

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

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In this work we demonstrate how Scotogenic model can arise naturally from an  $SU(7)$  grand unified theory. Our model also includes a low scale Pati-Salam  $SU(4)_c \times SU(2)_L \times U(1)_R$  symmetry which unifies quarks and leptons.  $\mathbb{Z}_2$  symmetry needed for the realization of Scotogenic scenario is a residual symmetry and not *ad hoc*. A short fermion masses and dark matter analysis is included.

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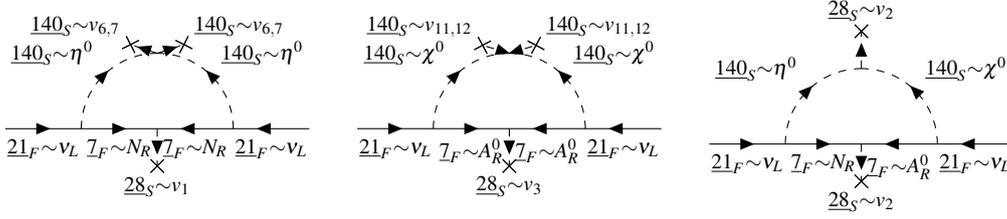
1. *Introduction:* Standard Model (SM) has been very successful in explaining many aspects of particles and their interactions but it predictions massless neutrinos. In order to generate neutrino masses one needs to go beyond the SM. There exist numerous proposals for generating Majorana (generated through the dim-5 Weinberg operator [1],  $\frac{LLHH}{\Lambda}$ ) as well as Dirac neutrino masses. The minimal cases are Seesaw-1 (SM+(1,1,0)<sub>F</sub>), Seesaw-2 (SM+(1,3,1)<sub>S</sub>), and Seesaw-3 (SM+(1,3,0)<sub>F</sub>), which are tree level Majorana cases. At 1-loop there are Zee model [2], Scotogenic model [3], and other less known Scotogenic inverse seesaw realization [4]. All possible pathways to tree and one-loop radiative Majorana and Dirac neutrino mass generation have been studied in ref. [7] and ref. [5] respectively. It shows that there are 4 possible ways to generate Dirac neutrino masses at tree level and only two possible topologies exist for one-loop Dirac neutrino mass. The aim of this letter is to demonstrate how Scotogenic model[3] of neutrino masses, which relates the existence of dark matter to the generation of neutrino masses, can be naturally obtained from the SU(7) grand unified theory (GUT) breaking with quarks and leptons unified through the Pati-Salam SU(4)<sub>c</sub> × SU(2)<sub>L</sub> × U(1)<sub>R</sub> gauge symmetry at the low scale ( $\sim O(10^3)$  TeV). In reference [6] it was shown how the  $\mathbb{Z}_2$  and U(1)<sub>D</sub> Scotogenic models can be naturally obtained from SU(6) and SU(7) GUT breaking respectively but without additional intermediate symmetries at low energy scales. The note is organized as follows: description of the model, unification of gauge couplings, fermion mass analysis, and short discussion of dark matter candidates and analysis.

