# Preliminary Exam

## In Defense of Thesis Proposal

“Using simulation to understand phonon propagation and quasiparticle coupling in silicon/aluminum devices designed for quantum computing and dark matter searches”

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10/19/2020

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# I. Motivation

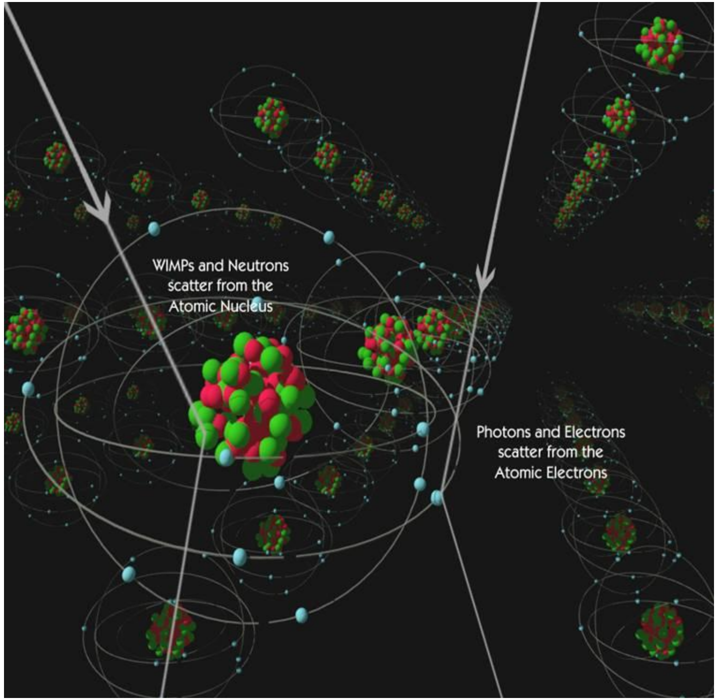
- The common interest
- Dark Matter Search
- Superconducting Transition Edge Sensor
- Quantum Computing
- Superconducting Quantum Bits
- More about Superconductors
- Energy Transport Overview
- The Benefit of Simulation

# The common interest

- Ultra-cold Silicon + Aluminum devices are used for quantum computers, dark matter detectors, and other sensor applications.
- They are sensitive to small amounts of energy. Understanding the energy transport will lead to better designs.
- This work uses a simulation built for dark matter detectors to study energy transport in quantum computers and dark matter detectors.
- Working at the intersection of two disjoint research fields has given us the opportunity to leverage the strengths of one field to address a problem in another.

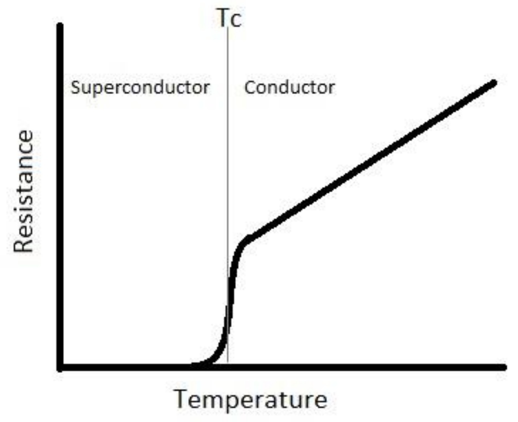
# Dark Matter Search

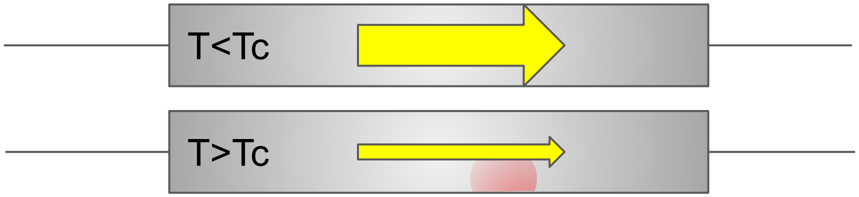
- **Theory**: Weakly interacting massive particles (WIMPs) explain the anomalous movement of stars and galaxies.
- **Strategy**: Direct detection of a dark matter particle interaction with an atom.
- **Problem**: Dark matter interaction response is similar to common background radiation interactions.
- **Need**: Ultra-sensitive device to accurately measure and distinguish small interactions.



