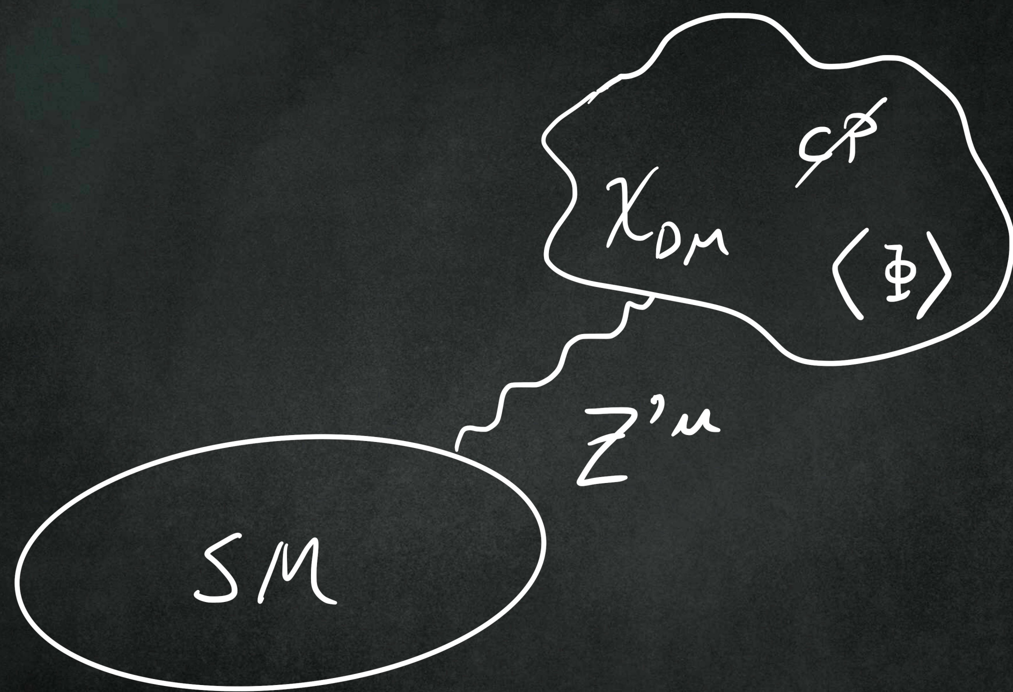
# Dirac dark matter, neutrino masses, and dark baryogengesis

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PRD 100 (2019) 3, 035029


Walter Tangarife

LOYOLA UNIVERSITY CHICAGO

*Preparing people to lead extraordinary lives*

Collaborators:
Diego Restrepo and Andrés Rivera
(U. Antioquia, Colombia)

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# Motivation

We want to explore (minimal) extensions of the standard model where the new fields work together towards the solution of three unanswered questions:

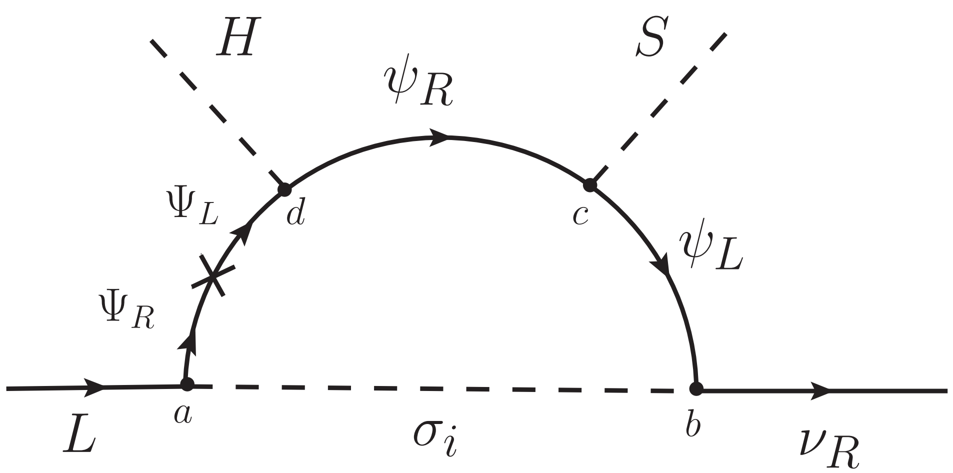
What's the origin of the small neutrino masses?

What is the dark matter particle?

What's the origin of the baryon asymmetry in the universe?

# Scotogenic Models:
# Singlet-Doublet Dark Matter

Restrepo, Rivera, Tangarife PRD (2020)




$$\mathcal{L}_5^D = -\frac{g_{\alpha\beta}}{\Lambda}\bar{L}_\alpha \widetilde{H}\nu_{R\beta}S$$

| Leptons and scalars fields | $(\mathrm{SU}(2)_L, \mathrm{U}(1)_Y)$ | $\mathbb{Z}_2$ (DM) | $\mathbb{Z}_2'$ | $U(1)_{B-L}$ |
|---|---|---|---|---|
| $L_\beta = \begin{pmatrix}\nu_L \\ l_L\end{pmatrix}_\beta$ | $(2, -1/2)$ | $+$ | $+$ | -1 |
| $l_R^\alpha$ | $(1, 0)$ | $+$ | $+$ | -1 |
| $H = \left(H^+, \frac{h^0+v}{\sqrt{2}}\right)^T$ | $(2, 1/2)$ | $+$ | $+$ | 0 |
| $S$ | $(1, 0)$ | $+$ | - | 0 |
| $\sigma_i$ | $(1, 0)$ | - | - | 0 |
| $\psi_L$ | $(1, 0)$ | - | $+$ | -1 |
| $\psi_R$ | $(1, 0)$ | - | - | -1 |
| $\Psi = \begin{pmatrix}\Psi^0 \\ \Psi^-\end{pmatrix}$ | $(2, -1/2)$ | - | - | -1 |
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No tree-level seesaw

