

# Minimal Scotogenic models

## with Dirac neutrino masses



UNIVERSIDAD DE ANTIOQUIA  
1803

Diego Restrepo

Oct 16, 2019 - ICTP-SAIFR Program on Particle Physics  
[PDF: <http://bit.ly/darkictp>]

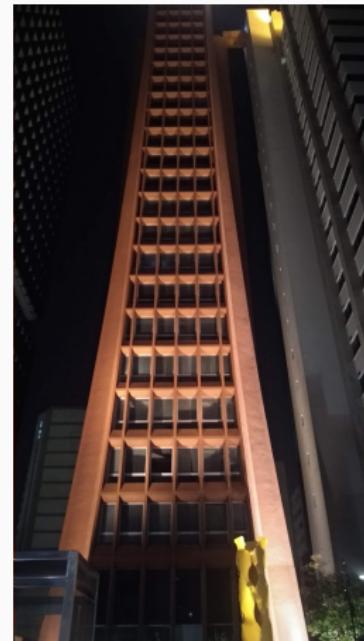
Instituto de Física  
Universidad de Antioquia  
Phenomenology Group  
<http://gfif.udea.edu.co>

### Focus on

arXiv:1811.11927 [PRD], arXiv:1906.09685 [PRD] and arXiv:1909.09574

### In collaboration with

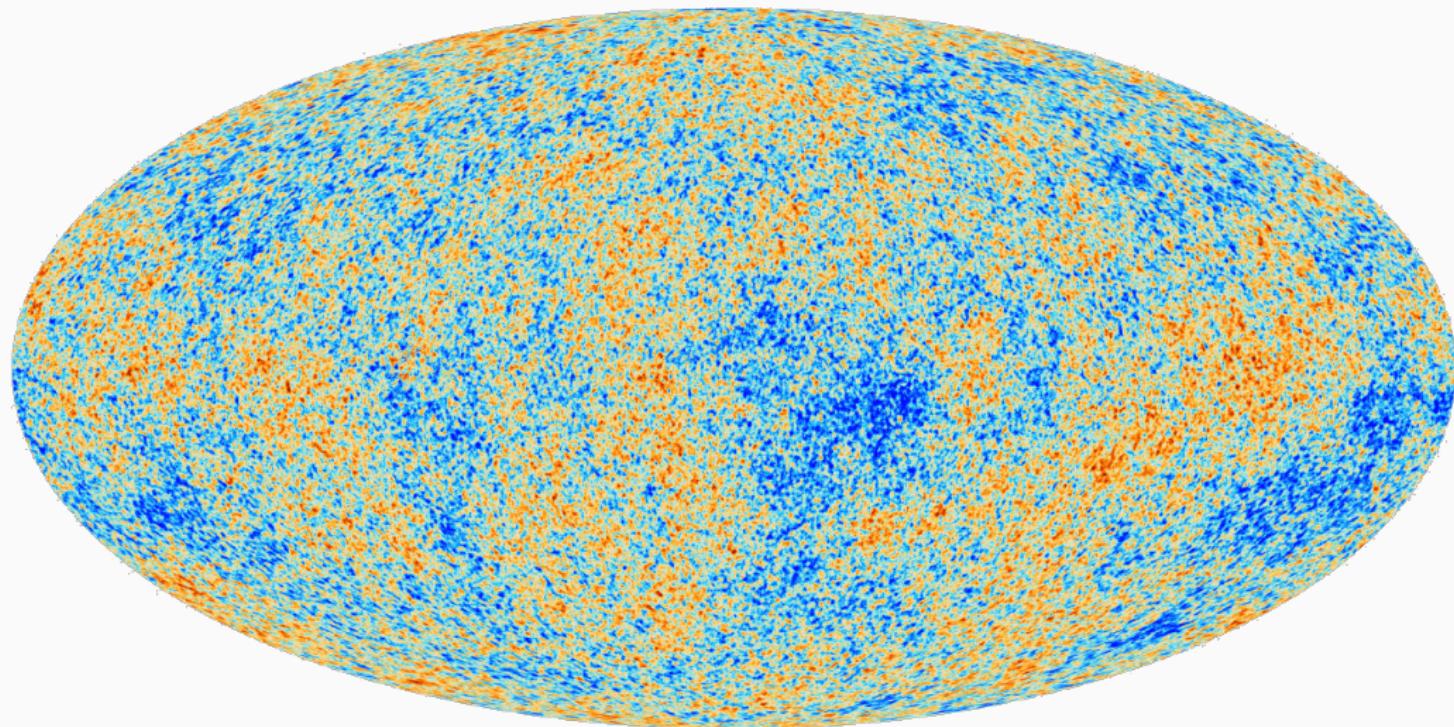
Carlos Yaguna (UPTC), Julian Calle, Óscar Zapata, Andrés Rivera (UdeA),  
Walter Tangarife (Loyola University Chicago)



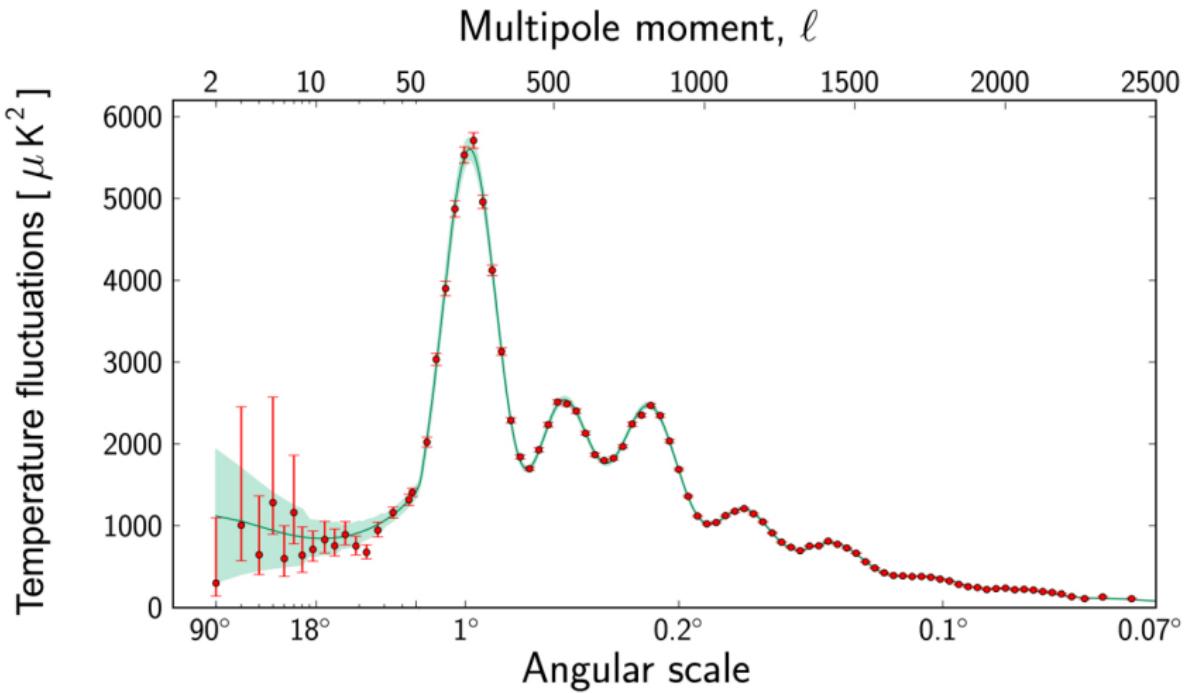
$\Lambda$ CDM paradigm (with baryonic effects)

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



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

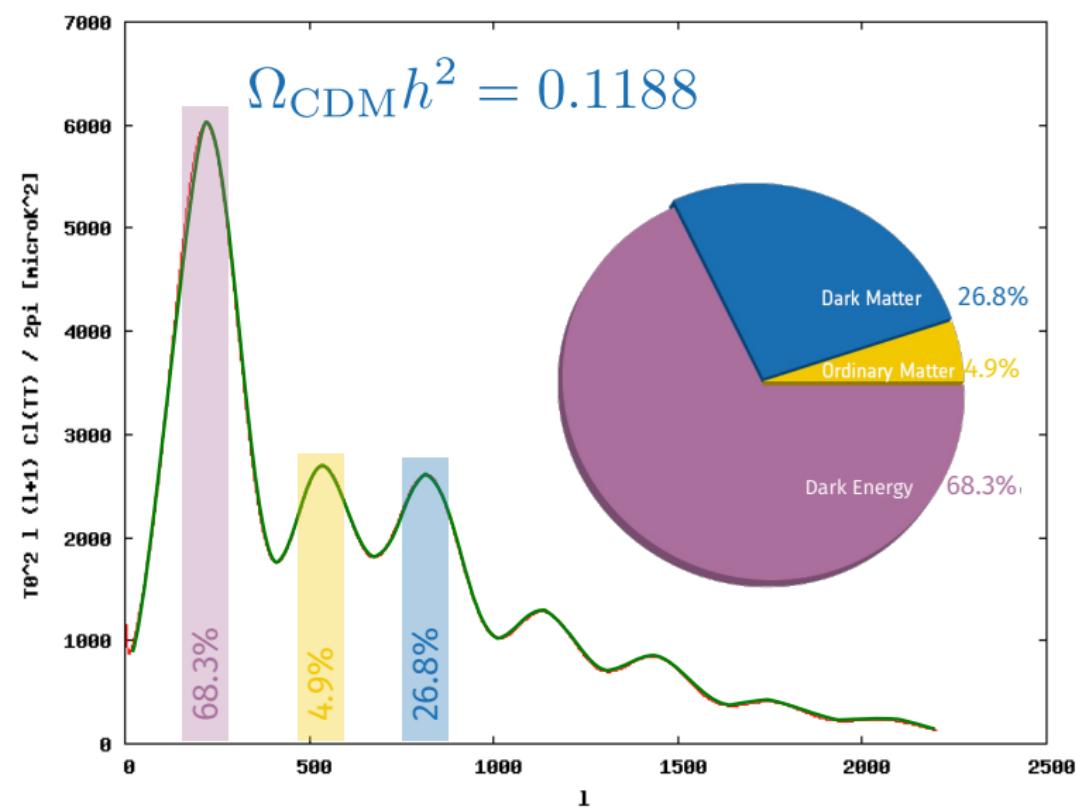


Planck's power spectrum of temperature fluctuations,  $\Delta T$ , in the Cosmic Microwave Background. Credit: ESA and the Planck Collaboration

$\Lambda\text{CDM}$ :  $\Omega = 1$ ,  $w = -1^\dagger$

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)
$\Delta_R^2$	$2.441 \times 10^{-9}$
$\tau$	0.066(12)

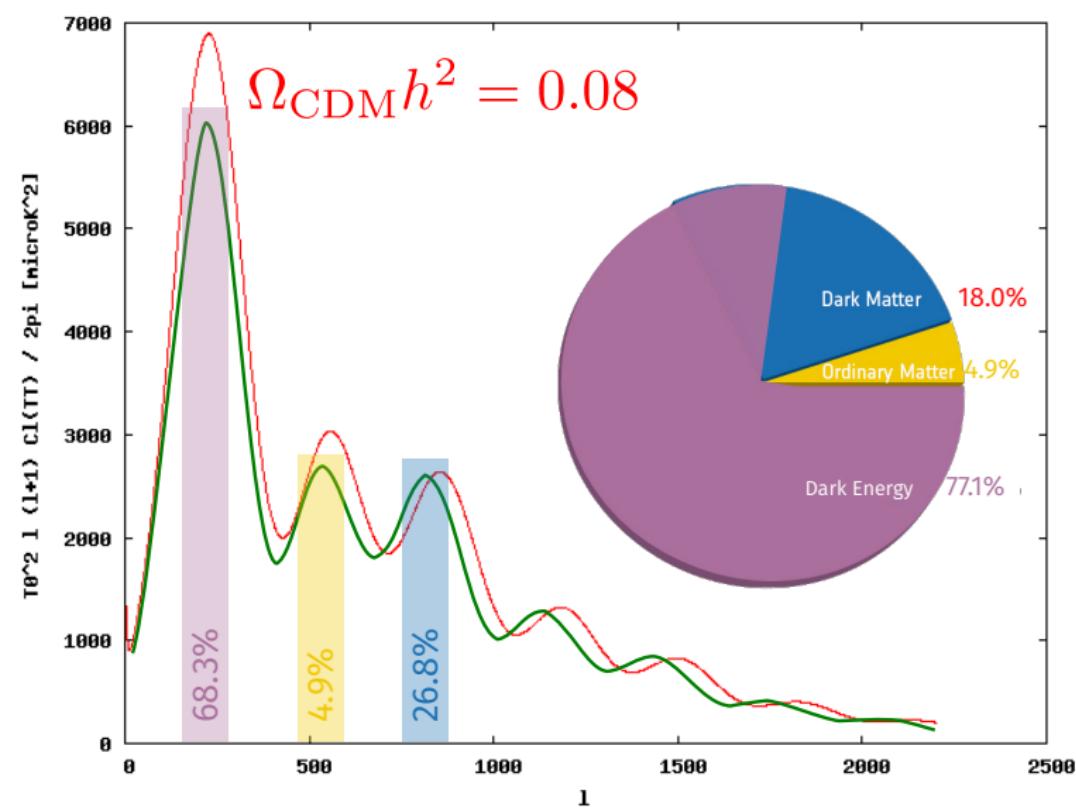
$^\dagger$  Cosmological constant



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# Cosmic Miso Soup

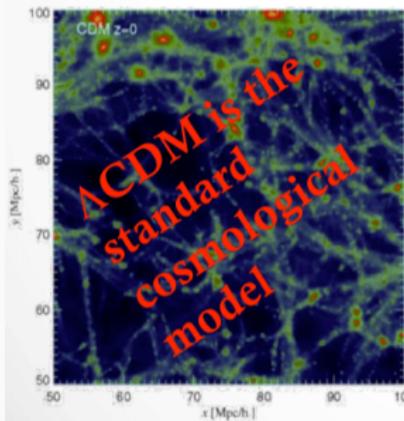
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching how ripples are created and propagate throughout the soup



