

Minimal Scotogenic models with (Dirac) neutrino masses



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Oct 14, 2019 - Cruzeiro do Sul U. [PDF: <http://bit.ly/darkcdsu>]

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Focus on

[arXiv:1811.11927 \[PRD\]](https://arxiv.org/abs/1811.11927), [arXiv:1906.09685 \[PRD\]](https://arxiv.org/abs/1906.09685) and [arXiv:1909.09574](https://arxiv.org/abs/1909.09574)

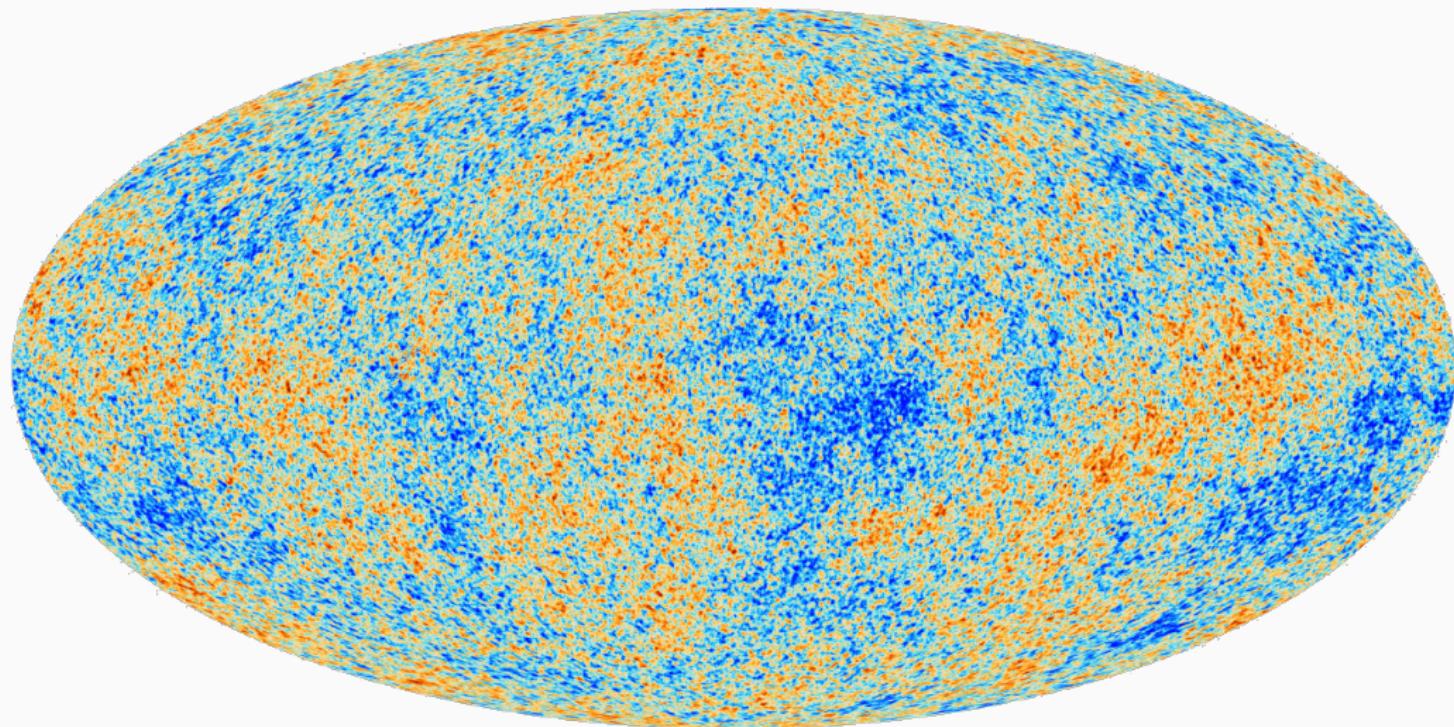
In collaboration with

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

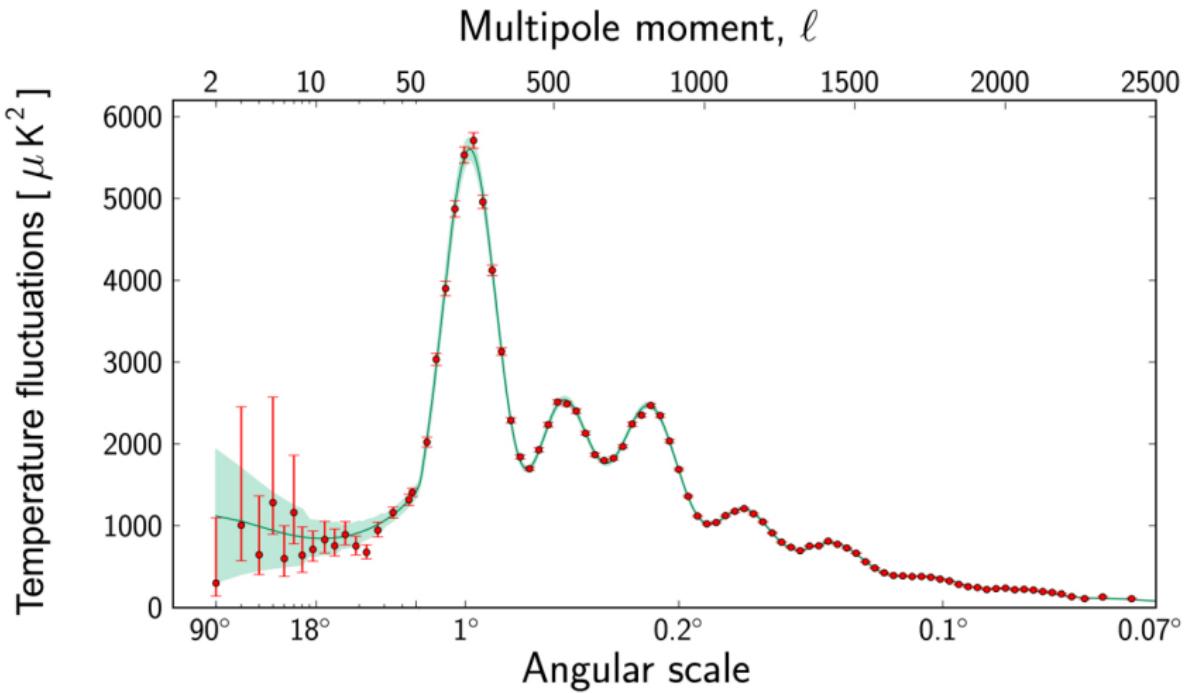


Λ CDM paradigm (with baryonic effects)

