Pacific Northwest
NATIONAL LABORATORY

# Ionizing Radiation and Superconducting Qubits

## Improving qubits using Nuclear Physics techniques

**Ben Loer**
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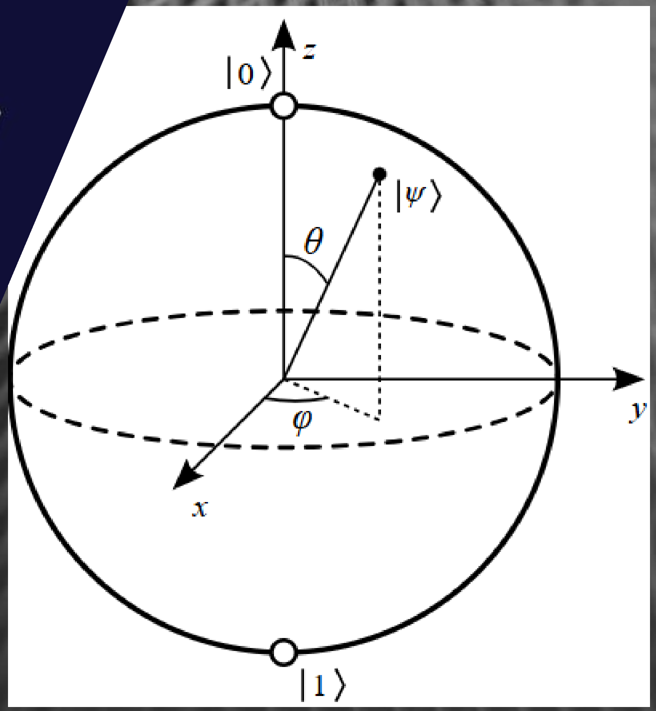


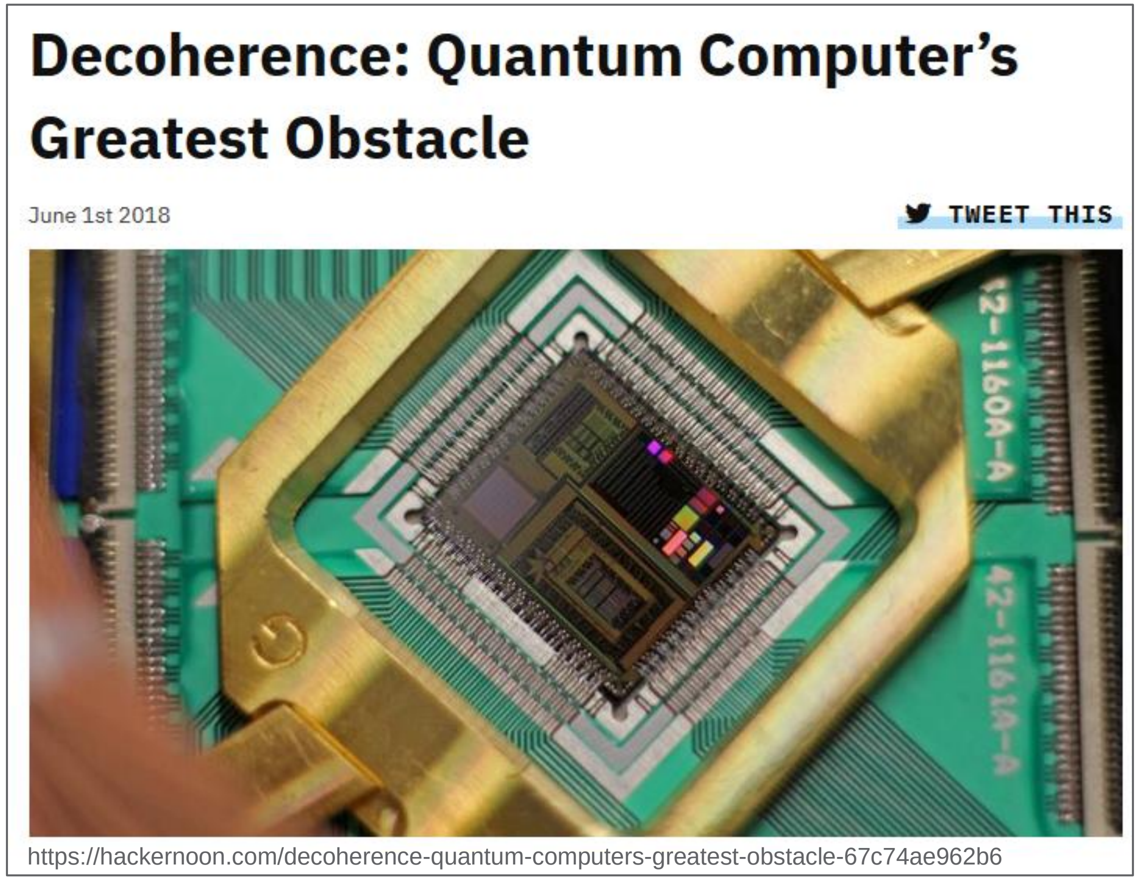
PNNL is operated by Battelle for the U.S. Department of Energy

# Outline

- Typical background radiation threatens superconducting qubit performance
- Protecting qubits from ionizing radiation
- What are the dominant sources?
- PNNL’s Low Background Cryogenic Facility

# Decoherence

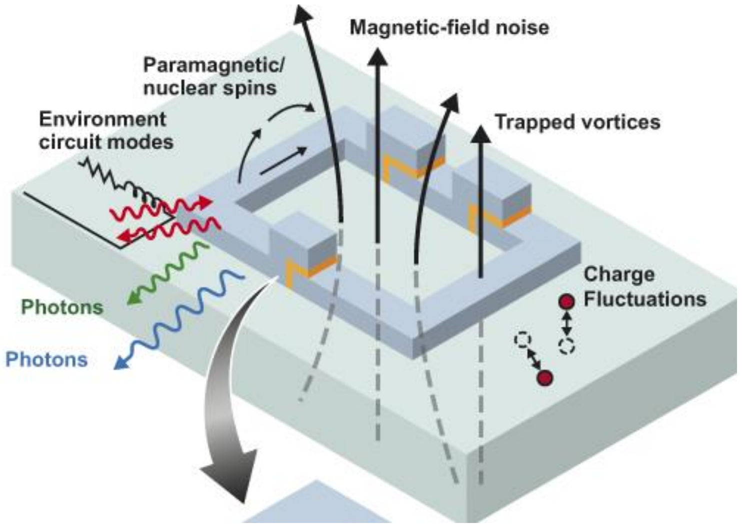
- One limit on quantum computing is finite coherence times – how long can the system remain in an isolated superposition state $(|0\rangle + |1\rangle)$ ?
- Decoherence can be caused by any interaction with the environment
- Lots of sources, some well-understood, some not
- An elephant in the room: Ultra 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)



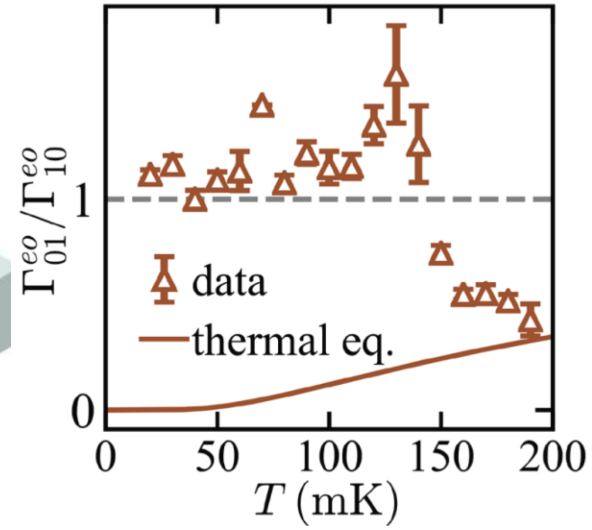
**Decoherence: Quantum Computer's Greatest Obstacle**

June 1st 2018

https://hackernoon.com/decoherence-quantum-computers-greatest-obstacle-67c74ae962b6



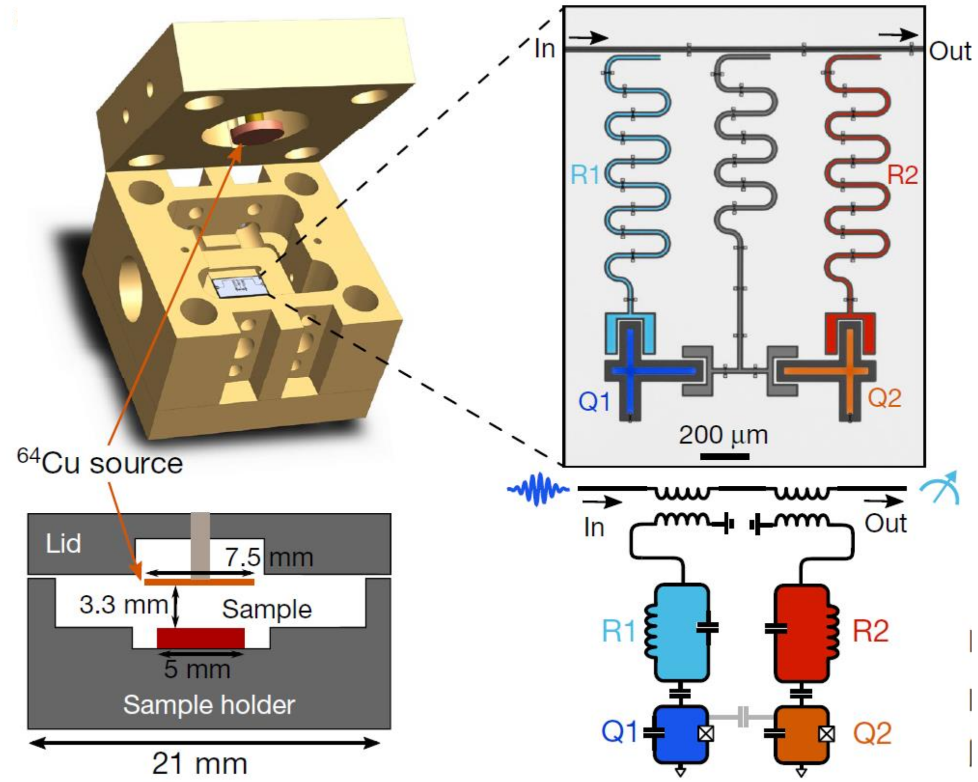
https://doi.org/10.1557/mrs.2013.229



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

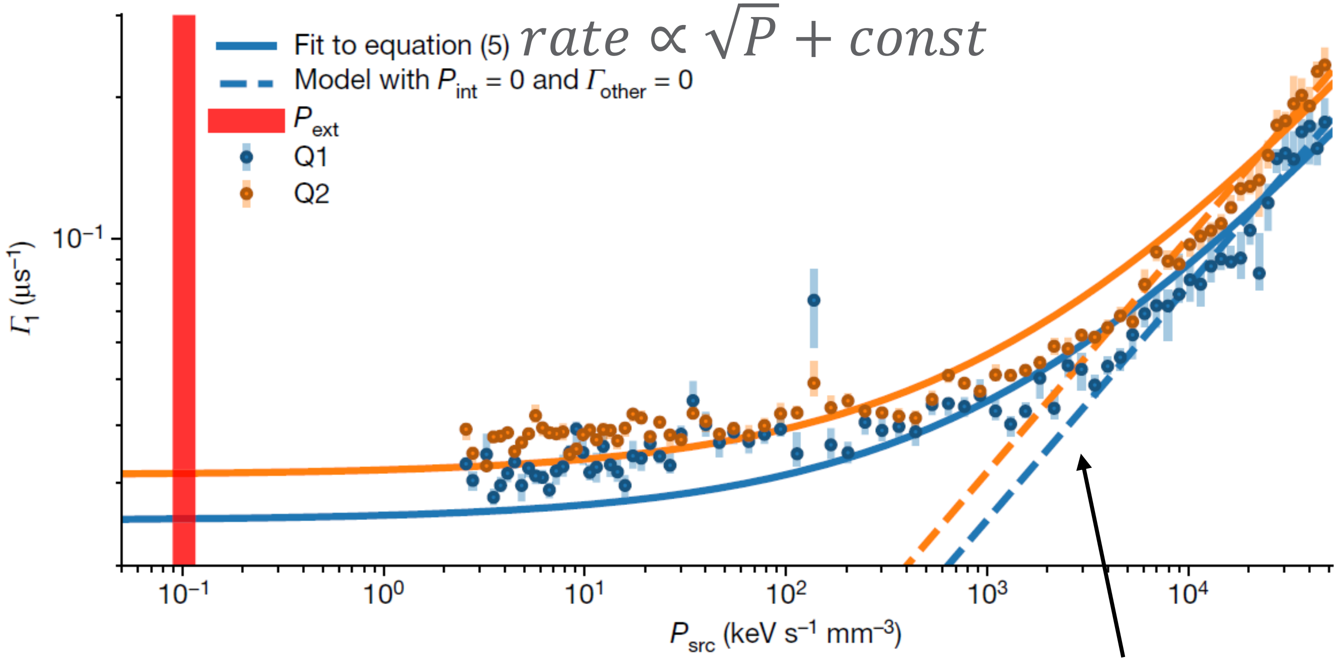
# Background ionizing radiation limits superconducting qubit coherence

- Qubits exposed to a radioactive source have decreased coherence times
- Projection to ambient background gives limit of few ms



Vepsäläinen, A. P. *et al.* Impact of ionizing radiation on superconducting qubit coherence. *Nature* **584**, 551–556 (2020).

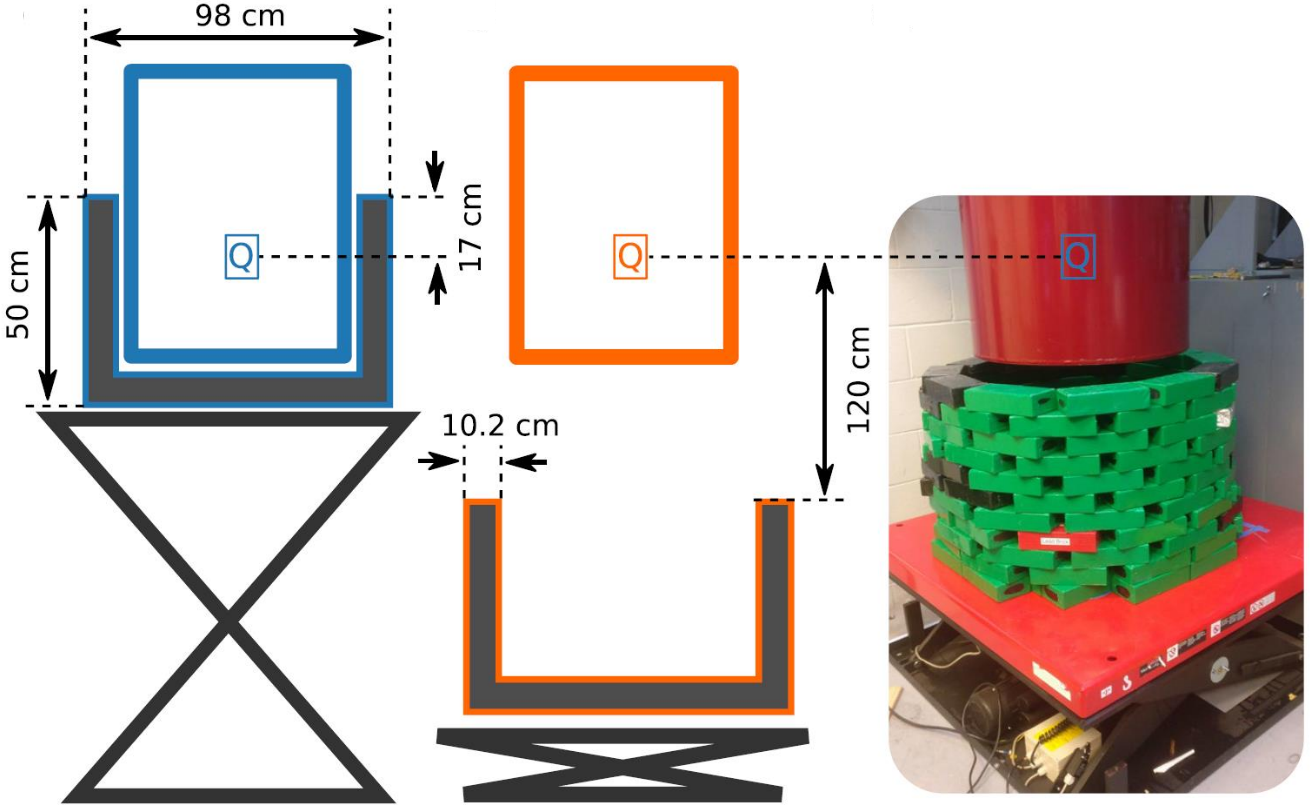
Qubit Decoherence rate vs radiation power

