

Dirac fermion dark matter

with Dirac neutrino masses



UNIVERSIDAD DE ANTIOQUIA
1803

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Focus on

1812.05523 [PRD] and 1905.NNNNN

In collaboration with

Carlos Yaguna (UPTC), Julian Calle, Oscar Zapata, Andrés River (UdeA), Walter Tangarife (Loyola University Chicago)

Hidden sectors



+

$$\frac{1}{\Lambda} L \cdot H L \cdot H$$

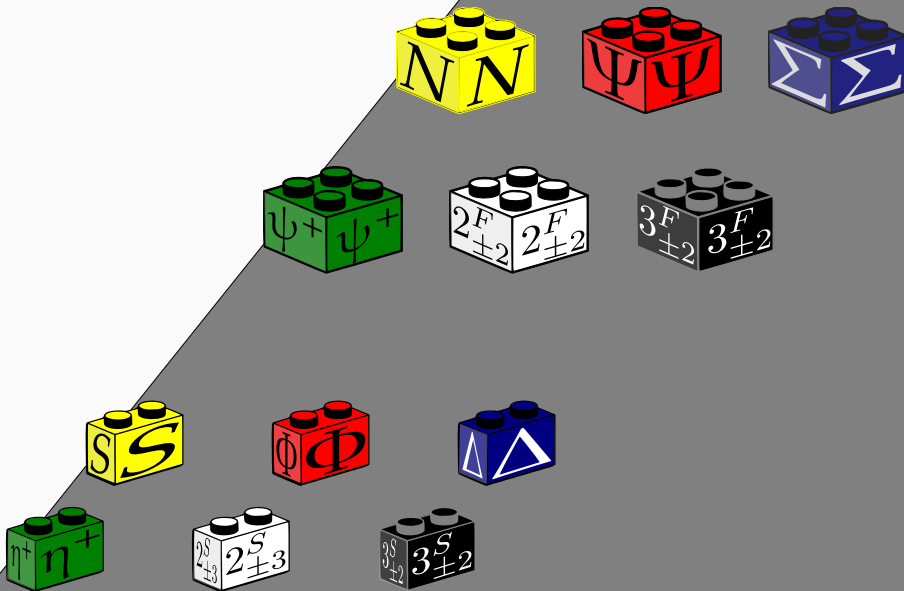
$$\frac{1}{\Lambda} (\nu_R)^\dagger L \cdot H S$$



+

$$\frac{1}{\Lambda} L \cdot H L \cdot H$$

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Dark matter and unification

Unification: $SO(10)$

$$16_{F_i} = \begin{pmatrix} u_R^\dagger \\ u_R^\dagger \\ u_R^\dagger \\ u_L \\ u_L \\ u_L \\ d_L \\ d_L \\ d_L \\ d_R^\dagger \\ d_R^\dagger \\ d_R^\dagger \\ \nu_L \\ e_L \\ e_R^\dagger \\ N \end{pmatrix}_i$$

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



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

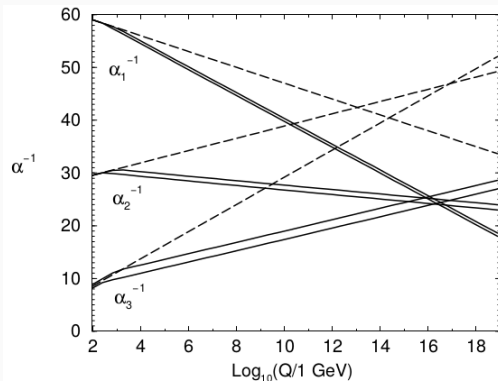
Scalars: $10_H, 45_H \dots$

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

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

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

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Split-SUSY like

arXiv:1509.06313 (C. Arbelaez, R. Longas, D.R, O. Zapata)

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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

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3_0	45 , 54, 210	144

$SU(3)_C$: 3 (T), 6, 8 (Λ)

1509.06313

SUSY-like spectrum: bino-higgsino-wino

+

↓

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

Left-Right symmetric realization

Singlet-doublet fermion dark matter

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.

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.

