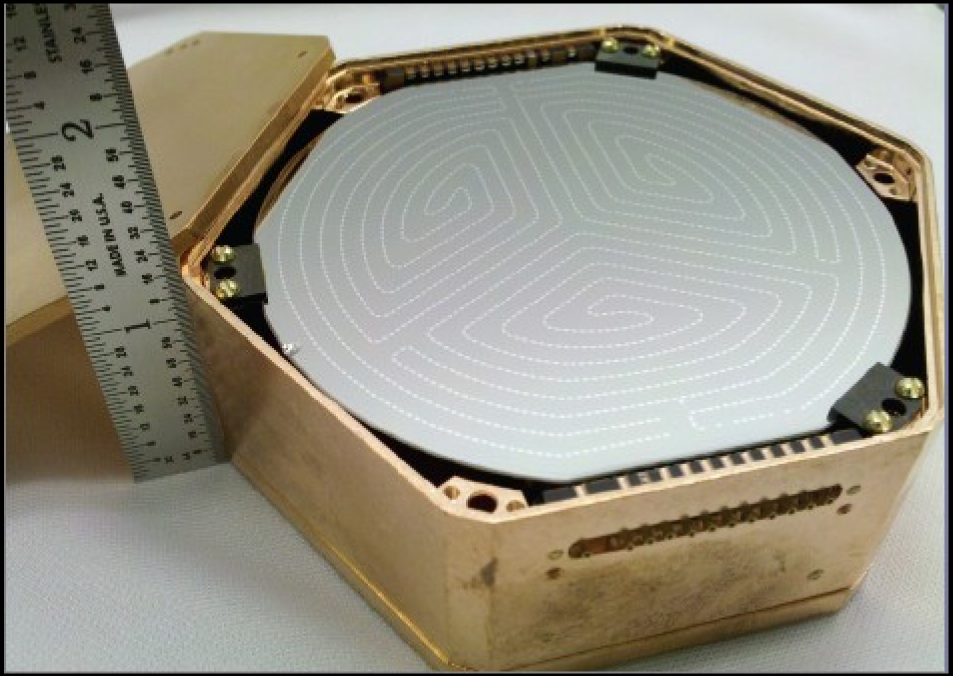
The SuperCDMS Dark Matter Experiment



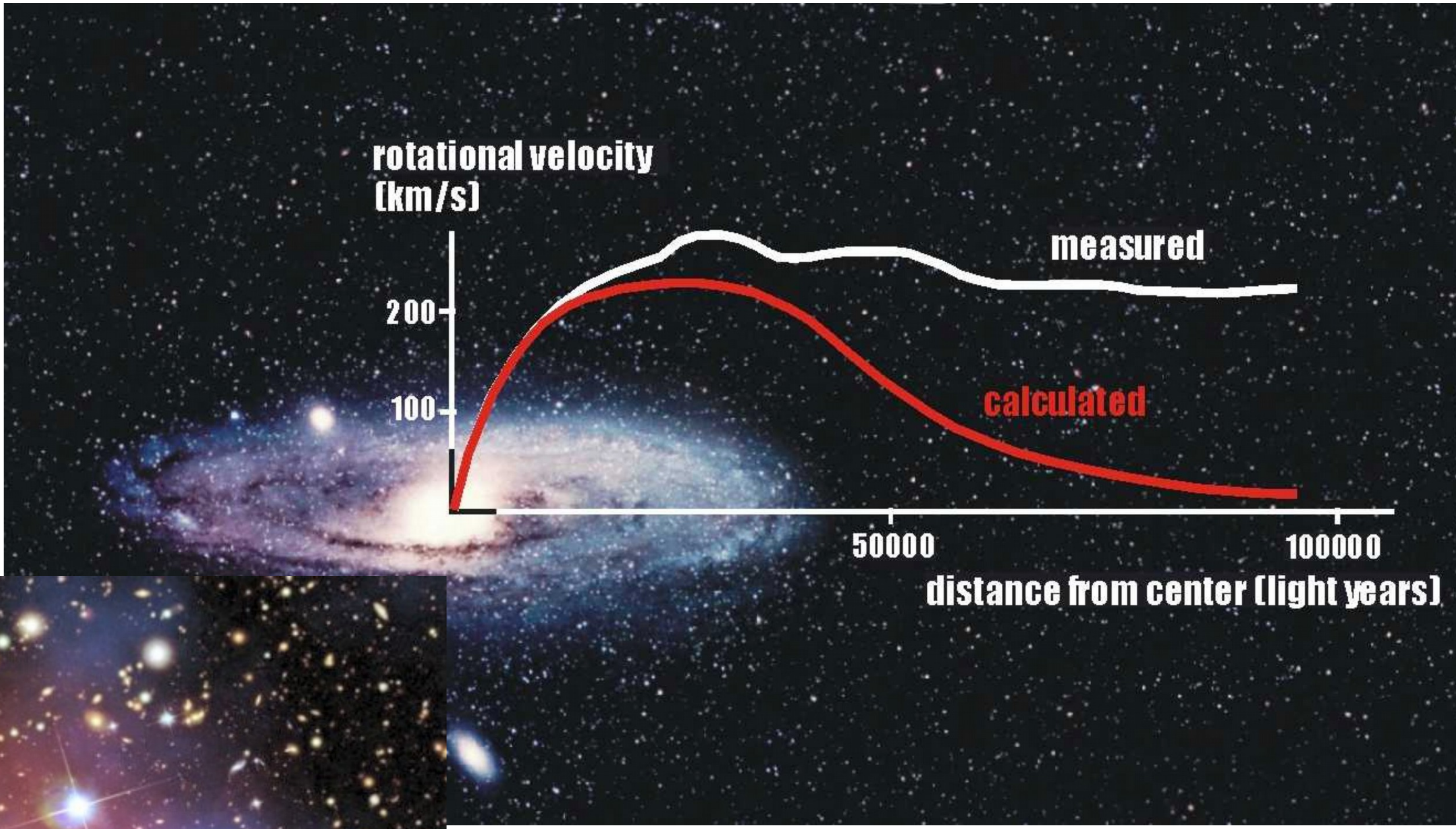
Scott Oser

CAP 2018, Halifax, NS

UBC

TRIUMF

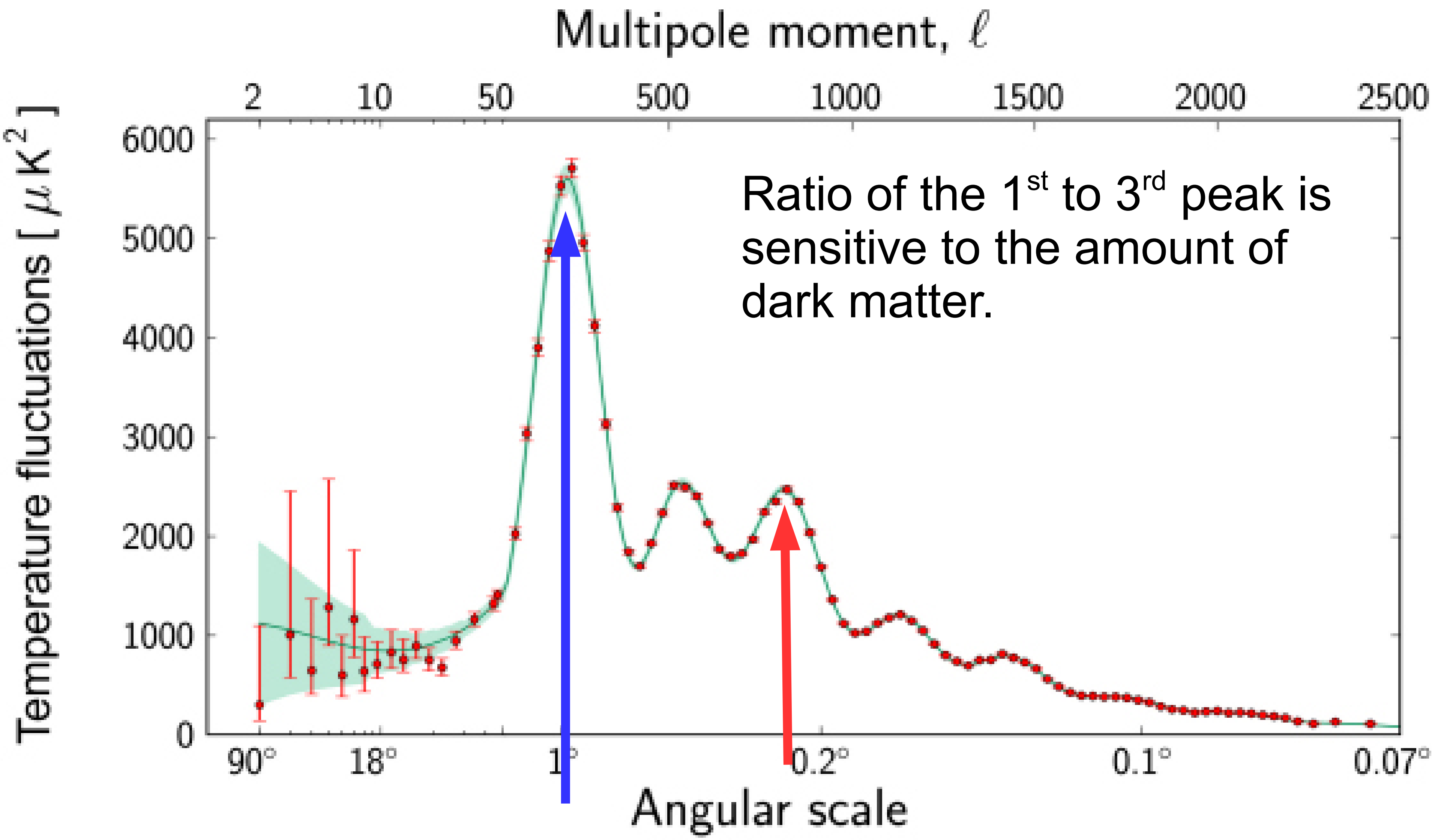
Evidence for Dark Matter



Gravitational effects amply confirm dark matter hypothesis.

Recent discovery of galaxy with no dark matter ironically strengthens case that dark matter exists!