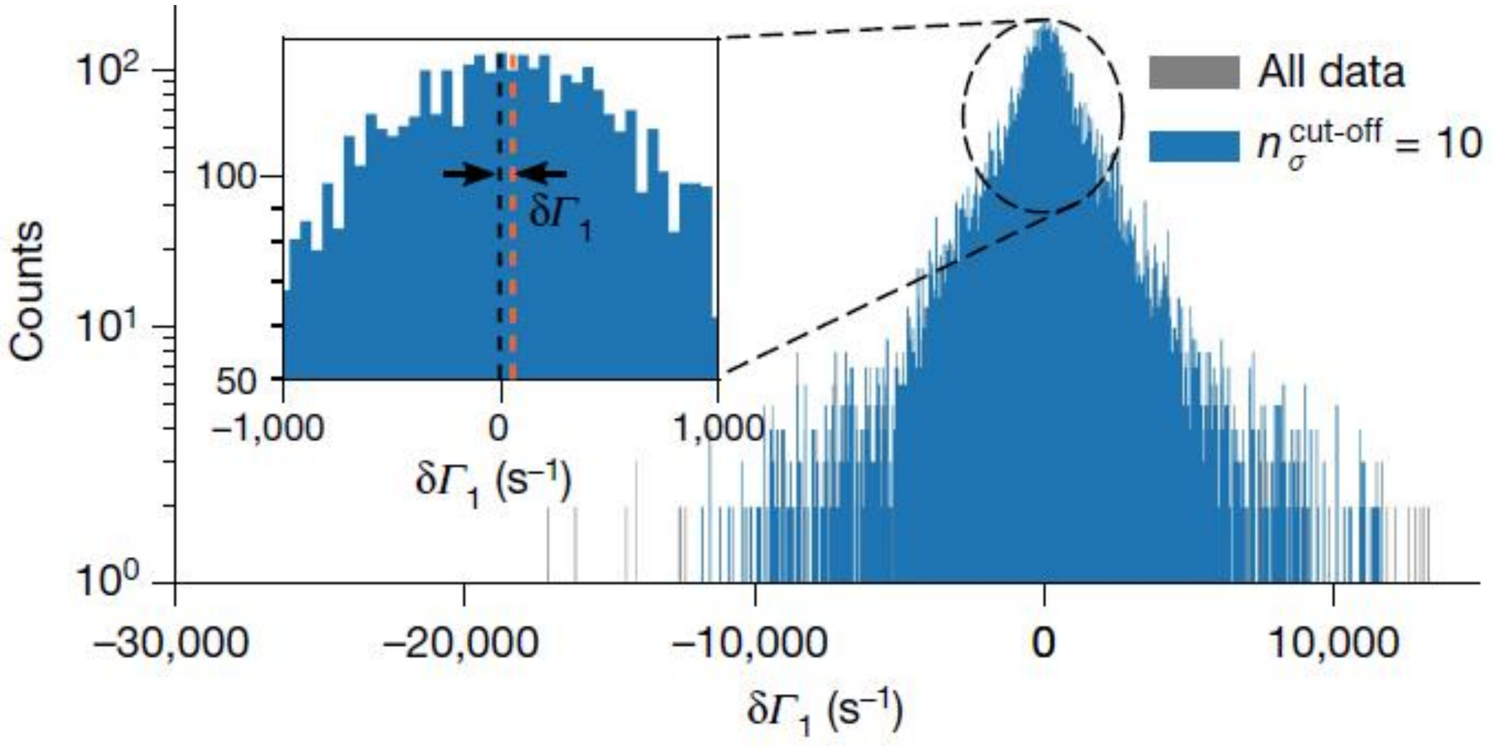


Expectation if radiation dominates

# Background ionizing radiation limits superconducting qubit coherence

- A lead shield that reduces external radiation dose by ~46% very slightly improved coherence times of qubits with $T_1 \sim 40\mu s$
- As coherence times improve, radiation will be a larger part of the error rate

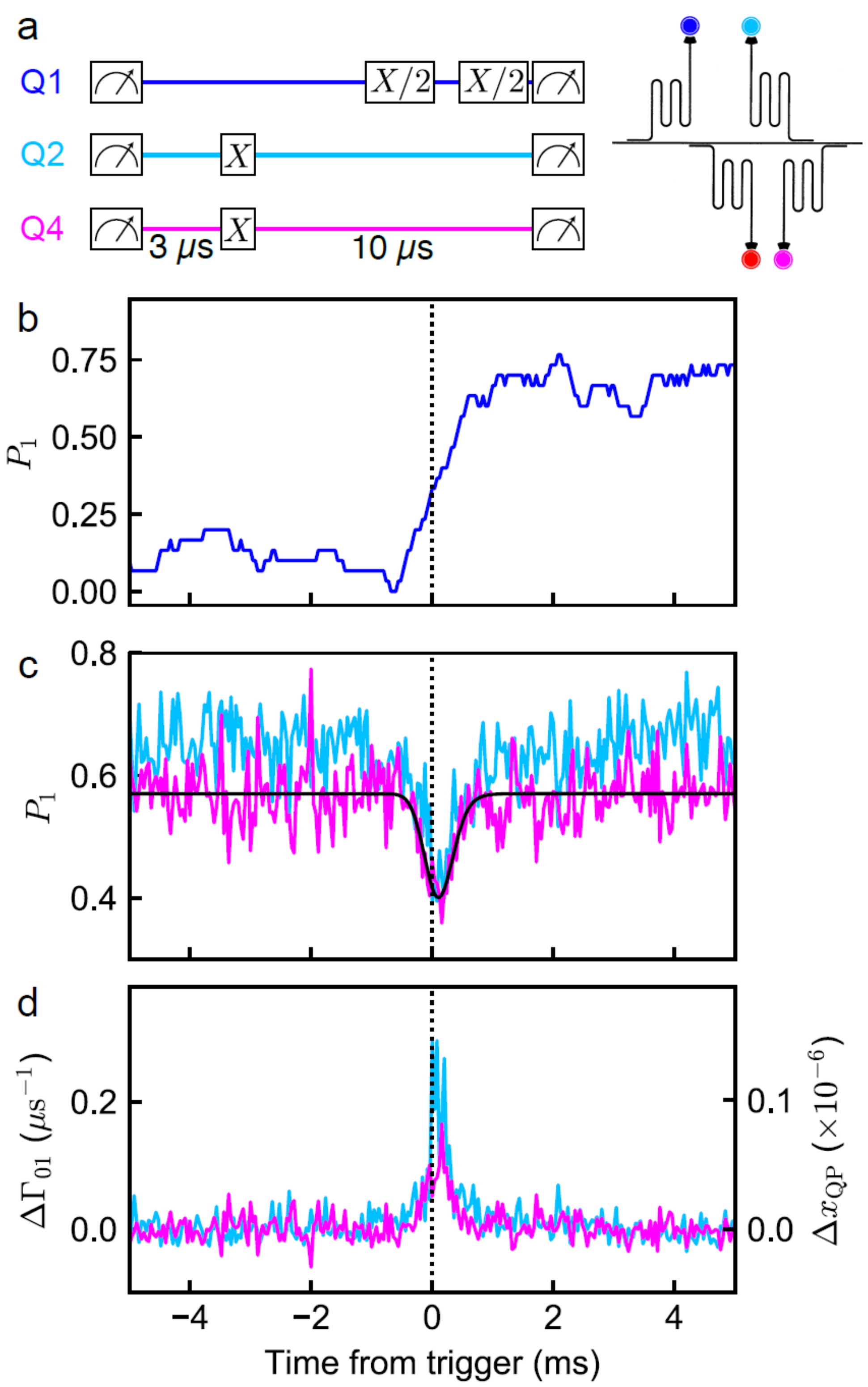




Vepsäläinen, A. P. *et al.* Impact of ionizing radiation on superconducting qubit coherence. *Nature* **584**, 551–556 (2020).

# Correlated qubit decoherence

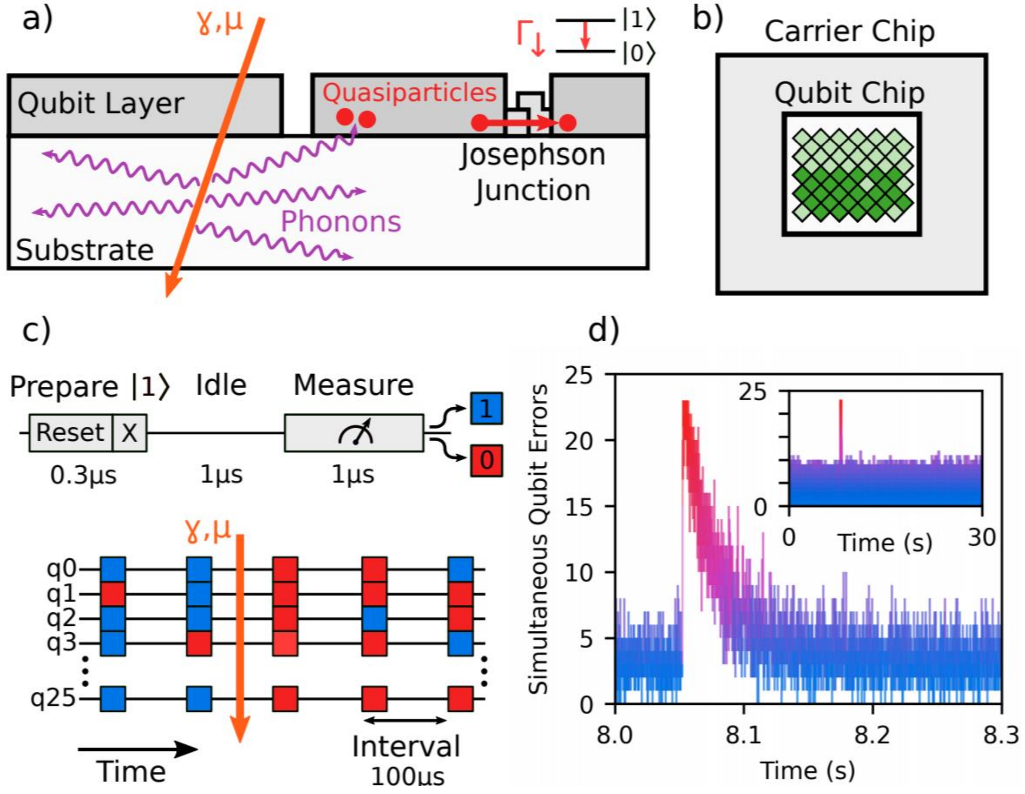
- One offset-charge-sensitive qubit acts as radiation sensor
- Measured time-correlated increase in decoherence rate in 2 neighbors

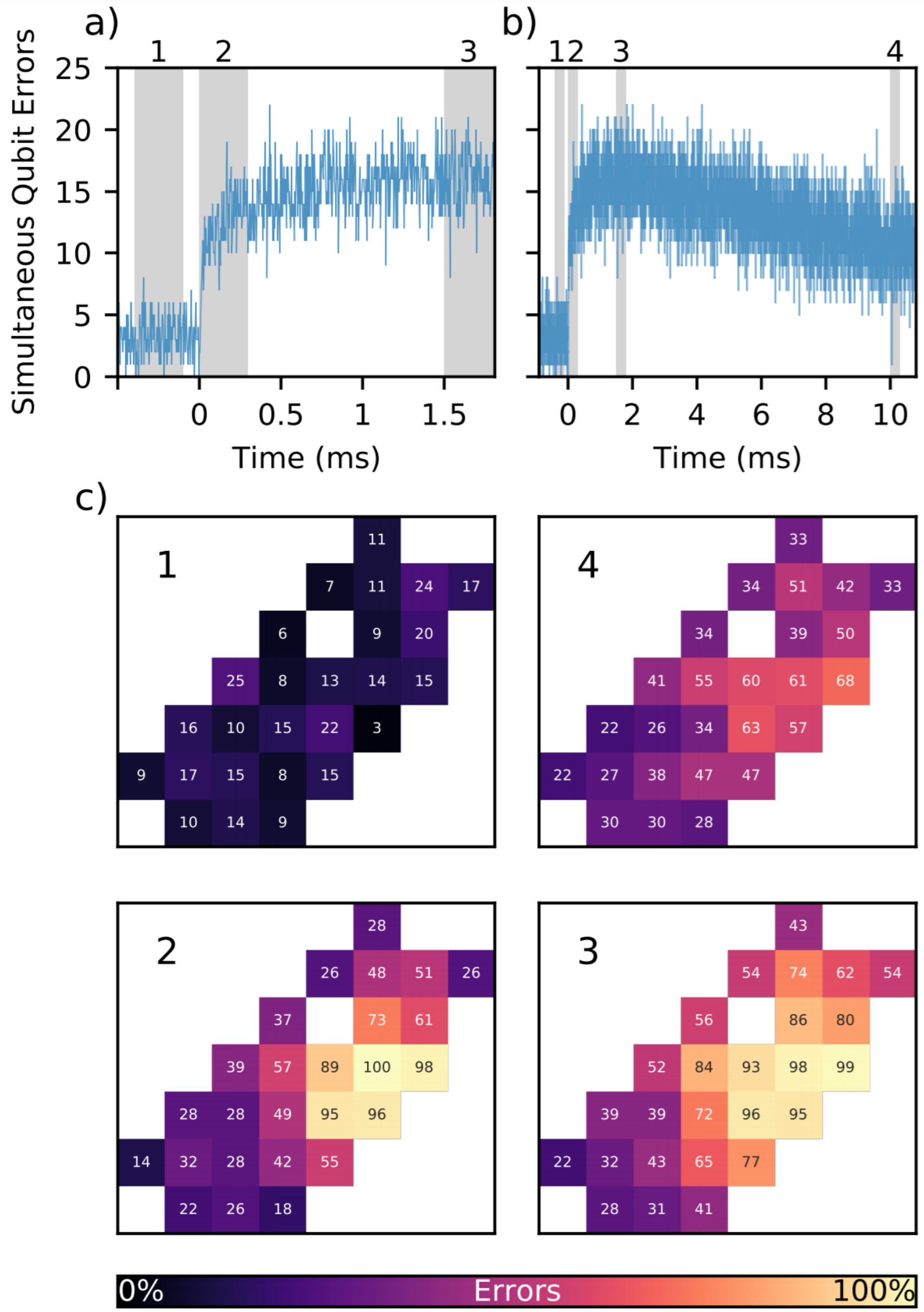


“Correlated Charge Noise and Relaxation Errors in Superconducting Qubits”
Wilen et al. Nature **594,** 369 (2021)

# “Catastrophic error bursts”

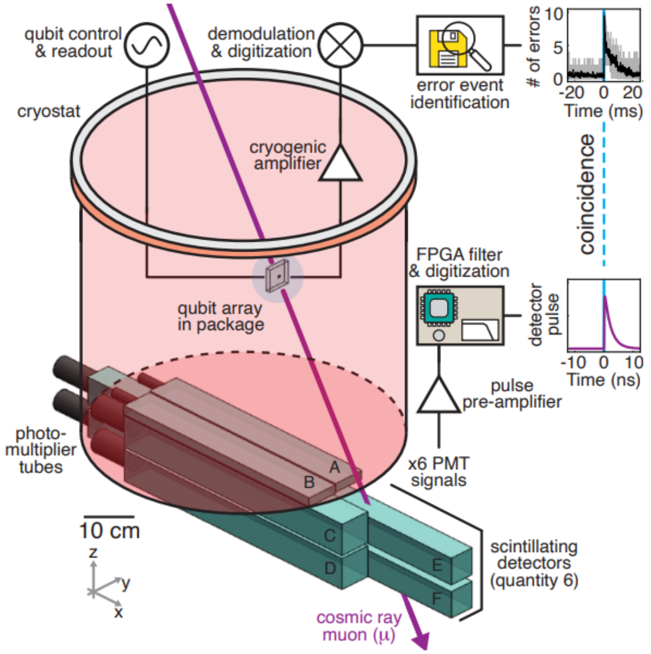
- Simultaneously measure |1⟩ → |0⟩ bit-flip errors on 26 qubits every 100 us
- Bursts of correlated errors occur every ~10s, consistent with radiation interaction rate
- Time and space profile consistent with phonon + quasiparticle “cloud”

