Dark matter from SM gauge extensions

with neutrino masses

Diego Restrepo
July 23, 2019 - PPC2019 - Cartagena

Instituto de Física
Universidad de Antioquia
Phenomenology Group
`http://gfif.udea.edu.co`

Focus on

In collaboration with
M. Hirsch (IFIC), C. Álvarez (UTFSM), A. Flórez (UniAndes), B. Dutta(Texas A& M), C. Yaguna (UPTC), J. Calle, O. Zapata, A. Rivera (UdeA), W. Tangarife (Loyola University Chicago)

Hidden sectors

SM

35 models

SM

+

$$m^{\nu}_{\text{Majorana}} = \frac{1}{\Lambda} L \cdot H L \cdot H \text{ (1-loop)}$$

arXiv:1308.3655 [JHEP] with C. Yaguna and Ó. Zapata

SM

+

$$m^{\nu}_{\text{Majorana}} = \frac{1}{\Lambda} L \cdot H L \cdot H$$

$$m^{\nu}_{\text{Dirac}} = \frac{1}{\Lambda} (\nu_R)^{\dagger} L \cdot H S$$

Local $U(1)_X \to Z_N$

SM

+

$$m^{\nu}_{\text{Majorana}} = \frac{1}{\Lambda} L \cdot H L \cdot H$$

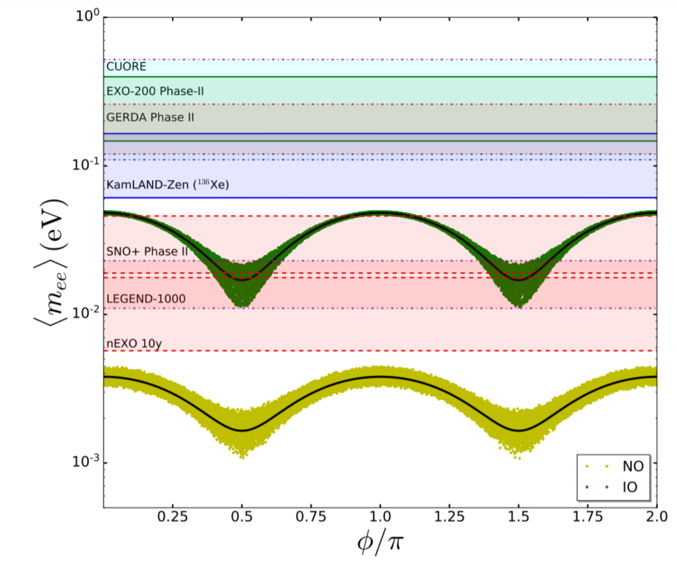
$$m^{\nu}_{\text{Dirac}} = \frac{1}{\Lambda} (\nu_R)^{\dagger} L \cdot H S$$

Neutrino masses

Lepton number

- Lepton number (L) is an accidental discret or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e, L_μ, L_τ are also conserved.
- The processes which violates individual L are called Lepton flavor violation (LFV) processes.
- All the neutrino mass models predict, to some extent, LFV processes
- Only models with Majorana neutrinos predict processes with total $L = L_e + L_\mu + L_\tau$ violation, like neutrino less doublet beta decay (NLDBD).
- NLDBD is experimentally challenging, specially if there is a massless neutrino in the spectrum.

NLDBD prospects for a model with a massless neutrino (arXiv:1806.09977 [PLB] with Reig, Valle and Zapata)



with M.Reig, J.W.F Valle, O. Zapata, arXiv:1806.09977

Total lepton number: $L = L_e + L_\mu + L_\tau$

Majorana ~~U(1)~~$_L$

Field	Z_2 ($\omega^2 = 1$)
SM	1
L	ω
$(e_R)^\dagger$	ω
$(\nu_R)^\dagger$	ω

$$\mathcal{L}_\nu = h_D\,(\nu_R)^\dagger\,L\cdot H + M_R\,\nu_R\nu_R + \text{h.c}\,.$$

$$h_D \sim \mathcal{O}(1)$$

Dirac U(1)$_L$

Field	Z_3 ($\omega^3 = 1$)
SM	1
L	ω
$(e_R)^\dagger$	ω^2
$(\nu_R)^\dagger$	ω^2

$$\mathcal{L}_\nu = h_D\,(\nu_R)^\dagger\,L\cdot H + \text{h.c}\,.$$

$$h_D \sim \mathcal{O}(10^{-11})$$

Total lepton number: $L = L_e + L_\mu + L_\tau$

Majorana $\cancel{\mathrm{U}(1)}_L$

Field	Z_2 $(\omega^2 = 1)$
SM	1
L	ω
$(e_R)^\dagger$	ω
$(\nu_R)^\dagger$	ω

$$\mathcal{L}_\nu = h_D\,(\nu_R)^\dagger\,L\cdot H + {\color{red}M_R\,\nu_R\nu_R} + \text{h.c}\,.$$

$$h_D \sim \mathcal{O}(1)$$

Dirac $\mathrm{U}(1)_{B-L}$

Field	Z_3 $(\omega^3 = 1)$
SM	1
L	ω
$(e_R)^\dagger$	ω^2
$(\nu_R)^\dagger$	ω^2

$$\mathcal{L}_\nu = h_D\,(\nu_R)^\dagger\,L\cdot H + \text{h.c}\,.$$

$$h_D \sim \mathcal{O}(10^{-11})$$

Explain smallness ala Peccei-Quinn:

$$\mathrm{U}(1)_{B-L}\underbrace{\longrightarrow}_{\color{red}\langle S\rangle} Z_N\,,\qquad N \geq 3\,.$$

Small Dirac neutrino masses

To explain the smallness of Dirac neutrino masses choose $\mathrm{U}(1)_{B-L}$ which:

- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

$$\begin{aligned}\mathcal{L}_{\mathrm{T.L}} =& h_D \epsilon_{ab} \left(\nu_R\right)^\dagger L^a H^b + \mathrm{h.c} \\ =& h_D \left(\nu_R\right)^\dagger L \cdot H + \mathrm{h.c}\end{aligned}$$

Small Dirac neutrino masses

To explain the smallness of Dirac neutrino masses choose $\mathrm{U}(1)_{B-L}$ which:

- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

$$\begin{aligned}\mathcal{L}_{\mathrm{T.L}} =& h_D \epsilon_{ab} \left(\nu_R\right)^\dagger L^a H^b + \text{h.c} \\ =& h_D \left(\nu_R\right)^\dagger L \cdot H + \text{h.c}\end{aligned}$$

- Forbids Majorana term: $\nu_R \nu_R$

Small Dirac neutrino masses

To explain the smallness of Dirac neutrino masses choose $\mathrm{U}(1)_{B-L}$ which:

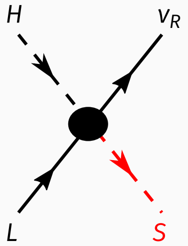
- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

$$\begin{aligned}\mathcal{L}_{\mathrm{T.L}} =& h_D \epsilon_{ab} \left(\nu_R\right)^\dagger L^a H^b + \mathrm{h.c} \\ =& h_D \left(\nu_R\right)^\dagger L \cdot H + \mathrm{h.c}\end{aligned}$$

- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

$$\mathcal{L}_{5-D} = \frac{h_\nu}{\Lambda} \left(\nu_R\right)^\dagger L \cdot H S + \mathrm{h.c}$$

$$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N$$



Small Dirac neutrino masses

To explain the smallness of Dirac neutrino masses choose $\mathrm{U}(1)_{B-L}$ which:

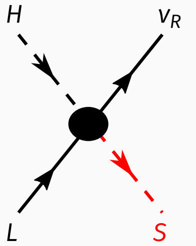
- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

$$\begin{aligned}\mathcal{L}_{\mathrm{T.L}} =& h_D \epsilon_{ab} \left(\nu_R\right)^\dagger L^a H^b + \mathrm{h.c} \\ =& h_D \left(\nu_R\right)^\dagger L \cdot H + \mathrm{h.c}\end{aligned}$$

- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

$$\mathcal{L}_{5-D} = \frac{h_\nu}{\Lambda} \left(\nu_R\right)^\dagger L \cdot H S + \mathrm{h.c}$$

$$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N$$



- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - N_{\mathrm{eff}}^{\mathrm{SM}}$ (see arXiv:1211.0186)

