Multicomponent fermionic dark matter and dark baryogenesis

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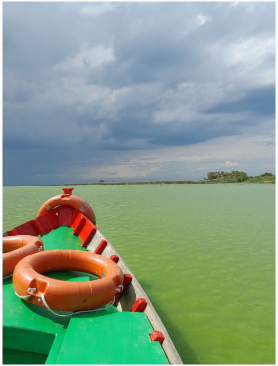

Local Abelian extensions of the SM

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 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,

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

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

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

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

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

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

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

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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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)` zenodo

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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.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: $\mathrm{U}(1)_D$

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

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

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

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

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

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

Simplest secluded model with SM-singlet massive chiral fermions from SSB: 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

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

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

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

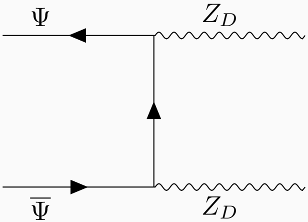
$$\mathcal{L} = i\psi_i^\dagger \not{\mathcal{D}}\psi_i - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \sum_{i<j} h_{ij}\psi_i\psi_j\phi^{(*)} + \text{h.c} \tag{9}$$

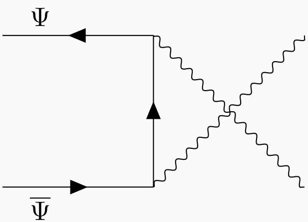
96 153 → 5 196 $\boxed{\text{multi-component DM}}$ $(N = 8, 12) \to 41$ with two Dirac-fermion DM

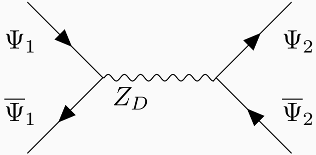
$$\boldsymbol{z} = [1, 2, 2, 4, -5, -5, -7, 8] \to \phi = 3 \to [(1,2), (2,-5), (-5,8), (4,-7)] \tag{10}$$

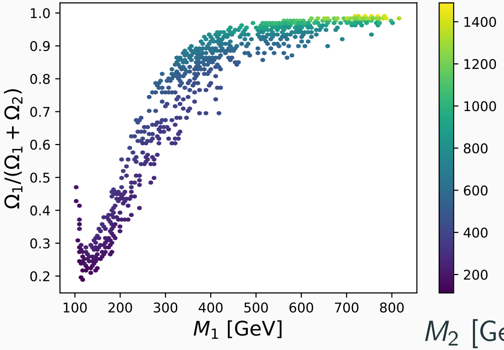
$$\mathcal{L} \subset \Psi^{\mathrm{T}} \begin{array}{c|c} & \begin{array}{cccccc} 1 & 2 & 2 & -5 & -5 & 8 \end{array} \\ \begin{array}{c} 1 \\ 2 \\ 2 \\ -5 \\ -5 \\ 8 \end{array} & \begin{bmatrix} 0 & h_{(1,2)} & h'_{(1,2)} & 0 & 0 & 0 \\ h_{(1,2)} & 0 & 0 & h_{(2,-5)} & h_{(2,-5)} & 0 \\ h'_{(1,2)}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

$\mathrm{U}(1)_D$: two dark matter candidates









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

M_2 [GeV]

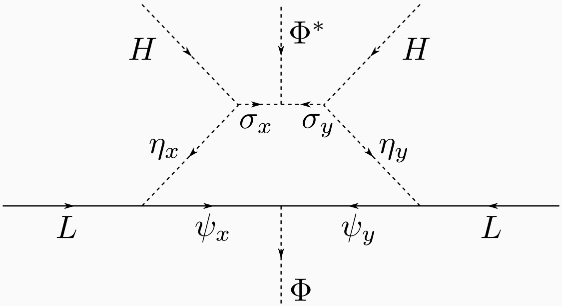
(xBit scan)

Majorana neutrino masses and mixings

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

Scotogenic Majorana neutrino masses and mixings

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



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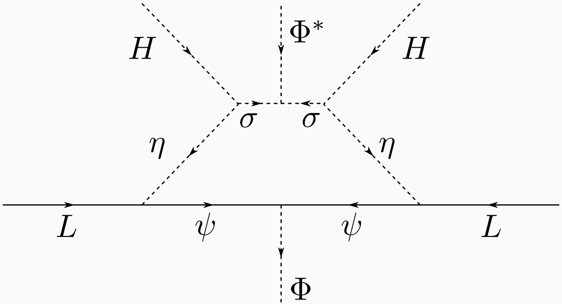


