Resonant leptogenesis at TeV-scale and neutrinoless double beta decay

Takahiro Yoshida (Niigata Univ.)

Based on arXiv: 1812.11323

in collaboration with Takehiko Asaka (Niigata Univ.)

2019/04/11 @Kavli IPMU

Outline

Introduction

Introduction

Seesaw mechanism

by right-handed neutrinos is an attractive mechanism for tiny neutrino masses

Leptogenesis

Such right-handed neutrinos can also generate the baryon asymmetry of the universe (BAU)

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

$$Y_B{}^{\rm OBS} = \left.\frac{n_B}{s}\right|_{\rm obs} = (0.870 \pm 0.006) \times 10^{-10}$$ [Planck 2018]

When right-handed neutrinos are hierarchical, they must be heavier than $\mathcal{O}(10^9)$ GeV .

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

Introduction

Resonant leptogenesis

When right-handed neutrinos are quasi-degenerate,
the production of the BAU is enhanced

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

→ Masses of right-handed neutrinos can be smaller than $\mathcal{O}(10^9)$ GeV

→ Flavor effect of leptogenesis becomes important

→ The BAU can depend on the mixing matrix of active neutrinos !

Introduction

In this talk

We consider resonant leptogenesis by TeV-scale right-handed neutrinos

1) The dependence of the BAU on CP-violating phases in the PMNS matrix

2) The impacts on $0\nu\beta\beta$ decay from resonant leptogenesis

Model

Model

- We consider the SM with 3 right-handed neutrinos ν_{RI} $(I=1,2,3)$

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

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

- Yukawa couplings for the seesaw mechanism

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

[Casas,Ibarra '01]

- Active neutrino masses $D_\nu = diag(m_1, m_2, m_3)$

mixing

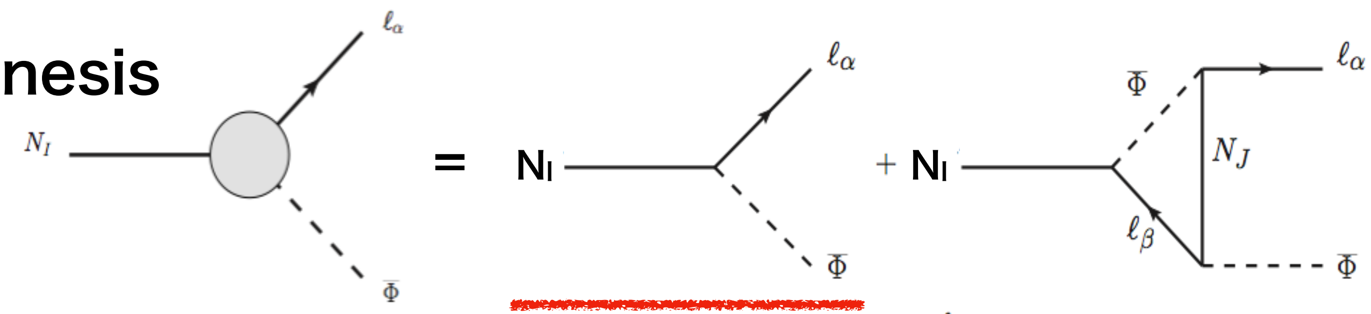
$$U_{PMNS} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta_{cp}} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta_{cp}} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta_{cp}} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta_{cp}} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta_{cp}}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

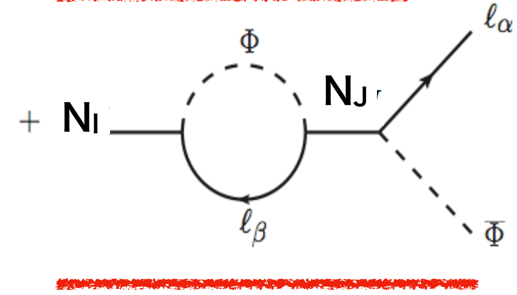
Dirac phase Majorana phases

- Orthogonal matrix for ν_R Ω

Leptogenesis and resonant leptogenesis

- Leptogenesis





Interference term of tree and self-energy correction becomes dominant to ε

CP asymmetry parameter

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

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

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

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

$$\Delta M_* \equiv A/(2M_N)$$

M_N : average value of M_I and M_J
ΔM : difference between M_I and M_J

Parameters

Assumptions

- Only two RH ν are responsible to leptogenesis and seesaw mechanism.
- The lightest active ν is massless.
- CP-violation occurs only in the active ν sector (ω_{IJ} is real)