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



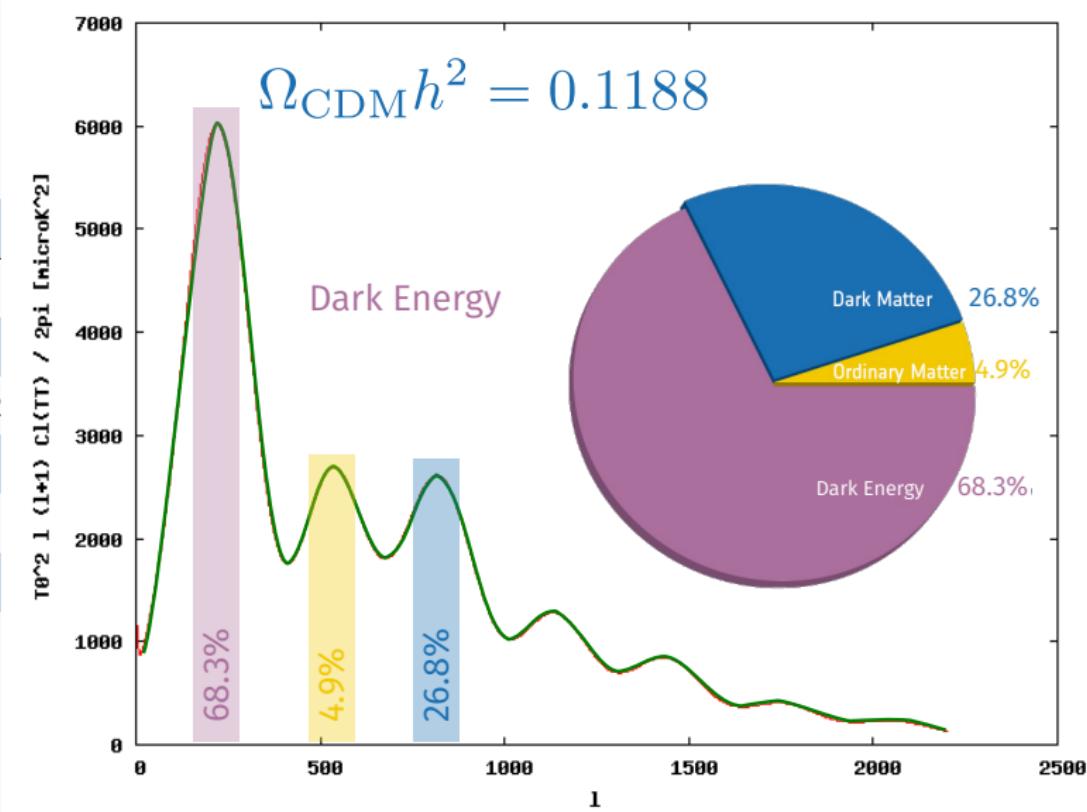
The Cosmic Microwave Background - as seen by Planck. Credit: ESA and the Planck Collaboration



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

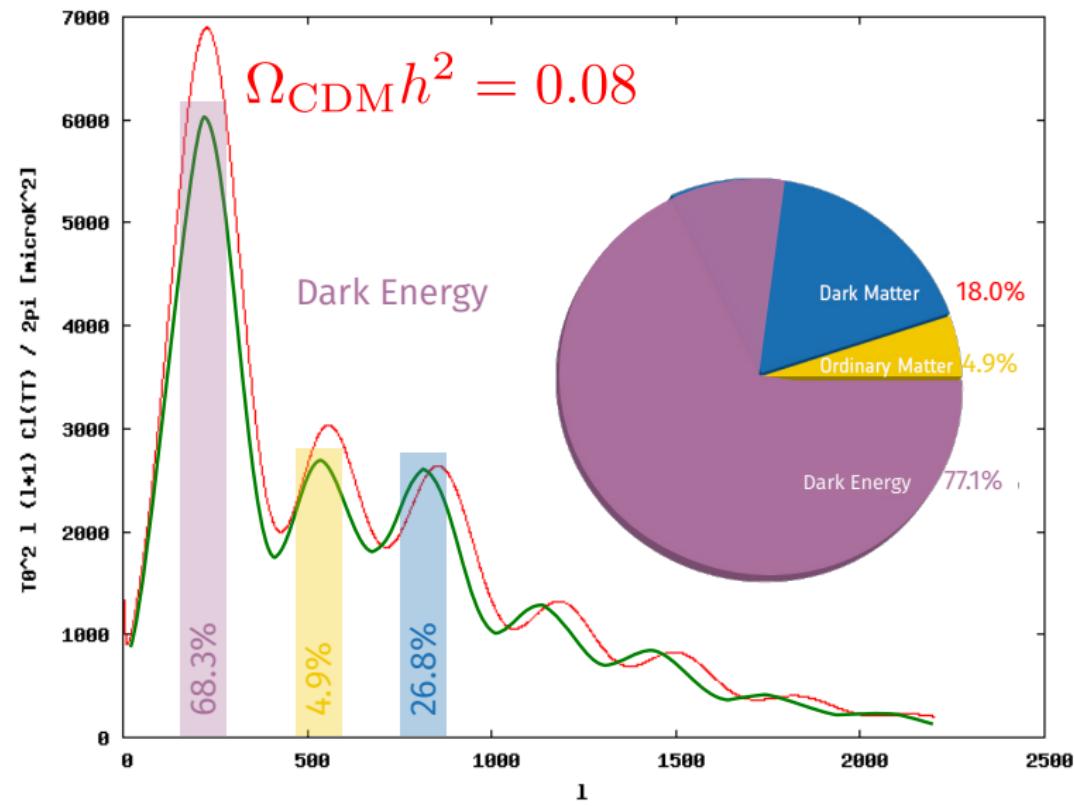
Λ CDM: $\Omega = 1$, $w = -1$

Symbol	Value
$\Omega_b h^2$	0.02230(14)
$\Omega_{\text{CDM}} h^2$	0.1188(10)
t_0	$13.799(21) \times 10^9$ year
n_s	0.9667(40)
Δ_R^2	2.441×10^{-9}
τ	0.066(12)



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Cosmic Miso Soup

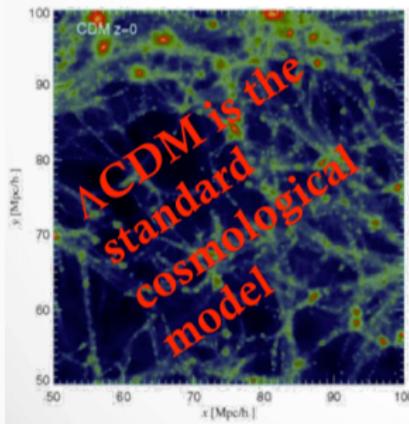
- When matter and radiation were hotter than 3000 K, matter was completely ionised. The Universe was filled with plasma, which behaves just like a soup
- Think about a Miso soup (if you know what it is). Imagine throwing Tofus into a Miso soup, while changing the density of Miso
- And imagine watching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



