

# Effective Dirac neutrino masses and baryogenesis

with gauged Baryon number



UNIVERSIDAD DE ANTIOQUIA

1893

Diego Restrepo

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



**Focus on**

arXiv:1111.1111

In collaboration with

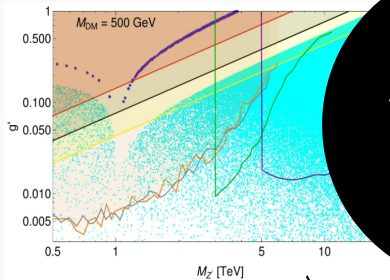
Andrés Rivera (UdeA), Walter Tangarife (Loyola University Chicago)

# 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 😊



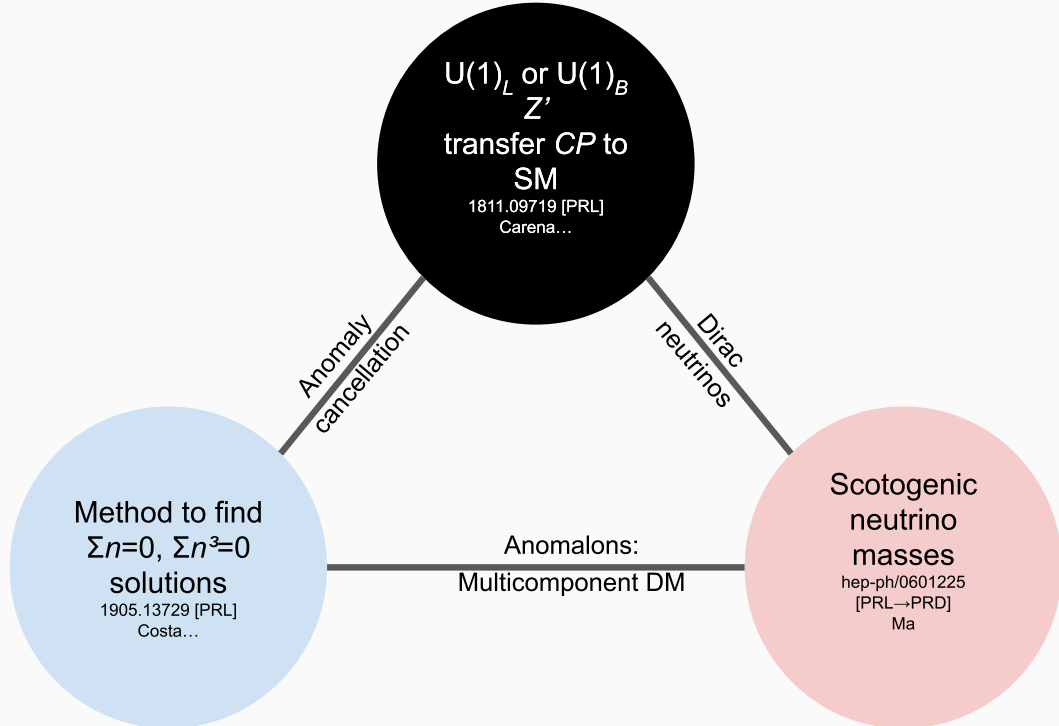
$U(1)_L$  or  $U(1)_B$   
 $Z'$   
 transfer  $CP$  to  
 SM

1811.09719 [PRL]  
 Carena...