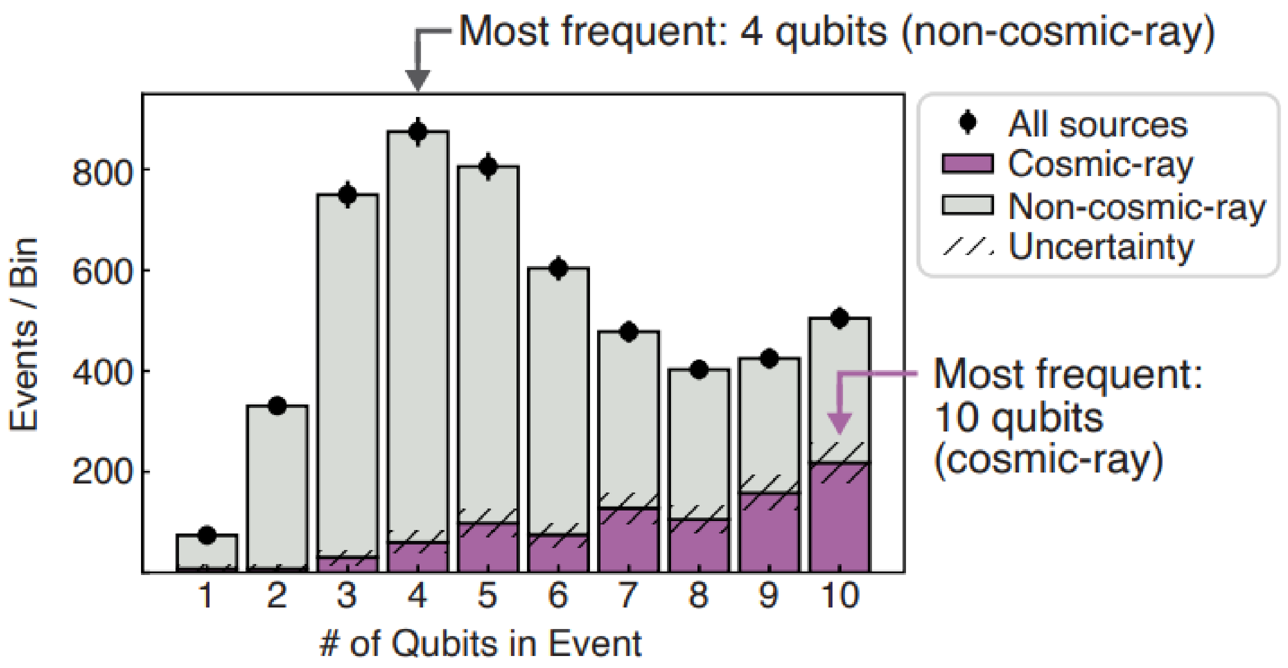


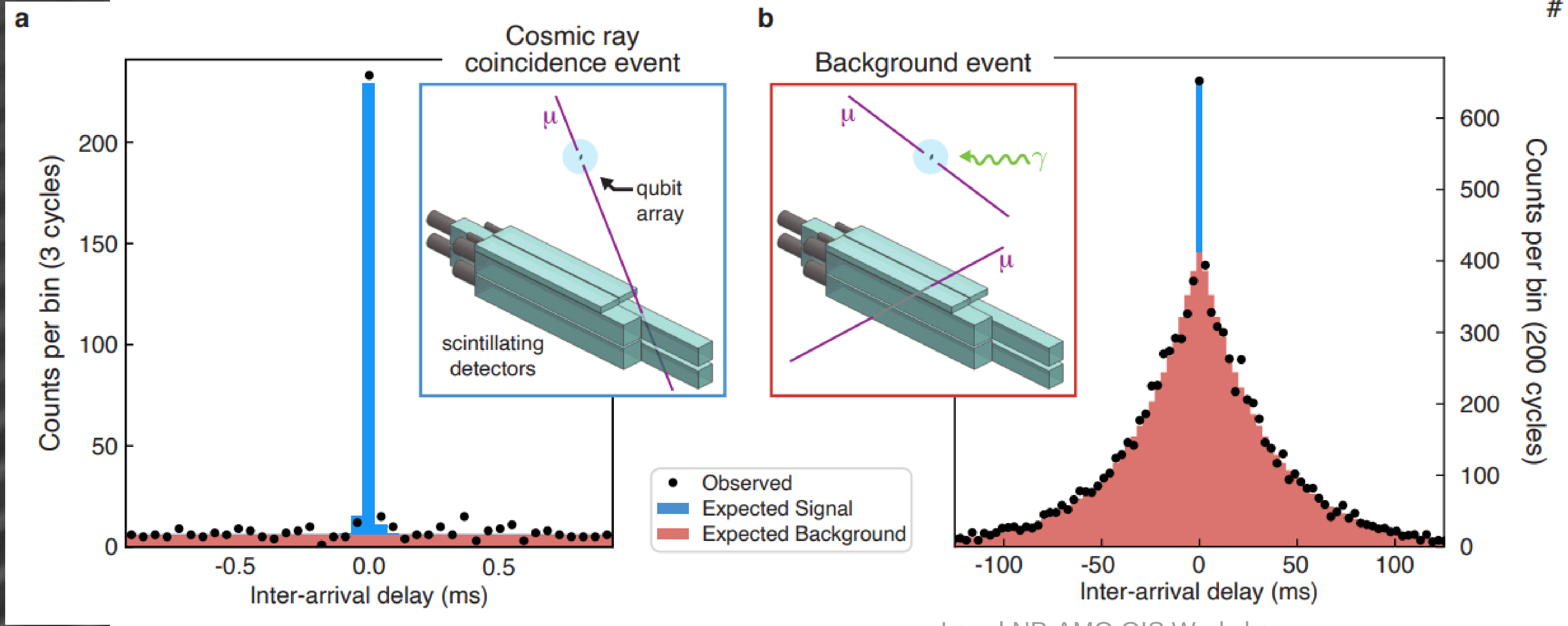


McEwen et al. “Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits.” Nature Physics **18**, 107 (2022)

# Errors and cosmic rays



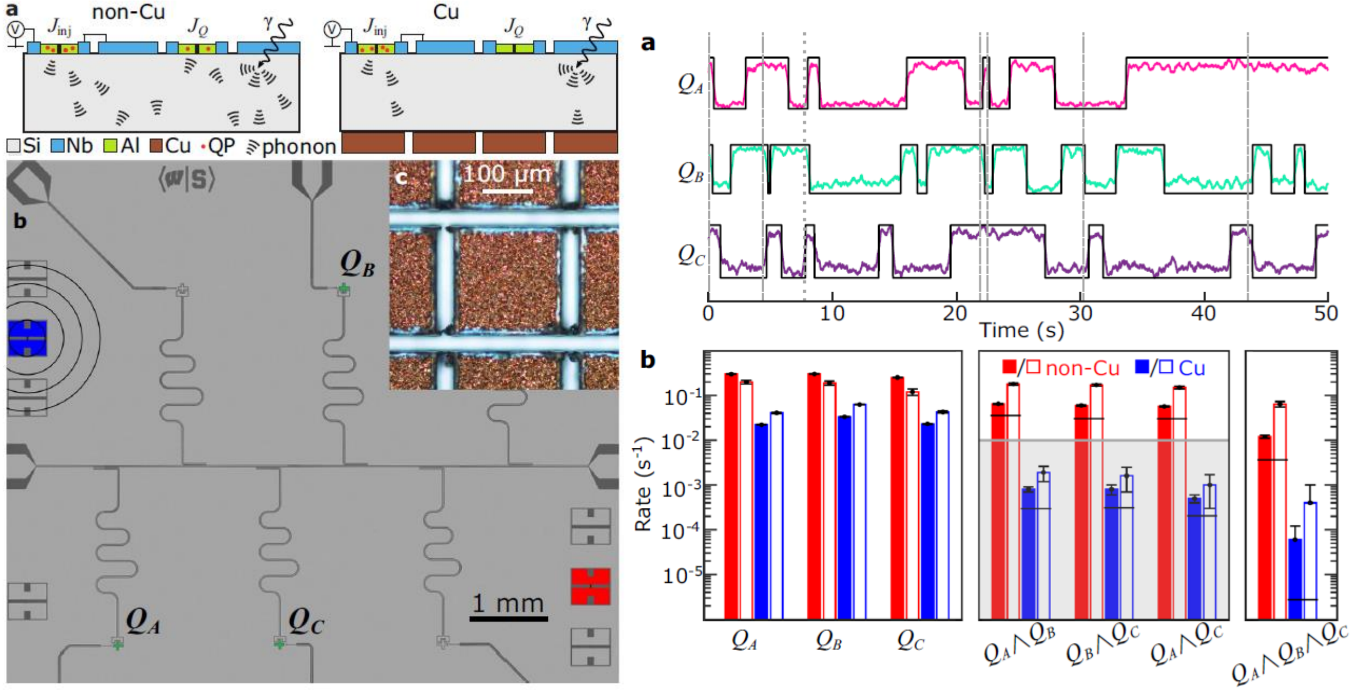




Harrington et al. “Synchronous Detection of Cosmic Rays and Correlated Errors in Superconducting Qubit Arrays”. arXiv:2402.03208

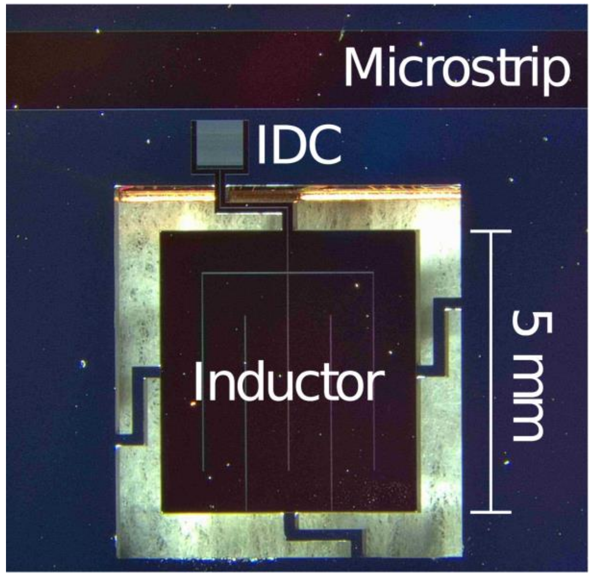
Xue-Gang Li et al. “Direct evidence for cosmic-ray-induced correlated errors in superconducting qubit array.” arXiv:2402.04245

# Phonon Protection



Normal metal on backside rapidly downconverts phonons to below superconducting gap

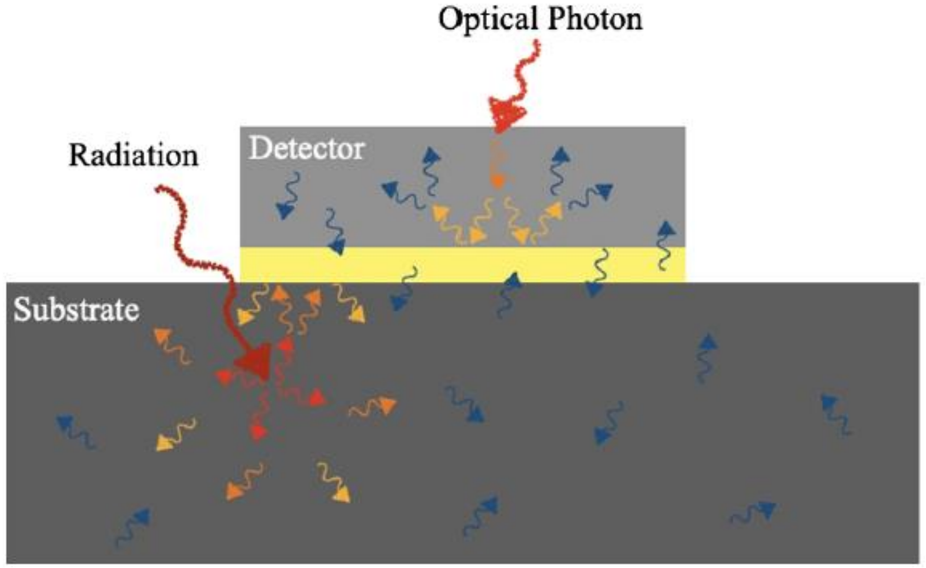
Iaia et al. “Phonon downconversion to suppress correlated errors in superconducting qubits.” Nature Communications **13**, 6425 (2022)



Physically isolate the active elements from the rest of the substrate

Fowler et al. “Spectroscopic Measurements and Models of Energy Deposition in the Substrate of Quantum Circuits by Natural Ionizing Radiation”. PRX Quantum **5** 040323 (2024)

See Paul Szypryt’s talk next

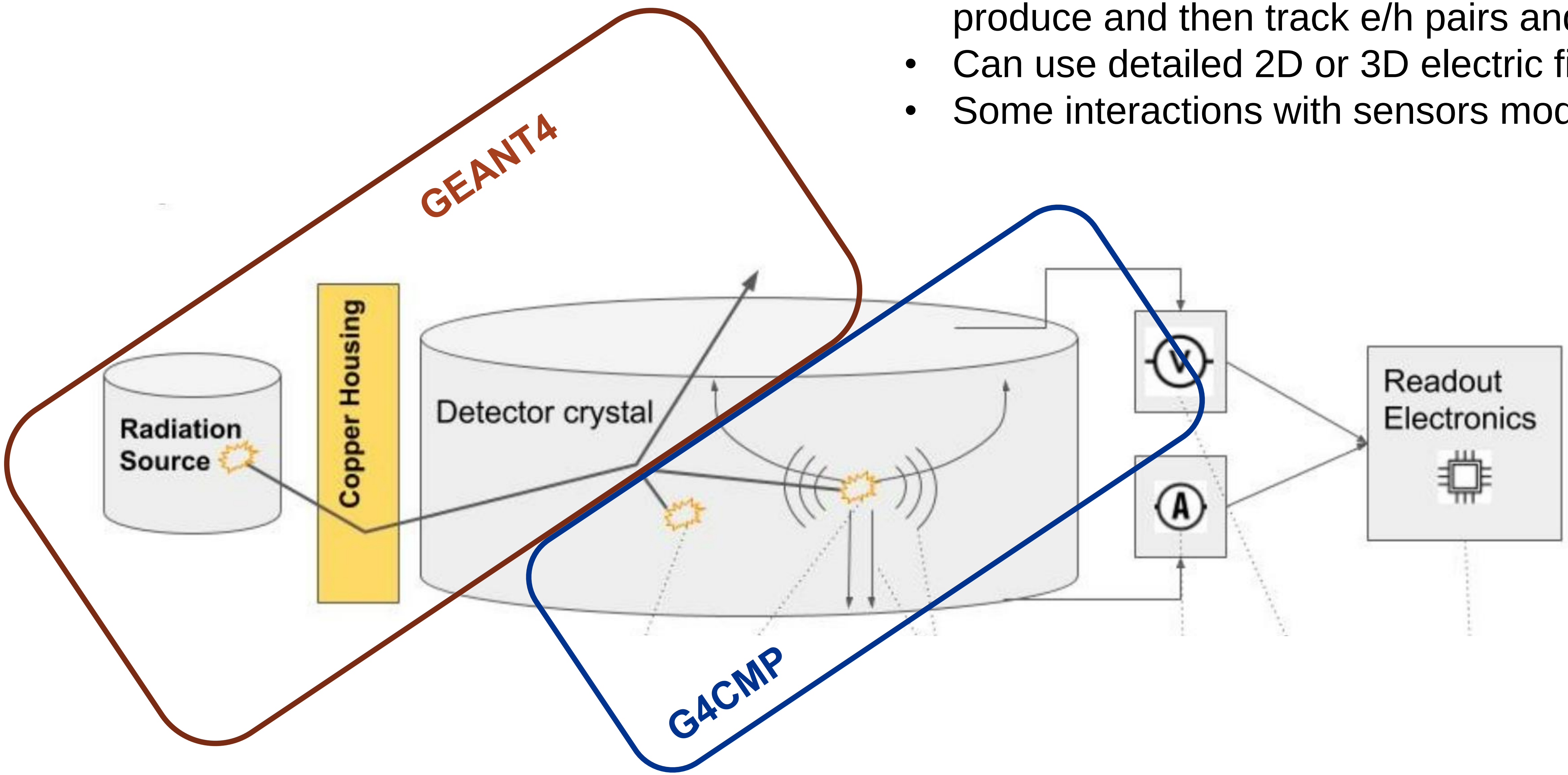


Zobrist et al. “Membraneless Phonon Trapping and Resolution Enhancement in Optical Microwave Kinetic Inductance Detectors”. Phys. Rev. Lett. **129**, 017701 (2022)

