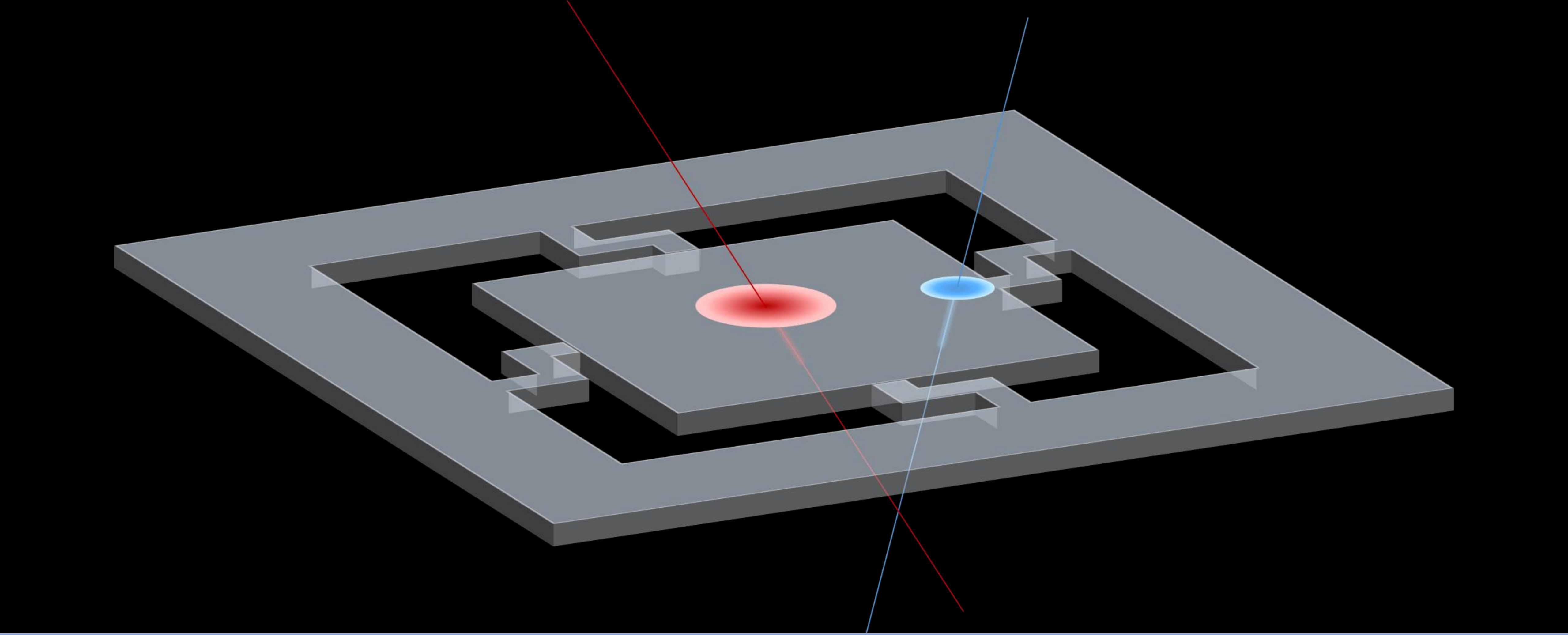


Applications of quantum calorimetry in nuclear physics

Paul Szypryt (paul.szypryt@nist.gov)

Quantum Information Science on the Intersections of Nuclear and AMO Physics

January 14, 2025

Team members

NIST / University of Colorado Boulder	**Paul Szypryt**, Ian Fogarty Florang, Joseph Fowler, Tom-Erik Haugen, Shannon Hoogerheide, Daniel Jardin, H. Pieter Mumm, Matthew Natale, Nathan Nakamura, Jeremy Paster, Thomas Rao, Daniel Swetz, Joel Ullom, Michael Vissers
Pacific Northwest National Laboratory	Raymond Bunker, Ellen Edwards, Ben Loer, John Orrell, Brent VanDevender
Other Collaborators	Jiansong Gao (AWS Center for Quantum Computing) Andrea Giachero (University of Milano Bicocca) Robert Harper (Centre College, NIST SURF) E. Mae Scott (Centre College)

Student
Postdoctoral Fellow

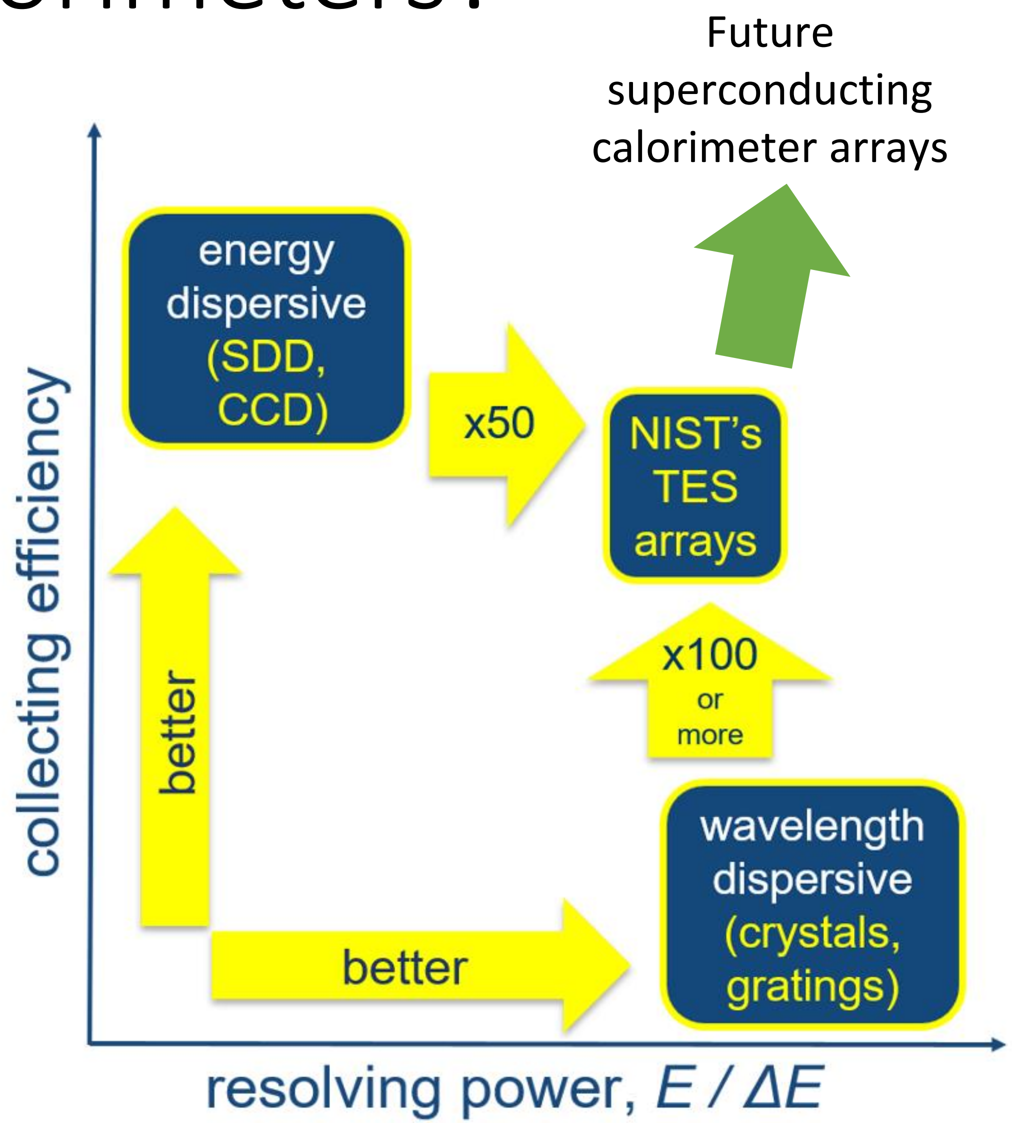
Overview

- Superconducting calorimeters background
  - Transition-edge sensor (TES) background
  - Kinetic inductance detector (KID) and thermal variant (TKID) background
- CP-TKID development and applications
  - Setting groundwork for new instrumentation at the NIST Center for Neutron Research (NCNR) – precision measurements of fundamental symmetries
  - Using current devices for spectroscopic measurements of the ionizing radiation background in quantum circuit substrates

Transition-edge sensor (TES) background

Why superconducting calorimeters?

- Combines the collection efficiency of energy dispersive detectors such as CCDs and SDDs with the energy resolving power of wavelength dispersive techniques such as crystals and gratings
- Broadband spectroscopy
- Low energy detection thresholds



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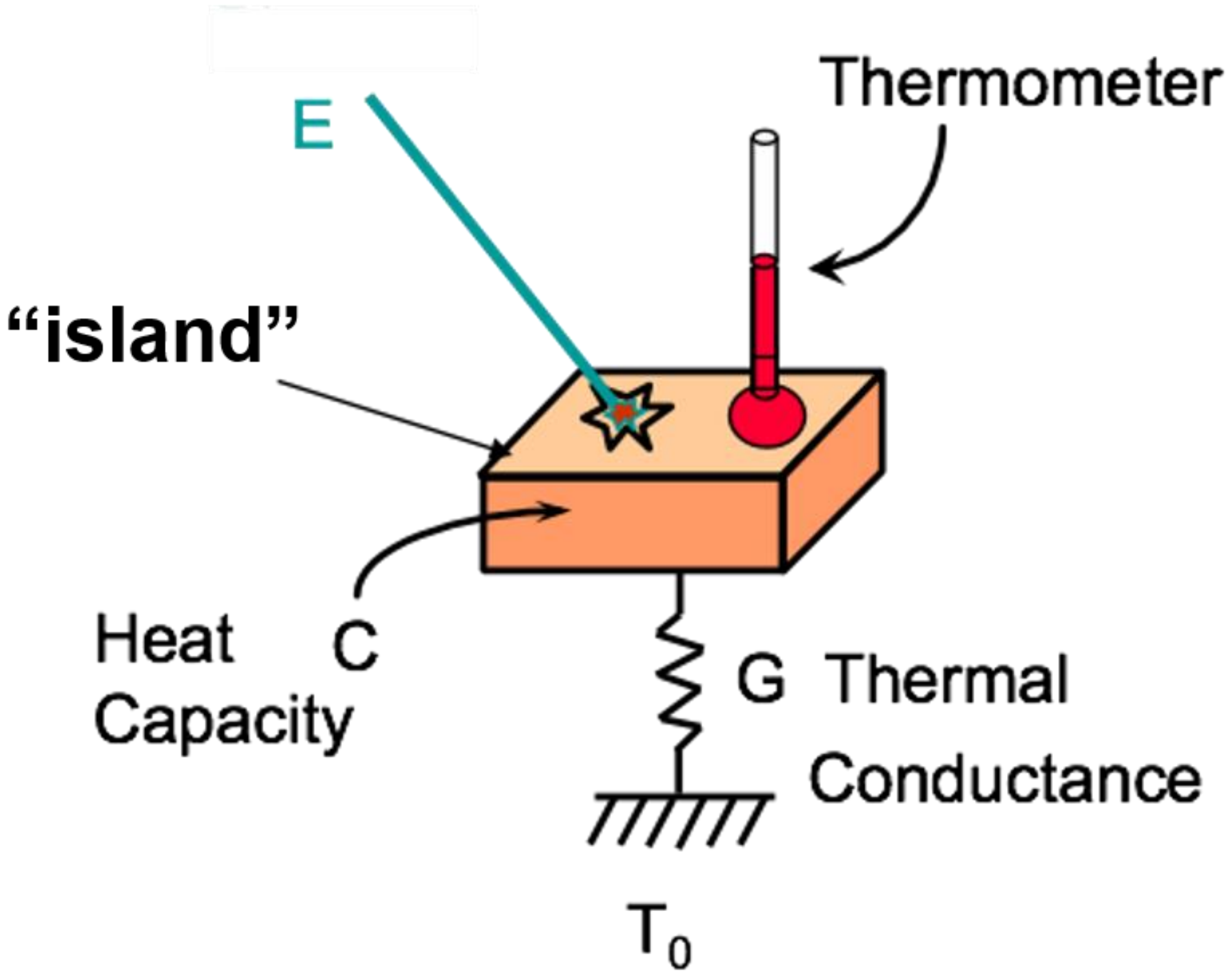
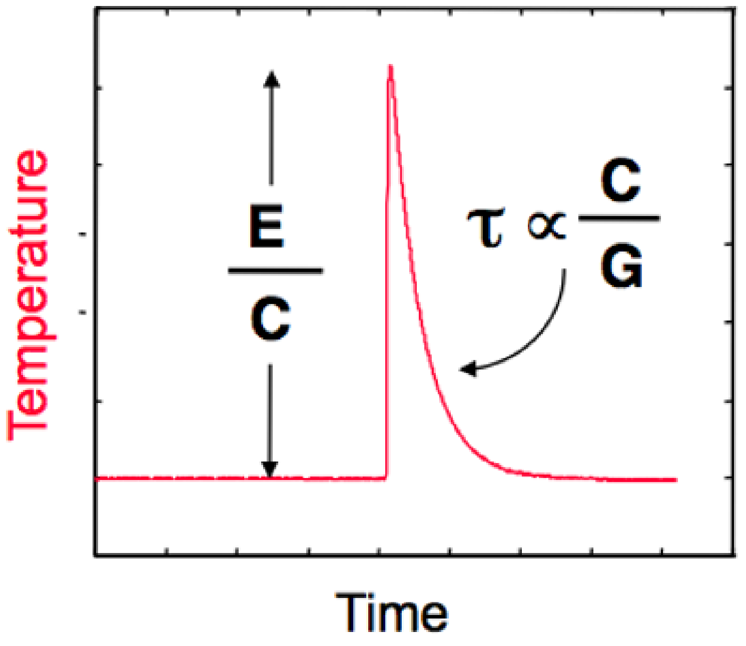
Cryogenic microcalorimeter

