



UNIVERSIDAD DE ANTIOQUIA  
1803

# Two component Dark Matter with neutrino masses

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

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Focus on

arXiv:1811.11927 [PRD]

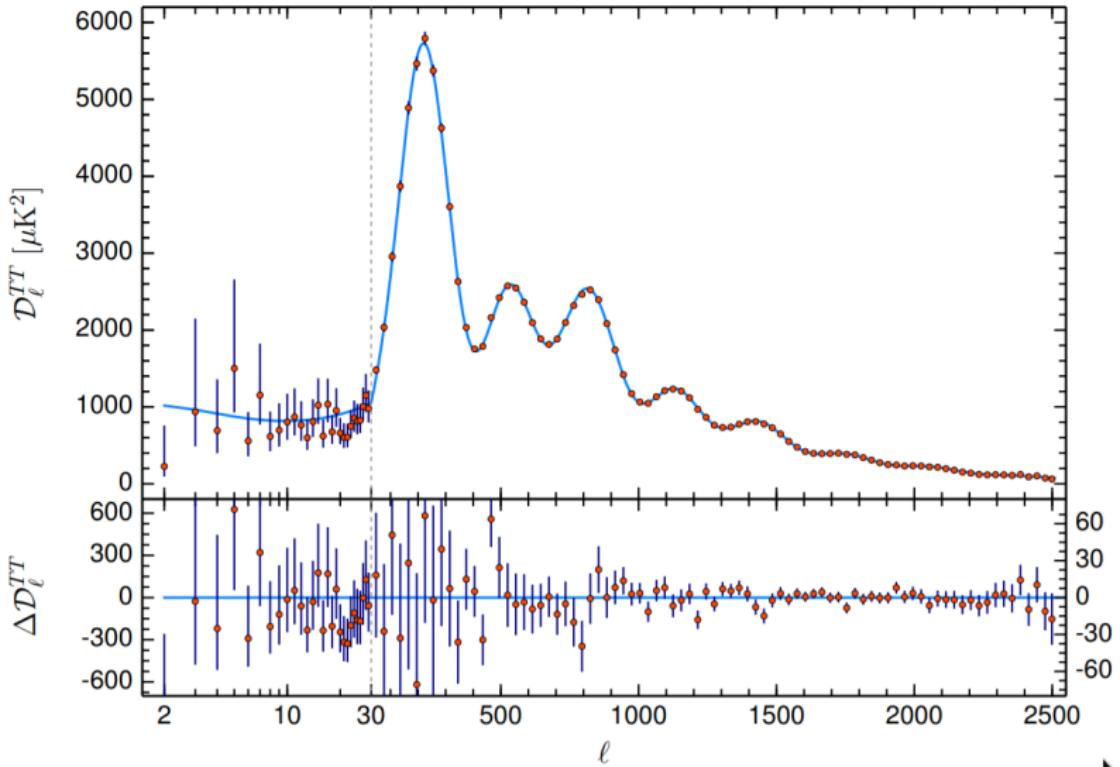
In collaboration with

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

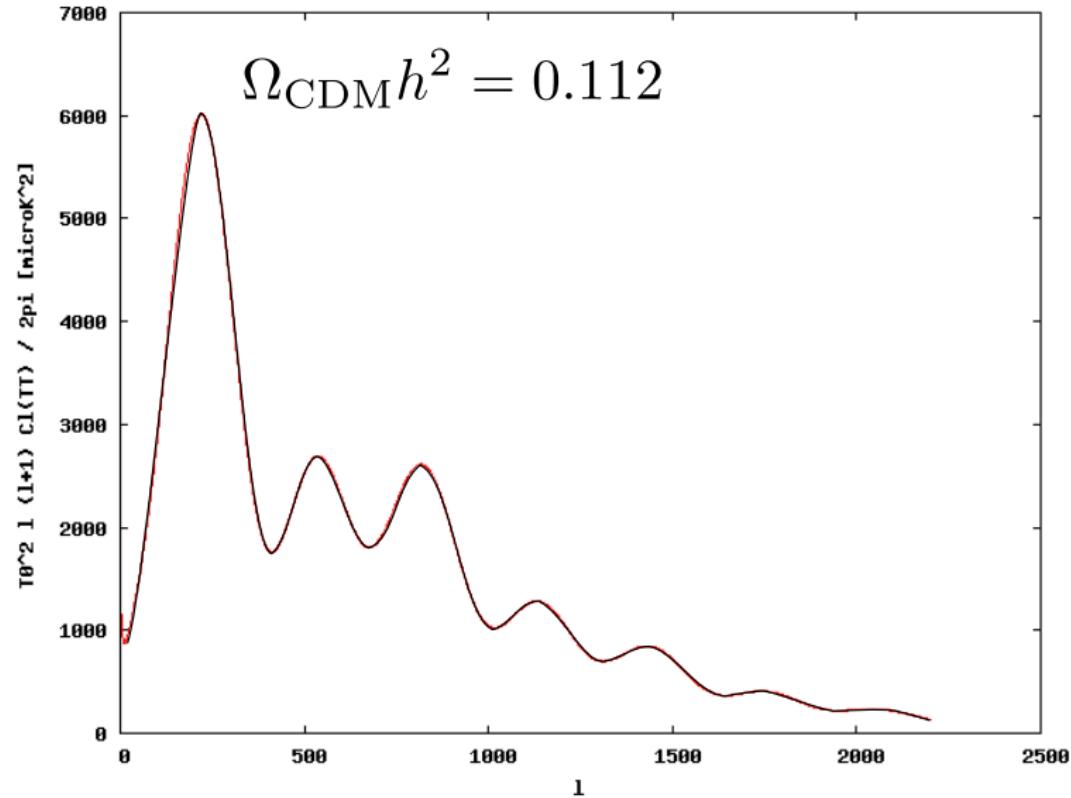


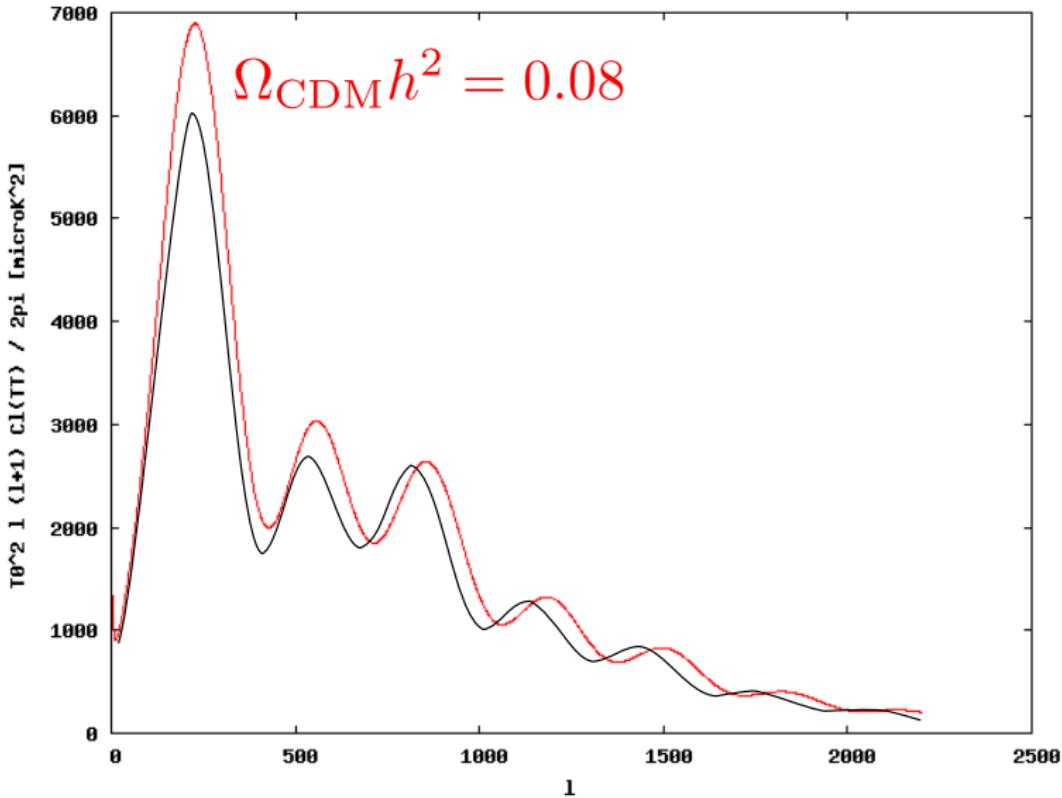
$\Lambda$ CDM paradigm (with baryonic effects)

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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 2018<sup>1</sup>

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<sup>1</sup>Video available



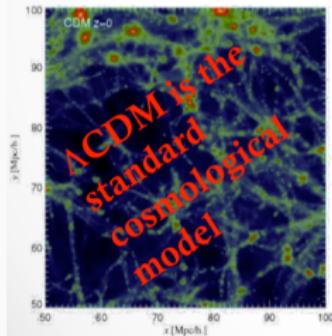
Credit: Komatsu, ICTP Summer School on Cosmology 2018<sup>1</sup>

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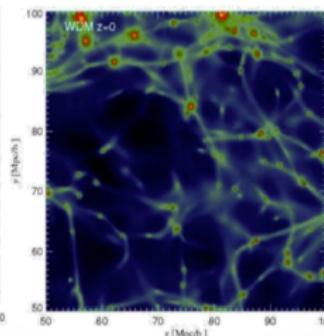
<sup>1</sup>Video available

