

Dirac fermion dark matter

with Dirac neutrino masses



UNIVERSIDAD DE ANTIOQUIA
1803

Diego Restrepo

December 4, 2018

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



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)

Table of Contents

1. Dirac fermion dark matter
2. Singlet-Doublet Dirac Dark matter Model
3. Neutrino masses
4. One-loop realization of \mathcal{L}_{5-D} with total L

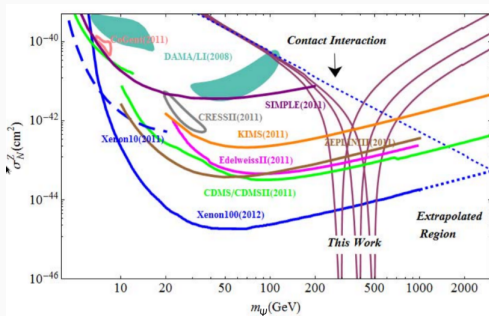
Dirac fermion dark matter

Isosinglet dark matter candidate

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

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

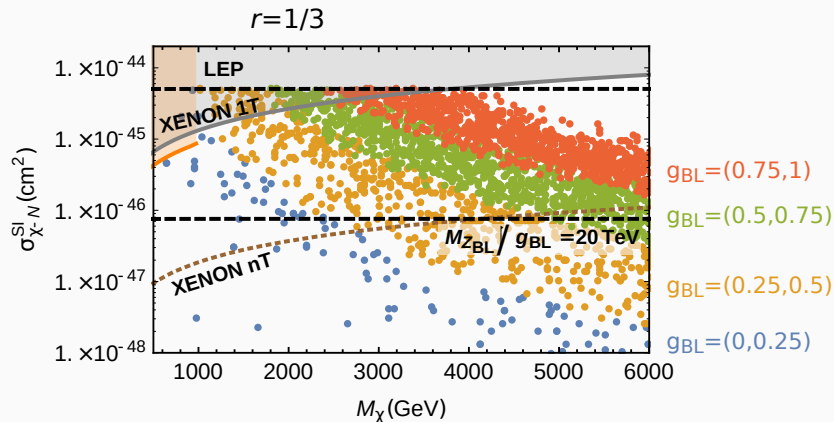
where f are the Standard Model fermions



Isosinglet Dirac fermion dark matter model

Left Field	$U(1)_{B-L}$
$(\nu_{R1})^\dagger$	+1
$(\nu_{R2})^\dagger$	+1
$(\nu_{R2})^\dagger$	+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

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

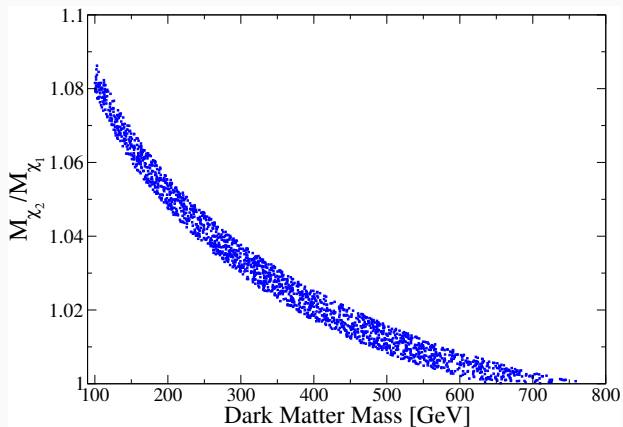
$$\mathcal{L} \supset \textcolor{red}{M}_\psi (\psi_R)^\dagger \psi_L + \textcolor{red}{M}_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + \textcolor{red}{y}_1 (\psi_R)^\dagger \Psi_L \cdot H + \textcolor{red}{y}_2 \widetilde{(\Psi_R)} \cdot \tilde{H} \psi_L + \text{h.c} \quad (1)$$

Four free parameters:

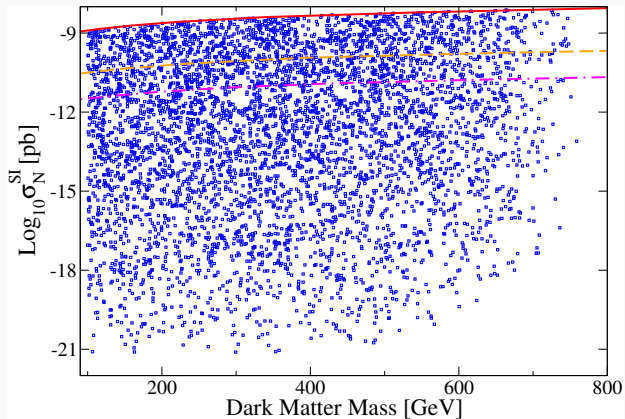
$$\textcolor{red}{M}_\psi, \textcolor{red}{M}_\Psi < 2 \text{ GeV}, \quad \textcolor{red}{y}_1, \textcolor{red}{y}_2 > 10^{-6} \quad (2)$$

Two neutral Dirac fermion eigenstates:

$$M = \begin{pmatrix} \textcolor{red}{M}_\psi & \textcolor{red}{y}_2 v / \sqrt{2} \\ \textcolor{red}{y}_1 v / \sqrt{2} & \textcolor{red}{M}_D \end{pmatrix}, \quad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \quad (3)$$



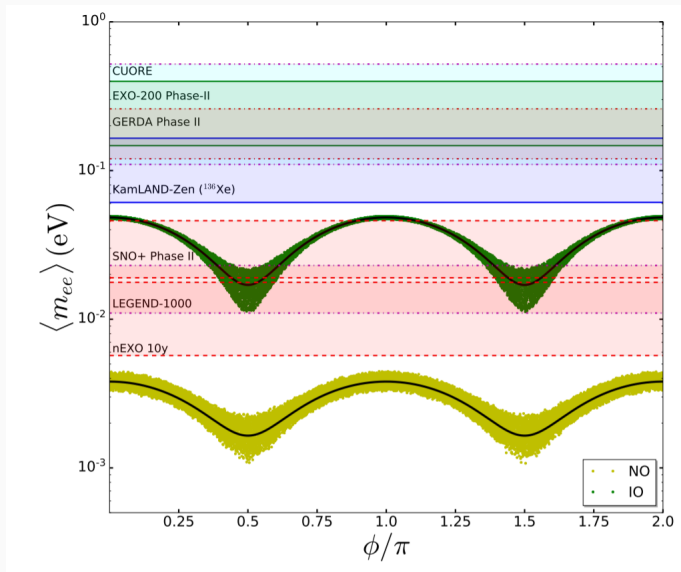
Compressed spectra region



LUX - XENON1T - LZ

Neutrino masses

- 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 $U(1)_L$

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
$(e_R)^\dagger$	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
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 $U(1)_{B-L}$

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:

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

Small Dirac neutrino masses

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

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

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

Small Dirac neutrino masses

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

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

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

- Forbids Majorana term: $\nu_R \nu_R$

Small Dirac neutrino masses

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

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

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

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

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

Small Dirac neutrino masses

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

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

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

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

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

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

Small Dirac neutrino masses

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

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

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

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

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

- 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

Dirac neutrino masses

$U(1)_X$
+

Dirac fermion dark matter



L

ν_R

r



Dirac neutrino masses

$$\nu_R \nu_R$$

$$(\nu_R)^\dagger LH$$

$$\nu_R \psi_R$$

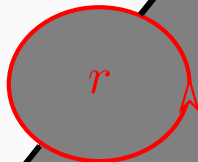
$$(\psi_L)^\dagger \nu_R$$

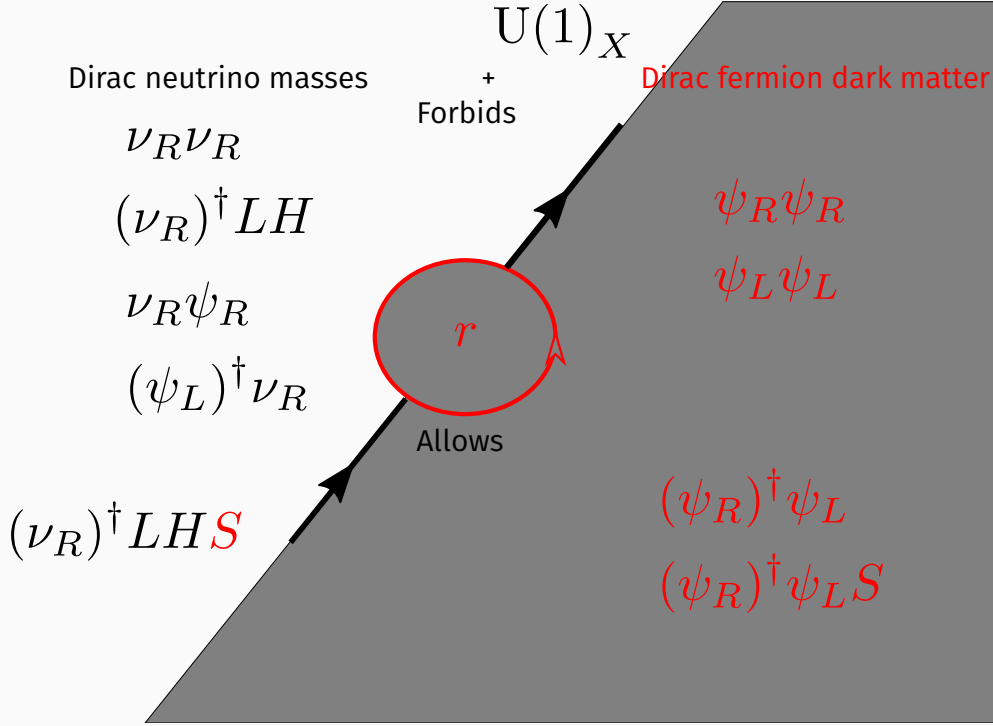
$U(1)_X$
+
Forbids

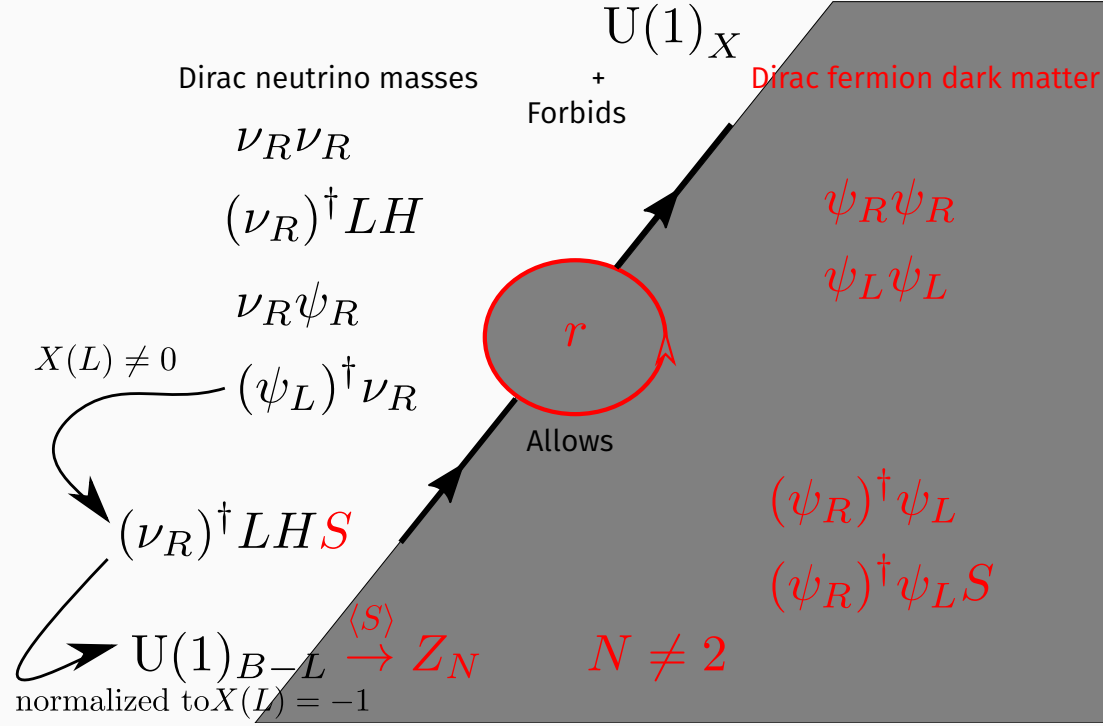
Dirac fermion dark matter

$$\psi_R \psi_R$$

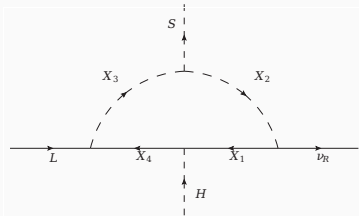
$$\psi_L \psi_L$$



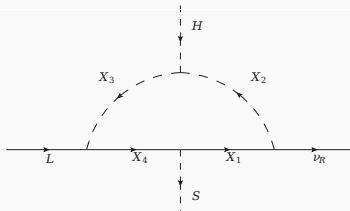




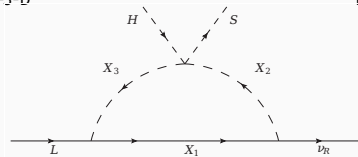
One loop topologies



T1-3-D

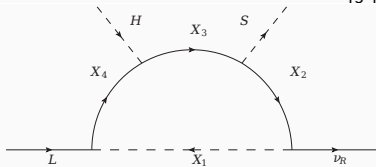


T1-3-E

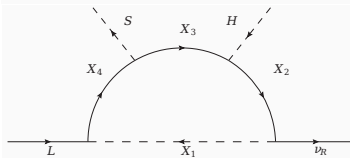


T3-1-A

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

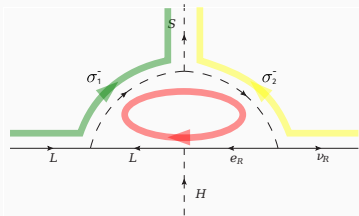


T1-2-A

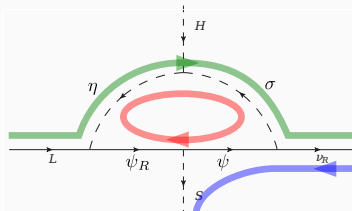


T1-2-B

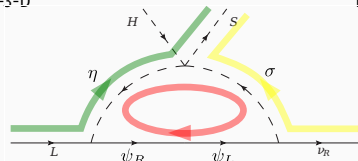
One loop topologies



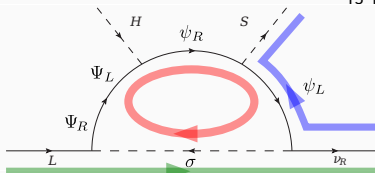
T1-3-D



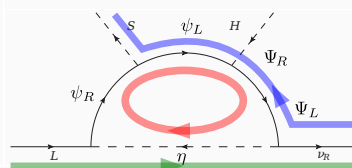
T1-3-E



T3-1-A



T1-2-A

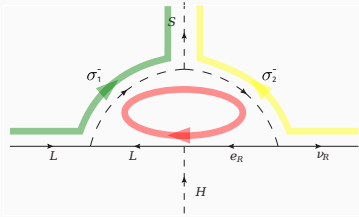


T1-2-B

$\psi_{L,R} \rightarrow$ Singlet fermions
 $\Psi_{L,R} \rightarrow$ Doublet fermions
 $\sigma \rightarrow$ Singlet scalar
 $\eta \rightarrow$ Doublet scalar