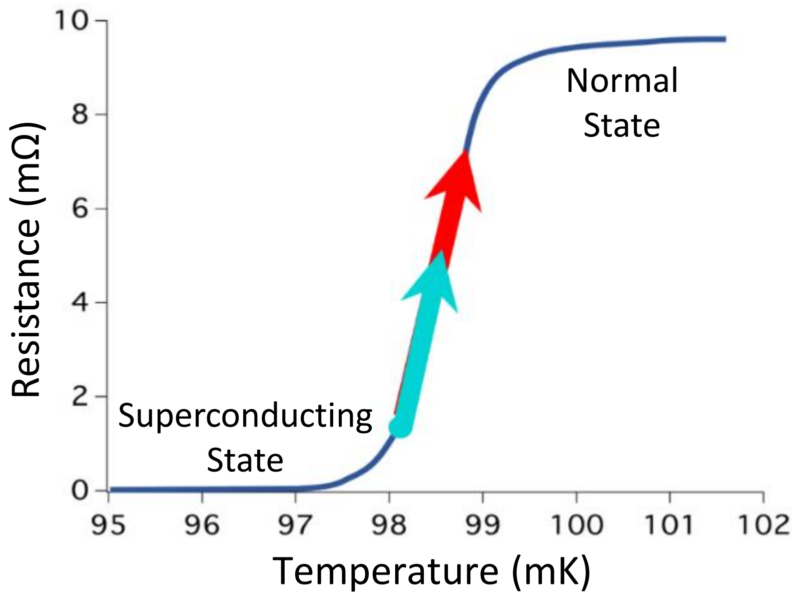


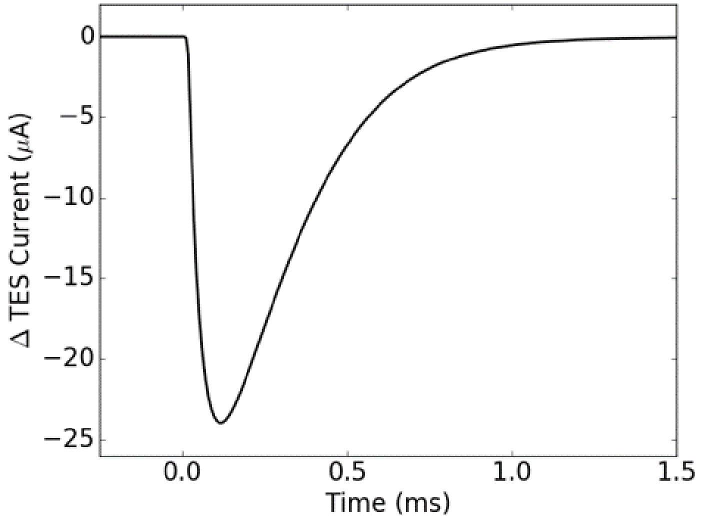


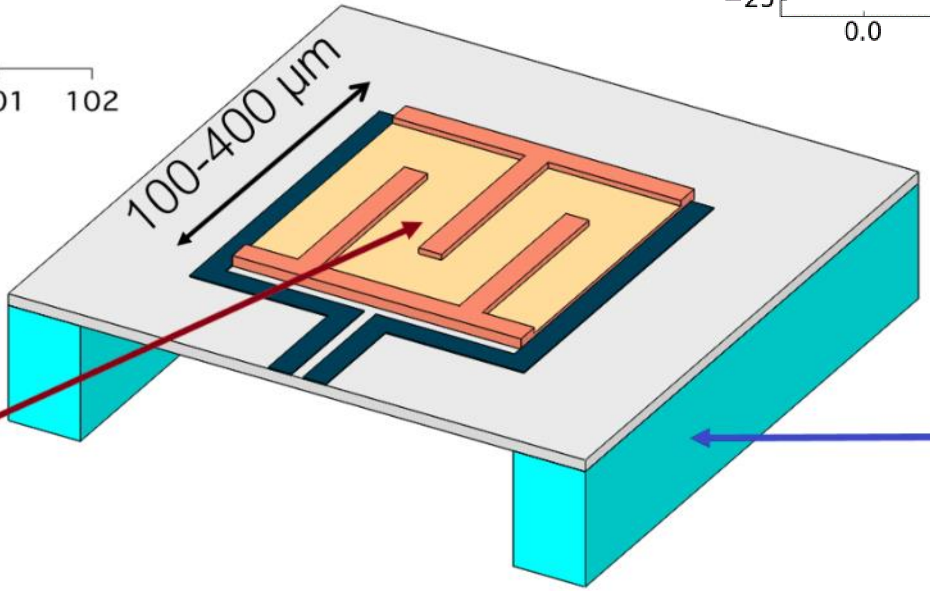
$$\Delta E \sim \sqrt{4 k_B T^2 C}$$

Temperature
~100 mK

TES microcalorimeter







Tc ~100 mK

Absorber coupled to TES to detect high energy events, decoupled optimizations!

Tbath < 100 mK

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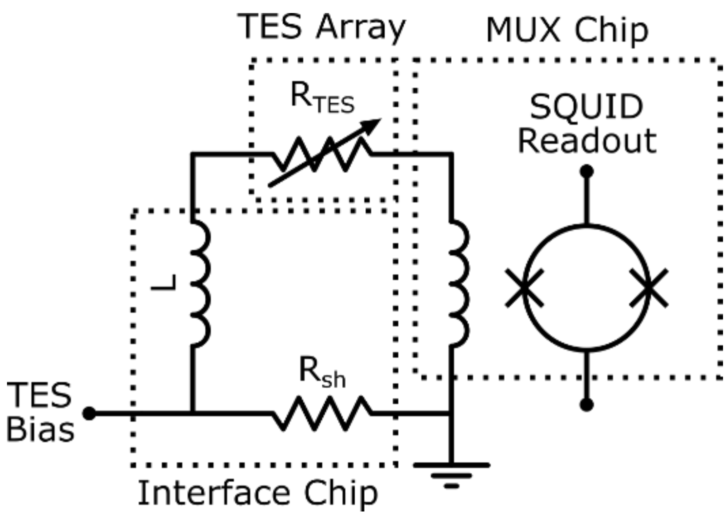
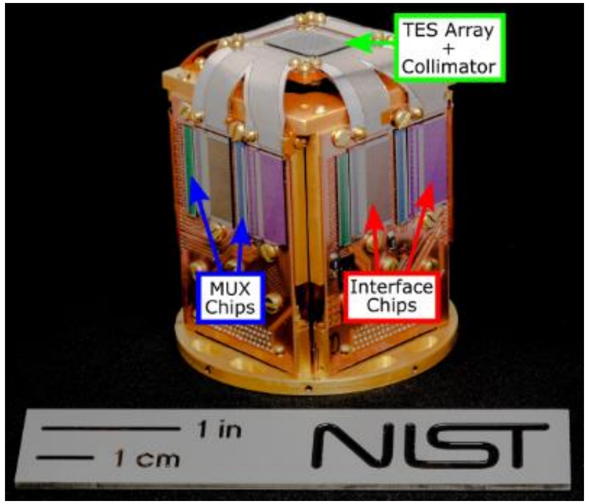
Readout electronics and multiplexing

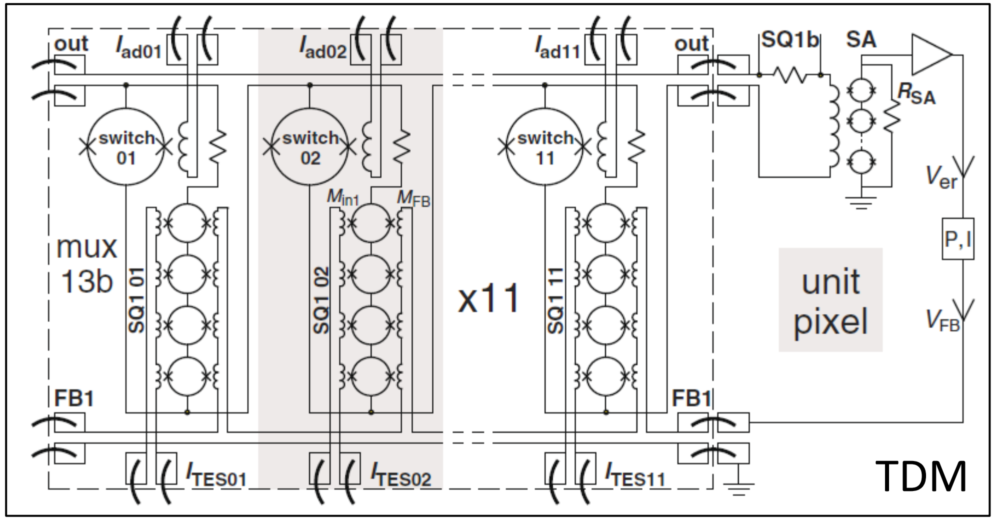
Typically read out and multiplexed using superconducting quantum interference devices (SQUIDs)

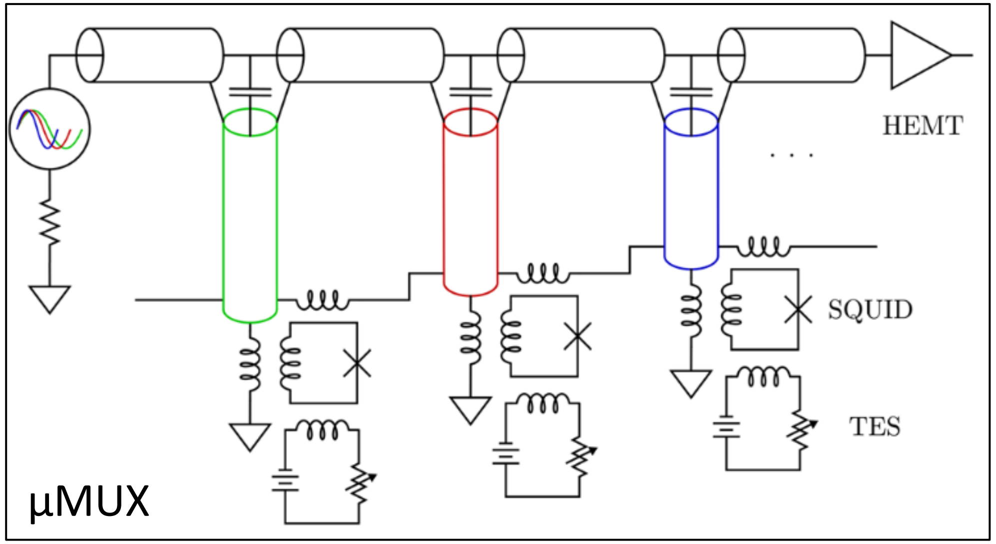




Adapted from Szypryt et al., 2019, https://doi.org/10.1063/1.5116717

Reprinted from Doriese et al., 2016, https://doi.org/10.1007/s10909-015-1373-z

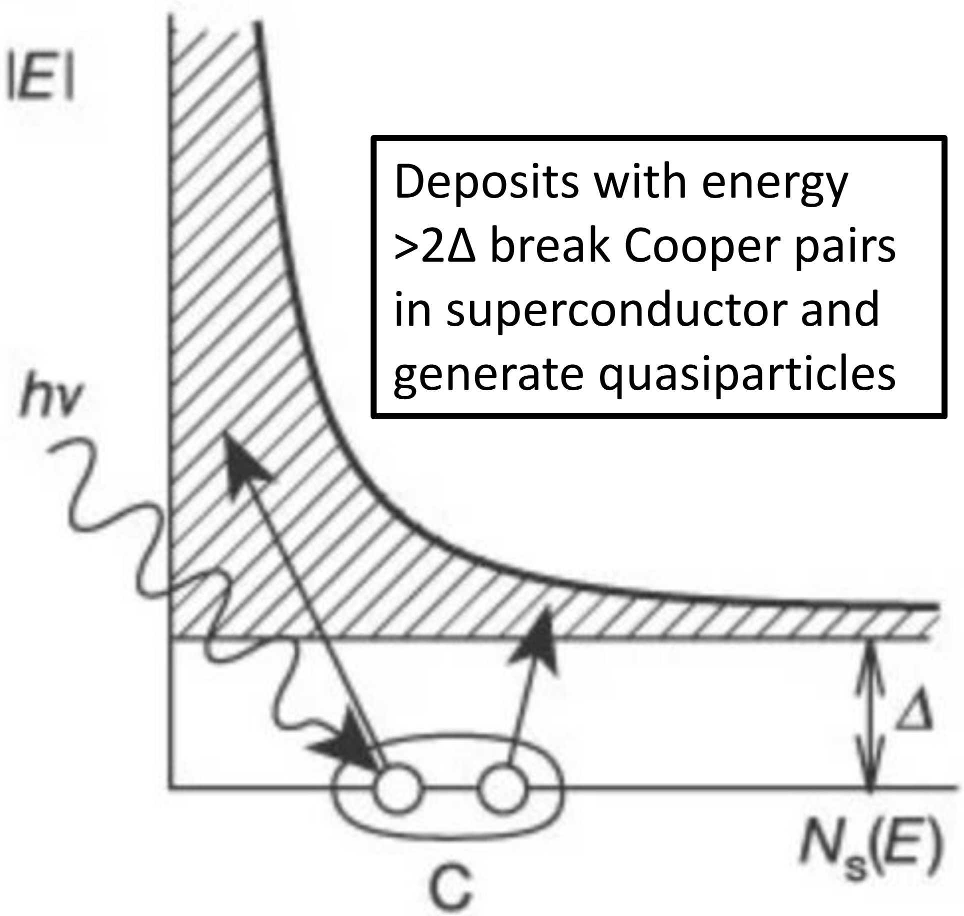




Reprinted from Mates et al., 2017, https://doi.org/10.1063/1.4986222

Kinetic inductance detector (KID) background

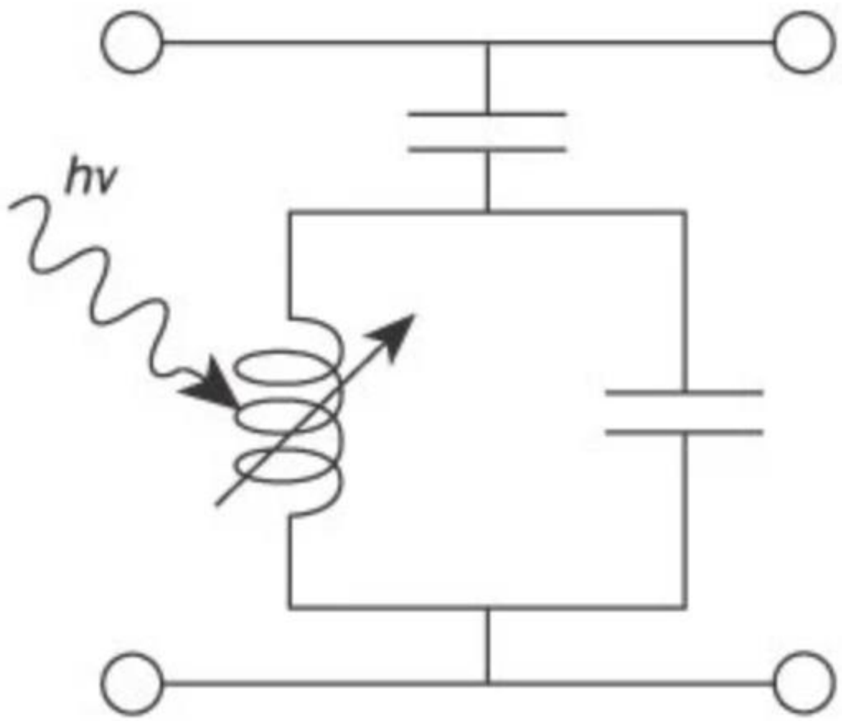
Kinetic inductance detector (KID) background



Deposits with energy >2Δ break Cooper pairs in superconductor and generate quasiparticles

Broken Cooper pairs result in increased sheet impedance (kinetic inductance)