See E. Ma, Rahul Srivastava: arXiv:1411.5042 [PLB] for tree-level realization

SM

+

$$m^{\nu}_{\text{Majorana}} = \frac{1}{\Lambda} L \cdot H L \cdot H$$

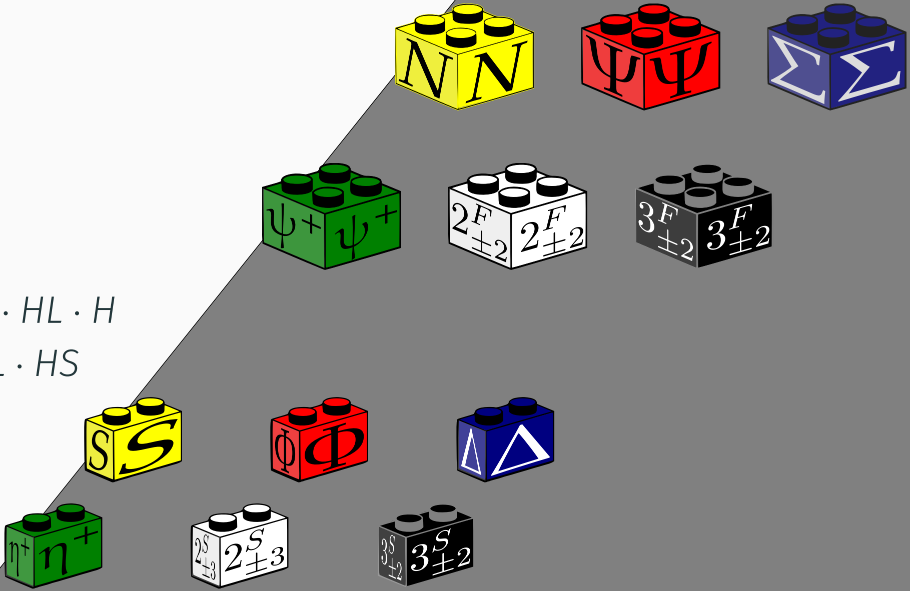
$$m^{\nu}_{\text{Dirac}} = \frac{1}{\Lambda} \left(\nu_R\right)^{\dagger} L \cdot H S$$

SM

+

$$m^{\nu}_{\text{Majorana}} = \frac{1}{\Lambda} L \cdot H L \cdot H$$

$$m^{\nu}_{\text{Dirac}} = \frac{1}{\Lambda} (\nu_R)^{\dagger} L \cdot HS$$



Dark matter and unification

Unification: SO(10)

$$= 16_{F_i} = \begin{pmatrix} (u_R)^\dagger \\ (u_R)^\dagger \\ (u_R)^\dagger \\ u_L \\ u_L \\ u_L \\ (d_R)^\dagger \\ (d_R)^\dagger \\ (d_R)^\dagger \\ d_L \\ d_L \\ d_L \\ \nu_L \\ e_L \\ (e_R)^\dagger \\ N \end{pmatrix}_i \quad \Rightarrow \mathcal{L}_{SM} \supset h\, \mathbf{16}_F \times \mathbf{16}_F \times \mathbf{10}_S + \text{h.c}$$

Unification: SO(10)

$$= \mathbf{16}_{F_i} = \begin{pmatrix} (u_R)^\dagger \\ (u_R)^\dagger \\ (u_R)^\dagger \\ u_L \\ u_L \\ u_L \\ (d_R)^\dagger \\ (d_R)^\dagger \\ (d_R)^\dagger \\ d_L \\ d_L \\ d_L \\ \nu_L \\ e_L \\ (e_R)^\dagger \\ (\nu_R)^\dagger \end{pmatrix}_i \qquad \Rightarrow \mathcal{L}_{SM} \supset h\, \mathbf{16}_F \times \mathbf{16}_F \times \mathbf{10}_S + \text{h.c}$$

SO(10) breakings

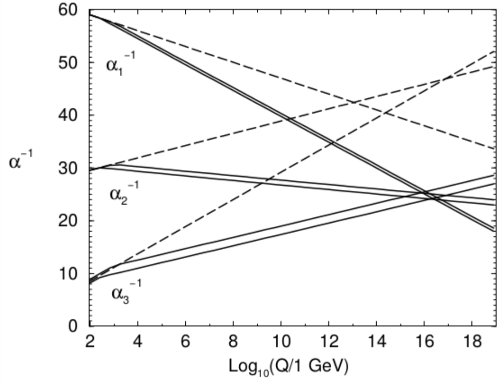
$$\mathrm{SO}(10) \to \begin{cases} \mathrm{SU}(5) \times \mathrm{U}(1)_X & \text{with} \begin{cases} Z_X \text{ at GUT: } \mathrm{U}(1)_X \to Z_N \\ Z_X \text{ at EW} \end{cases} \\ \mathrm{SU}(3)_c \times \mathrm{SU}(2)_R \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L} \end{cases}$$

Majorana neutrinos case

Not-susy SO(10) $\to SU(5) \to$ SU(3)$_C \times SU(2)_L \times$ U(1)$_Y \times Z_2$

Standard Model: Z_2-even	New Z_2-odd particles
Fermions: $\mathbf{16}_F$	$\mathbf{10}_F, \mathbf{45}_F, \cdots$
Scalars: $\mathbf{10}_H, \mathbf{45}_H \cdots$	$\mathbf{16}_H, \cdots$

Lightest Odd Particle (LOP) may be a suitable dark matter candidate, and can improve gauge coupling unification



Not-susy SO(10) $\to SU(5) \to$ SU(3)$_C \times SU(2)_L \times$ U(1)$_Y \times Z_2$

Standard Model: Z_2-even	New Z_2-odd particles
Fermions: **16**$_F$	**10**$_F$, **45**$_F$, $\cdots$
Scalars: **10**$_H$, **45**$_H$ $\cdots$	**16**$_H$, $\cdots$

Lightest Odd Particle (LOP) may be a suitable dark matter candidate, and can improve gauge coupling unification

	fermions	scalars
$SU(2)_L \times U(1)_Y$ representation	even $SO(10)$ representations	odd $SO(10)$ representations
1_0	45, 54, 126, 210	16, 144
$2_{\pm 1/2}$	10, 120, 126, 210, 210′	16, 144
3_0	45, 54, 210	144

$SU(3)_C$: 3 (T), 6, 8 (Λ)

$$m_{3_0} = 2.7 \text{ TeV}, \qquad m_\Lambda \sim 10^{10} \text{ TeV}, \qquad m_{\text{GUT}} \sim 10^{16} \text{ GeV}.$$

arXiv:0912.1545 [PRD] (Frigerio-Hambye)

Not-susy SO(10) $\to SU(5) \to \mathrm{SU}(3)_C \times SU(2)_L \times \mathrm{U}(1)_Y \times Z_2$

Standard Model: Z_2-even	New Z_2-odd particles
Fermions: $\mathbf{16}_F$	$\mathbf{10}_F, \mathbf{45}_F, \cdots$
Scalars: $\mathbf{10}_H, \mathbf{45}_H \cdots$	$\mathbf{16}_H, \cdots$

Lightest Odd Particle (LOP) may be a suitable dark matter candidate, and can improve gauge coupling unification

	fermions	scalars
$SU(2)_L \times U(1)_Y$ representation	even $SO(10)$ representations	odd $SO(10)$ representations
$\boxed{1_0}$	$\boxed{45}$, 54, 126, 210	16, 144
$\boxed{2_{\pm 1/2}}$	$\boxed{10,}$ 120, 126, 210, 210′	16, 144
$\boxed{3_0}$	$\boxed{45,}$ 54, 210	144

$SU(3)_C : 3\ (T),\ 6,\ 8\ \boxed{(\Lambda)}$

Split-SUSY like

arXiv:1509.06313 [PRD] with C. Arbelaez, R. Longas, and O. Zapata.

