Baryon number asymmetry in the radiative seesaw model with an inert doublet

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Based on S.K. and D.Suematsu (Kanazawa Univ.)
Phys. Rev. D86,053001 and EPJC73:2484

Introduction

Problems not explained by the SM

- Neutrino mass
- Dark matter
- Baryon number asymmetry

A radiative seesaw model with an inert doublet could be such a promising candidate which can explain these problems.

Radiative seesaw model

E.Ma Phys. Rev. D73. 077301

SM + a scalar doublet H_2 + 3 right-handed neutrinos N_i

Z_2 symmetry

even

odd

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_S + \mathcal{L}_{RH}$$

$$\mathcal{L}_S = (D_\mu H_2)^\dagger D^\mu H_2 - \mu_1^2|H_1|^2 - \mu_2^2|H_2|^2 - \lambda_1|H_1|^4 - \lambda_2|H_2|^4$$

$$-\lambda_3|H_1|^2|H_2|^2 - \lambda_4|H_1^\dagger H_2|^2 - \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

$$\mathcal{L}_{RH} = i\bar{N}_i \partial\!\!\!/ N_i - (h_{i\alpha}\bar{N}_i\tilde{H}_2^\dagger L_\alpha + \frac{1}{2}m_{N_i}N_iN_i + h.c.)$$

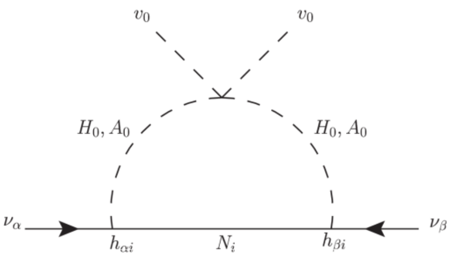
$$H_2 = \begin{pmatrix} H^+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$$

Inert doublet

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
H_2	**2**	$1/2$	-1
N_R	**1**	0	-1

Neutrino mass

Since Dirac mass terms at tree level are forbidden by Z_2 symmetry, neutrino masses are radiatively induced.



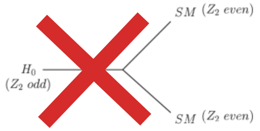
$$\mathcal{M}^\nu_{\alpha\beta} = \sum_{i=1}^{3} h_{i\alpha} h_{i\beta} \left[\frac{\lambda_5 v_0^2}{8\pi^2 m_{N_i}} \frac{m_{N_i}^2}{m_{H_2}^2 - m_{N_i}^2} \left(1 + \frac{m_{N_i}^2}{m_{H_2}^2 - m_{N_i}^2} \ln \frac{m_{N_i}^2}{m_{H_2}^2} \right) \right]$$

$$|\lambda_5| \ll 1$$

Small neutrino masses are realized even if masses of N_i are $O(1)$ TeV.

Dark matter

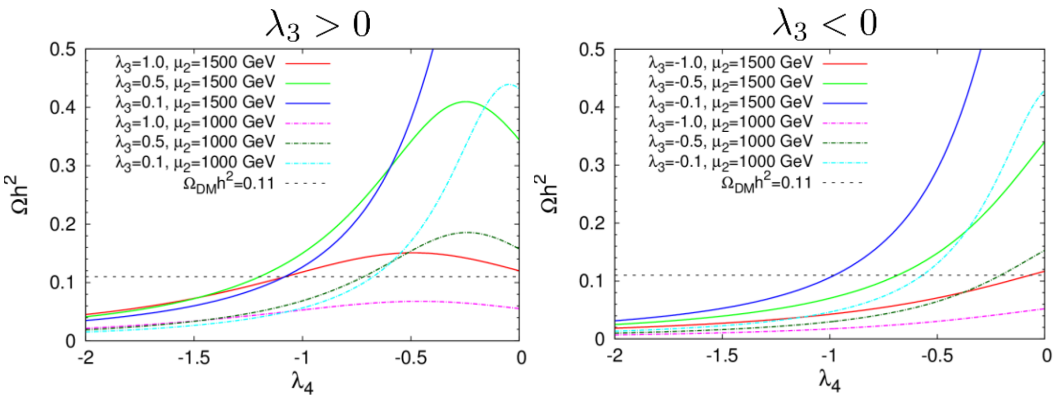
Z_2 symmetry also guarantee the stability of the lightest Z_2 odd particle.



