TEXAS A&M UNIVERSITY
Mitchell Institute

Dark Matter and Quantum Computing Devices

PsiQuantum
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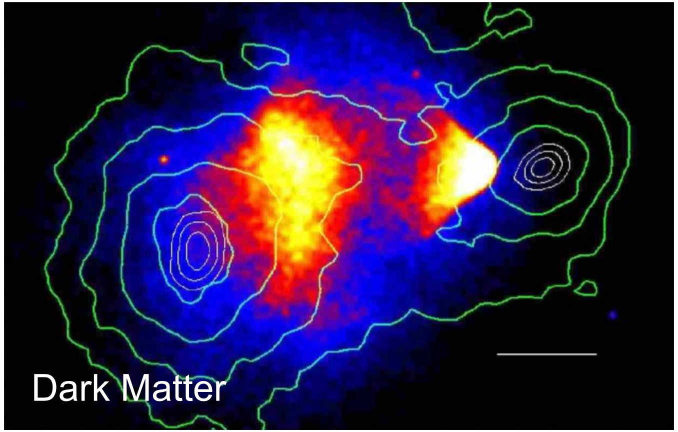
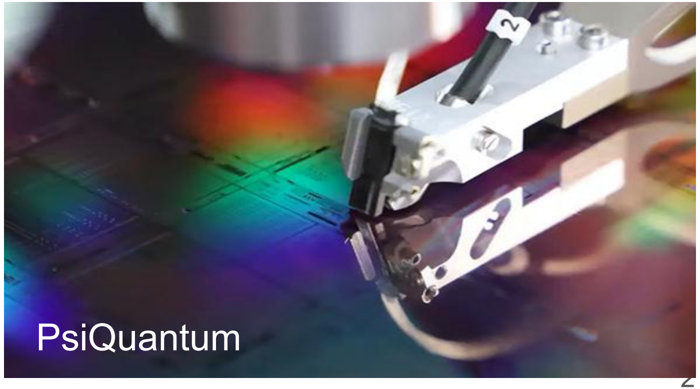
Sep 21, 2021

Outline

- Introduction to Searches for Dark Matter
- Dark Matter Searches and Quantum Computing Similarities
- Recent Projects:
    - Photon Interactions with Semiconductor and Superconducting Sensors
    - Trigger Validation
    - Electronics Testing and Calibration
- Summary



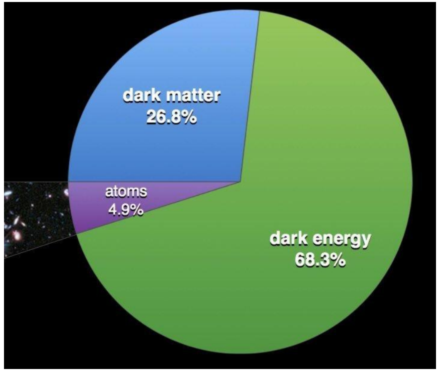


Introduction to Searches for Dark Matter

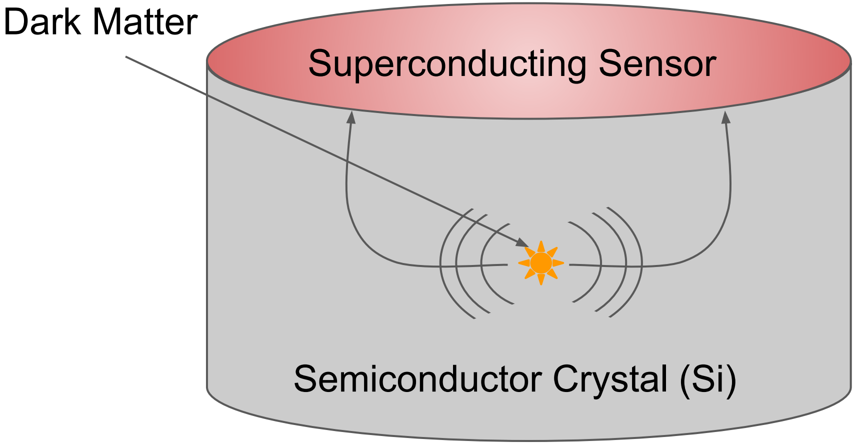
Finishing up PhD in Experimental High Energy Physics with SuperCDMS

SUPER CDMS Cryogenic Dark Matter Search

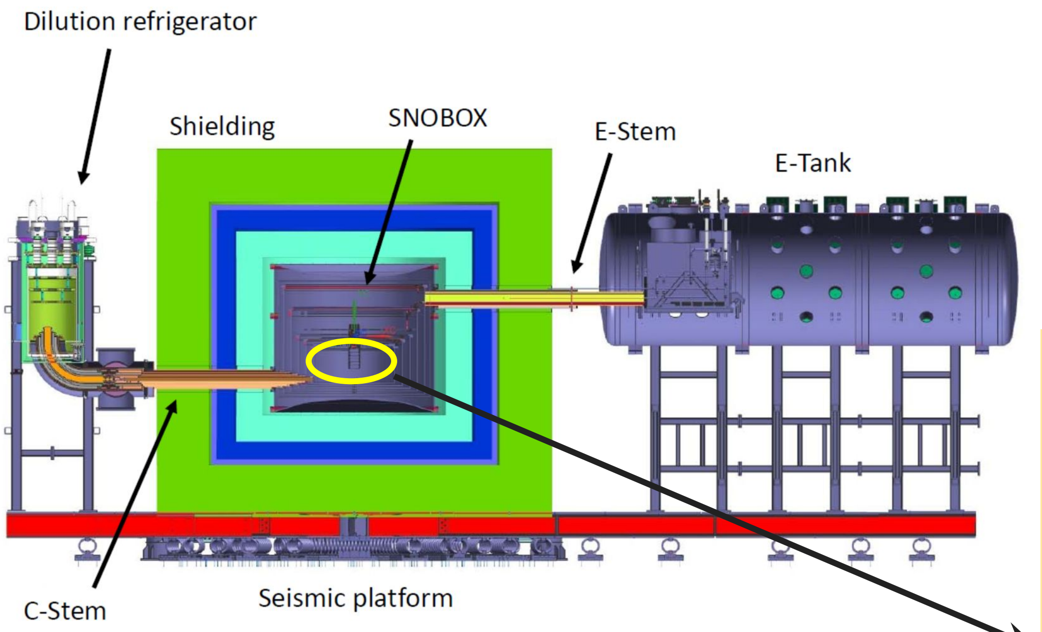
Dark Matter fills up more than 80% of the matter in the universe



DM interactions with normal matter are very low energy. We need low-noise and ultra-sensitive detectors



Introduction to Searches for Dark Matter



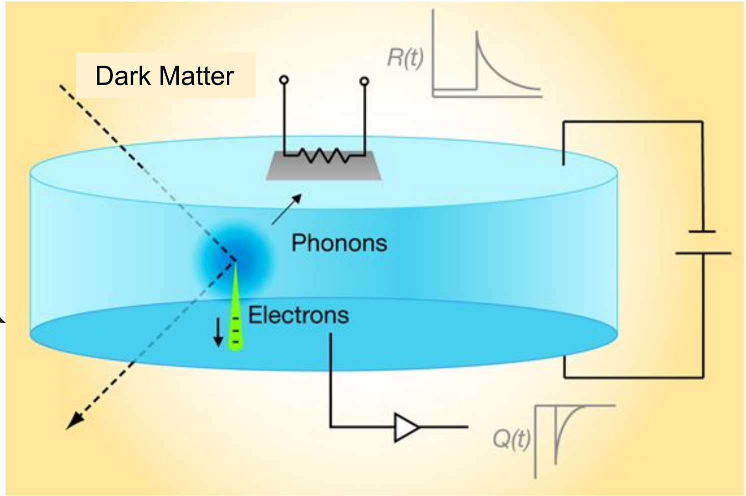
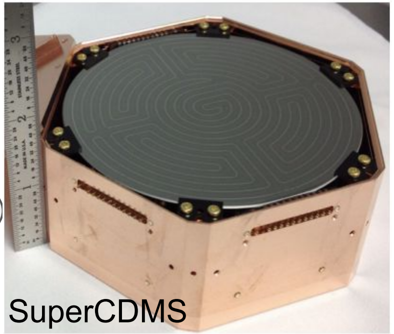


Illustration: Alan Stonebraker

Dark Matter and Quantum Computing Challenges

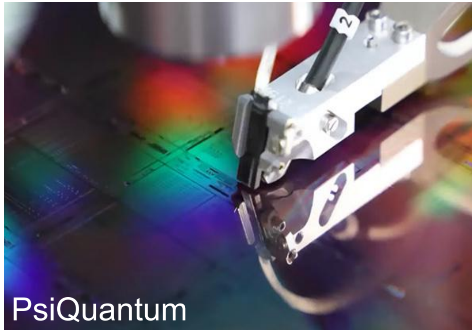
Dark Matter and Quantum Computing are Facing Similar Challenges

Dark Matter Detection



SuperCDMS

Quantum Computing



PsiQuantum

- Cryostat
- Shielding/ Fault Tolerance
- Nanofabrication/ Lithography
- Packaging/ Assembly
- Calibration
- Electronics
- DAQ & Triggering
- Data Handling

Integration: Everything should work together!

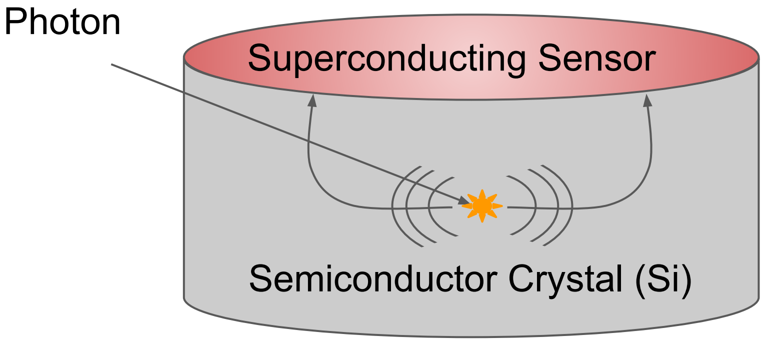
Comparing PsiQuantum and SuperCDMS

PsiQuantum

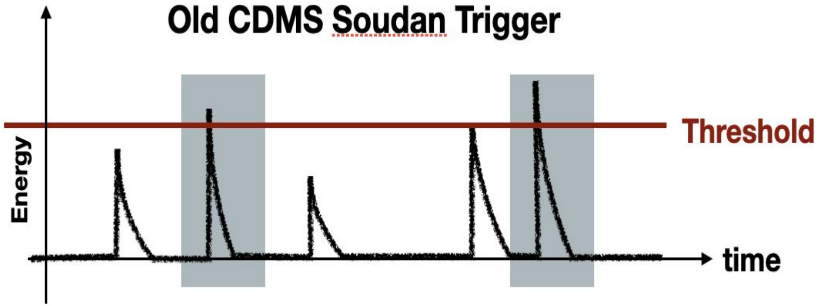
SUPER CDMS
Cryogenic Dark Matter Search

Uses Semiconductor and Superconding technologies to build a useful QC	Uses Semiconductor and Superconding technologies to discover Dark Matter
Superconducting Nanowire Single Photon Detectors	Superconducting Transition Edge Sensors
CMOS and Optical Fibers	Regular Electronics and Coax Cables
~4 K	~50 mK
~150 employees	~150 collaborators

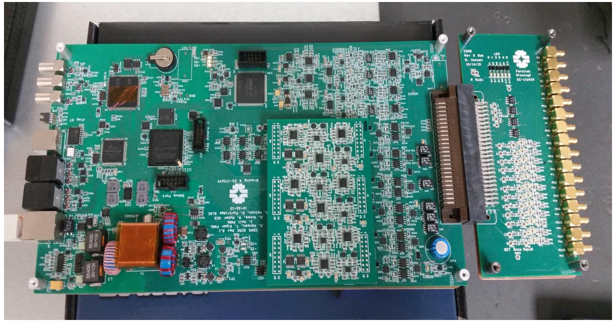
Quick Overview of My Experience



- Understanding the Photon Interactions with Semiconductor Crystals and Superconducting Sensors Using Simulations and Comparing to Data
- Simulations / Software