Not-susy SO(10) $\to SU(5) \to \mathrm{SU}(3)_C \times SU(2)_L \times \mathrm{U}(1)_Y \times Z_2$

Standard Model: Z_2-even	New Z_2-odd particles
Fermions: $\mathbf{16}_F$	$\mathbf{10}_F, \mathbf{45}_F, \cdots$
Scalars: $\mathbf{10}_H, \mathbf{45}_H \cdots$	$\mathbf{16}_H, \cdots$

Lightest Odd Particle (LOP) may be a suitable dark matter candidate, and can improve gauge coupling unification

	fermions	scalars
$SU(2)_L \times U(1)_Y$ representation	even $SO(10)$ representations	odd $SO(10)$ representations
1_0	45, 54, 126, 210	16, 144
$2_{\pm 1/2}$ $2^S_{1/2}$	10, 120, 126, 210, $210'$	16, 144
3_0	45, 54, 210	144

$SU(3)_C$: 3 (T), 6, 8 (Λ)

Radiative hybrid seesaw (Parida 1106.4137) or 1509.06313

Partial Split-SUSY-like spectrum: bino-higgsino-wino

$+ \qquad\qquad \downarrow$

$\mathbf{10}'_H$ with fermion DM or, $\qquad \mathbf{16}_H, \cdots$ with scalar DM

Not-susy SO(10) $\to SU(5) \to \mathrm{SU}(3)_C \times SU(2)_L \times \mathrm{U}(1)_Y \times Z_2$

Standard Model: Z_2-even	New Z_2-odd particles
Fermions: $\mathbf{16}_F$	$\mathbf{10}_F, \mathbf{45}_F, \cdots$
Scalars: $\mathbf{10}_H, \mathbf{45}_H \cdots$	$\mathbf{16}_H, \cdots$

Lightest Odd Particle (LOP) may be a suitable dark matter candidate, and can improve gauge coupling unification

	fermions	scalars
$SU(2)_L \times U(1)_Y$ representation	even $SO(10)$ representations	odd $SO(10)$ representations
1_0	45, 54, 126, 210	16, 144
$2_{\pm 1/2}$ $2^S_{1/2}$	10, 120, 126, 210, 210′	16, 144
3_0	45, 54, 210	144

$SU(3)_C$: 3 (T), 6, 8 (Λ)

1509.06313

SUSY-like spectrum: bino-higgsino-wino

+ $\downarrow$

$\mathbf{10}'_H$ with fermion DM or, $\mathbf{16}_H, \cdots$ with scalar DM

Singlet-Doublet-Triplet fermion dark-matter

The most general SO(10) invariant Lagrangian contains the following Yukawa terms

$$-\mathcal{L} \supset Y 10_F 45_F 10_H + M_{45_F} 45_F 45_F + M_{10_F} 10_F 10_F$$

Basis $\boldsymbol{\psi}^0 = \left(N, \Sigma^0, \psi_L^0, (\psi_R^0)^\dagger\right)^T$

$$\mathcal{M}_{\boldsymbol{\psi}^0} = \begin{pmatrix} M_N & 0 & -y\, c_\beta v/\sqrt{2} & y\, s_\beta v/\sqrt{2} \\ 0 & M_\Sigma & f\, c_{\beta'} v/\sqrt{2} & -f\, s_{\beta'} v/\sqrt{2} \\ -y\, c_\beta v/\sqrt{2} & f\, c_{\beta'} v/\sqrt{2} & 0 & -M_D \\ y\, s_\beta v/\sqrt{2} & -f\, s_{\beta'} v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$

$10_F \to \psi_L, (\psi_R)^\dagger$

$45_F \to \Sigma, \Lambda$

$45'_F \to N$

Singlet-Doublet-Triplet fermion dark-matter

The most general SO(10) invariant Lagrangian contains the following Yukawa terms

$$-\mathcal{L} \supset Y 10_F 45_F 10_H + M_{45_F} 45_F 45_F + M_{10_F} 10_F 10_F$$

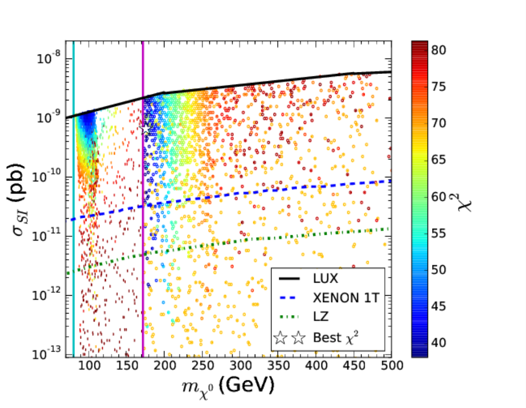
Basis $\psi^0 = \left(N, \Sigma^0, \psi_L^0, (\psi_R^0)^\dagger\right)^T$

$$\mathcal{M}_{\psi^0} = \begin{pmatrix} M_N & 0 & -y\,c_\beta v/\sqrt{2} & y\,s_\beta v/\sqrt{2} \\ 0 & M_\Sigma & f\,c_{\beta'} v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} \\ -y\,c_\beta v/\sqrt{2} & f\,c_{\beta'} v/\sqrt{2} & 0 & -M_D \\ y\,s_\beta v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$

$10_F \to \psi_L, (\psi_R)^\dagger$

$45_F \to \Sigma, \Lambda$

$45'_F \to N$



S. Horiuchi, O. Macias, DR, A. Rivera, O. Zapata, 1602.04788 (JCAP)

Singlet-Doublet-Triplet fermion dark-matter

The most general SO(10) invariant Lagrangian contains the following Yukawa terms

$$-\mathcal{L} \supset Y 10_F 45_F 10_H + M_{45_F} 45_F 45_F + M_{10_F} 10_F 10_F + \mathcal{L}(10_\Phi \qquad).$$

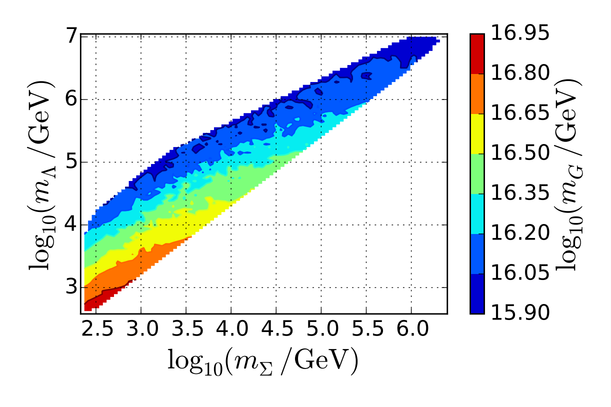
Basis $\boldsymbol{\psi}^0 = \left(N, \Sigma^0, \psi_L^0, (\psi_R^0)^\dagger\right)^T$

$$\mathcal{M}_{\boldsymbol{\psi}^0} = \begin{pmatrix} M_N & 0 & -y\,c_\beta v/\sqrt{2} & y\,s_\beta v/\sqrt{2} \\ 0 & M_\Sigma & f\,c_{\beta'} v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} \\ -y\,c_\beta v/\sqrt{2} & f\,c_{\beta'} v/\sqrt{2} & 0 & -M_D \\ y\,s_\beta v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$

$10_F \to \psi_L, (\psi_R)^\dagger$

$45_F \to \Sigma, \Lambda$

$45'_F \to N$



(See previous arXiv:1509.06313 [PRD]): Split-SUSY: like $M_\Phi = 2$ TeV

Not-susy SO(10) $\rightarrow$ SU(3)$_c$ $\times$ SU(2)$_R$ $\times$ SU(2)$_L$ $\times$ U(1)$_Y$ $\times$ U(1)$_{B-L}$

Field	Multiplicity	$3_c 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
Φ	1	$(1,2,2,0)$	0	10
χ, χ^c	1	$(1,2,2,0)$	1/2	10
N	1	$(1,1,1,0)$	1/2	45

Table 1: The relevant part of the field content. Note that, the two fermion doublets χ and χ^c come from an only fermionic LR bidoublet. In the third column the relevant fields are characterized by their SU(3)$_c$ $\times$ SU(2)$_L$ $\times$ SU(2)$_R$ $\times$ U(1)$_{B-L}$ quantum numbers while their SO(10) origin is specified in the fourth column.

