Preparing for First Science: Commissioning and Outlook of SuperCDMS SNOLAB

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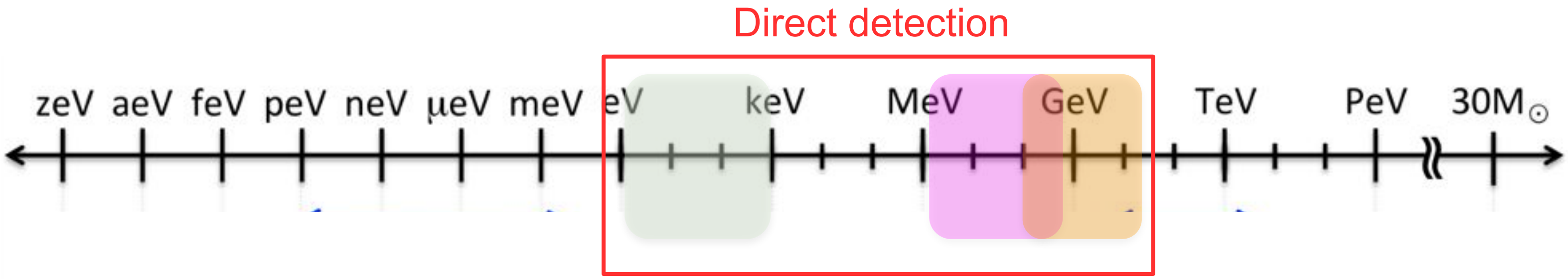
SLAC NATIONAL ACCELERATOR LABORATORY

SUPER CDMS Cryogenic Dark Matter Search

Stanford University

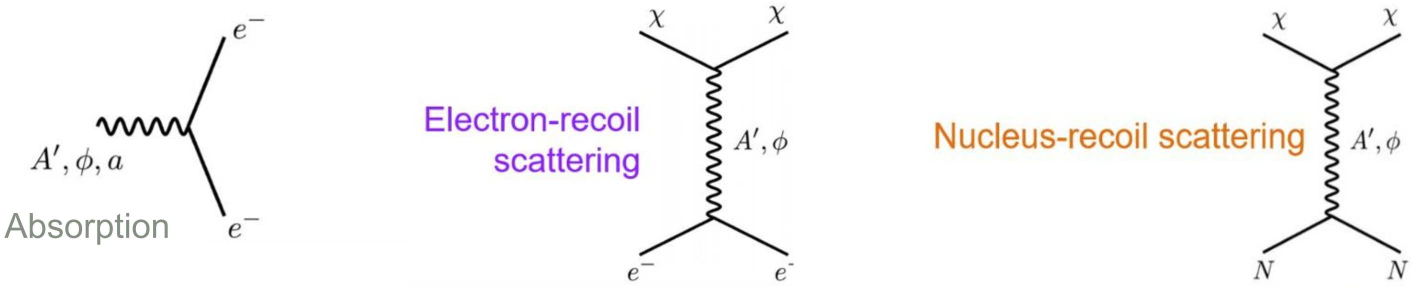
U.S. DEPARTMENT of ENERGY

The SuperCDMS SNOLAB experiment

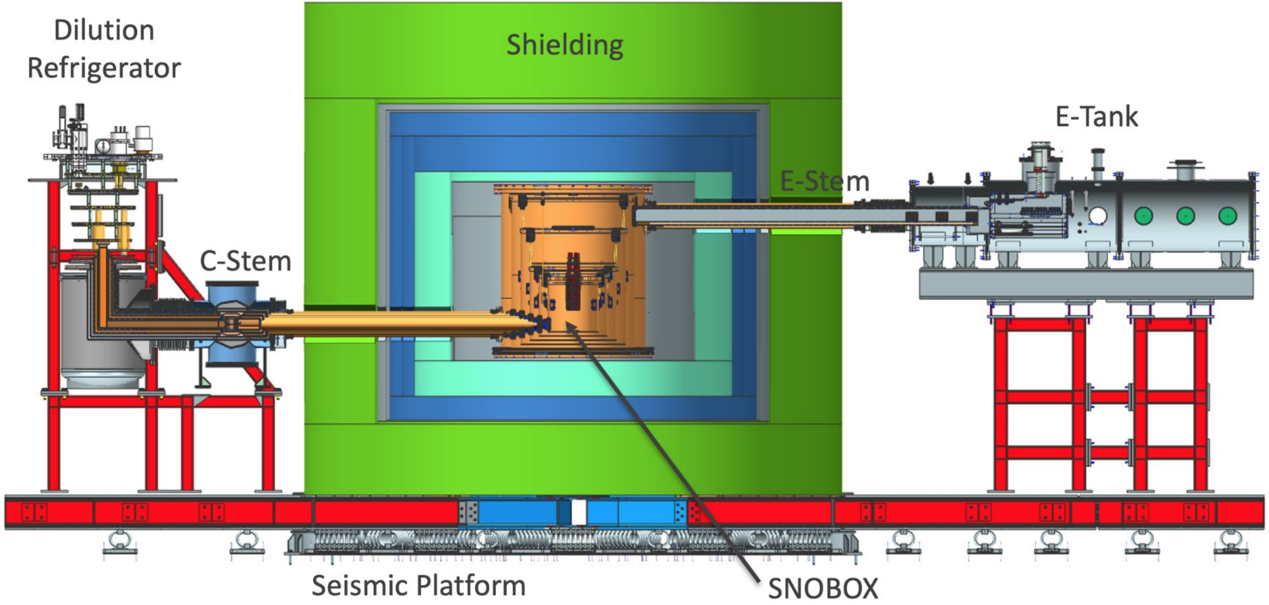


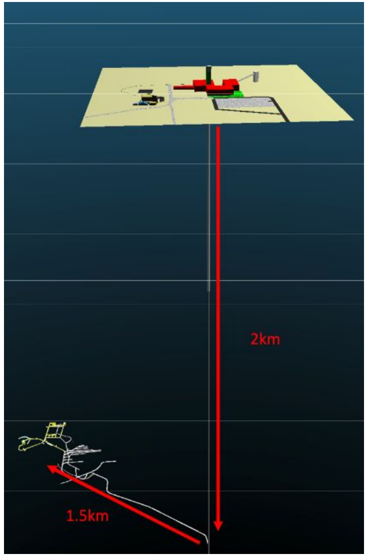
- Cryogenic experiment using **semiconductor targets (Si/Ge)**
- **Transition Edge Sensors** (TES) for **phonon readout**
- High Electron Mobility Transistor (**HEMT**) amplifier - based **ionization readout**

Broadband dark matter sensitivity via **multiple signal detection approaches**:



The SuperCDMS SNOLAB experiment

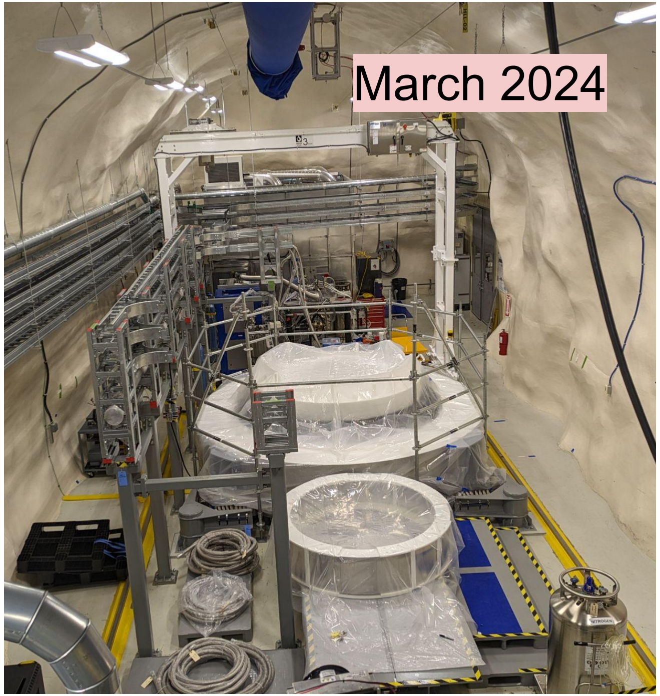




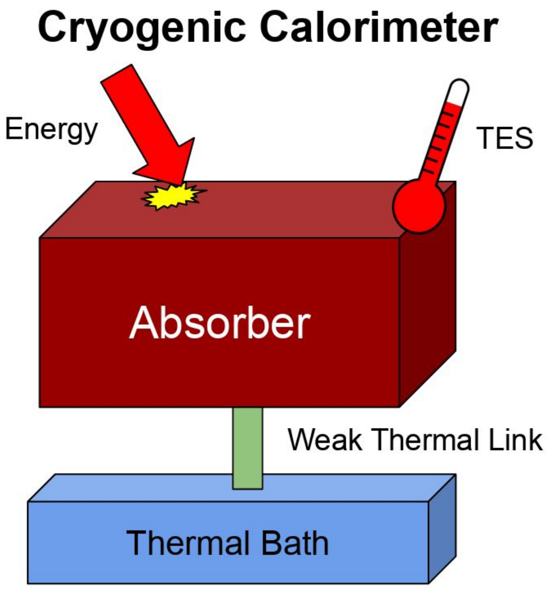
2 km of rock overburden (6000 m.w.e) at SNOLAB, Canada
→ Factor of 100 reduction in muon flux compared to previous generation

The experiment is preparing for its very first science run!

