Pacific Northwest
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C^{2}QA Perspectives on Radiation and Superconducting Qubits

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U.S. DEPARTMENT OF ENERGY BATTELLE
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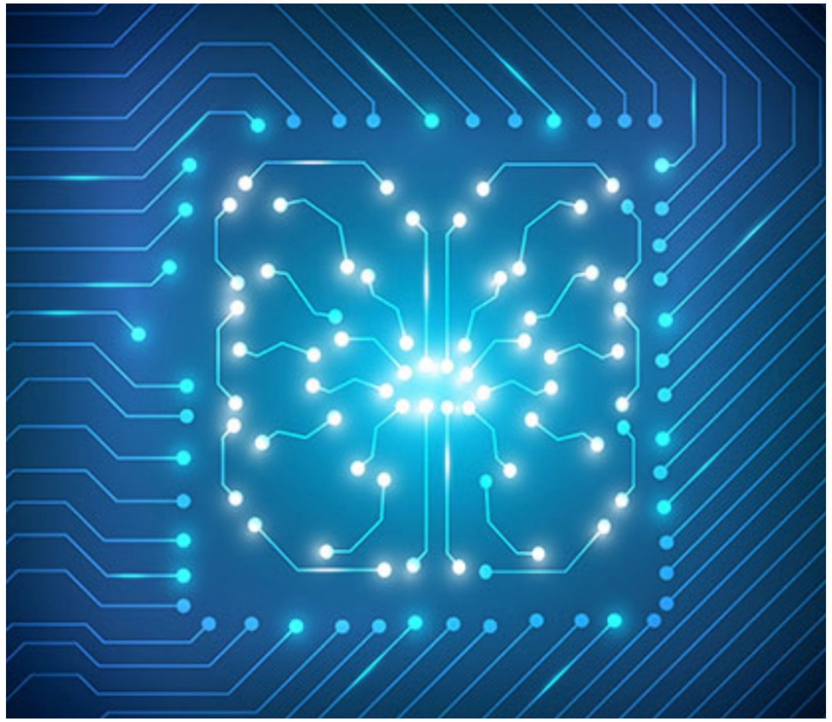
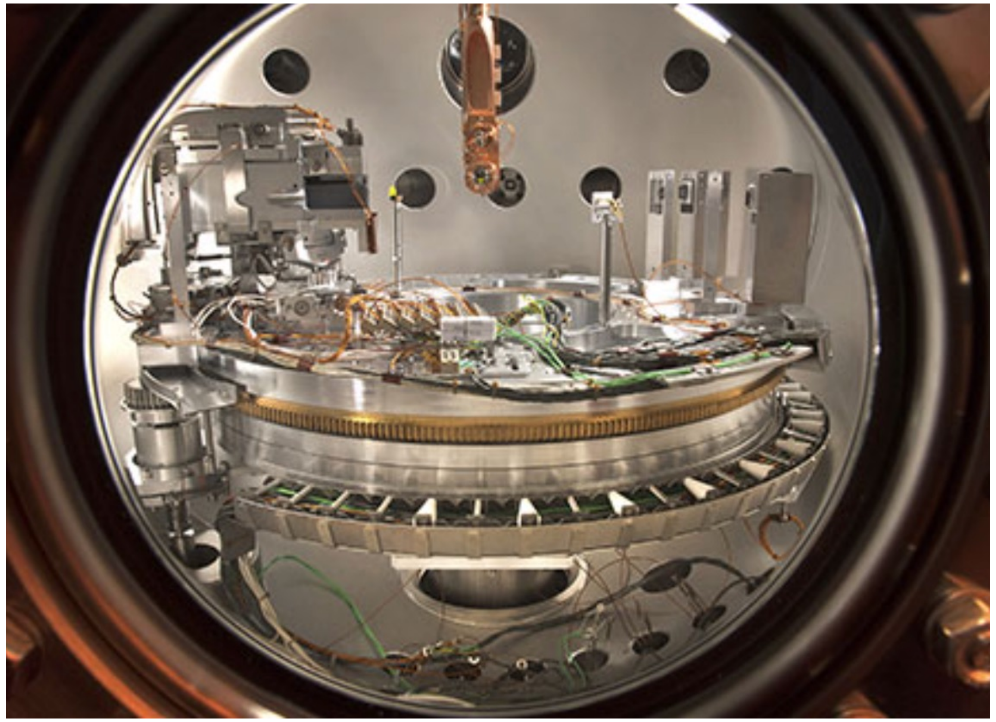
Outline

- Overview of Codesign Center for Quantum Advantage (C^2QA)
- Time scales for radiation interactions in superconducting qubits
- Coherence times are not strongly limited by radiation yet
- The oncology of two-level systems (TLS)
- Nonexhaustive examples of C^2QA efforts on TLS
- Proactively preparing C^2QA for the day when qubits will be radiation limited

Codesign Center for Quantum Advantage (C^{2}QA)

Developing and applying co-design principles across three research thrusts:





Software and Algorithms:

Develop applications, algorithms, and software that take advantage of the latest hardware advance

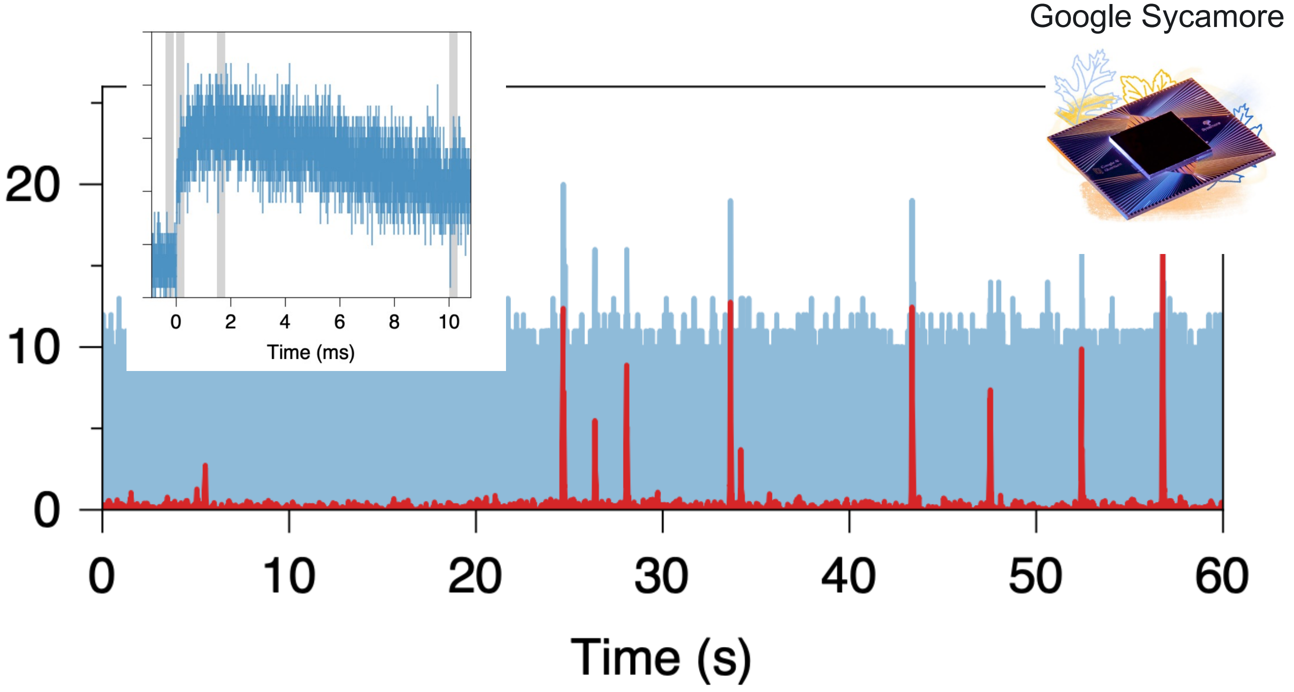
Devices:

Fabricate, characterize, and optimize devices to process and transmit quantum information. Focus on superconductors

Materials:

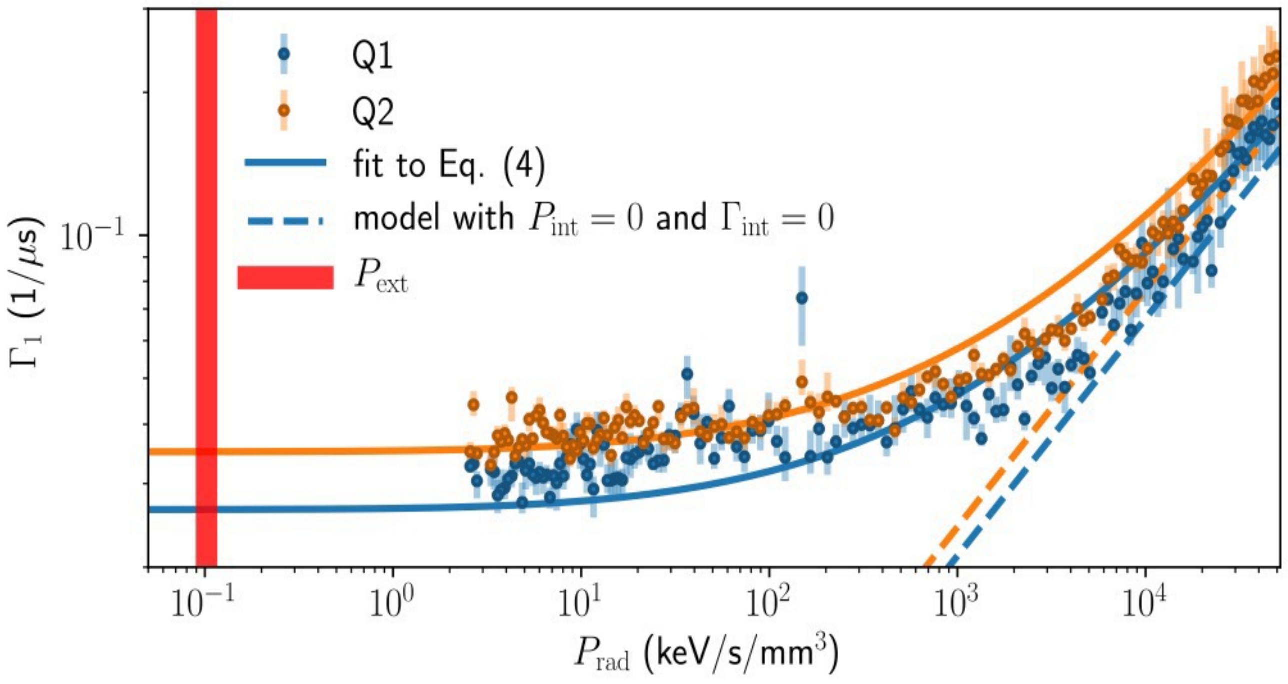
Uncover the microscopic mechanisms behind device errors with a cycle of theory, synthesis, and characterization.

Foreword: Time Scales for Radiation Interactions in Superconducting Qubits



- Radiation-induced bursts of errors: ~10 ms every few seconds [1,2]
- Naively implies that we have a few seconds to execute computations, but…

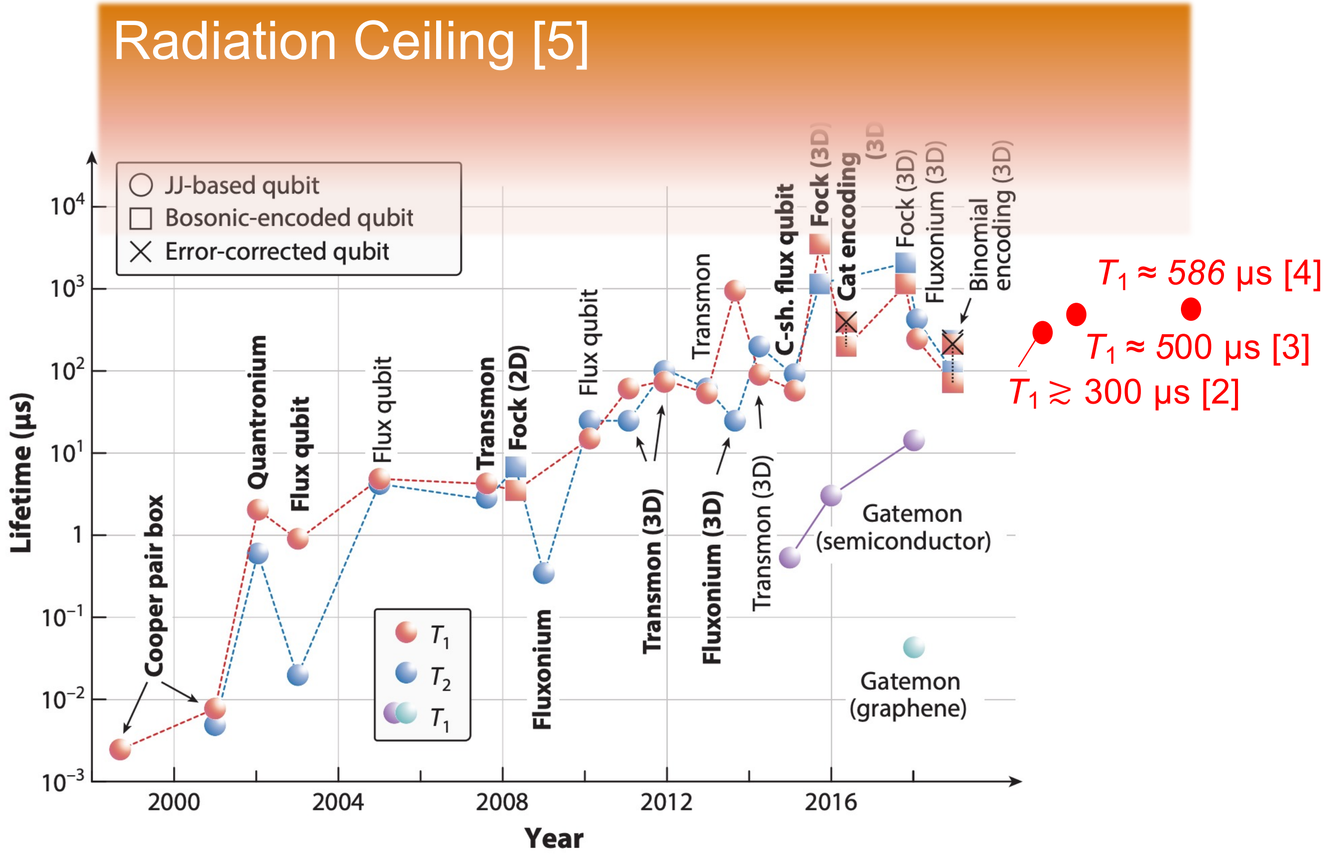
[1] McEwan *et al.,* Nature Communications **18** 107 (2022)
[2] Wilen *et al,* Nature **594** 369 (2021)



- Coherence times limited to a few ms by extrapolating the performance of irradiated qubits [3].
- But, superconducting qubits don't achieve multi-ms coherence times yet.

