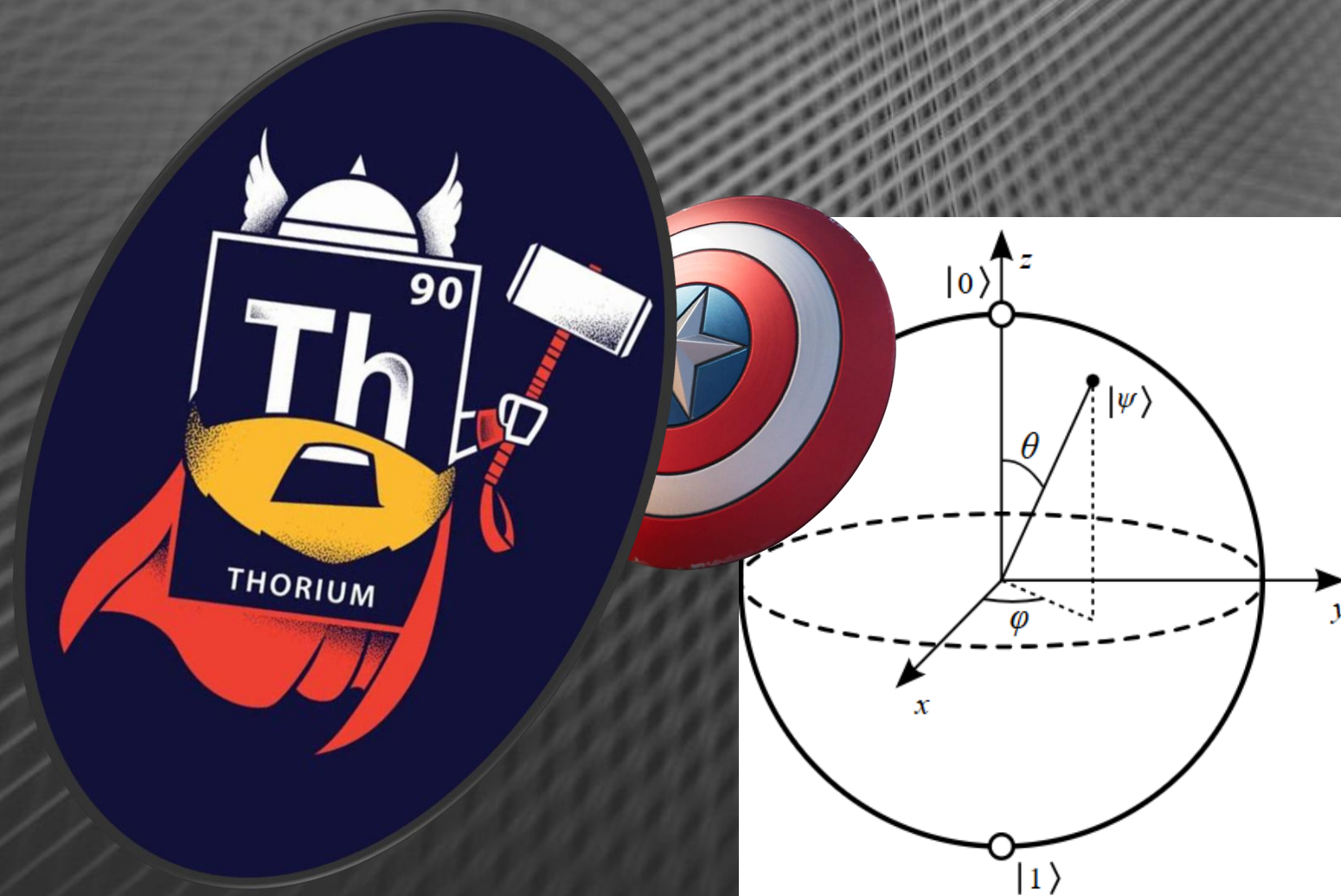


Ionizing radiation vs quantum computers

The battle continues

Ben Loer

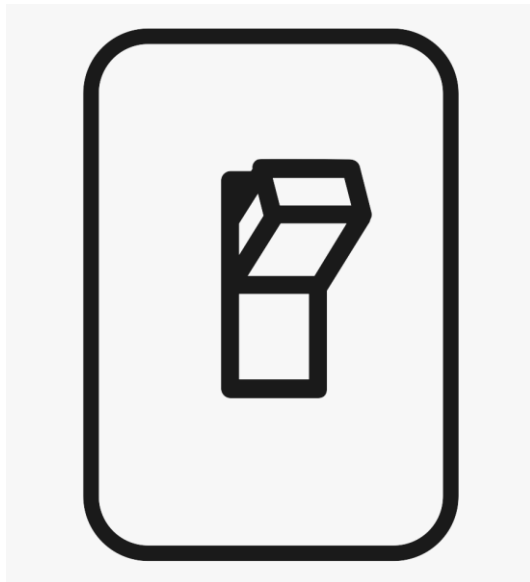
Pacific Northwest National Lab



Qubits and the Bloch sphere

Classical bits

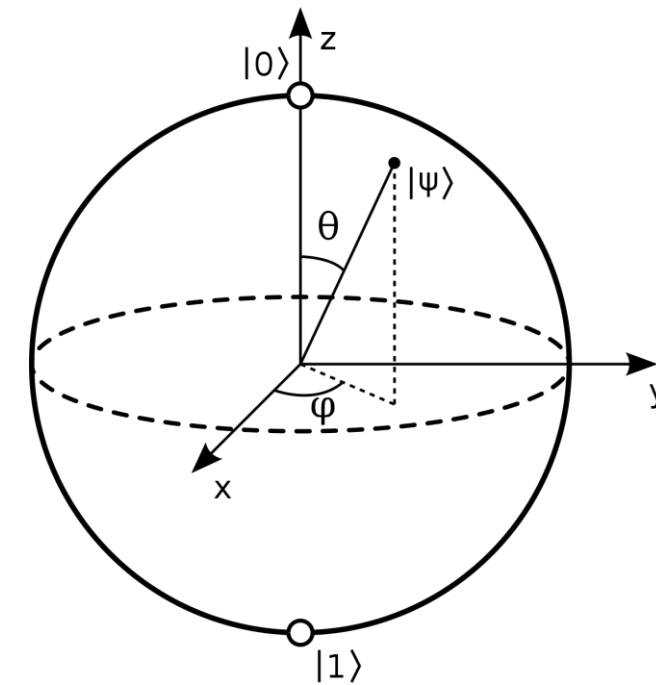
- Can take two values: **0** or **1**



- Need 128 bits to store a single qubit in double precision floating point format

Quantum bits (qubits)

- Superposition of two quantum states
- $a|0\rangle + b|1\rangle$; $|a|^2 + |b|^2 = 1$
- Visualized as points on Bloch sphere



