

Dark sectors

from (Dirac radiative) neutrino masses



UNIVERSIDAD DE ANTIOQUIA
1803

Diego Restrepo

December 16, 2019 - UdeA
[PDF: <http://bit.ly/comhep2019>]

Instituto de Física
Universidad de Antioquia
Phenomenology Group
<http://gfif.udea.edu.co>

Focus on

arXiv:1812.05523 [PRD], 1906.09685 [PRD], 1907.11938, 1909.09574

In collaboration with

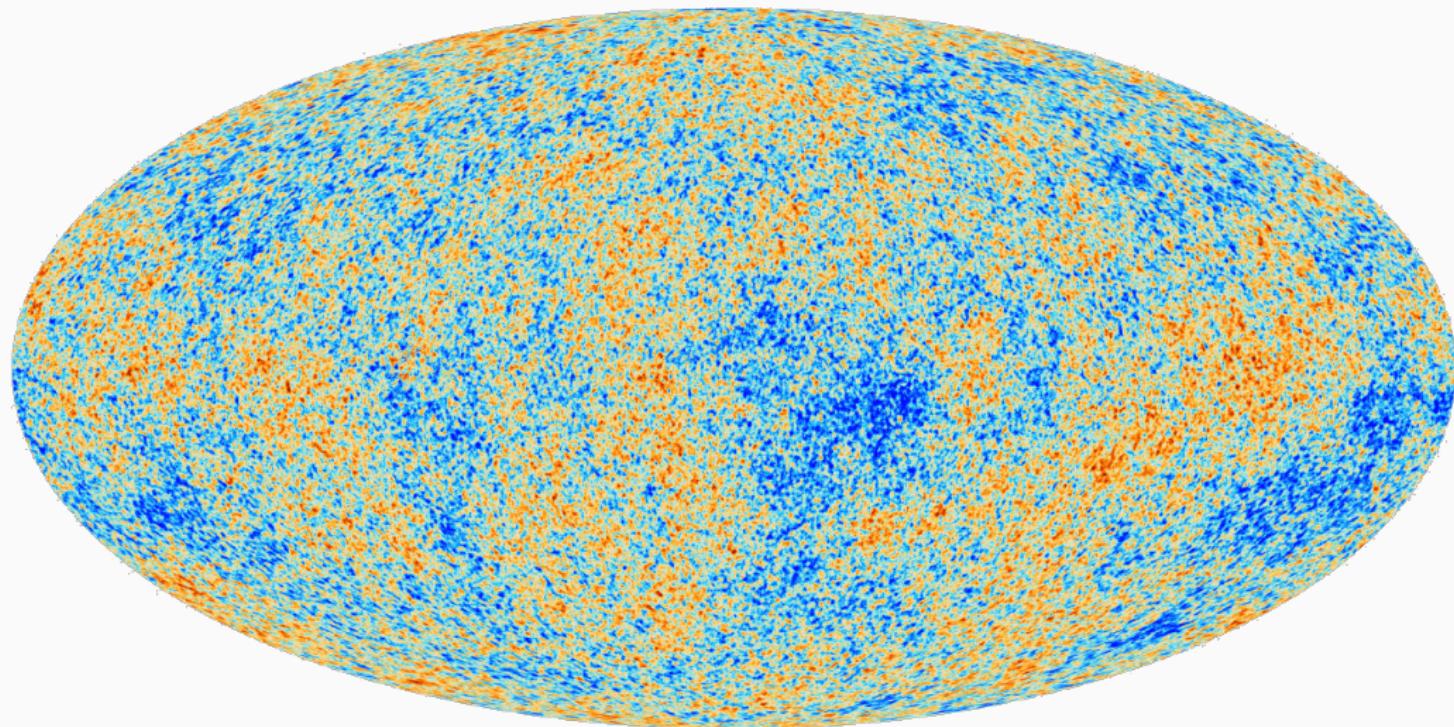
Carlos Yaguna (UPTC), Julian Calle, Óscar Zapata, Andrés Rivera (UdeA),
Walter Tangarife (Loyola University Chicago), Nicolás Bernal (UAN)



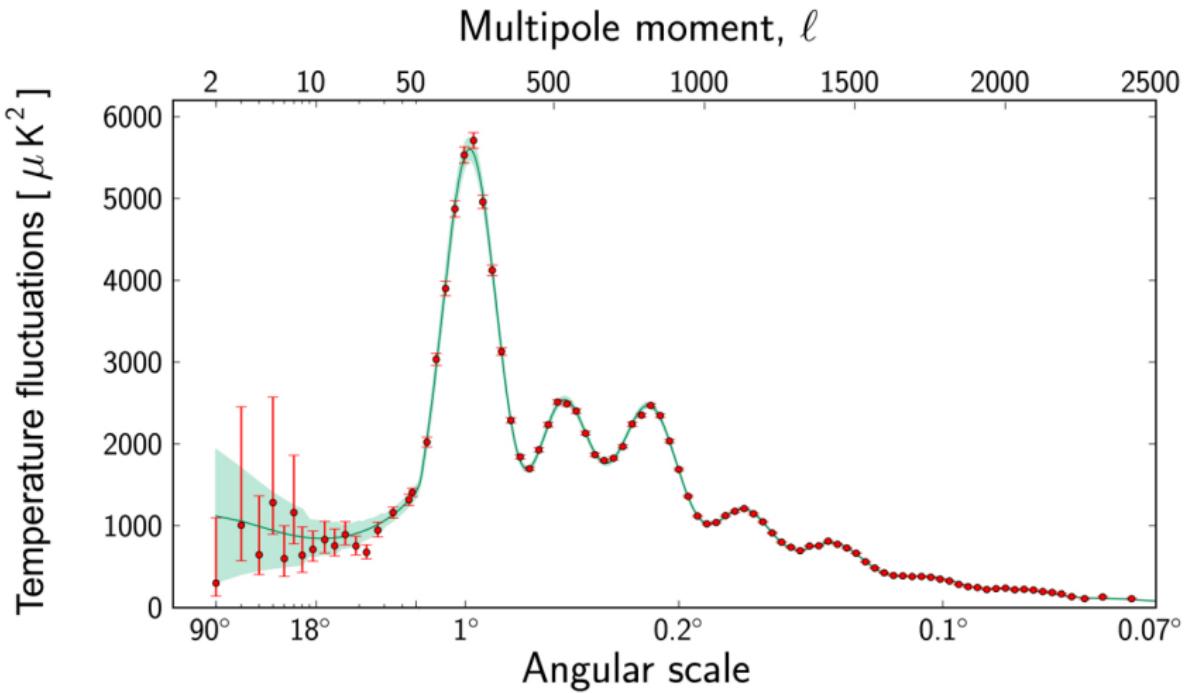
GRUPO DE
FENÓMENOLOGÍA DE INTERACCIONES FUNDAMENTALES

Λ CDM concordance model (with
baryonic effects)

Cosmic Microwave Background temperature: $T = 2.726 \text{ K}$ with $\Delta T/T \sim 10^{-6}$



The Cosmic Microwave Background - as seen by Planck. Credit: ESA and the Planck Collaboration

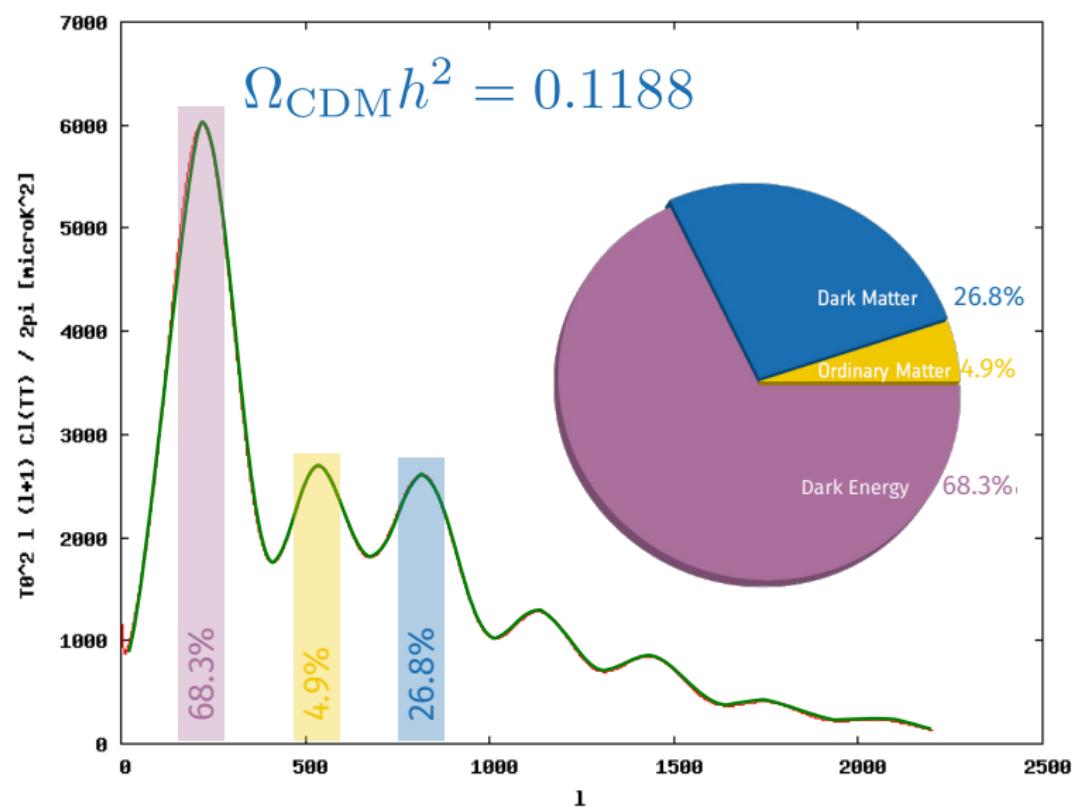


Planck's power spectrum of temperature fluctuations, ΔT , in the Cosmic Microwave Background. Credit: ESA and the Planck Collaboration

ΛCDM : $\Omega = 1$, $w = -1^\dagger$

Symbol	Value
$\Omega_b h^2$	0.02230(14)
$\Omega_{\text{CDM}} h^2$	0.1188(10)
t_0	$13.799(21) \times 10^9$ years
n_s	0.9667(40)
Δ_R^2	2.441×10^{-9}
τ	0.066(12)

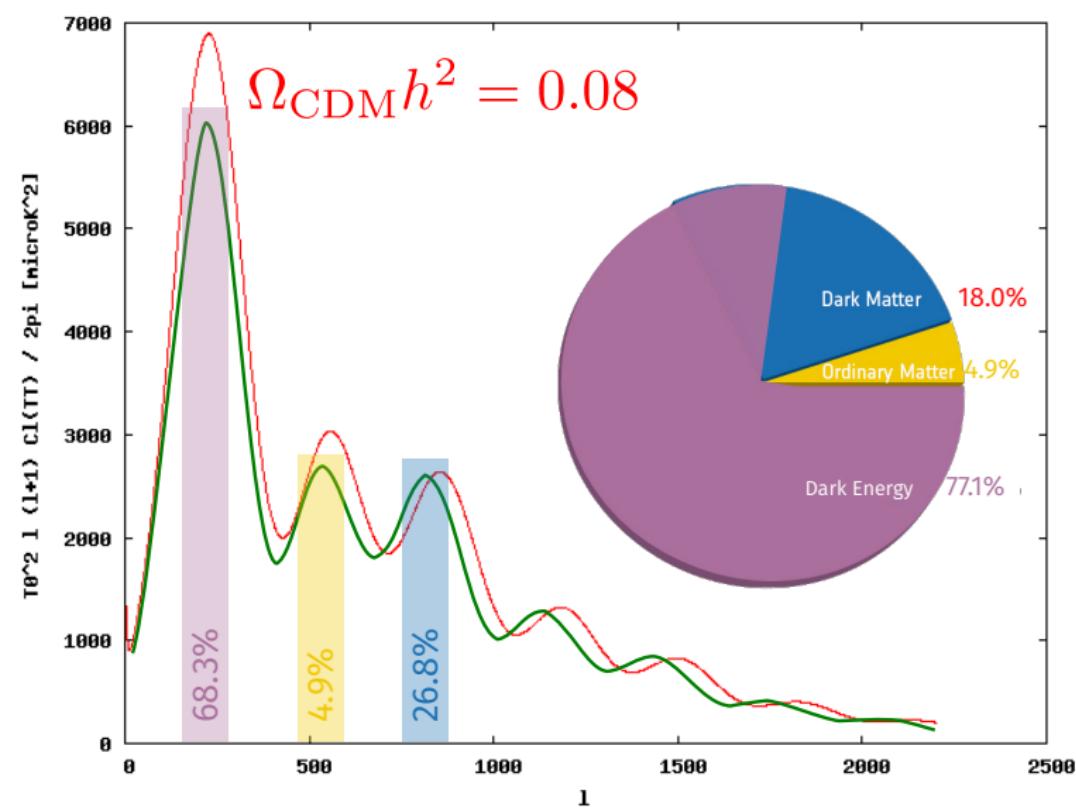
† Cosmological constant



ΛCDM : $\Omega = 1$, $w = -1^\dagger$

Symbol	Value
$\Omega_b h^2$	0.02230(14)
$\Omega_{\text{CDM}} h^2$	0.1188(10)
t_0	$13.799(21) \times 10^9$ years
n_s	0.9667(40)
Δ_R^2	2.441×10^{-9}
τ	0.066(12)

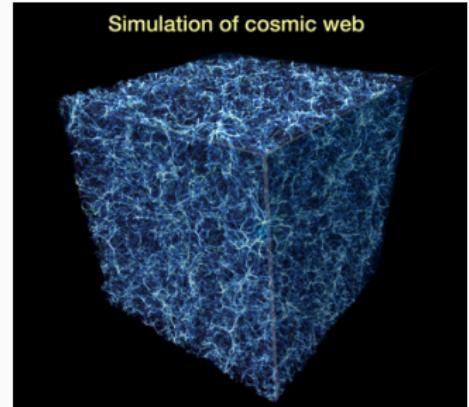
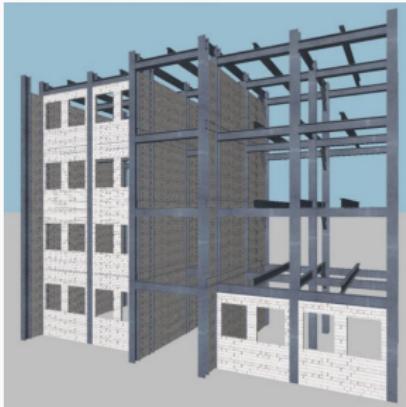
† Cosmological constant



Cosmic web

Dark matter connects clusters of galaxies with massive tendrils, forming a cosmic web that serves as an unseen skeleton for the universe.

