Quantum sensor for detection of dark matter

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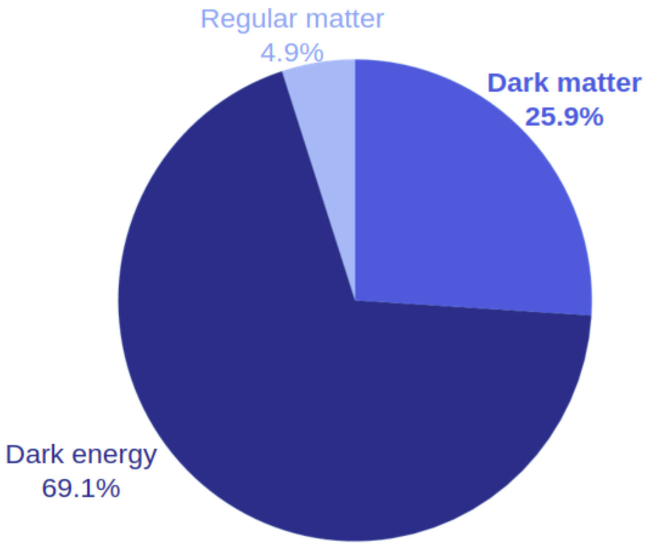
In partnership with:

Dark matter



Estimated energy density of the Universe.

Source: Planck

Dark matter

- Invisible matter known to interact with gravity
- Numerous evidence for existence of dark matter

Why study dark matter?

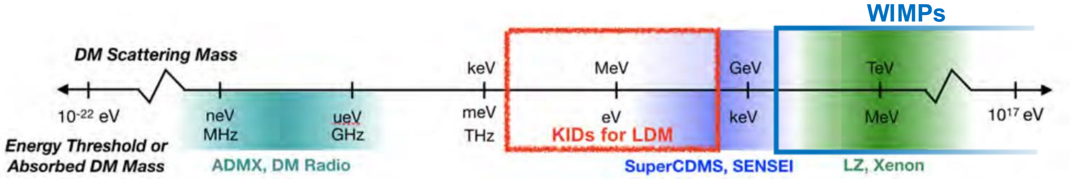
- Understand formation of galaxies
- Understand the origin and future of universe

Why is Dark Matter difficult to detect?

- Gravity is weak
- Constituents of dark matter are unknown
- The theoretical bounds for mass is very wide

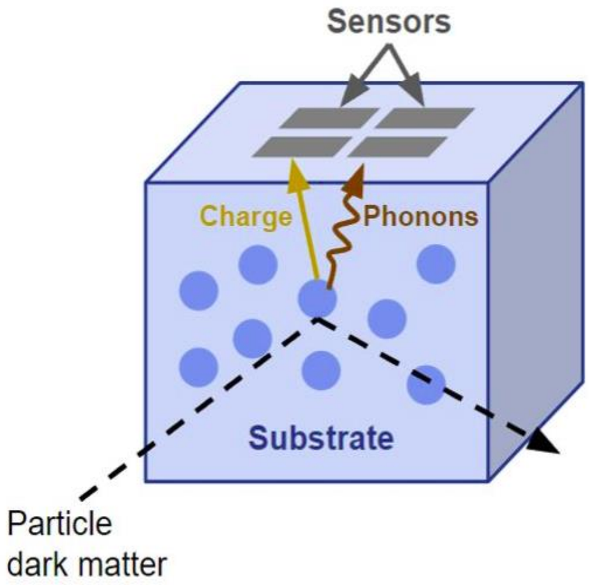
Searching for Dark Matter

- WIMPs have been historically favored
- No definitive evidence to date for WIMPs
- New approaches for detection involves looking into 'Hidden Sector'
  - Light Dark Matter (LDM)



Current and Future Coverage of LDM Parameter Space

Credit: Noah Kurinsky



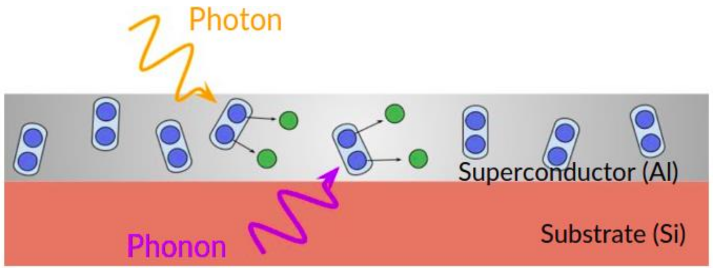
Particle dark matter interacting with substrate to create charge-hole pair and shower of phonons.