We assume that the neutral component of the inert doublet is the dark matter candidate.

$$H_2 = \begin{pmatrix} H^+ \\ (H_0 + iA_0)/\sqrt{2} \end{pmatrix}$$

$\mu_2 = 1000,\ 1500$ GeV, $\lambda_5 = -10^{-5}$



The required value of Ωh^2 can be realized for $|\lambda_3 + \lambda_4|$~O(1).

Lepton flavor structure

We assume that the neutrino Yukawa couplings are

Normal hierarchy

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

D.Suematsu, T. Toma and T. Yoshida Phys. Rev. D79.093004

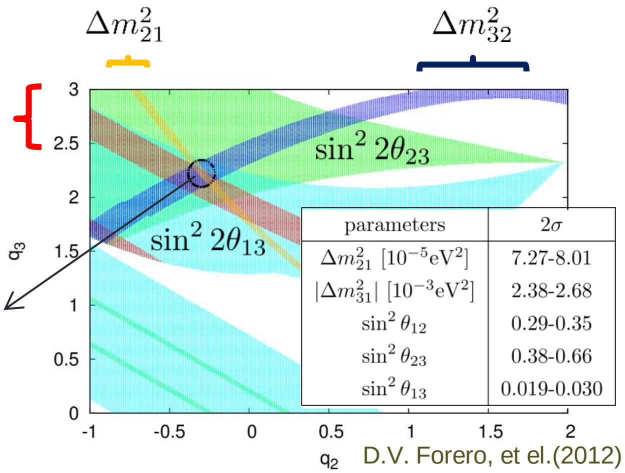
Inverted hierarchy

$$h_{e1}/p_1=-2h_{\mu 1}/q_1=2h_{\tau 1}=2h_1;$$
$$h_{e2}/p_2=h_{\mu 2}/q_2=-h_{\tau 2}=h_2;$$
$$h_{e3}=0, \quad h_{\mu 3}=h_{\tau 3}=h_3$$

so that the neutrino mass matrix is diagonalized by tri-bi maximal mixing form of PMNS matrix if $q_{1,2,3}$(or $q_{1,2}$, $p_{1,2}$)=1.

$m_\eta = 1000$ GeV
$m_{N_1} = 2000$ GeV
$m_{N_2} = 6000$ GeV
$m_{N_3} = 10000$ GeV

$q_1 = 0.85$
$|\lambda_5| = 10^{-5}$
$|h_1| = 3.0 \times 10^{-8}$



parameters	2σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.27-8.01
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	2.38-2.68
$\sin^2\theta_{12}$	0.29-0.35
$\sin^2\theta_{23}$	0.38-0.66
$\sin^2\theta_{13}$	0.019-0.030

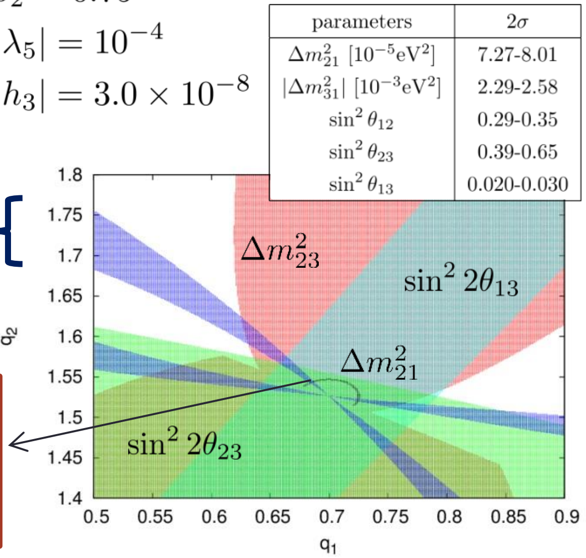
D.V. Forero, et el.(2012)

