Pacific Northwest NATIONAL LABORATORY

Lawrence Livermore National Laboratory

Radiation-Induced Correlated Events in Layered Superconducting Detectors

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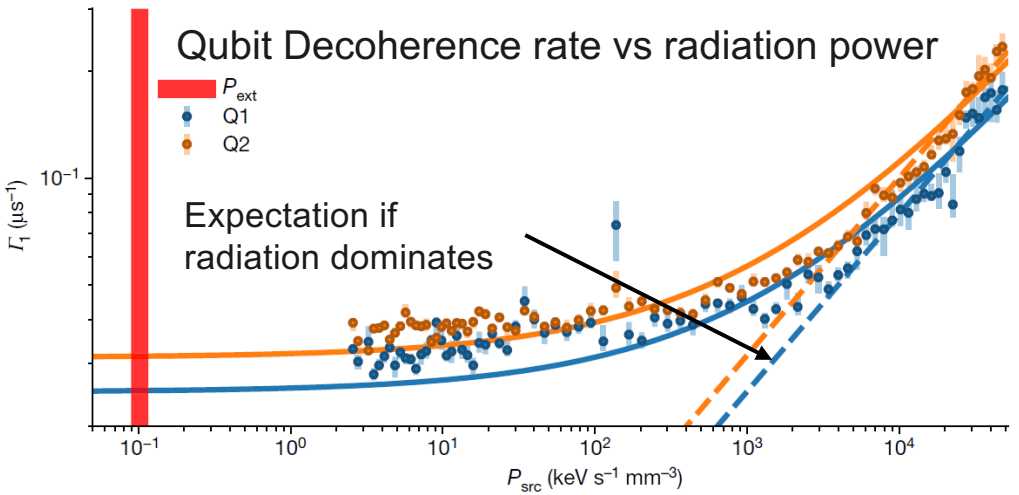
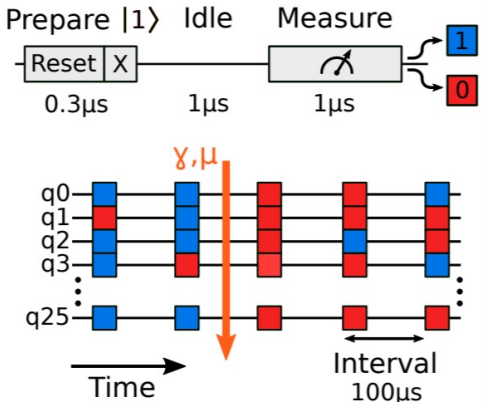
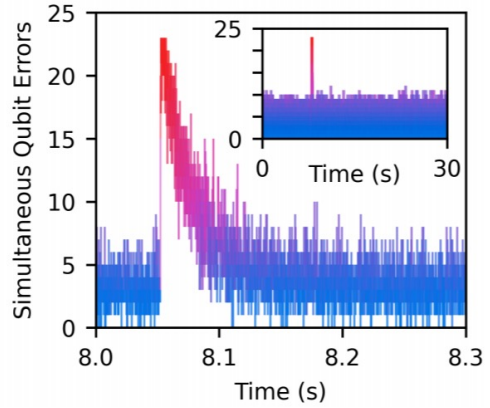
PNNL-SA-216879

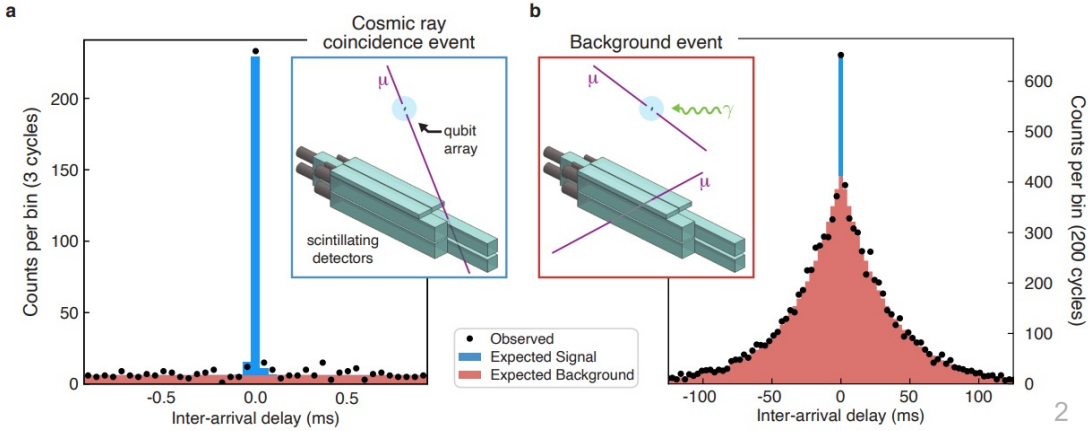
Ionizing radiation is a source of qubit errors

- Vepsäläinen et. al. [1] show reduced T_1 when a transmon is exposed to a radioactive source and demonstrate slightly improved T_1 with a <50% efficient lead shield.
- Wilen et. al. [2], McEwen et. al. [3] show correlated relaxation errors across multiple qubits; rates consistent with naturally occurring ionizing radiation.
- Harrington et. al. [4], Li et. al. [5] prove cosmic rays are the origin of some of the error burst events.
- Bandgap-engineered qubits are still limited by 1/hour rate events [6] that may be ionizing radiation-based
- ***Can we create a detector system to disentangle and characterize the most problematic ionizing radiation?***





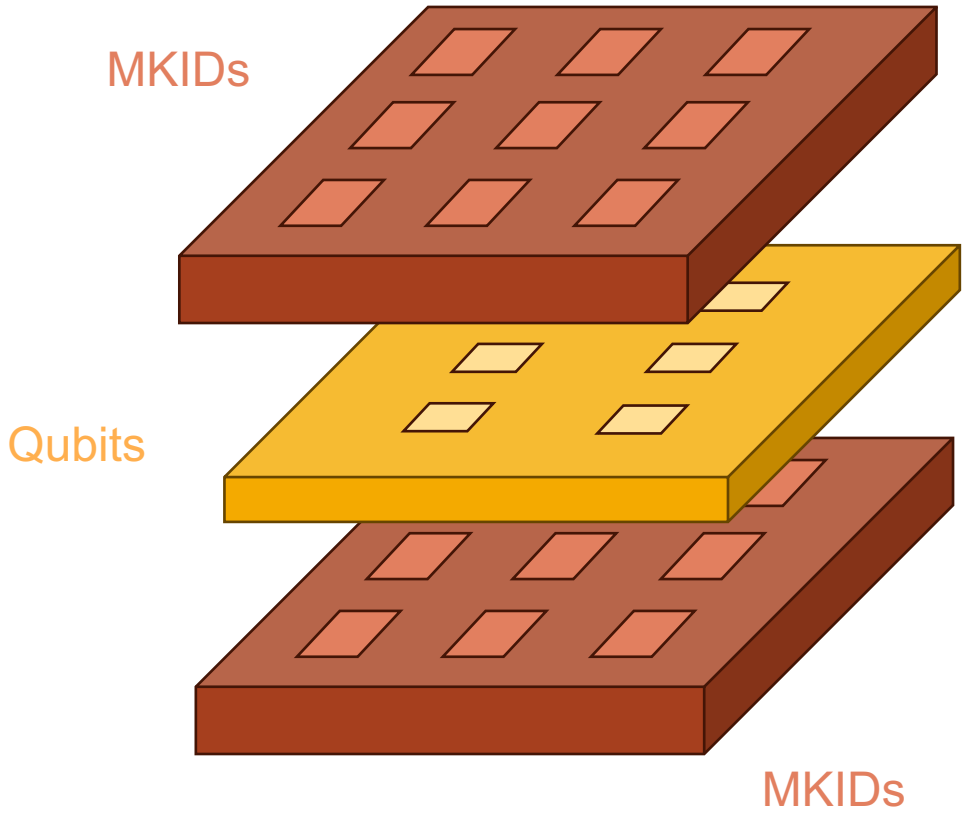




[1] Vepsäläinen *et al.* Nature **584**, 551–556 (2020)
[2] Wilen *et al.*, Nature **594,** 369 (2021)
[3] McEwen *et al.*, Nature Physics **18**, 107 (2022)
[4] Harrington *et al.*, Nat. Commun. **16**, 6428 (2025)
[5] Li *et al.*, Nat Commun **16** 4677 (2025)
[6] Google Quantum AI, Nature **638**, 920 (2025)

Presenting: *The Cosmic Sandwich* by LLNL

- A detector system optimized for:
  - Coincidence detection in 3D
  - Excellent energy resolution
  - Testing qubit(-like) devices
- Goal:
  - 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



