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

SM

Local $U(1)_X \to Z_7$

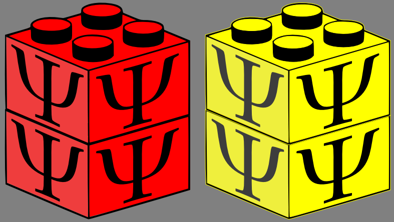
$$\mathcal{L} = y\,(N_R)^{\dagger} L\cdot\langle H\rangle + y'\langle S\rangle N_R N_R + \text{h.c}$$

$\langle$SM$\rangle$

+

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

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

$$
\begin{array}{lcl}
[\mathrm{SU}(3)_C]^2\,\mathrm{U}(1)_X & & [\mathrm{SU}(2)_L]^2\,\mathrm{U}(1)_X \\
[\mathrm{U}(1)_Y]^2\,\mathrm{U}(1)_X & \rightarrow & \mathrm{U}(1)_Y\,[\mathrm{U}(1)_X]^2\ .
\end{array}
$$

arXiv:1705.05388, Farinaldo Queiroz, *et al* [JHEP]

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u_R	3	1	$+2/3$	$u=-1-4l/3$
e_R	1	1	-1	$e=1+2l$
H	1	2	$1/2$	$h=-1-l$
$\sum_\alpha \psi_\alpha$	1	1	0	-3

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

$(N_R, N_R, \psi_{N-2}, \cdots \psi_1)$	arXiv
$(-1,-1,-1)$	hep-ph/0611205, Khalil [JPG]
$\left(-\frac{2}{3},-\frac{2}{3},-\frac{4}{3},-\frac{1}{3}\right)$	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]

General cancellation for

$$[\mathrm{U}(1)_X]^3 \qquad [\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_X:$$

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

with $\alpha=1,2,\cdots,N$.
Set of solutions with

$$e-2l=1$$

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$(-4,-4,+5)$	0706.0473, Montero, Pleitez [PLB]
$\left(-\frac{8}{5},-\frac{8}{5},-\frac{2}{5},-\frac{7}{5},\frac{10}{5}\right)$	1812.05523, with Calle, Yaguna, Zapata [PRD]

General cancellation for

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

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

Set of solutions with

$$e - 2l = 1$$

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

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

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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 (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

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

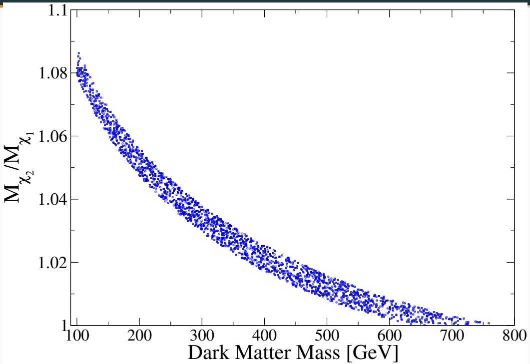
Four free parameters:

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

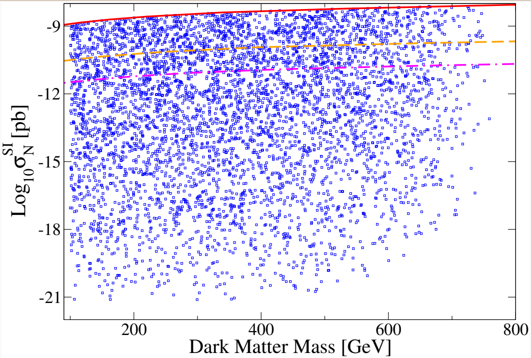
Two neutral Dirac fermion eigenstates:

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

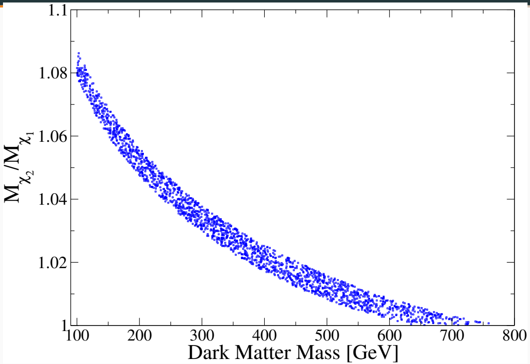
SD^3M By Carlos E. Yaguna. arXiv:1510.06151 [PRD].



