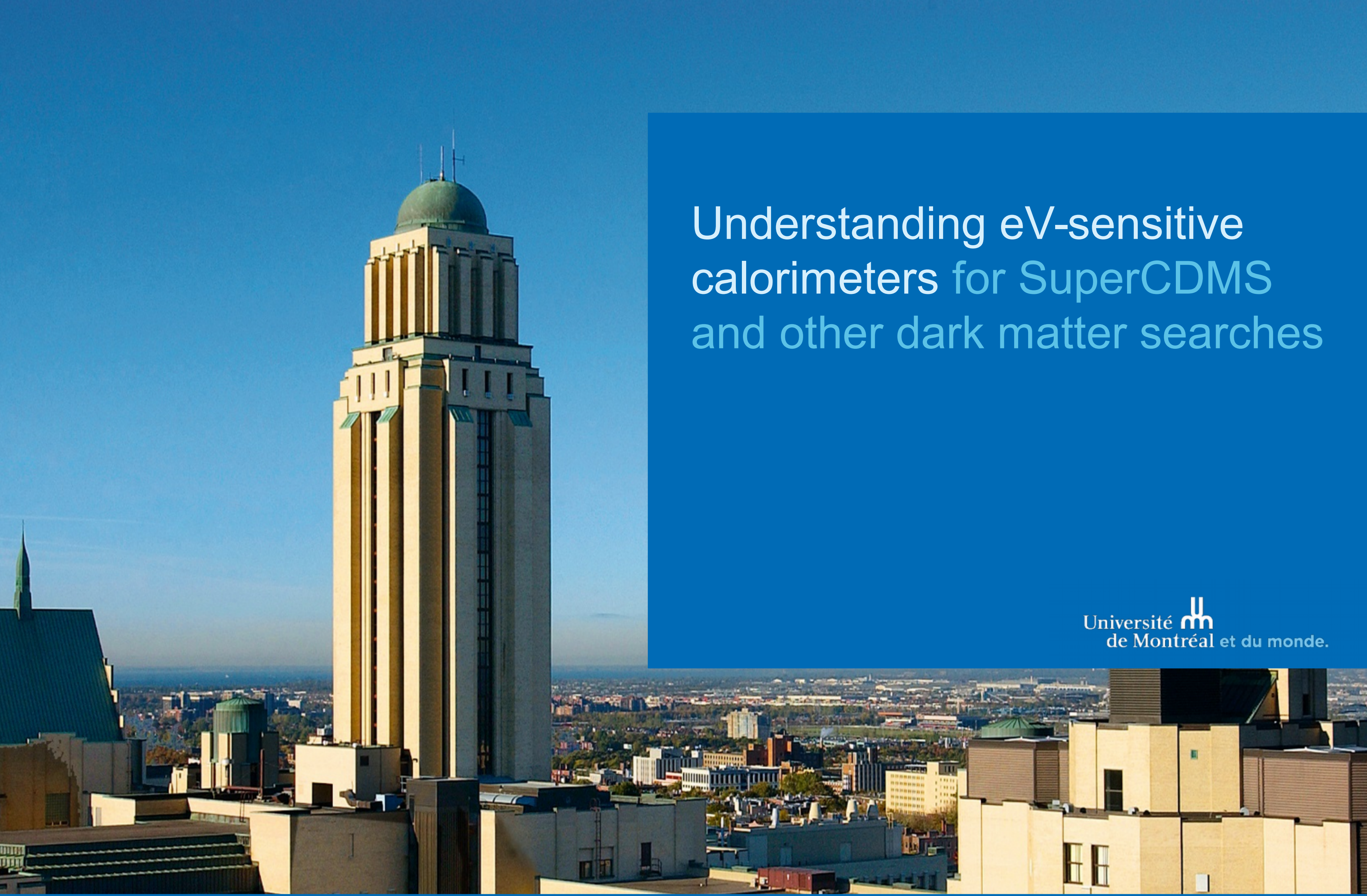


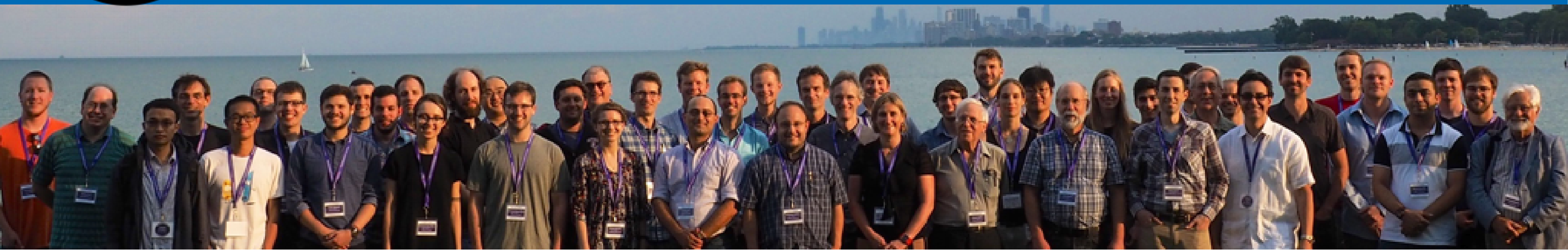
Understanding eV-sensitive calorimeters for SuperCDMS and other dark matter searches

Université de Montréal et du monde.

Alan Robinson
for the SuperCDMS collaboration

14 June 2018

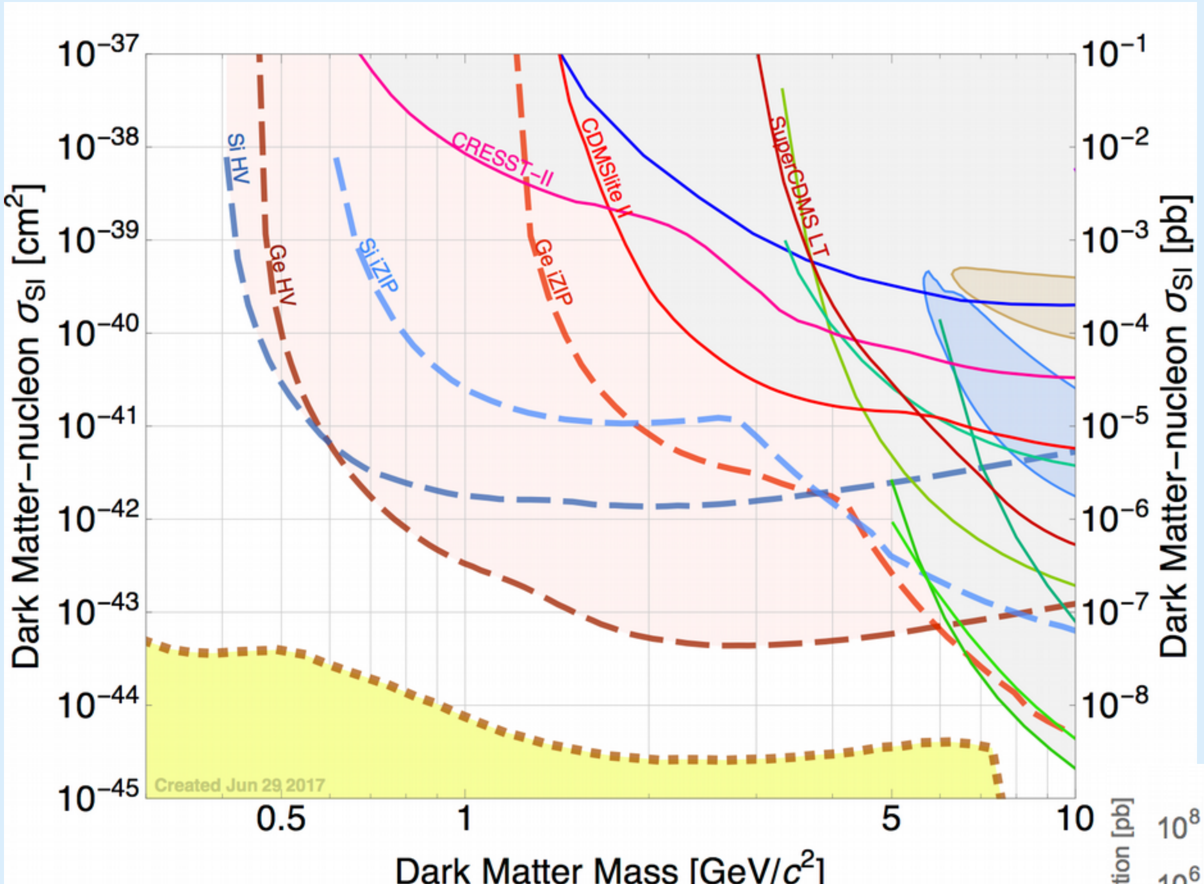
Collaboration



- California Inst. of Tech.
- CNRS-LPN*
- Durham University
- FNAL
- NISER
- NIST*
- Northwestern
- PNNL
- Queen's University
- Santa Clara University
- SLAC
- South Dakota SM&T
- SMU
- SNOLAB
- Stanford University
- Texas A&M University
- TRIUMF
- U. British Columbia
- U. California, Berkeley
- U. Colorado Denver
- U. Evansville
- U. Florida
- U. Montréal
- U. Minnesota
- U. South Dakota
- U. Toronto

