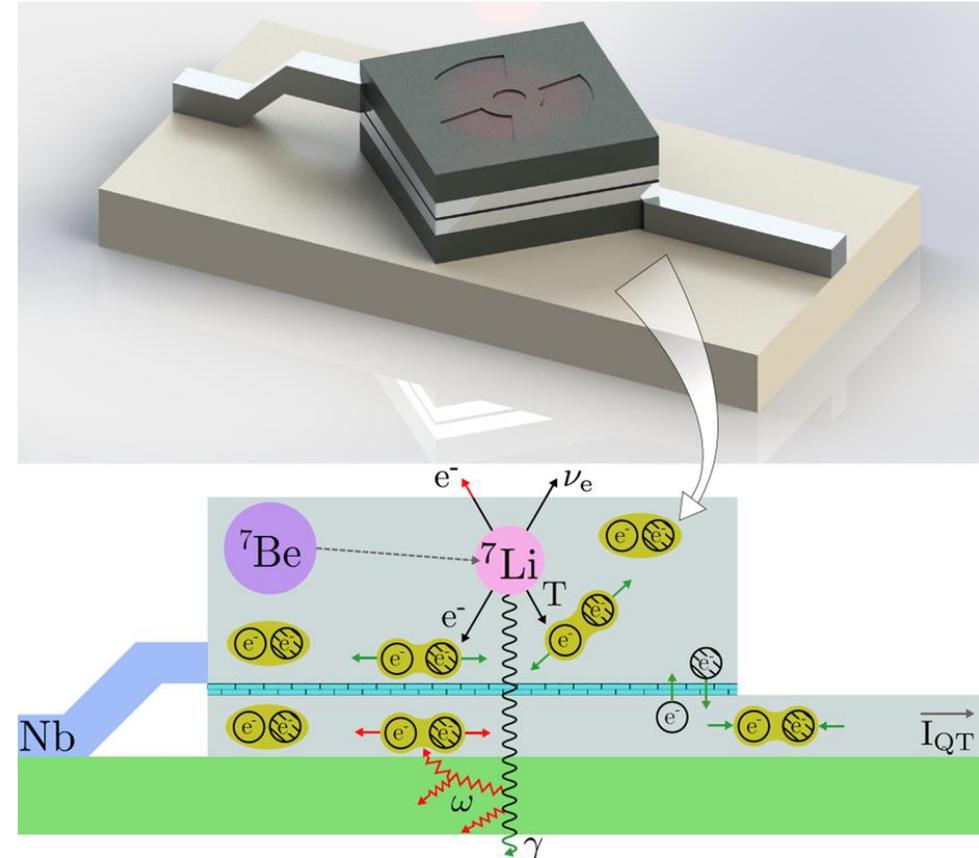
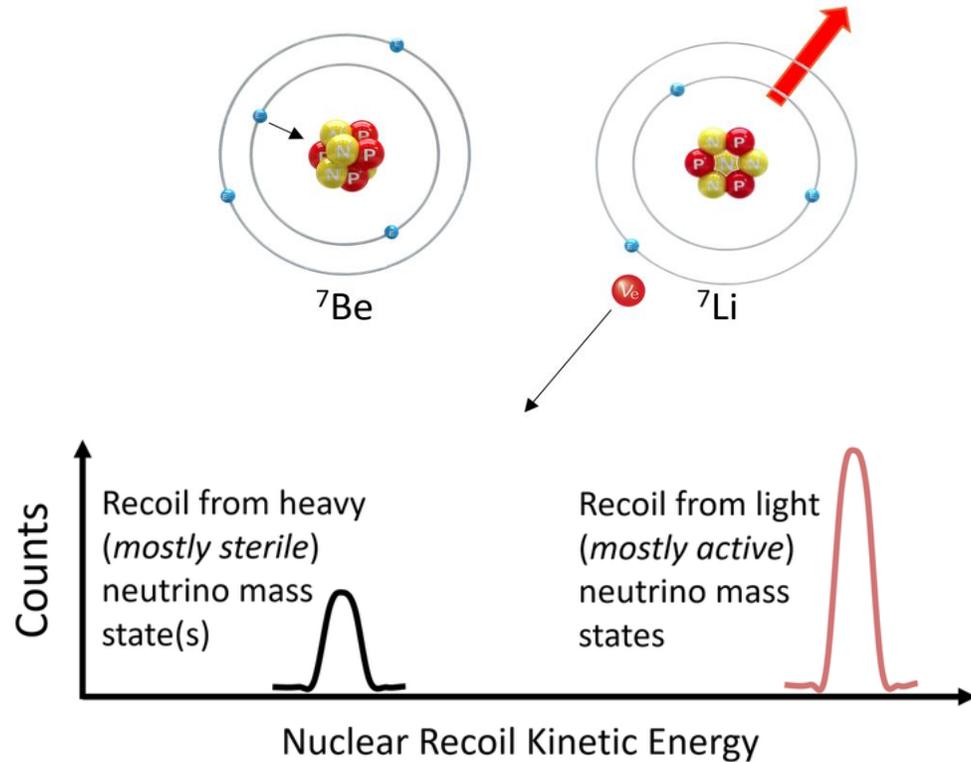


# Accurate Phonon Transport Across Interfaces in G4CMP for sub-eV Detector Simulations in the BeEST Experiment

---

Caitlyn Stone-Whitehead

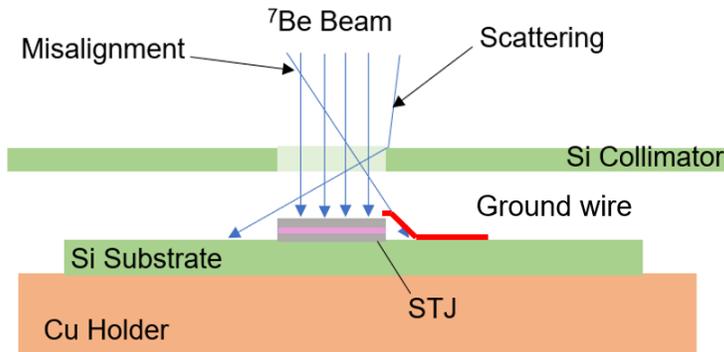
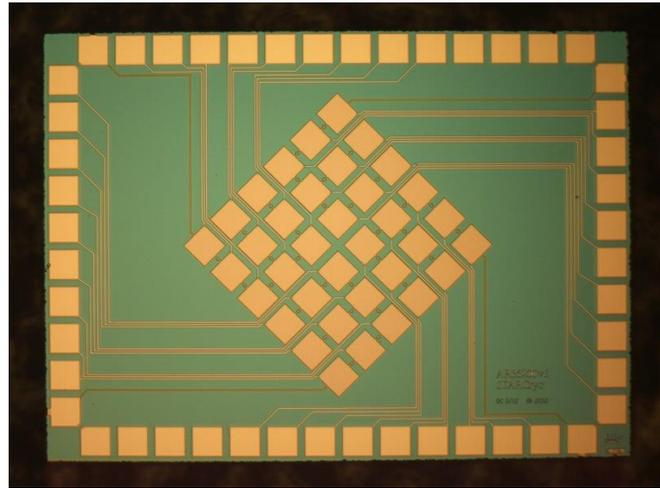
# The BeEST Experiment