Triplets

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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L	3	$(1, 2, 1, -1)$	1/2	16
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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

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

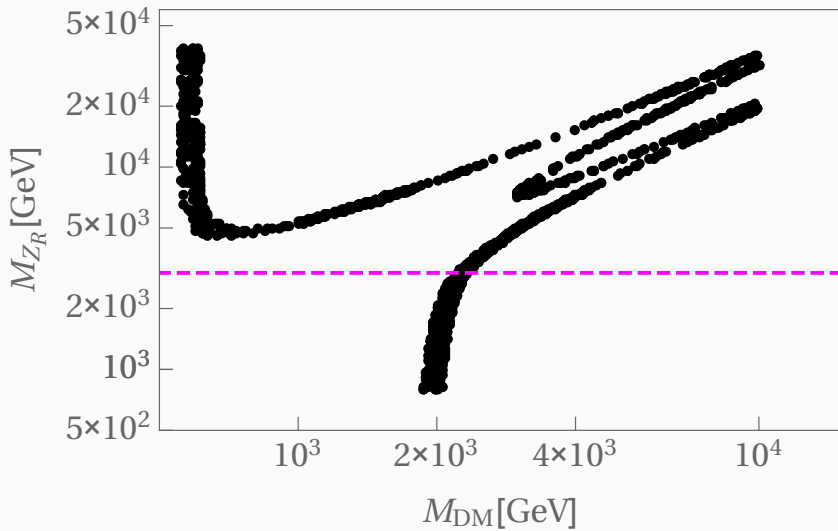


Figure 1: Proper relic density scan: $0.5 < v_R/\text{TeV} < 50$

Mixed Left-singlet right-triplet DM

Field	Multiplicity	$3_C 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
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
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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	$\overline{126}$

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

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

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

Blind spot at

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

Proper relic density scan

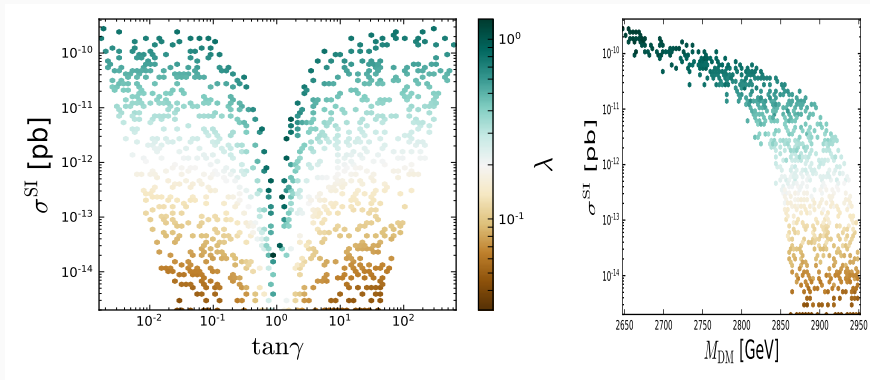


Figure 2: $M_{11} = 50$ TeV $2.7 < M_{23}/\text{TeV} < 3.1$ (Right: $\tan \gamma > 5$)

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

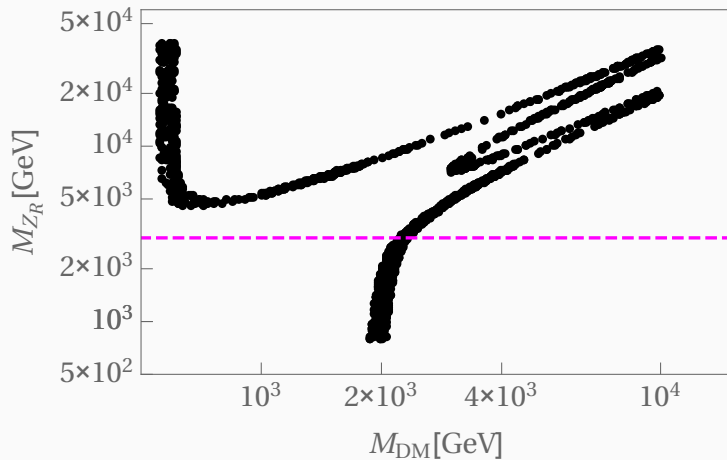


Figure 3:

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

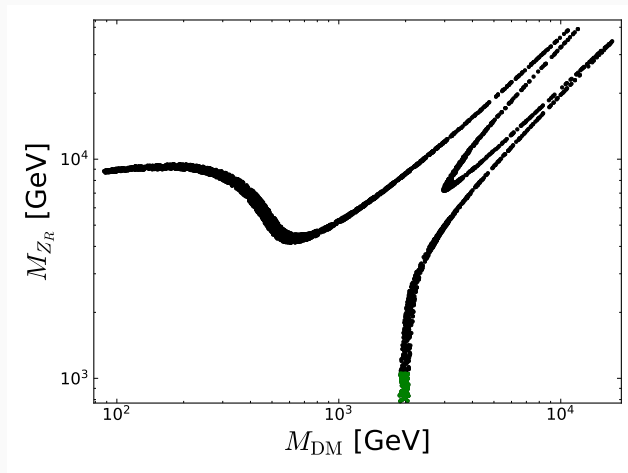


Figure 3: Proper relic density scan: $v_R : [2, 50]$ TeV, $M_{23} : [0.2, 50]$ TeV, $M_{11} : 50$ TeV, $\tan \gamma = -1$ and $\lambda = 0.14$.

Direct detection cross section

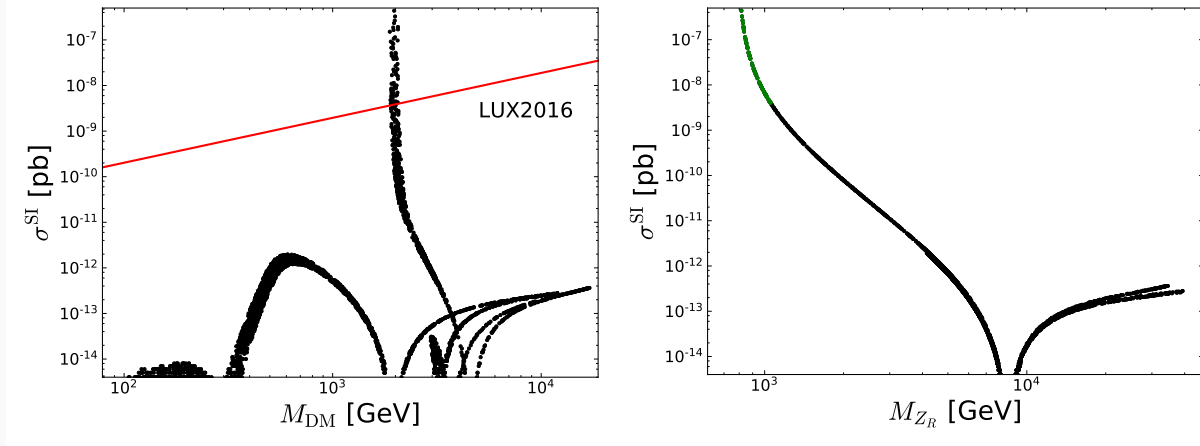


Figure 4: v_R : [2, 50] TeV, M_{23} : [0.2, 50] TeV, M_{11} : 50 TeV, $\tan \gamma = -1$ and $\lambda = 0.14$.

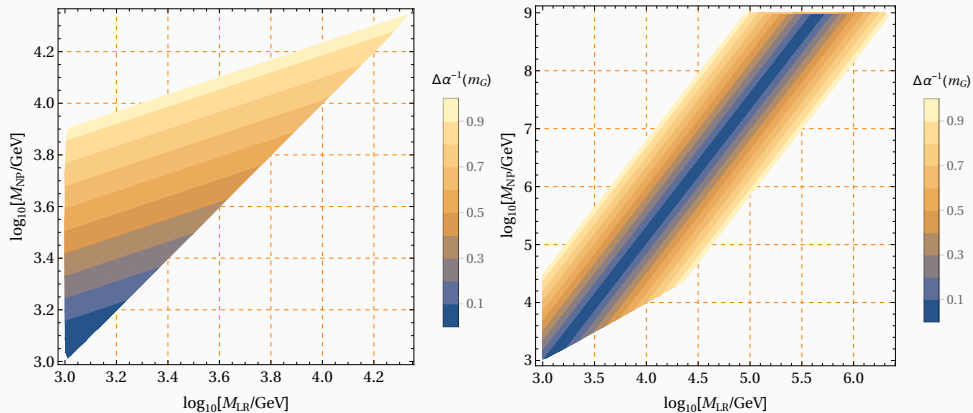
Unification

Field	Multiplicity	$3_C 2_L 2_R 1_{B-L}$	Spin	SO(10) origin
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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



