Two component Dark Matter

with neutrino masses

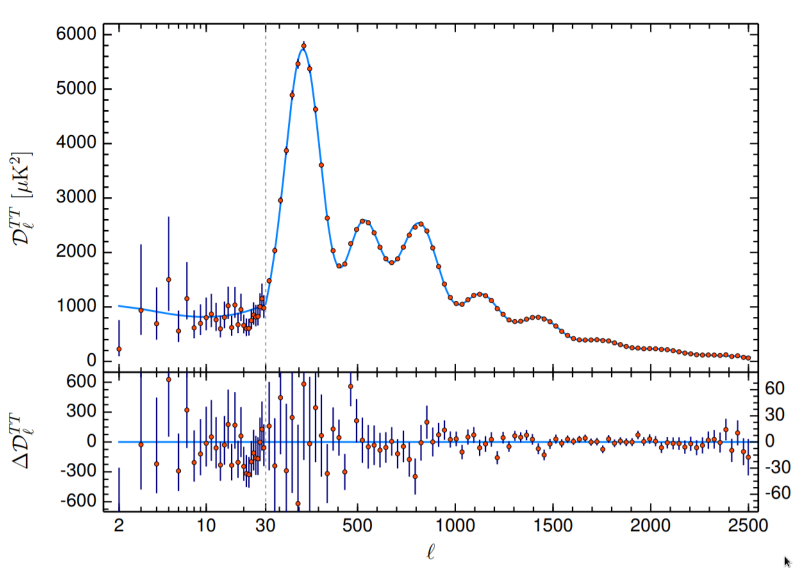
Diego Restrepo

Sep 6, 2019 - Darkwin - Natal

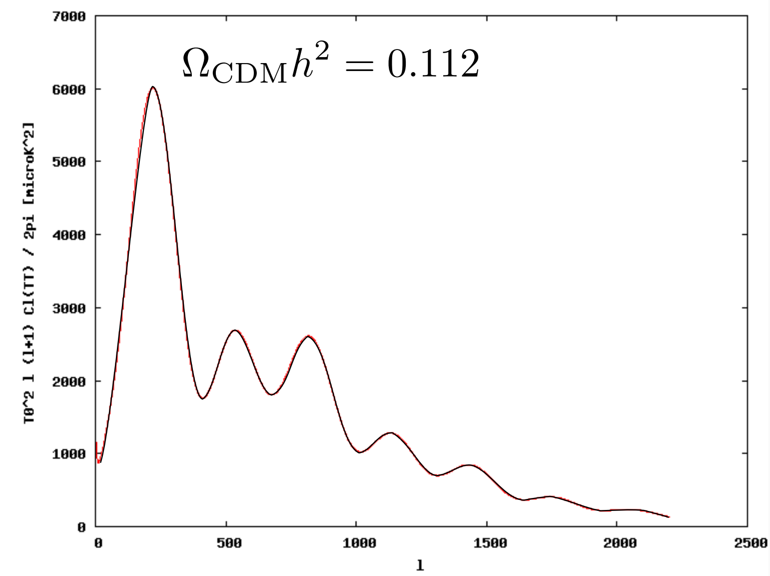
Instituto de Física
Universidad de Antioquia
Phenomenology Group
`http://gfif.udea.edu.co`

Focus on
arXiv:1811.11927 [PRD]
In collaboration with
N. Bernal (UAN), C. Yaguna (UPTC), Ó. Zapata, (UdeA)

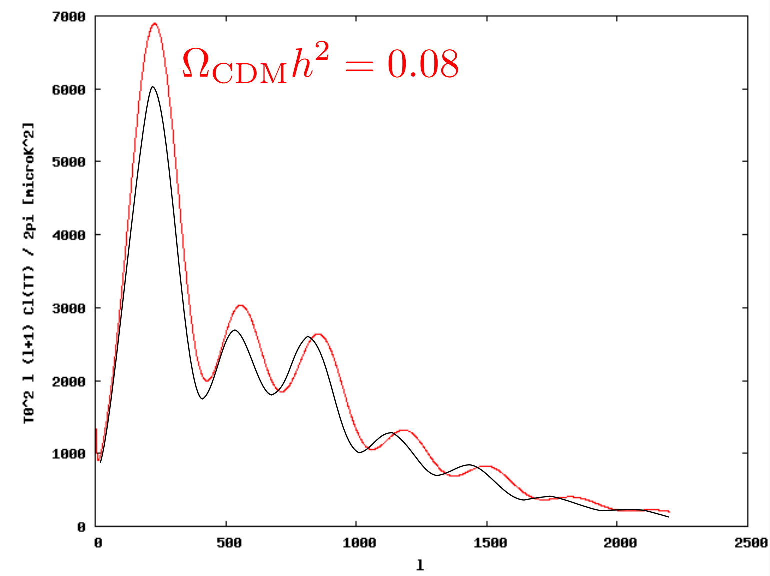
ΛCDM paradigm (with baryonic effects)