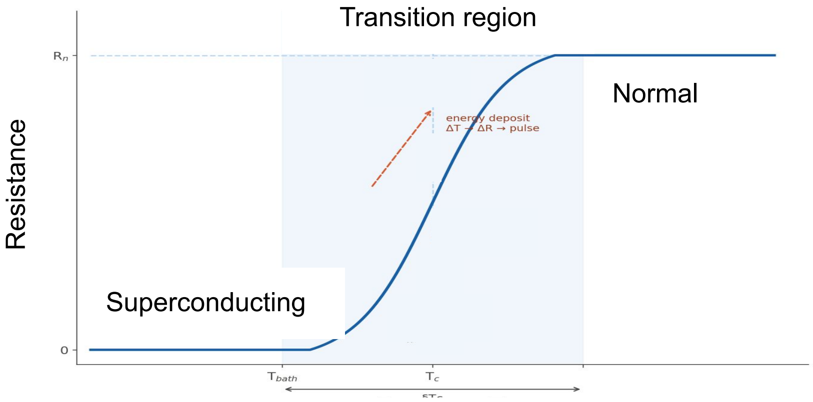
Installation and Integration phase formally ended in Jan 2026



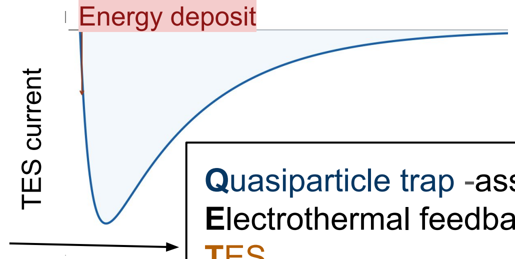
TES-based detection concept



Cryogenically cooled in dilution fridge



Quasiparticle traps to improve phonon collection efficiency



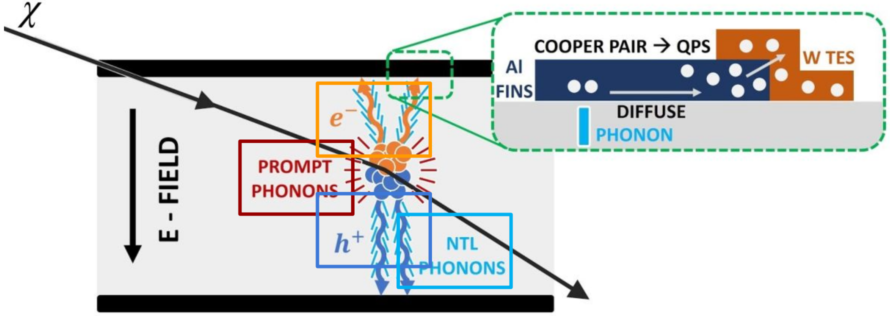
Quasiparticle trap -assisted **E**lectrothermal feedback **T**ES

Transition Edge Sensors combined with an energy absorber make excellent "cryogenic calorimeters"

Detection mechanism

Recoils from particle interactions can produce:

Prompt phonons
- Primary phonons
- Carry position information



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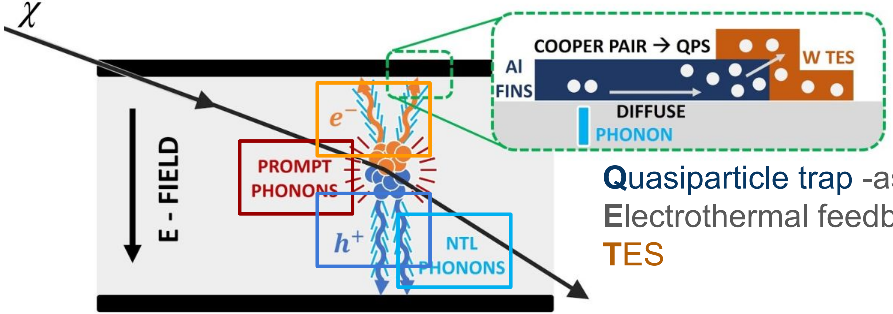

Quasiparticle trap -assisted **E**lectrothermal feedback **TES**

Prompt phonons

- Primary phonons
- Carry position information

Ionization (e^-/h^+)

- Charges are drifted with an E-field
- Amount of charge production (**ionization yield**) tied to nature of interaction (NR/ER)

Detection mechanism

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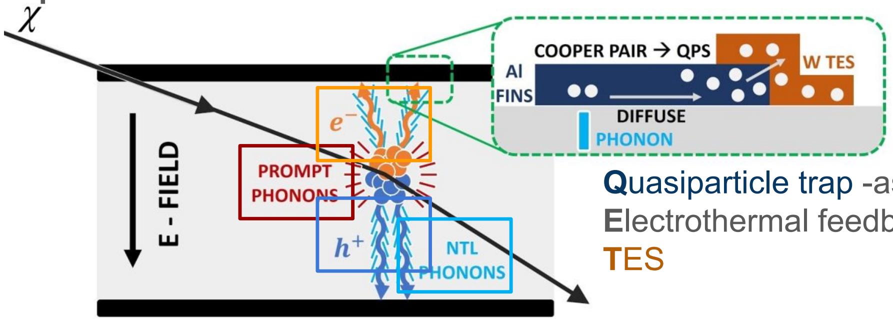

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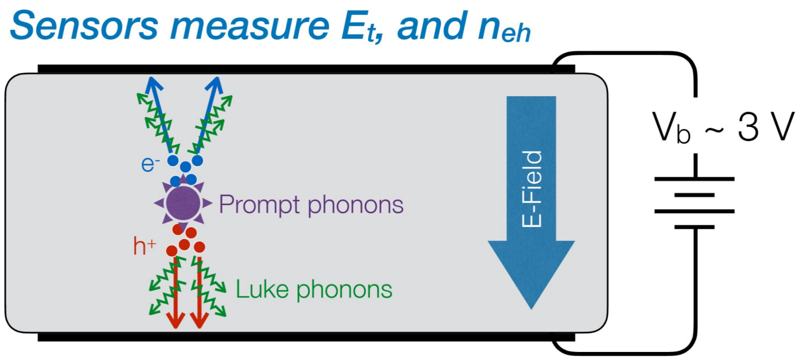
NTL phonons

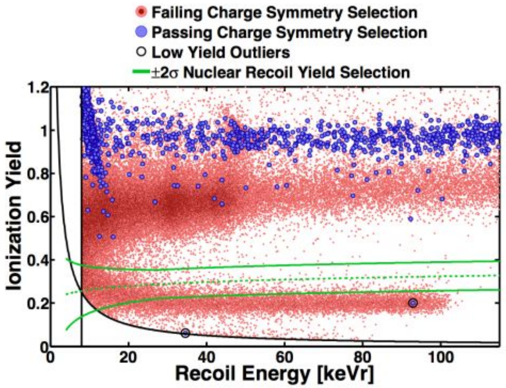
- Neganov-Trofimov-Luke effect
    - Accelerated charges produce phonons when drifted in an E-field
- Amplified phonon signal proportional to applied voltage

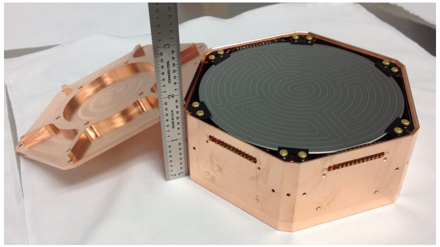
Optimized designs: SuperCDMS SNOLAB detectors

interleaved **Z**-sensitive **I**onization and **P**honon detectors (**iZIPs**)

- NR/ER discrimination leveraging heat and charge signals
  - Ionization yield acts as a good discriminant
- Enhanced fiducialization capabilities from charge signals







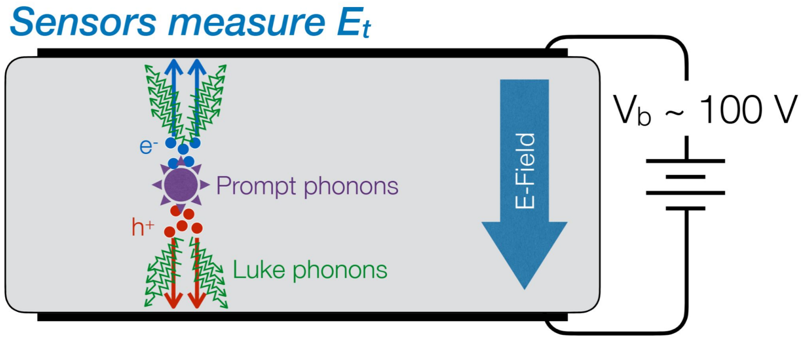
Optimized designs: SuperCDMS SNOLAB detectors

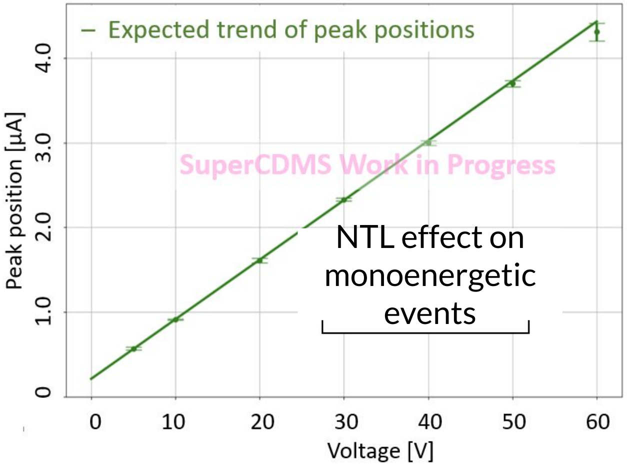
High Voltage detectors (HV)

