



UNIVERSIDAD DE ANTIOQUIA
1803

Two component Dark Matter with neutrino masses

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Sep 6, 2019 - Darkwin - Natal

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Focus on

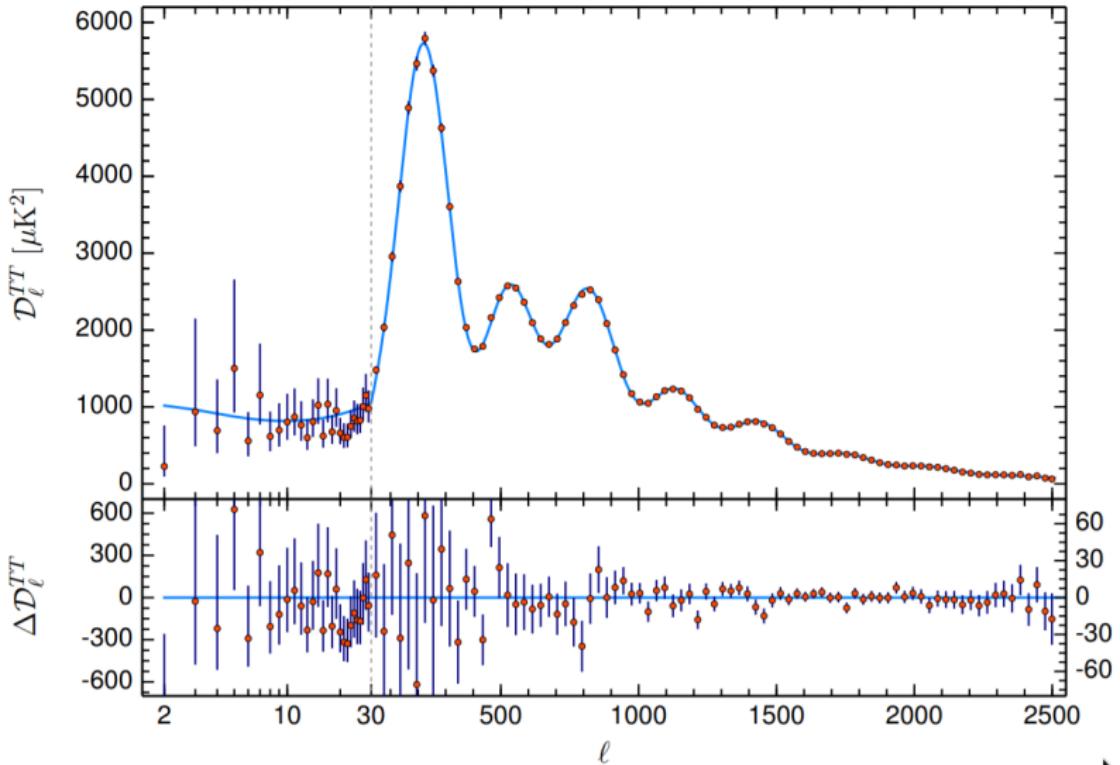
arXiv:1811.11927 [PRD]

In collaboration with

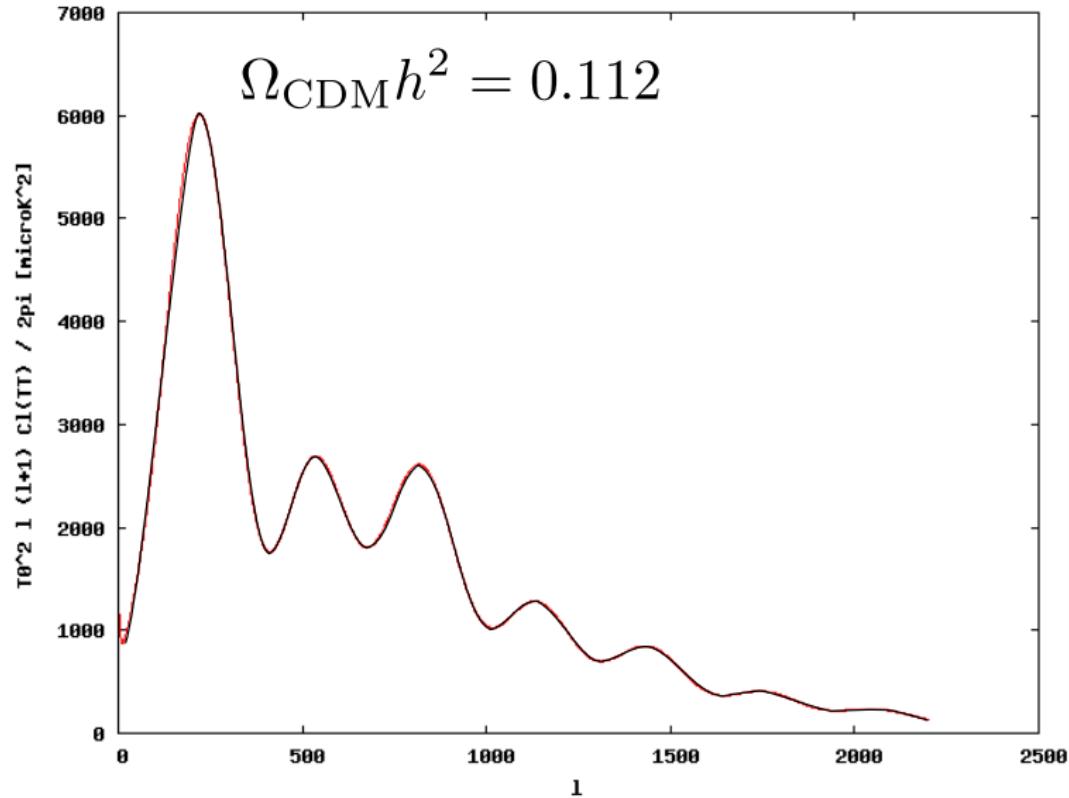
N. Bernal (UAN), C. Yaguna (UPTC), Ó. Zapata, (UdeA)