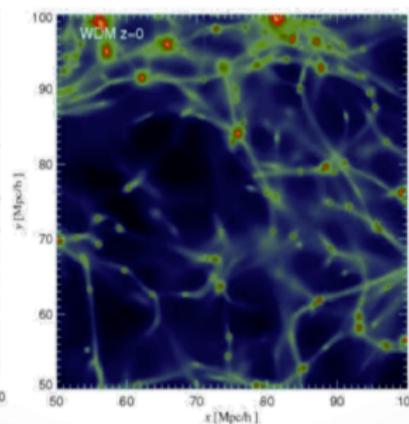
Nobu São Paulo version

Dark matter simulations

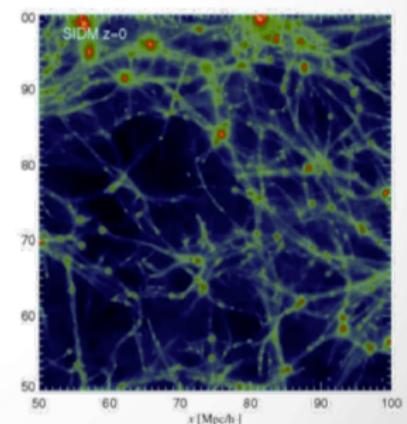
Cold Dark Matter
(Slow moving)
 $m \sim \text{GeV-TeV}$
Small structures form
first, then merge



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

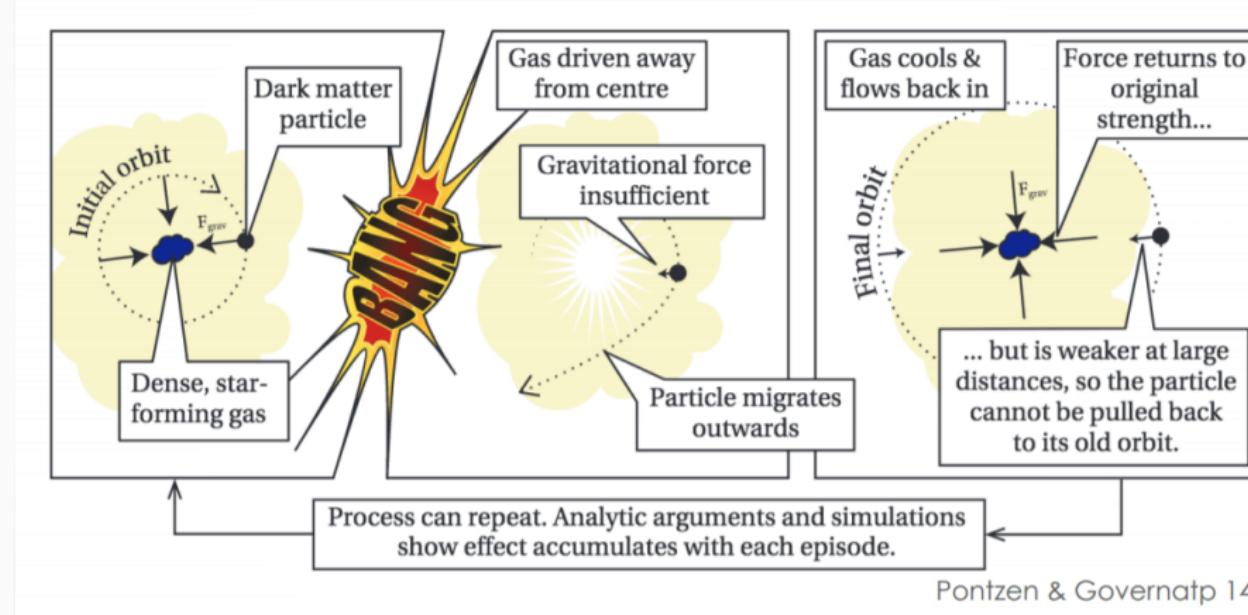


Self-Interacting Dark Matter
Strongly interact with itself
Large scale similar to CDM,
Small galaxies are different



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

Baryonic effects



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

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

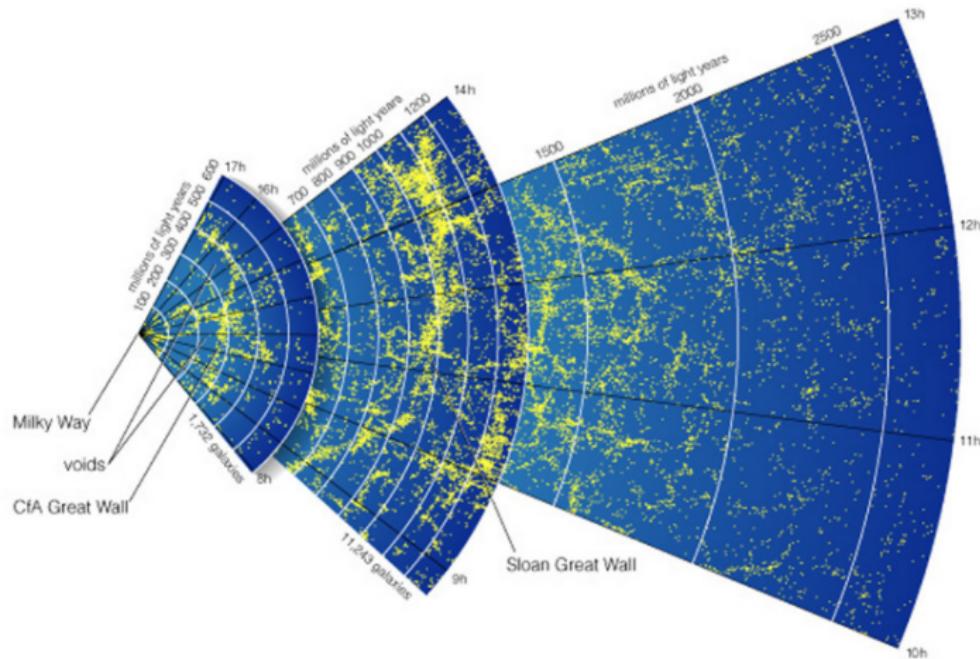
A.C Rodriguez *et al* arXiv:1801.09070 [CAC]

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.

