Superconducting Qubits for Dark Matter Detection

Ryan Linehan - Fermilab Cosmic Physics Center, Quantum Science Center

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Superconducting Qubits

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

What is a SC qubit?

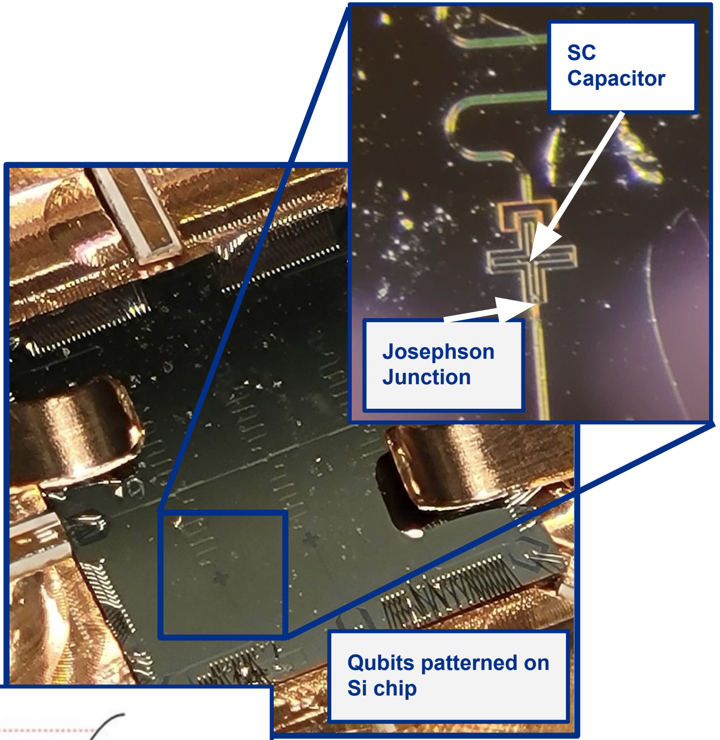
- Anharmonic LC circuit in SC film
- "Qubit" = lowest two energy states
- Energy spacing typically in few GHz range

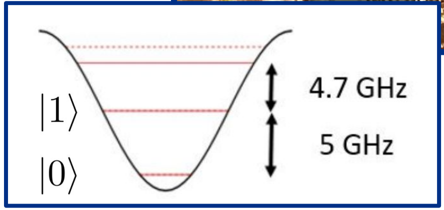
Qubits are versatile sensors:

- State preparation, readout, and gates performed with microwave signals, 4-6 GHz
- Variety of noise sensitivities and detection schemes possible!

Goal: build a capability for end-to-end estimates of how sensitive various qubit detection schemes are to particle impacts.

- Ultimate goal: find one with <<eV threshold.

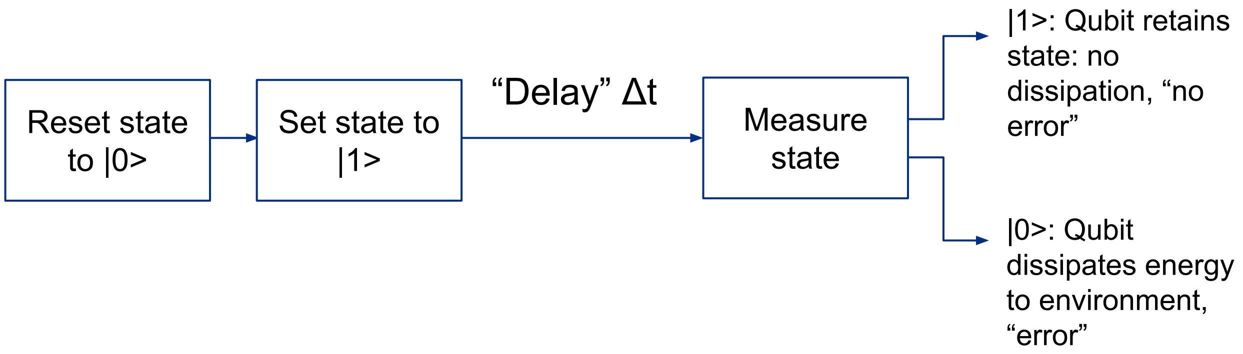




T. Roth, R. Ma and W. C. Chew, "The Transmon Qubit for Electromagnetics Engineers: An Introduction," in IEEE Antennas and Propagation Magazine, doi:10.1109/MAP.2022.3176593.

Detection Schemes: Energy Decoherence

Simplest, “example” detection sequence: looking for qubit de-excitations/**decoherence** from particle impacts.



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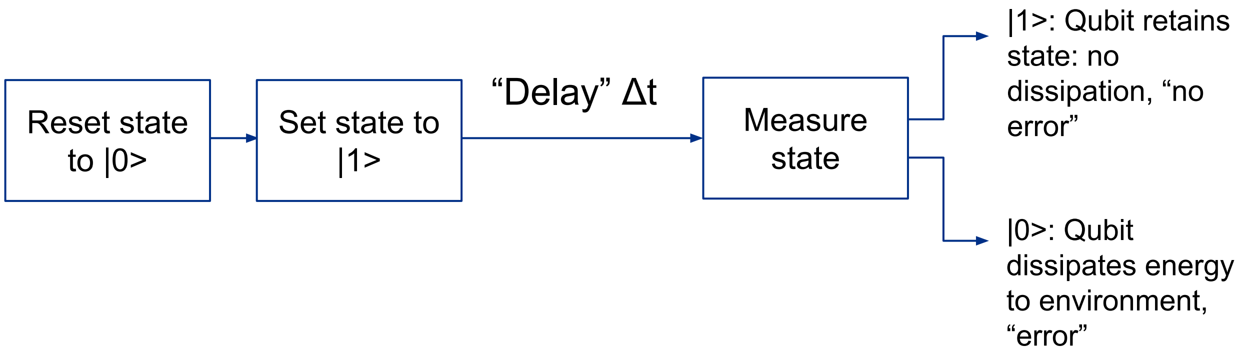

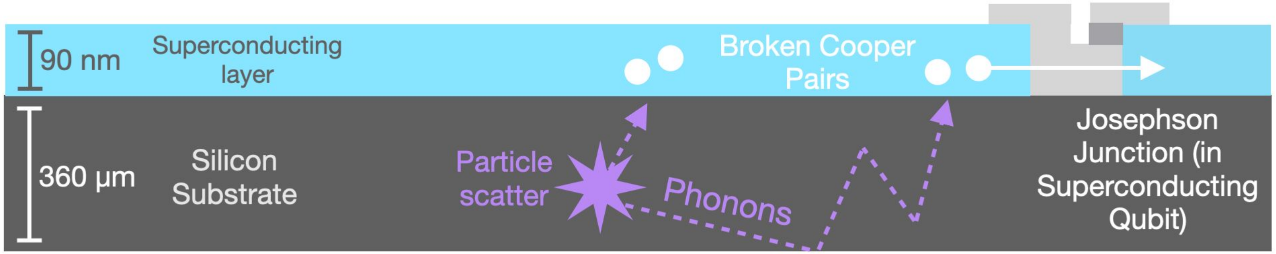

1. Energy deposit creates phonons
2. Phonons create QPs in SC qubit near junction (2Δ=0.3meV for Al)
3. Increase in decoherence rate ~ new density (~x_{qp}) of QPs near junction.

