

Scotogenic seesaw and baryogenesis

with gauged Baryon number



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<http://gfif.udea.edu.co>



Focus on

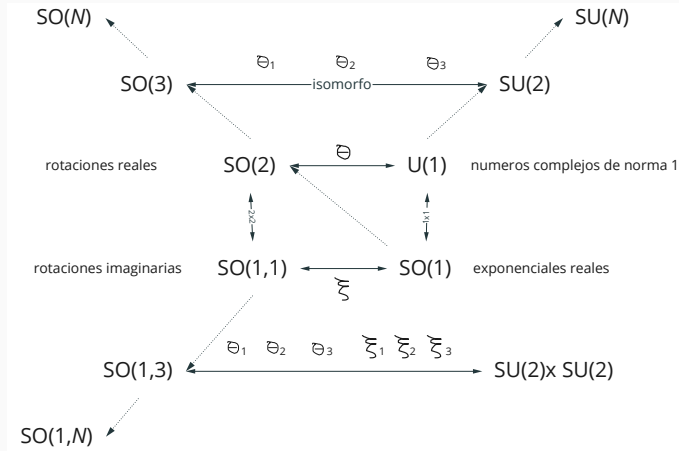
[arXiv:2205.05762](https://arxiv.org/abs/2205.05762)

In collaboration with

Andrés Rivera (UdeA), Walter Tangarife (Loyola University Chicago)

Model building

Lie groups



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

where θ^j are the parameters of the transformation and T_j are the generators.

Consider the 1×1

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

which generates an element of dilaton group, $SO(1)$, $R(\xi)$

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

which are just the group of the real exponentials. Such a number can be transformed as

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

that corresponds to a boost by e^{ξ} . We can define the invariant scalar product just as the division of real numbers, such that

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

Queremos obtener una representación 2×2 del álgebra

$$K = \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \rightarrow K^2 = -\mathbf{1}, \quad (6)$$

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

$$\Lambda = \exp(i\xi K) = \begin{pmatrix} \cosh \xi & \sinh \xi \\ \sinh \xi & \cosh \xi \end{pmatrix}, \quad (7)$$

La transformación de una coordenada temporaloide y otra espacialoide ($c = 1$)

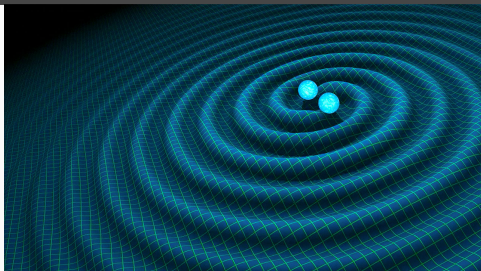
$$\begin{pmatrix} t \\ x \end{pmatrix} = \begin{pmatrix} x^0 \\ x^1 \end{pmatrix} \rightarrow \begin{pmatrix} x'^0 \\ x'^1 \end{pmatrix} \begin{pmatrix} \cosh \xi & \sinh \xi \\ \sinh \xi & \cosh \xi \end{pmatrix} \begin{pmatrix} x^0 \\ x^1 \end{pmatrix}$$

$$\cosh \xi = \gamma = \frac{1}{\sqrt{1 - v^2}}$$

Special: parameter ξ or v is constant, e.g, inertial system invariance: *Global* conservation of E and \mathbf{p} (still action at a distance!)

General: parameter $\xi(t, \mathbf{x})$ or $v(t, \mathbf{x})$ is constant, e.g, accelerated system invariance: *Local* conservation of E and \mathbf{p}

Inestability of binary particle systems



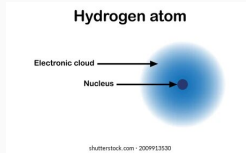
Gravitational wave discovery by LIGO



credits: science.org

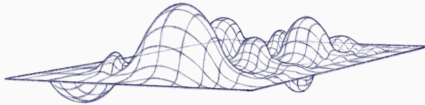
Noether's paradigm

U(1): From special θ to general $\theta(t, \mathbf{x})$



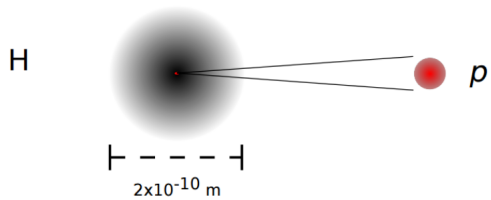
What is a *particle wavicle*? <https://www.quantamagazine.org/what-is-a-particle-20201112/>