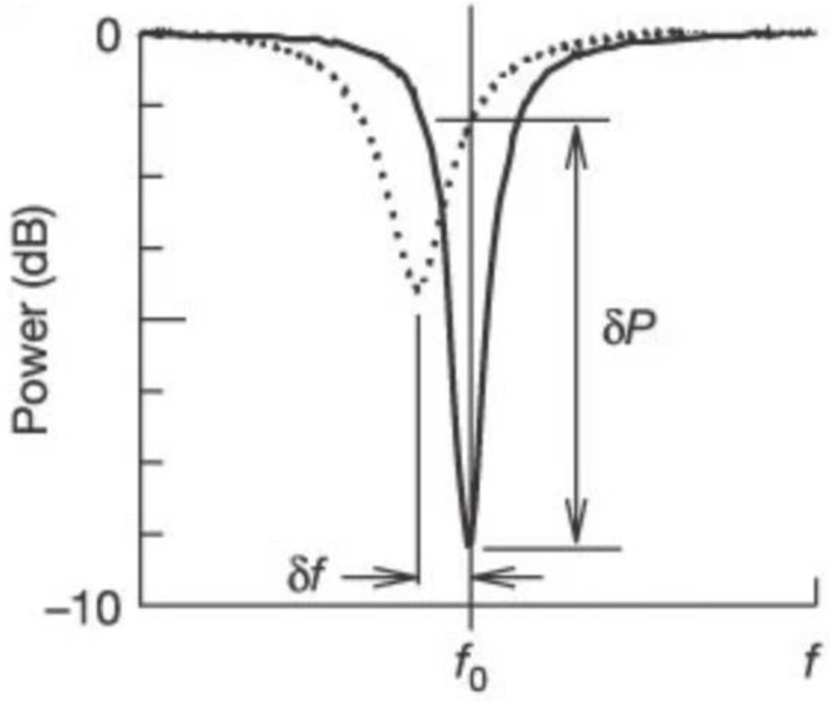
Thin-film superconductor patterned into LC resonator



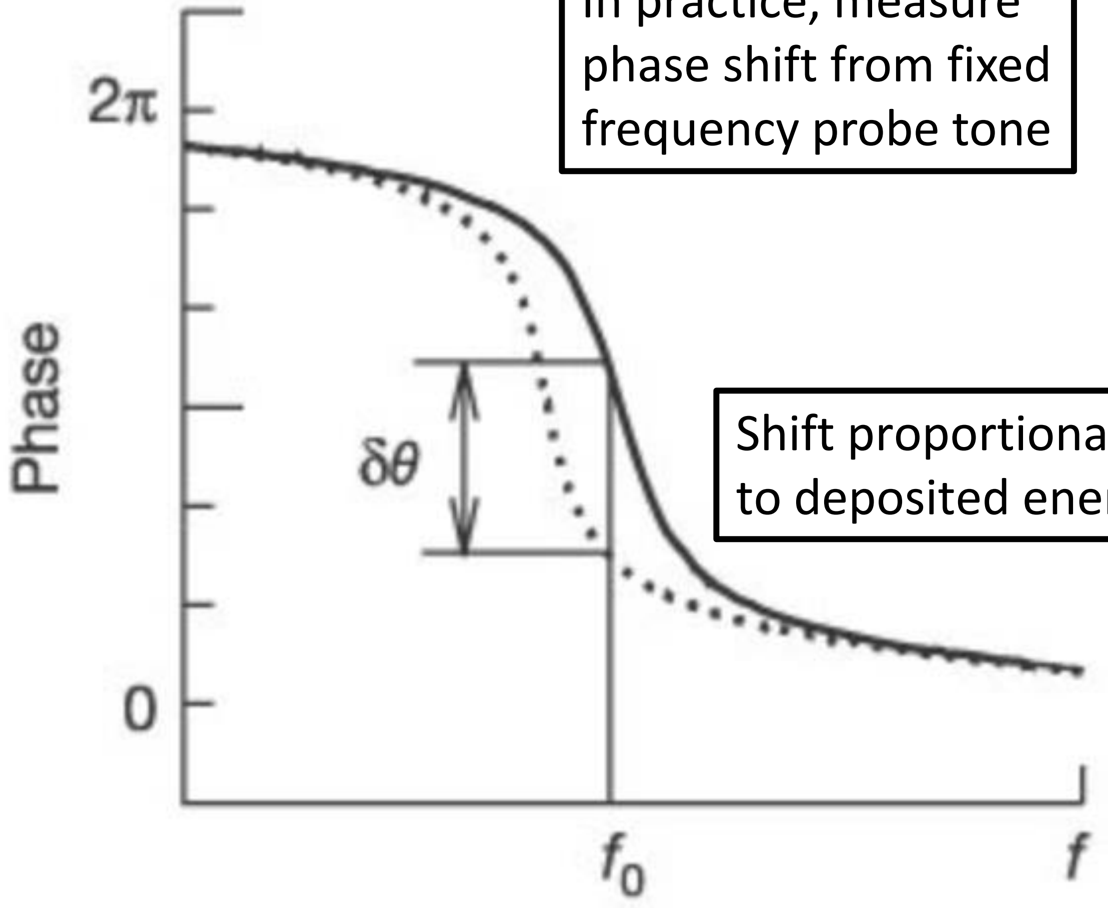
Adapted from Day et al., 2003, https://doi.org/10.1038/nature02037

KID background

Changing kinetic inductance temporarily shifts resonant frequency



In practice, measure phase shift from fixed frequency probe tone

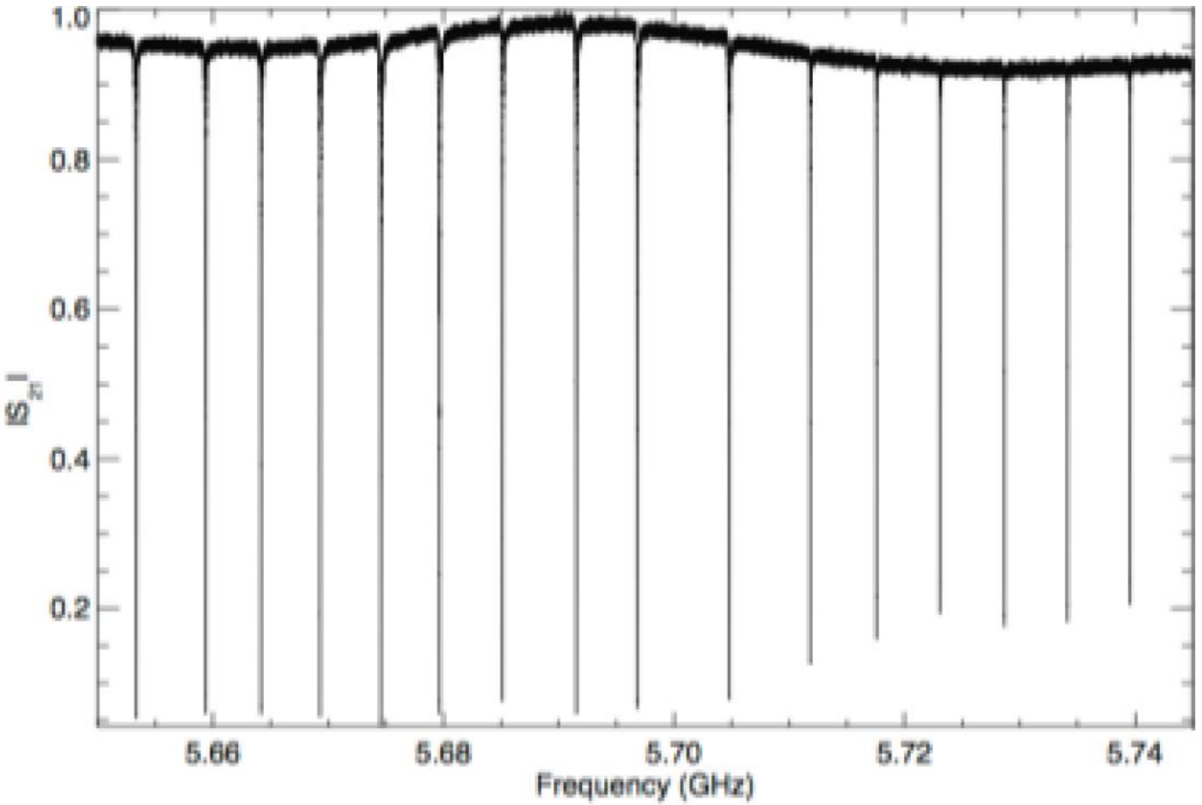


Shift proportional to deposited energy

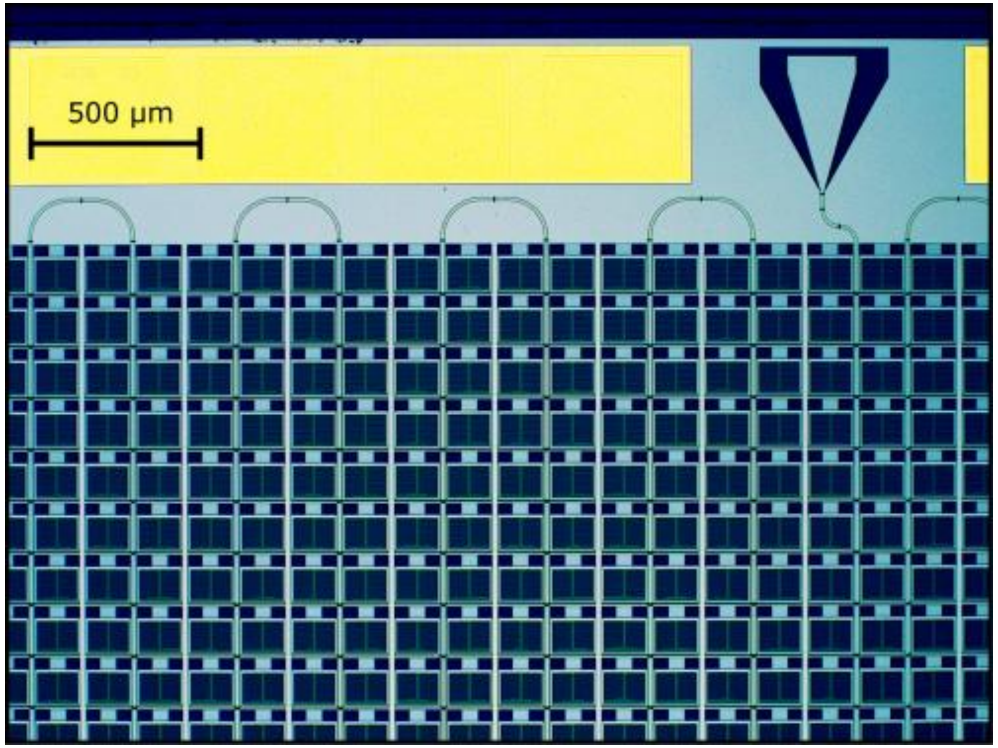
Adapted from Day et al., 2003, https://doi.org/10.1038/nature02037

KID readout

Each KID device tuned to unique resonant frequency



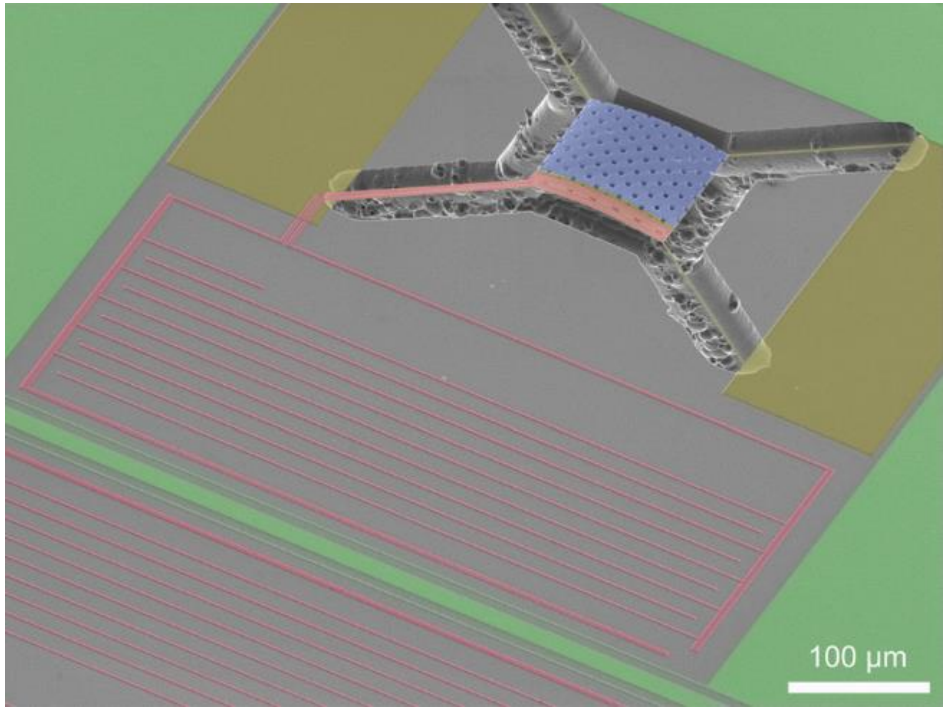
Reprinted from Szypryt et al., 2017, https://doi.org/10.1364/OE.25.025894



Many (on order 1000) KIDs can be coupled to and read out through a common microwave transmission line

Thermal kinetic inductance detector (TKID)

- KID coupled to dedicated absorber
  - Combines thermal properties of TES calorimeter with ease of multiplexing of KID
  - Enables separate optimization of detector and readout properties
  - Increased stopping power to high energy events
  - High dynamic range / linear response across broad energy range



Adapted from Ulbricht et al., 2015,
https://doi.org/10.1063/1.4923096

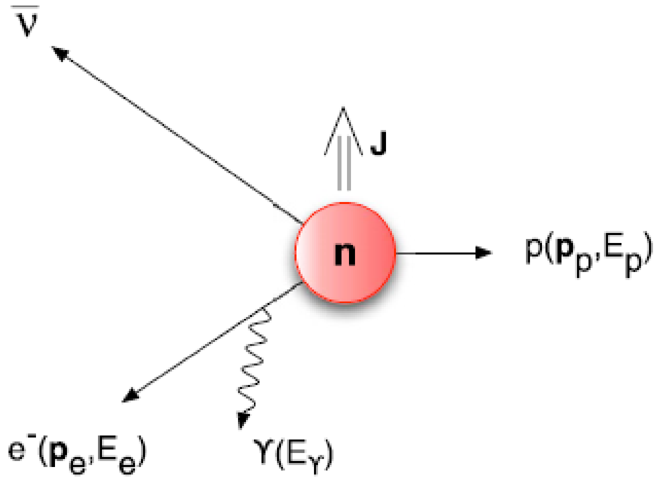
Charged-particle thermal kinetic inductance detector (CP-TKID) development and applications

