# Upgrading the Readout Electronics for the SuperCDMS Experiment to Discover Dark Matter

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# Outline

1. What is Dark Matter?
2. How CDMS is Searching for Dark Matter
3. The Role of *Detector Control and Readout Cards* (DCRCs) for the SuperCDMS Experiment at SNOLAB
4. Testing and Calibration for Experimental Functionality
5. Conclusion

# Dark Matter

1. Evidence
2. Detection Methods

# Dark Matter Interacts Gravitationally

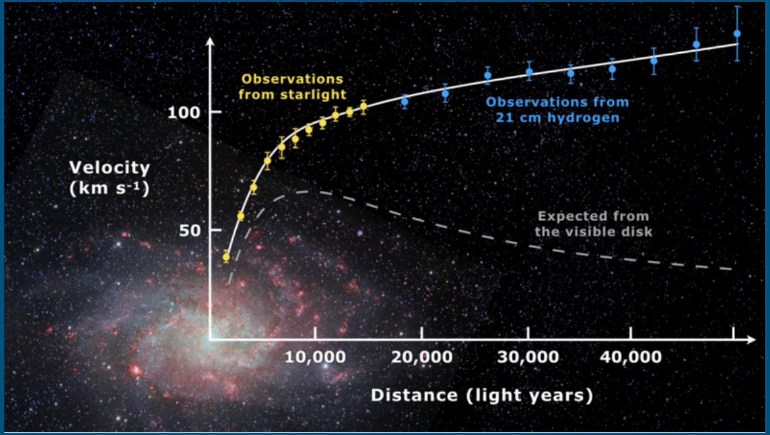
What is dark matter?

- Matter that doesn’t interact with light and therefore can’t be seen using telescopes

How do we know it exits?

One piece of evidence: rotation of the Milky Way

- Visible mass should rotate slower based on observed stellar mass
- Observation shows that it actually rotates faster
- Conclusion: more mass than we can see that is interacting gravitationally



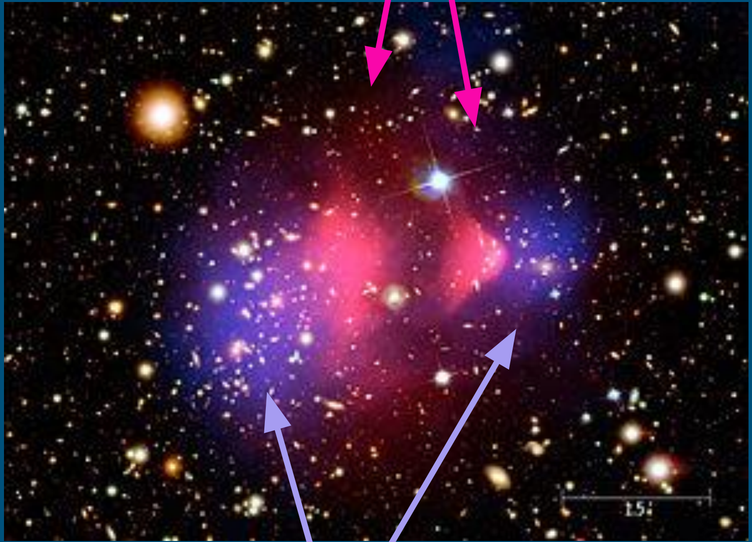
# Particle Dark Matter Interactions

More evidence from Bullet Cluster
This graphic contains three superimposed images of visible, x-ray, and gravitational lensing mass distribution plots

Clusters of galaxies passed through each other

After collision we see:

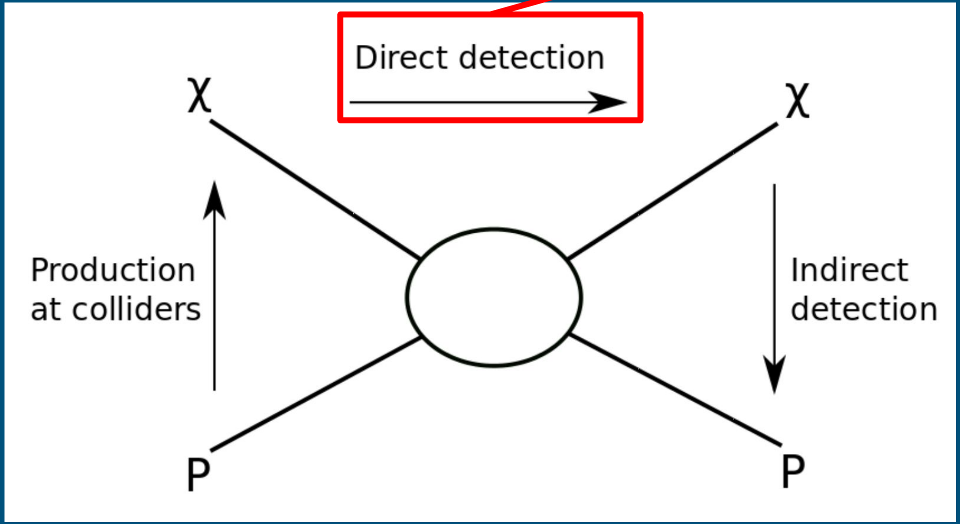
- Ordinary matter
  - Slows down from E&M interaction
- Dark matter
  - Little interaction
  - Mass stay clumped together
  - Indicative of particle interaction



# Possible Ways to Detect Dark Matter

1. Direct detection: dark matter particle interacts with ordinary matter
2. Production: ordinary matter particles collide and create dark matter
3. Indirect: Dark matter particles collide to produce ordinary matter