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

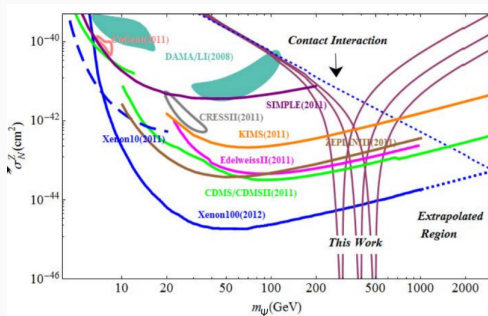
Dirac fermion dark matter

Isosinglet dark matter candidate

ψ as a isosinglet Dirac dark matter fermion charged under a local $U(1)_X$ (SM) couples to a SM-singlet vector mediator X as

$$\mathcal{L}_{\text{int}} = -g_\psi \bar{\psi} \gamma^\mu \psi X_\mu - \sum_f g_f \bar{f} \gamma^\mu f X_\mu,$$

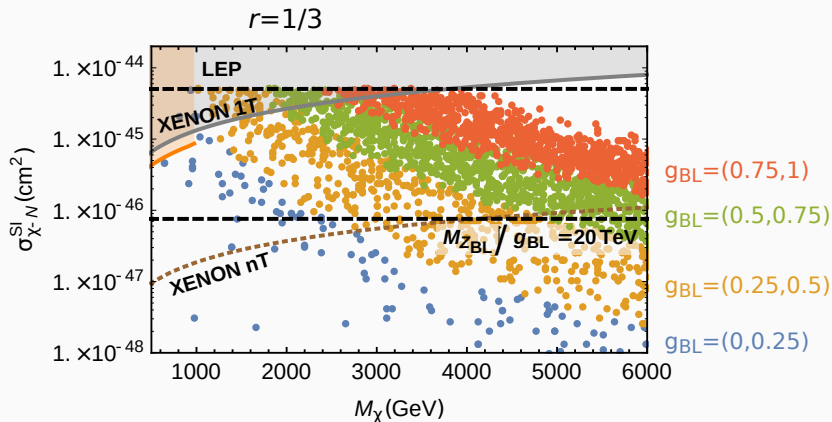
where f are the Standard Model fermions



Isosinglet Dirac fermion dark matter model and Seesaw scale

Left Field	$U(1)_{B-L}$
$(\nu_{R1})^\dagger$	+1
$(\nu_{R2})^\dagger$	+1
$(\nu_{R2})^\dagger$	+1
ψ_L	$-r$
$(\psi_R)^\dagger$	r
ϕ	2

$$\chi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$



Duerr et al: 1803.07462 [PRD]

Singlet-Doublet Dirac Dark matter Model (SD³M)

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

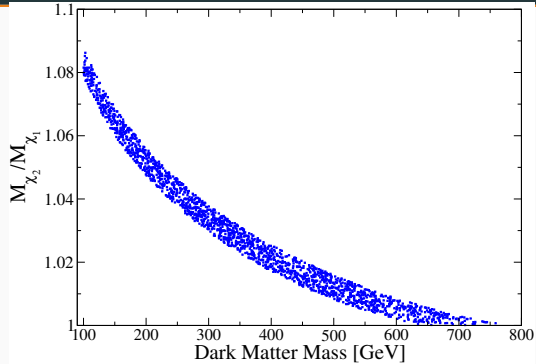
$$\mathcal{L} \supset \textcolor{red}{M}_\psi (\psi_R)^\dagger \psi_L + \textcolor{red}{M}_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + \textcolor{red}{y}_1 (\psi_R)^\dagger \Psi_L \cdot H + \textcolor{red}{y}_2 \widetilde{(\Psi_R)} \cdot \tilde{H} \psi_L + \text{h.c} \quad (5)$$

