Prospects for Direct Detection of Light Dark Matter in Semiconductors

Chiu-Tien Yu
YITP - Stony Brook

with Rouven Essig, Marivi Fernandez Serra, Jeremy Mardon, Adrián Soto, Tomer Volansky

May 1, 2014 New Perspectives on Dark Matter, Fermilab
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candidates for DM
candidates for DM

WIMPs
theoretically motivated
WIMP miracle
gives detectable signatures
current state of affairs
current state of affairs

\[ E_R = \frac{q^2}{2m_N} \sim \frac{m_N^2 v^2}{m_N} \]
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signal: heat phonons scintillation photons ionization electrons

\[ E_R = \frac{q^2}{2m_N} \sim \frac{m_N^2 v^2}{m_N} \]

\[ m_\chi = 100 \text{ GeV}, \quad E_R \sim 1 \text{ MeV} \]
$m_\chi = 100 \text{ MeV}, \ E_R \sim 1 \text{ eV}
sub-GeV DM is theoretically motivated

Hidden Photon Mediator

Hall et al [0911.1120]  
Essig et al [1108.5383]  
Lin et al [1111.0293]  
Chu et al [1112.0493]

MDM/EDM

Sigurdson et al,  
Banks et al [1007.5515]  
Graham et al [1203.2531]  
Kadota and Silk [1402.7295]
<table>
<thead>
<tr>
<th>Time</th>
<th>Monday Room: 1 West</th>
<th>Tuesday Room: 1 West</th>
<th>Wednesday Room: 1 West</th>
<th>Thursday Room: Curia II</th>
<th>Friday Room: Curia II</th>
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<tbody>
<tr>
<td>9:20-9:30</td>
<td>Workshop opening and welcome</td>
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<tr>
<td>9:30-10:05</td>
<td>Dave McKeen (U.Washington) &quot;Light Dark Matter and Proton Beam Dumps&quot;</td>
<td>Maxim Pospelov (U.Victoria/Perimeter) &quot;Search for New Physics Below 10 MeV with Underground Accelerators&quot;</td>
<td>Lauren Hsu (FNAL) &quot;Low Mass WIMP searches with SuperCDMS&quot;</td>
<td>Claudia Frugiuele (FNAL) &quot;Light dark matter discovery prospects with NuWa and MINOS&quot;</td>
<td>Tien-Tien Yu (Stony Brook) &quot;Prospects for Direct Detection of Light Dark Matter in Semiconductors&quot;</td>
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<td>10:05-10:40</td>
<td>Ranjan Dharmapalan (ANL) &quot;Dark Matter Searches at MiniBooNE&quot;</td>
<td>Surjeet Rajendran (Stanford) &quot;Cosmic Axion Spin Precession Experiment (CASPer)&quot;</td>
<td>Juan Estrada (FNAL) &quot;DAMIC: Direct Search for Low Mass Dark Matter with CCDs&quot;</td>
<td>Jae Yu (U.Texas at Arlington) &quot;Searching for Dark Matter at LBNE&quot;</td>
<td>Jong-Chul Park (U. Kansas) &quot;3.5 keV line observation and its dark matter interpretation&quot;</td>
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<td>10:40-11:20</td>
<td>Coffee</td>
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<td>11:20-11:55</td>
<td>Richard Van de Water (LANL) &quot;Probing the Dark Sector with Liquid Argon TPC Detectors&quot;</td>
<td>Gray Rybka (U.Washington) &quot;New Results and New Perspectives from ADMX&quot;</td>
<td>Juan Collar (U. Chicago) &quot;Parton model and color dipole model for dark matter detection in the DIS regime&quot;</td>
<td>Dave Soper (U. Oregon) &quot;Dark matter annihilations in the Galactic Center&quot;</td>
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<td>12:00-1:30</td>
<td>Lunch</td>
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<td>1:30-2:05</td>
<td>Hooman Davoudiasl (BNL) &quot;Dark Matter from Hidden Forces&quot;</td>
<td>Jeremy Mardon (Stanford) &quot;Ultra-light hidden photon dark matter&quot;</td>
<td>Yuhsin Tsai (U.C. Davis) &quot;Direct Detection with Dark mediators&quot;</td>
<td>Gordan Krnjaic (Perimeter) &quot;Next Generation Beam Dump Experiments to Search for Light Dark Matter&quot;</td>
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<td>2:05-2:40</td>
<td>Matt Graham (SLAC) &quot;Searching for dark photons in electron beams&quot;</td>
<td>Adam Para (FNAL) &quot;Discussion on Directional Dark Matter Detection&quot;</td>
<td>David Curtin (Stony Brook) &quot;Constraining Doubly Dark Portals&quot;</td>
<td>Ze'ev Surujon (Stony Brook) &quot;Strong Constraints on Sub-GeV Dark Matter and Other Light States From E137&quot;</td>
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<td>4:00-5:00</td>
<td>Wick Haxton (U.C. Berkeley) Colloquium &quot;The Nuclear Physics of Direct Dark Matter Detection&quot;</td>
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<td>Maxim Pospelov (U.Victoria/Perimeter) &quot;Wine and Cheese Broadening the Search for New Physics at Intensity Frontier Experiments&quot;</td>
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\[ E_R = \frac{q^2}{2m_e} \sim \frac{m_X^2 v^2}{m_e} \]
signal: a few ionized electrons