Unification

m_{LR} (GeV)	$3_C 2_L 2_R 1_{B-L}$	m_G (GeV)
2×10^3	$\Phi_{1,2,2,0} + 2\Phi_{1,1,3,-2} + \Psi_{1,1,3,0} + \Phi_{1,1,3,0} + \Phi_{8,1,1,0}$	1.65×10^{16}
$\vdots$	$\vdots$	$\vdots$

Table 2: $\Delta_{L,R} = 2\Phi_{1,1,3,-2}$. m_{LR} and m_G are given in GeV.

Minimal Left-Right Symmetric Standard Model

Field	Multiplicity	$3_c 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
Q	3	$(3, 2, 1, +\frac{1}{3})$	1/2	16
Q^c	3	$(\bar{3}, 1, 2, -\frac{1}{3})$	1/2	16
L	3	$(1, 2, 1, -1)$	1/2	16
L^c	3	$(1, 1, 2, +1)$	1/2	16
Φ	1	$(1, 2, 2, 0)$	0	10
Δ_R	1	$(1, 1, 3, -2)$	0	126

Left-singlet right-triplet DM

Field	Multiplicity	$3_c 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
Q	3	$(3, 2, 1, +\frac{1}{3})$	1/2	16
Q^c	3	$(\bar{3}, 1, 2, -\frac{1}{3})$	1/2	16
L	3	$(1, 2, 1, -1)$	1/2	16
L^c	3	$(1, 1, 2, +1)$	1/2	16
Φ	1	$(1, 2, 2, 0)$	0	10
Δ_R	1	$(1, 1, 3, -2)$	0	126
Ψ_{1130}	1	$(1, 1, 3, 0)$	1/2	45

$\Omega h^2 = 0.1199 \pm 0.0027$ at 3σ

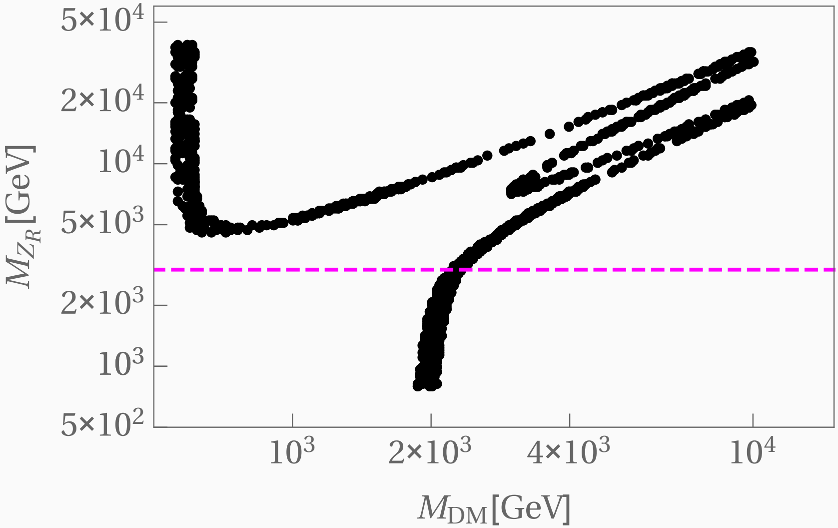


Figure 1: Proper relic density scan: $0.5 < v_R/\mathrm{TeV} < 50$

Mixed Left-singlet right-triplet DM

Field	Multiplicity	$3_c 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
Q	3	$(3, 2, 1, +\frac{1}{3})$	1/2	16
Q^c	3	$(\bar{3}, 1, 2, -\frac{1}{3})$	1/2	16
L	3	$(1, 2, 1, -1)$	1/2	16
L^c	3	$(1, 1, 2, +1)$	1/2	16
Φ	1	$(1, 2, 2, 0)$	0	10
Δ_R	1	$(1, 1, 3, -2)$	0	126
Ψ_{1130}	1	$(1, 1, 3, 0)$	1/2	45

Mixed Left-singlet right-triplet DM

Field	Multiplicity	$3_c 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
Q	3	$(3, 2, 1, +\frac{1}{3})$	1/2	16
Q^c	3	$(\bar{3}, 1, 2, -\frac{1}{3})$	1/2	16
L	3	$(1, 2, 1, -1)$	1/2	16
L^c	3	$(1, 1, 2, +1)$	1/2	16
Φ	1	$(1, 2, 2, 0)$	0	10
Δ_R	1	$(1, 1, 3, -2)$	0	126
Ψ_{1130}	1	$(1, 1, 3, 0)$	1/2	45
Ψ_{1132}	1	$(1, 1, 3, 2)$	1/2	126
Ψ_{113-2}	1	$(1, 1, 3, -2)$	1/2	$\overline{126}$

Setup

$$\Psi_{1132} = \begin{pmatrix} \Psi^{+}/\sqrt{2} & \Psi^{++} \\ \Psi^{0} & -\Psi^{+}/\sqrt{2} \end{pmatrix}, \qquad \bar{\Psi}_{113-2} = \begin{pmatrix} \Psi^{-}/\sqrt{2} & \overline{\Psi}^{0} \\ \Psi^{--} & -\Psi^{-}/\sqrt{2} \end{pmatrix}. \tag{1}$$

$$\begin{aligned} L \supset & M_{11}\,\mathrm{Tr}(\Psi_{1130}\Psi_{1130}) + M_{23}\,\mathrm{Tr}(\Psi_{1132}\bar{\Psi}_{113-2}) \\ & + \lambda_{13}\,\mathrm{Tr}(\Delta_R\bar{\Psi}_{113-2}\Psi_{1130}) + \lambda_{12}\,\mathrm{Tr}(\Delta_R^{\dagger}\Psi_{1132}\Psi_{1130}), \end{aligned} \tag{2}$$

$$\tan\gamma = \frac{\lambda_{13}}{\lambda_{12}}, \qquad \lambda = \sqrt{\lambda_{12}^2 + \lambda_{13}^2}. \tag{3}$$

Blind spot at

$$M_{23}\sin 2\gamma - M_{\mathrm{DM}} = 0 \tag{4}$$

Proper relic density scan

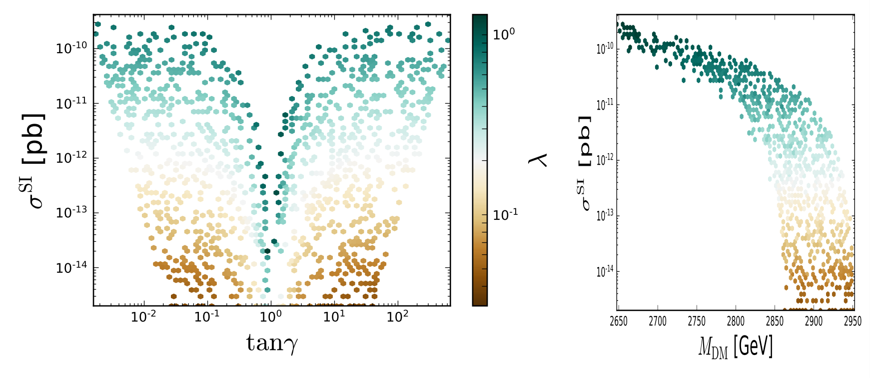


Figure 2: $M_{11} = 50$ TeV $2.7 < M_{23}/\text{TeV} < 3.1$ (Right: $\tan\gamma > 5$)

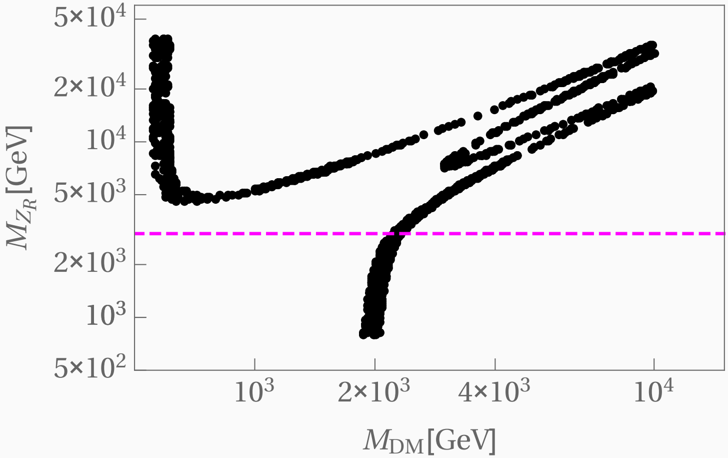

5×10^4
2×10^4
10^4
5×10^3
2×10^3
10^3
5×10^2
M_{Z_R}[GeV]
10^3
2×10^3
4×10^3
10^4
M_DM[GeV]

