Dirac dark matter, neutrino masses,

and dark baryogenesis

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XLII Encontro
Nacional de Física de
Partículas e campos

Focus on
arXiv:2205.05762
In collaboration with
Andrés Rivera (UdeA), Walter Tangarife (Loyola University Chicago)

Model building

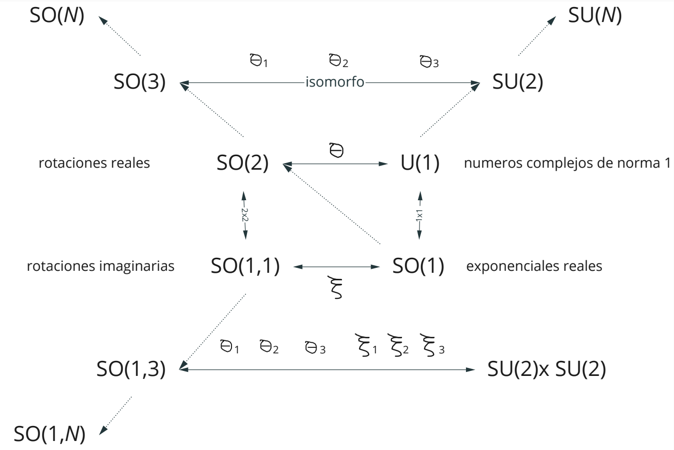
SO(3) **scalar product**

$$L = \frac{1}{2} m v^2 - V(|\boldsymbol{r}|) = \frac{1}{2} m \boldsymbol{v} \cdot \boldsymbol{v} - V(|\boldsymbol{r}|)$$

SO(3) **scalar product**

$$L = \frac{1}{2} m v^2 - V(|\boldsymbol{r}|) = \frac{1}{2} m \boldsymbol{v} \cdot \boldsymbol{v} - V(|\boldsymbol{r}|).$$

Lie groups



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

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

SO(1)

Consider the 1×1

$$K = -i\,, \tag{2}$$

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

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

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

$$x \to x' = \mathrm{e}^{\xi}\, x\,, \tag{4}$$

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

$$x \cdot y \to x' \cdot y' \equiv \frac{x'}{y'} = \frac{\mathrm{e}^{\xi}\, x}{\mathrm{e}^{\xi}\, y} = \frac{x}{y} = x \cdot y\,. \tag{5}$$

Queremos obtener una representación 2×2 del álgebra

$$K = \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \to K^2 = -\mathbf{1}\,, \tag{6}$$

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

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

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

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

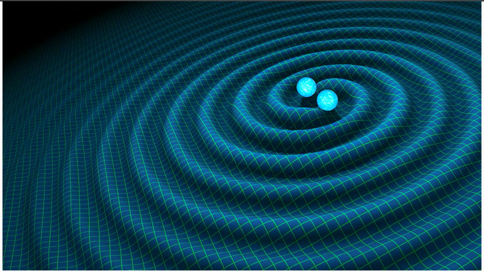
$$x'^\mu = \Lambda^\mu{}_\nu x^\nu\,, \qquad \mu = 0, 1\,.$$

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

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

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

Inestability of binary particle systems

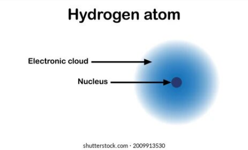


Gravitational wave discovery by LIGO

credits: science.org

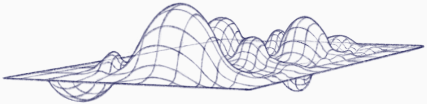
Noether's paradigm $\rightarrow$ Lagrangian formulation of classical field theory

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

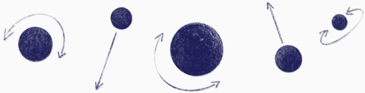


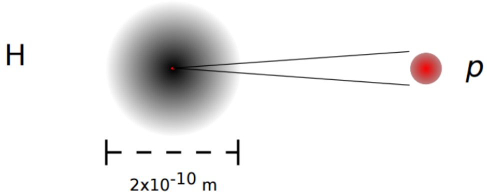
What is a ~~particle~~ *wavicle*? https://www.quantamagazine.org/what-is-a-particle-20201112/

Is a "Quantum Excitation of a Field"



Is a "Irreducible Representation of a Group"




H
p
2x10-10 m

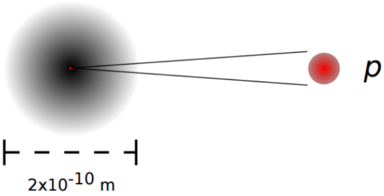
Interacción → Fuerza = $\Delta \mathbf{p}/\Delta t$

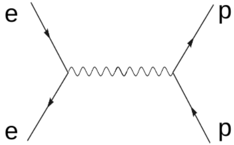
Introducción

campos de materia

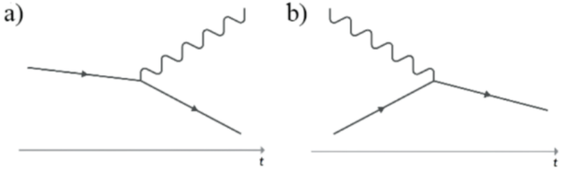
Campos de radiación

H





doi:10.1088/1742-6596/1287/1/012045



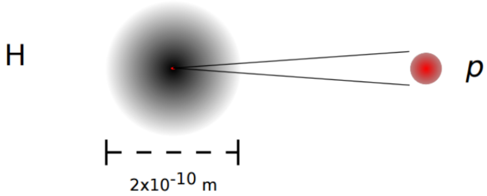
Emisión absorción

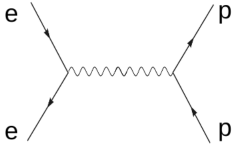
Interacción → Fuerza = Δ**p**/Δt

Introducción

Campos de materia

Campos de radiación





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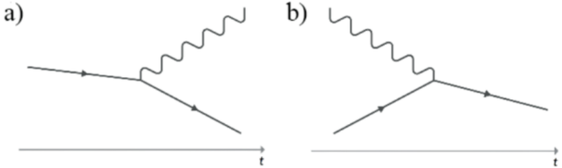
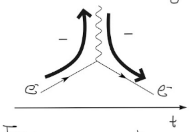


