Minimal Scotogenic (DM) models

with Dirac neutrino masses

Diego Restrepo

Oct 11, 2019 - USP [PDF: http://bit.ly/darkusp]

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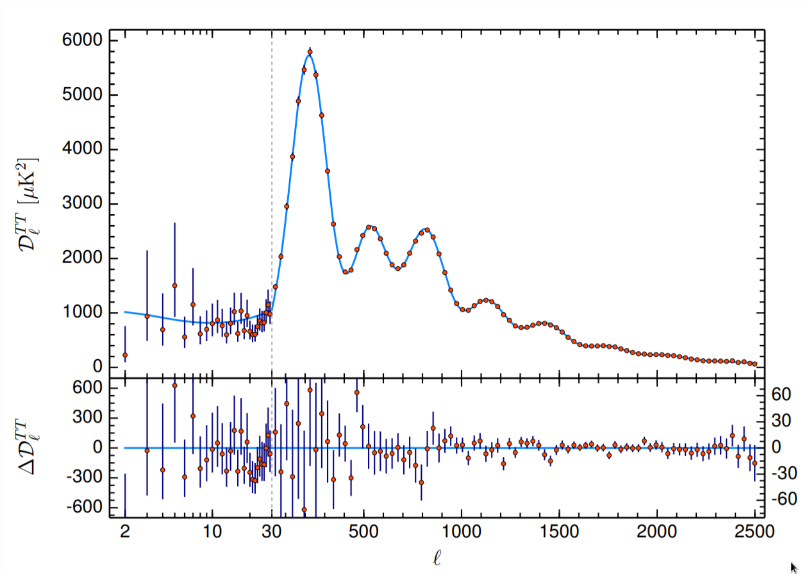
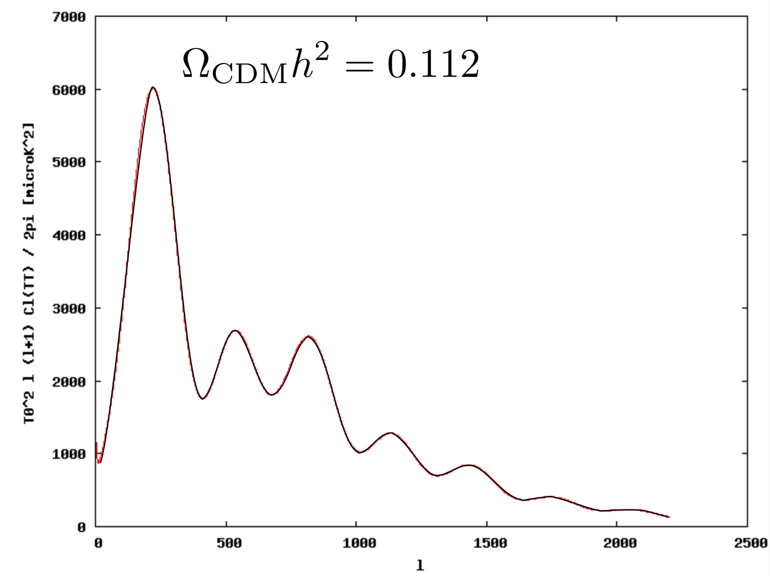
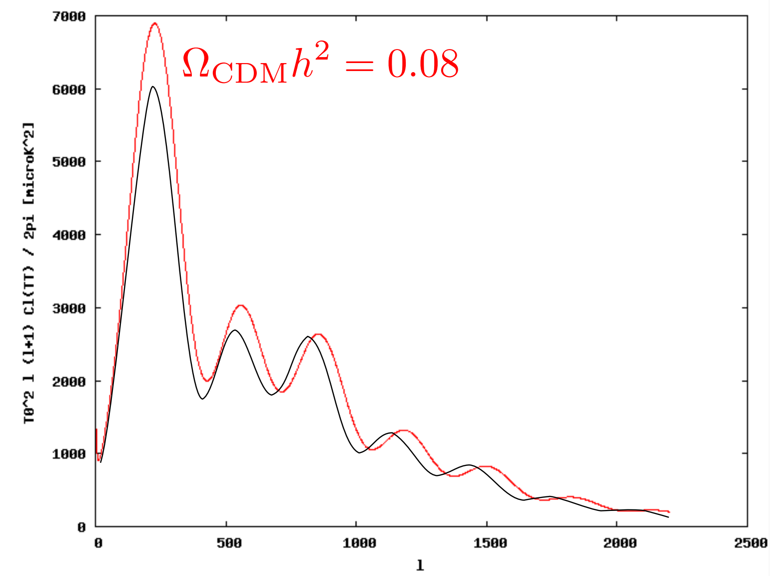
Focus on
arXiv:1811.11927 [PRD], arXiv:1906.09685 [PRD] and arXiv:1909.09574
In collaboration with
Carlos Yaguna (UPTC), Julian Calle, Óscar Zapata, Andrés Rivera (UdeA), Walter Tangarife (Loyola University Chicago)