The method we will use to search for DM



# *Cryogenic Dark Matter Search* (CDMS) Experiment

1. CDMS Experiment
2. Detector Configuration

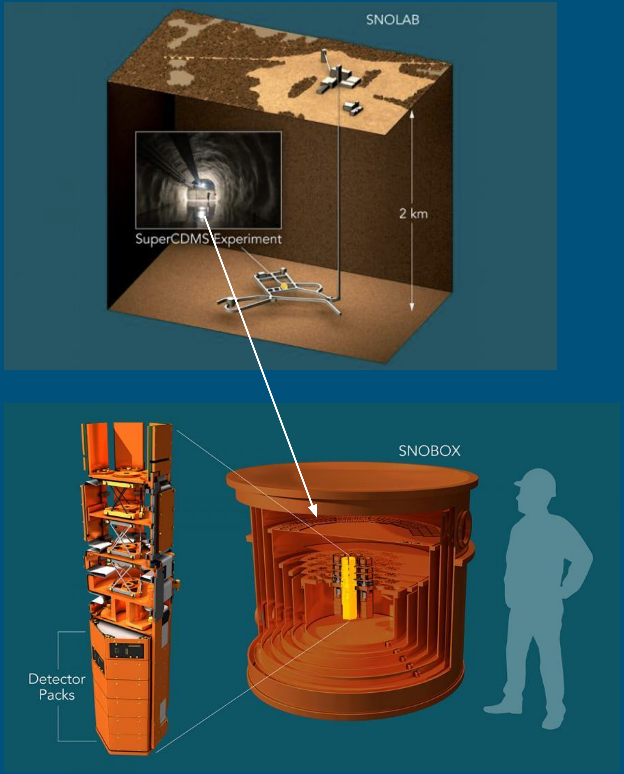
# The Next CDMS Experiment at SNOLAB

CDMS is looking for dark matter using direct detection methods

- The experiment at SNOLAB will be placed deep underground ~2 km to minimize cosmic particles that could reach the detector

Detector

- Hockey-puck shaped Si and Ge crystals
  - Measure ionization and vibrations
- Surrounded by lead to block natural underground contaminants
  - Radon
- As the earth orbits the galaxy,  we predict dark matter will come into contact with the detector producing detectable interactions



# How to Detect Dark Matter

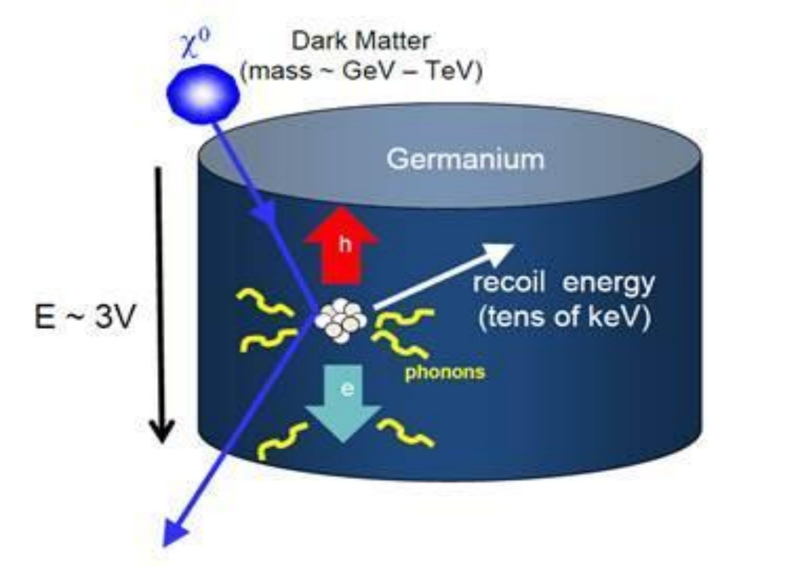
The detector is sensitive to two types of interactions–nuclear and electron recoils

- **Nuclear recoils** occur when particles collide with the nucleus
- **Electron recoils** happen when particles collide with electrons

Both recoils can ionize the electrons out of the lattice (also creates a hole) and cause vibrations in the crystal (*phonons*)

Phonons, electrons, and holes can propagate through the crystal

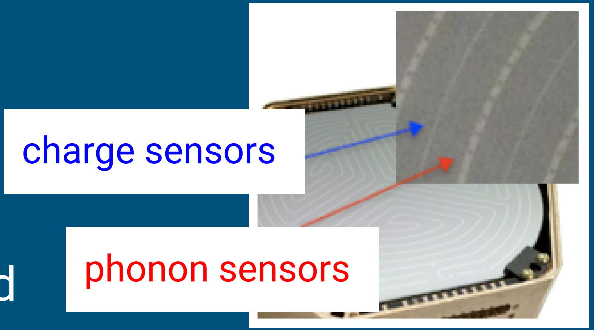
Applying a voltage across the crystal amplifies all these effects (numbers of phonons, electrons, and holes)

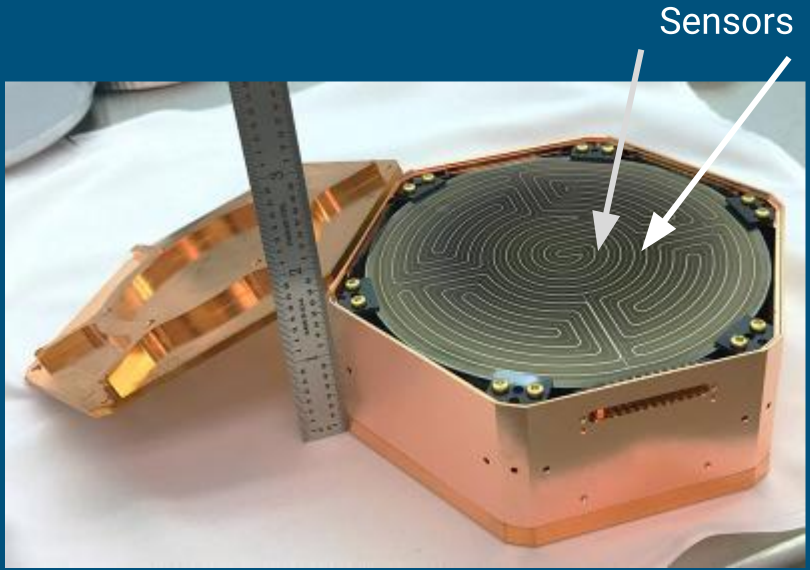


# The Sensors

Basic details of detector crystal

- The electrons and holes are collected on the electrodes
- Vibrational energy collected in heating up of crystal
- Voltage bias gives energy to electrons for amplified readout of charge and phonon energy
- Signals are digitized then read out by *Data AcQuisition* (DAQ) system



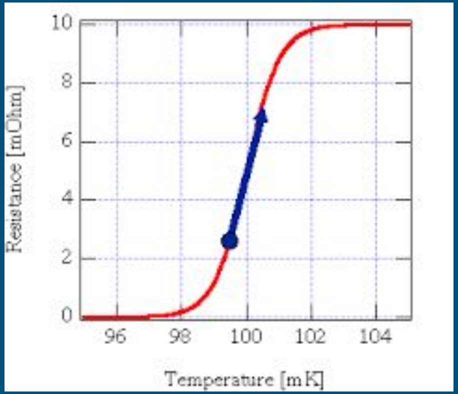



# How Sensors Work

*Transition Edge Sensor* (TES)

