

Dark sectors

from (Dirac radiative) neutrino masses



UNIVERSIDAD DE ANTIOQUIA
1803

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[PDF: <http://bit.ly/comhep2019>]

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Focus on

[arXiv:1812.05523 \[PRD\]](https://arxiv.org/abs/1812.05523), [1906.09685 \[PRD\]](https://arxiv.org/abs/1906.09685), [1907.11938](https://arxiv.org/abs/1907.11938), [1909.09574](https://arxiv.org/abs/1909.09574)

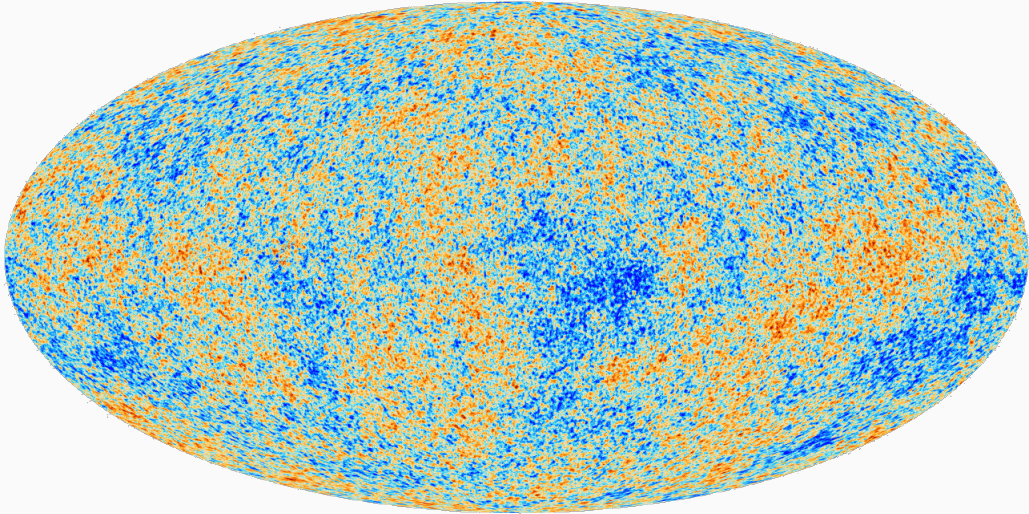
In collaboration with

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

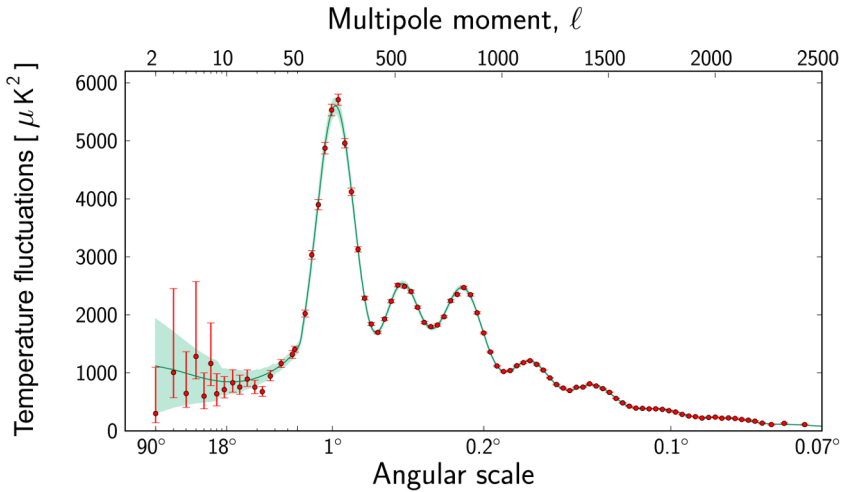


Λ CDM concordance model (with
baryonic effects)

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



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

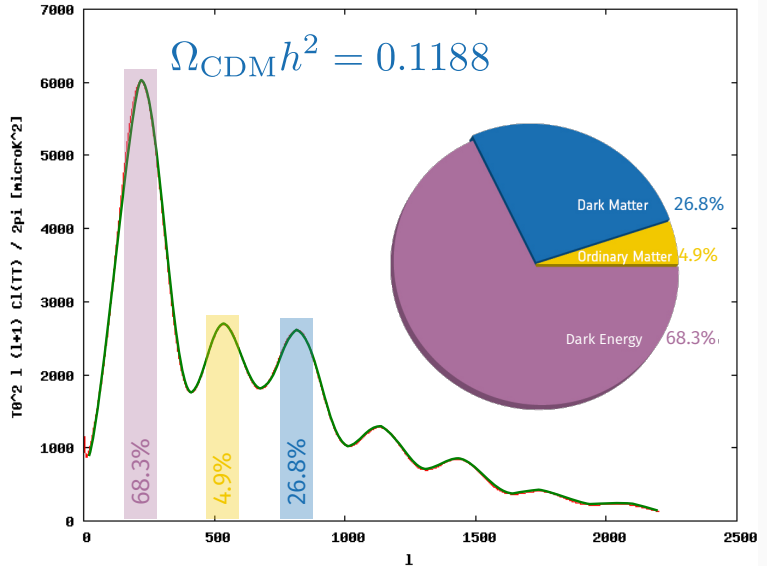


Planck's power spectrum of temperature fluctuations, ΔT , in the Cosmic Microwave Background. Credit: ESA and the Planck Collaboration

Λ CDM: $\Omega = 1$, $w = -1^\dagger$

Symbol	Value
$\Omega_b h^2$	0.022 30(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)

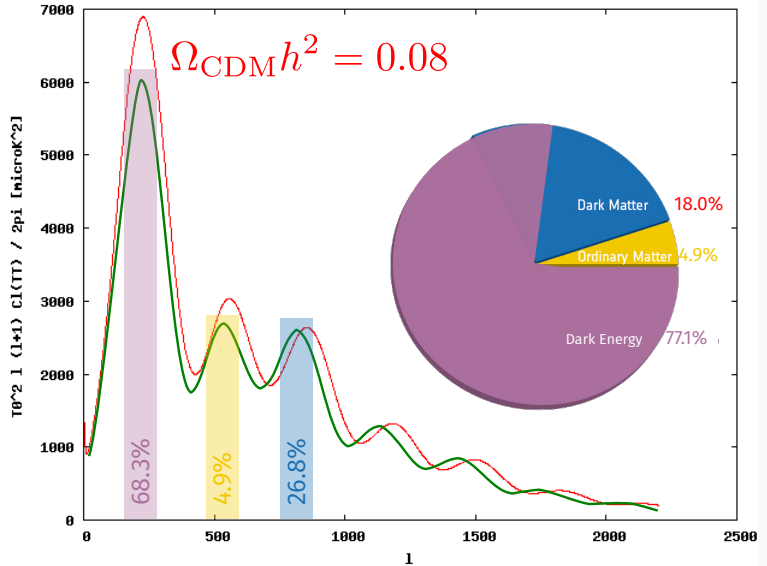
† Cosmological constant



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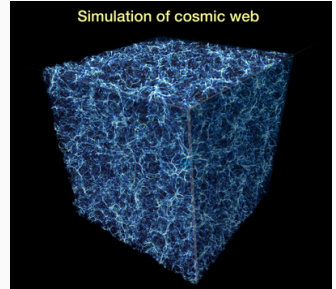
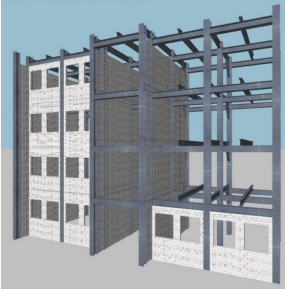
† Cosmological constant