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

Vepsäläinen, A.P., Karamlou, A.H., Orrell, J.L. *et al.* "Impact of ionizing radiation on superconducting qubit coherence." *Nature* 584, 551–556 (2020). https://doi.org/10.1038/s41586-020-2619-8

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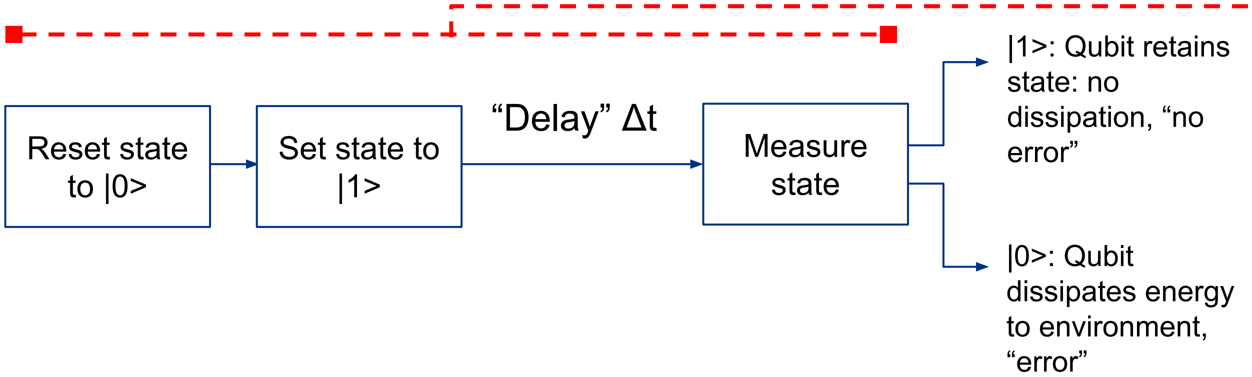

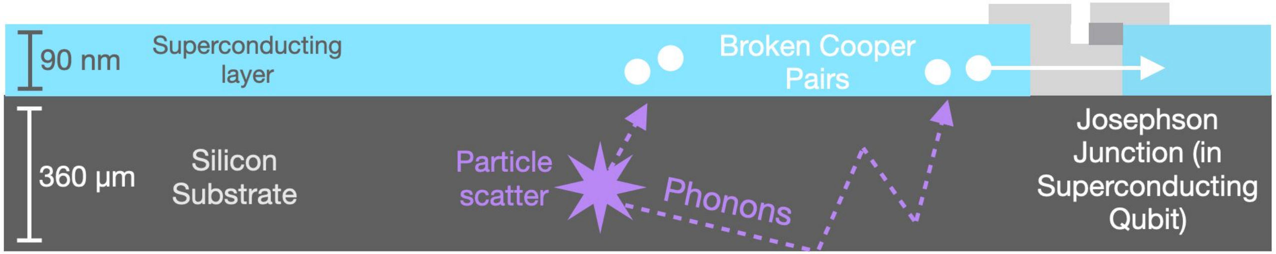

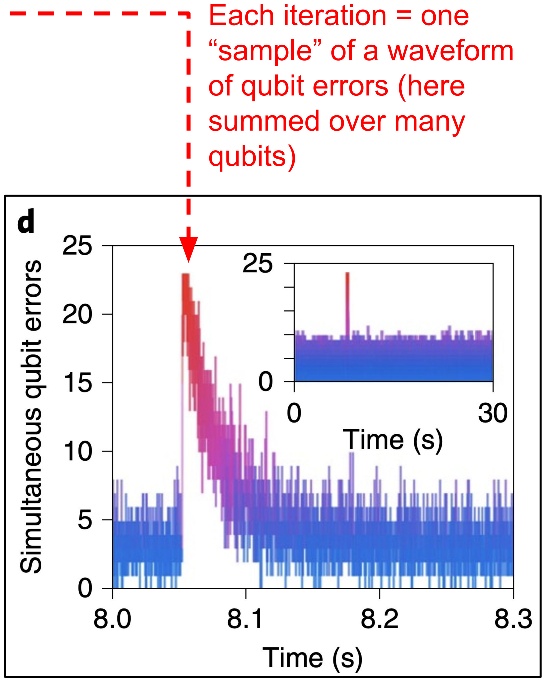

McEwen et al., *Nat. Phys.* 18, 107–111 (2022).
https://doi.org/10.1038/s41567-021-01432-8

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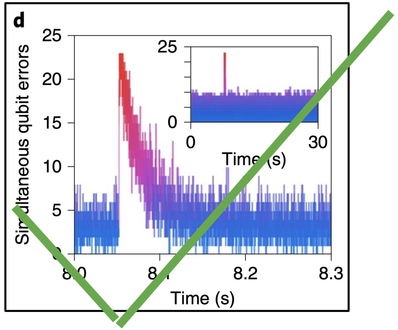
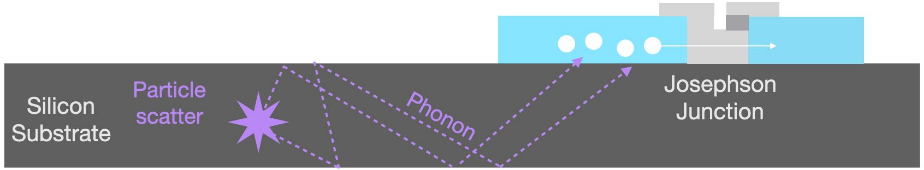
Relationship between Qubits for DM and for QIS

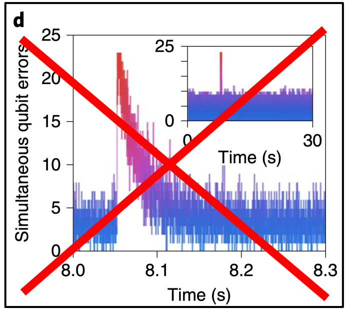
Qubits for Dark Matter Searches: energy decoherence "waveforms" desired!



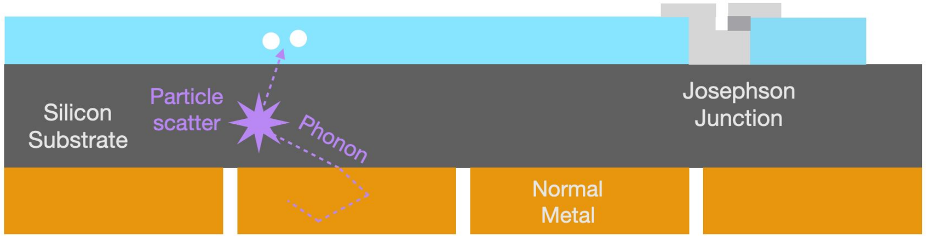
Goal: <u>maximize</u> phonon absorption by qubits



Qubits for QIS: energy decoherence "waveforms" undesired.



Goal: <u>minimize</u> phonon absorption by qubits



Estimating the sensitivity of energy decoherence

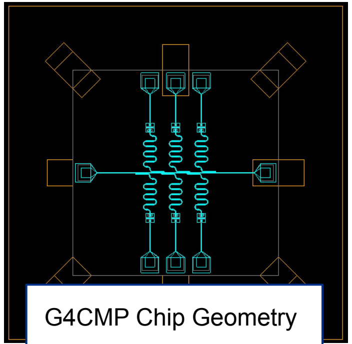
Goal: understand the energy threshold of this energy decoherence detection scheme.

- Estimating this using simulations is reasonably straightforward with G4CMP: solid state G4 package
- Also need a “sensor response” simulation to complete sims chain

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

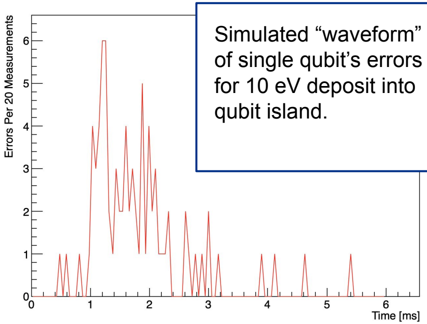
- Geant4-based
- Phonon and e/h pair tracking
- Simple QP modeling
- Extensions being developed by community



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 single qubit’s errors for 10 eV deposit into qubit island.