Credit: Planck 2018



$\Omega_{\mathrm{CDM}} h^2 = 0.112$
T0^2 l (l+1) Cl(TT) / 2pi [microK^2]
l
0
1000
2000
3000
4000
5000
6000
7000
500
1500
2500



$\Omega_{\rm CDM}h^2 = 0.08$
T0^2 l (l+1) Cl(TT) / 2pi [microK^2]
7000
6000
5000
4000
3000
2000
1000
0
0
500
1000
1500
2000
2500
l

Credit: Komatsu, ICTP Summer School on Cosmology 2018[1]

[1] Video avalaible

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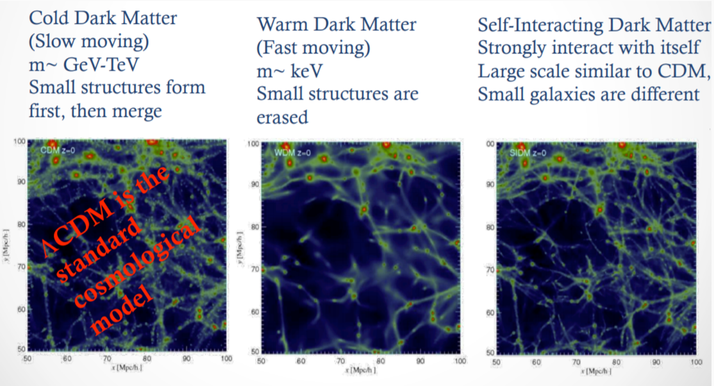
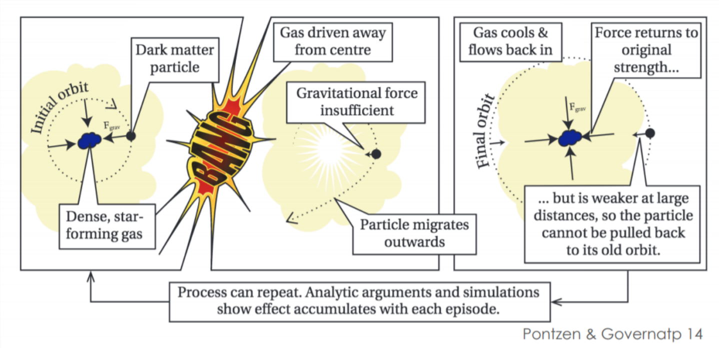
Dark matter simulations



Credit: Arianna Di Cintio (Conference on Shedding Light on the Dark Universe with Extremely Large Telescopes, ICTP - 2018)

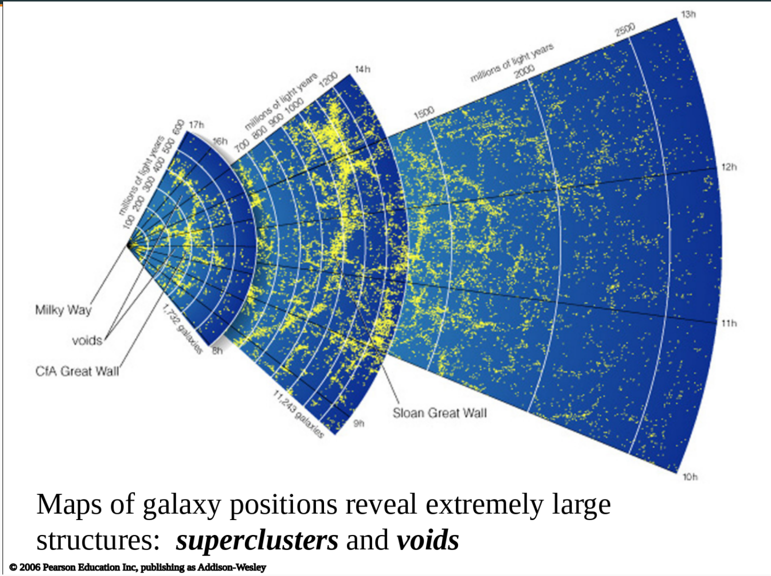
Baryonic effects



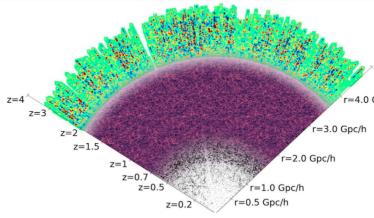
Once the effect of baryonic physics is included, it is hard to distinguish between WDM/SIDM/CDM