Cosmic web

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

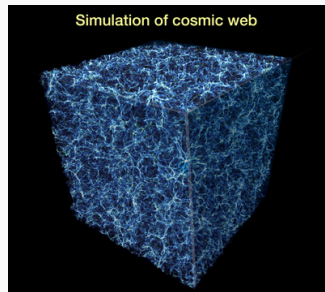
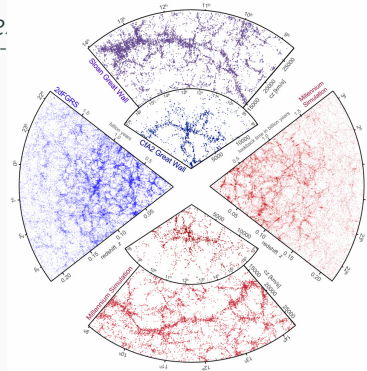
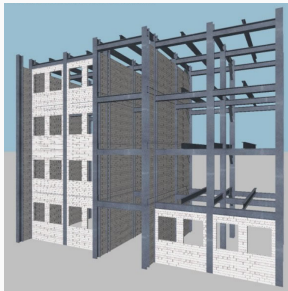
<https://phys.org/news/2018-06-years-scientists-account-universe.html>



Cosmic web

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

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

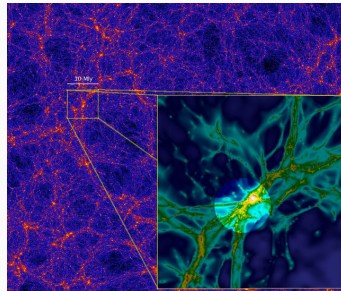
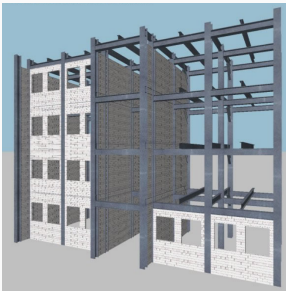


Galaxy redshift surveys vs large scale structure formation simulations: V. Springel, *et al* astro-ph/0604561 [Nature]

Cosmic web

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

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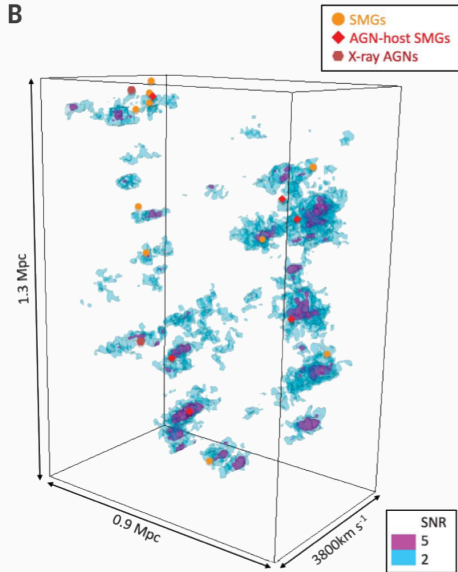
These great filaments are made largely of **dark matter** located in the space between galaxies and filled with 60% of the **primordial gas**!

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



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





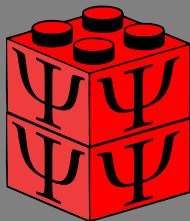


$$F_{\mu\nu} V^{\mu\nu}$$

Local $U(1)_D$

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

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



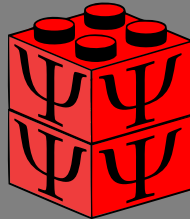


$$F_{\mu\nu} V^{\mu\nu}$$

Local $U(1)_D$

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

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



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.

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

with solution

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

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which satisfy

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

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

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

with solution

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

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 : $r \equiv e - 2l$

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

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

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

with solution

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

which satisfy

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

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

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

Since $f \rightarrow f' \rightarrow f/r$, without loss 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

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]
$(-\frac{2}{3}, -\frac{2}{3}, -\frac{4}{3}, -\frac{1}{3})$	 arXiv:1607.04029, S. Patra, W. Rodejohann, C. Yaguna [JHEP]
$(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, +2)$	 arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]
$(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7})$	 1808.03352, with N. Bernal, C. Yaguna, Ó. Zapata [PRD]
$(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3})$	  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]

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

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

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

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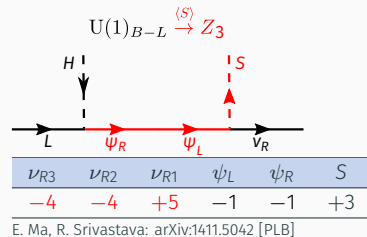
Or... combine known solutions

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$(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3})$	  In progress...  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

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



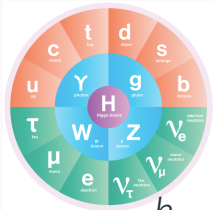
$$m_{\text{Majorana}}^\nu + = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H$$

Type-I
seesaw

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

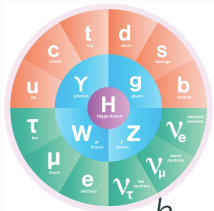
$$m_{\text{Majorana}}^\nu = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H \frac{S}{\Lambda}$$

Type-I arXiv:1808.03352

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

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

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

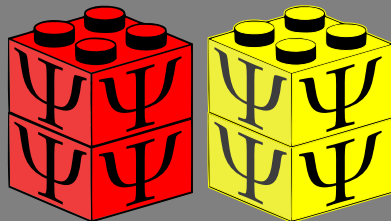


ν_{R3}	ν_{R2}	$\overline{\psi_{L1}}$	ψ_{R1}	ψ_{R2}	$\overline{\psi_{L2}}$	S	S'
-1	-1	$-\frac{10}{7}$	$-\frac{4}{7}$	$-\frac{2}{7}$	$\frac{9}{7}$	2	1

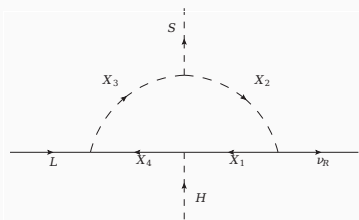
$$m_{\text{Majorana}}^\nu = \frac{h_\nu}{\Lambda} L \cdot H L \cdot H \frac{S}{\Lambda}$$

