Minimal Scotogenic models

with Dirac neutrino masses

Diego Restrepo

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

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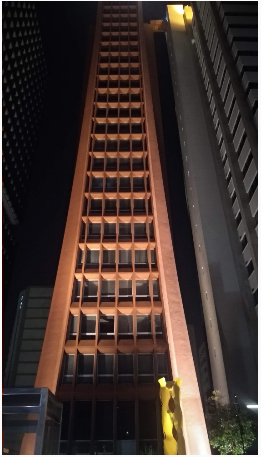
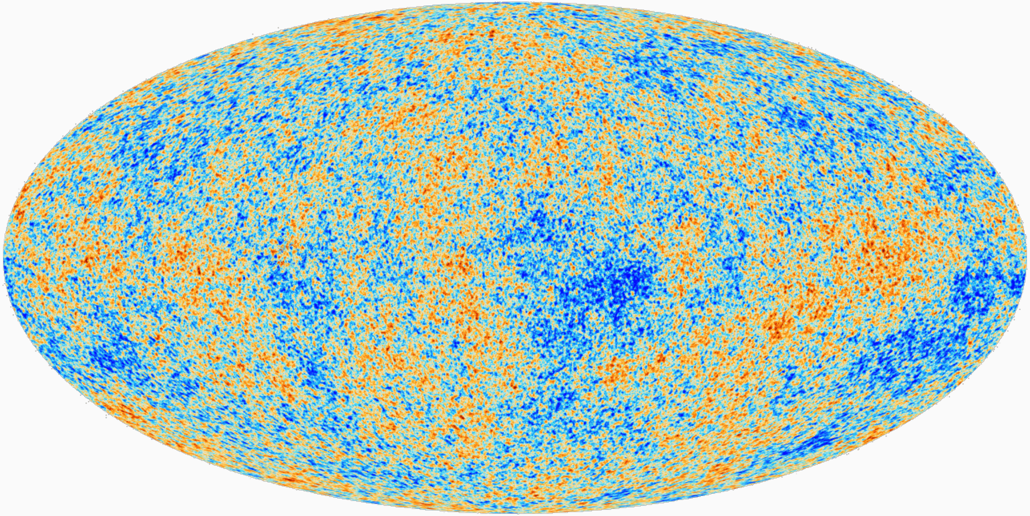


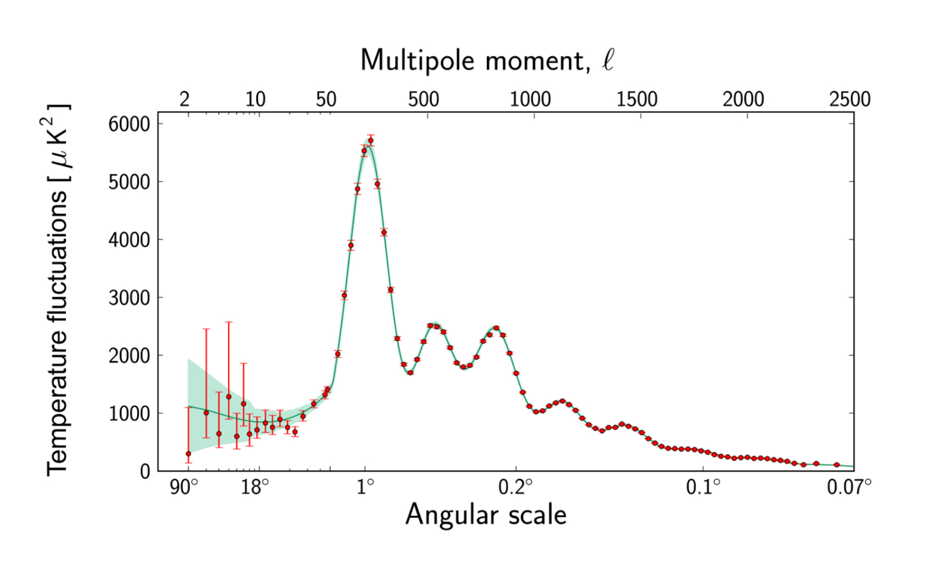
Focus on
arXiv:1811.11927 [PRD], arXiv:1906.09685 [PRD] and arXiv:1909.09574
In collaboration with
Carlos Yaguna (UPTC), Julian Calle, Óscar Zapata, Andrés Rivera (UdeA),
Walter Tangarife (Loyola University Chicago)