Is a “Quantum Excitation of a Field”



Is a “Irreducible Representation of a Group”



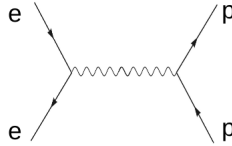
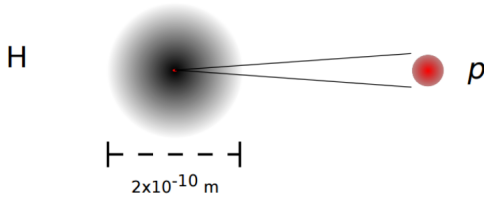


Interacción \rightarrow Fuerza = $\Delta p / \Delta t$

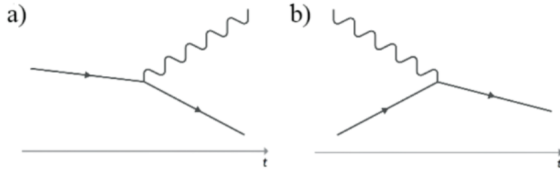
Introducción

Campos de materia \longrightarrow

Campos de radiación $\sim\sim\sim$



[doi:10.1088/1742-6596/1287/1/012045](https://doi.org/10.1088/1742-6596/1287/1/012045)



Emisión

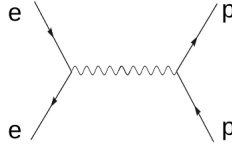
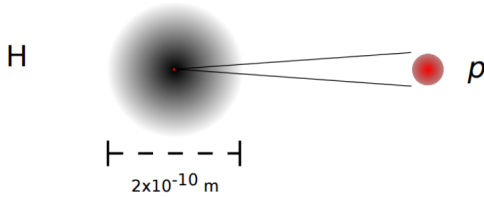
absorción

Interacción \rightarrow Fuerza = $\Delta p / \Delta t$

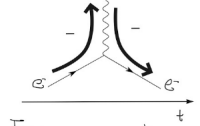
Introducción

Campos de materia \longrightarrow

Campos de radiación \sim



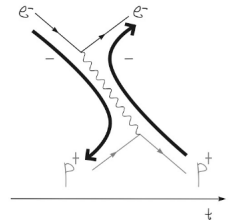
Single charge



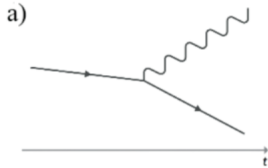
Fuerza $\frac{\Delta \vec{p}}{\Delta t} \neq 0$

$$(e^-)^* = e^+$$

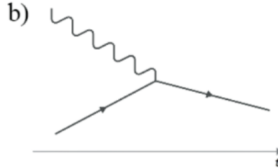
\sim fotón neutro



[doi:10.1088/1742-6596/1287/1/012045](https://doi.org/10.1088/1742-6596/1287/1/012045)



Emisión



absorción

$$e^- \rightarrow e^{-iEt}$$

$$e^+ \rightarrow e^{-iE(-t)}$$

Under a general Lorentz transformation we have.

$$A^\mu(x) \rightarrow A'^\mu(x) = \Lambda^\mu{}_\nu A^\nu(\Lambda^{-1}x). \quad (8)$$

A pure underscript 4-vector is

$$\partial_\mu = \frac{\partial}{\partial x^\mu} = \left(\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right) = (\partial_0, \nabla). \quad (9)$$

From

$$\frac{1}{x'^\mu} = (\Lambda^{-1})^\nu{}_\mu \frac{1}{x^\nu}, \quad (10)$$

the tranformation properties for a $\partial_\mu = \partial/\partial x^\mu$, are

$$\partial'_\mu = (\Lambda^{-1})^\nu{}_\mu \partial_\nu. \quad (11)$$

In this way, the invariant scalar product between the 4-vector field and the four-gradient is just

$$\partial_\mu A^\mu \rightarrow \partial'_\mu A'^\mu = \partial_\mu A^\mu . \quad (12)$$