Credit: Kelly Stifter

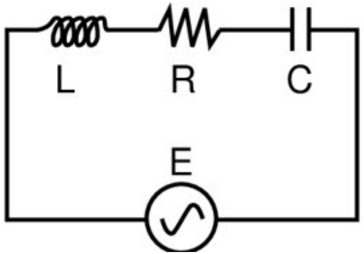
Quantum sensor : MKID

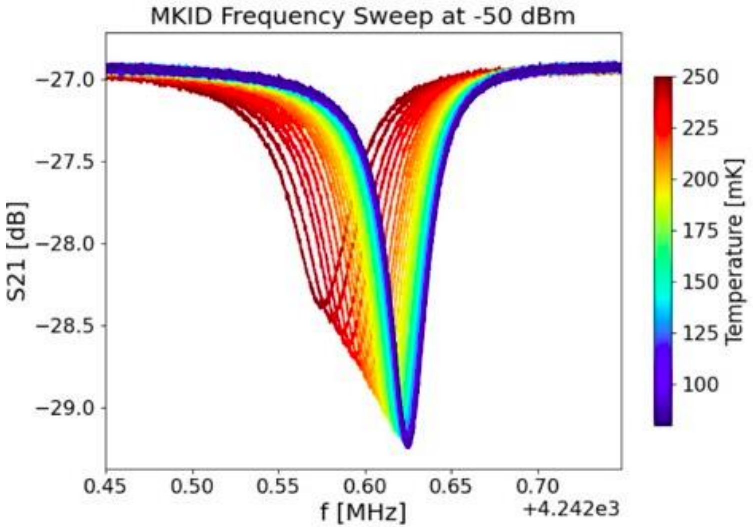
Microwave Kinetic Inductance Detector

Working Principle: Incident energetic particle changes quasiparticle density of the superconductor strip which leads to change in its inductance.



Microwave Kinetic Inductance Detector (MKID)
Credit: Gabriel Spahn





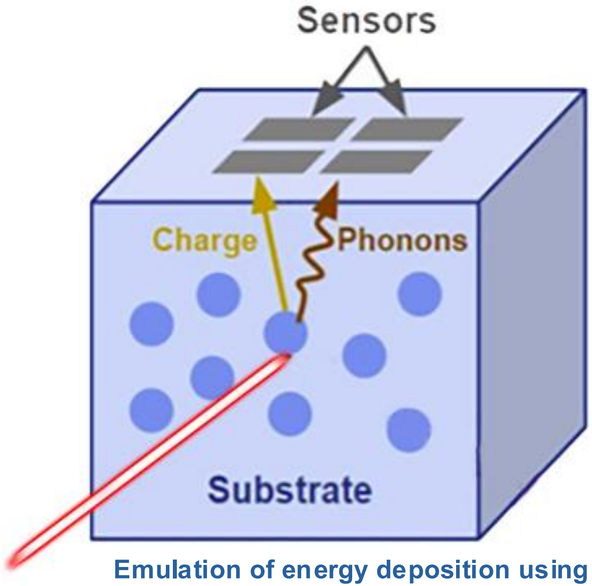
Frequency response of the Al resonator at different temperature

Credit : Osmond Wen.