Already found by Chi-Fong Wong in arXiv:2008.08573 (subset with $N \leq 9$ and $z_{\text{max}} \leq 10$)

$$\boldsymbol{z} = [\underbrace{1,1}_{\psi},2,3,-4,-4,-5,6] \to \phi = 2 \to [\,(1,1)_a,(2,-4),(4,-6),(4,-7)] \qquad (11)$$

Additional conditions to reduce multiplicity

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:

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

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3, \tag{12}$$

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

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

$$\phi = -\frac{\nu}{\delta}, \tag{13}$$

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:

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

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3, \quad X(L_i) = -L, \; X(H) = h \qquad \to m = L - h \tag{12}$$

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

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

$$\phi = -\frac{(\nu + m)}{\delta}, \tag{13}$$

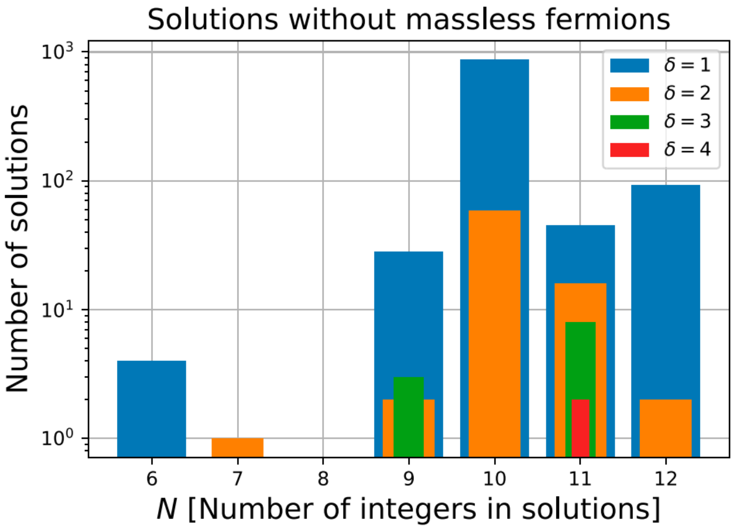
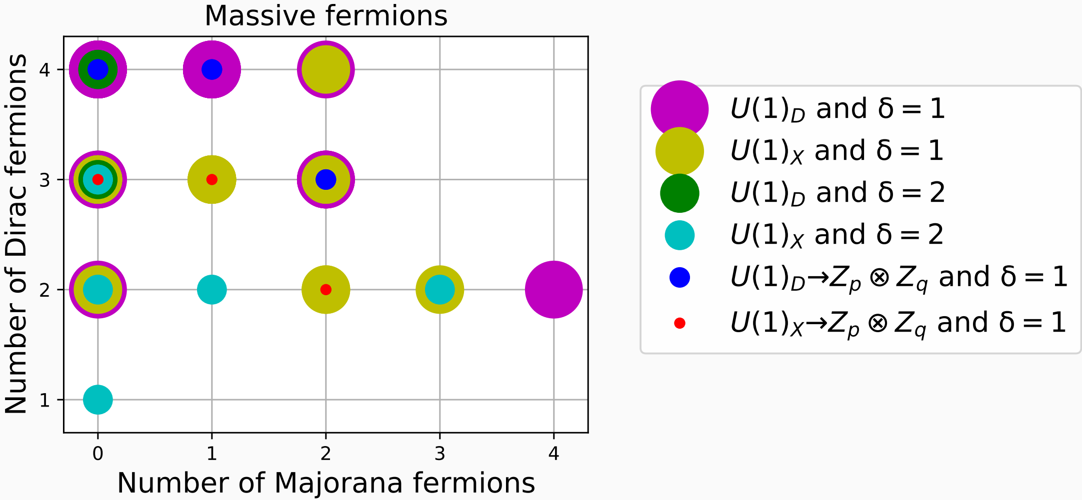
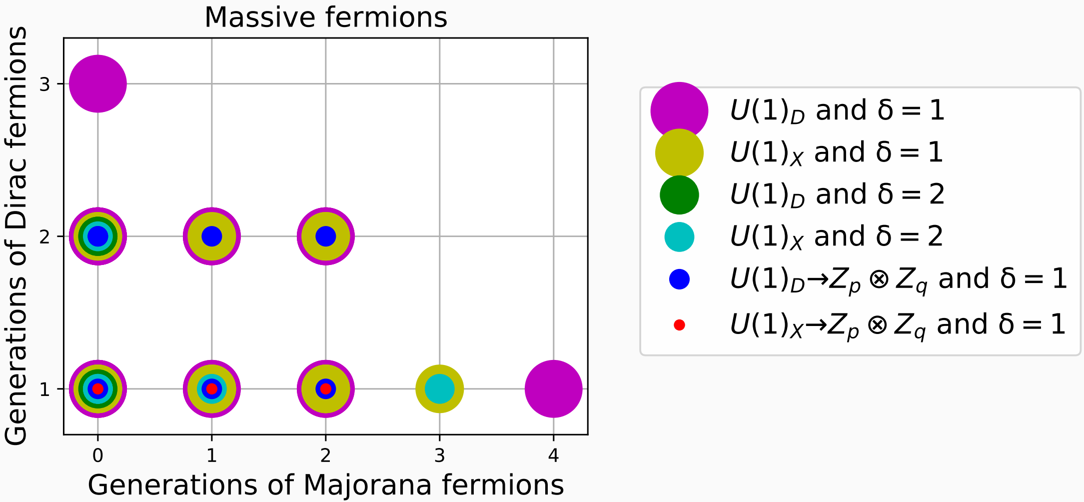


