Pacific Northwest NATIONAL LABORATORY

R&D Needs for studying radiation effects on qubits

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U.S. DEPARTMENT OF ENERGY BATTELLE

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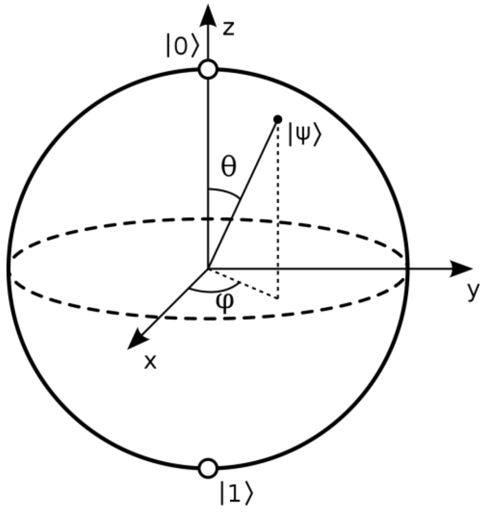
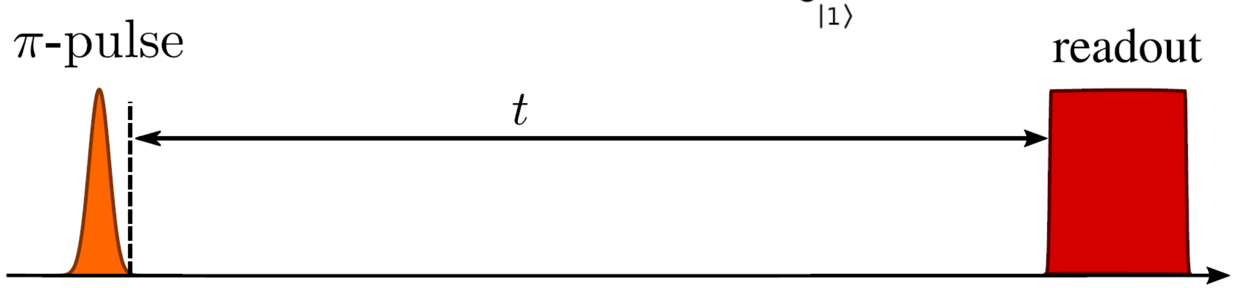
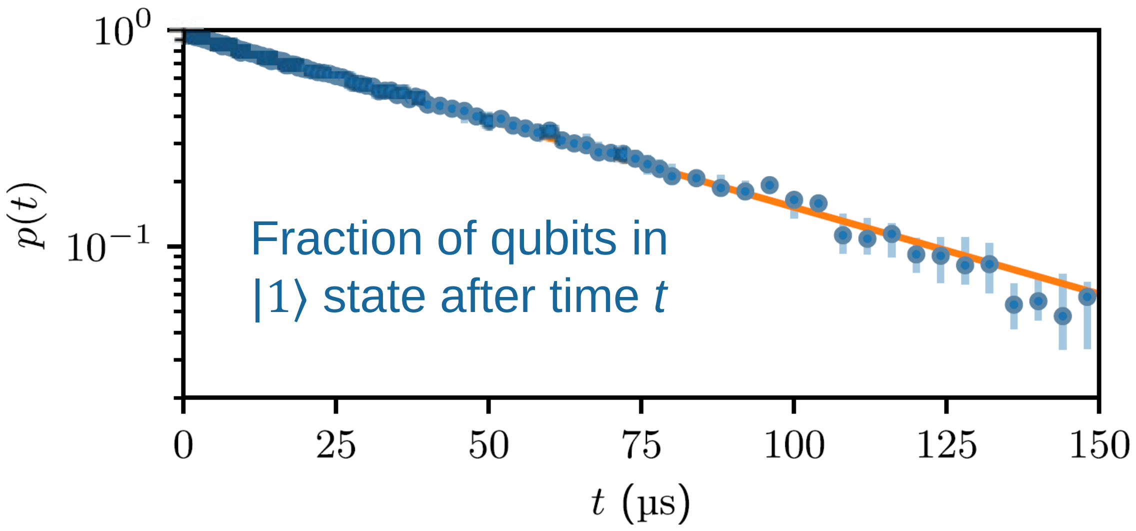
Quantum state decoherence

- Quantum calculations rely on manipulation of well-defined device quantum states
- Spontaneous state change “decoherence” limits calculations
- Also true for any quantum sensors exploiting entanglement

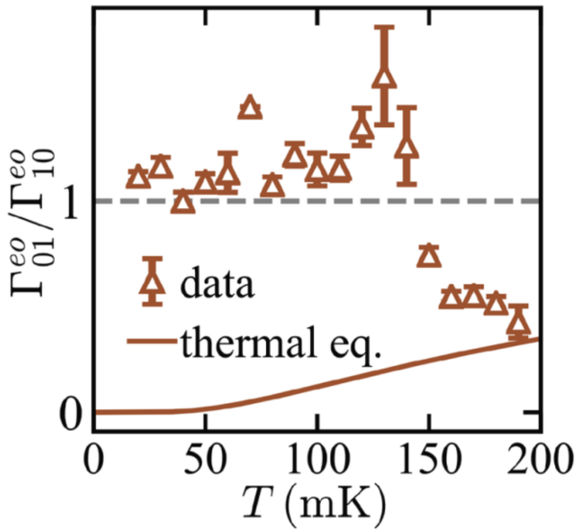




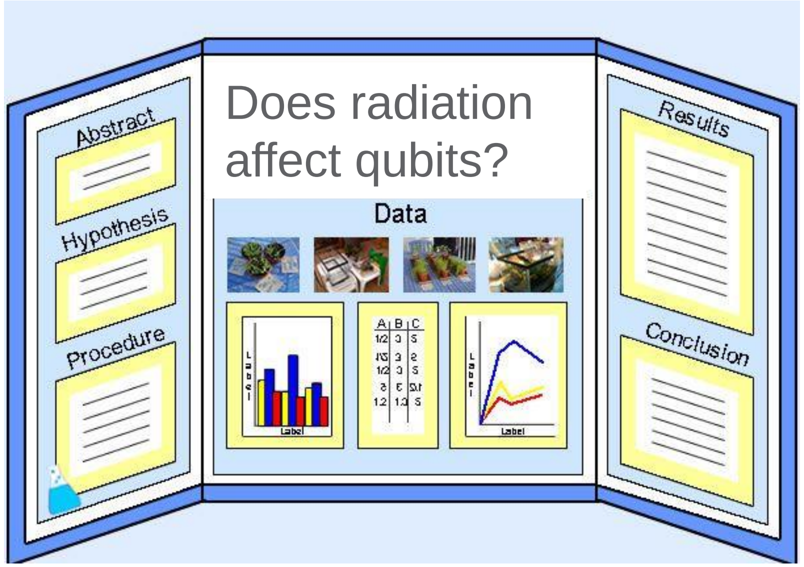


Does radiation cause decoherence?

