Dirac dark matter with a charged mediator: a comprehensive one-loop analysis of the direct detection phenomenology

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Based on 1503.03382 (Alejandro Ibarra, SW)
Consider a Dirac dark matter particle $\chi$. If $\chi$ can scatter of nucleons $N$ at tree-level via the exchange of a $Z$...:

$$\ni \rightarrow L_e = f_N \bar{\chi} \gamma^\mu \chi \bar{N} \gamma^\mu N$$

with $f_N \sim G_F \frac{4}{\sqrt{2}} \ni \rightarrow \sigma_{SI}(\chi p) \approx \mu^2 N \frac{G_F^2}{32 \pi} \approx 5 \cdot 10^{-40} \text{cm}^2 \gg \sigma_{LUX}(\chi p)$

If the vector-vector coupling is induced at the one-loop level...:

$$\ni \rightarrow \sigma_{SI}(\chi p) \approx 5 \cdot 10^{-40} \text{cm}^2 \cdot \left(\frac{1}{16\pi^2}\right)^2 \cdot (0.5)^4 \approx 10^{-45} \text{cm}^2 \approx \sigma_{LUX}(\chi p)$$

Direct detection experiments are getting sensitive to loop-induced scattering!
Consider a **Dirac dark matter** particle $\chi$.

If $\chi$ can scatter of nucleons $N$ at **tree-level** via the exchange of a $Z$...:

\[ \mathcal{L}_{\text{eff}} = f_N \bar{\chi} \gamma^\mu \chi \bar{N} \gamma_{\mu} N \quad \text{with} \quad f_N \sim \frac{G_F}{4 \sqrt{2}} \]
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Loop effects in direct detection: some simple estimates

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  - $\leftrightarrow \mathcal{L}_{\text{eff}} = f_N \bar{\chi}\gamma^\mu\chi \bar{N}\gamma_\mu N$ with $f_N \sim \frac{G_F}{4\sqrt{2}}$
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Direct detection experiments are getting sensitive to loop-induced scattering!
A simplified model of Dirac dark matter

- **Dark matter particle** $\chi$: Dirac fermion, SM singlet $(1, 1)_0$
  $\leftrightarrow$ no tree-level coupling to $Z$, $W^\pm$ or $h$

- **Scalar mediator** $\eta$
  $\leftrightarrow$ couples $\chi$ to one SM fermion $f_R$ via $\mathcal{L} = -y \eta^\dagger \bar{\chi} f_R$
  $\leftrightarrow m_\eta > m_\chi$
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<table>
<thead>
<tr>
<th>Coupling to...</th>
<th>Quantum numbers of $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_R, \mu_R$ or $\tau_R$</td>
<td>$(1, 1)_{-1}$</td>
</tr>
<tr>
<td>$u_R, c_R$ or $t_R$</td>
<td>$(3, 1)_{2/3}$</td>
</tr>
<tr>
<td>$d_R, s_R$ or $b_R$</td>
<td>$(3, 1)_{-1/3}$</td>
</tr>
</tbody>
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- Scenarios with coupling to a left-handed SM fermion doublet are very similar
  $\hookrightarrow$ see the paper for detailed discussion of all the possible cases
Thermal parameter space

- Only three parameters:
  - DM mass $m_\chi$, mass splitting $m_\eta/m_\chi$, Yukawa coupling $y$
- The requirement of $\Omega_\chi h^2 \approx 0.12$ fixes $y \equiv y_{\text{thermal}}(m_\chi, m_\eta/m_\chi)$
  - $\rightarrow$ main annihilation channel for the freeze-out: $\chi \chi \rightarrow f \bar{f}$
  - $\rightarrow$ For $m_\eta/m_\chi \lesssim 1.2$, also coannihilations are important, e.g. $\eta \bar{\eta} \rightarrow \gamma \gamma$

Highly testable models!
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For every coupling scenario ($e_R, u_R, \ldots$), the **thermal parameter space** is only two-dimensional, spanned by $m_\chi$ and $m_\eta/m_\chi$

**Highly testable models!**
In the paper, we analyze the direct detection phenomenology for all 15 possible coupling scenarios:

\[ e_R, (\nu_e, e_L), u_R, d_R, (u_L, d_L) \times \text{three generations} \]