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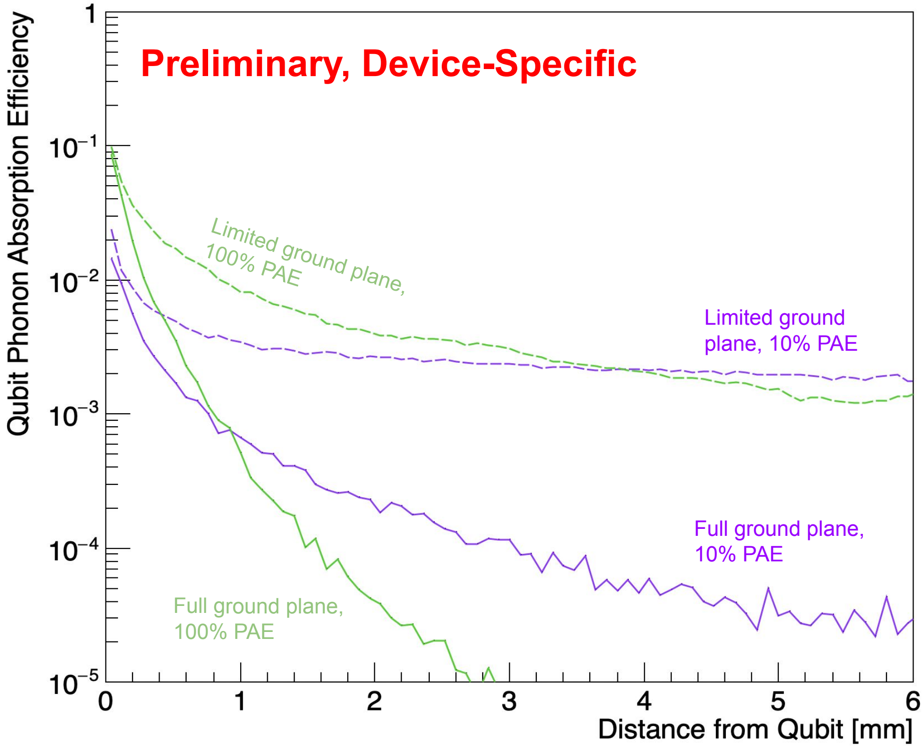
Uncertainties in Phonon Propagation

How much energy makes it from the interaction to the sensor?

Significant uncertainties in simulating phonon response in chip:

1. Phonon absorption probabilities (PAE) at interfaces
2. Full Quasiparticle response in superconductor is rather complex (especially for multiple SC types!)
   a. Phonon “recycling” possible
3. Phonon coupling to thermal bath nontrivial to predict



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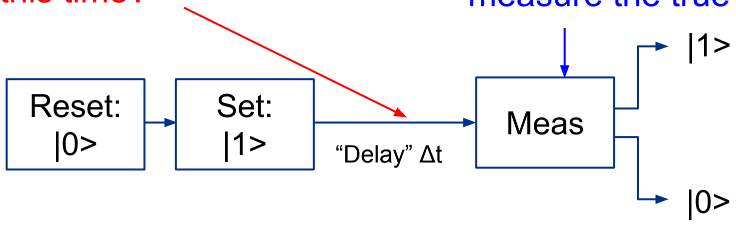
Uncertainties in Sensor Response

Uncertainties in readout scheme → more or fewer "dark counts"

$T_{1,base}$: Do we decohere due to other dissipation in this time?

Single-shot fidelity (SSF): how faithfully do we measure the true state?



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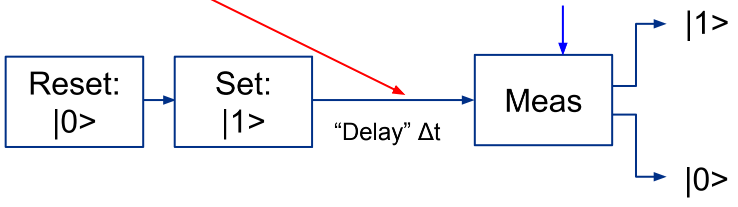
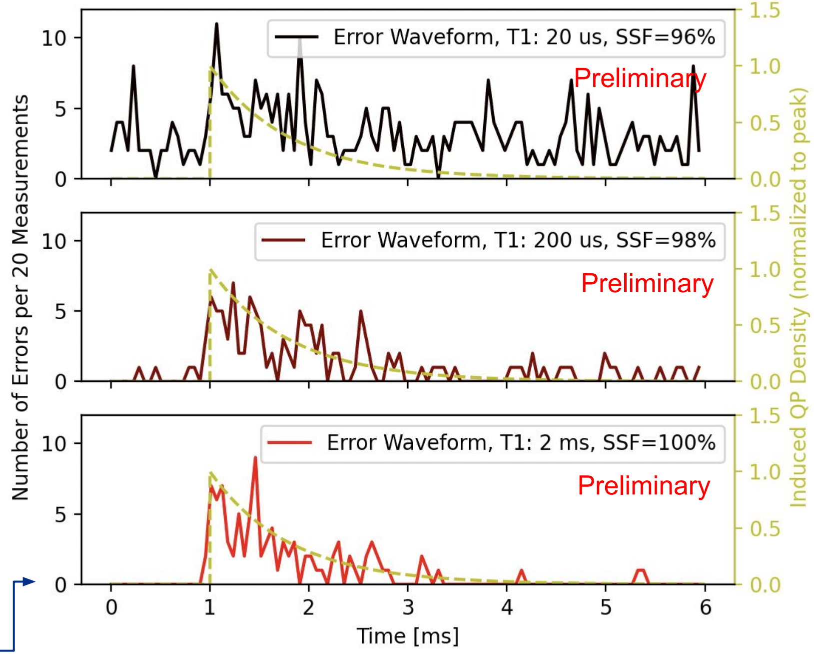


Example simulation parameters:

1. Aluminum qubit island
2. E_{dep} = 10 eV, direct into island at t=1ms.
3. Coarse QP density generated: ~E_{dep} / 2Δ
4. Assume that QP diffusion equalizes junction x_{QP} with island x_{QP}.
5. Assume that QP recombination happens over 1ms timescale
6. Use x_{qp} to estimate additional decoherence rate at a given point in time (delay Δt = 2μs)

Simulated qubit readout response for example values of $T_{1,base}$ and SSF



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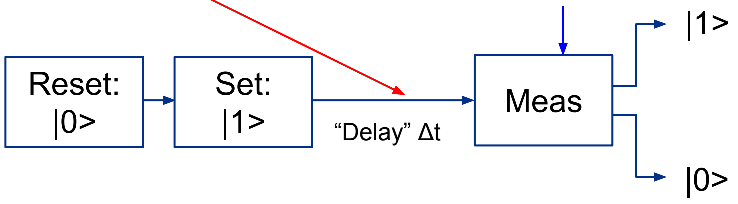
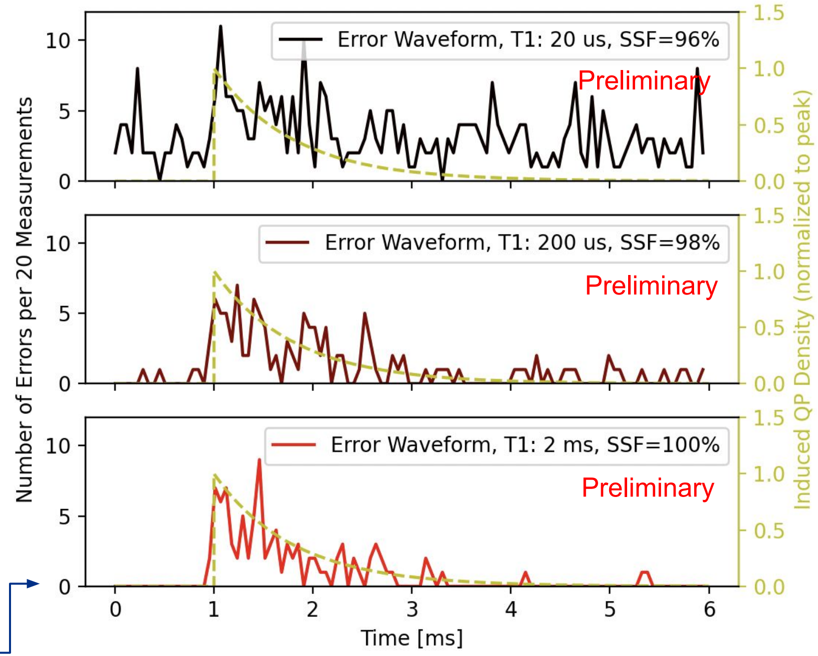


