Secluded Abelian extensions of the SM

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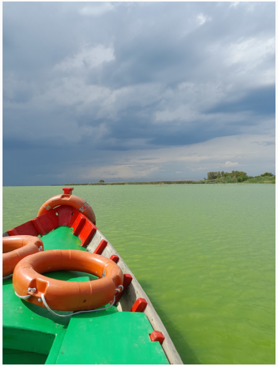

Anomaly cancellation of a gauge $U(1)_X$ extension

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:

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

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

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

- 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:

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

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

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

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

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

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

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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]

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

Versions

Version v2 Sep 24, 2021
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Solution	N	ν	δ	ϕ	N_D	N_M	G_D	G_M
$(5, 5, -2, -3, 1, -6)$	6	5	1	-5	2	0	1	0
$(1, -2, 3, 4, 6, -7, -7, -7, 9)$	9	-7	1	7	3	0	1	0
$(1, 1, -4, -5, 9, 9, 9, -10, -10)$	9	9	1	-9	3	0	2	0
$(1, -2, -2, 3, 3, -4, -4, 6, 6, -7)$	10	6	1	$\mathbf{-6}$	3	2	2	2
$(1, -2, -2, 3, 4, -5, -5, 7, 7, -8)$	10	-5	1	5	4	0	2	0
$(1, -2, -2, 3, 5, -6, -6, 8, 8, -9)$	10	-6	1	$\mathbf{6}$	4	0	2	0
$(2, 2, 3, 4, 4, -5, -6, -6, -7, 9)$	10	2	1	-2	4	2	2	2
$(1, 1, 5, 5, 5, -6, -6, -6, -9, 10)$	10	1	1	-1	4	0	3	0
$(2, 2, 4, 4, -7, -7, -9, -9, 10, 10)$	10	10	2	-5	3	0	2	0
$(1, 2, 2, -3, 6, 6, -8, -8, -9, 11)$	10	-8	1	8	4	1	2	1
$(1, -2, -3, 5, 6, -8, -9, 11, 11, -12)$	10	11	1	-11	4	0	1	0
$(1, 1, -3, 4, 4, -7, 8, -10, -10, 12)$	10	-10	2	5	4	0	2	0
$(1, 1, -2, -2, -4, 6, -10, 11, 12, -13)$	10	-2	1	2	3	2	1	2
$(3, 4, 4, 4, 4, -5, -8, -8, -11, 13)$	10	-8	1	8	2	4	1	4
$(4, 4, 5, 6, 6, -9, -10, -10, -11, 15)$	10	6	1	$\mathbf{-6}$	4	0	2	0
$(1, -2, -4, 7, 7, -10, -12, 14, 14, -15)$	10	14	1	$\mathbf{-14}$	3	2	1	2
$(1, 2, 2, -3, 4, -6, 12, -13, -14, 15)$	10	2	1	-2	4	1	1	1
$(1, 4, 4, -7, 8, 8, -9, -12, -12, 15)$	10	8	1	-8	4	2	2	2
$(1, 2, 2, -9, -9, 16, 16, 17, -18, -18)$	10	-18	1	18	3	2	2	2
$(1, -3, -6, 7, -10, 11, -16, 18, 18, -20)$	10	18	2	-9	4	0	1	0
$(1, -4, 5, -6, -6, 10, -14, 15, 20, -21)$	10	-6	1	$\mathbf{6}$	4	0	1	0
$(2, -3, -6, 7, 12, -14, -14, 17, 20, -21)$	10	-14	1	$\mathbf{14}$	4	1	1	1
$(3, 6, 6, -7, 8, 8, -14, -14, -17, 21)$	10	-14	1	$\mathbf{14}$	4	1	2	1
$(8, 8, 9, 10, 10, -13, -18, -18, -27, 31)$	10	-18	1	18	4	1	2	1

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:

$$[5, 5, -3, -2, 1, -6]$$

$$\chi_1 \to \nu_{R\,1}, \;\chi_2 \to \nu_{R\,2}, \qquad N_\nu = 2\,,$$

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

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

$$\phi = -\nu = -5\,,$$

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Minimal secluded model with D-5 effective Dirac neutrino masses

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

$\boxed{\text{multi-component DM}}$ with two Dirac-fermion DM particles

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$\boxed{\text{multi-component DM}}$ with two Dirac-fermion DM particles

$$\boldsymbol{z} = [5, 5, -3, -2, 1, -6] \to \phi = -5 \to [(5, 5), (-3, -2), (1, -6)] \tag{4}$$

Minimal secluded model with D-5 effective Dirac neutrino masses

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

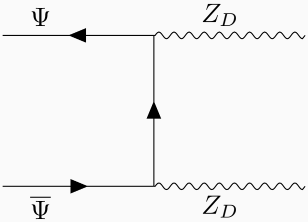
$\boxed{\text{multi-component DM}}$ with two Dirac-fermion DM particles

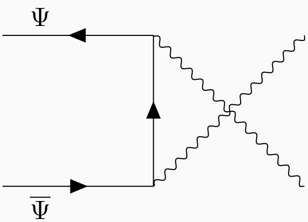
$$z = [5, 5, -3, -2, 1, -6] \to \phi = -5 \to [(5, 5), (-3, -2), (1, -6)] \tag{4}$$

