

Radiative seesaw and baryogenesis

with gauged Lepton number



UNIVERSIDAD DE ANTIOQUIA
1803

Diego Restrepo

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



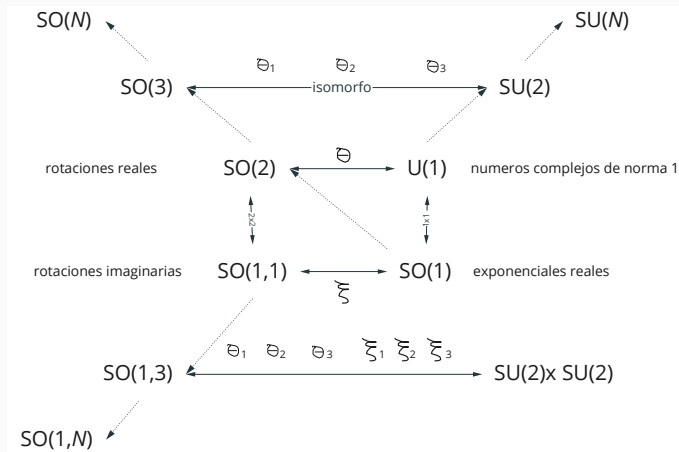
Focus on

arXiv:xxxx.xxxxx

In collaboration with

W. Novelo, L. Leite, O. Peres (UNICAMP)

Model building



$$U = \exp \left(i \sum_j T_j \theta^j \right), \quad (1)$$

donde θ^j son los parámetros del grupo y T_j los generadores.

Considere el generador 1×1

$$K = -i, \quad (2)$$

que genera el elemento del grupo dilaton, $SO(1)$, $R(\xi)$

$$\lambda(\xi) = e^{\xi}, \quad (3)$$

que corresponde simplemente al grupo de las exponenciales reales. Un número real puede sufrir una transformación

$$x \rightarrow x' = e^{\xi} x, \quad (4)$$

que corresponde a su vez a un boost por la cantidad e^{ξ} . Podemos definir un producto escalar invariante como la división de números reales tal que

$$x \cdot y \rightarrow x' \cdot y' \equiv \frac{x'}{y'} = \frac{e^{\xi} x}{e^{\xi} y} = \frac{x}{y} = x \cdot y. \quad (5)$$

Queremos obtener una representación 2×2 del álgebra

$$K^2 = -\mathbf{1}, \quad (6)$$

donde K es el único generador. Para hallar una representación de esta álgebra en términos de matrices 2×2 considere el generador

$$K = \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix}. \quad (7)$$

que genera un elemento del grupo $SO(1, 1)$ con parámetro ξ

$$\Lambda = \exp(i\xi K). \quad (8)$$

Para realizar la expansión de Taylor, considere

$$K^0 = \mathbf{1}_{2 \times 2}, \quad K = \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix}, \quad K^2 = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}, \quad K^3 = \begin{pmatrix} 0 & i \\ i & 0 \end{pmatrix}, \dots$$

$$K^{2n} = (-1)^n \mathbf{1}_{2 \times 2}, \quad K^{2n+1} = (-1)^n \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix}.$$

Entonces,

$$\begin{aligned}
 \Lambda = \exp(i\xi K) &= \sum_{n=0}^{\infty} \frac{(i\xi K)^n}{n!} \\
 &= \sum_{n=0}^{\infty} (i)^{2n} \frac{(\xi K)^{2n}}{2n!} + \sum_{n=0}^{\infty} (i)^{2n+1} \frac{(\xi K)^{2n+1}}{(2n+1)!} \\
 &= \sum_{n=0}^{\infty} (-1)^n \frac{\xi^{2n}}{2n!} (-1)^n \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \sum_{n=0}^{\infty} i(-1)^n \frac{\xi^{2n+1}}{(2n+1)!} (-1)^n \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \\
 &= \sum_{n=0}^{\infty} \frac{\xi^{2n}}{2n!} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \sum_{n=0}^{\infty} \frac{\xi^{2n+1}}{(2n+1)!} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \\
 &= \begin{pmatrix} \cosh \xi & 0 \\ 0 & \cosh \xi \end{pmatrix} + \begin{pmatrix} 0 & \sinh \xi \\ \sinh \xi & 0 \end{pmatrix} \\
 &= \begin{pmatrix} \cosh \xi & \sinh \xi \\ \sinh \xi & \cosh \xi \end{pmatrix}, \tag{9}
 \end{aligned}$$

Podemos entonces definir el grupo $SO(1, 1)$ como el grupo de las matrices 2×2 que satisfacen la condición

$$\Lambda^T g \Lambda = g, \quad (10)$$

donde

$$g = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (11)$$

Bajo una transformación de Lorentz.

$$x^\mu \rightarrow x'^\mu = \Lambda^\mu{}_\nu x^\nu. \quad (12)$$

Introducimos ahora un cuadrivector que lleva intrínsecamente el índice abajo

$$\partial_\mu = \frac{\partial}{\partial x^\mu} = \left(\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) = (\partial_0, \nabla). \quad (13)$$

