Dirac neutrino masses

with dark Majorana mediatiors

Diego Restrepo

Oct 24, 2019 - Dark Universe Workshop
[PDF: http://bit.ly/darkuniverseworkshop]

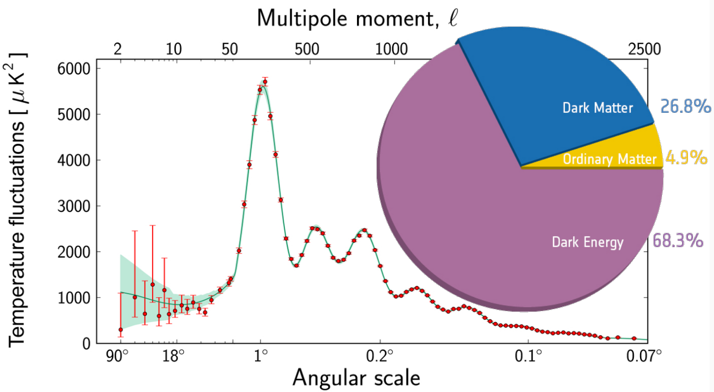
Instituto de Física
Universidad de Antioquia
Phenomenology Group
http://gfif.udea.edu.co

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)

ΛCDM: $\Omega = 1$, $w = -1$†

Symbol	Value
$\Omega_b h^2$	0.022 30(14)
$\Omega_{CDM} h^2$	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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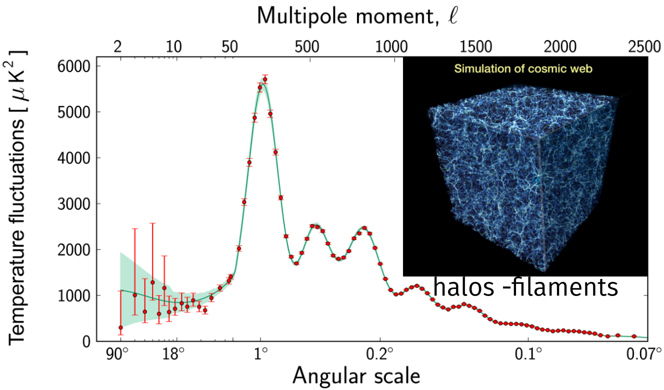
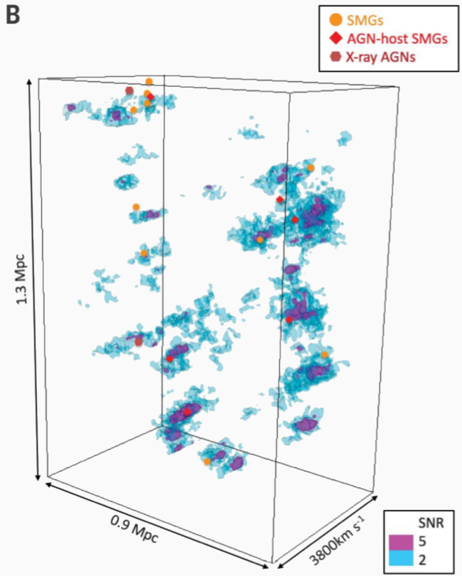


Three-dimensional pictures of Lyα filaments



The 3D distribution of Lyα filaments shown with

signal-to-noise ratio (SNR) > 5

signal-to-noise ratio (SNR) > 2

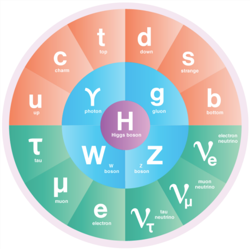
H. Umehata *et al*, Science **366**, 97, 4 Oct 2019

