The SuperCDMS SNOLAB Experiment
Mining Dark Matter in Northern Canada

16th Marcel Grossman Meeting

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Outline

• Fundamental Principles of Dark Matter Detection:
  How dark matter interacts

• Dark Matter Detection Techniques:
  The principles behind the SuperCDMS approach
  The road to low mass / energy resolution

• The SuperCDMS Experiment in Action:
  • Current results
  • Future Plans
Detection Principles

How dark matter interacts with material
Dark Matter Interactions & Detector Physics

- Interactions fall into three categories, with differing energy scales
  - **Nuclear recoils** - particle interacts with the nucleus
    - Traditional “WIMP” Dark matter signal
    - Neutron and neutrino backgrounds
  - **Electron recoils** - particle interacts with atomic electrons
    - Electron recoil, Dark Photon and Axion signals
    - Most background sources
  - **Excitation recoils** - particle interacts with background excitations in target material
    - i.e. Phonons, Cooper pairs, …

- Detector response often is different for the three categories. Can be used to reject some backgrounds
- Energy scale of the interaction dictates detection approach
- Backgrounds and detection techniques drive science reach
Dark Matter Interaction

- Heavy DM
  - Nuclear Scattering
    - Recoil energies $\gg$ atomic energies
    - Simple elastic collisions
    - Nucleus mass determines DM mass sensitivity
    - Long exposure time, limited by detector mass

- Mid-weight DM
  - Nuclear Scattering & Electron Scattering
    - Recoil energies $\sim$ atomic energies
    - Inelastic collisions dominated by orbital mechanics
    - Mass reach determined by band gap
      Short exposure time, limited by background

- Light DM
  - Absorption
    - Recoil energies $\sim$ atomic energies
    - Inelastic collisions dominated by orbital mechanics
    - Mass reach determined by band gap
      Short exposure time, limited by background
The SuperCDMS Detectors

What happens when DM interacts with a detector?
**SuperCDMS/EDELWEISS Detector Technology**

**Discriminating iZIP Detector:**
- Prompt phonon and ionization signals allow for discrimination between nuclear and electron recoil events.

**Low Threshold HV Detector:**
- Drifting electrons/holes across a potential ($V_b$) generates a large number of phonons (Luke phonons).
- Enables very low thresholds!
- Trade-off: No event-by-event NR/ER discrimination.

Mathematically:

$$E_t = E_r + N_{eh} eV_b$$

Where:
- $E_t$ is the total phonon energy.
- $E_r$ is the primary recoil energy.
- $N_{eh}$ is the number of electron-hole pairs.
- $e$ is the electronic charge.
- $V_b$ is the bias voltage.

**Sensors measure $E_t$, and $n_{eh}$**

**Sensors measure $E_t$**
SuperCDMS Detectors: Posing for the Cameras

- Detectors made of high-purity Ge and Si Crystals
  - Si (0.6 kg) provides sensitivity to lower dark matter masses, Ge (1.5 kg) provides sensitivity to lower dark matter cross-sections
- Low operation temperature: ~15mK
  - Athermal phonon measurement with TESs
  - Ionization measurement (iZIP) with HEMTs
- Multiple channels per detector to identify event position
- Initial payload will consist of 4 towers
  - 6 detectors each
  - 2 iZIP: 10 Ge / 2 Si
  - 2 HV: 4 Ge / 4 Si
Comparison of Low Threshold vs Discrimination Modes

**HV → Low Threshold**
- Ultra high resolution indirect charge measurement
- Thresholds 75 eVee and 56 eVee
- No yield or detector face discrimination

**iZIPS → Low Background**
- High resolution phonon and charge readout
- All surface and ER backgrounds above few keV removed (red dots)

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**PRL 116, 071301, 2016**

**APL 103, 164105 (2013)**
Inelastic Nuclear Recoils: Migdal and Bremsstrahlung Effect

- Given a dark matter elastic scatter with nucleus:
  - Induces “instantaneous” change in momentum of nucleus wrt orbital electrons
  - Results in a kinematic boost of the electrons.
  - Leads to Bremsstrahlung emission and
  - Ionization and/or excitation of the atom (Migdal effect)

\( m_\chi = 1 \text{ GeV/c}^2 \)
\( \sigma_{SI}^{\chi N} = 10^{-36} \text{ cm}^2 \)
\( E_{\text{th}} = 160 \text{ eVee} \)

Counts (evts/keV/kg/day)

- Migdal effect
- Bremsstrahlung
- NR

- \( n=2 \)
- \( n=3 \)
- \( n=4 \)

Small-, Mini-, Micro-, HVeV Detectors

- SuperCDMS has also developed gram scale R&D detectors
  - Single electron-hole pair resolution devices will have sensitivity to a variety of sub-GeV DM models with gram*day exposures
  - Largest “quantum resolution” detectors available
  - Powerful tool for low-energy rare event searches

- 0.93 g Si crystal (1x1x0.4 cm$^3$) operated at 33-36 mK at a surface test facility.

