Effective Dirac neutrino masses in local Abelian symmetries

with *dark* matter and *dark* baryogenesis

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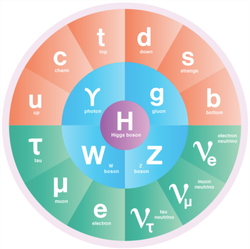
Focus on
arXiv:2112.09524 [Frontiers in Physics] arXiv:2205.05762 [PRD]
In collaboration with
Andrés Rivera (UdeA), David Suárez (UdeA), Walter Tangarife (Loyola University Chicago)

Dark sectors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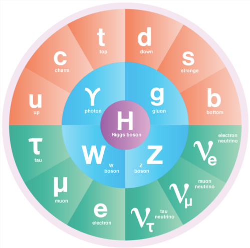

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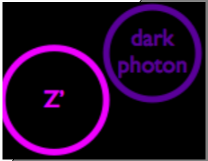
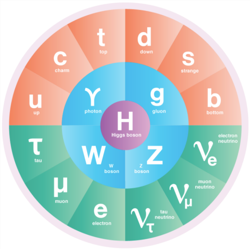


dark photon
Z'



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

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i {\psi_i}^\dagger \not{D} \psi_i$$
$$-h \left(\psi_1 \psi_2 \Phi + \text{h.c} \right)$$

Anomalons: SM-singlet Dirac fermion

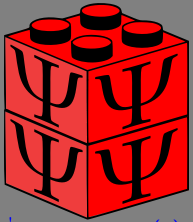
dark matter $m_\Psi = h\langle\Phi\rangle$

LHC production:

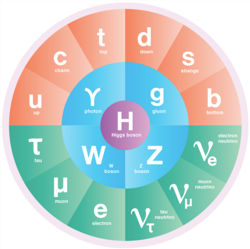
$F_{\mu\nu}$ $V^{\mu\nu}$

Gauged Symmetry: $\mathcal{X} \to D$:

Gauged Symmetry: $\mathcal{X} \to X$:



$\overline{\Psi}\Psi = \psi_1\psi_2 + \psi_1^\dagger\psi_2^\dagger \to \psi_\alpha\psi_\beta\Phi^{(*)}$, $\alpha = 1, \dots N \to N > 4$



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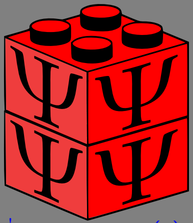
LHC production:

Gauged Symmetry: $\mathcal{X} \to B$: $q\bar{q} \to Z' \to \text{jets}$

Gauged Symmetry: $\mathcal{X} \to L$:



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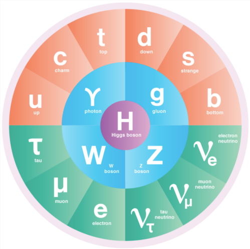

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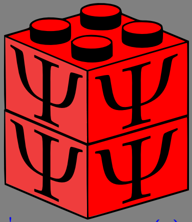
Gauged Symmetry: $\mathcal{X} \to L$:



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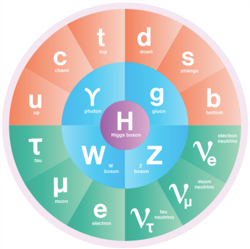

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$$-y\left(\psi_1\psi_2 S + \text{h.c}\right)$$

Anomalons: SM-singlet Dirac fermion

CP violation Yukawa y

LHC production:

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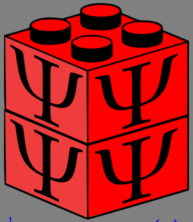

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Anomaly cancellation

Any local Abelian extension of the Standard Model can be reduced to a set of integers which must satisfy the gravitational anomaly, $[\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_Y$, and the cubic anomaly, $[\mathrm{U}(1)_X]^3$ conditions:

$$\sum_{\alpha=1}^{N} z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} z_\alpha^3 = 0\,, \tag{1}$$