Las propiedades de transformación para ∂_μ

$$\begin{aligned} (\Lambda^{-1})^\mu{}_\alpha x'^\alpha &= (\Lambda^{-1})^\mu{}_\alpha \Lambda^\alpha{}_\nu x^\nu \\ &= \delta^\mu{}_\nu x^\nu \\ &= x^\mu, \end{aligned} \quad (14)$$

$$\frac{1}{x'^{\nu}} = (\Lambda^{-1})^{\mu}_{\nu} \frac{1}{x^{\mu}}, \quad (15)$$

o

$$\frac{1}{x'^{\mu}} = (\Lambda^{-1})^{\nu}_{\mu} \frac{1}{x^{\nu}}, \quad (16)$$

de modo que la transformación de Lorentz para $\partial_{\mu} = \partial/\partial x^{\mu}$, es

$$\begin{aligned} \frac{\partial}{\partial x'^{\mu}} &= (\Lambda^{-1})^{\nu}_{\mu} \frac{\partial}{\partial x^{\nu}} \\ \partial'_{\mu} &= (\Lambda^{-1})^{\nu}_{\mu} \partial_{\nu}. \end{aligned} \quad (17)$$

De esta manera, un producto escalar invariante entre la cuádriderivada y un cuádrivector de Lorentz $A^{\mu}(x)$ es

$$\partial_{\mu} A^{\mu} \rightarrow \partial'_{\mu} A'^{\mu} = \partial_{\mu} A^{\mu}. \quad (18)$$

Nombre	Símbolo	SU(N)
N -plete escalar	Ψ	$U\Psi$
anti- N -plete escalar	Ψ^\dagger	$\Psi^\dagger U^\dagger$

Nombre	Símbolo	Lorentz
fotón	A^μ	$\Lambda^\mu{}_\nu A^\nu$
derivada	∂_μ	$\partial_\nu (\Lambda^{-1})^\nu{}_\mu$

Table 1: Productos escalares: $\Psi^\dagger \Psi$, $\partial_\mu A^\mu$, $A^\nu A_\nu$, $\partial_\mu \partial^\mu$

donde, $g_{\alpha\beta} = \Lambda^\mu{}_\alpha g_{\mu\nu} \Lambda^\nu{}_\beta$, $g^{\mu\nu} = (\Lambda^{-1})^\mu{}_\alpha g^{\alpha\beta} (\Lambda^{-1})^\nu{}_\beta$.

Nombre	Símbolo	Lorentz	$U(1)$
e_L : electrón izquierdo	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta} \xi_\alpha$
$(e_R)^\dagger$: positrón izquierdo	η^α	$\eta^\beta [S^{-1}]_\beta{}^\alpha$	$\eta^\alpha e^{-i\theta}$
$(e_L)^\dagger$: positrón derecho	$(\xi_\alpha)^\dagger = \xi_{\dot{\alpha}}$	$\xi_{\dot{\beta}}^\dagger [S^\dagger]_{\dot{\beta}}{}^{\dot{\alpha}}$	$\xi_{\dot{\alpha}}^\dagger e^{-i\theta}$
e_R : electrón derecho	$(\eta^\alpha)^\dagger = \eta^{\dagger\dot{\alpha}}$	$[(S^{-1})^\dagger]^{\dot{\alpha}}{}_{\dot{\beta}} \eta^{\dagger\dot{\beta}}$	$e^{i\theta} \eta^{\dagger\dot{\alpha}}$

Table 2: Definición de transformaciones de Lorentz

Productos escalares

- Escalares de Majorana: $\xi^\alpha \xi_\alpha + \xi_{\dot{\alpha}}^\dagger \xi^{\dagger\dot{\alpha}}, \eta^\alpha \eta_\alpha + \eta_{\dot{\alpha}}^\dagger \eta^{\dagger\dot{\alpha}}.$
- Escalar de Dirac: $\eta^\alpha \xi_\alpha + \xi_{\dot{\alpha}}^\dagger \eta^{\dagger\dot{\alpha}}.$
- Escalar subgrupo $SL(2, \mathbb{C})$ pero vector bajo $SO(1, 3)$: $S^\dagger \bar{\sigma}^\mu S = \Lambda^\mu{}_\nu \bar{\sigma}^\nu$

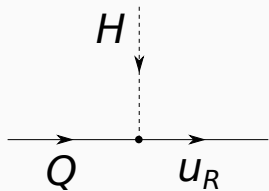
Campos	Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Q	ξ_α^1	3	2	1/6
L	ξ_α^2	1	2	-1/2
$(u_R^-)^\dagger$	η_1^α	$\bar{\mathbf{3}}$	1	-2/3
$(d_R^-)^\dagger$	η_2^α	$\bar{\mathbf{3}}$	1	1/3
$(e_R^-)^\dagger$	η_3^α	1	1	1
H	-	1	2	1/2

Table 3: Campos fundamentales del modelo estándar

como por ejemplo,

$$(u_R)^\dagger Q \cdot H, \quad (19)$$

Que se puede representar con la Ley De Kircchoff:



Dark sectors







Local $U(1)_\chi$

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i \chi_i^\dagger \not{D} \chi_i - h(\chi_1 \chi_2 \Phi + \text{h.c.})$$

Anomalons: SM-singlet Dirac fermion

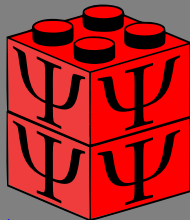
dark matter $m_\psi = h\langle\Phi\rangle$

LHC production:

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

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

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



$$\bar{\Psi}\Psi = \chi_1 \chi_2 + \chi_1^\dagger \chi_2^\dagger \rightarrow \chi_\alpha \chi_\beta \Phi^{(*)},$$

$$\alpha = 1, \dots N' \rightarrow N' > 4$$



Local $U(1)_\chi$

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i \chi_i^\dagger \not{D} \chi_i - h(\chi_1 \chi_2 \Phi + \text{h.c.})$$

Anomalons: SM-singlet Dirac fermion

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

LHC production:

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

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

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



multi-component
dark matter

$$\bar{\Psi}\Psi = \chi_1\chi_2 + \chi_1^\dagger\chi_2^\dagger \rightarrow \chi_\alpha\chi_\beta\Phi^{(*)},$$

$$\alpha = 1, \dots N' \rightarrow N' > 4$$



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

Local $U(1)_\chi$

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i \chi_i^\dagger \not{D} \chi_i - h(\chi_1 \chi_2 \Phi + \text{h.c.})$$

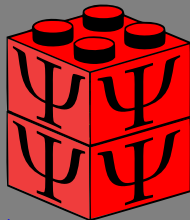
Anomalons: SM-singlet Dirac fermion

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

LHC production:

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

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



multi-component
dark matter

$$\bar{\Psi}\Psi = \chi_1\chi_2 + \chi_1^\dagger\chi_2^\dagger \rightarrow \chi_\alpha\chi_\beta\Phi^{(*)},$$

$$\alpha = 1, \dots N' \rightarrow N' > 4$$



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

Local $U(1)_\chi$

$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i \chi_i^\dagger \not{D} \chi_i - y(\chi_1 \chi_2 S + \text{h.c.})$$

Anomalons: SM-singlet Dirac fermion

CP violation Yukawa y

LHC production:

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

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



multi-component
dark matter

$$\bar{\Psi}\Psi = \chi_1 \chi_2 + \chi_1^\dagger \chi_2^\dagger \rightarrow \chi_\alpha \chi_\beta \Phi^{(*)},$$

$$\alpha = 1, \dots, N' \rightarrow N' > 4$$

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	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	$1/2$	$-\mathcal{X}'$
L''_R	2	$-1/2$	\mathcal{X}''
e'_R	1	-1	\mathcal{X}'
$(e''_L)^\dagger$	1	1	$-\mathcal{X}''$
Φ	1	0	ϕ
S	1	0	s

Table 4: A minimal set of new fermion content: $L = e = 0$ for $\mathcal{X} = B$. Or $Q = u = d = 0$ for $\mathcal{X} = L$.
 $i = 1, 2, 3, \alpha = 1, 2, \dots, N'$

$$\chi_1 \rightarrow \nu_{R1}, \dots, \chi_{N_\nu} \rightarrow \nu_{RN_\nu}, \quad 2 \leq N_\nu \leq 3, \quad (20)$$

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

S is the complex singlet scalar responsible for the SSB of the anomaly-free gauge symmetry with D or X -charge

$$\phi = -(\nu + L)/\delta, \quad (21)$$

Anomaly cancellation I

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

$$u = -e - \frac{2}{3}L - \frac{1}{9}(x' - x''), \quad d = e + \frac{4}{3}L - \frac{1}{9}(x' - x''), \quad Q = -\frac{1}{3}L + \frac{1}{9}(x' - x''), \quad (22)$$

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

$$(e + L)(x' - x'') = 0. \quad (23)$$

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

$$e = -L, \quad (24)$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}(x' - x''). \quad (25)$$

If $B = 0 \rightarrow U(1)_L$

Anomaly cancellation II

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,

$$\sum_{\alpha=1}^N z_{\alpha} = 0, \quad \sum_{\alpha=1}^N z_{\alpha}^3 = 0, \quad (26)$$

where $N = N' + 5$ and

$$\begin{aligned} z_{N'+1} &= -x', & z_{N'+2} &= x'', \\ z_{N'+2+i} &= L, \quad i = 1, 2, 3 \end{aligned} \quad (27)$$

→

$$9Q = - \sum_{\alpha=N'+1}^{N'+5} z_{\alpha} = -x' + x'' + L + L + L, \quad (28)$$

