

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

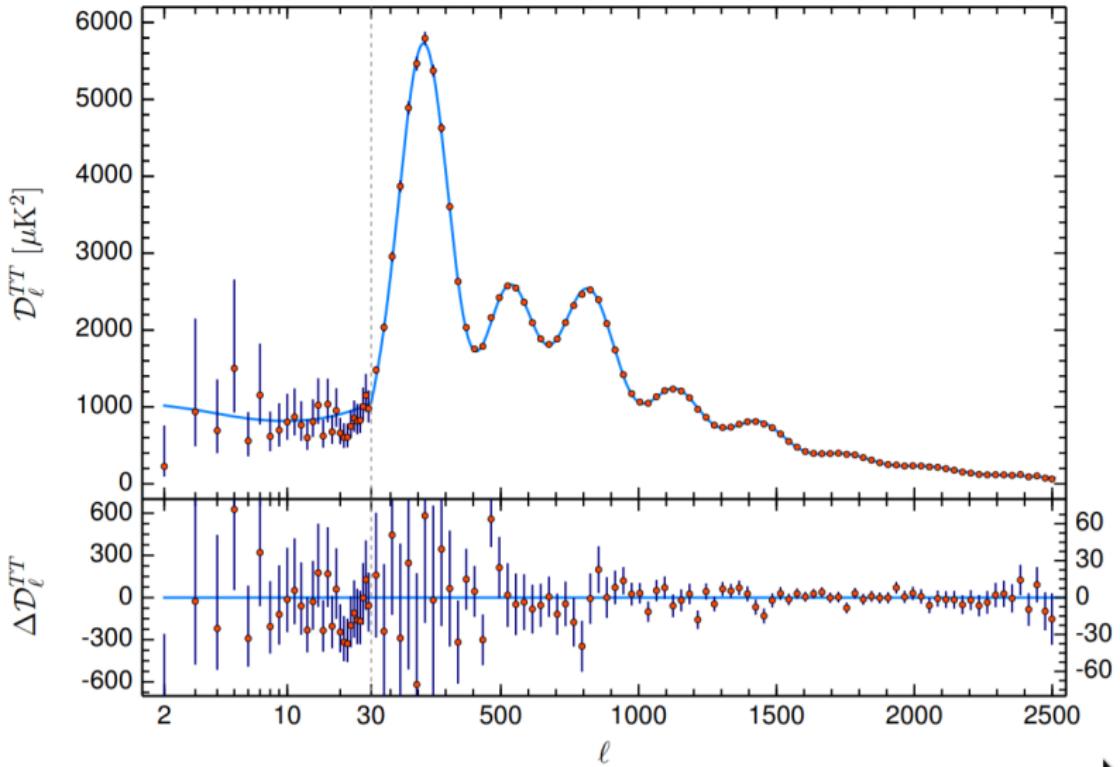
[arXiv:1811.11927 \[PRD\]](https://arxiv.org/abs/1811.11927), [arXiv:1906.09685 \[PRD\]](https://arxiv.org/abs/1906.09685) and [arXiv:1909.09574](https://arxiv.org/abs/1909.09574)

In collaboration with

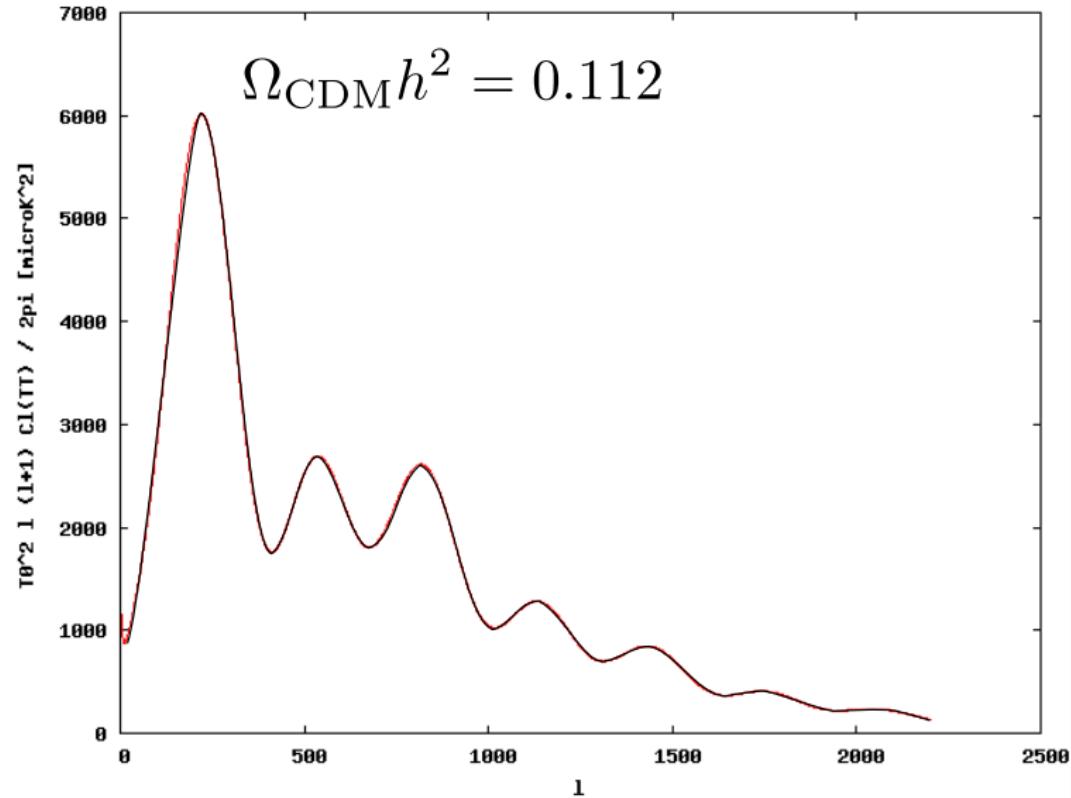
Carlos Yaguna (UPTC), Julian Calle, Óscar Zapata, Andrés Rivera (UdeA),
Walter Tangarife (Loyola University Chicago)

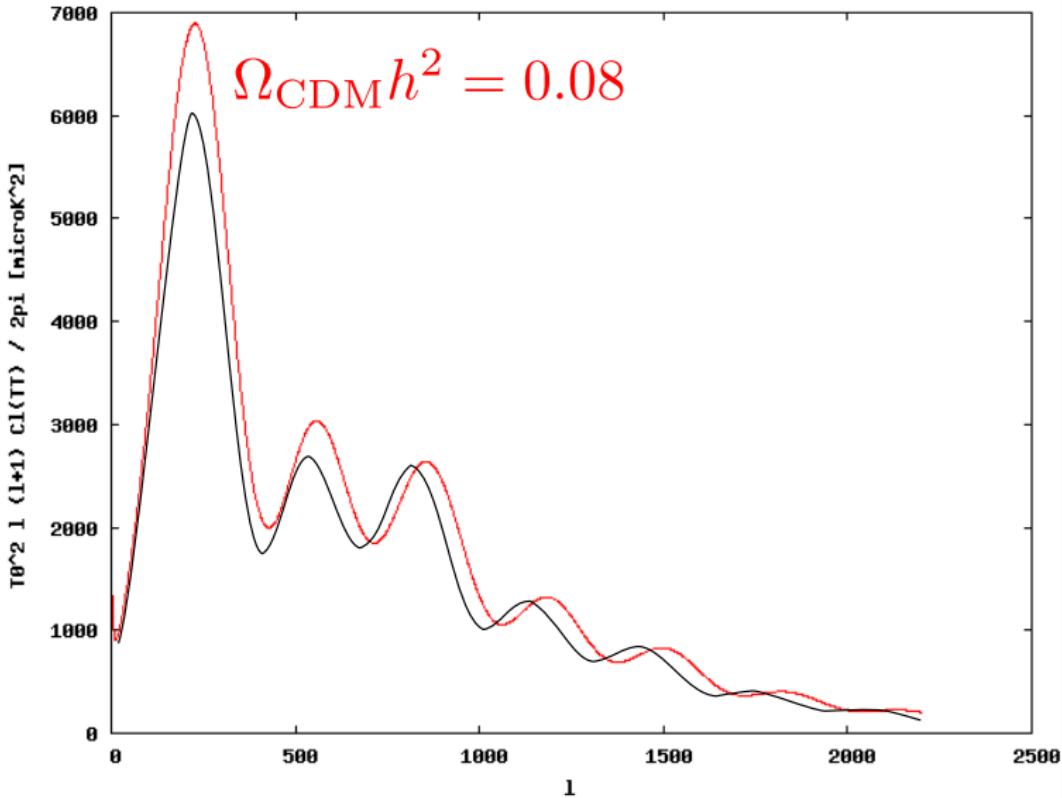


Λ CDM paradigm (with baryonic effects)



