Model of radiative neutrino mass and dark matter with $SU(2)_1 \times SU(2)_2$ gauge symmetry

Takaaki Nomura (KIAS)

In collaboration with: Chuan-Hung Chen (NCKU)
Hiroshi Okada (NCTS)

(Based on work in progress)
1. Introduction
Many observation indicate the existence of dark matter

- Rotation of spiral galaxies

\[ v(r) \propto \sqrt{M(r)/r} \]

\[ M(r) \propto r \text{ in outside of visible region} \]

- Clusters of galaxies

- Gravitational lensing

- Formation of Large scale structure

- CMB anisotropy : WMAP, Planck

\[ \Omega_{DM} h^2 \approx 0.12 \]

By Planck observation

One motivation to consider new physics
1. Introduction

Non-zero neutrino masses also indicate new physics

Mass generation mechanism could relate to DM
1. Introduction

Non-zero neutrino masses also indicate new physics

Mass generation mechanism could relate to DM

Ex) Scotogenic Model (Ma Model)

E. Ma, PRD 73 (2006) 077301

- $\mathbb{Z}_2$ odd particle inside loop
- There are DM candidates
- There are many extension of the model

DM is stabilized by the $\mathbb{Z}_2$ symmetry

But $\mathbb{Z}_2$ is arbitrary introduced in many models → What is origin?
1. Introduction

**One attractive scenario for DM stability**

Remnant $Z_2$ symmetry from extra gauge symmetry

*(Ex.) Extra local $U(1)$ gives simple picture*

- $U(1)$ is broken by some scalar field with charge 2
- A particle with odd charge (1, 3, 5, ...) is odd under remnant $Z_2$

- Larger arbitrariness in choosing extra $U(1)$ charge

we consider extra $SU(2)$ symmetry giving remnant $Z_2$

- Choice of representation is more limited
- Remnant $Z_2$ remains by choosing reps. of $SU(2)$ breaking scalar
2. Our model
2. Our Model

**Construction of our model**

- **Gauge symmetry**: $SU(3) \times SU(2)_1 \times SU(2)_2 \times U(1)_Y$

- **Particle contents (including SM lepton sector):**

<table>
<thead>
<tr>
<th></th>
<th>Lepton Fields</th>
<th>Scalar Fields</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L_L$</td>
<td>$e_R$</td>
</tr>
<tr>
<td>$SU(2)_1$</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$SU(2)_2$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$U(1)_Y$</td>
<td>$-\frac{1}{2}$</td>
<td>$-1$</td>
</tr>
</tbody>
</table>

- **Singlet under $SU(3)$**
- **All SM fermions are singlet under $SU(2)_2$**

- **Gauge symmetry breaking**

$$SU(2)_1 \times SU(2)_2 \times U(1)_Y \rightarrow U(1)_{em} \times Z_2$$

  $Q = T_3(SU(2)_1) + T_3(SU(2)_2) + Y$

- By VEVs of $H_1$ and $\Delta$
- Discrete $Z_2$ symmetry remains from $SU(2)_2$
2. Our Model

Scalar sector in our model

Scalar potential:

\[
\mathcal{V} = -m_{H_1}^2 H_1^\dagger H_1 + m_{H_2}^2 H_2^\dagger H_2 - m_\Delta^2 \text{Tr}[\Delta^\dagger \Delta] + \mu [H_2^T (i\tau_2) \Delta^\dagger H_2 + \text{h.c.}]
+ \lambda_{H_1}|H_1^\dagger H_1|^2 + \lambda_{H_2}|H_2^\dagger H_2|^2 + \lambda_\Delta [\text{Tr}(\Delta^\dagger \Delta)]^2 + \lambda'_\Delta \text{Tr}[(\Delta^\dagger \Delta)^2] + \lambda_{H_1\Delta} (H_1^\dagger H_1) \text{Tr}[\Delta^\dagger \Delta]
+ \lambda_{H_2\Delta} (H_2^\dagger H_2) \text{Tr}[\Delta^\dagger \Delta] + \lambda'_{H_2\Delta} \sum_{i=1}^3 (H_2^\dagger \tau_i H_2) \text{Tr}[\Delta^\dagger \tau_i \Delta],
\]

Components of scalar fields:

\[
H_1 = \begin{bmatrix}
G_1^+ \\
v + h_1 + iG_1
\end{bmatrix}, \quad H_2 = \begin{bmatrix}
H_2^+ \\
h_2 + i a_2
\end{bmatrix}, \quad \Delta = \begin{bmatrix}
\frac{1}{\sqrt{2}} G_\Delta^+ \\
v_\Delta + \delta_R + i G_\Delta
\end{bmatrix}
\]