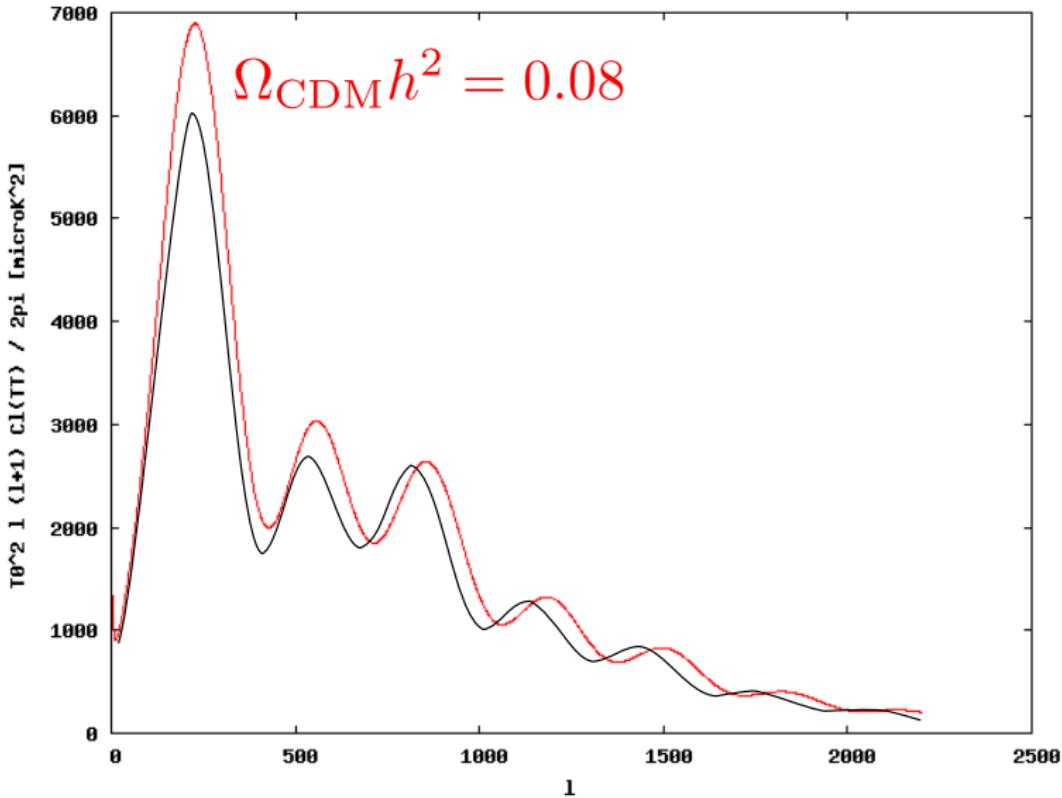


Λ CDM paradigm (with baryonic effects)



Credit: Planck 2018





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 2018¹

¹Video available

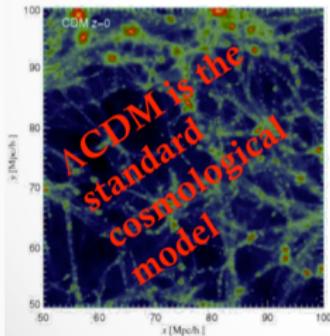


Credit: Komatsu, ICTP Summer School on Cosmology 2018¹

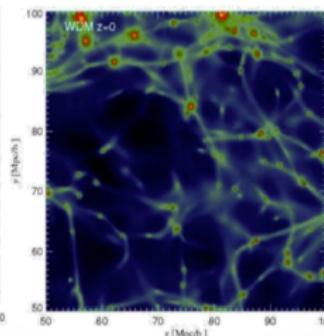
¹Video available

Dark matter simulations

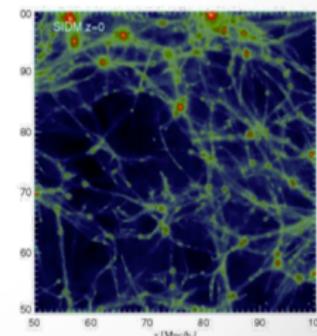
Cold Dark Matter
(Slow moving)
 $m \sim \text{GeV-TeV}$
Small structures form first, then merge



