Dirac fermion dark matter

with Dirac neutrino masses

Diego Restrepo

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Instituto de Fsica
Universidad de Antioquia
Phenomenology Group
`http://gfif.udea.edu.co`

Focus on

1803.08528 [PRD], 1806.09977, 1808.03352

In collaboration with

Nicols Bernal (UAN), Mario Reig, Jose Valle (IFIC), Carlos Yaguna (UPTC), Julian Calle, Oscar Zapata (UdeA)

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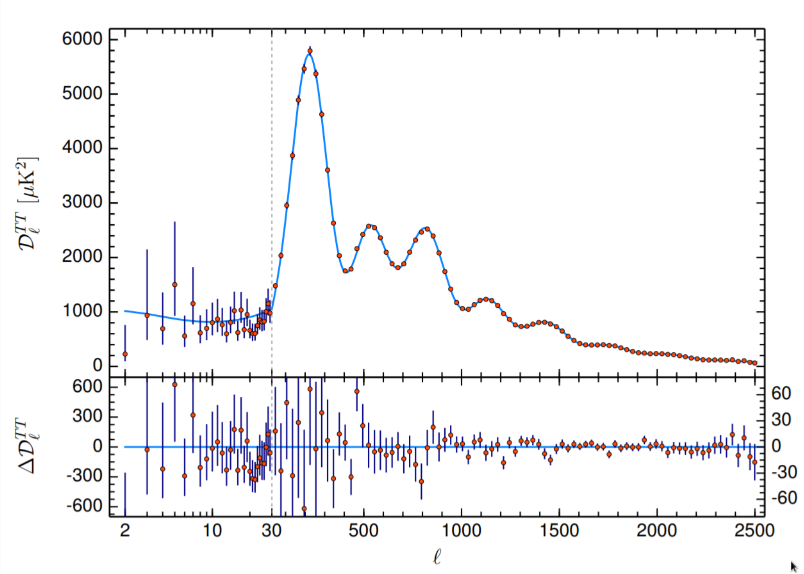
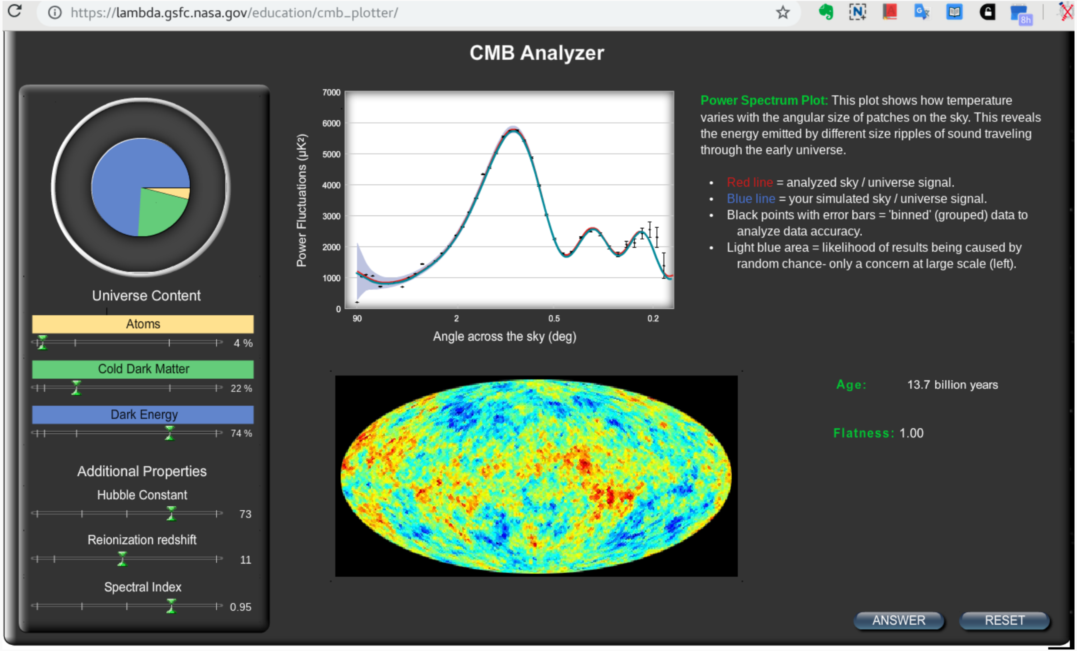
ΛCDM paradigm (with baryonic effects)

