Dirac fermion dark matter

with Dirac neutrino masses

Diego Restrepo

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

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)

Background: from William Balunas ATLAS talk at Mitchell Conference on Collider, Dark Matter, and Neutrino Physics 2019

3 broad classes of DM models:

Effective Field Theories

– We don't know what the higher-scale physics is, but we can integrate it out.

“Simplified Models”

– We introduce a few additional degrees of freedom, but don't try to make statements about the complete theory.

Complete Theories

– We add a full set of new DoF's and expect them to explain everything (e.g. SUSY).

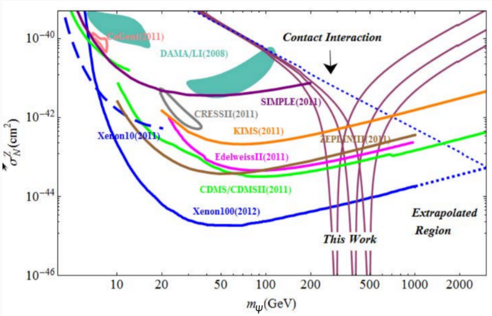
Dirac fermion dark matter

Isosinglet dark matter candidate

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

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

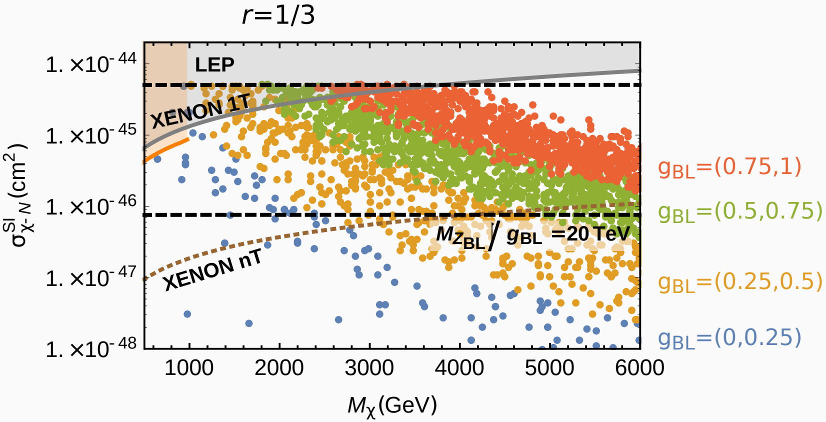
where f are the Standard Model fermions



1305.7008. Chua, Hsieh

Left Field	$U(1)_{B-L}$
$(\nu_{R_1})^\dagger$	$+1$
$(\nu_{R_2})^\dagger$	$+1$
$(\nu_{R_2})^\dagger$	$+1$
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 (SD^{3}M)

Singlet-Doublet Dirac Dark Matter (SD^3M) 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

$$\mathcal{L} \supset M_\psi \left(\psi_R\right)^\dagger \psi_L + M_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + y_1 \left(\psi_R\right)^\dagger \Psi_L \cdot H + y_2 \widetilde{(\Psi_R)} \cdot \widetilde{H} \psi_L + \text{h.c} \tag{1}$$

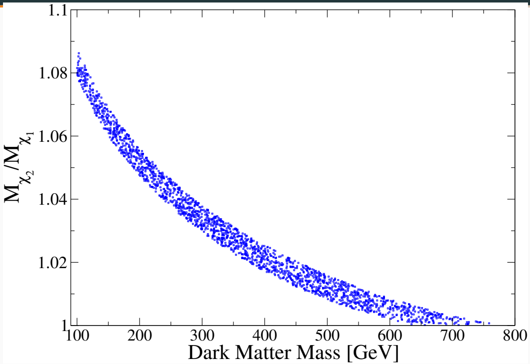
Four free parameters:

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

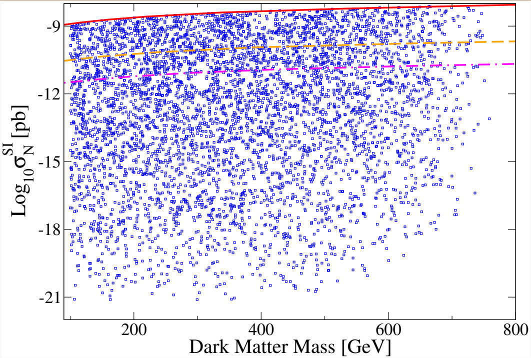
Two neutral Dirac fermion eigenstates:

$$M = \begin{pmatrix} M_\psi & y_2 v/\sqrt{2} \\ y_1 v/\sqrt{2} & M_D \end{pmatrix}, \qquad\qquad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \tag{3}$$