Warm Dark Matter
(Fast moving)
 $m \sim \text{keV}$
Small structures are erased

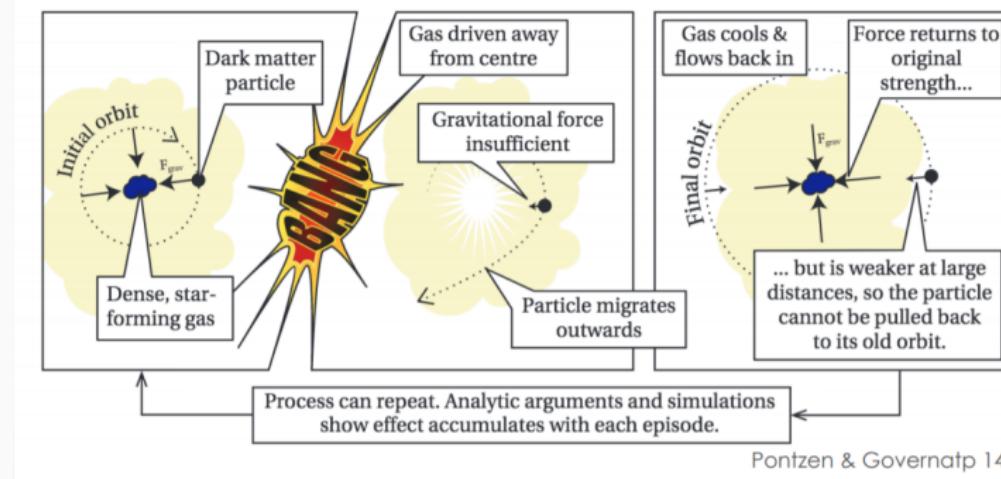


Self-Interacting Dark Matter
Strongly interact with itself
Large scale similar to CDM,
Small galaxies are different



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

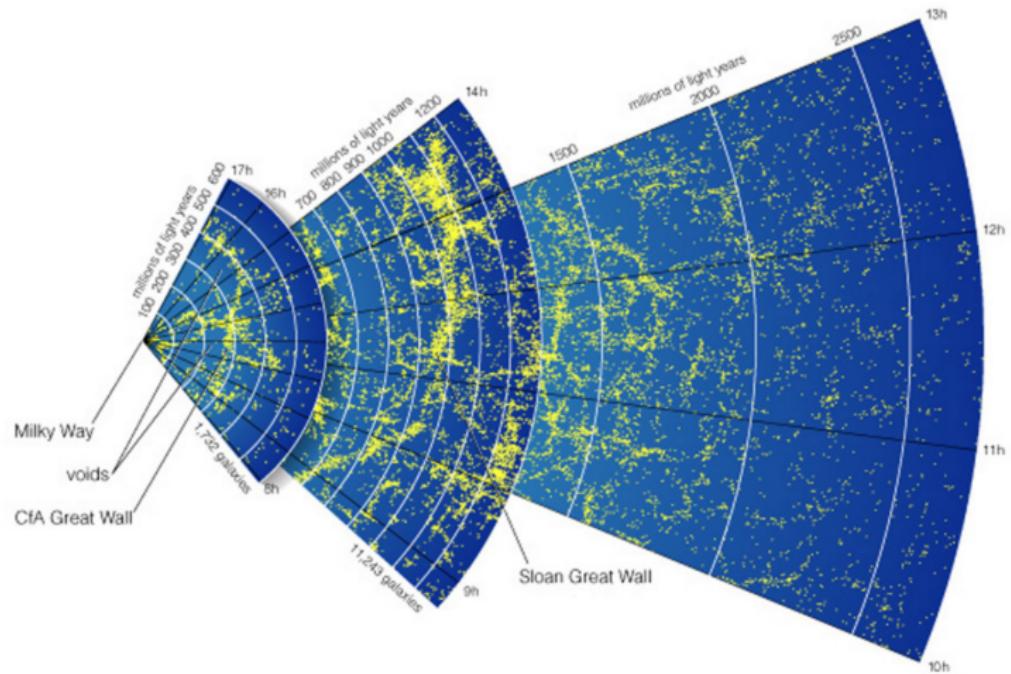
Baryonic effects



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]