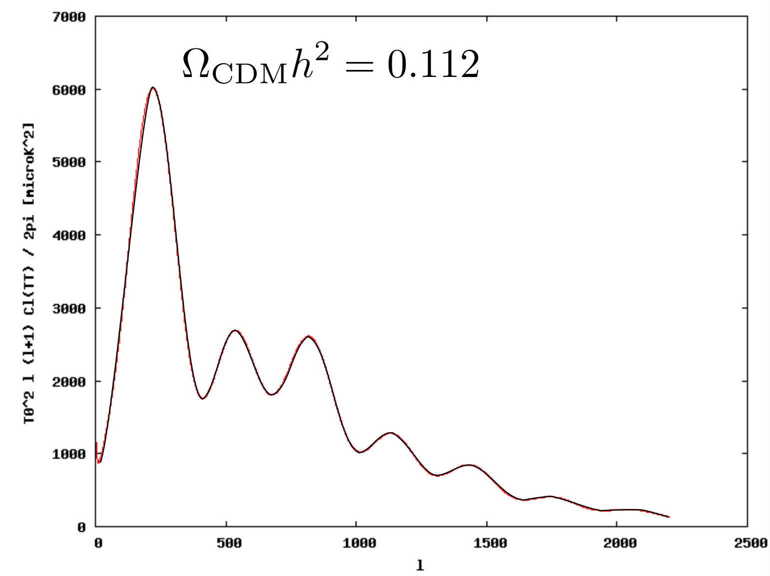


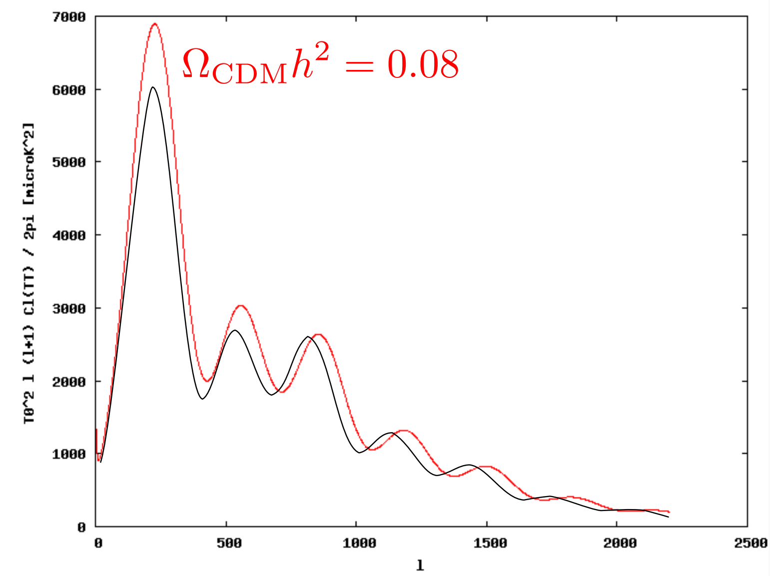
Credit: Planck 2018

Why was the temperature of the CMB the same in all directions?
What was the origin of the small temperature fluctions?



See also `https://lambda.gsfc.nasa.gov/toolbox/tb_camb_form.cfm`


$\Omega_{\rm CDM}h^2 = 0.112$
T0^2 l (l+1) Cl(TT) / 2pi [microK^2]
l
0
1000
2000
3000
4000
5000
6000
7000
500
1500
2500



$\Omega_{\rm CDM} h^2 = 0.08$
T0^2 l (l+1) Cl(TT) / 2pi [microK^2]
l
0
1000
2000
3000
4000
5000
6000
7000
500
1500
2500

Credit: Komatsu, ICTP Summer School on Cosmology 2018[1]

[1] Video avalaible

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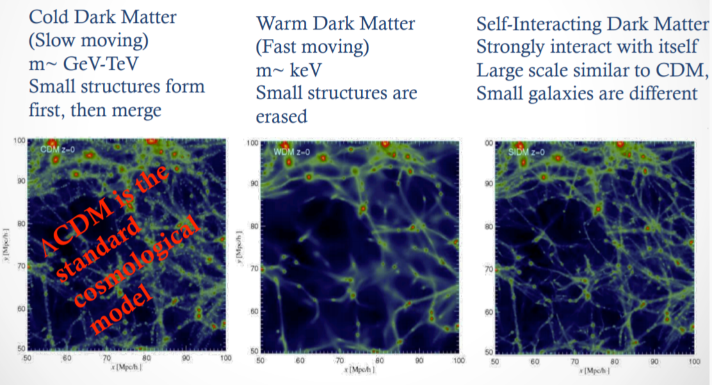
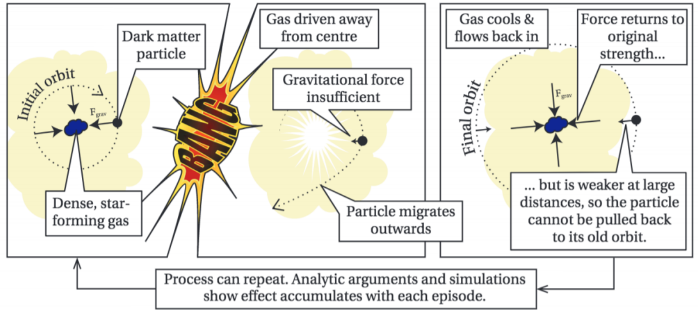
[1] Video avalaible

Dark matter simulations



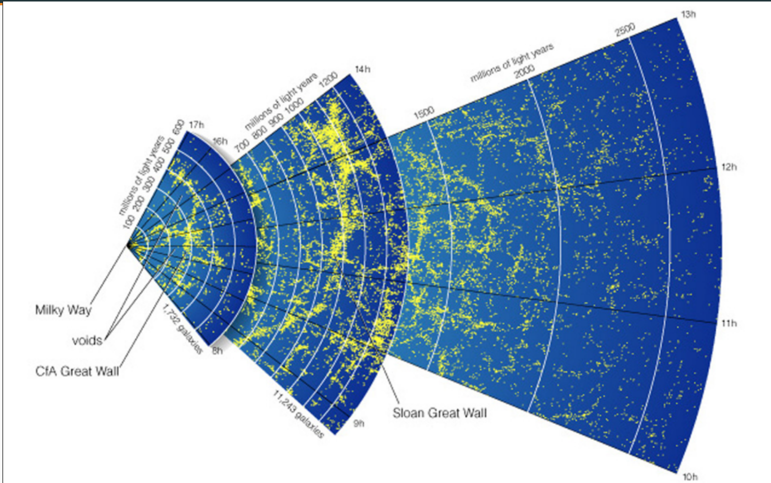
Credit: Arianna Di Cintio (Conference on Shedding Light on the Dark Universe with Extremely Large Telescopes, ICTP - 2018)

