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Baryon asymmetry and dark matter in a radiative neutrino mass model

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Based on S.Kashiwase and D.S,
arXiv:1207.2594, to be published in PRD

Outline

- Basic idea
- A model and its features
- Baryon number asymmetry in the model
- Summary

Basic idea

Neutrino oscillation data suggest neutrino masses are small : $m_\nu \lesssim O(10^{-1})$ eV. ($\sum m_\nu < 0.58$ eV @WMAP7)

- Dirac mass terms exist at tree level

  ⇒ right-handed neutrinos should be heavy enough.

  ordinary seesaw mechanism

- Dirac mass terms are forbidden at tree level by some symmetry

  ⇒ small neutrino masses may be induced radiatively even for rather light right-handed neutrinos.

  radiative seesaw mechanism

The same symmetry may guarantee the stability of some neutral particle (a dark matter candidate).

origin of neutrino mass ⟺ origin of dark matter

A radiative neutrino mass model

E. Ma

Z_2 is imposed to forbid Dirac neutrino masses at tree level.

- Field contents

	Z_2
SM fields	$+1$
η (SU(2) inert doublet)	-1
N_k (right handed neutrinos)	-1

$$\langle H \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\langle \eta \rangle = 0$$

The lightest one is stable

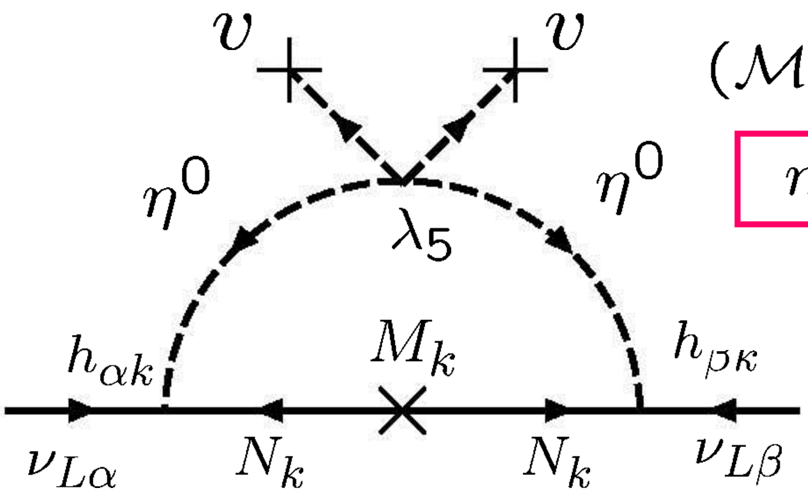
DM $\Rightarrow$ η_R^0

- Z2 invariant interaction and potential

$$\mathcal{L}_N = h_{\alpha k} \bar{L}_\alpha \eta N_k + \frac{1}{2} M_k N_k N_k + \text{h.c.}$$

$$\begin{aligned} V &= m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger \eta + \frac{\lambda_1}{2} (H^\dagger H)^2 + \frac{\lambda_2}{2} (\eta^\dagger \eta)^2 \\ &+ \lambda_3 (H^\dagger H)(\eta^\dagger \eta) + \lambda_4 (H^\dagger \eta)(\eta^\dagger H) + \frac{\lambda_5}{2} [(H^\dagger \eta)^2 + \text{h.c.}] \end{aligned}$$

Neutrino mass



$$I(x) = \frac{\lambda_5 v^2}{8\pi^2}\left(\frac{x}{1-x}\right)\left[1+\frac{x\ln x}{1-x}\right]$$

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_k \frac{h_{\alpha k} h_{\beta k} I(M_k^2/m_\eta^2)}{M_k}$$

$$\boxed{m_\eta < M_k}$$

$$\simeq \sum_k \frac{h_{\alpha k} h_{\beta k} v^2}{M_k}\frac{\lambda_5}{8\pi^2}\ln\frac{M_k^2}{m_\eta^2}$$

Correction to the ordinary Seesaw formula

$|\lambda_5| \ll 1$

⬇ even if masses of N_k are $O(1)$ TeV

small neutrino masses are realized

New physics is expected in lepton sector at TeV regions.

