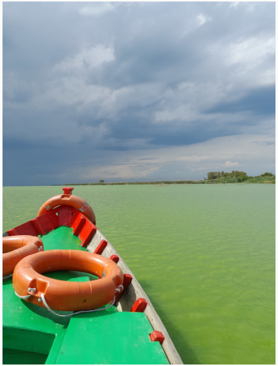
Multicomponent fermionic dark matter and dark baryogenesis

Diego Restrepo

Instituto de Física
Universidad de Antioquia
Phenomenology Group
`http://gfif.udea.edu.co`



Local Abelian extensions of the SM

Anomaly cancellation of a gauge $U(1)_{x}$ extension

Any *universal* local Abelian extension of the Standard Model can be reduced to a set of integers

$$\boldsymbol{S} = [z_1, z_2, \cdots, z_N] \,,$$

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:

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

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

zenodo Search Upload Communities Log in Sign up

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

Secluded gauge $U(1)_D$ without vector-like fermions:

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

- *Higgs mechanism*: Singlet scalar ϕ acquires a vev and give mass to the dark photon

$$\mathcal{L} = i\psi_a^\dagger \overline{\sigma^\mu} \left(\partial_\mu - ig_D A'_\mu\right) \psi_a - \frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \sum_{a<b} h_{ab} \psi_a \psi_b \phi^{(*)} + \text{h.c} - V(\phi)\,. \tag{2}$$

- z_α are the charges of SM-singlet left-handed chiral fermions with $N \geq 5$
  - χ_i *massless fermions* with $i = 1, \cdots, N'$ with $N' \leq N$
  - ψ_a *multi-component dark matter*: massive after the spontaneous symmetry breaking of $U(1)_D$ with $a = N' + 1, \cdots, N$
- *Larger parameter space*: Dark photon exclusions instead of Z'

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:

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

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

ϕ is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry and **give mass to *all* ψ_a**

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

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:

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

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

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

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

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

$$\mathcal{L} = i\psi_i^\dagger \not{D}\psi_i - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \sum_{i<j} h_{ij}\psi_i\psi_j\phi^{(*)} + \text{h.c} - V(\phi)\,. \tag{3}$$

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: U(1)$_D$

$$\mathcal{L} = i\psi_i^\dagger \not{D}\psi_i - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \sum_{i<j} h_{ij}\psi_i\psi_j\phi^{(*)} + \text{h.c} - V(\phi)\,. \tag{3}$$

96 153 → 5 196 $\boxed{\text{multi-component DM}}$ $(N = 8, 12)$ → 142 with three Dirac-fermion DM

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

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

$$\mathcal{L} = i\psi_i^\dagger \not{D}\psi_i - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \sum_{i<j} h_{ij}\psi_i\psi_j\phi^{(*)} + \text{h.c} - V(\phi)\,. \tag{3}$$

96 153 → 5 196 $\boxed{\text{multi-component DM}}$ $(N = 8, 12)$ → 142 with three Dirac-fermion DM

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

$$\mathcal{L} \subset h_{(1,8)}\psi_1\psi_8\phi^*\phi^{(*)} + \underbrace{\sum_{a,b=1}^{2} h_{(-2a,-7b)}\psi_2\psi_{-7}\phi}_{\boxed{\text{multi-flavor DM}}} + h_{(4,5)}\psi_4\psi_5\phi^*\phi^{(*)} + \text{h.c.} \tag{5}$$

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

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

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

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

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

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

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

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

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

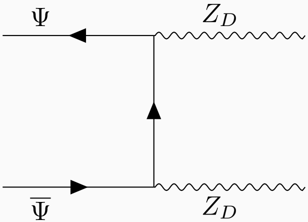
96 153 → 5 196 $\boxed{\text{multi-component DM}}$ $(N = 8, 12)$ → 41 with two Dirac-fermion DM

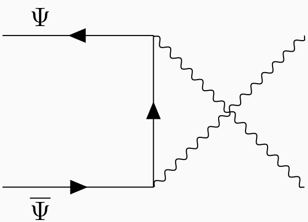
$$\boldsymbol{z} = [1, 2, 2, 4, -5, -5, -7, 8] \to \phi = 3 \to [(1, 2), (2, -5), (-5, 8), (4, -7)] \tag{7}$$

