

$p \rightarrow ?$

# Exotic proton decays and the GUT Models

Oleg Popov

Korean Advanced Institute of Science and Technology  
Scuola Normale Superiore

*opopo001@ucr.edu*

Workshop on Particle Physics and Cosmology 2021  
2021.11.28

In collaboration with Lisa L. Everett  
arXiv:2108.09316, 2111.xxxx

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

Pros and Cons

# Overview

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

Pros and Cons

## 1 Introduction

## 2 Review

## 3 Model

- Content
- Anomalies
- Lagrangian
- Potential
- Currents
- Decomposition
- Masses

## 4 Unification

## 5 $p$ decay

- Scenarios
- Topologies
- Sample proton decay diagrams for  $SU(7)$  model

## 6 Discussion

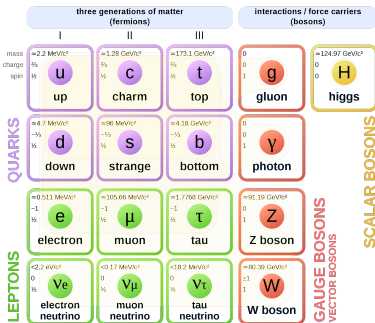
- Dark Matter Candidates
- Neutrino Sector and Variety of options
- Pros and Cons
- Future Prospects

## 7 Conclusion

# Standard Model

$p \rightarrow ?$

## Standard Model of Elementary Particles



Gauge symmetry group  $G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}^Y = \bar{u} Y_u Q H + \bar{Q} Y_d d H + \text{h.c.}$$

$$\langle h^0 \rangle = v \rightarrow m_f = Y_f v$$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

# Introduction/Motivation

$p \rightarrow ?$

## Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

## Unification

## $p$ decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

## Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

Pros and Cons

- Exotic proton decays
- Stability of proton
- Unification of gauge forces
- Accommodate dark matter
- Different options for neutrino mass sector

# $SU(5)$ and $SO(10)$ examples

p → ?

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

p decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

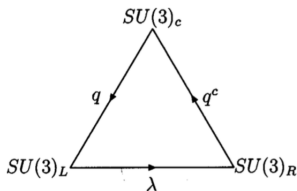
Pros and Cons

- $\bar{5}_F, 10_F + 5_S, 24_S$  in  $SU(5) \rightarrow \mathcal{G}_{SM}$  naturally predicts 2 body proton decay via  $(\mathbf{3}, 2, -\frac{5}{3})$  vector leptoquark. All decays in  $SU(5)$  case accidentally conserve  $B - L$  symmetry.
- 16 spinor representation of  $SO(10)$  with  $SO(10) \rightarrow SU(5) \times U(1)_{B-L}$ . Proton decays similar to  $SU(5)$  case.
- Trinification and quartification (partial unification) with extension to  $E_6$  and  $E_8$ , respectively. No gauge mediated proton decay

# $[SU(3)]^3$ trinification, $SU(3)_C \otimes SU(3)_L \otimes SU(3)_R$

$p \rightarrow ?$

$$q = \begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} \quad q^c = \begin{pmatrix} d^c & d^c & d^c \\ u^c & u^c & u^c \\ h^c & h^c & h^c \end{pmatrix} \quad \lambda = \begin{pmatrix} N & E^c & \nu \\ E & N^c & e \\ \nu^c & e^c & S \end{pmatrix}$$



Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

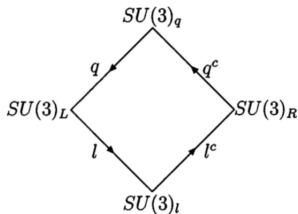
Pros and Cons

# $[SU(3)]^4$ quartification, $SU(3)_C \otimes SU(3)_L \otimes SU(3)_I \otimes SU(3)_R$

$p \rightarrow ?$

$$q = \begin{pmatrix} d & u & h \\ d & u & h \\ d & u & h \end{pmatrix} \quad q^c = \begin{pmatrix} d^c & d^c & d^c \\ u^c & u^c & u^c \\ h^c & h^c & h^c \end{pmatrix}$$

$$l = \begin{pmatrix} x_1 & x_2 & \nu \\ y_1 & y_2 & e \\ z_1 & z_2 & N \end{pmatrix} \quad l^c = \begin{pmatrix} x_1^c & y_1^c & z_1^c \\ x_2^c & y_2^c & z_2^c \\ \nu^c & e^c & N^c \end{pmatrix}$$



\*K. S. Babu, E. Ma, and S. Willenbrock, Phys. Rev. D69, 051301(R) (2004).

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

# Scotogenic model in $SU(6)$ GUT\*

$p \rightarrow ?$

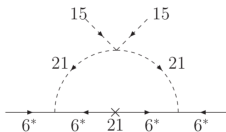
Simple case: Extend  $SU(5)$  to  $SU(6)$  to include BSM particles needed

$\underline{5}_F^* \times \underline{10}_F \times \underline{5}_S^*$ ,  $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$   $SU(5)$  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<sup>†</sup>

$p \rightarrow ?$

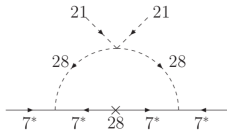
Less simple case: Extend  $SU(5)$  to  $SU(7)$  to include BSM particles needed

$\underline{5}_F^* \times \underline{10}_F \times \underline{5}_S^*$ ,  $\underline{10}_F \times \underline{10}_F \times \underline{5}_S$   $SU(5)$  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:  $\underline{7}_F^* \times \underline{7}_F^* \times \underline{28}_S$ ,  $\underline{21}_S^* \times \underline{21}_S^* \times \underline{28}_S \times \underline{28}_S$



<sup>†</sup>10.1088/1742-6596/539/1/012001

# Symmetry and Fields

p → ?

- $\bar{7}_F, 21_F, 3\bar{5}_F$
- $7_S, 48_S, 84_S, (210_S, 21_S)$
- 

$$\begin{aligned} SU(7) &\longrightarrow SU(3)_c \times SU(2)_L \times U(1)_{F,1} \times U(1)_{1'} \times U(1)_Y \\ &\langle 48_S \rangle \\ &\longrightarrow SU(3)_c \times SU(2)_L \times U(1)_{F,1} \times U(1)_Y \\ &\langle 7_{S,1'} \rangle \\ &\longrightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times \mathbb{Z}_n \\ &\langle 84_S \vee 210_S \rangle \\ &\longrightarrow SU(3)_c \times U(1)_{em} \times \mathbb{Z}_n \\ &\langle 7_{S,2} \rangle \end{aligned}$$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

p decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

Pros and Cons

# Anomalies

p → ?

