Effective Dirac neutrino masses

with multi-coponent fermionic dark matter

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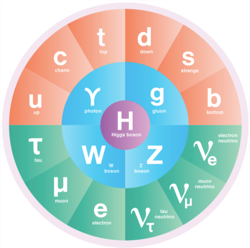
Focus on
arXiv:2108.05907
In collaboration with
Nicolás Bernal

Dark sectors



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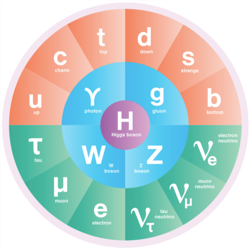

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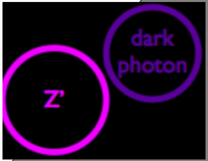
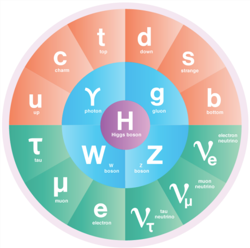


Z'
dark photon



$F_{\mu\nu}$ $V^{\mu\nu}$

Local $U(1)_{\mathcal{X}}$

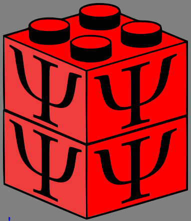
$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i\overline{\Psi}\not{D}\Psi - h\overline{\Psi}\Psi S$$

Diracness protected chiral fermion dark matter $m_\Psi = h\langle S\rangle$

Relic abundance:

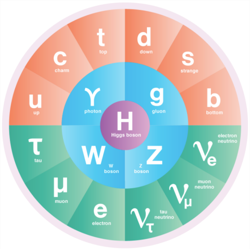
Active Symmetry: $\mathcal{X} \to X$: $\Psi\overline{\Psi} \to \text{SM}\,\text{SM}$

Dark Symmetry: $\mathcal{X} \to D$: $\Psi\overline{\Psi} \to \gamma_D\gamma_D$



$\overline{\Psi}\Psi = \psi_1\psi_2 + \psi_1^\dagger\psi_2^\dagger \to \psi_\alpha\,,\qquad \alpha = 1,\ldots N' \to N' > 4$

Local $U(1)_{\mathcal{X}}$



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Diracness protected chiral fermion

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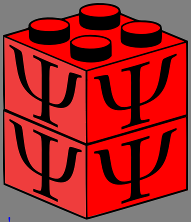

$$\overline{\Psi}\Psi = \psi_1\psi_2 + \psi_1^\dagger\psi_2^\dagger \to \psi_\alpha\,, \qquad \alpha = 1,\ldots N' \to N' > 4$$

Standard model extended with $U(1)_\mathcal{X}$ gauge symmetry

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_\mathcal{X}$
$L^\dagger$	$\mathbf{2}$	$+1/2$	l
$Q^\dagger$	$\mathbf{2}$	$-1/6$	q
d_R	$\mathbf{1}$	$-1/2$	d
u_R	$\mathbf{1}$	$+2/3$	u
e_R	$\mathbf{1}$	-1	e
H	$\mathbf{2}$	$-1/2$	h
ψ_α	$\mathbf{1}$	0	n_α

Table 1: $l = q = d = u = e = h = 0$ for $\mathcal{X} = D$

$$
\begin{aligned}
[\mathrm{SU}(3)_c]^2\,\mathrm{U}(1)_X: &\qquad [3u+3d]-[3\cdot 2q] = 0\\
[\mathrm{SU}(2)_L]^2\,\mathrm{U}(1)_X: &\qquad [2l+3\cdot 2q] = 0\\
[\mathrm{U}(1)_Y]^2\,\mathrm{U}(1)_X: &\qquad \left[(-2)^2e+3\left(\tfrac{4}{3}\right)^2u+3\left(-\tfrac{2}{3}\right)^2d\right]-\left[2(+1)^2l+3\cdot 2\left(-\tfrac{1}{3}\right)^2q\right] = 0
\end{aligned}
$$

with solution

$$u = -e - \frac{2l}{3}, \qquad d = e + \frac{4l}{3}, \qquad q = -\frac{l}{3},$$

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which satisfy

$$\mathrm{U}(1)_Y [\mathrm{U}(1)_X]^2: \qquad \left[(-2)e^2 + 3\left(\tfrac{4}{3}\right)u^2 + 3\left(-\tfrac{2}{3}\right)d^2\right] - \left[2(+1)l^2 + 3\cdot 2\left(-\tfrac{1}{3}\right)q^2\right] = 0$$

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For N extra quiral fields ψ_α $(\alpha = 1, \dots, N')$ with $\mathcal{X}$-charges n_α:

$$[\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_{\mathcal{X}}: \qquad \sum_\alpha n_\alpha + 3(e - 2l) = 0\,, \tag{1}$$

$$[\mathrm{U}(1)_{\mathcal{X}}]^3\,, \qquad \sum_\alpha n_\alpha^3 + 3(e - 2l)^3 = 0 \tag{2}$$

with solution

$$u = -m + \frac{4l}{3}\,, \qquad d = m - \frac{2l}{3}\,, \qquad q = -\frac{l}{3}\,, \qquad e = m - 2l\,,$$

which satisfy

$$\mathrm{U}(1)_Y[\mathrm{U}(1)_X]^2: \qquad \left[(-2)e^2 + 3\left(\tfrac{4}{3}\right)u^2 + 3\left(-\tfrac{2}{3}\right)d^2\right] - \left[2(+1)l^2 + 3\cdot 2\left(-\tfrac{1}{3}\right)q^2\right] = 0$$

For N extra quiral fields ψ_α $(\alpha = 1, \ldots, N')$ with $\mathcal{X}$-charges n_α: $m \equiv e - 2l$

$$[\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_{\mathcal{X}}: \qquad \sum_\alpha n_\alpha + 3m = 0\,, \tag{1}$$

$$[\mathrm{U}(1)_{\mathcal{X}}]^3\,, \qquad \sum_\alpha n_\alpha^3 + 3m^3 = 0 \tag{2}$$

with solution

$$u = -m + \frac{4l}{3}\,, \qquad d = m - \frac{2l}{3}\,, \qquad q = -\frac{l}{3}\,, \qquad e = m - 2l\,,$$

which satisfy

$$\mathrm{U}(1)_Y [\mathrm{U}(1)_X]^2 : \qquad \left[(-2)e^2 + 3\left(\tfrac{4}{3}\right)u^2 + 3\left(-\tfrac{2}{3}\right)d^2\right] - \left[2(+1)l^2 + 3\cdot 2\left(-\tfrac{1}{3}\right)q^2\right] = 0$$

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Any set of integers of integers $(n_1, n_2, \ldots n_N)$ which satisfy (**??**) and (**??**) can be interpreted as $\mathcal{X} \to D$ symmetry with N chiral fields.

If one integer, m is repetead 3 times, the set can be interpreted as $\mathcal{X} \to X$ symmetry with $N' = N - 3$ chiral fields.

From: arXiv:1905.13279 [PRL] Costa, *et al*

Let a vector $\boldsymbol{z}$ with N non-zero integer entries such that

$$\sum_{i=1}^{N} z_i = 0\,, \qquad \sum_{i=1}^{N} z_i^3 = 0\,.$$

We like to build this set of N integers from two subsets $\boldsymbol{\ell}$ and $\boldsymbol{k}$ with sizes

$$\dim(\boldsymbol{\ell}) = \begin{cases} \alpha = \frac{N}{2} - 1\,, & \text{if } N \text{ even} \\ \beta = \frac{N-3}{2}\,, & \text{if } N \text{ odd} \end{cases}\;; \qquad \dim(\boldsymbol{k}) = \begin{cases} \alpha = \frac{N}{2} - 1\,, & \text{if } N \text{ even} \\ \beta + 1 = \frac{N-1}{2}\,, & \text{if } N \text{ odd} \end{cases}$$

- N even: Consider the following two vector-like examples of $\boldsymbol{z}$ such that

$$\boldsymbol{x} = (\ell_1, k_1, \ldots, k_\alpha, -\ell_1, -k_1, \ldots, -k_\alpha)$$
$$\boldsymbol{y} = (0, 0, \ell_1, \ldots, \ell_\alpha, -\ell_1, \ldots, -\ell_\alpha)\,.$$

- N odd:

$$\boldsymbol{x} = (0, k_1, \ldots, k_{\beta+1}, -k_1, \ldots, -k_{\beta+1})$$

$$\boldsymbol{y} = (\ell_1, \ldots, \ell_\beta, k_1, 0, -\ell_1, \ldots, -\ell_\beta, -k_1)$$

From any of this, we can build a final $\boldsymbol{z}$ which can includes *chiral* solutions

$$\boldsymbol{x} \oplus \boldsymbol{y} \equiv \left(\sum_{i=1}^{N} x_i y_i^2\right) \boldsymbol{x} - \left(\sum_{i=1}^{N} x_i^2 y_i\right) \boldsymbol{y}\,.$$

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- N even: Consider the following two vector-like examples of $\boldsymbol{z}$ such that

$$\begin{aligned} \boldsymbol{x} &= (\ell_1, k_1, \ldots, k_\alpha, -\ell_1, -k_1, \ldots, -k_\alpha) \\ \boldsymbol{y} &= (0, 0, \ell_1, \ldots, \ell_\alpha, -\ell_1, \ldots, -\ell_\alpha)\ . \end{aligned}$$

- N odd:

$$\boldsymbol{x} = (0, k_1, \ldots, k_{\beta+1}, -k_1, \ldots, -k_{\beta+1})$$

$$\boldsymbol{y} = (\ell_1, \ldots, \ell_\beta, k_1, 0, -\ell_1, \ldots, -\ell_\beta, -k_1)$$

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https://pypi.org/project/anomalies

anomalies 0.1.4

pip install anomalies

https://github.com/restrepo/anomaly/raw/main/solutions.json.gz

390074 solutions: 4<N<13

Latest version

Released: Nov 30, 2020

Navigation

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- Release history
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Statistics