Figure 3:

$\Omega h^2 = 0.1199 \pm 0.0027$ at 3σ

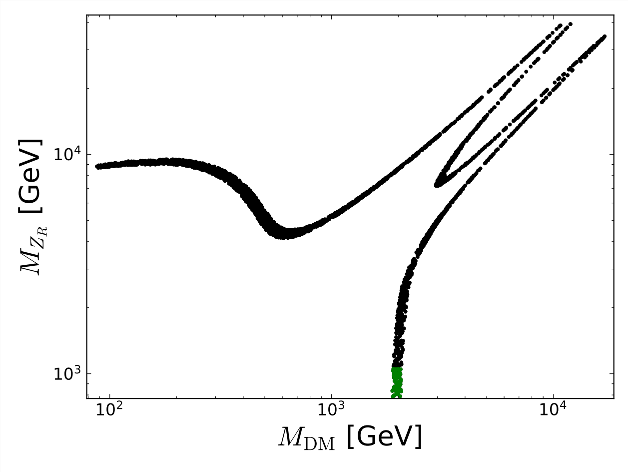


Figure 3: Proper relic density scan: v_R : $[2, 50]$ TeV, M_{23} : $[0.2, 50]$ TeV, M_{11} : 50 TeV, $\tan\gamma = -1$ and $\lambda = 0.14$.

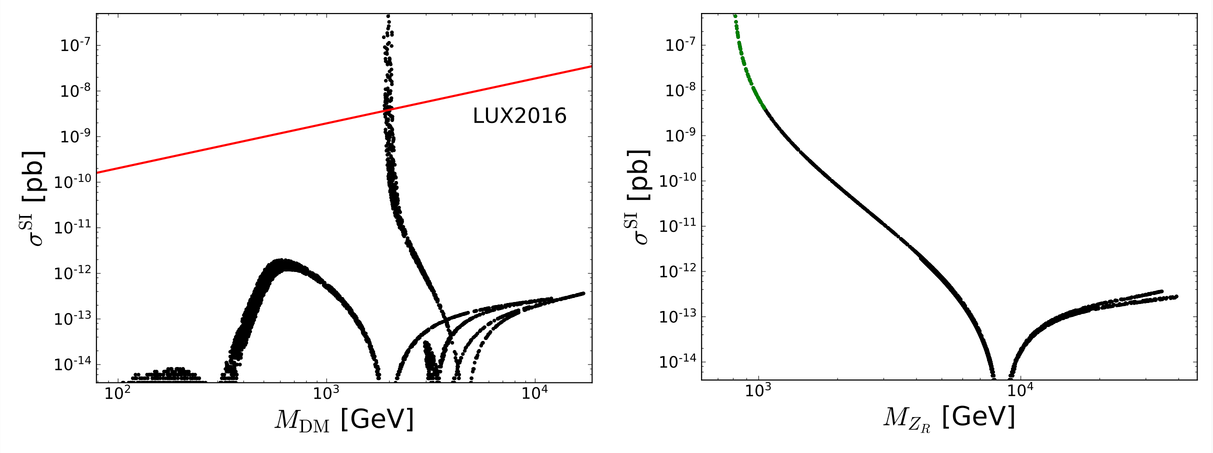


Figure 4: v_R : $[2, 50]$ TeV, M_{23} : $[0.2, 50]$ TeV, M_{11} : 50 TeV, $\tan\gamma = -1$ and $\lambda = 0.14$.

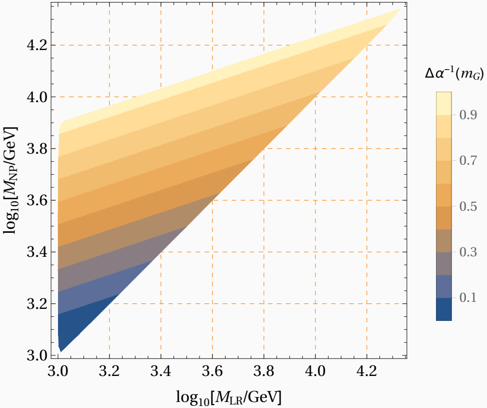
Unification

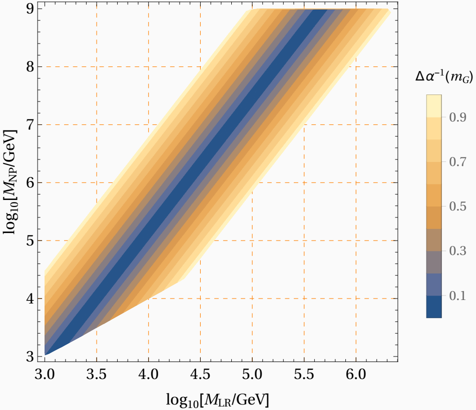
Field	Multiplicity	$3_c 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
Q	3	$(3, 2, 1, +\frac{1}{3})$	1/2	16
Q^c	3	$(\bar{3}, 1, 2, -\frac{1}{3})$	1/2	16
L	3	$(1, 2, 1, -1)$	1/2	16
L^c	3	$(1, 1, 2, +1)$	1/2	16
Φ	1	$(1, 2, 2, 0)$	0	10
Δ_R	1	$(1, 1, 3, -2)$	0	126
Ψ_{1130}	1	$(1, 1, 3, 0)$	1/2	45
Ψ_{1132}	1	$(1, 1, 3, 2)$	1/2	126
Ψ_{113-2}	1	$(1, 1, 3, -2)$	1/2	$\overline{126}$

Unification

Field	Multiplicity	$3_C 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
Q	3	$(3, 2, 1, +\frac{1}{3})$	1/2	16
Q^c	3	$(\bar{3}, 1, 2, -\frac{1}{3})$	1/2	16
L	3	$(1, 2, 1, -1)$	1/2	16
L^c	3	$(1, 1, 2, +1)$	1/2	16
Φ	1	$(1, 2, 2, 0)$	0	10
Δ_R	1	$(1, 1, 3, -2)$	0	126
Ψ_{1130}	1	$(1, 1, 3, 0)$	1/2	45
Ψ_{1132}	1	$(1, 1, 3, 2)$	1/2	126
Ψ_{113-2}	1	$(1, 1, 3, -2)$	1/2	$\overline{126}$
Ψ_{1310}	1	$(1, 3, 1, 0)$	1/2	45
Ψ_{8110}	1	$(1, 1, 8, 0)$	1/2	45
$\Psi_{321\frac{1}{3}}$	1	$(3, 2, 1, 1/3)$	1/2	16
$\Psi_{321-\frac{1}{3}}$	1	$(1, 2, 3, -1/3)$	1/2	$\overline{16}$

Unification quality





Remarks

In addition to accommodate usual simplified dark matter models, Left-right symmetric standard models have additional DM portals:

New Δ_R portal for direct detection of left-singlet right-triplet mixed dark matter, in companion with left-singlets charged and doubly charged fermions.