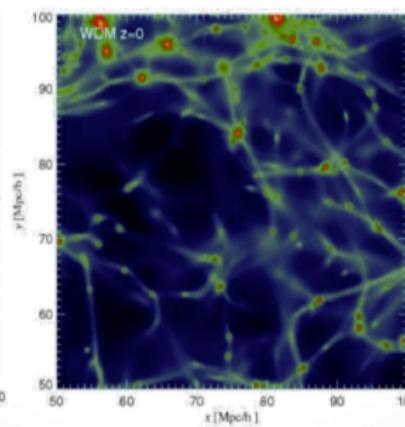
Nobu São Paulo version

# Large scale structure simulations: Gas of not hot and almost collisionless dark matter particles

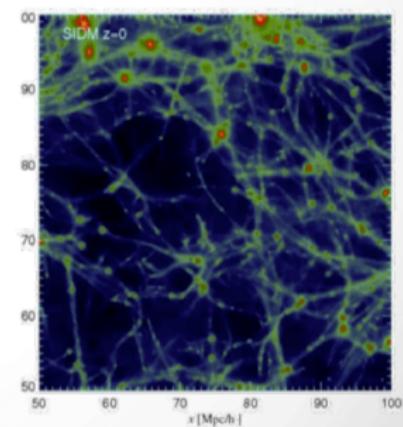
Cold Dark Matter  
(Slow moving)  
 $m \sim \text{GeV-TeV}$   
Small structures form first, then merge



Warm Dark Matter  
(Fast moving)  
 $m \sim \text{keV}$   
Small structures are erased



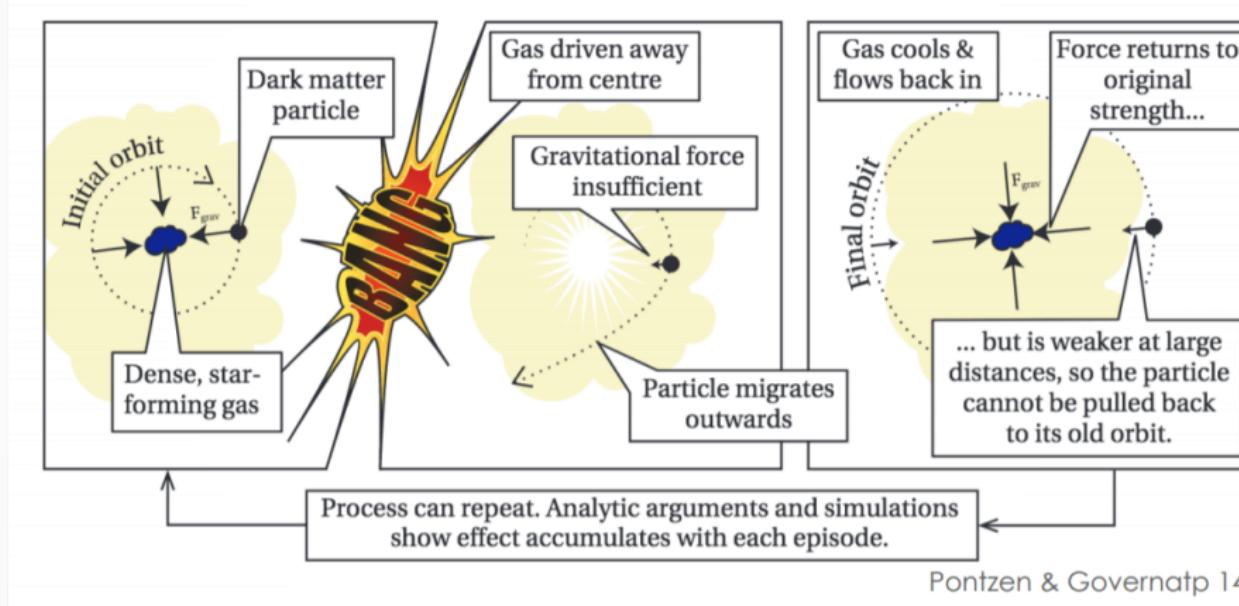
Self-Interacting Dark Matter  
Strongly interact with itself  
Large scale similar to CDM,  
Small galaxies are different



Credit: Arianna Di Cintio (Conference on Shedding Light on the Dark Universe with Extremely Large Telescopes, ICTP - 2018)

**Particle:** from elementary sub-eV to Primordial Black Hole of several solar masses

# Baryonic effects



Pontzen & Governato 14

Once the effect of baryonic physics is included, it is **hard to distinguish between WDM/SIDM/CDM**

- For a review see: Gravitational probes of dark matter physics, M.R. Buckley, *et al*, arXiv:1712.06615 [PR]
- Distinguish WDM/CDM with subhaloes detection: See arXiv:1910.06617

## Cosmic web

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Dark matter in the universe evolves through gravity to form a complex network of halos, filaments, sheets and voids, that is known as the cosmic web

A.C Rodriguez *et al* arXiv:1801.09070 [CAC]

Cosmological simulations of structure formation predict that the majority of gas in the intergalactic medium (IGM) is distributed in a cosmic web of sheets and filaments as a consequence of gravitational collapse. The intersections of these structures become the locations at which galaxies and their supermassive black holes (SMBHs) form and evolve.

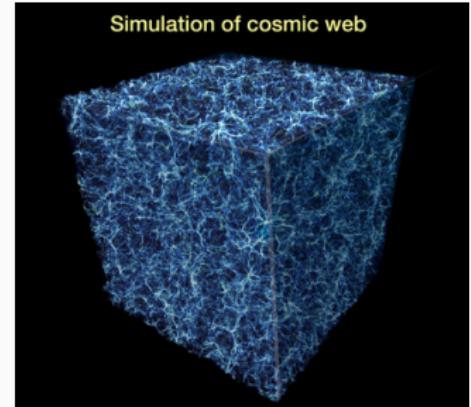
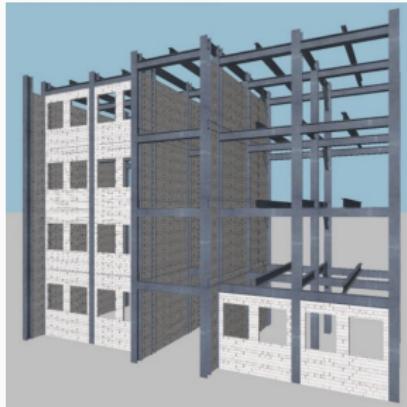
[...] 60% of all gas in the Universe resides in filaments

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

## Cooking the soup: Cosmic web

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

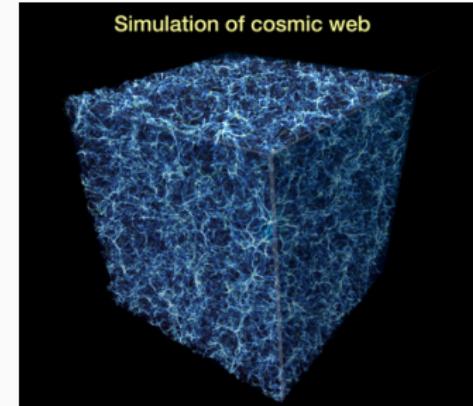
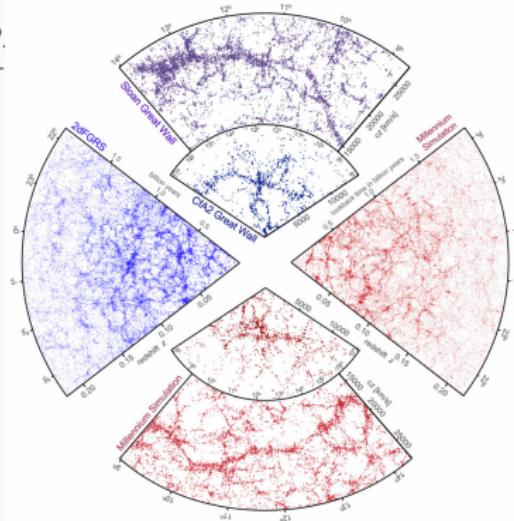
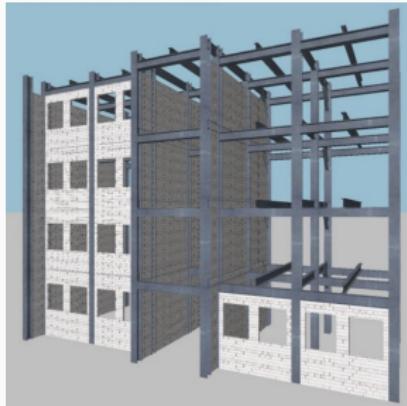
<https://phys.org/news/2018-06-years-scientists-account-universe.html>



# Cooking the soup: Cosmic web

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

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

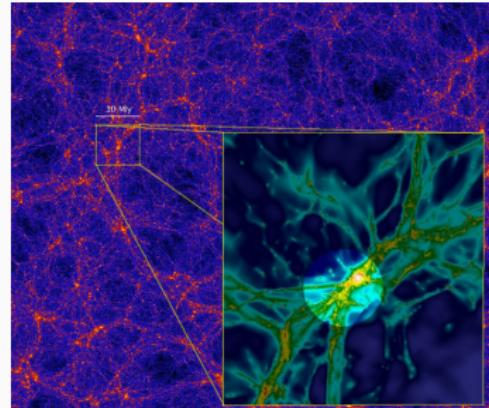
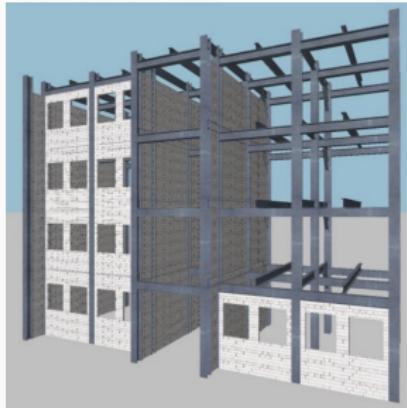


Galaxy redshift surveys vs large scale structure formation simulations: V. Springel, et al [astro-ph/0604561](#) [Nature]

# Cooking the soup: Cosmic web

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

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



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

An excess of a gas ( $20\sigma$ ) is observed between Milky Way and Andromeda (M31): arXiv:1403.7528 [MNRAS]<sup>1</sup>

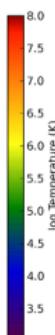
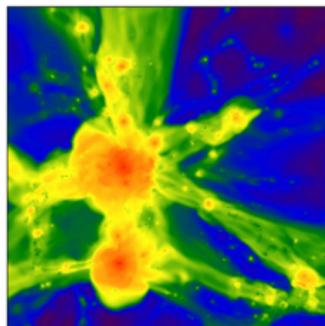
Clouds of HI likely embedded in a filament between M31 and M33: arXiv:1305.1631 [nature]

<sup>1</sup> See also: arXiv:1603.05400 [A&A]

# Direct observations of filaments

## Where are the Baryons? (Cen, Ostriker, astro-ph/9806281 [AJ])

*Thus, not only is the universe dominated by dark matter, but more than one half of the normal matter is yet to be detected. (the muscles)*



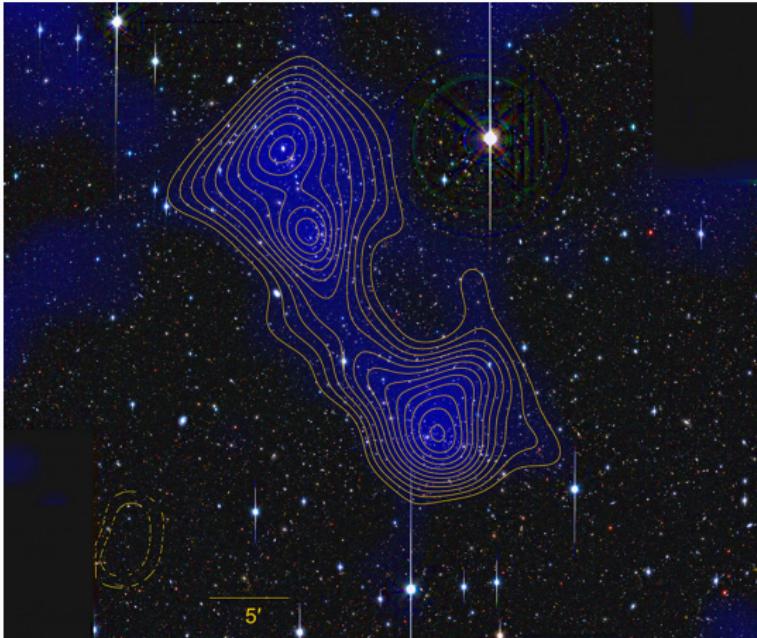
Warm-hot intergalactic medium (WHIM)  
Density-weighted temperature projection of a portion of the refinement box of the C run of size  $(18 h^{-1}\text{Mpc})^3$ .  
Low temperature WHIM confirmed by O VI line that peak at  $T \sim 3 \times 10^5 \text{ K}$

Credit: Cen, arXiv:1112.4527 [AJ]



Hotter phases of the WHIM: Observations of the missing baryons in the warm-hot intergalactic medium (Nicastro, et al. arXiv:1806.08395 [Nature]).

