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Multi-MeV Energy Depositions as a Source of Chip-Wide Correlated Events in Superconducting Devices

Samuel L. Watkins

CPAD Workshop 2026

PNNL-SA-228522

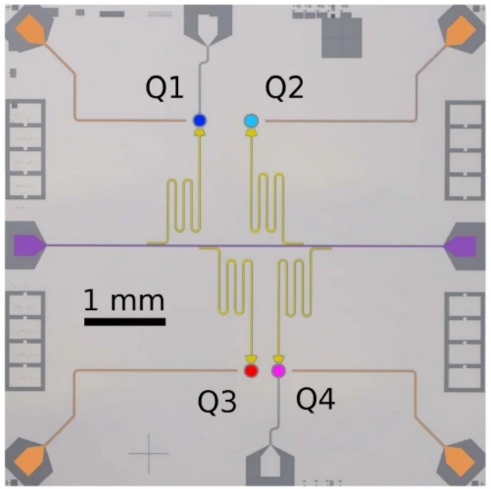


U.S. DEPARTMENT OF ENERGY BATTELLE

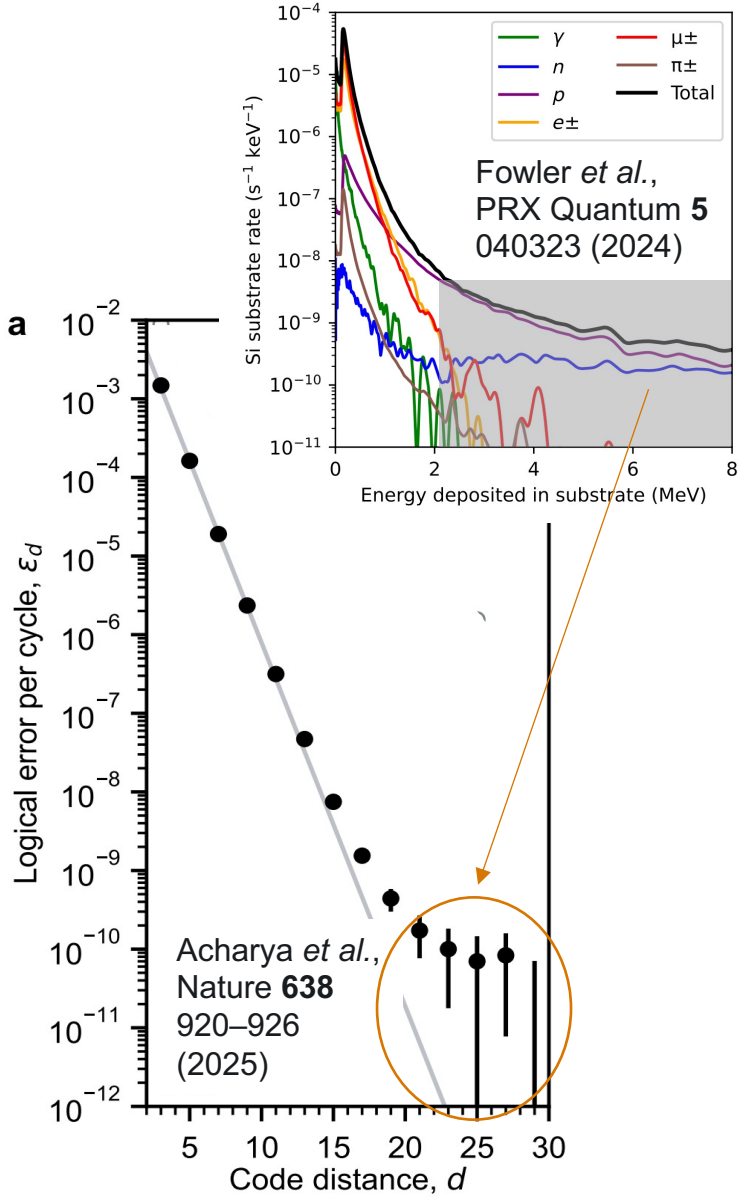
PNNL is operated by Battelle for the U.S. Department of Energy

Evidence for high-*E* cosmic rays as Culprit of Chipwide Events

- Order 1/hour/cm^2 cosmic protons (p) and neutrons (n) w/ $E \gtrsim 2$ MeV modeled and measured by Fowler is suggestive as an explanation of 1/hour uncorrectable faults in Acharya.
- Separate regional charging (ionization → e/h trapping) and global T_1 suppression (phonon-mediated) phenomenology in Wilen and Bratrud.



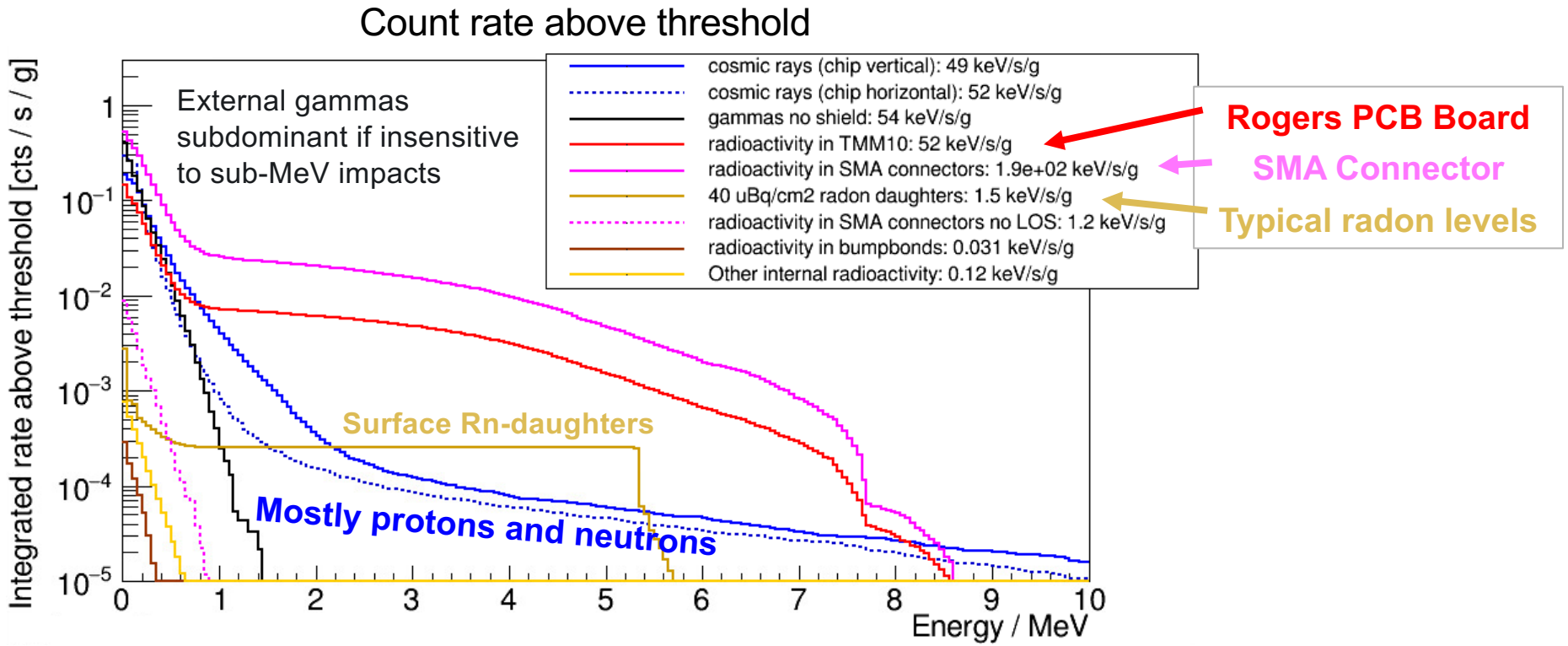
1. Regional ($\lesssim$1 mm): correlated charging events ($Q_1 \leftrightarrow Q_2$, $Q_3 \leftrightarrow Q_4$) scale w/ γ rate
2. Chip-wide: correlated T_1 suppression, but charging events ($Q_1 \leftrightarrow Q_3$) suppressed underground



Wilen *et al.*, Nature **594** 369 (2021).
Bratrud *et al.*, Nature Comm. **16** 9906 (2025).