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
0
500
1000
1500
2000
2500


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

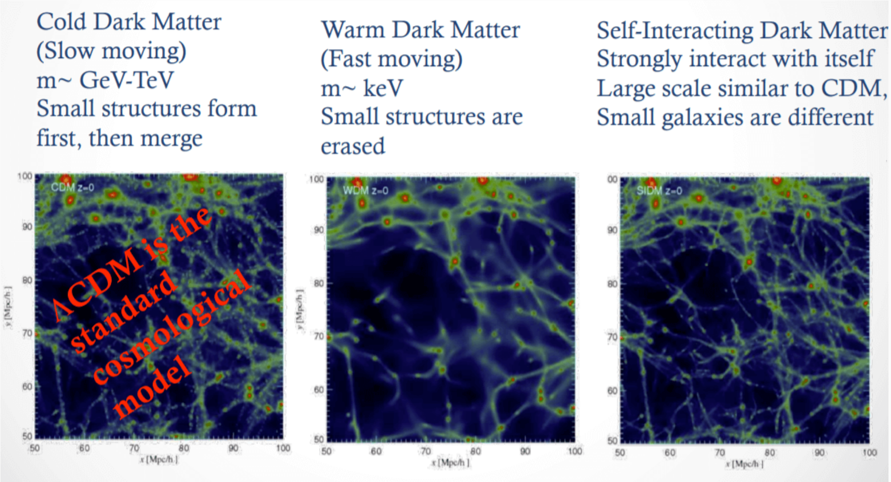
Cosmic Miso Soup

- 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)

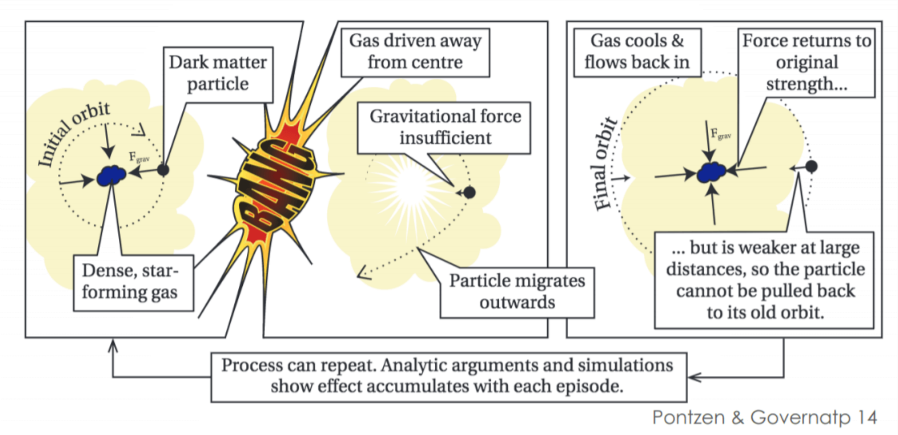

Nobu São Paulo version

Dark matter simulations



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

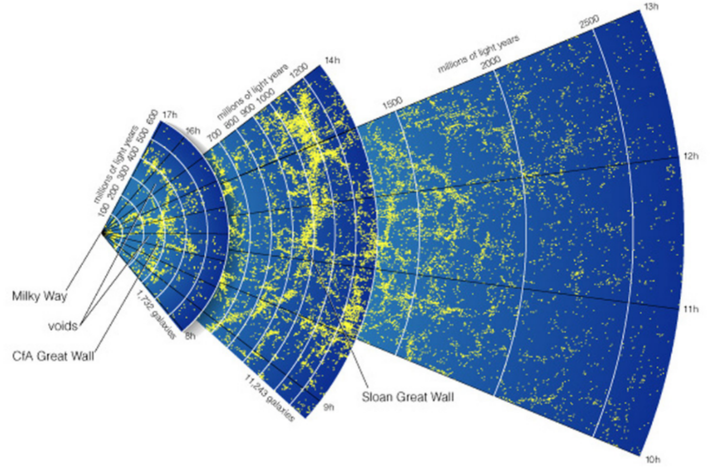
Baryonic effects



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

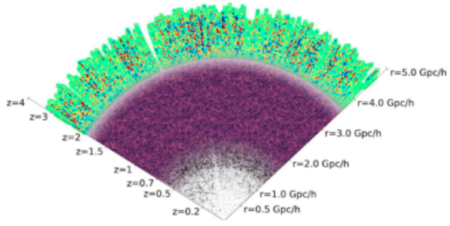
See: Gravitational probes of dark matter physics, M.R. Buckley, A.H.G. Peter, arxiv:1712.06615 [PR]

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

A.C Rodriguez *et al* arXiv:1801.09070 [CAC]

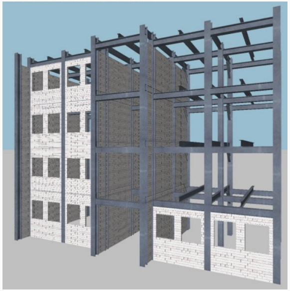
Cosmological simulations of structure formation predict that the majority of gas in the intergalactic medium (IGM) is distributed in a cosmic web of sheets and filaments as a consequence of gravitational collapse. The intersections of these structures become the locations at which galaxies and their supermassive black holes (SMBHs) form and evolve.