Emisión absorción

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

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

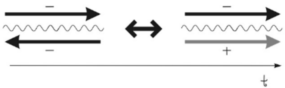
Single charge

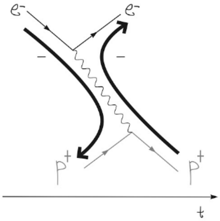


Fuerza $\frac{\Delta \vec{p}}{\Delta t} \neq 0$

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

fotón neutro





Under a general Lorentz transformation we have for a pure upperscript 4-vector

$$A^\mu(x) \to A'^\mu(x) = \Lambda^\mu{}_\nu A^\nu(\Lambda^{-1}x), \tag{8}$$

where $\mu = 0, 1, 2, 3$. A pure underscript 4-vector is

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

From $x'^\mu = \Lambda^\mu{}_\nu x^\nu$

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

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

$$\partial'_\mu = \partial_\nu \left(\Lambda^{-1}\right)^\nu{}_\mu\,. \tag{11}$$

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

$$\partial_\mu A^\mu \to \partial'_\mu A'^\mu = \partial_\mu A^\mu\,. \tag{12}$$

Photon: Representation of the Poincaré Groupwhich transform as a vector under $\mathrm{SO}(1,3)$

Name	Symbol	SO(1, 3)
Photon	A^μ	$\Lambda^\mu{}_\nu A^\nu$
4-gradient	∂_μ	$\partial_\nu \left(\Lambda^{-1}\right)^\nu{}_\mu$

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

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

Table 2: Scalar products: $\Psi^\dagger \Psi$

Photon: $\hat{\boldsymbol{p}} \oplus \mathrm{SO}(1,3) = i\partial^\mu \oplus \mathrm{SO}(1,3) \to i D^\mu \oplus \mathrm{SO}(1,3)$

Name	Symbol	SO(1, 3)
Photon	A^μ	$\Lambda^\mu{}_\nu A^\nu$
4-gradient	∂_μ	$\partial_\nu \left(\Lambda^{-1}\right)^\nu{}_\mu$

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

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

Table 2: Scalar products: $\Psi^\dagger \Psi$

Name	Symbol	SL(2, C)	$U(1)_Q$
e_L: electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta}\xi_\alpha$
$(e_L)^\dagger$: positron right	$(\xi_\alpha)^\dagger = \xi^\dagger_{\dot\alpha}$	$\xi^\dagger_{\dot\beta}\left[S^\dagger\right]^{\dot\beta}{}_{\dot\alpha}$	$\xi^\dagger_{\dot\alpha}e^{-i\theta}$
e_R: electron right	$(\eta^\alpha)^\dagger = \eta^{\dagger\,\dot\alpha}$	$\left[\left(S^{-1}\right)^\dagger\right]^{\dot\alpha}{}_{\dot\beta}\,\eta^{\dagger\,\dot\beta}$	$e^{i\theta}\eta^{\dagger\,\dot\alpha}$
$(e_R)^\dagger$: positron left	η^α	$\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$	$e^{-i\theta}\eta^\alpha$

Table 3: electron left: SL(2, C) $\times$ $U(1)$ inferior and positron left: SL(2, C) $\times$ $U(1)$ superior

Scalar products

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

$$\sigma^0 = \not{1}\,, \qquad \overline{\sigma}^\mu = (\sigma^0, -\boldsymbol{\sigma}), \qquad \sigma^\mu = (\sigma^0, \boldsymbol{\sigma}).$$

Name	Symbol	SL(2, C)	$U(1)_Q$
e_L: electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta}\xi_\alpha$
$(e_L)^\dagger$: positron right	$(\xi_\alpha)^\dagger = \xi^\dagger_{\dot\alpha}$	$\xi^\dagger_{\dot\beta}\left[S^\dagger\right]^{\dot\beta}{}_{\dot\alpha}$	$\xi^\dagger_{\dot\alpha} e^{-i\theta}$
e_R: electron right	$(\eta^\alpha)^\dagger = \eta^{\dagger\,\dot\alpha}$	$\left[\left(S^{-1}\right)^\dagger\right]^{\dot\alpha}{}_{\dot\beta}\eta^{\dagger\,\dot\beta}$	$e^{i\theta}\eta^{\dagger\,\dot\alpha}$
$(e_R)^\dagger$: positron left	η^α	$\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$	$e^{-i\theta}\eta^\alpha$

Table 4: electron left: SL(2, C) $\times$ $U(1)$ inferior and positron left: SL(2, C) $\times$ $U(1)$ superior

General theory: QED $\rightarrow D_\mu = i\partial_\mu - ieA_\mu$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$\xi^\alpha \rightarrow \xi'^\alpha = e^{i\theta(x)}\xi^\alpha \qquad \eta_\alpha \rightarrow \eta'_\alpha = e^{-i\theta(x)}\eta_\alpha$$

$$D_\mu\xi^\alpha \rightarrow (D_\mu\xi^\alpha)' = e^{i\theta(x)}D_\mu\xi^\alpha \qquad D_\mu\eta_\alpha \rightarrow (D_\mu\eta_\alpha)' = e^{-i\theta(x)}D_\mu\eta_\alpha$$

$$\mathcal{L} = i\xi^\dagger_{\dot\alpha}\bar\sigma^{\mu\,\dot\alpha\alpha}D_\mu\xi_\alpha + i\eta^\alpha\sigma^\mu_{\alpha\dot\alpha}D_\mu\eta^{\dagger\,\dot\alpha} - m\left(\eta^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\eta^{\dagger\,\dot\alpha}\right) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

