

$SU(7)$ unification of Scotogenic model with Pati-Salam $SU(4)_C \otimes SU(2)_L \otimes U(1)_R$ gauge symmetry

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Based on current work (1808.xxxx) in collaboration with Prof.
Dr. Sin Kyu Kang and Arnab Dasgupta

Overview

Pati-
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model+ $SU(7)$

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- Generate neutrino masses
- Dark matter existence connected to neutrino masses
- Low scale lepton-quark unification in $SU(4)_c \otimes SU(2)_L \otimes U(1)_R$ model
- Scotogenic scenario and Pati-Salam symmetry in the context of unification of gauge interactions

Short Neutrino Mass Review

Pati-Salam+Scotoge model+SU(7)

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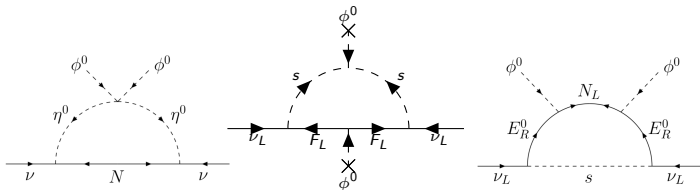
Scotogenic Neutrino Model in SU(7)

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d-5 Weinberg operator: $\frac{f_{ij}}{2\Lambda} (\nu_i \phi^0 - l_i \phi^+) (\nu_j \phi^0 - l_j \phi^+) + \text{h.c.} \rightarrow$ Majorana neutrino masses

- See-saw-1, Add SM singlet fermion, $m_\nu = -\frac{m_D^2}{M_N} \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} 0 & m_1 & m_2 \\ m_1 & m_A & m_3 \\ m_2 & m_3 & m_B \end{pmatrix}$
- See-saw-2, add SM triplet scalar, $m_\nu = -\frac{f_{\mu\nu}}{M^2}$
- See-saw-3, add SM triplet fermion, $m_\nu = -\frac{m_D^2}{M_\Sigma}$



Dirac case requires extra symmetries and more additional fields[†]

- 4 tree level realizations
- 2 1-loop level realizations

* Phys. Rev. Lett. 43(1979), 1566; Phys. Rev. Lett. 81 (1998) 1171

[†] arXiv:1609.02538

Scotogenic model[‡]

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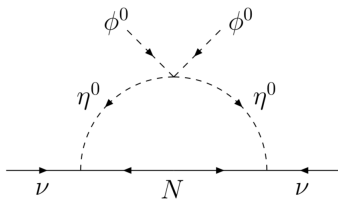
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BSM toolkit: $\eta, N \sim -$ under \mathbb{Z}_2 discrete symmetry.
DM candidates: η, N



[‡]hep-ph/0601225

Scotogenic model in $SU(6)$ GUT[§]

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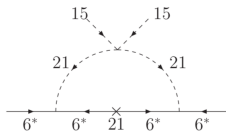
Simple case: Extend $SU(5)$ to $SU(6)$ to include BSM particles needed

$\underline{5}_F^* \times \underline{10}_F \times \underline{5}_S$, $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$ $SU(5)$ Yukawa terms are extended to

$\underline{6}_F^* \times \underline{15}_F \times \underline{6}_S^*$, $\underline{15}_F \times \underline{15}_F \times \underline{15}_S$ $SU(6)$ Yukawas

Anomaly free combinations: $\underline{5}_F^* + \underline{10}_F$ for $SU(5)$,
 $\underline{6}_F^* + \underline{6}_F^* + \underline{15}_F$ for $SU(6)$. New $SU(6)$ $\underline{21}_S$ scalar is added to obtain 2'nd Higgs doublet ($\mathbb{Z}_2 \sim -$) with new interactions

$\underline{6}_F^* \times \underline{6}_F^* \times \underline{21}_S$, $\underline{15}_S^* \times \underline{15}_S^* \times \underline{21}_S \times \underline{21}_S$



[§]10.1088/1742-6596/539/1/012001

Scotogenic model in $SU(7)$ GUT[¶]

