Inelastic Dirac Dark Matter in $U(1)_{B-L}$

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Introduction

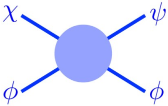
⋆ The WIMP dark matter typically requires a thermally averaged annihilation cross section $\langle \sigma v \rangle \sim 2 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$.

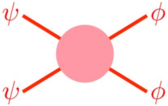
⋆ Well known three exceptions [Phys. Rev. D 43, 3191 (1991)]

- Coannihilation: mutual annihilation of multiple species
- Forbidden: annihilation into heaver states
- Resonance: annihilation near a pole in the cross section

⋆ The fourth exception [Phys.Rev.Lett. 119 (2017) 6, 061102]

- Coscattering: inelastic conversions with its heavier partner
- χ/ψ interchange : $\chi\phi \to \psi\phi$
- ψ annihilation: $\psi\psi \to \phi\phi$





A Toy Model

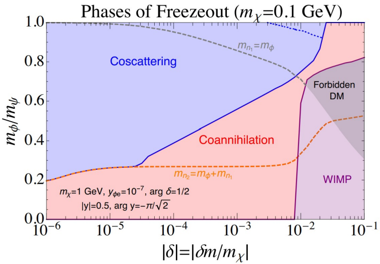
⋆ χ, ψ are Majorana fermions, and ϕ is a real scalar

$$\mathcal{L} \supset -\frac{m_\chi}{2}\chi^2 - \frac{m_\psi}{2}\psi^2 - \delta m\, \chi\psi - \frac{y}{2}\phi\psi^2 + \text{h.c.} \tag{1}$$

Define the dimensionless parameter $\delta = \delta m / m_\chi$.
When $\delta \ll 1$, $\chi\chi$ and $\chi\psi$ annihilations are suppressed.

⋆ Different phases of Freeze out [JHEP 08 (2018) 079]

- Coscattering: $\chi\phi \to \psi\phi$ decouples before $\psi\psi \to \phi\phi$
- Coannihilation: $\psi\psi \to \phi\phi$ decouples before $\chi\phi \to \psi\phi$



Coscattering

- Coscattering Conditions:
  - $\psi\psi \to \phi\phi$ is in equilibrium.
  - $\chi\chi, \chi\psi \to \phi\phi$ can be neglected.
  - $\psi \to \phi\chi$ decay is forbidden.
- The Boltzmann equations

$$\dot{n}_\chi + 3Hn_\chi = -n_\phi^{\text{eq}} \langle \sigma_{\chi\to\psi} v \rangle (n_\chi - n_\chi^{\text{eq}}) \quad (2)$$

where thermally averaged inelastic cross section is

$$\langle \sigma_{\chi\to\psi} v \rangle = \frac{n_\psi^{\text{eq}}}{n_\chi^{\text{eq}}} \langle \sigma_{\psi\to\chi} v \rangle \approx \frac{m_\psi^{3/2}}{m_\chi^{3/2}} e^{-x\Delta} \langle \sigma_{\psi\to\chi} v \rangle \quad (3)$$

- The relic density ($r = m_\phi / m_\chi$)

$$\frac{\Omega_\chi}{\Omega_{\text{DM}}} \approx \frac{0.6\ \text{pb}}{\langle \sigma_{\psi\to\chi} v \rangle} \frac{p x_f e^{x_f (r+\Delta-1)}}{\sqrt{g_*} r^{3/2} (1+\Delta)^{3/2}} \quad (4)$$