Next: Search for them in compressed spectra scenarios at the LHC

Dirac neutrinos case:

$$\mathrm{SO}(10) \to \mathrm{SU}(5) \times U(1)_X$$

From 1210.6350 and 1805.02025: $\Delta N_{\rm eff} = 3\,(T_{\nu_R}/T_{\nu_L})^4$

$$\Gamma_{\nu_R}(T) = n_{\nu_R}(T)\sum_f \langle\sigma_f(\nu_R\bar\nu_R \to f\bar f)v\rangle$$

$$= \sum_f \frac{g^2_{\nu_R}}{n_{\nu_R}} \int \frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3} f_{\nu_R}(p) f_{\nu_R}(q)\sigma_f(s)(1-\cos\theta),$$

$$s = 2pq(1-\cos\theta), \qquad f_{\nu_R}(k) = 1/(e^{k/T}+1)$$

$$n_{\nu_R}(T) = g_{\nu_R}\int \frac{d^3k}{(2\pi)^3} f_{\nu_R}(k), \qquad \text{with } g_{\nu_R} = 2$$

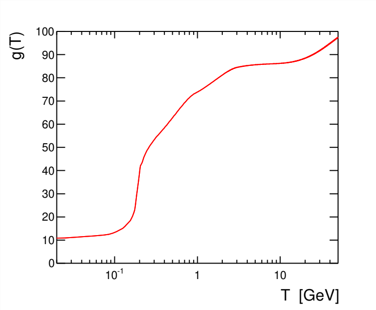
$$\sigma_f(s) \simeq \frac{N_C^f (Q^f_{BL})^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \quad \text{In the limit } M^2_{Z'} \gg s\,.$$

with three right-handed neutrinos, the Hubble parameter is

$$H(T) = \sqrt{\frac{4\pi^3 G_N\,[g(T)+21/4]}{45}}\,T^2.$$

The right-handed neutrinos decouple when

$$\Gamma_{\nu_R}(T^{\nu_R}_{\rm dec}) = H(T^{\nu_R}_{\rm dec}).$$



A. Solaguren-Beascoa, M. C. Gonzalez-Garcia: arXiv:1210.6350 [PLB]

From 1210.6350 and 1805.02025: $\Delta N_{\rm eff} = 3\,(T_{\nu_R}/T_{\nu_L})^4$

$$\Gamma_{\nu_R}(T) = n_{\nu_R}(T)\sum_f \langle \sigma_f(\nu_R\bar{\nu}_R \to f\bar{f})v\rangle$$

$$= \sum_f \frac{g_{\nu_R}^2}{n_{\nu_R}} \int \frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3} f_{\nu_R}(p) f_{\nu_R}(q)\sigma_f(s)(1-\cos\theta),$$

$$s = 2pq(1-\cos\theta), \qquad f_{\nu_R}(k) = 1/(e^{k/T}+1)$$

$$n_{\nu_R}(T) = g_{\nu_R}\int \frac{d^3k}{(2\pi)^3} f_{\nu_R}(k), \qquad \text{with } g_{\nu_R} = 2$$

$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s\,.$$

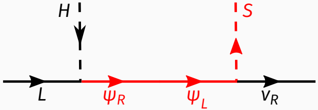
with three right-handed neutrinos, the Hubble parameter is

$$H(T) = \sqrt{\frac{4\pi^3 G_N\,[g(T)+21/4]}{45}}\,T^2.$$

The right-handed neutrinos decouple when

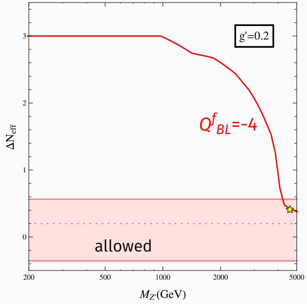
$$\Gamma_{\nu_R}(T_{\rm dec}^{\nu_R}) = H(T_{\rm dec}^{\nu_R}).$$

$$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S\rangle} Z_3$$



ν_{R3}	ν_{R2}	ν_{R1}	ψ_L	ψ_R	S
-4	-4	$+5$	-1	-1	$+3$

E. Ma, R. Srivastava: arXiv:1411.5042 [PLB]



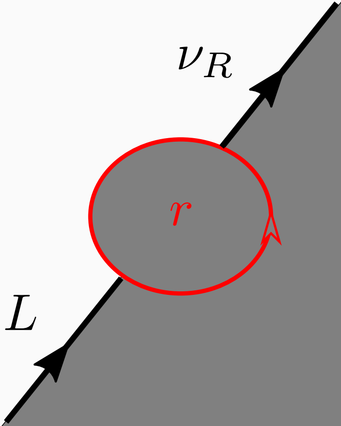
Z.-L. Han, W. Wang: arXiv:1805.02025 [EJPC]

(also: Planck 1807.06209, Riess *et al* 1903.07603)

One-loop realization of $\mathcal{L}_{5-D}$ with total L

$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter



$\mathrm{U}(1)_X$

Dirac neutrino masses

+

Forbids

Dirac fermion dark matter

$\nu_R \nu_R$

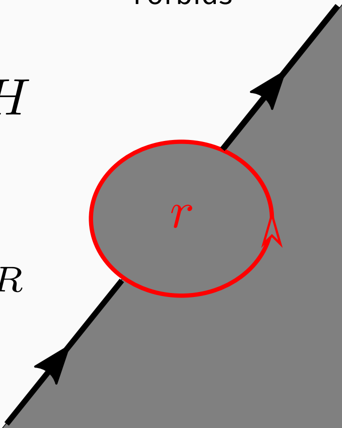
$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$



$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$

r

Allows

$(\nu_R)^\dagger L H S$

$(\psi_R)^\dagger \psi_L$

$(\psi_R)^\dagger \psi_L S$

$$\mathrm{U}(1)_{B-L} \xrightarrow[\langle S \rangle]{} Z_N \qquad N \neq 2$$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$

r

Allows

$X(L) \neq 0$

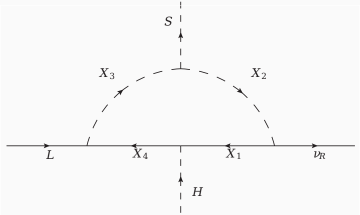
$(\nu_R)^\dagger L H S$

$(\psi_R)^\dagger \psi_L$

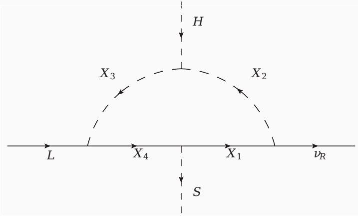
$(\psi_R)^\dagger \psi_L S$

normalized to$X(L) = -1$

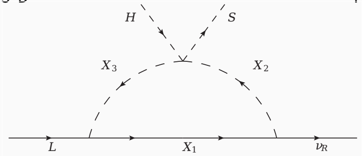
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

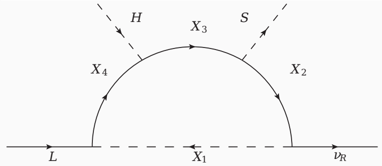


T1-3-E

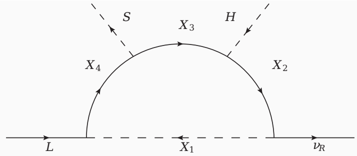


T3-1-A

Chang-Yuan Yao and Gui-Jun Ding, arXiv:1802.05231 [PRD]

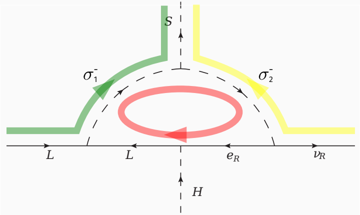


T1-2-A

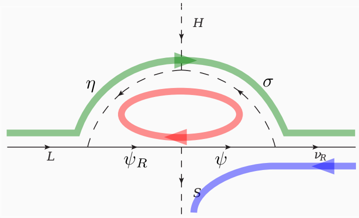


T1-2-B

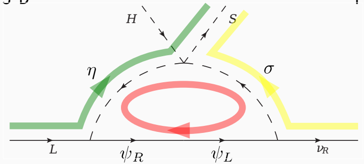
One loop topologies U(1)$_{B-L}$ only!