Type-I arXiv:1808.03352

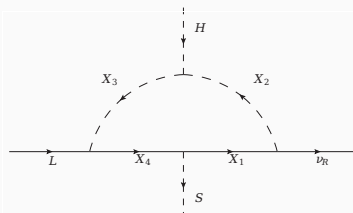
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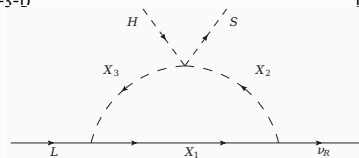
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



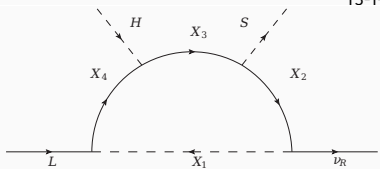
T1-3-D



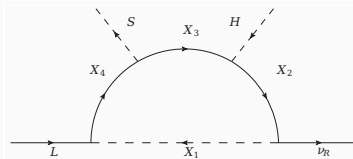
T1-3-E



T3-1-A



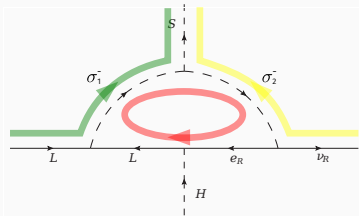
T1-2-A



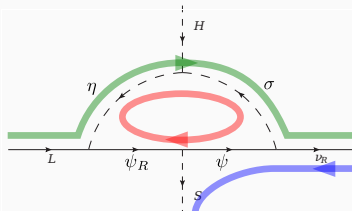
T1-2-B

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

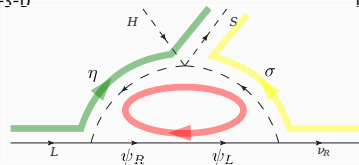
One loop topologies $U(1)_{B-L}$ only!



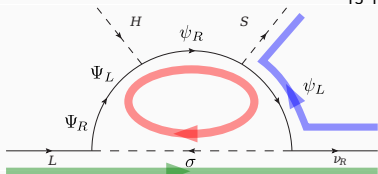
T1-3-D



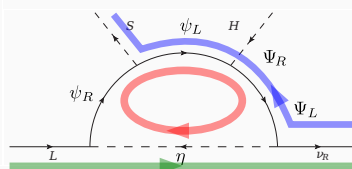
T1-3-E



T3-1-A



T1-2-A



T1-2-B

$\psi_{L,R}$ → Singlet fermions

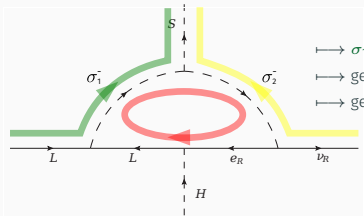
$\Psi_{L,R}$ → Vector-like doublet fermions

σ → Singlet scalar

η → 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]

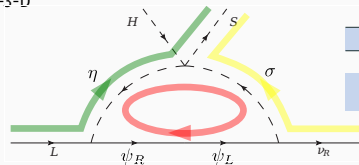


$$\rightarrow \sigma_1 = -2, \quad \sigma_2 = -5,$$

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

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

T1-3-D



T3-1-A

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

$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar

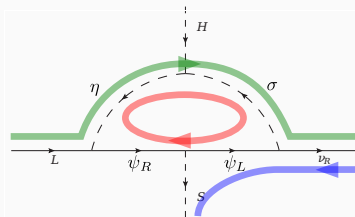
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	+4	+4	-5	-r	r	+3

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

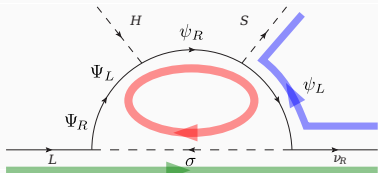
One loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



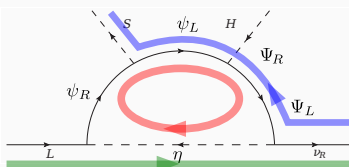
T1-3-E

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

- $\psi_{L,R}$ → Singlet fermions (quiral)
- $\Psi_{L,R}$ → Vector-like doublet fermions
- σ → Singlet scalar
- η → Doublet scalar



T1-2-A



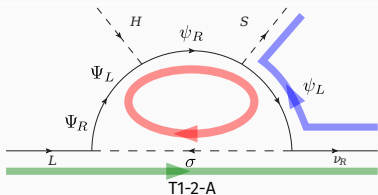
T1-2-B

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

- $\psi_{L,R}$ → Singlet fermions (quiral)
- $\Psi_{L,R}$ → Vector-like doublet fermions : 10/5
- σ → 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

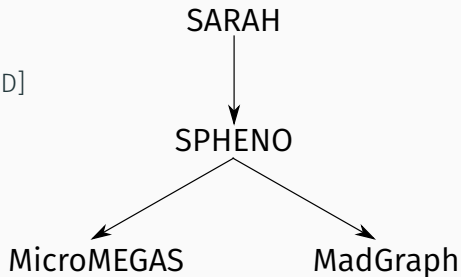
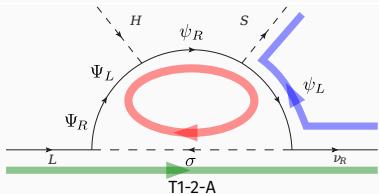
$$\sum_i f_i = 3$$

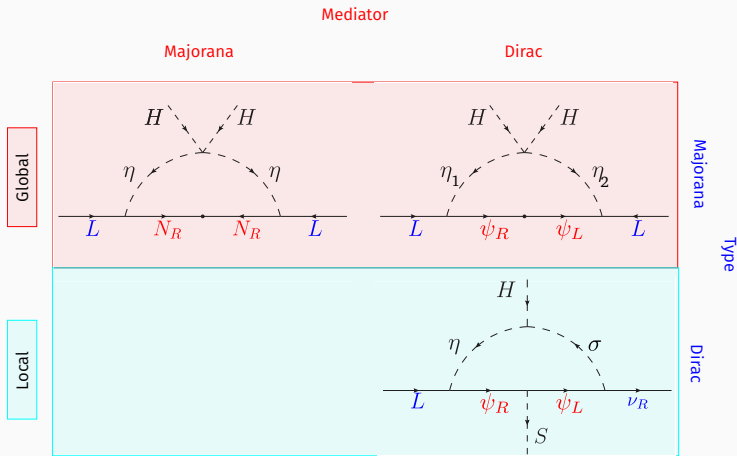
$$\sum_i f_i^3 = 3$$

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

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

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





For radiative Dirac models with only $U(1)_X$ see also:

arXiv:1812.01599, 1901.06402, 1902.07259, 1903.01477,

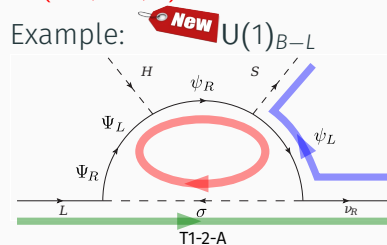
1904.07407, 1907.08630, 1910.09537 1909.00833 1907.11557,

