The Dominion of Light
Dark Matter

James Dent

René Magritte, L’empire des lumières
The Migdal Effect and Photon Bremsstrahlung in effective field theories of dark matter direct detection and coherent elastic neutrino-nucleus scattering

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ATM

VT
Momentum Exchanged $O(<100\text{MeV})$

\[ q = \sqrt{2m_T E_R} \]

Recoil energy $O(10\text{keV})$

\[ E_R = \frac{\mu^2 \chi T v^2}{m_T} (1 - \cos \theta) \]

Incident energy

\[ E_i = \frac{m_{\chi} v^2}{2} \]

\[ v \sim O(10^{-3}) \]

\[ E_{R,\text{max}} = \frac{2\mu^2 \chi T v^2}{m_T} \]
Direct Detection Review

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For: $m_\chi = 100 \text{ GeV}$ $m_T = 130 \text{ GeV}$, $E_{R,\text{max}} \simeq 50 \text{ keV}$.

For: $m_\chi = 10 \text{ GeV}$ $m_T = 130 \text{ GeV}$, $E_{R,\text{max}} \simeq 1.3 \text{ keV}$. 
Alternative Signals for sub-GeV Probes

Bremsstrahlung

Migdal
Bremsstrahlung in $\chi + N \rightarrow \chi + N + \gamma$ DM scattering has been explored as a means of accessing sub-GeV mass DM.

C. Kouvaris and J. Pradler, PRL 2017, 1607.01789
C. McCabe, PhysRevD (2017) 1702.04730

We want to examine the possibility of brem signals when nuclear recoil energies are below threshold.

Also see the recent paper: A. Millar, G. Raffelt, L. Stodolsky, and E. Vitagliano, 1810.06584 for very low $E_\nu$, with an examination of neutrino mass effects.
Bremsstrahlung in the process $\chi + N \rightarrow \chi + N + \gamma$
Can be used to detect scattering processes that produce nuclear recoils below detector thresholds.

The endpoints of the maximum nuclear recoil energy and emitted photon are key to the extended reach

$\nu_{min} = \frac{m_T E_R + \mu_T \delta}{\mu_T \sqrt{2m_T E_R}}$

For the case of dark matter much lighter than the target nucleus

$m_T \gg m_\chi$

$E_{R,\text{max}} \approx 2 \left( \frac{m_\chi}{\text{GeV}} \right)^2 \left( \frac{\text{GeV}}{m_T} \right) \left( \frac{\nu_{\text{max}}^2}{10^{-6}} \right) \text{keV}$

$\delta_{\text{max}} \approx \frac{1}{2} \left( \frac{m_\chi}{\text{GeV}} \right) \left( \frac{\nu_{\text{max}}^2}{10^{-6}} \right) \text{keV}$
Typically one finds that sub-GeV dark matter creates

\[ E_{R,\text{max}} \approx 2 \left( \frac{m_X}{\text{GeV}} \right)^2 \left( \frac{\text{GeV}}{m_T} \right) \left( \frac{v_{\text{max}}^2}{10^{-6}} \right) \text{ keV} \]

\[ \delta_{\text{max}} \approx \frac{1}{2} \left( \frac{m_X}{\text{GeV}} \right) \left( \frac{v_{\text{max}}^2}{10^{-6}} \right) \text{ keV}, \]

Typically one finds that sub-GeV dark matter creates

\[ \delta_{\text{max}} > E_{R,\text{max}} \]

For example, a 1 GeV particle incident on xenon will produce

\[ E_{R,\text{max}} \lesssim 10^{-1} \text{ keV} \text{ and } \delta_{\text{max}} \sim 3 \text{ keV} \]
The double differential cross-section factorizes into kinematic terms multiplied by the 2-2 elastic differential cross-section

\[
\frac{d^2\sigma}{dE_R d\omega} = \frac{4\alpha Z^2}{3\pi} \frac{E_R}{m_T \omega} \left( \frac{d\sigma}{dE_R} \right)_{(2\to 2)}
\]

C. Kouvaris and J. Pradler, PRL 2017, 1607.01789
The Migdal Effect

Ionization and excitation of electron states from the relative momentum arising when the nucleus is given an impulse.

(above figure adapted from this paper)

Does not suffer from the same suppression as brems.