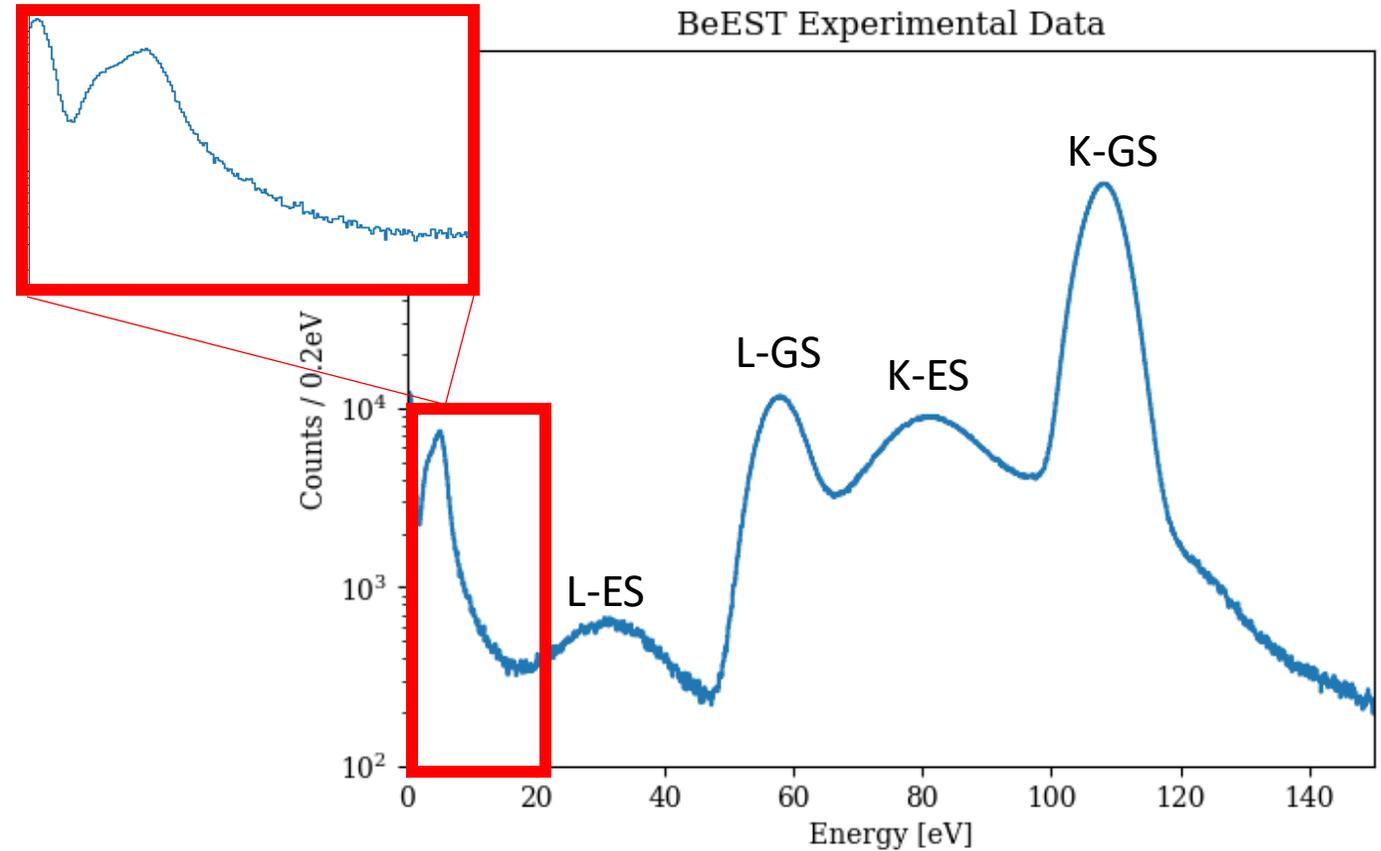
The **Beryllium Electron capture in Superconducting Tunnel junctions Experiment**

BeEST — Kyle G. Leach ([kgleach.org](http://kgleach.org))

# The BeEST Experiment



[1]



[2]

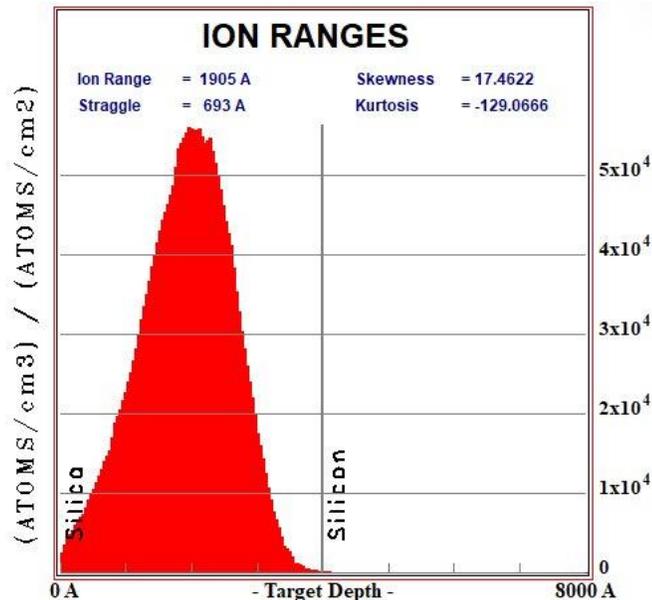
[1] A. Lamm, APS April Meeting, B19:4 (2024)

[2] I. Kim et al., "The Beryllium Electron Capture in Superconducting Tunnel Junctions (BeEST) Experiment: Phase-III Optimized Procedures for Signal Processing and Spectral Fitting,"

# The BeEST Simulation Framework



Where are the implanted isotopes?

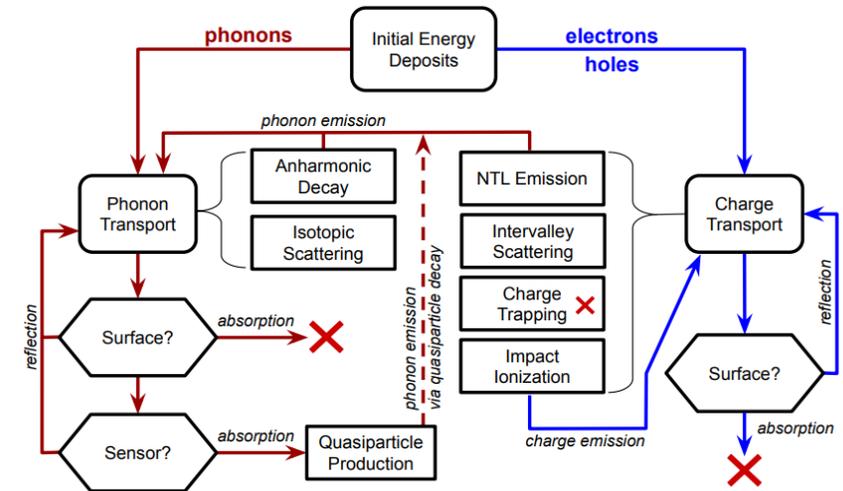


How do the decay products deposit energy in the material?



What phonons/charges are excited and how do they interact with the detector?

