

Dark matter from SM gauge extensions

with neutrino masses



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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





+

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

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

35 models



+

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

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

Local $U(1)_X \rightarrow Z_N$



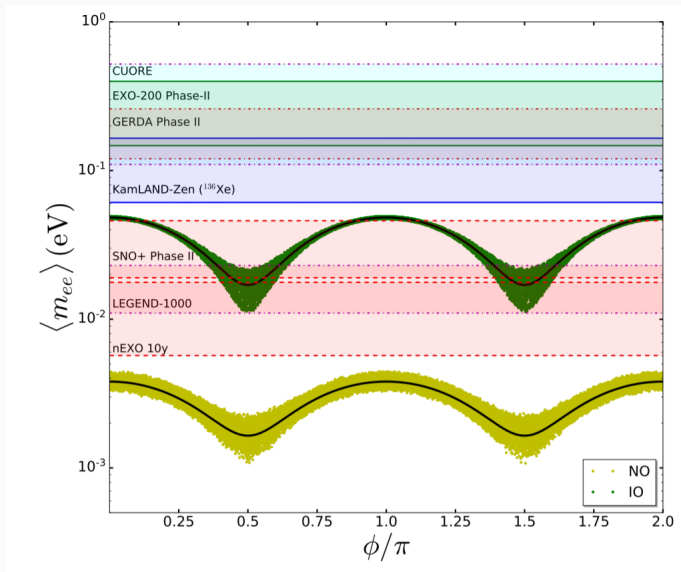
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Neutrino masses

- Lepton number (L) is an accidental discrete or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e , L_μ , L_τ are also conserved.
- The processes which violate 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.



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: $L = L_e + L_\mu + L_\tau$

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

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

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:

$$U(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N, \quad N \geq 3.$$

Small Dirac neutrino masses

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

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

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

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- Forbids Majorana term: $\nu_R \nu_R$

Small Dirac neutrino masses

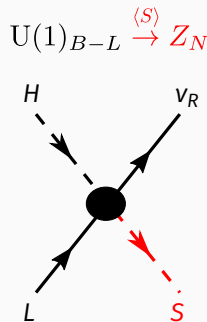
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- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$:

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



Small Dirac neutrino masses

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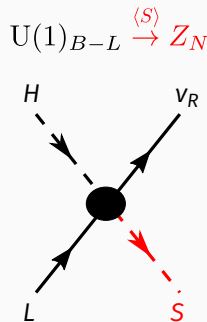
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- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$ (see arXiv:1211.0186)



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



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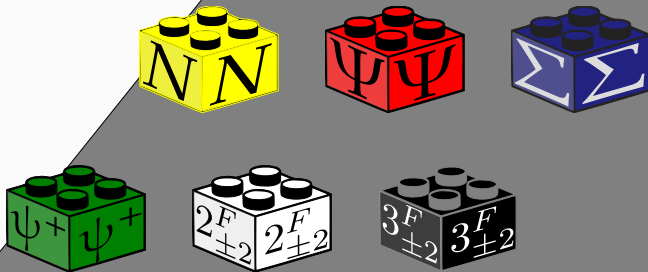
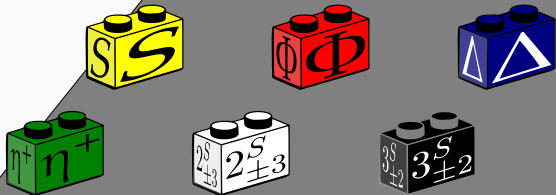
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Dark matter and unification

Unification: SO(10)



$= 16_{F_i}$

$$\begin{pmatrix} (u_R)^\dagger \\ (u_R)^\dagger \\ (u_R)^\dagger \\ u_L \\ u_L \\ u_L \\ (d_R)^\dagger \\ (d_R)^\dagger \\ (d_R)^\dagger \\ d_L \\ d_L \\ d_L \\ \nu_L \\ e_L \\ (e_R)^\dagger \\ N \end{pmatrix}_i$$

$$\Rightarrow \mathcal{L}_{SM} \supset h \, 16_F \times 16_F \times 10_S + \text{h.c}$$



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$$\Rightarrow \mathcal{L}_{SM} \supset h 16_F \times 16_F \times 10_S + \text{h.c}$$