Name	Symbol	SL(2, C)	$U(1)_Q$
e_L: electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta}\xi_\alpha$
$(e_L)^\dagger$: positron right	$(\xi_\alpha)^\dagger = \xi^\dagger_{\dot\alpha}$	$\xi^\dagger_{\dot\beta}\left[S^\dagger\right]^{\dot\beta}{}_{\dot\alpha}$	$\xi^\dagger_{\dot\alpha} e^{-i\theta}$
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$(e_R)^\dagger$: positron left	η^α	$\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$	$e^{-i\theta}\eta^\alpha$

Table 4: electron left: SL(2, C) × $U(1)$ inferior and positron left: SL(2, C) × $U(1)$ superior

General theory: QED → $D_\mu = i\partial_\mu - ieA_\mu$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.

$$\xi^\alpha \to \xi'^\alpha = e^{i\theta(x)}\xi^\alpha \qquad \eta_\alpha \to \eta'_\alpha = e^{-i\theta(x)}\eta_\alpha$$

$$D_\mu\xi^\alpha \to (D_\mu\xi^\alpha)' = e^{i\theta(x)}D_\mu\xi^\alpha \qquad D_\mu\eta_\alpha \to (D_\mu\eta_\alpha)' = e^{-i\theta(x)}D_\mu\eta_\alpha$$

$$\mathcal{L} = i\xi^\dagger_{\dot\alpha}\bar\sigma^{\mu\,\dot\alpha\alpha}D_\mu\xi_\alpha + i\eta^\alpha\sigma^\mu_{\alpha\dot\alpha}D_\mu\eta^{\dagger\,\dot\alpha} - m\left(\eta^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\eta^{\dagger\,\dot\alpha}\right) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$\mathcal{L} = i\bar\psi\gamma^\mu D_\mu\psi - m\bar\psi\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\,.$$

Dirac spinor

$$\psi = \begin{pmatrix} e_L \\ e_R \end{pmatrix}$$

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar\sigma^\mu & 0 \end{pmatrix}$$

$$\bar\psi = \psi^\dagger\gamma^0\,.$$

Name	Symbol	SL(2, C)	$U(1)_Q$
e_L: electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta}\xi_\alpha$
$(e_L)^\dagger$: positron right	$(\xi_\alpha)^\dagger = \xi^\dagger_{\dot\alpha}$	$\xi^\dagger_{\dot\beta}\left[S^\dagger\right]^{\dot\beta}{}_{\dot\alpha}$	$\xi^\dagger_{\dot\alpha}e^{-i\theta}$
e_R: electron right	$(\eta^\alpha)^\dagger = \eta^{\dagger\,\dot\alpha}$	$\left[\left(S^{-1}\right)^\dagger\right]^{\dot\alpha}{}_{\dot\beta}\eta^{\dagger\,\dot\beta}$	$e^{i\theta}\eta^{\dagger\,\dot\alpha}$
$(e_R)^\dagger$: positron left	η^α	$\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$	$e^{-i\theta}\eta^\alpha$

Table 4: electron left: SL(2, C) × $U(1)$ inferior and positron left: SL(2, C) × $U(1)$ superior

General theory: QED $\to D_\mu = i\partial_\mu - ieA_\mu$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

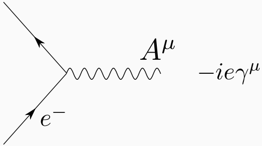
$$\xi^\alpha \to \xi'^\alpha = e^{i\theta(x)}\xi^\alpha \qquad \eta_\alpha \to \eta'_\alpha = e^{-i\theta(x)}\eta_\alpha$$

$$D_\mu\xi^\alpha \to (D_\mu\xi^\alpha)' = e^{i\theta(x)}D_\mu\xi^\alpha \qquad D_\mu\eta_\alpha \to (D_\mu\eta_\alpha)' = e^{-i\theta(x)}D_\mu\eta_\alpha$$

$$\mathcal{L} = i\xi^\dagger_{\dot\alpha}\bar\sigma^{\mu\,\dot\alpha\alpha}D_\mu\xi_\alpha + i\eta^\alpha\sigma^\mu_{\alpha\dot\alpha}D_\mu\eta^{\dagger\,\dot\alpha} - m\left(\eta^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\eta^{\dagger\,\dot\alpha}\right) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$\mathcal{L} = i\bar\psi\gamma^\mu D_\mu\psi - m\bar\psi\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\,. \to e\bar\psi\gamma^\mu\psi\,A_\mu$$

Dirac spinor



Name	Symbol	SL(2, C)	$U(1)_Q$
e_L: electron left	ξ_α	$S_\alpha{}^\beta \xi_\beta$	$e^{i\theta}\xi_\alpha$
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e_R: electron right	$(\eta^\alpha)^\dagger = \eta^{\dagger\,\dot\alpha}$	$\left[\left(S^{-1}\right)^\dagger\right]^{\dot\alpha}{}_{\dot\beta}\eta^{\dagger\,\dot\beta}$	$e^{i\theta}\eta^{\dagger\,\dot\alpha}$
$(e_R)^\dagger$: positron left	η^α	$\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$	$e^{-i\theta}\eta^\alpha$

Table 4: electron left: SL(2, C) $\times$ $U(1)$ inferior and positron left: SL(2, C) $\times$ $U(1)$ superior

General theory: QED $\to D_\mu = i\partial_\mu - ieA_\mu$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$\xi^\alpha \to \xi'^\alpha = e^{i\theta(x)}\xi^\alpha \qquad \eta_\alpha \to \eta'_\alpha = e^{-i\theta(x)}\eta_\alpha$$