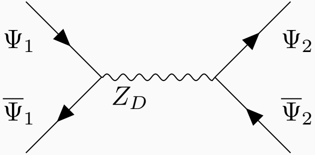
$$\mathcal{L} \subset \Psi^{\mathrm{T}} \begin{array}{c c} & \begin{array}{cccccc} 1 & 2 & 2 & -5 & -5 & 8 \end{array} \\ \begin{array}{c} 1 \\ 2 \\ 2 \\ -5 \\ -5 \\ 8 \end{array} & \begin{bmatrix} 0 & h_{(1,2)} & h'_{(1,2)} & 0 & 0 & 0 \\ h_{(1,2)} & 0 & 0 & h_{(2,-5)} & h_{(2,-5)} & 0 \\ h'_{(1,2)}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

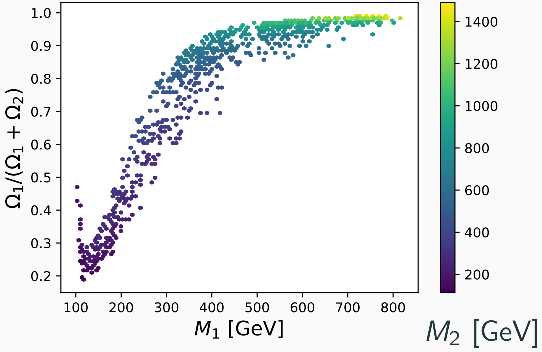
$U(1)_D$: two dark matter candidates

in progress...









$M_{Z_D} < 200\,,\mathrm{GeV}$

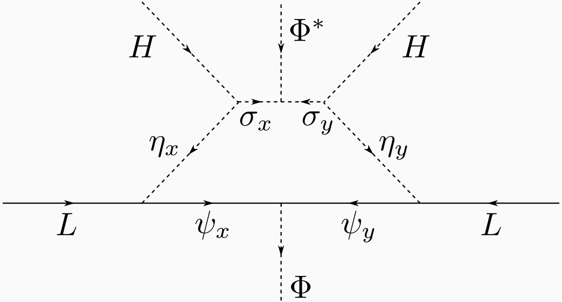
(xBit scan)

Majorana neutrino masses and mixings

$$\frac{y}{\Lambda} LLHH$$

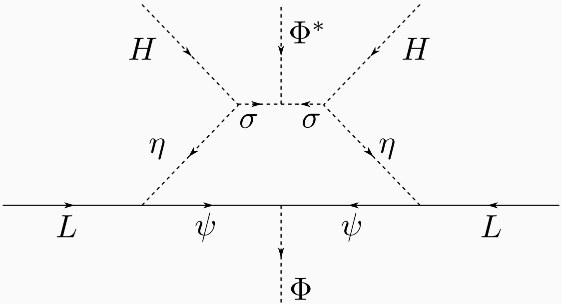
Scotogenic Majorana neutrino masses and mixings

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



Scotogenic Majorana neutrino masses and mixings

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



Already found by Chi-Fong Wong in arXiv:2008.08573 (subset with $N \leq 9$ and $z_{\max} \leq 10$)

$$\boldsymbol{z} = [\underbrace{1,1}_{\psi},2,3,-4,-4,-5,6] \to \phi = 2 \to [\,(1,1)_a,(2,-4),(4,-6),(4,-7)] \tag{8}$$

