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

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(Based on work in progress)

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1. Introduction

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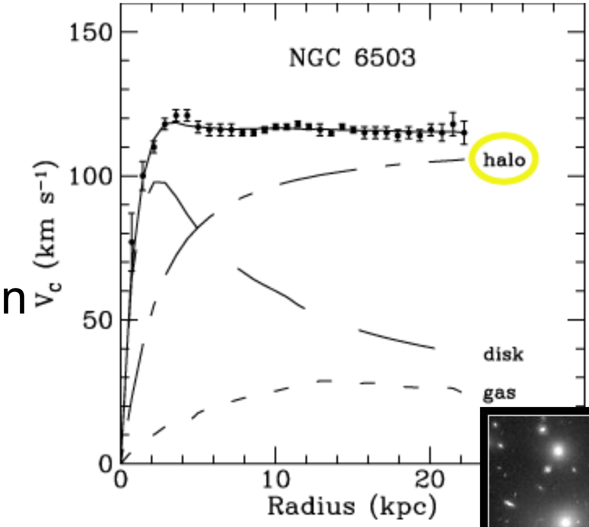
Many observation indicate the existence of dark matter

❖**Rotation of spiral galaxies**

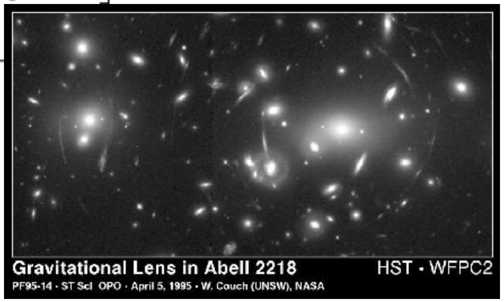
$$v(r) \propto \sqrt{M(r)/r}$$

M(r) ∝ r in outside of visible region



❖**Clusters of galaxies**

❖**Gravitational lensing**

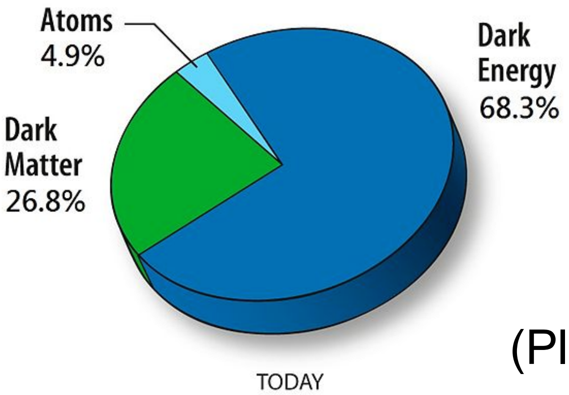


❖**Formation of Large scale structure**

❖**CMB anisotropy : WMAP, Planck**

➡ $$\Omega_{DM} h^2 \approx 0.12$$

By Planck observation



(Planck)

One motivation to consider new physics

Non-zero neutrino masses also indicate new physics

→ Mass generation mechanism could relate to DM

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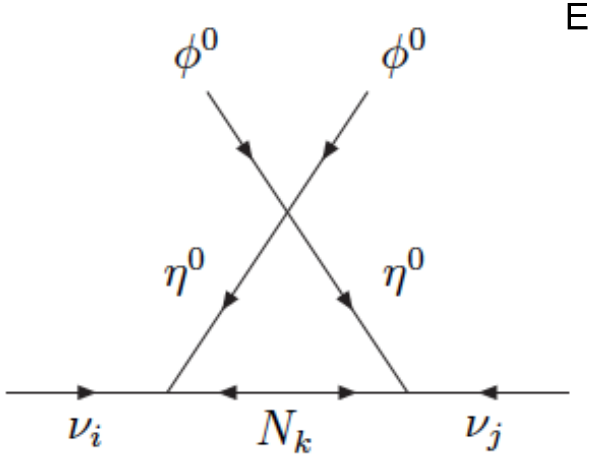
Ex) Scotogenic Model (Ma Model)

E. Ma, PRD 73 (2006) 077301



- ✓ Z_2 odd particle inside loop
- ✓ There are DM candidates
- ✓ There are many extension of the model

DM is stabilized by the Z_2 symmetry

But Z_2 is arbitrary introduced in many models → What is origin?