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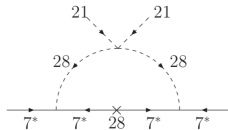
Less simple case: Extend $SU(5)$ to $SU(7)$ to include BSM particles needed

$\underline{5}_F^* \times \underline{10}_F \times \underline{5}_S^*$, $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$ $SU(5)$ Yukawa terms are extended to

$\underline{7}_F^* \times \underline{21}_F \times \underline{7}_S^*$, $\underline{21}_F \times \underline{21}_F \times \underline{35}_S$ $SU(7)$ Yukawas

Anomaly free combination for $SU(7)$: $\underline{7}_F^* + \underline{7}_F^* + \underline{7}_F^* + \underline{21}_F$.

New $\underline{28}_S$ scalar needed to accommodate $SU(2)_N$ doublet, with new interactions: $\underline{7}_F^* \times \underline{7}_F^* \times \underline{28}_S$, $\underline{21}_S^* \times \underline{21}_S^* \times \underline{28}_S \times \underline{28}_S$



[¶]10.1088/1742-6596/539/1/012001

Low scale Lepto-Quark unification model^{||}

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Gauge symmetry: $G_{QL} = SU(4)_C \otimes SU(2)_L \otimes U(1)_R$,

$$F_{QL} = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix} \sim (4, 2, 0),$$

$$F_u = (u^c \ \nu^c) \sim (\bar{4}, 1, -1/2),$$

$$F_d = (d^c \ e^c) \sim (\bar{4}, 1, 1/2).$$

Fields:

$$\chi = (\chi_u, \chi_R^0) \sim (4, 1, 1/2)$$

$$H^T = (H^+, H^0) \sim (1, 2, 1/2)$$

$$\Phi = \begin{pmatrix} \Phi_8 & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2 \sim (15, 2, 1/2)$$

$$A_\mu = \begin{pmatrix} G_\mu & X_\mu/\sqrt{2} \\ X_\mu^*/\sqrt{2} & 0 \end{pmatrix} + T_4 B'_\mu \sim (15, 1, 0)$$

$$M_X > 10^3 \text{ TeV}$$

$$\begin{aligned} \mathcal{L}_{QL}^Y &= Y_1 F_{QL} F_u H + Y_2 F_{QL} F_u \Phi \\ &+ Y_3 H^\dagger F_{QL} F_d + Y_4 \Phi^\dagger F_{QL} F_d + \text{h.c.}, \end{aligned}$$

$$\Phi_3 = \tilde{R}_2^* \sim (\bar{3}, 2, -1/6)_{SM}, \quad \Phi_4 = R_2 \sim (3, 2, 7/6)_{SM}$$

$$\begin{aligned} \mathcal{L} \supset & Y_2 Q_L \Phi_3 \nu^c + Y_2 \ell_L \Phi_4 u^c + \\ & Y_4 Q_L \Phi_4^\dagger e^c + Y_4 \ell_L \Phi_3^\dagger d^c + \text{h.c.} \end{aligned}$$

^{||}arXiv:1307.6213

Model particle content

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$$G_{GUT} = SU(7) \rightarrow G_{LQ} = SU(4)_c \otimes SU(2)_L \otimes U(1)_R \rightarrow G_{SM} = SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \rightarrow SU(3)_c \otimes U(1)_{em}$$

$$\text{Fields: } \underline{21}_F, \underline{7}_F^*, \underline{35}_F^*, \underline{140}_S, \underline{28}_S, (\underline{7}_S)$$

$$\text{Triangular anomalies: } \frac{3}{2} - \frac{1}{2} - 1 = 0$$

Decompositions:

$$\underline{21}_F \rightarrow (6, 1, 1)_{PS} \rightarrow (\bar{3}, 1, 4/3)_{SM}, (3, 1, 2/3)_{SM}$$

$$\mathbf{F}_{QL} \sim (\mathbf{4}, \mathbf{2}, \mathbf{0})_{PS} \rightarrow (\mathbf{3}, \mathbf{2}, \mathbf{1/6})_{SM}, (\mathbf{1}, \mathbf{2}, \mathbf{-1/2})_{SM}$$