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

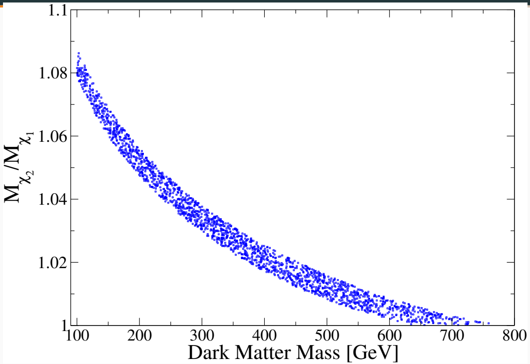


Compressed spectra region



LUX - XENON1T - LZ

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



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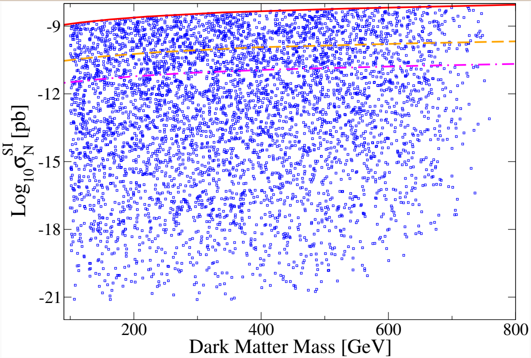
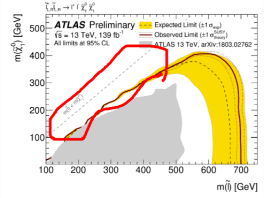


LUX - XENON1T - LZ

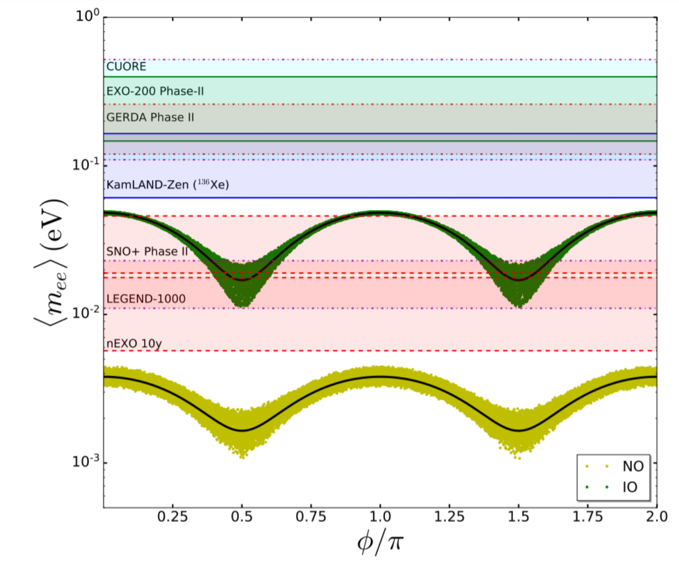


Neutrino masses

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

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

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

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

Dirac U(1)$_L$

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

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

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

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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:

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

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 ($Y(H) = +1/2$)

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

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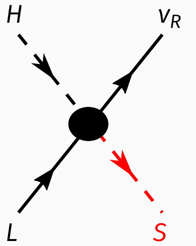
- Realizes of the 5-dimension operator which conserves lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

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

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



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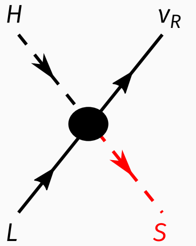

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- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - N_{\mathrm{eff}}^{\mathrm{SM}}$ (see arXiv:1211.0186)

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

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

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

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

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

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

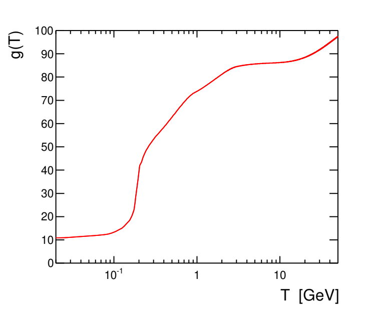
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \quad \text{In the limit } M^2_{Z'} \gg s\,.$$

