Dirac neutrino masses

with dark Majorana mediatiors

UNIVERSIDAD DE ANTIOQUIA
1803

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December 2, 2019 - COMHEP
[PDF: `http://bit.ly/comhep2019`]

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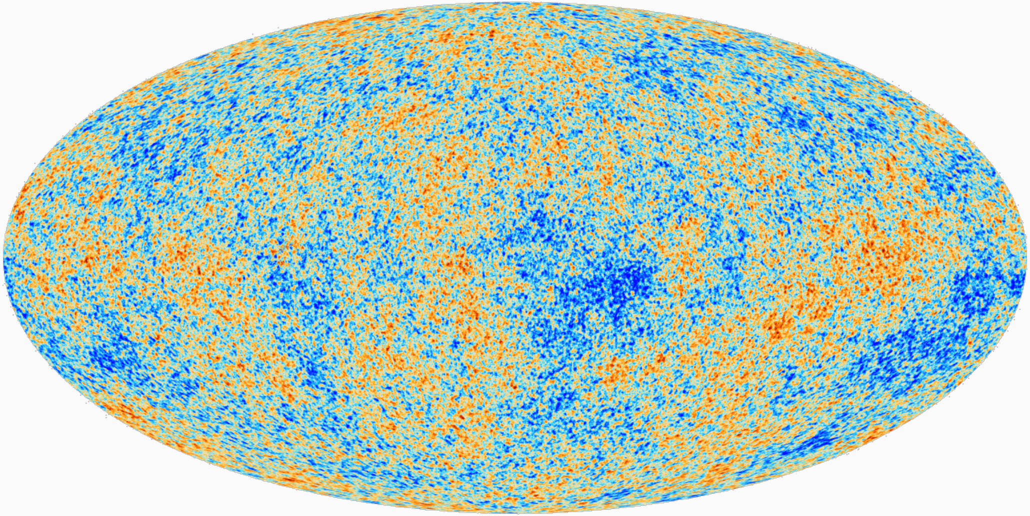
`http://gfif.udea.edu.co`

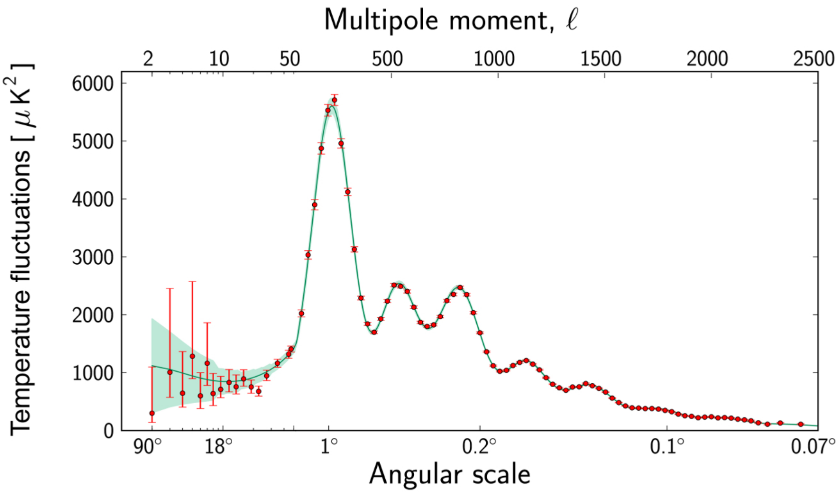
Focus on
arXiv:1812.05523 [PRD], 1906.09685 [PRD], 1907.11938, 1909.09574
In collaboration with
Carlos Yaguna (UPTC), Julian Calle, Óscar Zapata, Andrés Rivera (UdeA),
Walter Tangarife (Loyola University Chicago)

ΛCDM paradigm (with baryonic effects)

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



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

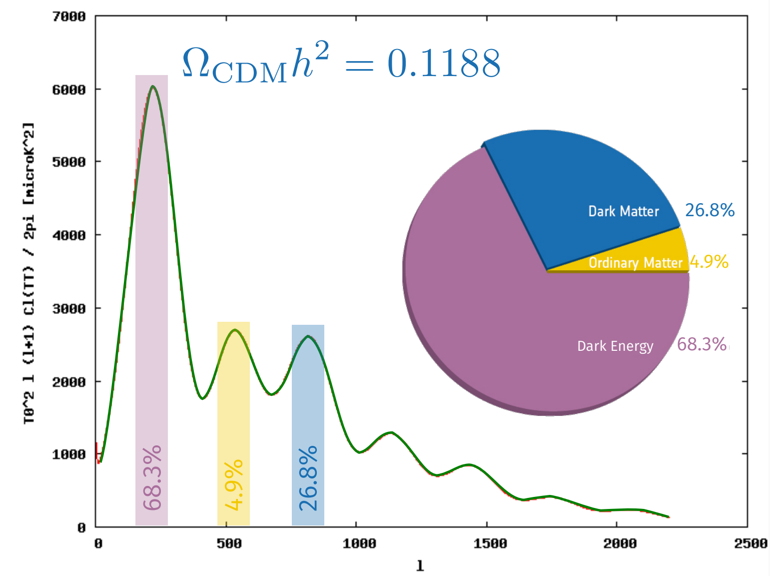


Planck's power spectrum of temperature fluctuations, ΔT, in the Cosmic Microwave Background. Credit: ESA and the Planck Collaboration