Four free parameters:

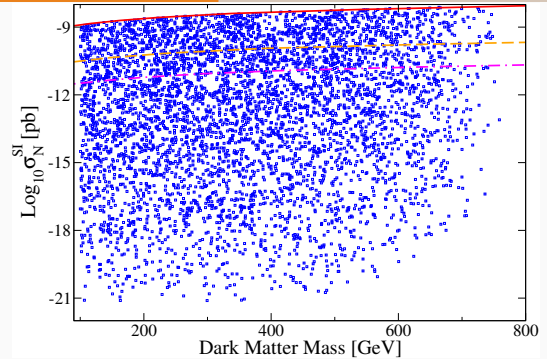
$$\textcolor{red}{M}_\psi, \textcolor{red}{M}_\Psi < 2 \text{ GeV}, \quad \textcolor{red}{y}_1, \textcolor{red}{y}_2 > 10^{-6} \quad (6)$$

Two neutral Dirac fermion eigenstates:

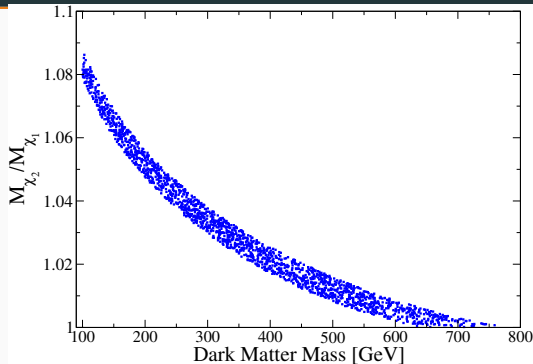
$$M = \begin{pmatrix} \textcolor{red}{M}_\psi & \textcolor{red}{y}_2 v / \sqrt{2} \\ \textcolor{red}{y}_1 v / \sqrt{2} & \textcolor{red}{M}_D \end{pmatrix}, \quad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \quad (7)$$



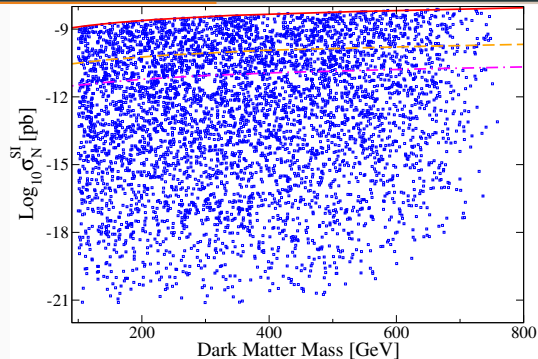
Compressed spectra region



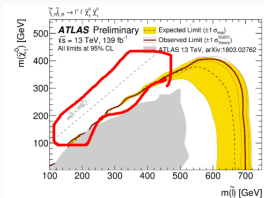
LUX - XENON1T - LZ



Compressed spectra region

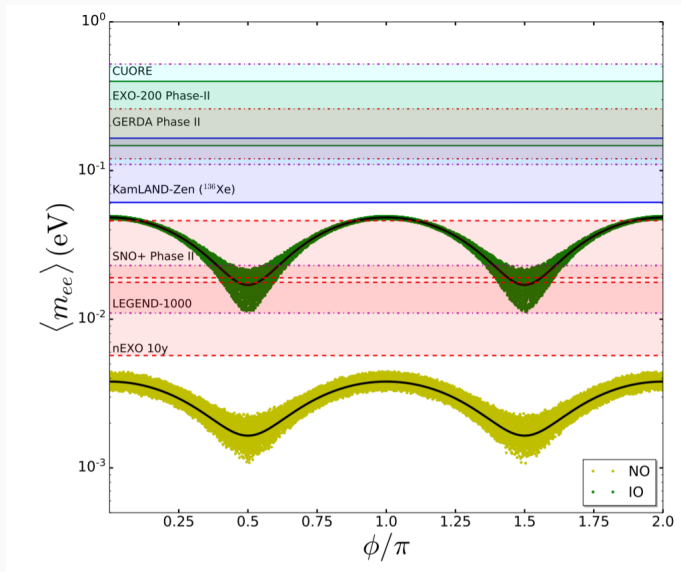


LUX - XENON1T - LZ



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 $\cancel{U(1)}_L$

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

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

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

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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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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Small Dirac neutrino masses