[3] Vepsäläinen *et al*., Nature **584** 551–556 (2020)

Towards the Radiation Ceiling



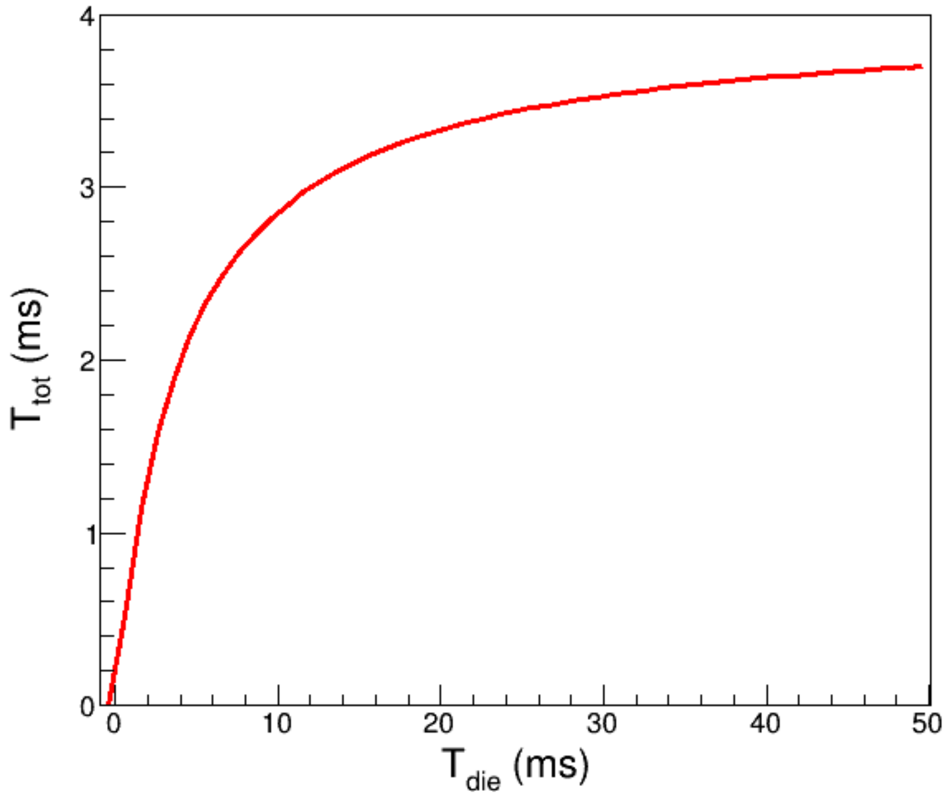
Moore's law for SC qubits follows progress in device design and material improvements. Plot from [1] with new points and radiation ceiling added.

- Radiation effects in C^{2}QA are implicit in the Materials and Device thrusts.
- Moore's law for superconducting qubits is approaching a ceiling at about 3–4 ms (T_1) implied by [5].
- C^{2}QA progress [2] and follow-up work [3], e.g., in Ta and Ni processes for transmon qubits will soon hit the limit.
- DOE Nuclear Physics support and PNNL internal investments are preparing C^{2}QA to meet, and hopefully evade that limit.

[1] Siddiqi, Nature Reviews Materials **6** 875 (2021)
[2] Place *et al*., Nature Comm. **12** 1779 (2021)
[3] Wang *et al*., npj Quantum Information **8** 3 (2022)
[4] Bal *et al*., npj Quantum Information **10** 43 (2024)
[5] Vepsäläinen *et al*., Nature **584** 551–556 (2020)

Quantifying the Radiation Ceiling

$$T_1^{tot} = \frac{1}{\left(\frac{1}{T_1^{die}} + \frac{1}{T_1^{rad}}\right)}$$



Assume two loss mechanisms: dielectric losses characterized by T_1^{die} and radiation losses with $T_1^{rad} = 4$ ms*:

- Effects on world leading qubits with $T_1^{die} \lesssim 1$ ms are currently small ($\lesssim$10%)
- Radiation effects become significant (>20%) when $T_1^{die} \gtrsim$ 1 ms
- Qubits with $T_1^{die} \gtrsim 10$ ms are futile without radiation mitigation.

CAVEAT: $T_1^{rad} = 4$ ms is derived from only 1 experiment on 1 transmon design [Vepsäläinen *et al.*].

Better 2D Transmon Qubits With Tantalum

- 2D transmon coherence times are limited by dielectric losses.
- Loss from *bulk* sapphire ($\delta \lesssim 10^{-9}$) is low [1].

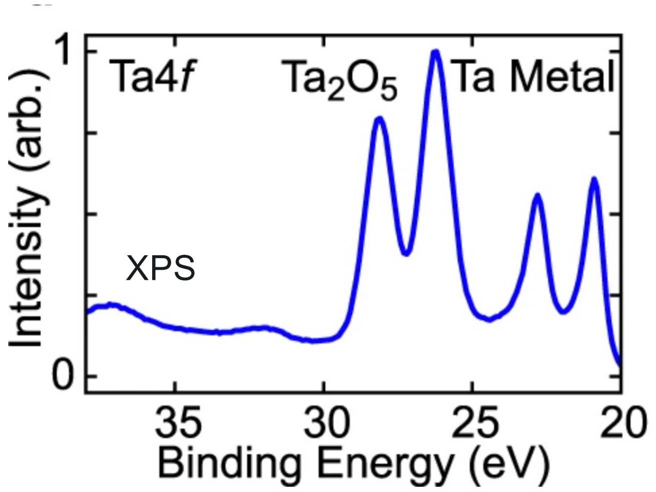
→ implicates defects at surfaces and interfaces as the dominant microscopic source of loss.

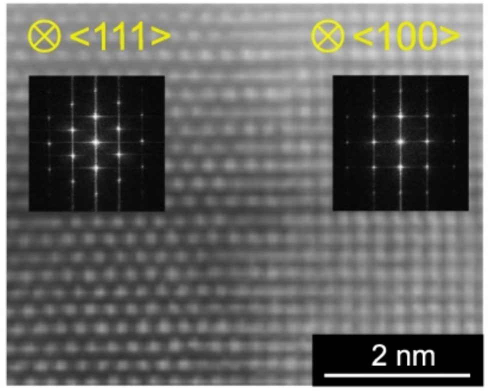
- Hypothesize that a superconductor with a thinner and simpler oxide stoichiometry will be less lossy.

→ Find that exchanging niobium → tantalum (complicated → simple oxide) consistently improves coherence times.

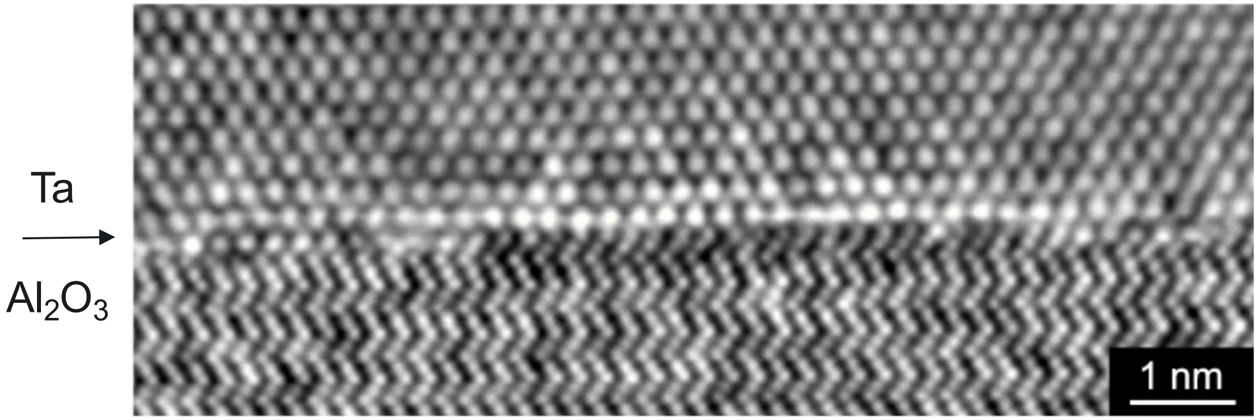
- Place *et al.* [2] observe a mean $\langle T_1 \rangle$ = 0.26 ms (T_1^{max} > 0.3 ms) across 17 tantalum devices. World record 2D transmon, until…
- Wang *et al.* [3] observe T_1 = 0.503 ms with improved tantalum dry etch process.