- Trigger Validation

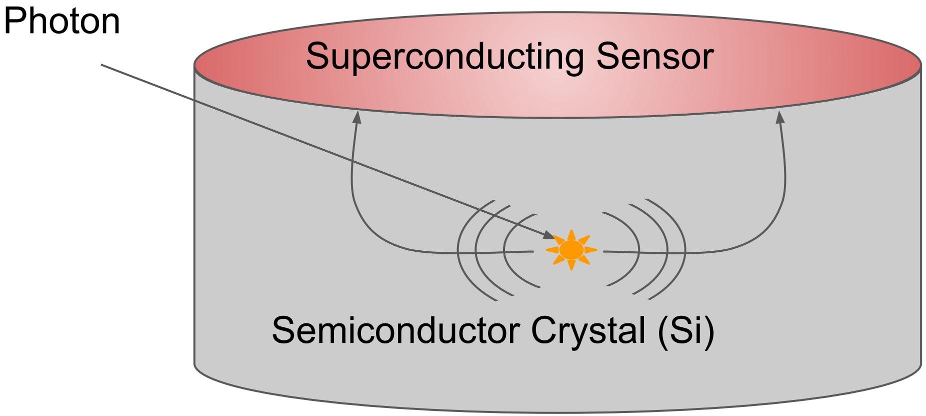


- Developing Reliability Test for Warm Electronics
- Hardware / Software

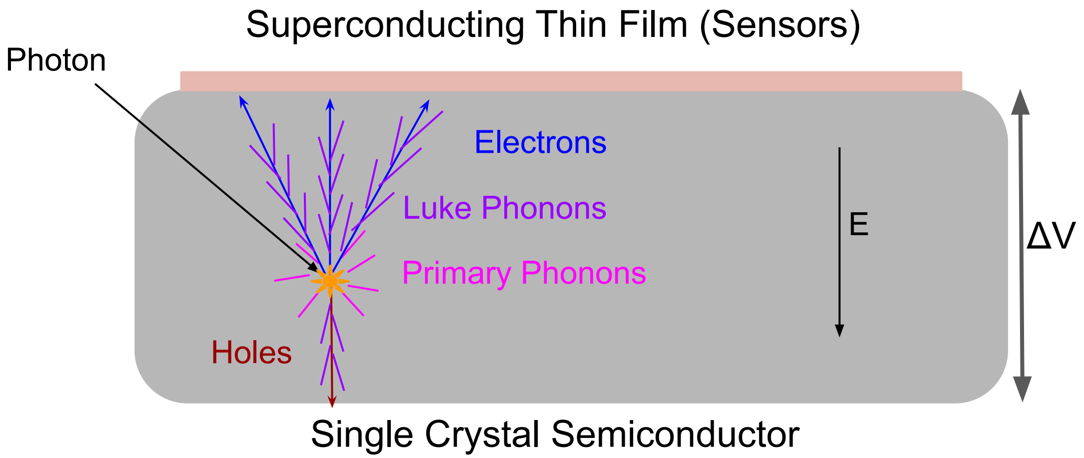
Understanding the Photon Interactions with Semiconductor Crystals and Superconducting Sensors Using Simulations

The need for Understanding the Physics of Detectors with Simulations

- The sensitivity of our detectors is limited by the lack of understanding of the physics of the experiment and devices
- Using simulations can play a significant role in enhancing our understanding
- In this project we studied well-understood photon interactions with our detectors to validate the simulation and compare to data



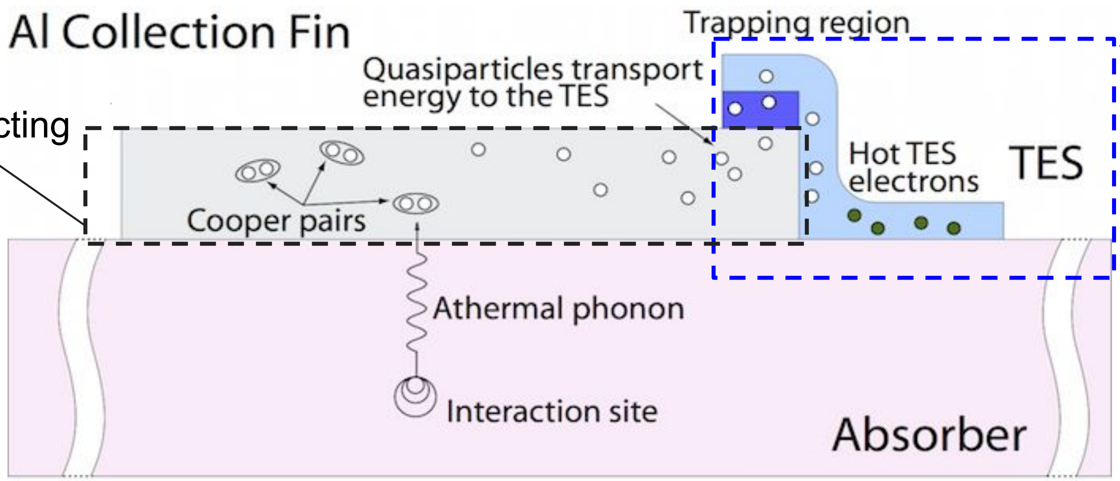
Overview of the Detector Concept



- The focus of this project was to understand detector response to the laser calibration photons
- Photons will interact with the crystal lattice, energy propagates in the crystal structure and we can measure it using the superconducting sensors

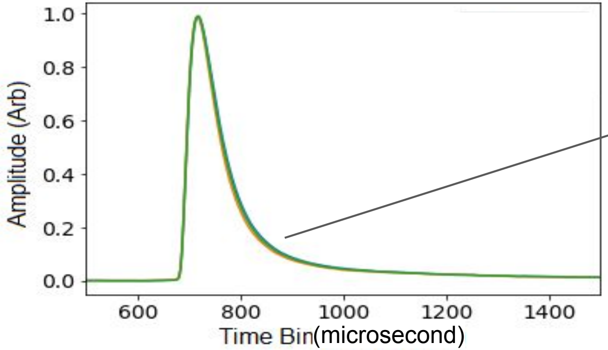
Sensor Component: Al fins and Transition Edge Sensors

Al Fin: Superconducting



TES: biased with a voltage to be in the middle of the transition

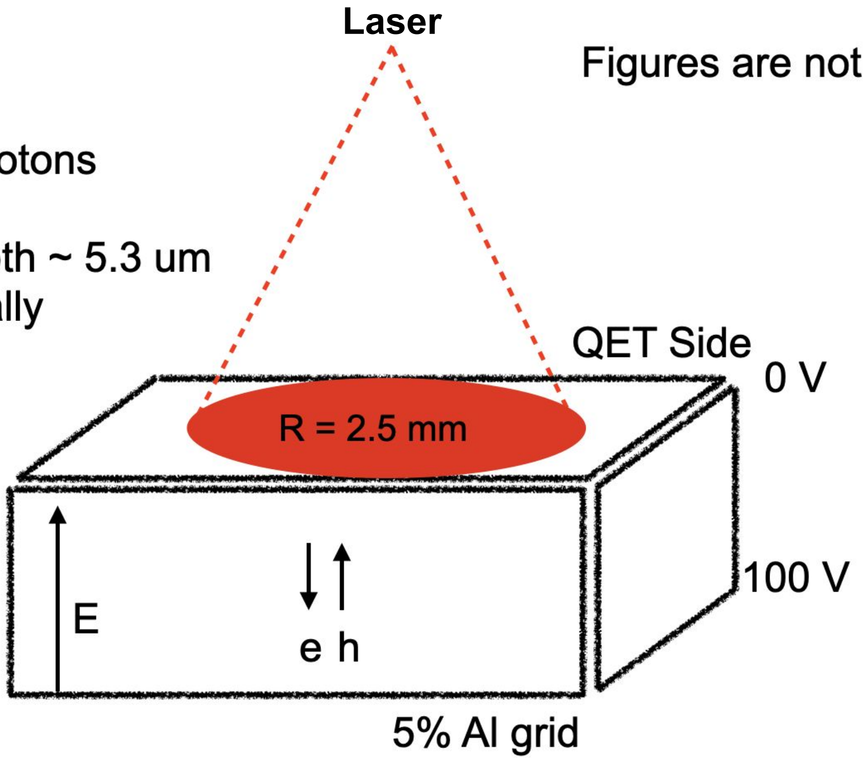
TES Pulse Readout by SQUIDS



Laser Calibration Experiment

Figures are not to the scale

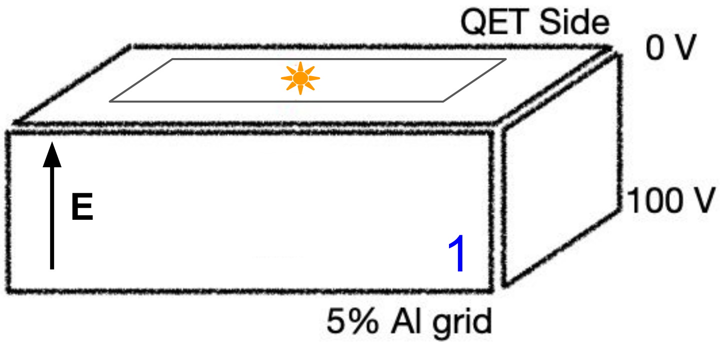
Photon Source:
1.95 eV Red Photons
Lambda = 1
Penetration Depth ~ 5.3 um
Falls exponentially



Si band gap is 1.1 eV so 1.95 eV photons can only liberate one eh pair

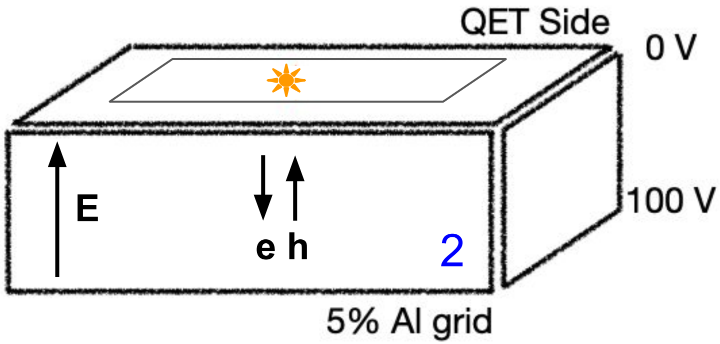
Collected Phonon Energy: 1 Photon

One photon hits the middle of the top surface of the detector. There are two possible o



The generated eh pair recombines or is trapped at the surface immediately.

- Initial Photon Energy = 1.95 eV
- Luke Amplification = 0 e * 100 V =0 eV
- **Collected Phonon E = 1.95 eV**



The generated eh pair that goes through full Luke amplification.

- Initial Photon Energy = 1.95 eV
- Luke Amplification = 1 e * 100 V =100 eV
- **Collected Phonon E = 101.95 eV**

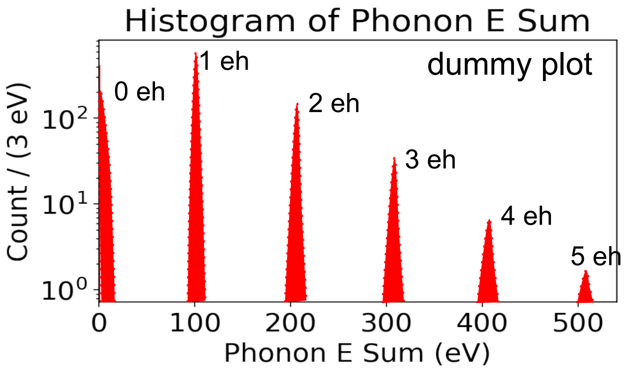
E= N*1.95 + M*100

N: Number of Photons;

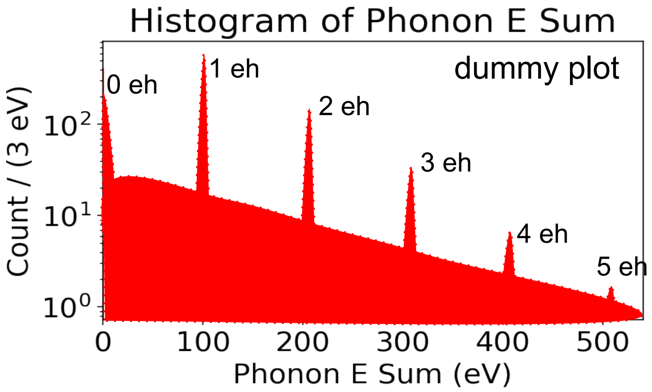
M: Number of ehs fully amplified; M<=N

Expected Spectrum and Impurity Effects

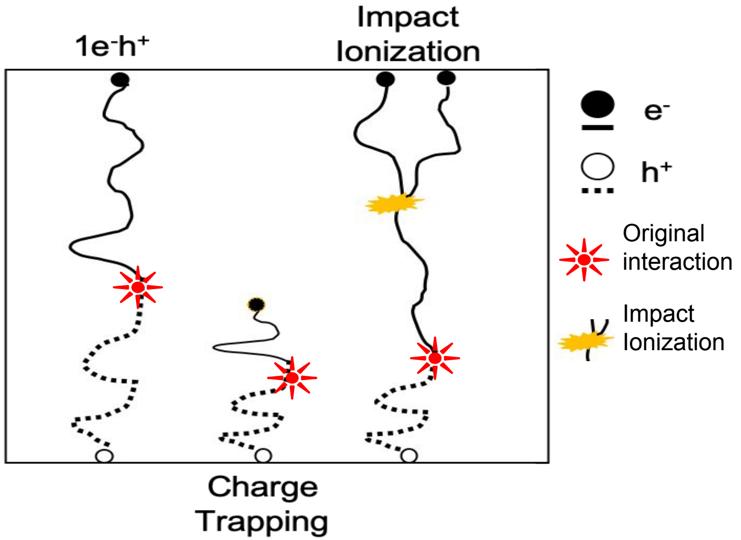
Perfect Crystal with no impurities



Reality



Charge Trapping and Impact Ionization happen because of crystal impurities => Background between the peaks

