Cryogenic Crystal Phonon Detectors for meV-keV Signals

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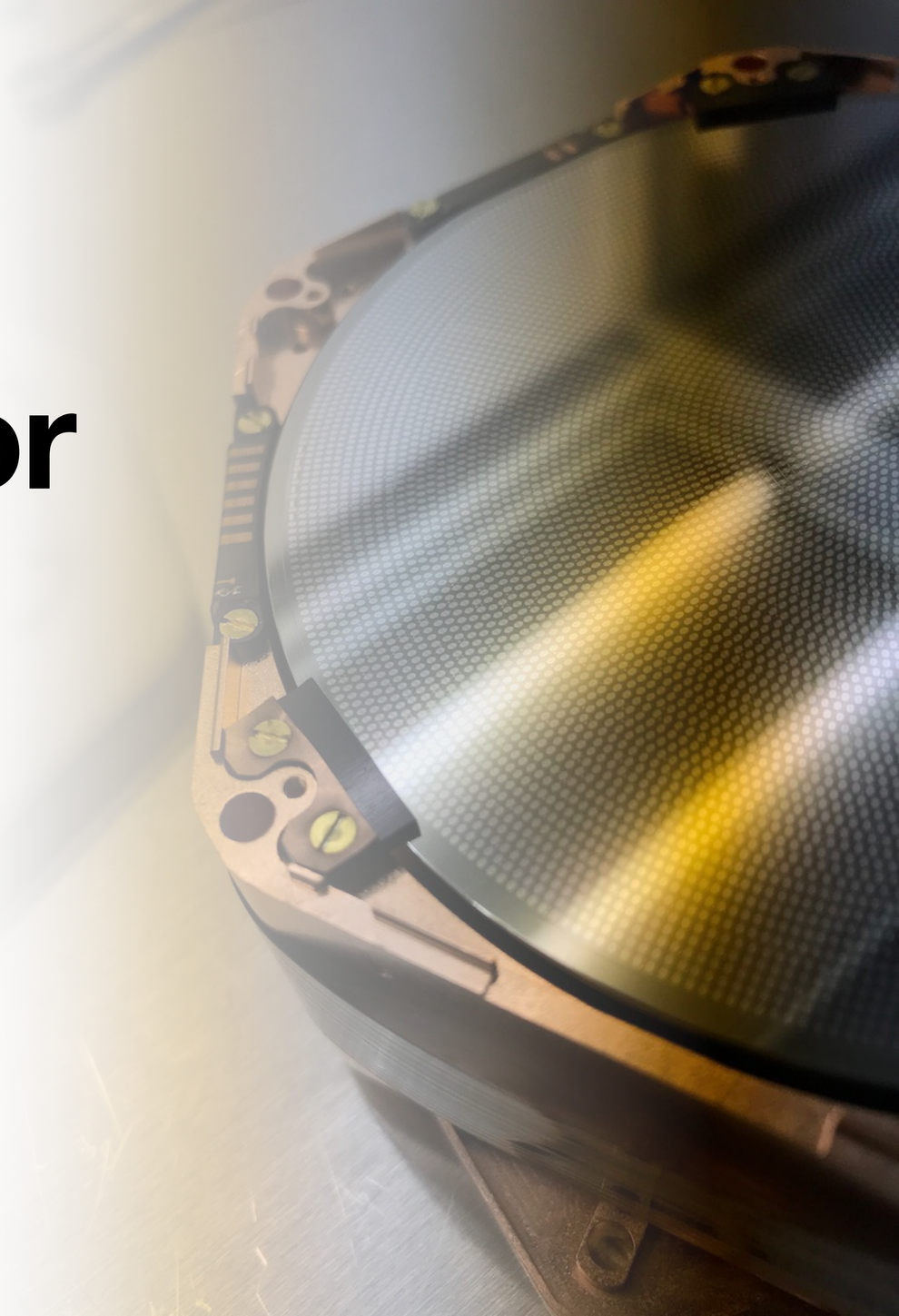
CPAD Workshop 2023
November 8

SLAC NATIONAL ACCELERATOR LABORATORY

SUPER CDMS Cryogenic Dark Matter Search



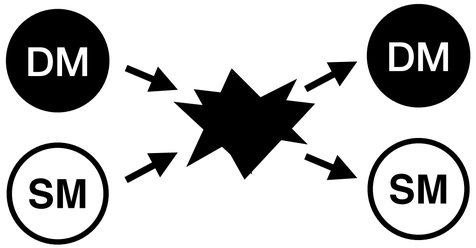
Outline

- Scientific background
- SuperCDMS SNOLAB detectors
- Detectors for meV-keV signals