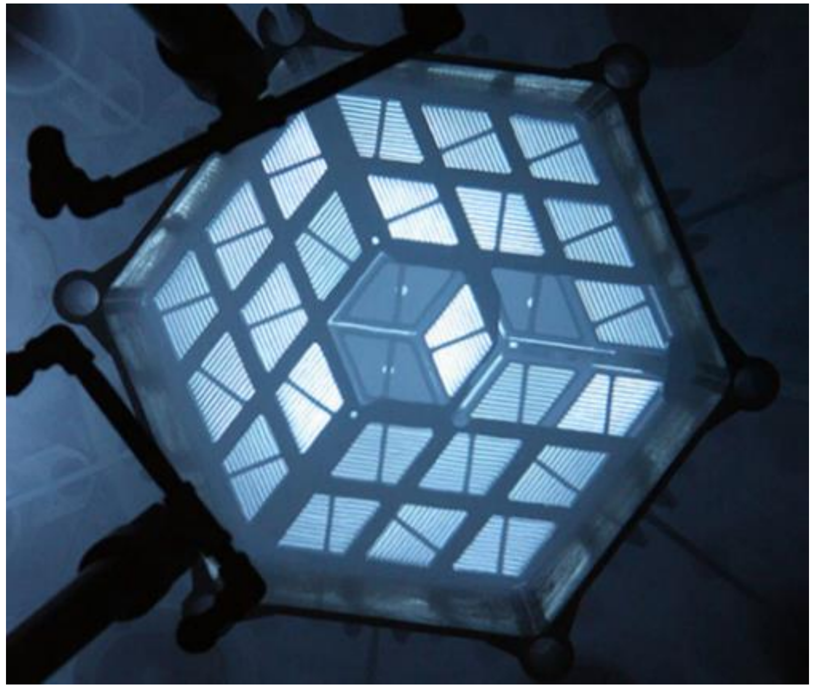
- Ultra cold (mK) superconductors universally observe orders of magnitude more low energy excitations (broken Cooper pairs) than expected
  - Measured densities equivalent to 165 mK (in 20 mK devices)
- Hypothesis: ionizing radiation accounts for some of the decoherence rate in superconducting qubits
- Ideally want a knob to control radiation rate and measure response
- Experiment 1: Increase radiation dose rate with a radioactive source
- Experiment 2: Decrease radiation dose rate with a lead shield



Hayes et al., Phys. Rev. Lett **212**, 157701 (2018)

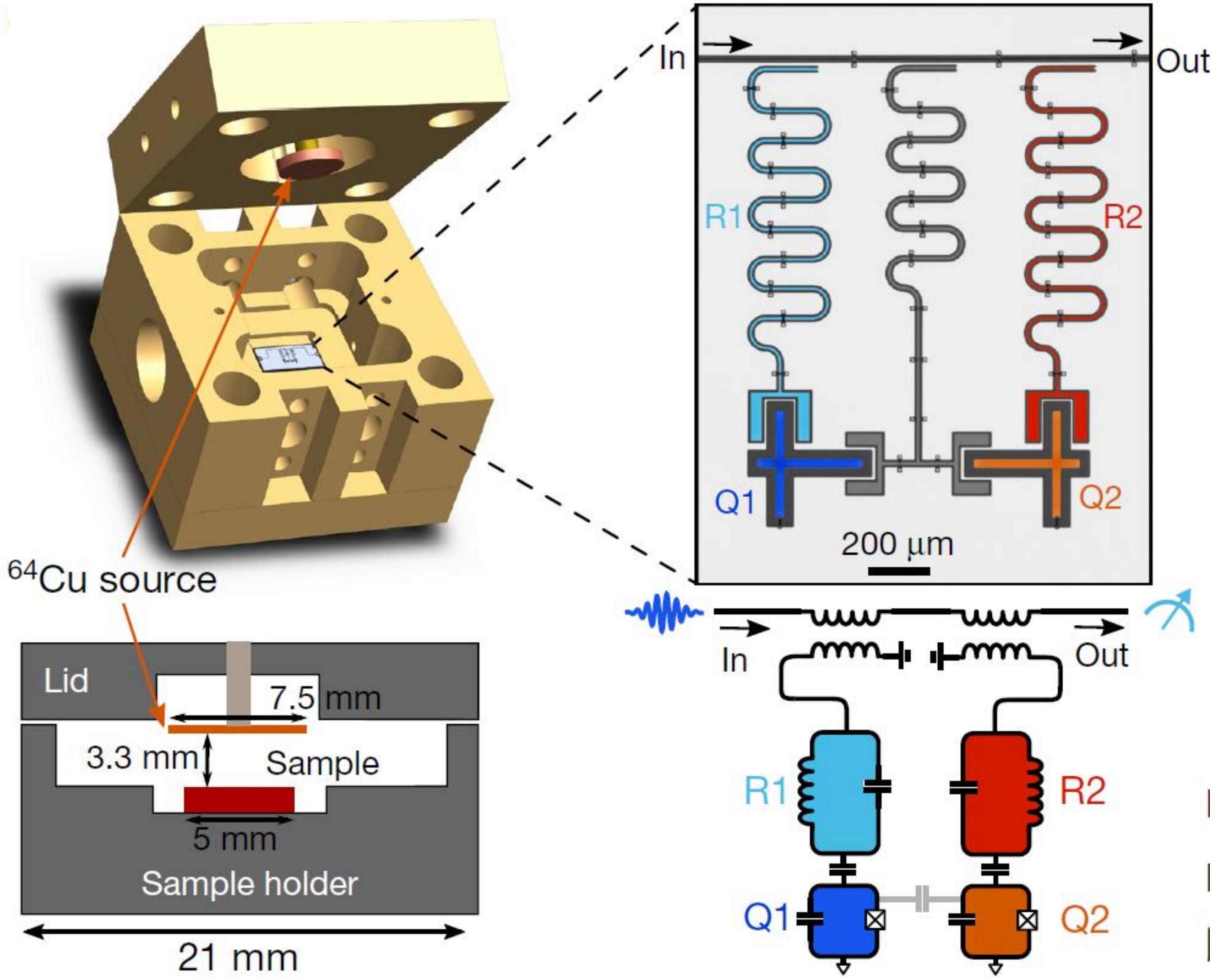


Experiment 1: Expose qubit to activated copper foil



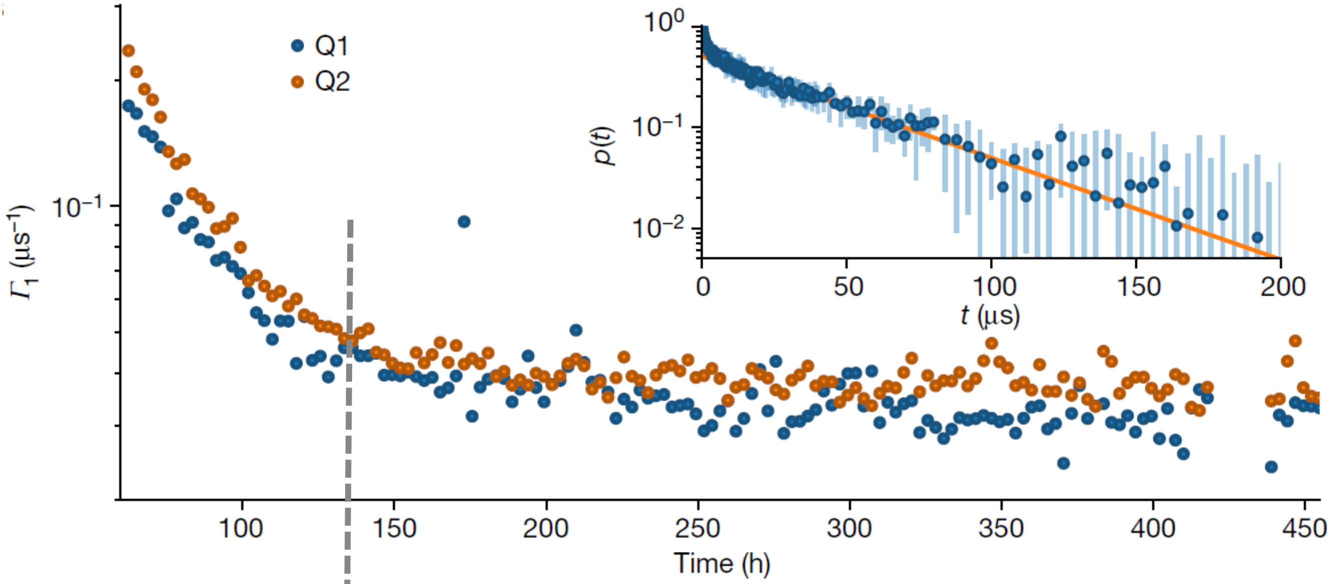
^{64}Cu produced by neutron activation in MIT research reactor

12.7 hour half-life allows observation of behavior from highly irradiated down to background levels in a single fridge cycle