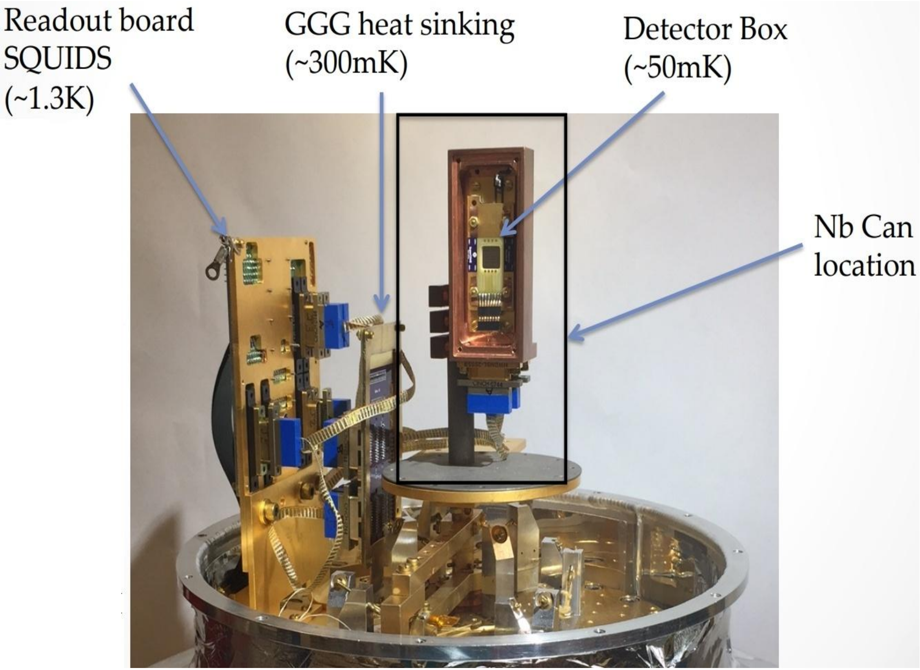


Facility and Experimental Setup

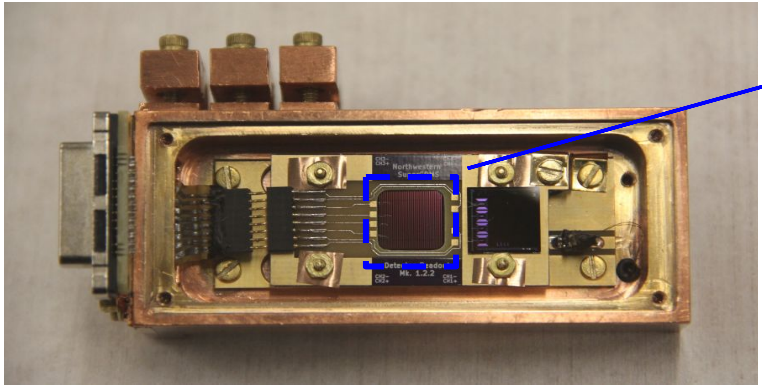
Data Acquisition and Monitoring System

Lab Setup

Vericold ADR Fridge (The detector is here)



Detector Geometry

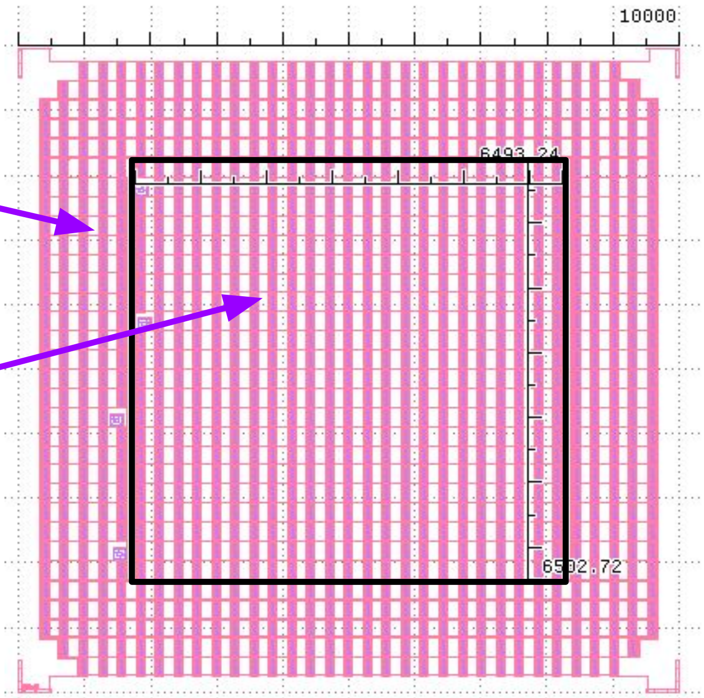


Si HVeV mounted in the copper holder

Detector

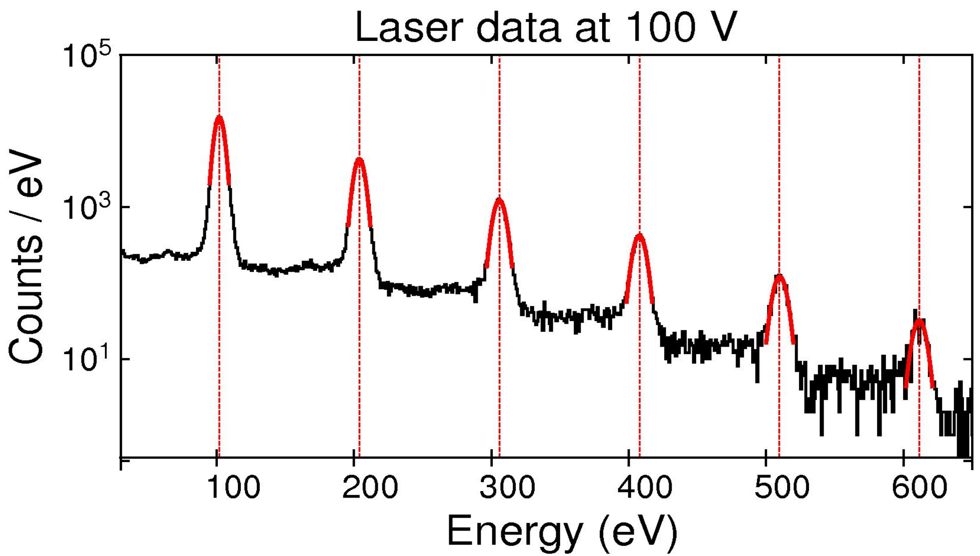
Channel 2

Channel 1



- 10×10×4 mm^3 silicon chip with a total mass of 0.93 g
- Two channels, with 1044 TES's and critical temperature of 65 mK

Recoil Energy Spectrum from Real Data: Main Features and Goals



The goal of the simulation is to understand and reproduce these features:

- **Location of the peaks**
- **Width of the peaks (Which can hopefully tell us about the detector resolution)**
- **Understand the events between them to understand the detector response**

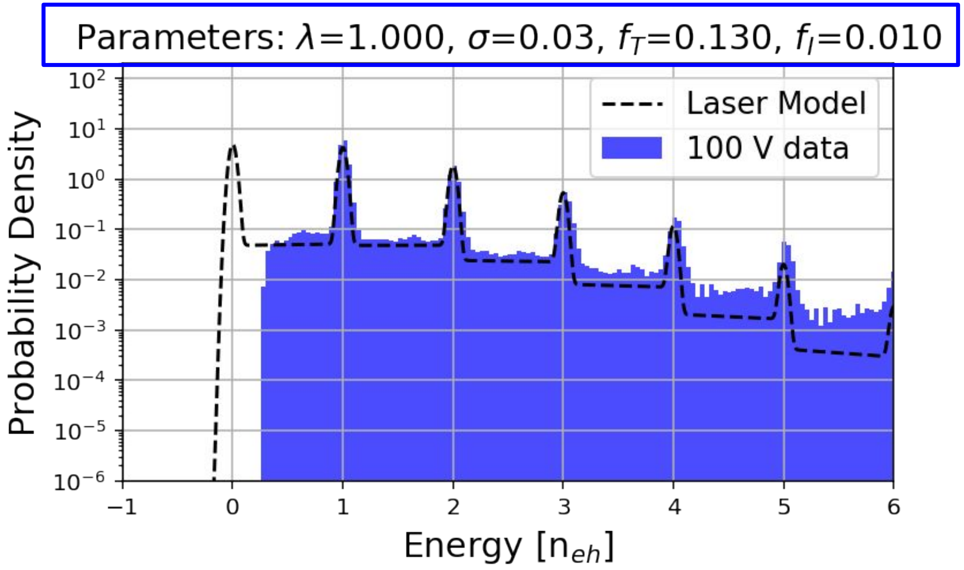
Finding Important Simulation Parameters Using a Toy Model

- The rate of **Charge Trapping** and **Impact Ionization** depends on the quality of the crystal

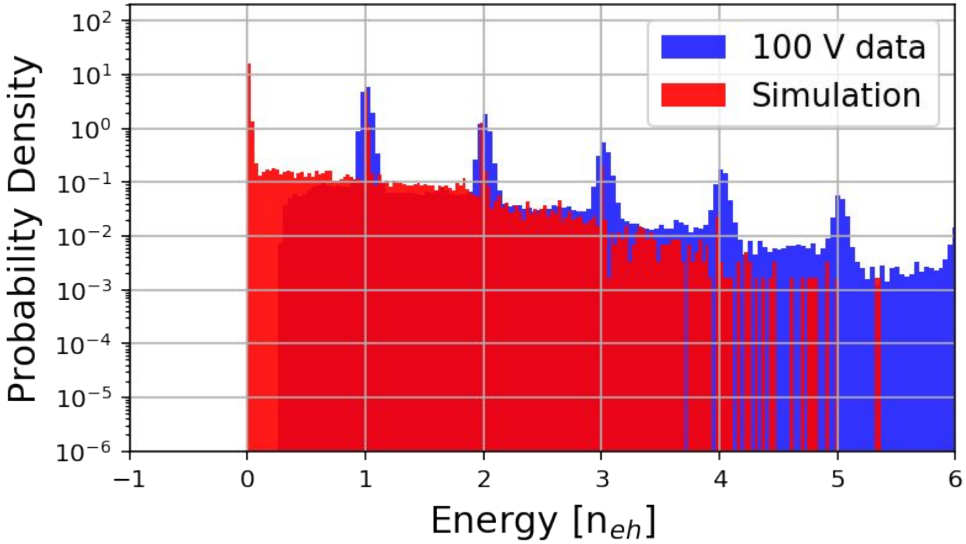
- To estimate the parameter values for the simulation we start with an analytical toy model for the data

This model has free parameters for:

- Lambda of the Poisson Photon Spectrum of the Laser : λ
- Detector Resolution: σ
- Charge Trapping Rate: f_T
- Impact Ionization Rate: f_I



First Results of Comparison of Data to Full Simulation

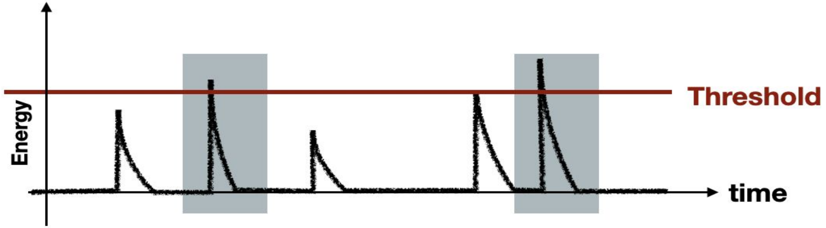


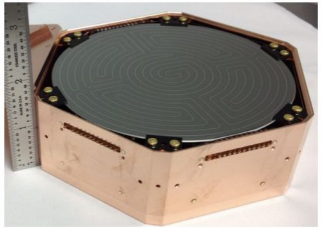
- Overall shape of the data and simulations are similar. Peaks and backgrounds appear as expected
- The peaks are sharper in the simulation because noise is not yet added
- Trigger cuts out lowest energy events. We have not added trigger simulations here
- Will get the higher peaks when we move to higher statistics simulations

Validating the Performance of the Trigger

Trigger

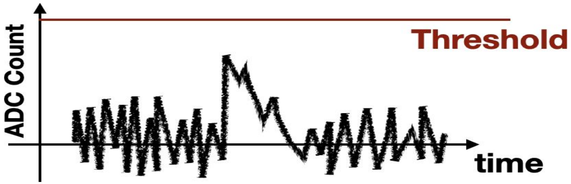
The trigger is part of the DAQ and looks at the analog signals. The first thing it does is digitize them, and THEN it decides whether to write them out. The decision to write them out is called the Trigger.