Introduction

Review

Model

Content

**Anomalies**

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

p decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

Pros and Cons

- $-\frac{1}{2} (\bar{7}_F) + \frac{3}{2} (21_F) - 1 (3\bar{5}_F) = 0$
- After  $SU(7)$  breaking there are two SM-like sectors and two  $SM^*$ -like sectors, each of which is anomaly free under  $G_{SM}$

# $SU(7)$ Lagrangian

p → ?

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

p decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

Pros and Cons



$$-\mathcal{L}^{\text{Yuk}} = Y_d \bar{7}_F 21_F 7_S^\dagger + Y_u 21_F \bar{35}_F 7_S + Y_e \bar{35}_F \bar{35}_F 7_S^\dagger + \text{h.c.}$$



$$-\mathcal{L}_{21}^{\text{Yuk}} = Y_{21} \bar{7}_F \bar{7}_F 21_S + \text{h.c.}$$

# SU(7) Potential

p → ?

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

p decay

Scenarios

Topologies

Sample proton decay diagrams for SU(7) model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons



$$V_{\text{main}} = \left(7_5^\dagger 7_5\right) + \left(7_5^\dagger 7_5\right)^2 + \text{Tr} [48_5 48_5] + \text{Tr} [48_5 48_5 48_5] + \left(\text{Tr} [48_5 48_5]\right)^2 \\ + \text{Tr} [48_5 48_5 48_5 48_5] + 7_5^\dagger 48_5 7_5 + 7_5^\dagger 7_5 \text{Tr} [48_5 48_5] + 7_5^\dagger 48_5 48_5 7_5$$



$$V_{84} = \left(84_5^\dagger 84_5\right) + \left(84_5^\dagger 84_5\right)^2 + \left(7_5^\dagger 7_5\right) \left(84_5^\dagger 84_5\right) + \left(84_5^\dagger 7_5 7_5 7_5 + \text{h.c.}\right)$$



$$V_{210} = \left(210_5^\dagger 210_5\right) + \left(210_5^\dagger 210_5\right)^2 + \left(7_5^\dagger 7_5\right) \left(210_5^\dagger 210_5\right)$$



$$V_{21} = 21_5^\dagger 21_5 + \left(21_5^\dagger 21_5\right)^2 + 7_5^\dagger 7_5 21_5^\dagger 21_5 + 7_5^\dagger 21_5 21_5^\dagger 7_5 + \left(7_5 21_5^\dagger 7_5 + 21_5 21_5^\dagger 7_5 \epsilon + \text{h.c.}\right)$$



$$V_{\text{rest}} = V_{\times \text{trivial}} + \left(210_5^\dagger 84_5 7_5 + \text{h.c.}\right)$$

# Vacuum expectation values

p → ?

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

p decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

- $\langle 48_S \rangle \sim \text{Diag} [v_C, v_C, v_C, v_1, v_1', v_2, v_2]$
- $\langle 7_S \rangle \sim (0, 0, 0, 0, v_1', 0, v_2)$
- $\langle 84_{S,111'} \rangle \sim v_{84}$  (2 body)
- $\langle 210_{S,1111} \rangle \sim v_{210}$  (3 body)

# Currents

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

**Currents**

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

$$\begin{pmatrix} T_{SU3}^1 \\ T_{SU3}^2 \\ Q_{F=A} \\ Q_B \\ Y \\ T_3^{SU2} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2\sqrt{\frac{5}{3}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 2\sqrt{21} & 0 & 0 \\ 0 & 0 & 0 & 0 & -\sqrt{\frac{5}{3}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{3}{\sqrt{10}} & -\frac{1}{5\sqrt{6}} & -\frac{7}{30} & -\frac{\sqrt{7}}{6} \\ 0 & 0 & 0 & \sqrt{\frac{14}{15}} & -\frac{\sqrt{7}}{6} & -\frac{1}{6} \\ 0 & 0 & \frac{1}{\sqrt{10}} & \frac{\sqrt{3}}{5} & \frac{7}{10} & \frac{\sqrt{7}}{2} \\ 0 & 0 & 0 & 0 & -\frac{\sqrt{5}}{2} & \frac{\sqrt{7}}{2} \end{pmatrix} \begin{pmatrix} T_{SU7}^1 \\ T_{SU7}^2 \\ T_{SU7}^3 \\ T_{SU7}^4 \\ T_{SU7}^5 \\ T_{SU7}^6 \end{pmatrix}$$

# SU(7) Decomposition

p → ?

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

p decay

Scenarios

Topologies

Sample proton decay diagrams for SU(7) model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

## Fermions

SU(7)	SU(3) <sub>C</sub> × SU(2) <sub>L</sub> × U(1) <sub>A</sub> × U(1) <sub>B</sub> × U(1) <sub>C</sub> content
<b>7</b>	$\{ \bar{\mathbf{3}} \otimes \mathbf{1} \otimes -\frac{1}{3} \otimes -1 \otimes \frac{1}{3}, \mathbf{1} \otimes \mathbf{1} \otimes \frac{5}{3} \otimes -1 \otimes 0, \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes 6 \otimes 0, \mathbf{1} \otimes \mathbf{2} \otimes -\frac{1}{3} \otimes -1 \otimes -\frac{1}{2} \}$
<b>21</b>	$\{ \bar{\mathbf{3}} \otimes \mathbf{1} \otimes \frac{2}{3} \otimes 2 \otimes -\frac{2}{3}, \mathbf{3} \otimes \mathbf{1} \otimes -\frac{4}{3} \otimes 2 \otimes -\frac{1}{3}, \mathbf{3} \otimes \mathbf{1} \otimes \frac{1}{3} \otimes -5 \otimes -\frac{1}{3}, \mathbf{3} \otimes \mathbf{2} \otimes \frac{2}{3} \otimes 2 \otimes \frac{1}{6}, \mathbf{1} \otimes \mathbf{1} \otimes -\frac{5}{3} \otimes -5 \otimes 0, \mathbf{1} \otimes \mathbf{2} \otimes -\frac{4}{3} \otimes 2 \otimes \frac{1}{2}, \mathbf{1} \otimes \mathbf{2} \otimes \frac{1}{3} \otimes -5 \otimes \frac{1}{2}, \mathbf{1} \otimes \mathbf{1} \otimes \frac{2}{3} \otimes 2 \otimes 1 \}$
<b>35</b>	$\{ \mathbf{1} \otimes \mathbf{1} \otimes -1 \otimes -3 \otimes 1, \mathbf{3} \otimes \mathbf{1} \otimes 1 \otimes -3 \otimes \frac{2}{3}, \mathbf{3} \otimes \mathbf{1} \otimes -\frac{2}{3} \otimes 4 \otimes \frac{2}{3}, \mathbf{3} \otimes \mathbf{2} \otimes -1 \otimes -3 \otimes \frac{1}{6}, \bar{\mathbf{3}} \otimes \mathbf{1} \otimes \frac{4}{3} \otimes 4 \otimes \frac{1}{3}, \bar{\mathbf{3}} \otimes \mathbf{2} \otimes 1 \otimes -3 \otimes -\frac{1}{6}, \bar{\mathbf{3}} \otimes \mathbf{2} \otimes -\frac{2}{3} \otimes 4 \otimes -\frac{1}{6}, \bar{\mathbf{3}} \otimes \mathbf{1} \otimes -1 \otimes -3 \otimes -\frac{2}{3}, \mathbf{1} \otimes \mathbf{2} \otimes \frac{4}{3} \otimes 4 \otimes -\frac{1}{2}, \mathbf{1} \otimes \mathbf{1} \otimes 1 \otimes -3 \otimes -1, \mathbf{1} \otimes \mathbf{1} \otimes -\frac{2}{3} \otimes 4 \otimes -1 \}$