No Majorana mass

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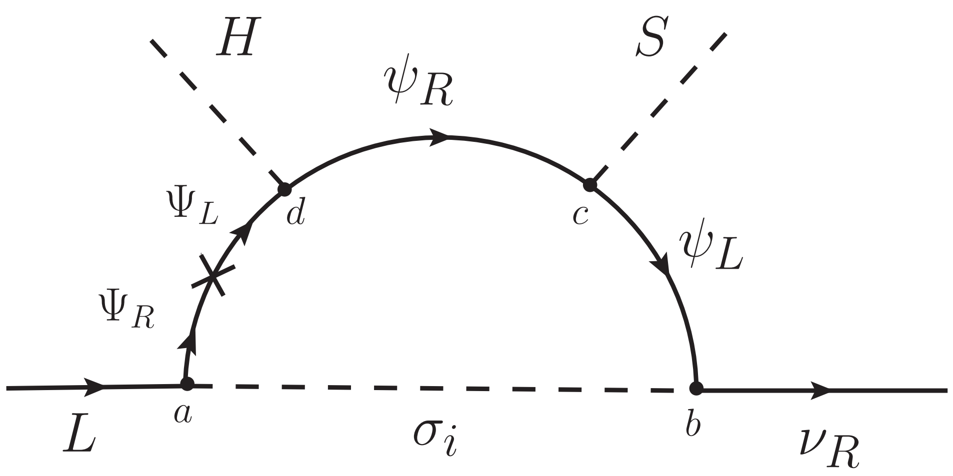


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| $\psi_R$ | $(1, 0)$ | - | - | -1 |
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No tree-level seesaw

No Majorana mass

$$\mathcal{L}_5^D = -\frac{g_{\alpha\beta}}{\Lambda} \bar{L}_\alpha \widetilde{H} \nu_{R\beta} S$$

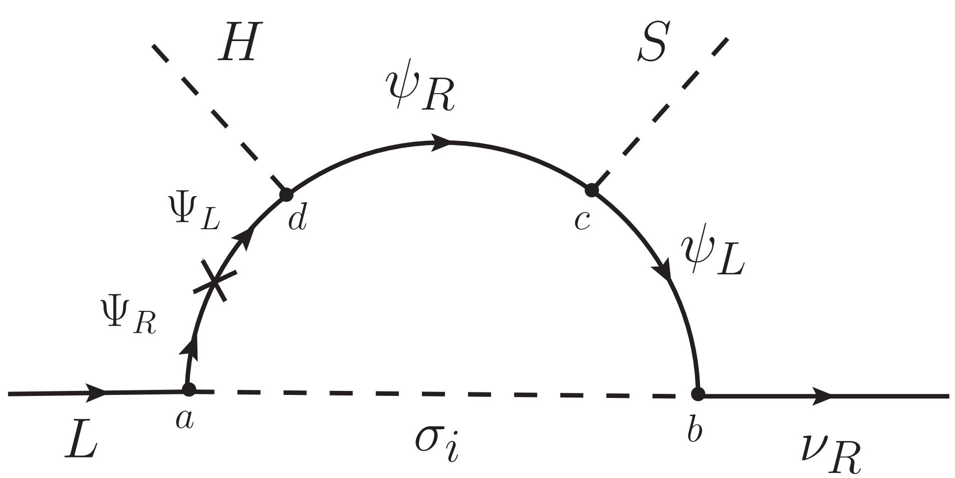
$$\chi_j^0 = (\chi_L, \chi_R^\dagger)_j \qquad \chi_{Lj} = V_{ji} \begin{pmatrix} \Psi_L^0 \\ \psi_L \end{pmatrix}_i \qquad \chi_{Rj}^\dagger = U_{ji} \begin{pmatrix} \Psi_R^{0\,\dagger} \\ \psi_R^\dagger \end{pmatrix}_i$$

$$\mathcal{M}_{\alpha\beta} = \sum_{i=1}^{2} \sum_{j=1}^{2} \frac{U_{j1} V_{j2}}{16\pi^2} \times h_b^{\alpha i} h_a^{\beta i} m_{\chi_j^0} \times \left[ \frac{m_{\chi_j^0}^2 \ln(m_{\chi_j^0}^2) - m_{\sigma_i}^2 \ln(m_{\sigma_i}^2)}{\left(m_{\chi_j^0}^2 - m_{\sigma_i}^2\right)} \right]$$

We can invert the problem and use the PMNS matrix and neutrino data to obtain 12 of the unknown parameters

# Scotogenic Models:

# Singlet-Doublet Dark Matter

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$$\chi_j^0 = (\chi_L, \chi_R^\dagger)_j \qquad \chi_{Lj} = V_{ji} \begin{pmatrix} \Psi_L^0 \\ \psi_L \end{pmatrix}_i \qquad \chi_{Rj}^\dagger = U_{ji} \begin{pmatrix} \Psi_R^{0\dagger} \\ \psi_R^\dagger \end{pmatrix}_i$$