Observations (for this example simulation):

1. T1,base: want >ms scale (best published O(500μs))
2. SSF: want >95%
3. For reasonable near-term parameters, single-qubit "threshold" is O(eV) deposited in the qubit.

Simulated qubit readout response for example values of $T_{1,base}$ and SSF



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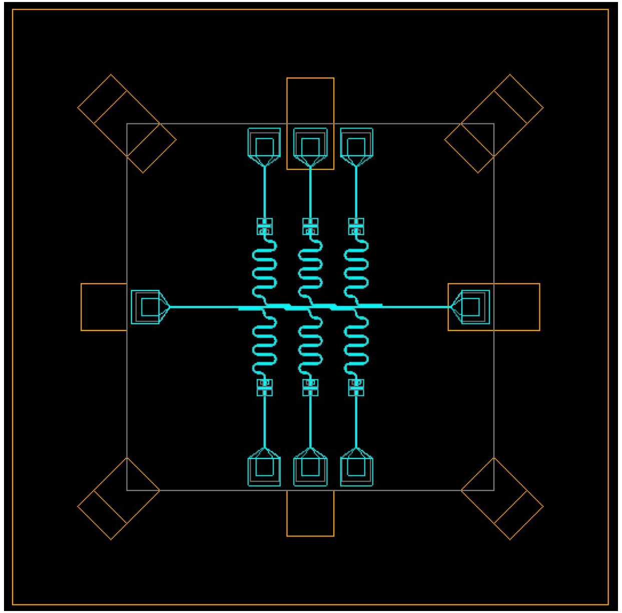
Example Energy Scale for Multi-Qubit Detection

Can estimate detection "threshold" for events with >1 qubit triggered.

Example chip (Si + Al):

1. Feedline + 6 transmon qubits + λ/4 resonators + flux lines
2. Restricted ground plane to minimize phonon loss
3. 100% phonon absorption efficiency at Al/Si interface



For this design/readout scheme, need O(100 eV) deposited in chip to see >10% of scatters with 2 or more qubits.

Reminder: this is "example" chip design, with an example readout scheme

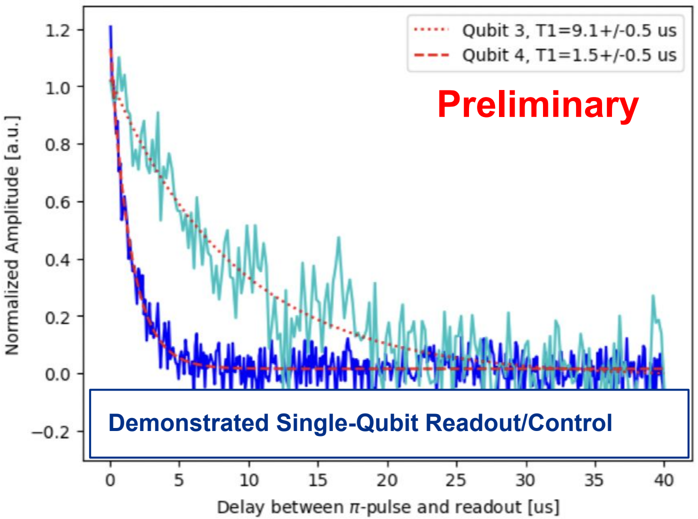
- Can further optimize for DM detection – QP traps, larger island, varying SC materials
- Other designs/detection schemes more sensitive: starting to probe these with the same sims chain/tools

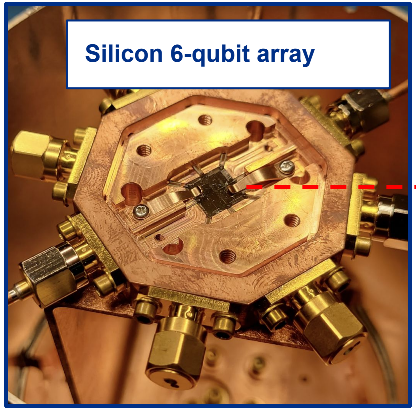
Sims/sensitivity paper coming soon to discuss many of these knobs!

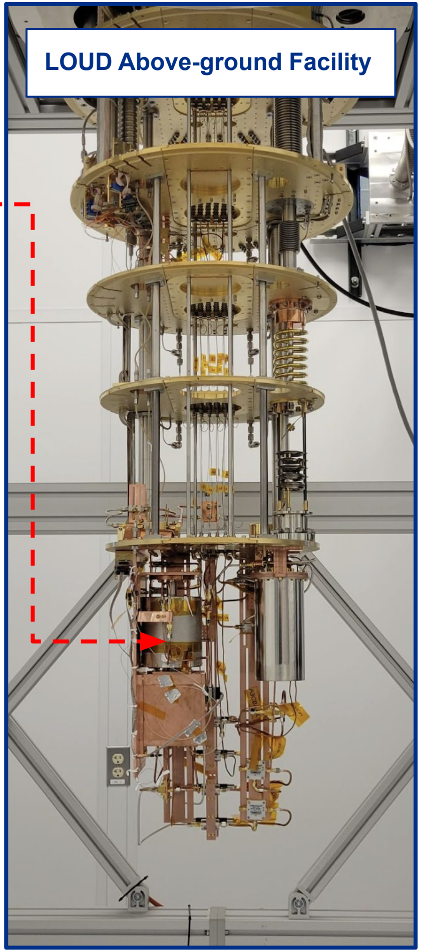
Ultimately, this is testable!

At FNAL, we have assembled the tools needed to probe the threshold of a qubit-based detector.