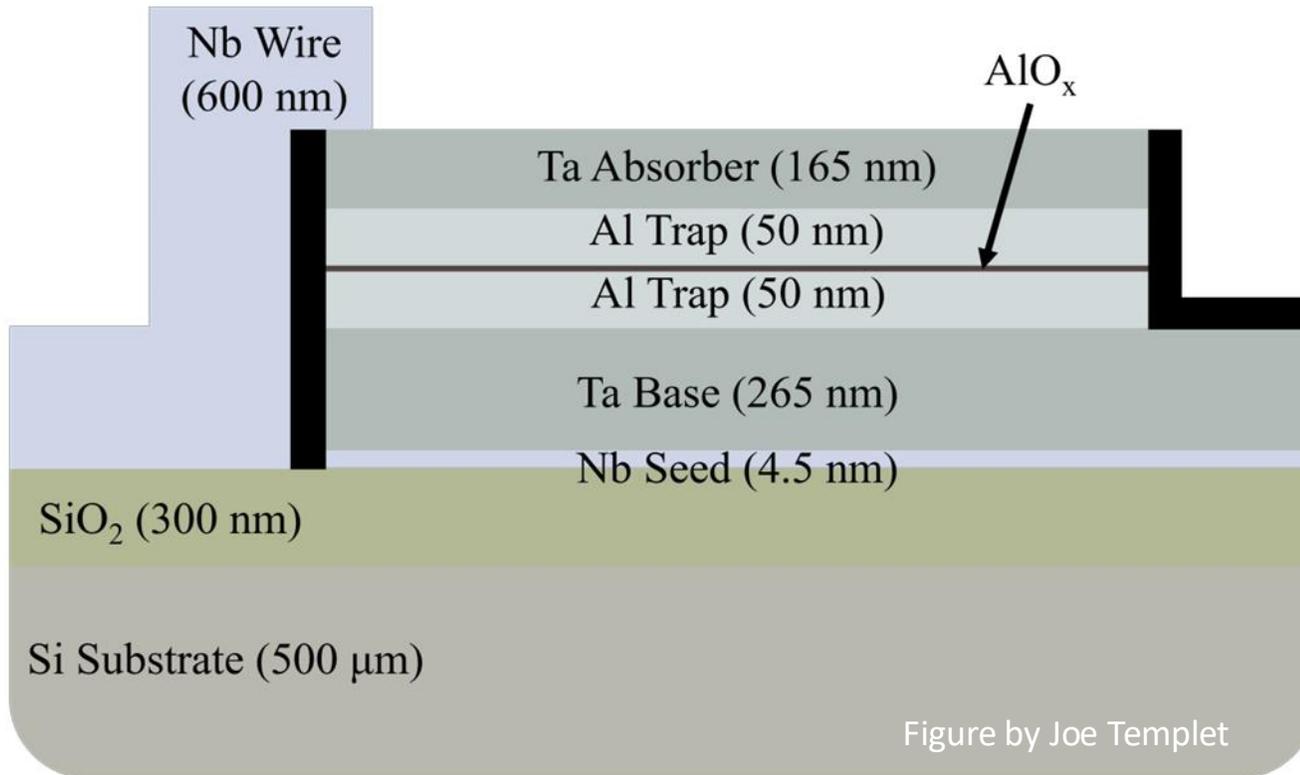
## G4CMP



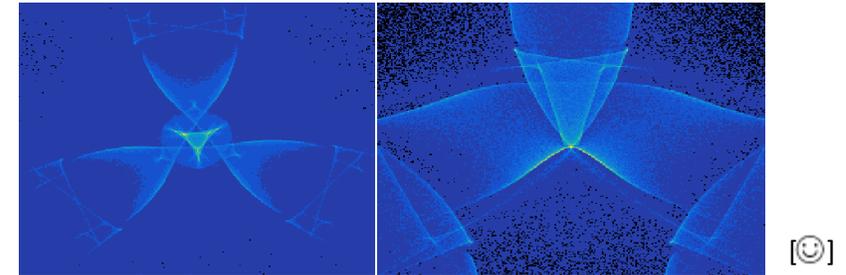
[3]

[3] D. Brandt et al., "Semiconductor phonon and charge transport Monte Carlo simulation using Geant4," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 1055, 16847 (2023).

# Motivation for Phonon Refraction in G4CMP



SiO<sub>2</sub> now available in the G4CMP repo!



## Other Applications

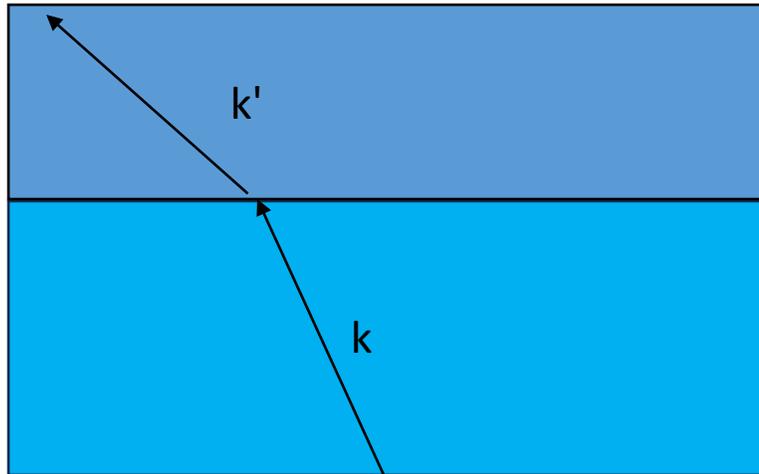
- Model phonon collection efficiency in complex geometries
- Model mitigation of quasiparticle poisoning in qubits

*Design complex detector geometries with G4CMP to meet your specific goals*

[☺] "Integration of Silica in G4CMP for Phonon Simulations: Framework and Tools for Material Integration" - just submitted to arxiv!

# Isotropic Phonon Refraction

Snell's law in 3D for acoustic phonons



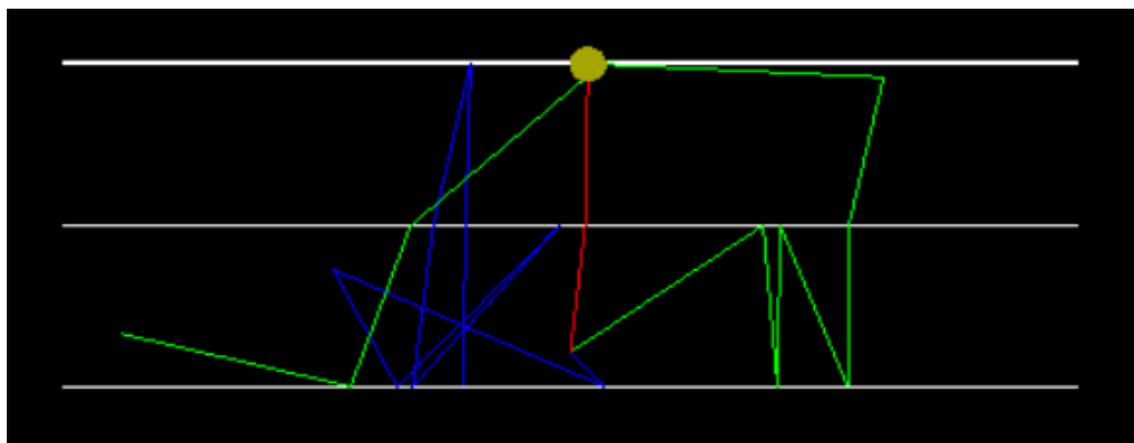
1. Compute  $k'$  with Snell's law
2. Use the Christoffel matrix to get the phonon propagation direction and velocity
3. Assign phonon the new propagation direction, group velocity and refracted wavevector

Valid for phonon refraction **from** an **isotropic** medium **to** an **isotropic** medium

