Minimal Scotogenic (DM) models

with Dirac neutrino masses

Diego Restrepo

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

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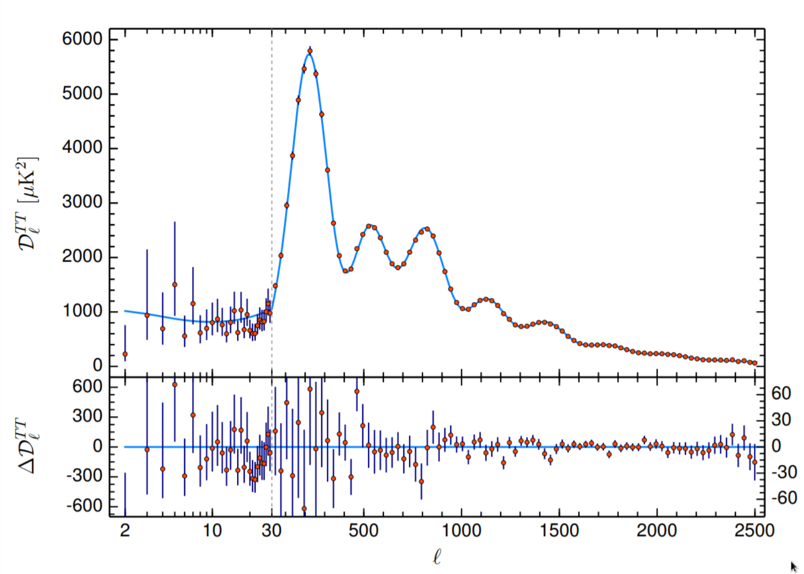
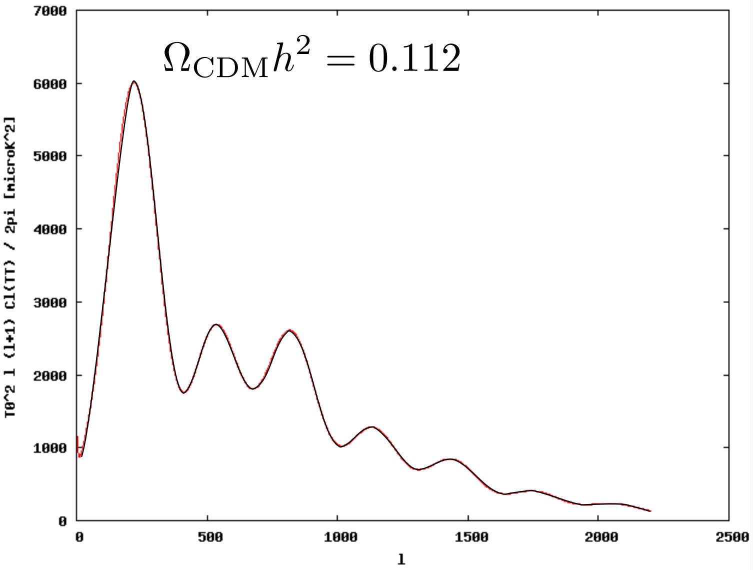
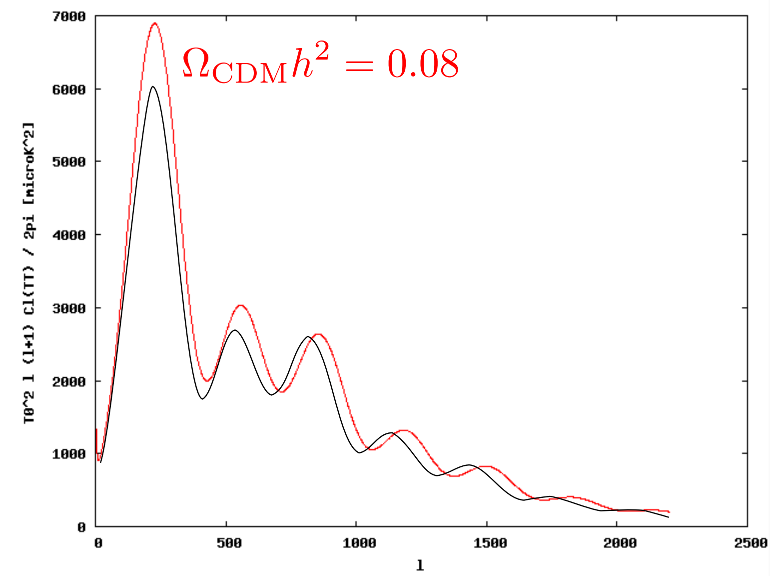
Focus on
arXiv:1811.11927 [PRD], arXiv:1906.09685 [PRD] and arXiv:1909.09574
In collaboration with
Carlos Yaguna (UPTC), Julian Calle, Óscar Zapata, Andrés Rivera (UdeA), Walter Tangarife (Loyola University Chicago)