Dark matter abundance

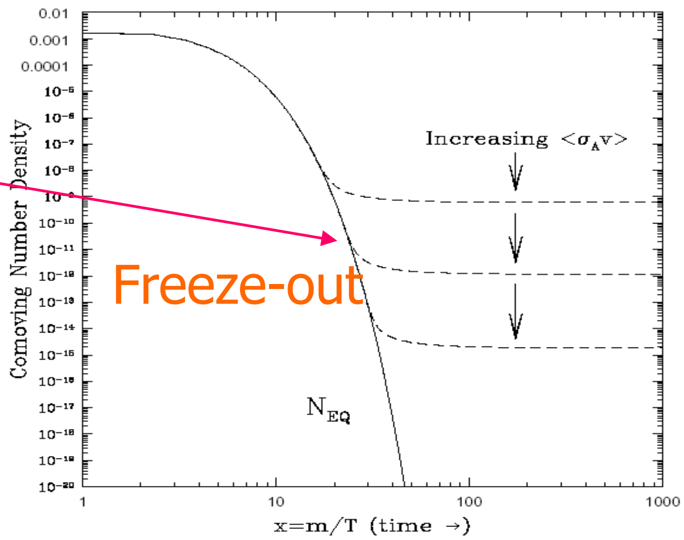
DM abundance follows the usual thermal relic scenario.

It is determined by the number density at the freeze-out temperature T_F.

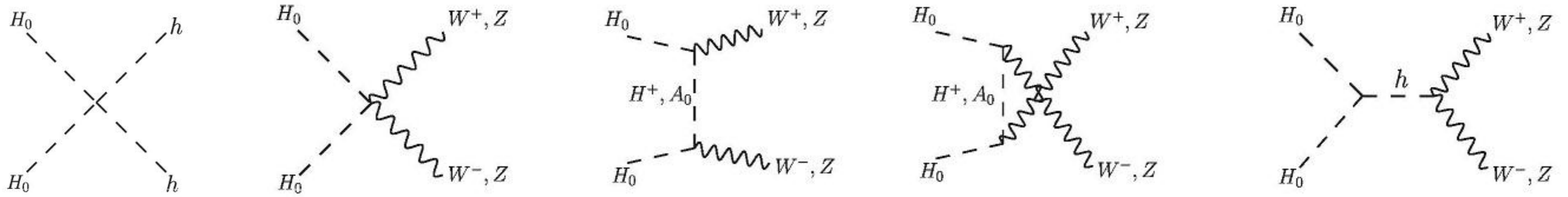
$$\langle\sigma v\rangle_{T_F} n(T_F) \sim H(T_F)$$

DM is η_R^0 that is the lightest neutral component of inert doublet

Dominant parts of cross section could be determined by the scalar quartic couplings $\lambda_{3,4}$.