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 filed with charge 2
- ✓ A particle with odd charge (1,3,5…) is odd under remnant Z_2

❖ Lager 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

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):

	Lepton Fields			Scalar Fields		
	L_L	e_R	F	H_1	H_2	Δ
$SU(2)_1$	2	1	2	2	1	1
$SU(2)_2$	1	1	2	1	2	3
$U(1)_Y$	$-\frac{1}{2}$	-1	0	$\frac{1}{2}$	$\frac{1}{2}$	1

Singlet under SU(3)

❖ **All SM fermions are singlet under $SU(2)_2$**

- Gauge symmetry breaking

$$SU(2)_1\times SU(2)_2\times U(1)_Y \rightarrow U(1)_{em}\times Z_2 \qquad \left(Q = T_3(SU(2)_1) + T_3(SU(2)_2) + Y \right)$$

✓ By VEVs of H_1 and Δ

✓ Discrete Z_2 symmetry remains from $SU(2)_2$

Scalar sector in our model

Scalar potential:

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

Components of scalar fields:

$$H_1 = \begin{bmatrix} G_1^+ \\ \frac{v+h_1+iG_1}{\sqrt{2}} \end{bmatrix}, \quad H_2 = \begin{bmatrix} H_2^+ \\ \frac{h_2+ia_2}{\sqrt{2}} \end{bmatrix}, \quad \Delta = \begin{bmatrix} \frac{1}{\sqrt{2}}G_\Delta^+ & \Delta^{++} \\ \frac{v_\Delta+\delta_R+iG_\Delta}{\sqrt{2}} & -\frac{1}{\sqrt{2}}G_\Delta^+ \end{bmatrix},$$

G: NG bosons absorbed by gauge bosons

✓ **H_2 does not develop a VEV: it becomes Z_2 odd inert scalar**

Gauge symmetry breaking

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

  $\hookrightarrow U(1)_{em} \times Z_2$ (Component of Δ 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(TeV) to avoid constraints

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

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

$$\left(\begin{array}{l} \tilde{H}_2 = i\sigma_2 H_2^* \\ F^{\tilde{c}} = i\sigma_2 F^c i\sigma_2 \end{array} \right)$$

✓ Terms with M_L and M_R violate lepton number

✓ Yukawa interaction with f and f' are source of neutrino mixing

Fermion sector in our model

◆ Mass eigenstates of exotic neutral fermion

$$\vec{N} M_N \vec{N}^T \equiv (\bar{N}_{1L}, \bar{N}_{2R}^C) \begin{pmatrix} M_D & -M_L \\ -M_R & M_D^T \end{pmatrix} \begin{pmatrix} N_{1R} \\ N_{2L}^C \end{pmatrix} + \text{c.c.}$$

✓ **Mass matrix**

(we assume M_L=M_R)

It can be diagonalized as…

$$O M_N O^T = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} M_D & -m_{LR} \\ -m_{LR} & M_D \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} M_D - m_{LR} & 0 \\ 0 & M_D + m_{LR} \end{pmatrix}$$

