# Synchronous Detection of Cosmic Rays and Qubit Relaxation

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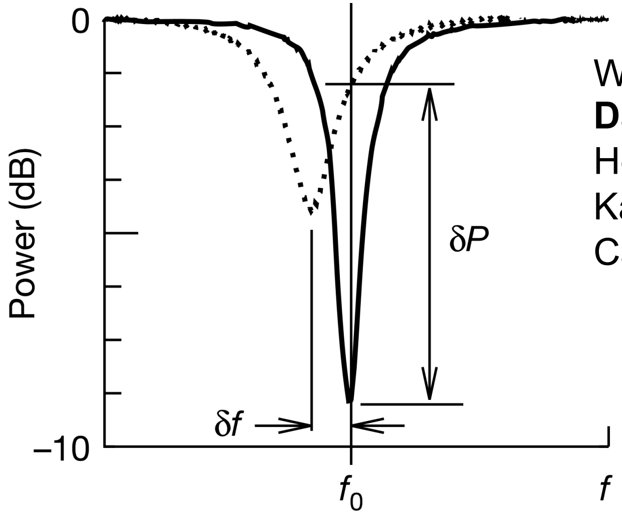
arXiv:2402.03208

**Radiation Impact on Superconducting Qubits (RISQ 2024)**
**May 30, 2024**

# Ionizing Radiation & Superconducting Circuits

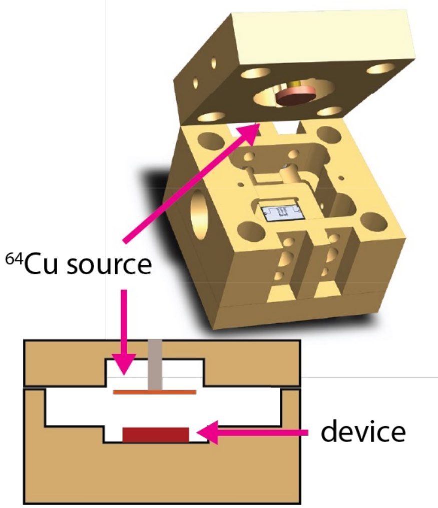
*Ionizing radiation generates quasiparticles in superconducting circuits*

## Cooper pair-breaking detectors




Wood, APL 15, 237 (1969)
**Day, Nature 425, 817 (2003)**
Henriques, APL 115 (2019)
Karatsu, APL 114, 032601 (2019)
Cardani, Nat. Comm. 12, 2733 (2021)

## Superconducting qubits




**Vepsäläinen, Nature 584, 551 (2020)**
Wilen, Nature 594, 369 (2021)
Gusenkova, APL 120, 054001 (2022)
Iaia, Nat. Comm. 13, 6425 (2022)
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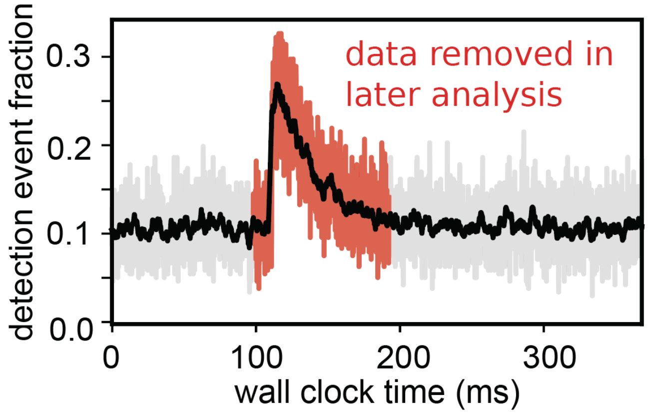



## Spatiotemporally correlated qubit errors

– *problematic for conventional quantum error correction codes*

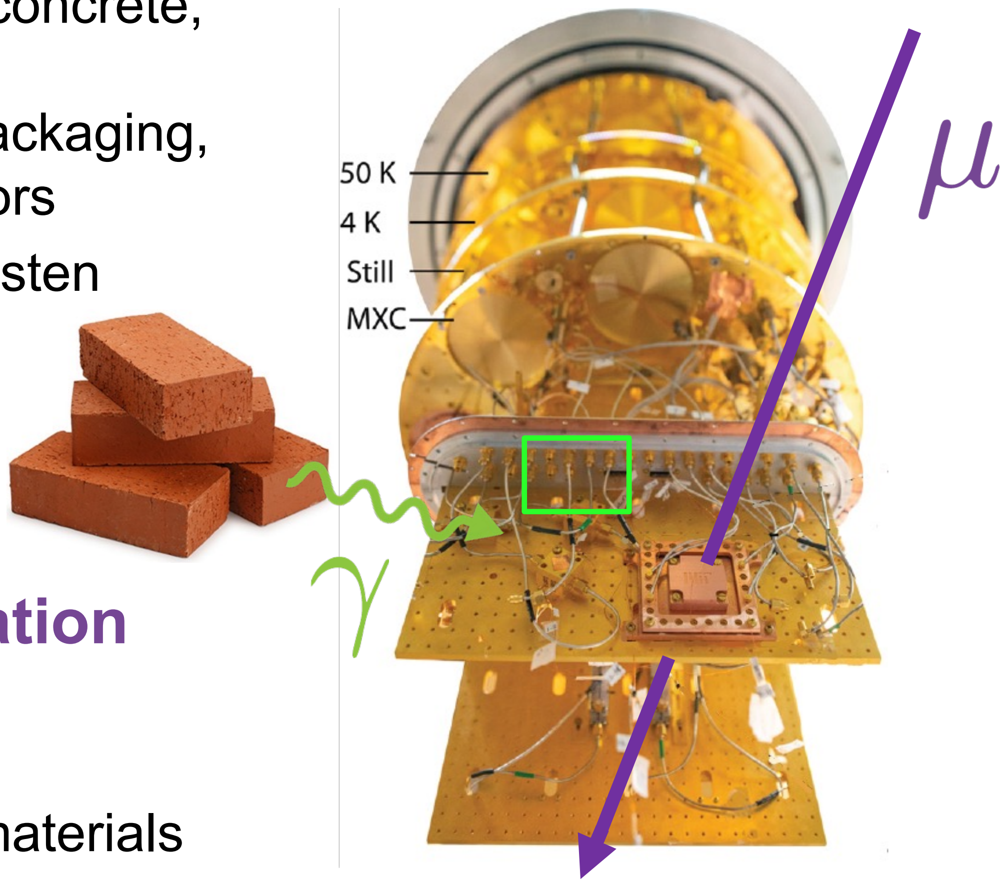
**Chen, Nature 595, 383 (2021)**
McEwen, Nat. Phys. 18, 107 (2022)
Acharya, Nature 614, 676 (2023)
Li, et al. arXiv:2402.04245 (2024)
McEwen, et al. arXiv:2402.15644 (2024)

**This work**
- **Cosmic rays account for 17% of multi-qubit relaxation events**
- **Essentially every cosmic-ray impact causes qubit errors**

