Multi-component secluded WIMP dark matter and Dirac neutrino masses with an extra Abelian gauge symmetry

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Overview

1. Motivation

2. Model

3. Parameter Space

Standard Model of Elementary Particles

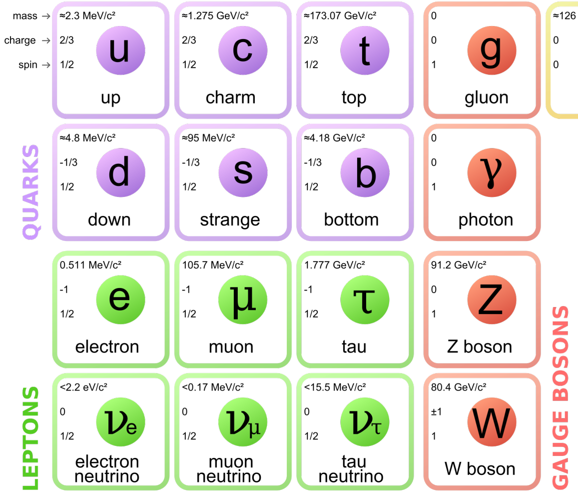
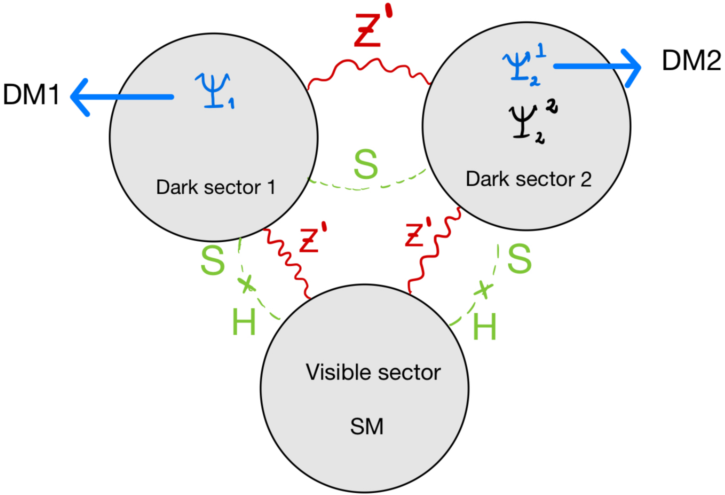


Figure:

Motivation

Dark Sectors



Field Content

Field s	Generations	$SU(2)_L$	$U(1)_Y$	$U(1)_D$
$(\nu_{R\alpha})^\dagger$	3	$\mathbf{1}$	0	-9
χ_L	1	$\mathbf{1}$	0	4
$(\chi_R)^\dagger$	1	$\mathbf{1}$	0	5
ψ_L	2	$\mathbf{1}$	0	10
$(\psi_R)^\dagger$	2	$\mathbf{1}$	0	-1
H	1	$\mathbf{2}$	$-1/2$	0
S	1	$\mathbf{1}$	0	-9
η	1	$\mathbf{2}$	$-1/2$	-1
Φ	1	$\mathbf{1}$	0	-1

Table: Fermion and scalar content with its quantum numbers.

Lagrangian of the Model

The Lagrangian of the model:

$$-\mathcal{L} \supset y_c \chi_R^\dagger \chi_L S + (y_x)^{ij} \psi_{Ri}^\dagger \psi_{Lj} S + (y_{nR})^{\alpha i} \nu_{R\alpha}^\dagger \psi_{Li} \Phi + (y_{nL})^{i\alpha} \psi_{Ri}^\dagger L_\alpha \cdot \tilde{\eta} + \text{h.c.}$$

where:

$$\begin{aligned} V(H, \eta, S, \Phi) = & -\mu^2 \tilde{H} \cdot H + m_\eta^2 \tilde{\eta} \cdot \eta + m_\Phi^2 |\Phi|^2 - \mu_S^2 |S|^2 - [\mu_c \tilde{\eta} \cdot H \Phi + \text{h.c.}] \\ & + \frac{1}{2}\lambda_1 (\tilde{H} \cdot H)^2 + \frac{1}{2}\lambda_2 (\tilde{\eta} \cdot \eta)^2 + \lambda_3 \tilde{H} \cdot H \tilde{\eta} \cdot \eta + \lambda_4 \tilde{H} \cdot \eta \tilde{\eta} \cdot H + \frac{1}{2}\lambda_5 |S|^4 \\ & + \lambda_6 \tilde{H} \cdot H |S|^2 + \lambda_7 |S|^2 \tilde{\eta} \cdot \eta + \frac{1}{2}\lambda_8 |\Phi|^4 + \lambda_9 |\Phi|^2 \tilde{H} \cdot H \\ & + \lambda_{10} |\Phi|^2 |S|^2 + \lambda_{11} |\Phi|^2 \tilde{\eta} \cdot \eta \end{aligned}$$

Scalar Fields that acquire VEV

The mass matrix for scalars that acquire VEV:

$$m_h^2 = \begin{pmatrix} -\mu^2 + \frac{1}{2}\lambda_6 v_s^2 - \frac{3\lambda_1 v^2}{2} & \lambda_6 v v_s \\ \lambda_6 v v_s & -\mu_s^2 + \frac{3}{2}\lambda_5 v_s^2 + \frac{\lambda_6 v^2}{2} \end{pmatrix}$$

that is diagonalized by a unitary transformation $Z_H m_h^2 Z_H^T = m_{h,\text{diag}}^2$, such that:

$$\begin{pmatrix} h_0 \\ S^0 \end{pmatrix} = Z_H \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Lambda couplings

We can write the λ_1, λ_5, and λ_6 couplings can be written in terms of the mixing angle θ and the eigenvalues $m_{h_{1,2}}$ as:

$$\lambda_1 = \frac{1}{2v^2}\left(m_{h_1}^2 + m_{h_2}^2 - \frac{(m_{h_2}^2 - m_{h_1}^2)}{\sqrt{1+\tan^2(2\theta)}}\right)$$

$$\lambda_5 = \frac{1}{2v_s^2}\left(m_{h_1}^2 + m_{h_2}^2 + \frac{(m_{h_2}^2 - m_{h_1}^2)}{\sqrt{1+\tan^2(2\theta)}}\right)$$

$$\lambda_6 = \frac{1}{2vv_s}\frac{m_{h_2}^2 - m_{h_1}^2}{\sqrt{1+\tan^2(2\theta)}}\tan(2\theta)$$

Extra Scalars

$$\mathcal{L} = \Xi^T m^2 \Xi = \begin{pmatrix} \eta^0 & \Phi \end{pmatrix} \begin{pmatrix} m_\eta^2 + \frac{1}{2}\lambda_7 v_s^2 + \frac{1}{2}\lambda_3 v^2 + \frac{1}{2}\lambda_4 v^2 & -\frac{1}{2} v \mu_c \\ -\frac{1}{2} v \mu_c & m_\Phi^2 + \frac{1}{2}\lambda_{10} v_s^2 + \frac{1}{2}\lambda_9 v^2 \end{pmatrix} \begin{pmatrix} \eta^0 \\ \Phi \end{pmatrix}$$

where the mass matrix m_Ξ^2 can be diagonalized via an orthogonal transformation:

$$U_\Xi m_\Xi^2 U_\Xi^T = (m_\Xi)^{\text{diag}} = \text{diag}(m_1, m_2)$$

with:

$$U_\Xi = \begin{pmatrix} \cos\theta_\Xi & \sin\theta_\Xi \\ -\sin\theta_\Xi & \cos\theta_\Xi \end{pmatrix}$$

Dirac Fermions

The mass Lagrangian for fermions in the second dark sector is:

$$\mathcal{L} = \frac{v_s}{\sqrt{2}} \begin{pmatrix} \psi_L^1 & \psi_L^2 \end{pmatrix} \begin{pmatrix} y_x^{11} & y_x^{12} \\ y_x^{21} & y_x^{22} \end{pmatrix} \begin{pmatrix} \psi_R^1 \\ \psi_R^2 \end{pmatrix} + \text{h.c.} = \psi_L^T m_\psi \psi_R + \text{h.c.}$$

