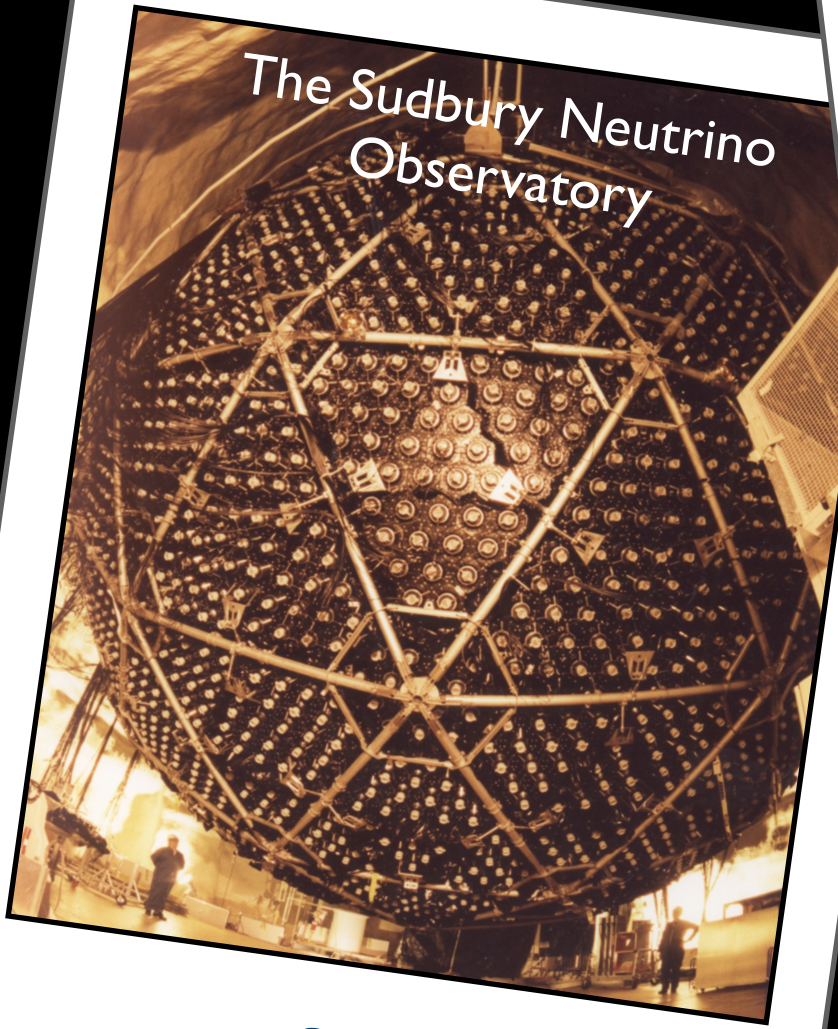
Quantum Computing Underground (?)

Joseph Formaggio

Massachusetts Institute of Technology

My day job…



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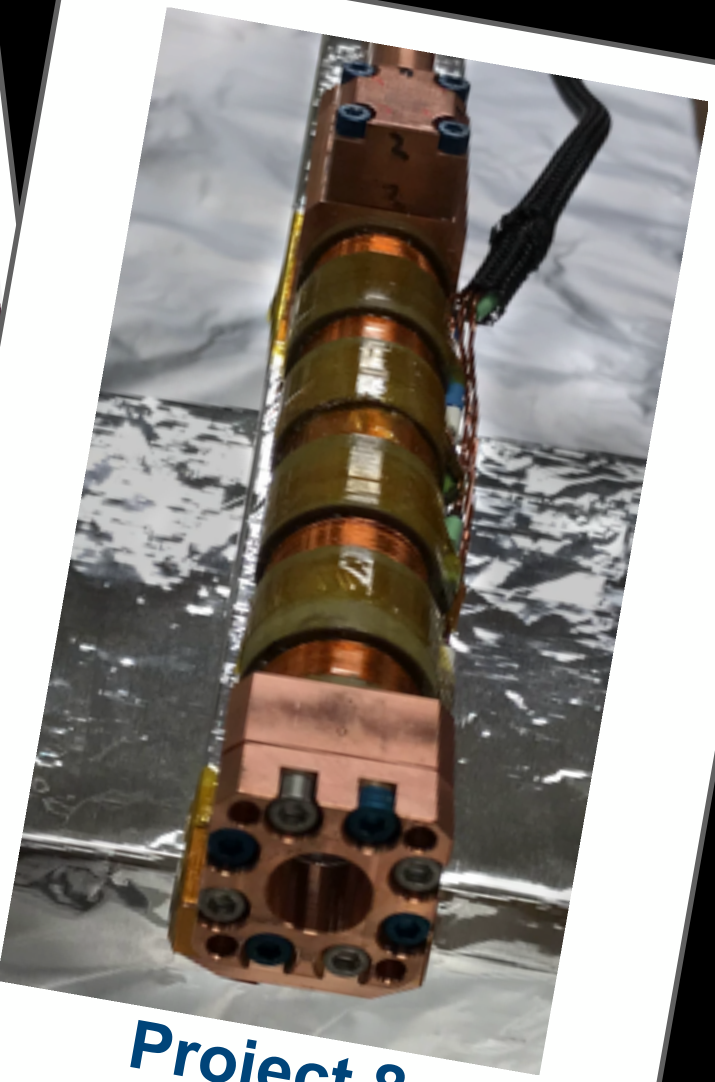
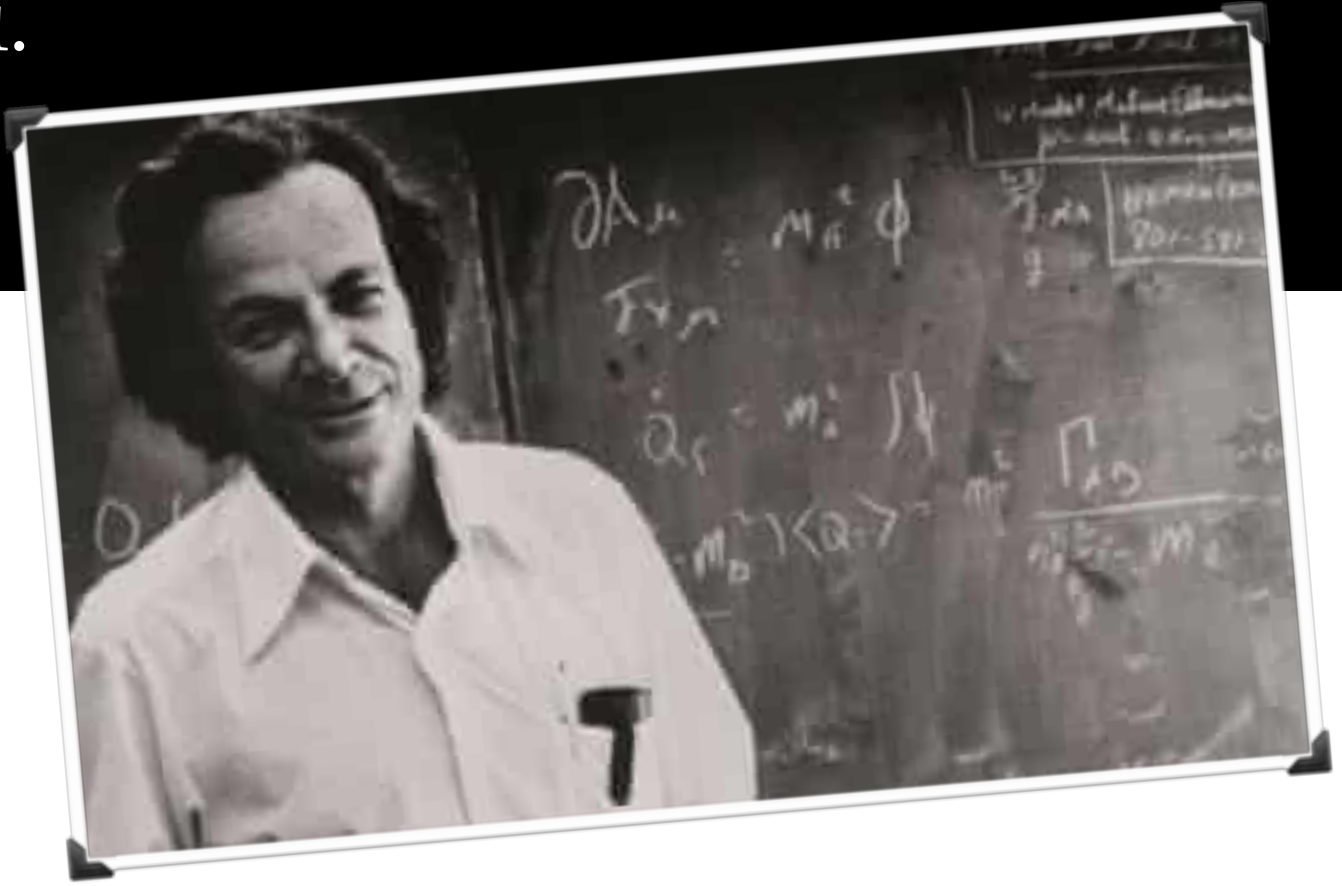


Project 8

…which I will not even mention for today.

"... trying to find a computer simulation of physics seems to me to be an excellent program to follow out. ... the real use of it would be with quantum mechanics. ... Nature isn't classical ... and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

—Richard Feynman, Keynote address at the MIT Physics of Computation Conference, 1981.



Quantum computing holds great promise for solving some (but not all!) difficult problems; particularly in quantum **chemistry**, **physics**, and **mathematics**.

