Sterile neutrinos of the left-right symmetric model as dark matter

Kazarkin Dmitrii[1,2],
in collaboration with
Mikhail Dubinin[2] and Elena Fedotova [2]

[1] Lomonosov Moscow State University, Moscow
[2] Skobeltsyn Institute of Nuclear Physics research, Moscow

28th International Scientific Conference of Young Scientists and Specialists

AYSS-2024

Problems of the Standard Model

- **Presence of dark matter** → hint to new elementary particles beyond the SM.

$$\Omega_{DM,0}h^2 = 0.120 \pm 0.001 \quad [\textit{Planck}\ 2018\ \text{results}]$$

- **Neutrino oscillation phenomenon** → there is no mechanism for small neutrino mass generation in the SM

$$m_\nu \lesssim 0.2\ \text{eV}$$

- **Baryon asymmetry of the Universe** → 3 Sakharov's conditions (We need a source of B-violation, C and CP-violation, no thermal equilibrium)

$$Y_{B,0} = \frac{n_B - n_{\bar{B}}}{s} \sim 10^{-10} - 10^{-11}$$

Theoretical motivation: Grand Unification

Gauge group of Left-Right Symmetric Model (LRSM) can occur as a chain link of SO(10) Grand Unified Theory symmetry breaking. $\mathcal{G}_{3221}$ corresponds to so-called Minimal Left Right symmetric model (MLRM).

Notations:

$$\mathcal{G}_{51} = SU(5)\times U(1)$$
$$\mathcal{G}_{5} = SU(5)$$
$$\mathcal{G}_{PS} = SU(4)_C\times SU(2)_L\times SU(2)_R$$
$$\mathcal{G}_{421} = SU(4)_C\times SU(2)_L\times U(1)_{B-L}$$
$$\mathcal{G}_{3221} = SU(3)_C\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}$$
$$\mathcal{G}_{3211} = SU(3)_C\times SU(2)_L\times U(1)_R\times U(1)_{B-L}$$

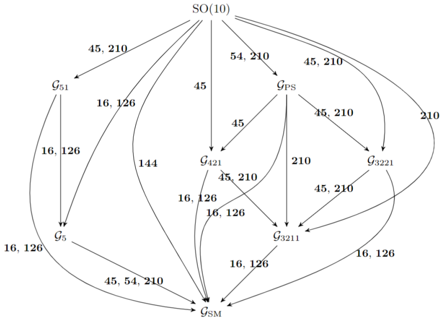


Figure: Possible breaking chains of SO(10) to $\mathcal{G}_{SM}$. [Fig. from M.Pernow,"Models of SO(10) Grand Unified Theories", 2021, Doctoral thesis]

LRSM: Fermion fields

LR-model gauge group:

$$G_{LR} = SU(3)_c \times SU(2)_R \times SU(2)_L \times U(1)_{B-L} \times \mathcal{P},$$

where $\mathcal{P}$ is $L \longleftrightarrow R$ discrete symmetry.

Fermions	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$L_{\alpha_L} = \begin{pmatrix} \nu_{\alpha_L} \\ l_{\alpha_L} \end{pmatrix}$	**1**	**2**	**1**	-1
$L_{\alpha_R} = \begin{pmatrix} \nu_{\alpha_R} \\ l_{\alpha_R} \end{pmatrix}$	**1**	**1**	**2**	-1
$Q_{a_L} = \begin{pmatrix} u_{a_L} \\ d_{a_L} \end{pmatrix}$	**1**	**2**	**1**	$\frac{1}{3}$
$Q_{a_R} = \begin{pmatrix} u_{a_R} \\ d_{a_R} \end{pmatrix}$	**1**	**1**	**2**	$\frac{1}{3}$

Table: Representations of the fermion fileds in LRSM

LRSM: Higgs fields

Higgs fields	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$\Delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \delta_L^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$	**1**	**3**	**1**	2
$\Delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \delta_R^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix}$	**1**	**1**	**3**	2
$\Phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix}$	**1**	**2**	**2**	0
η	**1**	**1**	**1**	0