MKID = Microwave Kinetic Inductance Detector

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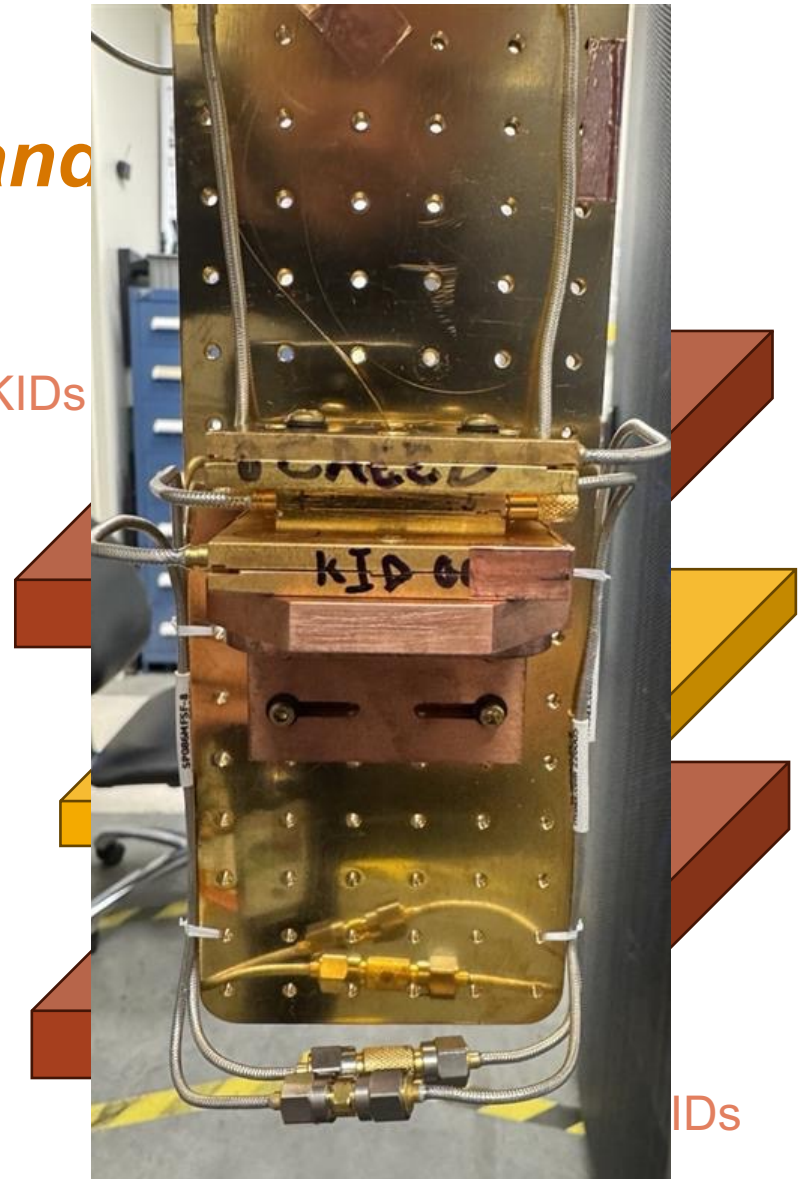
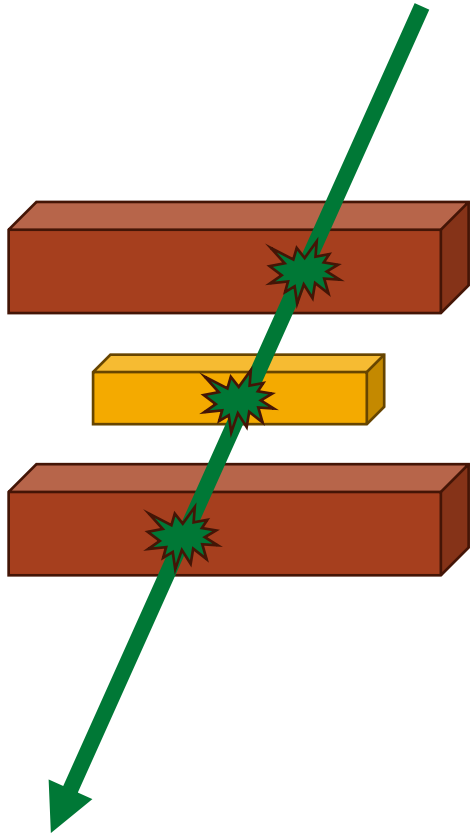


MKID = Microwave Kinetic Inductance Detector

Distinguishing Radiation Types

- Cosmic rays
  - Will penetrate and deposit energy in all three layers
  - At our surface lab, these events are for free!



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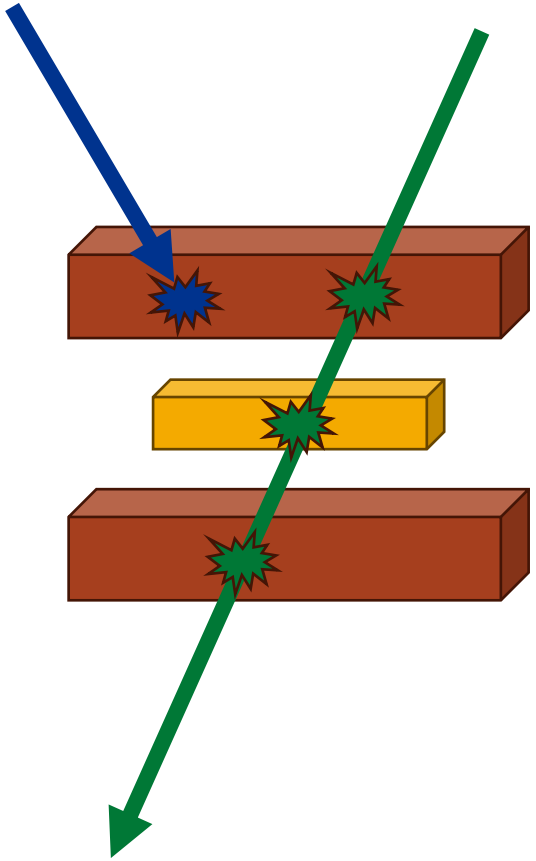

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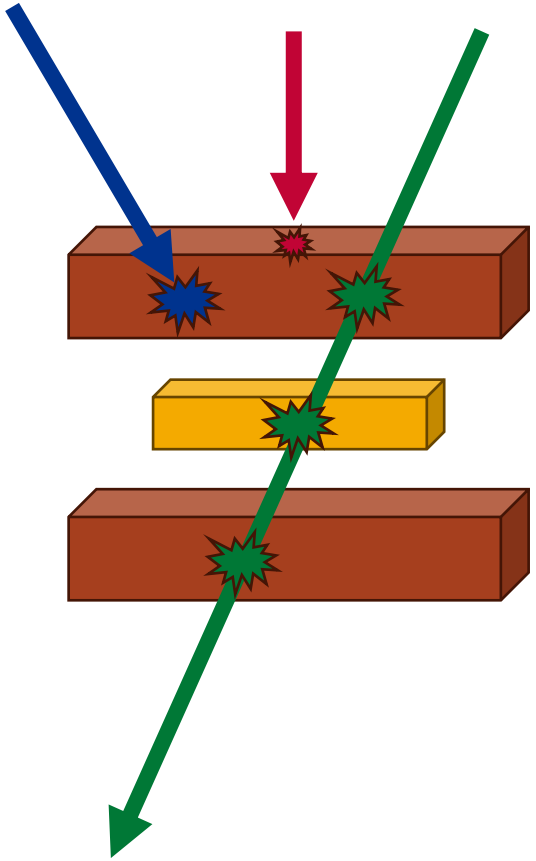
- UV Photons
  - Fiber-coupled LED installed for precise control of event rate and location
  - Detected in one layer, highly localized