The essence of a quantum computation is to interact groups of qubits together so that the interference produces a final state conveying information

Entanglement and exponential state space

- Non-entangled qubits can be represented by $2 \times n$ real numbers (polar angle θ and phase ϕ on the Bloch sphere)

$$|\Psi\rangle = (c_0^1|0\rangle_1 + c_1^1|1\rangle_1) \otimes (c_0^2|0\rangle_2 + c_1^2|1\rangle_2) \otimes (c_0^3|0\rangle_3 + c_1^3|1\rangle_3)$$

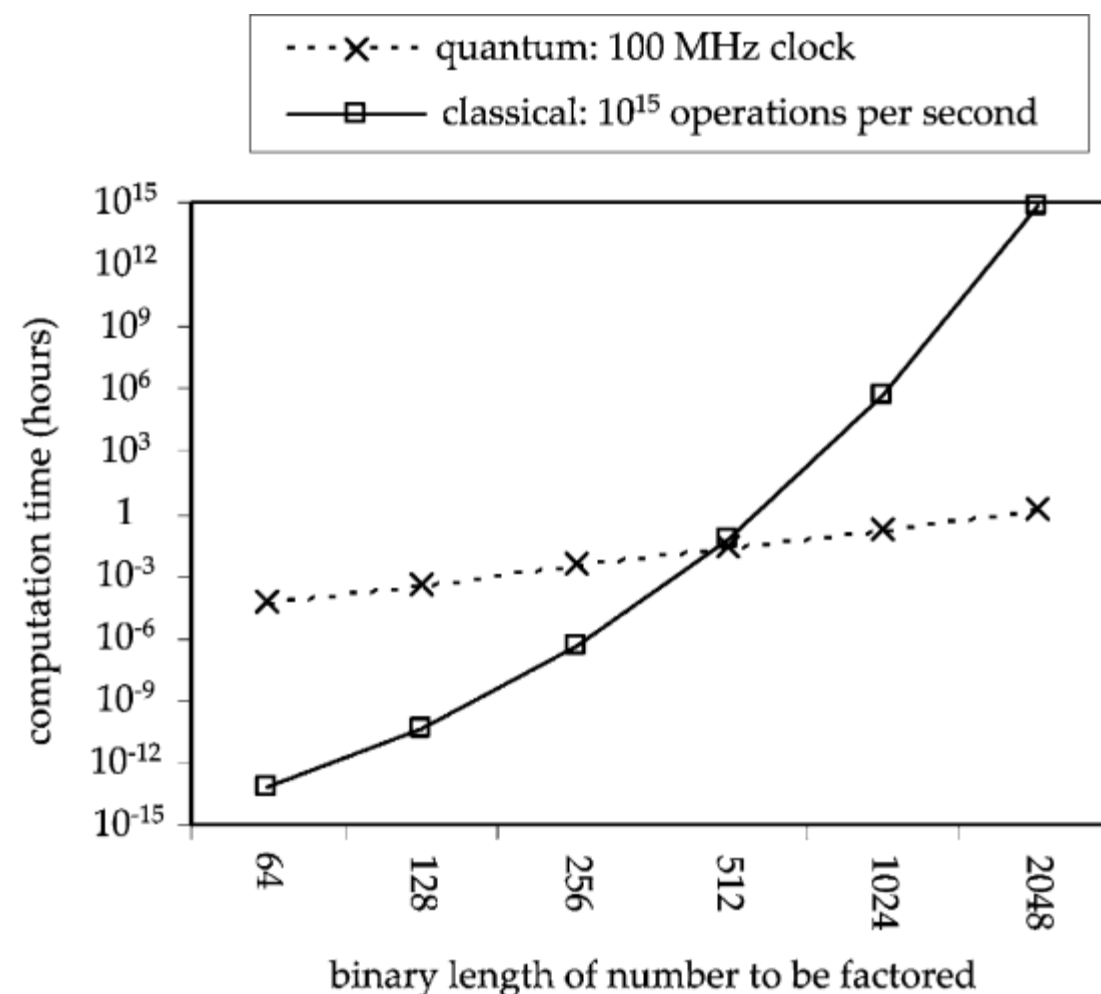
- Entangled require 2^n real numbers

$$|\Psi\rangle = c_0|000\rangle + c_2|001\rangle + c_3|010\rangle + c_4|011\rangle + c_5|100\rangle + c_6|101\rangle + c_7|110\rangle + c_8|111\rangle$$

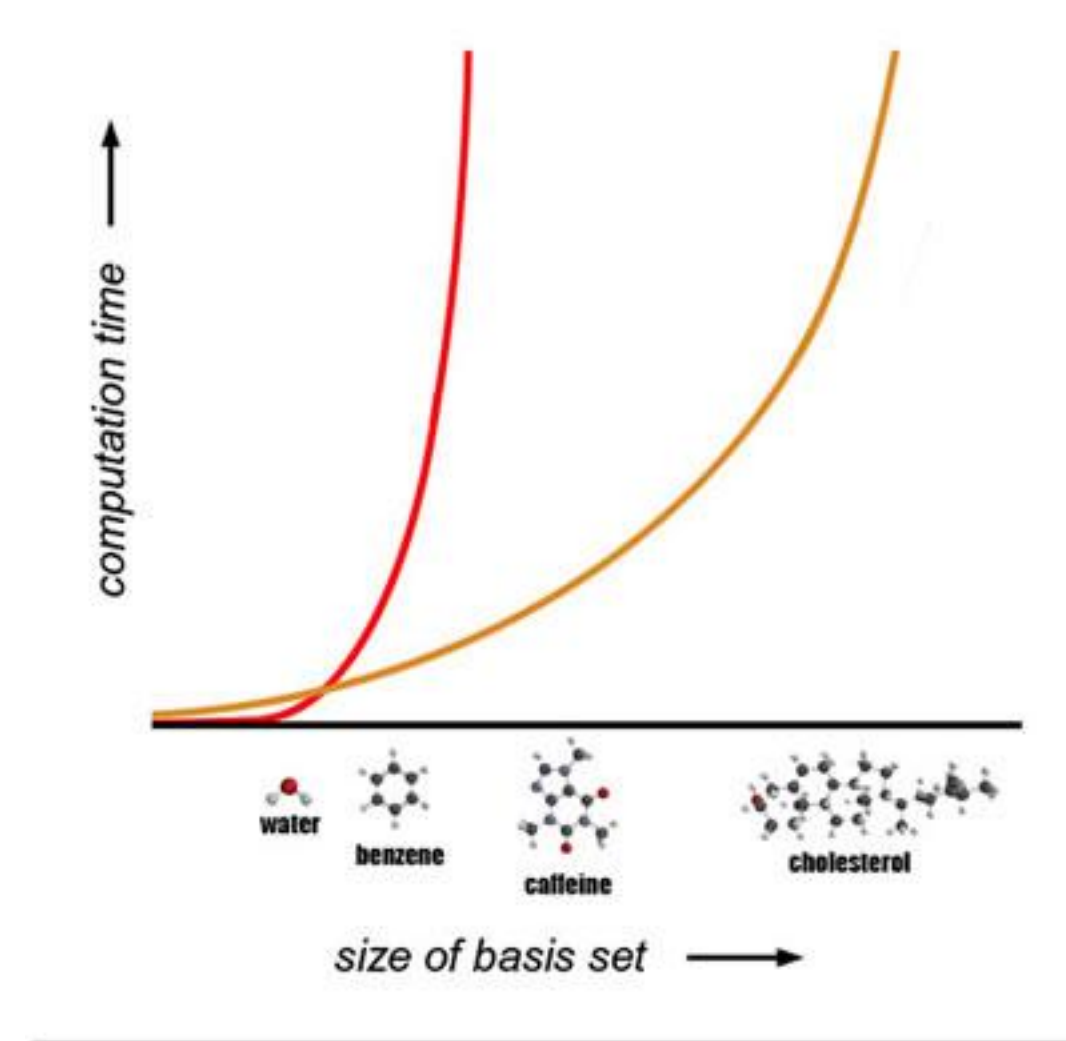
- Representing a 50 qubit state in double-precision floating point requires:
 - Unentangled: 800 bytes
 - Arbitrarily-entangled: **9 PB**

