Two component Dark Matter

with neutrino masses

UNIVERSIDAD DE ANTIOQUIA
1803

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Sep 6, 2019 - Darkwin - Natal [PDF: http://bit.ly/darkwin]

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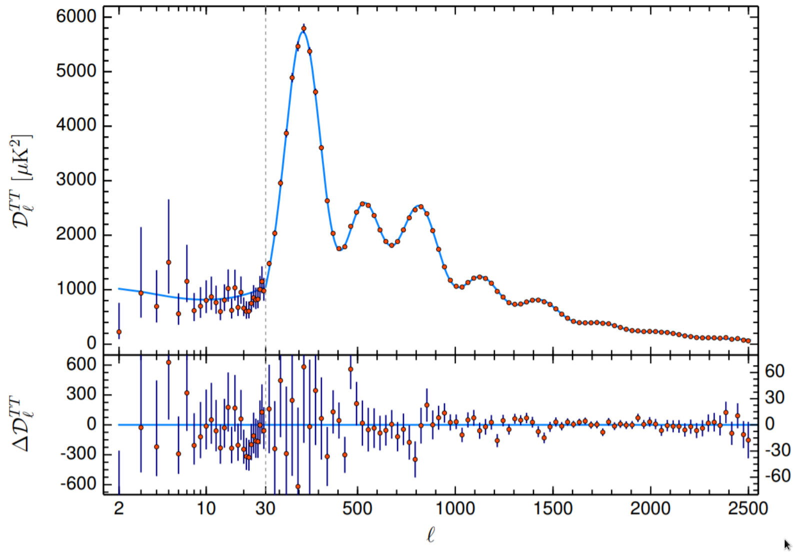
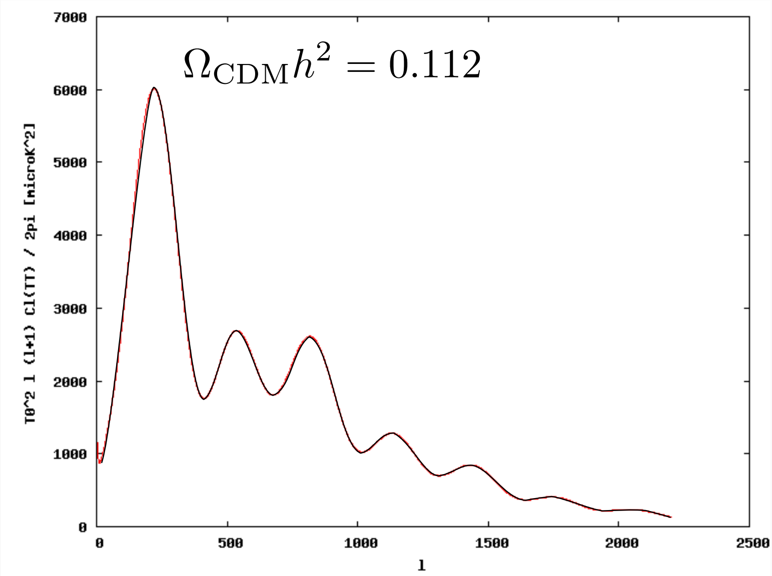
Focus on
arXiv:1811.11927 [PRD]
In collaboration with
N. Bernal (UAN), C. Yaguna (UPTC), Ó. Zapata, (UdeA)