* Associate members

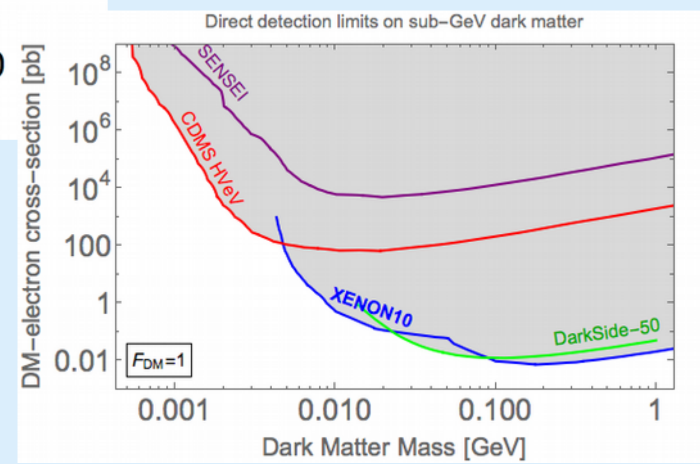
SuperCDMS SNOLAB projected dark matter-nucleon recoil sensitivity



eV sensitive calorimeters can discover dark matter

Via detection of either nuclear recoils or electron recoils

Recent limits on dark matter-electron recoils



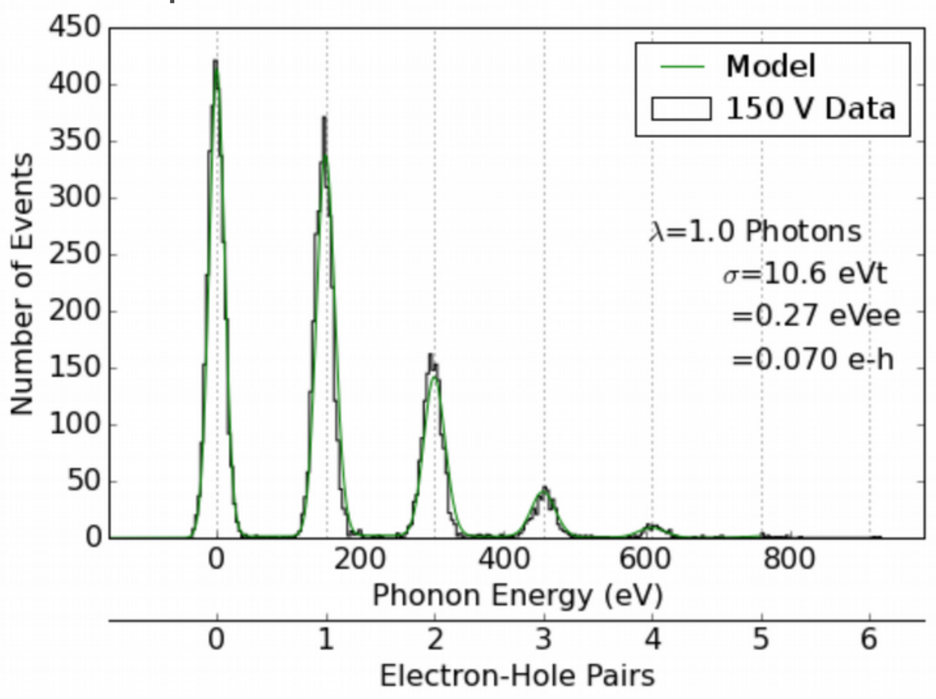
Combined plot from Résonances blog 2018-05-07
SuperCDMS arXiv 1804.10697
SENSEI arXiv 1804.00088

See also "Cosmic Visions Community Report" arXiv:1707.04591

Experiments have eV sensitivity **today**

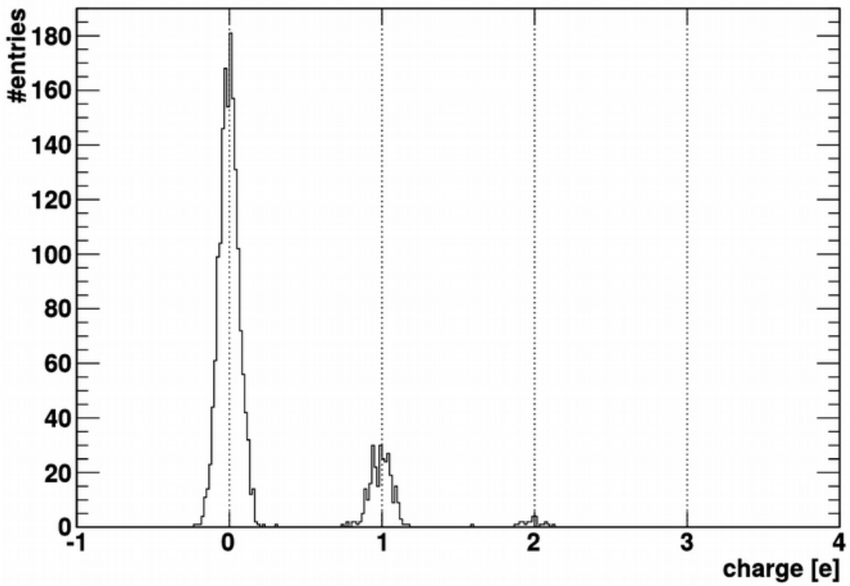
Using cryogenic phonon detectors (SuperCDMS) or CCDs (SENSEI)

SuperCDMS HVeV arXiv:1804.10697



SENSEI

J. Tiffenberg, 2016 Berkeley Workshop on Dark Matter



Calibration at eV energies

How do measured ionization and phonons map onto the properties of a collision with **nuclei** or **electrons**?