Entanglement powers quantum advantage

- A quantum computer with enough logical qubits can solve certain *exponentially* hard problems in *polynomial* time



K. K. Berggren, "Quantum computing with superconductors," in *Proceedings of the IEEE*, vol. 92, no. 10, pp. 1630-1638, Oct. 2004, doi: 10.1109/JPROC.2004.833672



<https://www2.lbl.gov/Science-Articles/Archive/CSD-quantum-chemistry.html>

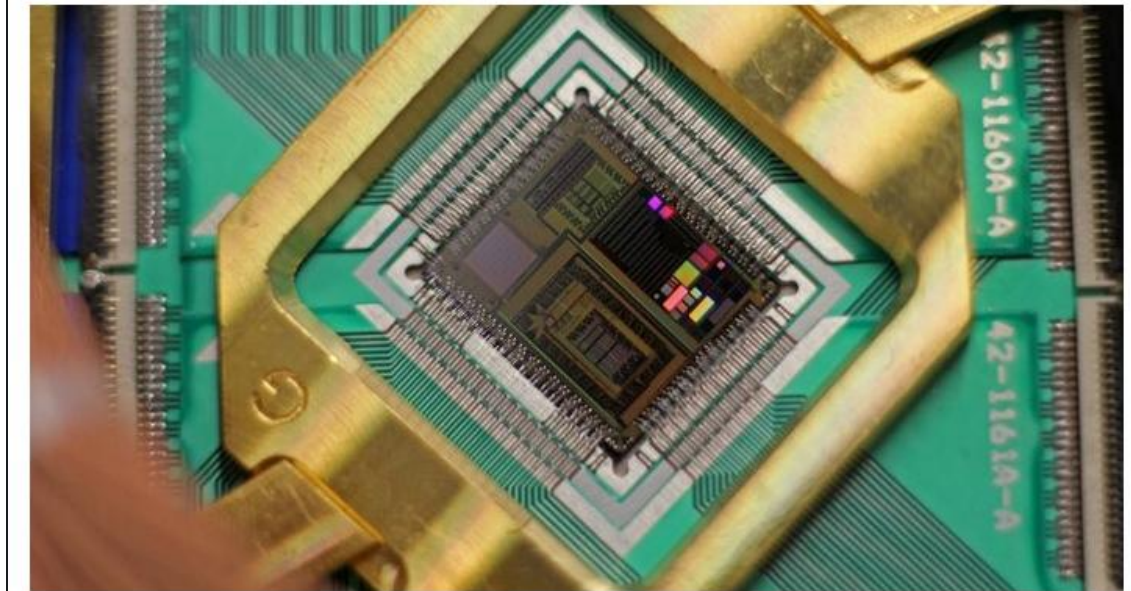
Decoherence

- One limit on quantum computing is finite coherence times – **how long can the system remain in an isolated superposition state ($|0\rangle + |1\rangle$) ?**
- Decoherence can be caused by any interaction with the environment
- Lots of sources, some well-understood, some not
- An elephant in the room: Ultra cold (mK) superconductors **universally** observe orders of magnitude more low energy excitations (broken Cooper pairs) than expected
 - Measured densities equivalent to **165 mK** (in 20 mK devices)

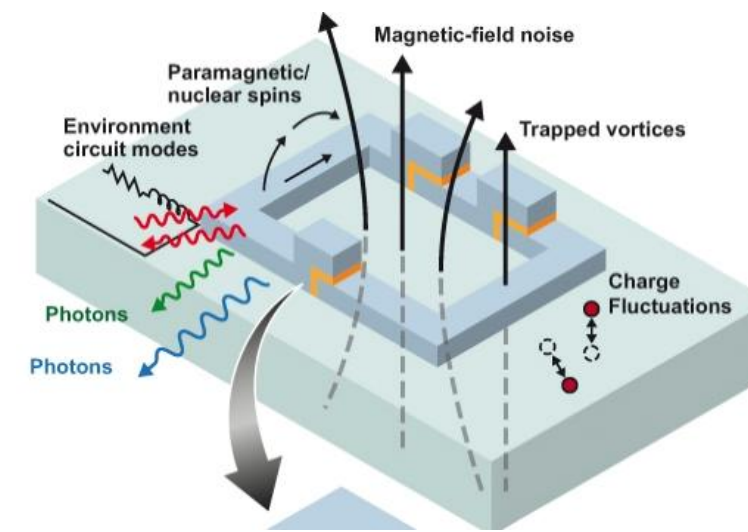
Decoherence: Quantum Computer's Greatest Obstacle

