Dirac fermion dark matter

with Dirac neutrino masses

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Focus on
1803.08528 [PRD], 1806.09977, 1808.03352
In collaboration with
Nicolás Bernal (UAN), Mario Reig, Jose Valle (IFIC), Carlos Yaguna (UPTC), Julian Calle, Oscar Zapata (UdeA)

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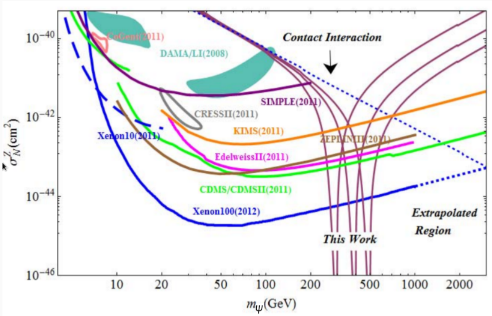
Dirac fermion dark matter

Isosinglet dark matter candidate

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

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

where f are the Standard Model fermions

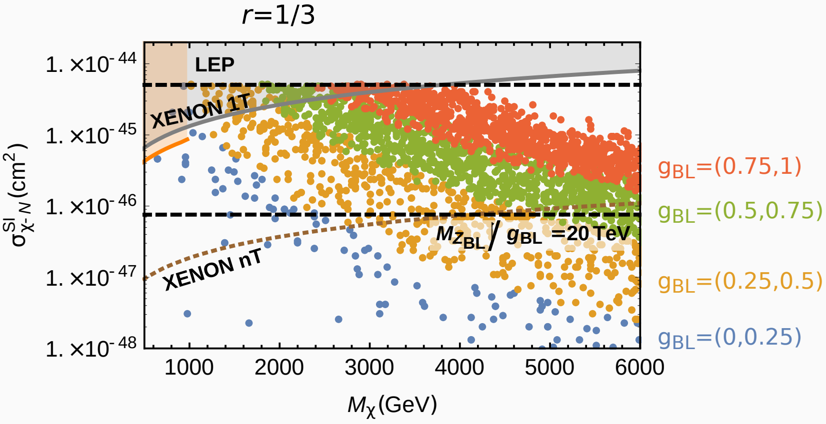


1305.7008. Chua, Hsieh

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]

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

Singlet-Doublet Dirac Dark Matter 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

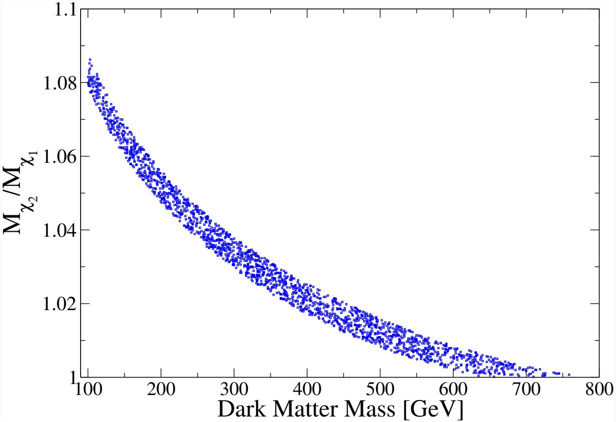
$$\mathcal{L} \supset M_\psi \left(\psi_R\right)^\dagger \psi_L + M_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + y_1 \left(\psi_R\right)^\dagger \Psi_L \cdot H + y_2 \widetilde{(\Psi_R)} \cdot \widetilde{H} \psi_L + \text{h.c} \tag{1}$$

Four free parameters:

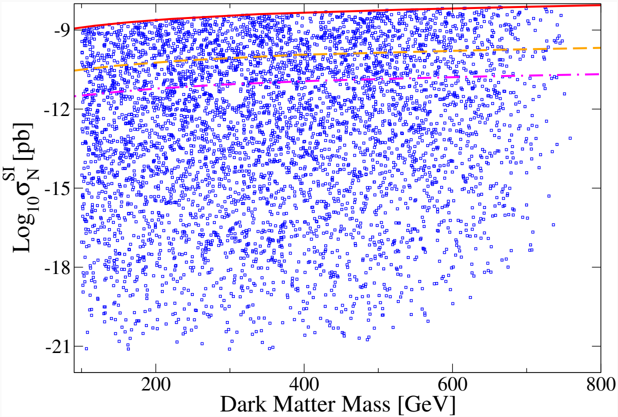
$$M_\psi, M_\Psi \ < 2\ \text{GeV}\,, \qquad\qquad y_1,\ y_2 > 10^{-6} \tag{2}$$