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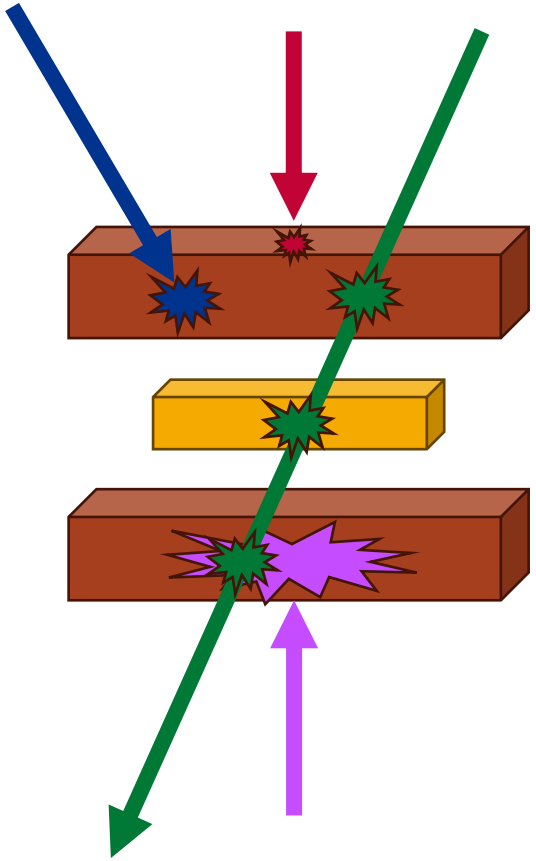
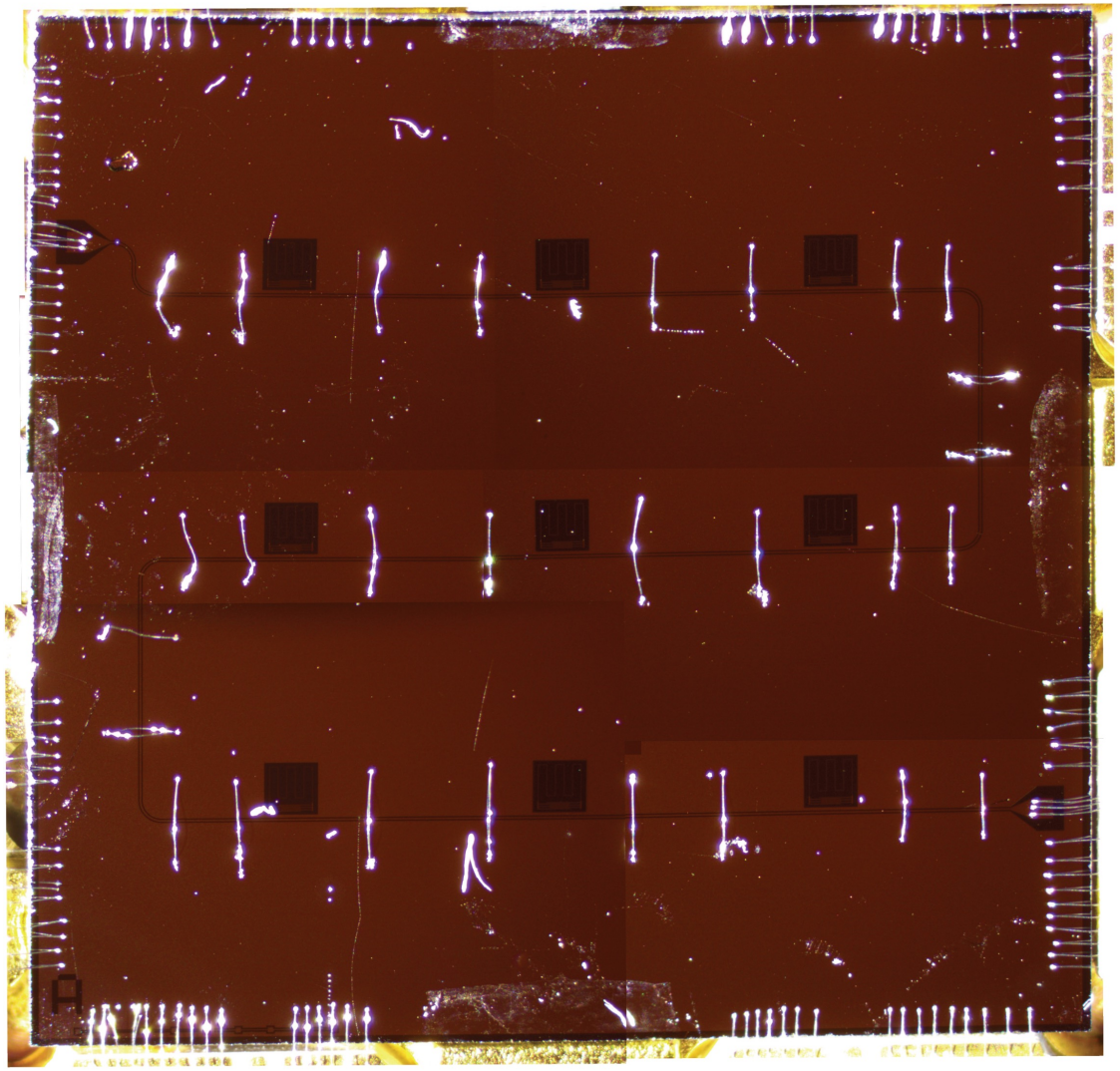
- UV Photons
  - Fiber-coupled LED installed for precise control of event rate and location
  - Detected in one layer, highly localized
- Alphas
  - Deposit MeV-scale energy very near the surface
  - Custom alpha sources from ^{210}Po developed at PNNL for direct placement next to detectors



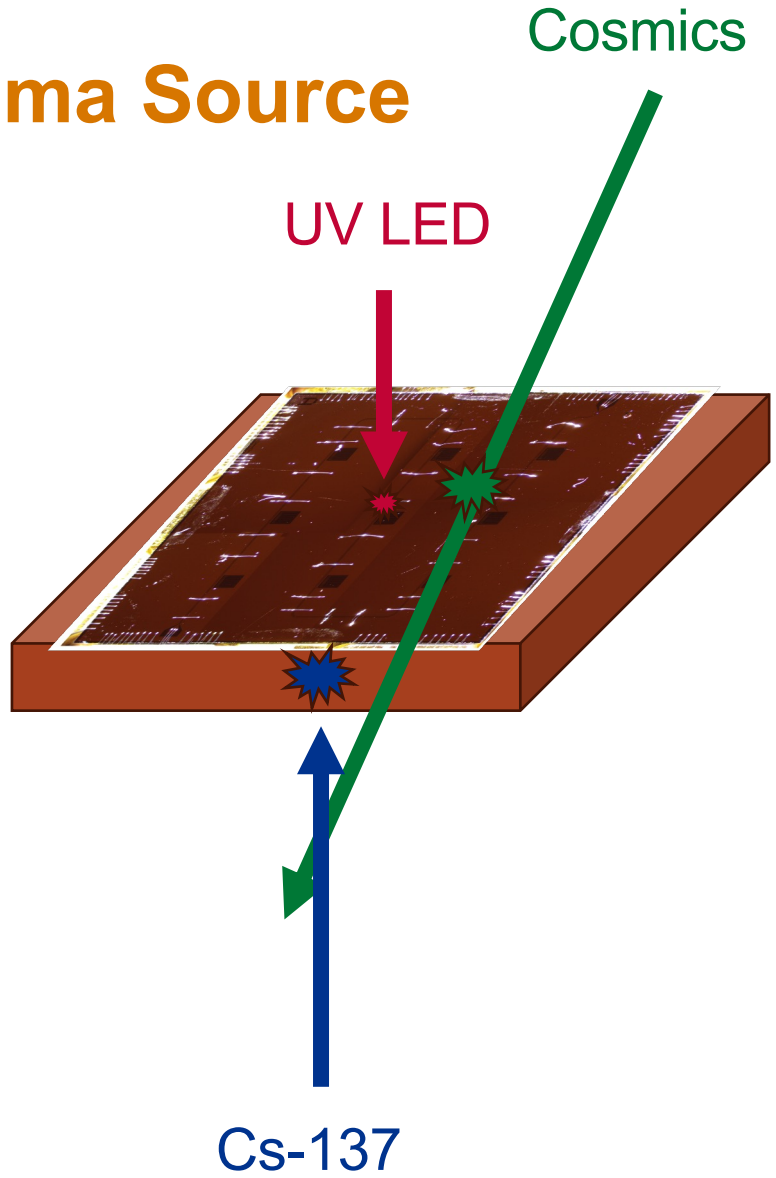
First Data with a 3x3 Array of MKIDs

- Frequencies range from 5.48 GHz to 5.58 GHz
- Readout:
  - Using Quantum Machines OPX+
- Continuous data with offline triggering via Optimal Filter
  - SPLENDAQ triggering system, arXiv:2310.01279
  - 10-sigma trigger with simple chi-square goodness-of-fit cut