Potential Problematic Radiation Sources

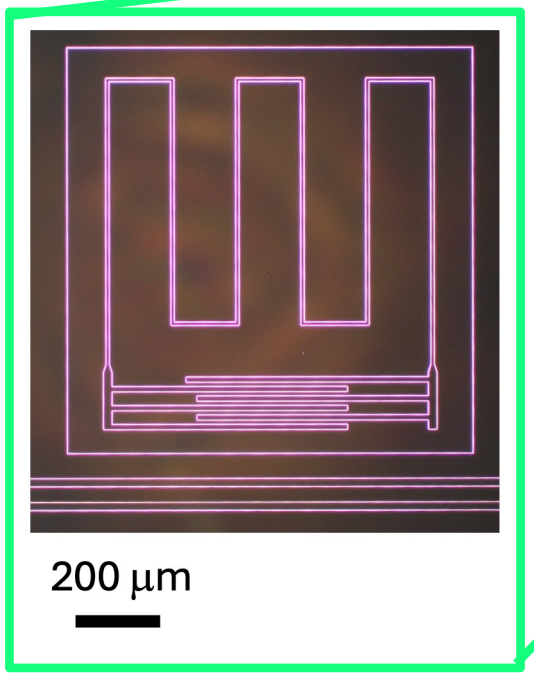
Loer *et. al.* [1] identified some internal components that can dominate the total radiation budget, especially at higher energies.

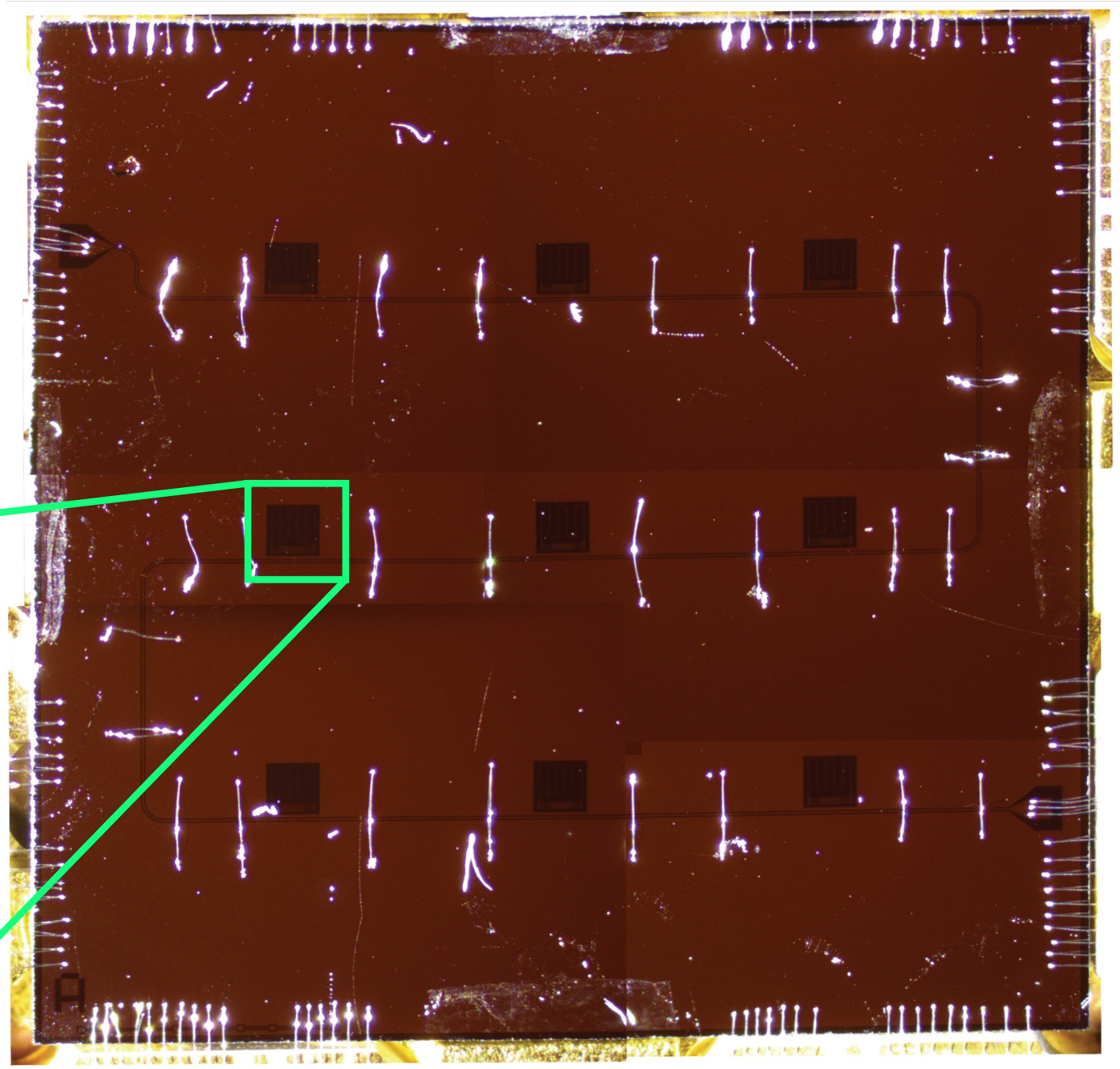


[1] Loer *et al.*, JINST **19** P09001 (2024)
w/ additions stimulated by Poudel, Temples et al. arXiv:2606.00473

Device Setup

- 3x3 MKID array from LLNL
  - Sapphire substrate (1 g)
  - 19.6 mm x 19.6 mm x 0.65 mm
  - Full ground plane

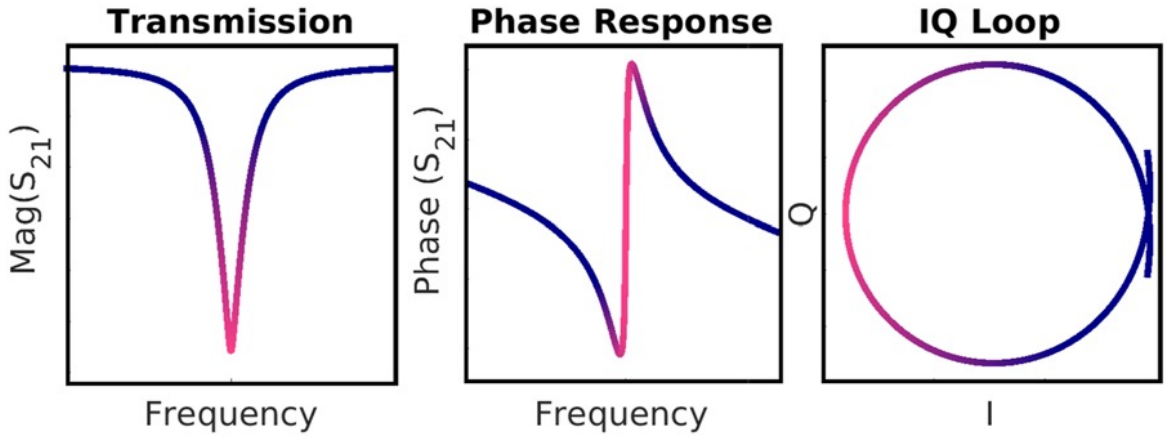


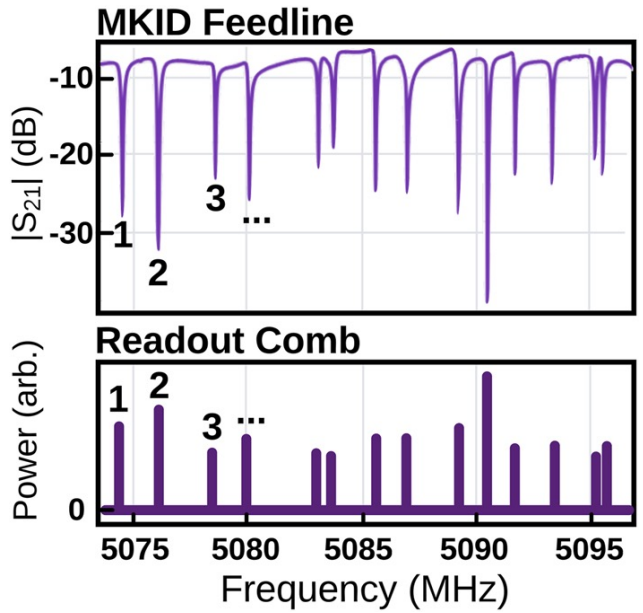


MKID Readout Basics

$$S_{21}(f) = 1 - \frac{Q_r/Q_c}{1 + 2jQ_r\left(\frac{f - f_r}{f_r}\right)}$$

- Send a tone at the resonant frequency of the MKID
- Read out the complex transmission (S_{21}) over time
- Absorption of energy will shift and broaden a device's LC resonance
- To read out many resonators simultaneously, send a comb of frequencies
  - *i.e.*, frequency multiplexing
- Threshold trigger on phase, which is highly sensitive to energy depositions