GitHub statistics:

- Stars: 0
- Forks: 1
- Open issues/PRs: 0

View statistics for this project via Libraries.io, or by using our public dataset on Google BigQuery

Meta

License: BSD

Author: restrepo

Maintainers

Anomalies

Implement the anomaly free solution of arXiv:1905.13729 [PRL]:

Obtain a numpy array `z` of `N` integers which satisfy the Diophantine equations

```
>>> z.sum()
0
>>> (z**3).sum()
0
```

The input is two lists `l` and `k` with any `(N-3)/2` and `(N-1)/2` integers for `N` odd, or `N/2-1` and `N/2-1` for `N` even (`N>4`). The function is implemented below under the name: `free(l,k)`

Install

```
$ pip install anomalies
```

USAGE

```
>>> from anomalies import anomaly
>>> anomaly.free([-1,1],[4,-2])
array([  3,   3,   3, -12, -12,  15])
>>> anomaly.free.gcd
3
>>> anomaly.free.simplified
array([ 1,  1,  1, -4, -4,  5])
```

$N=6$

$\Downarrow$

$\alpha=2$

$\vec{l}=(-1,1)$

$\vec{k}=(4,-2)$

https://doi.org/10.5281/zenodo.5526707

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September 24, 2021

Dataset Open Access

Set of N integers between -30 and 30 with sum and cubic sum up to zero for 4<N<13

Diego Restrepo

Anomalies

Solutions obtained with the python package: anomalies based on the method to find anomaly free solutions of the standard model extended with an Abelian Dark Symmetry with *N* right-handed singlet chiral fields described in arXiv:1905.13729 [PRL]:

Data scheme

- 'l': integer lists → input to obtain the 'solution' by using the anomalies package
- 'k': integer lists → input to obtain the 'solution' by using hte anomalies package
- 'solution': list → of integers, z_i which satisfy $\sum_{i=1}^{N} z_i = 0$ and $\sum_{i=1}^{N} z_i^3 = 0$.
- 'n': integer → number of integers in 'solution', *N*.

```
USAGE
```

```
#Example of JSON file usage in Python with pandas (see also json module)
>>> import pandas as pd
>>> df=pd.read_json('solutions.json')
>>> df[:2]
         l        k            solution  gcd  n
0    [1, 2]  [0, -3]   [1, 5, -7, -8, 9]    1  5
1  [-2, -1]  [0, -1]  [2, 4, -7, -9, 10]    1  5
```

Data:

390074 solutions with $5 \leq N \leq 12$ integers until `|32|` [JSON]

Publication date:
September 24, 2021

DOI:
DOI 10.5281/zenodo.5526707

Keyword(s):
Anomaly free Diophantine equations Abelian symmetry Gauge Symmetry

Versions

Version 1 Sep 24, 2021
10.5281/zenodo.5526707

Effective Dirac neutrino mass operator

$$\mathcal{L}_{\text{eff}} = h_\nu^{\alpha i}\,(\nu_{R\alpha})^\dagger\,\epsilon_{ab}\,L_i^a\,H^b\left(\frac{S^*}{\Lambda}\right)^\delta + \text{H.c.}, \qquad \text{with } i = 1,2,3\,,$$

and $\delta = 1, 2, \ldots$ for dimension 5 (D-5) or 6 (D-6) operators, etc. Here $h_\nu^{\alpha i}$ correspond to dimensionless induced couplings, $\nu_{R\alpha}$ are at least two RHNs ($\alpha = 1, 2, \ldots$) with the same D or X-charge ν, L_i are the lepton doublets with X-charge $-L$, H is the SM Higgs doublet with X-charge $h = L - m$, S is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry with D or X-charge

$$s = -(\nu + m)/\delta\,,$$

Diracness of non-zero DM and Dirac neutrinos masses from $U(1)_{\mathcal{X}}$

Starting from the extended dataset with the solutions with N integers to the Diophantine equations (**??**) (**??**), we apply the following steps

- Check that the solution has two (three) repeated integers to be identified as ν and fix $N_\nu = 2$ ($N_\nu = 3$).
- For $\delta = 1, 2, \ldots$ and all the possible combinations for m and ν in the solution, including $m = 0$, find the s value compatible with the effective Dirac neutrino mass operator of D-4 $+\,\delta$ according to eq. (**??**).
- Interpret the integers in the solution which are different from m and ν as the D-charges for $m = 0$ or X-charges for $m \neq 0$ of a set of singlet chiral fermions: ψ_i, $i = 1, \ldots, N_{\text{chiral}} - N_\nu$. Then select the solutions for which the condition

$$|n_i + n_j| = |s| \tag{3}$$

  which guarantees that all the singlet chiral fermions, ψ_i, acquire masses after the spontaneous symmetry breaking of the gauge Abelian symmetry through $\langle S \rangle$.

Unconditional stability

Two DM candidates with *unconditional* stability. This happens when there are two remnant symmetries such that $\mathbb{Z}_{|s|} \cong \mathbb{Z}_p \otimes \mathbb{Z}_q$ with p and q coprimes and $|s| = pq$, which guarantee the stability of each lightest state under $\mathbb{Z}_p$ and $\mathbb{Z}_q$ respectively, without imposing any kinematical restriction. For the two DM candidates associated to the set of chiral fields ψ_i and χ_j, we consider below the following two possibilities for $|s|$

- $\mathbb{Z}_6 \cong \mathbb{Z}_2 \otimes \mathbb{Z}_3$: solutions with at least a set of chiral fields with $\psi_i \sim \left[\omega_6^2 \vee \omega_6^4\right]$ under $\mathbb{Z}_6$, and at least a set of chiral fields with $\chi_i \sim \omega_6^3$ under $\mathbb{Z}_6$,
- $\mathbb{Z}_{14} \cong \mathbb{Z}_2 \otimes \mathbb{Z}_7$: solutions with at least a set of chiral fields with $\psi_i \sim \left[\omega_{14}^2 \vee \omega_{14}^6 \vee \omega_{14}^8 \vee \omega_{14}^{10} \vee \omega_{14}^{12}\right]$ under $\mathbb{Z}_{14}$ and at least a set of chiral fields with $\chi_i \sim \omega_{14}^7$ under $\mathbb{Z}_{14}$,

where $\omega_{|s|} = e^{i2\pi/|s|}$.

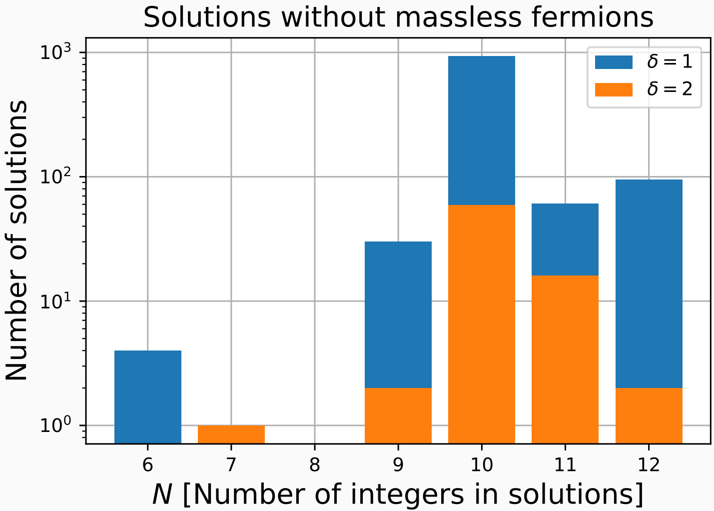


Figure 1: Distribution of solutions with N integers to the Diophantine equations (**??**) which allow the effective Dirac neutrino operator at D-4 $+\ \delta$ for at least two right-handed neutrinos and have non-vanishing Dirac o Majorana masses for the other singlet chiral fermions in the solution.

48 type of representative solutions

Solution	N	N_{chiral}	m	ν	δ	s	N_D	N_M	G_D	G_M
$(1, -2, -3, 5, 5, -6)$	6	6	0	5	1	-5	2	0	1	0
$(3, 3, 3, -5, -5, -7, 8)$	7	4	3	-5	2	1	1	0	1	0
$(1, -2, 3, 4, 6, -7, -7, -7, 9)$	9	9	0	-7	1	7	3	0	1	0
$(1, 1, -4, -5, 9, 9, 9, -10, -10)$	9	9	0	9	1	-9	3	0	2	0
$(1, 2, -6, -6, -6, 8, 9, 9, -11)$	9	6	-6	9	1	-3	2	0	1	0
$(1, -3, 8, 8, 8, -12, -12, -17, 19)$	9	6	8	-12	2	2	2	1	1	1
$(8, 8, 8, -12, -12, 15, -17, -23, 25)$	9	6	8	-12	2	2	2	0	1	0
$(1, -2, -2, 3, 3, -4, -4, 6, 6, -7)$	10	10	0	6	1	-6	3	2	2	2
$(1, -2, -2, 3, 4, -5, -5, 7, 7, -8)$	10	10	0	-5	1	**5**	4	0	2	0
$(1, -2, -2, 3, 5, -6, -6, 8, 8, -9)$	10	10	0	-6	1	6	4	0	2	0
$(2, 2, 3, 4, 4, -5, -6, -6, -7, 9)$	10	10	0	2	1	**−2**	4	2	2	2
$(1, 1, 5, 5, 5, -6, -6, -6, -9, 10)$	10	10	0	1	1	-1	4	0	3	0
$(2, 2, 4, 4, -7, -7, -9, -9, 10, 10)$	10	10	0	10	2	-5	3	0	2	0
$(1, 2, 2, -3, 6, 6, -8, -8, -9, 11)$	10	10	0	-8	1	8	4	1	2	1
$(1, -2, -3, 5, 6, -8, -9, 11, 11, -12)$	10	10	0	11	1	-11	4	0	1	0
$(1, 1, -3, 4, 4, -7, 8, -10, -10, 12)$	10	10	0	-10	2	5	4	0	2	0
$(1, 1, -2, -2, -4, 6, -10, 11, 12, -13)$	10	10	0	-2	1	2	3	2	1	2
$(3, 4, 4, 4, 4, -5, -8, -8, -11, 13)$	10	10	0	-8	1	8	2	4	1	4
$(4, 4, 5, 6, 6, -9, -10, -10, -11, 15)$	10	10	0	6	1	-6	4	0	2	0
$(1, -2, -4, 7, 7, -10, -12, 14, 14, -15)$	10	10	0	14	1	**−14**	3	2	1	2
$(1, 2, 2, -3, 4, -6, 12, -13, -14, 15)$	10	10	0	2	1	**−2**	4	1	1	1
$(1, 4, 4, -7, 8, 8, -9, -12, -12, 15)$	10	10	0	8	1	-8	4	2	2	2
$(1, 2, 2, -9, -9, 16, 16, 17, -18, -18)$	10	10	0	-18	1	18	3	2	2	2
$(1, -3, -6, 7, -10, 11, -16, 18, 18, -20)$	10	10	0	18	2	-9	4	0	1	0