Additional conditions to reduce multiplicity

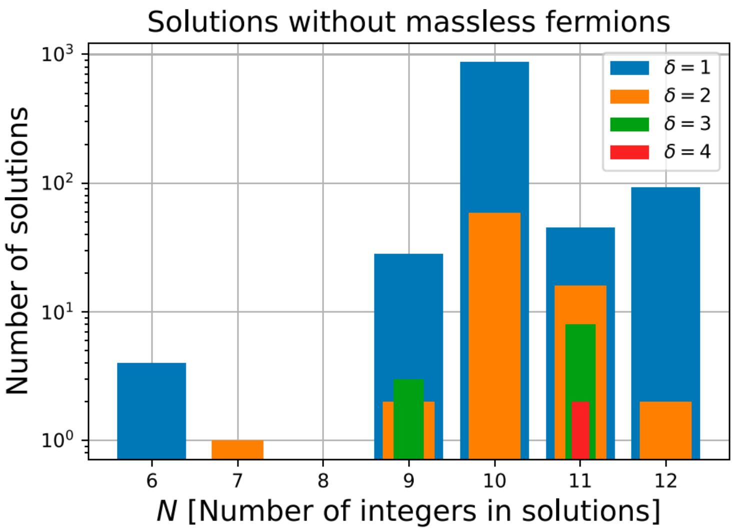
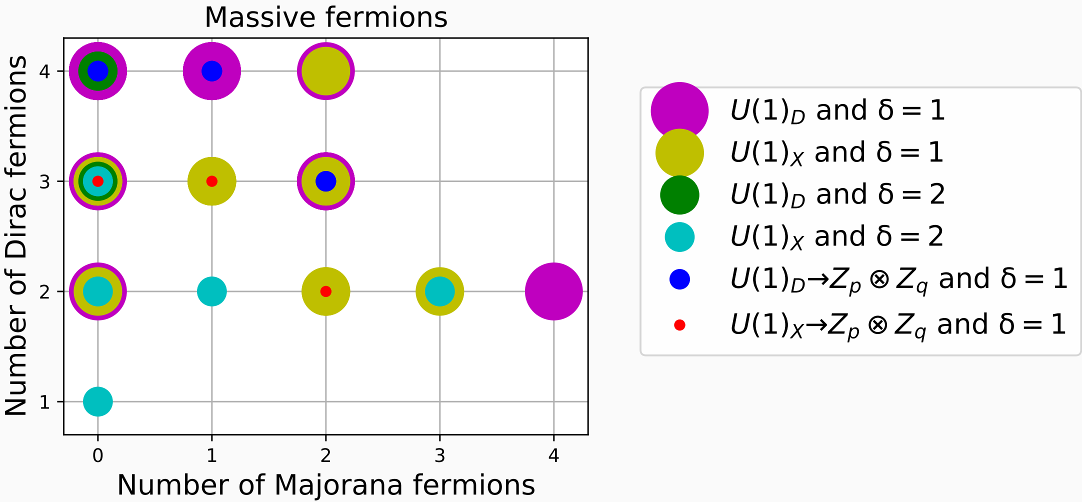
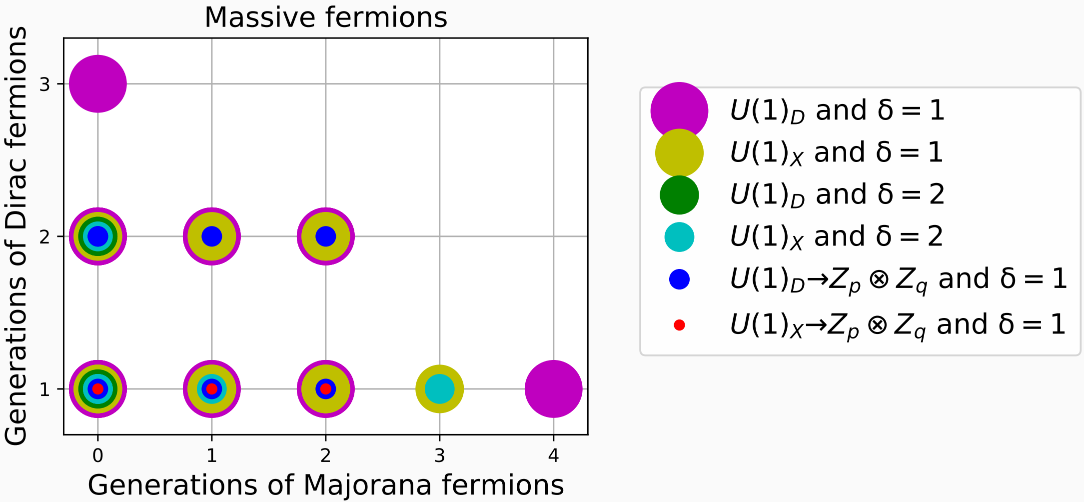