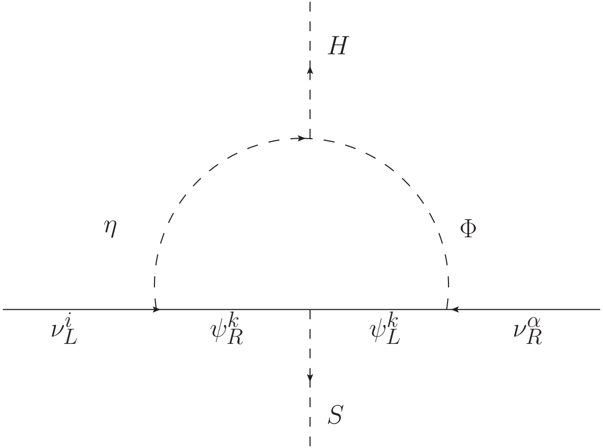
where the matrix m_ψ is diagonalized as:

$$Z_L m_{\psi_2} Z_R^\dagger = (m_\psi)^{\text{diag}} = \text{diag}(m_{\Psi_2^1}, m_{\Psi_2^2}) \quad (1)$$

with

$$Z_{L,R} = \begin{pmatrix} \cos\theta_{L,R} & \sin\theta_{L,R} \\ -\sin\theta_{L,R} & \cos\theta_{L,R} \end{pmatrix} \quad (2)$$

Neutrino masses



Kinetic Mixing and EW Gauge Bosons

This model has a new gauge boson B'_μ associated with the new $U(1)_D$ gauge symmetry that interacts with the SM sector via kinetic mixing ϵ. The Lagrangian for B'_μ reads:

$$\mathcal{L}_{B'} = -\frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\epsilon}{2}B'_{\mu\nu}B^{\mu\nu} + \frac{i}{2}\sum_{k=1}^{2}\left[\overline{\Psi}_k\gamma^\mu(a_k + b_k\gamma^5)B'_\mu\Psi_k\right]$$

$$+ (\mathcal{D}^X_\mu X)^\dagger \mathcal{D}^{X\mu} X + 9i\sum_{\alpha=1}^{2}\overline{\nu}_\alpha\gamma^\mu(1+\gamma^5)B'_\mu\nu_\alpha$$

where, $a_k = q_{\psi^k_L} - q_{\psi^k_R}$, $b_k = q_{\psi^k_L} + q_{\psi^k_R}$, $B'_{\mu\nu} = \partial_\mu B'_\nu - \partial_\nu B'_\mu$, $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ are the strength tensor for B'_μ and B_μ respectively, and:

$$\mathcal{D}^X_\mu = \partial_\mu - iq_X g_D B'_\mu$$

for $X = S, \Phi, \eta$ and q_X are the charges under $U(1)_D$ of the scalar fields, g_D is the new gauge coupling and ν_α are Dirac neutrinos.

Kinetic Mixing and EW Gauge Bosons II

In the basis $V_\mu = (B_\mu, W^3_\mu, B'_\mu)^T$, the mass matrix for the neutral gauge bosons reads:

$$\mathcal{L}_M = \frac{1}{2} V^{T\mu} M_G^2 V_\mu$$

where:

$$M_G^2 = \frac{1}{4} v^2 \begin{pmatrix} g_1^2 & -g_1 g_2 & -g_1^2 \epsilon \\ -g_1 g_2 & g_2^2 & g_1 g_2 \epsilon \\ -g_1^2 \epsilon & g_1 g_2 \epsilon & 324 g_D^2 \frac{v_s^2}{v^2} + g_1^2 \epsilon^2 \end{pmatrix}$$

After the diagonalization of this matrix, we have three eigenstates. Those are the massless γ photon, the SM Z gauge boson with a mass $m_Z \approx 91.1$ GeV, and the new dark photon Z' with a mass $m_{Z'} \approx 9 g_D v_s/(1+\epsilon^2)$.