1909.09574

$\mathcal{O}(50)$ new models mostly with

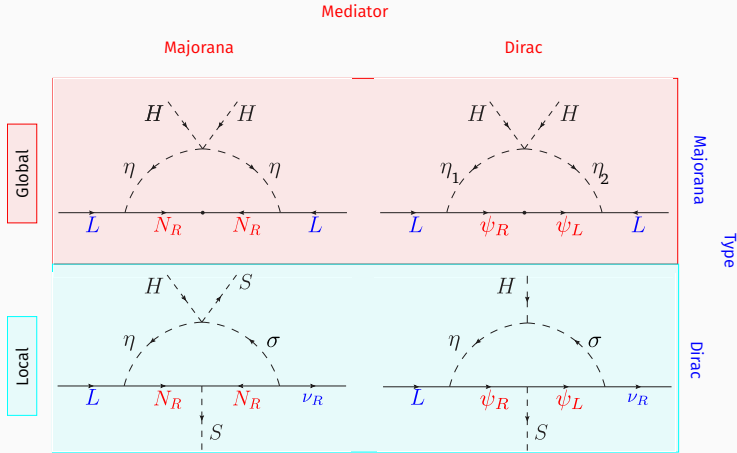
$\sim (-4, -4, 5)$

Example:



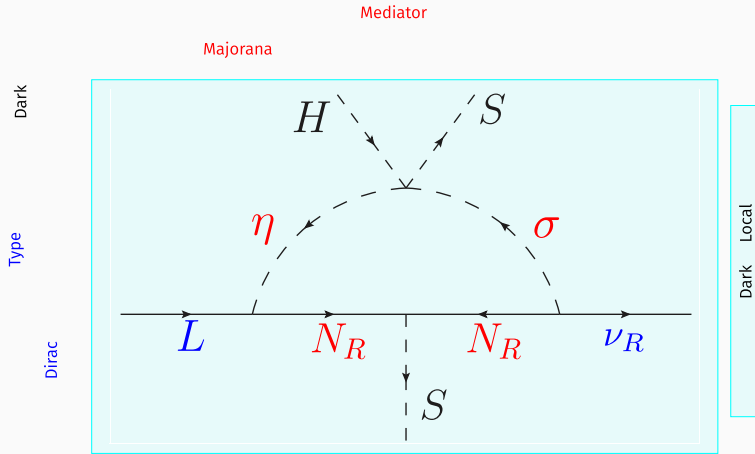
Pheno analysis with

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



Dirac Radiative Type-I seesaw with Majorana mediators

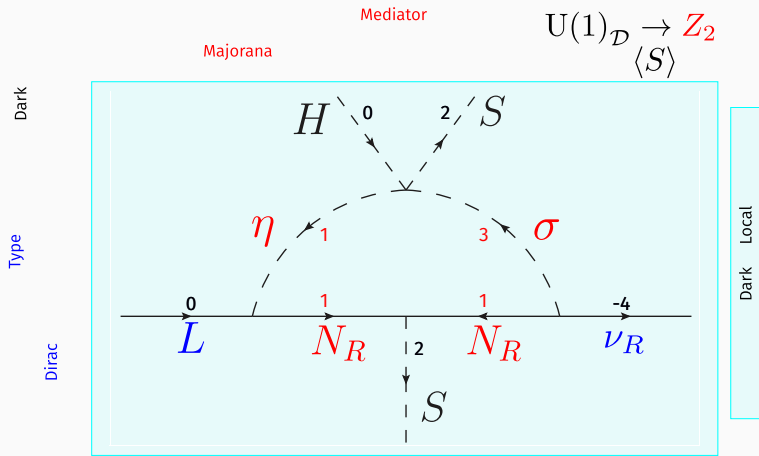
with J. Calle and Ó. Zapata, arXiv:1909.09574



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

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

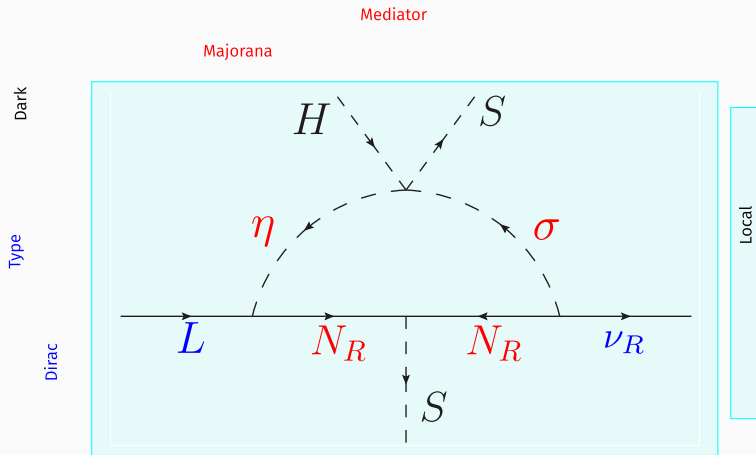
Dirac Radiative Type-I seesaw with Majorana mediators with J. Calle and Ó. Zapata, arXiv:1909.09574



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

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

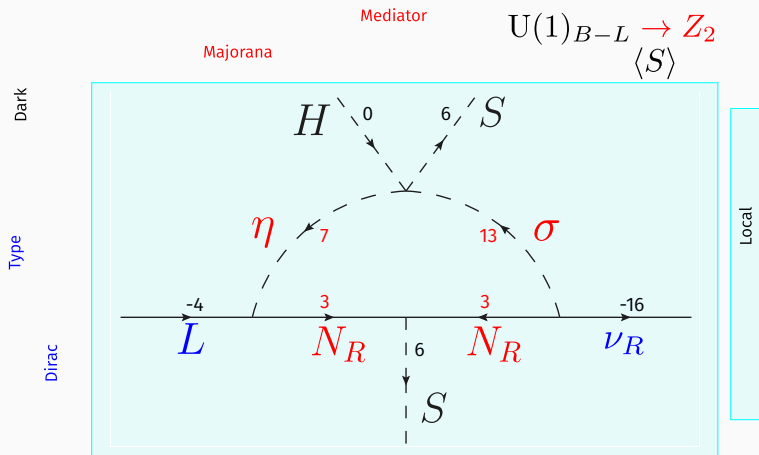
Dirac Radiative Type-I seesaw with Majorana mediators with J. Calle and Ó. Zapata, arXiv:1909.09574



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

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	$3/4^{15}$

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



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

Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
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	$3/4$