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

Majorana neutrinos case

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

Standard Model: Z_2 -even

Fermions: 16_F

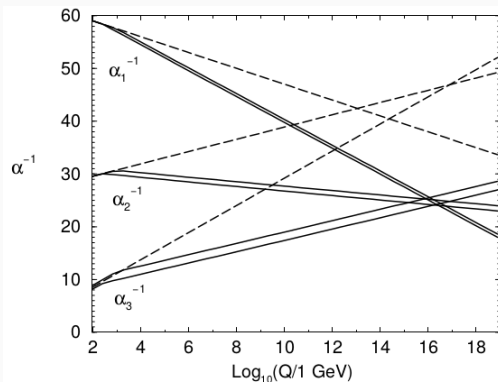
Scalars: $10_H, 45_H \dots$

New Z_2 -odd particles

$10_F, 45_F, \dots$

$16_H, \dots$

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



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	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

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

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

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

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Split-SUSY like

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

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

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

Radiative hybrid seesaw (Parida 1106.4137) or 1509.06313

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

+

↓

$10'_H$ with fermion DM or, $16_H, \dots$ with scalar DM

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

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$SU(3)_C$: 3 (T), 6, 8 (Λ)

1509.06313

SUSY-like spectrum: bino-higgsino-wino

+

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$10'_H$ with fermion DM or, $16_H, \dots$ with scalar DM

Singlet-Doublet-Triplet fermion dark-matter

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

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

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

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

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

$$45_F \rightarrow \Sigma, \Lambda$$

$$45'_F \rightarrow N$$

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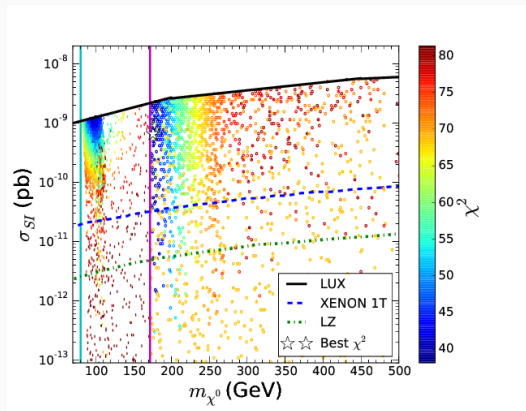
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S. Horiuchi, O. Macias, DR, A. Rivera, O. Zapata, 1602.04788 (JCAP)

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

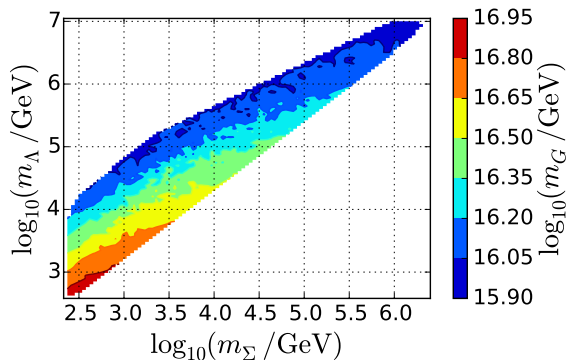
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$$10_F \rightarrow \psi_L, (\psi_R)^\dagger$$

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

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

Fermionic triplet dark matter in an $SO(10)$ -inspired left right model, with C. Arbeláez and M. Hirsch, arXiv:1703.08148 [PRD]

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
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Ψ_{1132}	1	$(1, 1, 3, 2)$	1/2	126
Ψ_{113-2}	1	$(1, 1, 3, -2)$	1/2	$\overline{126}$