Extended Studies

- Quark Portal: $\lambda_\chi \tilde{q}\bar{q}\frac{1-\gamma_5}{2}\chi$ [Phys.Rev.D 96 (2017) 10, 103521; Phys.Rev.D 105 (2022) 5, 055004; Phys.Rev.D 110 (2024) 1, 1; JHEP 06 (2024) 179]
- Top Portal: $\tilde{t}\bar{t}\frac{1-\gamma_5}{2}\chi$ [Phys.Rev.D 97 (2018) 7, 075002]
- Fraternal Twin Higgs: $\hat{\nu}\hat{\gamma} \to \hat{\tau}\hat{\gamma}$ [JHEP 09 (2018) 098]
- Leptophilic: $\lambda_\chi \phi \bar{\chi} l_R$ [JHEP 07 (2019) 136]
- Singlet-Triplet: $\frac{\lambda}{\Lambda}\chi\psi^a H^\dagger \tau^a H$ [JHEP 01 (2020) 113; SciPost Phys. 13 (2022) 124]
- Dark Photon Portal: $g_D \bar{\chi}_1 \gamma^\mu \chi_2 A'_\mu$ [JHEP 06 (2022) 048]
- Scotogenic: $y_{\alpha j}\bar{L}_\alpha \tilde{\eta} N_j$ [Phys.Rev.D 107 (2023) 1, 015028]
- Leptogenesis: $\lambda_{ki}\phi \bar{l}_{R,k}\chi_i$ [Phys.Rev.Lett. 133 (2024) 19, 19]
- Higgs Portal: $\lambda_{12} S_1 S_2 |H|^2$ [JCAP 10 (2024) 001]
- Dark Photon DM: $\phi F'_{\mu\nu}\tilde{F}^{\mu\nu}$ [Phys.Dark Univ. 48 (2025) 101852]

Inelastic Dirac Dark Matter in $U(1)_{B-L}$

- ⋆ Dirac fermion $\tilde{\chi}_1, \tilde{\chi}_2$ with $U(1)_{B-L}$ charge $Q_{\tilde{\chi}_1} = 0, Q_{\tilde{\chi}_2} = -1$
- ⋆ A mass term $\delta m \bar{\tilde{\chi}}_1 \tilde{\chi}_2$ induces the mixing

$$\begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{\chi}_1 \\ \tilde{\chi}_2 \end{pmatrix}. \tag{5}$$

- ⋆ The Z' portal interactions are

$$\begin{aligned} \mathcal{L} \supset \; & +Z'_\mu g' (\cos^2\theta \bar{\chi}_2 \gamma^\mu \chi_2 - \sin 2\theta \bar{\chi}_2 \gamma^\mu \chi_1 + \sin^2\theta \bar{\chi}_1 \gamma^\mu \chi_1) \\ & -Z'_\mu g' Q_f^{B-L} \bar{f} \gamma^\mu f \end{aligned} \tag{6}$$