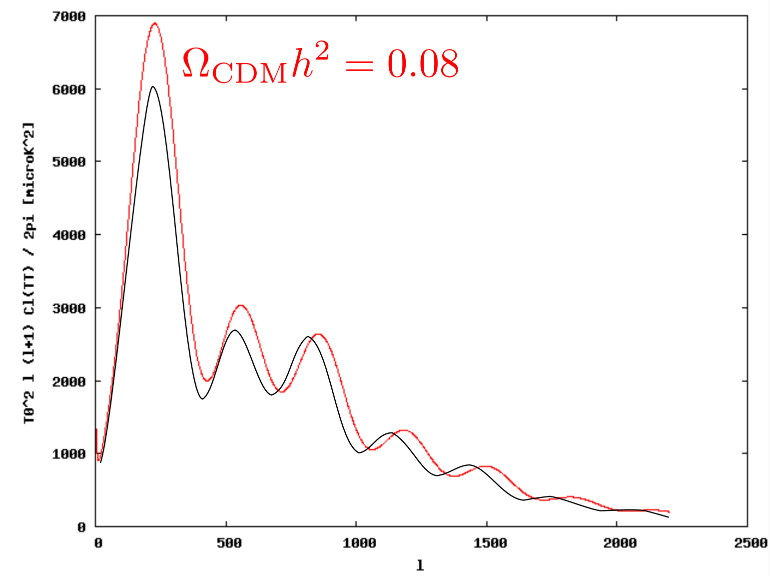
ΛCDM paradigm (with baryonic effects)



Credit: Planck 2018



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



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

Cosmic Miso Soup

- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching how ripples are created and propagate throughout the soup

Credit: Komatsu, ICTP Summer School on Cosmology 2018 (Video avalaible)

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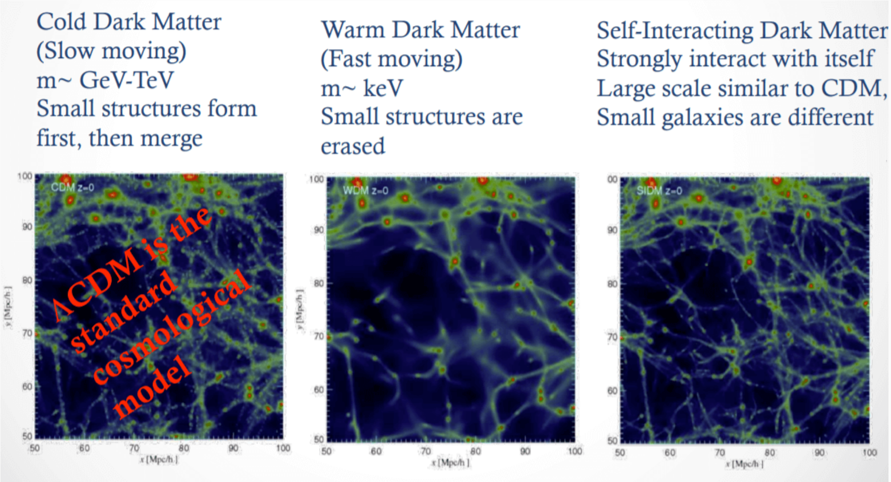
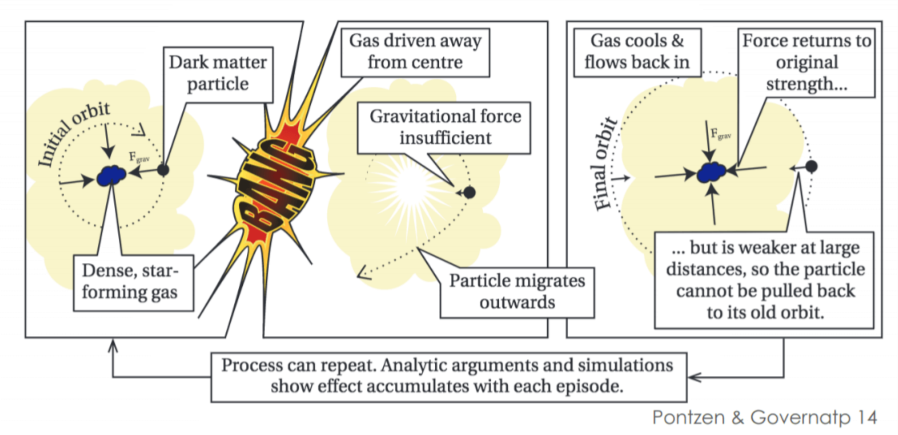
Dark matter simulations