Credit: Planck 2018





Cosmic Miso Soup

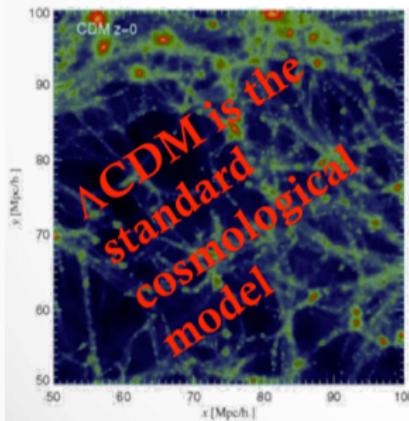
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching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



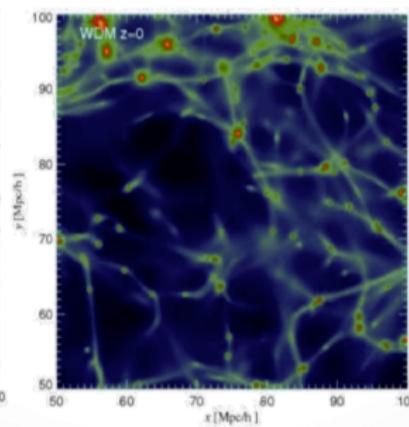
Nobu São Paulo version

Dark matter simulations

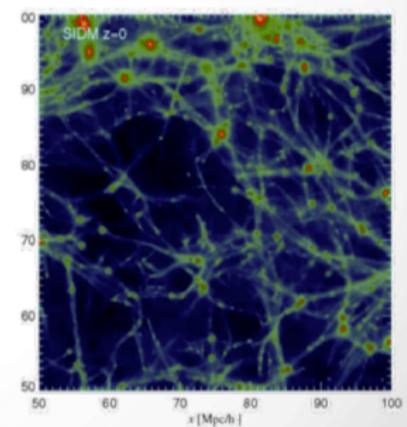
Cold Dark Matter
(Slow moving)
 $m \sim \text{GeV-TeV}$
Small structures form
first, then merge



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

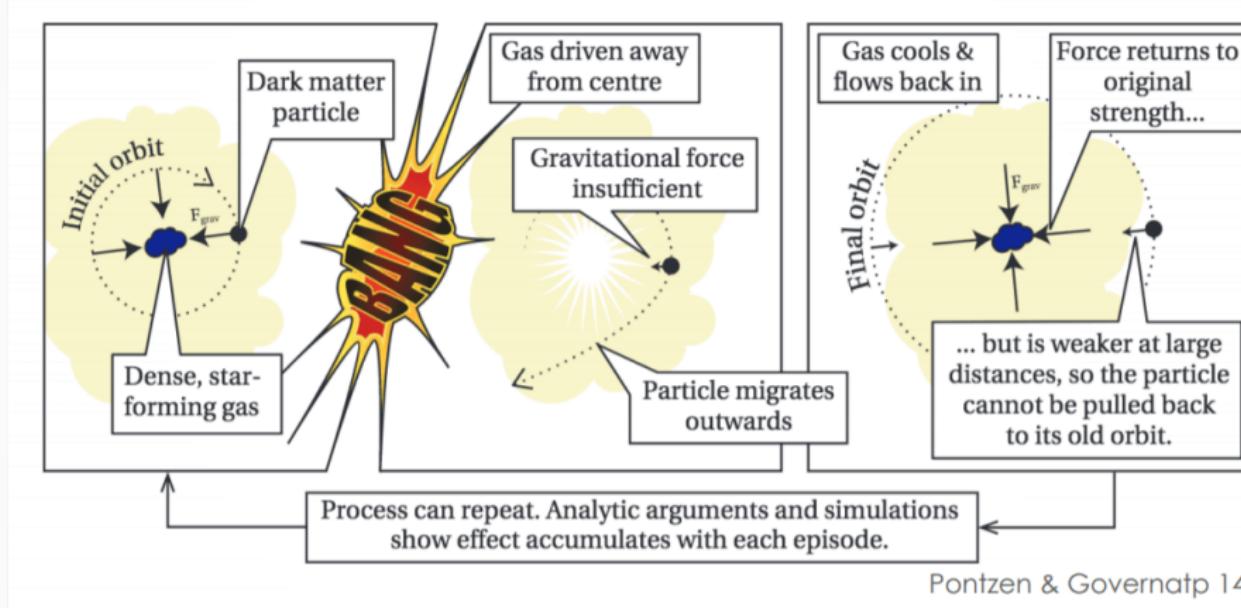


Self-Interacting Dark Matter
Strongly interact with itself
Large scale similar to CDM,
Small galaxies are different



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

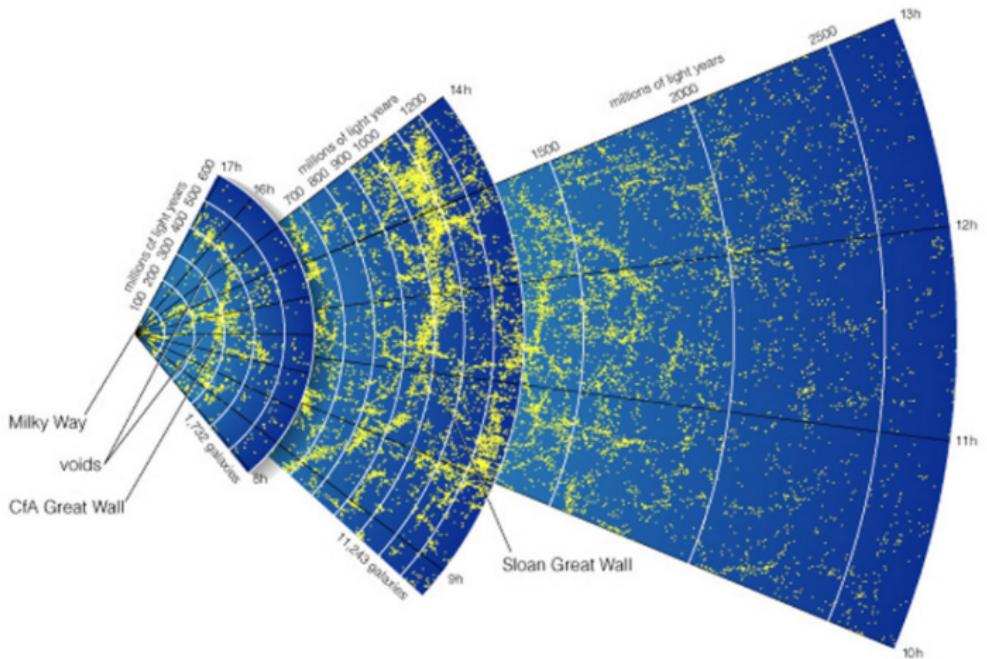
Baryonic effects



Pontzen & Governato 14

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

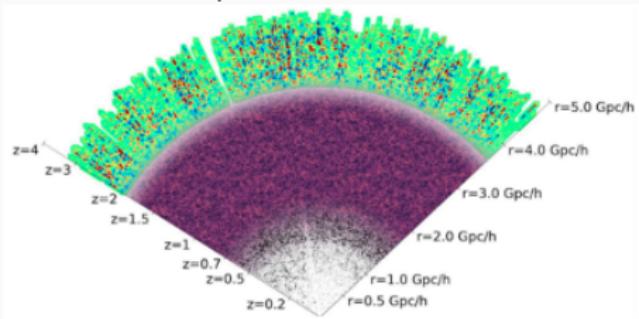
Goal



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.

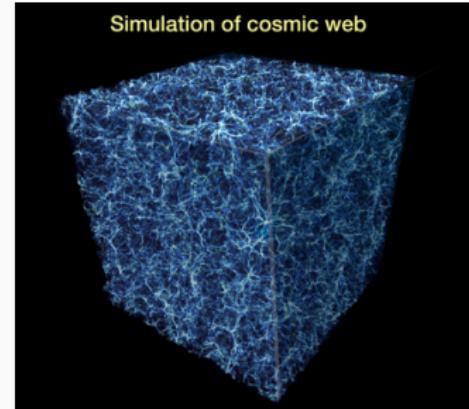
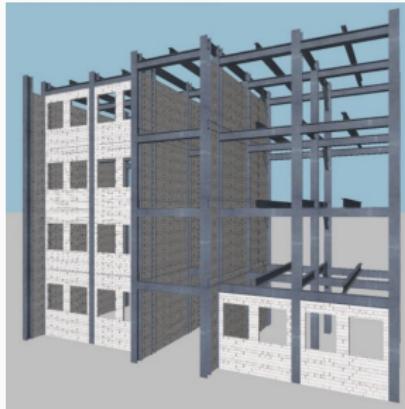
[...] at a z of ~ 3 , $> 60\%$ of all gas in the Universe resides in filaments

