

Dirac neutrino masses with dark Majorana mediators



UNIVERSIDAD DE ANTIOQUIA
1803

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

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Focus on

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

In collaboration with

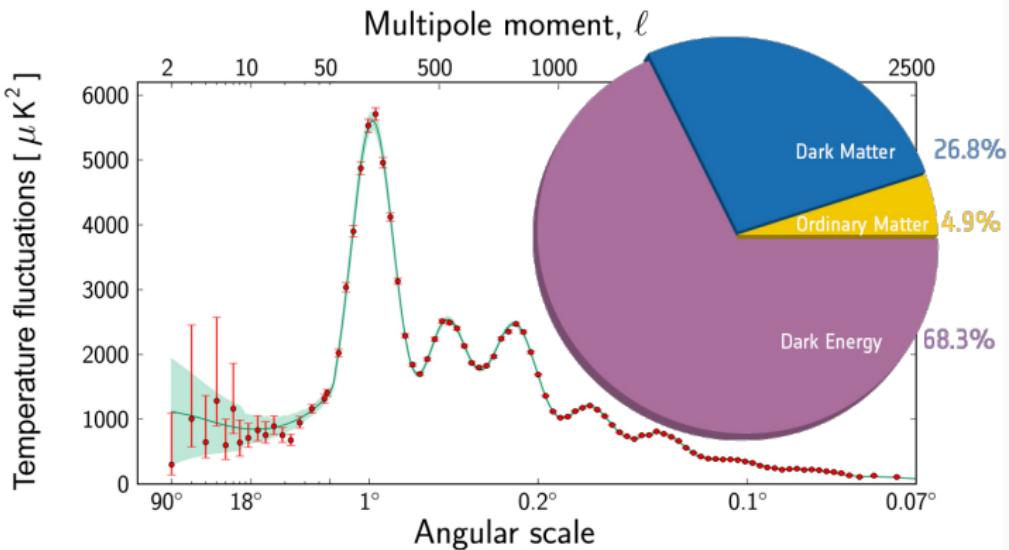
Carlos Yaguna (UPTC), Julian Calle, Óscar Zapata, Andrés Rivera (UdeA),
Walter Tangarife (Loyola University Chicago)



Λ CDM: $\Omega = 1, w = -1^\dagger$

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)

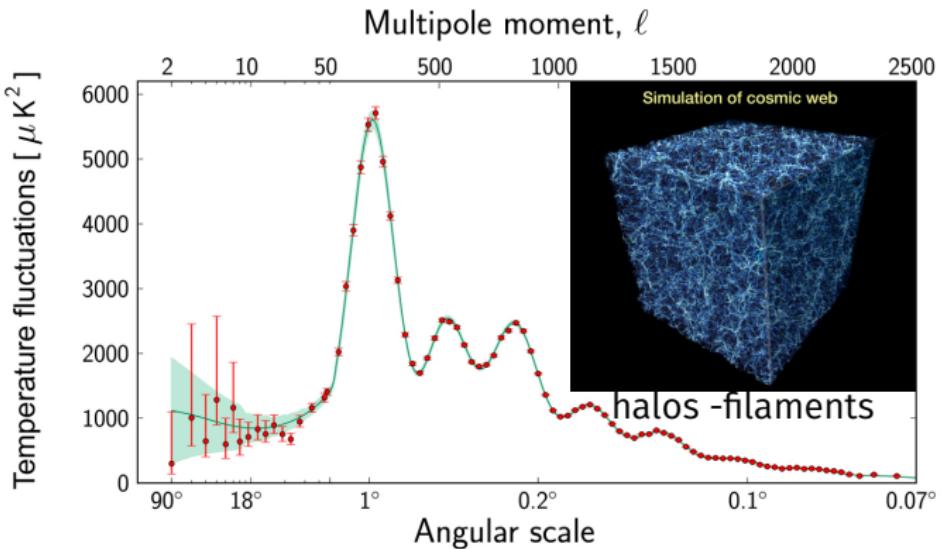
† Cosmological constant



ΛCDM : $\Omega = 1$, $w = -1^\dagger$

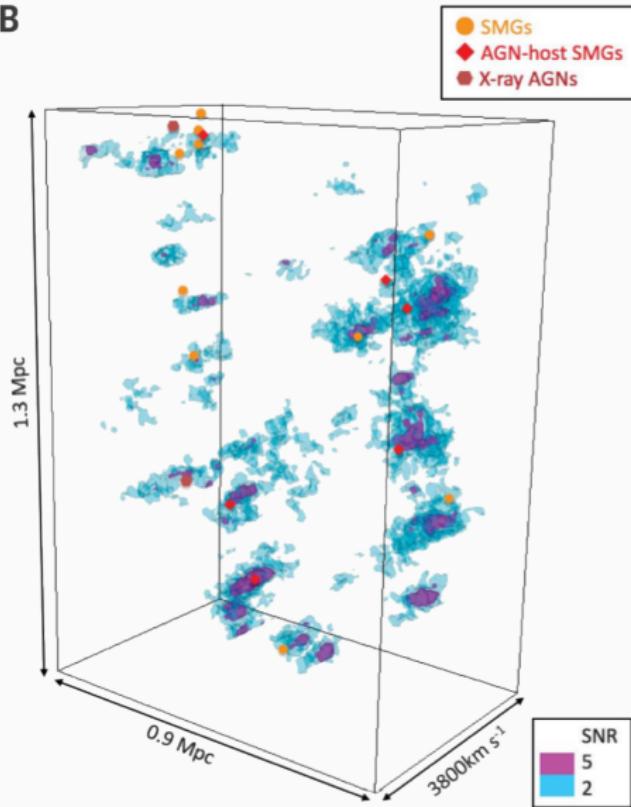
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Three-dimensional pictures of Ly α filaments

B



The 3D distribution of Ly α filaments shown with

signal-to-noise ratio (SNR) > 5

signal-to-noise ratio (SNR) > 2

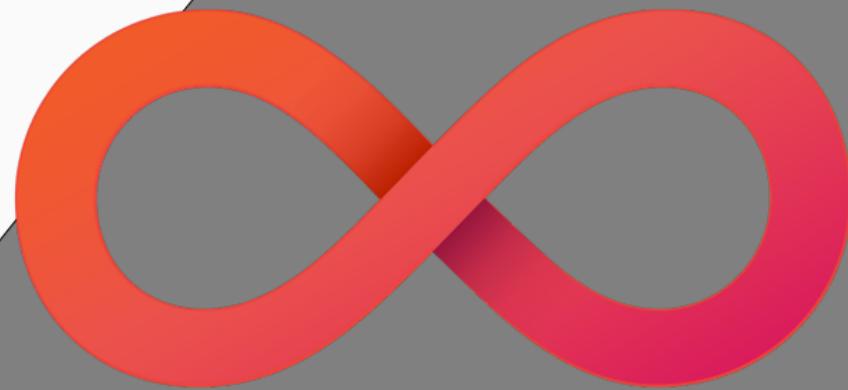
H. Umehata *et al*, Science 366, 97, 4 Oct 2019

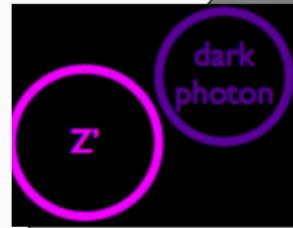
Dark matter properties

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



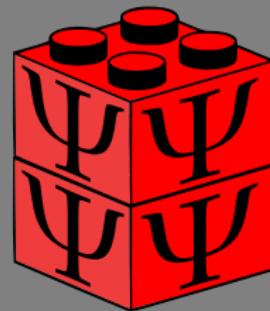
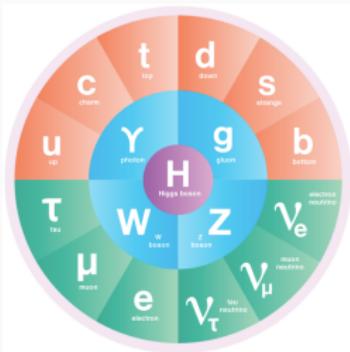


Local $U(1)_{\mathcal{D}}$

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

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.