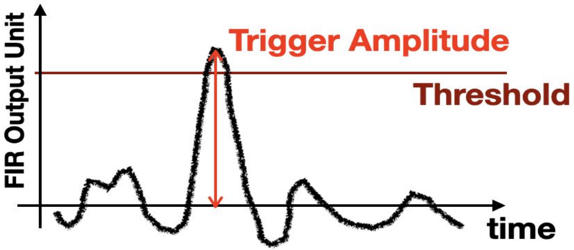


Regular Triggering Misses Low Energy Events

Detector



Optimal Filter



FPGA-based online triggering algorithm that uses an optimal filter to make the separation between noise and signal more pronounced

Goals and Trigger Validation Method

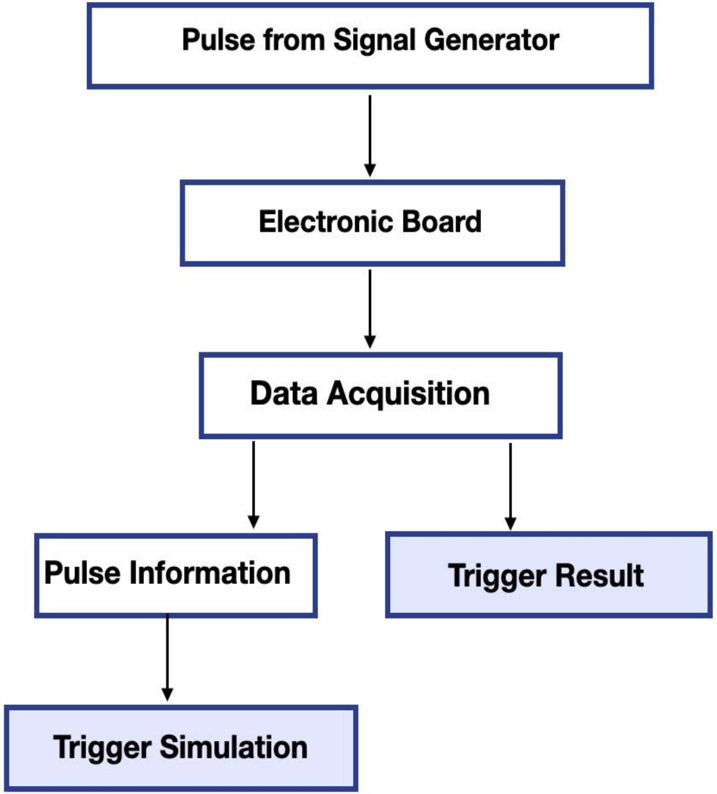
- Goal: Validate the performance of the trigger
- We wanted to answer the following questions:
  - Does the Trigger do what it is supposed to do?
  - How often, when there is no input pulse, do we fire? How does that change as a function of the threshold?
  - How often does the trigger make the right decision? How is this affected by the noise?
- Used an Arbitrary Waveform Generator and a Bit-wise Trigger Simulation

To Simulate the Detector Pulse

Bit-wise Trigger Simulation to be used as our benchmark

```
class Trigger(object):
    def __init__(self,
                 bits_phonon, bits_charge,
                 phonon_DF_R, phonon_DF_N, phonon_DF_M, phonon_start,
                 charge_DF_R, charge_DF_N, charge_DF_M, charge_start,
                 LC_coeffs, LC_bits_coeff, LC_bits_out, LC_discard_MSBs,
                 FIR_coeffs, FIR_bits_coeff, FIR_bits_out, FIR_discard_MSBs,
                 ThL_selectors, ThL_activation_thresholds, ThL_deactivation_thresholds,
                 PS_max_window_lengths, PS_saturated_pulse_offsets,
                 TrL_selectors, TrL_enables, TrL_requires, TrL_vetos, TrL_prescales):
```

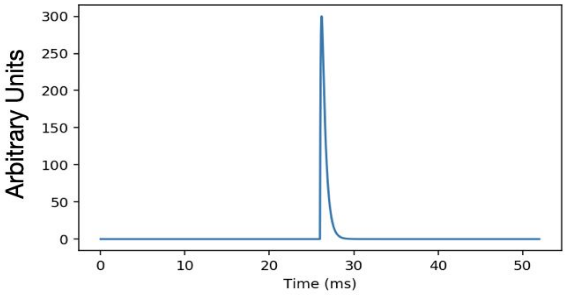
Validating Trigger Using Trigger Simulation



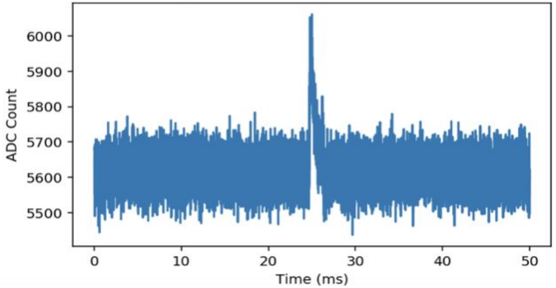
Signal Generator

Midas DAQ

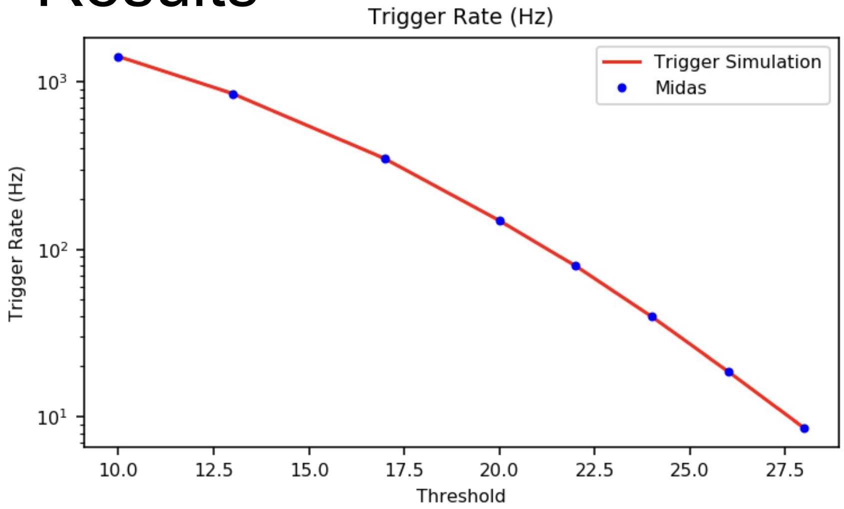
Simulated Low Energy Pulse in the Electronics

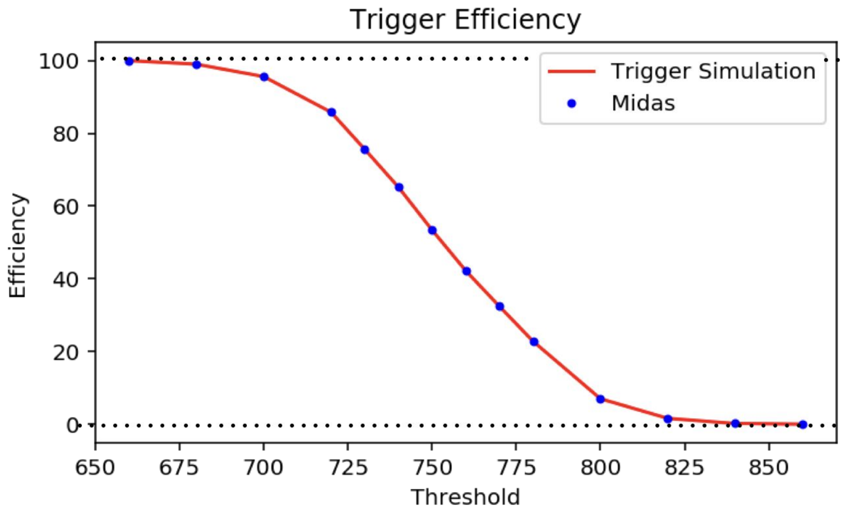


Digitized Readout



Results





- No input pulse
- How many triggers per seconds do we get at each threshold?
- Trigger Rate is sharply falling as expected

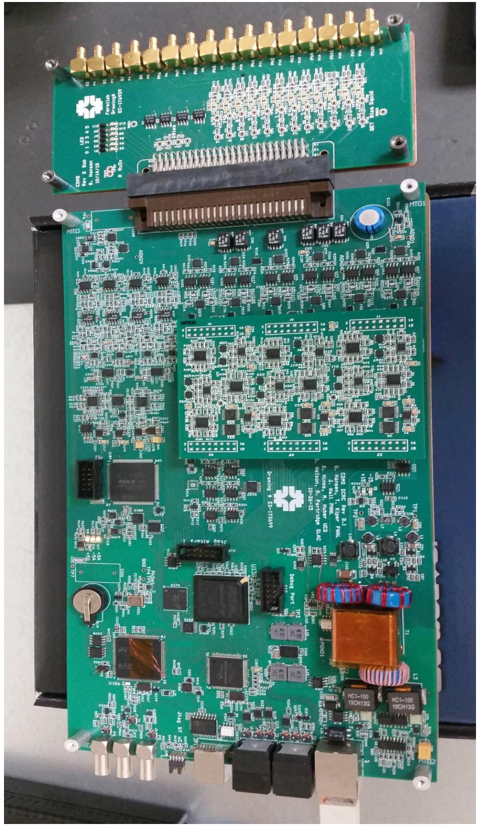
- We change the threshold and count the number of time the trigger accepts the event
- We get the expected turn-on curve
- The width is due to the Noise

Trigger Simulation and Midas Trigger Result are identical!

Calibration and Testing of Electronics

Electronics Automated Calibration and Testing

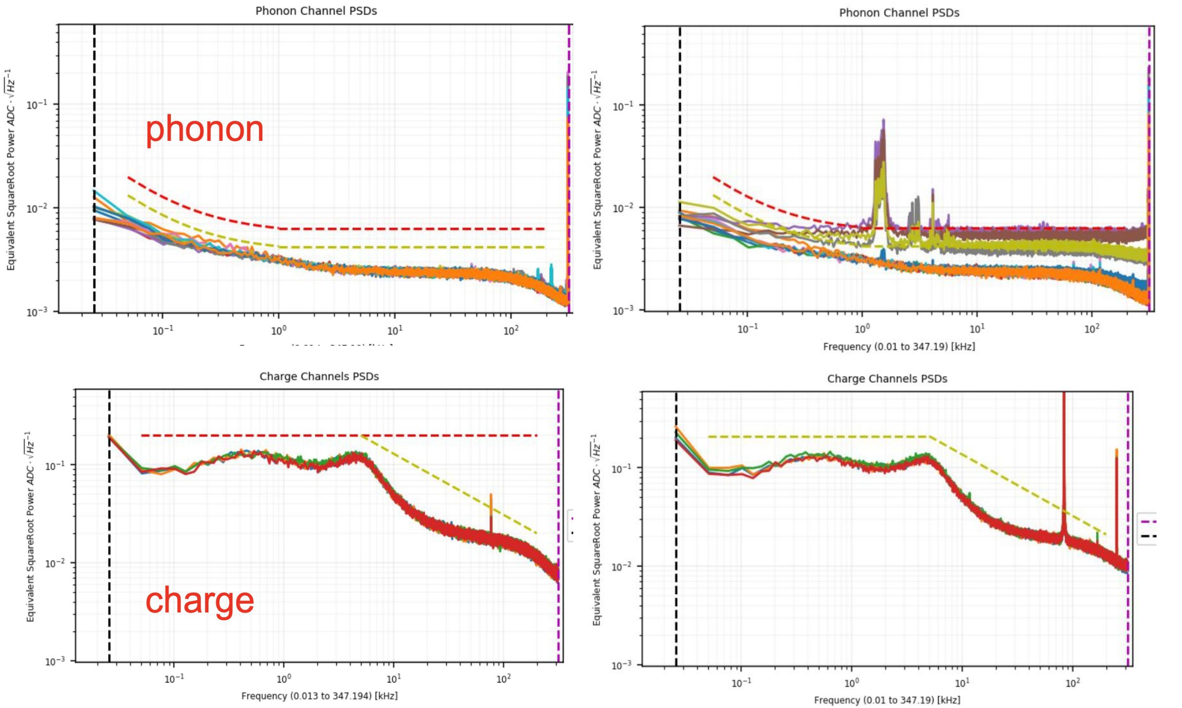
- Both analog and digital electronics on the same board
- Very low noise measurement devices
- Contain more than 100 components: Amplifiers, ADC Offsets, SQUID Bias, TES Bias, Test Signal Generators, …
- Want high quality assurance for our electronics so we have reliable experiments/measurements
- Goal: Developing automated python-based calibration and testing protocols to test the full functionality of electronic boards
- Challenges:
  - Reliable testing protocols that successfully identify problems
  - Building automation tools



Electronics Tests

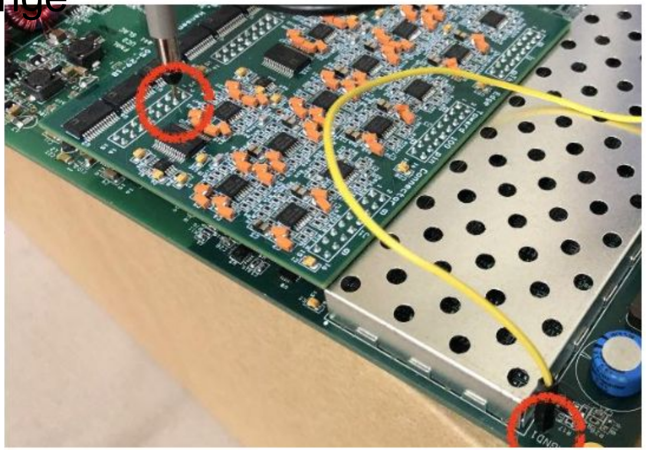
- We need Automated Quality Control Tests for:
  - Noise
  - Switches
  - Amplifiers
  - LEDs
  - Test Signals
  - ...
- We collect noise pulses from all channels
- Calculated PSDs and compare them with our limits

Passed | Failed



Calibration and DAQ Validation

- 40 board and ~120 registers / board! => Very time consuming to calibrate all!
- Our code would write the values to the register, measure the pulse, calculate the voltage, and do the calibration
- After calculating the calibration values, we input our calculated slope and offsets to DAQ
- To fully validate our calibration, we set all registers to zero and then measured again to make sure we are within -1.5 mV and 1.5 mV range



Summary

- Dark Matter and QC devices are very similar: both use semiconductor and superconducting technologies and require low noise cryogenic operation
- Foundational Challenges are very similar including:
    - Understanding the Interactions of Photons with Semiconductor and Superconducting Devices
    - Developing Reliability Test for Electronics and Triggering

Thank You!