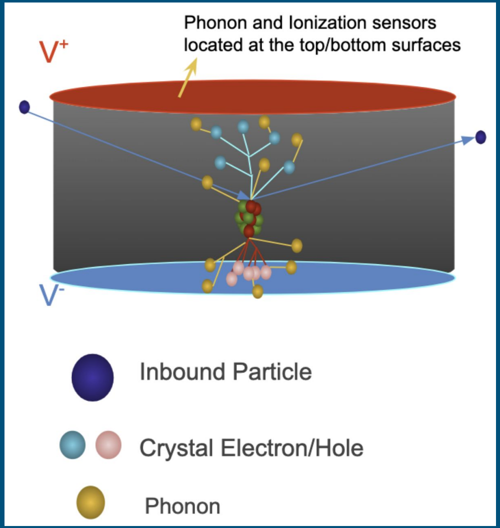
- Tungsten sensor held at the superconducting temperatures (~40 mK)
- Tungsten absorbs the phonon energy which is turn changes the resistance, allowing current to flow
- More energy deposition, yields a larger readout signal

Example plot




*Field-effect Transistor* (FET)

- Regulated by the amount of charge passing electrodes
- The electric field in the crystal pulls electron/holes to electrodes inducing a readable voltage from ionization energy



# Introducing *Detector Control and Readout Cards* (DCRCs)

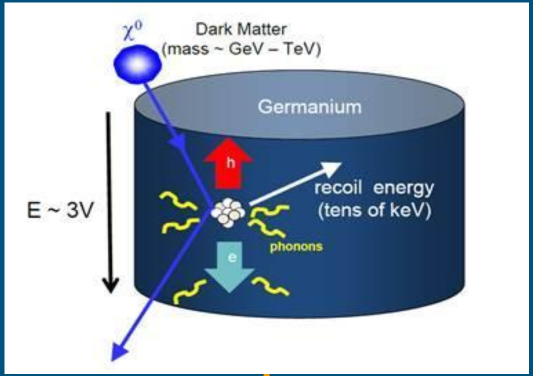
There are many steps once an event takes place

Charges and vibrations will spread/scatter through the detector until they are gathered by the sensors

But how do we get from physical events to data we can analyze?

We need computer boards that

- ➔ Read out the analog data from sensors as it is taken
- ➔ Sort out the interesting data from the rest
- ➔ Control the various parts of the detector




Analog signal gets converted to digital signal

# DCRCs and Processing Data

1. Readout
2. Triggering
3. Detector Control

# DCRC

- Complex computer board that communicates with detectors
- Reads in the signals from the detector in various channels (12 phonon, 4 charge)
- Runs a built-in trigger on digital signal
- Other computers interface with the DCRC to process and save data to disk
- DCRC can control detectors

Digital signal readout from here

Signal Readout

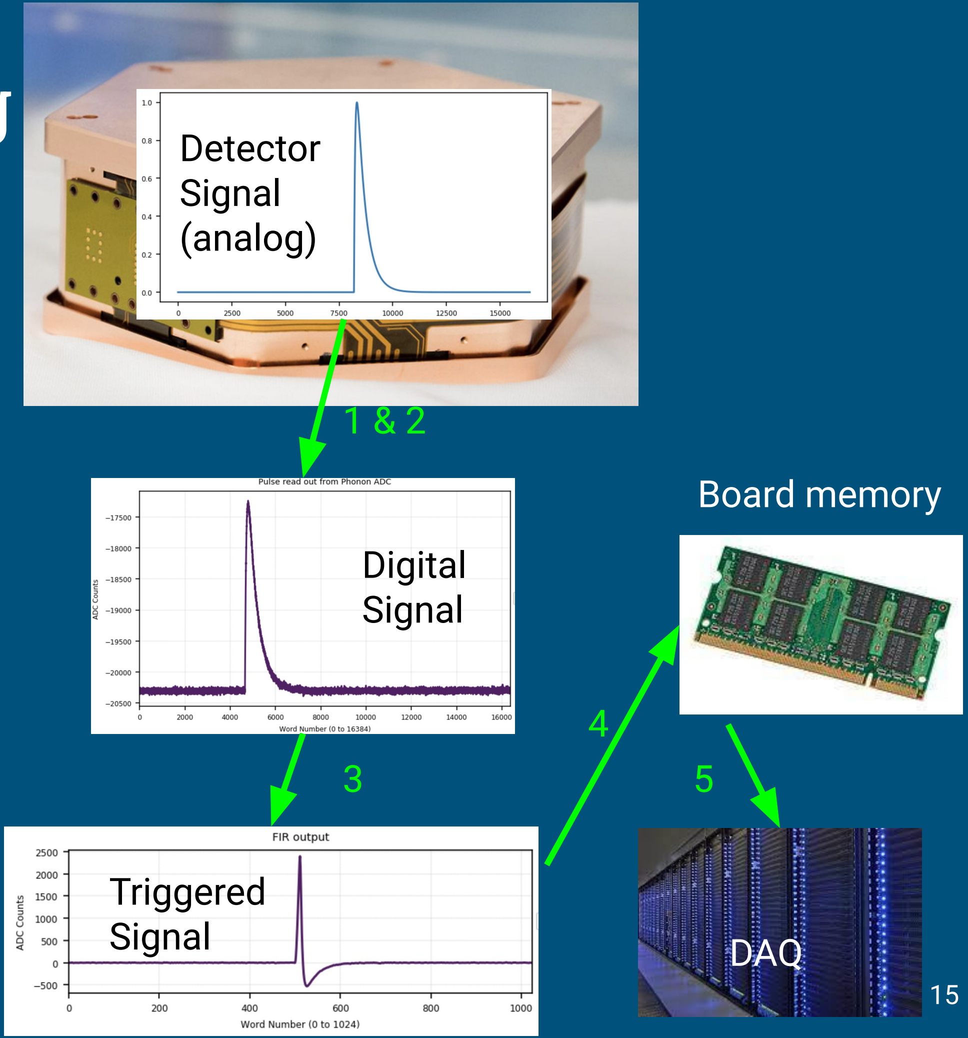

Detector signal comes in from here

Detector signal

# How DCRCs Work During Regular Data Taking

**Processing Analog Data**

1. Data from the FET and TES are sent to the phonon and charge channels on the DCRC
2. *Analog to Digital Converters* (ADCs) take the voltage signal and convert to digital signal (ADC units)
3. Digital signal sent through a custom filtering algorithm and compared to a threshold
4. If above the threshold, event fires the "trigger" and both digital signal and processed signal and stored to board memory
5. Full event information sent to DAQ when requested