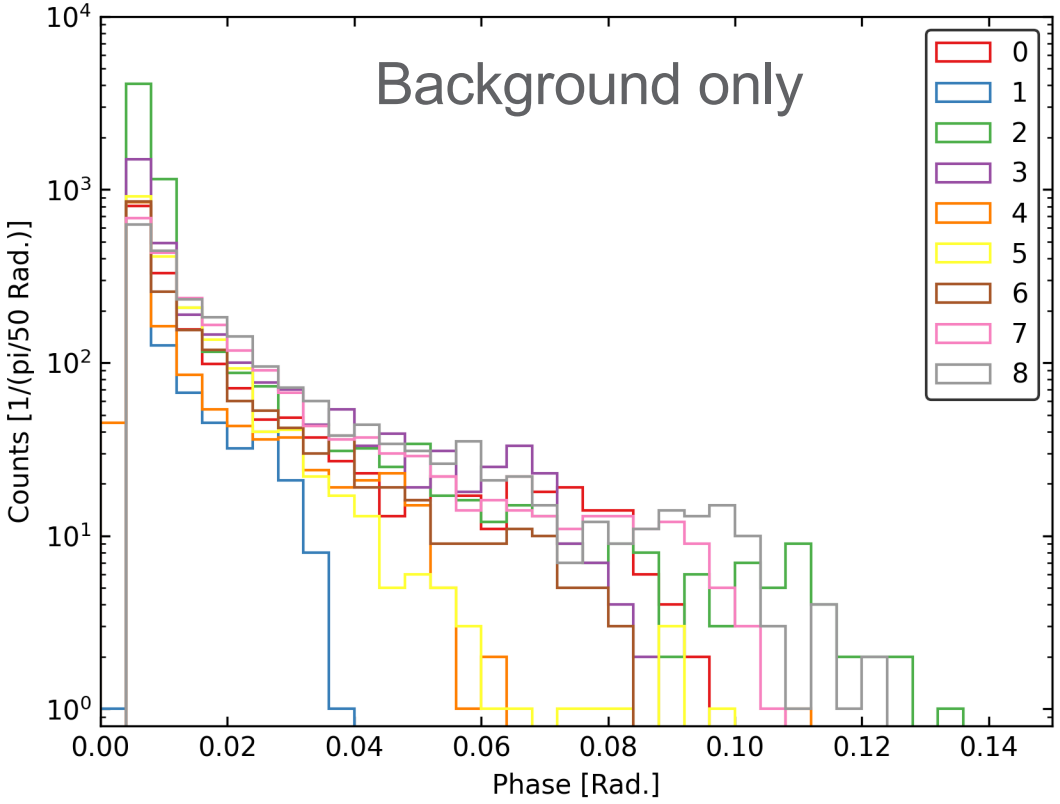
First Data with and without Gamma Source

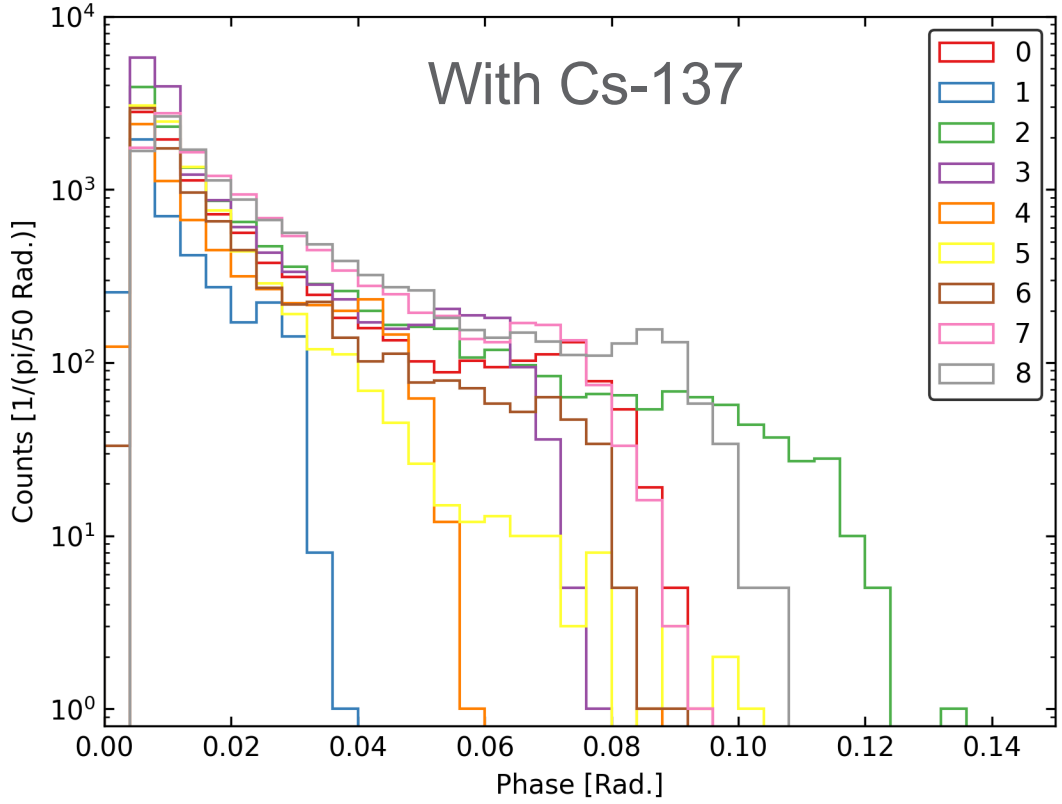
- Read out one 3x3 array in two configurations:
  - Background-only data
  - With Cs-137 source placed under dilution refrigerator
- Cosmics present in both datasets, but not taggable with one detector
- Fiber-coupled UV LED pulses incident on center MKID
- About 10 hours of exposure in both cases
- Not fully multiplexed for higher live time
  - Limited to ~18 us time bins



Spectra Comparison

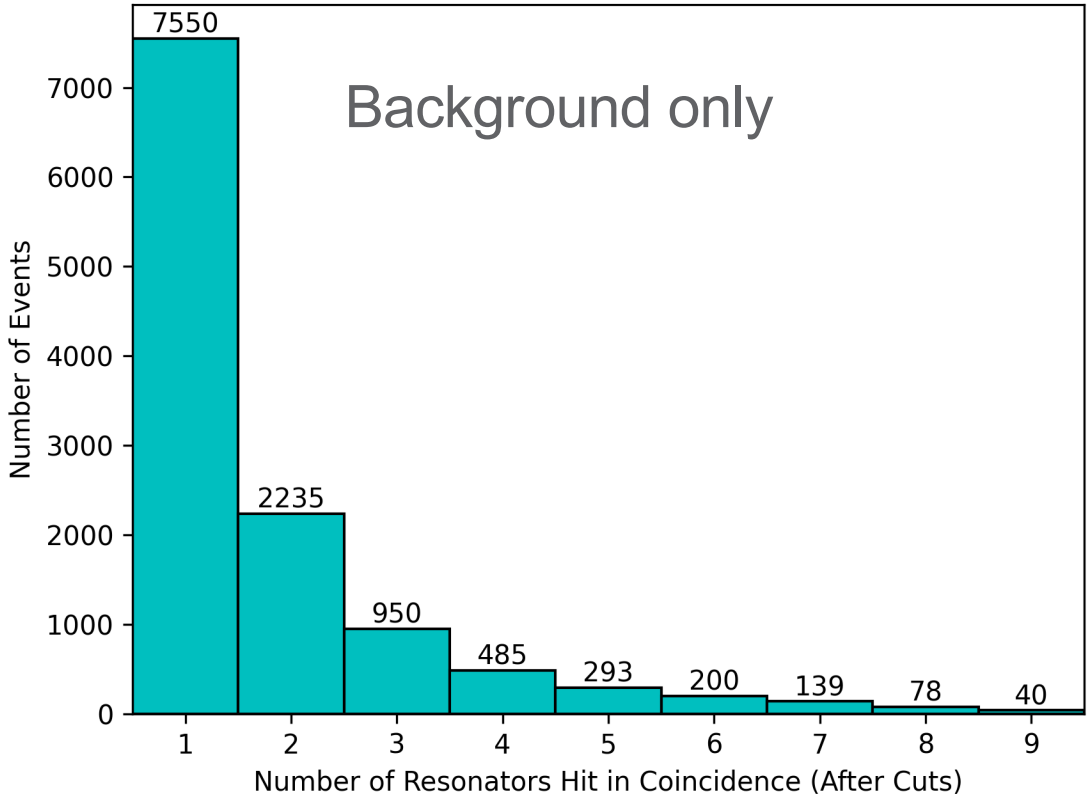
- Shows expected higher rate of events with Cs-137 source
- Each resonator has a different gain, need a calibration source!

