

Singlet-Doublet Dark Matter and Neutrino Masses



Diego Restrepo

Sep 11, 2019 - Darkwin - Natal [PDF: <http://bit.ly/darkwin2>]

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Focus on

[arXiv:1811.11927 \[PRD\]](#) and [arXiv:1906.09685 \[PRD\]](#)

In collaboration with

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



Previously at tree level

Dark sectors



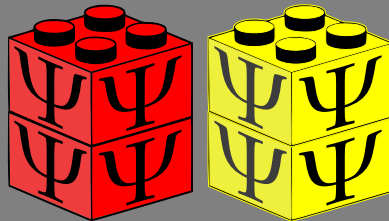
Local $U(1)_X \rightarrow Z_7$

$$\mathcal{L} = y (N_R)^\dagger L \cdot \langle H \rangle + y' \langle S \rangle N_R N_R + \text{h.c}$$



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

Type-I arXiv:1808.03352



Standard model extended with $U(1)_X$ gauge symmetry

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
L	1	2	$-1/2$	l
Q	3	2	$-1/6$	q
d_R	3	1	$-1/2$	d
u_R	3	1	$+2/3$	u
e_R	1	1	-1	e
H	1	2	$1/2$	h

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L	1	2	$-1/2$	l
Q	3	2	$-1/6$	$q = -l/3$
d_R	3	1	$-1/2$	$d = e - 4l/3$
u_R	3	1	$+2/3$	$u = -e + 2l/3$
e_R	1	1	-1	e
H	1	2	$1/2$	$h = -e + l$
$\sum_\alpha \psi_\alpha$	1	1	0	$\sum_\alpha \psi_\alpha$



Linear anomaly cancellation conditions

$$\begin{array}{ll}
 [SU(3)_c]^2 U(1)_X & [SU(2)_L]^2 U(1)_X \\
 [U(1)_Y]^2 U(1)_X & \rightarrow U(1)_Y [U(1)_X]^2 .
 \end{array}$$

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e_R	1	1	-1	$e = 1 + 2l$
H	1	2	$1/2$	$h = -1 - l$
$\sum_{\alpha} \psi_{\alpha}$	1	1	0	-3

$$\sum_{\alpha} \psi_{\alpha}^3 = -3, \quad \sum_{\alpha} \psi_{\alpha} = -3$$

$(N_R, N_R, \psi_{N-2}, \dots, \psi_1)$	arXiv
$(-1, -1, -1)$	hep-ph/0611205, Khalil
$\left(-\frac{2}{3}, -\frac{2}{3}, -\frac{4}{3}, -\frac{1}{3}\right)$	 1607.04029, Patra, Rodejohann, Yaguna [JHEP]
$\left(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7}\right)$	 1808.03352, with Bernal, Yaguna, Zapata [PRD]

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General cancellation for

$$[U(1)_X]^3 \quad [SO(1,3)]^2 U(1)_X :$$

$$\sum_\alpha \psi_\alpha^3 + 3(e - 2l)^3 = 0, \quad \sum_\alpha \psi_\alpha + 3(e - 2l) = 0,$$

with $\alpha = 1, 2, \dots, N$.

Set of solutions with

$$\sum_\alpha \psi_\alpha^3 = -3, \quad \sum_\alpha \psi_\alpha = -3$$

$(\nu_R, \nu_R, \psi_{N-2}, \dots, \psi_1)$	arXiv
$(-1, -1, -1)$	hep-ph/0611205, Khalil
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$(-4, -4, +5)$	0706.0473, Montero, Pleitez [PLB]
$(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, \frac{10}{5})$	1812.05523, with Calle, Yaguna, Zapata [PRD]

$$e - 2l = 1$$

https://en.wikipedia.org/wiki/Sums_of_three_cubes

Only known integer solutions for -3 (1953)