Tow neutral Dirac fermion eigenstates:

$$M = \begin{pmatrix} M_\psi & y_2 v/\sqrt{2} \\ y_1 v/\sqrt{2} & M_D \end{pmatrix}, \qquad\qquad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \tag{3}$$



Compressed spectra region



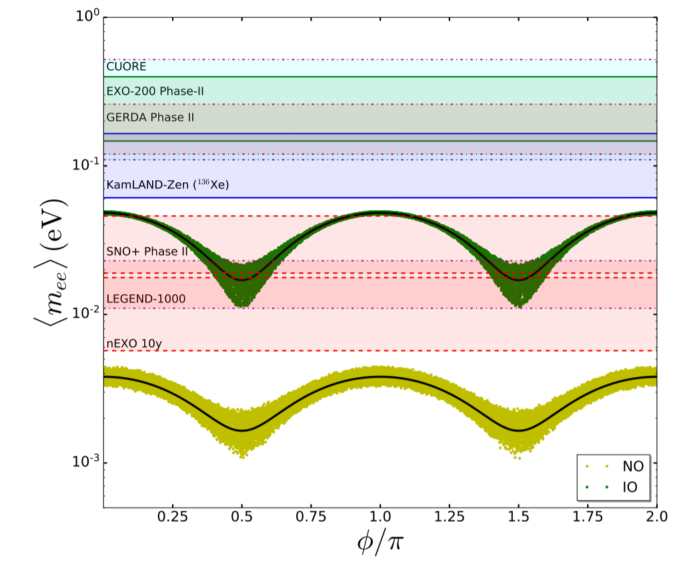
LUX - XENON1T - LZ

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

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

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

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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 $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$:

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

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

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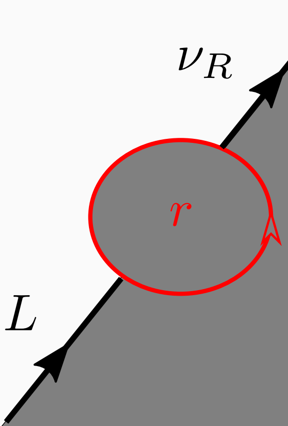
- Prediction of extra relativistic degrees of freedom N_{eff}

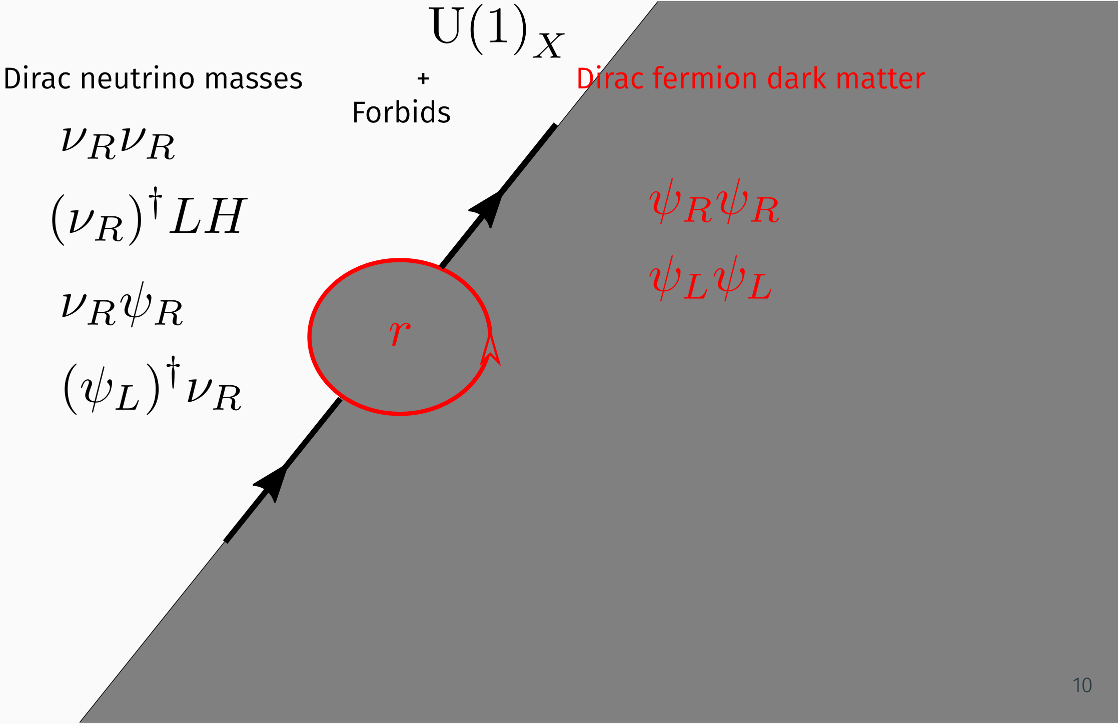
See E. Ma, Rahul Srivastava: arXiv:1411.5042 [PLB] for tree-level realization