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

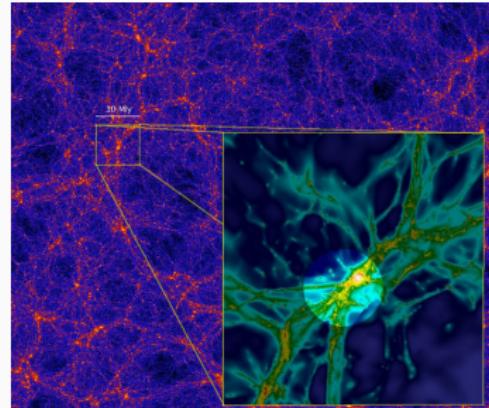
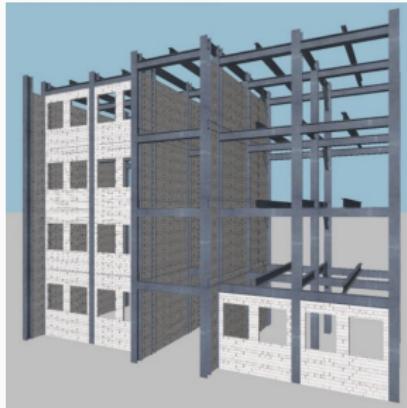
Clouds of HI likely embedded in a filament between M31 and M33: arXiv:1305.1631 [nature]

¹ See also: arXiv:1603.05400 [A&A]

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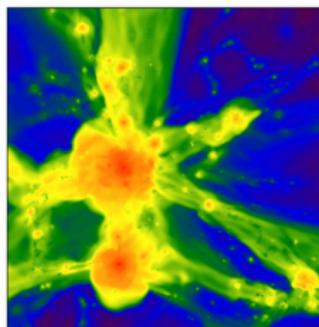
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Direct observations of filaments

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)



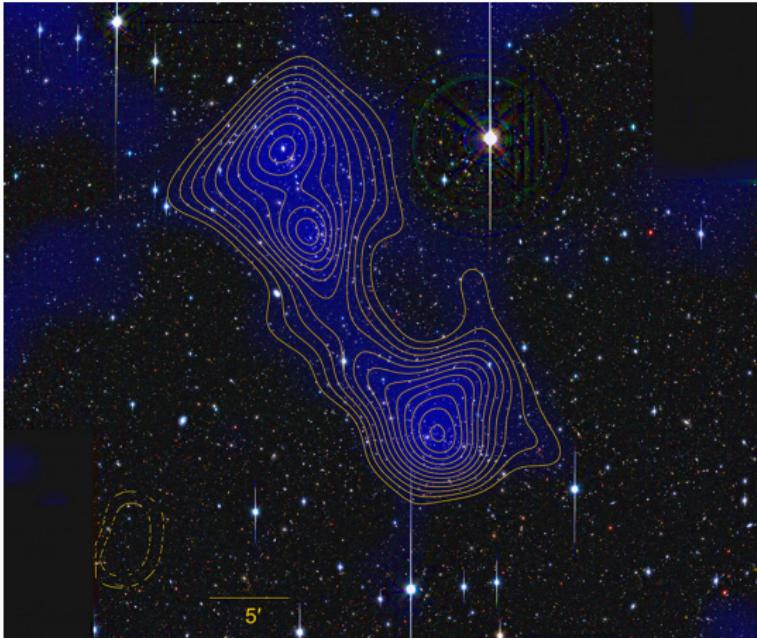
Warm-hot intergalactic medium (WHIM)
Density-weighted temperature projection of a portion of the refinement box of the C run of size $(18 h^{-1}\text{Mpc})^3$.
Low temperature WHIM confirmed by O VI line that peak at $T \sim 3 \times 10^5 \text{ K}$

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]).

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)

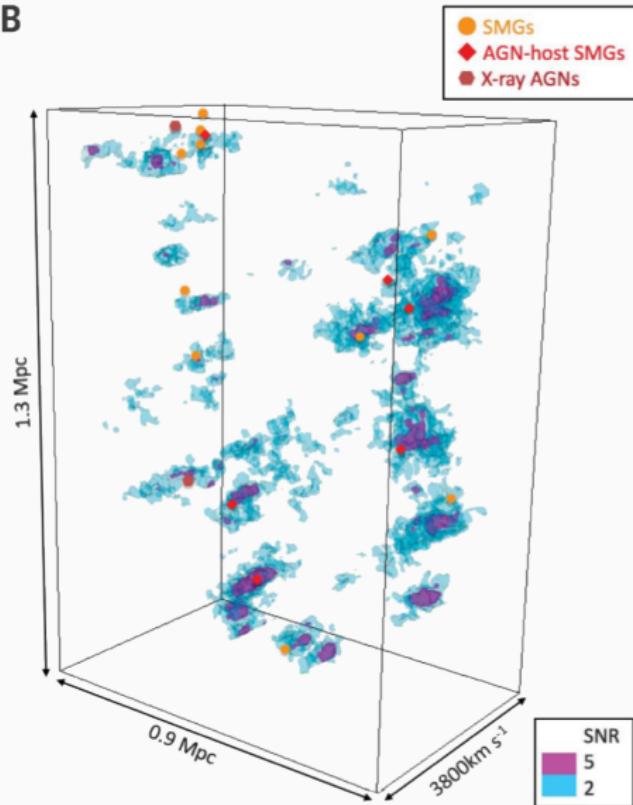
significance contours from 0.5σ to 2.5σ

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

For a recent review see: arXiv:1905.08991

Three-dimensional pictures of Ly α filaments

B



The 3D distribution of Ly α 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

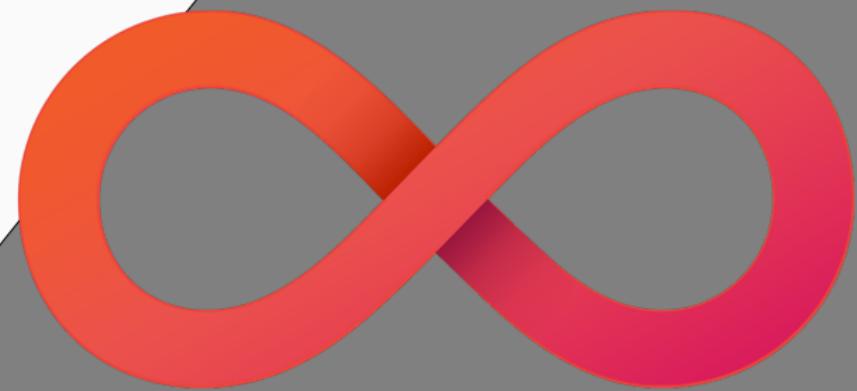
$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, \quad L_i = \begin{pmatrix} \nu_{Li} \\ e_{Li}^- \end{pmatrix}. \quad (1)$$

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

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



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



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

Type-I
seesaw



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

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 $U(1)_X \rightarrow Z_7$

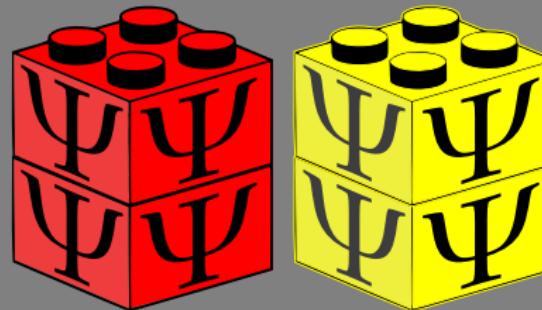
$$\mathcal{L} = y(N_R)^\dagger L \cdot \langle H \rangle + y' \langle S \rangle N_R N_R + \text{h.c}$$



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

Type-I arXiv:1808.03352

: Also new terms arise
from spontaneous
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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.

$$[\mathrm{SU}(3)_c]^2 \mathrm{U}(1)_X :$$

$$[3u + 3d] - [3 \cdot 2q] = 0$$

$$[\mathrm{SU}(2)_L]^2 \mathrm{U}(1)_X :$$

$$-[2\textcolor{blue}{l} + 3 \cdot 2q] = 0$$

$$[\mathrm{U}(1)_Y]^2 \mathrm{U}(1)_X :$$

$$\left[(-2)^2 e + 3 \left(\frac{4}{3}\right)^2 u + 3 \left(-\frac{2}{3}\right)^2 d \right] - \left[2(-1)^2 \textcolor{blue}{l} + 3 \cdot 2 \left(\frac{1}{3}\right)^2 q \right] = 0 \quad (2)$$

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

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

with solution

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

which satisfy

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

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

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

with solution

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

which satisfy

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

For N extra quiral fields ψ_α ($\alpha = 1, \dots, N$) with X -charges n_α : $\textcolor{violet}{r} \equiv e - 2\textcolor{blue}{l}$

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

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

$$X(\textcolor{violet}{r}, \textcolor{blue}{l}) = \textcolor{violet}{r}R + \textcolor{blue}{l}Y.$$

with solution

$$u = -1 - \frac{4l}{3}, \quad d = 1 + \frac{2l}{3}, \quad q = -\frac{l}{3}, \quad e = 1 + 2l, \quad (2)$$

which satisfy

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

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

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

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

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

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	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$U(1)_{B-L}$	$U(1)_R$	$U(1)_D$	$U(1)_G$	$U(1)_D^*$
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 $\sum n_\alpha^3 = -3$

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

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

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \dots)$	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:

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

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

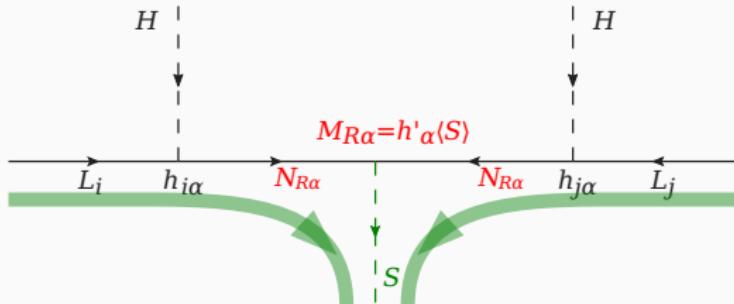
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Not known solution for
one-loop neutrino Majorana masses
with local $U(1)_X$.