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

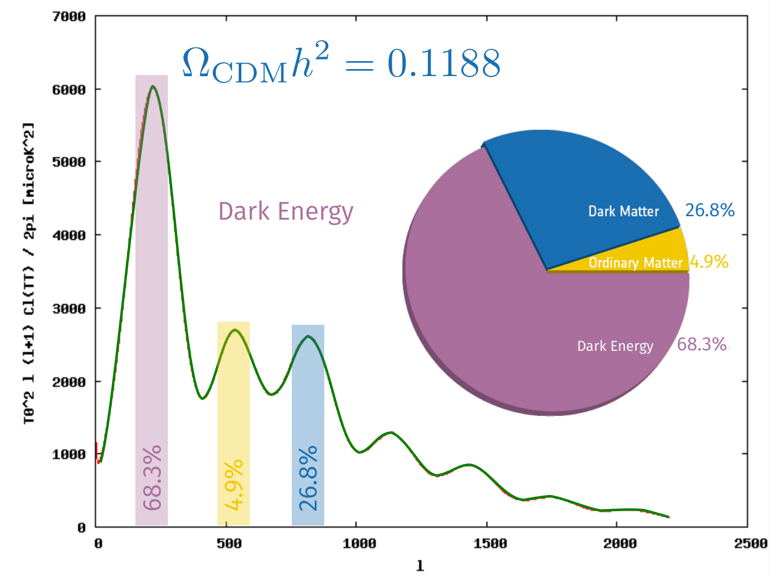


Planck's power spectrum of temperature fluctuations, ΔT, in the Cosmic Microwave Background. Credit: ESA and the Planck Collaboration

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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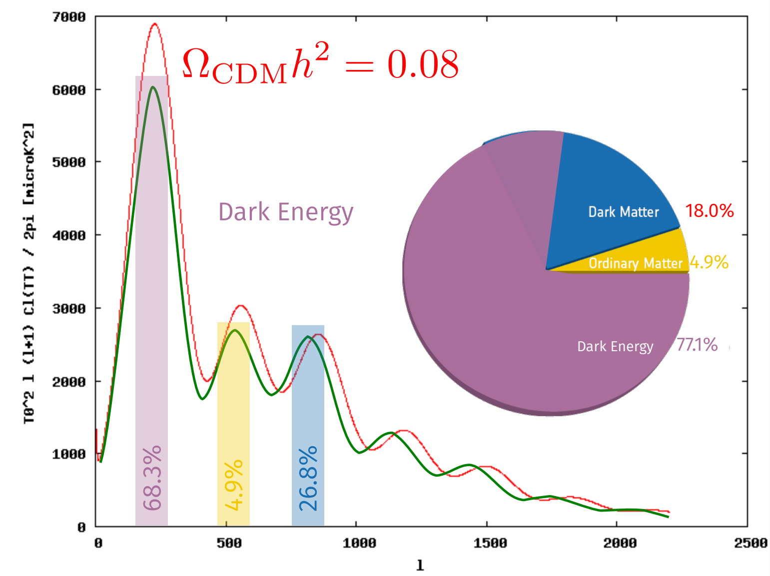


Cosmic Miso Soup

- 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

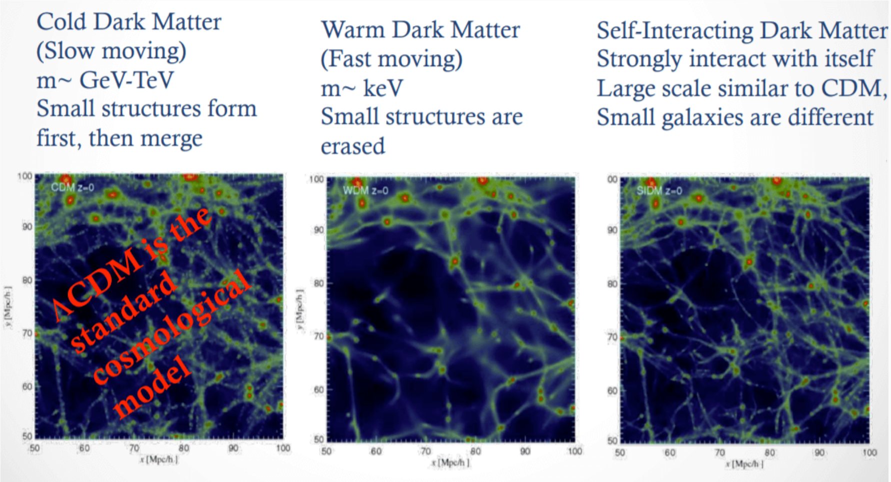
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso

- And imagine watching how ripples are created and propagate throughout the soup

Credit: Komatsu, ICTP Summer School on Cosmology 2018 (Video avalaible)


Nobu São Paulo version

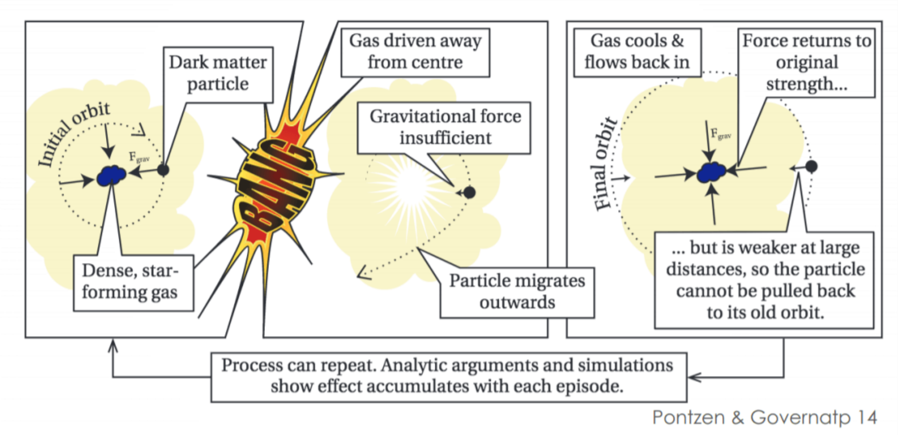
Large scale structure simulations: Gas of not hot and almost collisionless dark matter particles