[...] at a z of ~ 3 , $> 60\%$ of all gas in the Universe resides in filaments

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

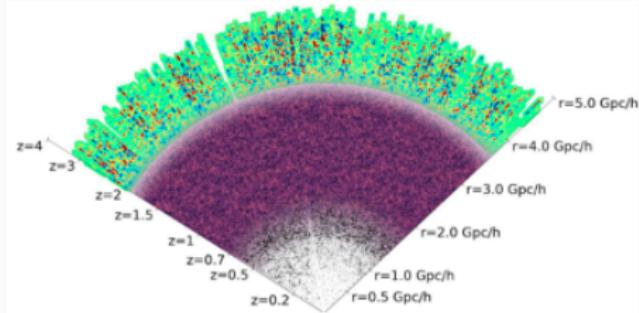
Galaxy catalogs



Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids***

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The DESI experiment



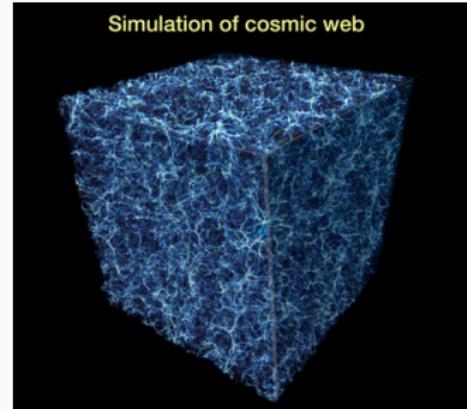
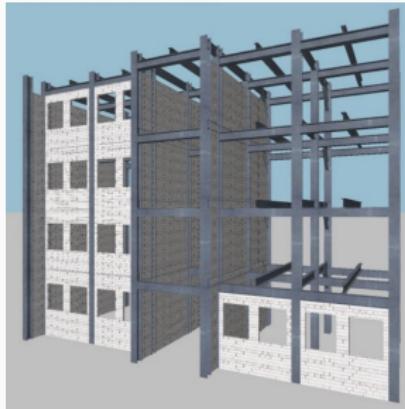
Credits: J. Forero

<http://cosmology.univalle.edu.co/>

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**!

[<https://hubblesite.org>]

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

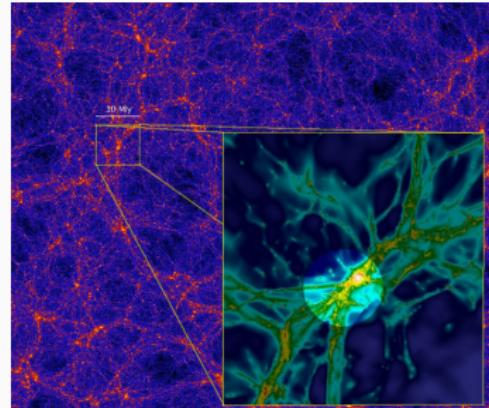
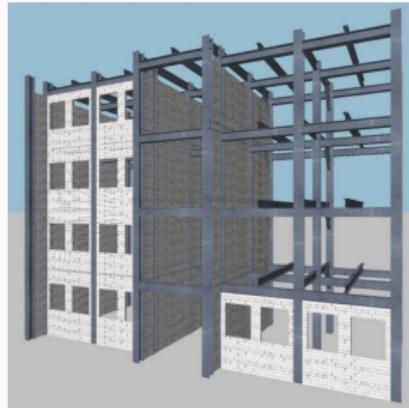
Clouds of HI likely embedded in a filament between M31 and M33: arXiv:1305.1631 [nature]

¹ See also: arXiv:1603.05400 [A&A]

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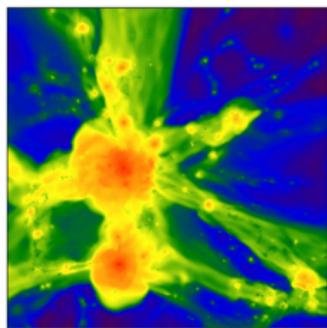
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Direct observations of filaments

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)



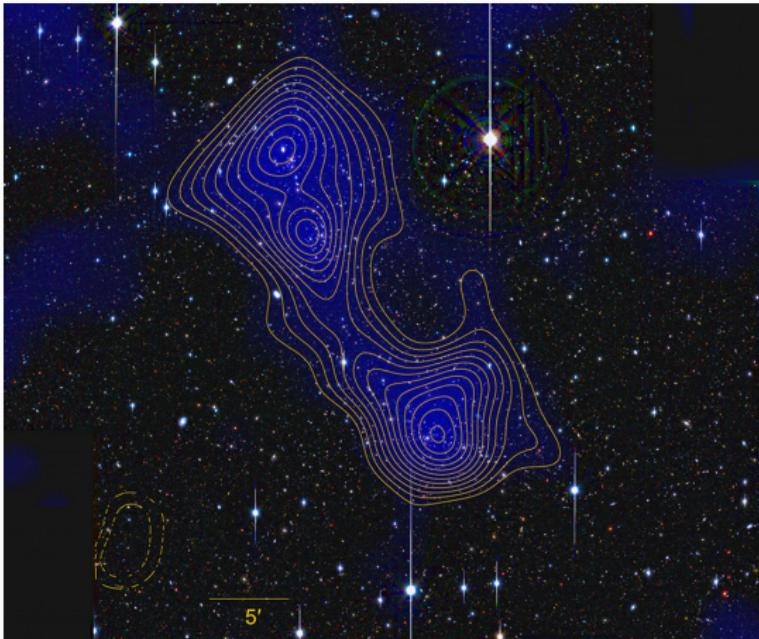
Warm-hot intergalactic medium (WHIM)
Density-weighted temperature projection of a portion of the refinement box of the C run of size $(18 h^{-1}\text{Mpc})^3$.
Low temperature WHIM confirmed by O VI line that peak at $T \sim 3 \times 10^5 \text{ K}$

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)