Calibration of Detector

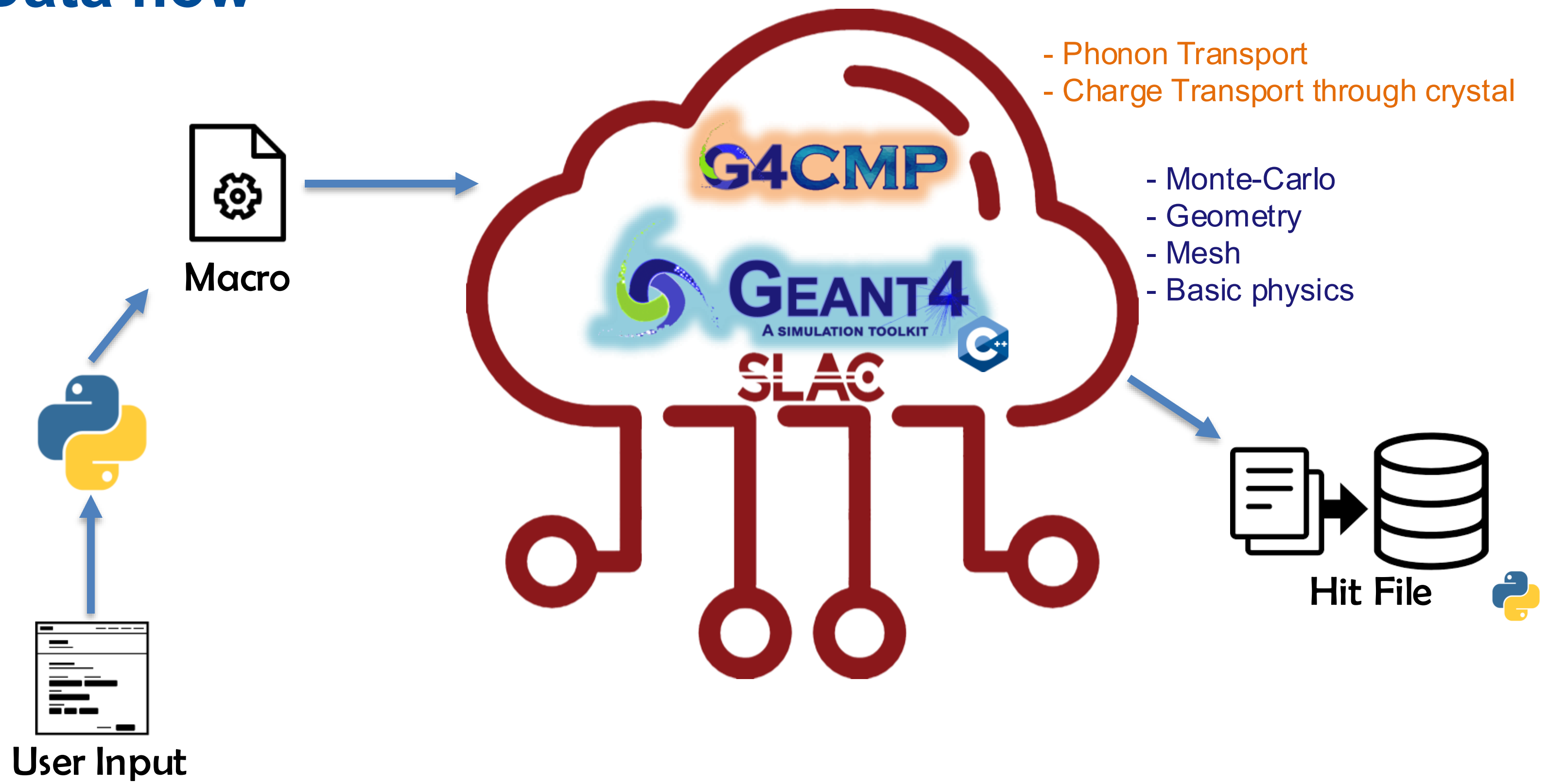
- The energy deposition due to interaction with dark matter can be emulated using laser
- Understand the signal from experiment
- Establish fidelity of simulation

- Simulate the detector with varying configurations:
    - Energy
    - Position of interaction
    - Initial momenta of electron, hole