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

- Take M_N = 1 TeV and evaluate the maximal Y_B by setting the mass difference as $\Delta M = \Delta M_*$

$$\Delta M_* \equiv A/(2M_N)$$

- Take the central values of θ_{ij} and Δm^2_{ij}

	θ_{12}	θ_{23}	θ_{13}	Δm^2_{21} [eV^2]	$\Delta m^2_{3\ell}$ [eV^2]
NH	33.62°	47.2°	8.54°	7.40×10^{-5}	$+2.494 \times 10^{-3}$ ($\ell = 1$)
IH	33.62°	48.1°	8.58°	7.40×10^{-5}	-2.465×10^{-3} ($\ell = 2$)

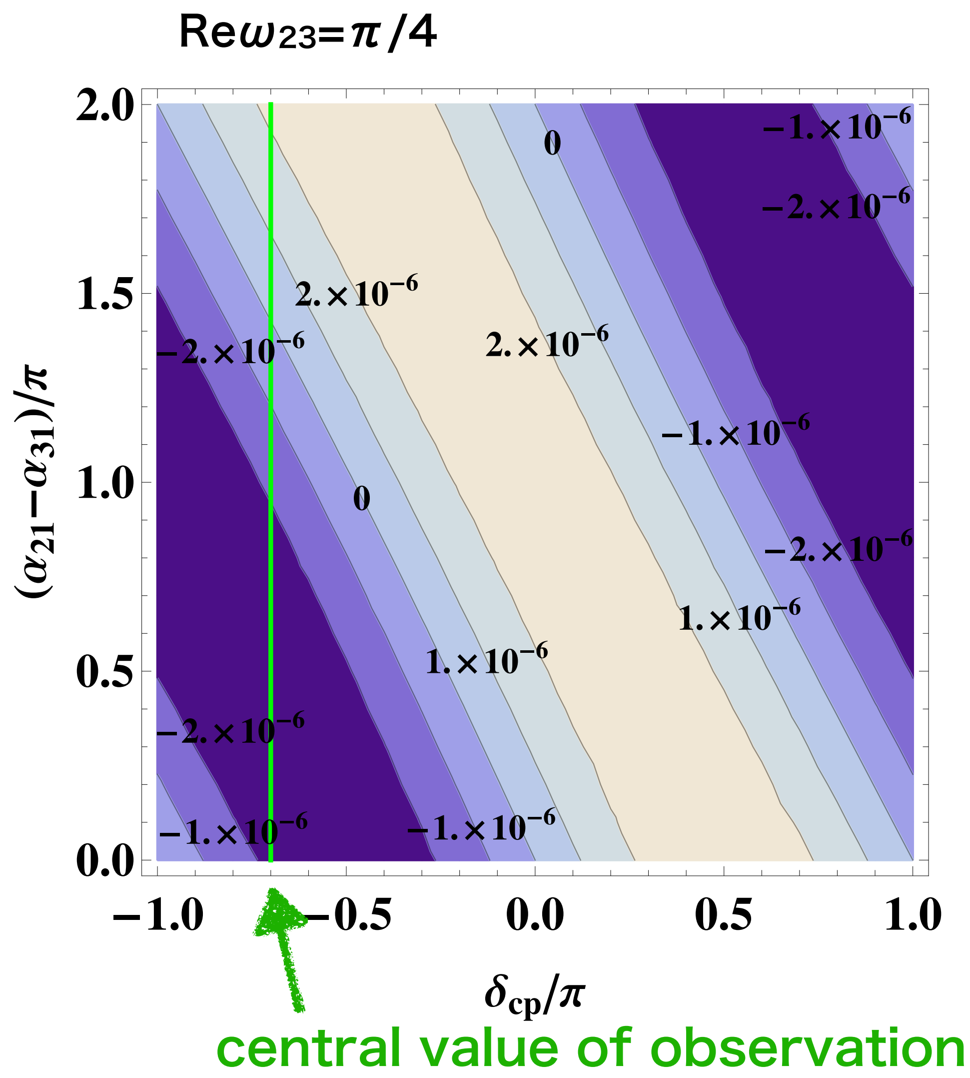
[NuFIT 2018]