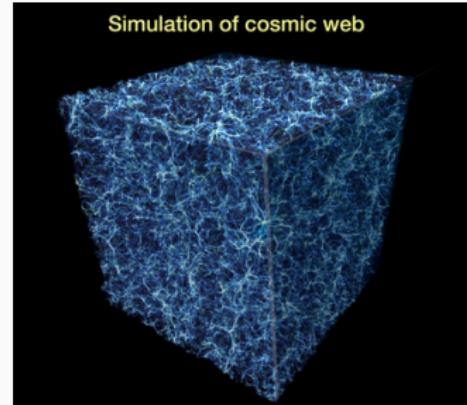
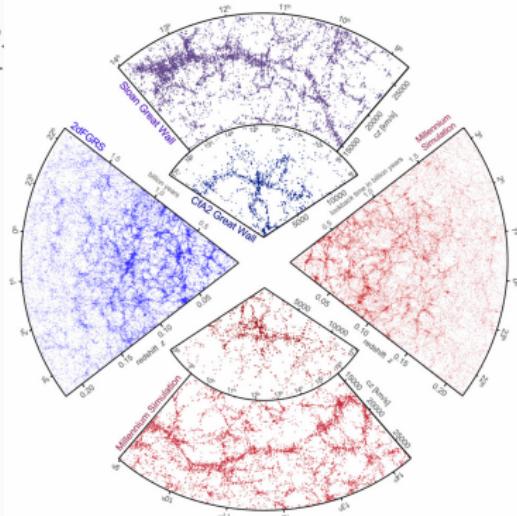
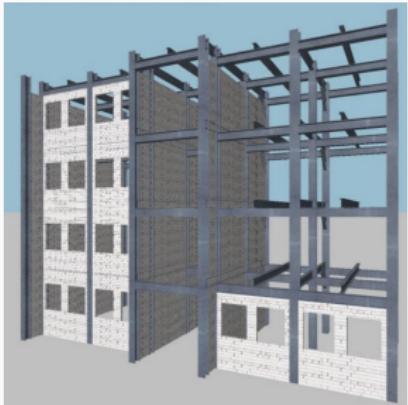
<https://phys.org/news/2018-06-years-scientists-account-universe.html>



Cosmic web

Dark matter connects clusters of galaxies with massive tendrils, forming a cosmic web that serve.

<https://phys.org/news/2018-06->

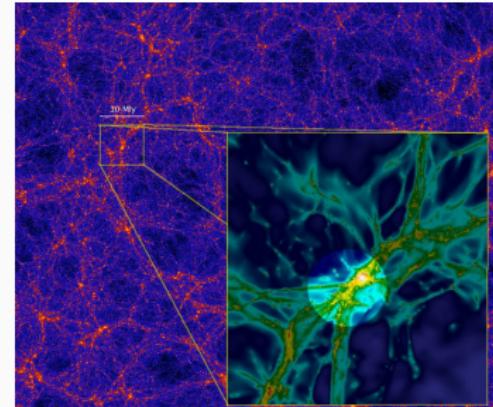
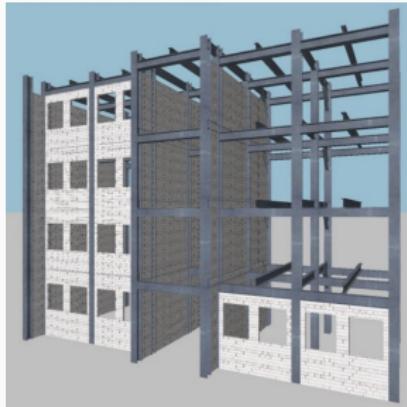


Galaxy redshift surveys vs large scale structure formation simulations: V. Springel, et al [astro-ph/0604561](#) [Nature]

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**!

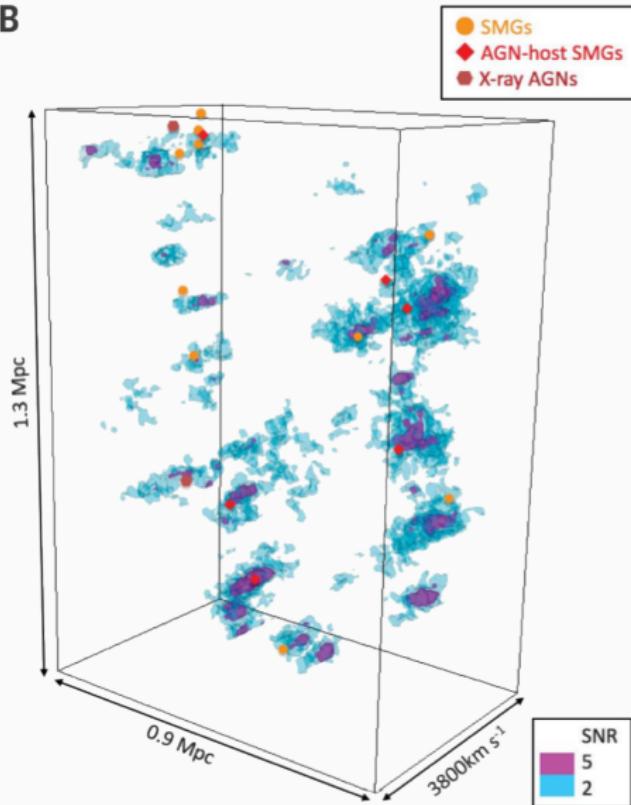
An excess of a gas (20σ) is observed between Milky Way and Andromeda (M31): arXiv:1403.7528 [MNRAS]¹

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

¹ See also: arXiv:1603.05400 [A&A]

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

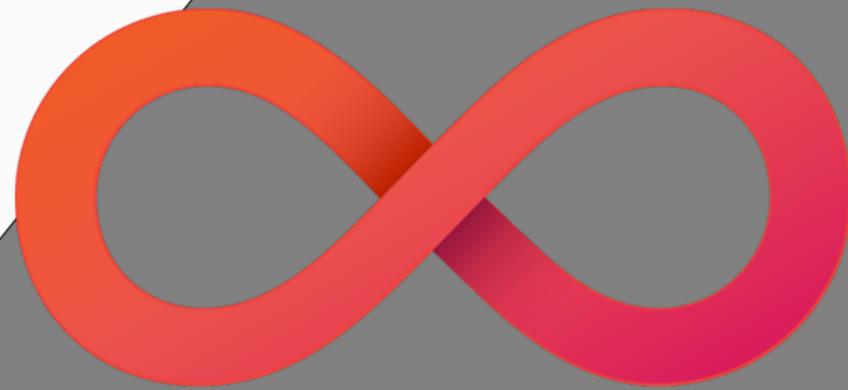
H. Umehata *et al.*, Science 366, 97, 4 Oct 2019

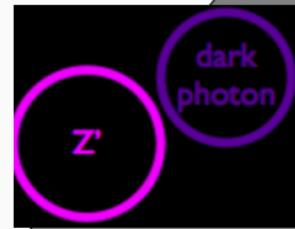
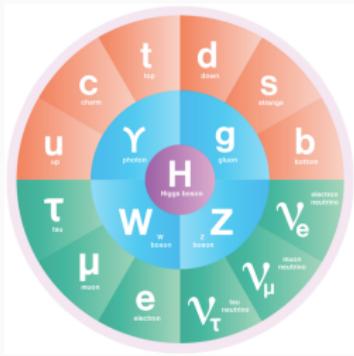
Dark matter properties

Apart from its manifold gravitational influences, (particle) dark matter has so far eluded detection, prompting model builders to think more broadly about what dark matter can be and in the process consider other and more subtle ways to search for it.

Agrawal, et al, arXiv:1610.04611 [JCAP]

Dark sectors



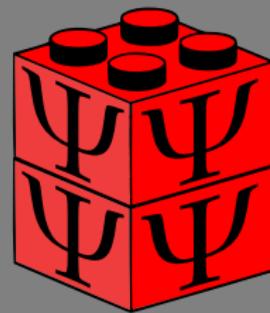
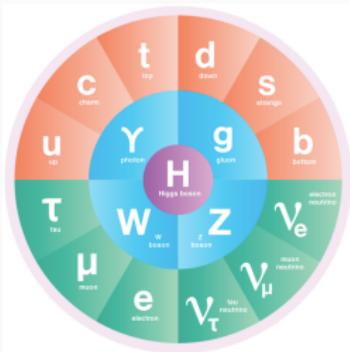


Local $U(1)_{\mathcal{D}}$

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + i\bar{\psi}\mathcal{D}\psi - m\bar{\psi}\psi,.$$

Relic abundance $\psi\bar{\psi} \rightarrow \gamma_{\mathcal{D}}\gamma_{\mathcal{D}}$

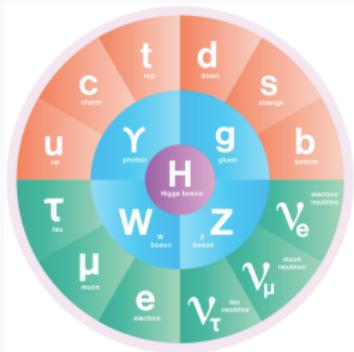
$$F_{\mu\nu} V^{\mu\nu}$$



Local $U(1)_{\mathcal{D}}$

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + i\bar{\psi}\mathcal{D}\psi - m\bar{\psi}\psi,.$$

Relic abundance $\psi\bar{\psi} \rightarrow \gamma_{\mathcal{D}}\gamma_{\mathcal{D}}$



$$F_{\mu\nu} V^{\mu\nu}$$



Explain also small neutrino masses

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

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

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

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

with solution

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

which satisfy

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

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

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

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

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

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	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$U(1)_{B-L}$	$U(1)_R$	$U(1)_D$	$U(1)_G$	$U(1)_{\mathcal{D}}^*$
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

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]
$\left(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3}\right)$	  In progress...  New method [†]

Table 2: Possible solutions with at least two repeated charges and until six chiral fermions.

[†] General $\sum n_\alpha = 0$ solutions: see D.B Costa, et al, arXiv:1905.13729 [PRL]

Or... combine known solutions with $\sum n_\alpha = 0$ and $\sum n_\alpha^3 = 0$

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \dots)$	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 [PRD]
$\left(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, +2\right)$	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]
$\left(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3}\right)$	In progress...  method [†]

Table 2: Possible solutions with at least two repeated charges and until six chiral fermions.

[†] General $\sum n_\alpha = 0$ solutions: see D.B Costa, et al, arXiv:1905.13729 [PRL]

https://en.wikipedia.org/wiki/Sums_of_three_cubes

Only known integer solutions for -3 (1953)
September 2019:

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

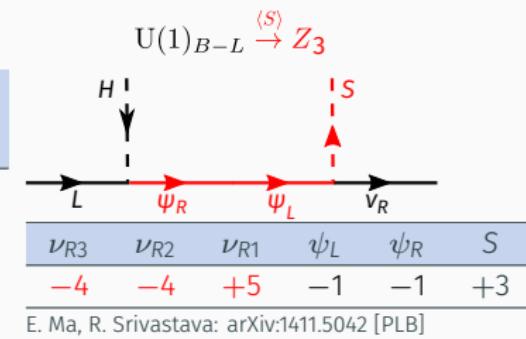
Or... combine known solutions

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \dots)$	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, O. Zapata [PRD]
$\left(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, +2\right)$	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]
$\left(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3}\right)$	In progress... New method [†]

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

Table 2: Possible solutions with at least two repeated charges and until six chiral fermions.

[†] General $\sum n_\alpha = 0$ solutions: see D.B Costa, et al, arXiv:1905.13729 [PRL]





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

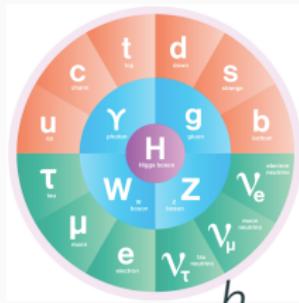


3 models

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

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

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



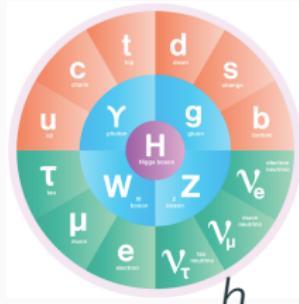
$$m_\text{Majorana}^\nu + = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H$$



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

$$U(1)_{B-L} \rightarrow Z_7$$

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



ν_{R3}	ν_{R2}	S
-1	-1	2

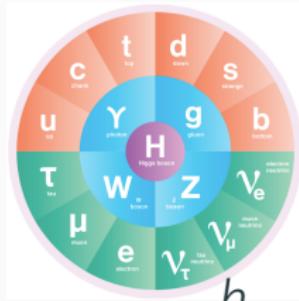
$$m_\text{Majorana}^\nu = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H \frac{S}{\Lambda}$$

Type-I arXiv:1808.03352

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

Local $U(1)_{B-L} \rightarrow Z_7$

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

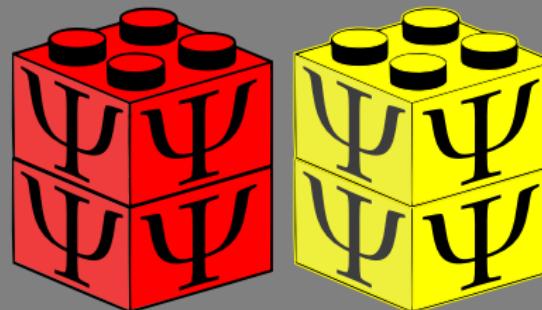


ν_{R3}	ν_{R2}	$\overline{\psi}_{L1}$	ψ_{R1}	ψ_{R2}	$\overline{\psi}_{L2}$	S	S'
-1	-1	$-\frac{10}{7}$	$-\frac{4}{7}$	$-\frac{2}{7}$	$\frac{9}{7}$	2	1

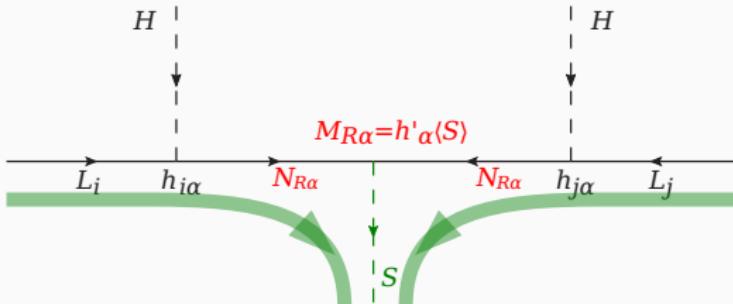
$$m_\text{Majorana}^\nu = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H \frac{S}{\Lambda}$$

