Dirac dark matter, neutrino masses,

and dark baryogenesis

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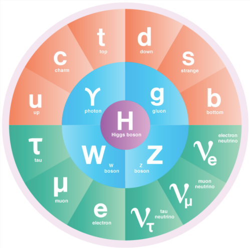
Focus on
arXiv:2205.05762 [PRD]
In collaboration with
Andrés Rivera (UdeA), Walter Tangarife (Loyola University Chicago)

Dark sectors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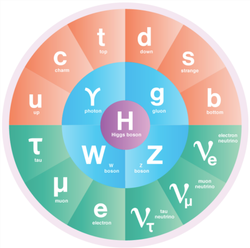
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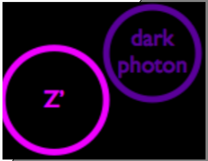
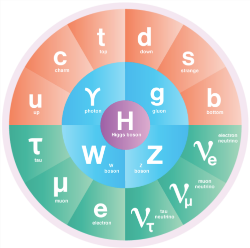

Z'
dark
photon

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

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



Anomalons: SM-singlet Dirac fermion

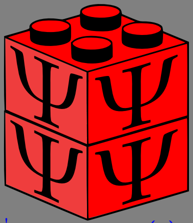
dark matter $m_\Psi = h \langle \Phi \rangle$

LHC production:

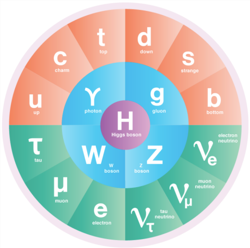
$F_{\mu\nu}$ $V^{\mu\nu}$

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

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



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



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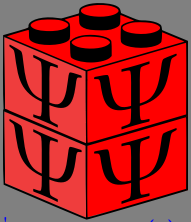

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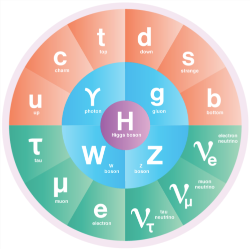

$F_{\mu\nu}$ $V^{\mu\nu}$

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

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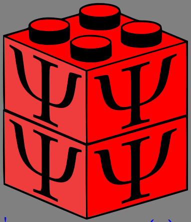

multi-component
dark matter

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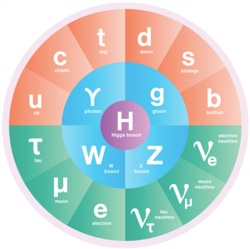

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Anomalons: SM-singlet Dirac fermion

CP violation Yukawa y

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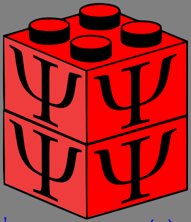

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Anomaly cancellation

Any local Abelian extension of the Standard Model can be reduced to a set of integers which must satisfy the gravitational anomaly, $[\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_Y$, and the cubic anomaly, $[\mathrm{U}(1)_X]^3$ conditions:

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

Methology based on: Costa-Dobrescu-Fox arXiv:1905.13729 [PRL]

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

$$\boldsymbol{q} = [l_1, l_2, \cdots, l_n, k_1, k_2, \cdots, k_n], \qquad n = (N-2)/2\,. \tag{2}$$

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

$$\boldsymbol{x} = [l_1, k_1, \cdots k_n, -l_1, -k_1, \cdots - k_n,] \qquad \boldsymbol{y} = [0, 0, l_1, \cdots l_n, -l_1, \cdots - l_n] \tag{3}$$

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

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

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

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

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Simplest secluded model with SM-singlet massive chiral fermions from SSB

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

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

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

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

Simplest secluded model with SM-singlet massive chiral fermions from SSB

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$$\mathcal{L} \subset \Psi^T \begin{array}{c|cccccc} & 1 & 2 & 2 & -5 & -5 & 8 \\ \hline 1 & 0 & h_{(1,2)} & h_{(1,2)} & 0 & 0 & 0 \\ 2 & h_{(1,2)} & 0 & 0 & h_{(2,-5)} & h_{(2,-5)} & 0 \\ 2 & h_{(1,2)} & 0 & 0 & 0 & 0 & 0 \\ -5 & 0 & h_{(2,-5)} & 0 & 0 & 0 & h_{(-5,8)} \\ -5 & 0 & h_{(2,-5)} & 0 & 0 & 0 & h_{(-5,8)} \\ 8 & 0 & 0 & 0 & h_{(-5,8)} & h_{(-5,8)} & 0 \end{array} \Psi\phi^{(*)} + h_{(4,-7)}\psi_4\psi_{-7}\phi^* \tag{8}$$