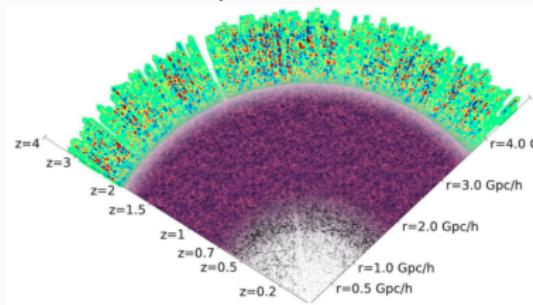
Goal



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

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The DESI experiment



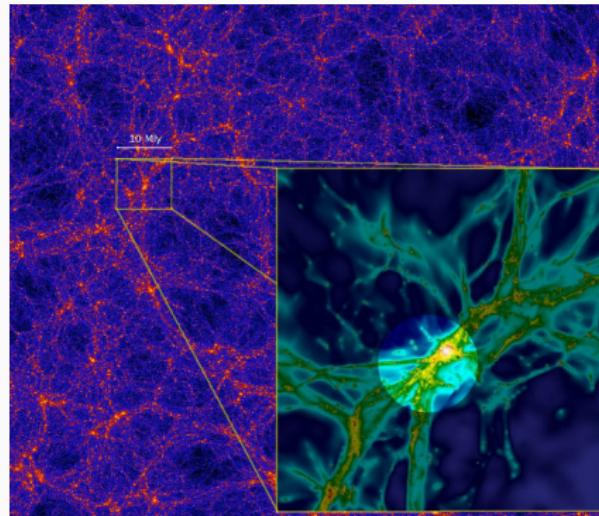
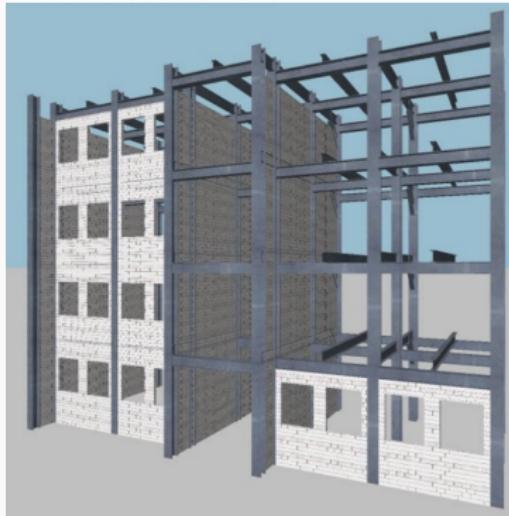
J. Forero <http://cosmology.univalle.edu.co/>

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>

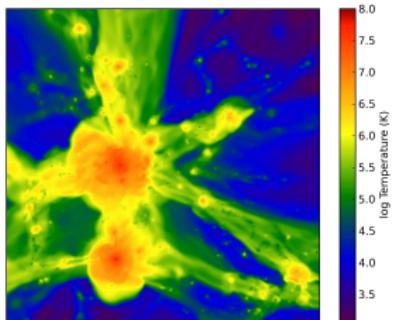


An excess of a gas is observed between Milky Way and Andromeda

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)



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

Credit: Cen, arXiv:1112.4527 [AJ]



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

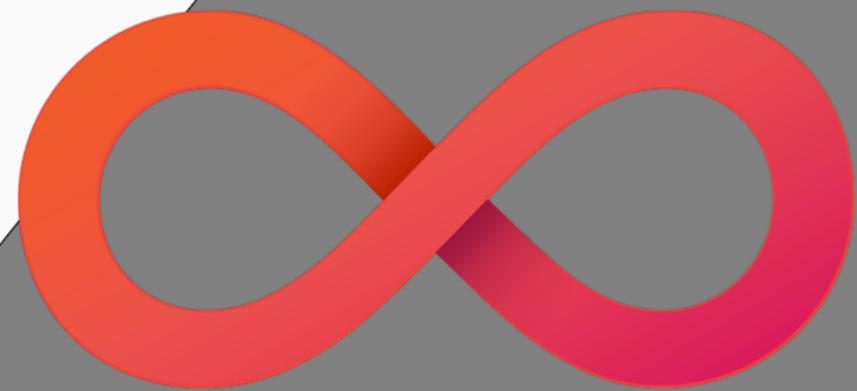
In the following discussion we use the following doublets in Weyl Notation

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

corresponding to the Higgs doublet and the lepton doublets respectively.



SM





SM

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

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



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



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

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

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

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



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

Type-I arXiv:1808.03352

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

Local $U(1)_X \rightarrow Z_7$

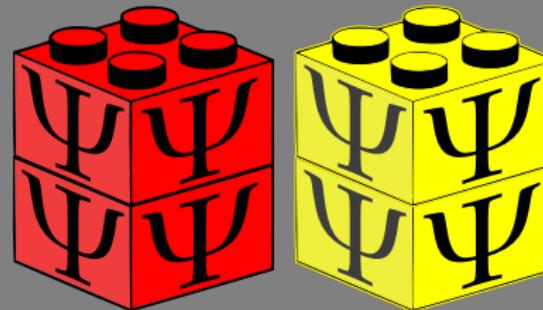
$$\mathcal{L} = y(N_R)^\dagger L \cdot \langle H \rangle + y' \langle S \rangle N_R N_R + \text{h.c}$$



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

Type-I arXiv:1808.03352

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



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.

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

with solution

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

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

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 $[U(1)_X]^3$ and $[SO(1, 3)]^2 U(1)_X$ 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

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

which satisfy

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

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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
$(-1, -1, -1)$	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}

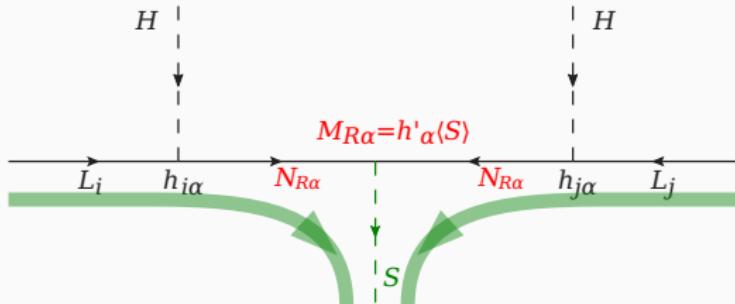
Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$U(1)_{B-L}$	$U(1)_B$	$U(1)_D$	$U(1)_G$
L	2	-1/2	l	-1	0	-3/2	-1/2
Q	2	-1/6	$-l/3$	1/3	0	1/2	1/6
d_R	1	-1/2	$1+2l/3$	1/3	1	0	2/3
u_R	1	+2/3	$-1-4l/3$	1/3	-1	1	-1/3
e_R	1	-1	$1+2l$	-1	1	-2	0
H	2	-1/2	$-1-l$	0	-1	1/2	-1/2
S	1	0	$2\psi_N$	$2\psi_N$	$2\psi_N$	$2\psi_N$	$2\psi_N$
$\sum_\alpha \psi_\alpha$	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	$U(1)_{B-L}$	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	-	+
$\psi_2 \rightarrow \eta_R X$	-4/7	-	+
$\psi_3 \rightarrow \zeta_R$	-2/7	+	-
$\psi_4 \rightarrow (\chi_L)^\dagger$	+9/7	+	-
S'	1	+	+