Table: Representations of the Higgs fileds in LRSM

$$\mathcal{L}_{Higgs} = tr|D_\mu \Phi|^2 + tr|D_\mu \Delta_R|^2 + tr|D_\mu \Delta_L|^2 - V(\Phi, \Delta_L, \Delta_R)$$

Spontaneous symmetry breaking

Steps of SSB:

1. $\mathcal{P}$ broke at scale $M_{\mathcal{P}} \sim M_{GUT} \sim 10^{15}$ GeV due to non-zero vacuum expectation value (VEV) of Higgs singlet scalar field $\eta = (1,1,1,0)$

$$\mathcal{P}: \quad l_L \leftrightarrow l_R, \quad q_L \leftrightarrow q_R, \quad \Delta_L \leftrightarrow \Delta_R, \quad \Phi \leftrightarrow \Phi^\dagger$$

2. $$\boxed{SU(2)_R \times U(1)_{B-L} \xrightarrow[M_R \sim \mathcal{O}(1\ \text{TeV})]{\langle \Delta_R \rangle} U(1)_Y \times \mathbb{Z}_2}$$
   with VEV of Higgs right triplet Δ_R

3. Electroweak SSB at the $M_{W,Z}$-scale due to non-zero VEVs of the Higgs bi-doublet Φ and the left triplet Δ_L:

$$\boxed{SU(2)_L \times U(1)_Y \xrightarrow{\langle \Phi \rangle, \langle \Delta_L \rangle} U(1)_{em}}, \quad Q_{\rm em} = T_{3R} + T_{3L} + \frac{B-L}{2}$$

$$\langle \Delta_{L,R} \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_{L,R} & 0 \end{pmatrix} \quad \langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}, \quad \sqrt{k_1^2 + k_2^2} = 246\ \text{GeV}$$

Seesaw for VEVs

β-sector of the Higgs potential:

$$V_\beta(\Phi,\Delta_L,\Delta_R) = \beta_1\Big(Tr[\phi\Delta_R\phi^\dagger\Delta_L^\dagger]+Tr[\phi^\dagger\Delta_L\phi\Delta_R^\dagger]\Big)+\beta_2\Big(Tr[\tilde{\phi}\Delta_R\phi^\dagger\Delta_L^\dagger]+Tr[\tilde{\phi}^\dagger\Delta_L\phi\Delta_R^\dagger]\Big)+ \beta_3\Big(Tr[\phi\Delta_R\tilde{\phi}^\dagger\Delta_L^\dagger]+Tr[\phi^\dagger\Delta_L\tilde{\phi}\Delta_R^\dagger]\Big),$$

Additional GUT and/or SUSY assumptions $\rightarrow \beta_i = 0$ or $\beta_i \simeq 0$

Seesaw relation between v_L and v_R

$$v_L = \gamma\,\frac{(246\ \text{GeV})^2}{v_R}, \qquad \text{where} \quad \gamma \equiv \frac{\beta_2 k_1^2 + \beta_1 k_1 k_2 + \beta_3 k_2^2}{(2\rho_1 - \rho_3)(246\ \text{GeV})^2},$$

$\beta_i = 0$

$(2\rho_1 - \rho_3)v_R v_L = 0$

$v_L = 0 \ \big(v_R \neq 0$ and $(2\rho_1 - \rho_3) \neq 0\big)$

$\beta_i \rightarrow 0$

$v_L \simeq \frac{(246\ \text{GeV})^2}{v_R}$

$v_L \simeq 0 \ (v_R \gg 246$ GeV or $\gamma \ll 1)$

LRSM: Gauge sector

- New $SU(2)_R$-gauge field $V^j_{R,\mu}$, $(j = \overline{1,3})$
- SM gauge fields G^a_μ, $V^i_{L,\mu}$ and B_μ, $(a = \overline{1,8},\ i = \overline{1,3})$

