Dark matter from SM gauge extensions

with neutrino masses

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Focus on

In collaboration with

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Dark sectors

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

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, \qquad\qquad L_i = \begin{pmatrix} \nu_{Li} \\ e^-_{Li} \end{pmatrix}. \tag{1}$$

corresponding to the Higgs doublet and the lepton doublets respectively.

SM

3 models

SM

+

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

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

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

Type-I seesaw

SM

+

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

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

$$U(1)_X \textcolor{red}{\rightarrow Z_7}$$

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

$\langle \mathrm{SM} \rangle$

+

$$m^{\nu}_{\text{Majorana}} = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H \frac{\textcolor{red}{S}}{\Lambda}$$

Type-I arXiv:1808.03352

: Also new terms arise from spontaneous breakdown of a new gauge symmetry

Local $U(1)_X \to Z_7$

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

$\langle \text{SM} \rangle$

+

$$m^{\nu}_{\text{Majorana}} = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H \frac{S}{\Lambda}$$

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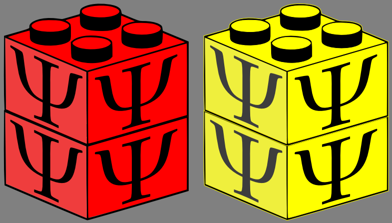

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
L	**2**	$-1/2$	l
Q	**2**	$-1/6$	q
d_R	**1**	$-1/2$	d
u_R	**1**	$+2/3$	u
e_R	**1**	-1	e
H	**2**	$-1/2$	h
ψ	**1**	0	ψ

Table 1: The new scalars and fermions with their respective charges. The SM fields have the usual $U(1)_{B-L}$ assignment. Now $\alpha = 1, 2$

$$\begin{aligned}
[\mathrm{SU}(3)_c]^2\,\mathrm{U}(1)_X: &\qquad [3u+3d]-[3\cdot 2q] = 0\\
[\mathrm{SU}(2)_L]^2\,\mathrm{U}(1)_X: &\qquad -[2l+3\cdot 2q] = 0\\
[\mathrm{U}(1)_Y]^2\,\mathrm{U}(1)_X: &\qquad \left[(-2)^2 e+3\left(\tfrac{4}{3}\right)^2 u+3\left(-\tfrac{2}{3}\right)^2 d\right]-\left[2(-1)^2 l+3\cdot 2\left(\tfrac{1}{3}\right)^2 q\right] = 0
\end{aligned} \tag{2}$$

with solution

$$u = -e + \frac{2l}{3}\,, \qquad d = e - \frac{4l}{3}\,, \qquad q = -\frac{l}{3}\,. \tag{2}$$

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which satisfy

$$\mathrm{U}(1)_Y\,[\mathrm{U}(1)_X]^2: \qquad \left[(-2)e^2 + 3\left(\tfrac{4}{3}\right)u^2 + 3\left(-\tfrac{2}{3}\right)d^2\right] - \left[2(-1)l^2 + 3\cdot 2\left(\tfrac{1}{3}\right)q^2\right] = 0 \tag{3}$$

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The most general cancellation for $[\mathrm{U}(1)_X]^3$ and $[\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_X$ is between families

$$\sum_\alpha \psi_\alpha^3 + 3(e-2l)^3 = 0, \qquad \sum_\alpha \psi_\alpha + 3(e-2l) = 0, \tag{4}$$

with $\alpha = 1, 2, \cdots, N$ or $X = Y$. We study the set of solutions with $e - 2l = 1$, e.g

$$\sum_\alpha \psi_\alpha^3 = -3, \qquad \sum_\alpha \psi_\alpha = -3, \tag{5}$$

with solution

$$u = -e + \frac{2l}{3}\,, \qquad d = e - \frac{4l}{3}\,, \qquad q = -\frac{l}{3}\,. \tag{2}$$

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$$\sum_\alpha \psi_\alpha^3 = -3\,, \qquad \sum_\alpha \psi_\alpha = -3\,, \tag{5}$$

We impose $N_R = \psi_N = \psi_{N-1}$, to have at most one massless neutrino.

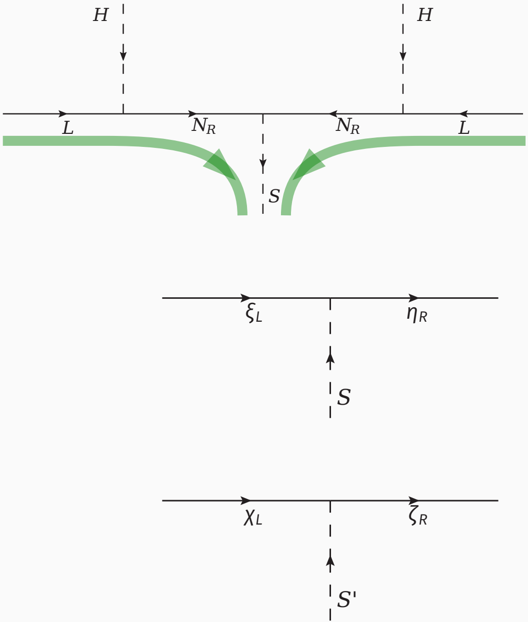
Known solutions with $\sum \psi_\alpha = -3$ and $\sum \psi_\alpha^3 = -3$

$(N_R, N_R, \psi_{N-2}, \cdots)$	Ref
$(-1, -1, -1)$	[]
$(-4, -4, +5)$	[?]
$\left(-\frac{2}{3}, -\frac{2}{3}, -\frac{4}{3}, -\frac{1}{3}\right)$	[?]
$\left(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, +2\right)$	[?]
$\left(-\frac{7}{3}, -\frac{7}{3}, +\frac{1}{3}, -\frac{5}{3}, +3\right)$	[]
$\left(-\frac{7}{10}, -\frac{7}{10}, -\frac{13}{10}, -\frac{1}{2}, +\frac{1}{5}\right)$	[]
$\left(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7}\right)$	[?]

