Dirac fermion dark matter

with Dirac neutrino masses

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Focus on
1812.05523 [PRD] and 1905.NNNNN
In collaboration with
Carlos Yaguna (UPTC), Julian Calle, Oscar Zapata, Andrés River (UdeA), Walter Tangarife (Loyola University Chicago)

Background: from William Balunas talk (Wednesday)

3 broad classes of DM models:

Effective Field Theories

- We don't know what the higher-scale physics is, but we can integrate it out.

"Simplified Models"

- We introduce a few additional degrees of freedom, but don't try to make statements about the complete theory.

Complete Theories

- We add a full set of new DoF's and expect them to explain everything (e.g. SUSY).

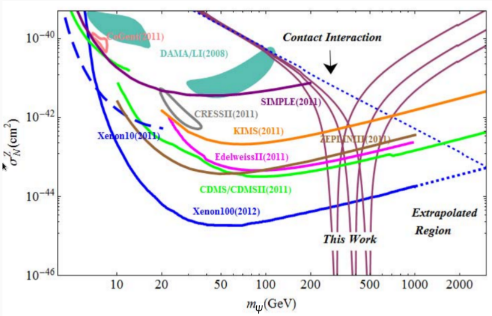
Dirac fermion dark matter

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

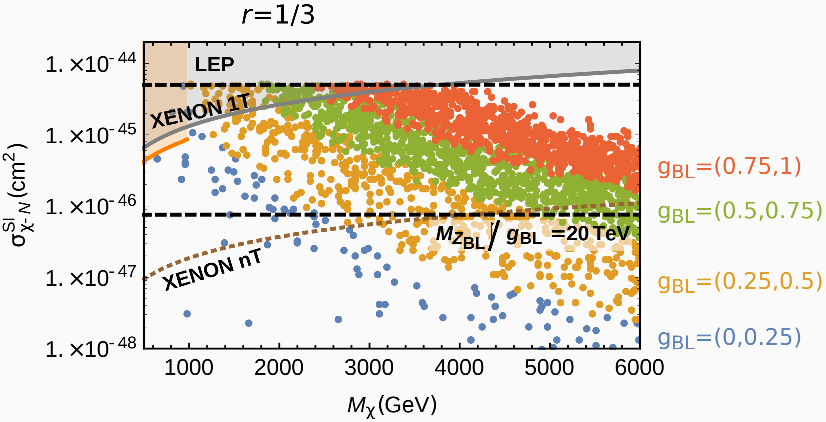


1305.7008. Chua, Hsieh

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

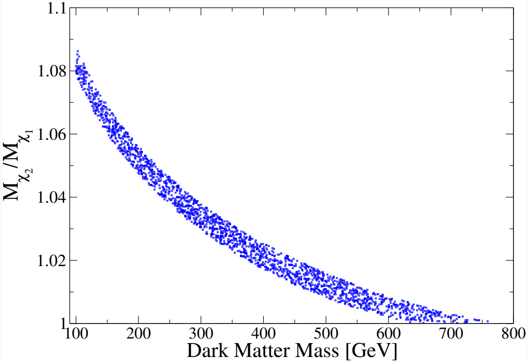
$$\mathcal{L} \supset M_\psi \left(\psi_R\right)^\dagger \psi_L + M_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + y_1 \left(\psi_R\right)^\dagger \Psi_L \cdot H + y_2 \widetilde{(\Psi_R)} \cdot \widetilde{H} \psi_L + \text{h.c} \tag{1}$$

Four free parameters:

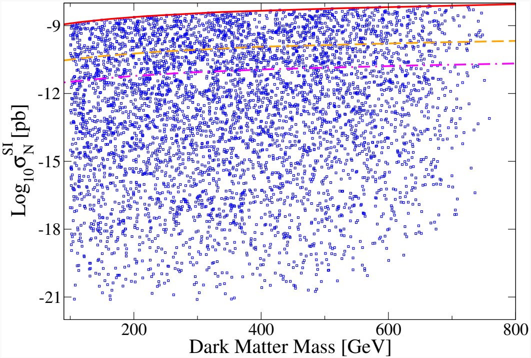
$$M_\psi, M_\Psi \; < 2\ \text{GeV}\,, \qquad\qquad y_1,\ y_2 > 10^{-6} \tag{2}$$

Two neutral Dirac fermion eigenstates:

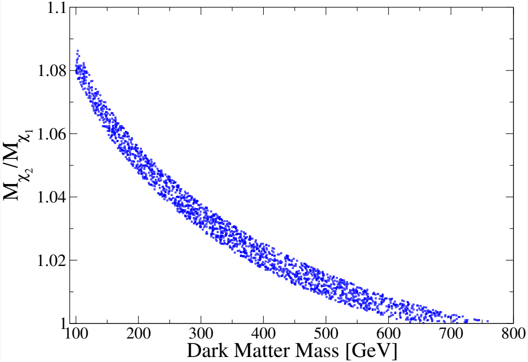
$$M = \begin{pmatrix} M_\psi & y_2 v/\sqrt{2} \\ y_1 v/\sqrt{2} & M_D \end{pmatrix}, \qquad\qquad M_{\text{diag}} = \begin{pmatrix} M_{\chi_1} & 0 \\ 0 & M_{\chi_2} \end{pmatrix} = U_L^\dagger M U_R \tag{3}$$

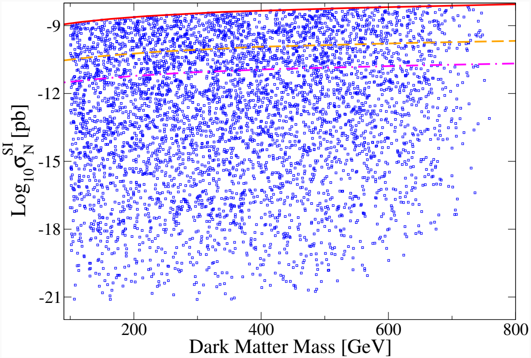


Compressed spectra region



LUX - XENON1T - LZ





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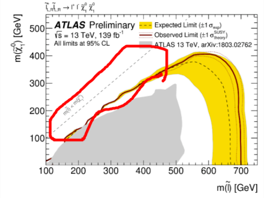
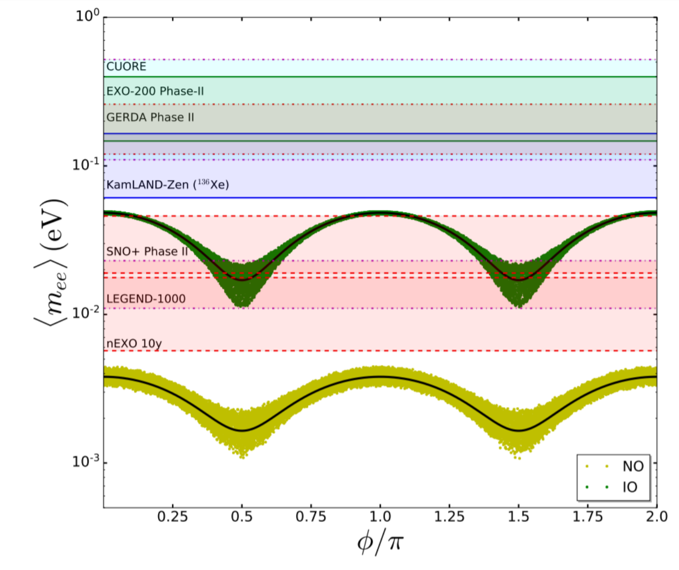


Neutrino masses

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
$(\nu_R)^\dagger$	ω^2

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

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

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

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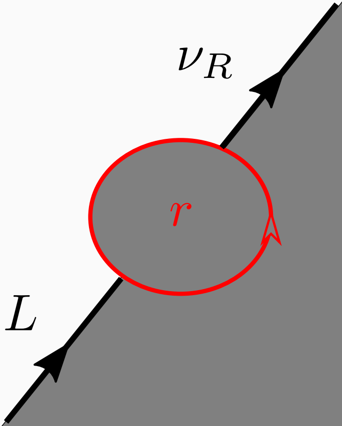
See E. Ma, Rahul Srivastava: arXiv:1411.5042 [PLB] for tree-level realization