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

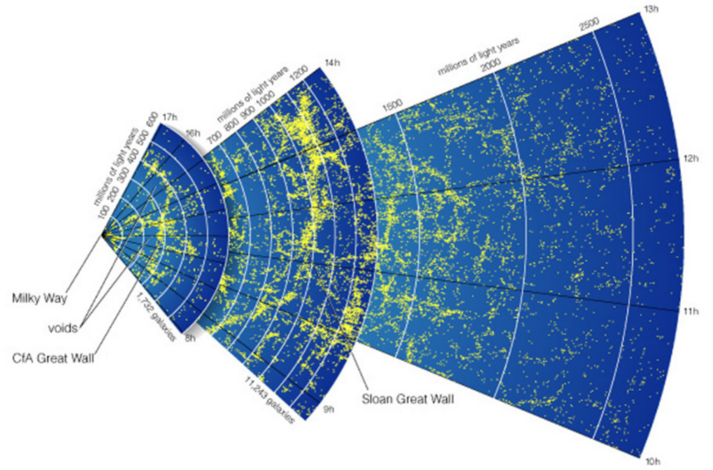
Baryonic effects



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

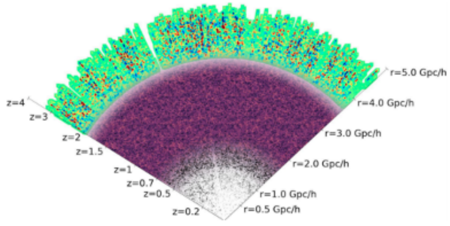
See: Gravitational probes of dark matter physics, M.R. Buckley, A.H.G. Peter, arxiv:1712.06615 [PR]

Goal



Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids***

The DESI experiment



Credits: J. Forero

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

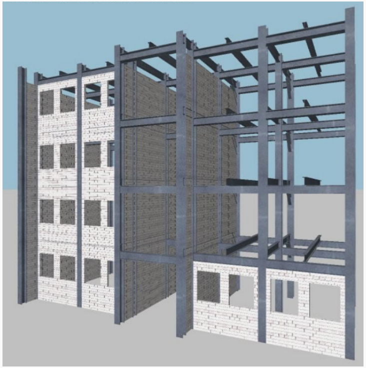
Cosmic web

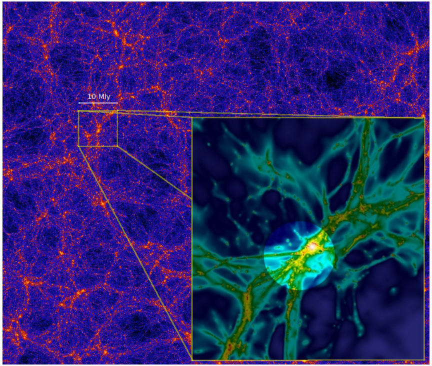
Dark matter in the universe evolves through gravity to form a complex network of halos, filaments, sheets and voids, that is known as the cosmic web [arXiv:1801.09070]

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`



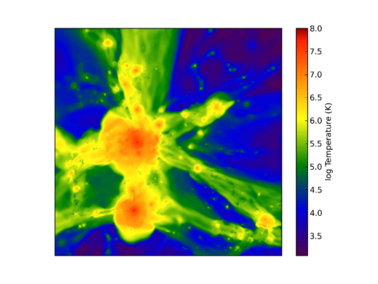


An excess of a gas is observed between Milky Way and Andromeda

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

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

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

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]