ΛCDM: $\Omega = 1$, $w = -1^{\dagger}$

Symbol	Value
$\Omega_b h^2$	0.022 30(14)
$\Omega_{\mathrm{CDM}} h^2$	0.1188(10)
t_0	$13.799(21) \times 10^9$ year
n_s	0.9667(40)
Δ_R^2	2.441×10^{-9}
τ	0.066(12)

† Cosmological constant



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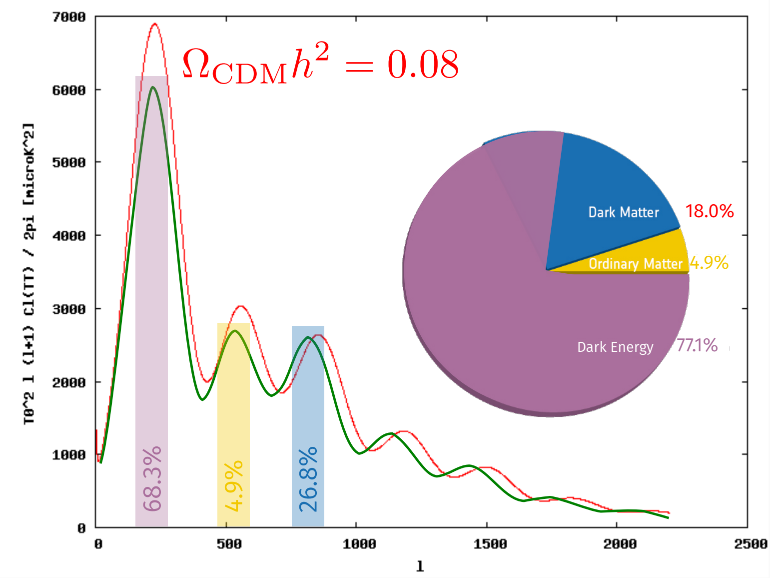
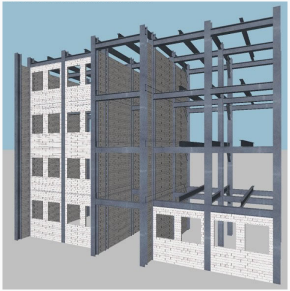
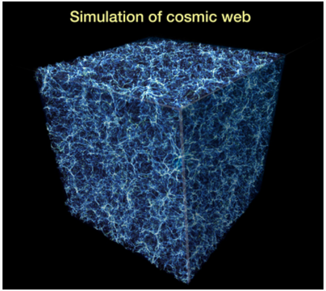


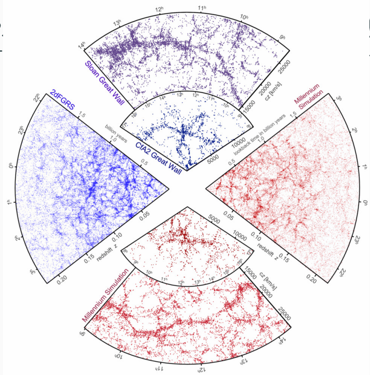
Cosmic web

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

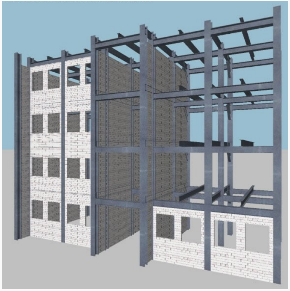


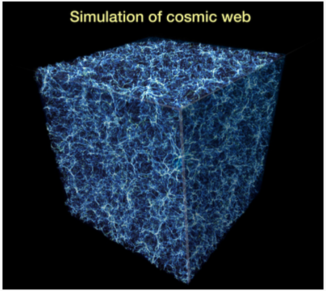


Cosmic web

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]