BAU depends on
- Active ν : δ_{CP}, α_{21}-α_{31}: NH (α_{21}: IH)
- Sterile ν : Reω_{23} : NH (Reω_{12} : IH)

Resonant leptogenesis by TeV-scale right-handed neutrinos

Contour plot of BAU (δ_{cp} and Majorana phase)

NH case

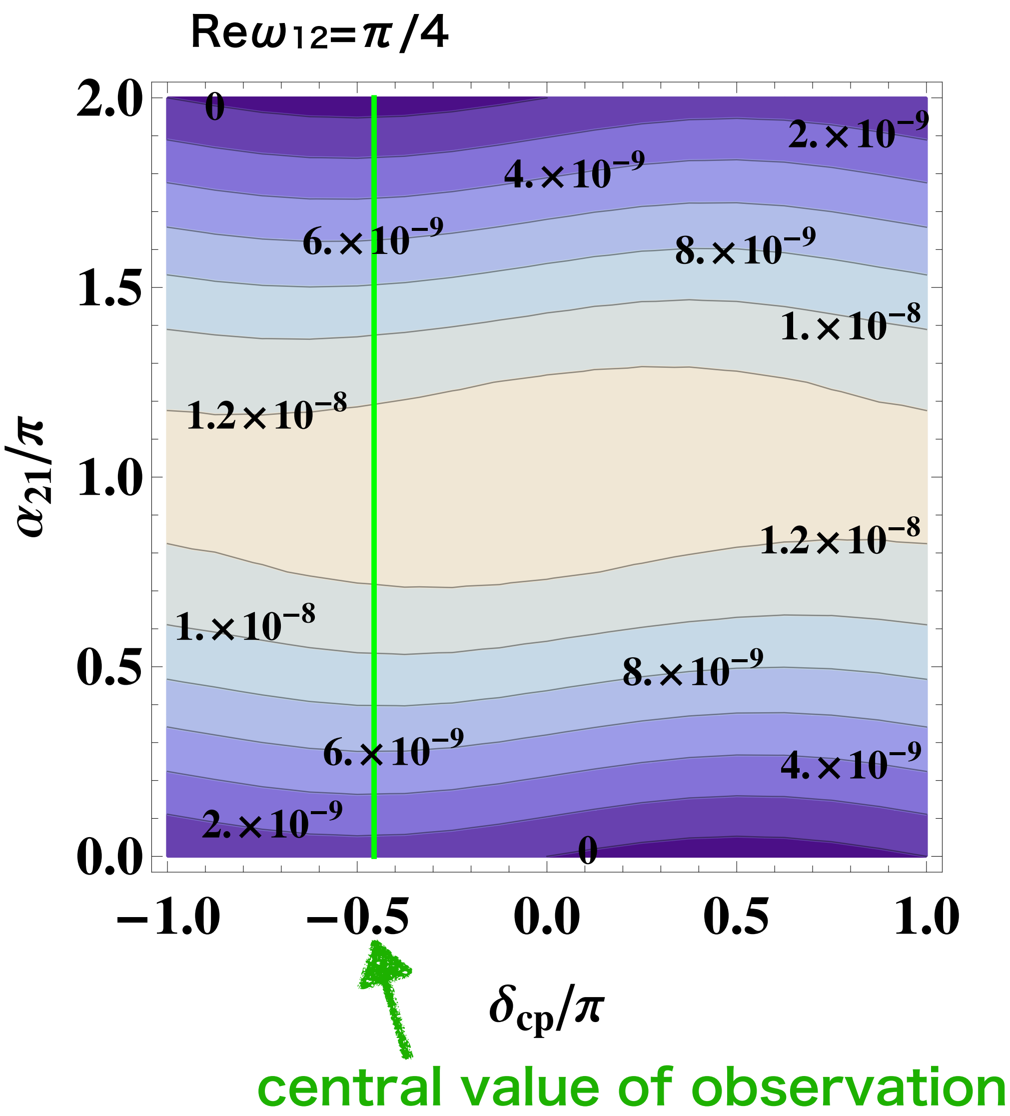


- Y_B can be large as O(10^{-6})
- Y_B depends on not only difference of Majorana phase(α_{21} - α_{31}) but also Dirac phase(δ_{cp})
- Dependence on CPV phases is approximately given by

$$Y_B \propto \sin\left(\frac{\alpha_{21}-\alpha_{31}}{2}+\delta_{CP}\right)$$

Contour plot of BAU (δ_{cp} and Majorana phase)

IH case



- Y_B can be large as $O(10^{-8})$
- Y_B depends on the Majorana phase significantly as the NH