Dark 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


t
top
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Higgs boson
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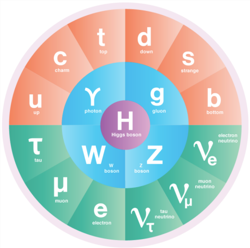
ν_τ
tau neutrino


t
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e
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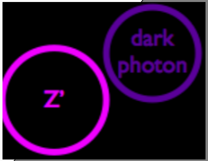
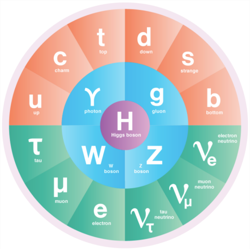
tau
neutrino


dark
photon
Z'

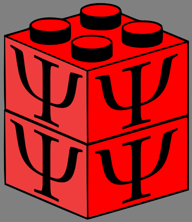
Local $U(1)_{\mathcal{D}}$

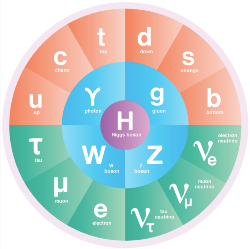


$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + i\overline{\psi}\not{\mathcal{D}}\psi - m\overline{\psi}\psi, .$$

Relic abundance $\psi\overline{\psi} \to \gamma_{\mathcal{D}}\gamma_{\mathcal{D}}$

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





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

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

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + i\overline{\psi}\not{\mathcal{D}}\psi - m\overline{\psi}\psi, ..$$

Relic abundance $\psi\overline{\psi} \to \gamma_{\mathcal{D}}\gamma_{\mathcal{D}}$

Explain also small neutrino masses

In the following discussion we use the following doublets

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

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

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

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.

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 $\sum n_\alpha^3 = -3$

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \cdots)$	Ref
$(-1, -1, -1)$	hep-ph/0611205, S. Khalil [JPG]
$(-4, -4, +5)$	arXiv:0706.0473, Montero, V. Pleitez [PLB]
$\left(-\frac{2}{3}, -\frac{2}{3}, -\frac{4}{3}, -\frac{1}{3}\right)$	arXiv:1607.04029, S. Patra , W. Rodejohann, C. Yaguna [JHEP]
$\left(-\frac{8}{5}, -\frac{8}{5}, -\frac{2}{5}, -\frac{7}{5}, +2\right)$	arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]
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$\left(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3}\right)$	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$\cdots$ combine known solutions with $\sum n_\alpha = 0$ and $\sum n_\alpha^3 = 0$

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \cdots)$	Ref
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https://en.wikipedia.org/wiki/Sums_of_three_cubes

Only known integer solutions for -3 (1953)

September 2019:

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

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Or$\cdots$ combine known solutions

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$\left(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3}\right)$	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.

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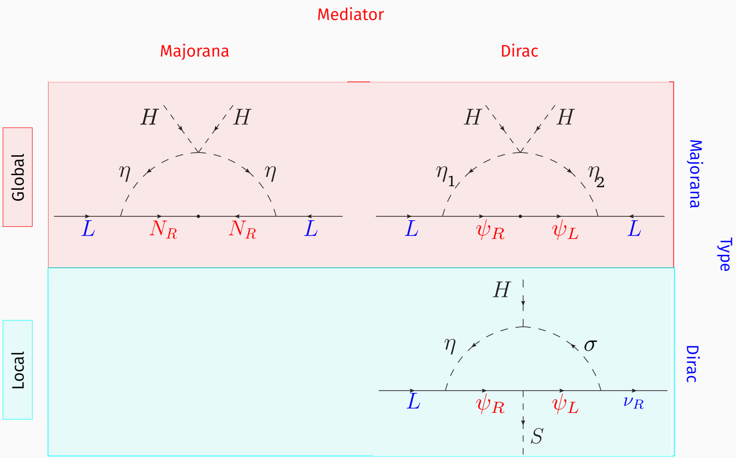
Radiative Type-I seesaw →Local: only $U(1)_{B-L}$! arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]