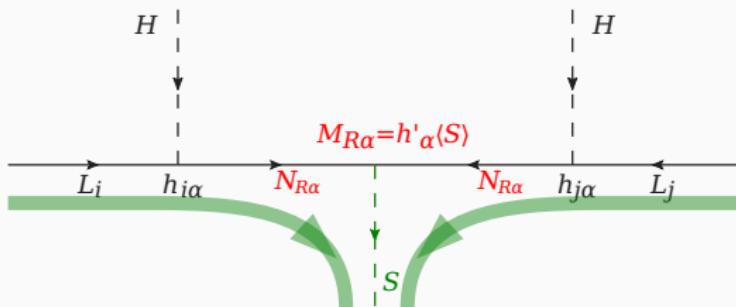


After integrating out heavy fermions, we obtain
light neutrino masses

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

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	-	+
$\psi_2 \rightarrow \eta_R \chi$	-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



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

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

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

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

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

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

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

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

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

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

$$\mathcal{L} = \textcolor{green}{M}_1 \overline{\chi_1} \chi_1 + \textcolor{blue}{M}_2 \overline{\chi_2} \chi_2 + M_{N1} \overline{N_{R1}^c} N_{R1} + M_{N2} \overline{N_{R2}^c} N_{R2}$$

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

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

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

$$\mathcal{L} = M_1 \overline{\chi}_1 \chi_1 + M_2 \overline{\chi}_2 \chi_2 + M_{N1} \overline{N}_{R1}^c N_{R1} + M_{N2} \overline{N}_{R2}^c N_{R2}$$

Relic abundance

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

Boltzman equation

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

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

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

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

$$x = m_\chi/T$$

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

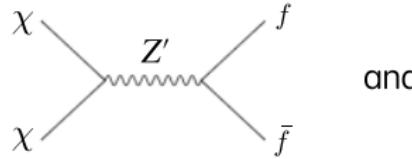
K_1 : Modified Bessel function

Reduced cross section

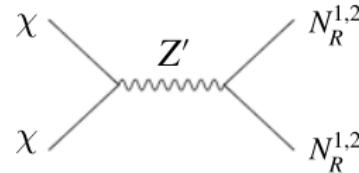
$$\hat{\sigma}(s) = 2(s - 4m_\chi^2 \sigma(s))$$

DM annihilation cross section

DM annihilation processes



and



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

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

$$\begin{aligned} \sigma_{N^i N^i}(s) &= \frac{400\pi}{3}\alpha_X^2 \sqrt{\frac{s - 4m_{N^i}^2}{s - 4m_\chi^2}} \frac{1}{(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2} \\ &\times \frac{1}{s} \left((s - 4m_\chi^2)(s - 4m_{N^i}^2) + 12 \frac{m_\chi^2 m_{N^i}^2}{m_{Z'}^4} (s - m_{Z'}^2)^2 \right) \theta(s - 4m_{N^i}^2) \end{aligned}$$

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

← → C https://colab.research.google.com/drive/1xeN7waRalpIV1mlWcwNtKdd1BulosJmM#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 expression 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]

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

CODE TEXT CELL CELL

CONNECTED

EDITING

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

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

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,ov = sigmav[0]):
    ...
    Ms [GeV] : Singlet Mass
    ov: [1/GeV^2] : (ov)
    ...

    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))*ov/(x**(-2)*H*x))*(yl**2 - (0.145*(g/gs)*(x)**(3/2
    return dyl
```

← → C https://colab.research.google.com/drive/1xeN7waRalpV1mlWcwNtKdd1BulosJmM#scrollTo=Rbeje9bV7au

+ CODE + TEXT ↑ CELL ↓ CELL

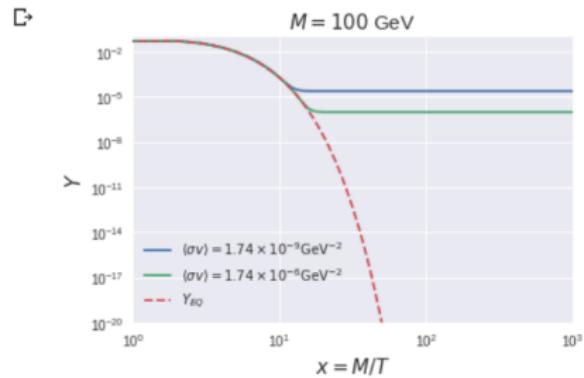
✓ CONNECTED

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'$\langle \sigma v \rangle = 1.74 \times 10^{-9} \text{ GeV}^{-2}$')
plt.loglog(x,yl1, label = r'$\langle \sigma v \rangle = 1.74 \times 10^{-6} \text{ GeV}^{-2}$')
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('$\langle \sigma v \rangle$', size= 15)
plt.title('$M = 100$ GeV', size= 15)
plt.legend(loc='best',fontsize=10)
plt.grid(True)
```