FIGURE 1 | Distribution of solutions with N integers to the Diophantine **Eq. 1** which allow the effective Dirac neutrino mass operator at $d = (4 + \delta)$ for at least two right-handed neutrinos and have non-vanishing Dirac o Majorana masses for the other SM-singlet chiral fermions in the solution.

Multi-component dark matter



Multi-flavor dark matter



$\mathrm{U}(1)_X$ selection 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 $\delta = 2 \to \nu = -5$:

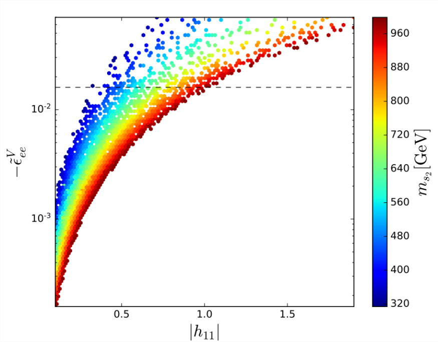
$$(-5, -5, 3, 3, 3, -7, 8)$$

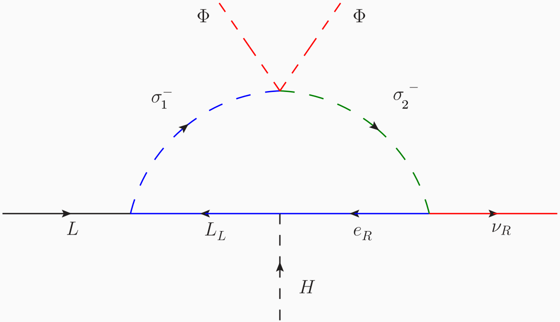
U(1)$_X$ selection with Dirac-fermionic DM

