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The role of parity in pseudo-Dirac inelastic dark matter

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We investigate the role of parity violation in inelastic dark matter (iDM) models featuring pseudo-Dirac fermions coupled through vector and scalar portals. By relaxing the usual assumption of parity conservation, we develop the *not-so-inelastic Dark Matter* (niDM) framework, which continuously interpolates between the Dirac, inelastic, and Majorana dark matter limits. In the dark photon–mediated scenario, parity violation generates small but nonzero diagonal couplings that enable large mass splittings while maintaining viable parameter space, much of which can be explored by current collider experiments such as Belle II. In the scalar portal case, parity violation reduces the number of degrees of freedom, leading to a minimal fermionic iDM realization—*minimal-inelastic Dark Matter* (miDM)—which provides an s-wave thermal target and a promising benchmark for future direct detection experiments like DARWIN. Overall, our results demonstrate that parity violation can open new predictive and testable regions of thermal dark matter parameter space, emphasizing the complementarity between collider, direct, and cosmological probes in exploring dark sectors.

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1. Introduction

Nearly a century has passed since the first hints of dark matter (DM), yet no evidence beyond its gravitational effects has been observed [1, 2]. Among the most studied DM candidates are those produced via the elegant thermal freeze-out mechanism. The freeze-out framework is highly predictive: the DM relic abundance depends only on the DM mass and its thermally averaged annihilation cross section—in particular, it is completely independent of the initial conditions of the Universe [3–6]. Moreover, the same interactions responsible for freeze-out can be probed across three complementary frontiers: indirect detection (ID), direct detection (DD), and collider searches.

However, stringent ID limits from the CMB [7] and DD bounds from the LZ experiment [8] severely constrain the parameter space of standard freeze-out scenarios. Motivated by this tension, new frameworks have been proposed that retain the thermal and predictive nature of standard freeze-out while relaxing some of its underlying assumptions [9, 10]. In this context, *inelastic Dark Matter* (iDM) offers a minimal and viable alternative [11, 12]. iDM can reproduce the observed relic density via (coannihilation) freeze-out while evading ID and DD bounds, and its non-trivial dark sector leads to distinctive collider signatures [13, 14]. The most studied realization, pseudo-Dirac DM [15, 16], typically assumes parity conservation in the dark sector.

In this work, we relax that assumption and consider a general pseudo-Dirac DM Lagrangian without parity conservation. The resulting framework—referred to as *not-so-inelastic Dark Matter* (niDM) [17]—smoothly interpolates between the Dirac, inelastic, and Majorana DM limits, as illustrated in fig. 1. The remainder is organized as follows. We define the niDM model in section 2, present results for the vector and scalar portal mediators in section 3 and section 4, respectively, and conclude in section 5.

2. The not-so-inelastic Dark Matter framework

Following Ref. [17], we consider a dark sector featuring a new $U'(1)$ gauge symmetry with coupling e' and fine-structure constant $\alpha' \equiv e'^2/4\pi$. The DM content consists of a Dirac fermion $\chi_d = \chi_L + \chi_R$ singlet under the SM gauge group but carrying a $U'(1)$ charge $q_\chi \equiv 1$. The dark sector also includes a complex scalar field $H' = (h' + w + ia')/\sqrt{2}$ with charge $q_{H'} = -2q_\chi$ under $U'(1)$, acquiring a vacuum expectation value (vev) $\langle H' \rangle = w/\sqrt{2}$.

The Lagrangian describing the new physics and its interaction with the SM reads

$$\mathcal{L}_{\rm NP} = \mathcal{L}_\chi + \mathcal{L}_V + \mathcal{L}_S\,, \tag{1}$$

where

$$\mathcal{L}_\chi = i\bar{\chi}_d \not{D} \chi_d - m_D^* \bar{\chi}_L \chi_R - y_L H' \bar{\chi}_L^c \chi_L - y_R H' \bar{\chi}_R^c \chi_R + \text{h.c.}, \tag{2}$$

$$\mathcal{L}_V = -\frac{1}{4} A'^{\mu\nu} A'_{\mu\nu} - \frac{1}{2}\frac{\epsilon}{\cos\theta_w} B^{\mu\nu} A'_{\mu\nu}, \tag{3}$$

$$\mathcal{L}_S = (D^\mu H')^*(D_\mu H') + \mu_{h'}^2 |H'|^2 - \lambda_{h'}|H'|^4 - \lambda_{h'h}|H'|^2|H|^2. \tag{4}$$