See: Gravitational probes of dark matter physics, M.R. Buckley, A.H.G. Peter, arxiv:1712.06615 [PR]

Goal



The DESI experiment



J. Forero `http://cosmology.univalle.edu.co/`

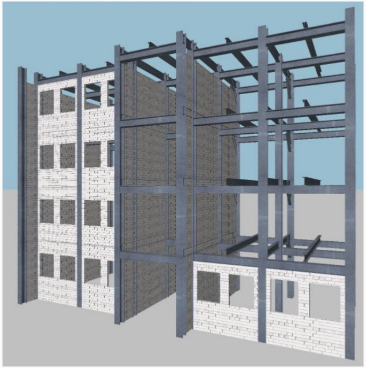
Cosmic web

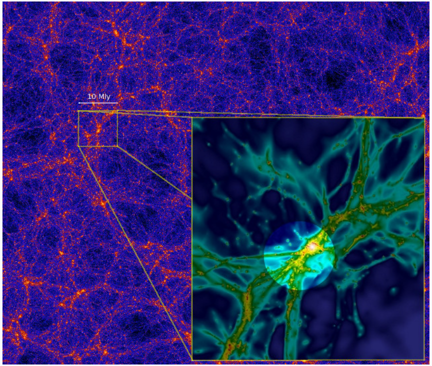
Dark matter in the universe evolves through gravity to form a complex network of halos, filaments, sheets and voids, that is known as the cosmic web [arXiv:1801.09070]

Cooking the soup: Cosmic web

Dark matter connects clusters of galaxies with massive tendrils, forming a cosmic web that serves as an unseen skeleton for the universe.

`https://phys.org/news/2018-06-years-scientists-account-universe.html`



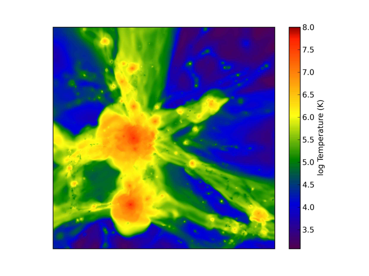


An excess of a gas is observed between Milky Way and Andromeda

Direct observations of filaments

Where are the Baryons? (Cen, Ostriker, astro-ph/9806281 [AJ])

> *Thus, not only is the universe dominated by dark matter, but more than one half of the normal matter is yet to be detected. (the muscles)*



Credit: Cen, arXiv:1112.4527 [AJ]

Warm-hot intergalactic medium (WHIM)
Density-weighted temperature projection of a portion of the refinement box of the C run of size $(18\,h^{-1}\mathrm{Mpc})^3$.
Low temperature WHIM confirmed by O VI line that peak at $T \sim 3 \times 10^5$ K

New Hotter phases of the WHIM: **Observations of the missing baryons in the warm-hot intergalactic medium** (Nicastro, *et al.* arXiv:1806.08395 [Nature]).

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]

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

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

$\langle \text{SM} \rangle$

+

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

Type-I arXiv:1808.03352

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

Local $U(1)_X \to Z_7$

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

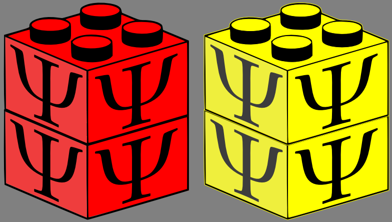
⟨SM⟩

+

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

Type-I arXiv:1808.03352

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



Standard model extended with U(1)$_X$ 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 and fermions with their respective charges.