Stabilizes DM

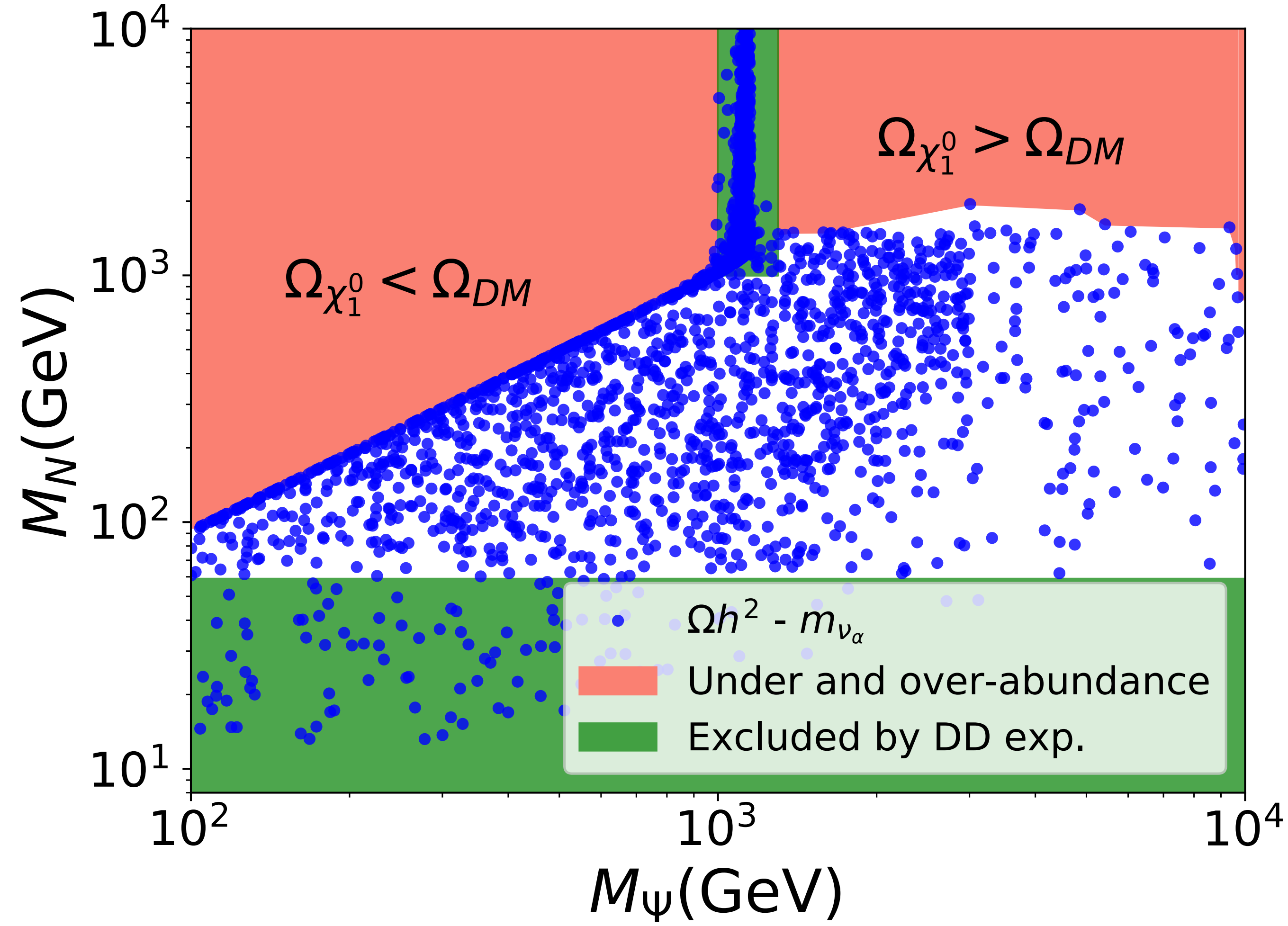
$\chi_1^0$ is the candidate for Dirac dark matter

It couples to the Higgs and Z-boson through the singlet-doublet mixing

# Scotogenic Models:
# Singlet-Doublet Dark Matter

SARAH+SPheno: Mass spectrum

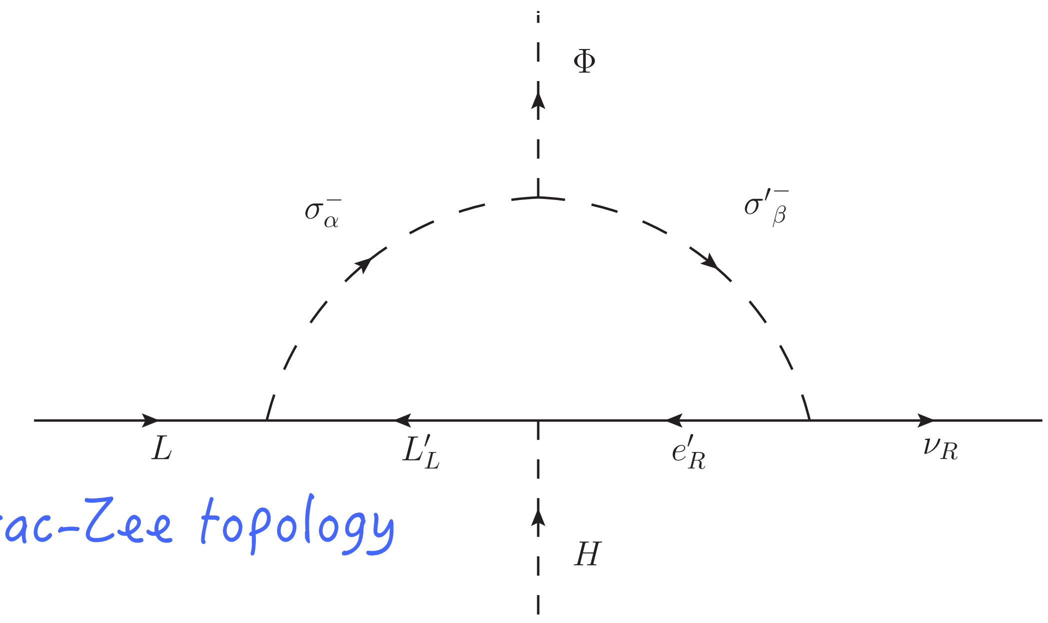
MicrOMEGAs: Relic abundance




The blue dots give the correct relic abundance and reproduce the neutrino parameters