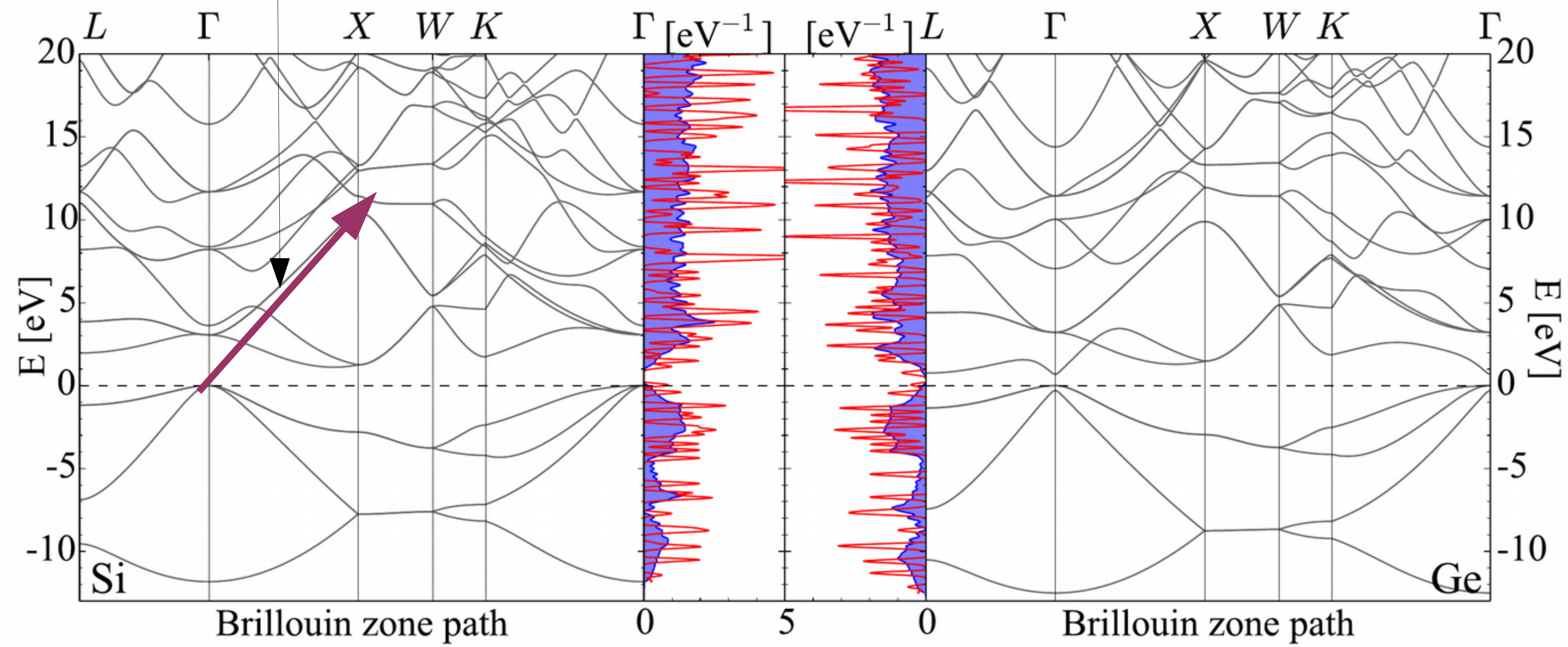
- Ionization yield → ionization probability distribution
- Detector specific effects (e.g. local saturation)
- Other energy loss mechanisms (e.g. crystal damage)

A variety of techniques providing detailed information is required to calibrate detector response.

What we already know - electrons

- High quality band theory calculations backed by experimental data
  - Still need to work on understanding Compton scattering from MeV photons: high-momentum transfer to higher conduction band.

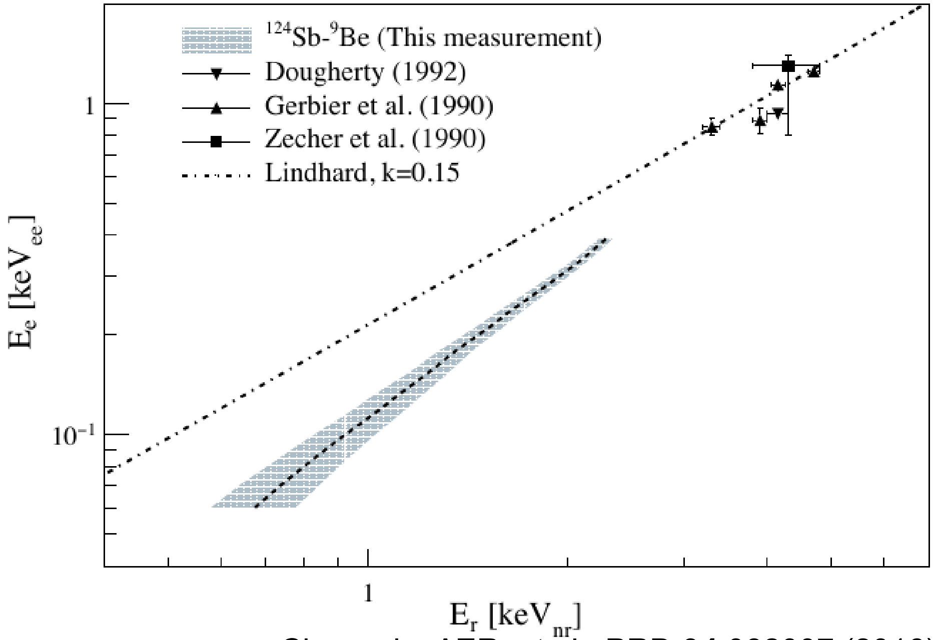
Essig et al. JHEP **2016** 46



What we already know - nuclei

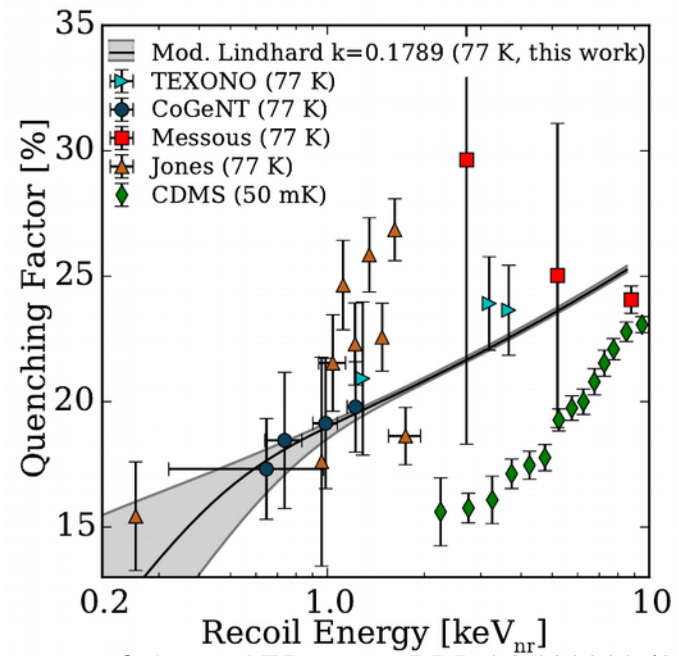
- Lindhard theory
  - Semi-classical theory with empirical inputs:
    no data below 200 eV & cannot trust a low-energy extrapolation
  - Discrepancy between Si and Ge results

Ionization in Si



Chavarria, AER, et al., PRD **94** 082007 (2016)

Ionization in Ge



Scholtz, AER, et al., PRD **94** 122003 (2016)

What we already know

- We are at the intersection of particle and solid-state physics

Solid state physics	Particle physics
E < 30 eV	E > keV
Multi-body system	Free particles
Allowed energies/momenta given by dispersion relation	$E = p^2/2m$
Particles may have effective masses	Particle masses well defined

