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

Oleg Popov
Seoul National University of Science and Technology
opopo001@ucr.edu

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Based on current work (1809.xxxx) in collaboration with Prof. Dr. Sin Kyu Kang and Arnab Dasgupta

Overview

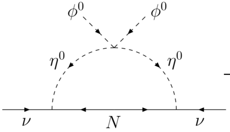
Introduction/Motivation

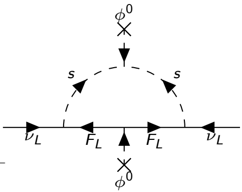
- Generate neutrino masses
- Dark matter existance connected to neutrino masses
- Low scale lepton-quark unification in $SU(4)_c \otimes SU(2)_L \otimes U(1)_R$ model
- Scotogenic scenario and Pati-Salam symmetry in the context of unification of gauge interactions

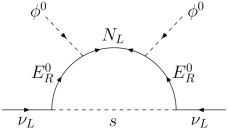
Short Neutrino Mass Review

d-5 Weinberg operator: $\frac{f_{ij}}{2\Lambda}\left(\nu_i\phi^0 - l_i\phi^+\right)\left(\nu_j\phi^0 - l_j\phi^+\right) + \text{h.c.}$.*$\rightarrow$ 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, $m_\nu = -\frac{f\mu v}{M^2}$
- See-saw-3, add SM triplet fermion, $m_\nu = -\frac{m_D^2}{M_\Sigma}$







Dirac case requires extra symmeries and more additional fields†

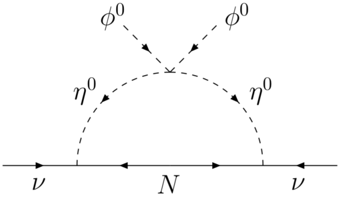
- 4 tree level realizations
- 2 1-loop level realizations

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

†arXiv:1609.02538

Scotogenic model‡

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



‡hep-ph/0601225

Scotogenic model in $SU(6)$ GUT[§]

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

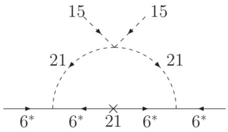
$\underline{5}^*_F \times \underline{10}_F \times \underline{5}^*_S$, $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$ $SU(5)$ Yukawa terms are extended to

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

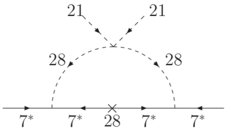
Less simple case: Extend $SU(5)$ to $SU(7)$ to incude BSM particles needed

$\underline{5}^*_F \times \underline{10}_F \times \underline{5}^*_S$, $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$ $SU(5)$ 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 accomodate $SU(2)_N$ 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[‖]

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

$$\begin{aligned} F_{QL} &= \begin{pmatrix} u & \nu \\ d & e \end{pmatrix} \sim (4,2,0), \\ F_u &= \begin{pmatrix} u^c & \nu^c \end{pmatrix} \sim (\bar{4},1,-1/2), \\ F_d &= \begin{pmatrix} d^c & e^c \end{pmatrix} \sim (\bar{4},1,1/2). \end{aligned}$$

Fields:

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

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

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

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

$M_X > 10^3$ TeV

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

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

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

[‖] arXiv:1307.6213

Model particle content

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

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

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

Decompositions:

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

$\boldsymbol{F_{QL} \sim (4,2,0)_{PS} \to (3,2,1/6)_{SM}, (1,2,-1/2)_{SM}}$

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

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

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

$\underline{7}^*_F \to \boldsymbol{F_u \sim \left(\bar{4},1,-1/2\right)_{PS} \to \left(\bar{3},1,-2/3\right)_{SM}, (1,1,0)_{SM}}$

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

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

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

$(6,2,-1/2)_{PS} \to \left(\bar{3},2,-1/6\right)_{SM}, (3,2,-5/6)_{SM}$

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

$\boldsymbol{F_d \sim \left(\bar{4},1,1/2\right)_{PS} \to \left(\bar{3},1,1/3\right)_{SM}, (1,1,1)_{SM}}$

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

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

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

$\underline{28}_S, \underline{140}_S$ decomposition

$\underline{28}_S \to (10,1,1)_{PS} \to (\bar{6},1,4/3)_{SM}, (3,1,2/3)_{SM}, (1,1,0)_{SM}$
$(4,2,0)_{PS} \to (3,2,1/6)_{SM}, (1,2,-1/2)_{SM}$
$(4,1,-1/2)_{PS} \to (3,1,-1/3)_{SM}, (1,1,-1)_{SM}$
$(1,3,-1)_{PS,SM}, (1,2,-3/2)_{PS,SM}, (1,1,-2)_{PS,SM}$
$\underline{140}_S \to (\bar{4},2,-2)_{PS} \to (\bar{3},2,-13/6)_{SM}, (1,2,-3/2)_{SM}$
$(\bar{4},1,-3/2)_{PS} \to (\bar{3},1,-5/3)_{SM}, (1,1-1)_{SM}$
$(15,1,-1)_{PS} \to (3,1,-1/3)_{SM}, (8,1,-1)_{SM}, (1,1-1)_{SM}, (\bar{3},1,-5/3)_{SM}$
$(1,3,-1)_{PS,SM}, (1,1,-1)_{PS,SM}, 2\times(1,2,-1/2)_{PS,SM}, \mathbf{(1,1,0)_{PS,SM}}$
$(15,2,-1/2)_{PS} \to$
$(3,2,1/6)_{SM}, (8,2,-1/2)_{SM}, (1,2,-1/2)_{SM}, (\bar{3},2,-7/6)_{SM}$
$(4,2,0)_{PS} \to (3,2,1/6)_{SM}, (1,2,-1/2)_{SM}$
$(20,1,1/2)_{PS} \to (8,1,0)_{SM}, (6,1,2/3)_{SM}, (3,1,2/3)_{SM}, (\bar{3},1,4/3)_{SM}$
$(4,3,1/2) \to (3,2,2/3)_{SM}, (1,3,0)_{SM}$
$2\times(4,1,1/2)_{PS} \to (3,1,2/3)_{SM}, (1,1,0)_{SM}$
$(4,2,1)_{PS} \to (3,2,7/6)_{SM}, (1,2,1/2)_{SM}$
$(6,2,3/2)_{PS} \to (\bar{3},2,11/6)_{SM}, (3,2,7/6)_{SM}$
$(6,1,2)_{PS} \to (\bar{3},1,7/3)_{SM}, (3,1,5/3)_{SM}$

