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Leptogenesis and dark matter in a radiative neutrino mass model

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based on PRD86 (2012) 053001; EPJC73 (2013) 2484; arXiv1406.XXXX (in preparation)

1.Introduction

The SM still has the serious problems

- Neutrino mass
- Dark matter
- Baryon number asymmetry

➡ A radiative neutrino mass model is a promising candidate which can explain these problems simultaneously.

2.Radiative neutrino mass model

E.Ma,Phys.Rev.D87 (2006) 077301

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

Z_2 symmetry: SM even; H_2, N_i odd

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

$$\mathcal{L}_S = (D_\mu H_2)^\dagger D^\mu H_2 - \mu_1^2|H_1|^2 - \mu_2^2|H_2|^2 - \lambda_1|H_1|^4 - \lambda_2|H_2|^4 - \lambda_3|H_1|^2|H_2|^2 - \lambda_4|H_1^\dagger H_2|^2 - \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$

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

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

H_1: the SM higgs
L_α: the SM leptons

Inert doublet scalar

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

This new scalar doublet has no vacuum expectation value.

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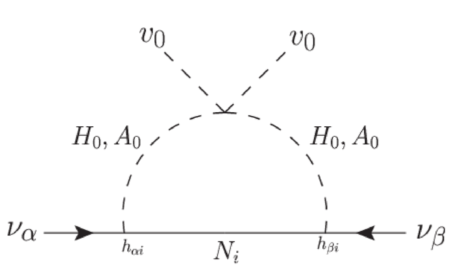
The Z_2 symmetry is kept as the unbroken symmetry.

Neutrino mass

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



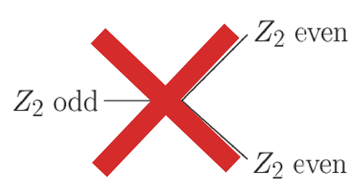
Mass matrix

$$\mathcal{M}^\nu_{\alpha\beta} = \sum_{i=1}^{3} h_{\alpha i}h_{\beta i}\left[\frac{\lambda_5 v_0^2}{16\pi^2 m_{N_i}}\frac{m_{N_i}^2}{m_{H_2}^2 - m_{N_i}^2}\left(1 + \frac{m_{N_i}^2}{m_{H_2}^2 - m_{N_i}^2}\ln\frac{m_{N_i}^2}{m_{H_2}^2}\right)\right]$$

$|\lambda_5| \ll 1$ ➡ Small neutrino masses are realized even if masses of N_i are O(1) TeV.

New physics is expected at TeV regions.

Dark matter



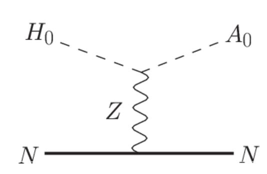
The Z_2 symmetry also guarantees the stability of the lightest Z_2 odd particle.

➡ If we assume the lightest Z_2 odd particle is neutral, it can be a dark matter candidate.

In this model, the origin of neutrino mass and dark matter is closely related.

We assume that the lightest Z_2 odd particle is the neutral component of the inert doublet and its mass is O(1).TeV. Here we consider the case that H_0 is the dark matter.

In this case, the constraint from the inelastic scattering between the dark matter and a nucleus N through Z exchange should be taken into account.



Although the interaction cross section is sufficiently large, it has not been found.

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

⬇

This interaction should be kinematically forbidden by the mass difference between H_0 and A_0.

$$m^2_{H_0,A_0} = \mu_2^2 + \frac{(\lambda_3 + \lambda_4 \pm \lambda_5)}{2}v_0^2$$

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

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

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

Y. Cui, D. E. Marrissey, D. Poland and L. Randall, JHEP0905 (2009) 076
C. Ari, F. -S. Ling and M. H. G. Tytgat, JCAP0910 (2009) 018

3.Leptogenesis

Lepton flavor structure

We assume that the neutrino Yukawa couplings are

Normal hierarchy

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

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 the tri-bi maximal mixing form of PMNS matrix if $q_{1,2,3}$(or $q_{1,2}$, $p_{1,2}$)=1.

D.Suematsu, T. Toma and T. Yoshida Phys. Rev. D79 (2009) 093004

The experimental results indicate that θ_{13} is non-zero.

➡ We look for the values of $q_{1,2,3}$ (and $q_{1,2}$, $p_{1,2}$) in order to satisfy all the neutrino oscillation data.

