Gauged Lepton number

with *dark* matter and *dark* baryogenesis

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Focus on

...

In collaboration with

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Local Abelian extensions of the SM

Anomaly cancellation

Any *universal* 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]

- 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,

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

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

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

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

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

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

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

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

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

$$\boldsymbol{q} = [l_1 = 2, l_2 = 3, k_1 = -1, k_2 = -3]\,, \qquad n = 2\,. \tag{2}$$

in the range $[-3,3]$, build two vector-like solutions of 6 integers,

$$\boldsymbol{x} = [2, -1, -3, -2, 1, 3,] \qquad\qquad \boldsymbol{y} = [0, 0, 2, \cdots 3, -2, \cdots - 3] \tag{3}$$

- Obtain a (some times) non vector-like solution with $z_{\text{max}} = 2 \times 3 = 6$

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

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

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

https://pypi.org/project/anomalies/

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anomalies 0.2.5

`pip install anomalies`

Latest version

Released: Sep 6, 2022

Anomaly cancellation

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- Stars: 0

Project description

Anomalies

Python package passing | Upload Python Package passing | DOI 10.5281/zenodo.5526558

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)` https://doi.org/10.5281/zenodo.7380817

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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.gz')
>>> 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:

2 296 615 solutions with $5 \leq N \leq 12$ integers until `|32|` [JSON]

Publication date:
September 24, 2021

DOI:
DOI 10.5281/zenodo.7380817

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

Versions

Version v2 Sep 24, 2021
10.5281/zenodo.7380817

Minimal secluded model with SM-singlet massive chiral fermions from SSB: 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 $\rightarrow$ 5 196 $\boxed{\text{multi-component DM}}$ $(N = 8, 12) \rightarrow$ 142 with three Dirac-fermion DM

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

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96 153 $\rightarrow$ 5 196 multi-component DM $(N = 8, 12) \rightarrow$ 142 with three Dirac-fermion DM

$$\boldsymbol{z} = [1, -2, -2, 4, 5, -7, -7, 8] \rightarrow \phi = 9 \rightarrow [(1, 8), (-2, -7), (4, 5)] \tag{7}$$

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

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96 153 $\rightarrow$ 5 196 **multi-component DM** $(N = 8, 12) \rightarrow$ 142 with three Dirac-fermion DM

$$\boldsymbol{z} = [1, -2, -2, 4, 5, -7, -7, 8] \rightarrow \phi = 9 \rightarrow [(1, 8), (-2, -7), (4, 5)] \tag{7}$$

$$\mathcal{L} \subset h_{(1,8)}\psi_1\psi_8\phi^*\phi^{(*)} + \underbrace{\sum_{a,b=1}^{2} h_{(-2a,-7b)}\psi_4\psi_{-7}\phi}_{\boxed{\text{multi-flavor DM}}} + h_{(4,5)}\psi_4\psi_5\phi^*\phi^{(*)} + \text{h.c.} \tag{8}$$

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

$$\mathcal{L} = i\psi_i^\dagger \not{\mathcal{D}} \psi_i - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \sum_{i<j} h_{ij}\psi_i\psi_j\phi^{(*)} + \text{h.c} \tag{9}$$

$96\,153 \to 5\,196$ $\boxed{\text{multi-component DM}}$ $(N = 8, 12) \to 41$ with two Dirac-fermion DM

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

$$\mathcal{L} = i\psi_i^\dagger \not{D}\psi_i - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \sum_{i<j} h_{ij}\psi_i\psi_j\phi^{(*)} + \text{h.c} \tag{9}$$

$96\,153 \to 5\,196$ $\boxed{\text{multi-component DM}}$ $(N = 8, 12) \to 41$ with two Dirac-fermion DM

$$\boldsymbol{z} = [1, 2, 2, 4, -5, -5, -7, 8] \to \phi = 3 \to [(1, 2), (2, -5), (-5, 8), (4, -7)] \tag{10}$$

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

$$\mathcal{L} = i\psi_i^\dagger \not{\mathcal{D}} \psi_i - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \sum_{i<j} h_{ij} \psi_i \psi_j \phi^{(*)} + \text{h.c} \tag{9}$$