arXiv: 2103.15328

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

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

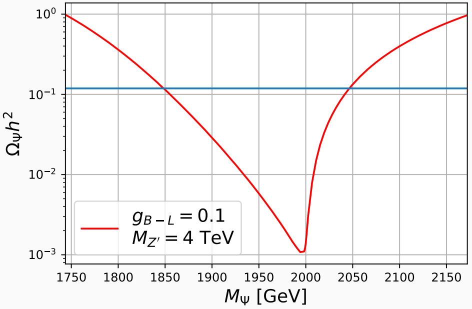


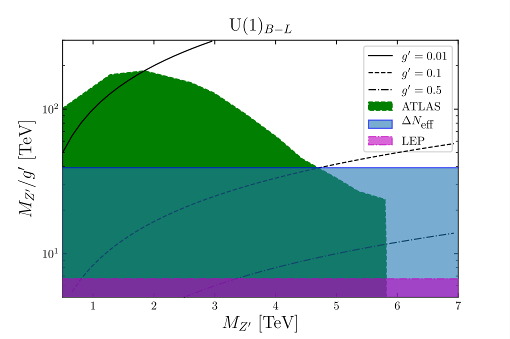


$U(1)_X$ selection with Dirac-fermionic DM

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

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





$U(1)_X$ selection with Dirac-fermionic DM

arXiv: 2103.15328

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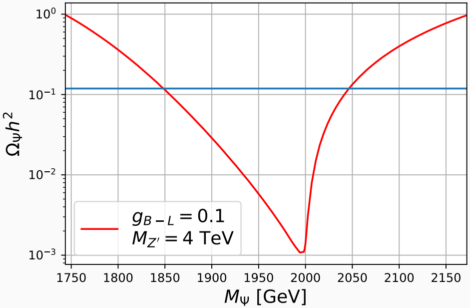
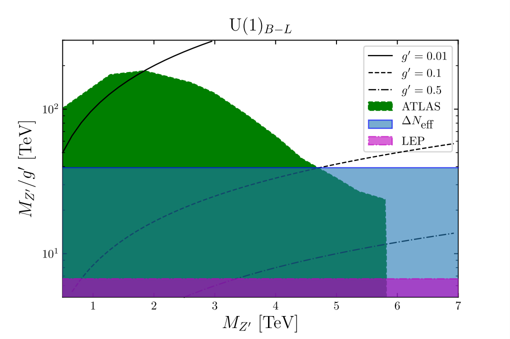
- Dirac-fermionic DM: $(\psi_L)^\dagger \, \psi''_R \Phi^* \to z_6 = -7, \; z_7 = 8$

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





Beyond SM-fermion singlets

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

$$u = -e - \frac{2}{3}L - \frac{1}{9}\left(x' - x''\right)\,, \quad d = e + \frac{4}{3}L - \frac{1}{9}\left(x' - x''\right)\,, \quad Q = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,, \tag{14}$$

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

$$(e + L)(x' - x'') = 0\,. \tag{15}$$

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

$$e = -L\,, \tag{16}$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,. \tag{17}$$

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,

$$\sum_{\alpha=1}^{N} z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} z_\alpha^3 = 0\,, \tag{18}$$

where

$$z_1 = -x'\,, \qquad z_2 = x''\,,$$
$$z_{2+i} = L\,, \quad i = 1,2,3 \tag{19}$$

$\rightarrow$

$$9Q = -\sum_{\alpha=1}^{5} z_\alpha = -x' + x'' + L + L + L\,, \tag{20}$$

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

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

- $L = 0$

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

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959 solutions

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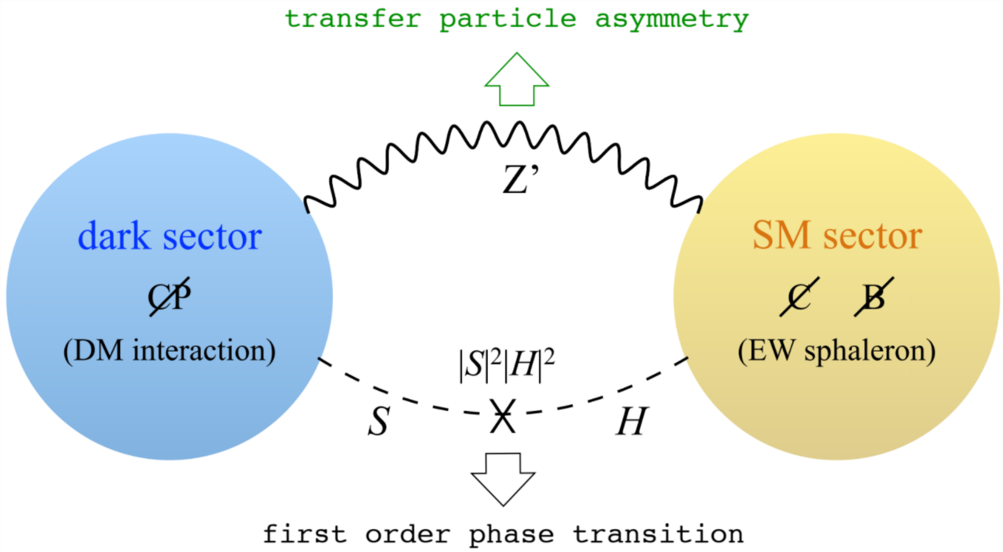
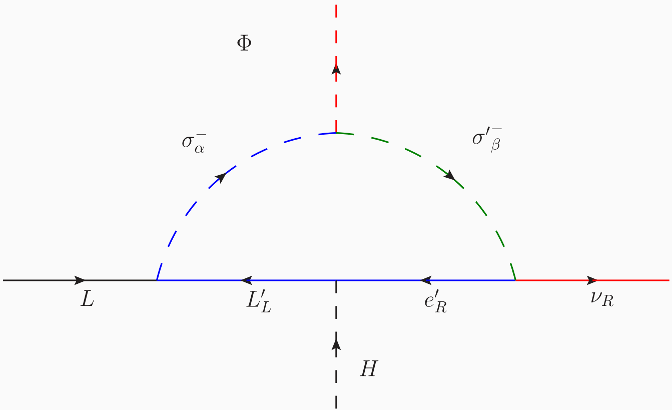
Dark sector baryogenesis