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

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

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

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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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
$(-1, -1, -1)$	hep-ph/0611205, S. Khalil [JPG]
$(-4, -4, +5)$	arXiv:0706.0473, Montero, V. Pleitez [PLB]
$\left(-\frac{2}{3}, -\frac{2}{3}, -\frac{4}{3}, -\frac{1}{3}\right)$	arXiv:1607.04029, S. Patra , W. Rodejohann, C. Yaguna [JHEP]
$\left(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, +2\right)$	arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]
$\left(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7}\right)$	1811.11927, with N. Bernal, C. Yaguna, Ó. Zapata [PRD]

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

U(1)$_X$ with two Majorana masses: ψ_N, ψ_{N-1}

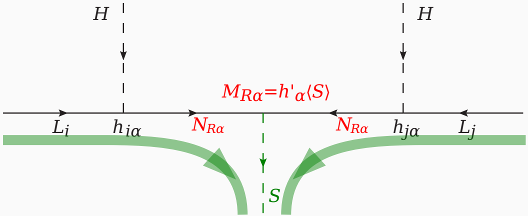
Fields	SU(2)$_L$	U(1)$_Y$	U(1)$_X$	U(1)$_{B-L}$	U(1)$_B$	U(1)$_D$	U(1)$_G$
L	**2**	$-1/2$	l	-1	0	$-3/2$	$-1/2$
Q	**2**	$-1/6$	$-l/3$	$1/3$	0	$1/2$	$1/6$
d_R	**1**	$-1/2$	$1+2l/3$	$1/3$	1	0	$2/3$
u_R	**1**	$+2/3$	$-1-4l/3$	$1/3$	-1	1	$-1/3$
e_R	**1**	-1	$1+2l$	-1	1	-2	0
H	**2**	$-1/2$	$-1-l$	0	-1	$1/2$	$-1/2$
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

Solutions in terms of a parameter: arXiv:1811.11927, N. Okada, *et al* [PRD];

and some specific examples from: arXiv:1705.05388, Farinaldo Queiroz, *et al* [JHEP]

All previous U(1)$_{B-L}$ (radiative) neutrino solutions apply for U(1)$_X$

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

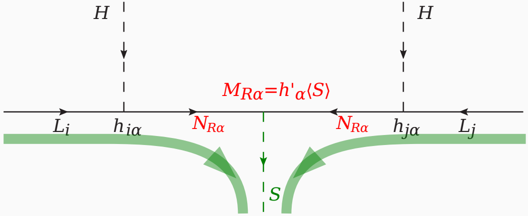


After integrating out heavy fermions, we obtain light neutrino masses

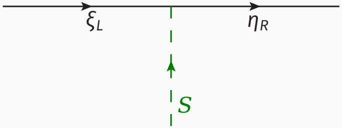
$$\mathcal{M}_\nu^{ij} = \sum_{\alpha=1}^{2} \left(h^{i\alpha} v\right) \frac{1}{M_R^\alpha} \left(h^{j\alpha} v\right)$$

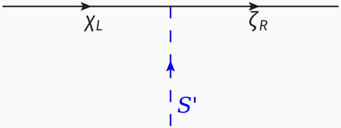
With only two heavy fermions, one massless neutrino is left

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





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

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

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

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

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

$$G', \ A$$

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

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

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

Parameter space

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

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

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

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

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

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

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

11 parameters

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

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

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

100% χ_1 case

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

velocity-averaged cross section $\langle \sigma v \rangle$

$\langle \sigma v \rangle$

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

where

n_{EQ}: DM number density

K_1: Modified Bessel function

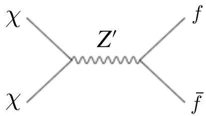
Reduced cross section

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

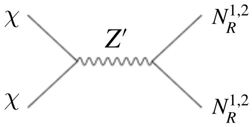
DM annihilation cross section

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

DM annihilation processes



and



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

CODE TEXT CELL CELL CONNECT EDITING

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 $\to$ WIMP.ipynb $\to$ Open in Colab

WIMP.ipynb - Colaboratory

https://colab.research.google.com/drive/1xeN7waRalplV1mlWcwNtKdd1BulosJmM#scrollTo=CCa0bZIfk7bf

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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]
```python
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)
```

```python
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

WIMP.ipynb - Colaboratory

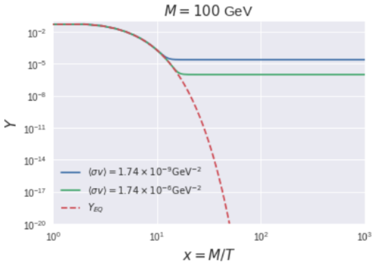
https://colab.research.google.com/drive/1xeN7waRalplV1mlWcwNtKdd1BulosJmM#scrollTo=Rbeje9bVk7au

CODE TEXT CELL CELL CONNECTED EDITING