# Physics Sanity Check

*Does the implementation work as expected?*

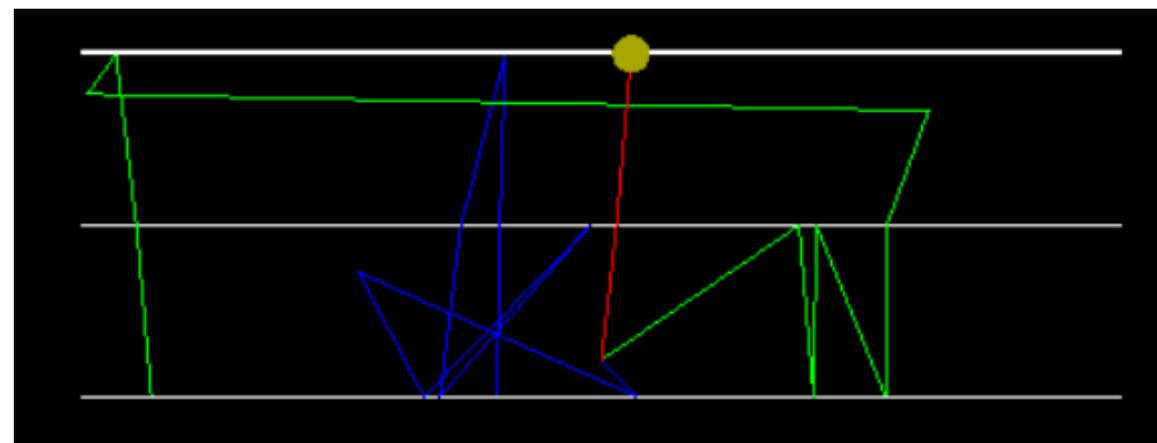
Ge



Si

TIR ✓

LiF

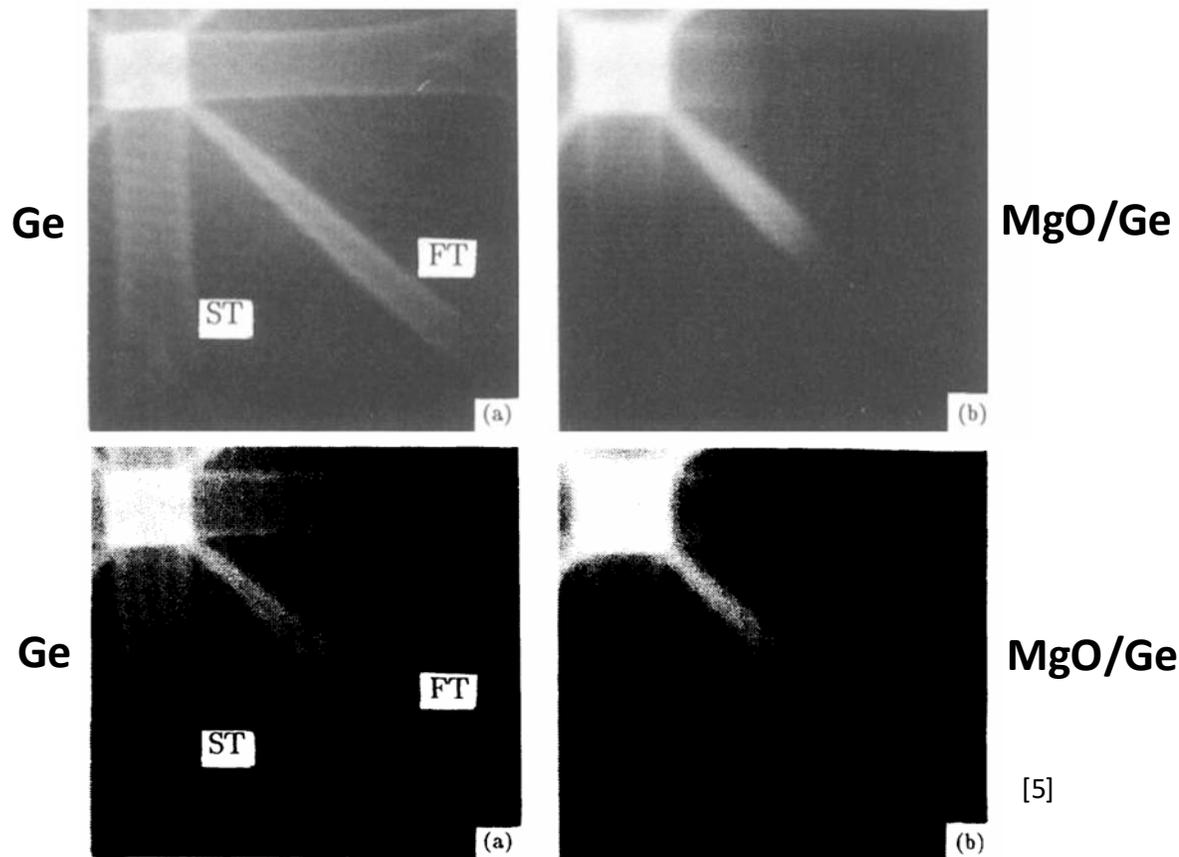
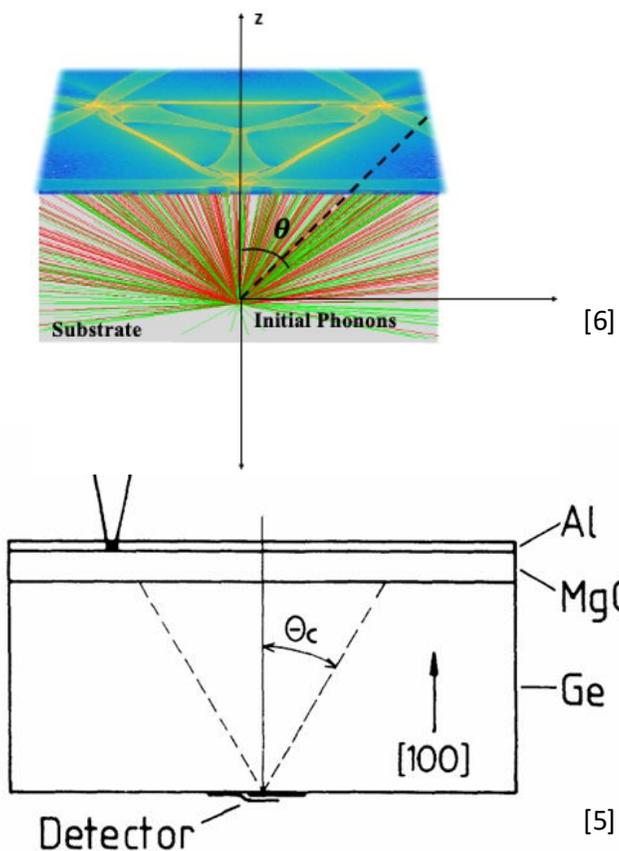


Si

Material Dependence ✓

TS=Red, TF=Green, L=Blue

# Phonon Refraction Measurements



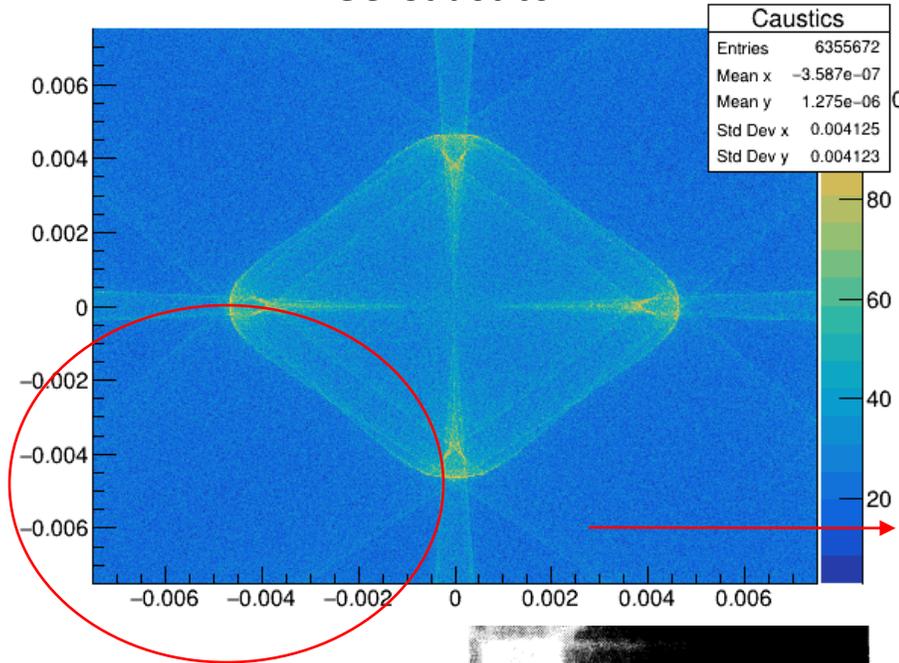
**CLAIM: ST modes suppressed by TIR**

[6] I. Hernandez et al, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1073**, 170172 (2025)

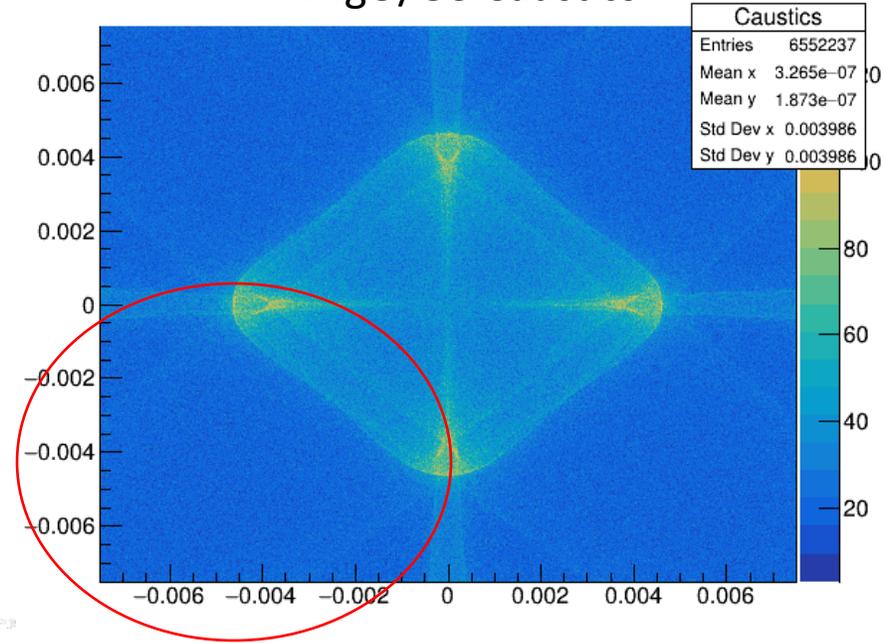
[5] Höss, C., Wolfe, J. P., & Kinder, H. "Total internal reflection of high-frequency phonons: A test of specular refraction." *Phys. Rev. Lett.* **64**, 1134–1137 (1990)