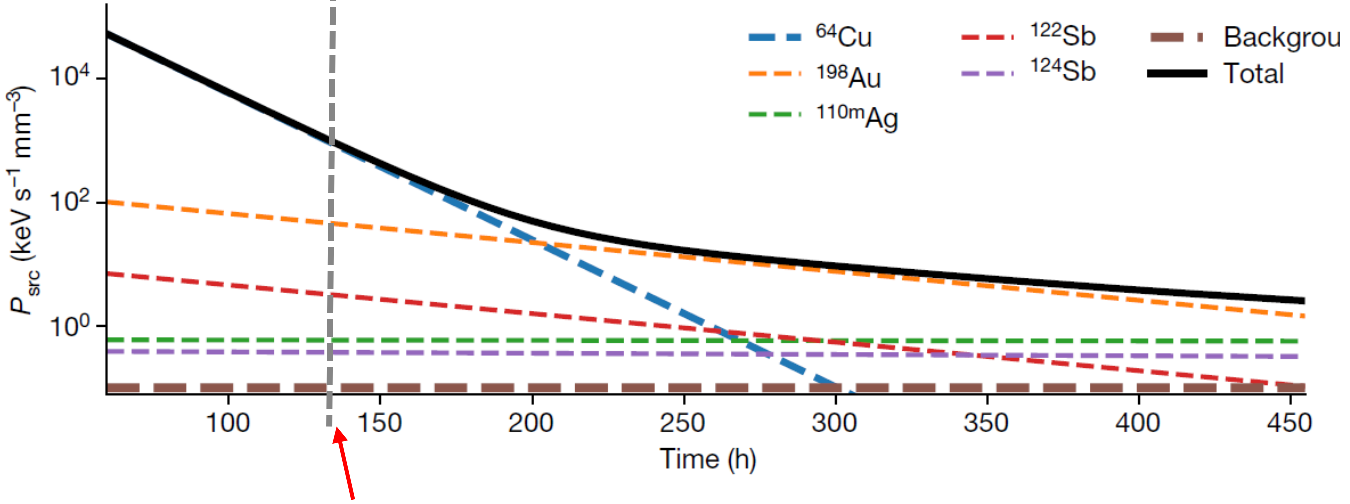


Experiment 1 results

Qubit Decoherence rate

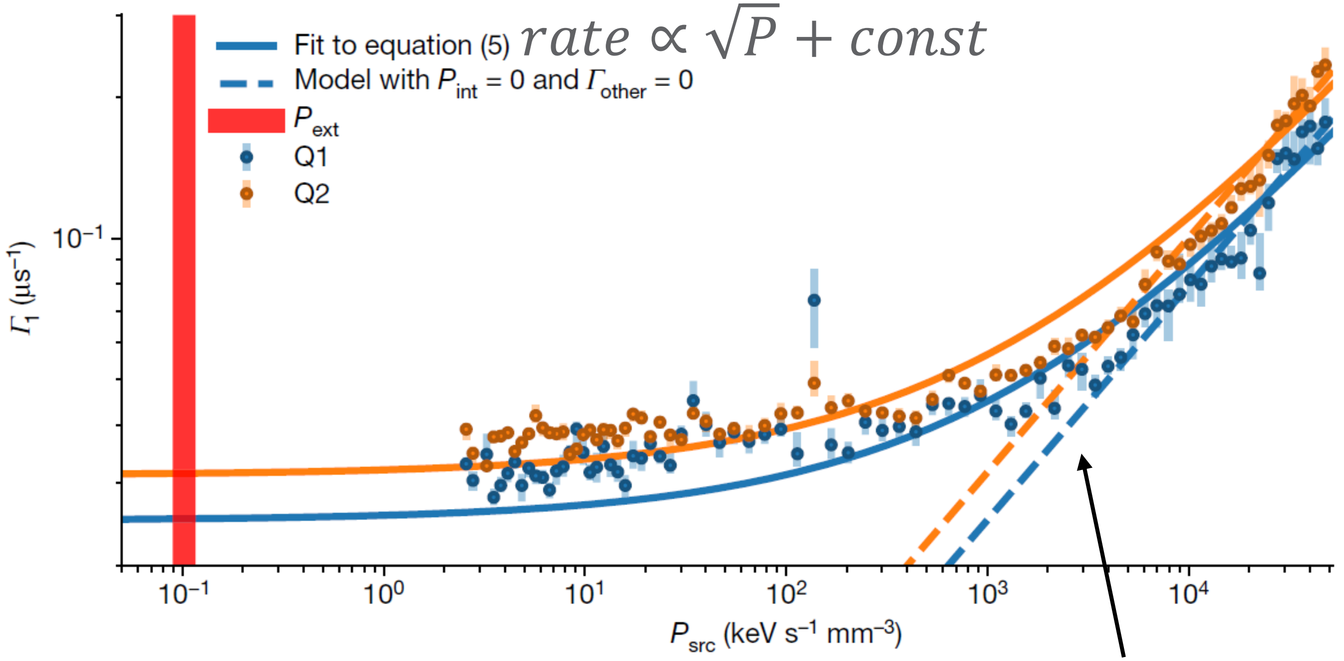


Radiation power into qubit



Approximate transition to non-radiation-driven

Qubit Decoherence rate vs radiation power

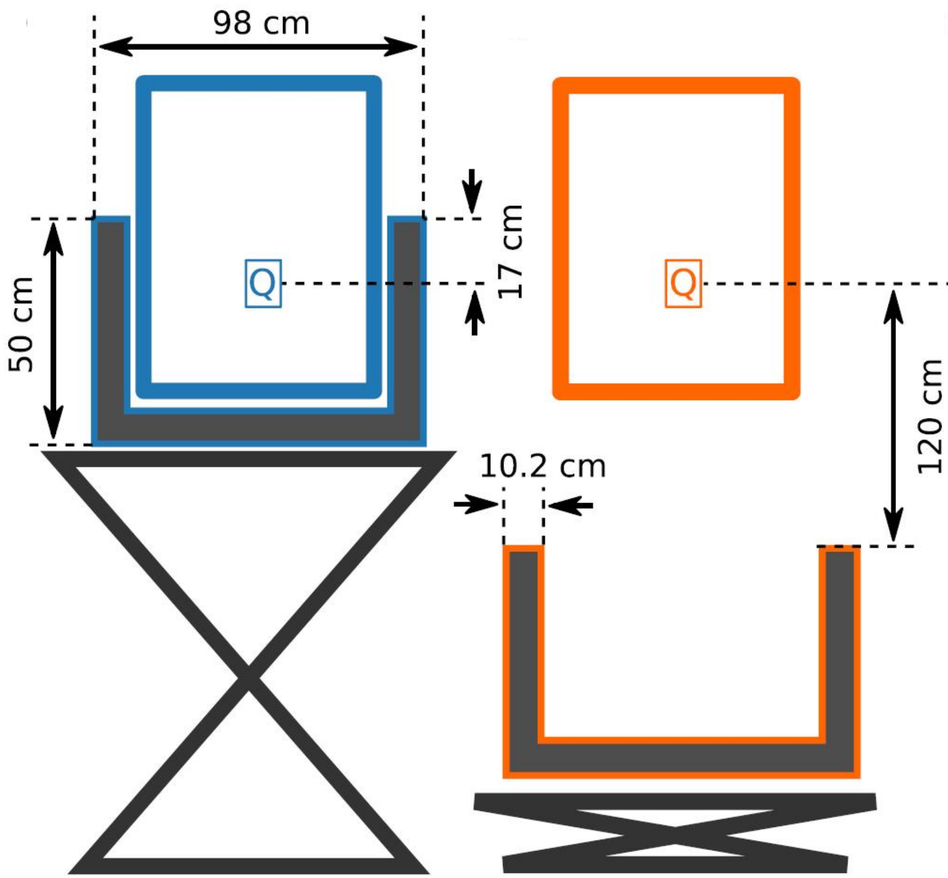


Expectation if radiation dominates

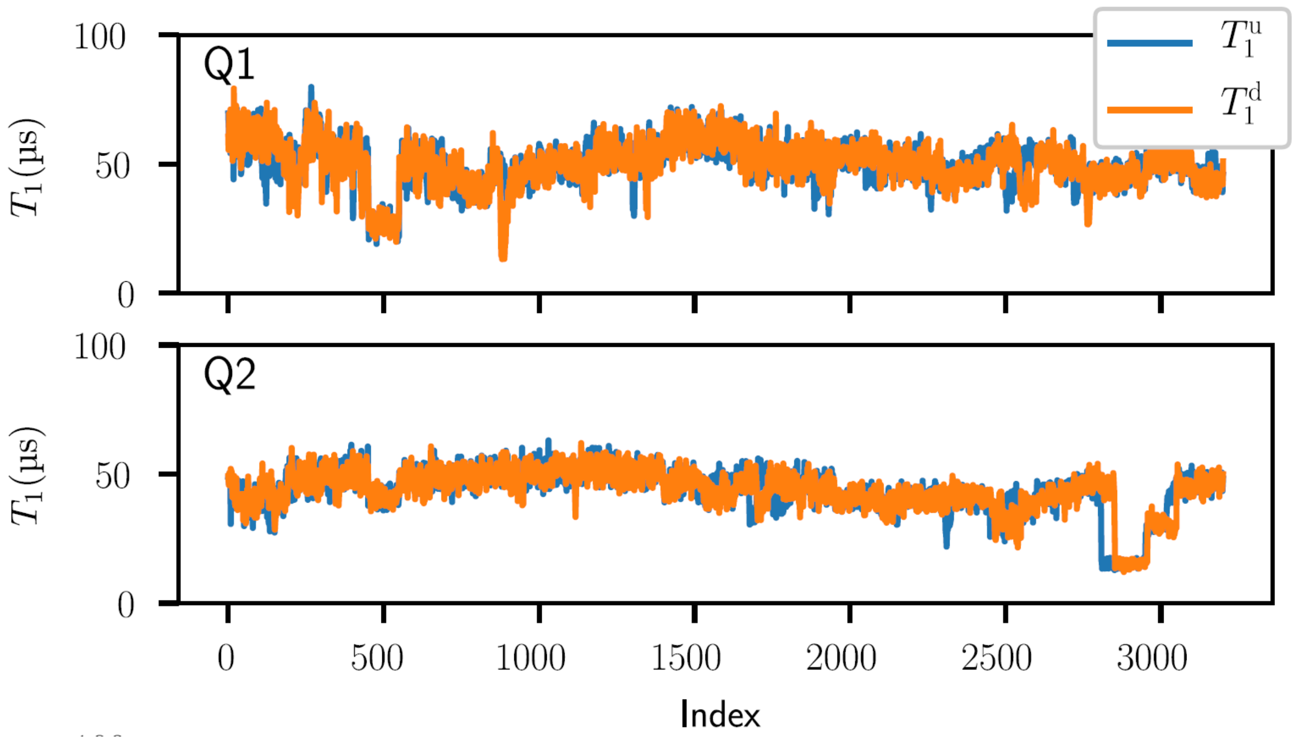
Conclusion: high levels of radiation have obvious negative effects. But what about ordinary background levels?