48 type of representative solutions

Solution	N	N_{chiral}	m	ν	δ	s	N_D	N_M	G_D	G_M
$(1, -4, 5, -6, -6, 10, -14, 15, 20, -21)$	10	10	0	-6	1	6	4	0	1	0
$(2, -3, -6, 7, 12, -14, -14, 17, 20, -21)$	10	10	0	-14	1	**14**	4	1	1	1
$(3, 6, 6, -7, 8, 8, -14, -14, -17, 21)$	10	10	0	-14	1	**14**	4	1	2	1
$(8, 8, 9, 10, 10, -13, -18, -18, -27, 31)$	10	10	0	-18	1	**18**	4	1	2	1
$(1, 1, 1, -2, -2, -5, -5, 6, 6, 7, -8)$	11	8	1	-2	1	1	3	0	2	0
$(1, -2, -2, -2, -3, 4, 4, -5, 6, 7, -8)$	11	8	-2	4	1	-2	3	1	1	1
$(1, 1, 2, 2, 2, -4, -4, 7, -8, -9, 10)$	11	8	2	-4	1	2	2	2	1	2
$(2, 2, 2, -4, -4, -5, 7, -8, 9, 10, -11)$	11	8	2	-4	1	2	3	0	1	0
$(1, -2, -3, -3, -3, 5, 5, -7, 8, 10, -11)$	11	8	-3	5	2	-1	3	0	1	0
$(3, 3, 3, -4, -4, 7, 7, -8, -9, -9, 11)$	11	8	3	-9	2	3	3	0	2	0
$(1, 3, 5, -6, -6, -6, 8, -9, 12, 12, -14)$	11	8	-6	12	1	-6	3	1	1	1
$(1, -2, 6, 6, 6, -7, 8, -9, -12, -12, 15)$	11	8	6	-12	1	**6**	3	0	1	0
$(1, 3, 3, 6, 6, 6, -7, -10, -12, -12, 16)$	11	8	6	-12	1	**6**	2	2	1	2
$(1, -2, -2, -2, 3, 3, 4, 4, -5, -5, -5, 6)$	12	9	-5	-2	1	**7**	3	0	2	0
$(1, 1, -3, 4, 5, 5, 5, -6, -7, -7, -8, 10)$	12	9	5	-7	1	2	3	2	1	2
$(1, 1, 1, -2, 4, -7, -7, -7, 8, 9, 9, -10)$	12	9	-7	9	1	-2	2	3	1	3
$(1, 1, -3, -3, -5, -5, -5, 7, 7, 7, 9, -11)$	12	9	-5	7	1	-2	3	2	2	2
$(1, -3, -3, -3, 4, 6, 7, 9, -10, -10, -10, 12)$	12	9	-3	-10	1	13	3	0	1	0
$(1, 1, 1, 3, 3, -5, 7, 7, -11, -11, -11, 15)$	12	9	1	-11	1	10	3	1	2	1
$(1, 1, 1, 3, 5, 5, -5, 5, -9, -9, -13, 15)$	12	9	5	-9	2	2	2	3	1	3
$(1, -2, -2, 3, 6, -10, -10, -10, 13, 14, 14, -17)$	12	9	-10	14	1	-4	4	2	2	2
$(1, -3, 9, -11, -13, -13, -13, 15, 15, 15, 21, -23)$	12	9	-13	15	1	-2	3	1	1	1

Multi-component dark matter I

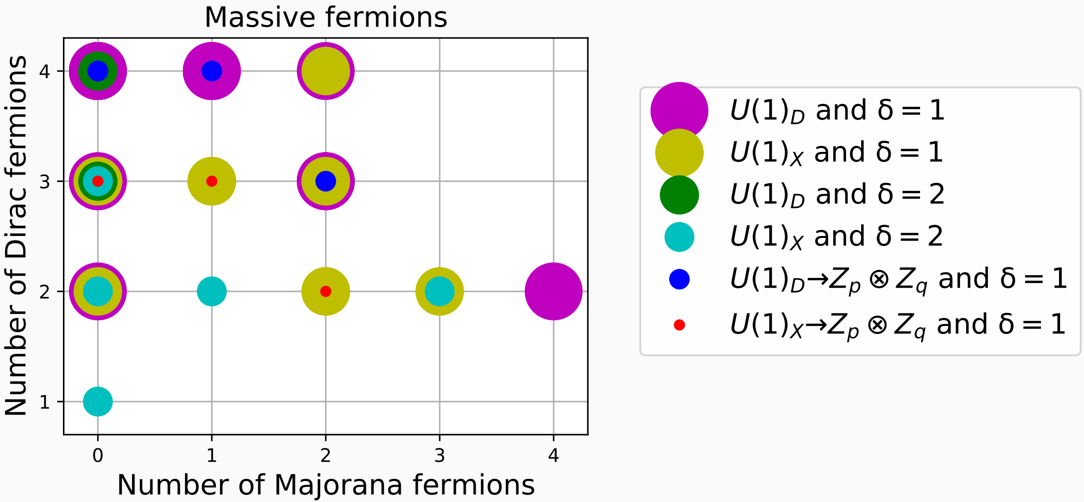


Figure 2: Number of massive Dirac and Majorana fermions in each type of the 48 types of solutions

Multi-component dark matter II

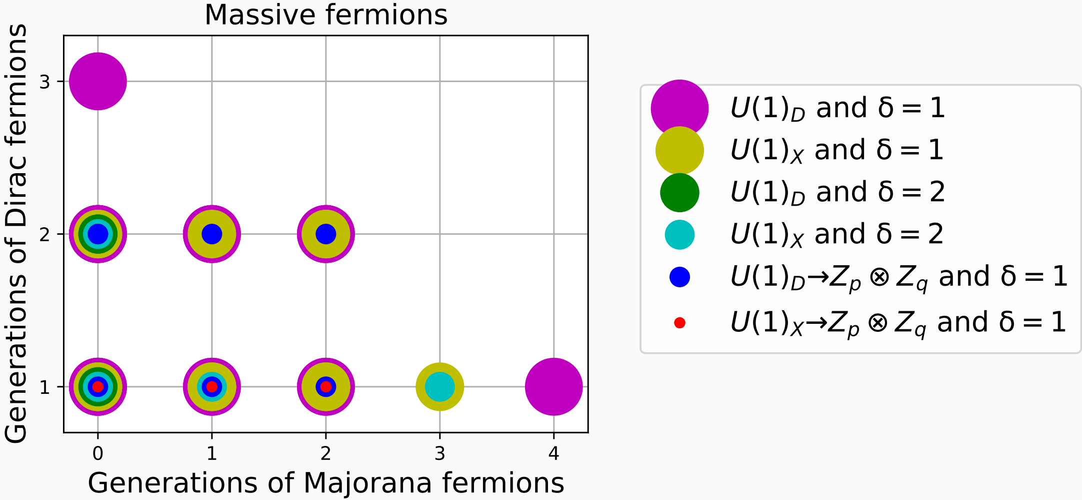


Figure 3: Same as Fig. ?? but for number generations of massive Dirac and Majorana fermions in

Solution: $(3, 3, 3, -5, -5, -7, 8)$

Field	$SU(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_X$	$\mathrm{U}(1)_{B-L}$
L_i	$\mathbf{2}$	$-1/2$	$-L$	-1
e_{Ri}	$\mathbf{1}$	-2	$3-2L$	-1
$\nu_{R\alpha}$	$\mathbf{1}$	0	-5	$-5/3$
ψ_1	$\mathbf{1}$	0	-7	$-7/3$
ψ_2	$\mathbf{1}$	0	8	$8/3$
H	$\mathbf{2}$	$1/2$	$L-3$	0
S	$\mathbf{1}$	0	1	$1/3$
σ_1^+	$\mathbf{1}$	$+2$	$2L$	2
σ_2^+	$\mathbf{1}$	$+2$	$-(2-2L)$	$4/3$

Table 2: Charges for last solution. $i=1,2,3$, $\alpha=1,2,3$. Note that $\left(\omega_n^d\right)^* = \omega_n^{-d} = \omega_n^{n-d}$.