- The dependence on the Dirac phase is much milder than the NH case
- Dependence on CPV phases is approximately given by

$$Y_B \propto \sin\left(\frac{\alpha_{12}}{2}\right)$$

Resonant leptogenesis and neutrinoless double beta decay

0νββ decay

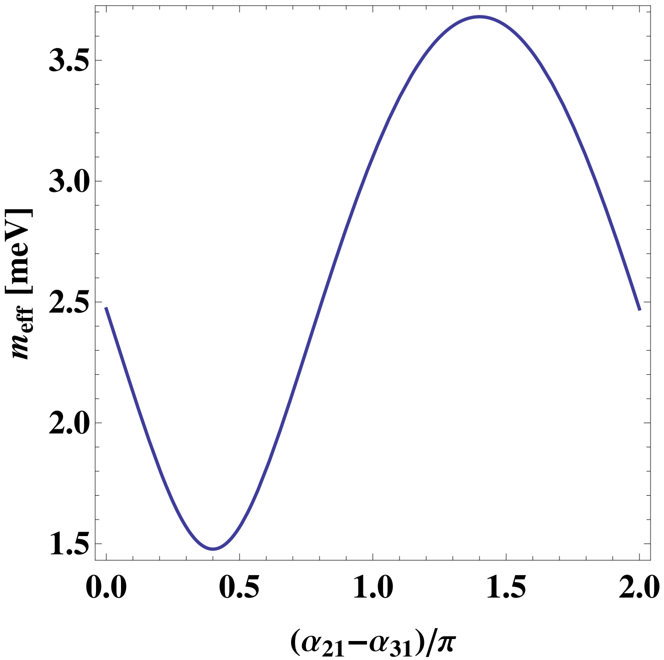
- In the seesaw mechanism neutrinos are Majorana fermions.
- The lepton number is then broken.
- If there is lepton number violation, it occurs neutrinoless double beta decay. $(A,Z) \rightarrow (A,Z+2) + 2e^-$

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

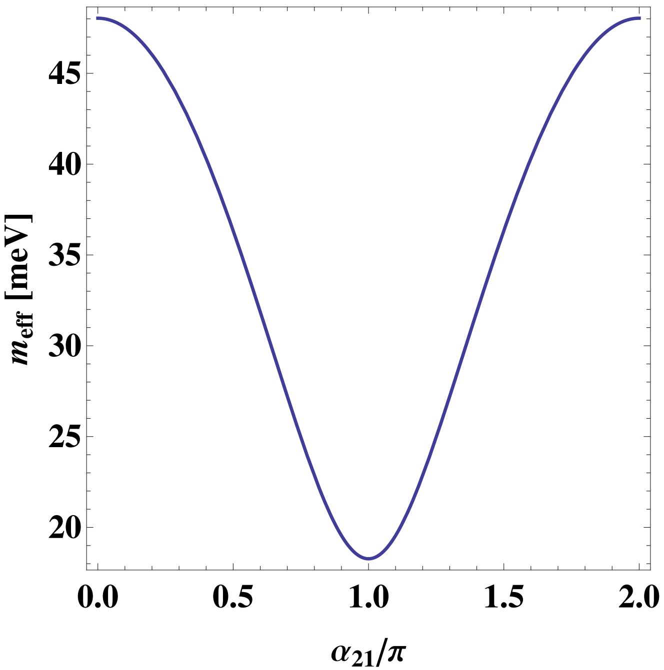
$\Gamma_{0\nu\beta\beta} \propto m_{\rm eff}^2$