> *“. . . trying to find a computer simulation of physics seems to me to be an excellent program to follow out. . . . the real use of it would be with quantum mechanics. . . . Nature isn’t classical . . . and if you want to make a simulation of Nature, you’d better make it quantum mechanical, and by golly it’s a wonderful problem, because it doesn’t look so easy.”*
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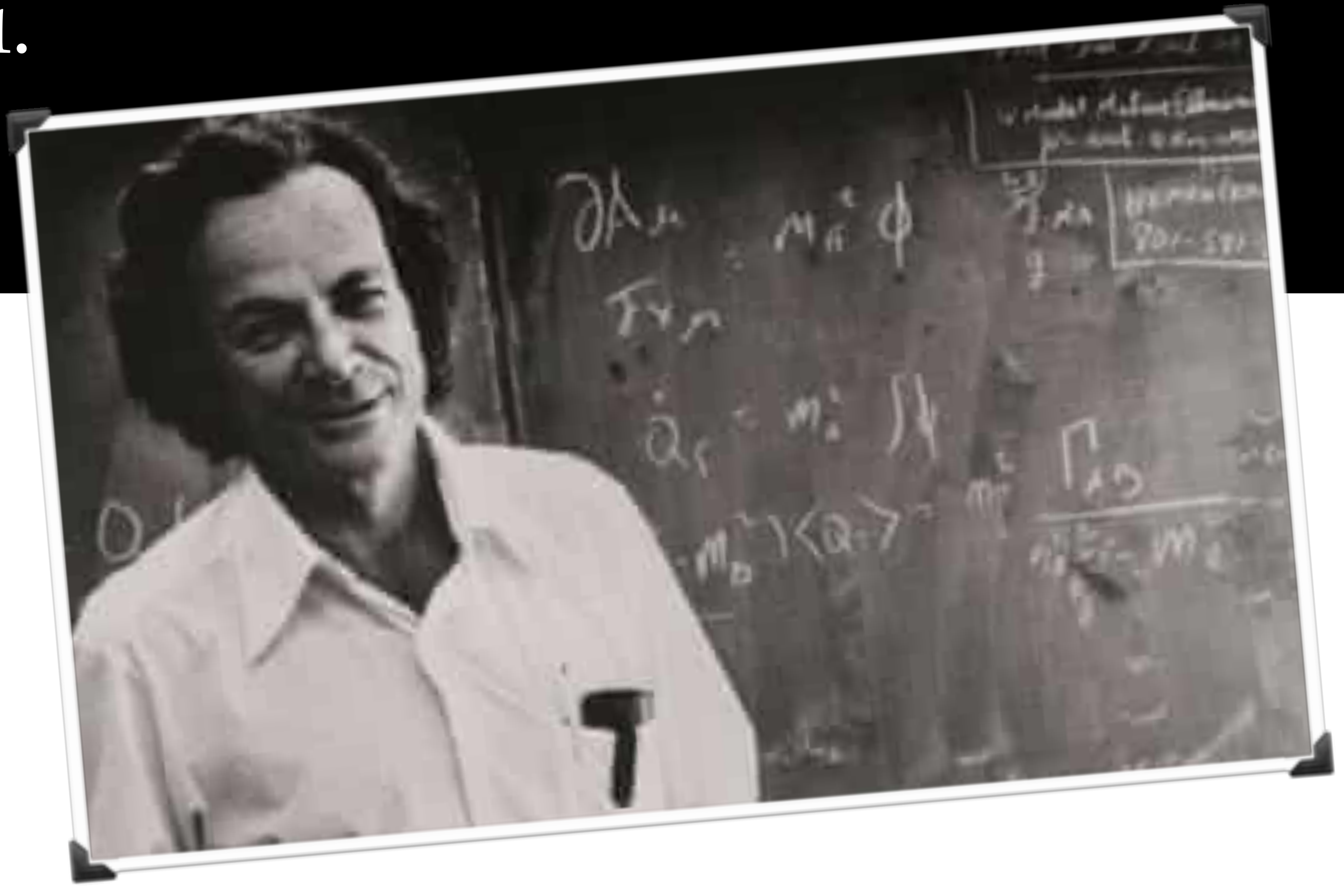
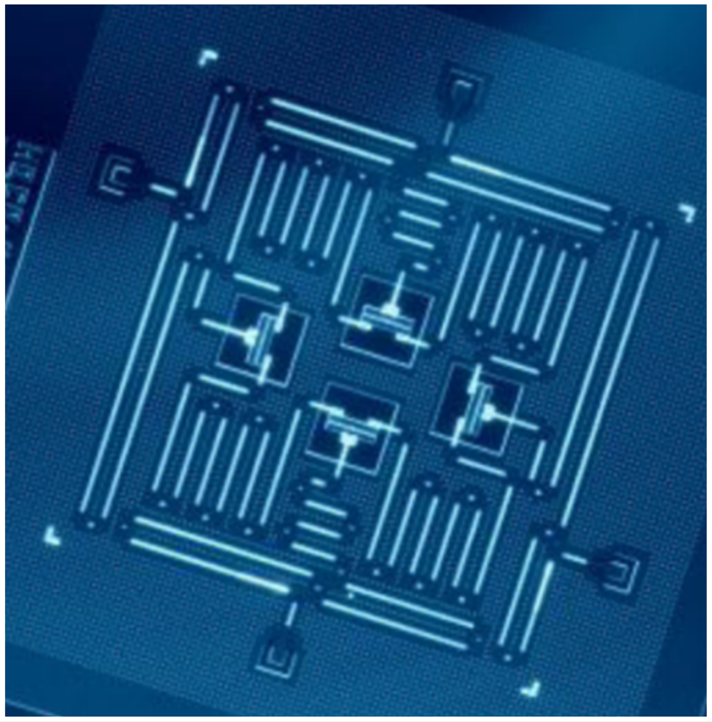
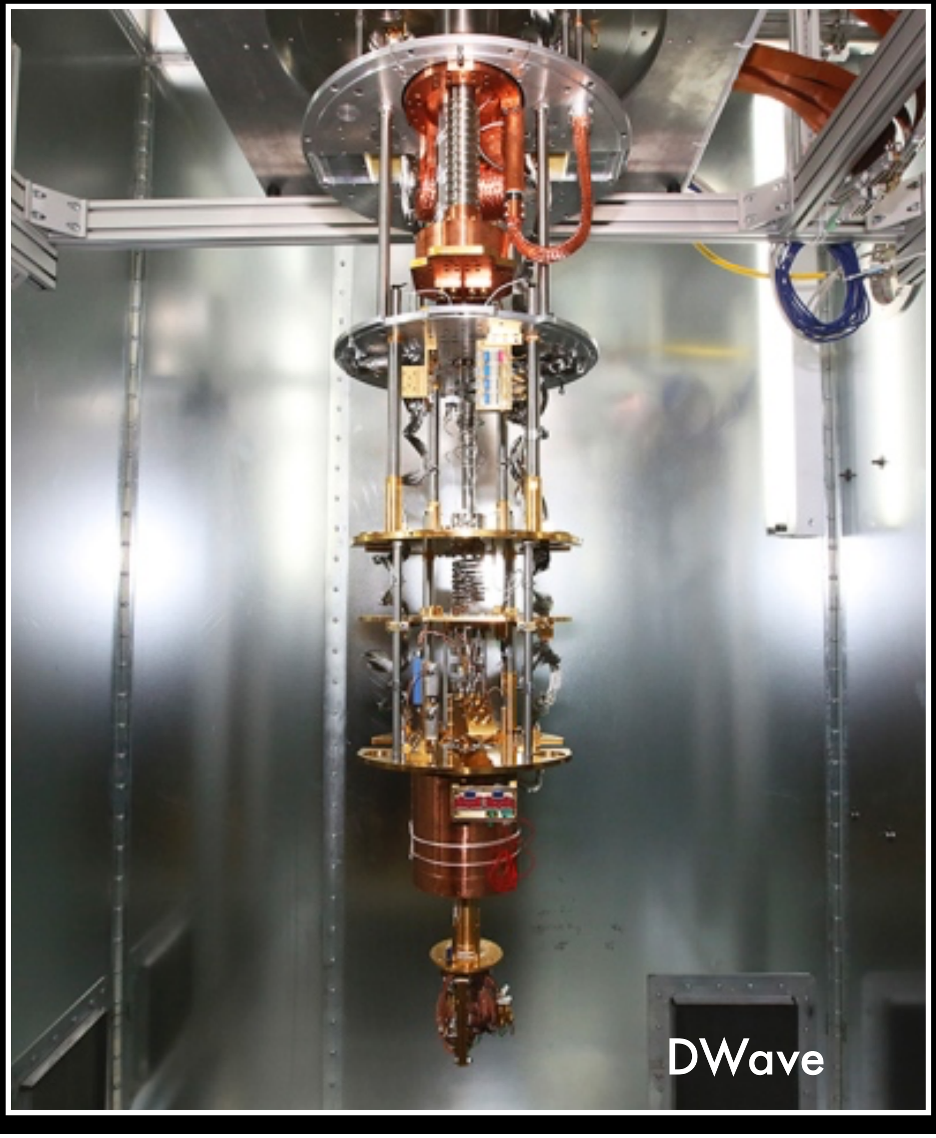


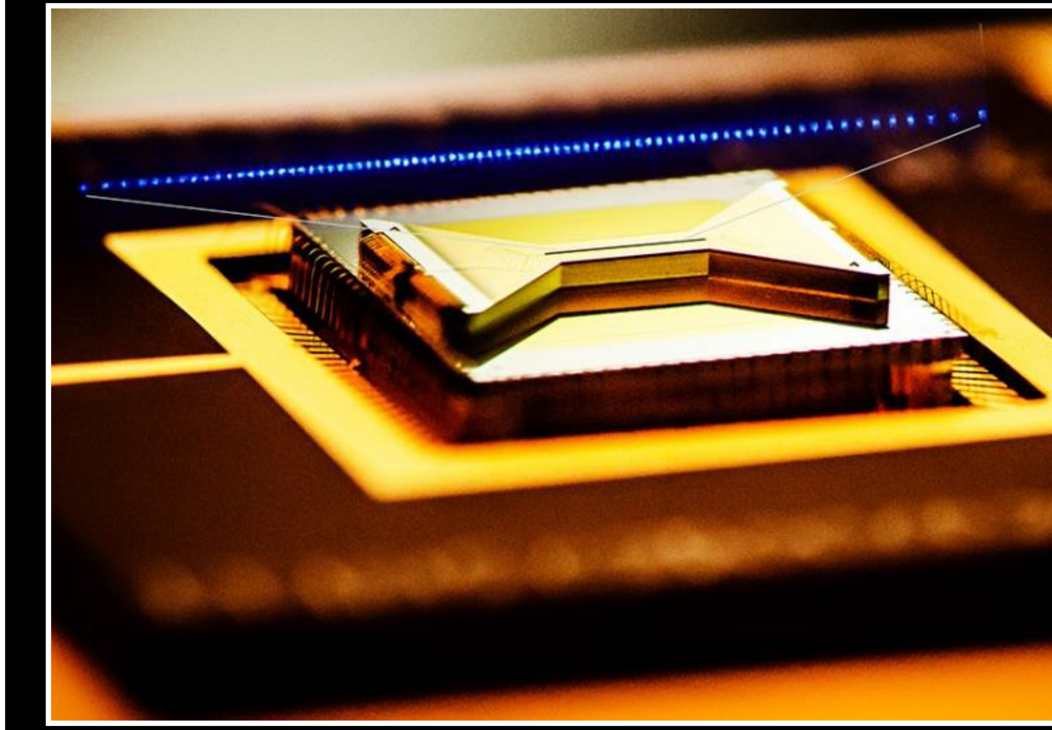
Quantum computers offer the possibility of utilizing **superposition** and **entanglement** to carryout certain otherwise difficult computations.



superconducting qubits



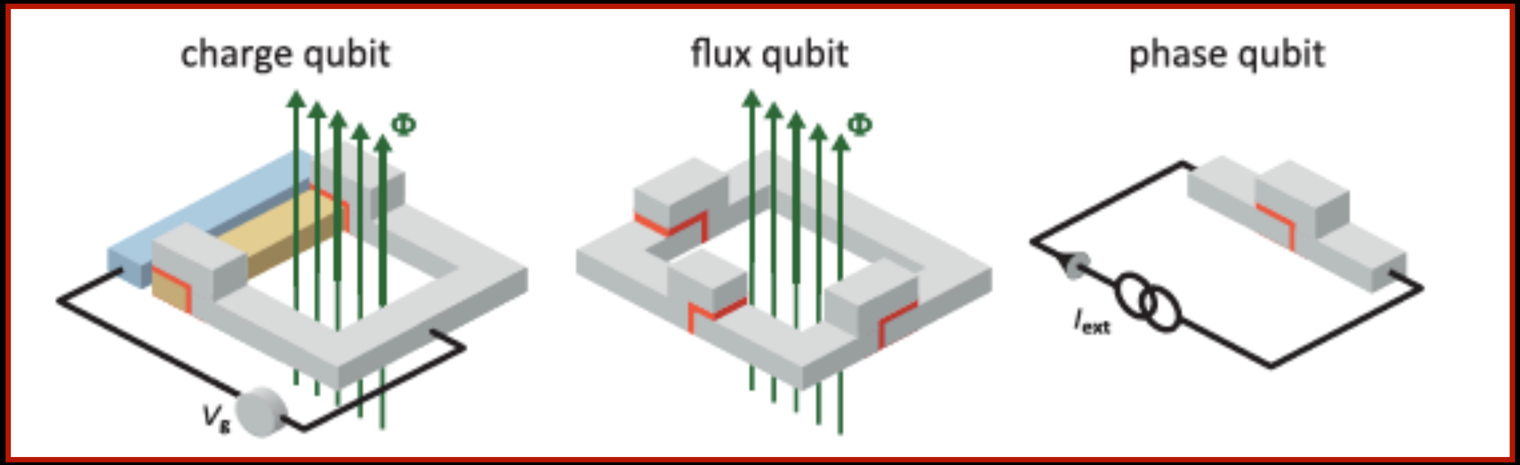
DWave

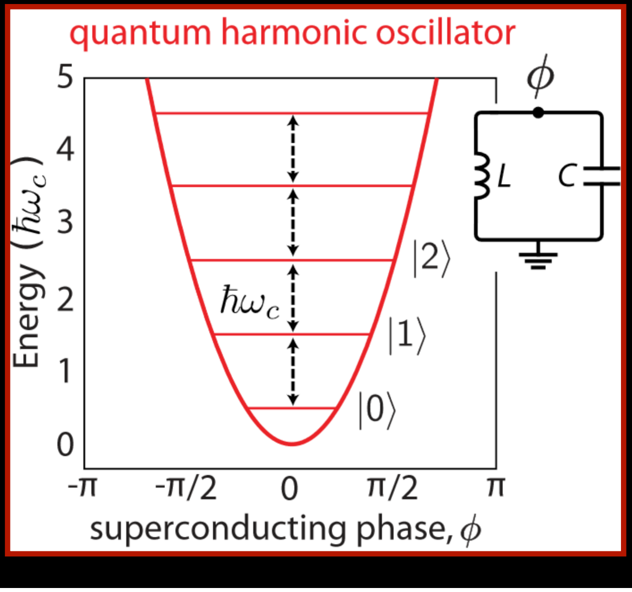


ion traps

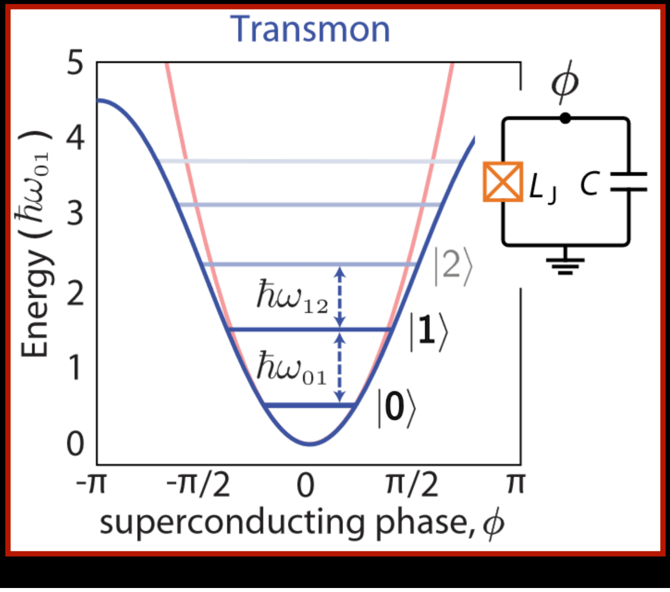
Over the past several decades, remarkable strides have been made in developing *scalable* quantum systems.