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

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

$\langle \text{SM} \rangle$

+

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

Type-I arXiv:1808.03352

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

Local $U(1)_X \to Z_7$

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

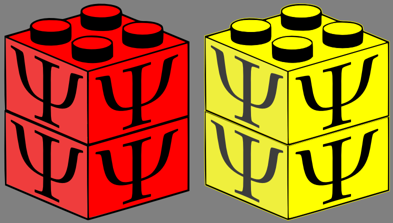
$\langle$SM$\rangle$

+

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

Type-I arXiv:1808.03352

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



Standard model extended with $\mathrm{U}(1)_X$ gauge symmetry

Fields	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_X$
L	$\mathbf{2}$	$-1/2$	l
Q	$\mathbf{2}$	$-1/6$	q
d_R	$\mathbf{1}$	$-1/2$	d
u_R	$\mathbf{1}$	$+2/3$	u
e_R	$\mathbf{1}$	-1	e
H	$\mathbf{2}$	$-1/2$	h
ψ	$\mathbf{1}$	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]
$\left(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7}\right)$	1808.03352, 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}

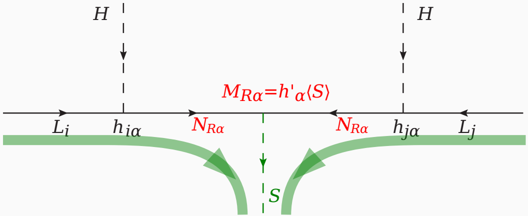
Fields	SU(2)$_L$	U(1)$_Y$	U(1)$_X$	U(1)$_{B-L}$	U(1)$_B$	U(1)$_D$	U(1)$_G$
L	**2**	$-1/2$	l	-1	0	$-3/2$	$-1/2$
Q	**2**	$-1/6$	$-l/3$	$1/3$	0	$1/2$	$1/6$
d_R	**1**	$-1/2$	$1+2l/3$	$1/3$	1	0	$2/3$
u_R	**1**	$+2/3$	$-1-4l/3$	$1/3$	-1	1	$-1/3$
e_R	**1**	-1	$1+2l$	-1	1	-2	0
H	**2**	$-1/2$	$-1-l$	0	-1	$1/2$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

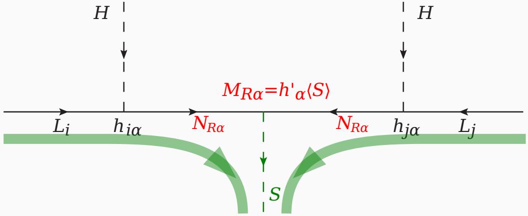


After integrating out heavy fermions, we obtain light neutrino masses

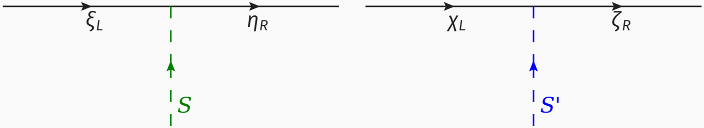
$$\boxed{\mathcal{M}_\nu^{ij} = \sum_{\alpha=1}^{2} \left(h^{i\alpha} v\right) \frac{1}{M_R^\alpha} \left(h^{j\alpha} v\right)}$$

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



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

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

Parameter space

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

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

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

$$S = \frac{1}{\sqrt{2}}(v_1 + h_1) + \frac{i}{\sqrt{2}} A_1$$
$$S' = \frac{1}{\sqrt{2}}(v_2 + h_2) + \frac{i}{\sqrt{2}} A_2$$