Neutrino phenomenology with J. Calle and O. Zapata: arXiv:2103.15328 [PRD]

DM Phenomenology: arXiv:1506.05107

Conclusions

In general, we can see that multi-component and multi-generation DM candidates are the trend for gauge Abelian extensions of the SM with massive singlet chiral fermions compatible with the effective Dirac neutrino mass operator of dimension

One parameter $U(1)_X$ SM extension

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$U(1)_{B-L}$	$U(1)_R$	$U(1)_D$	$U(1)_G$	$U(1)_{\mathcal{D}}^*$
L	**2**	$-1/2$	l	-1	0	$-3/2$	$-1/2$	0
Q	**2**	$-1/6$	$-l/3$	$1/3$	0	$1/2$	$1/6$	0
d_R	**1**	$-1/2$	$1+2l/3$	$1/3$	1	0	$2/3$	0
u_R	**1**	$+2/3$	$-1-4l/3$	$1/3$	-1	1	$-1/3$	0
e_R	**1**	-1	$1+2l$	-1	1	-2	0	0
H	**2**	$1/2$	$-1-l$	0	-1	$1/2$	$-1/2$	0
$\sum_\alpha n_\alpha$	**1**	0	-3	-3	-3	-3	-3	0
$\sum_\alpha n_\alpha^3$	**1**	0	-3	-3	-3	-3	-3	0

solutions with $\sum n_\alpha = -3$ and $\sum n_\alpha^3 = -3$

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \cdots)$	Ref
$(-1, -1, -1)$	hep-ph/0611205, S. Khalil [JPG]
$(-4, -4, +5)$	arXiv:0706.0473, Montero, V. Pleitez [PLB]
$\left(-\frac{2}{3}, -\frac{2}{3}, -\frac{4}{3}, -\frac{1}{3}\right)$	arXiv:1607.04029, S. Patra , W. Rodejohann, C. Yaguna [JHEP]
$\left(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, +2\right)$	arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]
$\left(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7}\right)$	1808.03352, with N. Bernal, C. Yaguna, Ó. Zapata [PRD]
$\left(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3}\right)$	In progress... New method†

Table 3: Possible solutions with at least two repeated charges and until six chiral fermions.

† General $\sum n_\alpha = 0$ solutions: see D.B Costa, *et al*, arXiv:1905.13729 [PRL]

Or$\cdots$ combine known solutions with $\sum n_\alpha = 0$ and $\sum n_\alpha^3 = 0$

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \cdots)$	Ref
$(-1, -1, -1)$	hep-ph/0611205, S. Khalil [JPG]
$(-4, -4, +5)$	arXiv:0706.0473, Montero, V. Pleitez [PLB]
$\left(-\frac{2}{3}, -\frac{2}{3}, -\frac{4}{3}, -\frac{1}{3}\right)$	arXiv:1607.04029, S. Patra , W. Rodejohann, C. Yaguna [JHEP]
$\left(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, +2\right)$	arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]
$\left(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7}\right)$	1808.03352, with N. Bernal, C. Yaguna, Ó. Zapata [PRD]
$\left(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3}\right)$	In progress... New method†

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

Only known integer solutions for -3 (1953)

September 2019:

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

Table 3: Possible solutions with at least two repeated charges and until six chiral fermions.

† General $\sum n_\alpha = 0$ solutions: see D.B Costa, *et al*, arXiv:1905.13729 [PRL]

Or$\cdots$ combine known solutions

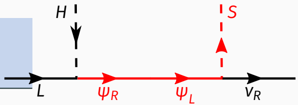
$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \cdots)$	Ref
$(-1,-1,-1)$	hep-ph/0611205, S. Khalil [JPG]
$(-4,-4,+5)$	arXiv:0706.0473, Montero, V. Pleitez [PLB]
$\left(-\frac{2}{3},-\frac{2}{3},-\frac{4}{3},-\frac{1}{3}\right)$	arXiv:1607.04029, S. Patra , W. Rodejohann, C. Yaguna [JHEP]
$\left(-\frac{8}{5},-\frac{8}{5},-\frac{2}{5},-\frac{7}{5},+2\right)$	arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]
$\left(-1,-1,-\frac{10}{7},-\frac{4}{7},-\frac{2}{7},\frac{9}{7}\right)$	1808.03352, with N. Bernal, C. Yaguna, Ó. Zapata [PRD]
$\left(-\frac{5}{3},-\frac{5}{3},-\frac{7}{3},\frac{8}{3}\right)$	In progress... New method†

Not known solution for one-loop neutrino Majorana masses with local $U(1)_X$.

Table 3: Possible solutions with at least two repeated charges and until six chiral fermions.

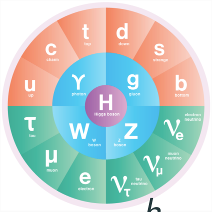
† General $\sum n_\alpha = 0$ solutions: see D.B Costa, *et al*, arXiv:1905.13729 [PRL]

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



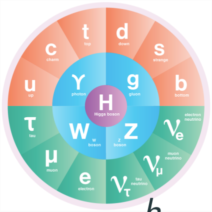
ν_{R3}	ν_{R2}	ν_{R1}	ψ_L	ψ_R	S
-4	-4	$+5$	-1	-1	$+3$

E. Ma, R. Srivastava: arXiv:1411.5042 [PLB]



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

3 models



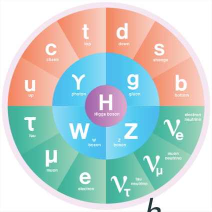
$$m^{\nu}_{\text{Majorana}} \; + = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H \quad \text{(three-level)}$$

Type-I arXiv:1808.03352, II arXiv:1607.04029, III arXiv:1908.04308

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

Type-I

seesaw

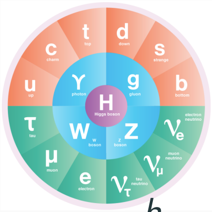


$$m^{\nu}_{\text{Majorana}} + = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H$$

Type-I arXiv:1808.03352, with N. Bernal, C. Yaguna, and Ó. Zapata [PRD]

$$U(1)_{B-L} \to Z_7$$

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



ν_{R3}	ν_{R2}	S
-1	-1	2

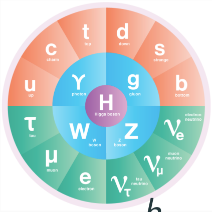
$$m^{\nu}_{\text{Majorana}} + = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H \frac{S}{\Lambda}$$

Type-I arXiv:1808.03352

: Also new terms arise from spontaneous breakdown of a new gauge symmetry

Local $U(1)_{B-L} \to Z_7$

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

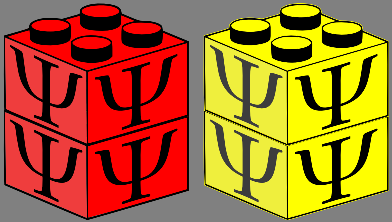


ν_{R3}	ν_{R2}	$\overline{\psi_{L1}}$	ψ_{R1}	ψ_{R2}	$\overline{\psi_{L2}}$	S	S'
-1	-1	$-\frac{10}{7}$	$-\frac{4}{7}$	$-\frac{2}{7}$	$\frac{9}{7}$	2	1

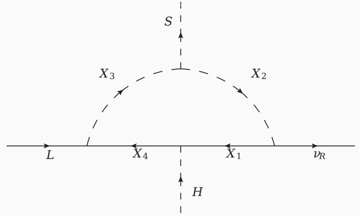
$$m^{\nu}_{\text{Majorana}} + = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H \frac{S}{\Lambda}$$

Type-I arXiv:1808.03352

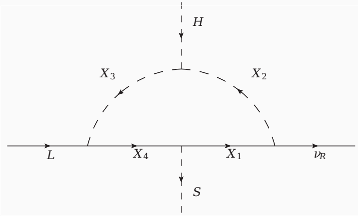
: Also new terms arise from spontaneous breakdown of a new gauge symmetry



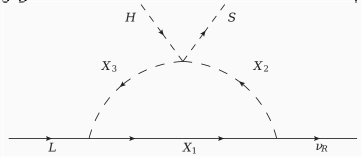
One loop topologies $\mathrm{U}(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

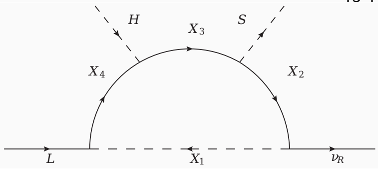


T1-3-E

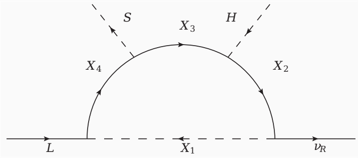


T3-1-A

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

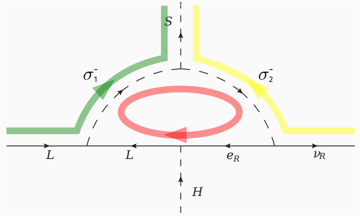


T1-2-A

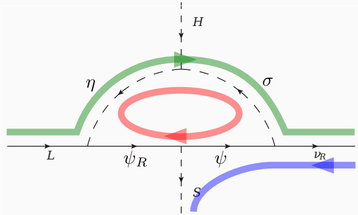


T1-2-B

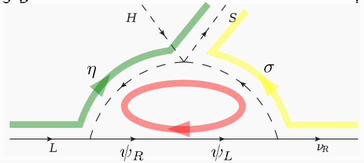
One loop topologies $U(1)_{B-L}$ only!



