Superconducting Qubits for Dark Matter Detection

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Outline

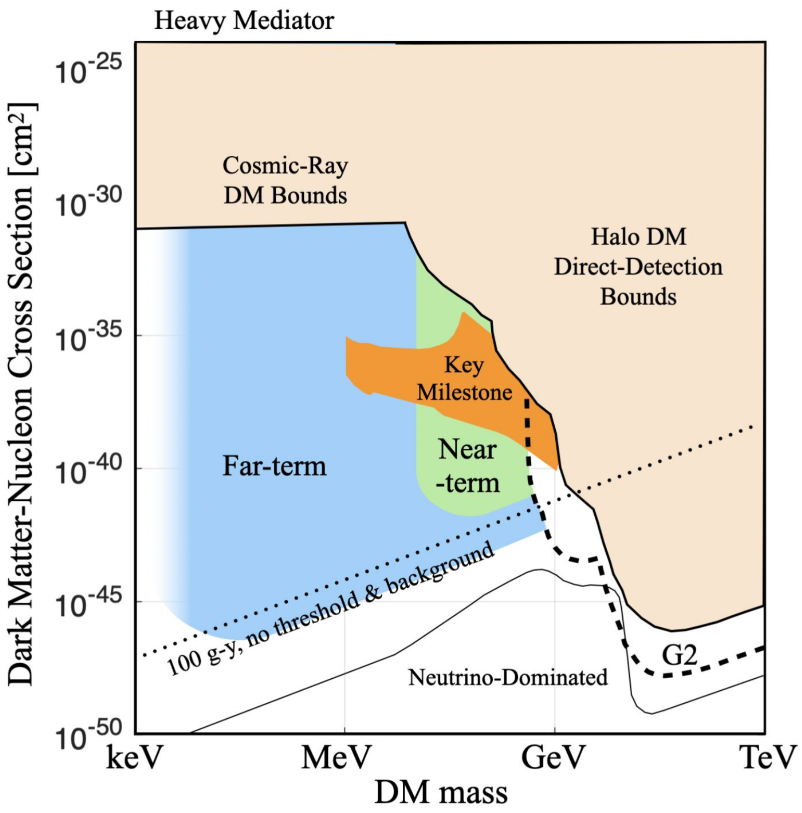
1. What is dark matter (DM), and why searches for low-mass DM motivated?
2. What are superconducting qubits, and why might they be useful for DM detection?
3. What are we doing at Fermilab to explore qubits for DM detection?

Dark Matter

Dark matter: fundamentally unknown type of matter comprising ~85% of the universe's matter density.

- No direct detection of DM-SM scatters yet
- WIMPs one historical favorite, but continue to be increasingly excluded by experiment
- Predictive dark sector models for low-mass candidates
- Energy threshold limitations: sub-GeV largely unexplored

Need new technology to push to lower mass…



Essig et al., *Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade*, https://arxiv.org/abs/2203.08297

Superconducting Qubits

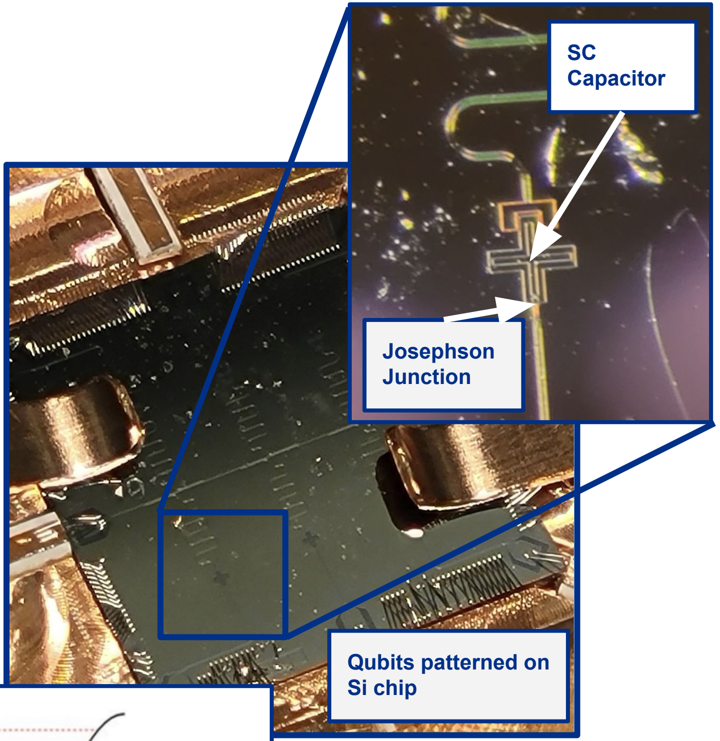
Superconducting (SC) qubits are promising sensors for low-energy DM scatters.

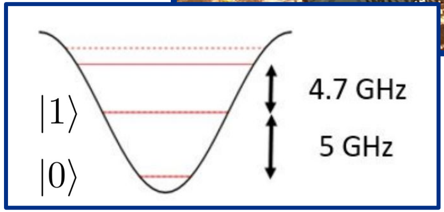
What is a SC qubit?

- Anharmonic LC circuit in SC film
- “Qubit” = lowest two energy states
- Energy spacing typically in few GHz range (μeV)

Qubits are versatile sensors:

- State preparation, readout, and gates performed with microwave signals, 4-6 GHz
- Fab/geometry decisions enable flexibility in operation and noise susceptibility
- Coupling with other quantum systems provides multiple detection schemes





T. Roth, R. Ma and W. C. Chew, "The Transmon Qubit for Electromagnetics Engineers: An Introduction," in IEEE Antennas and Propagation Magazine, doi:10.1109/MAP.2022.3176593.