Methology based on: Costa-Dobrescu-Fox arXiv:1905.13729 [PRL]

- From a list of $N-2$ integers, e.g., for N even

$$\boldsymbol{q} = [l_1, l_2, \cdots, l_n, k_1, k_2, \cdots, k_n]\,, \qquad n = (N-2)/2\,. \tag{2}$$

in the range $[-m, m]$, build two vector-like solutions of N integers,

$$\boldsymbol{x} = [l_1, k_1, \cdots k_n, -l_1, -k_1, \cdots - k_n,] \qquad \boldsymbol{y} = [0, 0, l_1, \cdots l_n, -l_1, \cdots - l_n] \tag{3}$$

Methology based on: Costa-Dobrescu-Fox arXiv:1905.13729 [PRL]

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in the range $[-m,m]$, build two vector-like solutions of N integers,

$$\boldsymbol{x}=\left[l_1,k_1,\cdots k_n,-l_1,-k_1,\cdots-k_n,\right]\qquad \boldsymbol{y}=\left[0,0,l_1,\cdots l_n,-l_1,\cdots-l_n\right] \tag{3}$$

- Obtain a (some times) non vector-like solution with $z_{\text{max}}=2m$

$$\boldsymbol{z}=\boldsymbol{x}\oplus\boldsymbol{y}=\left(\sum_{i=1}^{N}x_iy_i^2\right)\boldsymbol{x}+\left(\sum_{i=1}^{N}x_i^2y_i\right)\boldsymbol{y}\,, \tag{4}$$

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The parameter space to be explored with $z_{\text{max}} = 20$ $(m = 10)$ has 96 153 non vector-like solutions

$$\#\text{ of } \boldsymbol{q} \text{ lists} = (2m+1)^{N-2} = \begin{cases} 9261 \to 3 & N = 5 \\ 194841 \to 38 & N = 6 \\ \vdots & \vdots \\ 1.6\times 10^{13} \to 65910 & N = 12\,, \qquad \text{instead } 10^{19} \end{cases} \tag{5}$$

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$$\#\text{ of } \boldsymbol{q} \text{ lists} = (2m+1)^{N-2} = \begin{cases} 9261 \to 3 & N = 5 \to [1, 5, -7, -8, 9] \\ 194841 \to 38 & N = 6 \\ \vdots & \vdots \\ 1.6 \times 10^{13} \to 65910 & N = 12\,, \qquad \text{instead } 10^{19} \end{cases} \tag{5}$$

Simplest secluded model with SM-singlet massive chiral fermions from SSB: $\mathrm{U}(1)_D$

$$\mathcal{L} = i\psi_i^\dagger \not{D}\psi_i - \frac{1}{4}V_{\mu\nu}V'^{\mu\nu} + \sum_{i<j} h_{ij}\psi_i\psi_j\phi^{(*)} + \text{h.c} \tag{6}$$

96 153 → 5 196 multi-component DM ($N = 8, 12$) → 28 with two Dirac-fermion DM

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$$\boldsymbol{z} = [1, 2, 2, 4, -5, -5, -7, 8] \to \phi = 3 \to [(1, 2), (2, -5), (-5, 8), (4, -7)] \tag{7}$$

Simplest secluded model with SM-singlet massive chiral fermions from SSB: $\mathrm{U}(1)_D$

