Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Testing the Jump Finding Code for NEXUS Qubit Analysis

Grace Wagner
Advisor: Dan Baxter

SULI Presentations
6 December 2023

a.This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.
b.This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI).

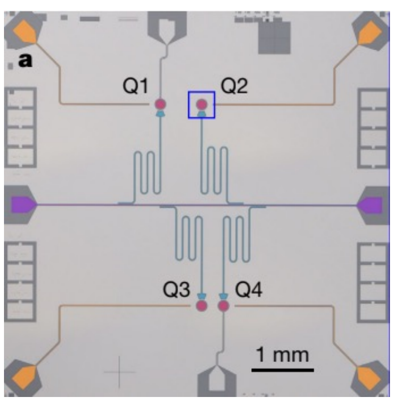
Superconducting Qubits

- Qubits: quantum bits with information encoded on it
- Qubit Error: When any of the above information is lost
  - Decoherance Errors
  - Dephasing Errors

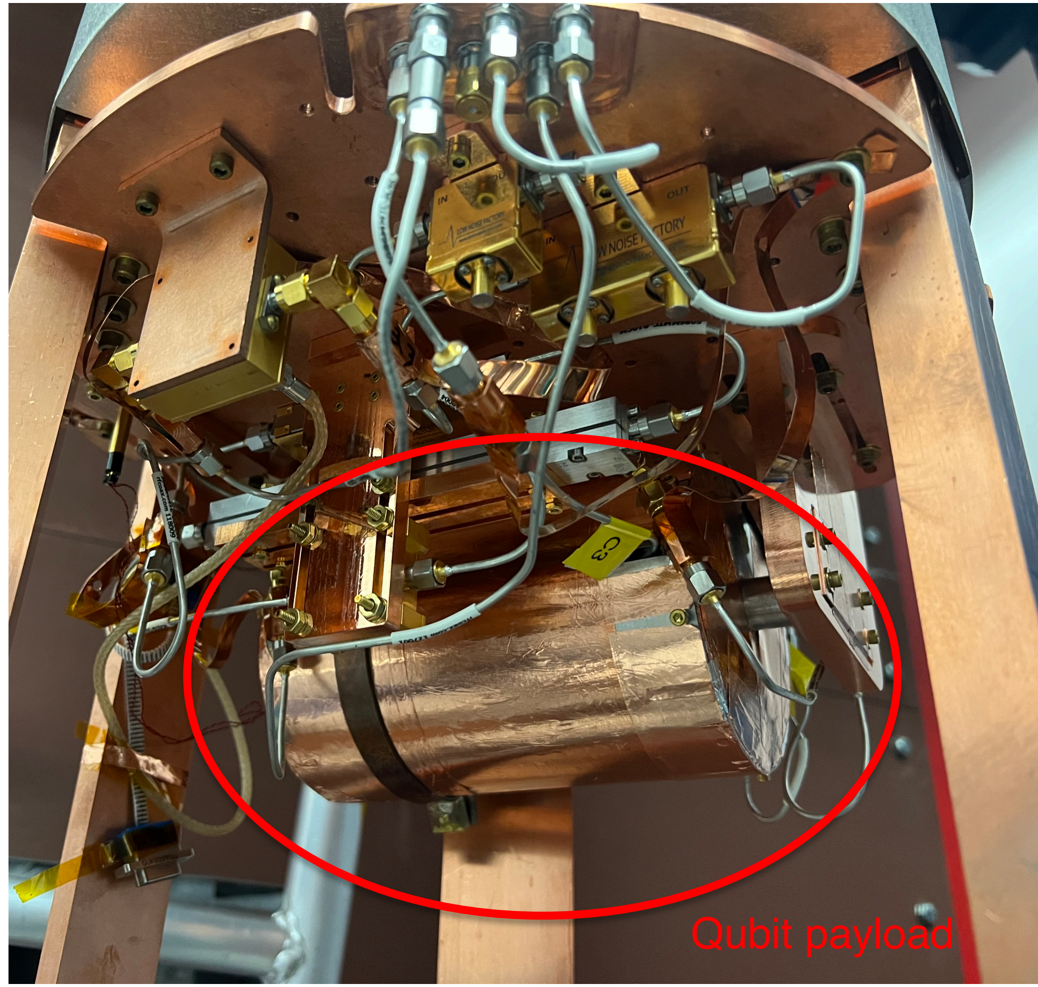
What are Qubit Errors?

What causes them?