# Sources of Ionizing Radiation

## Gamma Rays

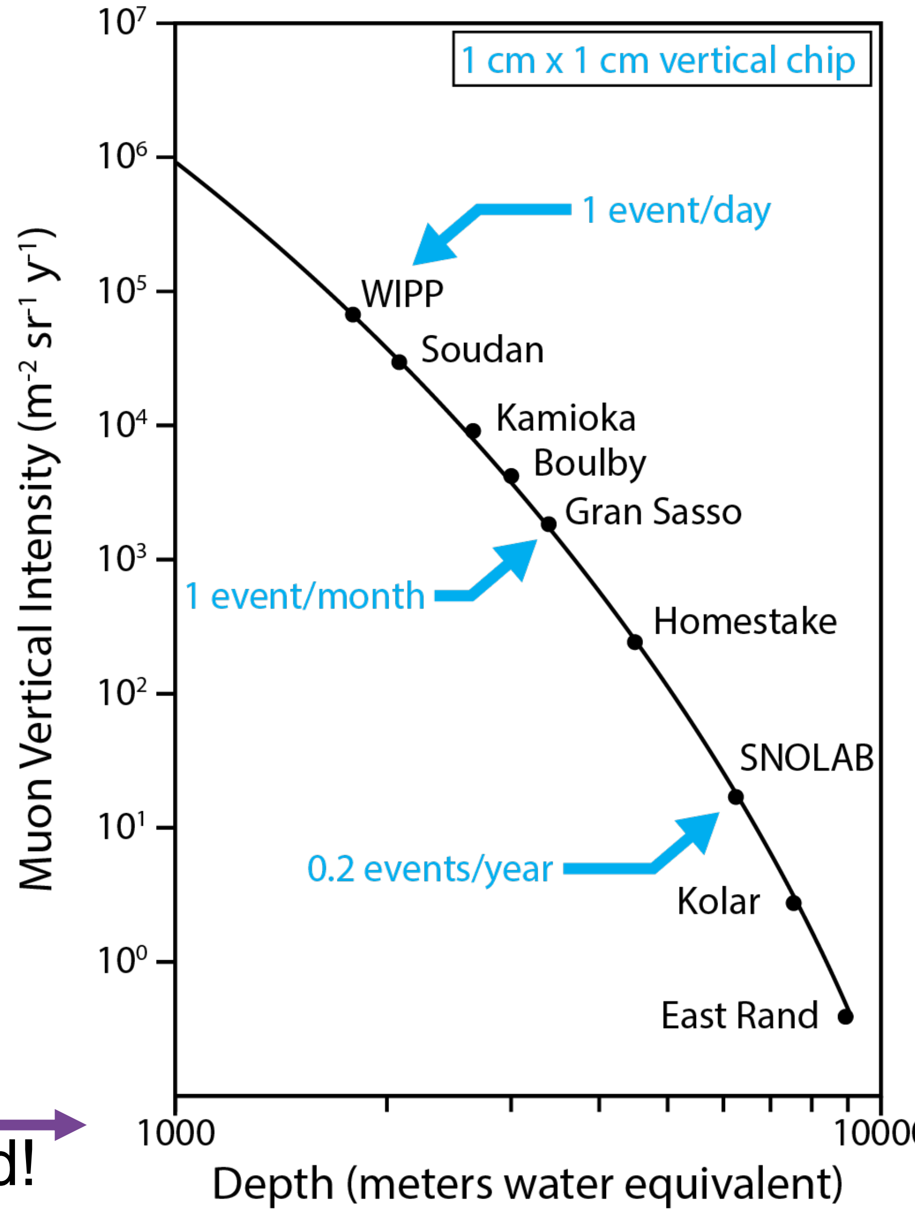
- Uranium, Thorium, Potassium
- Common materials: concrete, metal fixtures
- "Internal" sources: packaging, PCB, BeCu connectors
- Shield with lead/tungsten




## Cosmogenic Radiation

- Created in the upper atmosphere
- Muons penetrate all materials (>1 GeV/c per muon)

can only shield underground!



# Sources of Ionizing Radiation

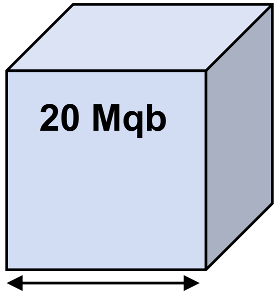
## Cosmic Ray Muons

can only shield underground!

**How deep is deep enough?**

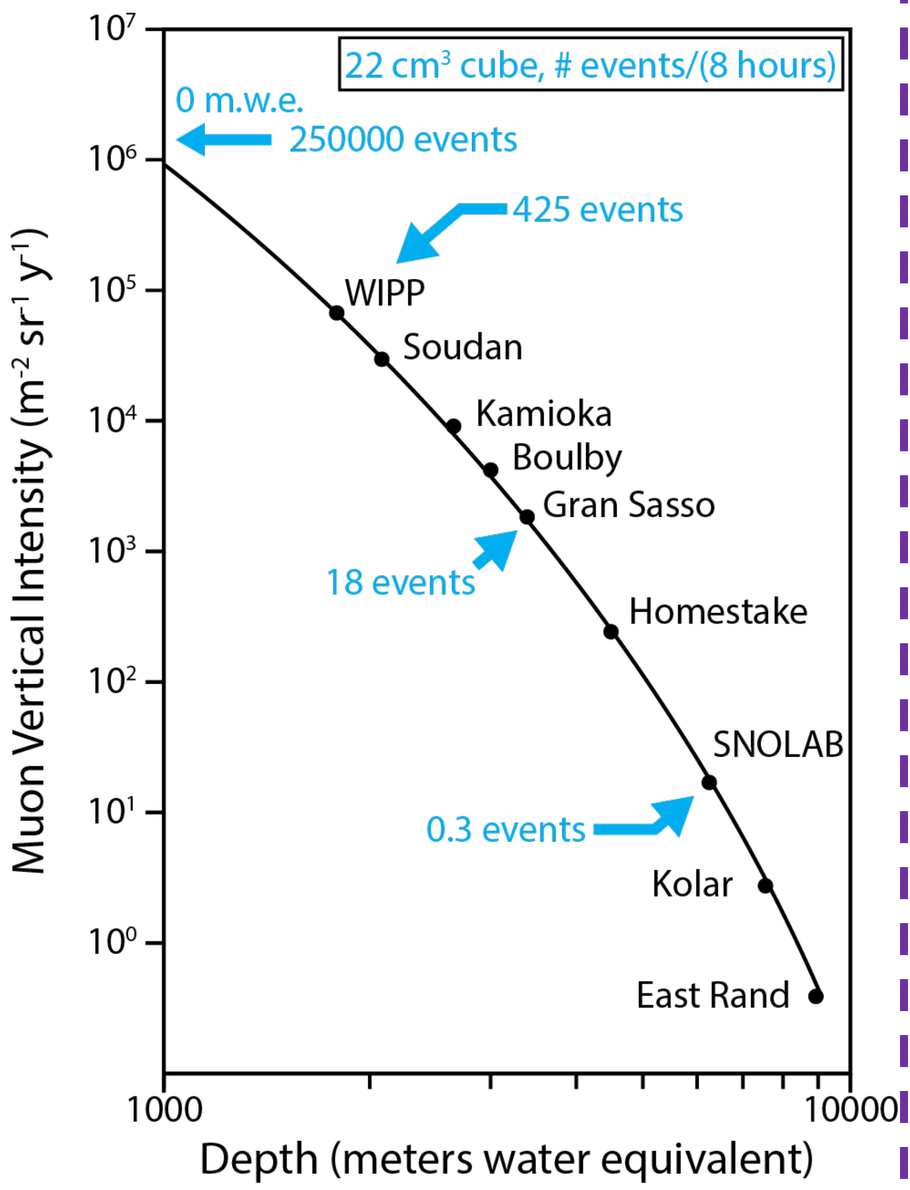
**RSA-2048**
**20 million qubits, 8 hours**