Anomaly  
 cancellation

Dirac  
 neutrinos

Anomalons:  
 DM

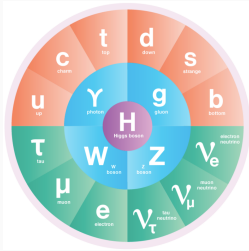


## Dark sectors

---









# Local $U(1)_\chi$

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

Anomalons: SM-singlet Dirac fermion

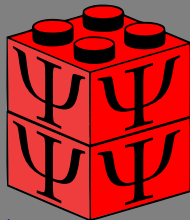
dark matter  $m_\Psi = h\langle\Phi\rangle$

LHC production:

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

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

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



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

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



# Local $U(1)_\chi$

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

Anomalons: SM-singlet Dirac fermion

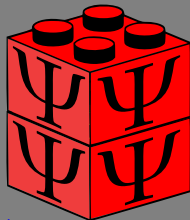
dark matter  $m_\Psi = h\langle\Phi\rangle$

LHC production:

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

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

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



multi-component  
dark matter

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

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



# 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

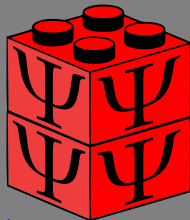
dark matter  $m_\Psi = h\langle\Phi\rangle$

LHC production:

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

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

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



multi-component  
dark matter

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

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



# 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

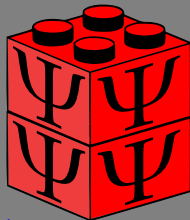
$CP$  violation Yukawa  $y$

LHC production:

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

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

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



multi-component  
dark matter

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

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

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

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{\mathcal{X}=\textcolor{red}{B} \text{ or } \textcolor{blue}{L}}$
$Q_i^\dagger$	<b>2</b>	$-1/6$	$\textcolor{red}{Q}$
$d_{Ri}$	<b>1</b>	$-1/2$	$\textcolor{red}{d}$
$u_{Ri}$	<b>1</b>	$+2/3$	$\textcolor{red}{u}$
$L_i^\dagger$	<b>2</b>	$+1/2$	$\textcolor{blue}{L}$
$e_{Ri}$	<b>1</b>	$-1$	$\textcolor{blue}{e}$
$H$	<b>2</b>	$1/2$	$h = 0$
$\chi_\alpha$	<b>1</b>	$0$	$z_\alpha$
$(L'_L)^\dagger$	<b>2</b>	$1/2$	$-x'$
$L''_R$	<b>2</b>	$-1/2$	$x''$
$e'_R$	<b>1</b>	$-1$	$x'$
$(e''_L)^\dagger$	<b>1</b>	$1$	$-x''$
$\Phi$	<b>1</b>	$0$	$\phi$
$S$	<b>1</b>	$0$	$s$

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

$$\chi_1 \rightarrow \nu_{R1}, \dots, \chi_{N_\nu} \rightarrow \nu_{R N_\nu}, \quad 2 \leq N_\nu \leq 3, \quad (1)$$

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

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

$$\phi = -(\nu + L)/\delta, \quad (2)$$

## 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

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

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

$$(e + L)(x' - x'') = 0 . \quad (4)$$

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

$$e = -L , \quad (5)$$

so that ( $L$  is still a free parameter)

$$Q = -u = -d = -\frac{1}{3}L + \frac{1}{9}(x' - x'') . \quad (6)$$

If  $L = 0 \rightarrow U(1)_B$



## 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,

$$\sum_{\alpha=1}^N z_{\alpha} = 0, \quad \sum_{\alpha=1}^N z_{\alpha}^3 = 0, \quad (7)$$

where  $N = N' + 5$  and

$$\begin{aligned} z_{N'+1} &= -x', & z_{N'+2} &= x'', \\ z_{N'+2+i} &= L, \quad i = 1, 2, 3 \end{aligned} \quad (8)$$

→

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

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

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...](#)

Indexed in

OpenAIRE

## Publication date:

September 24, 2021

## DOI:

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

## Keyword(s):

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

## License (for files):

[Creative Commons Attribution 4.0 International](#)

