

# Dirac fermion dark matter

with Dirac neutrino masses

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Focus on

1812.05523 [PRD]

In collaboration with

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

## Dirac fermion dark matter

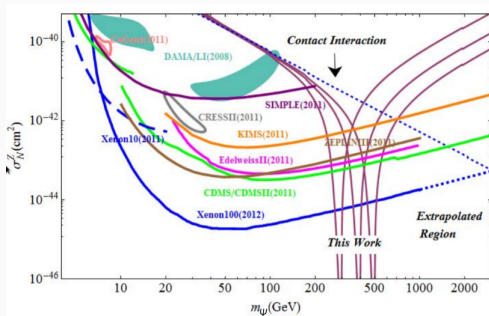
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# Isosinglet dark matter candidate

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

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

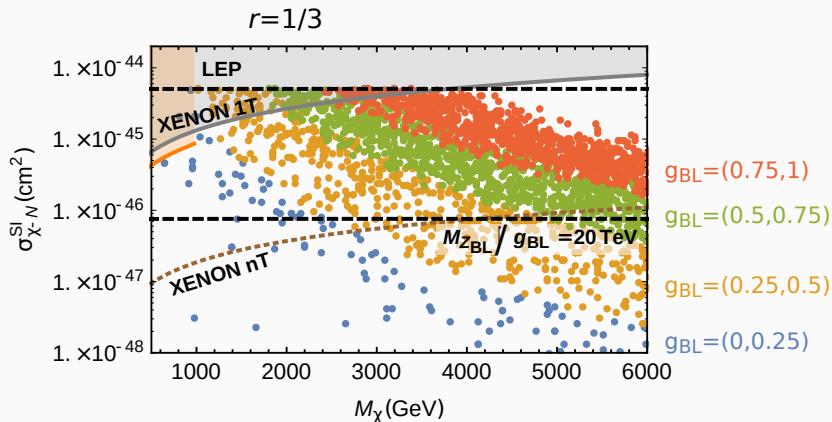
where  $f$  are the Standard Model fermions



# Isosinglet Dirac fermion dark matter model

Left Field	$U(1)_{B-L}$
$(\nu_{R1})^\dagger$	+1
$(\nu_{R2})^\dagger$	+1
$(\nu_{R2})^\dagger$	+1
$\psi_L$	$-r$
$(\psi_R)^\dagger$	$r$
$\phi$	2

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



Duerr et al: 1803.07462 [PRD]

## Singlet-Doublet Dirac Dark matter Model (SD<sup>3</sup>M)

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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  $\psi_{LR}$  that interact among themselves and with the SM fields

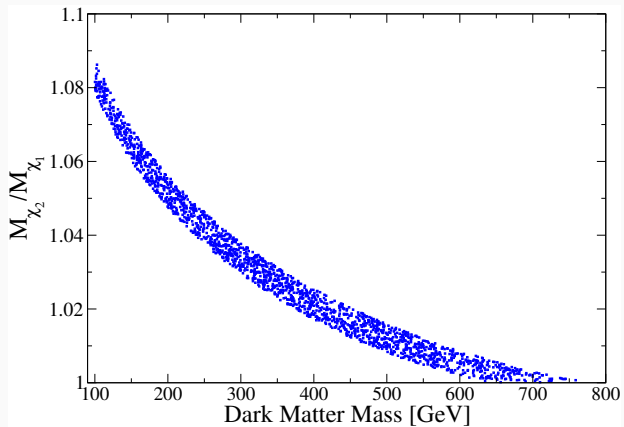
$$\mathcal{L} \supset \textcolor{red}{M}_\psi (\psi_R)^\dagger \psi_L + \textcolor{red}{M}_\Psi \widetilde{(\Psi_R)} \cdot \Psi_L + \textcolor{red}{y}_1 (\psi_R)^\dagger \Psi_L \cdot H + \textcolor{red}{y}_2 \widetilde{(\Psi_R)} \cdot \tilde{H} \psi_L + \text{h.c} \quad (1)$$

Four free parameters:

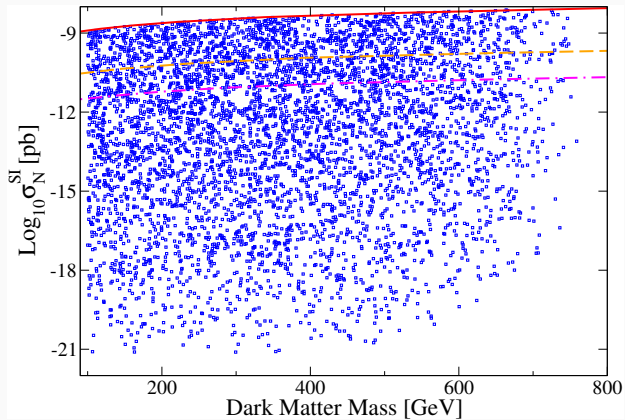
$$\textcolor{red}{M}_\psi, \textcolor{red}{M}_\Psi < 2 \text{ GeV}, \quad \textcolor{red}{y}_1, \textcolor{red}{y}_2 > 10^{-6} \quad (2)$$