Volume estimate ~




**250000 cosmic rays/ 8 hours @ sea level**

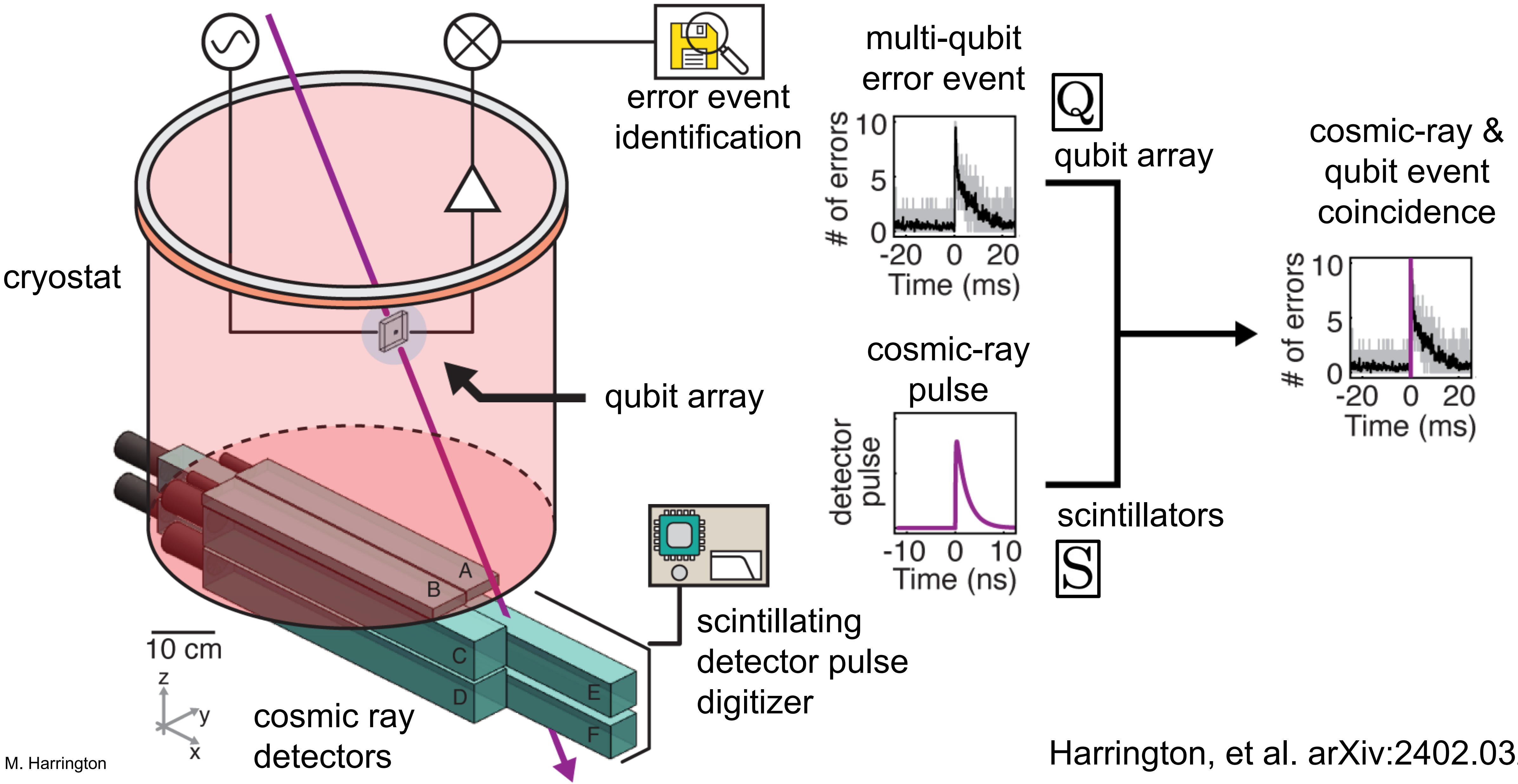
**0.3 cosmic rays/ 8 hours @ SNOLAB**




**How often do cosmic-ray impacts cause correlated errors?**

Formaggio, Martoff. Annu. Rev. Nucl. Part. (2004) Gidney, Ekera. arXiv:1905.09749 (2019)

# Synchronous Detection of Cosmic Rays and Qubit Relaxation – Experiment Setup



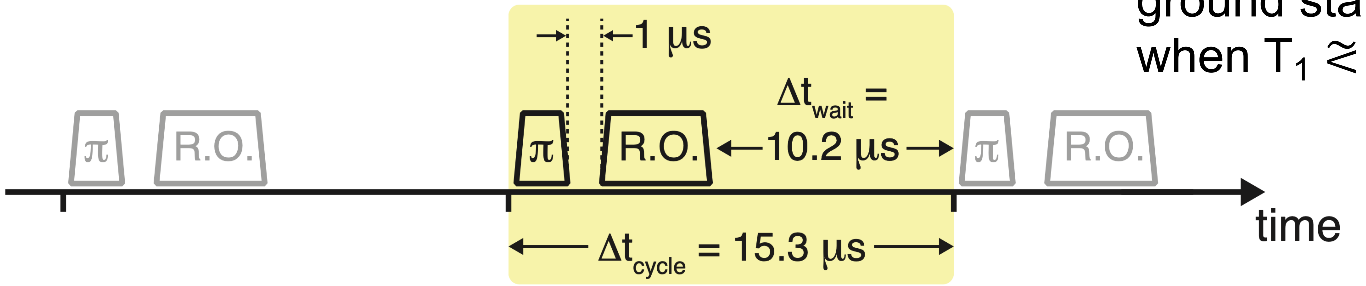

P. M. Harrington

Harrington, et al. arXiv:2402.03208

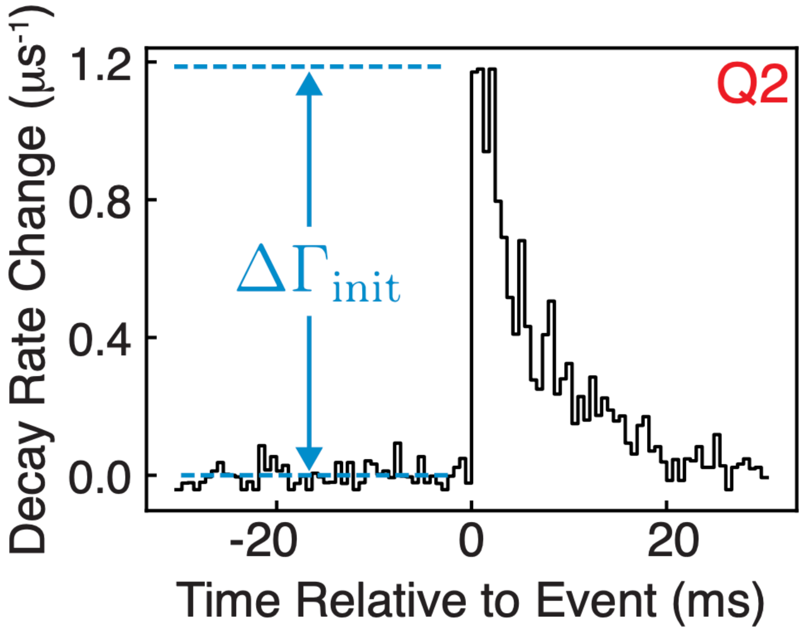
# Identification of Correlated Qubit Relaxation

**Goal:** identify transients of relaxation rates when multiple qubits have $T_1 \lesssim 1$ μs for a duration $\gtrsim 1$ ms

Control & readout of 10 transmon qubits (repeated every 15.3 μs)