Detection Schemes

Related: see Grace Bratrud's talk from Monday on correlated charge jumps!

Qubits enable significant flexibility to select the detection/sensing method:

- Wilen et. al: correlated charge jumps in nearby qubits
- Dixit et al: single photon counting in RF cavities
- McEwen et al: correlated errors from quasiparticle-induced energy decoherence
- …and more!

Searching for Dark Matter with a Superconducting Qubit

Akash V. Dixit, Srivatsan Chakram, Kevin He, Ankur Agrawal, Ravi K. Naik, David I. Schuster, and Aaron Chou
Phys. Rev. Lett. **126**, 141302 – Published 8 April 2021

Correlated charge noise and relaxation errors in superconducting qubits

C. D. Wilen, S. Abdullah, N. A. Kurinsky, C. Stanford, L. Cardani, G. D'Imperio, C. Tomei, L. Faoro, L. B. Ioffe, C. H. Liu, A. Opremcak, B. G. Christensen, J. L. DuBois & R. McDermott

Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits

Matt McEwen, Lara Faoro, Kunal Arya, Andrew Dunsworth, Trent Huang, Seon Kim, Brian Burkett, Austin Fowler, Frank Arute, Joseph C. Bardin, Andreas Bengtsson, Alexander Bilmes, Bob B. Buckley, Nicholas Bushnell, Zijun Chen, Roberto Collins, Sean Demura, Alan R. Derk, Catherine Erickson, Marissa Giustina, Sean D. Harrington, Sabrina Hong, Evan Jeffrey, Julian Kelly, … Rami Barends + Show authors

Detection Schemes: Energy Decoherence

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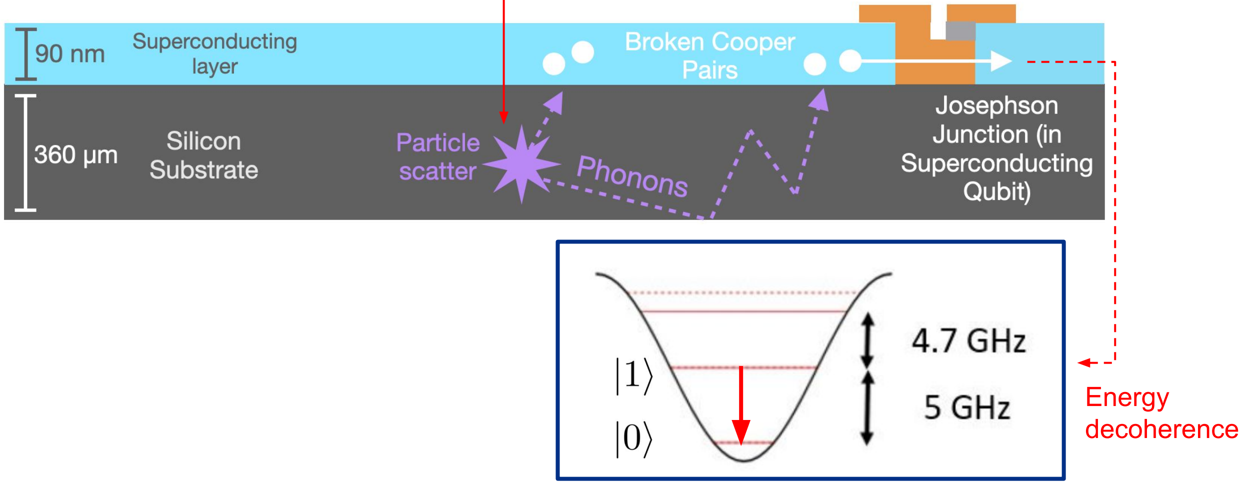

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Detection Schemes: Energy Decoherence

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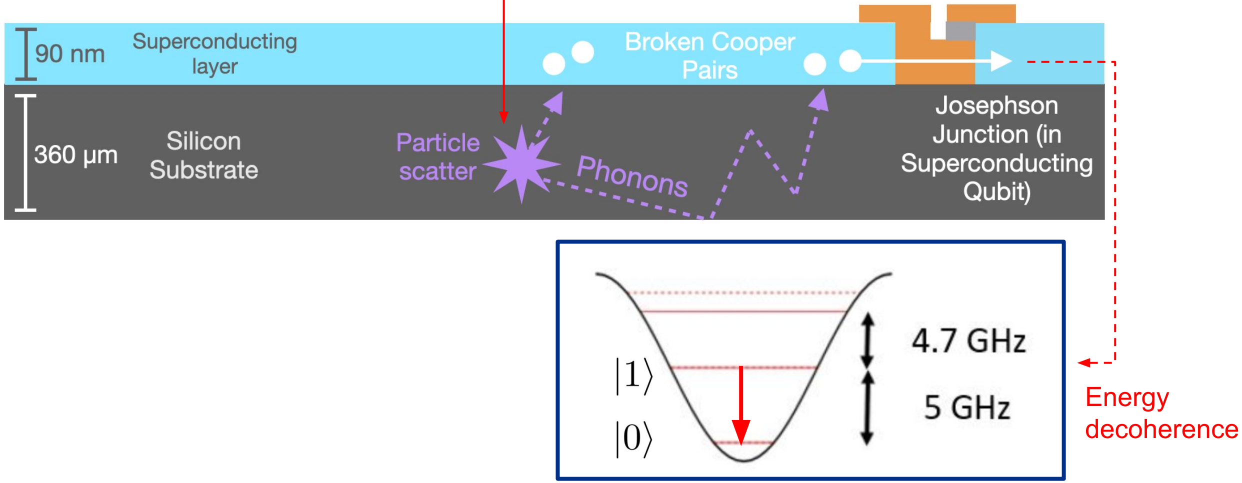
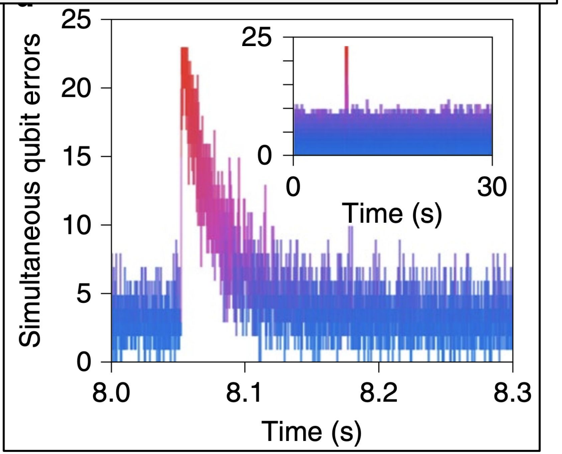