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

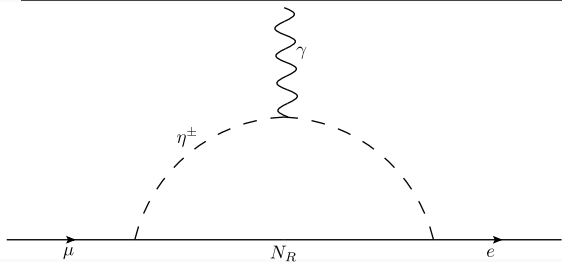
$F(\phi)$ denote the new fermions (scalars)

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

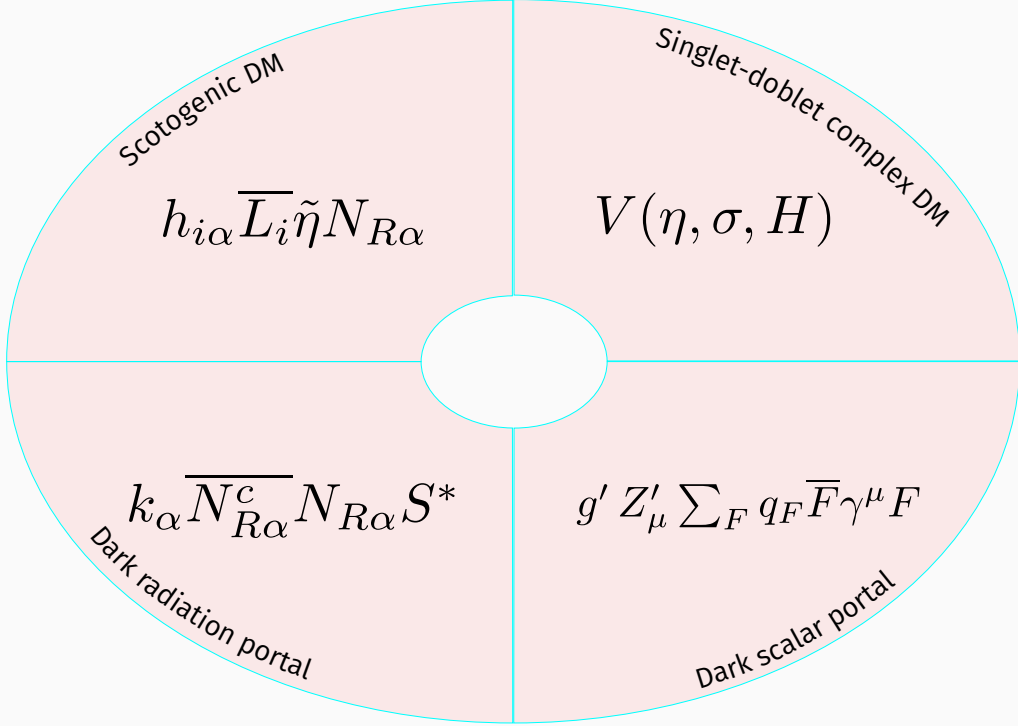
$$(\mathcal{M}_\nu)_{ij} = \frac{1}{32\pi^2} \frac{\lambda_8 v_S^2 v_H}{m_{\eta_R}^2 - m_{\sigma_R}^2} \sum_{\alpha=1}^3 h_{i\alpha} k_\alpha y_{j\alpha}^* \left[F\left(\frac{m_{\eta_R}^2}{M_{N\alpha}^2}\right) - F\left(\frac{m_{\sigma_R}^2}{M_{N\alpha}^2}\right) \right] + (R \rightarrow l),$$

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

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

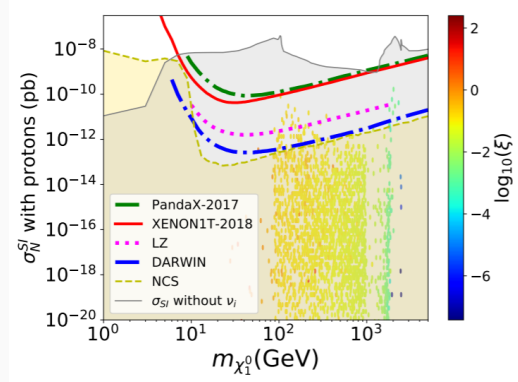
A. Ibarra, C. Yaguna, Ó. Zapata,
arXiv:1601.01163 [PRD]

Scotogenic DM

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

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

with A. Rivera, arXiv:1907.11938



$$(\chi_1^0 \ \chi_2^0)^T = R(N_R \ \Sigma)^T$$

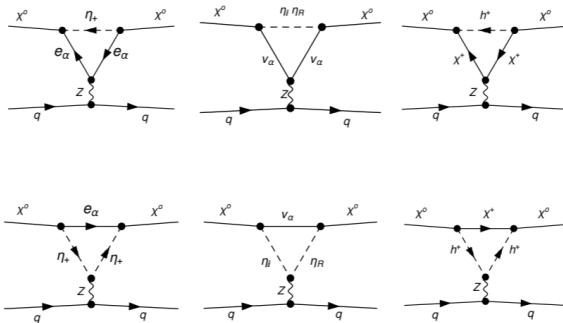
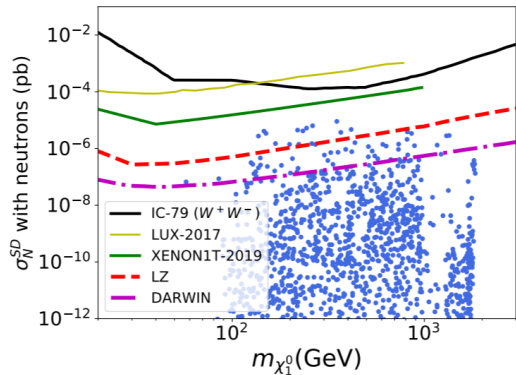
$$\xi = \frac{|M_\Sigma - m_{\chi_1^0}|}{m_{\chi_1^0}}$$