CP-TKIDs for precision measurements of fundamental symmetries

Motivation

Neutron Beta Decay, the simplest example of the hadronic weak interaction, is an ideal laboratory for testing the Standard Model and searching for new physics

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto g_v^2(1+3\lambda^2)p_e E_e (E_0 - E_e)^2 \times \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \langle\vec{\sigma_n}\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$



Observable	Physics
Neutron lifetime (τ_n)	Helium abundance in Big Bang Nucleosynthesis
Neutron lifetime (τ_n), electron-antineutrino correlation (a), Beta Decay Asymmetry (A)	CKM Unitarity Parity violation Vector-axial vector currents
Fierz interference (b)	BSM Scalar/Tensor contributions to the weak interaction
Time-reversal violating parameter (D)	T-violation Right-handed neutrinos

Measurement challenges/opportunities

High precision measurements require high statistics, but limited by neutron sources, long neutron lifetimes

- Large-area detectors with high solid angle coverage

Electron energies ~1 MeV and proton energies ~1 keV, state of the art pixelated silicon detectors limited to few keV energy resolution

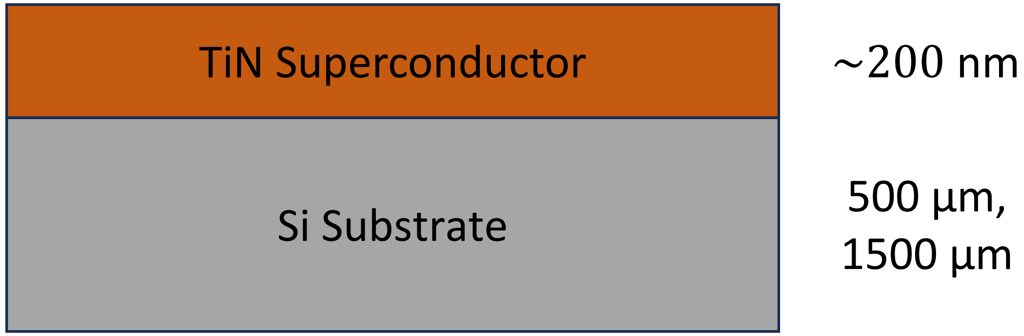
- Detector technology with improved energy resolution and threshold energy limitations

Electron energy spectrum further degraded due to backscattering

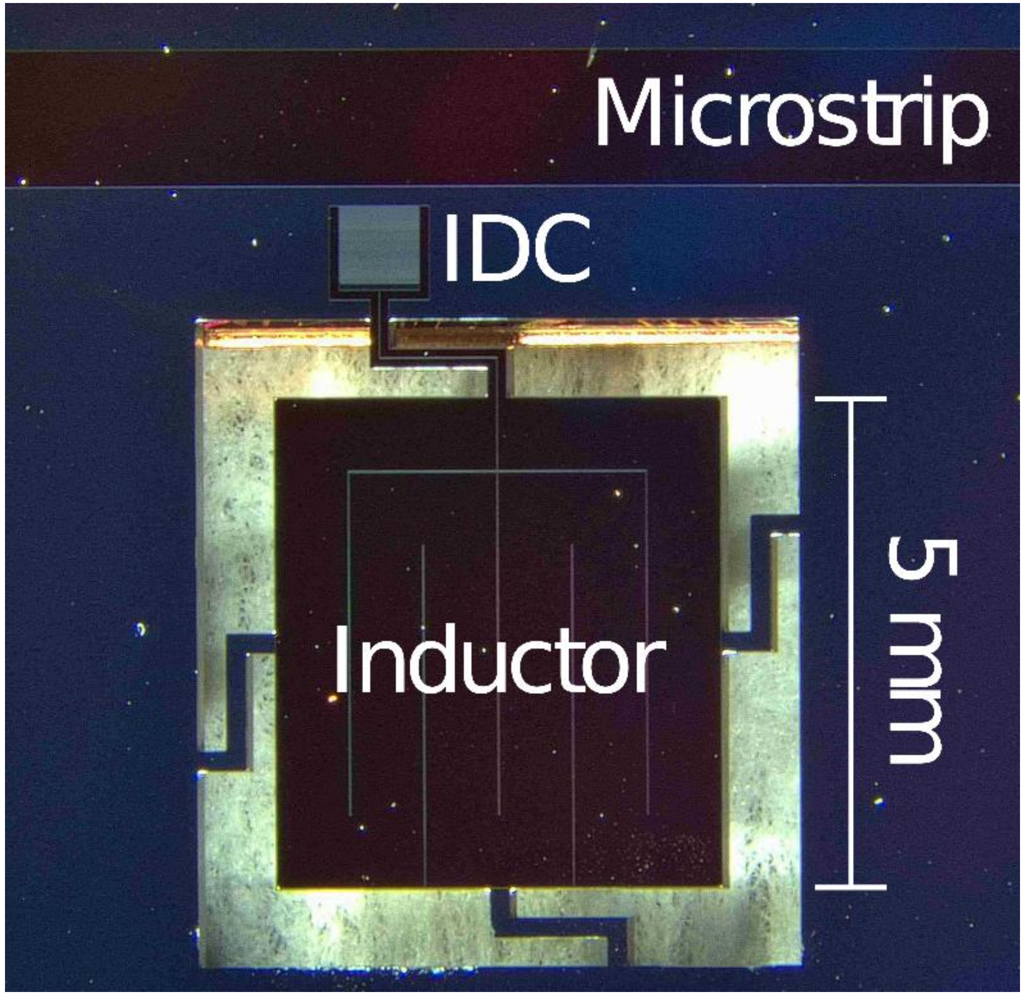
- Detectors that can support backscatter suppression techniques

CP-TKID design and fabrication

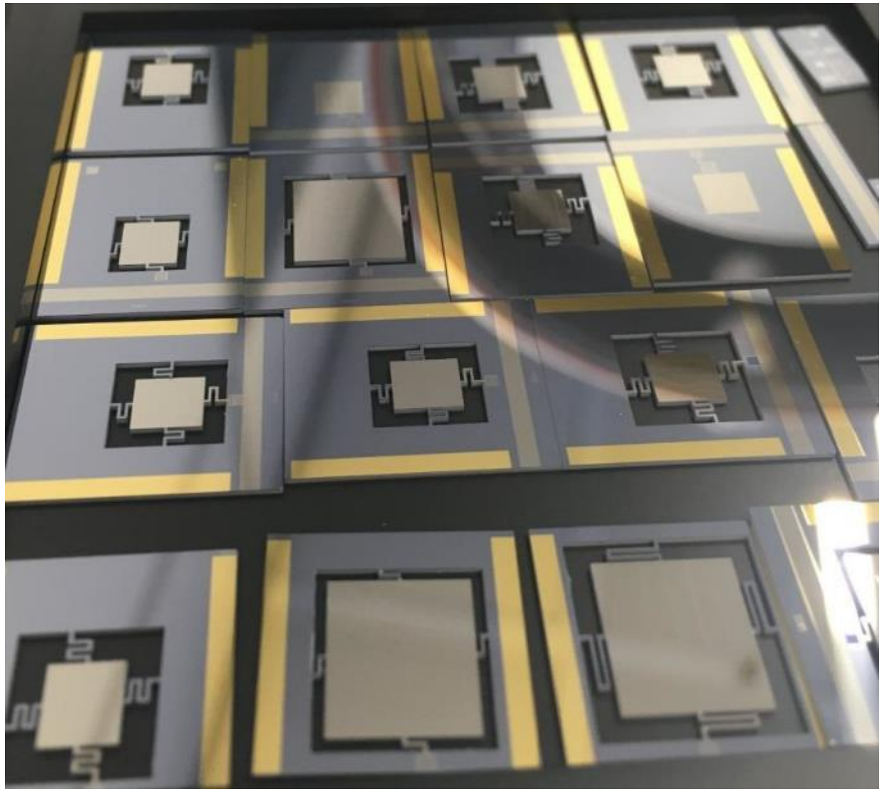
Utilizes more macroscopic absorber, optimized for charged-particle and gamma-ray detection in the 10s of keV to few MeV range

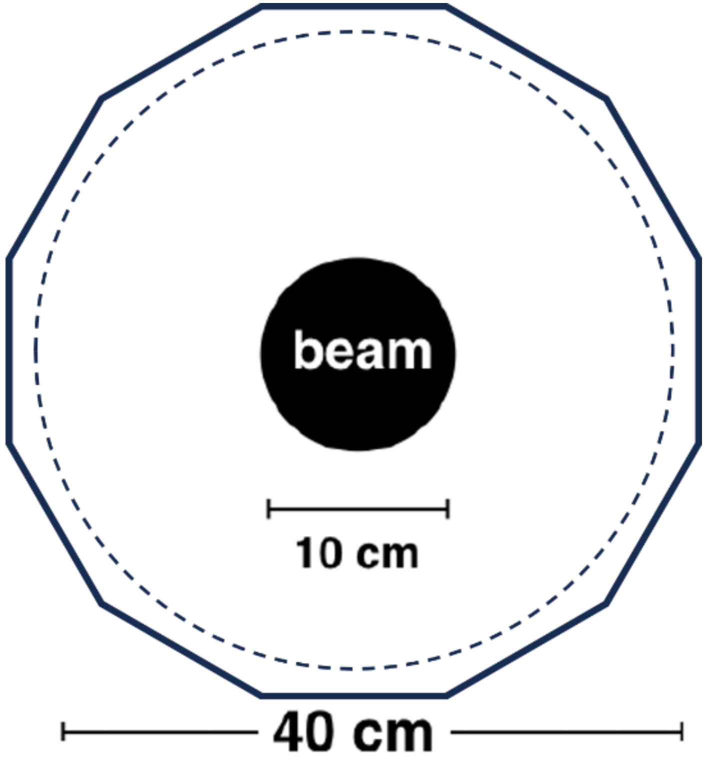


Relatively simple fabrication with single patterned metal layer (TiN), DRIE to define absorber island

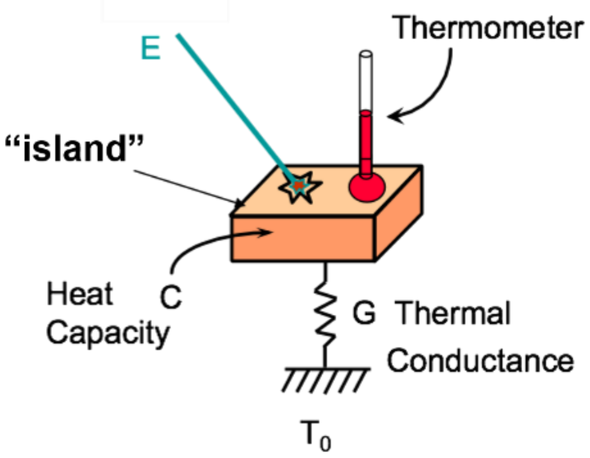


CP-TKID: active area and energy resolution





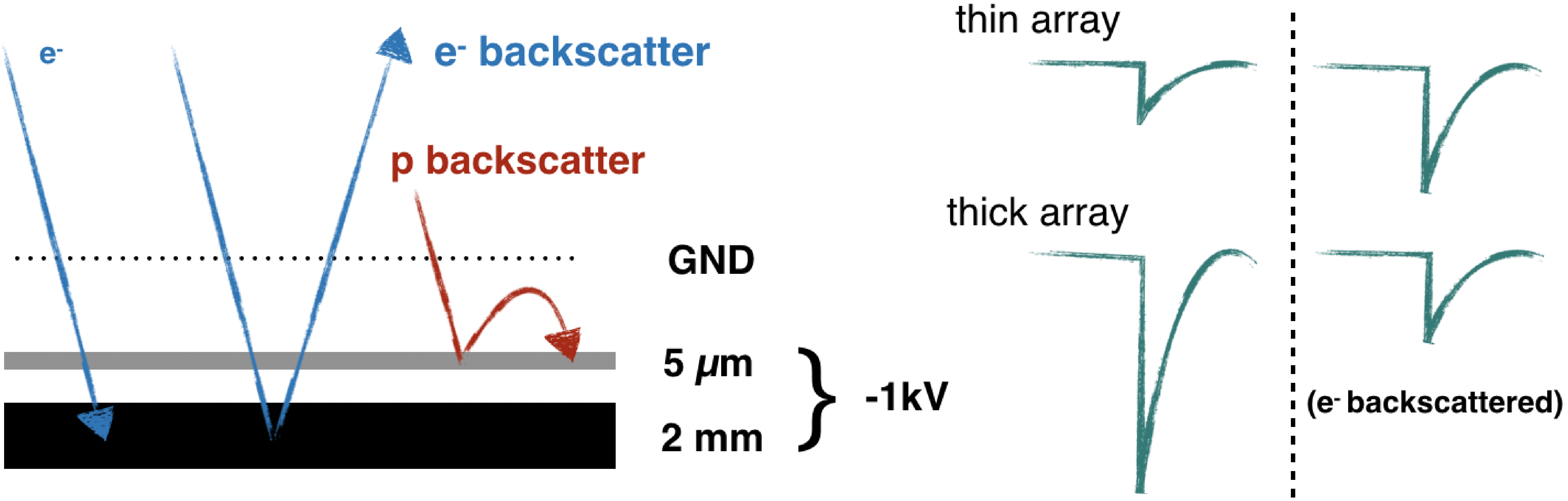
Energy resolution targets:
Electrons (1 MeV): ΔE < 100 eV
Protons (1 keV): ΔE < 10 eV



Calorimeter 'thermal' energy resolution limit, can achieve resolutions better than part per thousand:

$$\Delta E \sim \sqrt{4 k_B T^2 C}$$

CP-TKID: backscatter suppression



Improving CP-TKID energy resolution

Historically, achieved TKID energy resolution has been considerably worse than theoretical limits. Potential causes:

- Position-dependent response
- ‘Gain’ drift (thermal or magnetic)
- Athermal effects
- Unique pulse processing complexities
- Other effects?