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

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



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

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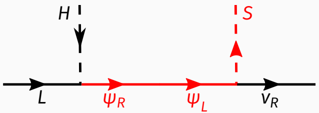
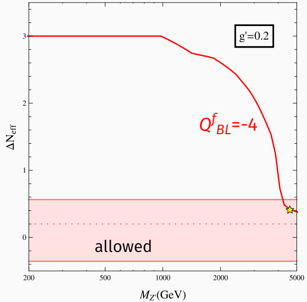
$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S\rangle} Z_3$



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]



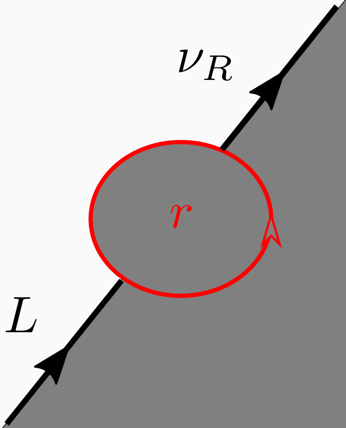
Z.-L. Han, W. Wang: arXiv:1805.02025 [EJPC]

(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 + Dirac fermion dark matter

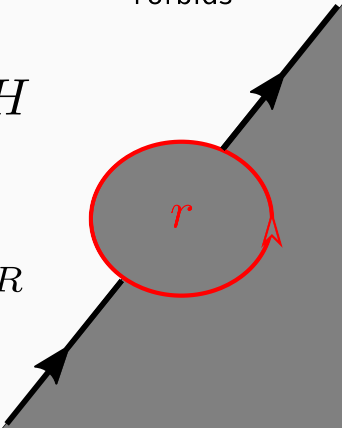
Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$



$\psi_R \psi_R$

$\psi_L \psi_L$

$\mathrm{U}(1)_X$

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

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$X(L) \neq 0$

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

r

Allows

$\psi_R \psi_R$

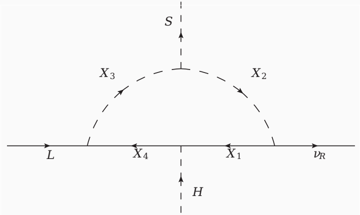
$\psi_L \psi_L$

$(\psi_R)^\dagger \psi_L$

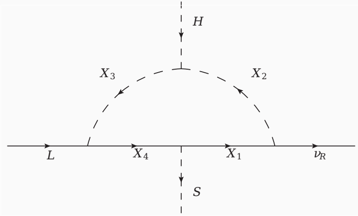
$(\psi_R)^\dagger \psi_L S$

normalized to $X(L) = -1$

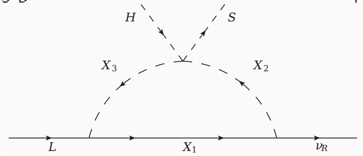
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

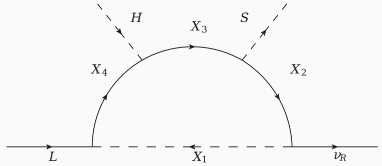


T1-3-E

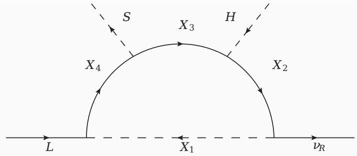


T3-1-A

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

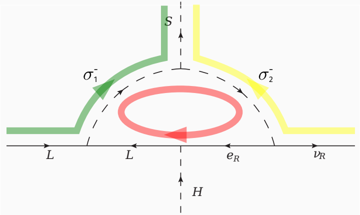


T1-2-A

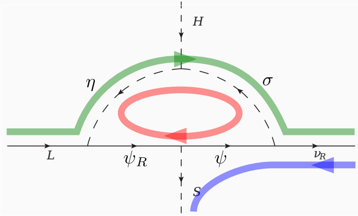


T1-2-B

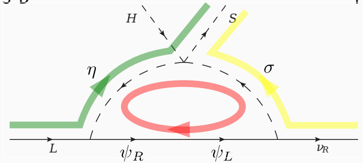
One loop topologies $U(1)_{B-L}$ only!