Lagrangian interactions

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

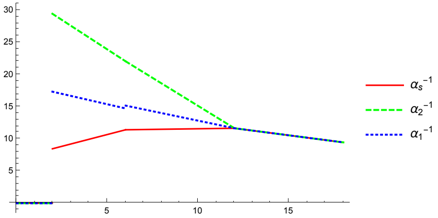
List of VEVs

#	Scale	$\text{Rep}_{SU(7)}$	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	$\underline{140}_S$	$(4,2,1)$	$(1,2,1/2)$

$SU(7)$ structure, breaking, generators

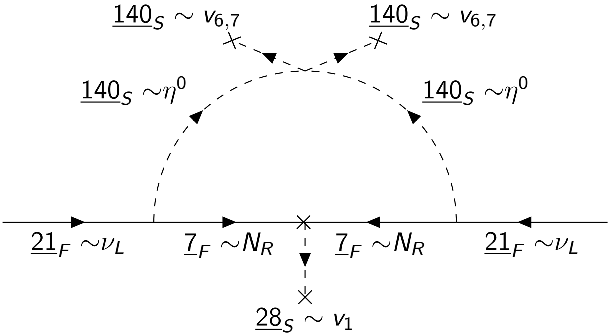
- 48 generators, 6 diagonal (rank)
- $SU(7) \underset{v_8}{\to} SU(4)_c \otimes SU(2)_L \otimes U(1)_R$ (rank 5)
- 29 generators become massive,
  $Z_7 = \left(\frac{\sqrt{7}}{5} T_4 + \frac{\sqrt{\frac{14}{3}}}{5} T_5 - 2\sqrt{\frac{2}{15}} T_6 \right)_{SU(7)}$
- $SU(4)_c \otimes SU(2)_L \otimes U(1)_R \underset{v_{1,11,12}}{\to} SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ (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

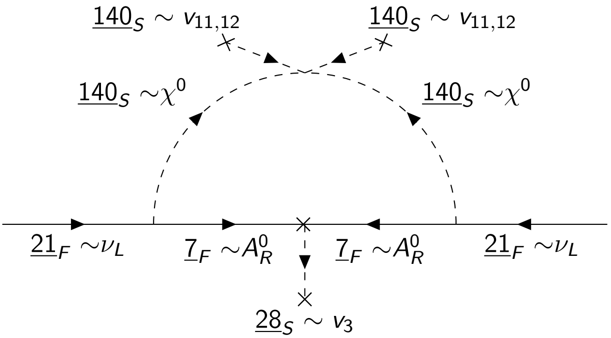


- $\alpha_s(m_Z) = 0.1182$, $\alpha_{em}(m_Z) = 1/127.916$, $\alpha_2(m_Z) = \frac{\sqrt{2}m_W^2 G_F}{\pi} = 0.03393$
- $M_{PS} = 10^3$ TeV, $n_Y = \sqrt{\frac{17}{3}}$, $n_R = \sqrt{5}$, $M_U = 10^{12}$ GeV, $\alpha_U(M_U) = 0.08577$
- $\text{Sin}^2\theta_W(m_Z) = \frac{3}{8}$

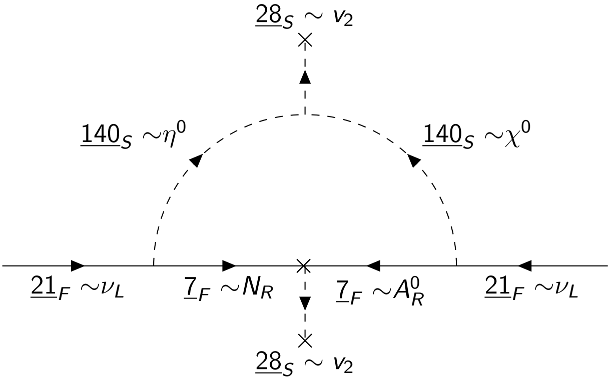
Neutrino mass diagram



Neutrino mass diagram



Neutrino mass diagram



Fermion masses(General)

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

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

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

Fermion masses(Scotogenic)

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

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

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

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

Fermion masses(Splitted)

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

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

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

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

Conclusions

- 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 $\mathrm{Sin}^2\theta_W(m_Z) = \frac{3}{8}$
- Lepton-quark unification @10^6 GeV
- Natural framework for different see-saw scenarios
- Rich phenomenology

Thank you!