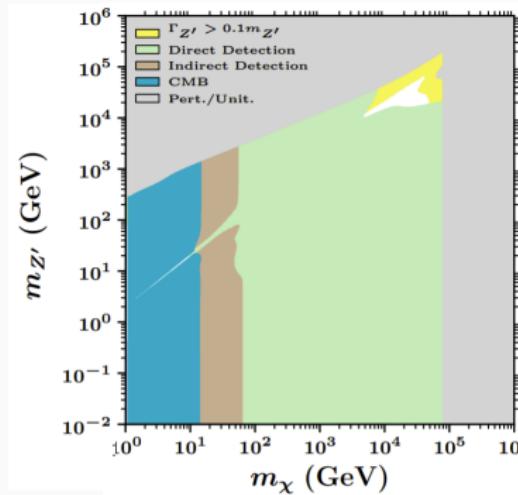


Isosinglet dark matter candidate

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

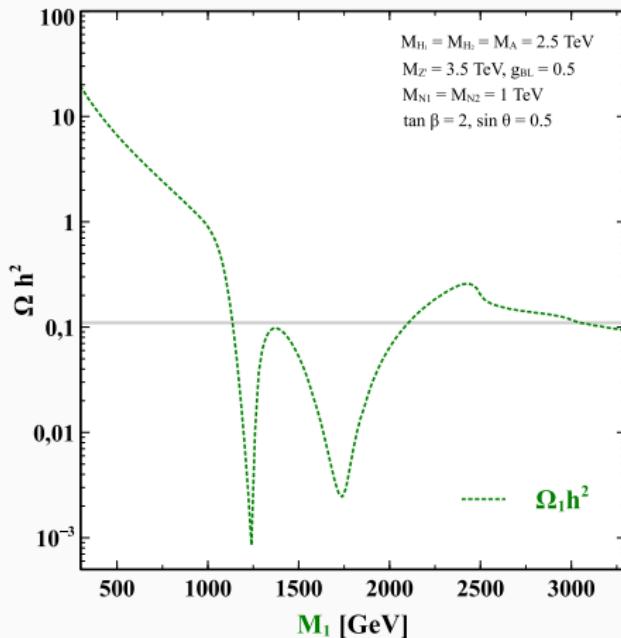
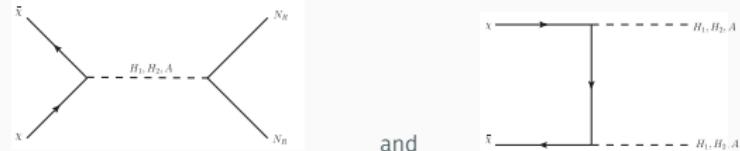
$$\mathcal{L}_{\text{int}} = -g_{BL} \bar{\chi} \gamma^\mu \chi, Z'_\mu - \sum_f g_f \bar{f} \gamma^\mu f, Z'_\mu,$$

where f are the Standard Model fermions: Resonances excluded!



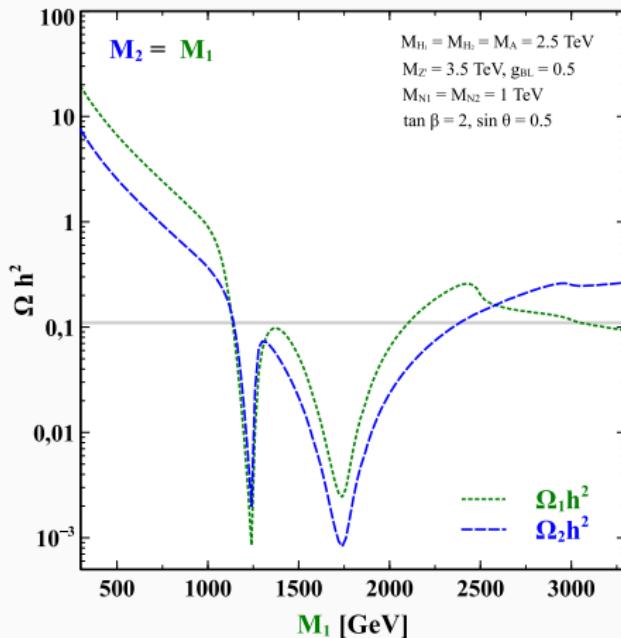
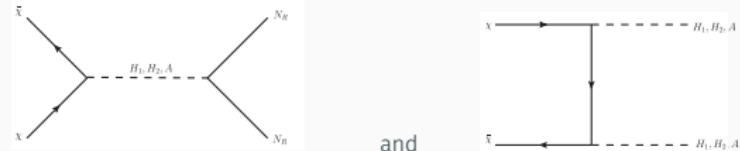
Exotic scalar portal