In this talk, I will present the results for coupling to:

1) \( u_R \)
2) \( \tau_R \)
3) \( b_R \)
4) \( t_R \)

→ this selection encapsulates most of the interesting features appearing in all possible coupling scenarios

Some of these cases have (partially) already been discussed:

Agrawal\& [1109.3516,1402.7369,1404.1373], Bai, Berger [1308.0612,1402.6696], Chang\& [1307.8120,1402.7358], Kopp\& [1401.6457]
Case (1): Coupling to $u_R$

- If $\chi$ couples to the $u$ or $d$ quark, scattering off nuclei is possible at tree-level:

$$\Rightarrow \mathcal{L}_{\text{eff}}^{(\text{SI})} \propto \frac{y^2}{m_\eta^2 - m_\chi^2} \bar{\chi} \gamma^\mu \chi N \gamma_\mu N$$
Case (1): Coupling to $u_R$

- If $\chi$ couples to the $u$ or $d$ quark, scattering off nuclei is possible at tree-level:

$$L_{\text{eff}}^{(SI)} \propto \frac{y^2}{m^2_\eta - m^2_\chi} \bar{\chi} \gamma^\mu \chi N \gamma_\mu N$$

For coupling to $u_R$ to $d_R$, LUX already excludes almost the whole thermal parameter space.
Case (1): Coupling to $u_R$

- If $\chi$ couples to the $u$ or $d$ quark, scattering off nuclei is possible at tree-level:

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For coupling to $u_R$ to $d_R$, LUX already excludes almost the whole thermal parameter space.

- However: $\mathcal{L}_{\text{eff}}^{(\text{SI})} \equiv 0$ for coupling to $f_R \notin \{u_R, d_R\}$
  $\Rightarrow$ in these scenarios, there is no SI interaction at tree-level!
Case (2): Coupling to $\tau_R$ - Leptophilic dark matter

Dark matter coupling to $\tau_R$ (or any other RH or LH lepton):

- One-loop diagrams induce an effective DM-photon coupling:

\[
\chi \chi \gamma = \chi \chi f \eta \eta \gamma + \chi \chi \eta \eta \gamma
\]

\[\mu_{\chi}^2 = m_{\chi}^2 \chi \sigma_{\mu \nu} \chi F_{\mu \nu} \text{ magnetic dipole moment} + b_{\chi} \chi \gamma \mu_{\chi} \partial_{\nu} F_{\mu \nu} \text{ charge radius} \]

Similar diagrams induce an effective coupling $\bar{\chi} \chi Z \rightarrow$ suppressed by $(m_f/m_{\chi})^2 \Rightarrow$ irrelevant for leptophilic dark matter
Case (2): Coupling to $\tau_R$ - Leptophilic dark matter

Dark matter coupling to $\tau_R$ (or any other RH or LH lepton):

- One-loop diagrams induce an **effective DM-photon coupling**:

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\mathcal{L}_{\text{eff}}^{(\gamma)} = \frac{\mu_\chi}{2} \overline{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu} + b_\chi \overline{\chi} \gamma^\mu \chi \partial^\nu F_{\mu\nu}
\]

- $\mu_\chi$ and $b_\chi$ are calculable (finite) functions of $m_\chi$, $m_\eta$ and $y$
Case (2): Coupling to $\tau_R$ - Leptophilic dark matter

Dark matter coupling to $\tau_R$ (or any other RH or LH lepton):

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- Similar diagrams induce an effective coupling $\overline{\chi} \chi Z$

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Case (2): Coupling to $\tau_R$ - Leptophilic dark matter

\[
\mathcal{L}_{\text{eff}}^{(\gamma)} = \frac{\mu_X}{2} \overline{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu} + b_X \overline{\chi} \gamma^\mu \chi \partial^\nu F_{\mu\nu}
\]

