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

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

corresponding to the Higgs doublet and the lepton doublets respectively.

SM

3 models

SM

+

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

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

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

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]

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

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

$\langle$**SM**$\rangle$

+

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

Type-I arXiv:1808.03352

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

Local $U(1)_X \to Z_7$

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

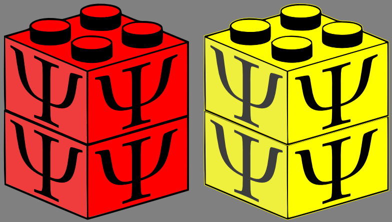
$\langle$SM$\rangle$

+

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

Type-I arXiv:1808.03352

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



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 $\alpha = 1, 2$

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

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

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

with solution

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

which satisfy

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

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

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

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

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

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

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

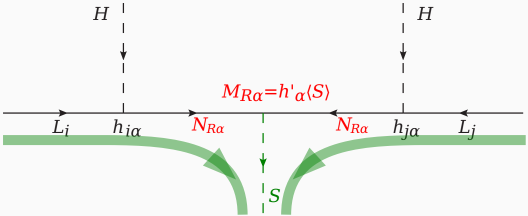
Known solutions with $\sum \psi_\alpha = -3$ and $\sum \psi_\alpha^3 = -3$

$(N_R, N_R, \psi_{N-2}, \cdots)$	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	$U(1)_{B-L}$	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	$+$	$+$
$\psi_1 \to (\xi_L)^\dagger$	$-10/7$	$-$	$+$
$\psi_2 \to \eta_R X$	$-4/7$	$-$	$+$
$\psi_3 \to \zeta_R$	$-2/7$	$+$	$-$
$\psi_4 \to (\chi_L)^\dagger$	$+9/7$	$+$	$-$
S'	1	$+$	$+$

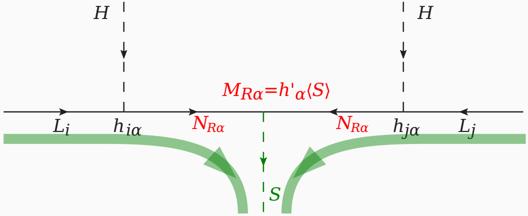


After integrating out heavy fermions, we obtain light neutrino masses

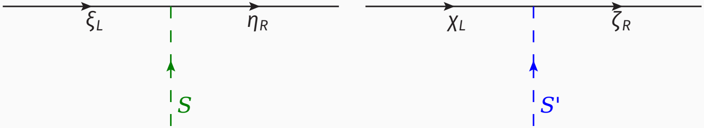
$$\boxed{\mathcal{M}_\nu^{ij} = \sum_{\alpha=1}^{2} (h^{i\alpha} v) \, \frac{1}{M_R^\alpha} \, (h^{j\alpha} v)}$$

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	$+$	$+$
$\psi_1 \to (\xi_L)^\dagger$	$-10/7$	$-$	$+$
$\psi_2 \to \eta_R X$	$-4/7$	$-$	$+$
$\psi_3 \to \zeta_R$	$-2/7$	$+$	$-$
$\psi_4 \to (\chi_L)^\dagger$	$+9/7$	$+$	$-$
S'	1	$+$	$+$



Two component Dirac fermion dark matter



$$\chi_1 = \begin{pmatrix} \xi_L \\ \eta_R \end{pmatrix}, \qquad \chi_2 = \begin{pmatrix} \chi_L \\ \zeta_R \end{pmatrix}$$

$$\mathcal{L} = M_1 \overline{\chi_1}\chi_1 + M_2 \overline{\chi_2}\chi_2$$

Parameter space

$$S = \frac{1}{\sqrt{2}} (v_1 + h_1) + \frac{i}{\sqrt{2}} A_1$$

$$S' = \frac{1}{\sqrt{2}} (v_2 + h_2) + \frac{i}{\sqrt{2}} A_2$$

Parameter space

$$S = \frac{1}{\sqrt{2}}(v_1 + h_1) + \frac{i}{\sqrt{2}}A_1$$

$$S' = \frac{1}{\sqrt{2}}(v_2 + h_2) + \frac{i}{\sqrt{2}}A_2$$

$$G',\ A$$

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

$$M_{Z'}^2 = g_{BL}^2 v_2^2 \left(4 + \tan^2\beta\right)$$

Parameter space

$$S = \frac{1}{\sqrt{2}}(v_1 + h_1) + \frac{i}{\sqrt{2}}A_1$$

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$$\tan\beta = \frac{v_2}{v_1}$$