Additional DM annihilation processes



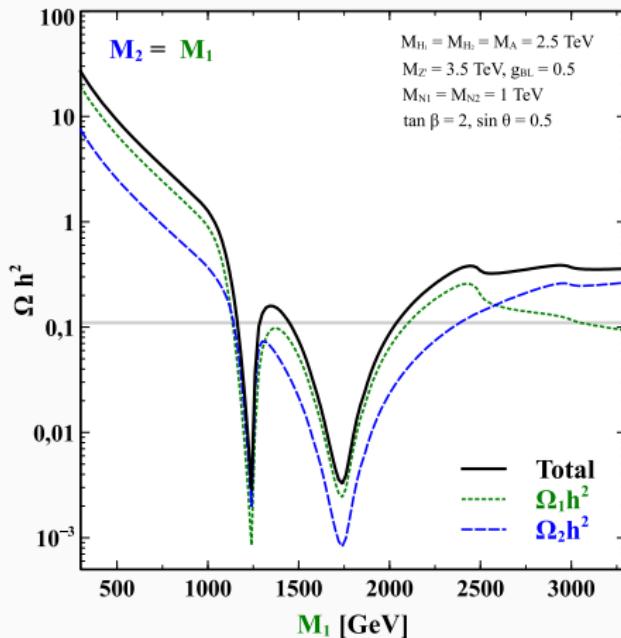
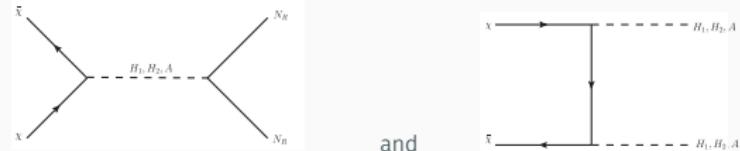
Exotic scalar portal

Additional DM annihilation processes



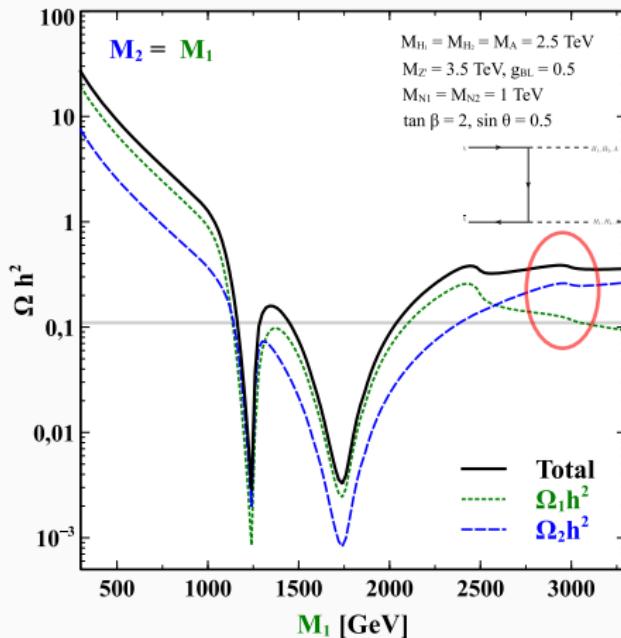
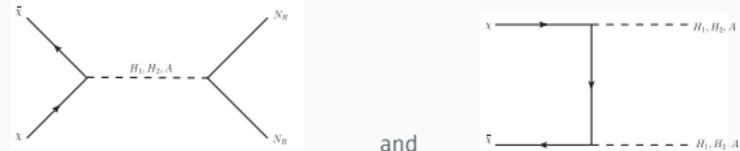
Exotic scalar portal

Additional DM annihilation processes



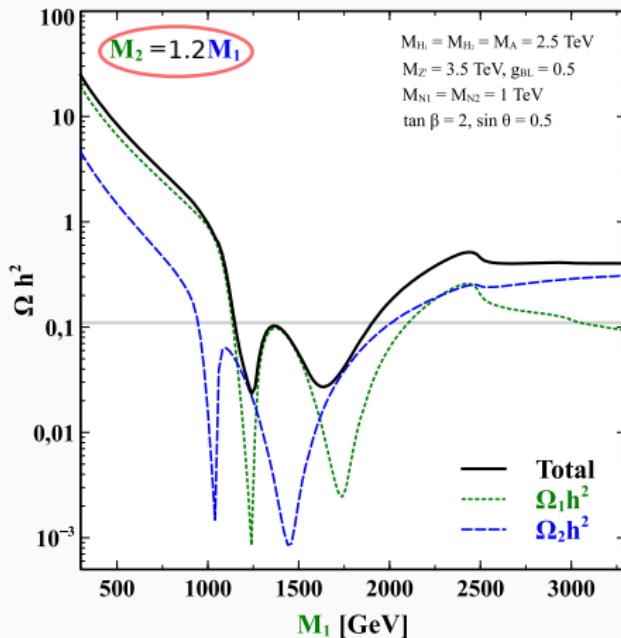
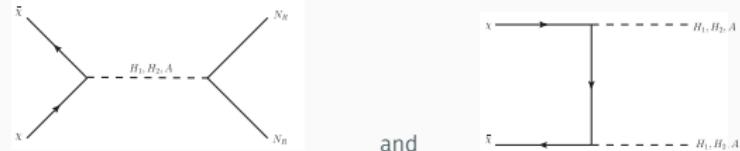
Exotic scalar portal

