



UNIVERSIDAD DE ANTIOQUIA  
1803

# Multicomponent fermionic dark matter and dark baryogenesis

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

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

- From a list of  $N - 2$  integers, e.g., for  $N$  even

$$\mathbf{q} = [l_1, l_2, \dots, l_n, k_1, k_2, \dots, k_n], \quad n = (N - 2)/2. \quad (2)$$

in the range  $[-m, m]$ , build two vector-like solutions of  $N$  integers,

$$\mathbf{x} = [l_1, k_1, \dots, k_n, -l_1, -k_1, \dots, -k_n], \quad \mathbf{y} = [0, 0, l_1, \dots, l_n, -l_1, \dots, -l_n] \quad (3)$$

- From a list of  $N - 2$  integers, e.g., for  $N$  even

$$\mathbf{q} = [l_1, l_2, \dots, l_n, k_1, k_2, \dots, k_n], \quad n = (N - 2)/2. \quad (2)$$

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

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

- From a list of  $N - 2$  integers, e.g., for  $N$  even

$$\mathbf{q} = [l_1, l_2, \dots, l_n, k_1, k_2, \dots, k_n], \quad n = (N - 2)/2. \quad (2)$$

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

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

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

- From a list of  $N - 2$  integers, e.g., for  $N$  even

$$\mathbf{q} = [l_1 = 2, l_2 = 3, k_1 = -1, k_2 = -3], \quad n = 2. \quad (2)$$

in the range  $[-3, 3]$ , build two vector-like solutions of 6 integers,

$$\mathbf{x} = [2, -1, -3, -2, 1, 3,] \quad \mathbf{y} = [0, 0, 2, \dots 3, -2, \dots -3] \quad (3)$$

- Obtain a (some times) **non vector-like** solution with  $z_{\max} = 2 \times 3 = 6$

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

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

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



restrepo ▾

# anomalies 0.2.5

`pip install anomalies`



Latest version

Released: Sep 6, 2022

Anomaly cancellation

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## Statistics

GitHub statistics:

Stars 0

## Project description

### Anomalies

Python package passing Upload Python Package passing DOI [10.5281/zenodo.5526558](https://doi.org/10.5281/zenodo.5526558)

Implement the anomaly free solution of [arXiv:1905.13729](https://arxiv.org/abs/1905.13729) [PRL]:

Obtain a numpy array  $\mathbf{z}$  of  $N$  integers which satisfy the Diophantine equations

```
>>> z.sum()  
0  
>>> (z**3).sum()  
0
```

The input is two lists  $\mathbf{l}$  and  $\mathbf{k}$  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)`



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 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

## Publication date:

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](#)

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

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

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

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

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

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

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

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

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

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

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

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

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

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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: $U(1)_D$

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

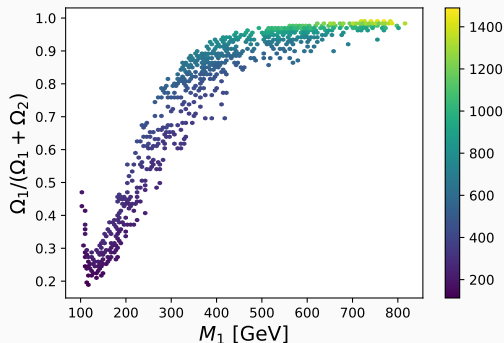
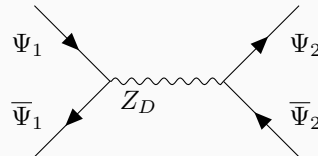
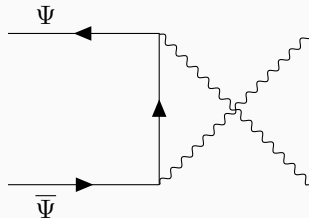
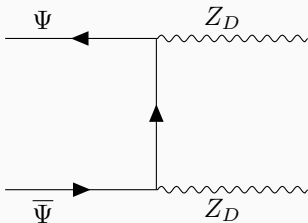
96 153  $\rightarrow$  5 196 **multi-component DM** ( $N = 8, 12$ )  $\rightarrow$  41 with two Dirac-fermion DM

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

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

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

in progress...