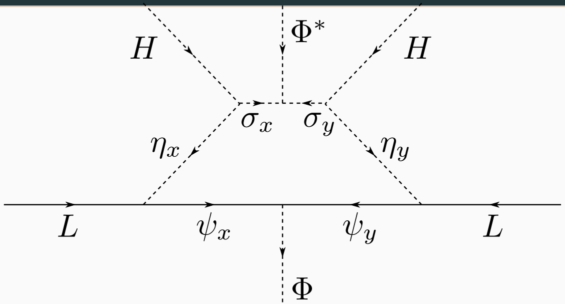
96 153 → 5 196 $\boxed{\text{multi-component DM}}$ $(N = 8, 12) \to 41$ with two Dirac-fermion DM

$$\boldsymbol{z} = [1, 2, 2, 4, -5, -5, -7, 8] \to \phi = 3 \to [(1,2), (2,-5), (-5,8), (4,-7)] \tag{10}$$

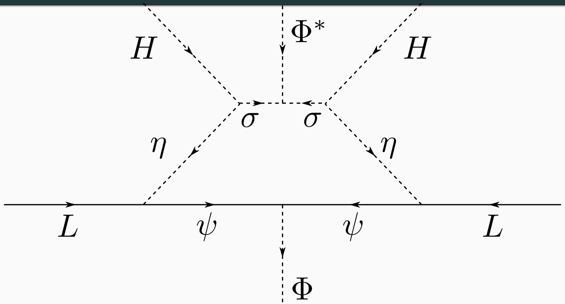
$$\mathcal{L} \subset \Psi^{\mathrm{T}} \begin{array}{c|cccccc|} & 1 & 2 & 2 & -5 & -5 & 8 \\ 1 & 0 & h_{(1,2)} & h'_{(1,2)} & 0 & 0 & 0 \\ 2 & h_{(1,2)} & 0 & 0 & h_{(2,-5)} & h_{(2,-5)} & 0 \\ 2 & h'_{(1,2)} & 0 & 0 & 0 & 0 & 0 \\ -5 & 0 & h_{(2,-5)} & 0 & 0 & 0 & h_{(-5,8)} \\ -5 & 0 & h_{(2,-5)} & 0 & 0 & 0 & h'_{(-5,8)} \\ 8 & 0 & 0 & 0 & h_{(-5,8)} & h'_{(-5,8)} & 0 \end{array} \Psi \phi^{(*)} + h_{(4,-7)} \psi_4 \psi_{-7} \phi^* \tag{11}$$

neutrino masses and mixings

$$\frac{y}{\Lambda}LLHH \to \frac{y}{\Lambda}LLHH\frac{\Phi}{\Lambda}\frac{\Phi^*}{\Lambda}$$



$$\frac{y}{\Lambda}LLHH \to \frac{y}{\Lambda}LLHH\frac{\Phi}{\Lambda}\frac{\Phi^*}{\Lambda}$$



Already found in arXiv:2008.08573 ($N \leq 9$ and $z_{\text{max}} \leq 10$)

$$\boldsymbol{z} = [\underbrace{1, 1}_{\psi}, 2, 3, -4, -4, -5, 6] \to \phi = 2 \to [\ (1, 1)_a, (2, -4), (4, -6), (4, -7)] \qquad (12)$$

Additional conditions to reduce multiplicity

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:

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

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3, \tag{13}$$

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

Φ is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry and $\boxed{\text{give mass to } \textit{all } \psi_i}$

$$\phi = -\frac{\nu}{\delta}, \tag{14}$$

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:

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

Active case:

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

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3\,, \quad X(L_i) = -L\,,\ X(H) = h \qquad \to m = L - h \tag{13}$$

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

Φ is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry and $\boxed{\text{give mass to } \textit{all } \psi_i}$ $\to$ $\cancel{[-4, -4, 1, 1, 1, 5]}$