# Superconducting Transition Edge Sensor

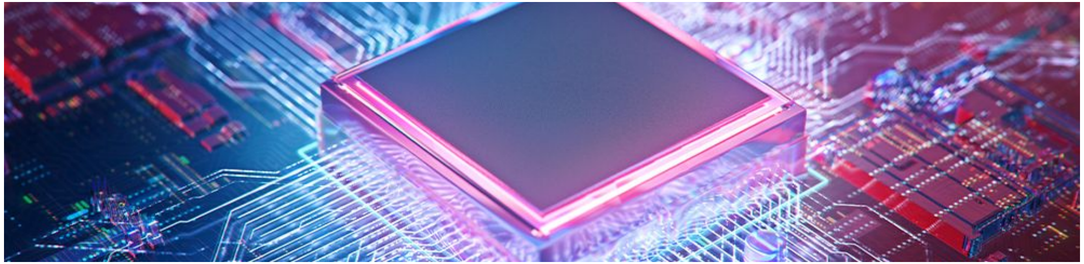
- **Given**: Superconductors have zero resistance below their critical temperature and normal resistance above it.
- **Idea**: Hold a superconductor very near its critical temperature and monitor the current through it.
- **Good**: Small amounts of energy have a huge measurable effect.
- **Bad**: Time resolution limited by time needed to cool back down.



# Quantum Computing

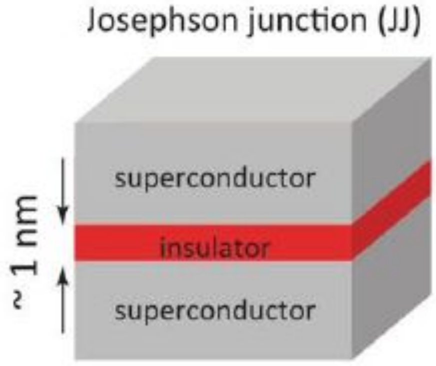
- **Goal**: Use quantum effects, such as superposition and entanglement, to perform specific computations faster.
- **Strategy**: The quantum bit, which stores quantum information in a quantum state and can be manipulated without destroying the information.



- **Problem**: Many quantum bits are required to implement quantum algorithms that solve real world problems.
- **Need**: Robust, customizable, and scalable quantum bits.

# Superconducting Quantum Bits

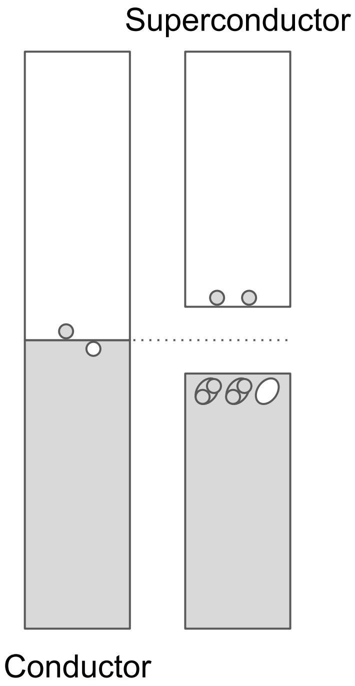
- **Given**: Superconducting current can tunnel in the quantum sense.
- **Idea**: A josephson junction has quantized current; so design a circuit with two distinguishable states.




- **Good**: Construction is easy; similar to transistors. Everything on one chip.
- **Bad**: Superconductor is sensitive to heat. Quantum state easily disrupted.

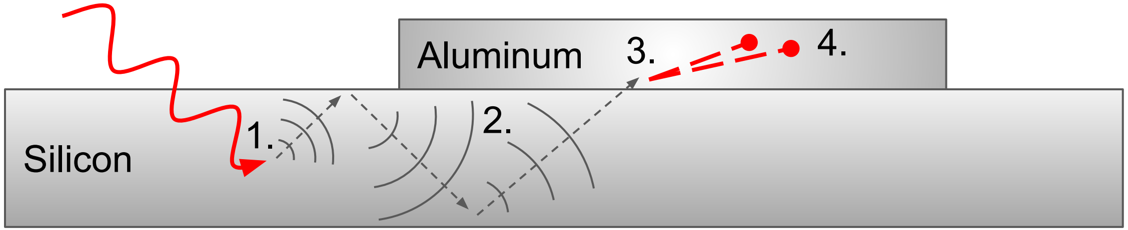
# More about Superconductors

- **Theory**: Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity predicts that electrons are weakly attracted to each other via mutual attraction to small atomic deviations, and form bound pairs called Cooper pairs. This creates a gap in the conduction band where the unpaired states used to be.
- **Definition**: An unpaired electron can be called a quasiparticle, similar to electrons and holes. (They are “created” in pairs.)



# Energy Transport Overview

- **Construction**: Superconducting aluminum attached to a silicon substrate.
- **Feature**: Silicon is an excellent non-conductor, but it can still transport energy.




1. An external energy source, such as radiation, strikes a silicon atom.
2. Silicon supports propagation of vibrations (called phonons) long-distance.
3. Phonons that enter aluminum interact with superconducting electrons, breaking Cooper pairs into multiple Quasiparticles.
4. Quasiparticles wander around, disrupting the superconductor.