FIGURE 1 | Distribution of solutions with N integers to the Diophantine **Eq. 1** which allow the effective Dirac neutrino mass operator at $d = (4 + \delta)$ for at least two right-handed neutrinos and have non-vanishing Dirac o Majorana masses for the other SM-singlet chiral fermions in the solution.

Multi-component dark matter




Massive fermions
Generations of Dirac fermions
Generations of Majorana fermions
0
1
2
3
4
1
2
3
$U(1)_D$ and $\delta = 1$
$U(1)_X$ and $\delta = 1$
$U(1)_D$ and $\delta = 2$
$U(1)_X$ and $\delta = 2$
$U(1)_D \to Z_p \otimes Z_q$ and $\delta = 1$
$U(1)_X \to Z_p \otimes Z_q$ and $\delta = 1$

$\mathrm{U}(1)_X$ selection with Dirac-fermionic DM

- Active symmetry $m = 3$

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

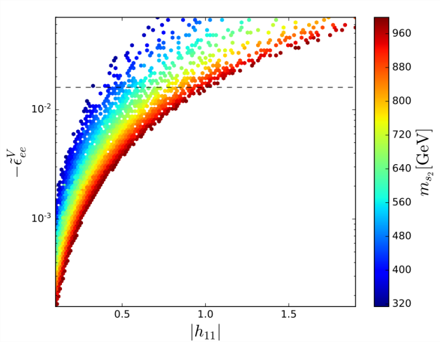
$\mathrm{U}(1)_X$ selection with Dirac-fermionic DM

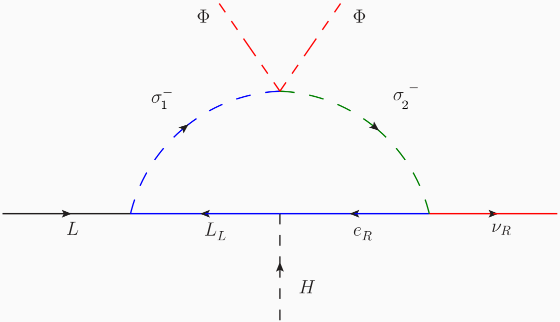
- Active symmetry $m = 3$
- Effective neutrino mass $\delta = 2 \to \nu = -5$:

$$\left(-5, -5, 3, 3, 3, -7, 8\right)$$

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

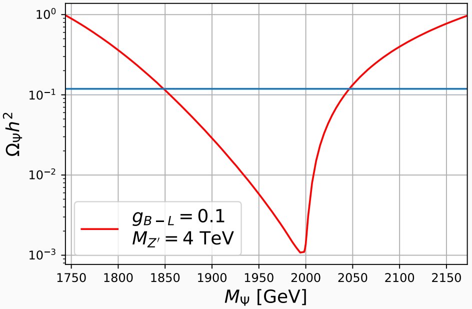
$$(-5, -5, 3, 3, 3, -7, 8)$$

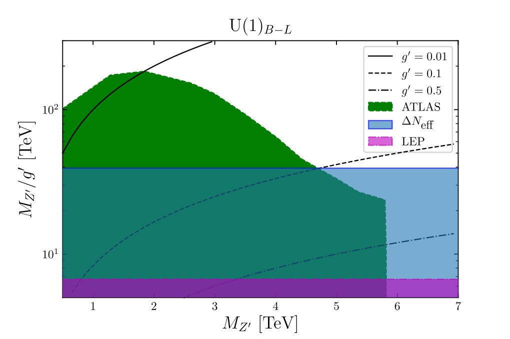




- Active symmetry $m = 3$
- Effective neutrino mass $\delta = 2 \to \nu = -5$:
- Active symmetry: $m = 3 \to \phi = -(\nu + m)/\delta = 1$
- Dirac-fermionic DM: $(\psi_L)^\dagger \psi''_R \Phi^* \to z_6 = -7,\ z_7 = 8$