Baryonic effects



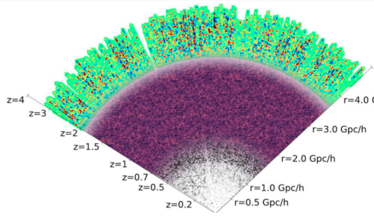
Pontzen & Governatp 14

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



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

The DESI experiment



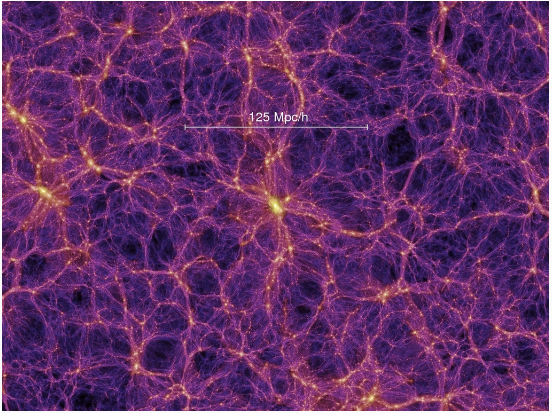
J. Forero

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

Cooking the soup: 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 [arXiv:1801.09070]

An excess of a gas is observed between Milky Way and Andromeda



Milenium simulation: `https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/`

Cosmic Anatomy

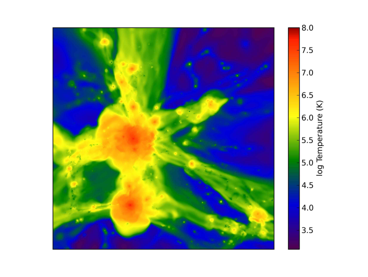
Baryons Missing Baryons Dark Matter

The muscles

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]

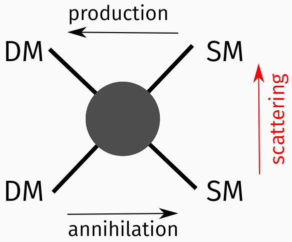
Warm-hot intergalactic medium (WHIM)
Density-weighted temperature projection of a portion of the refinement box of the C run of size $(18\,h^{-1}\mathrm{Mpc})^3$.
Low temperature WHIM confirmed by O VI line that peak at $T \sim 3 \times 10^5$ K