September 2019:

$$42 = (-80538738812075974)^3 + 80435758145817515^3 + 12602123297335631^3$$

Standard model extended with $U(1)_X$ gauge symmetry

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$	$U(1)_R$	$U(1)_D$	$U(1)_G$
L	1	2	$-1/2$	$l = -1$	0	$-3/2$	$-1/2$
Q	3	2	$-1/6$	$q = 1/3$	0	$+1/2$	$+1/6$
d_R	3	1	$-1/2$	$d = 1/3$	+1	0	$+2/3$
u_R	3	1	$+2/3$	$u = 1/3$	-1	+1	$-1/3$
e_R	1	1	-1	$e = -1$	+1	-2	0
H	1	2	$1/2$	$h = 0$	-1	$+1/2$	$-1/2$
$\sum_\alpha \psi_\alpha$	1	1	0	-3	-3	-3	-3

$$\sum_\alpha \psi_\alpha^3 = -3, \quad \sum_\alpha \psi_\alpha = -3$$

$(\nu_R, \nu_R, \psi_{N-2}, \dots, \psi_1)$	arXiv
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Not known solution for
one-loop neutrino Majorana masses
with local $U(1)_X$.

Beyond Dirac fermion dark matter

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

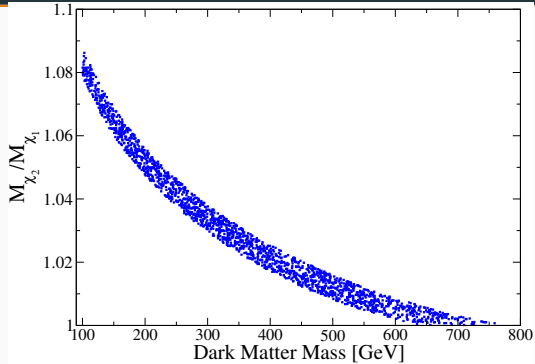
$$\mathcal{L} \supset M_\psi (\psi_R)^\dagger \psi_L + M_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + y_1 (\psi_R)^\dagger \Psi_L \cdot H + y_2 \widetilde{(\Psi_R)} \cdot \tilde{H} \psi_L + \text{h.c} \quad (1)$$

Four free parameters:

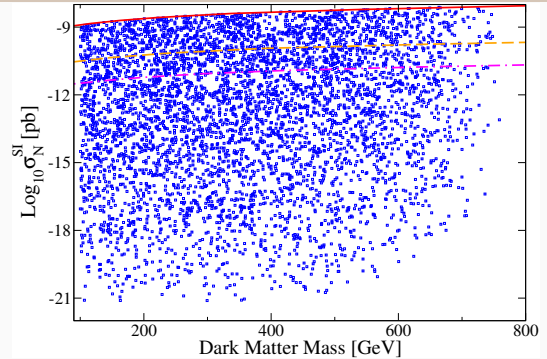
$$M_\psi, M_\Psi < 2 \text{ GeV}, \quad y_1, y_2 > 10^{-6} \quad (2)$$

Two neutral Dirac fermion eigenstates:

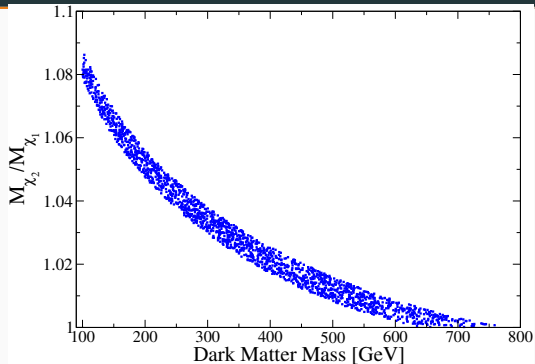
$$M = \begin{pmatrix} M_\psi & y_2 v / \sqrt{2} \\ y_1 v / \sqrt{2} & M_D \end{pmatrix}, \quad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \quad (3)$$