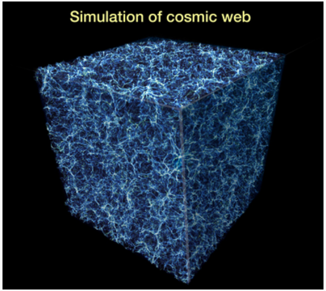
[...] at a z of ~ 3, $> 60\%$ of all gas in the Universe resides in filaments

H. Umehata *et al*, Science **366**, 97, 4 Oct 2019

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





These great filaments are made largely of dark matter located in the space between galaxies and filled with 60% of the primordial gas! [https://hubblesite.org]

An excess of a gas (20σ) is observed between Milky Way and Andromeda (M31): arXiv:1403.7528 [MNRAS] [1]

Clouds of HI likeky embeded in a filament between M31 and M33: arXiv:1305.1631 [nature]

[1] See also: arXiv:1603.05400 [A&A]

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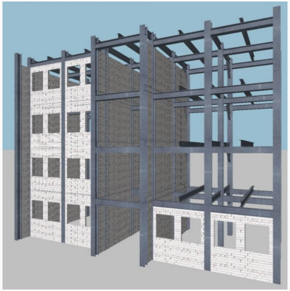

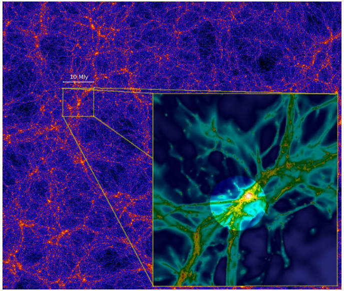

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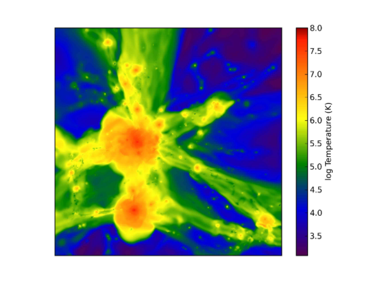
Direct observations of filaments

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

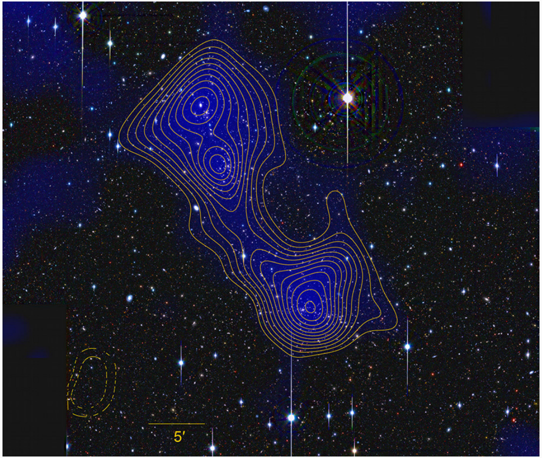
> *Thus, not only is the universe dominated by dark matter, but more than one half of the normal matter is yet to be detected. (the muscles)*



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]).



Supercluster system of three galaxy clusters

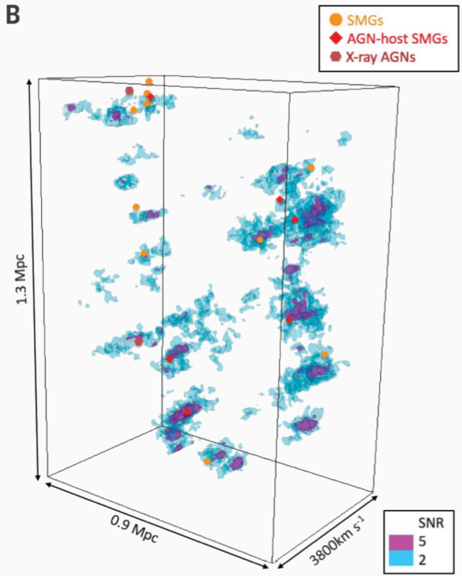
- Abell 222 (south) detected at $\sim 8\sigma$
- Abell 223 (north) double galaxy cluster seen at $\sim 7\sigma$

reconstructed surface mass density (blue)

significance contours from 0.5σ to 2.5σ

J.P. Dietrich *et al*, arXiv:1207.0809 [Nature]

For a recent review see: arXiv:1905.08991



The 3D distribution of Lyα filaments shown with

signal-to-noise ratio (SNR) > 5

signal-to-noise ratio (SNR) > 2

H. Umehata *et al*, Science **366**, 97, 4 Oct 2019

Dark sectors

In the following discussion we use the following doublets

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

corresponding to the Higgs doublet and the lepton doublets (in Weyl Notation) respectively, such that

$$L_i \cdot H = \epsilon_{ab} L_i^a H^b, \qquad a, b = 1, 2$$

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]