$$\phi = -\frac{(\nu + m)}{\delta}\,, \tag{14}$$

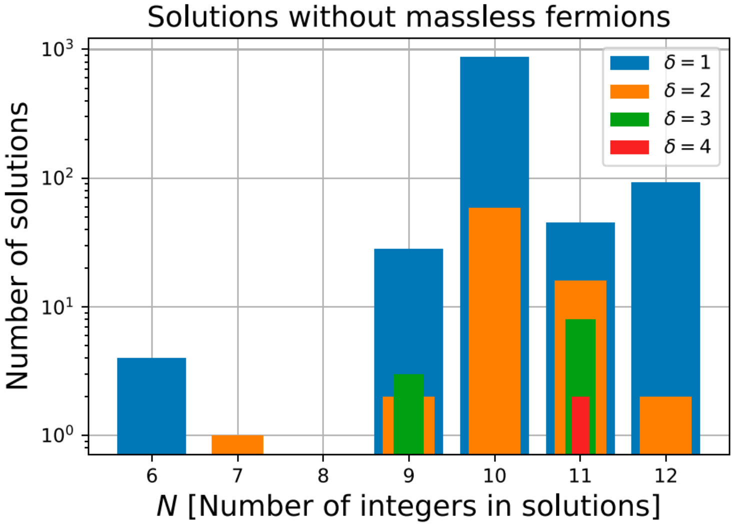
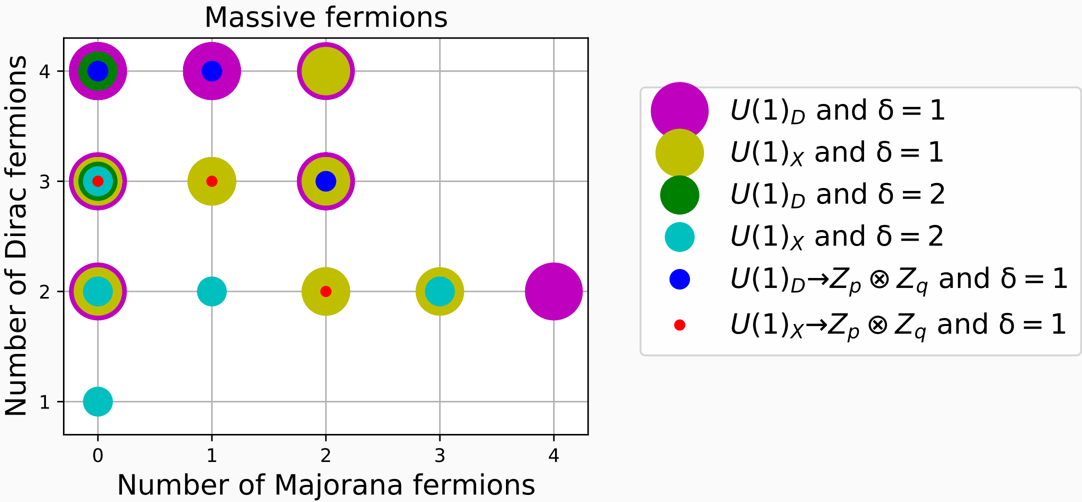
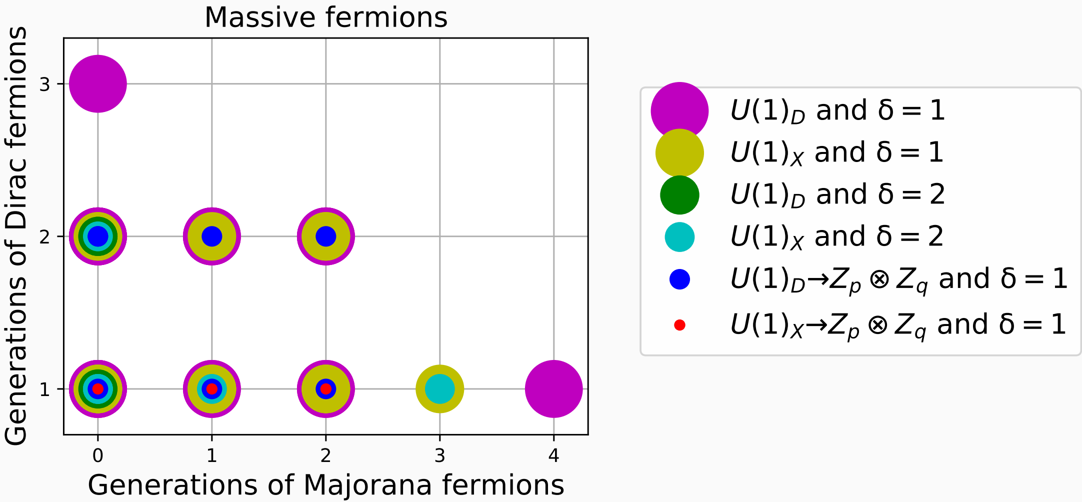


FIGURE 1 | Distribution of solutions with N integers to the Diophantine **Eq. 1** which allow the effective Dirac neutrino mass operator at $d = (4 + \delta)$ for at least two right-handed neutrinos and have non-vanishing Dirac o Majorana masses for the other SM-singlet chiral fermions in the solution.