## Scalars

SU(7)	SU(3) <sub>C</sub> × SU(2) <sub>L</sub> × U(1) <sub>A</sub> × U(1) <sub>B</sub> × U(1) <sub>C</sub> content
<b>7</b>	$\{ \mathbf{3} \otimes \mathbf{1} \otimes \frac{1}{3} \otimes 1 \otimes -\frac{1}{3}, \mathbf{1} \otimes \mathbf{1} \otimes -\frac{5}{3} \otimes 1 \otimes 0, \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes -6 \otimes 0, \mathbf{1} \otimes \mathbf{2} \otimes \frac{1}{3} \otimes 1 \otimes \frac{1}{2} \}$
<b>48</b>	$\{ \mathbf{3} \otimes \mathbf{2} \otimes 0 \otimes 0 \otimes -\frac{5}{6}, \mathbf{3} \otimes \mathbf{1} \otimes \frac{1}{3} \otimes 7 \otimes -\frac{1}{3}, \mathbf{3} \otimes \mathbf{1} \otimes 2 \otimes 0 \otimes -\frac{1}{3}, \mathbf{8} \otimes \mathbf{1} \otimes 0 \otimes 0 \otimes 0, \mathbf{1} \otimes \mathbf{3} \otimes 0 \otimes 0 \otimes 0, \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes 0 \otimes 0, \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes 0 \otimes 0, \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes 0 \otimes 0, \mathbf{1} \otimes \mathbf{2} \otimes -2 \otimes 0 \otimes -\frac{1}{2}, \mathbf{1} \otimes \mathbf{1} \otimes -\frac{5}{3} \otimes 7 \otimes 0, \mathbf{1} \otimes \mathbf{2} \otimes -\frac{1}{3} \otimes -7 \otimes -\frac{1}{2}, \mathbf{1} \otimes \mathbf{2} \otimes \frac{1}{3} \otimes 7 \otimes \frac{1}{2}, \mathbf{1} \otimes \mathbf{1} \otimes \frac{5}{3} \otimes -7 \otimes 0, \mathbf{1} \otimes \mathbf{2} \otimes 2 \otimes 0 \otimes \frac{1}{2}, \bar{\mathbf{3}} \otimes \mathbf{1} \otimes -2 \otimes 0 \otimes \frac{1}{3}, \bar{\mathbf{3}} \otimes \mathbf{1} \otimes -\frac{1}{3} \otimes -7 \otimes \frac{1}{3}, \bar{\mathbf{3}} \otimes \mathbf{2} \otimes 0 \otimes 0 \otimes \frac{5}{6} \}$
<b>84</b>	$\{ \mathbf{10} \otimes \mathbf{1} \otimes 1 \otimes 3 \otimes -1, \bar{\mathbf{6}} \otimes \mathbf{1} \otimes -1 \otimes 3 \otimes -\frac{2}{3}, \bar{\mathbf{6}} \otimes \mathbf{1} \otimes \frac{2}{3} \otimes -4 \otimes -\frac{2}{3}, \bar{\mathbf{6}} \otimes \mathbf{2} \otimes 1 \otimes 3 \otimes -\frac{1}{6}, \mathbf{3} \otimes \mathbf{1} \otimes -3 \otimes 3 \otimes -\frac{1}{3}, \mathbf{3} \otimes \mathbf{1} \otimes -\frac{4}{3} \otimes -4 \otimes -\frac{1}{3}, \mathbf{3} \otimes \mathbf{2} \otimes -1 \otimes 3 \otimes \frac{1}{6}, \mathbf{3} \otimes \mathbf{1} \otimes \frac{1}{3} \otimes -11 \otimes -\frac{1}{3}, \mathbf{3} \otimes \mathbf{2} \otimes \frac{2}{3} \otimes -4 \otimes \frac{1}{6}, \mathbf{3} \otimes \mathbf{3} \otimes 1 \otimes 3 \otimes \frac{2}{3}, \mathbf{1} \otimes \mathbf{1} \otimes -5 \otimes 3 \otimes 0, \mathbf{1} \otimes \mathbf{1} \otimes -\frac{10}{3} \otimes -4 \otimes 0, \mathbf{1} \otimes \mathbf{2} \otimes -3 \otimes 3 \otimes \frac{1}{2}, \mathbf{1} \otimes \mathbf{1} \otimes -\frac{5}{3} \otimes -11 \otimes 0, \mathbf{1} \otimes \mathbf{2} \otimes -\frac{4}{3} \otimes -4 \otimes \frac{1}{2}, \mathbf{1} \otimes \mathbf{3} \otimes -1 \otimes 3 \otimes 1, \mathbf{1} \otimes \mathbf{1} \otimes 0 \otimes -18 \otimes 0, \mathbf{1} \otimes \mathbf{2} \otimes \frac{1}{3} \otimes -11 \otimes \frac{1}{2}, \mathbf{1} \otimes \mathbf{3} \otimes \frac{2}{3} \otimes -4 \otimes 1, \mathbf{1} \otimes \mathbf{4} \otimes 1 \otimes 3 \otimes \frac{3}{2} \}$



# SU(7) Decomposition

p → ?

