Cryogenic Platforms at Fermilab: Recent Results and Outlook

Dylan J Temples, Fermilab

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GUINEAPIG Workshop @ UToronto

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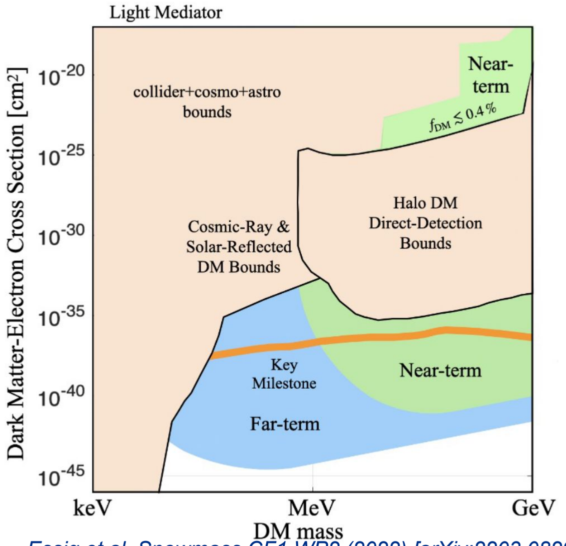
GeV and Under Invisibles

Sub-GeV regime is an interesting parameter space to look for dark matter!

Advantages: high DM number density, larger cross-sections still unexplored

Challenges: low DM kinetic energy (~1 eV for 1 MeV/c^2 DM), new backgrounds



Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

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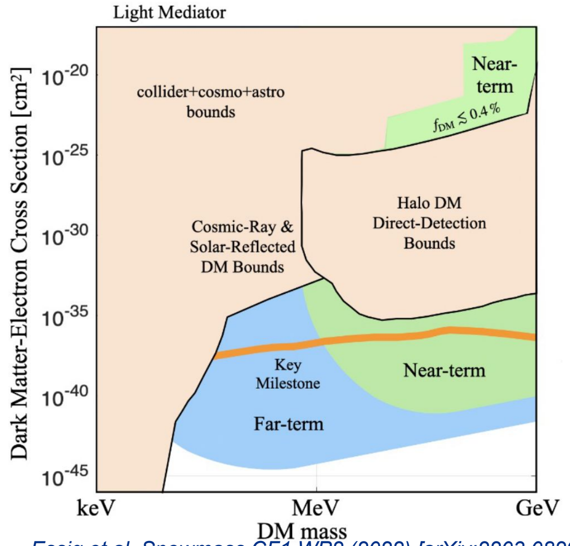
Energy threshold: sensitivity to sub-eV quanta

- Ballistic / athermal phonons (~1 meV)
- Cooper pairs / quasiparticles (10s-100s µeV)



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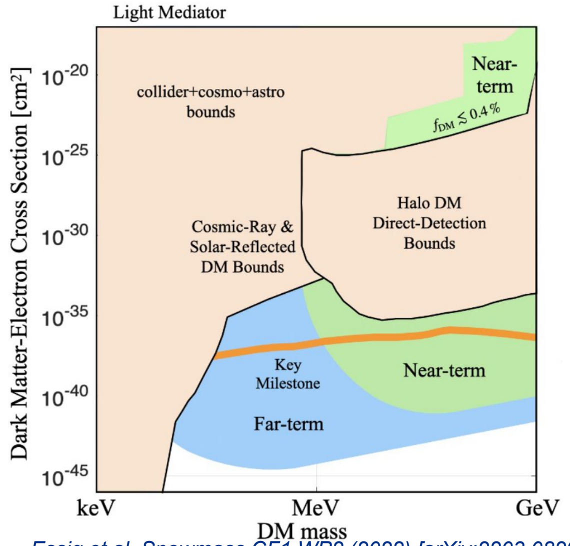
Backgrounds: new characterization and mitigation

- Radiogenic (“all-surface” detectors)
- Non-radiogenic (e.g., stress release)



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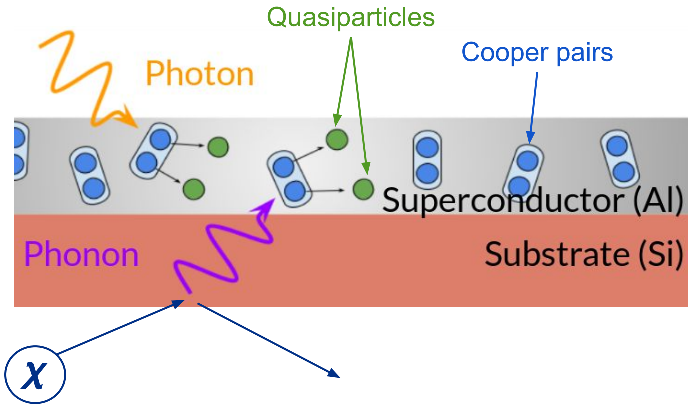
Sub-GeV DM Direct Detection with Superconducting Sensors



Scattering target: crystalline substrate (Si, Sapph, ++)

- DM-nuclear scattering
- DM-electron scattering / Bosonic DM absorption
- DM coupling into collective modes (phonons)

Ballistic phonons propagate to superconducting film → break Cooper pairs into quasiparticles (QPs)

Primary signal channel: QP density (n_{qp})

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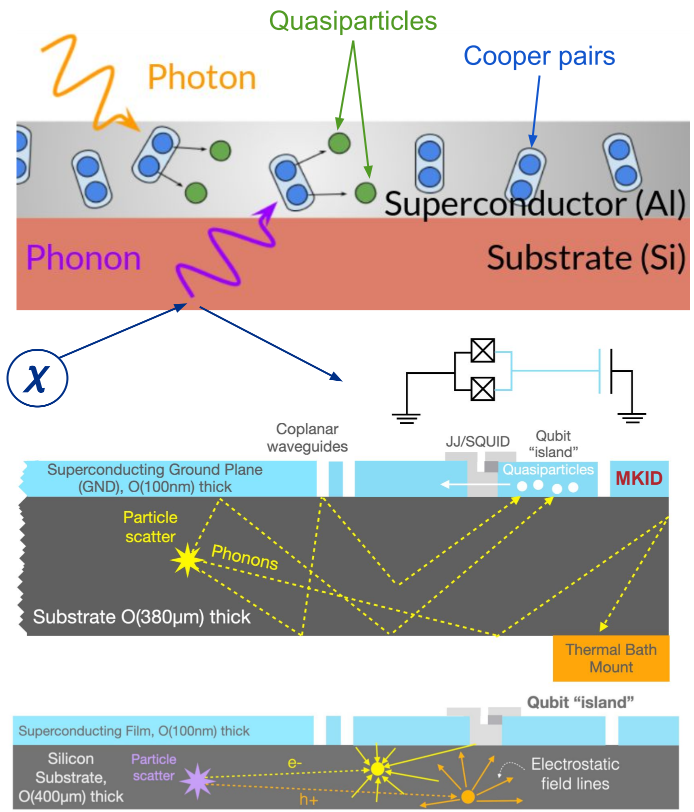

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Sensor architectures:

- Kinetic Inductance Phonon-Mediated Detectors (KIPMDs)
  - n_{qp} modulates resonant frequency of MKID
- Superconducting qubits
  - n_{qp} sets rate of QP tunneling through junction
  - *Non-quasiparticle sensing schemes possible*
- TES, SNSPD, QCD (not in this talk)

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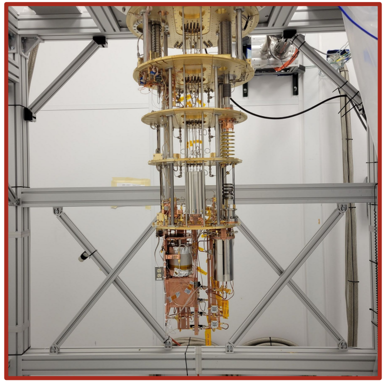
Northwestern NEXUS Experimental Underground Site @Fermilab

- CryoConcept HexaDry dilution refrigerator (10 mK)
- 107 m rock overburden
- Moveable lead shield
- RF + DC payloads for qubits and DM detectors

LOUD



- Oxford Proteox dilution refrigerator (20 mK)
- Surface-level facility
- Qubit-based sensor characterization & calibration
- Scannable optical source

QUIET

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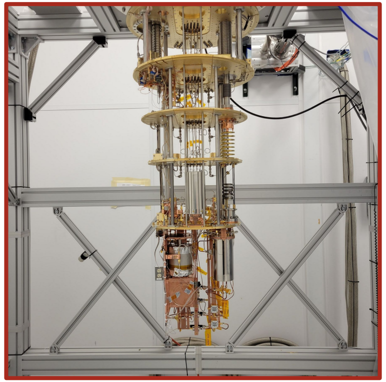

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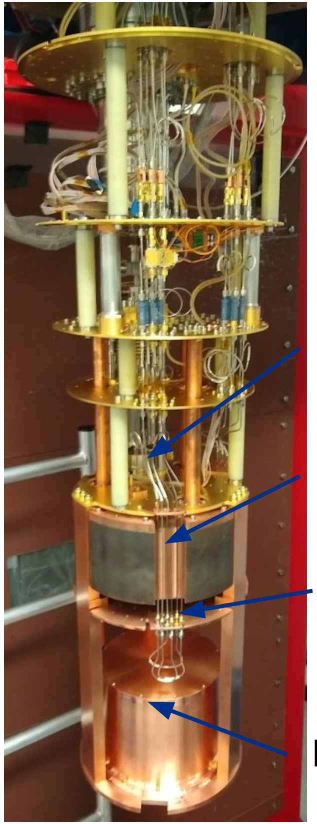
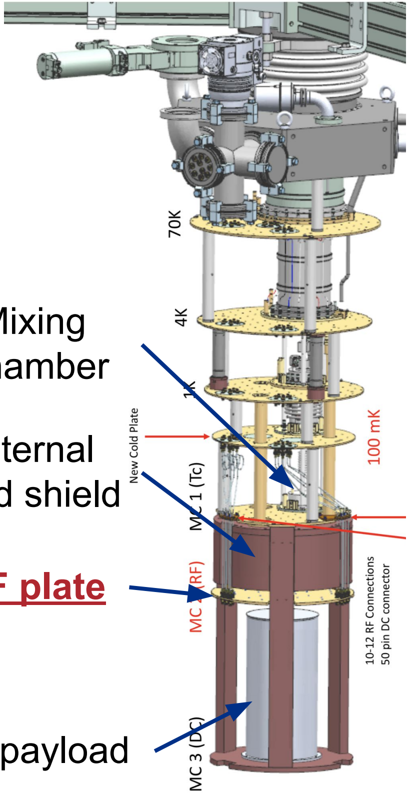


Mixing Chamber

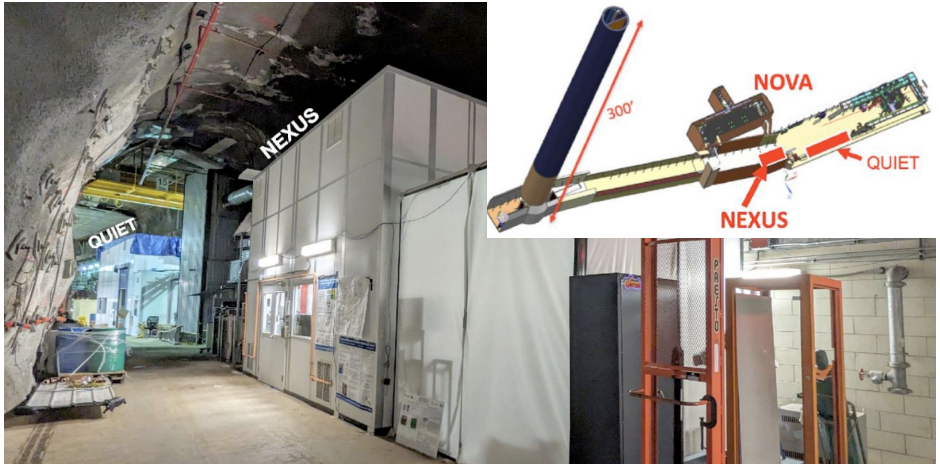
Internal lead shield

RF plate

DC payload



107 m rock overburden: reduction in cosmic muon flux by 2 orders of magnitude (7 muons/cm^2/day)