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

NH



IH



Take central value of δ_{CP}

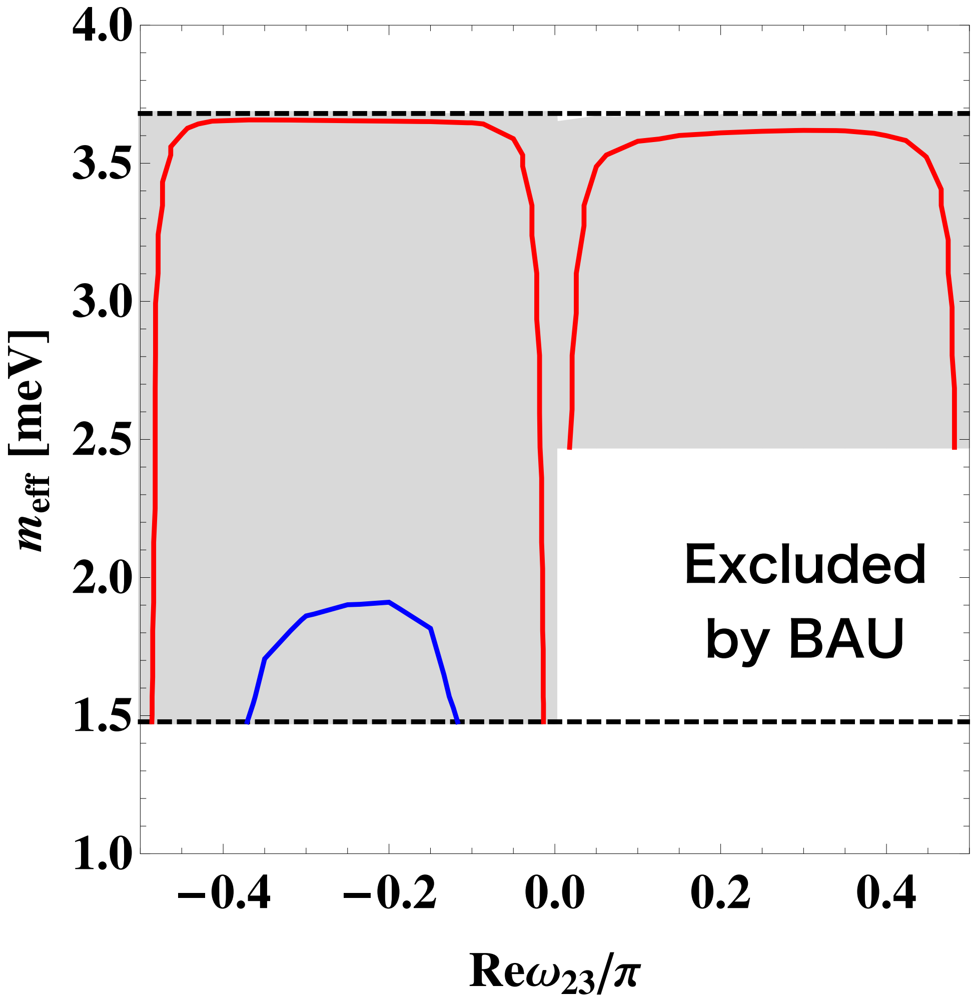
$$\delta_{\rm CP} = \begin{cases} -0.700\pi \quad (234\,^\circ) & \text{for the NH} \\ -0.456\pi \quad (278\,^\circ) & \text{for the IH} \end{cases}$$

The possible range

$$m_{\rm eff} = \begin{cases} (1.5 - 3.7)\ \text{meV} & \text{for the NH} \\ (18 - 48)\ \text{meV} & \text{for the IH} \end{cases}$$