# The Benefit of Simulation

Simulations have a number of specific advantages

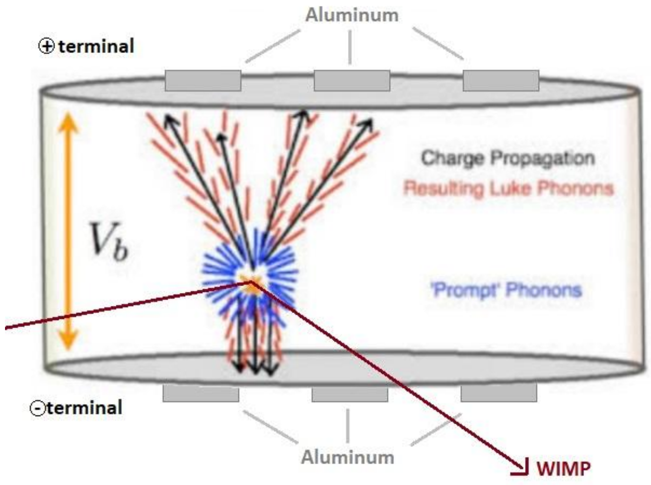
- Simulation allow us to investigate the microscopic details of the energy transport under realistic conditions.
- Simulation allows us to explore the relationship between design choices and measurement outcomes.

# II. Dark Matter Search

- The Transition Edge Sensor
- Background-dominated analysis

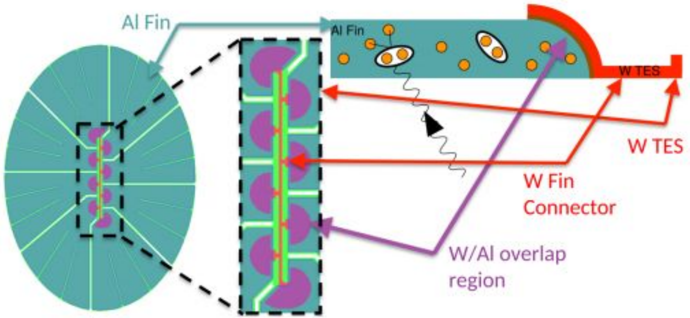
# Direct Detection Strategy

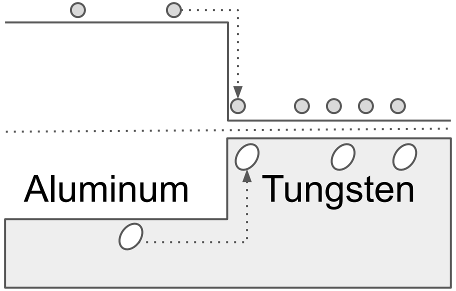
1. When a particle interacts with silicon it results in some combination of free charges and prompt phonons. For example, the WIMP scatter in the figure.
2. Free charges are drawn towards biased terminals to remove them from the crystal. Luke phonons are created along the way.
3. Phonons eventually hit Aluminum where they are absorbed. The aluminum is part of a Transition Edge Sensor.

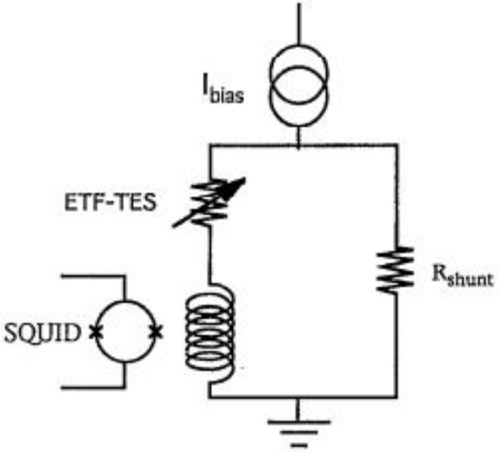


# Transition Edge Sensor Construction

- **Quasiparticle Trap**: Aluminum fins convert energy from phonons into quasiparticles. Quasiparticles enter the tungsten and are trapped.
- **Measuring Quasiparticles**: The tungsten wire has a constant bias applied, which is inductively coupled to readout SQUID.




K. D. Irwin, S. W. Nam, B. Cabrera,
B. Chugg, and B. A. Young
Rev Sci Instruments 66, 1995

# Background dominated analysis

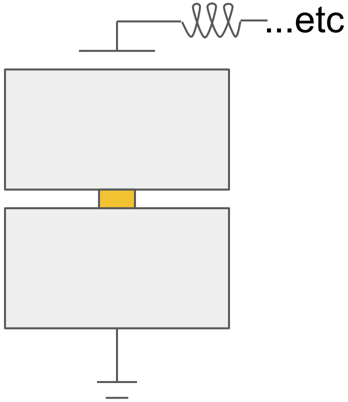
- A single particle interaction with the silicon crystal can create thousands of phonons. These spread out across the crystal before being eventually absorbed.
- The expected difference between a WIMP event and a similar background event is not large.
- The number of background events dwarfs the expected number of WIMP events.
- Any information from the pattern of sensor responses that can be used to filter out background events is very helpful.