Developed TKID model starting with work of Lindeman, 2014, https://doi.org/10.1063/1.4890018

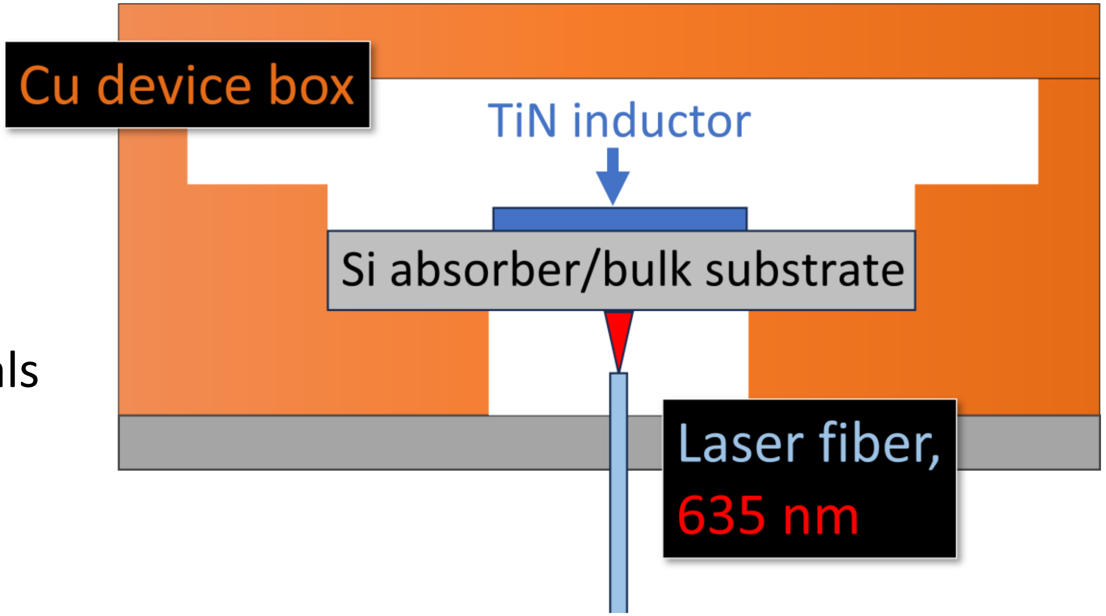
$$\frac{dr}{dt} = -\left(\frac{\omega_0}{2Q} + \frac{\omega_0 \beta_A}{2Q_\mathrm{i}}\right) r - \left(\frac{\omega_0 \alpha_A}{T_0 Q_i}\right) T$$

$$\frac{d\theta}{dt} = \frac{+\omega_0 \beta_\phi}{2Q_\mathrm{i}} r - \left(\frac{\omega_0}{2Q}\right) \theta + \left(\frac{\omega_0 \alpha_\phi}{T_0 Q_i}\right) T$$

$$\frac{dT}{dt} = +\left(\frac{P_0}{C}\left(1 + \frac{\beta_A}{2}\right)\right) r + \left(\frac{P_0 \alpha_A}{C T_0} - \frac{G}{C}\right) T$$

Coupled differential equations governing TKID response

CP-TKID response model



- Lindeman 2014 model assumed negligible frequency detuning between resonance and probe tune, small signals
- This model did not sufficiently capture observed pulse shapes
- Expanded model for nonzero detuning:

$$\frac{dr}{dt} = -\left(\frac{\omega_0}{2Q} + \frac{\omega_0(\beta_A - 2Qx\beta_\phi)}{2(1+4Q^2x^2)Q_i}\right)r - \left(\omega_0 x - \frac{\omega_0 Qx(\beta_A - 2Qx\beta_\phi)}{(1+4Q^2x^2)Q_i}\right)\theta - \left(\frac{\omega_0\alpha_A - 2\omega_0 Qx\alpha_\phi}{(1+4Q^2x^2)Q_i T_0}\right)T$$

$$\frac{d\theta}{dt} = +\left(\omega_0 x + \frac{\omega_0(2Qx\beta_A + \beta_\phi)}{2(1+4Q^2x^2)Q_i}\right)r - \left(\frac{\omega_0}{2Q} + \frac{\omega_0 Qx(2Qx\beta_A + \beta_\phi)}{(1+4Q^2x^2)Q_i}\right)\theta + \left(\frac{2\omega_0 Qx\alpha_A + \omega_0\alpha_\phi}{(1+4Q^2x^2)Q_i T_0}\right)T$$

$$\frac{dT}{dt} = +\left(\frac{P_0}{C}\left(1 + \frac{\beta_A}{2}\right)\right)r - \left(\frac{P_0 Qx}{C}(2+\beta_A)\right)\theta + \left(\frac{P_0\alpha_A}{CT_0} - \frac{G}{C}\right)T$$

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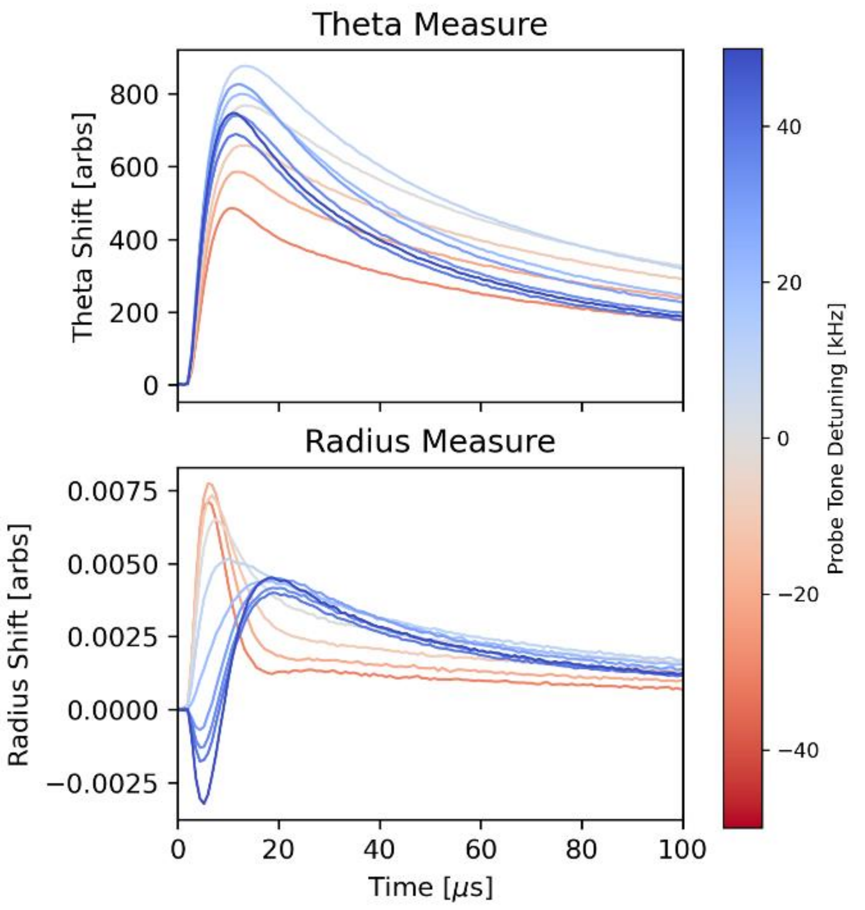
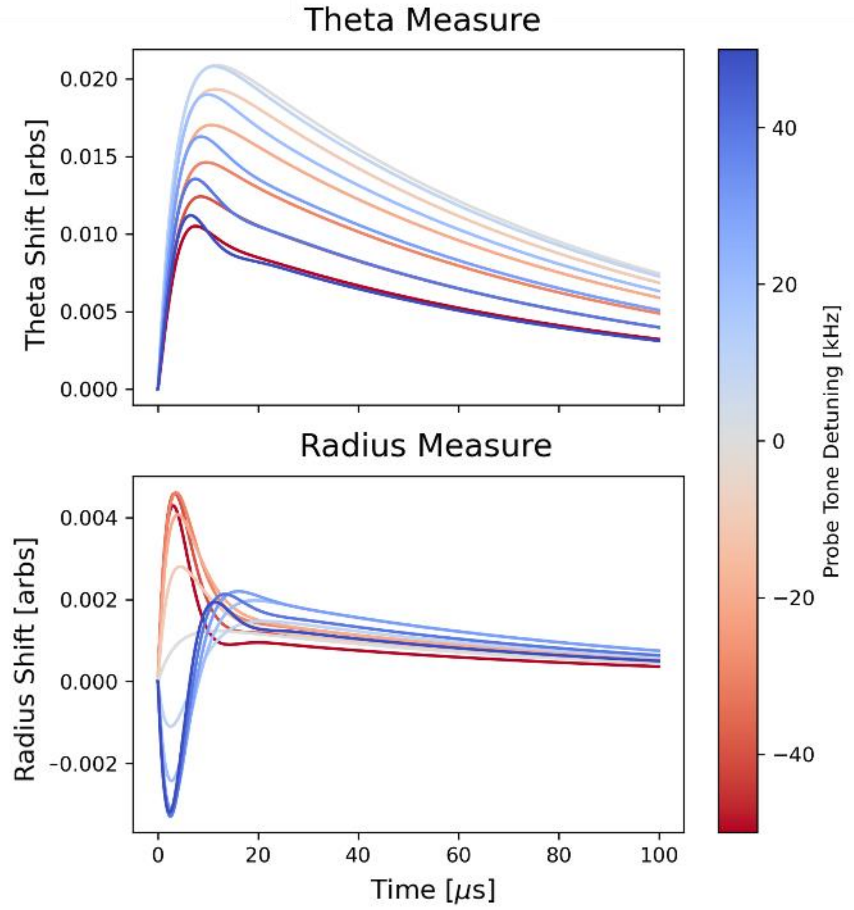
CP-TKID response model

Data



Model



- Expanded TKID model still work in progress, but already shows good qualitative agreement with data

- Work led by graduate student, Ian Fogarty Florang!

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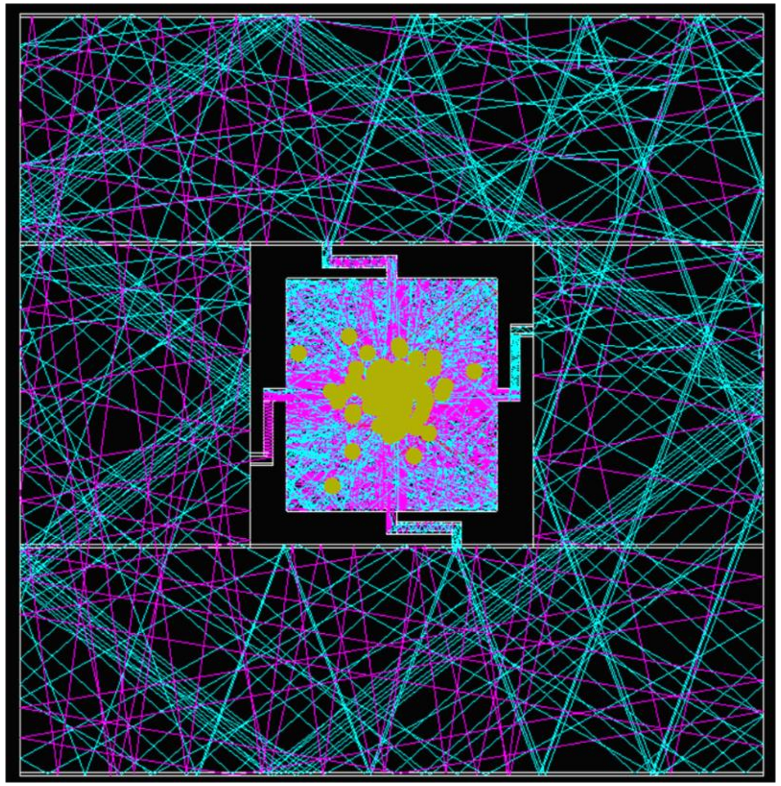
G4CMP simulations

Phonon transport simulations used to guide device design, e.g. by revealing position-dependent response

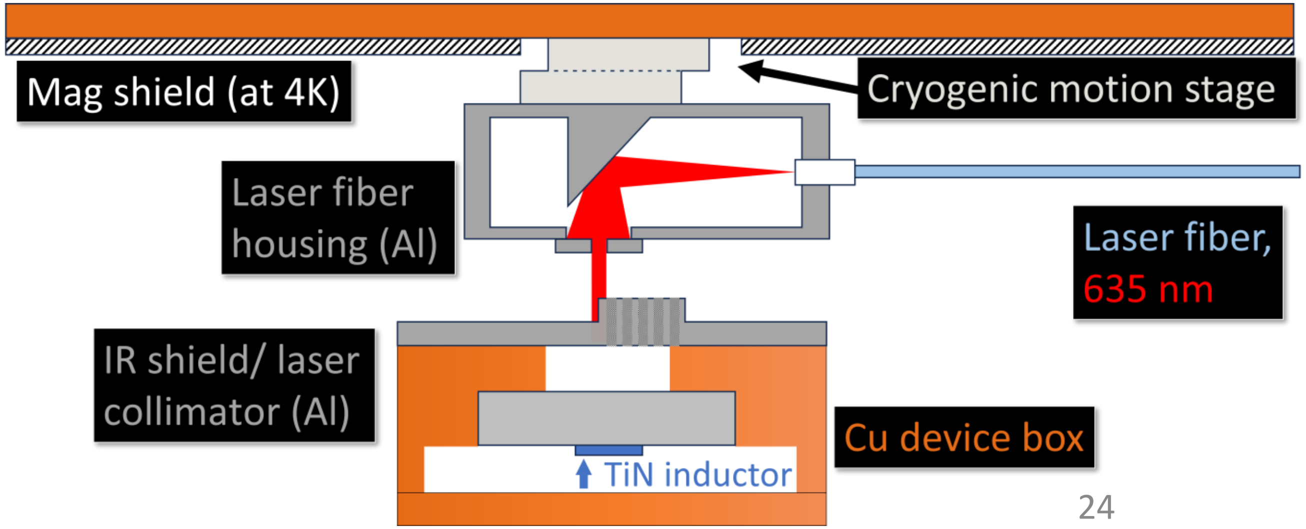
Example simulation details:

- Phonons generated at center of CP-TKID absorber
- Phonons detected at surface level superconducting film shown as yellow circles.
- Tracks showing different phonon propagation modes:
  - Slow transverse
  - Fast transverse
  - Longitudinal



G4CMP work led by summer undergraduate student, Robbie Harper!

