# Calibrating energy scale of SuperCDMS Si HVeV detectors in keV range and studying the Compton Steps

Sudipta Das on behalf of SuperCDMS collaboration
National Institute of Science Education and Research, HBNI, India
XXV DAE BRNS High Energy Physics Symposium, IISER, Mohali
@SuperCDMS

## Abstract

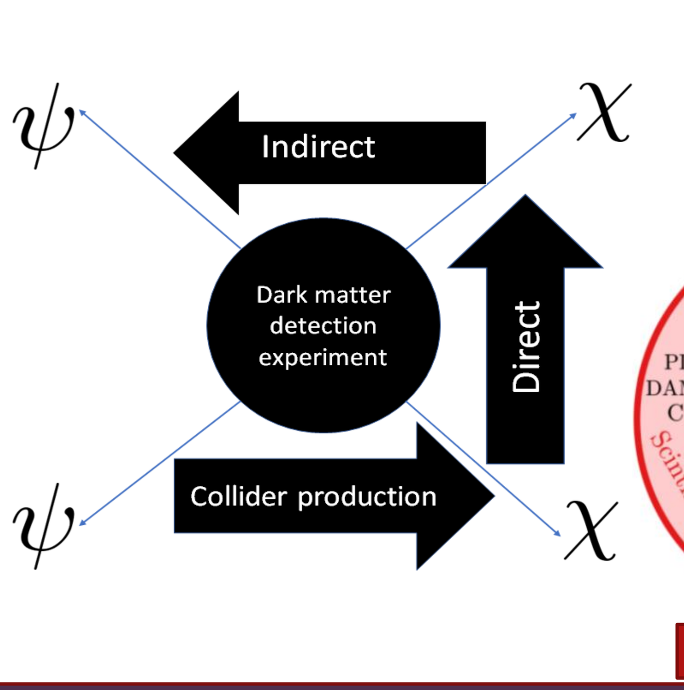
We present an overview of SuperCDMS (Super Cryogenic Dark Matter Search) HVeV (High Voltage eV resolution) detectors, 1 g Si High Voltage (HV) detectors, that have ~eV resolution and dynamic range up to ~keV. Using LED and $^{137}$Cs data, we aim to calibrate the energy scale of the detectors up to the keV range and study the Compton steps. The understanding of Compton steps for these detectors will be used to calibrate the big SuperCDMS HV detectors for the 2nd generation SuperCDMS experiment at SNOLAB.

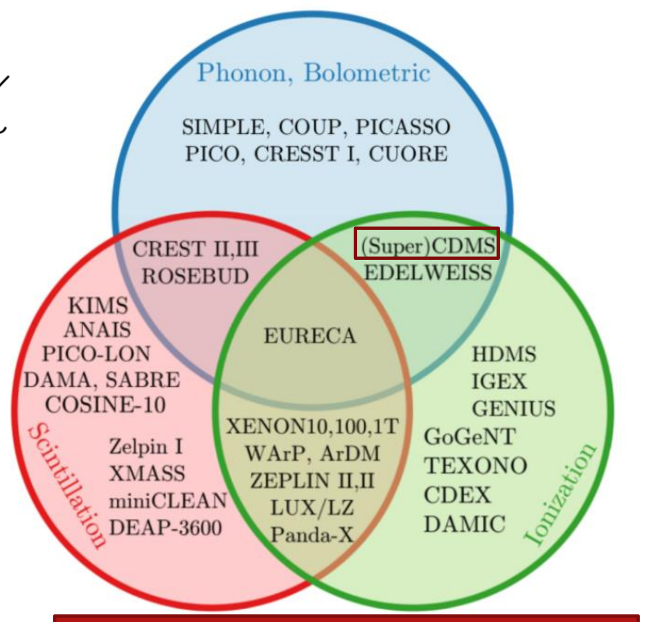
## 1. Dark matter search experiments

Astrophysical observations support existence of dark matter.
Known properties
- Interacts gravitationally
- Non-relativistic / Cold
- Electrically neutral
- Very weak interaction cross-section

$\psi \rightarrow$ Standard model particle
$\chi \rightarrow$ Dark matter particle