Nuclear recoils at eV energies

Challenge: Penetrating sources for calibration are generally at high energy

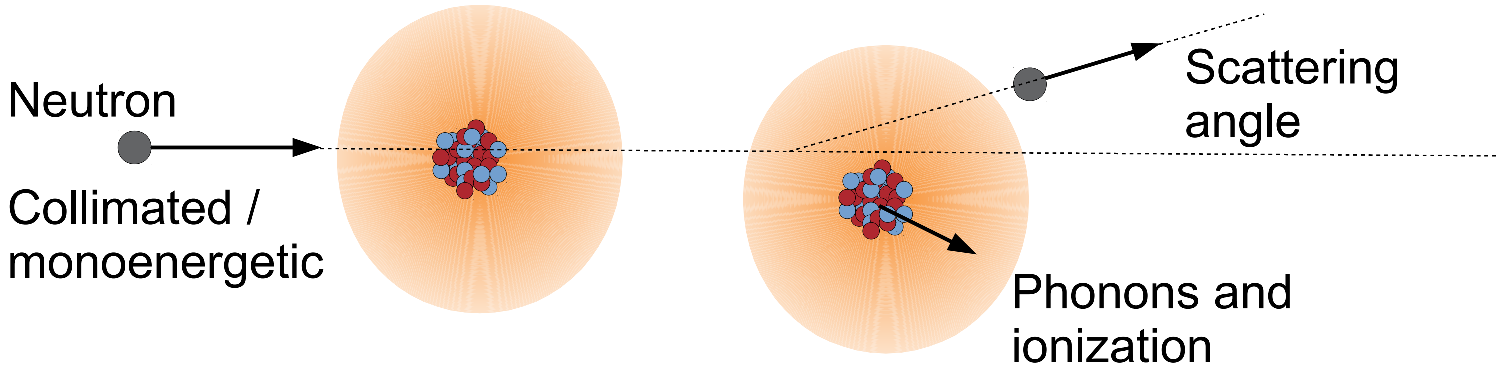
Techniques

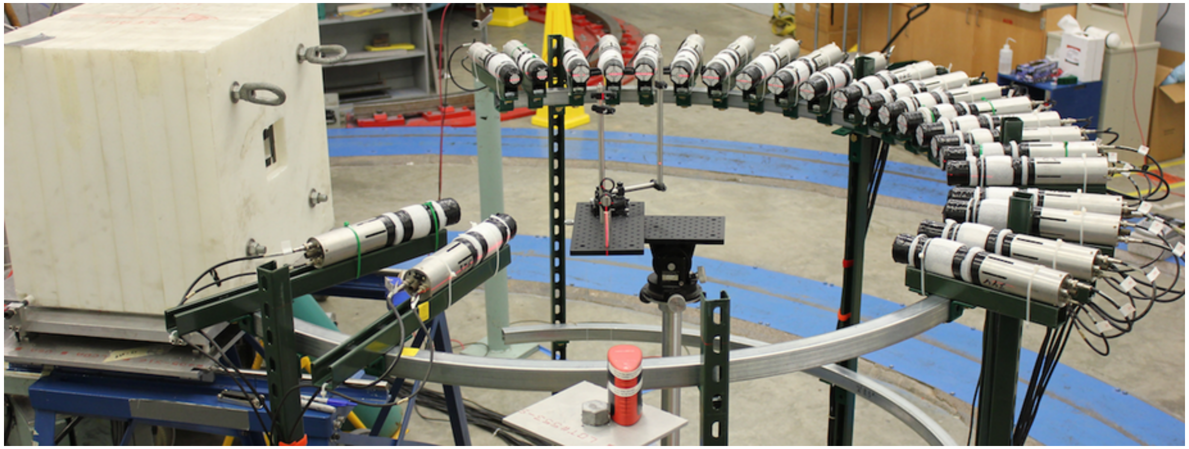
- Fast (keV) neutron scattering
- Recoils from photon emission after thermal neutron capture
- Nuclear Thomson scattering of gamma rays

Fast neutron scattering

Small angle scattering with backing detectors

- At TUNL (collaboration w/ P. Barbeau) using ~ 30 to 500 keV neutrons
  - Precision measurement of intrinsic properties of Si, Ge





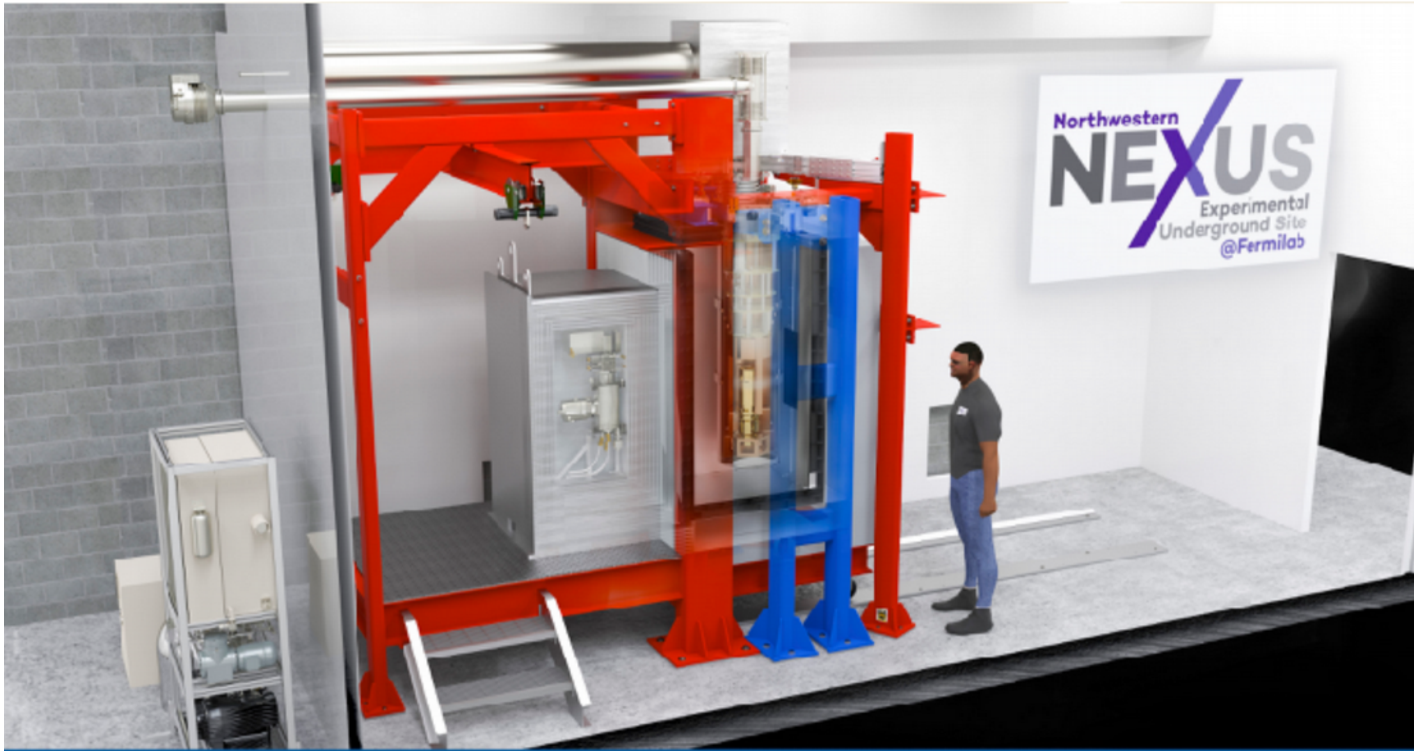
Measurement of NaI quenching

P. Barbeau
TUNL

Fast neutron scattering

Small angle scattering with backing detectors

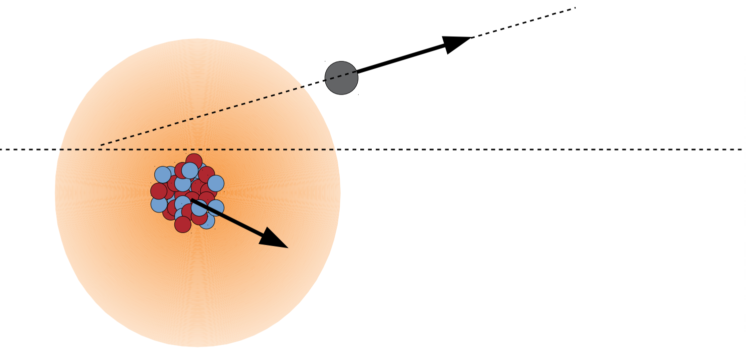
- At Fermilab in a low-background facility using 2.5 MeV neutrons
    - Using full size dark matter search detectors