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96 153 → 5 196 multi-component DM ($N = 8, 12$) → 28 with two Dirac-fermion DM

$$\boldsymbol{z} = [1,2,2,4,-5,-5,-7,8] \to \phi = 3 \to [(1,2),(2,-5),(-5,8),(4,-7)] \tag{7}$$

$$\mathcal{L} \subset \Psi^{\mathrm{T}} \begin{array}{c} \\ 1 \\ 2 \\ 2 \\ -5 \\ -5 \\ 8 \end{array} \begin{array}{c} \begin{array}{cccccc} 1 & 2 & 2 & -5 & -5 & 8 \end{array} \\ \begin{bmatrix} 0 & h_{(1,2)} & h'_{(1,2)} & 0 & 0 & 0 \\ h_{(1,2)} & 0 & 0 & h_{(2,-5)} & h_{(2,-5)} & 0 \\ h'_{(1,2)} & 0 & 0 & 0 & 0 & 0 \\ 0 & h_{(2,-5)} & 0 & 0 & 0 & h_{(-5,8)} \\ 0 & h_{(2,-5)} & 0 & 0 & 0 & h'_{(-5,8)} \\ 0 & 0 & 0 & h_{(-5,8)} & h'_{(-5,8)} & 0 \end{bmatrix} \end{array} \Psi\phi^{(*)} + h_{(4,-7)}\psi_4\psi_{-7}\phi^* \tag{8}$$

Effective Dirac neutrino mass operator

Decrease the number of charges to be assigned to dark matter particles, ψ_i below

$$[\chi_1, \chi_2, \cdots, \psi_1, \psi_2, \cdots, \psi_{N'}]$$

Secluded case:

$[\nu, \nu, (\nu), \psi_1, \psi_2, \cdots, \psi_{N'}]$

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3\,, \tag{9}$$

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

Φ is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry with D-charge

$$\delta\phi = -\ \nu \qquad , \tag{10}$$

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Decrease the number of charges to be assigned to dark matter particles, ψ_i below

$$[\chi_1, \chi_2, \cdots, \psi_1, \psi_2, \cdots, \psi_{N'}]$$

Secluded case: Active case:

$$[\nu, \nu, (\nu), \psi_1, \psi_2, \cdots, \psi_{N'}] \qquad [\nu, \nu, (\nu), m, m, m, \psi_1, \psi_2, \cdots, \psi_{N'}]$$

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3, \quad X(L_i) = -L, \; X(H) = h \qquad \to m = L - h \tag{9}$$

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

Φ is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry with X-charge

$$\phi = -(\nu + m)/\delta, \tag{10}$$

Standard model extended with $\mathrm{U}(1)_{\mathcal{X}=X \text{ or } D}$ gauge symmetry

Fields	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{\mathcal{X}=D \text{ or } X}$
$Q_i^\dagger$	$\mathbf{2}$	$-1/6$	Q
d_{Ri}	$\mathbf{1}$	$-1/2$	d
u_{Ri}	$\mathbf{1}$	$+2/3$	u
$L_i^\dagger$	$\mathbf{2}$	$+1/2$	L
e_{Ri}	$\mathbf{1}$	-1	e
H	$\mathbf{2}$	$1/2$	h
χ_α	$\mathbf{1}$	0	z_α
Φ	$\mathbf{1}$	0	ϕ

Table 1:
$i = 1, 2, 3,\ \alpha = 1, 2, \ldots, N'$

Standard model extended with $\mathrm{U}(1)_{\mathcal{X}=L \text{ or } B}$ gauge symmetry

Fields	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{\mathcal{X}=B \text{ or } L}$
$Q_i^\dagger$	$\mathbf{2}$	$-1/6$	Q
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u_{Ri}	$\mathbf{1}$	$+2/3$	u
$L_i^\dagger$	$\mathbf{2}$	$+1/2$	L
e_{Ri}	$\mathbf{1}$	-1	e
H	$\mathbf{2}$	$1/2$	$h=0$
χ_α	$\mathbf{1}$	0	z_α
$(L'_L)^\dagger$	$\mathbf{2}$	$1/2$	$-x'$
L''_R	$\mathbf{2}$	$-1/2$	x''
e'_R	$\mathbf{1}$	-1	x'
$(e''_L)^\dagger$	$\mathbf{1}$	1	$-x''$
Φ	$\mathbf{1}$	0	ϕ
S	$\mathbf{1}$	0	s