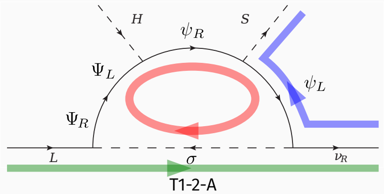


For radiative Dirac models with only $U(1)_X$ see also:

arXiv:1812.01599, 1901.06402, 1902.07259, 1903.01477, 1904.07407, 1907.08630, 1907.11557, 1910.09537

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

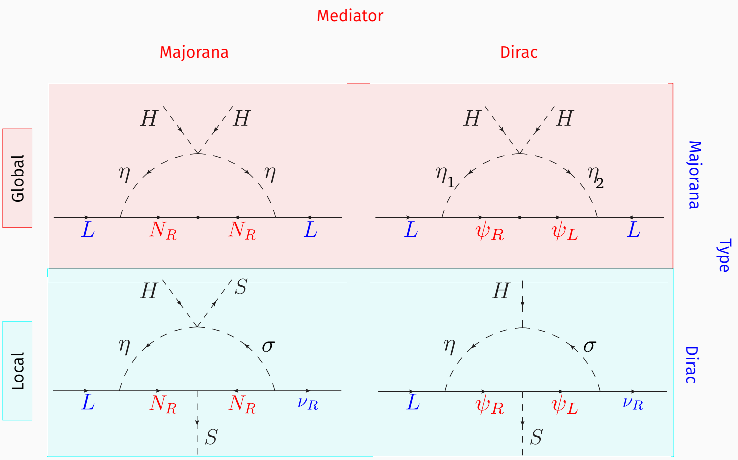
Example: New $U(1)_{B-L}$



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



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

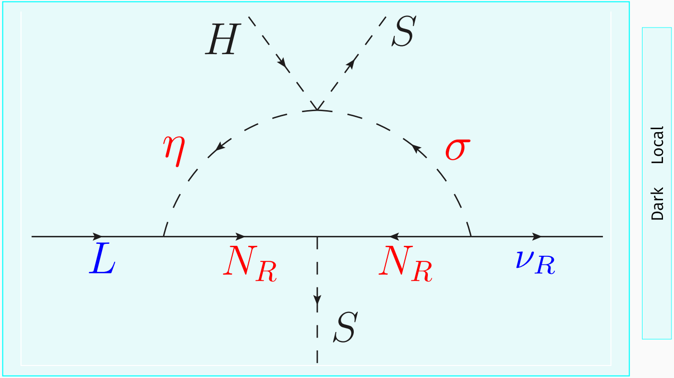
Mediator

Majorana

Dark

Type

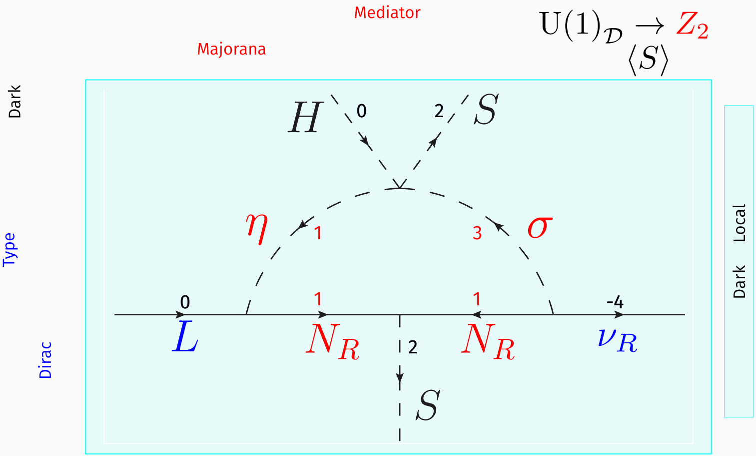
Dirac



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

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

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



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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