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

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{X}=B \text{ or } L}$
$Q_i^\dagger$	$\mathbf{2}$	$-1/6$	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 1: 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

$$\chi_1 \to \nu_{R1}, \cdots, \chi_{N_\nu} \to \nu_{R\,N_\nu}, \qquad 2 \leq N_\nu \leq 3\,, \tag{9}$$

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

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

$$\phi = -(\nu + L)/\delta\,, \tag{10}$$

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

$$u = -e - \frac{2}{3}L - \frac{1}{9}\left(x' - x''\right)\,, \quad d = e + \frac{4}{3}L - \frac{1}{9}\left(x' - x''\right)\,, \quad Q = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,, \tag{11}$$

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

$$(e + L)(x' - x'') = 0\,. \tag{12}$$

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

$$e = -L\,, \tag{13}$$

so that (L is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}\left(x' - x''\right)\,. \tag{14}$$

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,

$$\sum_{\alpha=1}^{N} z_\alpha = 0\,, \qquad \sum_{\alpha=1}^{N} z_\alpha^3 = 0\,, \tag{15}$$

where $N = N' + 5$ and

$$z_{N'+1} = -x'\,, \qquad z_{N'+2} = x''\,,$$
$$z_{N'+2+i} = L\,, \quad i = 1,2,3 \tag{16}$$

$\rightarrow$

$$9Q = -\sum_{\alpha=N'+1}^{N'+5} z_\alpha = -x' + x'' + L + L + L\,, \tag{17}$$

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

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

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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]

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Keyword(s):

Anomaly free Diophantine equations Abelian symmetry Gauge Symmetry

Versions

Version 1 Sep 24, 2021

10.5281/zenodo.5526707

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

- $L = 0$

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

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- $L = 0$
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  $(L'_L)^\dagger L''_R \Phi^* \to x' = -1,\ x'' = 6$

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

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

- $L = 0$
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$$(5, 5, -3, -2, 1, -6)$$

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

- $L = 0$
- Effective neutrino mass: $\phi = -\nu = -5$
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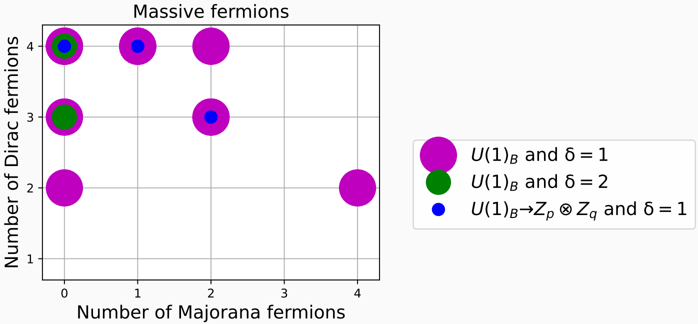
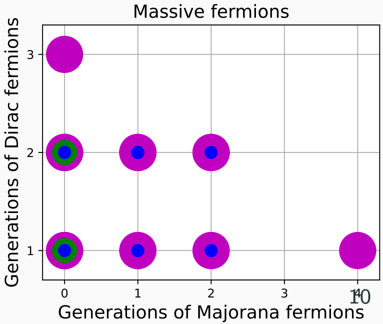
959 solutions from $\sim 400,000$