- Collider search ($\psi\psi \rightarrow \chi\chi$)
- Indirect search ($\chi\chi \rightarrow \psi\psi$)
- Direct search ($\psi\chi \rightarrow \psi\chi$)



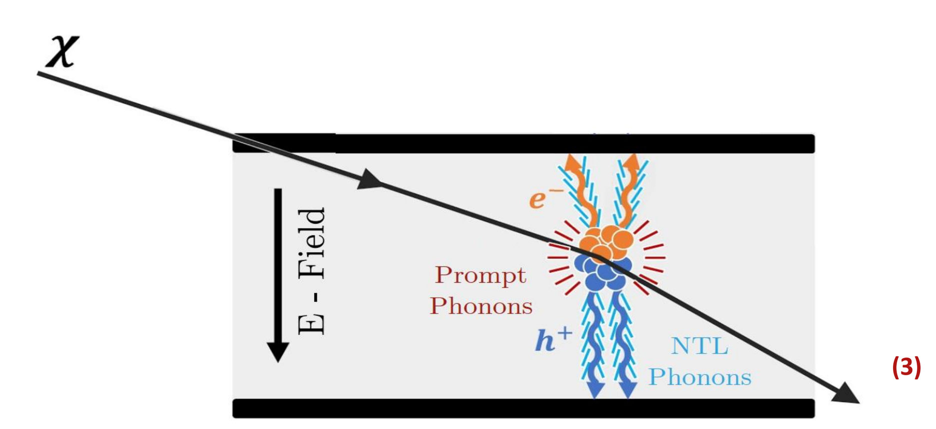



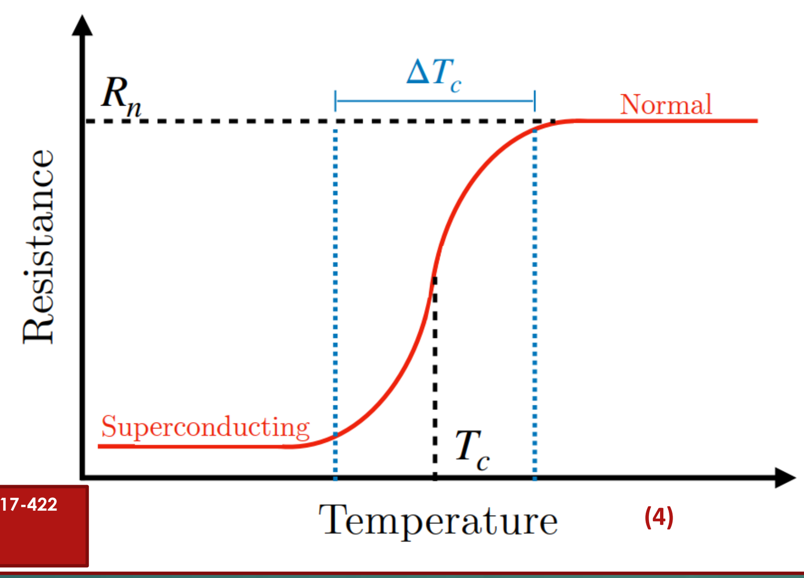

Ref: M. pepin, 'Low mass dark matte search...' https://supercdms.slac.stanford.edu/dissertations

## 2. Detection principle of SuperCDMS detectors

**Energy deposition from incoming particles** → **Drifting of ions through the crystal due to applied bias voltage** → **Transition edge sensor (TES) as the phonon sensor**

- 3eV/3.8 eV energy is needed for 1 e⁻h⁺ pair creation (Bandgap: 0.74/1.17 eV) in Ge/Si [2]
- NTL[1] phonons are created during drifting though the crystal. $E_t = E_r + eV_bN_{e/h} = E_r(1+\frac{eV_b}{\epsilon_\gamma})$
- Thin superconducting film operated in the transition state between super conducting and normal state