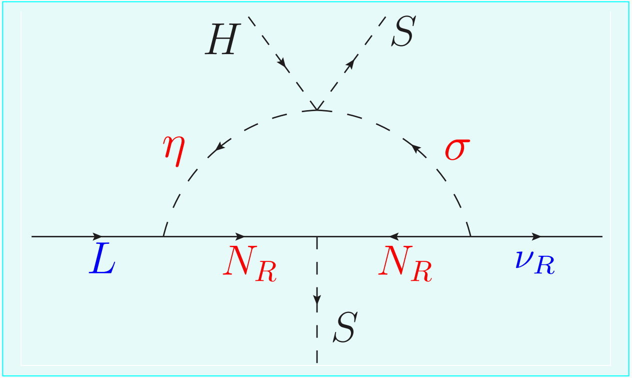
Mediator

Majorana

Dark

Type

Dirac



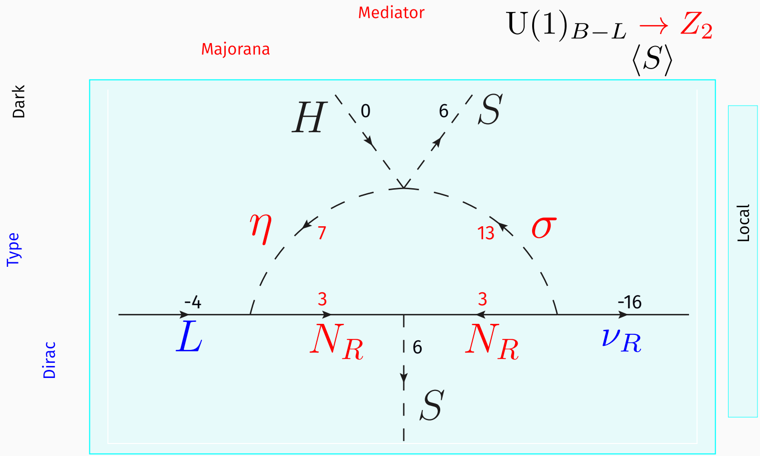
Local

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

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	$3/4$

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

$$\mathrm{U}(1)_{B-L} \to Z_2 \quad \langle S \rangle$$



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

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	$3/4$

The model

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

F (ϕ) denote the new fermions (scalars)

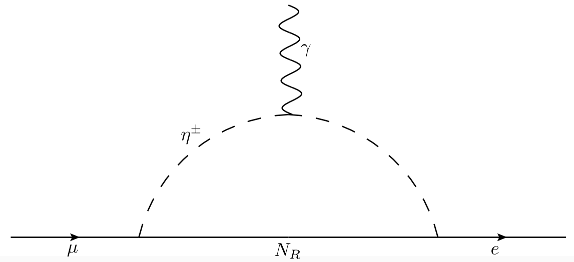
$$\begin{aligned} \mathcal{V}(H, S, \eta, \sigma) =& V(H) + V(S) + V(\eta) + V(\sigma) \\ & + \lambda_{HS}(H^\dagger H)(S^* S) + \lambda_2 (H^\dagger H)(\sigma^* \sigma) + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) \\ & + \lambda_4 (S^* S)(\sigma^* \sigma) + \lambda_5 (S^* S)(\eta^\dagger \eta) + \lambda_6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

Neutrino masses and LFV

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

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

$\mu \to e\gamma$



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

Scotogenic DM

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

Singlet-doblet complex DM

$$V(\eta, \sigma, H)$$

Dark radiation portal

$$k_\alpha \overline{N^c_{R\alpha}} N_{R\alpha} S^*$$

Dark scalar portal

$$g'\, Z'_\mu \sum_F q_F \overline{F}\gamma^\mu F$$

Scotogenic DM

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

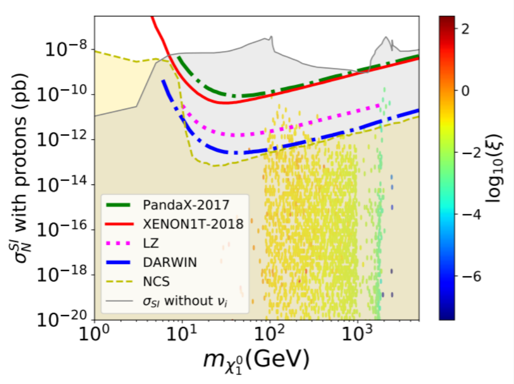
A. Ibarra, C. Yaguna, Ó. Zapata,
arXiv:1601.01163 [PRD]