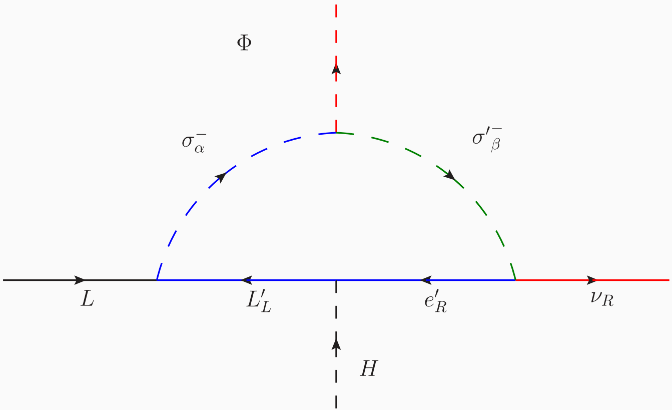
$$(5, 5, -3, -2, 1, -6)$$





Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



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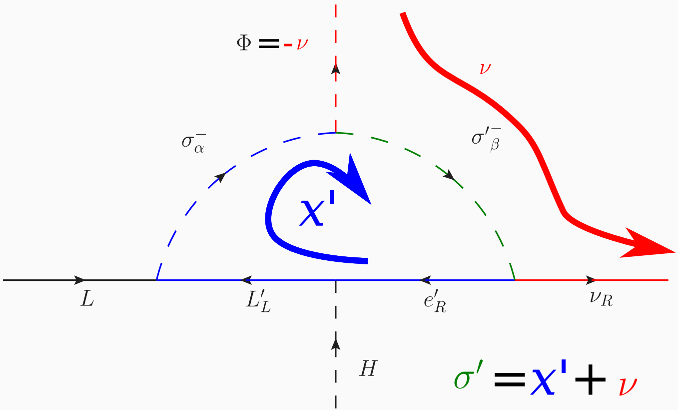

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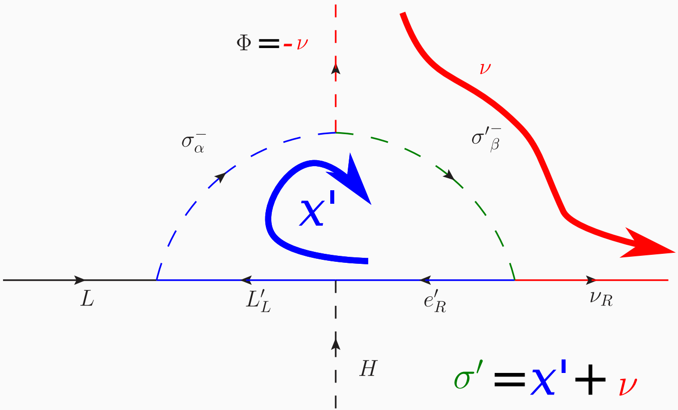


Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	**1**	$2/3$	$u = 1/3$
d_{Ri}	**1**	$-1/3$	$d = 1/3$
$(Q_i)^\dagger$	**2**	$-1/6$	$Q = -1/3$
$(L_i)^\dagger$	**2**	$1/2$	$L = 0$
e_R	**1**	-1	$e = 0$
$(L'_L)^\dagger$	**2**	$1/2$	$-x' = -3/5$
e'_R	**1**	-1	$x' = 3/5$
L''_R	**2**	$-1/2$	$x'' = 18/5$
$(e''_L)^\dagger$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

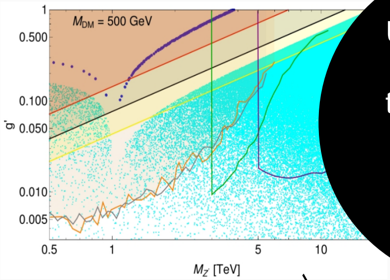
Electroweak baryogenesis

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)$_B$
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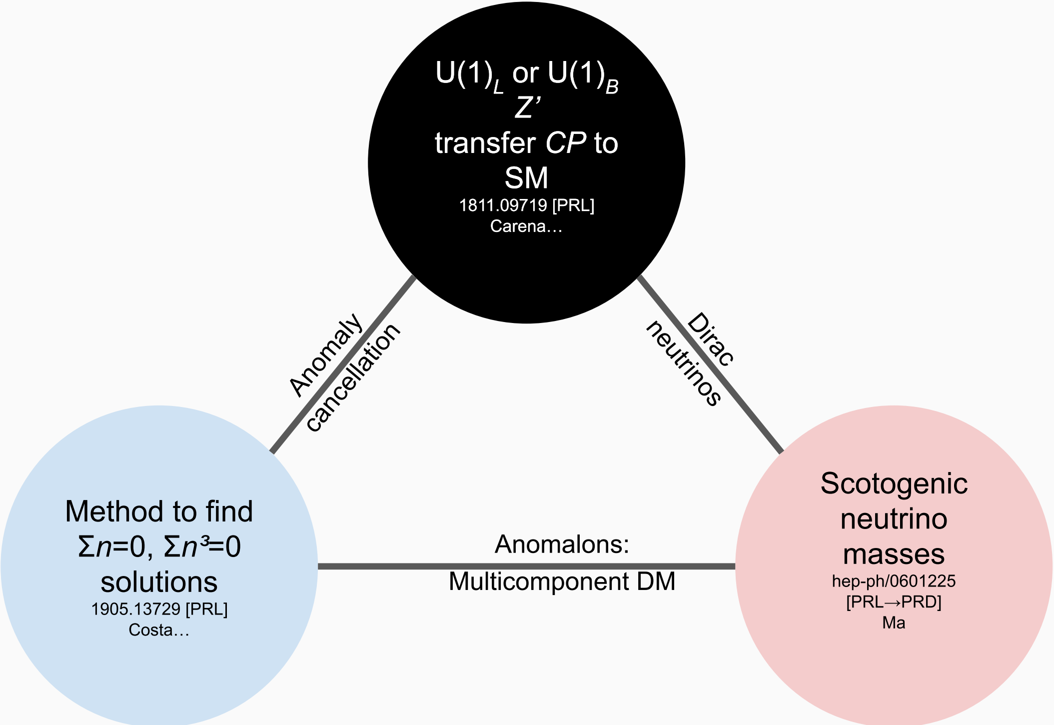
transfer *CP* to SM
1811.09719 [PRL]
Carena…