McEwan et. al. 2021 shows that ionizing radiation and comic ray muons can cause qubit errors. (That's one reason we're doing this 100+ m underground)



Layout of the qubit chip currently being used in NEXUS; Image Credit: Wilen et. al. 2021



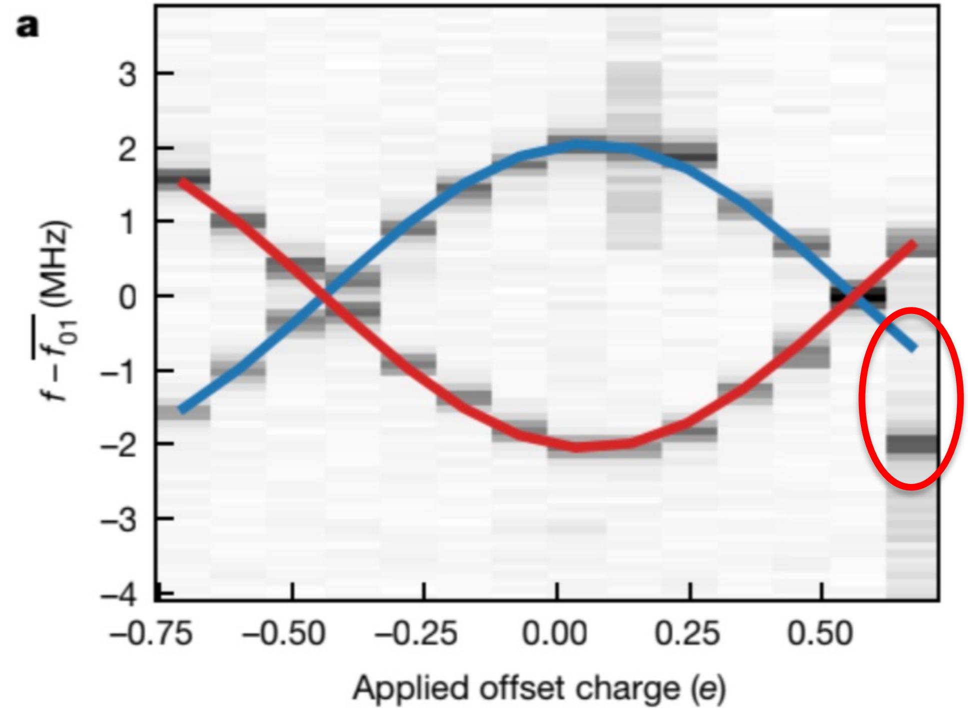
NEXUS Qubit Payload, along with other experiments in the NEXUS Dil Fridge (KIPMDS, etc.)

Qubit Jumps

A **charge jump** in a qubit is when a particle is incident on the chip, causing the qubit to decohere, resulting in a **jump** in offset charge.

Ex. A cosmic ray muon passes through a qubit, resulting in a phonon being released, which causes errors in nearby qubits.

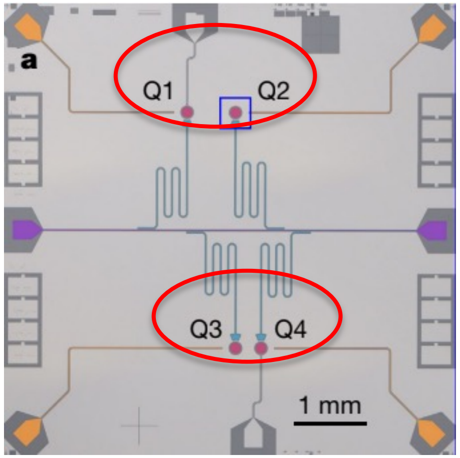
Correlated Qubit Error: when two qubits that are spatially nearby see errors that are correlated in time as well.



Qubit spectroscopy versus charge the applied offset charge, the red and blue lines trace the qubit parity. A jump is seen in the rightmost column.