$\sin^2 2\theta_{13} = 0.089$
$|h_2| = 3.50 \times 10^{-3}$
$|h_3| = 1.60 \times 10^{-3}$

$m_\eta = 1000$ GeV
$m_{N_1} = 8000$ GeV
$m_{N_2} = 2000$ GeV
$m_{N_3} = 2000$ GeV

$p_1 = 1.35$
$p_2 = 0.75$
$|\lambda_5| = 10^{-4}$
$|h_3| = 3.0 \times 10^{-8}$

D.V. Forero, et el.(2012)

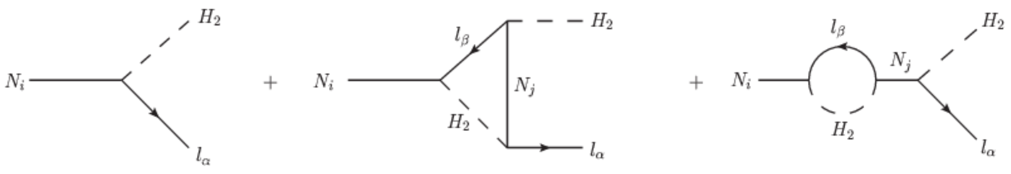


parameters	2σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.27-8.01
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	2.29-2.58
$\sin^2\theta_{12}$	0.29-0.35
$\sin^2\theta_{23}$	0.39-0.65
$\sin^2\theta_{13}$	0.020-0.030

$\sin^2 2\theta_{13} = 0.104$
$|h_1| = 6.70 \times 10^{-4}$
$|h_2| = 7.50 \times 10^{-4}$

Baryon number asymmetry

Baryon number asymmetry can be generated via TeV scale leptogenesis.



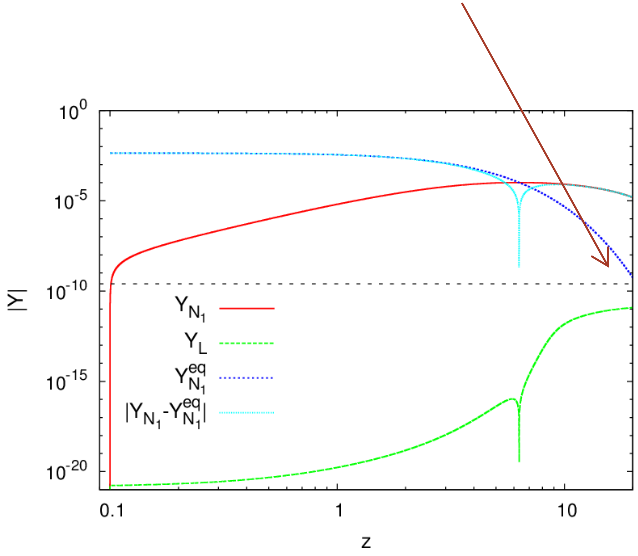
The decay of the lightest right-handed neutrino

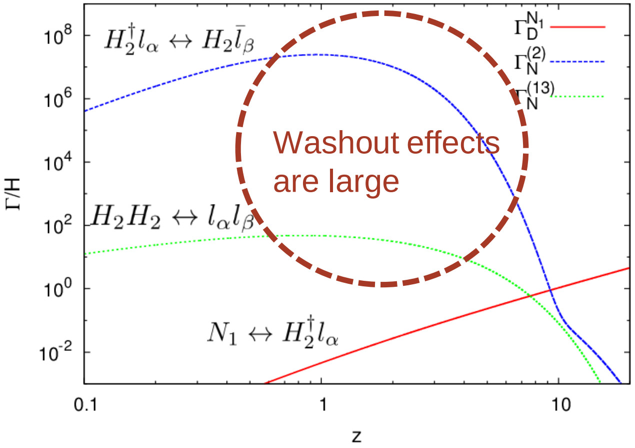
Numerical results

The generated lepton number asymmetry is too small !!

$$H_2^\dagger l_\alpha \leftrightarrow H_2 \bar{l}_\beta$$
$$H_2 H_2 \leftrightarrow l_\alpha l_\beta$$

Lepton number violating scatterings





Washout effects are large

Resonant leptogenesis

We make neutrino Yukawa couplings smaller to suppress the washout processes.