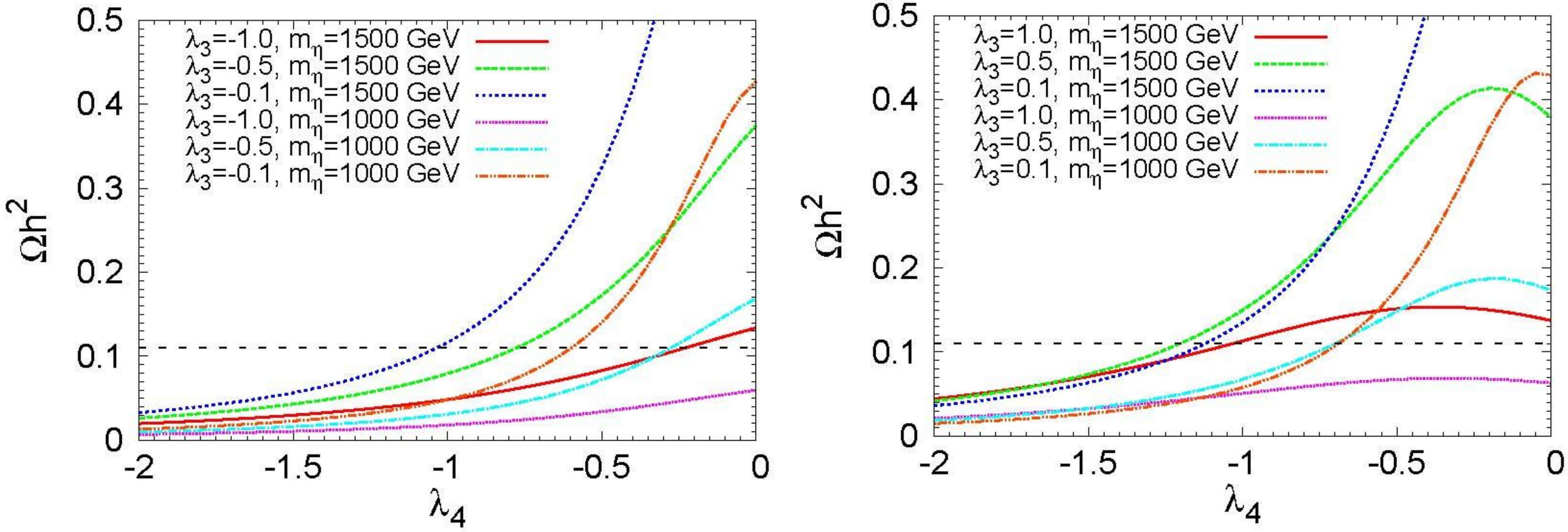


T.Hambye, et al., JHEP07 (2009) 090



Longitudinal components of gauge bosons give large contribution.

Relic η_R^0 abundance $m_\eta = 1,\ 1.5\ \text{TeV}$



$\lambda_3 < 0$ $\lambda_3 > 0$

- $|\lambda_3 + \lambda_4| = O(1)$ ⇒ required relic abundance is realized
- Neutrino Yukawa couplings are irrelevant to the relic abundance.

⇒ Neutrino Yukawa couplings could be small.

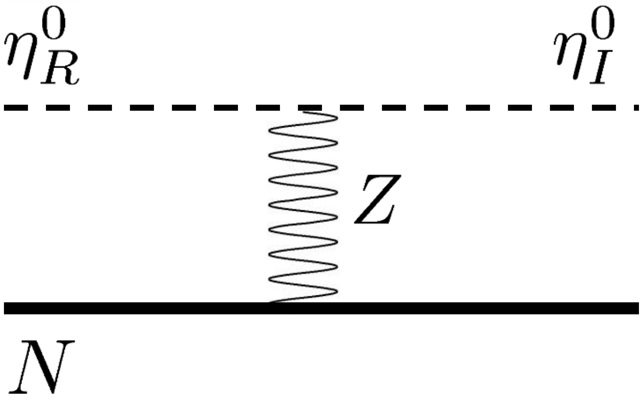
Other constraints

- DM direct search

$$M^2_{\eta_{\substack{R\\I}}} = m_\eta^2 + (\lambda_3 + \lambda_4 \pm \lambda_5)v^2$$

$$|\lambda_5| \ll 1 \;\Rightarrow\; M_{\eta_I^0} \simeq M_{\eta_R^0}$$

Inelastic scattering can contribute to the direct search experiments.



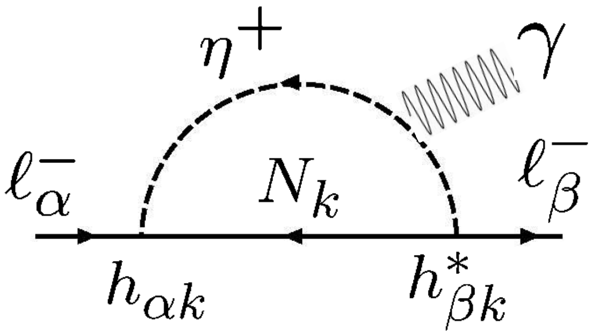
The present experimental bound imposes the mass difference δ > 150 keV .

Cui, et al., JHEP05 (2009) 076
C.Arina, et al., JCAP10 (2009) 018

$$|\lambda_5| \gtrsim 5 \times 10^{-6} \left(\frac{M_{\eta_R}}{1\ \mathrm{TeV}}\right)\left(\frac{\delta}{150\ \mathrm{keV}}\right)$$

◆ Lepton flavor violation

Lepton flavor violating processes $\ell_\alpha \to \ell_\beta\gamma$



$$Br(\ell_\alpha \to \ell_\beta\gamma) = \frac{3\alpha}{64\pi(G_F m_\eta^2)^2} C_{\alpha\beta}^2$$

$$C_{\alpha\beta} = \left| \sum_k h_{\alpha k} h_{\beta k}^* F_2(M_k^2/m_\eta^2) \right|^{1/2}$$

- If the lightest right-handed neutrino is DM, the neutrino Yukawa coupling should be $O(1)$ from its relic abundance.