Scotogenic DM

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

$$N_{R2} \to \Sigma$$

with A. Rivera, arXiv:1907.11938



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

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

Scotogenic DM

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

$$N_{R2} \to \Sigma$$

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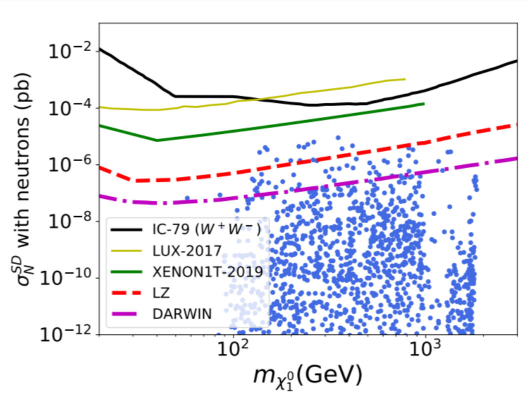

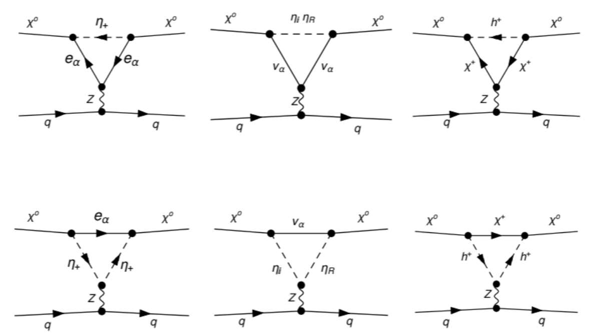

Scotogenic DM

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

$$N_{R2} \to \Sigma$$

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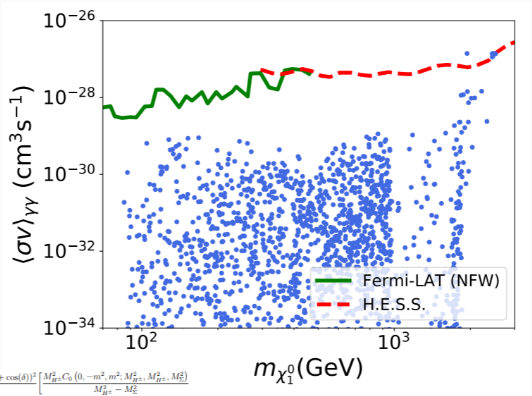


$$\sigma v\left(\chi_1^0\chi_1^0 \to \gamma\gamma\right) = \frac{|\mathcal{B}|^2}{32\pi m_{\chi_1^0}^2}$$

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

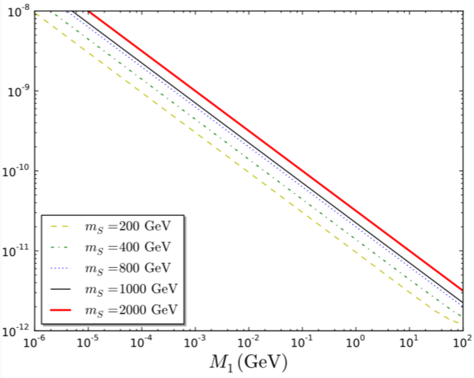
Scotogenic DM

FIMP Scenario

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

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

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



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

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

Chacko. *et al* arXiv:1505.04192 [PRD]

$$N_R N_R \to \nu_R \nu_R$$

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

$$k_\alpha \overline{N^c_{R\alpha}} N_{R\alpha} S^*$$

Dark radiation portal

$$g' \, Z'_\mu \sum_F q_F \overline{F} \gamma^\mu F$$

Dark scalar portal

(One-loop) Dirac neutrino masses

Small Dirac neutrino masses

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

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

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

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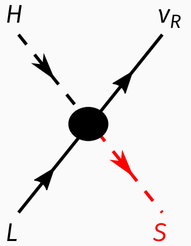
$$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N$$