# A filament of dark matter between two clusters of galaxies



Supercluster system of three galaxy clusters

- Abell 222 (south) detected at  $\sim 8\sigma$
- Abell 223 (north) double galaxy cluster seen at  $\sim 7\sigma$

reconstructed surface mass density (blue)

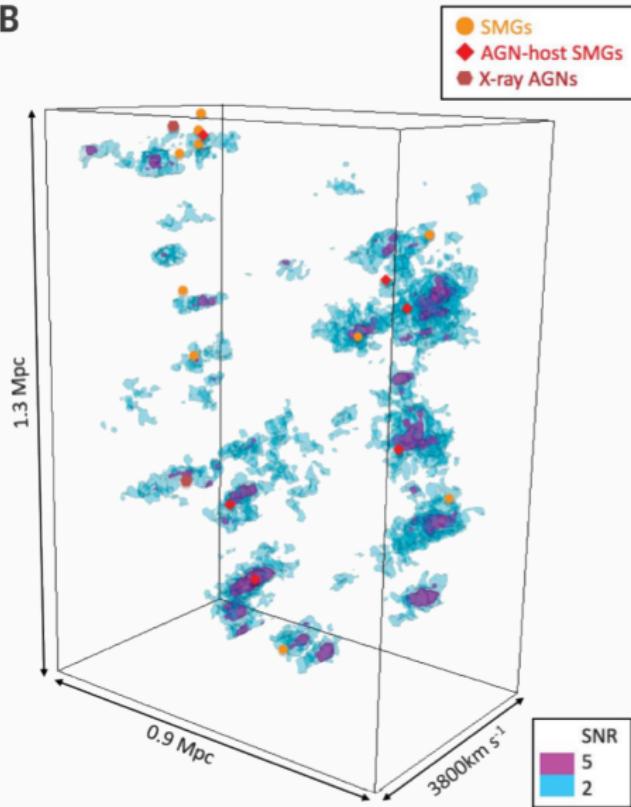
significance contours from  $0.5\sigma$  to  $2.5\sigma$

J.P. Dietrich *et al*, arXiv:1207.0809 [Nature]

For a recent review see: arXiv:1905.08991

# Three-dimensional pictures of Ly $\alpha$ filaments

B



The 3D distribution of Ly $\alpha$  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.*

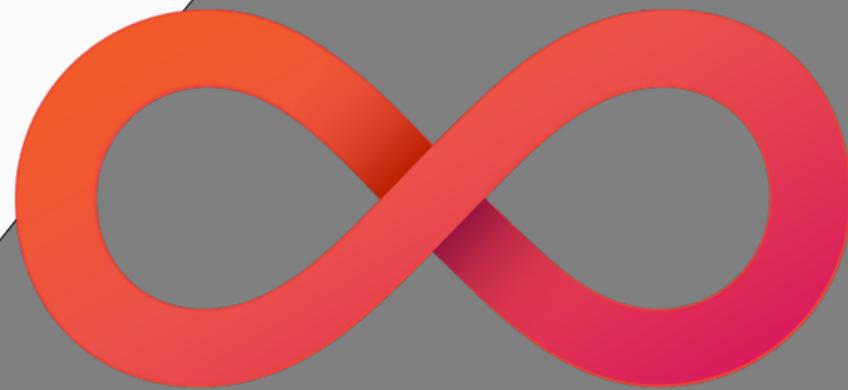
*Agrawal, et al, arXiv:1610.04611 [JCAP]*

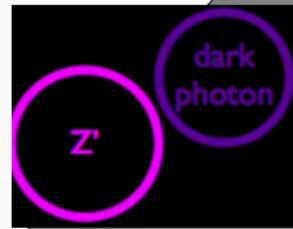
## Dark sectors

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## Dark sectors

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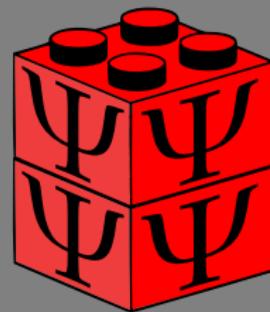


# Local $U(1)_{\mathcal{D}}$

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

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

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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	$h$
$\psi$	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  $\sum n_\alpha = 0$  and  $\sum n_\alpha^3 = 0$

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## 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 <sup>†</sup>

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

<sup>†</sup> 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](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

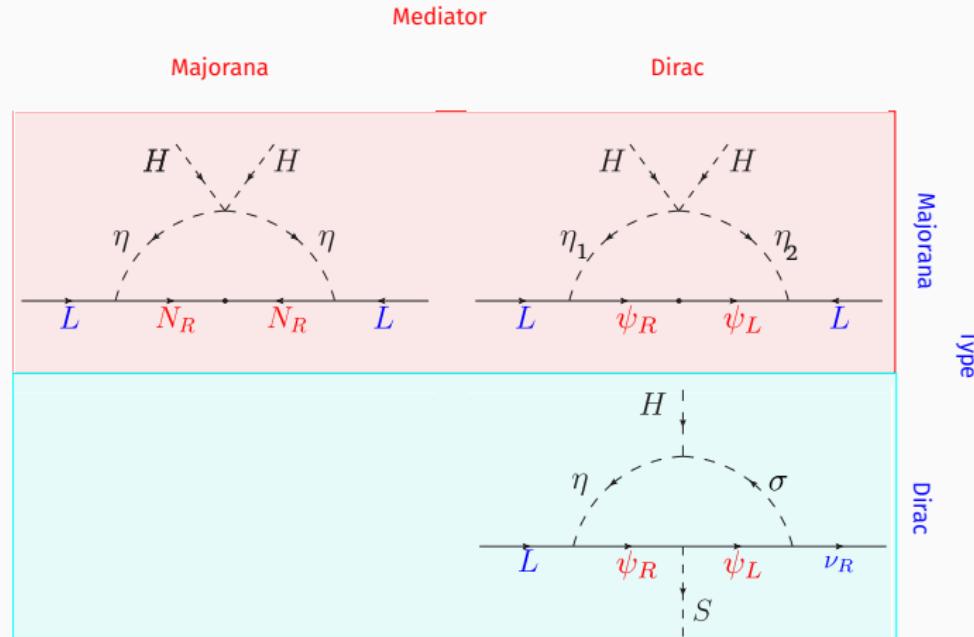
$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \dots)$	Ref
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$\left(-\frac{5}{3}, -\frac{5}{3}, -\frac{7}{3}, \frac{8}{3}\right)$	In progress...   method <sup>†</sup>

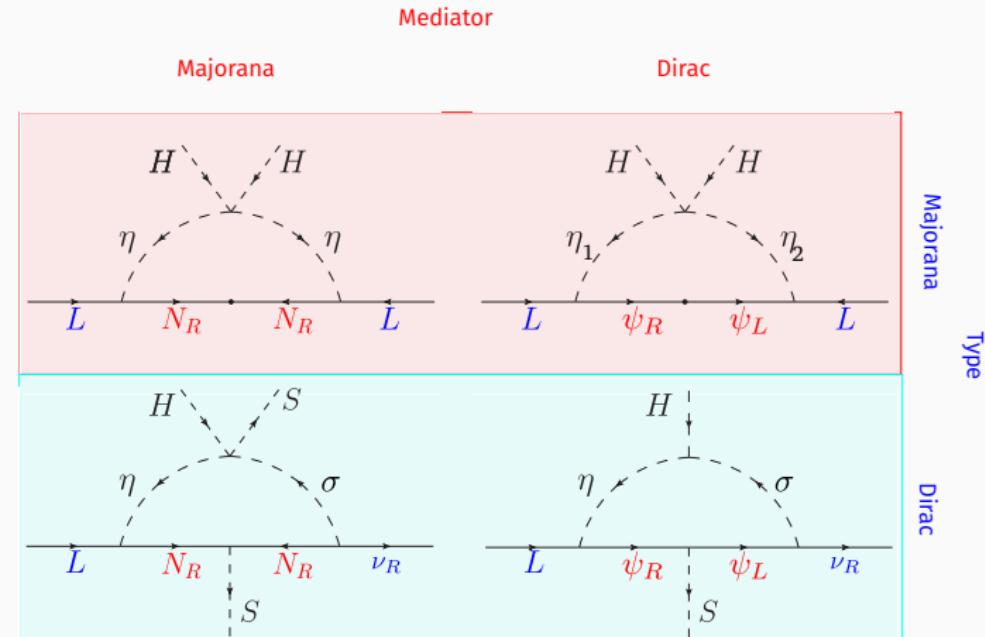
Not known solution for  
one-loop neutrino Majorana masses  
with local  $U(1)_X$ .

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

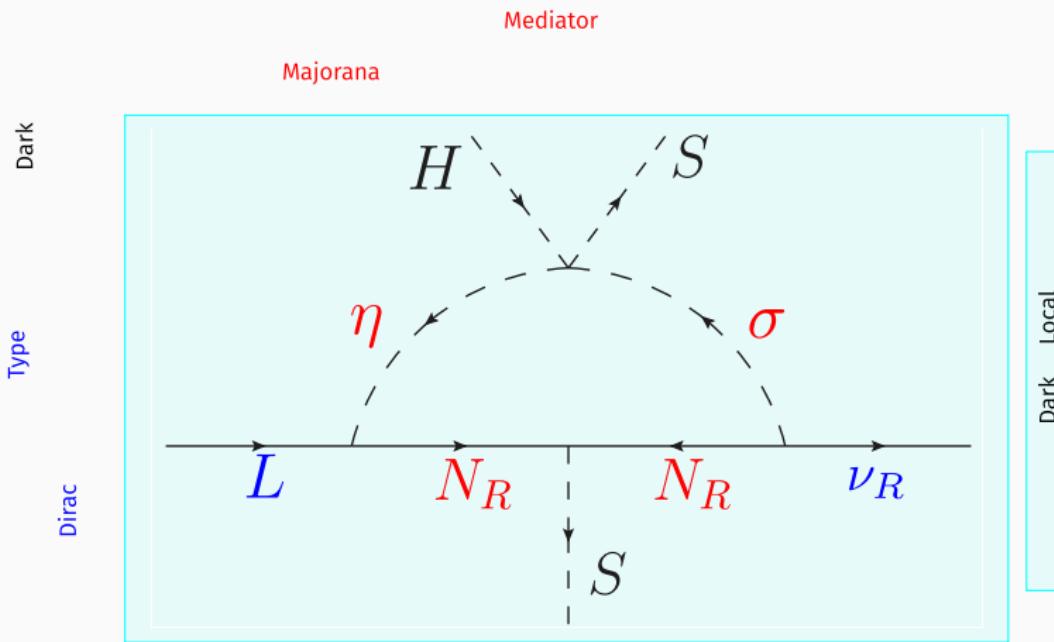
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# Radiative Type-I seesaw





# Radiative Type-I seesaw

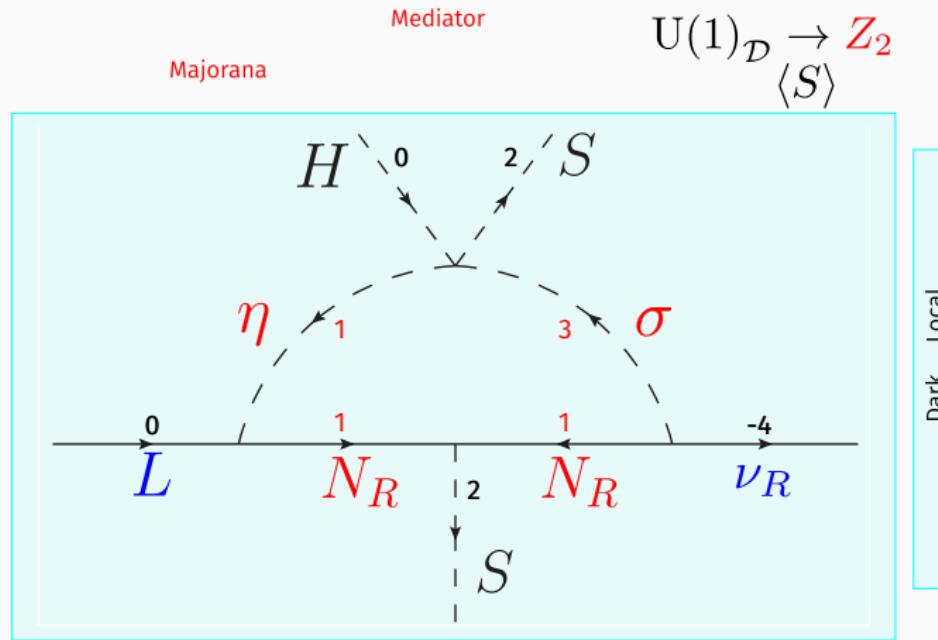


$$N = -\frac{\nu}{4} \quad , \quad \eta = -\frac{\nu}{4} \quad , \quad \sigma = -\frac{3\nu}{4} \quad .$$