Table 1: minimal set of new fermion content: $L=e=0$ for $\mathcal{X}=B$. Or $Q=u=d=0$ for $\mathcal{X}=L$. $i=1,2,3$, $\alpha=1,2,\ldots,N'$

Anomaly cancellation: $\mathcal{X} = X$

The anomaly-cancellation conditions on $[SU(3)_c]^2\, U(1)_X$, $[SU(2)_L]^2\, U(1)_X$, $[U(1)_Y]^2\, U(1)_X$, allow us to express three of the X-charges in terms of the others

$$u = -e - \frac{2}{3}L - \frac{1}{9}\left(x' - x''\right) , \quad d = e + \frac{4}{3}L - \frac{1}{9}\left(x' - x''\right) , \quad Q = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right) , \tag{11}$$

while the $[U(1)_X]^2\, U(1)_Y$ anomaly condition reduces to

$$(e + L)(x' - x'') = 0 . \tag{12}$$

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- If: $x' = x''$ or $x' = x'' = 0$
- We need $h = -e - L = L - m$:

$$u = \frac{4L}{3} - m , \qquad d = m - \frac{2L}{3} , \qquad Q = -\frac{L}{3} , \qquad e = m - 2L , \qquad h = L - m ,$$

Anomaly cancellation: $\mathcal{X} = X$

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- If: $x' = x''$ or $x' = x'' = 0$
- We need $h = -e - L = L - m$:

$$u = \frac{4L}{3} - m\,, \qquad d = m - \frac{2L}{3}\,, \qquad Q = -\frac{L}{3} \neq 0\,, \qquad e = m - 2L\,, \qquad h = L - m\,,$$

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

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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:

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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