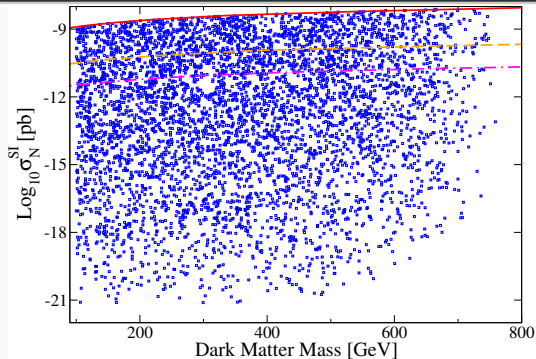
Compressed spectra region



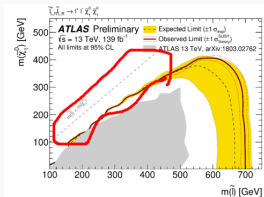
LUX - XENON1T - LZ



Compressed spectra region

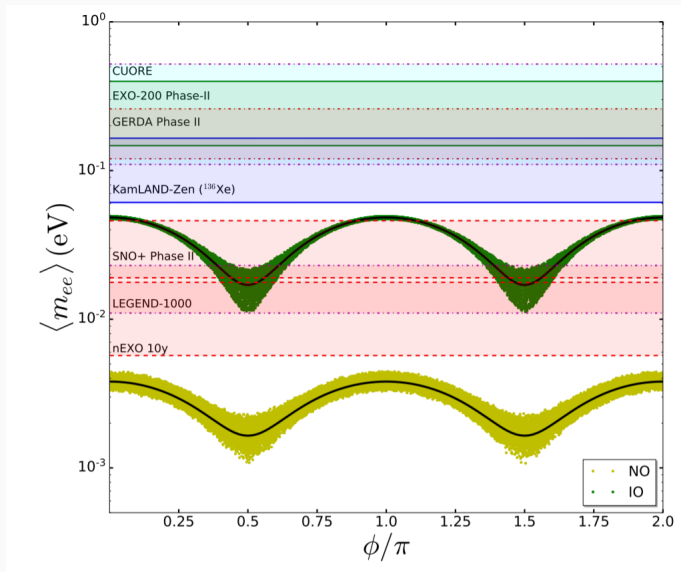


LUX - XENON1T - LZ



One-loop Dirac 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: $L = L_e + L_\mu + L_\tau$

Majorana $U(1)_L$

Field	Z_2 ($\omega^2 = 1$)
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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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Small Dirac neutrino masses

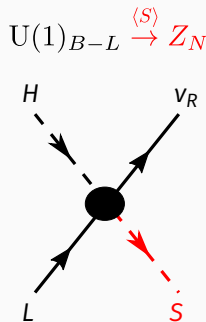
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- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$:

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



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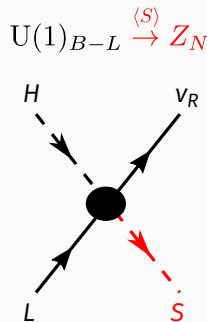
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- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$ (see arXiv:1211.0186)



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

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

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

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

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

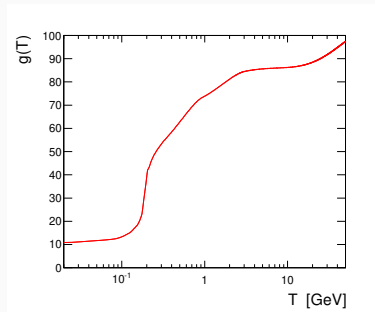
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left(\frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

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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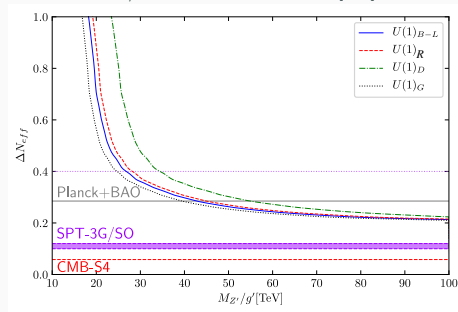
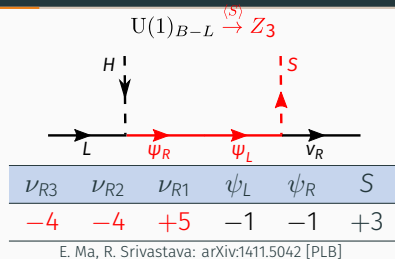
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with J. Calle and Ó. Zapata, in progress