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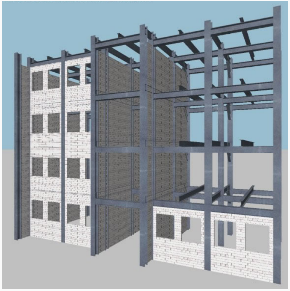
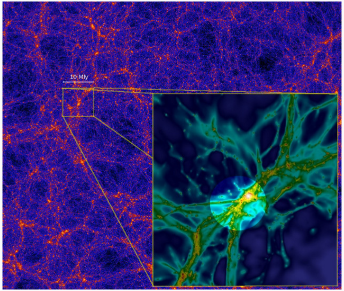
`https://phys.org/news/2018-06-years-scientists-account-universe.html`





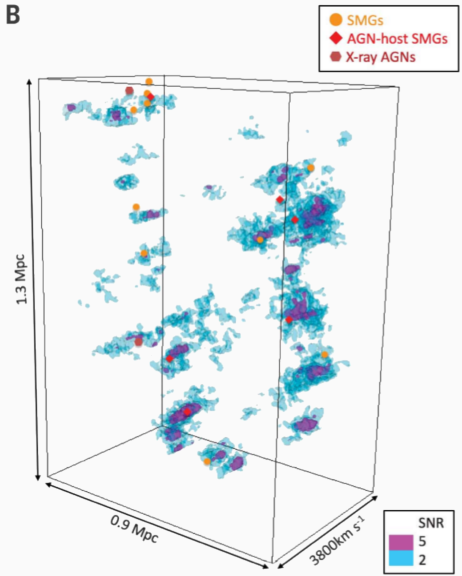
These great filaments are made largely of dark matter located in the space between galaxies and filled with 60% of the primordial gas!

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

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

[1] See also: arXiv:1603.05400 [A&A]

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

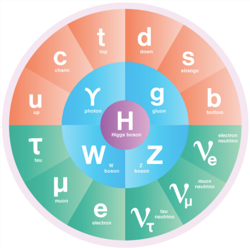
H. Umehata *et al*, Science **366**, 97, 4 Oct 2019

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
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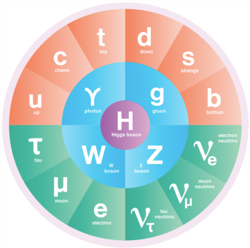
t
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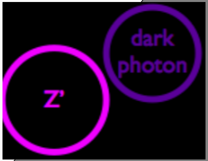
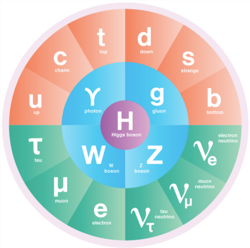

dark
photon
Z'

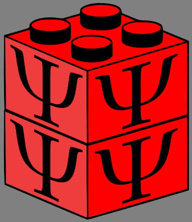
Local $U(1)_{\mathcal{D}}$



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

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

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



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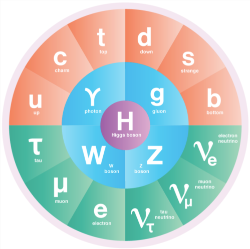

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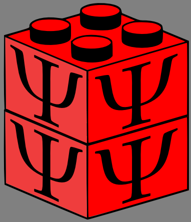

Explain also small neutrino masses

In the following discussion we use the following doublets

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

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

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

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.

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

with solution

$$u = -e + \frac{2l}{3}, \qquad d = e - \frac{4l}{3}, \qquad q = -\frac{l}{3}, \tag{2}$$

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which satisfy

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

with solution

$$u = -e + \frac{2l}{3}\,, \qquad d = e - \frac{4l}{3}\,, \qquad q = -\frac{l}{3}\,, \tag{2}$$

which satisfy

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

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

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

with solution

$$u = -r - \frac{4l}{3}, \qquad d = r + \frac{2l}{3}, \qquad q = -\frac{l}{3}, \qquad e = r + 2l, \tag{2}$$

which satisfy

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

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

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

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

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

with solution

$$u = -1 - \frac{4l}{3}\,, \qquad d = 1 + \frac{2l}{3}\,, \qquad q = -\frac{l}{3}\,, \qquad e = 1 + 2l\,, \tag{2}$$

which satisfy

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

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

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

$$[\mathrm{U}(1)_X]^3\,, \qquad \sum_\alpha n_\alpha^3 + 3 = 0$$

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

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

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

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \cdots)$	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]
$\left(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7}\right)$	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$\cdots$ 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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$\left(-1, -1, -\frac{10}{7}, -\frac{4}{7}, -\frac{2}{7}, \frac{9}{7}\right)$	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 $U(1)_X$.