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

Only known integer solutions for -3 (1953)

September 2019:

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

Or... combine known solutions

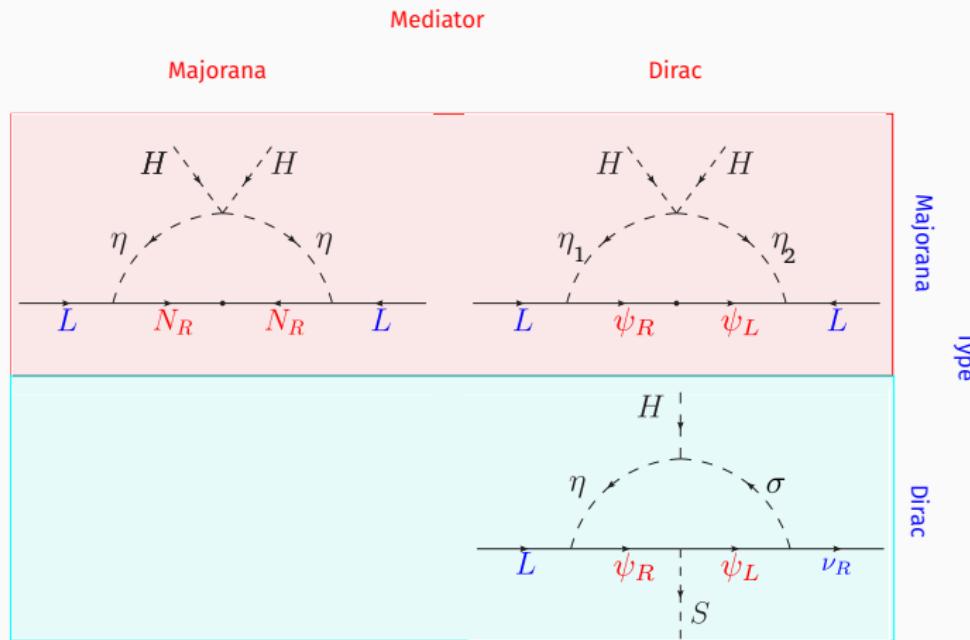
$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \dots)$	Ref	
$(-1, -1, -1)$	hep-ph/0611205, S. Khalil [JPG]	
$(-4, -4, +5)$	arXiv:0706.0473, Montero, V. Pleitez [PLB]	Not known solution for one-loop neutrino Majorana masses with local $U(1)_X$.
$\left(-\frac{2}{3}, -\frac{2}{3}, -\frac{4}{3}, -\frac{1}{3}\right)$	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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Global

Local



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

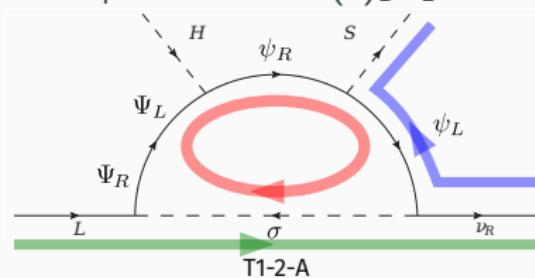
arXiv:1812.01599, 1901.06402, 1902.07259, 1903.01477,