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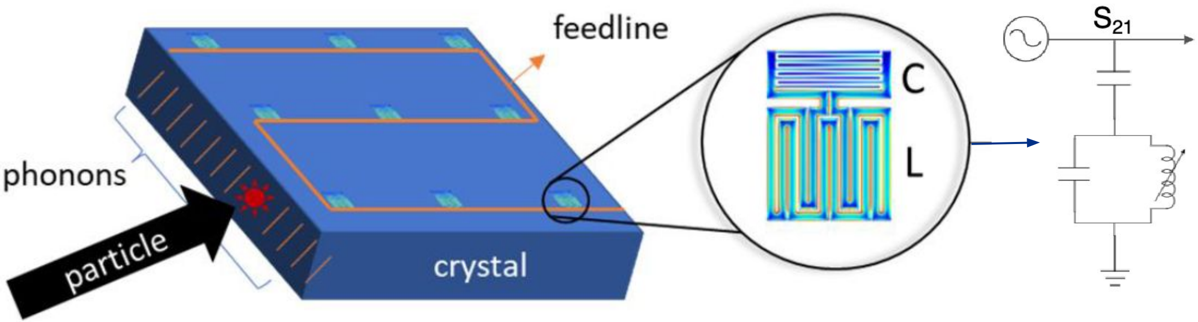
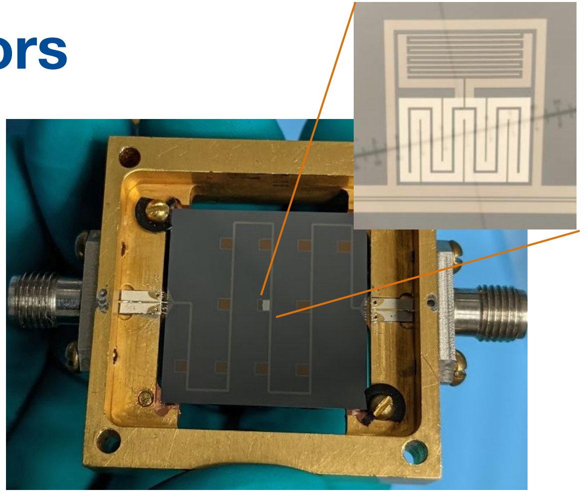
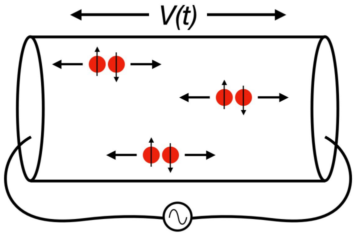
Kinetic Inductance Phonon-Mediated Detectors





Kinetic Inductance Detector (KID)-based microcalorimeters

- RLC resonator with nonlinear inductance (inertia of charge carriers)
- Probe complex transmission (S_{21}) of RF stimulus at resonant frequency
- Frequency-domain multiplexability: simple scaling, pixelized readouts
- Path to sub-eV resolution on phonon channel!



Collaborators and Acknowledgements

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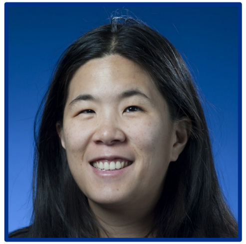
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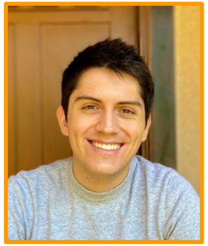
K. Ramanathan


S. Golwala


T. Aralis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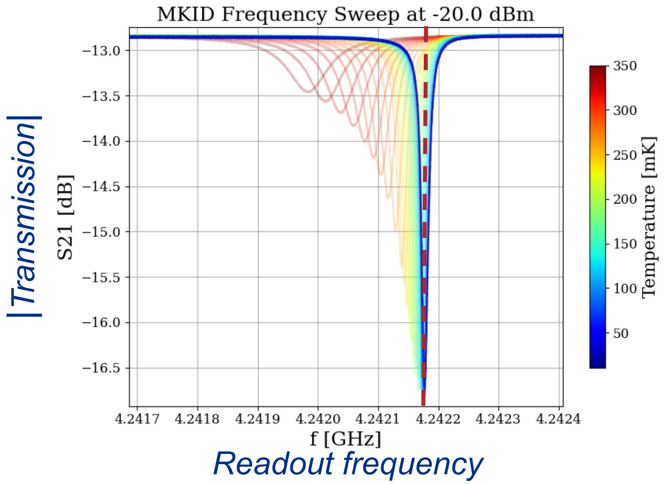
S. Kevane (Stanford)
S. Ray (Northwestern)
G. Spahn (UMN)
C. Cap (Caltech)

KIPM Detector Readout

1. Park your radio at $f_{r,0}(T_{op})$
   - Measure (in time) flat transmission **+ noise**



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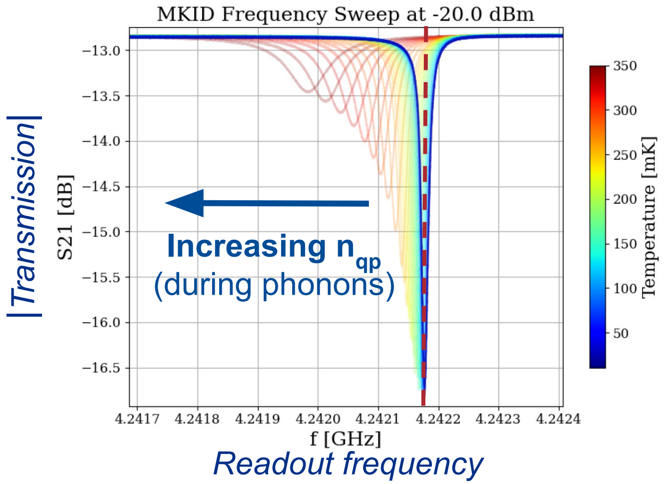
   - Shift f_r, Q_r down



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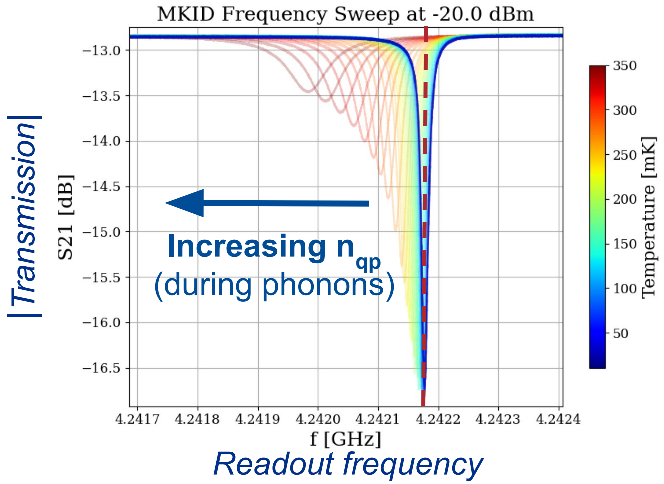

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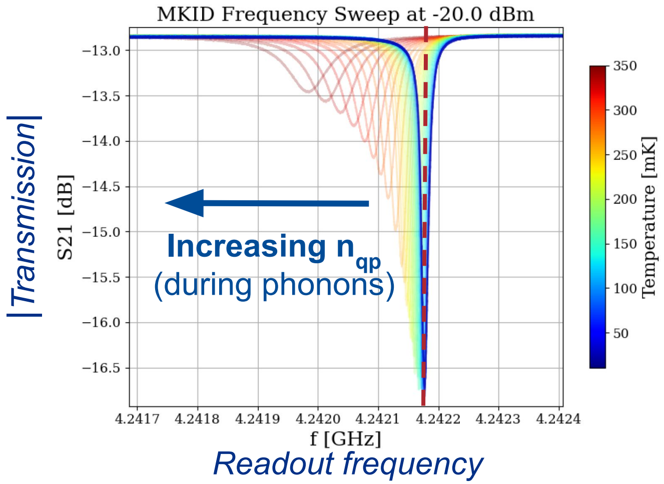
   - Dependent on quasiparticle lifetime τ_{qp}



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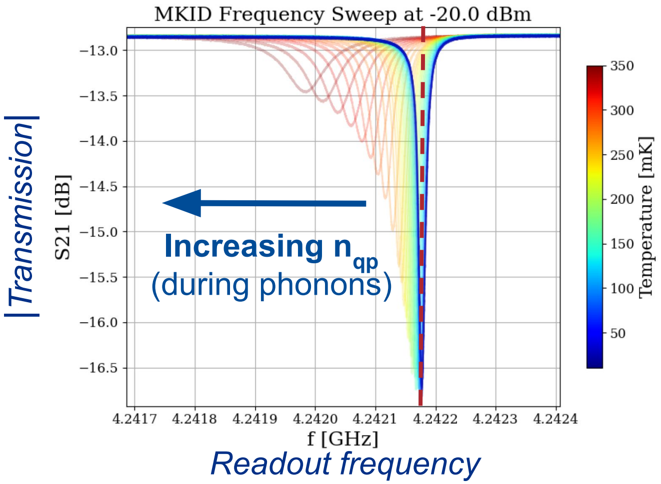
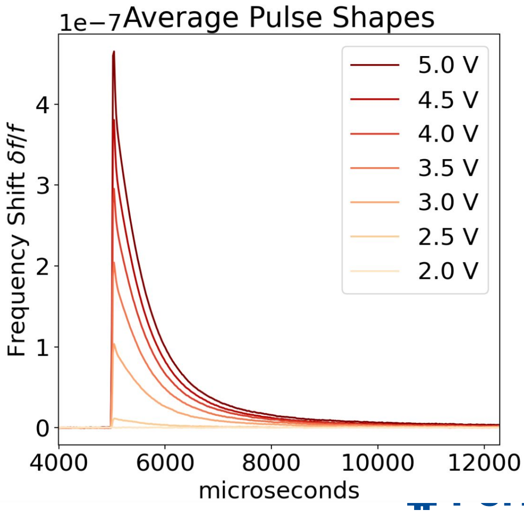
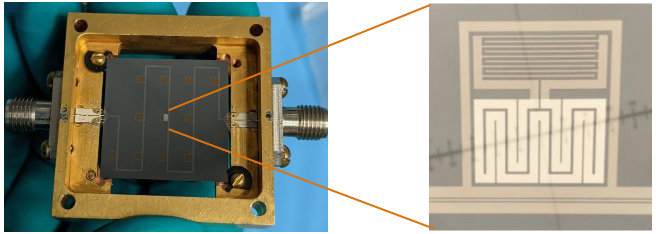
   - Dependent on quasiparticle lifetime τ_{qp}
5. Time domain response: pulses!
   - Frequency (S_{21} phase): $\delta f/f$
   - Dissipation (S_{21} amplitude): $\delta(1/Q)$
   - Pulse amplitude ∝ n_{qp} (∝ Energy)





DJT, O. Wen, et al. [arxiv:2402.04473]

KIPMD Calibration at NEXUS

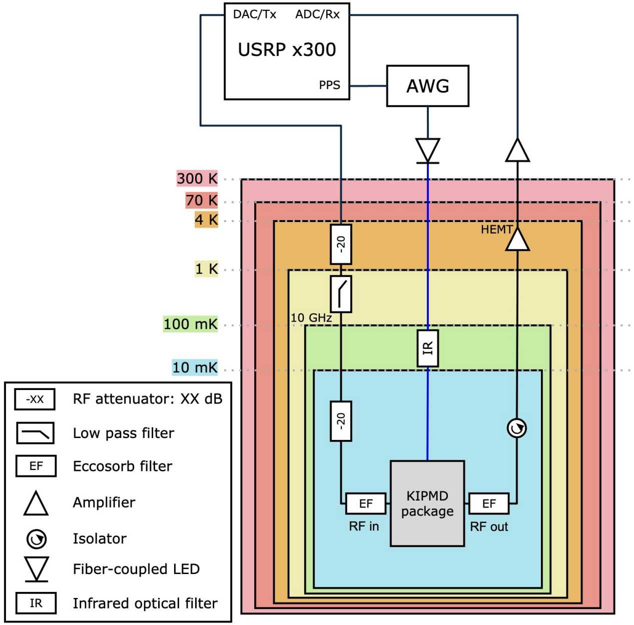


Exploit Poisson statistics of photon bursts to infer total energy deposited

- Expose KIPMD substrate to pulsed optical source of varying optical power
- Phonon energy absorbed by sensor measured by change in n_{qp} (via $\delta f/f$)

Simultaneous measurement of absolute energy resolution and phonon collection efficiency

$$\sigma_E = \frac{\sigma_E^{abs}}{\eta_{ph}} = \frac{\sigma_{n_{qp}} V \Delta}{\eta_{ph}}$$



Energy Resolution Model

Two-component energy resolution model

- Intrinsic device noise (σ_0)
- Photon shot noise (σ_{LED}) $\propto \sqrt{\bar{N}_\gamma}$