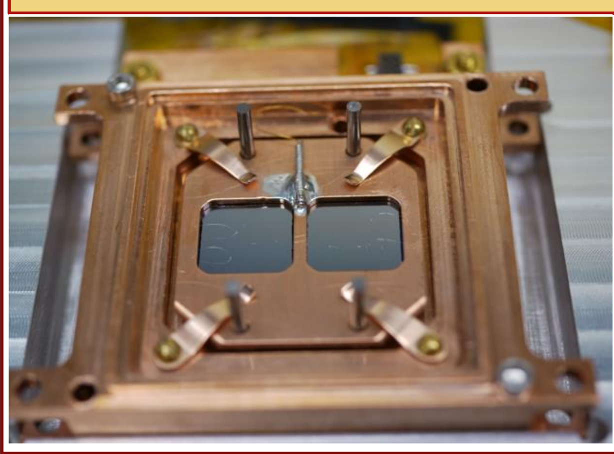


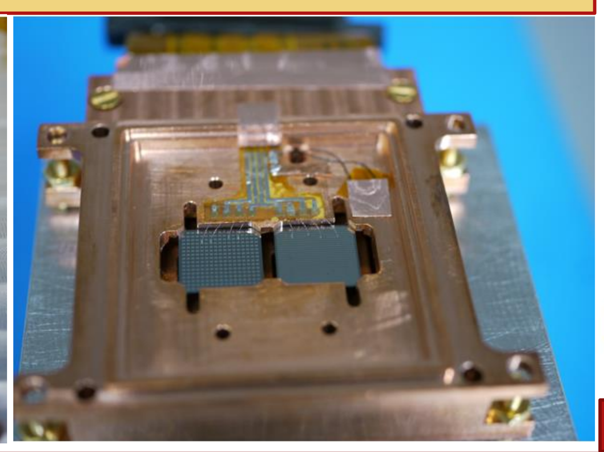



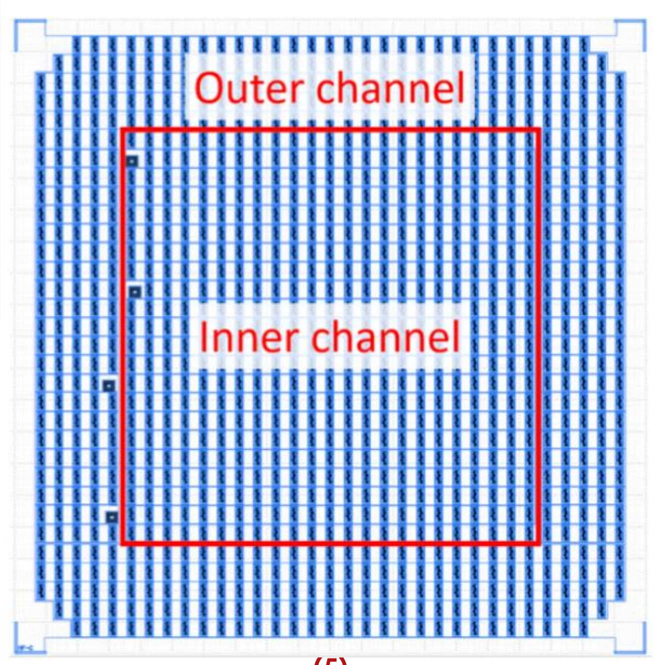

(1) NTL (Neganov–Trofimov–Luke) phonon: Ref: Neganov B., Trofimov V. and Stepankin V.J. Low Temp. Phys., 93 (1993), pp. 417-422
(2) Ref: M. Pepin. 'Low mass dark matter search and...', https://supercdms.slac.stanford.edu/dissertations
(3,4) Ref: M. Wilson. 'A new search for low mass dark matter...', https://supercdms.slac.stanford.edu/dissertations

## 3. NEXUS@FNAL


NEXUS (SuperCDMS Test facility):
- 0.93g (~1g) Si HVeV detector with ~eV resolution
- Detectors: NFE, NFH, NFC1 & NFC2
- Single charge sensitive, eV scale threshold with keV scale dynamic range !! [5]
- Sensitive to sub-GeV dark matter particles








(5)