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

$$\nu_R \nu_R$$

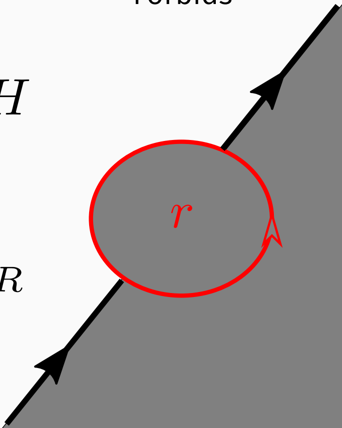
$$(\nu_R)^\dagger L H$$

$$\nu_R \psi_R$$

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

$$\psi_R \psi_R$$

$$\psi_L \psi_L$$



$\mathrm{U}(1)_X$

+

Forbids

Dirac neutrino masses

$\nu_R \nu_R$

$(\nu_R)^\dagger L H$

$\nu_R \psi_R$

$(\psi_L)^\dagger \nu_R$

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

Dirac fermion dark matter

$\psi_R \psi_R$

$\psi_L \psi_L$

r

Allows

$(\psi_R)^\dagger \psi_L$

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

$\mathrm{U}(1)_X$

Dirac neutrino masses + Dirac fermion dark matter

Forbids

$\nu_R\nu_R$

$(\nu_R)^\dagger LH$

$\nu_R\psi_R$

$X(L)\neq 0$

$(\psi_L)^\dagger\nu_R$

$\psi_R\psi_R$

$\psi_L\psi_L$

r

Allows

$(\nu_R)^\dagger LHS$

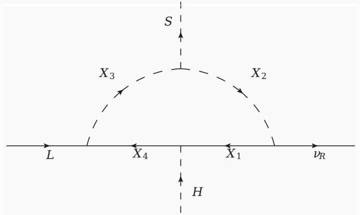
$(\psi_R)^\dagger\psi_L$

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

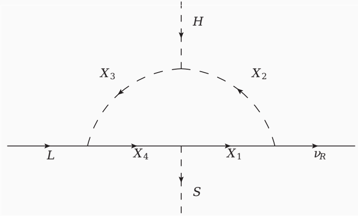
$\mathrm{U}(1)_{B-L} \xrightarrow{\langle S\rangle} Z_N \qquad N\neq 2$

normalized to $X(L)=-1$

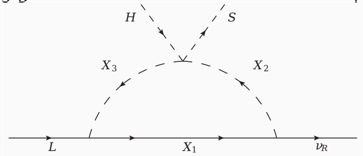
One loop topologies $\mathrm{U}(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

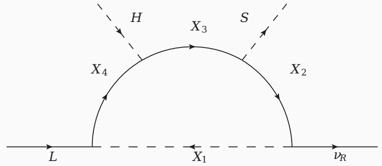


T1-3-E

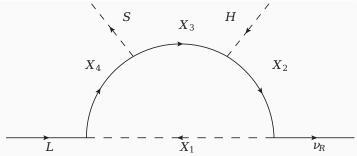


T3-1-A

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

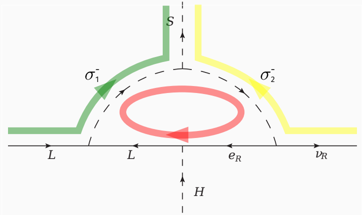


T1-2-A

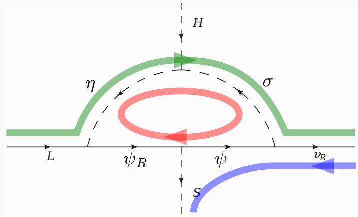


T1-2-B

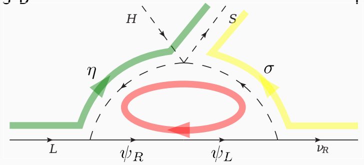
One loop topologies U(1)$_{B-L}$ only!



T1-3-D



T1-3-E



T3-1-A

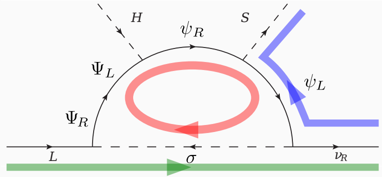
$\psi_{L,R}$ $\longrightarrow$Singlet fermions

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

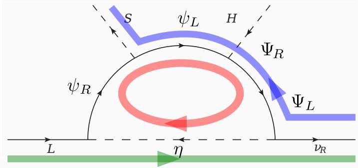
σ $\longrightarrow$Singlet scalar

η $\longrightarrow$Doublet scalar

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

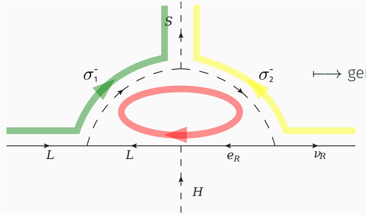


T1-2-A



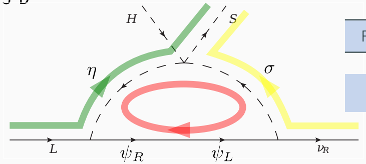
T1-2-B

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



T1-3-D

$\longmapsto$ generalization to two and three loops: Shaikh Saad arXiv:1902.07259