- Low thresholds from amplified phonon signals
  - Up to ~x34 (27) in Ge (Si) via NTL effect

$$E_t = E_r + n_{eh}eV$$

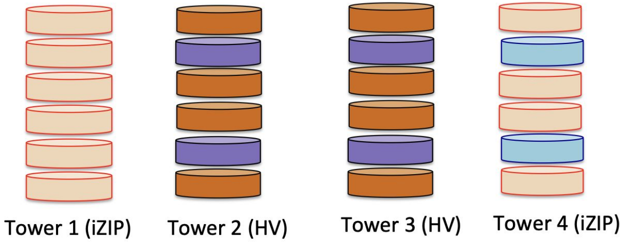
E_t → Total phonon energy
E_r → primary recoil energy
n_{eh} → avg. number of e^-/h^+ pairs
V → applied voltage

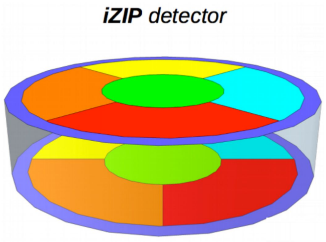


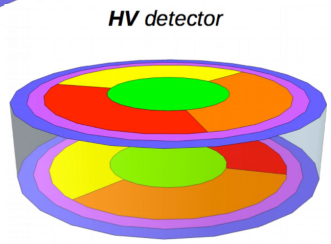


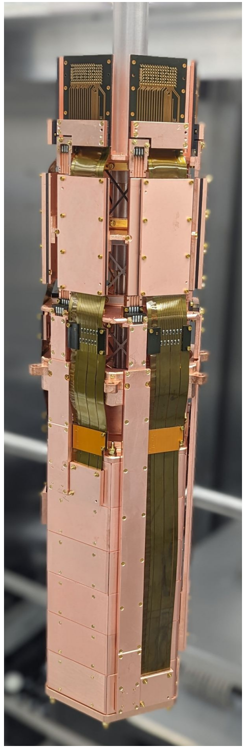
SuperCDMS SNOLAB payload

- **4 towers, 6 detectors each**
  - 10 Ge iZIPs
  - 2 Si iZIPs
  - 8 Ge HVs
  - 4 Si HVs
- **28.8 kg payload**
  - 0.6 kg per Si detector
  - 1.4 kg per Ge detector
- **Channel segmentation for position reconstruction**
  - 12 phonon channels
  - 4 charge channels on iZIPs





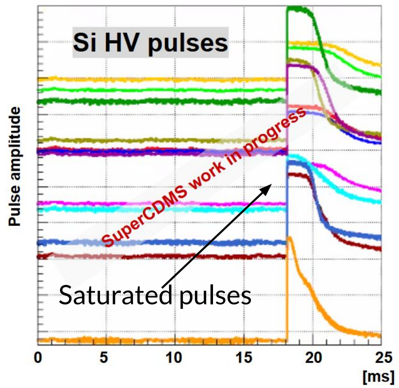


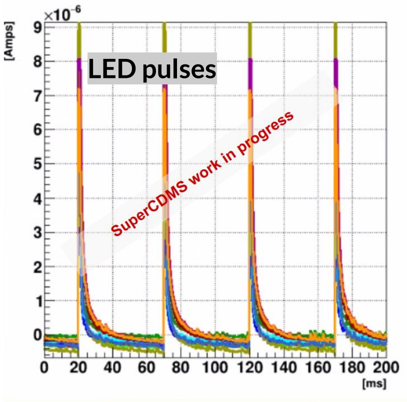


SuperCDMS SNOLAB status

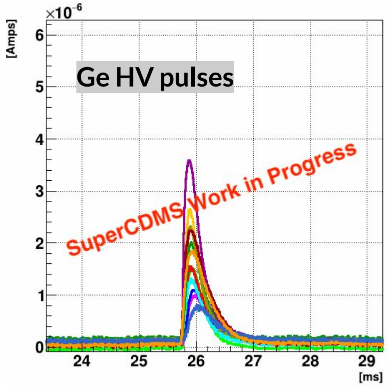
Experiment commissioning began in Jan 2026

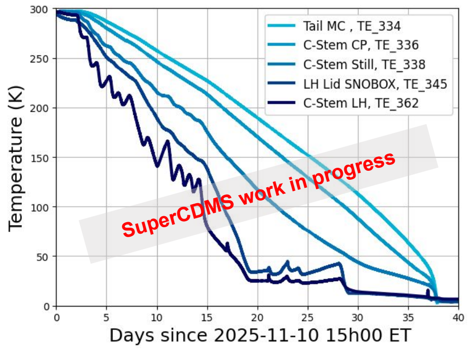
- ★ Lowest base temperature achieved: ~20 mK
- ★ Successful operation of cold detectors
  - ○ 100% of SQUIDs confirmed functional
  - ○ 100% of phonon channels go superconducting at 20 mK





Detailed detector characterization in progress





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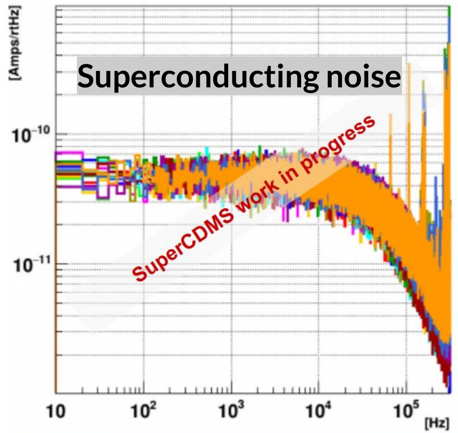
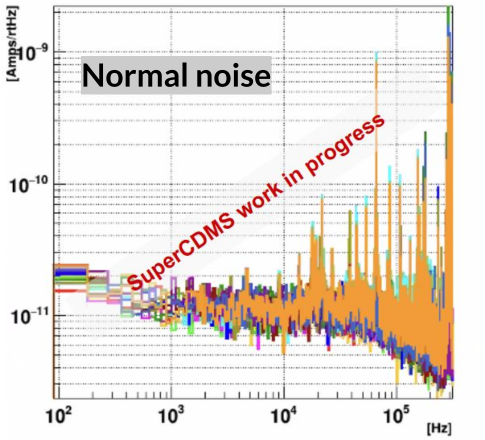
<u>**Up next:**</u>

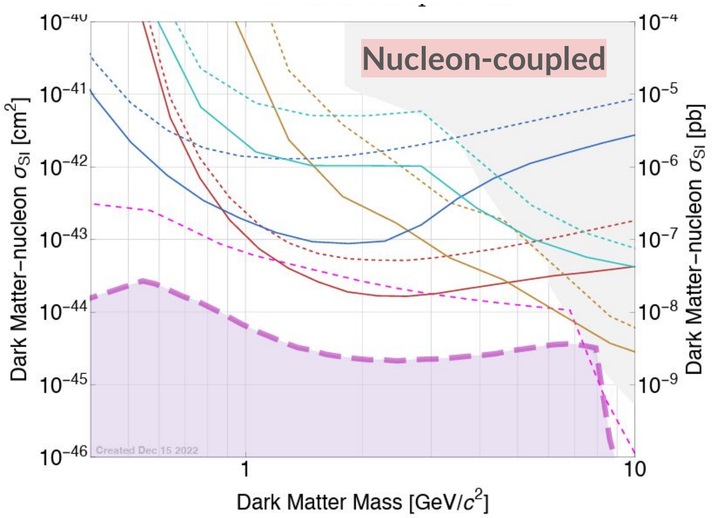
- ★ **Noise mitigation campaigns in progress**
- ★ **Science Run 1a expected to commence in Aug 2026**
- ★ **Calibration runs**