# Preliminary Physics Validation

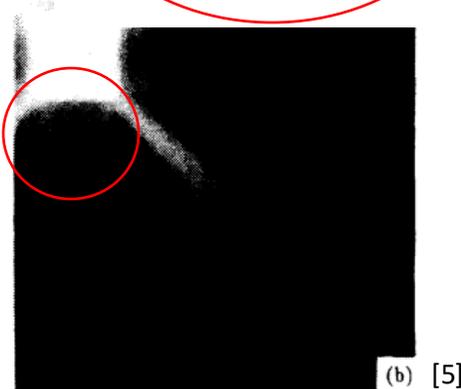
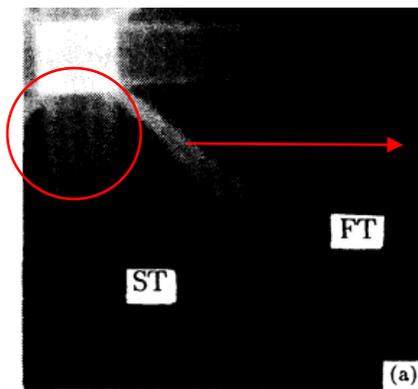
Ge Caustics



MgO/Ge Caustics

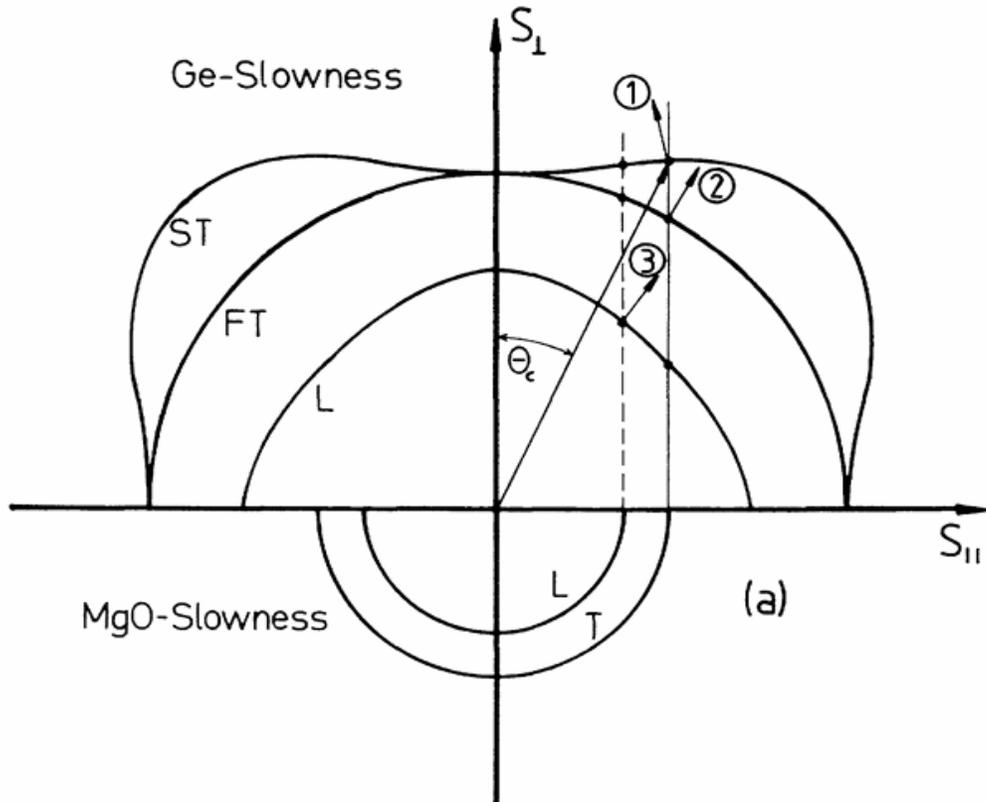


○ TS Modes (red)



★ Reproduced increased ST suppression from TIR

# Anisotropic Refraction Development



[5]

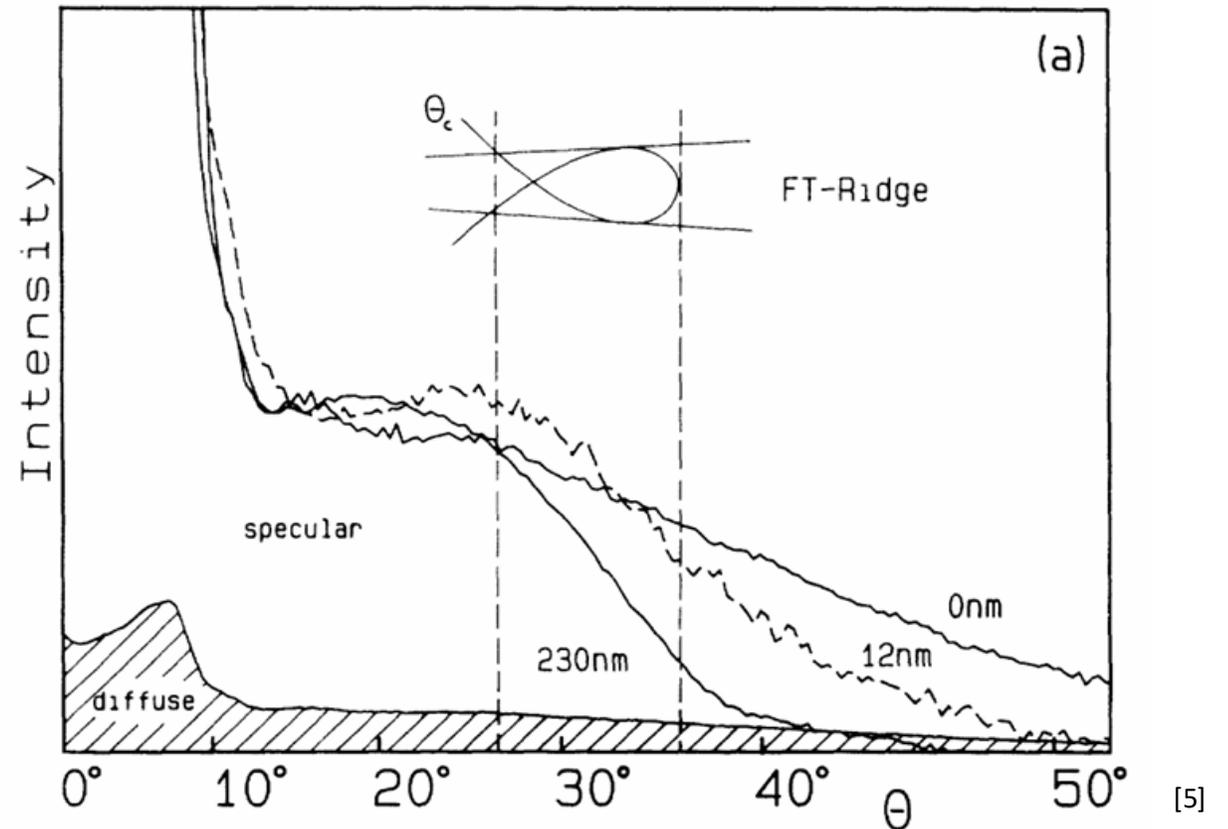
1. Conserve component of  $k$  parallel to the interface
2. Calculate slowness for mode  $m$  and the incident  $k$
3. Find refracted wave vector solutions from above conditions
4. Compute the new group velocity direction and magnitude