Basis of mass states:

$$\begin{pmatrix} V^3_L \\ V^3_R \\ B \end{pmatrix} = \begin{pmatrix} c_W c_\phi & c_W s_\phi & s_W \\ -s_W s_M c_\phi - c_M s_\phi & -s_W s_M s_\phi + c_M c_\phi & c_W s_M \\ -s_W c_M c_\phi + s_M s_\phi & -s_W c_M s_\phi - s_M c_\phi & c_W c_M \end{pmatrix} \begin{pmatrix} Z_1 \\ Z_2 \\ A \end{pmatrix},$$

$$\begin{pmatrix} W^\pm_L \\ W^\pm_R \end{pmatrix} = \begin{pmatrix} \cos\zeta & \sin\zeta \\ -\sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W^\pm_1 \\ W^\pm_2 \end{pmatrix}, \qquad W^\pm_{L,R} = \frac{1}{\sqrt{2}} \left(V^1_{L,R} \mp V^2_{L,R} \right)$$

$$M^2_{W_{1,2}} = \frac{g^2}{4}\left[k_+^2 + v_R^2 \mp \sqrt{v_R^4 + 4\,k_1^2\,k_2^2}\,\right], \quad (1)$$

$$M^2_{Z_{1,2}} = \frac{1}{4}\left[g^2 k_+^2 + 2v_R^2(g^2 + g'^2)\right] \mp \frac{1}{4}\sqrt{\left[g^2 k_+^2 + 2v_R^2(g^2 + g'^2)\right]^2 - 4g^2(g^2 + 2g'^2)\,k_+^2 v_R^2}. \quad (2)$$

Masses of Higgs and gauge bosons

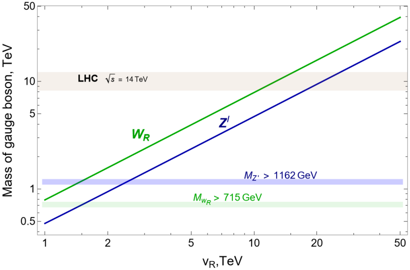


Figure: Masses of new vector gauge bosons Z_2 and W_2

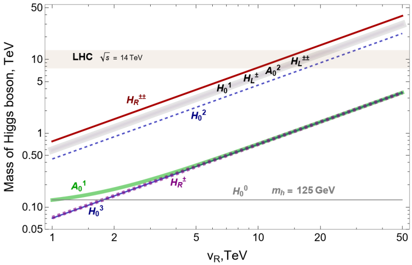


Figure: Masses of all 14 Higgs bosons in LRSM with tuning of self-interaction constants:
$\alpha_3 = 0.01\ \rho_1 = 0.1,\ \rho_2 = 0.3,\ \rho_3 = 0.9,$
$\lambda_1 = \lambda_{SM} = 0.118,$
$\lambda_2 = 0.01,\ \lambda_3 = 0.1$

Neutrino mixing: seesaw II

In flavor basis:

$$\mathcal{L} \supset (\overline{\nu_L}, \quad \overline{\nu_R^c}) \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}, \qquad \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} = P_L\, \mathcal{U} \begin{pmatrix} \nu \\ N \end{pmatrix} \quad (3)$$

$$M_D = \frac{1}{\sqrt{2}}(h_L k_1 + \tilde{h}_L k_2), \qquad M_L = \sqrt{2} h_M v_L, \qquad M_R = \sqrt{2} h_M v_R,$$

where $h_L, \ \tilde{h}_L, \ h_M$ are the Yukawa constants
Move to mass basis with unitary transformation $\mathcal{U}$:

$$\mathcal{L} \supset (\overline{\nu}, \quad \overline{N}) \begin{pmatrix} \hat{m} & 0 \\ 0 & \hat{M} \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}, \quad (4)$$

Form of $\mathcal{U}$ choose as a generalization of *Casas-Ibarra* approach
[Casas J., Ibarra A., Nucl.Phys.B 618 (2001) 171.]

