

Dirac dark matter, neutrino masses, and dark baryogenesis



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Focus on

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

In collaboration with

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

Dark sectors







Local $U(1)_\chi$

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

Anomalons: SM-singlet Dirac fermion

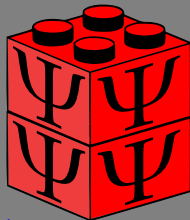
dark matter $m_\Psi = h\langle\Phi\rangle$

LHC production:

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

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

$$F_{\mu\nu} \quad V_{\mu\nu}$$



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

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



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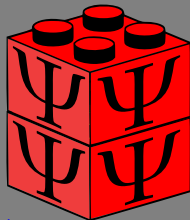
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multi-component
dark matter

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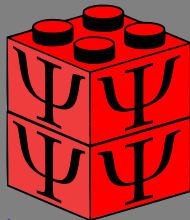
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$$\mathcal{L} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + i \sum_i \chi_i^\dagger \not{D} \chi_i - y (\chi_1 \chi_2 S + \text{h.c.})$$

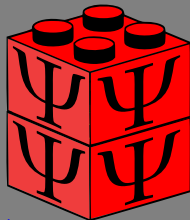
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CP violation Yukawa y

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

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

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

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

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

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

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

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

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

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

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

$$\mathcal{L} = i\psi_i \bar{\sigma}^\mu \mathcal{D}_\mu \psi_i - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \sum_{i < j} h_{ij} \psi_i \psi_j \phi^{(*)} + \text{h.c.} \quad (6)$$

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

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

$$\mathcal{L} \subset \Psi^T \begin{array}{c} \begin{array}{cccccc} & 1 & 2 & 2 & -5 & -5 & 8 \\ \begin{array}{l} 1 \\ 2 \\ 2 \\ -5 \\ -5 \\ 8 \end{array} & \left[\begin{array}{cccccc} 0 & h_{(1,2)} & h_{(1,2)} & 0 & 0 & 0 \\ h_{(1,2)} & 0 & 0 & h_{(2,-5)} & h_{(2,-5)} & 0 \\ h_{(1,2)} & 0 & 0 & 0 & 0 & 0 \\ 0 & h_{(2,-5)} & 0 & 0 & 0 & h_{(-5,8)} \\ 0 & h_{(2,-5)} & 0 & 0 & 0 & h_{(-5,8)} \\ 0 & 0 & 0 & h_{(-5,8)} & h_{(-5,8)} & 0 \end{array} \right] \end{array} \Psi \phi^{(*)} + h_{(4,-7)} \psi_4 \psi_{-7} \phi^* \end{array} \quad (8)$$

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	$1/2$	$-x'$
L''_R	2	$-1/2$	x''
e'_R	1	-1	x'
$(e''_L)^\dagger$	1	1	$-x''$
Φ	1	0	ϕ
S	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 $\mathcal{X} = L$.
 $i = 1, 2, 3, \alpha = 1, 2, \dots, N'$

$$\chi_1 \rightarrow \nu_{R1}, \dots, \chi_{N_\nu} \rightarrow \nu_{R N_\nu}, \quad 2 \leq N_\nu \leq 3, \quad (9)$$

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

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

$$\phi = -(\nu + L)/\delta, \quad (10)$$

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

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

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

$$(e + L)(x' - x'') = 0 . \quad (12)$$

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

$$e = -L , \quad (13)$$

so that (L is still a free parameter)

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

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,

$$\sum_{\alpha=1}^N z_{\alpha} = 0, \quad \sum_{\alpha=1}^N z_{\alpha}^3 = 0, \quad (15)$$

where $N = N' + 5$ and

$$\begin{aligned} z_{N'+1} &= -x', & z_{N'+2} &= x'', \\ z_{N'+2+i} &= L, \quad i = 1, 2, 3 \end{aligned} \quad (16)$$

→

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

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

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

- $L = 0$

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

$U(1)_B$ selection

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

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

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 $(L'_L)^\dagger L''_R \Phi^* \rightarrow x' = -1, x'' = 6$
- Dirac-fermionic DM: $(\chi_L)^\dagger \chi''_R \Phi^* \rightarrow z_3 = -3, z_4 = -2$