Image credit: Wilen et. al. 2021

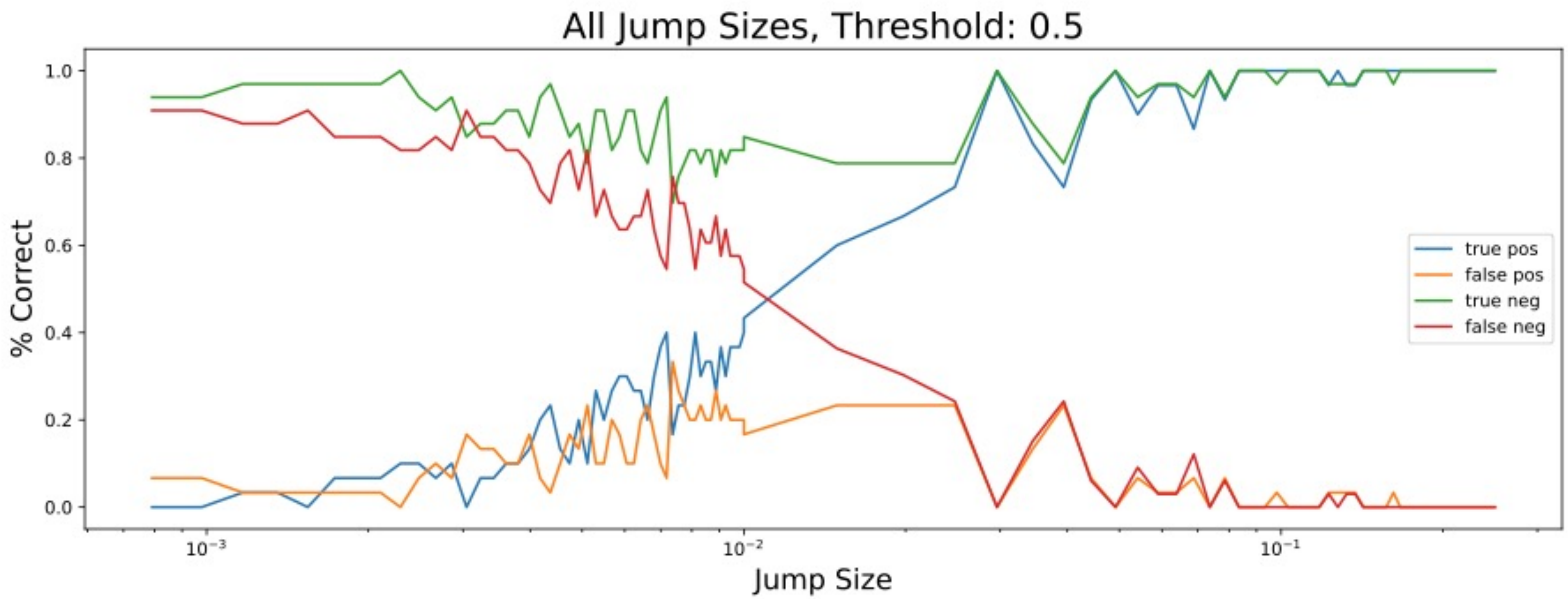
Correlated errors can not be solved with error correction.



Correlated Errors + Quantum Computing = **BAD**

Correlated Errors + Particle Detection = **GOOD**

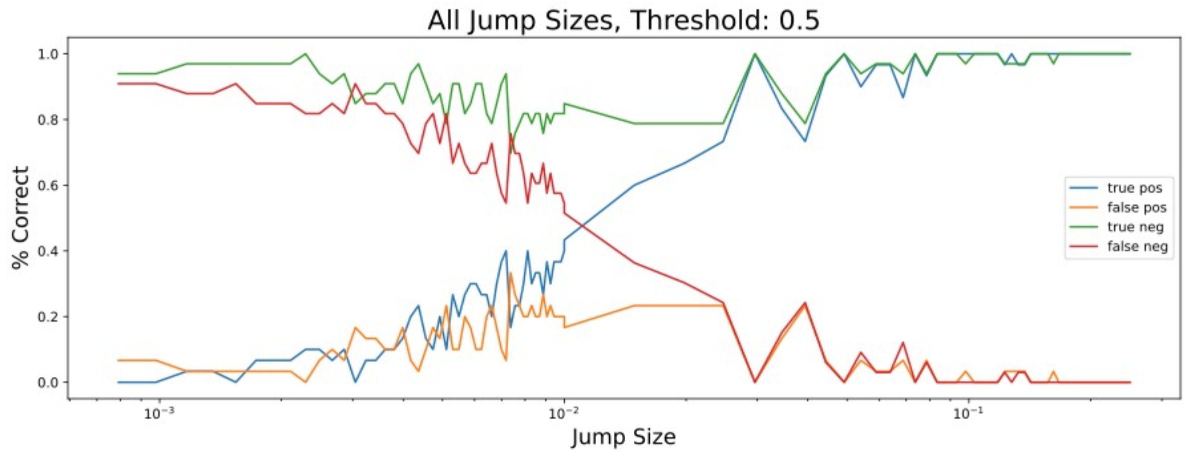
How Efficient is the Jump Code?