G: NG bosons absorbed by gauge bosons

✓ H_2 does not develop a VEV: it becomes Z_2 odd inert scalar
2. Our Model

**Gauge symmetry breaking**

- SU(2)$_1 \times$ SU(2)$_2 \times$ U(1)$_Y$ symmetry is broken by VEVs of $H_1$ and $\Delta$

  \[ U(1)_{em} \times Z_2 \]  
  (Component of $\Delta$ with $T_3(SU(2)_2) = 1$ get VEV)

- Particles with eigenvalue of $T_3(SU(2)_2)$ is 1, 2, 3… → $Z_2$ even
- Particles with eigenvalue of $T_3(SU(2)_2)$ is 1/2, 3/2, 5/2… → $Z_2$ odd

**We have new gauge bosons $Z'$, $W'^\pm$**

- Here we omit detailed discussion of these gauge bosons
- The mass scale is assumed to be $M_V > O(\text{TeV})$ to avoid constraints
2. Our Model

**Fermion sector in our model**

- **Bi-doublet fermion F**

\[
F_{L(R)} = \begin{pmatrix}
N_1 & E_2^+ \\
E_1^- & N_2
\end{pmatrix}_{L(R)}
\]

- It has lepton number (LN) 1
- Positively charged \(E_2\) has LN 1

- **Mass term and Yukawa interaction with F**

\[
L \supset M_D \text{Tr}[\bar{F}_L F_R] + M_R \text{Tr}[\bar{F}_R^c F_R] + M_L \text{Tr}[\bar{F}_L^c F_L] \\
+ (y_l)_{ab} \bar{L}_L e_{Rb} H_1 + f_a \bar{L}_L F_R \tilde{H}_2 + f'_a \bar{L}_L F_R^c \tilde{H}_2 + h.c.
\]

- Terms with \(M_L\) and \(M_R\) violate lepton number
- Yukawa interaction with \(f\) and \(f'\) are source of neutrino mixing
2. Our Model

**Fermion sector in our model**

- **Mass eigenstates of exotic neutral fermion**

\[
\mathcal{N}M_N\mathcal{N}^T = (\mathcal{N}_1^L, \mathcal{N}_2^R) \begin{pmatrix} M_D & -M_L \\ -M_R & M_D^T \end{pmatrix} \begin{pmatrix} N_{1R} \\ N_{2L}^C \end{pmatrix} + \text{c.c.}
\]

\(\hat{\mathcal{N}}M_N\hat{\mathcal{N}}^T\) is a mass matrix (we assume \(M_L = M_R\))

It can be diagonalized as...

\[
OM_NO^T = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} M_D & -m_{LR} \\ -m_{LR} & M_D \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} M_D - m_{LR} & 0 \\ 0 & M_D + m_{LR} \end{pmatrix}
\]

Mass eigenstate \(\psi_1\) and \(\psi_2\) are Majorana fermion which are given by

\[
N_{1L} = \frac{1}{\sqrt{2}} P_L (\psi_1 + \psi_2), \quad N_{2R} = \frac{1}{\sqrt{2}} P_R (\psi_1 - \psi_2),
\]

Mass eigenstate of exotic charged scalar is given by similar way
3. Phenomenology or our model
3. Phenomenology of our model

**Generating neutrino mass matrix**

- The mass matrix is generated at one loop level
- We consider interaction in mass eigenbasis

\[ -L \supset \left( Y_a \bar{\nu}_L \psi_{1R} + Y'_a \bar{\nu}_L \psi_{2R} \right) \left( h_2 - i a_2 \right) + c.c. \]

\[ Y \equiv (f + f') / 2, \quad Y' \equiv (f - f') / 2 \]

✓ Majorana mass of \( \Psi \) is source of LNV

\[
\left(m_\nu\right)_{ab} = -2 \frac{Y_a m_{\psi_1} Y_b}{(4\pi)^2} \left[m_{\psi_1}^2 m_{h_2}^2 \ln \left(\frac{m_{\psi_1}}{m_{h_2}}\right) + m_{a_2}^2 m_{h_2}^2 \ln \left(\frac{m_{h_2}}{m_{a_2}}\right) + m_{\psi_1}^2 m_{a_2}^2 \ln \left(\frac{m_{a_2}}{m_{\psi_1}}\right) \right]
\]

\[
-2 \frac{Y'_a m_{\psi_2} Y'_b}{(4\pi)^2} \left[m_{\psi_2}^2 m_{h_2}^2 \ln \left(\frac{m_{\psi_2}}{m_{h_2}}\right) + m_{a_2}^2 m_{h_2}^2 \ln \left(\frac{m_{h_2}}{m_{a_2}}\right) + m_{\psi_2}^2 m_{a_2}^2 \ln \left(\frac{m_{a_2}}{m_{\psi_2}}\right) \right]
\]
3. Phenomenology of our model