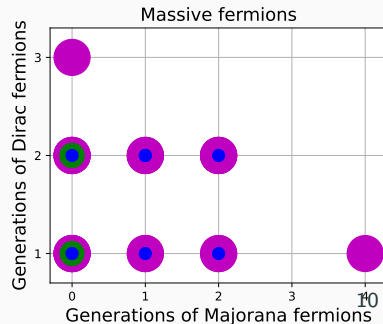
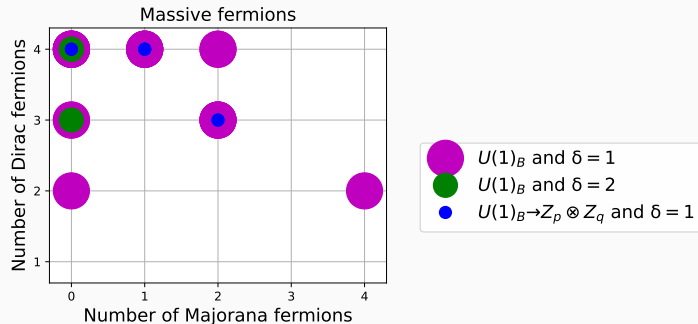
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$U(1)_B$ selection

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- Effective neutrino mass: $\phi = -\nu = -5$
- Electroweak-scale vector-like fermions:
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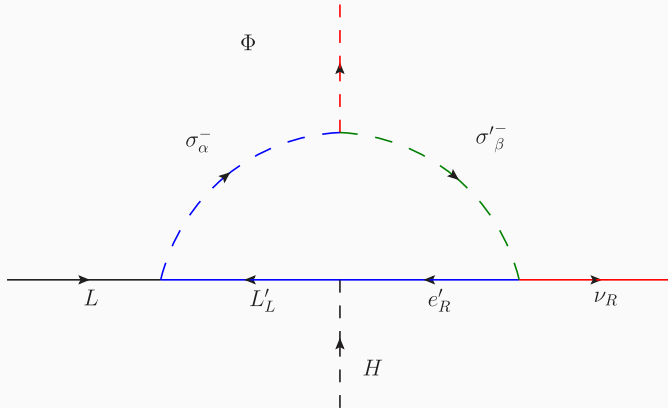
959 solutions from $\sim 400,000$

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



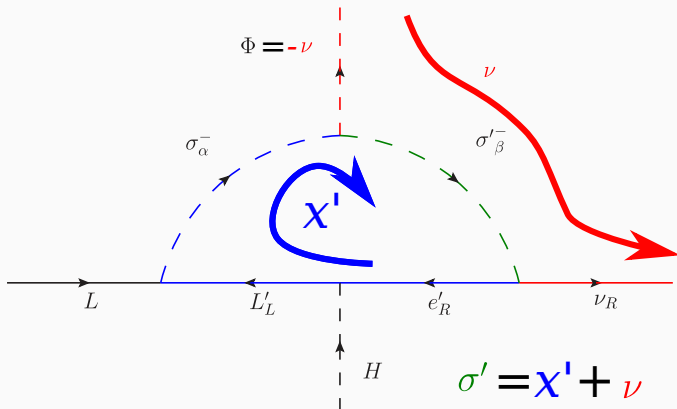
Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed



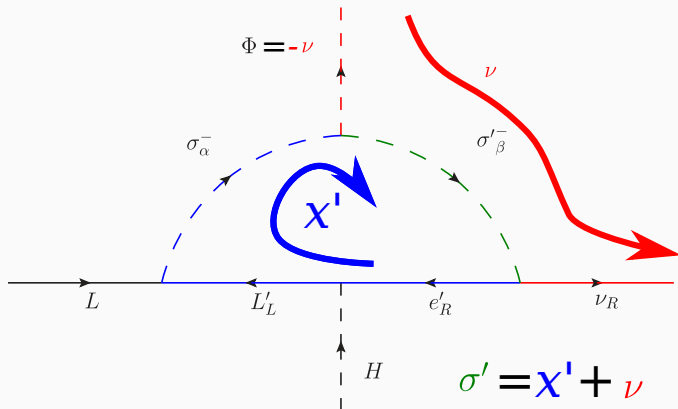
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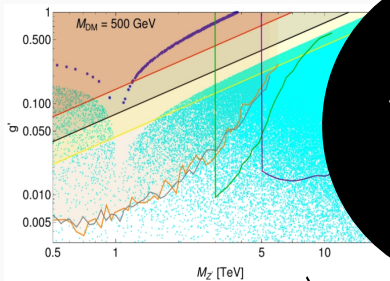


Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
u_{Ri}	1	2/3	$u = 1/3$
d_{Ri}	1	-1/3	$d = 1/3$
$(Q_i)^\dagger$	2	-1/6	$Q = -1/3$
$(L_i)^\dagger$	2	1/2	$L = 0$
e_R	1	-1	$e = 0$
$(L'_L)^\dagger$	2	1/2	$-x' = -3/5$
e'_R	1	-1	$x' = 3/5$
L''_R	2	-1/2	$x'' = 18/5$
$(e'_L)^\dagger$	1	1	$-x'' = -18/5$
$\nu_{R,1}$	1	0	-3
$\nu_{R,2}$	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) $m_h \sim 40$ 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 😊



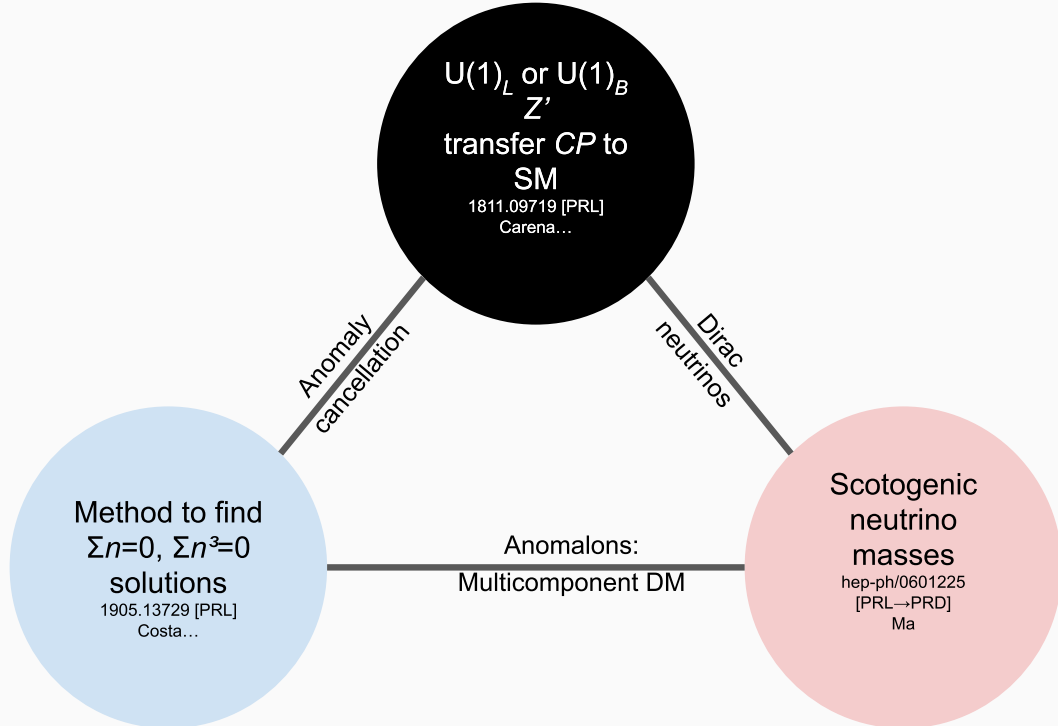
$U(1)_L$ or $U(1)_B$
 Z'
 transfer CP to
 SM

1811.09719 [PRL]
 Carena...