# Modeling phonon and charge transport with G4CMP (Condensed Matter Physics)

https://github.com/kelseymh/g4cmp

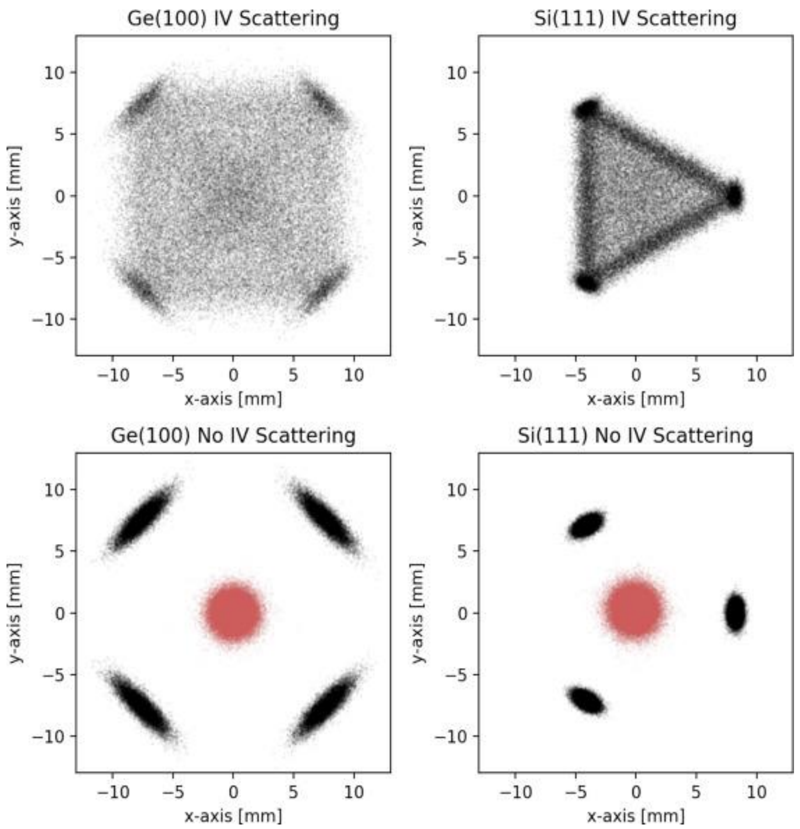
- G4CMP takes energy deposits from GEANT4 to produce and then track e/h pairs and phonons
- Can use detailed 2D or 3D electric field meshes
- Some interactions with sensors modeled

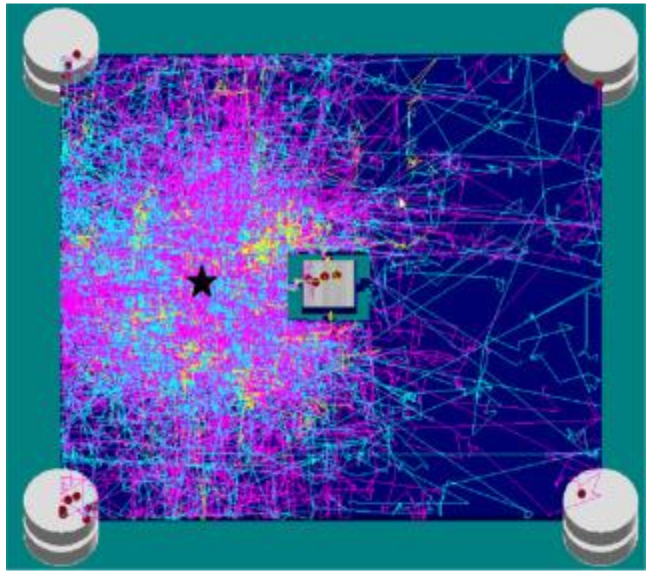


# What is G4CMP?

Kelsey et al. “G4CMP: Condensed matter physics simulation using the GEANT4 toolkit”. NIM A 1055 (2023) 168473

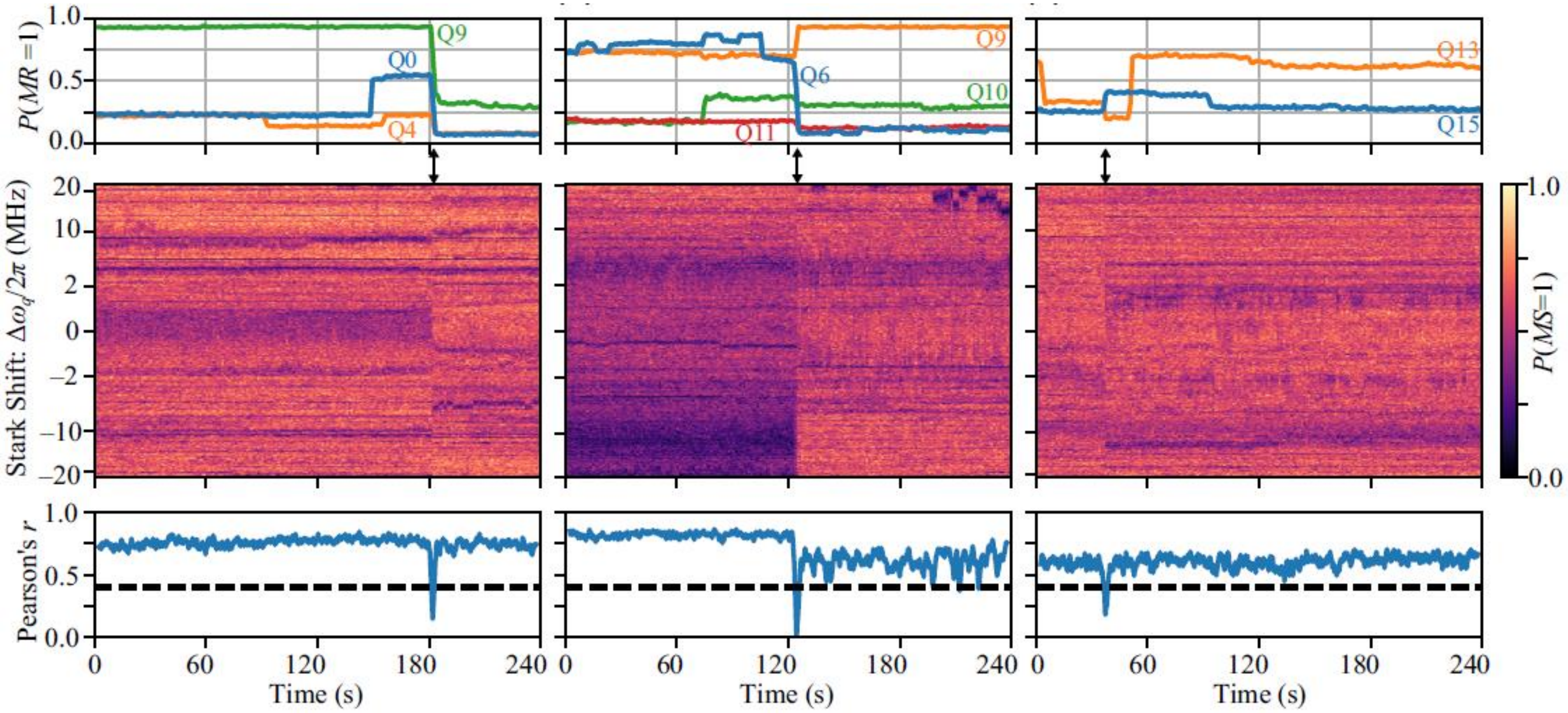
- Software library that extends GEANT4 particle transport to include phonons and electron/hole pair propagation in semiconductor crystals
- Models *athermal, transient* excitations
- Similar in some ways to treatment of optical photons in GEANT4:
  - Based on well-understood condensed matter physics models
  - but requires many empirical values especially for surface interactions
- Built-in parameterizations for Ge and Si
  - Still need to specify parameters like charge trapping mean free paths





# Two Level Systems

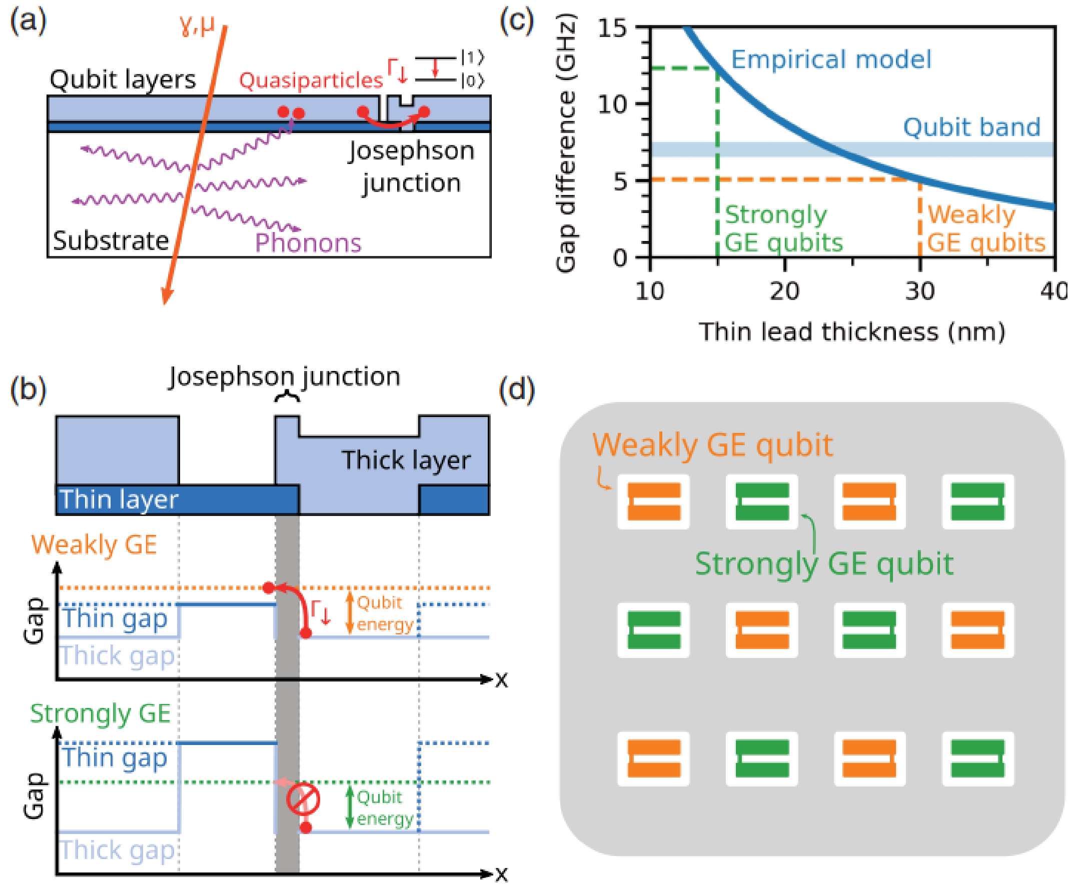
- Beyond prompt response: observed correlated jumps in two-level-system spectroscopy on IBM qubits

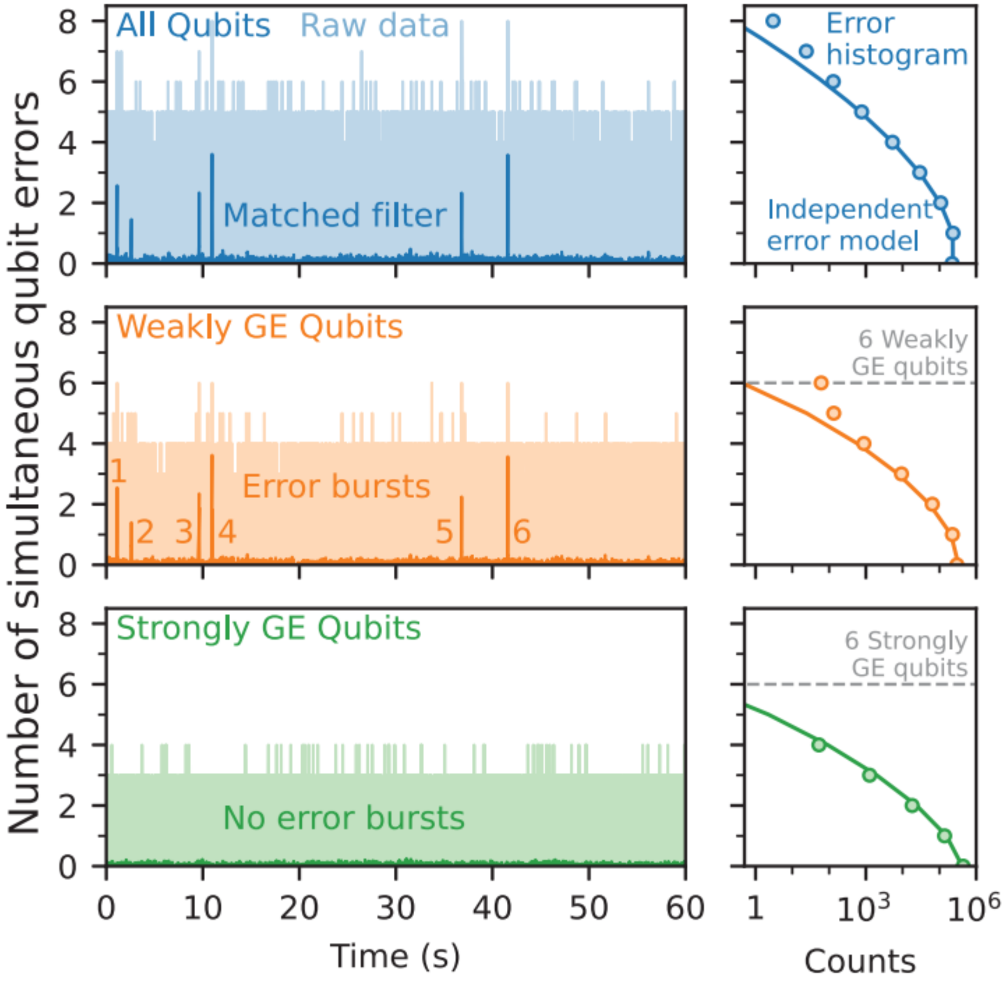


Thorbeck *et. al.* “Two-Level-System Dynamics in a Superconducting Qubit Due to Background Ionizing Radiation.” PRX Quantum **4**, 020356 (2023)

# Gap Engineering

- Asymmetric Josephson junctions raise the barrier above the qubit excitation energy. Significantly reduces quasiparticle poisoning



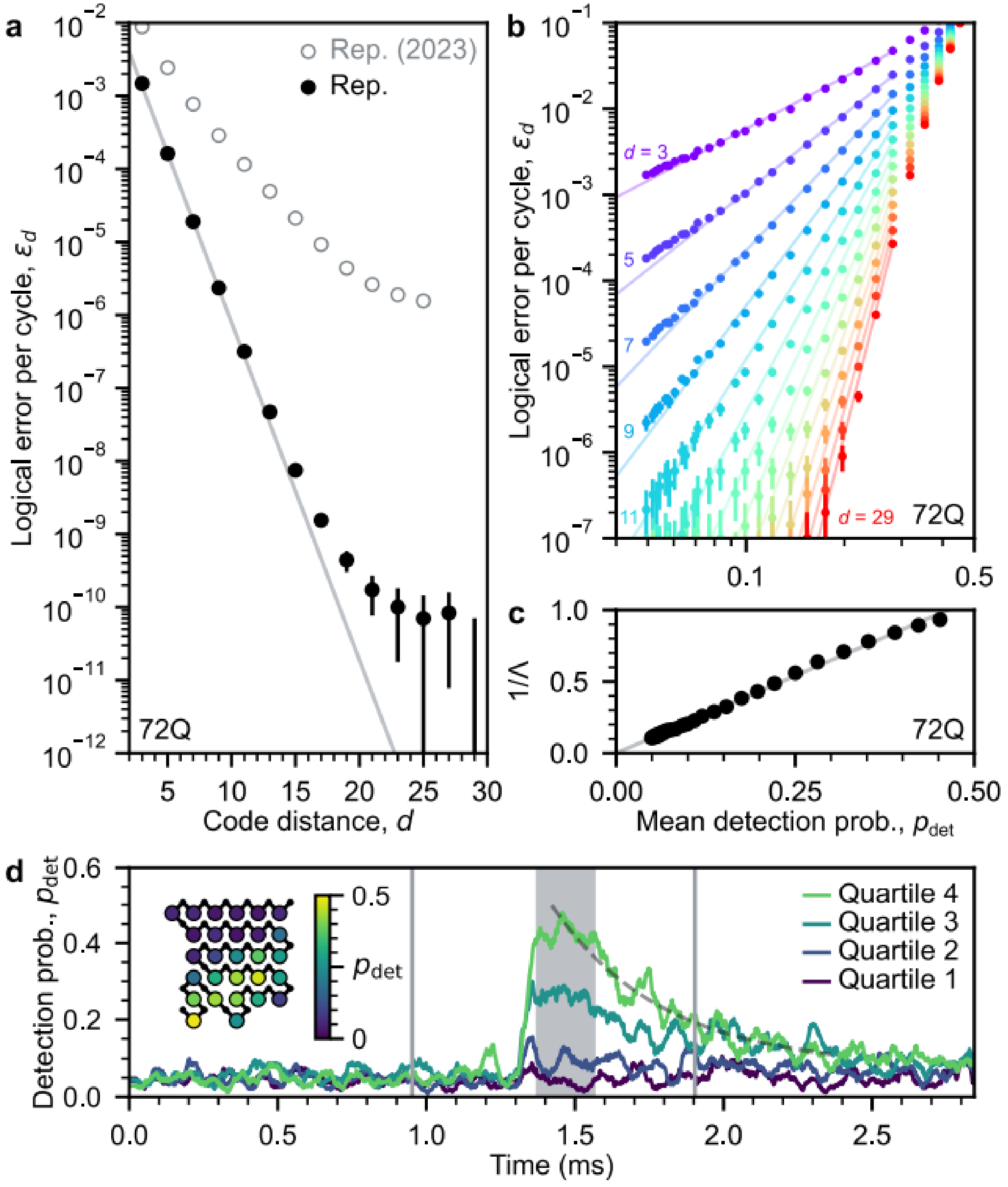


McEwen et al. “Resisting High-Energy Impact Events through Gap Engineering in Superconducting Qubit Arrays”. Phys. Rev. Lett. **133,** 240601 (2024)