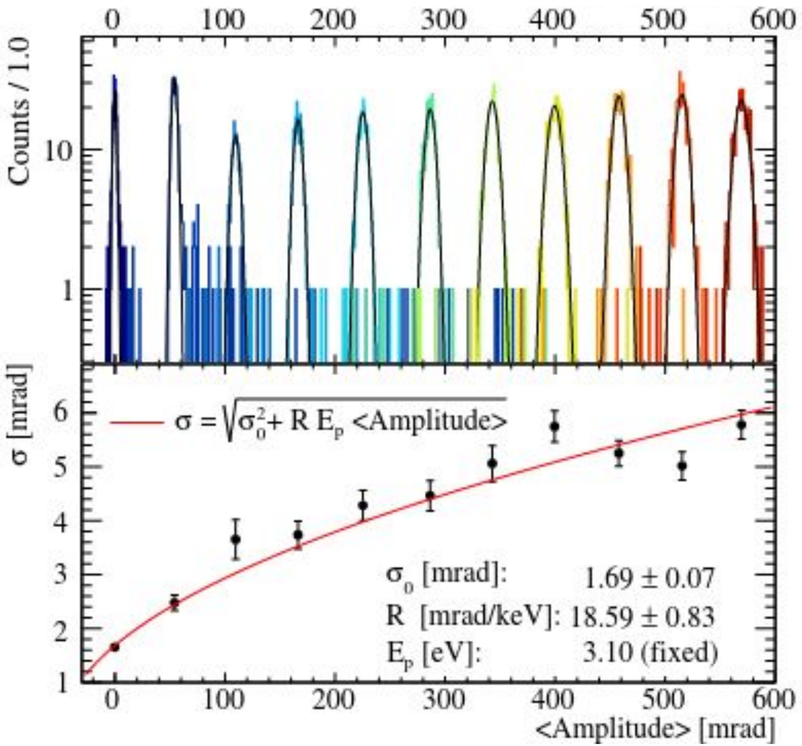
Cardani et al. *Supercond. Sci. Technol.* **31** 075002 (2018)
Cruciani et al. *Eur. Phys. J. C* **81**, 636 (2021)
Cardani et al. *Appl. Phys. Lett.* **121**, 213504 (2022)

$$\sigma_E = \sqrt{\sigma_0^2 + \sigma_{\mathrm{LED}}^2} = \sqrt{\sigma_0^2 + r \times \mu}$$

Responsivity per unit energy (r)

Average pulse amplitude for a given $\bar{N}_\gamma$ (μ)

Example: Cardani et al. *Appl. Phys. Lett.* **121**, 213504 (2022)



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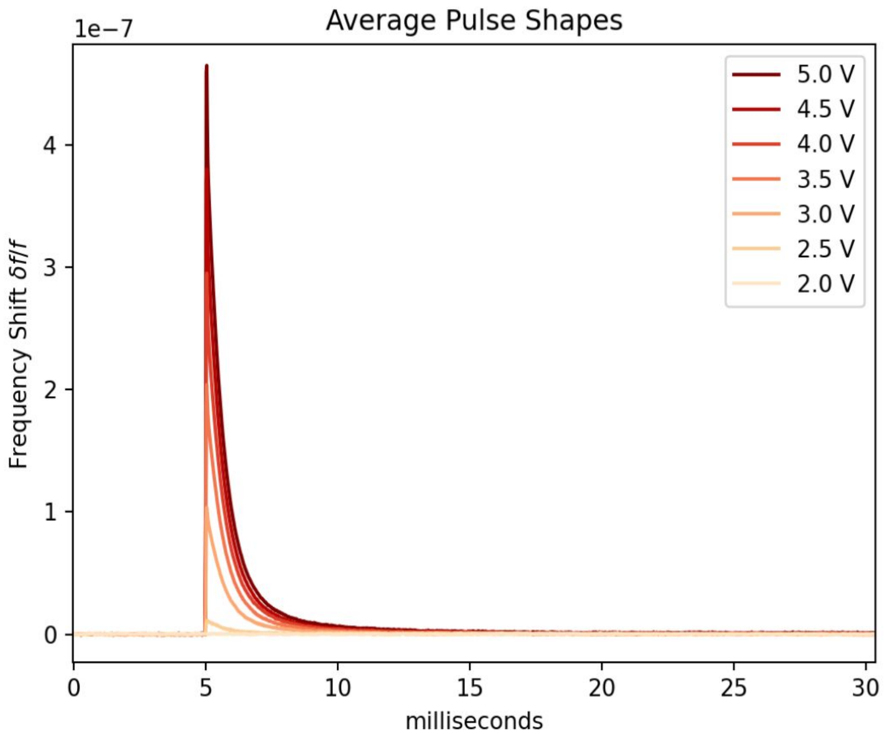
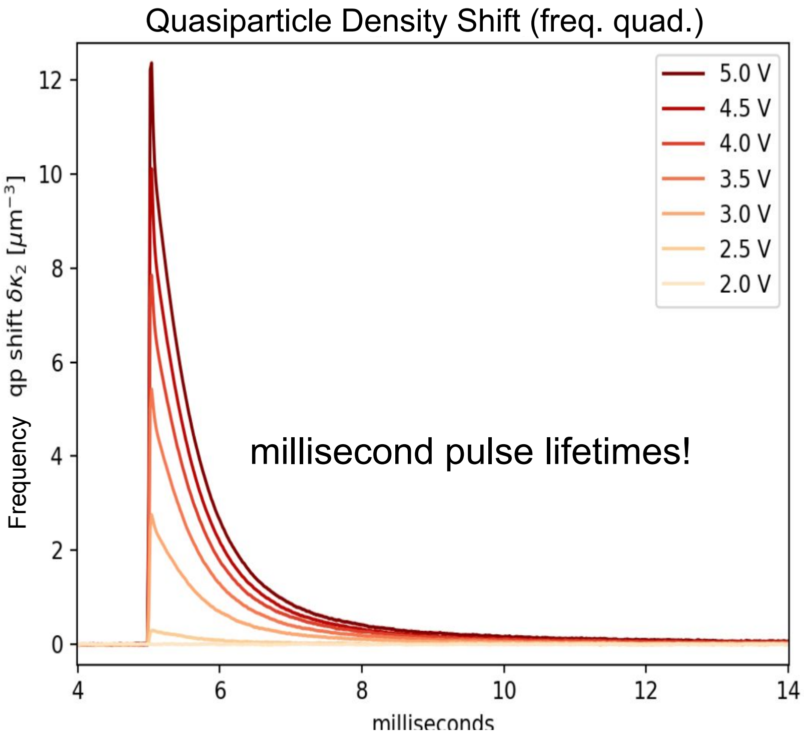
Average LED Pulses





millisecond pulse lifetimes!

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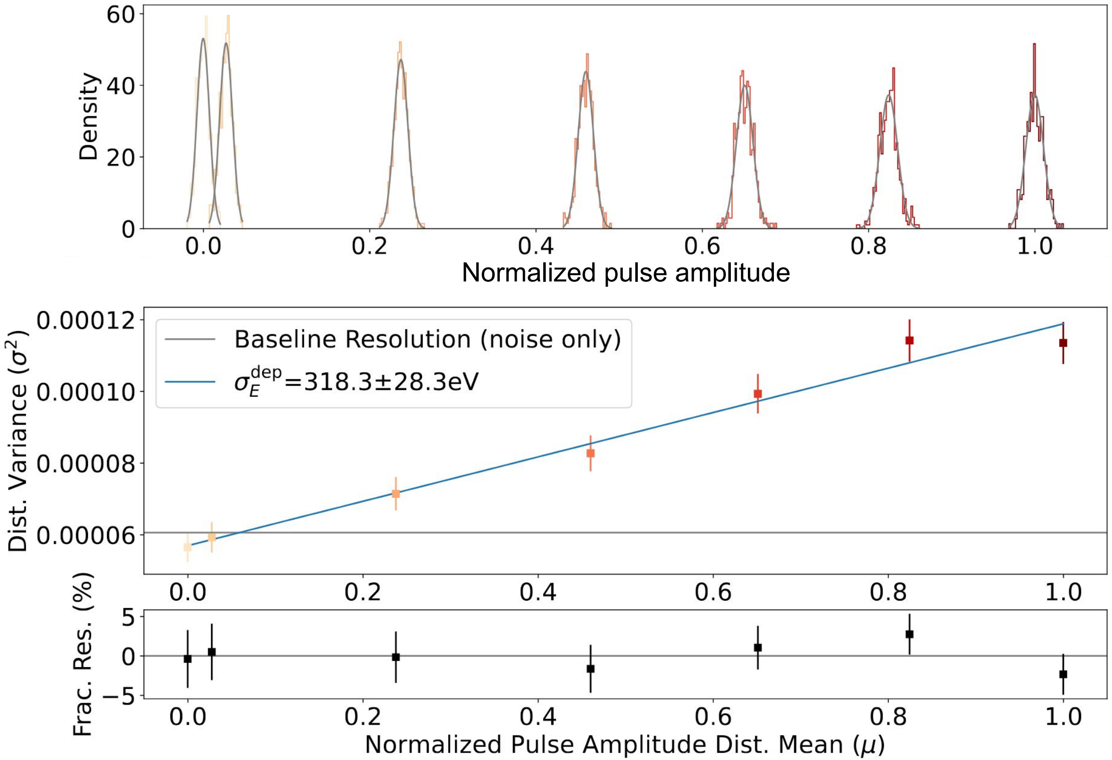
DJT, O. Wen, et al. [arxiv:2402.04473]

Device Performance: Energy Resolution



From pulse amplitude in δf/f:

"1.0" = $s_{\delta f/f} = 4.65 \times 10^{-7}$

Resolution on qp density:

$$\sigma_{qp}^{\kappa_2} = \frac{2}{\alpha \kappa_2}\left(\sigma_0 s_{\delta f/f}\right) = 0.47\ \mu\mathrm{m}^{-3}$$

Resolution on energy absorbed by sensor:

$$\sigma_E^{abs} = \sigma_{qp} V \Delta = 2.5 \pm 0.4\ \mathrm{eV}$$

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DJT, O. Wen, et al. [arxiv:2402.04473]

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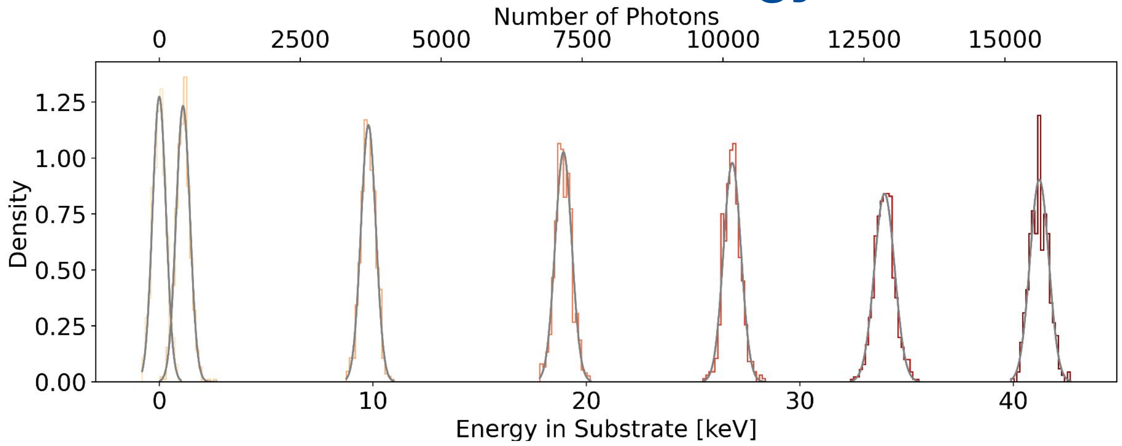
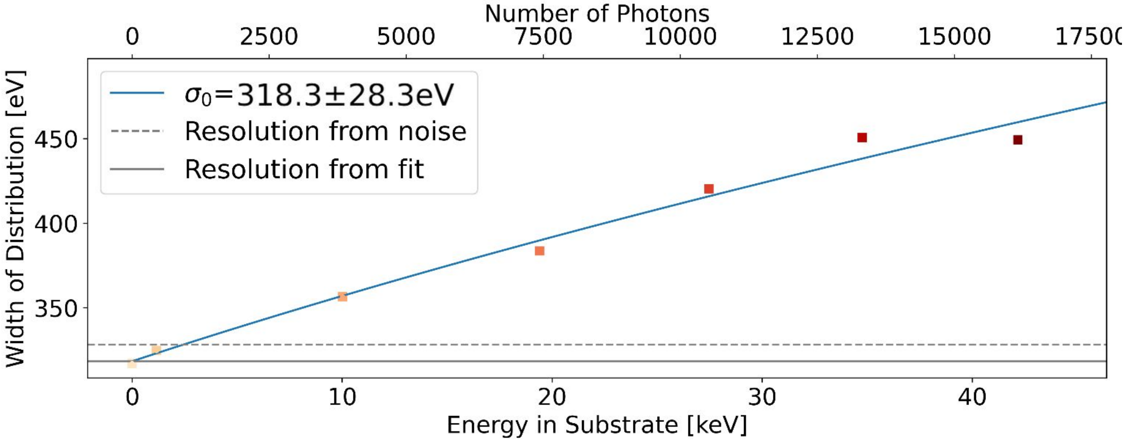


Date	Feb 15, 2023	Jul 13, 2023
σ_E^{abs} [eV]	2.1 ± 0.2	2.8 ± 0.3
$\sigma_E [eV]$	318 ± 28	315 ± 28
$\eta_{ph} [\%]$	0.66 ± 0.1	0.89 ± 0.11