$M_{Z_D} < 200$ , GeV

$M_2$  [GeV]

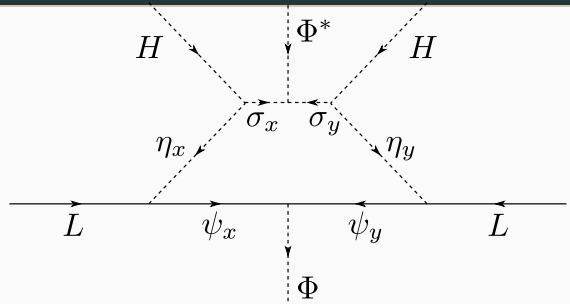
(xBit scan)



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

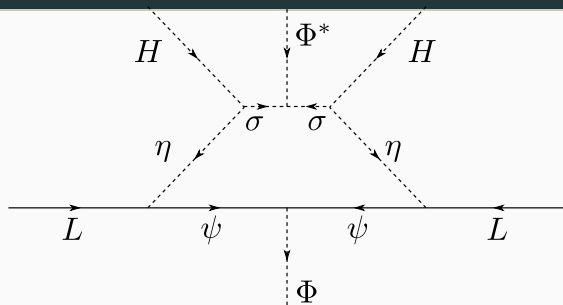
# Scotogenic Majorana neutrino masses and mixings

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



# Scotogenic Majorana neutrino masses and mixings

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



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

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

## **Additional conditions to reduce multiplicity**

---

Decrease the number of charges to be assigned to dark matter particles,  $\psi_i$  below

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

Secluded case:

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

$$\chi_1 \rightarrow \nu_{R1}, \dots, \chi_{N_\nu} \rightarrow \nu_{RN_\nu}, \quad 2 \leq N_\nu \leq 3, \quad (12)$$

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

$\Phi$  is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry and give mass to all  $\psi_i$

$$\phi = -\frac{\nu}{\delta}, \quad (13)$$

Decrease the number of charges to be assigned to dark matter particles,  $\psi_i$  below

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

Secluded case:

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

Active case:

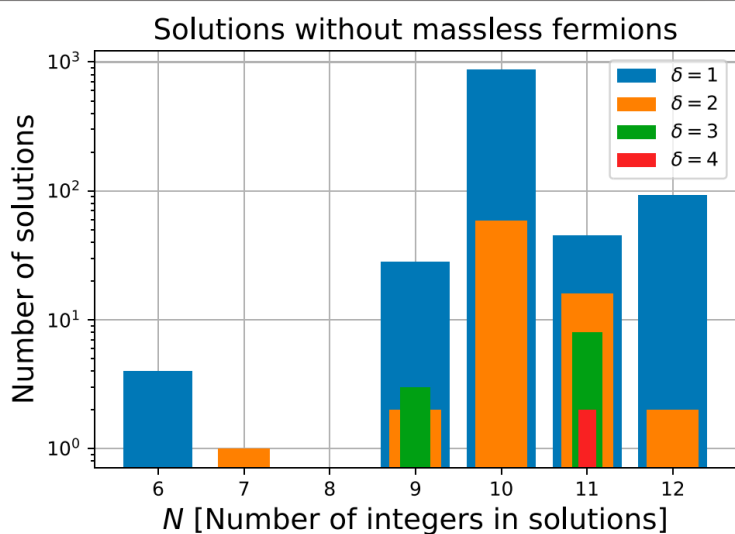
$$[\nu, \nu, (\nu), m, m, m, \psi_1, \psi_2, \dots, \psi_{N'}]$$

$$\chi_1 \rightarrow \nu_{R1}, \dots, \chi_{N_\nu} \rightarrow \nu_{RN_\nu}, \quad 2 \leq N_\nu \leq 3, \quad X(L_i) = -L, \quad X(H) = h \quad \rightarrow m = L - h \quad (12)$$