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

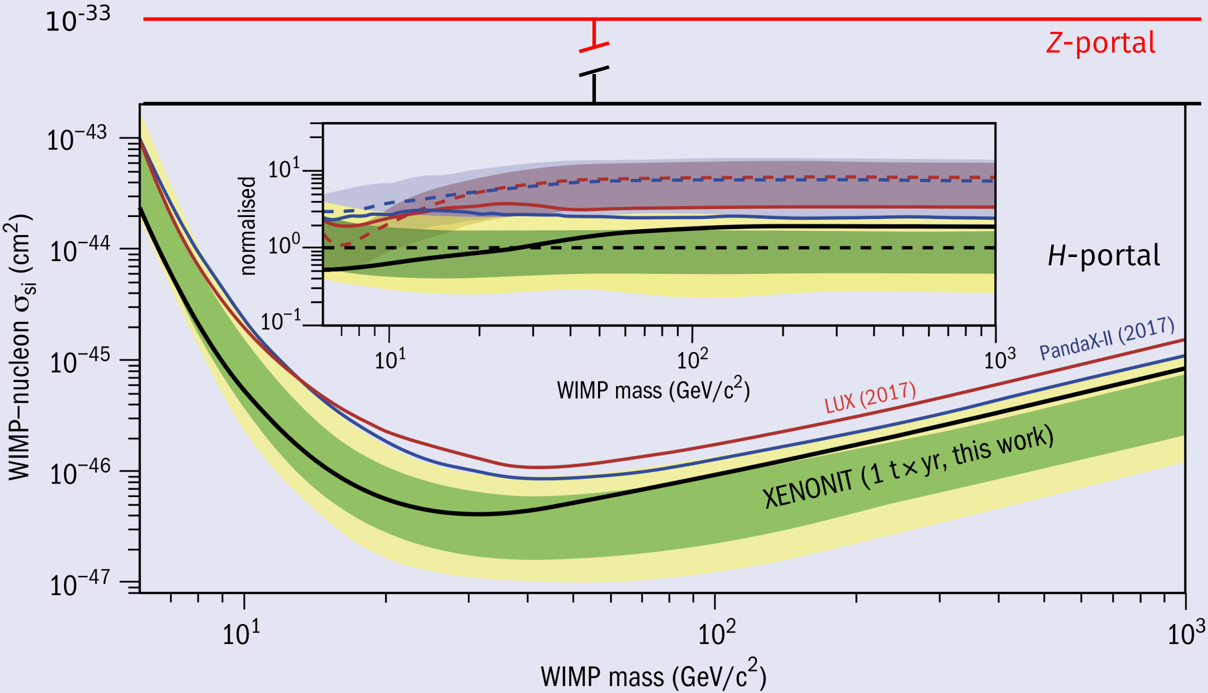
The skeleton

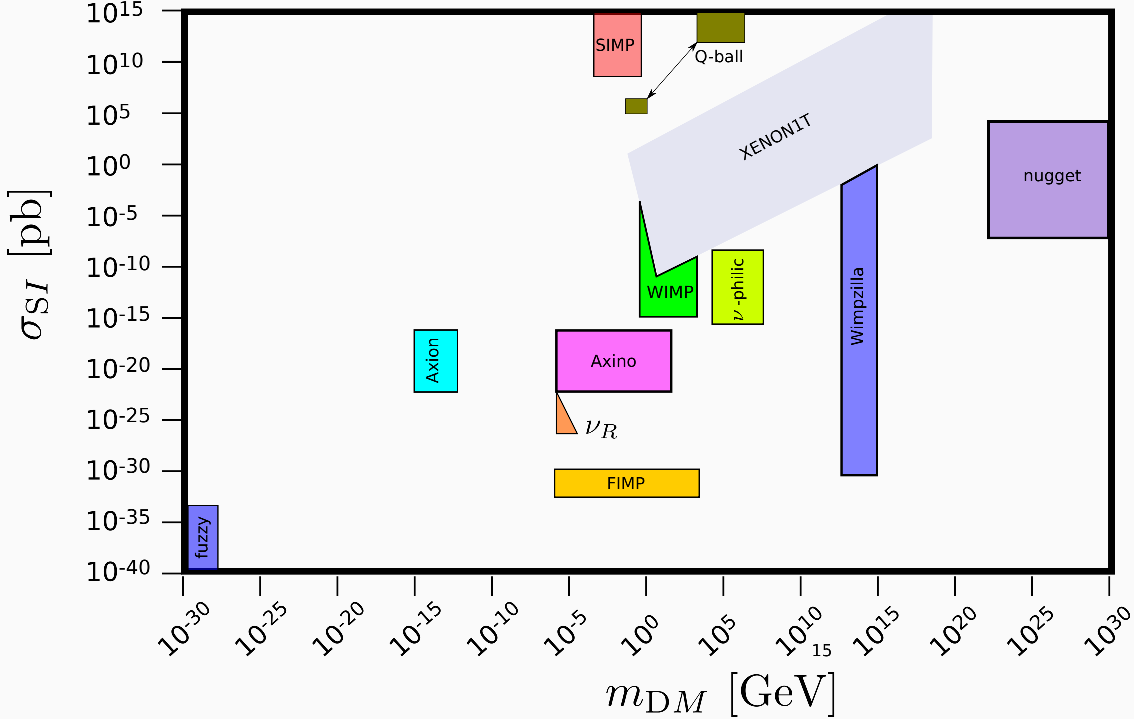
Credit: `https://www.disnola.com`


WIMP

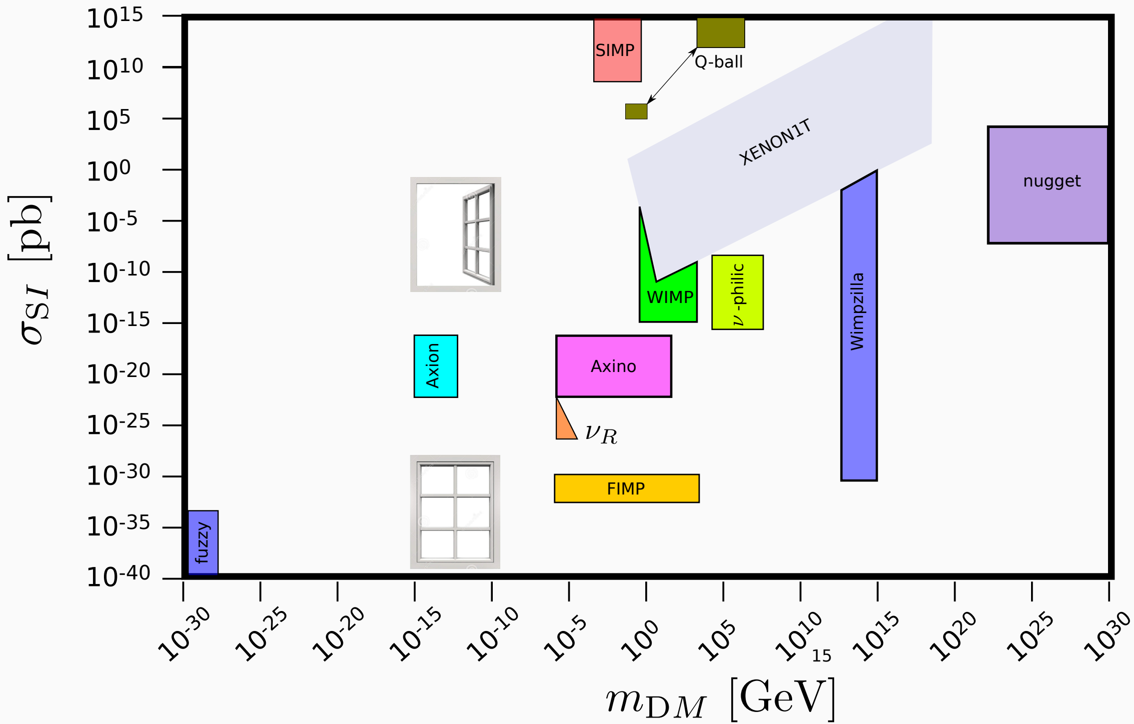

production
DM
SM
scattering
DM
SM
annihilation


WIMP


10^{-33}
Z-portal
H-portal
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
WIMP–nucleon σ_{SI} (cm^2)
10^1
10^2
10^3
WIMP mass (GeV/c^2)
normalised
10^{-1}
10^0
10^1
LUX (2017)
PandaX-II (2017)
XENON1T (1 t × yr, this work)