1904.07407, 1907.08630, 1907.11557, 1910.09537

$\mathcal{O}(100)$ new models

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

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

Global

Local

Mediator

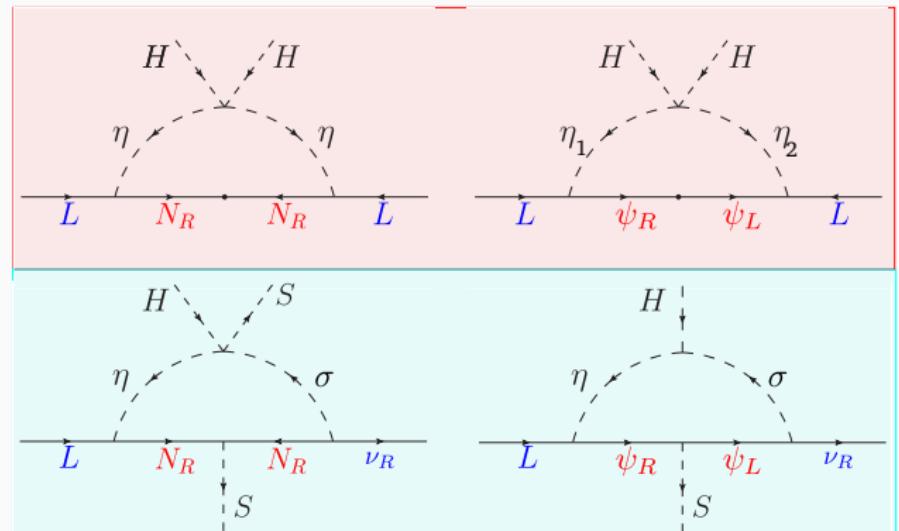
Majorana

Dirac

Majorana

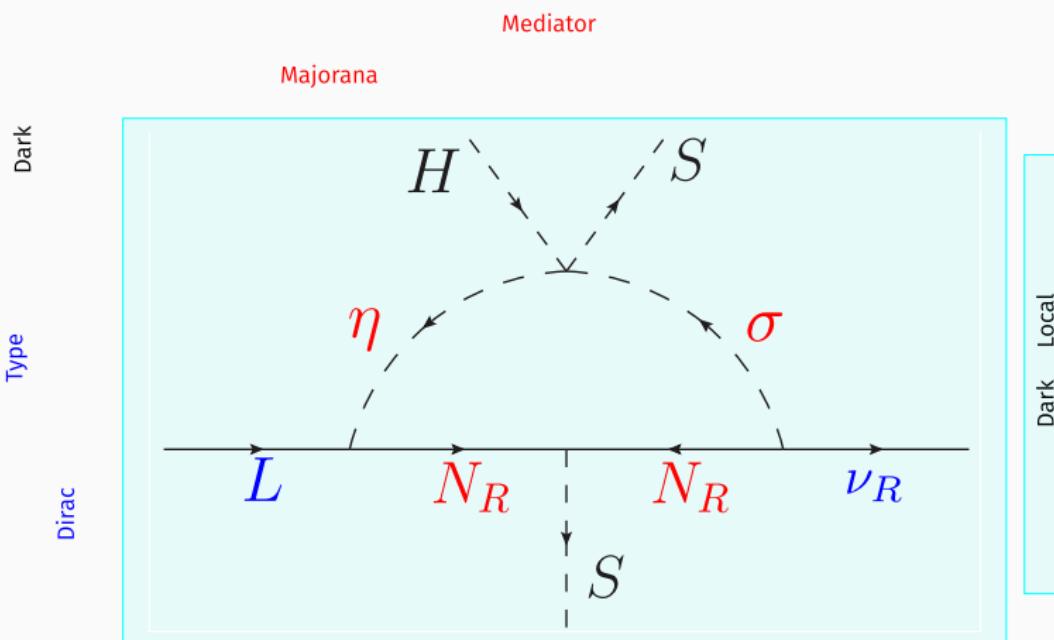
Type

Dirac



Dirac Radiative Type-I seesaw with Majorana mediators

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



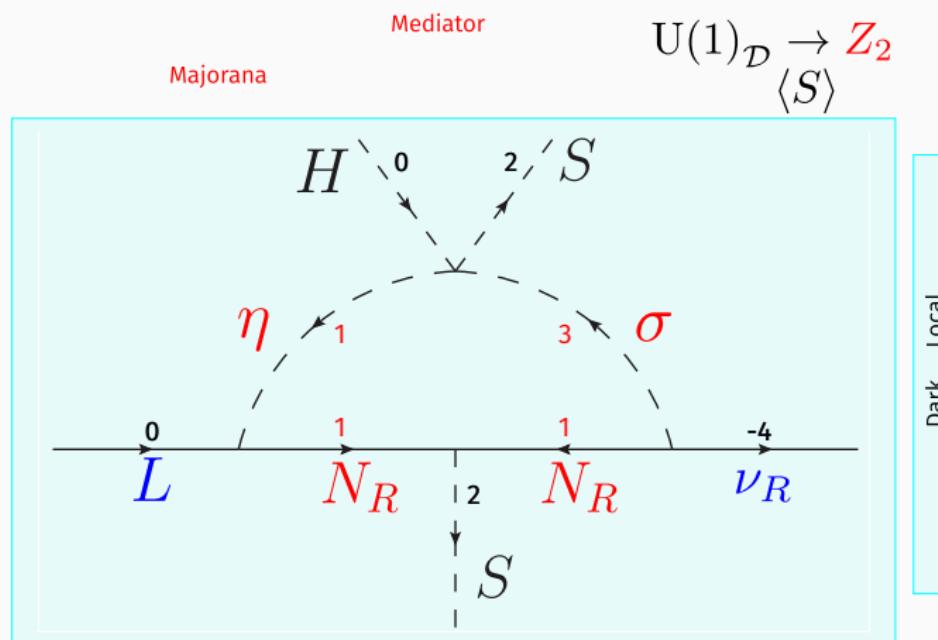
Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_D$
L	2	-1/2	0
Q	2	-1/6	0
d_R	1	-1/2	0
u_R	1	+2/3	0
e_R	1	-1	0
H	2	1/2	0
η	2	1/2	1
S	1	0	2
σ	1	0	3
ν_{R1}	1	0	-4
ν_{R2}	1	0	-4
ν_{R3}	1	0	5
N_{R1}	1	0	1
N_{R2}	1	0	1
N_{R3}	1	0	1
TOTAL			0

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

Dirac Radiative Type-I seesaw with Majorana mediators

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

Dark
Type
Dirac

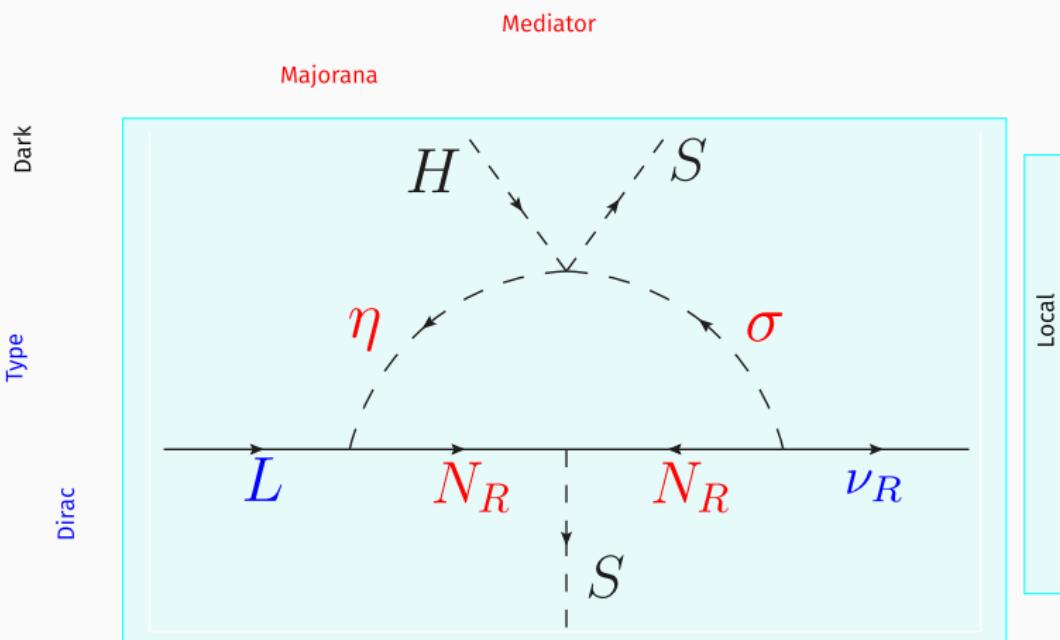


$$N = -\frac{\nu}{4} \quad , \quad \eta = -\frac{\nu}{4} \quad , \quad \sigma = -\frac{3\nu}{4} \quad .$$

Fields	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{\mathcal{D}}$
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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

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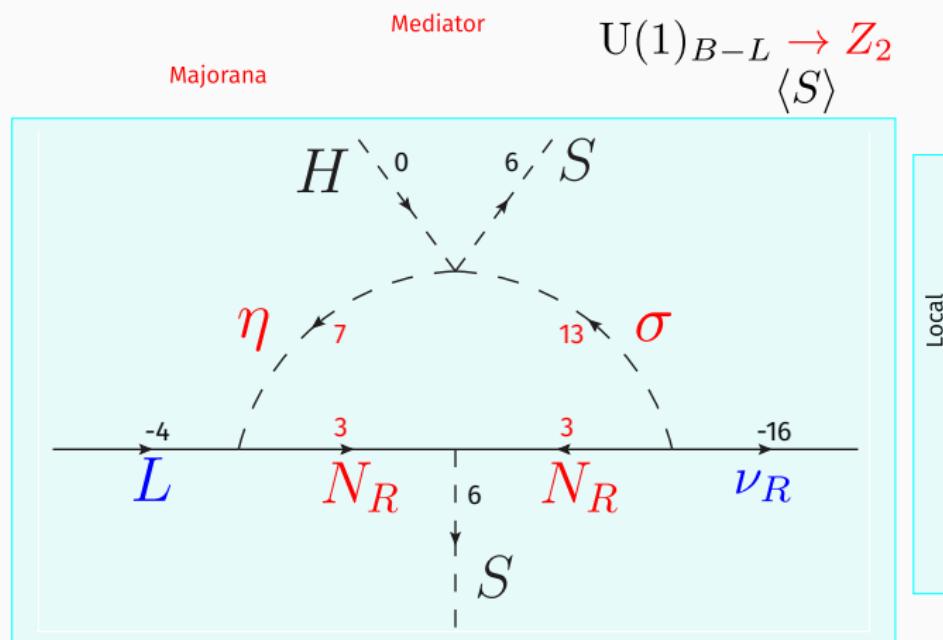
$$N = -\frac{\nu}{4} - \frac{1}{4}, \quad \eta = -\frac{\nu}{4} - \frac{1}{4} - l, \quad \sigma = -\frac{3\nu}{4} + \frac{1}{4}.$$

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	$3/4^9$

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

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)