⇒ LFV imposes severe constraints.

E.Ma, J.Kubo, D.S.
D.S., T.Toma, T.Yoshida

- In the present case, the Yukawa coupling could be irrelevant to the relic abundance of DM.

Small neutrino Yukawa couplings make it possible to escape this constraint easily.

Lepton flavor structure

To consider the neutrino oscillation, we assume flavor structure

$$h_{ei} = 0, \quad h_{\mu i} = h_i, \quad h_{\tau i} = q_1 h_i, \quad (i = 1, 2);$$
$$h_{e3} = h_3, \quad h_{\mu 3} = -q_2 h_3, \quad h_{\tau 3} = -q_3 h_3$$

In case of $q_{1,2,3} = 1$, $\mathcal{M}_\nu$ can be diagonalized by PMNS-matrix

$$U = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

tri-bi maximal mixing

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_k h_{\alpha k} h_{\beta k} \Lambda_k \qquad \Lambda_k \simeq \frac{\lambda_5 v2}{8\pi^2 M_k} \ln \frac{M_k^2}{m_\eta^2}$$

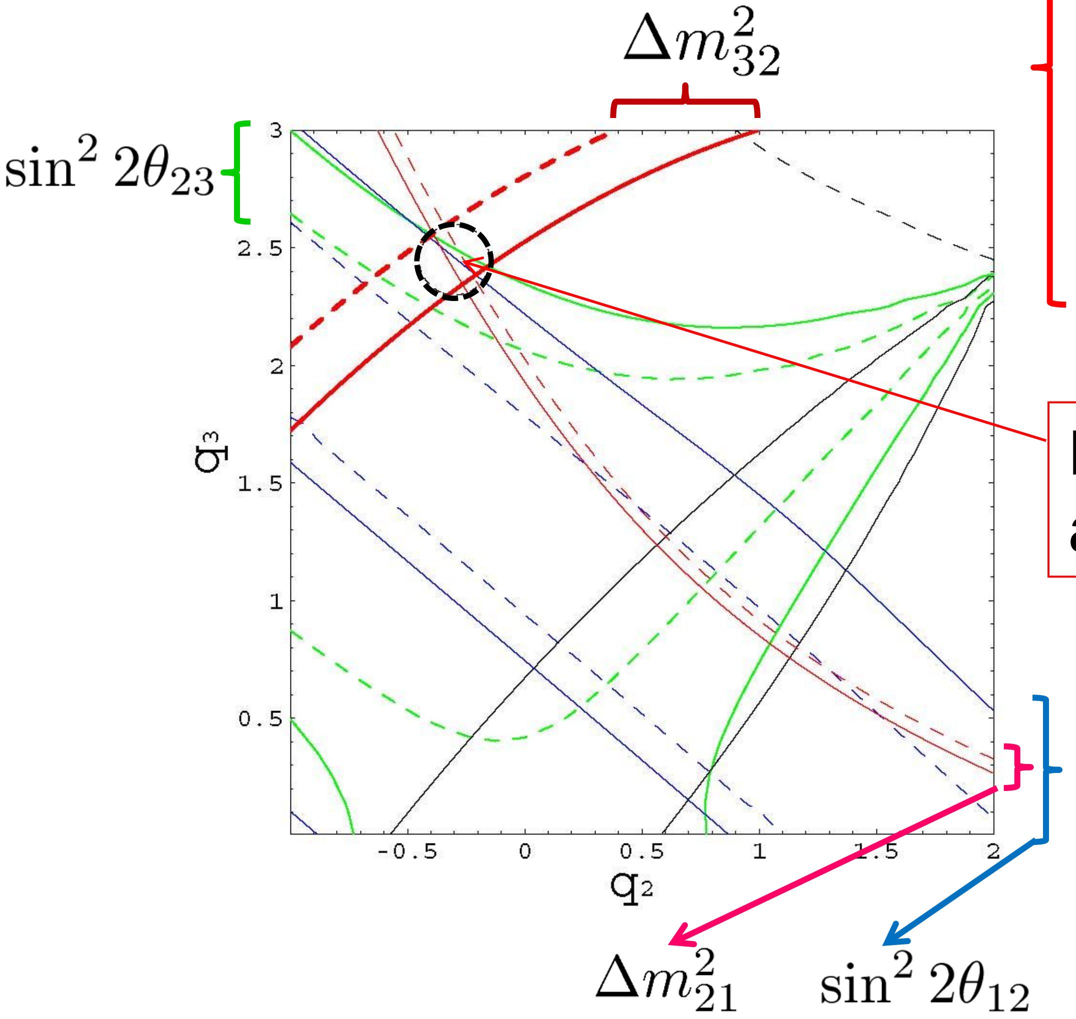
$$|h_2|^2 \Lambda_2 \simeq \frac{\sqrt{\Delta m^2_{\rm atm}}}{2}, \quad |h_3|^2 \Lambda_3 \simeq \frac{\sqrt{\Delta m^2_{\rm sol}}}{2}$$