10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
$\sigma_{\rm SI}$ [pb]
SIMP
Q-ball
XENON1T
nugget
WIMP
ν -philic
Wimpzilla
Axion
Axino
ν_R
FIMP
fuzzy
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
15
10^{15}
10^{20}
10^{25}
10^{30}
$m_{{\rm D}M}$ [GeV]



σ_{SI} [pb]
10^{15}
10^{10}
10^{5}
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
SIMP
Q-ball
XENON1T
nugget
WIMP
ν-philic
Wimpzilla
Axion
Axino
ν_R
FIMP
fuzzy
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
10^{0}
10^{5}
10^{10}
15
10^{15}
10^{20}
10^{25}
10^{30}
m_{DM} [GeV]

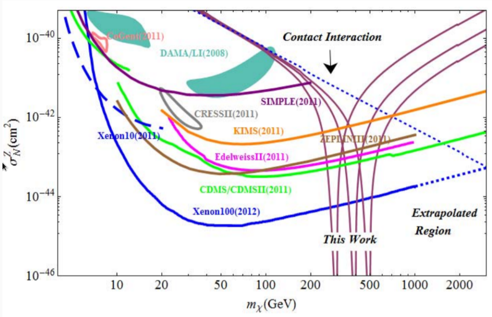
Dirac fermion dark matter

Isosinglet dark matter candidate

ψ as a isosinglet Dirac dark matter fermion charged under a local U(1)$_X$ (SM) cuples to a SM-singlet vector mediator X as

$$\mathcal{L}_{\text{int}} = -\, g_\psi\, \overline{\psi}\gamma^\mu \psi X_\mu - \sum_f g_f\, \overline{f}\gamma^\mu f X_\mu\,,$$

where f are the Standard Model fermions

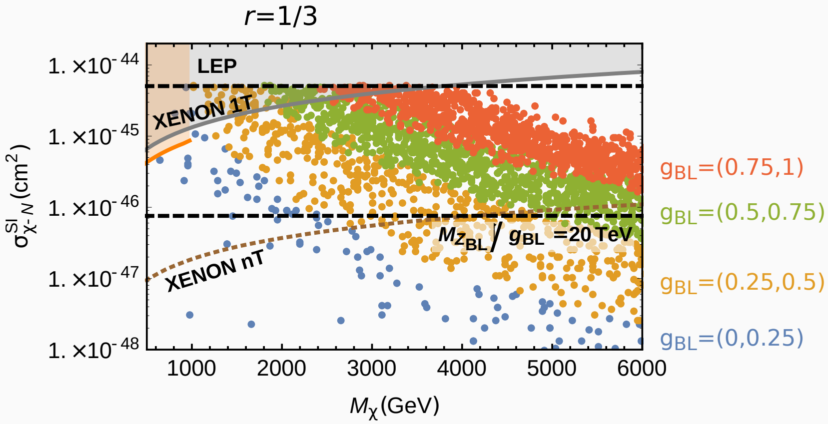


1305.7008. Chua, Hsieh

Isosinglet Dirac fermion dark matter model

Left Field	$U(1)_{B-L}$
$(\nu_{R_1})^\dagger$	$+1$
$(\nu_{R_2})^\dagger$	$+1$
$(\nu_{R_2})^\dagger$	$+1$
ψ_L	$-r$
$(\psi_R)^\dagger$	r
ϕ	2

$$\chi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

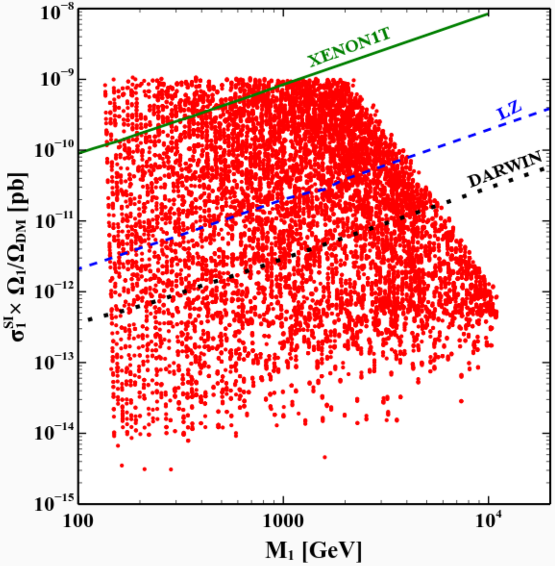


Duerr et al: 1803.07462 [PRD]