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



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

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]

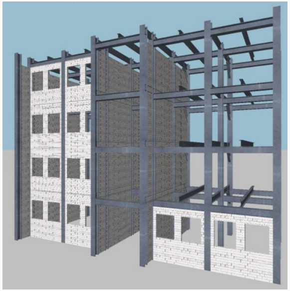
Cosmological simulations of structure formation predict that the majority of gas in the intergalactic medium (IGM) is distributed in a cosmic web of sheets and filaments as a consequence of gravitational collapse. The intersections of these structures become the locations at which galaxies and their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

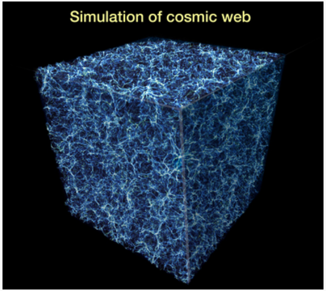
[...] 60% of all gas in the Universe resides in filaments

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





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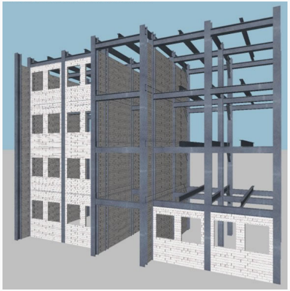
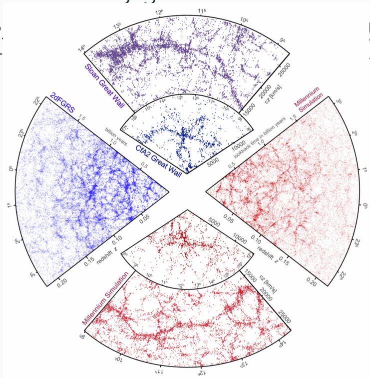
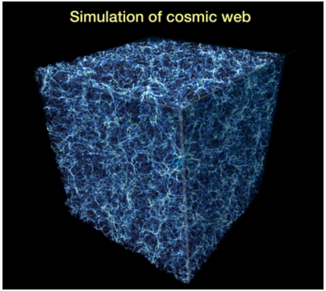
`https://phys.org/news/2018-06-`







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

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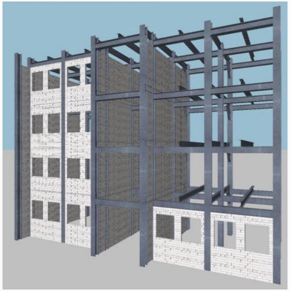
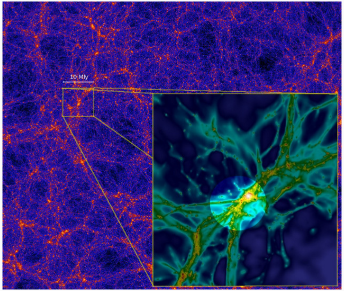




These great filaments are made largely of dark matter located in the space between galaxies

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]

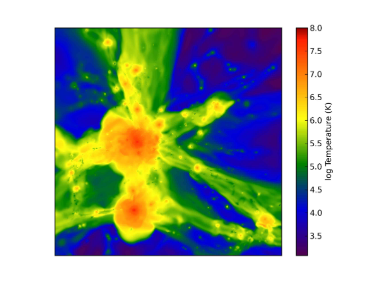
Clouds of HI likeky embeded in a filament between M31 and M33: arXiv:1305.1631 [nature]

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

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)*

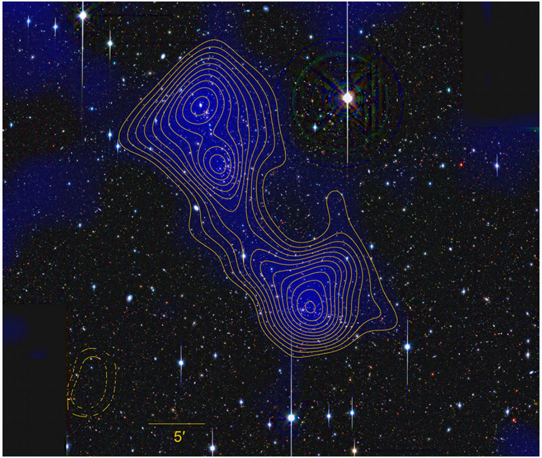


Credit: Cen, arXiv:1112.4527 [AJ]

