

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

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

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]

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

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



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

Type-I arXiv:1808.03352

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

Local $U(1)_X \rightarrow Z_7$

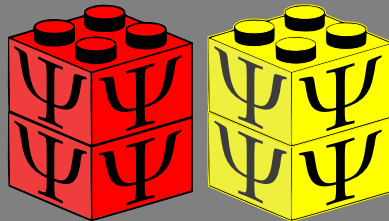
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Type-I arXiv:1808.03352

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



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 $\alpha = 1, 2$

$$[\mathrm{SU}(3)_c]^2 \mathrm{U}(1)_X : \quad [3u + 3d] - [3 \cdot 2q] = 0$$

$$[\mathrm{SU}(2)_L]^2 \mathrm{U}(1)_X : \quad -[2l + 3 \cdot 2q] = 0$$

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

with solution

$$u = -e + \frac{2l}{3},$$

$$d = e - \frac{4l}{3},$$

$$q = -\frac{l}{3}. \quad (2)$$

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which satisfy

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

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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

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

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

$$\sum_{\alpha} \psi_{\alpha}^3 = -3, \quad \sum_{\alpha} \psi_{\alpha} = -3, \quad (5)$$

with solution

$$u = -e + \frac{2l}{3}, \quad d = e - \frac{4l}{3}, \quad q = -\frac{l}{3}. \quad (2)$$

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$$\sum_{\alpha} \psi_{\alpha}^3 = -3, \quad \sum_{\alpha} \psi_{\alpha} = -3, \quad (5)$$

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

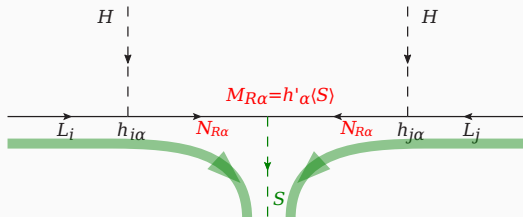
Known solutions with $\sum \psi_\alpha = -3$ and $\sum \psi_\alpha^3 = -3$

$(N_R, N_R, \psi_{N-2}, \dots)$	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	2	$-1/2$	l	-1	0	$-3/2$	$-1/2$
Q	2	$-1/6$	$-l/3$	$1/3$	0	$1/2$	$1/6$
d_R	1	$-1/2$	$1 + 2l/3$	$1/3$	1	0	$2/3$
u_R	1	$+2/3$	$-1 - 4l/3$	$1/3$	-1	1	$-1/3$
e_R	1	-1	$1 + 2l$	-1	1	-2	0
H	2	$-1/2$	$-1 - l$	0	-1	$1/2$	$-1/2$
S	1	0	$2\psi_N$	$2\psi_N$	$2\psi_N$	$2\psi_N$	$2\psi_N$
$\sum_{\alpha} \psi_{\alpha}$	1	0	-3	-3	-3	-3	-3
$\sum_{\alpha} \psi_{\alpha}^3$	1	0	-3	-3	-3	-3	-3

Fields	$U(1)_{B-L}$	Z_2^1	Z_2^1
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	$+$	$+$
$\psi_1 \rightarrow (\xi_L)^\dagger$	$-10/7$	$-$	$+$
$\psi_2 \rightarrow \eta_R$	$-4/7$	$-$	$+$
$\psi_3 \rightarrow \zeta_R$	$-2/7$	$+$	$-$
$\psi_4 \rightarrow (\chi_L)^\dagger$	$+9/7$	$+$	$-$
S'	1	$+$	$+$

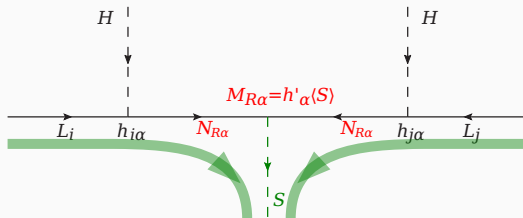


After integrating out heavy fermions, we obtain
light neutrino masses

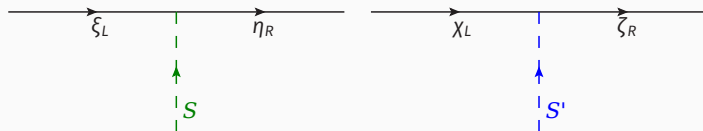
$$\mathcal{M}_{\nu}^{ij} = \sum_{\alpha=1}^2 (h^{i\alpha} v) \frac{1}{M_R^{\alpha}} (h^{j\alpha} v)$$

With only two heavy fermions, one massless neutrino is left

Fields	$U(1)_{B-L}$	Z_2^1	Z_2^1
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	$+$	$+$
$\psi_1 \rightarrow (\xi_L)^\dagger$	$-10/7$	$-$	$+$
$\psi_2 \rightarrow \eta_R$	$-4/7$	$-$	$+$
$\psi_3 \rightarrow \zeta_R$	$-2/7$	$+$	$-$
$\psi_4 \rightarrow (\chi_L)^\dagger$	$+9/7$	$+$	$-$
S'	1	$+$	$+$