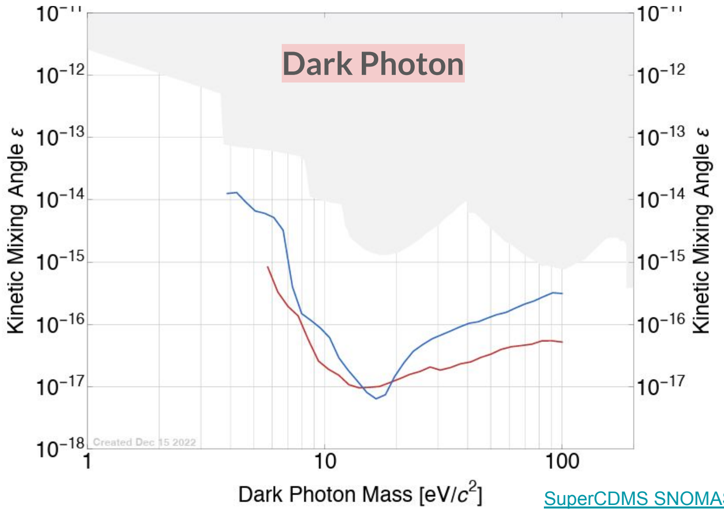




SuperCDMS SNOLAB science targets

Ge HV, Si HV, Ge iZIP, Si iZIP, current limits





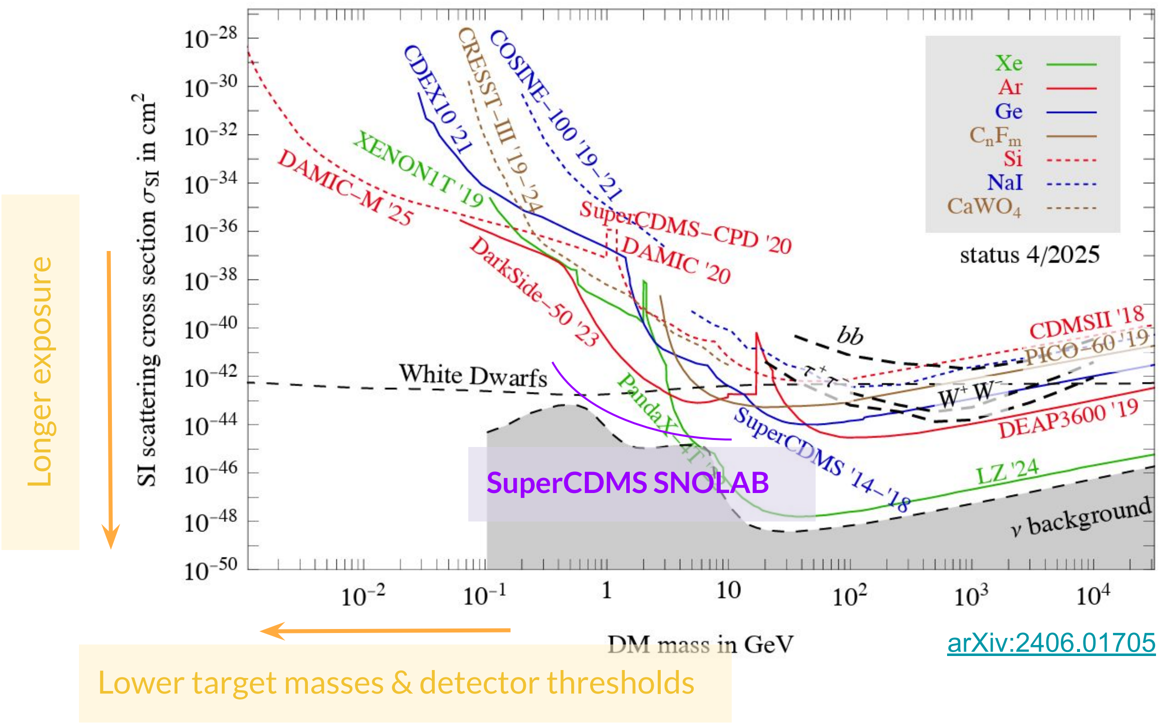
SuperCDMS SNOMASS projections

- ★ Low mass NR sensitivity → Si HV wins
- ★ Low cross section NR sensitivity at GeV-scale → Ge HV wins
- ★ Probing specific exotic models via ERs → Si/Ge HV

Looking beyond SuperCDMS SNOLAB

Low Energy Excess mitigation is key to opening up the sub-GeV regime for discovery

Direct Detection constraints on SI scattering

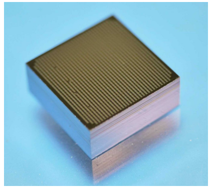


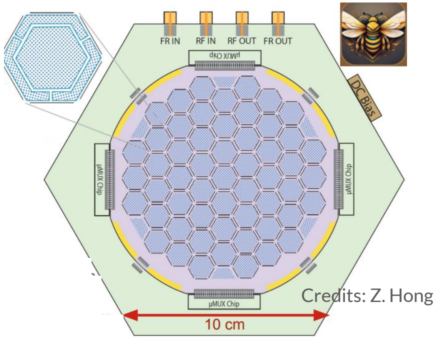
arXiv:2406.01705

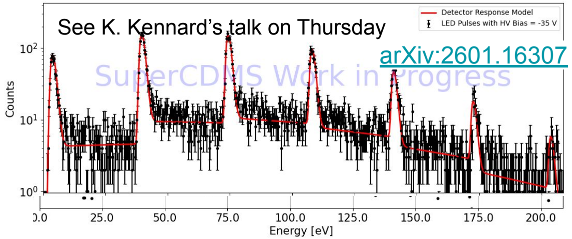
Many pathways for a SuperCDMS upgrade are being explored!!

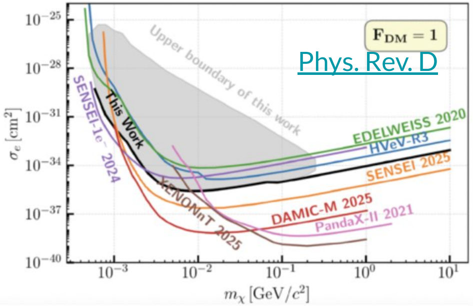
TES-based potential future payloads (HVeV, HoneyComb)

- **HVeV detectors (**🔼 energy resolution, ✅ low threshold)
  - Gram-scale chips; 1-2 cm wide
  - Excellent resolution : ~ 600 meV
  - Probing ERDM and dark photon parameter space, but lighter targets (e.g. SiC, C) can improve NRDM sensitivity
  - Position reconstruction possible with cryogenic, MEMs-based optical calibration source (**see A. Simchony's talk on Wednesday**)
- **HoneyComb (**🔼 energy resolution, ✅ low threshold, 🔼 position resolution, 🔼 exposure)
  - Scaling up HVeV without fully dicing wafers, leaving a small "bridge" for thermal conduction
  - Multiplexed readout
  - Potential means to mitigate Low Energy EXCESS backgrounds with "stress-free mounting"





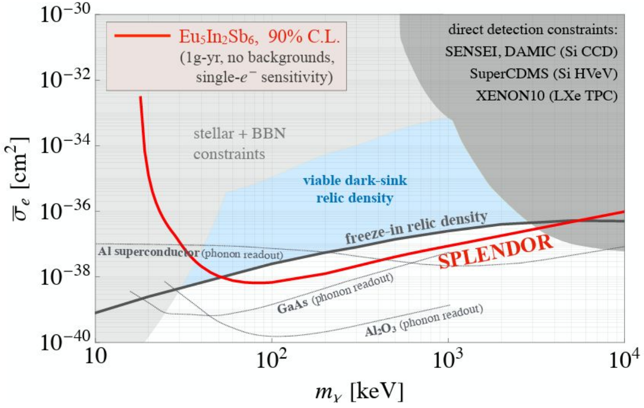


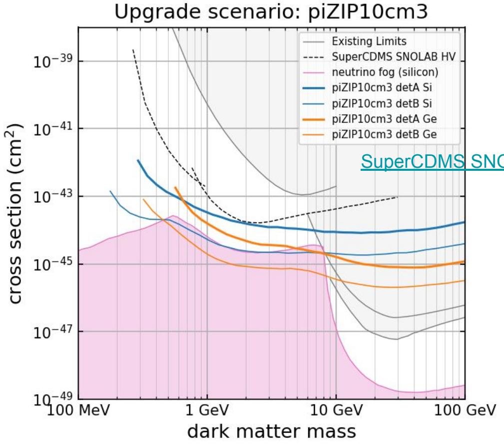


Charge-based potential future payloads (piZIPs, SPLENDOR)

- **SPLENDOR** (✅ low threshold, 🔼 position resolution)
  - Charge pulses are faster than phonon → better position resolution
  - Novel low bandgap semiconductors for charge-only detection
  - sub-eV detection thresholds, measured 7 electron resolution
  - Plans to further enhance resolution with quantum sensing readout
- phonon-**iZIPs** (✅ low threshold, 🔼 position resolution, 🔼 exposure)
  - iZIPs with power to discriminate between NTL and prompt phonons
  - Lower threshold from NTL gain, but retains good position sensitivity

arxiv:/2507.17782





SuperCDMS SNOMASS projections

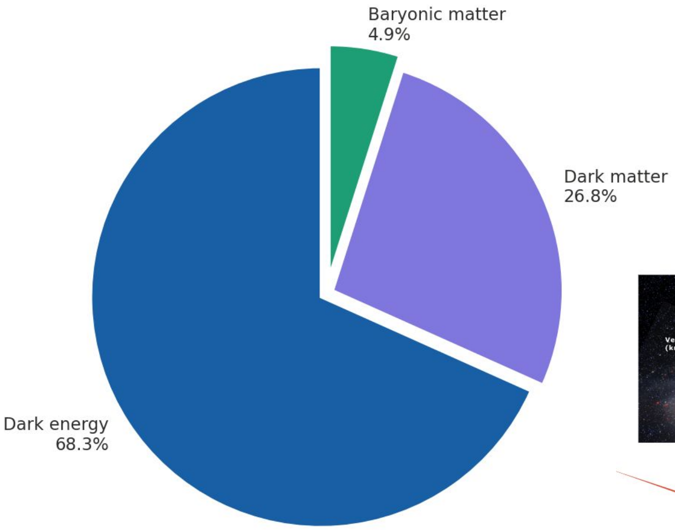
Summary

- Installation of SuperCDMS SNOLAB is complete
- Detector commissioning and characterization is underway
- Science R1a is planned for Aug, 2026
- Calibration runs will follow after
- SuperCDMS is anticipated to set world leading limits below 10 GeV/c^2
- Work towards SuperCDMS SNOLAB 2.0 is progressing actively with many viable candidates
    - HVeV, Honeycomb, SPLENDOR, piZIP (and maybe even quantum sensing (**see A. Droster's talk on Tuesday**)

SuperCDMS gratefully acknowledges supported from:

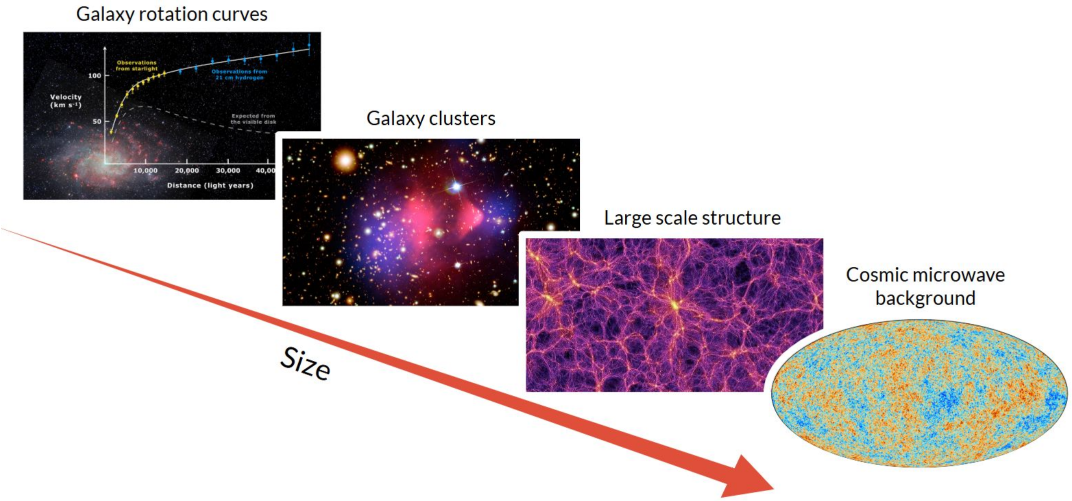
Backup slides

The familiar story of dark matter…



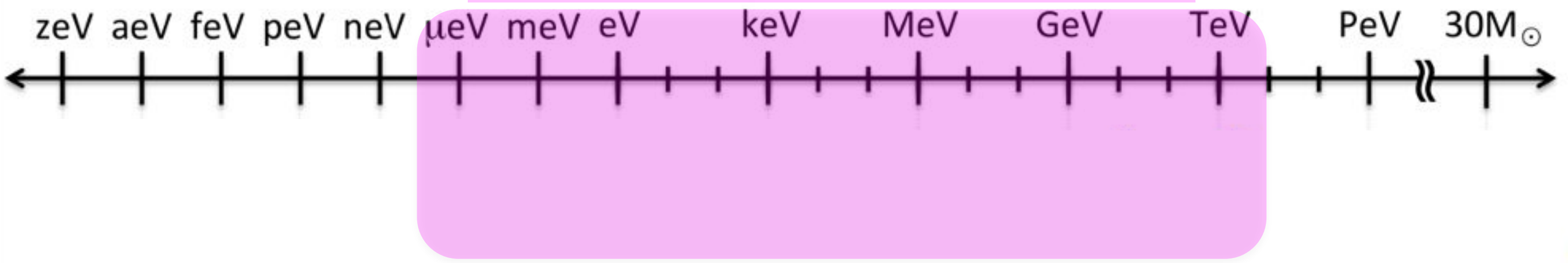
Source: Planck Collaboration, arXiv:1807.06209

Presence of dark matter is strongly supported by evidence at various astrophysical scales



Current dark matter landscape

ON-shell and OFF-shell searches

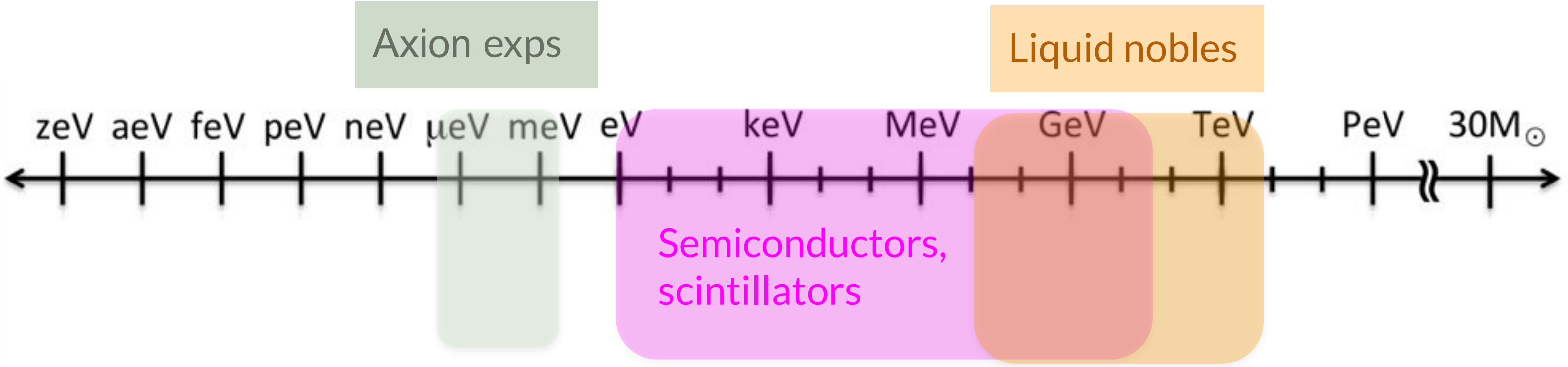


Collider searches probe a vast model set and multiple parameter spaces

On-shell searches look for resonance peaks; off-shell searches have a broad spectrum

Often limited by trigger thresholds and large “backgrounds”

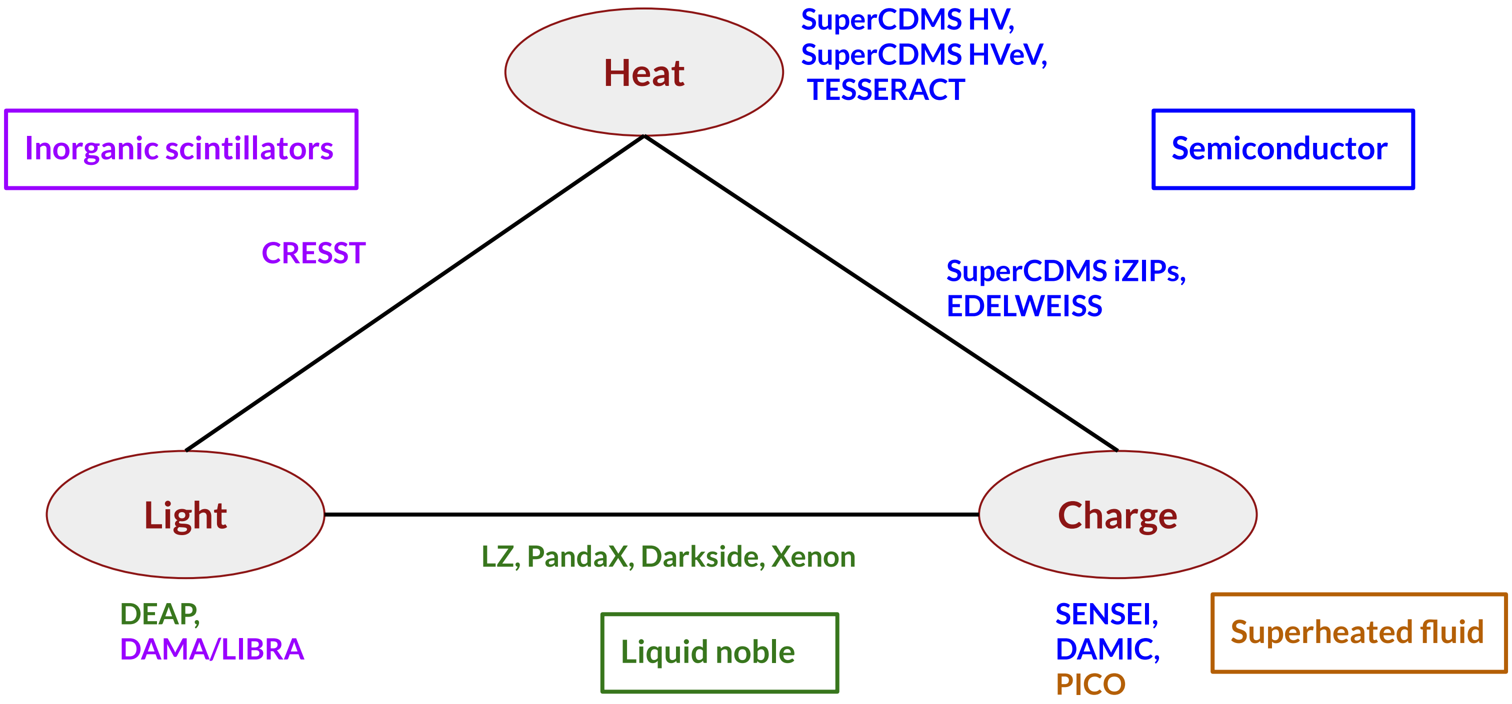
Direct detection focus



Specific category of candidates require specific target properties

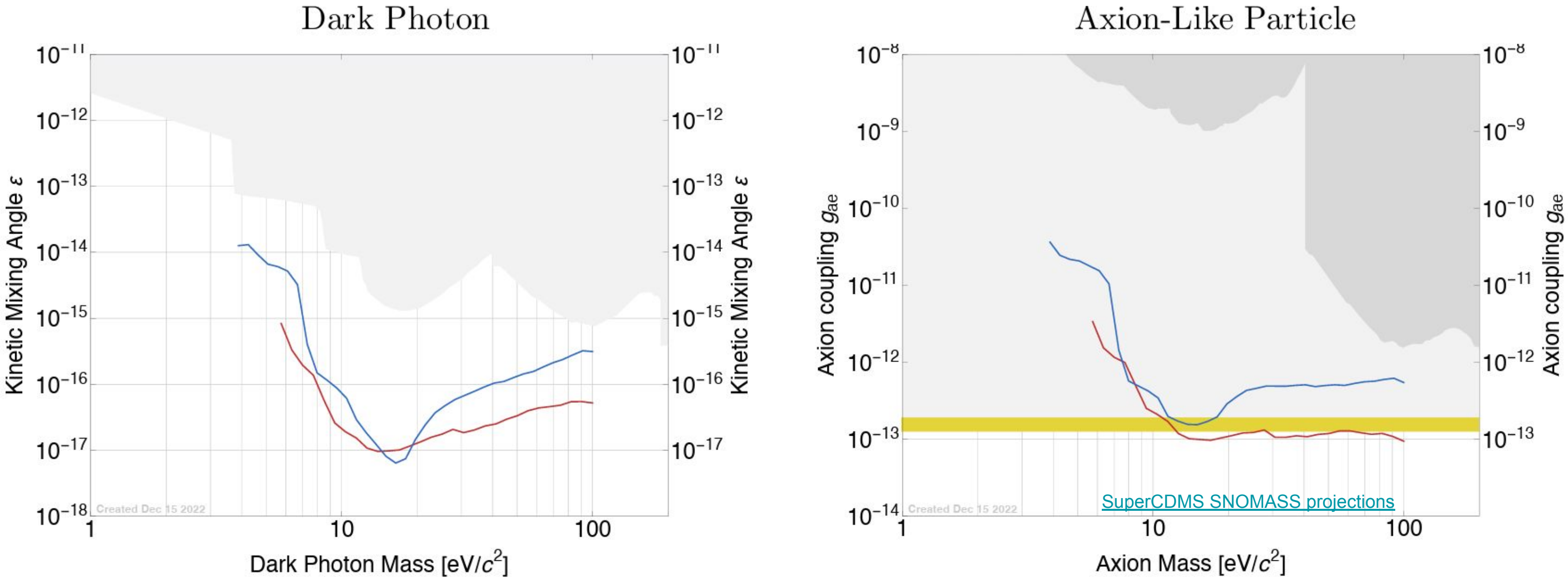
- Often probe same parameter space → directly comparable
  - Complimentary searches
- Every experiment is fairly broadband → capable of probing many models
- Require very low background environments