$$\Omega h^2 = 0.1199 \pm 0.0027 \text{ at } 3\sigma$$

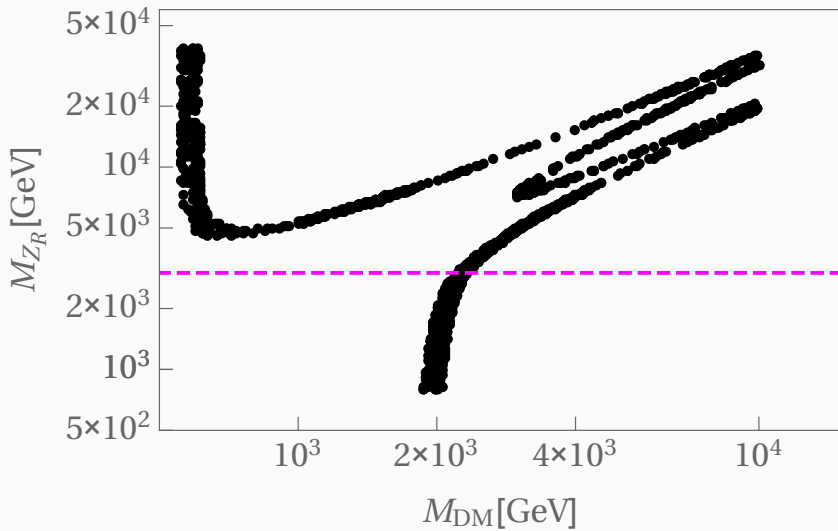


Figure 1: Proper relic density scan: $0.5 < v_R/\text{TeV} < 50$

Mixed Left-singlet right-triplet DM

Field	Multiplicity	$3_C 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
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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
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$$\Psi_{1132} = \begin{pmatrix} \Psi^+/\sqrt{2} & \Psi^{++} \\ \Psi^0 & -\Psi^+/\sqrt{2} \end{pmatrix}, \quad \bar{\Psi}_{113-2} = \begin{pmatrix} \Psi^-/\sqrt{2} & \bar{\Psi}^0 \\ \Psi^{--} & -\Psi^-/\sqrt{2} \end{pmatrix}. \quad (1)$$

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

$$\tan \gamma = \frac{\lambda_{13}}{\lambda_{12}}, \quad \lambda = \sqrt{\lambda_{12}^2 + \lambda_{13}^2}. \quad (3)$$

Blind spot at

$$M_{23} \sin 2\gamma - M_{\text{DM}} = 0 \quad (4)$$

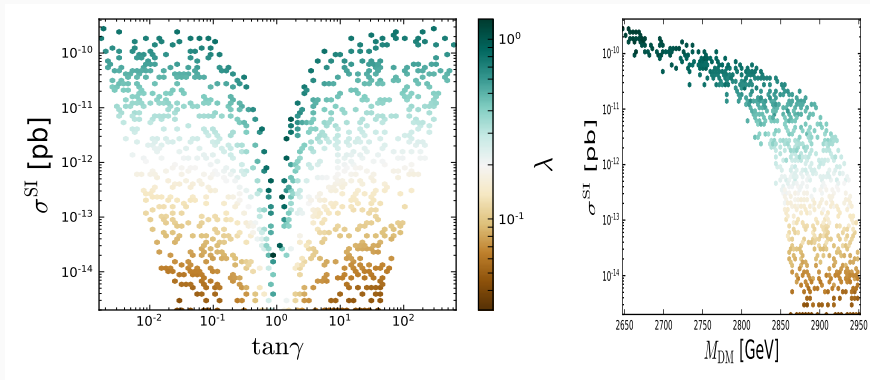


Figure 2: $M_{11} = 50$ TeV $2.7 < M_{23}/\text{TeV} < 3.1$ (Right: $\tan \gamma > 5$)

$$\Omega h^2 = 0.1199 \pm 0.0027 \text{ at } 3\sigma$$

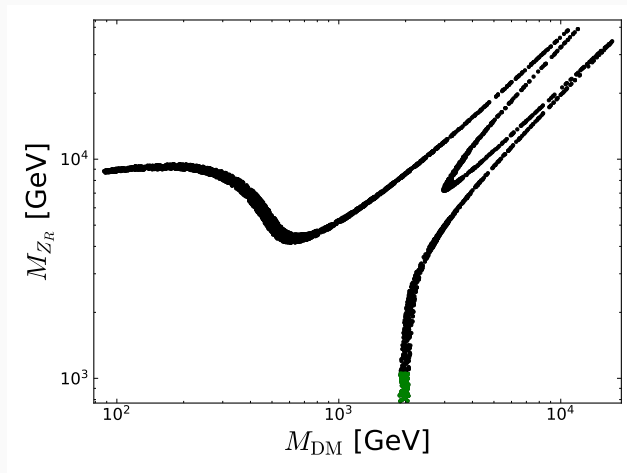


Figure 3:

Direct detection cross section

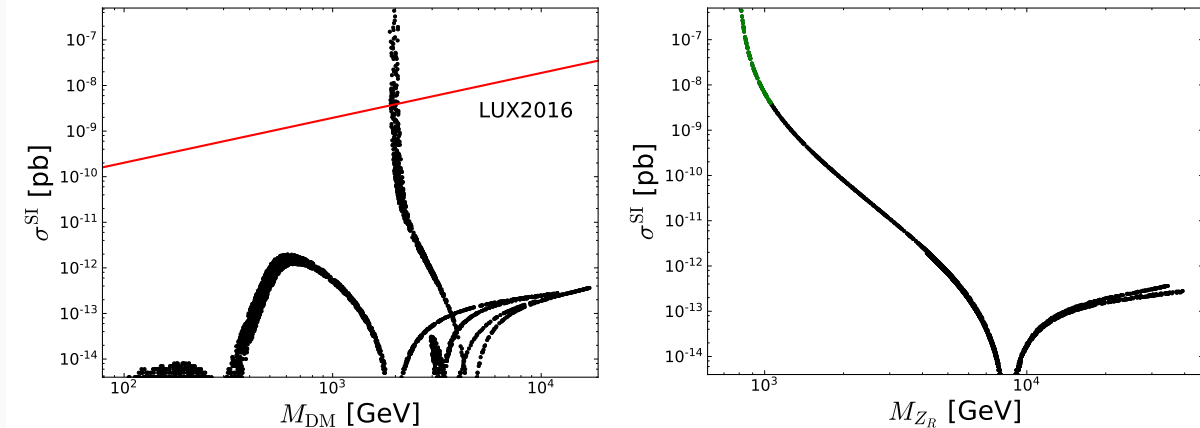


Figure 4: v_R : [2, 50] TeV, M_{23} : [0.2, 50] TeV, M_{11} : 50 TeV, $\tan \gamma = -1$ and $\lambda = 0.14$.

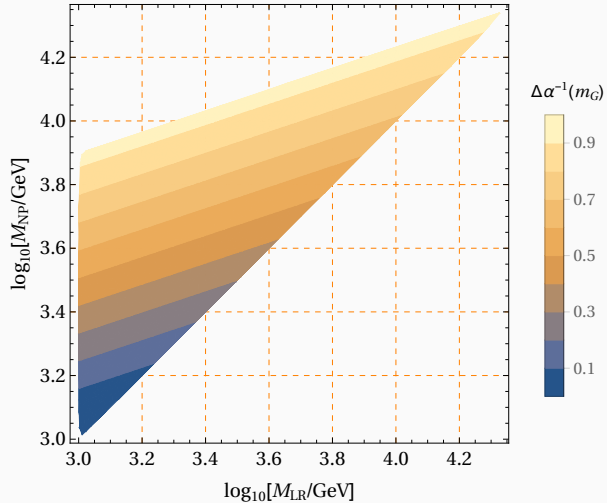
Unification

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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



NP: Ψ_{1310}

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:

$$SO(10) \rightarrow SU(5) \times U(1)_X$$

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

$$\begin{aligned}\Gamma_{\nu_R}(T) &= n_{\nu_R}(T) \sum_f \langle \sigma_f(\nu_R \bar{\nu}_R \rightarrow f\bar{f}) v \rangle \\ &= \sum_f \frac{g_{\nu_R}^2}{n_{\nu_R}} \int \frac{d^3 p}{(2\pi)^3} \frac{d^3 q}{(2\pi)^3} f_{\nu_R}(p) f_{\nu_R}(q) \sigma_f(s) (1 - \cos \theta),\end{aligned}$$

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

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

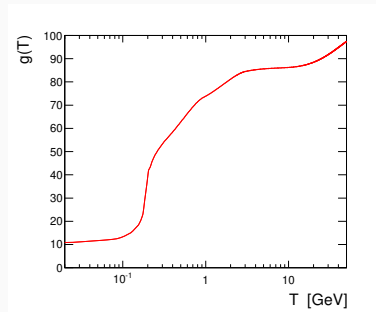
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left(\frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

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

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



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

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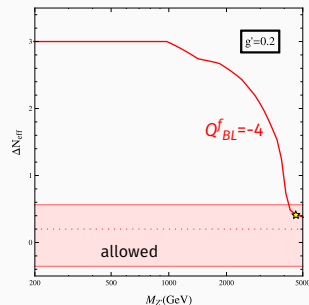
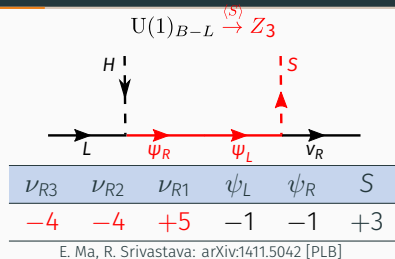
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Z.-L. Han, W. Wang: arXiv:1805.02025 [EJPC]

(also: Planck 1807.06209, Riess et al 1903.07603)