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

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

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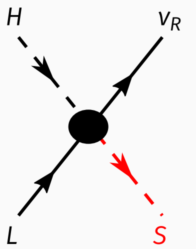


- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{eff} = N_{eff} - N_{eff}^{SM}$ (see arXiv:1211.0186)

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

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

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

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

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

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

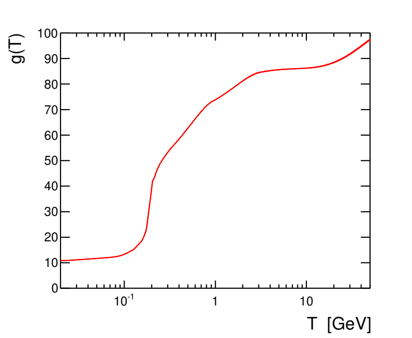
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s\,.$$

with three right-handed neutrinos, the Hubble parameter is

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

The right-handed neutrinos decouple when

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



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

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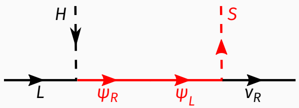
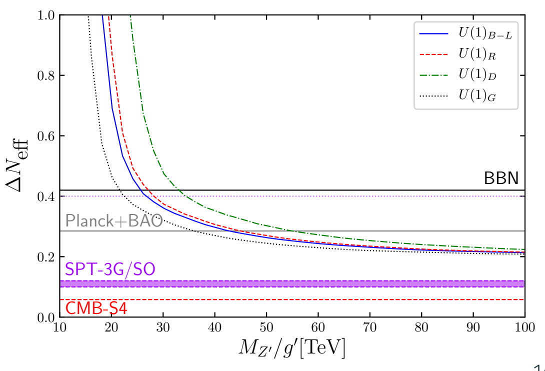


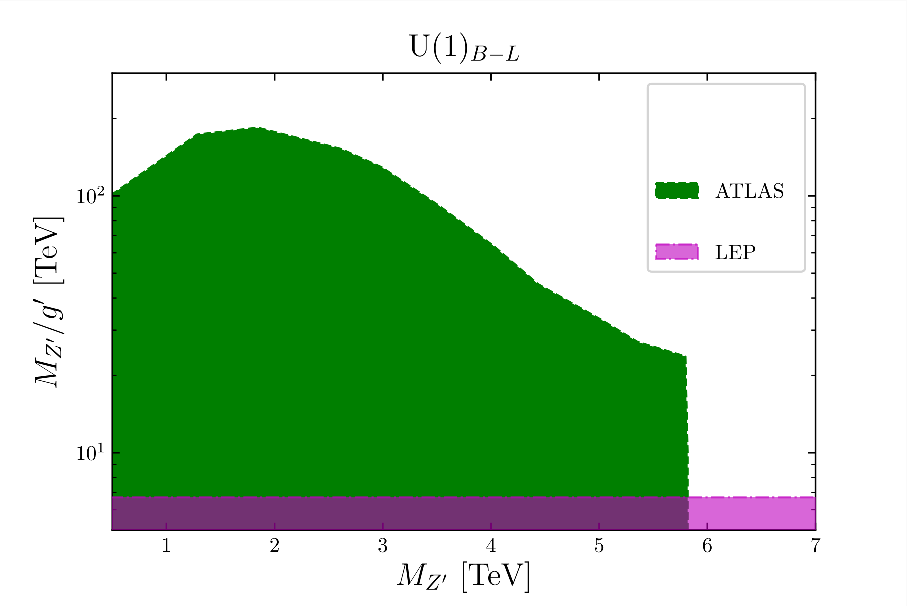
ν_{R3}	ν_{R2}	ν_{R1}	ψ_L	ψ_R	S
-4	-4	$+5$	-1	-1	$+3$