- Exposure: 0.49 gram-days (16.1 hours)
  - energy resolution: $\sigma_{\text{ph}} \sim 1.4$ eV   \hspace{2cm} $\sigma_{\text{ph}} \sim 3$ eV
  - charge resolution: $\sigma_{\text{eh}} \sim 0.1$ e-h$^+$   \hspace{2cm} $\sigma_{\text{eh}} \sim 0.06$ e-h$^+$
  - operation voltage: 140 V   \hspace{2cm} $V_{\text{bias}} \sim 50$ V

arXiv: 1710.09335  
arXiv: 1804.10697  
arXiv: 1903.06517
SuperCDMS Detectors & Dark Matter Mass Scales

- Dark Matter Mass Ranges
  - "Traditional" Nuclear Recoil: Full discrimination, \( \gtrsim 5 \text{ GeV} \)
  - Low Threshold NR: Limited discrimination, \( \gtrsim 1 \text{ GeV} \)
  - CDMSlite: HV, no discrimination, \( \sim 0.3 - 10 \text{ GeV} \)
  - Migdal & Bremsstrahlung: no discrimination, \( \sim 0.01 - 10 \text{ GeV} \)
  - Electron recoil: HV, no discrimination, \( \sim 0.5 \text{ MeV} - 10 \text{ GeV} \)
  - Absorption (Dark Photons, ALPs): HV, no discrimination, \( \sim 1 \text{ eV} - 500 \text{ keV} \) ("peak search")
SNOLAB

- 2 km underground (6000 m water equiv.)
- Cleanroom (class 2000 or better)
- Large lab (~5,000 m²)
- Cosmic radiation: muon rate reduced by ~$10^6$
- Surface facilities, support staff (>100)
SuperCDMS @ SNOLAB

- Low-radon clean-room

- Collaborating with:
  - Cryogenic Underground TEST facility (CUTE)
  - Rapid-turn around detector testing
  - First data from SuperCDMS SNOLAB towers.
The SuperCDMS SNOLAB Experiment

Electron Recoil Backgrounds:
- External and facility: $O(0.1 \text{ /keV/kg/d})$
- Det. setup: $O(0.1(\text{Ge})-1(\text{Si}) \text{ /keV/kg/d})$
- Total: $O(0.1-1 \text{ /keV/kg/d})$

Solar $\nu$-dominated NR background

Vibration isolation:
- Seismic: spring loaded platform
- Cryo coolers: soft couplings (braids, bellows)
- Copper cans: hanging on Kevlar ropes

Facility:
- 6800 m.w.e. overburden
- 15 mK base temperature
- Initial Payload: ~30 kg total
  4 towers (2 iZIP, 2 HV)
Dark Matter Search Results

... and future reach
Low Mass: Dark Photon Searches

\[ R = V_{\text{dir}} \frac{\rho_{\text{DM}}}{m_V} \varepsilon_{\text{eff}}^2 (m_V, \tilde{\sigma}) \sigma_1 (M_V) \]

Kinetic Mixing Angle \( \varepsilon \)

Dark Photon Mass [keV/c^2]
Mid Mass: Electron Recoil Dark Matter Searches

\[
\frac{dR}{d(\ln E_R)} = V_{\text{det}} \frac{\rho_{\text{DM}}}{m_V} \frac{\rho_{\text{Si}}}{2m_{\text{Si}}} \overline{\sigma}_{\text{ER}} \frac{m_e^2}{\mu_{\text{DM}}^2} I_{\text{Crystal}}(E_e; F_{\text{DM}})
\]

Rapidly Growing Catalog of Limits and Projections

- Central repository for cataloging data & references, and plotting dark matter limits
  - Includes limits from several “Dark Matter” channels, i.e. **Nuclear recoil**, **Electron recoil**, **Dark Photon** and **Axion** interactions
  - Downloadable, runs locally*
    - https://supercdms.slac.stanford.edu/dark-matter-limit-plotter
  - Submissions welcome from all experiments
    - https://ufl.qualtrics.com/jfe/form/SV_9KVMNJhVg0cPb

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*you can even run it on your iPad if you are so inclined, but I don’t recommend it

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but what about adding accelerator limits?

or will that bring the plotter to its knees!!
Conclusion

... the end
Conclusions

• SuperCDMS detectors aiming to reach “neutrino floor” in 1-10 GeV NR mass range

• Technology being adapted in smaller detectors to search for light dark matter, down to
  • $\mathcal{O}(10)$ MeV via inelastic Nuclear recoil channels (Migdal, Bremsstrahlung)
  • $\mathcal{O}(1)$ MeV via Electron recoil channels and
  • $\mathcal{O}(1)$ eV via Dark Photon Absorption channels
    • With sensitivity to Axion dark matter in the same range

• SuperCDMS designed a powerful complex cryogenic system that is being installed at SNOLAB
  • CUTE is operational – deepest dilution fridge in the world
    • Plans for early science reach with CUTE facility
  • SuperCDMS Detector installation – next spring/summer
    • Initial run – late 2022

• SuperCDMS is particularly competitive at low masses, including electronic interactions.

• Stay tuned! Experiments are producing results at a fast pace, more sensitive experiments are soon to come online.
Dark Matter Searches: Executive Summary

First, it was thought neutrinos can't be detected, …

And then they were (1930—1956)

But then many said Gravitational Waves will never be detected, …. 

Until they were, in plenty, (1893—2015)

So, now they all ask, … when the h@#% are you going to finally see this dark matter stuff, …. 

…. soon, I hope?!

Dark Matter Searches, 90 years and counting!

At least the size of potential DM parameters space isn’t expanding exponentially!