Here H denotes the SM Higgs doublet, B the hypercharge gauge boson, θ_w the weak mixing angle, and $A^{\mu\nu}$ the field-strength tensor of the vector field A. The covariant derivative is defined as $iD_\mu\phi = i\partial_\mu\phi - q_\phi e' A'_\mu \phi$, and the charge-conjugated field as $\psi^c = C\gamma_0^T \psi^*$.

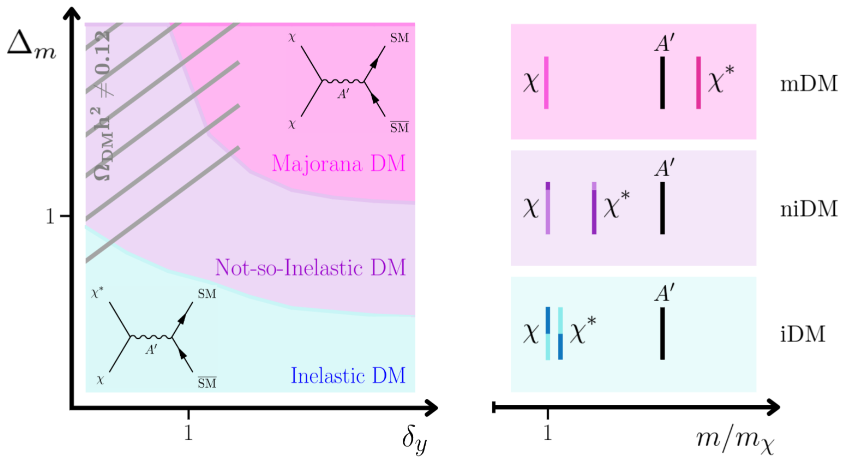

Figure 1: Schematic relation between the inelastic and Majorana DM regimes in the niDM framework.

Spontaneous symmetry breaking of $U'(1)$ via the vev w generates a mass for the dark photon, $m_{A'} = 2e'w$, and induces Majorana mass terms for both χ_L and χ_R:

$$\mathcal{L}_\chi \supset -m_D^* \bar{\chi}_L \chi_R - \frac{1}{2} m_L \bar{\chi}_L^c \chi_L - \frac{1}{2} m_R \bar{\chi}_R^c \chi_R + \text{h.c.}, \tag{5}$$

with $m_{L/R} = \sqrt{2} y_{L/R} w$. The fermion mass matrix is diagonalized using the Takagi [18] transformation on the Weyl basis $(\chi_L, \chi_R^c)^T$, yielding two Majorana mass eigenstates χ and χ^*, with $m_{\chi^*} > m_\chi$ by convention. The resulting interactions include both diagonal and off-diagonal couplings between χ, χ^*, and the mediators A' and h'.

In what follows, we analyze each mediator scenario separately, summarizing the relevant parameters and their phenomenology. Full details of the diagonalization can be found in Ref. [17].

3. The (standard) vector portal and colliders

We first focus on the vector portal scenario, where the dark Higgs is effectively integrated out.[1] Assuming a real Dirac mass and parity conservation ($y_L = y_R$), one recovers the pseudo-Dirac iDM model. For parity violation in Yukawa sector ($y_L \neq y_R$), the mixing between χ_L and χ_R leads to diagonal and off-diagonal couplings between DM and the dark photon A',

$$\mathcal{L}^I_{\chi,V} = \frac{i}{2} e' \cos 2\theta A'^\mu (\bar{\chi}\gamma_\mu \chi - \bar{\chi}^* \gamma_\mu \chi^*) + e' \sin 2\theta A'^\mu \bar{\chi}\gamma_\mu \chi^*, \tag{6}$$

where θ is the fermionic mixing angle determined by the Yukawas and mass splitting (δ_y, Δ_m) defined in Ref. [17]. The pseudo-Dirac limit corresponds to $\delta_y = 0$ (purely off-diagonal couplings), while the opposite regime of large δ_y and Δ_m yields a Majorana DM scenario with dominantly diagonal couplings—see fig. 1.