Compressed spectra region



LUX - XENON1T - LZ



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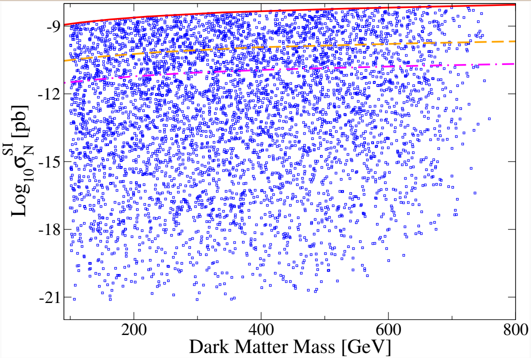

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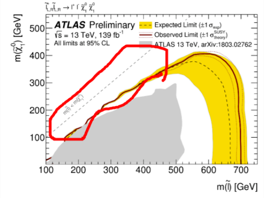
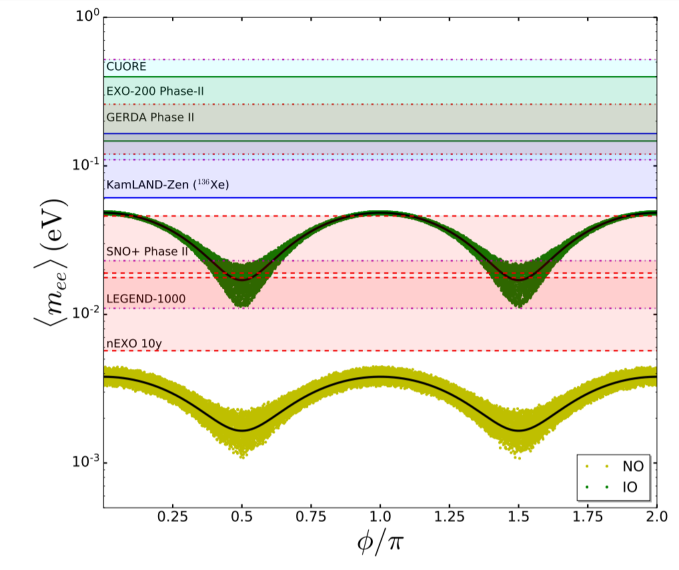


One-loop Dirac neutrino masses

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 $\mathrm{U}(1)_L$

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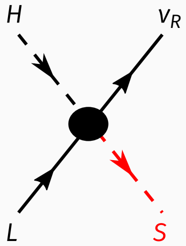
$$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N$$



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

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

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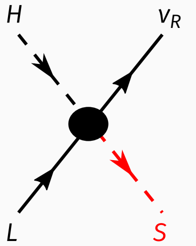


- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - N_{\mathrm{eff}}^{\mathrm{SM}}$ (see arXiv:1211.0186)

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

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

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

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

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

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

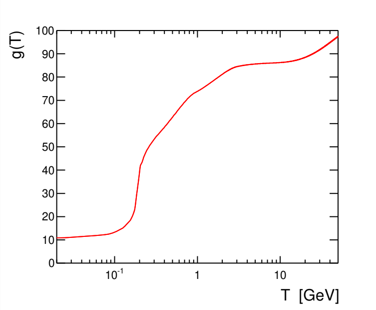
$$\sigma_f(s) \simeq \frac{N_C^f (Q^f_{BL})^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \quad \text{In the limit } M^2_{Z'} \gg s\,.$$

with three right-handed neutrinos, the Hubble parameter is

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

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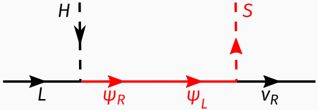
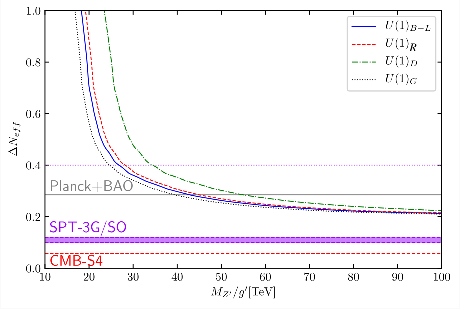
$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S\rangle} Z_3$



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]