[1] Read *et al.*, Phys. Rev. Applied **19** 034064 (2023)
[2] Place *et al.*, Nature Comm. **12** 1779 (2021)
[3] Wang *et al.*, NPJ Quantum Information **8** 3 (2022)





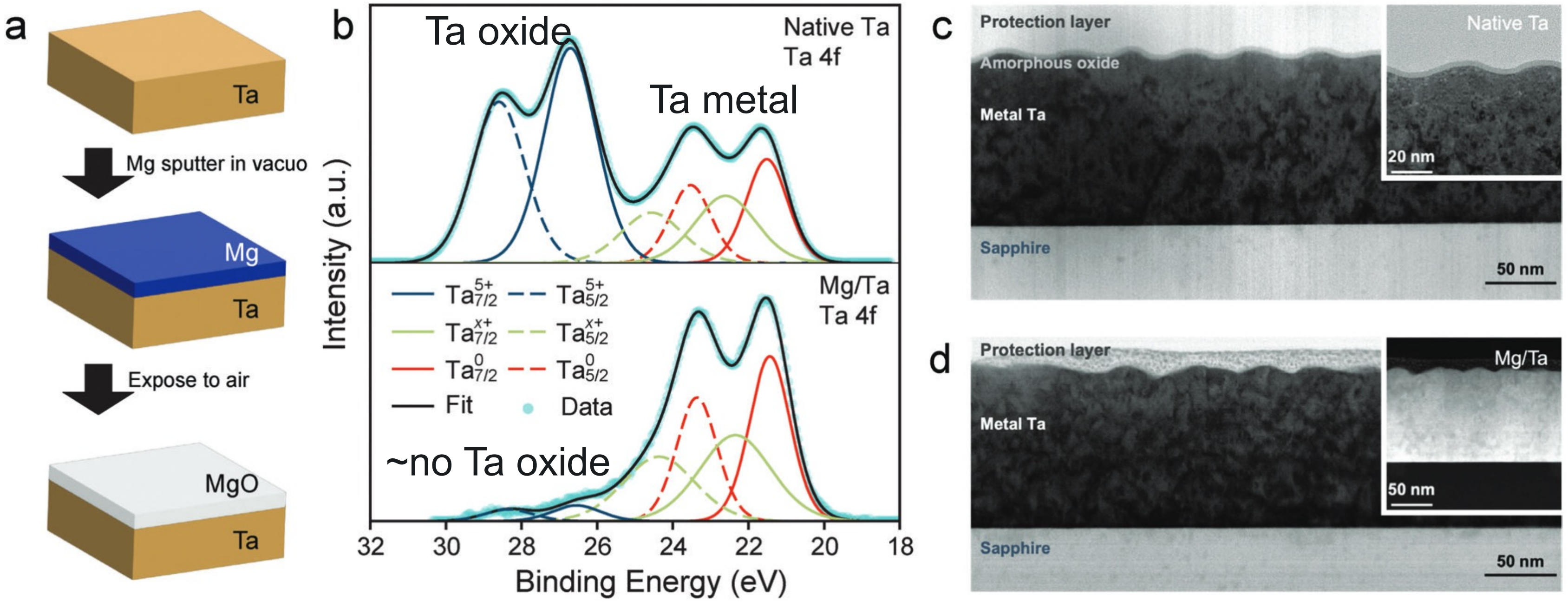
Ta-Ta boundary

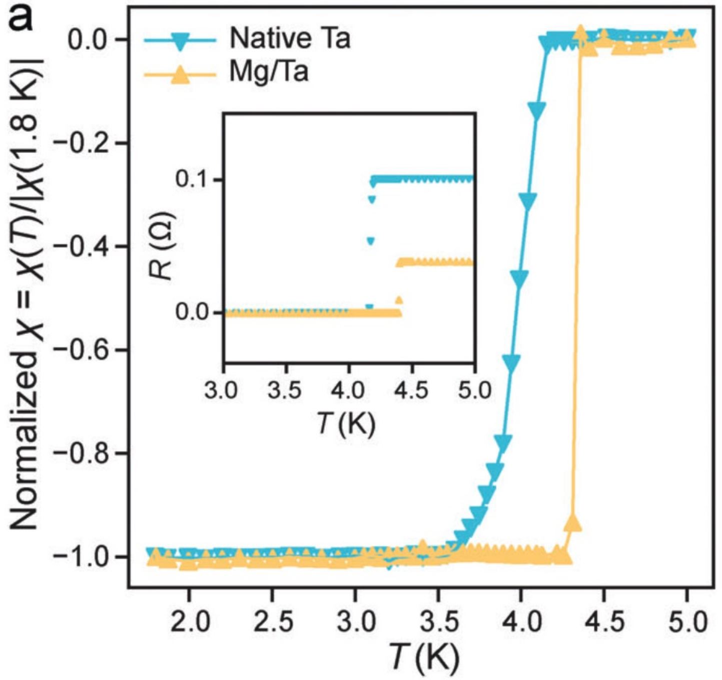


Ta-sapphire boundary

X-ray photoelectron spectrum (XPS) of tantalum oxide-metal interface, differently oriented bulk tantalum regions, and epitaxial sapphire-tantalum interface. Images from [2].