Dirac Neutrino Masses

The easiest way to generate Dirac neutrinos masses is to add right-handed neutrinos which couplet to the SM lepton doublet through the term:

$$\mathcal{L} = h^{\nu}_{ij}\epsilon^{\alpha\beta}L^{i}_{\alpha}H_{\beta}(\nu^{j}_{R})^{\dagger}$$

The Dirac neutrino mass matrix:

$$M^{\nu}_{ij} = y^{\nu}_{ij}\frac{v}{\sqrt{2}}$$

then the Yukawa couplings must be of order 10^{-13}.

Boltzmann Equations

The relic abundance of DM Ω_i $(i = 1, 2)$ for (Ψ_1, Ψ_2^1) in the standard freeze-out is obtained after solving the Boltzmann equations:

$$\frac{\mathrm{d}\, n_1}{\mathrm{d}\, t} = -\, \sigma_v^{1100}(n_1^2 - \overline{n}_1^2) - \sigma_v^{1122}\left(n_1^2 - n_2^2\frac{\overline{n}_1^2}{\overline{n}_2}\right) - 3Hn_1$$

$$\frac{\mathrm{d}\, n_2}{\mathrm{d}\, t} = -\, \sigma_v^{2200}(n_2^2 - \overline{n}_2^2) - \sigma_v^{2211}\left(n_2^2 - n_1^2\frac{\overline{n}_2^2}{\overline{n}_1}\right) - 3Hn_2$$

where $n_i (i = 1, 2)$ is the number density for the DM particle, $\overline{n}_i$ their respective equilibrium values and σ_v^{abcd} is the thermally averaged cross section, that satisfies $\overline{n}_a\overline{n}_b\sigma_v^{abcd} = \overline{n}_c\overline{n}_d\sigma_v^{cdab}$.

Annihilation and Conversion

It allows us to study the relevant processes that play a role in the evolution of the Boltzmann equations and affect the relic density of DM:

$$\zeta^i_{anni}(T) = \frac{\sigma_v^{ii00}(T)}{\sigma_v^{ii00}(T) + \sigma_v^{iijj}(T)}$$

$$\zeta^i_{conv}(T) = \frac{\sigma_v^{iijj}(T)}{\sigma_v^{ii00}(T) + \sigma_v^{iijj}(T)}$$

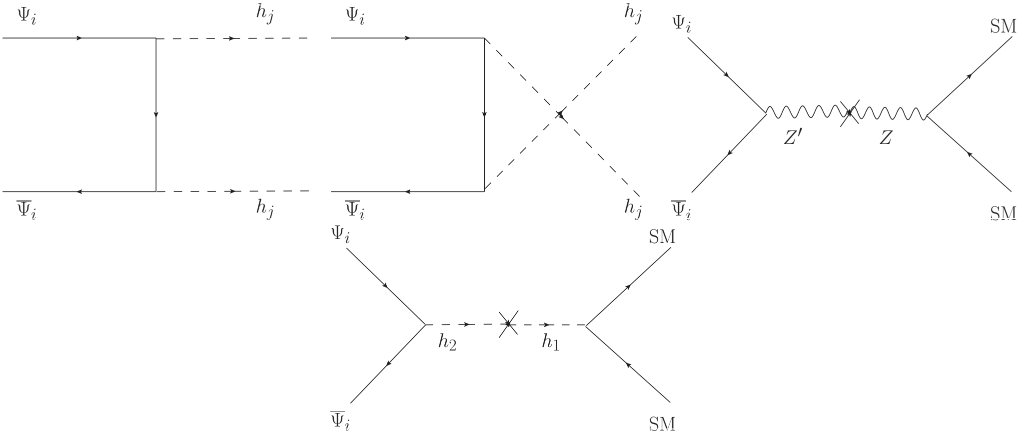
$i \neq j = 1, 2$. Those parameters are evaluated at the typical freeze-out temperature: $T \approx m_{\chi_1}/25$. Notice that by construction,