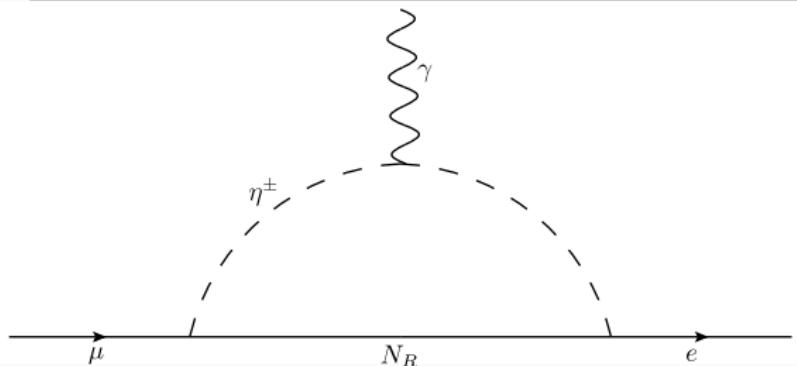
$$\begin{aligned}\mathcal{V}(H, S, \eta, \sigma) = & V(H) + V(S) + V(\eta) + V(\sigma) \\ & + \lambda_{HS} (H^\dagger H)(S^* S) + \lambda_2 (H^\dagger H)(\sigma^* \sigma) + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) \\ & + \lambda_4 (S^* S)(\sigma^* \sigma) + \lambda_5 (S^* S)(\eta^\dagger \eta) + \lambda_6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

Neutrino masses and LFV

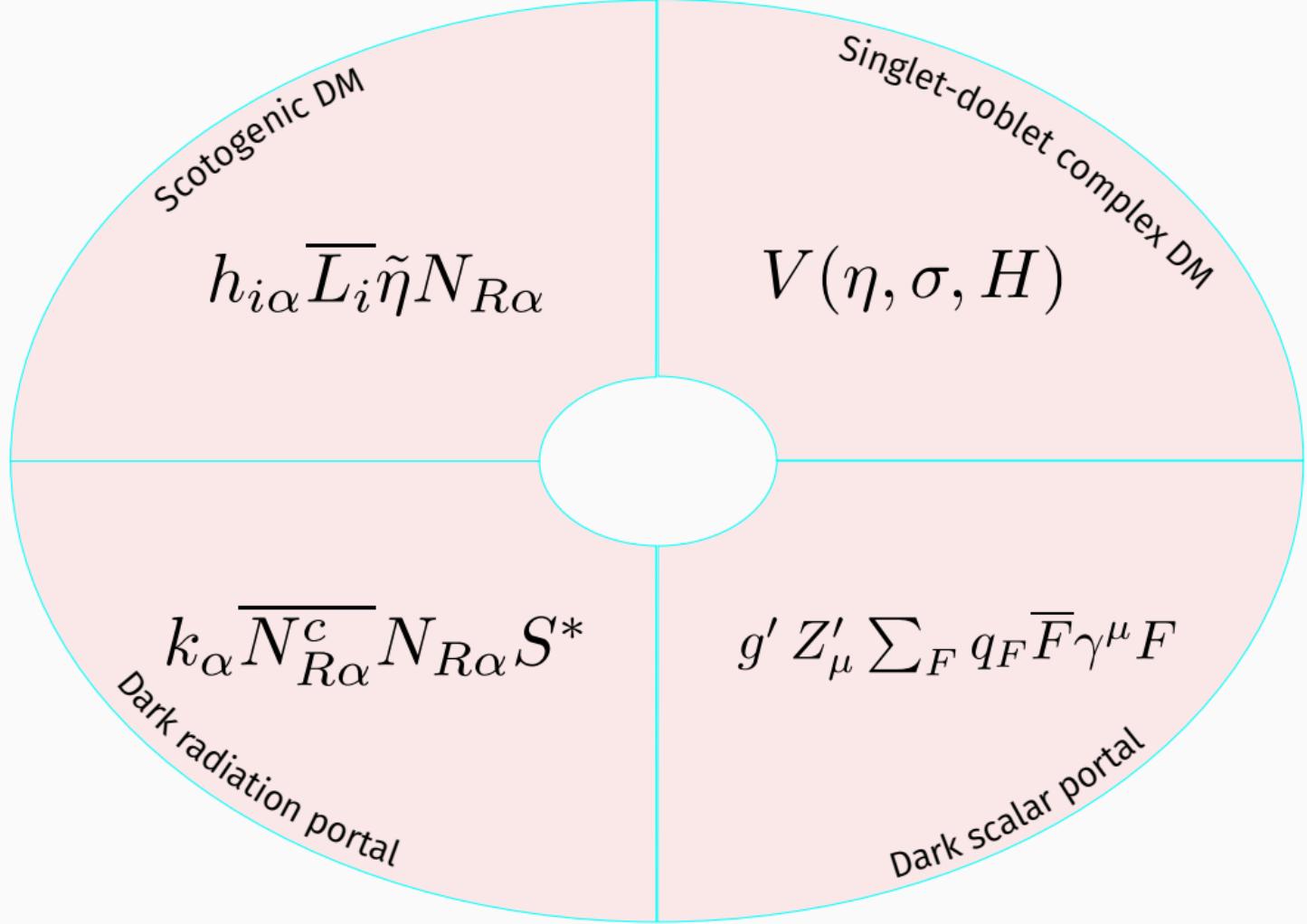
$$(\mathcal{M}_\nu)_{ij} = \frac{1}{32\pi^2} \frac{\lambda_8 v_S^2 v_H}{m_{\eta_R^0}^2 - m_{\sigma_R^0}^2} \sum_{\alpha=1}^3 h_{i\alpha} k_{\alpha} y_{j\alpha}^* \left[F\left(\frac{m_{\eta_R^0}^2}{M_{N_\alpha}^2}\right) - F\left(\frac{m_{\sigma_R^0}^2}{M_{N_\alpha}^2}\right) \right] + (R \rightarrow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

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

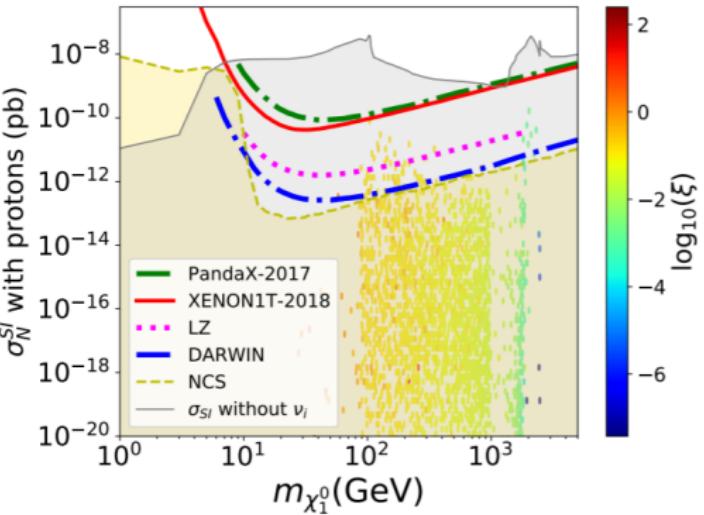
$$h_{i\alpha} \overline{L}_i \tilde{\eta} N_{R\alpha}$$