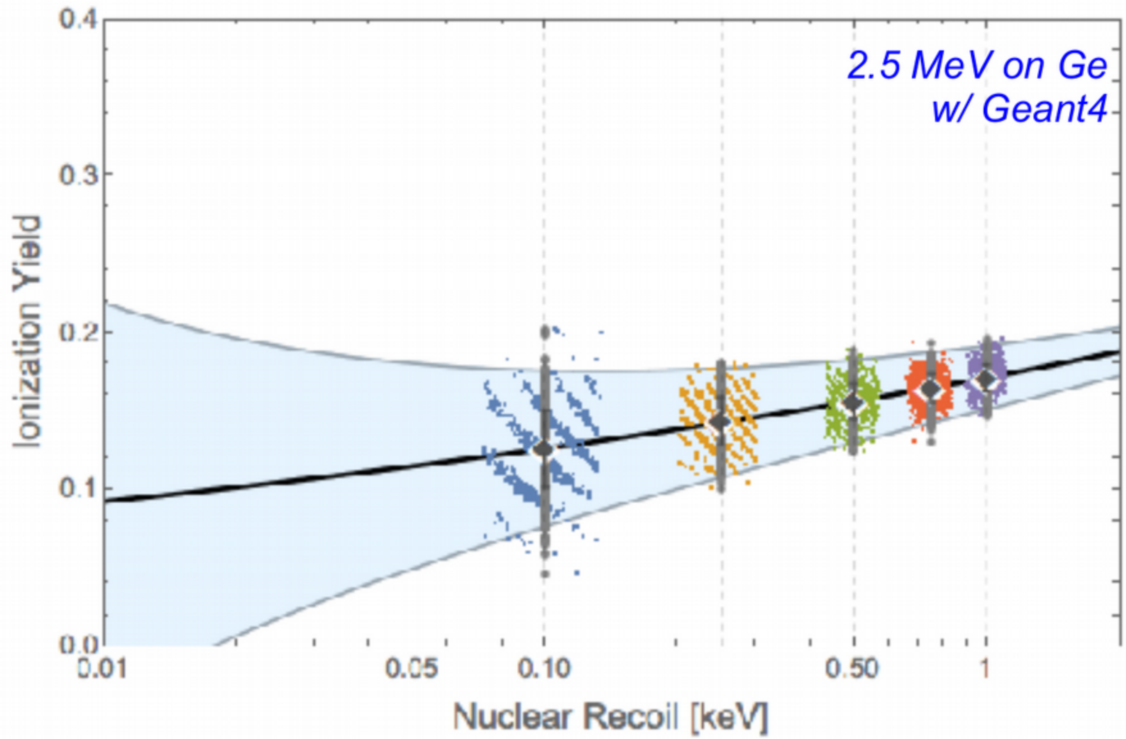
Fast neutron scattering

Small angle scattering with backing detectors to get better than 10% level calibration at or below 100 eV

- Challenges: Coincident backgrounds, multiple neutron scattering, optimizing detector performance with new devices.



Simulated signal from neutron scattering at Fermilab



Fast neutron scattering

Recoil spectrum endpoint measurement

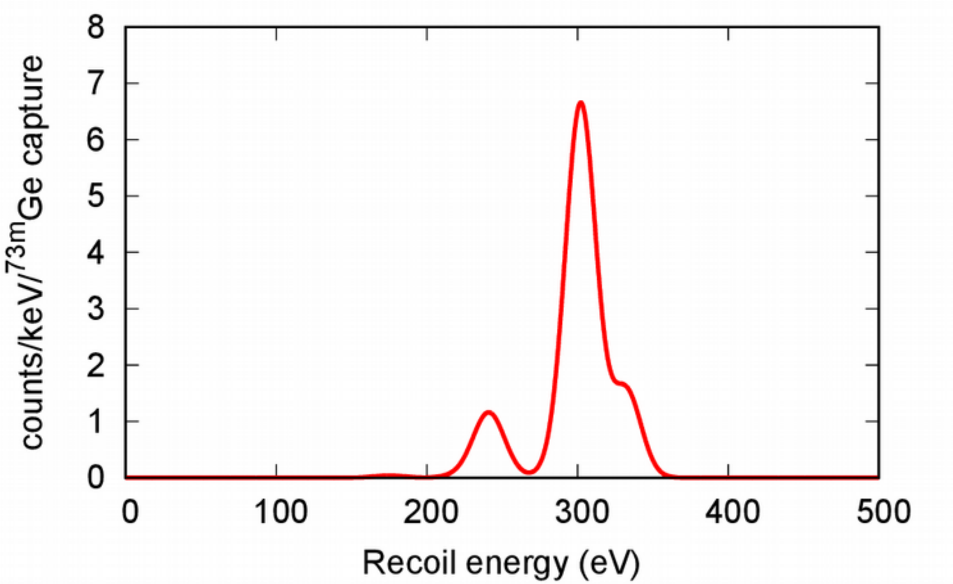
- Using 4.8 keV (960 km/s) neutrons at the University of Montréal
  - 640 eV max in Si, 270 eV max in Ge.
  - Check for velocity dependence of ionization yield.
    (Velocity of dark matter < 544 km/s.)

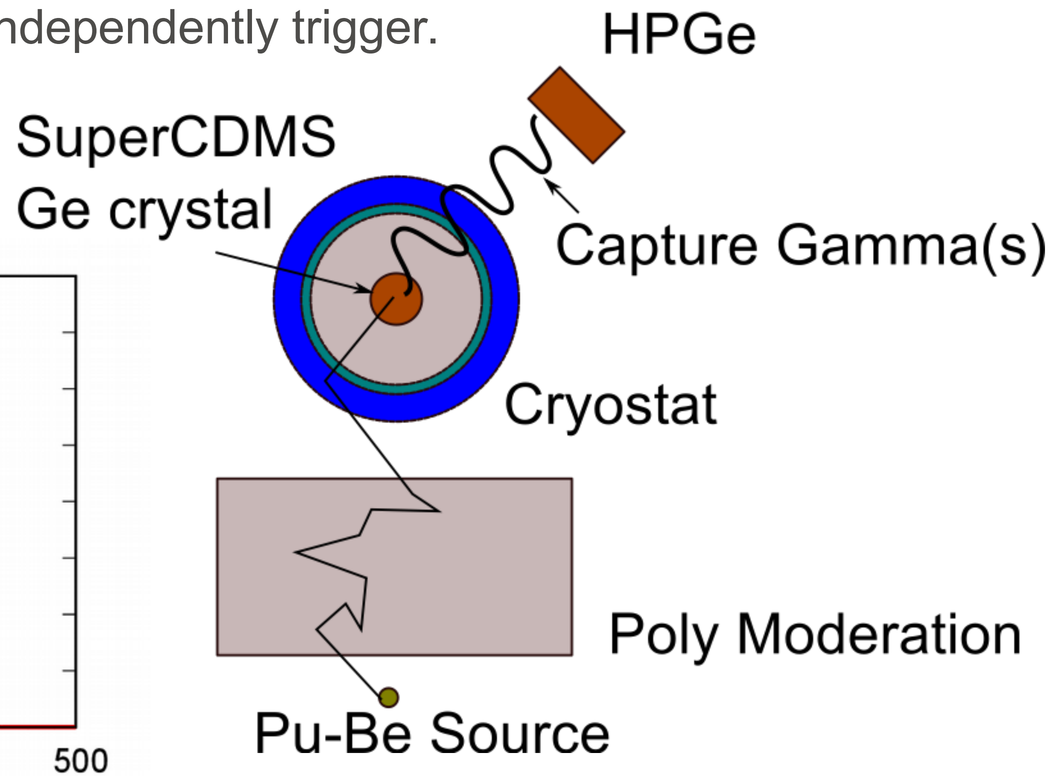
Photon emission from neutron capture

Recoils of ~200 to 2000 eV from line emission of high-energy photons

- *in situ* calibration
- Gamma coincidence used to independently trigger.

Expected spectrum in coincidence with ^{73m}Ge decay

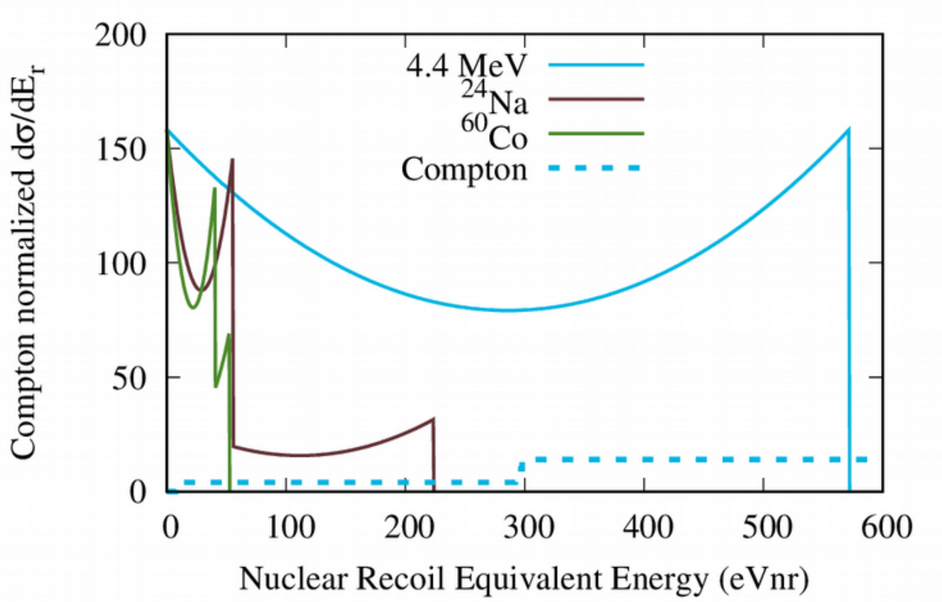




Nuclear Thomson scattering

Recoils of 0 to 1500 eV in Si (600 eV in Ge) from rare scattering of high energy photons

- Planned at Montreal using γ-rays from short-lived radioisotopes and in-beam coulomb excitation.
- These recoils have never directly observed; may be an important background mechanism in eV dark matter searches.