Readout (R.O.) ground state when $T_1 \lesssim 1$ μs

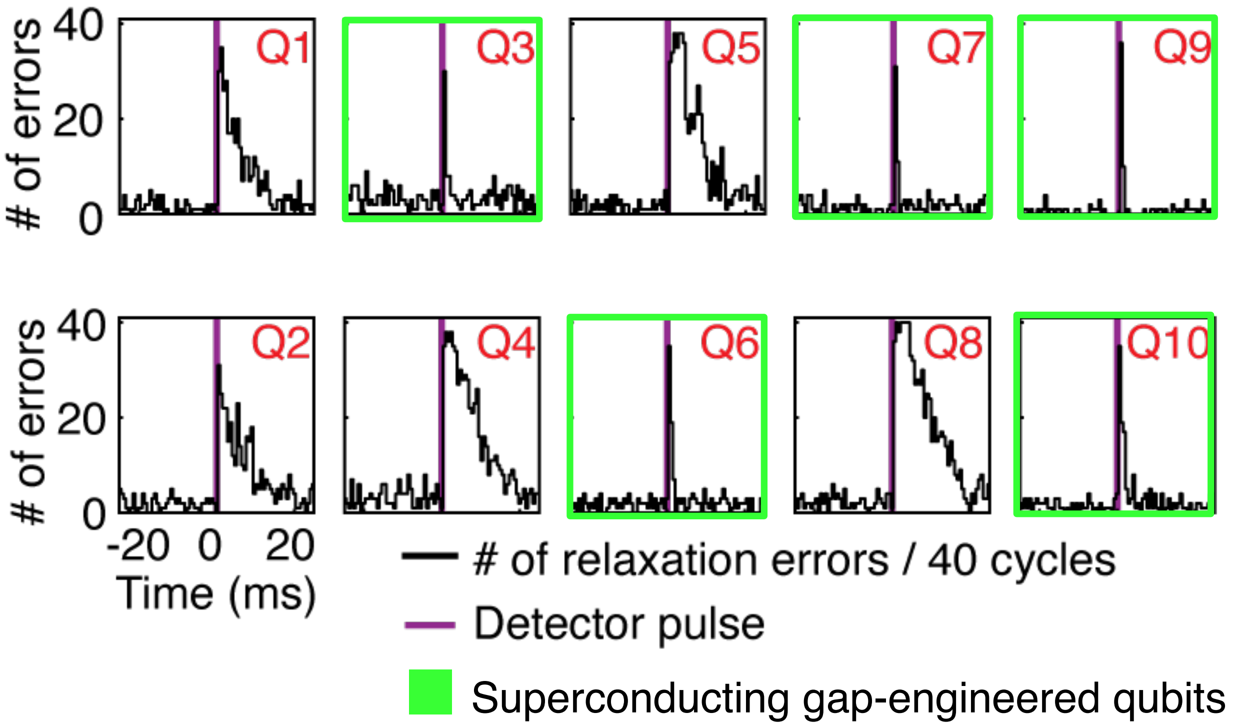


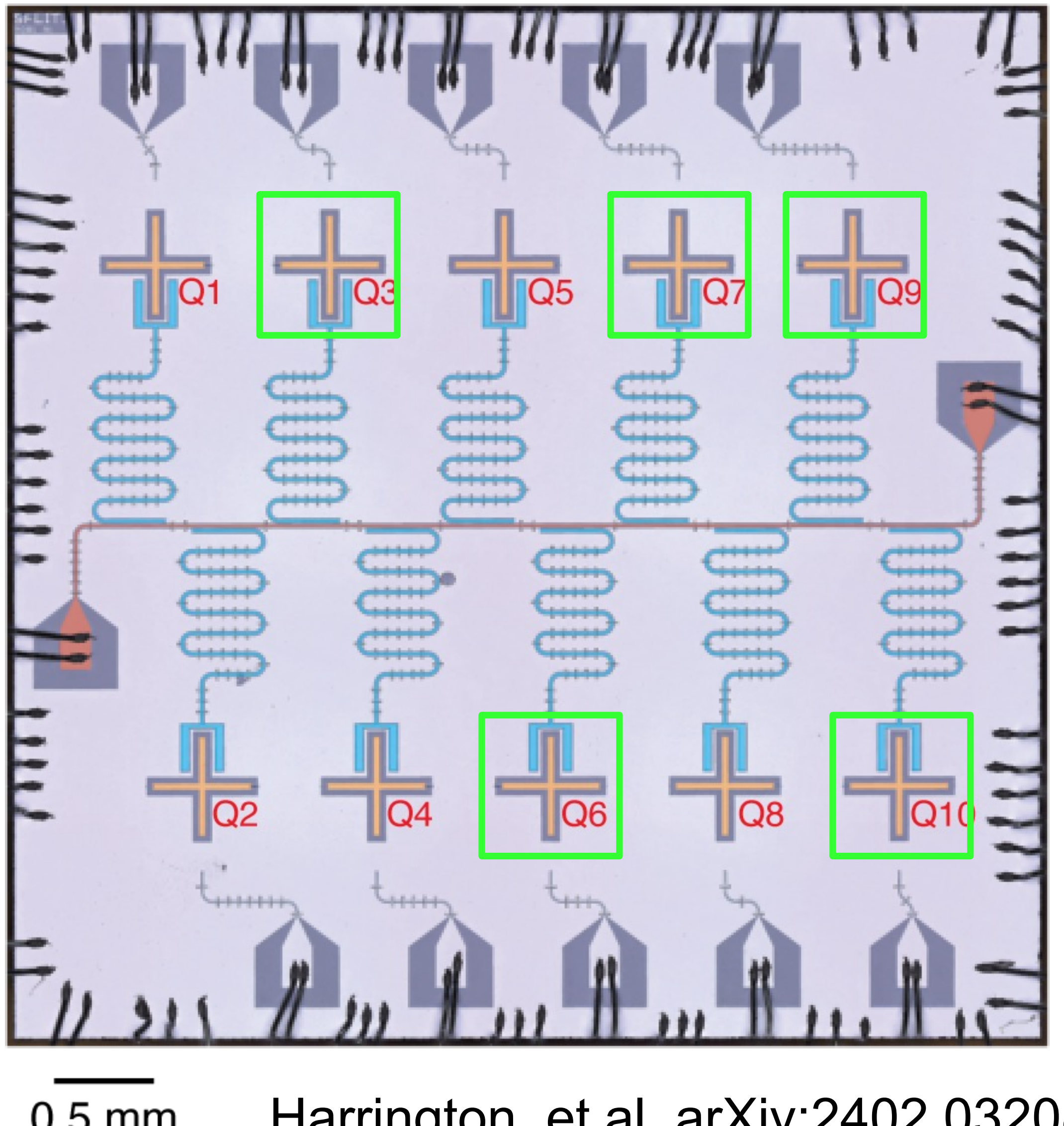

**Qubit event** → multiple qubits with $T_1 \lesssim 1$ μs for a duration $\gtrsim 1$ ms

Occurrence rate: 9460 events/(266.5 hours) = 1/(101±1 s)

# Multi-qubit Relaxation Events & Gap-engineering

- Error rate of each qubit during a cosmic-ray coincidence event
  - high superconducting gap energy of a Josephson junction electrode blocks QPs from the transmon capacitor → fast (< 1 ms) recovery