0νββ decay

NH case



The BAU constraints on $m_{\rm eff}$

when Reω_{23}<0 :

no

when Reω_{23}>0 :

the lower bound

When ΔM becomes large,
BAU gives the upper bound on $m_{\rm eff}$

$\Delta M = 1.0 \times 10^4\, \Delta M_*$: red line

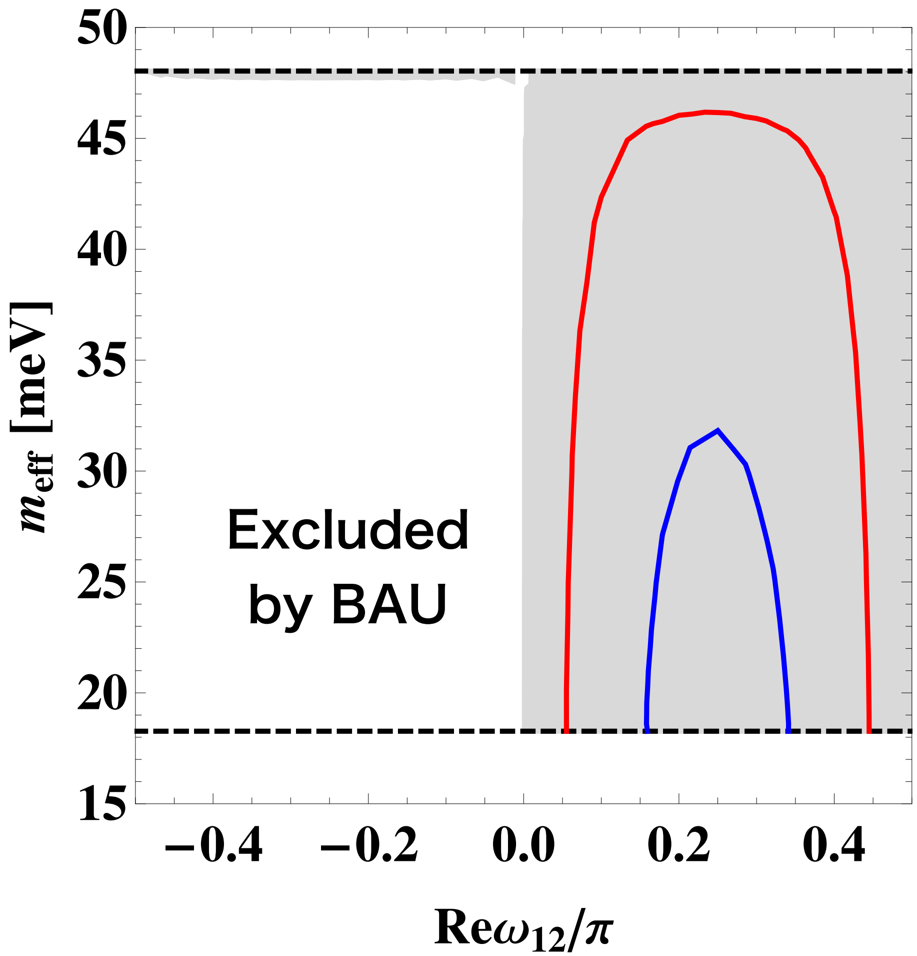
$\Delta M = 6.0 \times 10^4\, \Delta M_*$: blue line

The allowed region disappears when

$$\Delta M \geq \mathcal{O}(10^5)\Delta M_*$$

0νββ decay

IH case



The BAU constraints on m_{eff}

when Reω_{23}<0 :

maximal value of m_{eff}

(α_{21} ~ 2π)

when Reω_{23}>0 :

no

When ΔM becomes large,
BAU gives the upper bound on m_{eff}

$\Delta M = 1.0 \times 10^2\, \Delta M_*$: red line

$\Delta M = 2.5 \times 10^2\, \Delta M_*$: blue line

The allowed region disappears when

$$\Delta M \gtrsim 300\, \Delta M_*$$

Summary

Summary

- We investigated resonant leptogenesis at TeV-scale.
- We found that sufficient baryon number can be generated.
- 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.