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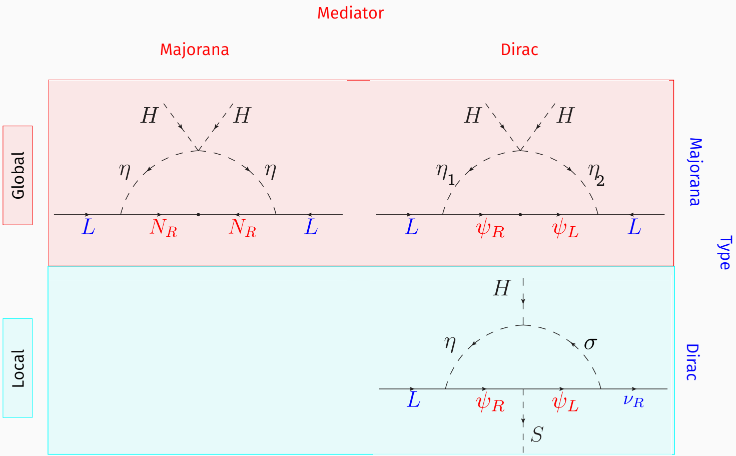
Radiative Type-I seesaw →Local: only $U(1)_{B-L}$! arXiv:1812.05523, with J. Calle, C. Yaguna, Ó. Zapata [PRD]



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

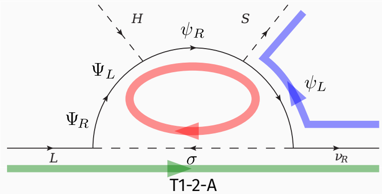
arXiv:1812.01599, 1901.06402, 1902.07259, 1903.01477,

1904.07407, 1907.08630, 1910.09537 1909.00833 1907.11557,

1909.09574

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

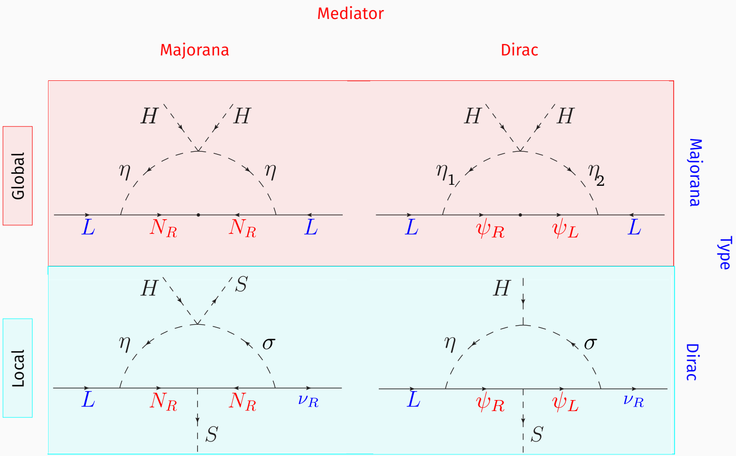
Example: New $U(1)_{B-L}$



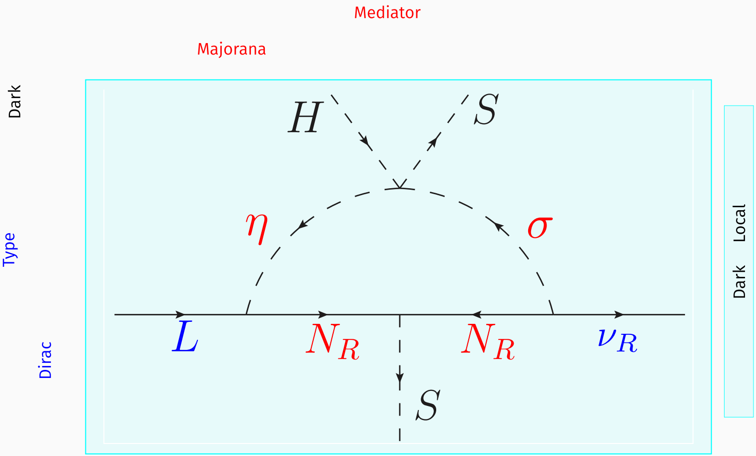
Pheno analysis with

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



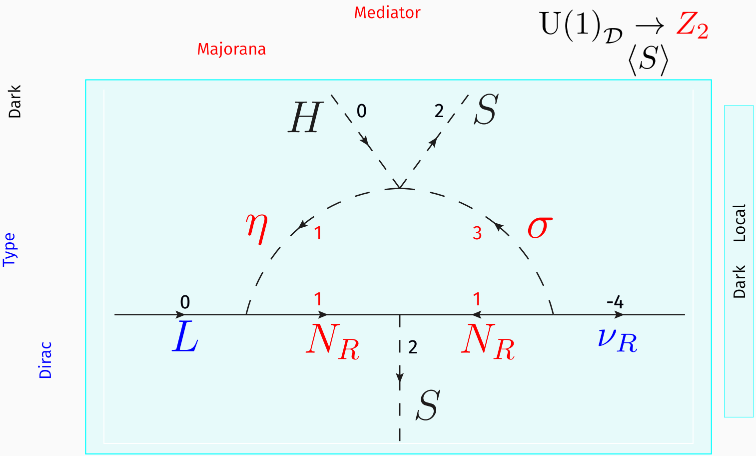
Dirac Radiative Type-I seesaw with Majorana mediators with J. Calle and Ó. Zapata, arXiv:1909.09574