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

Dirac neutrino masses

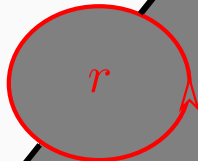
$U(1)_X$
+

Dirac fermion dark matter



L

ν_R



Dirac neutrino masses

$$\nu_R \nu_R$$

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

$$\nu_R \psi_R$$

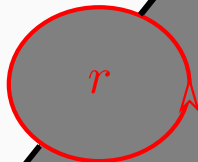
$$(\psi_L)^\dagger \nu_R$$

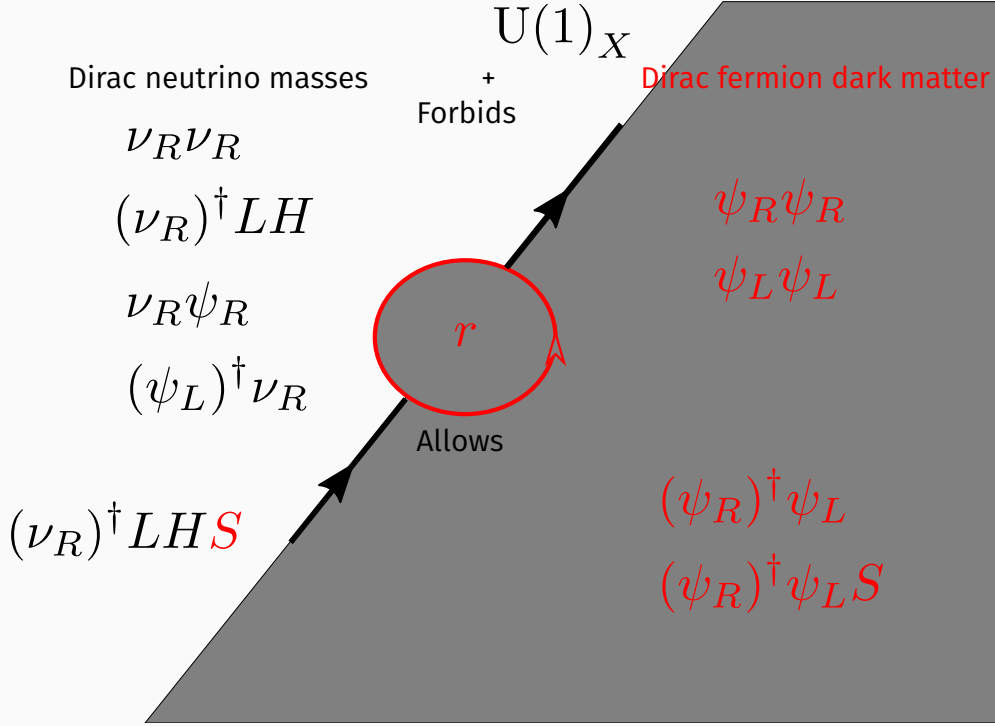
$U(1)_X$
+
Forbids

Dirac fermion dark matter

$$\psi_R \psi_R$$

$$\psi_L \psi_L$$





Dirac neutrino masses

$$\nu_R \nu_R$$

$$(\nu_R)^\dagger LH$$

$$\nu_R \psi_R$$

$$(\psi_L)^\dagger \nu_R$$

$$(\nu_R)^\dagger LH \textcolor{red}{S}$$

$X(L) \neq 0$

+
Forbids

$U(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N \quad N \neq 2$
 Dirac fermion dark matter

$$\psi_R \psi_R$$

$$\psi_L \psi_L$$

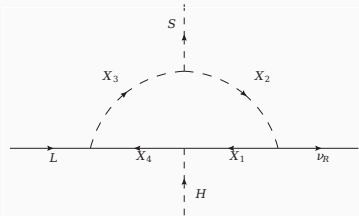
Allows

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

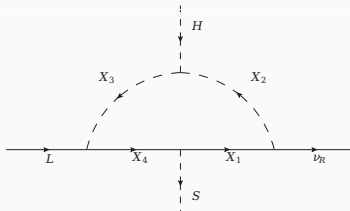
$$(\psi_R)^\dagger \psi_L \textcolor{red}{S}$$

normalized to $X(L) = -1$

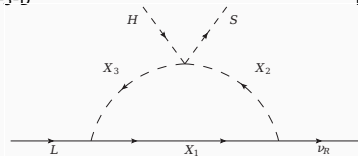
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

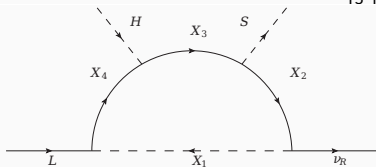


T1-3-E

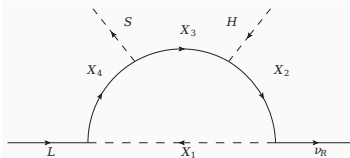


T3-1-A

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

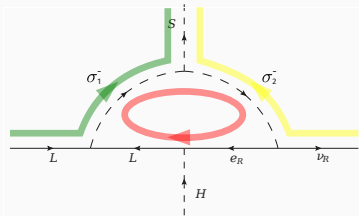


T1-2-A

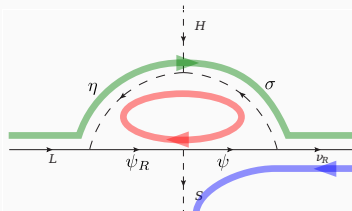


T1-2-B

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



T1-3-D



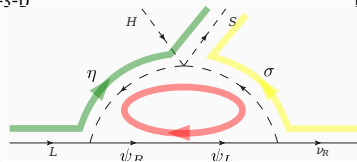
T1-3-E

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

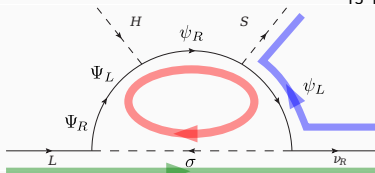
$\Psi_{L,R} \rightarrow$ Vector-like doublet fermions