Direct detection experiments



SuperCDMS SNOLAB science goals

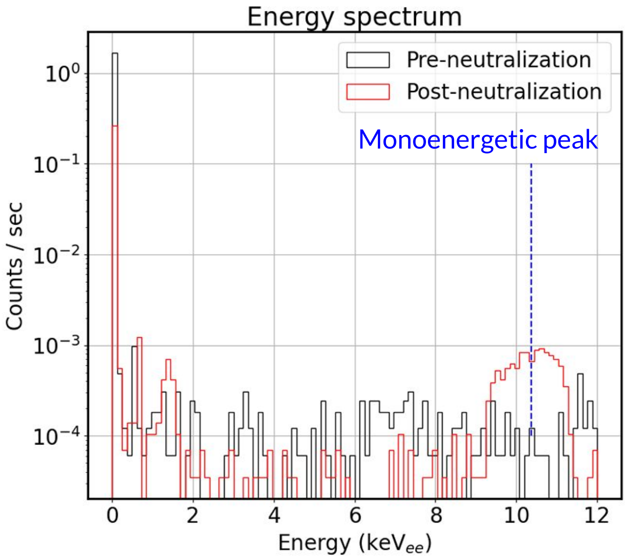
Ge HV, Si HV, current limits, ALP stellar cooling band



- ★ Dark photon sensitivity through absorption; signature is a spectral line
  - ○ Cross section tied to photoelectric cross section (x10 larger in Ge)
- ★ Axioelectric coupling probed via absorption for ALP searches
- ★ Migdal effect - based, Lightly Ionizing Particle searches, etc also possible

SuperCDMS SNOLAB : System-level challenges

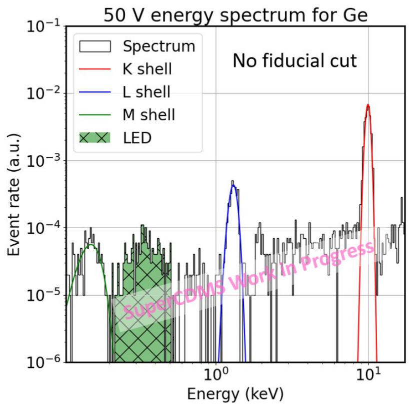
- **Turning on a large system with many moving parts for the first time…**
  - Understanding impacts of cryogenic infrastructure and electronics on detector noise
  - Optimizing charge readout performance
  - Developing detector neutralization schemes



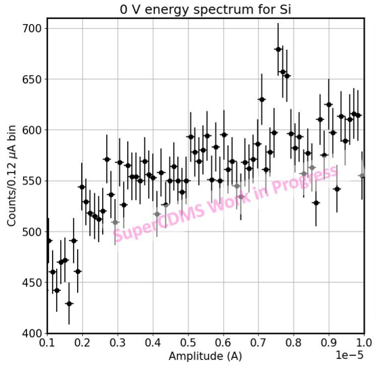
SuperCDMS SNOLAB Calibration plan

- ★ **Ge calibration with neutron activation**
  - ○ **Electron capture decay of ^{71}Ge** produces peak corresponding to atomic shells
  - ○ Calibration as low as ~100 eV
- ★ **Si calibration with Compton steps**
  - ○ Compton scattering off of atomic electrons produces “steps” corresponding to atomic shells
  - ○ Calibration as low as ~ 100 eV

Ge calibration spectrum

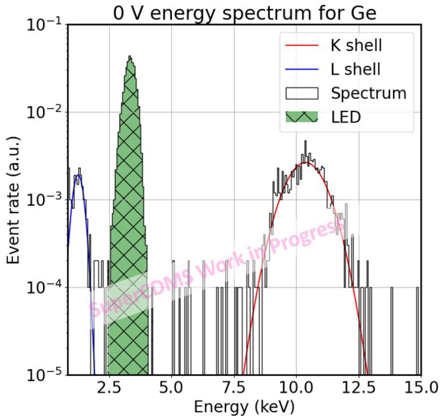


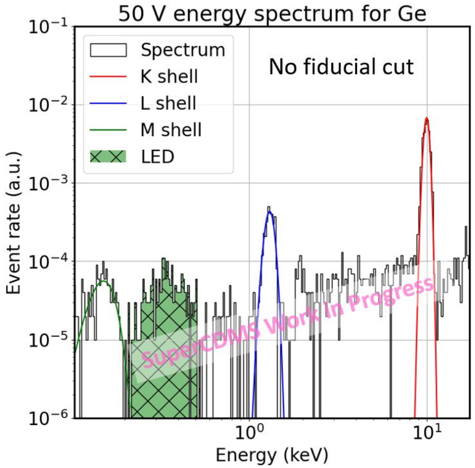
Si calibration spectrum



SuperCDMS SNOLAB: Calibration of Ge

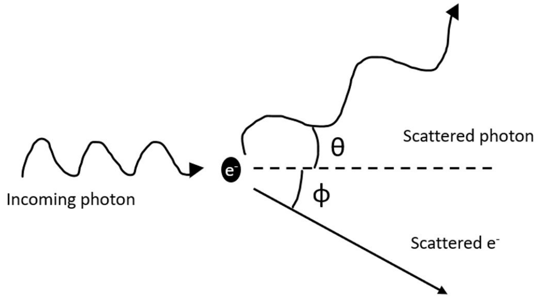
- Low energy calibration for Ge is simple
  - Neutron capture in ^{70}Ge produces ^{71}Ge
  - ^{71}Ge decays via electron capture
  - Produces calibration peaks at K-, L- and M- shell energy
- NTL effect brings M shell peak above detection threshold of SuperCDMS detectors

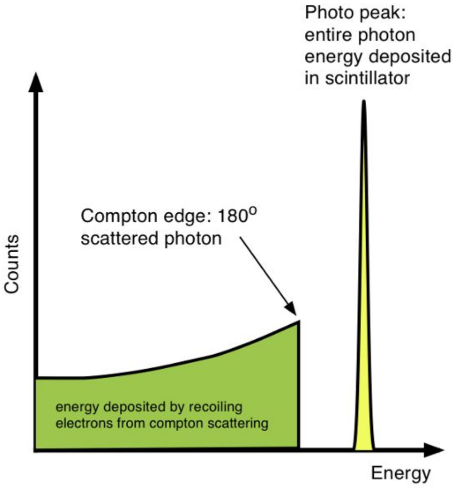




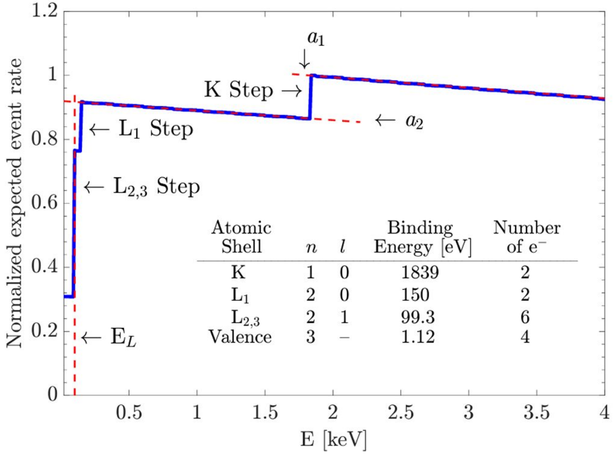
SuperCDMS SNOLAB: Calibration of Si

- Compton scattering



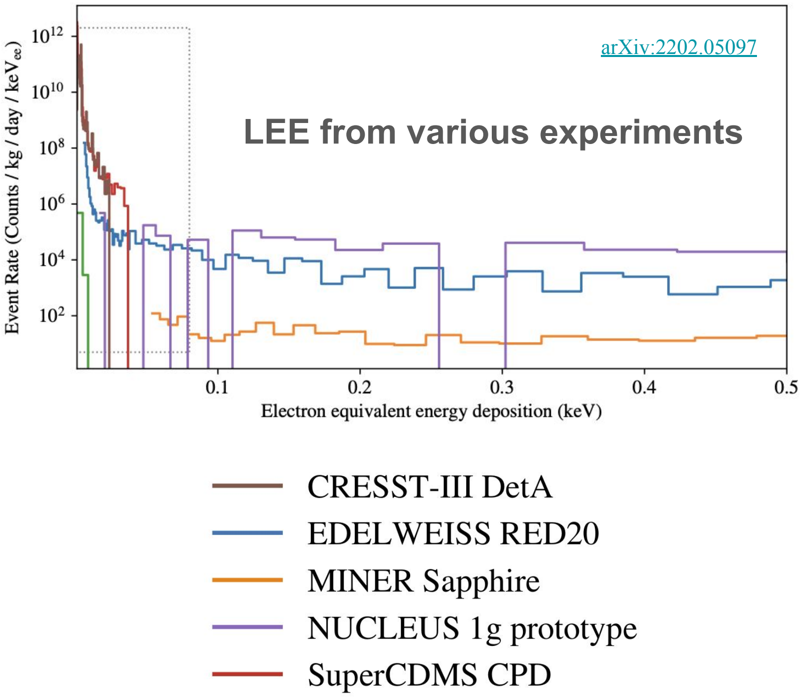


Relativistic Impulse approximation
to the Klein-Nishina formula



SuperCDMS SNOLAB: Background challenges

- Multiple layers of shielding (gamma and neutron shields)
- **Anticipating a background limited search on HV detectors**
  - **^{3}H from cosmogenic activation** - fixed by cosmic exposure time
  - **Naturally occurring ^{32}Si** - fixed at time of crystal growth
  - **Low Energy Excess** maybe a background for low mass searches