June 1st 2018

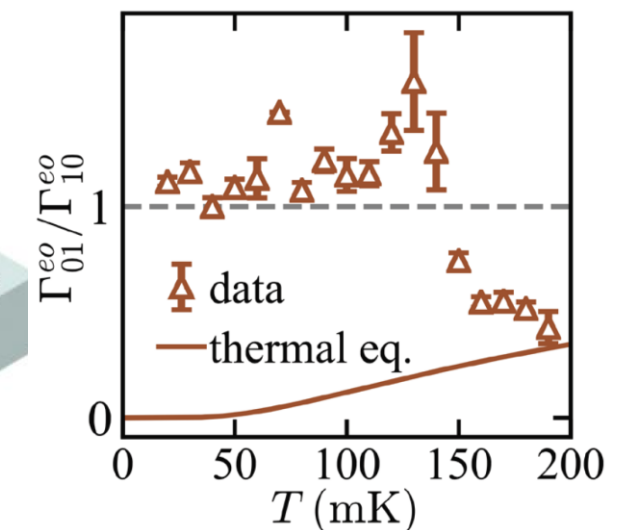
TWEET THIS



<https://hackernoon.com/decoherence-quantum-computers-greatest-obstacle-67c74ae962b6>



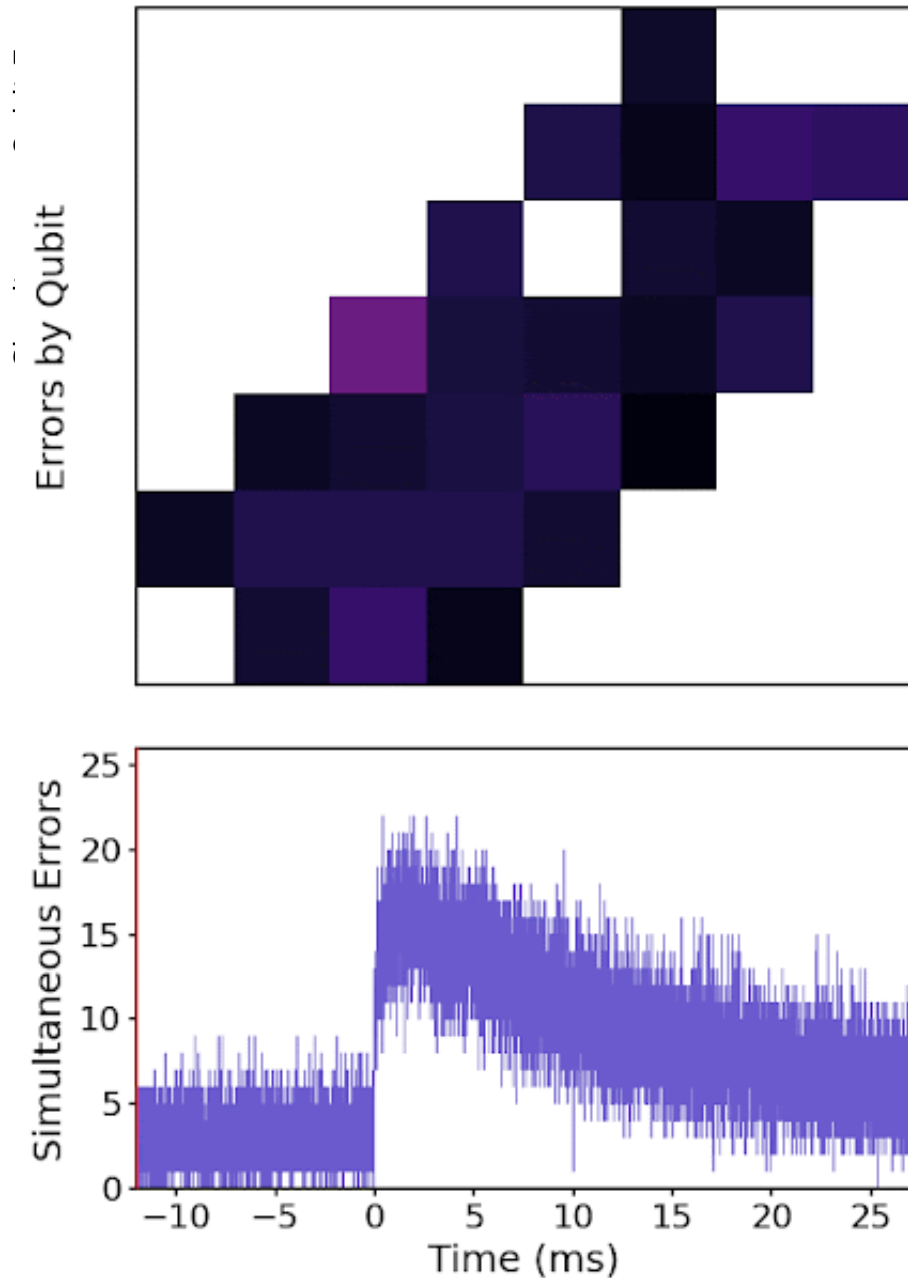
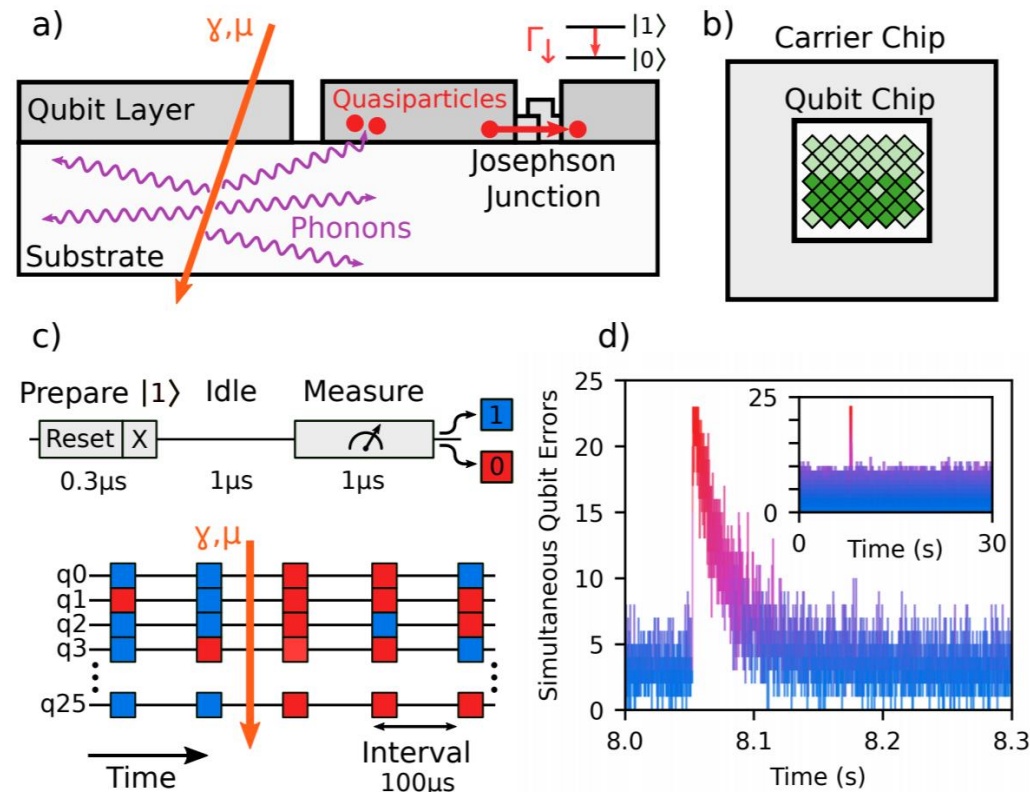
<https://doi.org/10.1557/mrs.2013.229>



