



UNIVERSIDAD DE ANTIOQUIA
1803

Secluded Abelian extensions of the SM

Diego Restrepo

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



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

$$\mathbf{S} = [z_1, z_2, \dots, z_N] ,$$

which must satisfy the gravitational anomaly, $[SO(1,3)]^2 U(1)_Y$, and the cubic anomaly, $[U(1)_X]^3$ conditions:

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

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

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

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

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

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

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

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

Secluded case:

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

$$\chi_1 \rightarrow \nu_{R1}, \dots, \chi_{N_\nu} \rightarrow \nu_{R N_\nu}, \quad 2 \leq N_\nu \leq 3,$$

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

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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September 24, 2021

Dataset

Open Access

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

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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 the [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 'j32' [JSON]

141

views

351

downloads

[See more details...](#)

Indexed in

OpenAIRE

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September 24, 2021

DOI:

DOI [10.5281/zenodo.7380817](#)

Keyword(s):

[Anomaly free](#) [Diophantine equations](#) [Abelian symmetry](#)
[Gauge Symmetry](#)

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Versions

Version v2

Sep 24, 2021

[10.5281/zenodo.7380817](#)

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	-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	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	-6	4	0	2	0
(1, -2, -4, 7, 7, -10, -12, 14, 14, -15)	10	14	1	-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	6	4	0	1	0
(2, -3, -6, 7, 12, -14, -14, 17, 20, -21)	10	-14	1	14	4	1	1	1
(3, 6, 6, -7, 8, 8, -14, -14, -17, 21)	10	-14	1	14	4	1	2	1
(8, 8, 9, 10, 10, -13, -18, -18, -27, 31)	10	-18	1	18	4	1	2	1

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

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

Secluded case:

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

$$\chi_1 \rightarrow \nu_{R1}, \chi_2 \rightarrow \nu_{R2}, \quad N_\nu = 2,$$

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

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

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

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Minimal secluded model with D-5 effective Dirac neutrino masses

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

multi-component DM with two Dirac-fermion DM particles

Minimal secluded model with D-5 effective Dirac neutrino masses

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multi-component DM with two Dirac-fermion DM particles

$$z = [5, 5, -3, -2, 1, -6] \rightarrow \phi = -5 \rightarrow [(5, 5), (-3, -2), (1, -6)] \quad (4)$$

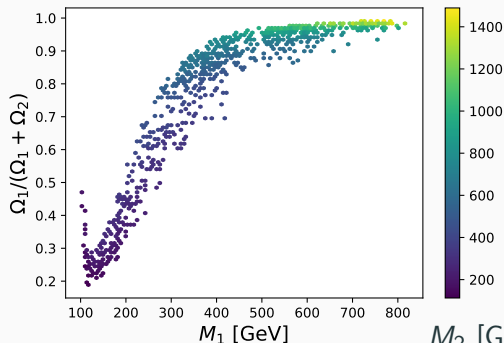
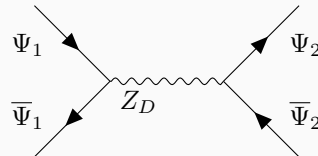
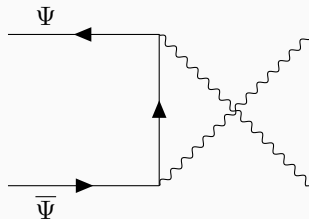
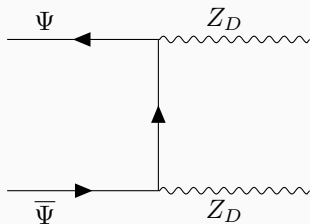
Minimal secluded model with D-5 effective Dirac neutrino masses

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multi-component DM with two Dirac-fermion DM particles

$$z = [5, 5, -3, -2, 1, -6] \rightarrow \phi = -5 \rightarrow [(5, 5), (-3, -2), (1, -6)] \quad (4)$$