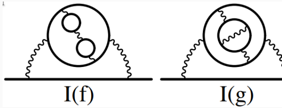
$$D_\mu\xi^\alpha \to (D_\mu\xi^\alpha)' = e^{i\theta(x)}D_\mu\xi^\alpha \qquad D_\mu\eta_\alpha \to (D_\mu\eta_\alpha)' = e^{-i\theta(x)}D_\mu\eta_\alpha$$

$$\mathcal{L} = i\xi^\dagger_{\dot\alpha}\bar\sigma^{\mu\,\dot\alpha\alpha}D_\mu\xi_\alpha + i\eta^\alpha\sigma^\mu_{\alpha\dot\alpha}D_\mu\eta^{\dagger\,\dot\alpha} - m\left(\eta^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\eta^{\dagger\,\dot\alpha}\right) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

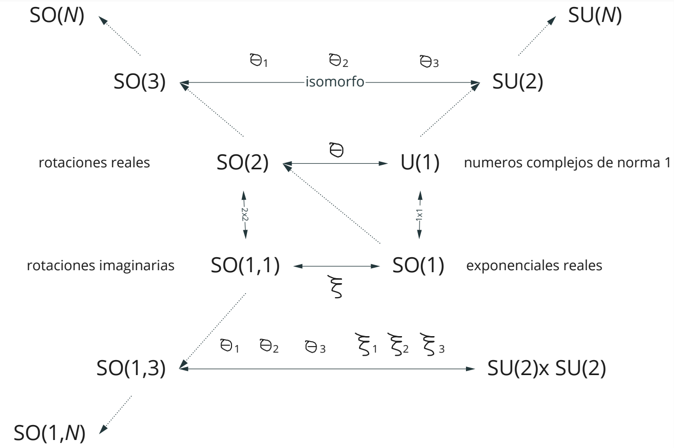
$$\mathcal{L} = i\bar\psi\gamma^\mu D_\mu\psi - m\bar\psi\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\,. \to e\bar\psi\gamma^\mu\psi\,A_\mu$$

Dirac spinor

non-bare



Lie groups



$$U = \exp\left(i \sum_j T_j \theta^j\right), \tag{13}$$

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

Consider the 1×1

$$K = -i\,, \tag{14}$$

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

$$\lambda(\xi) = \mathrm{e}^{\xi}\,, \tag{15}$$

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

$$x \to x' = \mathrm{e}^{\xi}\, x\,, \tag{16}$$

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

$$x \cdot y \to x' \cdot y' \equiv \frac{x'}{y'} = \frac{\mathrm{e}^{\xi}\, x}{\mathrm{e}^{\xi}\, y} = \frac{x}{y} = x \cdot y\,. \tag{17}$$

Under a general Lorentz transformation we have.

$$A^\mu(x) \to A'^\mu(x) = \Lambda^\mu{}_\nu A^\nu(\Lambda^{-1}x). \tag{18}$$

A pure underscript 4-vector is

$$\partial_\mu = \frac{\partial}{\partial x^\mu} = \left(\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) = (\partial_0, \mathbf{\nabla}). \tag{19}$$

From

$$\frac{1}{x'^\mu} = \left(\Lambda^{-1}\right)^\nu{}_\mu \frac{1}{x^\nu}\,, \tag{20}$$

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

$$\partial'_\mu = \left(\Lambda^{-1}\right)^\nu{}_\mu \partial_\nu\,. \tag{21}$$

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

$$\partial_\mu A^\mu \to \partial'_\mu A'^\mu = \partial_\mu A^\mu \,. \tag{22}$$

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

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

Table 5: Scalar products: $\Psi^\dagger\Psi$, $\partial_\mu A^\mu\,, \quad A^\nu A_\nu\,, \quad \partial_\mu\partial^\mu$

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	$(\xi_\alpha)^\dagger = \xi^\dagger_{\dot\alpha}$	$\xi^\dagger_{\dot\beta}\left[S^\dagger\right]^{\dot\beta}{}_{\dot\alpha}$	$\xi^\dagger_{\dot\alpha} e^{-i\theta}$
e_R: electron right	$(\eta^\alpha)^\dagger = \eta^{\dagger\,\dot\alpha}$	$\left[\left(S^{-1}\right)^\dagger\right]^{\dot\alpha}{}_{\dot\beta}\eta^{\dagger\,\dot\beta}$	$e^{i\theta}\eta^{\dagger\,\dot\alpha}$
$(e_R)^\dagger$: positron left	η^α	$\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$	$e^{-i\theta}\eta^\alpha$

Table 6: electron components

Scalar products

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

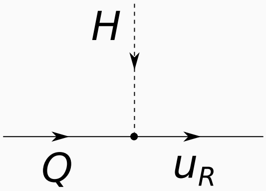
Field	Lorentz	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Q	ξ^1_α	$\mathbf{3}$	$\mathbf{2}$	$1/6$
L	ξ^2_α	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$\left(u^-_R\right)^\dagger$	η^α_1	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
$\left(d^-_R\right)^\dagger$	η^α_2	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$
$\left(e^-_R\right)^\dagger$	η^α_3	$\mathbf{1}$	$\mathbf{1}$	1
H	-	$\mathbf{1}$	$\mathbf{2}$	$1/2$

Table 7: Standard Model fundamental fields

like for example,

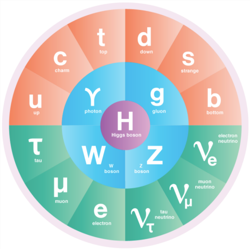
$$\eta_1^{\alpha}\xi_{\alpha}^1 \cdot H = (u_R)^\dagger\, Q \cdot H\,, \tag{23}$$

which can be represented by the “Kircchoff Law”:



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

Dark sectors


t
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d
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c
charm
s
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u
up
b
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γ
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g
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H
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Z
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μ
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muon neutrino
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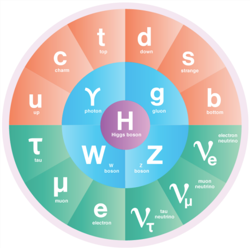
electron
ν_τ
tau neutrino


t
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H
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W
boson
Z
Z
boson
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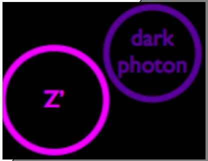
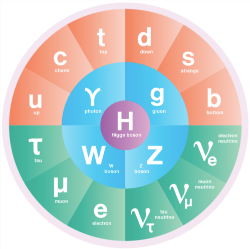