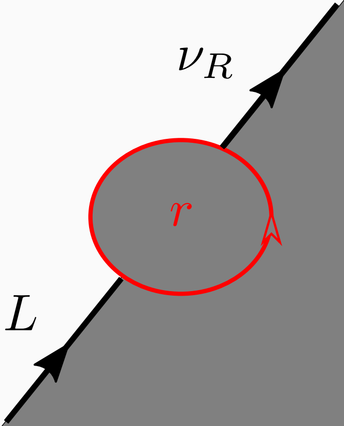
with J. Calle and Ó. Zapata, in progress

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

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

$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter



$\mathrm{U}(1)_X$

Dirac neutrino masses

+

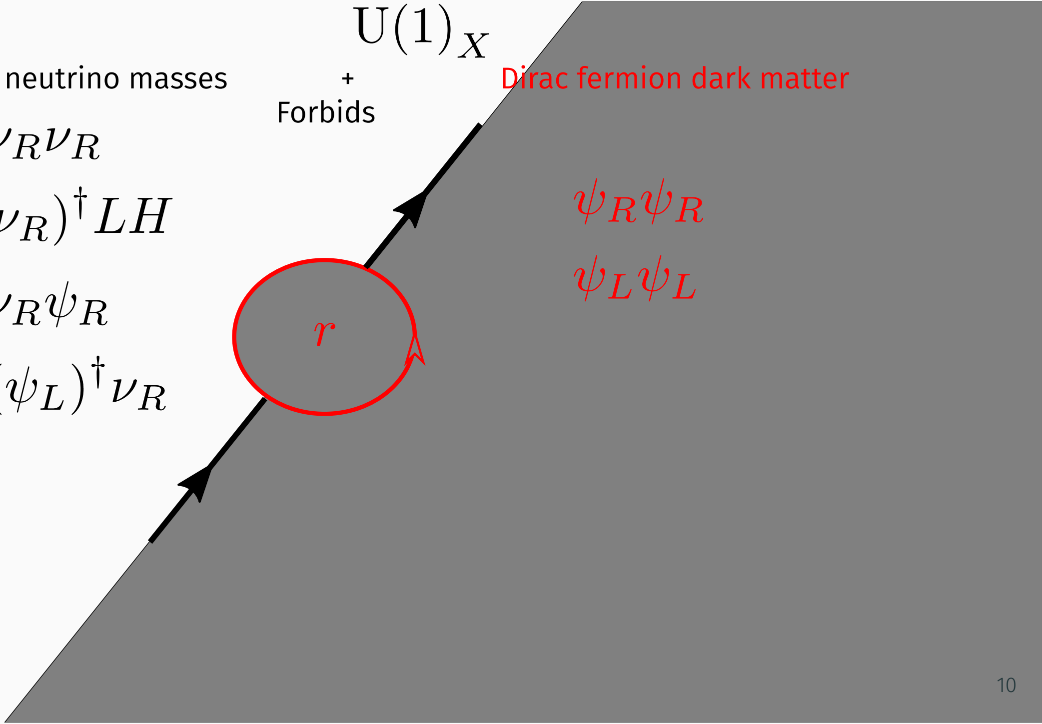
Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$



$$\mathrm{U}(1)_X$$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$$\nu_R \nu_R$$

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

$$\nu_R \psi_R$$

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

$$\psi_R \psi_R$$

$$\psi_L \psi_L$$

$$r$$

Allows

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

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

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

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

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$

r

Allows

$X(L) \neq 0$

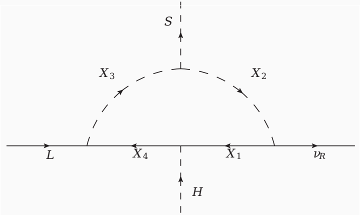
$(\nu_R)^\dagger L H S$

$(\psi_R)^\dagger \psi_L$

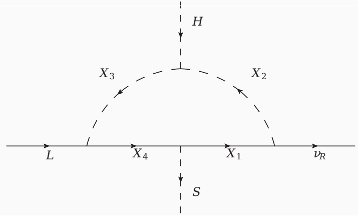
$(\psi_R)^\dagger \psi_L S$

normalized to $X(L) = -1$

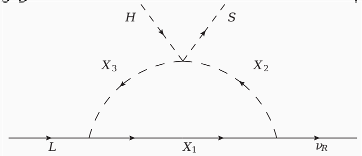
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