Mass eigenstate ψ_1 and ψ_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

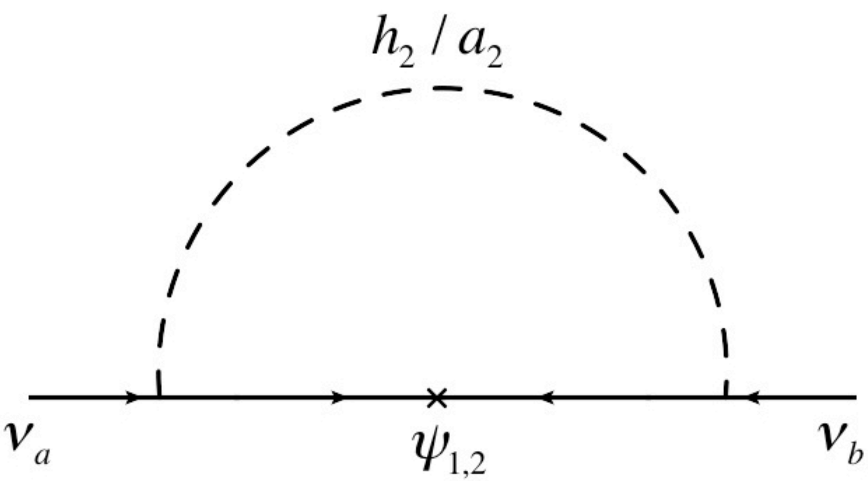
3. Phenomenology or our model

Generating neutrino mass matrix

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

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

$$Y \equiv (f + f')/2, Y' \equiv (f - f')/2$$



✓ Majorana mass of Ψ is source of LNV

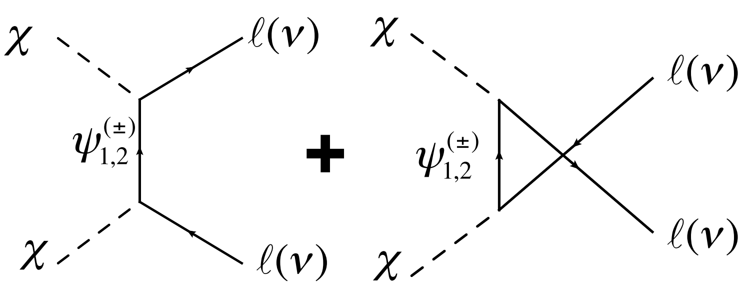
$$(m_\nu)_{ab} = -2\frac{Y_a m_{\psi_1} Y_b}{(4\pi)^2}\left[\frac{m_{\psi_1}^2 m_{h_2}^2 \ln\left(\frac{m_{\psi_1}}{m_{h_2}}\right) + m_{a_2}^2 m_{h_2}^2 \ln\left(\frac{m_{h_2}}{m_{a_2}}\right) + m_{\psi_1}^2 m_{a_2}^2 \ln\left(\frac{m_{a_2}}{m_{\psi_1}}\right)}{(m_{\psi_1}^2 - m_{h_2}^2)(m_{\psi_1}^2 - m_{a_2}^2)}\right]$$
$$-2\frac{Y'_a m_{\psi_2} Y'_b}{(4\pi)^2}\left[\frac{m_{\psi_2}^2 m_{h_2}^2 \ln\left(\frac{m_{\psi_2}}{m_{h_2}}\right) + m_{a_2}^2 m_{h_2}^2 \ln\left(\frac{m_{h_2}}{m_{a_2}}\right) + m_{\psi_2}^2 m_{a_2}^2 \ln\left(\frac{m_{a_2}}{m_{\psi_2}}\right)}{(m_{\psi_2}^2 - m_{h_2}^2)(m_{\psi_2}^2 - m_{a_2}^2)}\right]$$

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)

$$\sigma v_{\rm rel} \approx \frac{m_\chi^6 v_{\rm rel}^4}{60\pi(M_\psi^2+m_\chi^2)^4}\sum_{a,b=1}^{3}\left[|Y_a Y_b^\dagger|^2 + |Y'_a Y'^\dagger_b|^2 + \frac{|(Y+Y')_a(Y^\dagger+Y'^\dagger)_b|^2 + |(Y-Y')_a(Y^\dagger-Y'^\dagger)_b|^2}{128}\right]$$