# Dark matter simulations

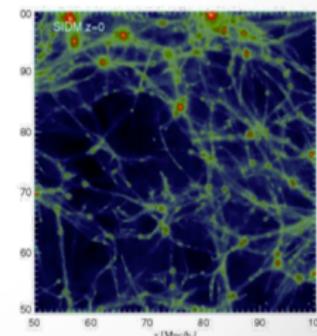
Cold Dark Matter  
(Slow moving)  
 $m \sim \text{GeV-TeV}$   
Small structures form first, then merge



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

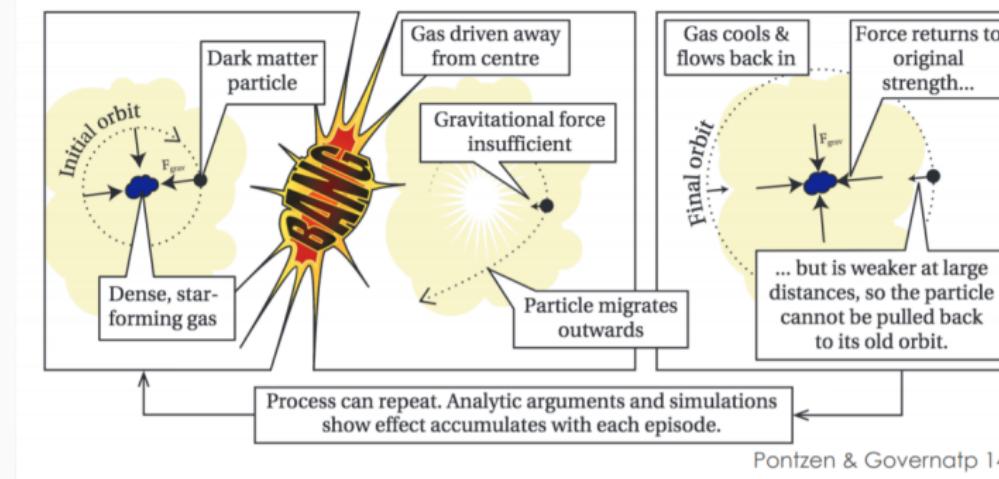


Self-Interacting Dark Matter  
Strongly interact with itself  
Large scale similar to CDM,  
Small galaxies are different



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

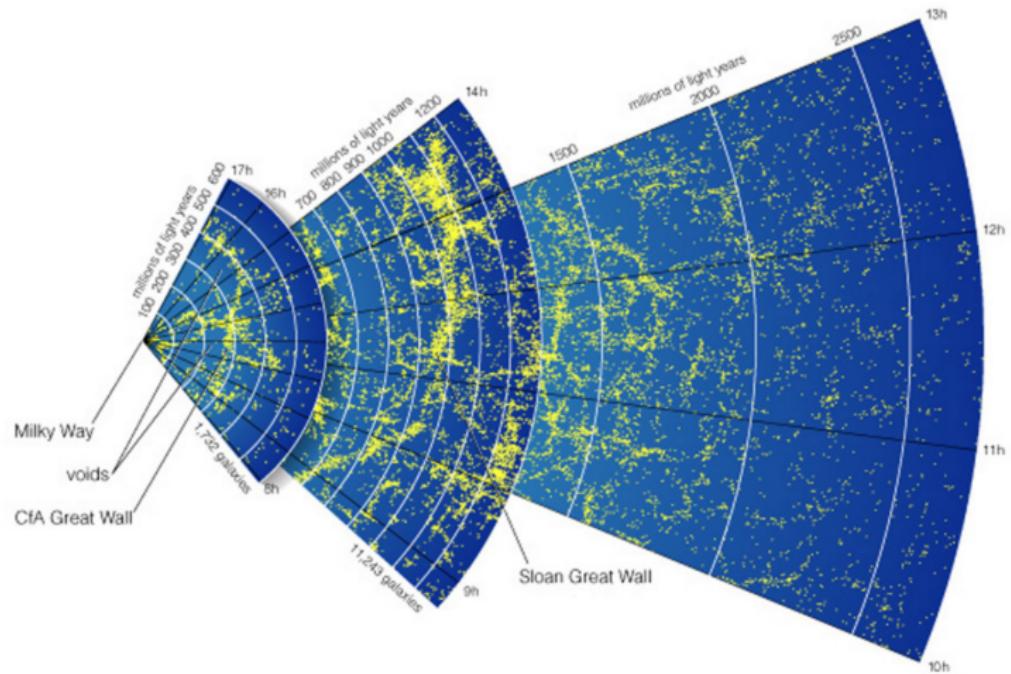
# Baryonic effects



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]