The double differential cross-section factorizes into the ionization rate multiplied by the 2-2 elastic differential cross-section

$$\frac{d^2 R}{dE_R dv} = \frac{d^2 R_{\chi T}}{dE_R dv} \times |Z_{\text{ion}}|^2$$

The ionization rate is given in terms of the ionization probability

$$|Z_{\text{ion}}|^2 = \frac{1}{2\pi} \sum_{n,\ell} \int dE_e \frac{d}{dE_e} p_{q_e}^c (n\ell \rightarrow (E_e))$$

The differential rate is then

$$\frac{d^3 R}{dE_R dE_{EM} dv} = \frac{d^2 R_0}{dE_R dv} \times \frac{1}{2\pi} \sum_{n,\ell} \frac{d}{dE_e} p_{q_e}^c (n\ell \rightarrow (E_e))$$
Ionization Probabilities have been calculated: Flexible Atomic Code

The Migdal effect has been used to place new bounds on sub-GeV dark matter.

We have examined the Migdal effect and photon brem in the context of the EFT approach, placing new limits on Xe1T.

\[ \mathcal{O}_1 \]

\[ \frac{1}{m_N} \chi \frac{1}{N} \]

\[ \mathcal{O}_4 \]

\[ \frac{1}{m_N} \chi \cdot \bar{S}_N \]

\[ \mathcal{O}_6 \]

\[ \left( \frac{\vec{q}}{m_N} \cdot \bar{S}_X \right) \left( \frac{\vec{q}}{m_N} \cdot \bar{S}_N \right) \]

\[ \mathcal{O}_{10} \]

\[ \frac{1}{\chi} \left( i \frac{\vec{q}}{m_N} \cdot \bar{S}_N \right) \]

We’ve also reassessed the neutrino background in the presence of these effects.
\[ \rho_{\chi, \odot} = 0.3 \text{ GeV} \cdot \text{cm}^{-3} \]

\[ v_{\text{esc}} = 544 \text{ km} \cdot \text{s}^{-1} \]

\[ v_0 = 220 \text{ km} \cdot \text{s}^{-1} \]
Constraints on spin-independent nucleus scattering with sub-GeV WIMP dark matter from the CDEX-1B Experiment at CJPL

939 g Germanium detector at CJPL
737.1 kg·day exposure and 160 eVee threshold
To include the Migdal effect for coherent neutrino-nucleus scattering, we include the ionization rate

$$\frac{d\sigma}{dE_R} = \frac{G_F^2}{4\pi} Q_V^2 m_T \left(1 - \frac{m_T E_R - E_{EM}^2}{2 E_\nu^2}\right) F(q)^2 \times |Z_{FI}|^2$$

The kinematic endpoints are

$$\frac{(E_e + E_{n\ell})^2}{2 m_T} < E_R < \frac{(2 E_\nu - (E_e + E_{n\ell}))^2}{2(m_T + 2 E_\nu)}$$

Including the incident fluxes from solar and atmospheric neutrinos, we have calculated the new rates as a function of detected energy.
There is a small window where the Migdal effect induced signal is comparable in rate to the nuclear recoil signal.
Cosmic ray induced dark matter scattering

C.V. Cappiello, K.C.Y. Ng, and J.F. Beacom PRD 2019, 1810.07705
Bringmann and Pospelov PRL 2019, 1810.10543

JBD, B.Dutta, J.L.Newstead, I.Shoemaker, to appear soon
From Observations near the Earth to the Local Interstellar Spectra
Conference: C16-09-04.3
Bringmann and Pospelov PRL 2019, 1810.10543

\[
\frac{d\Phi_X}{dT_i} = \int \frac{d\Omega}{4\pi} \int_{l.o.s.} d\ell \sigma_{\chi i} \frac{\rho_{\chi}}{m_{\chi}} \frac{d\Phi_i}{dT_i} \equiv \sigma_{\chi i} \frac{\rho_{\chi}^{\text{local}}}{m_{\chi}} \frac{d\Phi_i^{\text{LIS}}}{dT_i} D_{\text{eff}}
\]

\[
\frac{d\Phi_X}{dT_{\chi}} = \int_0^\infty dT_i \frac{d\Phi_i}{dT_i} \frac{1}{T_{\chi}^{\text{max}}(T_i)} \Theta \left[ T_{\chi}^{\text{max}}(T_i) - T_{\chi} \right]
\]

\[m_{\chi} = 1 \text{ MeV}\]

\[m_{\chi} = 10 \text{ GeV}\]
\[ \mathcal{L} \supset g_\chi \phi \bar{\chi} \chi + g_n \phi \bar{n} n \]

\[ m_\phi = 100 \text{ MeV}, \; g = \sqrt{\text{MeV}/m_x} \]

\[ \left( \frac{d\sigma}{dT_\chi} \right)_{\text{scalar,CR}} = g_{s_\chi}^2 g_{s_{\text{CR}}}^2 \frac{(4m_\chi m^2 + 2T_\chi (m_\chi^2 + m^2) + m_\chi T_\chi^2)}{8\pi (2m_\chi T_\chi + m_\phi^2)^2 (T_i^2 + 2mT_i)} \]