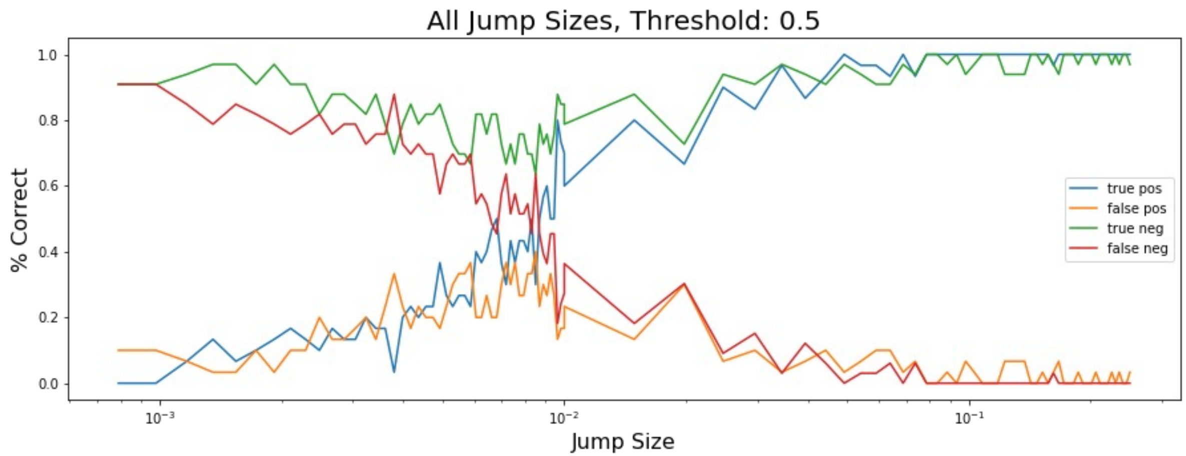
- True Positive: jump detected where jump injected
- False Positive: jump detected where no jump injected
- True Negative: no jump detected where no jump injected
- False Negative: no jump detected where jump injected

Smoothing/Filter Choice

More smoothing →
(8x)



Less smoothing →
(4x)

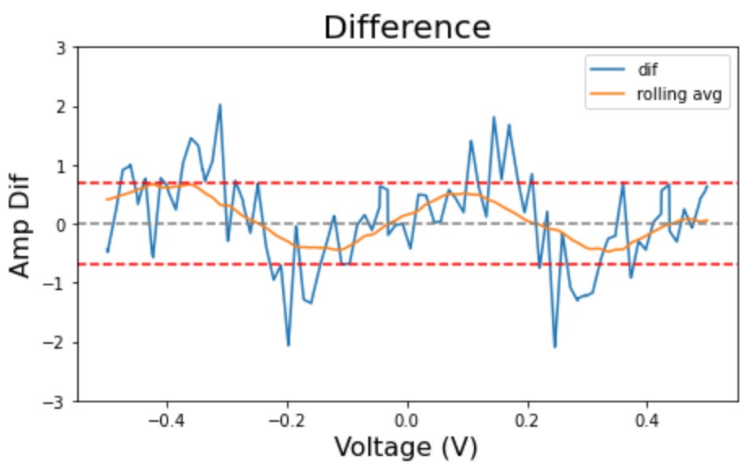


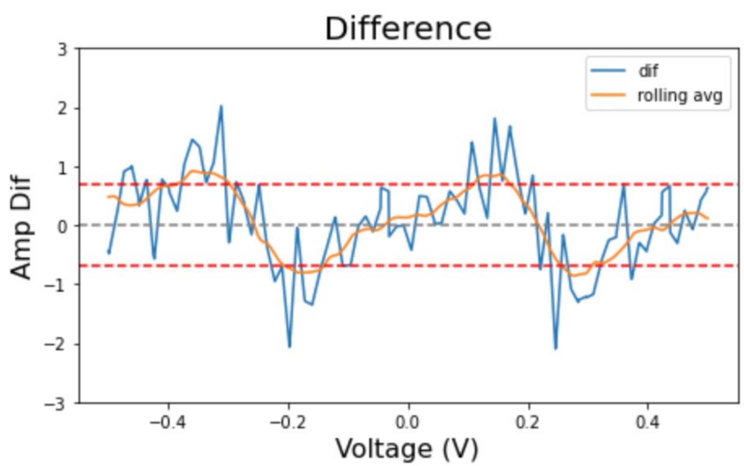
Smoothing/Filter Choice

```
dif = q1data_extend[i,] - scantemp
rollingavg = uniform_filter1d(dif, size=avgwindow)
```