Today's discussion will focus mainly on semi- and super- conducting qubits, though other technologies (e.g. ion traps) are also being pushed forward.





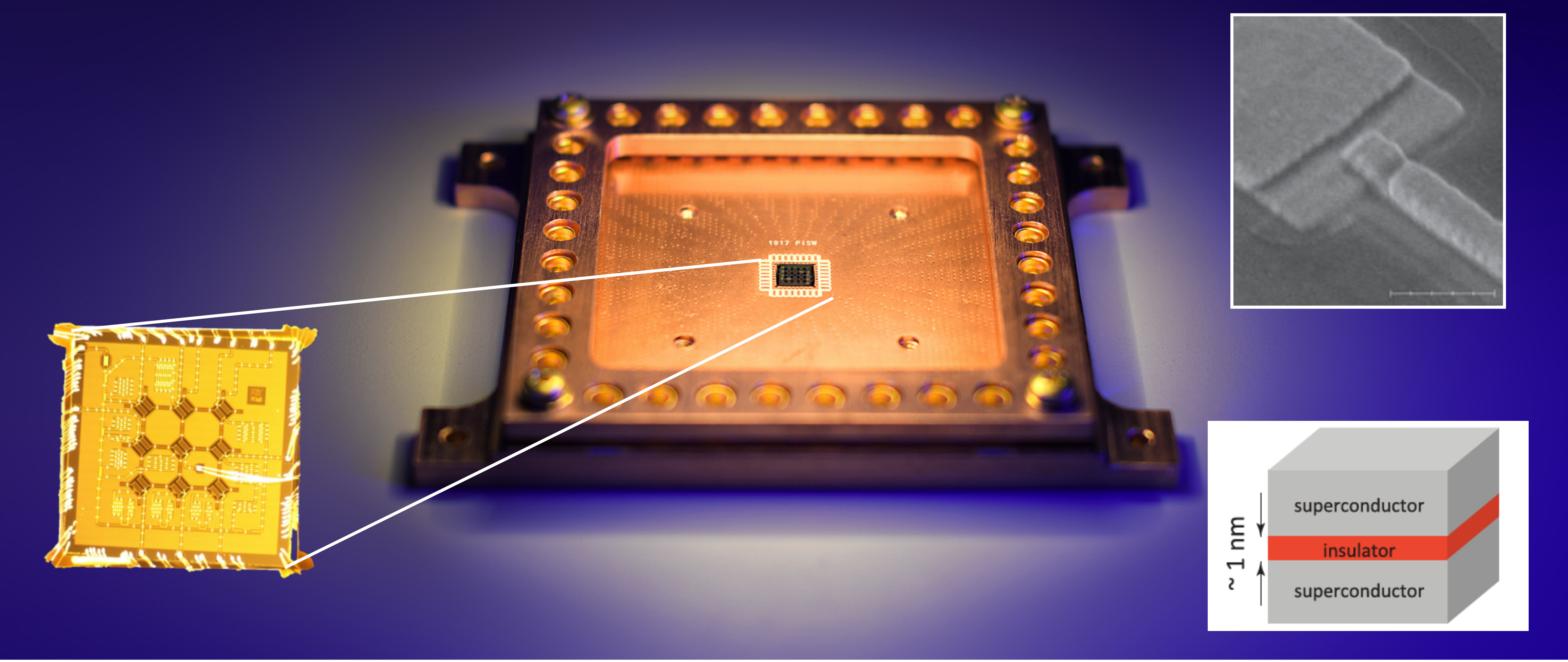
$$L_J = \frac{\Phi_0}{2\pi I_c \cos\phi}$$



The insertion of a superconducting Josephson junction (non-linear) allows a quantum harmonic oscillator (degenerate) to behave as an anharmonic oscillator.

Quantum "bits" now uniquely addressable, since each level has a unique energy (microwave frequency).

Two important metrics in quantum computing include *fidelity* and coherence times.



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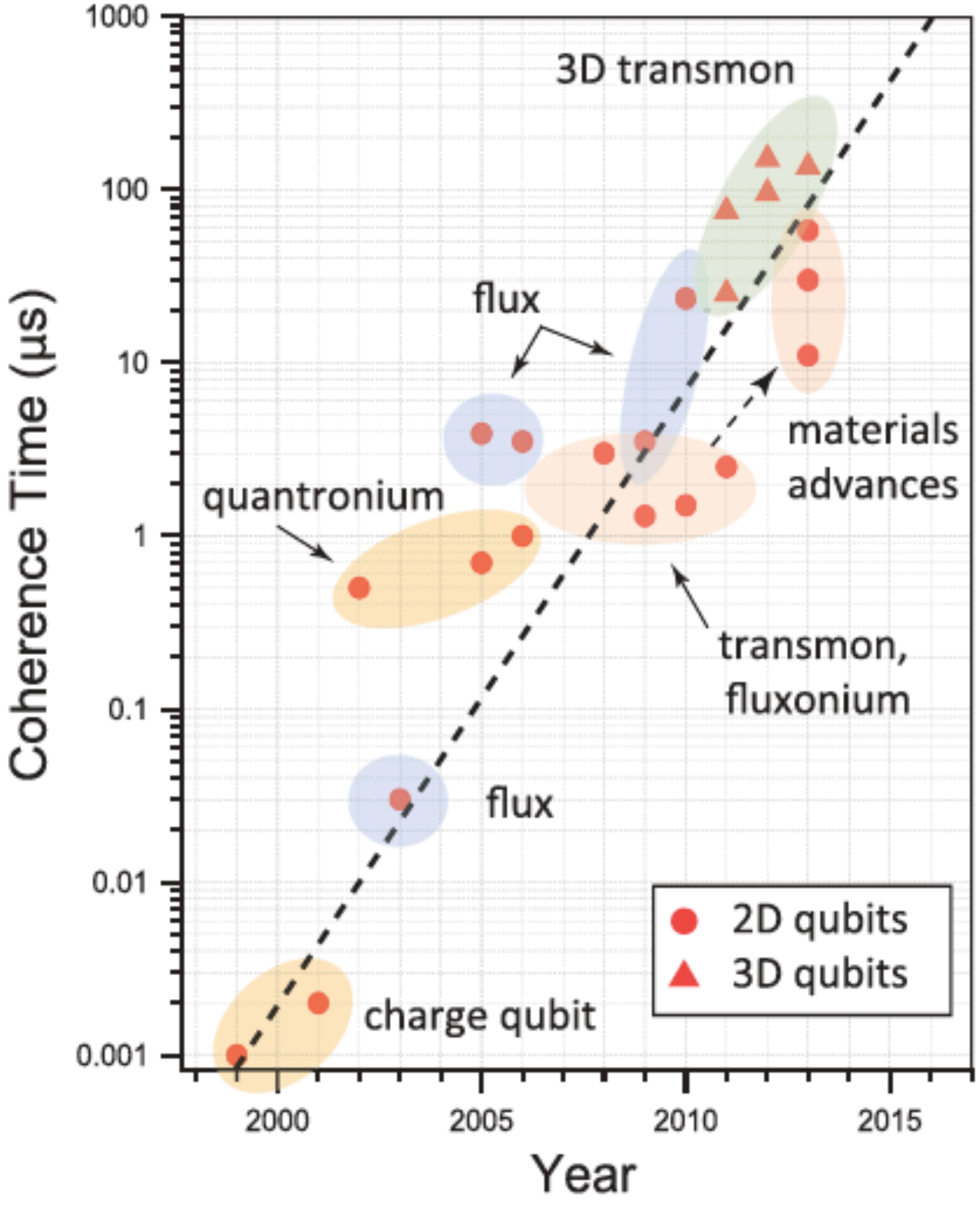


Moore's Law for qubits
(already outdated..)

Just in the past 20 years, there has been amazing progress in increasing the coherence times of superconducting qubits

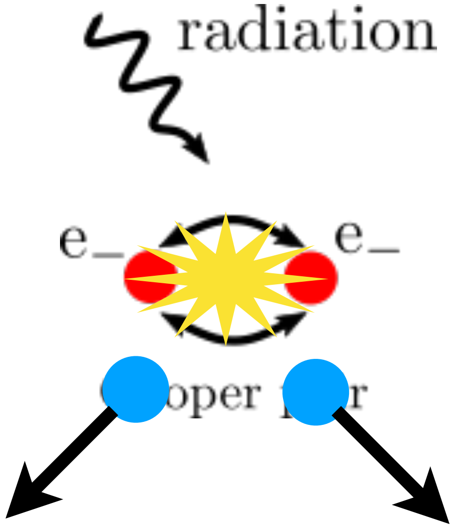
(from nanoseconds to hundred of microseconds)

However, these coherence times still fall far short from theoretical projections based superconductors at thermal equilibrium.

Problem seems common regardless of lab, type of readout configuration, etc.

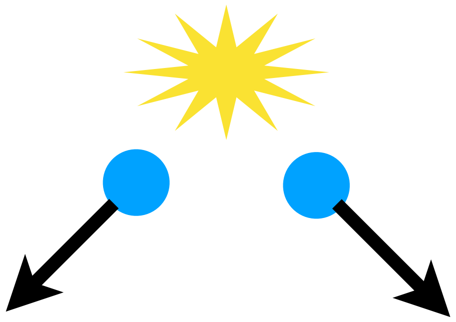
What is the impact of background radiation on coherence times?

Relaxation Mechanisms



Broken Cooper pair

Relaxation Mechanisms



Broken Cooper pair

Quasiparticles (broken Cooper pairs / free electrons) decohere (poison) superconducting qubits.

In transmons, this manifests as an energy relaxation ($\Gamma_1 = 1/T_1$).

This decoherence time is proportional to the density of quasi-particles.

$$\Gamma_q = \sqrt{2\omega_{01}\Delta/\pi^2\hbar}\; x_{qp} + \Gamma_{\text{other}}$$

ω_{01} = qubit frequency

Δ = s.c. gap

$x_{qp} = n_{qp}/n_{cp}$ =quasi-particle fraction

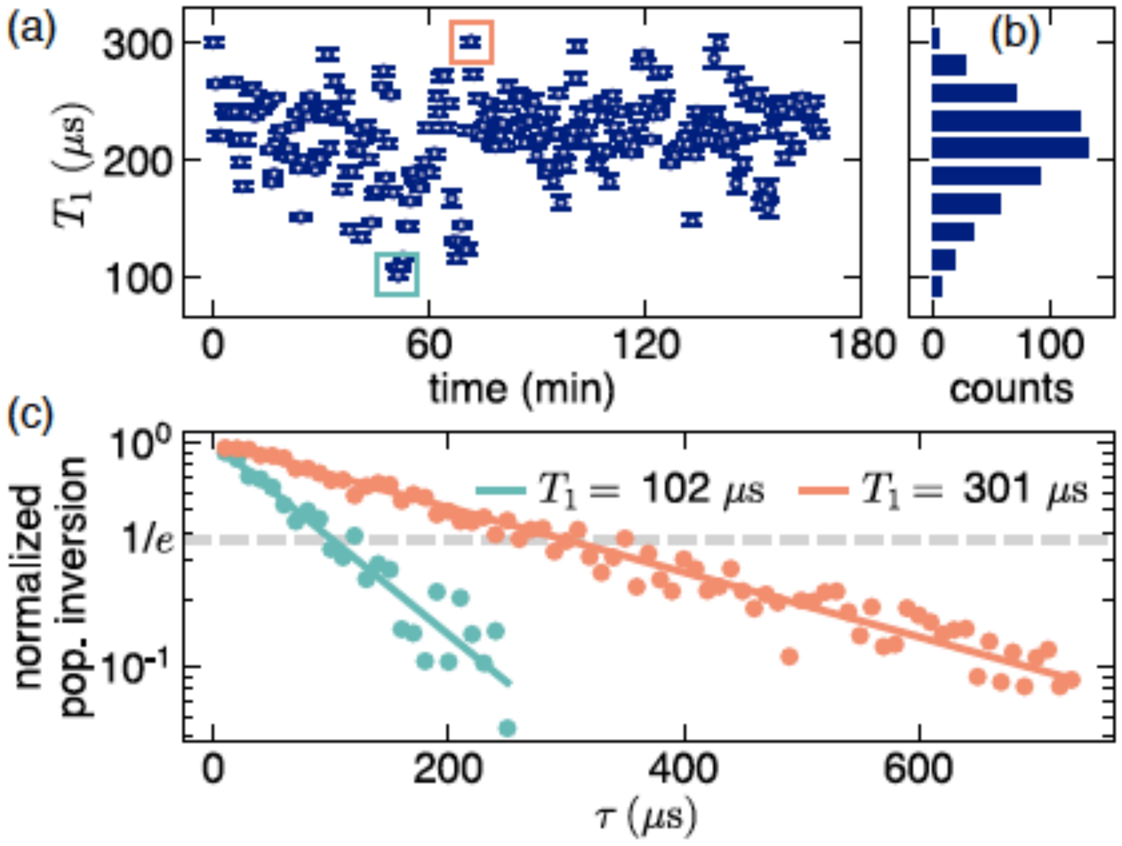
Potential Radioactive Sources

(1) Infrared Photons

This is a known source of decoherence. Recently shown that can be suppressed by using high frequency filters.