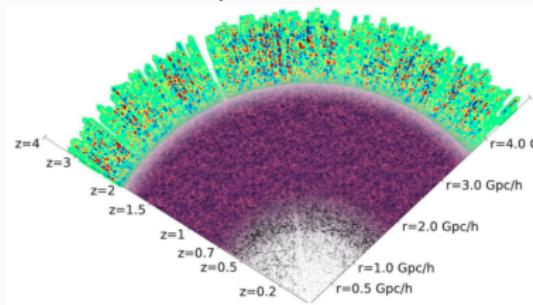
# Goal



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

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## The DESI experiment



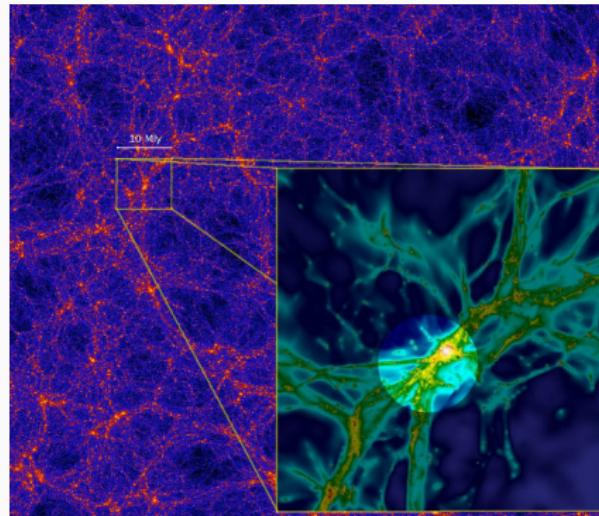
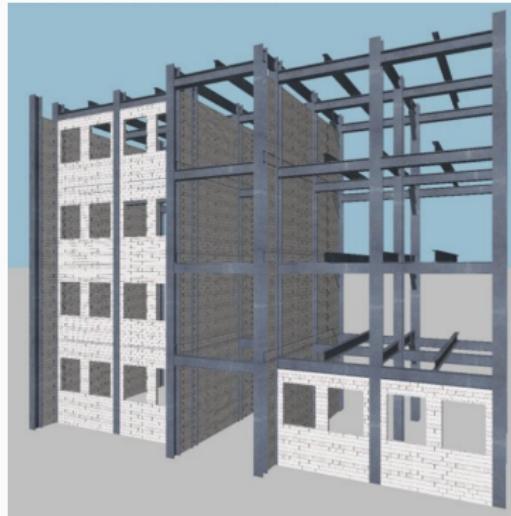
J. Forero <http://cosmology.univalle.edu.co/>

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>

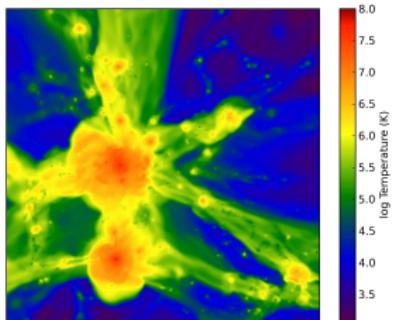


An excess of a gas is observed between Milky Way and Andromeda

# 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

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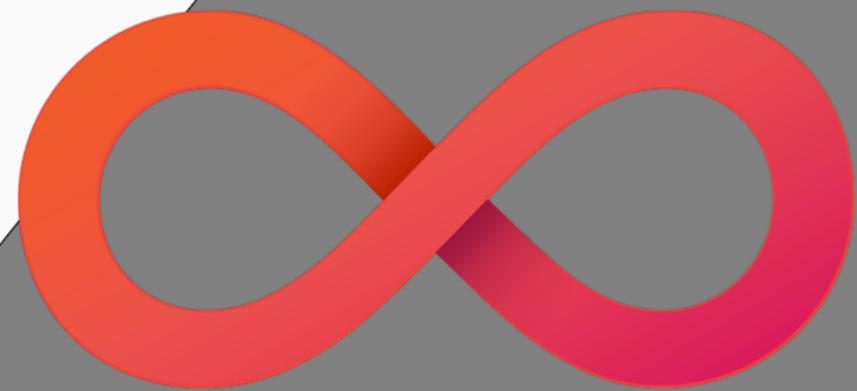
In the following discussion we use the following doublets in Weyl Notation

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

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  $U(1)_X \rightarrow Z_7$

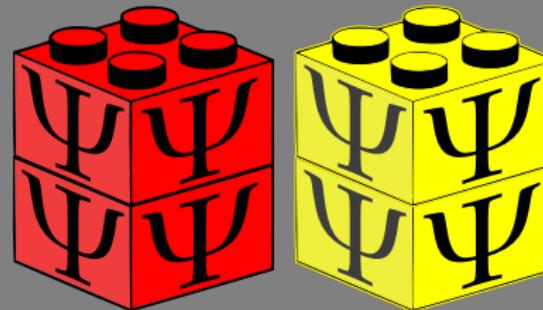
$$\mathcal{L} = y(N_R)^\dagger L \cdot \langle H \rangle + y' \langle S \rangle N_R N_R + \text{h.c}$$