ΛCDM paradigm (with baryonic effects)



Credit: Planck 2018


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

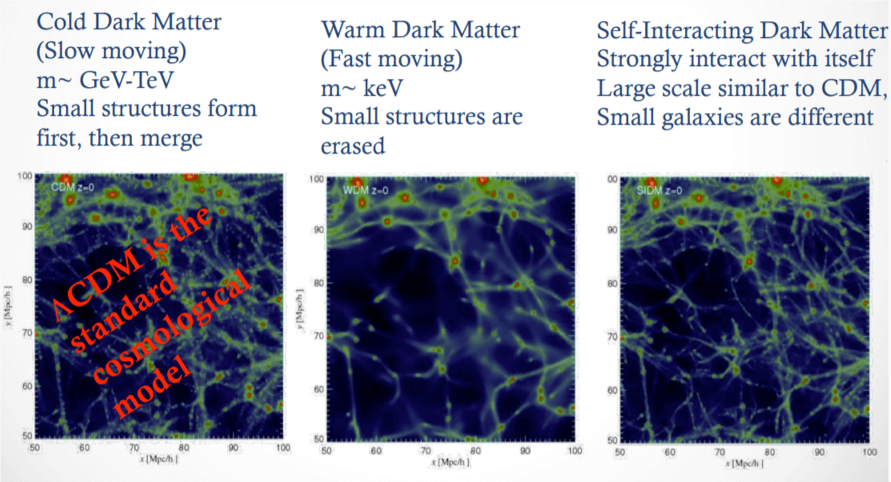
Cosmic Miso Soup

- 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)