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

New 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 $\sim 7\sigma$

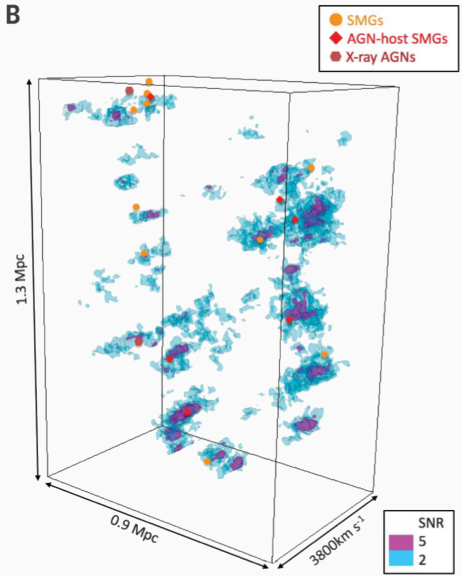
reconstructed surface mass density (blue)

significance contours from 0.5σ to 2.5σ

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

For a recent review see: arXiv:1905.08991

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

SM

SM

Dark
interaction

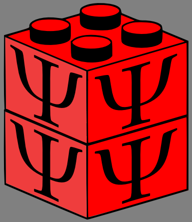
Local $U(1)_X$

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

$\mathcal{D}_\mu = Z_\mu + ig'Z'_\mu$: Relic abundance: Z' portal

SM

$\bar{f}\not{\mathcal{D}}f$ $\overline{\psi}\not{\mathcal{D}}\psi$



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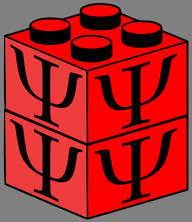

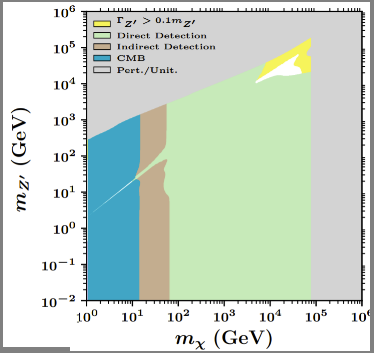

$g_{BL}/g_{SM} = 10$. arXiv:1907.05893. C. Blanco, *et al.* [PRD]

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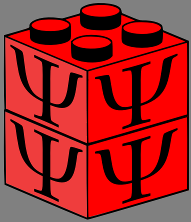

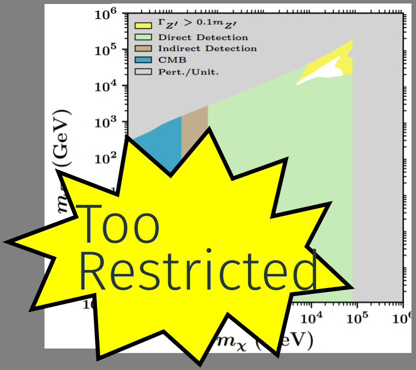

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Explain also small neutrino masses

In the following discussion we use the following doublets

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

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

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

Standard model extended with U(1)$_X$ gauge symmetry

Fields	SU(2)$_L$	U(1)$_Y$	U(1)$_X$
L	**2**	$-1/2$	l
Q	**2**	$-1/6$	q
d_R	**1**	$-1/2$	d
u_R	**1**	$+2/3$	u
e_R	**1**	-1	e
H	**2**	$-1/2$	h
ψ	**1**	0	n

Table 1: The new and fermions with their respective charges.

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

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

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

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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 $\mathrm{U}(1)_X$ SM extension

Fields	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_X$	$\mathrm{U}(1)_{B-L}$	$\mathrm{U}(1)_R$	$\mathrm{U}(1)_D$	$\mathrm{U}(1)_G$
L	**2**	$-1/2$	l	-1	0	$-3/2$	$-1/2$
Q	**2**	$-1/6$	$-l/3$	$1/3$	0	$1/2$	$1/6$
d_R	**1**	$-1/2$	$1+2l/3$	$1/3$	1	0	$2/3$
u_R	**1**	$+2/3$	$-1-4l/3$	$1/3$	-1	1	$-1/3$
e_R	**1**	-1	$1+2l$	-1	1	-2	0
H	**2**	$1/2$	$-1-l$	0	-1	$1/2$	$-1/2$
$\sum_\alpha n_\alpha$	**1**	0	-3	-3	-3	-3	-3
$\sum_\alpha n_\alpha^3$	**1**	0	-3	-3	-3	-3	-3

Solutions in terms of a parameter: arXiv:1811.11927, N. Okada, *et al* [PRD];

and some specific examples from: arXiv:1705.05388, Farinaldo Queiroz, *et al* [JHEP]

All known $\mathrm{U}(1)_{B-L}$ (radiative) neutrino solutions apply for $\mathrm{U}(1)_X$:

Known 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]