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



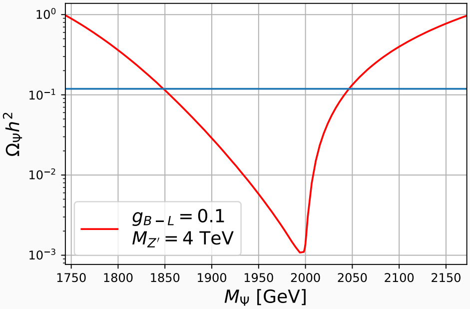


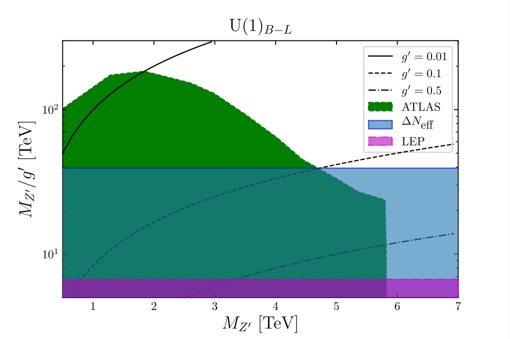
$\mathrm{U}(1)_X$ selection with Dirac-fermionic DM

arXiv: 2103.15328

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

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





Beyond SM-fermion singlets

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

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{X}=D \text{ or } X}$
$Q_i^\dagger$	**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

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

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

$$(e + L)(x' - x'') = 0\,. \tag{10}$$

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

$$e = -L\,, \tag{11}$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,. \tag{12}$$

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

$$\sum_{\alpha=1}^{N} z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} z_\alpha^3 = 0\,, \tag{13}$$

where

$$z_1 = -\,x'\,, \qquad z_2 = x''\,,$$
$$z_{2+i} = L\,, \quad i = 1,2,3 \tag{14}$$

$\to$

$$9Q = -\sum_{\alpha=1}^{5} z_\alpha = -x' + x'' + L + L + L\,, \tag{15}$$

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

$\mathrm{U}(1)_B$ selection: Neutrinos, dark matter and baryogenesis

- $L = 0$

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

$\mathrm{U}(1)_B$ selection: Neutrinos, dark matter and baryogenesis

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

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

$\mathrm{U}(1)_B$ selection: Neutrinos, dark matter and baryogenesis

- $L = 0$
- Effective Dirac neutrino masses: $\phi = -\nu = -5$
- 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: Neutrinos, dark matter and baryogenesis

- $L = 0$
- Effective Dirac neutrino masses: $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:
  $(L'_L)^\dagger L''_R \Phi^* \to x' = -1,\ x'' = 6$
- Dirac-fermionic DM: $(\chi_L)^\dagger \chi''_R \Phi^* \to z_3 = -3,\ z_4 = -2$

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

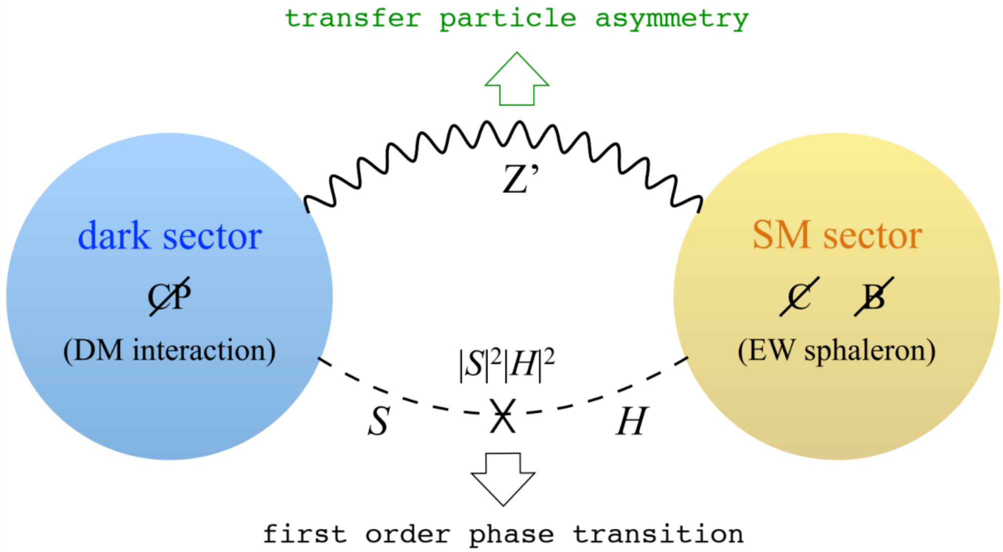
U(1)$_B$ selection: Neutrinos, dark matter and baryogenesis