Experiment 2:
Operate qubits inside a lead shield

Shield reduces incoming radiation dose by ~46%

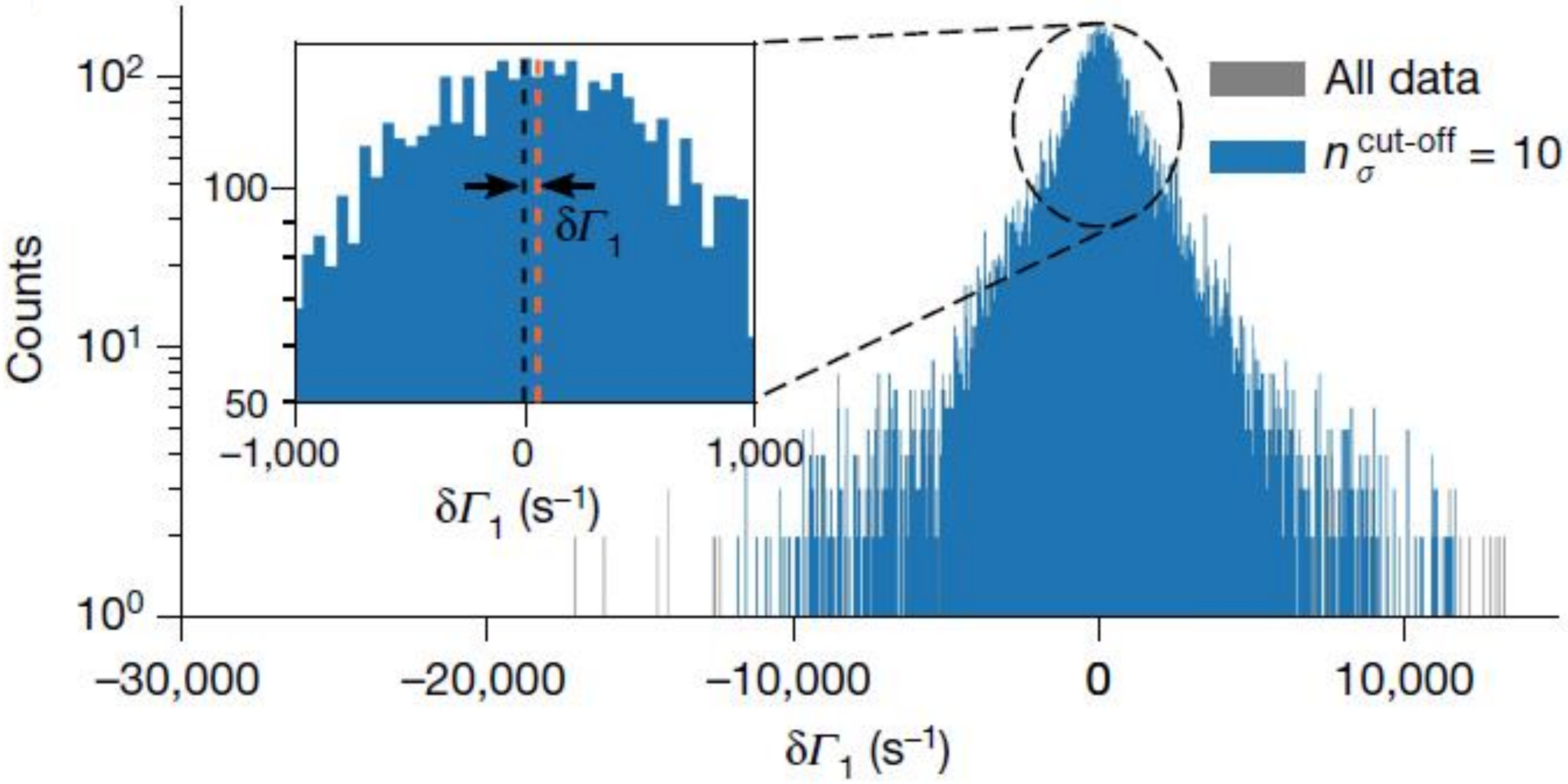


Cycle shield every 15 minutes due to slow drifts in decoherence rate much larger than signal



Experiment 2 results

Histogram of differences for 7 qubits



Very small but statistically significant ($p=0.006$) improvement in coherence time with lead shield