## Versions

Version 1

Sep 24, 2021

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

- $L = 0$

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

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

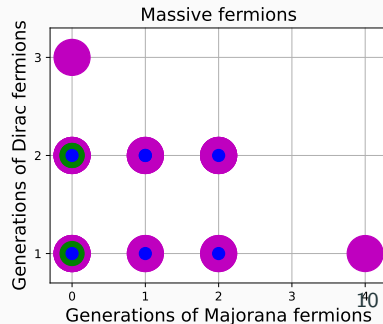
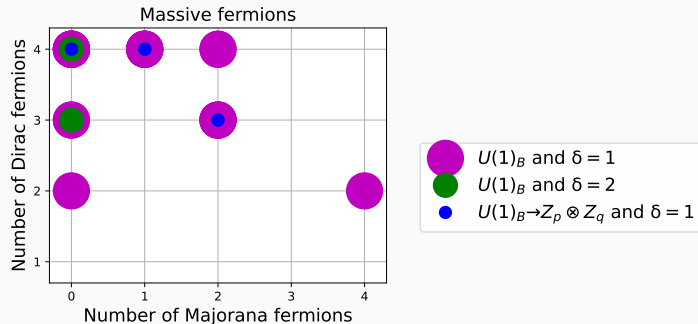
$$(5, 5, -3, -2, 1, -6)$$

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

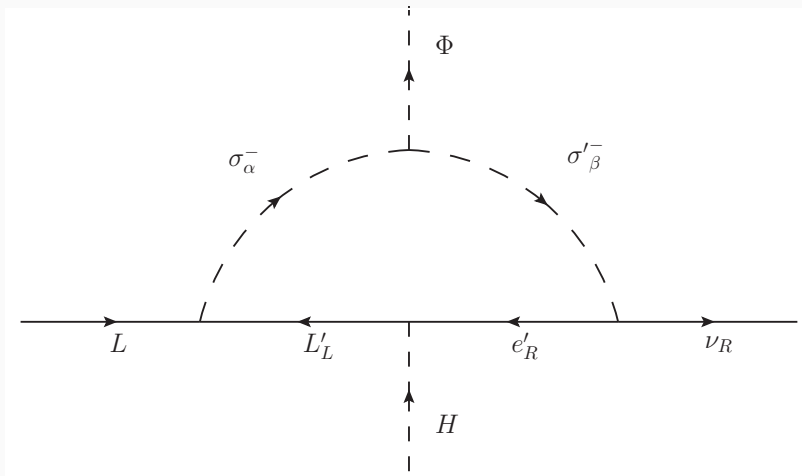
959 solutions from  $\sim 400,000$

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



## Scotogenic realization

Any realization which does not affect anomaly cancellation is allowed





# Full $U(1)_B$ model

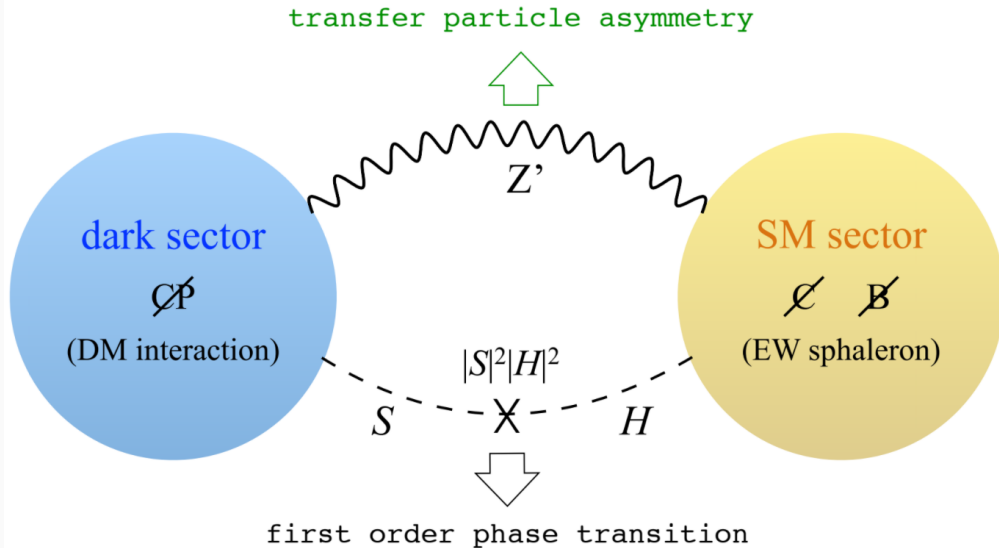
Field	$SU(2)_L$	$U(1)_Y$	$U(1)_B$
$u_{Ri}$	1	2/3	$u = -5/9$
$d_{Ri}$	1	-1/3	$d = -5/9$
$(Q_i)^\dagger$	2	-1/6	$Q = 5/9$
$(L_i)^\dagger$	2	1/2	$L = 0$
$e_R$	1	-1	$e = 0$
$(L'_L)^\dagger$	2	1/2	$-x' = 1$
$e'_R$	1	-1	$x' = -1$
$L''_R$	2	-1/2	$x'' = -6$
$(e''_L)^\dagger$	1	1	$-x'' = 6$
$\nu_{R,1}$	1	0	5
$\nu_{R,2}$	1	0	5
$\chi_R$	1	0	-2
$(\chi_L)^\dagger$	1	0	-3
$H$	2	1/2	0
$\Phi$	1	0	-5
$S$	1	0	-5
$\sigma^-_\alpha$	1	1	-1
$\sigma'^-_\alpha$	1	-1	4