SU(7)	SU(3) <sub>C</sub> × SU(2) <sub>L</sub> × U(1) <sub>A</sub> × U(1) <sub>B</sub> × U(1) <sub>C</sub> content
<b>196</b>	$\{ 6 \otimes 1 \otimes \frac{4}{3} 4 \otimes -\frac{4}{3}, 8 \otimes 1 \otimes -\frac{2}{3} 4 \otimes -1, 8 \otimes 1 \otimes 1 \otimes -3 \otimes -1, \\ 8 \otimes 2 \otimes \frac{4}{3} 4 \otimes -\frac{1}{2}, \bar{6} \otimes 1 \otimes -\frac{8}{3} 4 \otimes -\frac{2}{3}, \bar{6} \otimes 1 \otimes -1 \otimes -3 \otimes -\frac{2}{3}, \bar{3} \otimes 1 \otimes -1 \otimes -3 \otimes -\frac{2}{3}, \\ \bar{6} \otimes 2 \otimes -\frac{2}{3} 4 \otimes \frac{1}{6}, \bar{3} \otimes 2 \otimes -\frac{2}{3} 4 \otimes -\frac{1}{6}, \bar{6} \otimes 1 \otimes \frac{2}{3} 3 \otimes -10 \otimes -\frac{2}{3}, \bar{6} \otimes 2 \otimes 1 \otimes -3 \otimes -\frac{1}{6}, \\ \bar{3} \otimes 2 \otimes 1 \otimes -3 \otimes -\frac{1}{6}, \bar{6} \otimes 3 \otimes \frac{4}{3} 4 \otimes \frac{1}{3}, \bar{3} \otimes 1 \otimes \frac{4}{3} 4 \otimes \frac{1}{3}, 3 \otimes 1 \otimes -3 \otimes -3 \otimes -\frac{1}{3}, \\ 3 \otimes 2 \otimes -\frac{8}{3} 4 \otimes \frac{1}{6}, 3 \otimes 1 \otimes -\frac{4}{3} 3 \otimes -10 \otimes -\frac{1}{3}, 3 \otimes 2 \otimes -1 \otimes -3 \otimes \frac{1}{6}, 3 \otimes 2 \otimes -1 \otimes -3 \otimes \frac{1}{6}, \\ 3 \otimes 3 \otimes -\frac{2}{3} 4 \otimes \frac{2}{3}, 3 \otimes 1 \otimes -\frac{2}{3} 4 \otimes \frac{2}{3}, 3 \otimes 2 \otimes \frac{2}{3} 3 \otimes -10 \otimes \frac{1}{6}, 3 \otimes 3 \otimes 1 \otimes -3 \otimes \frac{2}{3}, \\ 3 \otimes 1 \otimes 1 \otimes -3 \otimes \frac{2}{3}, 3 \otimes 2 \otimes \frac{4}{3} 4 \otimes \frac{7}{6}, 1 \otimes 1 \otimes -\frac{10}{3} 3 \otimes -10 \otimes 0, 1 \otimes 2 \otimes -3 \otimes -3 \otimes \frac{1}{2}, \\ 1 \otimes 3 \otimes -\frac{8}{3} 4 \otimes 1, 1 \otimes 2 \otimes -\frac{4}{3} 3 \otimes -10 \otimes \frac{1}{2}, 1 \otimes 3 \otimes -1 \otimes -3 \otimes 1, 1 \otimes 1 \otimes -1 \otimes -3 \otimes 1, \\ 1 \otimes 2 \otimes -\frac{2}{3} 4 \otimes \frac{3}{2}, 1 \otimes 3 \otimes \frac{2}{3} 3 \otimes -10 \otimes 1, 1 \otimes 2 \otimes 1 \otimes -3 \otimes \frac{3}{2}, 1 \otimes 1 \otimes \frac{4}{3} 4 \otimes 2 \}$
<b>210'</b>	$\{ 15' \otimes 1 \otimes \frac{4}{3} 4 \otimes -\frac{4}{3}, 10 \otimes 1 \otimes -\frac{2}{3} 4 \otimes -1, 10 \otimes 1 \otimes 1 \otimes -3 \otimes -1, \\ 10 \otimes 2 \otimes \frac{4}{3} 4 \otimes -\frac{1}{2}, \bar{6} \otimes 1 \otimes -\frac{8}{3} 4 \otimes -\frac{2}{3}, \bar{6} \otimes 1 \otimes -1 \otimes -3 \otimes -\frac{2}{3}, \bar{6} \otimes 2 \otimes -\frac{2}{3} 4 \otimes -\frac{1}{6}, \\ \bar{6} \otimes 1 \otimes \frac{2}{3} 3 \otimes -10 \otimes -\frac{2}{3}, \bar{6} \otimes 2 \otimes 1 \otimes -3 \otimes -\frac{1}{6}, \bar{6} \otimes 3 \otimes \frac{4}{3} 4 \otimes \frac{1}{3}, 3 \otimes 1 \otimes -\frac{14}{3} 4 \otimes -\frac{1}{3}, \\ 3 \otimes 1 \otimes -3 \otimes -3 \otimes -\frac{1}{3}, 3 \otimes 2 \otimes -\frac{8}{3} 4 \otimes \frac{1}{6}, 3 \otimes 1 \otimes -\frac{4}{3} 3 \otimes -10 \otimes -\frac{1}{3}, 3 \otimes 2 \otimes -1 \otimes -3 \otimes \frac{1}{6}, \\ 3 \otimes 3 \otimes -\frac{2}{3} 4 \otimes \frac{2}{3}, 3 \otimes 1 \otimes \frac{1}{3} 3 \otimes -17 \otimes -\frac{1}{3}, 3 \otimes 2 \otimes \frac{2}{3} 3 \otimes -10 \otimes \frac{1}{6}, 3 \otimes 3 \otimes 1 \otimes -3 \otimes \frac{2}{3}, \\ 3 \otimes 4 \otimes \frac{4}{3} 4 \otimes \frac{7}{6}, 1 \otimes 1 \otimes -\frac{20}{3} 4 \otimes 0, 1 \otimes 1 \otimes -5 \otimes -3 \otimes 0, 1 \otimes 2 \otimes -\frac{14}{3} 4 \otimes \frac{1}{2}, \\ 1 \otimes 1 \otimes -\frac{10}{3} 3 \otimes -10 \otimes 0, 1 \otimes 2 \otimes -3 \otimes -3 \otimes \frac{1}{2}, 1 \otimes 3 \otimes -\frac{8}{3} 4 \otimes 1, 1 \otimes 1 \otimes -\frac{5}{3} 3 \otimes -17 \otimes 0, \\ 1 \otimes 2 \otimes -\frac{4}{3} 3 \otimes -10 \otimes \frac{1}{2}, 1 \otimes 3 \otimes -1 \otimes -3 \otimes 1, 1 \otimes 4 \otimes -\frac{2}{3} 4 \otimes \frac{3}{2}, 1 \otimes 1 \otimes 0 \otimes -24 \otimes 0, \\ 1 \otimes 2 \otimes \frac{1}{3} 3 \otimes -17 \otimes \frac{1}{2}, 1 \otimes 3 \otimes \frac{2}{3} 3 \otimes -10 \otimes 1, 1 \otimes 4 \otimes 1 \otimes -3 \otimes \frac{3}{2}, 1 \otimes 5 \otimes \frac{4}{3} 4 \otimes 2 \}$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

p decay

Scenarios

Topologies

Sample proton decay diagrams for SU(7) model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