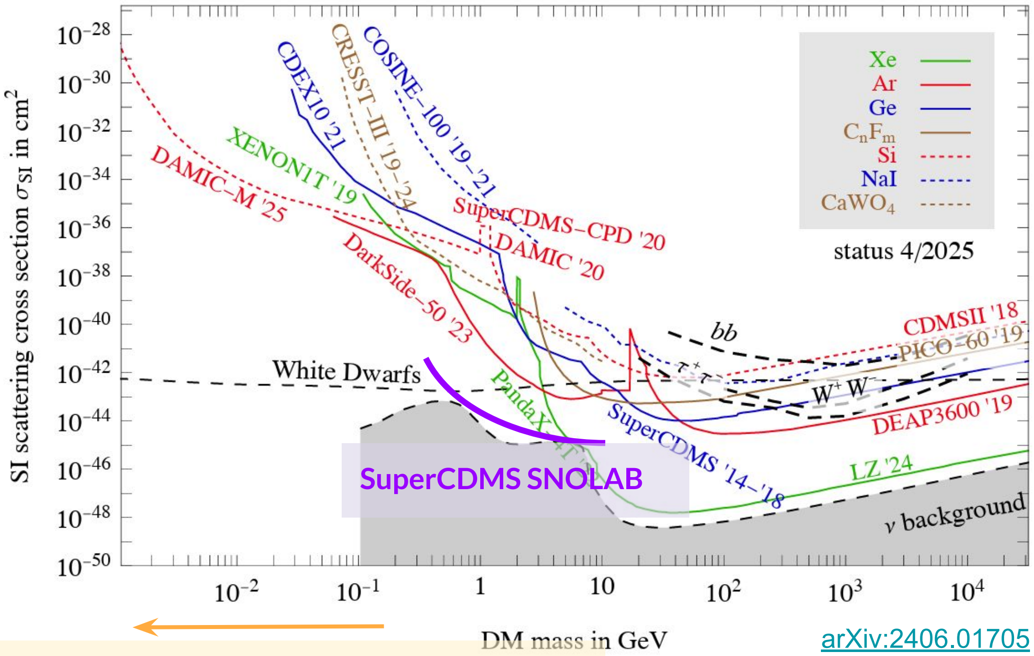


Exploring uncharted territory…

Discovery potential will only come when we overcome irreducible signal-like backgrounds

Direct Detection constraints on SI scattering

Longer exposure



arXiv:2406.01705

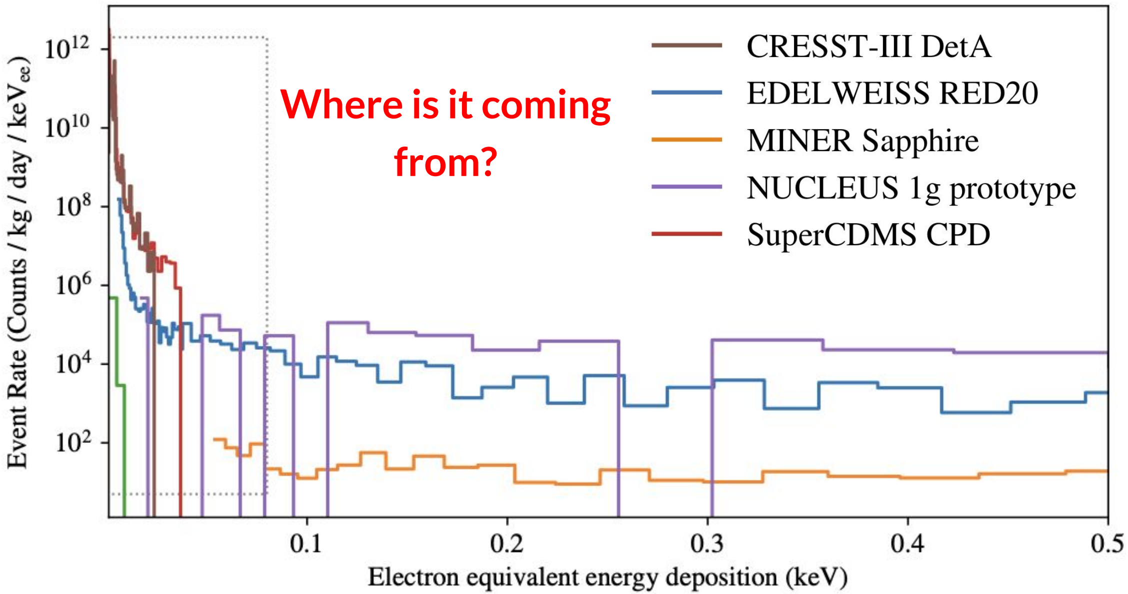
Lower target masses & detector thresholds

Reducing “irreducible” backgrounds - Low Energy Excess

- Exponentially rising background below 200 eV
- Seen in multiple experiments in diverse technology

Substrate?

Environment?



Leakage?

Housing?

Something else?

Reducing "irreducible" backgrounds

The clues…

Rate decreasing with time
Rate resets with every cooldown
Rate reduced by low-stress mounting scheme
Non-ionizing
Not external background
Seen in QIS devices as increased rate of quasiparticle tunneling
Seen in multiple substrates

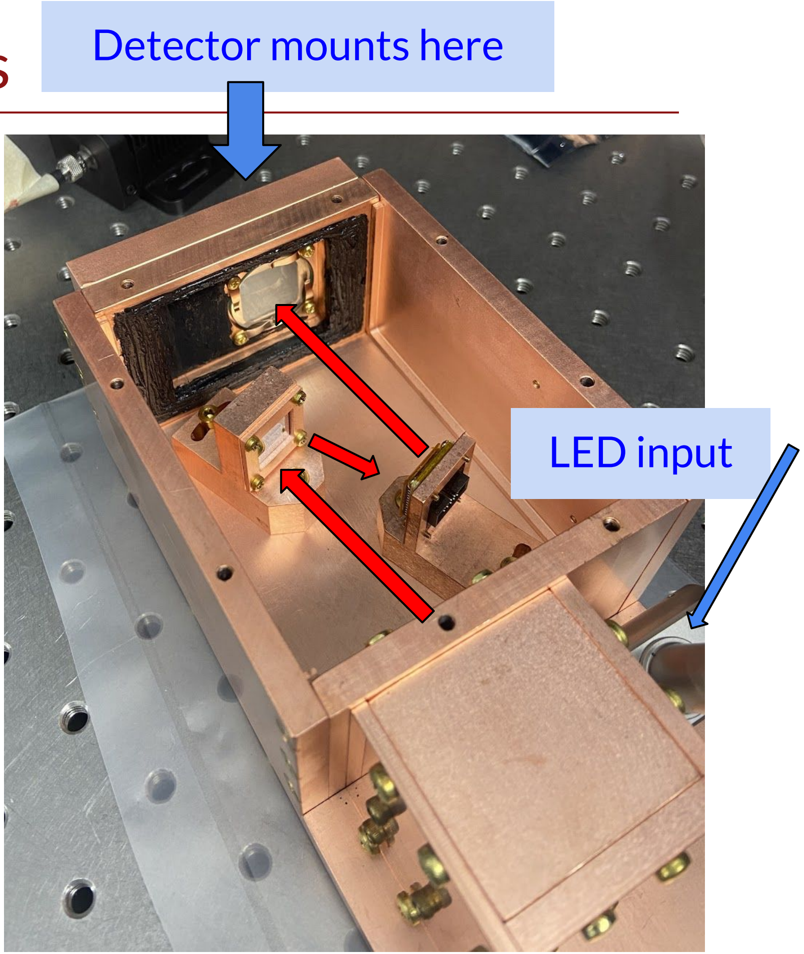
Tied to intrinsic detector physics; **position dependence**?

Need multiple experiments; **multiple technologies**

Reducing "irreducible" backgrounds

How do we get to an LEE-free dark matter search?