[1]This holds for $m_{h'} \gtrsim 1.5 m_\chi$, avoiding a secluded [19] or forbidden [20] freeze-out regime. Although the scalar h' may induce additional signatures [21], its impact on current constraints and collider observables considered here is negligible.

3.1 Relic abundance

We focus on an intermediate regime, $\Delta_m \sim 1$ and $\delta_y \gtrsim 1$, where standard annihilations $\chi\chi \to \overline{\text{SM}}\text{SM}$ dominate the freeze-out despite suppressed elastic couplings $\alpha'_{\text{el}} \ll \alpha'_{\text{inel}}$, thanks to the Boltzmann suppression of the heavier state χ^*. This is the *not-so-inelastic* regime. The relic density is computed using `MicrOmegas` [22] with a `CalcHEP` [23] model file generated via `FeynRules` [24]. Non-perturbative QCD corrections are included following Refs. [15, 16, 25, 26]. We find that for $\Delta_m \gtrsim 0.4$, parity breaking makes the freeze-out transition from co-annihilation ($\chi^*\chi \to \overline{\text{SM}}\text{SM}$) to annihilation ($\chi\chi \to \overline{\text{SM}}\text{SM}$) dominated regimes [17].

3.2 Experimental constraints

Indirect detection: Off-diagonal interactions are negligible since the excited states χ^* are too heavy and short-lived to present significant cosmological abundances or to be efficiently produced in astrophysical environments or DM scattering [27–30]. The diagonal annihilation channel is highly suppressed, being p-wave dominated [31], and thus also yields no relevant indirect detection constraints. Finally, DM self-interactions are negligible for both coupling types, as we consider relatively heavy mediators ($m_{A'} > m_\chi$) and DM masses $m_\chi \gtrsim 10$ MeV [17, 27, 32].

Direct detection: Inelastic scattering is suppressed by the relatively large mass splittings considered, whereas elastic scattering arises because α'_{el} is nonzero and is induced by the effective operators $\mathcal{O}_8^N \propto \mathbf{v}_\perp$ and $\mathcal{O}_9^N \propto \mathbf{q}$ [33, 34]. Despite their suppression, LZ [8] can probe thermal targets for $m_\chi \gtrsim 10$ GeV. Results are computed with `DDCalc` [35], including the impact of the Large Magellanic Cloud [36], with projected sensitivities for SuperCDMS [37] and DARWIN [38].

Colliders: At high energies experiments, neither velocity nor inelastic suppression applies. Consequently, for scattering searches at fixed-target and beam-dump experiments (LSND [39, 40], E137 [41, 42], and MiniBooNE [43]), we follow the analysis of Ref. [44]. Searches for semi-visible χ^* decays at proton beam dumps are recast using `SensCalc` [45], with NA62 [46] currently providing the strongest bound. Missing-energy searches by NA64 [47] and BaBar [48] constrain invisibly decaying dark photons, while semi-visible χ^* decays can partially evade these limits. To evaluate such effects, dedicated simulations for e^+e^- colliders (BaBar, Belle II [49]) and semi-analytical methods for NA64 were developed in Ref. [17]. Finally, electroweak precision tests at LEP [50] set additional bounds on the kinetic mixing parameter ϵ at higher masses.

3.3 Results

Figure 2 (left) shows the regions in the (δ_y, Δ_m) plane where the kinetic mixing ϵ reproducing the observed relic density is experimentally excluded. The not-so-inelastic regime retains viable parameter space, as χ^* decays weaken BaBar bounds; for $\Delta_m > 1$, only dark photon decays into ground-state are allowed, restoring the usual limits. Figure 2 (right) compares current bounds and projected sensitivities. Belle II [49, 51] can extend the mono-photon coverage well beyond BaBar, fully probing $m_\chi \lesssim 3$ GeV for $m_{A'} \geq 3m_\chi$. LZ [8] complements collider bounds at $m_\chi \gtrsim 7$ GeV, leaving a small gap near $m_\chi \sim 5$ GeV where solar ^{8}B neutrino backgrounds dominate [52]. Exploring new experimental strategies to close this gap remains an exciting direction for future research.