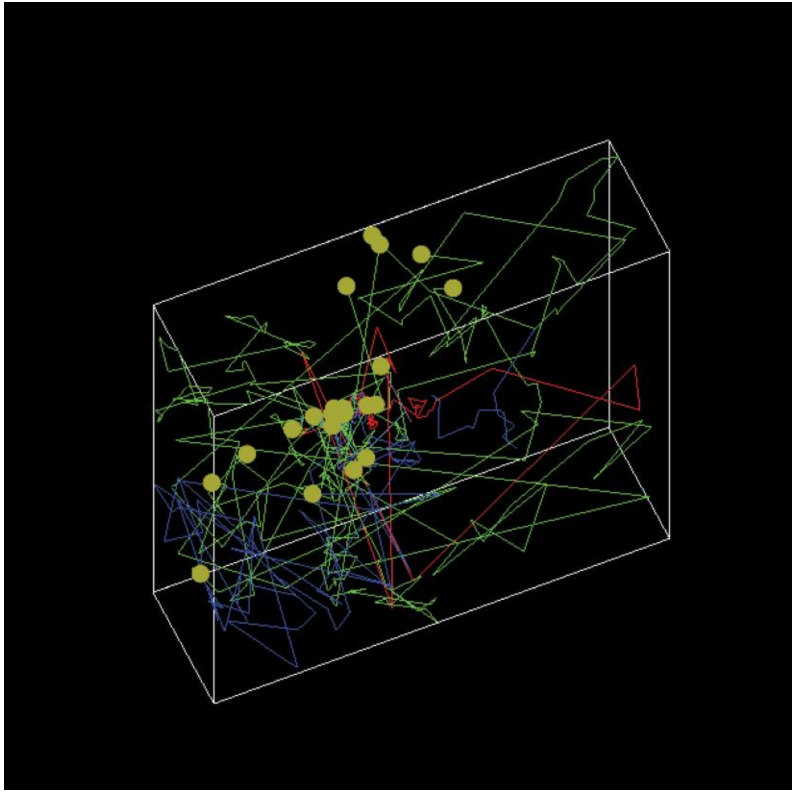
Emulation of energy deposition using laser

Data flow



Dataflow in Simulation

Simulation



Simulation Configuration

Geometry
Silicon Substrate : 2 mm x 2 mm x 600 nm
Aluminum superconductor : 100 nm

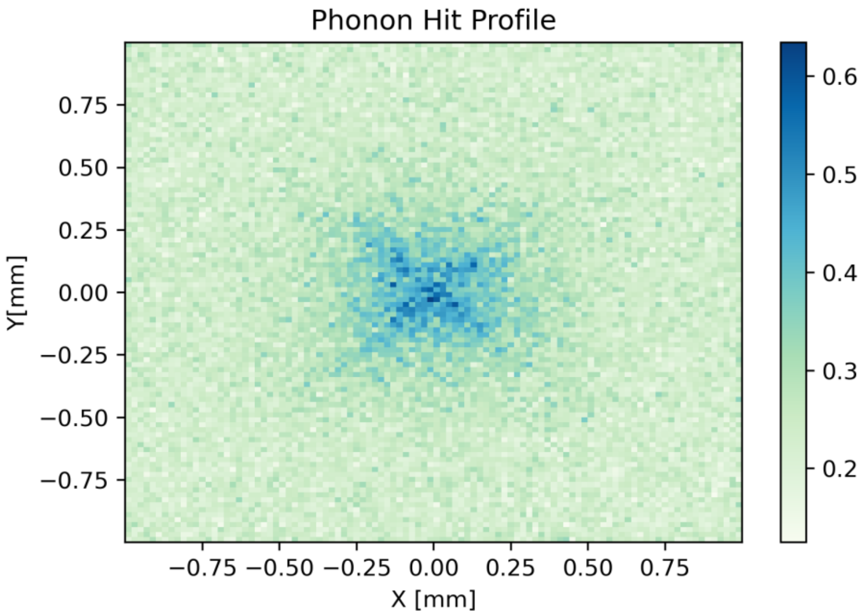
Energy
635-nm laser (E_l) : 1.95 eV
Band-gap of Si (E_g) : 1.17 eV
Charge-hole pair ($E_l - E_g$) : **0.78 eV**