$$M_{Z'}^2 = g_{BL}^2 v_2^2 \left(4 + \tan^2\beta\right)$$

$$\mathcal{L} = {\color{green}M_1}\overline{\chi_1}\chi_1 + {\color{blue}M_2}\overline{\chi_2}\chi_2 + M_{N1}\overline{N_{R1}^c}N_{R1} + M_{N2}\overline{N_{R2}^c}N_{R2}$$

Parameter space

$$S = \frac{1}{\sqrt{2}}\left(v_1 + h_1\right) + \frac{i}{\sqrt{2}} A_1$$

$$S' = \frac{1}{\sqrt{2}}\left(v_2 + h_2\right) + \frac{i}{\sqrt{2}} A_2$$

$$G', A$$

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

11 parameters

$$M_{Z'}^2 = g_{BL}^2 v_2^2 \left(4 + \tan^2\beta\right)$$

$$m_\chi = M_1 \text{or } M_2$$

$$\mathcal{L} = M_1 \overline{\chi_1}\chi_1 + M_2 \overline{\chi_2}\chi_2 + M_{N1} \overline{N_{R1}^c} N_{R1} + M_{N2} \overline{N_{R2}^c} N_{R2}$$

Relic abundance

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

Boltzman equation

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

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

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

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

$x = m_\chi / T$

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

$g_\chi = 4$: the number of DM d.o.f

$g_* = 106.75$: for the SM particles

K_2 : the modified Bessel function

sigmav

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

where

n_{EQ}: DM number density

K_1: Modified Bessel function

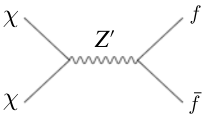
Reduced cross section

$$\hat{\sigma}(s) = 2\left(s - 4m_\chi^2 \sigma(s)\right)$$

DM annihilation cross section

From 1811.11927, Okada, et al, [PRD] and talk at SUSY 2019

DM annihilation processes



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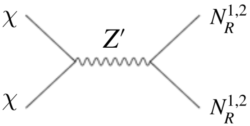

Total annihilation cross section: $\sigma(s) = \sigma_{SM}(s) + \sum_{i=1}^{2} \sigma_{N^i N^i}(s)$

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

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

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

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

→https://github.com/restrepo/WIMP → WIMP.ipynb → Open in Colab

WIMP.ipynb - Colaboratory

https://colab.research.google.com/drive/1xeN7waRalplV1mlWcwNtKdd1BulosJmM#scrollTo=0Ox2eXrZk7bX

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Dark Matter Boltzmann equation

This program is made to reproduce the behavior of dark matter yield in WIMP and FIMP frameworks based on Chapter 5th, Kolb Turner (Early Universe)

```
[ ] %pylab inline
    import numpy as np
    from numpy import arange
    from scipy.integrate import odeint
```

```
[ ] # parameters

    Ms = 100                                 #GeV Singlet Mass
    Mp = 1.22e19                             #GeV Planck Mass
    g = 100                                  # Degrees of freedom
    gs = 106.75                              # Entropy degrees of freedom
    H0 = 2.133*(0.7)*1e-42                    # GeV Hubble parameter (unused)
```

Boltzmann equation

The general expresion for the thermal evolution of DM is as follows (see eq (5.26) Kolb and Turner):

$$\frac{x}{Y_{EQ}(x)}\frac{dY}{dx} = -\frac{n_{EQ}(x)\langle\sigma v\rangle}{H(x)}\left[\left(\frac{Y}{Y_{EQ}(x)}\right)^2 - 1\right],$$

donde

$$n_{EQ}(x) = 2\left(\frac{M^2}{2\pi x}\right)^{3/2} e^{-x}$$

and []see (eq 5.16) Kolb & Turner]

$$H(x) = 1.67x^{-2}g_*^{1/2}\frac{M^2}{Mp}$$

+https://github.com/restrepo/WIMP → WIMP.ipynb → Open in Colab

WIMP.ipynb - Colaboratory

https://colab.research.google.com/drive/1xeN7waRalplV1mlWcwNtKdd1BulosJmM#scrollTo=CCa0bZlfk7bf