# Latest from Google

- Beyond break-even error correction achieved using gap-engineered qubits
- Still observe large correlated error bursts, but with frequency ~1/hour
- Fundamentally limits error correction

Quantum Error Correction Below the Surface Code Threshold. Google Quantum AI and Collaboration. arXiv:2408.13687



# Modeling ionizing radiation

B. Loer *et al.* “Abatement of ionizing radiation for superconducting quantum devices.” JINST **19** P09001, 2024

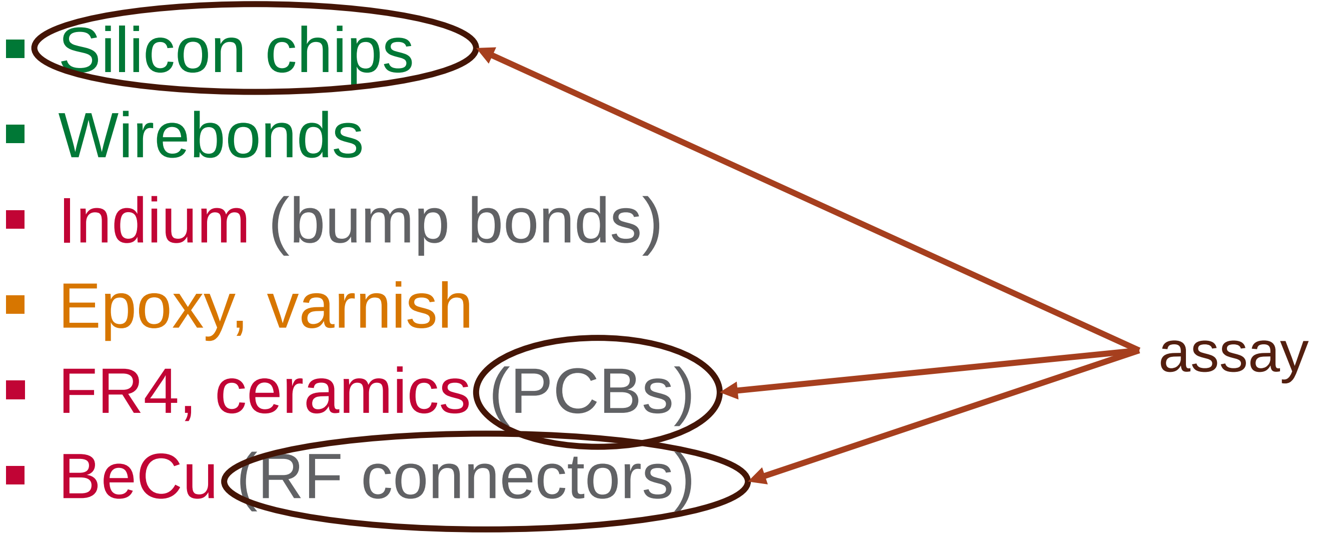
- First Google “Catastrophic” paper saw correlated errors ~1/10s
  - Roughly matches the expectation from ionizing radiation interactions
- Gap engineered floor ~1/hour
  - Can we understand the origin of this?
- Until qubits are completely “rad hard”, how best to reduce the radiation environment?

# Sources of ionizing radiation

Low Radioactivity
Moderate or Variable Radioactivity
High Radioactivity/Rate

**Most high radioactivity materials are very small mass**
**BUT**
**Many of them are very close to the devices**

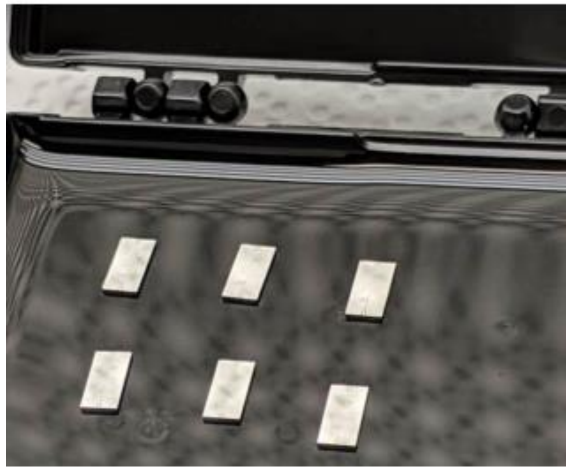
- External sources
  - Gammas
  - Cosmic ray secondaries (muons)
- Most mass of the fridge is:
  - Copper, gold plating
  - Aluminum (radiation shields)
  - Steel (Vacuum flange)
  - Mumetal (magnetic shielding)

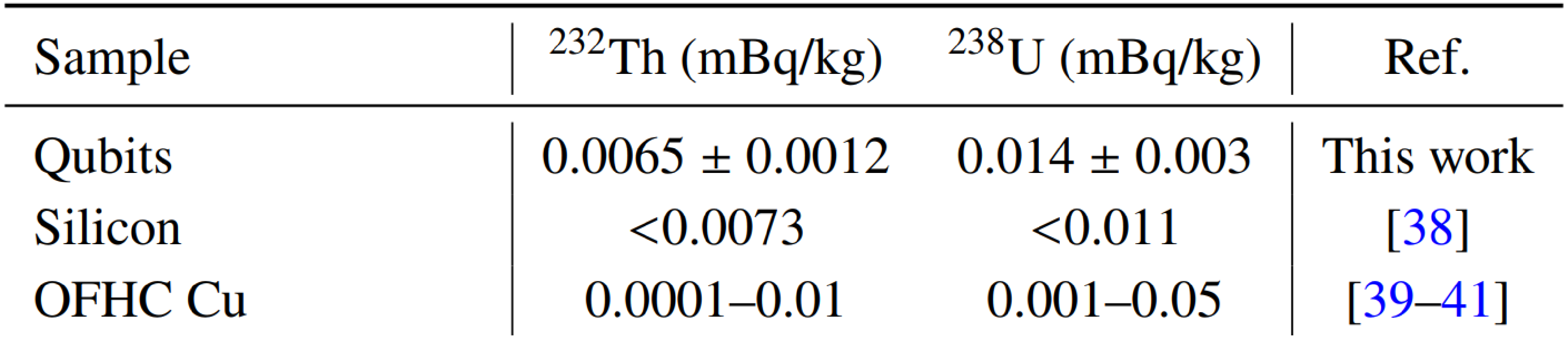


- Packaging and readout:
  - Silicon chips
  - Wirebonds
  - Indium (bump bonds)
  - Epoxy, varnish
  - FR4, ceramics (PCBs)
  - BeCu (RF connectors)
  - Copper

# Assay of critical components

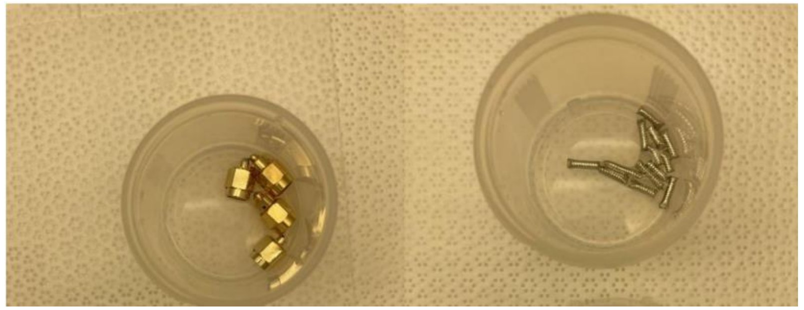
- Qubits (ICP-MS)
  - Fabricated at MIT-Lincoln Labs, each chip 2.5x5x0.3 mm
  - 3 replicates measured, only 1 above detection limit
  - Not significantly any dirtier than pure silicon



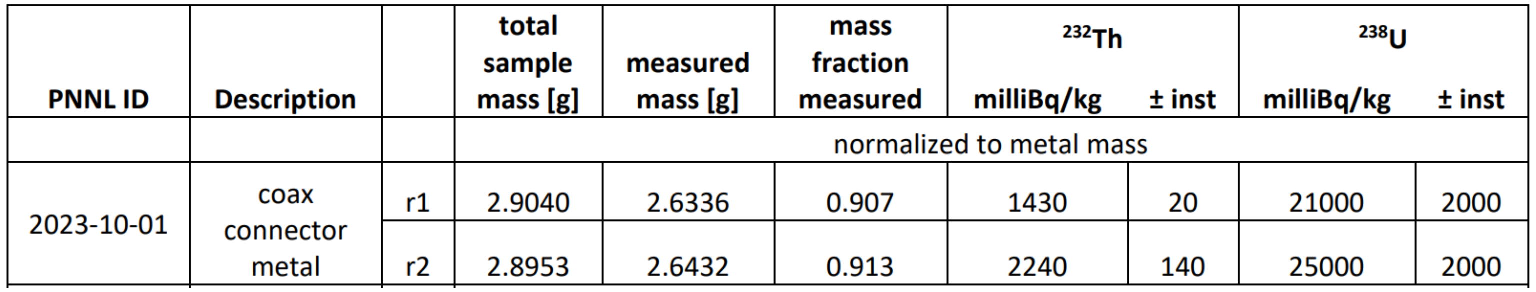


| Sample | $^{232}$Th (mBq/kg) | $^{238}$U (mBq/kg) | Ref. |
|---|---|---|---|
| Qubits | 0.0065 ± 0.0012 | 0.014 ± 0.003 | This work |
| Silicon | <0.0073 | <0.011 | [38] |
| OFHC Cu | 0.0001–0.01 | 0.001–0.05 | [39–41] |

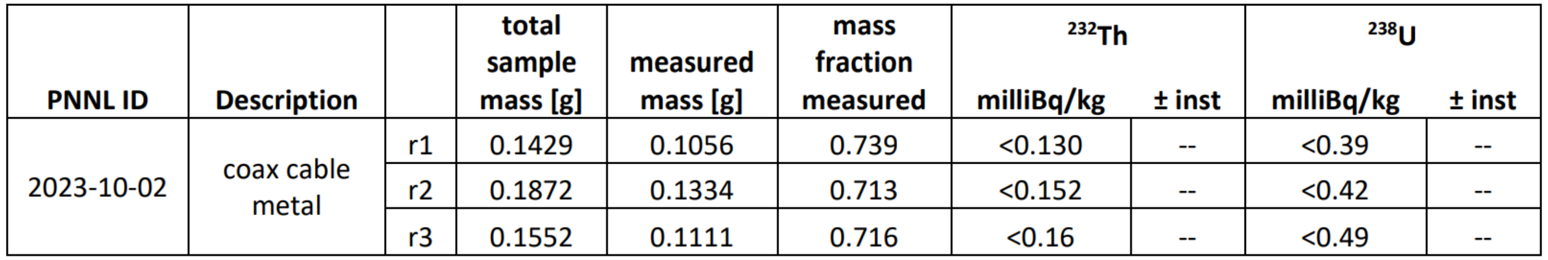
# Assay of critical components



- Qubits (ICP-MS)
- Cryogenic SMA connector and semirigid coax cable (ICP-MS)
  - Only metal parts digested (e.g. not PTFE dielectric)
  - Cables fairly clean, connectors dirty (likely BeCu)

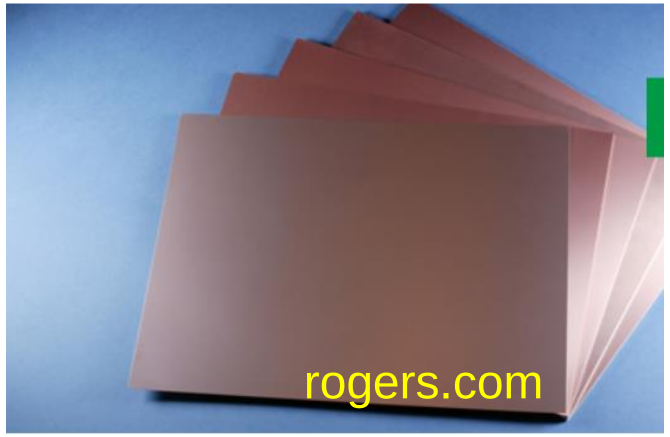


| PNNL ID | Description | | total sample mass [g] | measured mass [g] | mass fraction measured | $^{232}$Th milliBq/kg | ± inst | $^{238}$U milliBq/kg | ± inst |
|---|---|---|---|---|---|---|---|---|---|
| | | | normalized to metal mass | | | | | | |
| 2023-10-01 | coax connector metal | r1 | 2.9040 | 2.6336 | 0.907 | 1430 | 20 | 21000 | 2000 |
| | | r2 | 2.8953 | 2.6432 | 0.913 | 2240 | 140 | 25000 | 2000 |



| PNNL ID | Description | | total sample mass [g] | measured mass [g] | mass fraction measured | $^{232}$Th milliBq/kg | ± inst | $^{238}$U milliBq/kg | ± inst |
|---|---|---|---|---|---|---|---|---|---|
| 2023-10-02 | coax cable metal | r1 | 0.1429 | 0.1056 | 0.739 | <0.130 | -- | <0.39 | -- |
| | | r2 | 0.1872 | 0.1334 | 0.713 | <0.152 | -- | <0.42 | -- |
| | | r3 | 0.1552 | 0.1111 | 0.716 | <0.16 | -- | <0.49 | -- |

# Assay of critical components

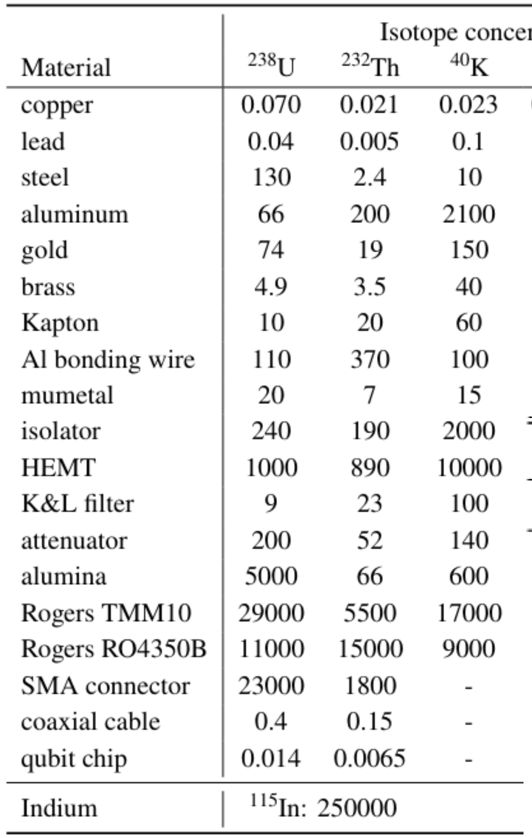

rogers.com

- Qubits (ICP-MS)
- Cryogenic SMA connector and semirigid coax cable (ICP-MS)
- Low loss ceramic PCB substrates Rogers TMM10 and RO4350B (HPGe)

| Sample | Mass | $^{40}$K | $^{208}$Tl | $^{212}$Pb | $^{214}$Bi | $^{214}$Pb | $^{226}$Ra | $^{210}$Pb |
|---|---|---|---|---|---|---|---|---|
| TMM10 | 200 g | 17.3(9) | 1.51(6) | 5.5(3) | 28.9(4) | 25.4(8) | 29(2) | - |
| RO4350B | 30 g | 9.1(8) | 4.9(2) | 15.1(9) | - | 11.2(4) | 8(4) | 11(2) |