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

For general $\sum n_\alpha = 0$ solutions: see D.B Costa, *et al*, 1905.13729

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

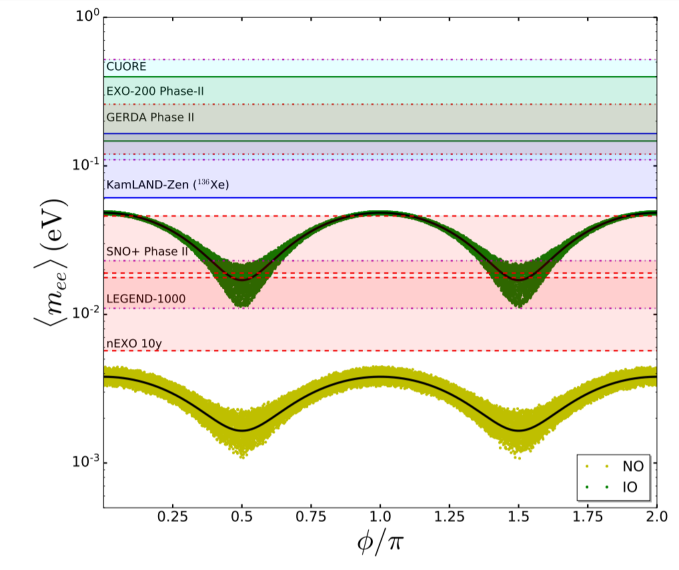
Table 2: Possible solutions with at least two repeated charges and until six chiral fermions.
For general $\sum n_\alpha = 0$ solutions: see D.B Costa, *et al*, 1905.13729

(One-loop) Dirac neutrino masses

Lepton number

- Lepton number (L) is an accidental discret or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e, L_μ, L_τ are also conserved.
- The processes which violates 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.

NLDBD prospects for a model with a massless neutrino (arXiv:1806.09977 [PLB] with Reig, Valle and Zapata)



with M.Reig, J.W.F Valle, O. Zapata, arXiv:1806.09977

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

Majorana ~~U(1)~~$_L$

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

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

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

Dirac U(1)$_L$

Field	Z_3 $(\omega^3 = 1)$
SM	1
L	ω
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$$h_D \sim \mathcal{O}(1)$$

Dirac $\mathrm{U}(1)_{B-L}$

Field	Z_3 ($\omega^3 = 1$)
SM	1
L	ω
$(e_R)^\dagger$	ω^2
$(\nu_R)^\dagger$	ω^2

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

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

Explain smallness ala Peccei-Quinn:

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

Small Dirac neutrino masses

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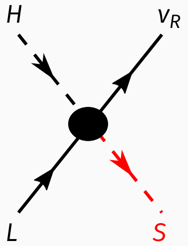
- Forbids Majorana term: $\nu_R \nu_R$
- Realizes of the 5-dimension operator which conserves lepton number in $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

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

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



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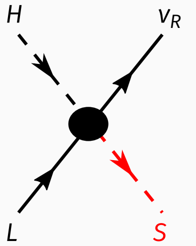


- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$ (see arXiv:1211.0186)

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

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

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

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

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

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

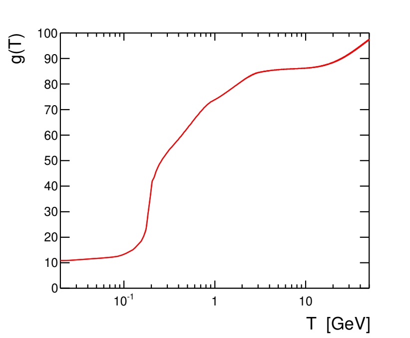
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi}\left(\frac{g'}{M_{Z'}}\right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s\,.$$

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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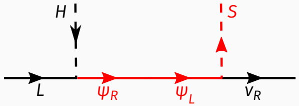
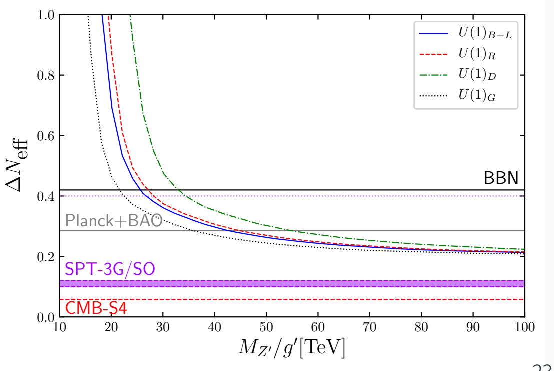
$$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S\rangle} Z_3$$



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

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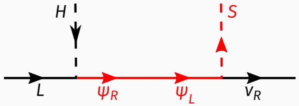