T1-3-D



T1-3-E



T3-1-A

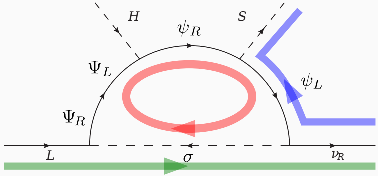
$\psi_{L,R}$ $\rightarrow$Singlet fermions

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

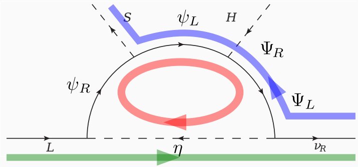
σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar

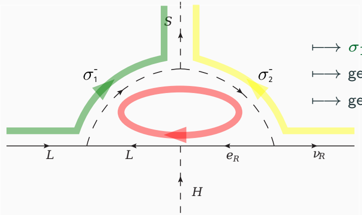
with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



T1-2-A



T1-2-B



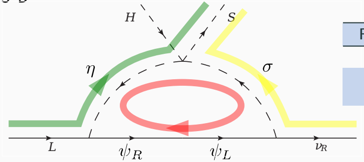
T1-3-D

$\longmapsto$ $\sigma_1 = -2$, $\sigma_2 = -5$,

$\longmapsto$ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]

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

$\uparrow$



T3-1-A

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

σ $\rightarrow$ Singlet scalar

η $\rightarrow$ Doublet scalar

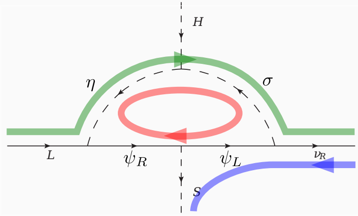
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

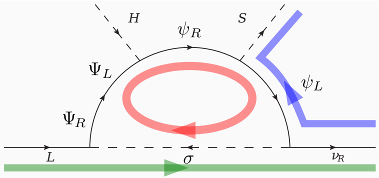
One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



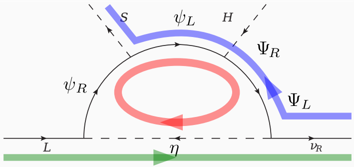
T1-3-E

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

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

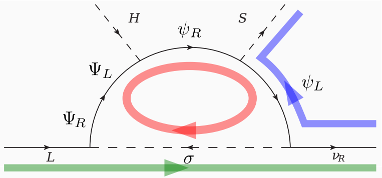
SD^{3}M+SSDM: σ_a $(a=1,2)$ with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

$\psi_{L,R}$ $\rightarrow$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)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$



T1-2-A

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

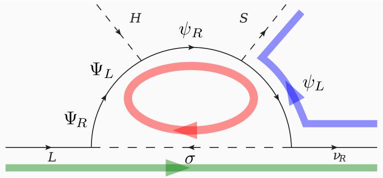
$$\sum_i f_i^3 = 3$$

SD^{3}M+SSDM: σ_a $(a = 1, 2)$

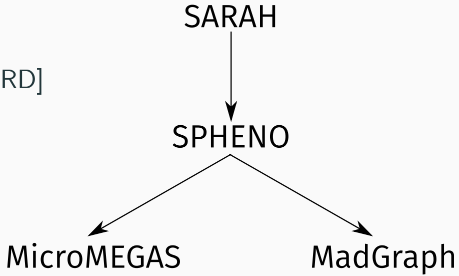
$M_\psi = h_1 \langle S \rangle$, $y_2 = 0$:

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

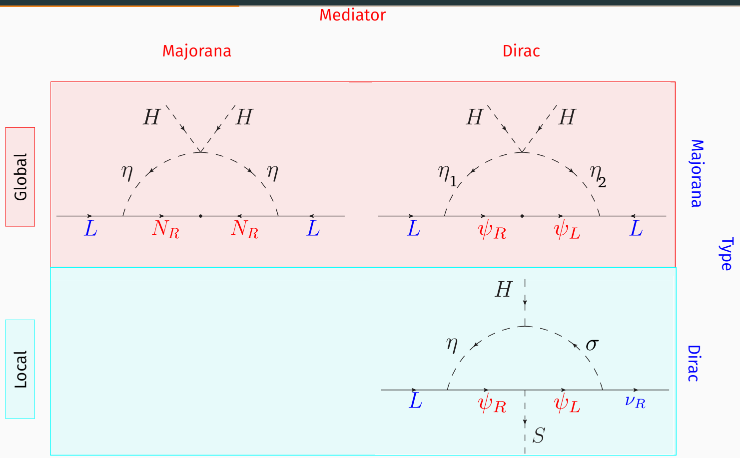
with A.F Rivera, W. Tangarife, arXiv:1906.09685 [PRD]



T1-2-A



Radiative Type-I seesaw $\rightarrow$Local: only $\mathrm{U}(1)_{B-L}$! arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]

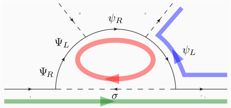


For radiative Dirac models with only $\mathrm{U}(1)_X$ see also:

arXiv:1812.01599, 1901.06402, 1902.07259, 1903.01477, 1904.07407, 1907.08630, 1910.09537 1909.00833 1907.11557, 1909.09574

$\mathcal{O}(50)$ new models mostly with $\sim (-4, -4, 5)$

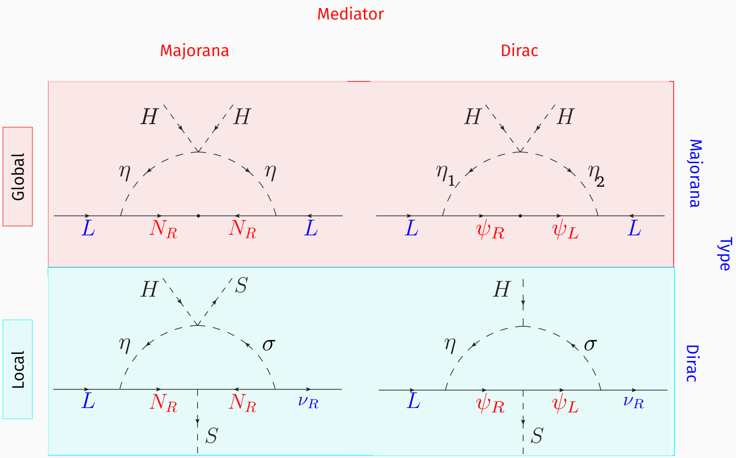
Example: New $\mathrm{U}(1)_{B-L}$



Pheno analysis with

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

Dirac Radiative Type-I seesaw with Majorana mediators with J. Calle and Ó. Zapata, arXiv:1909.09574



Dirac Radiative Type-I seesaw with Majorana mediators with J. Calle and Ó. Zapata, arXiv:1909.09574

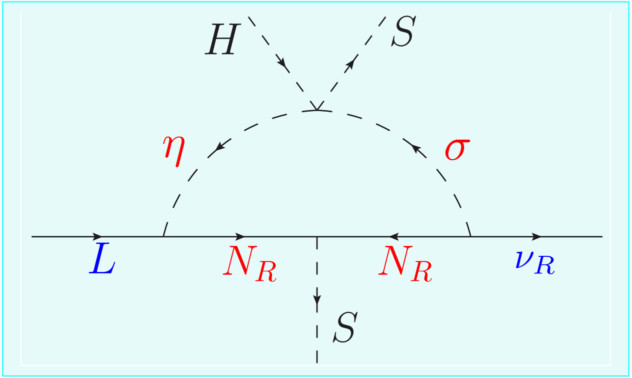
Mediator

Majorana

Dark

Type

Dirac



Local

Dark

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{D}}$
L	**2**	$-1/2$	0
Q	**2**	$-1/6$	0
d_R	**1**	$-1/2$	0
u_R	**1**	$+2/3$	0
e_R	**1**	-1	0
H	**2**	$1/2$	0
η	**2**	$1/2$	1
S	**1**	0	2
σ	**1**	0	3
ν_{R1}	**1**	0	-4
ν_{R2}	**1**	0	-4
ν_{R3}	**1**	0	5
N_{R1}	**1**	0	1
N_{R2}	**1**	0	1
N_{R3}	**1**	0	1
TOTAL			0

$$N = -\frac{\nu}{4} \quad , \quad \eta = -\frac{\nu}{4} \quad , \quad \sigma = -\frac{3\nu}{4} \quad .$$

Dirac Radiative Type-I seesaw with Majorana mediators with J. Calle and Ó. Zapata, arXiv:1909.09574

Mediator

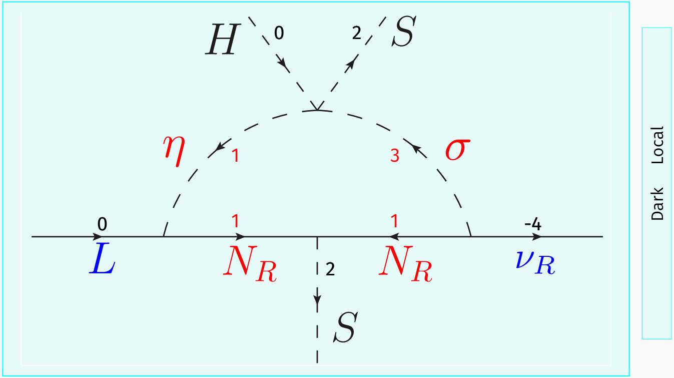
Majorana

$$\mathrm{U}(1)_{\mathcal{D}} \xrightarrow[\langle S \rangle]{} Z_2$$

Dark

Type

Dirac



$$N = -\frac{\nu}{4} \quad , \quad \eta = -\frac{\nu}{4} \quad , \quad \sigma = -\frac{3\nu}{4} \quad .$$

Fields	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{\mathcal{D}}$
L	**2**	$-1/2$	0
Q	**2**	$-1/6$	0
d_R	**1**	$-1/2$	0
u_R	**1**	$+2/3$	0
e_R	**1**	-1	0
H	**2**	$1/2$	0
η	**2**	$1/2$	1
S	**1**	0	2
σ	**1**	0	3
ν_{R1}	**1**	0	-4
ν_{R2}	**1**	0	-4
ν_{R3}	**1**	0	5
N_{R1}	**1**	0	1
N_{R2}	**1**	0	1
N_{R3}	**1**	0	1
TOTAL			0

Dirac Radiative Type-I seesaw with Majorana mediators with J. Calle and Ó. Zapata, arXiv:1909.09574