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

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')
>>> df[:2]
```

	1	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:

390074 solutions with $5 \leq N \leq 12$ integers until '[32]' [JSON]

17

views

4

downloads

[See more details...](#)

Indexed in

OpenAIRE

Publication date:

September 24, 2021

DOI:

DOI: [10.5281/zenodo.5526707](https://doi.org/10.5281/zenodo.5526707)

Keyword(s):

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

License (for files):

[Creative Commons Attribution 4.0 International](#)

Versions

Version 1

Sep 24, 2021

[10.5281/zenodo.5526707](https://doi.org/10.5281/zenodo.5526707)

- $B = 0 \rightarrow L = -3$ ($-x' + x'' + 3L = 0$)

$$(-3, -3, -3, -6, -6, -6, 2, 7, 4, 4, 5, 5)$$

$U(1)_L$ selection

- $B = 0 \rightarrow L = -3$ ($-x' + x'' + 3L = 0$)
- Effective neutrino mass $\nu = -6$:
 $\phi = -(\nu + L) = 9$

$$(-3, -3, -3, -6, -6, -6, 2, 7, 4, 4, 5, 5)$$

$U(1)_L$ selection

- $B = 0 \rightarrow L = -3$ ($-x' + x'' + 3L = 0$)
- Effective neutrino mass $\nu = -6$:
 $\phi = -(\nu + L) = 9$
- Electroweak-scale vector-like fermions:
 $(L'_L)^\dagger L''_R \Phi^* \rightarrow x' = -2, x'' = 7$

$$(-3, -3, -3, -6, -6, -6, 2, 7, 4, 4, 5, 5)$$

$U(1)_L$ selection

- $B = 0 \rightarrow L = -3$ ($-x' + x'' + 3L = 0$)

- Effective neutrino mass $\nu = -6$:

$$\phi = -(\nu + L) = 9$$

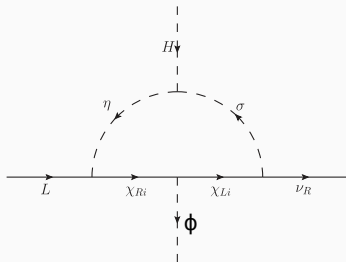
- Electroweak-scale vector-like fermions:

$$(L'_L)^\dagger L''_R \Phi^* \rightarrow x' = -2, x'' = 7$$

$$(-3, -3, -3, -6, -6, -6, 2, 7, 4, 4, 5, 5)$$

- At least two generations of heavy Dirac-fermionic DM:

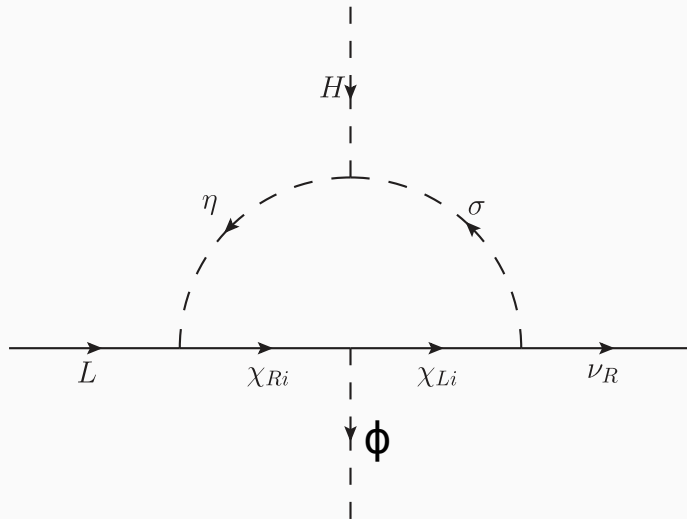
$$(\chi_{Li})^\dagger \chi_{Ri} \Phi^* \rightarrow z_3 = 4, z_4 = 5$$



Unique solution from $\sim 400,000!$

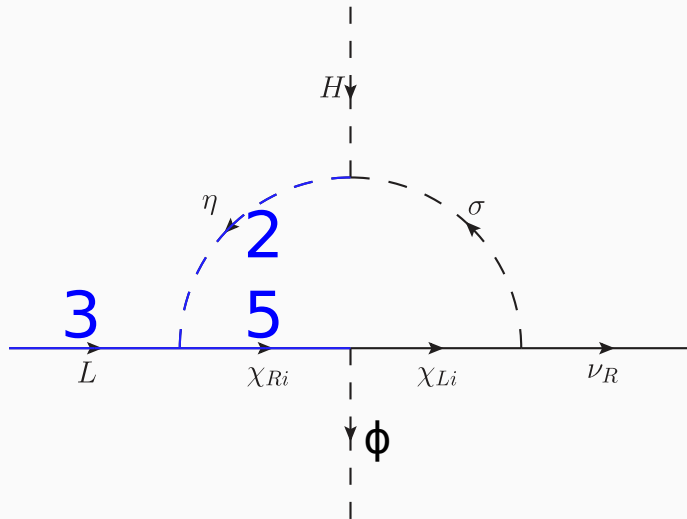
Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



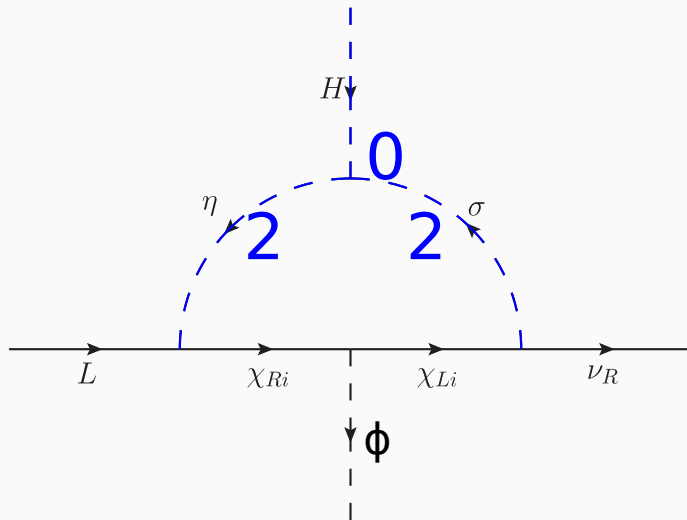
Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



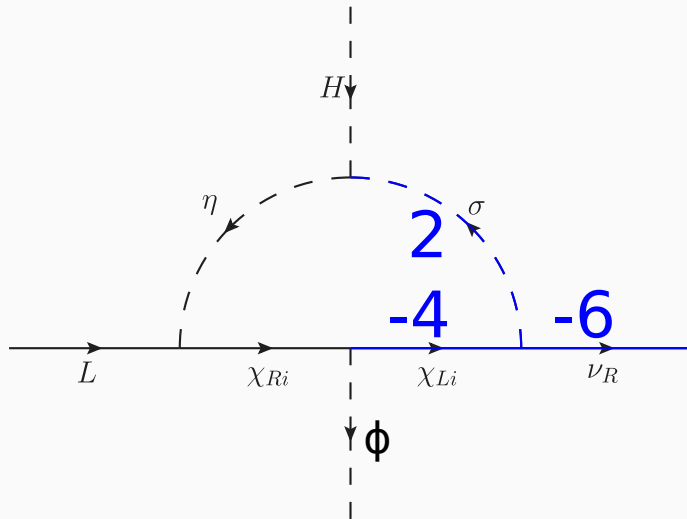
Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



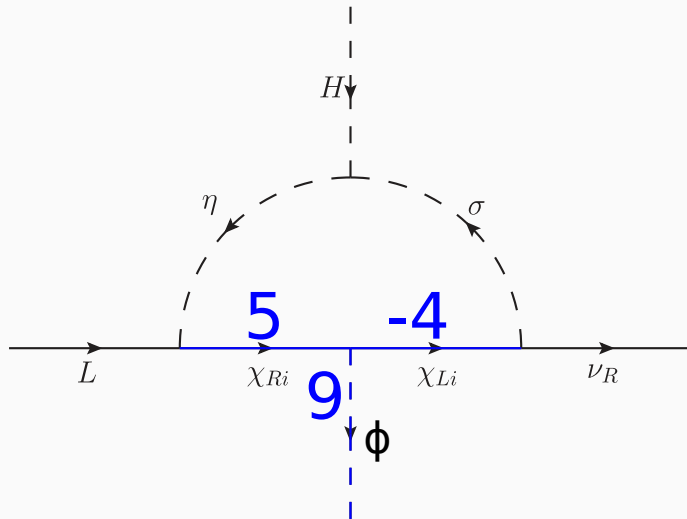
Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



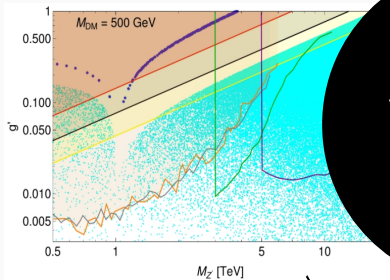
Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	1	$2/3$	$u = 0$
d_{Ri}	1	$-1/3$	$d = 0$
$(Q_i)^\dagger$	2	$-1/6$	$Q = 0$
$(L_i)^\dagger$	2	$1/2$	$L = 1$
e_R	1	-1	$e = -1$
$(L'_L)^\dagger$	2	$1/2$	$-x' = -2/3$
e'_R	1	-1	$x' = 2/3$
L''_R	2	$-1/2$	$x'' = -7/3$
$(e'_L)^\dagger$	1	1	$-x'' = 7/3$
$\nu_{R,i}$	1	0	2
χ_R	1	0	$-5/3$
$(\chi_L)^\dagger$	1	0	$-4/3$
H	2	$1/2$	0
Φ	1	0	-3
η	2	$1/2$	$2/3$
σ	1	0	$2/3$

Table 5: $i = 1, 2, 3$ normalized Lepton number charges with a global factor $-1/3$.

Electroweak baryogenesis

- Standard model (SM) $m_h \sim 125$ GeV. 😞
- Beyond the SM: Source of CP contains fields charged under SM
→ too large electric dipole moments 😞

- Inert SM-singlet complex scalar field which acquires vev with temperature to have strong electroweak phase transition 😊
- CP violation (CPV) triggered in dark sectors through SM gauge singlets
→ CPV Yukawa between SM-singlet complex scalar and SM-singlet quiral fermions 😊



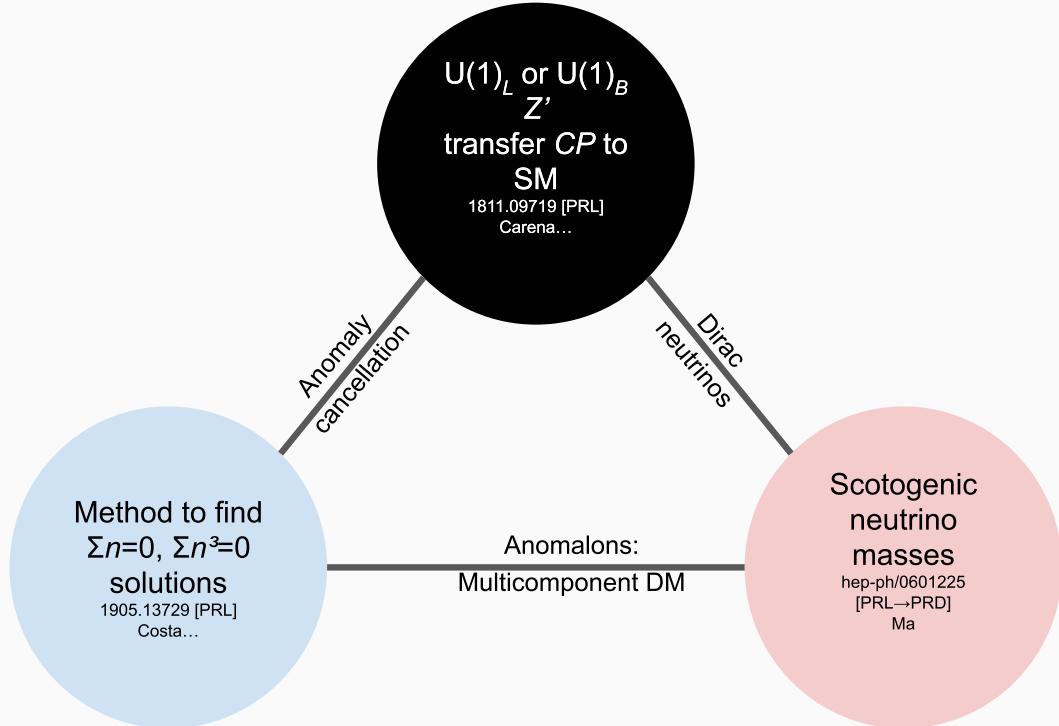
$U(1)_L$ or $U(1)_B$
 Z'
 transfer CP to
 SM

1811.09719 [PRL]
 Carena...

Anomaly
 cancellation

Dirac
 neutrinos

Anomalons:
 DM



- $L = 0$

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

$U(1)_B$ selection

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

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

- $L = 0$
- Effective neutrino mass: $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:
 $(L'_L)^\dagger L''_R \Phi^* \rightarrow x' = -1, x'' = 6$

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

- $L = 0$
- Effective neutrino mass: $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:
 $(L'_L)^\dagger L''_R \Phi^* \rightarrow x' = -1, x'' = 6$