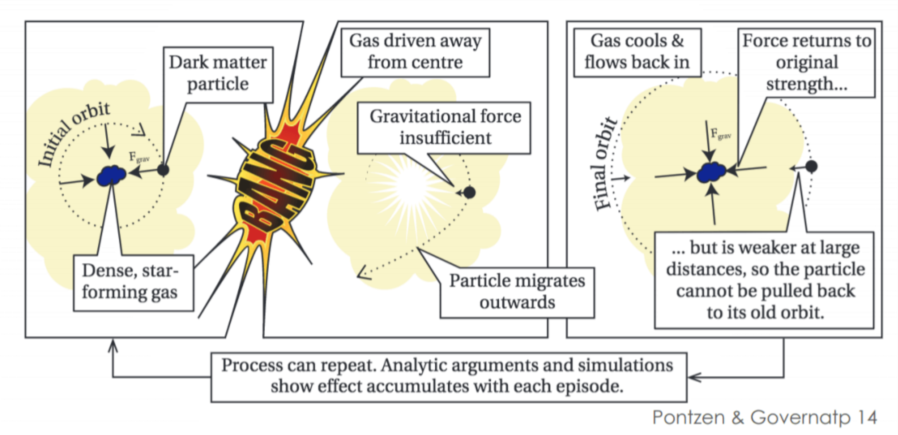

Nobu São Paulo version

Dark matter simulations



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

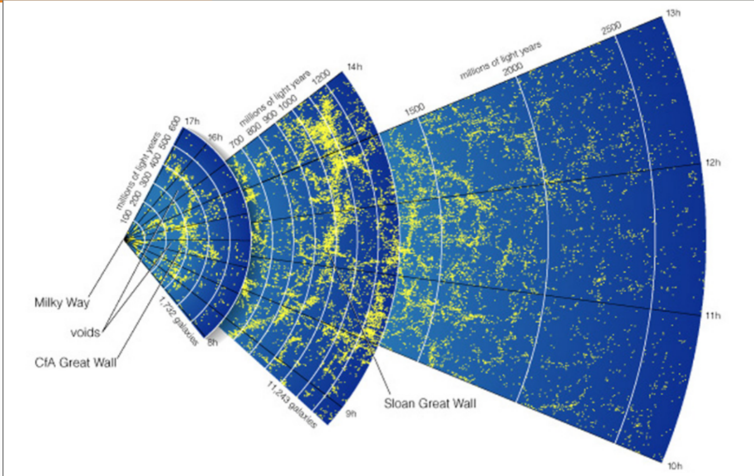
Baryonic effects



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***

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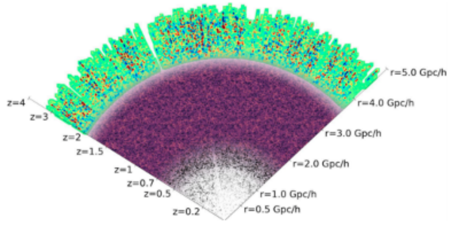
The DESI experiment



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]

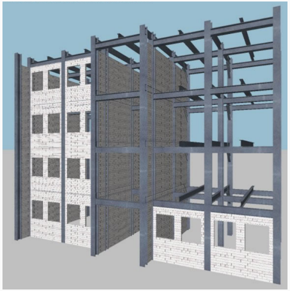
Cosmological simulations of structure formation predict that the majority of gas in the intergalactic medium (IGM) is distributed in a cosmic web of sheets and filaments as a consequence of gravitational collapse. The intersections of these structures become the locations at which galaxies and their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

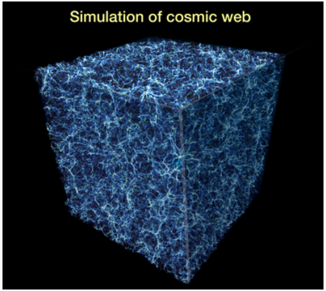
[...] at a z of ~ 3, $> 60\%$ of all gas in the Universe resides in filaments

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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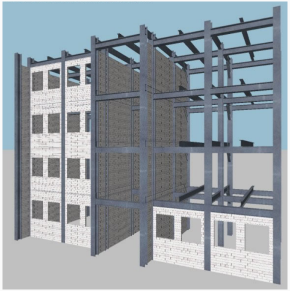

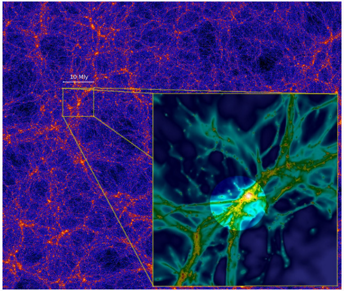

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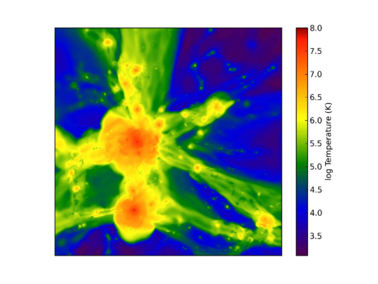
Direct observations of filaments

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)*

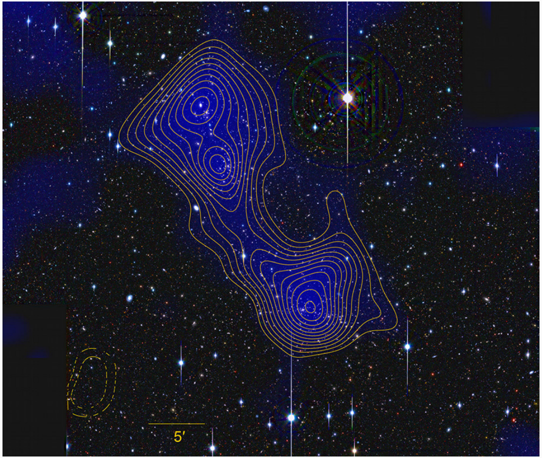


Credit: Cen, arXiv:1112.4527 [AJ]

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

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

A filament of dark matter between two clusters of galaxies



Supercluster system of three galaxy clusters

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

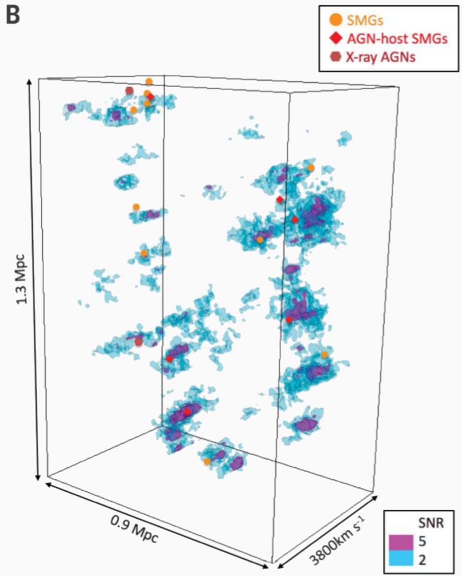
reconstructed surface mass density (blue)