ν_{R3}	ν_{R2}	ν_{R1}	ψ_L	ψ_R	S
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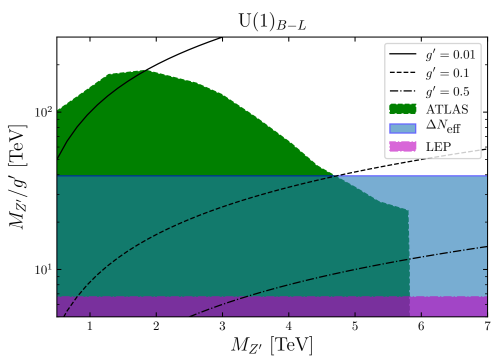
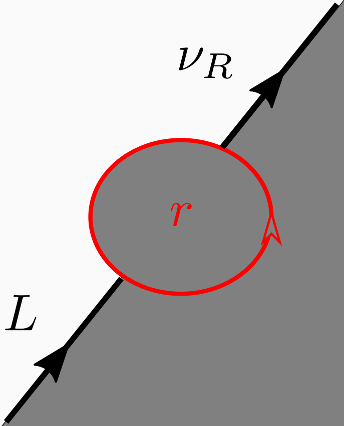


with J. Calle and Ó. Zapata, arXiv:1909.09574

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

$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter



$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$\nu_R \nu_R$

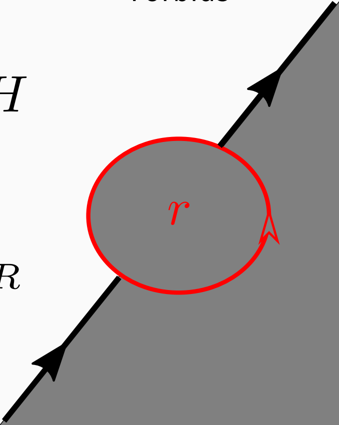
$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$



$\mathrm{U}(1)_X$

Dirac neutrino masses

+

Dirac fermion dark matter

Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$

r

Allows

$(\nu_R)^\dagger L H S$

$(\psi_R)^\dagger \psi_L$

$(\psi_R)^\dagger \psi_L S$

$\mathrm{U}(1)_{B-L} \xrightarrow[\langle S \rangle]{} Z_N \qquad N \neq 2$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$

$X(L) \neq 0$

r

Allows

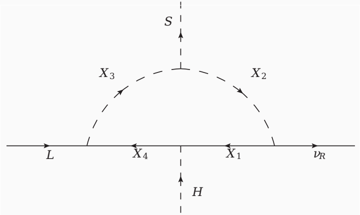
$(\nu_R)^\dagger L H S$

$(\psi_R)^\dagger \psi_L$

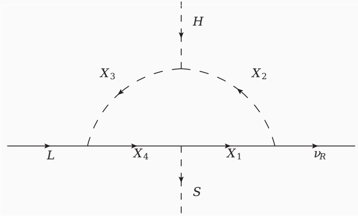
$(\psi_R)^\dagger \psi_L S$

normalized to $X(L) = -1$

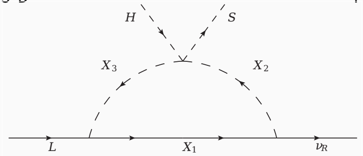
One-loop topologies $\mathrm{U}(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

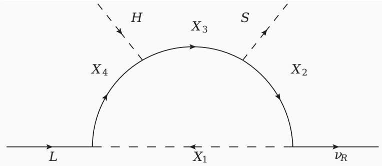


T1-3-E

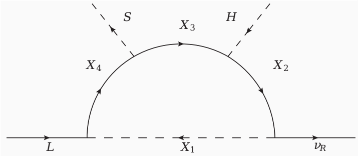


T3-1-A

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

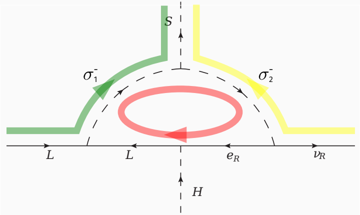


T1-2-A

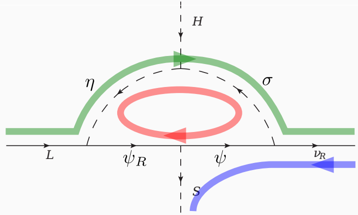


T1-2-B

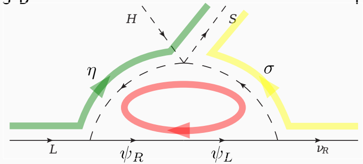
One-loop topologies U(1)$_{B-L}$ only!



T1-3-D



T1-3-E



T3-1-A

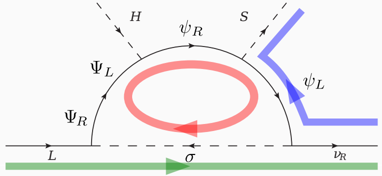
$\psi_{L,R}$ $\rightarrow$Singlet fermions

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

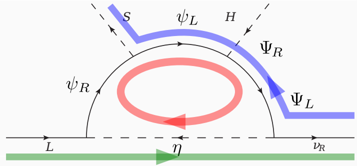
σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar

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

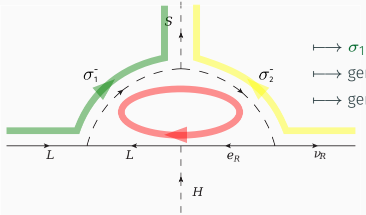


T1-2-A



T1-2-B

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



T1-3-D

$\longmapsto$ $\sigma_1 = -2$, $\sigma_2 = -5$,

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

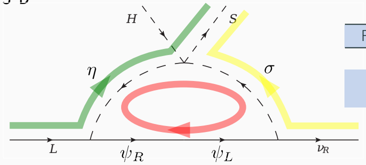
$\longmapsto$ generalization to $\mathrm{U}(1)_\mathrm{R}$: *et al*, S. Saad arXiv:1904.07407