**Relic density of our DM candidate**

In our scenario, DM candidate is $Z_2$ odd CP-even boson $h_2$ from $H_2$

Interaction for DM annihilation ($\chi = h_2$):

$$-\mathcal{L} \supset \left[ Y_a \bar{\nu}_{L_a} \psi_{1R} + Y'_a \bar{\nu}_{L_a} \psi_{2R} + \frac{(Y + Y')_a}{4} \bar{\ell}_{L_a} [\psi_{1R} - \psi_{2R}] + \frac{(Y - Y')_a}{4} \bar{\ell}_{L_a} [(\psi^{+}_{1L})^c - (\psi^{+}_{2L})^c] \right] \chi$$

DM annihilating into leptons (we assume small Higgs portal coupling)

$$\sigma v_{\text{rel}} \approx \frac{m_\chi^6 v_{\text{rel}}^4}{60\pi (M_\psi^2 + m_\chi^2)^4} \sum_{a,b=1}^3 \left[ |Y_a Y_b^\dagger|^2 + |Y'_a Y'_b^\dagger|^2 + |(Y + Y')_a (Y^\dagger + Y'^\dagger)_b|^2 + |(Y - Y')_a (Y^\dagger - Y'^\dagger)_b|^2 \right]$$

✔ The cross section is d-wave dominant

$$\Omega h^2 \approx \frac{10.7 \times 10^9 x_f^3}{20 g_*^{1/2} M_{\text{pl}} [\text{GeV}] d_{\text{eff}}}$$
3. Phenomenology of our model

**Allowed parameter regions**

Numerical analysis to search for parameter sets satisfying:

- Neutrino oscillation data
- Relic density of DM
- LFV constraints (such as $\mu \to e\gamma$)

We can obtain allowed parameter space with $O(100)$ GeV mass

More phenomenology could be considered
Summary and Discussions

- A Model of neutrino mass & DM with local SU(2)_1 × SU(2)_2
  - Residual Z_2 symmetry form second SU(2)
  - DM stability is guaranteed by the Z_2 symmetry
  - Lepton number violation from bi-doublet fermion mass term

- Analysis of our model
  - Neutrino mass matrix induced by bi-doublet fermion loop
  - Constraints from LFV
  - Relic density of DM

Thanks for your attention!
Appendix
Mass matrix of neutral gauge bosons

\[ \mathcal{L}_M = \frac{1}{8} \begin{pmatrix} W^3_\mu \\ W^3_\mu \\ B_\mu \end{pmatrix}^T \begin{pmatrix} v_2^2 g_2^2 & 0 & -v_2^2 g_2 g_Y \\ 0 & v_1^2 g^2 & -v_1^2 g g_Y \\ -v_2^2 g_2 g_Y & -v_1^2 g g_Y & (v_1^2 + v_2^2) g_Y^2 \end{pmatrix} \begin{pmatrix} W^3_\mu \\ W^3_\mu \\ B_\mu \end{pmatrix} \]

Mass eigenstates of neutral gauge bosons

\[ \begin{pmatrix} W^3_\mu \\ W^3_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} c_\theta & 0 & -s_\theta \\ 0 & 1 & 0 \\ s_\theta & 0 & c_\theta \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_W & s_W \\ 0 & -s_W & c_W \end{pmatrix} \begin{pmatrix} c_{\theta Z} & s_{\theta Z} & 0 \\ -s_{\theta Z} & c_{\theta Z} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} Z'_\mu \\ Z_\mu \\ A_\mu \end{pmatrix} \]
Mass eigenstates of exotic charged leptons

\[
E_{1L}^\pm = \frac{1}{\sqrt{2}} P_L(\psi_1^\pm + \psi_2^\pm), \quad \bar{E}_{1L} = \frac{1}{\sqrt{2}} (\bar{\psi}_1^\pm + \bar{\psi}_2^\pm) P_R, \\
E_{2R}^{(c)\pm} = \frac{1}{\sqrt{2}} P_R(\psi_1^\pm - \psi_2^\pm), \quad \bar{E}_{2R}^{(c)\pm} = \frac{1}{\sqrt{2}} (\bar{\psi}_1^\pm - \bar{\psi}_2^\pm) P_L
\]

Mass matrix for CP-even scalar (Z₂ even)

\[
M_H = \begin{bmatrix}
m_{h_1 h_1}^2 & -\sqrt{2}(\lambda_{H_1 \Delta} + \lambda'_{H_1 \Delta})\nu\nu_\Delta \\
-\sqrt{2}(\lambda_{H_1 \Delta} + \lambda'_{H_1 \Delta})\nu\nu_\Delta & m_{\Delta_{R \Delta R}}^2
\end{bmatrix},
\]

\[
m_{h_1 h_1}^2 = 2m_{H_1}^2 - \frac{1}{2} \lambda_{H_1 \Delta} v_\Delta^2, \quad m_{\Delta_{R \Delta R}}^2 = 2m_\Delta^2 - \frac{1}{2} \lambda_{H_1 \Delta} v^2.
\]