Direct Detection of Low-Mass Dark Matter

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Dark Interactions: Perspectives from Theory and Experiment
Brookhaven National Laboratory
October 2, 2018
Caveats/Apologies

-for many topics, I am not nearly the expert in this room

-many biases in what I think is important

-not educated enough to give an intelligent talk on ultralight DM

This talk: detection strategies for low-energy particle recoils
the low-mass direct detection game:

**find material excitations that**
- are efficiently produced by recoils
- efficiently propagate to sensors

**find sensors that**
- efficiently detect excitations
- don’t produce false signals
Big picture

exposure is `easy’ in this regime

Reason 1

all rates are interesting
Big picture

exposure is `easy' in this regime

Reason 2

Rate per kg
~ DM number density
~ [DM particle mass]$^{-1}$

exposure ➜ threshold

assuming heavy nuclei… if He say, shifted up and to the left
Big picture

nuclear recoils are increasingly poor at accepting recoil energy

threshold, threshold, threshold, and target mass

mismatch (‘impedance’) in dispersion relation
Big picture

lower momentum-per-energy excitations to the rescue

enable sensitivity to low-mass DM, typically with significant suppression

examples:
atom + photon (brems.)
back-to-back phonons
optical phonons

mismatch (‘impedance’) in dispersion relation
Big picture

**electron targets: two kinematic benefits**

1) lower target mass (of course)
2) not at rest (wide range of initial momentum states)

probability of high-efficiency recoil: highly dependent on electron momentum distribution.
large-area calorimetry: a universal sensor
large-area calorimetry: a universal sensor

The promise:
If we believe naive scaling laws… meV thresholds (on macroscopic absorbers) appear possible. This sensor can observe a wide variety of excitations from a wide variety of target materials.

The challenge:
Do the sensor scaling laws actually hold up, particularly with temperature? What new low-energy material processes will we discover?
large-area calorimetry: a universal sensor

**Thermal**
- technically simpler
  - fewer sensors per area
  - less sensitive to interface variation
- slow timescales (order-ms)
  - less information

**Athermal**
- technically harder
  - more sensors per area
  - more sensitive to interface variation
- faster timescales (order-µs)
  - more information

In both cases: key design goal is to match sensor bandwidth to signal timescales.
large-area calorimetry: a universal sensor

photo gallery of some thermal or quasi-thermal detectors

sensor: TES

sensor: KID

sensor: NTD
large-area calorimetry: a universal sensor

highly athermal design (ala cdms)

3” diameter Si wafer

order-10^3 sensors (in parallel)

2.5% Aluminum surface coverage

Aluminum

Sensor (W TES)
large-area calorimetry: a universal sensor

State of the Field

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Area [cm$^2$]</th>
<th>Baseline Resolution [eV]</th>
<th>Falltime [ms]</th>
<th>Sensor Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>CALDER 1801.08403</td>
<td>4.0</td>
<td>26</td>
<td>0.8</td>
<td>MKID Al/Ti/Al</td>
</tr>
<tr>
<td>CUPID 1704.01758</td>
<td>4.9</td>
<td>7.6</td>
<td>6.4</td>
<td>NTD</td>
</tr>
<tr>
<td>CRESST J. Rothe JLTP 18</td>
<td>12.6</td>
<td>4.1</td>
<td>O(1)</td>
<td>TES W, Tc~10-15mK</td>
</tr>
<tr>
<td>Pyle et al 2018 talk</td>
<td>45.6</td>
<td>3.5</td>
<td>0.06</td>
<td>TES W, Tc~41.5mK</td>
</tr>
</tbody>
</table>

Diagram showing a graph with axes labeled 'resolution [eV]' and 'active area [cm$^2$]'. The graph includes data points for CALDER, CUPID, CRESST, and Pyle et al, with annotations for scaling predictions and references to arXiv:1503.01200 and Pyle et al 2018 talk.
signals, one by one
The primary question is: what is the energy of an electronic signal quantum? The secondary question: what [p,E] states are available, both initial and final?

sensing electron recoils
assuming you can sense electron excitations well…

The primary question is: what is the energy of an electronic signal quantum? The secondary question: what [p,E] states are available, both initial and final?
Sensing single semiconductor e-h pairs: a solved problem!