Multi-component dark matter



Multi-flavor dark matter



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

- Active symmetry $m = 3$

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

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

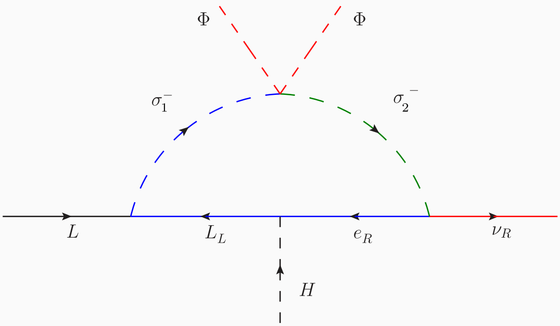
- Active symmetry $m = 3$
- Effective neutrino mass $\delta = 2 \to \nu = -5$:

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

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

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

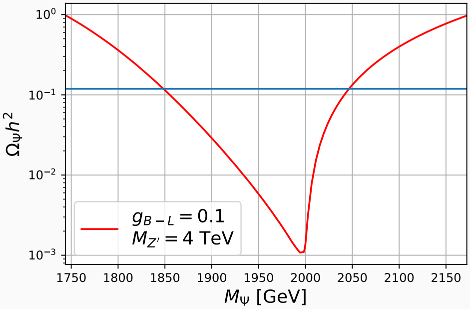
$$(-5, -5, 3, 3, 3, -7, 8)$$

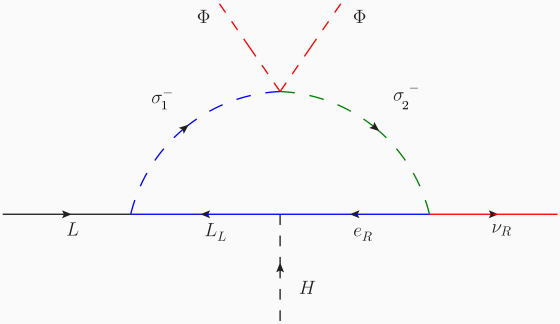


$\mathrm{U}(1)_X$ selection

- 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: $(\psi_L)^\dagger \psi''_R \Phi^* \to z_6 = -7,\ z_7 = 8$

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





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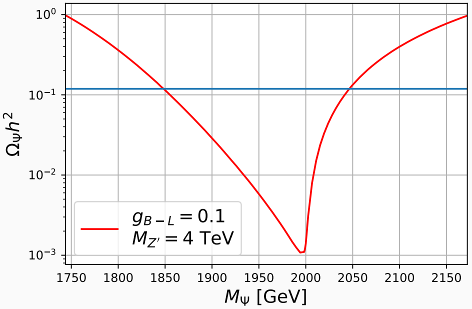
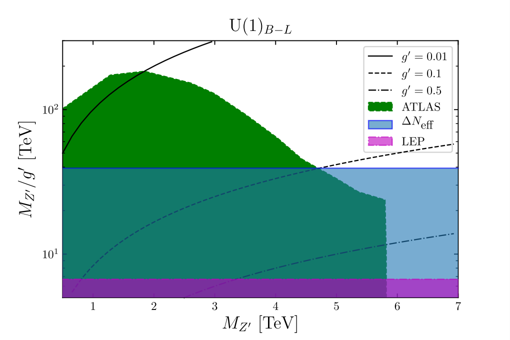
$$(-5, -5, 3, 3, 3, -7, 8)$$





Half active symmetries: gauged B or L

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

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

Table 1: LHC: hadronic production and dileptonic decay

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

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
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	$\mathbf{2}$	$1/2$	$h=0$
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: $\mathcal{X} = L$ or B: beyond SM-singlet fermions

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

$$u = -e - \frac{2}{3}L - \frac{1}{9}\left(x' - x''\right)\,,\quad d = e + \frac{4}{3}L - \frac{1}{9}\left(x' - x''\right)\,,\quad Q = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,, \tag{15}$$

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

$$(e+L)(x' - x'') = 0\,. \tag{16}$$

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

$$e = -L\,, \tag{17}$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,. \tag{18}$$

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

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

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,

$$\sum_{\alpha=1}^{N} z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} z_\alpha^3 = 0\,, \tag{19}$$

where

$$z_1 = -\,x'\,, \qquad z_2 = x''\,,$$
$$z_{2+i} = L\,, \quad i = 1,2,3 \tag{20}$$