Decoherence during high-energy event



McEwen et al., *Nat. Phys.* 18, 107–111 (2022). https://doi.org/10.1038/s41567-021-01432-8

QSC@FNAL: What's the reach of energy decoherence detection?

Energy decoherence detection relies on long <u>T1 decoherence times</u>.

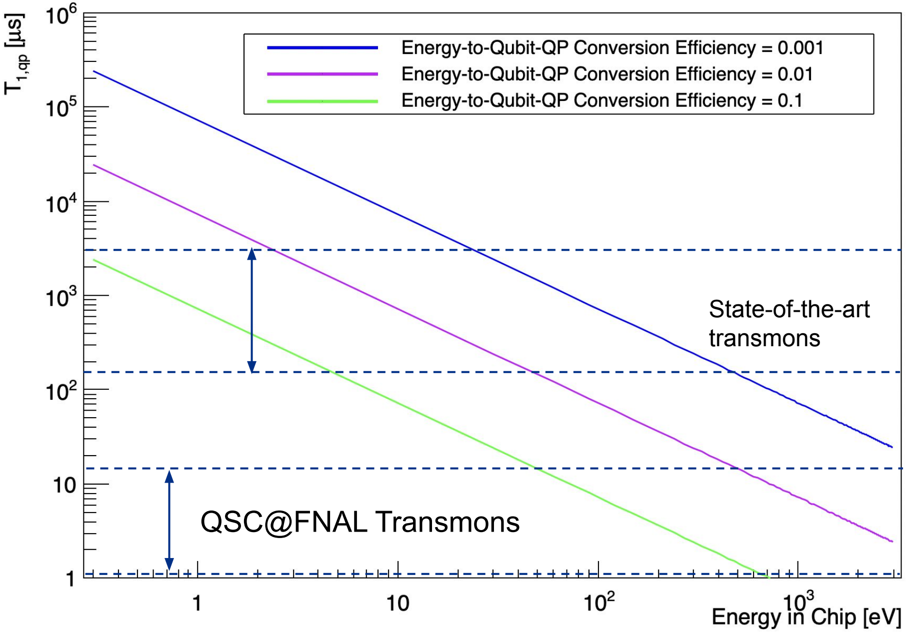
- "Base" energy decoherence timescale due to all environmental dissipation
- Often limited by qubit architecture (not QPs)
- Need base T_1 large enough that QPs can induce observable changes in it

Decoherence rate $1/T_{1,qp}$ — Qubit frequency — Superconducting gap — Reduced QP density

$$\Gamma_{qp} = \sqrt{\frac{2\omega_q \Delta}{\pi^2 \hbar}}\, x_{qp}$$

For 1% energy-to-QP conversion, state-of-the-art Al transmons could reach sensitivity to in-chip energy depositions around **O(10eV)**

Energy reach: an (over)simplified estimate



Rate equation from Wang, C., Gao, Y., Pop, I. et al. "Measurement and control of quasiparticle dynamics in a superconducting qubit." *Nat Commun* 5, 5836 (2014) (link)

Partial source on "state of the art": Kjaergaard et al., "Superconducting Qubits: Current State of Play," https://doi.org/10.48550/arXiv.1905.13641

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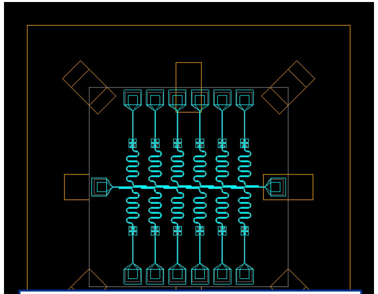
QSC@FNAL: Developing Simulations Chain

To get a mature estimate of reach, we need to simulate how energy deposits propagate through a detector to impact T1 decoherence times.

DM scattering, energy deposition → Energy propagation through chip → QP production in qubits → QP time evolution in qubits → $T_{1,qp}$ evolution in qubits

G4CMP simulation

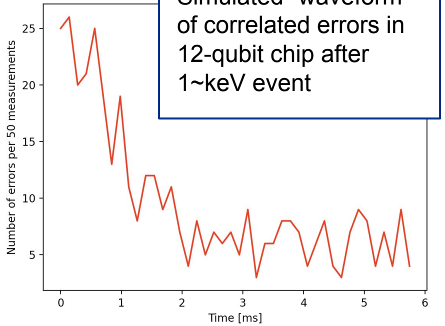
- Geant4-based
- Phonon and e/h pair tracking
- Simple QP modeling
- Extensions being developed by community