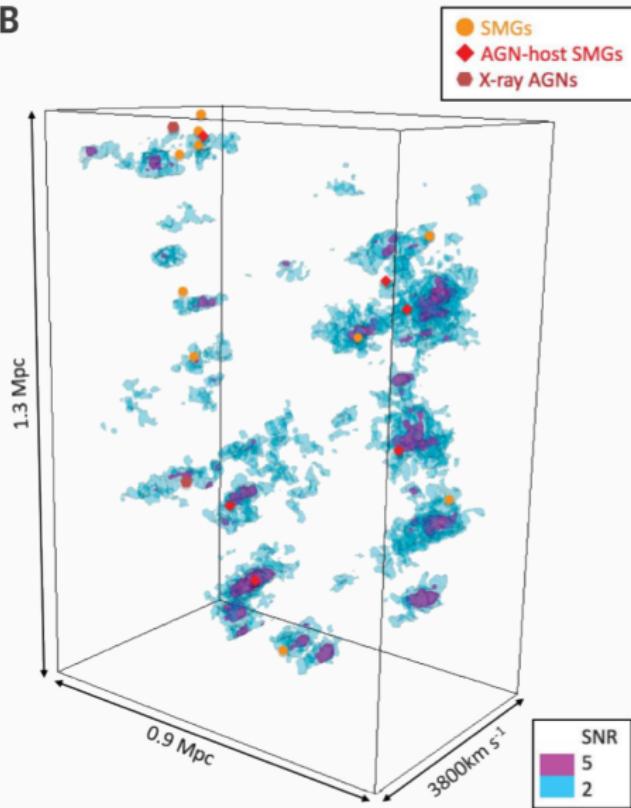
significance contours from 0.5σ to 2.5σ

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

For a recent review see: arXiv:1905.08991

Three-dimensional pictures of Ly α filaments

B



The 3D distribution of Ly α filaments shown with

signal-to-noise ratio (SNR) > 5

signal-to-noise ratio (SNR) > 2

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

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

Apart from its manifold gravitational influences, 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.

Dark sectors



SM





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

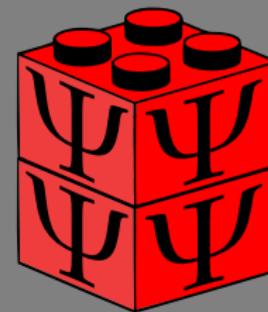
$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + i\bar{X}i\mathcal{D}X - m\bar{X}X.$$



SM

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

Relic abundance $X\bar{X} \rightarrow \gamma_{\mathcal{D}}\gamma_{\mathcal{D}}$



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

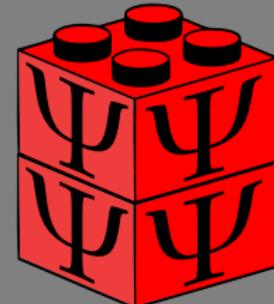
$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + i\bar{X}i\cancel{D}X - m\bar{X}X.$$



SM

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

Relic abundance $X\bar{X} \rightarrow \gamma_{\mathcal{D}}\gamma_{\mathcal{D}}$



Too
Restricted

Explain also small neutrino masses

In the following discussion we use the following doublets

$$H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, \quad L_i = \begin{pmatrix} \nu_{Li} \\ e_{Li}^- \end{pmatrix}. \quad (1)$$

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

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

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

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

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

$$[\mathrm{SU}(3)_c]^2 \mathrm{U}(1)_X :$$

$$[3u + 3d] - [3 \cdot 2q] = 0$$

$$[\mathrm{SU}(2)_L]^2 \mathrm{U}(1)_X :$$

$$-[2\textcolor{blue}{l} + 3 \cdot 2q] = 0$$

$$[\mathrm{U}(1)_Y]^2 \mathrm{U}(1)_X :$$

$$\left[(-2)^2 e + 3 \left(\frac{4}{3}\right)^2 u + 3 \left(-\frac{2}{3}\right)^2 d \right] - \left[2(-1)^2 \textcolor{blue}{l} + 3 \cdot 2 \left(\frac{1}{3}\right)^2 q \right] = 0 \quad (2)$$

with solution

$$u = -e + \frac{2l}{3}, \quad d = e - \frac{4l}{3}, \quad q = -\frac{l}{3}, \quad (2)$$

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which satisfy

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

with solution

$$u = -e + \frac{2\textcolor{blue}{l}}{3}, \quad d = e - \frac{4\textcolor{blue}{l}}{3}, \quad q = -\frac{\textcolor{blue}{l}}{3}, \quad (2)$$

which satisfy

$$\mathrm{U}(1)_Y [\mathrm{U}(1)_X]^2 : \quad [(-2)e^2 + 3\left(\frac{4}{3}\right)u^2 + 3\left(-\frac{2}{3}\right)d^2] - [2(-1)\textcolor{blue}{l}^2 + 3 \cdot 2\left(\frac{1}{3}\right)q^2] = 0 \quad (3)$$

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

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

with solution

$$u = -\textcolor{violet}{r} - \frac{4\textcolor{blue}{l}}{3}, \quad d = \textcolor{violet}{r} + \frac{2\textcolor{blue}{l}}{3}, \quad q = -\frac{\textcolor{blue}{l}}{3}, \quad e = \textcolor{violet}{r} + 2\textcolor{blue}{l}, \quad (2)$$

which satisfy

$$\mathrm{U}(1)_Y [\mathrm{U}(1)_X]^2 : \quad [(-2)e^2 + 3\left(\frac{4}{3}\right)u^2 + 3\left(-\frac{2}{3}\right)d^2] - [2(-1)\textcolor{blue}{l}^2 + 3 \cdot 2\left(\frac{1}{3}\right)q^2] = 0 \quad (3)$$

For N extra quiral fields ψ_α ($\alpha = 1, \dots, N$) with X -charges n_α : $\textcolor{violet}{r} \equiv e - 2\textcolor{blue}{l}$

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

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

$$X(\textcolor{violet}{r}, \textcolor{blue}{l}) = \textcolor{violet}{r}R + \textcolor{blue}{l}Y.$$

with solution

$$u = -1 - \frac{4l}{3}, \quad d = 1 + \frac{2l}{3}, \quad q = -\frac{l}{3}, \quad e = 1 + 2l, \quad (2)$$

which satisfy

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

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

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

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

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

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

* Use vector like fermions $\mathcal{D}(\psi_L) = \mathcal{D}(\psi_R) \rightarrow n - n = 0$

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

Or... combine known 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]

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:

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

Or... combine known solutions with $\sum n_\alpha = -3$ and $\sum n_\alpha^3 = -3$

$(\nu_{R1}, \nu_{R2}, \psi_{N-2}, \dots)$	Ref
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Not known solution for
one-loop neutrino Majorana masses
with local $U(1)_X$.