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

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	$h$
$\psi$	1	0	$\psi$

**Table 1:** The new and fermions with their respective charges.

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

with solution

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

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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]
$\left(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7}\right)$	 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: $\psi_N, \psi_{N-1}$

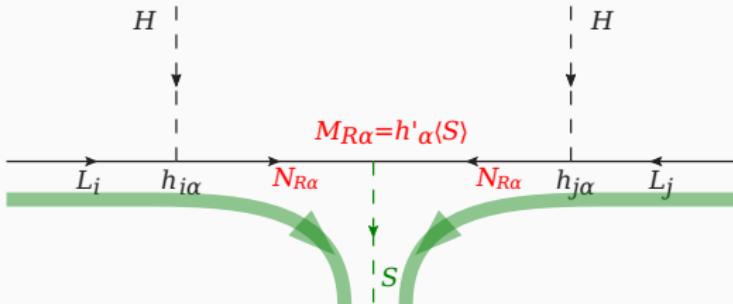
Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$U(1)_{B-L}$	$U(1)_B$	$U(1)_D$	$U(1)_G$
$L$	2	-1/2	$l$	-1	0	-3/2	-1/2
$Q$	2	-1/6	$-l/3$	1/3	0	1/2	1/6
$d_R$	1	-1/2	$1+2l/3$	1/3	1	0	2/3
$u_R$	1	+2/3	$-1-4l/3$	1/3	-1	1	-1/3
$e_R$	1	-1	$1+2l$	-1	1	-2	0
$H$	2	-1/2	$-1-l$	0	-1	1/2	-1/2
$S$	1	0	$2\psi_N$	$2\psi_N$	$2\psi_N$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

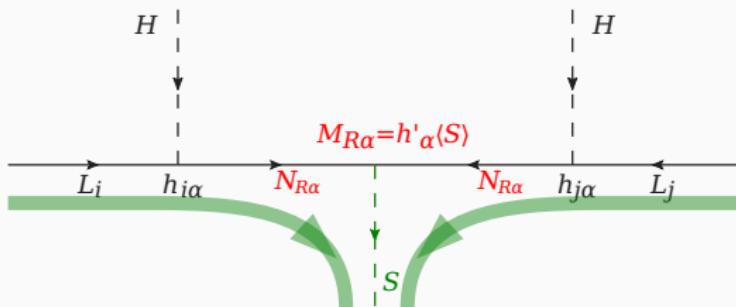


After integrating out heavy fermions, we obtain  
light neutrino masses

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

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

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

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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

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

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

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

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

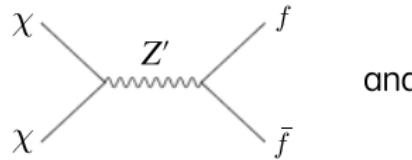
$K_1$ : Modified Bessel function

Reduced cross section

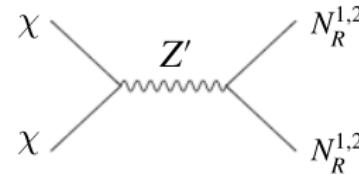
$$\hat{\sigma}(s) = 2(s - 4m_\chi^2 \sigma(s))$$

# 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

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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]

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

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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