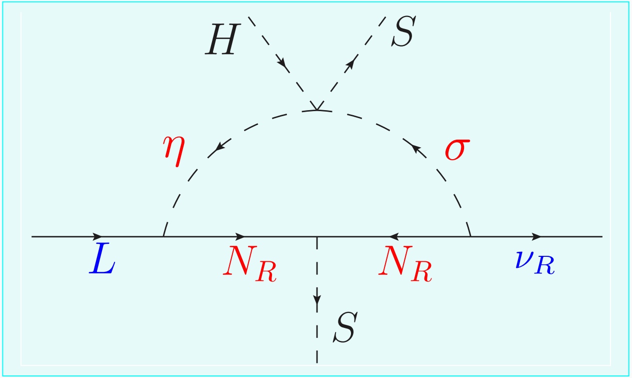
Mediator

Majorana

Dark

Type

Dirac

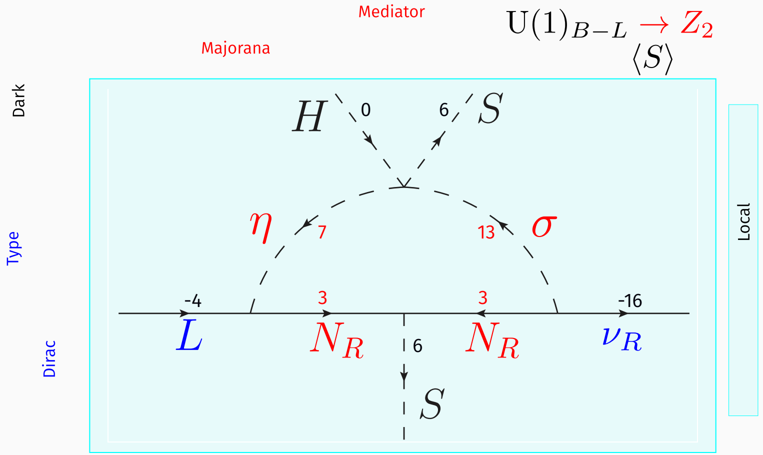


Local

$$N = -\frac{\nu}{4} - \frac{1}{4}, \quad \eta = -\frac{\nu}{4} - \frac{1}{4} - l, \quad \sigma = -\frac{3\nu}{4} + \frac{1}{4}.$$

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
L	**2**	$-1/2$	l
Q	**2**	$-1/6$	$-l/3$
d_R	**1**	$-1/2$	$1+2l/3$
u_R	**1**	$+2/3$	$-1-4l/3$
e_R	**1**	-1	$1+2l$
H	**2**	$1/2$	$-1-l$
η	**2**	$1/2$	$3/4-l$
S	**1**	0	$3/2$
σ	**1**	0	$13/4$
ν_{R1}	**1**	0	-4
ν_{R2}	**1**	0	-4
ν_{R3}	**1**	0	5
N_{R1}	**1**	0	$3/4$
N_{R2}	**1**	0	$3/4$
N_{R3}	**1**	0	$3/4$
$\xi_{L\alpha}$	**1**	0	$3/4$ [22]

Dirac Radiative Type-I seesaw with Majorana mediators with J. Calle and Ó. Zapata, arXiv:1909.09574



$$N = -\frac{\nu}{4} - \frac{1}{4}, \quad \eta = -\frac{\nu}{4} - \frac{1}{4} + 1, \quad \sigma = -\frac{3\nu}{4} + \frac{1}{4}.$$

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
L	**2**	$-1/2$	-1
Q	**2**	$-1/6$	$1/3$
d_R	**1**	$-1/2$	$1/3$
u_R	**1**	$+2/3$	$1/3$
e_R	**1**	-1	-1
H	**2**	$1/2$	0
η	**2**	$1/2$	$7/4$
S	**1**	0	$3/2$
σ	**1**	0	$13/4$
ν_{R1}	**1**	0	-4
ν_{R2}	**1**	0	-4
ν_{R3}	**1**	0	5
N_{R1}	**1**	0	$3/4$
N_{R2}	**1**	0	$3/4$
N_{R3}	**1**	0	$3/4$
$\xi_{L\alpha}$	**1**	0	$3/4$

The model

$$\mathcal{L} \supset - g' Z'_\mu \sum_F q_F \overline{F} \gamma^\mu F + \sum_\phi \left| \left(\partial_\mu + i g' q_\phi Z'_\mu \right) \phi \right|^2$$
$$- [h_{i\alpha} \overline{L_i} \tilde{\eta} N_{R\alpha} + y_{j\alpha} \overline{\nu_{R_j}} \sigma^* N^c_{R\alpha} + k_\alpha \overline{N^c_{R\alpha}} N_{R\alpha} S^* + \text{h.c.}] - \mathcal{V}(H, S, \eta, \sigma) \, .$$

F (ϕ) denote the new fermions (scalars)

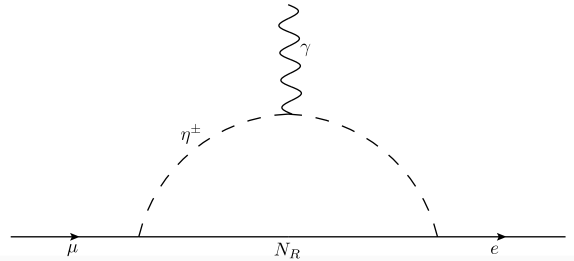
$$\begin{aligned}\mathcal{V}(H, S, \eta, \sigma) =& V(H) + V(S) + V(\eta) + V(\sigma) \\ &+ \lambda_{HS}(H^\dagger H)(S^* S) + \lambda_2 (H^\dagger H)(\sigma^* \sigma) + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) \\ &+ \lambda_4 (S^* S)(\sigma^* \sigma) + \lambda_5 (S^* S)(\eta^\dagger \eta) + \lambda_6 (\eta^\dagger \eta)(\sigma^* \sigma) + \lambda_7 (\eta^\dagger H)(H^\dagger \eta) \\ &+ \lambda_8 (\eta^\dagger H S^* \sigma + \text{h.c.}) \, ,\end{aligned}$$

Neutrino masses and LFV

$$(\mathcal{M}_\nu)_{ij} = \frac{1}{32\pi^2}\frac{\lambda_8 v_S^2 v_H}{m^2_{\eta^0_R} - m^2_{\sigma^0_R}} \sum_{\alpha=1}^{3} h_{i\alpha} k_\alpha y^*_{j\alpha} \left[F\left(\frac{m^2_{\eta^0_R}}{M^2_{N_\alpha}}\right) - F\left(\frac{m^2_{\sigma^0_R}}{M^2_{N_\alpha}}\right)\right] + (R \to I)\,,$$

where $F(x) = x\log x/(x-1)$.

$\mu \to e\gamma$



$$\left|\sum_\alpha h_{2\alpha} h^*_{1\alpha}\right| \lesssim 0.02 \left(\frac{m_\chi}{2\,\text{TeV}}\right)^2 .$$

Scotogenic DM

$$h_{i\alpha}\overline{L_i}\tilde{\eta}N_{R\alpha}$$

Singlet-doblet complex DM

$$V(\eta, \sigma, H)$$

$$k_\alpha \overline{N_{R\alpha}^c} N_{R\alpha} S^*$$

Dark radiation portal

$$g'\, Z'_\mu \sum_F q_F \overline{F}\gamma^\mu F$$

Dark scalar portal

Scotogenic DM

$$h_{i\alpha}\overline{L_i}\tilde{\eta}N_{R\alpha}$$

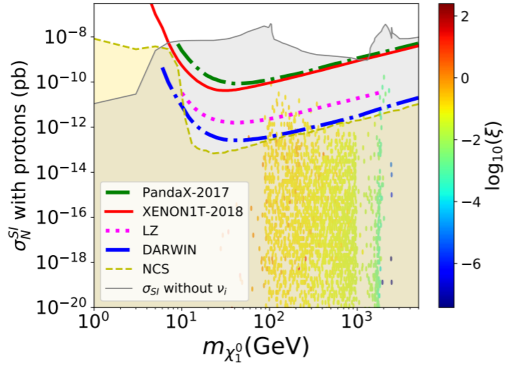
A. Ibarra, C. Yaguna, Ó. Zapata,
arXiv:1601.01163 [PRD]

Scotogenic DM

$$h_{i\alpha}\overline{L_i}\tilde{\eta}N_{R\alpha}$$

$$N_{R2}\to\Sigma$$

with A. Rivera, arXiv:1907.11938



$$(\chi_1^0\ \chi_2^0)^T = R(N_R\ \Sigma)^T$$

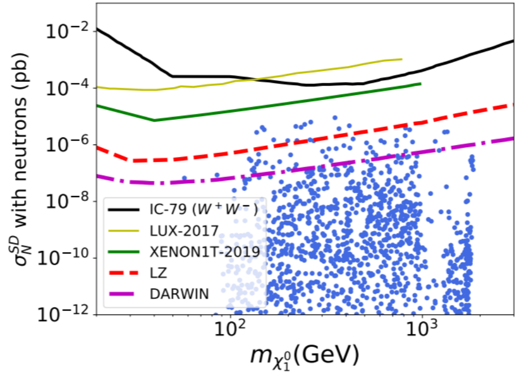
$$\xi = \frac{\left|M_\Sigma - m_{\chi_1^0}\right|}{m_{\chi_1^0}}$$