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

# Radiative Type-I seesaw

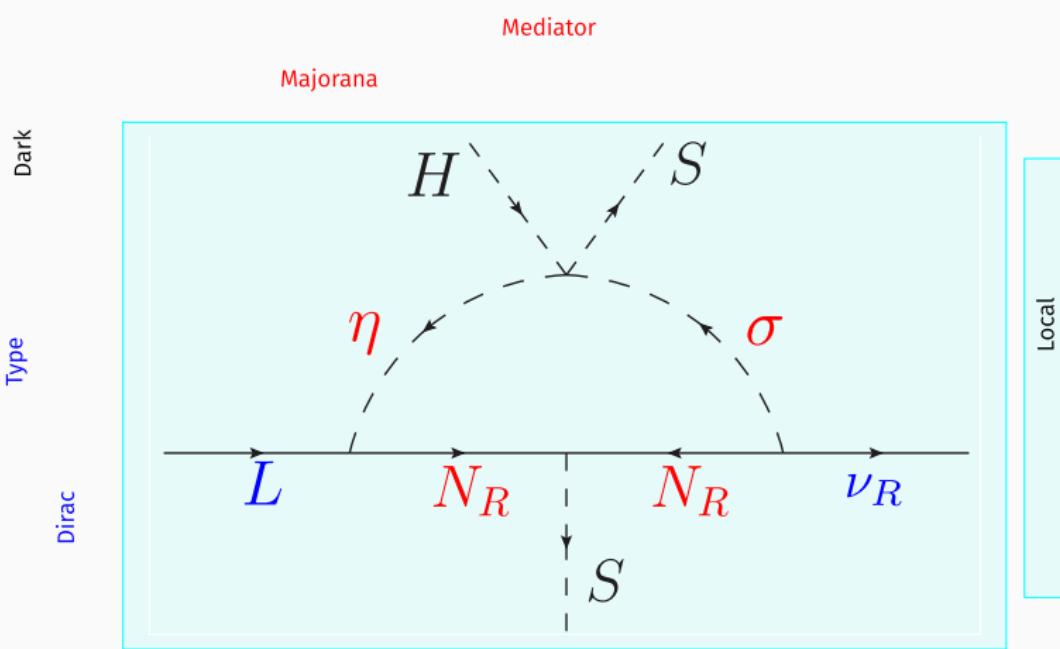
Dark  
Type  
Dirac



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

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

# Radiative Type-I seesaw

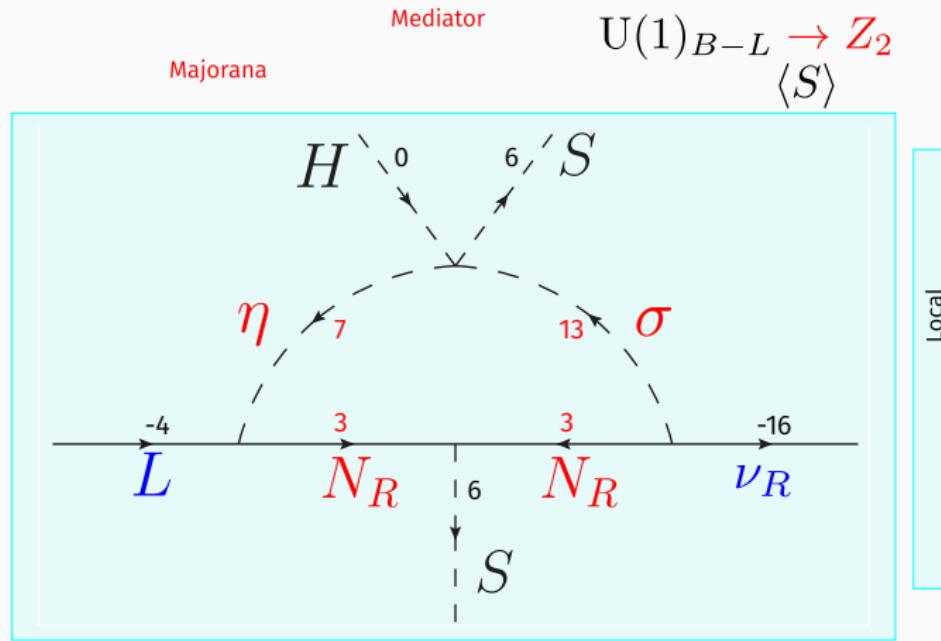


$$N = -\frac{\nu}{4} - \frac{1}{4}, \quad \eta = -\frac{\nu}{4} - \frac{1}{4} - l, \quad \sigma = -\frac{3\nu}{4} + \frac{1}{4}.$$

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	$-1-l$
$\eta$	2	1/2	$3/4-l$
$S$	1	0	$3/2$
$\sigma$	1	0	$13/4$
$\nu_{R1}$	1	0	-4
$\nu_{R2}$	1	0	-4
$\nu_{R3}$	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	$3/4^{19}$

# Radiative Type-I seesaw

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	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$
$L$	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
$\eta$	2	1/2	7/4
$S$	1	0	3/2
$\sigma$	1	0	13/4
$\nu_{R1}$	1	0	-4
$\nu_{R2}$	1	0	-4
$\nu_{R3}$	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

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

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

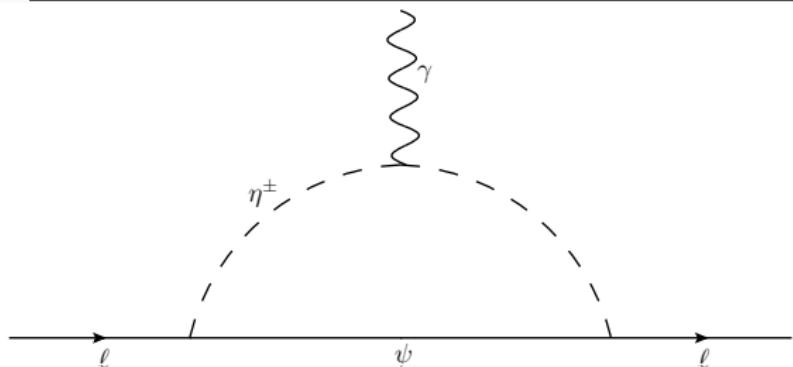
$$\begin{aligned}\mathcal{V}(H, S, \eta, \sigma) = & V(H) + V(S) + V(\eta) + V(\sigma) \\ & + \lambda_{HS} (H^\dagger H)(S^* S) + \lambda_2 (H^\dagger H)(\sigma^* \sigma) + \lambda_3 (H^\dagger H)(\eta^\dagger \eta) \\ & + \lambda_4 (S^* S)(\sigma^* \sigma) + \lambda_5 (S^* S)(\eta^\dagger \eta) + \lambda_6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

# Neutrino masses and LFV

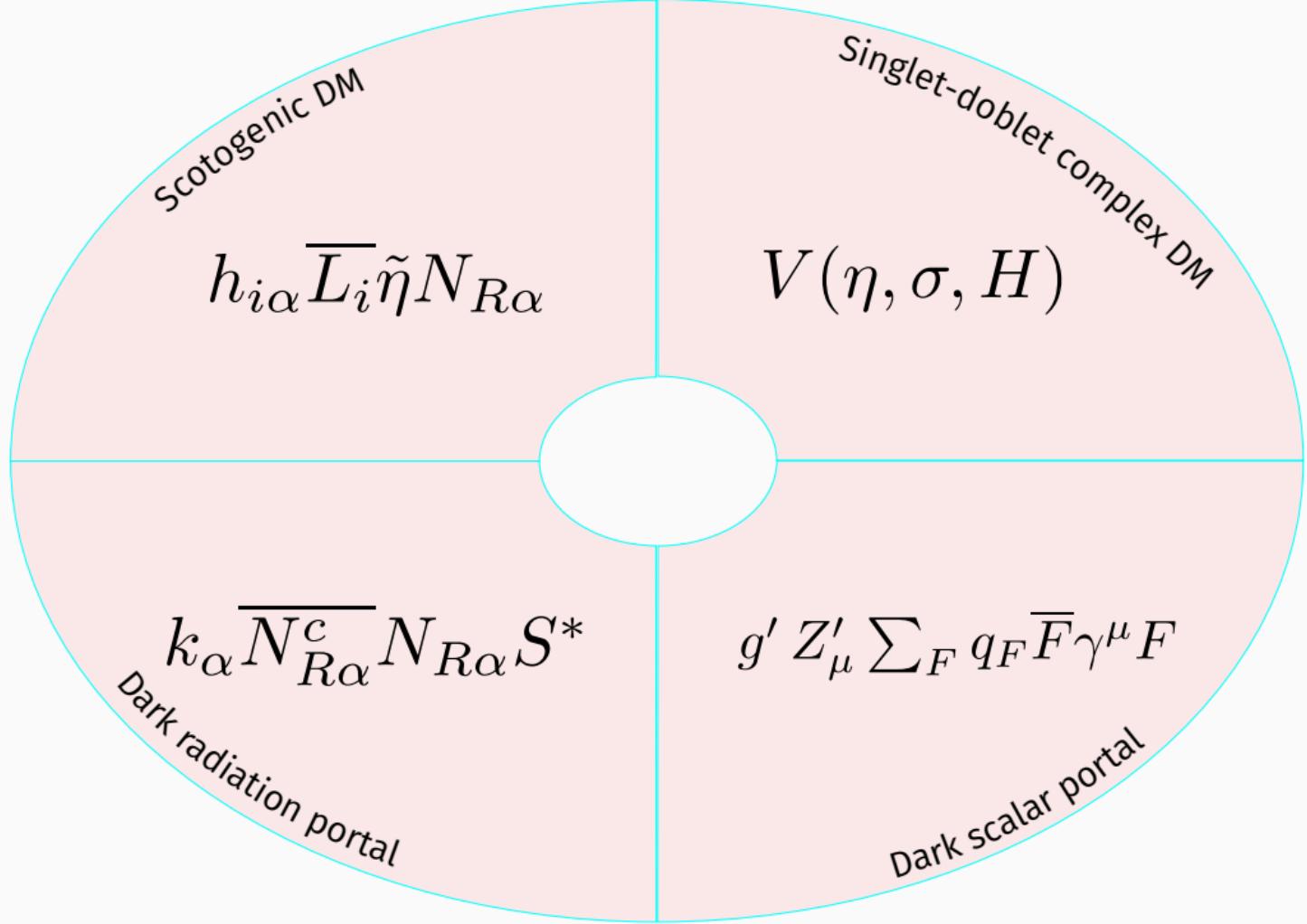
$$(\mathcal{M}_\nu)_{ij} = \frac{1}{32\pi^2} \frac{\lambda_8 v_S^2 v_H}{m_{\eta_R^0}^2 - m_{\sigma_R^0}^2} \sum_{\alpha=1}^3 h_{i\alpha} k_{\alpha} y_{j\alpha}^* \left[ F\left(\frac{m_{\eta_R^0}^2}{M_{N_\alpha}^2}\right) - F\left(\frac{m_{\sigma_R^0}^2}{M_{N_\alpha}^2}\right) \right] + (R \rightarrow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

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

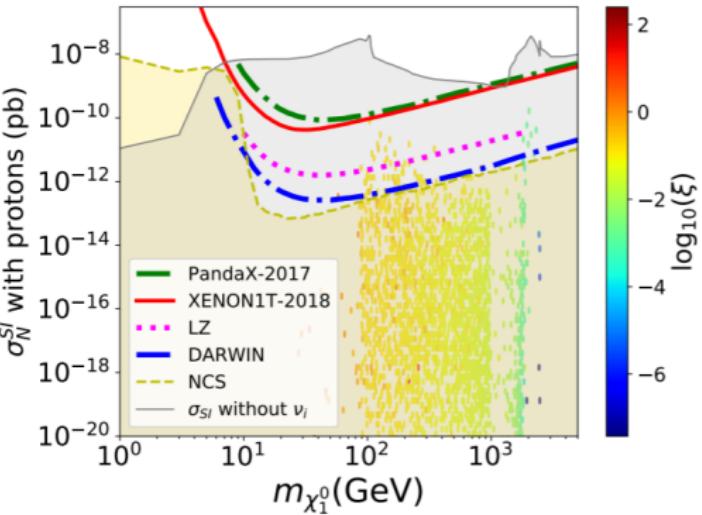
$$h_{i\alpha} \overline{L}_i \tilde{\eta} N_{R\alpha}$$

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



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

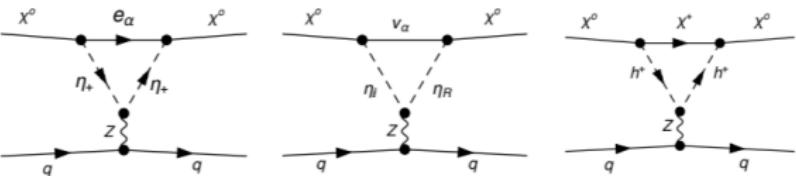
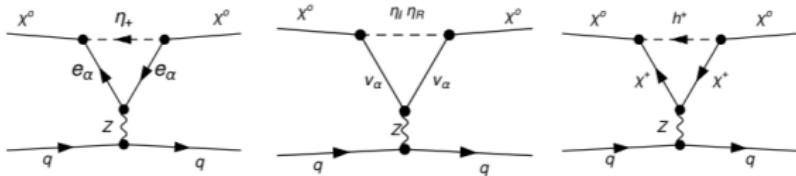
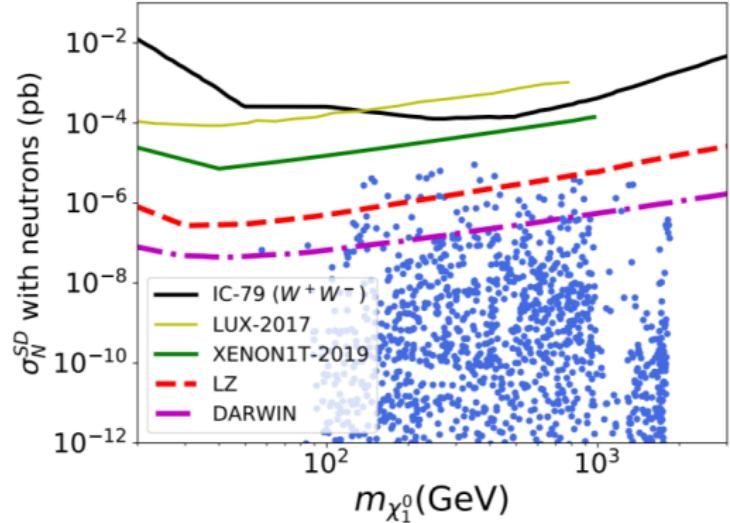
$$\xi = \frac{|M_\Sigma - m_{\chi_1^0}|}{m_{\chi_1^0}}$$