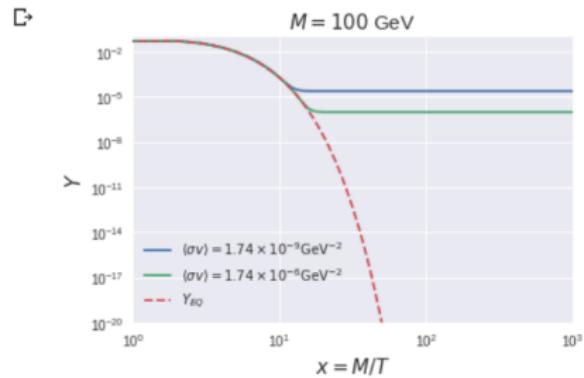
✓ CONNECTED

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)
```

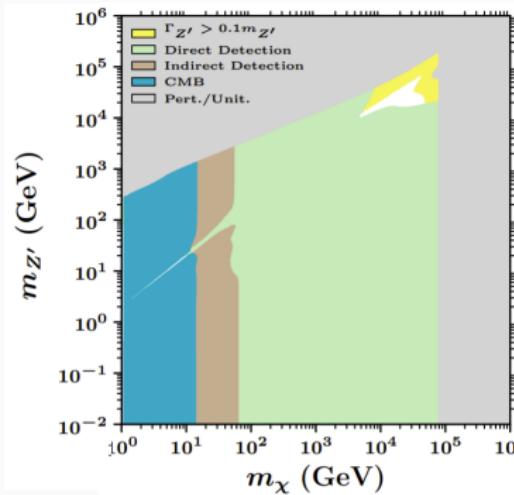


# Isosinglet dark matter candidate

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

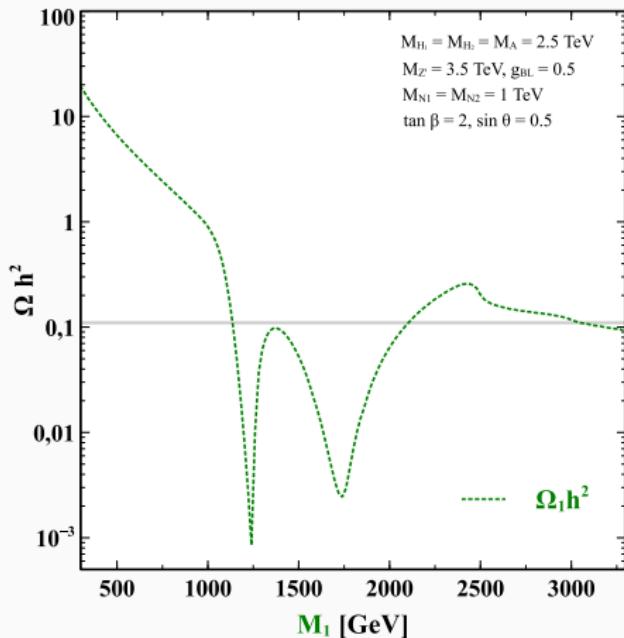
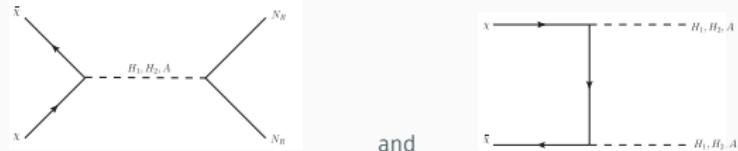
$$\mathcal{L}_{\text{int}} = -g_{BL} \bar{\chi} \gamma^\mu \chi Z'_\mu - \sum_f g_f \bar{f} \gamma^\mu f Z'_\mu,$$

where  $f$  are the Standard Model fermions: Resonances excluded!