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



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

Same constraints as before



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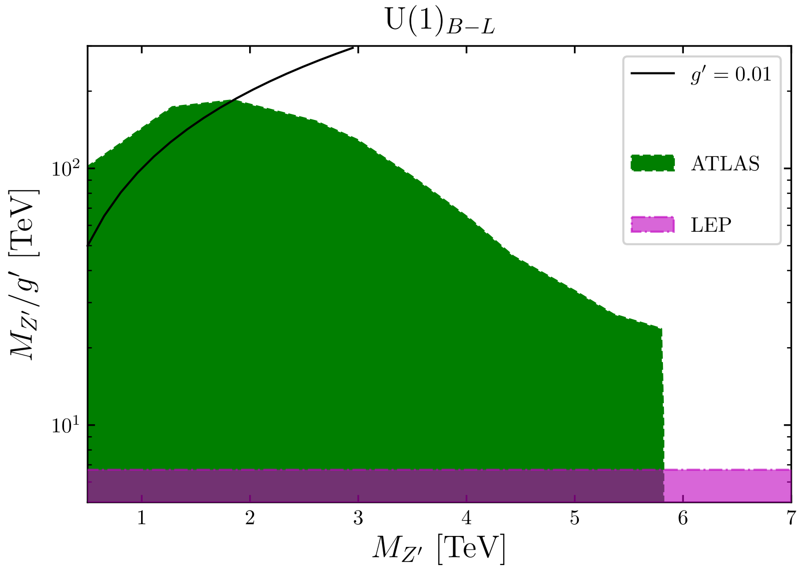

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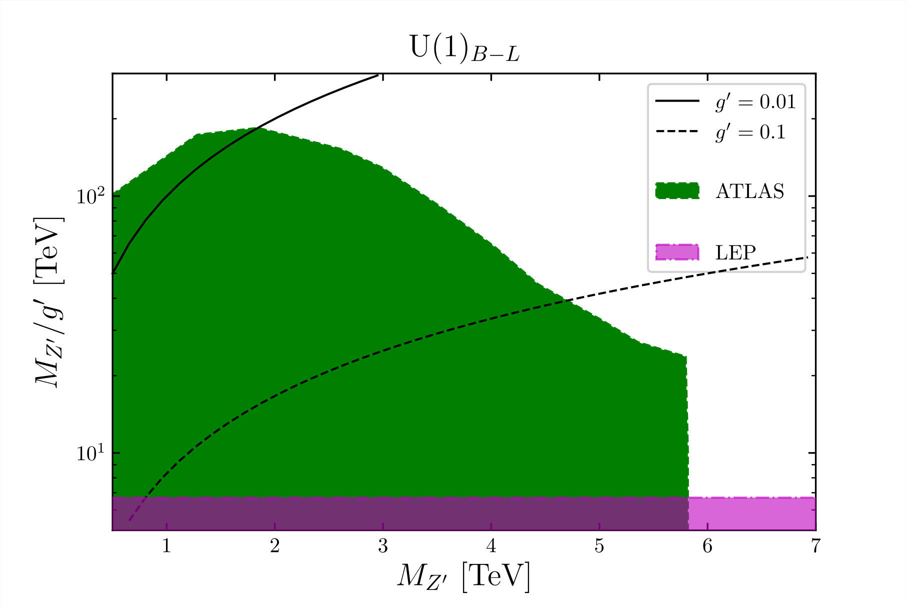