Thomson scattering spectrum in Ge (assuming 10% ionization yield)

Timelines

This year

- 1g-scale detector calibration at Montreal and TUNL.

Next year

- Fast neutron scattering and thermal neutron capture calibrations at Fermilab with kg-scale detectors.
- Follow up measurements at Montreal and TUNL

2020 and following

- Planning underway for *in situ* calibrations at SNOLAB using thermal neutron capture.
- Planning (at Montreal) to investigate nuclear recoils in CCDs using photon scattering techniques.

Outcomes

Model the ionization and phonons measured from electron and nuclear recoils at eV energies for dark matter searches.

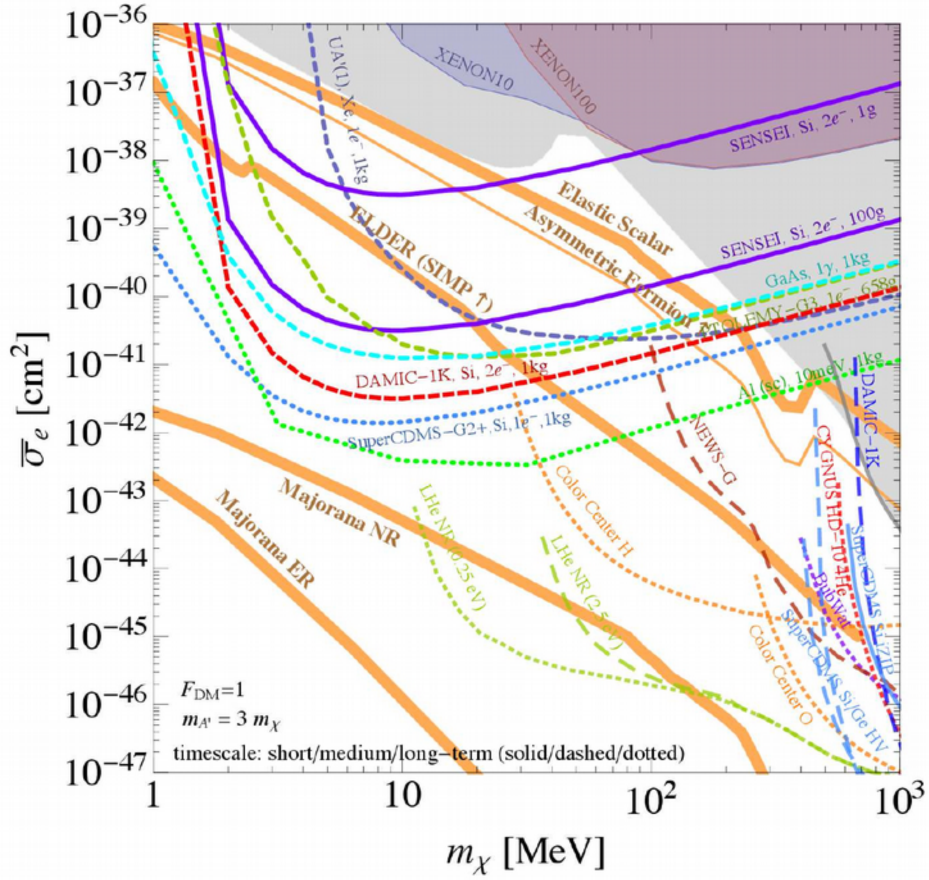
In the future

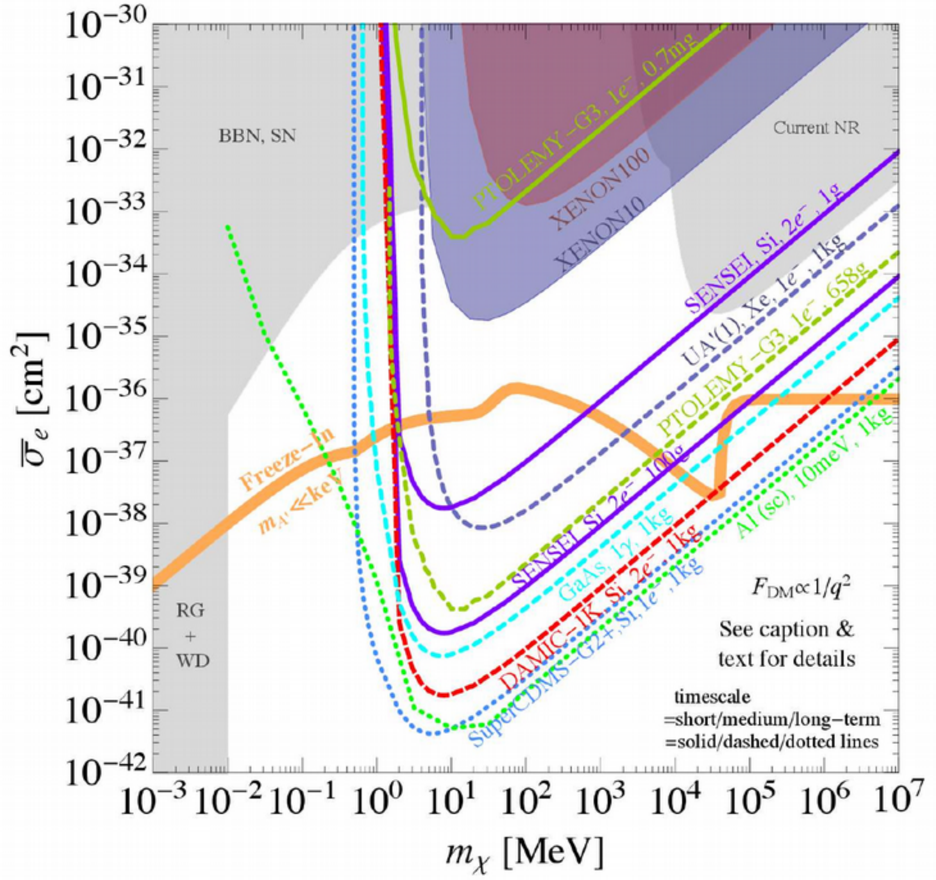
- Replace Lindhard theory with more predictive models
- Investigate detector directionality
- Exploit high-momentum transfer excitations for condensed matter measurements in a variety of materials.