(5)Ref: PRD 104.032010, (2021)
Ref: NIMA 963 (2020) 163757

## 4. About the Data & calibration process

**LED Data**

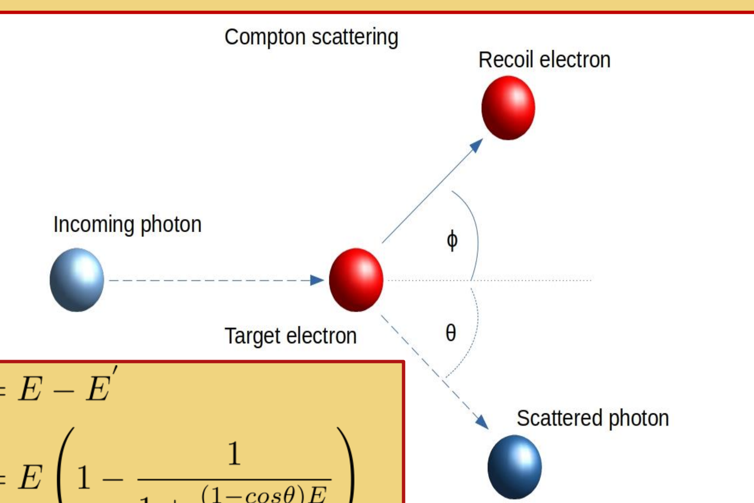
- HVeV detectors are sensitive to single charge excitations inside the detectors causing discrete e⁻h⁺ pair peaks in the energy spectrum.
- LED data series are taken for energy calibration in low energy regions (up to ~keV) using multiple e⁻h⁺ peaks.

**Cs Data**

- Due to the nonlinearity in detector response, we can not extrapolate the energy calibration to an arbitrarily high energy range ( $O(10^2)$keV )
- $^{137}$Cs source data is taken to calibrate the high energy scale using the features in the gamma spectrum (Photo peak, Compton edge, Compton steps, Cu X ray peak)

## 5. Expected features from Geant4 simulation

**Source information:** $^{137}$Cs ⟶ $^{137}$Ba + $\gamma$ (662 keV) + $\beta^-$
**Dominating interaction process:** Compton scattering
**Simulating platform:** SuperSim-V09-01-00, Genat4-10.06.p03
**Model:** G4EM-opt4
**Expected features:**
- **$^{137}$Cs photo peak (662 keV):** Full gamma energy deposition
- **$^{137}$Cs Compton edge (477 keV):** Backscattered gamma energy deposition
- **Cu X ray peak (8.1 keV):** Due to the Cu housing
- **Compton steps:** Due to electronic shell structure of Si



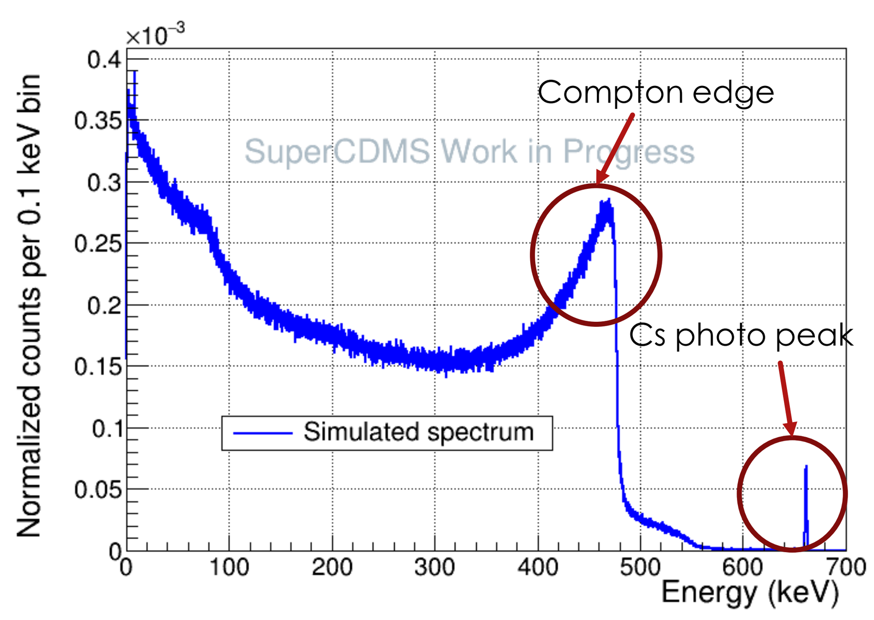

$$E_{dep} = E - E'$$
$$= E\left(1 - \frac{1}{1+\frac{(1-\cos\theta)E}{m_ec^2}}\right)$$
$$E_{dep_{max}} = \frac{2E^2}{2E+m_ec^2}$$