Serbian et al., Phys. Rev. Lett. 121 157701 (2018)

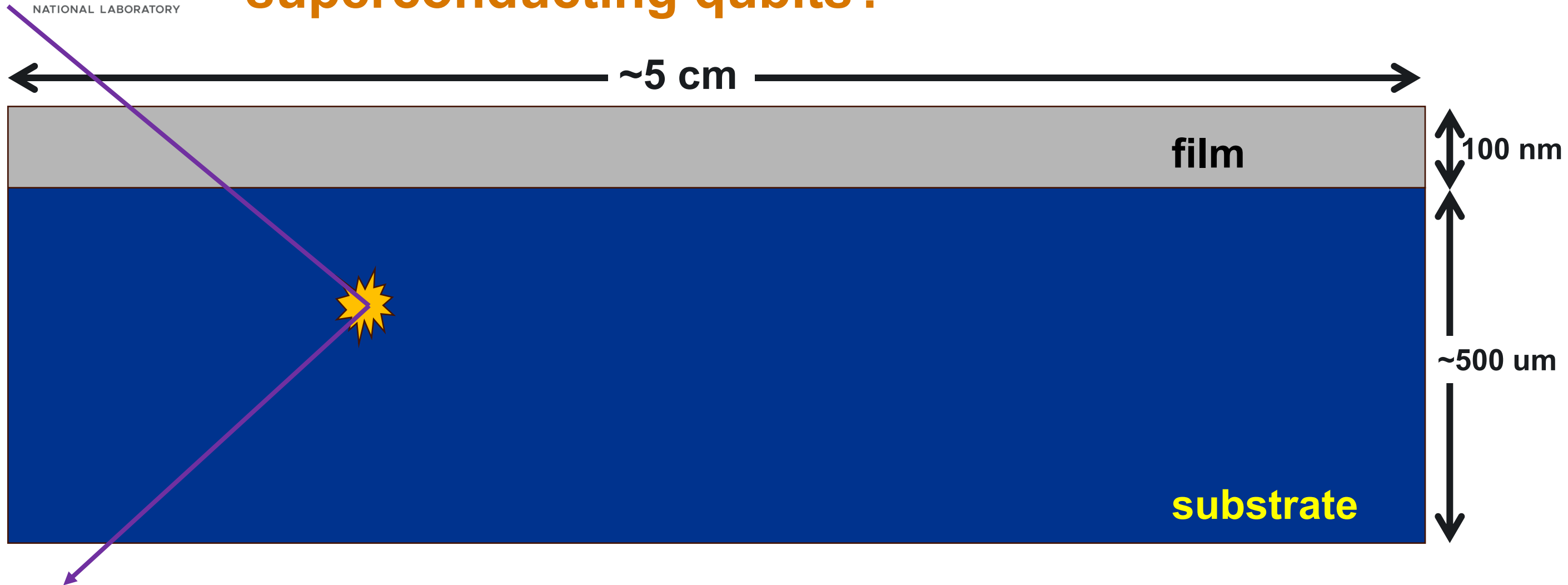
“Catastrophic error bursts”

- Simultaneously measure $|1\rangle \rightarrow |0\rangle$ bit-flip errors on 26 qubits every 100 μs
- **Bursts of correlated errors occurred every $\sim 10\text{s}$, consistent with radiation interaction rate**
- Time and space profile consistent with phonon + quasiparticle “cloud”



McEwen et al. “Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits.” *Nature Physics* **18**, 107 (2022)

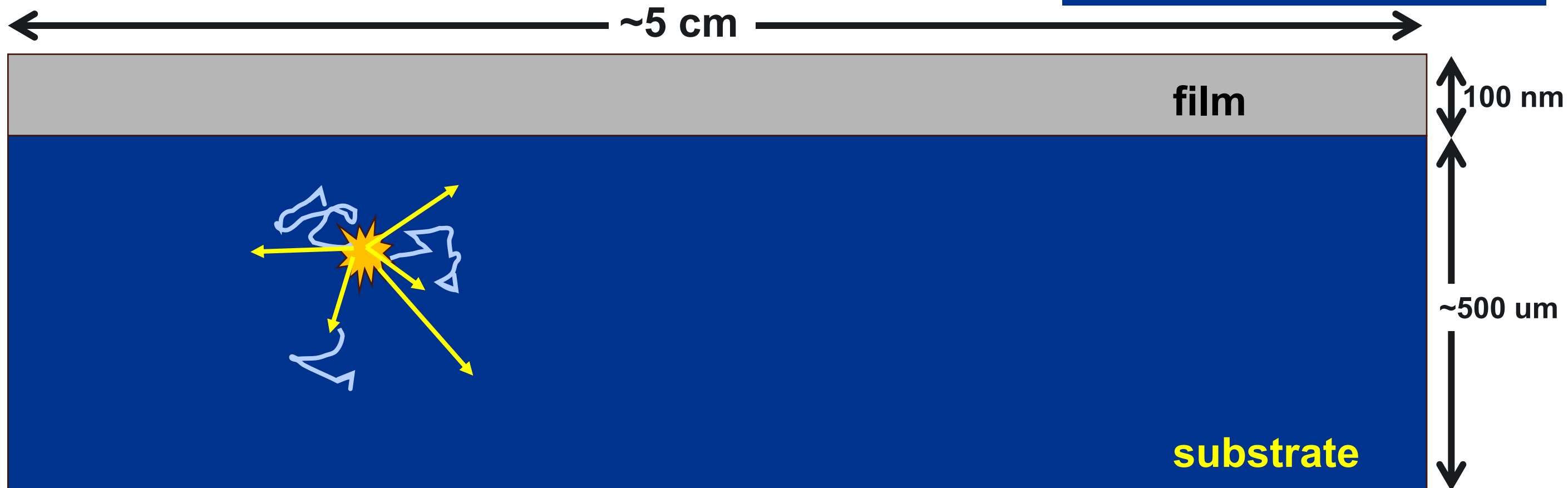
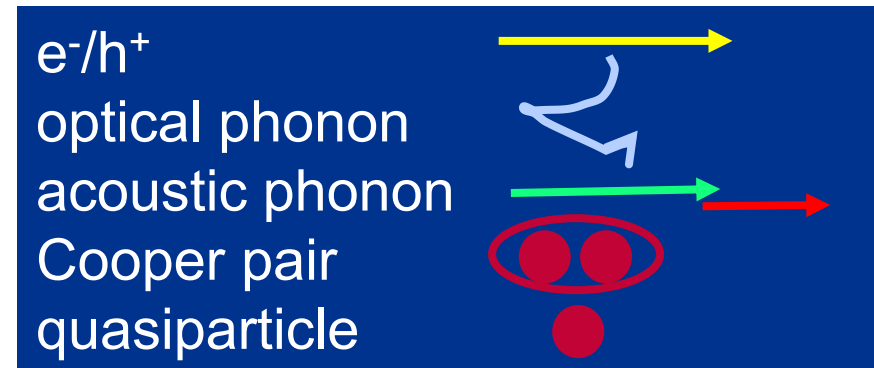
How does radiation affect superconducting qubits?