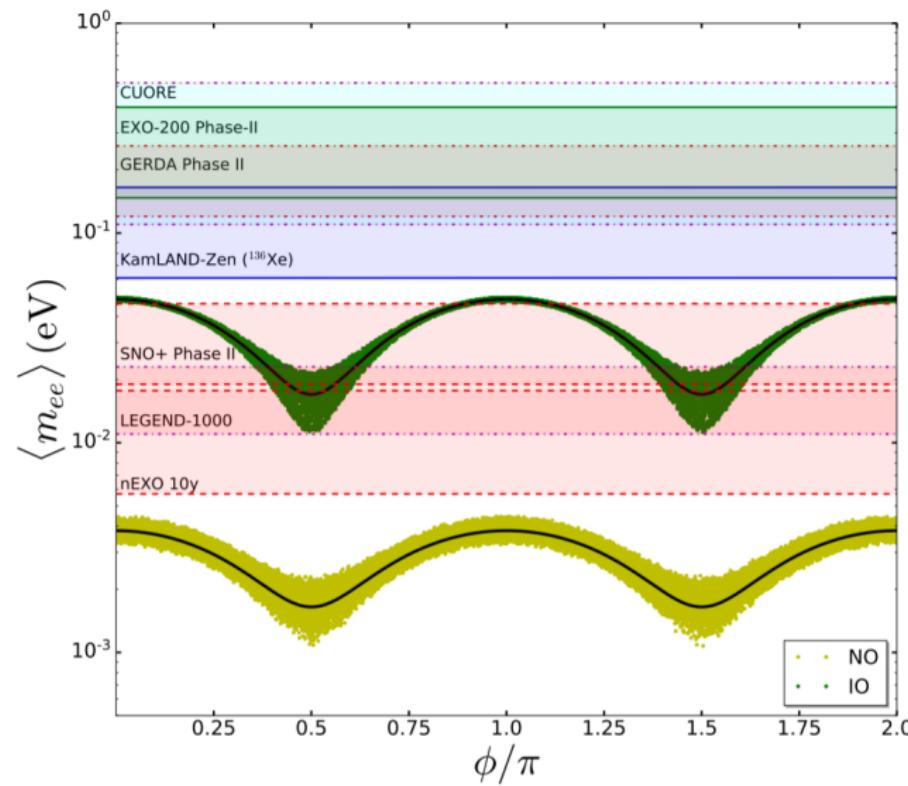
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(One-loop) Dirac neutrino masses

Lepton number

- Lepton number (L) is an accidental discrete or Abelian symmetry of the standard model (SM).
- Without neutrino masses L_e, L_μ, L_τ 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	ω
$(e_R)^\dagger$	ω
$(\nu_R)^\dagger$	ω

Dirac $U(1)_L$

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

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

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

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

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

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

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

Field	Z_2 ($\omega^2 = 1$)
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$(e_R)^\dagger$	ω
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Dirac $U(1)_{B-L}$

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

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

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

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

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

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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Small Dirac neutrino masses

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

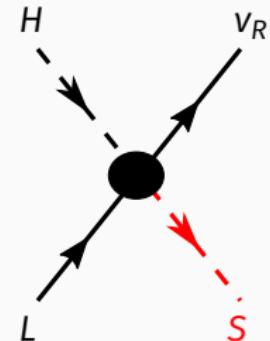
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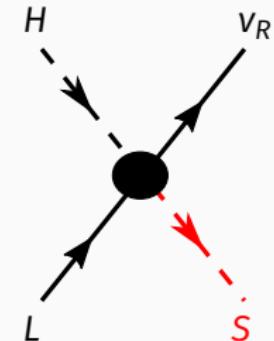
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- Enhancement to the *effective number of degrees of freedom in the early Universe* $\Delta N_{\text{eff}} = N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$ (see arXiv:1211.0186)

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

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

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

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

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

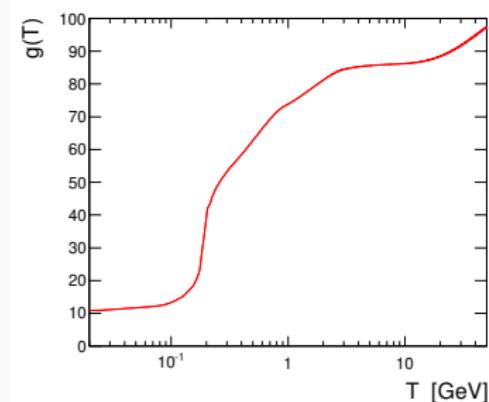
$$\sigma_f(s) \simeq \frac{N_C^f (Q_{BL}^f)^2 Q^2 s}{12\pi} \left(\frac{g'}{M_{Z'}} \right)^4, \quad \text{In the limit } M_{Z'}^2 \gg s.$$