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

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

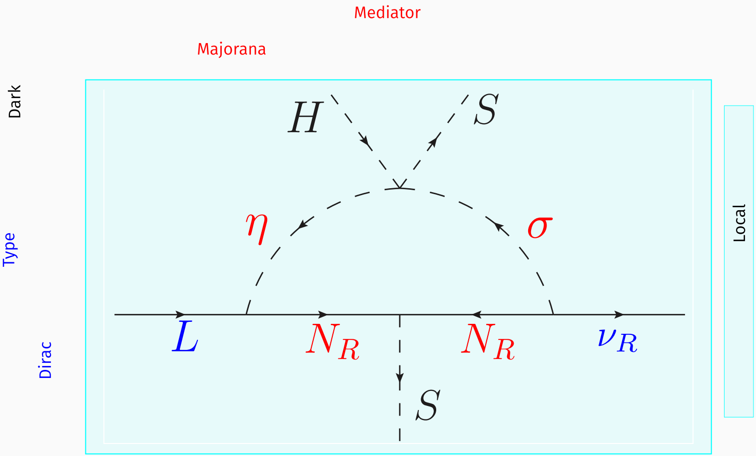
Dirac Radiative Type-I seesaw with Majorana mediators with J. Calle and Ó. Zapata, arXiv:1909.09574



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

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

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	$3/4$[13]

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

Mediator

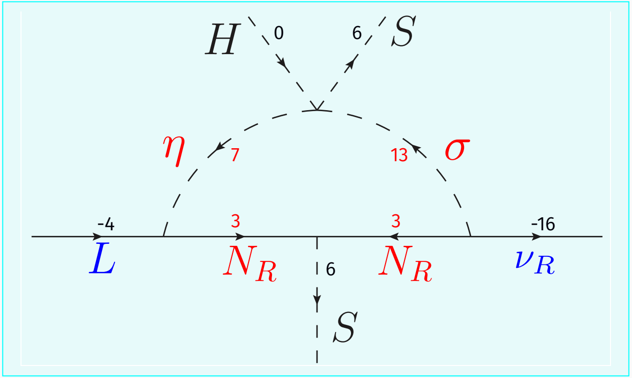
Majorana

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

Dark

Type

Dirac



Local

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

Fields	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{B-L}$
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

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

F (ϕ) denote the new fermions (scalars)

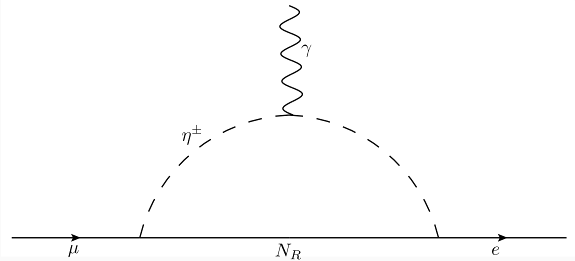
$$\begin{aligned}
\mathcal{V}(H, S, \eta, \sigma) =& V(H) + V(S) + V(\eta) + V(\sigma) \\
&+ \lambda_{HS}(H^\dagger H)(S^* S) + \lambda_2 (H^\dagger H)(\sigma^* \sigma) + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) \\
&+ \lambda_4 (S^* S)(\sigma^* \sigma) + \lambda_5 (S^* S)(\eta^\dagger \eta) + \lambda_6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

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

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

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

Dark radiation portal

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

Dark scalar portal

Scotogenic DM

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

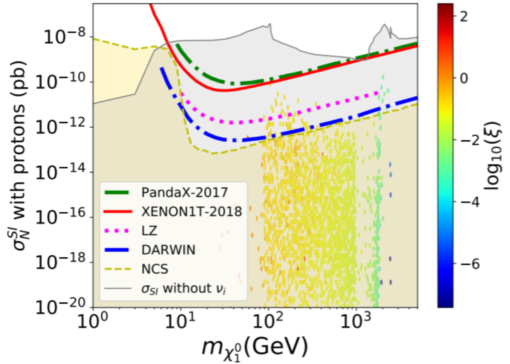
A. Ibarra, C. Yaguna, Ó. Zapata,
arXiv:1601.01163 [PRD]