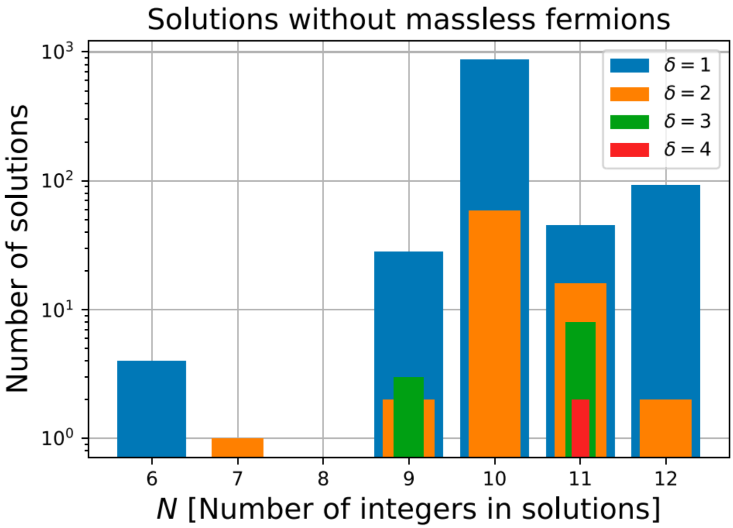
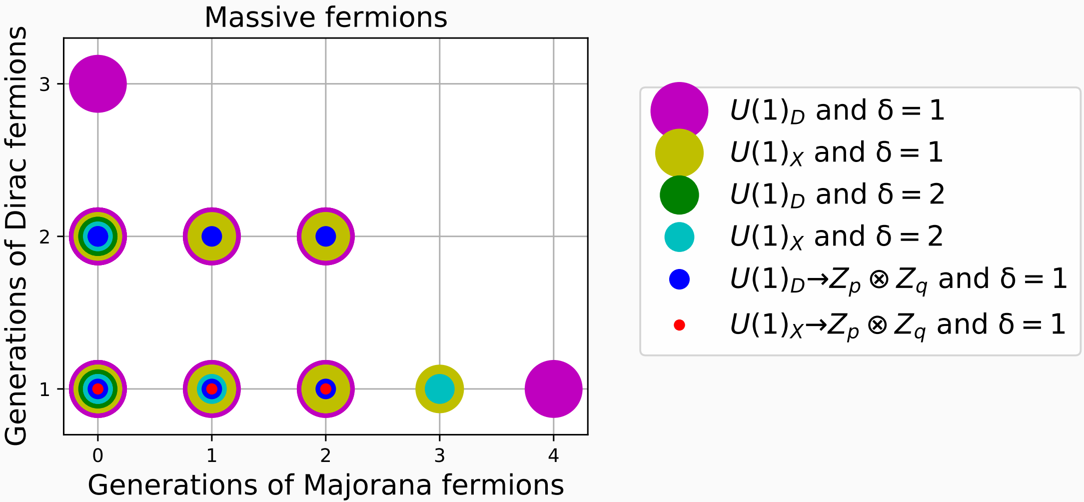
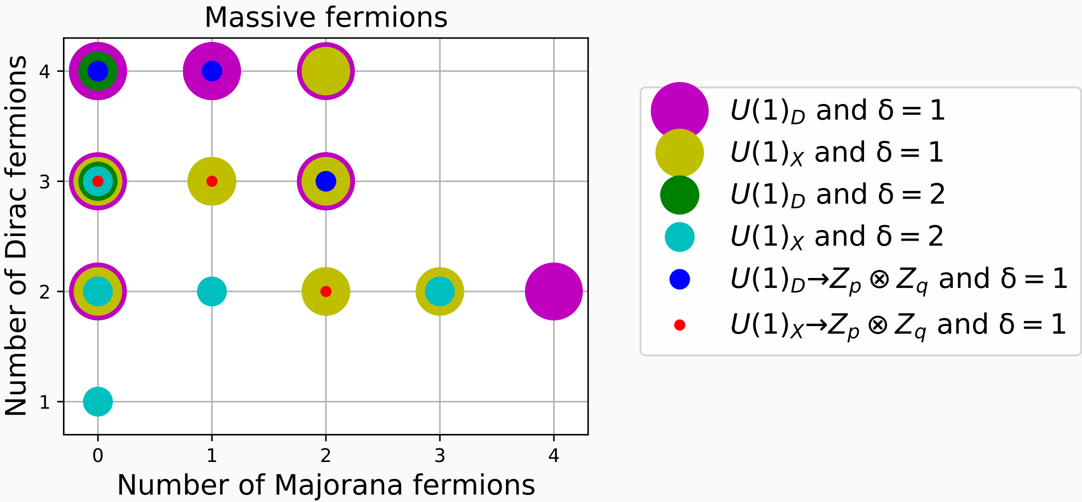


FIGURE 1 | Distribution of solutions with N integers to the Diophantine **Eq. 1** which allow the effective Dirac neutrino mass operator at $d = (4 + \delta)$ for at least two right-handed neutrinos and have non-vanishing Dirac o Majorana masses for the other SM-singlet chiral fermions in the solution.

Multi-generational dark matter



Multi-component dark matter



$U(1)_X$ selection

- Active symmetry $m = 3$

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

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

- Active symmetry $m = 3$
- Effective neutrino mass $\delta = 2 \to \nu = -5$:

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

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

- Active symmetry $m = 3$
- Effective neutrino mass $\delta = 2 \rightarrow \nu = -5$:
- Active symmetry: $m = 3 \rightarrow \phi = -(\nu + m)/\delta = 1$

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

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

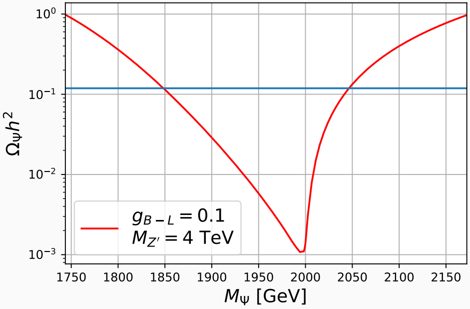
- Active symmetry $m = 3$
- Effective neutrino mass $\delta = 2 \to \nu = -5$:
- Active symmetry: $m = 3 \to \phi = -(\nu + m)/\delta = 1$
- Dirac-fermionic DM: $(\psi_L)^\dagger \psi''_R \Phi^* \to z_6 = -7,\ z_7 = 8$