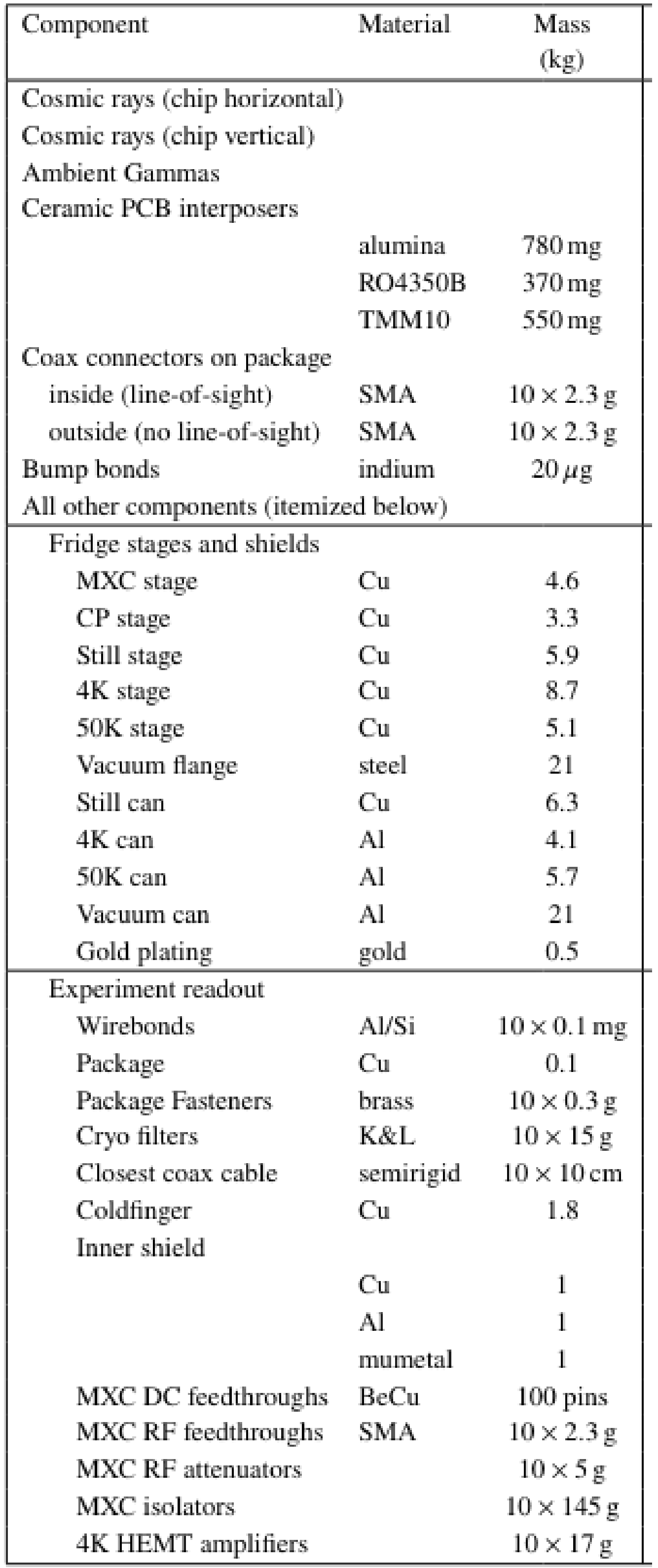
# Building a background model

Radioactivity assays



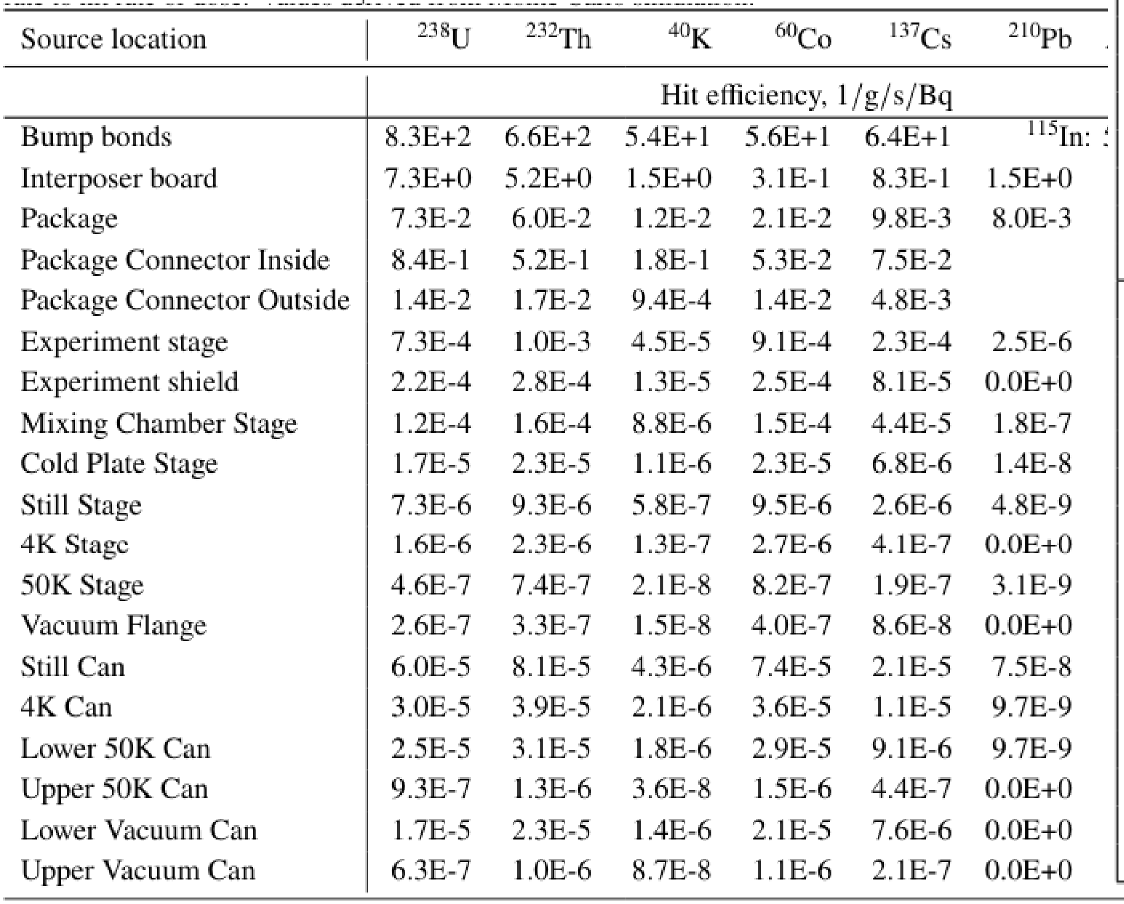
| Material | Isotope concentrations (mBq/kg) $^{238}$U | $^{232}$Th | $^{40}$K | $^{60}$Co | $^{137}$Cs | $^{210}$Pb$^{a}$ | Act.$^{b}$ | Ref. |
|---|---|---|---|---|---|---|---|---|
| copper | 0.070 | 0.021 | 0.023 | 0.002 | - | 40 | 6.6 | [46, 50, 51] |
| lead | 0.04 | 0.005 | 0.1 | - | - | 200000 | - | [45, 52, 53] |
| steel | 130 | 2.4 | 10 | 8.5 | 0.9 | - | - | [46] |
| aluminum | 66 | 200 | 2100 | - | - | - | - | [46] |
| gold | 74 | 19 | 150 | - | - | - | - | [45, 54] |
| brass | 4.9 | 3.5 | 40 | - | 2.6 | 40 | 6.6 | [49, 55] |
| Kapton | 10 | 20 | 60 | 3 | - | - | - | [47, 55] |
| Al bonding wire | 110 | 370 | 100 | - | - | - | - | [45] |
| mumetal | 20 | 7 | 15 | - | - | - | - | [56] |
| isolator | 240 | 190 | 2000 | | | | | |
| HEMT | 1000 | 890 | 10000 | | | | | |
| K&L filter | 9 | 23 | 100 | | | | | |
| attenuator | 200 | 52 | 140 | | | | | |
| alumina | 5000 | 66 | 600 | | | | | |
| Rogers TMM10 | 29000 | 5500 | 17000 | | | | | |
| Rogers RO4350B | 11000 | 15000 | 9000 | | | | | |
| SMA connector | 23000 | 1800 | - | | | | | |
| coaxial cable | 0.4 | 0.15 | - | | | | | |
| qubit chip | 0.014 | 0.0065 | - | | | | | |
| Indium | $^{115}$In: 250000 | | | | | | | |

Bill of materials



| Component | Material | Mass (kg) |
|---|---|---|
| Cosmic rays (chip horizontal) | | |
| Cosmic rays (chip vertical) | | |
| Ambient Gammas | | |
| Ceramic PCB interposers | | |
| | alumina | 780 mg |
| | RO4350B | 370 mg |
| | TMM10 | 550 mg |
| Coax connectors on package | | |
| inside (line-of-sight) | SMA | 10 × 2.3 g |
| outside (no line-of-sight) | SMA | 10 × 2.3 g |
| Bump bonds | indium | 20 $\mu$g |
| All other components (itemized below) | | |
| Fridge stages and shields | | |
| MXC stage | Cu | 4.6 |
| CP stage | Cu | 3.3 |
| Still stage | Cu | 5.9 |
| 4K stage | Cu | 8.7 |
| 50K stage | Cu | 5.1 |
| Vacuum flange | steel | 21 |
| Still can | Cu | 6.3 |
| 4K can | Al | 4.1 |
| 50K can | Al | 5.7 |
| Vacuum can | Al | 21 |
| Gold plating | gold | 0.5 |
| Experiment readout | | |
| Wirebonds | Al/Si | 10 × 0.1 mg |
| Package | Cu | 0.1 |
| Package Fasteners | brass | 10 × 0.3 g |
| Cryo filters | K&L | 10 × 15 g |
| Closest coax cable | semirigid | 10 × 10 cm |
| Coldfinger | Cu | 1.8 |
| Inner shield | | |
| | Cu | 1 |
| | Al | 1 |
| | mumetal | 1 |
| MXC DC feedthroughs | BeCu | 100 pins |
| MXC RF feedthroughs | SMA | 10 × 2.3 g |
| MXC RF attenuators | | 10 × 5 g |
| MXC isolators | | 10 × 145 g |
| 4K HEMT amplifiers | | 10 × 17 g |

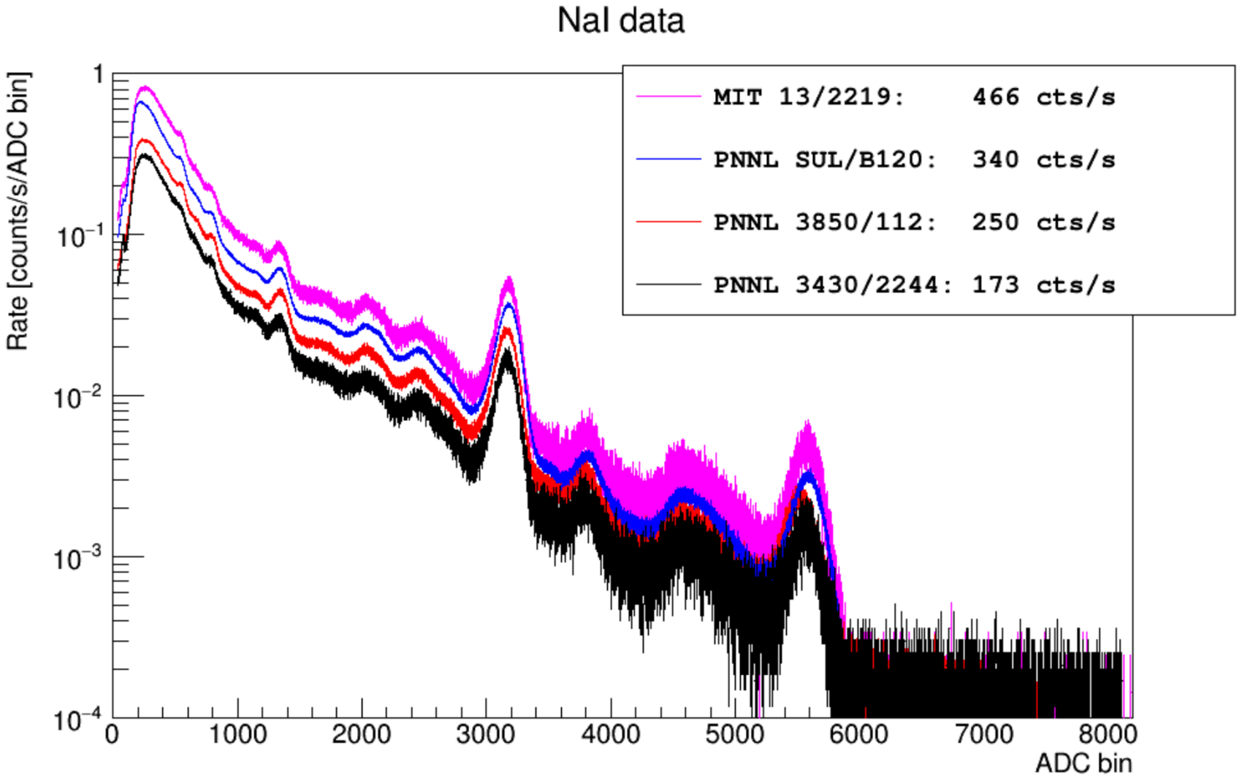
Simulated hit efficiencies

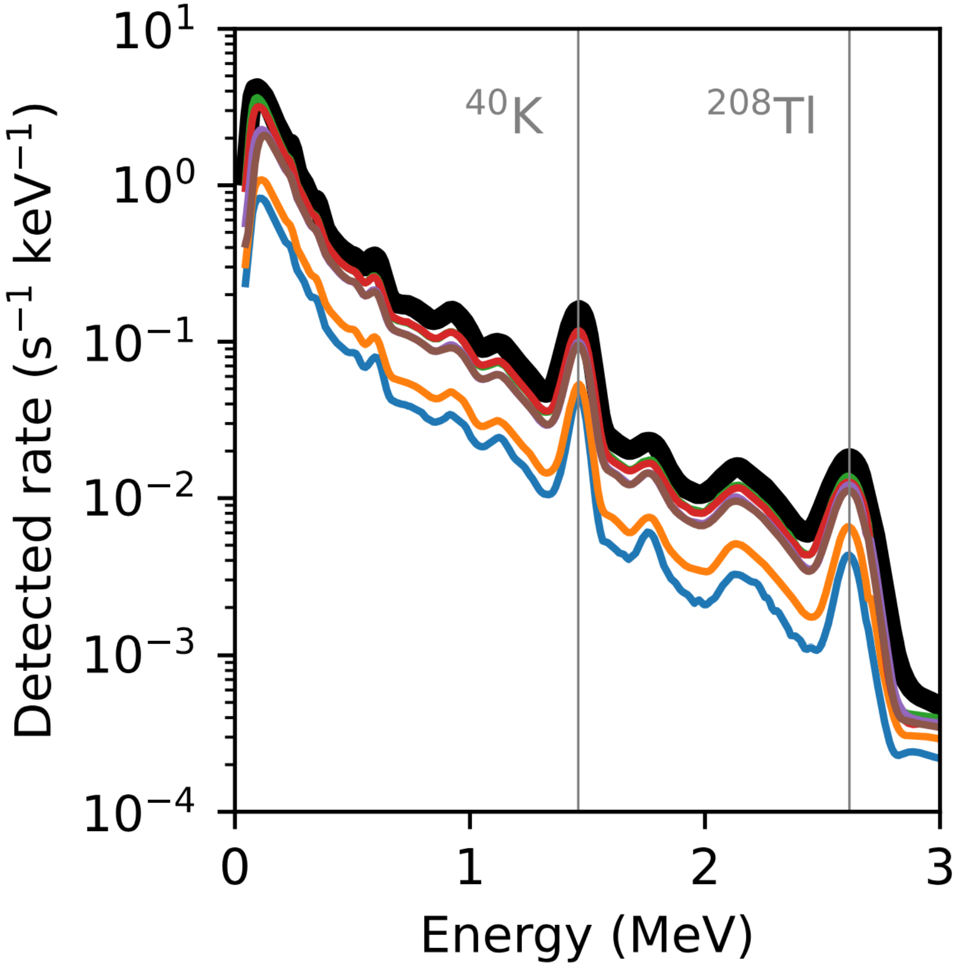


| Source location | $^{238}$U | $^{232}$Th | $^{40}$K | $^{60}$Co | $^{137}$Cs | $^{210}$Pb |
|---|---|---|---|---|---|---|
| | Hit efficiency, 1/g/s/Bq | | | | | |
| Bump bonds | 8.3E+2 | 6.6E+2 | 5.4E+1 | 5.6E+1 | 6.4E+1 | $^{115}$In: |
| Interposer board | 7.3E+0 | 5.2E+0 | 1.5E+0 | 3.1E-1 | 8.3E-1 | 1.5E+0 |
| Package | 7.3E-2 | 6.0E-2 | 1.2E-2 | 2.1E-2 | 9.8E-3 | 8.0E-3 |
| Package Connector Inside | 8.4E-1 | 5.2E-1 | 1.8E-1 | 5.3E-2 | 7.5E-2 | |
| Package Connector Outside | 1.4E-2 | 1.7E-2 | 9.4E-4 | 1.4E-2 | 4.8E-3 | |
| Experiment stage | 7.3E-4 | 1.0E-3 | 4.5E-5 | 9.1E-4 | 2.3E-4 | 2.5E-6 |
| Experiment shield | 2.2E-4 | 2.8E-4 | 1.3E-5 | 2.5E-4 | 8.1E-5 | 0.0E+0 |
| Mixing Chamber Stage | 1.2E-4 | 1.6E-4 | 8.8E-6 | 1.5E-4 | 4.4E-5 | 1.8E-7 |
| Cold Plate Stage | 1.7E-5 | 2.3E-5 | 1.1E-6 | 2.3E-5 | 6.8E-6 | 1.4E-8 |
| Still Stage | 7.3E-6 | 9.3E-6 | 5.8E-7 | 9.5E-6 | 2.6E-6 | 4.8E-9 |
| 4K Stage | 1.6E-6 | 2.3E-6 | 1.3E-7 | 2.7E-6 | 4.1E-7 | 0.0E+0 |
| 50K Stage | 4.6E-7 | 7.4E-7 | 2.1E-8 | 8.2E-7 | 1.9E-7 | 3.1E-9 |
| Vacuum Flange | 2.6E-7 | 3.3E-7 | 1.5E-8 | 4.0E-7 | 8.6E-8 | 0.0E+0 |
| Still Can | 6.0E-5 | 8.1E-5 | 4.3E-6 | 7.4E-5 | 2.1E-5 | 7.5E-8 |
| 4K Can | 3.0E-5 | 3.9E-5 | 2.1E-6 | 3.6E-5 | 1.1E-5 | 9.7E-9 |
| Lower 50K Can | 2.5E-5 | 3.1E-5 | 1.8E-6 | 2.9E-5 | 9.1E-6 | 9.7E-9 |
| Upper 50K Can | 9.3E-7 | 1.3E-6 | 3.6E-8 | 1.5E-6 | 4.4E-7 | 0.0E+0 |
| Lower Vacuum Can | 1.7E-5 | 2.3E-5 | 1.4E-6 | 2.1E-5 | 7.6E-6 | 0.0E+0 |
| Upper Vacuum Can | 6.3E-7 | 1.0E-6 | 8.7E-8 | 1.1E-6 | 2.1E-7 | 0.0E+0 |