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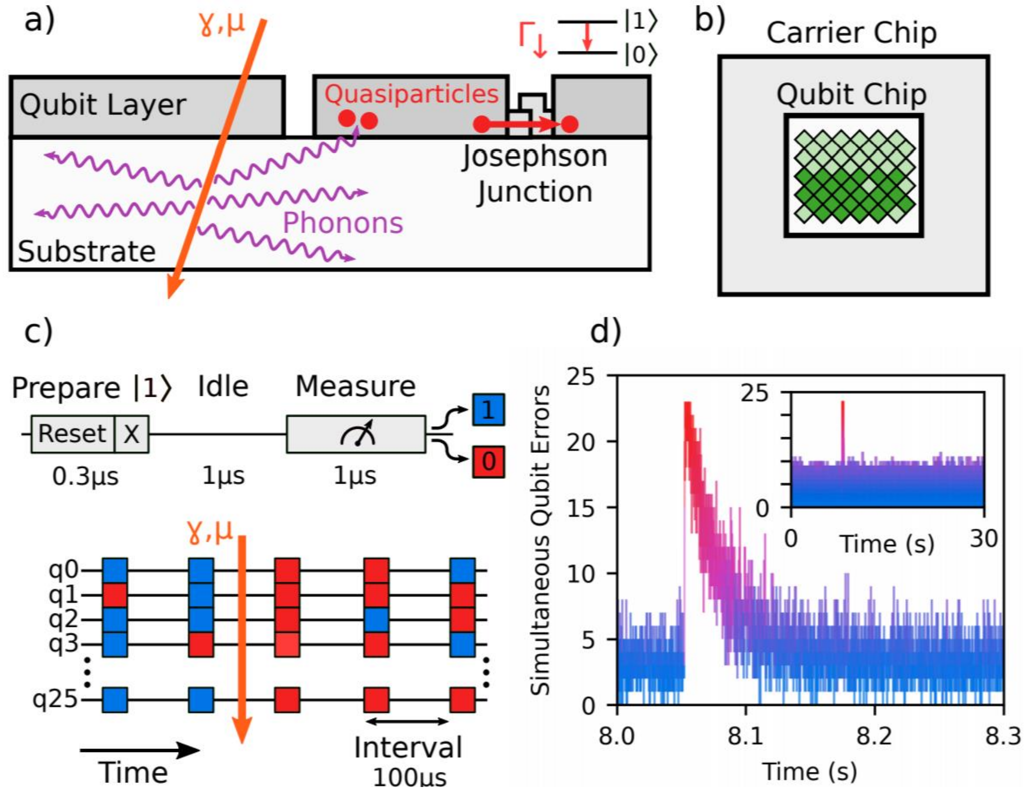
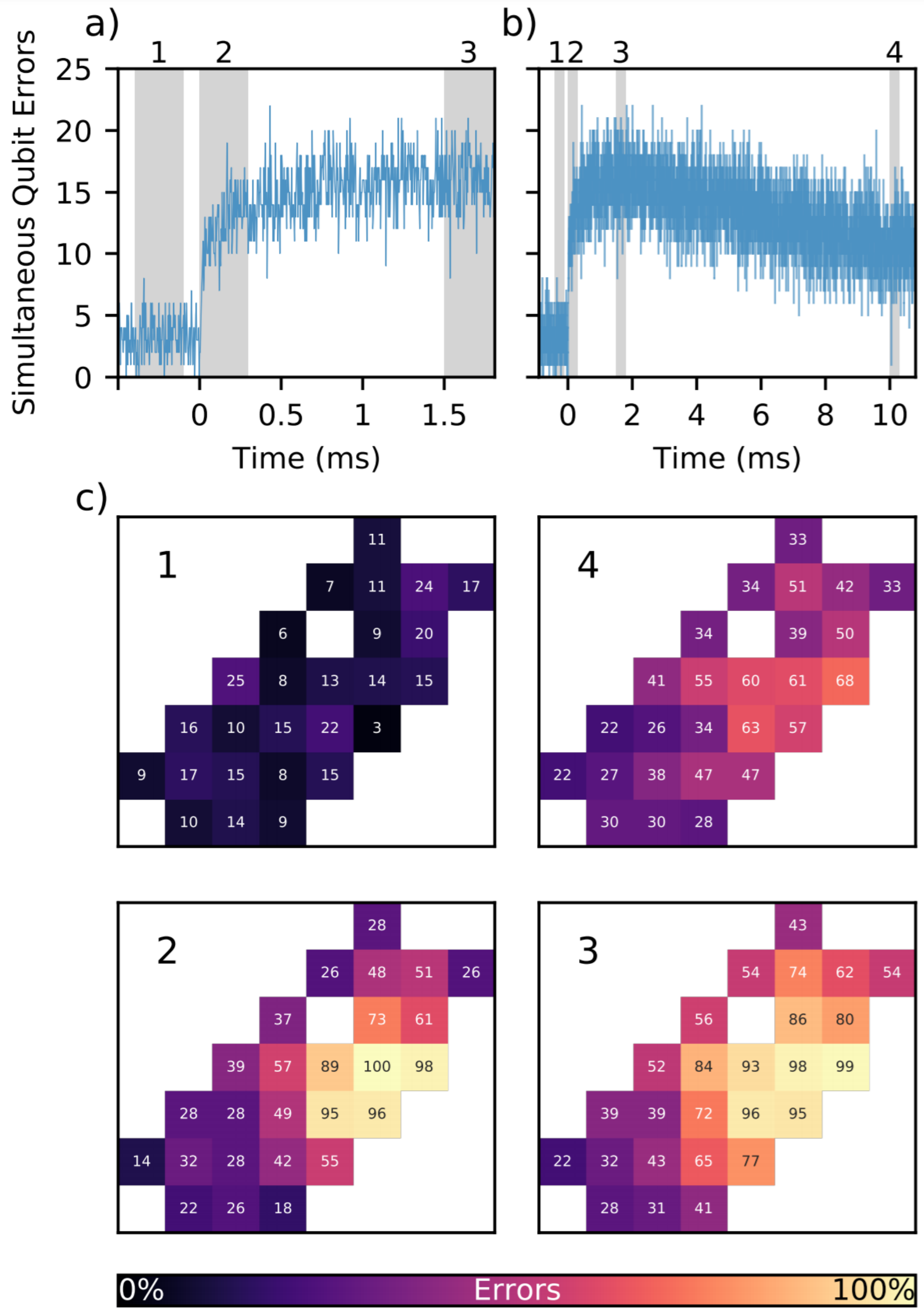
“Catastrophic error bursts”

https://arxiv.org/ftp/arxiv/papers/2104/2104.05219.pdf

- Simultaneously measure |1⟩ → |0⟩ bit-flip errors on 26 qubits every 100 us
- Bursts of correlated errors occur every ~10s, consistent with radiation interaction rate
- Time and space profile consistent with phonon + quasiparticle “cloud”





Existing quantum error correction algorithms require uncorrelated errors
Radiation defeats these schemes

How to move forward?

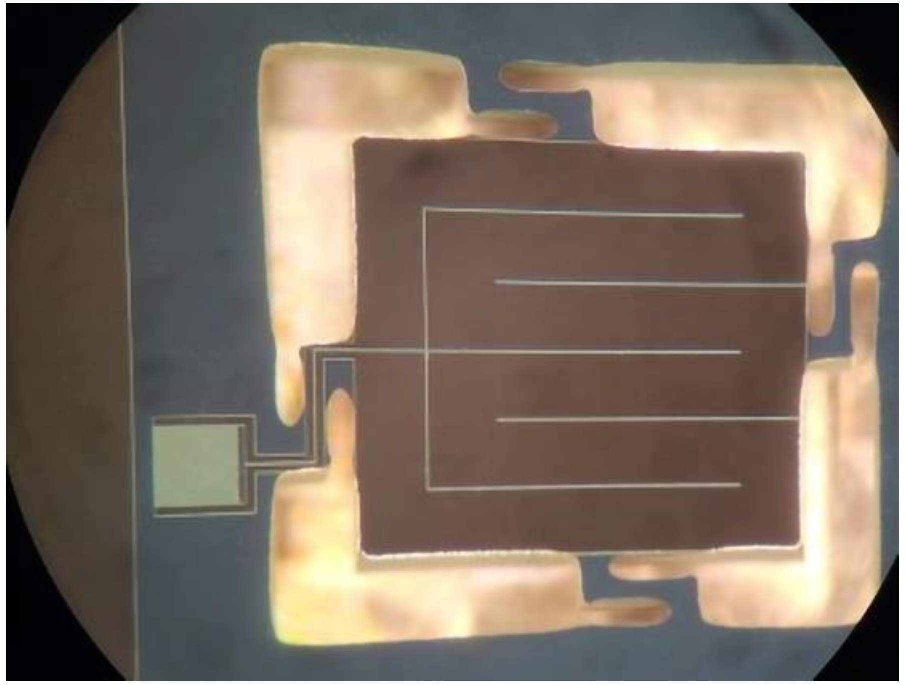
- Field is in infancy. Long term goals: EITHER:
  - Develop improved superconducting qubits insensitive to radiation* OR
  - Conclude that R&D focus should shift to other qubit technologies
  - *: stronger radiation sensitivity leads to better sensors
- To do that, need to:
  - More precisely understand the magnitude of the problem
  - Improve ability to model microphysical energy transfer (gamma photon > Compton electron > Cherenkov photon > e/h pairs > phonons > quasiparticles)
    - ✓ Spans ~10 orders of magnitude in energy
- To do that, we need:
  - New instrumentation
  - Control of background radiation -> underground shielded dilution refrigerators