Coherence times seen to increase up to 100-300 μs.

(Also note variability in coherence times)

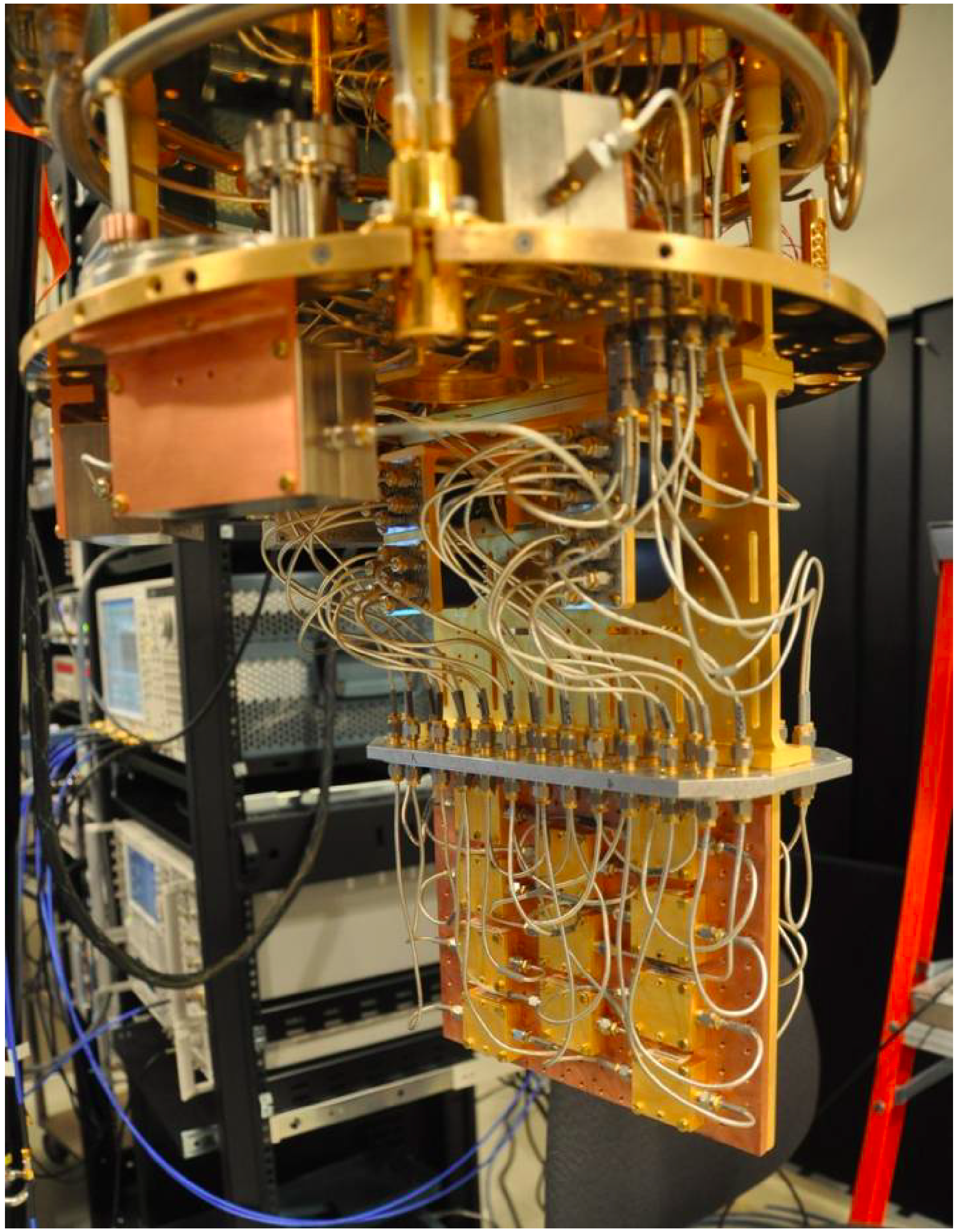


Direct Dispersive Monitoring of Charge Parity in Offset-Charge-Sensitive Transmons

K. Serniak,* S. Diamond, M. Hays, V. Fatemi, S. Shankar, L. Frunzio, R. J. Schoelkopf, and M. H. Devoret†

Department of Applied Physics, Yale University, New Haven, CT 06520, USA

Potential Radioactive Sources



(2) Environmental Gammas

Primary culprits:

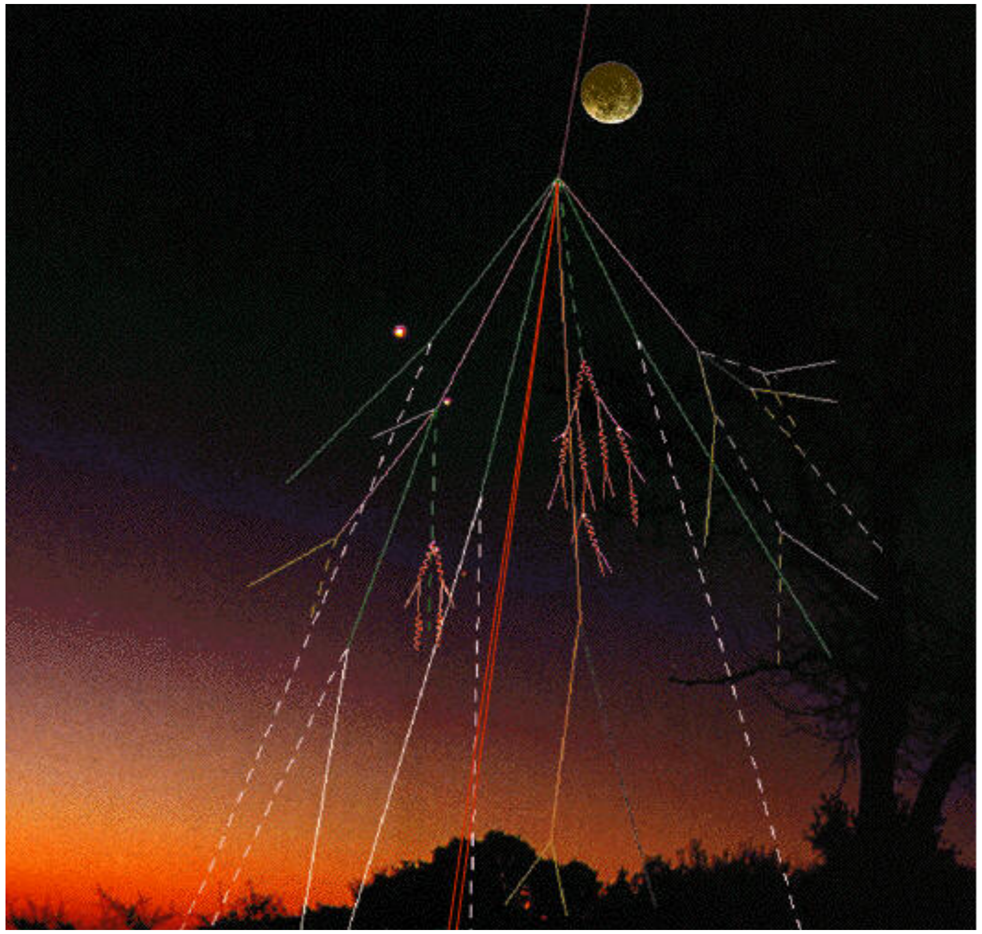
- Room contamination (concrete)
- Contamination from dilution fridge
- Impurities in qubit/package

Qubit materials typically very high purity/low contamination (Si, Al)

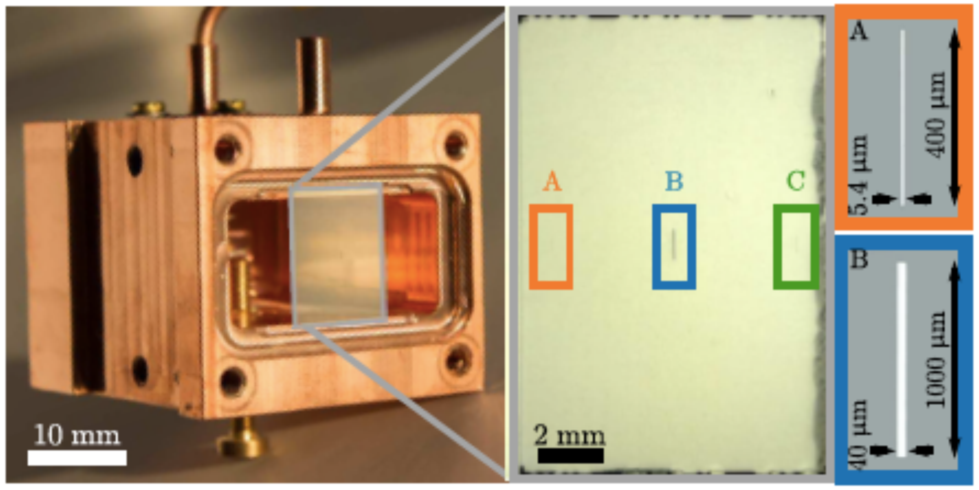
Main sources of gamma background radioactivity stem from **concrete** surrounding all qubit experiments.

Potential
Radioactive Sources

(3) Cosmic rays



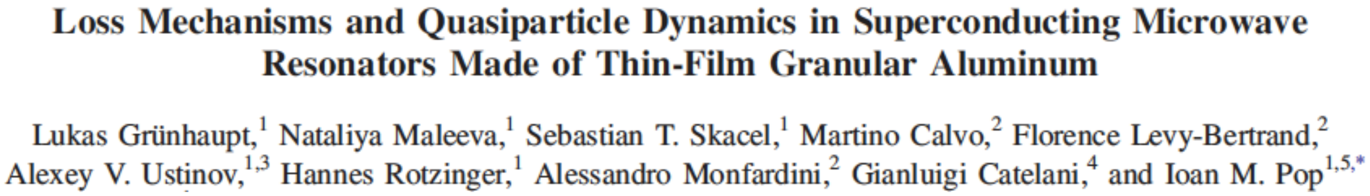
Highly penetrating and high energy deposition from ionization.



Cosmic rays are speculated to be the source of reduced Q in granular aluminum resonators.

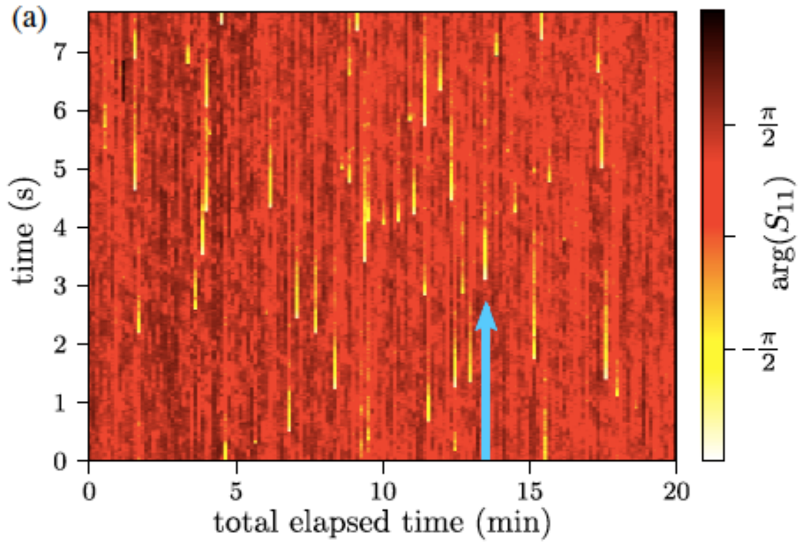
Difficult to shield (without going underground).

Fortunately, typically less impact than environmental U/Th contamination.