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
$\nu_R \nu_R$
$(\nu_R)^\dagger L H$
$\nu_R \psi_R$
$(\psi_L)^\dagger \nu_R$
$\psi_R \psi_R$
$\psi_L \psi_L$
r

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

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

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$X(L) \neq 0$

$(\psi_L)^\dagger \nu_R$

$\psi_R \psi_R$

$\psi_L \psi_L$

r

Allows

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

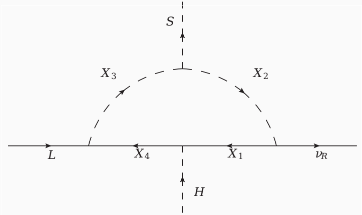
$(\psi_R)^\dagger \psi_L$

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

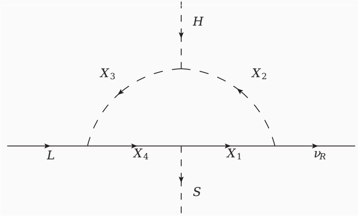
$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S \rangle} Z_N$ $\quad N \neq 2$

normalized to $X(L) = -1$

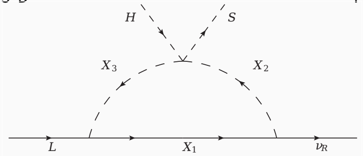
One loop topologies



T1-3-D

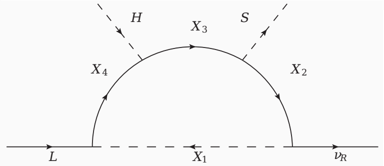


T1-3-E

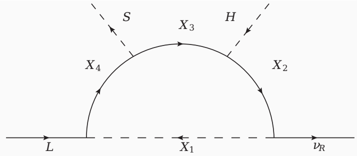


T3-1-A

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

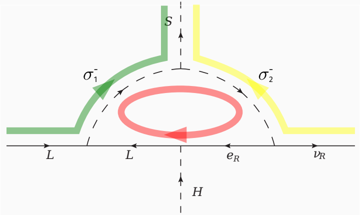


T1-2-A

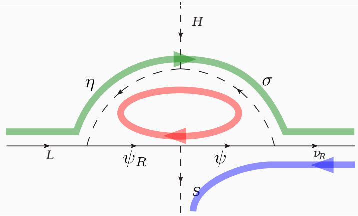


T1-2-B

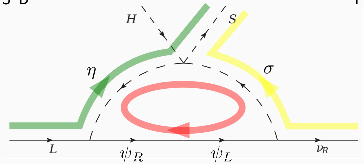
One loop topologies



T1-3-D



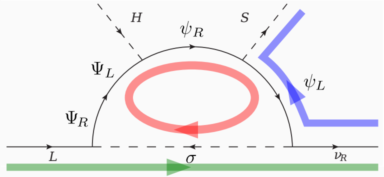
T1-3-E



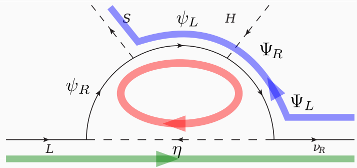
T3-1-A

- $\psi_{L,R}$ $\rightarrow$Singlet fermions
- $\Psi_{L,R}$ $\rightarrow$Doublet fermions
- σ $\rightarrow$Singlet scalar
- η $\rightarrow$Doublet scalar