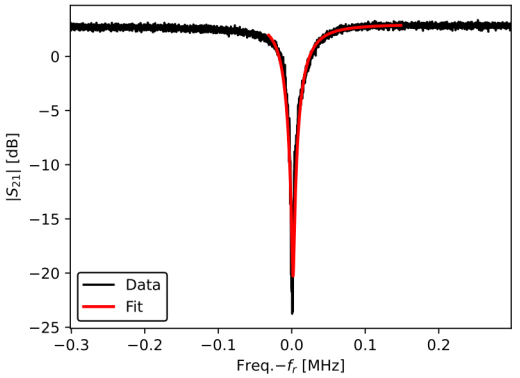


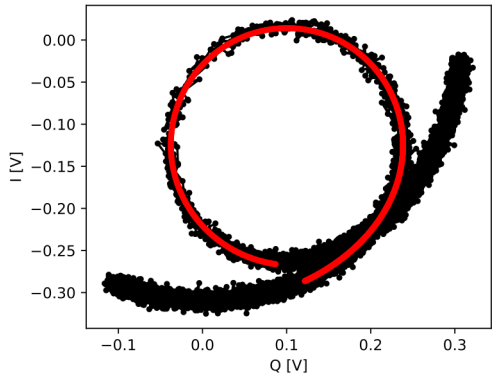
Figures from J.P. Smith, et al., *Rev. Sci. Instrum.* 95, 114705 (2024)

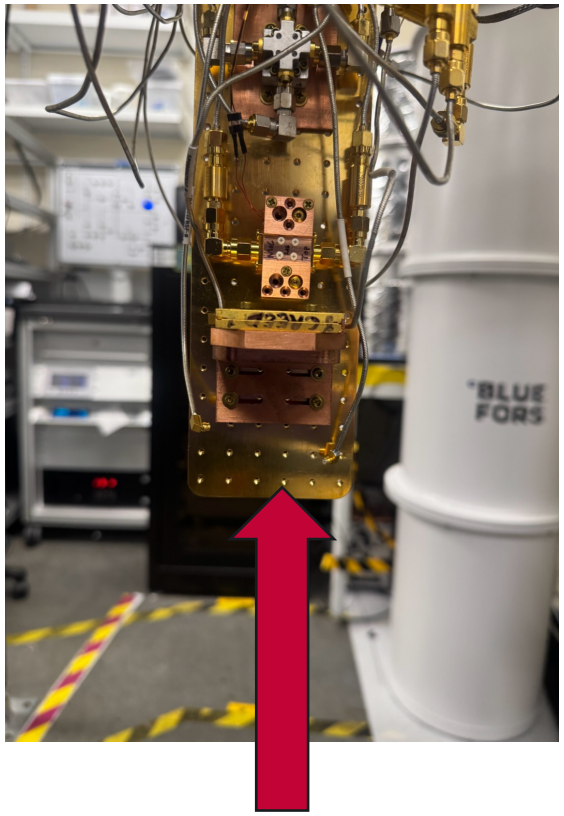
Device Setup

- 3x3 MKID array from LLNL
  - Sapphire substrate (1 g)
  - 19.6 mm x 19.6 mm x 0.65 mm
  - Full ground plane
- Resonator characteristics
  - $f_r \in (5.47, 5.58)$ GHz
  - Spacing: 4 MHz to 18 MHz
  - $Q_\ell \sim 10^5, Q_i \sim 10^6$
- Radiation sources:
  - Ambient background
  - Cs-137 (outside fridge)
  - Po-210 (in housing)

Example S_{21} fit:

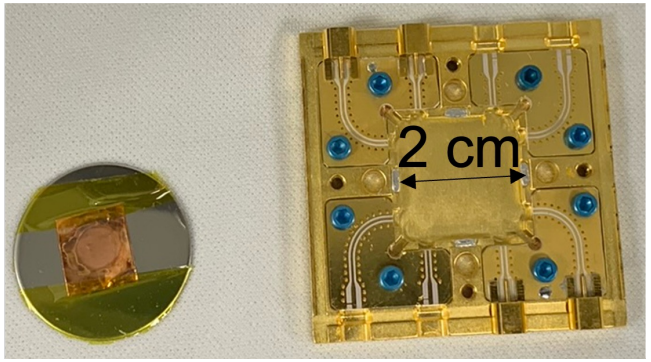






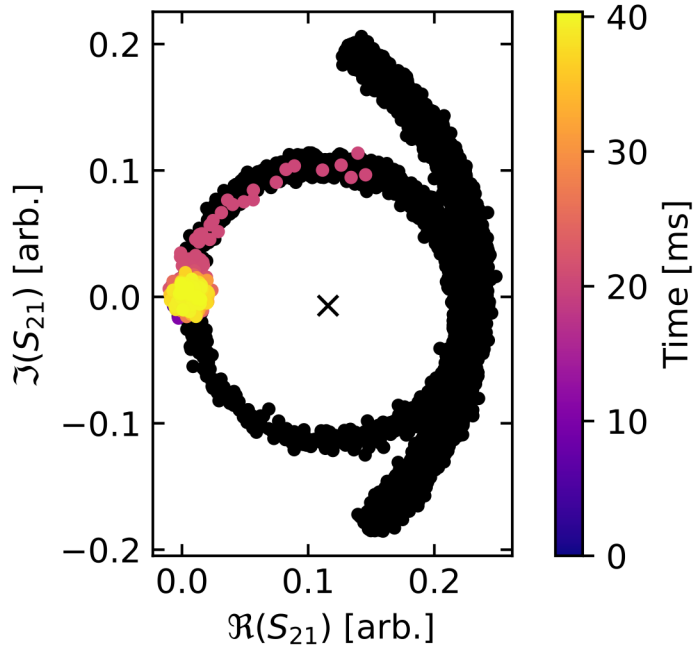
Cs-137 source (7.5 MBq)

Alpha source (~1 decay per min.)



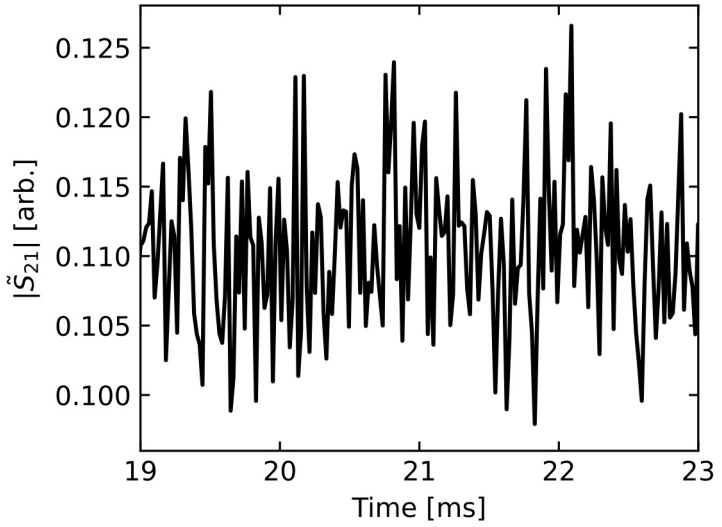
Example Event

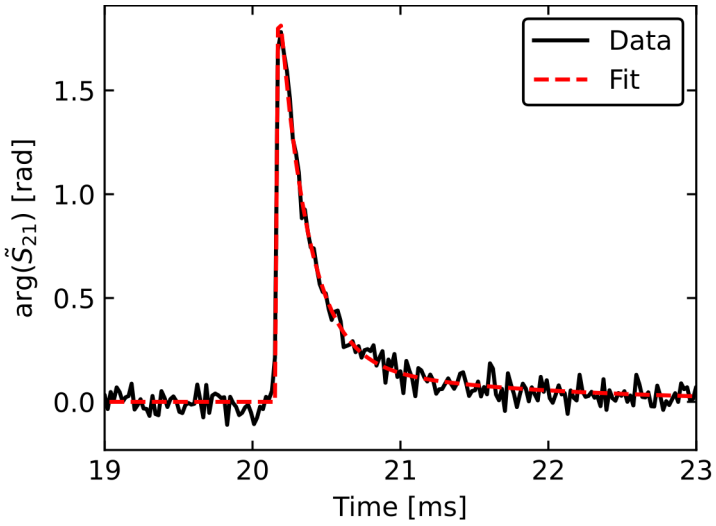
- Characteristic event for amplitude extraction
  - In this case, no other coincidence events

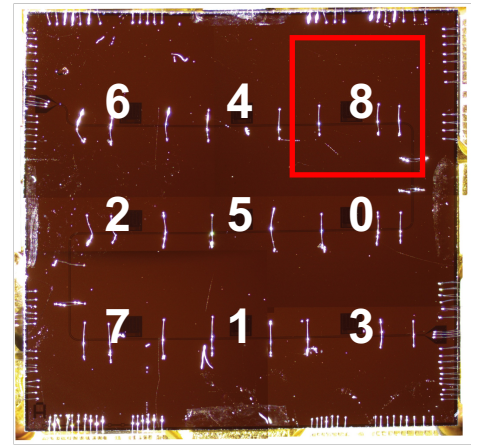


Abs.