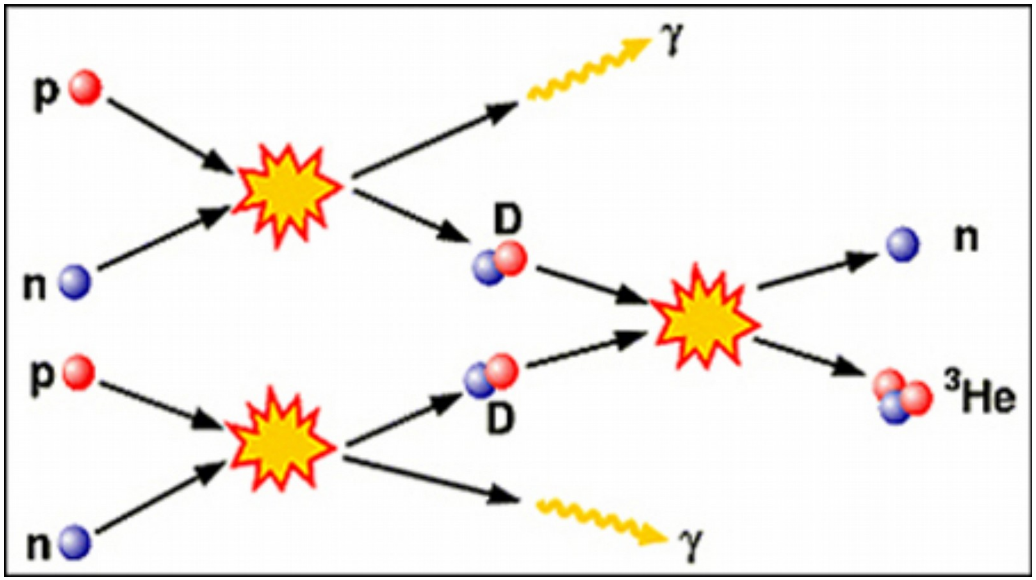
Dark Matter From Cosmology

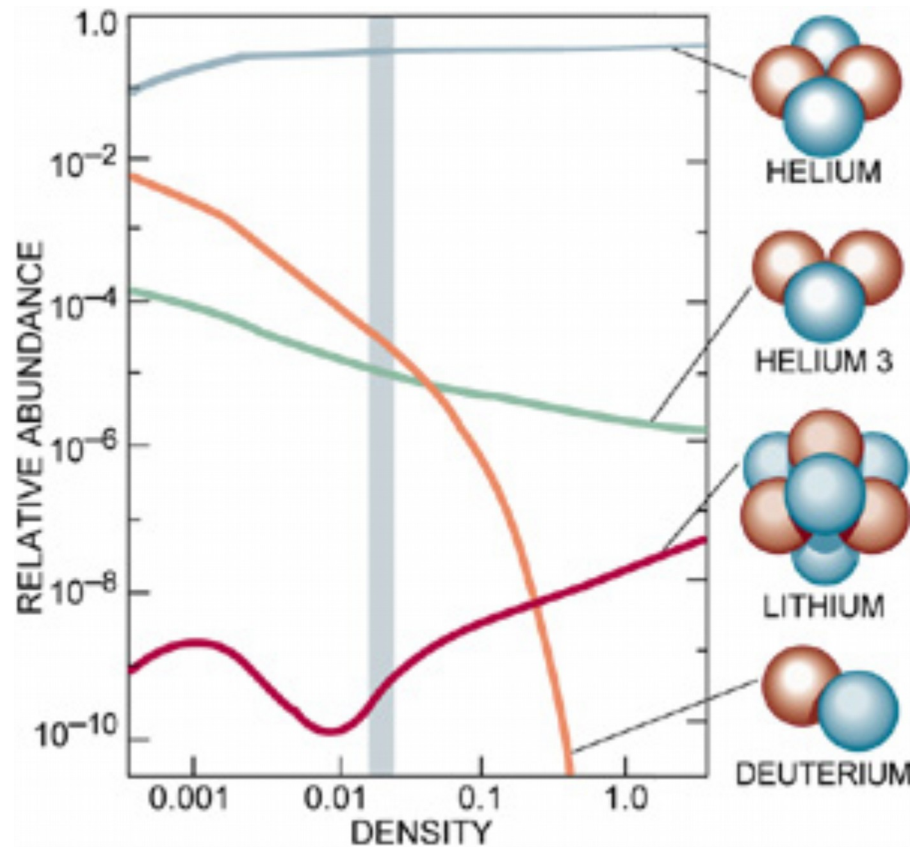


Ratio of the 1st to 3rd peak is sensitive to the amount of dark matter.

Planck angular power spectrum: A&A 594, A11 (2016)

Dark Matter Isn't Baryonic



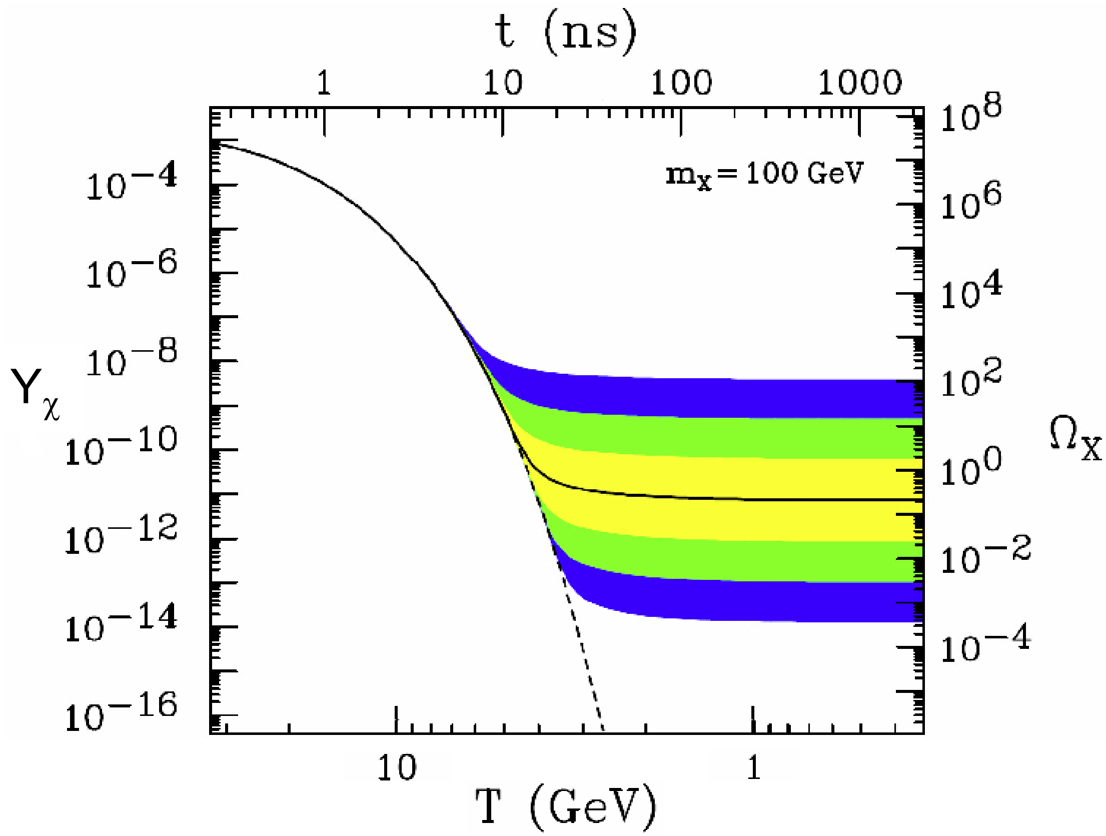


Abundances of light elements formed after the Big Bang are inconsistent with high baryonic density in present universe. Dark matter is non-baryonic.

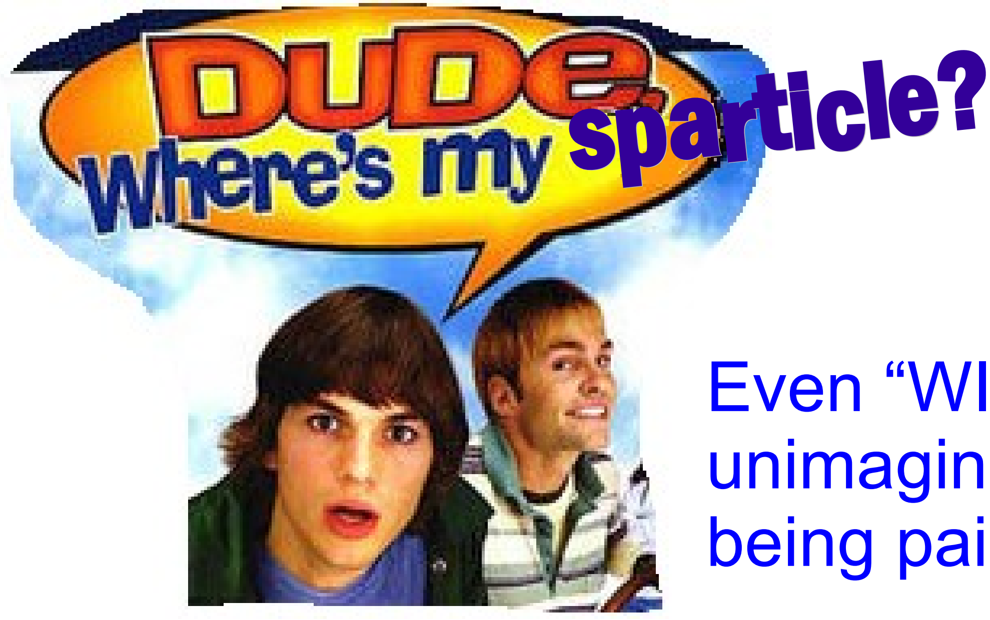
What is dark matter made of?

Mass>0, electrically neutral, *at best* weakly interacting, and not baryons

Generic WIMP hypothesis: a new particle with mass & cross section at the weak scale, produced in thermal equilibrium in the early universe, will have the right cosmological abundance.



SUSY fans have wanted such a particle for years in any case!