- Dirac-fermionic DM: $(\chi_L)^\dagger \chi''_R \Phi^* \rightarrow z_3 = -3, z_4 = -2$

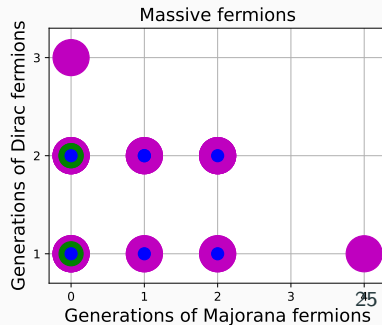
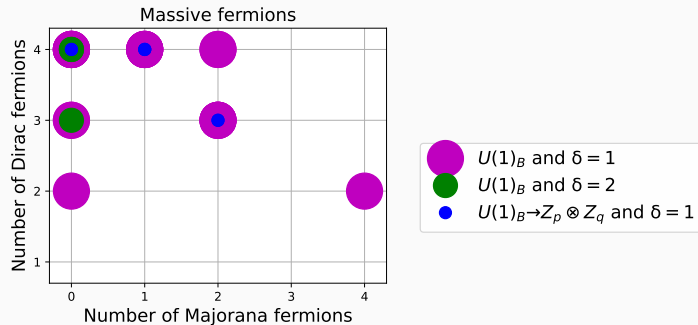
$$(5, 5, -3, -2, 1, -6)$$

$U(1)_B$ selection

- $L = 0$
- Effective neutrino mass: $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:
 $(L'_L)^\dagger L''_R \Phi^* \rightarrow x' = -1, x'' = 6$
- Dirac-fermionic DM: $(\chi_L)^\dagger \chi''_R \Phi^* \rightarrow z_3 = -3, z_4 = -2$

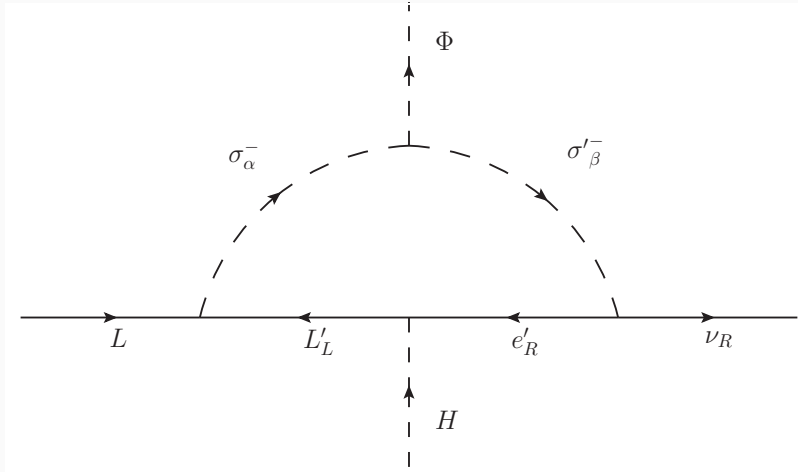
959 solutions from $\sim 400,000$

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

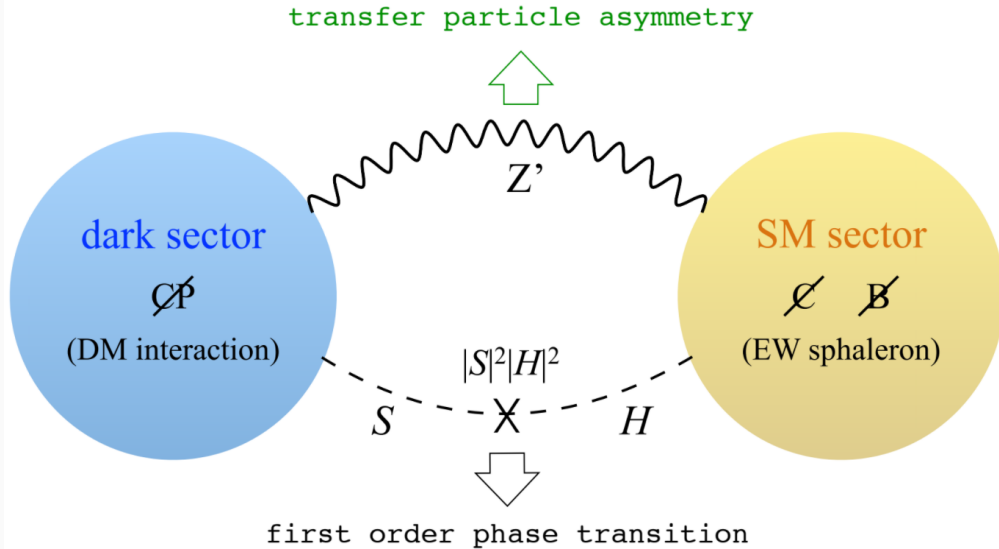


Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



Dark sector baryogenesis



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

- High scale fields: Φ , ($\langle\Phi\rangle \rightarrow L'_L, L''_R, e'_L, e''_R$: 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

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

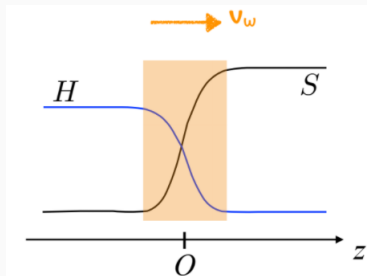
First-order phase transition: Effective potential ($T \neq 0$)

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

$$V_T(h, s) = \frac{\lambda_H v_c^4}{4} \left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H v_c^2}{m_{S,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (29)$$

where

$$c_h = \frac{1}{48} (9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}), \quad c_s = \frac{1}{12} (3\lambda_S + 2\lambda_{HS}). \quad (30)$$



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

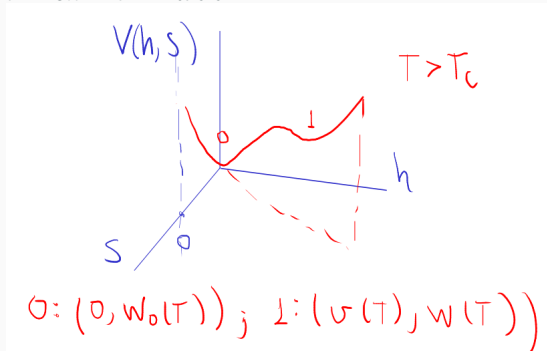
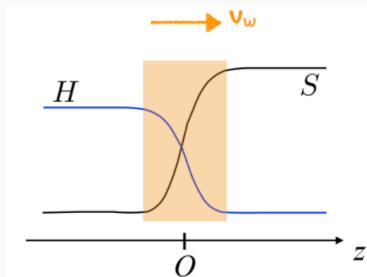
$h = H/\sqrt{2}$, $s = |S|$ with vevs: $v(T)$ and $w(T)$ such that $v(T_c) = w(T_c)$

$$V_T(h, s) = \frac{\lambda_H V_c^4}{4} \left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H V_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (29)$$

where

$$c_h = \frac{1}{48} (9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}), \quad c_s = \frac{1}{12} (3\lambda_S + 2\lambda_{HS}). \quad (30)$$