Type-I arXiv:1808.03352

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



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	+	+

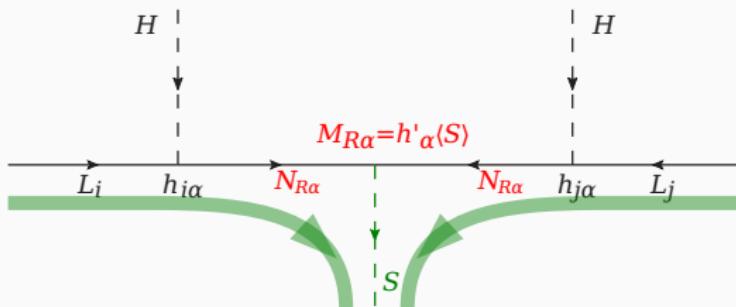


After integrating out heavy fermions, we obtain
light neutrino masses

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

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



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

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

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

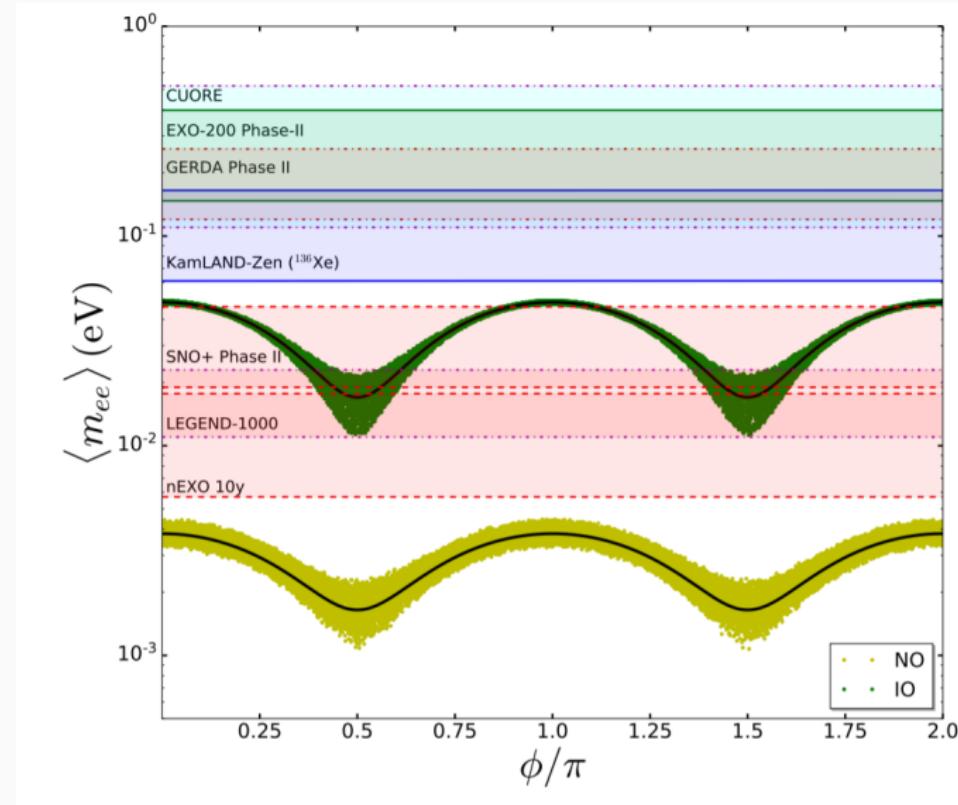
$$+ M_2 \overline{\chi}_2 \chi_2$$

(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

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

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

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

$$h_D \sim 10^{-11}$$

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:

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

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

$U(1)_X$

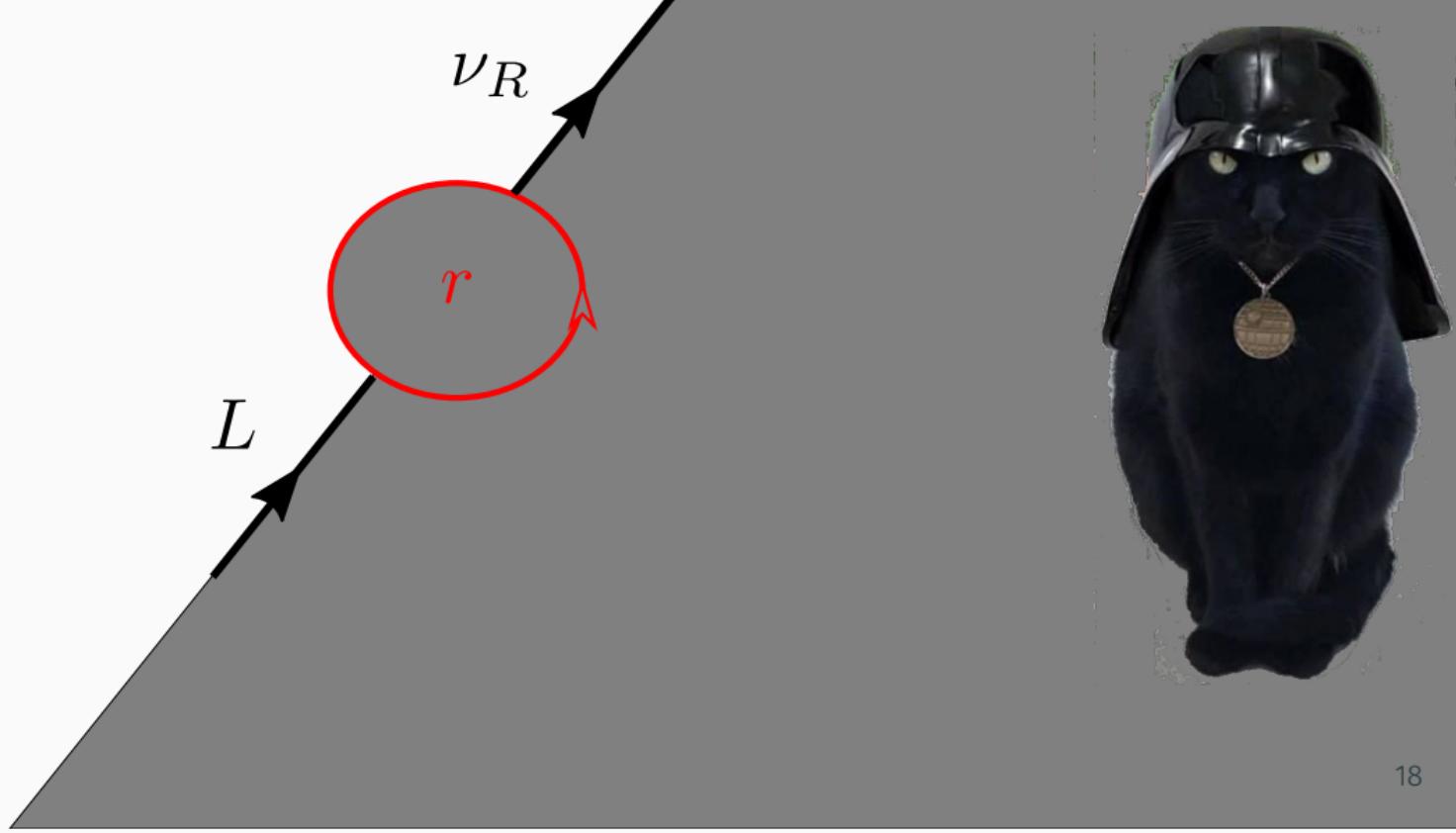
Dirac neutrino masses

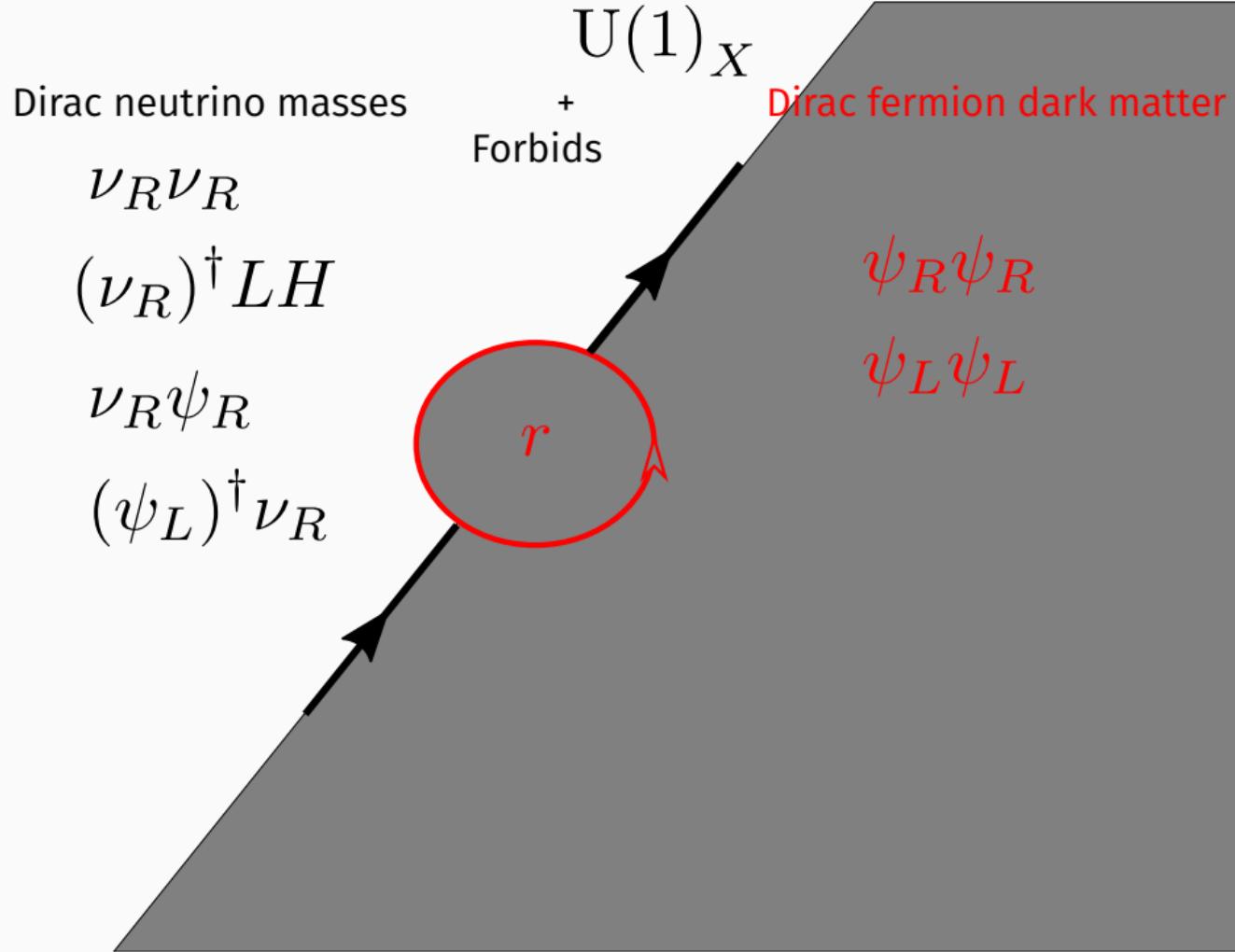
+

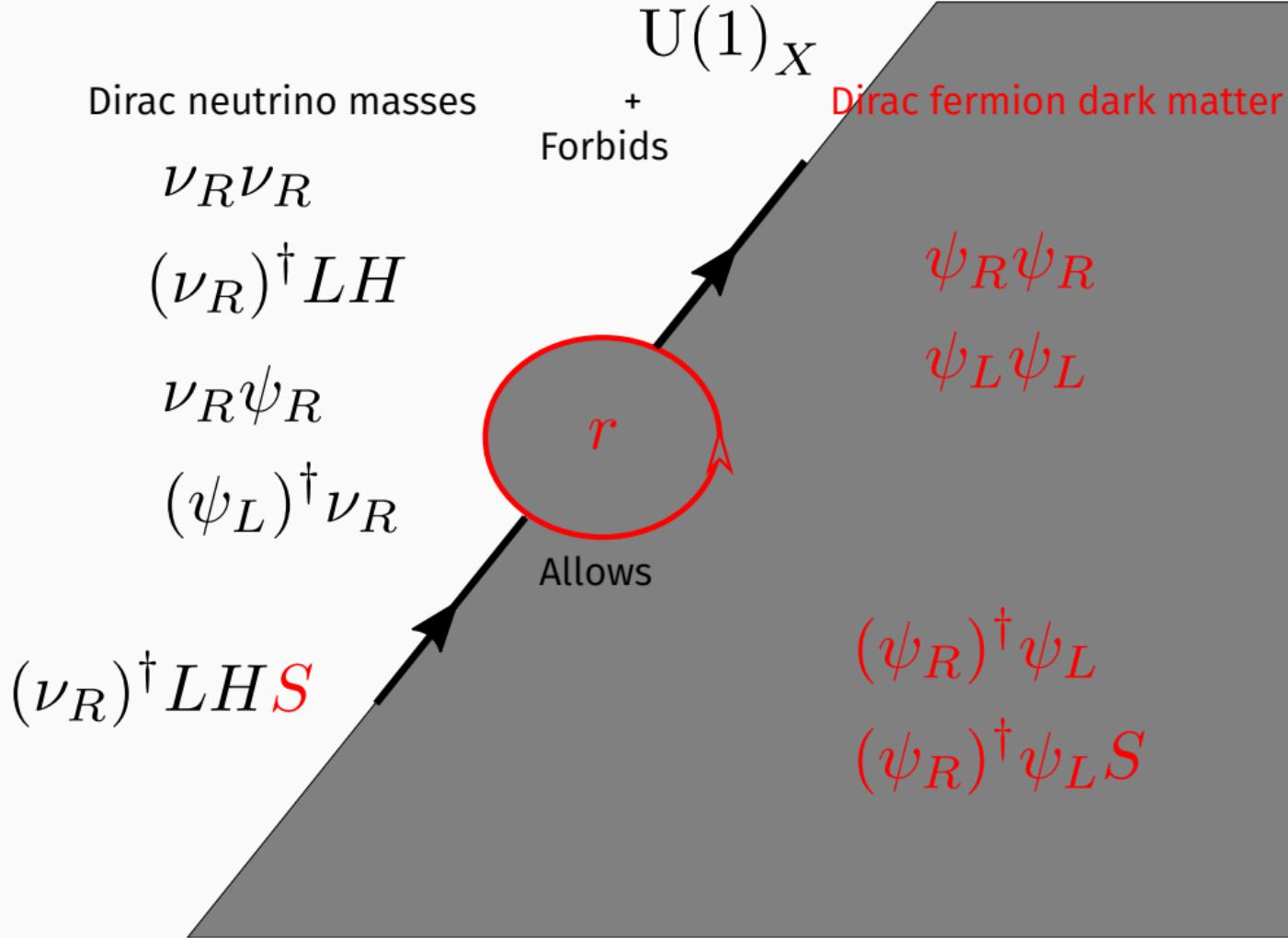
Dirac fermion dark matter

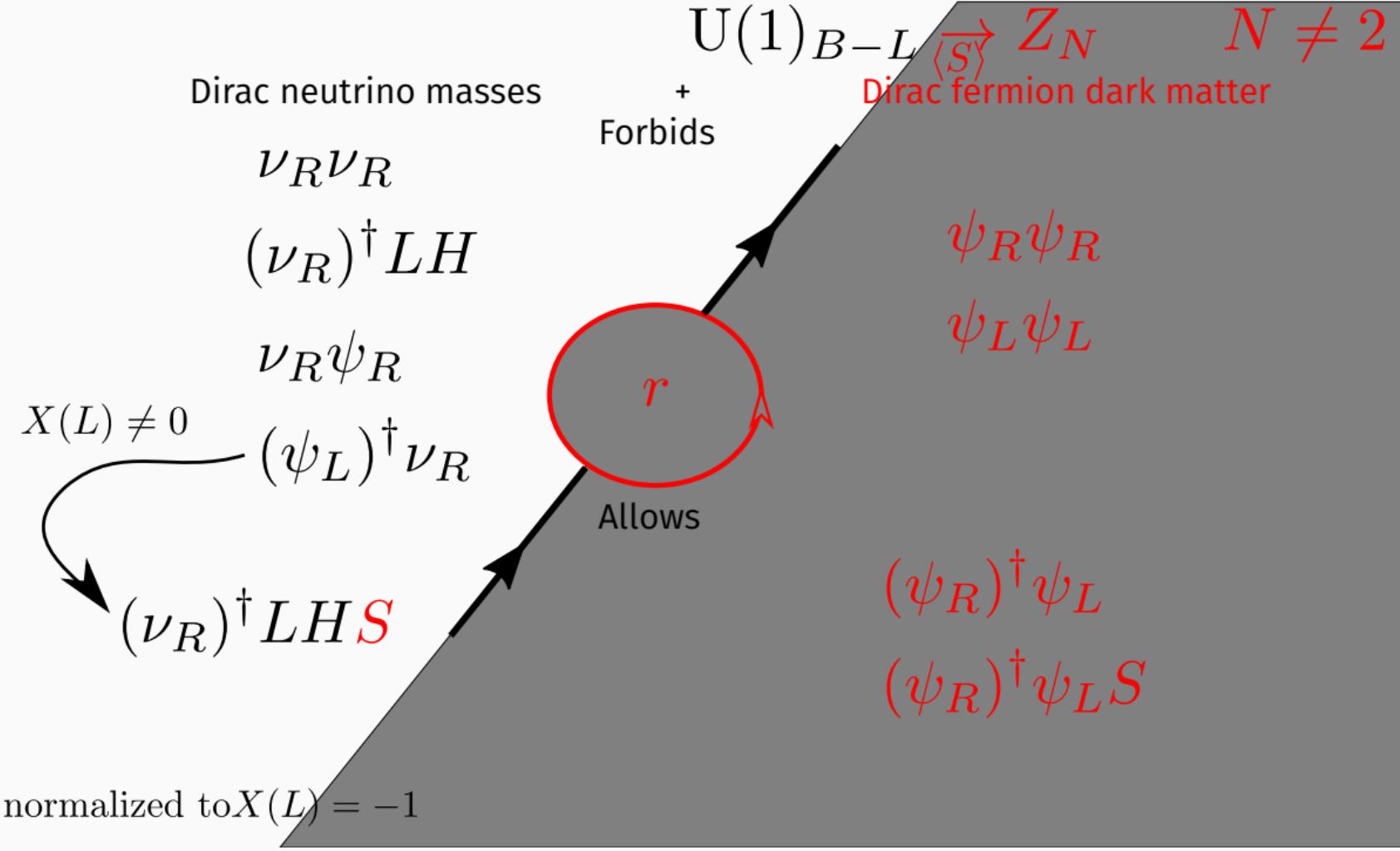


SM

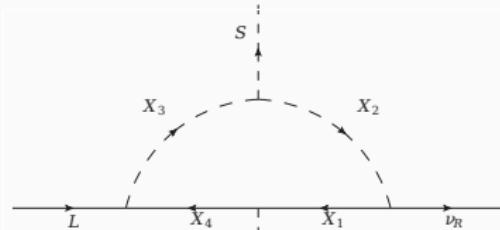




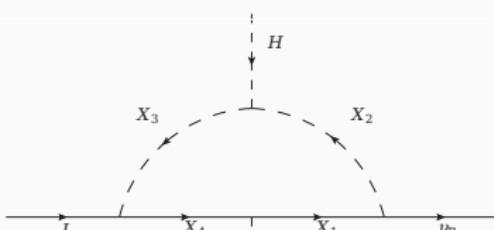




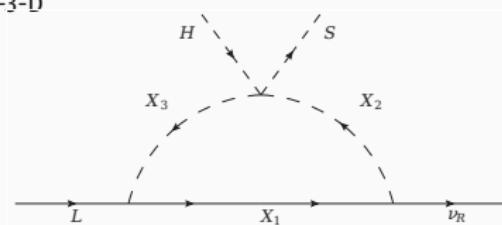
One loop topologies $U(1)_{B-L} \oplus \mathbb{Z}_2 \oplus \mathbb{Z}_2$



T1-3-D

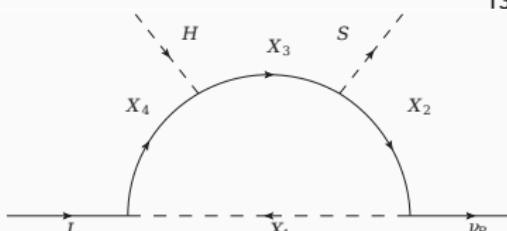


T1-3-E

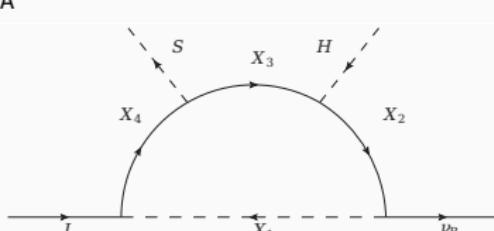


T3-1-A

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

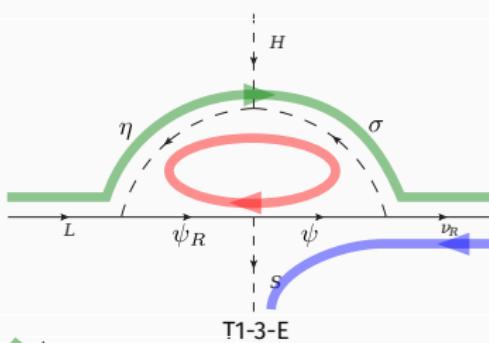
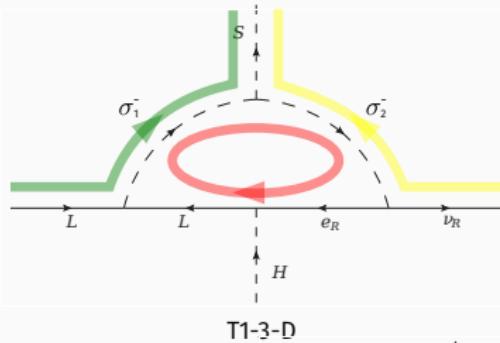


T1-2-A



T1-2-B

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



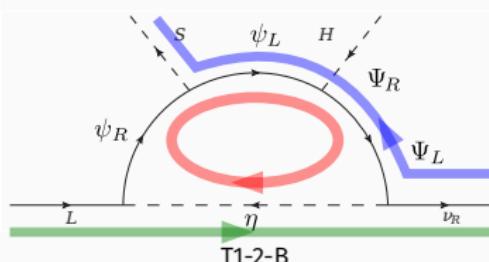
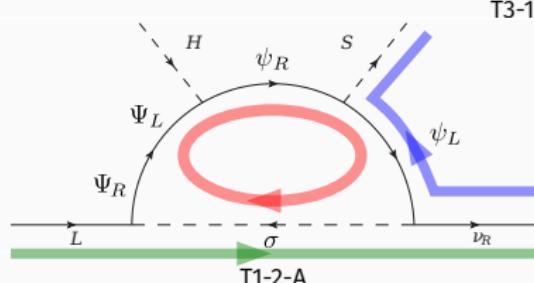
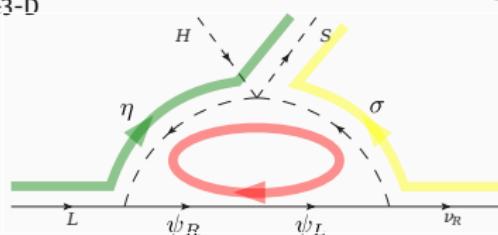
$\psi_{L,R} \rightarrow$ Singlet fermions

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

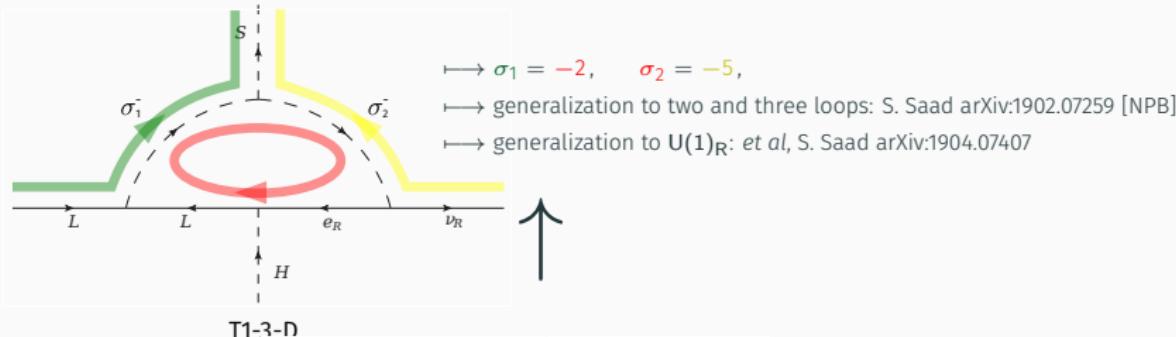
$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar

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



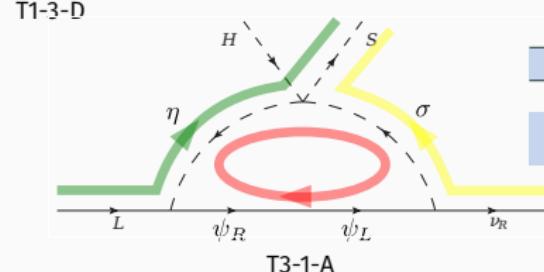
One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



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

$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar



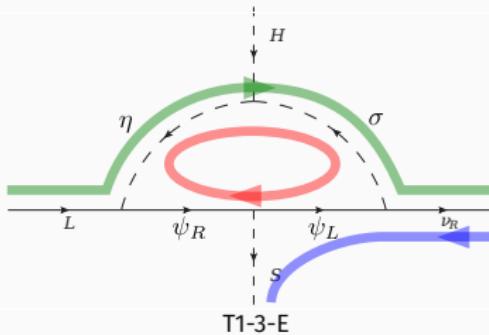
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3

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]



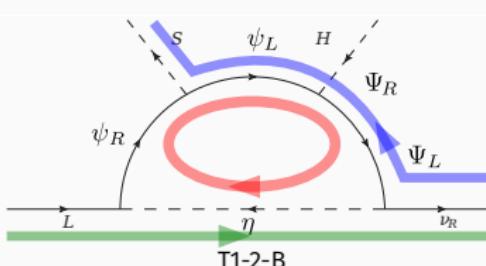
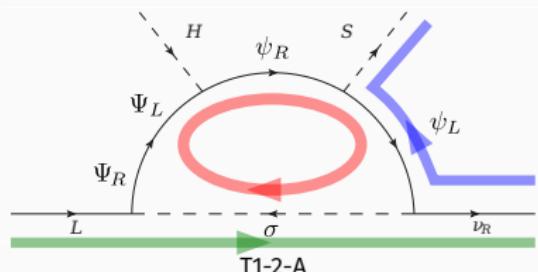
$\psi_{L,R} \rightarrow$ Singlet fermions (quiral)

$\Psi_{L,R} \rightarrow$ 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)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$



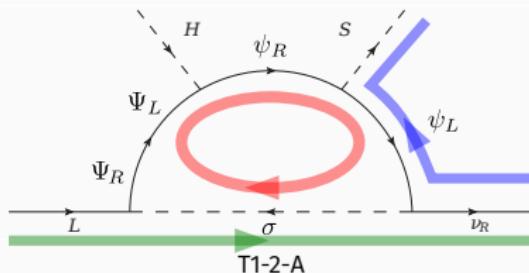
Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

$\psi_{L,R} \rightarrow$ Singlet fermions (quiral)
 $\Psi_{L,R} \rightarrow$ Vector-like doublet fermions : 10/5
 $\sigma \rightarrow$ 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)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$



Anomaly cancellation conditions

$$\sum_i f_i = 3$$

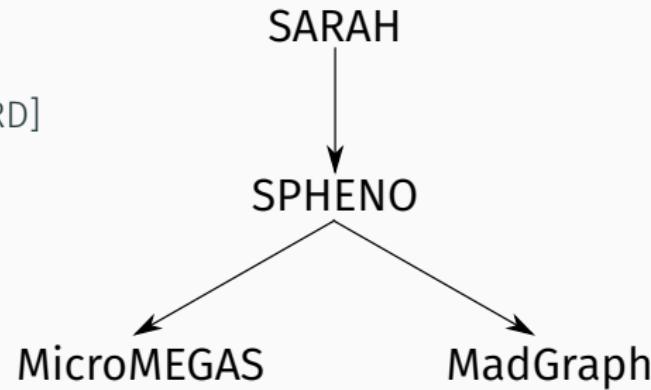
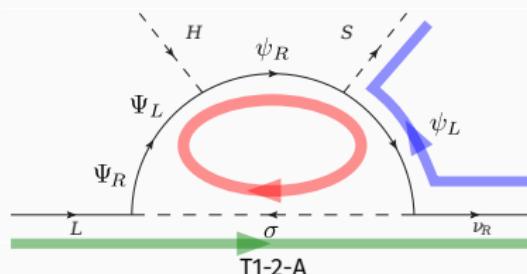
$$\sum_i f_i^3 = 3$$