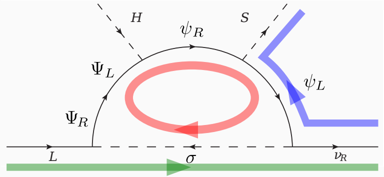
T1-3-D



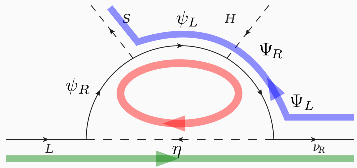
T1-3-E



T3-1-A



T1-2-A



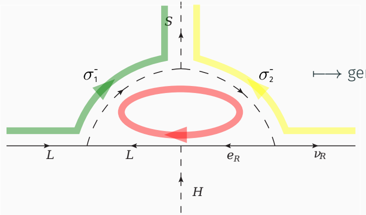
T1-2-B

$\psi_{L,R}$ $\rightarrow$Singlet fermions

$\Psi_{L,R}$ $\rightarrow$Vector-like doublet fermions

σ $\rightarrow$Singlet scalar

with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

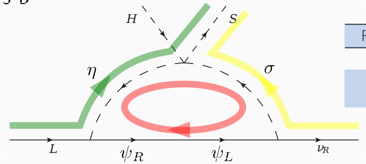


T1-3-D

$\longmapsto$ generalization to two and three loops: Shaikh Saad arXiv:1902.07259 [NPB]

$\psi_{L,R}$ $\rightarrow$Singlet fermions (vector-like)

σ $\rightarrow$Singlet scalar



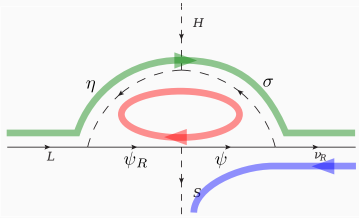
T3-1-A

Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$



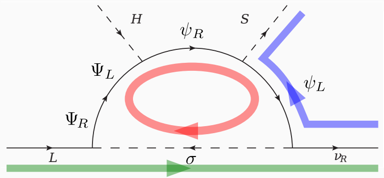
T1-3-E

$\psi_{L,R}$ →Singlet fermions (quiral)

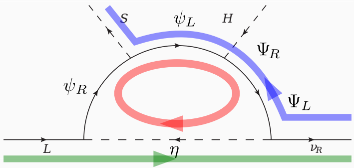
$\Psi_{L,R}$ →Vector-like doublet fermions

σ →Singlet scalar

Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$



T1-2-A



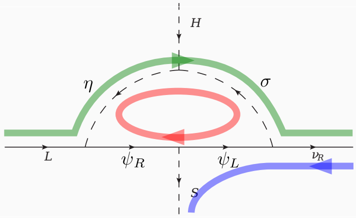
T1-2-B

Anomaly cancellation conditions

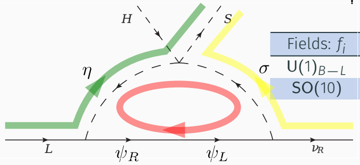
$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

Scotogenic Dirac from SO(10) E. Ma arXiv:1901.09091 [PLB]



T1-3-E



T3-1-A

$\psi_{L,R}$ $\longrightarrow$ Singlet fermions (quiral)

σ $\longrightarrow$ Singlet scalar

η $\longrightarrow$ Doublet scalar

Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	σ	η	S
$U(1)_{B-L}$	$+4$	$+4$	-5	$-r$	r	$4-r$	$1-r$	$+3$
SO(10)	16	16	16	126	126*	16	144	672

Anomaly cancellation conditions

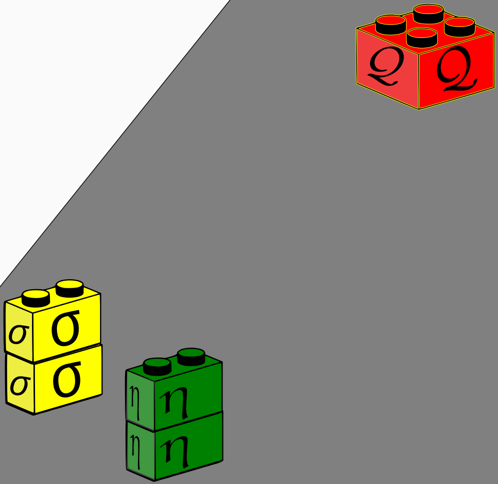
$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

SM

+

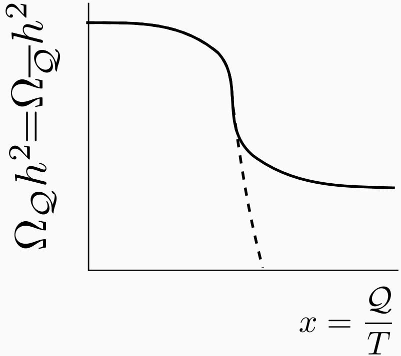
$(\nu_R)_i^\dagger$



(Switch to Dirac fermions)

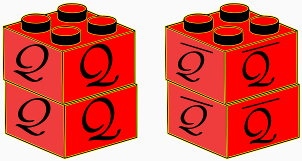
Because $\mathcal{Q}$ is a Dirac fermion, $\mathcal{Q}\mathcal{Q}$ is also stable

$$\mathcal{Q}\mathcal{Q} \not\to g\,, \qquad \overline{\mathcal{Q}\mathcal{Q}} \not\to g\,.$$



Step one

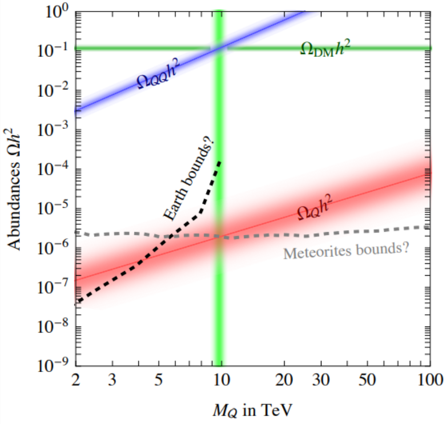
$\mathcal{Q}$-onlyum

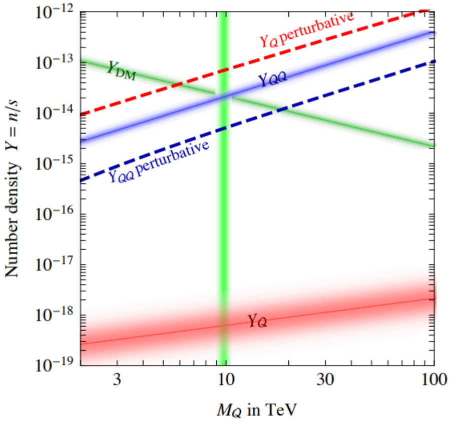


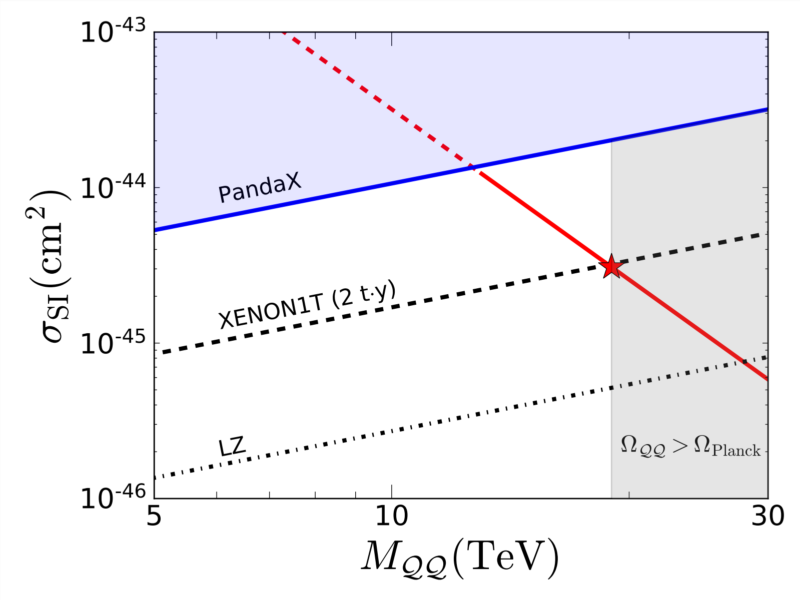
Step two

$$M_Q \simeq 9.5\,\mathrm{TeV}$$

$$\Omega_{\mathrm{hyb}} \sim 10^{-5}\Omega_{\mathrm{DM}}$$





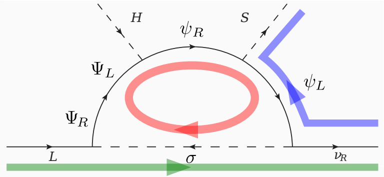

10^-43
10^-44
10^-45
10^-46
σ_SI(cm^2)
PandaX
XENON1T (2 t·y)
LZ
Ω_QQ > Ω_Planck
5
10
30
M_QQ(TeV)

SD^{3}M+σ_i $(i = 1, 2)$ with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

$\psi_{L,R}$ →Singlet fermions (quiral)