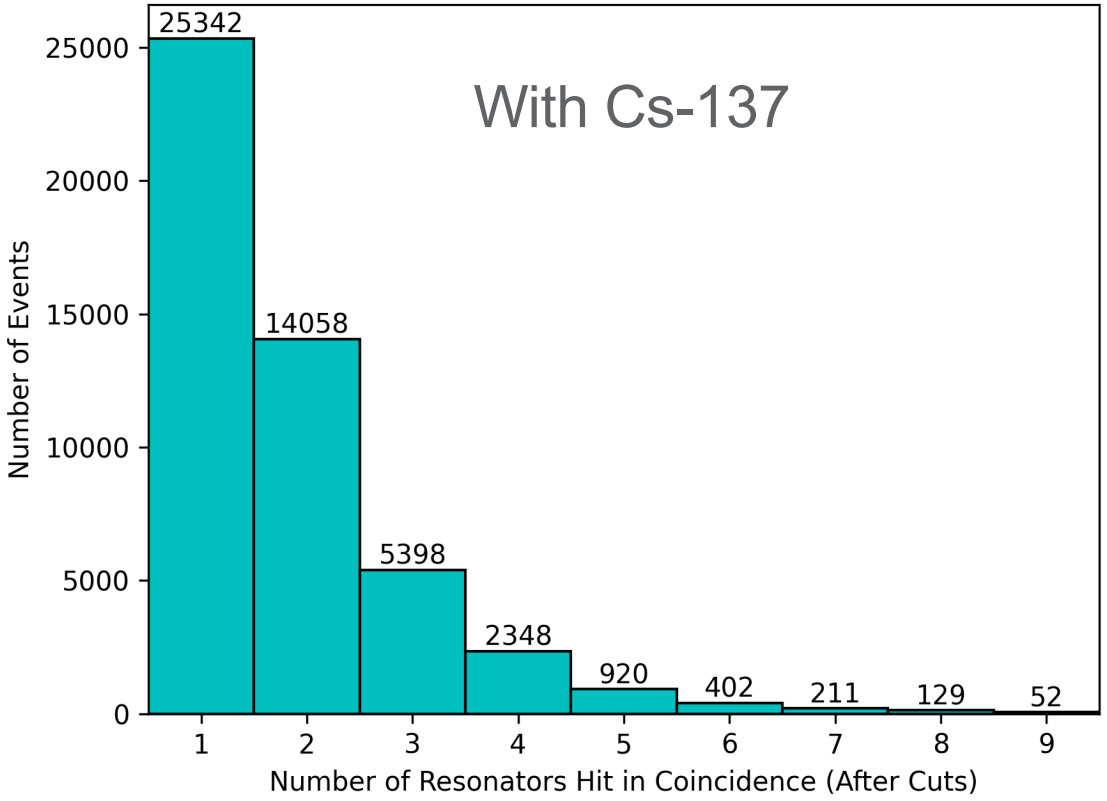




Coincidences Comparison

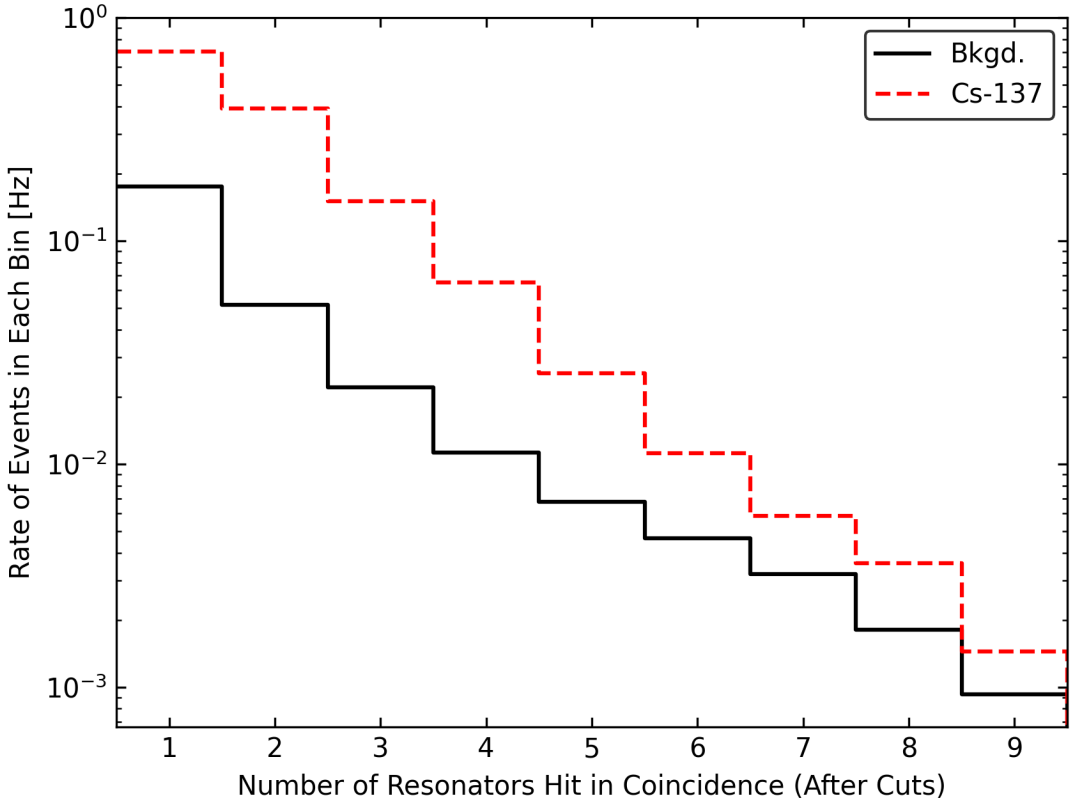
- Doubles-to-singles ratio is higher with Cs-137
- Higher overall numbers of all types of coincidences with Cs-137