Dark Matter

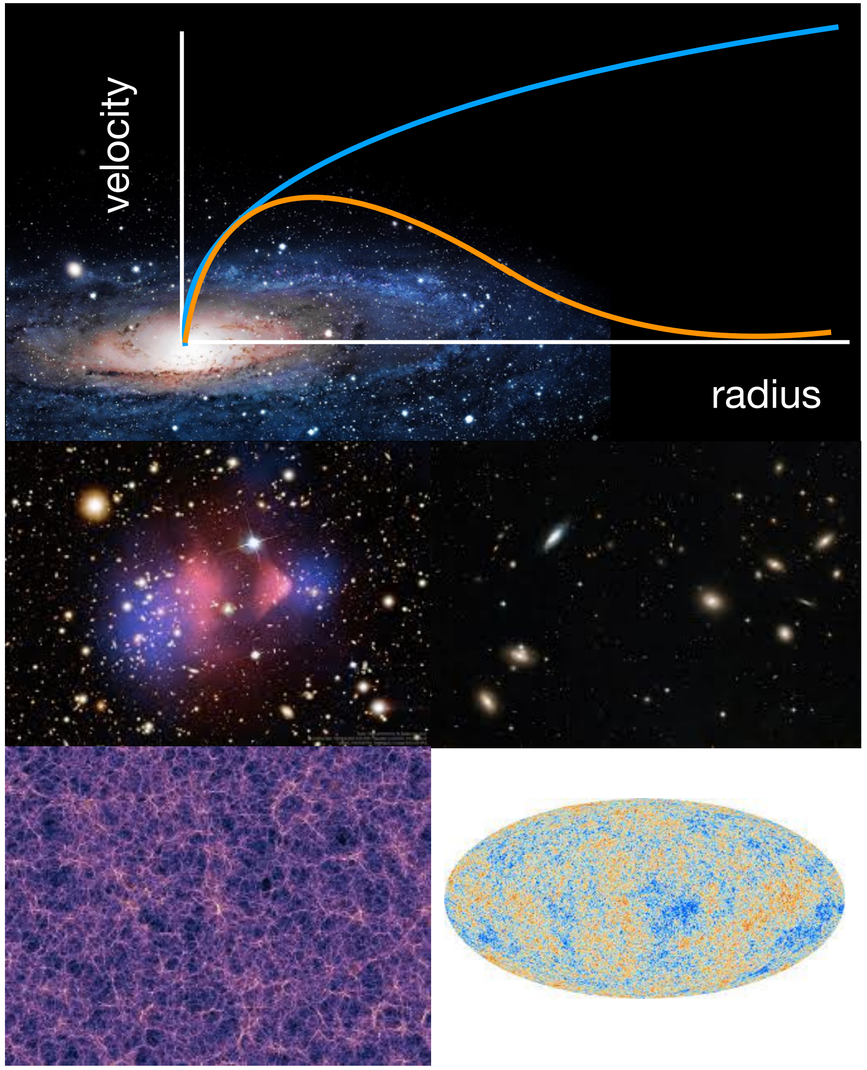
- There is evidence for dark matter (DM), but its nature remains unknown
- 84% of the matter in the Universe
- Global effort to find particle DM, following four main strategies:

1. Direct detection
2. Indirect detection
3. Collider searches
4. Astrophysical probes



$$R = N_{\text{targets}} \sigma \frac{\rho_{\text{DM}}}{M_{\text{DM}}} v_{\text{DM}}$$

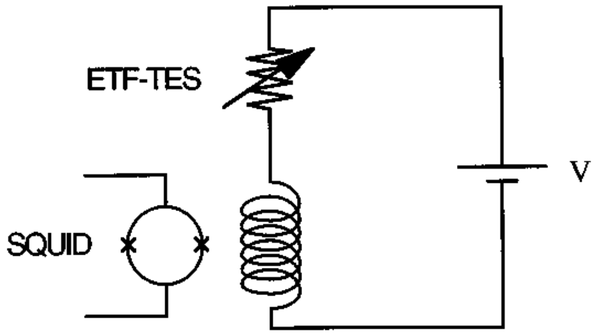
Goodman & Witten 1985
PRD 31 12



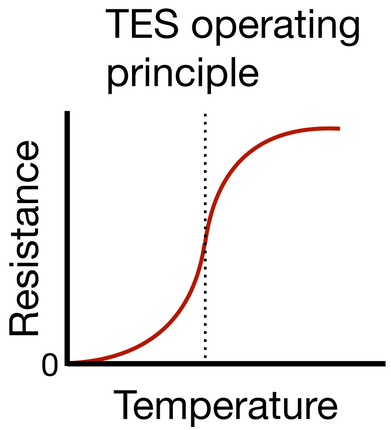
Transition-Edge Sensors on Crystals

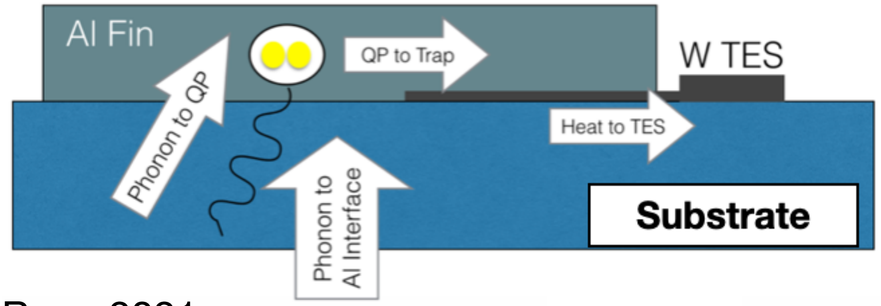
- Transition-edge sensors (TESs) operate in the superconducting transition region to sensitively measure temperature changes
- In particular, sensitivity to phonons or charges that break Cooper pairs
- Charge energy resolution enhanced by high voltage biasing (NTL effect)
- Single electron-hole resolution has been achieved