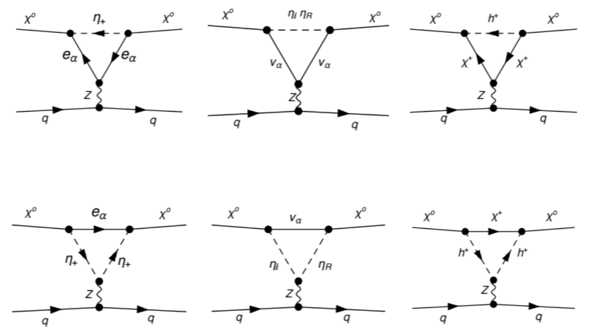
Scotogenic DM

$$h_{i\alpha}\overline{L_i}\tilde{\eta}N_{R\alpha}$$

$$N_{R2} \to \Sigma$$

with A. Rivera, arXiv:1907.11938





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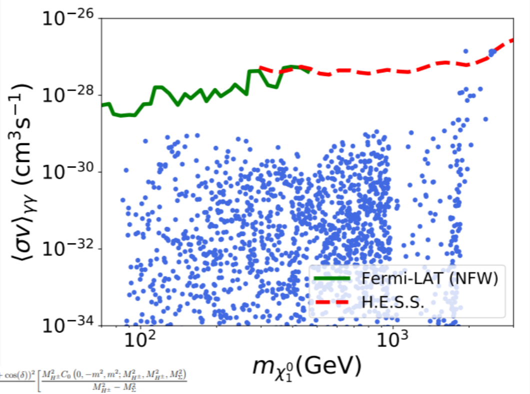


$$\sigma v\left(\chi_1^0\chi_1^0 \to \gamma\gamma\right) = \frac{|\mathcal{B}|^2}{32\pi m_{\chi_1^0}^2}$$

$$\begin{aligned}
\mathcal{B} = {} & \frac{\sqrt{2}\alpha m^2\sin^2(\alpha)Y_\Omega^2(\sin(\delta)+\cos(\delta))^2}{\pi}\left[\frac{M_{H^\pm}^2 C_0\left(0,-m^2,m^2;M_{H^\pm}^2,M_{H^\pm}^2,M_\Sigma^2\right)}{M_{H^\pm}^2-M_\Sigma^2}\right.\\
& -\frac{M_\Sigma\left(-2mM_{H^\pm}^2-M_\Sigma M_{H^\pm}^2+m^2M_\Sigma+2mM_\Sigma^2+M_\Sigma^3\right)C_0\left(0,-m^2,m^2;M_\Sigma^2,M_\Sigma^2,M_{H^\pm}^2\right)}{\left(M_{H^\pm}^2-M_\Sigma^2\right)\left(M_{H^\pm}^2+m^2-M_\Sigma^2\right)}\\
& \left.+\frac{2M_\Sigma\left(m+M_\Sigma\right)C_0\left(0,0,4m^2;M_\Sigma^2,M_\Sigma^2,M_\Sigma^2\right)}{-M_{H^\pm}^2-m^2+M_\Sigma^2}\right]\\
& +\frac{\alpha m^2\sin(\alpha)\cos(\alpha)Y_N^\alpha Y_\Sigma^\alpha}{\pi}\left[-\frac{m_\eta^2C_0\left(0,-m^2,m^2;m_\eta^2,m_\eta^2,m_{e_i}^2\right)}{m_\eta^2-m_{e_i}^2}\right.\\
& \left.+\frac{m_{e_i}^2\left(m_{e_i}^2+m^2-m_\eta^2\right)C_0\left(0,-m^2,m^2;m_{e_i}^2,m_{e_i}^2,m_\eta^2\right)}{\left(m_\eta^2-m_{e_i}^2\right)\left(-m_{e_i}^2+m^2+m_\eta^2\right)}+\frac{2m_{e_i}^2C_0\left(0,0,4m^2;m_{e_i}^2,m_{e_i}^2,m_{e_i}^2\right)}{-m_{e_i}^2+m^2+m_\eta^2}\right]\\
& +\frac{\alpha m^2\cos^2(\alpha)\left(Y_\Sigma^\alpha\right)^2}{2\sqrt{2}\pi}\left[\frac{m_\eta^2C_0\left(0,-m^2,m^2;m_\eta^2,m_\eta^2,m_{e_i}^2\right)}{m_\eta^2-m_{e_i}^2}\right.\\
& \left.-\frac{m_{e_i}^2\left(m_{e_i}^2+m^2-m_\eta^2\right)C_0\left(0,-m^2,m^2;m_{e_i}^2,m_{e_i}^2,m_\eta^2\right)}{\left(m_\eta^2-m_{e_i}^2\right)\left(-m_{e_i}^2+m^2+m_\eta^2\right)}-\frac{2m_{e_i}^2C_0\left(0,0,4m^2;m_{e_i}^2,m_{e_i}^2,m_{e_i}^2\right)}{-m_{e_i}^2+m^2+m_\eta^2}\right]\\
& +\frac{\sqrt{2}\alpha m^2\sin^2(\alpha)\left(Y_N^\alpha\right)^2}{2\pi}\left[\frac{m_\eta^2C_0\left(0,-m^2,m^2;m_\eta^2,m_\eta^2,m_{e_i}^2\right)}{m_\eta^2-m_{e_i}^2}\right.\\
& \left.-\frac{m_{e_i}^2\left(m_{e_i}^2+m^2-m_\eta^2\right)C_0\left(0,-m^2,m^2;m_{e_i}^2,m_{e_i}^2,m_\eta^2\right)}{\left(m_\eta^2-m_{e_i}^2\right)\left(-m_{e_i}^2+m^2+m_\eta^2\right)}-\frac{2m_{e_i}^2C_0\left(0,0,4m^2;m_{e_i}^2,m_{e_i}^2,m_{e_i}^2\right)}{-m_{e_i}^2+m^2+m_\eta^2}\right]\\
& -\frac{8\sqrt{2}\alpha m^2\cos^2(\alpha)M_W^2}{\pi\left(M_\Sigma^2-M_W^2\right)\left(4v_\Omega^2+v_\phi^2\right)\left(m^2-M_\Sigma^2+M_W^2\right)\left(m^2+M_\Sigma^2-M_W^2\right)}\\
& \left[4\left(m^2-M_W^2\right)\left(M_\Sigma^2-M_W^2\right)\left(m^2-M_\Sigma^2+M_W^2\right)C_0\left(0,0,4m^2;M_W^2,M_W^2,M_W^2\right)\right.\\
& +2M_\Sigma\left(2m-M_\Sigma\right)\left(M_\Sigma^2-M_W^2\right)\left(m^2+M_\Sigma^2-M_W^2\right)C_0\left(0,0,4m^2;M_\Sigma^2,M_\Sigma^2,M_\Sigma^2\right)\\
& -\left(m^2-M_\Sigma^2+M_W^2\right)\left(-M_W^2\left(m^2+M_\Sigma^2\right)-4mM_\Sigma\left(m^2+M_\Sigma^2-M_W^2\right)+4M_\Sigma^4+M_W^4\right)\\
& C_0\left(0,-m^2,m^2;M_W^2,M_W^2,M_\Sigma^2\right)-M_\Sigma\left(m^2+M_\Sigma^2-M_W^2\right)\left(4m^3-3m^2M_\Sigma+M_\Sigma^3-M_\Sigma M_W^2\right)\\
& \left.C_0\left(0,-m^2,m^2;M_\Sigma^2,M_\Sigma^2,M_W^2\right)\right].
\end{aligned}$$

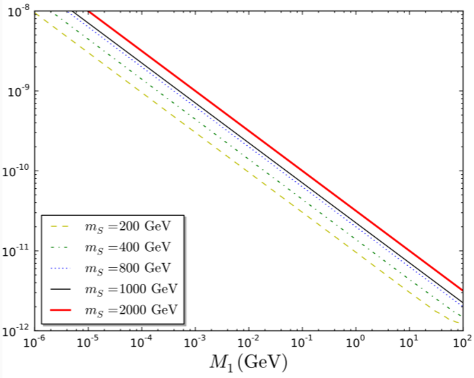
Scotogenic DM

FIMP Scenario

$$h_{i\alpha}\overline{L_i}\tilde{\eta}N_{R\alpha}$$

F. Molinaro, C. Yaguna, Ó. Zapata, arXiv:1405.1259 [JCAP]

$$h_1 \sim h_{1\alpha}$$



$$l\left(\eta^+\right) = 3\times 10^5\text{cm}\left(\frac{M_1}{1\text{GeV}}\right)\left(\frac{1\text{TeV}}{m_{\eta^+}}\right)^2$$

$$\lesssim 3 \text{ meters } \left(\frac{1\text{TeV}}{m_{\eta^+}}\right)^2 \quad \text{for} \quad M_1 \lesssim 1\text{MeV}$$

Chacko. *et al* arXiv:1505.04192 [PRD]

$$N_R N_R \to \nu_R \nu_R$$

$$\Delta N_{\mathrm{eff}} \sim 0.2$$

$$k_\alpha \overline{N^c_{R\alpha}} N_{R\alpha} S^*$$

Dark radiation portal

$$g' \, Z'_\mu \sum_F q_F \overline{F} \gamma^\mu F$$

Dark scalar portal

(One-loop) Dirac neutrino masses

Small Dirac neutrino masses

To explain the smallness of Dirac neutrino masses choose $\mathrm{U}(1)_X$ which:

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

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

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

- Forbids Majorana term: $\nu_R \nu_R$

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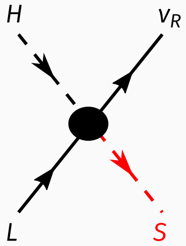
- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

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

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



Small Dirac neutrino masses

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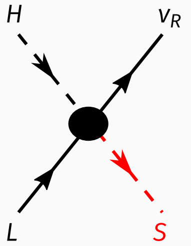
- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

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

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



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

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

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

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

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

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

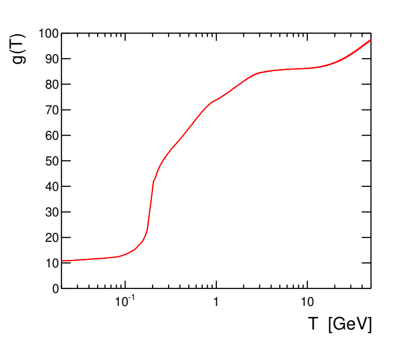
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \quad \text{In the limit } M^2_{Z'} \gg s.$$