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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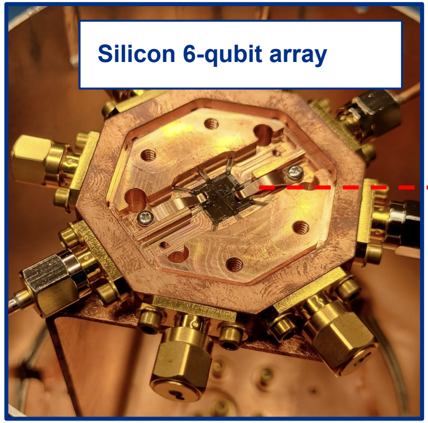
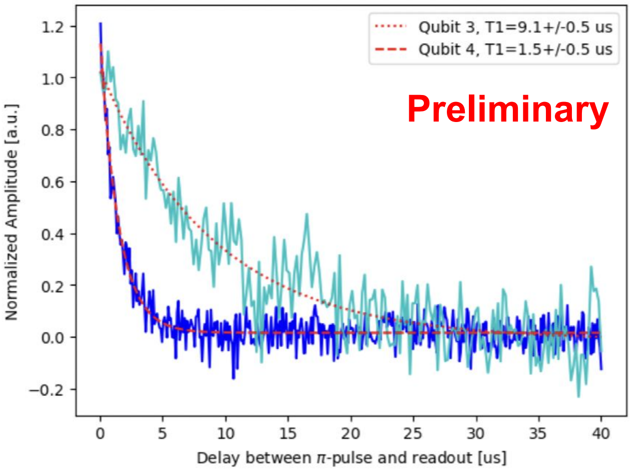
QSC@FNAL: Sensor Operation and R&D

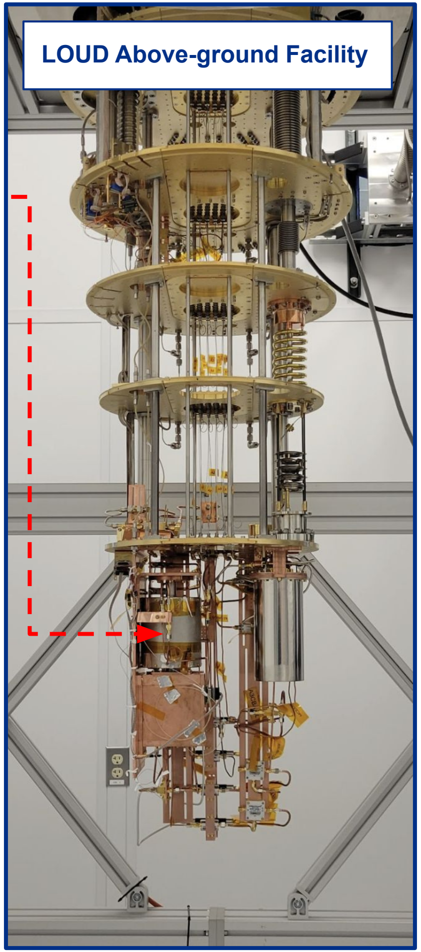
To actually build a qubit-based detector, a capability for clean control and readout is required.

LOUD: aboveground dilution fridge facility for quantum sensor testing

- Demonstrated single-qubit control and characterization of multiple qubits on test chip →
- Learning how to optimize quantum state control and readout from quantum community @FNAL







QSC@FNAL: Calibrations

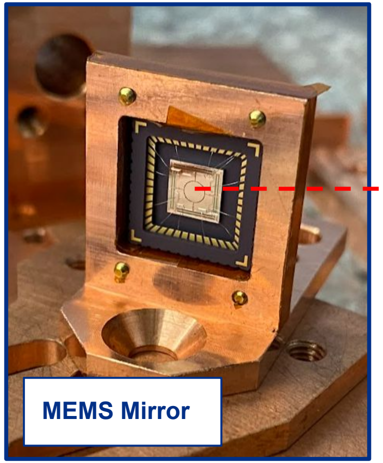
Calibration is needed to understand detector response and validate simulations.

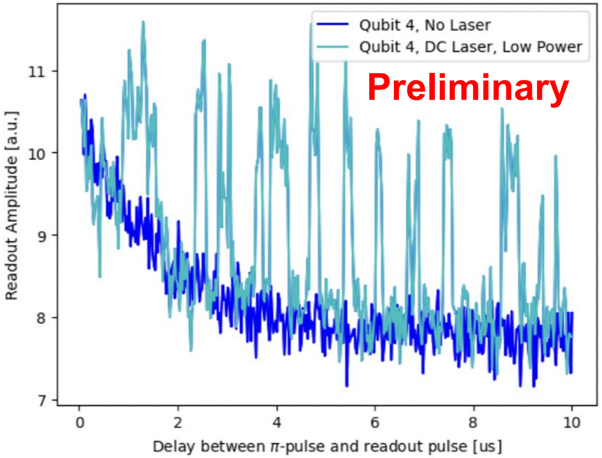
MEMS+Laser Calibration:

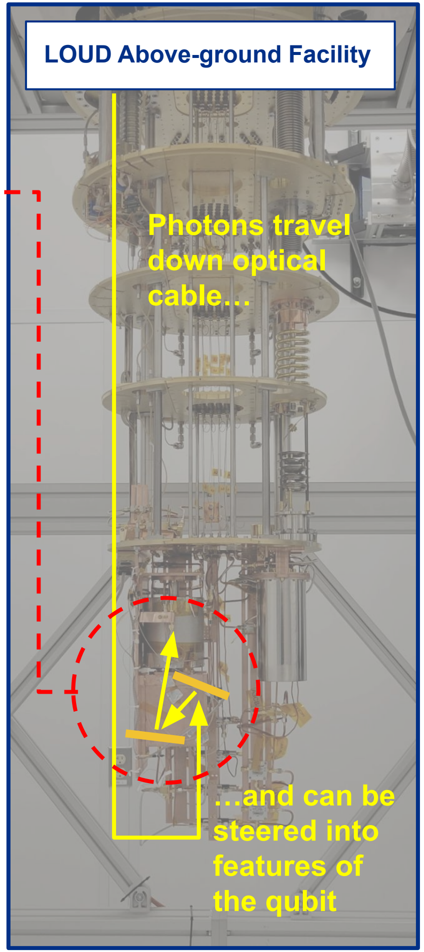
- Steerable MEMS mirror with low cryogenic power dissipation
- Enables laser scanning over qubit chip face

Status: first MEMS+laser light seen in LOUD!