Scotogenic DM

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

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

with A. Rivera, arXiv:1907.11938



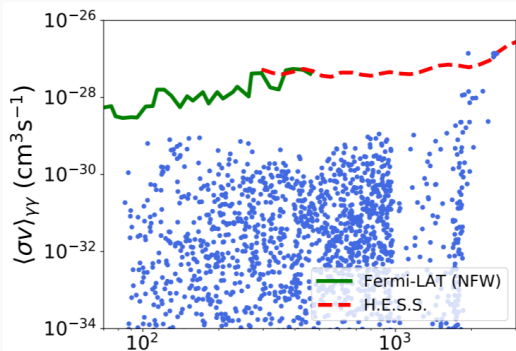
Scotogenic DM

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

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

with A. Rivera, arXiv:1907.11938

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



$$\mathcal{B} = \frac{\sqrt{2}\alpha m^2 \sin^2(\alpha) Y_{\tilde{g}}^2 (\sin(\delta) + \cos(\delta))^2}{\pi} \left[\frac{M_{H^\pm}^2 C_0 (0, -m^2, m^2; M_{H^\pm}^2, M_{H^\pm}^2, M_{\tilde{g}}^2)}{M_{H^\pm}^2 - M_{\tilde{g}}^2} \right. \\ - \frac{M_{\tilde{t}} (-2m M_{H^\pm}^2 - M_{\tilde{t}} M_{H^\pm}^2 + m^2 M_{\tilde{t}} + 2m M_{\tilde{g}}^2 + M_{\tilde{t}}^2) C_0 (0, -m^2, m^2; M_{\tilde{g}}^2, M_{\tilde{g}}^2, M_{H^\pm}^2)}{(M_{H^\pm}^2 - M_{\tilde{g}}^2) (M_{H^\pm}^2 + m^2 - M_{\tilde{g}}^2)} \\ + \frac{2M_{\tilde{t}} (m + M_{\tilde{t}}) C_0 (0, 0, 4m^2; M_{\tilde{g}}^2, M_{\tilde{g}}^2, M_{\tilde{t}}^2)}{-M_{H^\pm}^2 - m^2 + M_{\tilde{g}}^2} \left. \right] \\ + \frac{\alpha m^2 \sin(\alpha) \cos(\alpha) Y_{\tilde{g}}^2}{\pi} \left[- \frac{m_{\tilde{c}}^2 C_0 (0, -m^2, m^2; m_{\tilde{c}}^2, m_{\tilde{c}}^2, m_{\tilde{g}}^2)}{m_{\tilde{c}}^2 - m_{\tilde{g}}^2} \right. \\ + \frac{m_{\tilde{c}}^2 (m_{\tilde{c}}^2 + m^2 - m_{\tilde{g}}^2) C_0 (0, -m^2, m^2; m_{\tilde{c}}^2, m_{\tilde{c}}^2, m_{\tilde{g}}^2)}{(m_{\tilde{c}}^2 - m_{\tilde{g}}^2) (-m_{\tilde{c}}^2 + m^2 + m_{\tilde{g}}^2)} + \frac{2m_{\tilde{c}}^2 C_0 (0, 0, 4m^2; m_{\tilde{c}}^2, m_{\tilde{c}}^2, m_{\tilde{g}}^2)}{-m_{\tilde{c}}^2 + m^2 + m_{\tilde{g}}^2} \left. \right] \\ + \frac{\alpha m^2 \cos^2(\alpha) Y_{\tilde{g}}^2}{2\sqrt{2}\pi} \left[\frac{m_{\tilde{u}}^2 C_0 (0, -m^2, m^2; m_{\tilde{u}}^2, m_{\tilde{u}}^2, m_{\tilde{g}}^2)}{m_{\tilde{u}}^2 - m_{\tilde{g}}^2} \right. \\ - \frac{m_{\tilde{u}}^2 (m_{\tilde{u}}^2 + m^2 - m_{\tilde{g}}^2) C_0 (0, -m^2, m^2; m_{\tilde{u}}^2, m_{\tilde{u}}^2, m_{\tilde{g}}^2)}{(m_{\tilde{u}}^2 - m_{\tilde{g}}^2) (-m_{\tilde{u}}^2 + m^2 + m_{\tilde{g}}^2)} - \frac{2m_{\tilde{u}}^2 C_0 (0, 0, 4m^2; m_{\tilde{u}}^2, m_{\tilde{u}}^2, m_{\tilde{g}}^2)}{-m_{\tilde{u}}^2 + m^2 + m_{\tilde{g}}^2} \left. \right] \\ + \frac{\sqrt{2}\alpha m^2 \sin^2(\alpha) Y_{\tilde{g}}^2}{2\pi} \left[\frac{m_{\tilde{d}}^2 C_0 (0, -m^2, m^2; m_{\tilde{d}}^2, m_{\tilde{d}}^2, m_{\tilde{g}}^2)}{m_{\tilde{d}}^2 - m_{\tilde{g}}^2} \right. \\ - \frac{m_{\tilde{d}}^2 (m_{\tilde{d}}^2 + m^2 - m_{\tilde{g}}^2) C_0 (0, -m^2, m^2; m_{\tilde{d}}^2, m_{\tilde{d}}^2, m_{\tilde{g}}^2)}{(m_{\tilde{d}}^2 - m_{\tilde{g}}^2) (-m_{\tilde{d}}^2 + m^2 + m_{\tilde{g}}^2)} - \frac{2m_{\tilde{d}}^2 C_0 (0, 0, 4m^2; m_{\tilde{d}}^2, m_{\tilde{d}}^2, m_{\tilde{g}}^2)}{-m_{\tilde{d}}^2 + m^2 + m_{\tilde{g}}^2} \left. \right] \\ - \frac{8\sqrt{2}\alpha m^2 \cos^2(\alpha) M_{\tilde{g}}^2}{\pi (M_{\tilde{g}}^2 - M_{\tilde{H}^\pm}^2) (4m_{\tilde{g}}^2 + m_{\tilde{H}^\pm}^2) (m^2 - M_{\tilde{g}}^2 + M_{\tilde{H}^\pm}^2) (m^2 + M_{\tilde{g}}^2 - M_{\tilde{H}^\pm}^2)} \\ \left[4(m^2 - M_{\tilde{H}^\pm}^2) (M_{\tilde{g}}^2 - M_{\tilde{H}^\pm}^2) (m^2 - M_{\tilde{g}}^2 + M_{\tilde{H}^\pm}^2) C_0 (0, 0, 4m^2; M_{\tilde{H}^\pm}^2, M_{\tilde{H}^\pm}^2, M_{\tilde{g}}^2) \right. \\ + 2M_{\tilde{t}} (2m - M_{\tilde{t}}) (M_{\tilde{g}}^2 - M_{\tilde{H}^\pm}^2) (m^2 + M_{\tilde{g}}^2 - M_{\tilde{H}^\pm}^2) C_0 (0, 0, 4m^2; M_{\tilde{g}}^2, M_{\tilde{g}}^2, M_{\tilde{t}}^2) \\ - (m^2 - M_{\tilde{g}}^2 + M_{\tilde{H}^\pm}^2) (-M_{\tilde{H}^\pm}^2 (m^2 + M_{\tilde{g}}^2) - 4m M_{\tilde{t}} (m^2 + M_{\tilde{g}}^2 - M_{\tilde{H}^\pm}^2) + 4M_{\tilde{t}}^2 + M_{\tilde{H}^\pm}^2) \\ \left. C_0 (0, -m^2, m^2; M_{\tilde{H}^\pm}^2, M_{\tilde{H}^\pm}^2, M_{\tilde{g}}^2) - M_{\tilde{t}} (m^2 + M_{\tilde{g}}^2 - M_{\tilde{H}^\pm}^2) (4m^3 - 3m^2 M_{\tilde{t}} + M_{\tilde{g}}^2 - M_{\tilde{t}} M_{\tilde{H}^\pm}^2) \right. \\ \left. C_0 (0, -m^2, m^2; M_{\tilde{g}}^2, M_{\tilde{g}}^2, M_{\tilde{H}^\pm}^2) \right].$$

