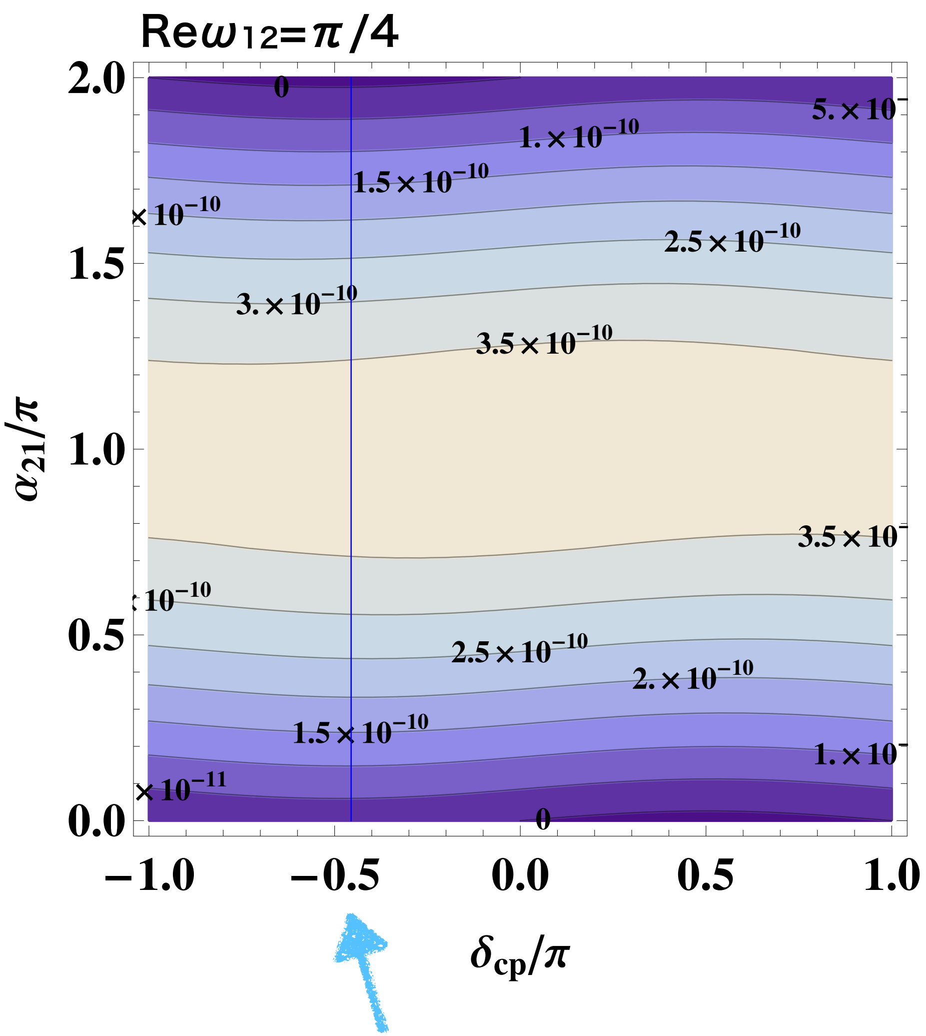

central value of observation

- Yield of baryon asymmetry depend on both Dirac phase($\delta_{cp}$) and the difference of Majorana phase.

Determining the Dirac phase in accelerator neutrino experiments such as T2K experiment is an important input in predicting baryon asymmetry.