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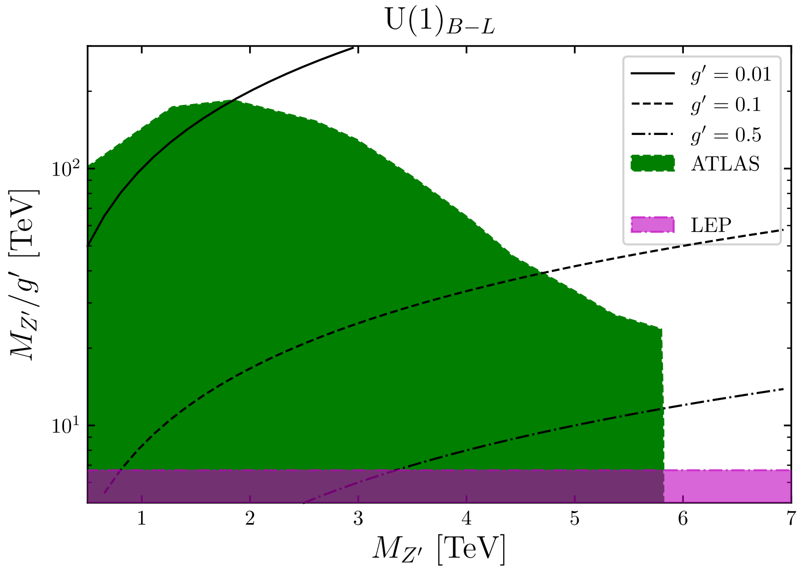
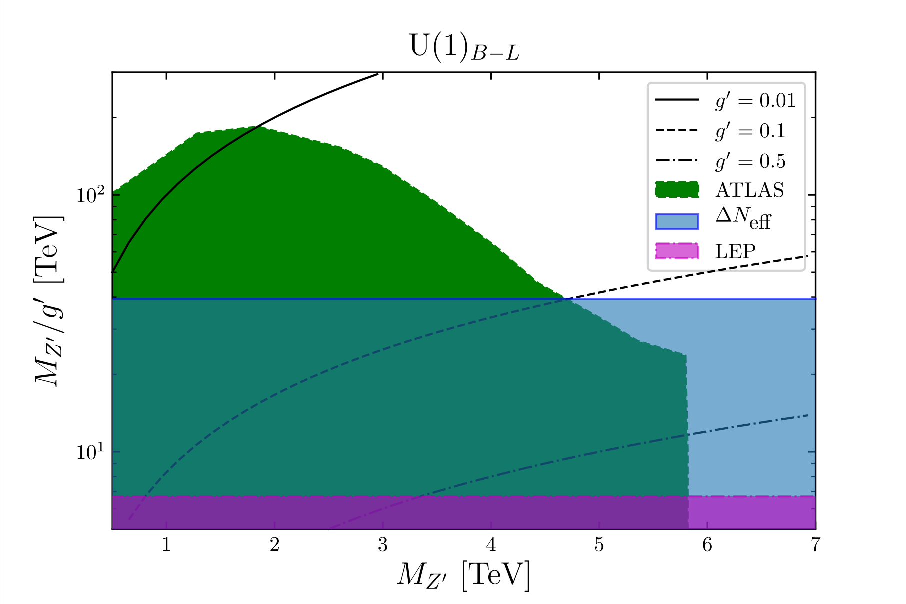


Same constraints as before



Conclusions

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

One-loop Dirac neutrino masses

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

- Spontaneously broken $U(1)_X$ generates a radiative Dirac neutrino masses
- A remnant symmetry makes the lightest field circulating the loop stable and good dark matter candidate.
- For T1-2-A: Either Singet Doublet Dirac Dark Matter or Singlet Scalar Dark Matter with extra scalar and vector portal
- Dark symmetry for Majorana mediatiors

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https://lawphysics.wordpress.com lawphysics@gmail.com

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Thanks!

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Thanks!