- 1.9 eV laser photons shone on SC surface of qubit chip
- Distinct response observed in chip
- Current goal: map qubit response as a function of laser position.







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Looking Forward

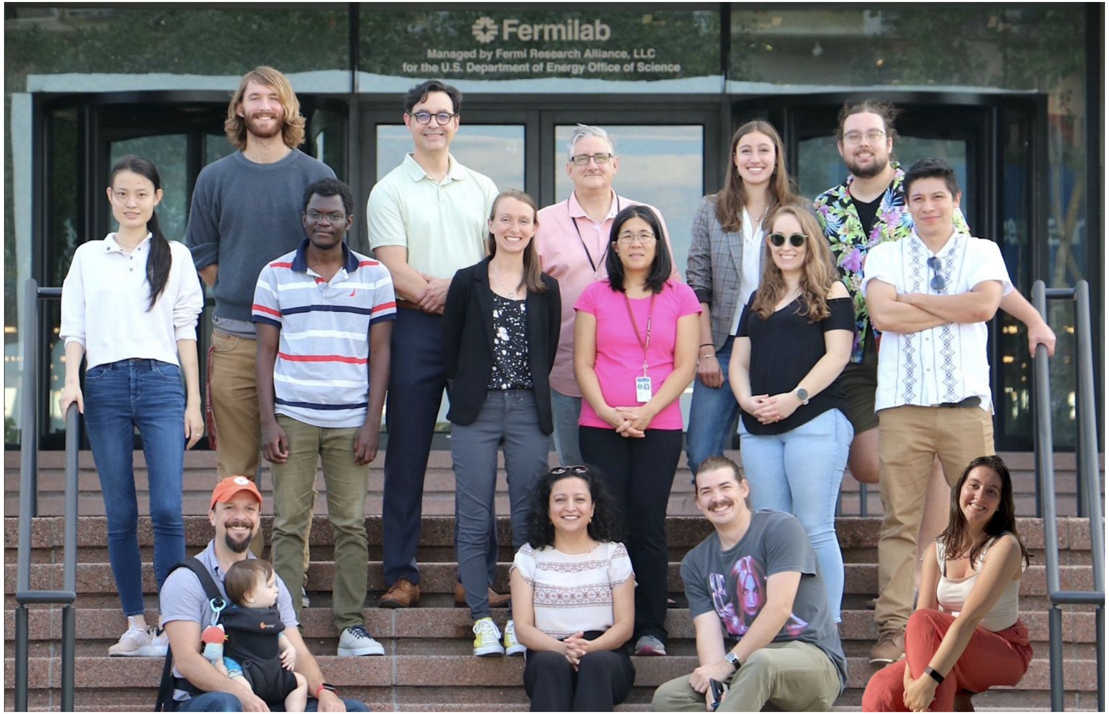
Long, exciting road ahead for qubits (and more generally quantum sensors) in the DM field!

1. Develop simulation, operation, and optimization of qubit systems at FNAL

2. Refine understanding of DM mass reach for energy-decoherence detection

3. Explore reach of additional qubit-based detection mechanisms

Acknowledgements



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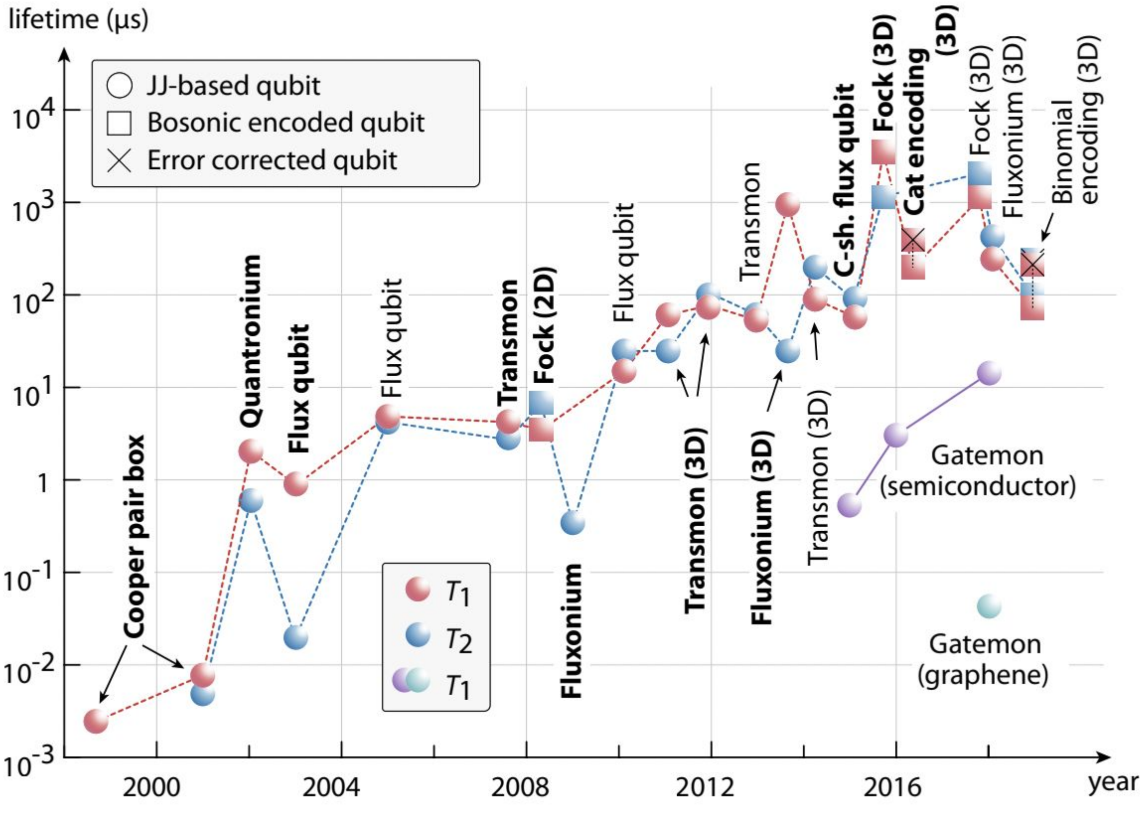
Backup