# $\delta_{cp}$ and Majorana phase

IH case



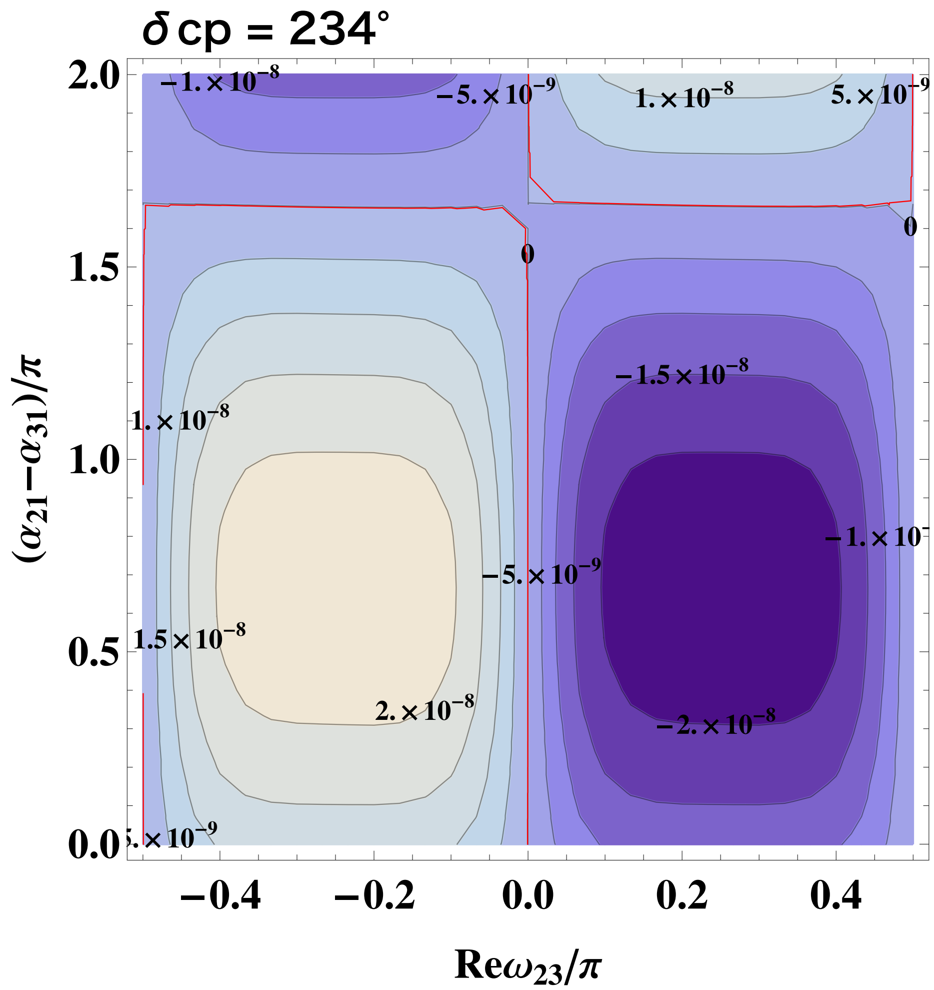

central value of observation

- Yield of baryon asymmetry is almost independent on Dirac phase.

It is possible that the baryon asymmetry of the universe restricts Majorana phases.

# Reω and Majorana phase

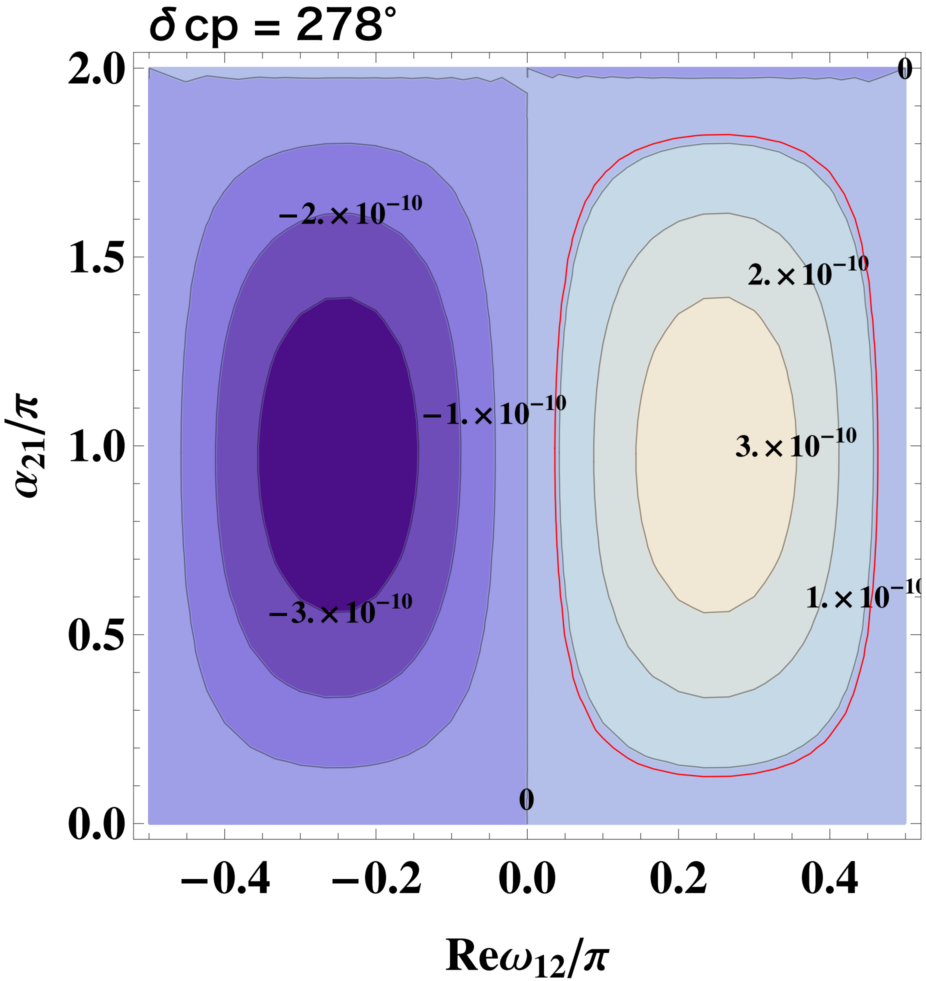
NH case




- In both regions $\mathrm{Re}\omega_{23}<0$ and $\mathrm{Re}\omega_{23}>0$, the observed BAU can be generated.