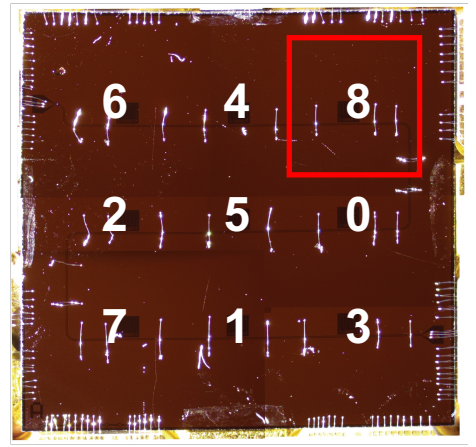
Phase



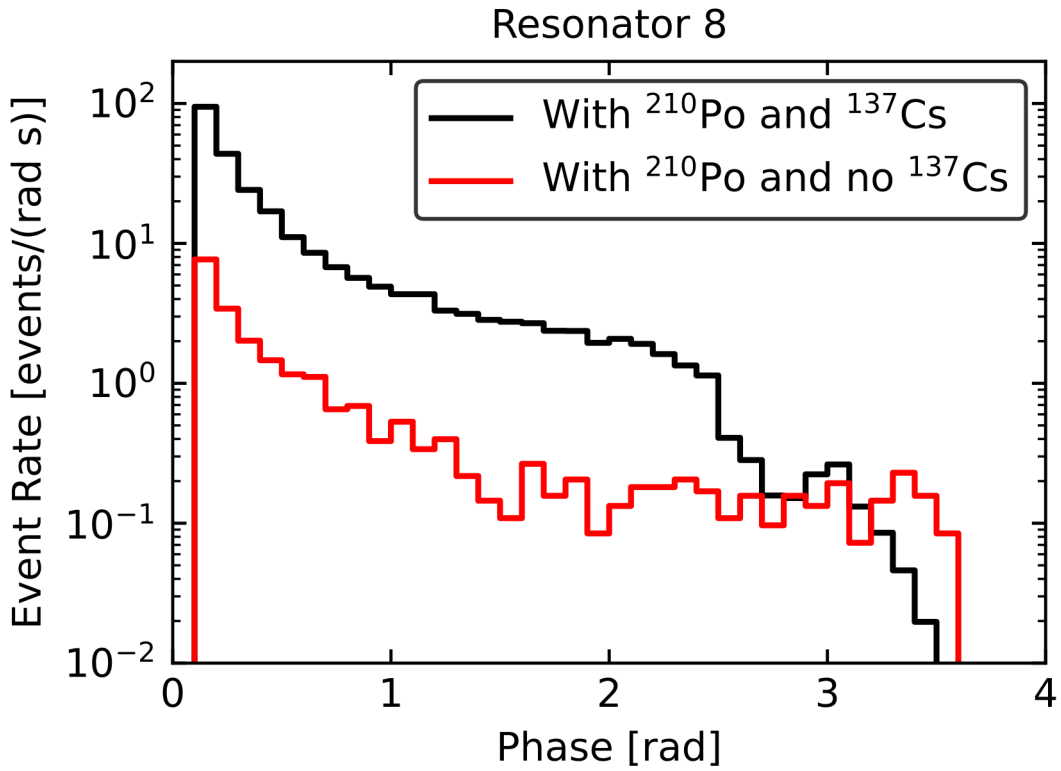




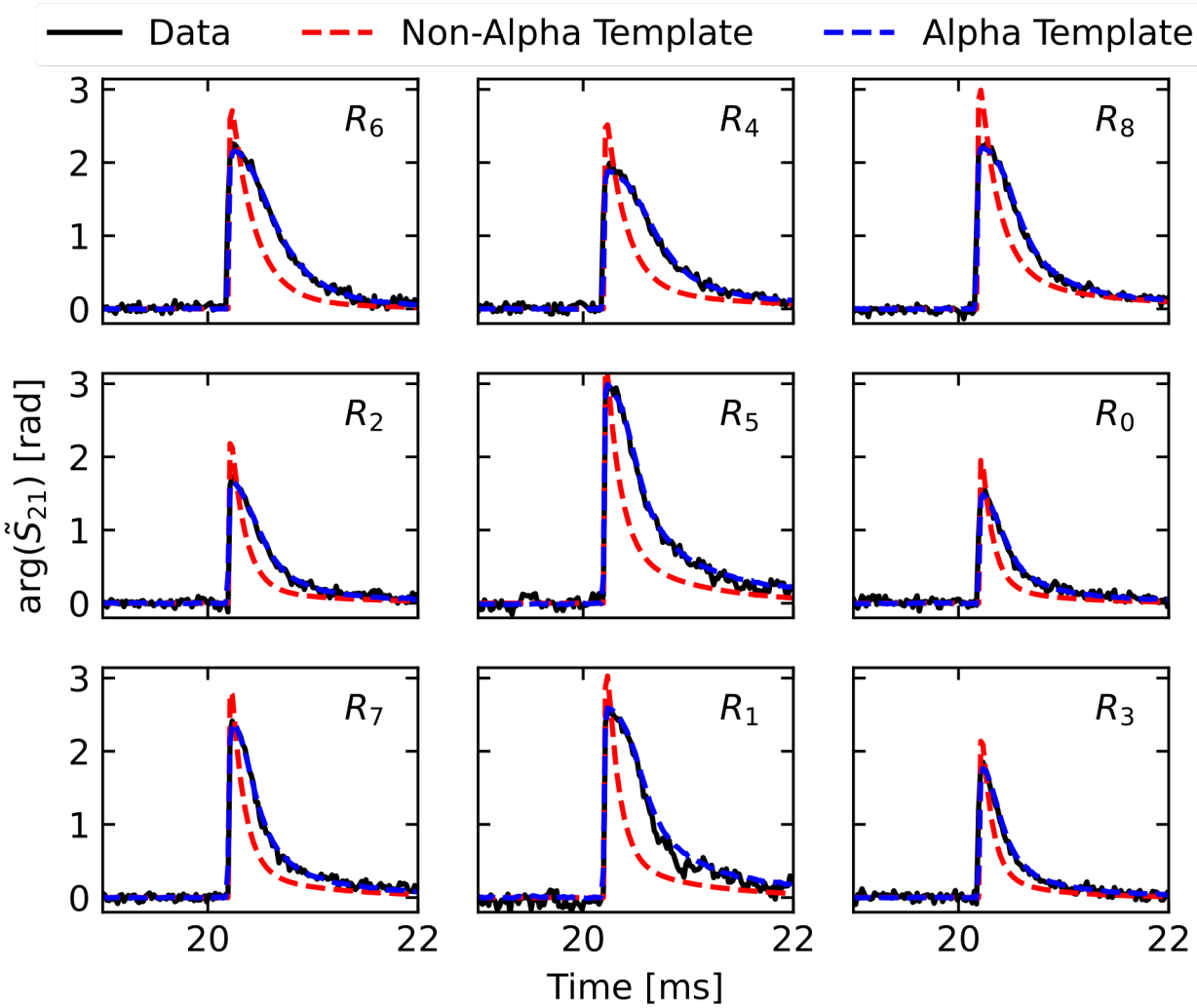
Characteristic Resonator Spectrum



- Compare spectra for a specific resonator
  - With and without Cs-137 source
- Cs-137 shows a clear increase in rate
- Only highest energies are consistent between the two spectra
- Number of variables hidden in these spectra
  - Let's dive in!