Z' Boson Decay

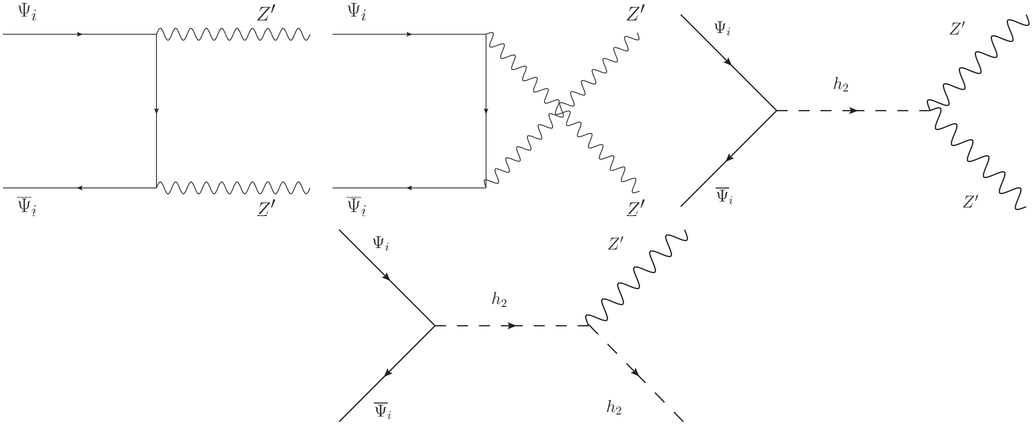
The decay width of the dark photon into neutrinos renders:

$$\Gamma_{Z' \to \overline{\nu}_i \nu_i} = 3\, M_{Z'} \frac{(g_1^2 \epsilon^2 + 4\, q_{\nu_R}^2\, g_D^2\,)}{64\pi}$$