# Scotogenic model with a gauged Abelian symmetry

Restrepo, Rivera, Tangarife PRD (2022)




Dirac-Zee topology

| Field | $SU(2)_L$ | $U(1)_Y$ | $U(1)_X$ |
|---|---|---|---|
| $u_{Ri}$ | $\mathbf{1}$ | $2/3$ | $u$ |
| $d_{Ri}$ | $\mathbf{1}$ | $-1/3$ | $d$ |
| $(Q_i)^\dagger$ | $\mathbf{2}$ | $-1/6$ | $Q$ |
| $(L_i)^\dagger$ | $\mathbf{2}$ | $1/2$ | $L$ |
| $e_{R_i}$ | $\mathbf{1}$ | $-1$ | $e$ |
| $(L'_L)^\dagger$ | $\mathbf{2}$ | $1/2$ | $-x'$ |
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| $\chi_\alpha$ | $\mathbf{1}$ | $0$ | $z_\alpha$ |

No discrete symmetries!

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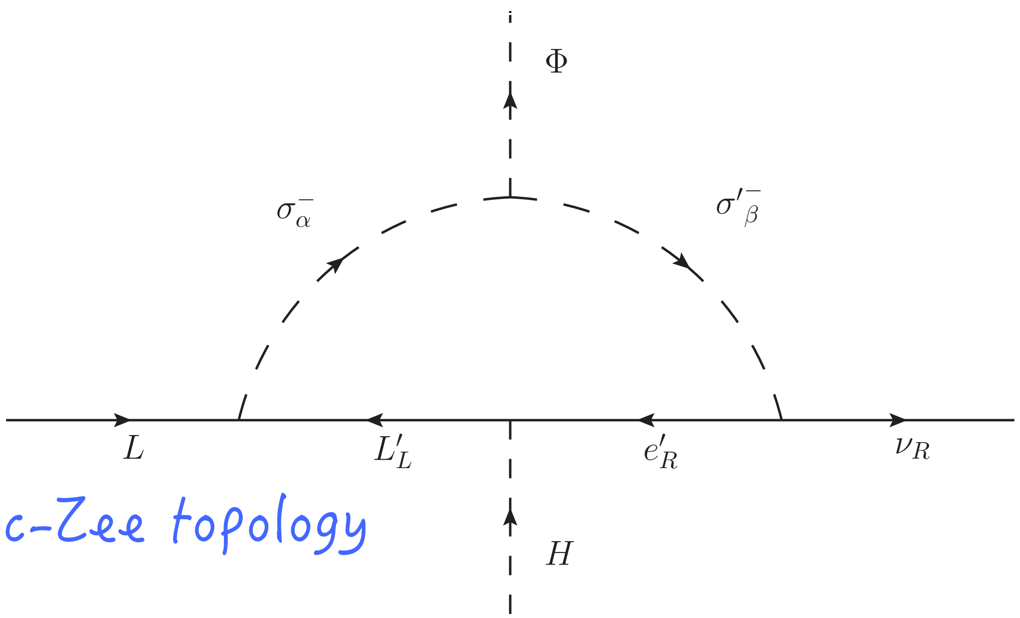


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At least two of the singlets must correspond to right-handed neutrinos associated with light Dirac neutrino masses

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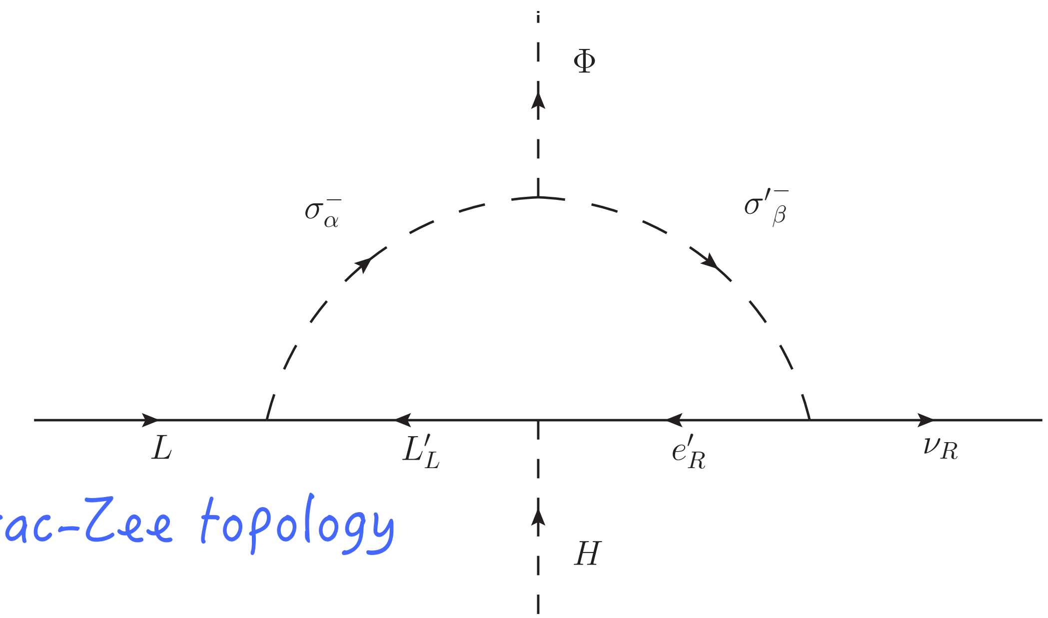


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Two of the singlets form the Dirac dark matter particle