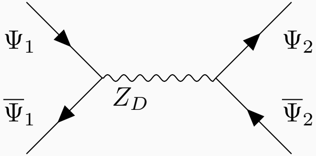
$$\mathcal{L} \subset h_{(-3,-2)}\psi_{-3}\psi_{-2}\phi^* + h_{(1,-5)}\psi_1\psi_{-6}\phi^* + \text{h.c.} \tag{5}$$

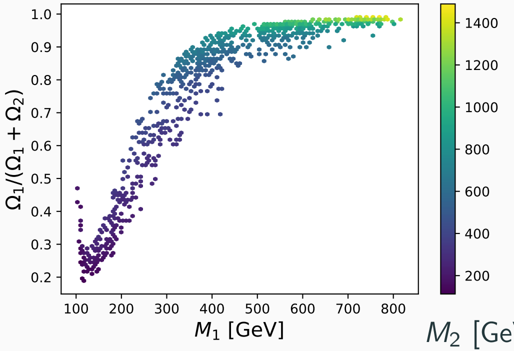
$\mathrm{U}(1)_D$: two dark matter candidates without kinetic mixing: $Z_D \to \overline{\nu}\nu$

in progress...







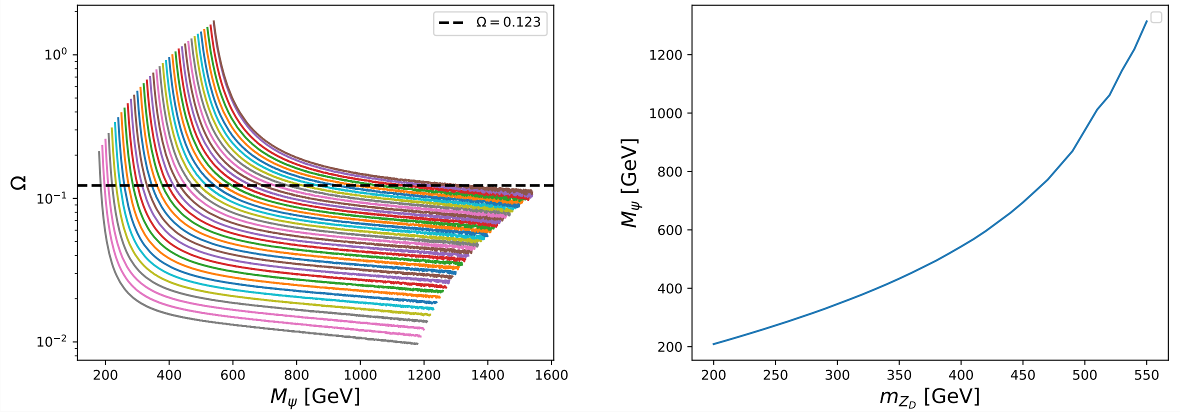


$M_{Z_D} < 200\,$GeV

M_2 [GeV]

(xBit scan)

$M_2 \gg M_1$ and $g_D = 0.1$



Majorana neutrino masses and mixings

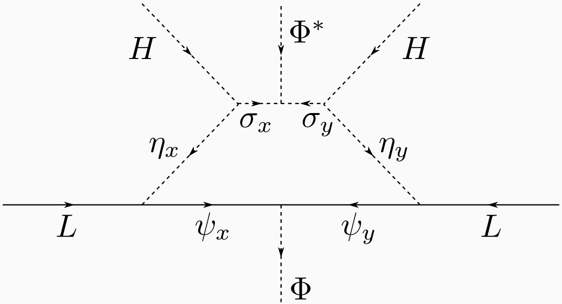
$$[\psi_1, \psi_2, \cdots, \psi_N]$$

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

Scotogenic Majorana neutrino masses and mixings

$$[\psi_1, \psi_2, \cdots, \psi_N]$$

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



ϕ $\boxed{\text{give mass to } \textit{all } \psi_a}$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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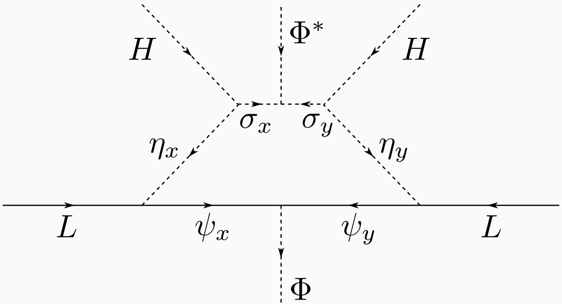

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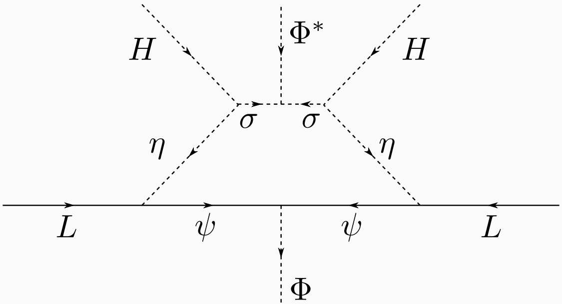

Already found by Chi-Fong Wong in arXiv:2008.08573 (subset with $N \leq 9$ and $z_{\text{max}} \leq 10$)

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

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.