$m_{\chi_1^0}$ (GeV)

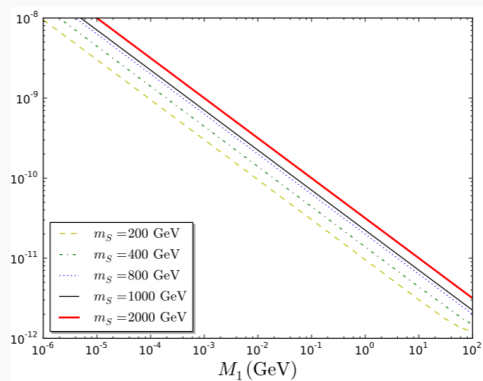
Scotogenic DM

FIMP Scenario

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

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

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

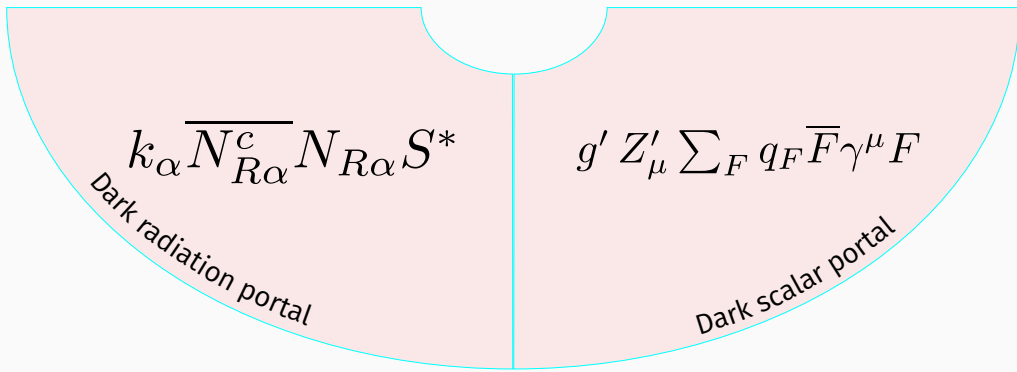


$$l(\eta^+) = 3 \times 10^5 \text{ cm} \left(\frac{M_1}{1 \text{ GeV}} \right) \left(\frac{1 \text{ TeV}}{m_{\eta^+}} \right)^2$$

$$\lesssim 3 \text{ meters} \left(\frac{1 \text{ TeV}}{m_{\eta^+}} \right)^2 \quad \text{for} \quad M_1 \lesssim 1 \text{ MeV}$$

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

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



(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 ($Y(H) = +1/2$)

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

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- Forbids Majorana term: $\nu_R \nu_R$

Small Dirac neutrino masses

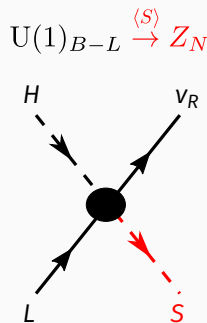
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- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$:

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



Small Dirac neutrino masses

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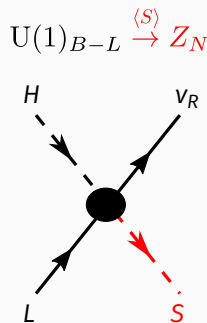
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$$\mathcal{L}_{5-D} = \frac{h_\nu}{\Lambda} (\nu_R)^\dagger L \cdot H S + \text{h.c.}$$

- 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)



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

$$\Gamma_{\nu_R}(T) = n_{\nu_R}(T) \sum_f \langle \sigma_f(\nu_R \bar{\nu}_R \rightarrow \bar{f} f) v \rangle$$

$$= \sum_f \frac{g_{\nu_R}^2}{n_{\nu_R}} \int \frac{d^3 p}{(2\pi)^3} \frac{d^3 q}{(2\pi)^3} f_{\nu_R}(p) f_{\nu_R}(q) \sigma_f(s) (1 - \cos \theta),$$

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

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

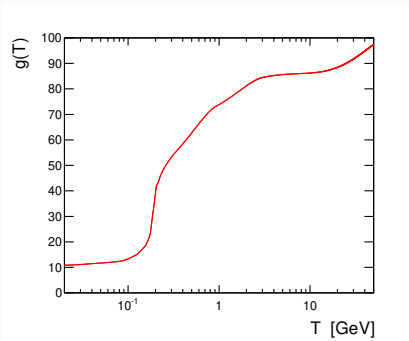
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left(\frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

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

$$\Gamma_{\nu_R}(T) = n_{\nu_R}(T) \sum_f \langle \sigma_f(\nu_R \bar{\nu}_R \rightarrow f\bar{f}) v \rangle$$

$$= \sum_f \frac{g_{\nu_R}^2}{n_{\nu_R}} \int \frac{d^3 p}{(2\pi)^3} \frac{d^3 q}{(2\pi)^3} f_{\nu_R}(p) f_{\nu_R}(q) \sigma_f(s) (1 - \cos \theta),$$