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

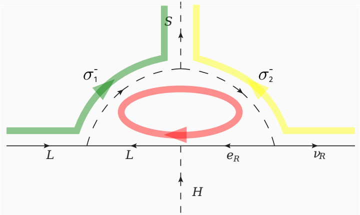


T1-2-A

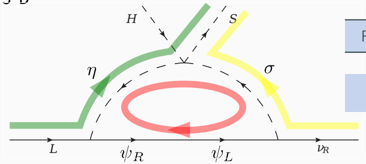


T1-2-B

One loop topologies



T1-3-D



T3-1-A

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

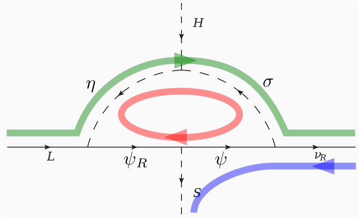
$\Psi_{L,R}$ $\rightarrow$Doublet fermions

σ $\rightarrow$Singlet scalar

η $\rightarrow$Doublet scalar

Fields	$(\nu_{Ri})^\dagger$	$(\nu_{Rj})^\dagger$	$(\nu_{Rk})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$

One loop topologies



T1-3-E

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

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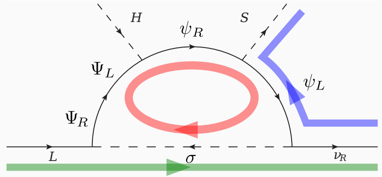
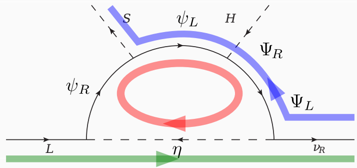
η $\rightarrow$Doublet scalar

Fields	$(\nu_{Ri})^\dagger$	$\left(\nu_{Rj}\right)^\dagger$	$(\nu_{Rk})^\dagger$	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

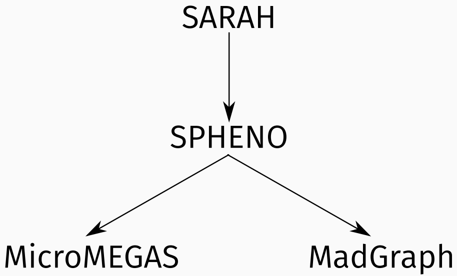


T1-2-B

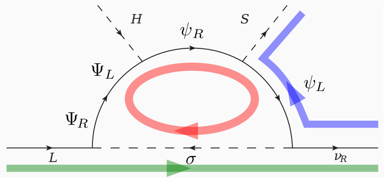
SD^{3}M+σ_i ($i = 1, 2$)