LOUD: aboveground dilution fridge facility for high-throughput quantum sensor testing







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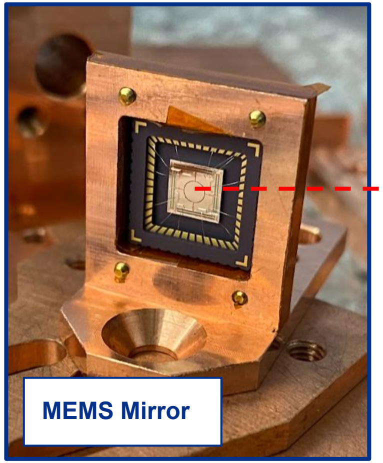
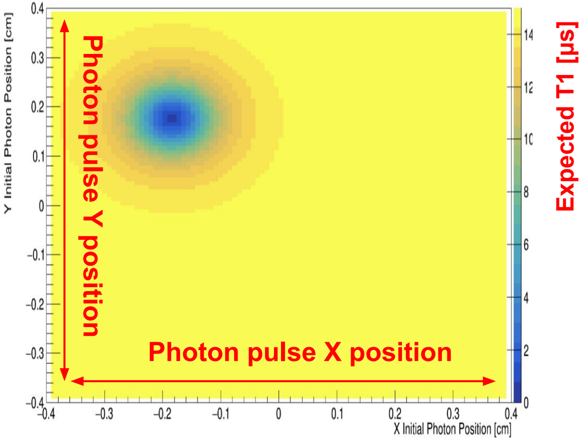
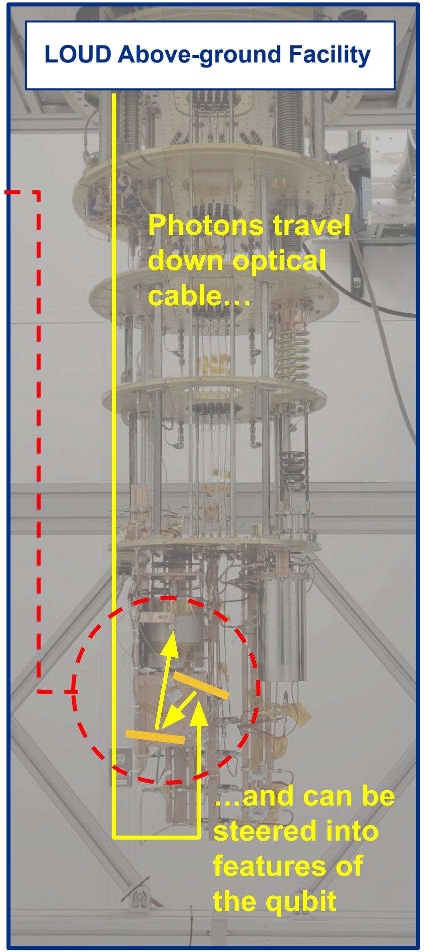
MEMS+Laser Calibration*:
- Steerable MEMS mirror with low cryogenic power dissipation
- Enables laser scanning over qubit chip face



Simulations estimating additional decoherence from a burst of laser light on chip:



Work by Israel Hernandez, IIT/FNAL



Development team*: Kelly Stifter, Noah Kurinsky, Hannah Magoon, Noshin Tabassum, Sukie Kevane

Ultimately, this is testable!

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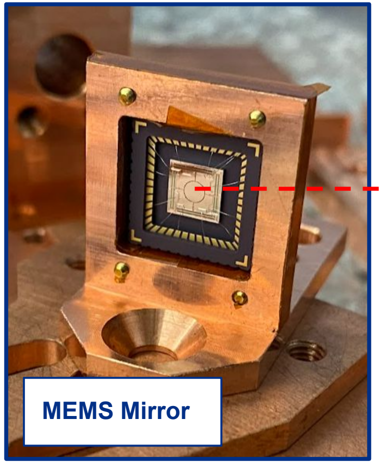
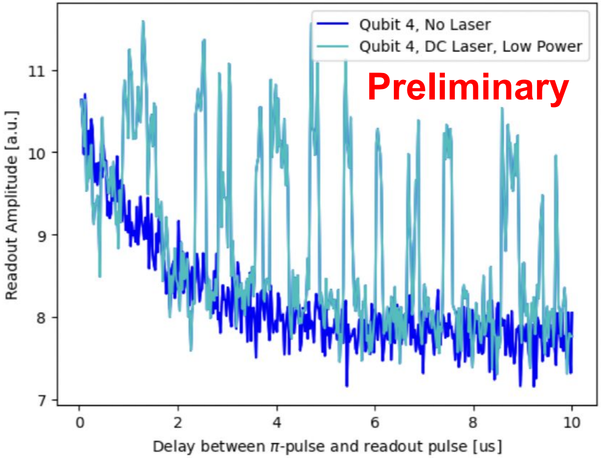
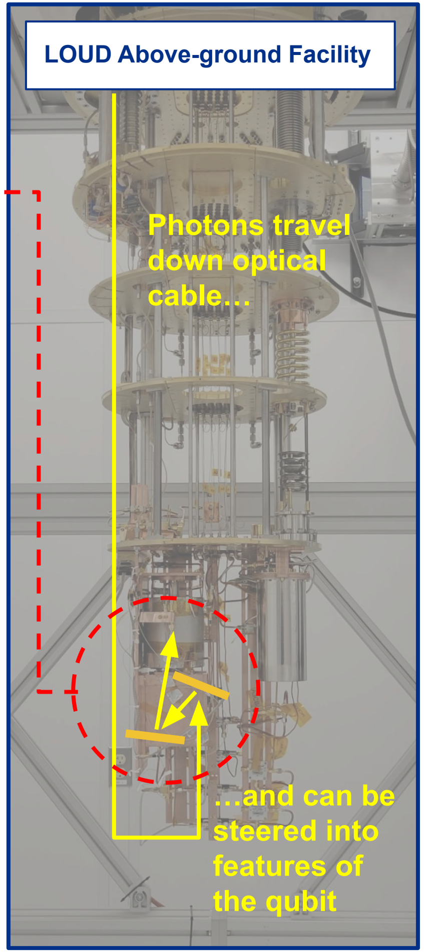
Status: first MEMS+laser light seen in LOUD!

- 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 in the DM field!

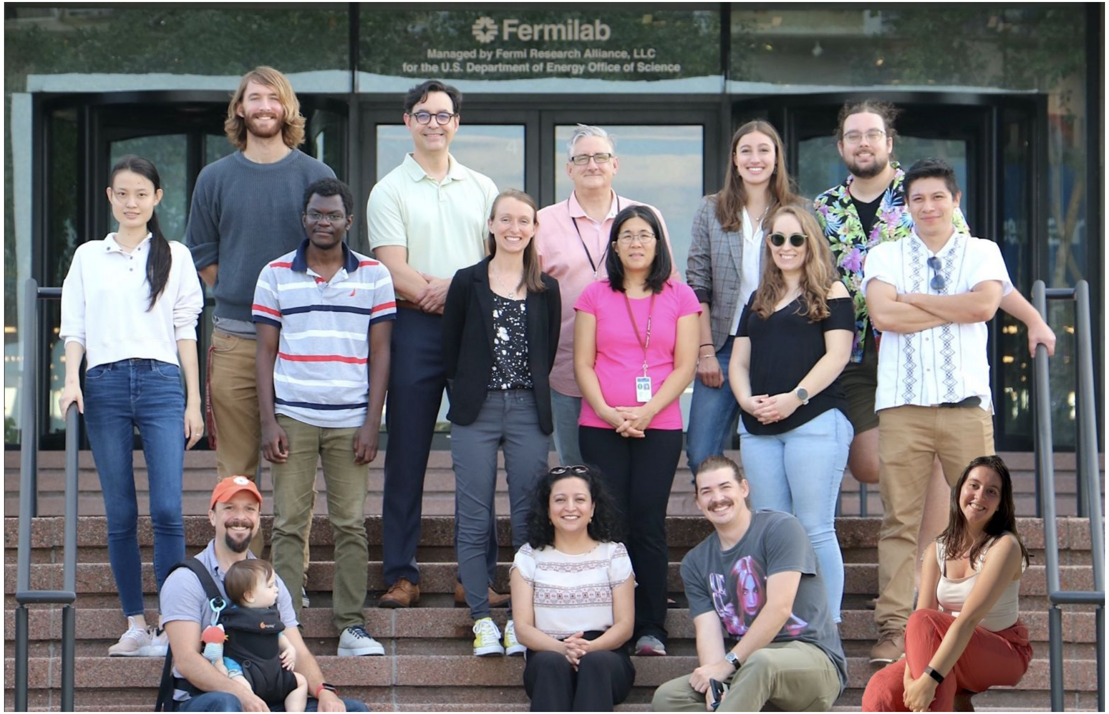
1. Finish refining threshold estimates for energy decoherence detection technique threshold and validate with MEMS at FNAL