- ⋆ The fractional mass splitting

$$\Delta_\chi \equiv \frac{m_{\chi_2} - m_{\chi_1}}{m_{\chi_1}}. \tag{7}$$

Coscattering/Conversion favors $\Delta_\chi \ll 1$

Relic Density: The Boltzmann equation

$$
\begin{aligned}
\frac{dY_{\chi_1}}{dx} &= -\frac{s}{Hx}\Bigg[\langle\sigma v\rangle_{\chi_1\chi_1\to f\bar{f}}\left(Y_{\chi_1}^2-(Y_{\chi_1}^{\rm eq})^2\right)+\langle\sigma v\rangle_{\chi_1\chi_2\to f\bar{f}}\left(Y_{\chi_1}Y_{\chi_2}-Y_{\chi_1}^{\rm eq}Y_{\chi_2}^{\rm eq}\right)\\
&- \langle\sigma v\rangle_{\chi_2 f\to\chi_1 f}\left(Y_{\chi_2}-\frac{Y_{\chi_2}^{\rm eq}}{Y_{\chi_1}^{\rm eq}}Y_{\chi_1}Y_f^{\rm eq}\right)-\langle\sigma v\rangle_{\chi_2\chi_2\to\chi_1\chi_1}\left(Y_{\chi_2}^2-\frac{(Y_{\chi_2}^{\rm eq})^2}{(Y_{\chi_1}^{\rm eq})^2}Y_{\chi_1}^2\right)\\
&- \langle\sigma v\rangle_{\chi_1\chi_2\to\chi_1\chi_1}\left(Y_{\chi_1}Y_{\chi_2}-\frac{Y_{\chi_2}^{\rm eq}}{Y_{\chi_1}^{\rm eq}}Y_{\chi_1}^2\right)-\langle\sigma v\rangle_{\chi_2\chi_2\to\chi_1\chi_2}\left(Y_{\chi_2}^2-\frac{Y_{\chi_2}^{\rm eq}}{Y_{\chi_1}^{\rm eq}}Y_{\chi_1}Y_{\chi_2}\right)\\
&- \frac{\tilde{\Gamma}_{\chi_2\to\chi_1 f\bar{f}}}{s}\left(Y_{\chi_2}-\frac{Y_{\chi_2}^{\rm eq}}{Y_{\chi_1}^{\rm eq}}Y_{\chi_1}\right)\Bigg] \qquad (8)\\
\frac{dY_{\chi_2}}{dx} &= -\frac{s}{Hx}\Bigg[\langle\sigma v\rangle_{\chi_2\chi_2\to f\bar{f}}\left(Y_{\chi_2}^2-(Y_{\chi_2}^{\rm eq})^2\right)+\langle\sigma v\rangle_{\chi_1\chi_2\to f\bar{f}}\left(Y_{\chi_1}Y_{\chi_2}-Y_{\chi_1}^{\rm eq}Y_{\chi_2}^{\rm eq}\right)\\
&+ \langle\sigma v\rangle_{\chi_2 f\to\chi_1 f}\left(Y_{\chi_2}Y_f^{\rm eq}-\frac{Y_{\chi_2}^{\rm eq}}{Y_{\chi_1}^{\rm eq}}Y_{\chi_1}Y_f^{\rm eq}\right)+\langle\sigma v\rangle_{\chi_2\chi_2\to\chi_1\chi_1}\left(Y_{\chi_2}^2-\frac{(Y_{\chi_2}^{\rm eq})^2}{(Y_{\chi_1}^{\rm eq})^2}Y_{\chi_1}^2\right)\\
&+ \langle\sigma v\rangle_{\chi_1\chi_2\to\chi_1\chi_1}\left(Y_{\chi_1}Y_{\chi_2}-\frac{Y_{\chi_2}^{\rm eq}}{Y_{\chi_1}^{\rm eq}}Y_{\chi_1}^2\right)+\langle\sigma v\rangle_{\chi_2\chi_2\to\chi_1\chi_2}\left(Y_{\chi_2}^2-\frac{Y_{\chi_2}^{\rm eq}}{Y_{\chi_1}^{\rm eq}}Y_{\chi_1}Y_{\chi_2}\right)\\
&+ \frac{\tilde{\Gamma}_{\chi_2\to\chi_1 f\bar{f}}}{s}\left(Y_{\chi_2}-\frac{Y_{\chi_2}^{\rm eq}}{Y_{\chi_1}^{\rm eq}}Y_{\chi_1}\right)\Bigg] \qquad (9)
\end{aligned}
$$

Benchmark Point

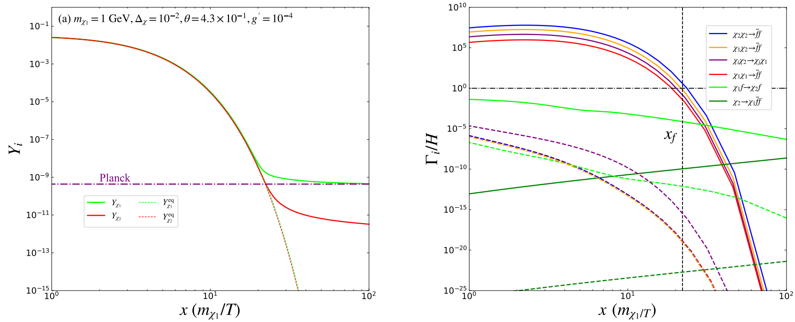


Figure: Panel (a): The evolutions of various abundances Y_i. The solid red and green lines represent the abundance evolution of χ_1 and χ_2.
Panel (b) : Thermal rates of all relevant interactions. Here, $\chi_i\chi_2 \to \chi_j\chi_1$ is the sum of the conversion channels $\chi_2\chi_2 \to \chi_1\chi_1$, $\chi_1\chi_2 \to \chi_1\chi_1$ and $\chi_2\chi_2 \to \chi_1\chi_2$. The black vertical dashed line corresponds to the thermal decoupling temperature when $Y_{\chi_1}/Y^{\rm eq}_{\chi_1} = 2.5$. The horizontal black line is $\Gamma_i = H$.