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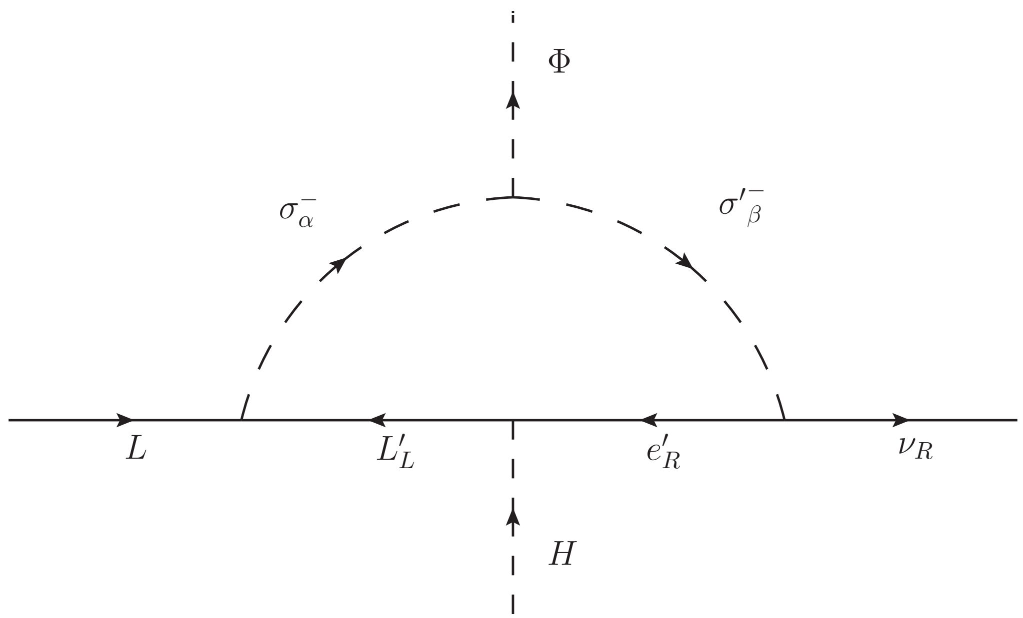


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## Anomaly cancellation

$$[\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_Y,\ [\mathrm{U}(1)_X]^3 \quad \longrightarrow \quad \sum_{\alpha=1}^{N} z_\alpha = 0\,, \quad \sum_{\alpha=1}^{N} z_\alpha^3 = 0$$

Costa, Dobrescu, Fox, PRL (2019)

$$[\mathrm{SU}(3)_c]^2\,\mathrm{U}(1)_X,\ [\mathrm{SU}(2)_L]^2\,\mathrm{U}(1)_X,\ [\mathrm{U}(1)_Y]^2\,\mathrm{U}(1)_X$$

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

$$[\mathrm{U}(1)_X]^2\,\mathrm{U}(1)_Y \quad \longrightarrow \quad (e + L)(x' - x'') = 0 \quad \longrightarrow \quad e = -L$$

See also Restrepo & Suarez, arXiv:2112.09529

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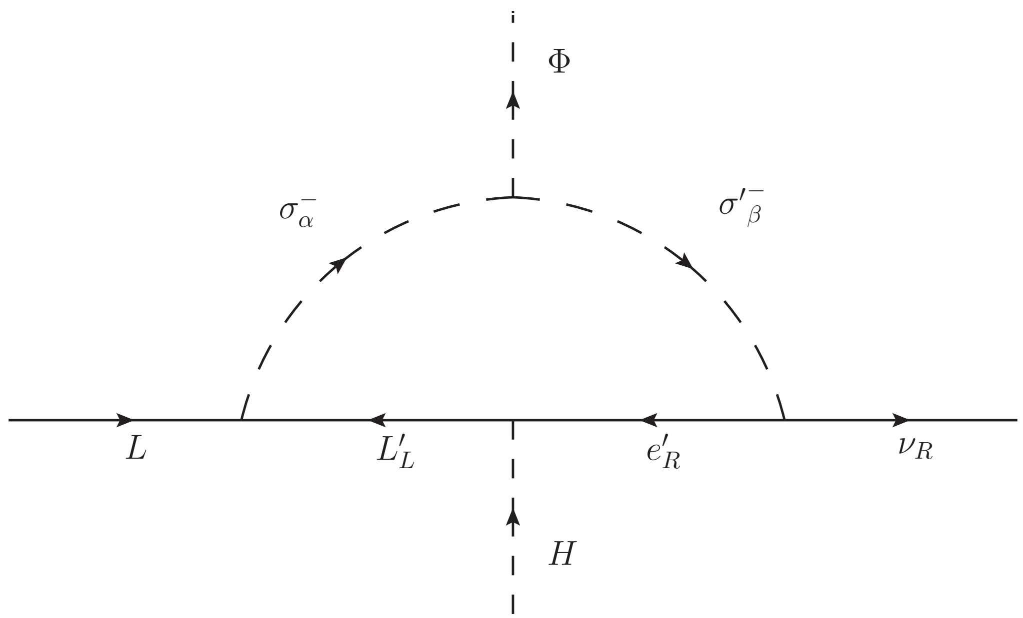