- magn. dipole moment
- charge radius

- Scattering off a nucleus with mass $m_A$ and spin $J_A$:

\[
\frac{d\sigma_{\chi A}}{dE_R} = \alpha_{\text{em}} \mu_X^2 Z^2 \left( \frac{1}{E_R} - \frac{m_A}{2\mu_{\text{red}} v^2} \right) [F_{\text{SI}}(E_R)]^2 + \frac{\mu_A^2 \mu_X^2 m_A}{\pi v^2} \cdot \frac{J_A + 1}{3J_A} [F_{\text{dipole}}(E_R)]^2 + \frac{2m_A Z^2 \alpha_{\text{em}}}{v^2} \left( b_X + \frac{\mu_X}{2m_X} \right)^2 [F_{\text{SI}}(E_R)]^2
\]

\[\rightarrow\]

- long-range dipole-charge interaction
- dipole-dipole interaction $\propto \mu_A^2$
- spin-independent contact interaction
Case (2): Coupling to $\tau_R$ - Leptophilic dark matter

$$\mathcal{L}_{\text{eff}}^{(\gamma)} = \frac{\mu_X}{2} \overline{\chi} \sigma^{\mu \nu} \chi F_{\mu \nu} + b_X \overline{\chi} \gamma^\mu \chi \partial^\nu F_{\mu \nu}$$

magn. dipole moment \hspace{1cm} \text{charge radius}

- LUX already excludes a thermal relic for $m_\chi \lesssim 100$ GeV
- Future DD experiments can completely close in on that scenario
  $\rightarrow$ even for $m_\chi \gtrsim 1$ TeV
  $\rightarrow$ despite the fact that the scattering is only loop-induced!
Case (3): Coupling to $b_R$

- Again, there is no tree-level scattering off nuclei
- Relevant one-loop diagrams:

\[
\begin{align*}
\chi & \rightarrow f \\
\eta & \rightarrow \gamma \\
\chi & \rightarrow f
\end{align*}
\]

$\Rightarrow$ charge radius & magnetic dipole moment of $\chi$

\[
\begin{align*}
\chi & \rightarrow \eta \\
\eta & \rightarrow \gamma \\
\chi & \rightarrow f
\end{align*}
\]

$\Rightarrow$ effective dark matter-gluon coupling $\bar{\chi}\chi G^{\mu\nu}G_{\mu\nu}$

$\L_{\text{eff}} = f_{S,\text{gluon}} \bar{\chi}\chi \bar{N}N$
Case (3): Coupling to $b_R$

- Excellent prospects for future direct detection experiments
- In this model, the dominant annihilation mode is $\chi \bar{\chi} \rightarrow b \bar{b}$
  - for $m_{DM} \approx 50$ GeV, this model could explain the **Galactic Center Excess** observed by Fermi
  - well within the reach of XENON-1T!
Case (4): Coupling to $t_R$

$\Rightarrow$ charge radius & magnetic dipole moment of $\chi$

$\Rightarrow$ effective dark matter-gluon coupling $\bar{\chi}\chi G^{\mu\nu} G_{\mu\nu}$

$\Leftarrow \mathcal{L}_{\text{eff}} = f_{S,\text{gluon}} \bar{\chi}\chi \bar{N}N$

$\Rightarrow$ effective $\bar{\chi}\chi Z$ vertex

$\Leftarrow \mathcal{L}_{\text{eff}} = f_{V,Z} \bar{\chi}\gamma^\mu \chi \bar{N}\gamma_\mu N$ with $f_{V,Z} \propto (m_f/m_\chi)^2$
Case (4): Coupling to $t_R$

For DM coupling to the top-quark, the one-loop $Z$ exchange is dominant for $m_\chi \lesssim 5$ TeV

LUX only constrains a rather small part of the thermal parameter space

However: XENON-1T will be sensitive to dark matter masses $\gtrsim 1$ TeV
Outlook: leptophilic dark matter in the Sun?

Can dark matter be captured and annihilate in the Sun, if it is **purely leptophilic**?