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	+	+
$\psi_1 \rightarrow (\xi_L)^\dagger$	-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	+	+

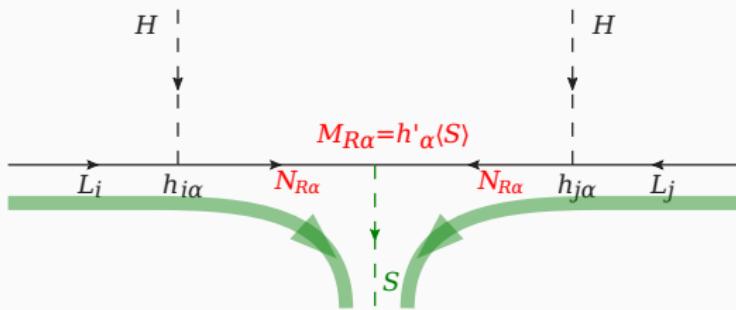


After integrating out heavy fermions, we obtain
light neutrino masses

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

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



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

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

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

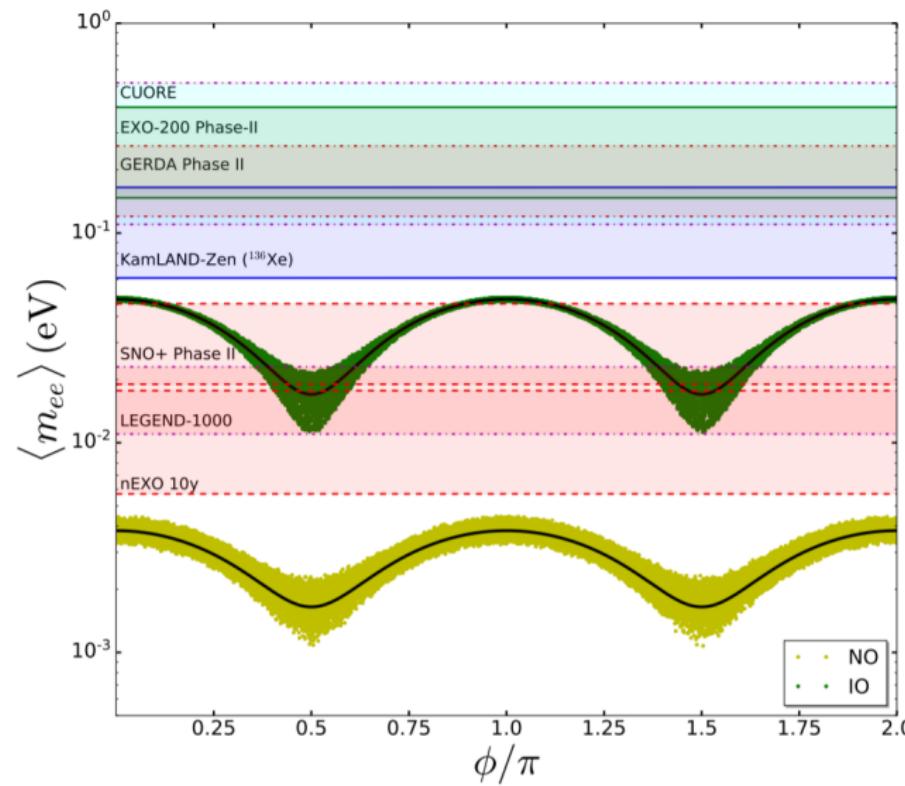
$$+ M_2 \overline{\chi}_2 \chi_2$$

(One-loop) Dirac neutrino masses

Lepton number

- Lepton number (L) is an accidental discrete or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e, L_μ, L_τ are also conserved.
- The processes which violate 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)



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

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

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

Dirac $U(1)_L$

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

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

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

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

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

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

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

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

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

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

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

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

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

Explain smallness ala Peccei-Quinn:

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

Small Dirac neutrino masses

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

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

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

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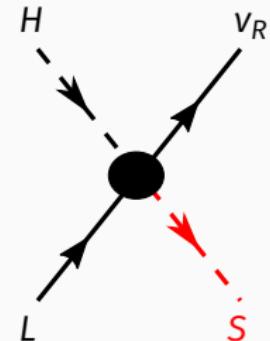
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- Realizes of the 5-dimension operator which conserves lepton number in $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$:

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

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



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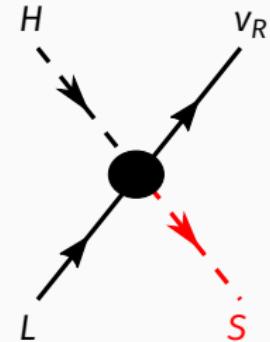
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- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$ (see arXiv:1211.0186)

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

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

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

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

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

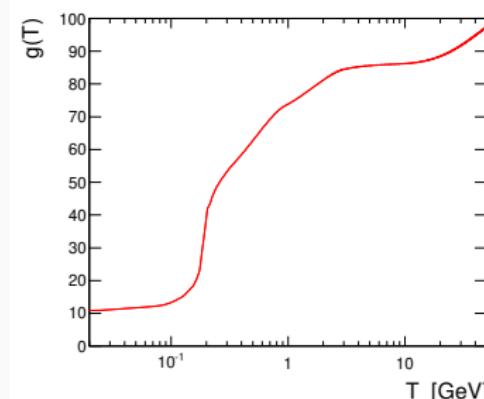
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left(\frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