An example of the result of numerical study

- Normal hierarchy

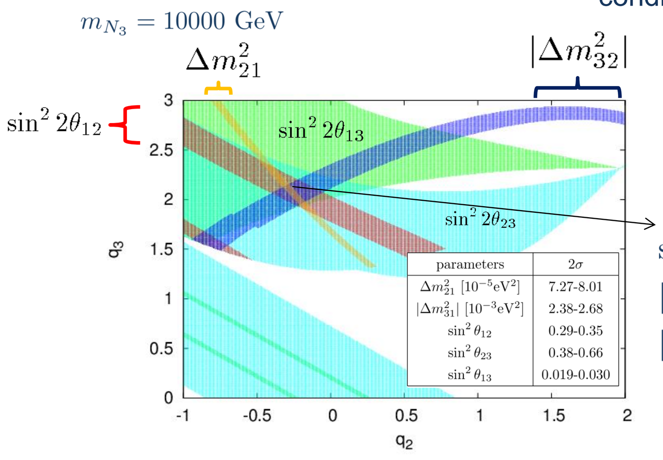
$m_\eta = 1000$ GeV, $q_1 = 0.85$
$m_{N_1} = 2000$ GeV, $|\lambda_5| = 10^{-5}$
$m_{N_2} = 2000$ GeV, $|h_1| = 3.0\times 10^{-8}$
$m_{N_3} = 10000$ GeV

- Inverted hierarchy

$p_1 = 1.35$, $m_\eta = 1000$ GeV
$p_2 = 0.75$, $m_{N_1} = 8000$ GeV
$|\lambda_5| = 10^{-4}$, $m_{N_2} = 2000$ GeV
$|h_3| = 3.0\times 10^{-8}$, $m_{N_3} = 2000$ GeV

Non-thermal equilibrium condition for leptogenesis

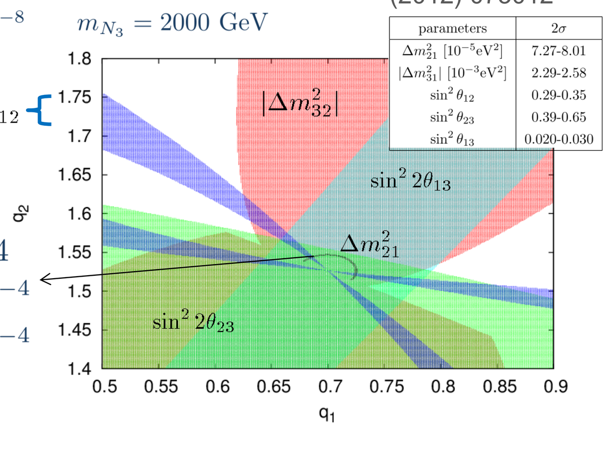
D.V. Forero, M. Tortola, J. F. Valle, Phys.Rev.D86 (2012) 073012



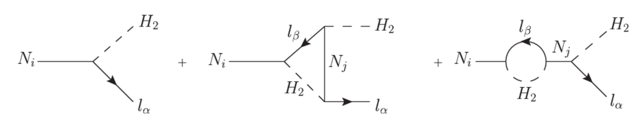
Region consistent with all neutrino oscillation data

Normal hierarchy: $\sin^2 2\theta_{13} = 0.089$, $|h_2| = 3.23\times 10^{-3}$, $|h_3| = 1.64\times 10^{-3}$

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



TeV scale resonant leptogenesis



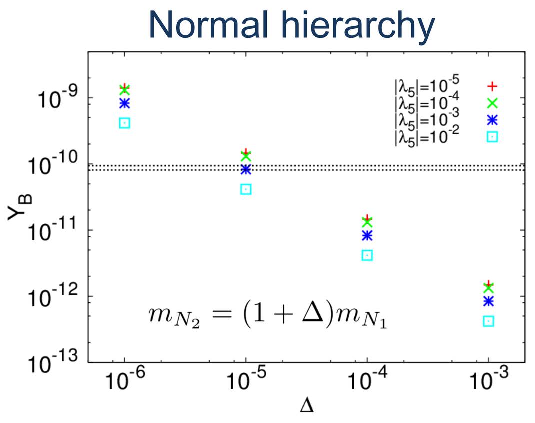
If we take the right-handed neutrino masses to be hierarchical, it is difficult to realize the required lepton number asymmetry due to the washout effects. ➡