Double Dirac fermion dark matter model

Field	$U(1)_{B-L}$
$(\nu_{R_1})^\dagger$	$+1$
$(\nu_{R_2})^\dagger$	$+1$
ξ_1	$10/7$
η_1	$4/7$
ξ_2	$-9/7$
η_2	$2/7$
ϕ_1	2
ϕ_1	1

$$U(1)_{B-L} \to Z_7\,.$$



with N. Bernal, C. Yaguna and C. Zapata, 1808.03352

Colored Dirac fermion dark matter

Colored Dirac fermion dark matter

$\mathrm{SU}(3)_c = \mathbf{8}$

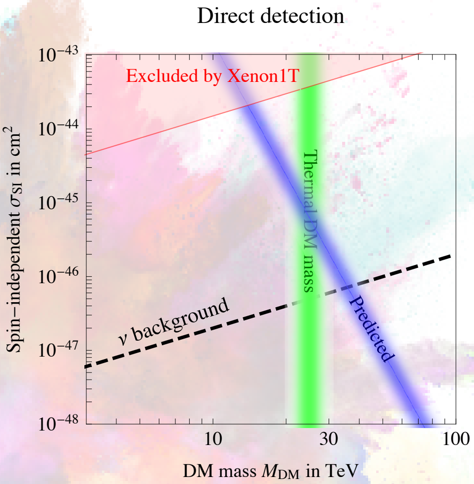
Field	$\mathrm{U}(1)_{\mathcal{Q}}$
ξ	r
η	$-r$

$$\mathcal{Q} = \begin{pmatrix} \xi \\ \eta^\dagger \end{pmatrix}$$

$$\mathcal{L} = i\overline{\mathcal{Q}}\gamma^\mu \mathcal{D}_\mu \mathcal{Q} - M_{\mathcal{Q}}\overline{\mathcal{Q}}\mathcal{Q}\,.$$

$$\chi = |\mathcal{Q}\mathcal{Q}\rangle$$

$M_{\mathrm{DM}} \approx 2M_{\mathcal{Q}}$



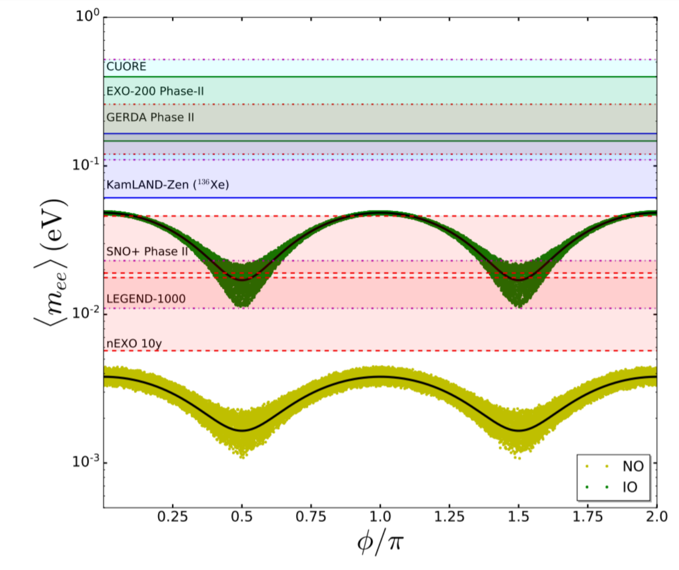
V. De Luca, *et al*, 1801.01135 [PRD]]

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 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 $\not{\mathrm{U}(1)}_L$

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 $\mathrm{U}(1)_L$

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

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

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

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

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

Field	Z_2 $(\omega^2 = 1)$
SM	1
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$$h_D \sim \mathcal{O}(1)$$

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

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

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

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

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

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

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

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- Prediction of extra relativistic degrees of freedom N_{eff}

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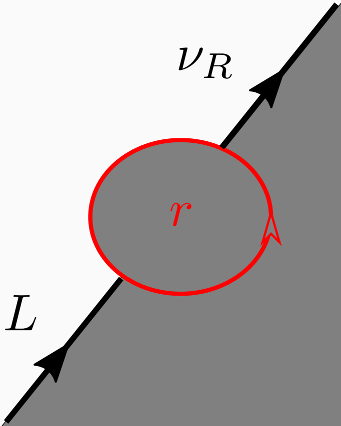
- Prediction of extra relativistic degrees of freedom N_{eff}