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Questions

- What are my future plans?
- Why am I interested in working in PsiQuantum?

Supplementary Slides

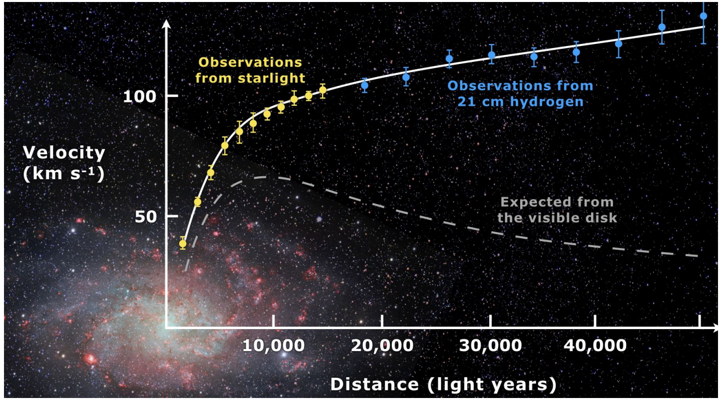
Outline

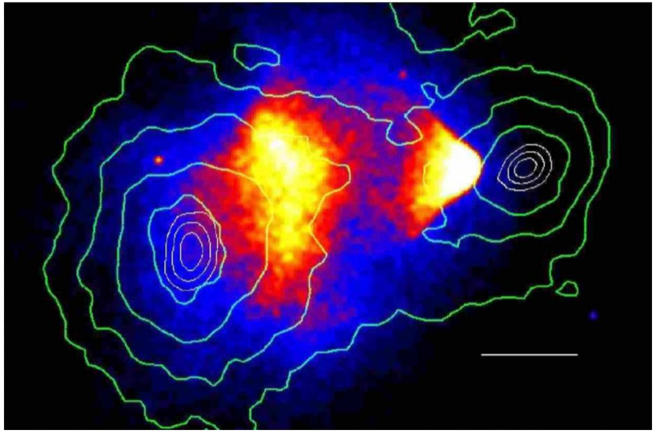
- Introduction to Searches for Dark Matter
- Dark Matter Searches and Quantum Computing Face Similar Challenges
  - Comparing PsiQuantum and Super Cryogenic Dark Matter Search
- Quick Overview of my Experience and Recent Projects:
  - Understanding the Photon Interactions with Semiconductor Crystals and Superconducting Sensors Using Simulations
  - Developing Reliability Tests for Warm Electronics and Triggering
- Summary

Dark Matter Evidence

Numerous observations indicate that the universe mostly consists of unseen massive particles that have no electromagnetic interactions:

- **Galaxy Rotation Curves:**
  Most of the visible mass of the galaxies is concentrated in the center. We would expect rotation velocity to decrease as we get further from the center. This is not consistent with observation.
- **Bullet Cluster:**
  Two galaxy clusters collided. We expect most of the matter in the yellow region where we get the x-rays. This is not consistent with the gravitational lensing map. (green curves)

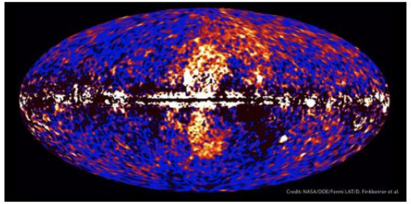




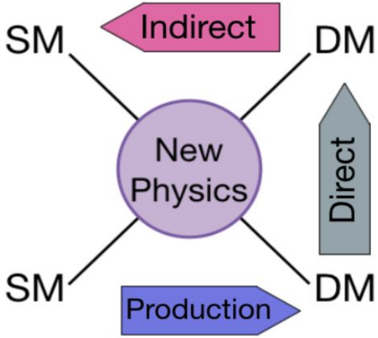
Dark Matter Properties and Detection Methods

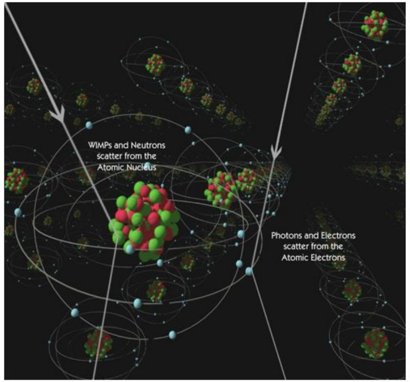
Particle solution does a nice job of explaining the data. Dark matter particles should be:

- Massive
- Neutral and Minimally Interacting
- Stable (Very Long Life-Time)
- Non-Relativistic

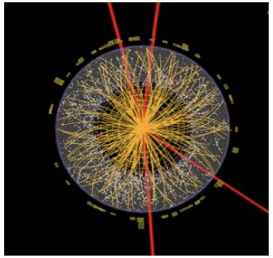


Cosmological Observation





Direct Detection: **SuperCDMS HVeV**



Collider Physics

SuperCDMS Cryogenics and Shielding

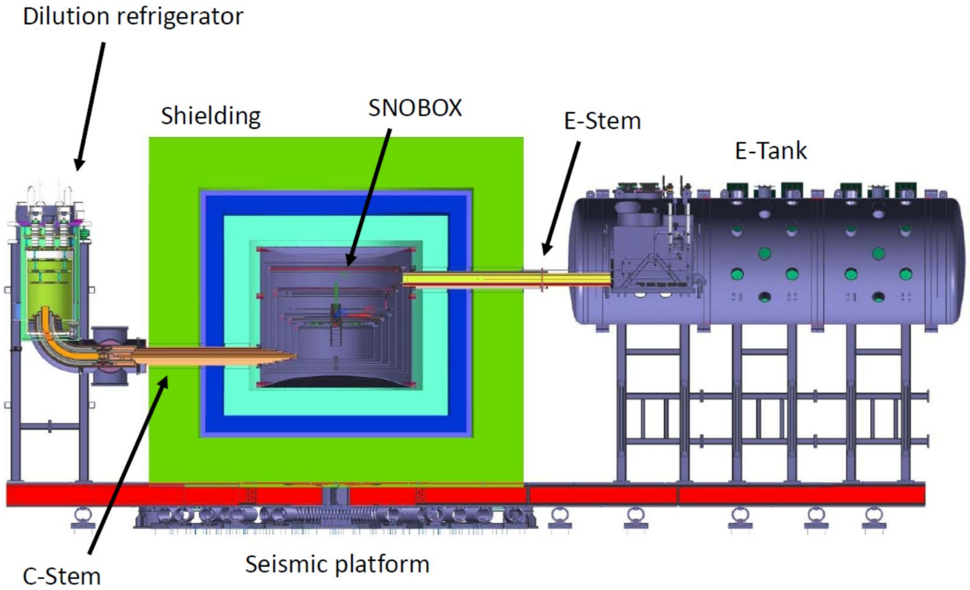
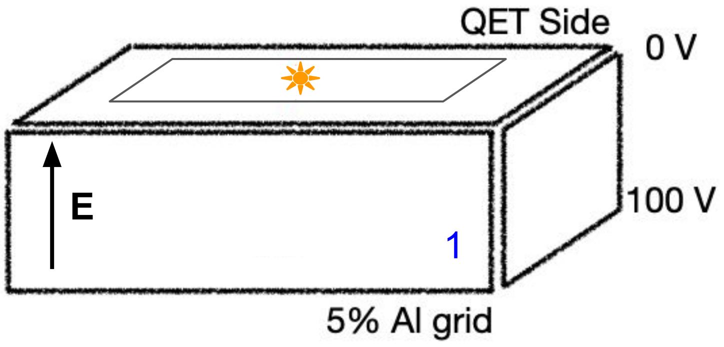
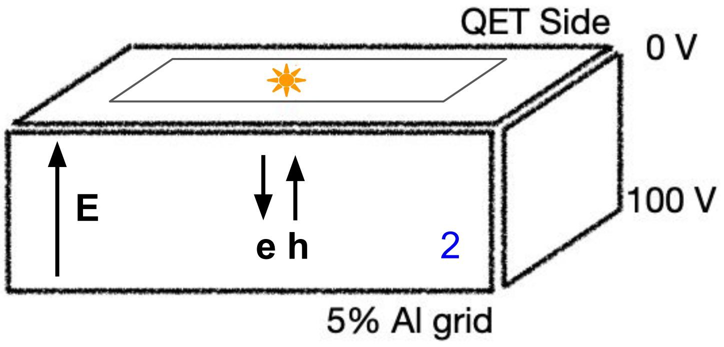


Figure 80: Sectional view of the SuperCDMS cryogenics and shielding. The dilution refrigerator is shown on the left, coupled through a cold stem (C-Stem) to the SNOBOX, which is in turn coupled through an electronics stem (E-stem) to the vacuum bulkhead (E-Tank) where detector signals emerge on the right. Also shown are the shielding layers described in Sect. 6. The entire assembly is mounted on a platform to isolate the experiment from seismic motion of the laboratory floor, described in detail in Sect. 7. More complete descriptions of the various components are provided in the text.

Collected Phonon Energy: 1 Photon

One photon hits the middle of the top surface of the detector. There are two possible o





The generated eh pair recombines or is trapped at the surface immediately.

- Initial Photon Energy = 1.95 eV
- Luke Amplification = 0 e * 100 V =0 eV
- **Collected Phonon E = 1.95 eV**

The generated eh pair that goes through full Luke amplification.

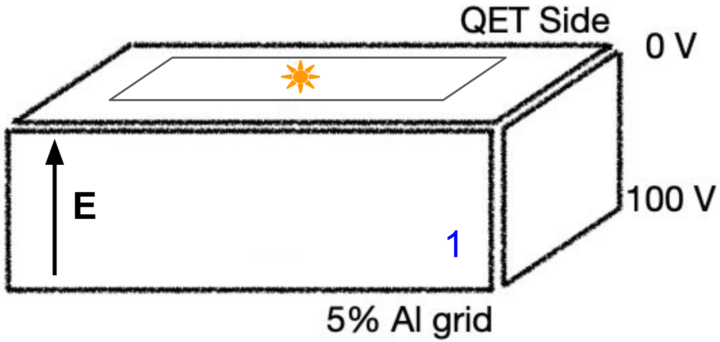
- Initial Photon Energy = 1.95 eV
- Luke Amplification = 1 e * 100 V =100 eV
- **Collected Phonon E = 101.95 eV**

E= N*1.95 + M*100

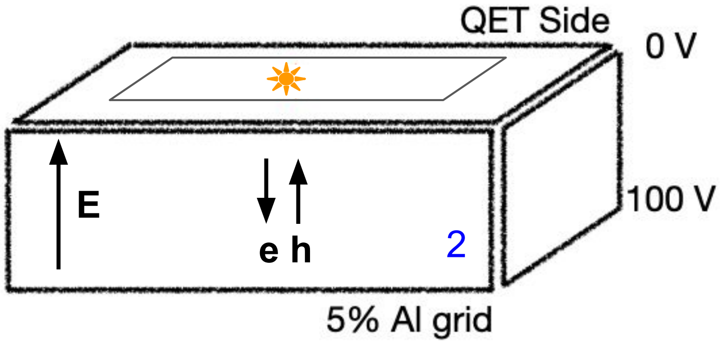
N: Number of Photons;

M: Number of ehs fully amplified; M<=N

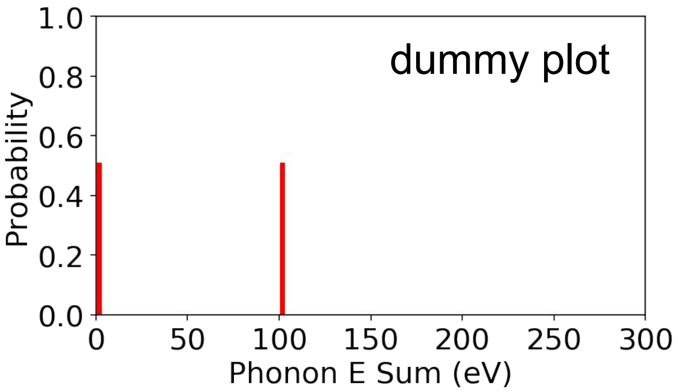
Collected Phonon Energy: 1 Photon



Collected Phonon E = 1.95 eV
Probability = 50%

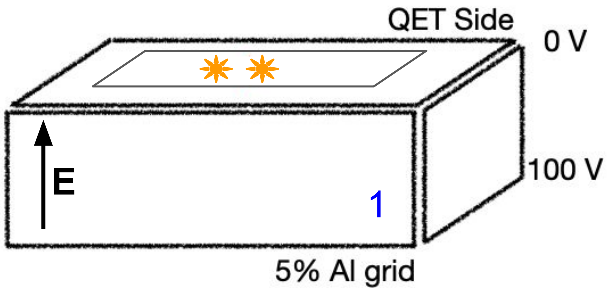


Collected Phonon E = 101.95 eV
Probability = 50%

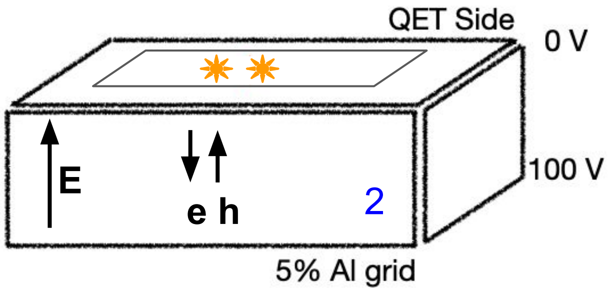


Collected Phonon Energy: 2 Photons

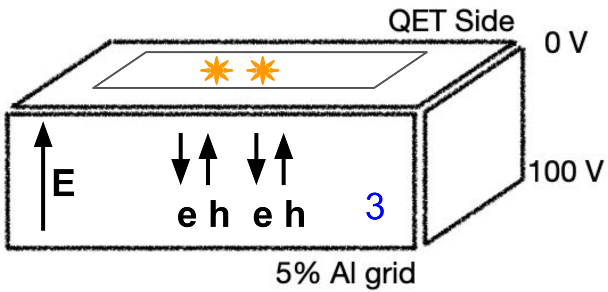
There are three possible outcomes:



Collected Phonon E = 3.9 eV
Probability = 25%



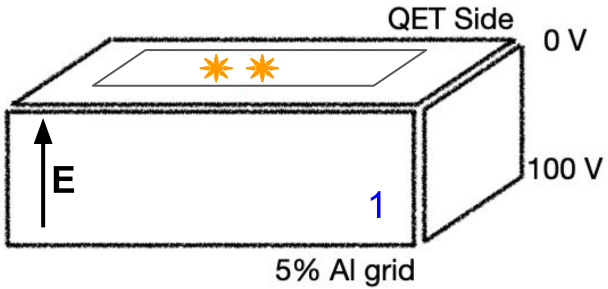
Collected Phonon E = 103.9 eV
Probability = 50%



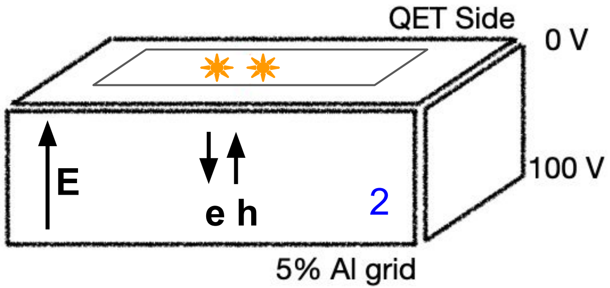
Collected Phonon E = 203.9 eV
Probability = 25%

E= N*1.95 + M*100
N: Number of Photons;
M: Number of ehs fully amplified;
M<=N

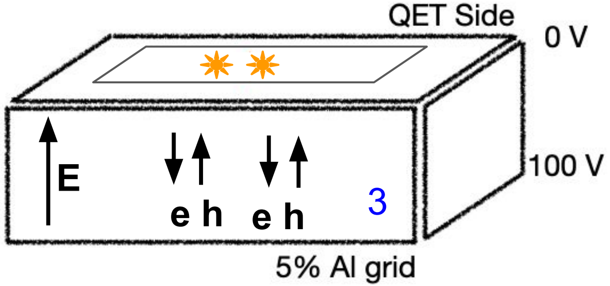
Collected Phonon Energy: 2 Photons



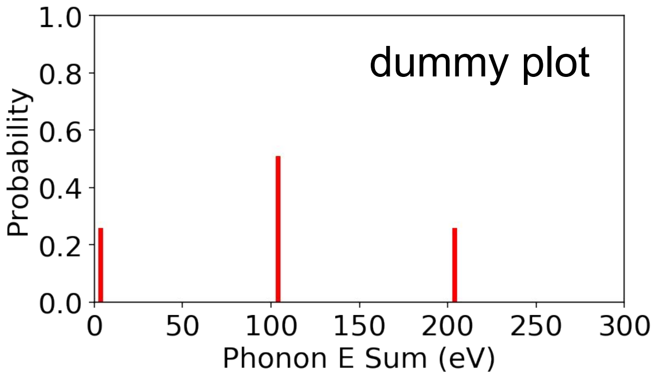
Collected Phonon E = 3.9 eV
Probability = ~25%



Collected Phonon E = 103.9 eV
Probability = ~50%

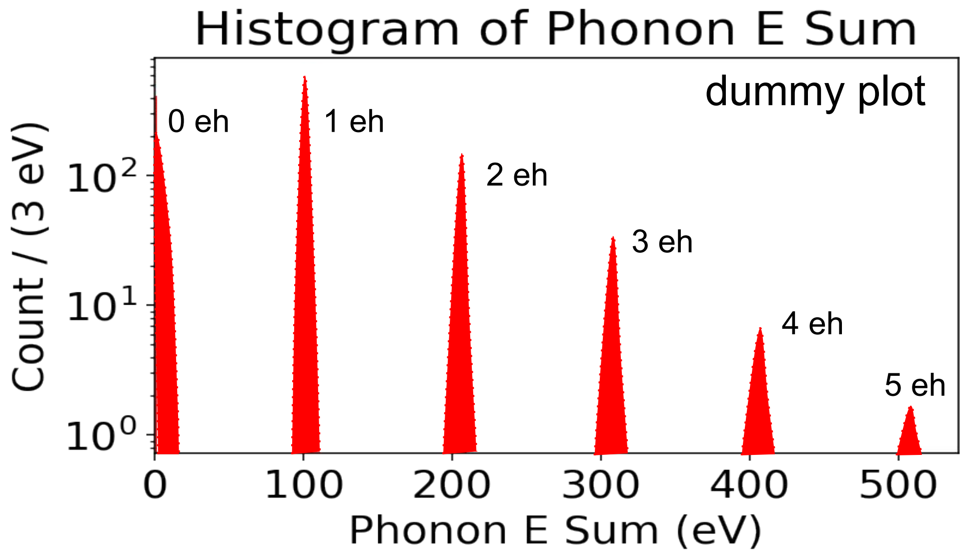


Collected Phonon E = 203.9 eV
Probability = ~25%



Moving to Larger Number of Photons and Adding Detector Resolution Effects

- Let's assume we have 1500 laser shots
- Each shot has N photons hitting the detector, where N follows a Poisson distribution with Lambda = 1
- The RHS plot is a dummy plot of what we would expect for those 1500 laser shots considering different combinations of N and M and some detector noise



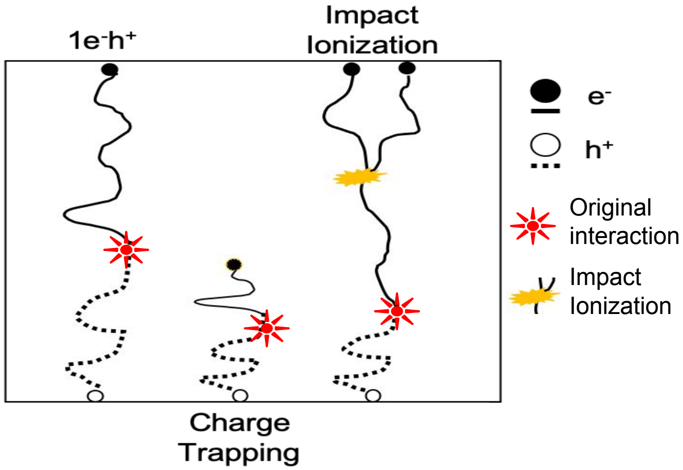
Charge Trapping and Impact Ionization

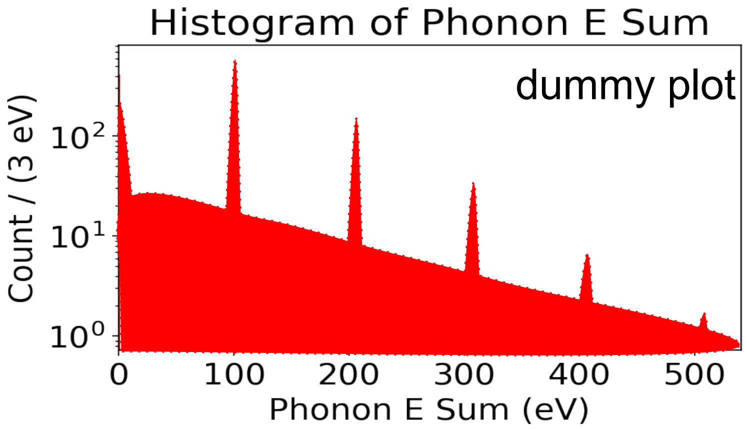
In reality, our crystals are have impurities and we don't get full energy collection all the time.

Charges traveling through the crystal can:

- Get trapped in defects so we lose some of the phonon energy
- Liberate additional charges that are stuck in overcharged impurity regions. These charges are accelerated, creating additional phonons

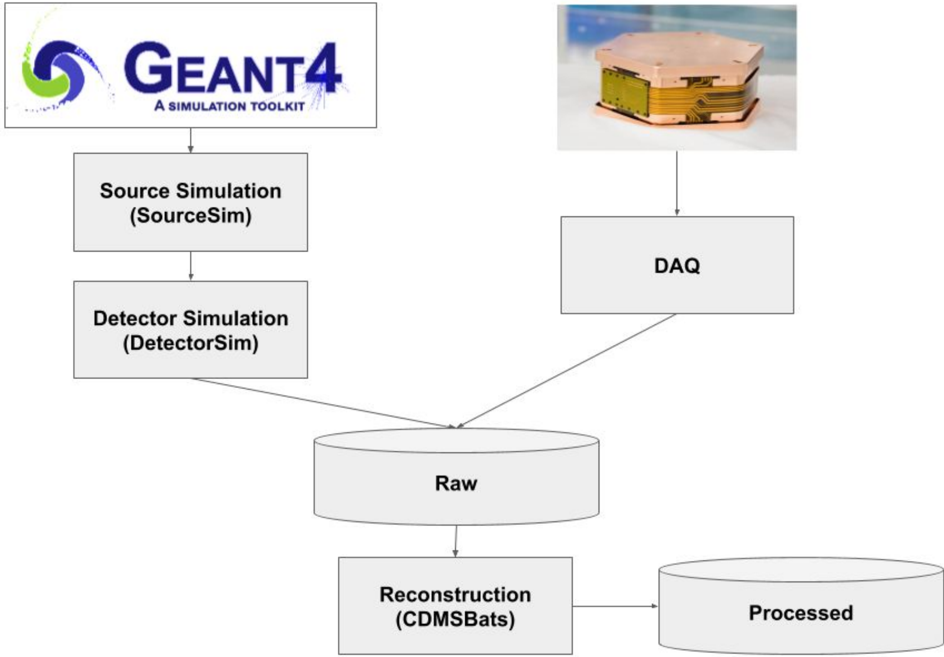
These processes will lead to partial energy collection which will show up as a background in between the peaks of the spectrum. They depend on the quality of the crystal used.





Overview of the Full Simulation

- We simulate particle interactions using Geant4, and a custom detector simulation which does condensed matter physics (G4CMP)
- SourceSim simulates the laser source
- DetectorSim consists of:
    - CrystalSim
    - TESSim
    - DAQSim and NoiseSim
- After creating the raw data, we can process them by running through Reconstruction
- We can compare processed simulation results and real data



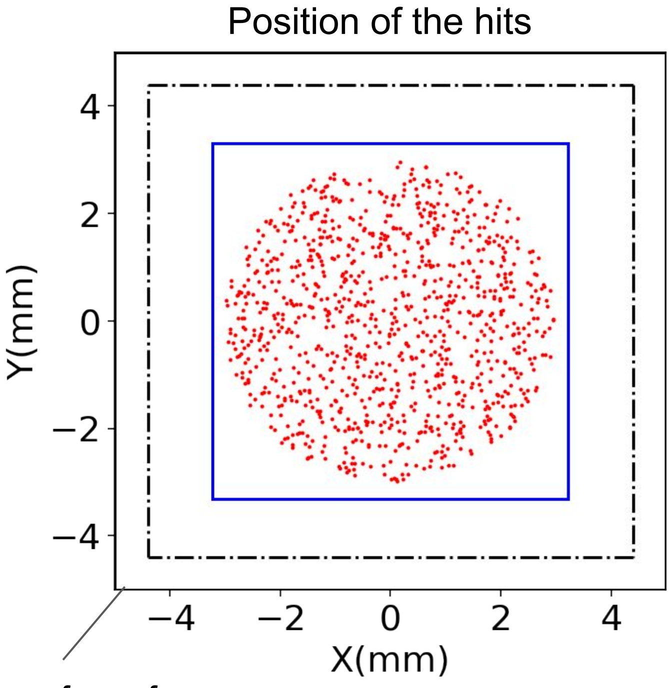
Simulation Information

Simulation Information	
Voltage	100 V Uniform Voltage
Energy	1.95 eV
Position of Energy Deposits	- Top surface of the detector with R < 3 mm - Exponential with SkinDepth of 5.3 um