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

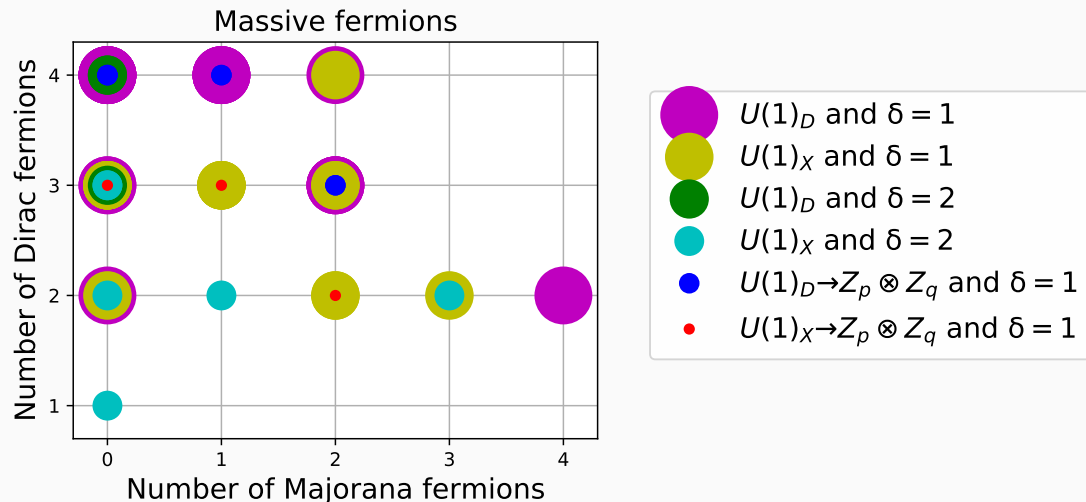
$\Phi$  is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry and give mass to all  $\psi_i$   $\rightarrow [-4, -4, 1, 1, 1, 5]$

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



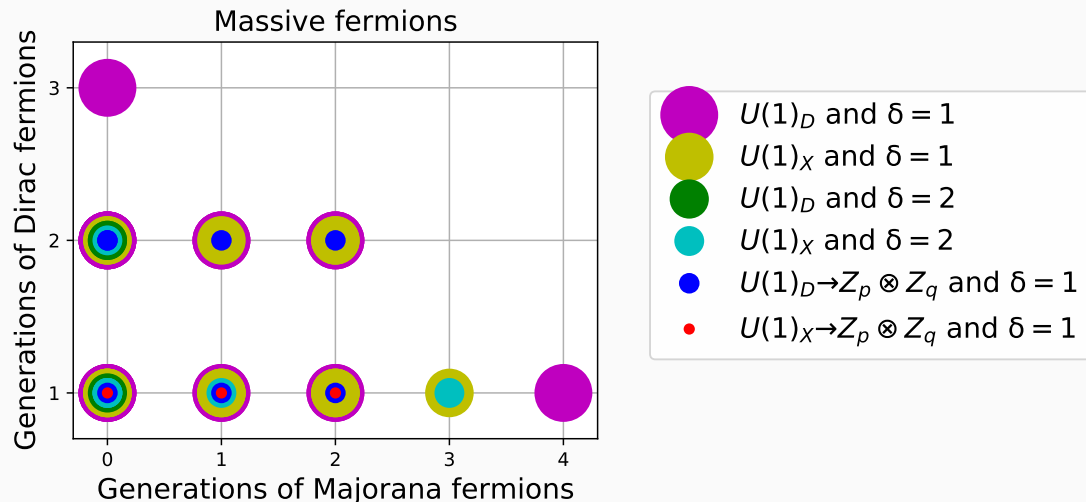
**FIGURE 1** | Distribution of solutions with  $N$  integers to the Diophantine Eq. 1 which allow the effective Dirac neutrino mass operator at  $d = (4 + \delta)$  for at least two right-handed neutrinos and have non-vanishing Dirac or Majorana masses for the other SM-singlet chiral fermions in the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