⇨ However, CP asymmetry also becomes smaller.

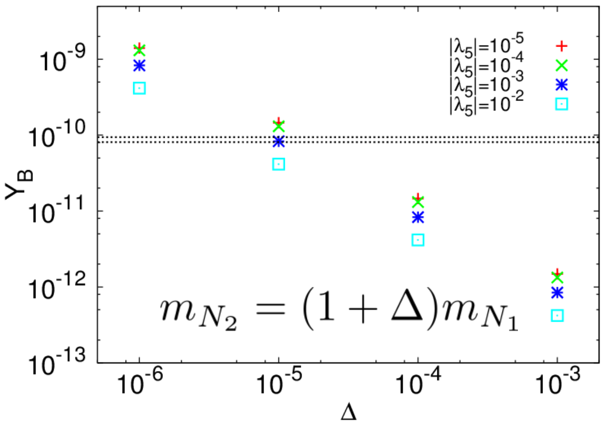
The contribution from the interference term between tree and self-energy diagram

$$\epsilon = \frac{\Gamma(N_i \to H_2 l_\alpha) - \Gamma(N_i \to H_2^\dagger \bar{l}_\alpha)}{\Gamma(N_i \to H_2 l_\alpha) + \Gamma(N_i \to H_2^\dagger \bar{l}_\alpha)} \propto \frac{(m_{N_1}^2 - m_{N_2}^2) m_{N_1} \Gamma_2}{(m_{N_1}^2 - m_{N_2}^2)^2 + m_{N_1}^2 \Gamma_2^2}$$

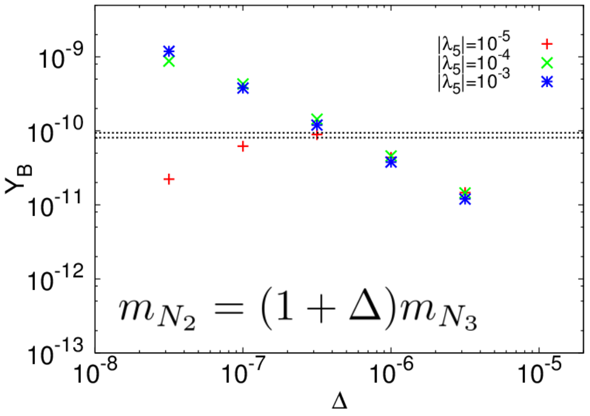
(Normal hierarchy case)

If we make the right-handed neutrino masses almost degenerate, the CP asymmetry becomes larger value.

Normal hierarch case



Inverted hierarch case



The required baryon number asymmetry can be generated for $\Delta \sim O(10^{-5})$ and $\Delta \sim O(10^{-7})$ respectively.

This is rather mild degeneracy compared with the ordinary case.

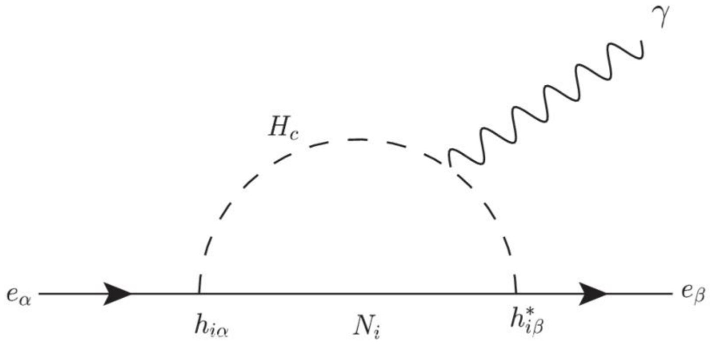
Summary

- The radiative seesaw model with an inert doublet could be such a promising candidate which explains neutrino mass, dark matter and baryon number asymmetry simultaneously.
- The nearly degenerated right-handed neutrino masses can realize the observed baryon asymmetry. This degeneracy is milder than the ordinary resonant leptogenesis.

