Gauged Lepton number

with *dark* matter and *dark* baryogenesis

Diego Restrepo

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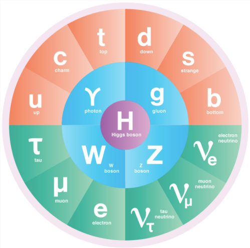
Focus on

...

In collaboration with

Leonardo Leite, Orlando Peres, William Novelo (UNICAMP), David Suárez (UdeA)

Dark sectors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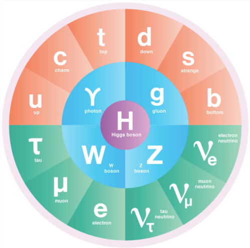
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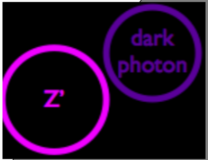
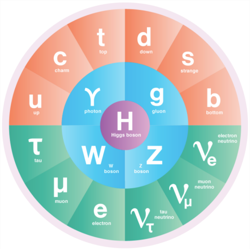

dark photon
Z'

Local $U(1)_{\mathcal{X}}$

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i \psi_i^\dagger \not{D} \psi_i$$
$$-h \left(\psi_1 \psi_2 \Phi + \text{h.c} \right)$$



$F_{\mu\nu}$ $V^{\mu\nu}$

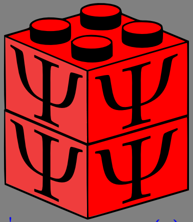
Anomalons: SM-singlet Dirac fermion

dark matter $m_\Psi = h \langle \Phi \rangle$

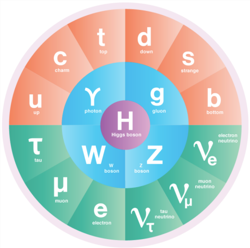
LHC production:

Gauged Symmetry: $\mathcal{X} \to D$:

Gauged Symmetry: $\mathcal{X} \to X$:



$\overline{\Psi}\Psi = \psi_1 \psi_2 + \psi_1^\dagger \psi_2^\dagger \to \psi_\alpha \psi_\beta \Phi^{(*)}$, $\alpha = 1, \ldots N \to N > 4$



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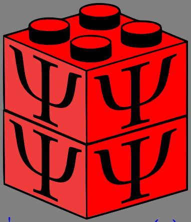
LHC production:

$F_{\mu\nu}$ $V^{\mu\nu}$

Gauged Symmetry: $\mathcal{X} \to B$: $q\bar{q} \to Z' \to$ jets

Gauged Symmetry: $\mathcal{X} \to L$:



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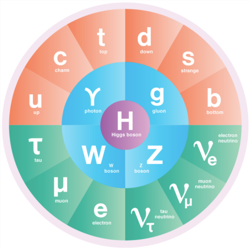

$F_{\mu\nu}$ $V^{\mu\nu}$

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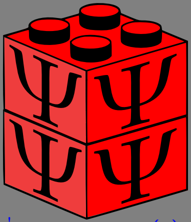

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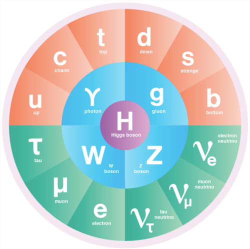

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$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + i\sum_i \psi_i^\dagger \not{D}\psi_i$$
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$F_{\mu\nu}$ $V^{\mu\nu}$

Anomalons: SM-singlet Dirac fermion

CP violation Yukawa y

LHC production:

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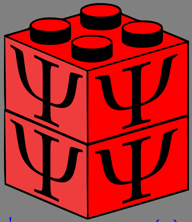

$$\overline{\Psi}\Psi = \psi_1\psi_2 + \psi_1^\dagger\psi_2^\dagger \to \psi_\alpha\psi_\beta\Phi^{(*)}\,, \qquad \alpha = 1,\dots N \to N > 4$$

Anomaly cancellation

Any 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 $z_{\max} = 2m$

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

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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

$$\boldsymbol{q}=[2,3,-1,-3]\,,\qquad n=6\,. \tag{2}$$

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 $z_{\text{max}}=2\times 3=6$

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

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

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

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restrepo

anomalies 0.2.5

```
pip install anomalies
```

Latest version

Released: Sep 6, 2022

Anomaly cancellation

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GitHub statistics:

- 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)` jupyter {book}

Advanced Computation

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Contents

chunksize=

Implementation.