# Multi-component dark matter





# Multi-flavor dark matter



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

- Active symmetry  $m = 3$

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

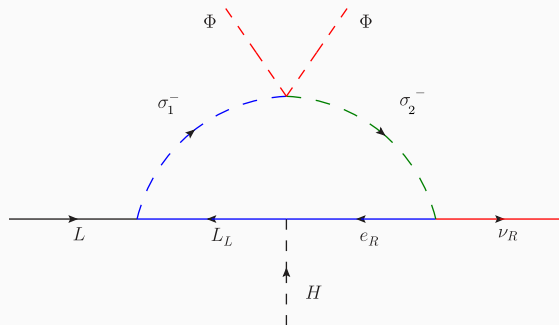
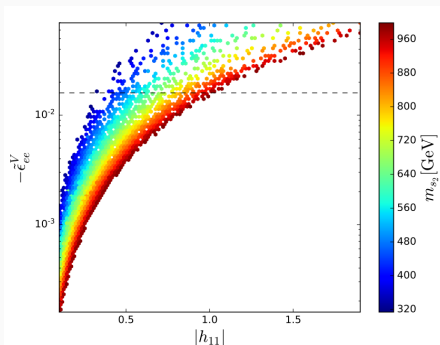
## $U(1)_X$ selection with Dirac-fermionic DM

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

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

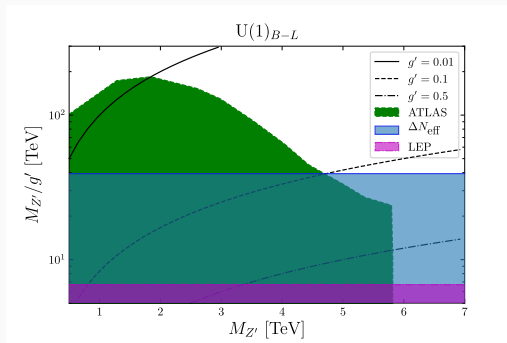
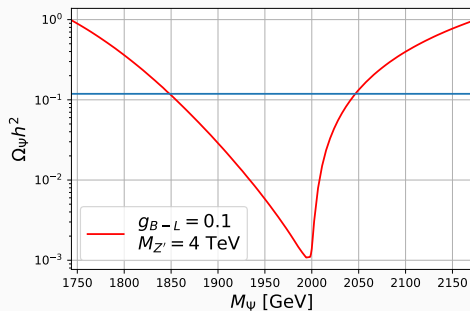
- Active symmetry  $m = 3$
- Effective neutrino mass  $\delta = 2 \rightarrow \nu = -5$ :
- Active symmetry:  $m = 3 \rightarrow \phi = -(\nu + m)/\delta = 1$

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



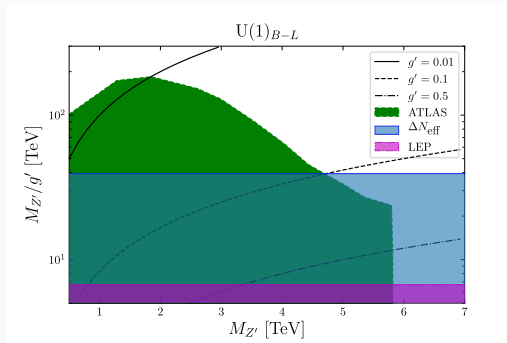
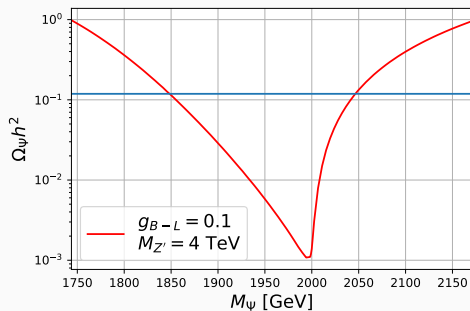
- Active symmetry  $m = 3$
- Effective neutrino mass  $\delta = 2 \rightarrow \nu = -5$ :
- Active symmetry:  $m = 3 \rightarrow \phi = -(\nu + m)/\delta = 1$
- Dirac-fermionic DM:  $(\psi_L)^\dagger \psi_R'' \Phi^* \rightarrow z_6 = -7, z_7 = 8$