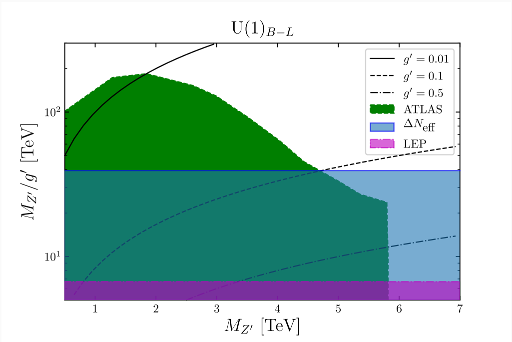
$$(-5, -5, 3, 3, 3, -7, 8)$$

- Active symmetry $m = 3$
- Effective neutrino mass $\delta = 2 \to \nu = -5$:
- Active symmetry: $m = 3 \to \phi = -(\nu + m)/\delta = 1$
- Dirac-fermionic DM: $(\psi_L)^\dagger \psi''_R \Phi^* \to z_6 = -7,\ z_7 = 8$

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

1 122 solutions from $\sim 400,000$





Anomaly cancellation: $\mathcal{X} = L$ or B

The anomaly-cancellation conditions on $[\mathrm{SU}(3)_c]^2\,\mathrm{U}(1)_X$, $[\mathrm{SU}(2)_L]^2\,\mathrm{U}(1)_X$, $[\mathrm{U}(1)_Y]^2\,\mathrm{U}(1)_X$, allow us to express three of the X-charges in terms of the others

$$u = -e - \frac{2}{3}L - \frac{1}{9}\left(x' - x''\right)\,, \quad d = e + \frac{4}{3}L - \frac{1}{9}\left(x' - x''\right)\,, \quad Q = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,, \tag{13}$$

while the $[\mathrm{U}(1)_X]^2\,\mathrm{U}(1)_Y$ anomaly condition reduces to

$$(e + L)(x' - x'') = 0\,. \tag{14}$$

- Previously: $x' = x''$
- We choose instead ($h = 0$):

$$e = -L\,, \tag{15}$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,. \tag{16}$$

If $B = 0 \to \mathrm{U}(1)_L$

Anomaly cancellation: $\mathcal{X} = B$

The gravitational anomaly, $[\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_Y$, and the cubic anomaly, $[\mathrm{U}(1)_X]^3$, can be written as the following system of Diophantine equations, respectively,

$$\sum_{\alpha=1}^{N} z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} z_\alpha^3 = 0\,, \tag{17}$$

where $N = N' + 5$ and

$$z_{N'+1} = -\,x'\,, \qquad z_{N'+2} = x''\,,$$
$$z_{N'+2+i} = L\,, \quad i = 1,2,3 \tag{18}$$

$\rightarrow$

$$9Q = -\sum_{\alpha=N'+1}^{N'+5} z_\alpha = -x' + x'' + L + L + L\,, \tag{19}$$

$L = 0 \rightarrow \mathrm{U}(1)_B$ but $Q = 0 \not\rightarrow \mathrm{U}(1)_L$

$\mathrm{U}(1)_B$ selection

- $L = 0$

$$(5, 5, -3, -2, 1, -6)$$

$U(1)_B$ selection

- $L = 0$
- Effective neutrino mass: $\phi = -\nu = -5$

$$(5, 5, -3, -2, 1, -6)$$

$\mathrm{U}(1)_B$ selection

- $L = 0$
- Effective neutrino mass: $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:
  $(L'_L)^\dagger L''_R \Phi^* \to x' = -1,\ x'' = 6$

$$(5, 5, -3, -2, 1, -6)$$

$\mathrm{U}(1)_B$ selection

- $L = 0$
- Effective neutrino mass: $\phi = -\nu = -5$
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$$(5, 5, -3, -2, 1, -6)$$