Extra slides

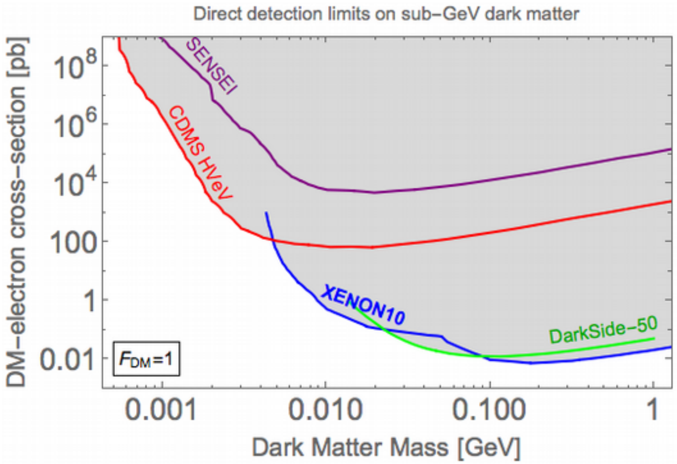
DM-electron scattering motivation

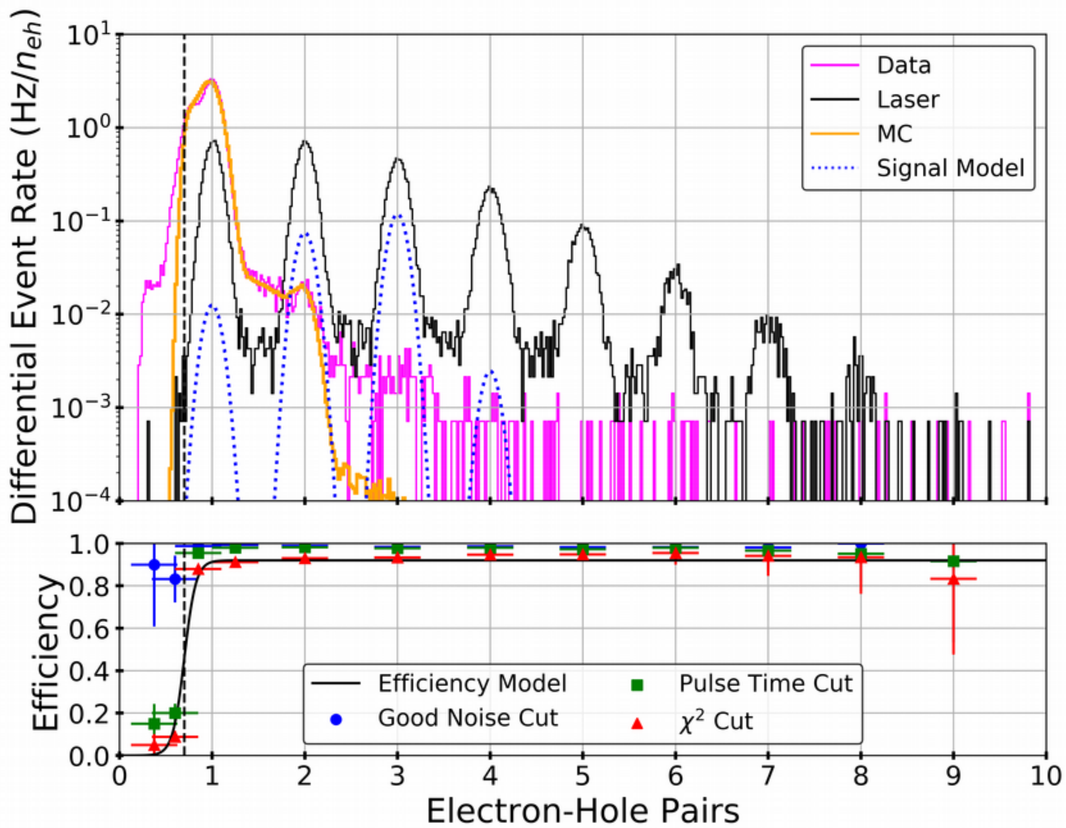
- Dark matter-electron scattering can target specific well-motivated models.



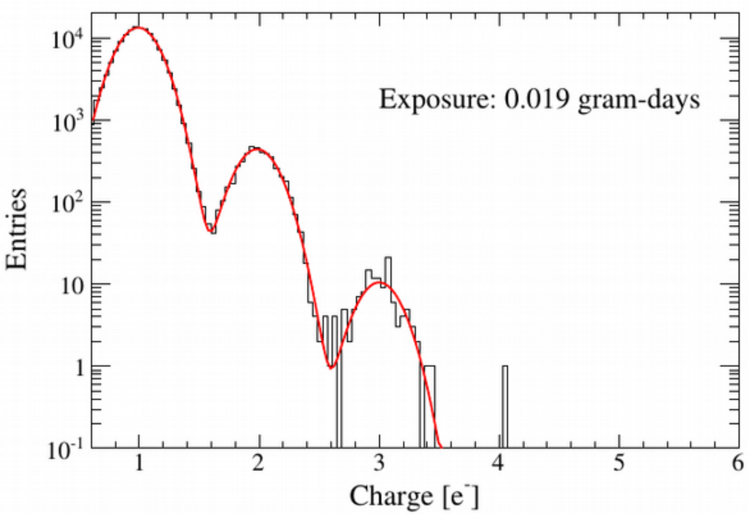


DM-electron scattering limits





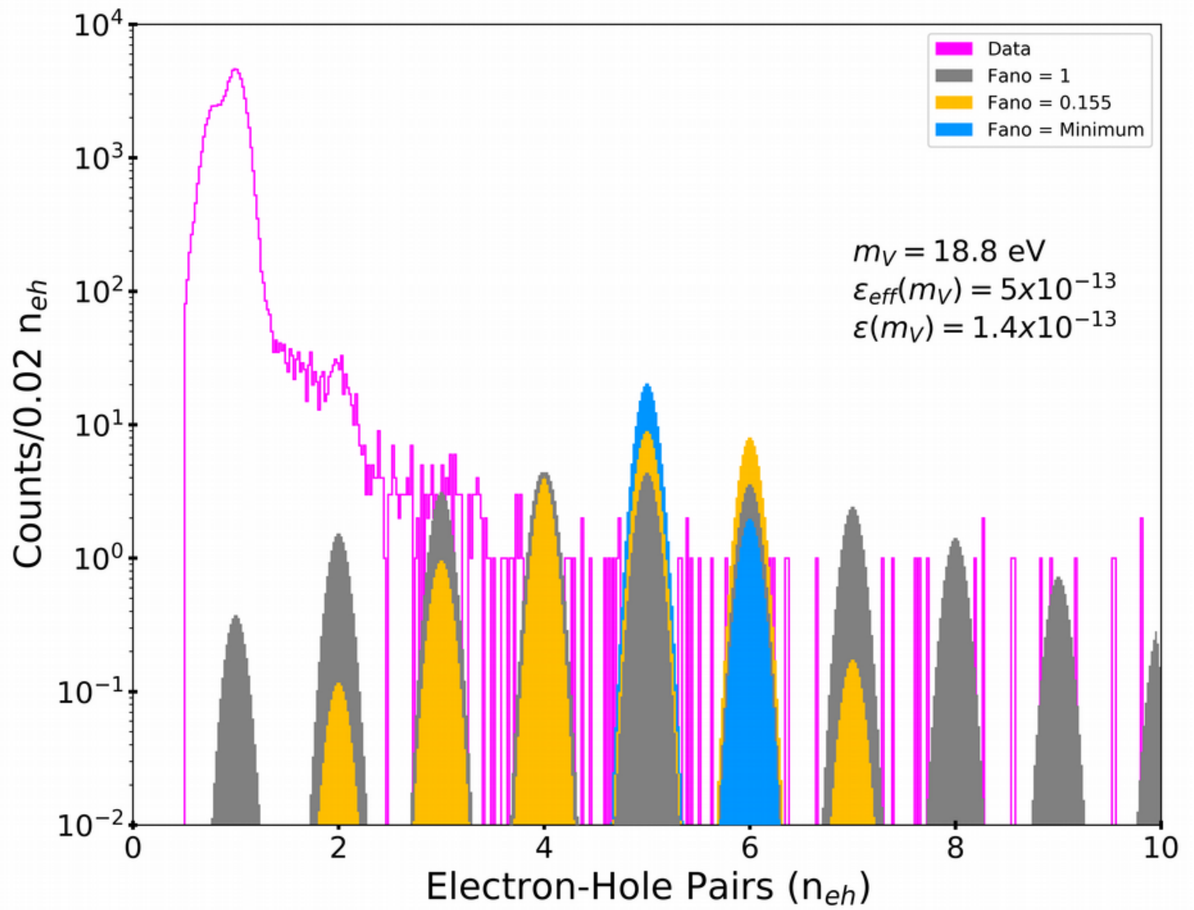
SuperCDMS arXiv 1804.10697



SENSEI arXiv 1804.00088

Electron recoil uncertainties

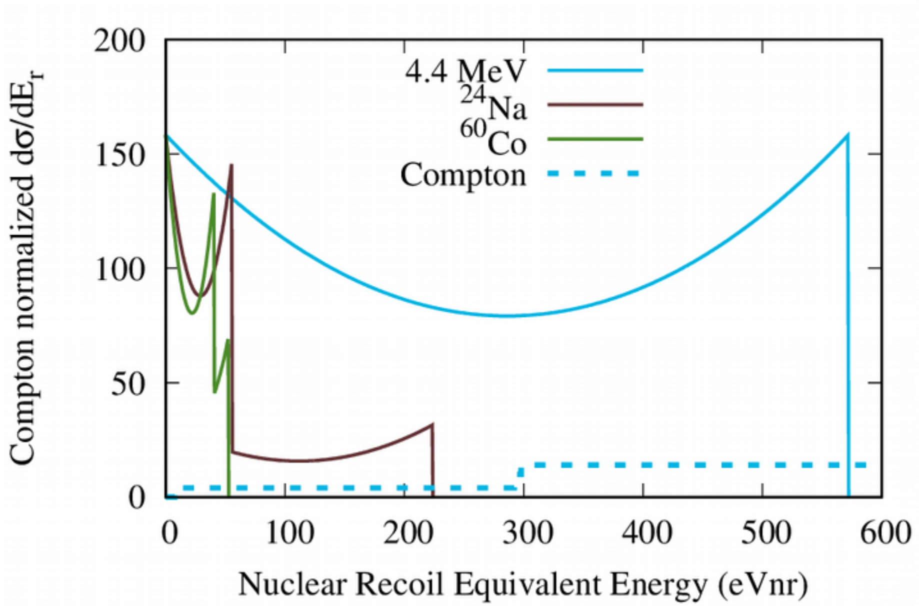
- We don't know if the ionization probability distribution from electron recoils at low-energies.