Position of interaction : Varied
Initial Momentum : Varied

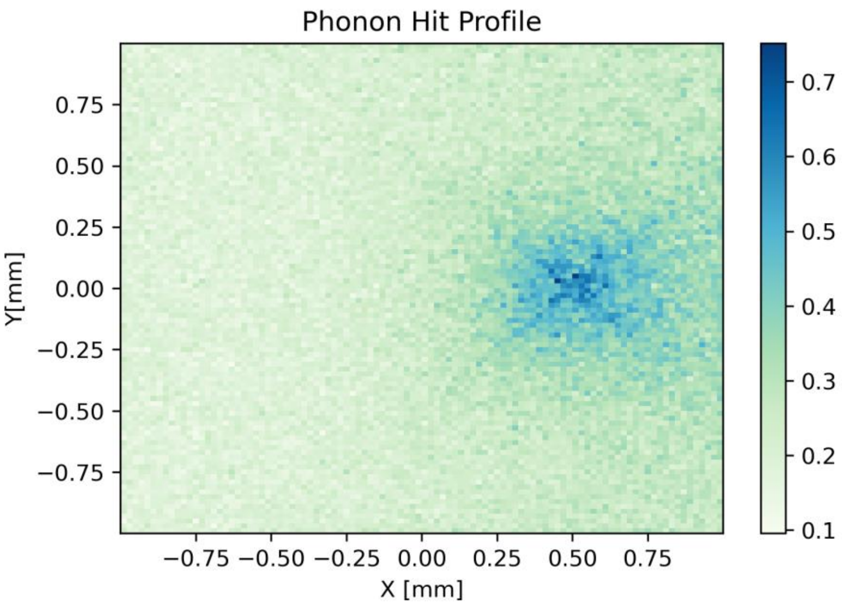
Phonon generation/propagation.
The image depicts the propagation of different kinds of phonons.
- Transverse Fast
- Transverse Slow
- Longitudinal
- The phonon track ends at an electrode which is registered as a hit

Source: Geant4, G4CMP

Preliminary Results



(a)