$$(4, 1, -1/2)_{PS} \rightarrow (3, 1, -1/2)_{SM}, (1, 1, -1)_{SM}$$

$$(1, 1, -1)_{PS, SM}$$

$$(1, 2, -3/2)_{PS, SM}$$

$$\underline{7}_F^* \rightarrow \mathbf{F}_U \sim (\mathbf{4}, \mathbf{1}, \mathbf{-1/2})_{PS} \rightarrow (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{-2/3})_{SM}, (\mathbf{1}, \mathbf{1}, \mathbf{0})_{SM}$$

$$(1, 2, -1/2)_{PS, SM}$$

$$(1, 1, 1)_{PS, SM}$$

$$\underline{35}_F^* \rightarrow (4, 1, -3/2)_{PS} \rightarrow (3, 1, -4/3)_{SM}, (1, 1, -2)_{SM}$$

$$(6, 2, -1/2)_{PS} \rightarrow (3, 2, -1/6)_{SM}, (3, 2, -5/6)_{SM}$$

$$(6, 1, 0)_{PS} \rightarrow (\bar{3}, 1, 1/3)_{SM}, (3, 1, -1/3)_{SM}$$

$$\mathbf{F}_d \sim (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{1/2})_{PS} \rightarrow (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1/3})_{SM}, (\mathbf{1}, \mathbf{1}, \mathbf{1})_{SM}$$

$$(1, 1, 2)_{PS, SM}$$

$$\underline{7}_S \rightarrow (4, 1, 1/2)_{PS} \rightarrow (3, 1, 2/3)_{SM}, (1, 1, 0)_{SM}$$

$$(1, 2, -1/2)_{PS, SM}, (1, 1, -1)_{PS, SM}$$

28_S, 140_S decomposition

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$$\underline{28}_S \rightarrow (10, 1, 1)_{PS} \rightarrow (\bar{6}, 1, 4/3)_{SM}, (3, 1, 2/3)_{SM}, (1, 1, 0)_{SM}$$

$$(4, 2, 0)_{PS} \rightarrow (3, 2, 1/6)_{SM}, (1, 2, -1/2)_{SM}$$

$$(4, 1, -1/2)_{PS} \rightarrow (3, 1, -1/3)_{SM}, (1, 1, -1)_{SM}$$

$$(1, 3, -1)_{PS,SM}, (1, 2, -3/2)_{PS,SM}, (1, 1, -2)_{PS,SM}$$

$$\underline{140}_S \rightarrow (\bar{4}, 2, -2)_{PS} \rightarrow (\bar{3}, 2, -13/6)_{SM}, (1, 2, -3/2)_{SM}$$

$$(\bar{4}, 1, -3/2)_{PS} \rightarrow (\bar{3}, 1, -5/3)_{SM}, (1, 1, -1)_{SM}$$

$$(15, 1, -1)_{PS} \rightarrow (3, 1, -1/3)_{SM}, (8, 1, -1)_{SM}, (1, 1, -1)_{SM}, (\bar{3}, 1, -5/3)_{SM}$$

$$(1, 3, -1)_{PS,SM}, (1, 1, -1)_{PS,SM}, 2 \times (1, 2, -1/2)_{PS,SM}, \mathbf{(1, 1, 0)_{PS,SM}}$$

$$(15, 2, -1/2)_{PS} \rightarrow$$

$$(3, 2, 1/6)_{SM}, (8, 2, -1/2)_{SM}, (1, 2, -1/2)_{SM}, (\bar{3}, 2, -7/6)_{SM}$$

$$(4, 2, 0)_{PS} \rightarrow (3, 2, 1/6)_{SM}, (1, 2, -1/2)_{SM}$$

$$(20, 1, 1/2)_{PS} \rightarrow (8, 1, 0)_{SM}, (6, 1, 2/3)_{SM}, (3, 1, 2/3)_{SM}, (\bar{3}, 1, 4/3)_{SM}$$