Z'
dark
photon



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

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

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

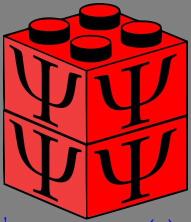
Anomalons: SM-singlet Dirac fermion

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

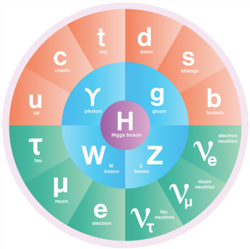
LHC production:

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

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



$$\overline{\Psi}\Psi = \chi_1\chi_2 + \chi_1^{\dagger}\chi_2^{\dagger} \to \chi_\alpha\chi_\beta\Phi^{(*)}, \qquad \alpha = 1, \ldots N' \to N' > 4$$



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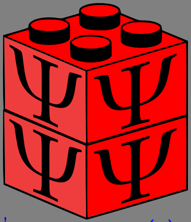

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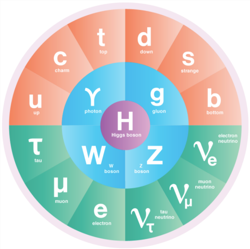

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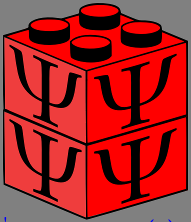
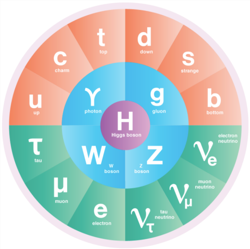


multi-component

dark matter

$$\overline{\Psi}\Psi = \chi_1\chi_2 + \chi_1^\dagger\chi_2^\dagger \to \chi_\alpha\chi_\beta\Phi^{(*)}\,, \qquad \alpha = 1,\ldots N' \to N' > 4$$



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

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$$-y\left(\chi_1 \chi_2 S + \text{h.c}\right)$$

Anomalons: SM-singlet Dirac fermion

CP violation Yukawa y

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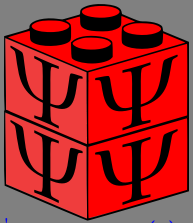

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Standard model extended with $\mathrm{U}(1)_{\mathcal{X}=L \text{ or } B}$ gauge symmetry

Fields	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{\mathcal{X}=B \text{ or } L}$
$Q_i^\dagger$	$\mathbf{2}$	$-1/6$	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	$\mathbf{2}$	$1/2$	$h=0$
χ_α	$\mathbf{1}$	0	z_α
$(L'_L)^\dagger$	$\mathbf{2}$	$1/2$	$-x'$
L''_R	$\mathbf{2}$	$-1/2$	x''
e'_R	$\mathbf{1}$	-1	x'
$(e''_L)^\dagger$	$\mathbf{1}$	1	$-x''$
Φ	$\mathbf{1}$	0	ϕ
S	$\mathbf{1}$	0	s

Table 8: A minimal set of new fermion content: $L=e=0$ for $\mathcal{X}=B$. Or $Q=u=d=0$ for $\mathcal{X}=L$. $i=1,2,3$, $\alpha=1,2,\ldots,N'$

Effective Dirac neutrino mass operator

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3\,, \tag{24}$$

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

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

$$\phi = -(\nu + L)/\delta\,, \tag{25}$$

Anomaly cancellation I

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

$$u = -\,e - \frac{2}{3}L - \frac{1}{9}\left(x' - x''\right)\,, \quad d = e + \frac{4}{3}L - \frac{1}{9}\left(x' - x''\right)\,, \quad Q = -\,\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,, \tag{26}$$

while the $[\mathrm{U}(1)_X]^2\,\mathrm{U}(1)_Y$ anomaly condition reduces to

$$(e+L)(x'-x'') = 0\,. \tag{27}$$

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

$$e = -L\,, \tag{28}$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,. \tag{29}$$

If $B = 0 \to \mathrm{U}(1)_L$

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,

$$\sum_{\alpha=1}^{N} z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} z_\alpha^3 = 0\,, \tag{30}$$

where $N = N' + 5$ and

$$z_{N'+1} = -x'\,, \qquad z_{N'+2} = x''\,,$$
$$z_{N'+2+i} = L\,, \quad i = 1,2,3 \tag{31}$$

$\rightarrow$

$$9Q = -\sum_{\alpha=N'+1}^{N'+5} z_\alpha = -x' + x'' + L + L + L\,, \tag{32}$$

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

https://doi.org/10.5281/zenodo.5526707

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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')
>>> 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:
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

Keyword(s):
Anomaly free Diophantine equations Abelian symmetry Gauge Symmetry

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Versions

Version 1 Sep 24, 2021
10.5281/zenodo.5526707

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

- $L = 0$

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

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

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

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

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

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

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

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

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

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

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

- $L = 0$
- Effective neutrino mass: $\phi = -\nu = -5$
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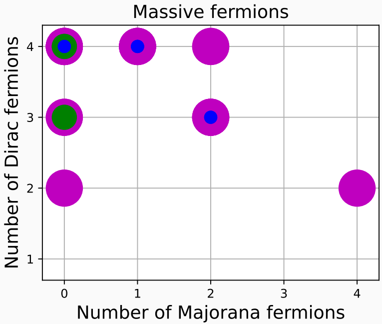
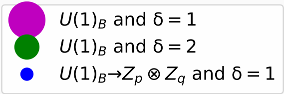
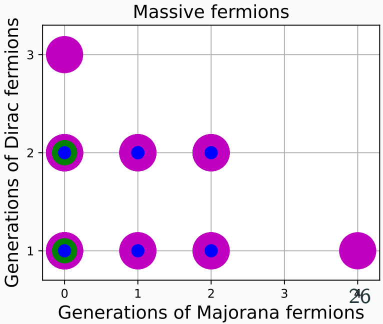
$$(5, 5, -3, -2, 1, -6)$$