(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

$$\nu_R \nu_R$$

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

$$\nu_R \psi_R$$

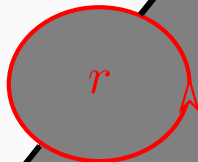
$$(\psi_L)^\dagger \nu_R$$

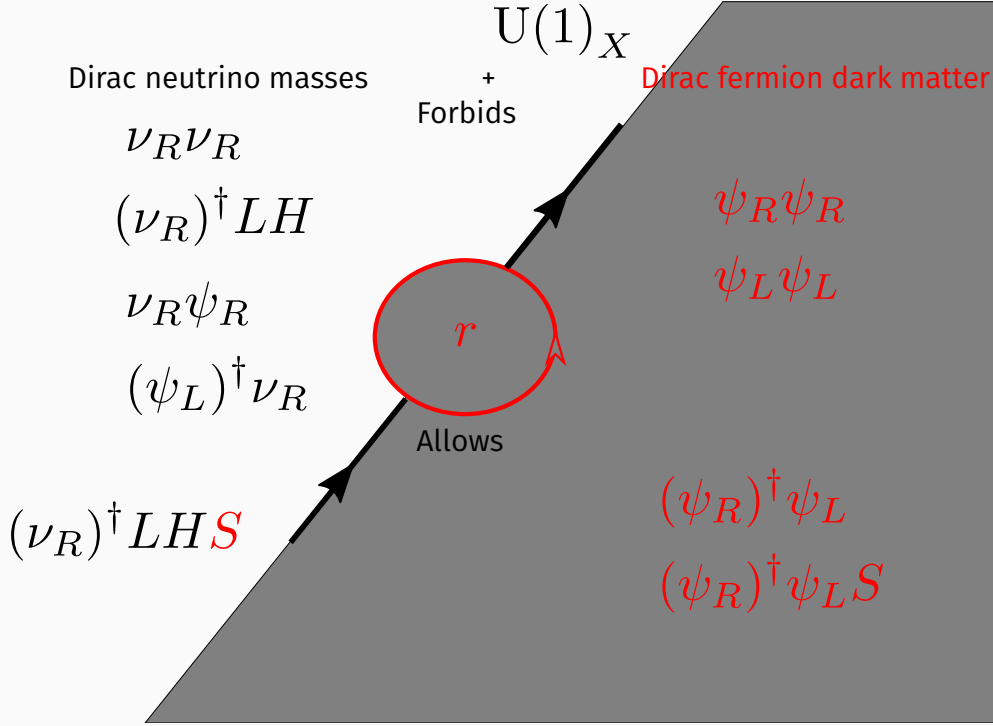
$U(1)_X$
+
Forbids

Dirac fermion dark matter

$$\psi_R \psi_R$$

$$\psi_L \psi_L$$





Dirac neutrino masses

$$\nu_R \nu_R$$

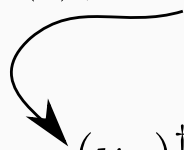
$$(\nu_R)^\dagger LH$$

$$\nu_R \psi_R$$

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

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

$X(L) \neq 0$



+
Forbids

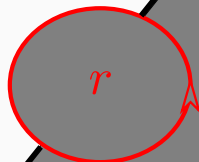
$U(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N$ $N \neq 2$
Dirac fermion dark matter