T1 Time Evolution over the Last Two Decades

Rapid progress has been made in increasing coherence times in the last 20 years.

Continued progress not guaranteed, but track record warrants optimism for energy-decoherence sensing.

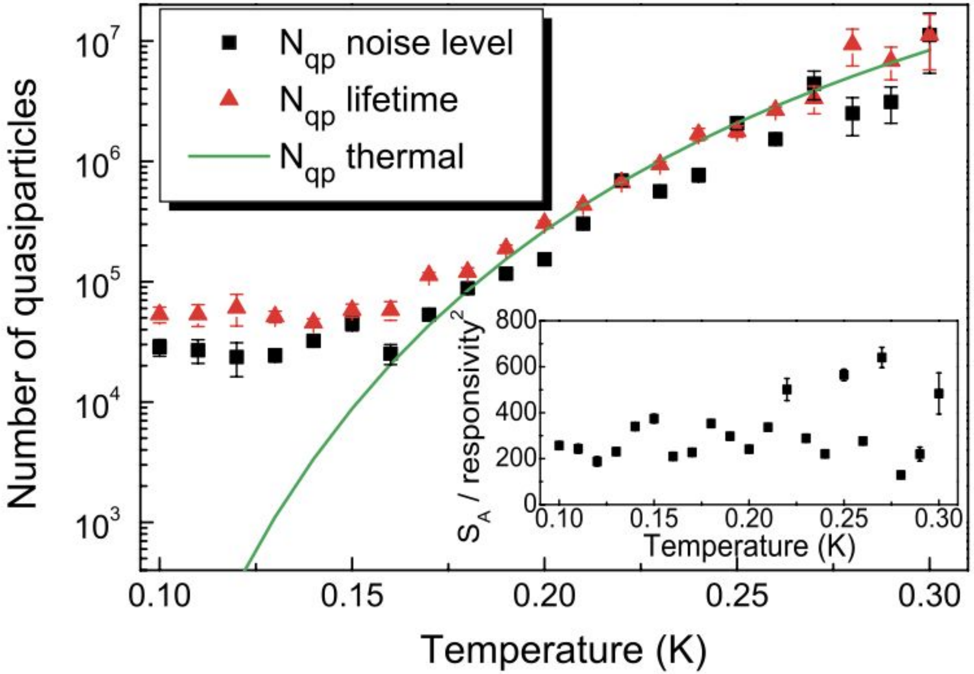


Source: Kjaergaard et al., "Superconducting Qubits: Current State of Play," https://doi.org/10.48550/arXiv.1905.13641

Potential Limitations on Threshold: Quiescent QP Density

Measurements of quasiparticle recombination times suggest a possible excess “nonequilibrium” quasiparticle density at low temperatures.

- Estimates at 25-55 µm^3
- Source not well understood
- If true, could place limit on qubit threshold



Source: P. J. de Visser, J. J. A. Baselmans, P. Diener, S. J. C. Yates, A. Endo, and T. M. Klapwijk
[“Number Fluctuations of Sparse Quasiparticles in a Superconductor,”]
Phys. Rev. Lett. 106, 167004 – Published 22 April 2011

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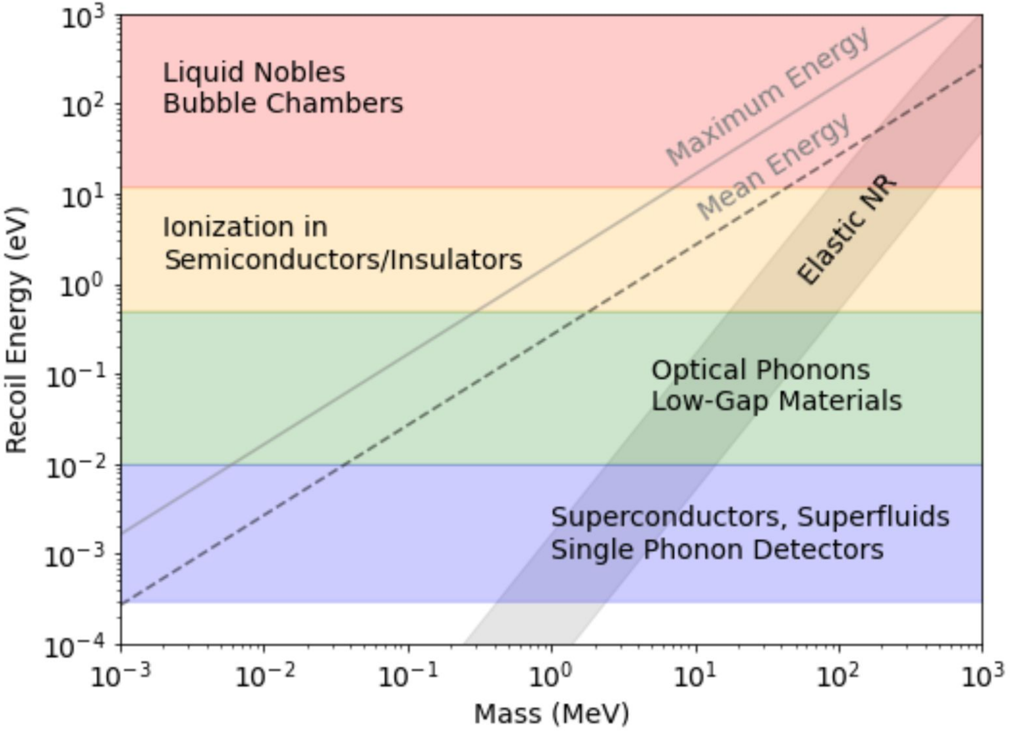
Energy Thresholds and Detector Technologies