959 solutions from $\sim 400,000$

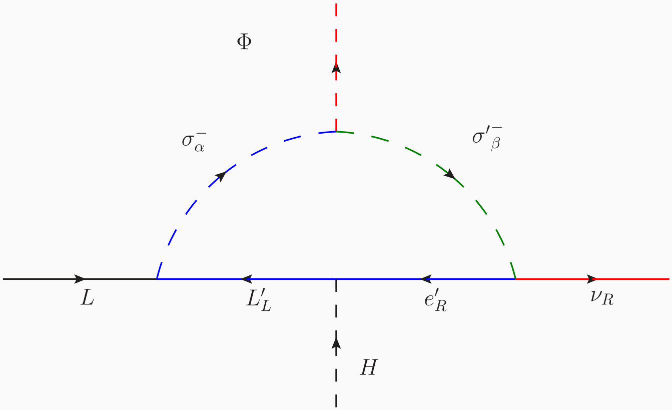






Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



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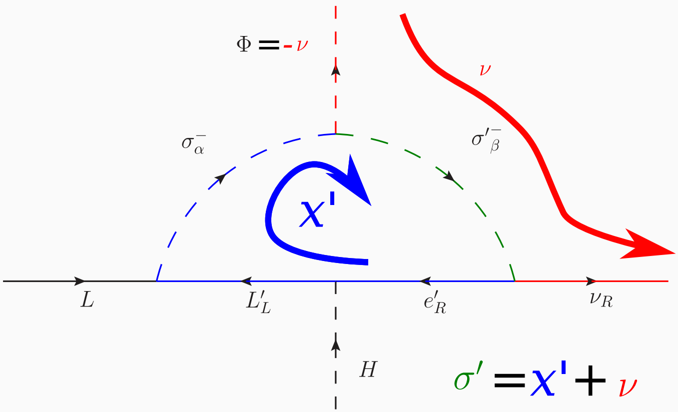

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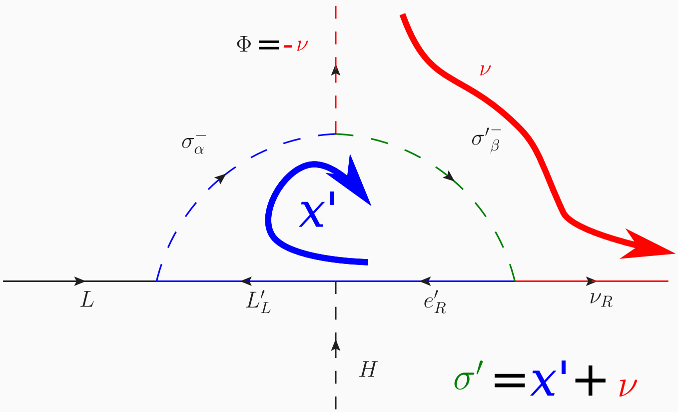


Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	**1**	$2/3$	$u = 1/3$
d_{Ri}	**1**	$-1/3$	$d = 1/3$
$(Q_i)^\dagger$	**2**	$-1/6$	$Q = -1/3$
$(L_i)^\dagger$	**2**	$1/2$	$L = 0$
e_R	**1**	-1	$e = 0$
$(L'_L)^\dagger$	**2**	$1/2$	$-x' = -3/5$
e'_R	**1**	-1	$x' = 3/5$
L''_R	**2**	$-1/2$	$x'' = 18/5$
$(e''_L)^\dagger$	**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	$-12/5$

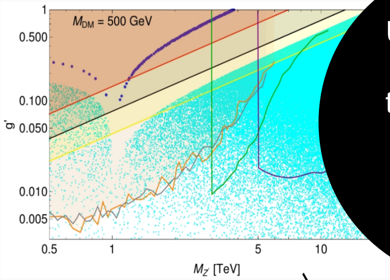
Electroweak baryogenesis

Problems

- Standard model (SM) $m_h \sim 40$ GeV. 😞
- Beyond the SM: Source of CP contains fields charged under SM
  $\rightarrow$ too large electric dipole moments 😩

Dark sectors

- 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
  $\rightarrow$ CPV Yukawa between SM-singlet complex scalar and SM-singlet quiral fermions 😀



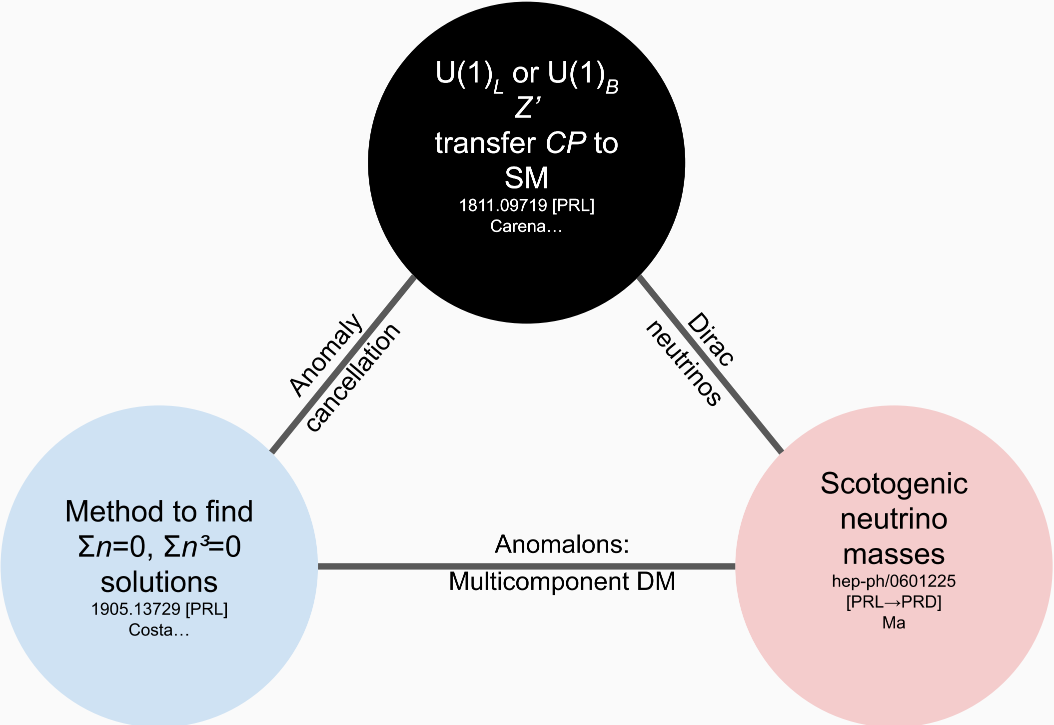
U(1)$_L$ or U(1)$_B$
Z'
transfer *CP* to SM
1811.09719 [PRL]
Carena…