- More smoothing: 8x avgwindow (left)
- Less smoothing: 4x avgwindow (right)

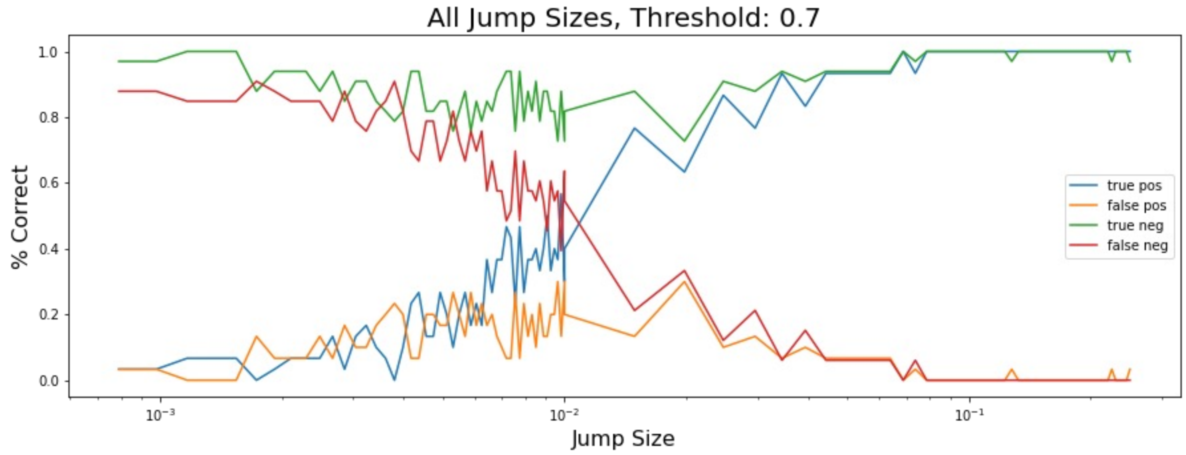
Over-smoothing can lead to detecting fewer jumps



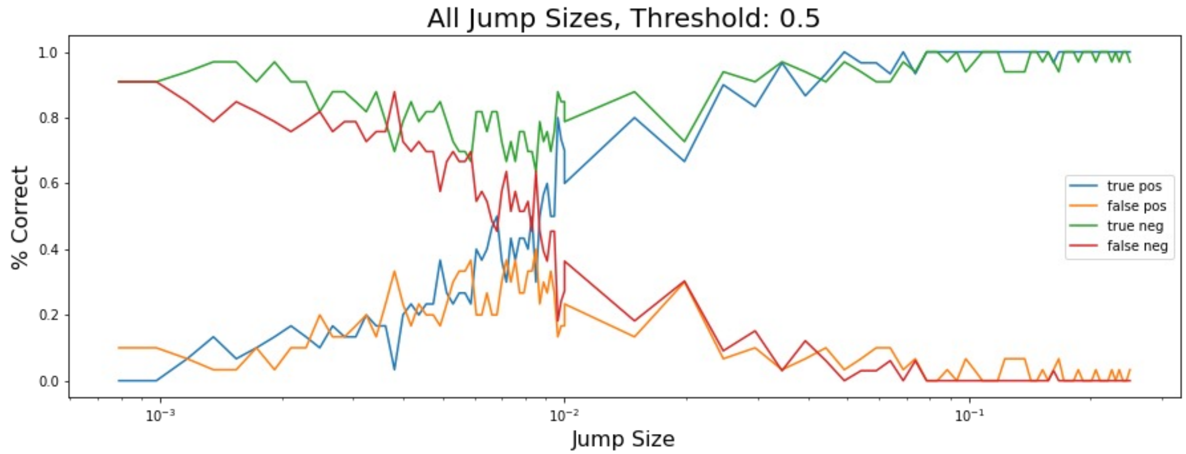


Jump Threshold
(Lower Smoothing)

Higher Threshold →
(0.7)



Lower Threshold →
(0.5)