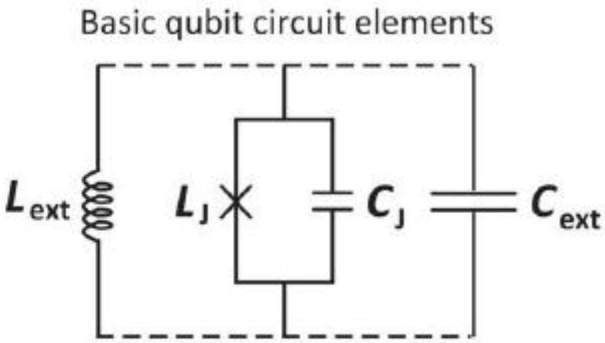
# III. Quantum computing performance

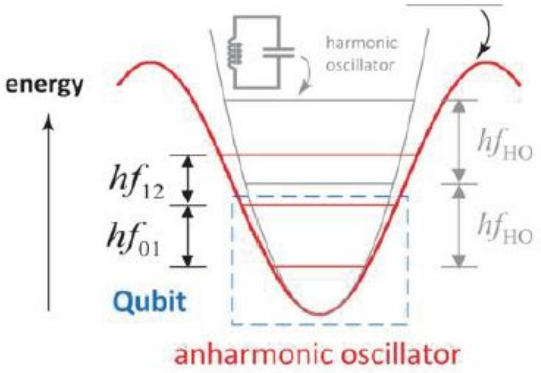
- Transmon Charge quantum bits
- Qubit control and Readout
- Quantum State Lifetime

# Transmon Charge Qubit

- **One Bit**: An anharmonic oscillator is an inductor-capacitor circuit with a nonlinear inductance. The states have unique transitions.
- **Construction**: Two large pads connected by junction. One pad is capacitively coupled to readout.

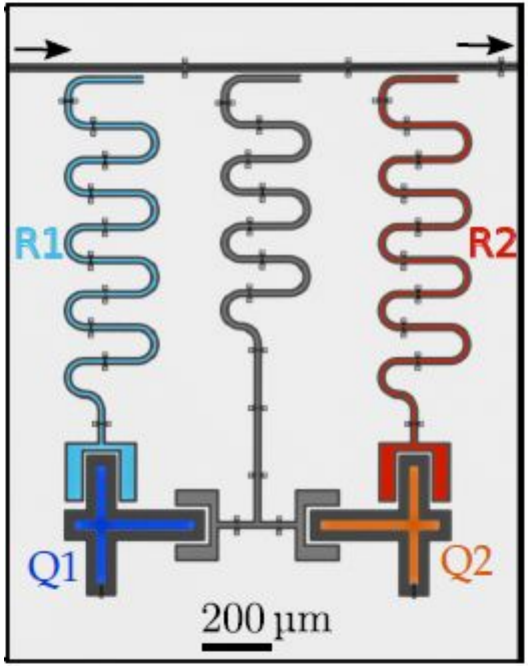


# Qubit Control and Readout

- Qubits are coupled to each other and to a microwave channel by superconducting resonators.
- Microwave pulses are used to both set and measure the qubit state.
- Addressing a qubit is done by sending its 0→1 transition frequency down the line. If it's in the 0 state, it will absorb and go to the 1 state. Measuring the transmission tells you if it absorbed or not.
- Other operations are possible by sending arbitrary waveforms down the line, but not necessary for this experiment.



# Quantum State Lifetime

- **Measurement**: prepare a 1 state, wait time *t*, and then measure to see if it's still in the 1 state.
- **Expectation**: If all processes are random, probability *p* of finding 1 state at time *t* goes like

  $$p(t) = e^{-t/T}$$

  Where T is the relaxation time.
- **Observed**: Probability is non-exponential.
  It is some combination of multiple exponentials.
- **Conclusion**: Outside interference is present.

# IV. Details of the Thesis

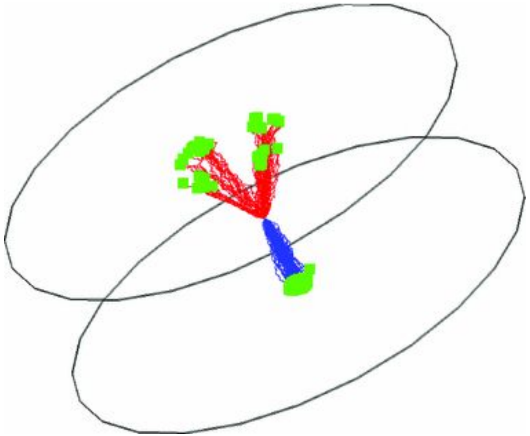
- The SuperCDMS Simulation
- Overview of the Work Plan

# The SuperCDMS Simulation

A great deal of effort has been put into a reliable, accurate simulation of the CDMS detector. It is a mix of particle physics and condensed matter physics.