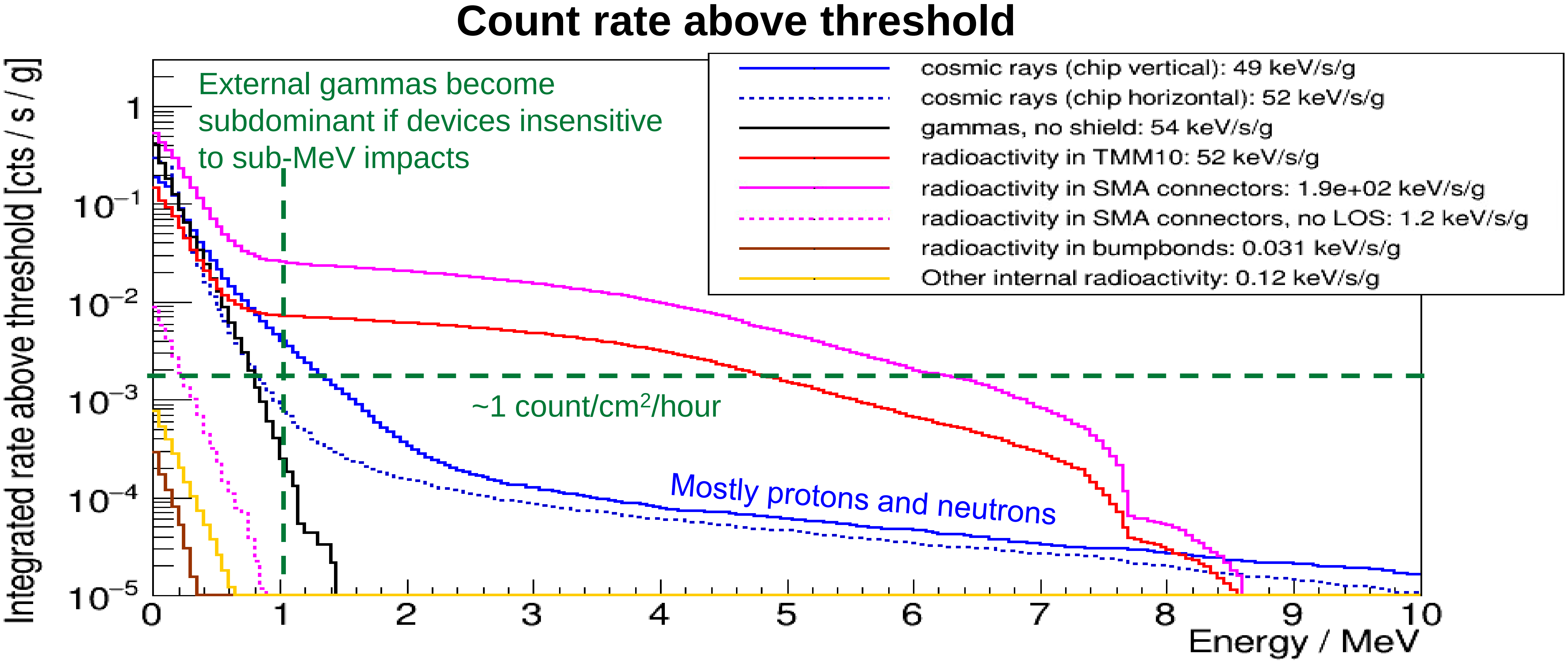
# Common Gamma Backgrounds

- Environmental gamma and muon rates measured in multiple buildings, laboratories, and institutions with same instrument
- All within factor of ~5





# Typical Radiation budget at surface



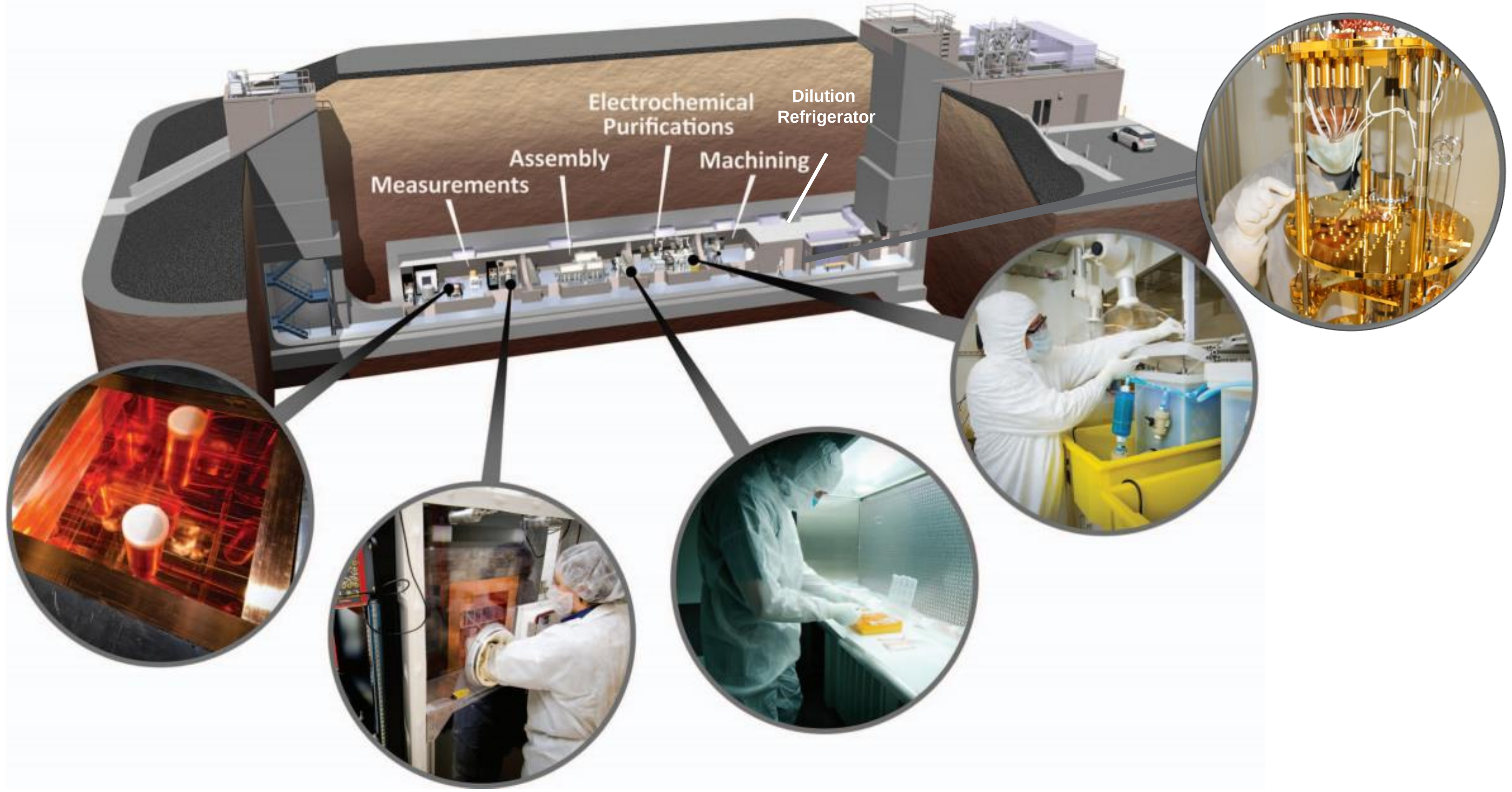
Similar method used to build background model observed in TKID at NIST, see Paul Szypryt’s talk next

# Key Takeaways

- Three dominant sources of ionizing radiation events:
  - Cosmic ray secondaries
  - Ambient gammas
  - Line-of-sight “dirty” components (ceramic PCBs, BeCu coax connectors)
- If devices are sensitive to low energy impacts, these sources contribute roughly equally
- If there is a significant threshold effect, line-of-sight alphas are the biggest concern, followed by cosmic rays (hadronic component), and gammas are very subdominant
- Feasible that remaining correlated errors not suppressed by gap engineering are cosmic ray neutrons and protons. These are attenuated ***much*** more efficiently than muons with overburden!

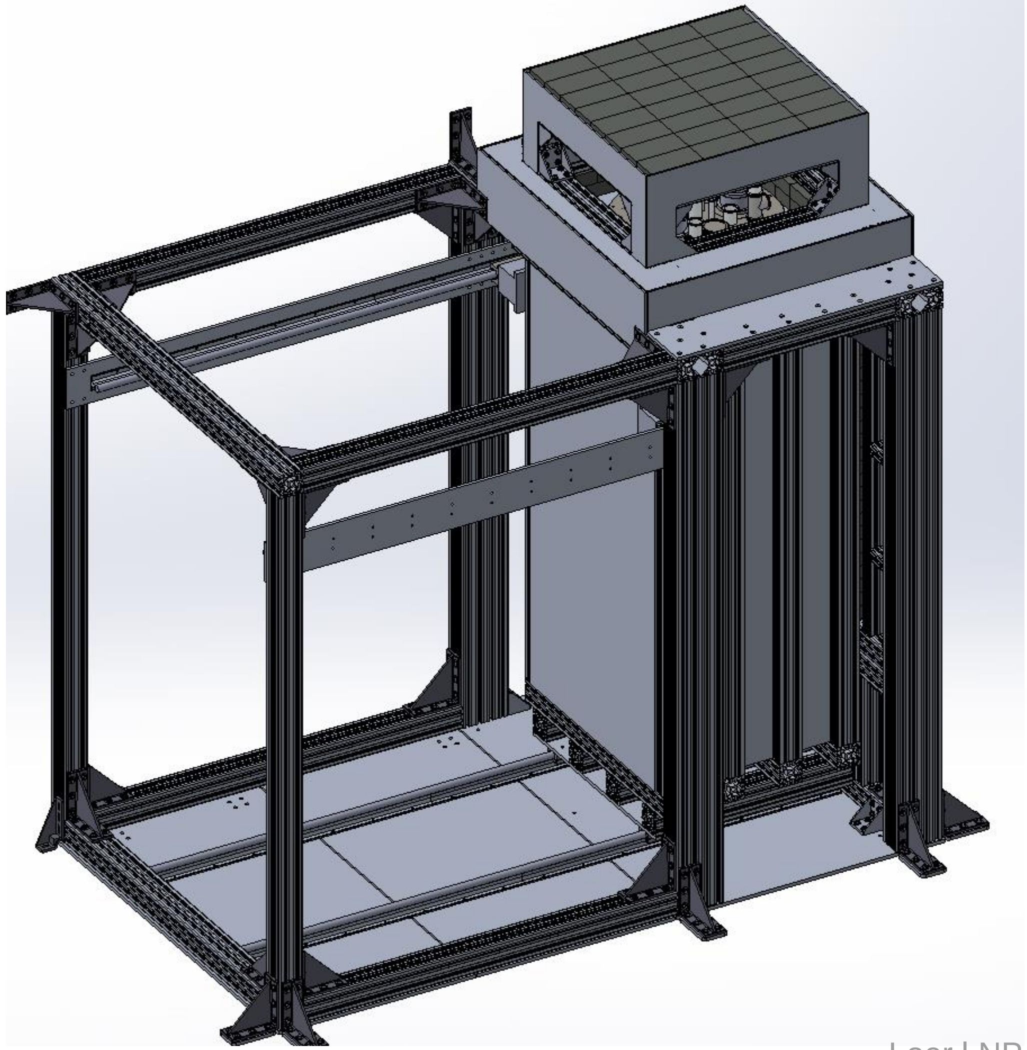
# PNNL Shallow Underground Laboratory and Low Background Cryogenic Facility (LBCF)

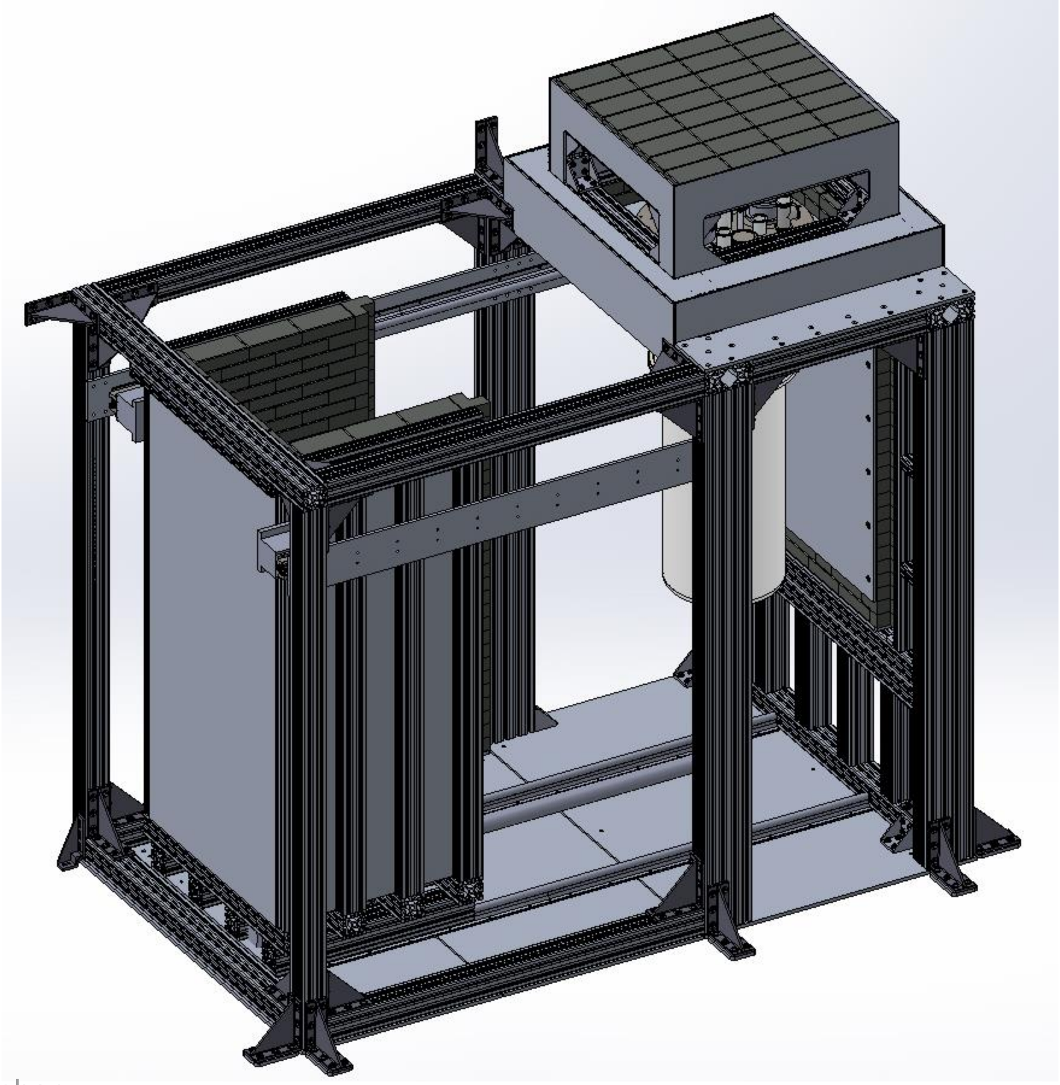
- SUL houses clean rooms (class 10,000 and 1,000) , world-leading ultra-pure material growth and characterization capability
- 19 m overburden reduces muon flux by 6X, neutron and proton flux by >100X
- Bluefors LD-400 operating for ~1.5 years