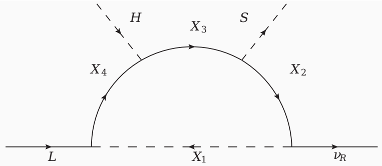


T1-3-E

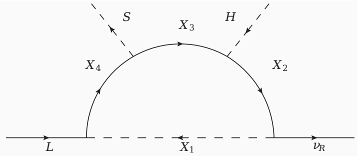


T3-1-A

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

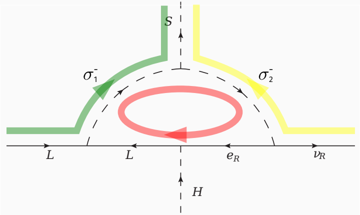


T1-2-A

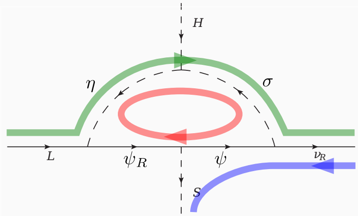


T1-2-B

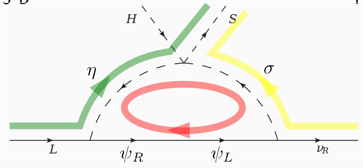
One loop topologies $U(1)_{B-L}$ only!



T1-3-D



T1-3-E



T3-1-A

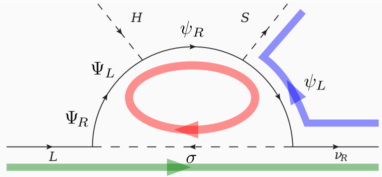
$\psi_{L,R}$ $\rightarrow$Singlet fermions

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

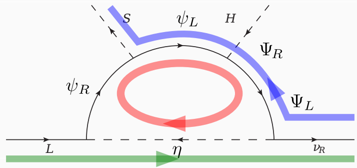
σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar

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

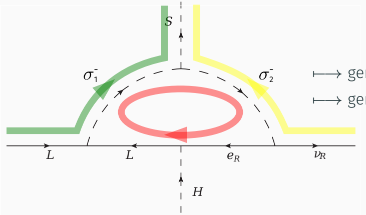


T1-2-A



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: S. Saad arXiv:1902.07259 [NPB]

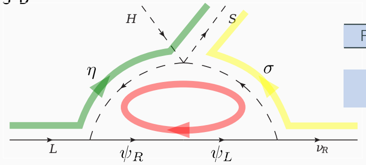
$\longmapsto$ generalization to $\mathrm{U(1)_R}$: *et al*, S. Saad arXiv:1904.07407

$\uparrow$

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

σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar



T3-1-A

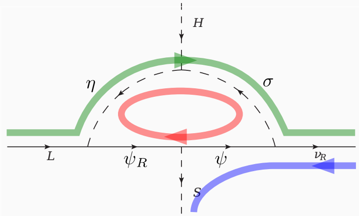
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

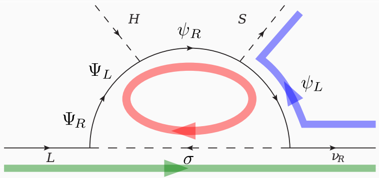
One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



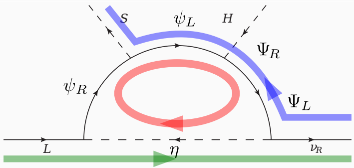
T1-3-E

- $\psi_{L,R}$ $\rightarrow$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

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

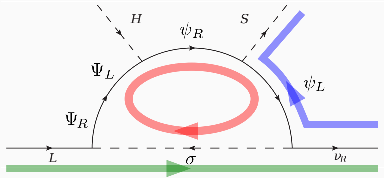
SD^{3}M+SSDM: σ_a $(a = 1, 2)$ with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