# Reω and Majorana phase

IH case




- It is only $\mathrm{Re}\omega_{12}>0$ regions when the observed BAU can be generated.

# Neutrino less double beta decay

# 0νββ decay

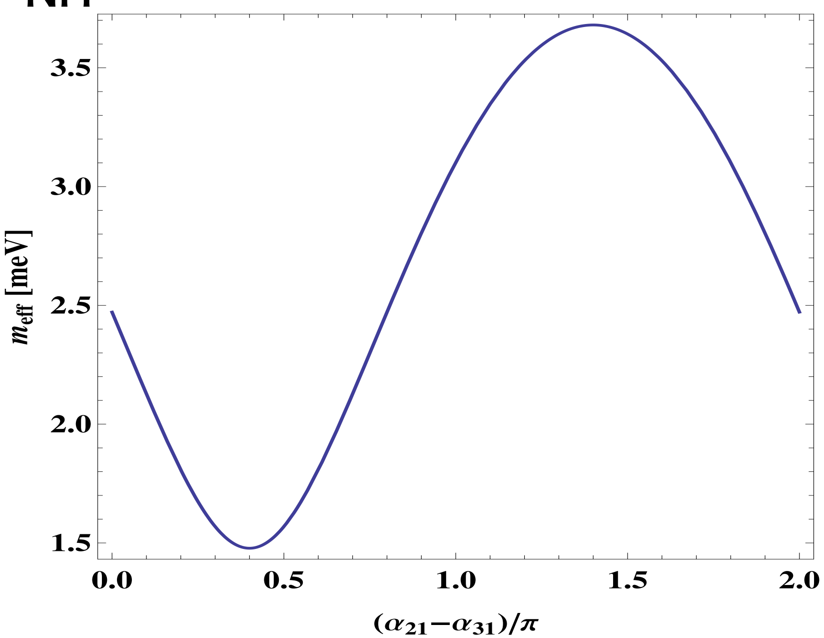
- In the seesaw mechanism, neutrinos are Majorana fermions.
- The lepton number is then broken.
- If there is lepton number violation, it occurs neutrinoless double beta decay. $(A,Z) \rightarrow (A,Z+2)+2e^-$

## Effective neutrino mass of $0\nu\beta\beta$

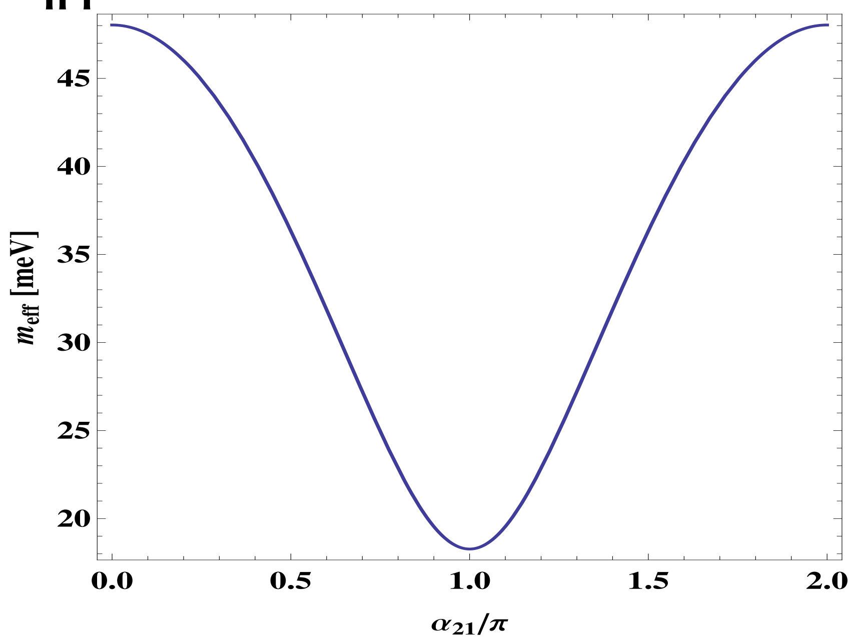
$\Gamma_{0\nu\beta\beta} \propto m_{eff}^2$