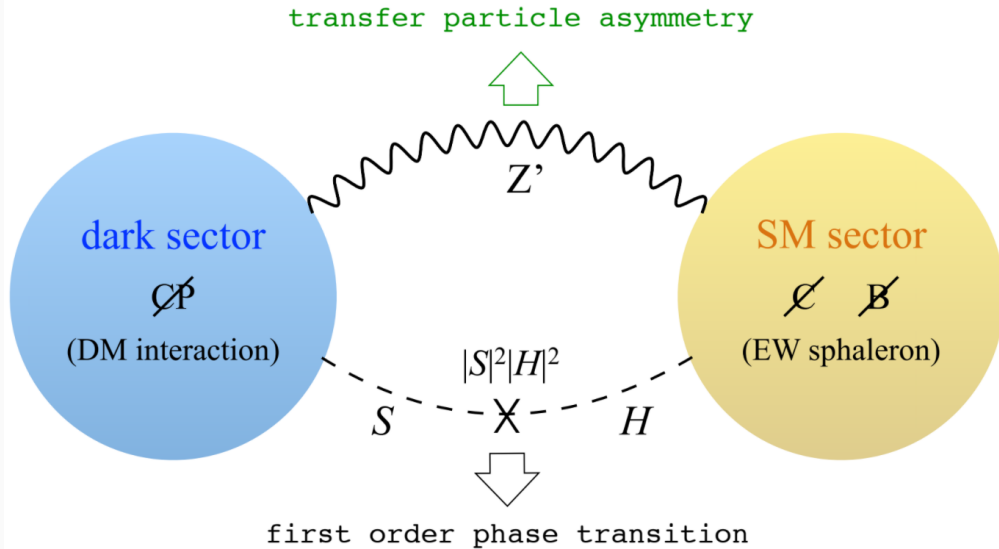
Anomaly
 cancellation

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

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

- Strong electroweak phase transition (EWPT) portal

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

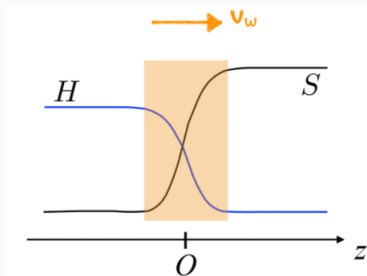
First-order phase transition: Effective potential ($T \neq 0$)

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

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

where

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



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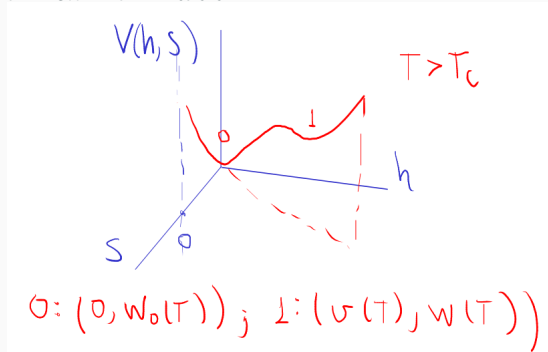
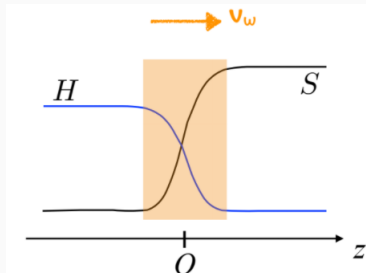
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arXiv: Sec. 4.1 arXiv:1107.5451



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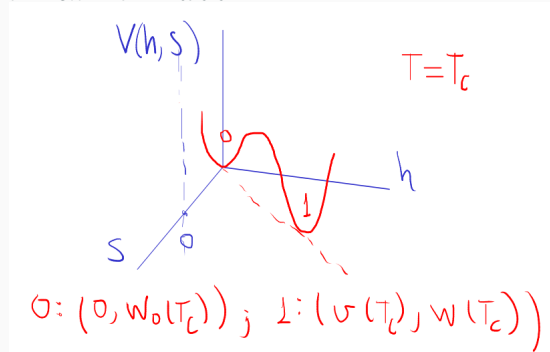
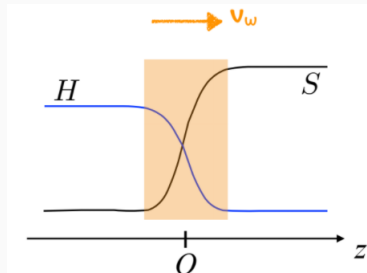
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$$V_T(h, s) = \frac{\lambda_H v_c^4}{4} \left(\frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (18)$$