Chip-Wide Alpha Event



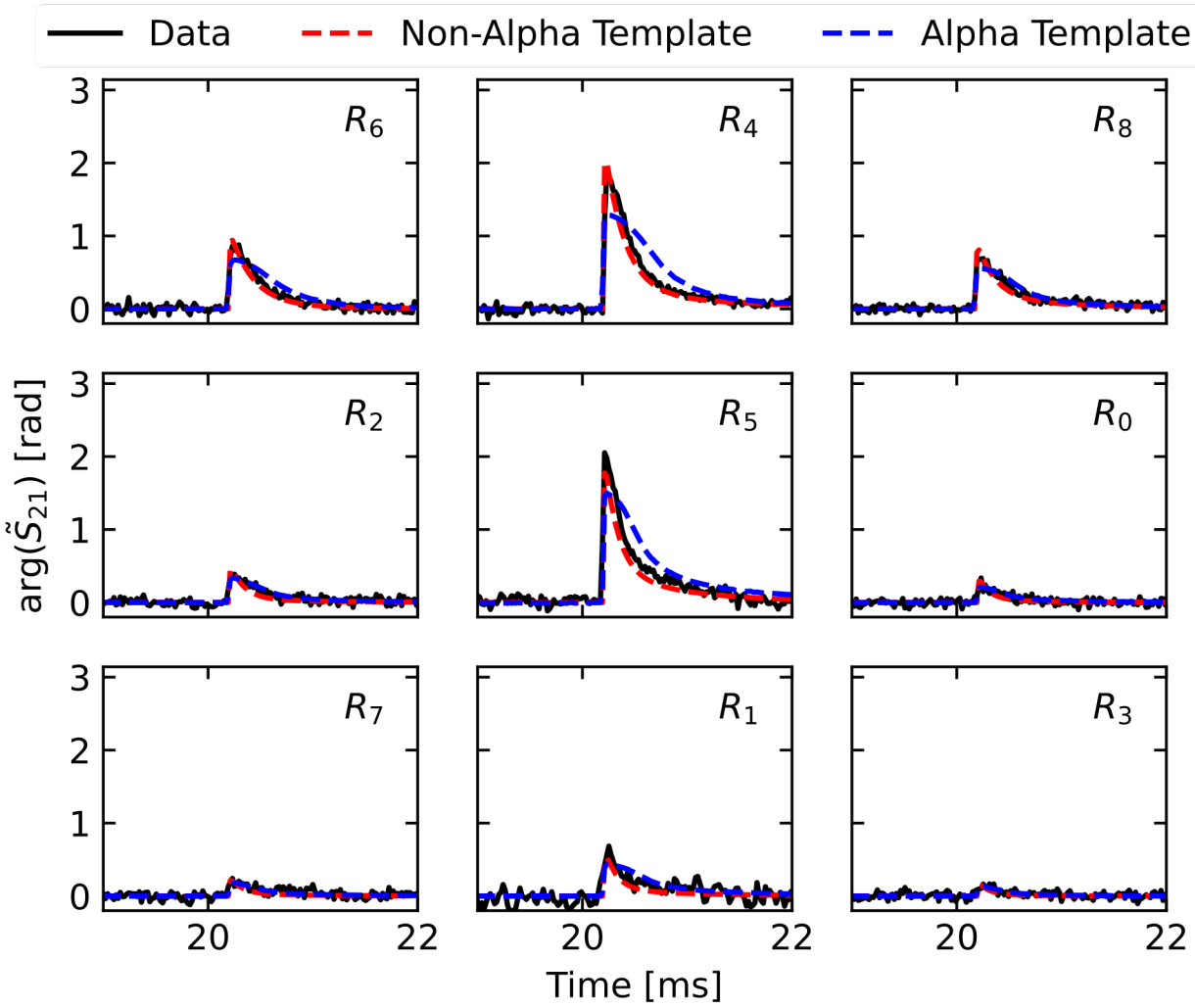


alpha-like

not alpha-like

- Alpha events:
  - Slow recovery times (~ms)
  - Saturated pulses (all resonators are pushed fully off resonance)
  - Delocalized (no positional dependence)

Chip-Wide non-Alpha Event



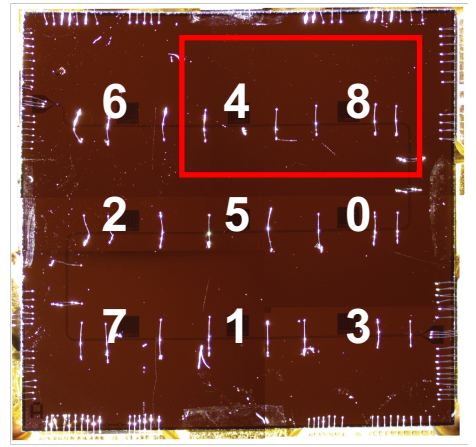


alpha-like

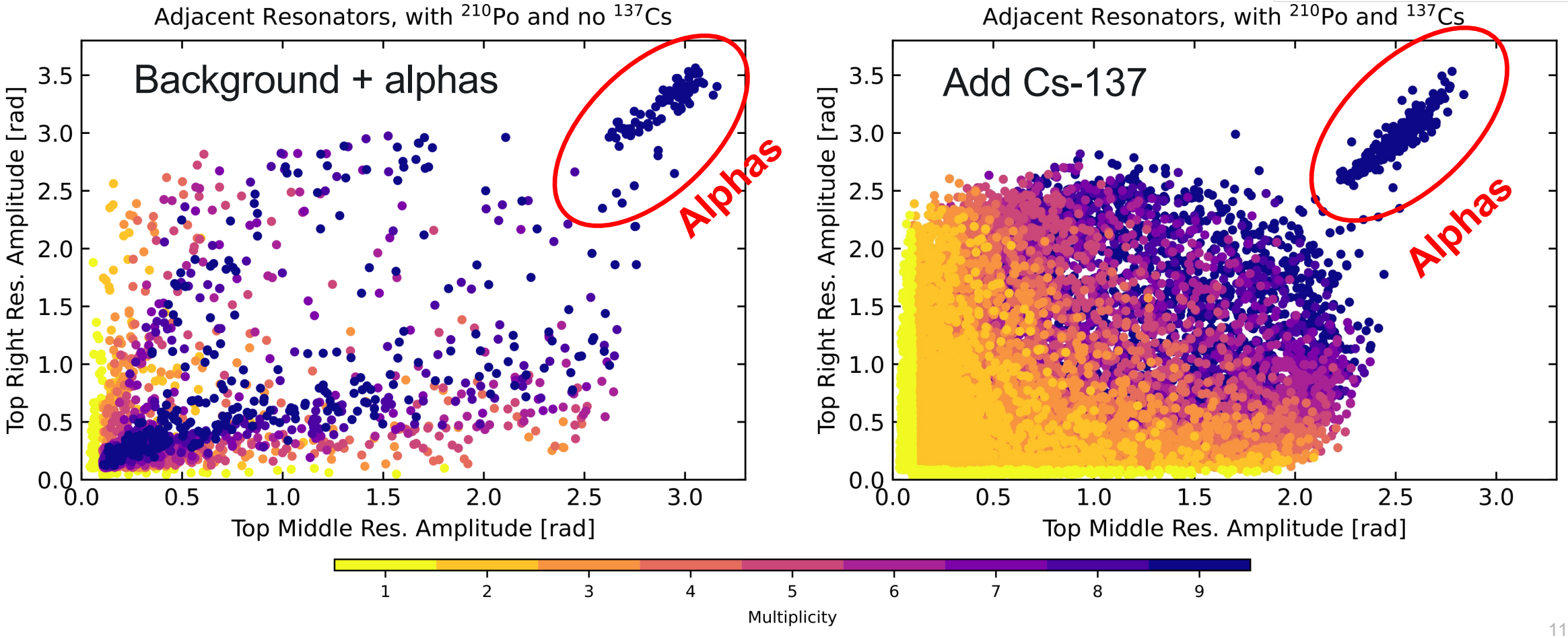
not alpha-like

- Non-alpha events:
  - Fast initial recovery times ($\sim 200\ \mu s$)
  - ms-scale secondary recovery times
  - No saturation
  - Significant pulse shape variation, in both energy and position