$$m_{\rm eff} = \left|\sum_i m_i U_{ei}^2\right|$$

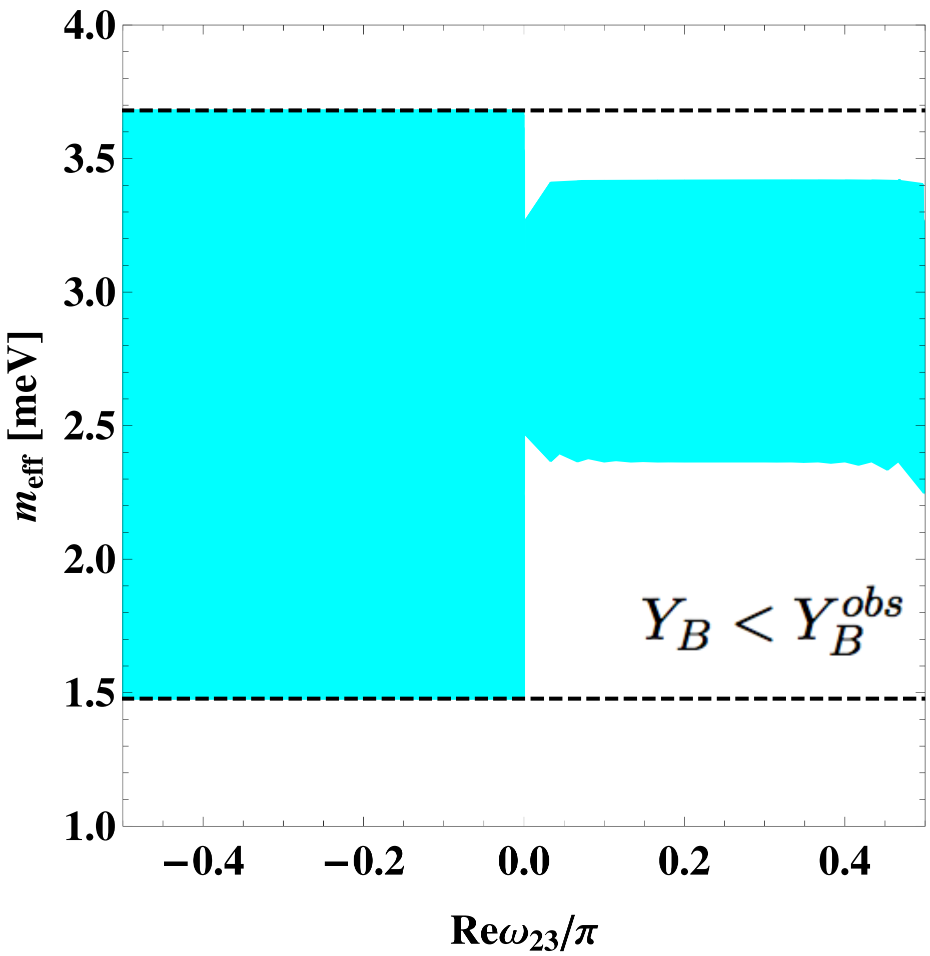
NH




IH



NH case




## BAU constraints on $m_{eff}$

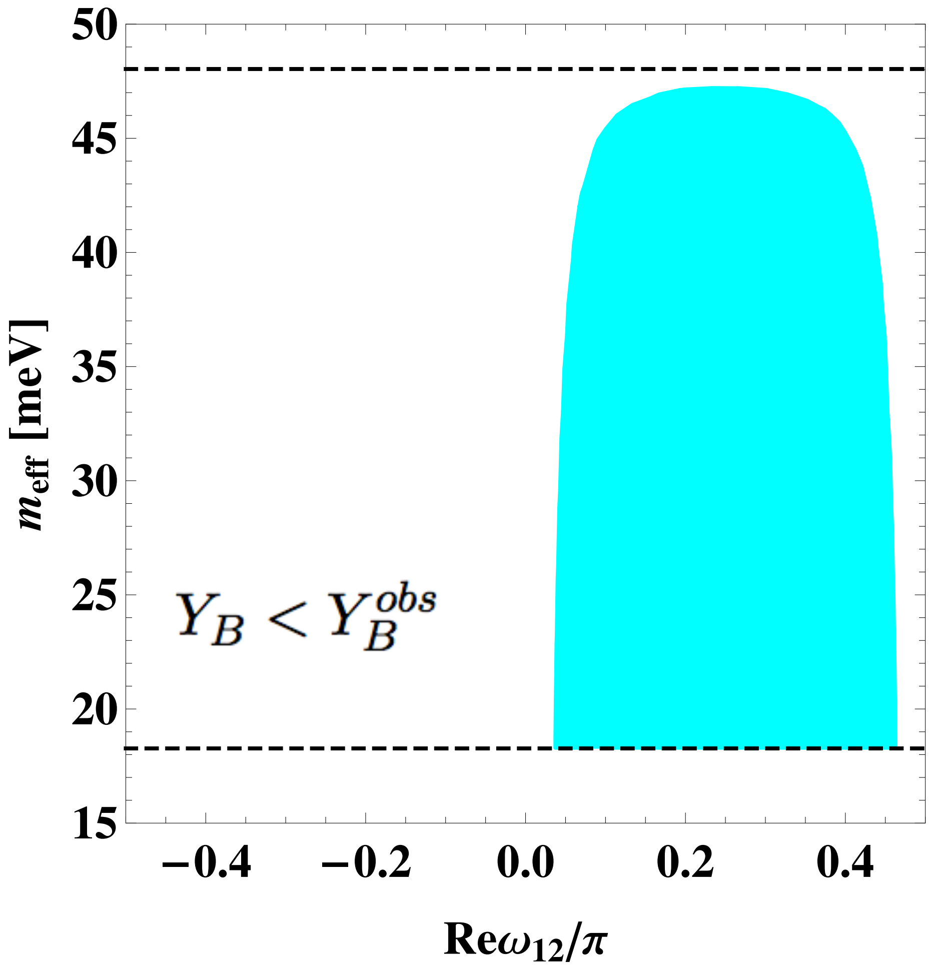
when $\mathrm{Re}\,\omega_{23}<0$ :

the range of $m_{eff}$ is unaffected

when $\mathrm{Re}\,\omega_{23}>0$ :

$m_{eff}$ receives both upper and lower bounds from BAU

IH case




BAU constraints on $m_{eff}$

Re$\omega_{12}$>0 only:

upper bound on $m_{eff}$

# Summary

## Summary

- We investigated resonant leptogenesis at TeV-scale.
- We found that sufficient baryon number can be generated even if the right-handed neutrinos are TeV-scale masses.
- We demonstrated how the baryon asymmetry correlates with CP-violating parameters in the PMNS matrix.