- Surface or bulk events? Stress-induced?
- **Requires excellent position resolution,** but most devices are limited
- **Cryogenic MEMS calibration system for precise beam steering**
  - LED source
  - Rotating MEMS mirror
  - Spot size: ~100 microns
    - Lower spot size possible with single-mode fibers
  - 3 cm x 3 cm scan range



1.JOM.5.2.024503

Reducing "irreducible" backgrounds

The clues…

- ➔ Rate decreasing with time
- ➔ Rate resets with every cooldown
- ➔ Rate reduced by low-stress mounting scheme
- ➔ Non-ionizing
- ➔ Not external background
- ➔ Seen in superconducting qubits as increased rate of quasiparticle tunneling
- ➔ Seen in multiple substrates

Many references within

PhysRevD arXiv:2202.05097 arXiv:2503.08859

arXiv:2404.02607 arXiv:2601.16307

arXiv:2208.02790 APL arXiv:2011.13939 arXiv:2112.14495

Small but growing body of research on LEE

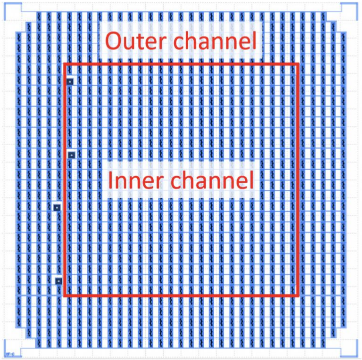
Reducing “irreducible” backgrounds

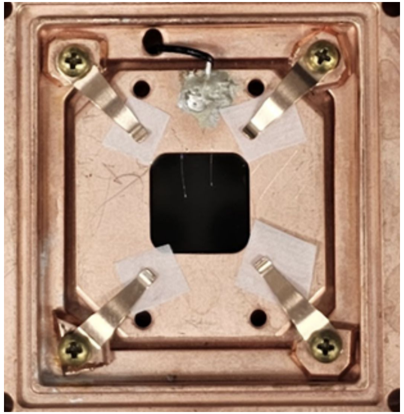
How do we get to an LEE-free dark matter search?

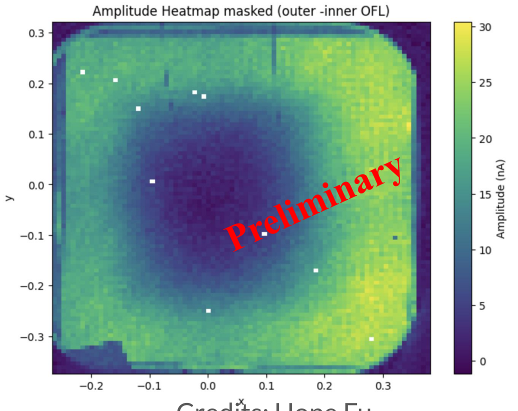
First tests on HVeV detectors

- Can we discriminate surface vs bulk events? Is LEE restricted to detector edges? Can we model it?
- Can we identify position dependence in any detector properties? How can we make better detectors?

YES!







Credits: Hope Fu

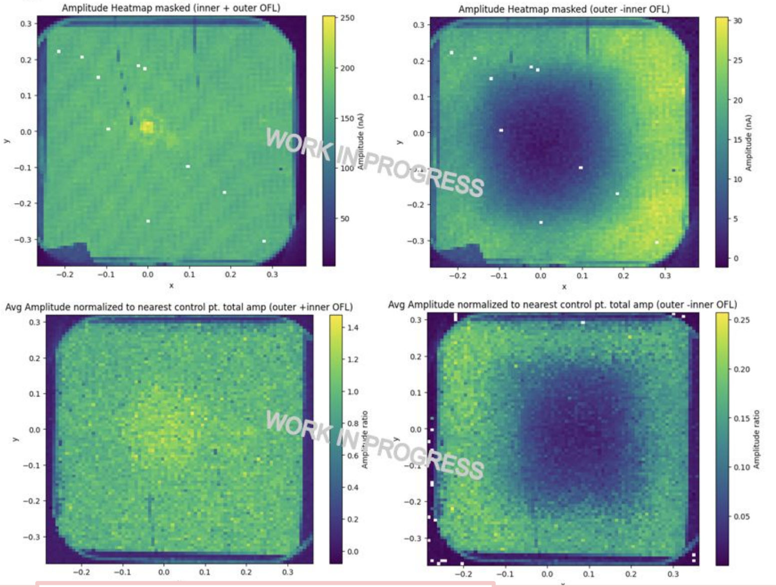
Lots of position-related studies underway…

Position dependence of detector properties

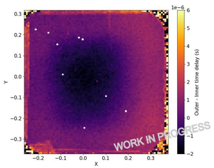
Pulse Amplitude maps: Credits: Hope Fu

0V:

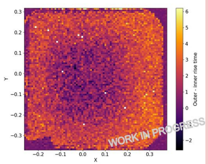
100V:



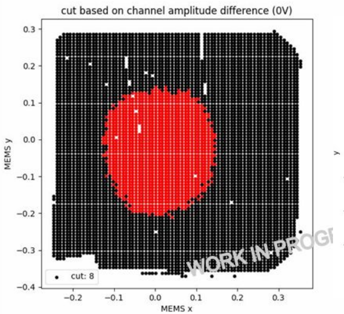
Pulse arrival times w.r.t trigger



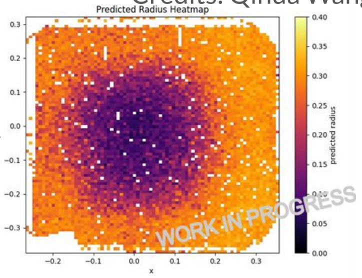
Pulse rise/fall times



Credits: Qihua Wang



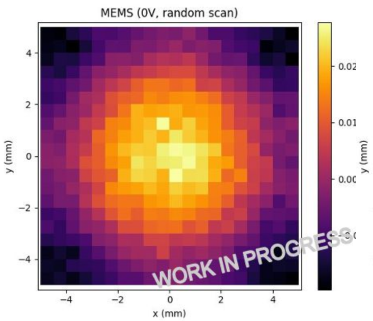
Pulse amplitude based cuts



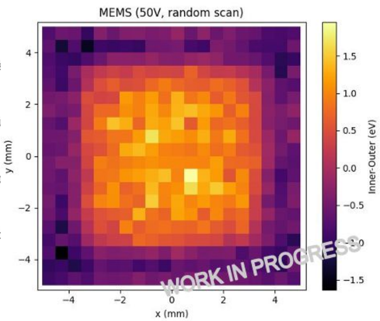
Machine learning based cuts

Position reconstruction

Detector simulations for improved response modeling



0 V



100 V

Credits: C. Stone-Whitehead

Driving sensitivity to lighter dark matter

Detectors on novel substrates can

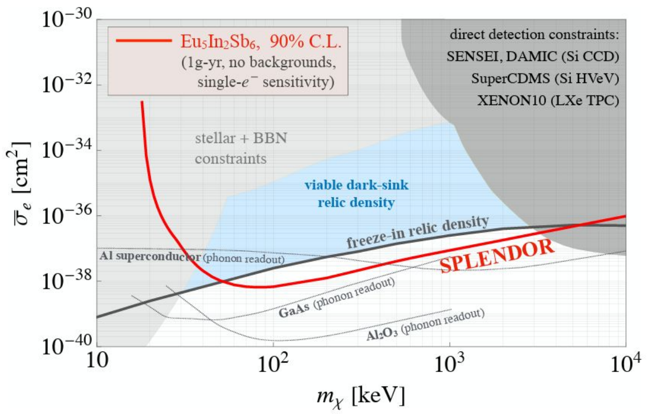
★ <u>**Lower detection thresholds**</u> **for better kinematic matching with light and ultra-light dark matter**

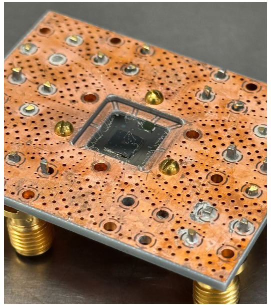
★ <u>**Benchmark LEE characteristics**</u> **across different technology by doing MEMS-system calibrations**

Driving sensitivity to lighter dark matter

- **Better kinematic matching for NRs**
  - **SiC- and C- based substrates** with lighter nuclei
- **Detection threshold optimization**
  - **SPLENDOR**: Novel materials with tuned bandgaps (O(10 meV)) to extend **charge-based detection** to low masses
    - $Eu_5In_2Sb_6$
    - $Eu_1Zn_2P_2$
  - Develop low-noise readout systems to achieve sub-eV resolutions
    - cavity-embedded Cooper Pair Transistor (cCPT)

arxiv:/2507.17782



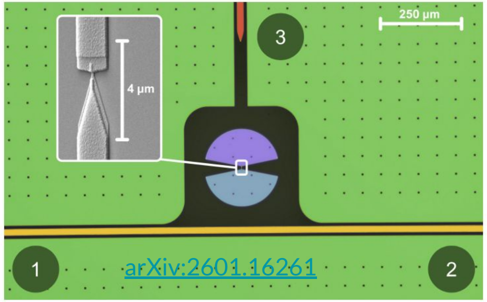


Credits: J. Anczarski

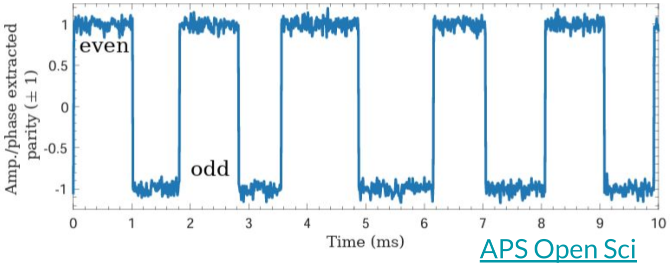
Alternate direction: Quantum sensing (KIDs, SQUATs, QPDs)

- Quasi particle generation requires much lower energies (meV scale) → ✅ Low threshold
- Not limited by thermal noise like TES-devices
- **Primarily targeting axions and sub-GeV dark matter candidates**
- Potential pathway beyond Low Energy Excess background
- Lots of exciting RnD from many groups in this direction:
    - Kinetic Inductance Detectors
    - Superconducting QUasiparticle Amplifying Transmons
    - Quantum Parity Detectors

SQUAT detector



Simulated time stream for a Quantum Parity Detector



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