2. Explore reach of additional qubit-based detection mechanisms

In other news…
Three postdoc positions available for cryogenic detector R&D and QIS (collaboration with FNAL)
Apply here: https://figueroa.physics.northwestern.edu/jobs/index.html

Also, see these wonderful talks:
- "Energy dissipation and phonon kinematics simulation in qubits with G4CMP" – Israel Hernandez
- "Studying Correlated Charge Fluctuations in Superconducting Qubits in a Low-Background Underground Facility" – Hannah Magoon
- "Sapphire substrate qubit-based detector for light dark matter search" – Kester Anyang
- "Cryogenic optical beam steering for calibration of superconducting sensors" – Noshin Tabassum

Acknowledgements



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FERMILAB-SLIDES-23-367-PPD

Collaborators

QSC@FNAL:
Aaron Chou
Lauren Hsu
Daniel Baxter
Rakshya Khatiwada
Daniel Bowring
Gustavo Cancelo
Sho Uemura
Sami Lewis
Dylan Temples
Sara Sussman
Kester Anyang
Israel Hernandez
Jialin Yu
Stella Dang
Matthew Hollister
Chris James
Grace Wagner

Northwestern:
Enectali Figueroa
Grace Bartrud
Shilin Ray

SLAC:
Noah Kurinsky
Kelly Stifter
Hannah Magoon
Noshin Tabassum

QSC@Purdue
Alex Ma
Botao Du

UW Madison
Robert McDermott
Sohair Abdullah

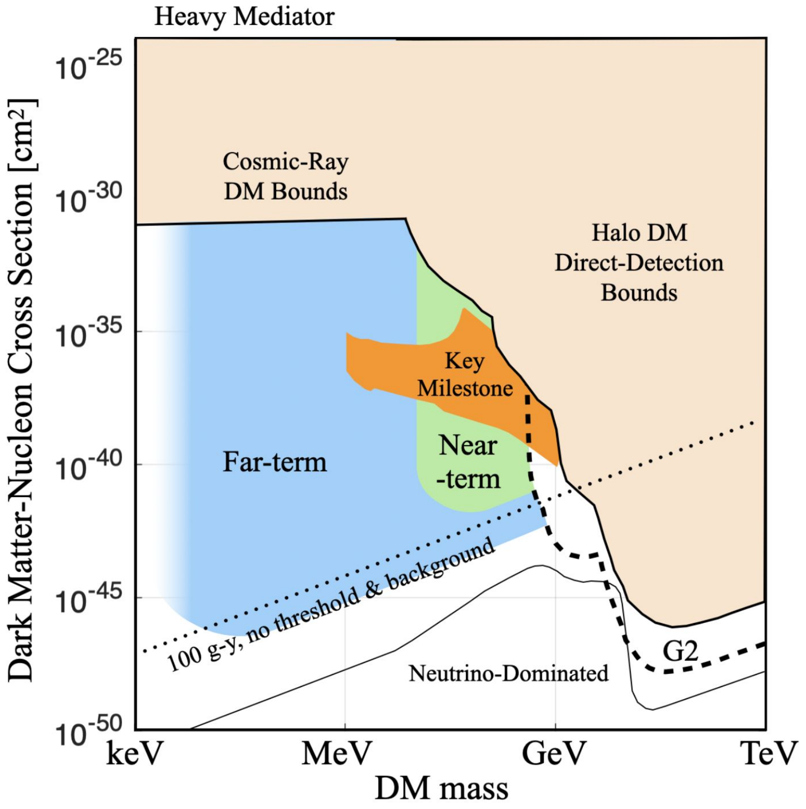
Backup

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

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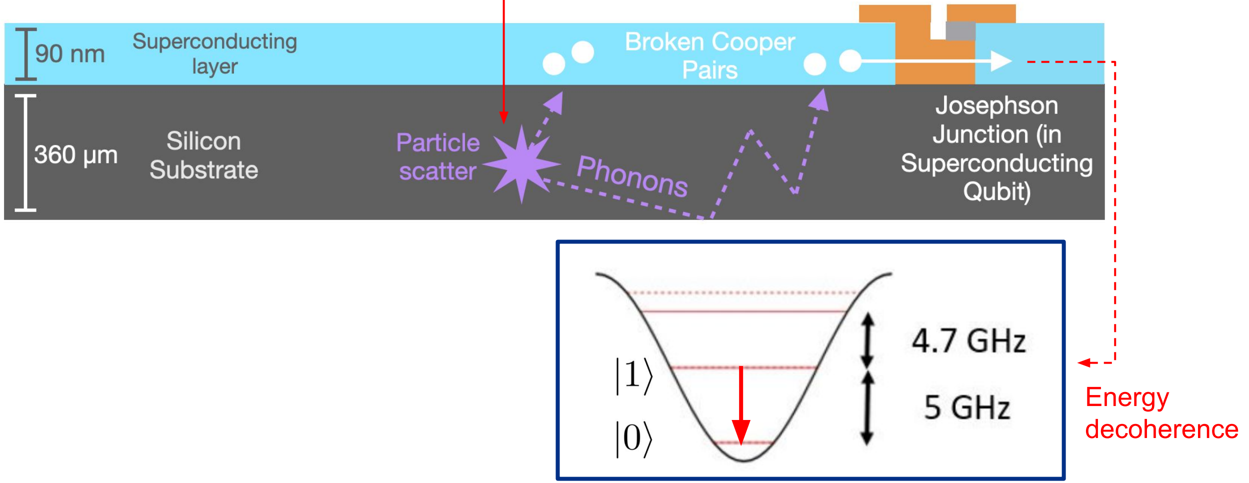
Detection Schemes: Energy Decoherence

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!



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

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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

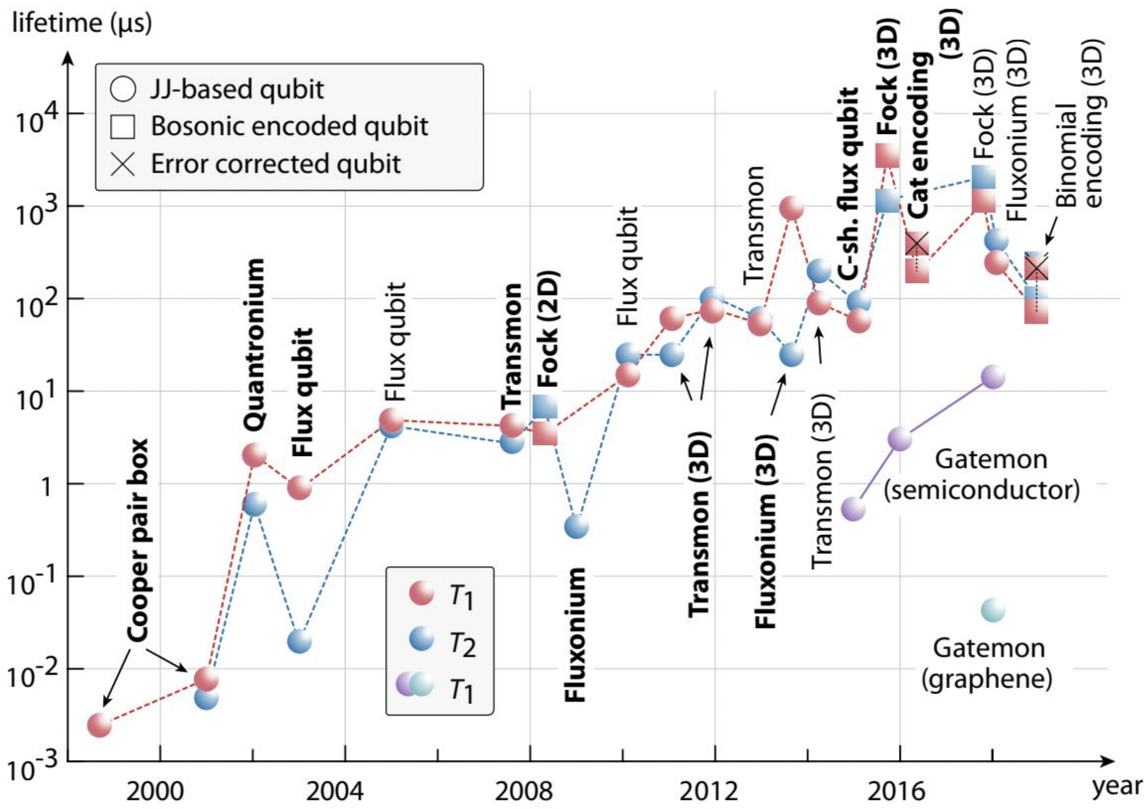
Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits

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

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

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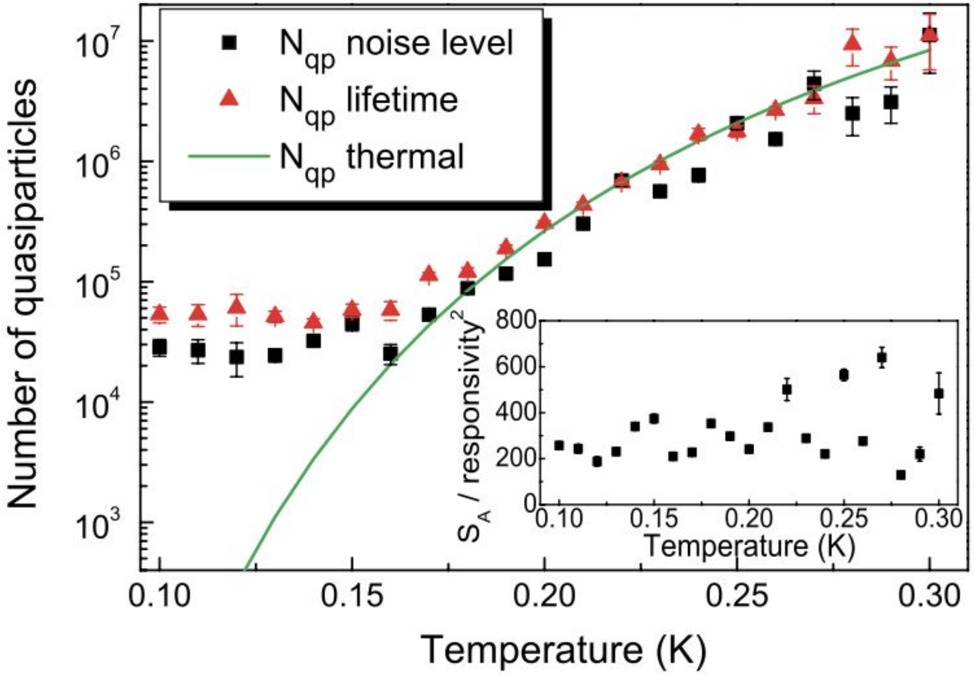
Potential Limitations on Threshold: Quiescent QP Density

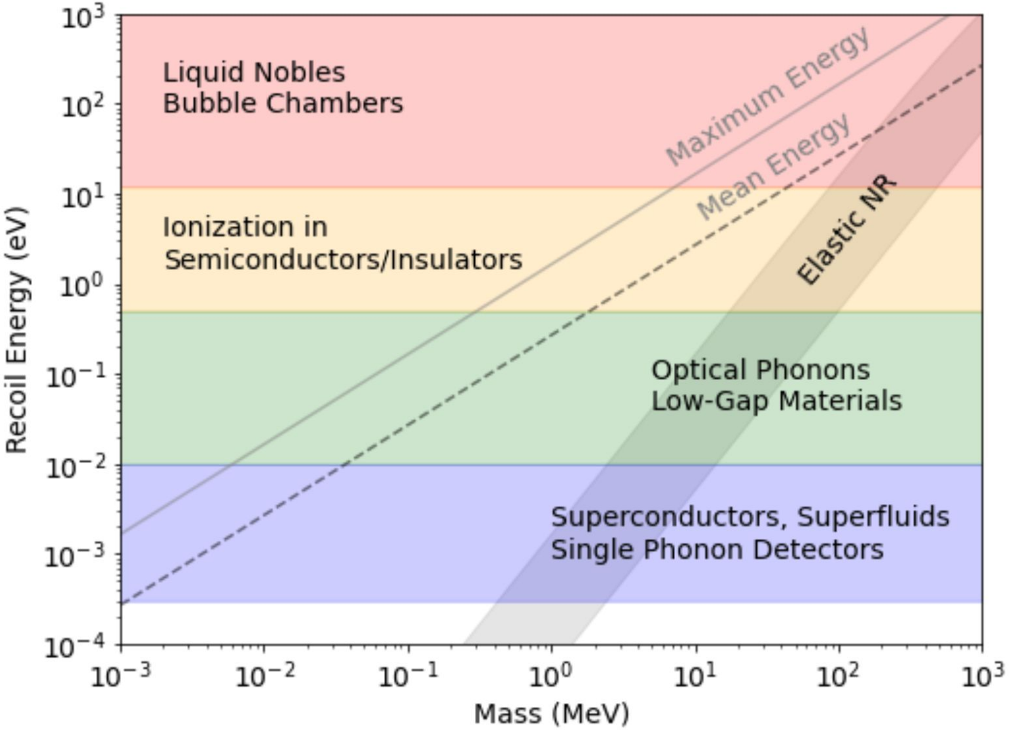
Measurements of quasiparticle recombination times suggest a possible excess “nonequilibrium” quasiparticle density at low temperatures.

- 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

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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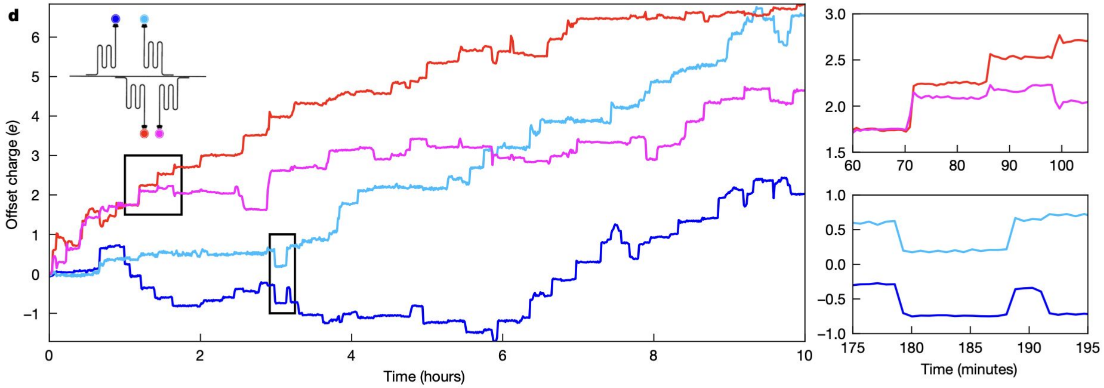
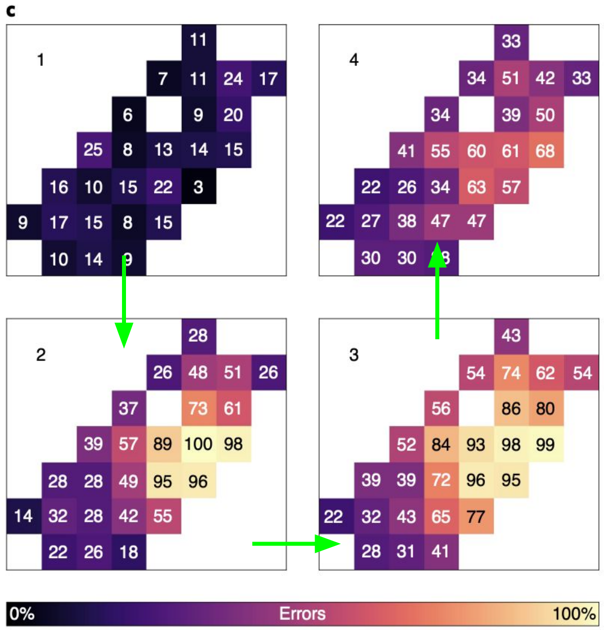
Radiation Impact on Superconducting Qubits