- We showed that the region of effective neutrino mass in neutrinoless double beta decay is restricted in order to explain the observed baryon asymmetry.

## Outlook

- We will investigate the impact of quantum effect and right-handed neutrino oscillation on yield of baryon asymmetry by using Kdanoff-Baym equation.
- We want to investigate other CP-violating process with this model.

# Back up

## $\varepsilon_1$(Inverted hierarchy)

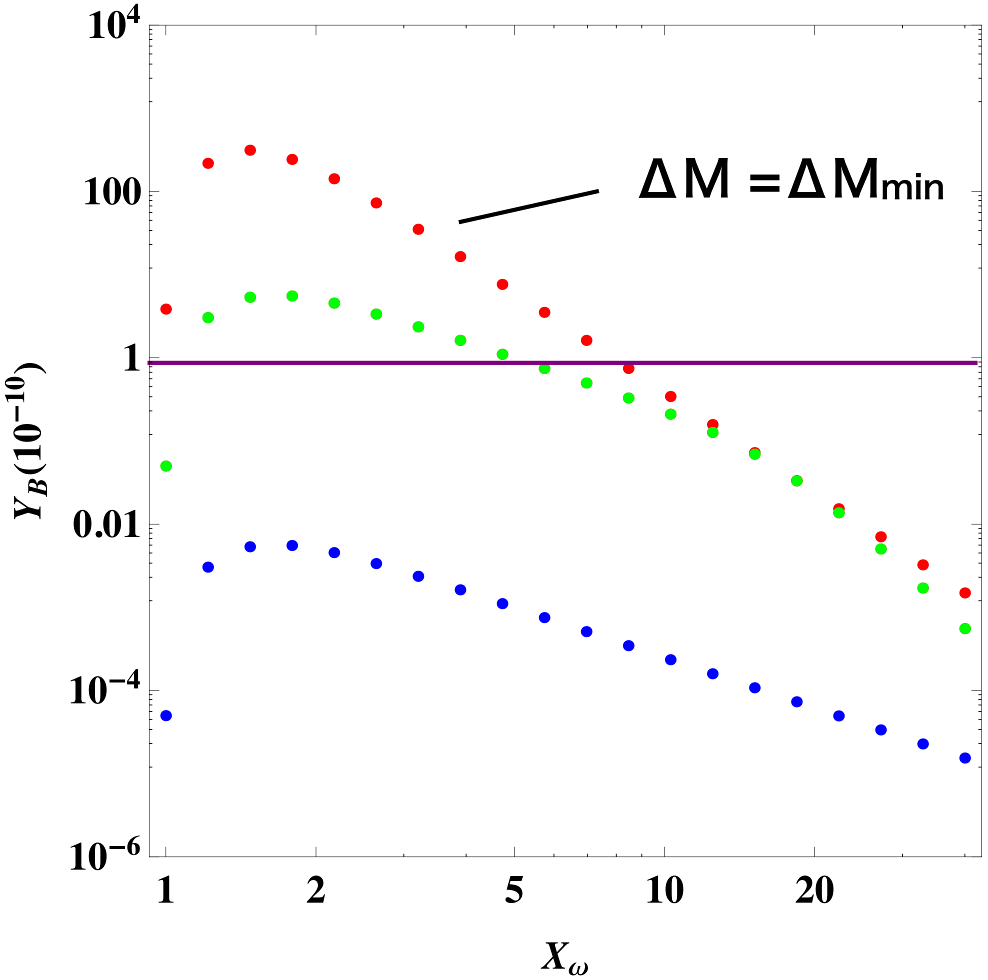
$$\Im[F^*_{\alpha 1}F_{\alpha 2}(F^\dagger F)_{12}] = \frac{M_1 M_2}{\langle\Phi\rangle^4}\frac{1}{2}\left[({m_1}^2|U_{\alpha 1}|^2 - {m_2}^2|U_{\alpha 2}|^2)\sin 2\Re\omega_{12}\sinh 2\Im\omega_{12}\right.$$
$$+\sqrt{m_1 m_2}\{(m_1+m_2)\Re[U^*_{\alpha 1}U_{\alpha 2}]\cos 2\Re\omega_{12}\sinh 2\Im\omega_{12}$$
$$\left.+(m_1-m_2)\Im[U^*_{\alpha 1}U_{\alpha 2}]\sin 2\Re\omega_{12}\cosh 2\Im\omega_{12}\}\right]$$