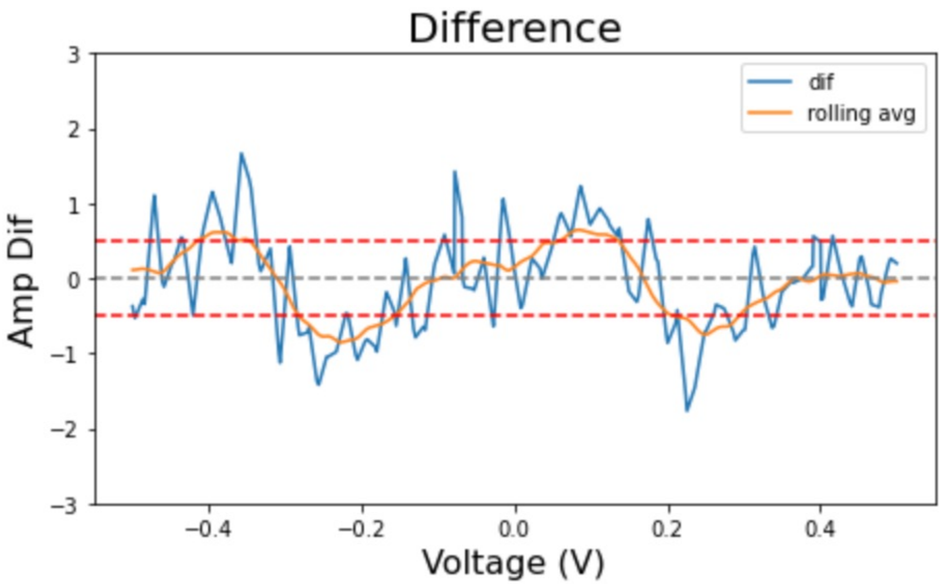
Jump Threshold

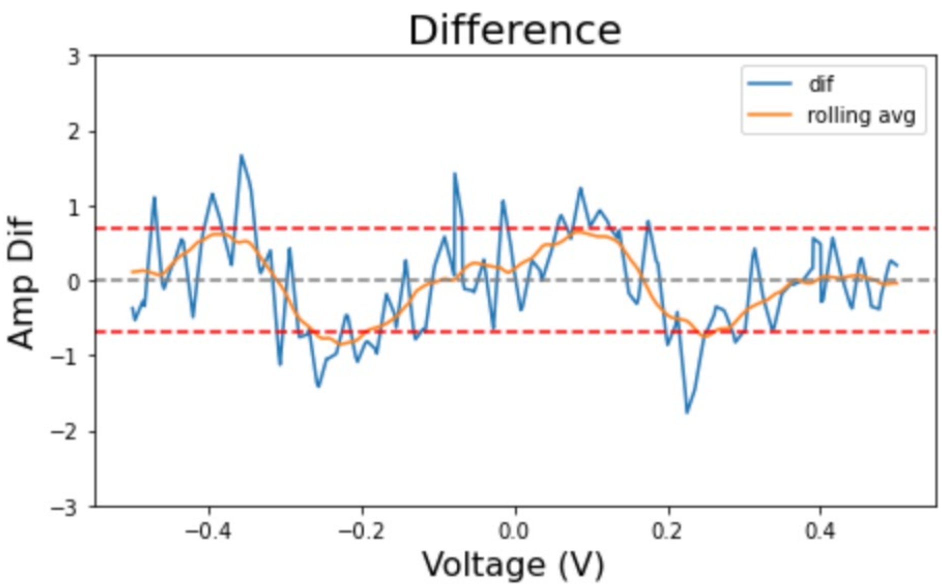
Same smoothing factor

- Top (Threshold = 0.5) counted as jump
- Bottom (Threshold = 0.7) not counted as jump

Currently, the orange line must cross the threshold both positively and negatively, however, this causes some jumps to not be counted as the rolling avg only crosses once (ex. Bottom)

- Should this be changed? Is this a reason for greater smoothing, to allow for a lower threshold/rolling average only crossing once?





What are we doing with this code?

Article

Correlated charge noise and relaxation errors in superconducting qubits

Expanding on previous work and further quantifying it

Specifically…

- Analyzing and identifying the effect of ionizing radiation and cosmic ray muons on qubits using
  - 4 radiation configurations
    - Lead shield closed, No Source
    - Lead shield open, No Source
    - Lead shield closed, Barium – 133 Source
    - Lead shield closed, Cesium – 137 Source
  - Muon veto
    - Muon paddles tag muons that pass through the experiment, so we can isolate jumps cause by cosmic ray muons

Lower incident rate

Higher incident rate

NEXUS
Lead shield

Fermilab

Summary

- Qubit Errors: Any loss of information

Correlated Errors + Quantum Computing = **BAD**

Correlated Errors + Particle Detection = **GOOD**

- Correlated Errors are good news in particle detectors as they indicate energy deposits
- To find these correlated errors, we need a **robustly tested jump detection code**
  - Testing different Smoothing Parameters
  - Testing different Jump Thresholds

- Future Work:
  - Chi^2 Analysis
  - Applying the Jump Detection Code to the real data