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]



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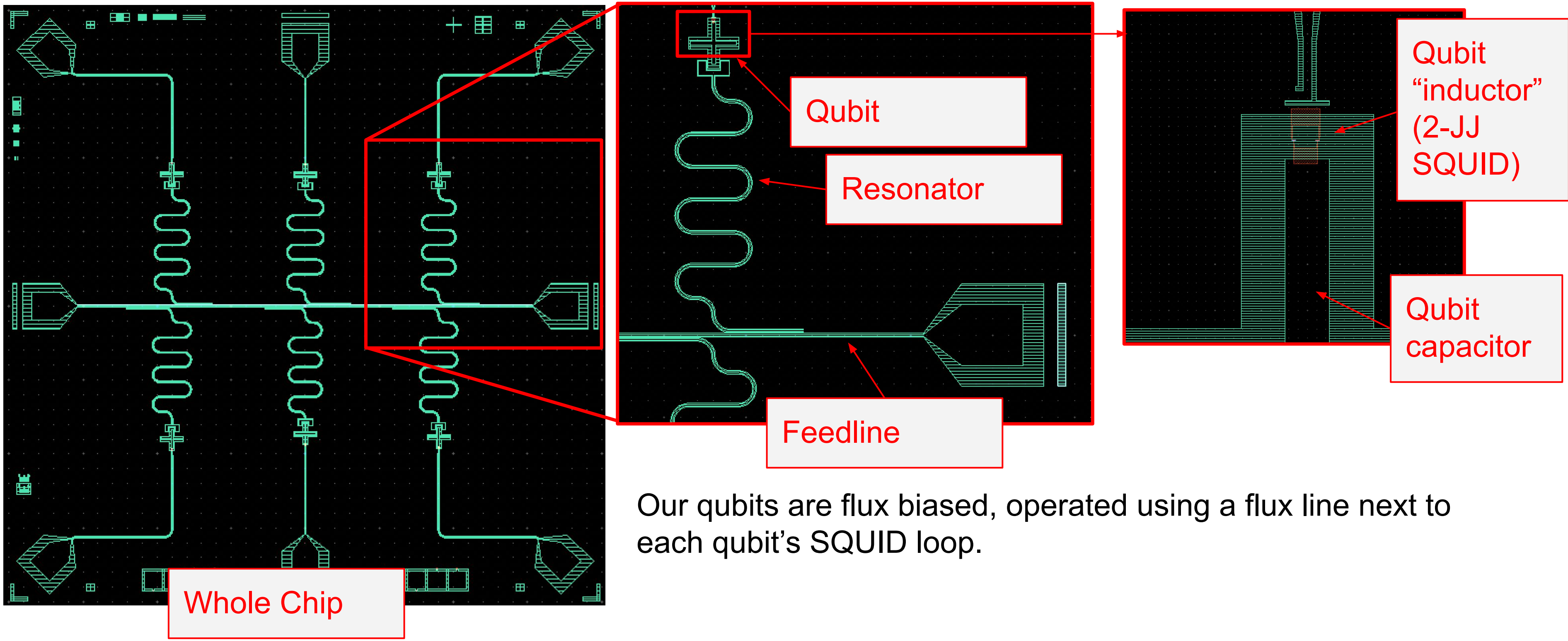
Device Design/Operation

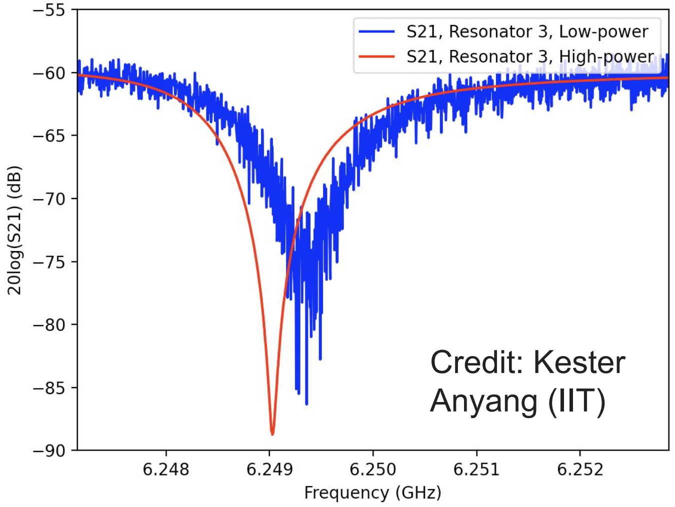
Qubits read out using coplanar waveguide resonators coupled to a shared RF feedline.



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

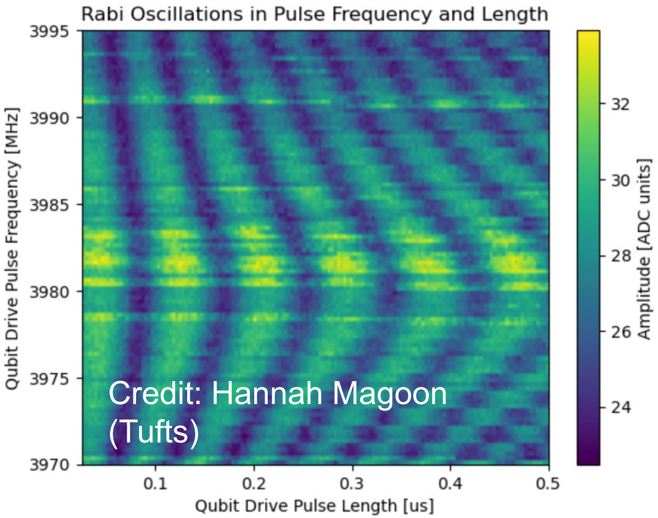
Qubit Bring-Up Tests

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



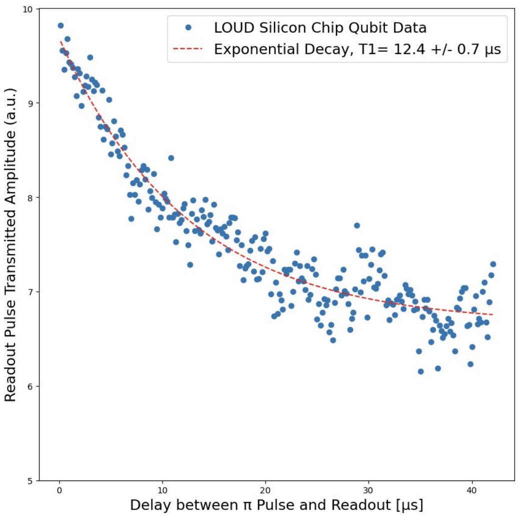
Purpose: determine that the qubit (i.e. the Josephson Junction) is “alive”, i.e. not burned out

Qubit spectroscopy + Rabi Oscillations



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

T1 Relaxation Time



Purpose: Probe qubit decoherence times

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