the coefficient of $X^2_{\omega_{12}}$ $\quad X_{\omega_{12}} = \mathrm{e}^{\Im\omega_{12}}$

$$\frac{M_1 M_2}{\langle\Phi\rangle^4}\frac{1}{4}\left[({m_1}^2|U_{\alpha 1}|^2 - {m_2}^2|U_{\alpha 2}|^2)\sin 2\Re\omega_{12} + \sqrt{m_1 m_2}V_\alpha\cos(2\Re\omega_{12}-\theta_\alpha)\right]$$

$$V_\alpha = \sqrt{({m_1}^2+{m_2}^2)|U_{\alpha 1}|^2|U_{\alpha 2}|^2 + 2m_1 m_2(\Re[U^*_{\alpha 1}U_{\alpha 2}]^2 - \Im[U^*_{\alpha 1}U_{\alpha 2}]^2)}$$
$$\tan\theta_\alpha = \frac{(m_1-m_2)\Im[U^*_{\alpha 1}U_{\alpha 2}]}{(m_1+m_2)\Re[U^*_{\alpha 1}U_{\alpha 2}]}$$

# dependence on Imω(IH case)



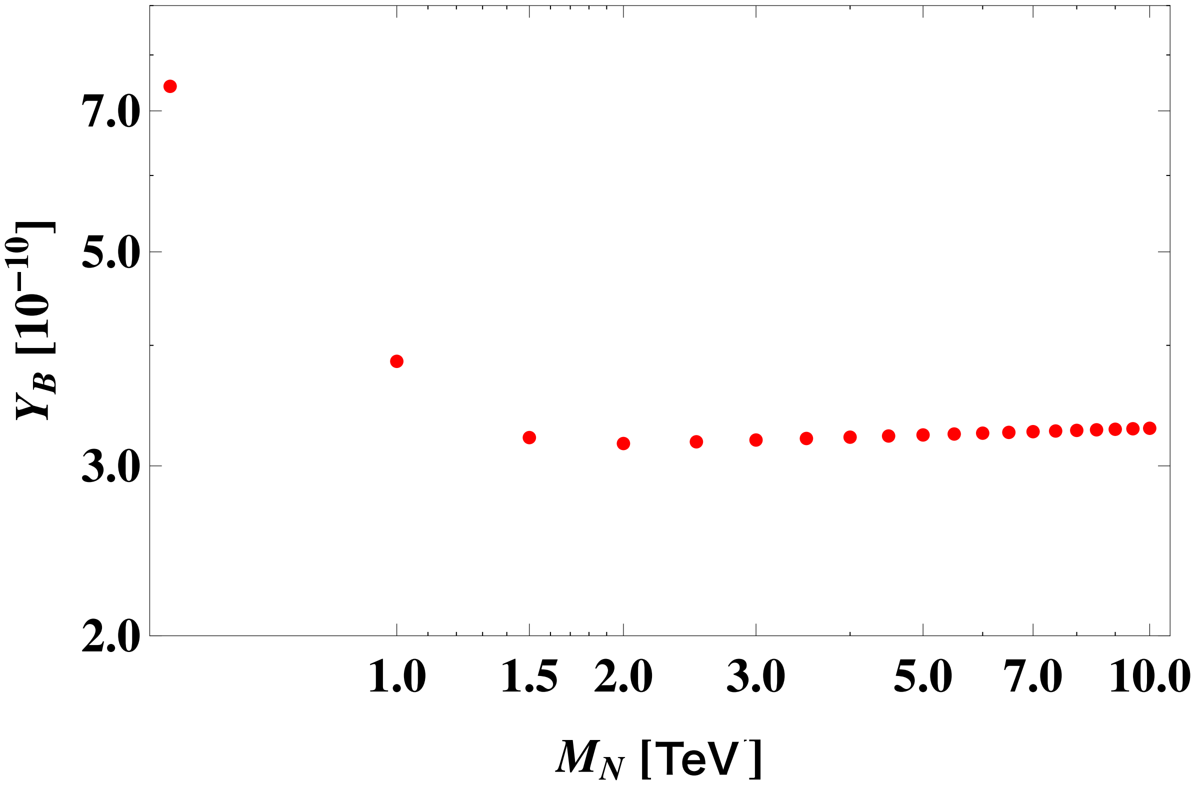

Im$\omega$ >>1

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

$X\omega$ ~ O(1)

sufficient baryon number
can be generated

# dependence on $M_N$




When ΔM is minimized,

$M_N$ > 1.5 TeV

$Y_B$ is almost independent on $M_N$.

$M_N$ < 1.5 TeV

Wash out effect is not effective.