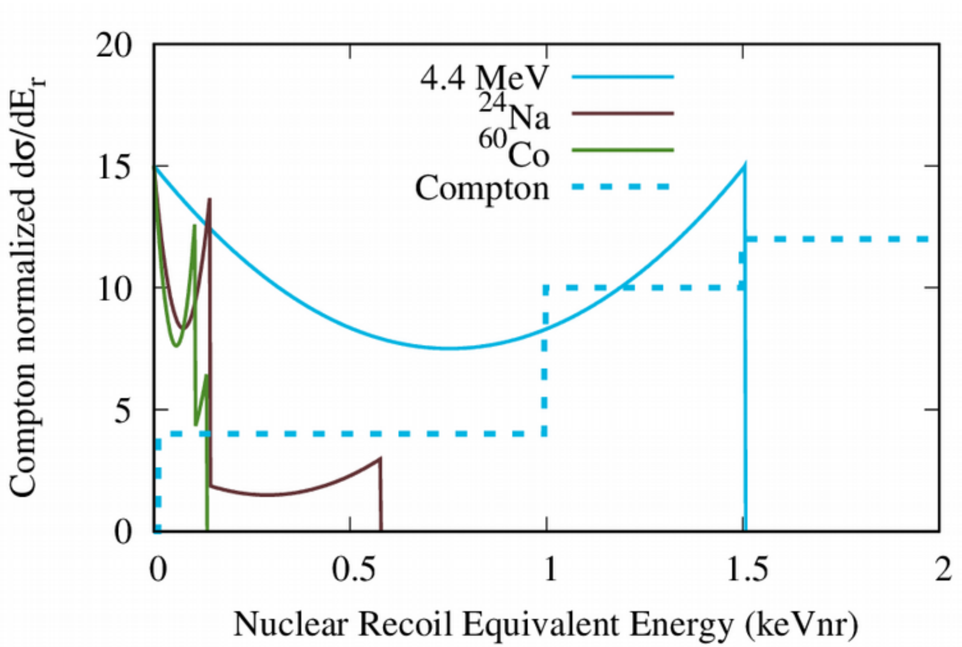
Thomson scattering in Si vs. Ge

Thomson scattering spectrum (assuming 10% ionization yield)

In Ge



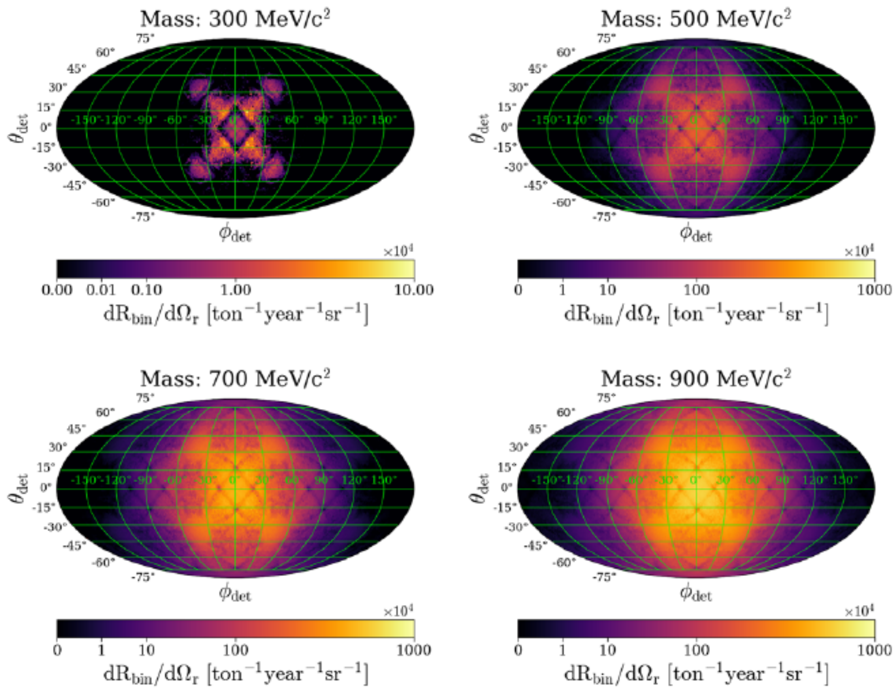
in Si



Calibrating detector directionality

Possible directionality in detector sensitivity / ionization yield at low energies.

See PRL **120** 111301 (2018)



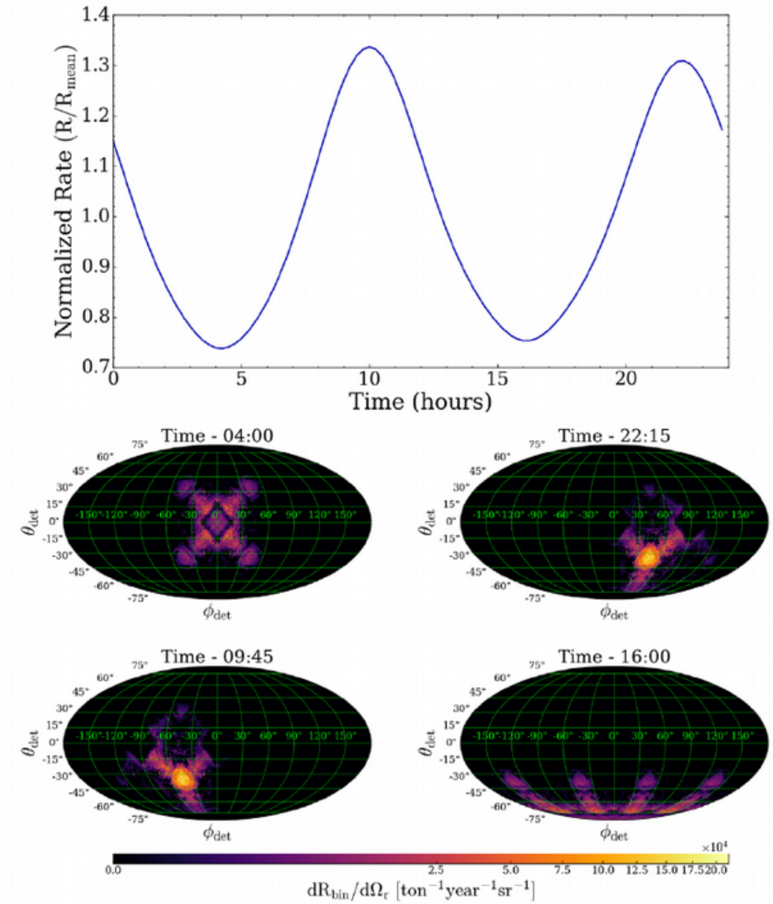


FIG. 2. (Top) Normalized integrated rate with respect to the mean over one day for a 300 MeV/c^2 WIMP at the SNOLAB site. (Bottom) Angular distribution of the differential rate per steradian for a nucleon cross section of 10^{-39} cm^2 over one day for a 300 MeV/c^2 WIMP at the SNOLAB site. Each angle plot corresponds to a local extremum of the integrated rate.

Experimental data on electrons in Ge/Si

Variety of experimental techniques available to measure band structures.

- Photo emission spectroscopy of occupied states
- Photoabsorption to conduction bands, diode junction studies of the band gap
- Raman spectroscopy provides a high energy / low momentum transfer probe.