JBD, B. Dutta, J.L. Newstead, I. Shoemaker, to appear soon
Energy dependence must be accounted for on the direct detection side as well.
Extension of the constraints for a scalar mediated interaction

JBD, B.Dutta, J.L.Newstead, I.Shoemaker, to appear soon
CRDM Preliminary Results

JBD, B.Dutta, J.L.Newstead, I.Shoeemaker, to appear soon
A tremendous variety of searches are being carried out for sub-GeV mass dark matter.

Utilizing complementary approaches from experiment and theory in astrophysics, cosmology, and particle physics, we expect a continued coverage of unexplored regions of parameter space.
Neutrino Floor
Solar neutrinos

\[ ^8\text{B} \rightarrow ^7\text{Be}^* + e^+ + \nu_e \]

\[ ^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e \]

\[ p + p \rightarrow ^2\text{H} + e^+ + \nu_e \]

\[ p + e^- + p \rightarrow ^2\text{H} + \nu_e \]

electron capture on \(^7\text{Be}\)

neutrinos from the CNO cycle

An irreducible background for direct DM searches

Atmospheric neutrinos

Diffuse SN background
Akimov et al. 1803.09183, Figure by L. Strigari
$S_1 = g_1 L_y E_{EM}$

$S_2 = g_2 Q_y E_{EM}$

$\frac{1}{W} = L_y + Q_y$

Migdal and Brem limits and experimental results
Published in Phys.Rev. D99 (2019) no.8, 082003

33.4 g Ge, 60 eV threshold
939 g Germanium detector at CJPL

1107.5 kg·day exposure and 250 eVee threshold for annual modulation search

**Constraints on spin-independent nucleus scattering with sub-GeV WIMP dark matter from the CDEX-1B Experiment at CJPL**


e-Print: [arXiv:1905.00354][hep-ex]
Published in Phys.Rev. D99 (2019) no.8, 082003
Published in Phys.Rev.Lett. 122 (2019) no.13, 131301

\[ E = W (n_\gamma + n_e) = W \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \]
C. Kouvaris and J. Pradler, PRL 2017, 1607.01789
Matrix element factorization for 2-to-3 into 2-2+ kinematic factors

\[ \frac{\omega}{m_\chi} \ll 1 \]

\[ \bar{u}_N(k') \Gamma N \bar{N}(k) \]

\[ u_N(k) \]

\[ \bar{u}_N(k') \]

\[ u_N(k) \]

\[ \bar{u}_N(k') \]

\[ \bar{u}(k') \Gamma_N u(k) \left( -\frac{k \cdot \epsilon}{k \cdot \omega} + \frac{k' \cdot \epsilon}{k' \cdot \omega} \right) \]

\[ \rightarrow |M|_{2-2}^2 (Ze)^2 \left( \frac{\bar{q} \cdot \bar{\epsilon}}{m_T \omega} \right)^2 \]
Discovery limits as a function of background neutrino events for Argon, Germanium, and Xenon.

A given experiment has a 90% probability to obtain at least a 3σ detection

6 GeV WIMP: Ge 240 kg-yr, Xe 130 kg-year

100 GeV WIMP: Ge 32.5 ton-yr, Xe 21.5 ton-year

The issue is that the spin-independent (and spin-dependent) WIMP-Nucleus scattering is practically indistinguishable from the coherent neutrino-nucleus scattering.
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$v \sim \mathcal{O}(10^{-3})$

$E_{R,\text{max}} = \frac{2\mu_{\chi T}^2 v^2}{m_T}$

\[
\frac{dR}{dE_R} = N_T \frac{\rho_{\chi, \odot}}{m_{\chi} m_T} \int_{v>v_{\text{min}}} \frac{d\sigma}{dE_R} v f(\vec{v}) d^3v
\]