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The equilibrium distribution of this particles is consider for the non-relativistic case, as follows (see eq 5.25):

$$Y_{EQ}(x) = \frac{45}{2\pi^4}\frac{g}{g_{*s}}x^{3/2}e^{-x} = 0.145\frac{g}{g_{*s}}x^{3/2}e^{-x},$$

where $x = M/T$ and $M = 100$ GeV is the singlet mass taken as constant.

WIMP

The initial condition to solve the evolution equation is $Y(x_i) = Y_{EQ}$, where $x_i = 0.01$, such that $T_i = M/x_i = 10^4$ GeV.

[7]
```
def Yeq(x):
    return 0.145*(g/gs)*(x)**(3/2)*np.exp(-x)

xi=1E-4
xe=1000
npts=3000
# For several order of magnitude:
x = np.linspace(0.01, 1000, 1000)
```

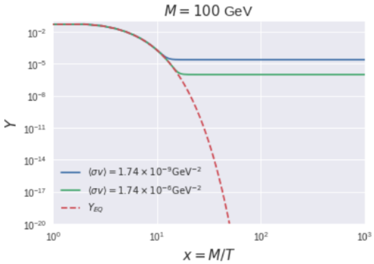
```
sigmav=[1.7475568196239999e-09,1.7475568196239999e-06]
def eqd(yl,x,Ms = 100,σv = sigmav[0]):
    '''
    Ms  [GeV]      : Singlet Mass
    σv: [1/GeV^2] : ⟨σv⟩
    '''

    Mp = 1.22e19
    g = 100                             # Degrees of freedom
    gs = 106.75                         # Entropy degrees of freedom

    H = 1.67*g**(1/2)*Ms**2/Mp

    dyl = -2*(((Ms**2/(2*np.pi*x))**(3/2)*np.exp(-x))*σv/(x**(-2)*H*x))*(yl**2 - (0.145*(g/gs)*(x)**(3/2

    return dyl
```

+https://github.com/restrepo/WIMP→ WIMP.ipynb → Open in Colab

```
[9] #Initial conditions
    y0 = Yeq(x[0])
    yl =  odeint( eqd, y0, x,args=(Ms,sigmav[0]) )
    yl1 = odeint( eqd, y0, x,args=(Ms,sigmav[1]) )
```

The following plot can be find in the reference book (Figure 5.1)

```
[10] plt.loglog(x,yl, label = r'$\langle σ v\rangle = 1.74 \times 10^{-9} {\rm GeV}^{-2}$')
     plt.loglog(x,yl1, label = r'$\langle σ v\rangle = 1.74 \times 10^{-6} {\rm GeV}^{-2}$')
     plt.loglog(x,Yeq(x), '--', label = '$Y_{EQ}$')
     plt.ylim(ymax=0.1,ymin=1e-20)
     plt.xlim(xmax=1e3,xmin=1)
     plt.xlabel('$x = M/T$', size= 15)
     plt.ylabel('$Y$', size= 15)
     plt.title('$M = 100$ GeV', size= 15)
     plt.legend(loc='best',fontsize=10)
     plt.grid(True)
```

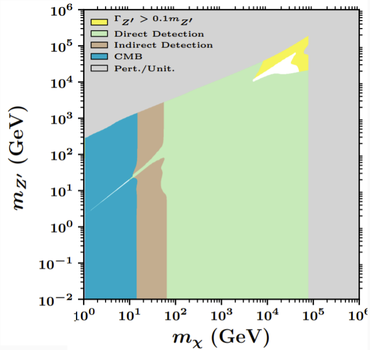


Isosinglet dark matter candidate

χ as a isosinglet Dirac dark matter fermion charged under a local $\mathrm{U}(1)_{B-L}$ (SM) cuples to a SM-singlet vector mediator Z'

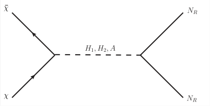
$$\mathcal{L}_{\text{int}} = -g_{BL}\,\overline{\chi}\gamma^{\mu}\chi\,,Z'_{\mu} - \sum_f g_f \bar{f}\gamma^{\mu} f\,,Z'_{\mu}\,,$$

where f are the Standard Model fermions: Resonances excluded!