e.g.
Romani+ 2018 APL 112 043501
Hong+ 2020 NIMPA 963 163757



Irwin+ 1995
RSI 66 5322

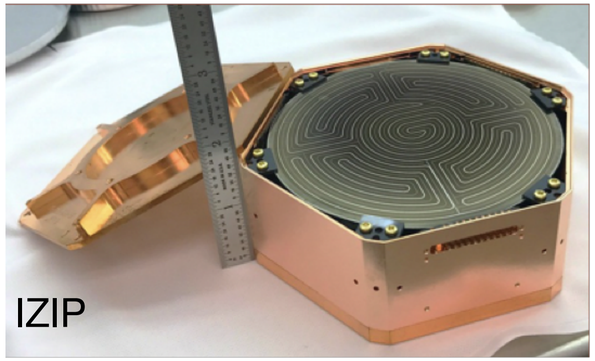


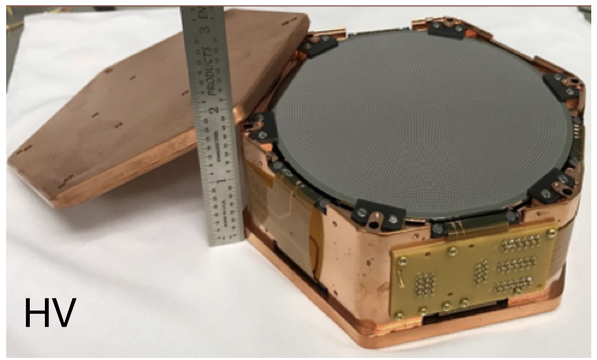


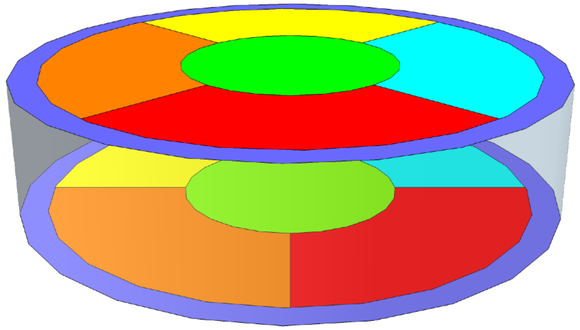
Ren+ 2021
PRD 104 032010

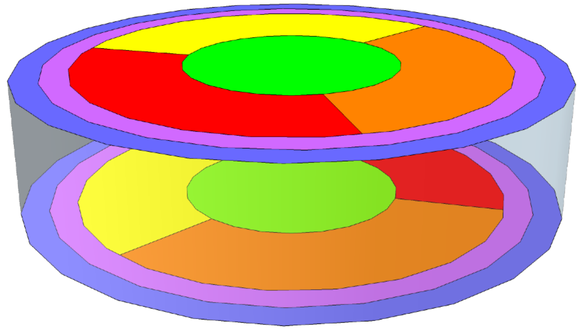
SuperCDMS Detectors

- High voltage (HV) and Interleaved Z-sensitive Ionization and Phonon (IZIP) designs
- SQUIDs for phonon circuit, HEMTs for charge