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

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

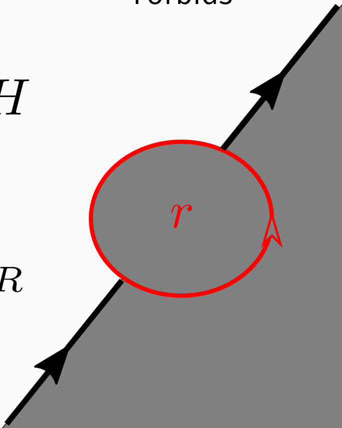
Forbids

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$



$\psi_R \psi_R$

$\psi_L \psi_L$

$\mathrm{U}(1)_X$

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

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

$(\psi_R)^\dagger \psi_L$

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

$\mathrm{U}(1)_X$

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

$X(L) \neq 0$

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

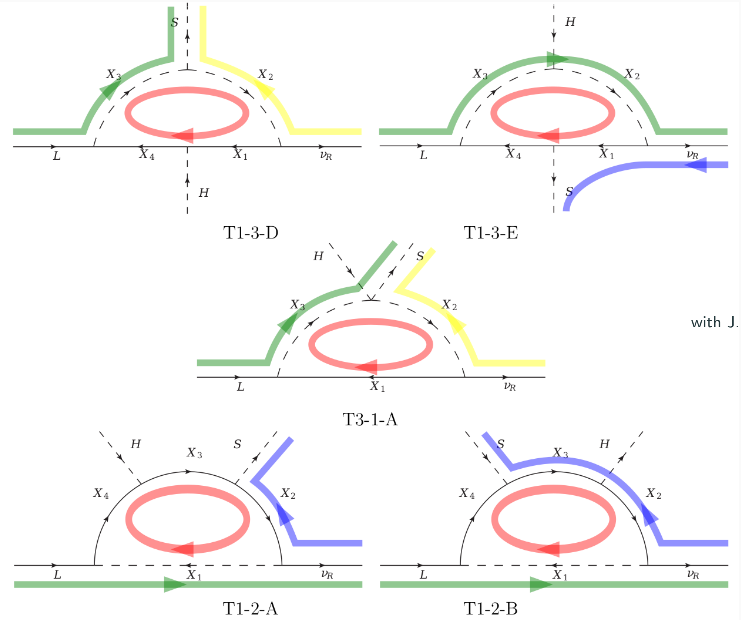
$(\psi_R)^\dagger \psi_L$

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

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

normalized to $X(L) = -1$

One loop topologies



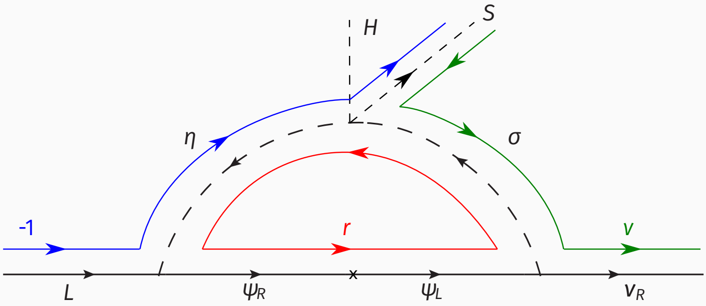
T1-3-D T1-3-E

T3-1-A

T1-2-A T1-2-B

with J. Calle, C. Yaguna, and O. Zapata, arXiv:1811.XXXX

T3-1-A

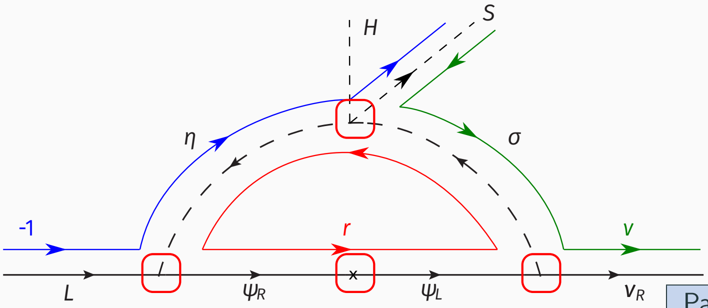


Soft breaking term induced:

$$\mathcal{L} \supset \kappa \sigma \eta^\dagger H \,,$$

where $\kappa = \lambda \langle S \rangle$.

Exotic $(\nu_R)^\dagger$ with $\nu \neq -1$, and vector-like Dirac fermion with $r \neq 1$



$$-1 + \eta = -\,r$$

$$-r = -\,r$$

$$-r = -\,\nu + \sigma$$

$$\sigma = \eta + s$$

$$N_c = 1\,.$$

Soft breaking term induced:

$$\mathcal{L} \supset \kappa \sigma \eta^\dagger H\,,$$

where $\kappa = \lambda\langle S\rangle\,.$

Particles	$\mathrm{U}(1)_{B-L}$	$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_Y$
L_i	-1	$(\mathbf{1},\mathbf{2})_{-1/2}$
H	0	$(\mathbf{1},\mathbf{2})_{1/2}$
$(\nu_{Ri})^\dagger$	ν	$(\mathbf{1},\mathbf{1})_0$
ψ_L	$-r$	$(\mathbf{N}_c,\mathbf{1})_0$
$(\psi_R)^\dagger$	r	$(\mathbf{N}_c,\mathbf{1})_0$
σ_a	$\nu - r$	$(\mathbf{N}_c,\mathbf{1})_0$
η_a	$1 - r$	$(\mathbf{N}_c,\mathbf{2})_{1/2}$
S	$\nu - 1$	$(\mathbf{N}_c,\mathbf{2})_{1/2}$

Neutrino masses and mixings

- ν_i are free parameter and could be fixed if we impose $\mathrm{U}(1)_{B-L}$ to be local

$$r \neq 1\,, \qquad \sum_i \nu_i = 3\,, \qquad \sum_i \nu_i^3 = 3$$

	$(\nu_R)_1^\dagger$	$(\nu_R)_2^\dagger$	$(\nu_R)_3^\dagger$
$\mathrm{U}(1)_{B-L}$	$+4$	$+4$	-5
$\mathrm{U}(1)_{B-L}$	-6	$+\frac{10}{3}$	$+\frac{17}{3}$

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- To have at least a rank 2 neutrino mass matrix we need either:
  - At least two heavy Dirac fermions Ψ_a, $a = 1, 2, \ldots$
  - At least two sets of scalars η_a, σ_a

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  - At least two sets of scalars η_a, σ_a

Neutrino masses and mixings

- ν_i are free parameter and could be fixed if we impose $\text{U}(1)_{B-L}$ to be local

$$r \neq 1\,, \qquad \sum_i \nu_i = 3\,, \qquad \sum_i \nu_i^3 = 3$$

	$(\nu_R)_1^\dagger$	$(\nu_R)_2^\dagger$	$(\nu_R)_3^\dagger$
$\text{U}(1)_{B-L}$	$+4$	$+4$	-5
$\text{U}(1)_{B-L}$	-6	$+\frac{10}{3}$	$+\frac{17}{3}$