$$\mathcal{U} \equiv \exp\begin{pmatrix} 0 & \theta \\ -\theta^\dagger & 0 \end{pmatrix} \cdot \begin{pmatrix} U_\nu & 0 \\ 0 & U_N^* \end{pmatrix} \simeq \begin{pmatrix} \left(1 - \frac{1}{2}\theta\theta^\dagger\right) U_\nu & \theta U_N^* \\ -\theta^\dagger U_\nu & \left(1 - \frac{1}{2}\theta^\dagger\theta\right) U_N^* \end{pmatrix},$$

$$\boxed{\Theta \equiv \theta U_N^*}$$

$$U_{PMNS} \equiv \left(1 - \frac{1}{2}\theta\theta^\dagger\right) U_\nu$$

Neutrino mixing: parametrization

Matrix equation system for transformation $\mathcal{U}$: (leading order accuracy)

$$\begin{cases} \theta \simeq M_D M_R^{-1}, \\ m_\nu = M_L - \theta M_R \theta^T, \\ M_N \simeq M_R \end{cases} \Rightarrow$$

seesaw II equation

$$\boxed{m_\nu = M_L - M_D M_N^{-1} M_D^T}$$

.

Orthogonality condition: (where $\hat{m} = diag(m_1, m_2, m_3)$, $\hat{M} = diag(M_1, M_2, M_3)$)

$$I = \Omega\Omega^T = \left[i\sqrt{\tilde{m}^{-1}} U_\nu^\dagger M_D U_N \sqrt{\hat{M}^{-1}}\right]^T \left[-i\sqrt{\tilde{m}^{-1}} U_\nu^\dagger M_D U_N \sqrt{\hat{M}^{-1}}\right],$$

$$\Theta = iU_\nu \left(\sqrt{\tilde{m}}\right) \Omega \sqrt{\hat{M}^{-1}}, \qquad \sqrt{\tilde{m}} = \sqrt{\hat{m} - U_{\text{PMNS}}^\dagger M_L U_{\text{PMNS}}^*}$$

Using approximation: $U_N = I$, $\theta^2 \ll 1$ we can write

$$h_M \simeq \frac{1}{\sqrt{2} v_R} (\theta^\dagger U_\nu \hat{m} U_\nu^T \theta^* + U_N^* \hat{M} U_N^\dagger) \simeq \frac{\hat{M}}{\sqrt{2} v_R} \Rightarrow \boxed{\tilde{m} = \hat{m} - \frac{v_L}{v_R} U_{\text{PMNS}}^\dagger \hat{M} U_{\text{PMNS}}^*}$$

Charged and Neutral currents

$$\mathcal{L}^{\nu}_{CC} = \frac{g}{\sqrt{2}}(U_{\mathrm{PMNS}})_{\alpha i}\; \bar{l}_\alpha\; \hat{W}_1 \left(\cos\zeta P_L - \sin\zeta P_R\right)\nu_i + \frac{g}{\sqrt{2}}(U_{\mathrm{PMNS}})_{\alpha i}\; \bar{l}_\alpha\; \hat{W}_2 \left(\sin\zeta P_L + \cos\zeta P_R\right)\nu_i + h.c. \tag{5a}$$

$$\mathcal{L}^{\nu}_{NC} = \frac{g}{2c_W}\left(U^{\dagger}_{\mathrm{PMNS}} U_{\mathrm{PMNS}}\right)_{ij} \bar{\nu}_i \sum_{X=Z_1,Z_2} \hat{X}\left(a^{(L)}_X P_L - a^{(R)}_X P_R\right)\nu_j \tag{5b}$$

$$\mathcal{L}^{N}_{CC} = -\frac{g}{\sqrt{2}}\Theta_{\alpha J}\; \bar{l}_\alpha\; \hat{W}_1 \left(\cos\zeta P_L - \sin\zeta P_R\right) N_J - \frac{g}{\sqrt{2}}\Theta_{\alpha J}\; \bar{l}_\alpha\; \hat{W}_2 \left(\sin\zeta P_L + \cos\zeta P_R\right) N_J + h.c. \tag{5c}$$

$$\mathcal{L}^{N}_{NC} = \frac{g}{2c_W}(\Theta^{\dagger}\Theta)_{IJ}\; \bar{N}_I \sum_{X=Z_1,Z_2} \hat{X}\left(a^{(L)}_X P_L - a^{(R)}_X P_R\right) N_J + \tag{5d}$$

$$+ \left(\frac{g}{2c_W}\left(U^{\dagger}_{\mathrm{PMNS}}\Theta\right)_{iJ}\; \bar{\nu}_i \sum_{X=Z_1,Z_2} \hat{X}\left(a^{(L)}_X P_L - a^{(R)}_X P_R\right) N_J + h.c.\right)$$

Sterile neutrino as warm DM

Warm Dark Matter: The lightest sterile neutrino with mass $\sim 1 - 10$ keV.