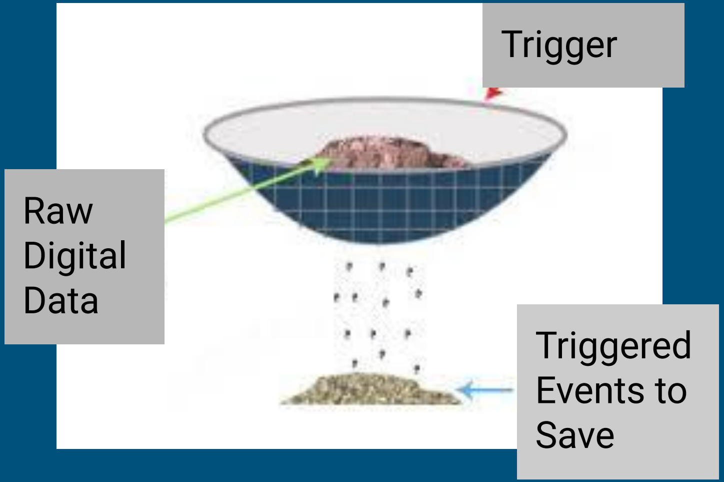


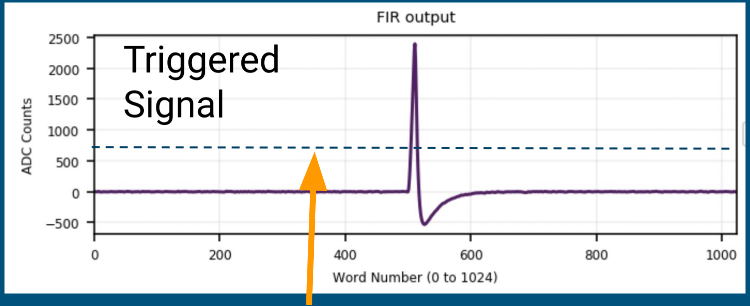
# Trigger System

A trigger is system that determines which experimental data is sent to DAQ

Why do we need a trigger?

- We mostly care about the events that are above a certain energy (signal)
- The trigger creates a threshold so only experiment-relevant data are saved
- Without a trigger all data would be recorded, even when no interaction occurred



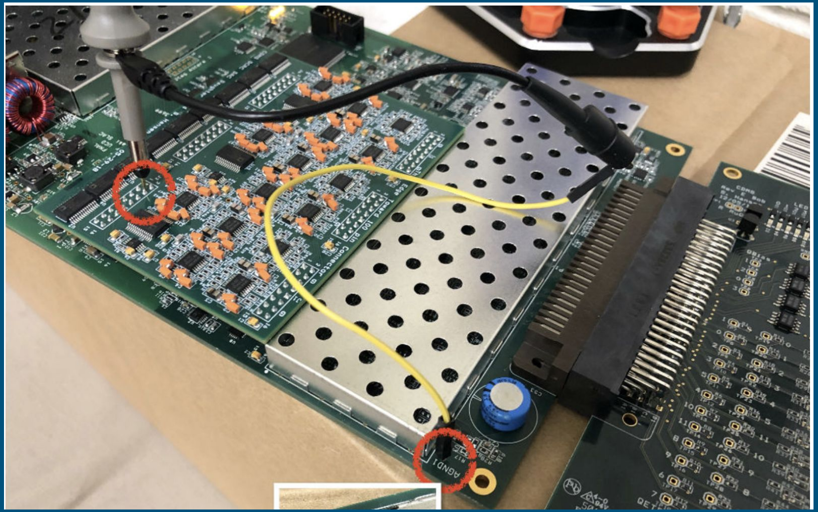

Signal above certain threshold triggers the data to be readout by DAQ

# Other Board Functionality: DCRC and Detector Control Using DACs

- A *Digital to Analog Converter* (DAC) performs the reverse process of an ADC

- We store numbers in registers on the board that are used by the DAC to set voltage on charge and phonon components
    - Why needed?
    - If board loses power and detector settings are lost, DACs reset value from default
    - The DAQ can set voltages and other settings which can be read out wirelessly (using telnet)

- Each is calibrated at TAMU using a voltmeter



# Testing the DCRCs at TAMU

1. Tests at TAMU
2. Calibration
3. Noise, Channels, and Trigger Checks
4. Next Steps

# DCRC Testing Overview

How do we trust boards will work in the experiment?

- TAMU has tests designed to check all the functionality for a full working board

**Regular running tasks:**

- Check that noise is low enough for experiment
- Make sure signal can be read out
- Verify that phonon channel amplifiers work as expected by testing signals in each setting

**Trigger Tests:**

- Verify that input pulses fire when expected, but doesn't fire when it shouldn't

**Control tasks:**

- Calibrate the DCRC and ensure calibrated board responds appropriately when values sent to DACs