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



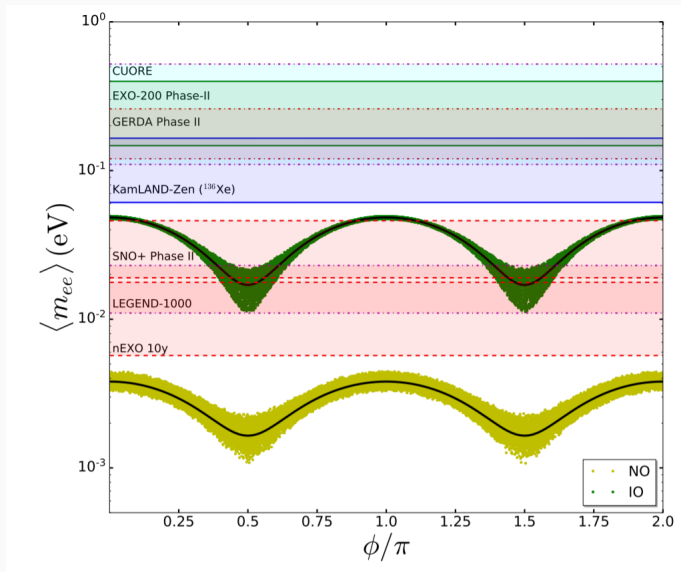
LUX - XENON1T - LZ

# Neutrino masses

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

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

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

Dirac  $U(1)_L$

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

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

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

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

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

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

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

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

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

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

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

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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  $L$