- Compton/ionization electron, nuclear recoil
- lattice defect formation from nuclear recoils

E: keV – MeV
t: 0 ns

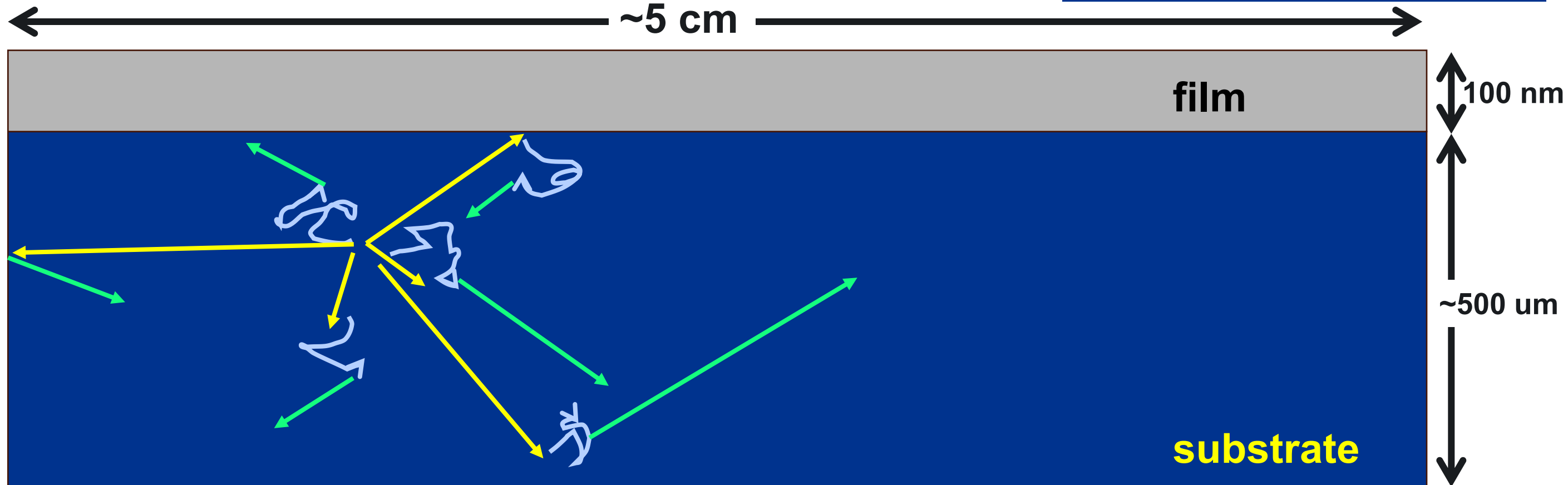
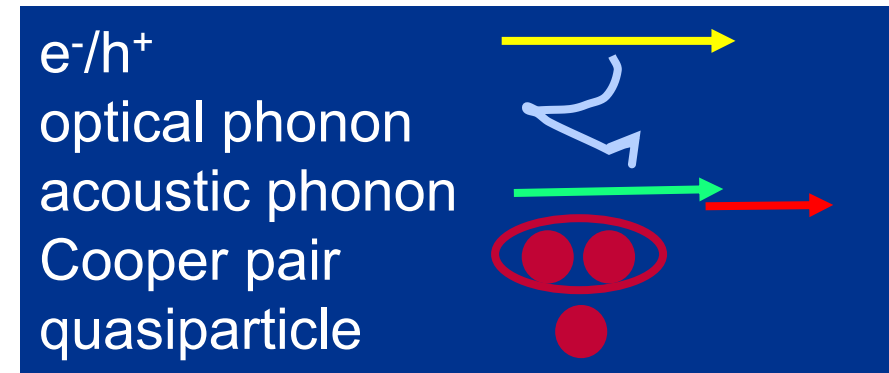
How does radiation affect superconducting qubits?



- electron-hole, optical phonon production

E: $0.05 - 1\text{ eV}$
t: 1 ns

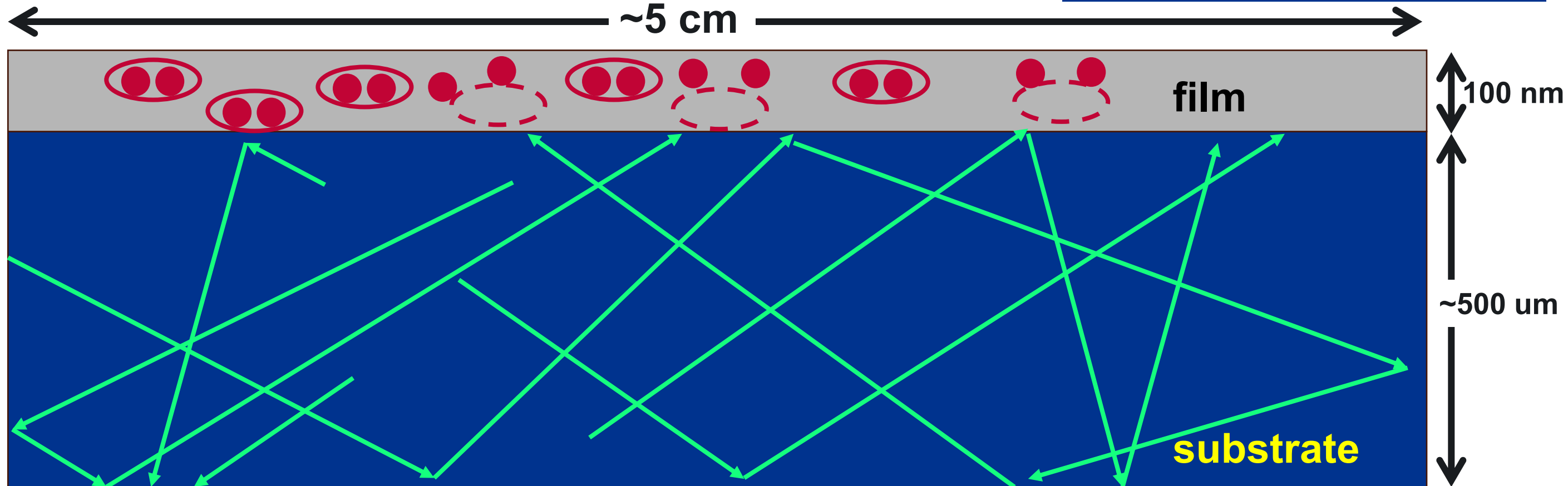
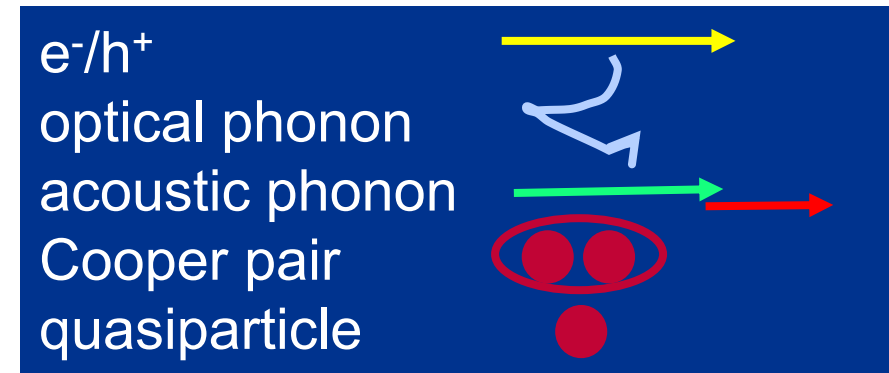
How does radiation affect superconducting qubits?