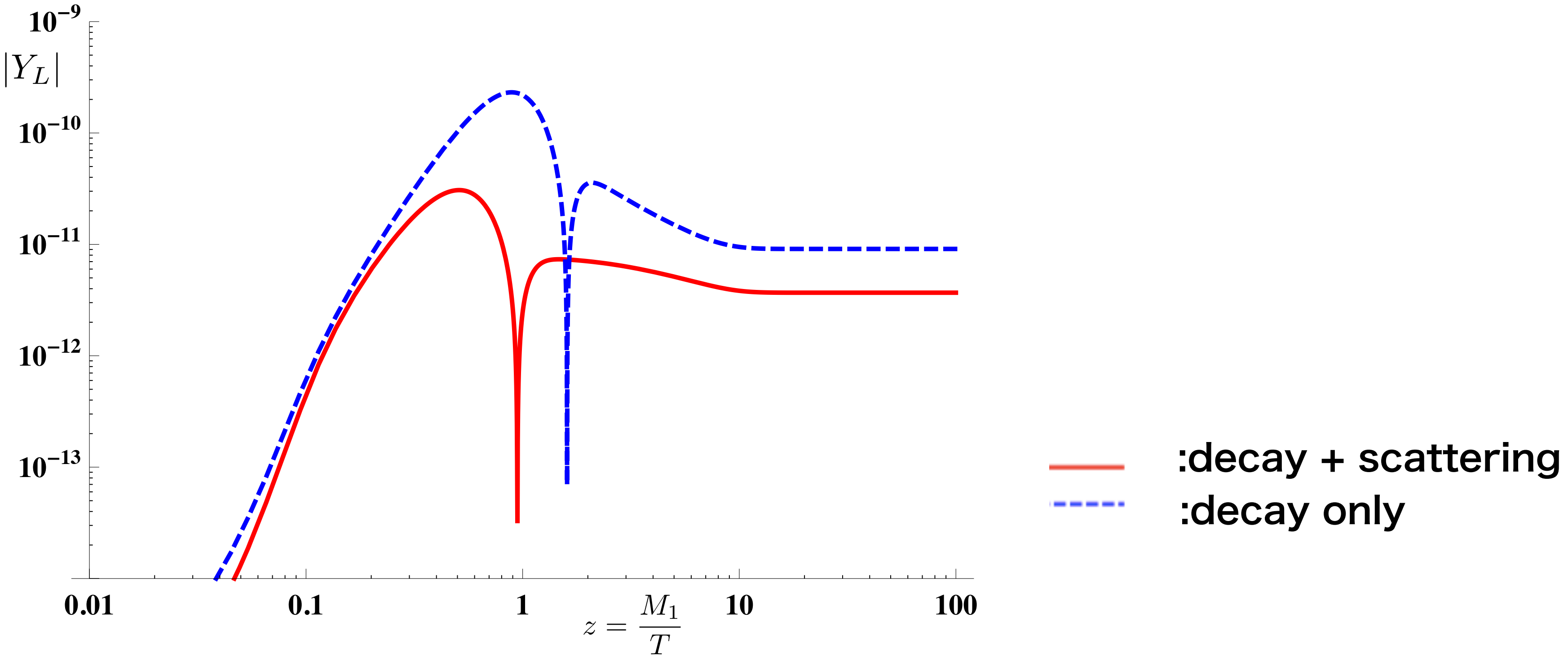
# Boltzmann equation

$$\frac{dY_{\nu_{RI}}}{dz} = -\frac{z}{sH(M_1)}\left\{\left(\frac{Y_{\nu_{RI}}}{Y^{eq}_{\nu_{RI}}}-1\right)(\gamma_I^{(\mathrm{A})}+2\gamma_I^{(\mathrm{B})}+4\gamma_I^{(\mathrm{C})})\right.$$
$$\left.+\sum_J\left(\frac{Y_{\nu_I}}{Y^{eq}_{\nu_I}}\frac{Y_{\nu_J}}{Y^{eq}_{\nu_J}}-1\right)(\gamma_{IJ}^{(\mathrm{D})}+\gamma_{IJ}^{(\mathrm{E})})\right\}$$

$$\frac{dY_{\Delta_\alpha}}{dz} = -\frac{z}{sH(M_1)}\left[\sum_I\left(\frac{Y_{\nu_{RI}}}{Y^{eq}_{\nu_{RI}}}-1\right)\varepsilon_{I\alpha}\gamma_I^{(\mathrm{A})}+\left[\sum_I\left\{-\frac{1}{2}(C^\ell_{\alpha\beta}-C^\Phi_\beta)\gamma_{I\alpha}^{(\mathrm{A})}\right.\right.\right.$$
$$\left.-\left(C^\ell_{\alpha\beta}\frac{Y_{\nu_{RI}}}{Y^{eq}_{\nu_{RI}}}-\frac{1}{2}C^\Phi_\beta\right)\gamma_{I\alpha}^{(\mathrm{B})}-\left(2C^\ell_{\alpha\beta}-\frac{1}{2}C^\Phi_\beta\left(1+\frac{Y_{\nu_{RI}}}{Y^{eq}_{\nu_{RI}}}\right)\right)\gamma_{I\alpha}^{(\mathrm{C})}\right\}$$
$$\left.\left.+\sum_\gamma\left\{-(C^\ell_{\alpha\beta}+C^\ell_{\gamma\beta}-2C^\Phi_\beta)(\gamma_{\alpha\beta}^{(\mathrm{F})}+\gamma_{\alpha\beta}^{(\mathrm{G})})-(C^\ell_{\alpha\beta}-C^\ell_{\gamma\beta})\gamma_{\alpha\beta}^{(D)}\right\}\right]\frac{Y_{\Delta_\beta}}{Y^{eq}}\right]$$