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 : 10/5

σ $\rightarrow$Singlet scalar : 15/5



Anomaly cancellation conditions

$$\sum_i f_i = 3$$

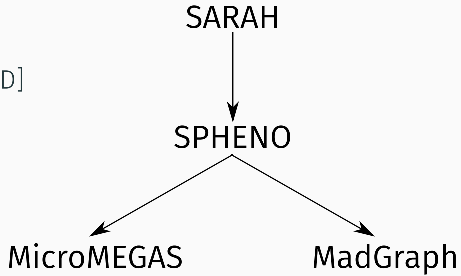
$$\sum_i f_i^3 = 3$$

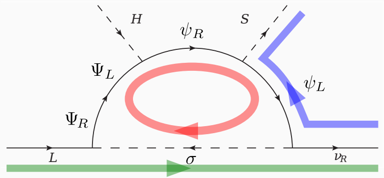
SD^{3}M+SSDM: σ_a $(a = 1, 2)$

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

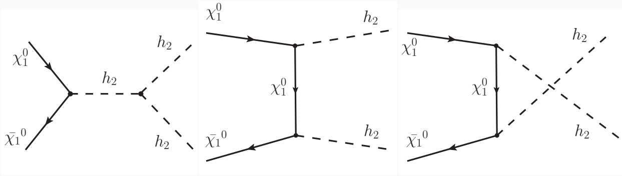
$$\mathcal{L} = \mathcal{L}_{\mathrm{SD^3M}} + h_3^{ia}\widetilde{(\Psi_R)} \cdot L_i\, \sigma_a + h_2^{\beta a}\, (\nu_{R\beta})^\dagger\, \psi_L\, \sigma_a^* - V(\sigma_a, S, H)\,.$$

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



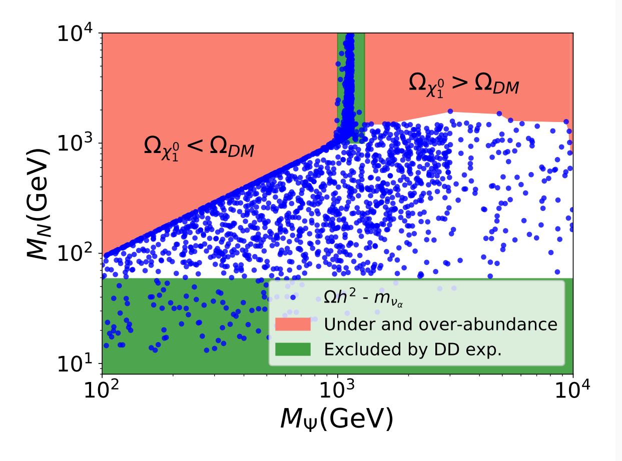


T1-2-A

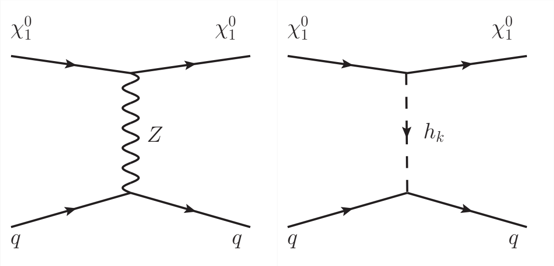


Decoupled Z' limit

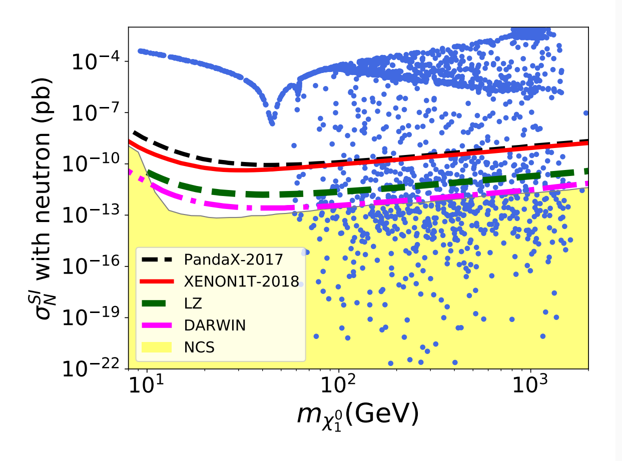
$$\begin{pmatrix} h \\ \mathrm{Re}(S) \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} .$$



Spin independent (SI) direct detection cross section



Decoupled Z' limit



Conclusions

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

Conclusions

A single $U(1)_X$ gauge 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!