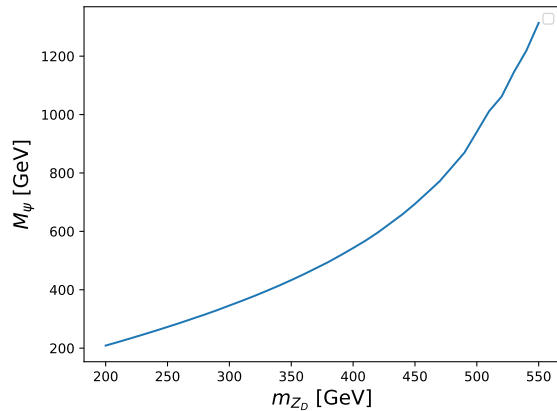
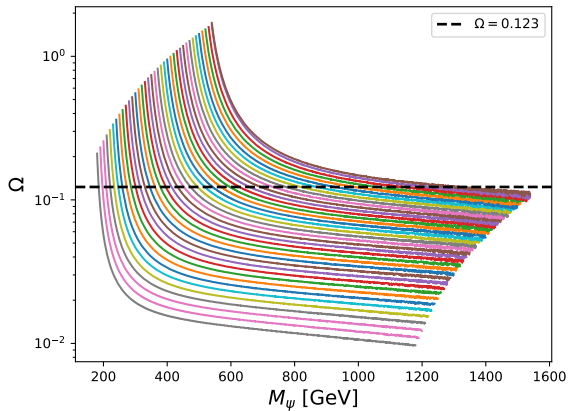
$$\mathcal{L} \subset h_{(-3,-2)} \psi_{-3} \psi_{-2} \phi^* + h_{(1,-5)} \psi_1 \psi_{-6} \phi^* + \text{h.c.} \quad (5)$$



$M_{Z_D} < 200$, GeV

(xBit scan)

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

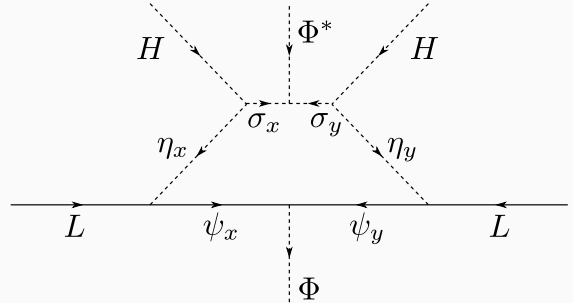


$$[\psi_1, \psi_2, \dots, \psi_N]$$

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

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

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



ϕ

give mass to all ψ_a

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

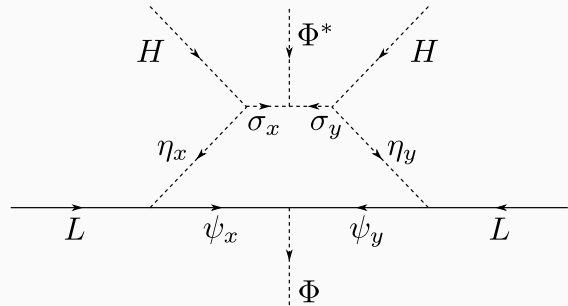
96 153 \rightarrow 5 196 **multi-component DM** ($N = 8, 12$) \rightarrow 41 with two Dirac-fermion DM

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

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

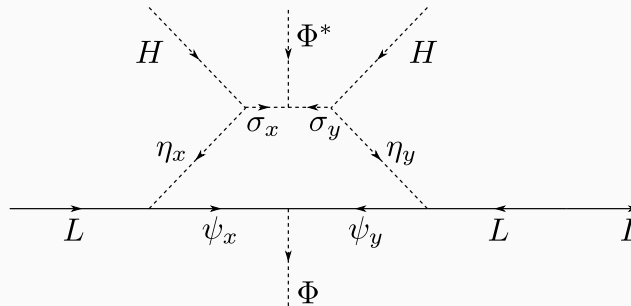
Majorana neutrino masses and mixings

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



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

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



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

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

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

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

which we thoroughly scan in an efficient way until $N = 12$ and $|z_{\max}| = 20$

Once the physical conditions are established, the full set of self-consistent models are found from a simple data-analysis procedure, providing enough freedom to solve several phenomenological problems.