Two complementary approaches:

Charge sensor

Si

DAMIC
SENSEI

Phonon sensor

Si

SuperCDMS
EDELWEISS

Phonons
(from
Luke-Neganov
production)
sensing electron recoils

Sensing single semiconductor e-h pairs: a solved problem!

two complementary approaches:

- **charge sensor**
  - DAMIC
  - SENSEI

- **phonon sensor**
  - SuperCDMS
  - EDELWEISS

(from Luke-Neganov production)

**Si**

**Si**

4k x 1k: 0.5g

10x10x4 mm: 1g
sensing electron recoils

Sensing single semiconductor e-h pairs: a solved problem!

two complementary approaches:

- **Charge sensor**: DAMIC, SENSEI
  - Si: 0.019 gram-days

- **Phonon sensor**: SuperCDMS, EDELWEISS
  - Si: 0.49 gram-days

(from Luke-Neganov production)
Sensing electron recoils

Sensing single semiconductor e-h pairs: a solved problem!

two complementary approaches:

charge sensor

phonon sensor

Si

Si

DAMIC
SENSEI

SuperCDMS
EDELWEISS

CDMS-HV
0.49 gram-days

SENSEI
0.019 gram-days

$F_{DM}(q) = 1$

$m_\chi [\text{MeV}]$

$10^{-38}$

$10^{-37}$

$10^{-36}$

$10^{-35}$

$10^{-34}$

$10^{-33}$

$10^{-32}$

$10^{-31}$

$10^{-30}$

$10^{-29}$

$10^{-28}$

$10^{-27}$

$10^{-26}$

$F_{DM}=1$
sensing electron recoils

doing the same thing via photons.... why bother?
  -easier to scale mass to kg or even ton-scale
  -No need to apply potential energies to the target (potential for even lower dark counts)

photonsensorgoals:
  photon-counting
  4pi coverage
  efficiency ~1
  dark count ~0

(cr)~1

scintillatore

crystalgoals:
  low band-gap (CsI: 6eV, GaAs: 1.5eV)
  photon energy just under that (GaAs: 1.3eV)
  high quantum efficiency (GaAs: 60%)
  low dark counts (GaAs: so far so good)

irradiation while cold, warming relaxes metastable states
sensing electron recoils

What electron excitations are available below the eV scale?

1-100 meV gap energies for 1-100 keV dark matter: a couple of the several ideas

<table>
<thead>
<tr>
<th>superconductors</th>
<th>1512.04533</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al: 0.6meV gap</td>
<td></td>
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<tr>
<td>calorimetric readout</td>
<td></td>
</tr>
<tr>
<td>(either of quasiparticles directly, or of phonons from qp decay)</td>
<td></td>
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<tr>
<td>alternative: qp-counting via qubit</td>
<td></td>
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<tr>
<td>requires significant R&amp;D</td>
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<table>
<thead>
<tr>
<th>semi-metals (meV-gap semiconductors)</th>
<th>1708.08929</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZrTe5: few-meV gap, tunable by doping</td>
<td></td>
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<tr>
<td>readout unclear, most promising idea is a FET-like resistance change</td>
<td></td>
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</tbody>
</table>

elephant in the room: what does the dark count do for meV-scale excitations?
sensing nuclear recoils

1) typically, less energy than electron recoil case (unless taking advantage of low-momentum-per-E states)

2) typically, low or no energy in the electronic signal quanta (plus side: no need to argue about ‘quenching’ anymore…)

![Diagram showing excitation production efficiency vs. recoil energy]

- ~1
- excitation production efficiency
- eV keV
- recoil energy

nuclear recoil case
- kinetic motion (phonons)
- electronic excitations (of all types)
sensing nuclear recoils

Generic two-pillar strategy:

1: use excitations of low momentum-per-E
   (low-mass nucleus or low-momentum phonon states)

2: push calorimetry threshold as low as possible
   (pull energy into calorimeter, match sensor and signal timescales, push Tc down, shrink all heat capacities)
sensing nuclear recoils

crystal target

1: use excitations of low momentum-per-E

(low-mass nucleus or low-momentum phonon states)

2: push calorimetry threshold as low as possible

(pull energy into calorimeter, match sensor and signal timescales, push Tc down, shrink all heat capacities)

`shovel ready’ from M. Pyle:

\[ \sigma_E^2 \sim N_{\text{sensor}} C_1 T^2 \]

\~2g
\~200 meV sigma
sensing nuclear recoils
superfluid 4He target mass

Two-pillar strategy:

1: use excitations of low momentum-per-E

(low-mass nucleus or low-momentum phonon states)

2: push calorimetry threshold as low as possible

plus some other good ideas if you can:

3: distinguishable ‘flavors’ of meV-scale excitations

phonons, R-, R+

(differ in velocity and transmission)

4: amplification of signal before reaching calorimeter

phonon

-> free atom (quantum evaporation)

-> electrostatic attraction (gain: x10-40)
summary points

keV-MeV mass range
meV-to-eV threshold requirements
gram (or even smaller) target masses can be world-leading useful
diverse ideas, very fun for an experimentalist

electron recoils
can benefit from electron momentum in bound-state
counting semiconductor e-h pairs: now ready to scale up
counting photons: R&D done, now ready for first exposure
meV-scale excitations: some good ideas, time to be doing this R&D

nuclear recoils
can benefit from optical phonon modes and other low-momentum states
great progress on calorimeter threshold in recent years
continuity with existing NR approaches, plus new phonon modes