\[ E_R = \frac{q^2}{2m_e} \sim \frac{m_x^2 v^2}{m_e} \]

\[ m_x = 100 \text{ MeV}, \quad E_R \sim 50 \text{ eV} \]
electron scattering

XENON10 limits

R. Essig, A. Manalaysay, J. Mardon, P. Sorenson, T. Volansky

![Graph showing the exclusion region for XENON10 data, with limits on the cross-section of Dark Matter (µm²) versus Dark Matter mass (MeV).]
electron energy

- noble gases: ~10 eV
- semiconductors: ~1 eV
current experimental results

What does it take for semiconductors to reach lower DM mass?
recoil energy spectrum

The graph shows the detection rate in events per eV per kg per day as a function of recoil energy $E_R$ in eV. The rate decreases exponentially with increasing $E_R$.
recoil energy spectrum

Q: How low do we need to push the threshold?
experimental efficiencies

Q: How low do we need to push the threshold?
Calculation Ingredients
ingredients

$$\frac{d\langle \sigma v \rangle}{d \ln E_R} = \frac{\overline{\sigma}_e}{8 \mu^2_{\chi e}} \int q \, dq \, |f(k, q)|^2 |F_{DM}(q)|^2 \eta(\nu_{\text{min}})$$

$$\overline{\sigma}_e = \frac{\mu^2_{\chi e}}{16\pi m^2_{\chi} m^2_e} \frac{\overline{\mathcal{M}_{\chi e}(q)}^2}{q^2 = \alpha^2 m^2_e}$$

$$\sigma(q) = \overline{\sigma}_e \times |F_{DM}(q)|^2$$
ingredients

\[
\frac{d\langle \sigma v \rangle}{d \ln E_R} = \frac{\bar{\sigma_e}}{8 \mu^2 \chi e} \int q \, dq |f(k, q)|^2 |F_{DM}(q)|^2 \eta(v_{\text{min}})
\]

\[
\eta(v_{\text{min}}) = \int_{v_{\text{min}}} \frac{d^3 v}{v} f_{MB}(\vec{v})
\]

\[
v_{\text{min}} = \frac{E_B + E_R}{q} + \frac{q}{2m_\chi}
\]
ingredients

\[
\frac{d\langle \sigma v \rangle}{d \ln E_R} = \frac{\overline{\sigma}_e}{8\mu^2} \int q \, dq |f(k, q)|^2 |F_{DM}(q)|^2 \eta(\nu_{min})
\]

\[
|f_{i \rightarrow i'}(\vec{q}, \vec{k})|^2 = \frac{V}{(2\pi)^3} \int_{BZ} d^3 k' \left| \int d^3 x \psi^*_{i', \vec{k}'}(\vec{x}) \psi_{i, \vec{k}}(\vec{x}) e^{i\vec{q} \cdot \vec{x}} \right|^2
\]
ingredients

\[
\frac{d\langle \sigma v \rangle}{d \ln E_R} = \frac{\bar{\sigma}_e}{8\mu^2_{\chi e}} \int q \, dq |f(k, q)|^2 |F_{DM}(q)|^2 \eta(v_{\text{min}})
\]

local DM density

\[
R = N_T \frac{\rho_{\chi}}{m_{\chi}} \int_{E_{R, \text{cut}}} d \ln E_R \frac{d\langle \sigma v \rangle}{d \ln E_R}
\]

number of target nuclei per unit mass

energy threshold
ingredients

\[ \frac{d \langle \sigma v \rangle}{d \ln E_R} = \frac{\sigma_e}{8 \mu^2 \chi_e} \int q \, dq |f(k, q)|^2 |F_{DM}(q)|^2 \eta(\nu_{min}) \]

\[ |f_{i \rightarrow i'}(\vec{q}, \vec{k})|^2 = \frac{V}{(2\pi)^3} \int_{BZ} d^3 k' \left| \int d^3 x \psi^*_{i', \vec{k}'}(\vec{x}) \psi_{i, \vec{k}}(\vec{x}) e^{i \vec{q} \cdot \vec{x}} \right|^2 \]