# Gauge Bosons' Masses

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

**Masses**

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

- $m^2 (\mathbf{3}, \mathbf{1}, \frac{1}{3}, 7, -\frac{1}{3}) \propto g_u^2 (v_c - v_1)^2$
- $m^2 (\mathbf{3}, \mathbf{1}, 2, 0, -\frac{1}{3}) \propto g_u^2 (v_c - v_{1'})^2$
- $m^2 (\mathbf{3}, \mathbf{2}, 0, 0, -\frac{5}{6}) \propto g_u^2 (v_c - v_l)^2$
- $m^2 (\mathbf{1}, \mathbf{2}, -2, 0, -\frac{1}{2}) \propto g_u^2 (v_l - v_1)^2$
- $m^2 (\mathbf{1}, \mathbf{2}, -\frac{1}{3}, -7, -\frac{1}{2}) \propto g_u^2 (v_l - v_{1'})^2$
- $m^2 (\mathbf{1}, \mathbf{1}, -\frac{5}{3}, 7, 0) \propto g_u^2 (v_1 - v_{1'})^2$
- $m_{U(1)_{1'}}^2 \propto g_{1'}^2 \langle 7_{S,1'} \rangle^2 + g_1^2 \langle 210_{11111} \rangle^2$
- $m_{F,1}^2 \propto g_{F,1}^2 \langle 210_{11111} \rangle^2$
- $m_{11'}^2 \propto g_1 g_{1'} \langle 210_{11111} \rangle^2$
- $m_{SM}^2 \propto g_2^2 \langle 7_{S,2} \rangle^2$

# Fermion (Quark) Masses

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

**Masses**

Unification

$p$  decay

Scenarios

Topologies

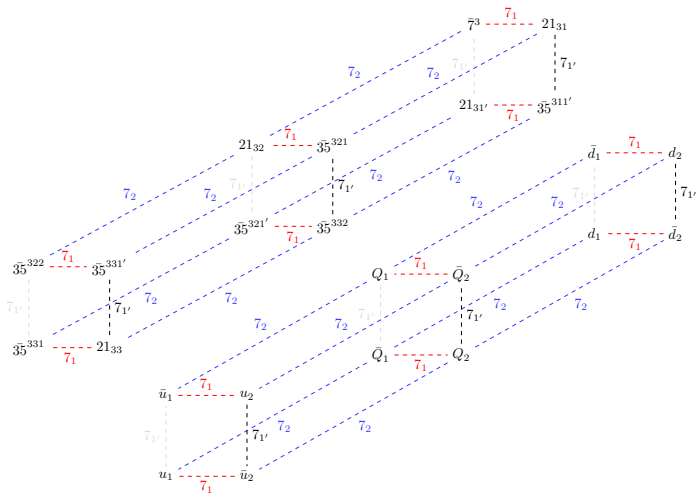
Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

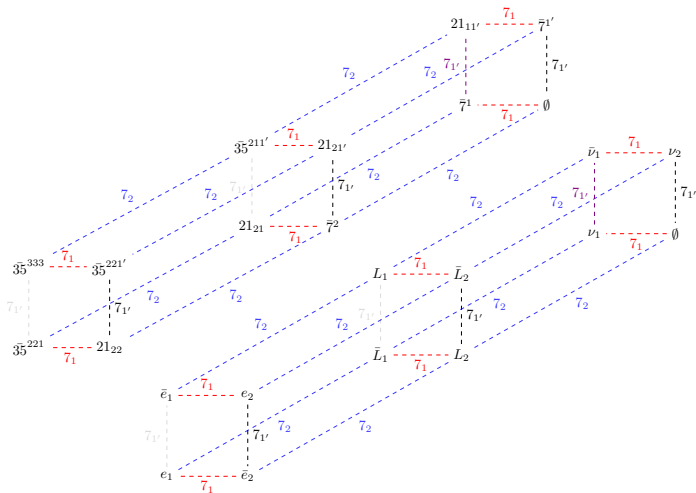
Neutrino Sector and Variety of options

Pros and Cons



# Fermion (Lepton) Masses

$p \rightarrow ?$



Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

**Masses**

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

# Unification of gauge couplings

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

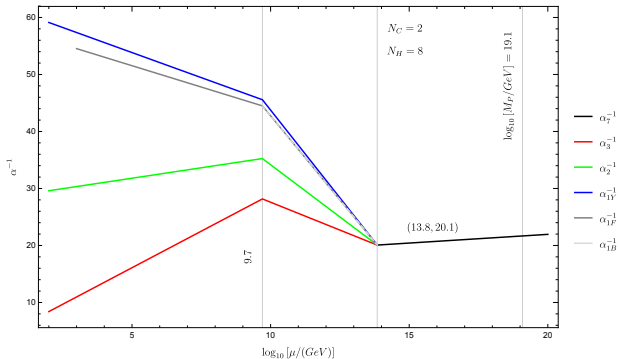
Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

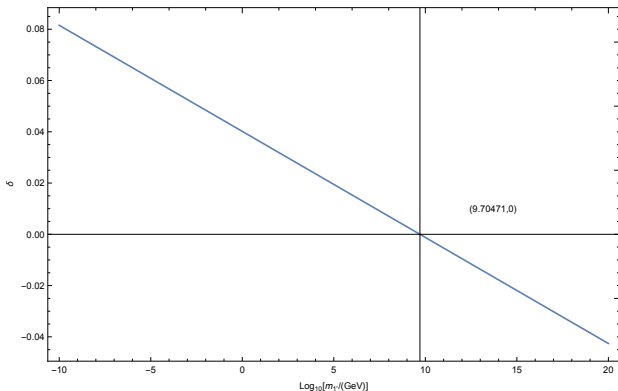


$$\alpha_i^{-1}(m_2) = \alpha_i^{-1}(m_1) + \frac{-b_i}{2\pi} \ln \left( \frac{m_2}{m_1} \right)$$

$$\beta_i(g_i) = \frac{-g_i^3}{(4\pi)^2} \left[ \frac{11}{3} C_2(G) - \frac{4}{3} \kappa_f S_2(R_F) - \frac{1}{3} \kappa_s S_2(R_S) + \frac{2\kappa_f}{(4\pi)^2} Y_4(R_F) \right]$$

# Unification of gauge couplings

$p \rightarrow ?$



$$\delta = \frac{\alpha_3^{-1}(m_Z) - \alpha_2^{-1}(m_Z) - (b_{3d} - b_{3u} - b_{2d} + b_{2u}) \ln\left(\frac{m_t}{m_Z}\right) / 2\pi}{\alpha_2^{-1}(m_Z) - \alpha_1^{-1}(m_Z) - (b_{2d} - b_{2u} - b_{1d} + b_{1u}) \ln\left(\frac{m_t}{m_Z}\right) / 2\pi} - \frac{b_{3u} - b_{2u}}{b_{2u} - b_{1u}}$$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