$\uparrow$

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

σ $\longrightarrow$Singlet scalar

η $\longrightarrow$Doublet scalar



T3-1-A

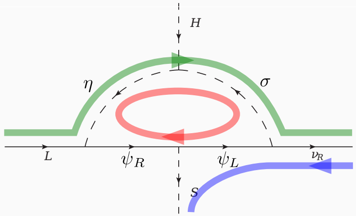
Fields: f_i	$(\nu_{R3})^\dagger$	$(\nu_{R2})^\dagger$	$(\nu_{R1})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

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



T1-3-E

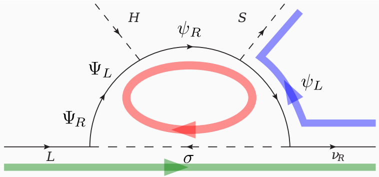
$\psi_{L,R}$ →Singlet fermions (quiral)

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

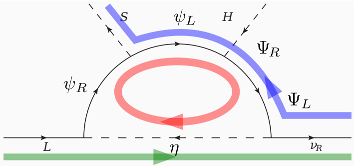
σ →Singlet scalar

η →Doublet scalar

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



T1-2-A



T1-2-B

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

$$\sum_i f_i^3 = 3$$

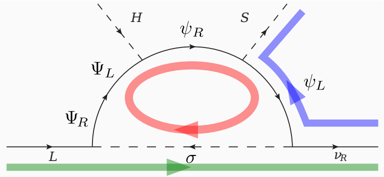
SD^{3}M+SSDM: σ_a $(a = 1, 2)$ with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

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

$\Psi_{L,R}$ $\to$Vector-like doublet fermions : 10/5

σ $\to$Singlet scalar : 15/5

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



T1-2-A

Anomaly cancellation conditions

$$\sum_i f_i = 3$$

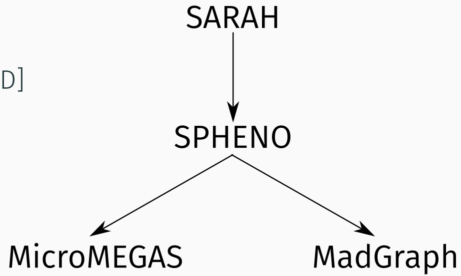
$$\sum_i f_i^3 = 3$$

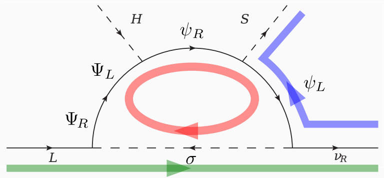
SD^{3}M+SSDM: σ_a $(a=1,2)$

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

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

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





T1-2-A

Singlet-Doublet Dirac Dark matter Model (SD^{3}M)

Singlet-Doublet Dirac Dark Matter (SD^3M) By Carlos E. Yaguna. arXiv:1510.06151 [PRD].

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

$$\mathcal{L} \supset M_\psi \left(\psi_R\right)^\dagger \psi_L + M_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + y_1 \left(\psi_R\right)^\dagger \Psi_L \cdot H + y_2 \widetilde{(\Psi_R)} \cdot \widetilde{H} \psi_L + \text{h.c} \tag{4}$$

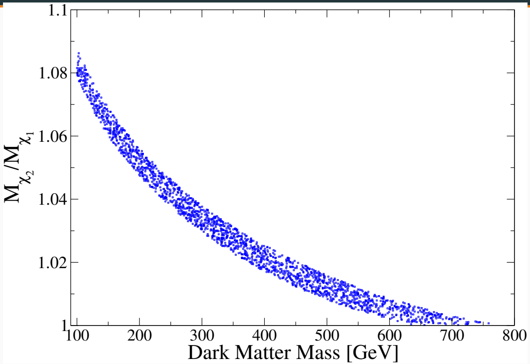
Four free parameters:

$$M_\psi, M_\Psi \ < 2\ \text{GeV}\,, \qquad\qquad y_1,\ y_2 > 10^{-6} \tag{5}$$

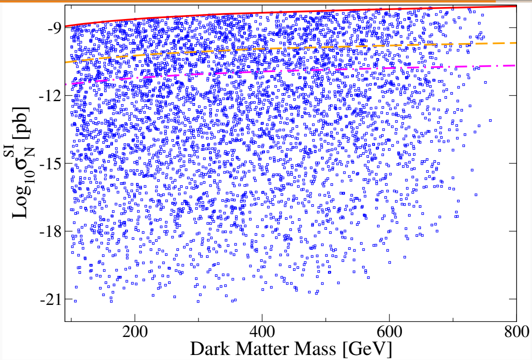
Two neutral Dirac fermion eigenstates:

$$M = \begin{pmatrix} M_\psi & y_2 v/\sqrt{2} \\ y_1 v/\sqrt{2} & M_D \end{pmatrix}, \qquad\qquad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \tag{6}$$

SD^{3}M By Carlos E. Yaguna. arXiv:1510.06151 [PRD].