$$(4, 3, 1/2) \rightarrow (3, 2, 2/3)_{SM}, (1, 3, 0)_{SM}$$

$$2 \times (4, 1, 1/2)_{PS} \rightarrow (3, 1, 2/3)_{SM}, (1, 1, 0)_{SM}$$

$$(4, 2, 1)_{PS} \rightarrow (3, 2, 7/6)_{SM}, (1, 2, 1/2)_{SM}$$

$$(6, 2, 3/2)_{PS} \rightarrow (\bar{3}, 2, 11/6)_{SM}, (3, 2, 7/6)_{SM}$$

$$(6, 1, 2)_{PS} \rightarrow (\bar{3}, 1, 7/3)_{SM}, (3, 1, 5/3)_{SM}$$

Lagrangian interactions

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$$\begin{aligned} & \underline{28}_S^* \times \underline{28}_S, \underline{140}_S^* \times \underline{140}_S \\ & \underline{140}_S \times \underline{140}_S \times \underline{28}_S^* \\ & \underline{21}_F \times \underline{35}_F^* \times \underline{140}_S \\ & \underline{21}_F \times \underline{7}_F^* \times \underline{140}_S^* \\ & \underline{35}_F \times \underline{35}_F \times \underline{140}_S \\ & \underline{7}_F^* \times \underline{7}_F^* \times \underline{28}_S \\ & \underline{28}_S \times \underline{28}_S \times \underline{28}_S^* \times \underline{28}_S^* \\ & \underline{140}_S \times \underline{140}_S \times \underline{140}_S^* \times \underline{140}_S^* \\ & \underline{28}_S \times \underline{28}_S^* \times \underline{140}_S \times \underline{140}_S^* \end{aligned}$$

List of VEVs

Pati-Salam+Scotogenic model+ $SU(7)$

#	Scale	Rep $_{SU(7)}$	Rep $_{PS}$	Rep $_{SM}$
1	PS	$\underline{28}_S$	(10, 1, 1)	(1, 1, 0)
2	EW	$\underline{28}_S$	(4, 2, 0)	(1, 2, -1/2)
3	EW	$\underline{28}_S$	(1, 3, -1)	(1, 3, -1)
4	EW	$\underline{140}_S$	(1, 3, -1)	(1, 3, -1)
5	EW	$\underline{140}_S$	(15, 2, -1/2)	(1, 2, -1/2)
6,7	EW	$\underline{140}_S$	(1, 2, -1/2)	(1, 2, -1/2)
8	GUT	$\underline{140}_S$	(1, 1, 0)	(1, 1, 0)
9	EW	$\underline{140}_S$	(4, 2, 0)	(1, 2, -1/2)
10	EW	$\underline{140}_S$	(4, 3, 1/2)	(1, 3, 0)
11,12	PS	$\underline{140}_S$	(4, 1, 1/2)	(1, 1, 0)
13	EW	$\underline{140}_S$	(4, 2, 1)	(1, 2, 1/2)

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$SU(7)$ structure, breaking, generators

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- 48 generators, 6 diagonal (rank)
- $SU(7) \rightarrow SU(4)_c \otimes SU(2)_L \otimes U(1)_R$ (rank 5)
 v_8
- 29 generators become massive,
$$Z_7 = \left(\frac{\sqrt{7}}{5} T_4 + \frac{\sqrt{\frac{14}{3}}}{5} T_5 - 2\sqrt{\frac{2}{15}} T_6 \right)_{SU(7)}$$
- $SU(4)_c \otimes SU(2)_L \otimes U(1)_R \xrightarrow{v_{1,11,12}} SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
(rank 4)
- $R = \left(\frac{4}{\sqrt{10}} T_4 + \frac{4}{\sqrt{15}} T_5 + \sqrt{\frac{7}{3}} T_6 \right)_{SU(7)}$
- $Y = \left(R + \frac{\sqrt{6}}{3} T_4 \right)_{PS}$
- $(I_3)_{SM,PS} = \left(-\sqrt{\frac{2}{5}} T_4 + \sqrt{\frac{3}{5}} T_5 \right)_{SU(7)}$
- $Q = (I_3 + Y)_{SM} = \left(I_3 + R + \frac{\sqrt{6}}{3} T_4 \right)_{PS} =$
 $\left(\sqrt{\frac{2}{3}} T_3 + \sqrt{\frac{2}{5}} T_4 + \frac{7}{\sqrt{15}} T_5 + \sqrt{\frac{7}{3}} T_6 \right)_{SU(7)}$