- The IceCube/Super-K limits can be very strong for leptophilic annihilations, e.g. $\text{DM DM} \rightarrow \tau^+\tau^-$ or $\text{DM DM} \rightarrow \nu\bar{\nu}$
- The magnetic dipole moment of $\chi$ leads to a dipole-dipole interaction with protons
  $\leftrightarrow$ similar to spin-dependent scattering off protons
Equilibration of leptophilic Dark Matter in the Sun

Again, we fix the coupling $y$ to its thermal value ($\Omega_{DM}h^2 = 0.12$)

$A_\odot = \frac{1}{2} C_\odot \tanh^2 \left( t_\odot / \tau_{eq} \right)$ with $\tau_{eq} \propto \frac{1}{\sqrt{\sigma_{\text{capture}} \cdot \langle \sigma v \rangle}}$

$\rightarrow$ **Equilibrium condition**: $t_\odot / \tau_{eq} \gg 1$

$\rightarrow$ contour lines show constant values of $t_\odot / \tau_{eq}$
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$\downarrow$

In our simplified model of leptophilic Dirac Dark Matter, we indeed have equilibration in the whole thermal parameter space.
IceCube and LUX limits on leptophilic Dirac dark matter
IceCube and LUX limits on leptophilic Dirac dark matter

![Graph showing the coupling to $\tau_R$ against $m_\chi$ (GeV) and $m_\eta/m_\chi$. The graph includes regions labeled GCE, LUX, XENON-1T, DARWIN, and IceCube, with boundaries indicating thermal relics and non-thermal relics.]

**Complementarity** between LUX and IceCube:

→ For large DM masses and small mass splitting of $\chi$ and $\eta$, IceCube is stronger than LUX

→ LUX and IceCube are affected differently by systematics, e.g. the dark matter velocity distribution
Conclusions

- Direct detection experiments have already reached the necessary sensitivity to probe dark matter-nucleon interactions mediated only at one-loop order.

- We demonstrated this in the context of a simplified model with a singlet Dirac fermion as the dark matter particle:
  - for any possible coupling scenario of dark matter, LUX already excludes part of the thermal parameter space.
  - future direct detection experiments have excellent prospects to probe large parts of the parameter space, even multi-TeV dark matter.
  - this approach is complementary and competitive to other searches:
    - LHC: monojet, direct production of $\eta$, ...
    - indirect detection with $\gamma$'s from dwarf galaxies
    - for leptophilic DM: indirect detection with $e^+/e^-$ (AMS-02)

- Furthermore, via the one-loop scattering diagrams, leptophilic dark matter can be captured in the Sun:
  - limits from IceCube can be competitive with LUX in some parts of the parameter space.
Backup slides
Equilibration of leptophilic Dark Matter in the Sun

- For this plot, we fix the coupling \( f \) to its thermal value \( \Omega_{\text{DM}} h^2 = 0.12 \)
Equilibration of leptophilic Dark Matter in the Sun

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Equilibration of leptophilic Dark Matter in the Sun

- For this plot, we fix the coupling $f$ to its **thermal value** ($\Omega_{\text{DM}} h^2 = 0.12$)

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  $\Leftarrow$ **Equilibrium condition**: $t_\odot / \tau_{\text{eq}} \gg 1$

  $\Leftarrow$ contour lines show constant values of $t_\odot / \tau_{\text{eq}}$

  $\Downarrow$

  *In our simplified model of leptophilic Dark Matter...*

  - **DM is** in equilibrium in the Sun if it is a **Dirac** fermion
  - **DM is not** in equilibrium in the Sun if it is a **Majorana** fermion
Dirac Dark Matter annihilates into $f \bar{f}$ (no helicity suppression)

$\leftrightarrow \textbf{strong neutrino signal}$ for DM coupling to $\tau_R$, or to any left-handed lepton doublet

$\leftrightarrow$ for coupling to $e_R$ or $\mu_R$ neutrinos (only) from weak FSR
IceCube and LUX limits on leptophilic Dirac Dark Matter

- Dirac Dark Matter annihilates into $f\bar{f}$ (no helicity suppression)
  - **strong neutrino signal** for DM coupling to $\tau_R$, or to any left-handed lepton doublet
  - for coupling to $e_R$ or $\mu_R$ neutrinos (only) from weak FSR

Leptophilic Dirac DM coupling to $\tau_R$ or to any left-handed lepton doublet:
For $m_\chi \gtrsim 100$ GeV, IceCube limits can be stronger than LUX

- Black line: Yukawa coupling $f$ leading to $\Omega h^2 = 0.12$

- Remark: Leptophilic Majorana Dark Matter is not in equilibrium in the Sun
  - no meaningful limits from IceCube