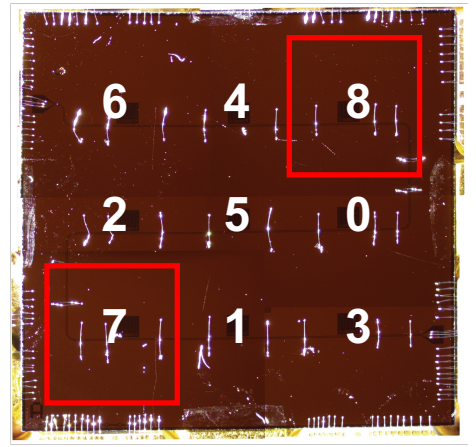
Shared Events on *Adjacent* Resonators



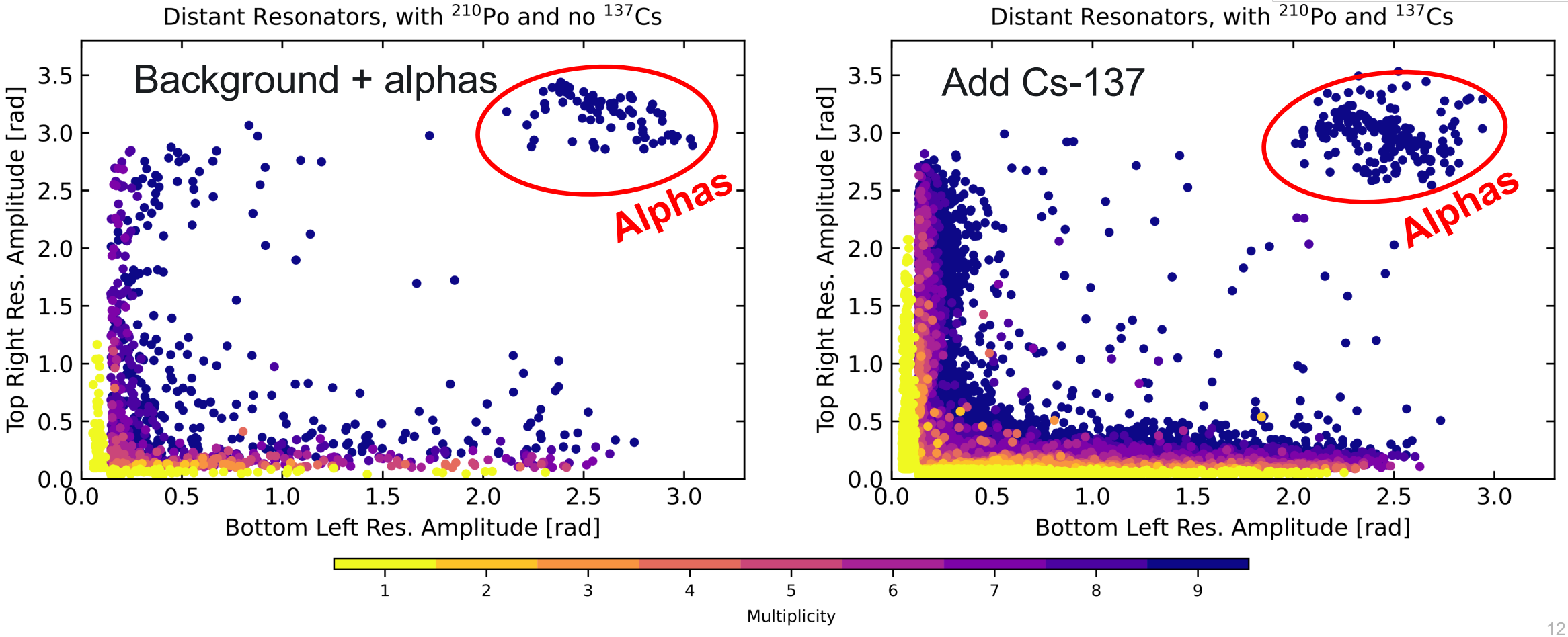
- Resonators 4 and 8 are adjacent



Shared Events on *Distant* Resonators

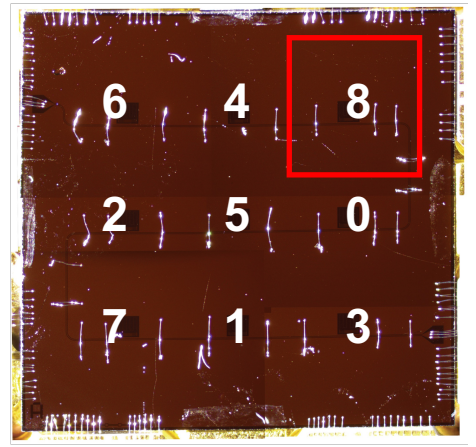


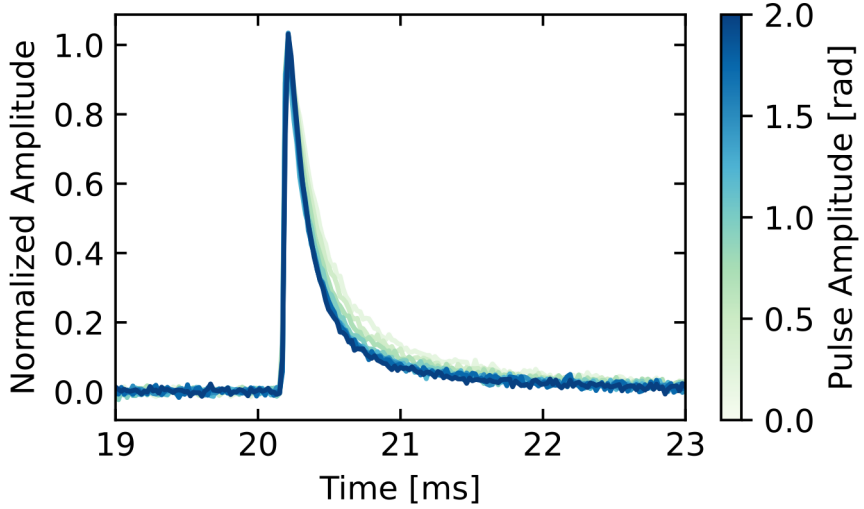
- Resonators 7 and 8 are opposite corners

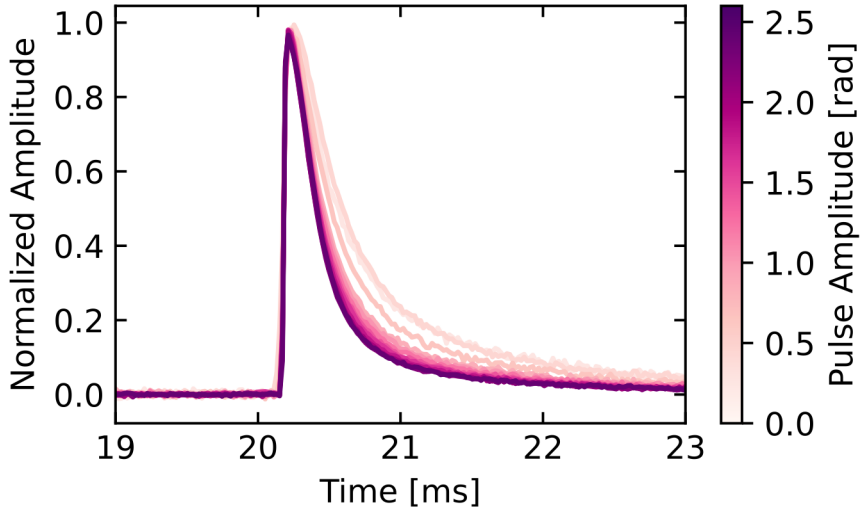


Non-Alpha Pulse Shape Variation

- Dependence on:
  - Energy (pulse height)
  - Multiplicity
  - Position
- Lots of underlying physics:
  - Faster recovery as pulse height increases (quasiparticle recombination)
  - Slower recovery as number of coincidences increases
- Modeling support from G4CMP
  - Ongoing work on matching these data to simulation







Alpha Event Rates



- Rate calculation:
  - Select via delta chi-square on alpha vs. non-alpha pulse shapes
  - Remove events with pileup
  - Correct efficiency via randoms
- Measured chip-wide event rates statistically consistent with simulation of Po-210 rates
  - Supports hypothesis multi-MeV events always create chip-wide correlations
  - The measured rate of chip-wide events leaves little-to-no room for other sources beyond these alphas