**Goal:**

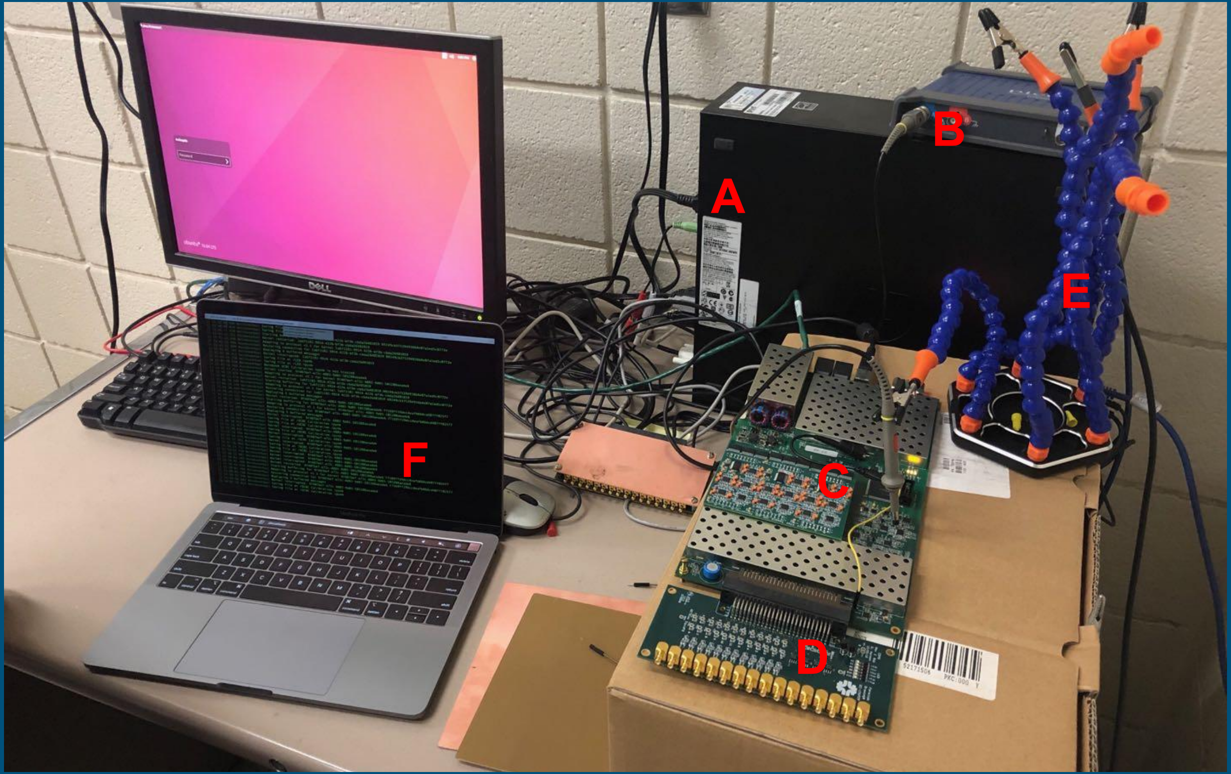
- Separate fully functioning board from those that aren't
- Identify problems so partially functioning boards can be fixed

# Test Stand at TAMU

We have one test stand** with two stations (setups)

Each has:

- (A) PC
- (B) Picoscope
- (C) DCRC
- (D) miniBOB
- (E) Helping hands
- (F) Laptop




**A big thanks to **Mitchell Institute** for the funding of this test stand and making this work possible

# Summary of Tests at TAMU

Boards are constructed at *Fermilab National Accelerator Lab* (FNAL) and sent to TAMU to test, then fully functional boards make their way to the experiment

1. Noise Test: Checks electronic noise amplitudes on all charge and phonon channels
2. Phonon Test: Checks functionality of of phonon channels and triggers
3. Charge Test: Checks functionality of of charge channels and triggers
4. Calibration: DAC voltages measured, calibration constants determined and saved to file

**Other tests at TAMU include: PowerUp, Hybrid Readout, Thermometry

# TAMU Board Tests

We won’t detail every test, but point out that these are automated and run on every board If a board passes each test, the board is declared good for the experiment

List of tests:

- PowerUp Test
- Noise Test
- Phonon Signal Test
- Charge Signal Test
- Hybrid Readout Test
- Thermometry Test
- Calibration
- DAQ Validation

| |
|---|
| 1.Name/Version Number |
| 2. FPGA/Micro Address/data Test |
| 3. SDRAM Test |
| 4. ADC Readout Test |
| 5. Noise Traces Check |
| 6. Phonon Trigger Test |
| 7. Trigger Amplitude Comparison |
| 8. Ph Channel Inversion Test |
| 9. Charge Offset Test |
| 10. Charge Pulse Injector Mapping |
| 11. Charge Trigger Test |
| 12. Random Trigger Test |
| 13. Readback Test |

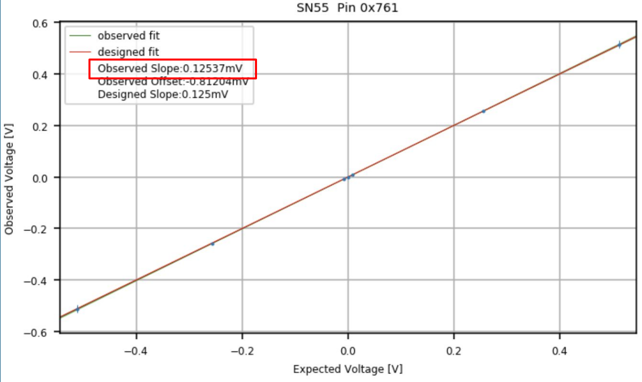
| |
|---|
| Trace&RMS Check |
| PSD evaluation |
| PSD outputs |
| Source Switch Check |
| Driver Gain Check |
| Input Gain Check |
| Trigger Test |
| Transfer Function |
| Fall/Rise Time |
| Trigger Test w/ DCRC pulser |
| Trigger Test w/ external pulse |
| Hybrid Readout Test |
| Thermometry Test |

| |
|---|
| **Calibrating** |
| TestSignal |
| ADCOffset |
| LockpointAdjust |
| SQUIDBias |
| QETBias |
| AmpOffset |
| QBiasDac |
| LEDMagnitude |
| **MIDAS files** |
| **Validating with DAQ** |
| Zeros |
| Lower Values |
| Higher Values |

# Calibration of Phonon and Charge DACs

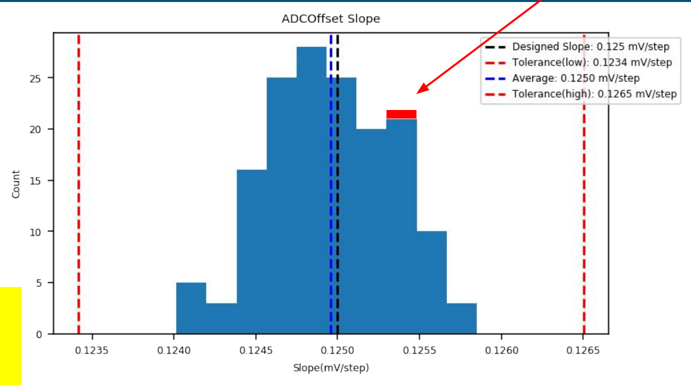
Boards need to be calibrated for the DAQ

1. We send values to board that is stored in registers for DAC use
2. DAC converts value to voltage that we measure
3. Voltages measured to determine calibration constants for later setting of desired voltages (top figure)
4. Compare with our expectations to see how well it works (bottom figure)
5. DAQ is supplied with calibration file for DCRC control
6. Calibration constants on DAQ checked using DAQ Validation




The fit of observed and designed voltage match, showing a good calibration

Board 55's 0x761 DAC measurement




Distribution of measured ADCOffset DAC on good boards used to decide goodness of calibration for other boards