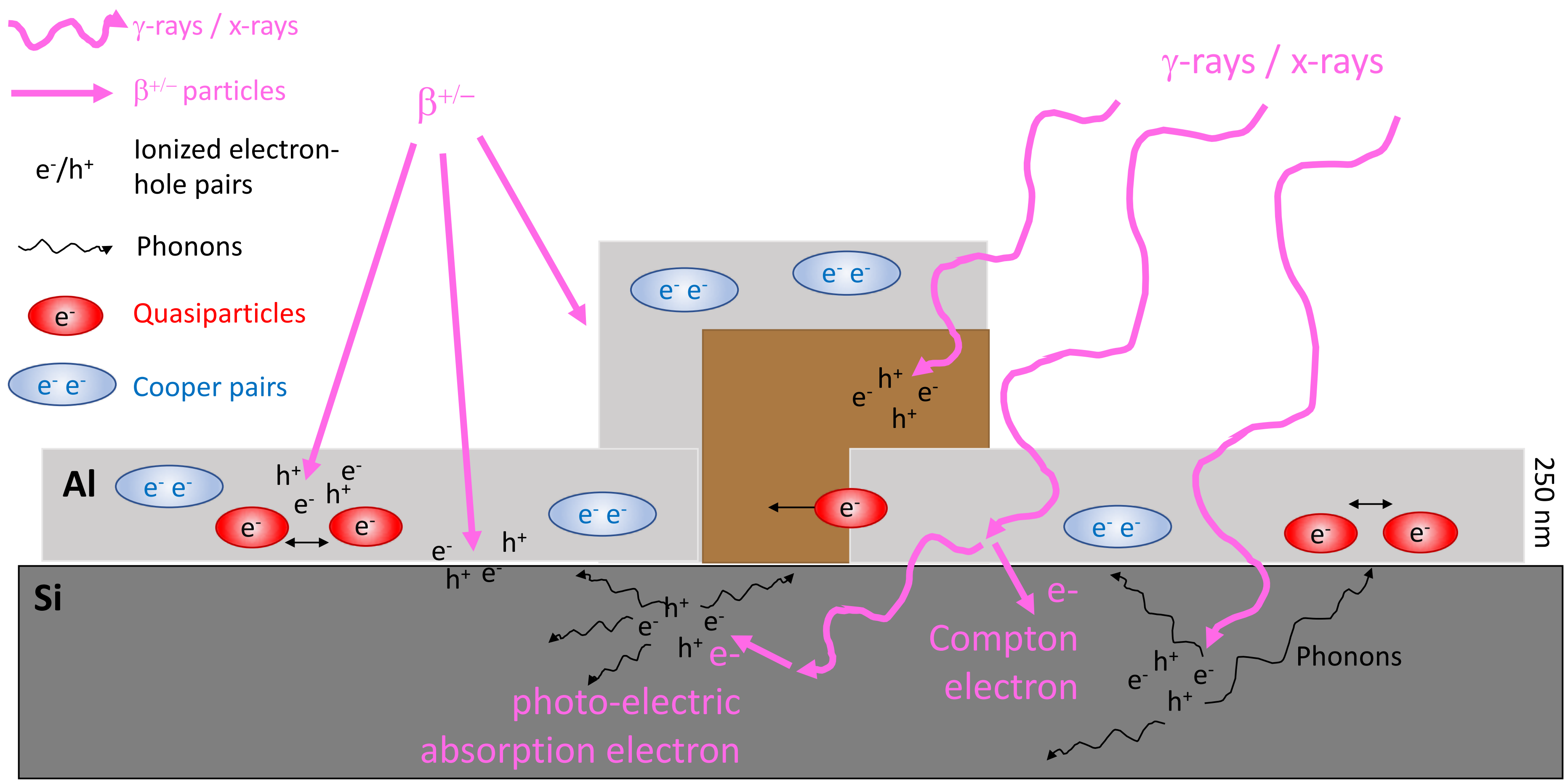


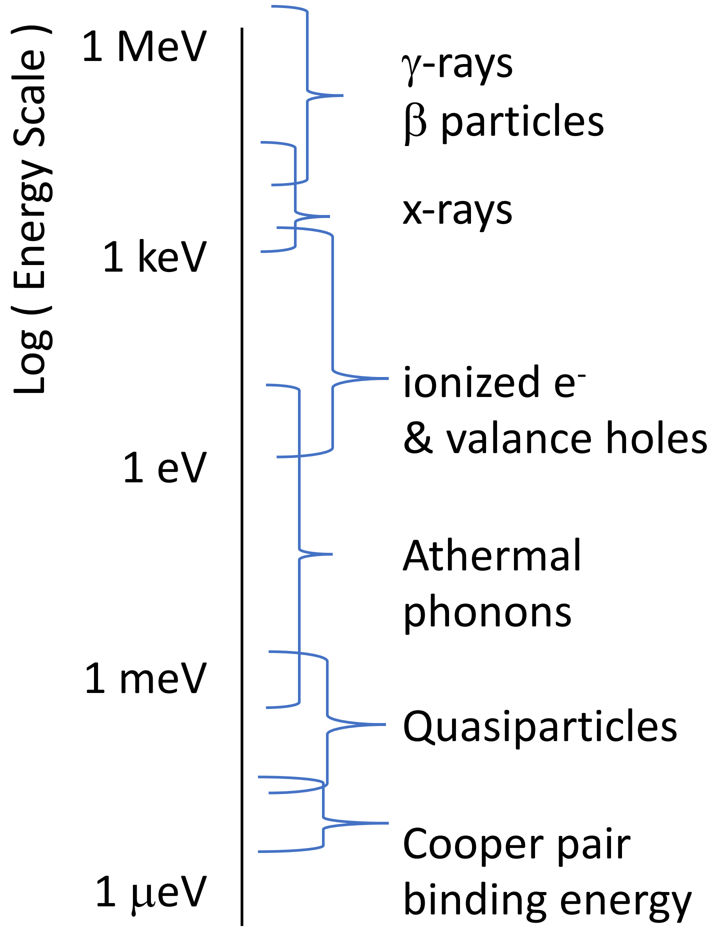
Loss Mechanisms and Quasiparticle Dynamics in Superconducting Microwave Resonators Made of Thin-Film Granular Aluminum

Lukas Grünhaupt,[1] Nataliya Maleeva,[1] Sebastian T. Skacel,[1] Martino Calvo,[2] Florence Levy-Bertrand,[2] Alexey V. Ustinov,[1,3] Hannes Rotzinger,[1] Alessandro Monfardini,[2] Gianluigi Catelani,[4] and Ioan M. Pop[1,5,*]



Hypothesis

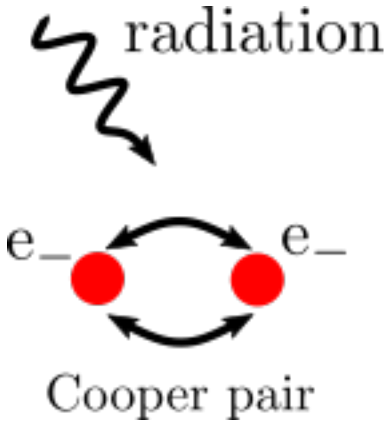




Ionization electrons/gamams (keV-scale) eventually cascade down to phonons (sub-eV scale) which eventually lead to break-up of Cooper pairs and decoherence.

It is of course expected that radiation would impact coherence, but at what level?

Quasi-particle Dynamics



Equilibrium quasiparticles at 40 mK: $x_{qp} \approx 10^{-24}$

Observed quasiparticle densitiesL $x_{qp} \approx 10^{-9} - 10^{-6}$

Quasiparticles are:

- generated by radiation power density (P)
- Annihilated by recombination (r)
- **η**= radiation power to generation rate conversion

Dynamics

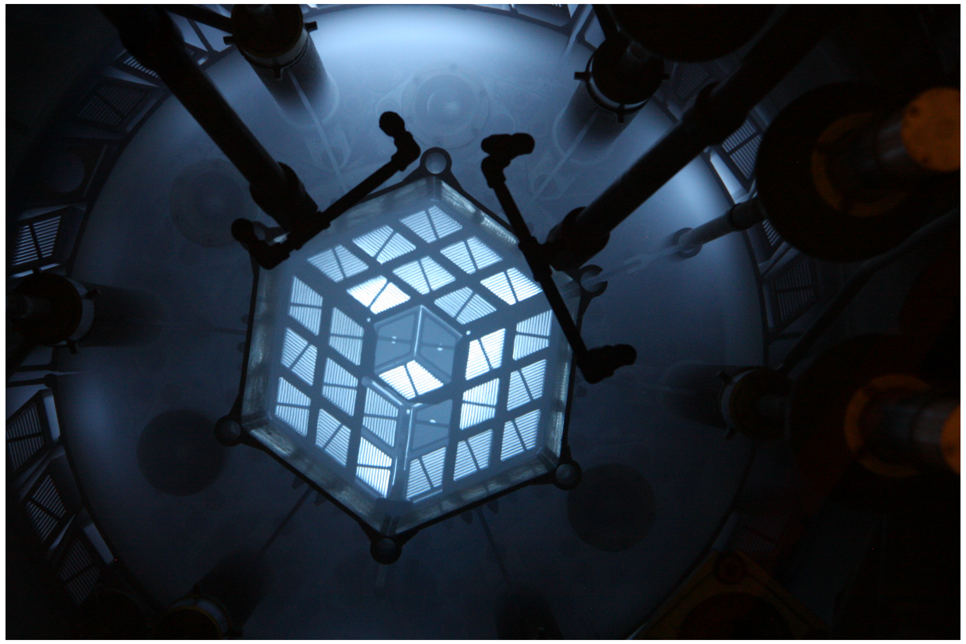
$$\dot{x}_{qp} = \eta P - r x_{qp}^2$$

Steady-state

$$x_{qp} = \sqrt{\eta P / r}$$

$$\Gamma_1 = k\sqrt{P} + \Gamma_{\text{other}}$$

Calibrating Coherence Time with Sources



We need a source that can survive the cool down process with O(1 day) half-life.

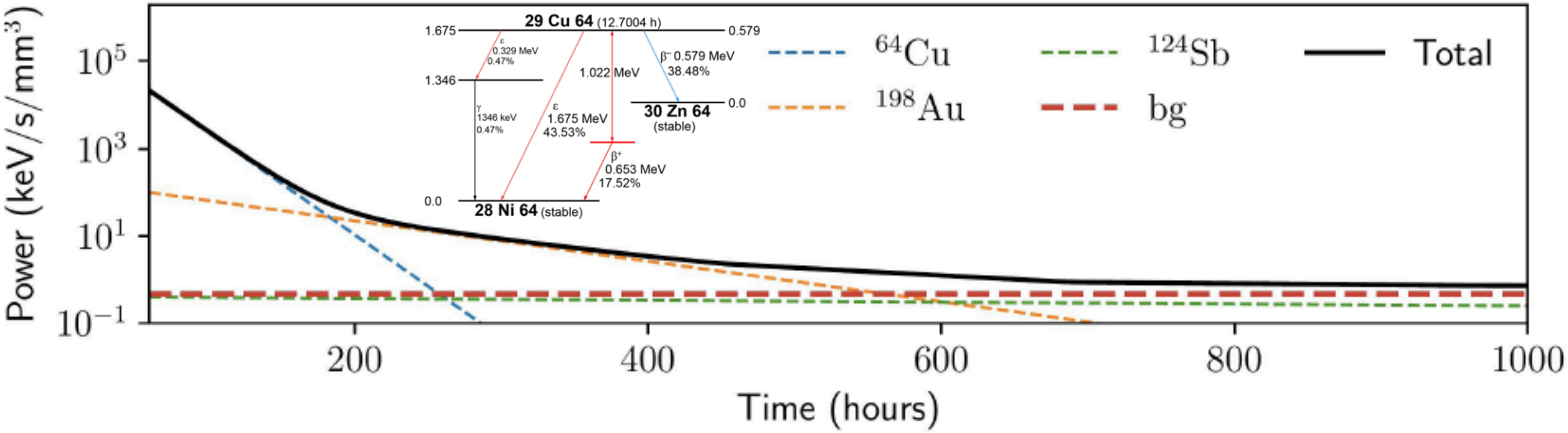
Copper-64 proved to be ideal.