Scotogenic DM

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

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

with A. Rivera, arXiv:1907.11938

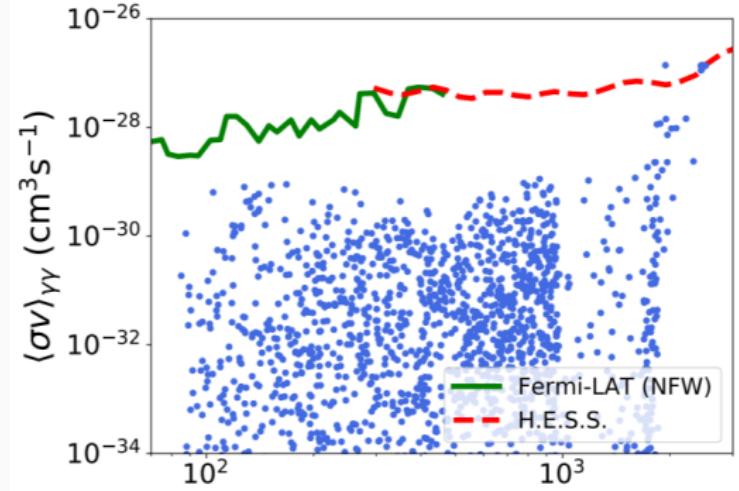


Scotogenic DM

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

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^2 - 3m^2 M_\Sigma + M_\Sigma^2 - M_\Sigma M_W^2) \\ & C_0(0, -m^2, m^2; M_\Sigma^2, M_\Sigma^2, M_W^2) \Big]. \end{aligned}$$

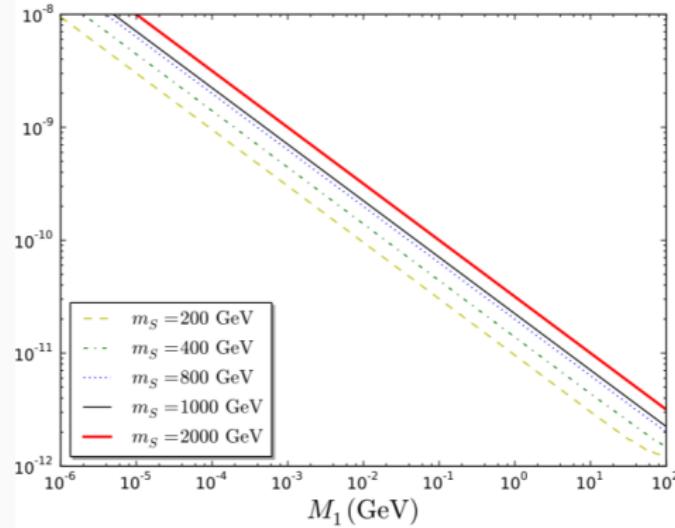
Scotogenic DM

## FIMP Scenario

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

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

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



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

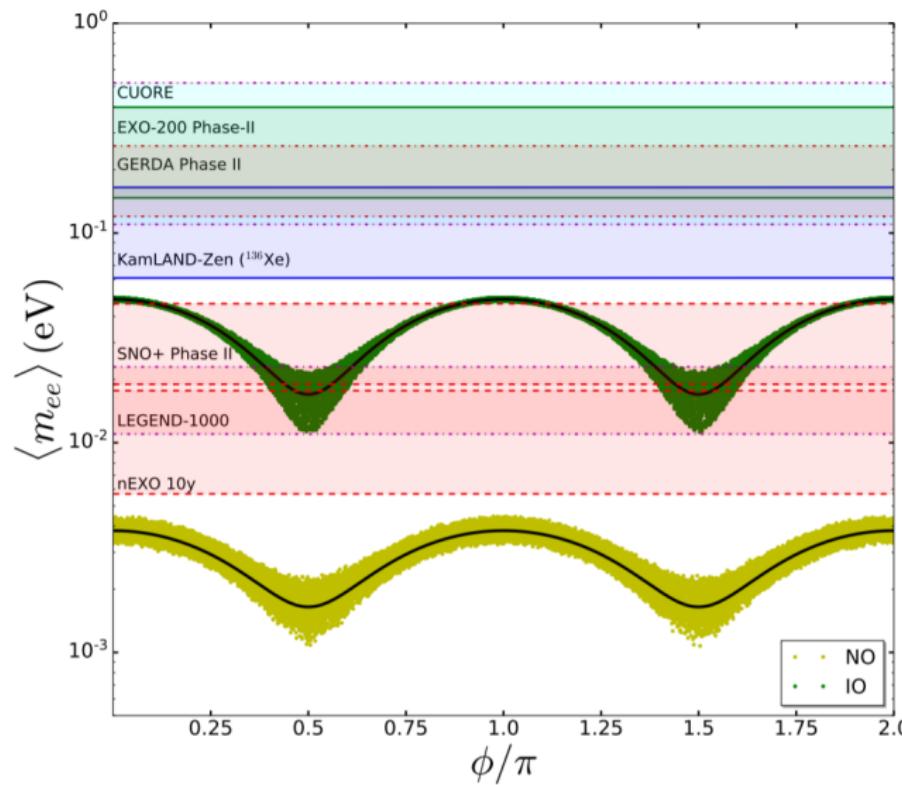
## (One-loop) Dirac neutrino masses

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## Lepton number

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- Lepton number ( $L$ ) is an accidental discrete or Abelian symmetry of the standard model (SM).
- Without neutrino masses  $L_e, L_\mu, L_\tau$  are also conserved.
- The processes which violate individual  $L$  are called Lepton flavor violation (LFV) processes.
- All the neutrino mass models predict, to some extent, LFV processes
- Only models with Majorana neutrinos predict processes with total  $L = L_e + L_\mu + L_\tau$  violation, like **neutrino less doublet beta decay** (NLDBD).
- NLDBD is experimentally challenging, specially if there is a massless neutrino in the spectrum.



Total lepton number:  $L = L_e + L_\mu + L_\tau$

### Majorana $\cancel{U(1)_L}$

Field	$Z_2$ ( $\omega^2 = 1$ )
SM	1
$L$	$\omega$
$(e_R)^\dagger$	$\omega$
$(\nu_R)^\dagger$	$\omega$

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

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

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

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

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

$$h_D \sim \mathcal{O}(10^{-11})$$

Explain smallness ala Peccei-Quinn:

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

## Small Dirac neutrino masses

To explain the **smallness** of Dirac neutrino masses choose  $U(1)_{B-L}$  which:

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

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

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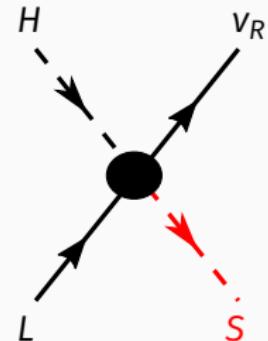
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- Realizes of the 5-dimension operator which conserves lepton number in  $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ :

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



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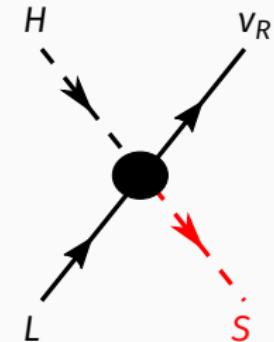
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- Enhancement to the *effective number of degrees of freedom in the early Universe*  $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$  (see arXiv:1211.0186)

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

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

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

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

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

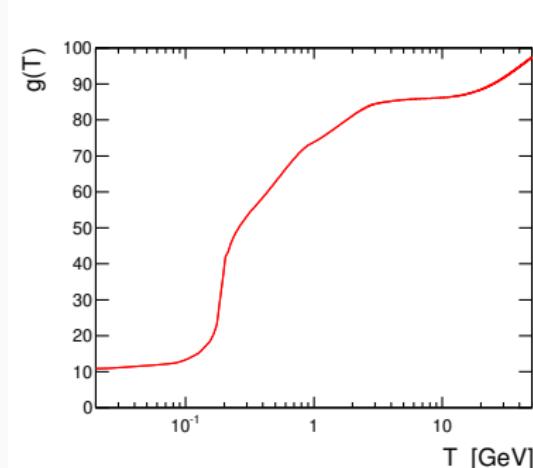
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left( \frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

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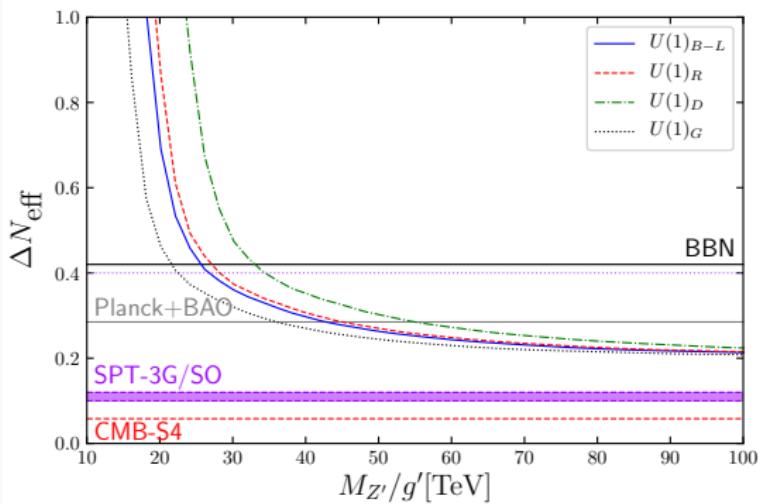
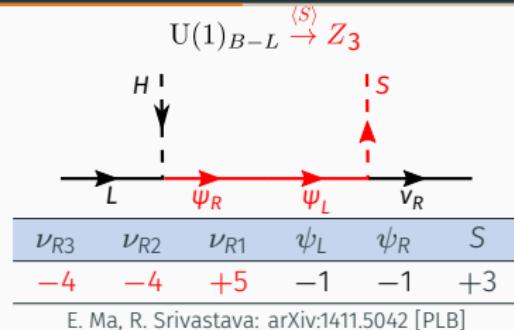
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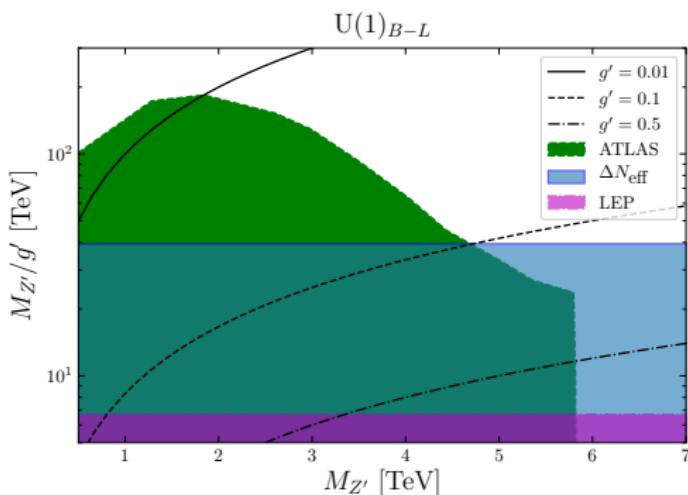
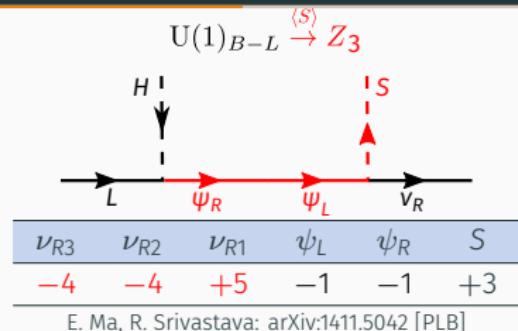
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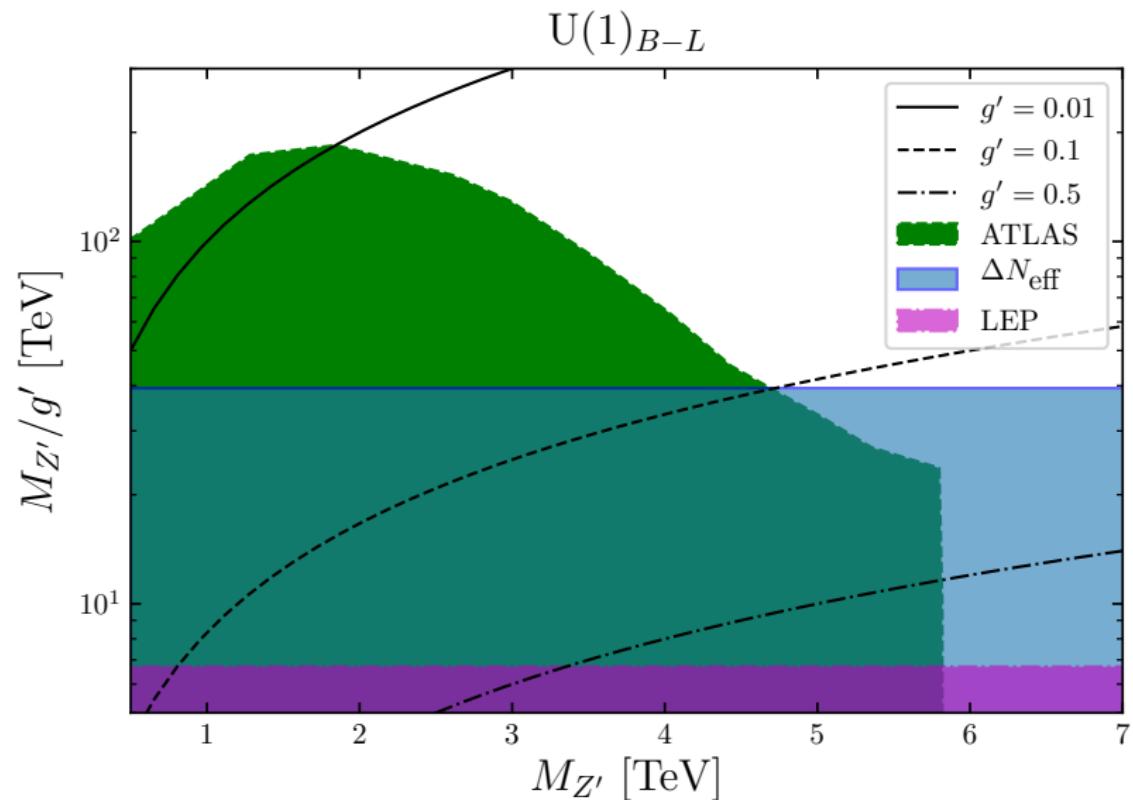
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with J. Calle and Ó. Zapata, arXiv:1909.09574