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

Three-dimensional pictures of Lyα filaments



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]

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

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

$\langle \text{SM} \rangle$

+

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

Type-I arXiv:1808.03352

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

Local $U(1)_X \to Z_7$

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

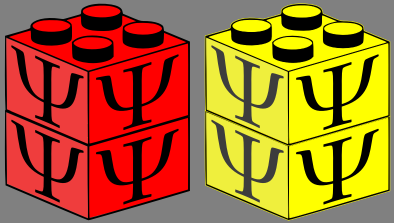
$\langle$SM$\rangle$

+

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

Type-I arXiv:1808.03352

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



Standard model extended with $U(1)_X$ 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.

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

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

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

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]
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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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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]
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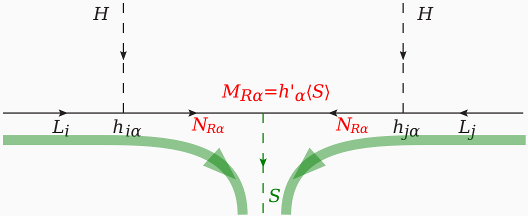
$\left(-\frac{8}{5},-\frac{8}{5},-\frac{2}{5},-\frac{7}{5},+2\right)$	arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]
$\left(-1,-1,-\frac{10}{7},-\frac{4}{7},-\frac{2}{7},\frac{9}{7}\right)$	1808.03352, with N. Bernal, C. Yaguna, Ó. Zapata [PRD]

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	$+$	$+$

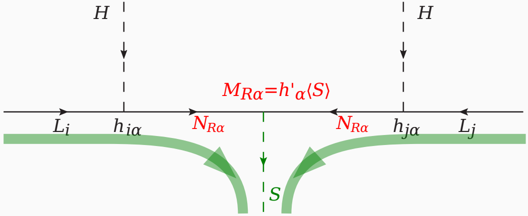


After integrating out heavy fermions, we obtain light neutrino masses

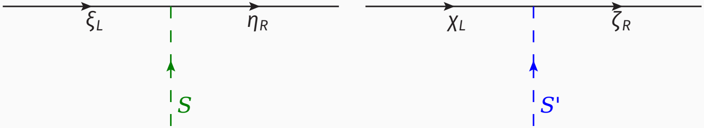
$$\boxed{\mathcal{M}_\nu^{ij} = \sum_{\alpha=1}^{2} (h^{i\alpha} v) \frac{1}{M_R^\alpha} (h^{j\alpha} v)}$$

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	$+$	$+$
$\psi_1 \to (\xi_L)^\dagger$	$-10/7$	$-$	$+$
$\psi_2 \to \eta_R X$	$-4/7$	$-$	$+$
$\psi_3 \to \zeta_R$	$-2/7$	$+$	$-$
$\psi_4 \to (\chi_L)^\dagger$	$+9/7$	$+$	$-$
S'	1	$+$	$+$



Two component Dirac fermion dark matter



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

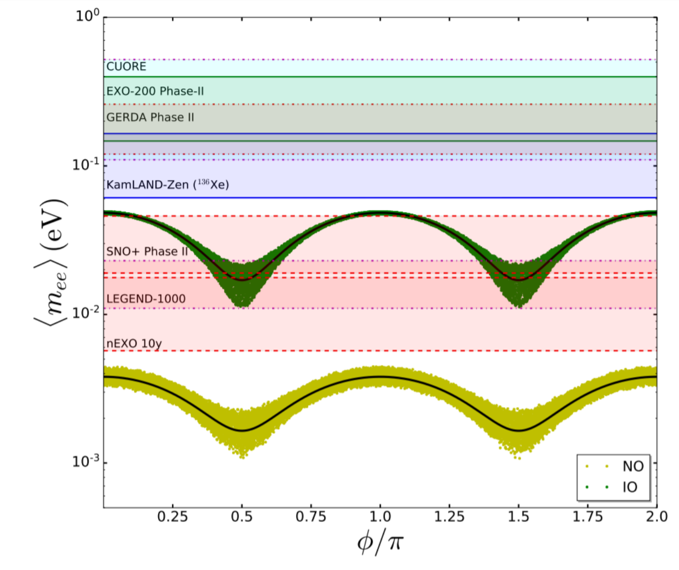
$$\mathcal{L} = M_1 \overline{\chi_1} \chi_1 + M_2 \overline{\chi_2} \chi_2$$