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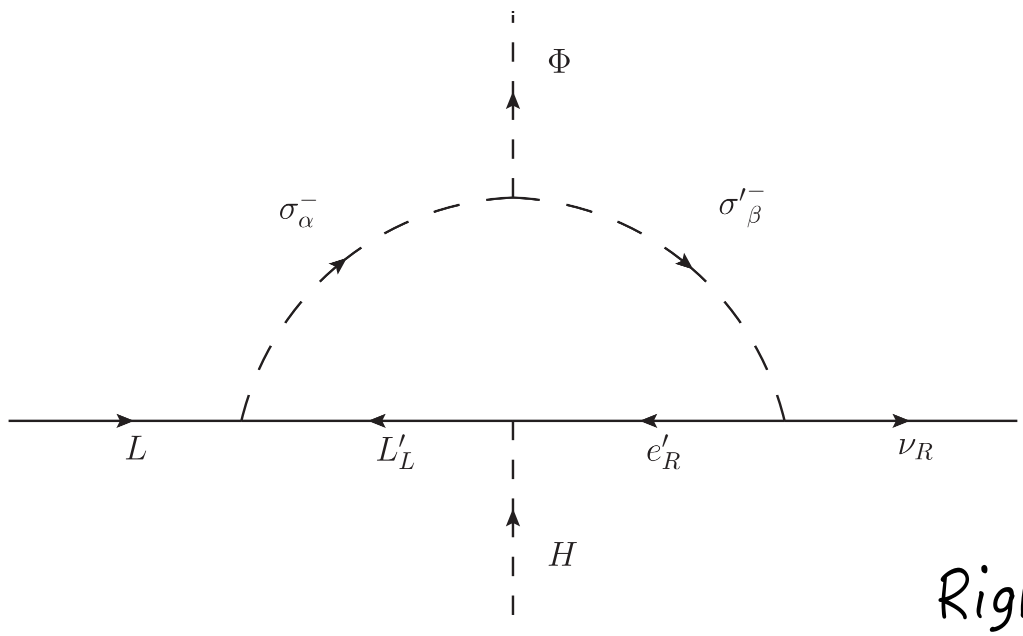
$$\longrightarrow \quad u = -e - \frac{2}{3}L - \frac{1}{9}(x' - x'')\,,\quad d = e + \frac{4}{3}L - \frac{1}{9}(x' - x'')\,,\quad Q = -\frac{1}{3}L + \frac{1}{9}(x' - x'')$$

$$[\mathrm{U}(1)_X]^2\,\mathrm{U}(1)_Y \longrightarrow (e+L)(x' - x'') = 0 \longrightarrow e = -L$$

See also Restrepo & Suarez, arXiv:2112.09529

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

# Scotogenic model with a gauged $\mathrm{U}(1)_B$




Right-handed neutrinos

Dirac DM

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|---|---|---|---|
| $u_{Ri}$ | $\mathbf{1}$ | $2/3$ | $u = 1/3$ |
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| $(Q_i)^\dagger$ | $\mathbf{2}$ | $-1/6$ | $Q = -1/3$ |
| $(L_i)^\dagger$ | $\mathbf{2}$ | $1/2$ | $L = 0$ |
| $e_R$ | $\mathbf{1}$ | $-1$ | $e = 0$ |
| $(L'_L)^\dagger$ | $\mathbf{2}$ | $1/2$ | $-x' = -3/5$ |
| $e'_R$ | $\mathbf{1}$ | $-1$ | $x' = 3/5$ |
| $L''_R$ | $\mathbf{2}$ | $-1/2$ | $x'' = 18/5$ |
| $(e''_L)^\dagger$ | $\mathbf{1}$ | $1$ | $-x'' = -18/5$ |
| $\nu_{R,1}$ | $\mathbf{1}$ | $0$ | $-3$ |
| $\nu_{R,2}$ | $\mathbf{1}$ | $0$ | $-3$ |
| $\chi_R$ | $\mathbf{1}$ | $0$ | $6/5$ |
| $(\chi_L)^\dagger$ | $\mathbf{1}$ | $0$ | $9/5$ |
| $H$ | $\mathbf{2}$ | $1/2$ | $0$ |
| $S$ | $\mathbf{1}$ | $0$ | $3$ |
| $\Phi$ | $\mathbf{1}$ | $0$ | $3$ |
| $\sigma_\alpha^-$ | $\mathbf{1}$ | $1$ | $3/5$ |
| $\sigma'^-_\alpha$ | $\mathbf{1}$ | $-1$ | $-12/5$ |

Dirac- neutrino mass mass

$$\mathcal{L}_{\rm eff} = h_\nu^{\alpha i}\,(\nu_{R\alpha})^\dagger\,\epsilon_{ab}\,L_i^a\,H^b\left(\frac{\Phi^*}{\Lambda}\right)$$