arXiv: Sec. 4.1 arXiv:1107.5451



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

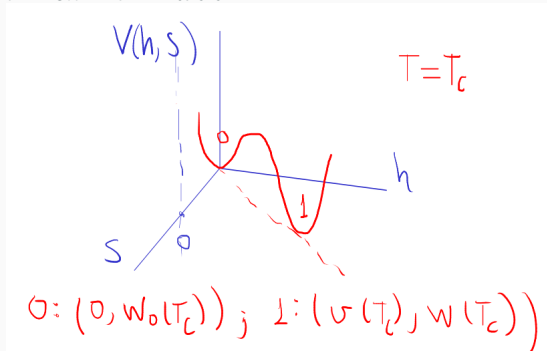
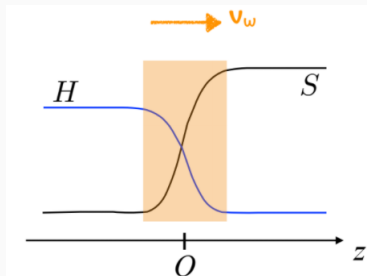
$h = H/\sqrt{2}$, $s = |S|$ with vevs: $v(T)$ and $w(T)$ such that $v(T_c) = w(T_c)$

$$V_T(h, s) = \frac{\lambda_H V_c^4}{4} \left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H V_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (29)$$

where

$$c_h = \frac{1}{48} (9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}), \quad c_s = \frac{1}{12} (3\lambda_S + 2\lambda_{HS}). \quad (30)$$

arXiv: Sec. 4.1 arXiv:1107.5451



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

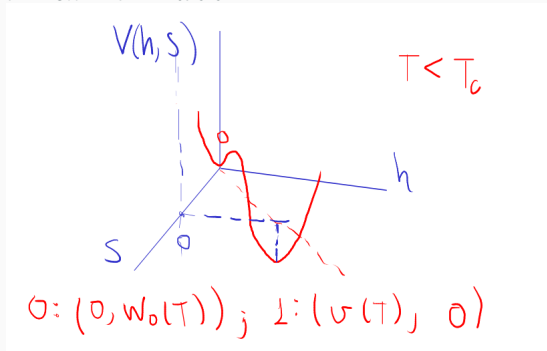
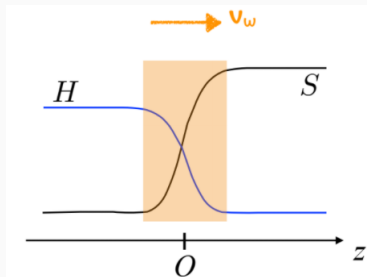
$h = H/\sqrt{2}$, $s = |S|$ with vevs: $v(T)$ and $w(T)$ such that $v(T_c) = w(T_c)$

$$V_T(h, s) = \frac{\lambda_H v_c^4}{4} \left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (29)$$

where

$$c_h = \frac{1}{48} (9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}), \quad c_s = \frac{1}{12} (3\lambda_S + 2\lambda_{HS}). \quad (30)$$

arXiv: Sec. 4.1 arXiv:1107.5451



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.

The *CP* violating phase, θ , from

$$M_\chi(z) = m_\chi(z) + |y| e^{i\theta} |S(z)|, \quad (31)$$

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 χ_L , which is related to the scattering rate Γ_L by

$$D_L = \frac{3x+2}{x^2+3x+2} \frac{1}{3\Gamma_L}, \quad x \equiv m_\chi/T \quad (32)$$

and

$$S_{\mathcal{CP}} = -\frac{\lambda}{2} \frac{v_w D_L}{\frac{3x+2}{x^2+3x+2} T} \frac{(1-x)e^{-x} + x^2 E_1(x)}{4m_\chi^2 K_2(x)} \frac{m_\chi w_0(T_n) \lambda \left(-2 + \cosh\left(\frac{2z}{L_w}\right) \right) \sin \theta}{L_w^3 \cosh^4\left(\frac{z}{L_w}\right)}, \quad (33)$$

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.