Resonant leptogenesis scenario

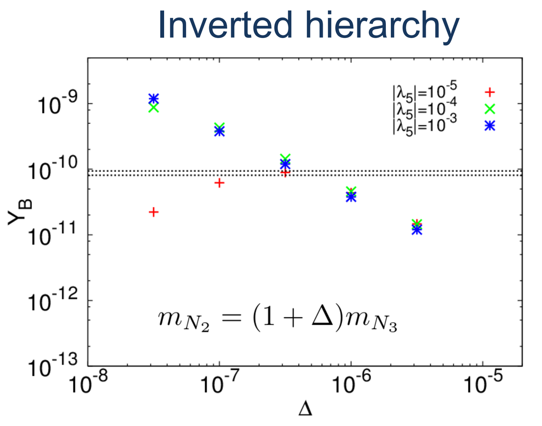
- Smaller yukawa — washout effects ↓
- Degenerate right-handed neutrino masses

$$\epsilon \propto \frac{(m_{N_1}^2 - m_{N_2}^2)m_{N_1}\Gamma_2}{(m_{N_1}^2 - m_{N_2}^2)^2 + m_{N_1}^2\Gamma_2^2}$$ CP asymmetry ↑

Normal hierarchy



Inverted hierarchy



The required baryon number asymmetry can be generated for Δ~O(10^{-5}) and Δ~O(10^{-7}) respectively.

⬇

This is rather mild degeneracy compared with the ordinary case Δ~O(10^{-8}-10^{-10}).

4.Dark matter abundance and direct search

Dark matter relic abundance follows the usual thermal relic scenario.

$$\Omega_{\rm DM}h^2 \simeq \frac{1.07\times 10^9\,\mathrm{GeV}^{-1}}{J(x_F)g_*^{1/2}m_{\rm pl}},\quad x_F = \ln\frac{0.038 m_{\rm pl}g_{\rm eff}m_{\rm DM}\langle\sigma_{\rm eff}v\rangle}{(g_* x_F)^{1/2}},\quad J(x_F) = \int_{x_F}^\infty \frac{\langle\sigma_{\rm eff}v\rangle}{x^2}dx,$$

$$\langle\sigma_{\rm eff}v\rangle = \frac{1}{g_{\rm eff}^2}\sum_{i,j}\langle\sigma^{ij}v\rangle\frac{n_i^{eq}}{n_0^{eq}}\frac{n_j^{eq}}{n_0^{eq}},\quad g_{\rm eff} = \sum_i\frac{n_i^{eq}}{n_0^{eq}},\quad n_i^{eq} = \left(\frac{m_iT}{2\pi}\right)^{3/2}e^{-m_i/T},\quad n = \sum_i n_i\quad (i = H_0,\ A_0,\ H_\pm, N_i),$$

K. Griest and D. Seckel, Phys. Rev. D43 (1991) 3191

Annihilation cross sections

$$\langle\sigma^{ij}v\rangle = a^{ij} + b^{ij}\langle v^2\rangle \simeq a_0^{ij} + \frac{\Lambda^{ij}}{32\pi m_{\rm DM}^2}$$

Gauge interactions

$$a_0^{H_0H_0} = a_0^{A_0A_0} = a_0^{H^+H^-} = \frac{(1+2c_w^4)g^4}{128\pi c_w^4 m_{\rm DM}^2}$$
$$a_0^{H_0H^+} = a_0^{H_0H^-} = a_0^{A_0H^+} = a_0^{A_0H^-} = \frac{s_w^2 g^4}{64\pi c_w^2 m_{\rm DM}^2}$$