Additional DM annihilation processes



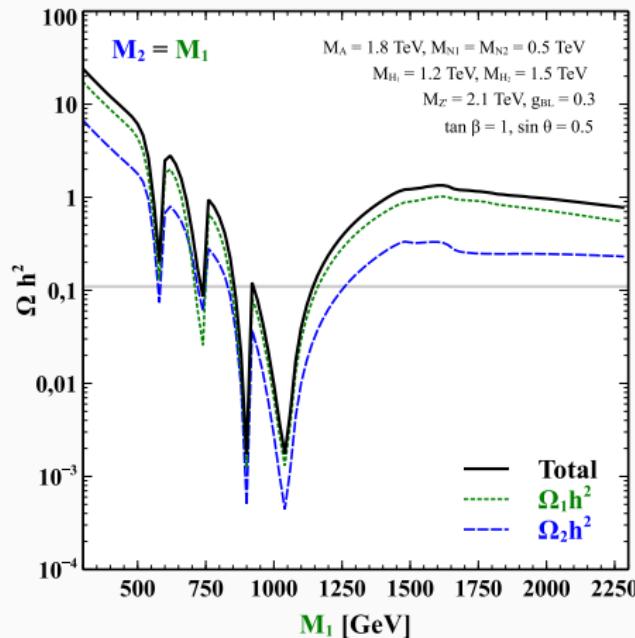
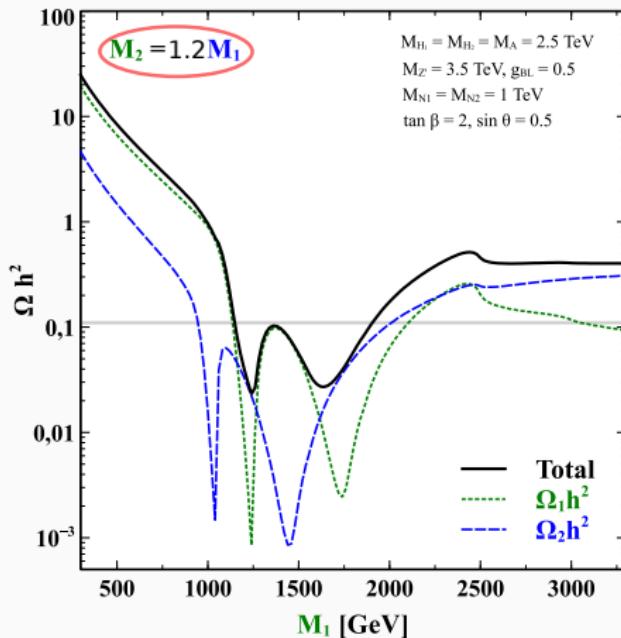
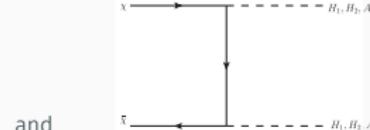
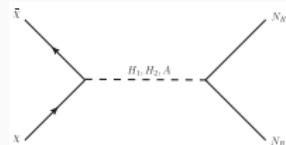
Exotic scalar portal

Additional DM annihilation processes



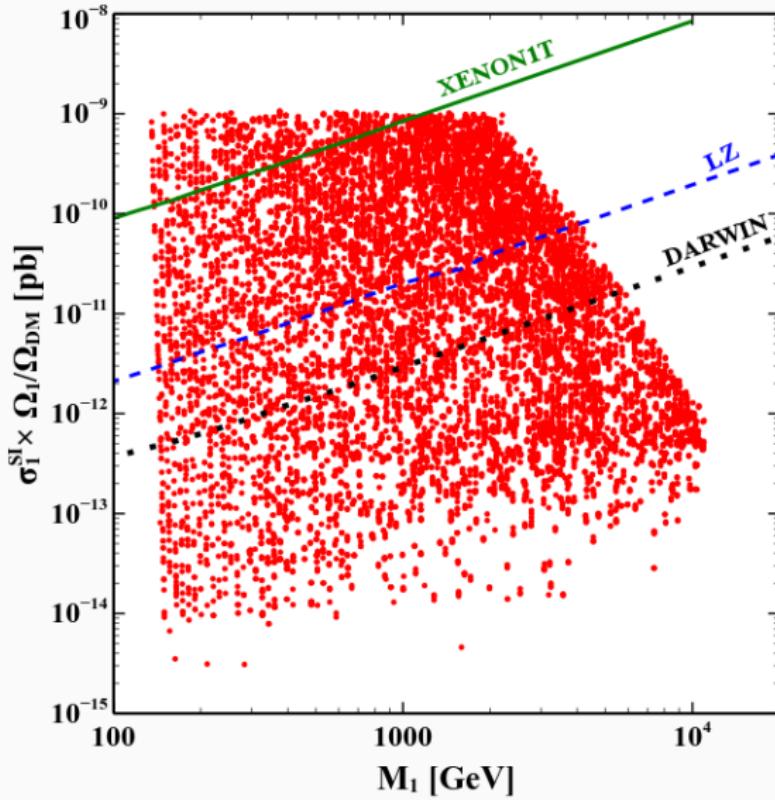
Exotic scalar portal

Additional DM annihilation processes



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



Conclusions

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

In this extension of the SM by an $U(1)_{B-L}$ gauge symmetry anomalies 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!