# LBCF Shield

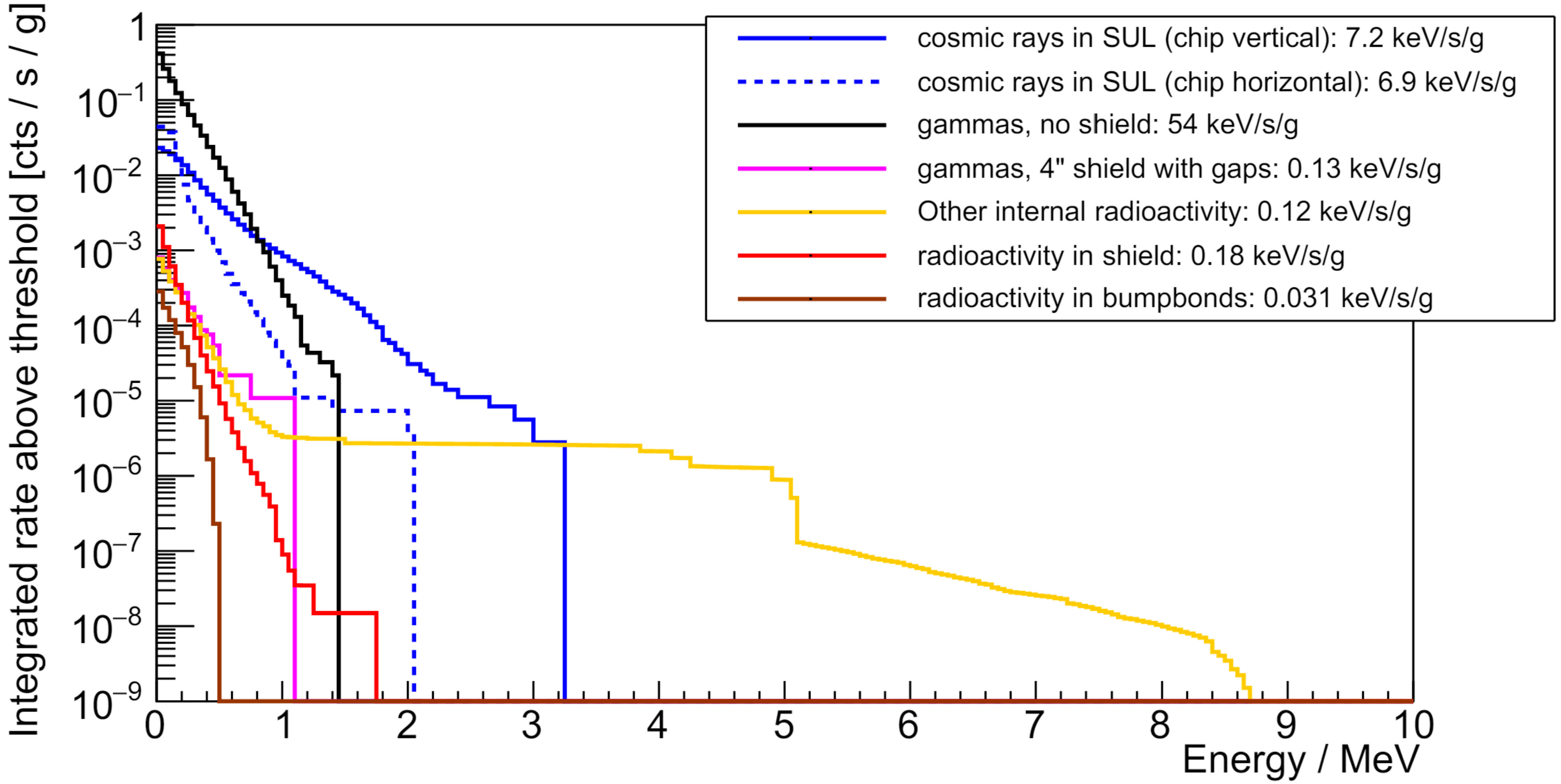
- Reduces gamma rate by ~99.8% -> dominated by residual cosmic ray muons
- Automated cage door open/close enables A/B tests for ambient radiation
- Expected completion Spring 2025





# Devices running in the LBCF

- Original McEwen et al. (Google) observed “catastrophic” error bursts with rate ~1/(10s)
- Estimated radiation dose in LBCF ~5% of “typical” surface lab if care is paid to line-of-sight components
- If McEwen error rate is 100% radiation-driven, naïve scaling suggests error burst rate in LBCF would be ~1/(2 minutes)
- Gap-engineered residual error rate ~1/hour
- LBCF rate >1 MeV ~1/month
    - $^{210}$Pb in copper housings likely dominates at high energy (~few/year)

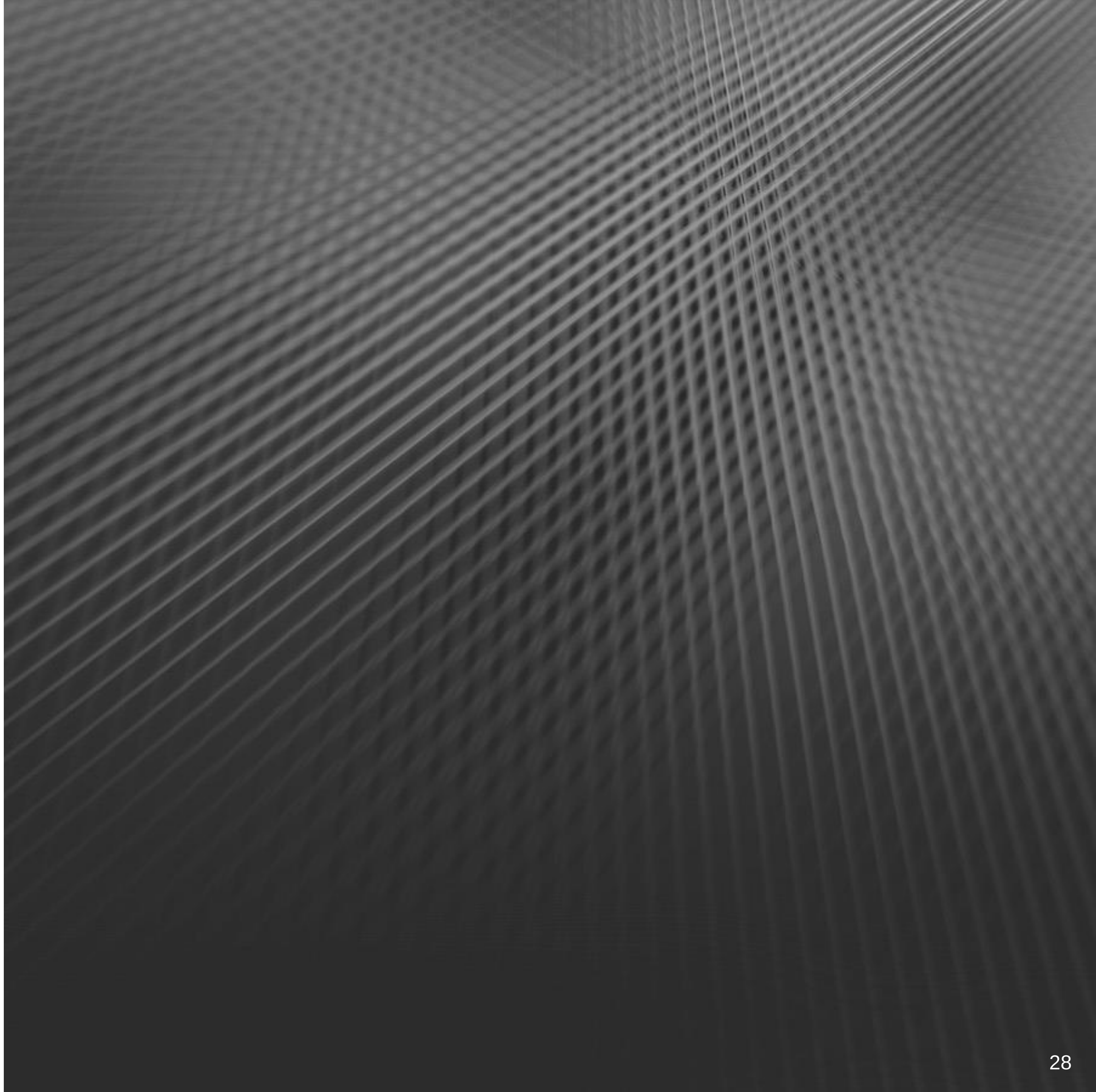


# Summary

- Ionizing radiation is not yet a dominant source of single-qubit errors, but becomes more important as coherence times improve
- It is likely the source of remaining correlated error events that currently set the floor of achievable error correction
- Which sources are the most important depends on energy sensitivity
- But environmental sources dominant in most cases
- Lots of good ideas for how to defeat this issue

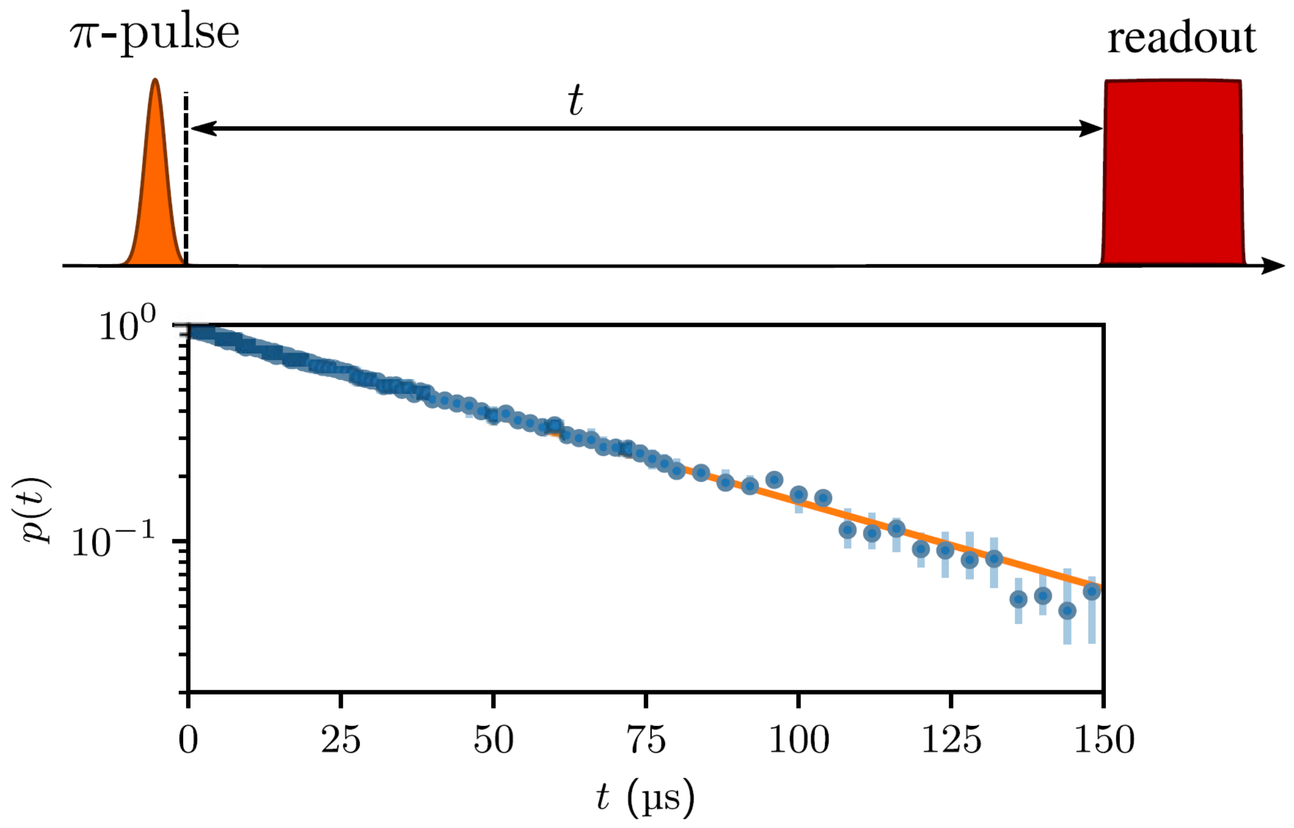

Radiation Impact on Superconducting Qubits (RISQ 2024)

# Thank you



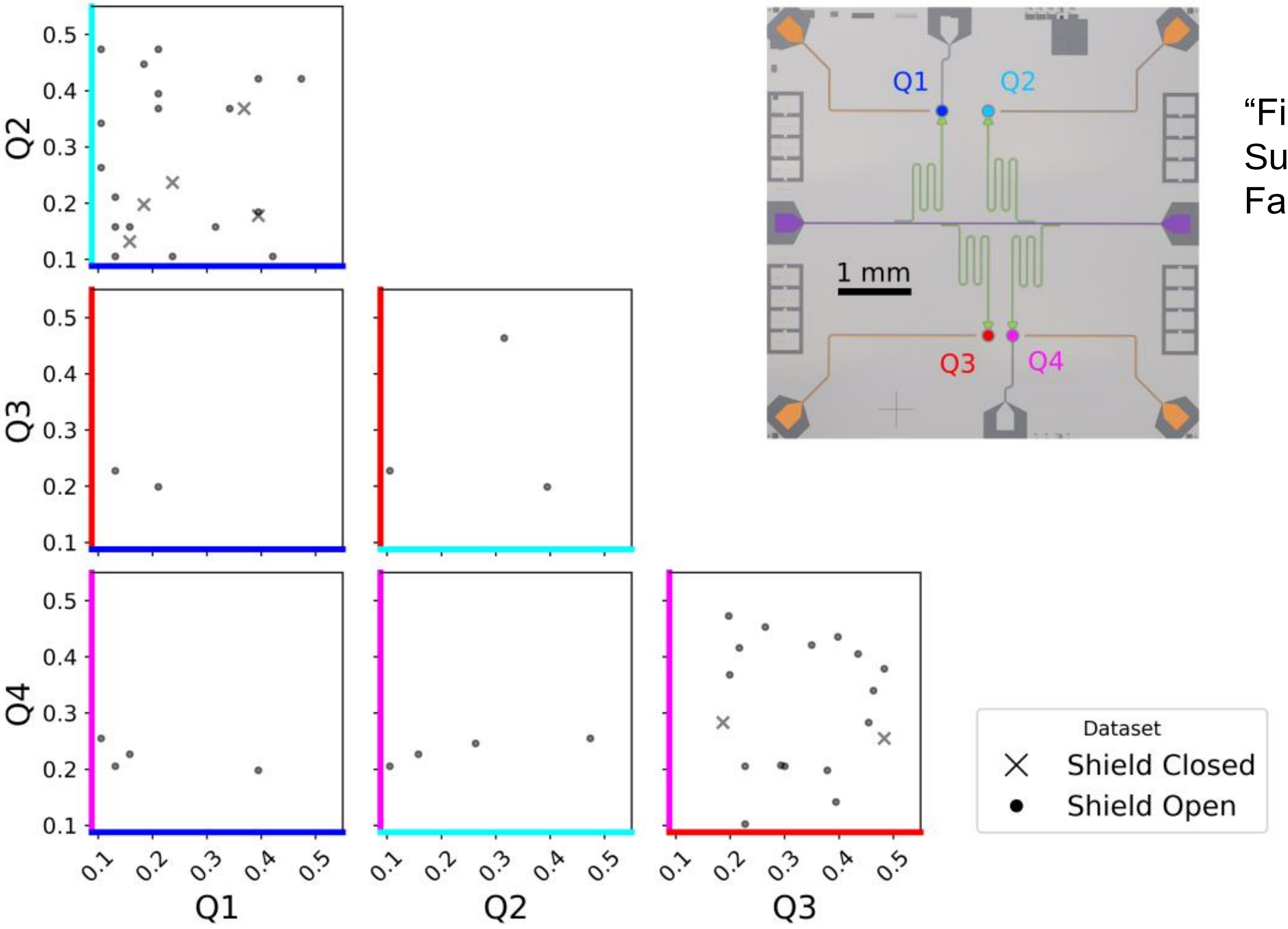
# How to measure coherence time?

```
let x=42;    sleep(t);    if(x != 42)
                             decoherence!
```



- π-pulse initializes qubit in an excited state
- Wait a fixed time *t* and measure: is it still in the excited state?
- Repeat many times to find the average excited state population
- Then repeat for different values of *t*

# Correlated errors underground



“First Measurement of Correlated Charge Noise in Superconducting Qubits at an Underground Facility”. arXiv:2405.04642

# Simulation setup