Name	Symbol	SU(N)
scalar N -plet	Ψ	$U\Psi$
scalar anti- N -plet	Ψ^\dagger	$\Psi^\dagger U^\dagger$

Name	Symbol	Lorentz
Photon	A^μ	$\Lambda^\mu{}_\nu A^\nu$
4-gradient	∂_μ	$\partial_\nu (\Lambda^{-1})^\nu{}_\mu$

Table 1: Scalar products: $\Psi^\dagger\Psi$, $\partial_\mu A^\mu$, $A^\nu A_\nu$, $\partial_\mu\partial^\mu$

Name	Symbol	Lorentz	$U(1)$
e_L : electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta} \xi_\alpha$
$(e_L)^\dagger$: positron right	$(\xi_\alpha)^\dagger = \xi_{\dot{\alpha}}$	$\xi_{\dot{\beta}}^\dagger [S^\dagger]_{\dot{\alpha}}{}^{\dot{\beta}}$	$\xi_{\dot{\alpha}}^\dagger e^{-i\theta}$
e_R : electron right	$(\eta^\alpha)^\dagger = \eta^{\dagger\dot{\alpha}}$	$[(S^{-1})^\dagger]^{\dot{\alpha}}{}_{\dot{\beta}} \eta^{\dagger\dot{\beta}}$	$e^{i\theta} \eta^{\dagger\dot{\alpha}}$
$(e_R)^\dagger$: positron left	η^α	$\eta^\beta [S^{-1}]_\beta{}^\alpha$	$e^{-i\theta} \eta^\alpha$

Table 2: electron components

Scalar products

- ~~$U(1)$~~ Majorana scalars: $\xi^\alpha \xi_\alpha + \xi_{\dot{\alpha}}^\dagger \xi^{\dagger\dot{\alpha}}, \eta^\alpha \eta_\alpha + \eta_{\dot{\alpha}}^\dagger \eta^{\dagger\dot{\alpha}}$.
- Dirac scalar: $\eta^\alpha \xi_\alpha + \xi_{\dot{\alpha}}^\dagger \eta^{\dagger\dot{\alpha}}$.
- Scalar under subgroup $SL(2, C)$ but vector under $SO(1, 3)$: $S^\dagger \bar{\sigma}^\mu S = \Lambda^\mu{}_\nu \bar{\sigma}^\nu$

Name	Symbol	Lorentz	$U(1)$
e_L : electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta} \xi_\alpha$
$(e_L)^\dagger$: positron right	$(\xi_\alpha)^\dagger = \xi_{\dot{\alpha}}$	$\xi_{\dot{\beta}}^\dagger [S^\dagger]_{\dot{\alpha}}{}^{\dot{\beta}}$	$\xi_{\dot{\alpha}}^\dagger e^{-i\theta}$
e_R : electron right	$(\eta^\alpha)^\dagger = \eta^{\dagger\dot{\alpha}}$	$[(S^{-1})^\dagger]_{\dot{\alpha}}{}^{\dot{\beta}} \eta^{\dagger\dot{\beta}}$	$e^{i\theta} \eta^{\dagger\dot{\alpha}}$
$(e_R)^\dagger$: positron left	η^α	$\eta_{\dot{\beta}}^\beta [S^{-1}]_{\beta}{}^{\dot{\alpha}}$	$e^{-i\theta} \eta^\alpha$

Table 3: electron components

General theory: QED $\rightarrow D_\mu = i\partial_\mu - ieA_\mu$

$$\xi^\alpha \rightarrow \xi'^\alpha = e^{i\theta(x)} \xi^\alpha$$

$$\eta \rightarrow \eta' = e^{-i\theta(x)} \eta$$

como

$$\mathcal{L} = i\xi_{\dot{\alpha}}^\dagger \bar{\sigma}^{\mu\dot{\alpha}\alpha} \partial_\mu \xi_\alpha + i\eta^\alpha \sigma_{\alpha\dot{\alpha}}^\mu \partial_\mu \eta^{\dagger\dot{\alpha}} - m \left(\eta^\alpha \xi_\alpha + \xi_{\dot{\alpha}}^\dagger \eta^{\dagger\dot{\alpha}} \right)$$