# Unification of gauge couplings

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

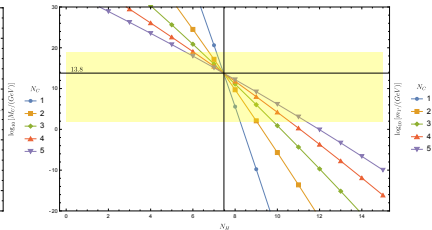
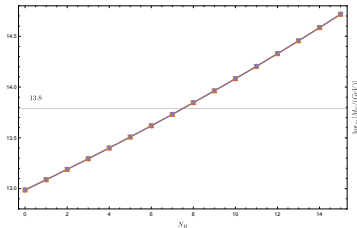
Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons



$$\begin{aligned}
 b_7 &= -\frac{5}{6} & b_{3u} &= 5 + \frac{N_C}{6} & b_{2u} &= \frac{26}{3} + \frac{N_H}{6} & b_{1yu} &= 16 + \frac{N_H}{10} & b_{1Fu} &= 16 + \frac{N_H}{90} \\
 b_{1(1')} &= 16 + \frac{N_H}{126} & b_{3d} &= -7 & b_{2d} &= -\frac{10}{3} + \frac{N_H}{6} & b_{1yd} &= 4 + \frac{N_H}{10} & b_{1Fd} &= 4 + \frac{N_H}{90}
 \end{aligned}$$

# Possible proton decay scenarios for $SU(7)$ model

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

- Set 1 :  $Q = 21_{32}, \bar{u} = \bar{35}^{322}, \bar{d} = \bar{7}^3, L = \bar{35}^{211'}, \bar{e} = \bar{35}^{333}, \nu = 21_{11}'$
- Set 2 :  $Q = \bar{35}^{332}, \bar{u} = 21_{33}, \bar{d} = \bar{35}^{311'}, L = \bar{35}^{211'}, \bar{e} = \bar{35}^{333}, \nu = 21_{11}'$
- If set 1 is chosen and  $\langle 7_1 \rangle = 0 \wedge \langle 84_{111}' \rangle \neq 0$  then proton decays can be categorized into two groups:  $B + L$  conserving decays require the presence of  $28_5$  in the model due to presence of accidental global symmetry in the yukawa sector. Therefore all such decays are proportional to the amount of violation of this symmetry, e.g.  $p \rightarrow \nu \pi^+$ . The other category is  $B - L$  conserving decays which are proportional to  $\langle 84_{111}' \rangle$ , e.g.  $p \rightarrow e^+ \pi^0$ .



# Possible proton decay scenarios for $SU(7)$ model

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

- If set 1 is chosen and  $\langle 7_1 \rangle = 0 \wedge \langle 84_{111'} \rangle = 0 \wedge \langle 210_{1111} \rangle \neq 0$  then proton decays proceed via three body decays with  $(B - L) = -4$ , e.g.  $p \rightarrow e^+ \bar{\nu} \bar{\nu}$ .
- If set 2 is chosen and  $\langle 7_1 \rangle = 0 \wedge \langle 84_{111'} \rangle \neq 0$  then proton decays are forbidden due to the combination of the residual symmetry  $U(1)_F \rightarrow \mathbb{Z}_n$  and Lorentz symmetry.
- Due to  $\langle 7_1 \rangle = 0$  fermion sector is split into even (SM) and odd (BSM) under  $\mathbb{Z}_2$  residual symmetry. This makes all B violating processes to proceed at loop level with odd fields inside the loop, similar to the scotogenic models.

# Possible topologies of diagrams for proton decay

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

**Topologies**

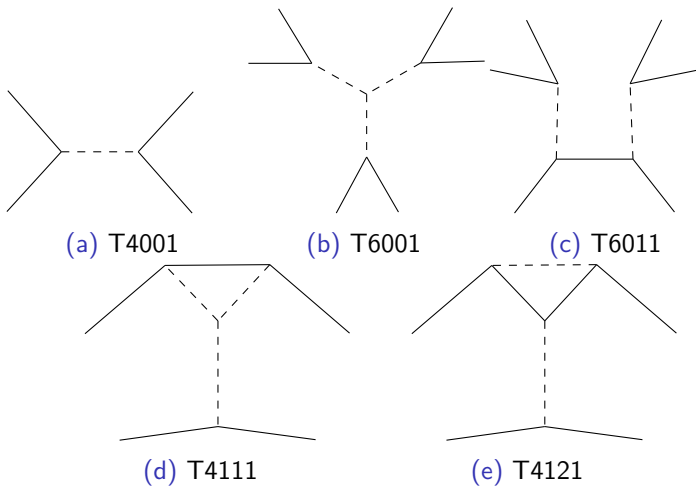
Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons



# Possible topologies of diagrams for proton decay

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

**Topologies**

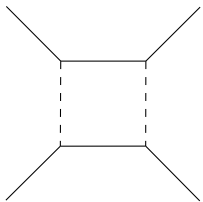
Sample proton decay diagrams for  $SU(7)$  model

Discussion

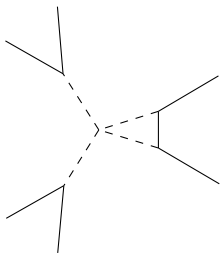
Dark Matter Candidates

Neutrino Sector and Variety of options

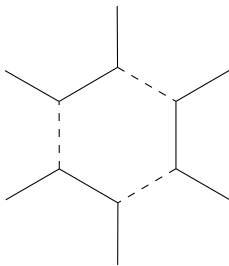
Pros and Cons



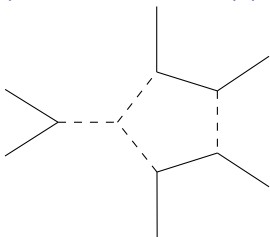
(f) T4122



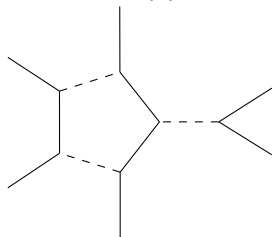
(g) T6111



(h) T6131



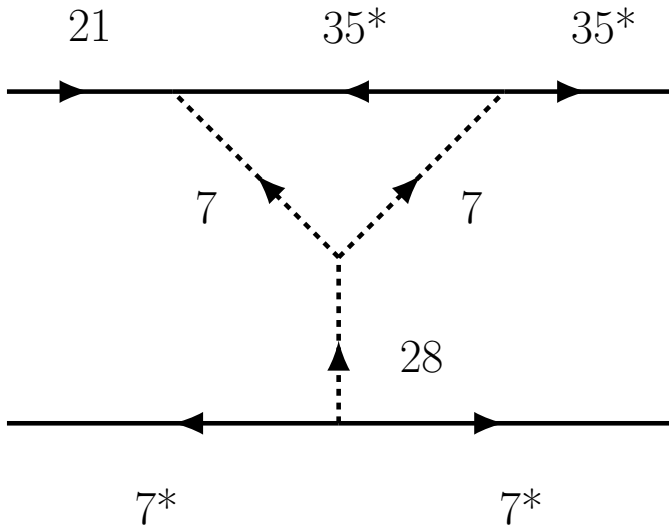
(i) T6121



(j) T6132

# Triangular loop diagram example (Penguin)

$p \rightarrow ?$



Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

# Triangular loop diagram example (Penguin)

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

$$O(p \rightarrow \nu \pi^+) \sim C_\mu \left( \bar{3}5_{211}'^\dagger \bar{\sigma}^\mu 21_{32} \right) \left( \bar{7}_3^\dagger \bar{7}_3^\dagger \right) \Lambda^{-3}$$