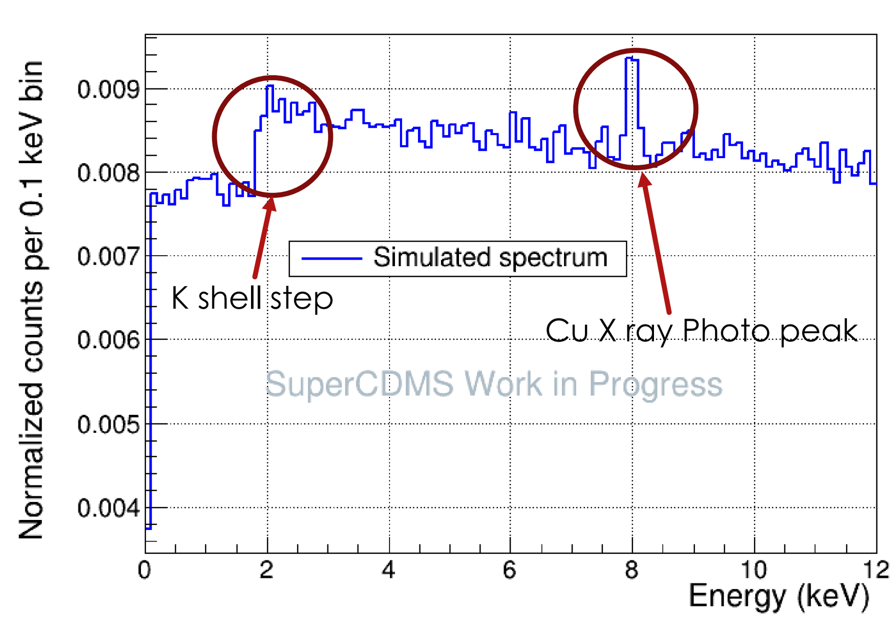
**Compton step**

- At energies comparable to the atomic binding energies, the free electron approximation fails
- If $E<E_{n,l}$ the energy spectrum forms a step
- The relative height of each step is given by the ratio of the electrons in each shell to the total number of available electrons
- Position of Compton steps in the energy spectrum depends on the atomic shell energies; hence it is material dependent

Ref: PRD 106.092001 (2022)

| Si Shell | Quantum number (n,l) | $E_{n,l}$ (keV) | Shell e⁻ |
|---|---|---|---|
| K | (1,0) | 1.839 | 2 |
| $L_1$ | (2,0) | 0.150 | 2 |
| $L_{2,3}$ | (2,1) | 0.099 | 6 |




## 6. Energy estimators

**OFL (Optimum Filter Limited):**
- Fits a noisy signal with the template to determine its amplitude.
- To maximize the S/N ratio, the fitting is performed in frequency space by distinguishing the noise from the underlying true signal
- Good energy resolution
- Fails for saturated pulses

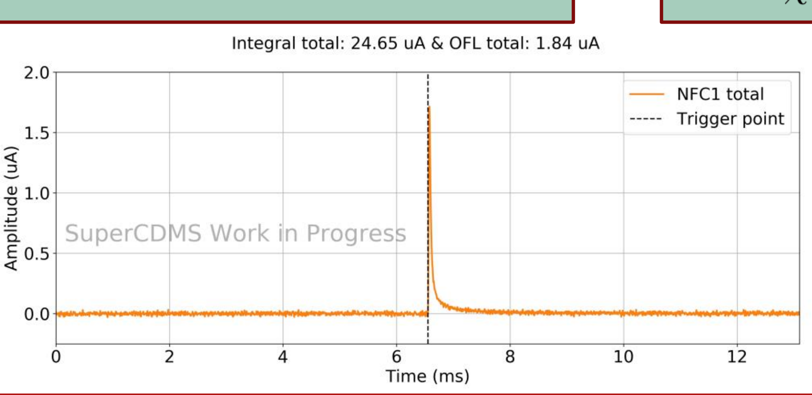
**INPUT**
Signal: $S(t)$
Pulse template: $A(t)$
Noise template: $\zeta(t)$
Sampling frequency: $f_s$