Anomaly cancellation

Dirac neutrinos

Anomalons:

DM



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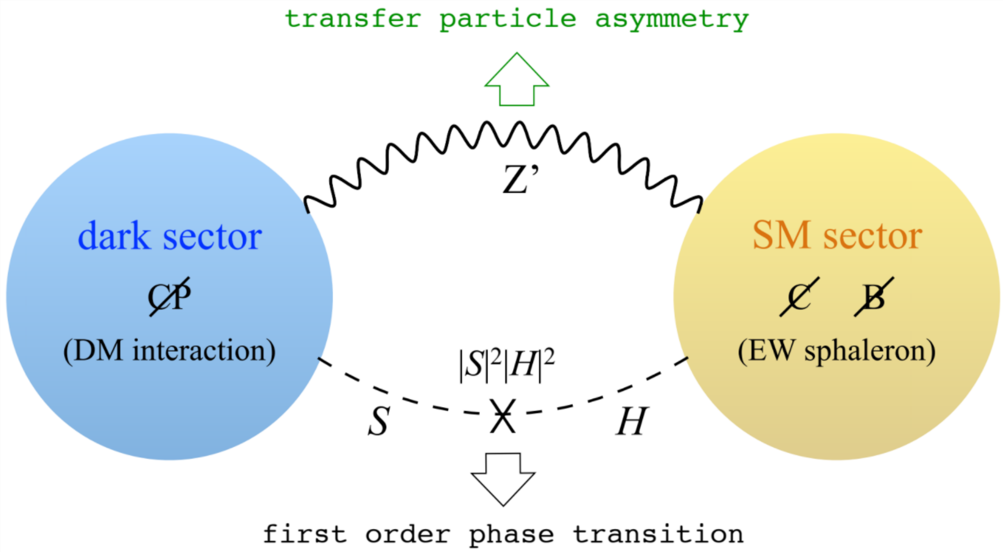
transfer *CP* to SM
1811.09719 [PRL]
Carena…
Anomaly cancellation
Dirac neutrinos
Method to find $\Sigma n=0$, $\Sigma n^3=0$ solutions
1905.13729 [PRL]
Costa…
Anomalons:
Multicomponent DM
Scotogenic neutrino masses
hep-ph/0601225
[PRL→PRD]
Ma

Dark sector baryogenesis



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

Baryogenesis

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

- High scale fields: Φ , $(\langle\Phi\rangle \to L'_L, L''_R, e'_L, e''_R$: EW-scale vector-like anomalons)
- Electroweak scale (EW) fields: $\boxed{Z'_\mu, S, \chi_L, \chi_R}$
- *CP*-violation

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

- *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

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

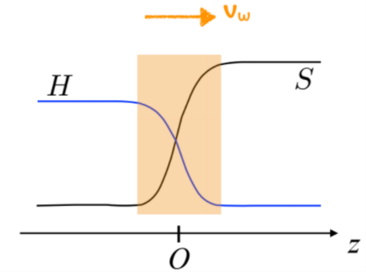
First-order phase transition: Effective potential ($T \neq 0$)

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

$$V_T(h,s) = \frac{\lambda_H v_c^4}{4}\left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1\right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2)\,, \qquad (33)$$

where

$$c_h = \frac{1}{48}\left(9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}\right)\,, \quad c_s = \frac{1}{12}\left(3\lambda_S + 2\lambda_{HS}\right)\,. \qquad (34)$$



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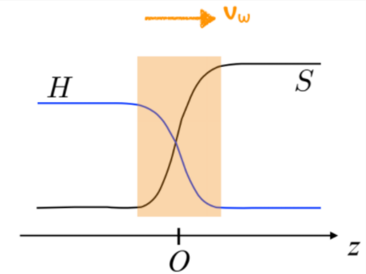
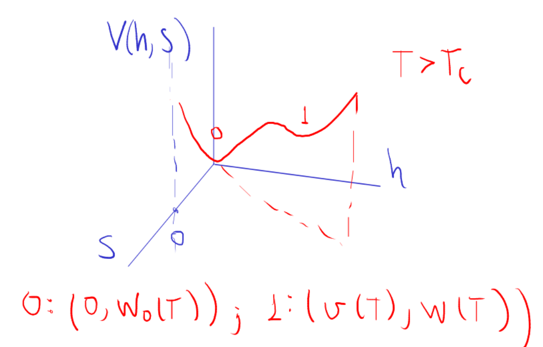


arXiv: Sec. 4.1 arXiv:1107.5451



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

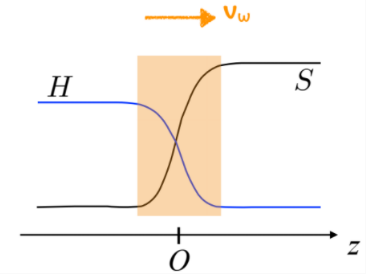
$\boxed{h = H/\sqrt{2},\ s = |S|}$ with vevs: $v(T)$ and $w(T)$ such that $v(T_c) = w(T_c)$