**IN PROGRESS**

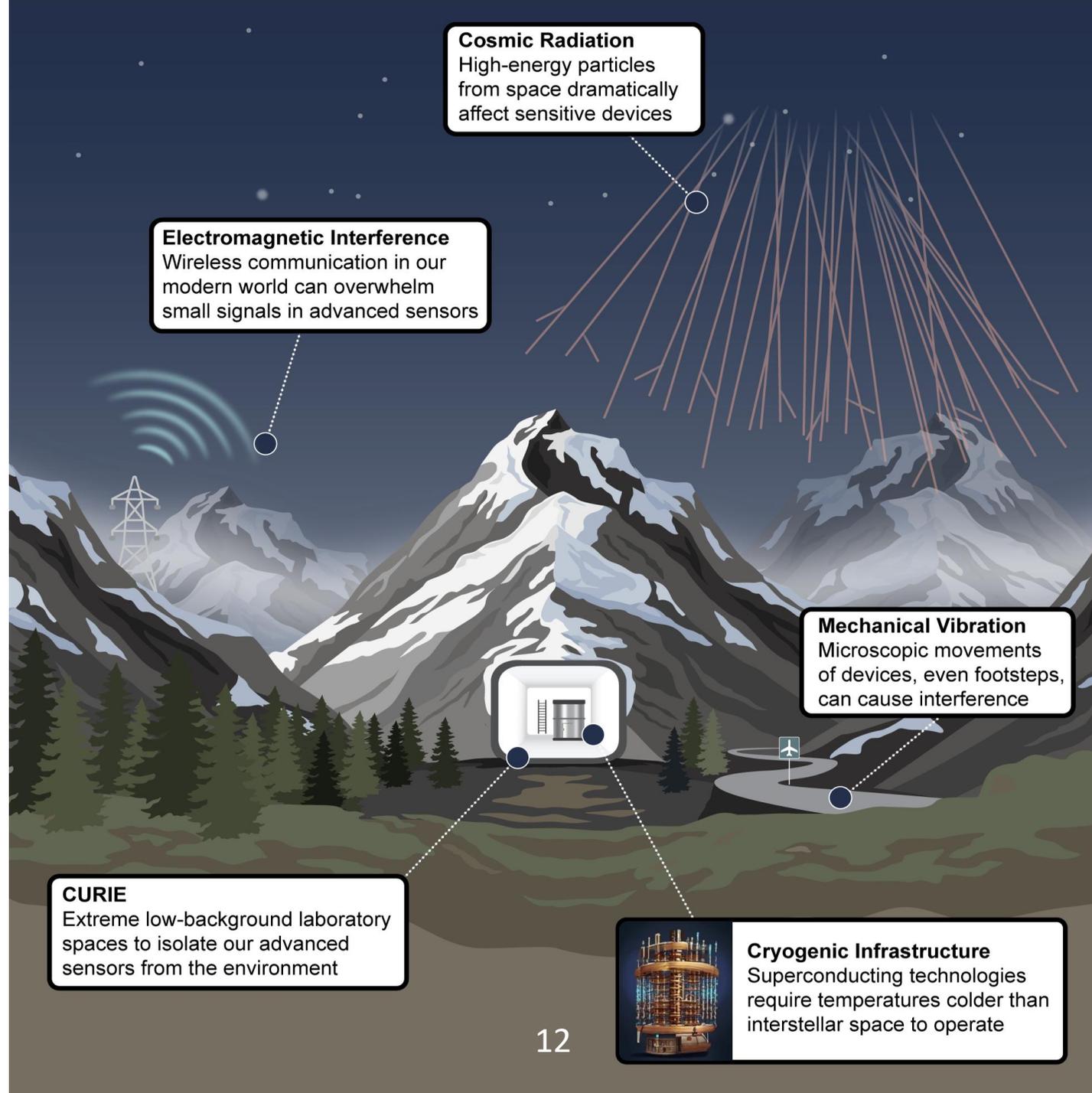
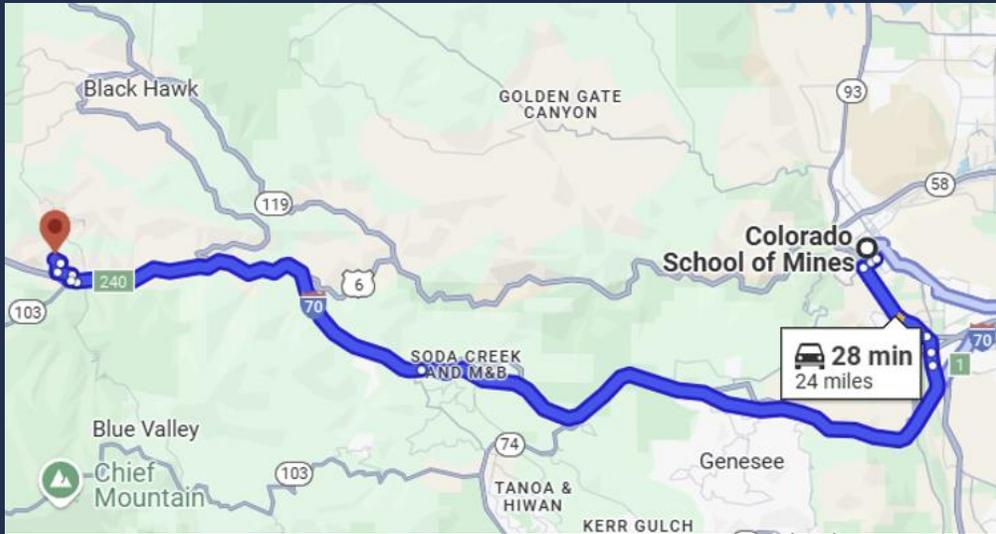
# Outlook for Phonon Refraction in G4CMP

- Finish anisotropic correction to phonon refraction
- Allow for mode conversion
- Reproduce all experimental plots in Ref. 5 for complete physics validation

**Expected completion in the next 1-2 months**



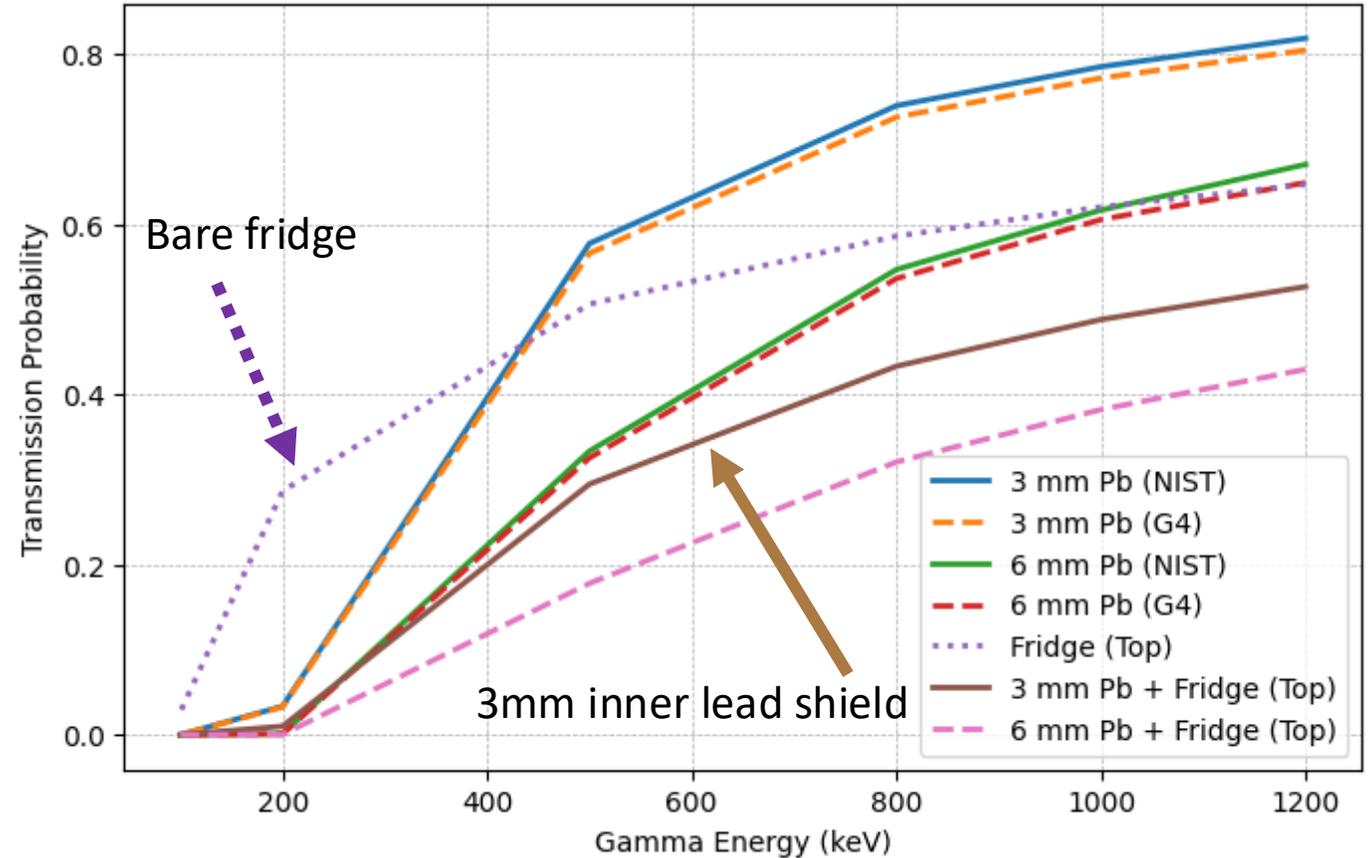
# Colorado Underground Research Institute



# CURIE Summary

## Status

- CURIE Cryogenic room being prepared with >400 m.w.e. shielding and 600x reduced muon flux
- Collaboration for low background dilution refrigerators with Maybell Quantum
  - Magnetic and ionization shielding design.
  - Optical feedthrough for photon injection using SMA/fibers.
  - SQUID magnetometer and cryogenic vibration sensing systems are in progress.