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

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

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

Parameter space

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

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

G', A

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

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

11 parameters

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

$m_\chi = M_1$ 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

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

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

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

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

$x = m_\chi / T$

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

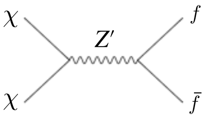
Reduced cross section

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

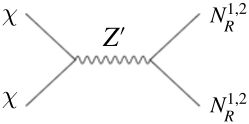
DM annihilation cross section

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

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]

```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

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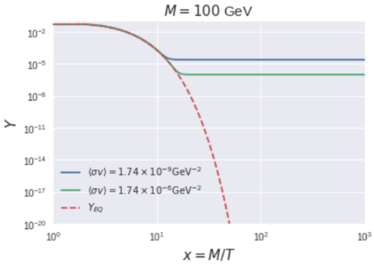
[9]
```python
#Initial conditions
y0 = Yeq(x[0])
yl =  odeint( eqd, y0, x,args=(Ms,sigmav[0]) )
yl1 = odeint( eqd, y0, x,args=(Ms,sigmav[1]) )
```

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

[10]
```python
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)
```

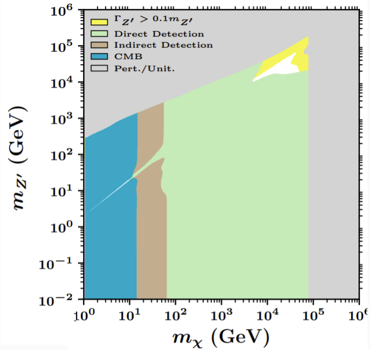


Isosinglet dark matter candidate

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'

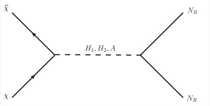