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

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

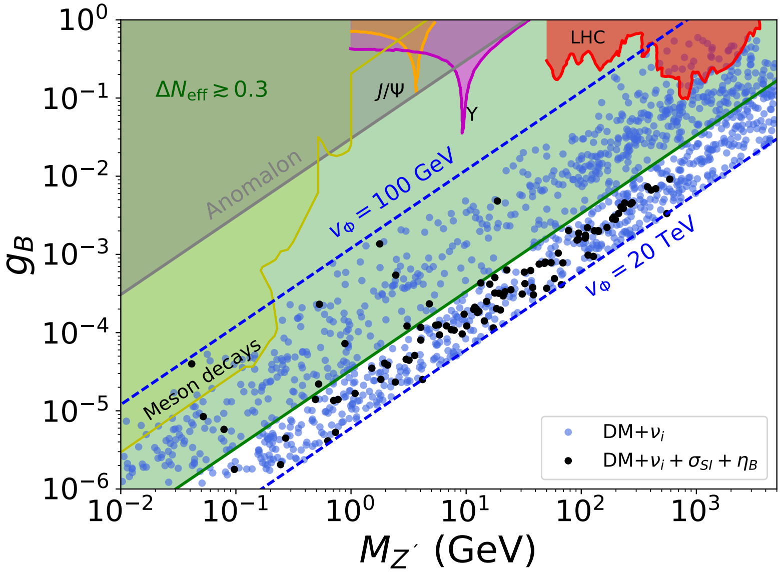
with Andrés Rivera (UdeA) and Walter Tangarife (Loyola U.)



Field	$SU(2)_L$	$U(1)_Y$	$\mathrm{U}(1)_B$
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

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

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.

Baryogenesis

CP violation occurs in the dark sector and is transmited to SM sector by the new Z' gauge boson.

- High scale fields: Φ , $(\langle\Phi\rangle \to L'_L, L''_R, e'_L, e''_R$: EW-scale vector-like anomalons)
- Electroweak scale (EW) fields: $\boxed{Z'_\mu, S, \chi_L, \chi_R}$
- *CP*-violation

$$\begin{aligned}\mathcal{L}_{\text{Dirac DM}} =& h\,(\chi_L)^\dagger\,\chi_R\Phi^* + y\,(\chi_L)^\dagger\,\chi_R S^* + \text{h.c}\,, \qquad\qquad y \in \mathbb{C}\\ \supset& \left(m_\chi + |y|\,\mathrm{e}^{i\theta}\,|S|\right)(\chi_L)^\dagger\,\chi_R + \text{h.c}\,.\end{aligned}$$

- *CP*-violation Portal

$$\mathcal{L}_{\text{anomalous}} \supset g'\,Z'_\mu\left[3\bar{\chi}_L\gamma^\mu\chi_L - 2\bar{\chi}_R\gamma^\mu\chi_R + \bar{Q}_i\gamma^\mu Q_i + \bar{q}_{Ri}\gamma^\mu q_{Ri}\right]$$