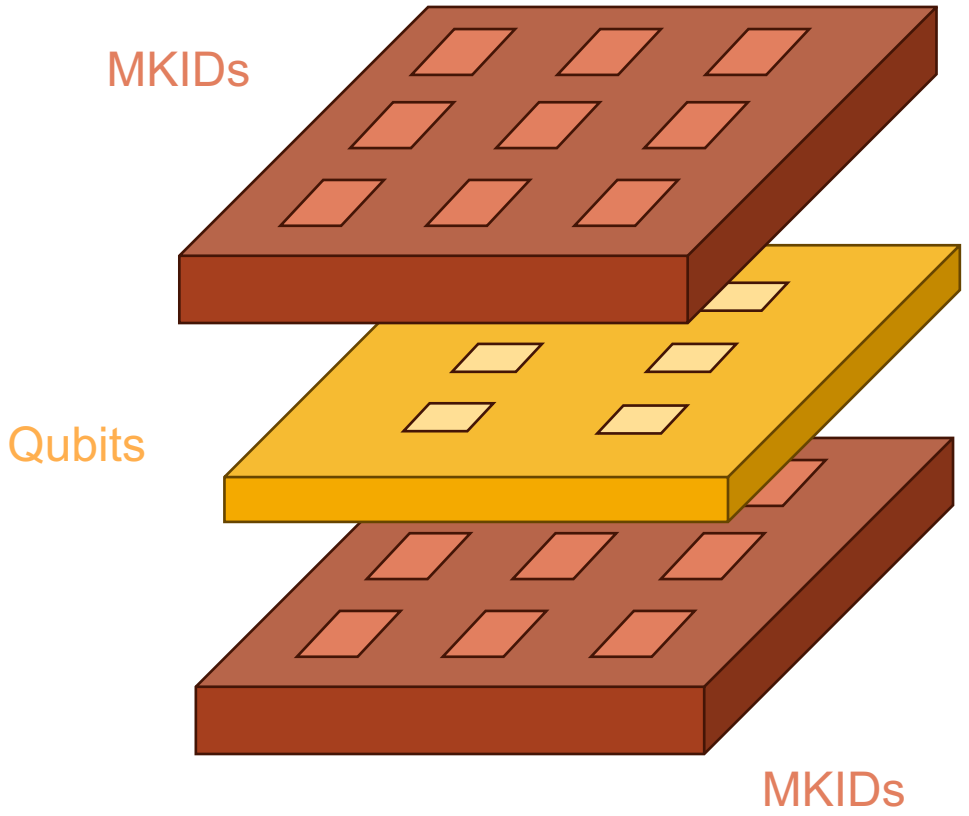
TABLE II. Measured and simulated interaction rates in the MKID chip attributed to alphas for both datasets.

Dataset	February 26	March 11
Livetime [min]	299.6	139.7
With ^{137}Cs Source	Yes	No
Pileup Cut Efficiency [%]	84.6 ± 0.7	98.8 ± 0.3
Chip-Wide Saturated Events	172	78
Measured ^{210}Po Rate [1/min]	0.68 ± 0.05	0.57 ± 0.06
Simulated ^{210}Po Rate[a] [1/min]	0.74 ± 0.11	0.70 ± 0.11

[a] Assumes 100% of alphas incident on the chip produce a saturated response in all nine resonators.

Towards Realizing *The LLNL Cosmic Sandwich*

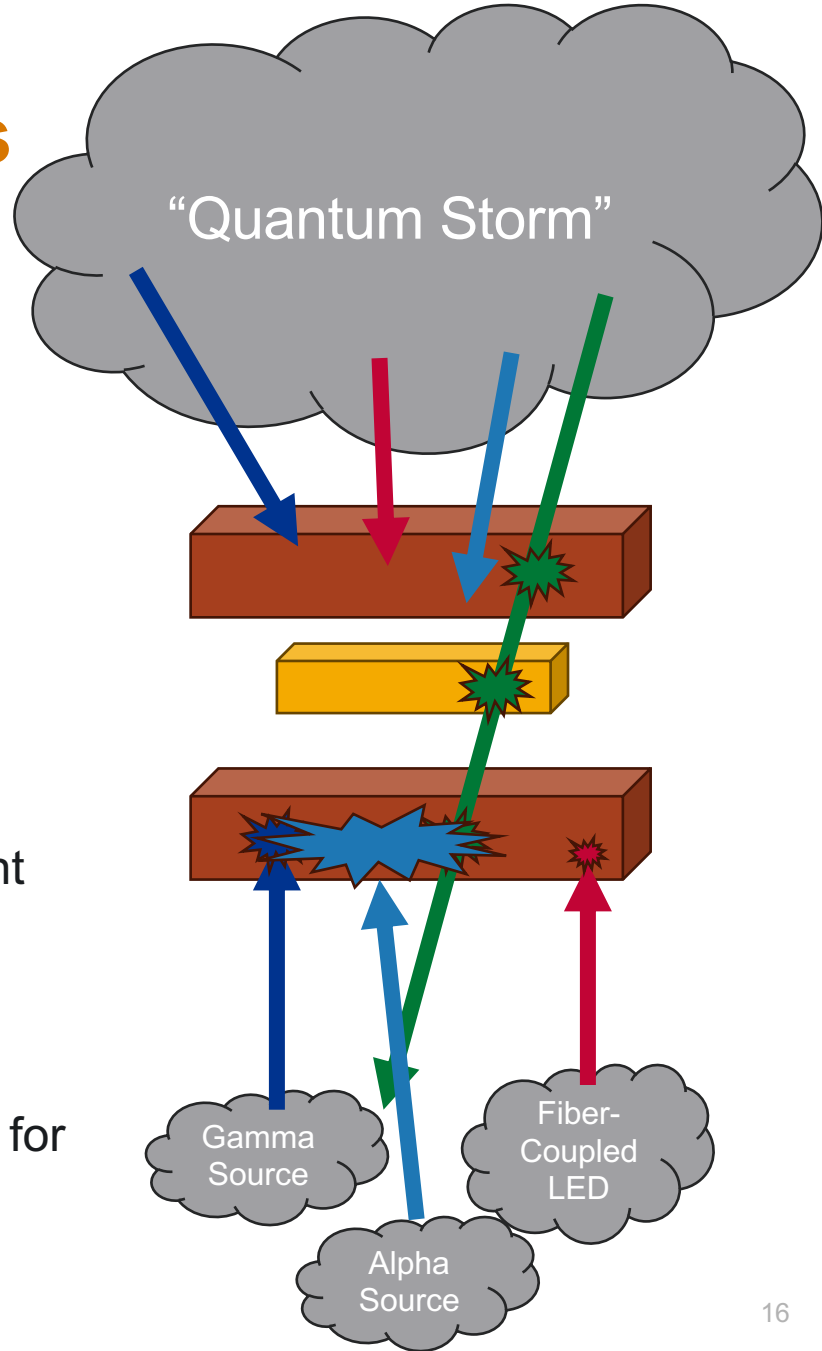
- A *quantum weather station* optimized for:
  - Coincidence detection in 3D
  - Excellent energy resolution
  - Testing qubit(-like) devices
- Goal: *quantum weather control*
  - Subject to various known radiation types
  - Identify which types cause the catastrophic, chip-wide errors
  - Further understand the underlying phonon dynamics with support from modeling



See also: A.R. Castelli, *et al.*, arXiv:2512.18171

Distinguishing Radiation Types

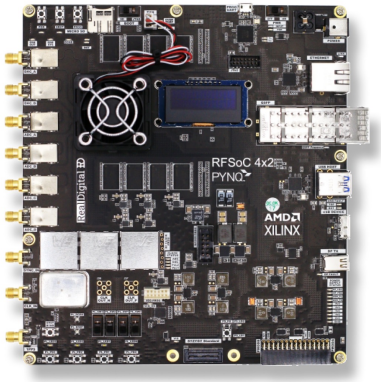
- Cosmic muons
  - Will penetrate and deposit energy in multiple layers
  - Tagging: add veto detectors with high solid angle
- X-rays/Gammas
  - Most likely to deposit energy in one layer
  - Tagging: introduce controlled gamma sources
- UV/Visible Photons
  - Detected in one layer, highly localized
  - Tagging: Fiber-coupled LED installed for precise control of event rate and location
- Alphas
  - Deposit MeV-scale energy very near the surface
  - Tagging: Custom alpha sources from ^{210}Po developed at PNNL for direct placement next to detectors



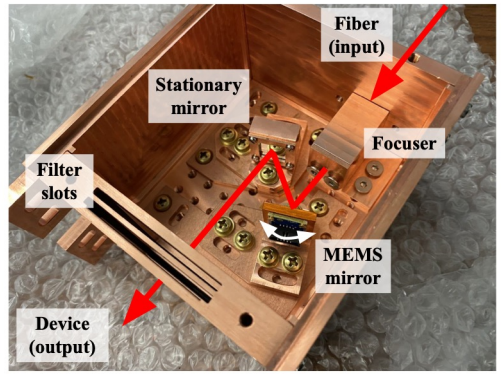
Summary and Outlook



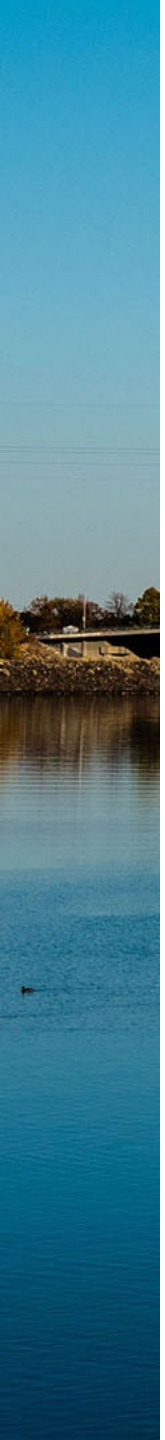
- **Alpha events *always* cause catastrophic events**
  - Detected event rates are consistent with expectation from Po-210
  - These events throw all MKIDs off their resonance
  - Cleanliness standards are critical for reduced correlated errors (e.g., radon plate-out)
- Addition of Cs-137 gamma source increases coincidences significantly, but not the amount of catastrophic events
  - Gap-engineered qubits are likely immune to these?
- Paper submitted to arXiv
- Future:
  - Full sandwich: multi-qubit chip sandwiched between two 25 MKID chips
  - RFSoC readout for multiplexing N resonators (SMuRF, t0 CRS)
  - MEMS scanner for positional sensitivity of optical photons (currently commissioning)