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



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

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



## Beyond SM-fermion singlets

---

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

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{X}=\textcolor{red}{D} \text{ or } \textcolor{blue}{X}}$
$Q_i^\dagger$	<b>2</b>	$-1/6$	$\textcolor{red}{Q}$
$d_{Ri}$	<b>1</b>	$-1/2$	$\textcolor{red}{d}$
$u_{Ri}$	<b>1</b>	$+2/3$	$\textcolor{red}{u}$
$L_i^\dagger$	<b>2</b>	$+1/2$	$\textcolor{blue}{L}$
$e_{Ri}$	<b>1</b>	$-1$	$\textcolor{blue}{e}$
$H$	<b>2</b>	$1/2$	$h$
$\chi_\alpha$	<b>1</b>	$0$	$z_\alpha$

$\Phi$	<b>1</b>	$0$	$\phi$
--------	----------	-----	--------

**Table 1:** LHC: hadronic production and dileptonic decay

$$i = 1, 2, 3, \alpha = 1, 2, \dots, N'$$



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

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{X}=B \text{ or } L}$
$Q_i^\dagger$	<b>2</b>	$-1/6$	$Q$
$d_{Ri}$	<b>1</b>	$-1/2$	$d$
$u_{Ri}$	<b>1</b>	$+2/3$	$u$
$L_i^\dagger$	<b>2</b>	$+1/2$	$L$
$e_{Ri}$	<b>1</b>	$-1$	$e$
$H$	<b>2</b>	$1/2$	$h = 0$
$\chi_\alpha$	<b>1</b>	$0$	$z_\alpha$
$(L'_L)^\dagger$	<b>2</b>	$1/2$	$-x'$
$L''_R$	<b>2</b>	$-1/2$	$x''$
$e'_R$	<b>1</b>	$-1$	$x'$
$(e''_L)^\dagger$	<b>1</b>	$1$	$-x''$
$\Phi$	<b>1</b>	$0$	$\phi$
$S$	<b>1</b>	$0$	$s$

**Table 1:** minimal set of new fermion content:  $L = e = 0$  for  $\mathcal{X} = B$ . Or  $Q = u = d = 0$  for  $\mathcal{X} = L$ .  
 $i = 1, 2, 3, \alpha = 1, 2, \dots, N'$

## Anomaly cancellation: $\mathcal{X} = L$ or $B$ : beyond SM-singlet fermions

The anomaly-cancellation conditions on  $[SU(3)_c]^2 U(1)_X$ ,  $[SU(2)_L]^2 U(1)_X$ ,  $[U(1)_Y]^2 U(1)_X$ , allow us to express three of the  $X$ -charges in terms of the others

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

while the  $[U(1)_X]^2 U(1)_Y$  anomaly condition reduces to

$$(e + L)(x' - x'') = 0 . \quad (15)$$

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

$$e = -L , \quad (16)$$

so that ( $L$  is still a free parameter)

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

## 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,

$$\sum_{\alpha=1}^N z_{\alpha} = 0, \quad \sum_{\alpha=1}^N z_{\alpha}^3 = 0, \quad (18)$$

where

$$\begin{aligned} z_1 &= -x', & z_2 &= x'', \\ z_{2+i} &= L, \quad i = 1, 2, 3 \end{aligned} \quad (19)$$

$\rightarrow$

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

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

- $L = 0$

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

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

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

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

- $L = 0$
- Effective Dirac neutrino masses:  $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:

$$(L'_L)^\dagger L''_R \Phi^* \rightarrow x' = -1, x'' = 6$$

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

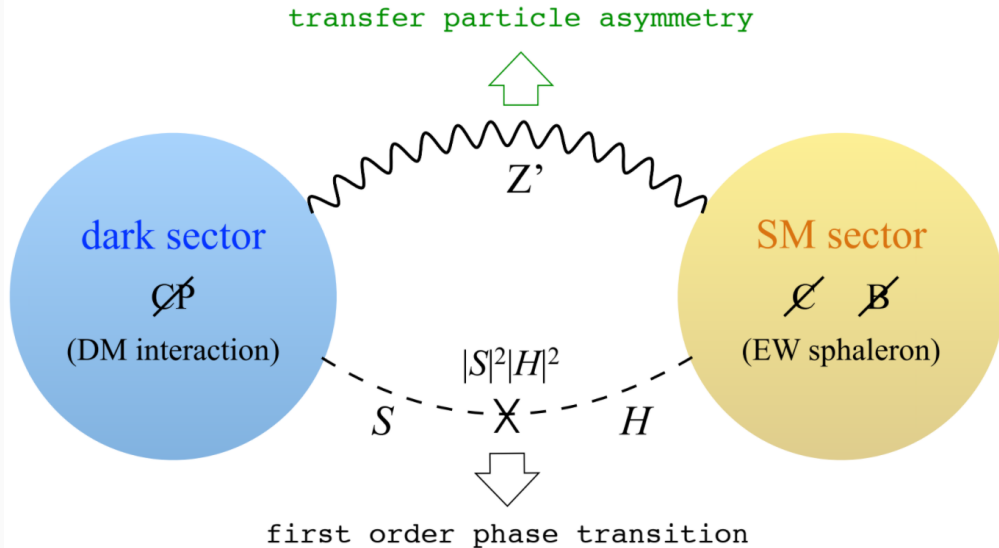
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959 solutions

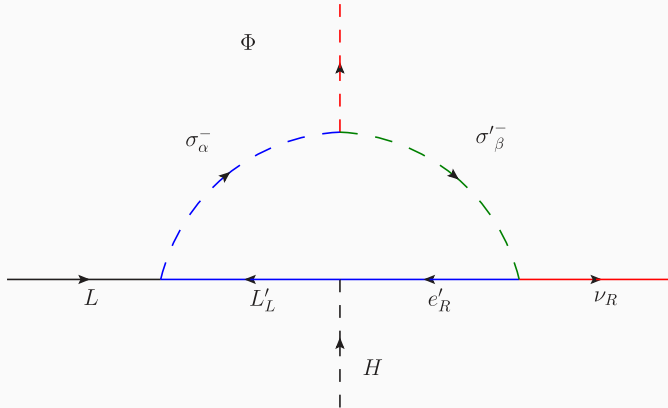


# Dark sector baryogenesis



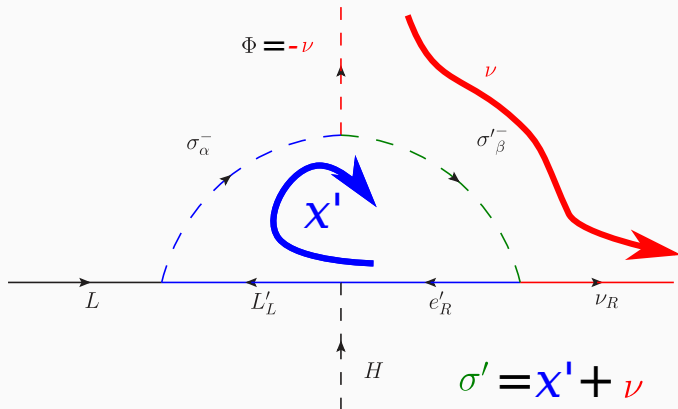
# Gauge Baryon number scotogenic realization: arXiv:2205.05762 [PRD]