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

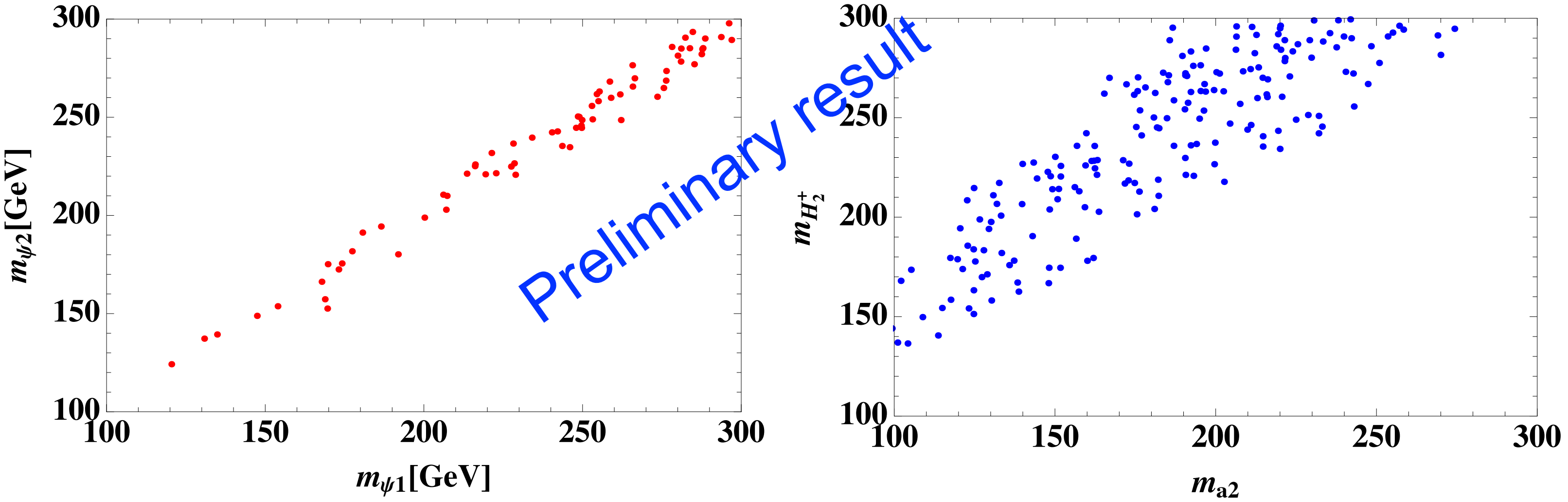
✓ **The cross section is d-wave dominant**

$$\left(\sigma v_{\rm rel} \approx d_{\rm eff} v_{\rm rel}^4\right)$$

Allowed parameter regions

Numerical analysis to search for parameter sets satisfying:

- ✓ Neutrino oscillation data
- ✓ Relic density of DM
- ✓ LFV constraints (such as μ→eγ)



- ✓ 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 $SU(2)_1 \times SU(2)_2$
  - ✓ 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

$$E^{\pm}_{1L} = \frac{1}{\sqrt{2}} P_L(\psi^{\pm}_1 + \psi^{\pm}_2), \quad \bar{E}_{1L} = \frac{1}{\sqrt{2}} (\bar{\psi}^{\pm}_1 + \bar{\psi}^{\pm}_2) P_R,$$

$$E^{(c)\pm}_{2R} = \frac{1}{\sqrt{2}} P_R(\psi^{\pm}_1 - \psi^{\pm}_2), \quad \bar{E}^{(c)\pm}_{2R} = \frac{1}{\sqrt{2}} (\bar{\psi}^{\pm}_1 - \bar{\psi}^{\pm}_2) P_L$$

Mass matrix for CP-even scalar (Z_2 even)

$$M_H = \begin{bmatrix} m^2_{h_1h_1} & -\sqrt{2}(\lambda_{H_1\Delta} + \lambda'_{H_1\Delta}) v v_\Delta \\ -\sqrt{2}(\lambda_{H_1\Delta} + \lambda'_{H_1\Delta}) v v_\Delta & m^2_{\Delta_R\Delta_R} \end{bmatrix},$$

$$m^2_{h_1h_1} = 2m^2_{H_1} - \frac{1}{2}\lambda_{H_1\Delta} v^2_\Delta, \quad m^2_{\Delta_R\Delta_R} = 2m^2_\Delta - \frac{1}{2}\lambda_{H_1\Delta} v^2.$$