with three right-handed neutrinos, the Hubble parameter is

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

The right-handed neutrinos decouple when

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



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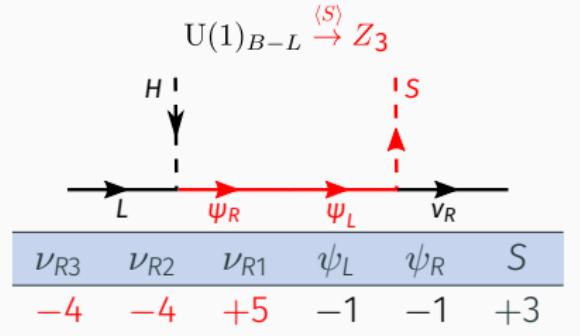
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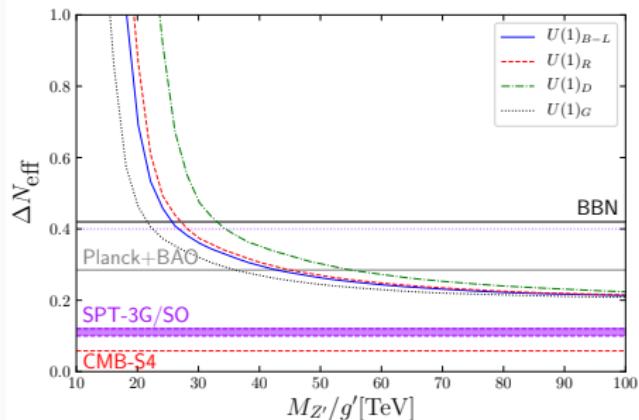
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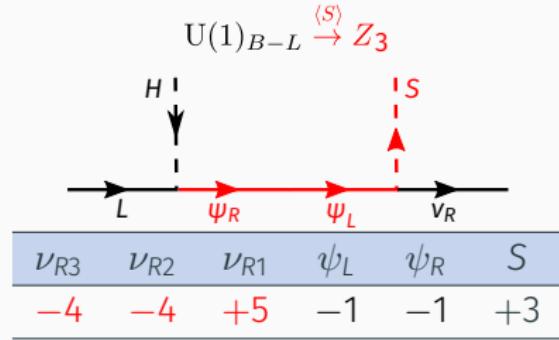
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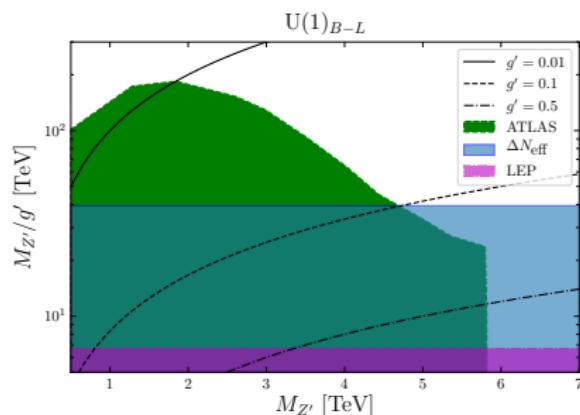
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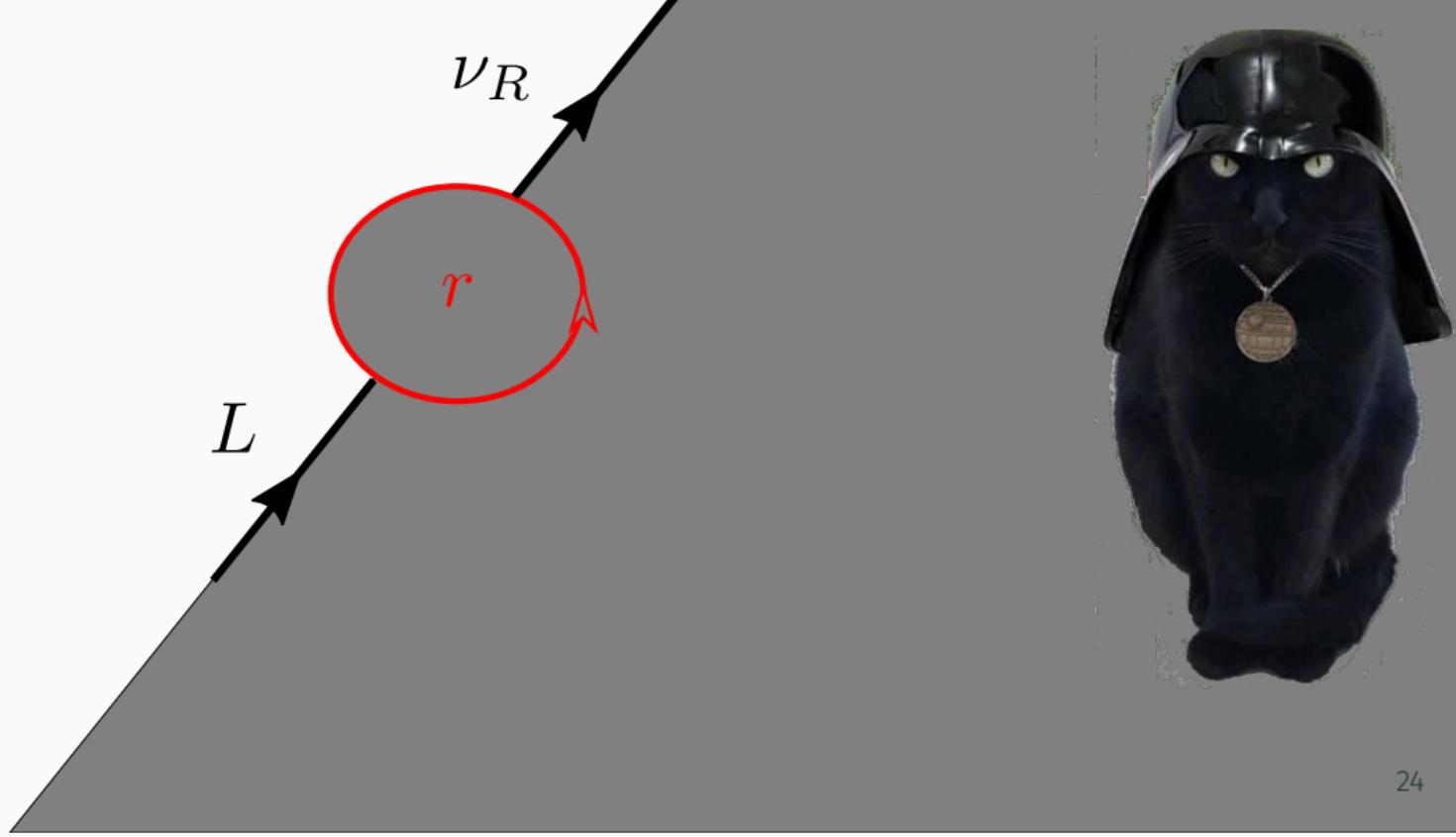
One-loop realization of \mathcal{L}_{5-D} with
total L