RFSoC4x2

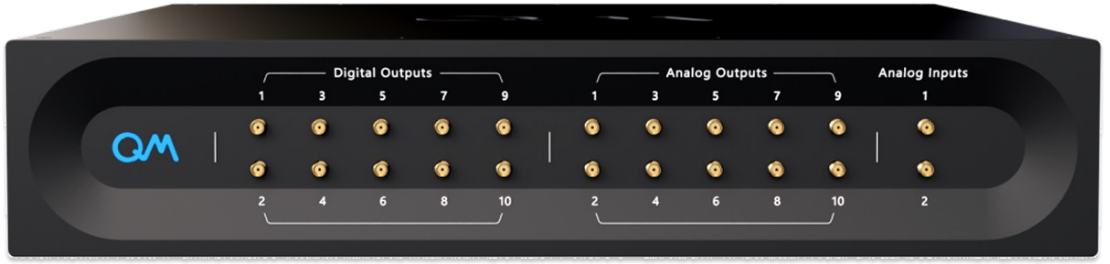


MEMS scanner: K. Stifter, *et al.*, arXiv:2405.02258

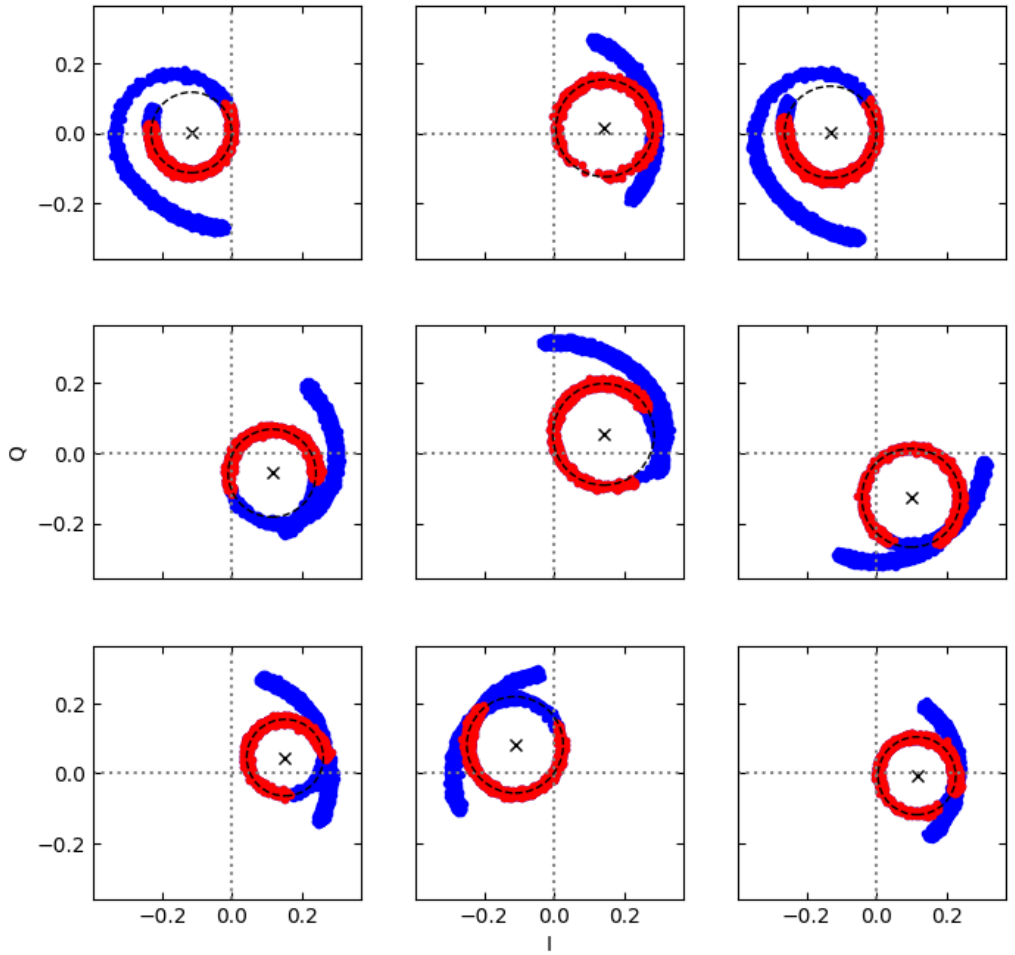


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Readout with OPX+

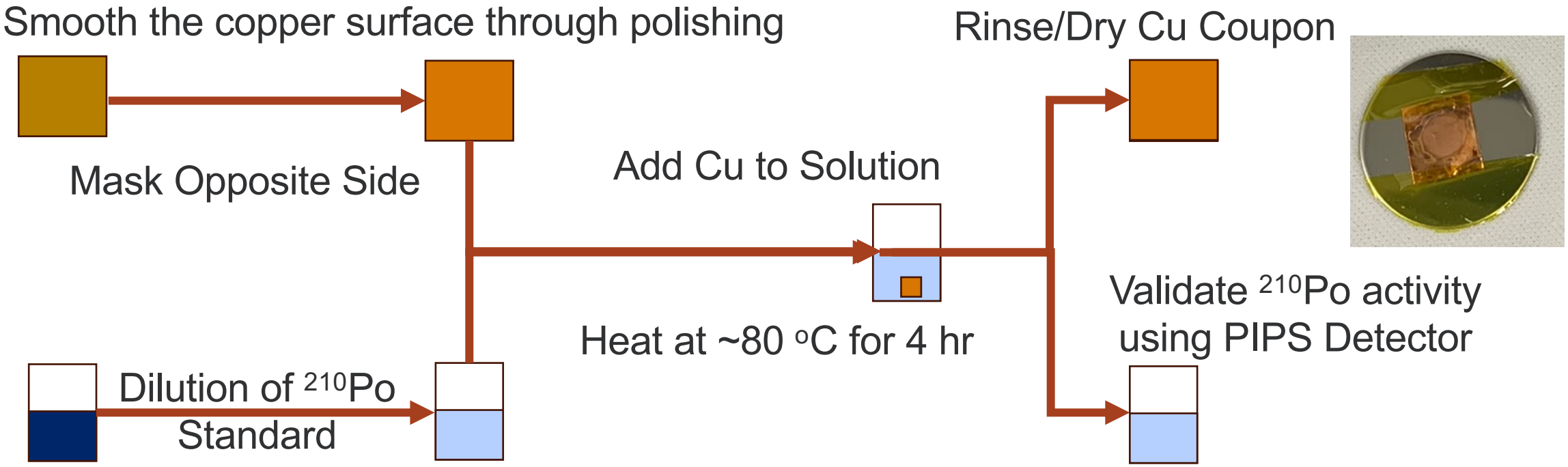


- All 9 resonators are multiplexed
  - Maximum possible with one QM OPX+
- To measure phase:
  1. Take frequency sweep of IQ
  2. Map the resonator loop to a circle
  3. Measure phase with respect to the center
- Continuous data is logged in ~7 s chunks
  - $\sim 20\ \mu s$ digitization rate with OPX+
- Apply offline optimum filter trigger with 5σ threshold to detect pulses
  - SPLENDAQ package (arXiv:2310.01279)
  - Merges coincident events into one event



Red = fit region

^{210}Po alpha source: Wet Chemistry Approach



Multiple copper coupons with deposited ^{210}Po can be made in a batch.
Various shapes/sizes can be accommodated. **Interested? Let us know.**
PNNL Max target activity to be at **releasable** levels is 20 dpm.

Monte Carlo Simulations

- Multiple MKID/qubit geometries recreated in Geant4
- Leverage G4CMP for phonon/QP transport