Towards Even Better Transmons Devices

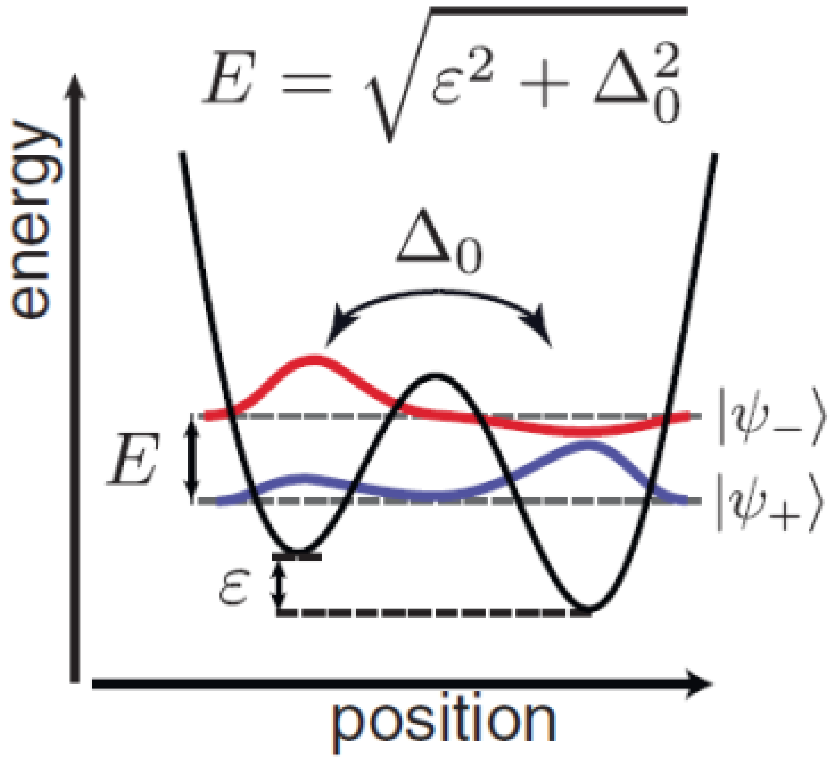




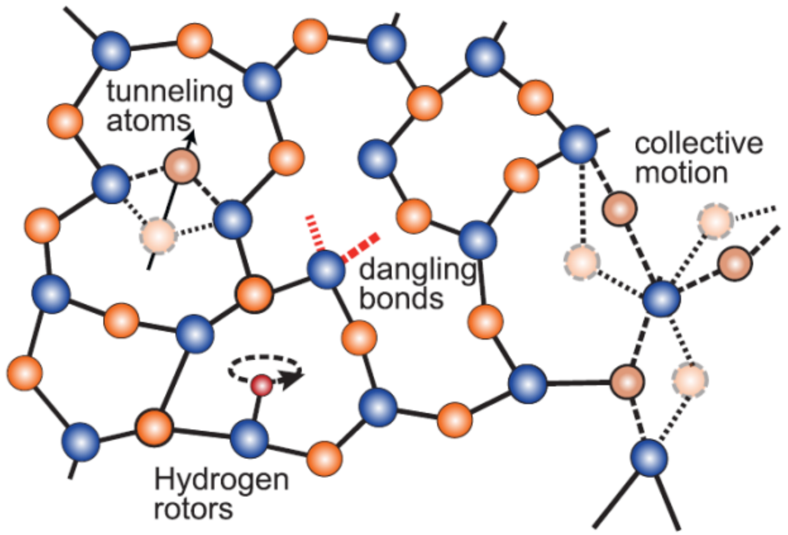
- C^{2}QA demonstrates that thin (~few nm) capping layer of magnesium suppresses tantalum oxidation [1].
- Magnesium oxide is much less lossy: tanδ ~10^{-6} versus 10^{-3} for tantalum oxide.
- Superconductivity also improved: sharper transition at higher temperature.
- Mg/Ta qubits presumably will improve over native Ta transmons…
- See also SQMS results demonstrating improvements by capping layers on niobium, and new record T_1 = 0.586 ms [2].

[1] Zhou *et al*., Adv. Mater. **36** 2310280 (2024), [2] Bal *et al*., npj Quantum Information **10** 43 (2024)

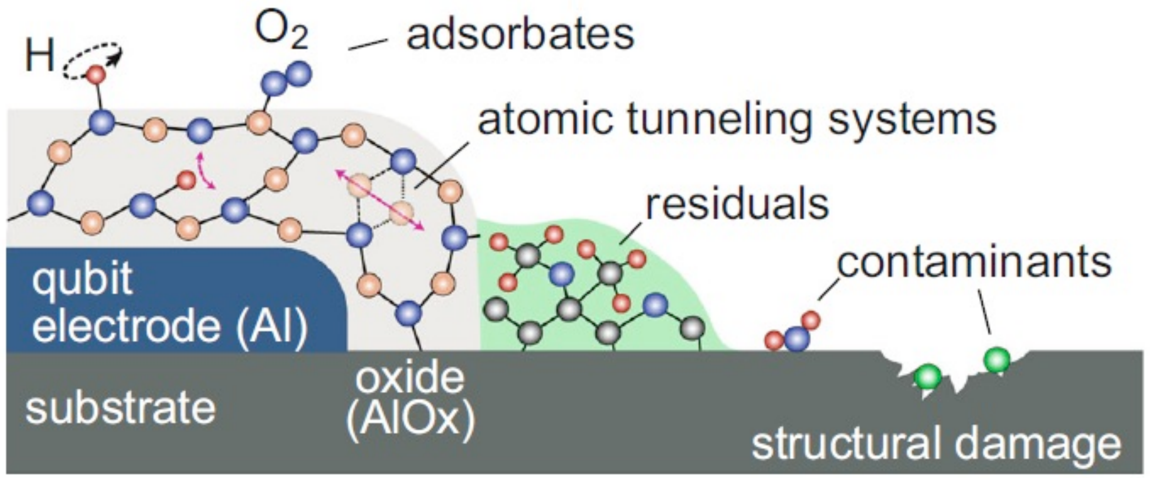
Microscopic Origins of Dielectric Loss: Two Level Systems (TLS)



Standard Tunneling Model (STM) of a TLS [1]



TLS in an amorphous solid, *e.g.*, oxide [1]



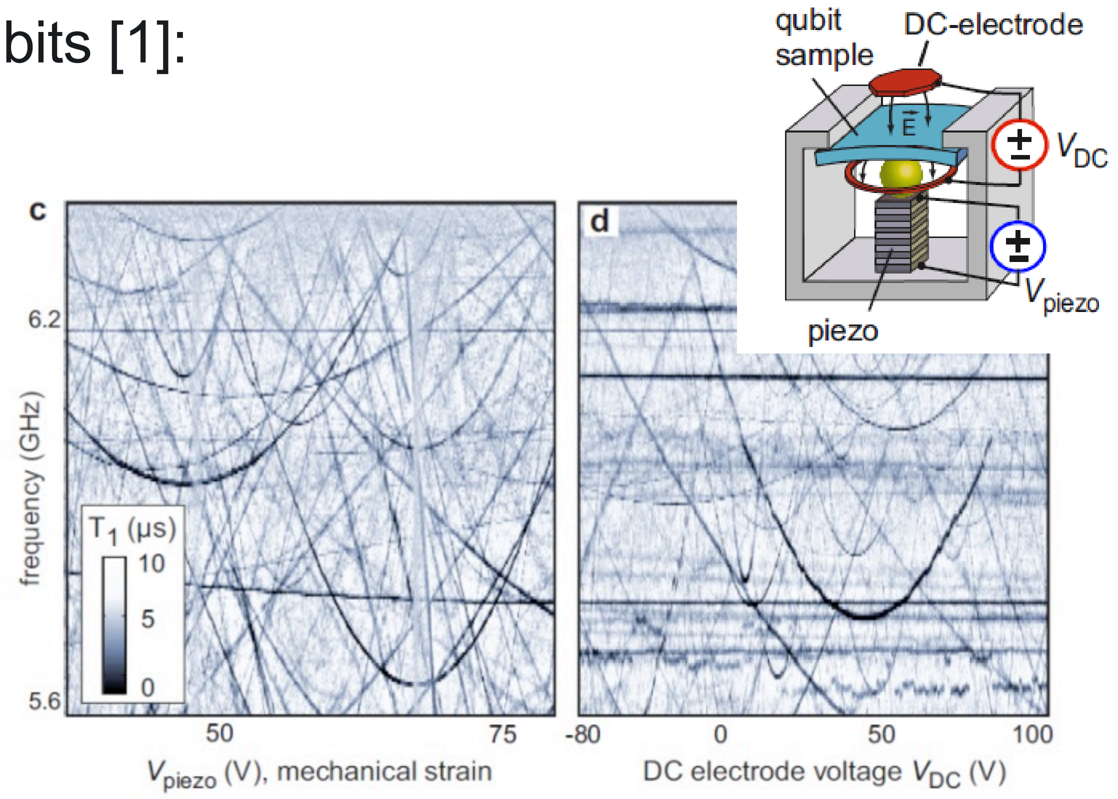
TLS in/on a device [2]

- Defects on surfaces and in bulk materials can behave as TLS that exchange energy with qubits.
- Modern transmons devices limited by TLS at surfaces.