$$\psi_R \psi_R$$

$$\psi_L \psi_L$$

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

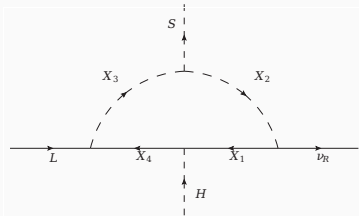
$$(\psi_R)^\dagger \psi_L S$$



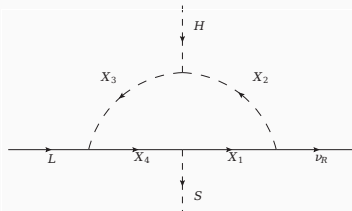
Allows

normalized to $X(L) = -1$

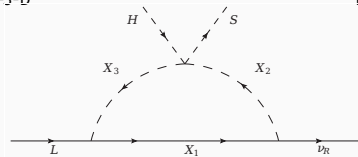
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



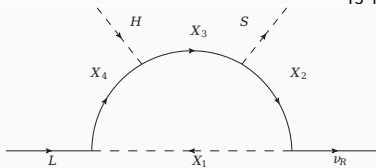
T1-3-D



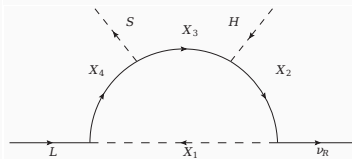
T1-3-E



T3-1-A



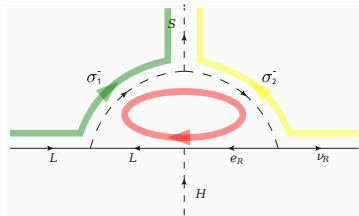
T1-2-A



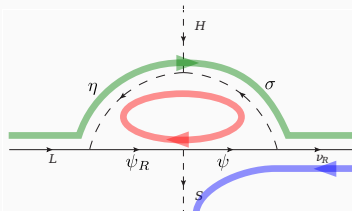
T1-2-B

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

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



T1-3-D



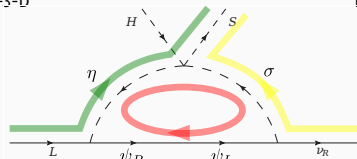
T1-3-E

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

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

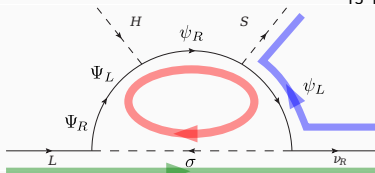
$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar

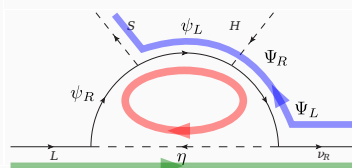


T3-1-A

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

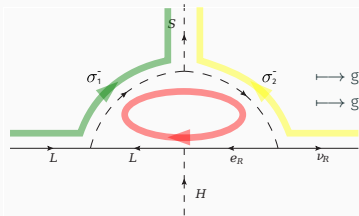


T1-2-A



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: S. Saad arXiv:1902.07259 [NPB]

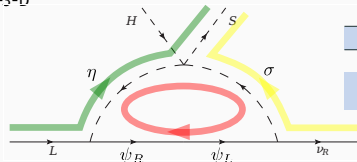
→ generalization to $U(1)_R$: et al, S. Saad arXiv:1904.07407

T1-3-D

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

$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar



T3-1-A

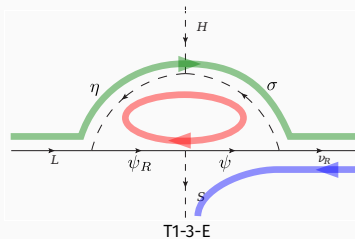
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3

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]



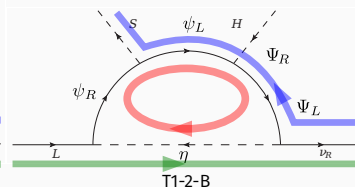
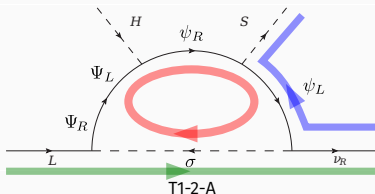
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$