Anomaly cancellation

Dirac neutrinos

Anomalons:

DM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Costa…
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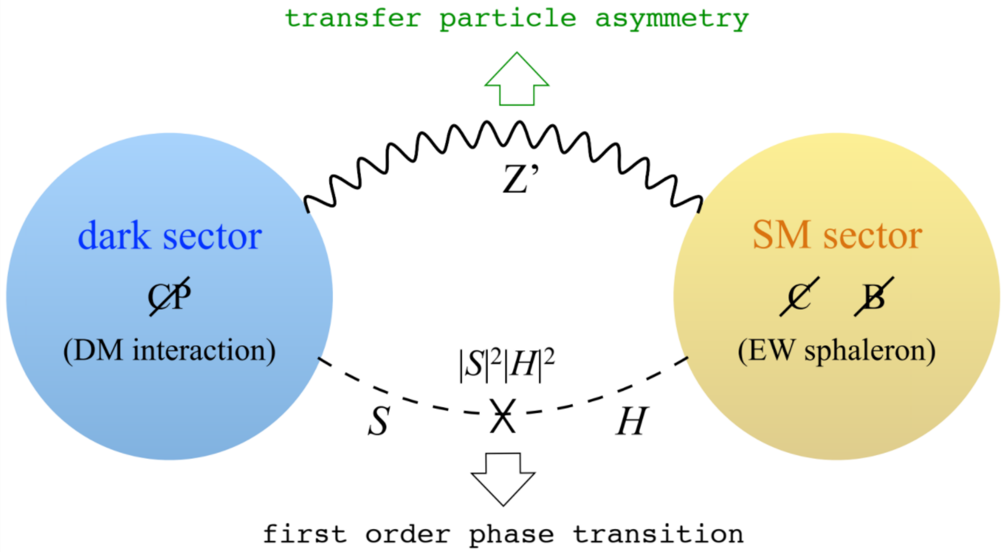
Scotogenic neutrino masses
hep-ph/0601225
[PRL→PRD]
Ma

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

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

- 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

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

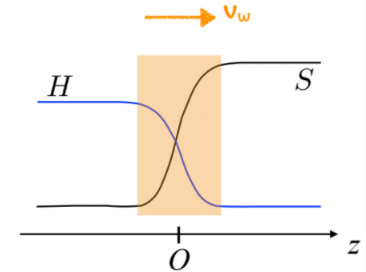
First-order phase transition: Effective potential ($T \neq 0$)

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

$$V_T(h,s) = \frac{\lambda_H v_c^4}{4}\left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1\right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2)\,, \tag{18}$$

where

$$c_h = \frac{1}{48}\left(9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}\right)\,, \quad c_s = \frac{1}{12}\left(3\lambda_S + 2\lambda_{HS}\right)\,. \tag{19}$$



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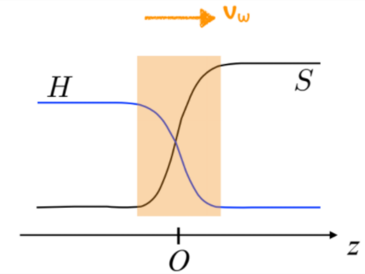
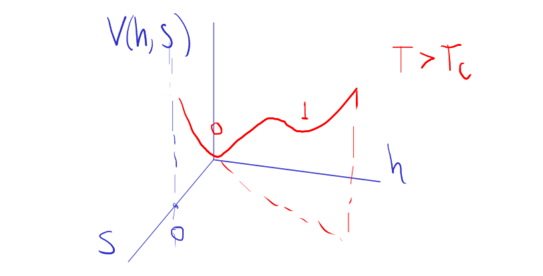
arXiv: Sec. 4.1 arXiv:1107.5451





0: (0, W_0(T)) ; 1: (v(T), w(T))

