UIC UNIVERSITY OF ILLINOIS CHICAGO

Reviving Minimal Dark Matter

with Boltzmann-Suppressed Freeze-in

Sagnik Mukherjee

In collaboration with Nicolás Bernal and James Unwin

Based on arXiv:2602.10112 arXiv:2604.00210

PIKIMO 21 (11/7/26), PITT PACC

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- **A concrete possibility for experimental discovery.** The mediators are the known electroweak bosons - targets for colliders and direct and indirect detection.

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- Conventional freeze-in models typically requires extremely feeble interactions, making experimental detection challenging if not entirely impractical.
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A discouraging prospect - but are we giving up on them too soon?

The minimal $SU(2)_L$ doublet Dark Matter

SM is extended by two LH Weyl doublets with equal and opposite Y.

$$\chi_1 \sim (\mathbf{2}, +\tfrac{1}{2}), \qquad \chi_2 \sim (\mathbf{2}, -\tfrac{1}{2}), \qquad \mathcal{L} \supset -M\chi_1\chi_2 + \text{h.c.}$$

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Minimal particle content

- After EWSB, we get

$$\psi^0 \equiv \begin{pmatrix} \chi_2^0 \\ \overline{\chi_1^0} \end{pmatrix}, \qquad \psi^+ \equiv \begin{pmatrix} \chi_1^+ \\ \overline{\chi_2^-} \end{pmatrix}.$$

- Radiative splitting $\Delta m \simeq 350$ MeV.
- A $\mathbb{Z}_2$ stabilizes the neutral state.

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$$\mathcal{L} \supset \frac{g_2}{2\cos\theta_W} Z_\mu \bar{\Psi}^0 \gamma^\mu \Psi^0$$

$$\sigma_{\text{SI}}^{(n)} \simeq 4.7 \times 10^{-40}\ \text{cm}^2$$

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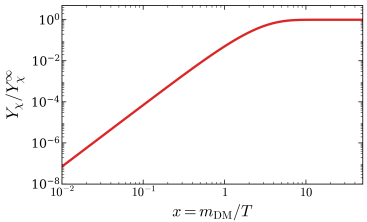
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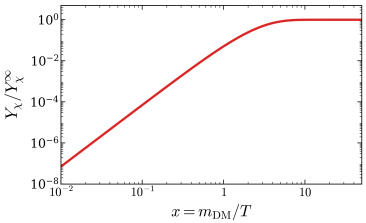
LZ bound (2025): $m \gtrsim 1.4 \times 10^{10}$ GeV - grossly overproduced by freeze-out.

Framework: Freeze-in at sizeable coupling



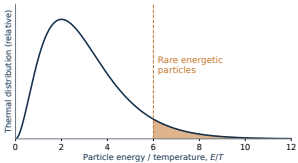
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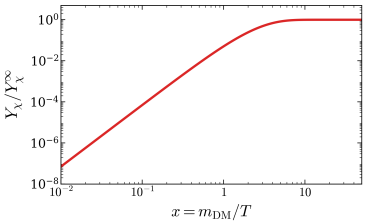
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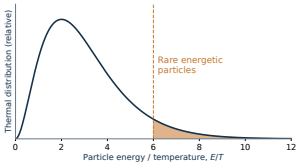
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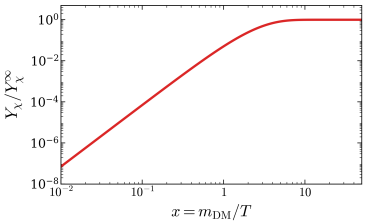
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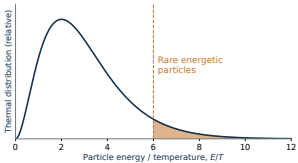
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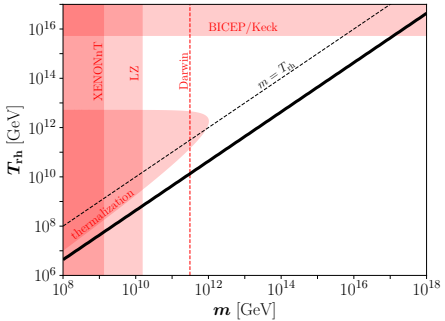
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- $\gamma_{\rm prod} \propto e^{-2m_{\rm DM}/T}$, $Y_\infty \propto e^{-2m_{\rm DM}/T_{\rm rh}}$.
- To reproduce the observed abundance, stronger couplings must compensate for Boltzmann suppression [*Cosme, Costa & Lebedev (2023)*].