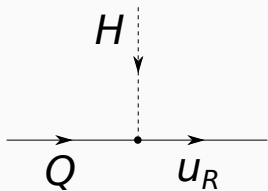
Field	Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Q	ξ_α^1	3	2	1/6
L	ξ_α^2	1	2	-1/2
$(u_R^-)^\dagger$	η_1^α	$\bar{\mathbf{3}}$	1	-2/3
$(d_R^-)^\dagger$	η_2^α	$\bar{\mathbf{3}}$	1	1/3
$(e_R^-)^\dagger$	η_3^α	1	1	1
H	-	1	2	1/2

Table 4: Standard Model fundamental fields

like for example,

$$\eta_1^\alpha \xi_\alpha^1 \cdot H = (u_R)^\dagger Q \cdot H, \quad (13)$$

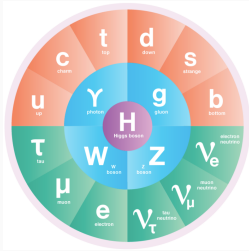
which can be represented by the “Kircchoff Law”:



$$Y_Q + Y_H = Y_u \rightarrow \frac{1}{6} + \frac{1}{2} = \frac{2}{3}$$

Dark sectors







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

Local $U(1)_\chi$

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

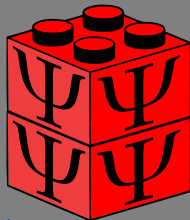
Anomalons: SM-singlet Dirac fermion

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



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

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



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

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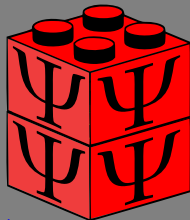
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multi-component
dark matter

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

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

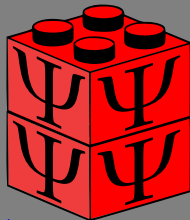
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multi-component
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Local $U(1)_\chi$

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

Anomalons: SM-singlet Dirac fermion

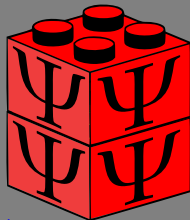
CP violation Yukawa y

LHC production:

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

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

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



multi-component
dark matter

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

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

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

$$\chi_1 \rightarrow \nu_{R1}, \dots, \chi_{N_\nu} \rightarrow \nu_{RN_\nu}, \quad 2 \leq N_\nu \leq 3, \quad (14)$$

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

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

$$\phi = -(\nu + L)/\delta, \quad (15)$$

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

$$u = -e - \frac{2}{3}L - \frac{1}{9}(x' - x''), \quad d = e + \frac{4}{3}L - \frac{1}{9}(x' - x''), \quad Q = -\frac{1}{3}L + \frac{1}{9}(x' - x''), \quad (16)$$

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

$$(e + L)(x' - x'') = 0. \quad (17)$$

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

$$e = -L, \quad (18)$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}(x' - x''). \quad (19)$$

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,

$$\sum_{\alpha=1}^N z_{\alpha} = 0, \quad \sum_{\alpha=1}^N z_{\alpha}^3 = 0, \quad (20)$$

where $N = N' + 5$ and

$$\begin{aligned} z_{N'+1} &= -x', & z_{N'+2} &= x'', \\ z_{N'+2+i} &= L, \quad i = 1, 2, 3 \end{aligned} \quad (21)$$

→

$$9Q = - \sum_{\alpha=N'+1}^{N'+5} z_{\alpha} = -x' + x'' + L + L + L, \quad (22)$$

$$Q = 0 \rightarrow \mathrm{U}(1)_L$$

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...](#)

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Keyword(s):

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

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Versions

Version 1

Sep 24, 2021

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

- $L = 0$

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

$U(1)_B$ 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: $(\chi_L)^\dagger \chi''_R \Phi^* \rightarrow z_3 = -3, z_4 = -2$