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

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

$\langle$SM$\rangle$

+

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

Type-I arXiv:1808.03352

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

Local $U(1)_X \to Z_7$

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

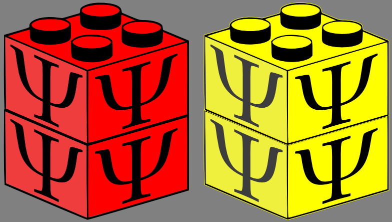
⟨SM⟩

+

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

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	n

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

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

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

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

with solution

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

which satisfy

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

For N extra quiral fields ψ_α ($\alpha = 1, \ldots, N$) with X-charges n_α:

$$\begin{aligned}
[\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_X: \qquad & \sum_\alpha n_\alpha + 3(e-2l) = 0\,, \\
[\mathrm{U}(1)_X]^3\,, \qquad & \sum_\alpha n_\alpha^3 + 3(e-2l)^3 = 0
\end{aligned}$$

with solution

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

which satisfy

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

For N extra quiral fields ψ_α ($\alpha = 1, \ldots, N$) with X-charges n_α: $r \equiv e - 2l$

$$\begin{aligned} [\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_X: & \qquad \sum_\alpha n_\alpha + 3r = 0\,, \\ [\mathrm{U}(1)_X]^3\,, & \qquad \sum_\alpha n_\alpha^3 + 3r^3 = 0 \end{aligned}$$

Then the general anomaly free two-parameter solution can be written as

$$X(r, l) = rR + lY\,.$$

with solution

$$u = -1 - \frac{4l}{3}\,, \qquad d = 1 + \frac{2l}{3}\,, \qquad q = -\frac{l}{3}\,, \qquad e = 1 + 2l\,, \tag{2}$$

which satisfy

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

For N extra quiral fields ψ_α $(\alpha = 1, \ldots, N)$ with X-charges n_α: $r \equiv e - 2l = 1$

$$[\mathrm{SO}(1,3)]^2\,\mathrm{U}(1)_X: \qquad \sum_\alpha n_\alpha + 3 = 0\,,$$

$$[\mathrm{U}(1)_X]^3\,, \qquad \sum_\alpha n_\alpha^3 + 3 = 0$$

Since $f \to f' \to f/r$, without lost of generality: $r \to 1$

$$X(\ l) = R + lY\,.$$

We impose $\nu_{R1} = \psi_N$, $\nu_{R2} = \psi_{N-1}$, to have at most one massless neutrino.

One parameter $U(1)_X$ SM extension

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$U(1)_{B-L}$	$U(1)_R$	$U(1)_D$	$U(1)_G$	$U(1)_{\mathcal{D}}^*$
L	**2**	$-1/2$	l	-1	0	$-3/2$	$-1/2$	0
Q	**2**	$-1/6$	$-l/3$	$1/3$	0	$1/2$	$1/6$	0
d_R	**1**	$-1/2$	$1+2l/3$	$1/3$	1	0	$2/3$	0
u_R	**1**	$+2/3$	$-1-4l/3$	$1/3$	-1	1	$-1/3$	0
e_R	**1**	-1	$1+2l$	-1	1	-2	0	0
H	**2**	$-1/2$	$-1-l$	0	-1	$1/2$	$-1/2$	0
$\sum_\alpha n_\alpha$	**1**	0	-3	-3	-3	-3	-3	0
$\sum_\alpha n_\alpha^3$	**1**	0	-3	-3	-3	-3	-3	0

* $r = l = 0$ $(n_\alpha \neq 0)$

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

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

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \cdots)$	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.

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

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \cdots)$	Ref
$(-1, -1, -1)$	hep-ph/0611205, S. Khalil [JPG]
$(-4, -4, +5)$	arXiv:0706.0473, Montero, V. Pleitez [PLB]
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https://en.wikipedia.org/wiki/Sums_of_three_cubes

Only known integer solutions for -3 (1953)

September 2019:

$$42 = (-80538738812075974)^3 + 80435758145817515^3 + 12602123297335631^3$$

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$\left(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, +2\right)$	arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]
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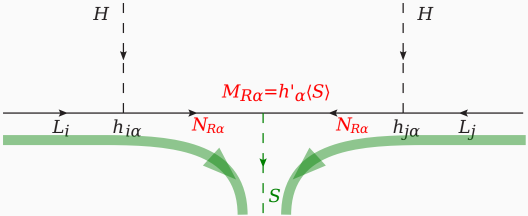
Not known solution for one-loop neutrino Majorana masses with local $U(1)_X$.