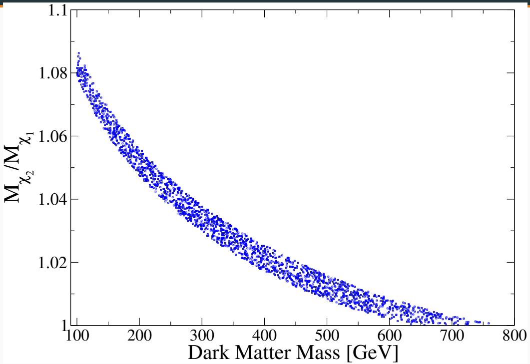


Compressed spectra region

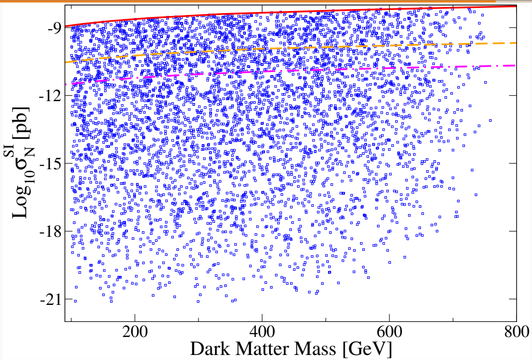


LUX - XENON1T - LZ

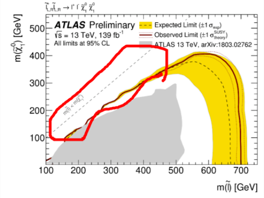
SD^{3}M By Carlos E. Yaguna. arXiv:1510.06151 [PRD].



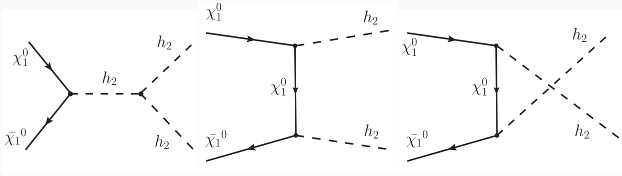
Compressed spectra region



LUX - XENON1T - LZ

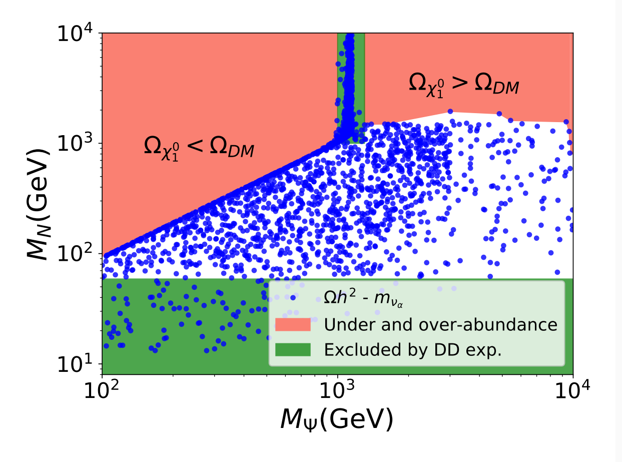


Dark matter relic density

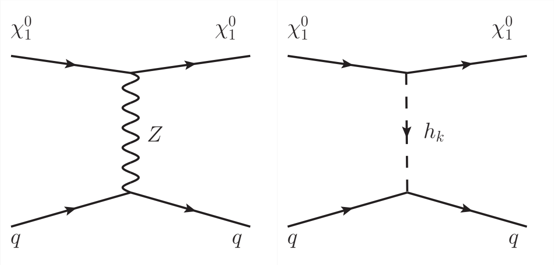


Decoupled Z' limit

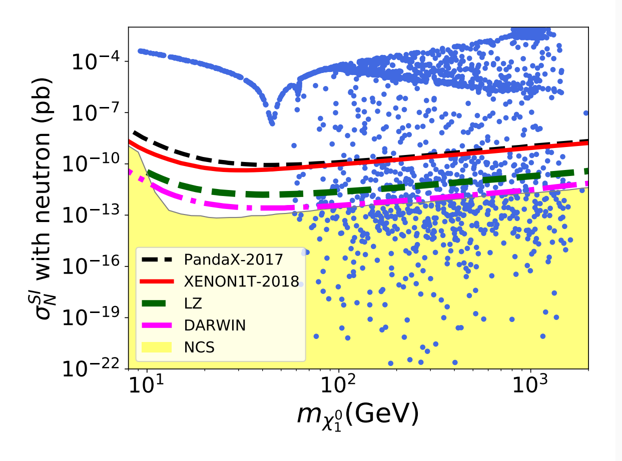
$$\begin{pmatrix} h \\ \mathrm{Re}(S) \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} .$$



Spin independent (SI) direct detection cross section



Decoupled Z' limit



Conclusions

It makes sense to focus our attention on models 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

Thanks!