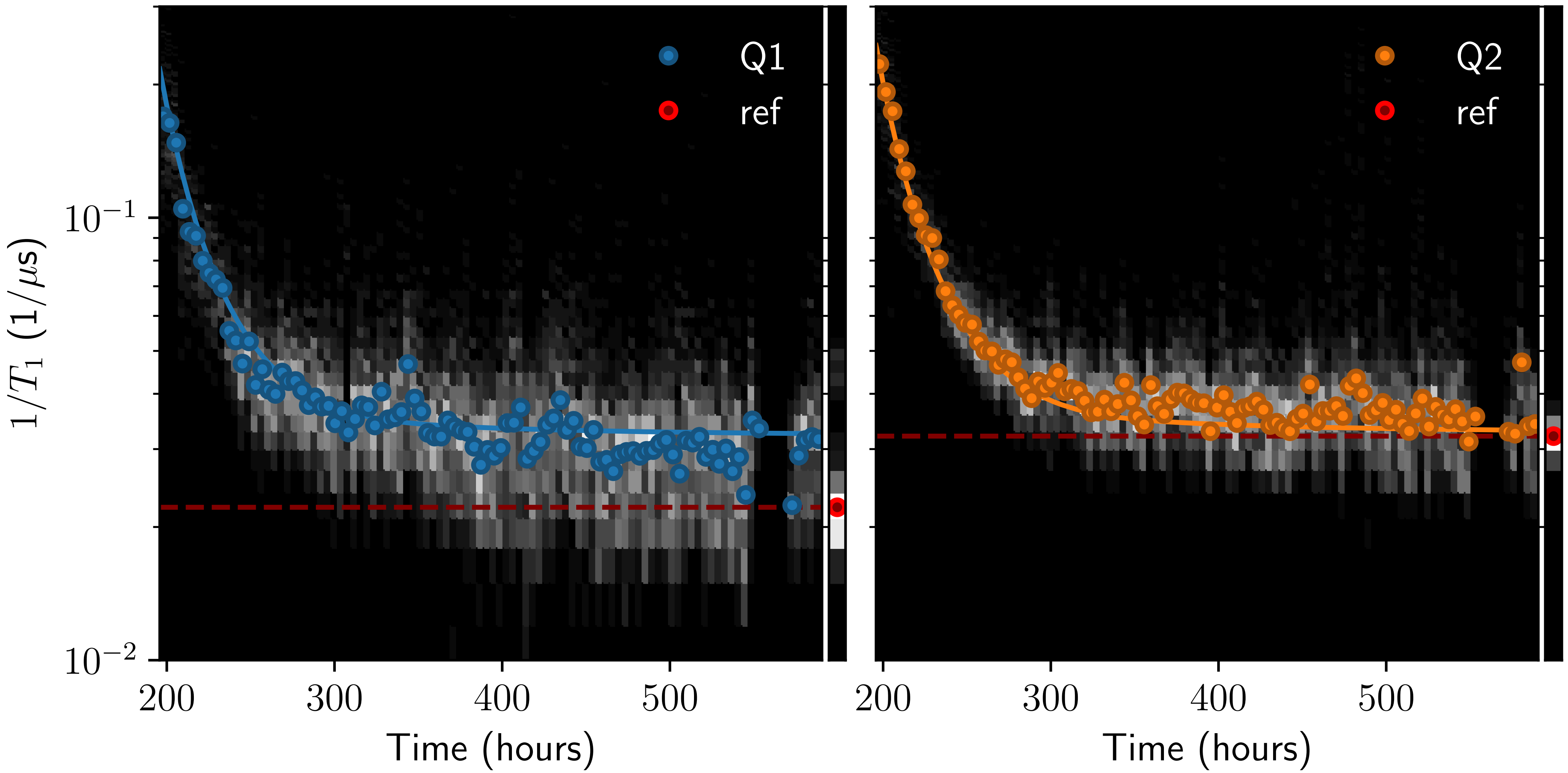
^{64}Cu Run

– 12.7 h half-life.

– Beta/gamma source (beta dominated)

– From irradiation at MIT's research reactor, 168 µCi created (small ^{198}Au contamination)



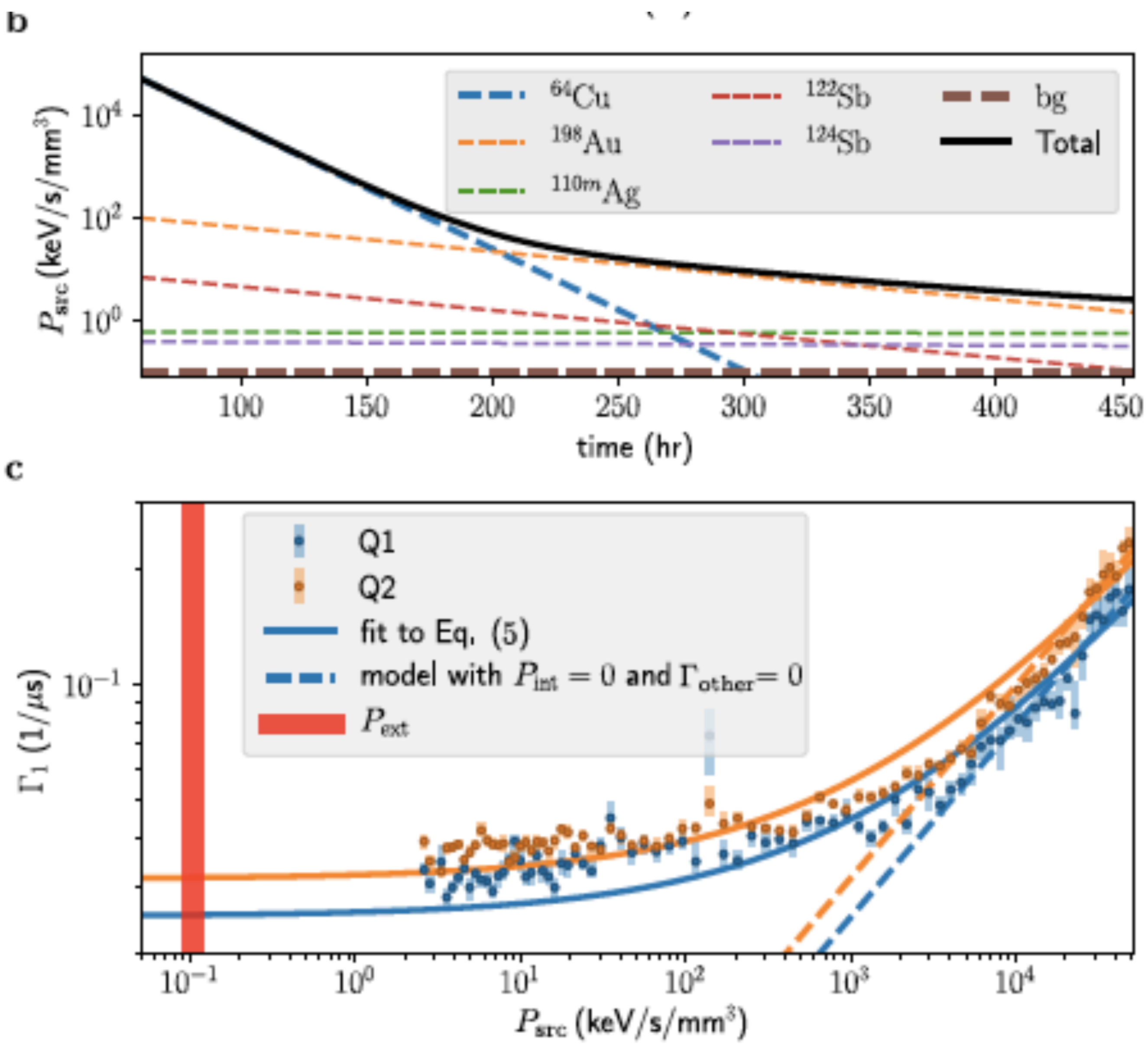


$$\Gamma_1 \equiv \frac{1}{T_1} = \sqrt{2\omega_{01}\Delta/\pi^2\hbar}\, x_{qp} + \frac{1}{T_{\mathrm{ex}}}$$

Over 19,000 data points collected over 4 weeks.

Coherence times also show exponential evolution.

How does the quasi-particle population (**x_{qp}**) evolve with time (power density)?



$$\Gamma_1 = k\sqrt{P} + \Gamma_{\rm other}$$

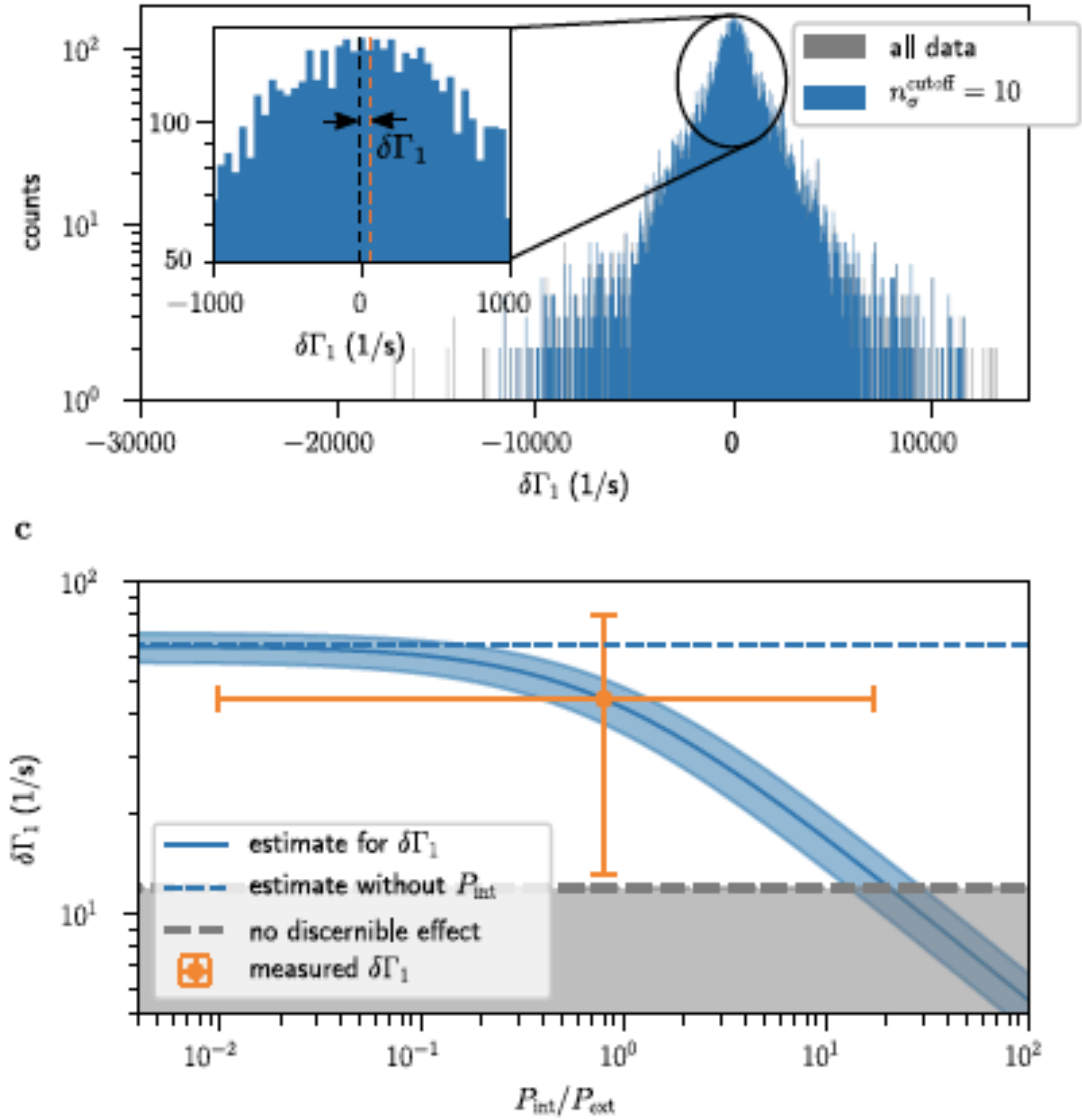
$$k \simeq 800\sqrt{\,{\rm mm}^3/({\rm keV\ s})}$$

$$P_{\rm ext} = 0.1\frac{\rm keV}{\rm s}/\ {\rm mm}^3$$

$\Gamma_1 \simeq 1/(4\ {\rm ms})$ **or** $x_{\rm qp} \simeq 7 \times 10^{-9}$

Extracted quasi-particle density consistent with measurements from other groups

Impact of Shielding



Nature
volume 584, 551–556 (2020)

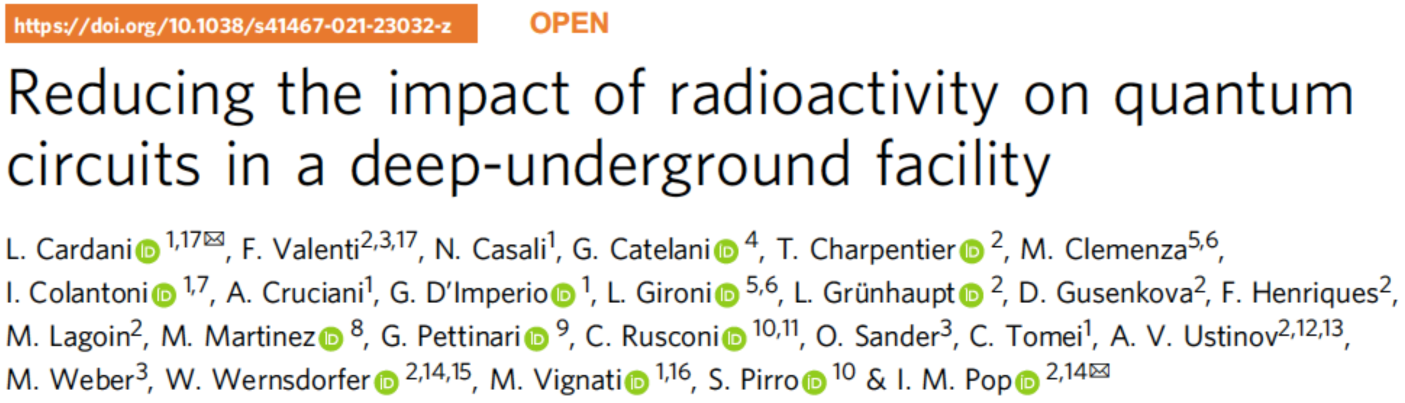
With the help of the ^{64}Cu data, we now have a **calibration** of the impact ionizing radiation can have on the qubit coherence time.