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

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	$+$	$+$

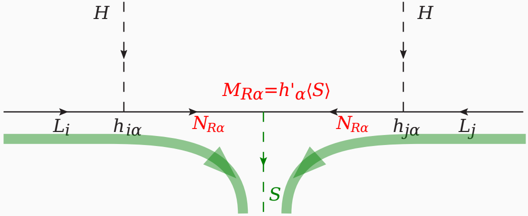


After integrating out heavy fermions, we obtain light neutrino masses

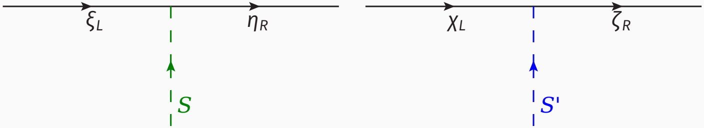
$$\boxed{\mathcal{M}_\nu^{ij} = \sum_{\alpha=1}^{2} \left(h^{i\alpha} v\right) \frac{1}{M_R^\alpha} \left(h^{j\alpha} v\right)}$$

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



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

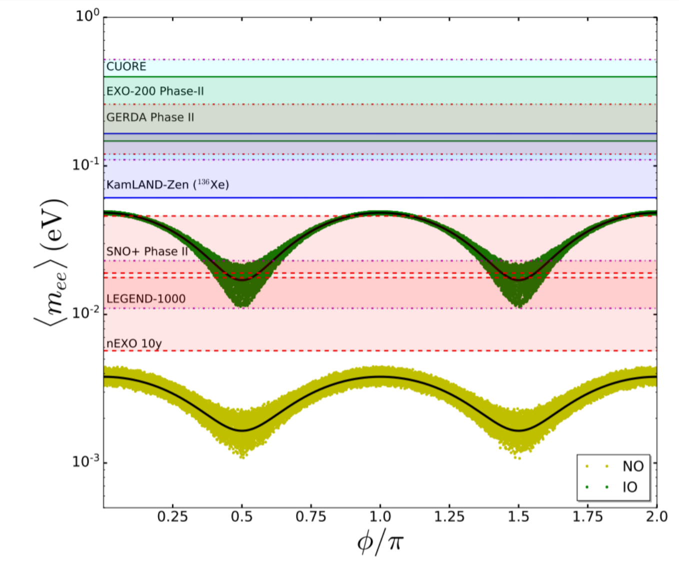
$$\mathcal{L} = M_1 \overline{\chi_1}\chi_1 + M_2 \overline{\chi_2}\chi_2$$

One-loop Dirac neutrino masses

Lepton number

- Lepton number (L) is an accidental discret or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e, L_μ, L_τ are also conserved.
- The processes which violates individual L are called Lepton flavor violation (LFV) processes.
- All the neutrino mass models predict, to some extent, LFV processes
- Only models with Majorana neutrinos predict processes with total $L = L_e + L_\mu + L_\tau$ violation, like neutrino less doublet beta decay (NLDBD).
- NLDBD is experimentally challenging, specially if there is a massless neutrino in the spectrum.

NLDBD prospects for a model with a massless neutrino (arXiv:1806.09977 [PLB] with Reig, Valle and Zapata)



with M.Reig, J.W.F Valle, O. Zapata, arXiv:1806.09977

Total lepton number: $L = L_e + L_\mu + L_\tau$

Majorana $\cancel{\mathrm{U}(1)_L}$

Field	Z_2 ($\omega^2 = 1$)
SM	1
L	ω
$(e_R)^\dagger$	ω
$(\nu_R)^\dagger$	ω

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

$$h_D \sim \mathcal{O}(1)$$

Dirac $\mathrm{U}(1)_L$

Field	Z_3 ($\omega^3 = 1$)
SM	1
L	ω
$(e_R)^\dagger$	ω^2
$(\nu_R)^\dagger$	ω^2

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

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

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

Field	Z_3 $(\omega^3 = 1)$
SM	1
L	ω
$(e_R)^\dagger$	ω^2
$(\nu_R)^\dagger$	ω^2

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

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

Explain smallness ala Peccei-Quinn:

$$\mathrm{U}(1)_{B-L} \underbrace{\longrightarrow}_{\langle S \rangle} Z_N\,, \quad N \geq 3\,.$$

Small Dirac neutrino masses

To explain the smallness of Dirac neutrino masses choose $\mathrm{U}(1)_{B-L}$ which:

- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

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

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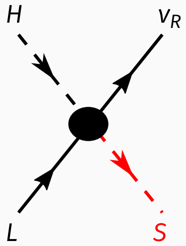
- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

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

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



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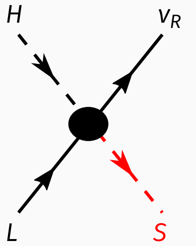


- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$ (see arXiv:1211.0186)

See E. Ma, Rahul Srivastava: arXiv:1411.5042 [PLB] for tree-level realization

From 1210.6350 and 1805.02025: $\Delta N_{\text{eff}} = 3\left(T_{\nu_R}/T_{\nu_L}\right)^4$

$$\Gamma_{\nu_R}(T) = n_{\nu_R}(T)\sum_f \langle\sigma_f(\nu_R\bar{\nu}_R \to f\bar{f})v\rangle$$
$$= \sum_f \frac{g_{\nu_R}^2}{n_{\nu_R}}\int \frac{d^3p}{(2\pi)^3}\frac{d^3q}{(2\pi)^3} f_{\nu_R}(p) f_{\nu_R}(q)\sigma_f(s)(1-\cos\theta),$$

$$s = 2pq(1-\cos\theta), \qquad f_{\nu_R}(k) = 1/(e^{k/T}+1)$$

$$n_{\nu_R}(T) = g_{\nu_R}\int \frac{d^3k}{(2\pi)^3} f_{\nu_R}(k), \qquad \text{with } g_{\nu_R} = 2$$