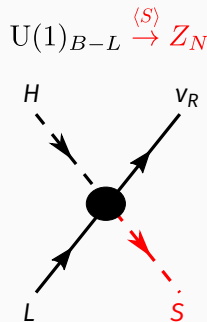
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- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$:

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



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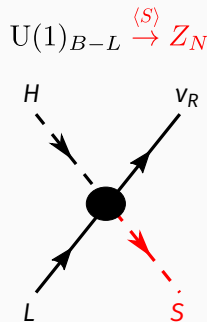
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$$\mathcal{L}_{5-D} = \frac{h_\nu}{\Lambda} (\nu_R)^\dagger L \cdot H S + \text{h.c}$$

- 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

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

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

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

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

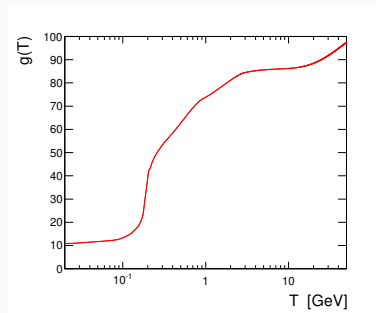
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left(\frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

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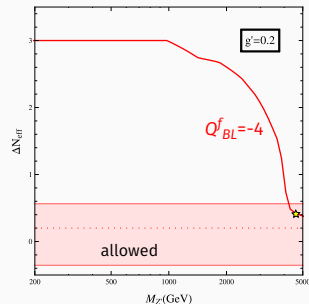
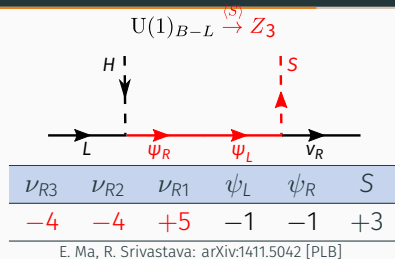
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Z.-L. Han, W. Wang: arXiv:1805.02025 [EJPC]