- electron-hole capture
- optical $\rightarrow$ acoustic phonon downconversion

E: 5 meV
t: 10 ns

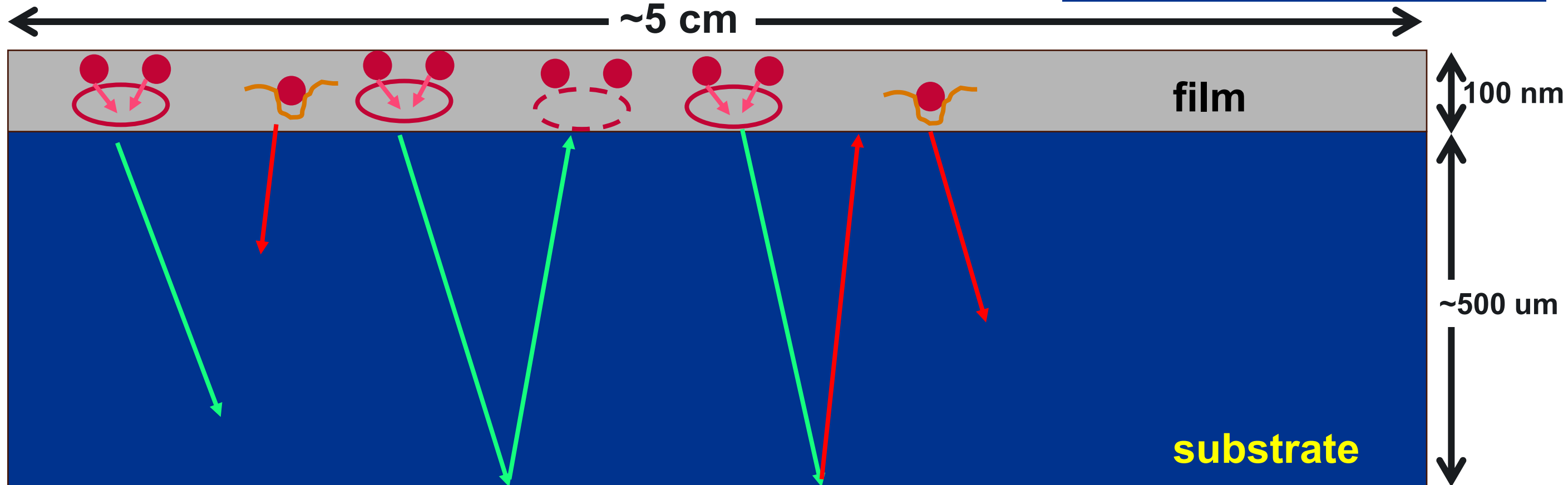
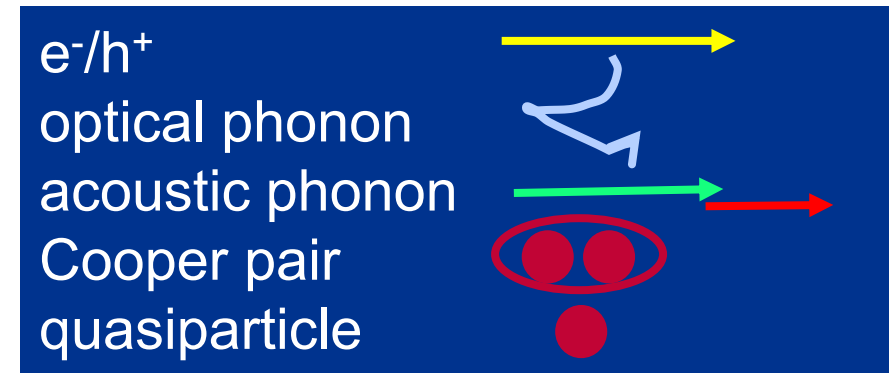
How does radiation affect superconducting qubits?



- Acoustic phonons propagate through substrate
- Phonons break Cooper pairs to form quasiparticles