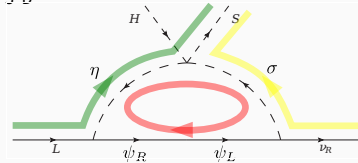
with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]

One loop topologies



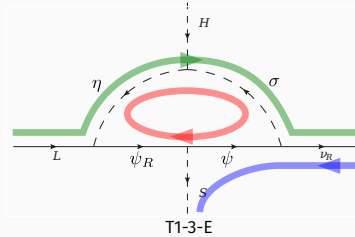
T1-3-D

- $\psi_{L,R} \rightarrow$ Singlet fermions
- $\Psi_{L,R} \rightarrow$ Doublet fermions
- $\sigma \rightarrow$ Singlet scalar
- $\eta \rightarrow$ Doublet scalar

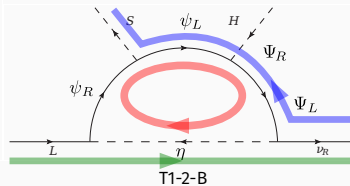
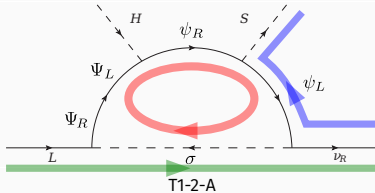


T3-1-A

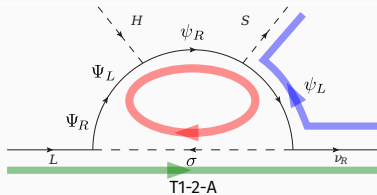
One loop topologies

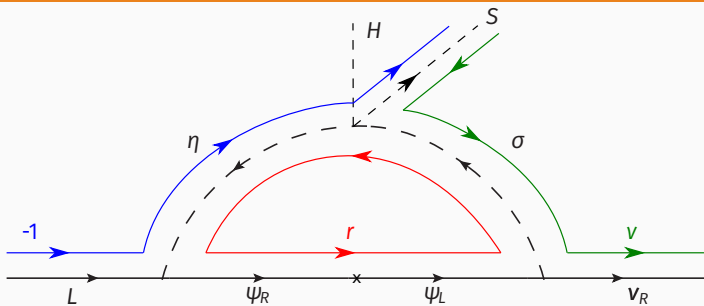


- $\psi_{L,R} \rightarrow$ Singlet fermions
- $\Psi_{L,R} \rightarrow$ Doublet fermions
- $\sigma \rightarrow$ Singlet scalar
- $\eta \rightarrow$ Doublet scalar



One loop topologies



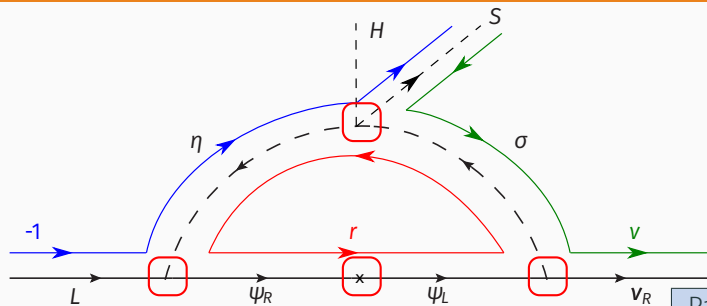


Soft breaking term induced:

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

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

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



Soft breaking term induced:

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

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

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

$$-r = -r$$

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

$$\sigma = \eta + S$$

$$N_c = 1.$$

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 $U(1)_{B-L}$ to be local

$$r \neq 1,$$

$$\sum_i \nu_i = 3,$$

$$\sum_i \nu_i^3 = 3$$

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

Neutrino masses and mixings

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

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

	$(\nu_R)_1^\dagger$	$(\nu_R)_2^\dagger$	$(\nu_R)_3^\dagger$
$U(1)_{B-L}$	+4	+4	-5
$U(1)_{B-L}$	-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 , $a = 1, 2, \dots$
 - 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 $U(1)_{B-L}$ to be local

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

	$(\nu_R)_1^\dagger$	$(\nu_R)_2^\dagger$	$(\nu_R)_3^\dagger$
$U(1)_{B-L}$	+4	+4	-5
$U(1)_{B-L}$	-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 , $a = 1, 2, \dots$
 - 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 $U(1)_{B-L}$ to be local

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

	$(\nu_R)_1^\dagger$	$(\nu_R)_2^\dagger$	$(\nu_R)_3^\dagger$
$U(1)_{B-L}$	+4	+4	-5
$U(1)_{B-L}$	-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 , $a = 1, 2, \dots$
 - At least two sets of scalars η_a, σ_a

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

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

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

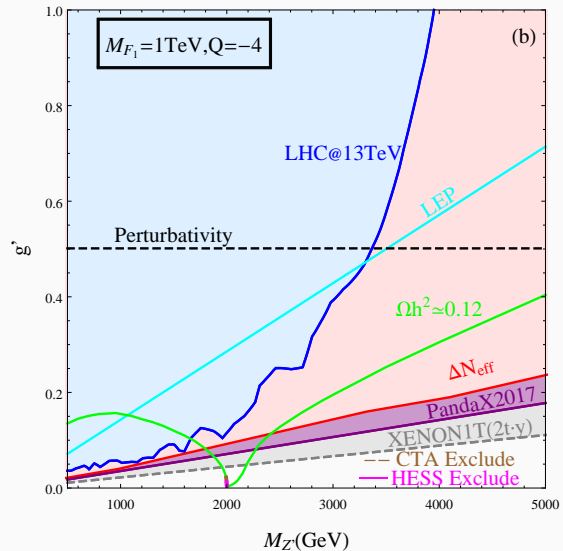
T3-1-A with only $U(1)_{B-L}$

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

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

$m = 0: \nu_{L_k}, \text{ and } \nu_{R_k} \rightarrow N_{\text{eff}}$

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



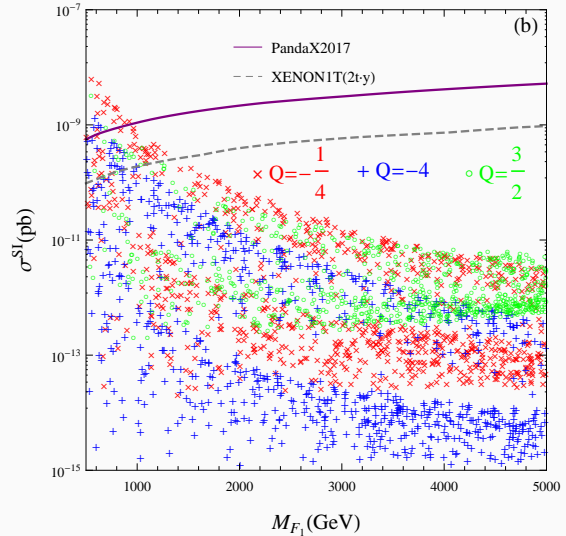
T3-1-A with only $U(1)_{B-L}$

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

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

$m = 0: \nu_{L_k}, \text{ and } \nu_{R_k} \rightarrow N_{\text{eff}}$

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



Conclusions I

Only gravitational evidence of dark matter so far which is fully compatible with the Λ CDM-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 smallness of Dirac neutrino masses and the stability of Dirac fermion dark matter

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

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

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!