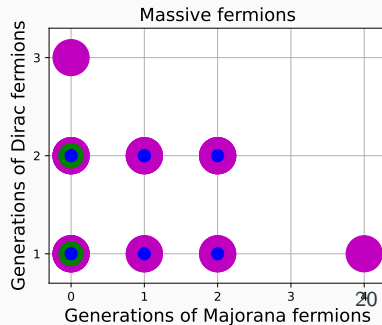
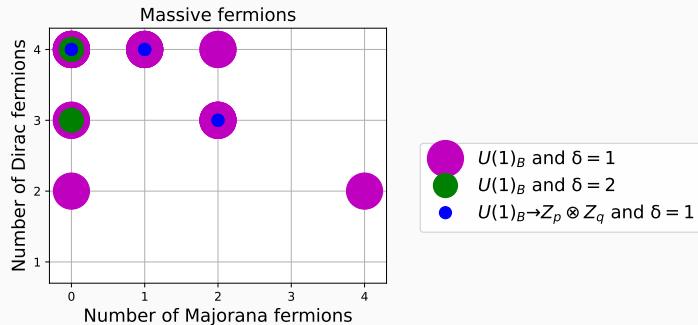
$$(5, 5, -3, -2, 1, -6)$$

$U(1)_B$ 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: $(\chi_L)^\dagger \chi''_R \Phi^* \rightarrow z_3 = -3, z_4 = -2$

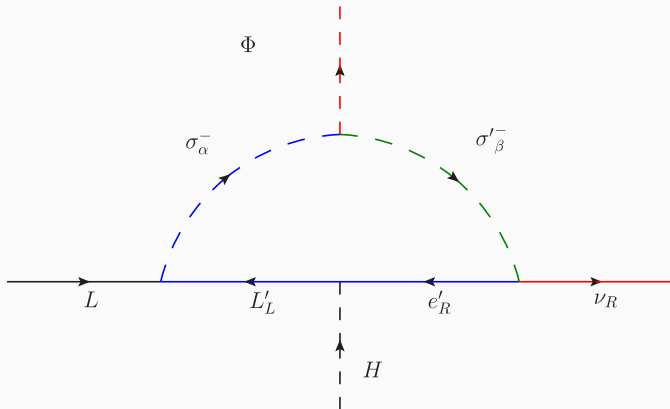
959 solutions from $\sim 400,000$

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



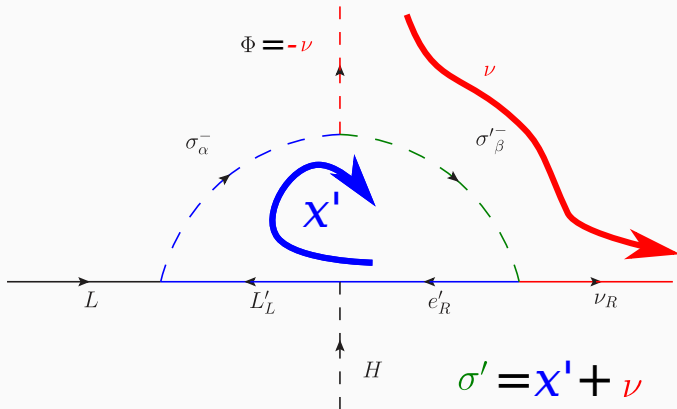
Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



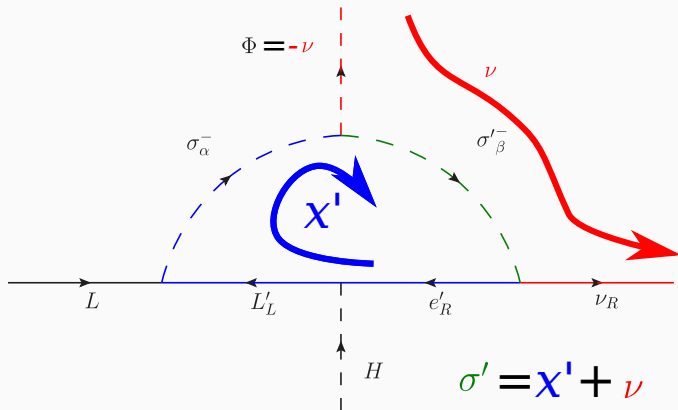
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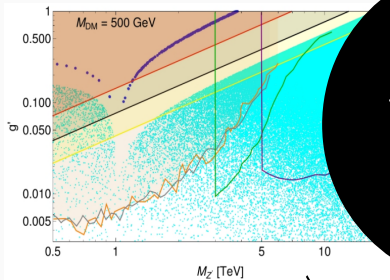


Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	1	2/3	$u = 1/3$
d_{Ri}	1	-1/3	$d = 1/3$
$(Q_i)^\dagger$	2	-1/6	$Q = -1/3$
$(L_i)^\dagger$	2	1/2	$L = 0$
e_R	1	-1	$e = 0$
$(L'_L)^\dagger$	2	1/2	$-x' = -3/5$
e'_R	1	-1	$x' = 3/5$
L''_R	2	-1/2	$x'' = 18/5$
$(e'_L)^\dagger$	1	1	$-x'' = -18/5$
$\nu_{R,1}$	1	0	-3
$\nu_{R,2}$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

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

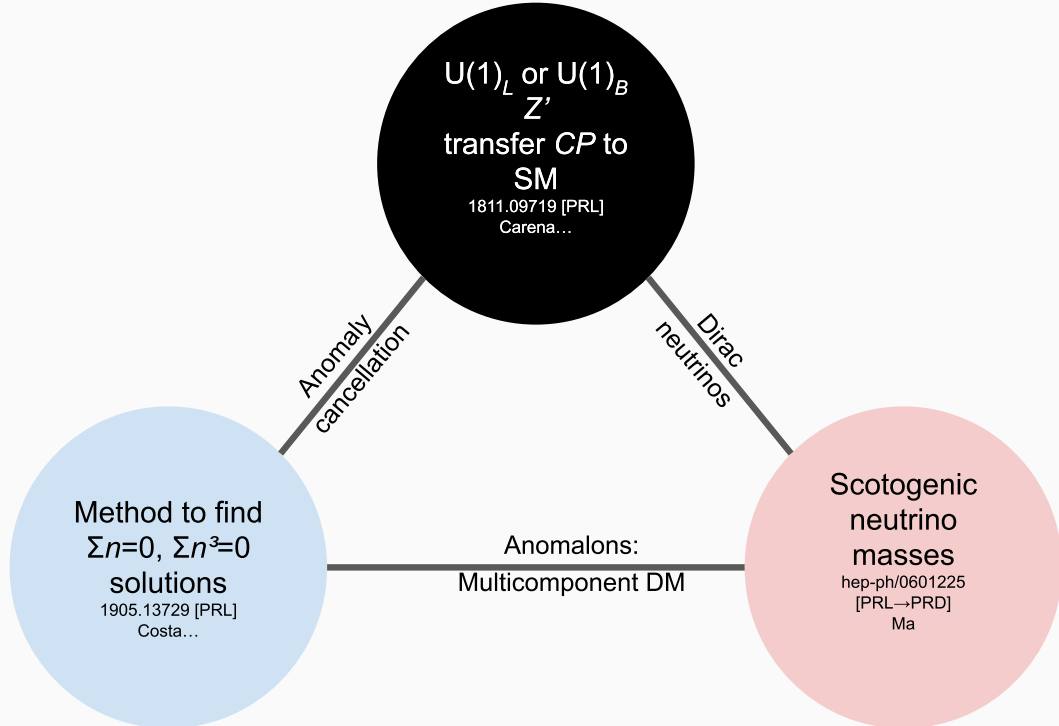
1811.09719 [PRL]
 Carena...