Modeling capability: current status

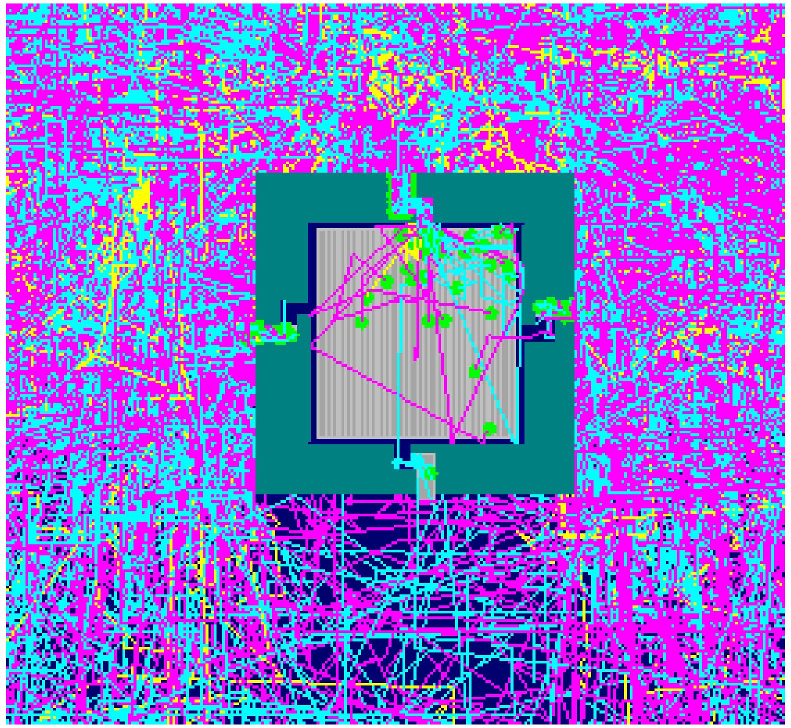
- SuperCDMS dark matter experiment leads modeling cryogenic phonon and charge propagation
- Large (~kg) Ge or Si crystals instrumented with multiple Transition Edge Sensors
- Phonons generate quasiparticles in aluminum fins that are collected in TES
- First-principles modeling capability and fidelity has advanced tremendously, but still requires substantial empirical tuning

Improving modeling capability

- Goal: predict behavior of any new device based on geometry, fab mask
- To get there, need a suite of simple, ad-hoc devices to help isolate and determine each of the many semi-empirical parameters
- Example:



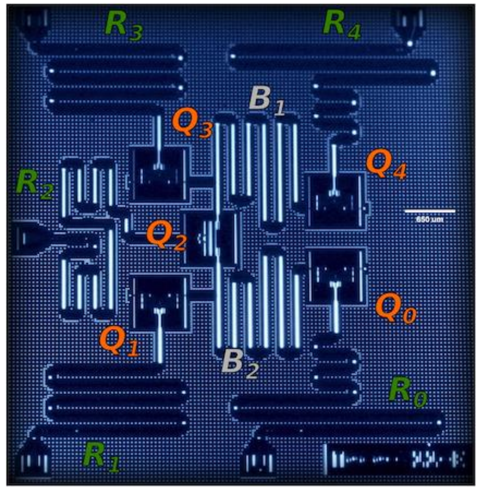
Energy-sensitive superconducting resonator on “island” made by NIST



Simulated phonon trajectories

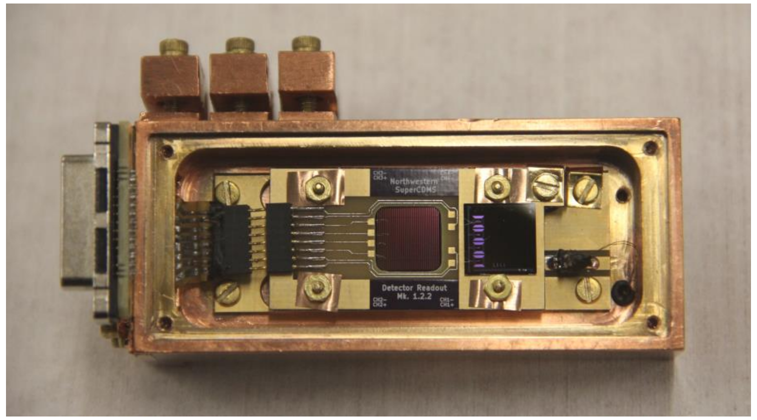
Qubit + calorimeter hybrid devices

- Qubits only give 0/1 reading. Instrumenting qubits with phonon/quasiparticle sensitive calorimeters will let us correlate errors to excitation density
- Also measure any negative effects of sensors on qubits
- Long-term: qubits packaged with a suite of sensors that all drive active fault mitigation