**Table 2:** Fermion (top) and scalar (bottom) content and its quantum numbers,  $i = 1, 2, 3$ ,  $\alpha = 1, 2$ .

# Baryogenesis

---

# 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:  $\Phi$ ,  $(\langle\Phi\rangle \rightarrow L'_L, L''_R, e'_L, e''_R)$ : 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

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

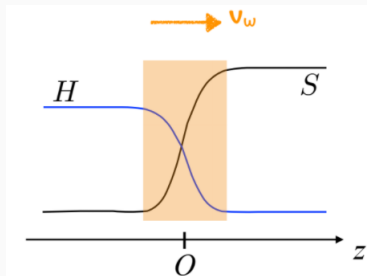
## First-order phase transition: Effective potential ( $T \neq 0$ )

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

$$V_T(h, s) = \frac{\lambda_H v_c^4}{4} \left( \frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (10)$$

where

$$c_h = \frac{1}{48} (9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}), \quad c_s = \frac{1}{12} (3\lambda_S + 2\lambda_{HS}). \quad (11)$$



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

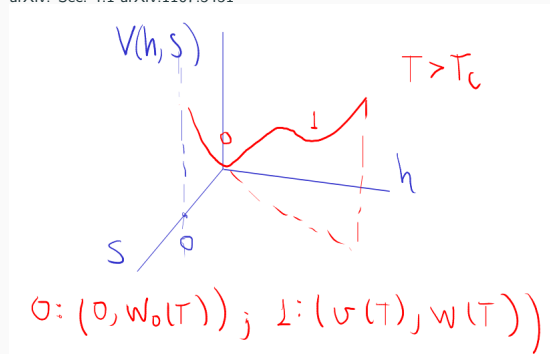
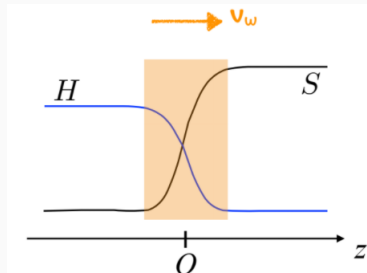
$h = H/\sqrt{2}$ ,  $s = |S|$  with vevs:  $v(T)$  and  $w(T)$  such that  $v(T_c) = w(T_c)$

$$V_T(h, s) = \frac{\lambda_H v_c^4}{4} \left( \frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (10)$$

where

$$c_h = \frac{1}{48} (9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}), \quad c_s = \frac{1}{12} (3\lambda_S + 2\lambda_{HS}). \quad (11)$$