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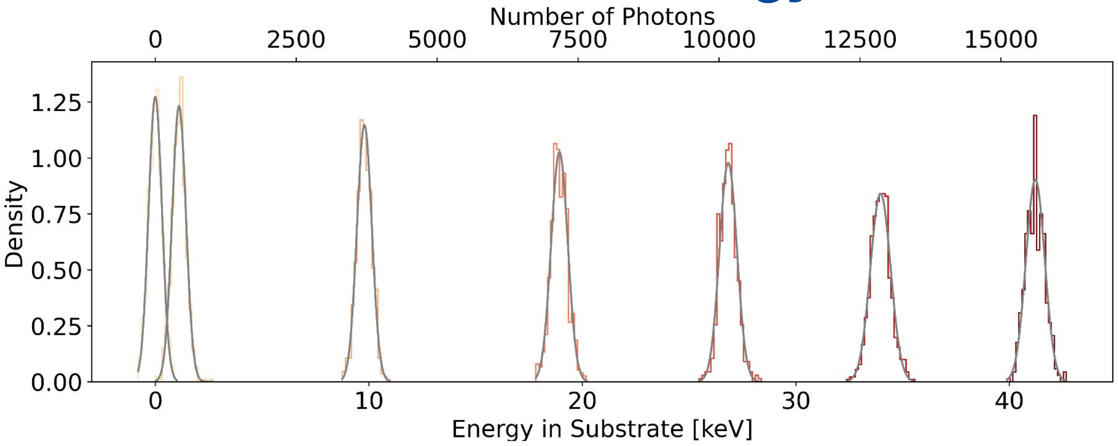

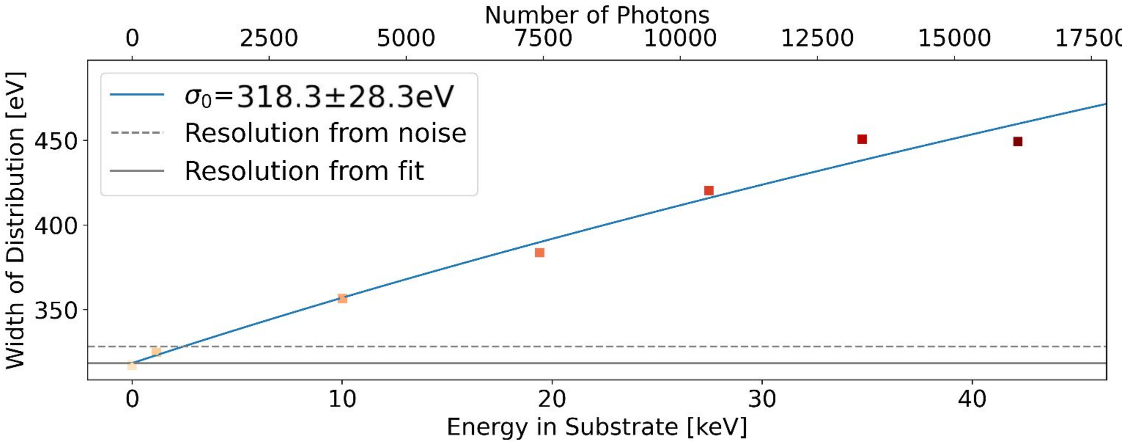

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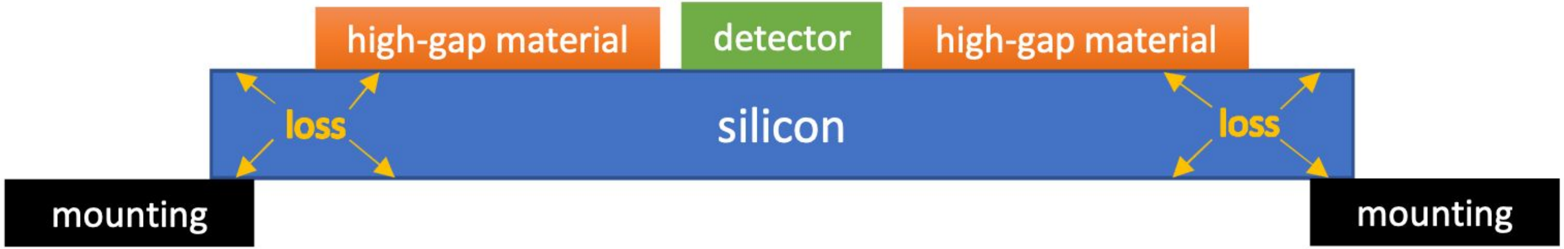
Energy resolution primarily limited by poor phonon collection efficiency!

	CALDER 2021	**BULLKID** 2022
σ_E^{dep}	34 eV	26 eV
η_{ph}	~12 %	24%
σ_E^{abs}	4.1 eV	6.25 eV
	Cruciani et al. *Eur. Phys. J. C* **81**, 6366 Cardani et al. *Supercond. Sci. Technol.* **31** 075002 (2018)	Cardani et al. *Appl. Phys. Lett.* **121**, 213504

Phonon Loss Mechanisms

- Phonon egress at device mounts
- Down-conversion in high-gap metals (e.g., Nb)
  - Recent simulation work indicates more down-conversion than initially expected
- Surface-mediated down-conversions ("fill fraction" 2% in prototype, 0.1% now)

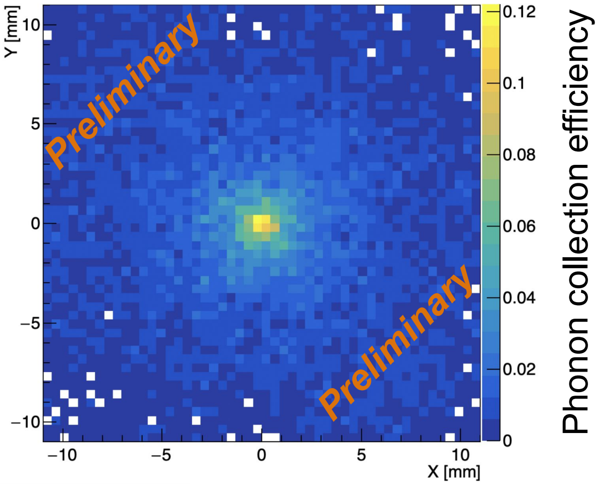


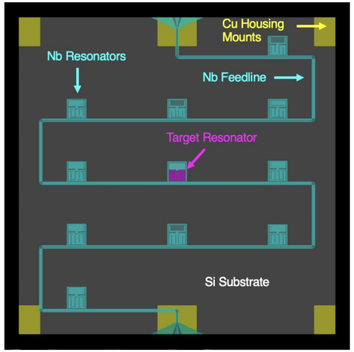
Can be investigated with device geometry/packaging and simulation!

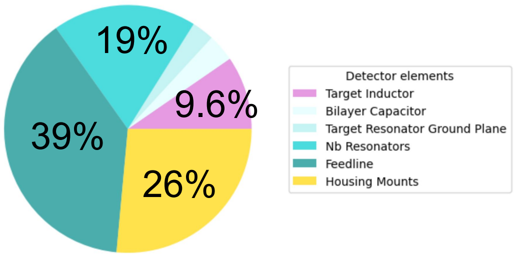
Slide from O. Wen

Work by S. Dang (Cornell undergrad)

KIPMDs - G4CMP Simulations







Share of phonons lost to detector elements

Goal: understand phonon loss contribution from various structures

- Requires phonon absorption probability at interface as simulation input

Simulation predicts larger η_{ph} than observed

- Ongoing investigation into signal generation and parameter inputs (using theory vs sweep)
- Expanding G4CMP processes (community effort led by Ryan Linehan @ FNAL)

Working on joint calibration with SLAC DMQIS group using steerable cryogenic optical system

- Position dependent calibration allows better reconstruction of phonon absorption prob.

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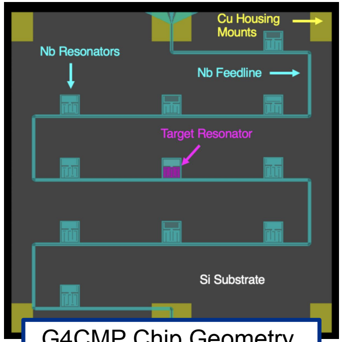
Simulating Sensor Signals from Energy Deposits in Substrate

Need a "sensor response" simulation to complete sims chain!

DM scattering, energy deposition → Energy propagation through chip → QP production in qubits & KIPMDs → QP time evolution in qubits & KIPMDs → State evolution KIPMD: df/f and d1/Q Qubit: |g> ; |e>

G4CMP simulation

- Geant4-based
- Phonon and e/h pair tracking
- Simple QP modeling
- Extensions being developed by community



G4CMP Chip Geometry

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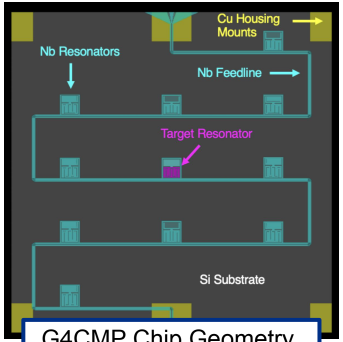
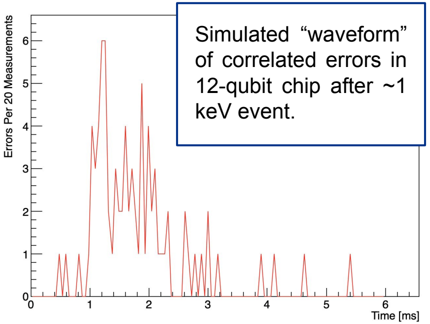


G4CMP Chip Geometry

Quantum Device Response (QDR)

- Folds in detection scheme, critical readout parameters
- Flexible: models multiple sensor types (MKIDs, Transmons), even on same chip!



Simulated "waveform" of correlated errors in 12-qubit chip after ~1 keV event.

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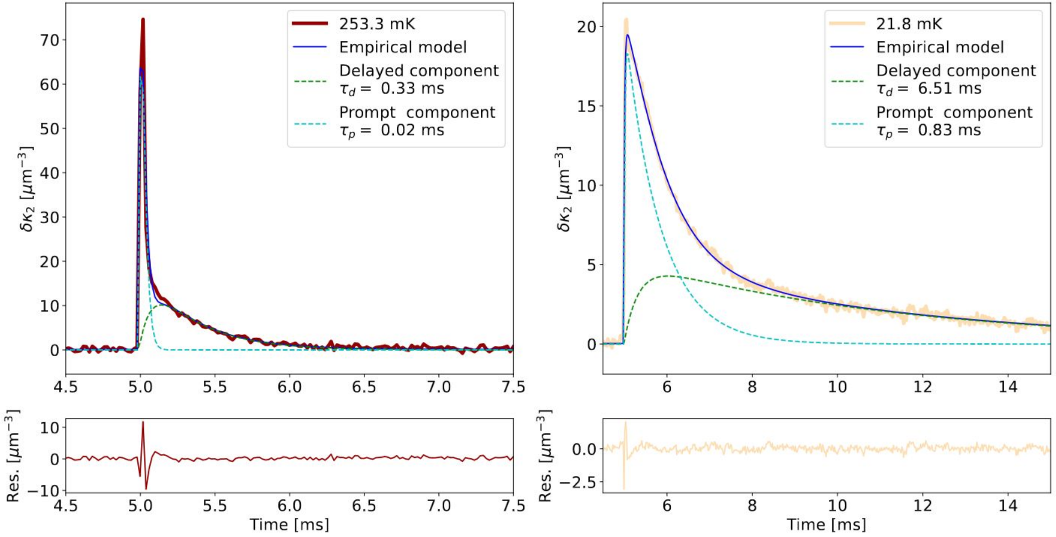
QDR Application: Understanding Pulse Shapes

Separating phonon dynamics from quasiparticle dynamics in MKID sensors

DJT, O. Wen, et al. [arxiv:2402.04473]



Two fall time constants: phonon lifetime & quasiparticle lifetime?

In simulation:

- Known quasiparticle lifetime
- Control over phonon time profile

1. Generate phonon bursts in G4CMP
2. Generate readout waveforms in QDR
3. Pipe through analysis framework to extract the fall time constants as is done with data

Allows us to confirm (or refute) the origin of the two fall-time constants and their dependence on device temperature.