# Noise Check

**Power Spectrum Density of noise** All frequencies are below the allowed limits (dotted red line)

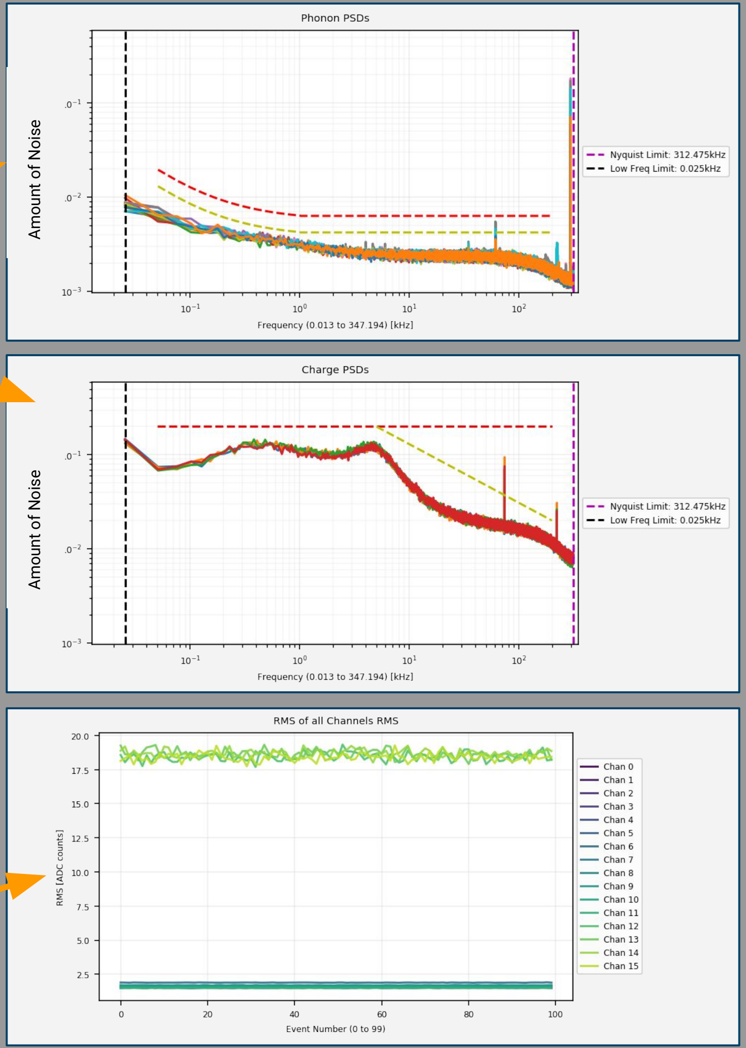
Why do we need the Noise Test to check board?

- Electronics produce noise
  How much? Too much for experiment?
  - Too high of noise could overshadow detector signal
- Need to check noise from amplification of phonon channels

**A problem in a noise test can infer a problem elsewhere in the electronics**

**RMS Test:** Another way of showing noise: RMSs are low compared to average
What we expect for low consistent noise

Passing Example



# Phonon Channel and Trigger Check

**Amplifying Readout:** Different amplifications show correct amplitudes

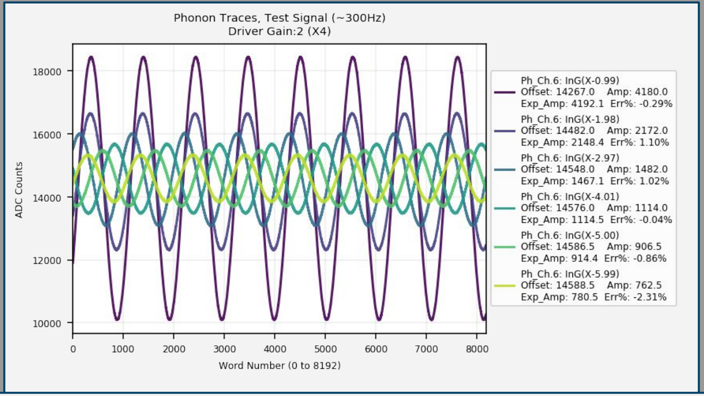
Checks phonon signal readout, proper amplification of readout and trigger

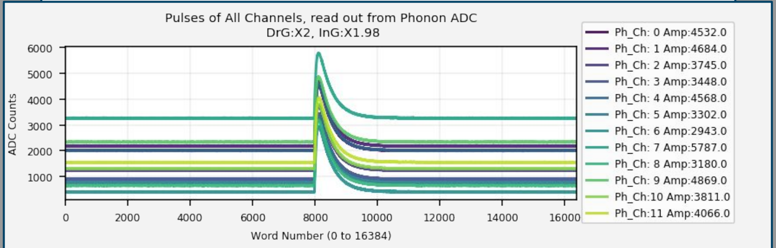
Why we check phonon channels?

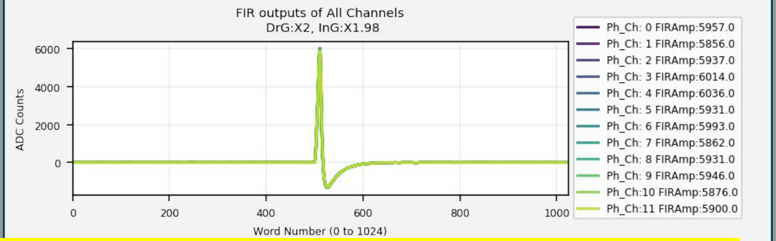
- Make sure that the phonon channels can be read out
- We need signal to amplify correctly (checked in phonon test)
- Mock pulse allows us to see if the phonon trigger fires as expected
- Phonon trigger compared against simulation

```
Trigger     Amplitude=  2396
Trigger_Sim Amplitude=  2396
GOOD!! PCh 0: Triggered successfully. Amplitude matches trigger simulation
```

Passing Example




**Phonon Trigger Test:** ADC count readout gets triggered, showing the data that would be saved
This output shows the trigger is working

# Charge Channel and Trigger Check

**DAC Offset:** Charge DACs can be manually set, showing that charge offset control is functioning

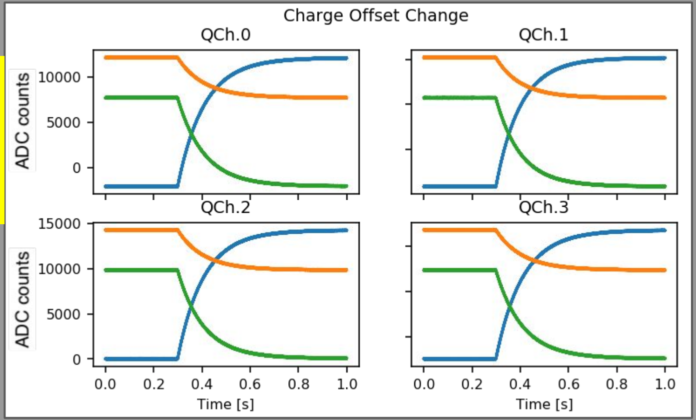
Checks charge signal readout, charge DAC functionality, and trigger