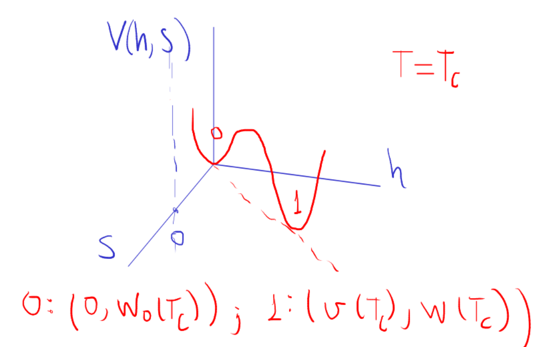
$$V_T(h,s) = \frac{\lambda_H v_c^4}{4}\left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1\right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2)\,, \qquad (33)$$

where

$$c_h = \frac{1}{48}\left(9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}\right)\,, \quad c_s = \frac{1}{12}\left(3\lambda_S + 2\lambda_{HS}\right)\,. \qquad (34)$$

arXiv: Sec. 4.1 arXiv:1107.5451





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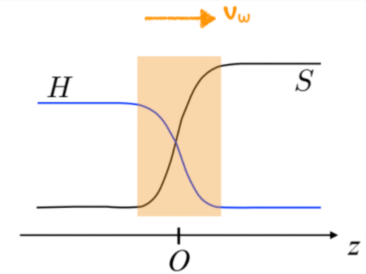
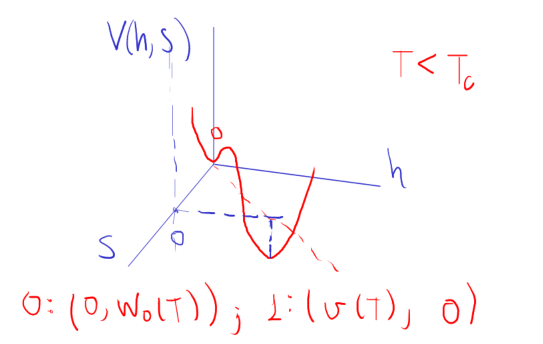




CP assymetry generation i

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

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

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

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

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

Boltzmann equation i

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

$$-D_L \xi''_{\chi_L} - v_w \xi'_{\chi_L} + \Gamma_L(\xi_{\chi_L} - \xi_{\chi_R}) = S_{\not{CP}}\,,$$

where D_L is the diffusion constant for χ_L, which is related to the scattering rate Γ_L by

$$D_L = \frac{3x+2}{x^2+3x+2}\frac{1}{3\Gamma_L}, \qquad x \equiv m_\chi/T \tag{35}$$

and

$$S_{\not{CP}} = -\frac{\lambda}{2}\frac{v_w D_L}{\frac{3x+2}{x^2+3x+2}T}\frac{(1-x)e^{-x}+x^2E_1(x)}{4m_\chi^2 K_2(x)}\frac{m_\chi w_0(T_n)\lambda\left(-2+\cosh\left(\frac{2z}{L_w}\right)\right)\sin\theta}{L_w^3\cosh^4\left(\frac{z}{L_w}\right)}\,, \tag{36}$$

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 $\mathrm{U}(1)_B$ charge density in the proximity of the wall. This results in a Z' background that couples to the SM fields with $\mathrm{U}(1)_B$ charge,

$$\langle Z_0'(z)\rangle = \frac{g_B\,(q_{\chi_L} - q_{\chi_R})\,T_n^3}{6M_{Z'}} \int_{-\infty}^{\infty} \mathrm{d}\,z_1\,\xi_{\chi_L}(z_1)\,e^{-M_{Z'}|z-z_1|}\,,$$

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

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

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

where $\Gamma_{\rm sph}$ 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

$$0.82 \times 10^{-10} < \eta_B < 0.92 \times 10^{-10}\,. \tag{37}$$

https://github.com/anferivera/DarkBariogenesis

- 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.

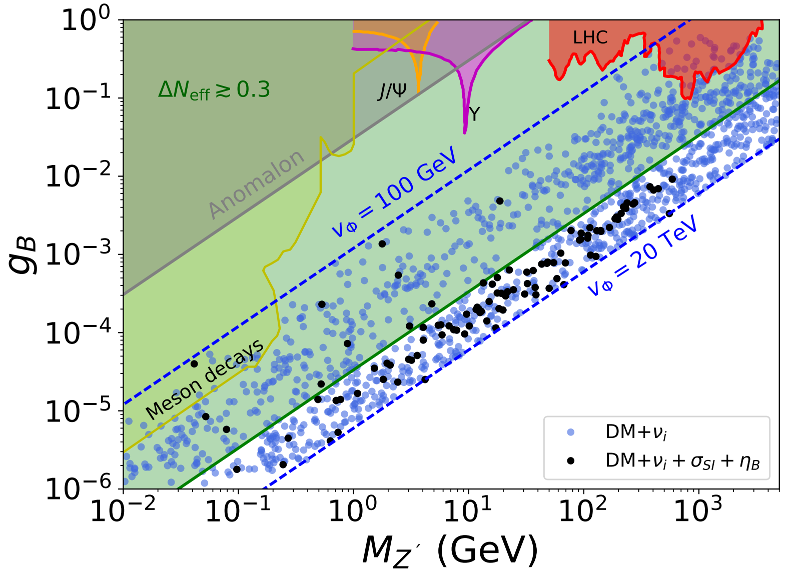
Results

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

Table 9: Scan ranges for the free parameters that are involved in the baryogenesis mechanism.

Black points: Dirac neutrinos with proper DM and baryon assymetry



Conclusions

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 assymmetry from the Dark sector into the SM.