Exploring experimental verification using cryogenic motion stage



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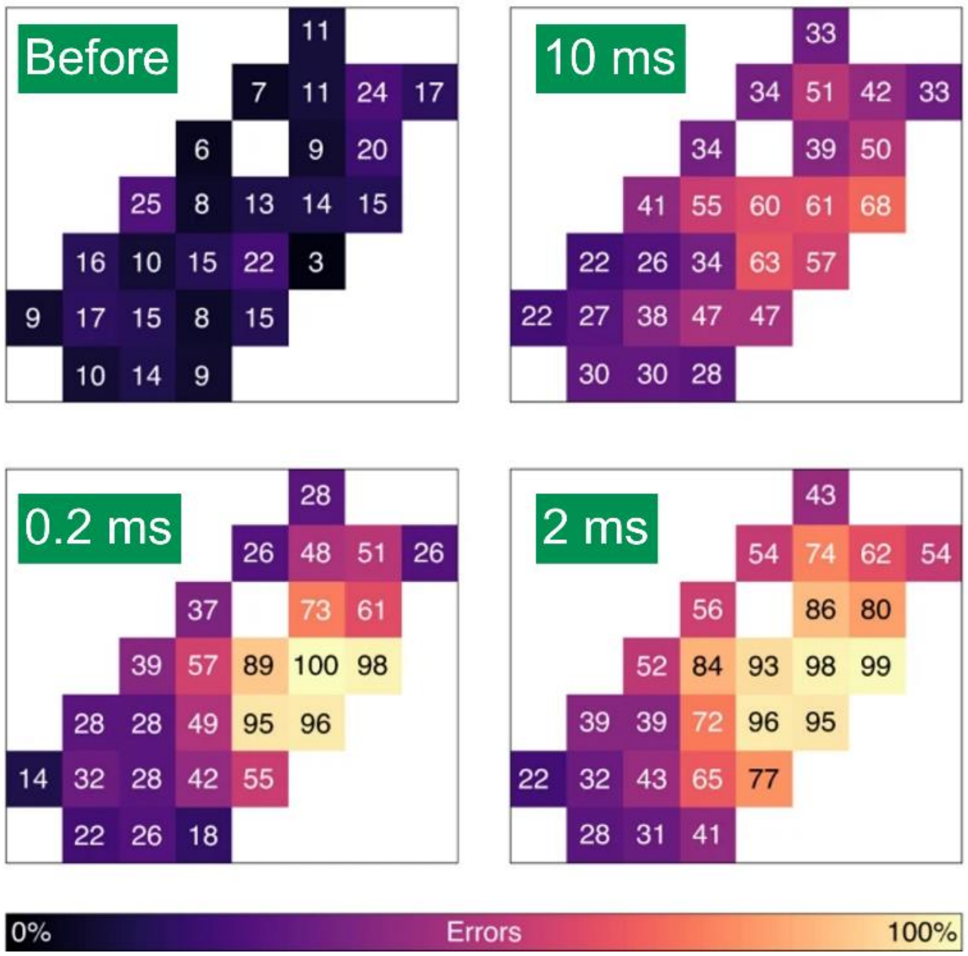
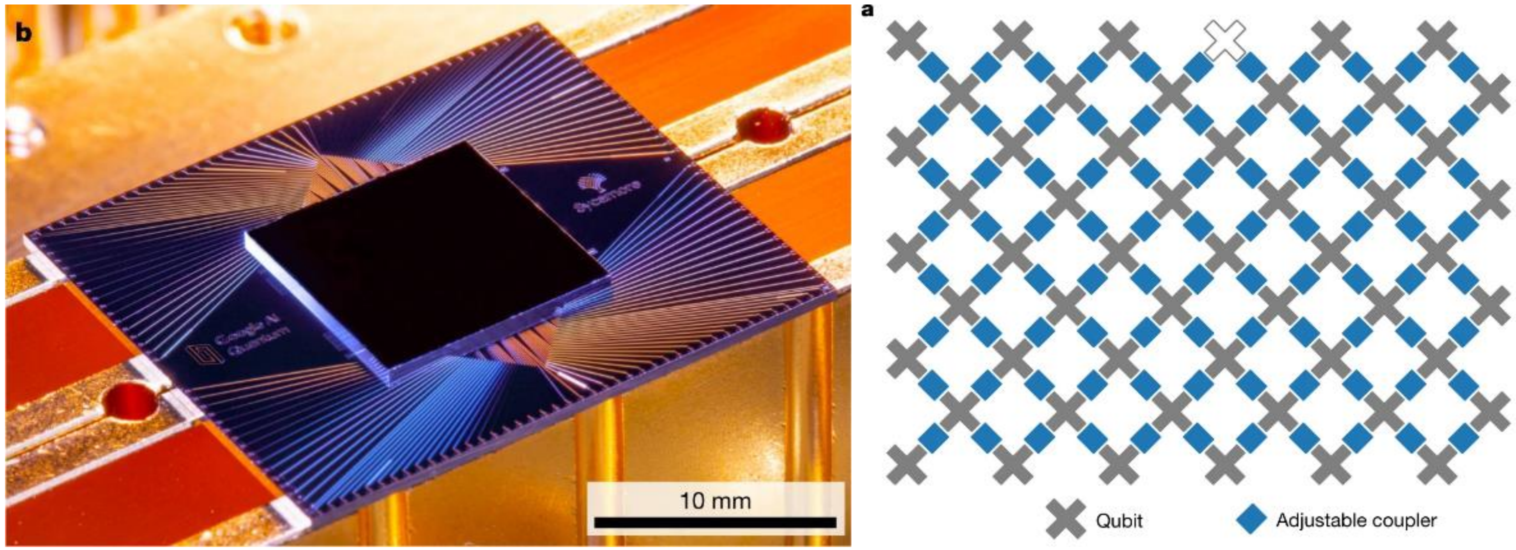
CP-TKIDs for ionizing radiation background measurements

Motivation

Correlated error bursts lasting multiple milliseconds



Google Quantum AI Sycamore chip



Adapted from Arule et al., 2019, https://doi.org/10.1038/s41586-019-1666-5

Adapted from McEwan et al., 2022, https://doi.org/10.1038/s41567-021-01432-8

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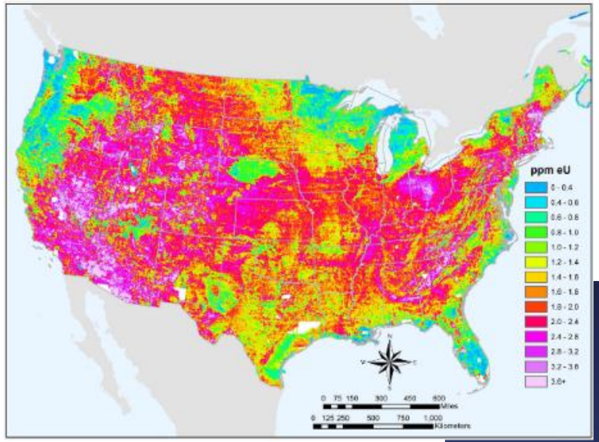
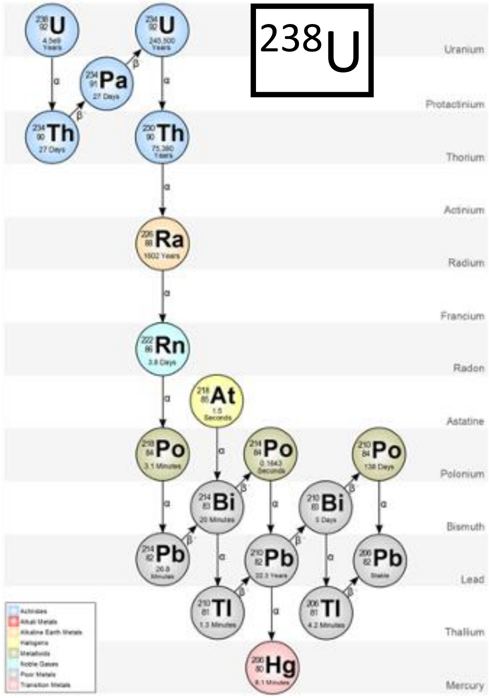
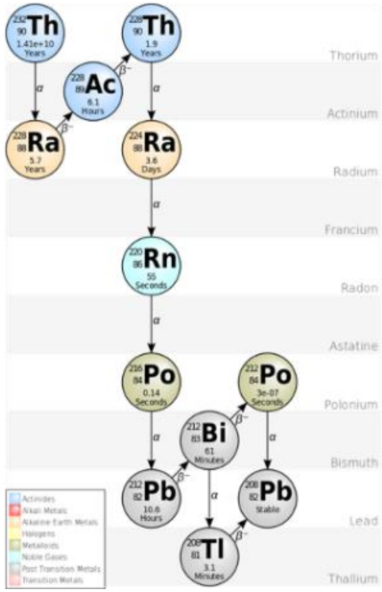
Motivation



Gamma rays

^{238}U ^{40}K ^{232}Th





Cosmic rays

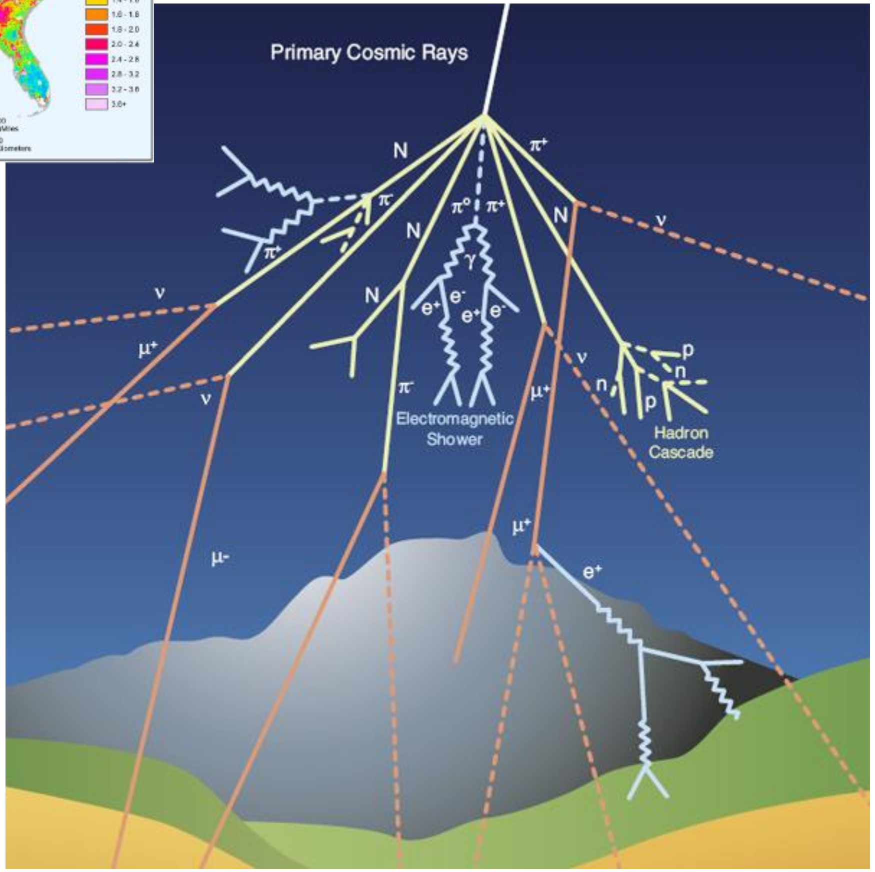


Image: Pierre Auger Observatory

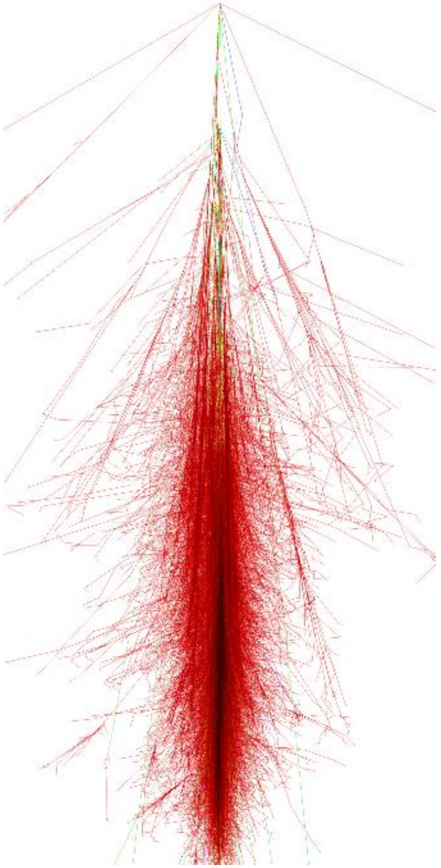
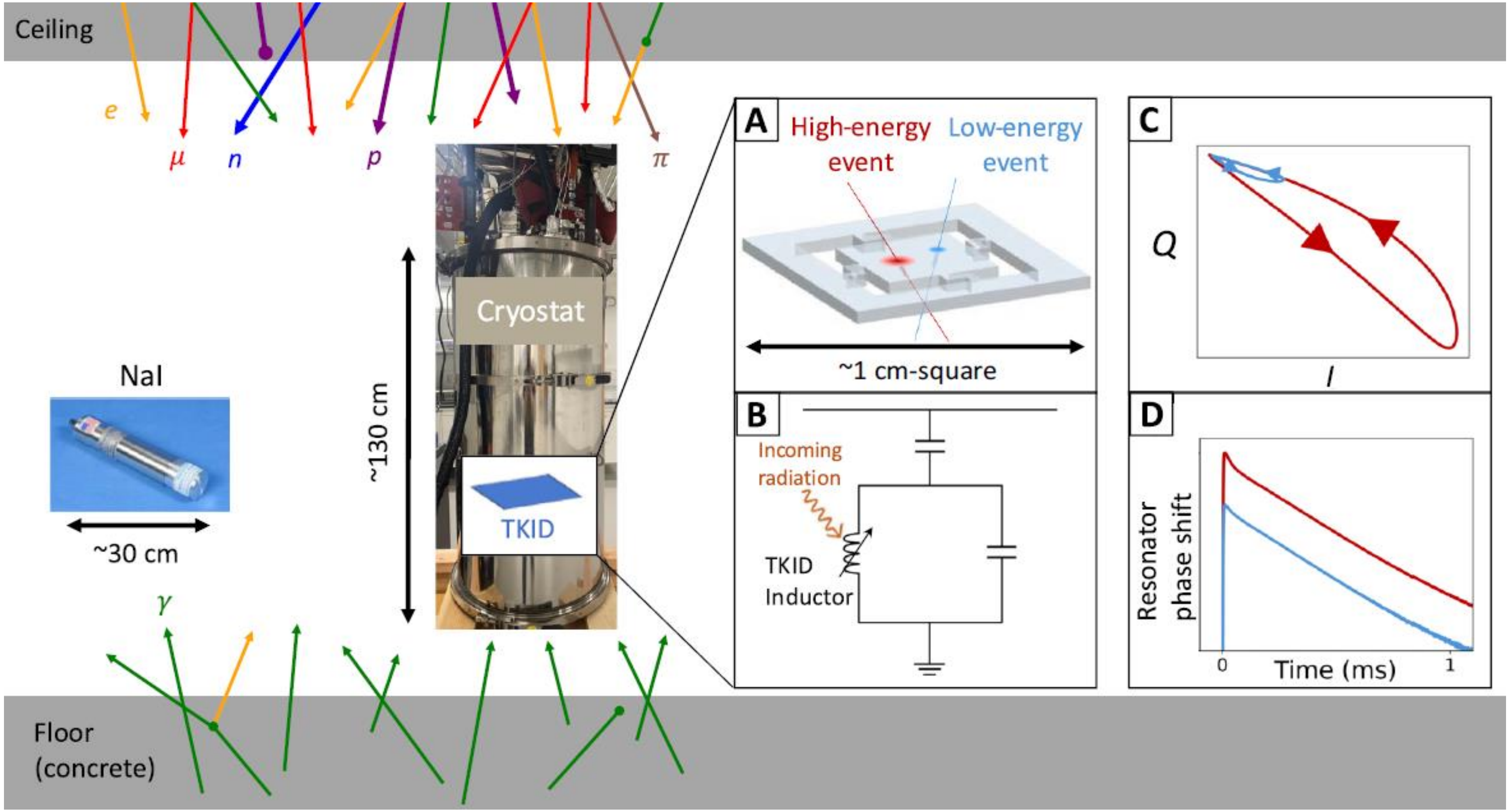