$\rightarrow$

$$9Q = -\sum_{\alpha=1}^{5} z_\alpha = -x' + x'' + L + L + L\,, \tag{21}$$

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

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

- $L = 0$

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

$\mathrm{U}(1)_B$ 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: $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:
  $(L'_L)^\dagger L''_R \Phi^* \to x' = -1,\ x'' = 6$
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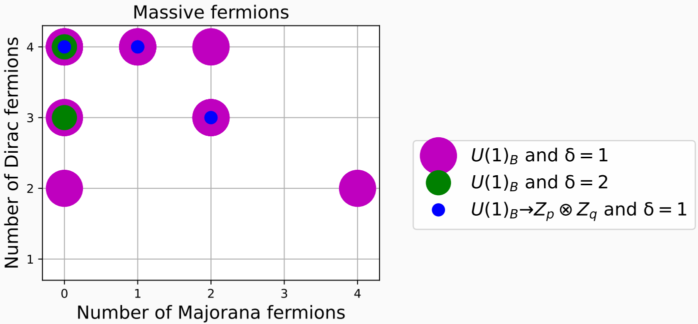
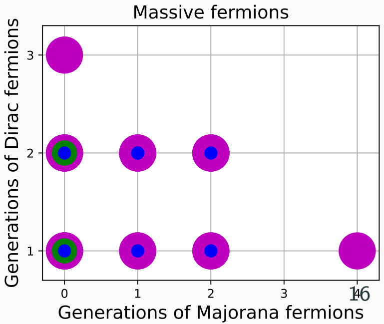
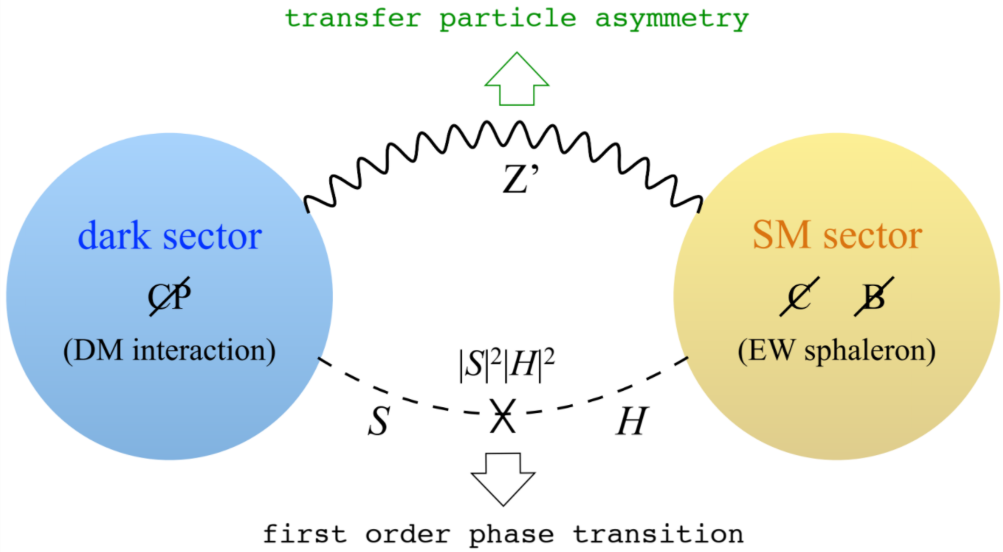
$$(5, 5, -3, -2, 1, -6)$$