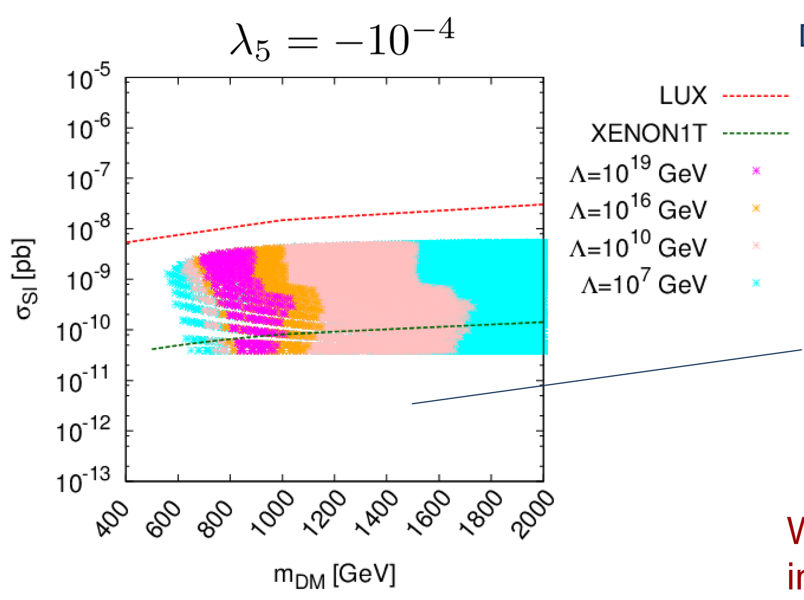
Scalar interactions

$$\Lambda^{H_0H_0} = \Lambda^{A_0A_0} = 2(\lambda_{H_0}^2 + \lambda_{A_0}^2 + 2\lambda_{H_c}^2)$$
$$\Lambda^{H^+H^+} = \Lambda^{H^-H^-} = 2\Lambda^{01} = 2(\lambda_{H_0} - \lambda_{A_0})^2$$
$$\Lambda^{H_0H^+} = \Lambda^{H_0H^-} = \Lambda^{A_0H^+} = \Lambda^{A_0H^-} = (\lambda_{H_0} - \lambda_{A_0})^2 + (\lambda_{A_0} - \lambda_{H_c})^2$$
$$\Lambda^{23} = (\lambda_{H_0} + \lambda_{A_0})^2 + 4\lambda_{H_c}^2$$

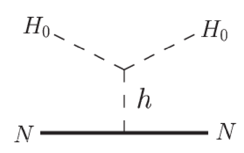
In this case the scalar couplings play a crucial role for the relic abundance.

T. Hambye, F. –S. Ling, L. L. Honorez, J. Rocher, JHEP 0907 (2009) 090

➡ We could estimate the dark matter mass region by taking into account the scalar coupling constraints such as vacuum stability, perturbativity and unitarity up to some cut-off scale.

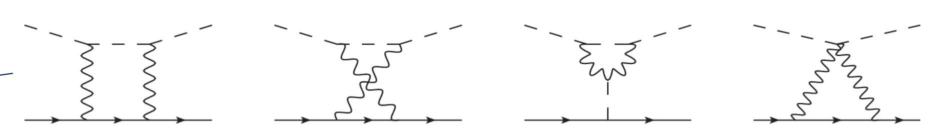


Dark matter direct search is a good tool for verifying this simple model.



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

Scalar coupling independent processes



M. Cirelli, N. Fornengo, A. Strumia, Nucl.Phys.B753 (2006) 178
M. Klasen, C. Yaguna, J. Ruiz-A;varez, Phys. Rev. D87 (2013) 075025

We could find the dark matter around 1 TeV mass region in the near future.

5.Conclusion

- The radiative seesaw model with an inert doublet could be 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.
- The dark matter direct search seems to be a promising experiment to examine this model. In particular, this simple scenario predicts the dark matter mass is around 1TeV.

6.U(1) gauge extension of the model

We now attempt to correlate the parameters we tuned in the previous work independently.

$$V = \mu_1^2|H_1|^2 + \mu_2^2|H_2|^2 + \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2M_*}\left[S^\dagger(H_1^\dagger H_2)^2 + h.c.\right] + \lambda_6|H_1|^2|S|^2 + \lambda_7|H_2|^2|S|^2 + \kappa|S|^4 + \mu_S^2|S|^2$$

$$-\mathcal{L}_N = h_{\alpha i}\bar{N}_i\tilde{H}_2^\dagger L_\alpha + f_{\alpha i}\frac{S^\dagger}{M_*}\bar{\tilde{N}}_i\tilde{H}_2^\dagger L_\alpha + M_iN_i\tilde{N}_i + \frac{y_i}{2}SN_iN_i + \frac{\tilde{y}_i}{2}S\tilde{N}_i\tilde{N}_i + h.c.$$

	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
H_2	**2**	1/2	1
$N_{1,2}$	**1**	0	1
$\tilde{N}_{1,2}$	**1**	0	−1
S	**1**	0	2

New particle contents

Cut-off scale: $M_* >> \langle S\rangle$

$S \to \langle S\rangle$, ~~$U(1)_X$~~ ⬇

Orign of the Z_2 sym.