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

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

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:

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

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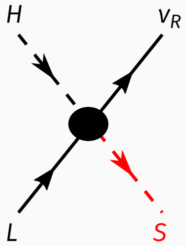
- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

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

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



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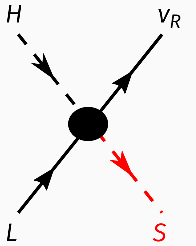


- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - N_{\mathrm{eff}}^{\mathrm{SM}}$ (see arXiv:1211.0186)

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

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

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

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

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

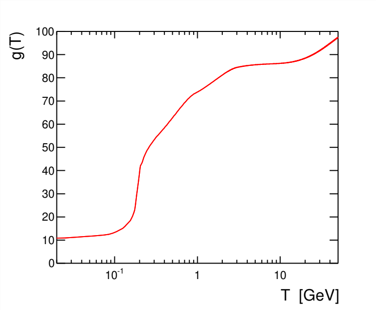
$$\sigma_f(s) \simeq \frac{N_C^f (Q^f_{BL})^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \qquad \text{In the limit } M^2_{Z'} \gg s\,.$$

with three right-handed neutrinos, the Hubble parameter is

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

The right-handed neutrinos decouple when

$$\Gamma_{\nu_R}(T^{\nu_R}_{\rm dec}) = H(T^{\nu_R}_{\rm dec}).$$



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

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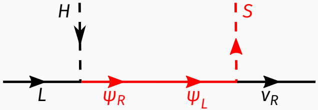
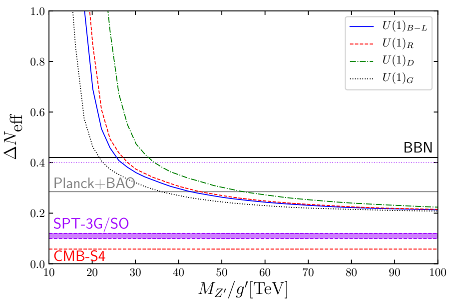
$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S\rangle} Z_3$



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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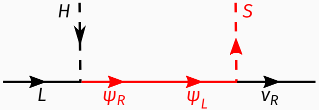

ν_{R3}	ν_{R2}	ν_{R1}	ψ_L	ψ_R	S
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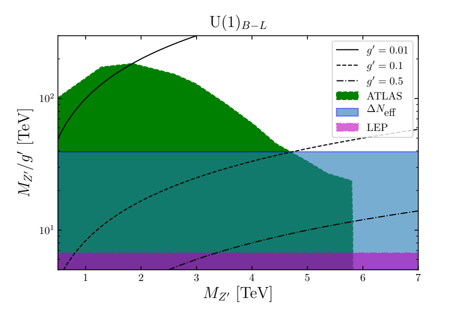
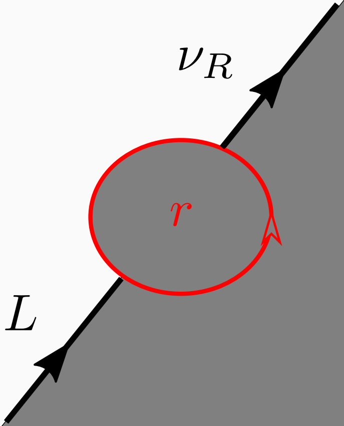


with J. Calle and Ó. Zapata, arXiv:1909.09574

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 + Dirac fermion dark matter