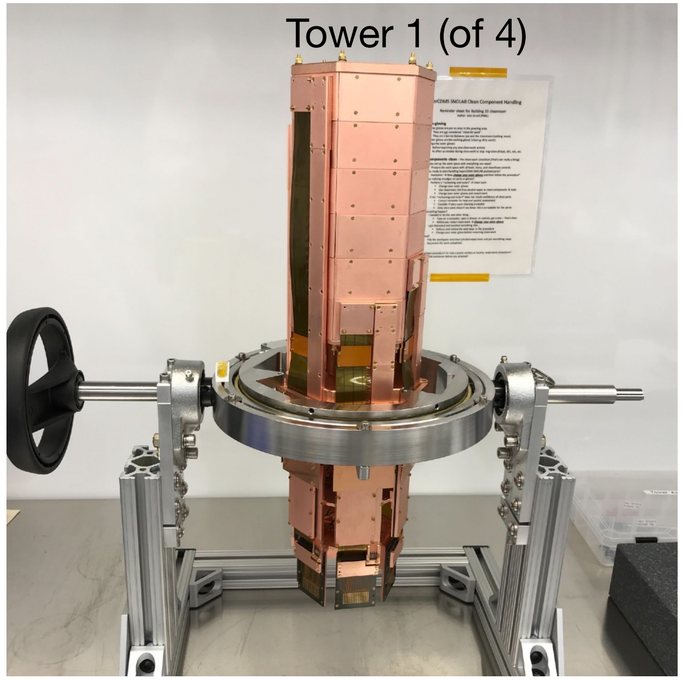






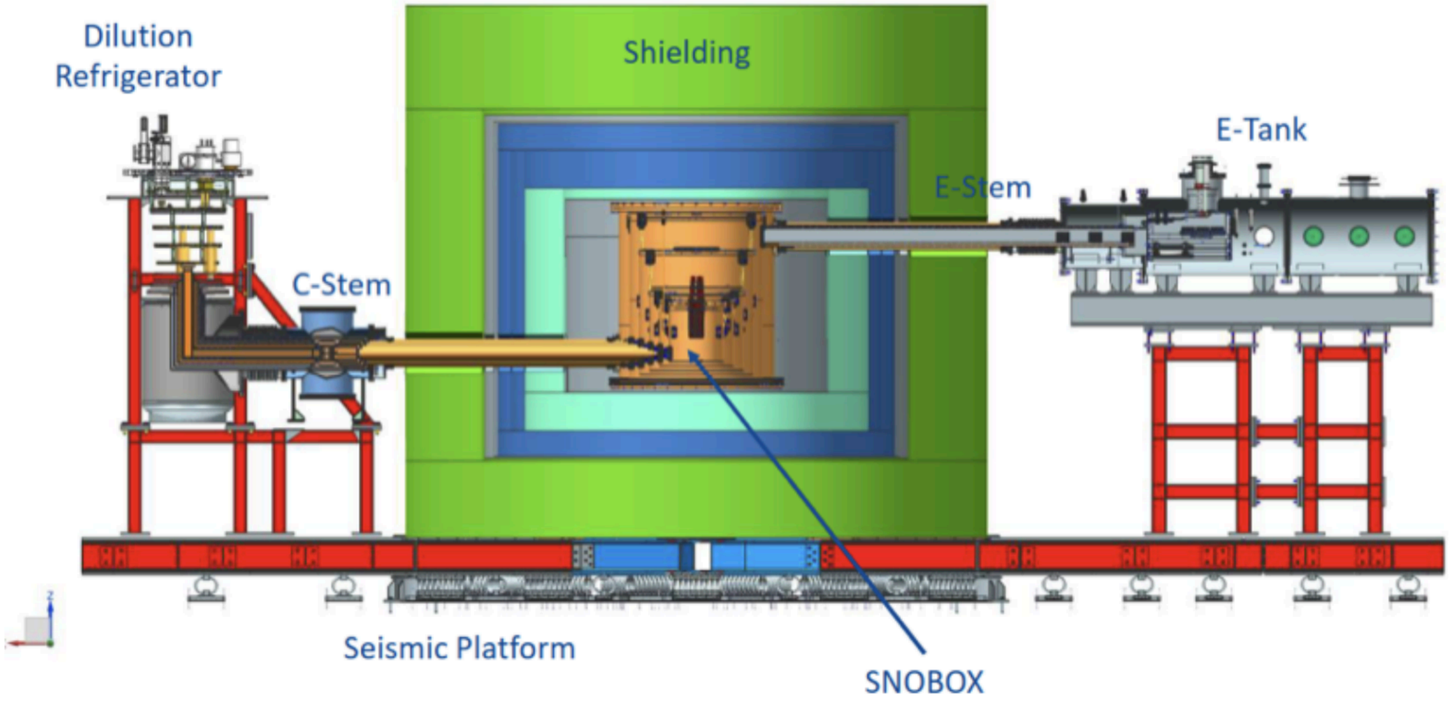
SuperCDMS 2022
arXiv:2203.08463

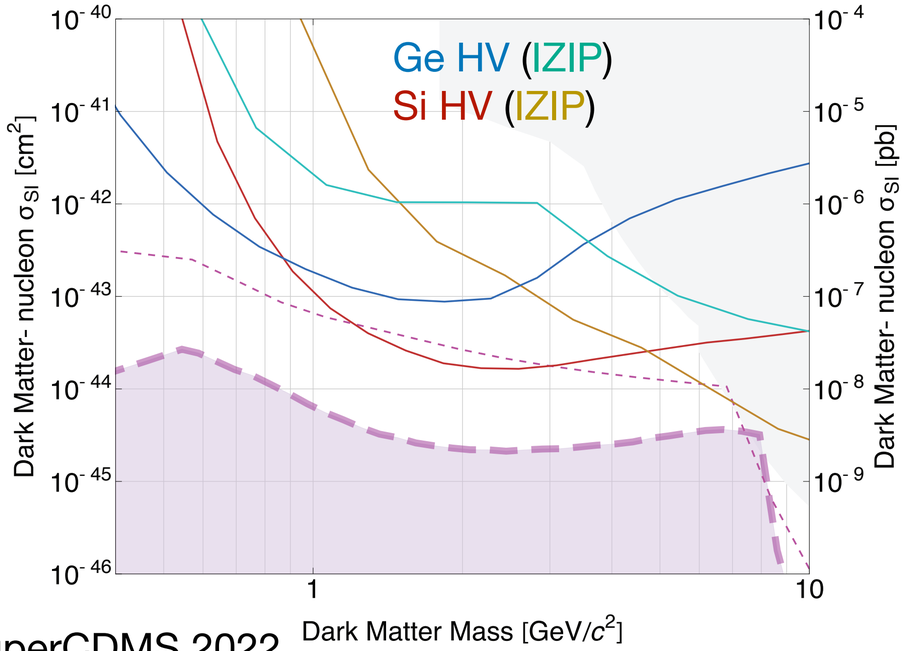
	iZIP		HV	
	Ge	Si	Ge	Si
Number of detectors	10	2	8	4
Total exposure [kg·yr]	45	3.9	36	7.8
Phonon resolution [eV]	33	19	34	13
Ionization resolution [eV_{ee}]	160	180	–	–
Voltage Bias ($V_+ - V_-$) [V]	6	8	100	100