An example of consistent parameters

$\sin\theta_{13} \neq 0$ solutions

$\Rightarrow \; q_{1,2,3} \neq 1$

$$
\left\{
\begin{array}{l}
q_1 = 0.85 \\
|\lambda_5| = 10^{-5}, \; |h_1| = 3 \times 10^{-8} \\
M_\eta = 1 \text{ TeV}, \; M_1 = 2 \text{ TeV} \\
M_2 = 6 \text{ TeV}, \; M_3 = 10 \text{ TeV} \\
|h_2| = 3.41 \times 10^{-3} \\
|h_3| = 1.50 \times 10^{-3}
\end{array}
\right.
$$



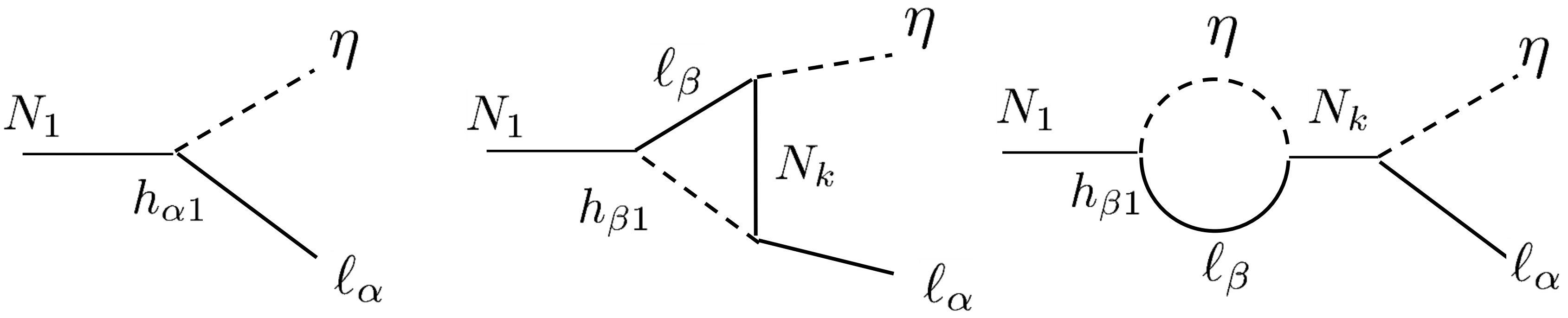
Region consistent with all neutrino oscillation data