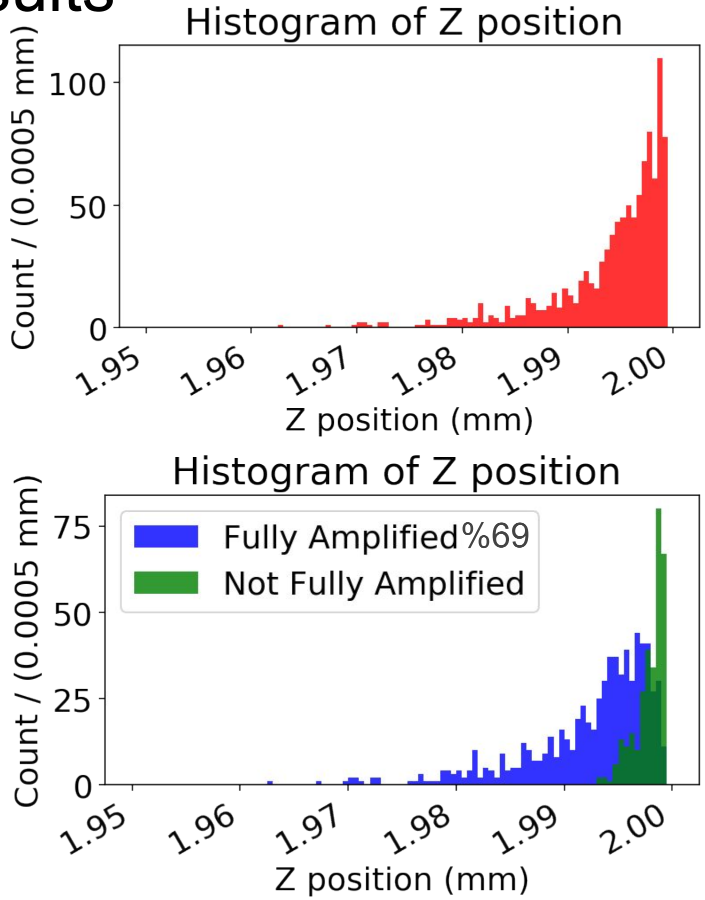
We will start with a simple case and add more effects as we go on. Will show results from three samples:

- Sample 1: 1k events where the number of energy deposits follows a Poisson distribution with Lambda = 1
- Sample 2: 25k events with Lambda = 1 and Charge Trapping and Impact Ionization

Sample 1: Source Simulation Results



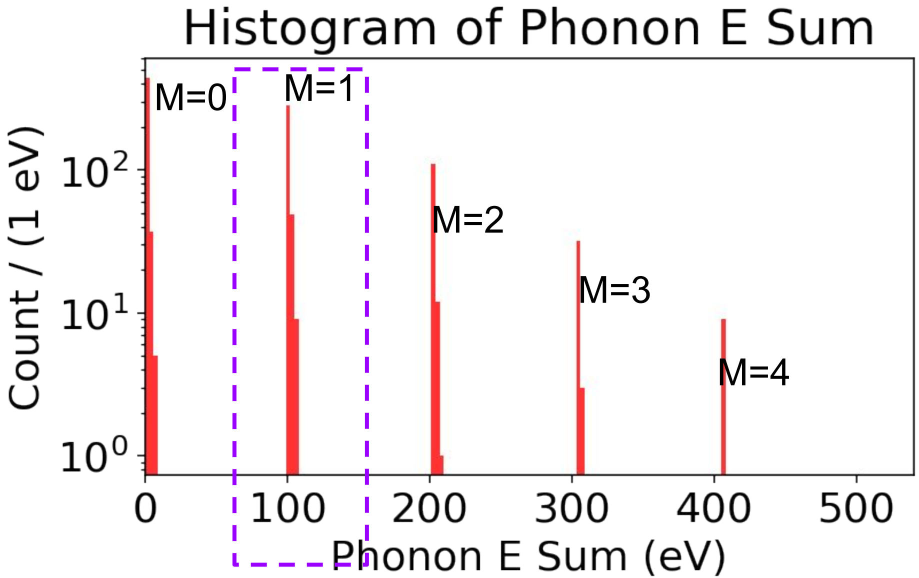
Top surface of the detector



Sample 1: Crystal Simulation Results

- Variation in the big peaks from the number of fully amplified eh pairs, M, appear at the right place

- Next Step: Let’s zoom into the peaks one by one. We start with the peak around 100 eV



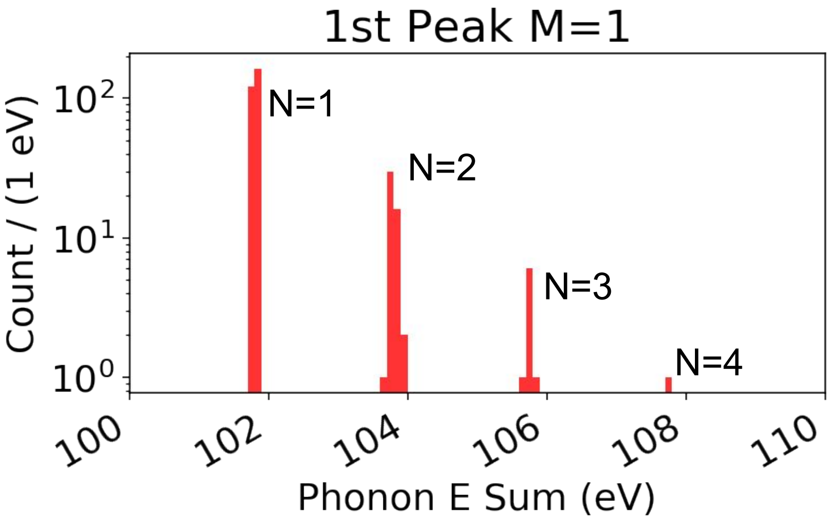
E= N*1.95 + M*100
N: Number of Photons = 0 to 4
M: Number of ehs fully amplified = 0 to 4; M<=N

Sample 1: CrystalSim Results (1st Peak Zoomed-In)

- Zooming into the events around 101.95 eV (the fully amplified energy) we see smaller peaks at 101.95, 103.80 etc. The additional energy is from a photon that deposited energy but the electron/hold pair wasn't amplified.

- Each of these small peaks also has a width, but this is the intrinsic resolution of the detector

- Next Step: Zoom into other electron-hole peaks

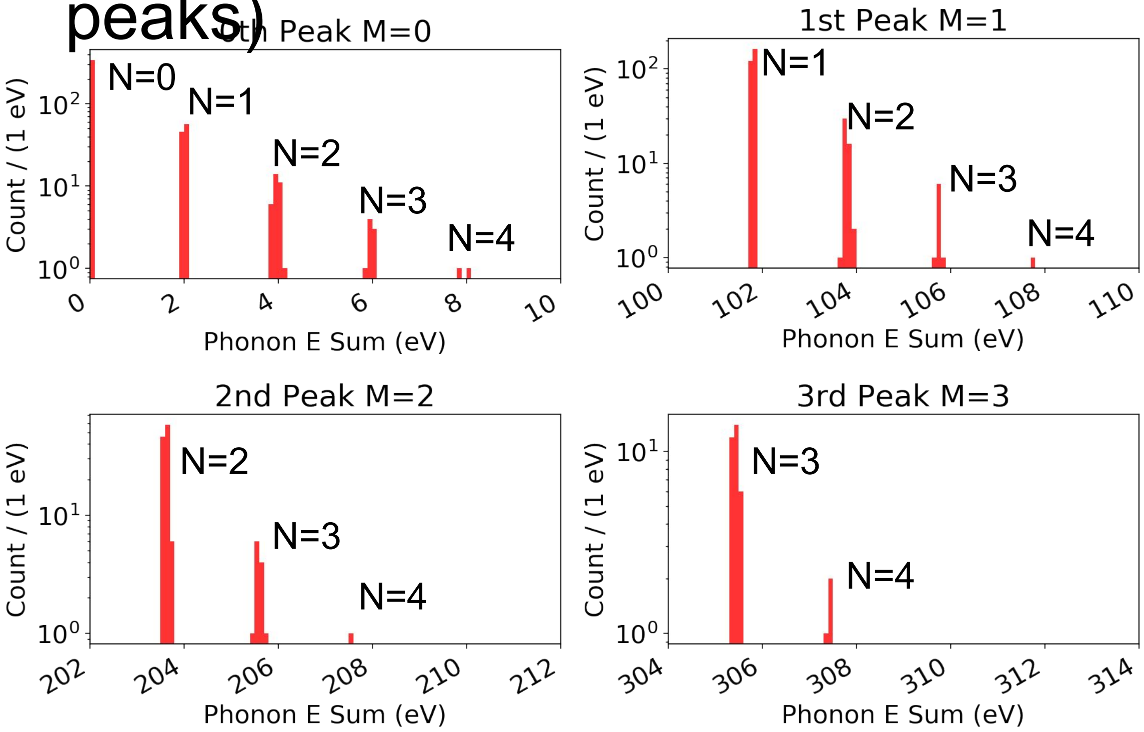


E= N*1.95 + M*100

N: Number of Photons = 0 to 4

M: Number of ehs fully amplified = 1 ; M<=N

Sample 1: CrystalSim Results (Zoomed on the other peaks)



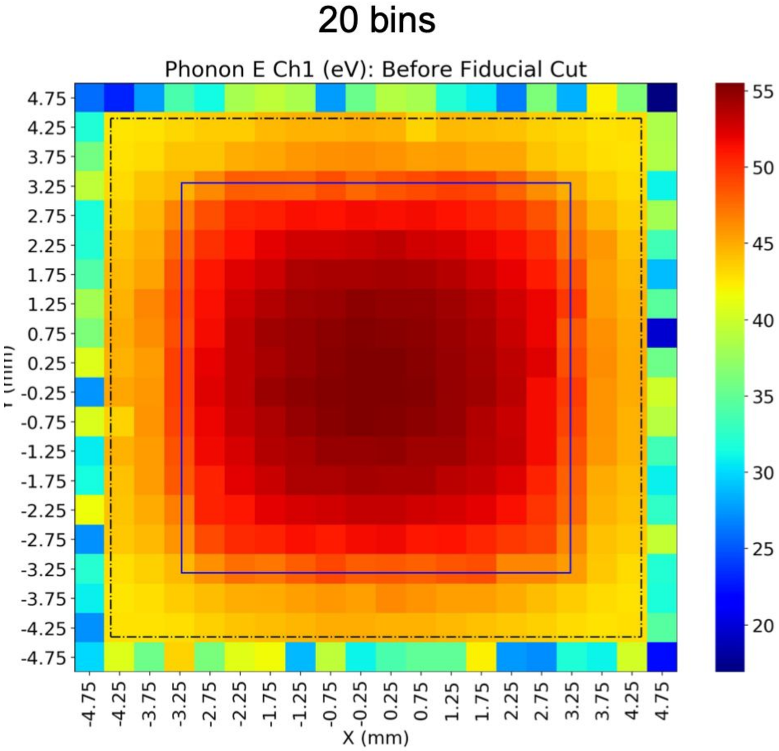
E= N*1.95 + M*100

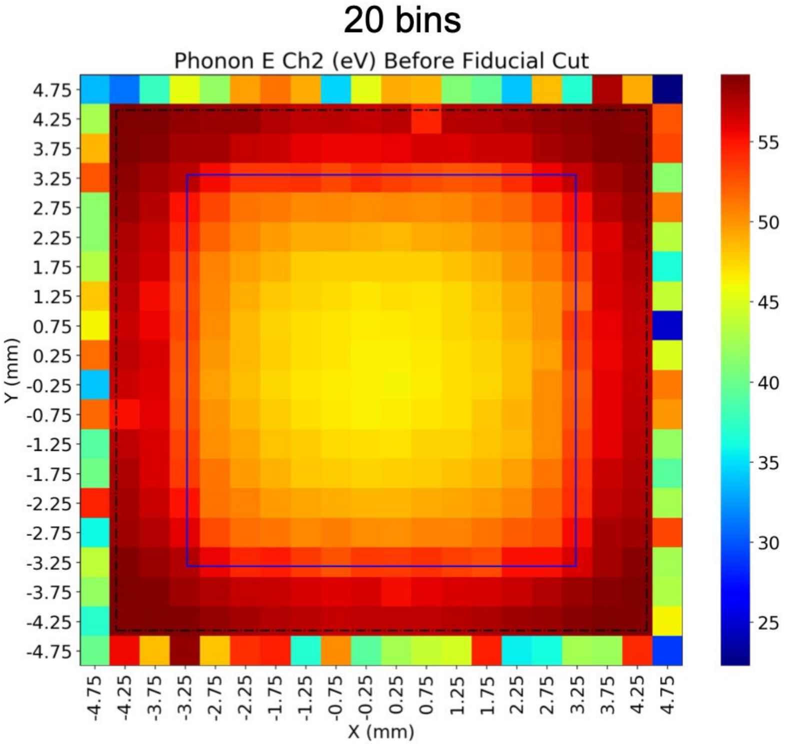
N: Number of Photons = 0 to 4

M: Number of ehs fully amplified = 0 to 4 ; M<=N

- We see small peaks that are caused by the variation in the number of photons, N.
- The variation within the peaks is due to the small detector resolution
- Next Step: Move to a bigger sample and add Charge Trapping and Impact Ionization