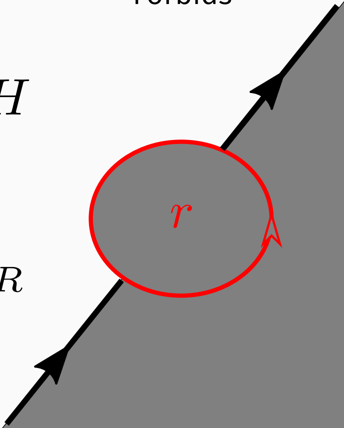
Forbids

$$\nu_R \nu_R$$

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

$$\nu_R \psi_R$$

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



$$\psi_R \psi_R$$

$$\psi_L \psi_L$$

$\mathrm{U}(1)_X$

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

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$X(L) \neq 0$

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

r

Allows

$\psi_R \psi_R$

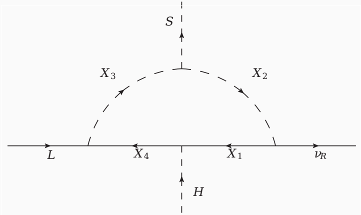
$\psi_L \psi_L$

$(\psi_R)^\dagger \psi_L$

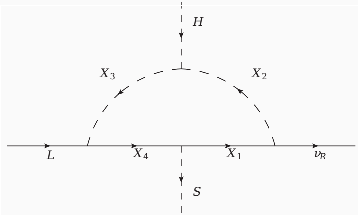
$(\psi_R)^\dagger \psi_L S$

normalized to $X(L) = -1$

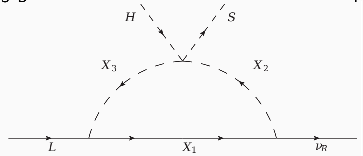
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

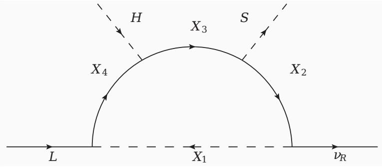


T1-3-E

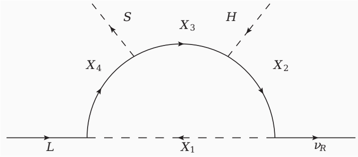


T3-1-A

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

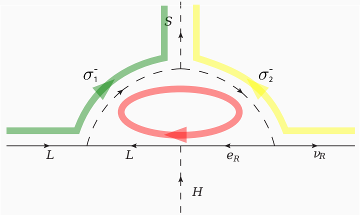


T1-2-A

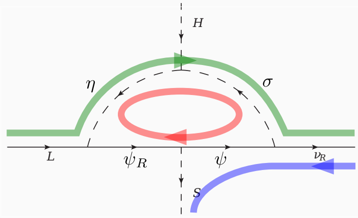


T1-2-B

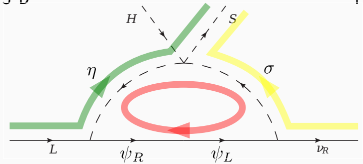
One loop topologies $U(1)_{B-L}$ only!



T1-3-D



T1-3-E



T3-1-A

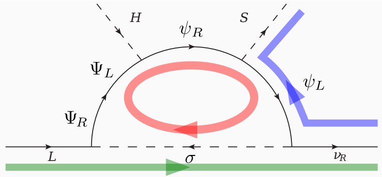
$\psi_{L,R}$ $\rightarrow$Singlet fermions

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

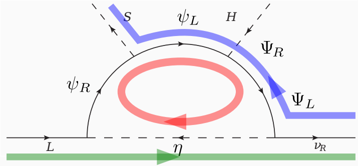
σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar

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

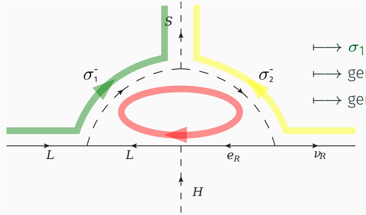


T1-2-A



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

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

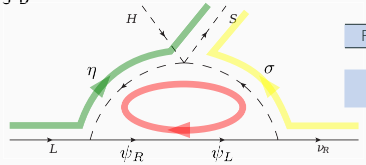
$\longmapsto$ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]