- Use the official module to find solutions
- filter the chiral ones with a maximum integer of 32
- Build a function suitable for multiprocessing

Functions

```python
import numpy as np
import itertools
import sys
from anomalies import anomaly
import numpy as np
import time
import warnings
warnings.filterwarnings("ignore")

global zmax
zmax=32

z=anomaly.free

def _get_chiral(q,q_max=np.inf):
    #Normalize to positive minimum
    if 0 in q:
        #q=q[q!=0]
        return None,None
```

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

https://pypi.org/project/yukawa/

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yukawa 0.0.2

```
pip install yukawa
```

Latest version

Released: about 9 hours ago

Get massive fermions from a given scalar Abelian charge

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Statistics

GitHub statistics:

- Stars: 0

Project description

Yukawa couplings with spontaneous symmetry breaking (SSB)

Python package passing | Upload Python Package passing

Given a list of integers as the Abelian charges of fermions, check if there is a scalar which which can generate Yukawa couplings and non-zero masses for all them after the SSB-

Install

```
$ pip install yukawa
```

USAGE

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

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

$96\,153 \to 5\,196$ multi-component DM ($N = 8, 12$) $\to 28$ with two Dirac-fermion DM

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96 153 $\rightarrow$ 5 196 multi-component DM ($N = 8, 12$) $\rightarrow$ 28 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: $\mathrm{U}(1)_D$

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

$96\,153 \to 5\,196$ multi-component DM ($N = 8, 12$) $\to 28$ with two Dirac-fermion DM

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

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

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

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

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{X}=B \text{ or } L}$
$Q_i^\dagger$	**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**	$1/2$	$h=0$
χ_α	**1**	0	z_α
$(L'_L)^\dagger$	**2**	$1/2$	$-x'$
L''_R	**2**	$-1/2$	x''
e'_R	**1**	-1	x'
$(e''_L)^\dagger$	**1**	1	$-x''$
Φ	**1**	0	ϕ
S	**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

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)

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

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,

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

where

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

$\rightarrow$

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

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

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

- $B = 0$ with $L = 6$

$$(6, 6, 6, -8, -10, 5, 13, -9, -9)$$

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

- $B = 0$ with $L = 6$
- Electroweak-scale vector-like fermions with $\Phi = 18$:
  $(L'_L)^\dagger L''_R \Phi \to x' = 8,\ x'' = -10$

$$(6, 6, 6, -8, -10, 5, 13, -9, -9)$$

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  $(L'_L)^\dagger L''_R \Phi \to x' = 8,\ x'' = -10$
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- Dirac-fermionic DM:
  $(\chi_L)^\dagger \chi'_R \Phi^* \to z_3 = 5,\ z_4 = 13$

$$(6, 6, 6, -8, -10, 5, 13, -9, -9)$$

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  $(\chi''_i)^\dagger \chi''_j \Phi \to z_5 = -9,\ z_6 = -9$

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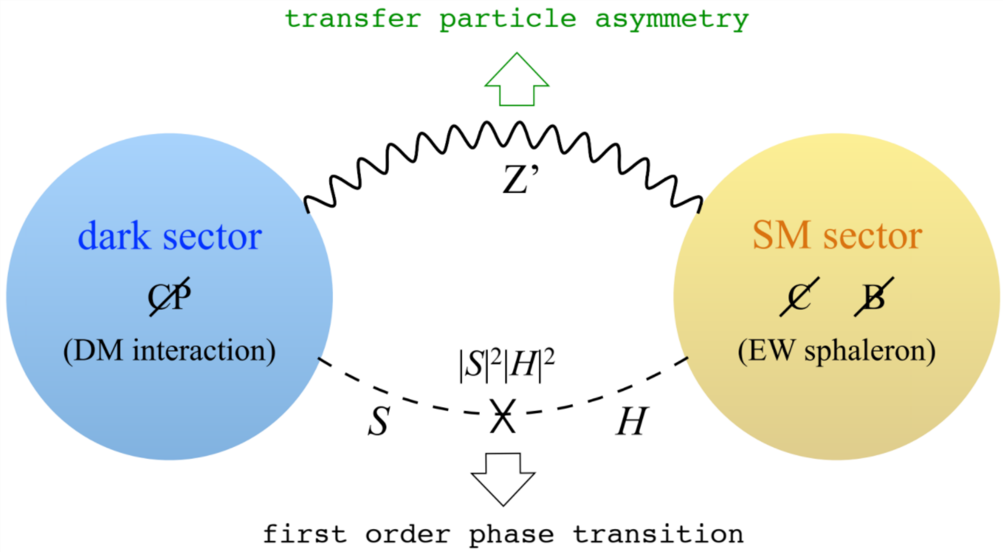
$$(6, 6, 6, -8, -10, 5, 13, -9, -9)$$