DD constrains and probes the doublet parameter space

$q\bar{q}' \to \Psi^0\bar{\Psi}^0, \qquad q\bar{q}' \to \Psi^+\Psi^-, \Psi^\pm \to \Psi^0\pi^\pm$

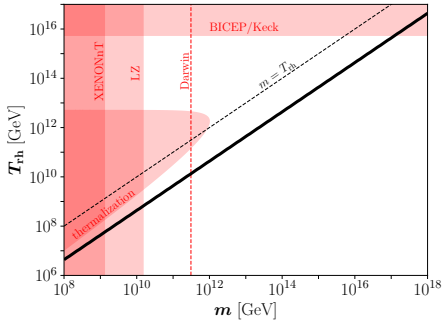


$$Y_\infty \simeq A_{\rm EW}\frac{M_{\rm Pl}}{m}e^{-2m/{\rm rh}}$$

$$mY_\infty \simeq 4.3\times 10^{-10}\ {\rm GeV} \implies m/T_{\rm rh} \approx 27.$$

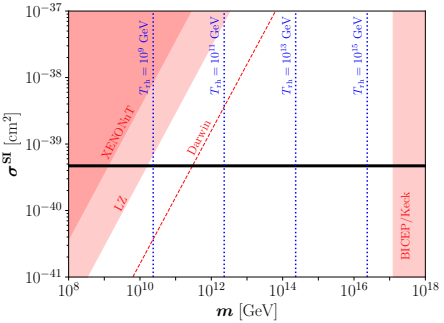
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Lower mass ranges excluded by LZ and XENONnT. DARWIN will probe deep into available parameter space.

A pseudo-Dirac splitting reopens lower masses

Allow a small Majorana mass for neutral Weyl components, say, by dimension-5 Higgs operators like $\frac{1}{\Lambda}(\chi_1 H)^2$:

$$\mathcal{L} \supset -M\chi_1^0\chi_2^0 - \frac{\delta_1}{2}\chi_1^0\chi_1^0 - \frac{\delta_2}{2}\chi_2^0\chi_2^0 + \text{h.c.},$$

Splits the Dirac Ψ^0 into a pseudo-Dirac pair (Ψ_1, Ψ_2) with masses $m_{1,2} \simeq M \mp \frac{1}{2}\delta$ for $\delta \equiv \delta_1 + \delta_2$:

$$\Psi_1 \simeq \frac{1}{\sqrt{2}}\left(\Psi^0 + (\Psi^0)^c\right), \qquad \Psi_2 \simeq \frac{-i}{\sqrt{2}}\left(\Psi^0 - (\Psi^0)^c\right),$$

The Z coupling becomes off-diagonal

$$Z_\mu \bar{\Psi}_2 \gamma^\mu \Psi_1$$

Inelastic channel $\Psi_1 + N \to \Psi_2 + N$ closes when $\delta > \frac{1}{2}\mu_{\chi N} v_{\text{max}}^2 \implies \delta > \mathcal{O}(100\ \text{keV})$.

Loop-induced scattering remains
$\sigma_{\text{SI}}^{\text{loop}} \sim 10^{-47}\ \text{cm}^2$

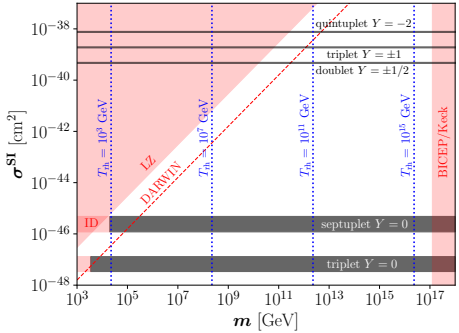
- Estimated lower mass: $m \gtrsim 300$ GeV.
- Projected DARWIN reach: $m \sim 6$ TeV.