- To have at least a rank 2 neutrino mass matrix we need either:
    - At least two heavy Dirac fermions Ψ_a, $a = 1, 2, \ldots$
    - At least two sets of scalars η_a, σ_a
-

$$\mathcal{L} \supset \left[M_\Psi\ (\psi_R)^\dagger\,\psi_L + h_i^a\,(\psi_R)^\dagger\,\widetilde{\eta}_a^\dagger L_i + y_i^a \overline{\nu_{Ri}}\ \sigma_a^* \psi_L + \text{h.c} \right] + \kappa^{ab}\,\sigma_a \eta_b^\dagger H + \ldots$$

Neutrino masses and mixings (with M.Reig, J.W.F Valle, O. Zapata, arXiv:1806.09977)

$$(\mathcal{M}_\nu)_{ij} = N_c \frac{M_\Psi}{64\pi^2} \sum_{a=1}^{2} h_i^a y_j^a \frac{\sqrt{2}\kappa_{aa} v}{m^2_{S^a_{2R}} - m^2_{S^a_{1R}}} \left[F\left(\frac{m^2_{S^a_{2R}}}{M^2_\Psi} \right) - F\left(\frac{m^2_{S^a_{1R}}}{M^2_\Psi} \right) \right] + (R \to I) \qquad (1)$$

where $F(m^2_{S_\beta}/M^2_\Psi) = m^2_{S_\beta} \log(m^2_{S_\beta}/M^2_\Psi)/(m^2_{S_\beta} - M^2_\Psi)$. The four CP-even mass eigenstates are denoted as $S^1_{1R}, S^1_{2R}, S^2_{1R}, S^2_{2R}$, with a similar notation for the CP-odd ones.

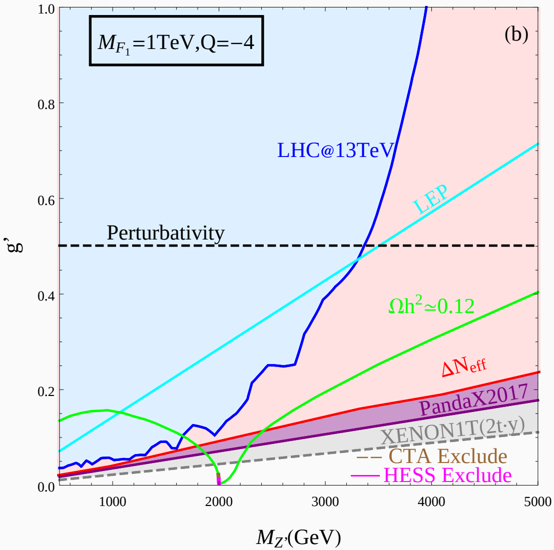
T3-1-A with only $U(1)_{B-L}$

Field	$U(1)_{B-L}$
$(\nu_{R_i})^\dagger$	$+4$
$(\nu_{R_j})^\dagger$	$+4$
$(\nu_{R_k})^\dagger$	-5
ψ_L	$-r$
$(\psi_R)^\dagger$	r
η_a	$r-4$
σ_a	$r-1$
S	-3

$a=1,2,\ i\neq j\neq k.$

$m=0$: ν_{L_k}, and $\nu_{R_k}\to N_{\rm eff}$

$$F_1=\begin{pmatrix}\psi_L\\ \psi_R\end{pmatrix}$$



Extra Z_2: Han, Wang, 1808.03352 [EJPC]

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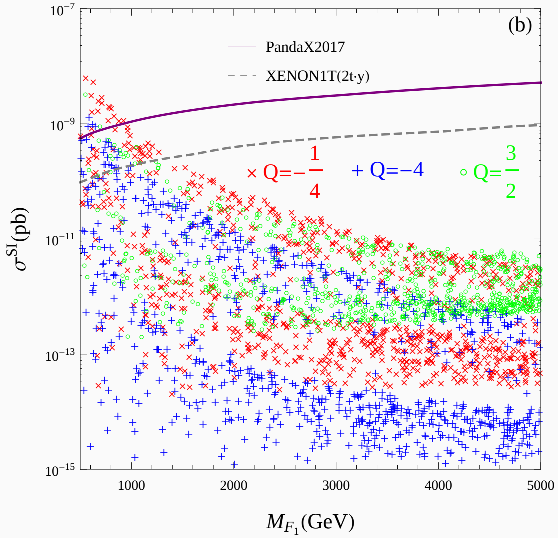

Extra Z_2: Han, Wang, 1808.03352 [EJPC]

Conclusions I

Only gravitational evidence of dark matter so far which is fully compatible with the ΛCDM-paradigm without simulation problems (~~cups vs core~~, ~~etc~~)

Not convincing signal at all

- ~~Galatic center excess~~
- ~~KeV lines~~
- ~~Positron excess~~
- ~~DAMA oscillation signal~~

Direct detection and LHC null results suggest to look

- Other (CDM) windows (Axion, FIMP, SIMP, . . .)
- Non-standard cosmology
- Other portals . . .

Z'-portal: A single $U(1)$ symmetry to explain both the smallnes of Dirac neutrino masses and the stability of Dirac fermion dark matter

Conclusions

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

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Dirac neutrino masses and DM

- Spontaneously broken $U(1)_{B-L}$ generates a radiative Dirac neutrino masses
- A remnant symmetry makes the lightest field circulating the loop stable and good dark matter candidate.
- If color is also circulating the loop, the colored dark matter scenario can be realized

Thanks!