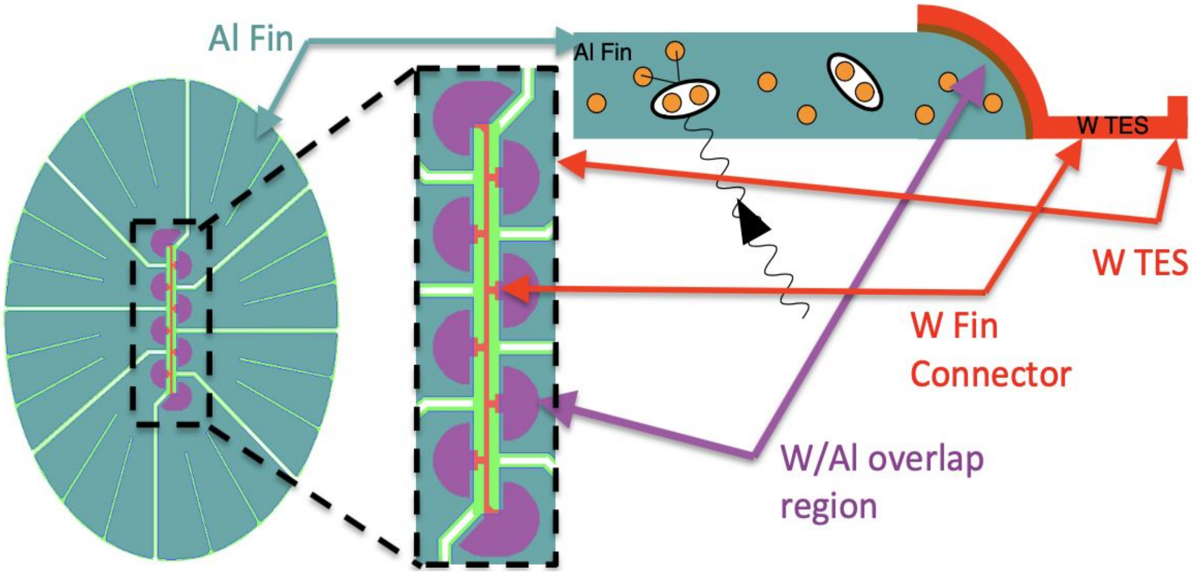
An Example of Something We Learned from Simulations





Looking at the energy distribution vs location of the photon hit, we could define a fiducial volume where our detector is doing a good measurement

TES



TES Circuit

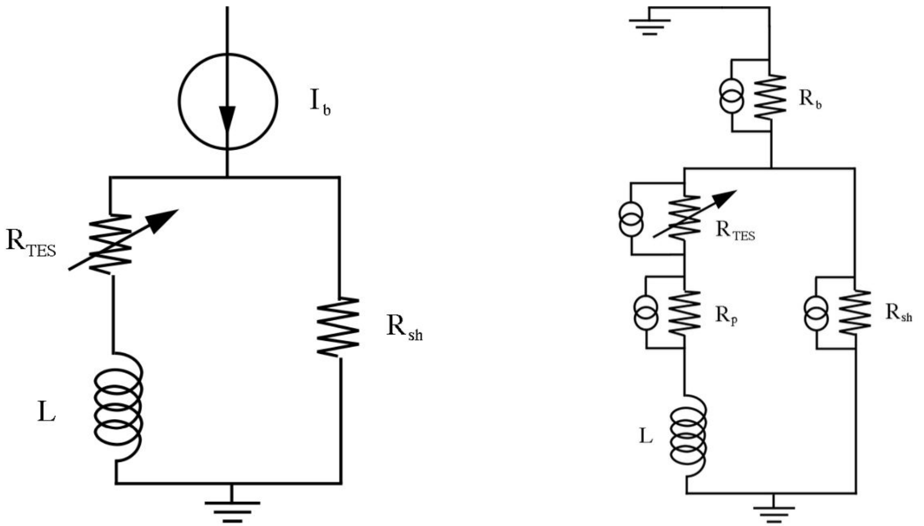
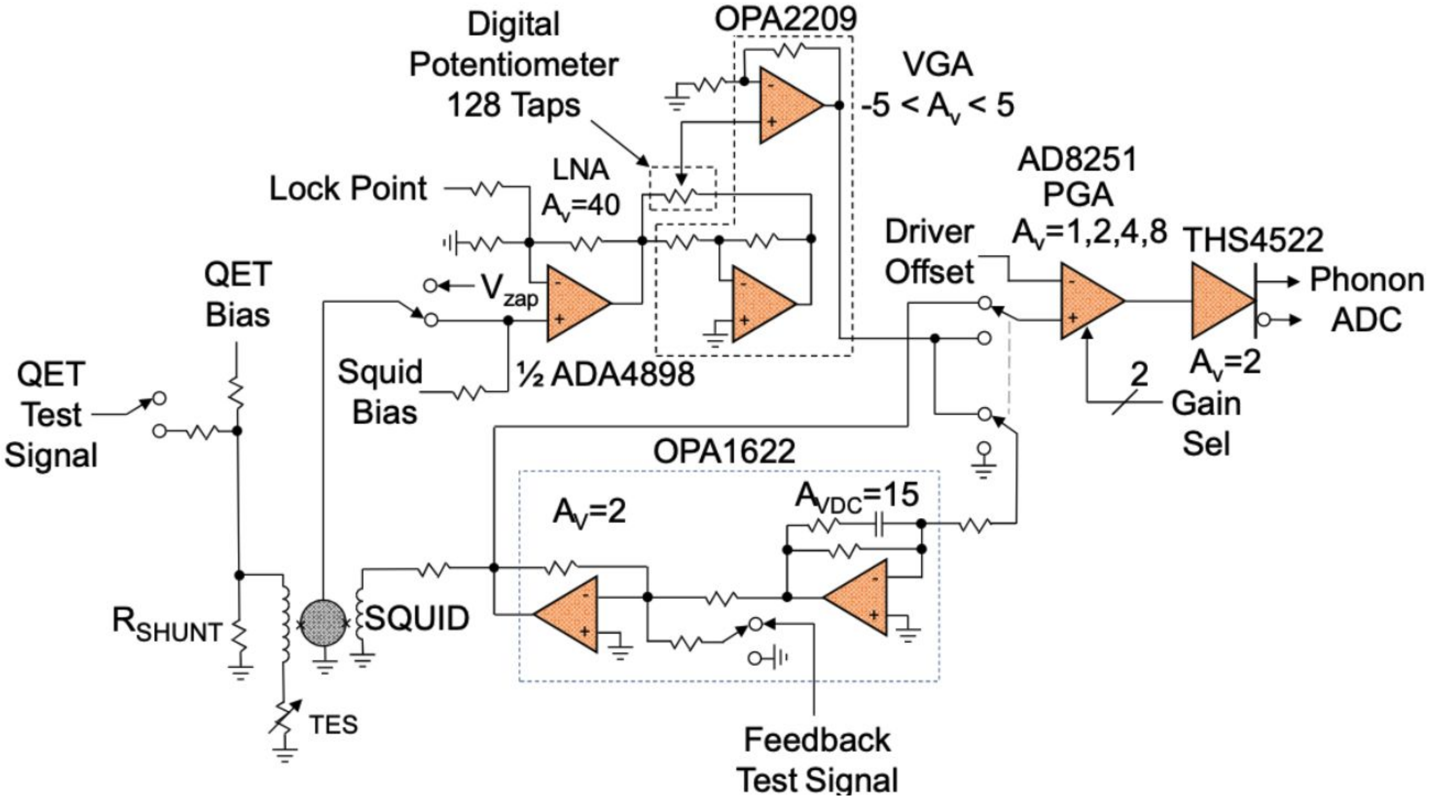
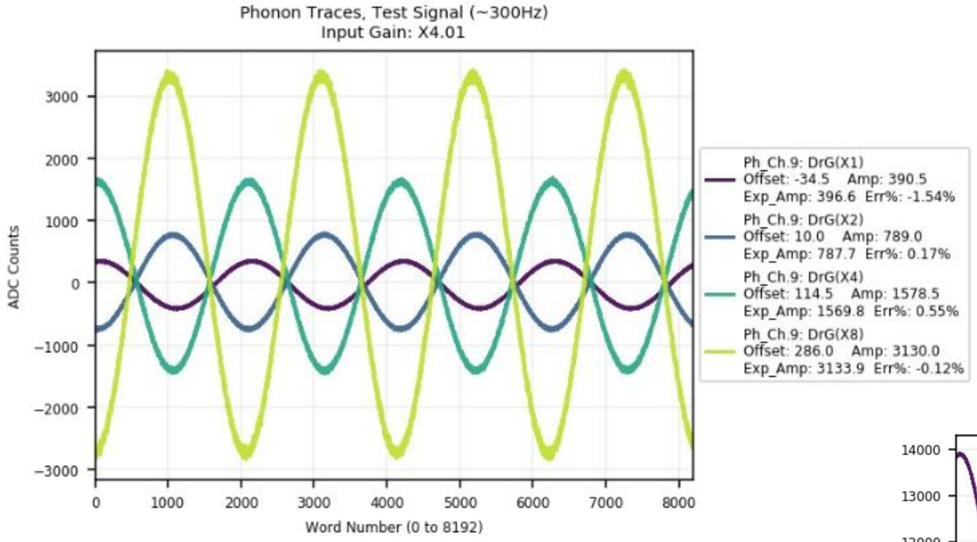


Figure 12: TES Bias Circuit (Left) Idealized TES bias circuit. R_{TES} is the TES resistance at the bias point. L is the total inductance in the circuit, including the SQUID input coil inductance. R_{sh} is the shunt resistor, $R_{sh} \ll R_{TES}$ to provide a voltage bias. I_b is an ideal current source that is in practice provided by a voltage bias in series with a resistor R_b. (Right) TES bias circuit with Johnson noise sources explicitly indicated. R_p appearing in the noise diagram is the parasitic resistance in the TES circuit.

Electronic Block Diagram

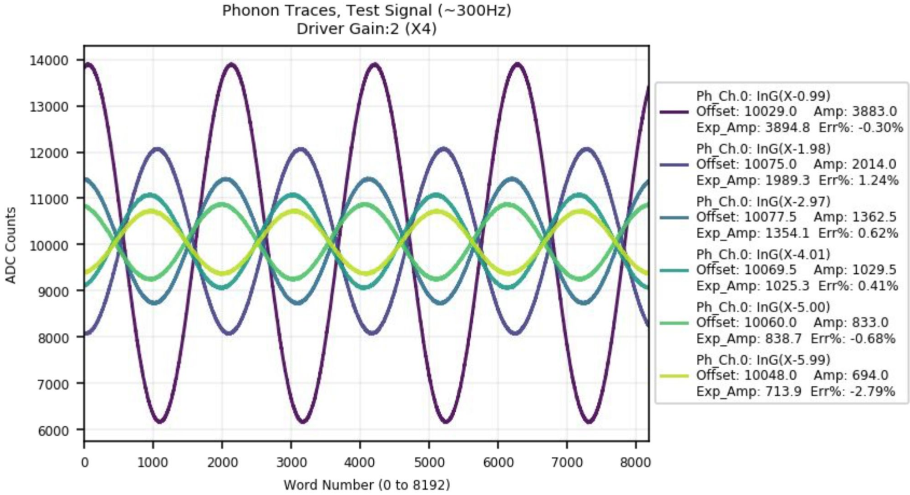


Phonon Test

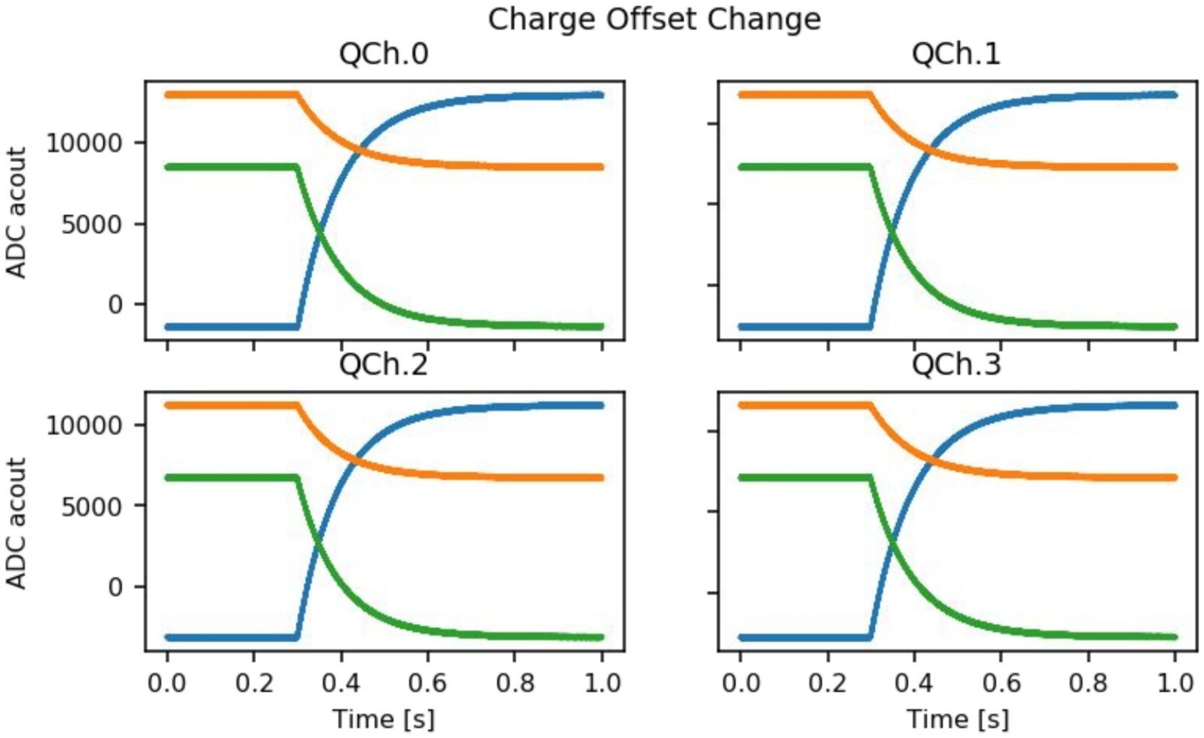


Changing input gains and checking if amplitude changed as expected

Changing driver gains and checking if amplitude changed as expected



Charge Test



Changing charge offsets and checking if the baseline shifted as expected