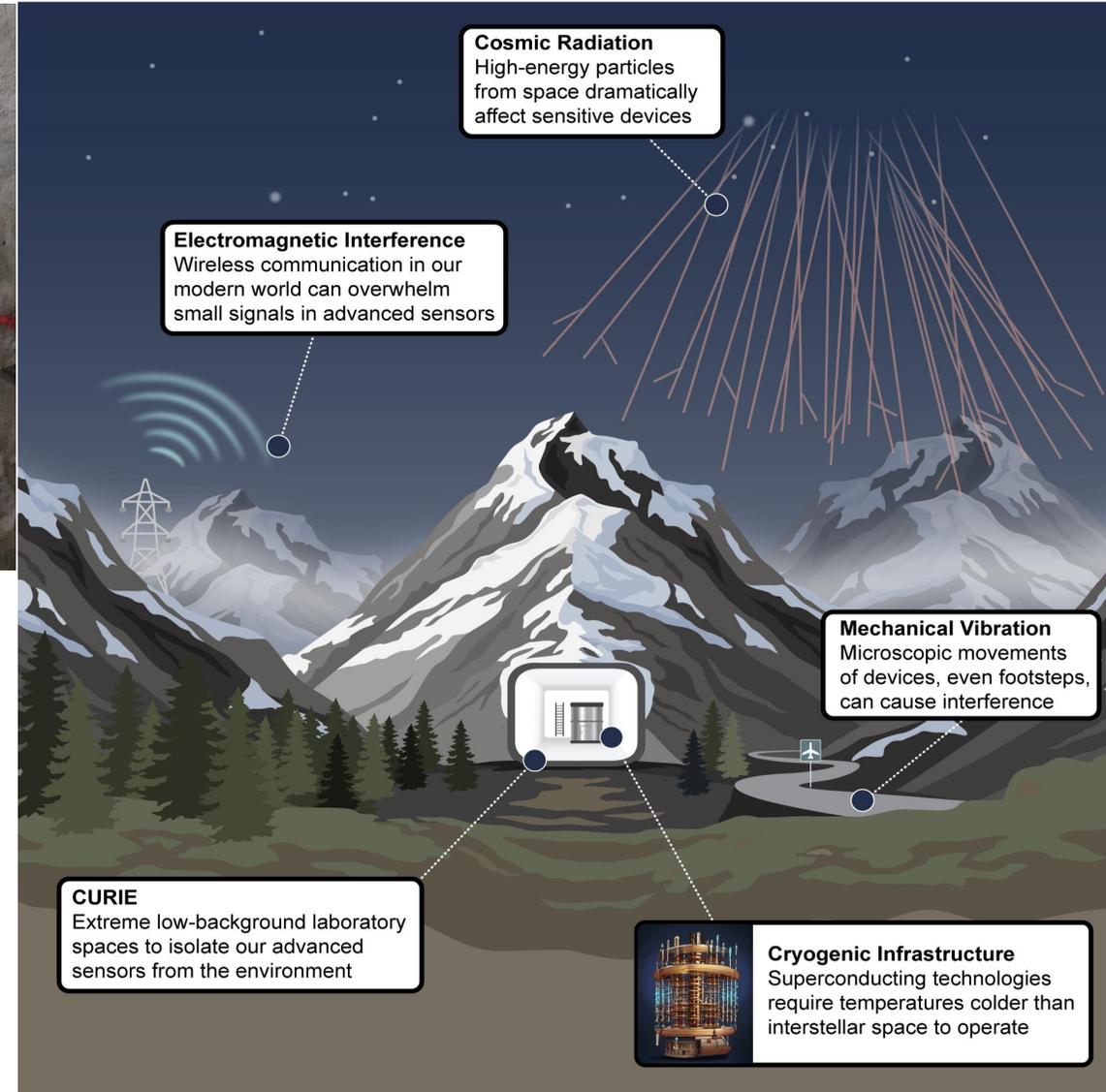


# The CURIE Collaboration



Uwe Greife, Kyle G. Leach, Eric Mayotte, Wouter Van De Pontseele, Dakota Keblbeck, Caitlyn Stone-Whitehead, Grace Wagner, Luke Wanner  
Colorado School of Mines, Golden CO USA

## We welcome new collaborators and users!

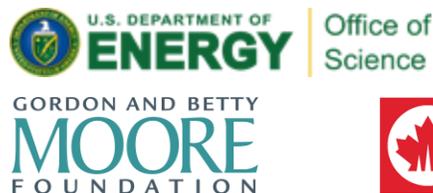


# The BeEST Collaboration

2025 Collaboration Meeting  
TRIUMF, Canada



CEA Paris-Saclay  
Colorado School of Mines  
Lawrence Livermore National Laboratory  
LPC Caen  
McGill University  
McMaster University  
NOVA School of Science and Technology  
Pacific Northwest National Laboratory  
SLAC National Accelerator Laboratory  
Star Cryoelectronics LLC  
TRIUMF  
Université Strasbourg  
XIA LLC  
Yale University



# The G4CMP Consortium

Developer group for modeling low-energy physics processes in cryogenic devices

- Started mid-2024
- Members from 31 institutions participating

UW-Madison

UMD LPS

University of Waterloo

INFN

HRL Labs

PNNL

SNOLAB

Caltech

LLNL

Colorado School of Mines

University of Florida

IN2P3

Fermilab

University of Montreal

Syracuse University

Google

Northeastern University

IIT

Northwestern University

Brookhaven National Lab

Texas A&M University

MIT

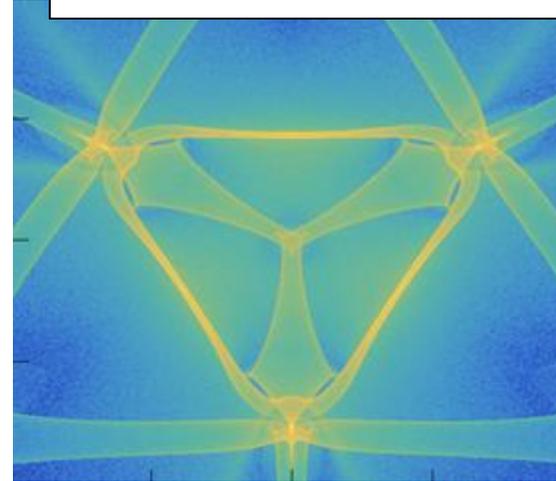
SLAC

WashU St. Louis

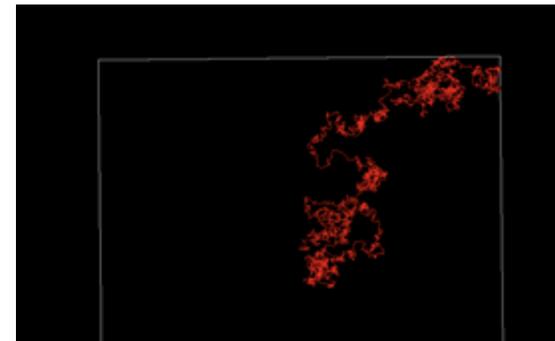
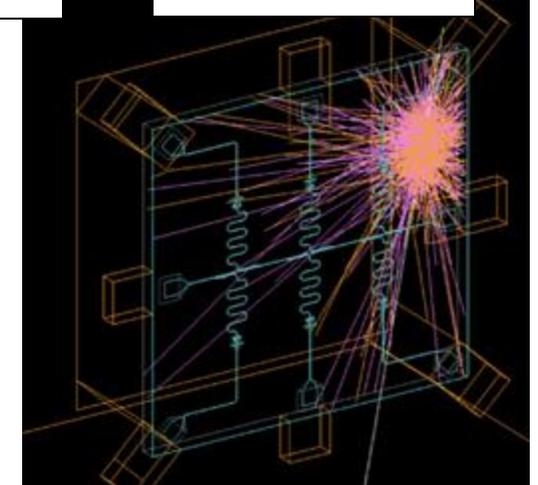
...and more!