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



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

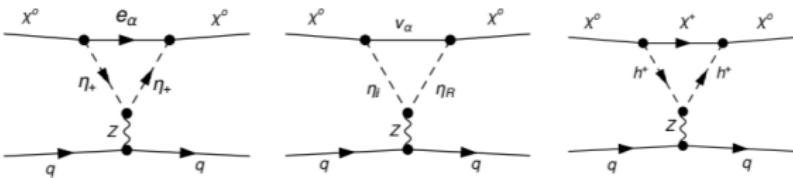
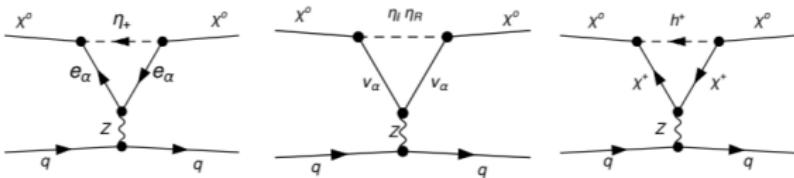
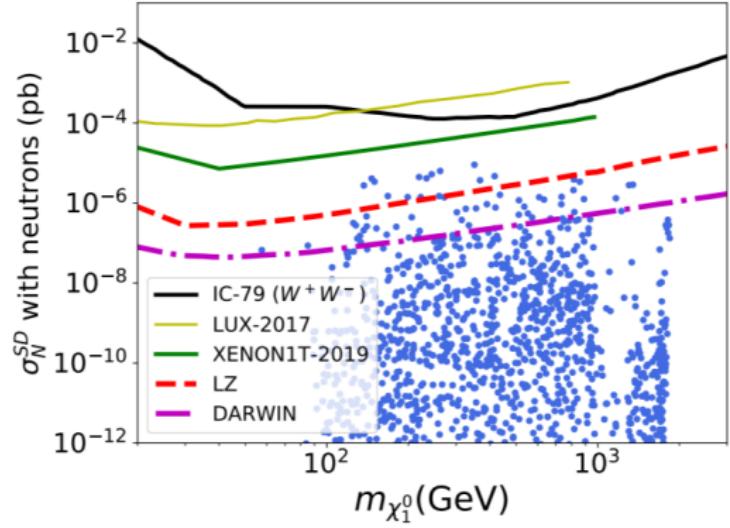
$$\xi = \frac{|M_\Sigma - m_{\chi_1^0}|}{m_{\chi_1^0}}$$

Scotogenic DM

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

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

with A. Rivera, arXiv:1907.11938

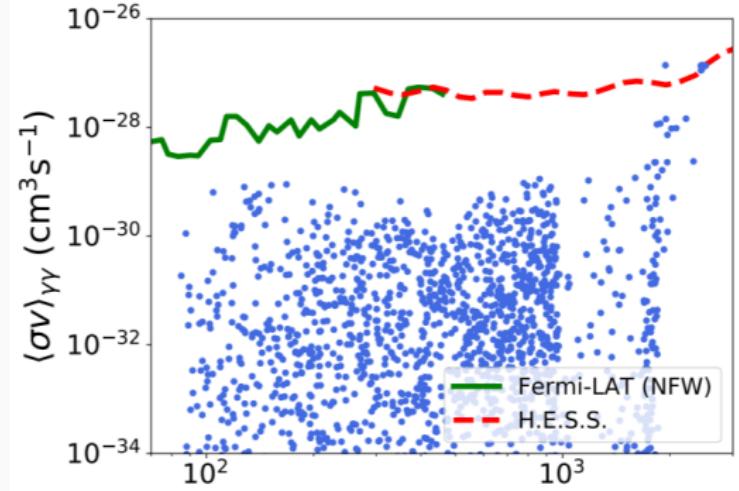


Scotogenic DM

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

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_q^2 C_0(0, -m^2, m^2; m_q^2, m_q^2, m_q^2)}{m_q^2 - m_{\bar{q}}^2} \right. \\ & + \frac{m_{\bar{q}}^2 (m_{\bar{q}}^2 + m^2 - m_q^2) C_0(0, -m^2, m^2; m_{\bar{q}}^2, m_{\bar{q}}^2, m_q^2)}{(m_{\bar{q}}^2 - m_q^2)(-m_{\bar{q}}^2 + m^2 + m_q^2)} + \frac{2m_{\bar{q}}^2 C_0(0, 0, 4m^2; m_{\bar{q}}^2, m_{\bar{q}}^2, m_q^2)}{-m_{\bar{q}}^2 + m^2 + m_q^2} \Big] \\ & + \frac{\alpha m^2 \cos^2(\alpha) Y_{\text{eff}}^2}{2\sqrt{2}\pi} \left[\frac{m_q^2 C_0(0, -m^2, m^2; m_q^2, m_q^2, m_{\bar{q}}^2)}{m_q^2 - m_{\bar{q}}^2} \right. \\ & - \frac{m_{\bar{q}}^2 (m_{\bar{q}}^2 + m^2 - m_q^2) C_0(0, -m^2, m^2; m_{\bar{q}}^2, m_{\bar{q}}^2, m_q^2)}{(m_{\bar{q}}^2 - m_q^2)(-m_{\bar{q}}^2 + m^2 + m_q^2)} - \frac{2m_{\bar{q}}^2 C_0(0, 0, 4m^2; m_{\bar{q}}^2, m_{\bar{q}}^2, m_q^2)}{-m_{\bar{q}}^2 + m^2 + m_q^2} \Big] \\ & + \frac{\sqrt{2}\alpha m^2 \sin^2(\alpha) Y_{\text{eff}}^2}{2\pi} \left[\frac{m_q^2 C_0(0, -m^2, m^2; m_q^2, m_q^2, m_{\bar{q}}^2)}{m_q^2 - m_{\bar{q}}^2} \right. \\ & - \frac{m_{\bar{q}}^2 (m_{\bar{q}}^2 + m^2 - m_q^2) C_0(0, -m^2, m^2; m_{\bar{q}}^2, m_{\bar{q}}^2, m_q^2)}{(m_{\bar{q}}^2 - m_q^2)(-m_{\bar{q}}^2 + m^2 + m_q^2)} - \frac{2m_{\bar{q}}^2 C_0(0, 0, 4m^2; m_{\bar{q}}^2, m_{\bar{q}}^2, m_q^2)}{-m_{\bar{q}}^2 + m^2 + m_q^2} \Big] \\ & - \frac{8\sqrt{2}\alpha m^2 \cos^2(\alpha) M_W^2}{\pi (M_\Sigma^2 - M_W^2) (4m_{\text{eff}}^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^4 - 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}$$