arXiv: Sec. 4.1 arXiv:1107.5451



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

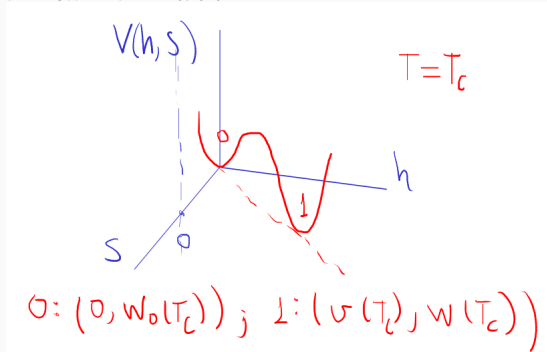
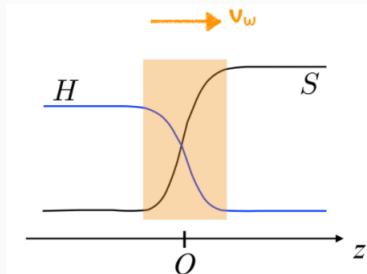
$h = H/\sqrt{2}$ ,  $s = |S|$  with vevs:  $v(T)$  and  $w(T)$  such that  $v(T_c) = w(T_c)$

$$V_T(h, s) = \frac{\lambda_H v_c^4}{4} \left( \frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (10)$$

where

$$c_h = \frac{1}{48} (9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}), \quad c_s = \frac{1}{12} (3\lambda_S + 2\lambda_{HS}). \quad (11)$$

arXiv: Sec. 4.1 arXiv:1107.5451



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

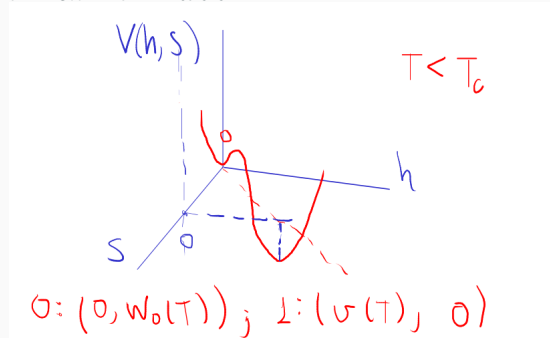
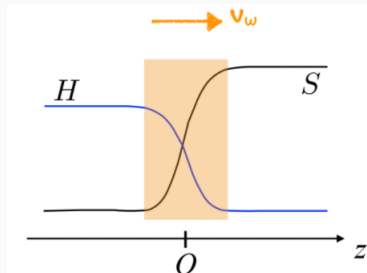
$h = H/\sqrt{2}$ ,  $s = |S|$  with vevs:  $v(T)$  and  $w(T)$  such that  $v(T_c) = w(T_c)$

$$V_T(h, s) = \frac{\lambda_H v_c^4}{4} \left( \frac{h^2}{v_c^2} + \frac{s^2}{w_c^2} - 1 \right)^2 + \frac{\lambda_H v_c^2}{m_{s,c}^2 w_{0,c}^4} h^2 s^2 + (T^2 - T_c^2)(c_h h^2 + c_s s^2), \quad (10)$$

where

$$c_h = \frac{1}{48} (9g_2^2 + 3g_1^2 + 12y_t^2 + 24\lambda_H + \lambda_{HS}), \quad c_s = \frac{1}{12} (3\lambda_S + 2\lambda_{HS}). \quad (11)$$

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

$$h(z) = \frac{1}{2}v(T_n)(1 - \tanh(z/L_w)) , \quad s(z) = \frac{1}{2}s_0(1 + \tanh(z/L_w)) ,$$

where  $z$  is the direction normal to the wall and  $L_w$  is the wall width.