$\Psi_{L,R}$ →Vector-like doublet fermions : 10/5

σ →Singlet scalar : 15/5



Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S	Ψ_L	$\widetilde{(\Psi_R)}$	σ
$U(1)_{B-L}$	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$	$\frac{10}{5}$	$-\frac{10}{5}$	$\frac{7}{5}$
SO(10)	16	16	16	45	45	126	10	10	16

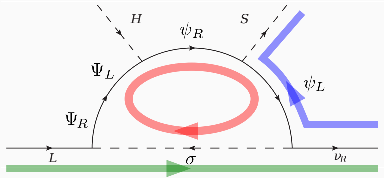
Second Scotogenic Dirac from SO(10) E. Ma
arXiv:1901.09091 [PLB]

SD^{3}M+σ_i ($i = 1, 2$)

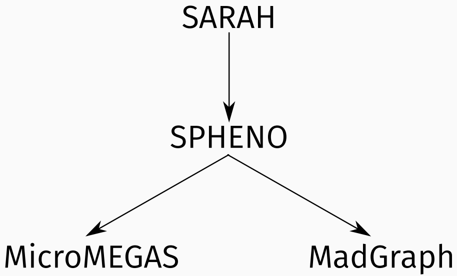
$M_\psi = h_1 \langle S \rangle$, $y_2 = 0$:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SD^3M}} + h_3^{ia}\widetilde{(\Psi_R)} \cdot L_i\,\sigma_a + h_2^{\beta a}\,(\nu_{R\beta})^\dagger\,\psi_L\,\sigma_a^* - V(\sigma_a, S, H)\,.$$

with A.F Rivera, W. Tangarife, arXiv:1906.09685



T1-2-A



Singlet-Doublet Dirac Dark Matter (SD^{3}M) By Carlos E. Yaguna. arXiv:1510.06151 [PRD].

The model extends the standard model (SM) particle content with Dirac Fermions: from SU(2) doublets of Weyl fermions: $\Psi_L = \left(\Psi_L^0,\, \Psi_L^-\right)^{\mathsf{T}}, \widetilde{(\Psi_R)} = \left((\Psi_R^-)^\dagger,\, -(\Psi_R^0)^\dagger\right)^{\mathsf{T}}$ and singlet Weyl fermions ψ_{LR} that interact among themselves and with the SM fields

$$\mathcal{L} \supset M_\psi \left(\psi_R\right)^\dagger \psi_L + M_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + y_1 \left(\psi_R\right)^\dagger \Psi_L \cdot H + y_2 \widetilde{(\Psi_R)} \cdot \widetilde{H} \psi_L + \text{h.c} \tag{5}$$

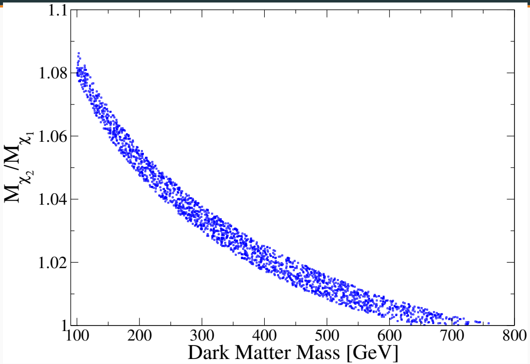
Four free parameters:

$$M_\psi, M_\Psi \;\; < 2\ \text{GeV}\,, \qquad\qquad y_1,\ y_2 > 10^{-6} \tag{6}$$

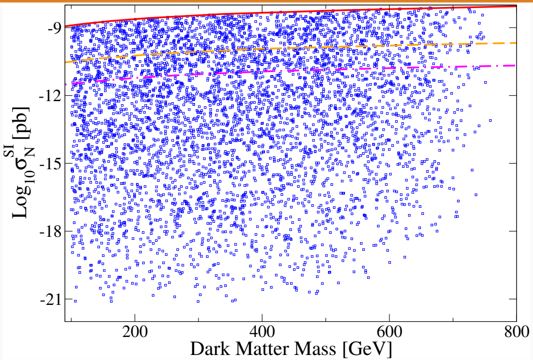
Two neutral Dirac fermion eigenstates:

$$M = \begin{pmatrix} M_\psi & y_2 v/\sqrt{2} \\ y_1 v/\sqrt{2} & M_D \end{pmatrix}, \qquad\qquad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \tag{7}$$

SD^{3}M By Carlos E. Yaguna. arXiv:1510.06151 [PRD].

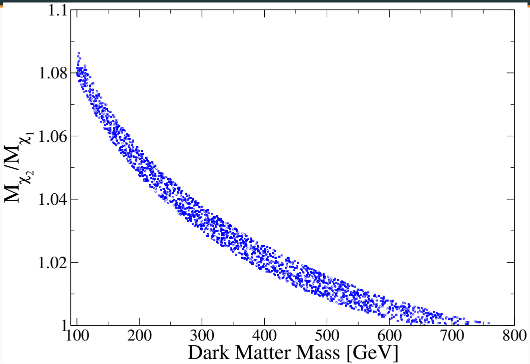


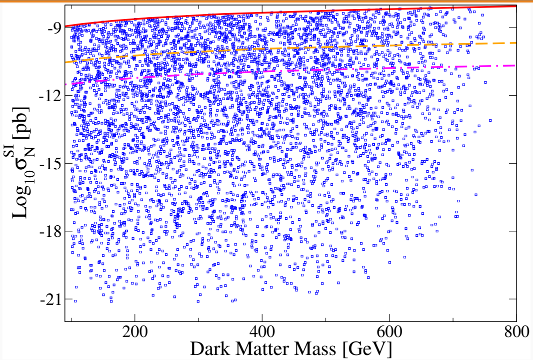
Compressed spectra region



LUX - XENON1T - LZ

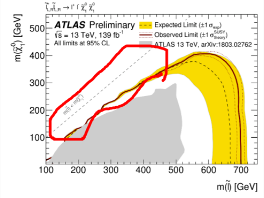
SD^{3}M By Carlos E. Yaguna. arXiv:1510.06151 [PRD].



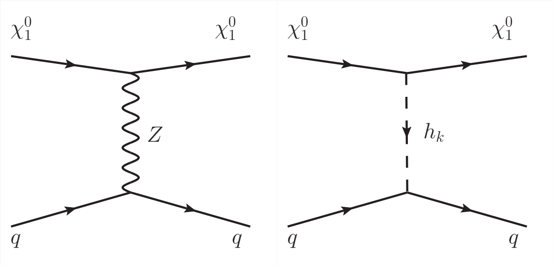


Compressed spectra region

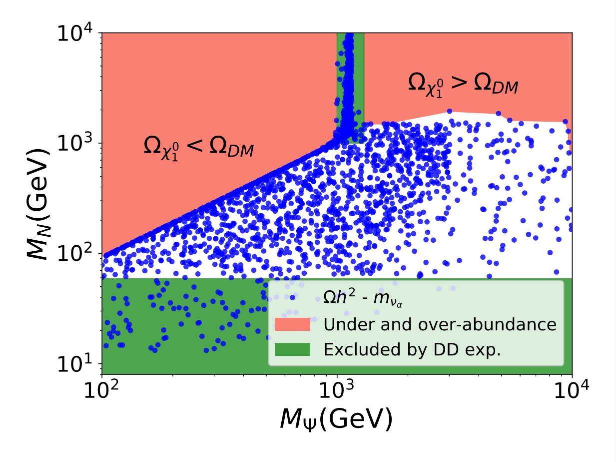
LUX - XENON1T - LZ



Spin independent (SI) direct detection cross section



Decoupled Z' limit



Vector SI (blue points) and scalar SI (green points)

Conclusions

A single $U(1)$ symmetry to explain both the smallnes of Dirac neutrino masses and the stability of Dirac fermion dark matter

Conclusions

A single $U(1)$ symmetry to explain both the smallnes of Dirac neutrino masses and the stability of Dirac fermion dark matter

Dirac neutrino masses and DM

- Spontaneously broken $U(1)_{B-L}$ generates a radiative Dirac neutrino masses
- A remnant symmetry makes the lightest field circulating the loop stable and good dark matter candidate.
- For T1-2-A: Either Singet Doublet Dirac Dark Matter or Singlet Scalar Dark Matter with extra scalar and vector portal
- With relaxed direct detection constraints

Thanks!