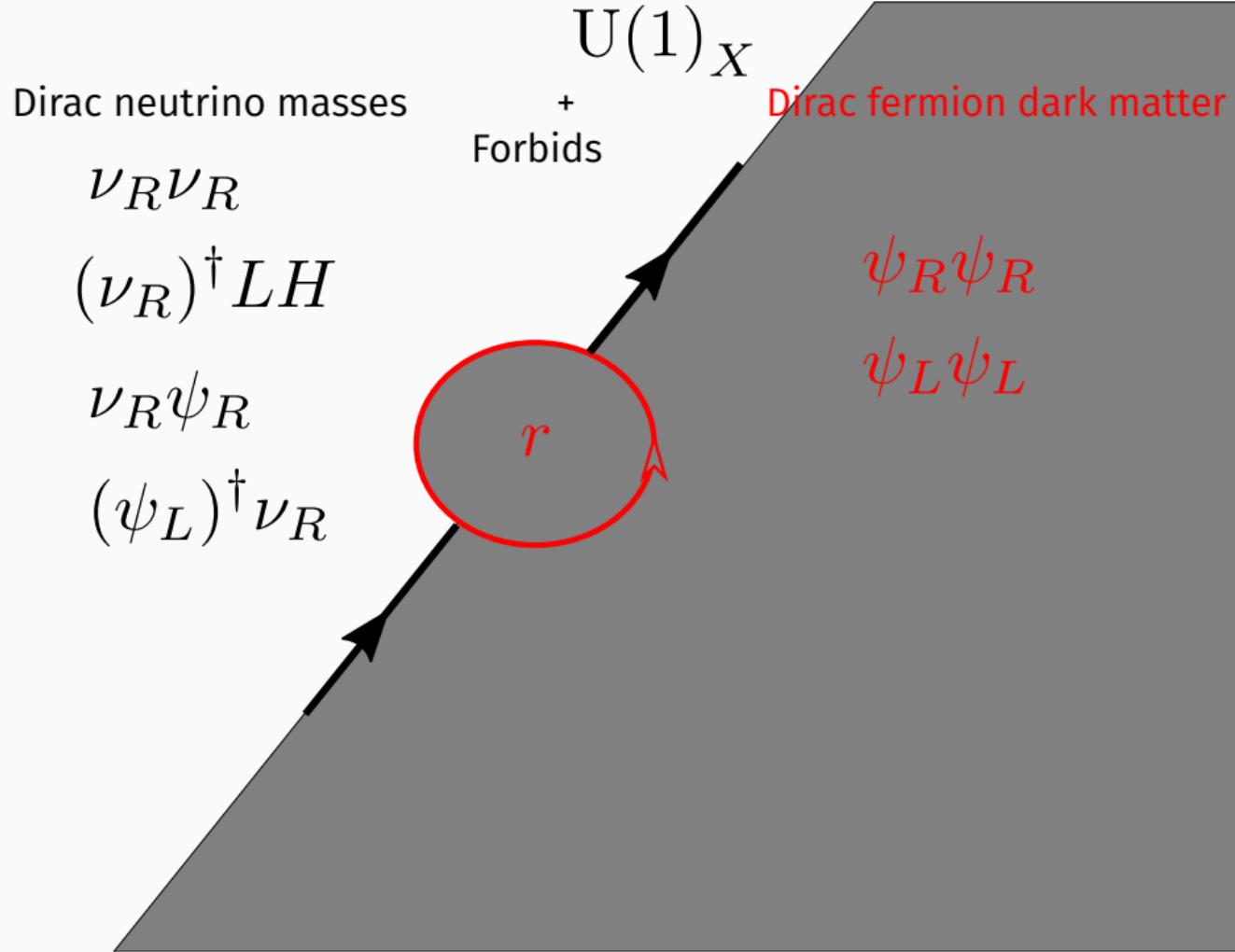
$U(1)_X$

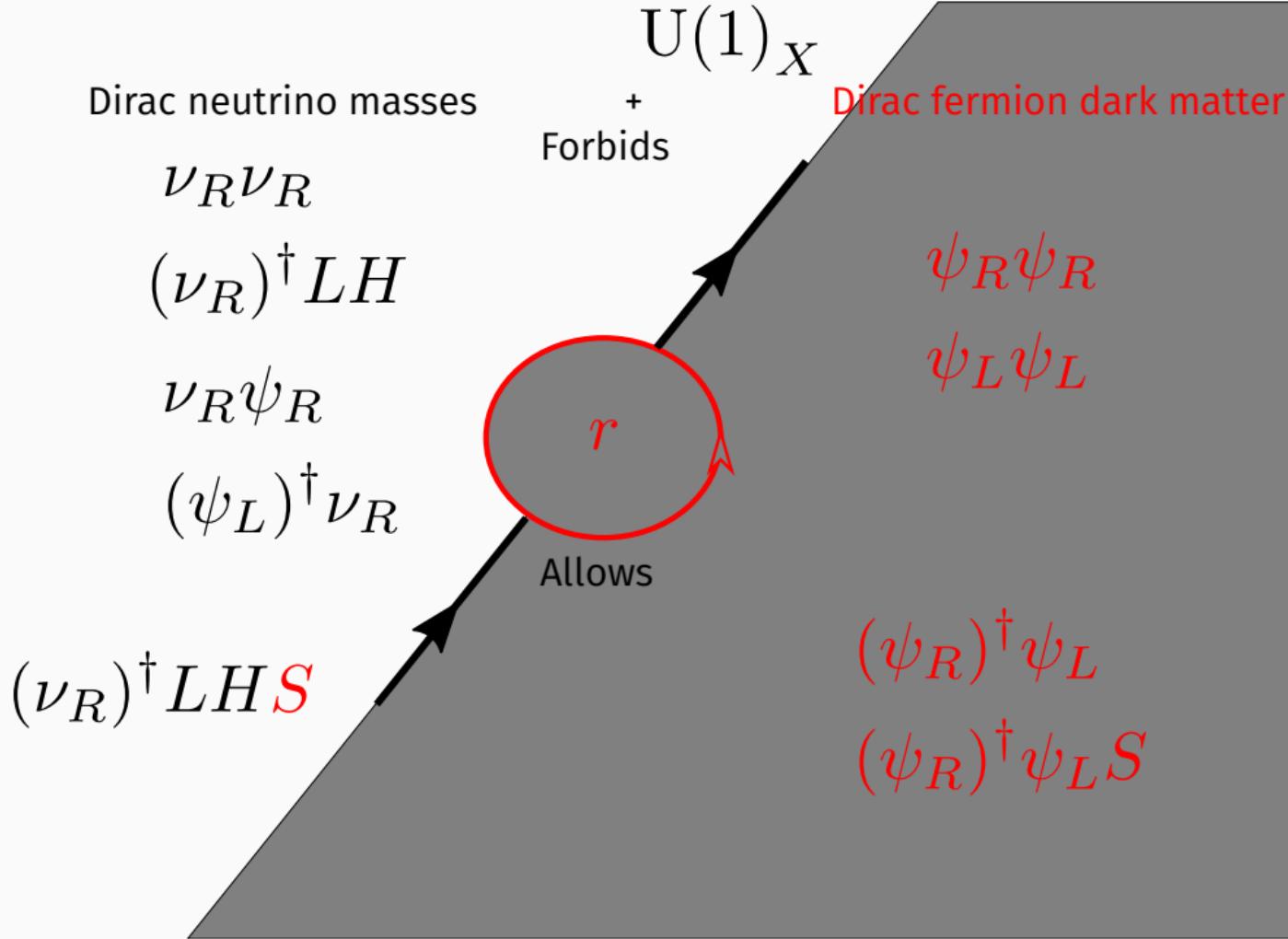
Dirac neutrino masses

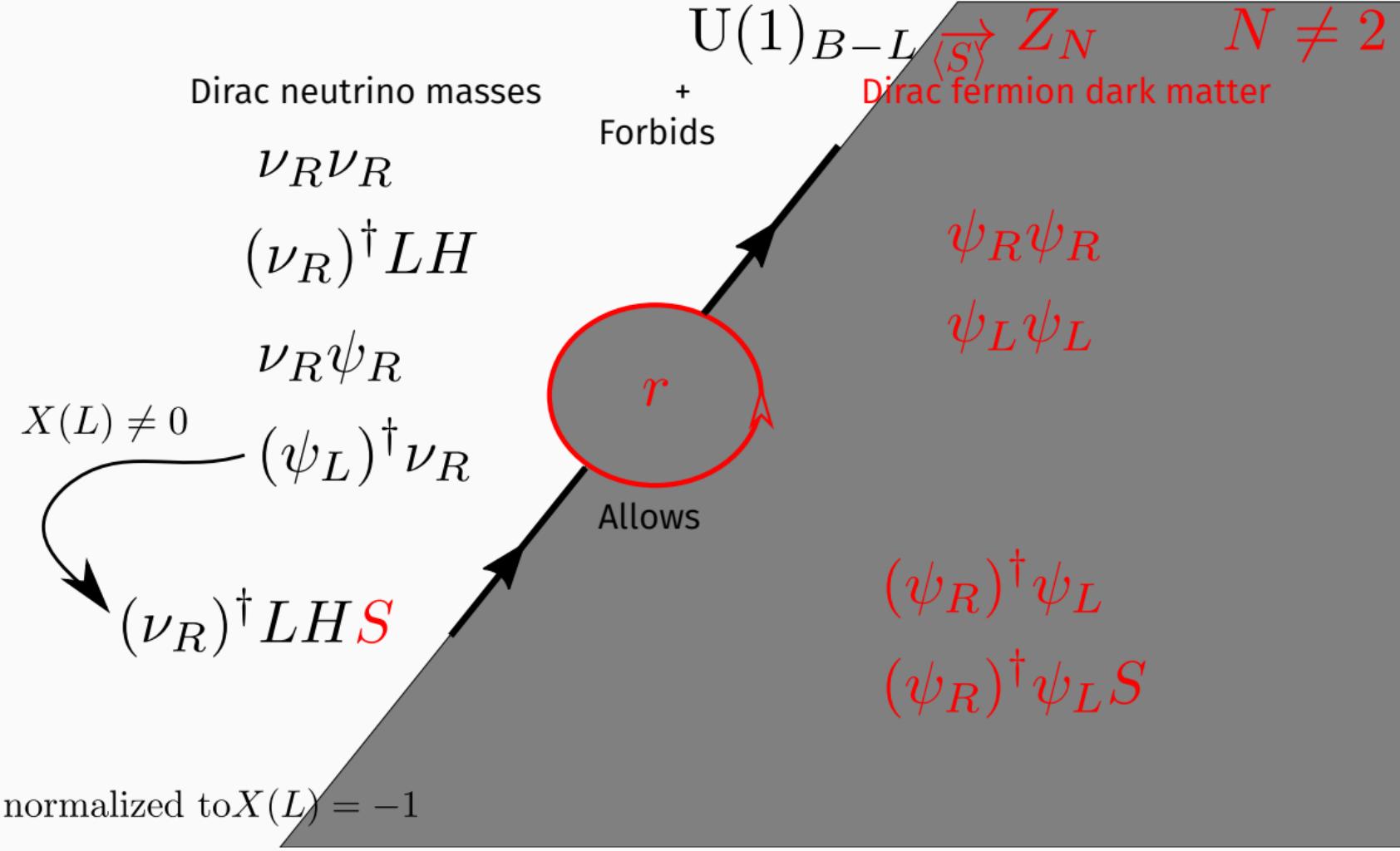
+

Dirac fermion dark matter

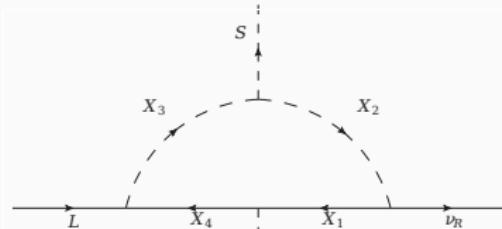




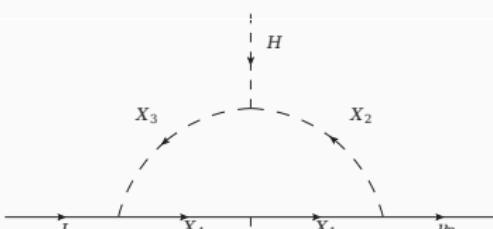




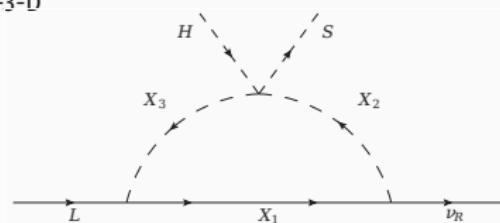
One loop topologies $U(1)_{B-L} \oplus \mathbb{Z}_2 \oplus \mathbb{Z}_2$



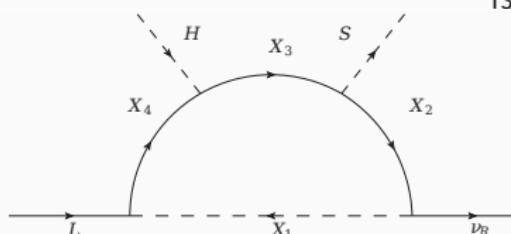
T1-3-D



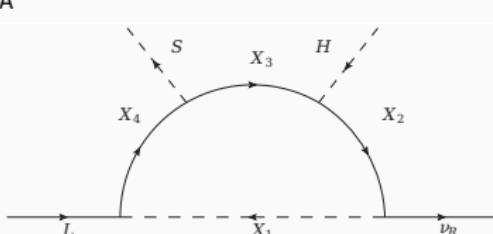
T1-3-E



T3-1-A



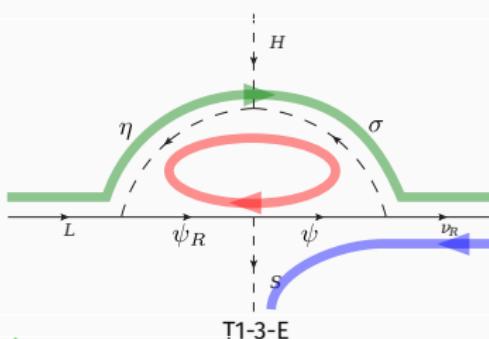
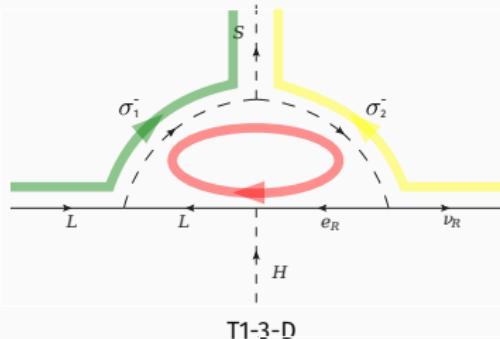
T1-2-A