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

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

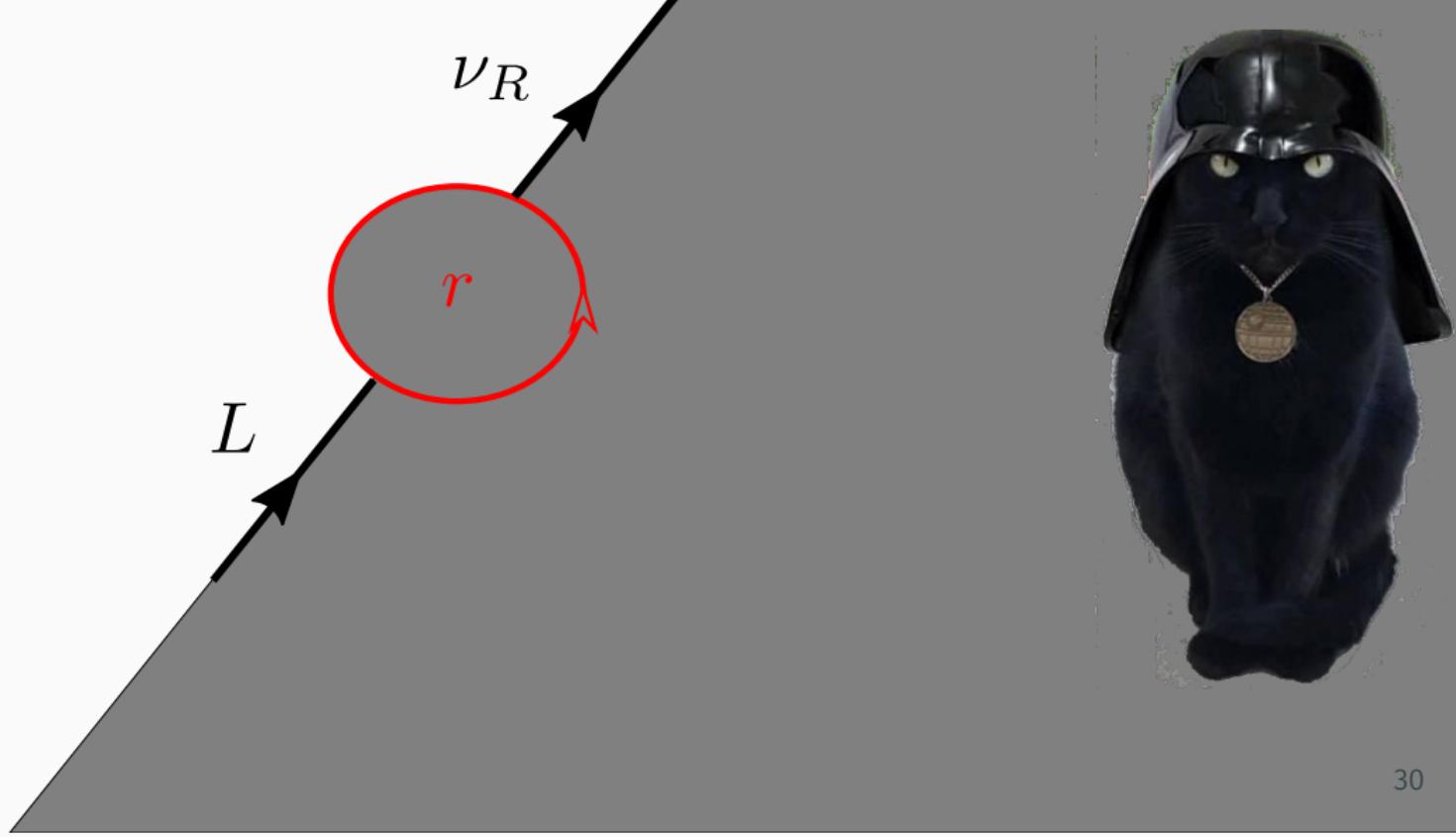
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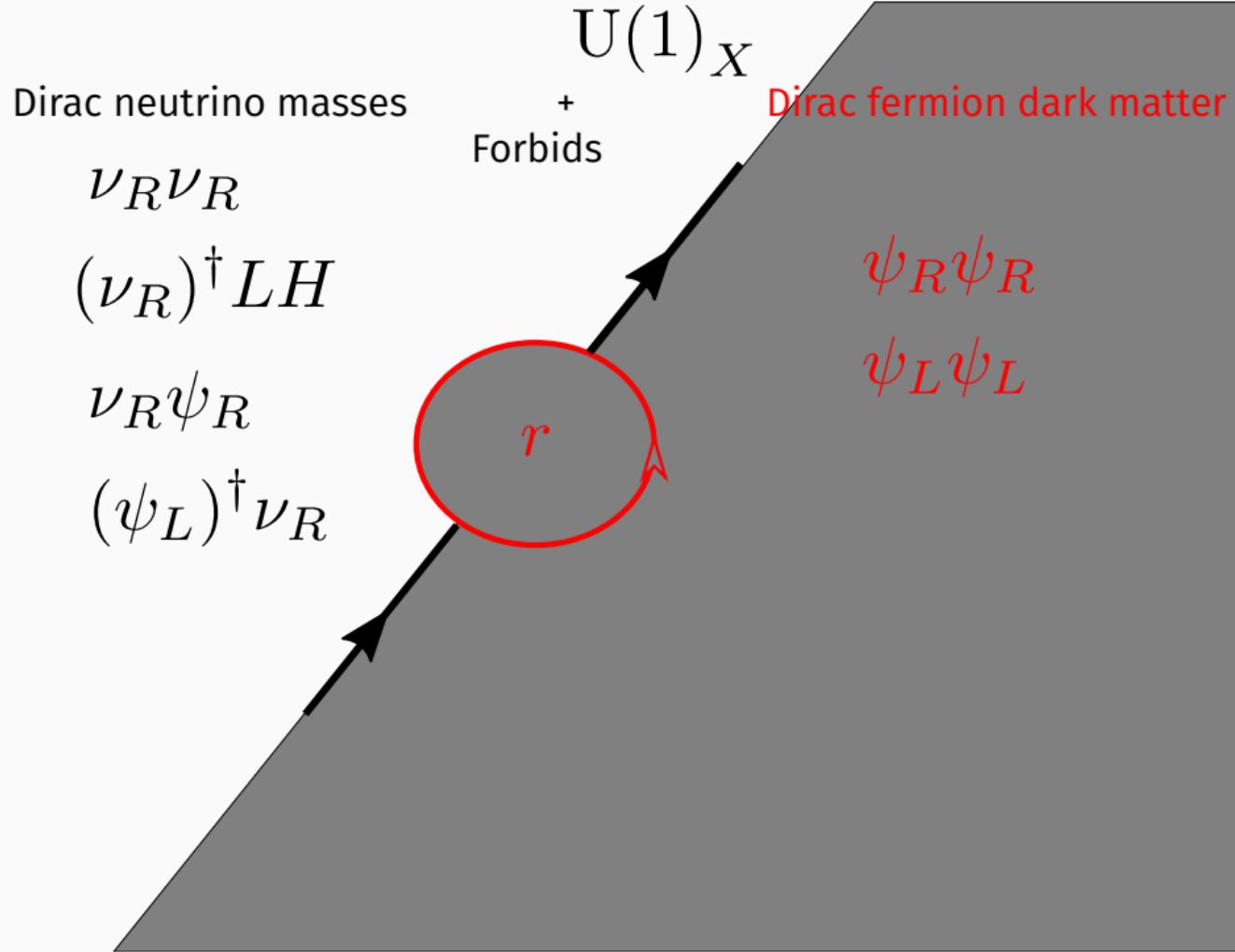
$U(1)_X$ 