R. Linehan, I. Hernandez, **DJT**, et al. [arxiv:2404.04423]

QDR Application: Estimating energy thresholds of qubit sensors

We can reconstruct an in-chip energy using η_{ph} and reconstructed single-qubit energies:

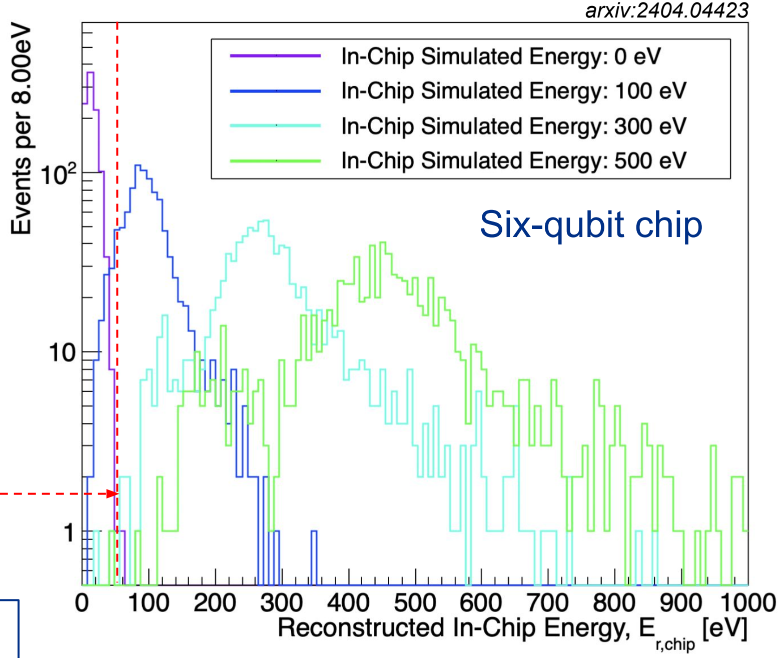
$$E_{r,\mathrm{chip}} = \frac{\sum_i E_{r,i}}{\eta_{ph,sp}}$$

This helps us understand how to find our in-chip threshold:

Equivalent to $5\sigma_{E,abs}$ for a sum of N_q qubits' energies

$$E_{\mathrm{thr,chip}} \simeq \frac{\sigma_{E,\mathrm{abs}}}{\eta_{ph,sp}} \left[\frac{N_q}{\sqrt{2\pi}} + a N_q^b \right]$$

(with a~4.27, b~0.44)

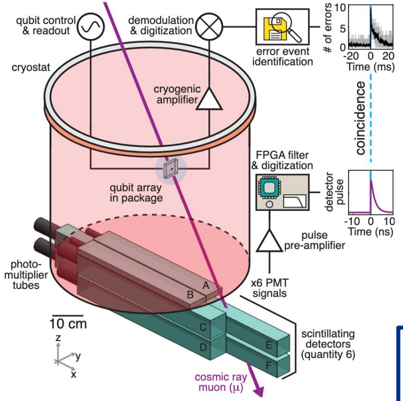


1. For "standard" transmon qubit designs, find **in-chip threshold in range of 40 eV–1200 eV**.
2. With collection fins and QP traps (and no added noise), could reduce to **O(100 meV).**

QDR Application: Extracting Muon Energy from Qubit Errors

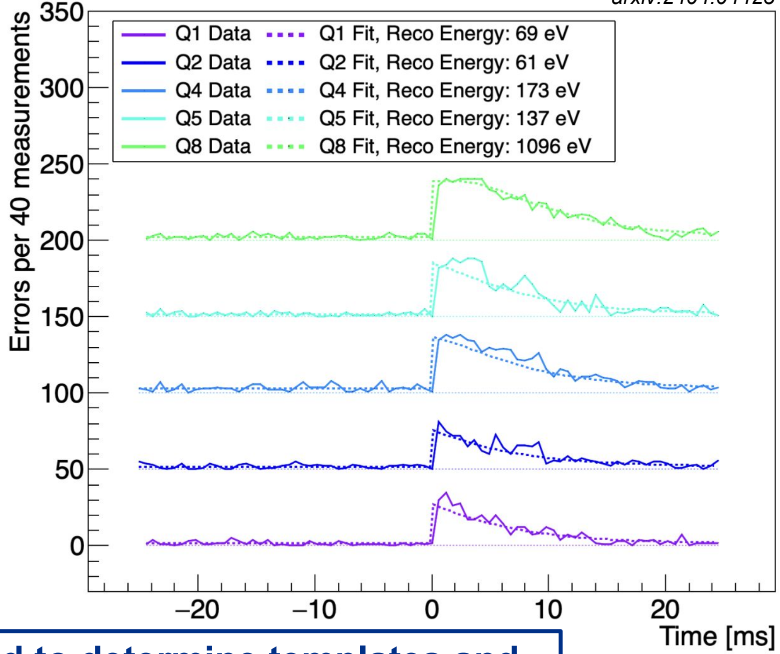
Applying sensor/chip energy reconstruction techniques to literature data gives reasonably self-consistent results!

- Single-qubit ML fits
- Best-guess $\eta_{ph,sp}$ given chip design
- In-chip energy ~ 440 keV
- Builds confidence in energy reconstruction technique

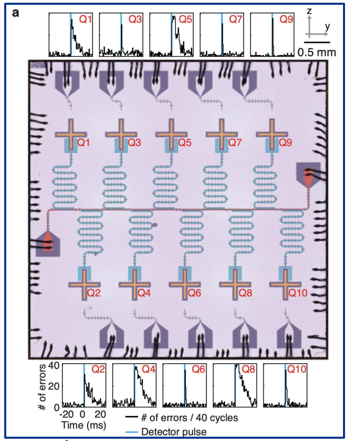


Harrington et al.(2024) arxiv:2402.03208

arxiv:2404.04423



arxiv:2402.03208



MIT (Harrington) waveforms fit using this technique

QDR used to determine templates and anchor to real energy scale

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G. Bratrud, S. Lewis, ... **DJT**, et al. [arxiv:2405.04642]

Qubits: Charge Sensing at NEXUS

Unique features of NEXUS allow us to directly control radiation environment

- Ionizing radiation shown to induce errors in qubit chips
- Investigate spatial and temporal correlations in a qubit chip under different ionizing radiation conditions

Goal: Understand and exploit radiation effects on qubits to optimize design for **quantum sensing**

Qubits: Charge Sensing at NEXUS

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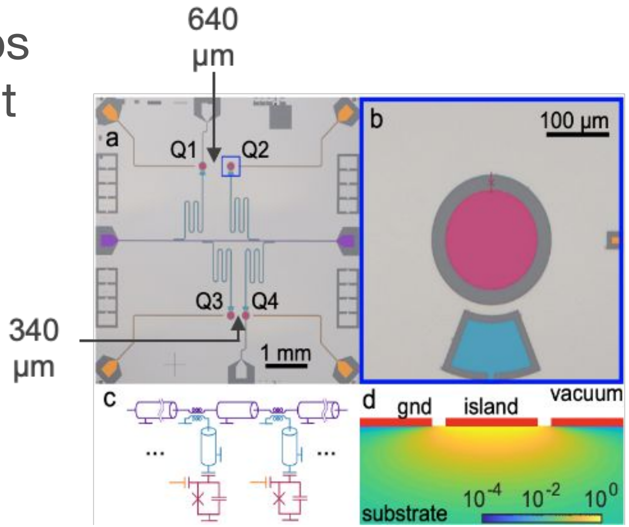
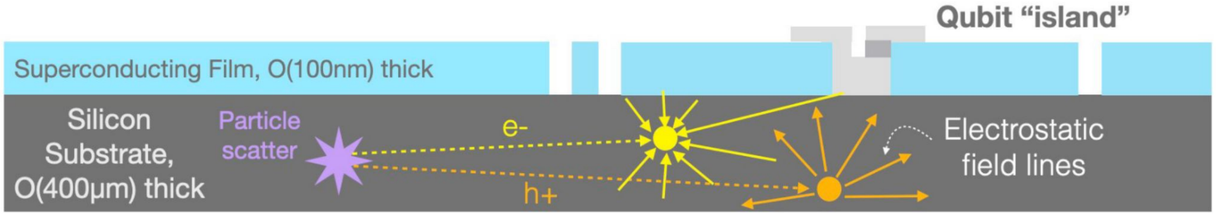


Qubit device used in this work
(McDermott group, UW Madison)
Wilen et al, Nature 594, 369 (2021)

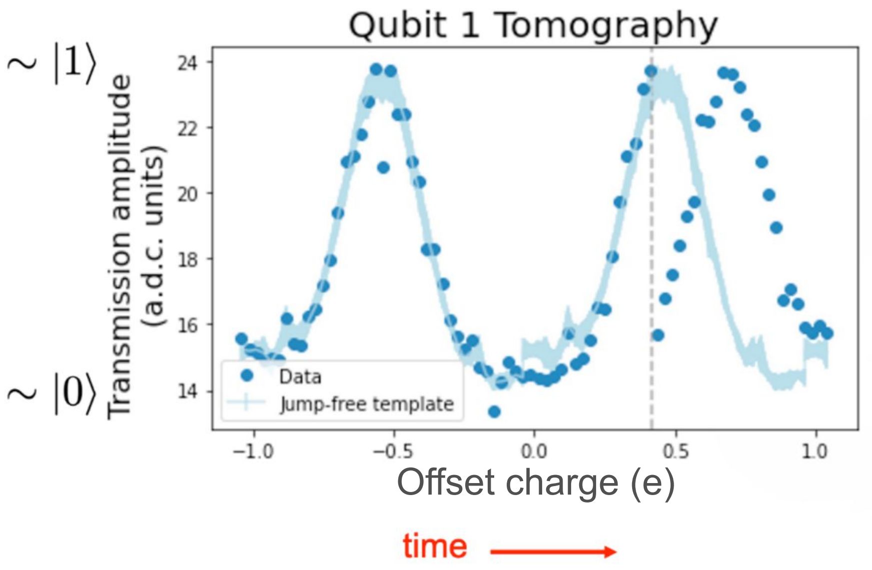
<u>Goal</u>: Understand and exploit radiation effects on qubits to optimize design for **quantum sensing**



Weakly charge-sensitive qubits: sense changes in local electric field via "<u>charge jumps</u>"

Charge trapping: in absence of applied electric field, burst effects can be "locked-in" on timescales of hours -- days

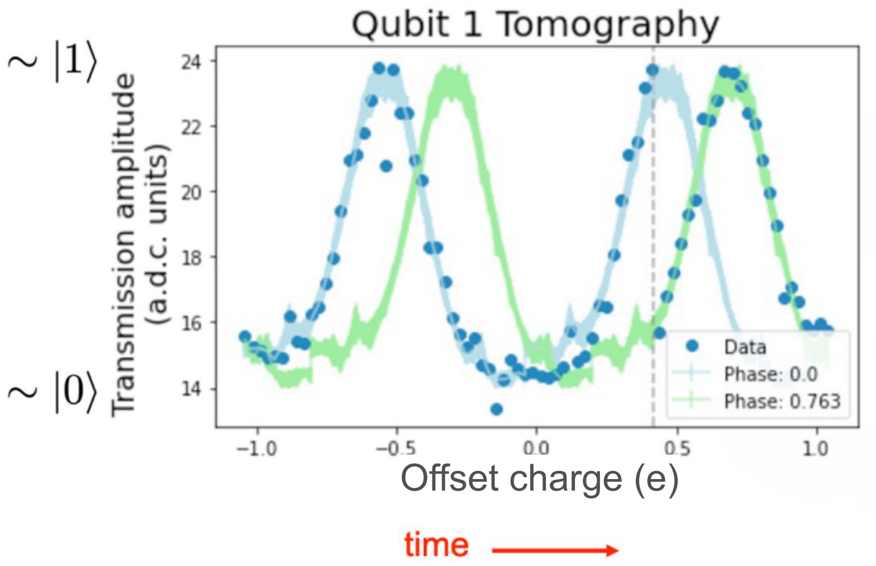
Qubits: Charge Sensing at NEXUS



Ramsey Tomography: maps "offset charge" to probability of measuring qubit in excited state

- Qubit state periodic in offset charge induced by an applied voltage bias

Qubits: Charge Sensing at NEXUS



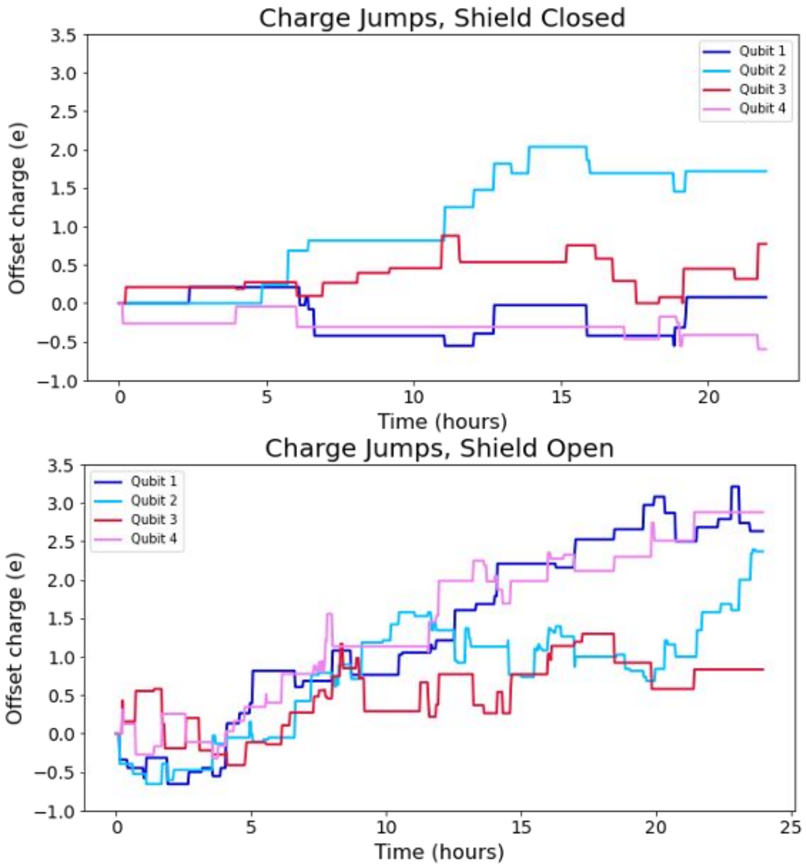
Ramsey Tomography: maps "offset charge" to probability of measuring qubit in excited state

- Qubit state periodic in offset charge induced by an applied voltage bias
- "Charge jump": Prompt change in local electric field environment leads to qubit state change
- Resolved as phase shift in a Ramsey tomography scan