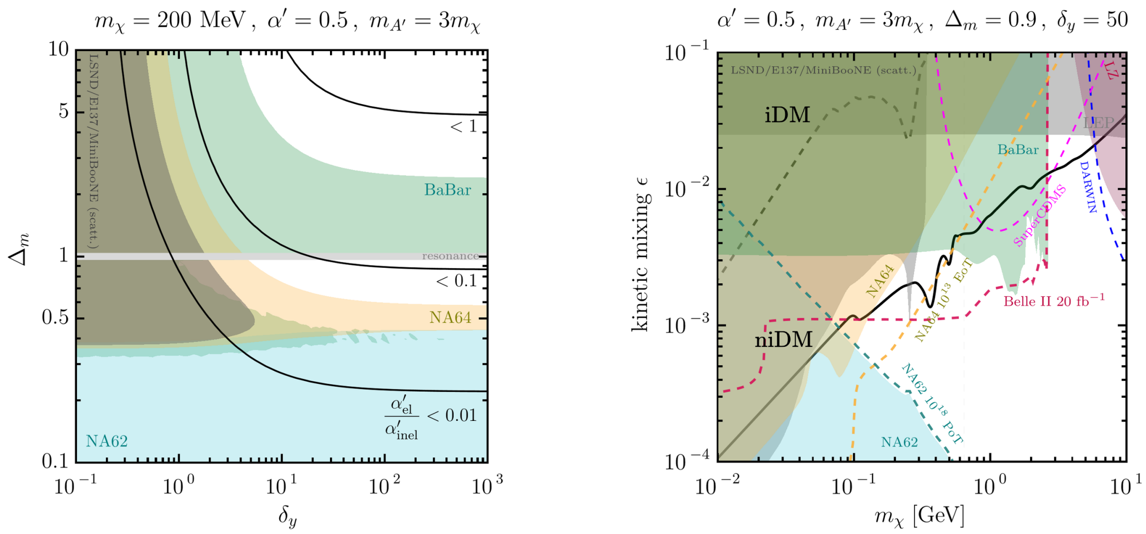

Figure 2: *Left:* Excluded regions in the (δ_y, Δ_m) plane where the required kinetic mixing ϵ reproducing the relic density is ruled out. *Right:* Current and projected sensitivities to ϵ as a function of m_χ. The solid (dashed) black curve corresponds to the niDM (iDM) thermal target. Reproduced from Ref. [17].

4. The (minimal) scalar portal and direct detection

We now focus on the scalar portal scenario, where the dark photon can be completely omitted since it does not affect the mass-splitting generation. One may construct this setup from eq. (1) by considering $m_{A'} \gg m_{h',\chi^{(*)}}$ and adopting a Dirac mass with a maximal $\mathcal{CP}$-phase, $m_D = i m_d$ ($m_d \in \mathbb{R}$), along with some parity violation. In practice, however, a simpler realization involves a real pseudoscalar mediator $A = a + w$, with vev $\langle A \rangle = w$, and a Dirac fermion $\chi_d = \chi_L + \chi_R$ as well as a Z_4 symmetry: $\chi_d \to i\chi_d$, $A \to -A$. Parity and $\mathcal{CP}$ are softly broken by a small parameter $\delta_P \ll 1$, related to eq. (1) by $\delta_y = 2\delta_P/(1-\delta_P)$. The mediator a couples to the SM through a mixing angle θ, analogous to the dark Higgs h'.[2]

In the pseudo-Dirac limit $w \ll m_d$—motivated by naturalness since $w \to 0$ restores a global $U(1)$ symmetry—the interaction Lagrangian becomes

$$\mathcal{L}^I_{\chi,S} \approx y(\delta_P - \delta_d)\, a\, \bar{\chi}\chi - y(\delta_P + \delta_d)\, a\, \bar{\chi}^*\chi^* + 2y\, \bar{\chi}\gamma_5\chi^* \,, \tag{7}$$

where $\delta_d = m_L/m_d \propto w/m_d \ll 1$ and $y = y_{R/L}/(1 \pm \delta_P)$, expanded at leading order in $\delta_{P,d}$. Also at leading order, the relative mass splitting is $\Delta_m = 2\delta_P\delta_d$. A non-zero parity violation is therefore required for inelastic transitions, while small δ_P ensures elastic interactions remain subdominant, yielding a (n)iDM candidate in the small δ_P and pseudo-Dirac limits. Owing to its reduced parameter space, we refer to this realization as *minimal-inelastic Dark Matter* (miDM).