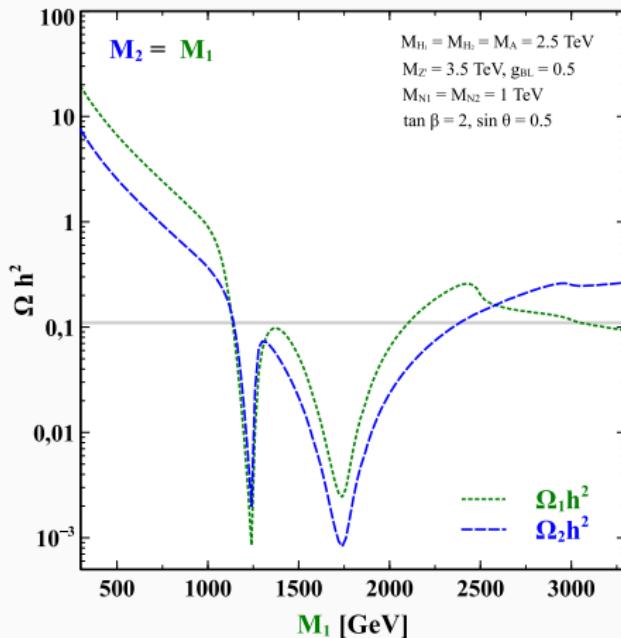
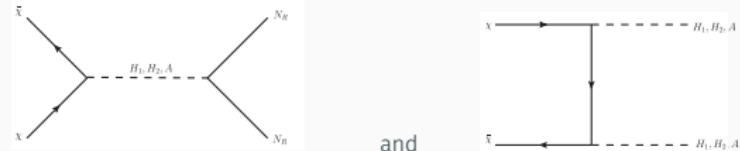
# Exotic scalar portal

## Additional DM annihilation processes



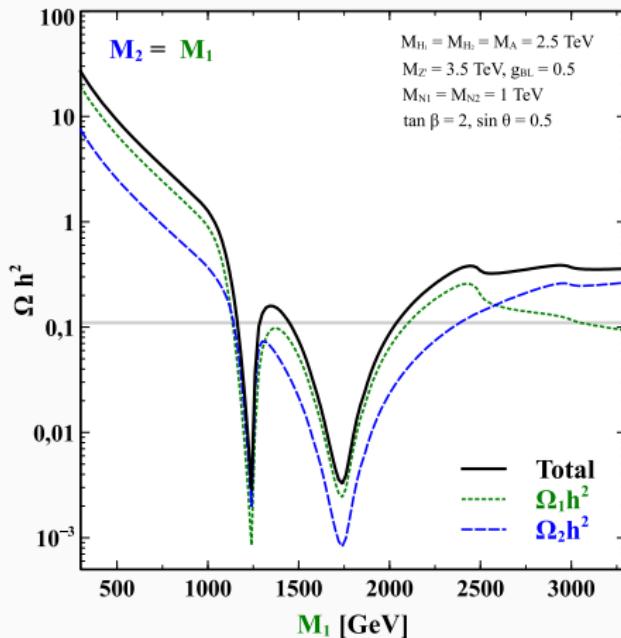
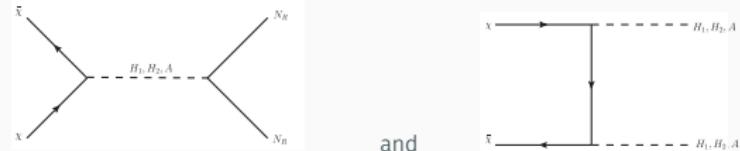
# Exotic scalar portal

## Additional DM annihilation processes



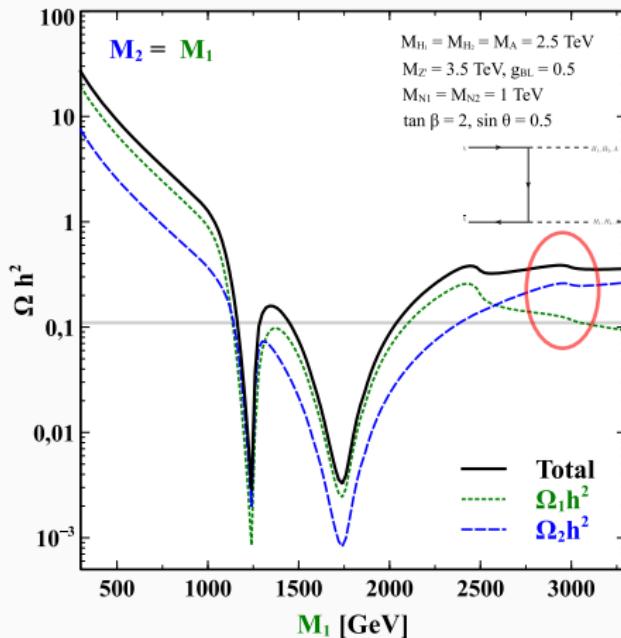
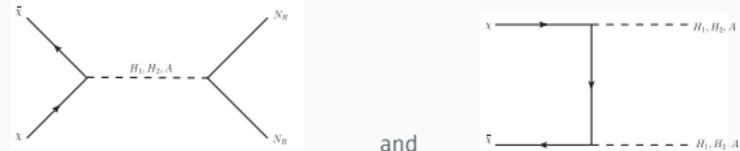
# Exotic scalar portal

## Additional DM annihilation processes



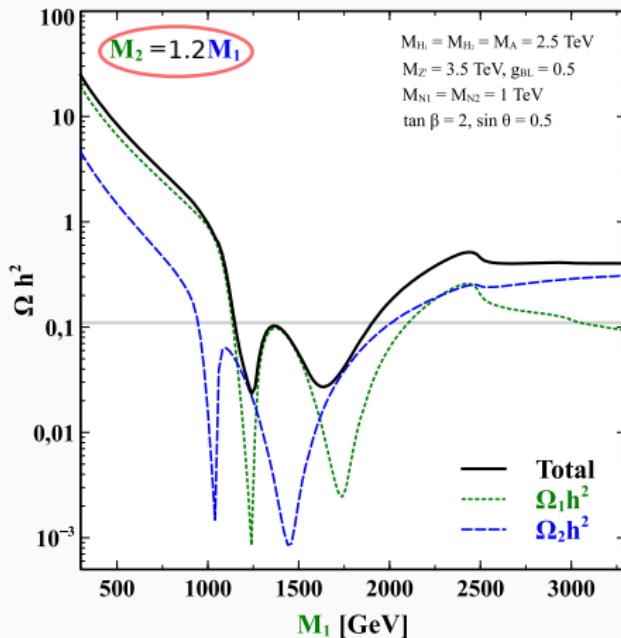