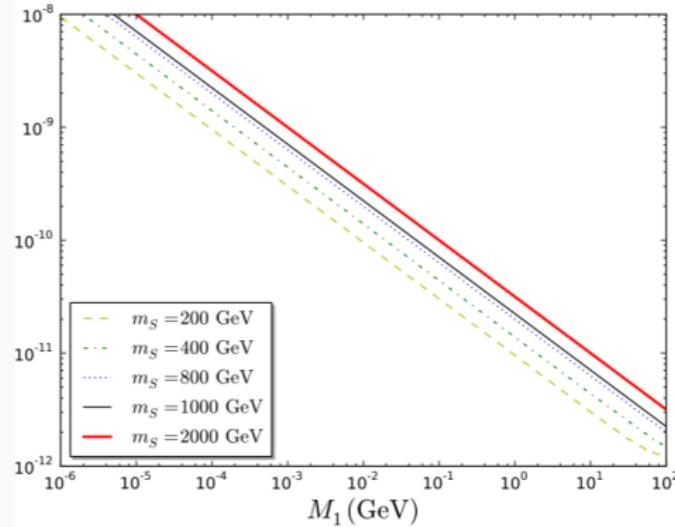
Scotogenic DM

FIMP Scenario

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

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

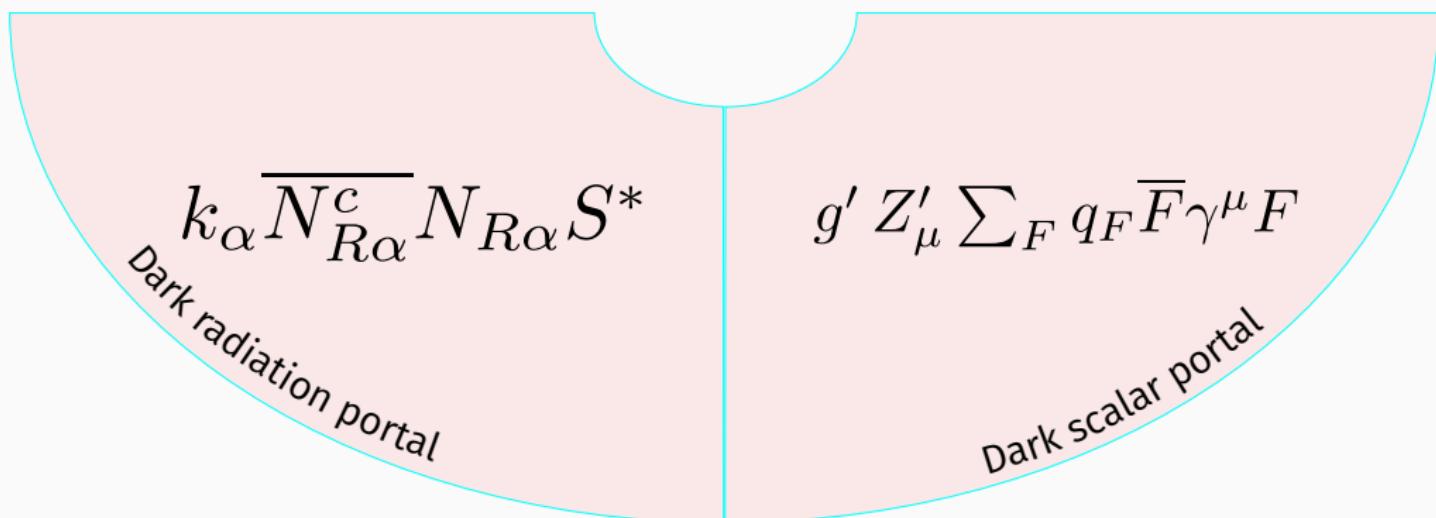
$$h_1 \sim h_{1\alpha}$$



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

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

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



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

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

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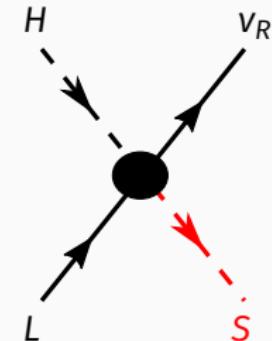
- Forbids tree-level mass (TL) term ($Y(H) = +1/2$)

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

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

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

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



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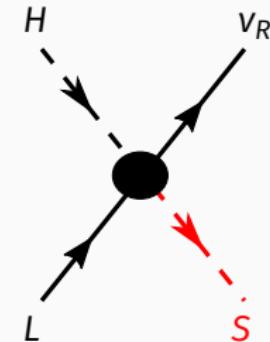
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- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$ (see arXiv:1211.0186)

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

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

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

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

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

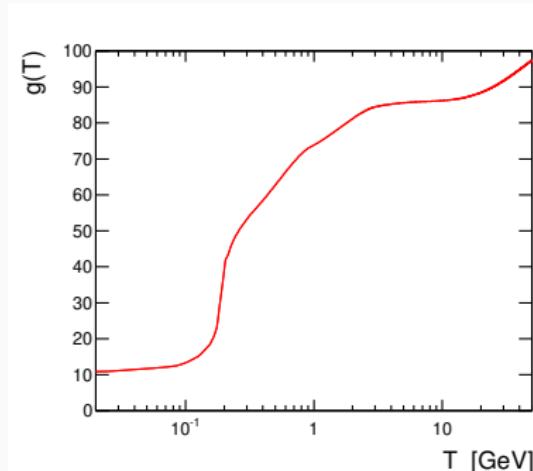
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left(\frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

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]