$\text{SD}^3\text{M+SSDM}$: 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]



Global

Local

Mediator

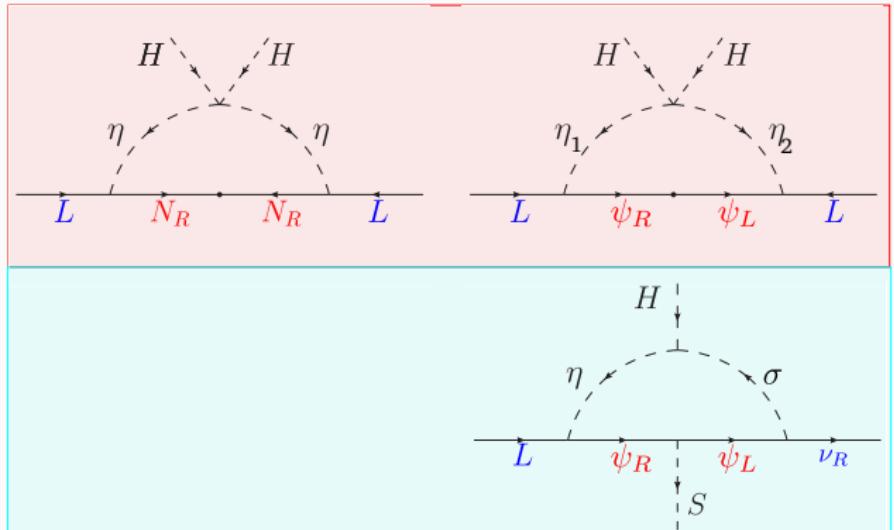
Majorana

Dirac

Majorana

Type

Dirac



For radiative Dirac models with

only $U(1)_X$ see also:

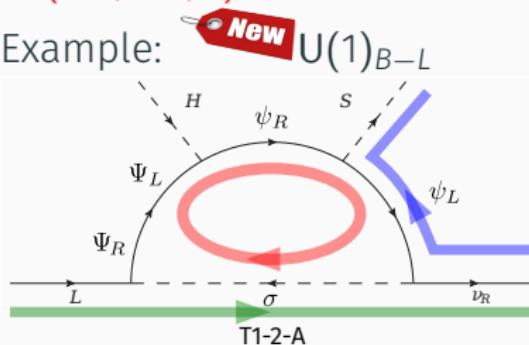
arXiv:1812.01599, 1901.06402, 1902.07259, 1903.01477,

1904.07407, 1907.08630, 1910.09537, 1909.00833, 1907.11557,

1909.09574

$\mathcal{O}(50)$ new models mostly with
 $\sim (-4, -4, 5)$

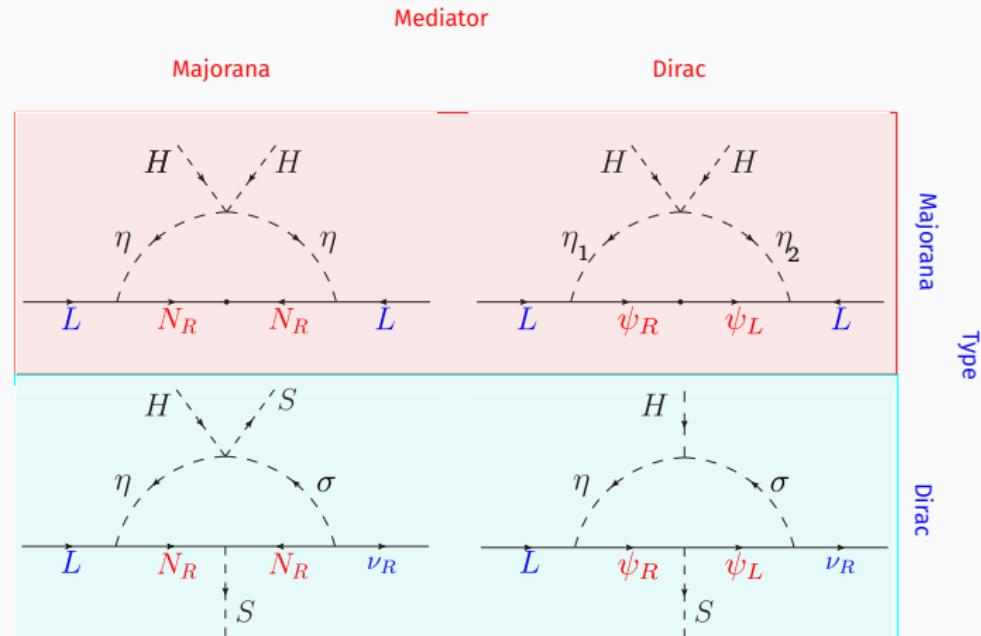
Example:



Pheno analysis with

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

Global



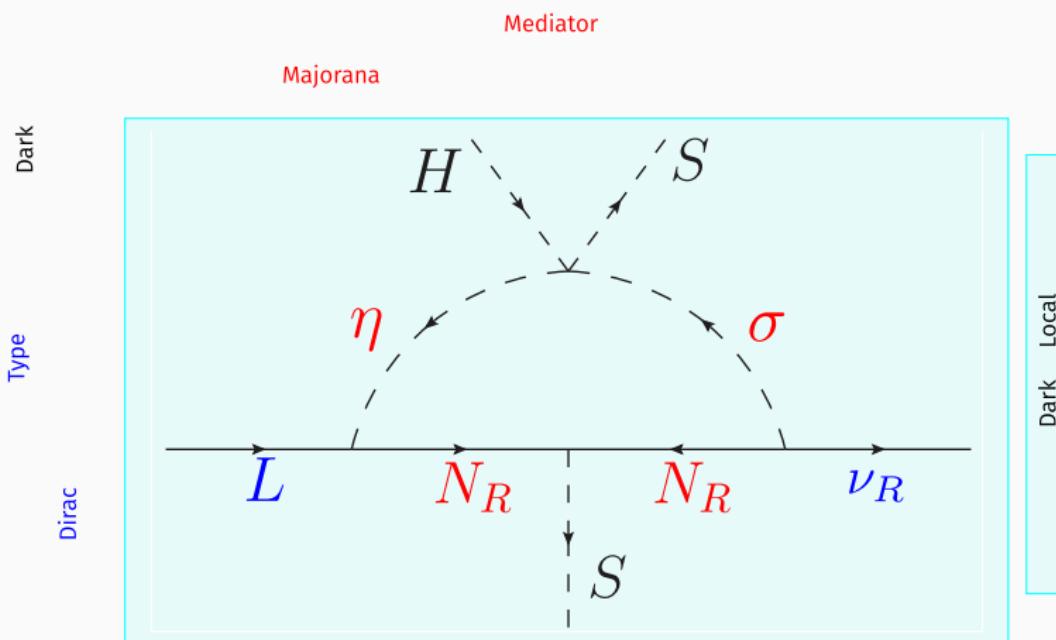
Majorana

Type

Dirac

Dirac Radiative Type-I seesaw with Majorana mediators

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



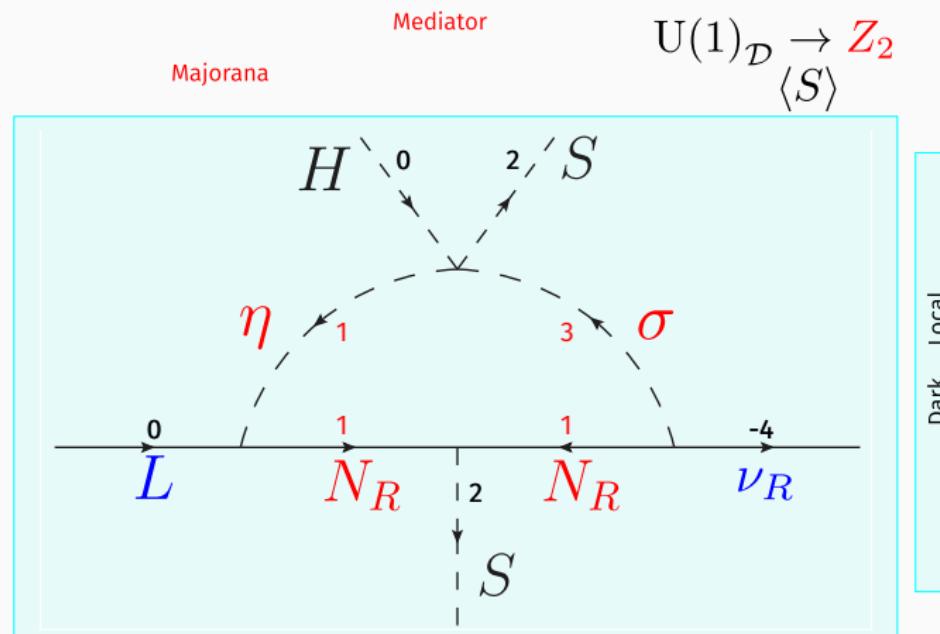
$$N = -\frac{\nu}{4} \quad , \quad \eta = -\frac{\nu}{4} \quad , \quad \sigma = -\frac{3\nu}{4} \quad .$$

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
N_{R1}	1	0	1
N_{R2}	1	0	1
N_{R3}	1	0	1
TOTAL			0

Dirac Radiative Type-I seesaw with Majorana mediators

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

Dark
Type
Dirac

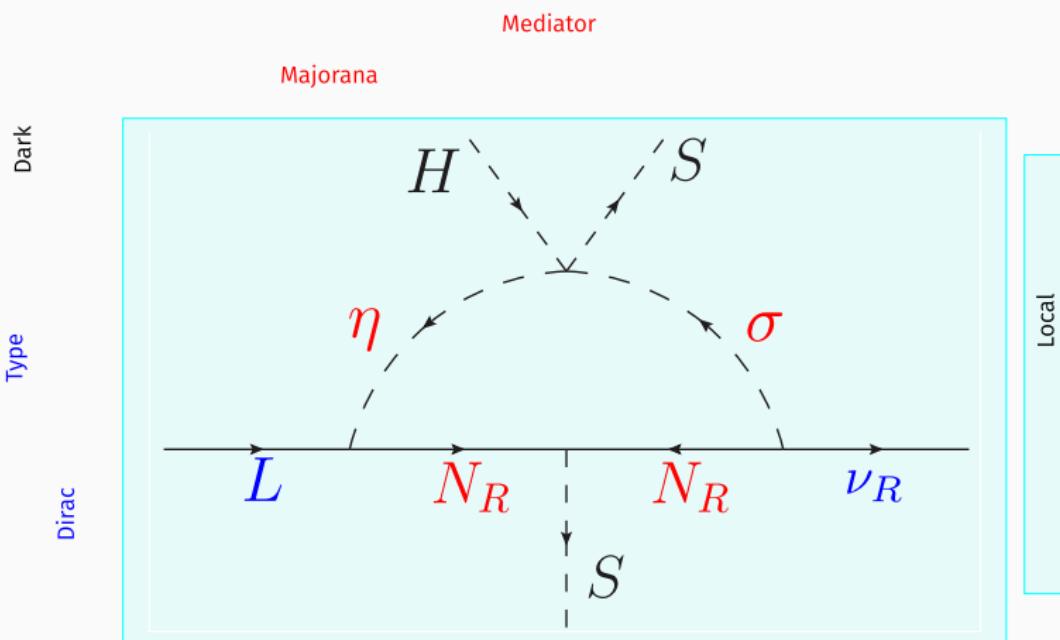


$$N = -\frac{\nu}{4} \quad , \quad \eta = -\frac{\nu}{4} \quad , \quad \sigma = -\frac{3\nu}{4} \quad .$$

Fields	$\text{SU}(2)_L$	$\text{U}(1)_Y$	$\text{U}(1)_{\mathcal{D}}$
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
N_{R1}	1	0	1
N_{R2}	1	0	1
N_{R3}	1	0	1
TOTAL			20

Dirac Radiative Type-I seesaw with Majorana mediators

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



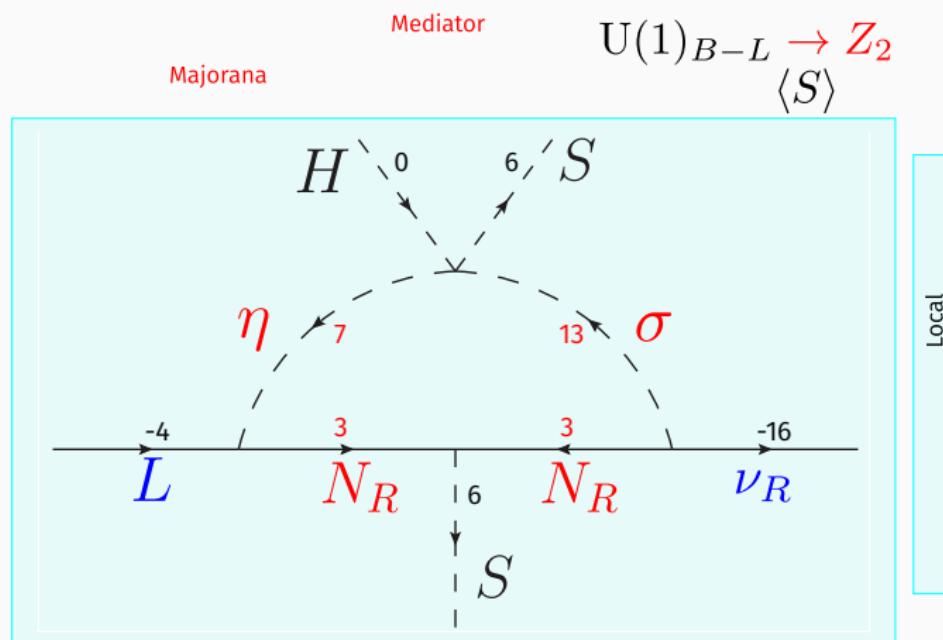
$$N = -\frac{\nu}{4} - \frac{1}{4}, \quad \eta = -\frac{\nu}{4} - \frac{1}{4} - l, \quad \sigma = -\frac{3\nu}{4} + \frac{1}{4}.$$