$$\mathcal{L}_{\rm int} = -g_{BL}\,\overline{\chi}\gamma^\mu\chi\,Z'_\mu - \sum_f g_f\bar{f}\gamma^\mu f\,Z'_\mu\,,$$

where f are the Standard Model fermions: Resonances excluded!



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

Additional DM annihilation processes



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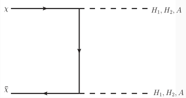
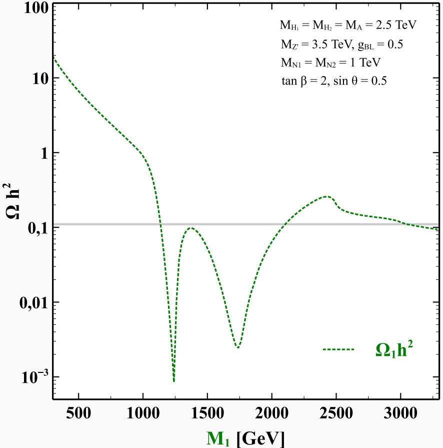
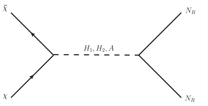




Additional DM annihilation processes



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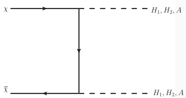
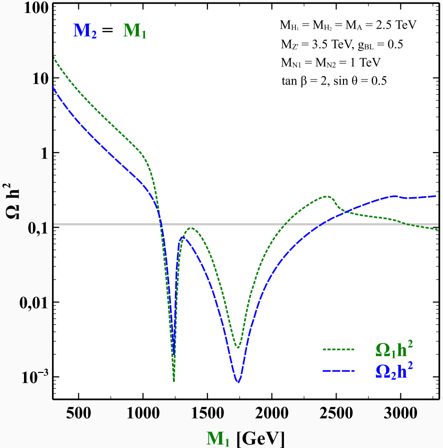
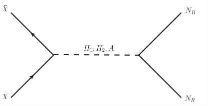




Exotic scalar portal

Additional DM annihilation processes



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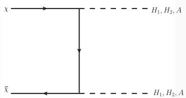
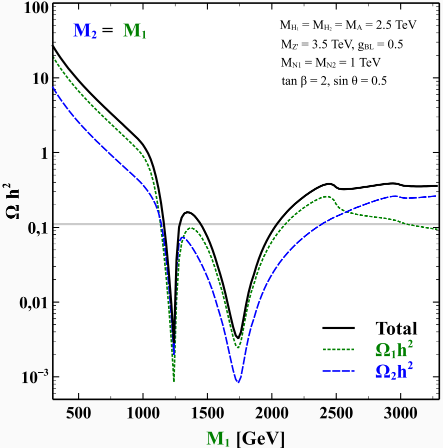
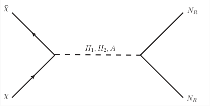




Exotic scalar portal

Additional DM annihilation processes



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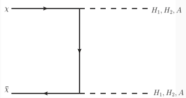

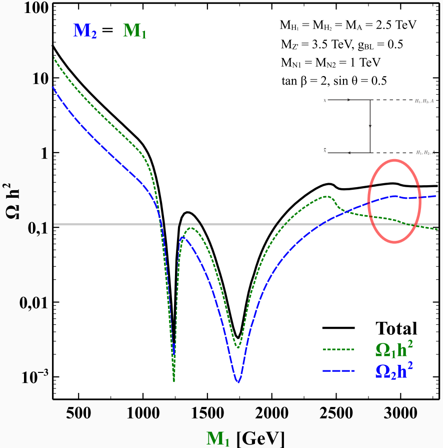

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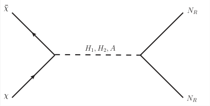

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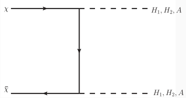
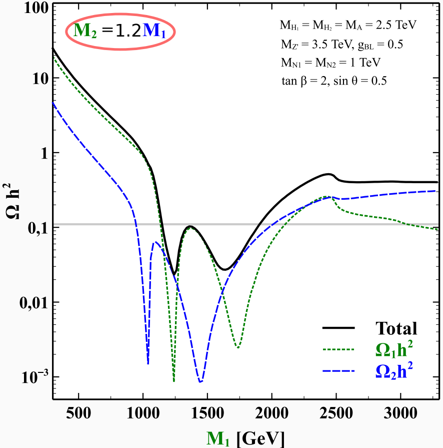
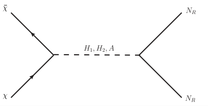




Exotic scalar portal

Additional DM annihilation processes



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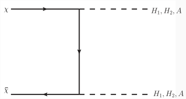
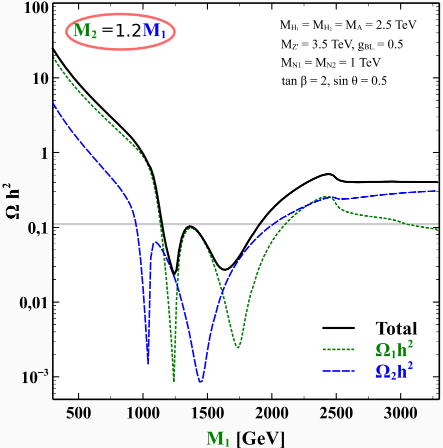
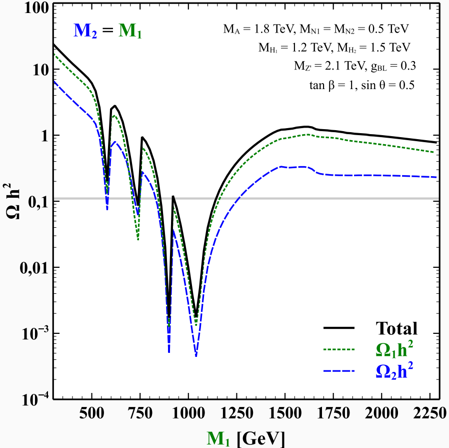
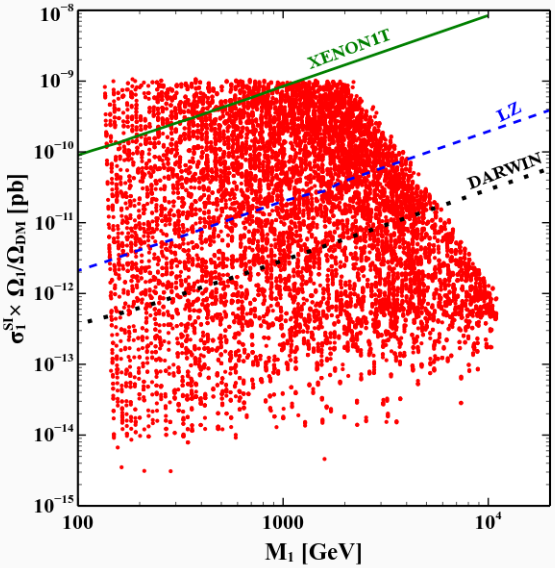






Two component Dirac fermion dark matter model

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!