- Strong electroweak phase transition (EWPT) portal

$$\mathcal{L}_{\text{first order EWPT}} \supset -\lambda_{SH}H^\dagger H\,S^*S\,.$$

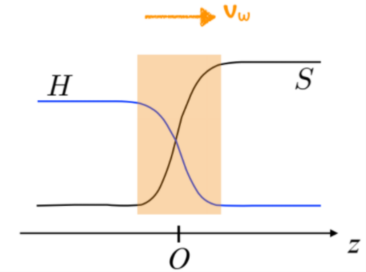
First-order phase transition: Effective potential ($T \neq 0$)

$\boxed{h = H/\sqrt{2},\ s = |S|}$ with vevs: $v(T)$ and $w(T)$ such that $v(T_c) = w(T_c)$

$$V_T(h, s) = \frac{\lambda_H v_c^4}{4} \left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2) \, , \qquad (21)$$

where

$$c_h = \frac{1}{48} \left(9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS} \right) \, , \quad c_s = \frac{1}{12} \left(3\lambda_S + 2\lambda_{HS} \right) \, . \qquad (22)$$



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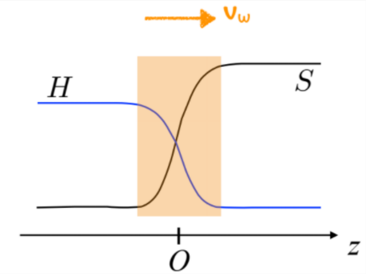
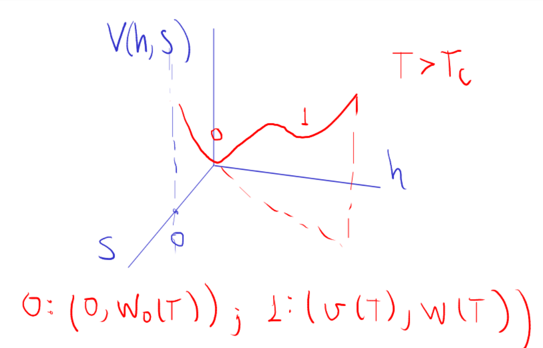
arXiv: Sec. 4.1 arXiv:1107.5451





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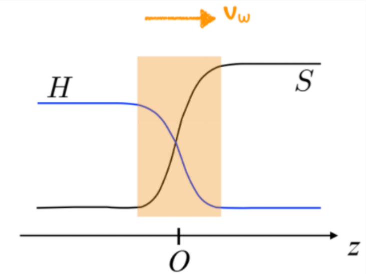

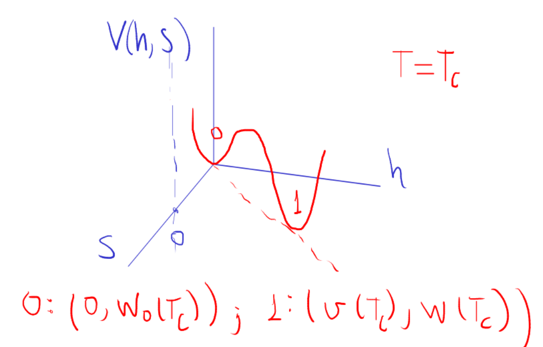

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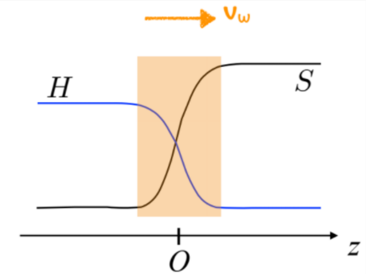

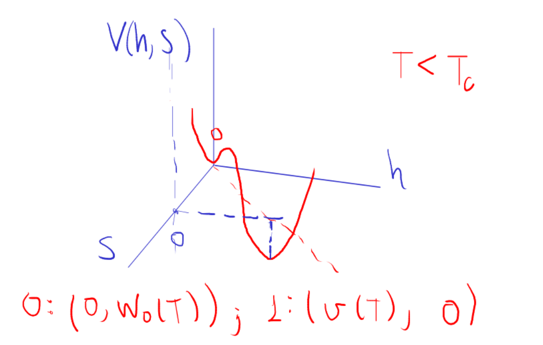

CP assymetry generation i

Using the thin wall approximantion for the nucleation bubbles, we use the ansatz in which the space dependence of the fields is given by

$$h(z) = \frac{1}{2}v(T_n)\left(1 - \tanh\left(z/L_w\right)\right) \,, \qquad s(z) = \frac{1}{2}w_0(T_n)\left(1 + \tanh\left(z/L_w\right)\right) \,,$$

where z is the direction normal to the wall and L_w is the wall width.