If radioactivity is *removed,* we should start to see improved coherence times.

Measured T_1 shift of 22 ms agrees well with 15 ms prediction from ^{64}Cu

Limits T_1 of our transmons to ≈ 4 ms (if left unshielded)

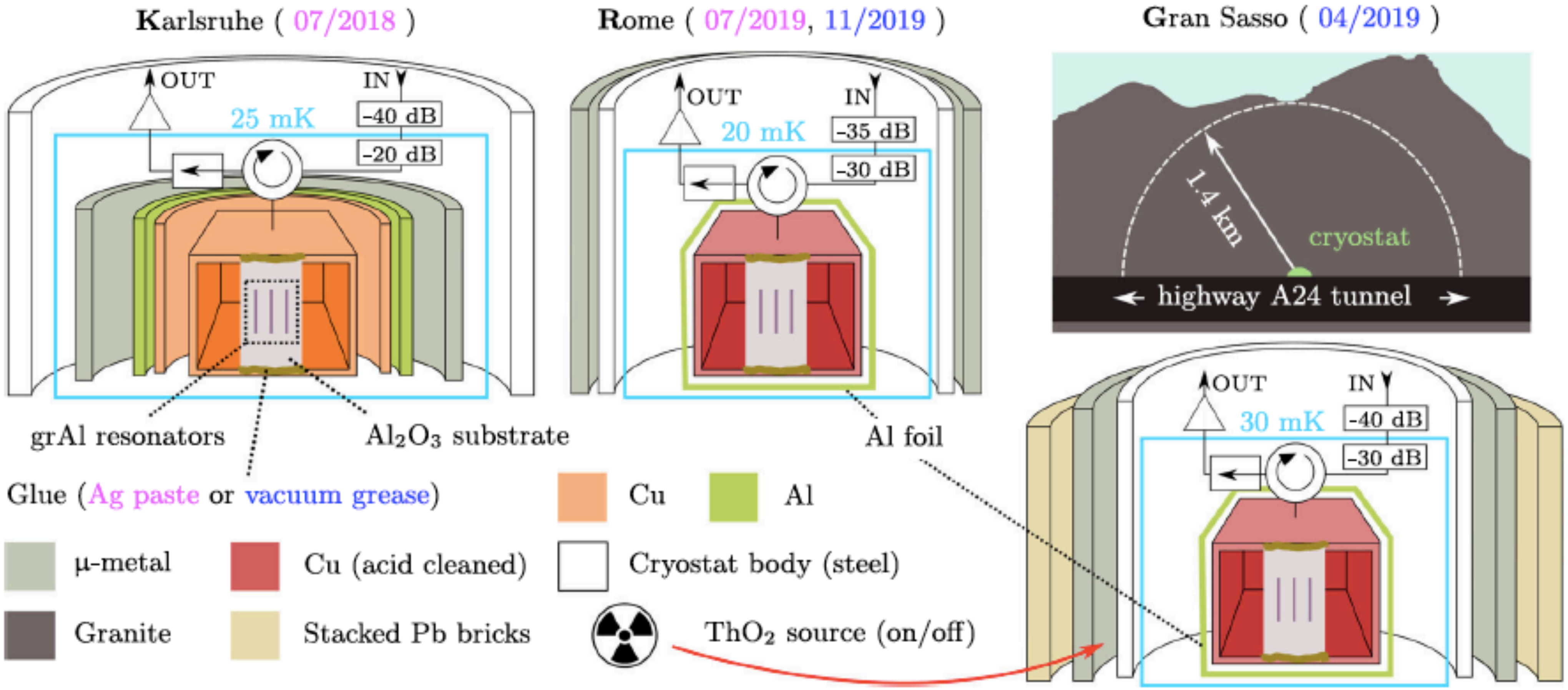
Underground Shielding



https://doi.org/10.1038/s41467-021-23032-z OPEN

Reducing the impact of radioactivity on quantum circuits in a deep-underground facility

L. Cardani[1,17✉], F. Valenti[2,3,17], N. Casali[1], G. Catelani[4], T. Charpentier[2], M. Clemenza[5,6], I. Colantoni[1,7], A. Cruciani[1], G. D'Imperio[1], L. Gironi[5,6], L. Grünhaupt[2], D. Gusenkova[2], F. Henriques[2], M. Lagoin[2], M. Martinez[8], G. Pettinari[9], C. Rusconi[10,11], O. Sander[3], C. Tomei[1], A. V. Ustinov[2,12,13], M. Weber[3], W. Wernsdorfer[2,14,15], M. Vignati[1,16], S. Pirro[10] & I. M. Pop[2,14✉]

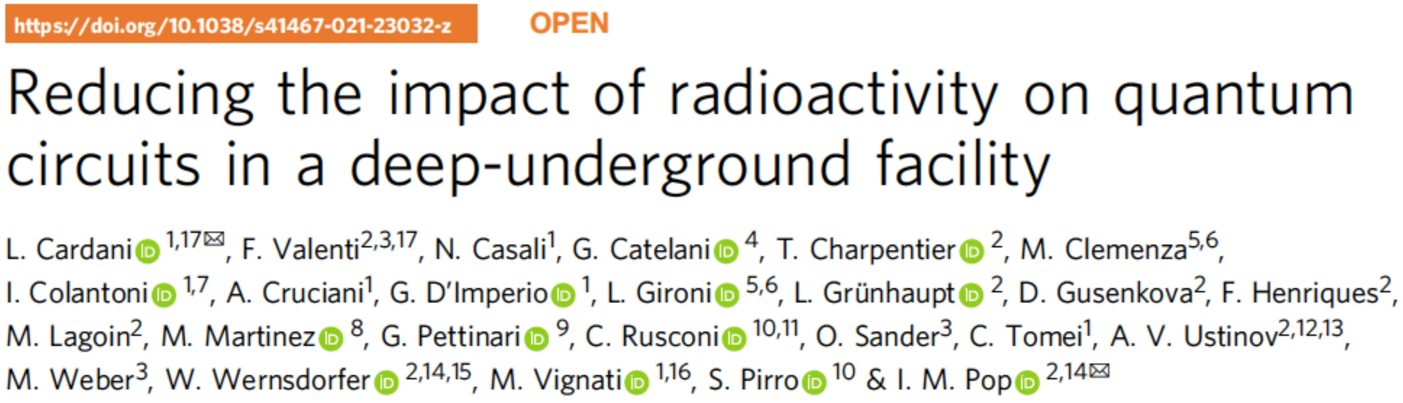


Nature Communications
v 12, Article number: 2733 (2021)

The impact of environmental radiation was studied under different shielding conditions

(normal, surface shielding, underground [Gran Sasso])

Underground Shielding



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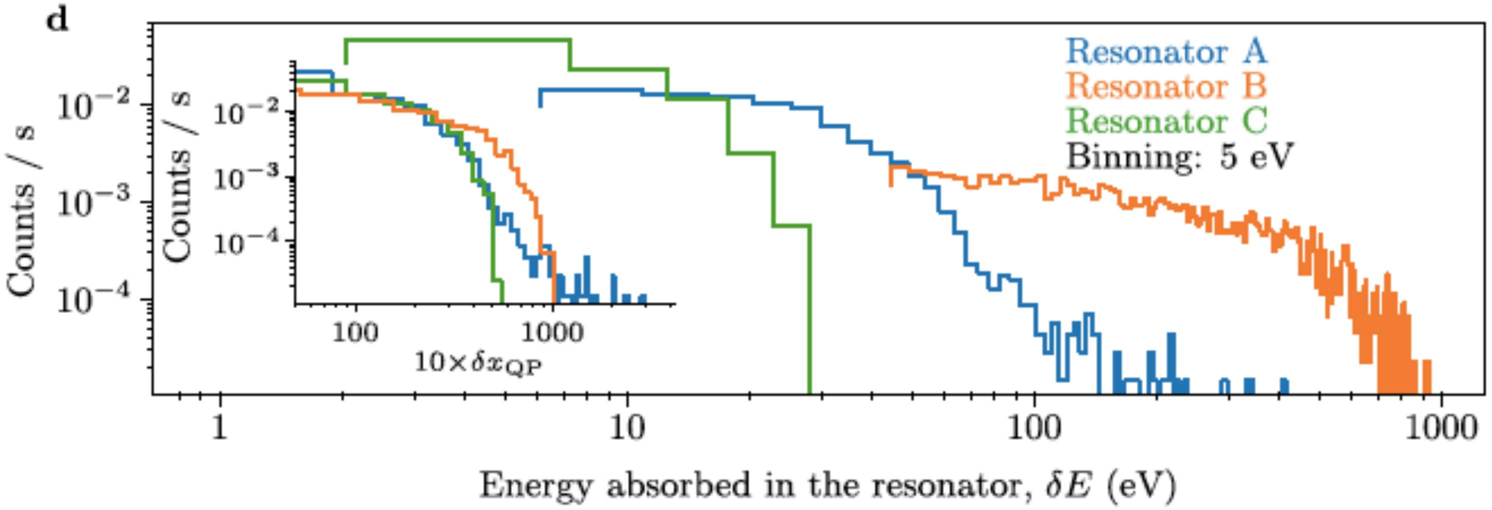

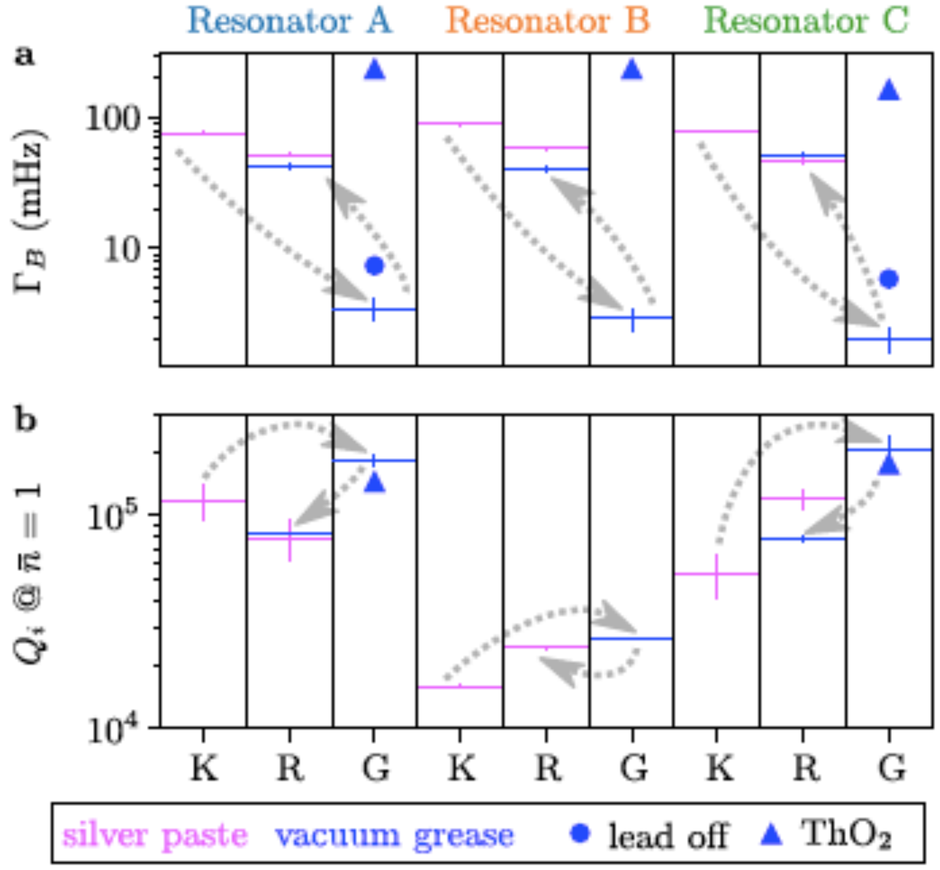

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The impact of environmental radiation was studied under different shielding conditions