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

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

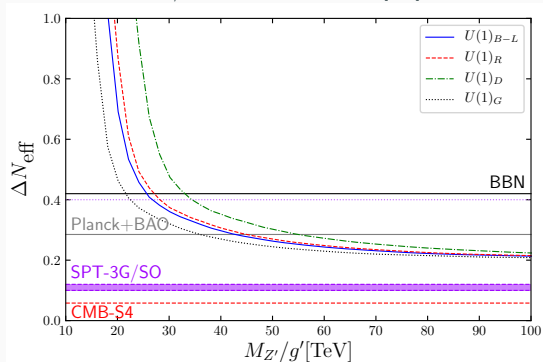
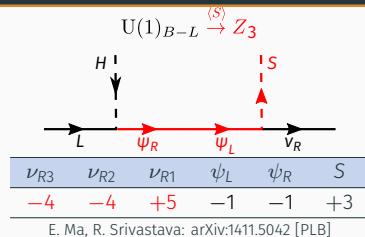
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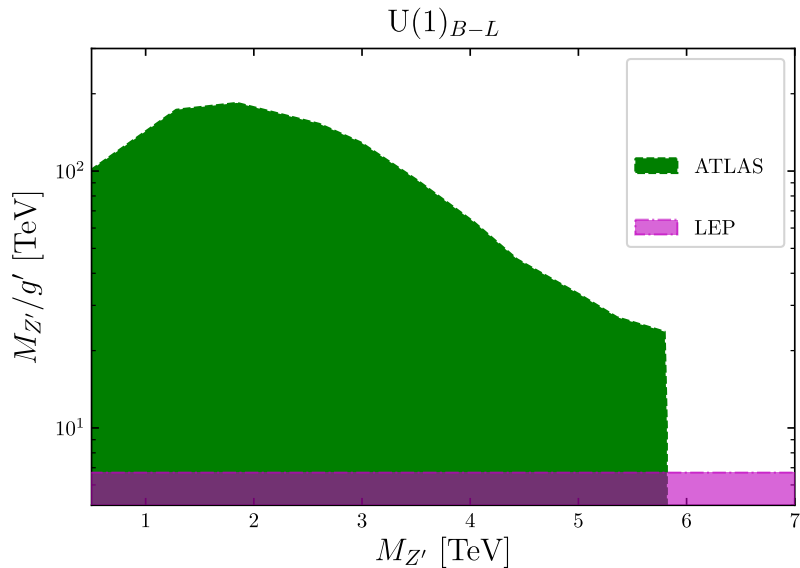
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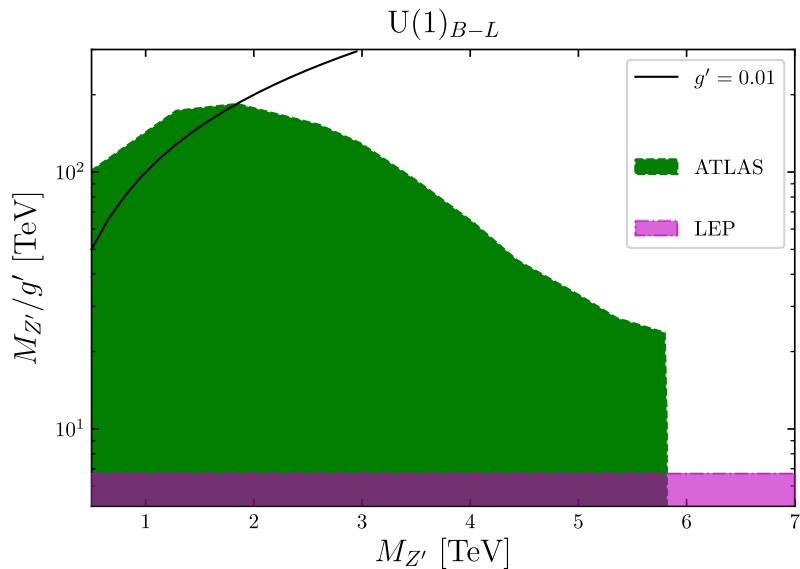


with J. Calle and Ó. Zapata, arXiv:1909.09574

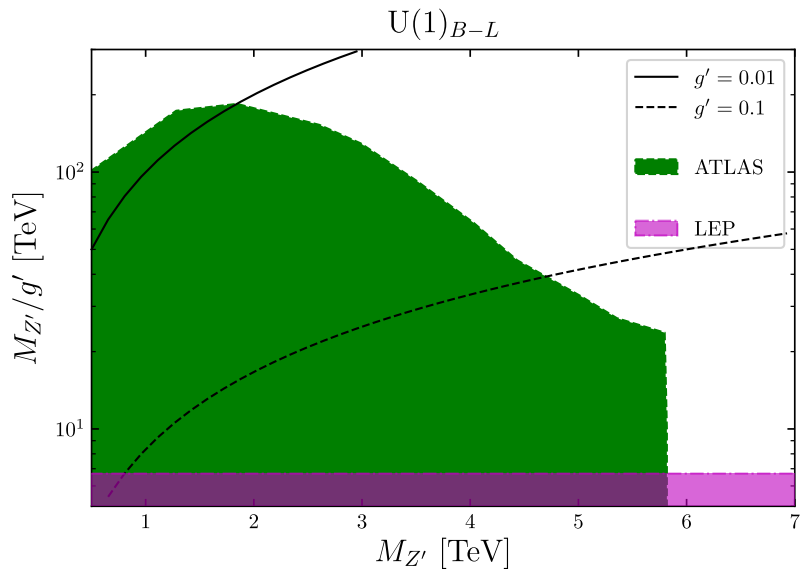
Same constraints as before



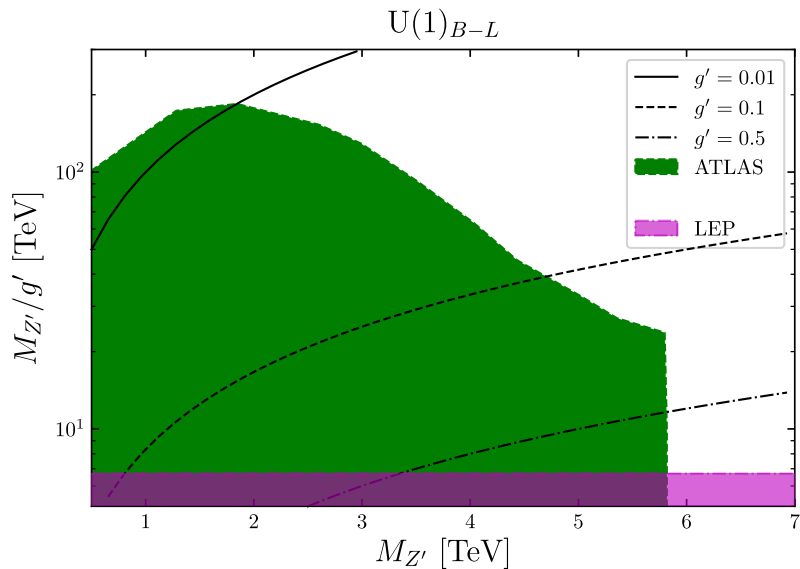
Same constraints as before



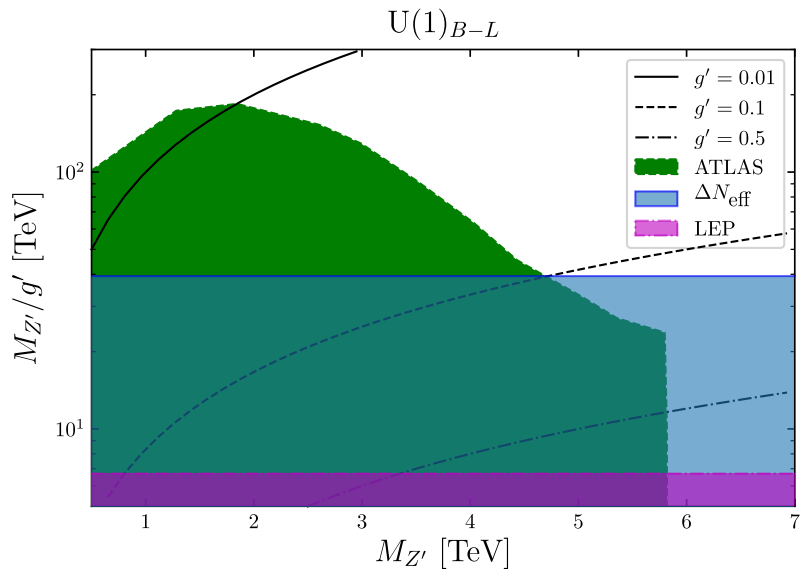
Same constraints as before



Same constraints as before



Same constraints as before



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!