Image: Johannes Knapp (DESY)

Experimental setup

Results recently reported in Fowler et al., 2024, https://doi.org/10.1103/PRXQuantum.5.040323



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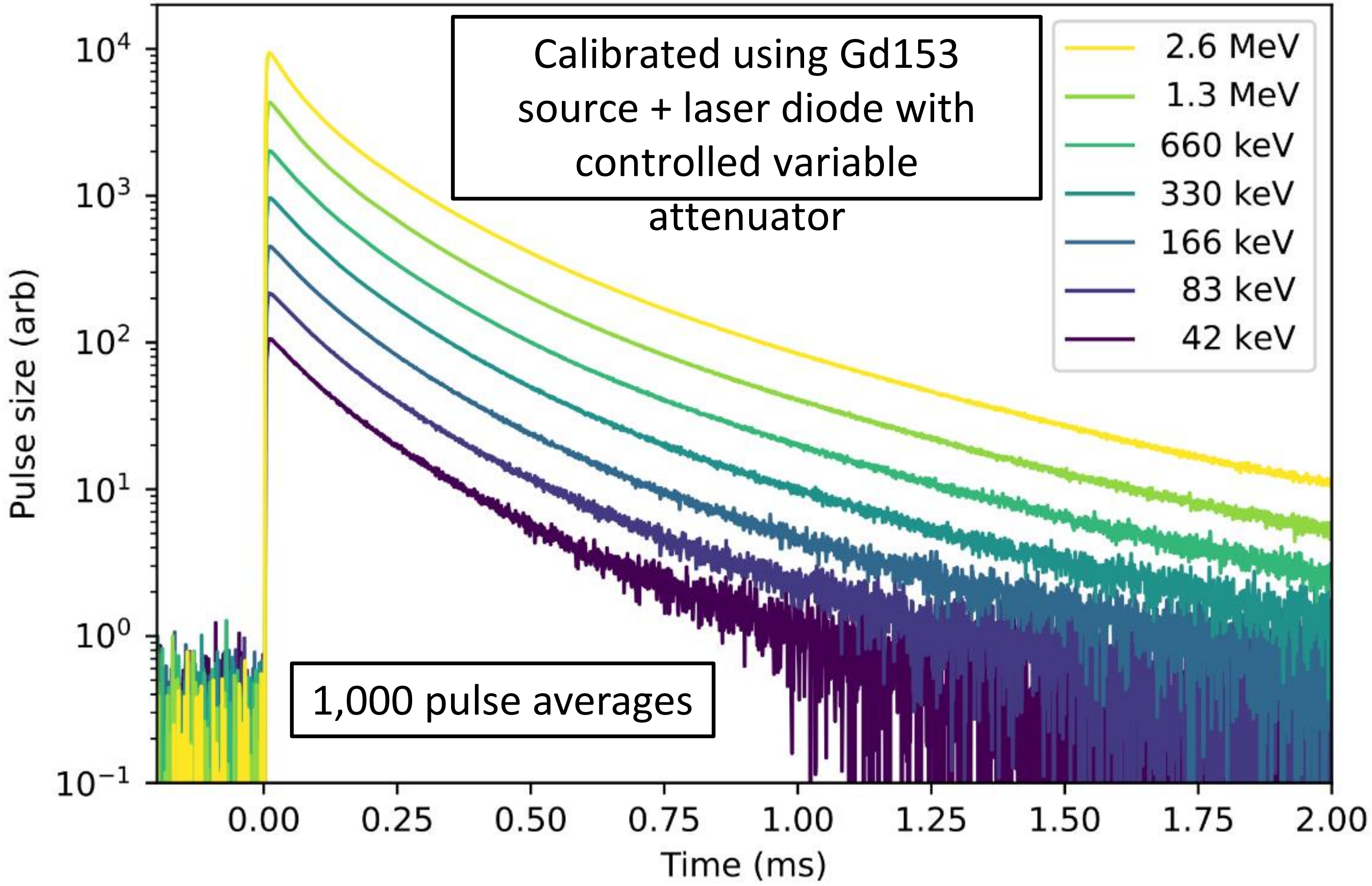
Linearity across broad energy range

Multiple nonlinearities:

- $C \propto T^3$
- $n_{\mathrm{QP}} \propto \sqrt{T} \exp(-\Delta/k_B T)$
- $\delta L \propto -\delta n_{\mathrm{QP}}$
- $f_0 \propto 1/\sqrt{LC}$

All combined, expect <20% nonlinearity up to several MeV, confirmed experimentally



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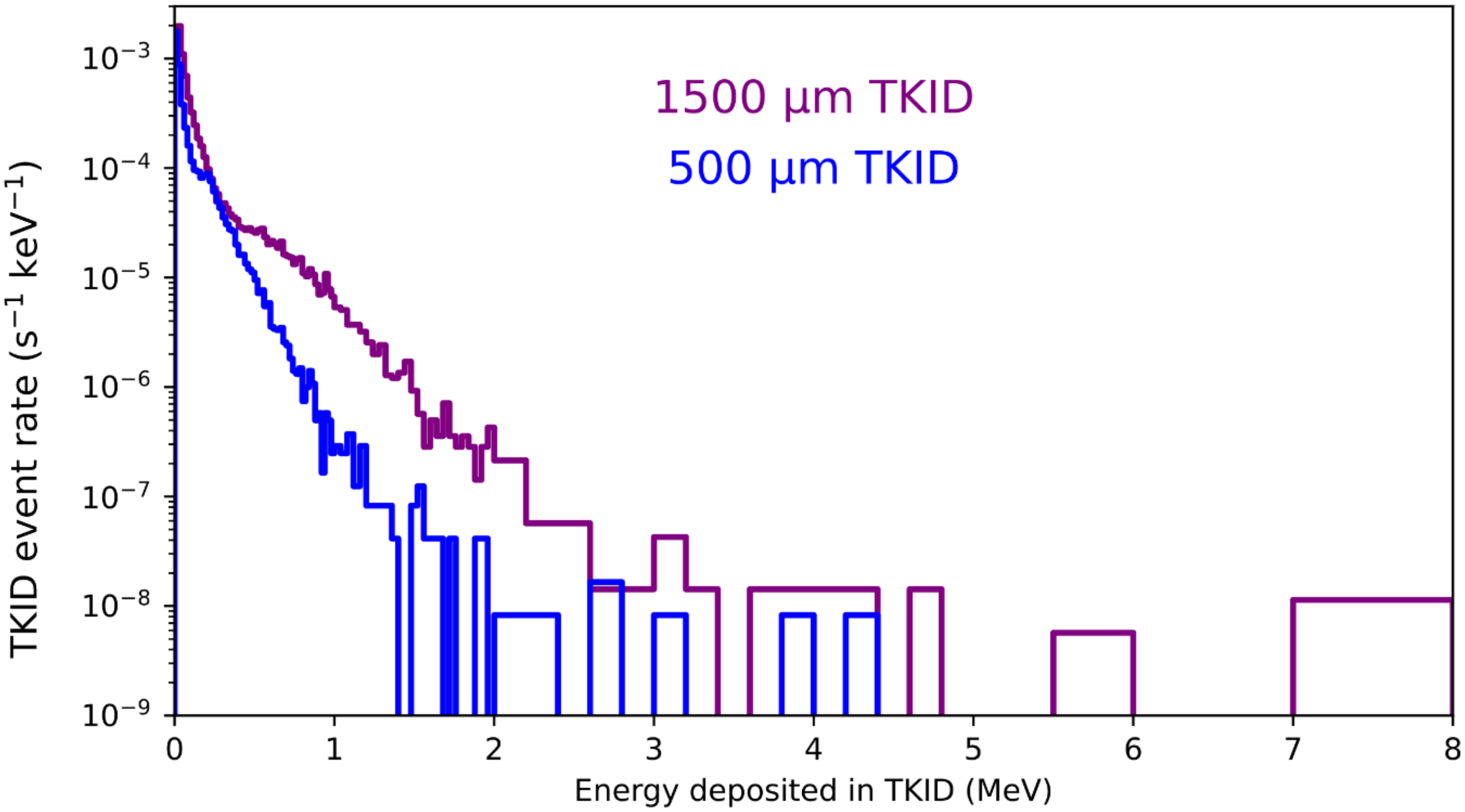
Measured spectra

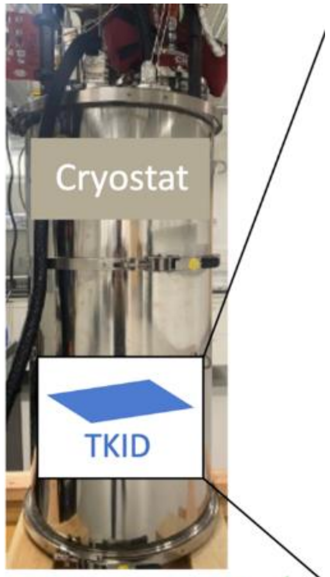


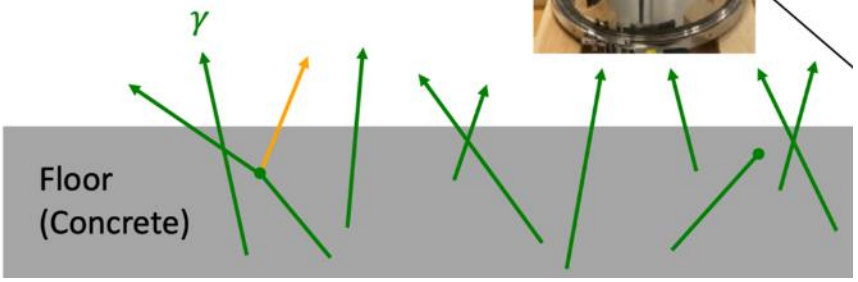
Collected cosmic + terrestrial ionizing radiation background data

- Two TKID devices: 1500 µm and 500 µm thicknesses
- >100 hours of data collected with each device
- Data spans 6 orders of magnitude in event rate
- Range of energies collected spans 40 keV to 8 MeV
- Median energy of 120 keV (1500 µm thick device)

Gamma-ray model

GEANT4 simulations controlled by TOPAS

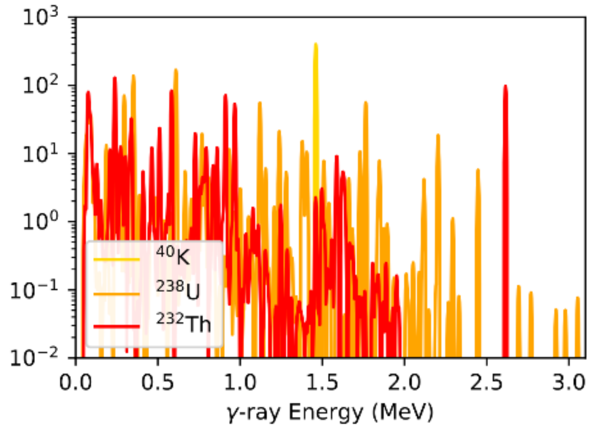




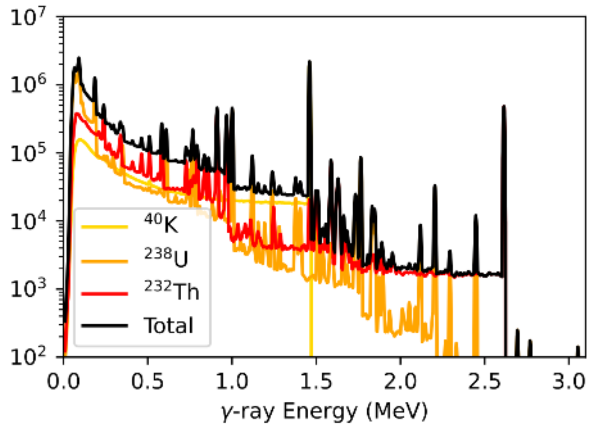
Additional modeling details in Fowler et al., 2024, https://doi.org/10.1109/TASC.2024.3512523

<u>Simulations performed in 2 steps:</u>

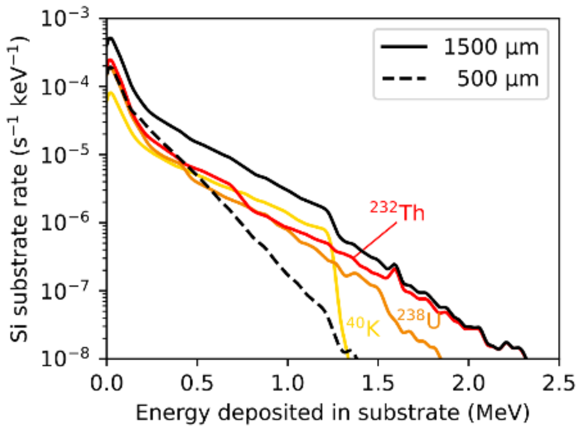
1) GEANT4: Distributed source in the concrete floor emits upwards.
   - Study particle types, and *E* and θ distribution
2) GEANT4: Transport through the silicon sensor substrate.
   - Record energy deposited in substrate.
   - Do this segregated by particle type (e^+, e^-, γ)