Back up

Constraints on the model

- Lepton flavor violating processes

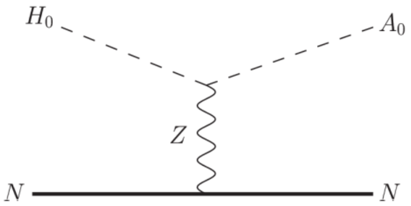


$$\mathrm{Br}(\mu \to e\gamma) < 2.4 \times 10^{-12}$$
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$
$$(90\% CL)$$

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

- Dark matter direct search

Inelastic scattering between the dark matter H_0 and a nucleus N through Z exchange



$$m^2_{H_0,A_0} = \mu_2^2 + (\lambda_3 + \lambda_4 \pm \lambda_5)v_0^2 \quad \xrightarrow{|\lambda_5| \ll 1} \quad m_{H_0} \simeq m_{A_0}$$

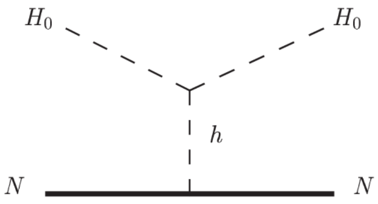
$$|\lambda_5| \gtrsim 6.7 \times 10^{-6} \left(\frac{m_{H_0}}{1\ \mathrm{TeV}}\right)\left(\frac{\delta}{200\ \mathrm{keV}}\right)$$

$$\delta \equiv m_{A_0} - m_{H_0}$$

δ is determined by the minimum velocity of dark matter which makes the inelastic scattering possible.