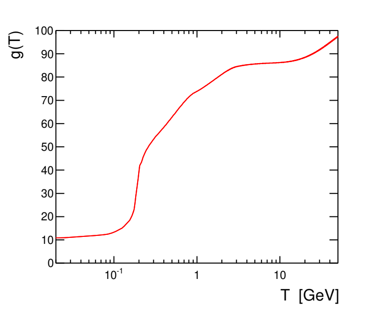
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s\,.$$

with three right-handed neutrinos, the Hubble parameter is

$$H(T) = \sqrt{\frac{4\pi^3 G_N\left[g(T) + 21/4\right]}{45}}\,T^2.$$

The right-handed neutrinos decouple when

$$\Gamma_{\nu_R}(T_{\text{dec}}^{\nu_R}) = H(T_{\text{dec}}^{\nu_R}).$$



A. Solaguren-Beascoa, M. C. Gonzalez-Garcia: arXiv:1210.6350 [PLB]

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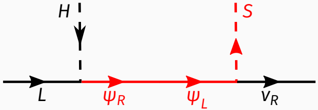
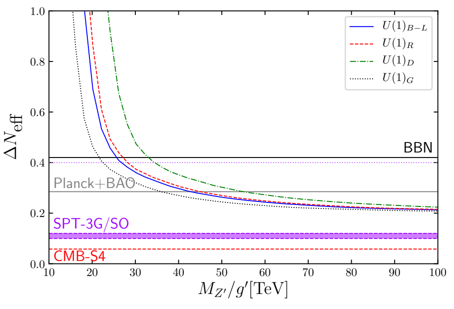
$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S\rangle} Z_3$



ν_{R3}	ν_{R2}	ν_{R1}	ψ_L	ψ_R	S
-4	-4	$+5$	-1	-1	$+3$

E. Ma, R. Srivastava: arXiv:1411.5042 [PLB]



with J. Calle and Ó. Zapata, arXiv:1909.09574

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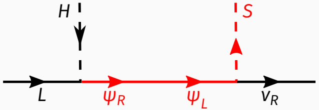

ν_{R3}	ν_{R2}	ν_{R1}	ψ_L	ψ_R	S
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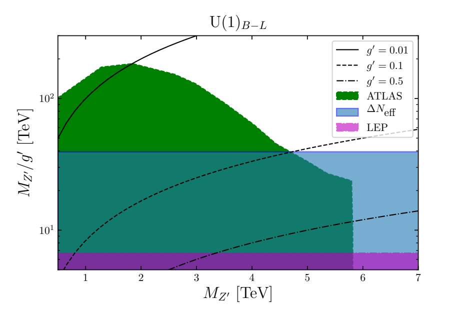
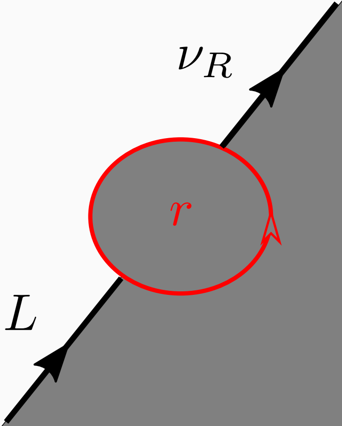


with J. Calle and Ó. Zapata, arXiv:1909.09574

One-loop realization of $\mathcal{L}_{5-D}$ with total L

$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter



$\mathrm{U}(1)_X$

Dirac neutrino masses + Forbids

Dirac fermion dark matter

$\nu_R \nu_R$

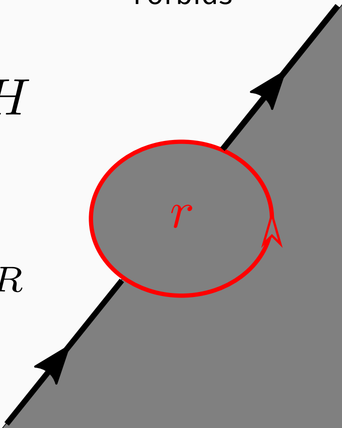
$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$



$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

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$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$

r

Allows

$(\nu_R)^\dagger L H S$

$(\psi_R)^\dagger \psi_L$

$(\psi_R)^\dagger \psi_L S$

$$\mathrm{U}(1)_{B-L} \xrightarrow[\langle S \rangle]{} Z_N \qquad N \neq 2$$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$$\nu_R \nu_R$$

$$(\nu_R)^\dagger L H$$

$$\nu_R \psi_R$$

$$(\psi_L)^\dagger \nu_R$$

$$\psi_R \psi_R$$

$$\psi_L \psi_L$$

r

Allows

$X(L) \neq 0$

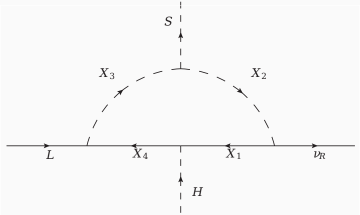
$$(\nu_R)^\dagger L H S$$

$$(\psi_R)^\dagger \psi_L$$

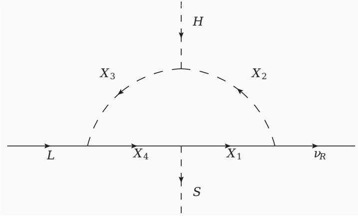
$$(\psi_R)^\dagger \psi_L S$$

normalized to $X(L) = -1$

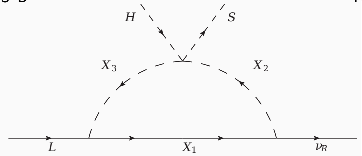
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