[1] Müller et al., Rep. Prog. Phys. **82** 124501 (2019), [2] Lisenfeld et al., npj Quant. Inf. **5** 105 (2019)

Two-Level System Spectroscopy with Resonators and Qubits

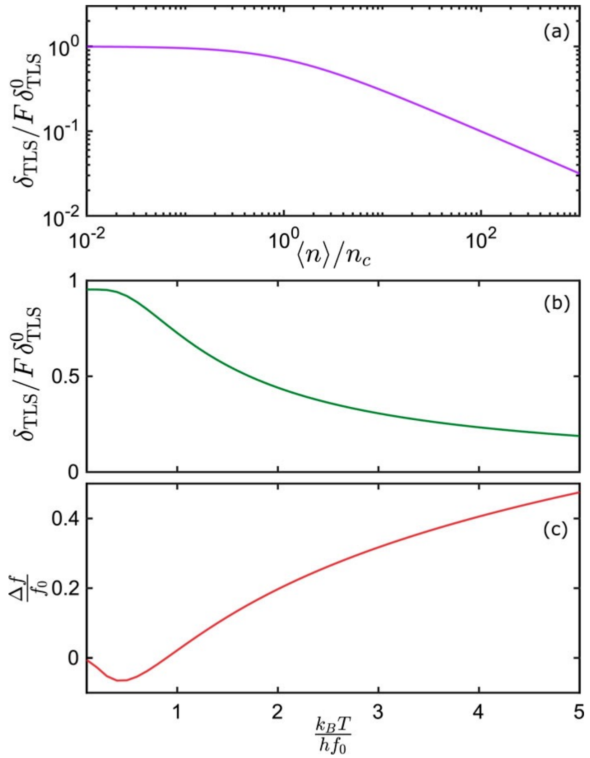
Qubits [1]:

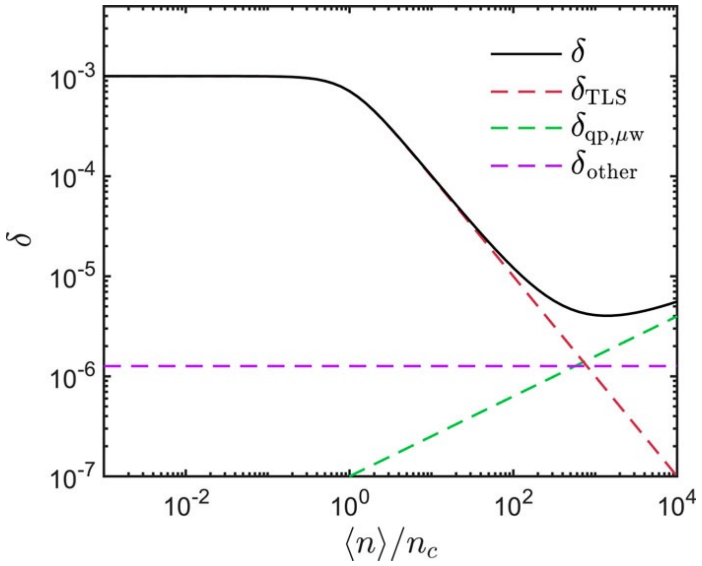


- Identifies the nature, density, and locations of your TLSs.
- *E.g.,* electric-dipole-like defects at surfaces revealed through voltage dependence.

[1] Lisenfeld et al., npj Quant. Inf. **5** 105 (2019)

Resonators [2]:





Exploit loss mechanisms' different dependence on power and temperature

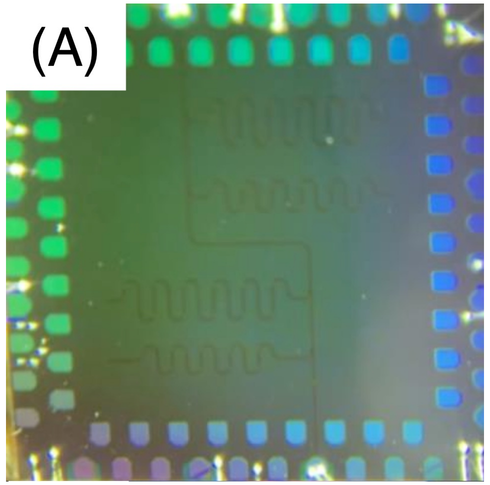
- Resonators are sensitive to many of the same loss effects as qubits and are much easier to fab and operate.
- Resonators enable a fast co-design cycle in C²QA:

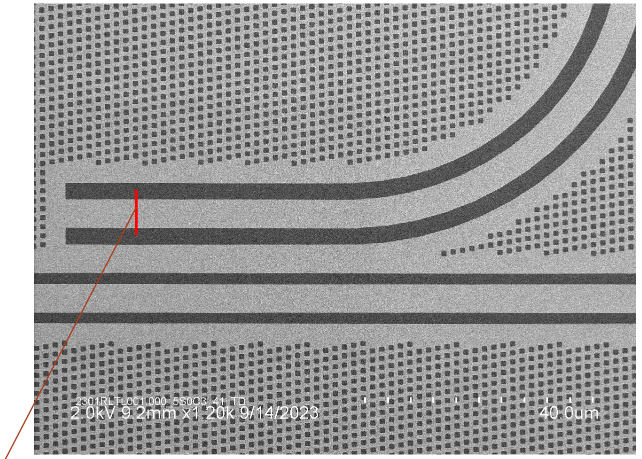
→ materials → device → evaluation →

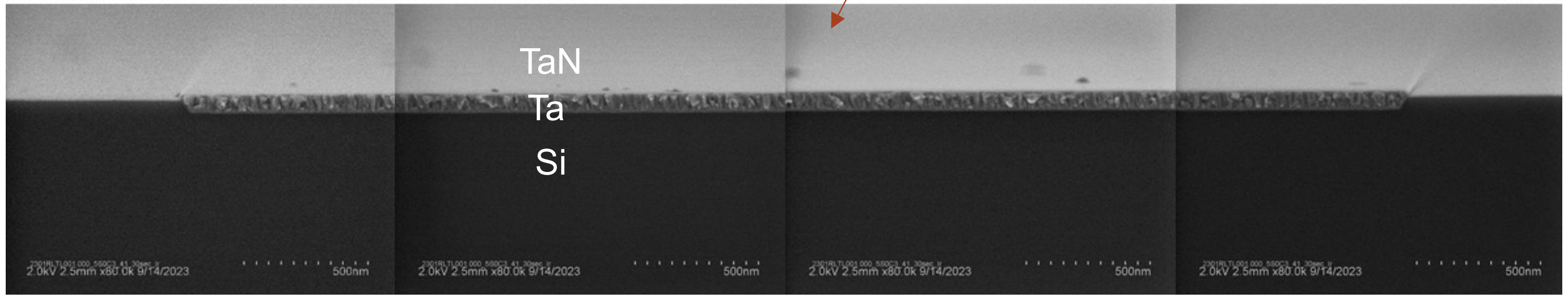
[2] McRae et al., Rev. Sci. Instrum. **91** 091101 (2020)