$\sigma \rightarrow$ Singlet scalar

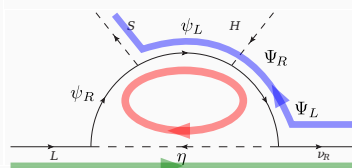
with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



T3-1-A

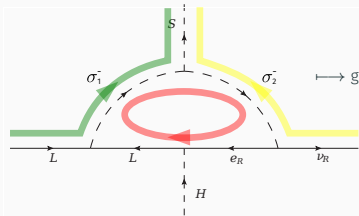


T1-2-A



T1-2-B

One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

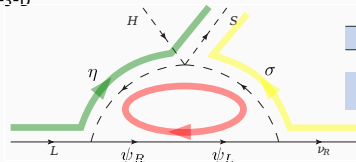


→ generalization to two and three loops: Shaikh Saad arXiv:1902.07259 [NPB]

T1-3-D

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

$\sigma \rightarrow$ Singlet scalar



T3-1-A

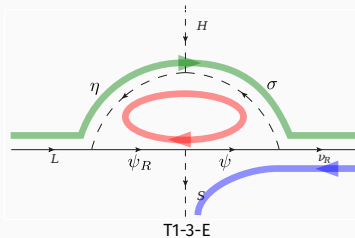
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

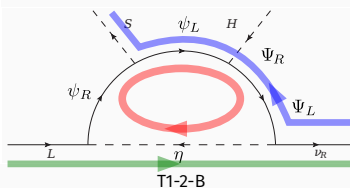
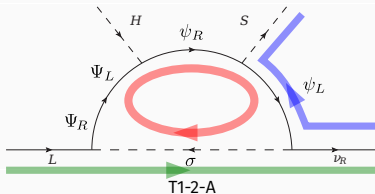
$$\sum_i f_i^3 = 3$$

One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



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)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$

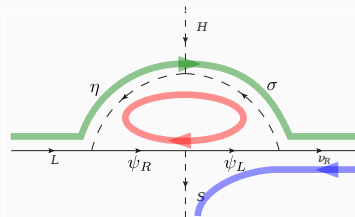
$\psi_{L,R} \rightarrow$ Singlet fermions (quiral)
 $\Psi_{L,R} \rightarrow$ Vector-like doublet fermions
 $\sigma \rightarrow$ Singlet scalar



Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

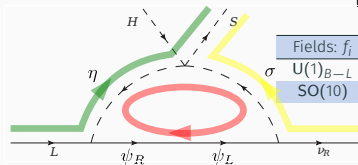


T1-3-E

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

$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar



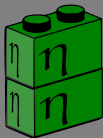
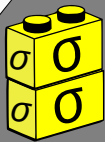
T3-1-A

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

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$



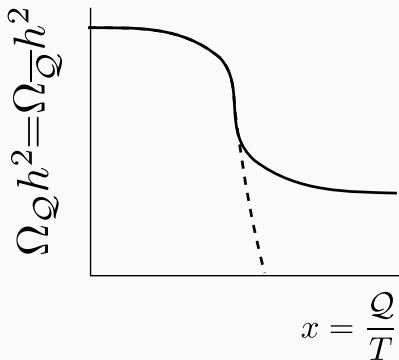


(Switch to Dirac fermions)