$$\Gamma = \frac{m_p}{32\pi} \left( 1 - \frac{m_{\pi^+}^2}{m_p^2} \right)^2 \frac{W_0^2}{m_s^4} \frac{|Y_e Y_u Y_{21}|^2}{(16\pi^2)^2} \frac{\mu_{21}^2}{m_s^2} x \left[ F_0(x) + F_1(x) \frac{q^2}{m_s^2} \right]^2$$

$$F_0(x) = \frac{1}{x-1} \left( 1 - \frac{x \ln x}{x-1} \right) \quad x = \frac{m_F^2}{m_s^2}$$

$$F_1(x) = -\frac{2x^2 + 5x - 1}{12(x-1)^3} + \frac{x^2 \ln x}{2(x-1)^4}$$

# Triangular loop diagram

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

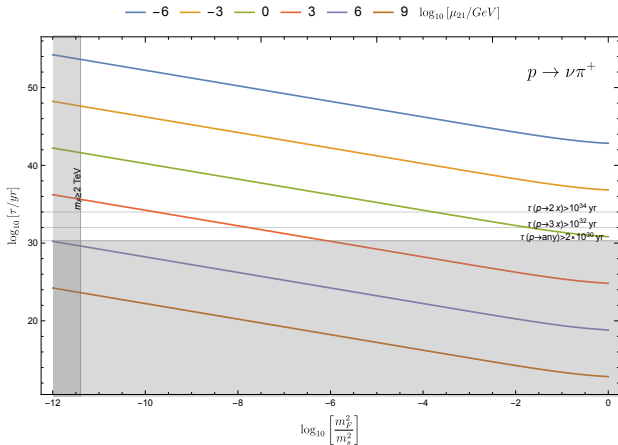
Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons



# Triangular loop function

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

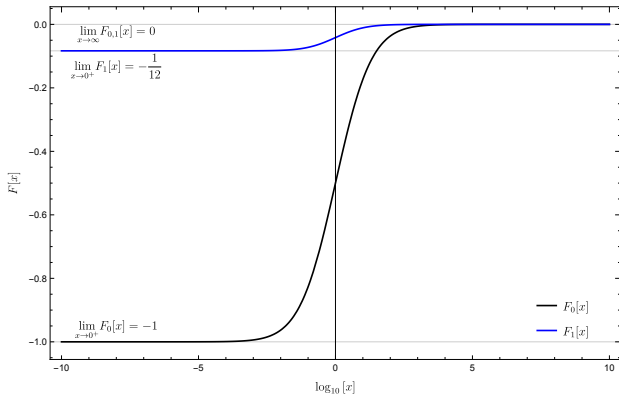
Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

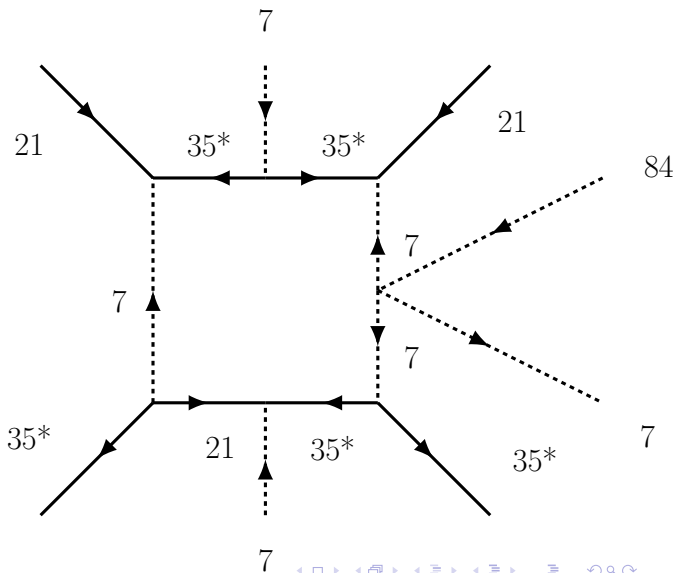
Neutrino Sector and Variety of options

Pros and Cons



# Box diagram example

$p \rightarrow ?$



Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons



# Box diagram example

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

$$O \sim (21_{32} 21_{32}) \left( \bar{35}_{322}^\dagger \bar{35}_{333}^\dagger \right) 7_1, 7_1, 7_1^{1'} 84_{1111'} \Lambda^{-6}$$

$$\Gamma(p \rightarrow e^+ \pi^0) = \frac{m_p}{32\pi} \left( 1 - \frac{m_{\pi^0}^2}{m_p^2} \right)^2 \frac{|Y_u^3 Y_e|^2}{(16\pi^2)^2}$$

$$\frac{\lambda^2 \langle 7_1 \rangle^2 \langle 84_{1111'} \rangle^2}{m_s^4} x^2 \left[ \frac{W_0}{m_s^2} F_0(x, y) + \frac{W_1}{m_s^2} F_1(x, y) \frac{q^2}{m_s^2} \right]^2$$

$$x = \frac{m_F^2}{m_S^2} \quad y = \frac{m_p^2}{m_S^2}$$

# Box diagram example

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

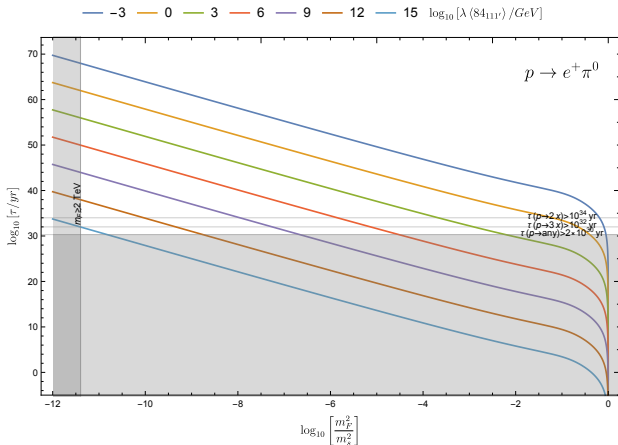
Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons