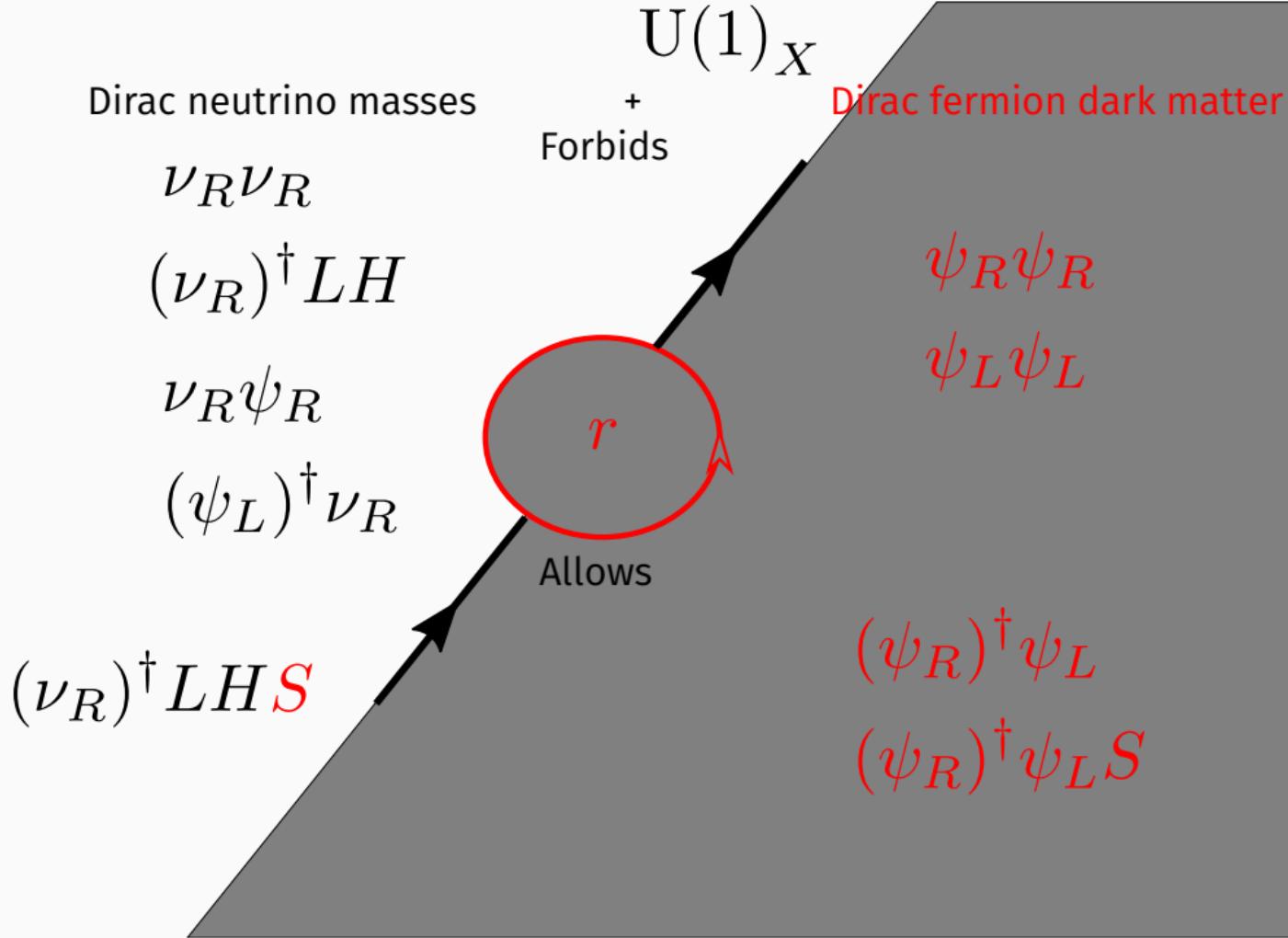
Dirac neutrino masses

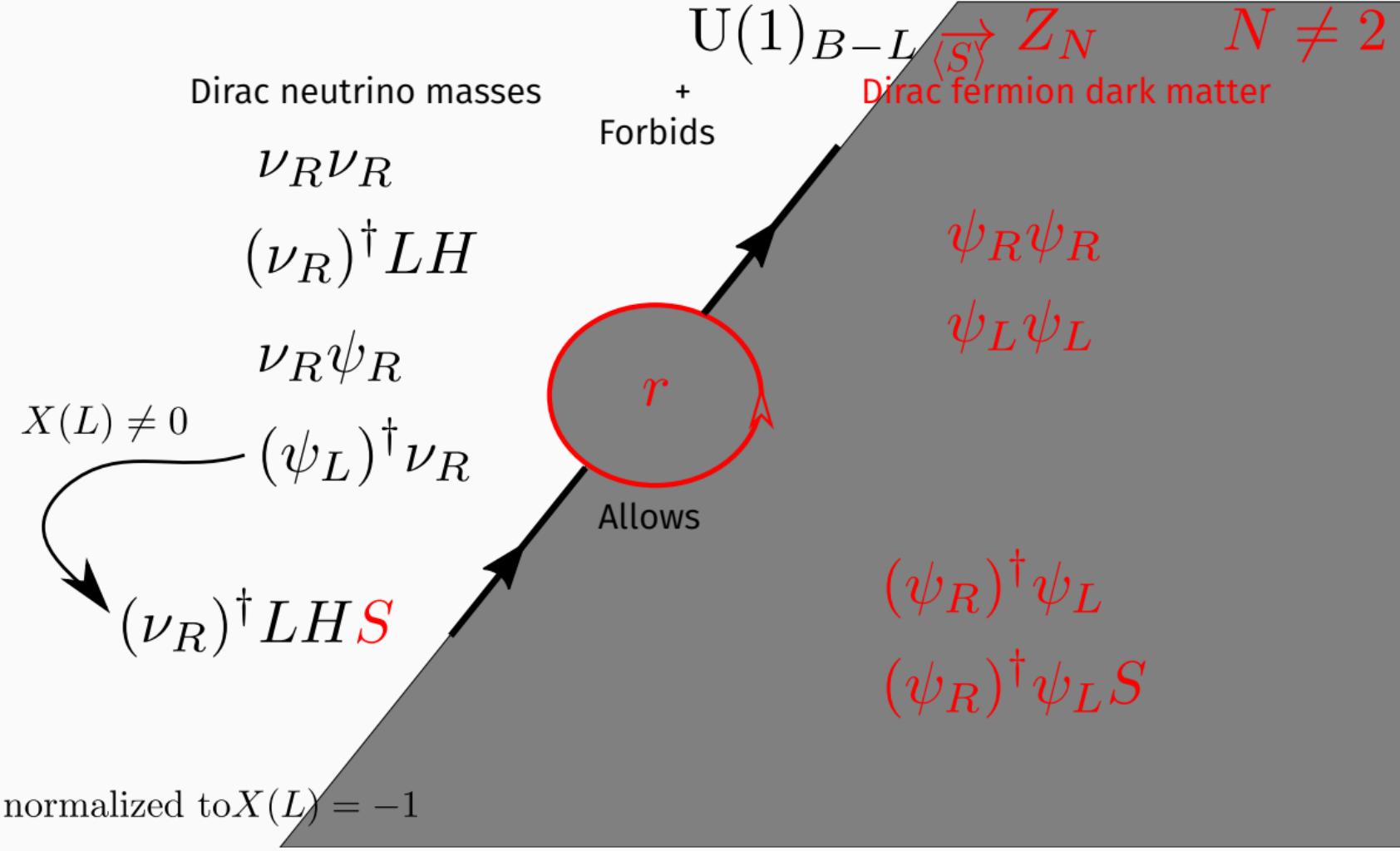
+

Dirac fermion dark matter

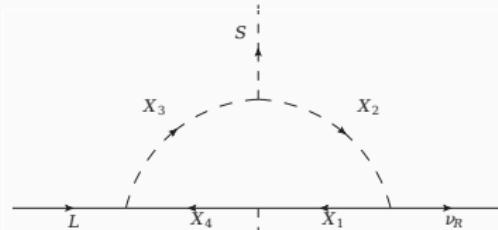




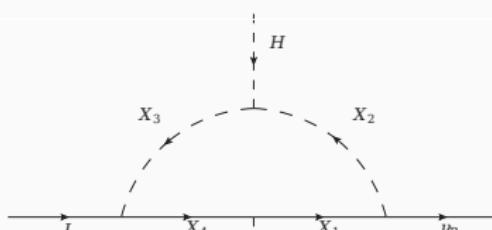




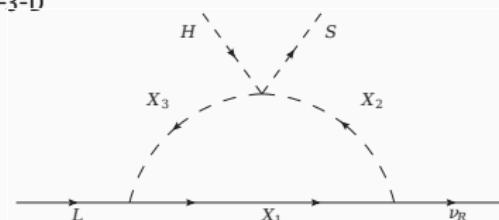
# One-loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



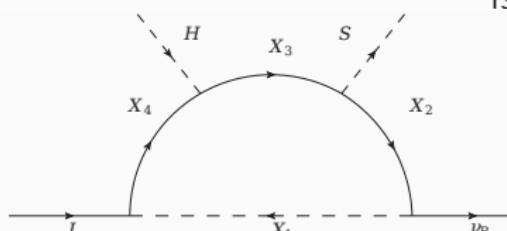
T1-3-D



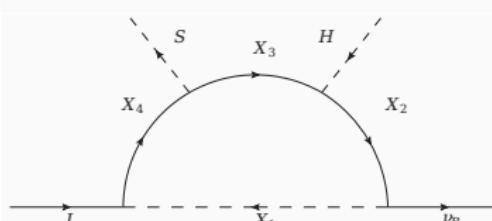
T1-3-E



T3-1-A



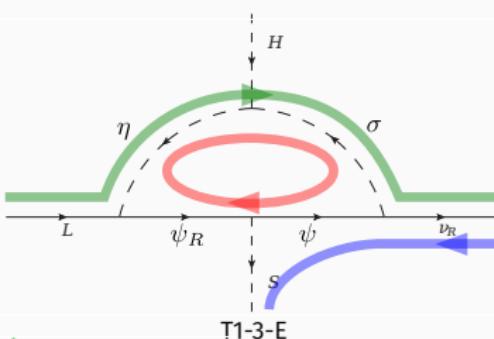
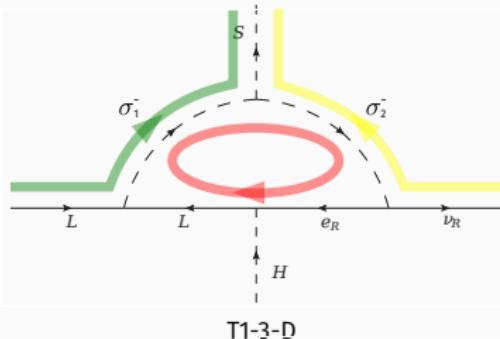
T1-2-A



T1-2-B

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

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

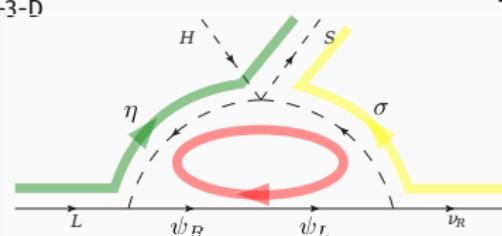


$\psi_{L,R} \rightarrow$  Singlet fermions

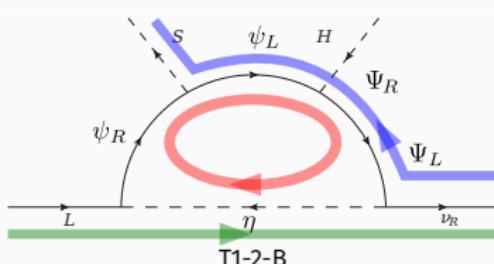
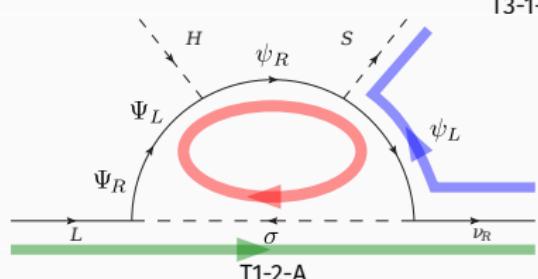
$\Psi_{L,R} \rightarrow$  Vector-like doublet fermions

$\sigma \rightarrow$  Singlet scalar

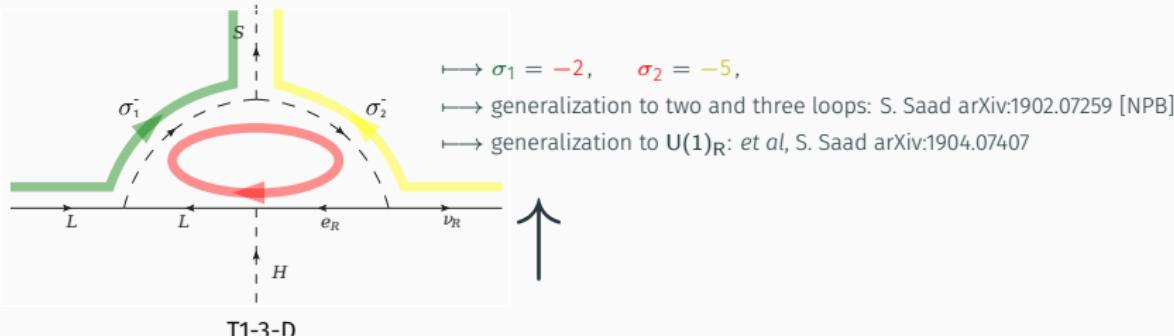
$\eta \rightarrow$  Doublet scalar



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



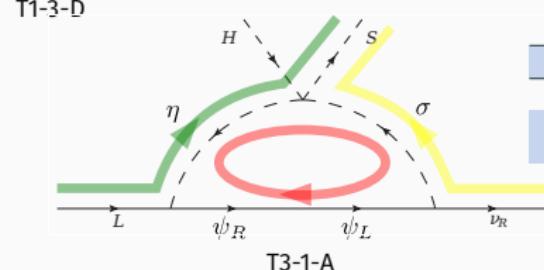
# One-loop topologies $U(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



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

$\sigma \rightarrow$  Singlet scalar

$\eta \rightarrow$  Doublet scalar



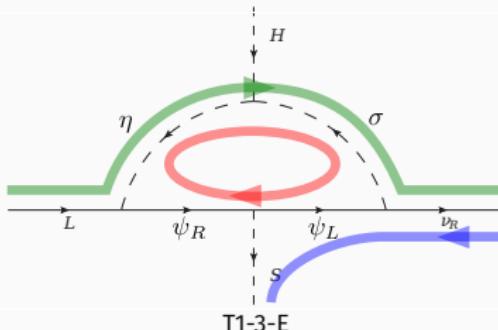
Fields: $f_i$	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	$\psi_L$	$(\psi_R)^\dagger$	$S$
(A)	+4	+4	-5	-r	r	+3

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

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



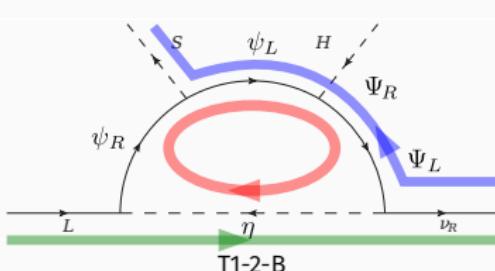
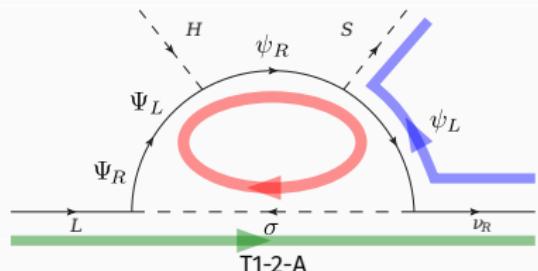
$\psi_{L,R} \rightarrow$ Singlet fermions (quiral)

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

$\sigma \rightarrow$ Singlet scalar

$\eta \rightarrow$ Doublet scalar

Fields: $f_i$	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	$\psi_L$	$(\psi_R)^\dagger$	$S$
(A)	+4	+4	-5	-r	r	+3
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$

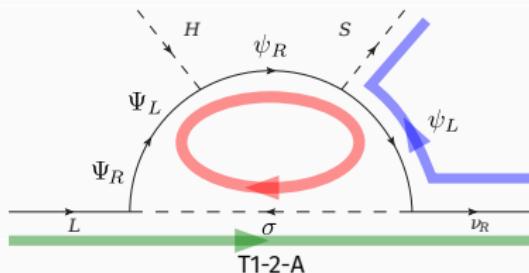


Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

$\psi_{L,R} \rightarrow$  Singlet fermions (quiral)  
 $\Psi_{L,R} \rightarrow$  Vector-like doublet fermions : 10/5  
 $\sigma \rightarrow$  Singlet scalar : 15/5