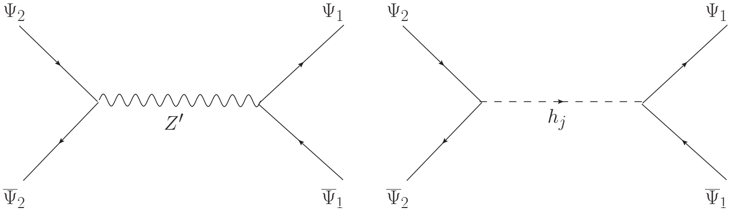
DM Annihilation I



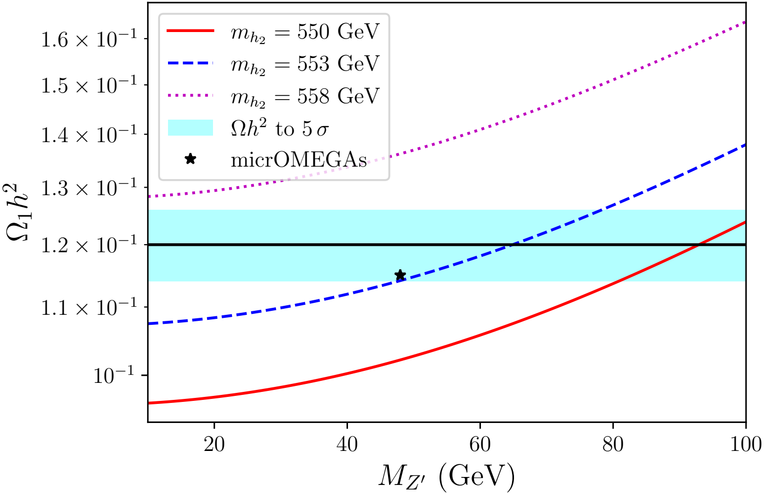
DM Annihilation II



DM Conversion



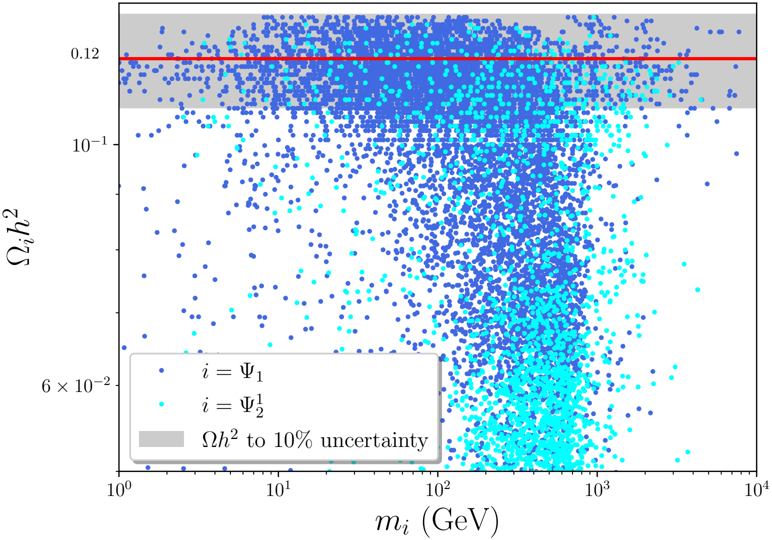
One-Component Limit



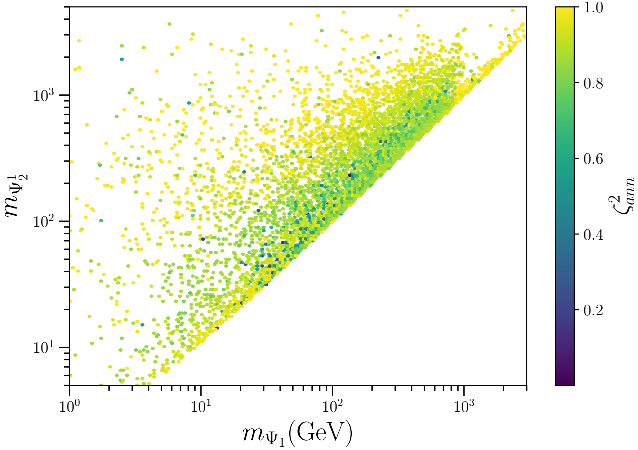
Parameter Space I

Parameter	Range
$M_{Z'}/\text{GeV}$	$1 - 10^3$
g_D	$10^{-3} - 1$
y_c	$10^{-3} - 1$
$(m_{\Psi_2^j} - m_{\Psi_1})/\text{GeV}$	$1 - 5 \times 10^3$
θ	$10^{-6} - 10^{-3}$
θ_L, θ_R	$10^{-3} - 2\pi$
λ_k	$10^{-4} - 1$
m_{h_2}/GeV	$125 - 5 \times 10^3$
m_η^2/GeV^2	$10^6 - 10^8$
m_Φ^2/GeV^2	$10^6 - 10^8$
μ_c/GeV	$10^2 - 2 \times 10^3$
ϵ	$10^{-12} - 10^{-2}$
y_{nL}	$10^{-4} - 1$