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

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

σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar



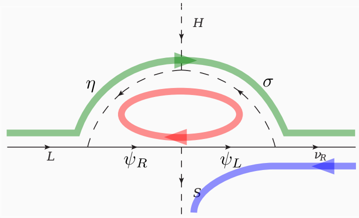
T3-1-A

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

$$\sum_i f_i = 3$$

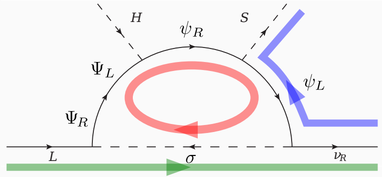
$$\sum_i f_i^3 = 3$$



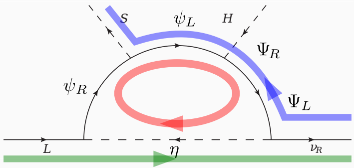
T1-3-E

- $\psi_{L,R}$ →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

$$\sum_i f_i = 3$$

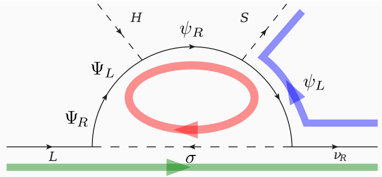
$$\sum_i f_i^3 = 3$$

SD^{3}M+SSDM: σ_a $(a = 1, 2)$ with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

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

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

σ $\rightarrow$Singlet scalar : 15/5



T1-2-A

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)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$

Anomaly cancellation conditions

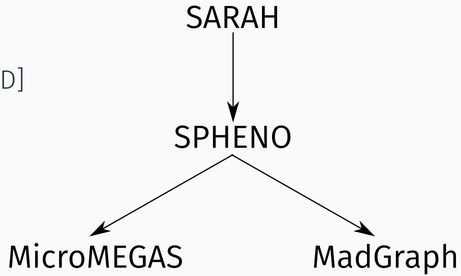
$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

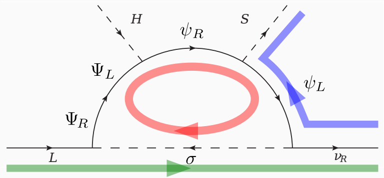
SD^{3}M+SSDM: σ_a ($a = 1, 2$)

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

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

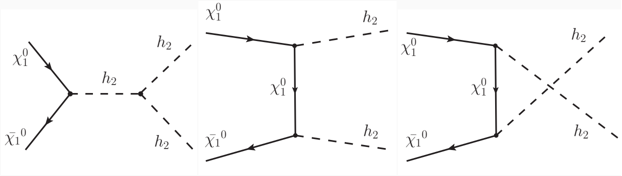


with A.F Rivera, W. Tangarife, arXiv:1906.09685 [PRD]



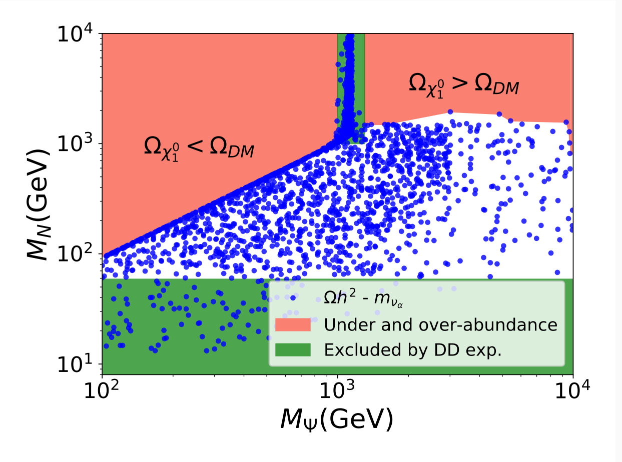
T1-2-A

Dark matter relic density

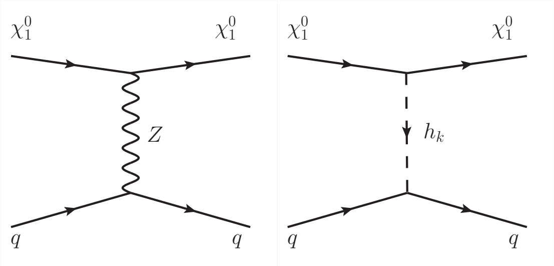


Decoupled Z' limit

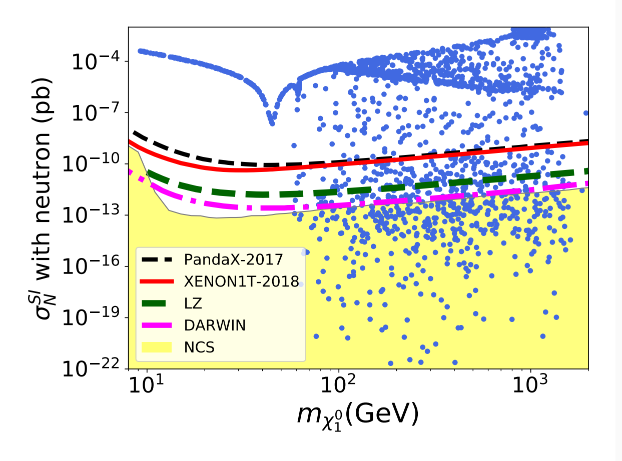
$$\begin{pmatrix} h \\ \mathrm{Re}(S) \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} .$$