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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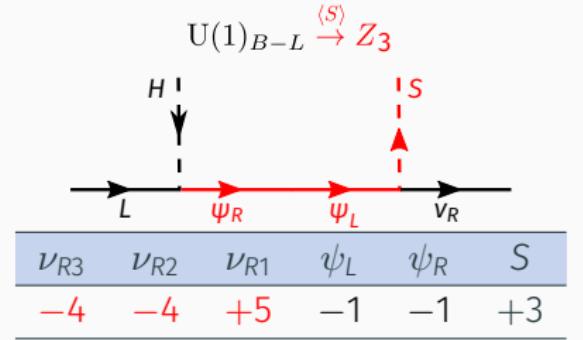
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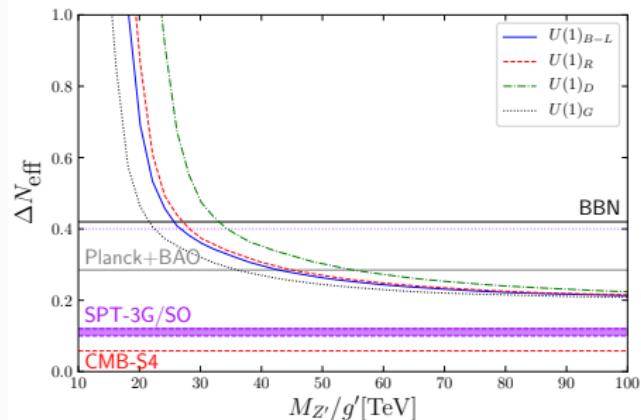
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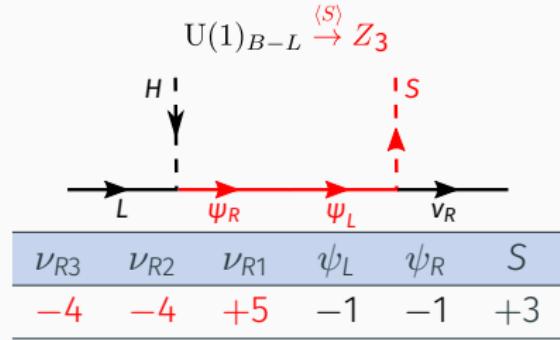
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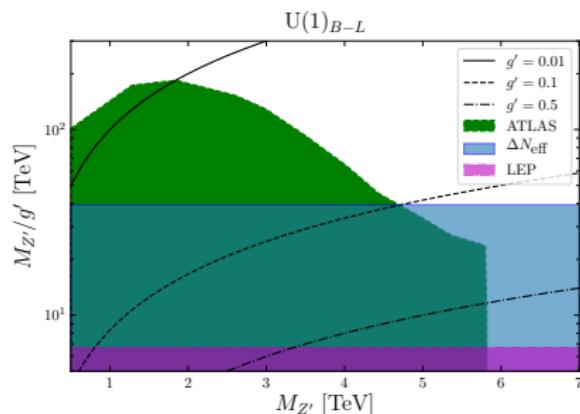
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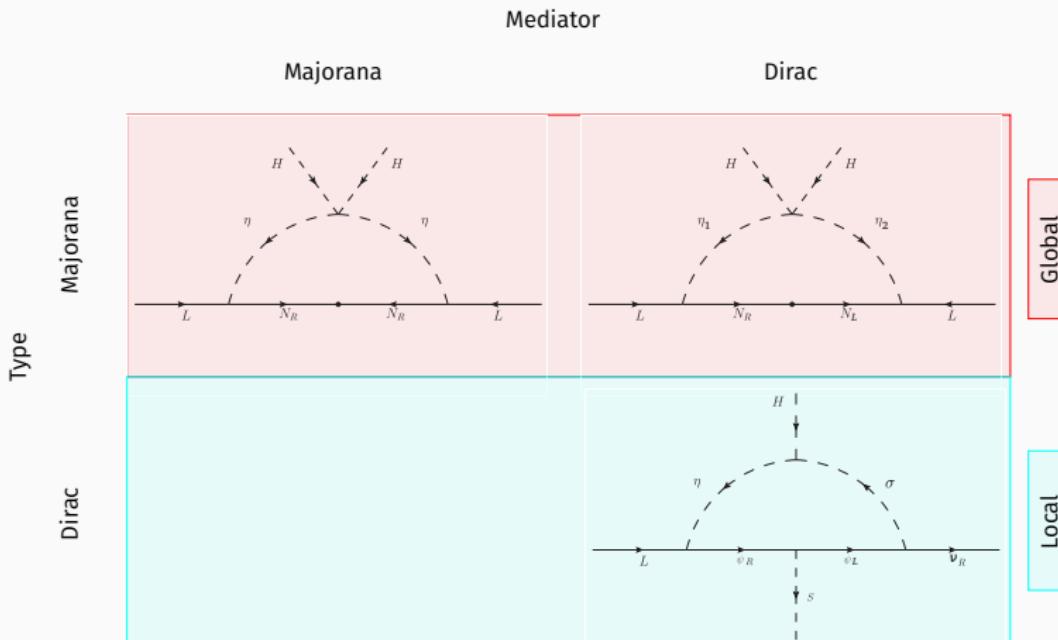
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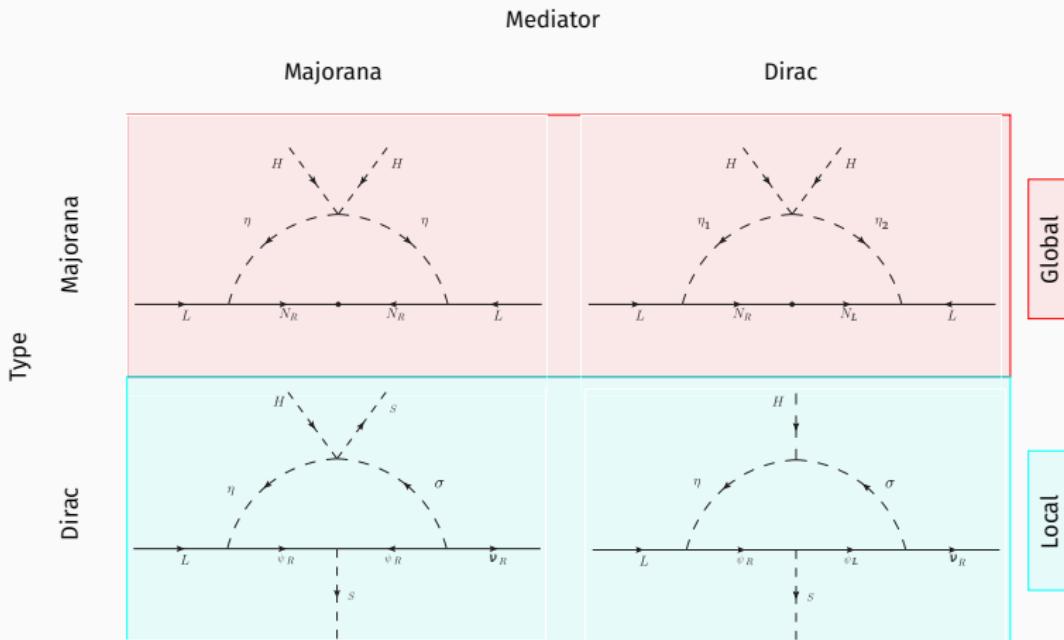


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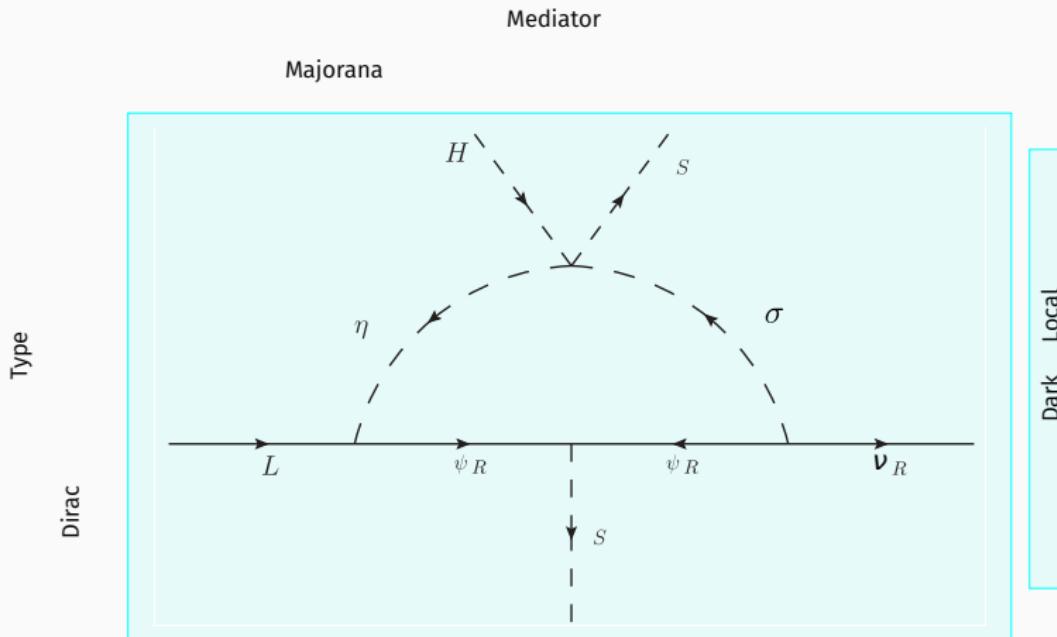
Dark symmetry