$$\langle\Phi\rangle = v_\Phi/\sqrt{2}$$

$$\langle H\rangle = v/\sqrt{2}$$

$$m_{Z'} = 3 g_B v_\Phi$$

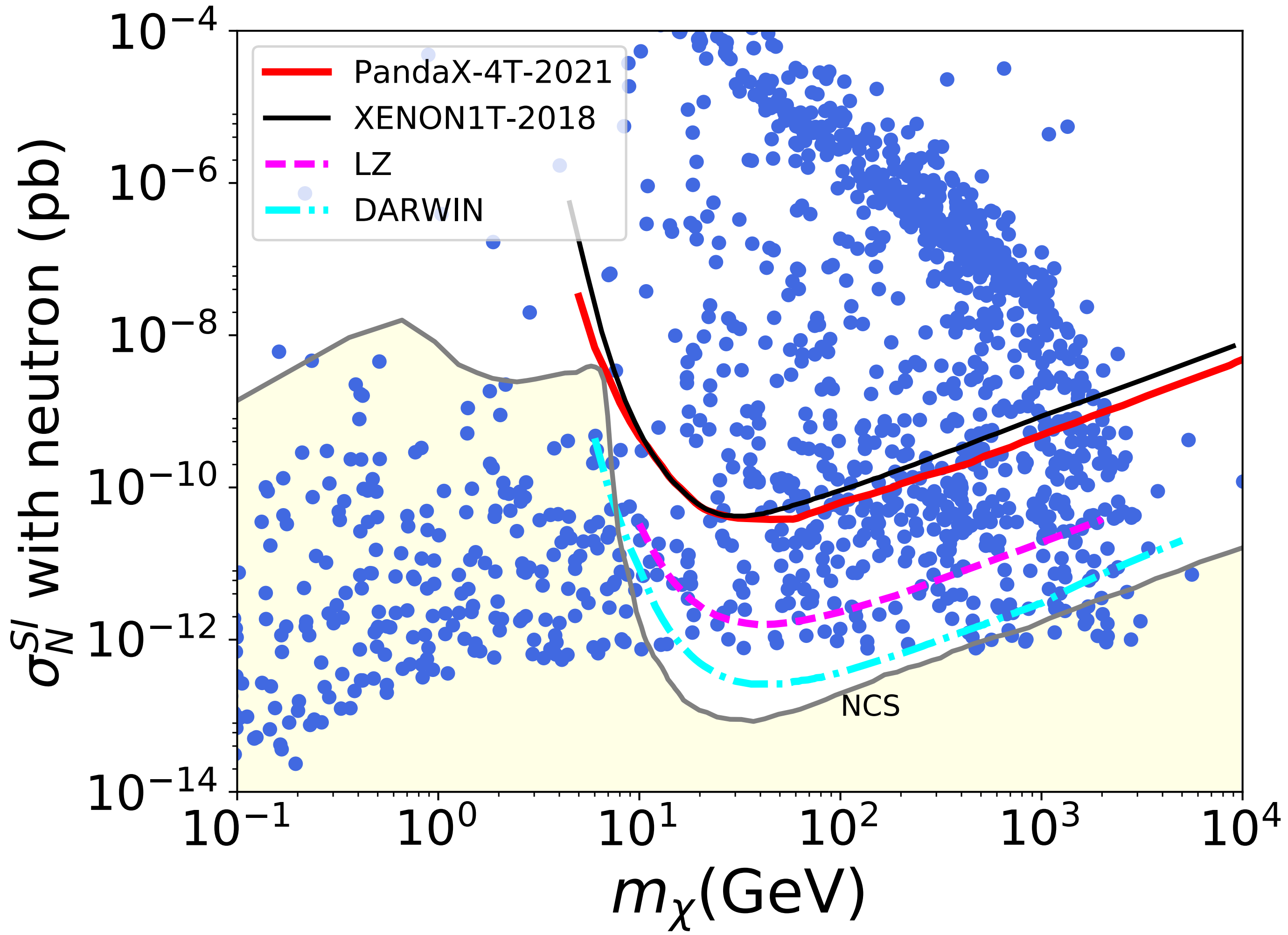
$$\begin{aligned}-\mathcal{L} \supset\ & h_{a,\Phi}\,(\chi_L)^\dagger\,\chi_R\Phi^* + h_{b,\Phi}\,(e'_R)^\dagger\,e''_L\Phi^* + h_{c,\Phi}(L'_L)^\dagger L''_R\Phi^* + h_d^{i\alpha} L'_L L_i \sigma_\alpha^+ \\ &+ h_{a,S}\,(\chi_L)^\dagger\,\chi_R S^* + h_{b,S}\,(e'_R)^\dagger\,e''_L S^* + h_{c,S}(L'_L)^\dagger L''_R S^* \\ &+ h_e^{\alpha\beta}\nu_{R,\alpha}e'_R\sigma'^+_\beta + h_g H^\dagger\,(e'_R)^\dagger\,L'_L + h_h(L''_R)^\dagger e''_L H + \text{ h.c.}\,,\end{aligned}$$

$$\begin{aligned}V(H,S,\Phi,\sigma_\alpha^\pm,\sigma'^\pm_\alpha) =& V(H)+V(S)+V(\Phi)+V(\sigma_\alpha^\pm)+V(\sigma'^\pm_\alpha) \\ &+\left[\kappa_S^{\alpha\beta}S\sigma_\alpha^+\sigma'^-_\beta + \kappa_\Phi^{\alpha\beta}\Phi\sigma_\alpha^+\sigma'^-_\beta\ + \lambda'_{S\Phi}\,(S^*\Phi)^2 + \text{h.c.}\right]\end{aligned}$$

# Scotogenic model with a gauged $U(1)_B$

SARAH+SPheno: Mass spectrum

MicrOMEGAs: Relic abundance




The blue dots give the correct relic abundance and reproduce the neutrino parameters

# Dark CP violation and electroweak baryogenesis

Baryogenesis results from the dynamics of the same hidden-sector fields that are also responsible for dark matter and neutrino masses.

At the first-order phase transition, bubbles nucleate and expand through the primordial plasma, causing perturbations on the particle and antiparticle densities.

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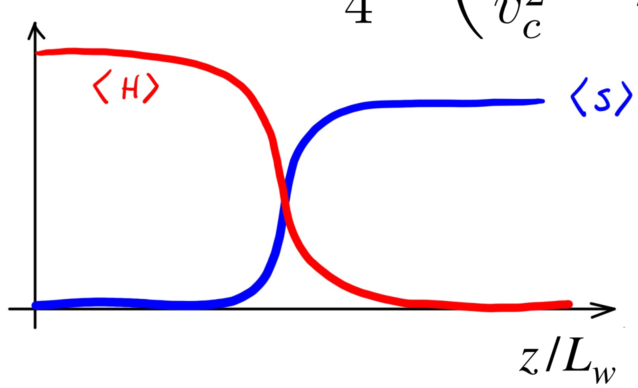
| $\chi_R$ | $\mathbf{1}$ | $0$ | $6/5$ |
| $(\chi_L)^\dagger$ | $\mathbf{1}$ | $0$ | $9/5$ |
| $H$ | $\mathbf{2}$ | $1/2$ | $0$ |
| $S$ | $\mathbf{1}$ | $0$ | $3$ |
| $\Phi$ | $\mathbf{1}$ | $0$ | $3$ |
| $\sigma_\alpha^-$ | $\mathbf{1}$ | $1$ | $3/5$ |
| $\sigma'^-_\alpha$ | $\mathbf{1}$ | $-1$ | $-12/5$ |

$$H = h/\sqrt{2} \qquad s = |S|$$

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




See also
Cline, Kainulainen, Tucker-Smith PRD (2017)
Carena, Quirós, Zhang PRL, PRD (2020)

# Dark CP violation and electroweak baryogenesis

At the first-order phase transition, bubbles nucleate and expand through the primordial plasma, causing perturbations on the particle and antiparticle densities.