Perturbative unitarity: To kinematically close the secluded freeze-out channel, one requires $m_a \approx \sqrt{2\lambda_a} w > m_\chi \approx m_d$. Further suppression of diagonal couplings demands $\delta_d \ll 1$, i.e., $\sqrt{2} y_L w \ll m_d$, which in turn drives λ_a toward large values potentially violating perturbativity.

[2] Here, θ denotes the scalar mixing angle between the pseudoscalar mediator and the SM Higgs, not the fermionic mixing angle.

Consequently, perturbative unitarity constraints play a key role in delineating the viable miDM parameter space.

4.1 Relic abundance

To compute the DM abundance, we developed a dedicated `Mathematica`® Boltzmann solver—validated against Ref. [31] for mDM and Ref. [14] for iDM—making use of the fact that the combined abundance of χ and χ^* evolves according to a single Boltzmann equation [53].

Figure 3 (left) exemplifies the miDM thermal target in comparison with the standard (p-wave-suppressed) mDM case. We see that the s-wave nature of miDM significantly relaxes the relic abundance constraint (for small mass splittings $\Delta_m \ll 1$ featuring negligible Boltzmann suppression).

4.2 Current constraints and projected sensitivities

Indirect detection: Bounds from (inelastic) coannihilations or χ^* decays are negligible when $\tau_* \ll 1$ s, as the excited-state abundance is then cosmologically irrelevant [27–30]. For $\tau_* \gtrsim 0.02$ s [54], late decays may impact BBN or CMB, though detailed studies are left for future work. The (elastic) annihilation is p-wave suppressed [31] and thus unconstrained. Mediator decays could affect cosmology, but for $m_a \gtrsim 10$ GeV and $\theta \gtrsim 10^{-2}$ we find $\tau_a \ll 0.02$ s, making their impact negligible during BBN.
Direct detection: Inelastic scattering is suppressed when $\Delta_m > v^2 \sim 10^{-6}$ or due to the pseudoscalar nature of the interaction, generating only momentum-suppressed operators $O_{10,11} \propto \vec{q}$ [33]. Elastic couplings, however, induce strong SI interactions tightly constrained by LZ [8]. The SI cross section reads $\sigma^{\rm SI} = (\delta_P - \delta_d)^2 \sigma^{\rm SI}_{\rm mDM}$, where $\sigma^{\rm SI}_{\rm mDM}$ is the standard Majorana DM result [31, 53]. Relaxing these limits requires $\delta_{P,d}$ to be small, yet much of the visible freeze-out regime consistent with perturbativity remains within reach of future detectors, such as DARWIN [55].
Colliders: We constrain the model via an analysis of the Higgs signal strength modifier μ, a modificiation affecting all production and decay modes equally while keeping SM branching ratios fixed. ATLAS and CMS measurements require $\mu > 0.93$ at 95% CL [56, 57]. For our scalar mixing case, the μ definition is given in Ref. [58]. Signal-strength bounds dominate for $m_a \gtrsim 10$ GeV in the visible freeze-out regime, where a decays invisibly [59]. Complementary searches at ATLAS [56, 60], CMS [61], and LEP [62] could also be included further probing the secluded regime.

4.3 Results

The right panel of fig. 3 shows the combined constraints on the freeze-out parameter space. For each (m_χ, m_a) pair, the dark Yukawa coupling y is fixed to reproduce $\Omega_\chi h^2 = 0.12$ [7]. Opaque regions are excluded by experiments or perturbativity; hatched areas show the reach of future detectors, and shaded regions are likely to be excluded but require further analysis. Gray bands indicate the resonant region $m_a \in (2 \pm 10\%) m_\chi$ where early kinetic decoupling may alter relic computations [63].