G. Bratrud, S. Lewis, ... **DJT**, et al. [arxiv:2405.04642]

Qubits: Charge Sensing at NEXUS

- NEXUS → muon rate negligible, dominated by γs (controlled by shield)
- Repeated tomography scans over ~20-hour periods of lead shield open vs shield closed
- Impact of shielding on charge jump rate is obvious!
- Can compare our charge jump rates to measurement of same qubit chip on surface [Wilen et al, Nature 594, 369 (2021)]
- Working on development of G4CMP + QDR implementation



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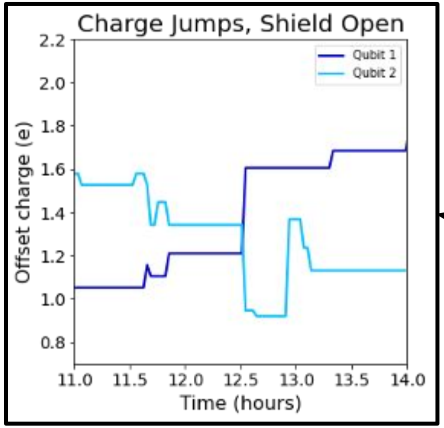
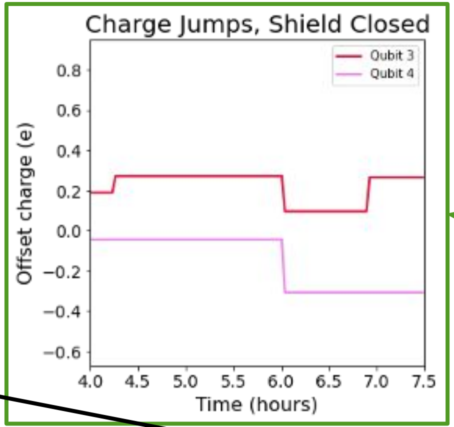
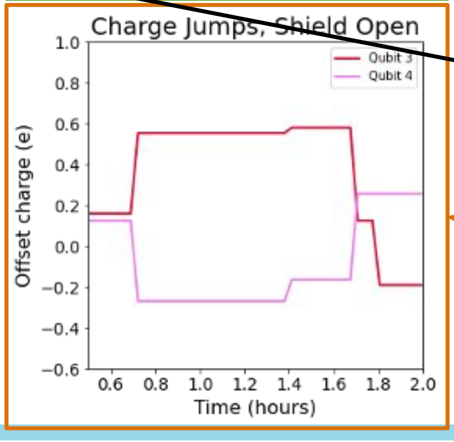
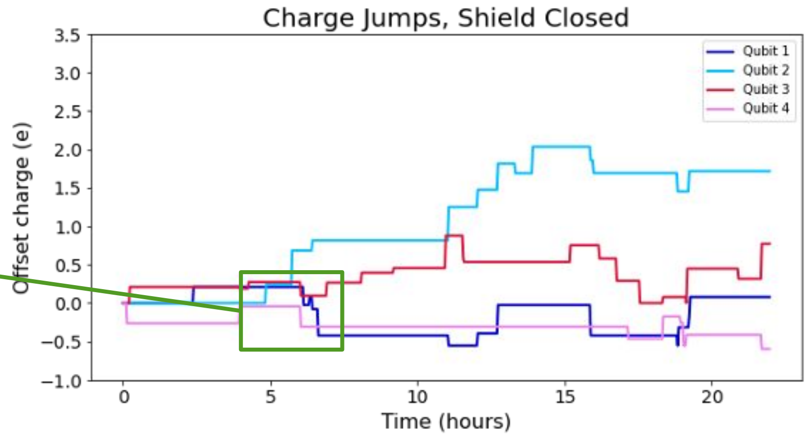
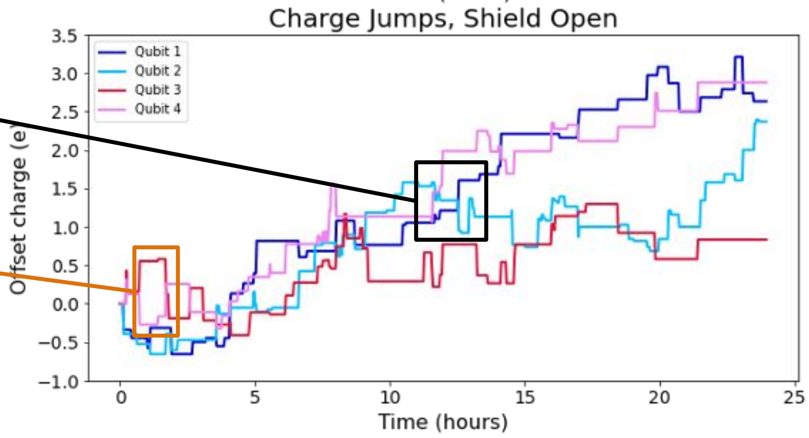
Qubits: Charge Sensing at NEXUS









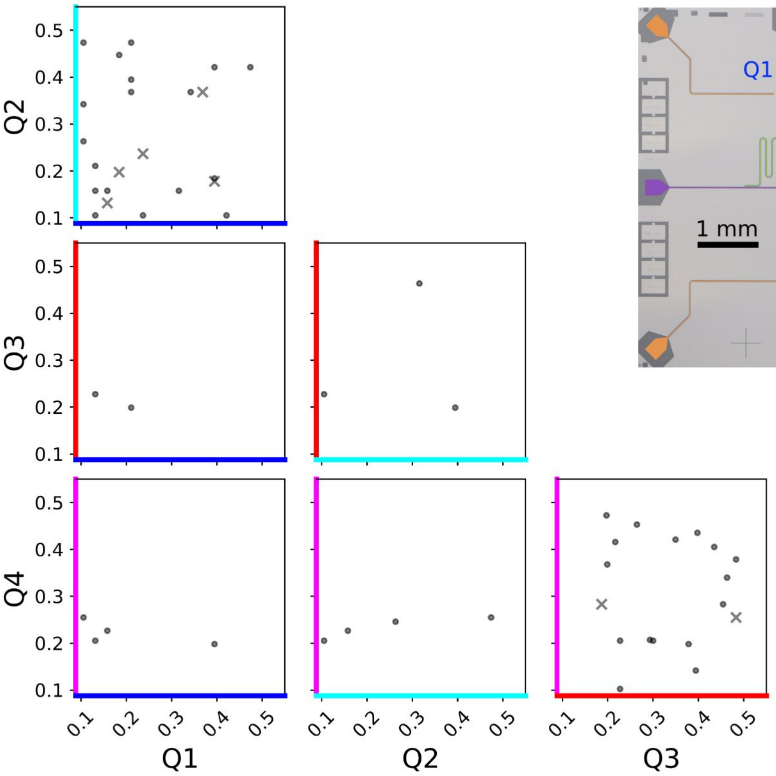


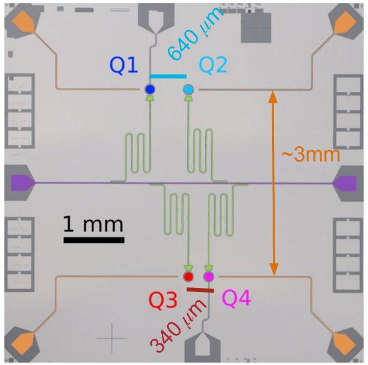
G. Bratrud, S. Lewis, ... **DJT**, et al. [arxiv:2405.04642]

Qubits: Charge Sensing at NEXUS

Underground & shielded operation:

We observe no correlated errors between qubits spaced ~3mm apart in 22 hours





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G. Bratrud, S. Lewis, ... **DJT**, et al. [arxiv:2405.04642]

Qubits: Charge Sensing at NEXUS

Compare to surface rate: 1.35 mHz

- Wilen et al, Nature 594, 369 (2021)

Measured γ flux with witness LMO detector 10 cm away from qubit (in fridge)

- Shield closed: 13x reduction in rate

	Shield Open	Shield Closed	Units
Average Rate	$0.51^{+0.05}_{-0.04}$	$0.19^{+0.04}_{-0.03}$	mHz

	Livetime (hr)	Q1	Q2	Q3	Q4
SO	23.9	$0.42^{+0.09}_{-0.08}$	$0.60^{+0.11}_{-0.09}$	$0.52^{+0.10}_{-0.08}$	$0.51^{+0.11}_{-0.09}$
SC	22.1	$0.20^{+0.07}_{-0.05}$	$0.19^{+0.07}_{-0.05}$	$0.19^{+0.07}_{-0.05}$	$0.16^{+0.07}_{-0.05}$

Charge jump rates (mHz) for individual qubits in each dataset. Statistical errors are provided as systematic errors are an order of magnitude smaller.

	Q1-Q2 640 µm	Q3-Q4 340 µm	Q1-Q3 3195 µm	Q1-Q4 3330 µm	Q2-Q3 3180 µm	Q2-Q4 3240 µm
SO	$0.27^{+0.09}_{-0.07}$	$0.29^{+0.09}_{-0.07}$	$0.03^{+0.04}_{-0.02}$	$0.08^{+0.06}_{-0.04}$	$0.05^{+0.05}_{-0.03}$	$0.08^{+0.06}_{-0.04}$
SC	$0.10^{+0.07}_{-0.04}$	$0.04^{+0.05}_{-0.03}$	< 0.03	< 0.04	< 0.03	< 0.04

Correlated charge jump rates (mHz) for individual qubits in each dataset. Separation distances listed below qubit numbers. Statistical errors are provided as systematic errors are an order of magnitude smaller.

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- Charge jump rate reduction: 4.2x

Excess rate of charge jumps!

Not explained by γ flux

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Average Rate	$0.51^{+0.05}_{-0.04}$	$0.19^{+0.04}_{-0.03}$	mHz
Corrected γ Rate	$0.34^{+0.07}_{-0.06}$	$0.02^{+0.06}_{-0.05}$	mHz
Calculated Excess Rate	$0.17^{+0.04}_{-0.03}$		mHz

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Fermilab

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Correlated charge jump rates (mHz) for individual qubits in each dataset. Separation distances listed below qubit numbers. Statistical errors are provided as systematic errors are an order of magnitude smaller.

Potential explanations:

- Local source of ionizing radiation
- Changes in electric field, non-radiogenic origin
- Stress release knocking free trapped charges

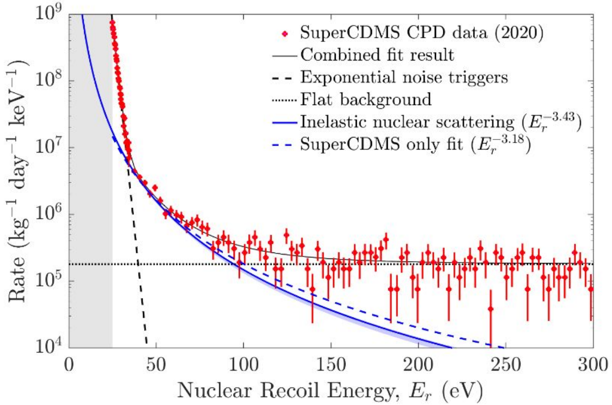
Segue: Low Energy [Phonon] Excess

Steeply rising low-energy background

Observed in cryogenic phonon detectors & superconducting qubits

1. **Non-ionizing:** no NTL amplification.
2. **Power law:** energy spectrum follows a power law.