Fields: $f_i$	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	$\psi_L$	$(\psi_R)^\dagger$	$S$
(A)	+4	+4	-5	-r	r	+3
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

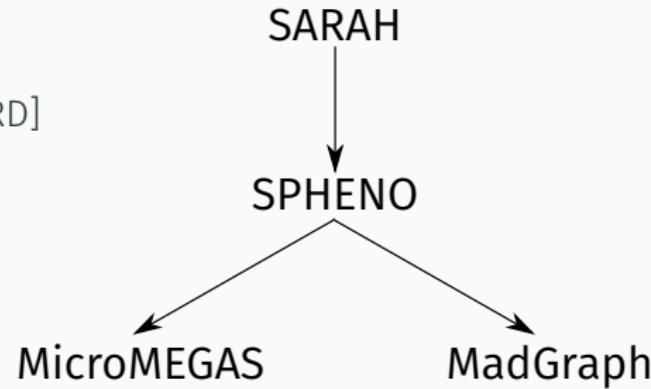
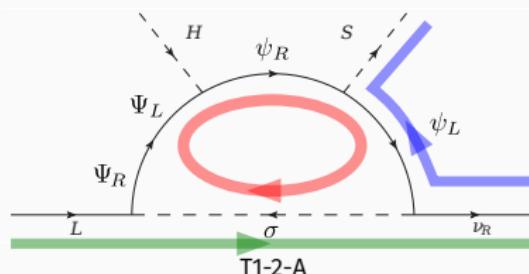
$$\sum_i f_i^3 = 3$$

## $\text{SD}^3\text{M+SSDM}$ : $\sigma_a$ ( $a = 1, 2$ )

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

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

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



# Singlet-Doublet Dirac Dark matter Model ( $SD^3M$ )

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The model extends the standard model (SM) particle content with Dirac Fermions: from SU(2) doublets of Weyl fermions:  $\Psi_L = (\Psi_L^0, \Psi_L^-)^T$ ,  $\widetilde{(\Psi_R)} = ((\Psi_R^-)^\dagger, -(\Psi_R^0)^\dagger)^T$  and singlet Weyl fermions  $\psi_{LR}$  that interact among themselves and with the SM fields

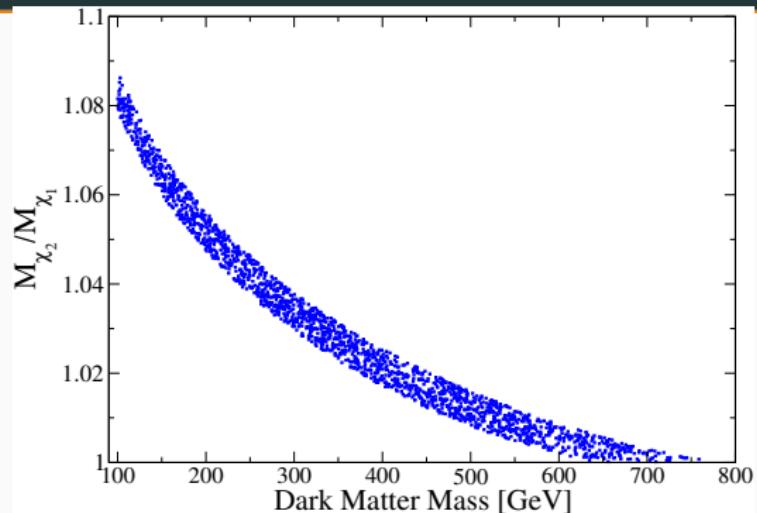
$$\mathcal{L} \supset M_\psi (\psi_R)^\dagger \psi_L + M_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + y_1 (\psi_R)^\dagger \Psi_L \cdot H + y_2 \widetilde{(\Psi_R)} \cdot \tilde{H} \psi_L + \text{h.c} \quad (2)$$

Four free parameters:

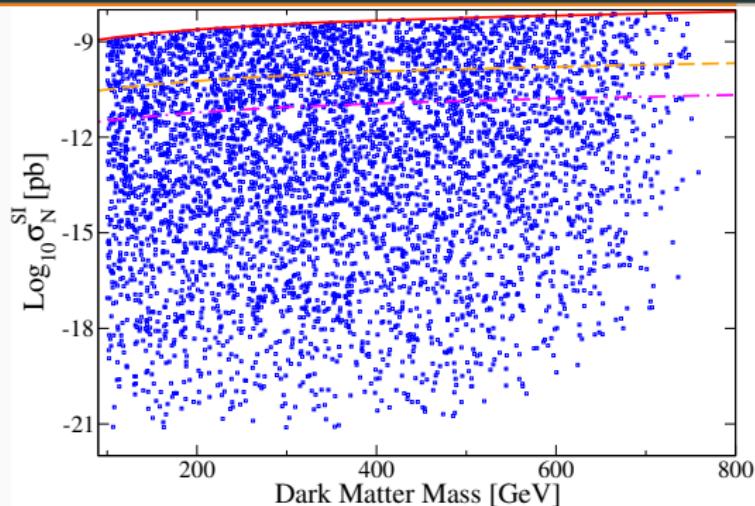
$$M_\psi, M_\Psi < 2 \text{ GeV}, \quad y_1, y_2 > 10^{-6} \quad (3)$$

Two neutral Dirac fermion eigenstates:

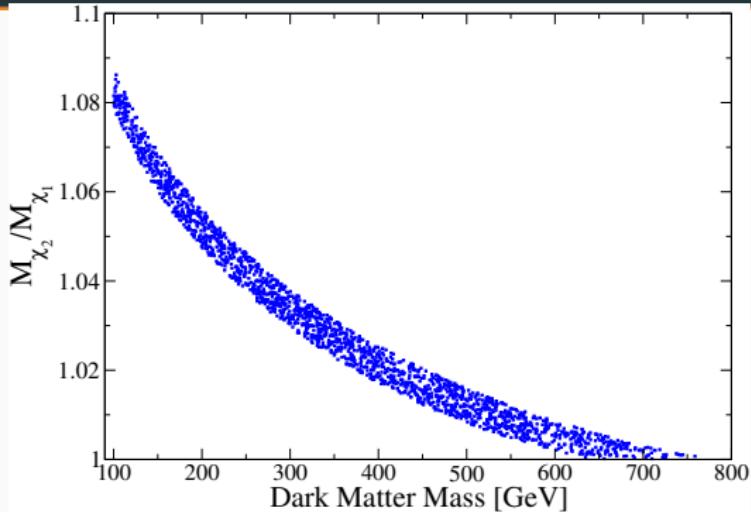
$$M = \begin{pmatrix} M_\psi & y_2 v / \sqrt{2} \\ y_1 v / \sqrt{2} & M_D \end{pmatrix}, \quad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \quad (4)$$



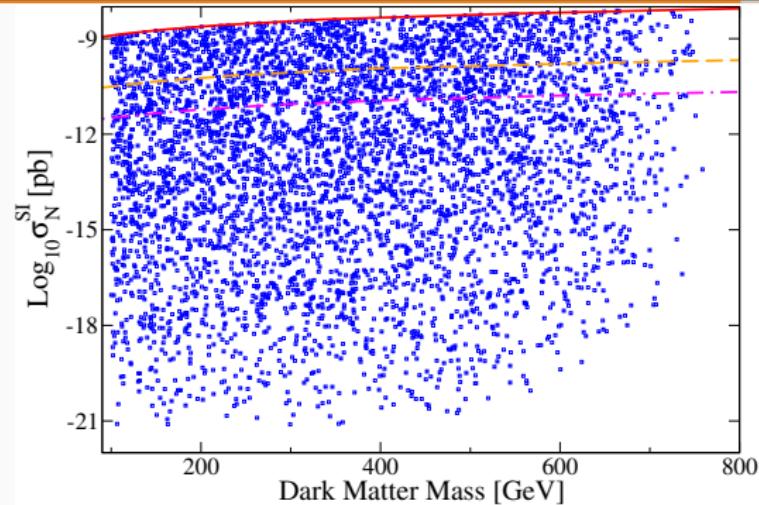
Compressed spectra region



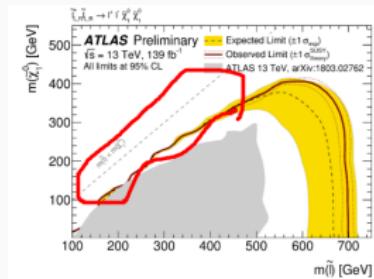
LUX - XENON1T - LZ



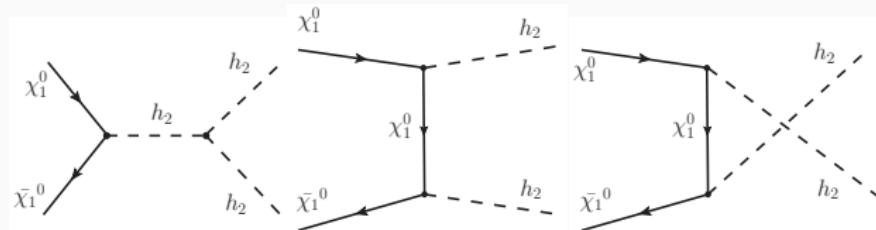
Compressed spectra region



LUX - XENON1T - LZ

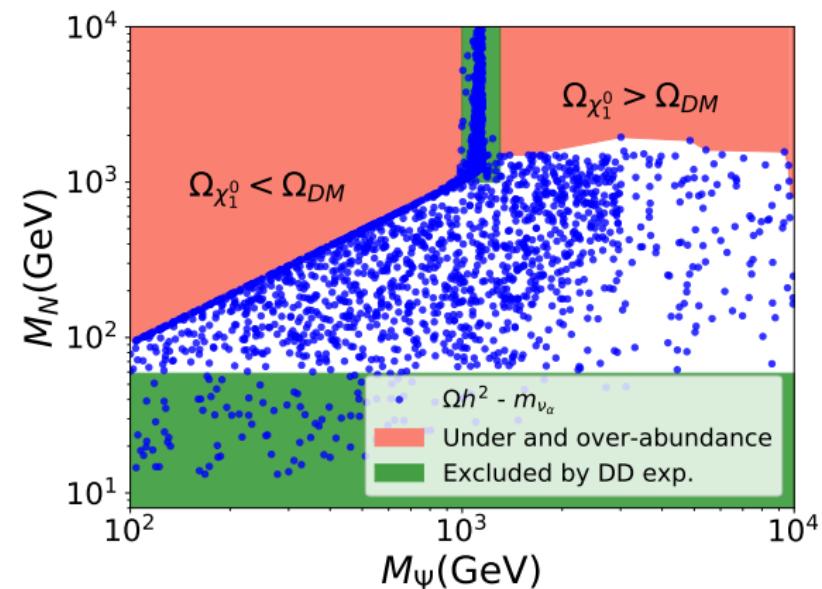


# Dark matter relic density

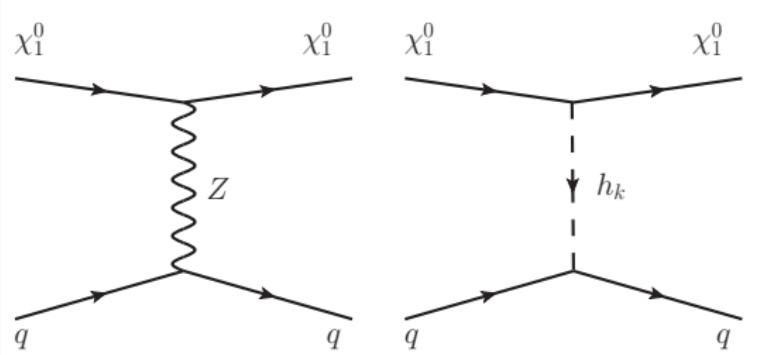


Decoupled  $Z'$  limit

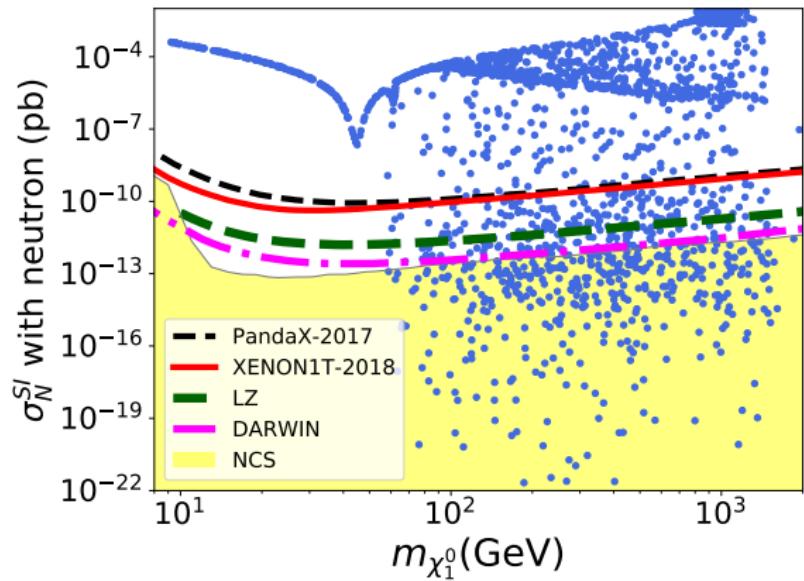
$$\begin{pmatrix} h \\ \text{Re}(S) \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}.$$



# Spin independent (SI) direct detection cross section



Decoupled  $Z'$  limit



# 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



Thanks!