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



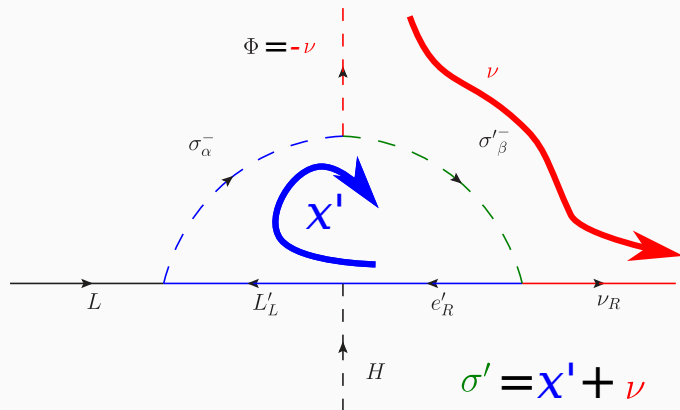
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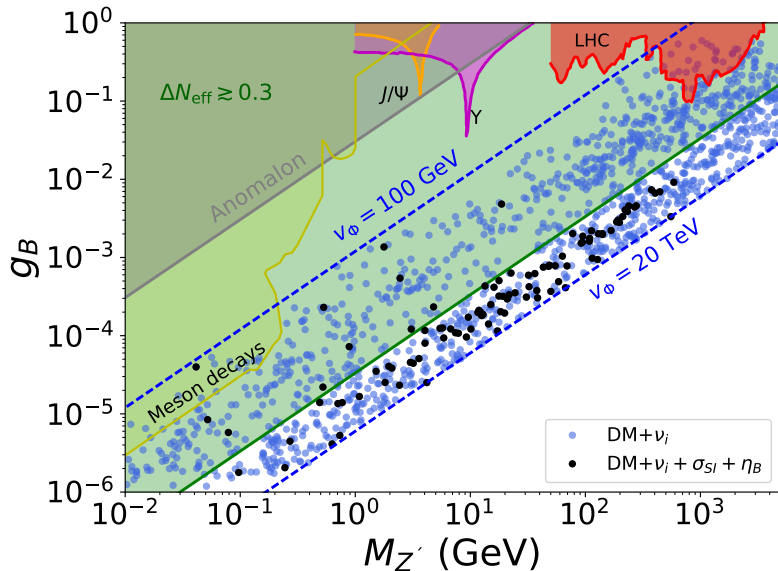
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Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$u_{Ri}$	1	2/3	$u = 1/3$
$d_{Ri}$	1	-1/3	$d = 1/3$
$(Q_i)^\dagger$	2	-1/6	$Q = -1/3$
$(L_i)^\dagger$	2	1/2	$L = 0$
$e_R$	1	-1	$e = 0$
$(L'_L)^\dagger$	2	1/2	$-x' = -3/5$
$e'_R$	1	-1	$x' = 3/5$
$L''_R$	2	-1/2	$x'' = 18/5$
$(e'_L)^\dagger$	1	1	$-x'' = -18/5$
$\nu_{R,1}$	1	0	-3
$\nu_{R,2}$	1	0	-3
$\chi_R$	1	0	6/5
$(\chi_L)^\dagger$	1	0	9/5
$H$	2	1/2	0
$S$	1	0	3
$\Phi$	1	0	3
$\sigma^-_\alpha$	1	1	3/5
$\sigma'^-_\alpha$	1	-1	-12/5

- SARAH→SPheno→MicroMegas
- $\eta_B$  calculation code
- Python notebook with the scan

## Black points: Dirac neutrinos with proper DM and baryon assymetry



A methodology to find all the *universal* gauge Abelian extensions of the standard model is designed.

All of the extensions can be reformulated as the solution of

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

which we fully scan 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. With enough freedom to solve several phenomenological problems.

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

- High scale fields:  $\Phi$ ,  $(\langle\Phi\rangle \rightarrow L'_L, L''_R, e'_L, e''_R)$ : EW-scale vector-like anomalous
- Electroweak scale (EW) fields:  $Z'_\mu, S, \chi_L, \chi_R$
- CP-violation

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

- 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

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



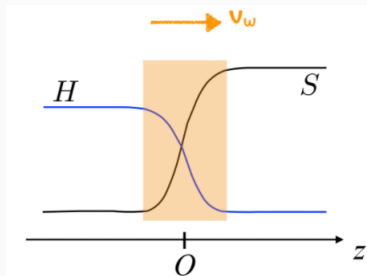
## First-order phase transition: Effective potential ( $T \neq 0$ )

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

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

where

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



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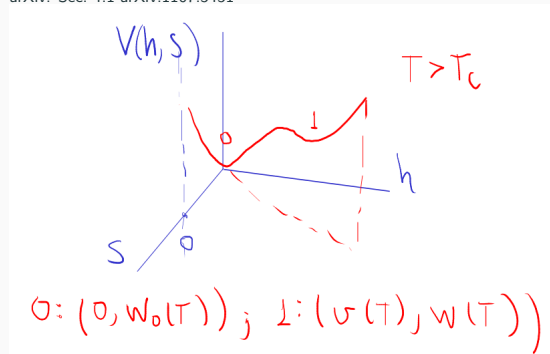
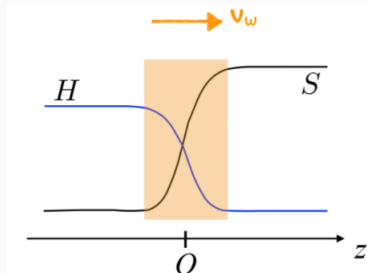
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arXiv: Sec. 4.1 arXiv:1107.5451