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

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

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

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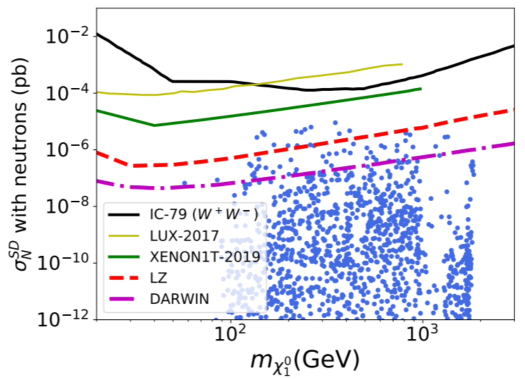

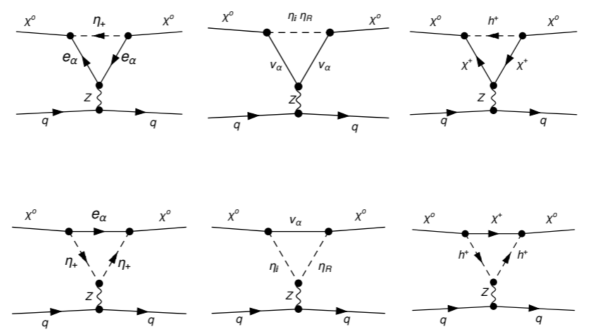

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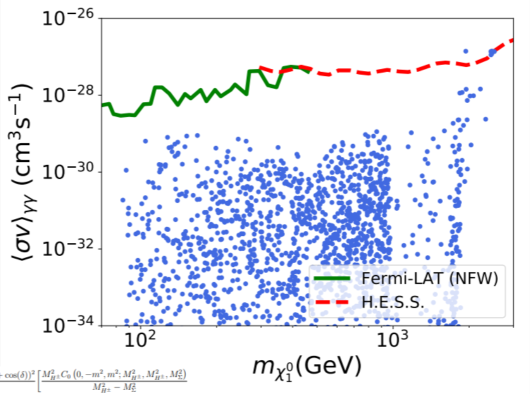


$$\sigma v \left(\chi_1^0 \chi_1^0 \to \gamma\gamma\right) = \frac{|\mathcal{B}|^2}{32\pi m_{\chi_1^0}^2}$$

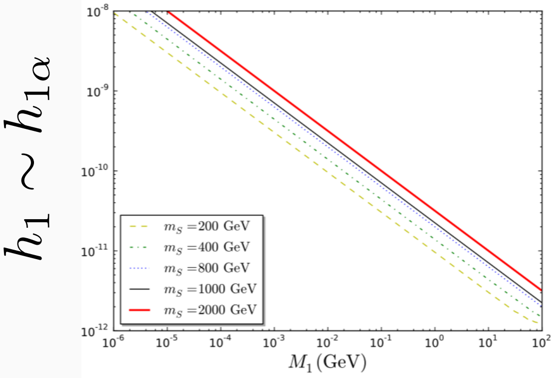
$$\begin{aligned}
\mathcal{B} = {} & \frac{\sqrt{2}\alpha m^2 \sin^2(\alpha) Y_\Omega^2 (\sin(\delta)+\cos(\delta))^2}{\pi}\left[\frac{M_{H^\pm}^2 C_0\left(0,-m^2,m^2;M_{H^\pm}^2,M_{H^\pm}^2,M_\Sigma^2\right)}{M_{H^\pm}^2-M_\Sigma^2}\right. \\
& -\frac{M_\Sigma\left(-2mM_{H^\pm}^2-M_\Sigma M_{H^\pm}^2+m^2M_\Sigma+2mM_\Sigma^2+M_\Sigma^3\right)C_0\left(0,-m^2,m^2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



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

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

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

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

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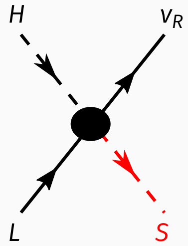
- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

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

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



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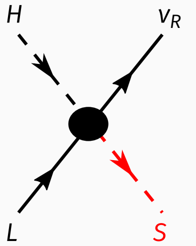


- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\mathrm{eff}} = N_{\mathrm{eff}} - N_{\mathrm{eff}}^{\mathrm{SM}}$ (see arXiv:1211.0186)

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

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

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

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

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

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

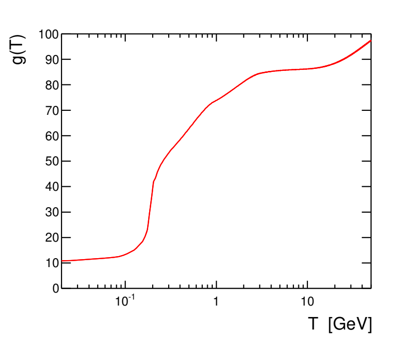
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s\,.$$