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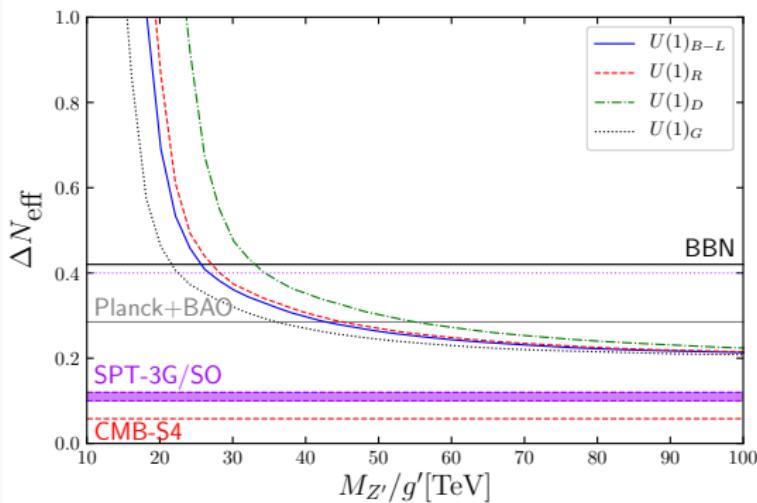
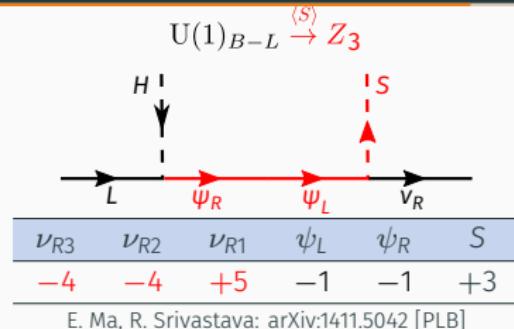
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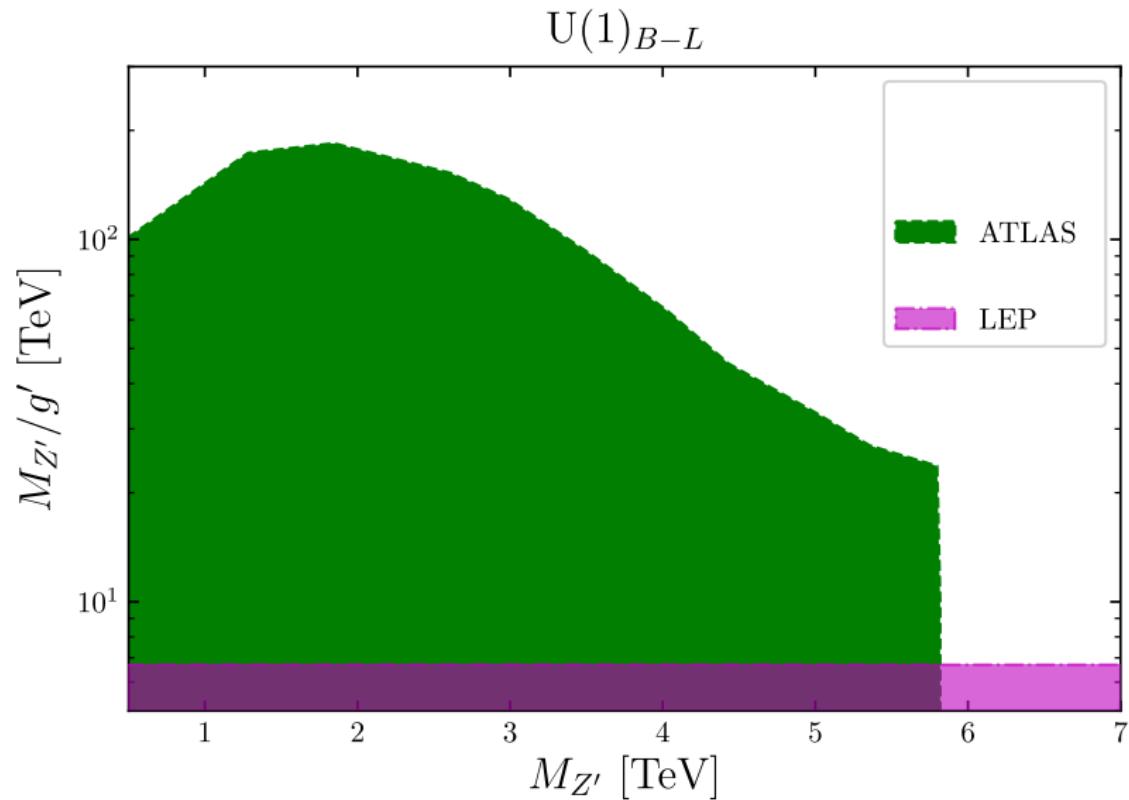
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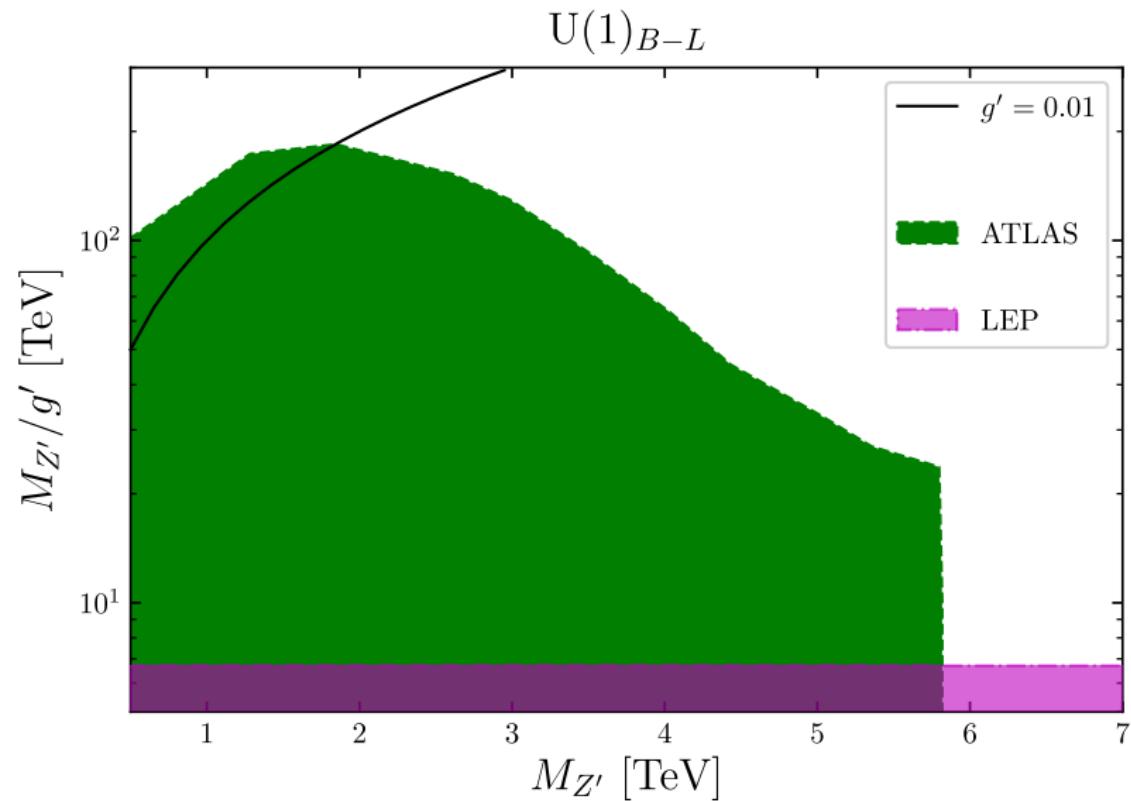
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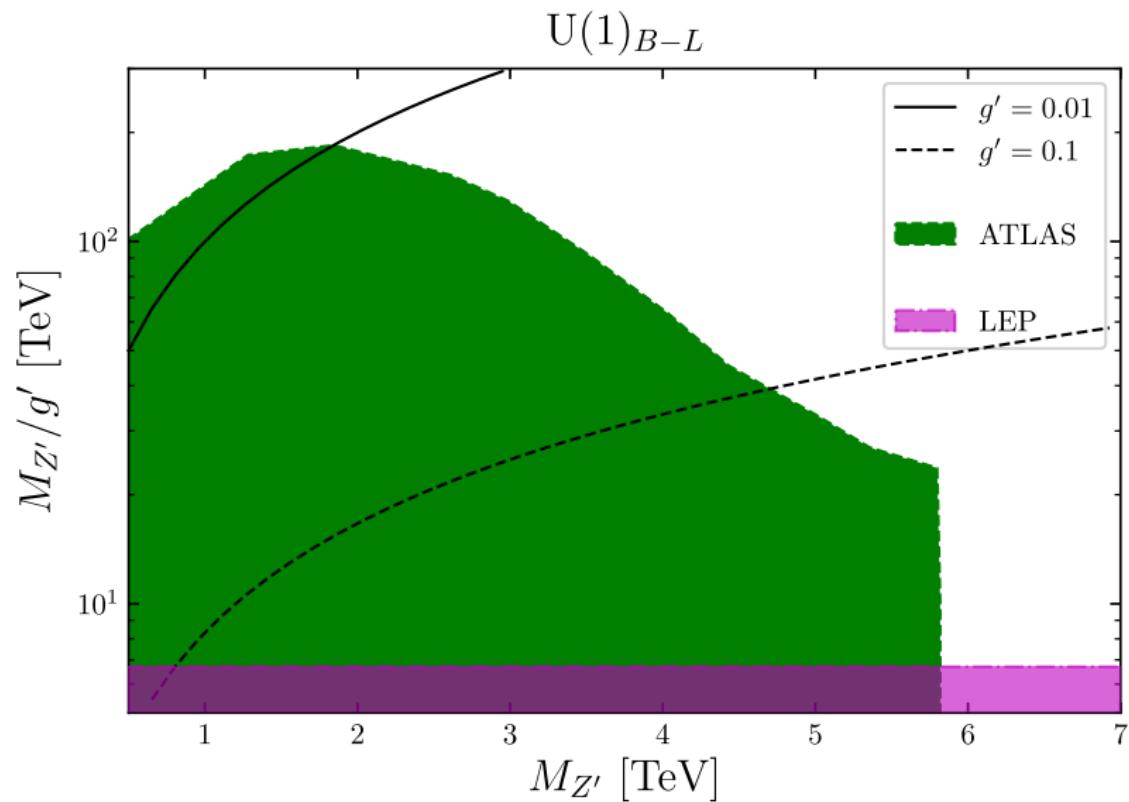
Same constraints as before