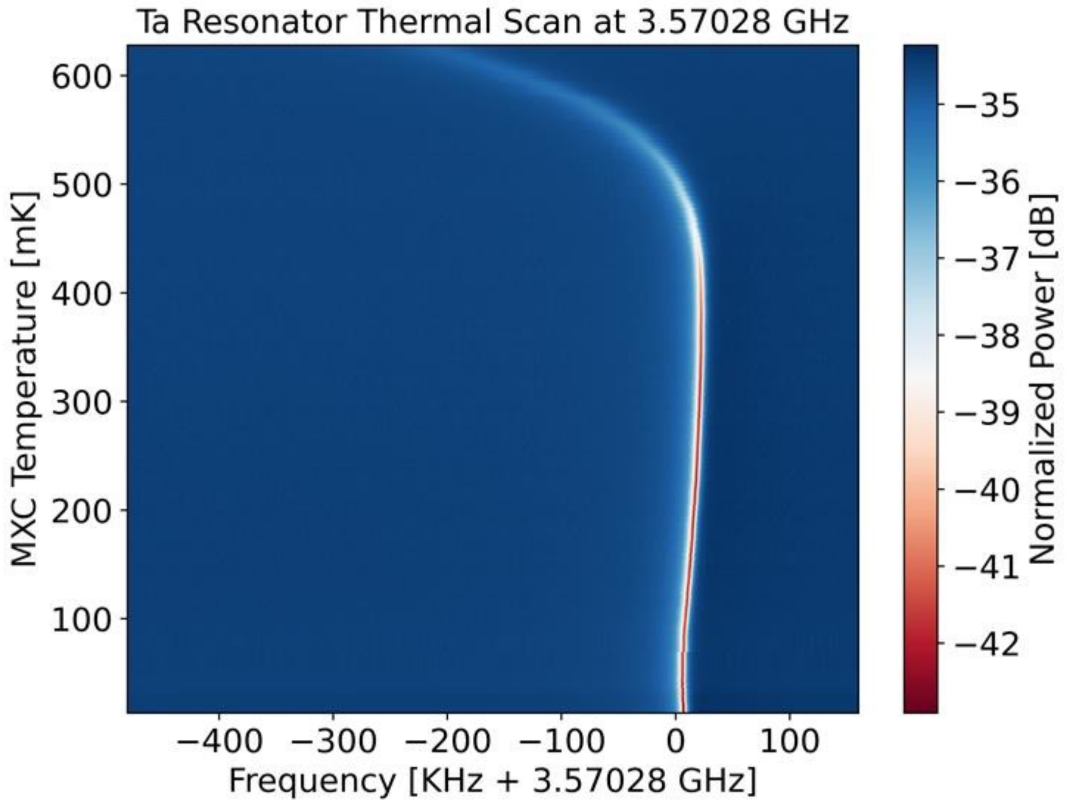
TLS Spectroscopy in C²QA

Damascene process for tantalum in/on silicon:









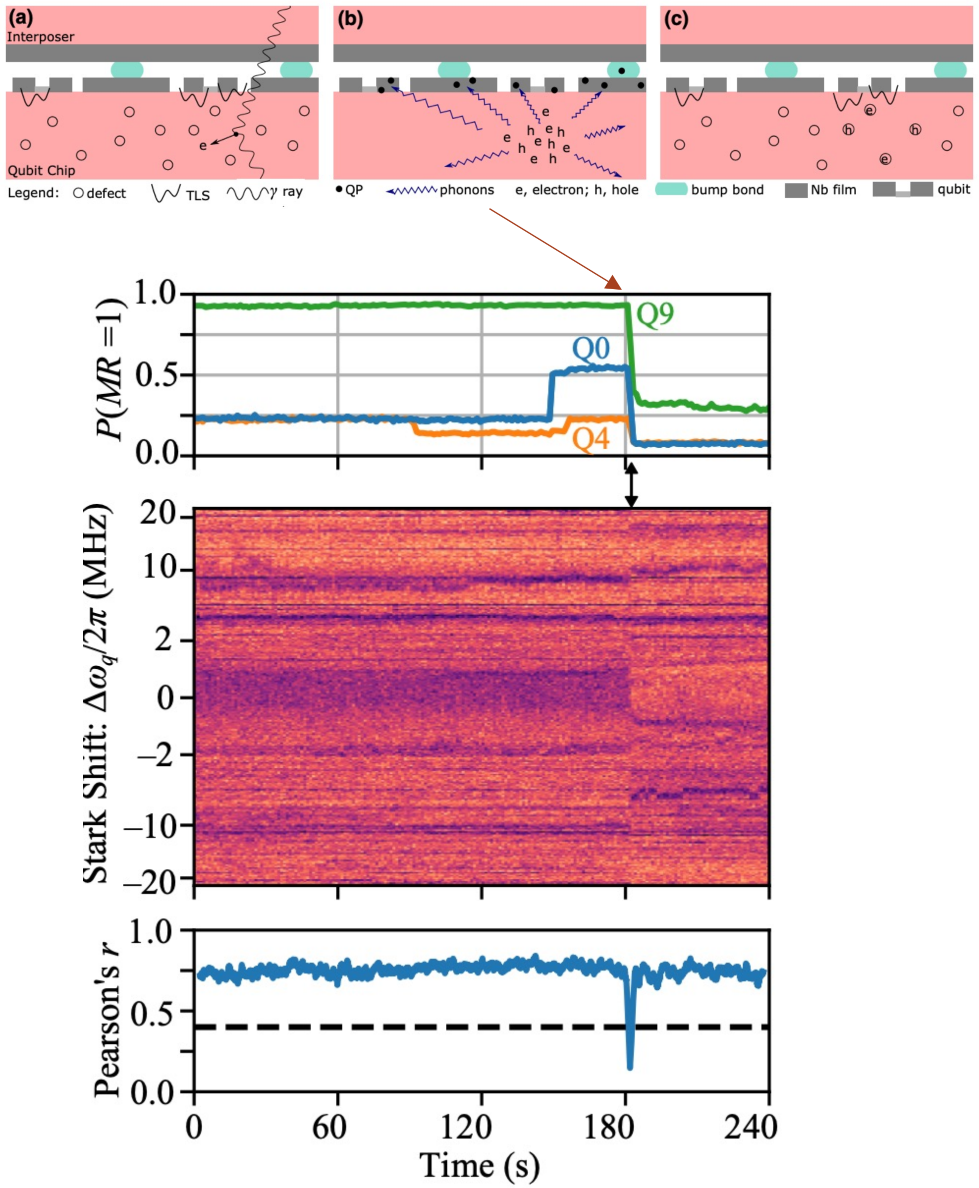
$$\frac{\delta f(T)}{f_0} = \left(\frac{\delta f(T)}{f_0}\right)_{\mathrm{TLS}} + \left(\frac{\delta f(T)}{f_0}\right)_{\mathrm{QP}}$$

- Tantalum deposited in a silicon channel and capped with tantalum nitride.
- Sample data to the right to distinguish TLS from quasiparticle (QP)-induced induced shifts follow analysis methods from [1]

[1] Crowley *et al.*, Phys. Rev. X **13** 041005 (2023)

*See poster by Francisco Ponce for more

Radiation and Two-Level Systems



- Two-level systems are seen to “scramble” in response to radiation events.