$P$ and $CP$ violation is incorporated by adding a term $\delta V(S,\Phi) = \tilde{\lambda}_{\Phi S}\Phi^{*2}S^2$

After $\Phi$ acquires a vacuum, $M_\chi = m_\chi + \lambda e^{i\theta} s$

This generates an asymmetry in the interior of the bubble,

$$\xi_i(z) \equiv \mu_i(z)/T = 6\,(n_i - \overline{n}_i)\,/T^3 \longrightarrow \langle Z_0' \rangle = \frac{g_B\,(q_{\chi_L} - q_{\chi_R})T_n^3}{6M_{Z'}} \int_{-\infty}^{\infty} \mathrm{d}\,z'\,\xi_{\chi_L}(z')\,e^{-M_{Z'}|z-z'|}$$

See also
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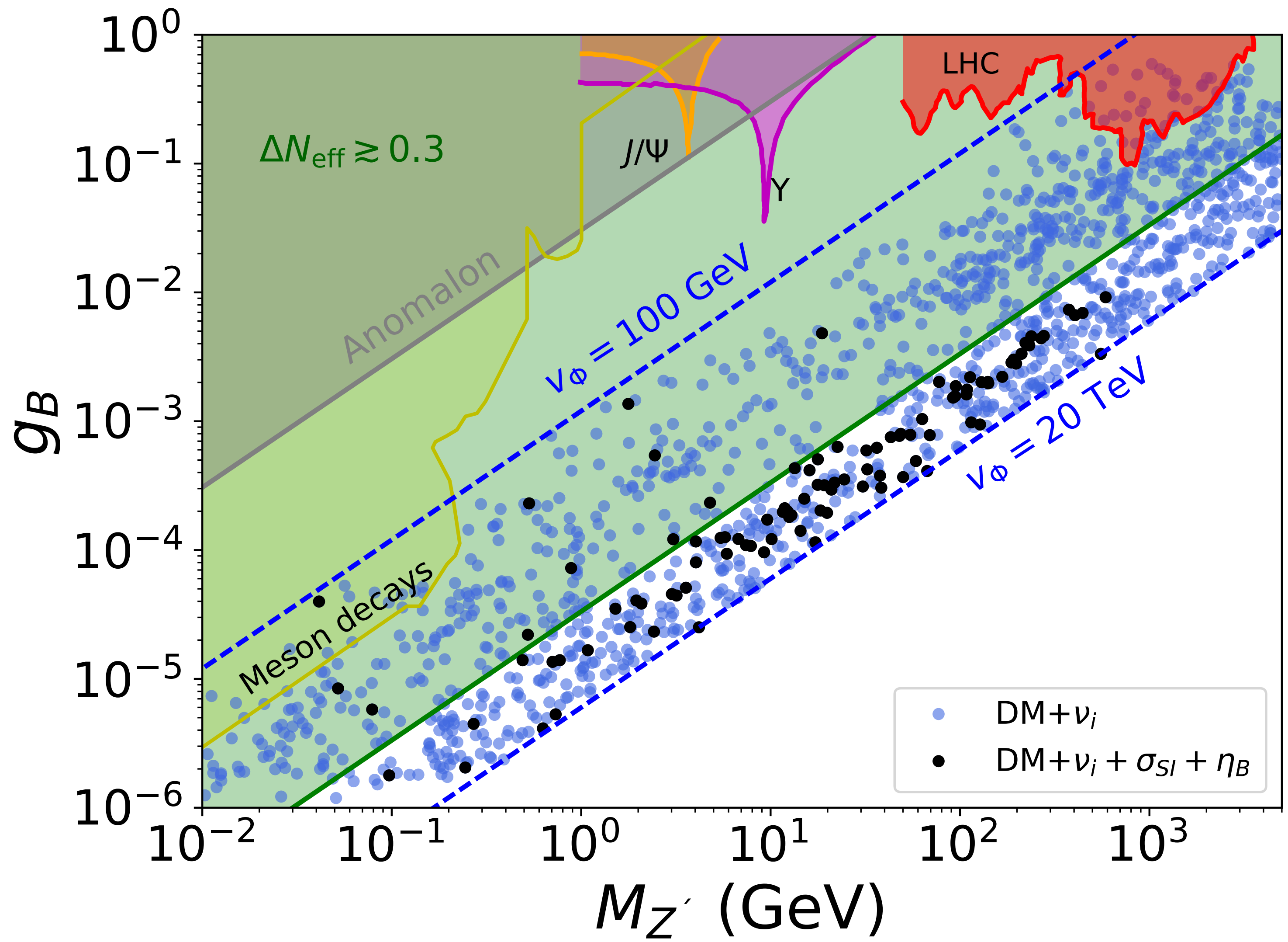


The blue points are the models that fulfill the relic abundance of DM and the neutrino masses. The black points are not excluded by direct detection of DM and give the observed baryon asymmetry at the Universe. The green-shaded region is in tension with the measured number of relativistic degrees of freedom

# Conclusions

We have presented a viable framework for small neutrino masses and Dirac dark matter, in which all new fields play an important role in solving both problems. Furthermore, these fields are also responsible for baryogenesis in the case of a gauged baryon number.

The gauging of baryon number eliminates the necessity of extra discrete symmetries to ensure the stability of DM and the absence of Majorana neutrino masses. In that model, the baryon asymmetry is generated in the hidden sector and is communicated to the visible sector via a non-zero background of the new vector boson.

¡Gracias!

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