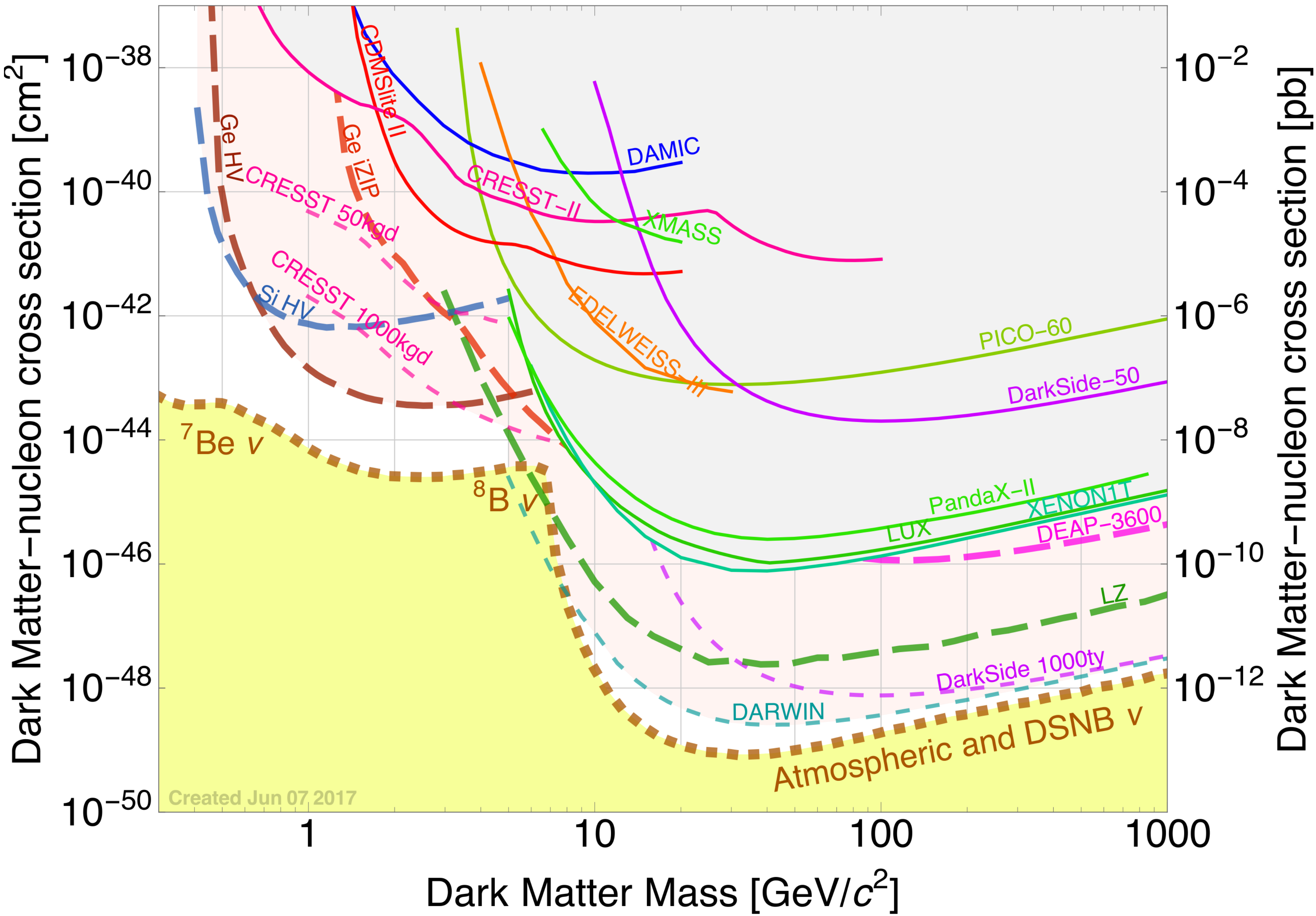


Even "WIMP" as a generic term is too unimaginative. Increasing attention is being paid to alternatives:

- hidden sector particles: dark photons from hidden U(1) symmetries
- asymmetric dark matter: dark matter consisting of baryons with masses ~5 x proton mass kills two birds with one stone
- axions
- massive sterile neutrinos

Many of these models motivate light dark matter candidates, with couplings (eg. Higgs or dark portal) that elude collider limits.

Above solid lines: currently excluded
Dashed lines: projected sensitivities of selected next-generation experiments

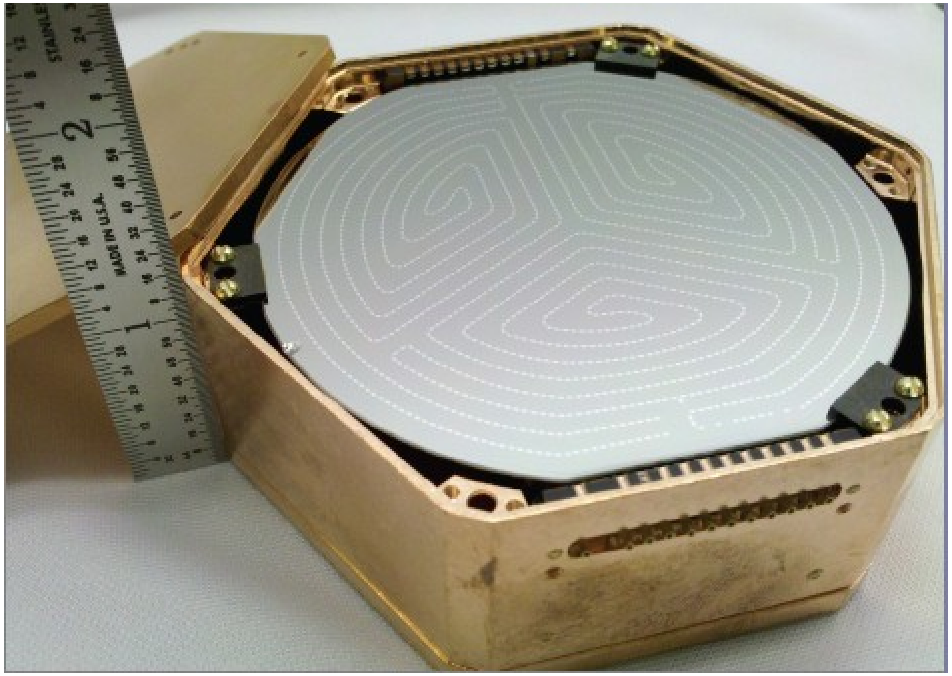


SuperCDMS collaboration

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 technology



Cryogenic semiconducting crystals (Ge or Si), with phonon and ionization sensors

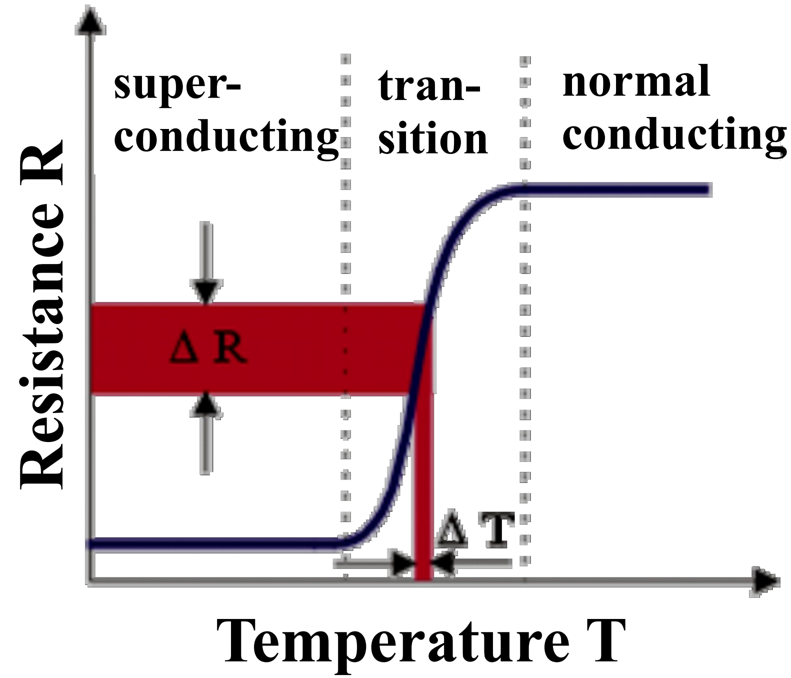
Heat capacity $\propto T^3$.
T ~ 10's of mK makes crystal heating easy to see

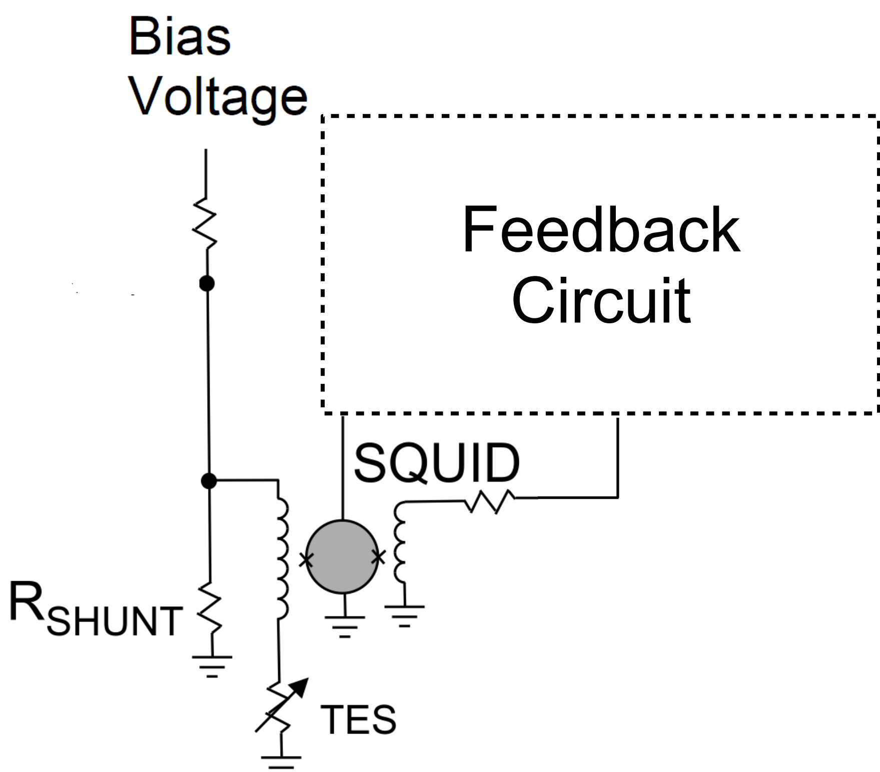
Nuclear recoils by WIMPs create phonon excitations (vibrations) in crystal. Ionization creates electron/hole pairs in crystal in proportion to energy and to yield factor *Y*:

$$N_{e/h} = \frac{Y E_r}{\epsilon} \qquad E_{phonon} = E_r + N_{e/h} V_{bias} e = E_r \left(1 + Y \frac{V_{bias} e}{\epsilon} \right)$$

Phonon sensors

Thin Al fins on the crystal surface absorb phonon energy and carry it to a thin tungsten film that is operated in transition between its normal and superconducting state: a **Transition Edge Sensor (TES)**