Two component Dirac fermion dark matter



$$\chi_1 = \begin{pmatrix} \xi_L \\ \eta_R \end{pmatrix},$$

$$\mathcal{L} = M_1 \bar{\chi}_1 \chi_1$$

$$\chi_2 = \begin{pmatrix} \chi_L \\ \zeta_R \end{pmatrix}$$

$$+ M_2 \bar{\chi}_2 \chi_2$$

Relic abundance

$$\Omega_{\text{DM}} h^2 = 0.1198 \pm 0.0015 \quad \text{Planck 2015}$$

Boltzman equation

$$\frac{dY}{dx} = -\frac{s\langle\sigma v\rangle}{xH(m_{\text{DM}})} \left(Y^2 - Y_{\text{EQ}}^2 \right)$$

$$s = \frac{2\pi^2}{45} g_{\star} \frac{m_{\text{DM}}^3}{x^3}$$

$$H(m_{\text{DM}}) = \sqrt{\frac{4\pi^3}{45}} g_{\star} \frac{m_{\text{DM}}^2}{M_{\text{Pl}}}$$

$$sY_{\text{EQ}} = \frac{g_{\text{DM}}}{2\pi^2} \frac{m_{\text{DM}}^3}{x} K_2(x)$$

$$x = m_{\text{DM}}/T$$

$M_{\text{Pl}} = 1.22 \times 10^{19} \text{ GeV}$: the Planck mass

$g_{\text{DM}} = 2$: the number of DM d.o.f

$g_{\star} = 106.75$: for the SM particles

K_2 : the modified Bessel function

sigmav

$$\langle \sigma v \rangle = \frac{g_{DM}^2}{64\pi^4} \left(\frac{m_{DM}}{x} \right) \frac{1}{n_{EQ}^2} \int_{4m_{DM}^2}^{\infty} ds \hat{\sigma}(s) \sqrt{s} K_1 \left(\frac{x\sqrt{s}}{m_{DM}} \right)$$

where

n_{EQ} : DM number density

K_1 : Modified Bessel function

Reduced cross section

$$\hat{\sigma}(s) = 2 (s - 4m_{DM}^2) \sigma(s)$$

DM annihilation cross section

DM annihilation processes



Total annihilation cross section: $\sigma(s) = \sigma_{SM}(s) + \sum_{i=1}^2 \sigma_{N^i N^i}(s)$

$$\sigma_{SM}(s) = \frac{25\pi}{3} \alpha_X^2 \frac{\sqrt{s(s - 4m_{DM}^2)}}{(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} F(x_H),$$

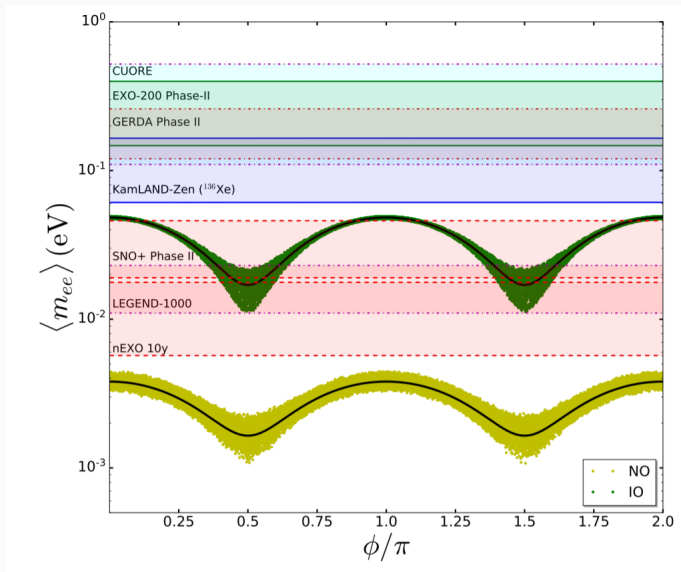
$$\sigma_{N^i N^i}(s) = \frac{400\pi}{3} \alpha_X^2 \sqrt{\frac{s - 4m_{N^i}^2}{s - 4m_{DM}^2}} \frac{1}{(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2}$$

$$\times \frac{1}{s} \left((s - 4m_{DM}^2)(s - 4m_{N^i}^2) + 12 \frac{m_{DM}^2 m_{N^i}^2}{m_{Z'}^4} (s - m_{Z'}^2)^2 \right) \theta(s - 4m_{N^i}^2)$$

$$F(x_H) = 13 + 16x_H + 10x_H^2 = 10 \left(x_H + \frac{4}{5} \right)^2 + \frac{33}{5}$$

Neutrino masses

- Lepton number (L) is an accidental discrete or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e , L_μ , L_τ 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	ω
$(e_R)^\dagger$	ω
$(\nu_R)^\dagger$	ω

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

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

Dirac $U(1)_L$

Field	$Z_3 (\omega^3 = 1)$
SM	1
L	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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Majorana $U(1)_L$

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

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:

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

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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- Forbids Majorana term: $\nu_R \nu_R$

Small Dirac neutrino masses

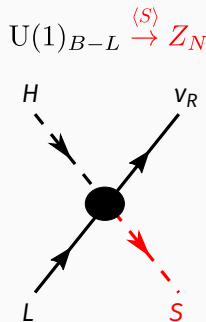
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- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$:

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



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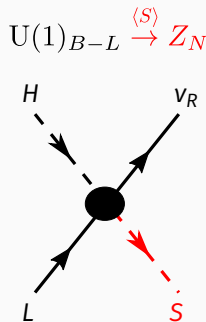
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$$\mathcal{L}_{5-D} = \frac{h_\nu}{\Lambda} (\nu_R)^\dagger L \cdot H S + \text{h.c.}$$

- 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



+

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

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



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