T1-2-B

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

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



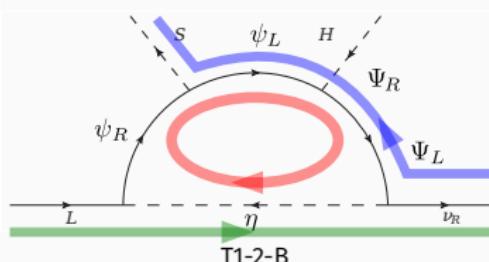
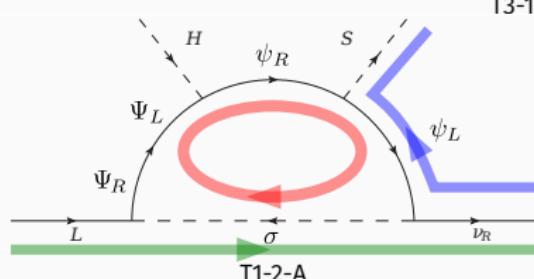
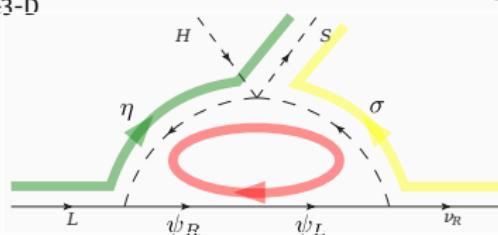
$\psi_{L,R} \rightarrow$ Singlet fermions

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

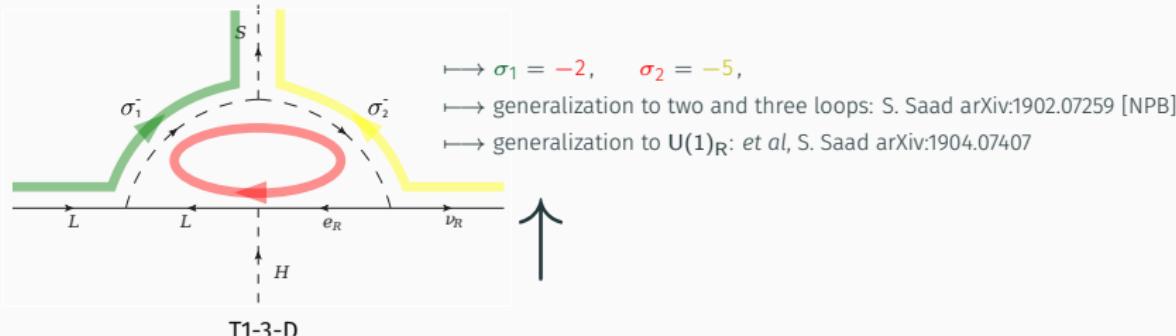
$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar

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



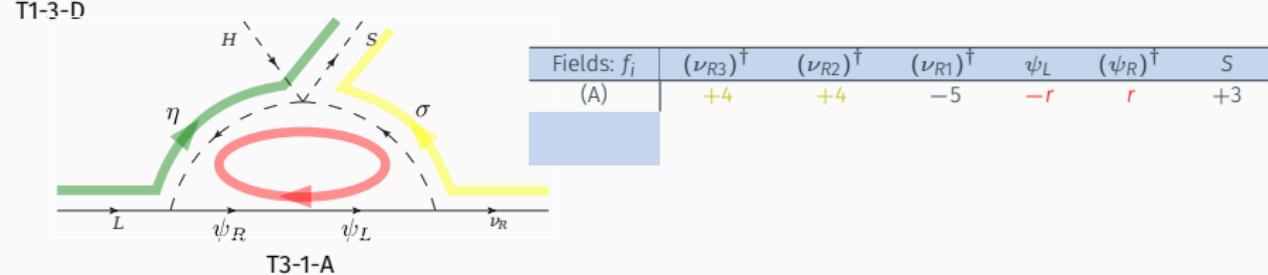
One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



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

$\sigma \rightarrow$ Singlet scalar

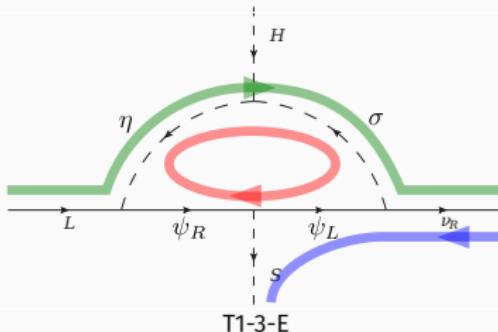
$\eta \rightarrow$ Doublet scalar



Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$



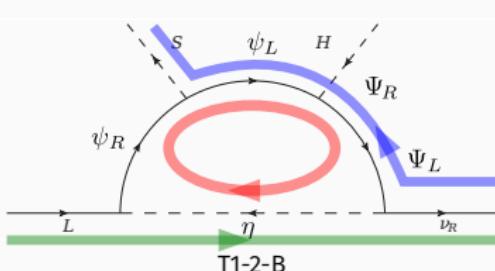
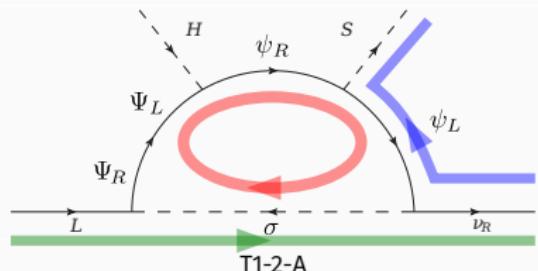
$\psi_{L,R} \rightarrow$ Singlet fermions (quiral)

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

$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ 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
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$



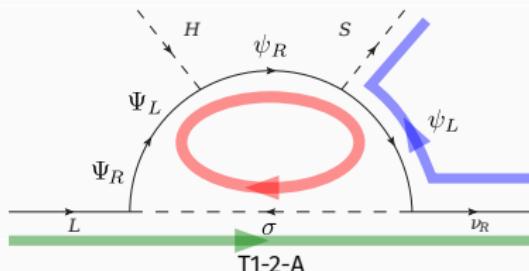
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$\psi_{L,R} \rightarrow$ Singlet fermions (quiral)
 $\Psi_{L,R} \rightarrow$ Vector-like doublet fermions : 10/5
 $\sigma \rightarrow$ Singlet scalar : 15/5

Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
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Anomaly cancellation conditions

$$\sum_i f_i = 3$$

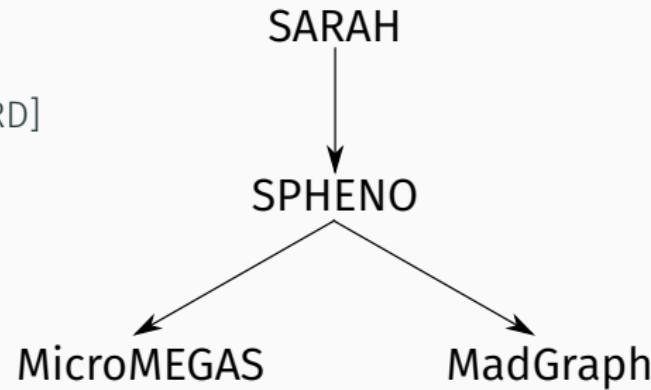
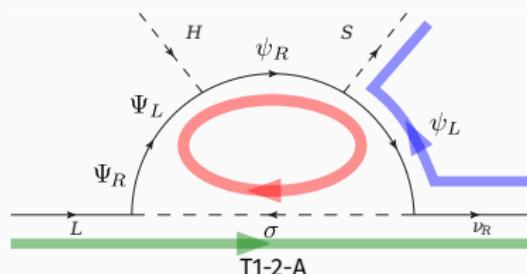
$$\sum_i f_i^3 = 3$$

$\text{SD}^3\text{M+SSDM}$: σ_a ($a = 1, 2$)

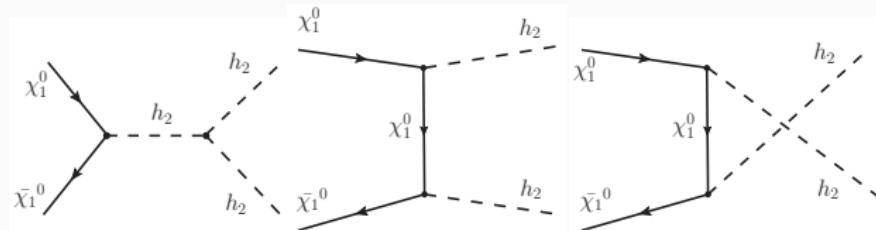
$M_\psi = h_1 \langle S \rangle$, $y_2 = 0$:

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

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

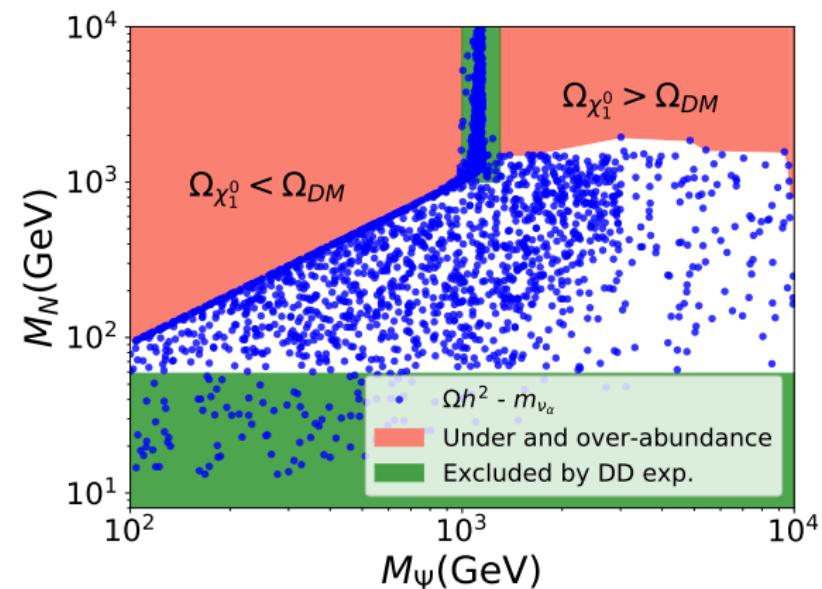


Dark matter relic density

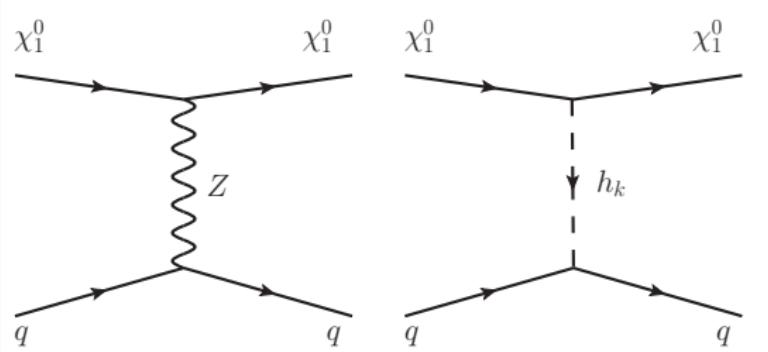


Decoupled Z' limit

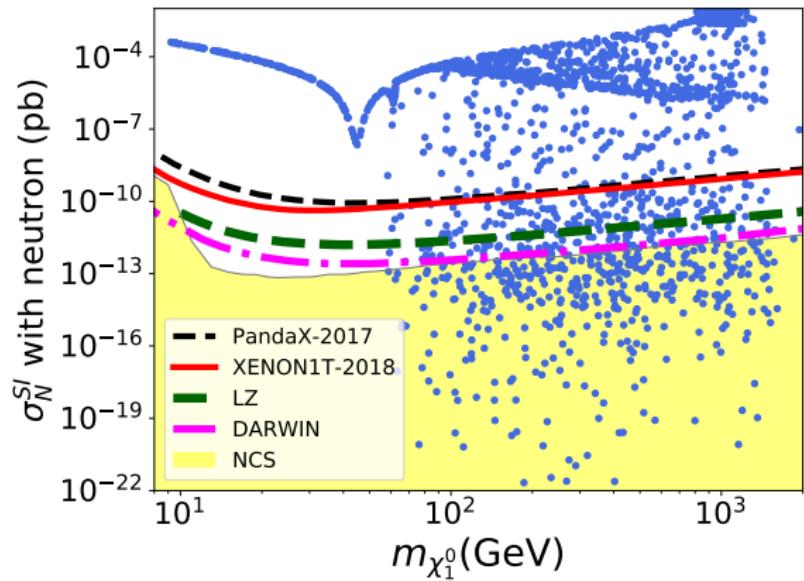
$$\begin{pmatrix} h \\ \text{Re}(S) \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}.$$



Spin independent (SI) direct detection cross section

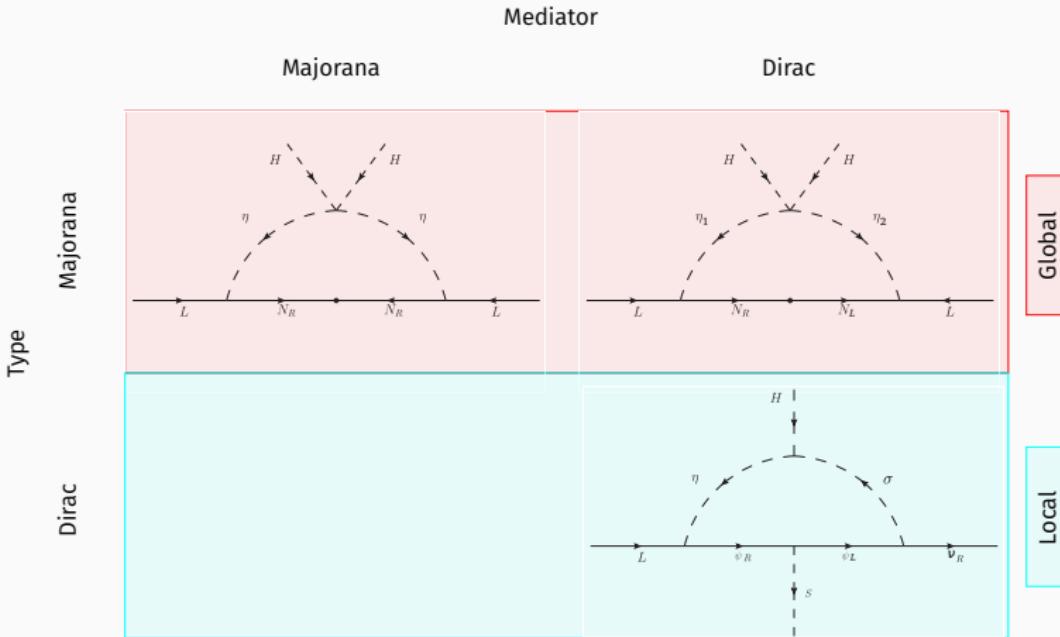


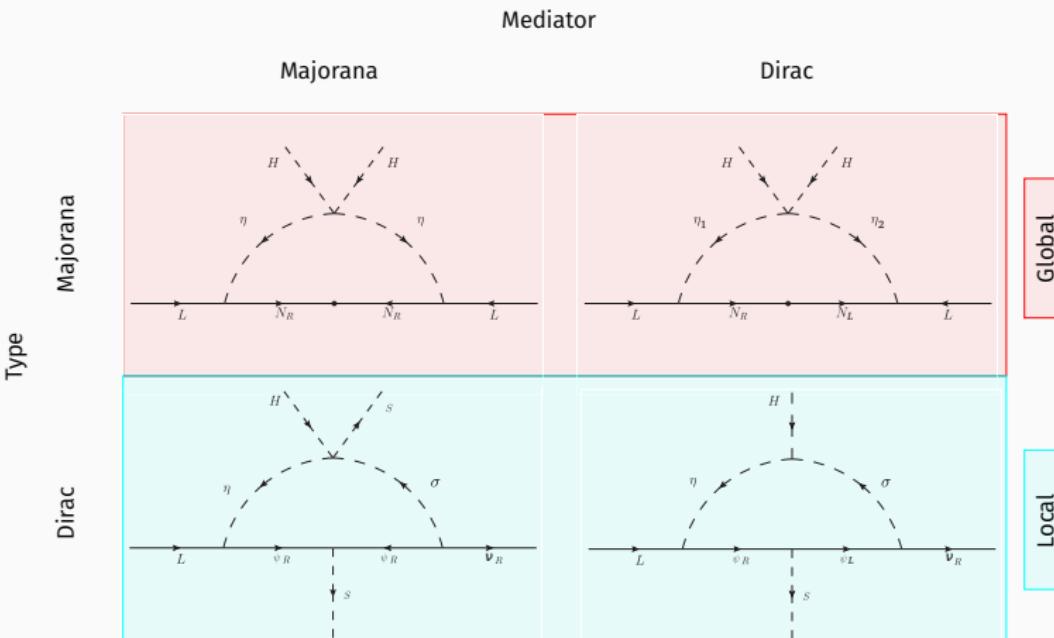
Decoupled Z' limit



Dark symmetry

Radiative Type-I seesaw





Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_D^*$
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 that 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 $U(1)_{B-L}$ 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.

Conclusions

It makes sense to focus our attention on models that 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 smallness 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 Singlet Doublet Dirac Dark Matter or Singlet Scalar Dark Matter with extra scalar and vector portal
- Dark symmetry for Majorana mediators

Conclusions

Thanks!