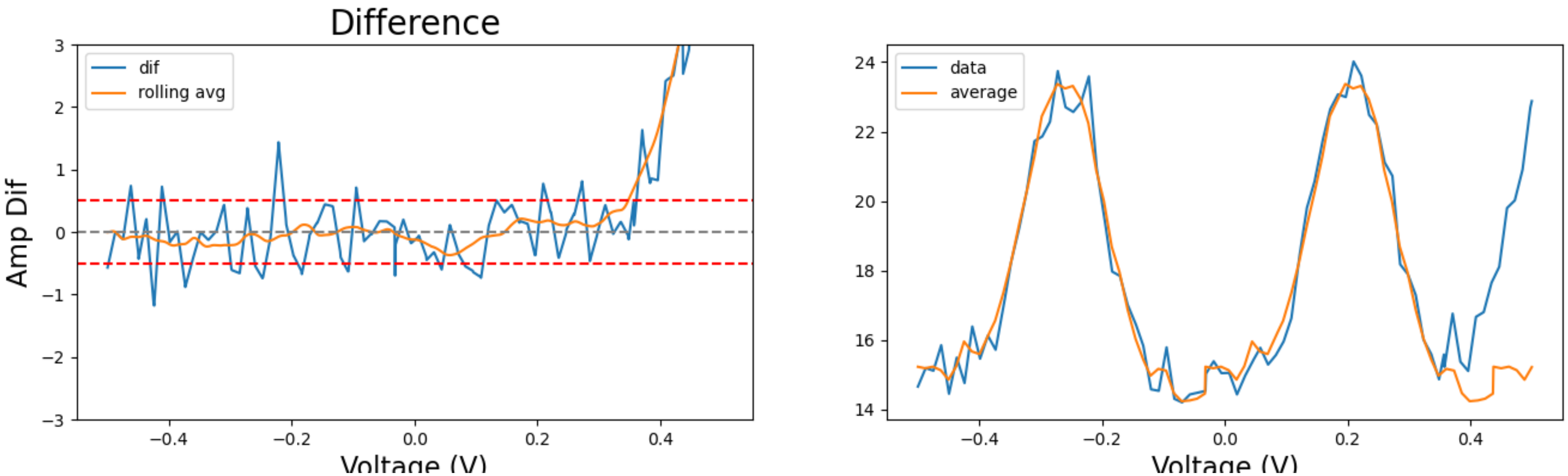
Works Cited

- O'Malley Dissertation 2016
- Wilen et. al. 2021
- McEwan et. al. 2021

Back Up

How do we identify jumps?

1. Make a no jump template out of first ~20 sweeps of Shield closed, no source configuration.
2. Subtract no jump template from data to isolate variations (both jumps and noise).
3. Set a threshold that the data must cross (both positively and negatively) to be considered a jump.
4. When a jump is detected, make a new no jump template from the data starting after the jump, comparing it to the original no jump template to ensure there is no jump.



Need to know:
1. How well the Jump finding code works on jumps of all sizes
2. What parameters (threshold, smoothing) to use to maximize true positives (i.e. not mistaking small jumps for noise or vice versa)

Collected Data from NEXUS

- T_1: Decoherance Time (aka **relaxation** rate)
  - Relaxation Time in which the qubit relaxes from the excited state to the ground state
- ~~T_2: Dephasing Time (ex. in Figure below)~~
  - ~~Loss of phase coherence, usually results in the ‘shrinkage’ of the Bloch vector~~
  - ~~Ramsey Tomography~~
- Fidelity: closeness of two quantum states
- More of a physical model of charge jump