Abbamonte et al, PRD 105, 123002 (2022) [arXiv:2202.03436]



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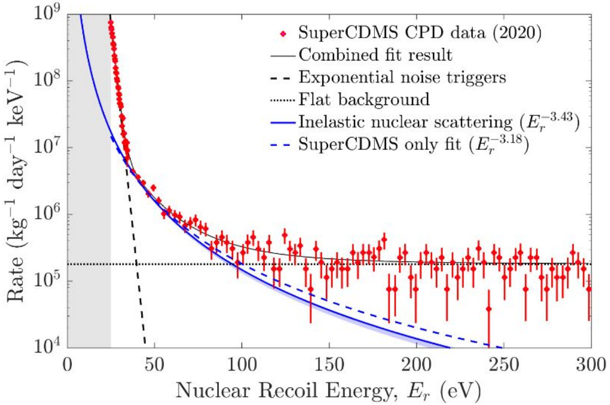

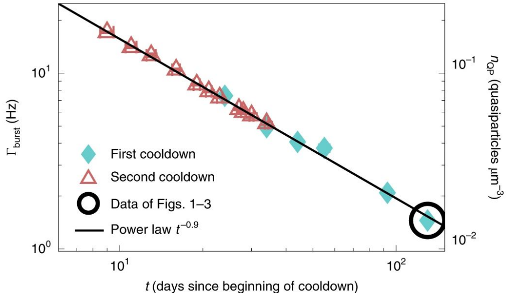

Mannila et al, Nat. Phys. **18**, 145–148 (2022)

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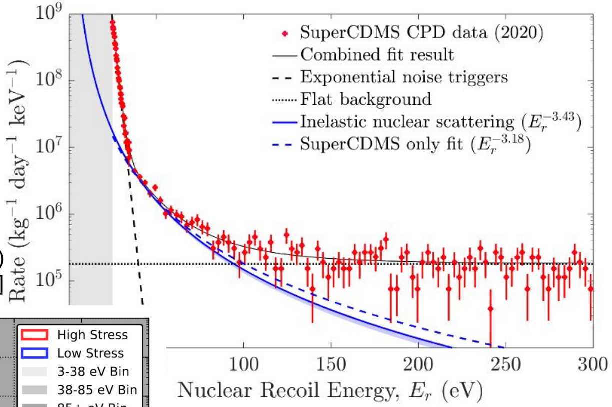
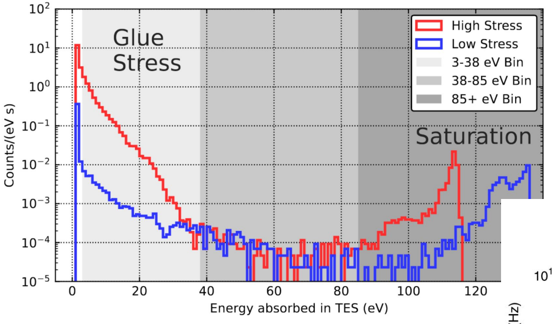
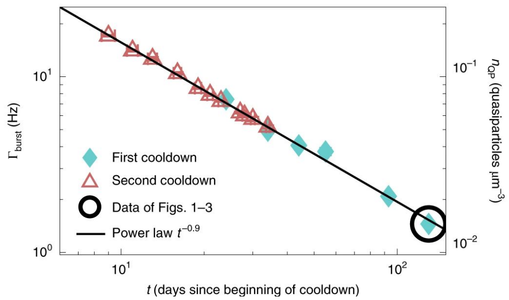
4. **Stress-dependent:** reducing mounting stress reduces background rate.
   a. Stress buildup in thin film depositions can release phonons into substrate
   R. Romani (2024) [arXiv:2406.1542]

Abbamonte et al, PRD 105, 123002 (2022) [arXiv:2202.03436]



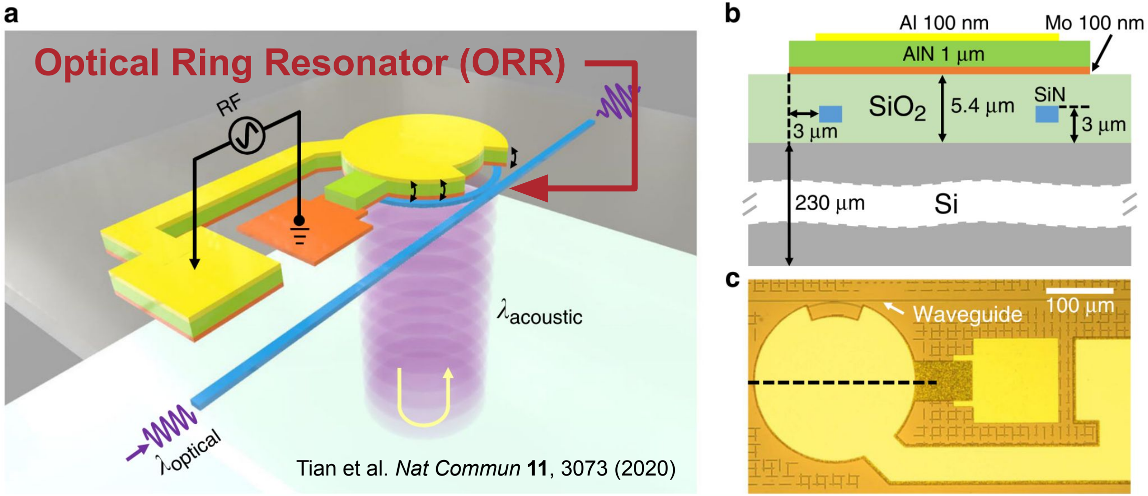
Anthony-Petersen et al, Nat. Commun. 15, 6444 (2024) [arXiv:2208.02790]





Mannila et al, Nat. Phys. **18**, 145–148 (2022)

Embedded SiN Optical Strain Sensors



OxideMEMS Lab, Purdue

S. Bhave (PI) *A. Attanasio*

Stress-optical effect: stress modulates the refractive index of the resonator.
→ Modulates transmission through waveguide for on-resonance λ

Provides readout channel to directly probe crystal stress and substrate deformation.

Embedded sensors: surface free for deposition of primary sensors (qubit, MKID, TES, CCD).

Fermilab

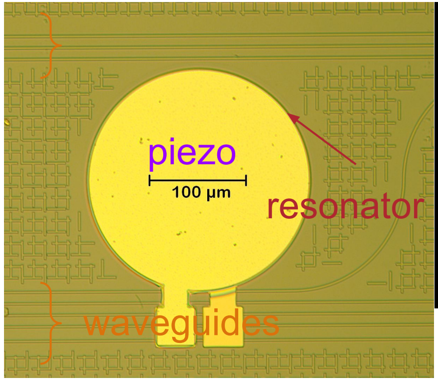
Embedded SiN Optical Strain Sensors

Photonics: microwave-optical transduction via piezo actuation Tian et al. *Nat Commun* **11**, 3073 (2020)

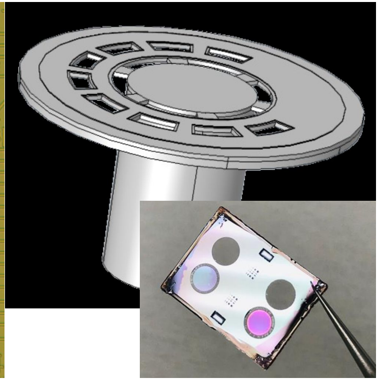
Sensing: micro-mechanical accelerometers with integrated test mass (Windchime)

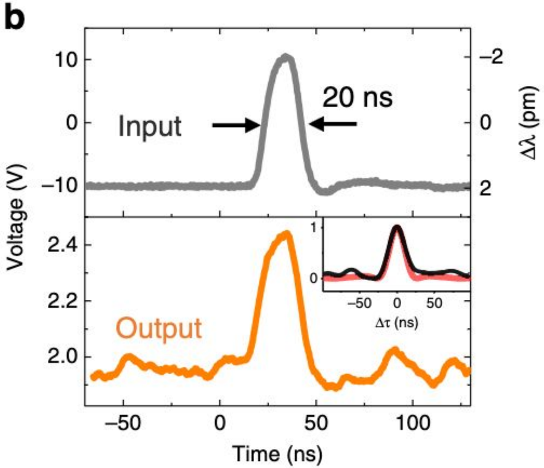
- Sub-ns optical response
- Optical Q ~ 10^6--10^8
- Sensitivity: 10^{-7} g/√Hz (accelerometer)

Piezo-actuated device

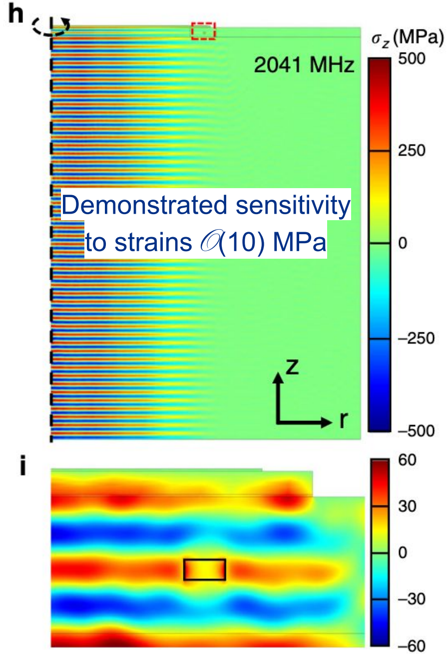


Accelerometer device





Device response to piezo impulse



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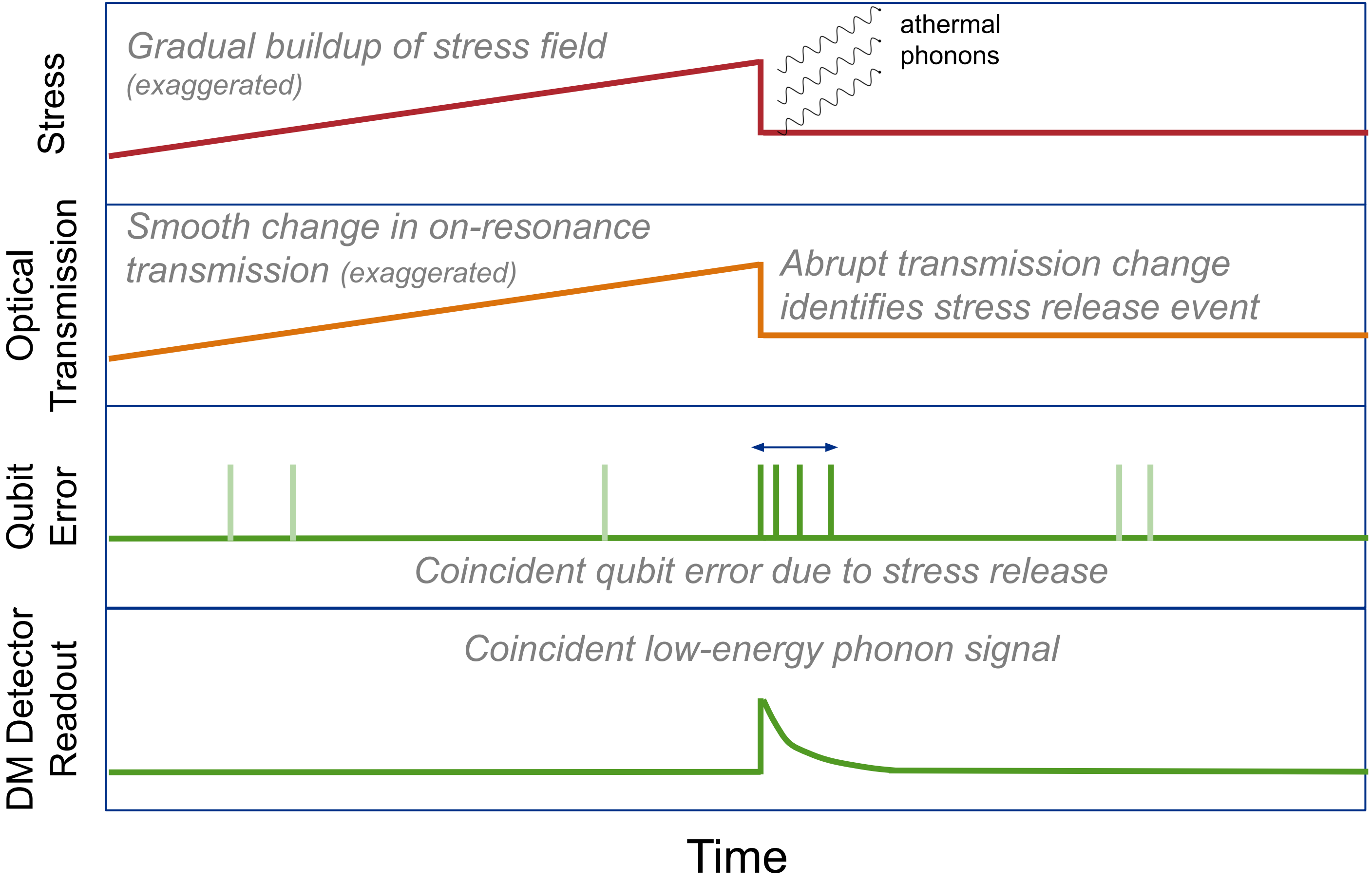


Case 1: ORRs largely inert to ballistic athermal phonon burst

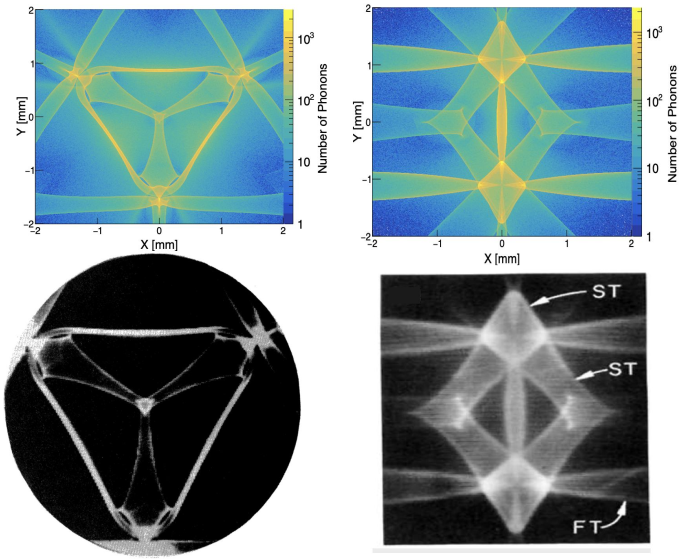
Demonstrate stress release is progenitor of phonon-burst-induced decoherence

Anticoincidence channel to reject low energy stress events

… and everything else!

