

# Dark matter from SM gauge extensions

## with neutrino masses

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Diego Restrepo

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



Focus on

In collaboration with

M. Hirsch (IFIC), C. Álvarez (UTFSM), A. Flórez (UniAndes), B. Dutta (Texas A&M), C. Yaguna (UPTC), J. Calle, O. Zapata, A. Rivera (UdeA), W. Tangarife (Loyola University Chicago)

## Dark sectors

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In the following discussion we use the following doublets in Weyl Notation

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, \quad L_i = \begin{pmatrix} \nu_{Li} \\ e_{Li}^- \end{pmatrix}. \quad (1)$$

corresponding to the Higgs doublet and the lepton doublets respectively.





$$m_{\text{Majorana}}^{\nu} = \frac{h_{\nu}}{\Lambda} L \cdot H L \cdot H \quad (\text{three-level})$$

Type-I arXiv:1808.03352, II arXiv:1607.04029, III arXiv:1908.04308

3 models

$$\mathcal{L} = y(N_R)^\dagger L \cdot H + M_N N_R N_R + \text{h.c.}$$

Type-I  
seesaw



$$m_{\text{Majorana}}^\nu = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H$$

Type-I arXiv:1808.03352, with N. Bernal, C. Yaguna, and Ó. Zapata [PRD]

$$\mathcal{L} = y (N_R)^\dagger L \cdot \langle H \rangle + y' \langle S \rangle N_R N_R + \text{h.c}$$

$$U(1)_X \rightarrow Z_7$$



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: Also new terms arise  
from spontaneous  
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Local  $U(1)_X \rightarrow Z_7$

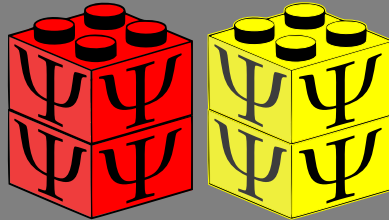
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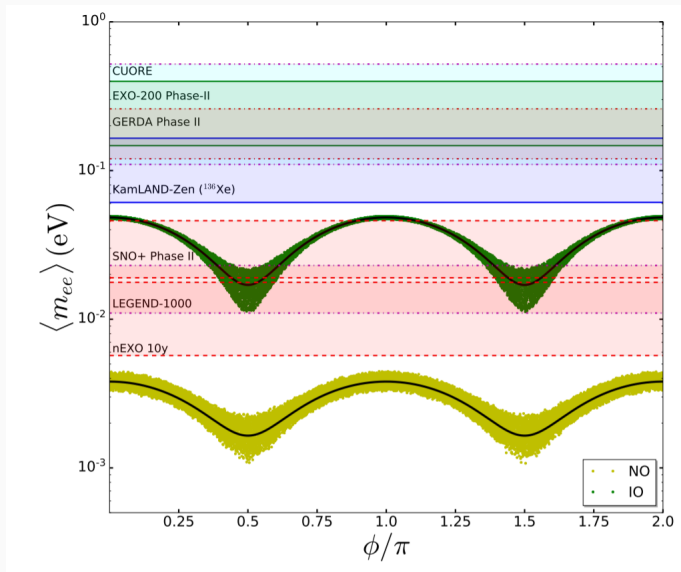




# Neutrino masses

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- Lepton number ( $L$ ) is an accidental discrete or Abelian symmetry of the standard model (SM).
- Without neutrino masses  $L_e$ ,  $L_\mu$ ,  $L_\tau$  are also conserved.
- The processes which violate individual  $L$  are called Lepton flavor violation (LFV) processes.
- All the neutrino mass models predict, to some extent, LFV processes
- Only models with Majorana neutrinos predict processes with total  $L = L_e + L_\mu + L_\tau$  violation, like **neutrino less doublet beta decay** (NLDBD).
- NLDBD is experimentally challenging, specially if there is a massless neutrino in the spectrum.



Total lepton number:  $L = L_e + L_\mu + L_\tau$

Majorana  $\cancel{U(1)}_L$

Field	$Z_2 (\omega^2 = 1)$
SM	1
$L$	$\omega$
$(e_R)^\dagger$	$\omega$
$(\nu_R)^\dagger$	$\omega$

$$\mathcal{L}_\nu = h_D (\nu_R)^\dagger L \cdot H + \textcolor{red}{M_R} \nu_R \nu_R + \text{h.c.}$$

$$h_D \sim \mathcal{O}(1)$$

Dirac  $U(1)_L$

Field	$Z_3 (\omega^3 = 1)$
SM	1
$L$	$\omega$
$(e_R)^\dagger$	$\omega^2$
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$$\mathcal{L}_\nu = h_D (\nu_R)^\dagger L \cdot H + \text{h.c.}$$

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Dirac  $U(1)_{B-L}$

Field	$Z_3$ ( $\omega^3 = 1$ )
SM	1
$L$	$\omega$
$(e_R)^\dagger$	$\omega^2$
$(\nu_R)^\dagger$	$\omega^2$

$$\mathcal{L}_\nu = h_D (\nu_R)^\dagger L \cdot H + \text{h.c.}$$

$$h_D \sim \mathcal{O}(10^{-11})$$

Explain smallness ala Peccei-Quinn:

$$U(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N, \quad N \geq 3.$$

# Small Dirac neutrino masses

To explain the **smallness** of Dirac neutrino masses choose  $U(1)_{B-L}$  which:

- Forbids tree-level mass (TL) term (  $Y(H) = +1/2$  )

$$\begin{aligned}\mathcal{L}_{\text{T.L}} &= h_D \epsilon_{ab} (\nu_R)^\dagger L^a H^b + \text{h.c.} \\ &= h_D (\nu_R)^\dagger L \cdot H + \text{h.c.}\end{aligned}$$

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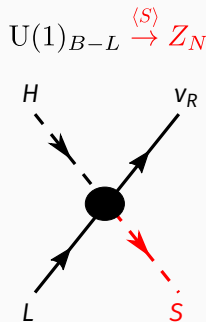
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- Forbids Majorana term:  $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ :

$$\mathcal{L}_{5-D} = \frac{h_\nu}{\Lambda} (\nu_R)^\dagger L \cdot H S + \text{h.c.}$$





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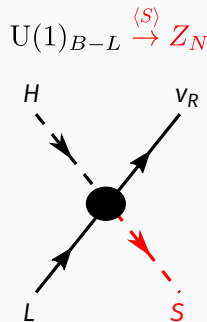
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- Enhancement to the *effective number of degrees of freedom in the early Universe*  $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$  (see arXiv:1211.0186)



See E. Ma, Rahul Srivastava: arXiv:1411.5042 [PLB] for tree-level realization



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