Gauge coupling unification

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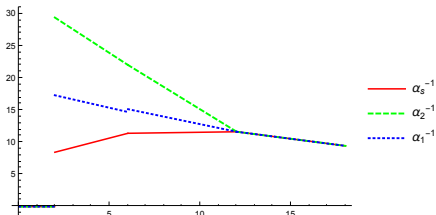
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- $\alpha_s(m_Z) = 0.1182$, $\alpha_{em}(m_Z) = 1/127.916$,
 $\alpha_2(m_Z) = \frac{\sqrt{2}m_W^2 G_F}{\pi} = 0.03393$
- $M_{PS} = 10^3$ TeV, $n_Y = \sqrt{\frac{17}{3}}$, $n_R = \sqrt{5}$, $M_U = 10^{12}$ GeV,
 $\alpha_U(M_U) = 0.08577$
- $\text{Sin}^2\theta_W(m_Z) = \frac{3}{8}$

Neutrino mass diagram

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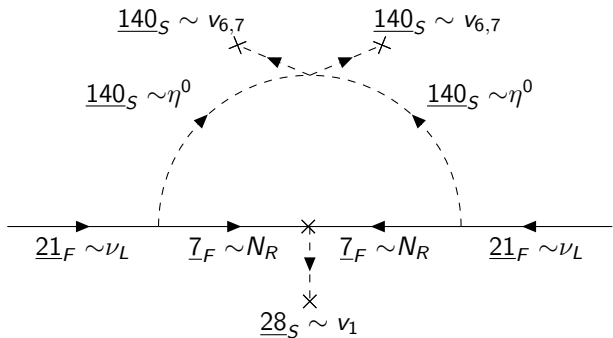
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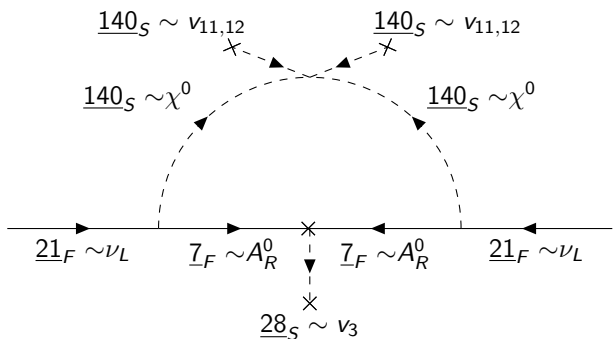
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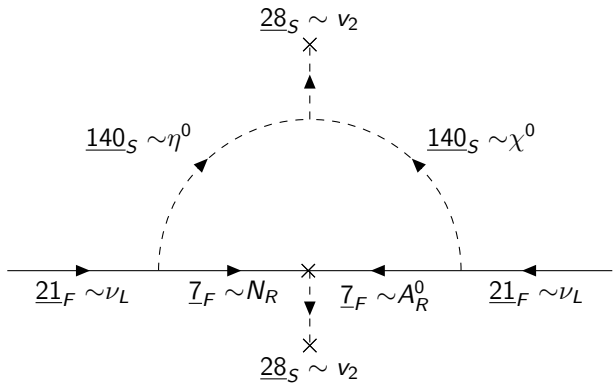
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Fermion masses(General)