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
L	2	-1/2	l
Q	2	-1/6	$-l/3$
d_R	1	-1/2	$1+2l/3$
u_R	1	+2/3	$-1-4l/3$
e_R	1	-1	$1+2l$
H	2	1/2	$-1-l$
η	2	1/2	$3/4-l$
S	1	0	$3/2$
σ	1	0	$13/4$
ν_{R1}	1	0	-4
ν_{R2}	1	0	-4
ν_{R3}	1	0	5
N_{R1}	1	0	$3/4$
N_{R2}	1	0	$3/4$
N_{R3}	1	0	$3/4$
$\xi_{L\alpha}$	1	0	$3/4^{20}$

Dirac Radiative Type-I seesaw with Majorana mediators

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

Dark
Type
Dirac



$$N = -\frac{\nu}{4} - \frac{1}{4}, \quad \eta = -\frac{\nu}{4} - \frac{1}{4} + 1, \quad \sigma = -\frac{3\nu}{4} + \frac{1}{4}.$$

Fields	$\text{SU}(2)_L$	$\text{U}(1)_Y$	$\text{U}(1)_{B-L}$
L	2	-1/2	-1
Q	2	-1/6	1/3
d_R	1	-1/2	1/3
u_R	1	+2/3	1/3
e_R	1	-1	-1
H	2	1/2	0
η	2	1/2	7/4
S	1	0	3/2
σ	1	0	13/4
ν_{R1}	1	0	-4
ν_{R2}	1	0	-4
ν_{R3}	1	0	5
N_{R1}	1	0	3/4
N_{R2}	1	0	3/4
N_{R3}	1	0	3/4
$\xi_{L\alpha}$	1	0	$3/4^{20}$

The model

$$\begin{aligned}\mathcal{L} \supset & - g' Z'_\mu \sum_F q_F \bar{F} \gamma^\mu F + \sum_\phi |(\partial_\mu + i g' q_\phi Z'_\mu) \phi|^2 \\ & - [h_{i\alpha} \bar{L}_i \tilde{\eta} N_{R\alpha} + y_{j\alpha} \bar{\nu}_{R_j} \sigma^* N_{R\alpha}^c + k_\alpha \bar{N}_{R\alpha}^c N_{R\alpha} S^* + \text{h.c.}] - \mathcal{V}(H, S, \eta, \sigma).\end{aligned}$$

$F(\phi)$ denote the new fermions (scalars)

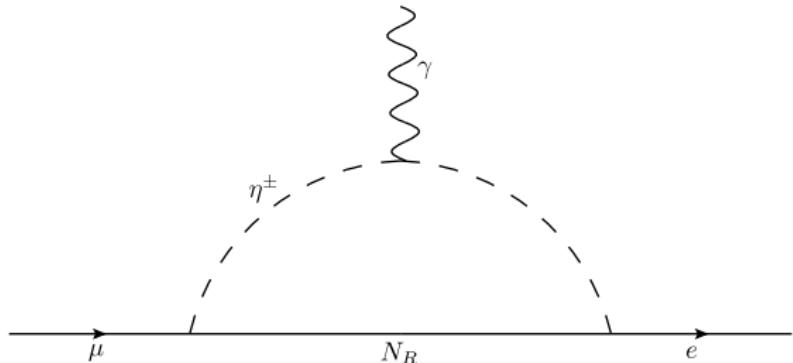
$$\begin{aligned}\mathcal{V}(H, S, \eta, \sigma) = & V(H) + V(S) + V(\eta) + V(\sigma) \\ & + \lambda_{HS} (H^\dagger H)(S^* S) + \lambda_2 (H^\dagger H)(\sigma^* \sigma) + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) \\ & + \lambda_4 (S^* S)(\sigma^* \sigma) + \lambda_5 (S^* S)(\eta^\dagger \eta) + \lambda_6 (\eta^\dagger \eta)(\sigma^* \sigma) + \lambda_7 (\eta^\dagger H)(H^\dagger \eta) \\ & + \lambda_8 (\eta^\dagger H S^* \sigma + \text{h.c.}),\end{aligned}$$

Neutrino masses and LFV

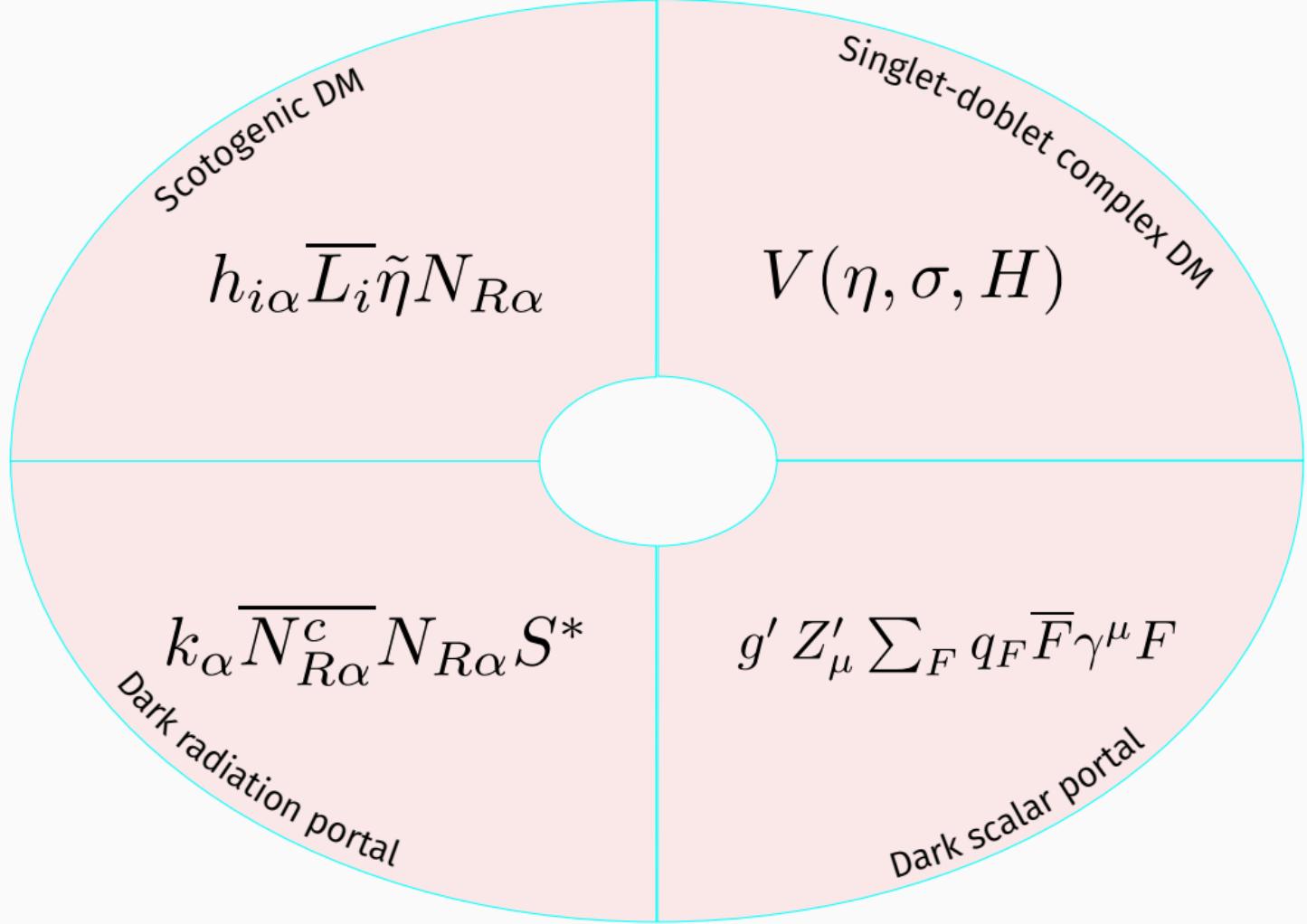
$$(\mathcal{M}_\nu)_{ij} = \frac{1}{32\pi^2} \frac{\lambda_8 v_S^2 v_H}{m_{\eta_R^0}^2 - m_{\sigma_R^0}^2} \sum_{\alpha=1}^3 h_{i\alpha} k_{\alpha} y_{j\alpha}^* \left[F\left(\frac{m_{\eta_R^0}^2}{M_{N_\alpha}^2}\right) - F\left(\frac{m_{\sigma_R^0}^2}{M_{N_\alpha}^2}\right) \right] + (R \rightarrow I),$$

where $F(x) = x \log x / (x - 1)$.

$$\mu \rightarrow e\gamma$$



$$\left| \sum_{\alpha} h_{2\alpha} h_{1\alpha}^* \right| \lesssim 0.02 \left(\frac{m_\chi}{2 \text{ TeV}} \right)^2.$$



Scotogenic DM

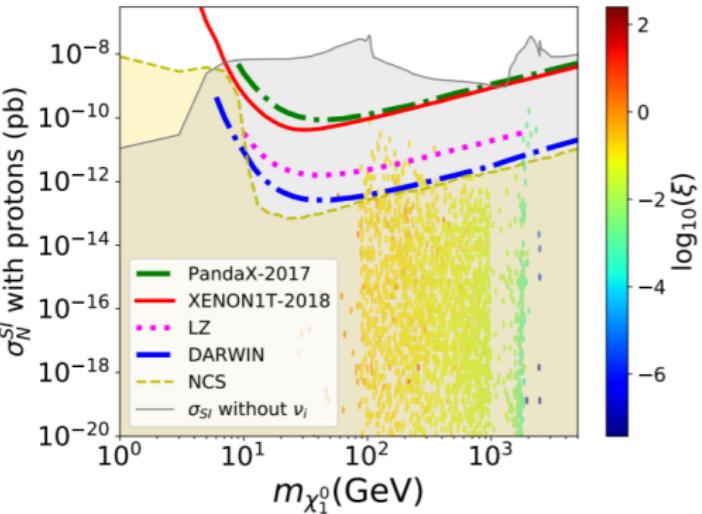
$$h_{i\alpha} \overline{L}_i \tilde{\eta} N_{R\alpha}$$

A. Ibarra, C. Yaguna, Ó. Zapata,
arXiv:1601.01163 [PRD]

Scotogenic DM

$$h_{i\alpha} \overline{L}_i \tilde{\eta} N_{R\alpha}$$
$$N_{R2} \rightarrow \Sigma$$

with A. Rivera, arXiv:1907.11938



$$(\chi_1^0 \ \chi_2^0)^T = R(\textcolor{red}{N}_{\textcolor{red}{R}} \ \Sigma)^T$$

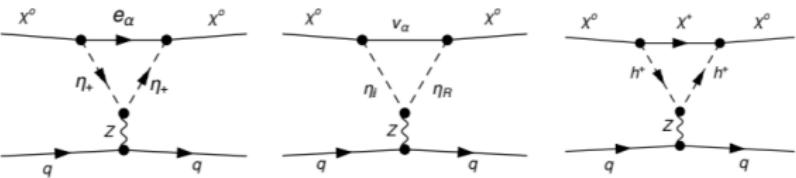
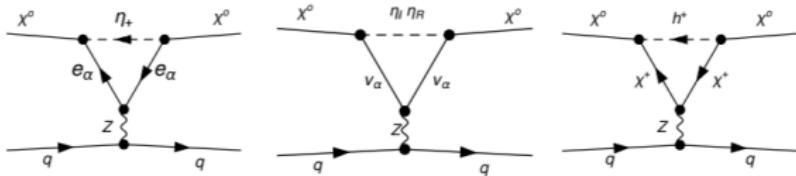
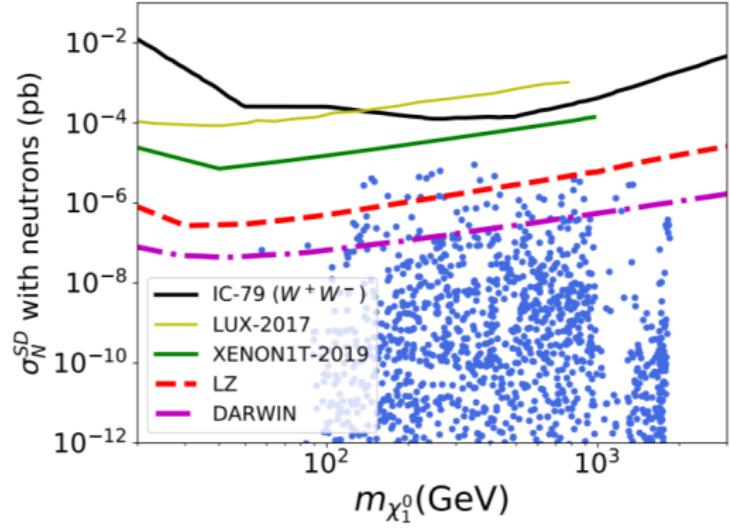
$$\xi = \frac{|M_\Sigma - m_{\chi_1^0}|}{m_{\chi_1^0}}$$