- $L = 0$
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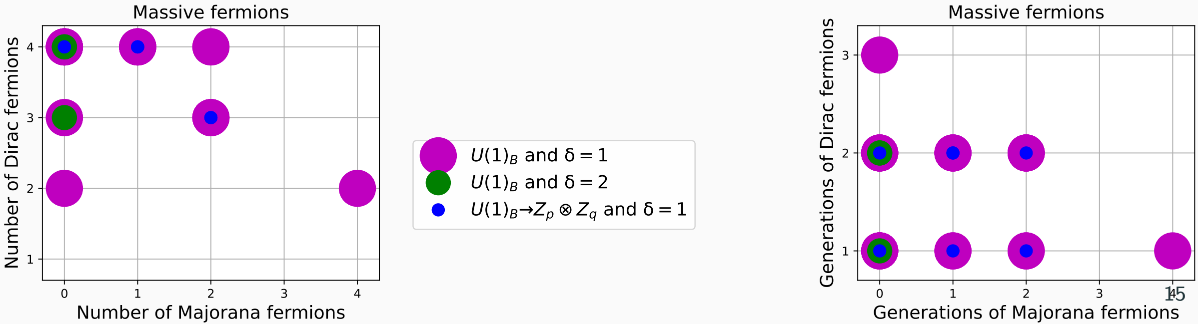
- Dirac-fermionic DM: $(\chi_L)^\dagger \chi''_R \Phi^* \to z_3 = -3,\ z_4 = -2$

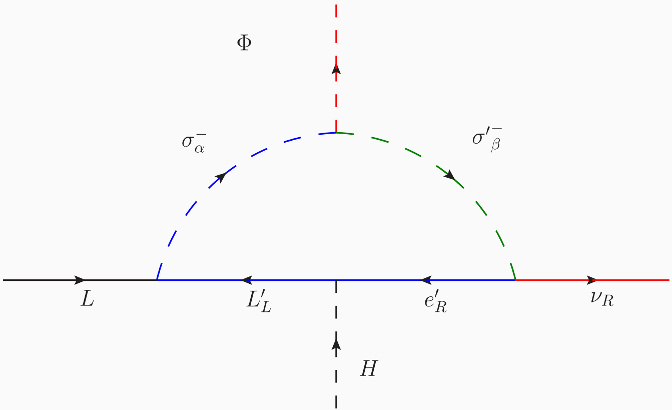
959 solutions from $\sim 400,000$ (as in $U(1)_D$)

$$(5, 5, -3, -2, 1, -6)$$



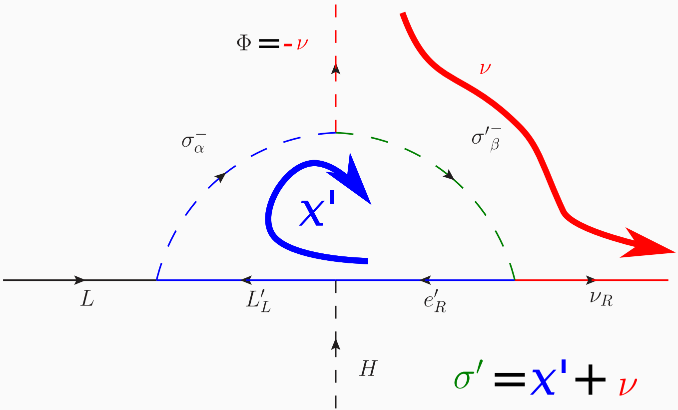
Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