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$$M_{\pm} = \begin{pmatrix} v_{5,7} & v_8 & v_{12} & v_{13} \\ v_{10} & v_9 & v_7 & v_4 \\ v_{13} & v_{11} & v_8 & v_6 \\ v_4 & v_{5,6} & v_9 & v_{10,11} \end{pmatrix} \quad M_{\pm 2} = \begin{pmatrix} v_{10,11} & v_5 \\ v_{6,7} & v_{11,12} \end{pmatrix}$$

$$M_{Q=0} = \begin{pmatrix} 0 & v_5 & v_{10} \\ v_5 & v_1 & v_2 \\ v_{10} & v_2 & v_3 \end{pmatrix} \quad M_{\pm 2/3} = \begin{pmatrix} v_5 & 0 \\ v_{10} & v_5 \end{pmatrix}$$

$$M_{\pm 1/3} = \begin{pmatrix} v_{5,7} & v_8 & v_9 & v_{11,12} \\ v_{10} & v_{13} & v_4 & v_{5,6,7} \\ v_9 & v_{11} & v_{5,6,7} & v_8 \\ v_4 & v_{5,6} & v_{10,12} & v_{13} \end{pmatrix} \quad M_{\pm 4/3} = \begin{pmatrix} 0 & v_5 \\ v_5 & v_{10,12} \end{pmatrix}$$

Fermion masses(Scotogenic)

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$$v_{5,10} = 0$$

$$M_{\pm} = \begin{pmatrix} v_7 & v_8 & v_{12} & v_{13} \\ \mathbf{0} & v_9 & v_7 & v_4 \\ v_{13} & v_{11} & v_8 & v_6 \\ v_4 & v_6 & v_9 & v_{11} \end{pmatrix} \quad M_{\pm 2} = \begin{pmatrix} v_{11} & \mathbf{0} \\ v_{6,7} & v_{11,12} \end{pmatrix}$$

$$M_{Q=0} = \begin{pmatrix} 0 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & v_1 & v_2 \\ \mathbf{0} & v_2 & v_3 \end{pmatrix} \quad M_{\pm 2/3} = \begin{pmatrix} \mathbf{0} & 0 \\ \mathbf{0} & \mathbf{0} \end{pmatrix}$$

$$M_{\pm 1/3} = \begin{pmatrix} v_7 & v_8 & v_9 & v_{11,12} \\ \mathbf{0} & v_{13} & v_4 & v_{6,7} \\ v_9 & v_{11} & v_{6,7} & v_8 \\ v_4 & v_6 & v_{12} & v_{13} \end{pmatrix} \quad M_{\pm 4/3} = \begin{pmatrix} 0 & \mathbf{0} \\ \mathbf{0} & v_{12} \end{pmatrix}$$

Fermion masses(Splitted)

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$$v_{5,6,7,9,11,12,13} = 0$$

$$M_{\pm} = \begin{pmatrix} v_8 & 0 & 0 & 0 \\ 0 & v_8 & 0 & 0 \\ 0 & 0 & v_{10} & v_4 \\ 0 & 0 & v_4 & v_{10} \end{pmatrix} \quad M_{\pm 2} = \begin{pmatrix} v_{10} & 0 \\ 0 & 0 \end{pmatrix}$$

$$M_{Q=0} = \begin{pmatrix} 0 & 0 & v_{10} \\ 0 & v_1 & v_2 \\ v_{10} & v_2 & v_3 \end{pmatrix} \quad M_{\pm 2/3} = \begin{pmatrix} 0 & 0 \\ v_{10} & 0 \end{pmatrix}$$

$$M_{\pm 1/3} = \begin{pmatrix} v_8 & 0 & 0 & 0 \\ 0 & v_8 & 0 & 0 \\ 0 & 0 & v_{10} & v_4 \\ 0 & 0 & v_4 & v_{10} \end{pmatrix} \quad M_{\pm 4/3} = \begin{pmatrix} 0 & 0 \\ 0 & v_{10} \end{pmatrix}$$

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- Generates neutrino masses via Scotogenic scenario
- \mathbb{Z}_2 symmetry is not *ad hoc*
- Naturally accomodates DM
- Unifies gauge couplings at $10^{12} - 10^{16}$ GeV
- Predicts $\text{Sin}^2\theta_W(m_Z) = \frac{3}{8}$
- Lepton-quark unification @ 10^6 GeV
- Natural framework for different see-saw scenarios
- Rich phenomenology

Thank you!