T1-3-D



T1-3-E



T3-1-A

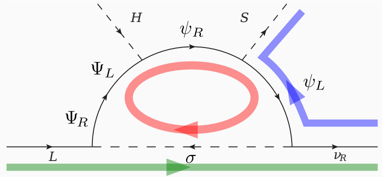
$\psi_{L,R}$ $\rightarrow$Singlet fermions

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

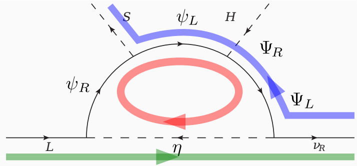
σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar

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

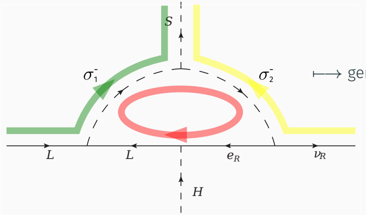


T1-2-A



T1-2-B

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



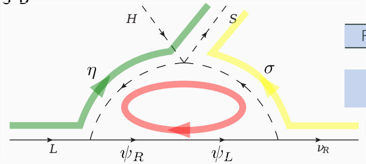
T1-3-D

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

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

σ $\rightarrow$Singlet scalar

η $\rightarrow$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

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

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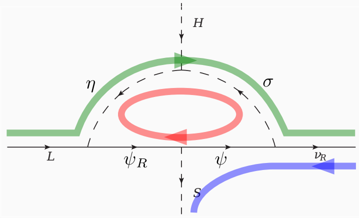
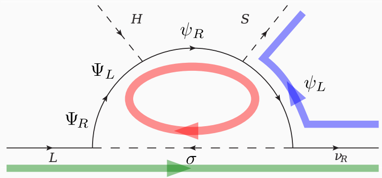


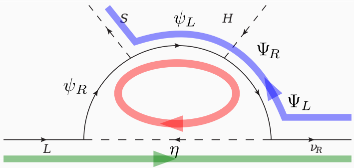
T1-3-E

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

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$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

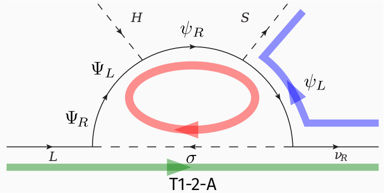
SD^{3}M+σ_i $(i=1,2)$ with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

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

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

σ $\rightarrow$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

$$\sum_i f_i = 3$$

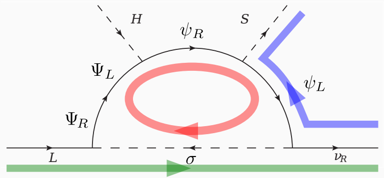
$$\sum_i f_i^3 = 3$$

SD^{3}M+σ_i $(i = 1, 2)$

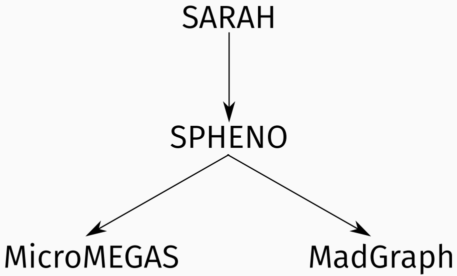
$$M_\psi = h_1 \langle S \rangle,\ y_2 = 0:$$

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

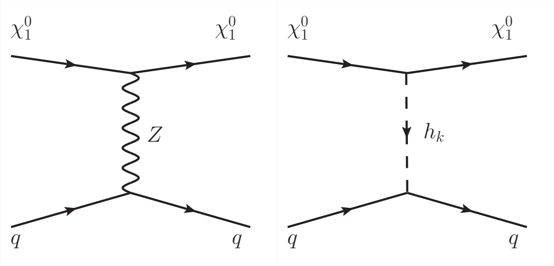
with A.F Rivera, W. Tangarife, arXiv:19nn.nnnnn



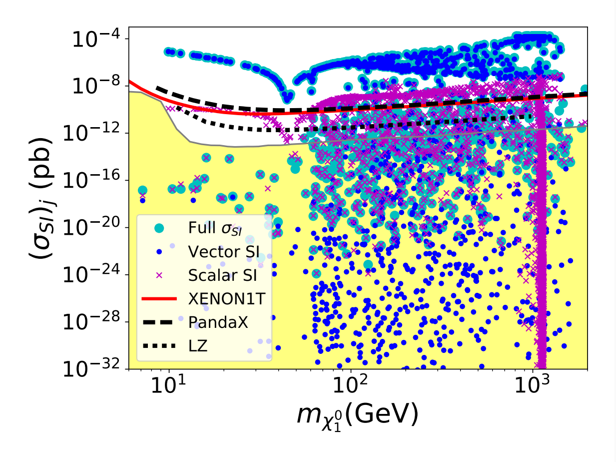
T1-2-A



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!