SuperCDMS SNOLAB

- Successor to the Cryogenic Dark Matter Search (CDMS)
- Uses Si and Ge detectors, cooled to 30 mK, 2 km underground (at SNOLAB)
- Sensitive to nucleon-coupled 0.5–5 GeV/c^2 DM, $\sigma_{SI} \sim 10^{-43}$ cm^2





SuperCDMS 2022
arXiv:2203.08463

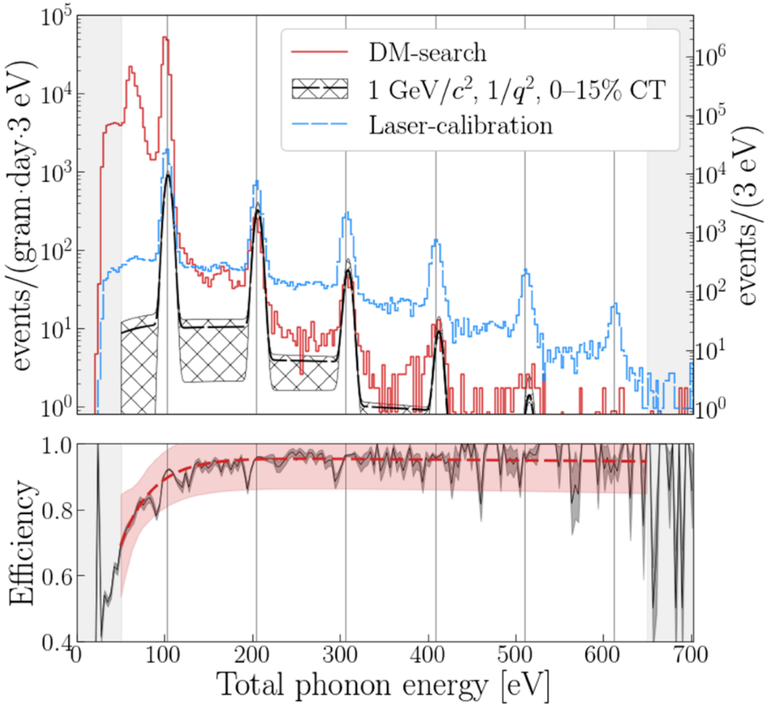
meV-keV Signals

- There is increasing interest in sub-MeV DM
  - axion-like particles, dark-sector dark matter, WIMPs
- The maximum energy transfer in an elastic scattering nuclear-recoil event is approximately:

$$\Delta E \approx \frac{2\ \mathrm{meV}}{A}\left(\frac{m_{\mathrm{DM}}}{1\ \mathrm{MeV}}\right)^2$$

Griffin+ 2021
PRD 103 075002

- Also a puzzling low-energy excess (Osmond Wen talk)

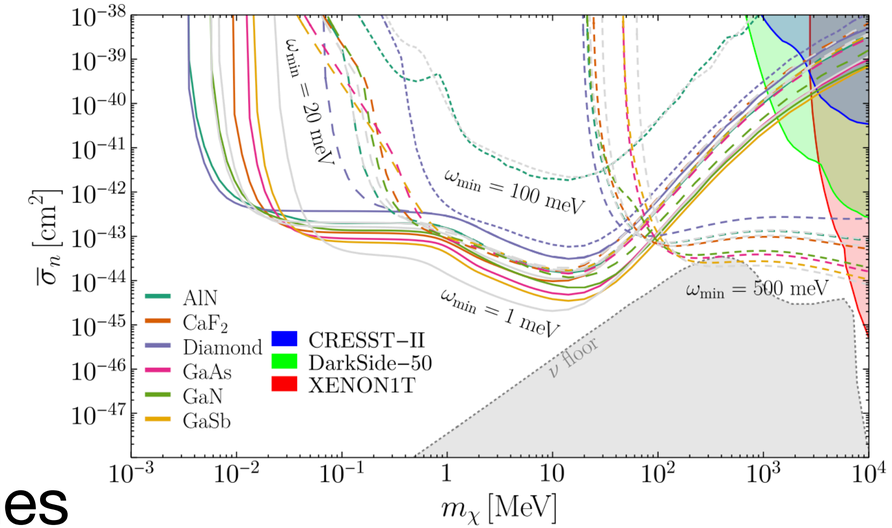


Amaral+ 2020
PRD 102 091101

Carbon-based Detectors

Kurinsky 2019 PRD 99 123005
Griffin+ 2021 PRD 103 075002

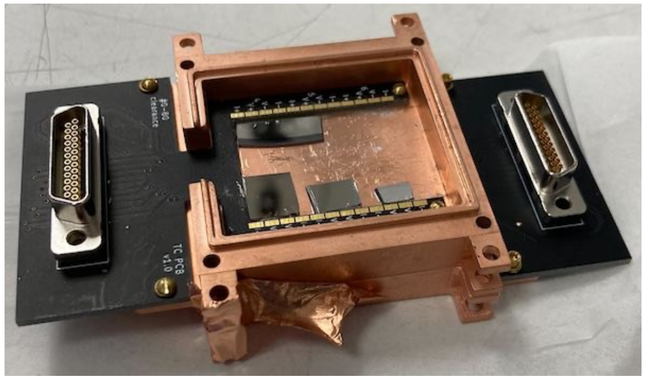
- Increased sensitivity to lighter DM particles due to lighter carbon nucleus (compared to Si, Ge)
  - Higher sound speed → longer-lived phonons
  - Higher bandgap → lower charge leakage
  - SiC structure also enables directional DM searches