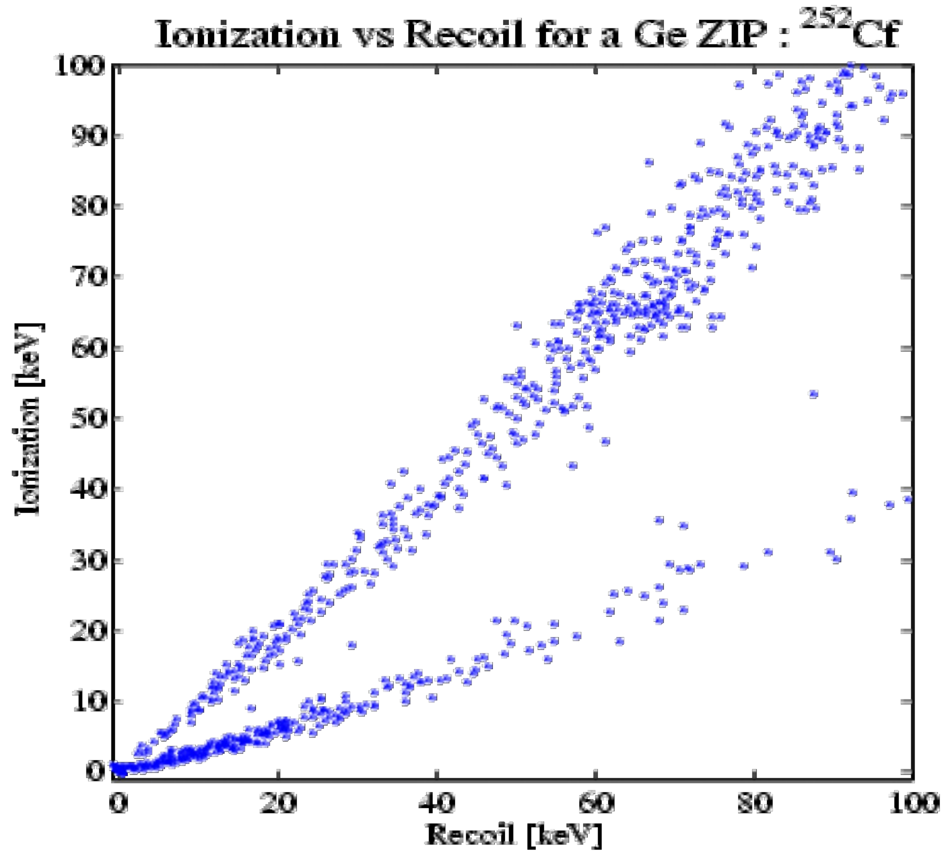




Changing TES resistance varies magnetic flux through SQUID. Feedback circuit adjusts current through a second inductor to compensate, and we measure that current.

IZIP Detectors

"Interleaved Z-Sensitive Ionization & Phonon Detectors"



Yield for nuclear recoils is lower than for electron recoils.

Ratio of ionization to recoil energy distinguishes nuclear recoils from most backgrounds, which produce electron recoils.

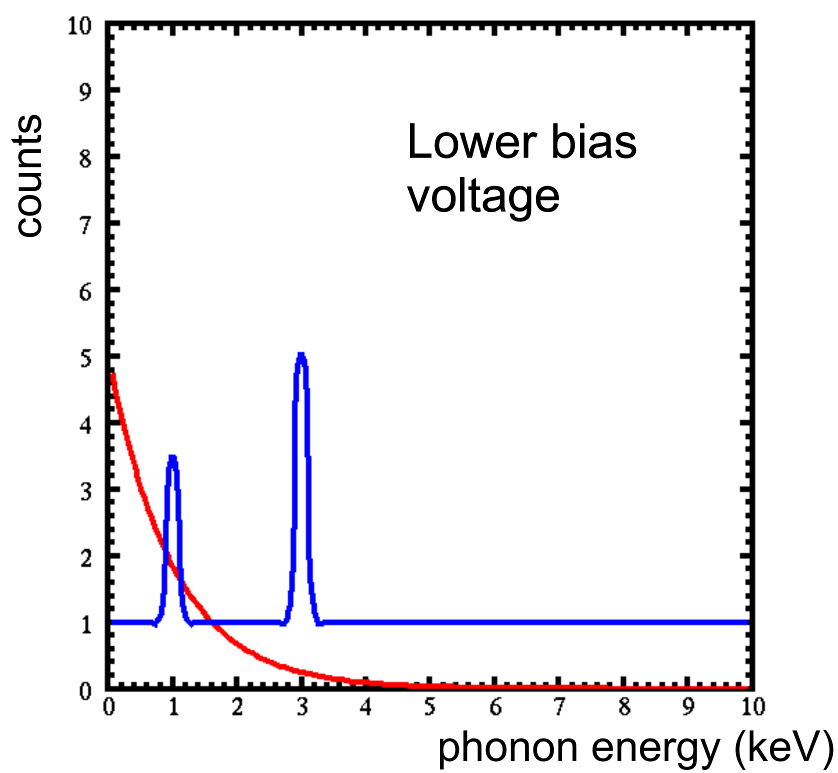
This background rejection works best at higher energies where the signal-to-noise is highest.

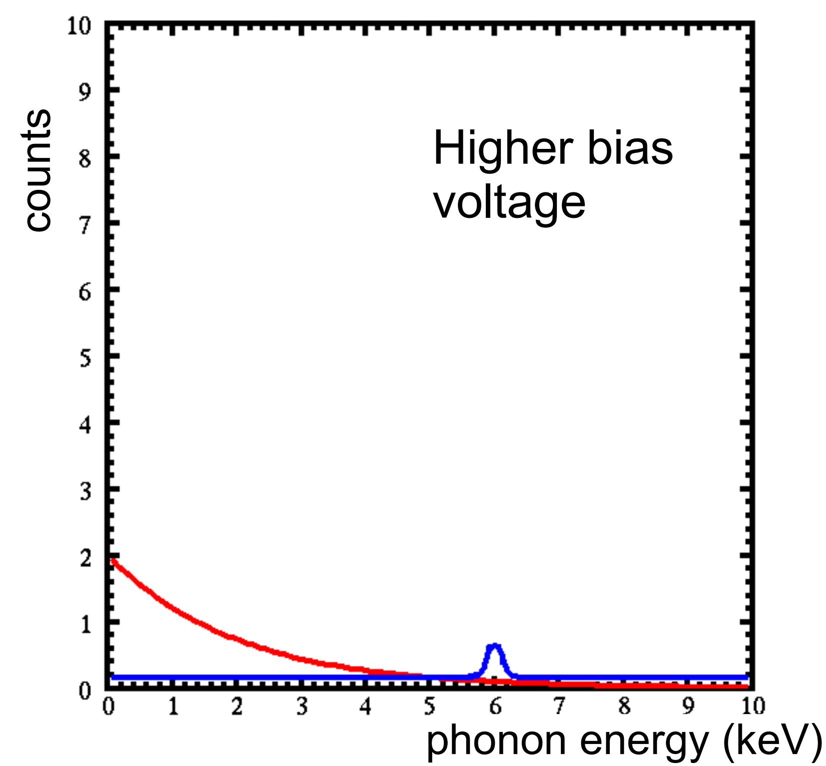
HV detectors

$$E_{phonon} = E_r \left(1 + Y \frac{V_{bias} e}{\epsilon} \right)$$

Neganov-Luke amplification: increasing V_{bias} from 4V to ~80V lowers energy threshold, giving sensitivity to much lighter WIMPs

The price: lose electron/nuclear recoil discrimination. But higher Y for electron recoils pushes them out in energy relative to nuclear recoils, diluting background at low energies.

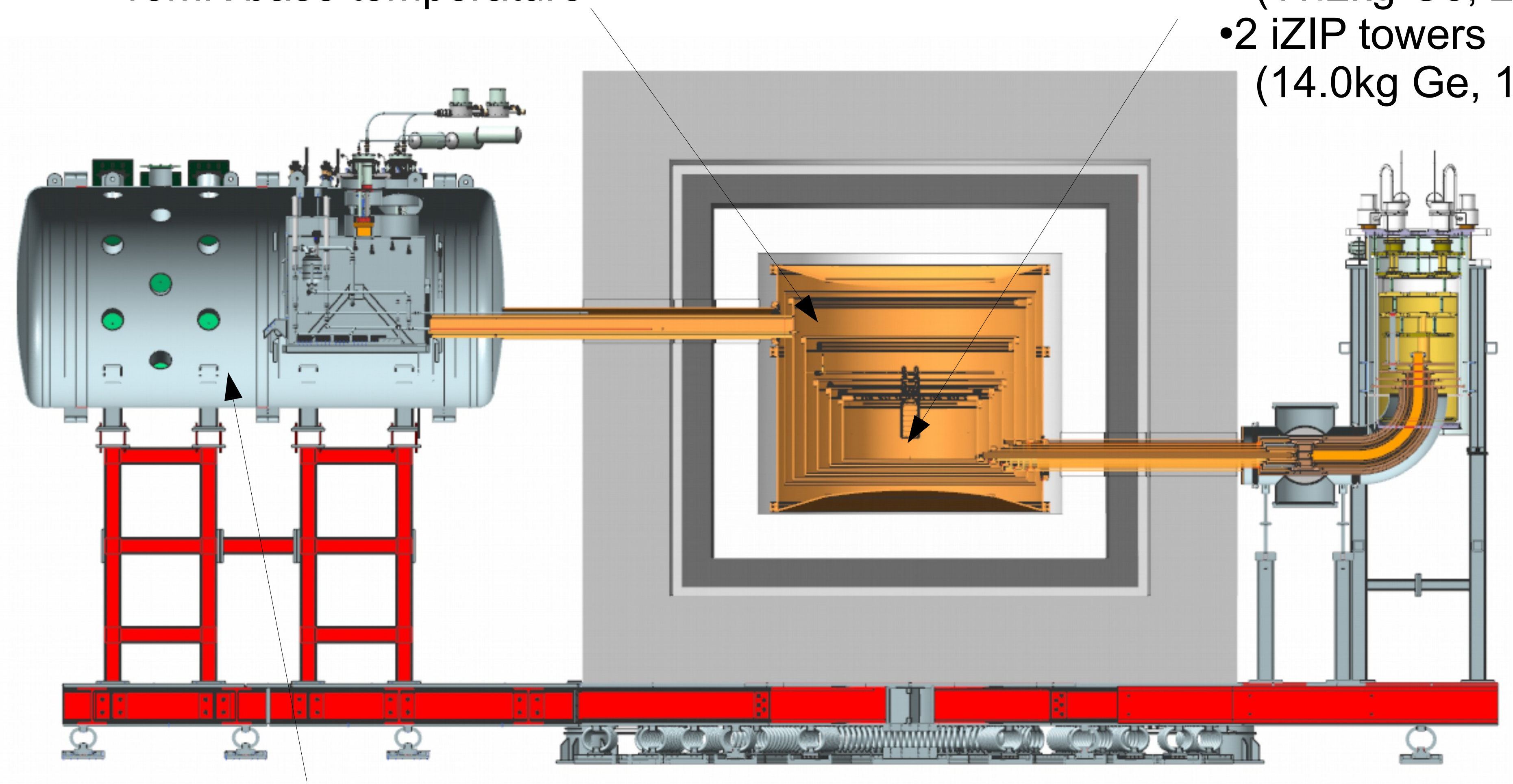




SuperCDMS at SNOLAB

Cryostat:
- Room for 31 towers
- 15mK base temperature

Detector payload:
- 2 HV towers
  (11.2kg Ge, 2.4 kg Si)
- 2 iZIP towers
  (14.0kg Ge, 1.2kg Si)