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

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

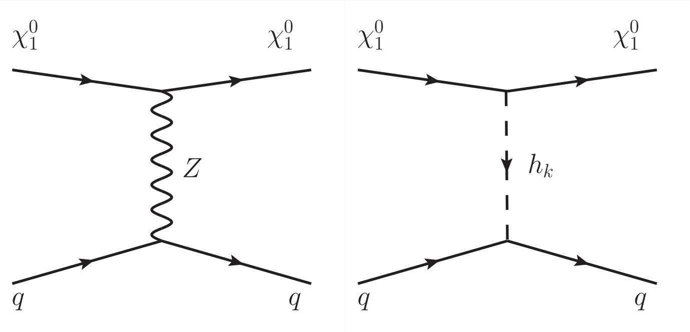


with A.F Rivera, W. Tangarife, arXiv:1905.NNNNN

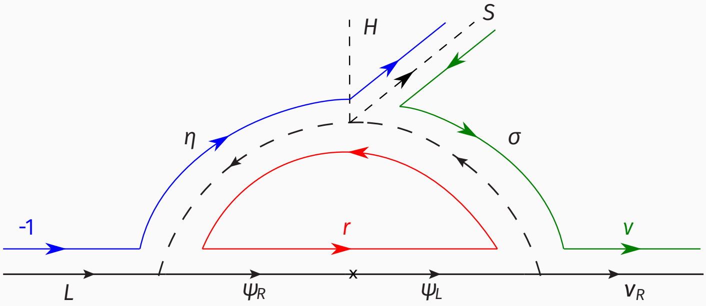


T1-2-A

SI



T3-1-A

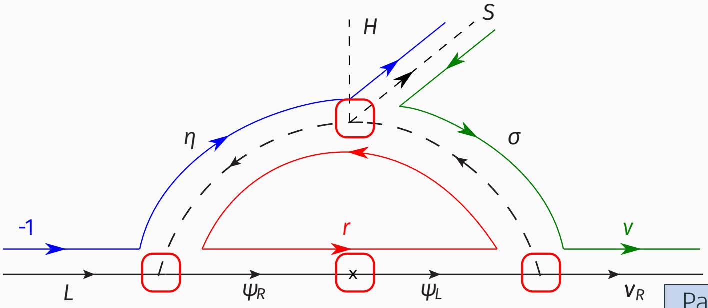


Soft breaking term induced:

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

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

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

	$(\nu_R)^\dagger_1$	$(\nu_R)^\dagger_2$	$(\nu_R)^\dagger_3$
$\mathrm{U}(1)_{B-L}$	$+4$	$+4$	-5
$\mathrm{U}(1)_{B-L}$	-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)

$$(\mathcal{M}_\nu)_{ij} = N_c \frac{M_\Psi}{64\pi^2} \sum_{a=1}^{2} h_i^a y_j^a \frac{\sqrt{2}\kappa_{aa} v}{m^2_{S^a_{2R}} - m^2_{S^a_{1R}}} \left[F\left(\frac{m^2_{S^a_{2R}}}{M^2_\Psi} \right) - F\left(\frac{m^2_{S^a_{1R}}}{M^2_\Psi} \right) \right] + (R \to I) \qquad (4)$$

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.

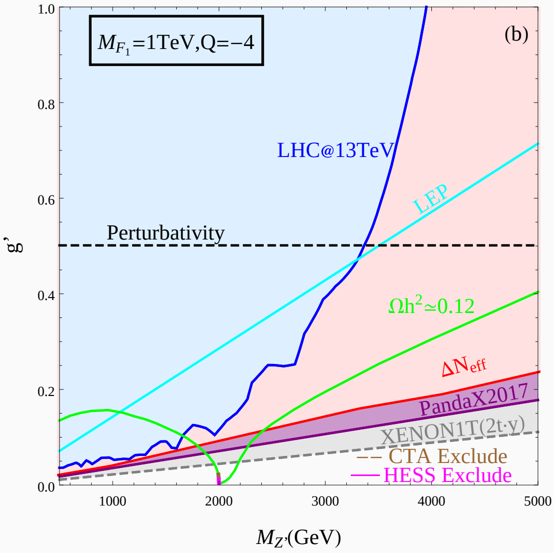
T3-1-A with only $U(1)_{B-L}$

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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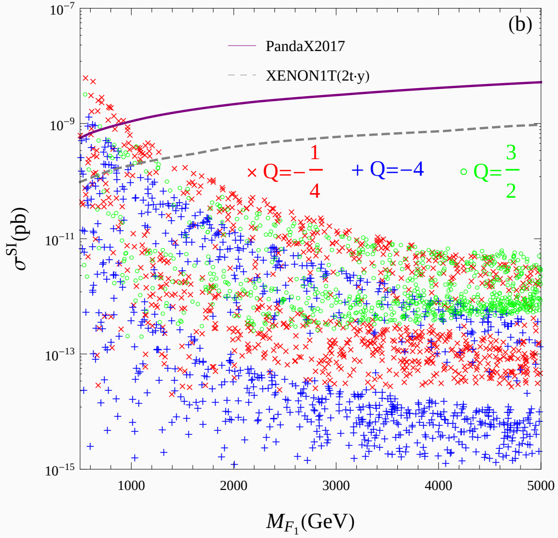

Extra Z_2: Han, Wang, 1808.03352 [EJPC]

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!