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

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

$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar

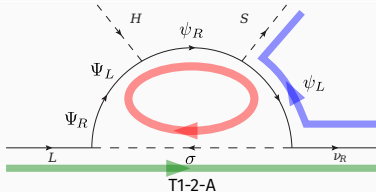


Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

$\psi_{L,R} \rightarrow$ 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

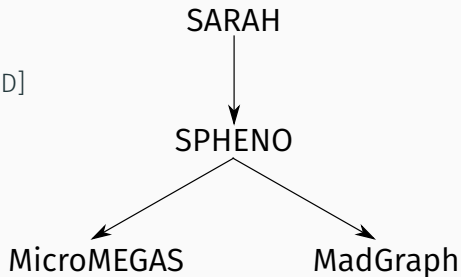
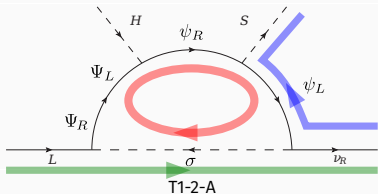
$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

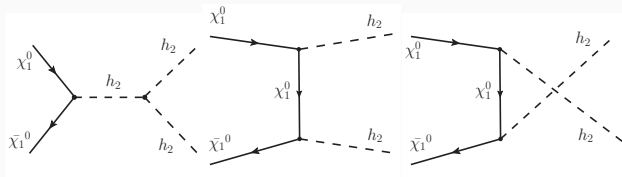
$$M_\psi = h_1 \langle S \rangle, y_2 = 0:$$

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

with A.F Rivera, W. Tangarife, arXiv:1906.09685 [PRD]

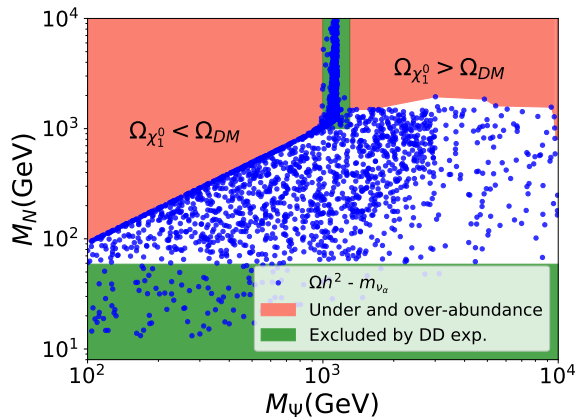


Dark matter relic density

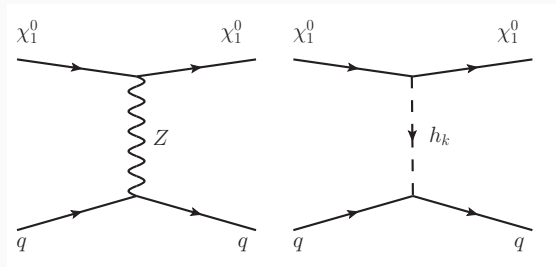


Decoupled Z' limit

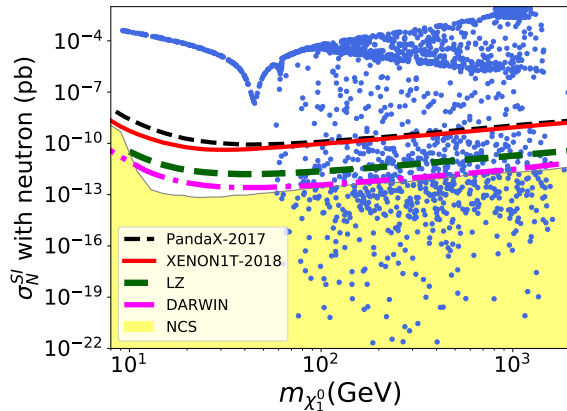
$$\begin{pmatrix} h \\ \text{Re}(S) \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}.$$



Spin independent (SI) direct detection cross section



Decoupled Z' limit



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!