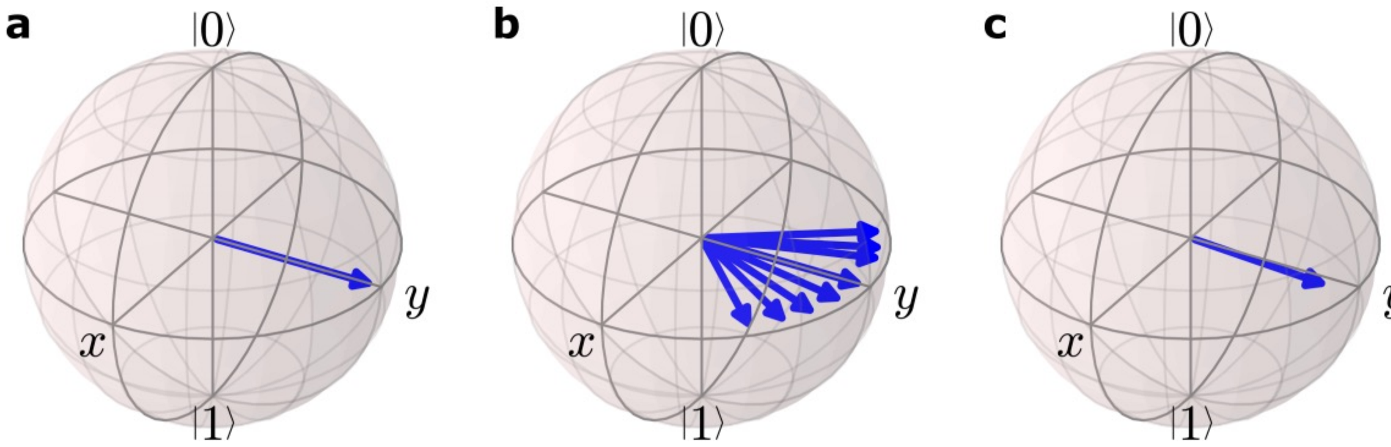


Image Credit: O’Malley 2016

Intro to Quantum Computing at Fermilab

Dilution Refrigerators: cryogenic cooling device that cools materials down to the millikelvin scale

- LOUD
  - Oxford Proteox
- **NEXUS (Northwestern Experimental Underground Site)**
  - MINOS Cavern
- **QUIET (Quantum Underground Instrumentation Experimental Testbed)**
  - MINOS Cavern
  - Oxford Proteox

Newly commissioned QUIET cleanroom

What are we cooling down in the fridges?

Correlated Qubit Jumps

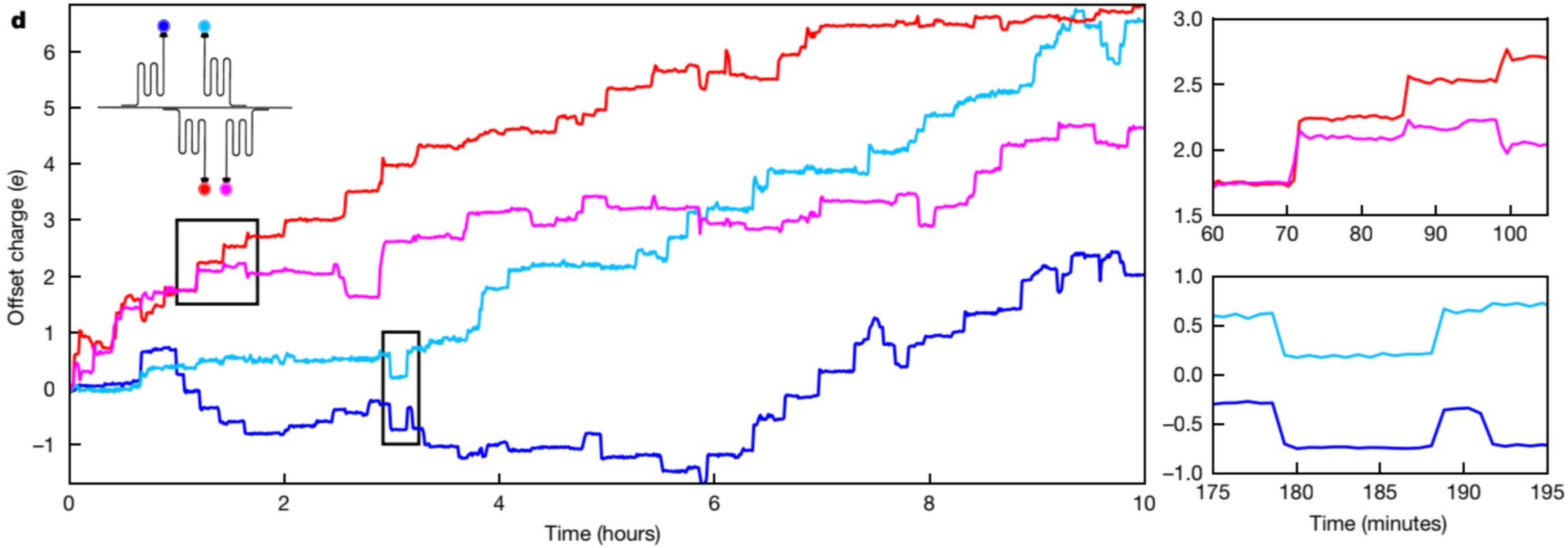


Image Credit: Wilen et. al. 2021