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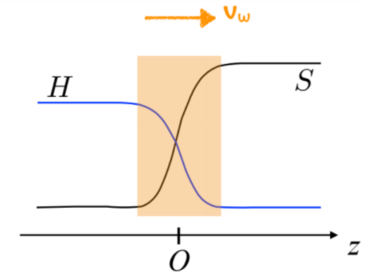

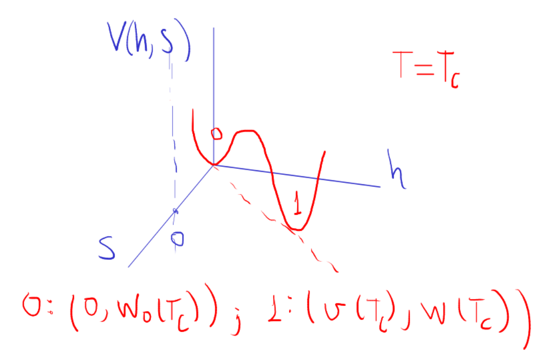

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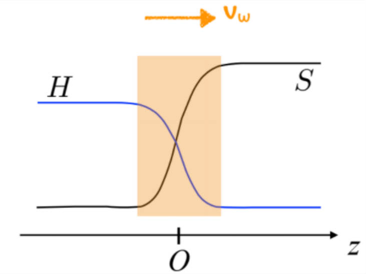
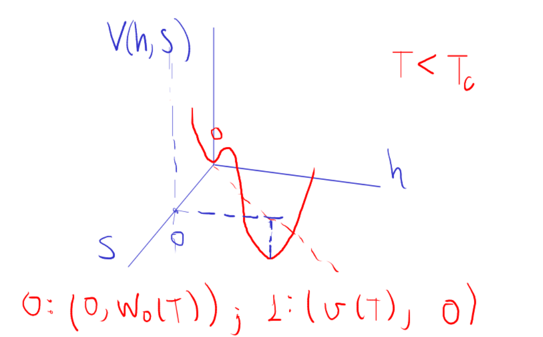




CP assymetry generation i

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

$$D_L = \frac{3x+2}{x^2+3x+2}\frac{1}{3\Gamma_L}, \qquad\qquad x \equiv m_\chi/T \tag{20}$$

and

$$S_{\not{CP}} = -\frac{\lambda}{2}\frac{v_w D_L}{\frac{3x+2}{x^2+3x+2}T}\frac{(1-x)e^{-x}+x^2E_1(x)}{4m_\chi^2 K_2(x)}\frac{m_\chi w_0(T_n)\lambda\left(-2+\cosh\left(\frac{2z}{L_w}\right)\right)\sin\theta}{L_w^3\cosh^4\left(\frac{z}{L_w}\right)}, \tag{21}$$

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. $y = \lambda\,\mathrm{e}^{i\theta - i\pi/2}$

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

$$0.82 \times 10^{-10} < \eta_B < 0.92 \times 10^{-10} . \tag{22}$$

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.

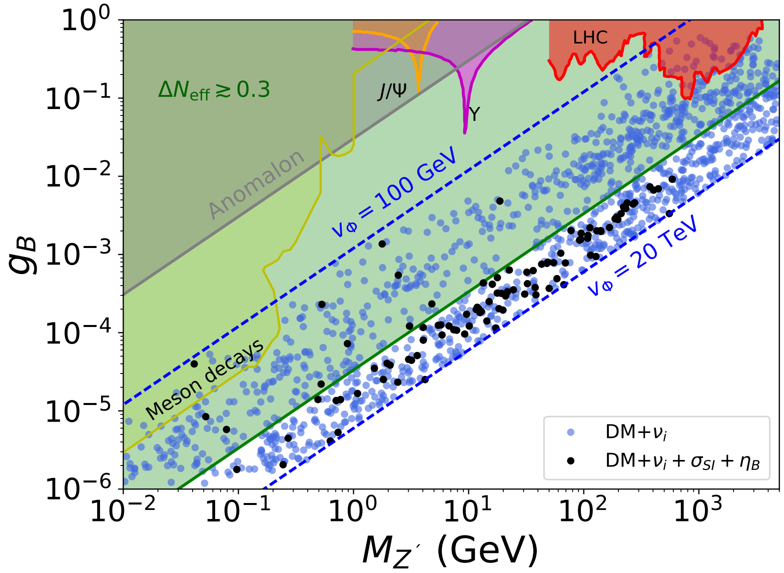
Results

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 2: 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.