Perturbativity excludes much of the visible freeze-out regime, disfavoring $\delta_d \ll 0.1$ and requiring $m_d \sim w$, leaving elastic interactions relevant for DD searches. Hence, although miDM opens new unconstrained regions, most remain testable by upcoming experiments like DARWIN [55], with

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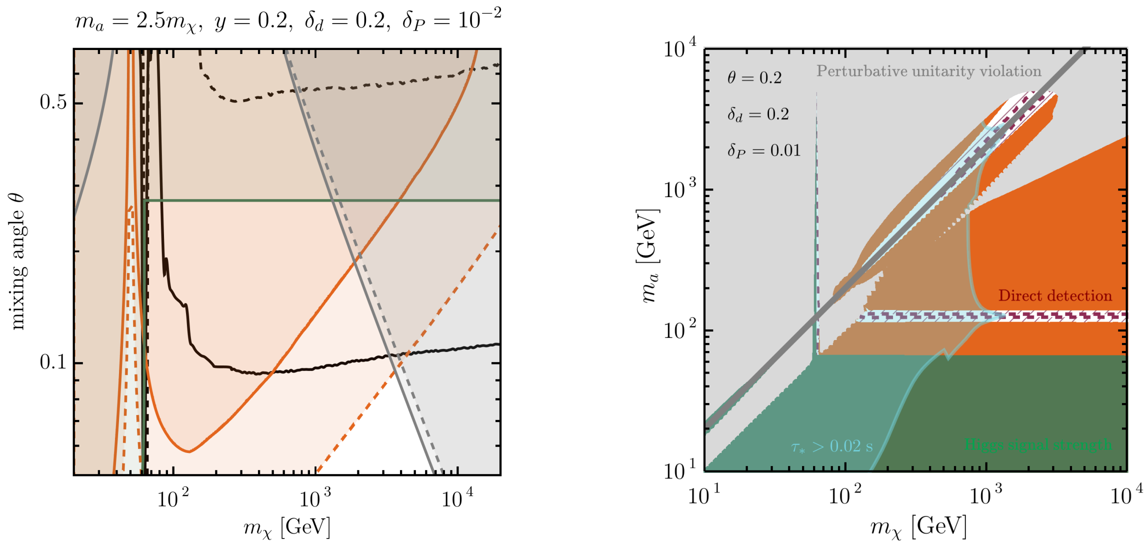

Figure 3: *Left:* Mixing angle θ reproducing $\Omega_\chi h^2 = 0.12$ [7] as a function of m_χ. Gray, green, and orange regions indicate perturbativity [31], Higgs signal strength [56, 57], and LZ [8] bounds, respectively. Solid lines correspond to miDM results, while dashed lines refer to the standard mDM case. *Right:* Excluded and projected regions in the (m_χ, m_a) plane. Light gray, green, and orange regions are defined as in the left panel; red-hatched areas show DARWIN sensitivity [55]; blue regions indicate long-lived χ^* states [54]; and the gray band marks the resonance region [63]. Reproduced from Ref. [53].

only fine-tuned $\delta_P \simeq \delta_d$ values fully evading constraints. Small $\theta \lesssim 0.1$ values are also limited by a combination of perturbativity and the $\Omega_\chi h^2 = 0.12$ constraint, keeping collider prospects strong.

In the secluded regime, large perturbativity-allowed regions persist since $m_a < m_\chi$, naturally suppressing DD limits for smaller δ_i. However, Higgs signal-strength constraints remain relevant unless $\theta \lesssim 10^{-2}$. Parts of the parameter space with $\tau_* \gtrsim 0.02$ s [54] may also be ruled out by BBN and CMB considerations. Reducing δ_i or θ weakens Earth-based bounds but enhances cosmological sensitivity, highlighting the complementarity of laboratory and cosmological probes in testing this framework.

5. Conclusions

We have shown that parity can play a crucial role in dark sector phenomenology, particularly in DM physics. By generalizing the pseudo-Dirac iDM framework, we found that in the dark photon–mediated scenario, small but nonzero diagonal couplings—arising only when parity is violated—allow for large mass splittings while maintaining unconstrained and predictive regions of parameter space, testable by current collider experiments. For the scalar mediator case, we demonstrated that parity violation enables a reduction in the number of degrees of freedom, leading to perhaps the most minimal fermionic iDM realization and providing an excellent target for upcoming direct detection searches.

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