Because Q is a Dirac fermion, QQ is also stable

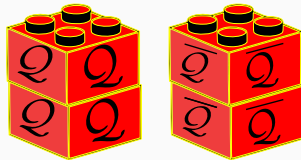
$$QQ \not\rightarrow g,$$

$$\overline{Q}\overline{Q} \not\rightarrow g.$$



Step one

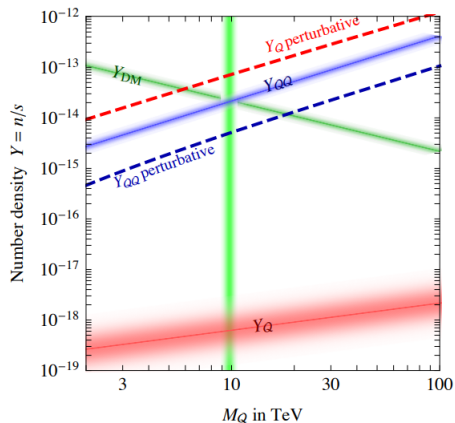
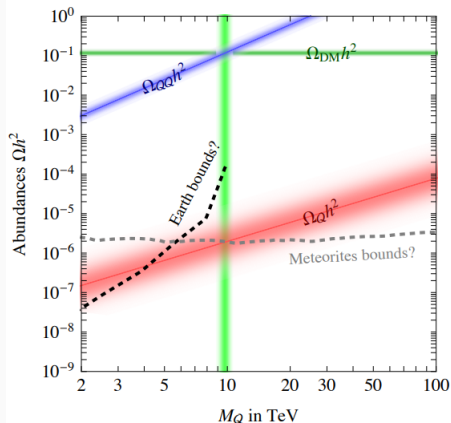
Q -onlyum



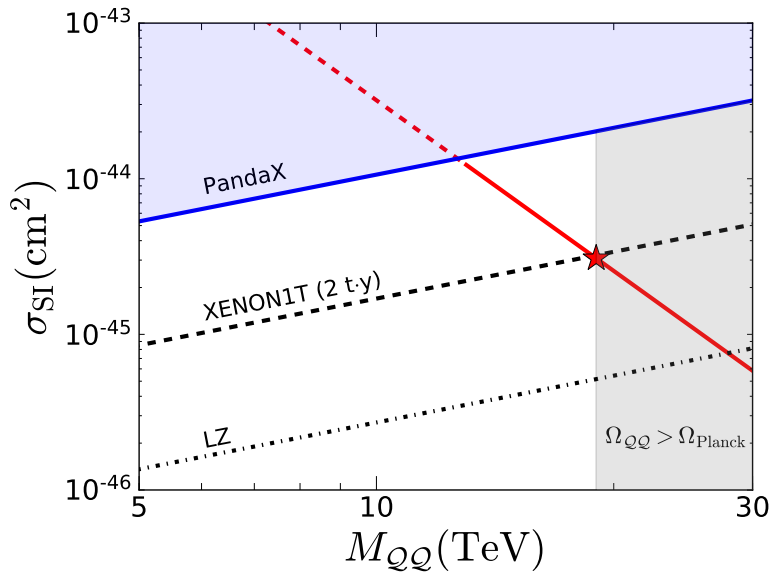
Step two

$$M_Q \simeq 9.5 \text{ TeV}$$

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



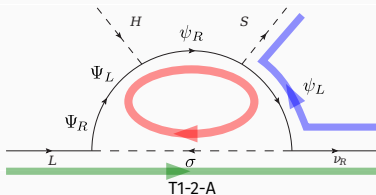
Direct detection



$\psi_{L,R} \rightarrow$ Singlet fermions (quiral)
 $\Psi_{L,R} \rightarrow$ Vector-like doublet fermions : 10/5
 $\sigma \rightarrow$ Singlet scalar : 15/5

Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S	Ψ_L	(Ψ_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

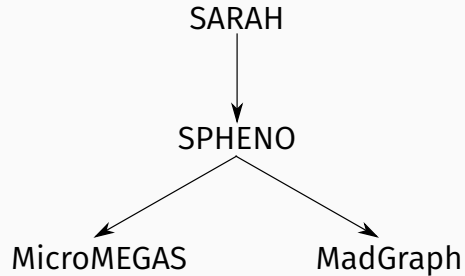
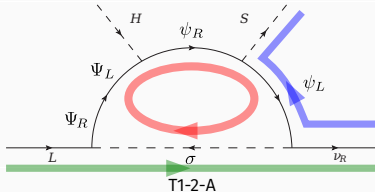
Second Scotogenic Dirac from $SO(10)$ E. Ma
 arXiv:1901.09091 [PLB]



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

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

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



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

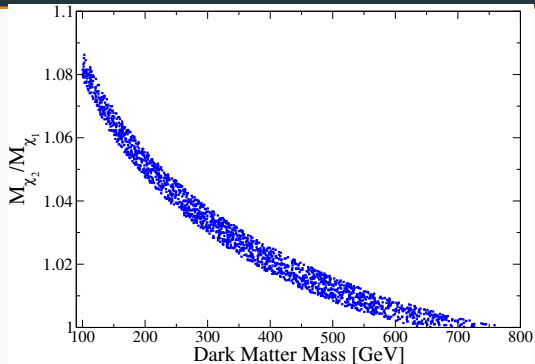
$$\mathcal{L} \supset \textcolor{red}{M}_\psi (\psi_R)^\dagger \psi_L + \textcolor{red}{M}_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + \textcolor{red}{y}_1 (\psi_R)^\dagger \Psi_L \cdot H + \textcolor{red}{y}_2 \widetilde{(\Psi_R)} \cdot \tilde{H} \psi_L + \text{h.c} \quad (5)$$