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

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



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

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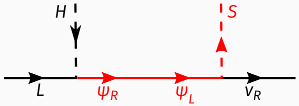
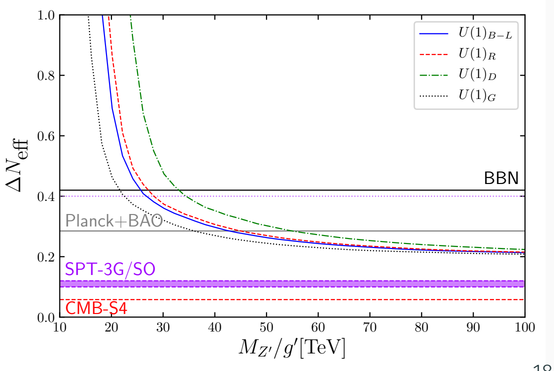


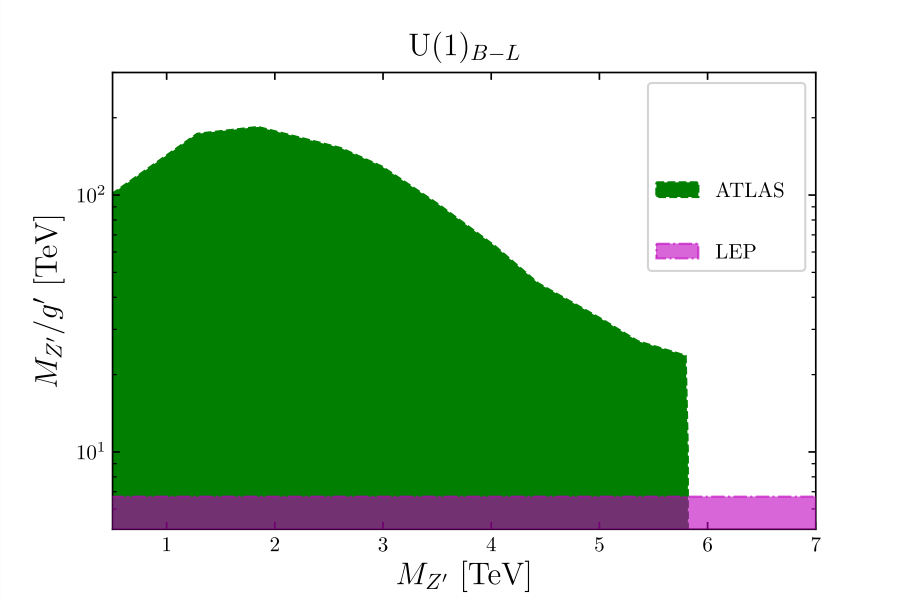
ν_{R3}	ν_{R2}	ν_{R1}	ψ_L	ψ_R	S
-4	-4	$+5$	-1	-1	$+3$

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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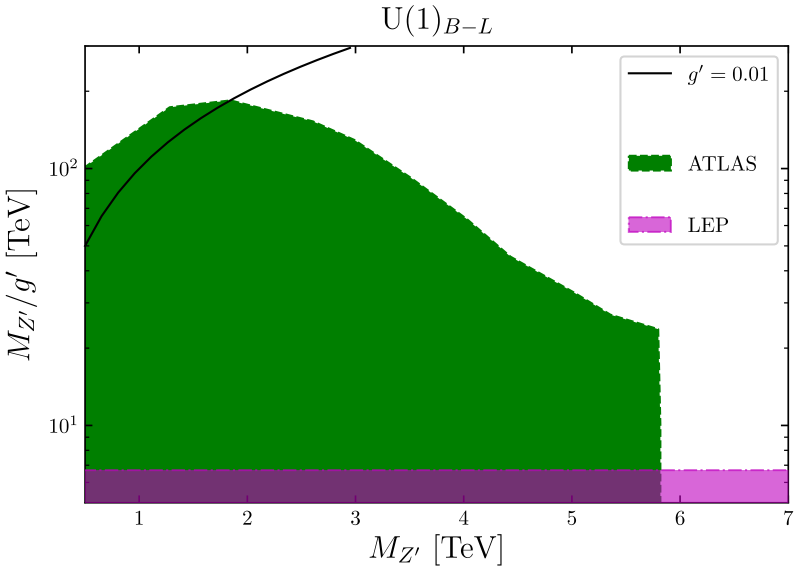