```
[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)
```

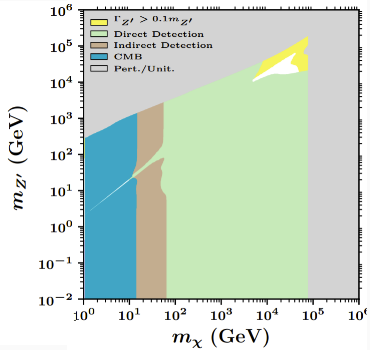


Isosinglet dark matter candidate

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'

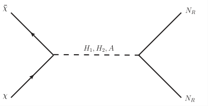
$$\mathcal{L}_{\rm int} = -g_{BL}\,\overline{\chi}\gamma^\mu\chi\,Z'_\mu - \sum_f g_f\bar{f}\gamma^\mu f\,Z'_\mu\,,$$

where f are the Standard Model fermions: Resonances excluded!



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

Additional DM annihilation processes



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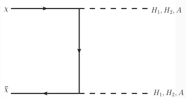

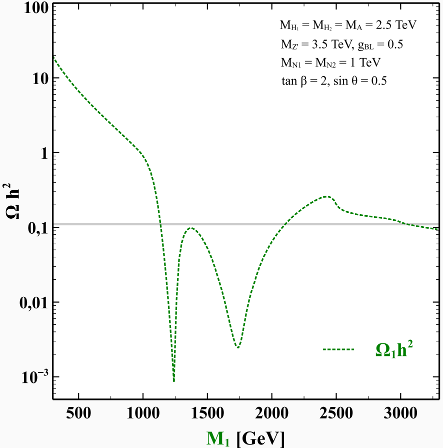

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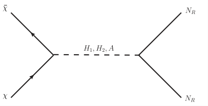

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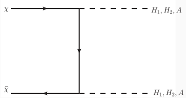
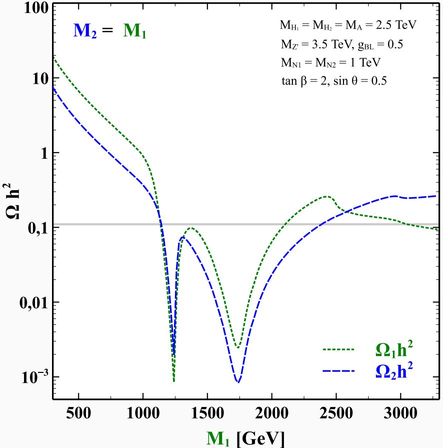
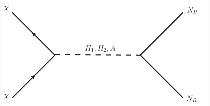




Additional DM annihilation processes



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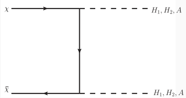
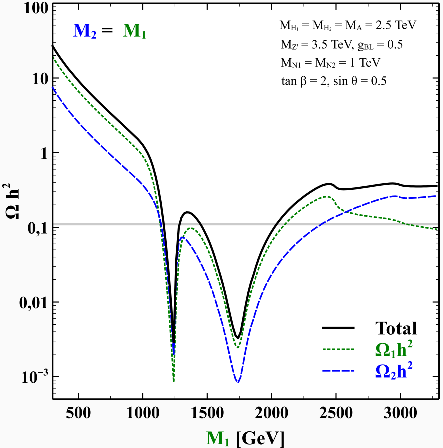
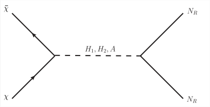




Exotic scalar portal

Additional DM annihilation processes



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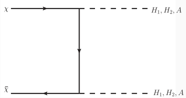
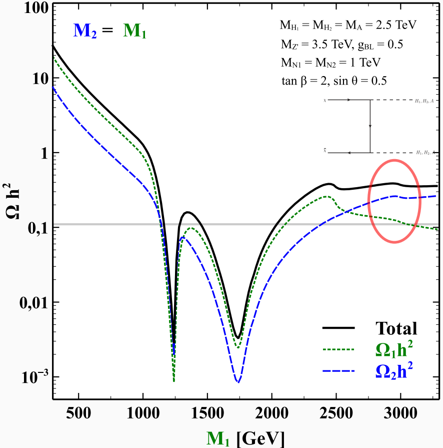
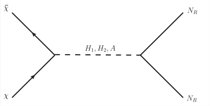




Exotic scalar portal

Additional DM annihilation processes



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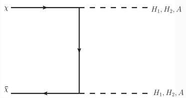
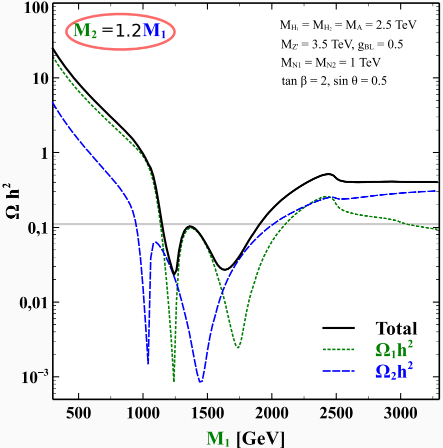