→

Signal: $\tilde{S}(\omega)$
Pulse template: $\tilde{A}(\omega)$
Noise PSD (Power Spectral Density): $\zeta(\omega)$
$$\chi^2 = \int_{-\infty}^{\infty} \frac{|\tilde{S}(\omega) - a\tilde{A}(\omega)|^2 d\omega}{\zeta(\omega)}$$

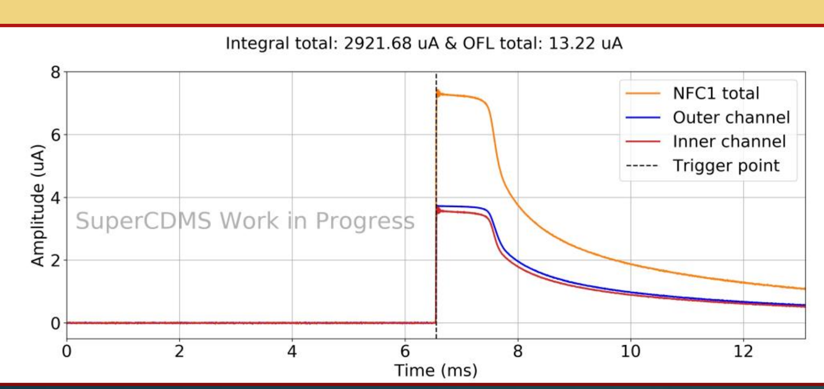
→

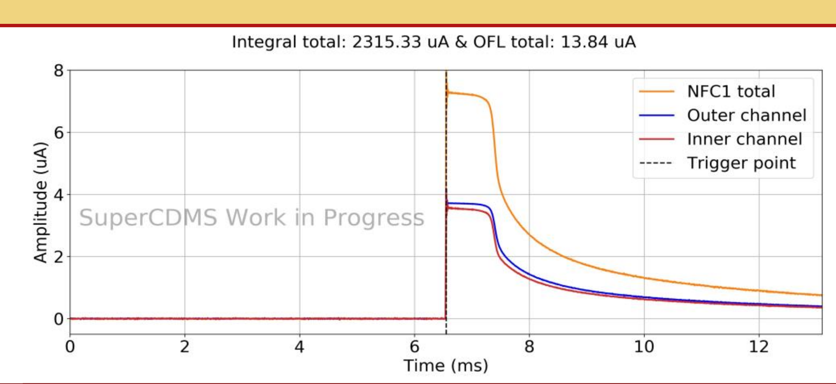
**OUTPUT**
OF amplitude: $a$
Time offset: $t_0$
OF $\chi^2$




**Analysis window**
- Sampling frequency: 625,000 Hz
- Down sampling factor: 4
- 1 sample = 6.4 us
- Analysis window: 2048 samples (1024 samples before and after trigger point) ~ 13.1 ms

**Integral:**
- Determines the pulse area inside the analysis window (~13.1 ms)
- Effective for saturated pulses also
- Less sensitive / Poorer resolution in comparison to OFL method




## 7. Outlooks

- Apply cuts to remove bad pulses / poorly reconstructed events from the science data
- Optimize the Matched Filter (MF) integral, a hybrid energy estimator of OFL and Integral
- Study 0V and HV (100V) data and look for K shell (1.8 keV) and L shell (150 eV) Compton steps
- Perform Energy calibration at low energy ranges in both 0V and HV bias modes using the Compton steps

*Acknowledgement*

*SD would like to thank the Department of Atomic Energy (DAE), Government of India, and the Department of Science and Technology (DST), Government of India, for funding support.*