The nucleation temperature, T_n, is defined by the condition

$$\exp\left(-S_3/T_n\right) = \frac{3}{4\pi}\left(\frac{H(T_n)}{T_n}\right)^4\left(\frac{2\pi T_n}{S_3}\right)^{\frac{3}{2}} \,,$$

where S_3 is the Euclidean action of the bubble and $H(T)$ is the Hubble rate.

$\xi_i(z) \equiv \mu_i(z)/T = 6\,(n_i - \overline{n}_i)\,/\,T^3,$

$$-D_L \xi''_{\chi_L} - v_w \xi'_{\chi_L} + \Gamma_L(\xi_{\chi_L} - \xi_{\chi_R}) = S_{\not{CP}},$$

where D_L is the diffusion constant for χ_L, which is related to the scattering rate Γ_L by

$$D_L = \frac{3x+2}{x^2+3x+2}\frac{1}{3\Gamma_L}, \qquad x \equiv m_\chi/T \tag{23}$$

and

$$S_{\not{CP}} = -\frac{\lambda}{2}\frac{v_w D_L}{\frac{3x+2}{x^2+3x+2}T}\frac{(1-x)e^{-x} + x^2 E_1(x)}{4m_\chi^2 K_2(x)}\frac{m_\chi w_0(T_n)\lambda\left(-2+\cosh\left(\frac{2z}{L_w}\right)\right)\sin\theta}{L_w^3\cosh^4\left(\frac{z}{L_w}\right)}, \tag{24}$$

where v_w is the wall's velocity $E_1(x)$ is the error function and $K_2(x)$ is the modified Bessel function of the second kind. $y = \lambda\, e^{i\theta - i\pi/2}$

Transfer DM assymetry to SM quarks

The chiral particle give rise to a non-zero $\mathrm{U}(1)_B$ charge density in the proximity of the wall. This results in a Z' background that couples to the SM fields with $\mathrm{U}(1)_B$ charge,

$$\langle Z_0'(z)\rangle = \frac{g_B\,(q_{\chi_L} - q_{\chi_R})\,T_n^3}{6M_{Z'}} \int_{-\infty}^{\infty} \mathrm{d}\, z_1\, \xi_{\chi_L}(z_1)\, e^{-M_{Z'}|z-z_1|}\,,$$

which generates a chemical potential for the SM quarks,

$$\mu_Q(z) = \mu_{d_R,u_R}(z) = 3 \times \frac{5}{9} \times g_B \langle Z_0'(z)\rangle.$$

This chemical potential sources a thermal-equilibrium asymmetry in the quarks, $\Delta n_Q^{\mathrm{EQ}}(z) \sim T_n^2\, \mu_Q(z)$.

From [1]

If the Z' is sufficiently light, it mediates a long range force that extends into the region outside the bubble wall with unbroken electroweak symmetry.

Finally, the baryon-number asymmetry is then given by

$$n_B = \frac{\Gamma_{\mathrm{sph}}}{v_w} \int_0^\infty \mathrm{d}\, z\, n_Q^{\mathrm{EQ}}(z)\, \exp\left(-\frac{\Gamma_{\mathrm{sph}}}{v_w}\, z \right) ,$$

where Γ_{sph} is the sphaleron rate. The baryon-to-photon-number ratio is then obtained by

$$\eta_B = \frac{n_B}{s(T_n)}, \quad s(T) \equiv \frac{2\pi^2}{45} g_{*S}(T)\, T^3 ,$$

where $g_{*S}(T)$ is the effective number of relativistic degrees of freedom.

Our goal is to find what regions of the parameter space yield

$$0.82 \times 10^{-10} < \eta_B < 0.92 \times 10^{-10} \,. \tag{25}$$