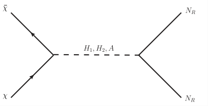




Exotic scalar portal

Additional DM annihilation processes



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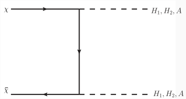
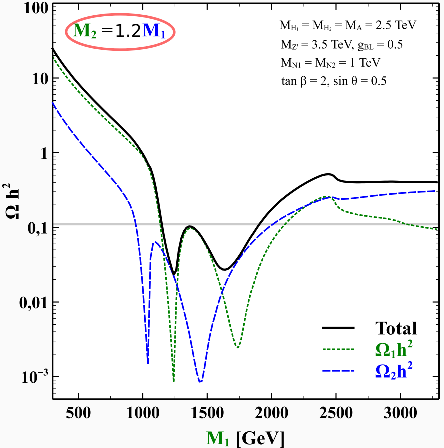
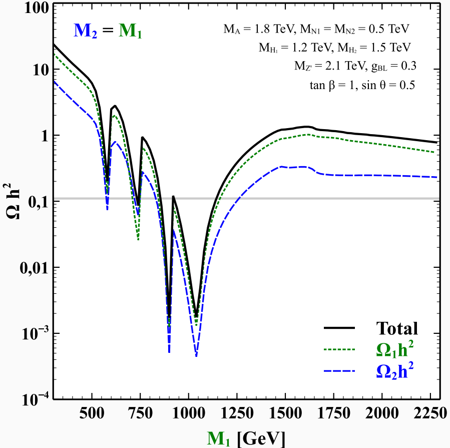
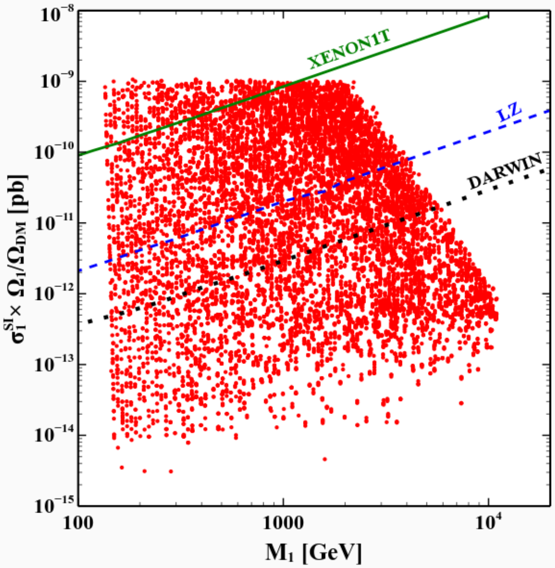






Two component Dirac fermion dark matter model

Parameter	Range
$M_{Z'}$	$(0.3, 20)$ TeV
$M_{1,2}$	$(0.35, 0.65)\ M_{Z'}$
g_{BL}	$(0.001, 1)$
$\sin\alpha$	$(0.001, 1)$
$\tan\beta$	$(0.03, 30)$
M_{R1}, M_{R2}	$(0.2, 10)$ TeV
M_{H1}, M_{H2}, M_A	$(0.2, 10)$ TeV



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

Conclusions

It makes sense to focus our attention on models tha can account for neutrino masses and dark matter (DM).

In this extension of the SM by an $\mathrm{U}(1)_{B-L}$ gauge symmetry amomalies are canceled partially by two right-handed neutrinos and partially by two component DM Dirac fermions, providing a connection between neutrinos and DM analogous to that one between leptons and quarks in the SM.

The model predicts the existence of three scalar fields beyond the SM Higgs: H_1, H_2, A

Model implemented in LanHEP. Implemented also in SARAH `https://github.com/restrepo/BSM-Submodules/tree/B-L+DM/BSM/SARAH/Models/B-L/DM` (Tested with SARAH-4.14.1) to analyse perturbativity and stability conditions and higher scales with two-loop RGEs.

After imposing the current bounds from LHC and direct detection experiments, there are regions of this model which remains unconstrained.

Easy to include an effective Z_7 breaking to get decaying dark matter.

Thanks!