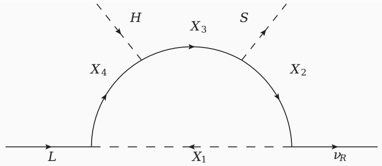


T1-3-E

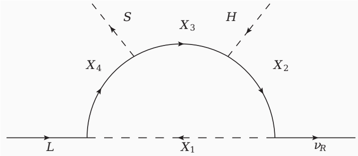


T3-1-A

Chang-Yuan Yao and Gui-Jun Ding, arXiv:1802.05231 [PRD]

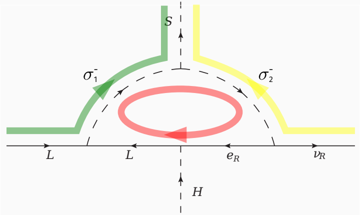


T1-2-A

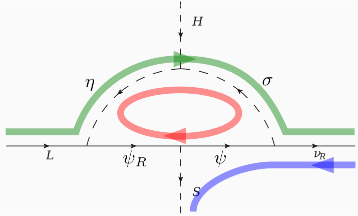


T1-2-B

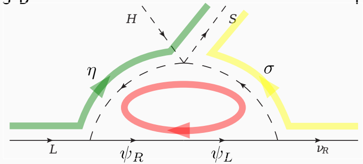
One loop topologies $U(1)_{B-L}$ only!



T1-3-D



T1-3-E



T3-1-A

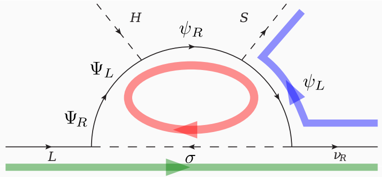
$\psi_{L,R}$ $\rightarrow$Singlet fermions

$\Psi_{L,R}$ $\rightarrow$Vector-like doublet fermions

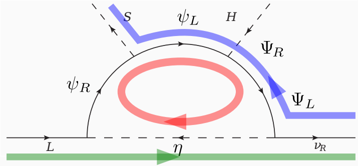
σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar

with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

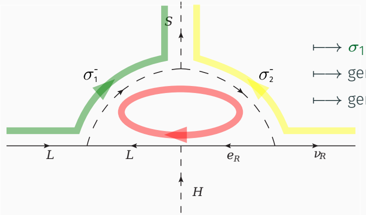


T1-2-A



T1-2-B

One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

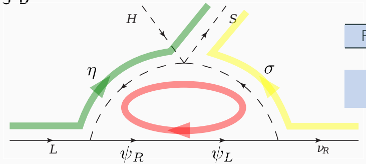


T1-3-D

$\longmapsto$ $\sigma_1 = -2, \qquad \sigma_2 = -5,$

$\longmapsto$ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]

$\longmapsto$ generalization to $\mathrm{U(1)_R}$: *et al*, S. Saad arXiv:1904.07407



T3-1-A

$\psi_{L,R}$ $\rightarrow$Singlet fermions (vector-like)

σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar

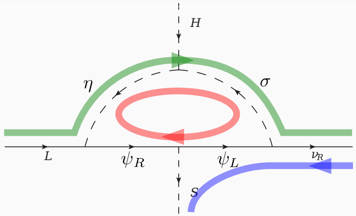
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



T1-3-E

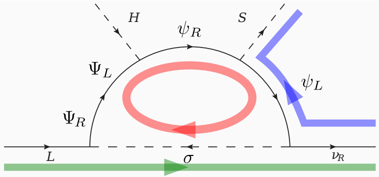
$\psi_{L,R}$ →Singlet fermions (quiral)

$\Psi_{L,R}$ →Vector-like doublet fermions

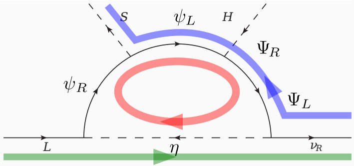
σ →Singlet scalar

η →Doublet scalar

Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$



T1-2-A



T1-2-B

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

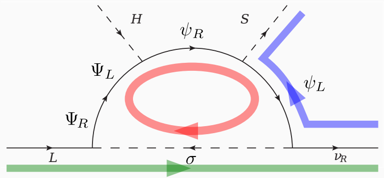
$$\sum_i f_i^3 = 3$$

$\psi_{L,R}$ $\rightarrow$Singlet fermions (quiral)