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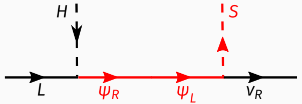
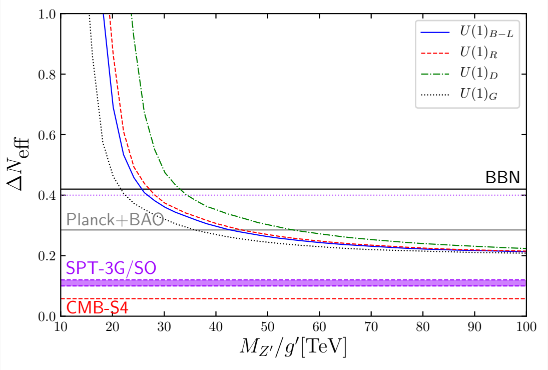
$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S\rangle} Z_3$



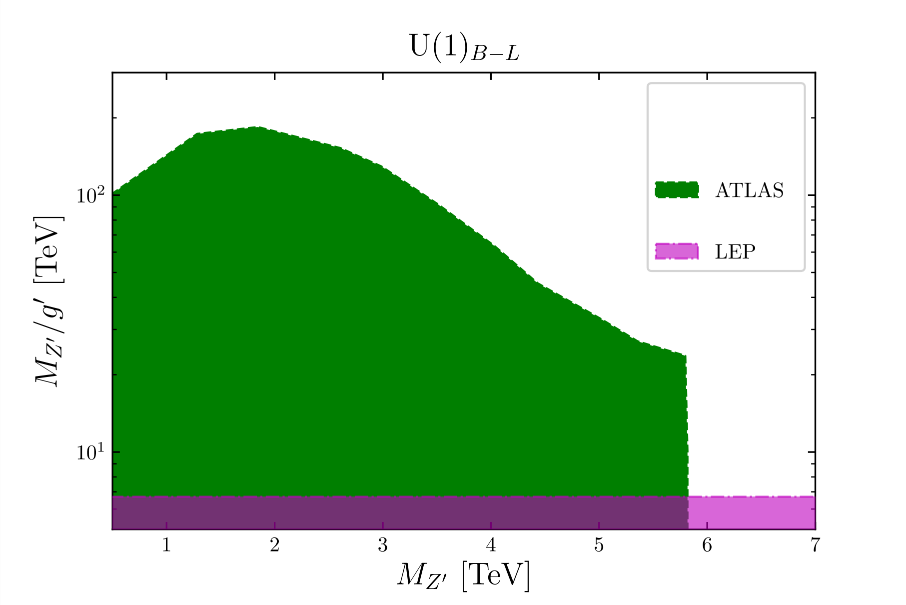
ν_{R3}	ν_{R2}	ν_{R1}	ψ_L	ψ_R	S
-4	-4	$+5$	-1	-1	$+3$

E. Ma, R. Srivastava: arXiv:1411.5042 [PLB]

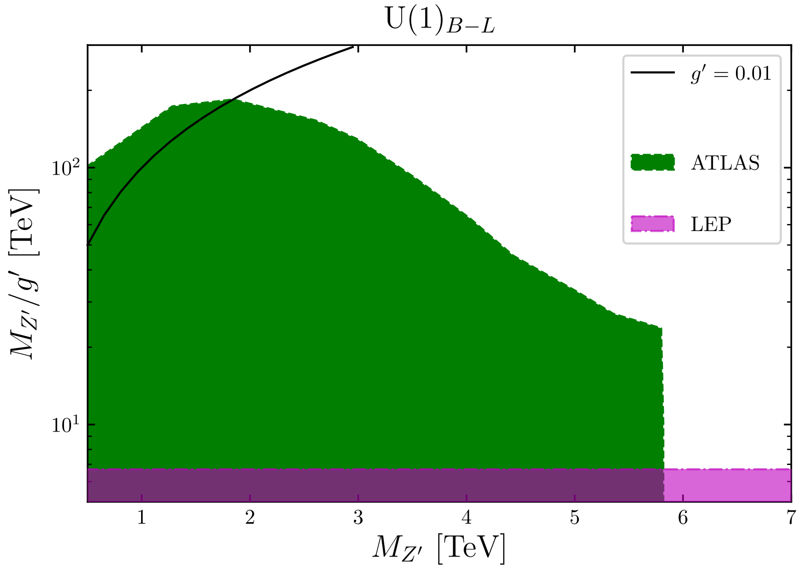


with J. Calle and Ó. Zapata, arXiv:1909.09574

Same constraints as before



Same constraints as before



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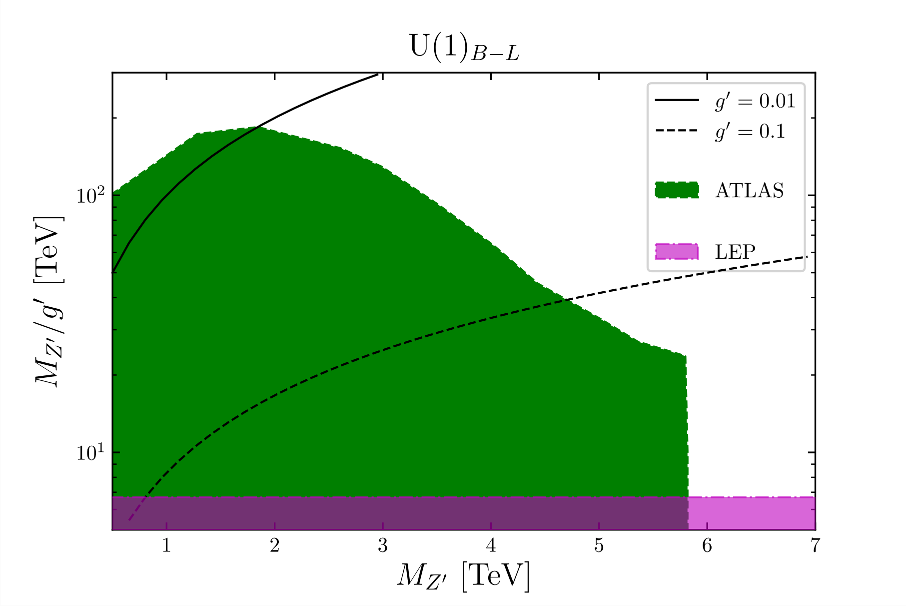

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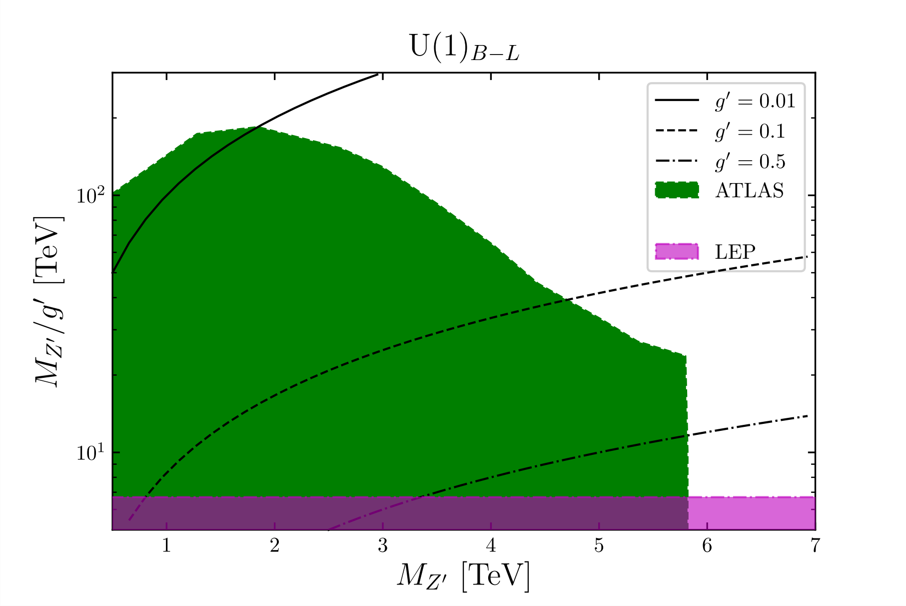
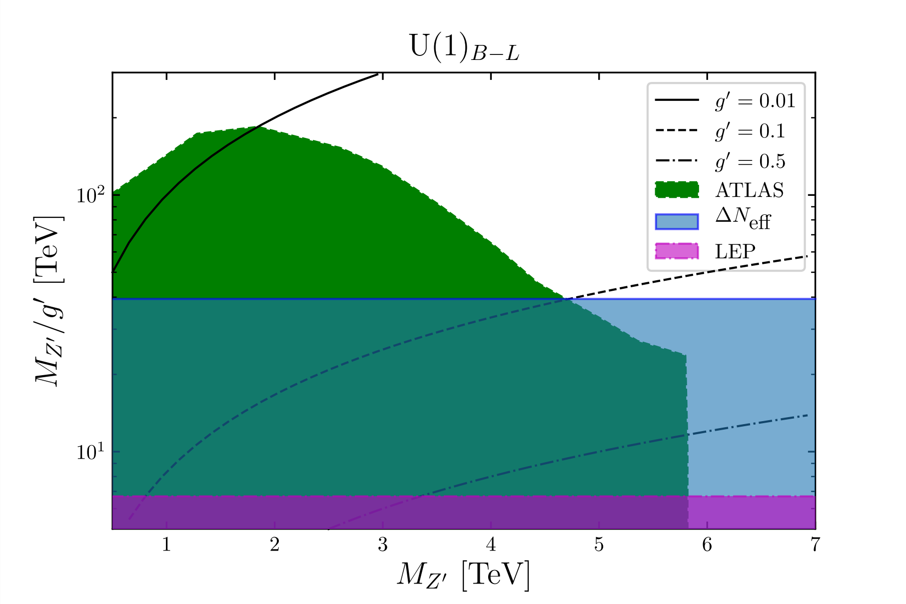


Same constraints as before



Conclusions

It makes sense to focus our attention on models tha can account for neutrino masses and dark matter (DM) without adhoc symmetries

One-loop Dirac neutrino masses

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

- Spontaneously broken $U(1)_X$ 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
- Dark symmetry for Majorana mediatiors

Thanks!