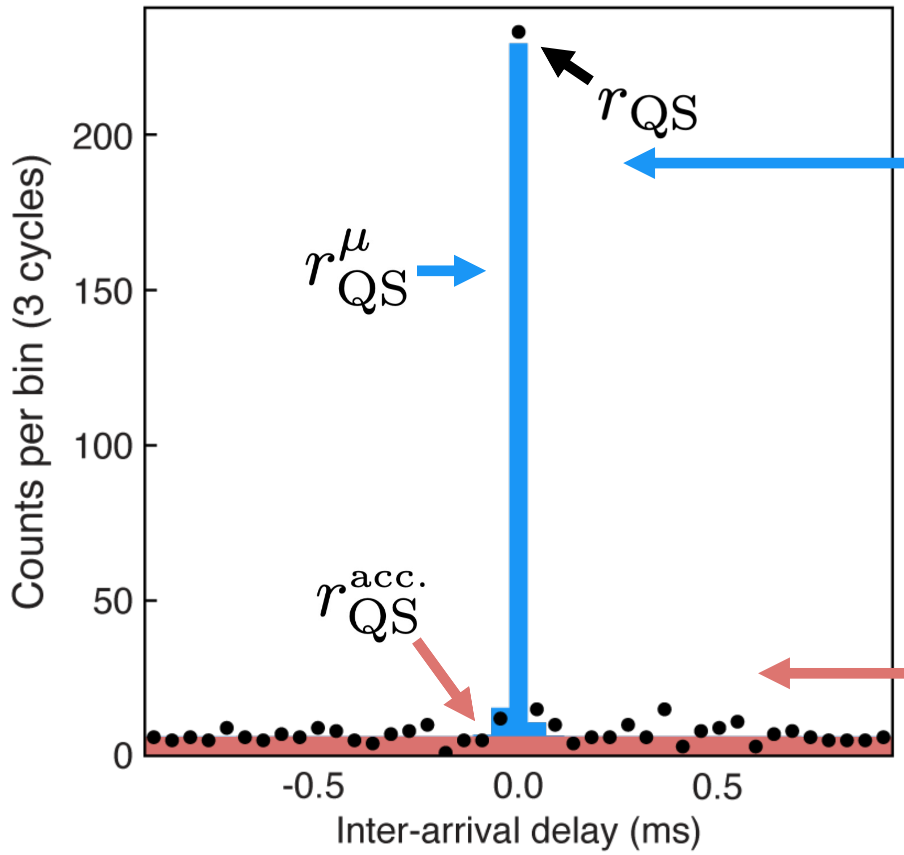


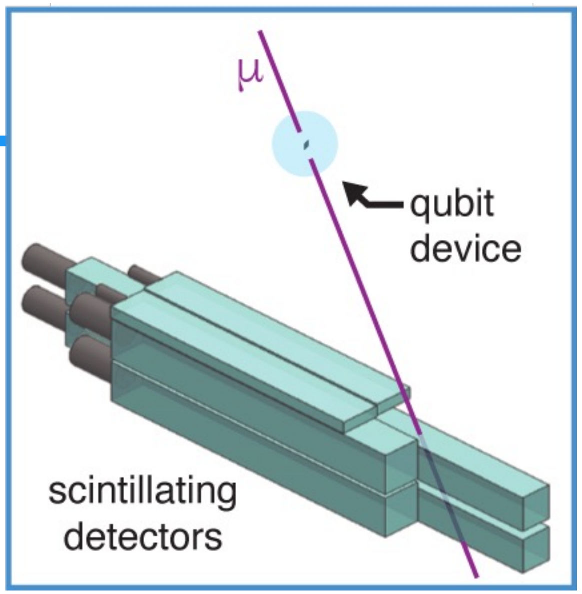

Harrington, et al. arXiv:2402.03208

# Identification of Qubit Events from Cosmic Rays

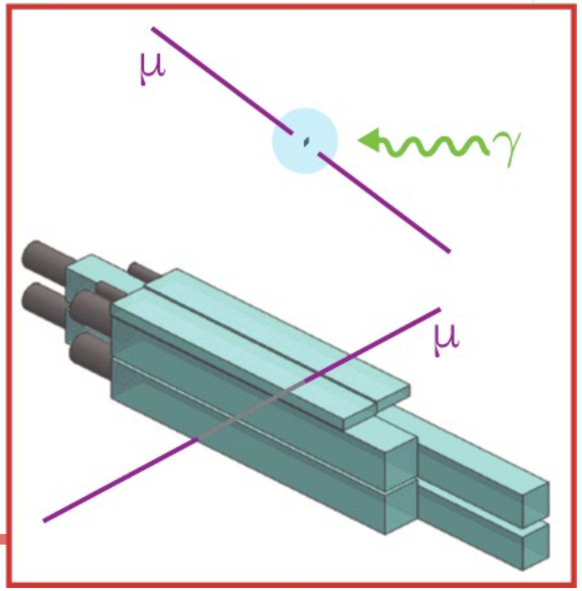
**Inter-arrival delay**
duration between each qubit event
and its nearest-in-time detector pulse




Cosmic ray & qubit event
coincidence rate



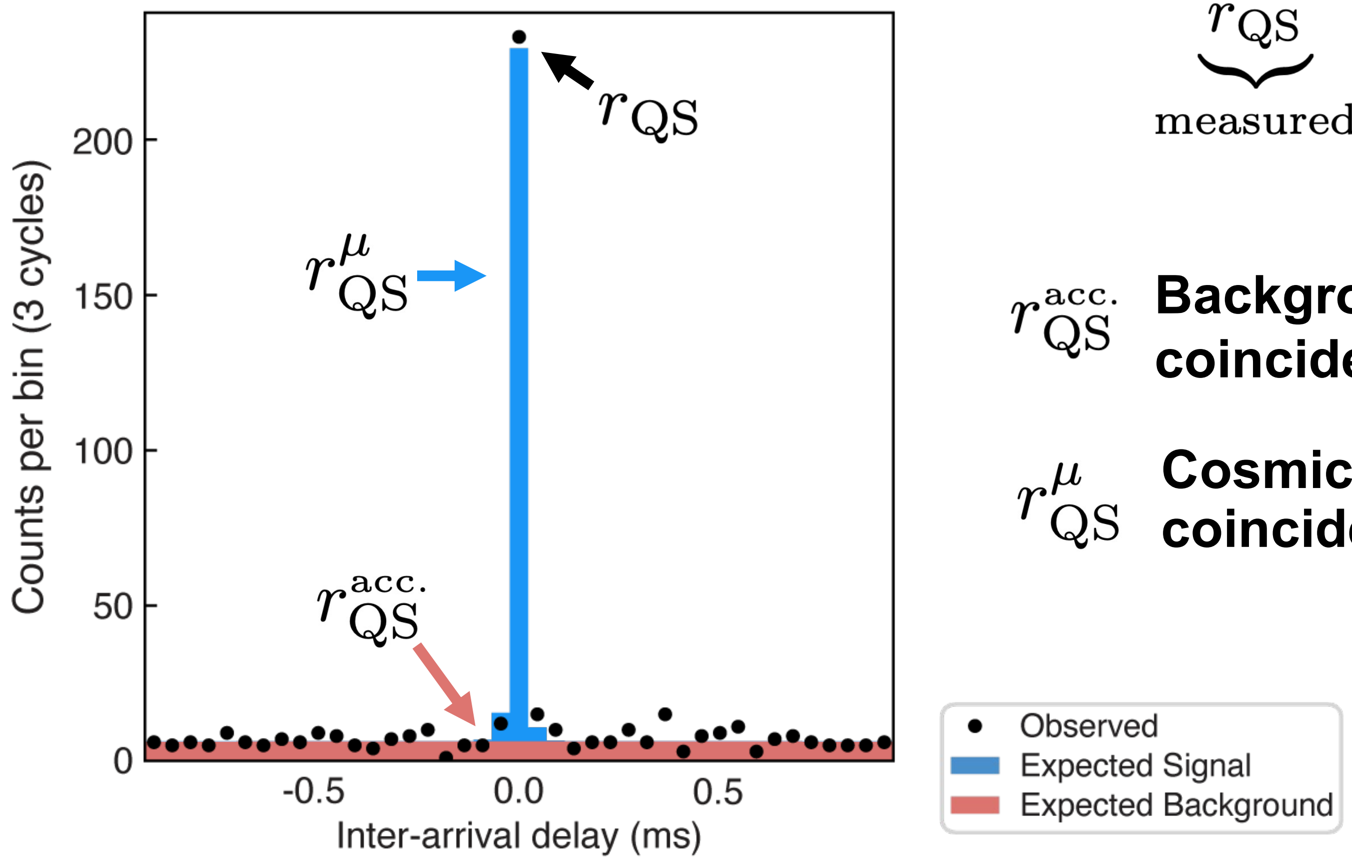

Background rate



# Identification of Qubit Events from Cosmic Rays

**Inter-arrival delay**
duration between each qubit event and its nearest-in-time detector pulse

**Coincidence:**
a qubit event with an inter-arrival delay < 23 μs (center bin)




$$\underbrace{r_{QS}}_{\text{measured}} = \underbrace{r_{QS}^{\mu}}_{\text{cosmic ray}} + \underbrace{r_{QS}^{acc.}}_{\text{accidental}}$$