	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
H_2	**2**	1/2	−
$N_{1,2}$	**1**	0	−
$\tilde{N}_{1,2}$	**1**	0	−
S	**1**	0	+

Small neutrino yukawa couplings

$$Y^-_{\alpha i} = e^{i\frac{\phi_i}{2}}(h_{\alpha i}\cos\theta_i + \tilde{h}_{\alpha i}e^{i\phi_i}\sin\theta_i)$$
$$Y^+_{\alpha i} = -ie^{i\frac{\phi_i}{2}}(h_{\alpha i}\sin\theta_i - \tilde{h}_{\alpha i}e^{i\phi_i}\cos\theta_i)$$
$$\tilde{h}_{\alpha i} \equiv f_{\alpha i}\frac{\langle S\rangle}{M_*}$$

Right-handed neutrino mass degeneracy

$$\Delta_i \equiv \frac{|M_{+i}| - |M_{-i}|}{M_{-i}} \simeq \frac{\langle S\rangle}{M_i}\frac{|y_i|\cos(\alpha_i + \phi_i) + |\tilde{y}_i|\cos(\tilde{\alpha}_i - \phi_i)}{\sin 2\theta_i}$$

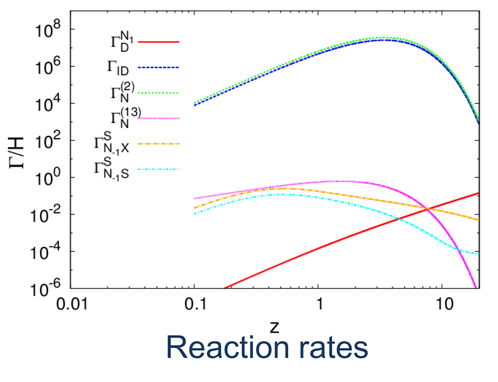
Unitary matrix which diagonalizes the right-handed neutrino mass matrix

$$U = \begin{pmatrix} \cos\theta_i & \sin\theta_i e^{-i\phi_i} \\ -\sin\theta_i e^{i\phi_i} & \cos\theta_i \end{pmatrix}\quad \tan\phi_i = \frac{|\tilde{y}_i|\sin\tilde{\alpha}_i - |y_i|\sin\alpha_i}{|y_i|\cos\alpha_i - |\tilde{y}_i|\sin\tilde{\alpha}_i},\quad \tan 2\theta_i = \frac{M_i}{\langle S\rangle}\frac{2}{|y_i|\cos(\alpha_i+\phi_i) - |\tilde{y}_i|\cos(\tilde{\alpha}_i - \phi_i)}\quad y_i = |y_i|e^{i\alpha_i},\ \tilde{y}_i = |\tilde{y}_i|e^{i\tilde{\alpha}_i}$$

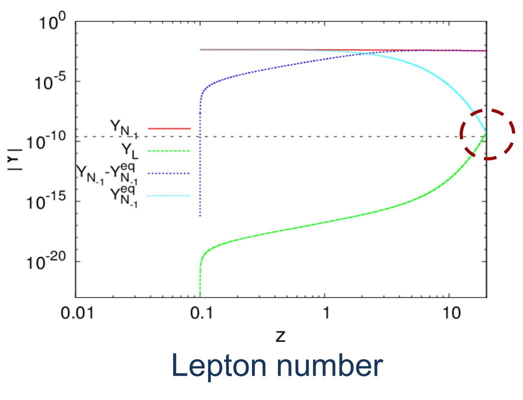
We could realize the conditions for leptogenesis simultaneously.

An example of this scenario

$M_i = \langle S\rangle = 2$ TeV
$h_1 = \tilde{h}_1 = 10^{-3}$
$m_X = 10^{-3}$ GeV
$m_S = 200$ GeV
$y_1 = 1.0\times 10^{-9}$, $\tilde{y}_1 = 1.0\times 10^{-6}$
$\alpha_1 = 0.013$, $\tilde{\alpha}_1 = 0.0$



Reaction rates



Lepton number

$|Y_L| \simeq 5.58\times 10^{-10} > |Y_L^{obs}| \simeq 2.52\times 10^{-10}$

The required value can be generated.