Low noise electronics with deadtime-free trigger and new DAQ

2km underground in SNOLAB
- Improved radiopurity, cleanliness, and shielding

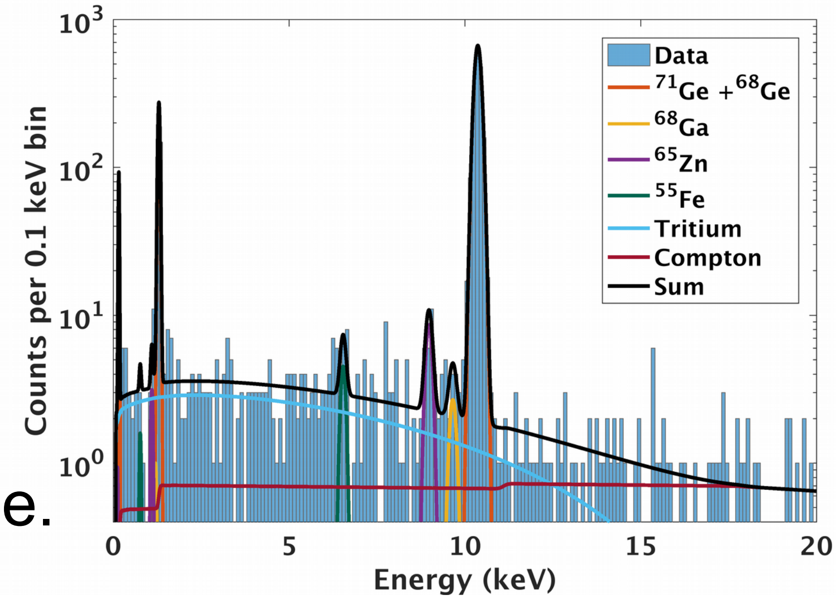
Science Drivers

Backgrounds:
- In energy range of interest, most important background is cosmogenic ^3H. Must limit unshielded exposure on surface. (See E. Fascione's talk 6/11, 17:30, M3-6 PPD)
- Careful assay and selection of materials essential

Resolution:
- Determines how low in energy threshold (mass) we can go
- Lower base temperature helps!
- Guard against microphonics, RF noise

Response to small energy deposits
- Optimal filter running in firmware to achieve lowest possible trigger thresholds
- Low energy calibrations to understand detector response to small energy deposits

Calibration methods



Ba & Cf sources: deploy Ba (γ source) and Cf (n source) inside cryostat for *in situ* calibrations. Use Ge activation lines to understand low energy response.

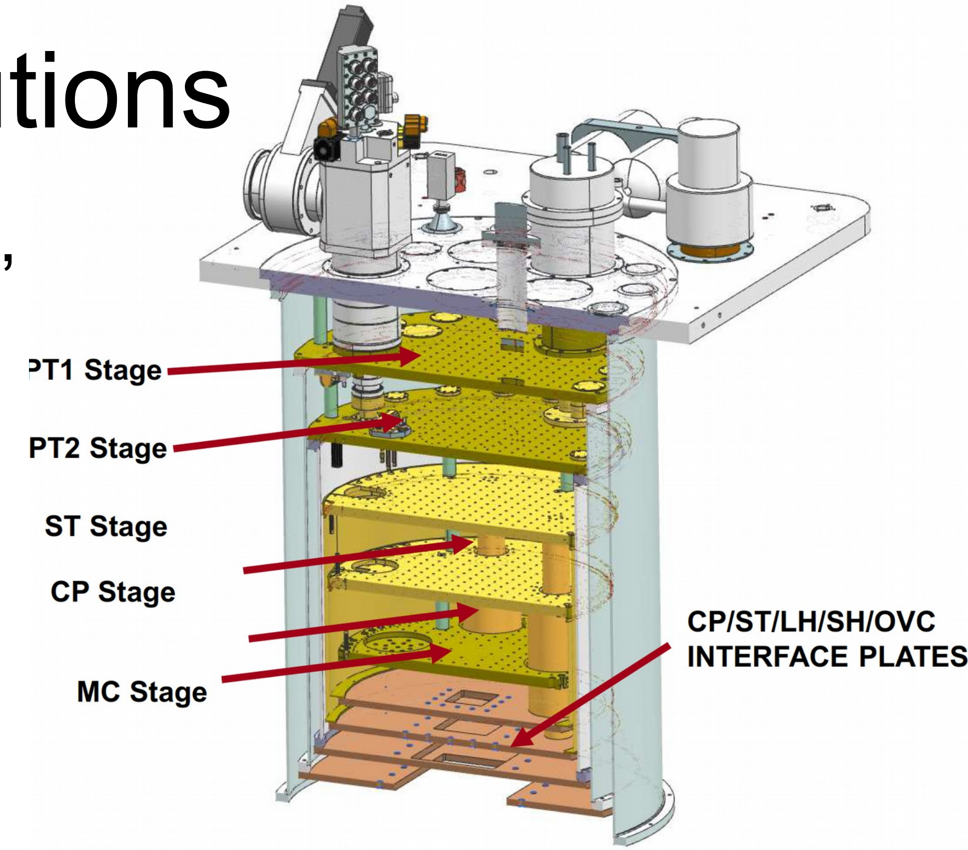
Photoneutron source: monoenergetic beam of neutrons from ^{88}YBe or ^{124}SbBe source to calibrate low energy nuclear recoils. (See Andrew Scarff's talk 6/14, 14:15, R3-3 PPD).

Infrared LED: flash detector with IR pulse to produce single electron/hole pairs. (See M. Ghaith's talk 6/13, 11:45, W2-3 PPD)

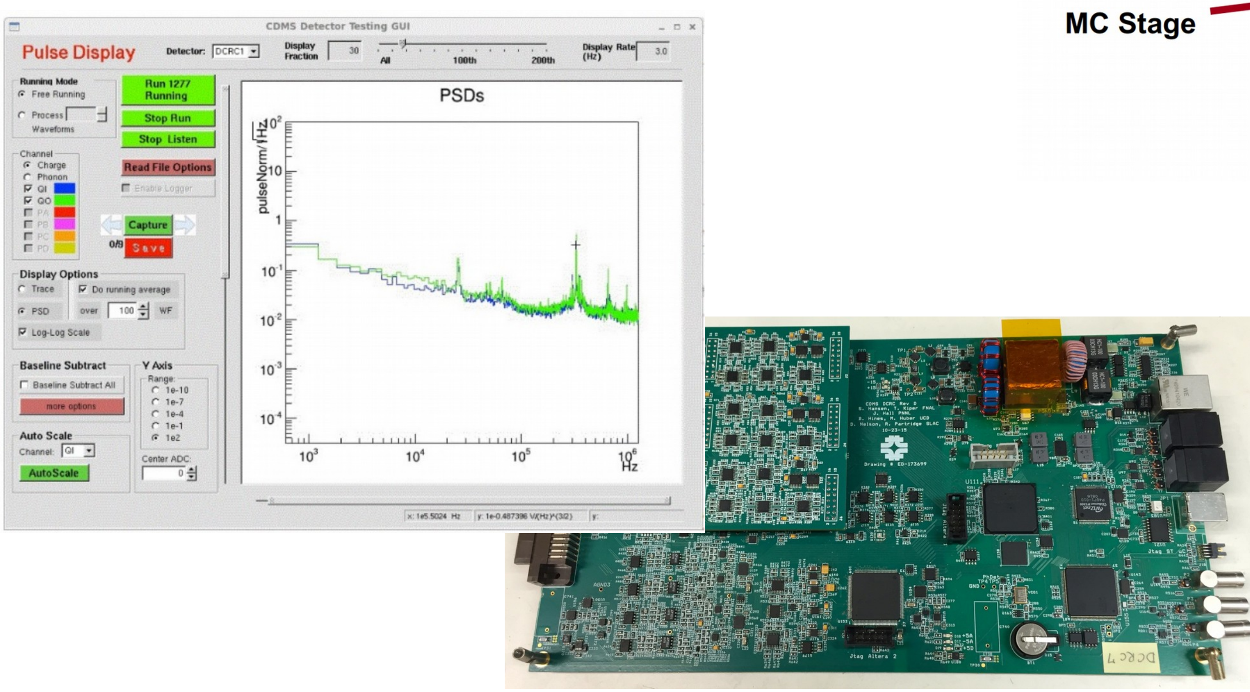
Ex situ neutron scattering measurements: calibration program at UdeM to understand nonlinear nature of detector response in the limit that individual excitation quanta are produced. (See A. Robison's talk 6/14, 14:30, R3-3 PPD)

Key Canadian contributions

CFI funding pays for our cryostat, underground infrastructure, and portions of the shielding