- Contact info: [linehan3@fnal.gov](mailto:linehan3@fnal.gov),  
[kelsey@slac.stanford.edu](mailto:kelsey@slac.stanford.edu)
- Biweekly coordination/technical meetings
- Join us!

Charge/Phonon Transport



Radiation Impacts



COMING SOON:  
*energy-dependent  
quasiparticle diffusion*

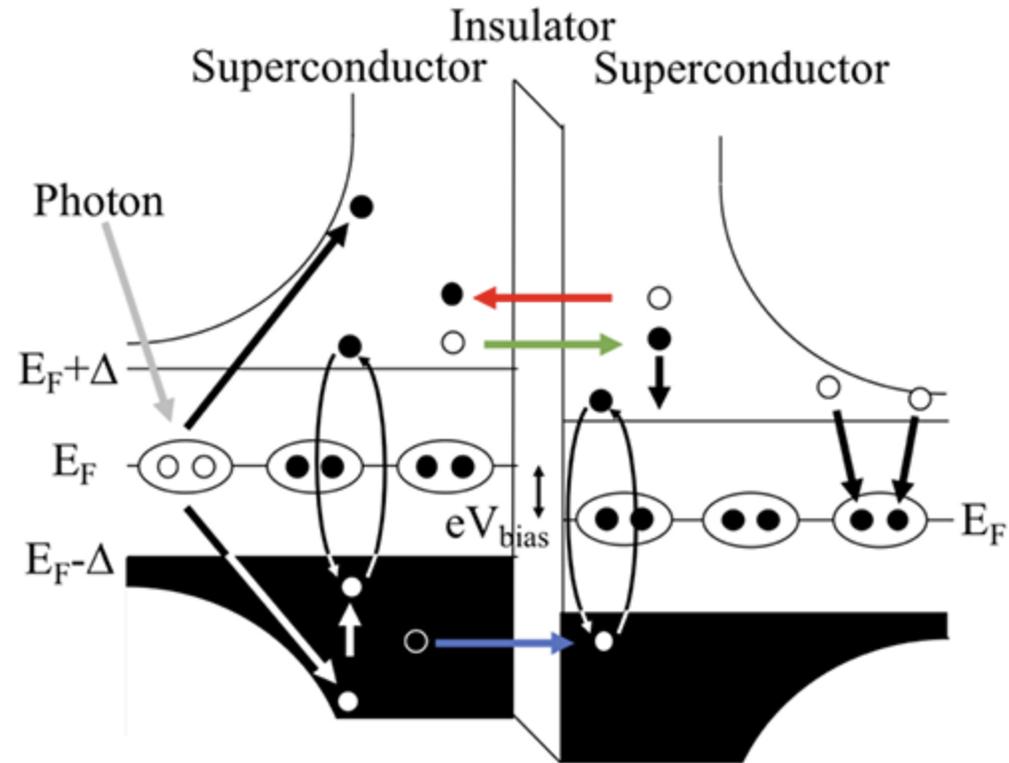


Consortium Info + Listserv

# Questions?

# Additional Slides

# STJ Band Diagram



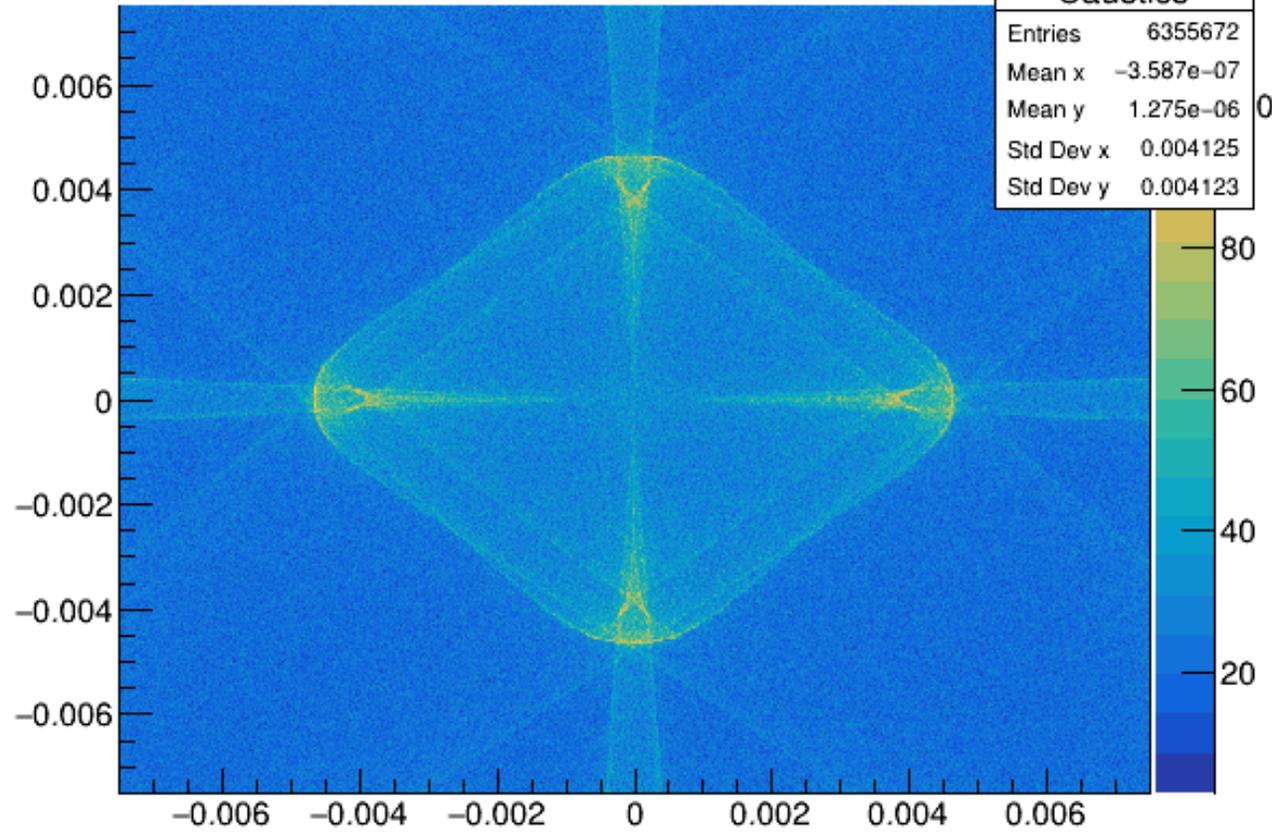
# Implementation of Isotropic Phonon Refraction

- 3D vector form of Snell's law
  - Enforces that the components of the incident and transmitted wavevectors parallel to the interface must match (s1=incident, N=normal, n1 and n2 = speed of sound in medium, s2 = refracted)

$$\hat{s}_2 = \frac{n_1}{n_2} [\tilde{N} \times (-\tilde{N} \times \hat{s}_1)] - \tilde{N} \sqrt{1 - \left(\frac{n_1}{n_2}\right)^2 (\tilde{N} \times \hat{s}_1) \cdot (\tilde{N} \times \hat{s}_1)}$$

- Computed in "GetRefractedVector()" in G4CMPPhononBoundary process
  - Takes the incident wavevector, surface normal, and the speed of sound in both materials for the incident wavevector and phonon mode
- "DoTransmission()" in G4CMPPhononBoundary process
  - Sets the wavevector to the refracted wavevector
  - Maps the refracted wavevector to a velocity and momentum direction in the second medium
- ApplyBoundaryAction in G4CMPBoundaryUtils
  - If lattices are registered, check for transmission and reflection
    - Assumes the absorption probability is now the transmission probability
    - Checks for the Total Internal Refraction condition (CheckTIR)
  - Else check for absorption and reflection

Ge Caustics



SiO2/Ge Caustics