Four free parameters:

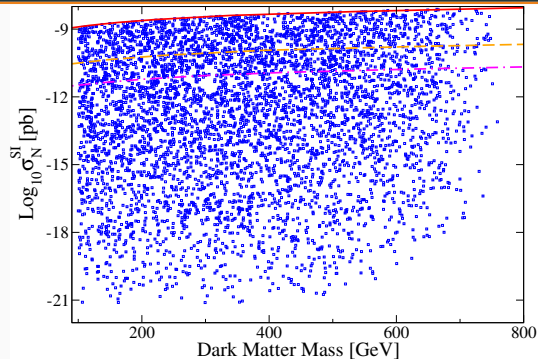
$$\textcolor{red}{M}_\psi, \textcolor{red}{M}_\Psi < 2 \text{ GeV}, \quad \textcolor{red}{y}_1, \textcolor{red}{y}_2 > 10^{-6} \quad (6)$$

Two neutral Dirac fermion eigenstates:

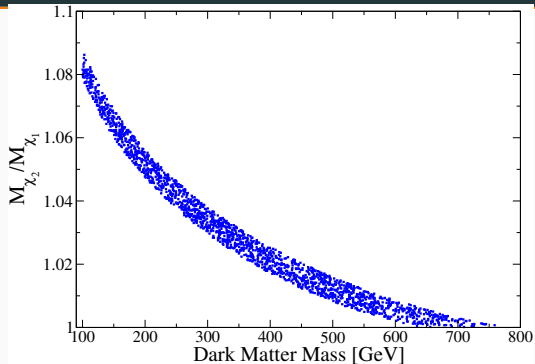
$$M = \begin{pmatrix} \textcolor{red}{M}_\psi & \textcolor{red}{y}_2 v / \sqrt{2} \\ \textcolor{red}{y}_1 v / \sqrt{2} & \textcolor{red}{M}_D \end{pmatrix}, \quad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \quad (7)$$



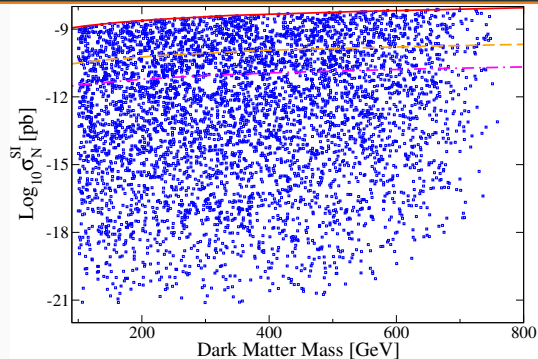
Compressed spectra region



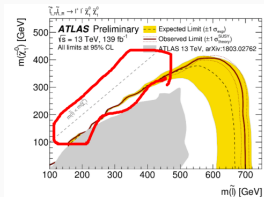
LUX - XENON1T - LZ



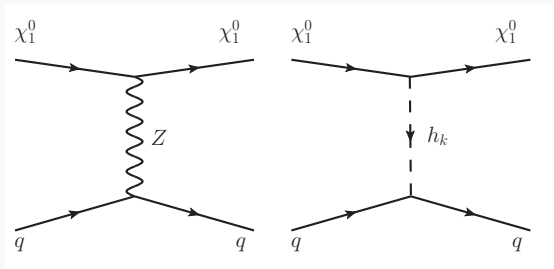
Compressed spectra region



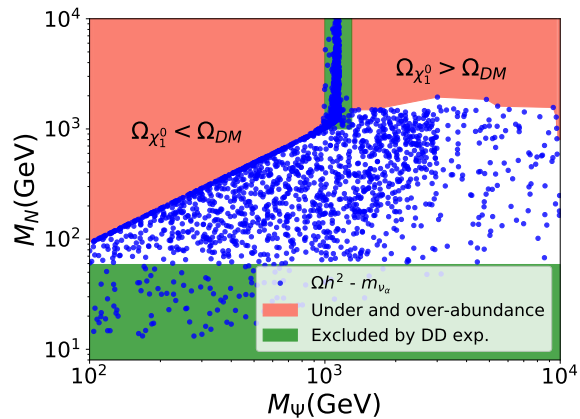
LUX - XENON1T - LZ



Spin independent (SI) direct detection cross section



Decoupled Z' limit



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

see E.Ma and U. Sarkar, arXiv:1707.07698 [PLB]

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

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

Neutrino masses and DM

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

Thanks!