1. Simulate particles traveling in a material
2. Particles interact, create recoil in crystal
3. Simulate detector response to a recoil
4. Add experimental readout noise
5. Process just like real data

Step 3 is used standalone to study the Quantum device.



Geant4 Simulations of the SuperCDMS iZIP Detector Charge Carrier Propagation and FET Readout
Agnese, R., Brandt, D., Asai, M. et al. J Low Temp Phys (2014) 176: 930.
https://doi.org/10.1007/s10909-014-1182-9

# Overview of the Work Plan

- **Scope**: We use the simulation to characterize the behavior of phonons in some simple pseudo-experiments.
- **Goals**:
  1. Develop, extend the simulation capabilities.
  2. Verify our expectations about the simulation behavior.
  3. Explore design choices that affect phonon behavior.
  4. Make a prediction about a future experimental measurement.
- **Timeline**:
  - Work plan has been completed. Writing of dissertation remains.
- **This presentation**:
  - Summary of Results.

# V. Simulation Software

- Project Infrastructure
- SuperSim project
- Quasiparticle Model

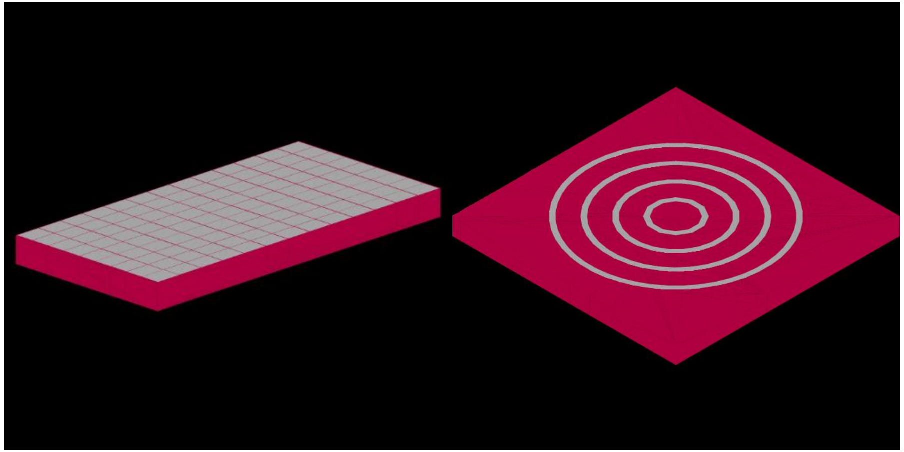
# Project Infrastructure

- **The Engine**: Geant4 handles geometry, tracking, and generic physics processes. Developed by CERN community.
- **The Application**: SuperSim implements detector geometry, readout, and user control. Developed by CDMS community.
- **The Library**: G4CMP implements crystal physics and limited superconductor physics. Developed by CDMS community.

# SuperSim project

The Simulation infrastructure required some modifications to be able to simulate the specific devices.
Implemented:

- Appropriate device classes.
- User control of surface reflection probability.
- New debugging tool, called Status Counter.



# Quasiparticle model

- Handling of quasiparticle downconversion process was corrected. Handling of sub-gab phonons has been improved.
- Verification of Phonon and Quasiparticle physics has been accomplished by inspecting the source code, stepping through execution with a debugger, and analysing the output.

# VI. Phonon Behavior Studies

- Methodology
- Basic survey
- Energy collection study
- Metalization study
- Caustics study

# Methodology

The model consists of a rectangular silicon crystal with rectangular aluminum pads, and nothing else.

Simulation starts with the direct creation of phonons and ends with energy deposited into aluminum pads, in integer multiple of the Cooper pair binding energy. Phonons killed without a deposit are also recorded. (Incoming particles are not simulated, nor is readout).

Experiments are designed to be simple, so one parameter can be varied to investigate its effect on the outcome.

# Basic survey

Phonon behavior was explored in several simple pseudo-experiments.

- Energy collected is proportional to initial energy.
- Distance between source and sensor affects the timing profile.
- Scattering and downconversion occurs at the appropriate energy and time scales.
- All phonon modes are well-populated.