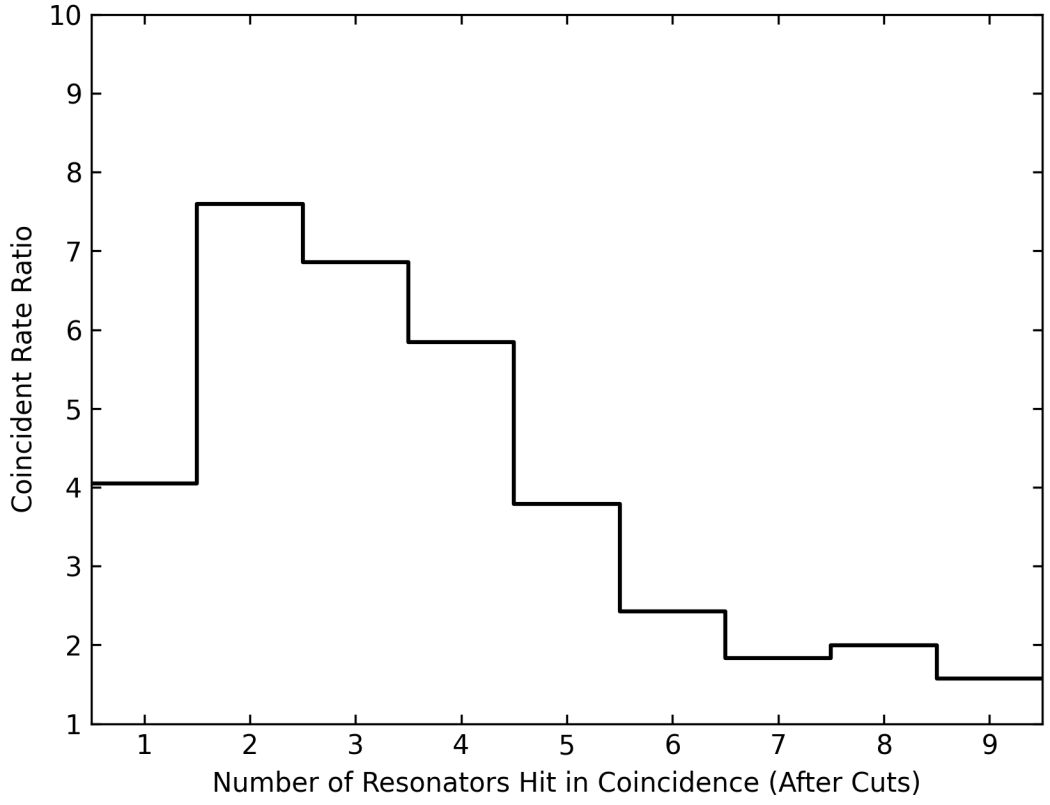




Comparison of Ratios and Rates

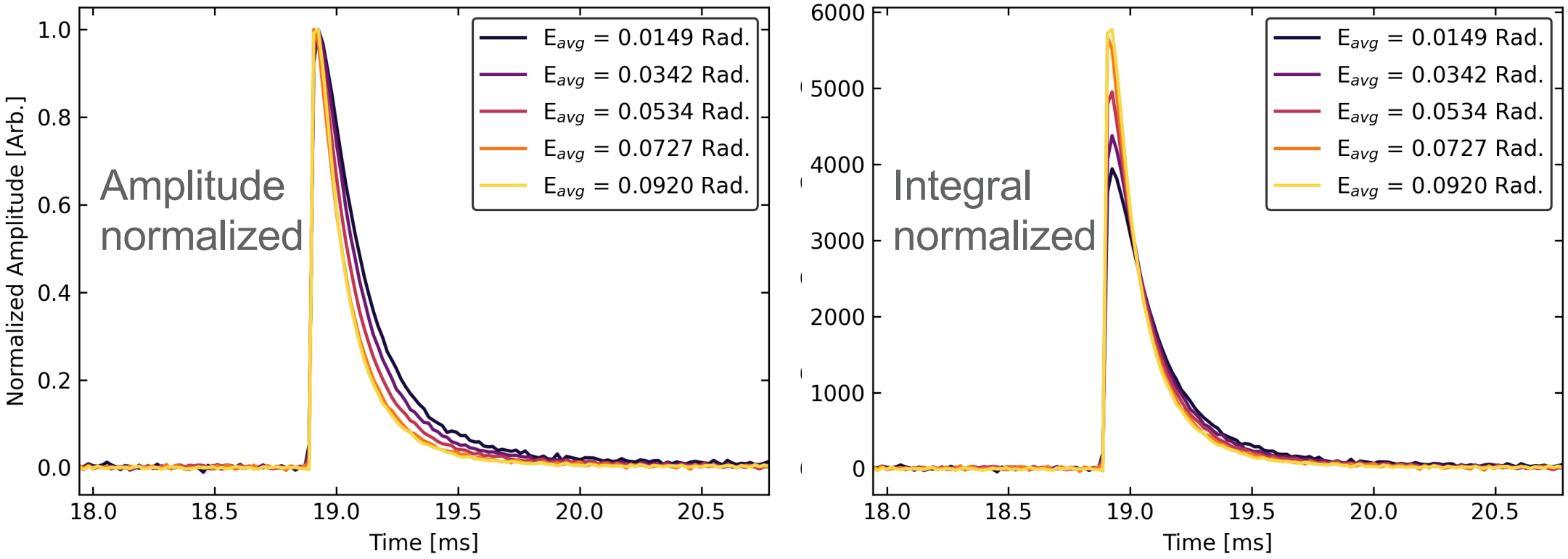
- Cs-137 significantly increases the < 6 coincidence rates
- Small increase of ≥ 6 coincidence rates





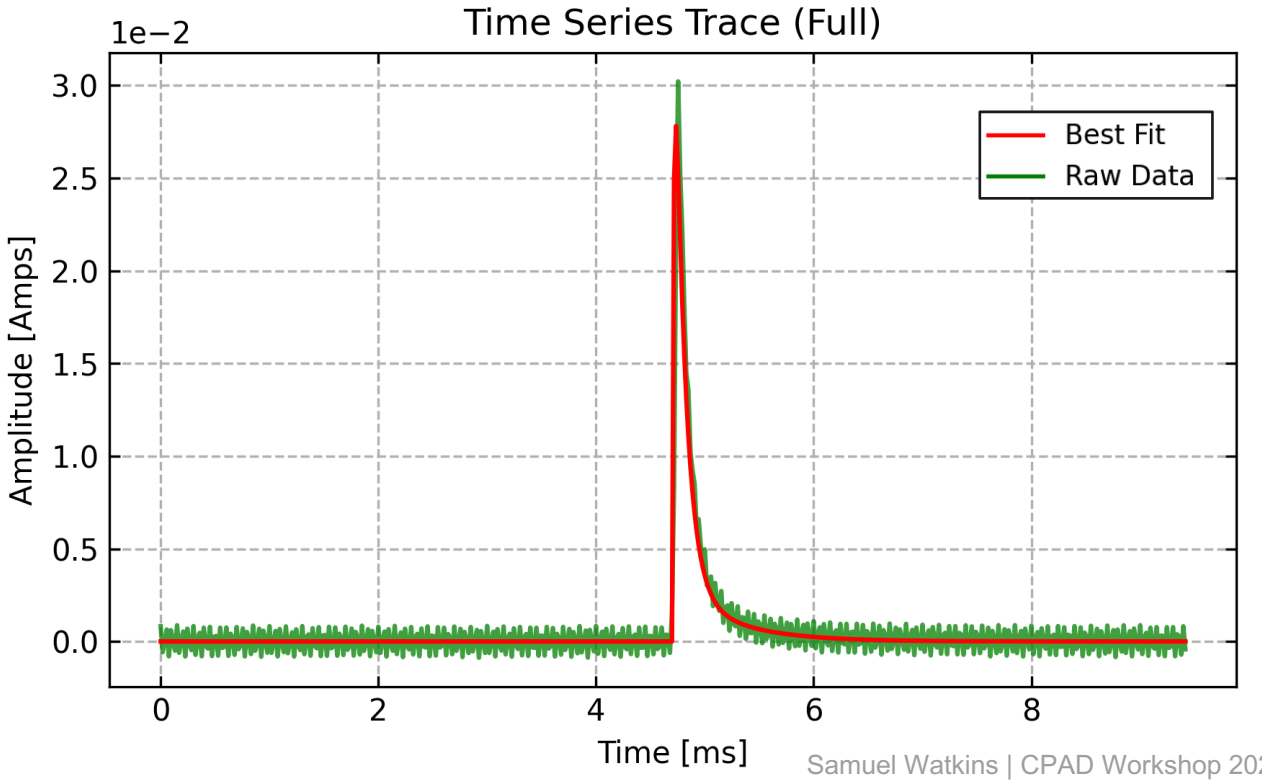
Energy Dependence of Pulse Shape

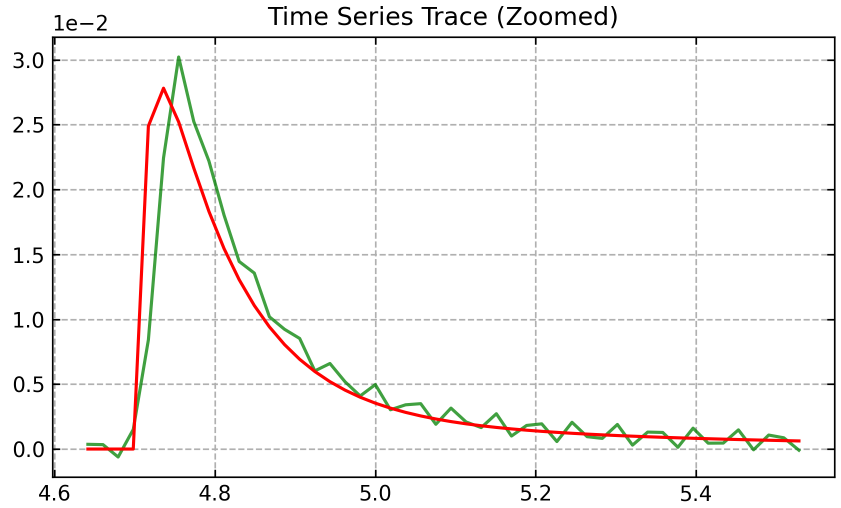
- As pulse height (energy) increases, the primary fall time becomes faster
  - Plots are for one resonator, averaging pulses in energy bin, only choosing singles (no other coincident resonators)



Fitting Average Pulses

- Nonlinear least square fit, allowing for two fall times
  - Here: average of LED pulses incident on one resonator