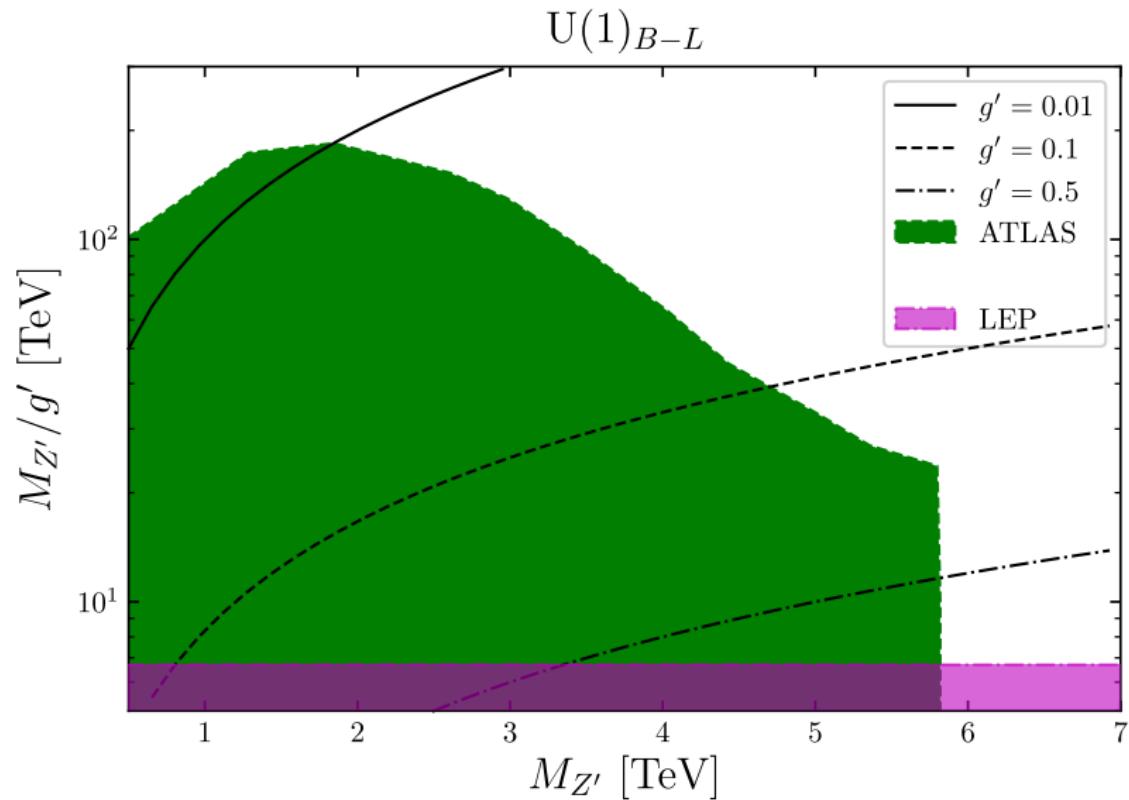
Same constraints as before



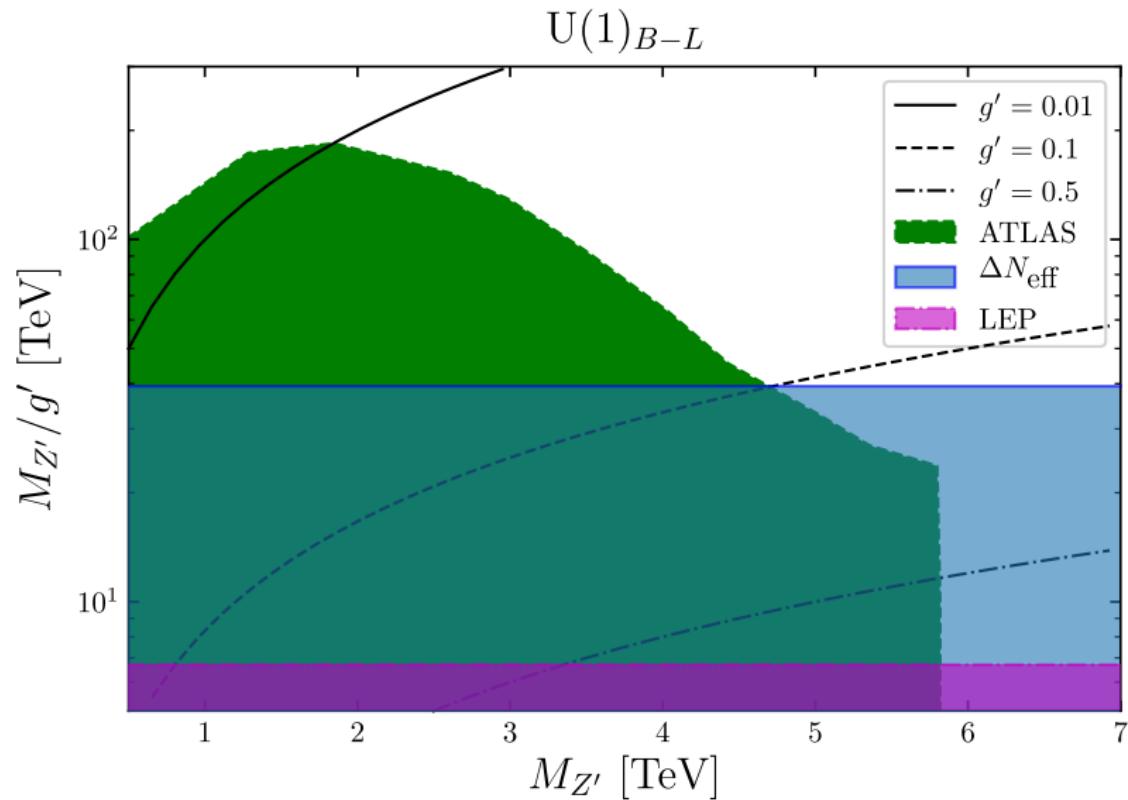
Same constraints as before



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

Symmetry Series: Latin America

This trilingual collection explores particle physics and astrophysics in Latin America.



10/01/19
From the father & month in Latin America

Latin America has reached a peak moment in experimental particle physics and astrophysics research. Throughout the month of October, Symmetry will explore how



10/03/19

The legacy of Cesar Lattes

Watkin physicist Cesar Lattes, considered a national hero for his discoveries, paved the way for trailing research projects in particle astrophysics across Latin America and beyond.



10/03/19
Building the future, one week at a time

A series of short physics schools organized in collaboration with CERN has had an outsized impact on the careers of scientists from Latin America.



10/15/19

Building on luck

Scholars return home to forge paths for future physicists where few exist.



10/23/19
Meeting the physics students

Having left out some traditional paths to community in particle physics, a group of Latin American researchers created their own way to connect.



10/23/19

New Argentina joined ATLAS

Maria Teresa Di Gioia has been instrumental in bringing scientists in Argentina new opportunities to participate in particle physics and astrophysics experiments, including one that co-discovered the Higgs boson.



10/08/19

Making a new set of rings at Fermilab

Many researchers from Latin America can trace their entry into experimental particle physics to an initiative started by former Fermilab Director Leon Lederman.



10/09/19

A crystal clear place to study the skies

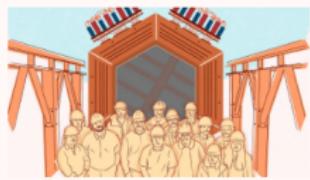
In the last few decades, Argentina and Chile have proven themselves prime spots for astronomical observation—a status that has been a boon in many ways for both countries.



10/15/19

How NAICE landed in Mexico

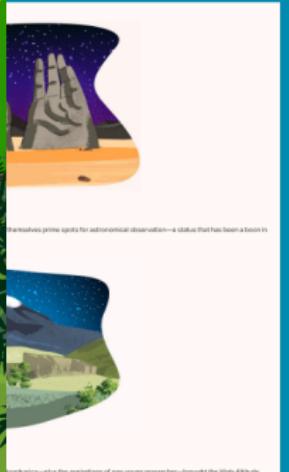
A strong regional tradition of high-energy physics and astrophysics—plus the ambitions of one young researcher—brought the High-Altitude Water Cherenkov Gamma-ray Observatory to Mexico.



10/16/19

A partnership turns to resilience

A collaboration with fewer than 100 members has played an important role in Fermilab's ongoing partnership with Latin-American scientists and institutions.



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Thanks!