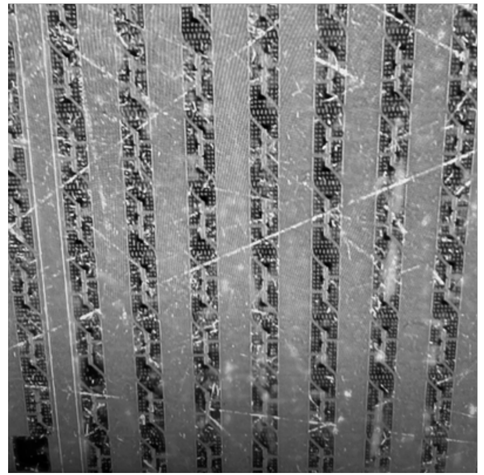
Griffin+ 2020 PhRvD 101 055004

- We are tuning fabrication procedure on PCVD diamond and 4H-SiC

Superconducting film deposition samples

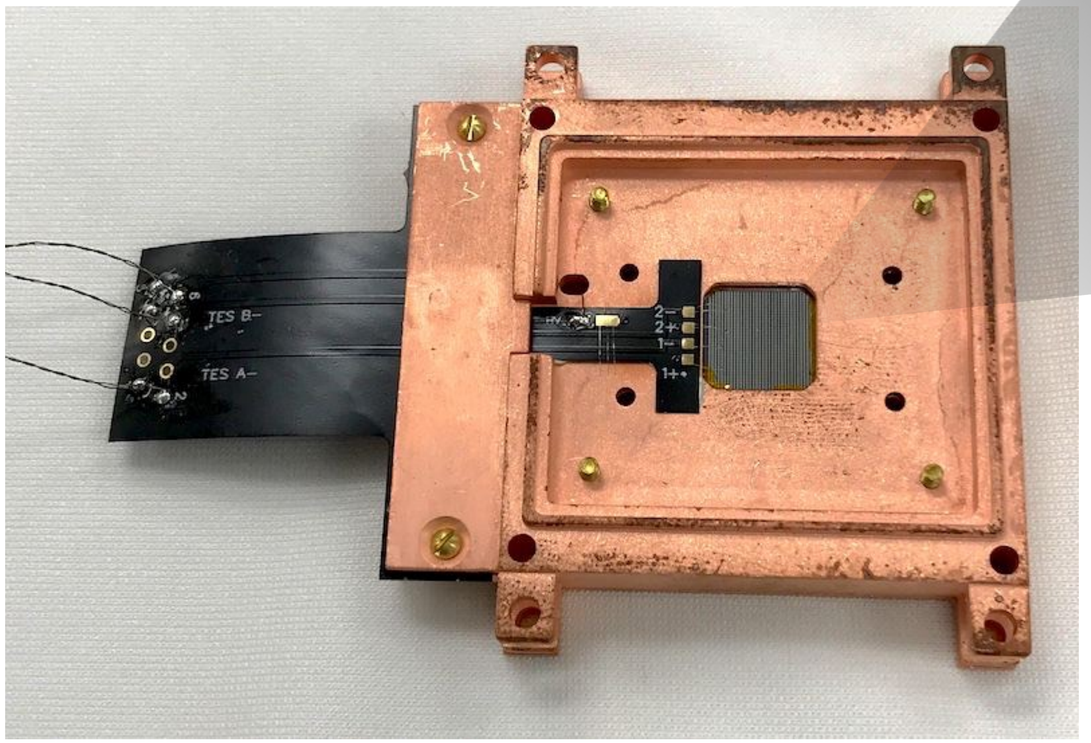


TESs on diamond

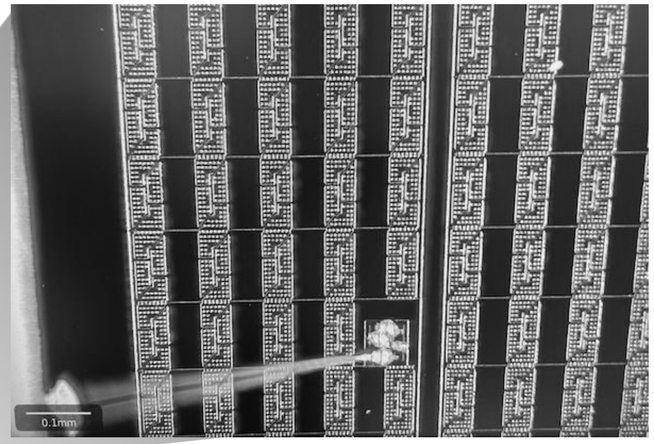


Detector Fabrication at Stanford

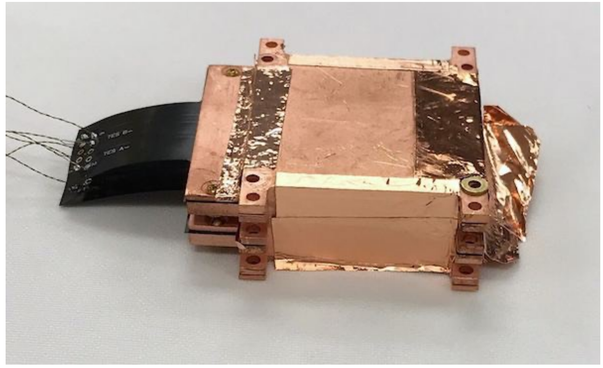
- 1cm^2 Si HVeV devices fabricated at SLAC
- Convenient detector box design
- Awaiting testing