# Box loop function

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

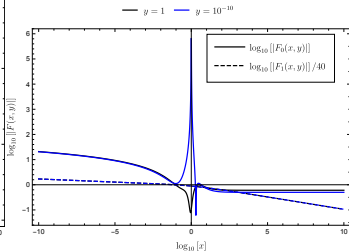
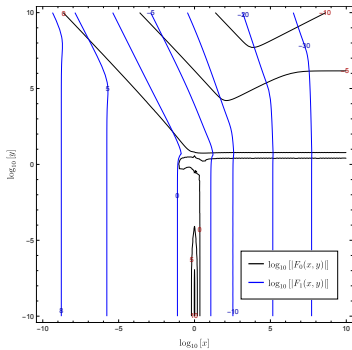
Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

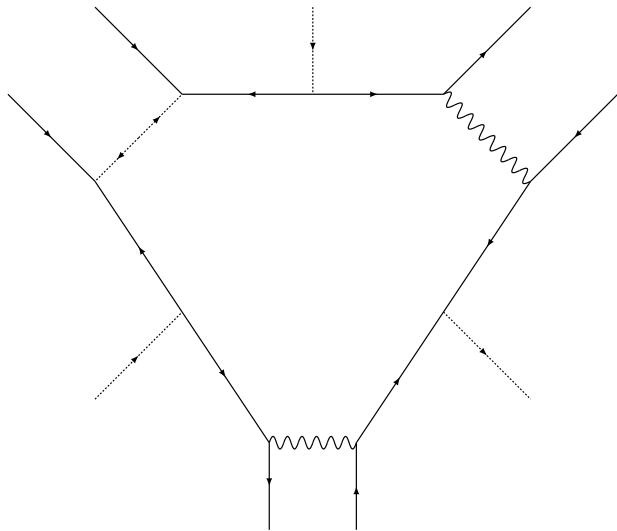
Neutrino Sector and Variety of options

Pros and Cons



# Hexagonal loop diagram

$p \rightarrow ?$



Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

Pros and Cons

# Hexagonal loop function

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

$$p \rightarrow e^+ e^+ e^-$$

$$O \sim \left( \bar{35}_{322}^\dagger \bar{\sigma}^\mu 21_{32} \right) \left( \bar{7}_3^\dagger \bar{\sigma}_\mu 35^{211'} \right) \left( \bar{35}^{211'} 35^{333} \right) 7_1, 7_1', 7^{\dagger 2} 7^{\dagger 1'} 84_{111'}, \Lambda^{-10}$$

$$\Gamma = \frac{m_p}{(8\pi)^3} \frac{1}{(16\pi^2)^2} (g_u^4 Y_u^2)^2 \left( \frac{\lambda \langle 84_{111'} \rangle}{m_S} \right)^2 \frac{v_2^2}{m_S^2} \frac{\alpha^2}{m_S^6} \frac{f(s, t, u, m_p, m_e)}{m_S^4} x^3 R(x, y, z)$$

$$x = \frac{m_F^2}{m_S^2} \quad y = \frac{m_S^2}{m_G^2} \sim 1 \quad z = \frac{m_p^2}{m_S^2} \ll 1$$

$R(x, y, z)$  is a two loop  $2 \times 7$  propagator loop function and calculated using *pySecDec*.

# Hexagonal loop diagram

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

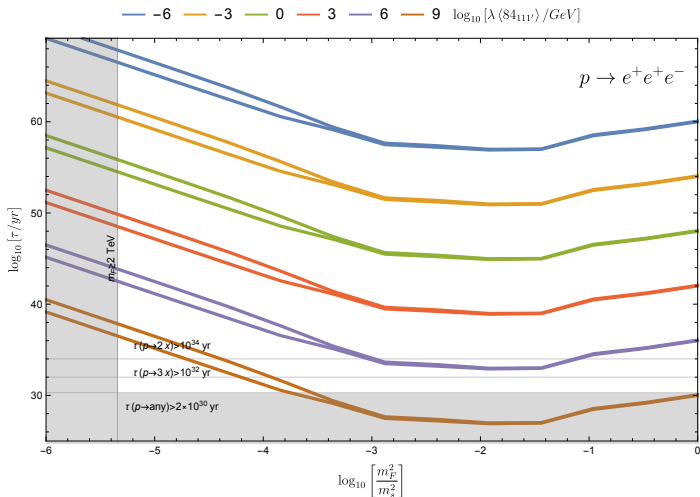
Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons



# Dark Matter Candidates

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

Pros and Cons

- BSM fermions are naturally lighter than BSM gauge and scalar bosons in the context of the model.
- There are total of 7 colorless and neutral fermions in the model. They are divided into two sectors by  $Z_2$  residual symmetry.
- Neutral sector containing Dirac neutrino pair contains 4 fermions. The other sector consisting of the 3 neutral fermions, one of which is a Majorana fermion will contain a natural dark matter candidate.
- Annihilation cross-section can be obtained via 2-to-2 t-channel with SM fermions (neutrinos) with  $Z_2$  odd scalar or vector boson propagator.

# Options for neutrino sector

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

- Neutral sector, even under  $\mathbb{Z}_2$  residual symmetry contains total of 4 fermions, 2 of which are Dirac neutrino pair.
- Depending on the relative size of the Yukawa couplings involved this can lead to the following neutrino scenarios: inverse seesaw, double seesaw, lopsided seesaw, Dirac seesaw.
- For the discussion of the proton decay mentioned earlier neutrinos are naturally pseudo–Dirac fermions.



# Advantages and Disadvantages

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay diagrams for  $SU(7)$  model

Discussion

Dark Matter Candidates

Neutrino Sector and Variety of options

- Rich options for proton decay scenarios, which include:  
2–body  $B + L$  and/or  $B - L$  conserving proton decays, no 2–body, *i.e.* 3–body leading order proton decays, no proton decay (proton stability at the GUT level)
- Proton decays at one–loop leading order which leads to suppressed decay widths.
- Naturally accommodates dark matter candidates.
- Several possibilities for the neutrino mass sector.
- Testable.
- Multistep phase transitions. (Gravitational waves).
- Splitting of scales in the fermion sector.

# Future Prospects

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

Pros and Cons

- Many options for stochastic gravitational waves sources from multistep first order phase transitions at low scale.
- Rich scalar sector structure.
- Dark matter candidates analysis.
- Possibilities for inverse seesaw, double seesaw, lopsided seesaw, and their extensions in the neutrino sector.
- Prospects at future  $e^+e^-$  and  $pp$  colliders.

# Conclusion

$p \rightarrow ?$

Introduction

Review

Model

Content

Anomalies

Lagrangian

Potential

Currents

Decomposition

Masses

Unification

$p$  decay

Scenarios

Topologies

Sample proton decay  
diagrams for  $SU(7)$   
model

Discussion

Dark Matter  
Candidates

Neutrino Sector and  
Variety of options

Pros and Cons

- Exotic proton decay channels
- Natural stability of proton
- Dark matter candidates
- Unification of gauge forces
- Testability

# Thanks for your attention!