$$C^\ell = \frac{1}{711}\begin{pmatrix} -211 & 16 & 16 \\ 16 & -211 & 16 \\ 16 & 16 & -211 \end{pmatrix}, \qquad C^\Phi = \frac{8}{79}\begin{pmatrix} 1, & 1, & 1 \end{pmatrix}$$

# Contribution of decay and scattering



# Equilibration temperatures

| | | |
|---|---|---|
| $T_{\rm ss}$ | $2.4 \times 10^{13}$ GeV | strong sphaleron |
| $T_{\rm ws}$ | $1.8 \times 10^{12}$ GeV | weak sphaleron |
| $T_b$ | $4.2 \times 10^{12}$ GeV | bottom-quark Yukawa |
| $T_c$ | $3.8 \times 10^{11}$ GeV | charm-quark Yukawa |
| $T_s$ | $2.5 \times 10^{9}$ GeV | strange-quark Yukawa |
| $T_u$ | $1.9 \times 10^{6}$ GeV | up-quark Yukawa |
| $T_d$ | $8.8 \times 10^{6}$ GeV | down-quark Yukawa |
| $T_\tau$ | $3.7 \times 10^{11}$ GeV | $\tau$-lepton Yukawa |
| $T_\mu$ | $1.3 \times 10^{9}$ GeV | $\mu$-lepton Yukawa |
| $T_e$ | $3.1 \times 10^{4}$ GeV | electron Yukawa |

**Table 1**. Equilibration temperatures $T_X$ for Yukawa- and instanton-mediated SM processes. Methods of the calculations and uncertainties are discussed in the text. Partial equilibration is relevant when the freeze-out of the lepton asymmetry happens at temperatures between $T_X$ and 20 $T_X$.

B. Garbrecht and P. Schwaller, JCAP **1410** (2014) no.10, 012