Scotogenic DM

$$h_{i\alpha} \overline{L}_i \tilde{\eta} N_{R\alpha}$$

$$N_{R2} \rightarrow \Sigma$$

with A. Rivera, arXiv:1907.11938

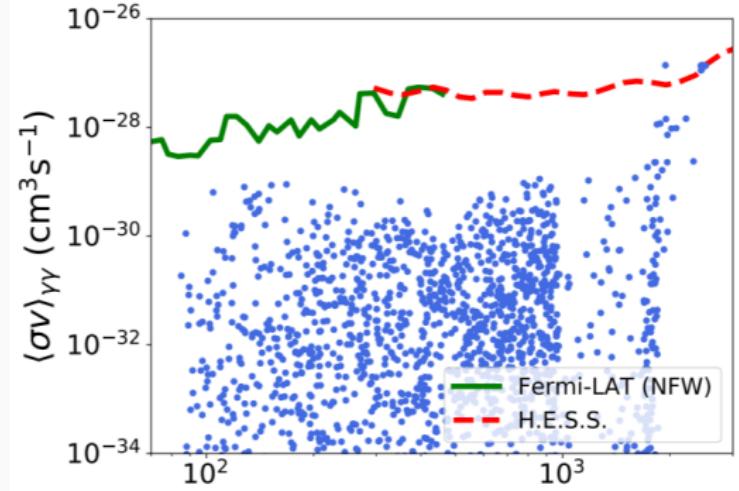


Scotogenic DM

$$h_{i\alpha} \overline{L}_i \tilde{\eta} N_{R\alpha} \\ N_{R2} \rightarrow \Sigma$$

with A. Rivera, arXiv:1907.11938

$$\sigma v (\chi_1^0 \chi_1^0 \rightarrow \gamma\gamma) = \frac{|\mathcal{B}|^2}{32\pi m_{\chi_1^0}^2}$$



$$\begin{aligned} \mathcal{B} = & \frac{\sqrt{2}\alpha m^2 \sin^2(\alpha) Y_{\text{eff}}^2 (\sin(\delta) + \cos(\delta))^2}{\pi} \left[\frac{M_{\Sigma}^2 C_0(0, -m^2, m^2; M_{H^\pm}^2, M_{H^\pm}^2, M_W^2)}{M_{H^\pm}^2 - M_W^2} \right. \\ & - \frac{M_{\Sigma} (-2mM_{H^\pm}^2 - M_\Sigma M_{H^\pm}^2 + m^2 M_\Sigma + 2mM_\Sigma^2 + M_W^2) C_0(0, -m^2, m^2; M_\Sigma^2, M_\Sigma^2, M_H^2)}{(M_{H^\pm}^2 - M_\Sigma^2)(M_{H^\pm}^2 + m^2 - M_\Sigma^2)} \\ & + \frac{2M_\Sigma(m + M_\Sigma) C_0(0, 0, 4m^2; M_\Sigma^2, M_\Sigma^2, M_H^2)}{-M_{H^\pm}^2 - m^2 + M_\Sigma^2} \Big] \\ & + \frac{\alpha m^2 \sin(\alpha) \cos(\alpha) Y_{\text{eff}}^2}{\pi} \left[- \frac{m_\eta^2 C_0(0, -m^2, m^2; m_\eta^2, m_\eta^2, m_\eta^2)}{m_\eta^2 - m_\eta^2} \right. \\ & + \frac{m_{\tau_i}^2 (m_{\tau_i}^2 + m^2 - m_\eta^2) C_0(0, -m^2, m^2; m_{\tau_i}^2, m_{\tau_i}^2, m_\eta^2)}{(m_{\tau_i}^2 - m_\eta^2)(-m_{\tau_i}^2 + m^2 + m_\eta^2)} + \frac{2m_{\tau_i}^2 C_0(0, 0, 4m^2; m_{\tau_i}^2, m_{\tau_i}^2, m_\eta^2)}{-m_{\tau_i}^2 + m^2 + m_\eta^2} \Big] \\ & + \frac{\alpha m^2 \cos^2(\alpha) Y_{\text{eff}}^2}{2\sqrt{2}\pi} \left[\frac{m_\eta^2 C_0(0, -m^2, m^2; m_\eta^2, m_\eta^2, m_{\tau_i}^2)}{m_\eta^2 - m_\eta^2} \right. \\ & - \frac{m_{\tau_i}^2 (m_{\tau_i}^2 + m^2 - m_\eta^2) C_0(0, -m^2, m^2; m_{\tau_i}^2, m_{\tau_i}^2, m_\eta^2)}{(m_{\tau_i}^2 - m_\eta^2)(-m_{\tau_i}^2 + m^2 + m_\eta^2)} - \frac{2m_{\tau_i}^2 C_0(0, 0, 4m^2; m_{\tau_i}^2, m_{\tau_i}^2, m_\eta^2)}{-m_{\tau_i}^2 + m^2 + m_\eta^2} \Big] \\ & + \frac{\sqrt{2}\alpha m^2 \sin^2(\alpha) Y_{\text{eff}}^2}{2\pi} \left[\frac{m_\eta^2 C_0(0, -m^2, m^2; m_\eta^2, m_\eta^2, m_{\tau_i}^2)}{m_\eta^2 - m_{\tau_i}^2} \right. \\ & - \frac{m_{\tau_i}^2 (m_{\tau_i}^2 + m^2 - m_\eta^2) C_0(0, -m^2, m^2; m_{\tau_i}^2, m_{\tau_i}^2, m_\eta^2)}{(m_{\tau_i}^2 - m_\eta^2)(-m_{\tau_i}^2 + m^2 + m_\eta^2)} - \frac{2m_{\tau_i}^2 C_0(0, 0, 4m^2; m_{\tau_i}^2, m_{\tau_i}^2, m_\eta^2)}{-m_{\tau_i}^2 + m^2 + m_\eta^2} \Big] \\ & - \frac{8\sqrt{2}am^2 \cos^2(\alpha) M_W^2}{\pi (M_\Sigma^2 - M_W^2) (4m_{\Omega_3}^2 + v_\phi^2) (m^2 - M_\Sigma^2 + M_W^2) (m^2 + M_\Sigma^2 - M_W^2)} \\ & \left[4(m^2 - M_W^2) (M_\Sigma^2 - M_W^2) (m^2 - M_\Sigma^2 + M_W^2) C_0(0, 0, 4m^2; M_W^2, M_W^2, M_W^2) \right. \\ & + 2M_\Sigma(2m - M_\Sigma) (M_\Sigma^2 - M_W^2) (m^2 + M_\Sigma^2 - M_W^2) C_0(0, 0, 4m^2; M_\Sigma^2, M_\Sigma^2, M_W^2) \\ & - (m^2 - M_\Sigma^2 + M_W^2) (-M_W^2 (m^2 + M_\Sigma^2) - 4mM_\Sigma (m^2 + M_\Sigma^2 - M_W^2) + 4M_\Sigma^2 + M_W^4) \\ & C_0(0, -m^2, m^2; M_W^2, M_W^2, M_W^2) - M_\Sigma (m^2 + M_\Sigma^2 - M_W^2) (4m^2 - 3m^2 M_\Sigma + M_\Sigma^2 - M_\Sigma M_W^2) \\ & C_0(0, -m^2, m^2; M_\Sigma^2, M_\Sigma^2, M_W^2) \Big]. \end{aligned}$$

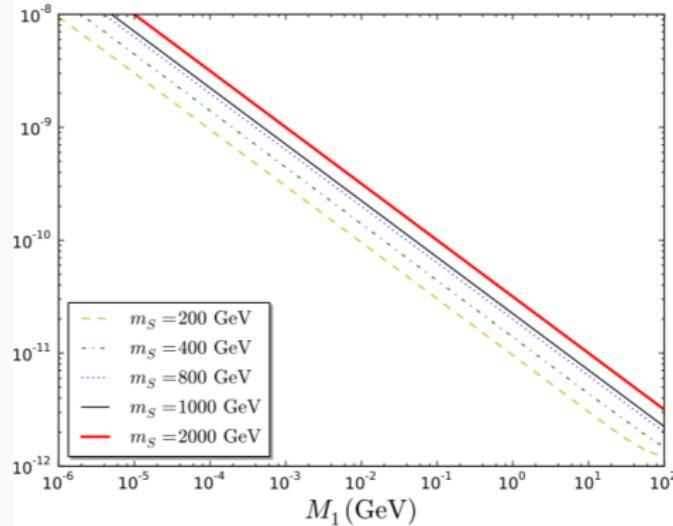
Scotogenic DM

FIMP Scenario

$$h_{i\alpha} \overline{L}_i \tilde{\eta} N_{R\alpha}$$

F. Molinaro, C. Yaguna, Ó. Zapata,
arXiv:1405.1259 [JCAP]

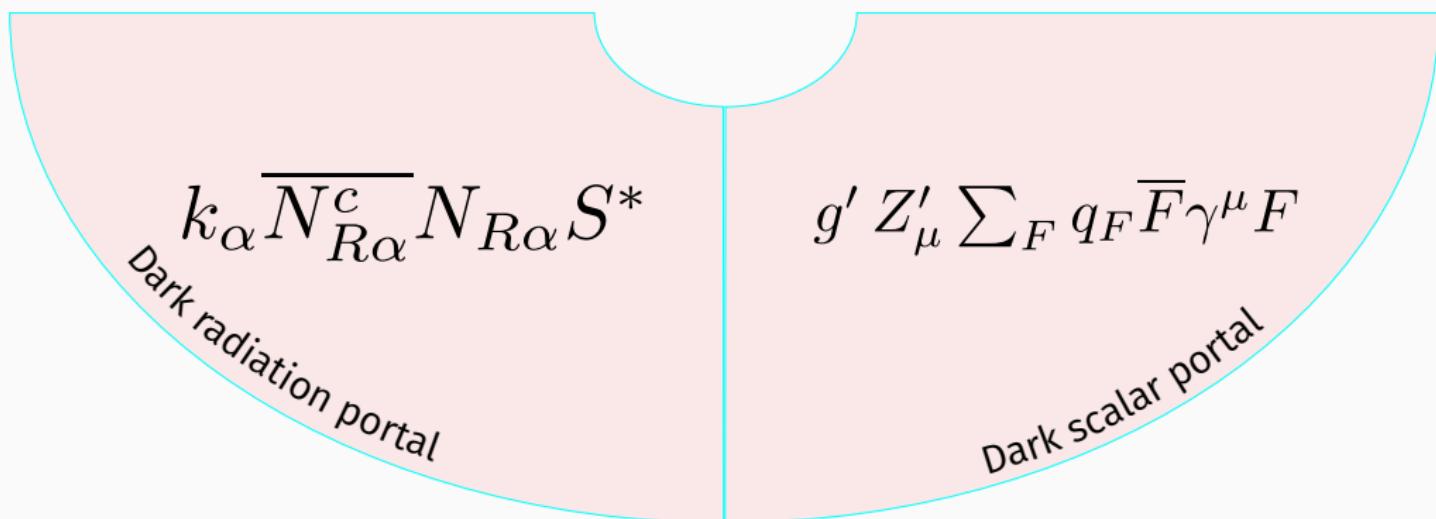
$$h_1 \sim h_{1\alpha}$$



$$\begin{aligned} l(\eta^+) &= 3 \times 10^5 \text{ cm} \left(\frac{M_1}{1 \text{ GeV}} \right) \left(\frac{1 \text{ TeV}}{m_{\eta^+}} \right)^2 \\ &\lesssim 3 \text{ meters} \left(\frac{1 \text{ TeV}}{m_{\eta^+}} \right)^2 \quad \text{for} \quad M_1 \lesssim 1 \text{ MeV} \end{aligned}$$

$$N_R N_R \rightarrow \nu_R \nu_R$$

$$\Delta N_{\text{eff}} \sim 0.2$$



(One-loop) Dirac neutrino masses

Small Dirac neutrino masses

To explain the **smallness** of Dirac neutrino masses choose $U(1)_X$ which:

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

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

Small Dirac neutrino masses

To explain the **smallness** of Dirac neutrino masses choose $U(1)_X$ which:

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

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

- Forbids Majorana term: $\nu_R \nu_R$

Small Dirac neutrino masses

To explain the **smallness** of Dirac neutrino masses choose $U(1)_X$ which:

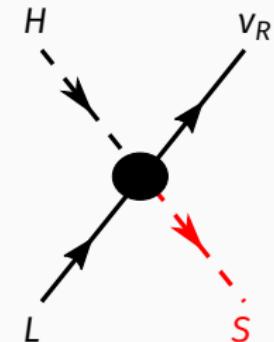
- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

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

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

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

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



Small Dirac neutrino masses

To explain the **smallness** of Dirac neutrino masses choose $U(1)_X$ which:

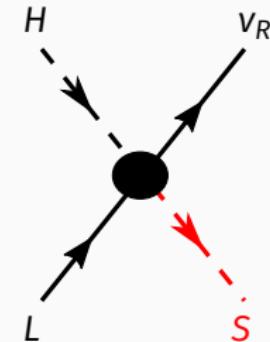
- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

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

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

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

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



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

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

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

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

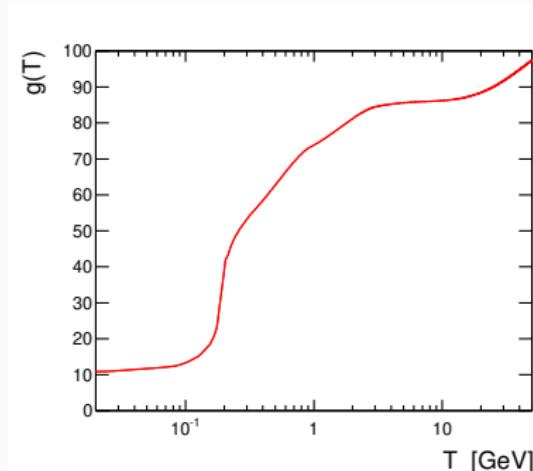
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left(\frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

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

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



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

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

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

$$s = 2pq(1 - \cos \theta),$$

$$f_{\nu_R}(k) = 1/(e^{k/T} + 1)$$

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

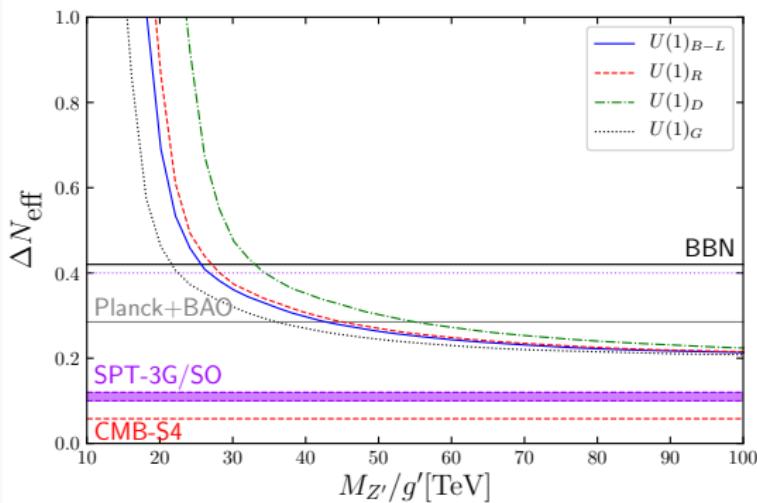
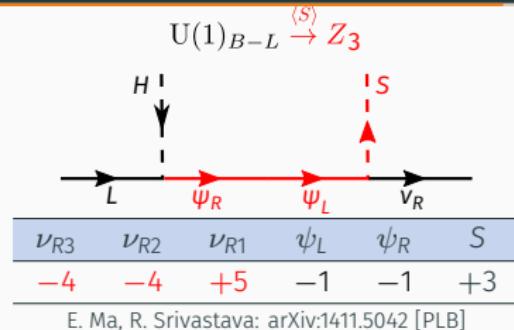
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left(\frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