2. *Model:* Our model consists of the  $\mathbb{G}_{GUT} = SU(7)$  with  $\underline{21}_F, \underline{7}_F^*, \underline{35}_F^*$  fermion and  $\underline{140}_S, \underline{28}_S$  scalar fields. The model is chiral anomaly free,  $\frac{3}{2} - \frac{1}{2} - 1 = 0$ . The SU(7) GUT is then spontaneously broken to  $\mathbb{G}_{PS} = SU(4)_c \times SU(2)_L \times U(1)_R$  by  $\underline{140}_S$ . The Yukawas of the model are  $\underline{21}_F \times \underline{35}_F^* \times \underline{140}_S, \underline{21}_F \times \underline{7}_F^* \times \underline{140}_S^*, \underline{35}_F \times \underline{35}_F \times \underline{140}_S, \underline{7}_F^* \times \underline{7}_F^* \times \underline{28}_S$  which generate the masses for all fermions.  $\underline{28}_S$  scalar field is required here in order to generate the Majorana mass for the neutral  $\mathbb{Z}_2$  odd fermion in the Scotogenic model. Next,  $\mathbb{G}_{PS}$  is broken down to  $\mathbb{G}_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$  at  $\sim O(10^3)$  TeV by  $\underline{140}_S$ . Electric charge, hypercharge, electroweak isospin, and U(1)<sub>R</sub> charge are  $Q=(I_3+Y)_{SM}=(I_3+R+\frac{\sqrt{6}}{3}T_4)_{PS}=(\sqrt{\frac{2}{3}}T_3+\sqrt{\frac{2}{5}}T_4+\frac{7}{\sqrt{15}}T_5+\sqrt{\frac{7}{3}}T_6)_{SU(7)}, Y=(R+\frac{\sqrt{6}}{3}T_4)_{PS}, (I_3)_{SM,PS}=(-\sqrt{\frac{2}{3}}T_4+\sqrt{\frac{3}{5}}T_5)_{SU(7)}, R=(\frac{4}{\sqrt{10}}T_4+\frac{4}{\sqrt{15}}T_5+\sqrt{\frac{7}{3}}T_6)_{SU(7)}$ . The model also includes one diagonal generator at the GUT scale, here labeled as  $Z_7$  which is  $Z_7=(\frac{\sqrt{2}}{5}T_4+\sqrt{\frac{14}{3}}\frac{1}{5}T_5-2\sqrt{\frac{2}{15}}T_6)_{SU(7)}$ . List of all vacuum expectation values (VEV) for this model is given in Tab. 1. Decomposition of SU(7)  $\underline{21}_F, \underline{7}_F^*, \underline{35}_F^*$  fermion and  $\underline{140}_S, \underline{28}_S$  scalar fields under SU(7) → SU(4)<sub>c</sub> × SU(2)<sub>L</sub> × U(1)<sub>R</sub> → SU(3)<sub>c</sub> × SU(2)<sub>L</sub> × U(1)<sub>Y</sub> breaking is given in Ref. [10].

3. *Neutrino Masses:* Neutrino masses are generated radiatively through the  $\mathbb{Z}_2$  odd sector, just like in Scotogenic model. Since our model has 3 neutral colorless fermions, there will be 2 neutral  $\mathbb{Z}_2$  odd fermions to mediate the radiative neutrino mass diagram. In order to get scotogenic scenario to work  $\nu_5$  and  $\nu_{10}$  VEV's from Tab. 1 need to be 0. The corresponding radiative neutrino mass diagrams are depicted in Fig. 1. Here  $N \sim (\mathbf{1}, \mathbf{1}, 0)_{SM}$  and  $A \sim (\mathbf{1}, \mathbf{2}, -\frac{1}{2})_{SM}$ .

4. *Unification:* Unification is achieved at  $M_{GUT} \sim O(10^{12-16})$  TeV scale with intermediate SU(4)<sub>c</sub> × SU(2)<sub>L</sub> × U(1)<sub>R</sub> Pati-Salam symmetry at  $\sim O(10^3)$  TeV). We used the following boundary conditions during gauge coupling unification:  $\alpha_s(m_Z) = 0.1182, \alpha_{em}(m_Z) = 1/127.916, \alpha_2(m_Z) = \frac{\sqrt{2}m_W^2 G_F}{\pi} = 0.03393$ . The intermediate Pati-Salam symmetry breaking scale is taken to be  $M_{PS} = 10^3$  TeV as in [8], and U(1) normalization given by  $n_Y = \sqrt{\frac{17}{3}}$  and  $n_R = \sqrt{5}$ . Then  $\alpha = \frac{g^2}{4\pi}$  at unification scale is  $\alpha_U(M_U) = 0.08577$  with  $M_U = 10^{12}$  GeV. This model, due to large amount of scalar fields,

#	Scale	Rep <sub>SU(7)</sub>	Rep <sub>PS</sub>	Rep <sub>SM</sub>
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)

 Table 1: List of vacuum expectation values for the  $SU(7)_{GUT}$  model.

 Figure 1: Scotogenic neutrino mass loop mediated by  $N \sim (\mathbf{1}, \mathbf{1}, 0)_{SM}$  (left),  $A^0 \in (\mathbf{1}, \mathbf{2}, -\frac{1}{2})_{SM}$  (center), and mixing of  $N \sim (\mathbf{1}, \mathbf{1}, 0)_{SM}$  and  $A^0 \in (\mathbf{1}, \mathbf{2}, -\frac{1}{2})_{SM}$  (right).

can easily predict the weak angle at  $m_Z$  scale to be given as  $\text{Sin}^2 \theta_W(m_Z) = \frac{3}{8}$ . When achieving gauge coupling unification we took only the relevant fields, fields from Ref. [8] and fields necessary for radiative neutrino mass generation, to be at the Pati-Salam scale or lighter with all other fields at the  $M_U$  GUT scale.