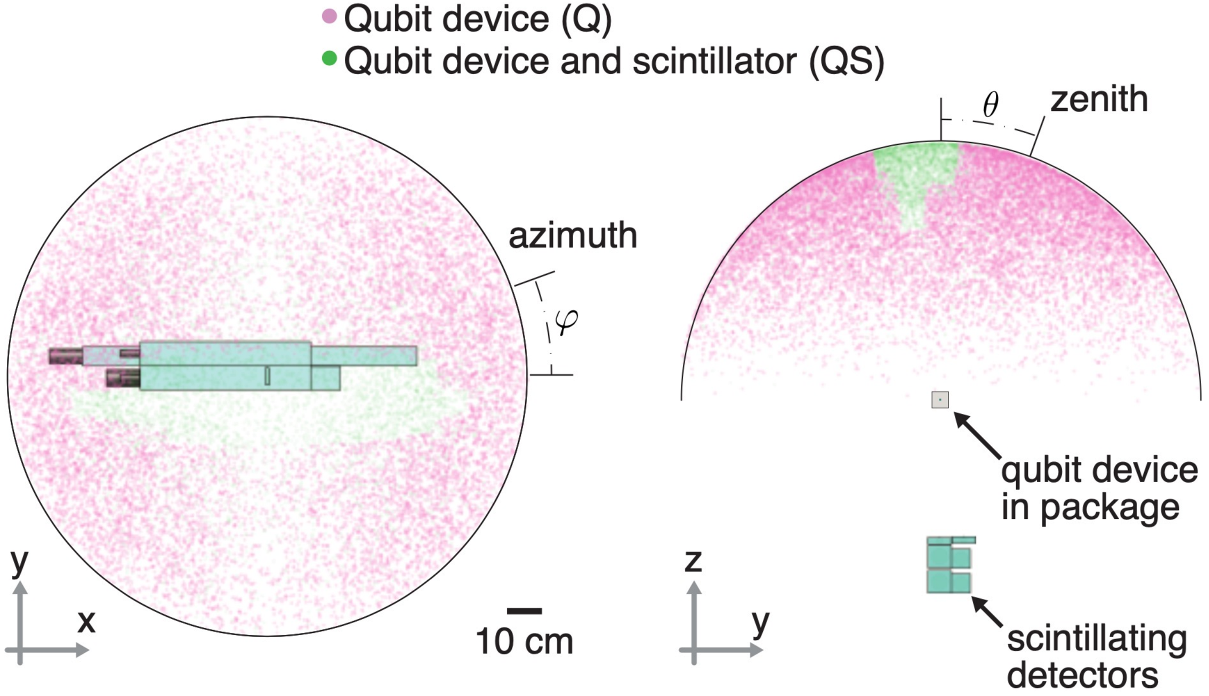
$r_{QS}^{acc.}$ **Background (accidental) coincidence rate:** 1/(42 hours)

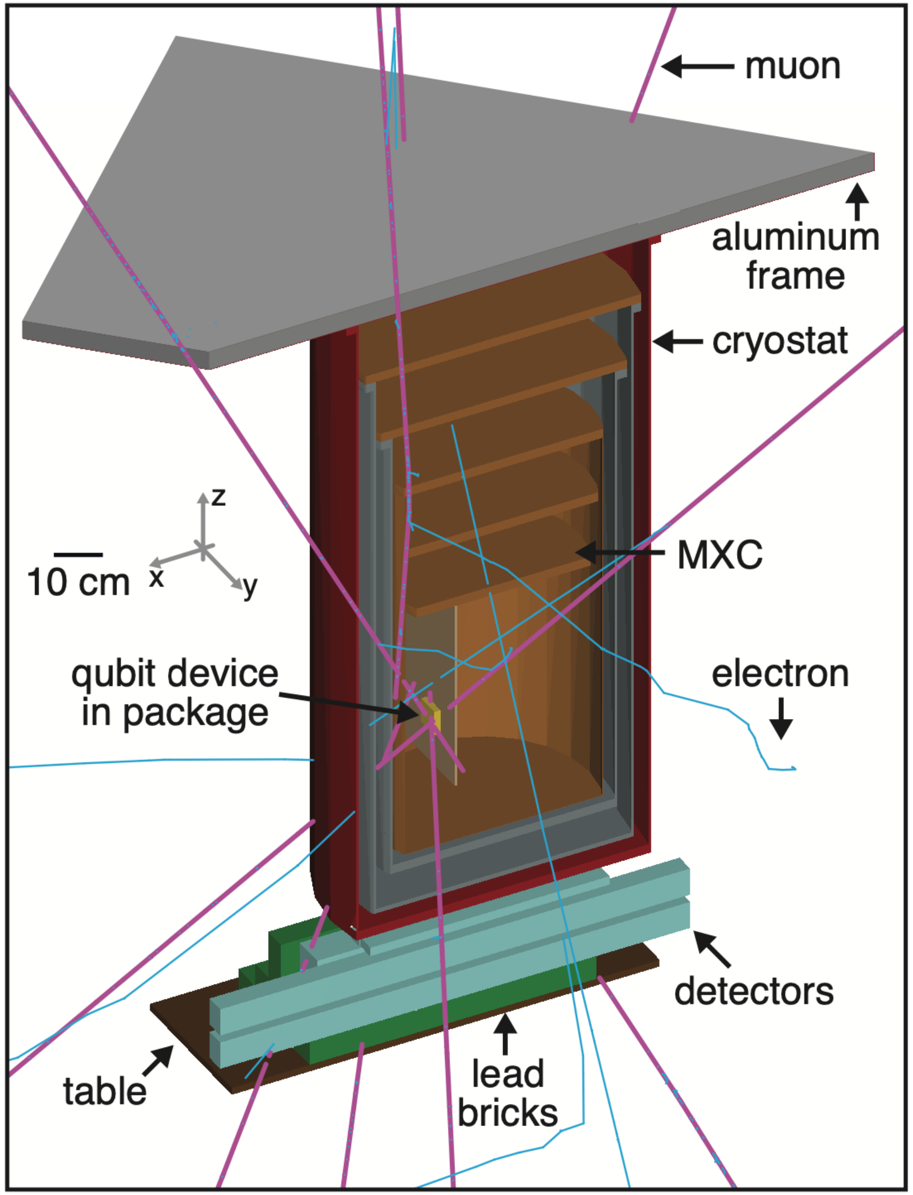
$r_{QS}^{\mu}$ **Cosmic ray & qubit event coincidence rate:** 1/(74 min)

# Rate of Relaxation Events from Cosmic Rays

**Coverage**: the portion of cosmic rays that impact the qubit array substrate *and* detectors

$$C_{\mathrm{QS}} = 13.3 \pm 0.4\%$$ (from Geant4 simulation)