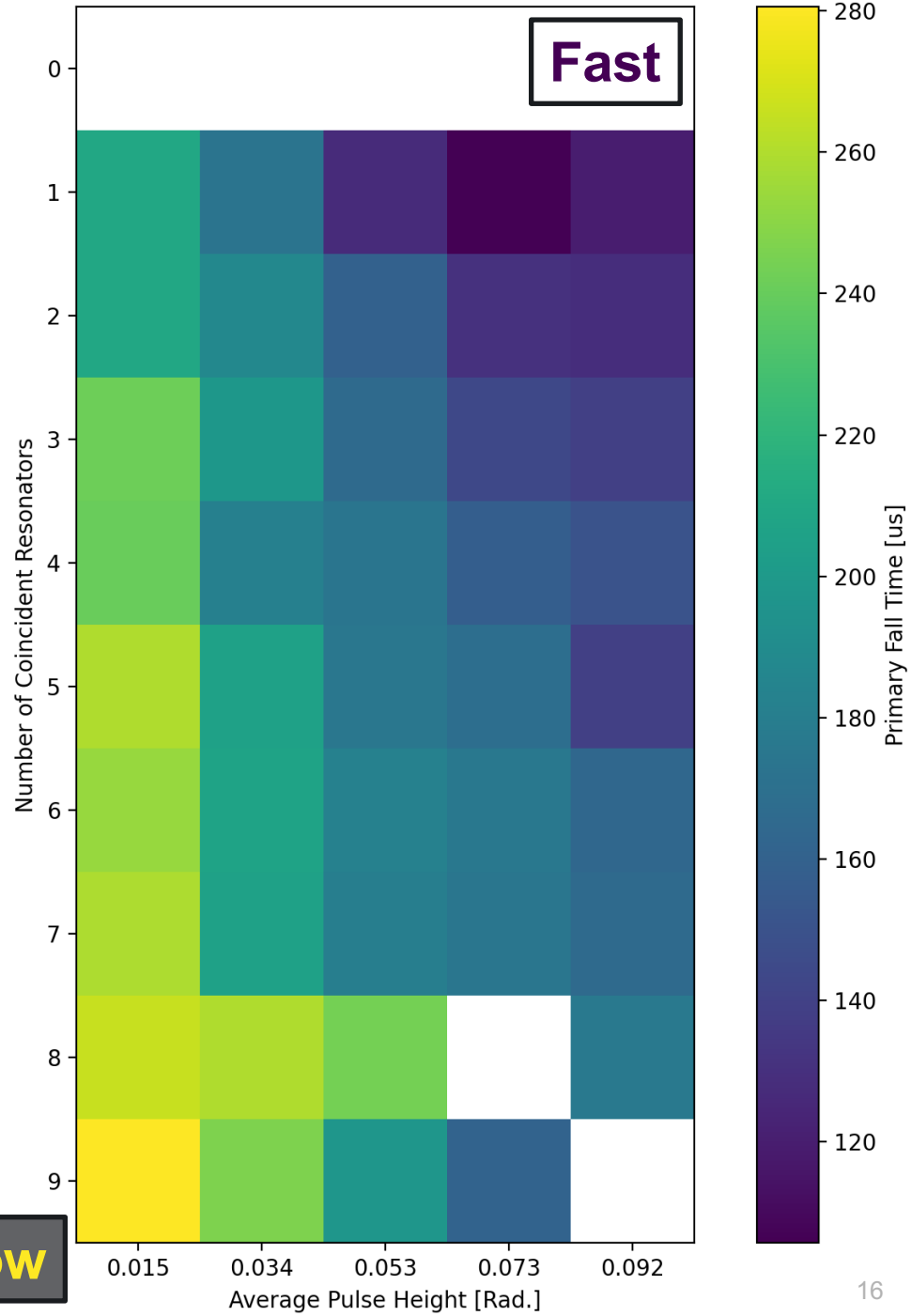


Best fit parameters of interest:

- *Primary* fall time of $95.3 \pm 0.8\ \mu s$
- *Secondary* fall time of $509 \pm 18\ \mu s$
- Amplitude ratio ~ 13

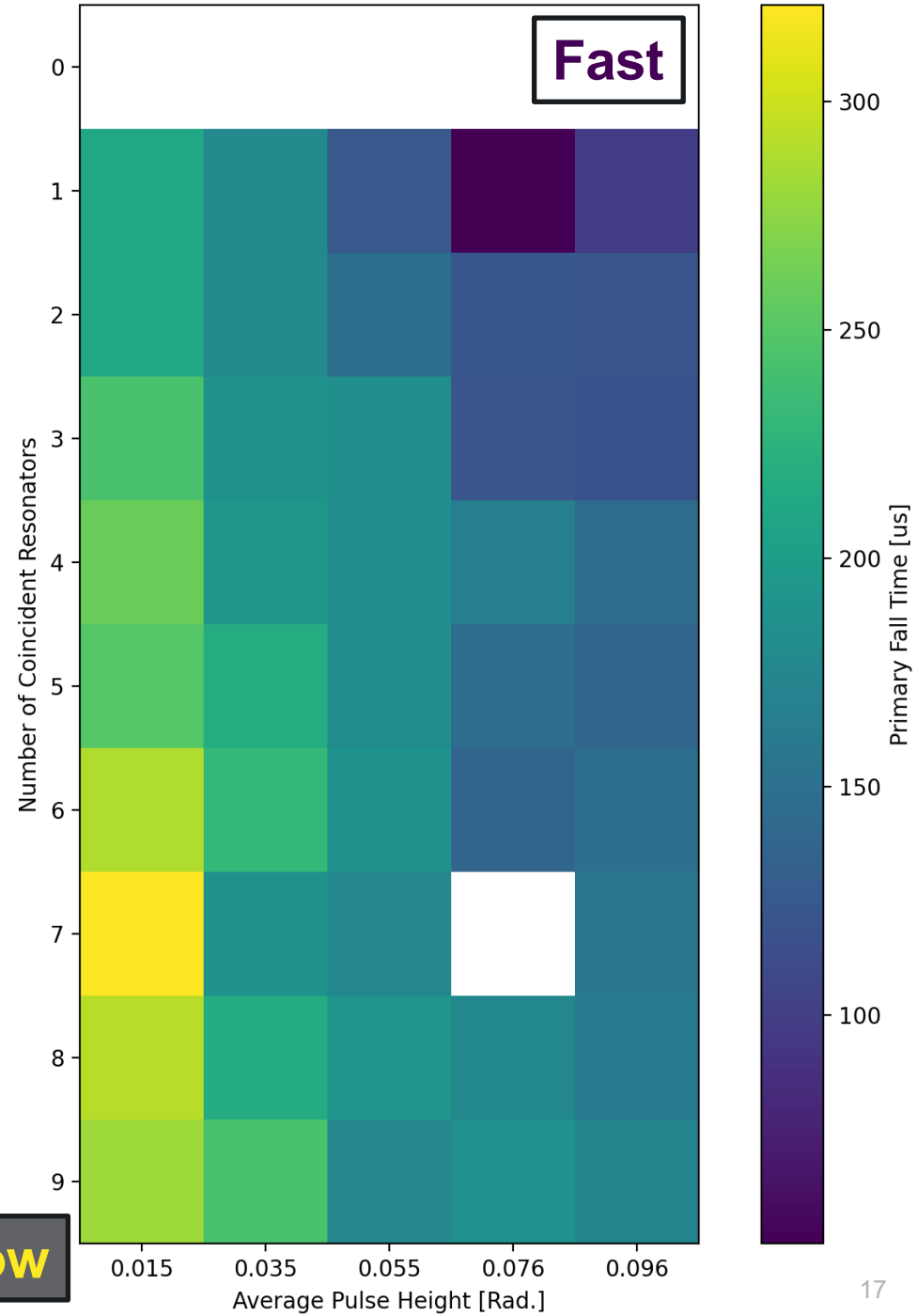
Primary fall time fits: Cs-137 Source

- How does the pulse shape change with pulse height and number of coincident detectors?
- Right plot:
  - Primary fall times as function of number of coincident resonators and average pulse height
- **Implies**:
  - Fall time decreases with higher coincidences
  - Fall time increases with energy deposited in resonator
- First thoughts:
  - Response to localized events is dictated by the MKID physics
  - Response to chip-wide events is dictated by phonon physics



Primary fall time fits: Background only

- Same trend as the Cs-137 dataset
  - This is some combination of high-energy cosmics and environmental radiation
- Next questions:
  - *What type/source of radiation is most problematic for qubits?*
  - *Are we doomed to underground labs?*



Summary and Future

- Leveraging multi-channel MKIDs and qubits for ionizing radiation characterization
- First results show an **energy dependence of highly-correlated events**
  - How do phonon and quasiparticle dynamics correlate with energy *and* localization?
- Future:
  - Use *in-house alpha sources* for confirmation of high-energy events causing chip-wide events
  - Run the *full multiplexed Sandwich on an RFSoC* for best performance (MKIDGen3)
  - Correlate and localize events across Sandwich layers with qubit decoherence
  - Improve positional sensitivity with new 5x5 MKID arrays
- **Are our correlated events cosmic in origin, or environmental?**
  - To be determined…

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Thank you!