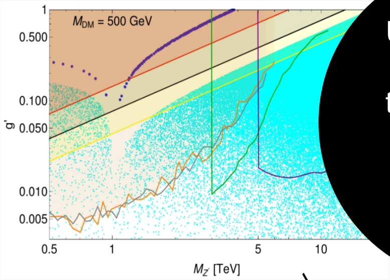
Only 4 solutions from 96 153

l	k	solution	gcd	n	zmax	hidden
[-2, -3, 0]	[1, 2, 3, 2]	[5, 6, 6, 6, -8, -9, -9, -10, 13]	4	9	13	[{'S': 18, 'ψ': [(-9, -9), (-8, -10), (5, 13)]}]
[2, 0, 3]	[-2, 1, -3, -1]	[2, 3, 3, 3, 6, -8, -11, -15, 17]	12	9	17	[{'S': 9, 'ψ': [(2, -11), (6, -15), (-8, 17)]}]
[-4, -2, 1]	[2, -4, 4, -2]	[1, -2, 6, 6, 6, -9, -9, -16, 17]	16	9	17	[{'S': 18, 'ψ': [(-9, -9), (1, 17), (-2, -16)]}]
[3, -2, -4]	[-2, -1, -2, 3]	[1, 2, 3, -6, -6, -6, 15, 16, -19]	2	9	19	[{'S': 18, 'ψ': [(1, -19), (3, 15), (2, 16)]}]

Dark sector baryogenesis



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



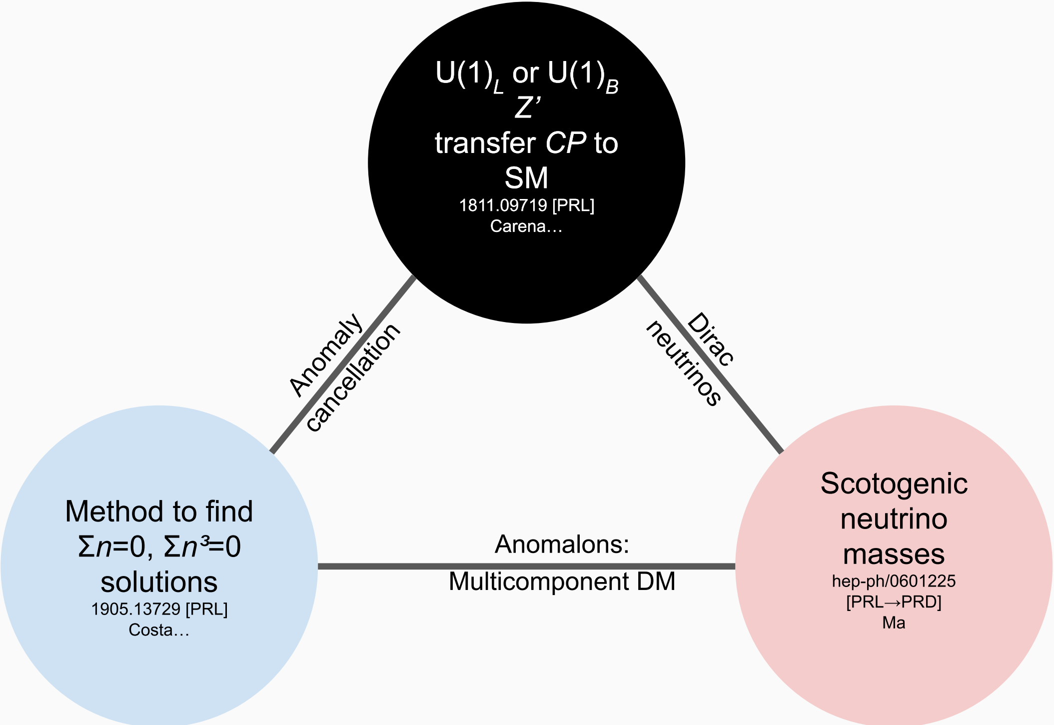
U(1)$_L$ or U(1)$_B$
Z'
transfer *CP* to SM
1811.09719 [PRL]
Carena…

Anomaly cancellation

Dirac neutrinos

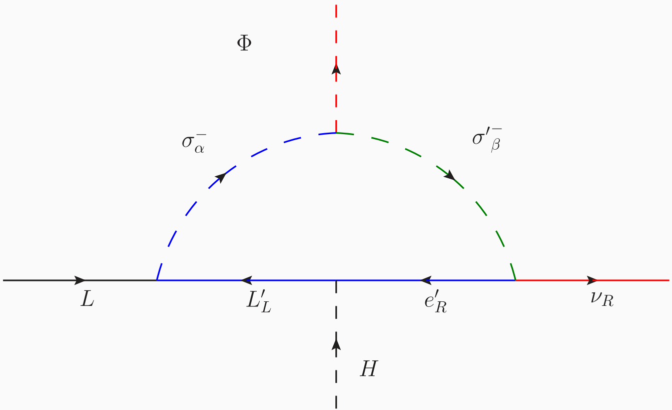
Anomalons:

DM


U(1)$_L$ or U(1)$_B$
Z'
transfer CP to SM
1811.09719 [PRL]
Carena…
Anomaly cancellation
Dirac neutrinos
Method to find Σn=0, Σn^3=0 solutions
1905.13729 [PRL]
Costa…
Anomalons:
Multicomponent DM
Scotogenic neutrino masses
hep-ph/0601225
[PRL→PRD]
Ma

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

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



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

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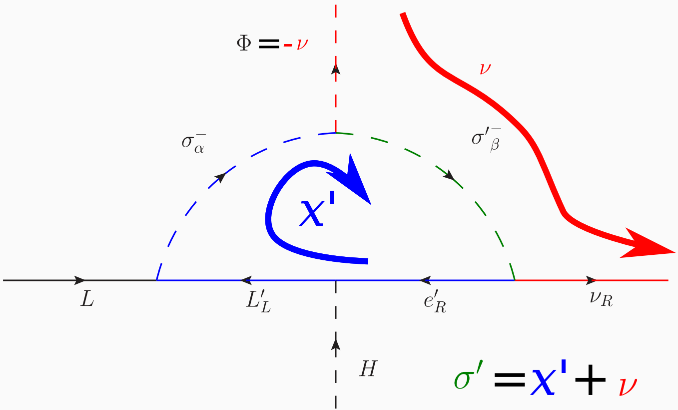

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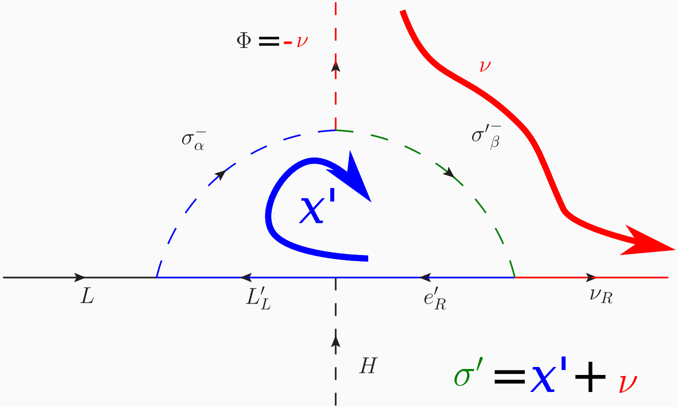
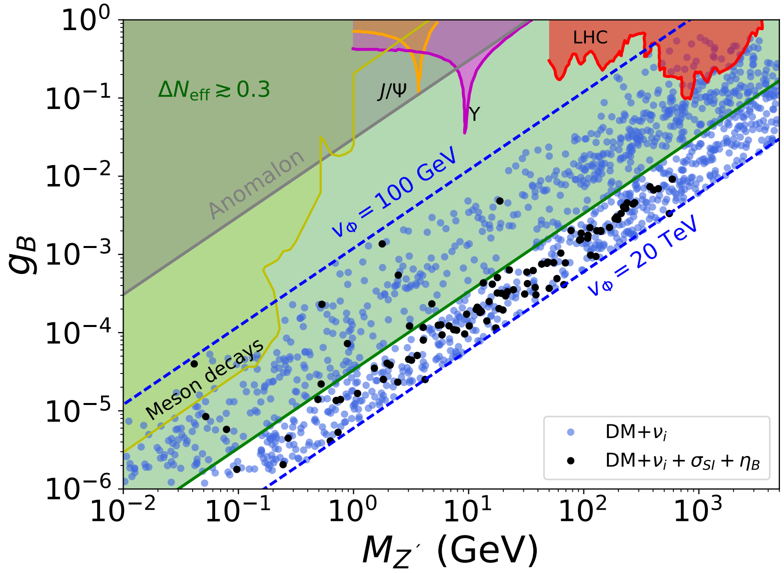


Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	**1**	2/3	$u = 1/3$
d_{Ri}	**1**	$-1/3$	$d = 1/3$
$(Q_i)^\dagger$	**2**	$-1/6$	$Q = -1/3$
$(L_i)^\dagger$	**2**	1/2	$L = 0$
e_R	**1**	-1	$e = 0$
$(L'_L)^\dagger$	**2**	1/2	$-x' = -3/5$
e'_R	**1**	-1	$x' = 3/5$
L''_R	**2**	$-1/2$	$x'' = 18/5$
$(e''_L)^\dagger$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