(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

r



Dirac neutrino masses

$$\nu_R \nu_R$$

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

$$\nu_R \psi_R$$

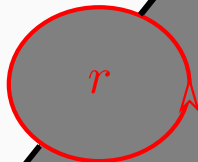
$$(\psi_L)^\dagger \nu_R$$

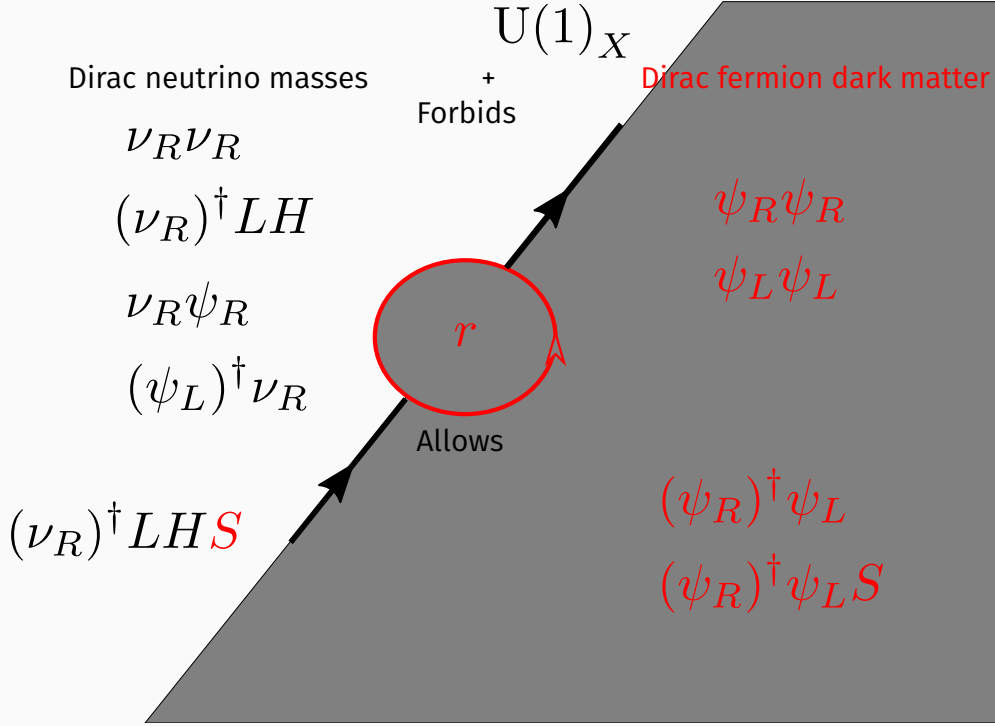
$U(1)_X$
+
Forbids

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

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

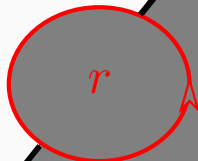
$$\psi_R \psi_R$$

$$\psi_L \psi_L$$

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

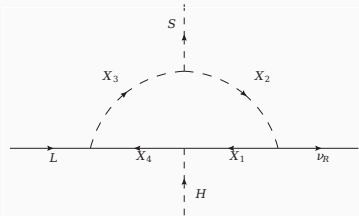
$$(\psi_R)^\dagger \psi_L S$$

Allows

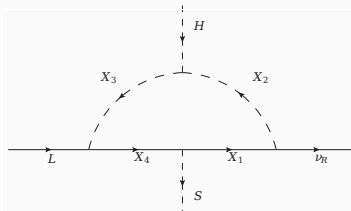


normalized to $X(L) = -1$

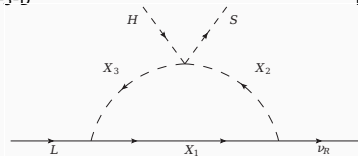
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



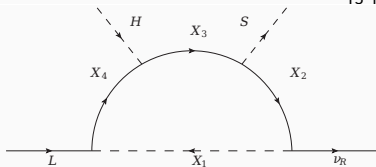
T1-3-D



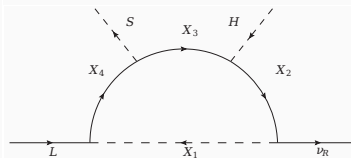
T1-3-E



T3-1-A



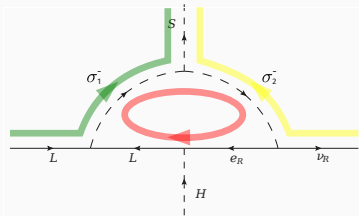
T1-2-A



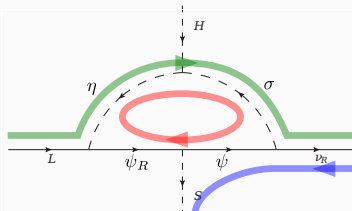
T1-2-B

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

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



T1-3-D



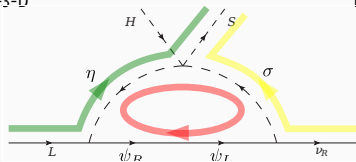
T1-3-E

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

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

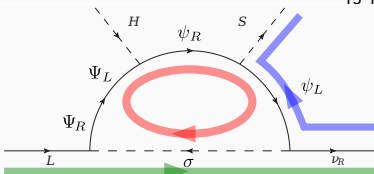
$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar

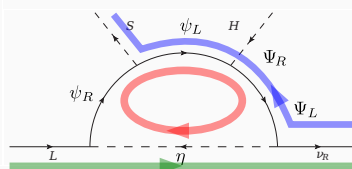


T3-1-A

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

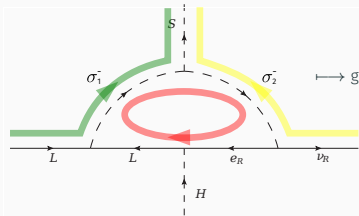


T1-2-A



T1-2-B

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



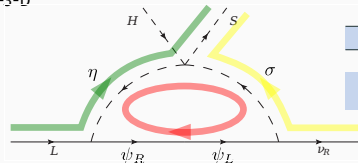
→ generalization to two and three loops: Shaikh Saad arXiv:1902.07259