Table 2: The possible solutions of the Dirac neutrino mass models with at least two repeated charges and until five chiral fermions.

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$U(1)_{B-L}$	$U(1)_B$	$U(1)_D$	$U(1)_G$
L	$\mathbf{2}$	$-1/2$	l	-1	0	$-3/2$	$-1/2$
Q	$\mathbf{2}$	$-1/6$	$-l/3$	$1/3$	0	$1/2$	$1/6$
d_R	$\mathbf{1}$	$-1/2$	$1+2l/3$	$1/3$	1	0	$2/3$
u_R	$\mathbf{1}$	$+2/3$	$-1-4l/3$	$1/3$	-1	1	$-1/3$
e_R	$\mathbf{1}$	-1	$1+2l$	-1	1	-2	0
H	$\mathbf{2}$	$-1/2$	$-1-l$	0	-1	$1/2$	$-1/2$
S	$\mathbf{1}$	0	$2\psi_N$	$2\psi_N$	$2\psi_N$	$2\psi_N$	$2\psi_N$
$\sum_\alpha \psi_\alpha$	$\mathbf{1}$	0	-3	-3	-3	-3	-3
$\sum_\alpha \psi_\alpha^3$	$\mathbf{1}$	0	-3	-3	-3	-3	-3

Fields	$U(1)_{B-L}$
L	-1
Q	$1/3$
d_R	$1/3$
u_R	$1/3$
e_R	-1
H	0
S	-2
N_{R1}	-1
N_{R2}	-1
$\psi_1 \to (\xi_L)^\dagger$	$-10/7$
$\psi_2 \to \eta_R$	$-4/7$
$\psi_3 \to \zeta_R$	$-2/7$
$\psi_4 \to (\chi_L)^\dagger$	$+9/7$
S'	1

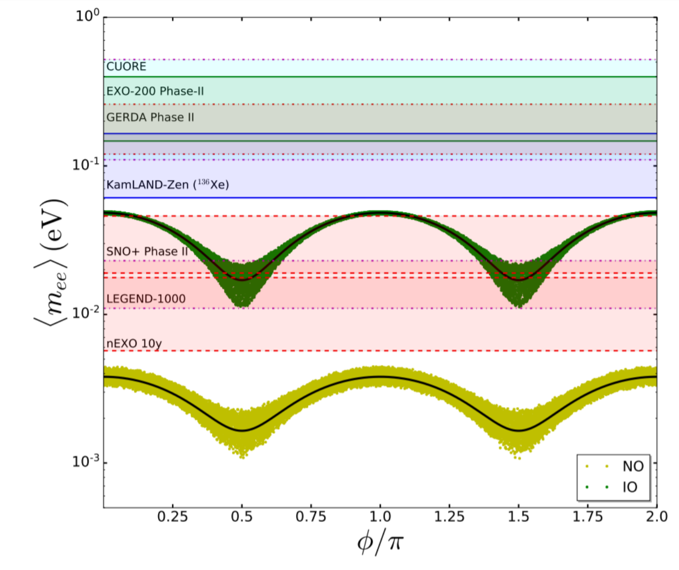


Neutrino masses

Lepton number

- Lepton number (L) is an accidental discret or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e, L_μ, L_τ are also conserved.
- The processes which violates 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.

NLDBD prospects for a model with a massless neutrino (arXiv:1806.09977 [PLB] with Reig, Valle and Zapata)



with M.Reig, J.W.F Valle, O. Zapata, arXiv:1806.09977

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

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

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

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

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

Dirac $\mathrm{U}(1)_L$

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

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

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

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

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

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

Small Dirac neutrino masses

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

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

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

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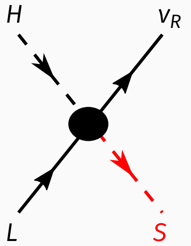
$$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N$$



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

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

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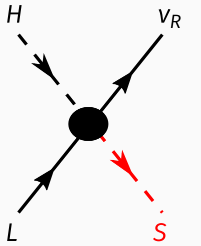

- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - N_{\mathrm{eff}}^{\mathrm{SM}}$ (see arXiv:1211.0186)

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

SM

+

$$m^{\nu}_{\text{Majorana}} = \frac{1}{\Lambda} L \cdot H L \cdot H$$

$$m^{\nu}_{\text{Dirac}} = \frac{1}{\Lambda} (\nu_R)^{\dagger} L \cdot H S$$

SM

+

$$m^{\nu}_{\text{Majorana}} = \frac{1}{\Lambda} L \cdot H L \cdot H$$

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