Anomaly
 cancellation

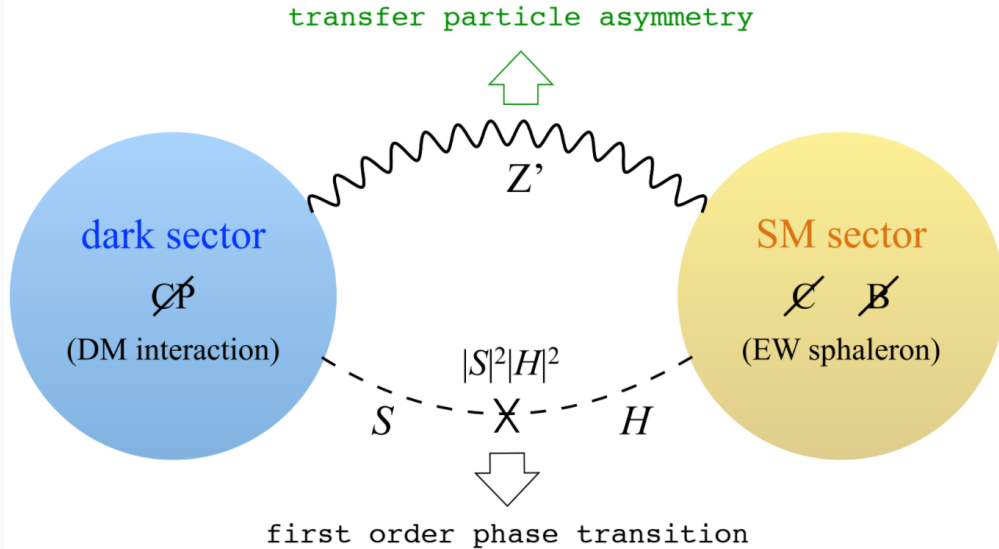
Dirac
 neutrinos

Anomalons:

DM



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

$$\mathcal{L}_{\text{anomalous}} \supset g' Z'_\mu [3\bar{\chi}_L \gamma^\mu \chi_L - 2\bar{\chi}_R \gamma^\mu \chi_R + \bar{Q}_i \gamma^\mu Q_i + \bar{q}_{Ri} \gamma^\mu q_{Ri}]$$

- Strong electroweak phase transition (EWPT) portal

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

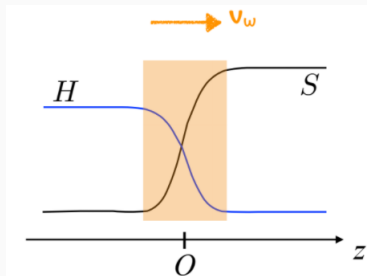
First-order phase transition: Effective potential ($T \neq 0$)

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

$$V_T(h, s) = \frac{\lambda_H v_c^4}{4} \left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H v_c^2}{m_{S,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (23)$$

where

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



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

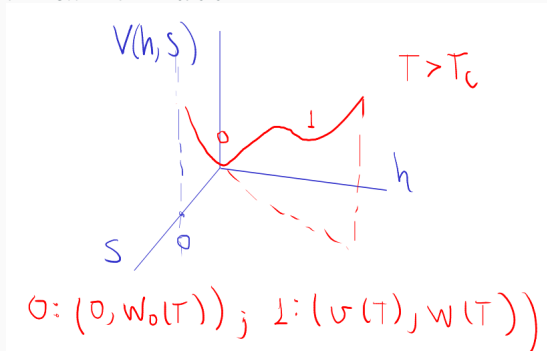
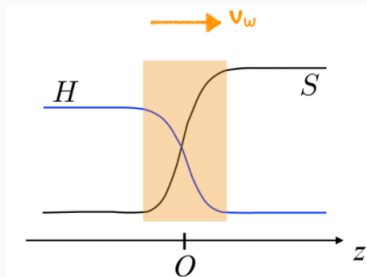
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arXiv: Sec. 4.1 arXiv:1107.5451



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

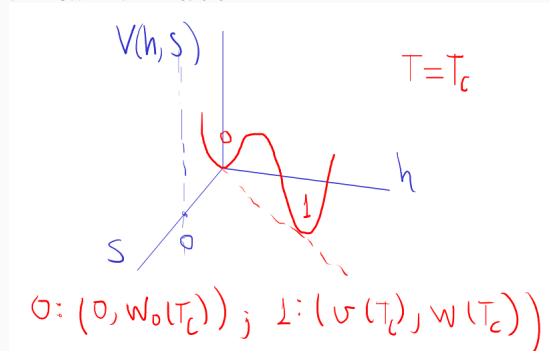
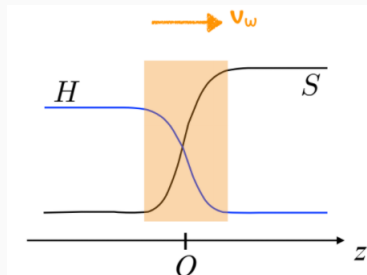
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arXiv: Sec. 4.1 arXiv:1107.5451