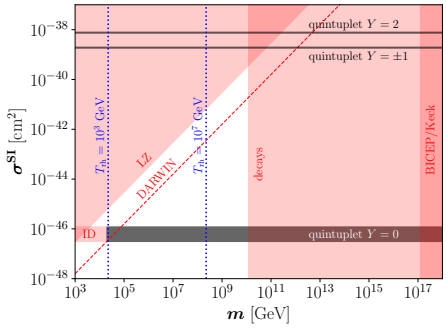
Larger electroweak representations

- **Doublet: imposed stability.** Permits gauge invariant, renormalizable couplings to SM leptons that allow DM decay - need additional $\mathbb{Z}_2$ symmetry.
- **Larger fermion multiplets: accidental stability**. For $n \geq 5$, gauge invariant decay modes only possible via non-renormalizable operators suppressed by a scale Λ - If $\Lambda \gtrsim M_{\rm Pl}$, TeV scale candidates can be cosmologically long-lived [*Cirelli, Fornengo & Strumia (2006)*].
- Does this protection survive the much larger masses accessible through Boltzmann-suppressed freeze-in? On the contrary - one might expect decay signatures from higher order reps.

Larger Electroweak Representations

Different representations show very different detection limits!





• **No tree level Z-coupling for $Y = 0$.** • **Indirect detection (ID) excludes lower mass ranges for $Y = 0$.** • **Decay limits on $n = 5$ model from Auger's γ-ray searches.**

Conclusions

1. **Freeze-in need not imply feeble interactions.**
   Boltzmann-suppressed production for $m_{\rm DM} > T_{\rm rh}$ permits sizeable couplings consistent with the observed relic abundance, bringing freeze-in dark matter within experimental reach.

2. **Revives the Electroweak doublet DM.**
   Within the framework of Boltzmann-suppressed freeze-in, minimal DM models, with interactions fixed solely by the SM gauge groups, are consistent with current searches and can be probed by future experiments.

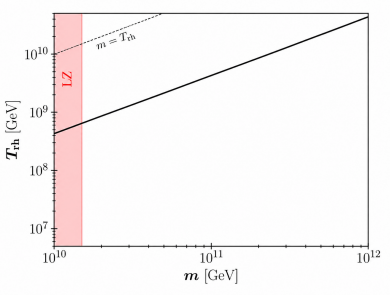
3. **Freeze-in with higher electroweak representations.**
   Need to reassess the strong stability statements in the context of higher masses required by freeze-in. Alternatively, gives rise to decay signals from higher representation models, potential target for γ-ray and neutrino telescopes.

arXiv:2510.01311 arXiv:2602.10112 arXiv:2604.00210

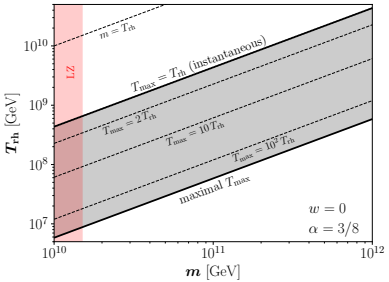
-Thanks!-

Generalization I: Non-instantaneous reheating

Instantaneous reheating - Relic contour is a line



Non-instantaneous reheating - Relic contour is a band



$$Y_{\rm FI}^{\rm tot} = Y_{\rm FI}^{\rm inst} + Y_{\rm FI}^{\rm rh}$$

Broadening the reheating era lowers $T_{\rm rh}$

Generalization II: Non-standard cosmologies

$$p_\phi = \omega \rho_\phi, \qquad T = T_{\rm rh}(a_{\rm rh}/a)^\alpha$$