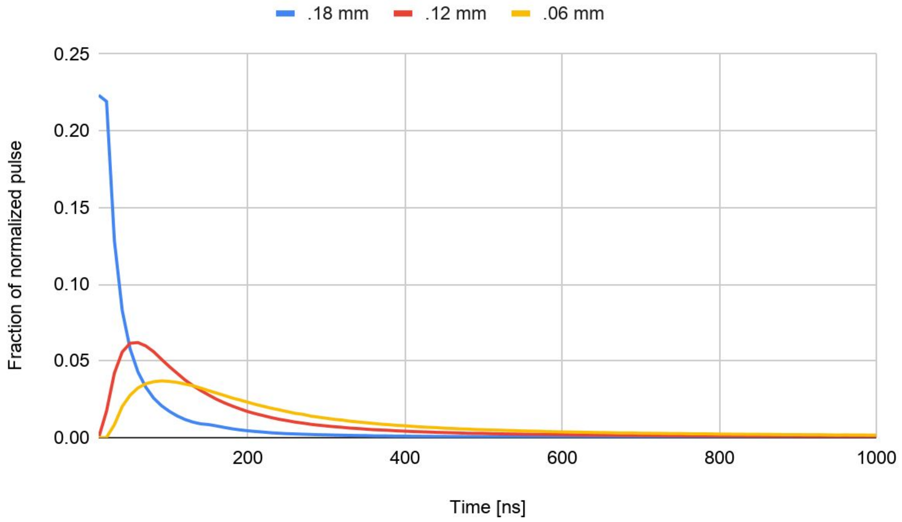
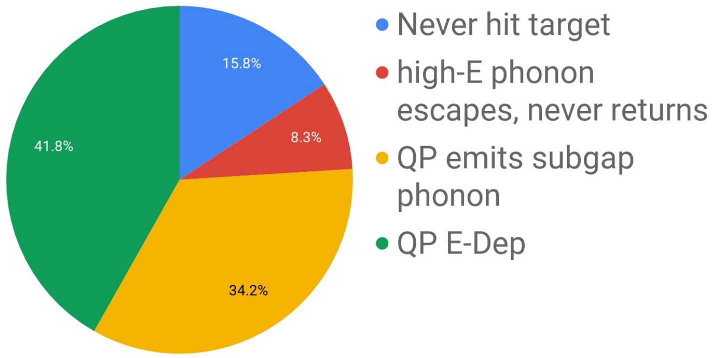



Fig. Distance affects shape of energy collection timing profile

# Energy collection study

Quasiparticle coupling was explored in a simple pseudo-experiment.

- Most of the phonon energy is not collected, because it is downconverted below the quasiparticle creation threshold while interacting with the aluminum.
- Below-threshold phonons bounce around until eventually being destroyed. All the phonon energy is accounted for.



# Metalization study

Phonon trapping was explored in several simple pseudo-experiments.

- Surface metalization makes a big difference for phonon propagation.
- This supports the popular hypothesis that quasiparticle traps can be used to control energy transport.

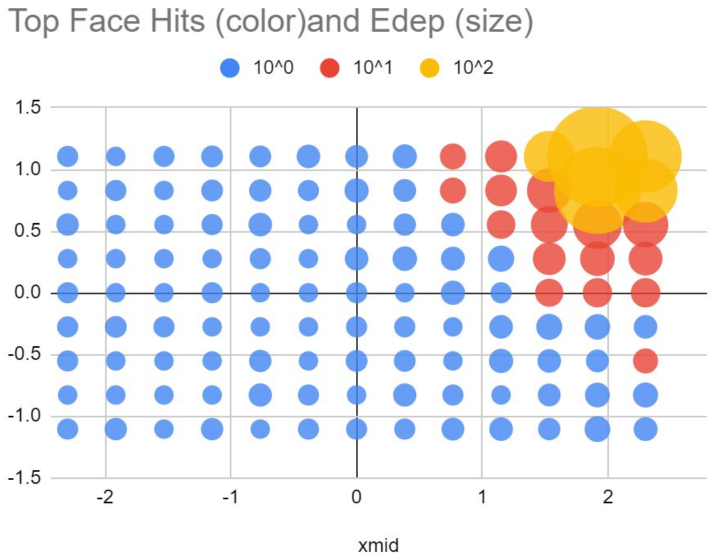
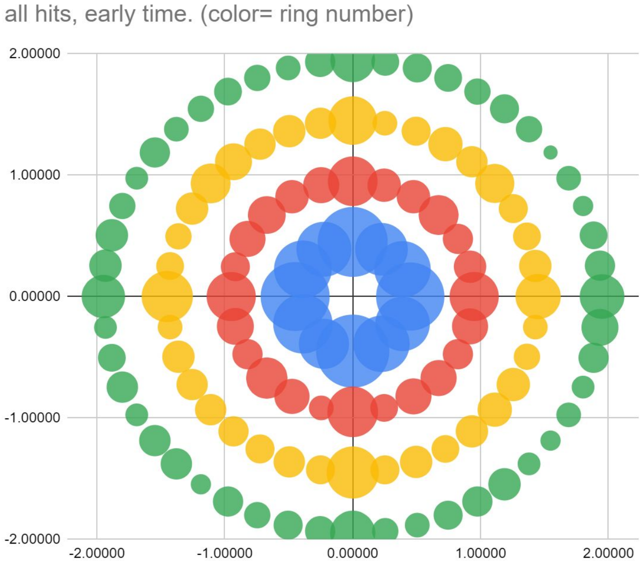



Fig. Energy injected near the corner is collected nearby. Long-distance transport is suppressed.