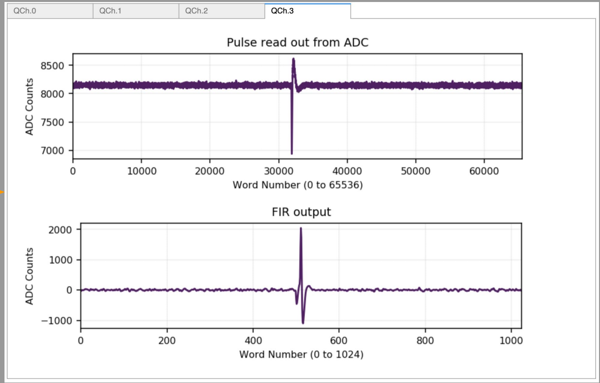
Why we check charge channels?

- Make sure charge channels can be read out
- Needs DACs to set the voltage bias on the top and bottom of detector
- Mock pulse allows us to see if the charge trigger fires as expected
- Charge trigger compared against simulation

```
Trigger     Amplitude = 2040
Trigger_Sim Amplitude = 2040
GOOD!! Triggered successfully. Amplitude matches trigger simulation
```

Passing Example

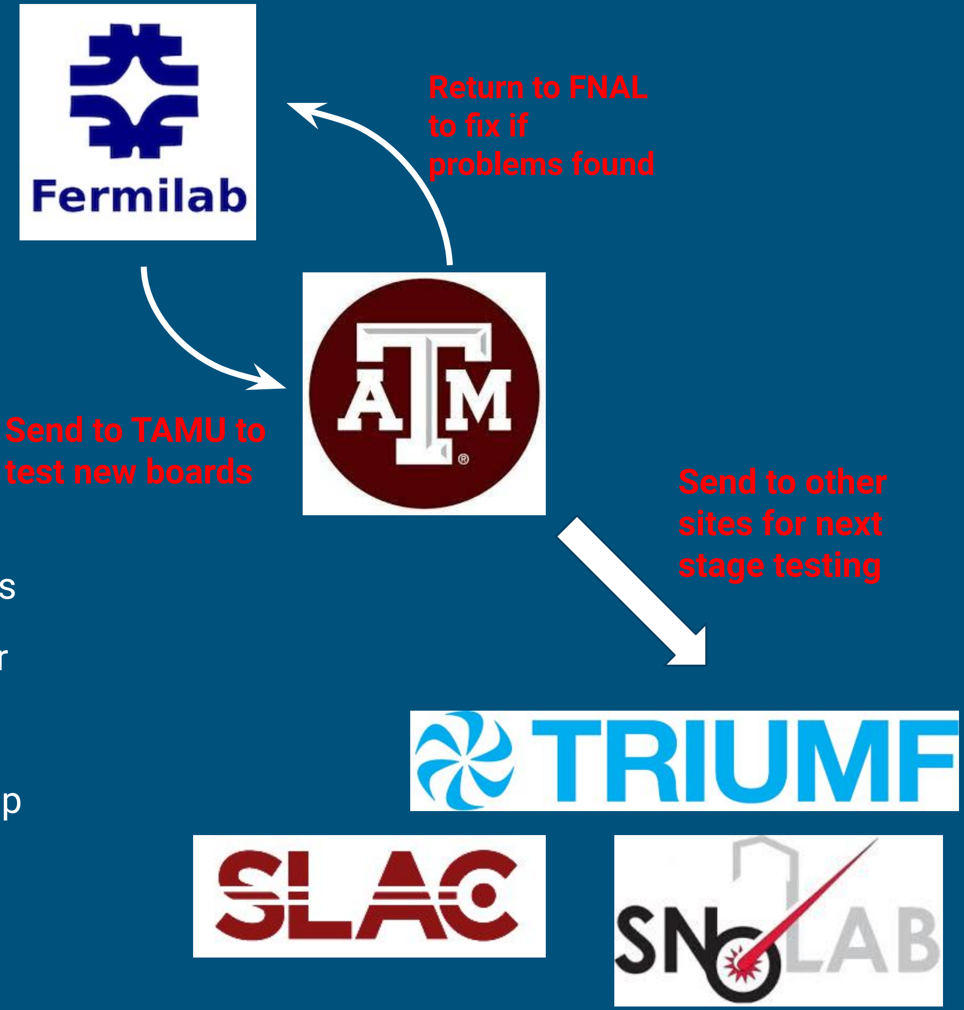



**Charge Trigger Test:** Similar to phonon trigger test, the charge pulse is also triggered This output shows pulse was trigger

# Current Status and Next Steps

- The first round of the DCRCs passed and calibrated at TAMU!
- Boards passing all tests were declared good for the experiment and sent out for other detector related testing
- Boards failing any part of the test were sent back to FNAL for further testing/fixes
- TAMU will continue to be a testing site for DCRCs, as more will arrive in the future
- I will be moving from helping build the experiment to simulations where I will help discover dark matter



# Conclusion

- The upgrade CDMS experiment at SNOLAB will have one of the most sensitive detectors to discover dark matter
- The new readout electronics, DCRCs, are sophisticated computer boards
  - Readout data and fire the trigger of charge and phonon channels
  - Communicate with DAQ
  - Control the detector
- We have developed testing procedures that test
  - Noise levels
  - Phonon/charge channel and trigger functionality
- First round of DCRCs tested and calibrated at TAMU
  - Good boards have been sent out for detector testing
  - Problematic boards are being fixed by FNAL
  - More boards will be tested using thorough testing procedures
- We are looking forward to the next experiment at SNOLAB in which the DCRCs will play an important role in the discovery of dark matter!