Transfer DM assymetry 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 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

$$0.82 \times 10^{-10} < \eta_B < 0.92 \times 10^{-10}. \quad (34)$$

- SARAH→SPheno→MicroMegas
- η_B calculation code
- Python notebook with the scan

arXiv:1810.08055

Ten Simple Rules for Reproducible Research in Jupyter Notebook Fernando Pérez, *et al*

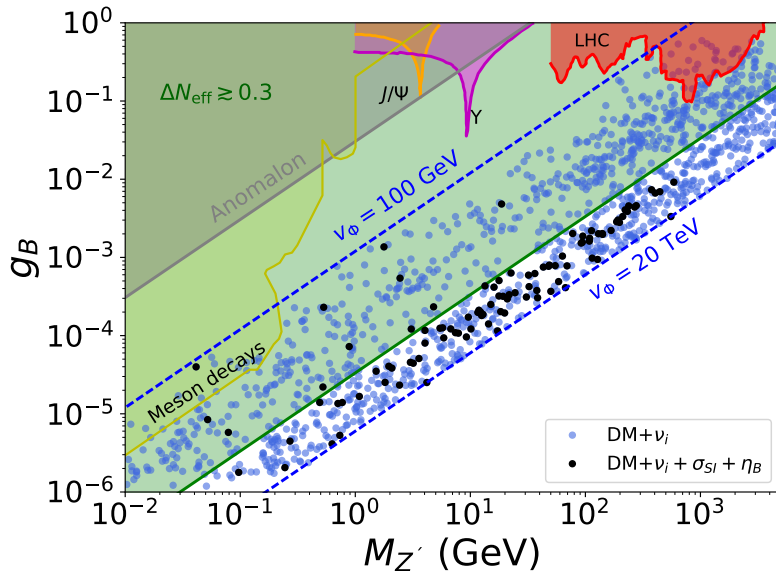
[...] In this paper, we address several questions about reproducibility [...] Combined with software repositories and open source licensing, notebooks are powerful tools for transparent, collaborative, reproducible, and reusable data analyses.

We vary the typical Dirac-fermion DM parameter space and for each point that satisfy neutrino oscillation data, relic density and DM direct detection constraints. For each point we ...

Parameter	Range
θ	$(-\pi/2, \pi/2)$
$w_0(T_n)/\text{GeV}$	100 – 500
T_n/GeV	100 – 200
L_w/GeV^{-1}	$1/T_n - 10/T_n$
v_w	0.05 – 0.5

Table 6: Scan ranges for the free parameters that are involved in the baryogenesis mechanism.

Black points: Dirac neutrinos with proper DM and baryon assymetry



A $U(1)_B$ is presented as an example of models where all new fermions required to cancel out the anomalies are used to solve phenomenological problems of the standard model (SM):

- EW-scale fermion vector-like doublets and iso-singlet charged singlets, in conjunction with right-handed neutrinos with repeated Abelian charges, participate in the generation of small neutrino masses through the Dirac-dark Zee mechanism
- The other SM-singlets are used to explain the dark matter in the universe, while their coupling to an inert singlet scalar is the source of the CP violation.

In the presence of a strong first-order electroweak phase transition, this “dark” CP violation allows for successful electroweak baryogenesis by using long range force mediated by a sufficiently light Z' which transfers the asymmetry from the Dark sector into the SM.