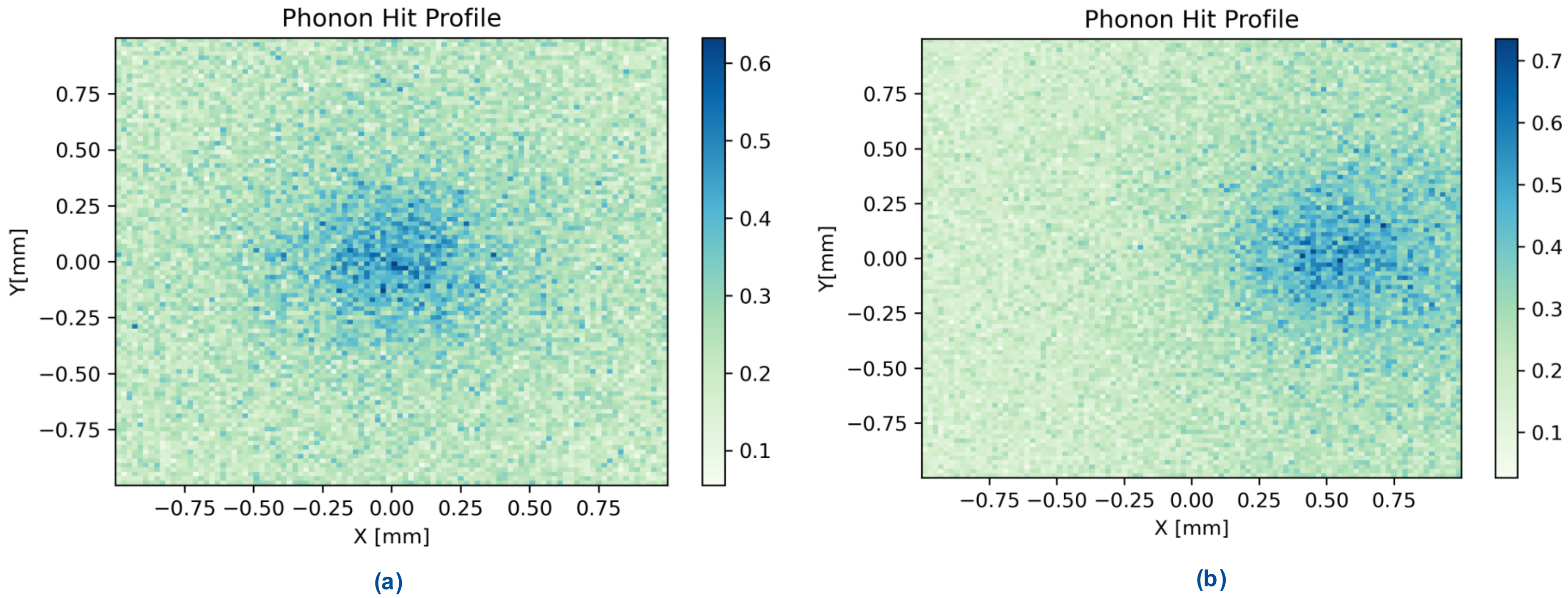


(b)

Phonon Hit profiles of Transverse Fast Phonon for different positions of interaction with dark matter