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

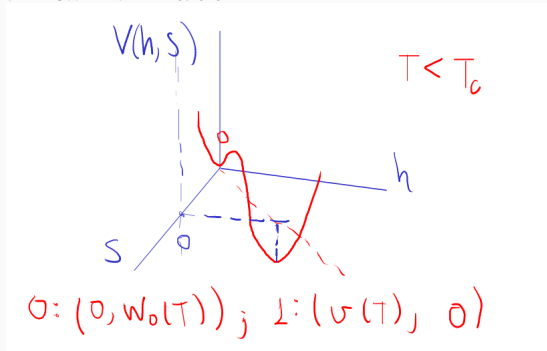
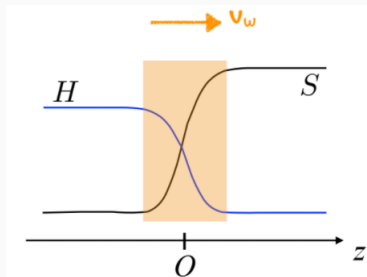
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arXiv: Sec. 4.1 arXiv:1107.5451



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.

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

$$D_L = \frac{3x+2}{x^2+3x+2} \frac{1}{3\Gamma_L}, \quad x \equiv m_\chi/T \quad (25)$$

and

$$S_{\mathcal{CP}} = -\frac{\lambda}{2} \frac{v_w D_L}{\frac{3x+2}{x^2+3x+2} T} \frac{(1-x)e^{-x} + x^2 E_1(x)}{4m_\chi^2 K_2(x)} \frac{m_\chi w_0(T_n) \lambda \left(-2 + \cosh\left(\frac{2z}{L_w}\right) \right) \sin \theta}{L_w^3 \cosh^4\left(\frac{z}{L_w}\right)}, \quad (26)$$

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 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,

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

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

$$0.82 \times 10^{-10} < \eta_B < 0.92 \times 10^{-10}. \quad (27)$$

- 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*

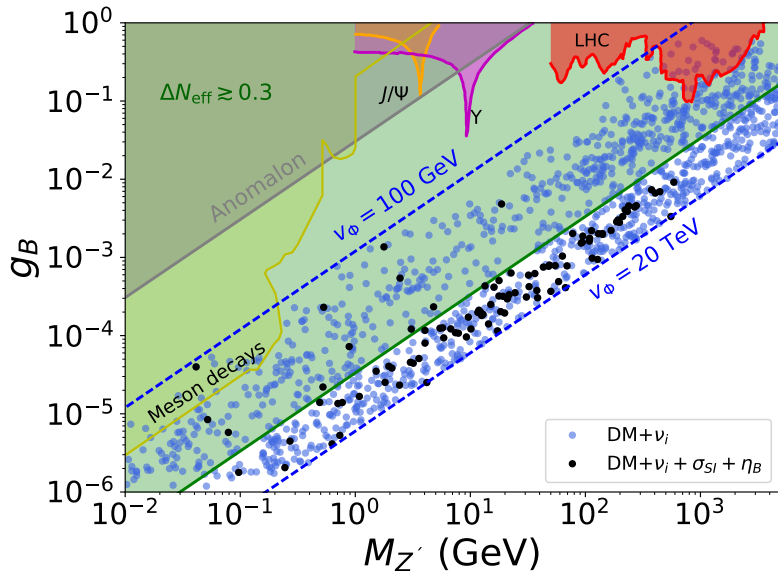
[...] In this paper, we address several questions about reproducibility [...] Combined with software repositories and open source licensing, notebooks are powerful tools for transparent, collaborative, reproducible, and reusable data analyses.

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.