We use notation

$m_D^{dm} \equiv \sum_\alpha |U_{\alpha i}(\sqrt{\tilde{m}})_{ij}\Omega_{j1}|^2 = M_1 \sum_\alpha |\Theta_{\alpha 1}|^2$, $\quad \Omega$ -3 $\times$ 3 orthogonal matrix

- **Lifetime:** quasi-stable because of very small mixing with active neutrino ($|\Theta_{\alpha 1}|^2 \ll 1$)

$$\tau_{N_1} = 10^{22} \left(\frac{M_1}{1 \text{ keV}}\right)^{-4} \left(\frac{m_D^{dm}}{1 \text{ eV}}\right)^{-1} \text{sec} \; > \; H_0^{-1} \simeq 10^{17} \text{ sec} \tag{6}$$

- **Non-observation of radiative one-loop decay** $N_1 \to \gamma, \nu$ with $E_\gamma = M_1/2$ lead to strong lifetime limit

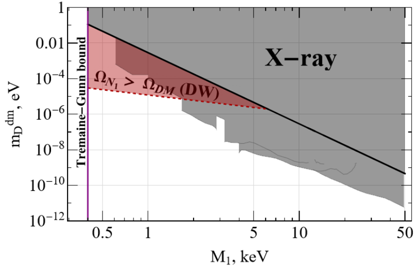
$\tau_{N_1} > 10^{25} sec$

[Aliev, Vysotsky, Sov. Phys. Usp. 24 (1981)]
[Boyarsky et al, arXiv:0811.2385v1]

.

DM mixing parameters

νMSM-**limit:** $v_L = 0 \to \sqrt{\tilde{m}} = \sqrt{\hat{m}}$



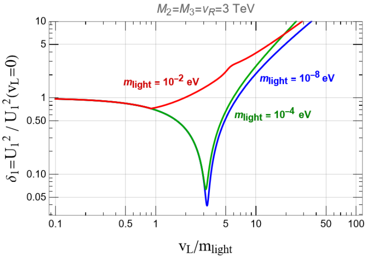
Strong constraints indicate an explicit form of Ω-matrix: (for normal/inverse hierarchy)

Ω_{NH}: $\Omega_{j1} \to \delta_{j1}$ Ω_{IH}: $\Omega_{j3} \to \delta_{j3}$

$$m_D^{dm}(v_L = 0) = m_{\text{light}}$$

- if $\hat{m} \gg \frac{v_L}{v_R}\hat{M} \to \nu MSM$ limit;
- if $\hat{m} \ll \frac{v_L}{v_R}\hat{M} \to$ high increase of effective interaction between active and sterile neutrinos;
- if $\hat{m} \simeq U^{\dagger}_{\text{PMNS}} M_L U^{*}_{\text{PMNS}} \to$ mixing decrease for $v_L \sim m_{light}$.

We illustrate it for normal hierarchy, $M_2 = M_3 = v_R = 3$ TeV and $\Omega_{j1} = \delta_{j1}$



Conclusions

- We considered the lightest sterile neutrino as warm DM in the framework of the MLRM.
- We proposed a modified seesaw type II expression for the mixing matrix

$$\Theta = iU_{\text{PMNS}}\sqrt{\tilde{m}}\Omega\sqrt{\hat{M}^{-1}}, \qquad \sqrt{\tilde{m}} = \sqrt{\hat{m} - U^{\dagger}_{\text{PMNS}} M_L U^{*}_{\text{PMNS}}}$$

- We found out that the mixing parameter significantly depends on v_L in the regime of $M_1 \sim \mathcal{O}(\text{keV})$ and $M_{2,3} \sim v_R$
- At the scale of m_{light} fixed, the mixing extremely rapidly increases in range of $v_L = (2-5)m_{light}$.

The research was carried out within the framework of the scientific program of the National Center for Physics and Mathematics, project *"Particle Physics and Cosmology"*

Thank you for your attention