**solid state physics**

**computationally difficult!**

- analytic
- numerical
analytic approximations

- semi-classical approach
- initial wave functions are spherical
- plane wave final states with altered mass
- no interference
- good for high q
Direct Detection of Sub-GeV Dark Matter

R. Essig, J. Mardon, T. Volansky

assumes zero threshold energy
Direct Detection of Sub-GeV Dark Matter

R. Essig, J. Mardon, T. Volansky

Cross section Sensitivity & Event Rate (per kg\cdot year)

\[ F_{DM}(q) = \alpha^2 m_e^2 / q^2 \]

Event Rate \( \bar{\sigma}_e = 10^{-37} \text{cm}^2 \)

Dark Matter Mass [MeV]
interlude
semiconductors

- Band gap: ~0.67 eV for Ge, ~1.11 eV for Si
semiconductors

- electron wave functions inside a crystal are complicated, but there are methods to approximate them
- we assume a wavefunction of the form:

\[
\psi_{i, \vec{k}}(\vec{x}) = \frac{1}{\sqrt{V}} \sum_{\vec{G}} \psi_i(\vec{k} + \vec{G}) e^{i(\vec{k} + \vec{G})\cdot\vec{x}}
\]

lives in Brillouin Zone

reciprocal lattice vector
ingredients

\[
\frac{d\langle \sigma v \rangle}{d \ln E_R} = \frac{\bar{\sigma}_e}{8\mu^2 \chi_e} \int q \, dq |f(k, q)|^2 |F_{DM}(q)|^2 \eta(\nu_{min})
\]

\[
|f_{i \rightarrow i'}(\vec{q}, \vec{k})|^2 = \frac{V}{(2\pi)^3} \int_{BZ} \, d^3 k' \left| \int \, d^3 x \psi_{i', \vec{k}'}^* (\vec{x}) \psi_{i, \vec{k}} (\vec{x}) e^{i\vec{q} \cdot \vec{x}} \right|^2
\]

probability of exciting an electron from valence band \(i\) to conduction band \(i'\)

solid state physics
probability of exciting an electron from valence band \( i \) to conduction band \( i' \)
ingredients

solid state physics

\[
\frac{\mathrm{d}\langle \sigma v \rangle}{\mathrm{d} \ln E_R} = \frac{\bar{\sigma}_e}{8 \mu^2 \chi e} \int q \, \mathrm{d}q |f(k, q)|^2 |F_{DM}(q)|^2 \eta(v_{\text{min}})
\]

\[
|f_{i \rightarrow i'}(q, k)|^2 = \frac{V}{(2\pi)^3} \int_{\text{BZ}} \mathrm{d}^3 k' \left| \int \mathrm{d}^3 x \psi_{i'}^*(\vec{k'}, \vec{x}) \psi_i(\vec{k}, \vec{x}) e^{i\vec{q} \cdot \vec{x}} \right|^2
\]

\[
|f_{i \rightarrow i'}(q, k)|^2 = \left| \sum_G \psi_{i'}^*(\vec{k} + \vec{G} + \vec{q}) \psi_i(\vec{k} + \vec{G}) \right|^2
\]

mild directional dependence
we ignore for now
• open source code that calculates electronic structure within density functional theory (DFT) using plane waves and pseudopotentials

• use a mesh of 64 k-vectors, 18 bands, and a regular grid of G-vectors

\[
\frac{\left| \vec{k} + \vec{G} \right|^2}{2m_e} < E_c \quad \text{cut-off energy } \sim 40 \text{ Ry}
\]
end of interlude
(very)preliminary results

*analytic approximation
(very) preliminary results

*analytic approximation
conclusions

• sub-GeV dark matter is theoretically motivated

• but this mass range is currently unexplored by direct detection experiments, which rely on nuclear recoil.

• exchanging nuclear recoil for electron recoil is a possible resolution

• The best projections so far are theory predictions for noble gases

• semiconductor experiments have the potential to have a further reach due to the small band gap

• ongoing discussions with CDMS and DAMIC