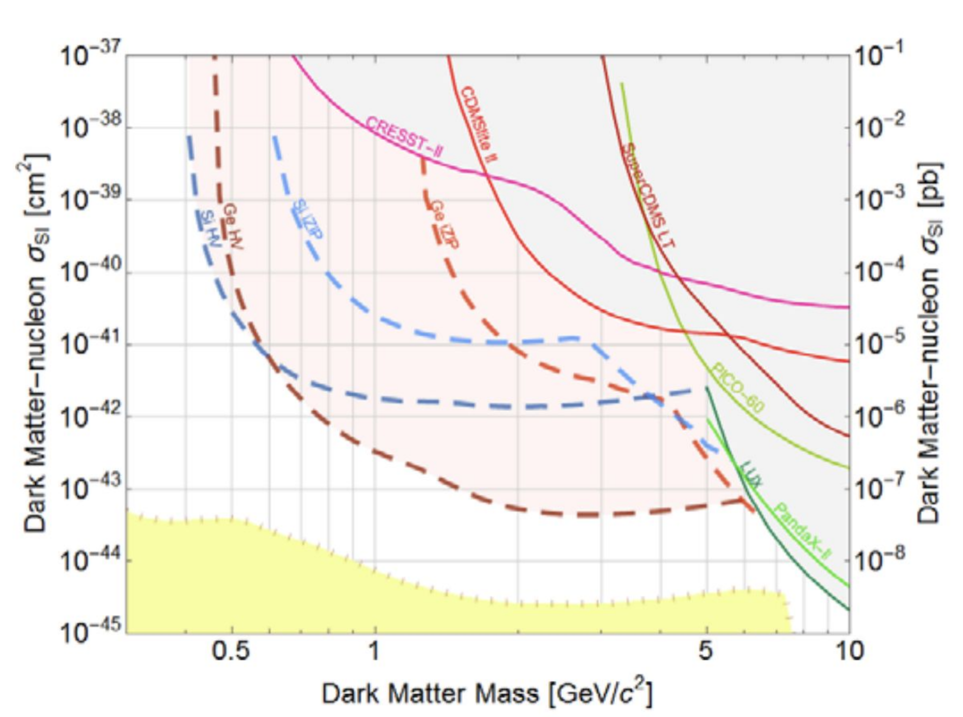
# Thank you!

# Backups

# Mass/Cross-section ranges at SNOLAB

Mass: 1–6 GeV/c^2

Cross-section: 10^-43 cm^2



# SuperCDMS Detector Specs

- 100 mm in diameter
- Each side has 1000 sensors
- 33 mm thick Si and Ge crystal

# Why Radon is Bad?

Radon can embed itself in the detector and cause its own electron recoils or nuclear recoils when it emits alpha particles in the detector

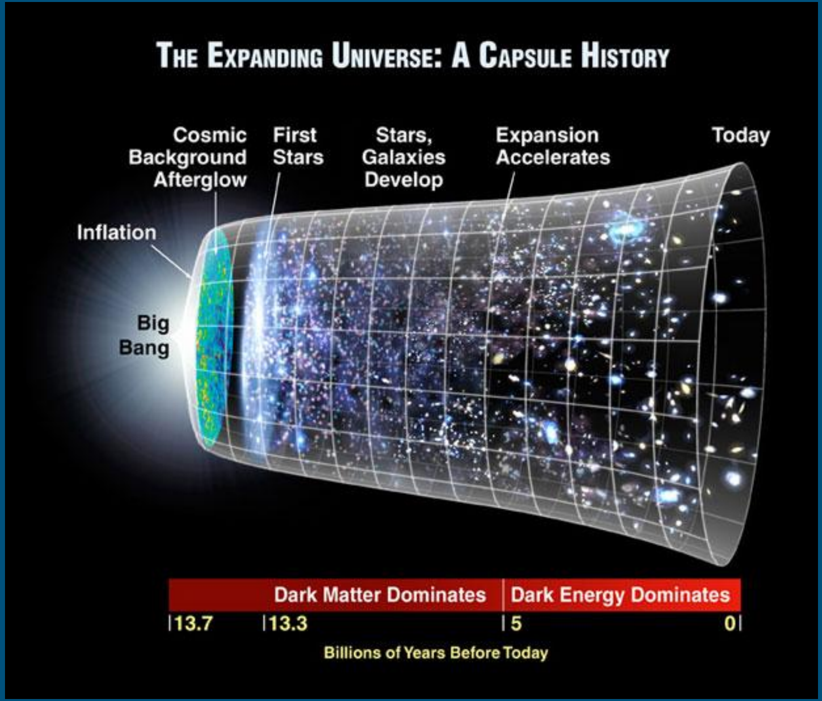
From an analysis standpoint, it is better to remove as much radon as possible because it is hard to remove its signal from the data

# Dark Matter and the Early Universe

From our current understanding of the universe dark matter has played an important role in its early formation

If we understand dark matter's proto universal role we can learn

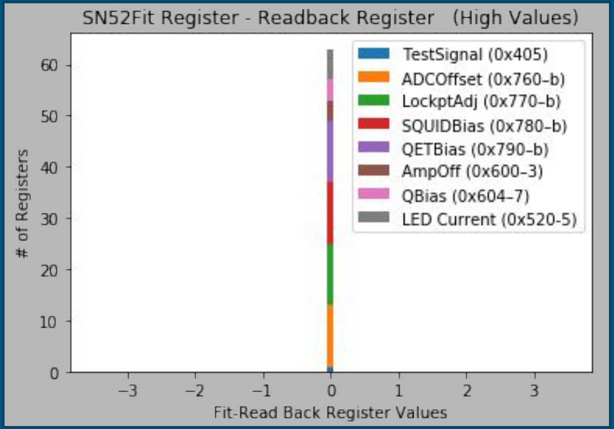
- Why dark matter particles remain abundant?
- How did dark matter particles react with
  - Visible Matter
  - Itself



# DAQ Validation

One last check (DAQ Validation) is used to make sure that boards respond properly to DAC voltage adjustments

This will also ensure that the correct calibration file matches the board




The DAQ Validation test shows that the difference in expected fit register value and board values is the same

All differences show 0 meaning DAQ controls DCRC registers as expected

# My Work

- Worked on finding bugs in the firmware versions during development
- Improved testing procedures
  - Automated PowerUp Test
  - Using voltmeter instead of picoscope for QBias registers
  - Wrote DAQ Validation code
  - Calibration now 2x faster
  - Wrote code to more easily save testing results
- Ran testing code on the 35 production boards that came from FNAL (massive effort)
  - Ran hundreds of tests (at least 10 per board) to check board functionality
  - Calibrated all 63 registers on 35 boards (with few exceptions)
- Solo worker on DCRC boards since COVID-19 (May 2020-present)