# Rate of Relaxation Events from Cosmic Rays

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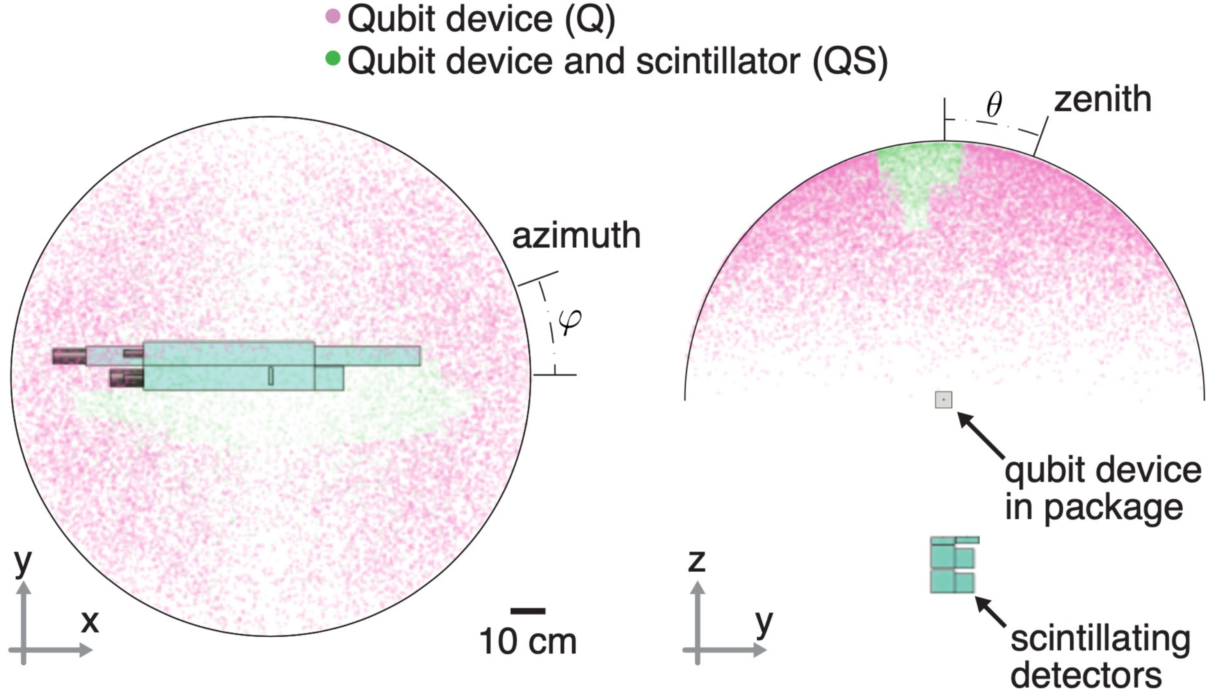
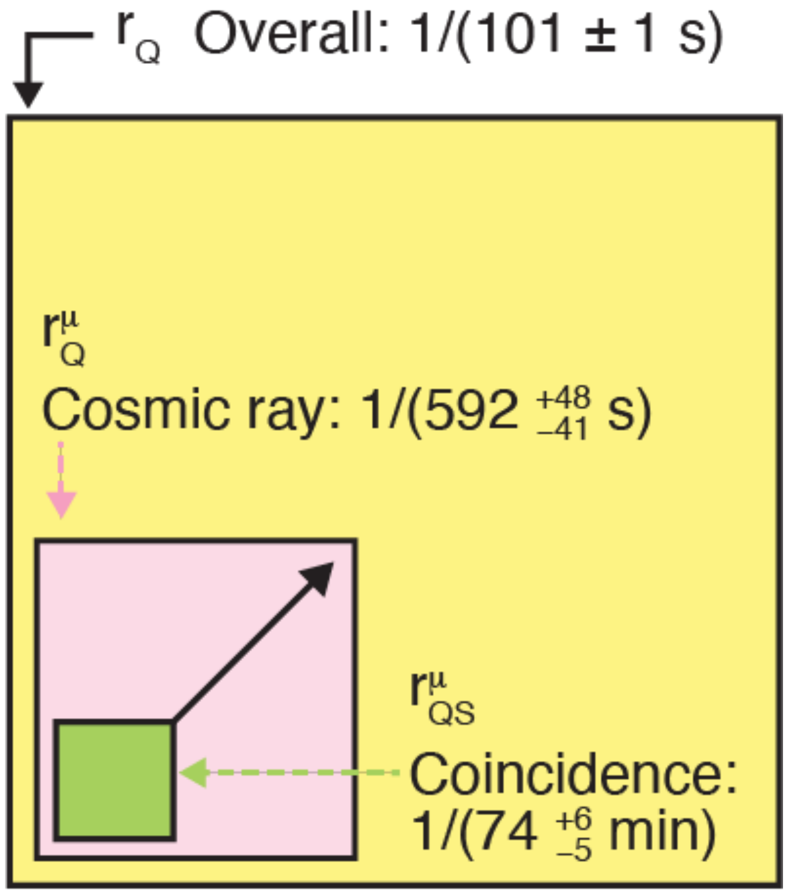


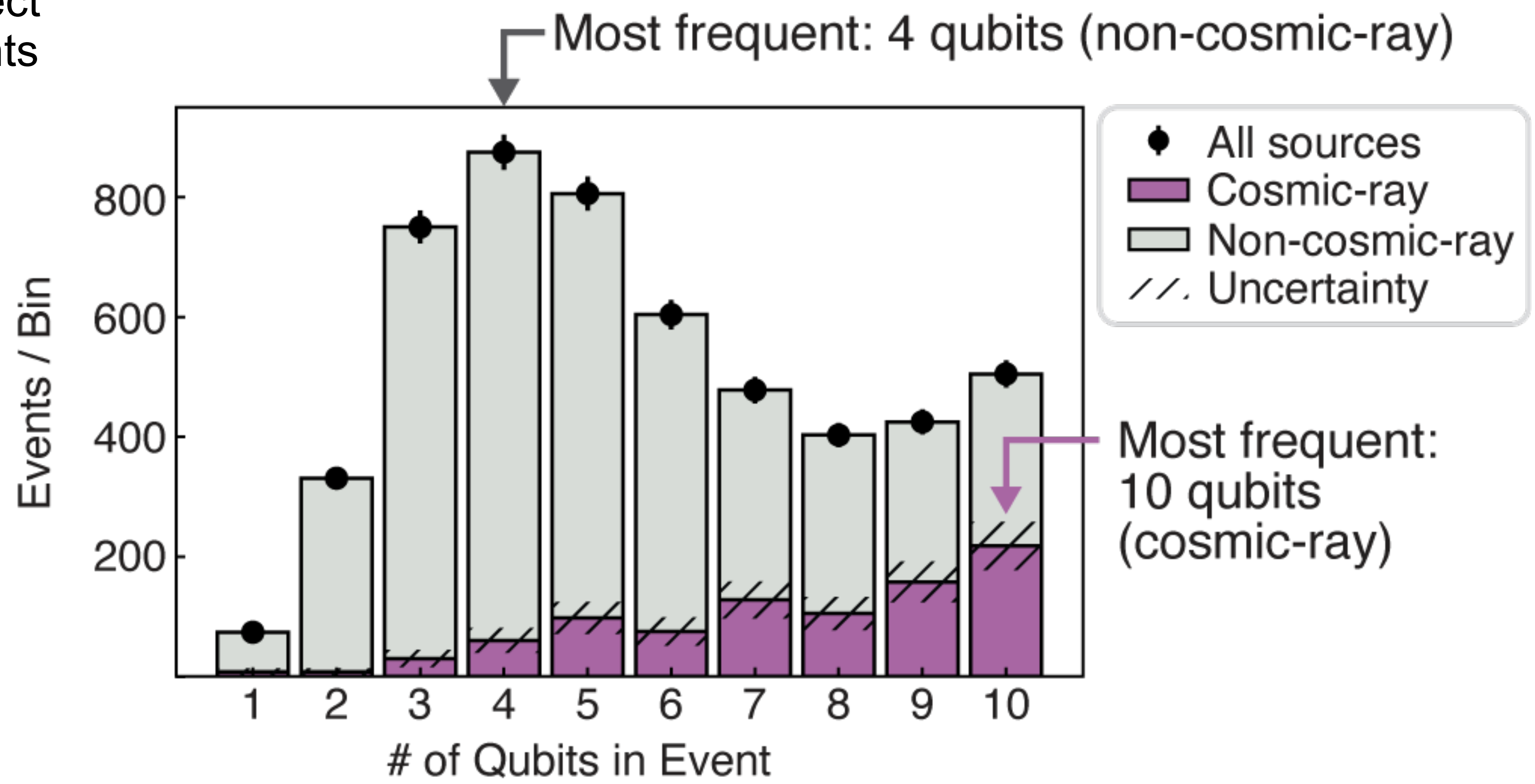

Cosmic rays account for 17±1 % of all spatiotemporally correlated relaxation events

$$r^{\mu}_{\mathrm{Q}} = (1/74\,\mathrm{min}^{-1})/13.3\% = 1/(10\,\mathrm{min})$$

consistent with muon flux!

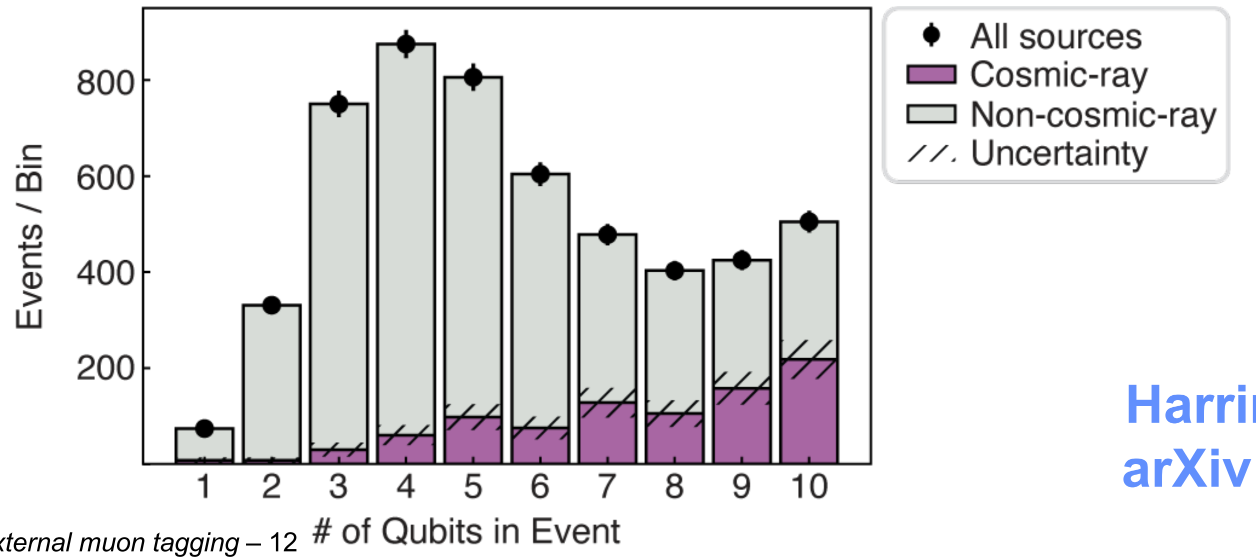
# Severity of Cosmic-ray Induced Qubit Errors