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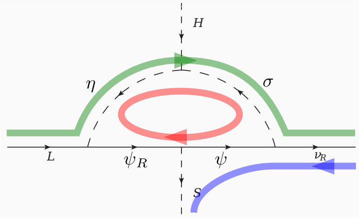
Fields	$(\nu_{Ri})^\dagger$	$(\nu_{Rj})^\dagger$	$(\nu_{Rk})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$

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



T1-3-E

Fields	$(\nu_{Ri})^\dagger$	$(\nu_{Rj})^\dagger$	$(\nu_{Rk})^\dagger$	ψ_L	$(\psi_R)^\dagger$	S
(A)	$+4$	$+4$	-5	$-r$	r	$+3$
(B)	$+\frac{8}{5}$	$+\frac{8}{5}$	$+\frac{2}{5}$	$\frac{7}{5}$	$-\frac{10}{5}$	$+\frac{3}{5}$

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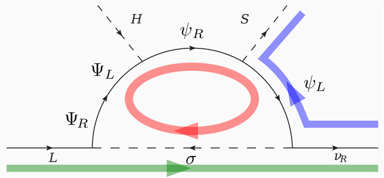
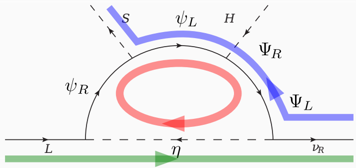


T1-2-A



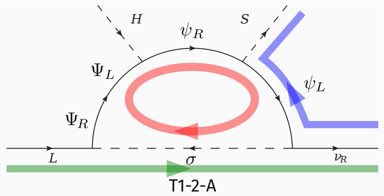
T1-2-B

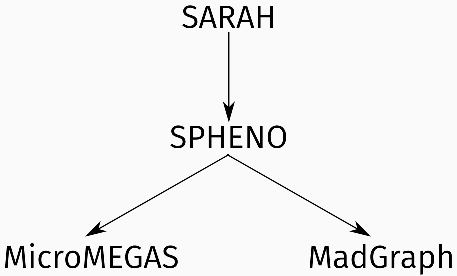
SD^{3}M+σ_i $(i = 1, 2)$

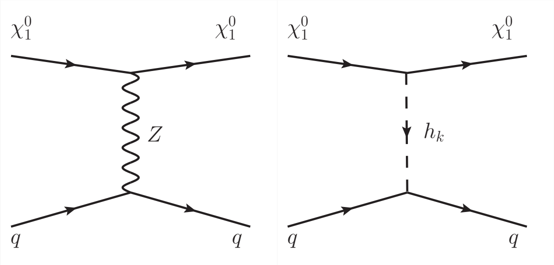
$M_\psi = h_1 \langle S \rangle$, $y_2 = 0$:

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

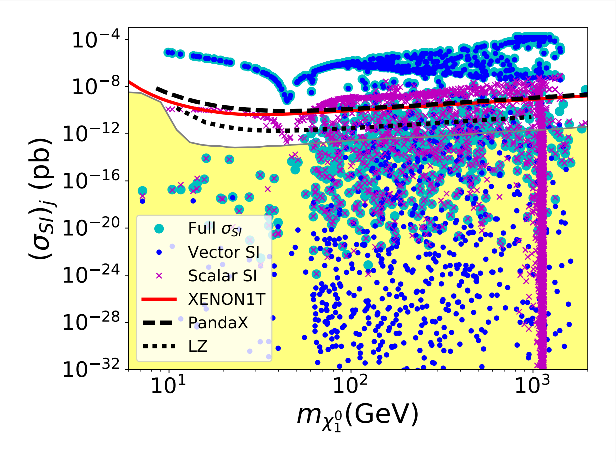
with A.F Rivera, W. Tangarife, arXiv:1905.NNNNN







Decoupled Z' limit



Vector SI (blue points) and scalar SI (green points)

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.
- For T1-2-A: Either Singet Doublet Dirac Dark Matter or Singlet Scalar Dark Matter with extra scalar and vector portal
- With relaxed direct detection constraints

Thanks!