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Backup

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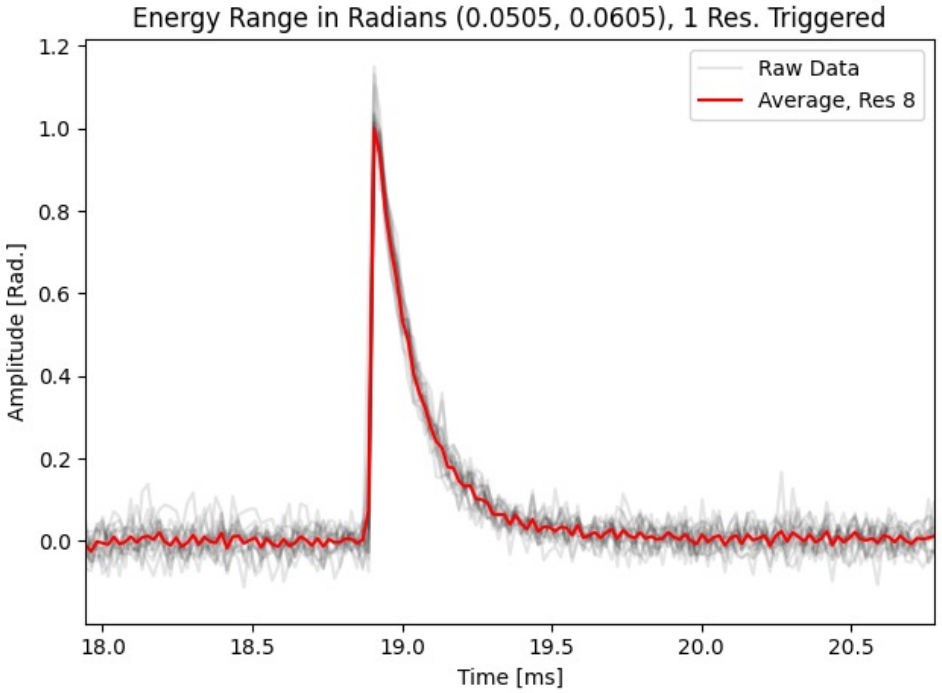
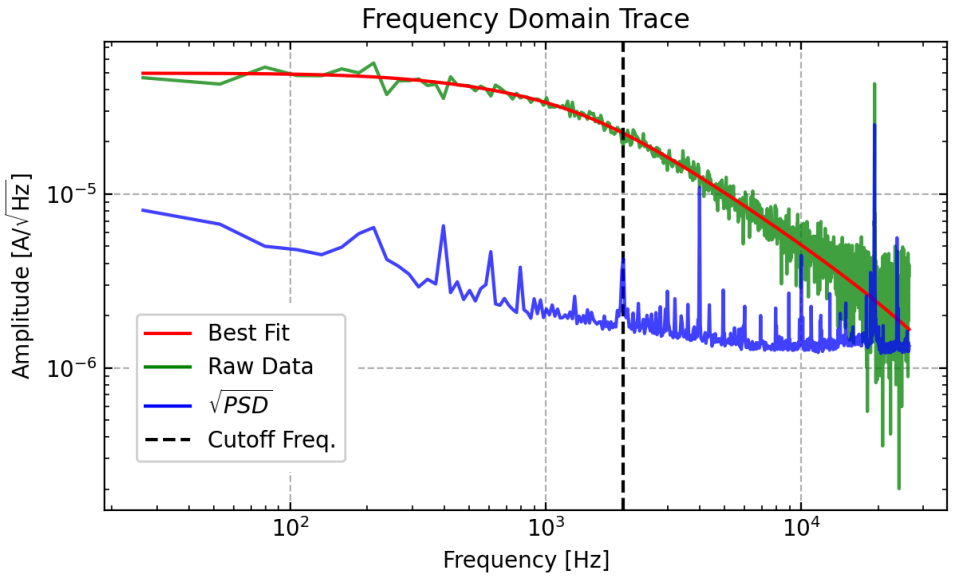
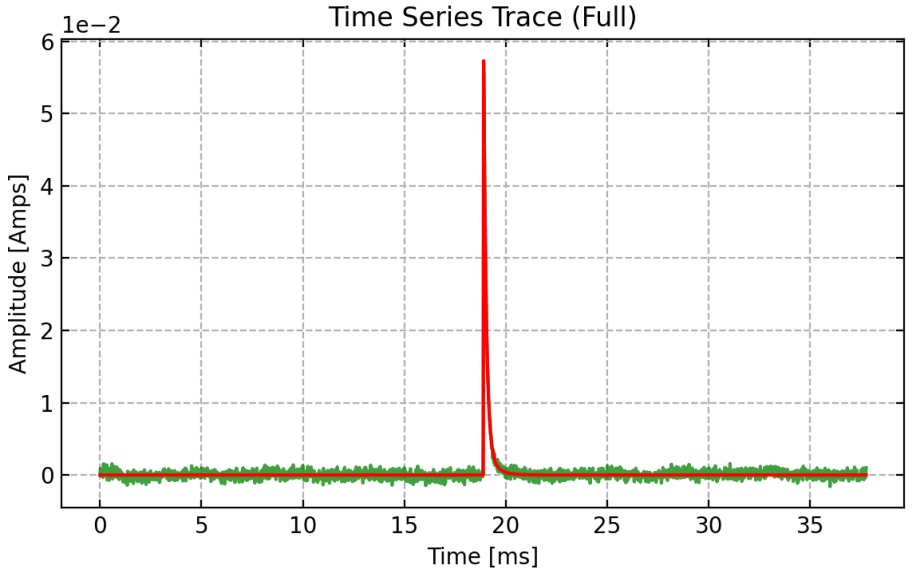
Fitting Average Pulses

- Nonlinear least square fit, allowing for two fall times
  - Here: single energy bin for events that are not coincident on one of the resonators



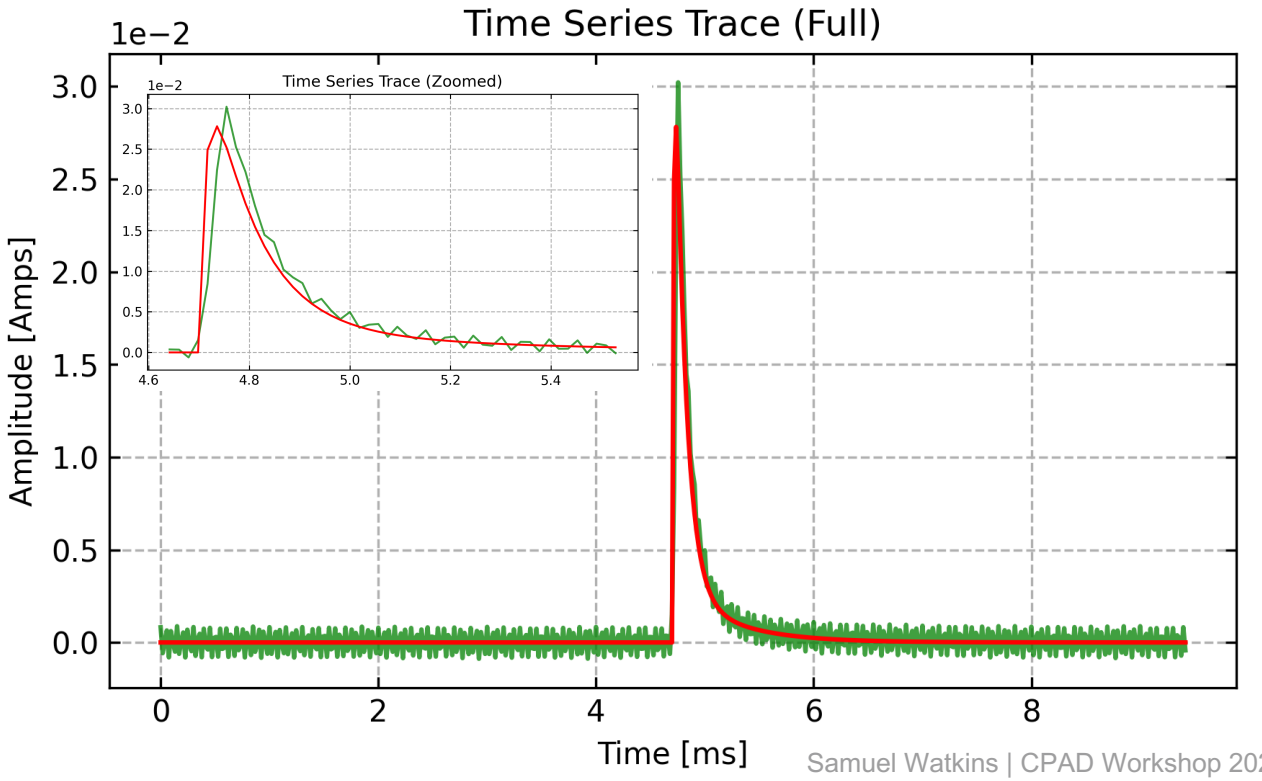




Primary fall time: $126 \pm 5\ \mu s$
Secondary fall time: $422 \pm 138\ \mu s$

Averaged LED pulse on Center Resonator

- Averaged 23774 LED pulses, fixed rise time to 15 μs due to time resolution constraints



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A: (42424.2421 +\- 205.7947) [μA]
B: (3160.4497 +\- 152.8959) [μA]
τ, f1: (95.3816 +\- 0.8103) [μs]
τ, f2: (508.8091 +\- 18.0866) [μs]
t_0: (4.7163 +\- 0.0001) [ms]
τ_r: (14.9999 +\- 0.1154) [μs]

Ringup Comparisons: Noise PSDs

- Noise is consistent between datasets