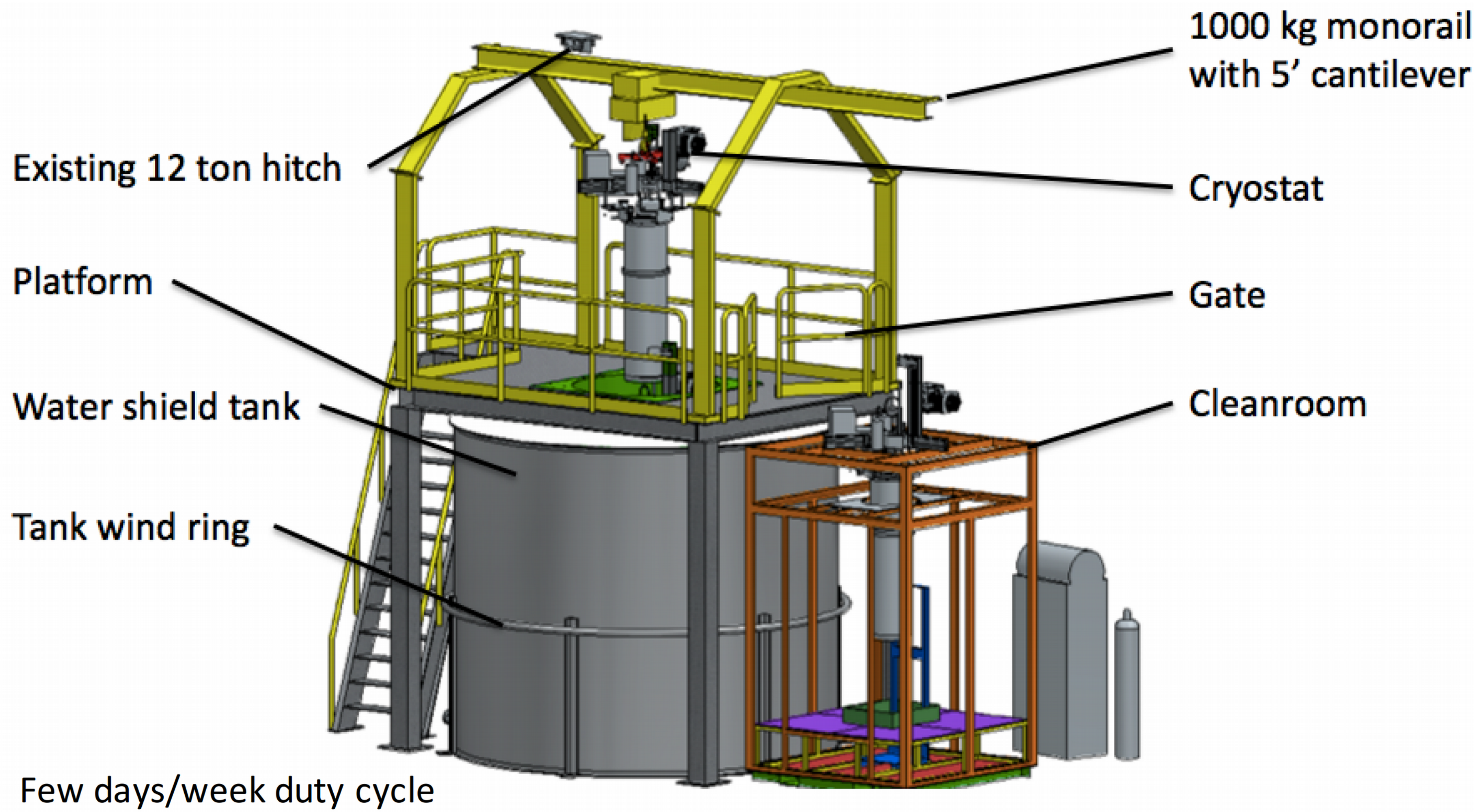
Extensive HV detector testing program at Queen's



Canadian group leads DAQ & trigger development

Backgrounds screening, calibration, and simulation efforts

CUTE



An underground test facility at SNOLAB for R&D and maybe early science results from SuperCDMS detectors

See S. Nagorny's talk 6/14, 8:30, R1-3 PPD) and P. Pakarha's poster (6/12, 18:00, PPD poster session)

Schedule

Summer/Fall 2018: CUTE installation in SNOLAB

2019: installation of full SuperCDMS experiment at SNOLAB

First half of 2020: commissioning

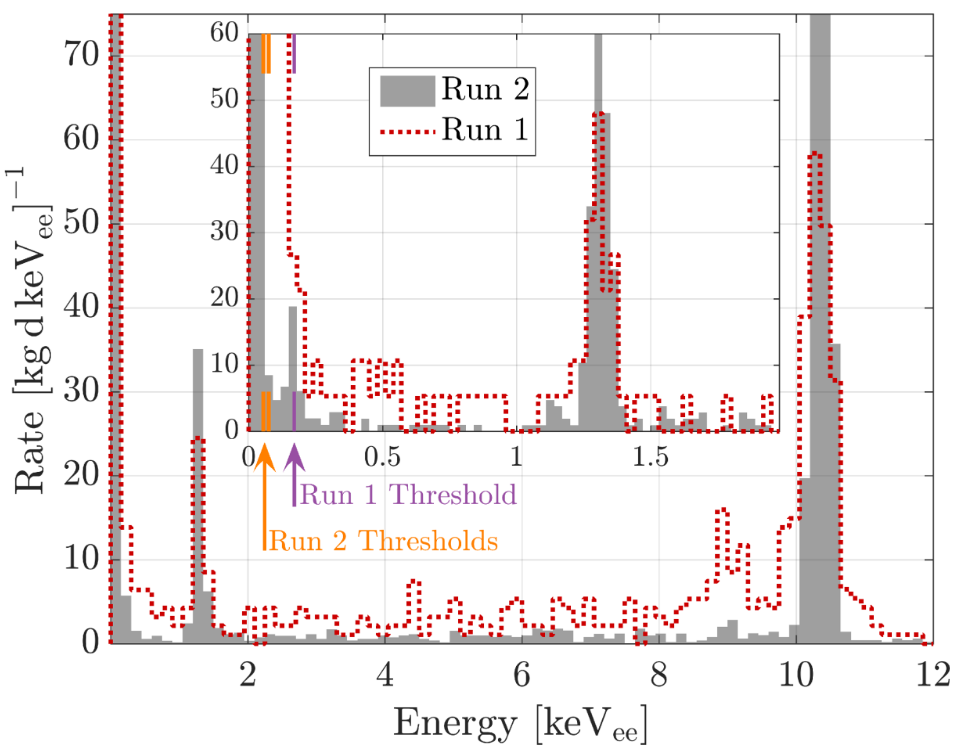
2020 – 2025: initial science run

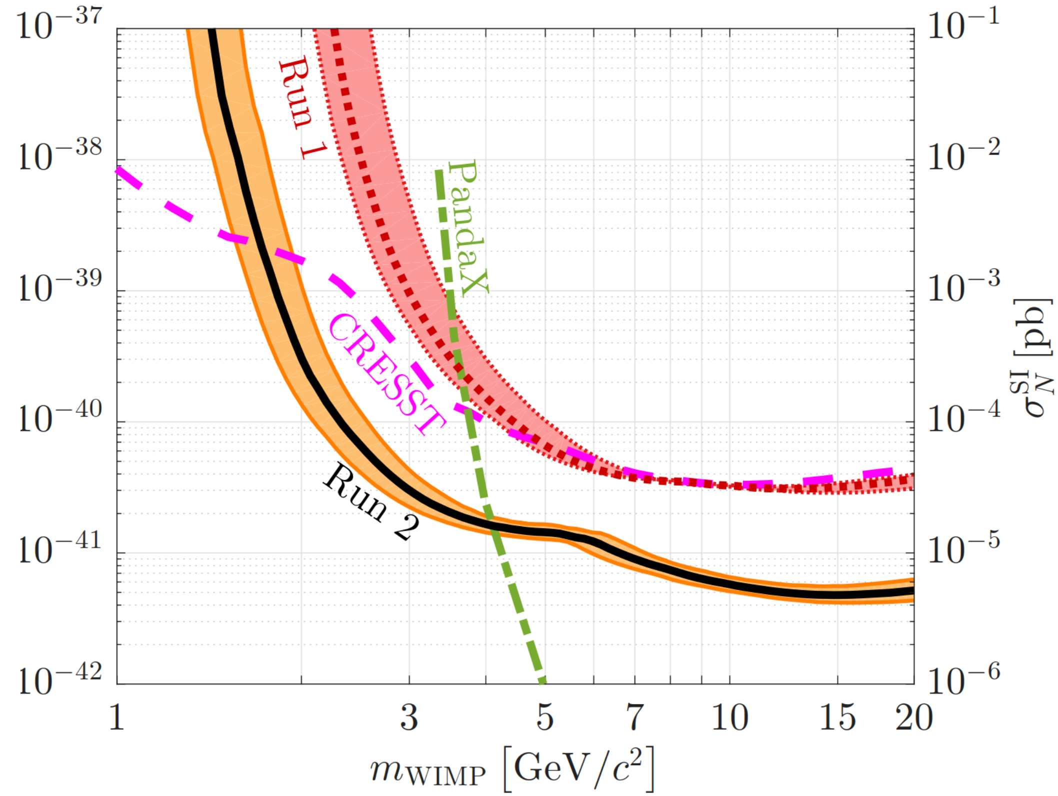
202X – upgrades to reach solar neutrino floor

Recent and upcoming results

Previous CDMSlite results

First published results from detectors run at ~70V to achieve low energy thresholds