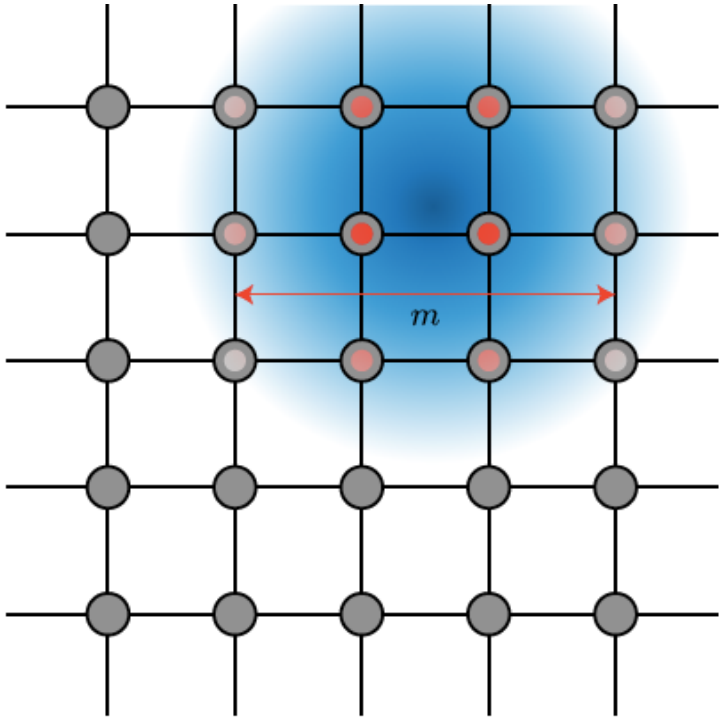
(normal, surface shielding, underground [Gran Sasso])

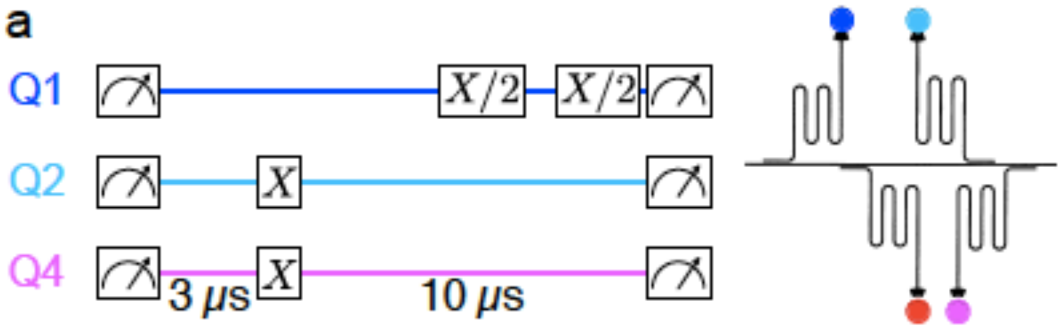
Evidence of *Correlated* Disruption

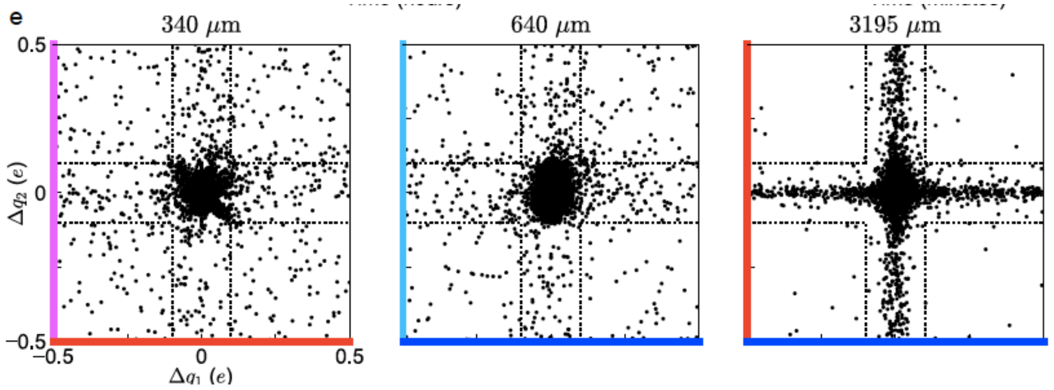
Correlated Charge Noise and Relaxation Errors in Superconducting Qubits

C. D. Wilen,[1] S. Abdullah,[1] N. A. Kurinsky,[2,3] C. Stanford,[4] L. Cardani,[5] G. D'Imperio,[5] C. Tomei,[5] L. Faoro,[1,6] L. B. Ioffe,[7] C. H. Liu,[1] A. Opremcak,[1] B. G. Christensen,[1] J. L. DuBois,[8] and R. McDermott[1,*]

Nature **volume 594, 369–373 (2021)**



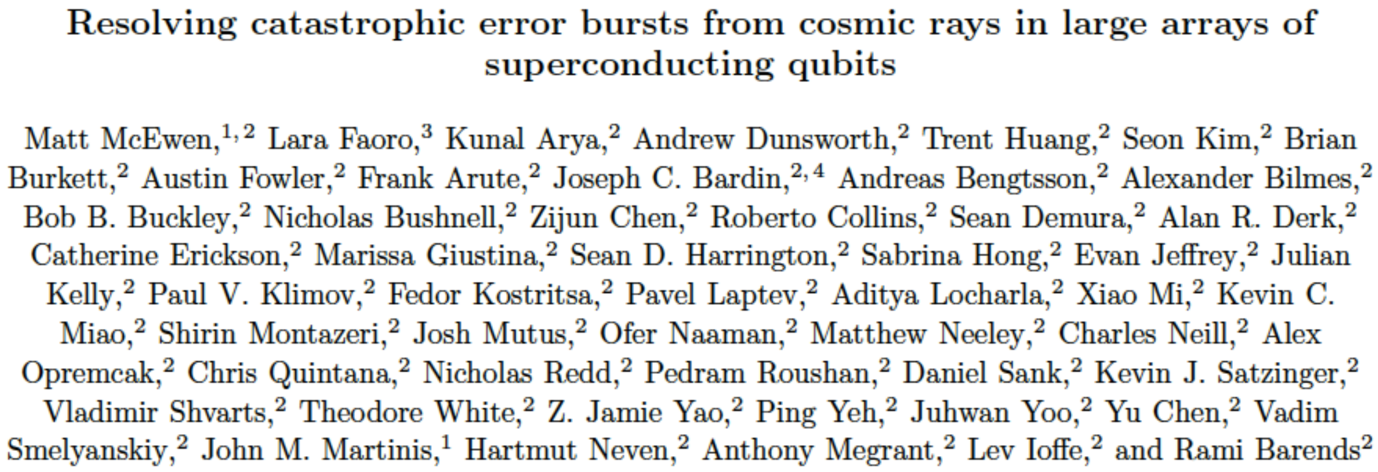




Recent evidence that cosmic rays/radioactivity can cause disruption across multiple qubits.

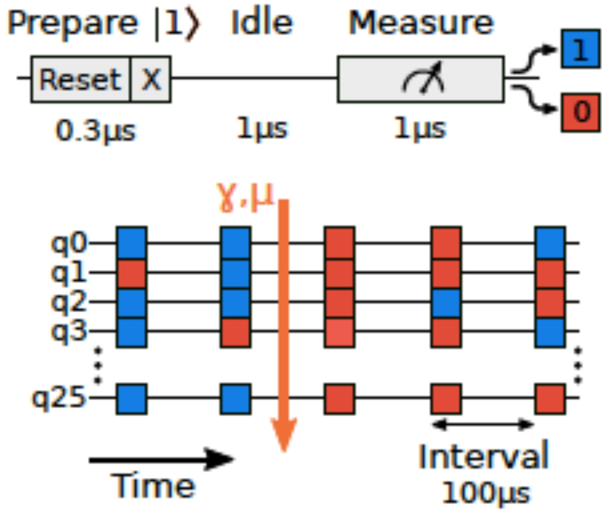
This particular effect is particularly worrisome, since it spoils correlations.

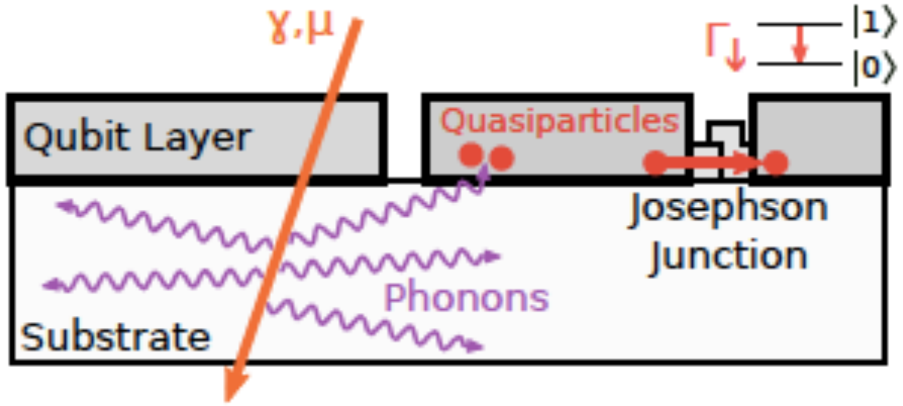
Evidence of *Correlated* Disruption

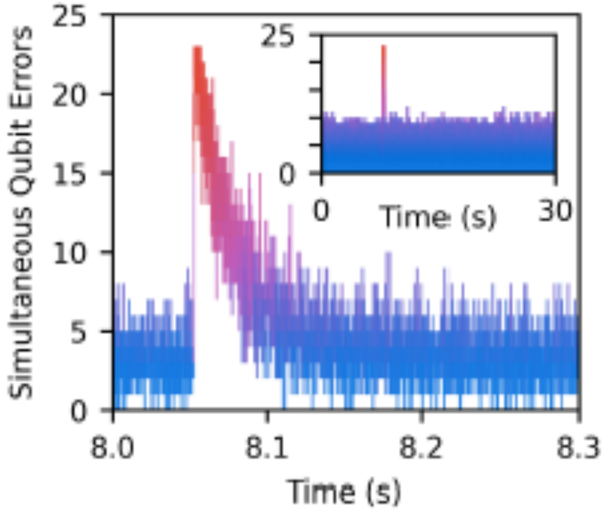


Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits

Matt McEwen,[1,2] Lara Faoro,[3] Kunal Arya,[2] Andrew Dunsworth,[2] Trent Huang,[2] Seon Kim,[2] Brian Burkett,[2] Austin Fowler,[2] Frank Arute,[2] Joseph C. Bardin,[2,4] Andreas Bengtsson,[2] Alexander Bilmes,[2] Bob B. Buckley,[2] Nicholas Bushnell,[2] Zijun Chen,[2] Roberto Collins,[2] Sean Demura,[2] Alan R. Derk,[2] Catherine Erickson,[2] Marissa Giustina,[2] Sean D. Harrington,[2] Sabrina Hong,[2] Evan Jeffrey,[2] Julian Kelly,[2] Paul V. Klimov,[2] Fedor Kostritsa,[2] Pavel Laptev,[2] Aditya Locharla,[2] Xiao Mi,[2] Kevin C. Miao,[2] Shirin Montazeri,[2] Josh Mutus,[2] Ofer Naaman,[2] Matthew Neeley,[2] Charles Neill,[2] Alex Opremcak,[2] Chris Quintana,[2] Nicholas Redd,[2] Pedram Roushan,[2] Daniel Sank,[2] Kevin J. Satzinger,[2] Vladimir Shvarts,[2] Theodore White,[2] Z. Jamie Yao,[2] Ping Yeh,[2] Juhwan Yoo,[2] Yu Chen,[2] Vadim Smelyanskiy,[2] John M. Martinis,[1] Hartmut Neven,[2] Anthony Megrant,[2] Lev Ioffe,[2] and Rami Barends[2]







Recently, Google Inc. group have used correlation measurements to provide evidence on the mechanism behind quasi-particle poisoning

(https://arxiv.org/abs/2104.05219 and https://arxiv.org/pdf/2012.06137.pdf).

Dominated by phonons created in the substrate holding qubits.

What Can an Underground Lab Offer?

Luckily, neutrino and dark matter experiments have been dealing with the unwanted presence of radioactivity for *decades*.

I suspect over the next few years, studies will proceed to determine the efficacy of various low background techniques:

Shielding

Material selection

Underground operations

On-chip mitigation

Discussion Points?

Access to on-site material selection and shielding?

How feasible are conducting underground computing operations? A completely remote access site?

How much depth is really needed? Can shallow sites provide the bulk of the mitigation?

Partnership with industry?