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





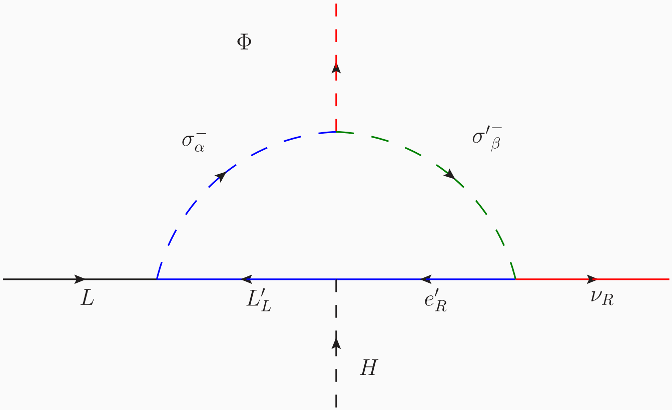
Dark sector baryogenesis



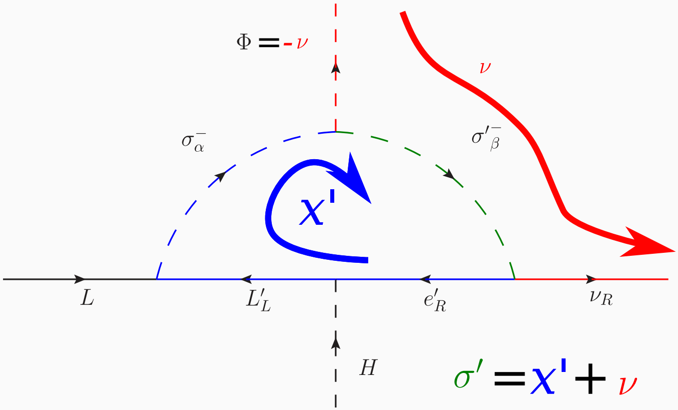
from: [1] Carena, *et al*, arXiv:1908.04818 [PRD] (see also: arXiv:1811.09719 [PRL])

Gauge Baryon number scotogenic realization: arXiv:2205.05762 [PRD]

with Andrés Rivera (UdeA) and Walter Tangarife (Loyola U.)



with Andrés Rivera (UdeA) and Walter Tangarife (Loyola U.)



Gauge Baryon number scotogenic realization: arXiv:2205.05762 [PRD]

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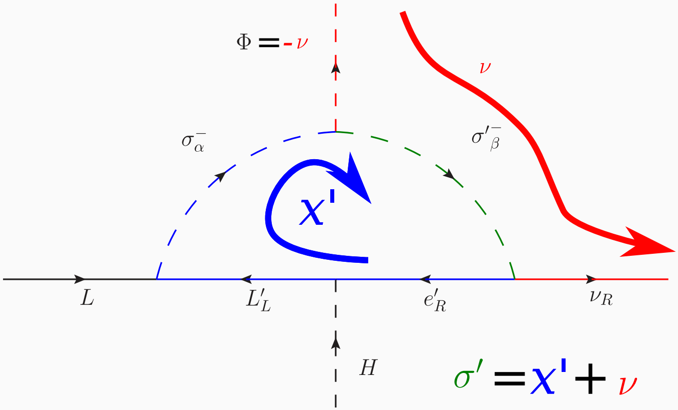
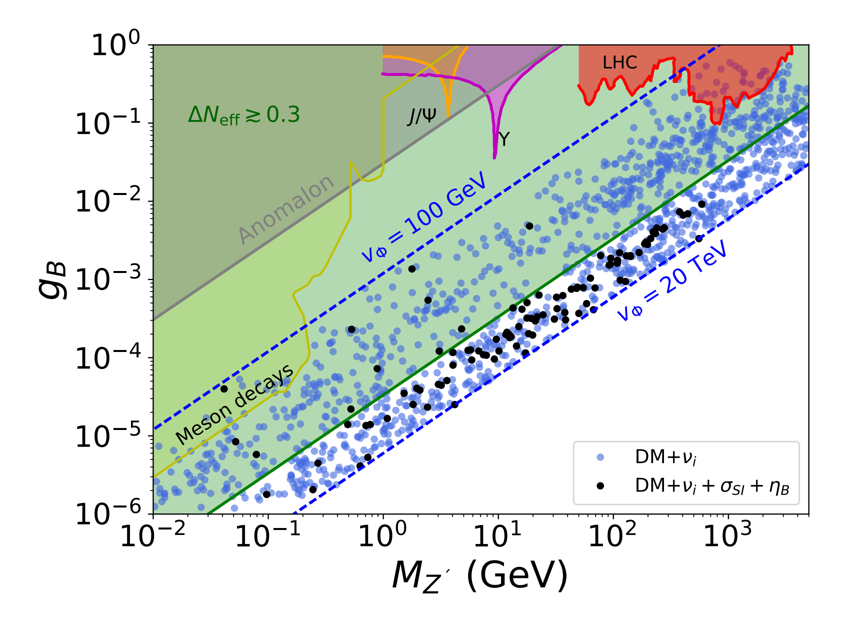


Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	**1**	$2/3$	$u = 1/3$
d_{Ri}	**1**	$-1/3$	$d = 1/3$
$(Q_i)^\dagger$	**2**	$-1/6$	$Q = -1/3$
$(L_i)^\dagger$	**2**	$1/2$	$L = 0$
e_R	**1**	-1	$e = 0$
$(L'_L)^\dagger$	**2**	$1/2$	$-x' = -3/5$
e'_R	**1**	-1	$x' = 3/5$
L''_R	**2**	$-1/2$	$x'' = 18/5$
$(e''_L)^\dagger$	**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	$-12/5$

arXiv:2205.05762 [PRD] https://github.com/anferivera/DarkBariogenesis

- 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