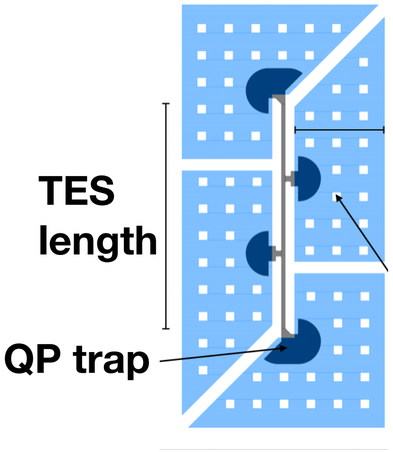


Parallel TES arrays



2-detector "tower"



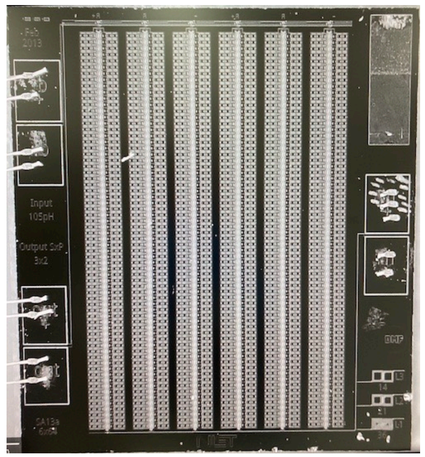


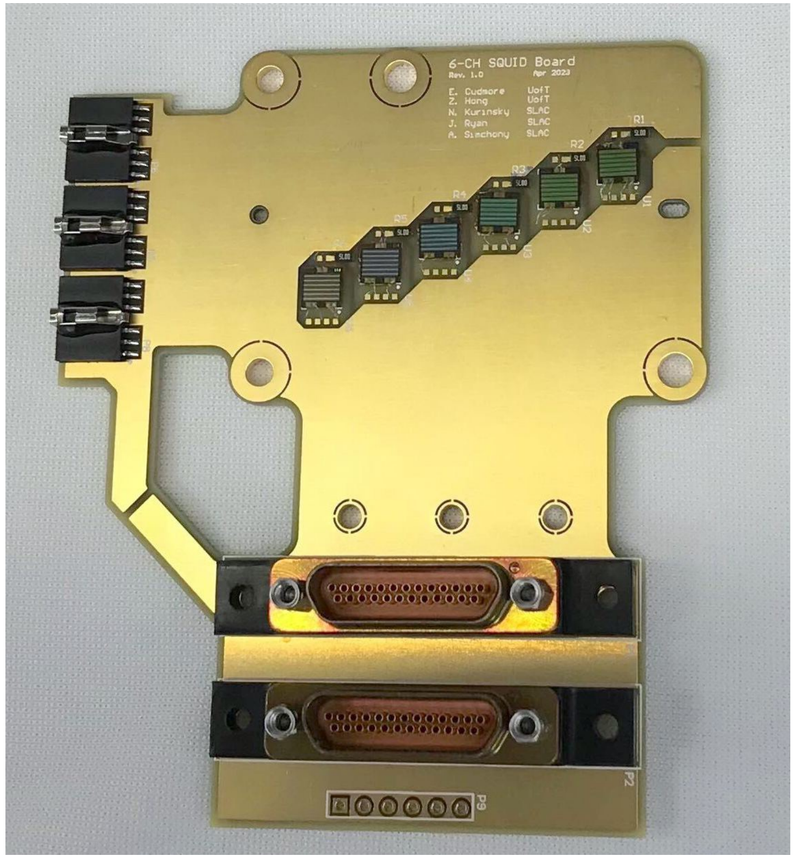
Ren+ 2021
PRD 104 032010

Readout System

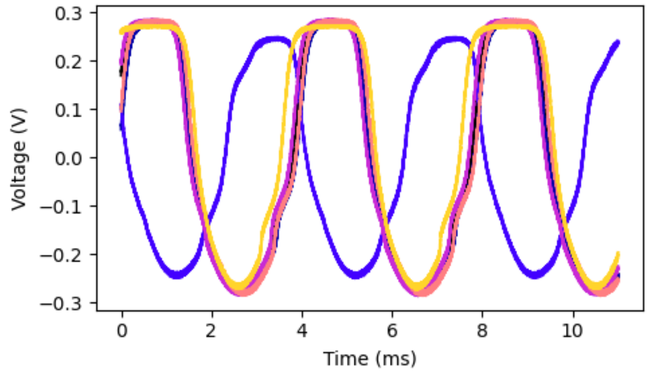
- New readout architecture, improving on SuperCDMS design, to facilitate device testing
- 6-channel SQUID board:

NIST SA13a

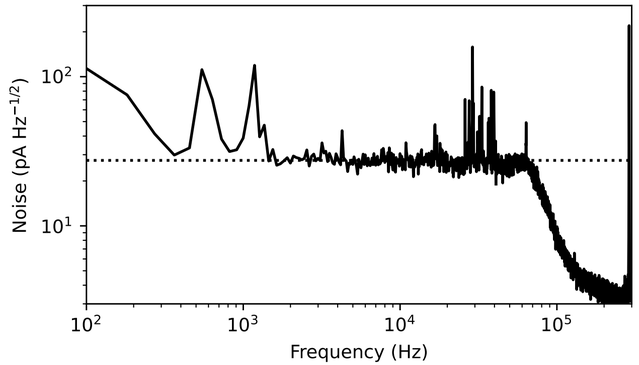




Modulation curves x6

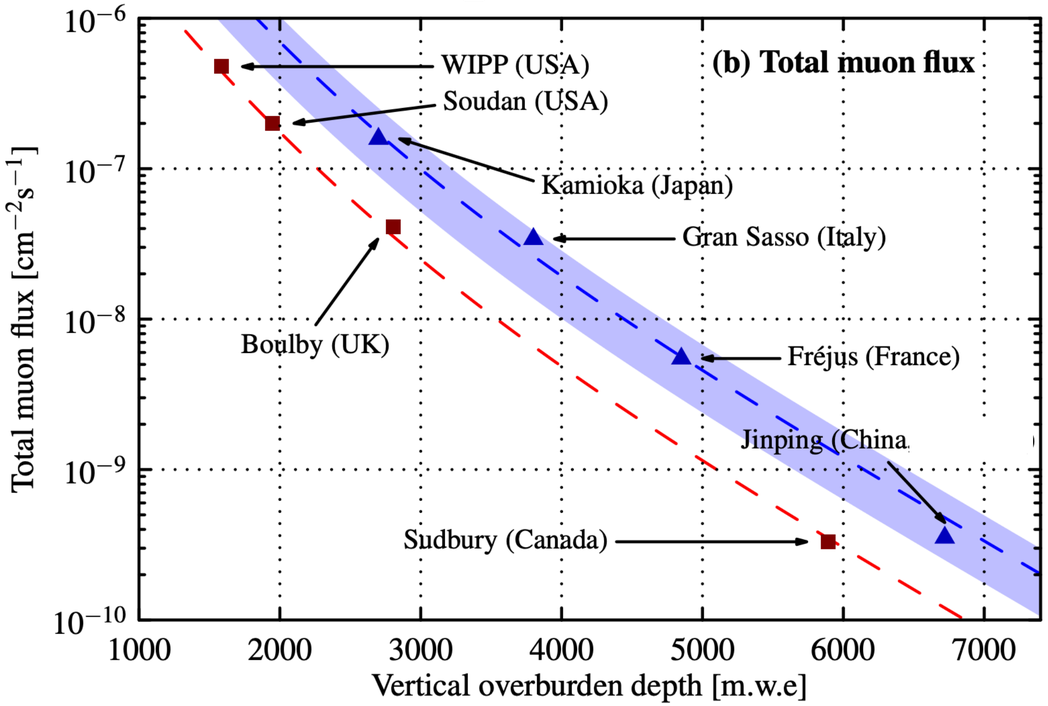


Noise with electrical short as "TES"



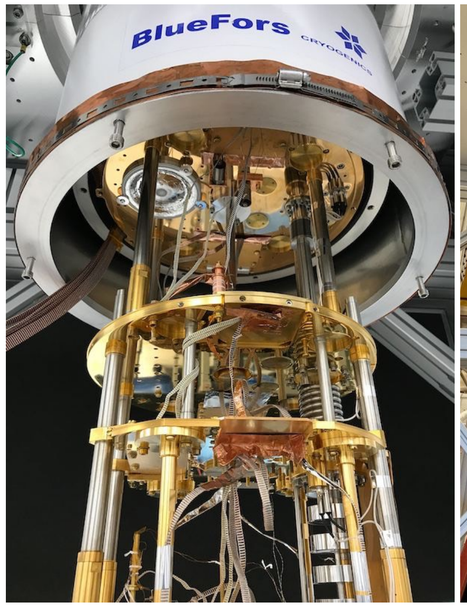
Detector R&D Pathway

- CDMS-related cryogenic testing at SLAC done in a BlueFors dilution refrigerator
- Recently added an Oxford with R&D focus
- Plans for detector testing in CUTE @ SNOLAB in 2024



Guo+ 2021 CPC 45 2 025001

SLAC dilution refrigerators



CUTE
@ SNOLAB

Other Ongoing Work

- Quantum sensors Chou+ 2023 arXiv:2311.01930
  - Kinetic inductance devices
  - SQUATs (Caleb Fink talk)
- Low-bandgap materials with SPLENDOR (Sam Watkins, Arran Phipps posters)
- Calibration with a micro-electromechanical system (Noshin Tabassum talk)

Summary

- SuperCDMS SNOLAB detectors allow search for 0.5–5 GeV/c^2 DM with unprecedented sensitivity
- Next-generation CDMS-style detectors in development, with focus on important lower-energy signals
- Work done in collaboration with:

Jadyn Anczarski
Paul Brink
Blas Cabrera
Elspeth Cudmore
Ziqing Hong
Noah Kurinsky
Richard Partridge
Chiara Salemi
Aviv Simchony
Zoë Smith
Kelly Stifter
Noshin Tabassum
Betty Young

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