$\Psi_{L,R}$ $\rightarrow$Vector-like doublet fermions : 10/5

σ $\rightarrow$Singlet scalar : 15/5

Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$



T1-2-A

Anomaly cancellation conditions

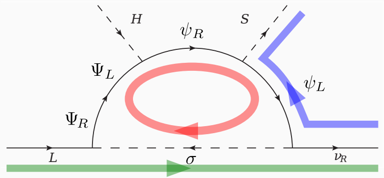
$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

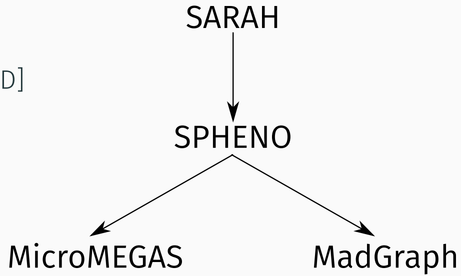
$M_\psi = h_1 \langle S \rangle$, $y_2 = 0$:

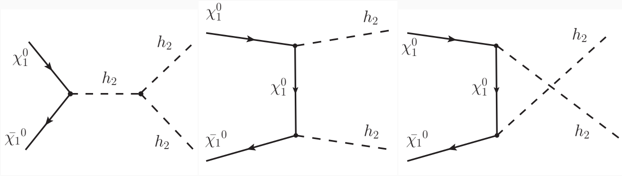
$$\mathcal{L} = \mathcal{L}_{\mathrm{SD^3M}} + h_3^{ia} \widetilde{(\Psi_R)} \cdot L_i \, \sigma_a + h_2^{\beta a} \, (\nu_{R\beta})^\dagger \, \psi_L \, \sigma_a^* - V(\sigma_a, S, H) \, .$$

with A.F Rivera, W. Tangarife, arXiv:1906.09685 [PRD]



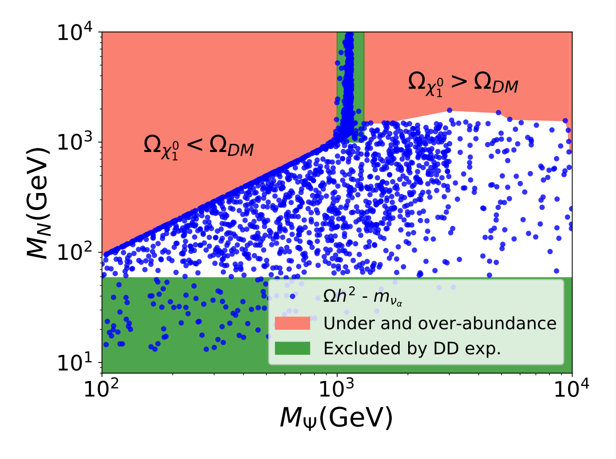
T1-2-A



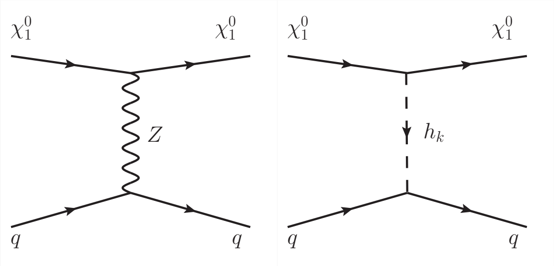


Decoupled Z' limit

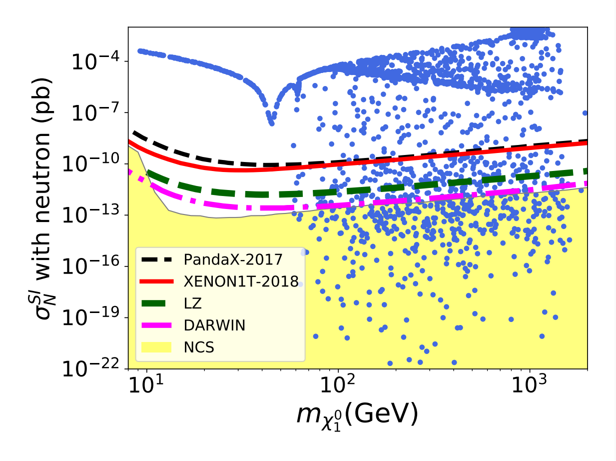
$$\begin{pmatrix} h \\ \mathrm{Re}(S) \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} .$$



Spin independent (SI) direct detection cross section



Decoupled Z' limit



Conclusions

A single $U(1)_X$ gauge symmetry to explain both the smallnes of Dirac neutrino masses and the stability of Dirac fermion dark matter

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Dirac neutrino masses and DM

- Spontaneously broken $U(1)_{B-L}$ generates a radiative Dirac neutrino masses
- A remnant symmetry makes the lightest field circulating the loop stable and good dark matter candidate.
- For T1-2-A: Either Singet Doublet Dirac Dark Matter or Singlet Scalar Dark Matter with extra scalar and vector portal
- With relaxed direct detection constraints

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!