Elastic nuclear recoils only have plausible reach down to ~MeV scale DM[6].

Inelastic recoils enable deposition of larger fraction of DM's energy in target, and probing of lower-mass DM models.

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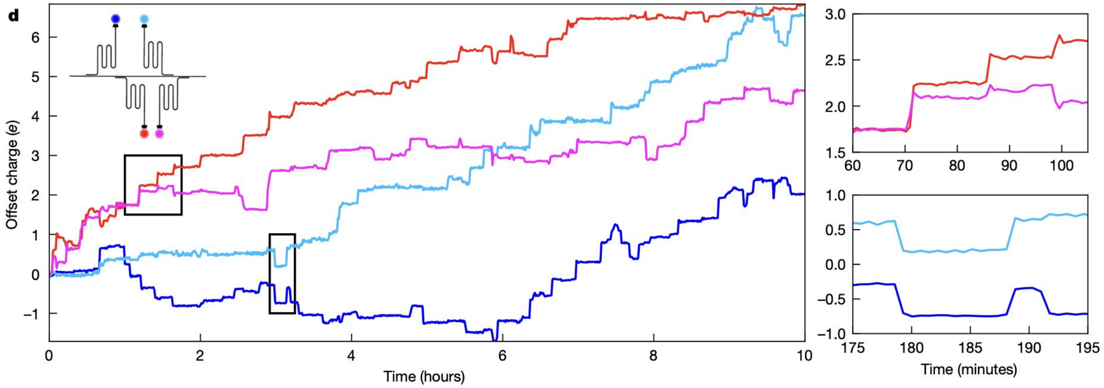
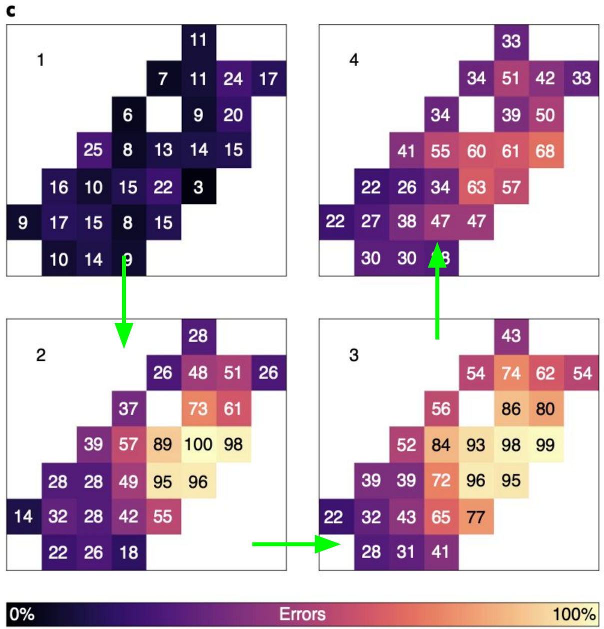
Radiation Impact on Superconducting Qubits

Wilen et al.,
Correlated charge noise between multiple qubits during high-energy events[5]