$\sin^2 2\theta_{13} \simeq 0.085$

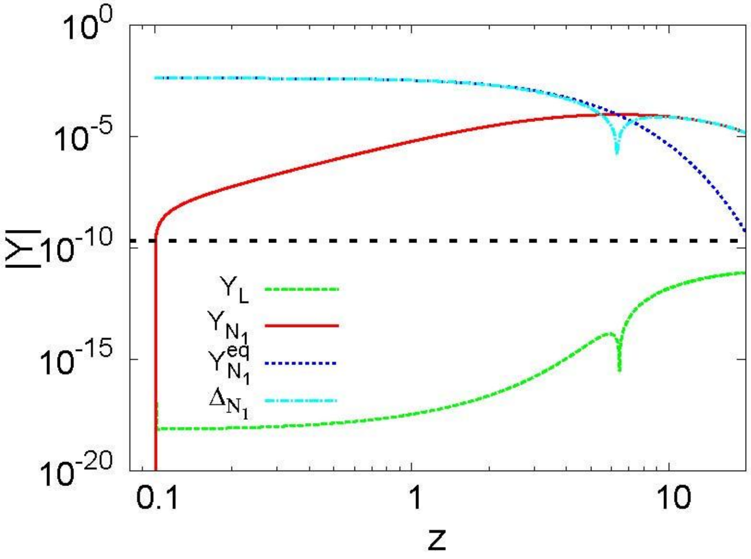
Analysis of baryon asymmetry

Baryon asymmetry in the model

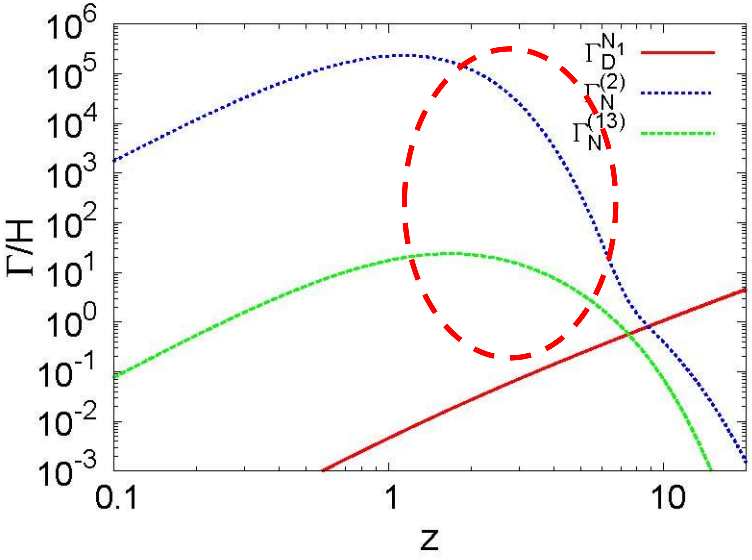
◆ Baryon asymmetry is expected to be generated through TeV-scale leptogenesis.



Generated lepton asymmetry
⇒ too small



Washout effects are large



Resonant leptogenesis

If we make neutrino Yukawa couplings smaller,

- suppress the washout processes

✓ smaller neutrino masses

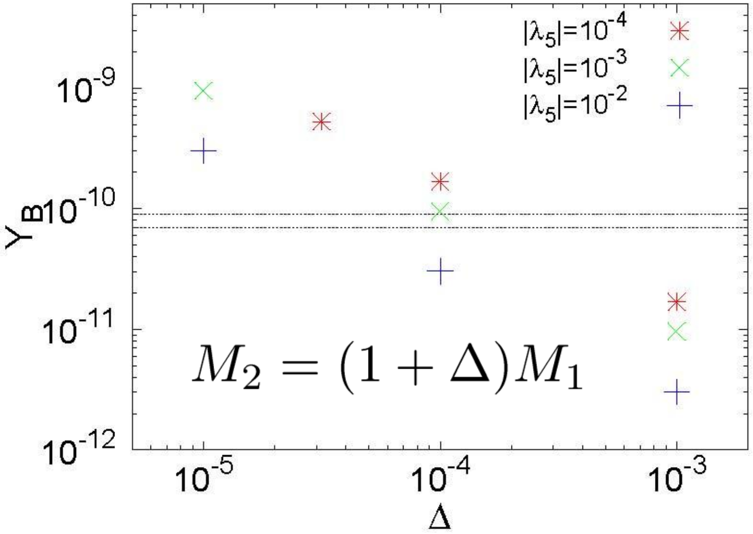
$$(\mathcal{M}_\nu)_{\alpha\beta} \propto \sum_k h_{\alpha k} h_{\beta k} \lambda_5$$

However, this can be recovered by larger λ_5

✓ smaller CP asymmetry

$$\varepsilon \propto \frac{(M_1^2 - M_2^2) M_1 \Gamma_2}{(M_1^2 - M_2^2)^2 + M_1^2 \Gamma_2^2}$$

However, this can be recovered by assuming the nearly degenerate $M_{1,2}$



The required baryon asymmetry can be generated for $\Delta = O(10^{-4})$

This is rather mild degeneracy compared with the ordinary case

Summary

◆ Neutrino masses and dark matter could be related each other. The radiative neutrino mass model gives a simple example for such an idea.

◆ If we identify DM with the lightest neutral component of the inert doublet, the constraint on the neutrino Yukawa couplings from DM abundance can disappear. As the result, the washout effect is suppressed in the leptogenesis.

◆ However, the observed baryon asymmetry requires the nearly degenerate right-handed neutrino masses. The required degeneracy can be rather mild compared with the ordinary resonant leptogenesis.