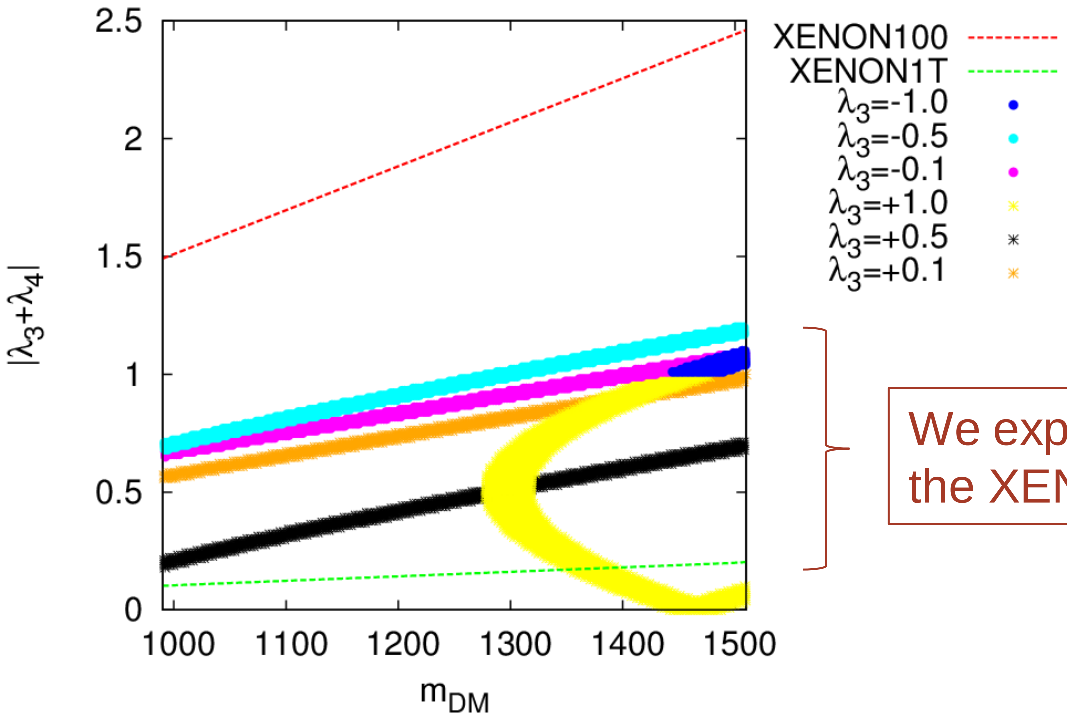
Dark matter direct search

Elastic scattering process through higgs exchange



$$\sigma_n^0 = \frac{(\lambda_3+\lambda_4+\lambda_5)^2}{8\pi}\frac{m_n^2 f_n^2}{m_{H_0}^2 m_h^4}$$

$|\lambda_5| \ll 1$

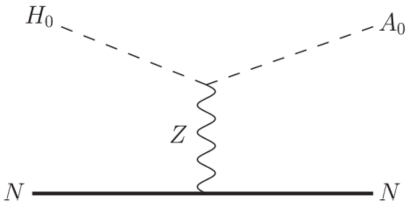


The required dark matter relic abundance can be realized for $|\lambda_3 + \lambda_4| \sim O(1)$.

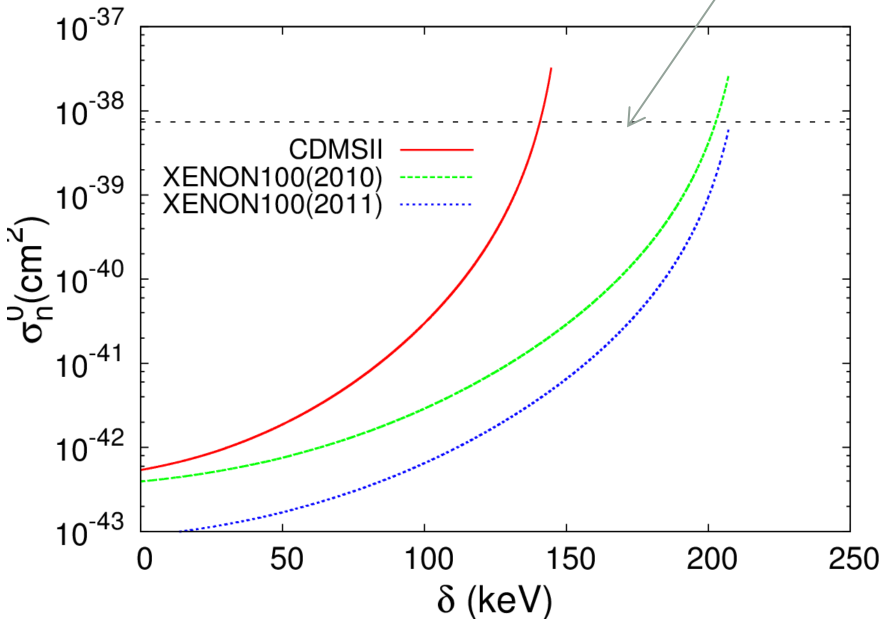
We expect the dark matter to be found in the XENON1T experiment.

Dark matter search

- Inelastic scattering process through Z exchange



$$\sigma_n^0 \simeq \frac{1}{2\pi} G_F^2 m_n^2 \sim 7.4 \times 10^{-39}\ \mathrm{cm}^2$$



$$E_R = 40\ [\mathrm{keV}],\ v_{\mathrm{esc}} = 544\ [\mathrm{km/s}]$$

The minimum velocity of dark matter which makes the inelastic scattering possible

$$v_{\min} = \frac{1}{\sqrt{2 m_N E_R}} \left(\frac{m_N E_R}{m_r} + \delta \right)$$

$$\delta \equiv m_{A_0} - m_{H_0}$$

$v_{\min} > v_{\mathrm{esc}}$ ➡ Inelastic scattering is kinematically forbidden.

The inelastic scattering is allowed only in the restricted parameter region.