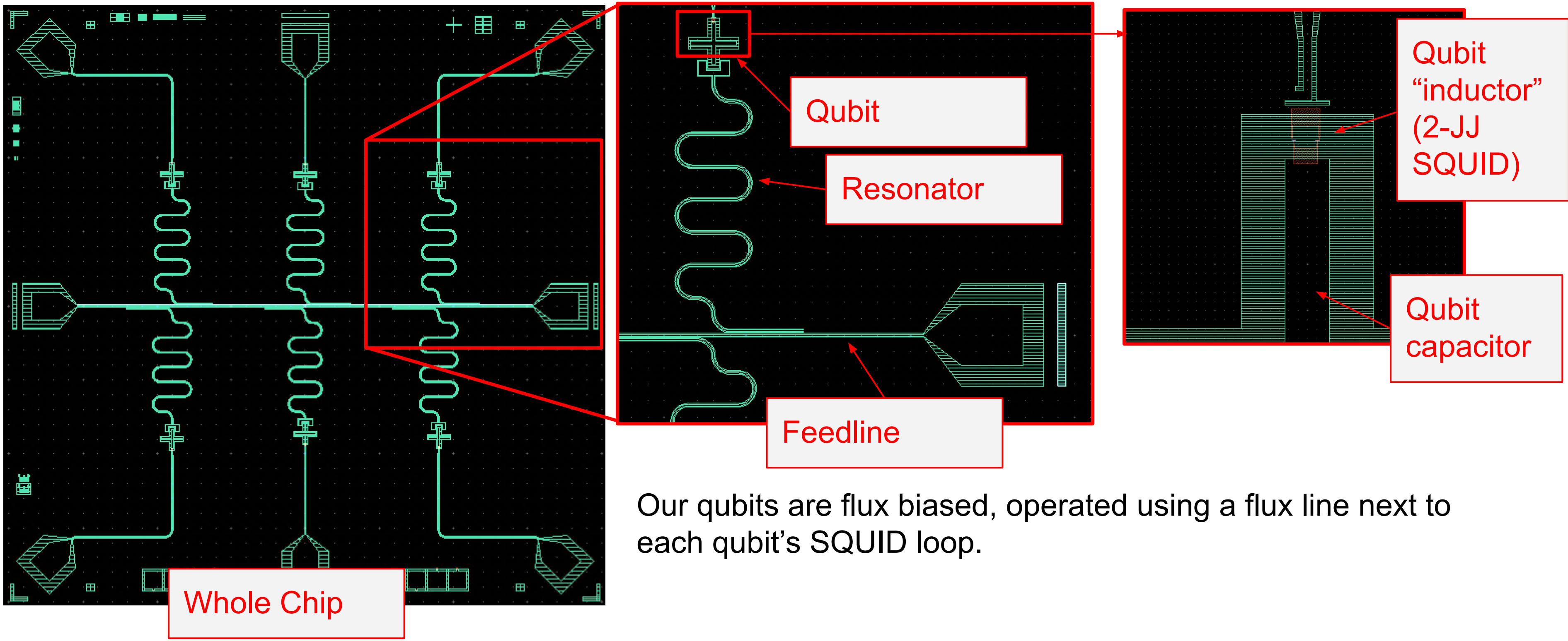


McEwen et al.,
Qubit errors after high-energy event in chip[1]



Device Design/Operation

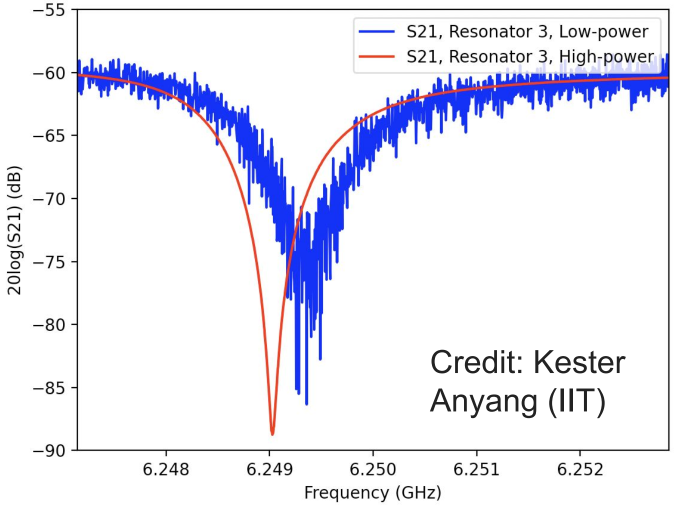
Qubits read out using coplanar waveguide resonators coupled to a shared RF feedline.



Our qubits are flux biased, operated using a flux line next to each qubit’s SQUID loop.

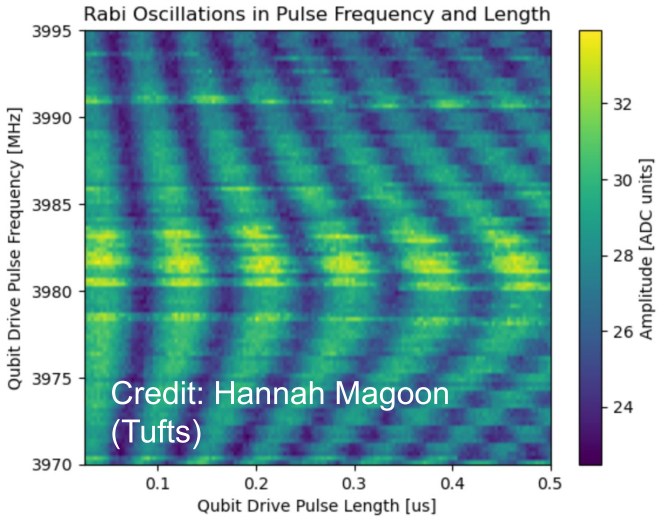
Qubit Bring-Up Tests

One-tone resonator spectroscopy (“punch-out”)



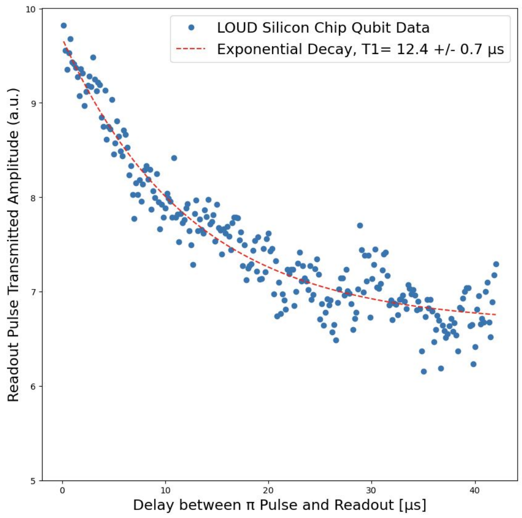
Purpose: determine that the qubit (i.e. the Josephson Junction) is “alive”, i.e. not burned out

Qubit spectroscopy + Rabi Oscillations



Purpose: find the qubit excitation frequency and calibrate a |0> → |1> pulse

T1 Relaxation Time



Purpose: Probe qubit decoherence times