T1-3-D

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

$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar



T3-1-A

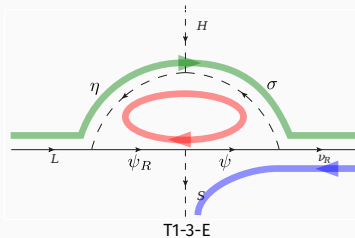
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3

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]



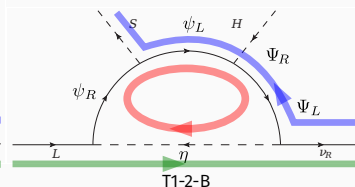
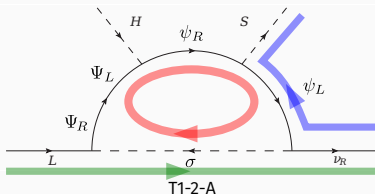
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$

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

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

$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar

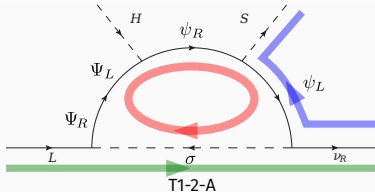


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$$\sum_i f_i^3 = 3$$

$\psi_{L,R} \rightarrow$ 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
(A)	+4	+4	-5	-r	r	+3
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$

Anomaly cancellation conditions

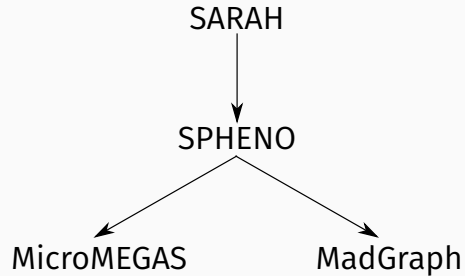
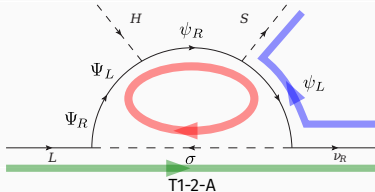
$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

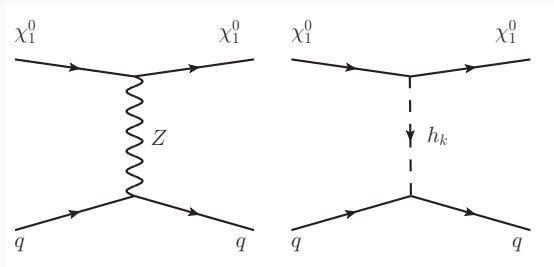
$$M_\psi = h_1 \langle S \rangle, y_2 = 0:$$

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

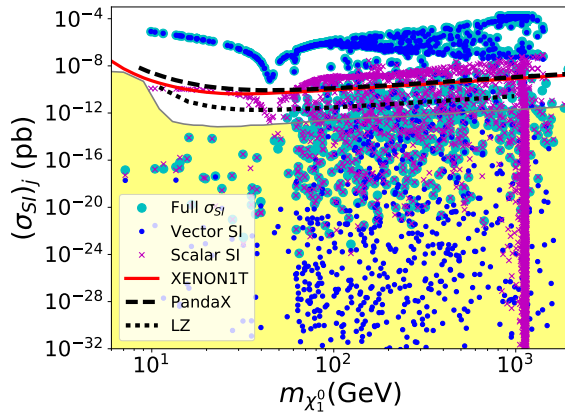
with A.F Rivera, W. Tangarife, arXiv:19nn.nnnnn



Spin independent (SI) direct detection cross section



Decoupled Z' limit



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

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

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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 Singlet Doublet Dirac Dark Matter or Singlet Scalar Dark Matter with extra scalar and vector portal
- With relaxed direct detection constraints

Thanks!