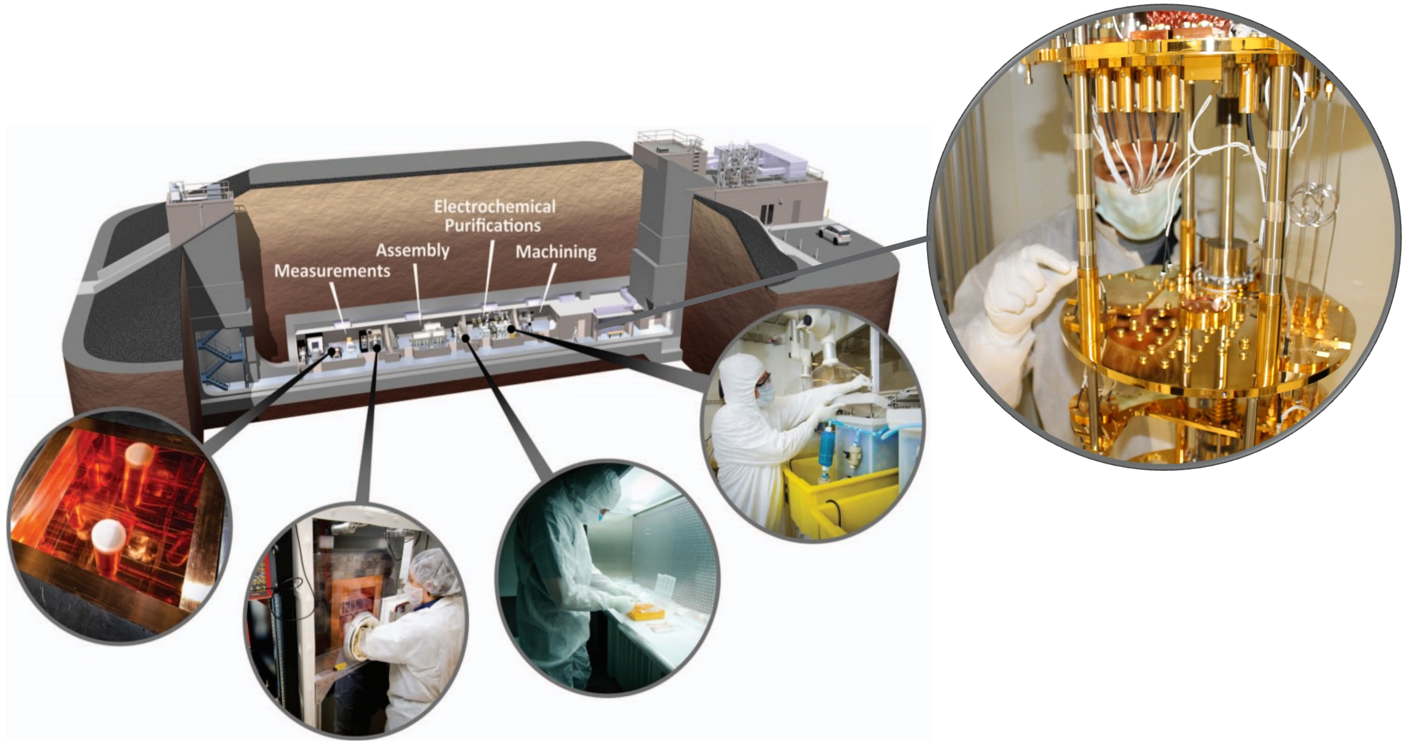
- Question to the room: can we extract useful information about TLSs by adding a radiation component to ongoing spectroscopy efforts?

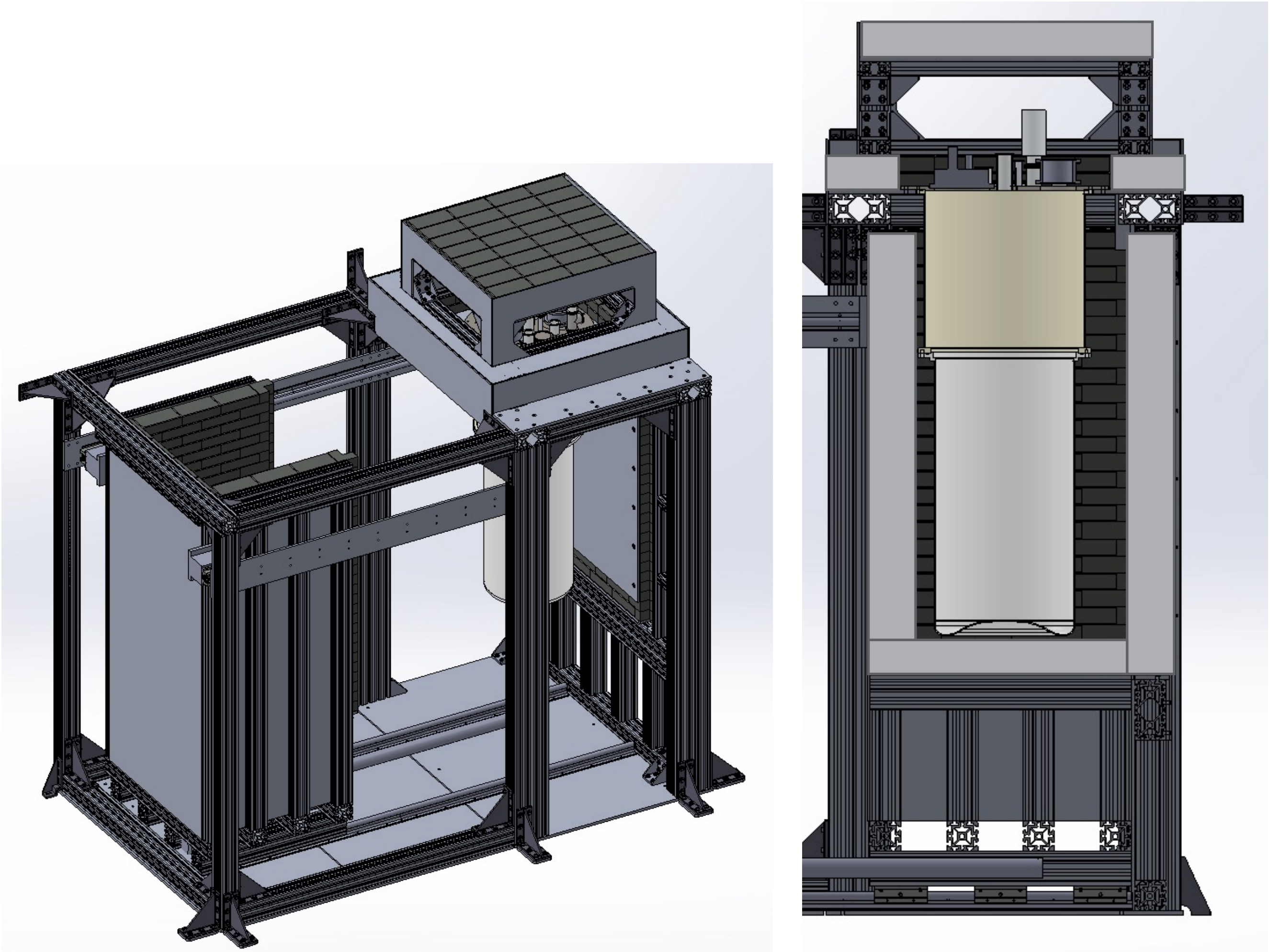
- IBM Falcon R6 is *not* susceptible to chip-wide bursts seen on other devices!

[1] Thorbeck *et al.*, PRX Quantum **4** 020356 (2023)

PNNL Low Background Cryogenic Facility

- 19 m (30 m.w.e.) overburden reduces cosmic ray muons by 6×, neutrons by 100×
- 4” lead shield with moderate sized gaps will reduce external gammas by 99.8%
- Overall ≈95% reduction in (low energy) ionizing radiation event rate





See Ben Loer’s talk tomorrow for more details.

Summary

- Overview of C^{2}QA and the Materials and Device thrust work leading to the radiation ceiling.
- Preparations at PNNL to get full benefit of material and device design improvements as transmon qubits reach and exceed millisecond coherence times in the next few years.
- PNNL and C^{2}QA invite collaboration on the topic of Radiation in Superconducting Qubits.

Acknowledgements

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Thank you