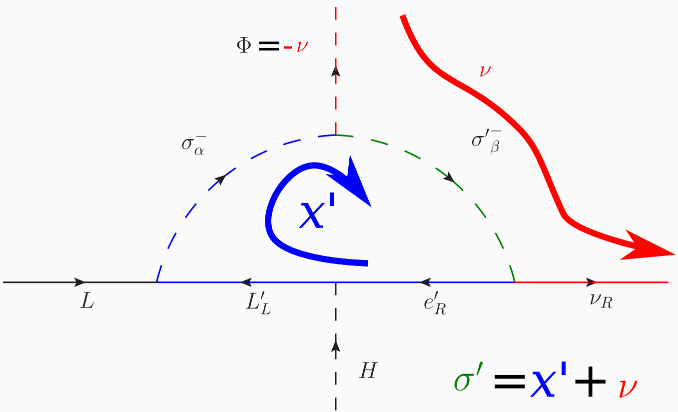
Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



Scotogenic realization

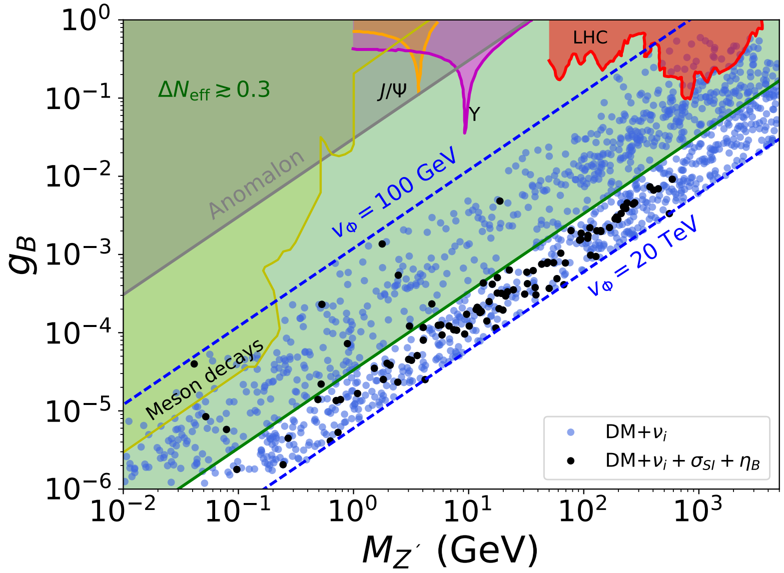
Any realization which does not affect anomaly cancellation is allowed



Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	**1**	$2/3$	$u = 1/3$
d_{Ri}	**1**	$-1/3$	$d = 1/3$
$(Q_i)^\dagger$	**2**	$-1/6$	$Q = -1/3$
$(L_i)^\dagger$	**2**	$1/2$	$L = 0$
e_R	**1**	-1	$e = 0$
$(L'_L)^\dagger$	**2**	$1/2$	$-x' = -3/5$
e'_R	**1**	-1	$x' = 3/5$
L''_R	**2**	$-1/2$	$x'' = 18/5$
$(e''_L)^\dagger$	**1**	1	$-x'' = -18/5$
$\nu_{R,1}$	**1**	0	-3
$\nu_{R,2}$	**1**	0	-3
χ_R	**1**	0	$6/5$
$(\chi_L)^\dagger$	**1**	0	$9/5$
H	**2**	$1/2$	0
S	**1**	0	3
Φ	**1**	0	3
σ^-_α	**1**	1	$3/5$
σ'^-_α	**1**	-1	$-12/5$

- SARAH→SPheno→MicroMegas
- η_B calculation code
- Python notebook with the scan

Black points: Dirac neutrinos with proper DM and baryon assymetry



Conclusions

A methodology to find all the *universal* Abelian extensions of the standard model is designed

All of the extensions can be reformulated as the solution of

$$\sum_{\alpha=1}^{N} z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} z_\alpha^3 = 0\,,$$

which we fully scan until $N = 12$ and $|z_{\text{max}}| = 20$

Once the physical conditions are stablished, the full set of self-consistent models are found from a simple data-analysis procedure