with three right-handed neutrinos, the Hubble parameter is

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

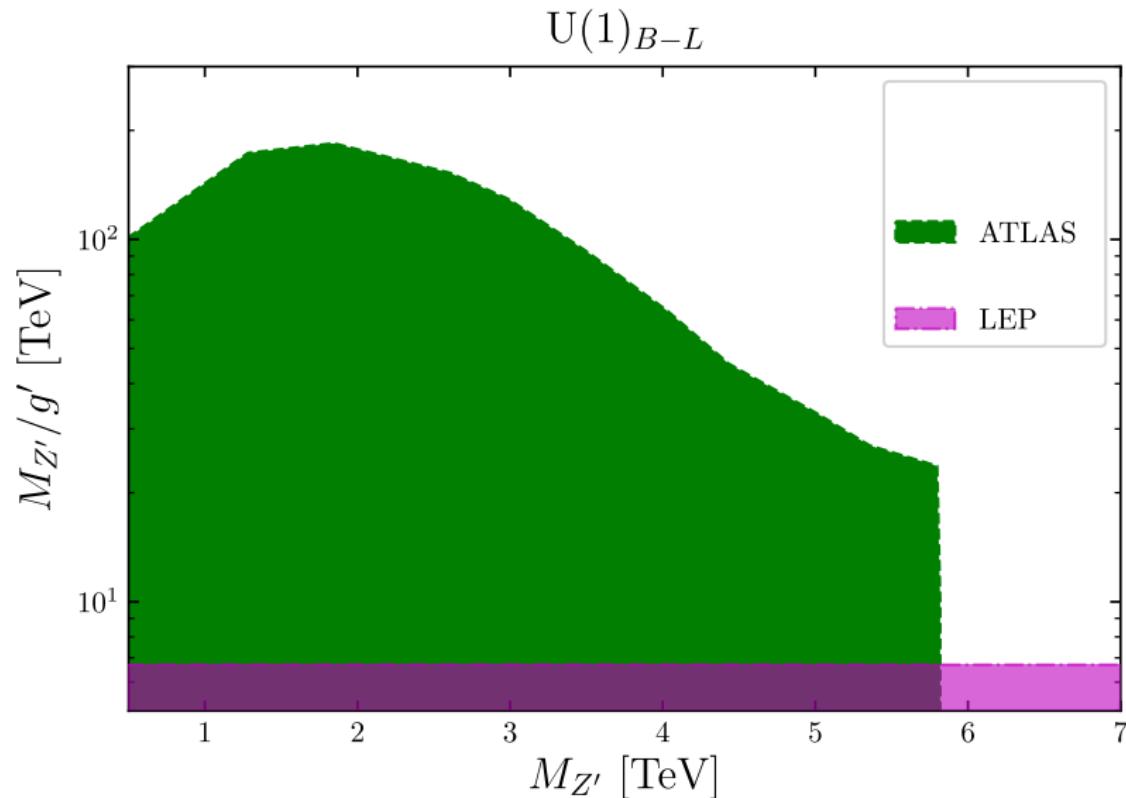
The right-handed neutrinos decouple when

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

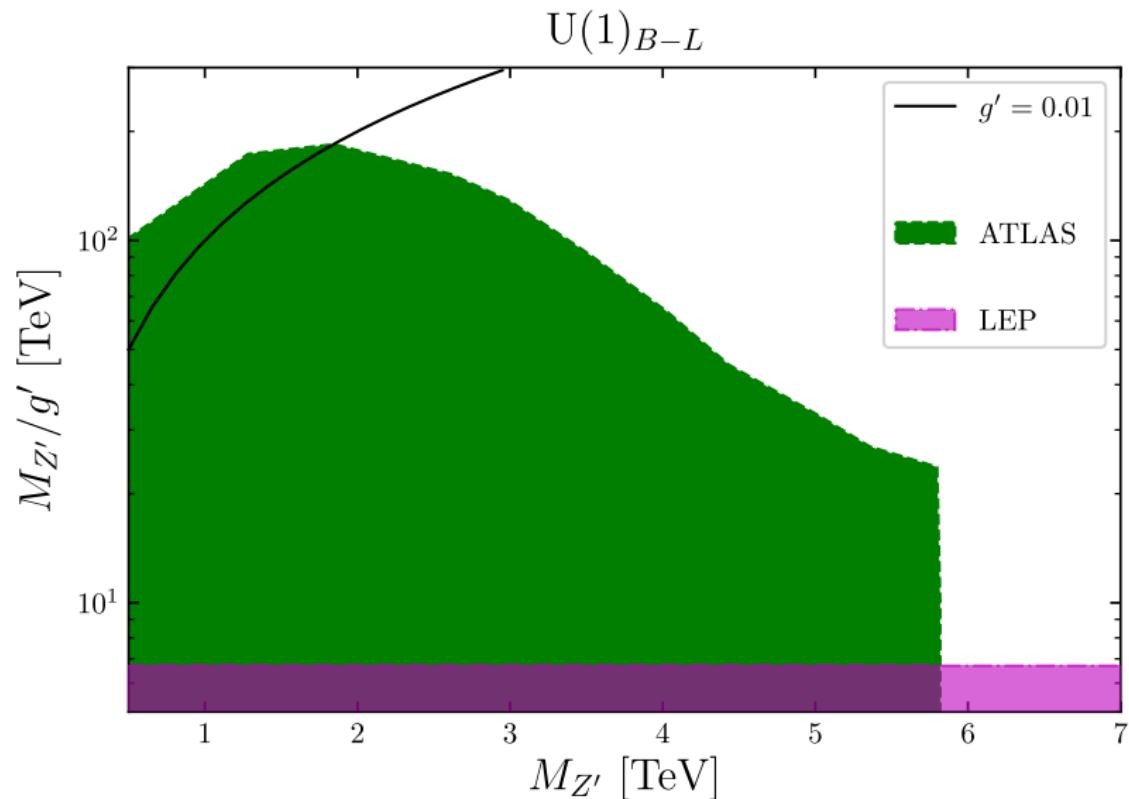


with J. Calle and Ó. Zapata, arXiv:1909.09574

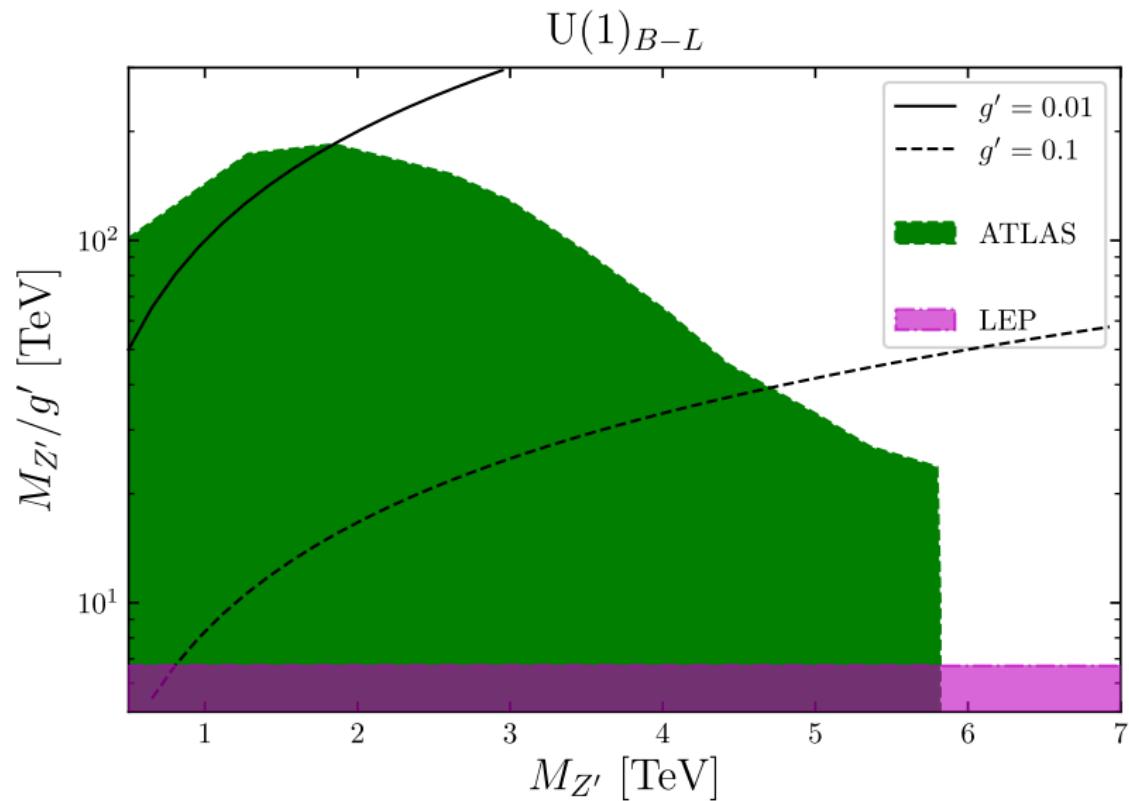
Same constraints as before



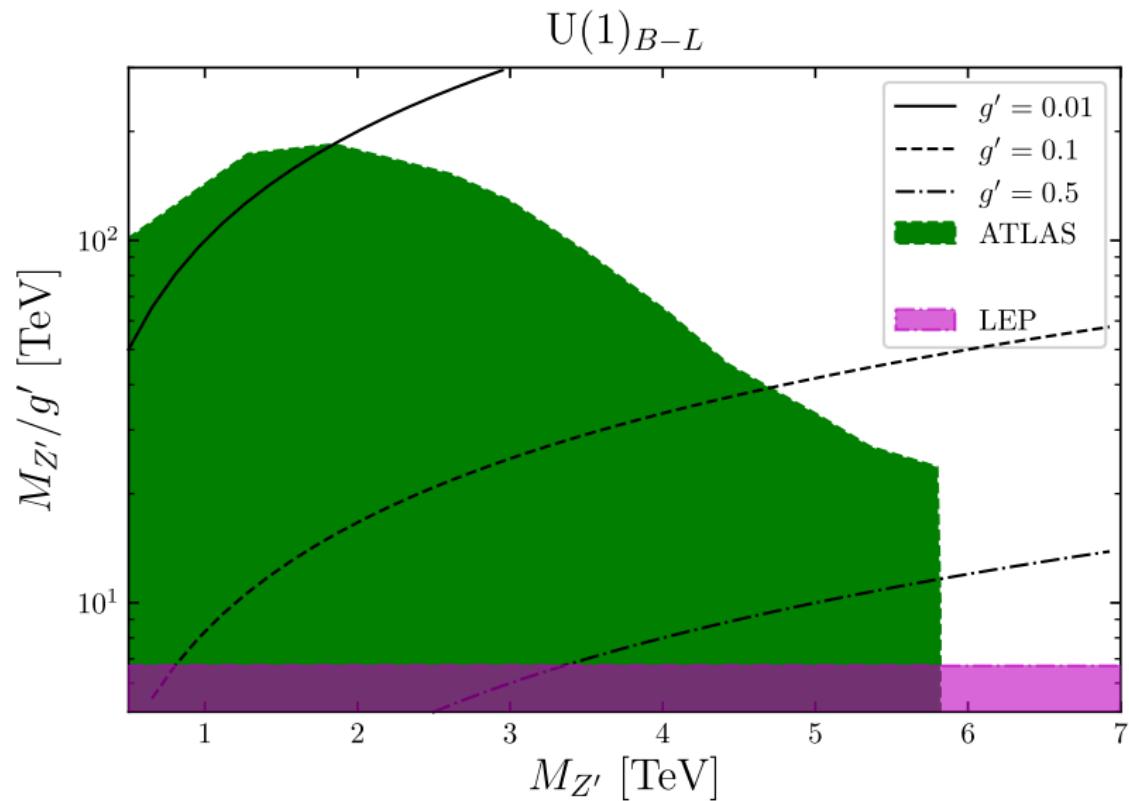
Same constraints as before



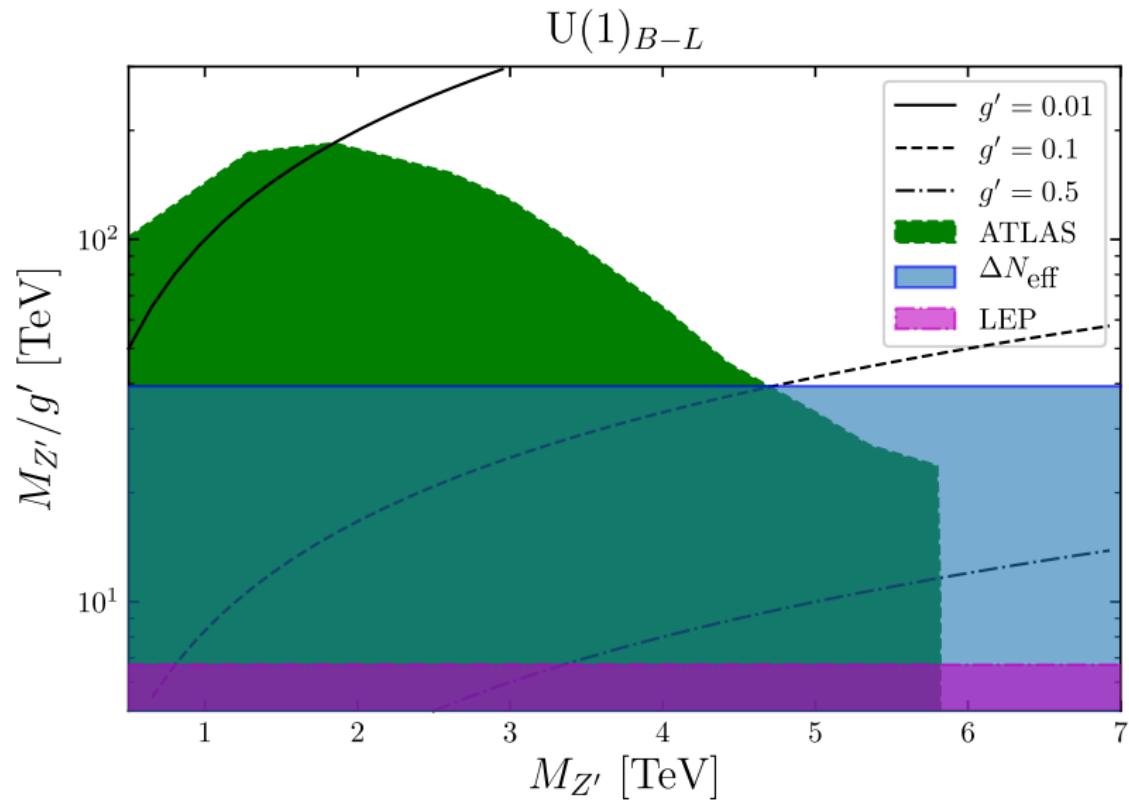
Same constraints as before



Same constraints as before



Same constraints as before



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

Thanks!