Radiative Type-I seesaw



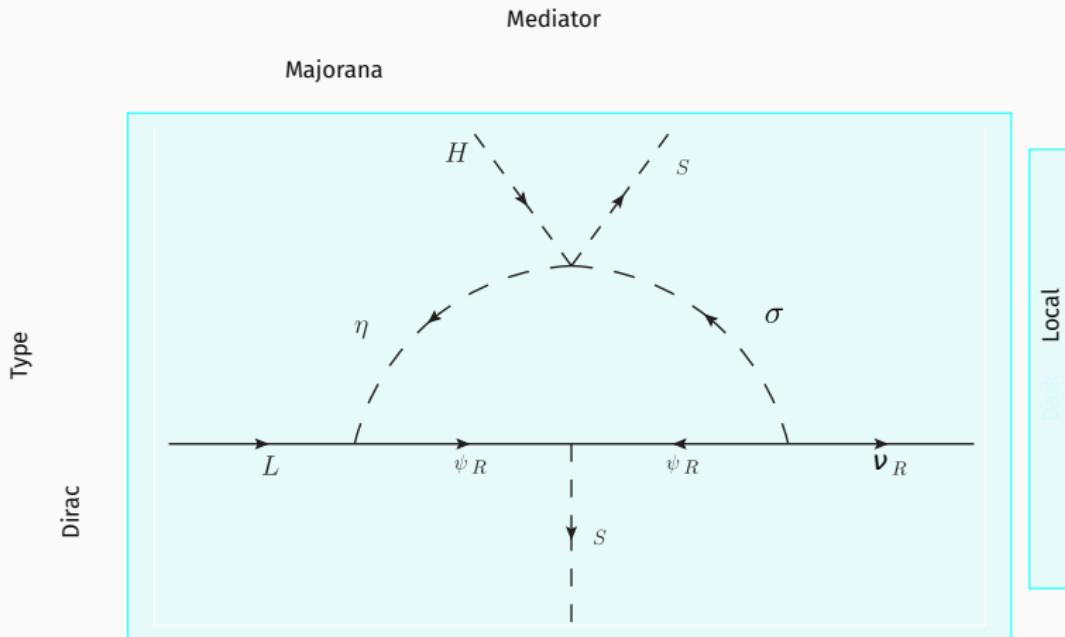


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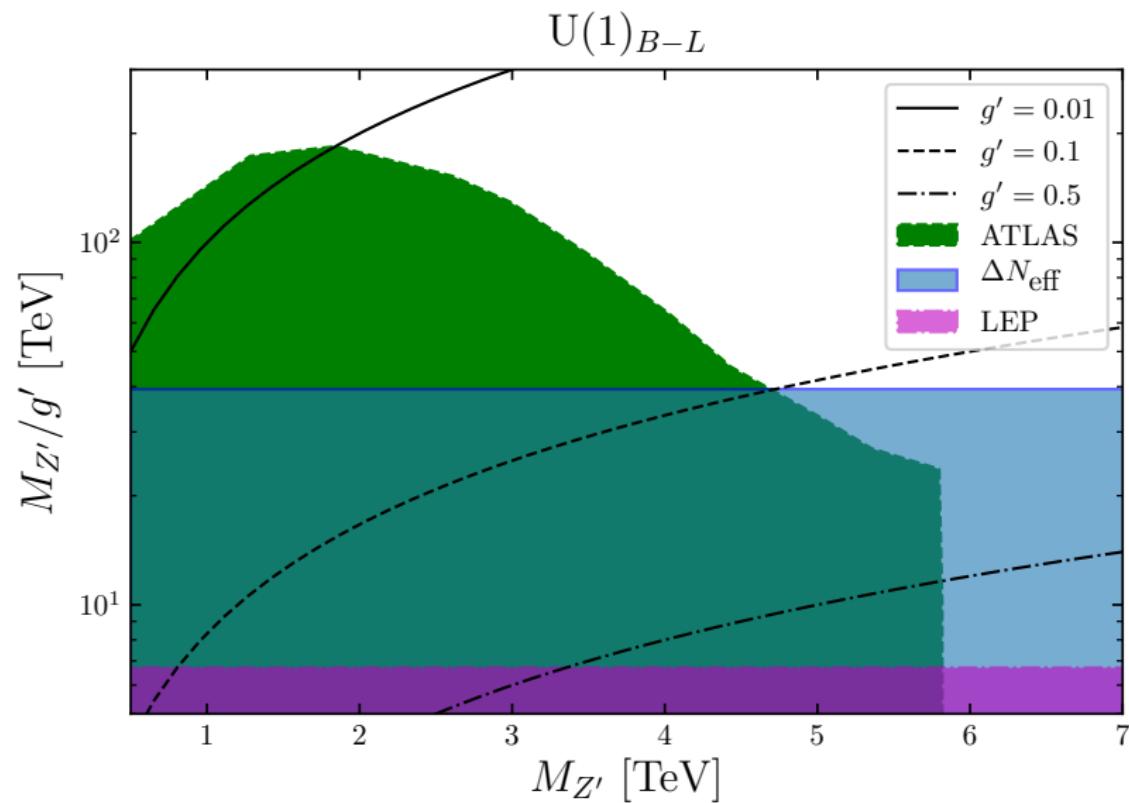
Fields	$SU(2)_L$	$U(1)_Y$	$U(1)_D$
L	2	-1/2	0
Q	2	-1/6	0
d_R	1	-1/2	0
u_R	1	+2/3	0
e_R	1	-1	0
H	2	1/2	0
η	2	1/2	1
S	1	0	2
σ	1	0	3
ν_{R1}	1	0	+4
ν_{R2}	1	0	+4
ν_{R3}	1	0	-5
ψ_{R1}	1	0	-1
ψ_{R2}	1	0	-1
ψ_{R3}	1	0	-1
TOTAL			0

Radiative Type-I seesaw



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
ψ_{R1}	1	0	$3/4$
ψ_{R2}	1	0	$3/4$
ψ_{R3}	1	0	$3/4$
$\xi_{L\alpha}$	1	0	$3/4^{25}$

Same constraints as before



Conclusions

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

One-loop Dirac neutrino masses

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

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



Thanks!