Parameter Dependence

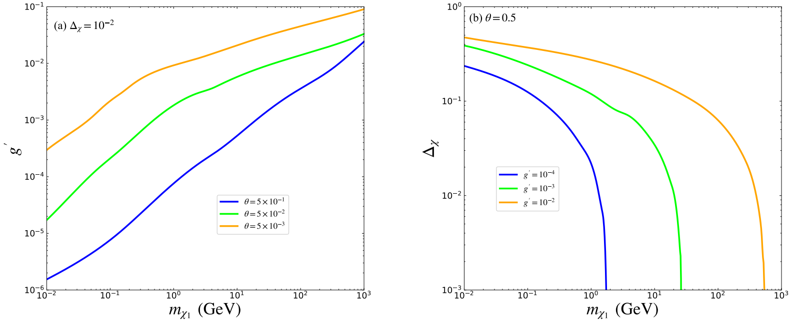


Figure: Viable regions with observed relic abundance for g' as a function of m_{χ_1} in panel (a), and for Δ_χ as a function of m_{χ_1} in panel (b). In panel (a), we fix $\Delta_\chi = 10^{-2}$. The blue, green, and orange lines represent $\theta = 5 \times 10^{-1}$, 5×10^{-2} and 5×10^{-3}, respectively. In panel (b), θ is fixed as 0.5, and the three colored curves correspond to $g' = 10^{-4}$, 10^{-3} and 10^{-2}.

Constraints on Z'

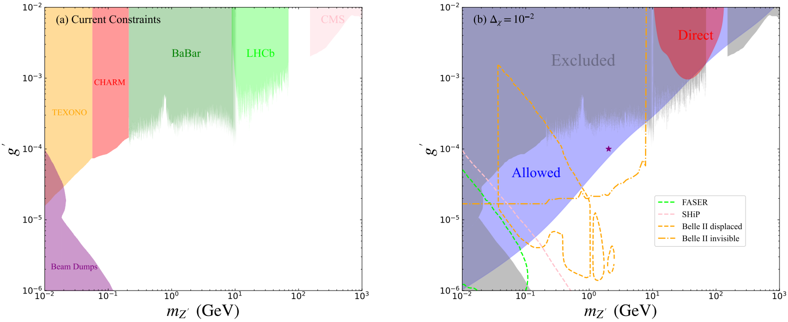


Figure: Panel (a): Various constraints on the Z' in $U(1)_{B-L}$.
Panel (b): Allowed parameter space for inelastic Dirac DM with $\theta < 0.5$. The purple star corresponds to the benchmark point in Fig. 1. The gray areas have been excluded by the current experimental search for Z'. The red shadow is excluded by the current direct detection experiments LZ and PandaX-4T.

Constraints on Dark Matter

⋆ Direct Detection: The spin-independent scattering cross section is:

$$\sigma_{\rm SI} = \frac{m_{\chi_1}^2 m_n^2 \sin^2\theta g'^4}{\pi m_{Z'}^4 (m_{\chi_1} + m_n)^2}, \tag{10}$$

where n stands for nucleons, and $m_n \simeq 0.939$ GeV.

⋆ Inelastic up-scattering $\chi_1 n \to \chi_2 n$ could lead to an observable signature when the mass splitting $m_{\chi_2} - m_{\chi_1}$ is less than $\mathcal{O}(100)$ keV. To avoid such small mass splitting, we consider the fractional mass splitting $\Delta_\chi > 10^{-3}$.

⋆ Indirect Detection: Dark matter is on the Z' pole $m_\chi \simeq m_{Z'}/2$, so the annihilation cross section is suppressed $\langle \sigma v \rangle < 10^{-32}$cm^{3}s^{-1}, which is below the CMB and Fermi-LAT limits.