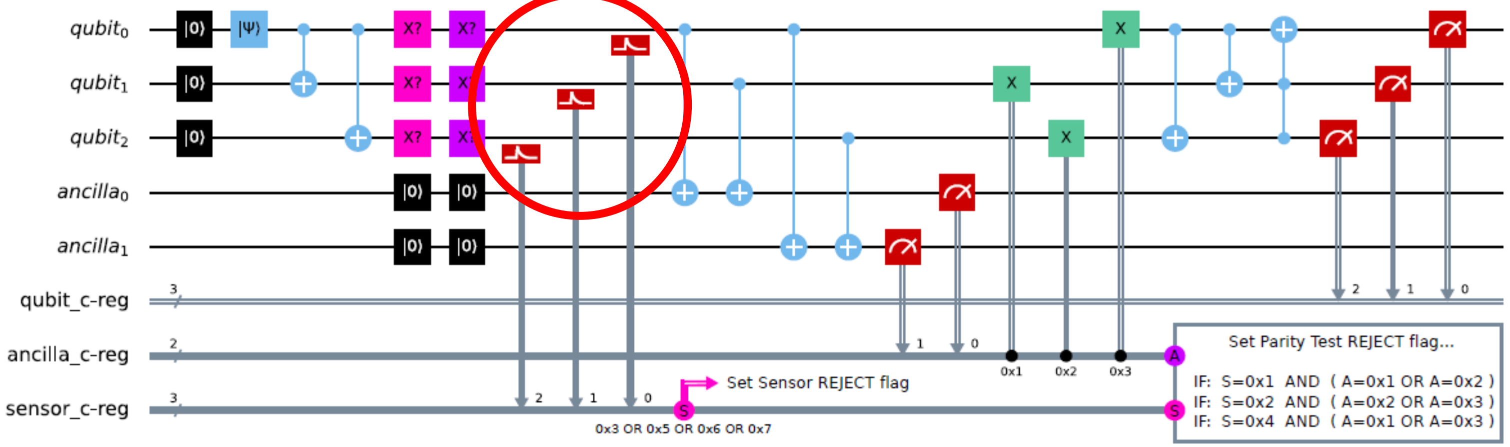


IBM 5 qubit circuit

+

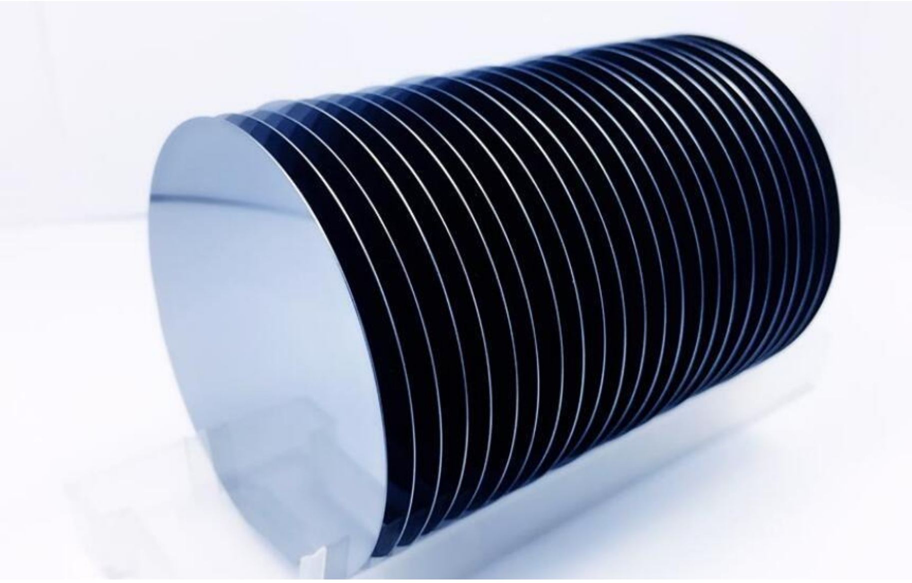

SuperCDMS cryogenic single-electron resolution particle detector

Classical sensor data incorporated into quantum error-correction circuit



In-situ sensing

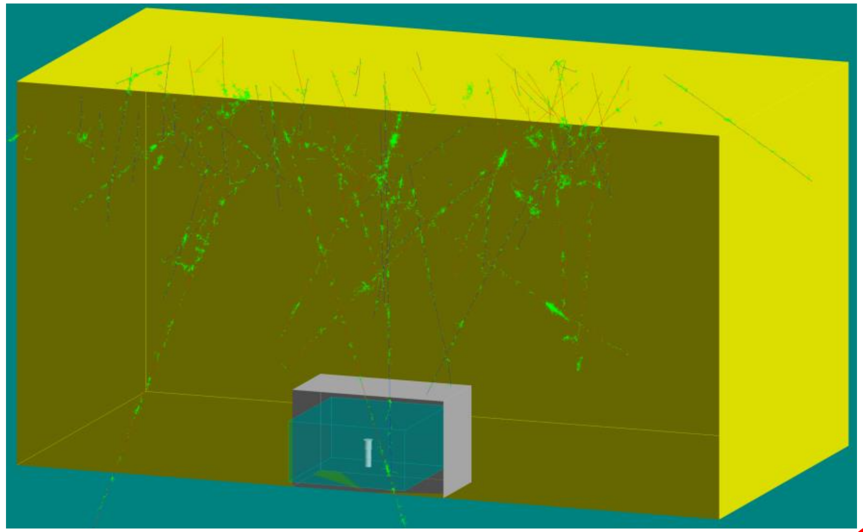
- Cryogenic calorimetry is an advanced art
- No off-the-shelf TESs or MKIDs, and they require significant expertise to make them work
- Almost no overlap in people with that expertise and people studying QIS
- PNNL developing low-cost in-situ cosmic ray veto based on (noisy) silicon charge detector coincidence



Low background quantum computing facilities

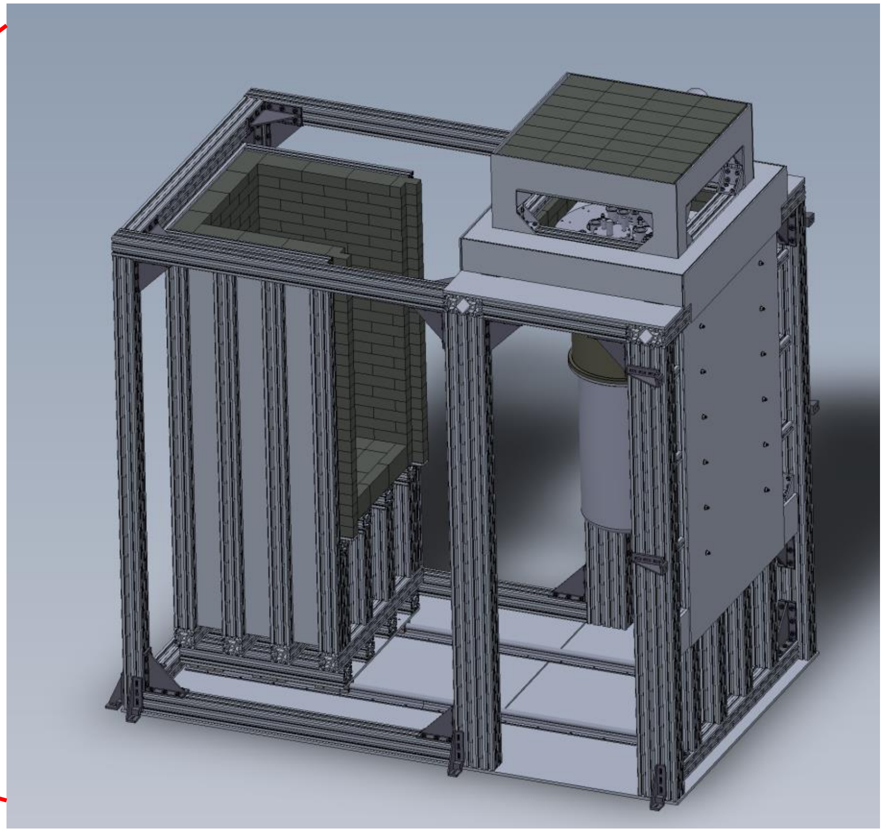
- Currently, radiation is subdominant contribution to error rates
- Becoming an ever-larger piece of the pie
- Underground, shielded dilution refrigerators will help
  - Better control radiation to help radiation-focused studies
  - Reach past radiation-dominated scales to identify the *next* issue
- In my view, this is an R&D-only need. Commercial-scale quantum computing in underground shielded locations will never be cost-effective
  - Again, the solution is to build a better device

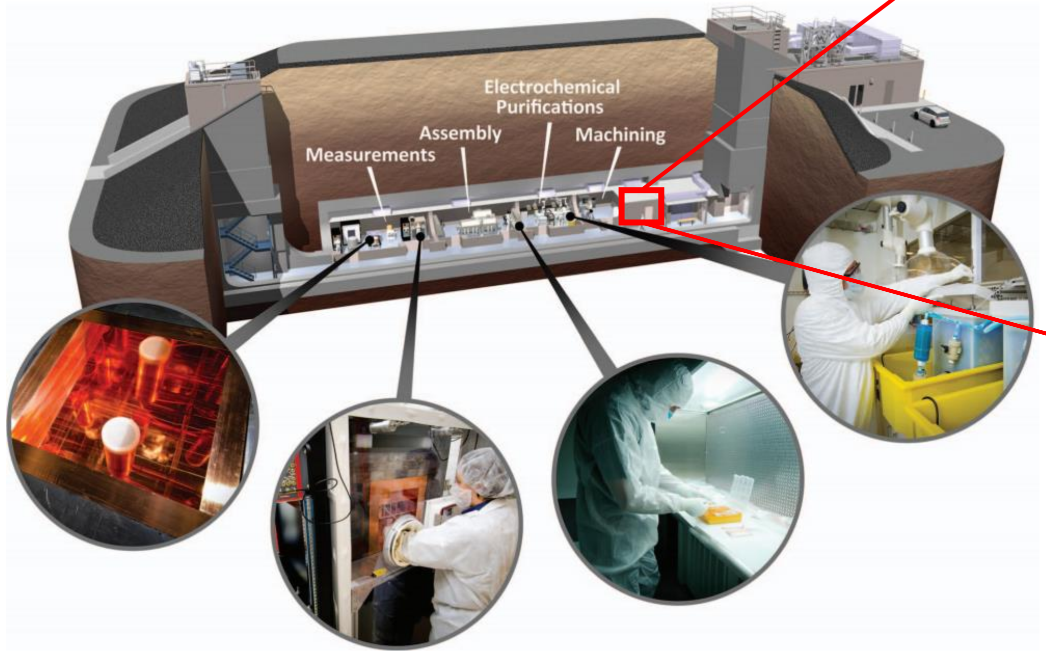
PNNL Low Background Dilution Refrigerator Operational by Fall 2022