$g_{BL}/g_{\mathrm{SM}} = 10$. arXiv:1907.05893. C. Blanco, *et al.* [PRD]

Additional DM annihilation processes



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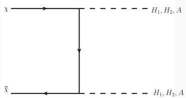
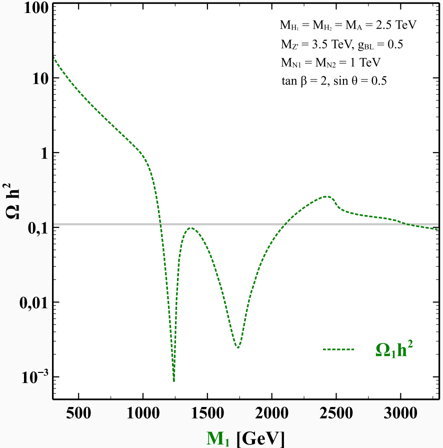
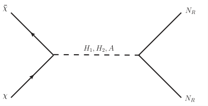


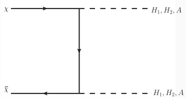


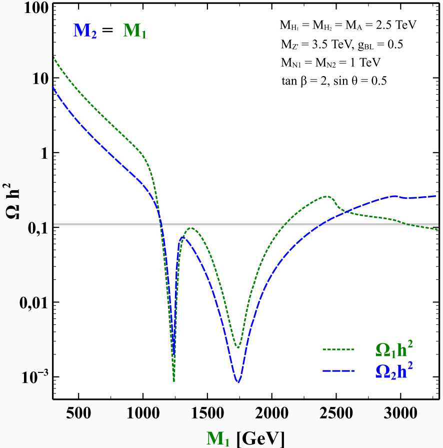
Exotic scalar portal

Additional DM annihilation processes



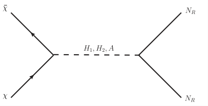
and





Exotic scalar portal

Additional DM annihilation processes



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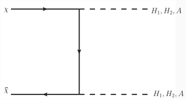

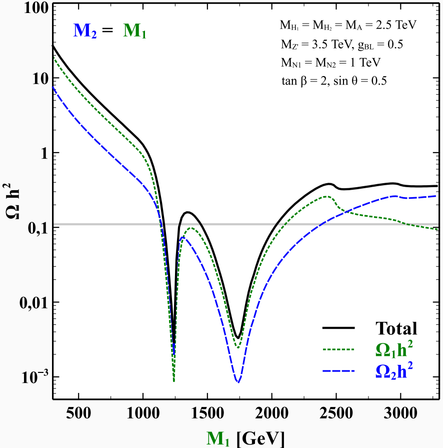

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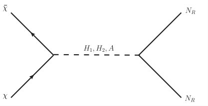

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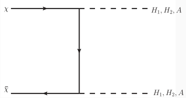

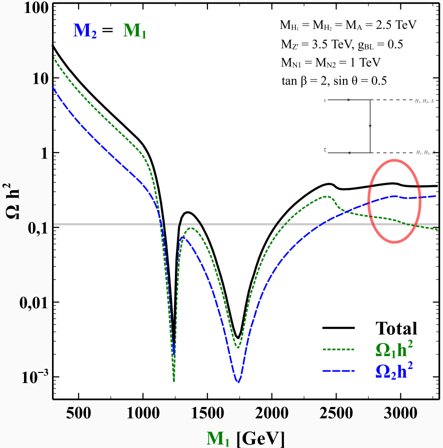

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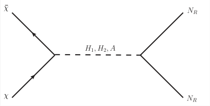