Constraints on Dark Matter

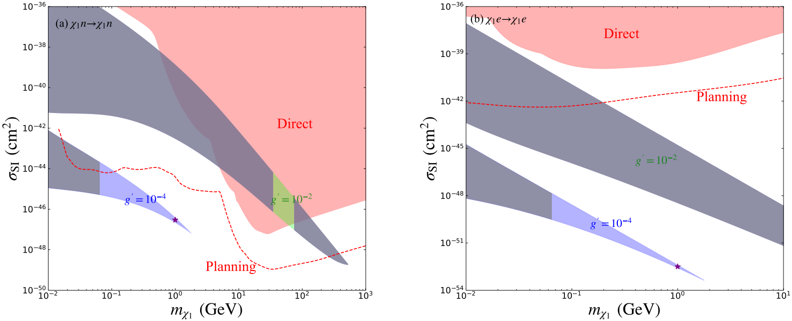


Figure: Panel (a): The spin-independent DM-nucleon scattering cross section. The green and blue regions correspond to $g' = 10^{-2}$ and $g' = 10^{-4}$, respectively. The gray region is already excluded by collider searches of Z'. The red region is excluded by the current direct detection experiments Panel (b): Same as panel (a), but for DM-electron scattering.

Constraints on Long-lived χ_2

⋆ Decay modes of χ_2

- Visible: $\chi_2 \to \chi_1 e^+ e^-$
- Invisible: $\chi_2 \to \chi_1 \nu\bar{\nu}$

$$\Gamma_{\chi_2 \to \chi_1 f\bar{f}} \simeq \frac{g'^4 \Delta_\chi^5 m_{\chi_1}^5 \sin^2 2\theta}{120\pi^3 m_{Z'}^4}. \quad (11)$$

In principle, the promising signature is

$$pp \to Z' \to \chi_2 \bar{\chi}_2 \to \chi_1 \bar{\chi}_1 e^+ e^- e^+ e^-$$

As the decay length $c\tau_{\chi_2} \gtrsim 10^{10}$ m, χ_2 is also invisible at colliders.
⋆ The energy injection from the delayed decay of χ_2 would affect the observations of CMB and BBN in the early universe.

Constraints on Long-lived χ_2

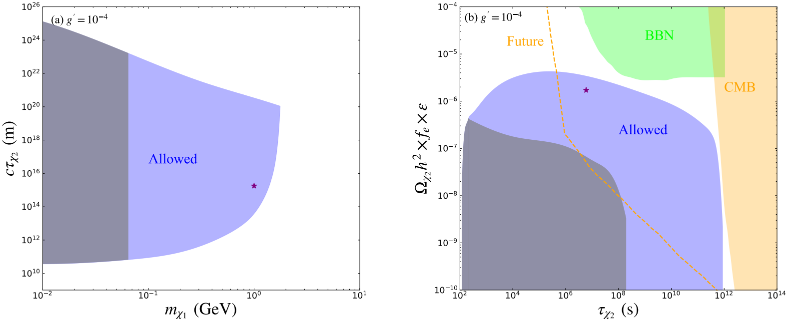


Figure: Panel (a): Decay length of χ_2 in the allowed parameter space. The gray and dark blue areas represent the same as that in (b) in Fig. 3. Panel (b): CMB and BBN constraints on long-lived χ_2. The orange and green areas are excluded by CMB and BBN . The orange dashed line represents the future CMB-S4 results.

Conclusion

⋆ Minimal Inelastic Dirac Dark Matter is viable in the $U(1)_{B-L}$ model.
⋆ Different from the conventional Z' models, the couplings of DM χ_1 to gauge boson are determined by the mixing angle θ.
⋆ The correct relic density of χ_1 is obtained via the coannihilation and conversion processes with a nearly degenerate mass spectrum of dark fermion $m_{\chi_2} \simeq m_{\chi_1}$.
⋆ The coscattering is not viable in the minimal model with $Q_{\tilde{\chi}_2} = 1$, but it can be realized with $Q_{\tilde{\chi}_2} \gg 1$.
⋆ The allowed parameter space is expected to be detected by future FASER, SHiP and Belle II experiments.