19m overburden reduces cosmic rays by ~85%

Lead shield reduces external gammas by ~99.5%





Underground space houses cleanroom and world class ultra pure materials facility

Estimate internal backgrounds at ~10% level
-> to benefit from going much deeper/better shield, need to have a low-background dil fridge!

CUTE @ SNOLAB
Cryogenic Undergound Test Facility

Features:

Operational temperature as low as 15 mK

Low overall radioactive background

Minimal mechanical vibrations

Low level of electromagnetic interference

Availability of calibration sources (gamma and Fe55, neutron soon)

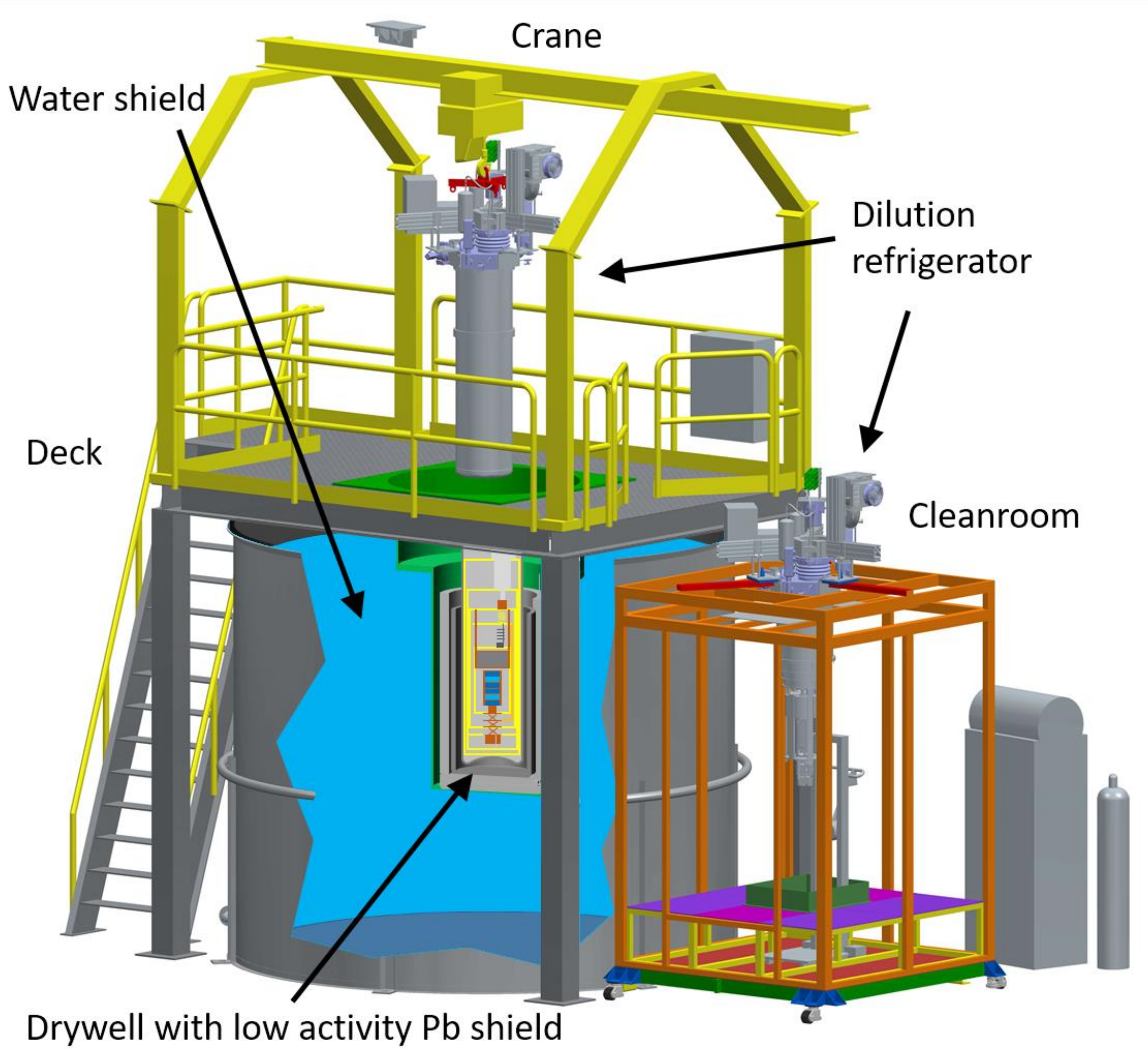
Low-radon cleanroom space to change payload

SNOLAB User Facility maintained and continuously improved

Near term use: SuperCDMS detector testing
MoU in place with SuperCDMS

Future use: proposal-based; expect to start soon

CUTE @ SNOLAB
Cryogenic Undergound Test Facility



1.5 m water shield

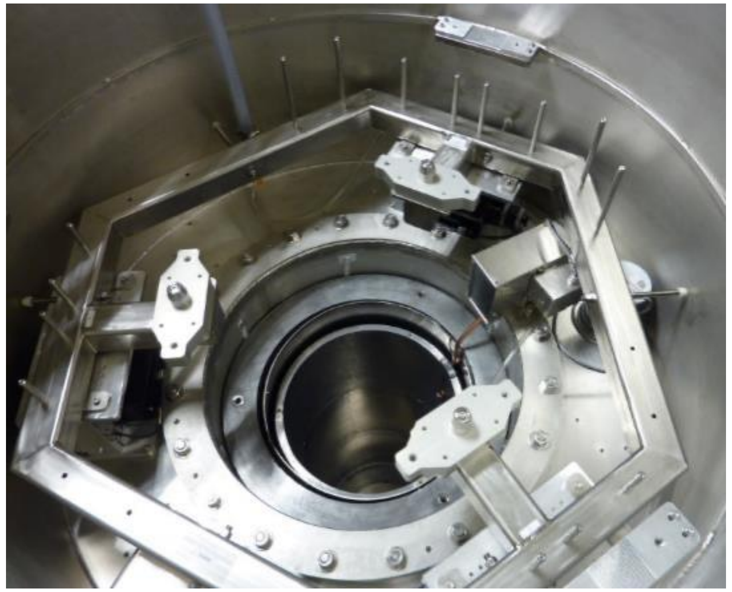
~10 cm of low activity lead

20 cm of polyethylene lid

MuMetal and copper shields

15 cm of internal lead plug + copper box

Total background: ~5 cts/kg/keV/day



Conclusions

- Understanding and mitigating superconducting device sensitivity to radiation (and other source of “quasiparticle poisoning”) is highly active right now
  - Could lead to major shifts in entire QIS industry in favor of different technology
  - Also affects advanced sensors e.g. for very low mass dark matter detection
- Need for in-situ sensors (not just radiation, but also magnetic fields, microwave, IR, etc.) to correlate to quantum device performance
- Lots of interesting research can be done in shallow underground facilities
- Benefitting from deeper sites much more complicated than just putting an off-the-shelf dil fridge underground; need dedicated low background facilities like CUTE

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Thank you