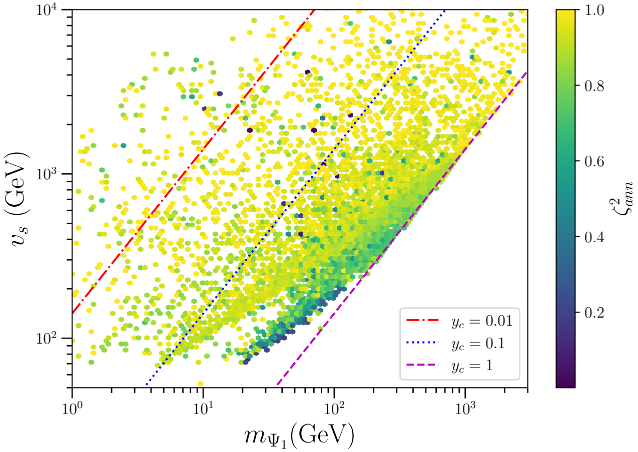
Parameter Space II



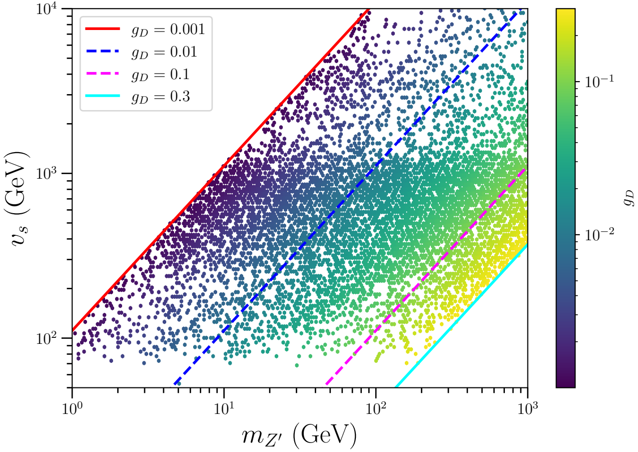
Parameter Space III



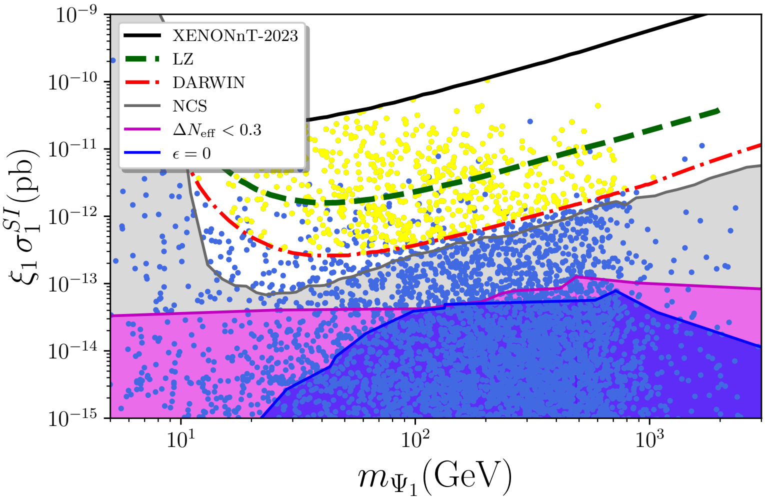
Parameter Space IV



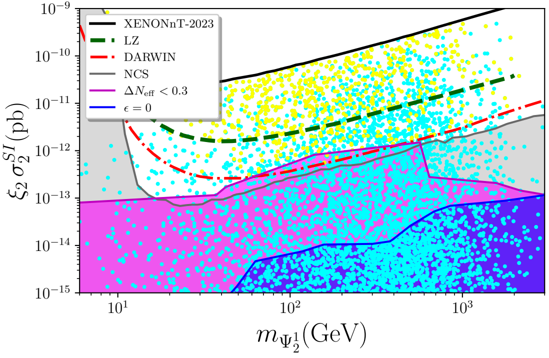
Parameter Space V



Parameter Space VI



Parameter Space VII



Conclusions

We show a complete UV realization of a secluded WIMP dark matter model with an extra Abelian gauge symmetry that includes two-component dark matter candidates, where Dirac neutrino masses are generated at one-loop via a scotogenic realization of the effective operator for Dirac neutrino masses in the SM. Our paper explains the relic abundance of dark matter, even without kinetic mixing. Also, it can be tested in direct detection experiments like DARWIN. However, the annihilation of dark matter particles into gamma rays is highly suppressed due to the dark nature of the Abelian gauge symmetry. The model's parameter space explains the relic abundance of DM and Dirac neutrino masses. It is also compatible with cosmological and theoretical constraints, including the branching ratio of SM into invisible, Big Bang nucleosynthesis restrictions, and the number of relativistic degrees of freedom in the early universe, even without kinetic mixing.

Thank you!