where

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

arXiv: Sec. 4.1 arXiv:1107.5451



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

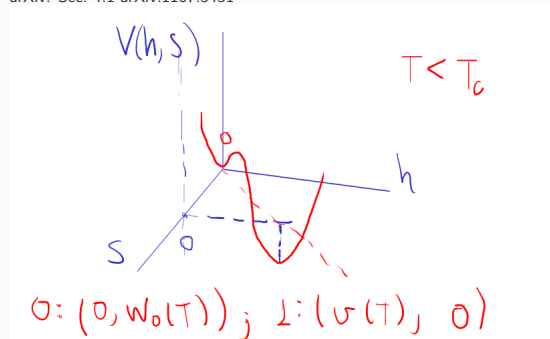
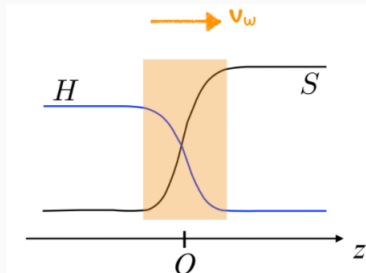
$h = H/\sqrt{2}$, $s = |S|$ with vevs: $v(T)$ and $w(T)$ such that $v(T_c) = w(T_c)$

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where

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

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

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

and

$$S_{\mathcal{CP}} = -\frac{\lambda}{2} \frac{v_w D_L}{\frac{3x+2}{x^2+3x+2} T} \frac{(1-x)e^{-x} + x^2 E_1(x)}{4m_\chi^2 K_2(x)} \frac{m_\chi w_0(T_n) \lambda \left(-2 + \cosh\left(\frac{2z}{L_w}\right) \right) \sin \theta}{L_w^3 \cosh^4\left(\frac{z}{L_w}\right)}, \quad (21)$$

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

Transfer DM asymmetry to SM quarks

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

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

which generates a chemical potential for the SM quarks,

$$\mu_Q(z) = \mu_{d_R, u_R}(z) = 3 \times \frac{5}{9} \times g_B \langle Z'_0(z) \rangle.$$

This chemical potential sources a thermal-equilibrium asymmetry in the quarks, $\Delta n_Q^{\text{EQ}}(z) \sim T_n^2 \mu_Q(z)$.

From [1]

If the Z' is sufficiently light, it mediates a long range force that extends into the region outside the bubble wall with unbroken electroweak symmetry.

Finally, the baryon-number asymmetry is then given by

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

where Γ_{sph} is the sphaleron rate. The baryon-to-photon-number ratio is then obtained by

$$\eta_B = \frac{n_B}{s(T)}, \quad s(T) \equiv \frac{2\pi^2}{45} g_{*S}(T) T^3,$$

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

$$0.82 \times 10^{-10} < \eta_B < 0.92 \times 10^{-10}. \quad (22)$$

- 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*

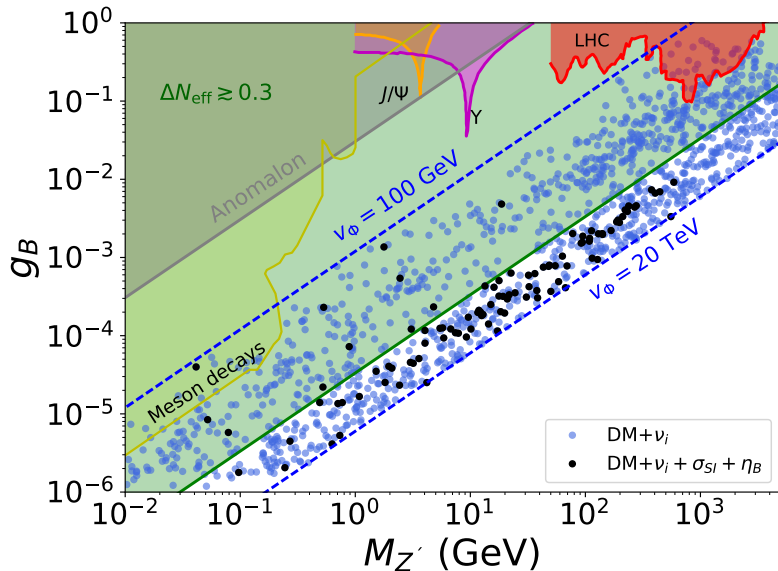
[...] In this paper, we address several questions about reproducibility [...] Combined with software repositories and open source licensing, notebooks are powerful tools for transparent, collaborative, reproducible, and reusable data analyses.

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 2: 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.