**5. Fermion Masses:** Fermion masses for our model are given as  $\begin{pmatrix} v_{10,11} & v_5 \\ v_{6,7} & v_{11,12} \end{pmatrix}_{M_{\pm 2}}, \begin{pmatrix} v_5 & 0 \\ v_{10} & v_5 \end{pmatrix}_{M_{\pm 2/3}}$ ,

$$\begin{pmatrix} v_{5,7} & v_8 & v_{12} & v_{13} \\ v_{10} & v_9 & v_7 & v_4 \\ v_{13} & v_{11} & v_8 & v_6 \\ v_4 & v_{5,6} & v_9 & v_{10,11} \end{pmatrix}_{M_{\pm}}, \begin{pmatrix} v_{5,7} & v_8 & v_9 & v_{11,12} \\ v_{10} & v_{13} & v_4 & v_{5,6,7} \\ v_9 & v_{11} & v_{5,6,7} & v_8 \\ v_4 & v_{5,6} & v_{10,12} & v_{13} \end{pmatrix}_{M_{\pm 1/3}}, \begin{pmatrix} 0 & v_5 & v_{10} \\ v_5 & v_1 & v_2 \\ v_{10} & v_2 & v_3 \end{pmatrix}_{M_{Q=0}}, \begin{pmatrix} 0 & v_5 \\ v_5 & v_{10,12} \end{pmatrix}_{M_{\pm 4/3}}.$$

$v_i$  entries in the mass matrices indicate to what VEV that entry is proportional to. Our model includes 4 Dirac  $Q = \pm 1$  leptons, 4 down-type quarks, 2 up-type quarks, 3 neutral fermions, 2 exotic Dirac  $Q = \pm 2$  leptons, 2 exotic up-type  $Q = \pm 4/3$  quarks. Exotic particles can be used to test this model. Focusing on neutral mass matrix we can see that for the scotogenic scenario we need  $v_5$  and  $v_{10}$  to be 0 which will split neutral fermion mass matrix in  $\mathbb{Z}_2$  even and odd parts. This requirement will also predict the up-type  $Q = \pm 2/3$  quark masses to be generated radiatively as well, due to quark-lepton unification symmetry. Another interesting thing to notice is that, because there are 3 neutral fermions predicted by the model we can naturally generate inverse see-saw, linear see-saw, double see-saw, *etc.* [9] in this model if we give up scotogenic scenario.

6. *Dark Matter*: Any of the  $\mathbb{Z}_2$  odd particles can be considered for light stable particle and be the dark matter candidate. A brief analysis of dark matter relic vs dark matter mass is given in Fig. 2. Scalar, pseudo-scalar, fermion dark matter candidates are possible in our model.

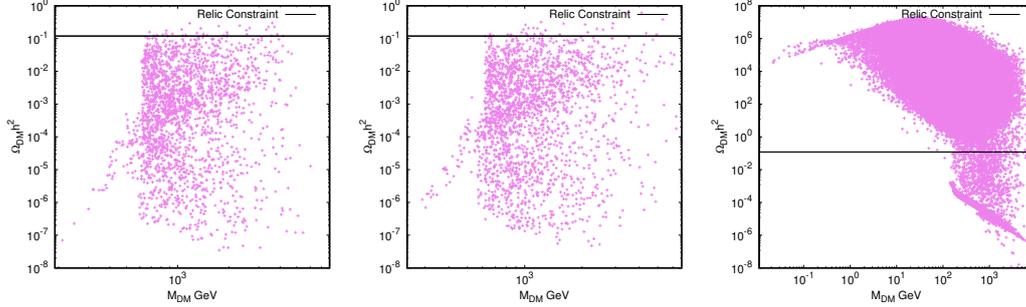


Figure 2: Dark matter relic density vs dark matter mass for real scalar DM (left), pseudo-real scalar DM (center), and fermionic DM (right).

7. *Conclusion*: In conclusion we have shown how Scotogenic model with residual  $\mathbb{Z}_2$  symmetry can be obtained from  $SU(7)$  GUT with low scale ( $O(\sim 10^3 \text{ TeV})$ ) quark-lepton unification through Pati-Salam symmetry. We have shown how neutrino masses are radiatively generated at one-loop, gauge couplings are unified at GUT scale  $O(10^{12-16} \text{ GeV})$  with correct weak angle prediction at electroweak scale. We have also shown how this model can naturally accommodate inverse seesaw, linear seesaw, double seesaw, *etc* scenarios. Brief discussion of dark matter candidates with analysis is included.

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