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Dirac neutrino masses

$U(1)_X$   
+

Dirac fermion dark matter



$L$

$\nu_R$

$r$



Dirac neutrino masses

$$\nu_R \nu_R$$

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

$$\nu_R \psi_R$$

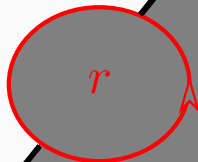
$$(\psi_L)^\dagger \nu_R$$

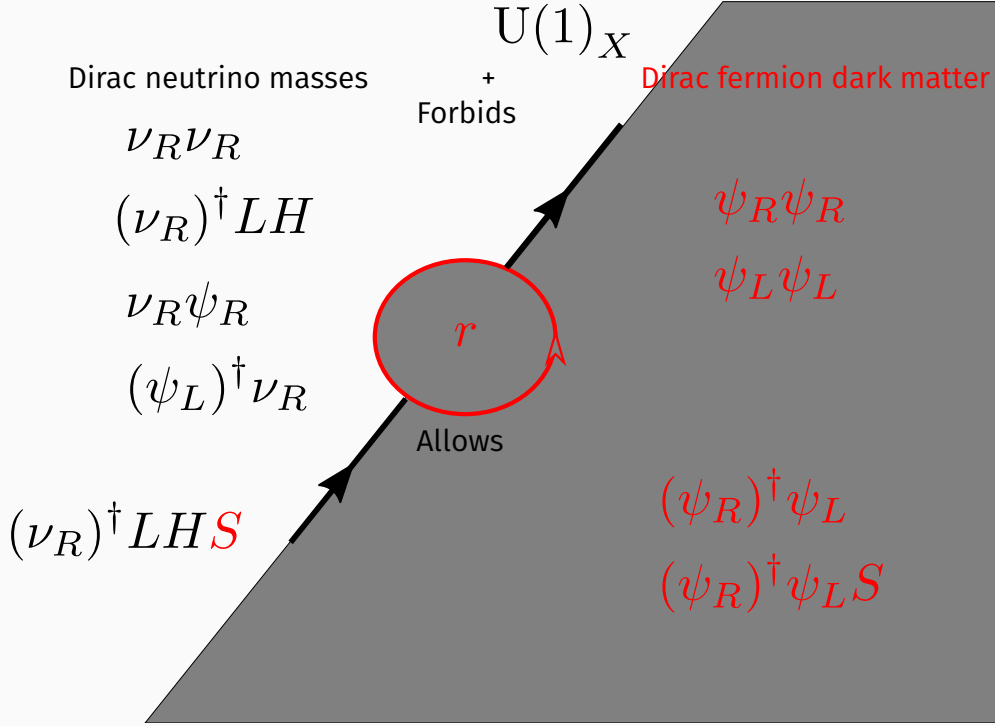
$U(1)_X$   
+  
Forbids

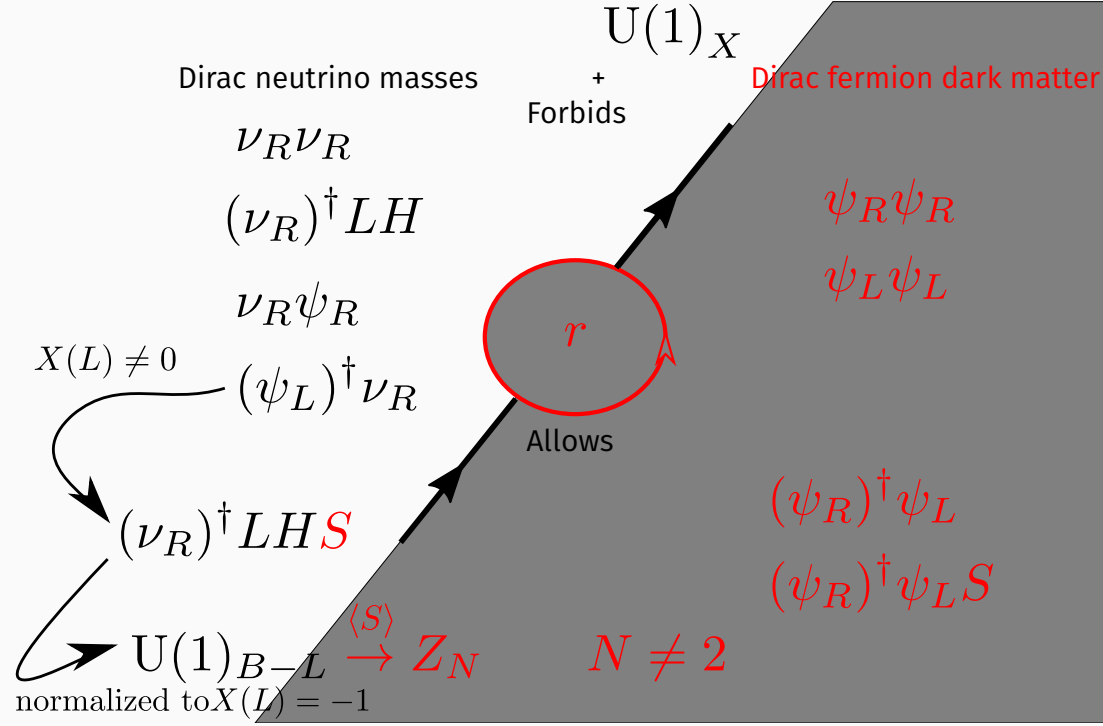
Dirac fermion dark matter

$$\psi_R \psi_R$$

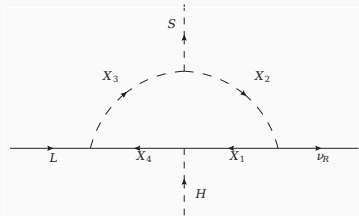
$$\psi_L \psi_L$$



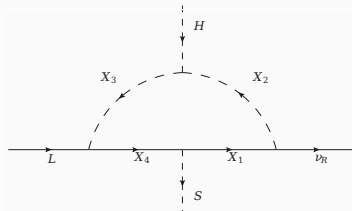




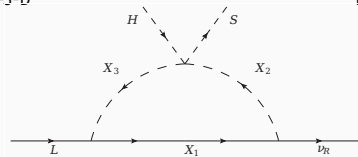
# One loop topologies



T1-3-D

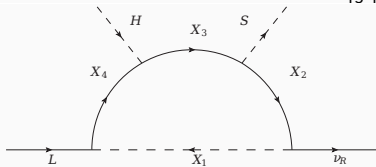


T1-3-E

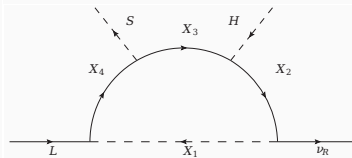


T3-1-A

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

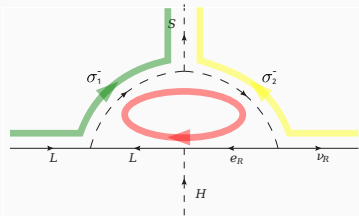


T1-2-A

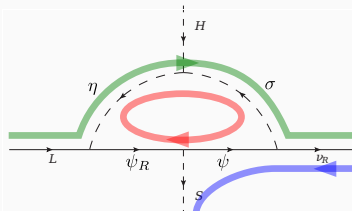


T1-2-B

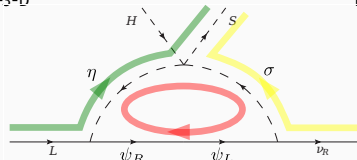
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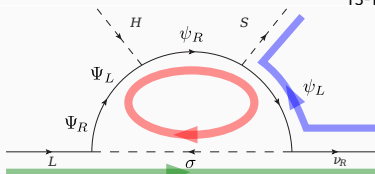
T1-3-D