# Caustics study

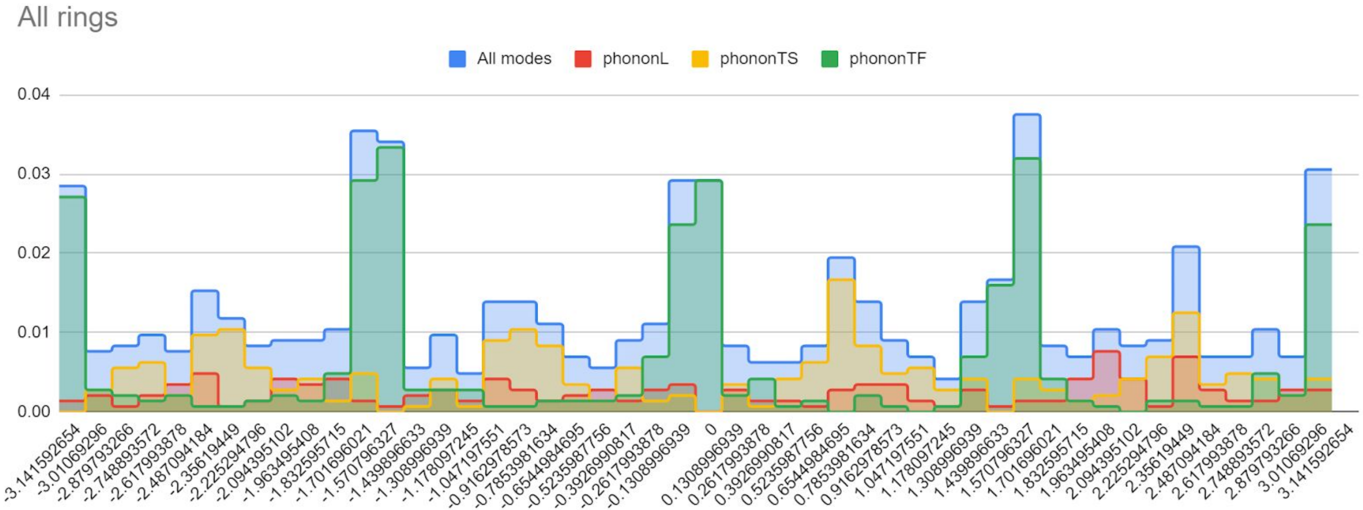
Phonon propagation direction is explored in this family of pseudo-experiments.

- Specular reflection is assumed.
- Phonon propagation favors specific directions.



# Caustics study (continued)

Inspecting the individual phonon modes reveals an underlying structure, dominated by the fast transverse phonon mode.



# VII. Discussion

- Simulation was successful
- New designs are possible
- Future work - beyond the dissertation
- Conclusion

# Simulation was successful

- A variety of geometries and measurements are achieved
- Qualitative behavior is correct
- Capable of making a verifiable prediction

# New designs are possible

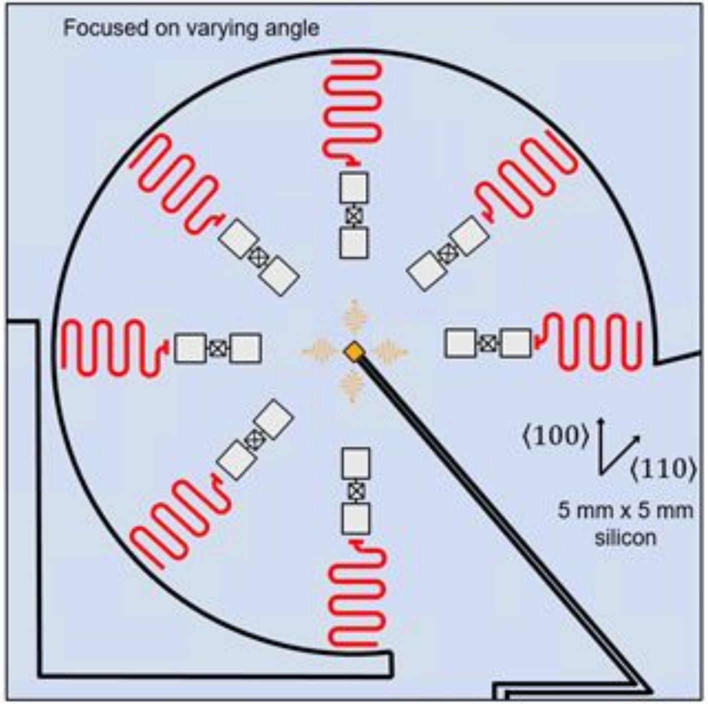
These simulations show that device design affects energy transport;

- amount of metal
- relative orientation of components
- bare surface properties

New designs could utilize this knowledge to optimize sensitivity.