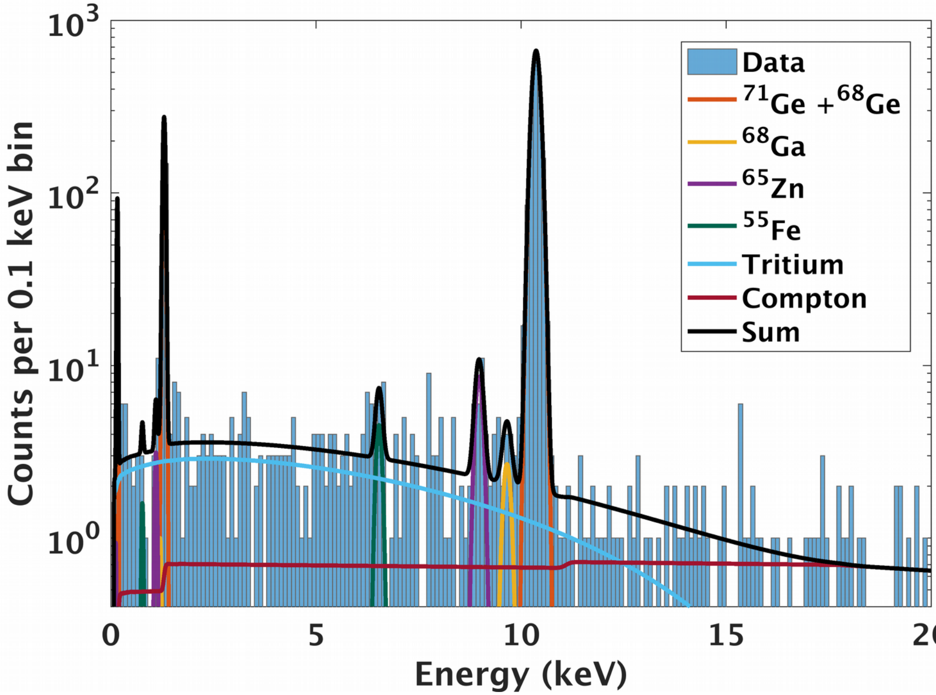


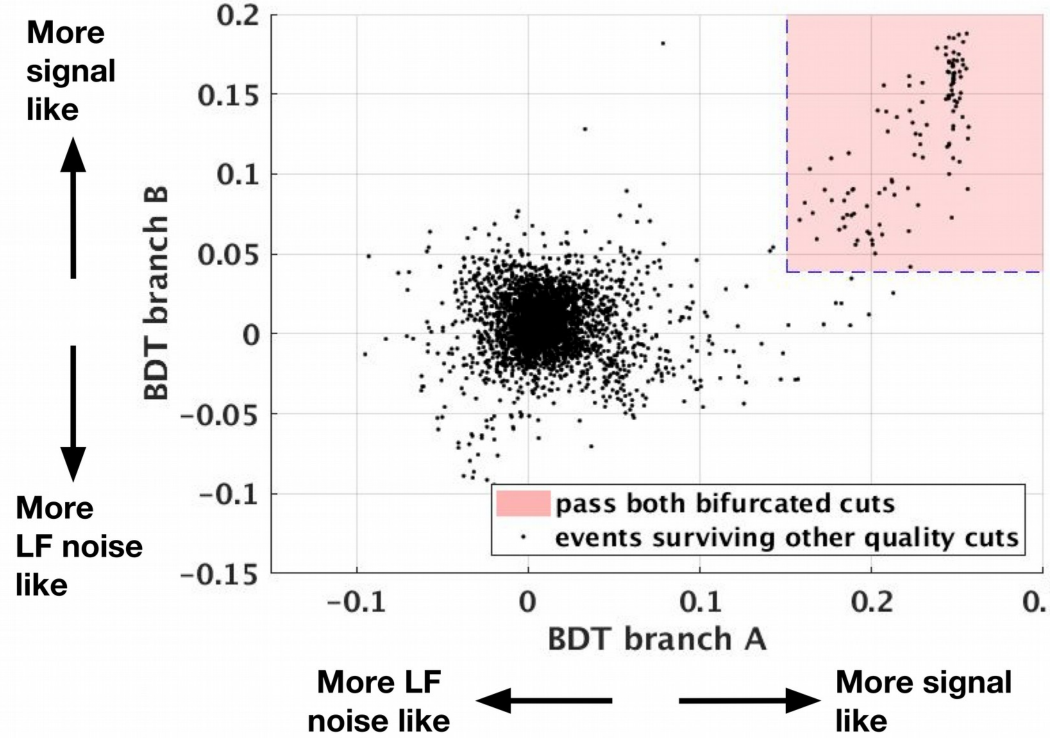


- Significant backgrounds from detector mechanical vibrations
- New radial cut to remove some backgrounds
- All events treated as potential signal: set conservative limits with optimal interval method without any background subtraction

Phys. Rev. D 97, 022002 (2018)

Upcoming CDMSlite Run 3 result





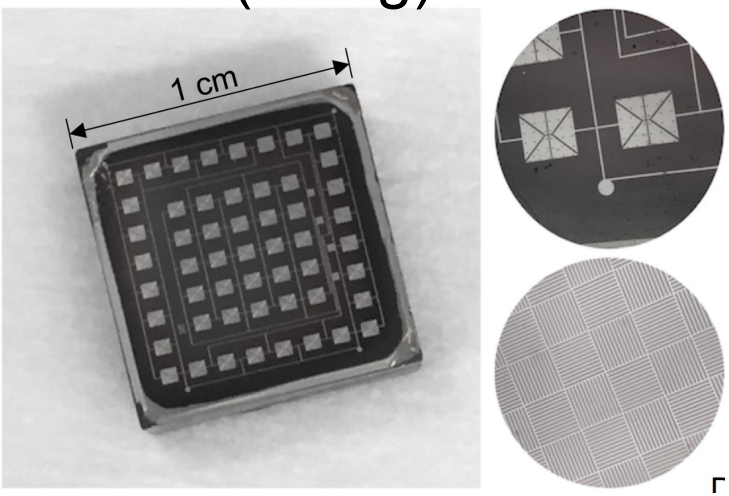
Additional data from Soudan running with multiple analysis improvements:

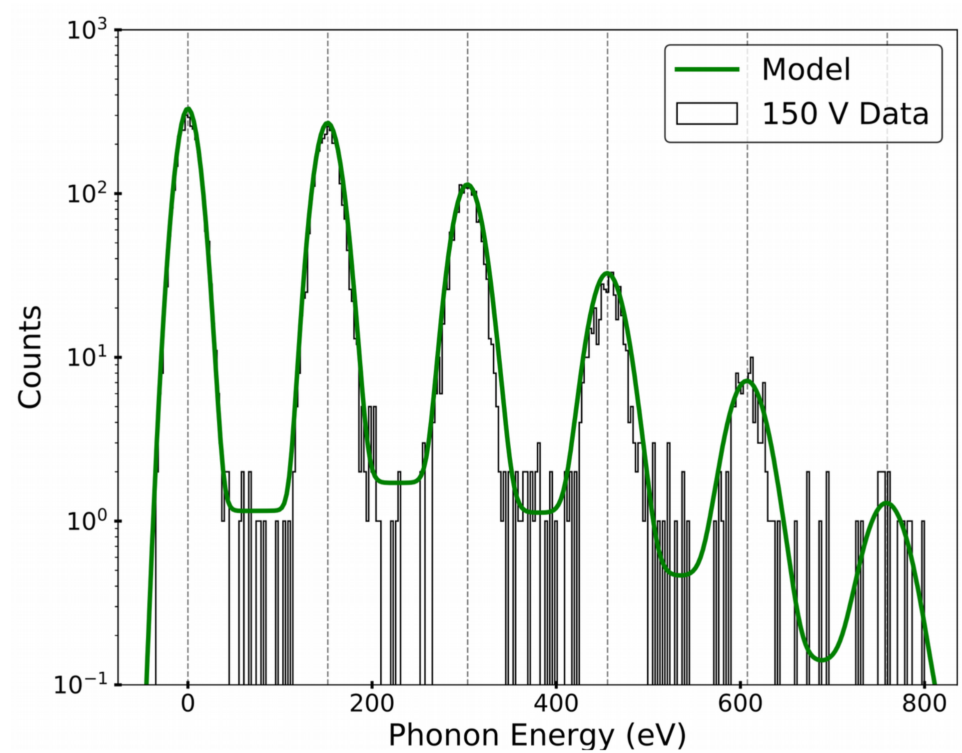
- New Boosted Decision Tree cuts to remove instrumental backgrounds such as triggers from vibrations
- Full likelihood fit of WIMP signal + background model to extract limit

(See R. Underwood’s talk 6/11, 17:15, M3-6 PPD)

Phonon detectors sensitive to single electron/hole excitations

Si prototype detector (0.93g)





Clearly count single excitations in phonon signal through Neganov-Luke gain!

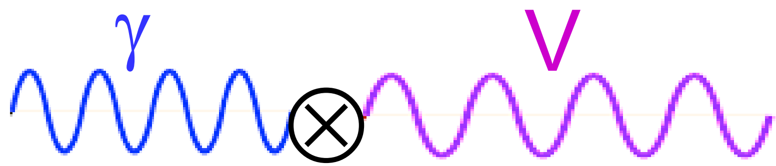
Electron recoils will dominantly occur only in peaks, while nuclear recoils, with much higher ratio of direct phonon to ionization yield, will fill in the valleys

$$E_{phonon} = E_r \left(1 + Y \frac{V_{bias} e}{\epsilon} \right)$$

Dark photons

Suppose a hidden sector contains particles with a U(1) gauge symmetry. The resulting "dark photon" will have the same quantum numbers as a photon. If the gauge symmetry is broken it may be massive.

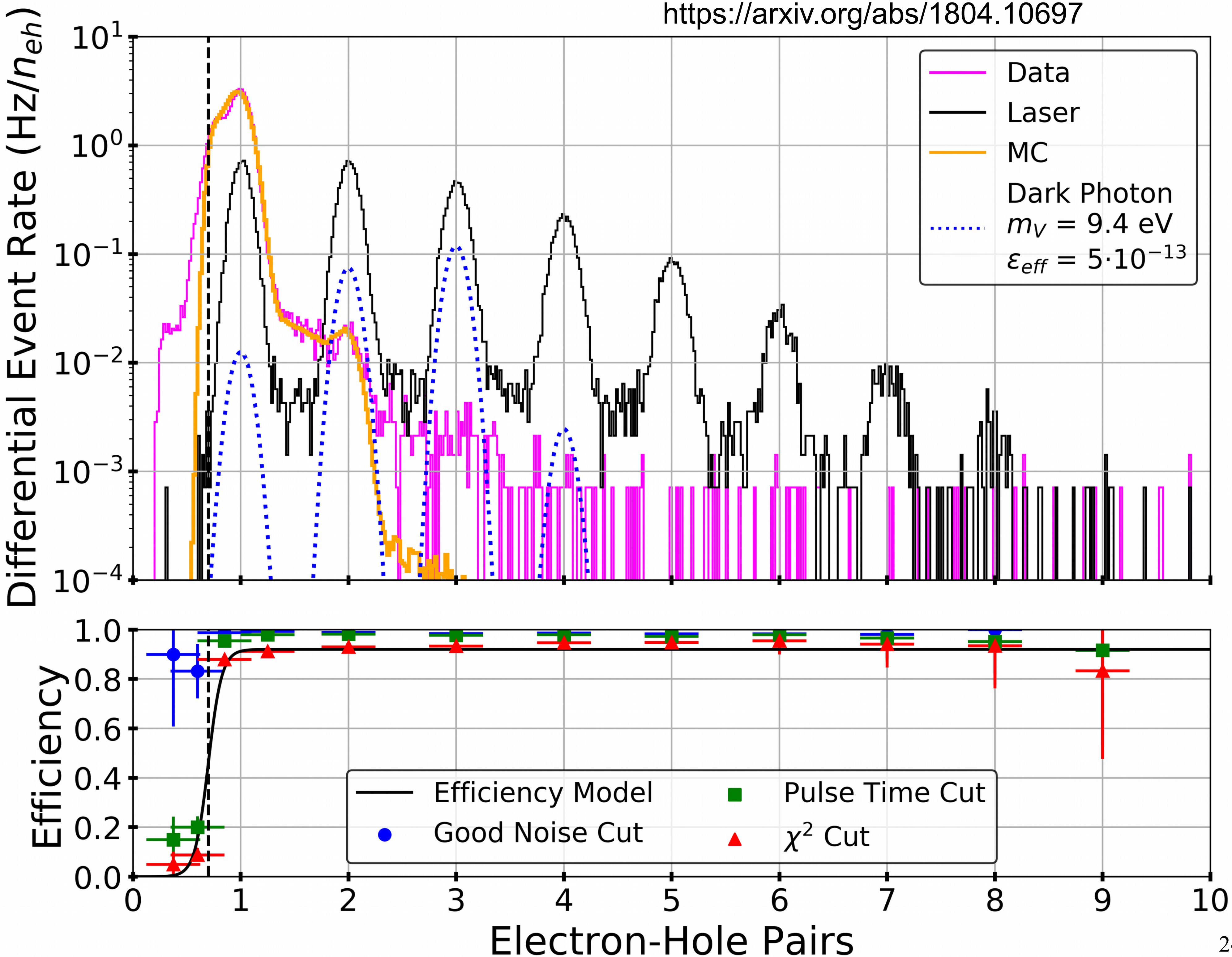
This massive dark photon can kinetically mix with the SM photon:



A dark photon interacting in our detectors can produce a "dark photoelectric" absorption, resulting in the production of one or more electron/hole pairs. The absorbed energy is the dark photon mass.

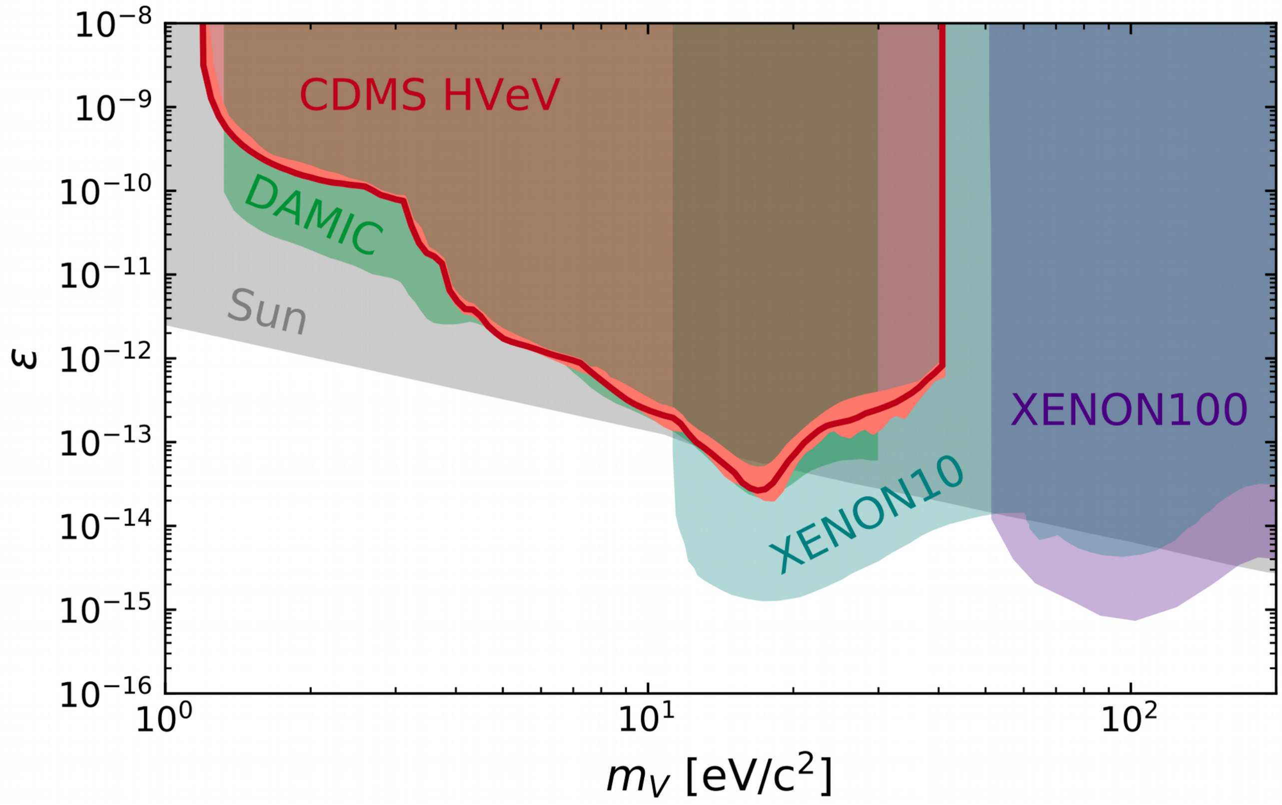
Search is sensitive down to masses given by the Si bandgap (few eV/c^2)!

https://arxiv.org/abs/1804.10697



Dark photon limits

$$R = V_{Det}\frac{\rho_{DM}}{m_V}\varepsilon_{eff}^2(m_V,\sigma)\sigma_1(m_V)$$



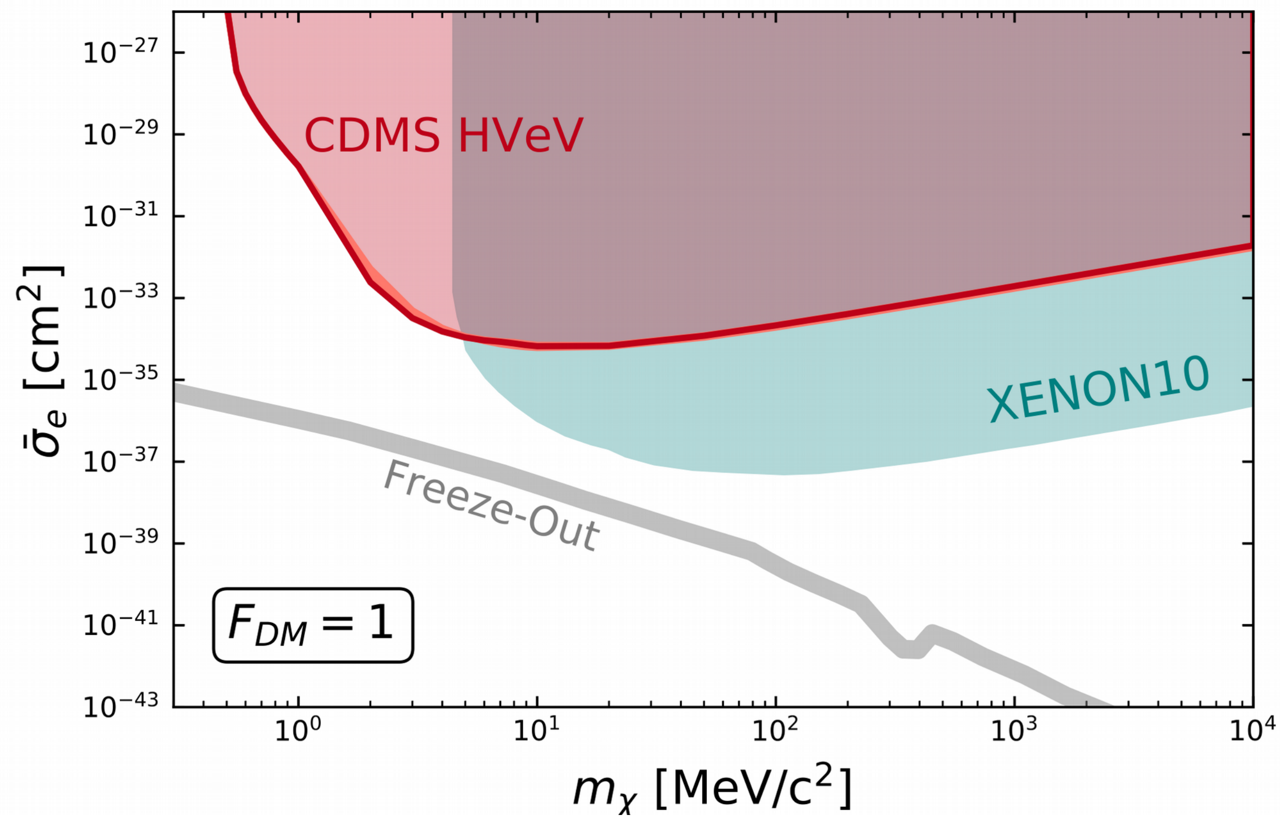
Competitive limits from just 0.49 g▪days of exposure from a test device

Mass sensitivity down to just above 1 eV!

https://arxiv.org/abs/1804.10697

Electron recoil DM

$$\frac{dR}{d(\ln(E_R))} = V_{Det}\frac{\rho_{DM}}{m_X}\frac{\rho_{Si}}{2m_{Si}}\bar{\sigma}_e\alpha\frac{m_e^2}{\mu_X^2}I_{Crystal}$$



Inelastic electron recoils can excite electrons across Si bandgap, giving us world's best limits on DM interactions with electrons at masses around 1 MeV/c^2 ... from a tiny test device!

https://arxiv.org/abs/1804.10697

Conclusions

SuperCDMS's cryogenic semiconductor technology gives world-leading sensitivity to light dark matter.

Next-generation experiment will be installed in SNOLAB next year!

Prototype detectors with sensitivity to individual electron/hole excitations provide exciting upgrade path for very low energy threshold searches.

Check out the many contributed talks and posters from our group during CAP.

Rapidly growing Canadian effort (6 institutions and counting)---new collaborators are welcome!

Backups

Assuming it's a WIMP, how does it interact?

Old paradigm: elastic scattering of spin 0 particle, mediated by Z boson (so M_{WIMP} > 45 GeV), with equal couplings to all up and down, with $\sigma \propto A^2$ at weak scale.

Unproven assertions:

- Spin 0: need to consider spin-dependent alternatives
- Elastic scattering: why not scatter to excited states, reducing deposited energy?
- Mediated by Z: why not Z'? Weakly mixed dark photons? Another new particle? Mass could easily be <45 GeV.
- Isospin symmetric: unproven, and can introduce nuclear target dependencies
- Cross section at weak scale: desirable to get $\Omega_{DM} \sim 0.25$, but not guaranteed
- Just one dominant species: what if DM mass budget is spread across 20 particles, some of which don't couple at all? Abundance could be lower than you thought!

Multiple targets are critical