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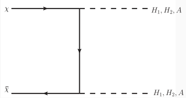
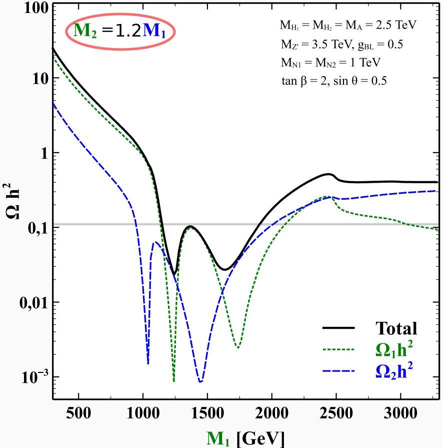
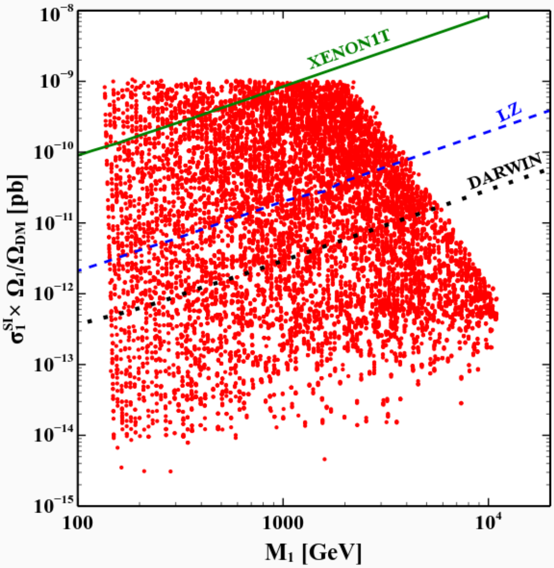




Two component Dirac fermion dark matter model

Field	$U(1)_{B-L}$
N_{R1}	-1
N_{R2}	-1
ξ_L	$+10/7$
η_R	$-4/7$
ζ_R	$-2/7$
χ_L	$-9/7$
S	-2
S'	1

$$U(1)_{B-L} \to Z_7 \,.$$



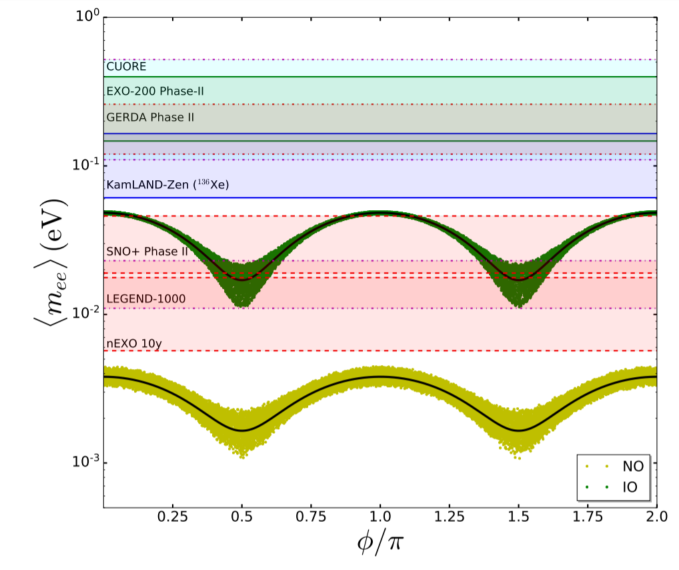
with N. Bernal, C. Yaguna and C. Zapata, 1808.03352 [PRD]

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 ~~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)$_L$

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

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

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

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 ($Y(H) = +1/2$)

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

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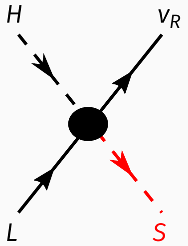
- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

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

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



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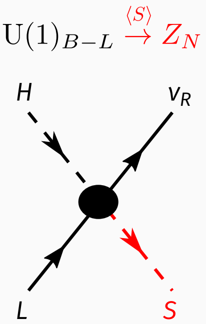
$$\mathcal{L}_{\mathrm{T.L}} = h_D \epsilon_{ab} (\nu_R)^\dagger L^a H^b + \mathrm{h.c}$$
$$= h_D (\nu_R)^\dagger L \cdot H + \mathrm{h.c}$$



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

- 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

+

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

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

SM

+

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

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