(a) at center, (b) displaced 0.5 mm in X axis,

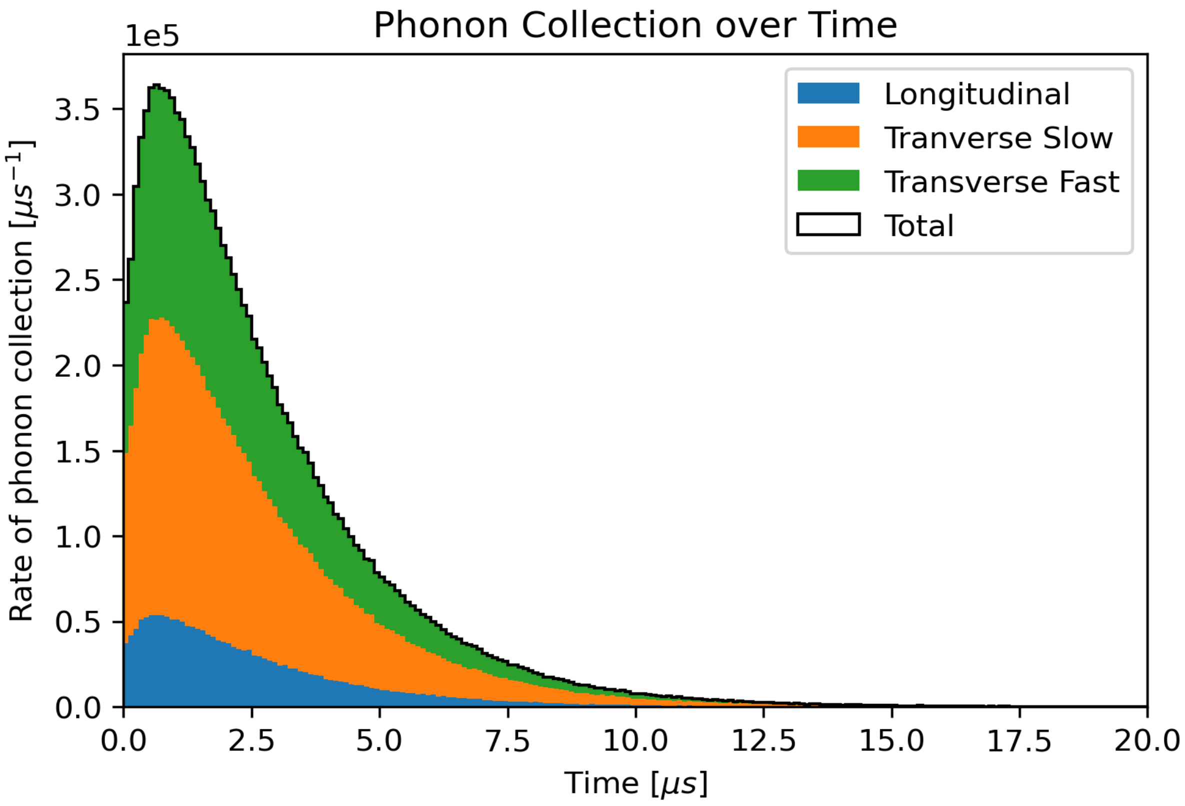
Preliminary Results



Phonon Hit profiles of Longitudinal Phonon for different positions of interaction with dark matter

(a) at center, (b) displaced 0.5 mm in X axis,

Preliminary Results



Future Works

- G4CMP library
  - Fixing Bugs: Energy assignment issue
  - Integrate G4CMP with Geant4
- Implement more realistic simulation
  - Granular geometry
  - Study on surface property for proper boundary conditions
- Further study
  - Study on crystal orientation
  - Further data analysis

Summary

- Fermilab aims to expand the section of mass range for dark matter search
- A novel detector is proposed that utilizes MKID to detect energy deposition
- Detector Design was simulated using Geant4 and G4CMP
- Python was used to create script for batch simulation and preliminary data analysis

Acknowledgment

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Kelly Stifter

Michael Kelsey

Israel Hernandez

Noah Kurinsky

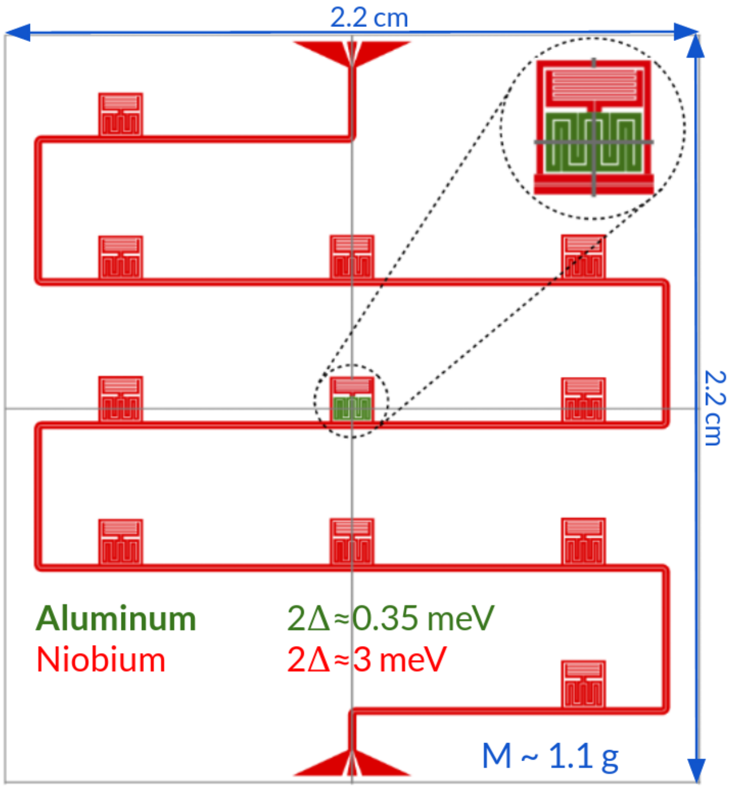
References

(K. Dilbert et. al.) *Development of MKIDs for measurement of the Cosmic Microwave Background with the South Pole Telescope*

(N. Kurinsky) *Developing meV-Threshold Microcalorimeters for Low-Mass Dark Matter Searches at NEXUS*

Questions?

Appendix I



Rendering of the KID device installed at NEXUS which features 10 all-Nb resonators and a single resonator with a Al inductor (green). The Nb feedline and resonators are inert to athermal phonons due to its higher Cooper-pair binding energy - and are thus insensitive to radiation-induced energy deposits in the Si substrate.

Image credit to Osmond Wen.