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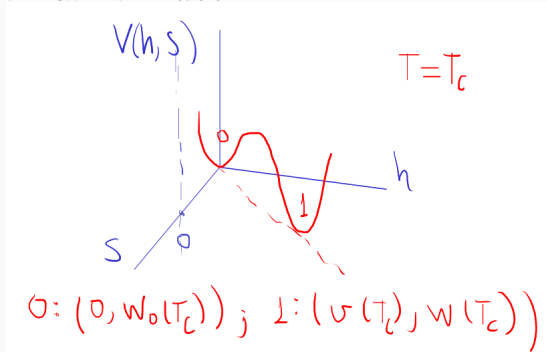
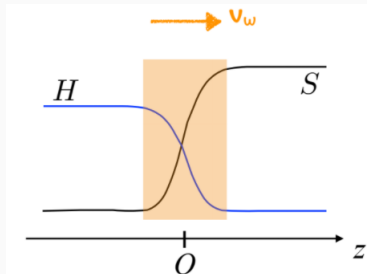
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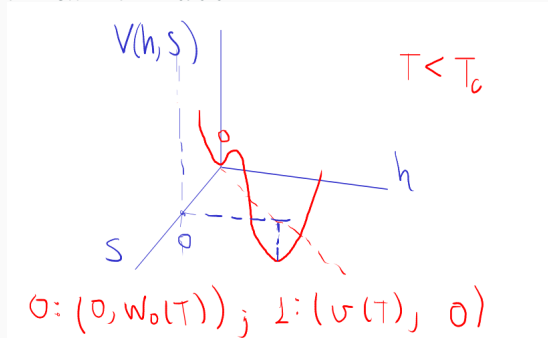
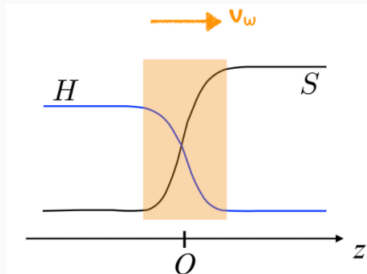
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Using the thin wall approximation for the nucleation bubbles, we use the ansatz in which the space dependence of the fields is given by

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

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

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

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

## Boltzmann equation i

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

$$-D_L \xi''_{\chi_L} - v_w \xi'_{\chi_L} + \Gamma_L (\xi_{\chi_L} - \xi_{\chi_R}) = S_{\mathcal{CP}},$$

where  $D_L$  is the diffusion constant for  $\chi_L$ , which is related to the scattering rate  $\Gamma_L$  by

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

and

$$S_{\mathcal{CP}} = -\frac{\lambda}{2} \frac{v_w D_L}{\frac{3x+2}{x^2+3x+2} T} \frac{(1-x)e^{-x} + x^2 E_1(x)}{4m_\chi^2 K_2(x)} \frac{m_\chi w_0(T_n) \lambda \left( -2 + \cosh\left(\frac{2z}{L_w}\right) \right) \sin \theta}{L_w^3 \cosh^4\left(\frac{z}{L_w}\right)}, \quad (24)$$

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 asymmetry to SM quarks

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

$$\langle Z'_0(z) \rangle = \frac{g_B (q_{\chi_L} - q_{\chi_R}) T_n^3}{6M_{Z'}} \int_{-\infty}^{\infty} dz_1 \xi_{\chi_L}(z_1) e^{-M_{Z'}|z-z_1|},$$

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,  $\Delta n_Q^{\text{EQ}}(z) \sim T_n^2 \mu_Q(z)$ .

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

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

where  $\Gamma_{\text{sph}}$  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

$$0.82 \times 10^{-10} < \eta_B < 0.92 \times 10^{-10}. \quad (25)$$