Spin independent (SI) direct detection cross section

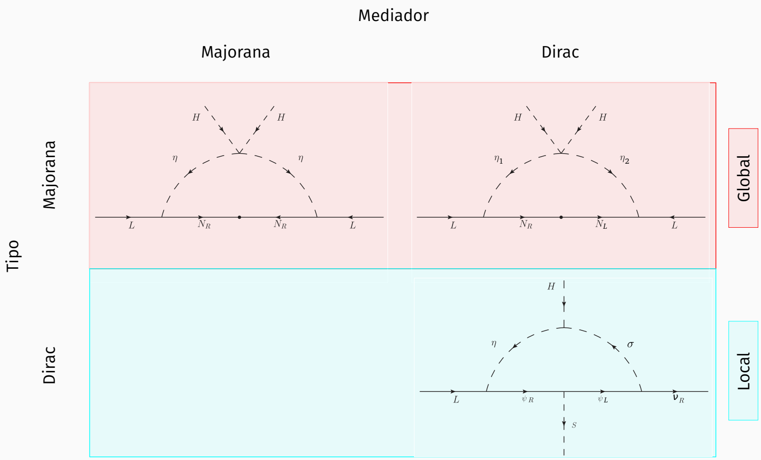


Decoupled Z' limit

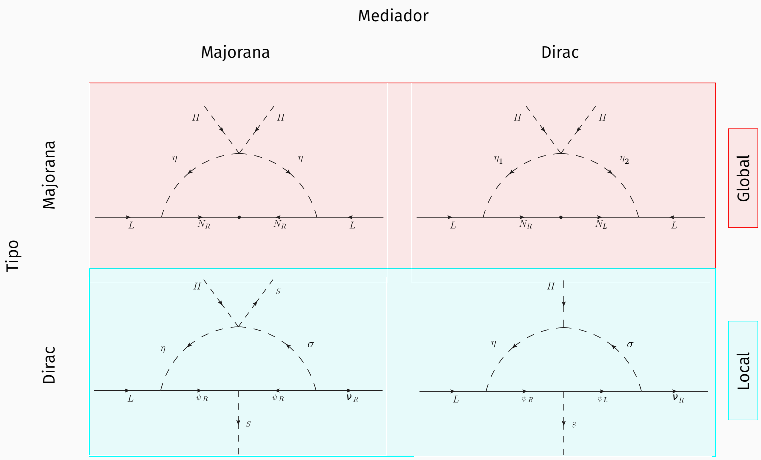


Dark symmetry

Radiative Type-I seesaw



Radiative Type-I seesaw with J. Calle and Ó. Zapata, arXiv:1909.09574



Fields	$SU(2)_L$	$U(1)_Y$	$U(1)^*_{\mathcal{D}}$
L	2	$-1/2$	0
Q	2	$-1/6$	0
d_R	1	$-1/2$	0
u_R	1	$+2/3$	0
e_R	1	-1	0
H	2	$1/2$	0
η	2	$1/2$	1
S	1	0	2
σ	1	0	3
ν_{R1}	1	0	4
ν_{R2}	1	0	4
ν_{R3}	1	0	-5
ψ_{R1}	1	0	-1
ψ_{R2}	1	0	-1
ψ_{R3}	1	0	-1
TOTAL			0

Conclusions

It makes sense to focus our attention on models tha can account for neutrino masses and dark matter (DM) without adhoc symmetries

Tree-level type-I-II-III seesaws

Type-I seesaw: Multicomponent dark matter: 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.

Conclusions

It makes sense to focus our attention on models tha can account for neutrino masses and dark matter (DM) without adhoc symmetries

One-loop Dirac neutrino masses

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

- Spontaneously broken $U(1)_X$ 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
- Dark symmetry for Majorana mediatiors

Conclusions

Thanks!