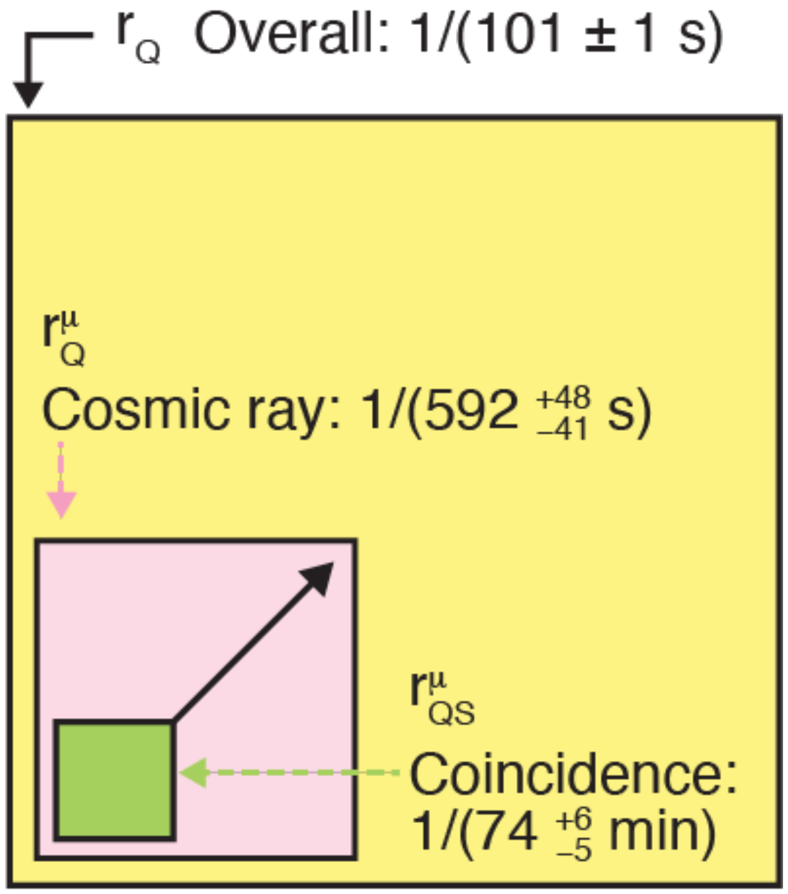
- Do more qubits participate in cosmic-ray induced events compared to events from other sources (e.g. gamma rays)?
  - Define qubit participation in an event if initial $T_1 \leq 5$ μs
  - Comic-ray events typically affect more qubits compared to events from non-cosmic-ray sources



# Key Results

- **Occurrence rate of qubit events from cosmic rays: 1/(10 min)**
  - **Consistent with the cosmic-ray muon flux**
  - **Effectively every cosmic-ray impact causes errors**
- **Cosmic rays account for 17±1 % of all observed events**
- **Cosmic rays affect more qubits compared to non-cosmogenic event sources**




**Harrington, et al. arXiv:2402.03208**

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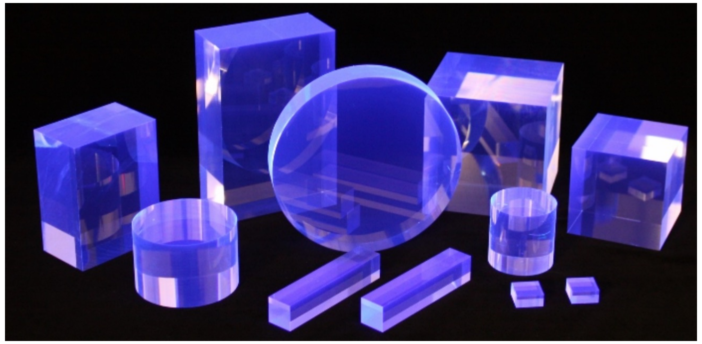
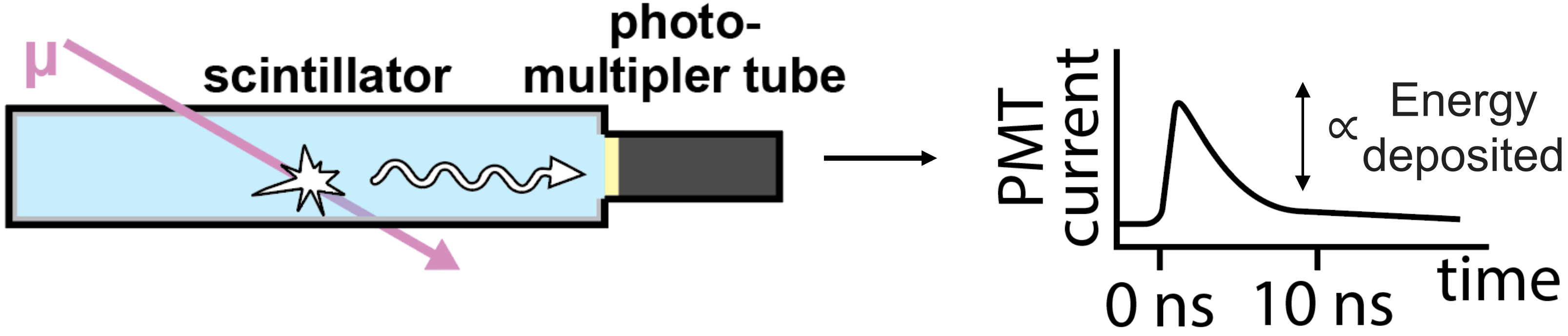
# Cosmic Rays in the Laboratory

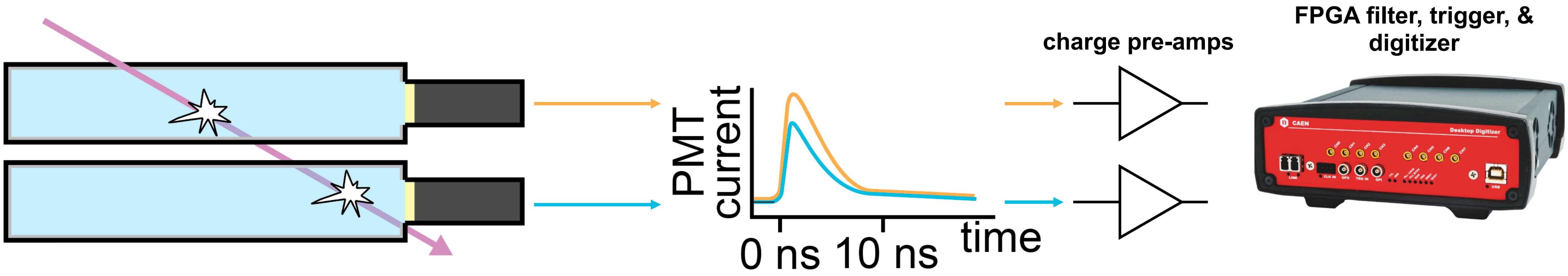
## Detection of ionizing radiation with a scintillating detector

**Scintillating polymer**






## Detector Coincidence Event



## Average Decay Rate Change (over all 9460 events)