The nucleation temperature,  $T_n$ , is defined by the condition

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

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

The *CP* violating phase,  $\theta$ , from

$$M_\chi(z) = m_\chi(z) + |y| e^{i\theta} |S(z)|, \quad (12)$$

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

$$-D_L \xi''_{\chi_L} - v_w \xi'_{\chi_L} + \Gamma_L (\xi_{\chi_L} - \xi_{\chi_R}) = S_{\mathcal{CP}},$$

where  $D_L$  is the diffusion constant for  $\chi_L$ , which is related to the scattering rate  $\Gamma_L$  by  $D_L = \langle v_{p_z}^2 \rangle / 3\Gamma_L$ . Here,  $\langle \rangle$  means thermal average.  $S_{\mathcal{CP}}$  is  $CP$ -violating source that results from the variation of  $\theta$

$$S_{\mathcal{CP}} = -\frac{\lambda}{2} \frac{v_w D_h}{\langle v_{p_z}^2 \rangle T} \left\langle \frac{|p_z|}{\omega^2} \right\rangle (M_\chi^2 \theta')'', \quad (13)$$

where  $v_w$  is the wall's velocity and

$$\langle v_{p_z}^2 \rangle = \frac{3x + 2}{x^2 + 3x + 2}, \quad \left\langle \frac{|p_z|}{\omega^2} \right\rangle = \frac{(1 - x)e^{-x} + x^2 E_1(x)}{4m_\chi^2 K_2(x)}, \quad x \equiv m_\chi/T,$$
$$(M_\chi^2 \theta')'' = \frac{m_\chi s_0 \lambda \left( -2 + \cosh \left( \frac{2z}{L_w} \right) \right) \sin \theta}{L_w^3 \cosh^4 \left( \frac{z}{L_w} \right)}.$$

$E_1(x)$  is the error function and  $K_2(x)$  is the modified Bessel function of the second kind.

## Transfer DM assymetry to SM quarks

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

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

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  $\Gamma_{\text{sph}}$  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.

- SARAH→SPheno→MicroMegas
- $\eta_B$  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.

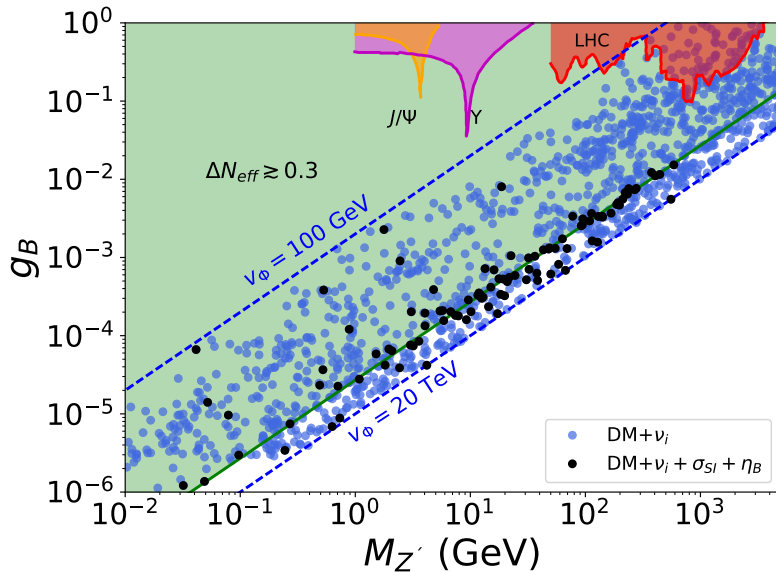
We vary the typical Dirac-fermion DM parameter space and for each point that satisfy neutrino oscillation data, relic density and DM direct detection constraints. For each point we ...

Parameter	Range
$\theta$	$(-\pi/2, \pi/2)$
$s_0/\text{GeV}$	100 – 500
$T_n/\text{GeV}$	100 – 200
$L_w/\text{GeV}^{-1}$	$1/T_n - 10/T_n$
$v_w$	0.05 – 0.5

**Table 3:** 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.