Modeling Athermal Phonons in Novel Materials using the G4CMP Simulation Toolkit

I. Hernandez[a,b,*], R. Linehan[b,*], R. Khatiwada[a,b], K. Anyang[a,b], D. Baxter[b,d], G. Bratrud[b,d], E. Figueroa-Feliciano[d,b], L. Hsu[b], M. Kelsey[c], D. Temples[b]

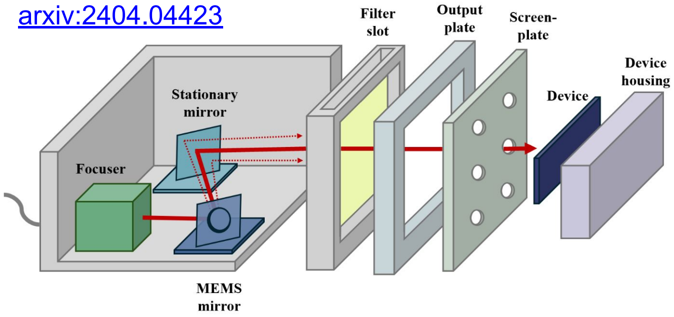


arxiv:2408.04732

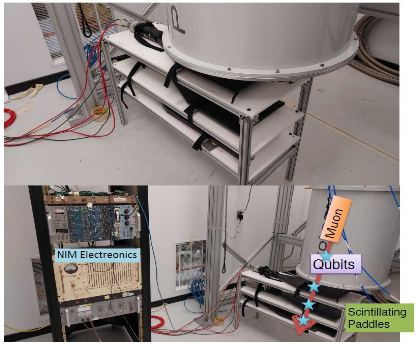
Cryogenic optical beam steering for superconducting device calibration

K. Stifter[1,2,3], H. Magoon[1,2,3,4,5], A.J. Anderson[1,6,7], D.J. Temples[1], N.A. Kurinsky[1,2,3], C. Stoughton[1], I. Hernandez[8,1], A. Nuñez[2,3,4], K. Anyang[8,1], R. Linehan[1], M.R. Young[1,6,7], P. Barry[9], D. Baxter[1,10], D. Bowring[1], G. Cancelo[1], A. Chou[1], K.R. Dibert[6,7,1], E. Figueroa-Feliciano[10,1], L. Hsu[1], R. Khatiwada[8,1], S.D. Mork[1], L. Stefanazzi[1], N. Tabassum[2,3,4], S. Uemura[1], B.A. Young[11]

arxiv:2404.04423

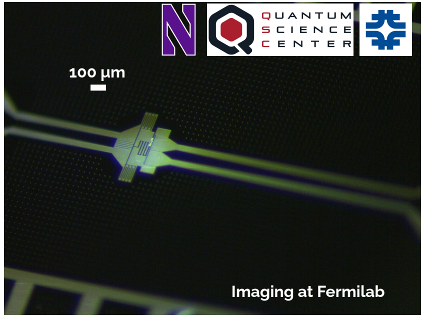


Cosmic ray tagging with sapphire qubit at LOUD



K. Anyang, C. Veihmeyer, R. Linehan, R. Khatiwada

Qubit design and fabrication



S. Sussman, R. Gaultieri

Outlook: Next Year at QUIET

Magnetic shielded payload installed!

- 1000x reduction in field

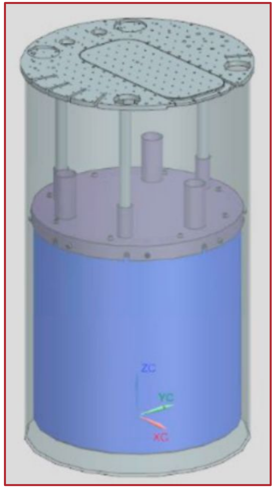
First device runs:

- Qubit chips galore!
- Superconducting Quasiparticle Amplifying Transmon (SQUAT)
- Kinetic Inductance Phonon-Mediated Detector
- Optical ring resonator strain sensor

Facility upgrades:

- Radiation shield (lead castle)
- Muon tagging system (for cosmic and NuMI beam)
- Full (remote) QICK control
- Expanding RF lines for ~100 qubit device

Looking to run your device in a low-background facility?
Talk to me or Dan Baxter
dtemples@fnal.gov | dbaxter9@fnal.gov

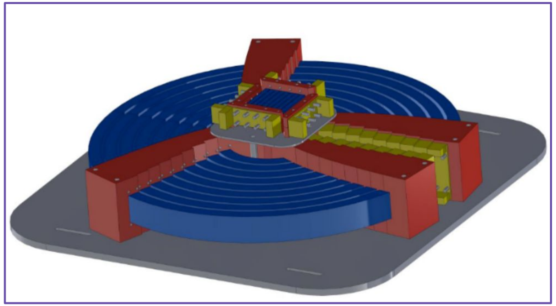


Outlook: Next Year at NEXUS

Northwestern NEXUS Experimental Underground Site @Fermilab

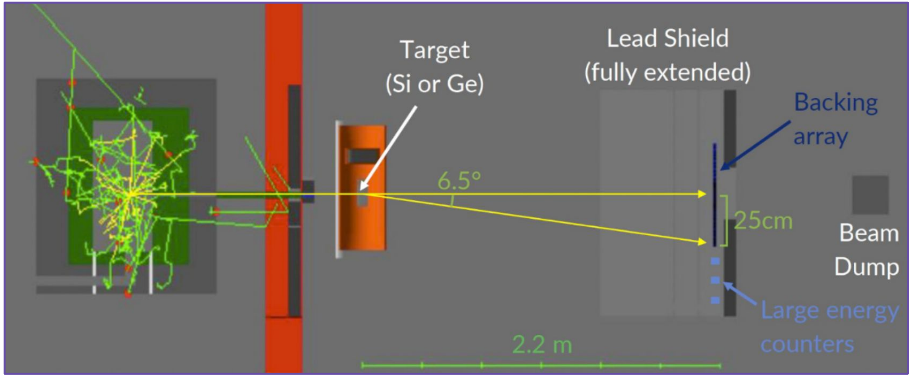
Continuing studies with charge-sensitive qubit

- QICK-216 w/ companion board -- lower noise
- Charge jump trigger for T_1 measurements
  - Separately probe ionization + phonon channels
- Gamma source studies for charge jumps
- Investigate charge trapping

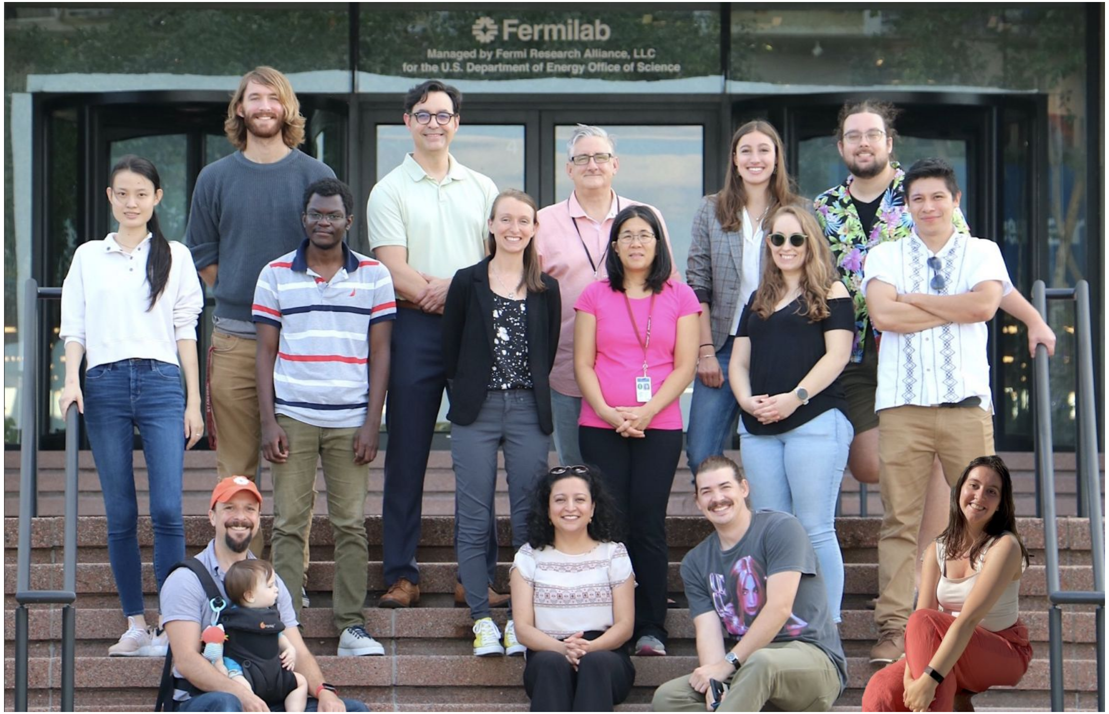


DD neutron generator comes online!

- Adelphi DD-108: 10^8 [2.45 MeV] n/sec into 4π
- Borated poly shield w/ beam tube egress
- Backing array allows for fixed-angle scattering experiments



DM searches with performant devices!



CosmiQuantum @ FNAL

FNAL Group
Daniel Baxter
Daniel Bowring
Gustavo Cancelo
Aaron Chou
Lauren Hsu
Sami Lewis*
Ryan Linehan
Kelly Stifter*
Sara Sussman
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Sho Uemura
Matthew Hollister
Chris James
Hannah Magoon*
Grace Wagner
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Enectalí Figueroa-Feliciano
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Grace Bratrud
Arianna Colón Cesaní
Deeksha Sabhari
Shilin Ray

IIT Group
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Kester Anyang
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Jialin Yu

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Osmond Wen
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SLAC/Stanford
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Sohair Abdullah

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Conclusions

- ❖ Superconducting phonon sensors leveraging quantum mechanics are a promising technology to probe the sub-GeV DM parameter space
  - ➢ KIPMDs: 2 eV sensor resolution provides path to eV-scale thresholds
  - ➢ Qubits: established a framework for energy reconstruction in relaxation readout mode
- ❖ Novel sensor architectures will require new calibration and background mitigation techniques
  - ➢ Qubits: excess rate of charge jumps inconsistent with γ flux
  - ➢ Stress release events may be identified with embedded optical strain sensors
- ❖ Device design optimization, low-background characterization, and simulation go hand-in-hand as we coalesce to a qubit-based detector architecture
- ❖ Lots of exciting work going on at Fermilab! Stay tuned.

QUIET

Looking to run your device in a low-background facility?
Talk to me or Dan Baxter
dtemples@fnal.gov | dbaxter9@fnal.gov

Northwestern NEXUS Experimental Underground Site @Fermilab

Thank You!

QUANTUM SCIENCE CENTER

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U.S. DEPARTMENT OF ENERGY Office of Science

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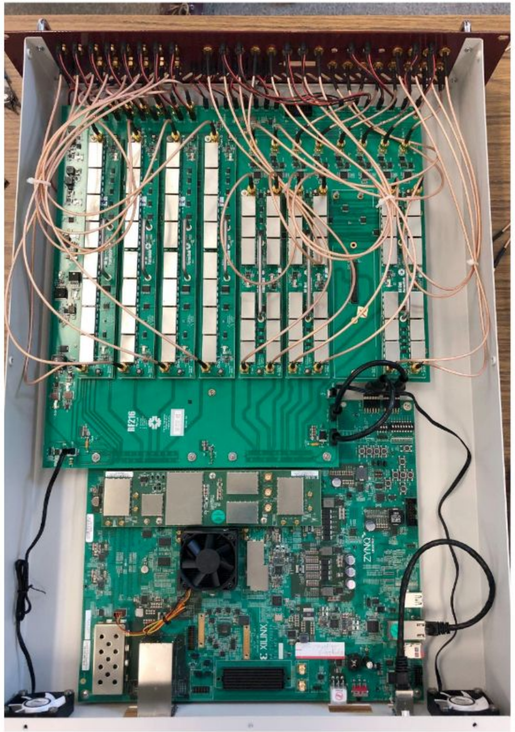
Abstract

Cryogenic Platforms at Fermilab: Recent Results and Outlook

The Cosmic Quantum group at Fermilab operates three cryogenic facilities dedicated to the development and calibration of superconducting low-threshold detectors and qubits. One of which (LOUD) is located at the surface, while the other two (NEXUS and QUIET) are located 100 m underground enabling low-background device characterization and rare event searches. Recently, we have demonstrated world-leading resolution in the quasiparticle channel for kinetic inductance phonon-mediated detectors as well as the lowest rate of spatially- and temporally- correlated errors (“charge jumps”) in superconducting qubit chips. We have additionally made significant progress in expanding the suite of tools for simulating signal production and readout of these devices. In this talk, I will review these recent results, discuss some nascent projects focused on enhancing sensitivity of these detectors to sub-GeV dark matter, and highlight activities in these facilities over the next year.

QICK
Quantum **I**nstrumentation **C**ontrol **K**it



- **Fully integrated readout & control system for QIS, quantum networks, and superconducting detectors**
  - No extra room temperature hardware needed!
  - Has already been adopted by QIS groups around the world (including many of you)
- A factor of ~20 cheaper compared to off-the-shelf equipment
- QICK team ongoing work includes paper on quantum measurement & readout fidelity, and major firmware upgrade

See demo in QUIET Lab Tour

Dark Matter Detectors (HEP) Superconducting Qubits (QIS)