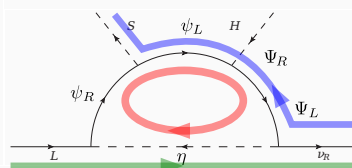
T1-3-E



T3-1-A



T1-2-A



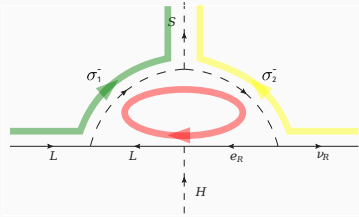
T1-2-B

$\psi_{L,R} \rightarrow$  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]

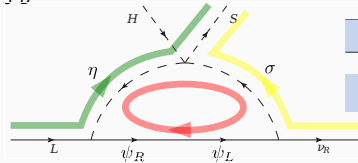


# One loop topologies



T1-3-D

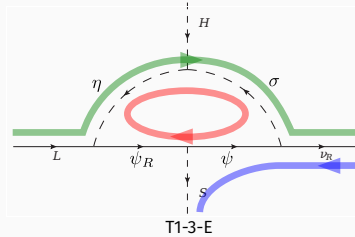
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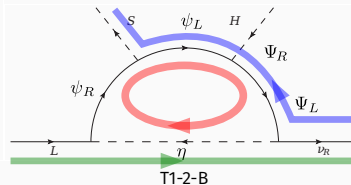
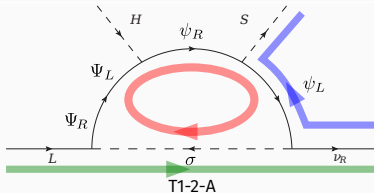
Fields	$(\nu_{Ri})^\dagger$	$(\nu_{Rj})^\dagger$	$(\nu_{Rk})^\dagger$	$\psi_L$	$(\psi_R)^\dagger$	$S$
(A)	+4	+4	-5	-r	r	+3

# One loop topologies



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

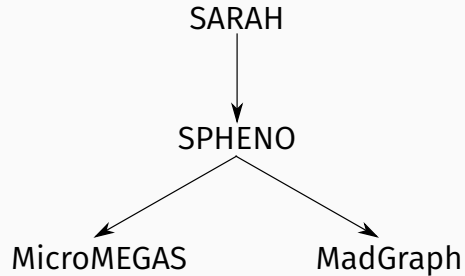
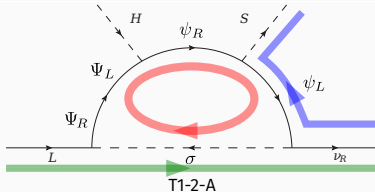
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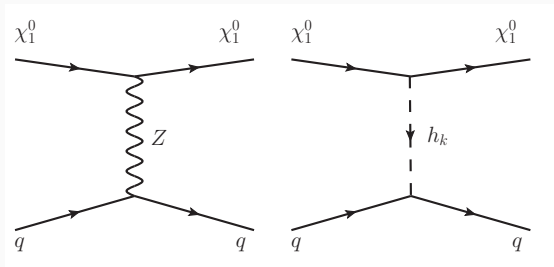
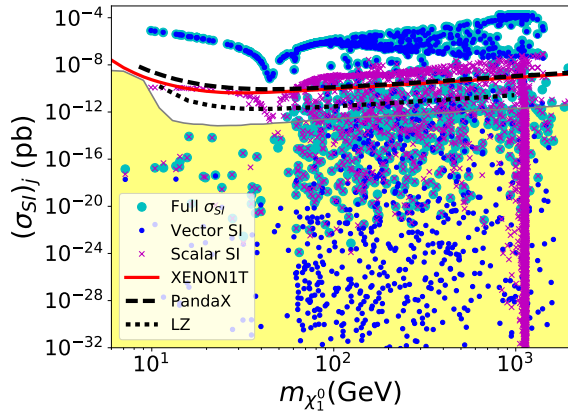


$$M_\psi = h_1 \langle S \rangle, y_2 = 0:$$

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

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



Decoupled  $Z'$  limit

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

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!