- $L = 0$
- Effective Dirac neutrino masses: $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:
  $(L'_L)^\dagger L''_R \Phi^* \to x' = -1,\ x'' = 6$
- Dirac-fermionic DM: $(\chi_L)^\dagger \chi''_R \Phi^* \to z_3 = -3,\ z_4 = -2$

959 solutions

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

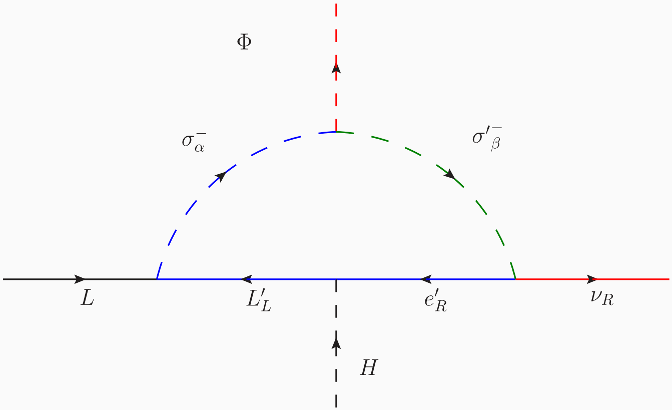
Dark sector baryogenesis



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

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

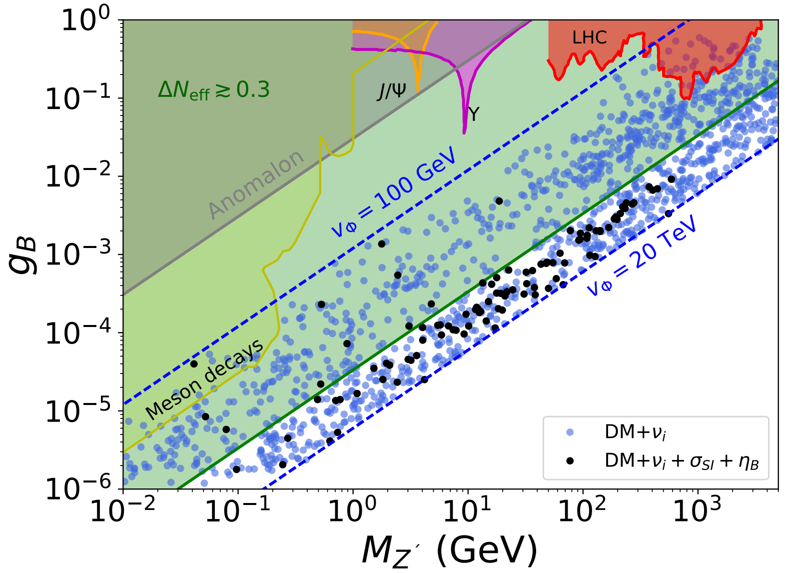
with Andrés Rivera (UdeA) and Walter Tangarife (Loyola U.)



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$\rightarrow$SPheno$\rightarrow$MicroMegas
- η_B calculation code
- Python notebook with the scan

Black points: Dirac neutrinos with proper DM and baryon assymetry



Conclusions

A methodology was designed to find all the *universal* gauge Abelian extensions of the standard model:

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 thoroughly scan in an efficient way 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, providing enough freedom to solve several phenomenological problems.