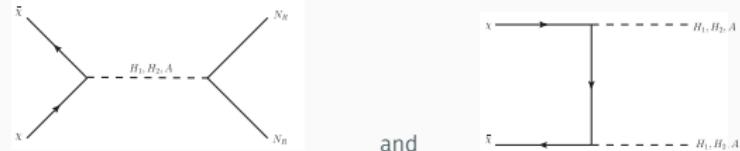
# Exotic scalar portal

## Additional DM annihilation processes



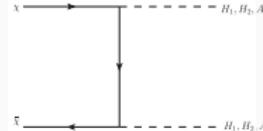
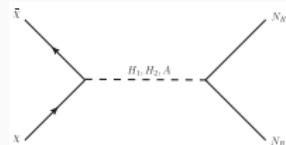
# Exotic scalar portal

## Additional DM annihilation processes

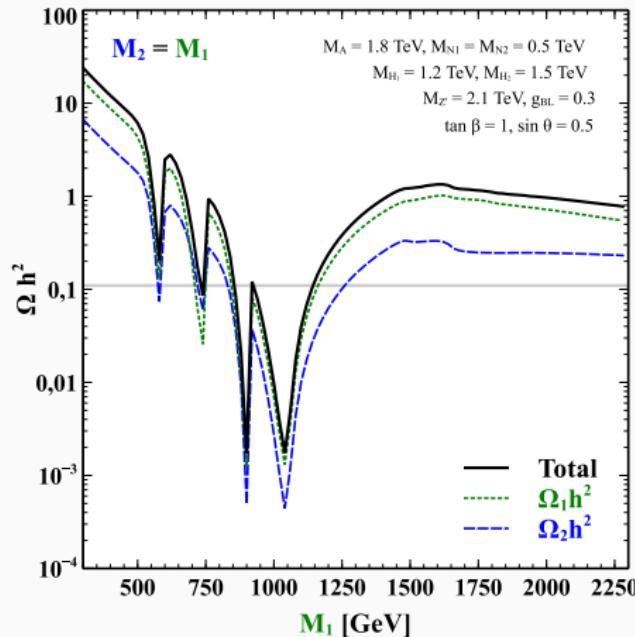
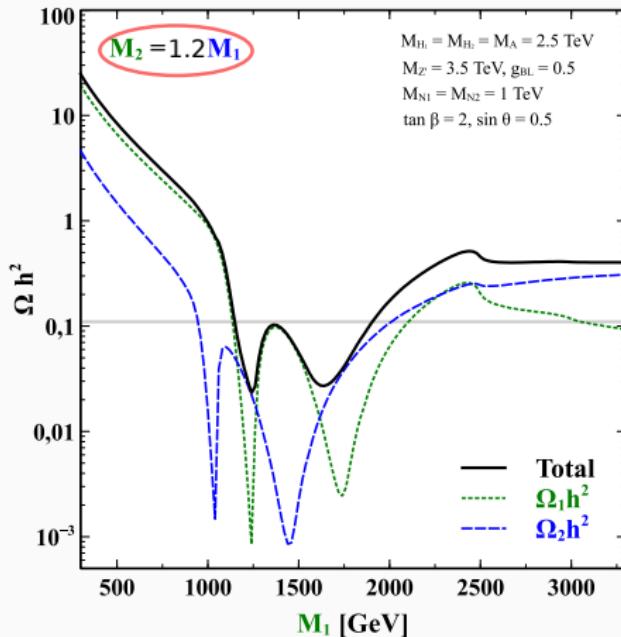


# Exotic scalar portal

## Additional DM annihilation processes

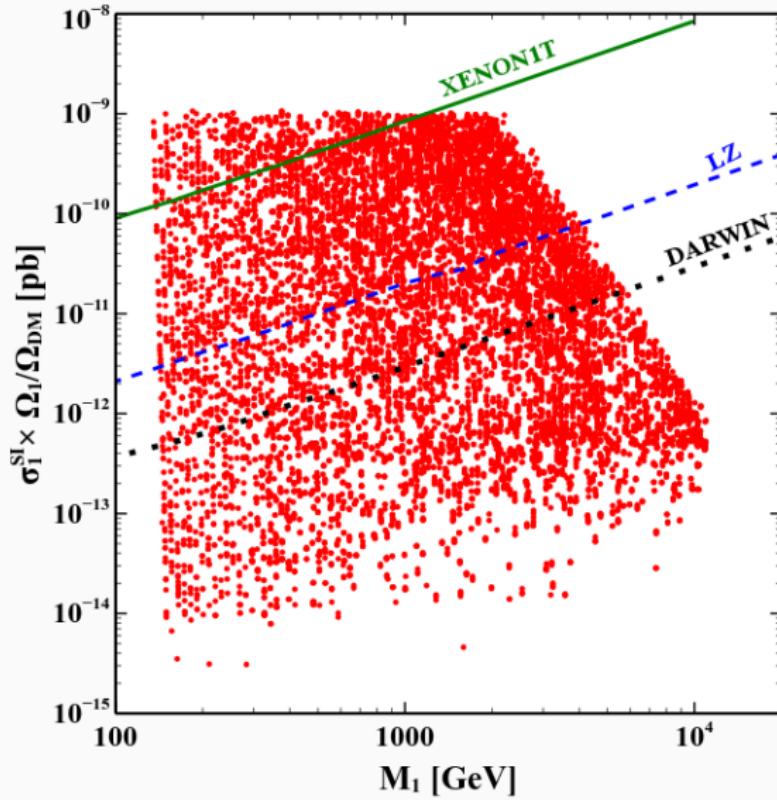


and



# 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!