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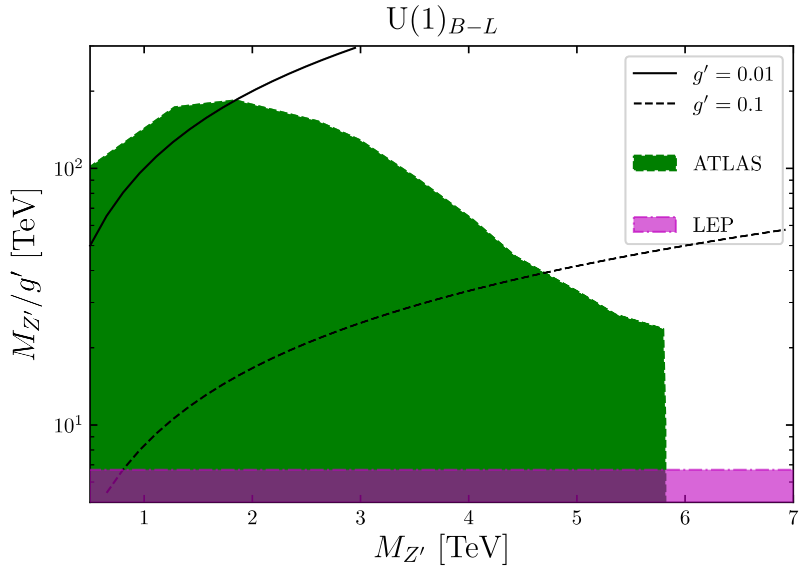

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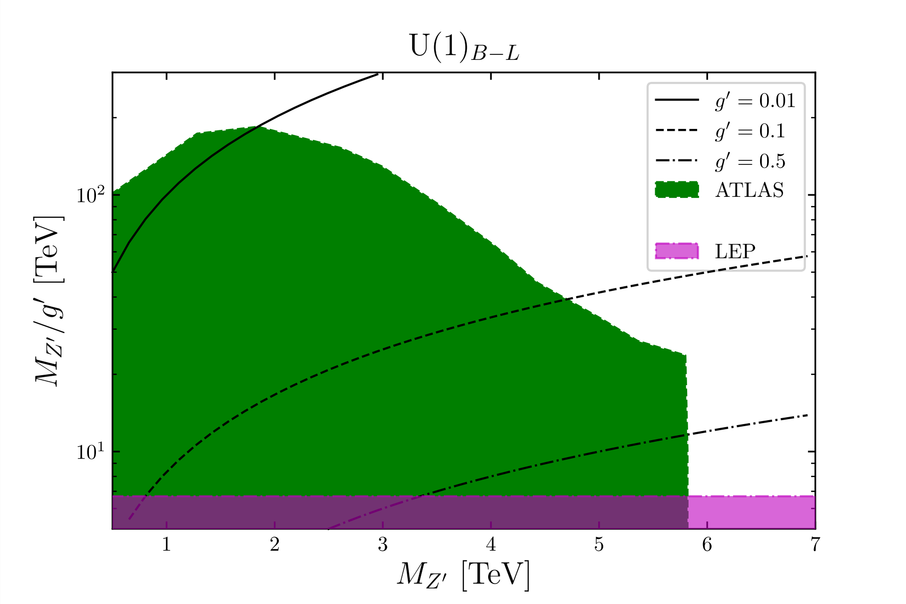

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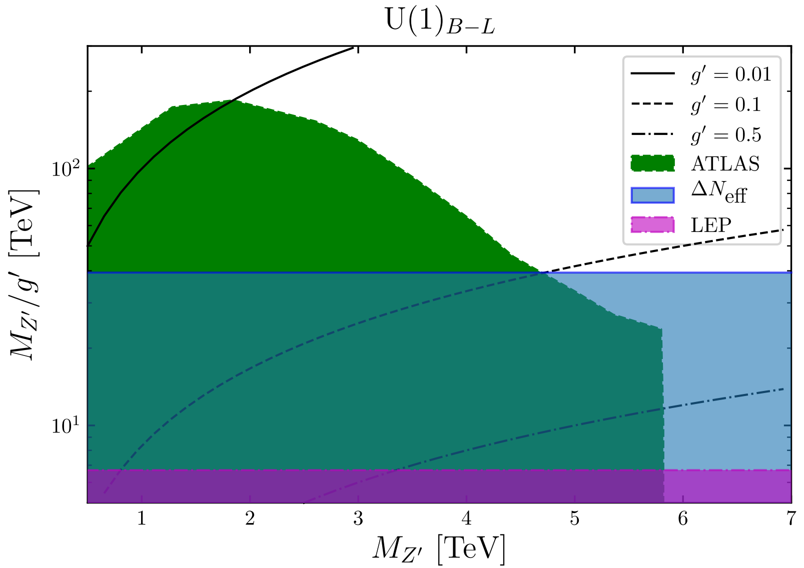

Conclusions

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

Thanks!