# Future Work - Beyond the Dissertation

1. **Phonon Injection experiment**: The caustics study lays the groundwork for a future physical experiment that will test a prediction made by the simulation.



# Future Work - Beyond the Dissertation

2. **Irradiation experiment**: Replicate a previous Qubit experiment in simulation to verify the simulation accuracy.
3. **Position Resolution experiment**: Simulate a rectangular dark matter detector to see if the caustics pattern can be used to pin down x,y coordinates of a particle interaction. (Would be useful for rejecting certain types of background events)

# Conclusion

Working at the intersection of two disjoint research fields has given us the opportunity to leverage the strengths of one field to address a problem in another. This is truly a worthy cause for any academic community.

These simulation results move both fields just a little closer to their respective goals of discovering Dark Matter and constructing a robust Quantum Computer.

# Thank you

# Backups

# Device Physics

- Superconductors
- The life of a quasiparticle

# Wimps maybe?

# The SuperCDMS experiment

# Charge Parity Flips

# Decoherence due to quasiparticles

- The mechanism by which quasiparticles interfere with quantum states is not well understood. It is known that they can tunnel across the junction.
- If average density of quasiparticles $\langle n_{qp} \rangle$ was fixed, the probability curve would be reduced by an extra factor:

$$p(t) = e^{\langle n_{\mathrm{qp}} \rangle \left( e^{-t/T_{1\mathrm{qp}}} - 1 \right)} e^{-t/T_{1\mathrm{R}}}$$

Where $T_{1qp}$ is the relaxation time due to one quasiparticle, and $T_{1R}$ the relaxation time due to everything else.

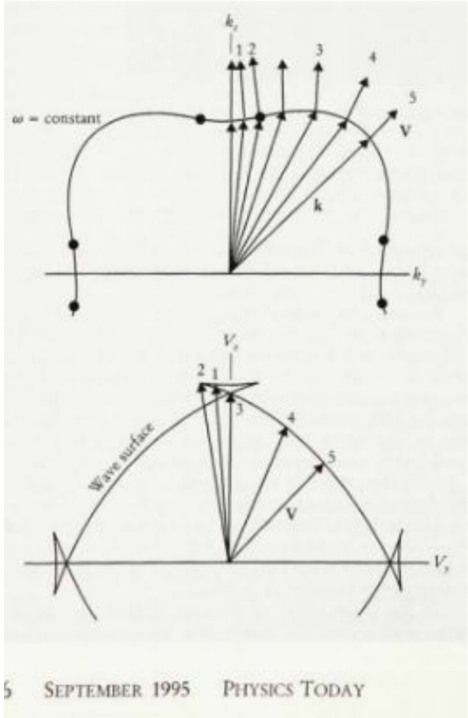
- In reality, $\langle n_{qp} \rangle$ also varies in time, i.e. quasiparticles are correlated.

# The life of a Quasiparticle

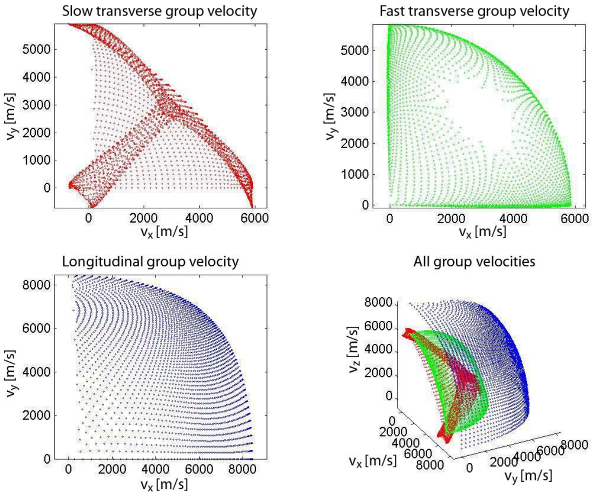
- An electron that's *not* bound in a Cooper pair is called a Quasiparticle.
- Quasiparticles band is separated from the Cooper pair band by a gap. Creation requires 2 times the gap to break a Cooper pair.
- Quasiparticles quickly shed their excess kinetic energy by radiating phonons back into the substrate. Most of these phonons are below-gap, and cannot create additional Quasiparticles.
- Quasiparticles eventually recombine into Cooper pairs after a long time.

# Phonon Physics

# Phonon Propagation




Silicon has a non-isotropic dispersion relation. Thus, some group velocities are more densely populated than others. This also breaks the mode degeneracy.



# Radiation