Isolated radionuclides



Above floor



TKID

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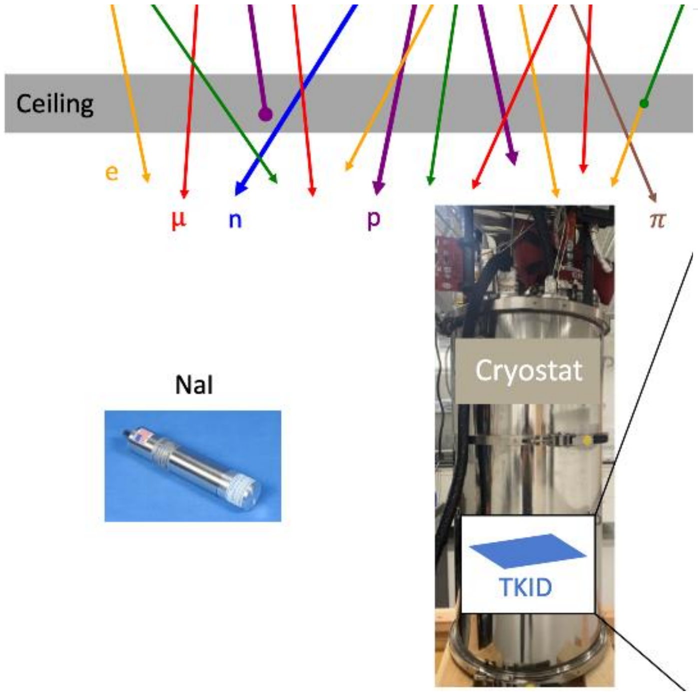
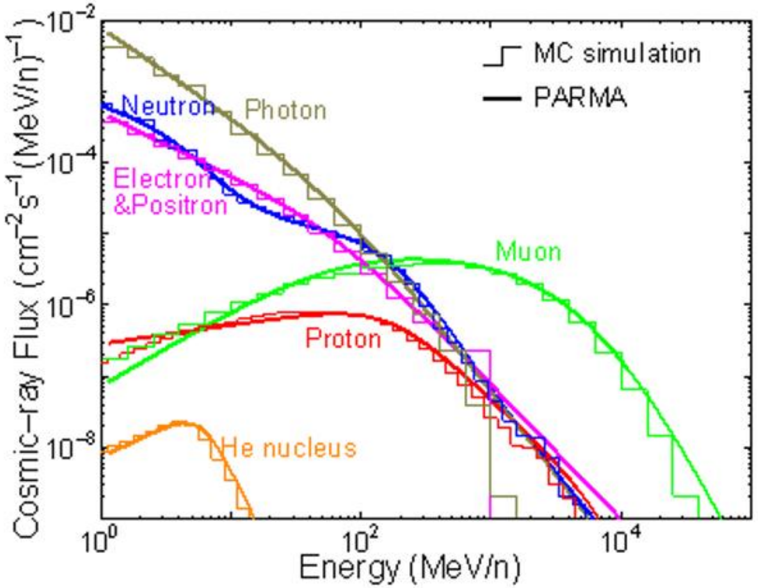
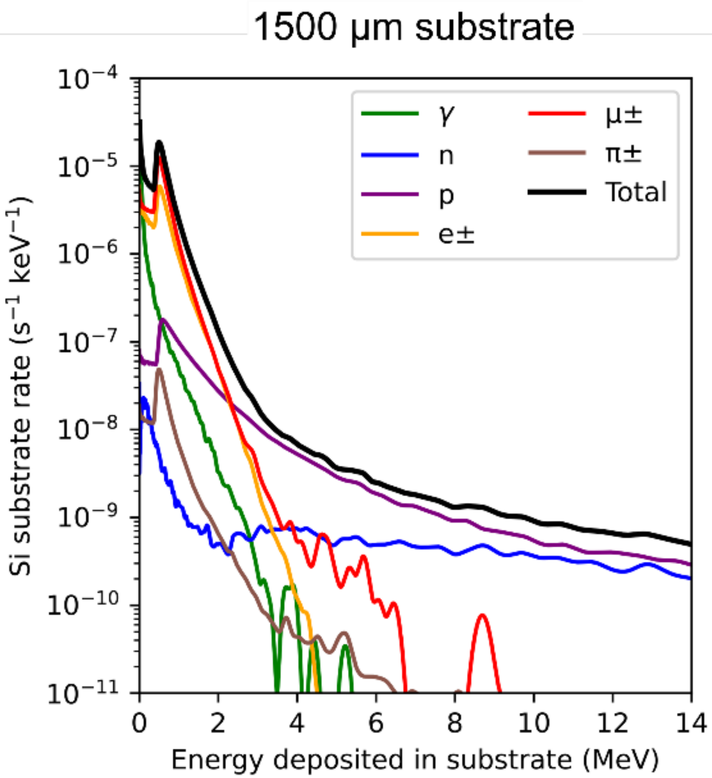
Cosmic-ray model

<u>Simulations in 3 steps</u>

1) PARMA generates {k, *E*, θ, ϕ} values
2) GEANT4: Pass through large concrete ceiling and thin aluminum cryostat.
3) GEANT4: Transport through the silicon sensor substrate.
   - Record energy deposited in substrate.
   - Do this segregated by particle type ($\mu^{\pm}$, $e^{\pm}$, γ, p, n)







<u>Ceiling effects include:</u>

- n ↔ p
- γ ↔ e±
- μ± → e-
- Any → γ
- Screening all species

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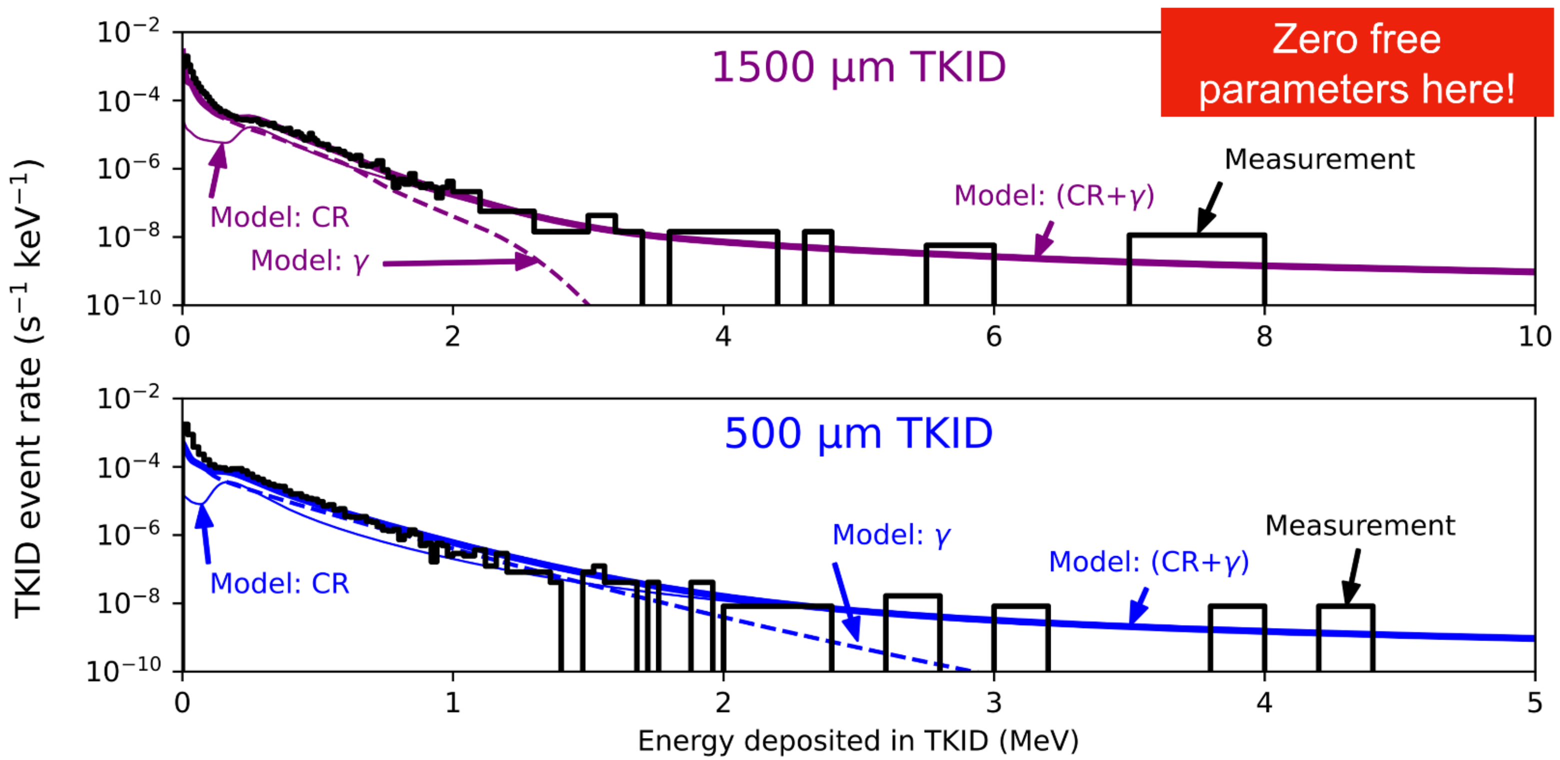
Comparison of data to model



TKID devices likely compatible with superconducting qubit designs for future extensions of this work!

Key findings / lessons learned:

- Data matches model to better than 10%, despite large range of event rates and deposited energies
- Total absorbed power and gamma-ray rate roughly proportional to thickness
- Cosmic-ray rate largely independent of thickness
- Average event energy of 215 (293) keV expected for 500 (1500) µm thick substrates
- Can partially reduce backgrounds through underground environment, low-activity building materials
- High-energy tail observed up to to multiple MeV, potentially problematic for on-chip mitigation techniques (e.g. gap engineering)
- Results can be extended to other laboratories/environments with some straightforward corrections

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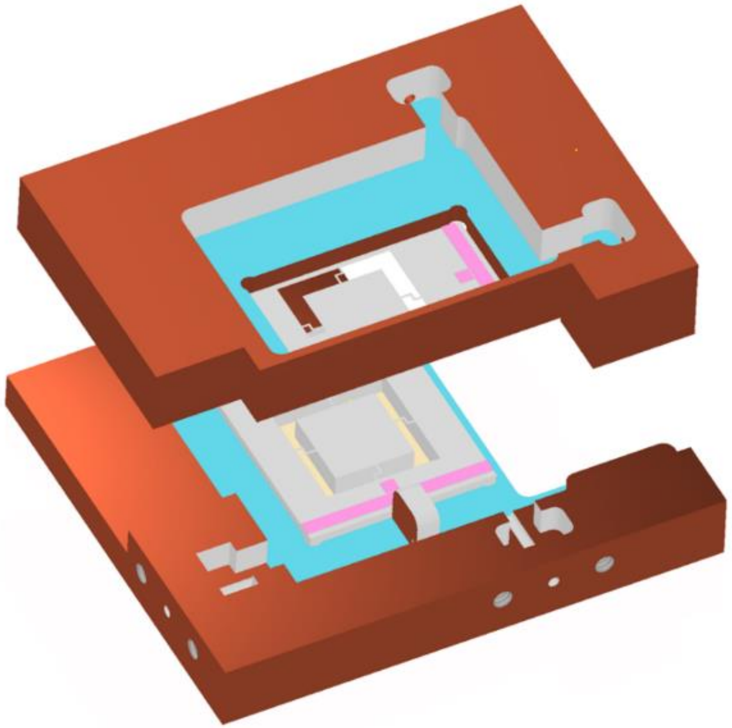
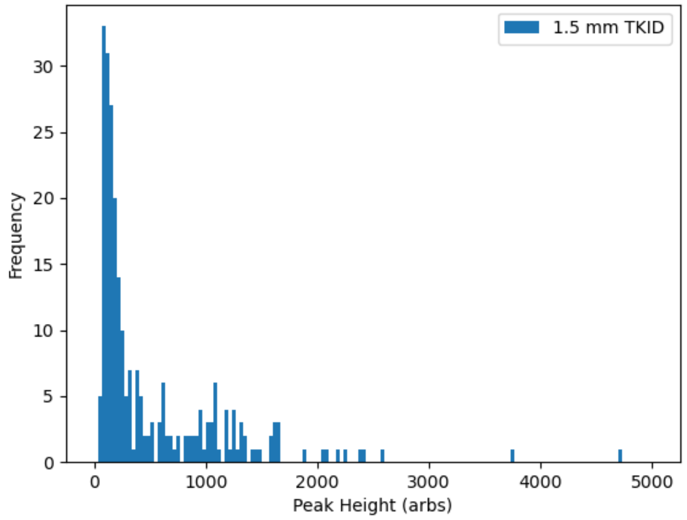
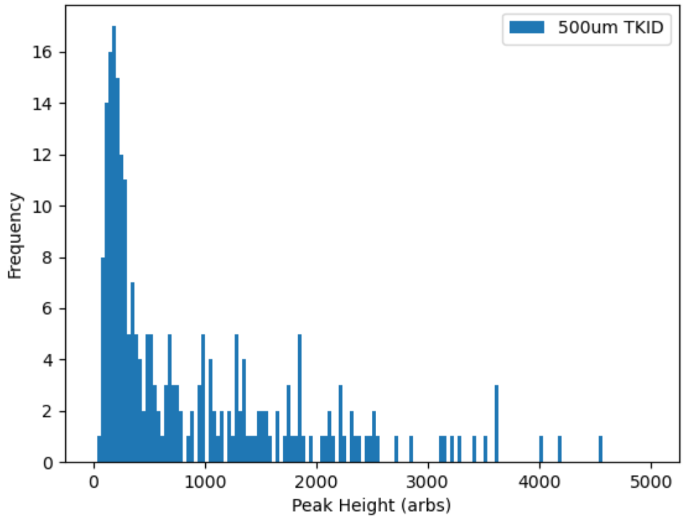
Stacked CP-TKID progress

Beginning early design work of stacked CP-TKID geometry



Performing preliminary stacked CP-TKID measurements using currently fabricated devices





Ionizing radiation background coincident event spectra

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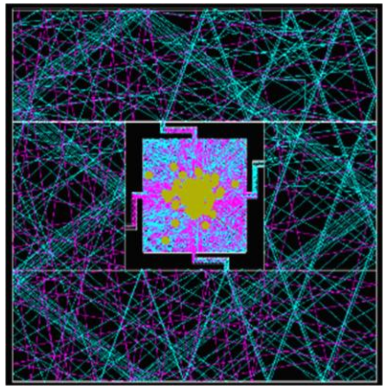
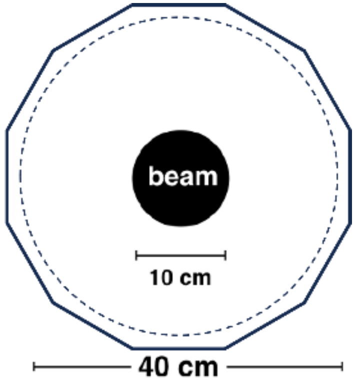
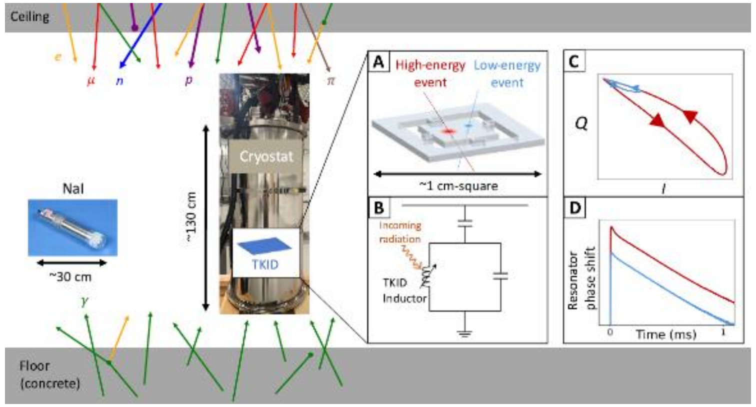
Conclusions







- The CP-TKID can be an extremely useful tool in quantum information science and nuclear physics applications
- Application 1: developing CP-TKIDs for studies of fundamental symmetries – aiming to improve energy resolution, active area, and background suppression over current state-of-the-art.
  - ➢ Quantum devices for nuclear physics
- Application 2: measured ionizing radiation background using a CP-TKID as a proxy for a quantum circuit + substrate, good agreement between data and model with zero free parameters
  - ➢ Quantum devices + nuclear physics for quantum information science

Students and postdocs interested in this work should visit https://www.nist.gov/programs-projects/kinetic-inductance-spectrophotometry or contact Paul Szypryt at paul.szypryt@nist.gov.

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