E: 5 meV
t: 10-100 ns

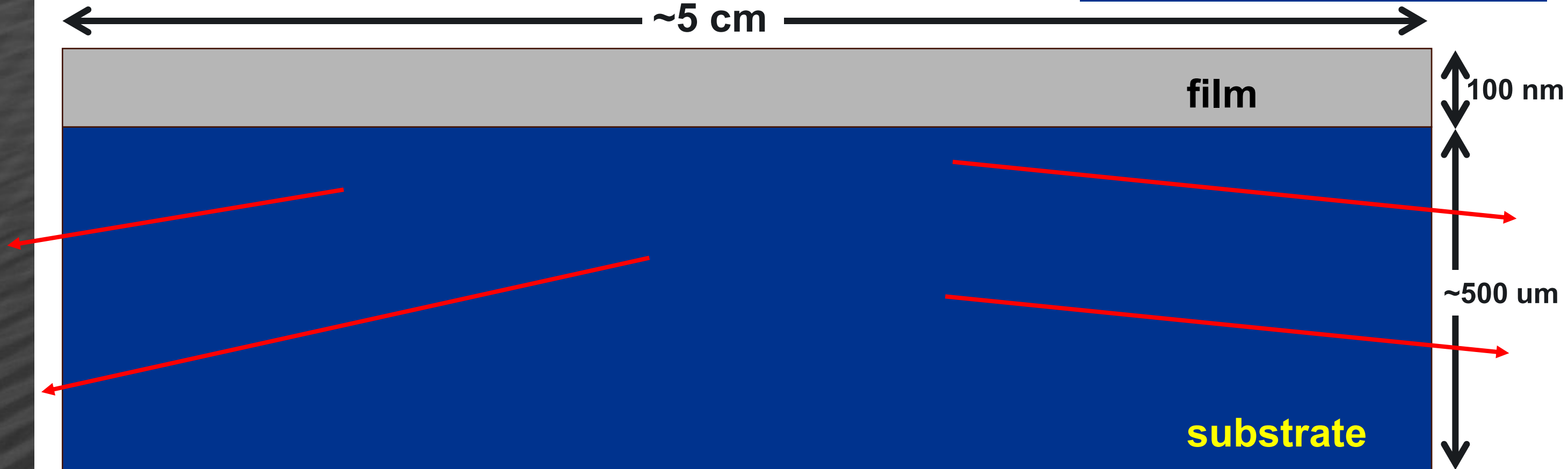
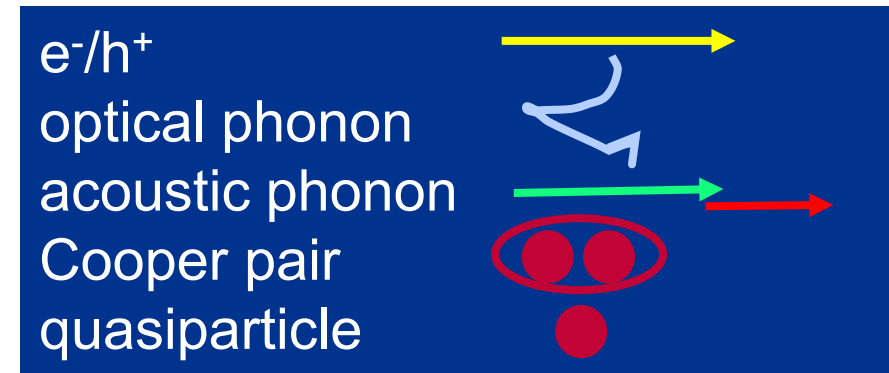
How does radiation affect superconducting qubits?



- QP recombination, trapping re-emit phonons into substrate
- System thermalizes to $T \sim E/C_V$
- QP recombination $\rightarrow$ resonant CP breaking persists athermal population

$E: \leq 180 \text{ ueV}$
 $t: 10\text{-}100 \text{ us}$

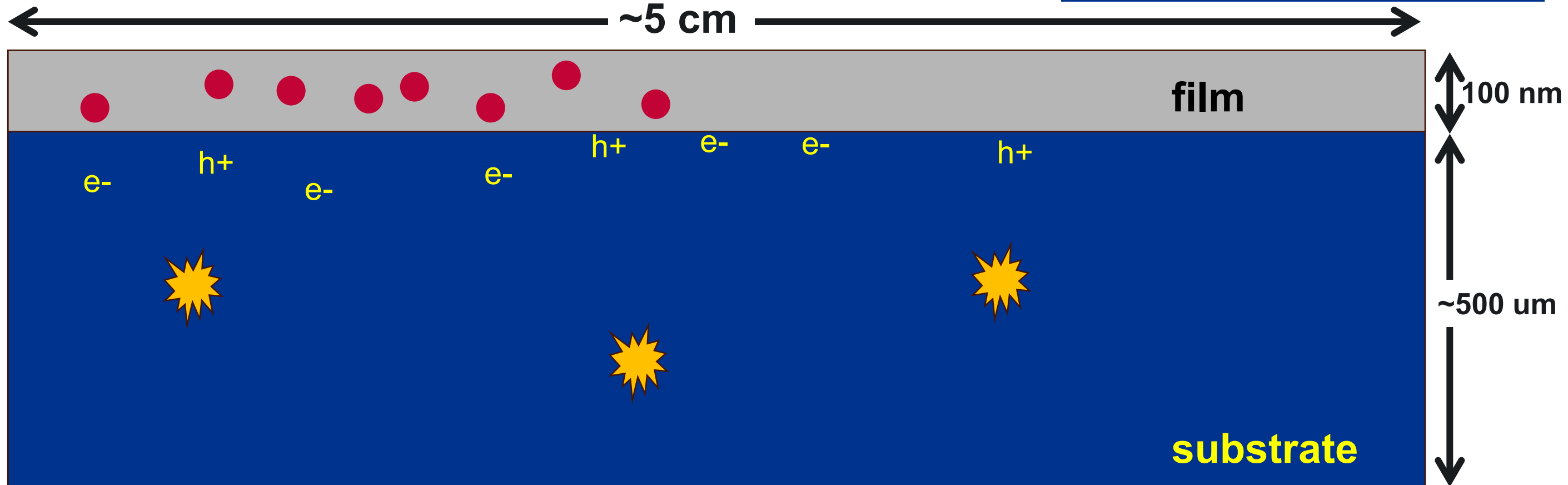
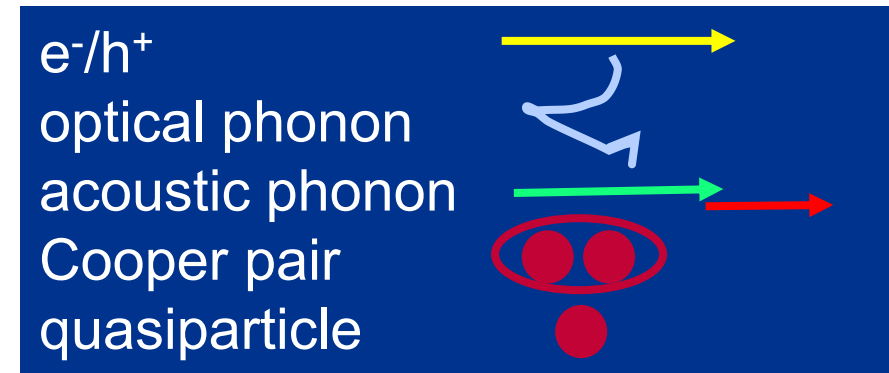
How does radiation affect superconducting qubits?



- Energy exits to the bath, system returns to base temperature
- If $C/G < \tau_{QP}$ or $E/C \ll T_C$, QP population might never be in thermal equilibrium

E: ~ μeV
t: 0.1 – 10 ms

How does radiation affect superconducting qubits?

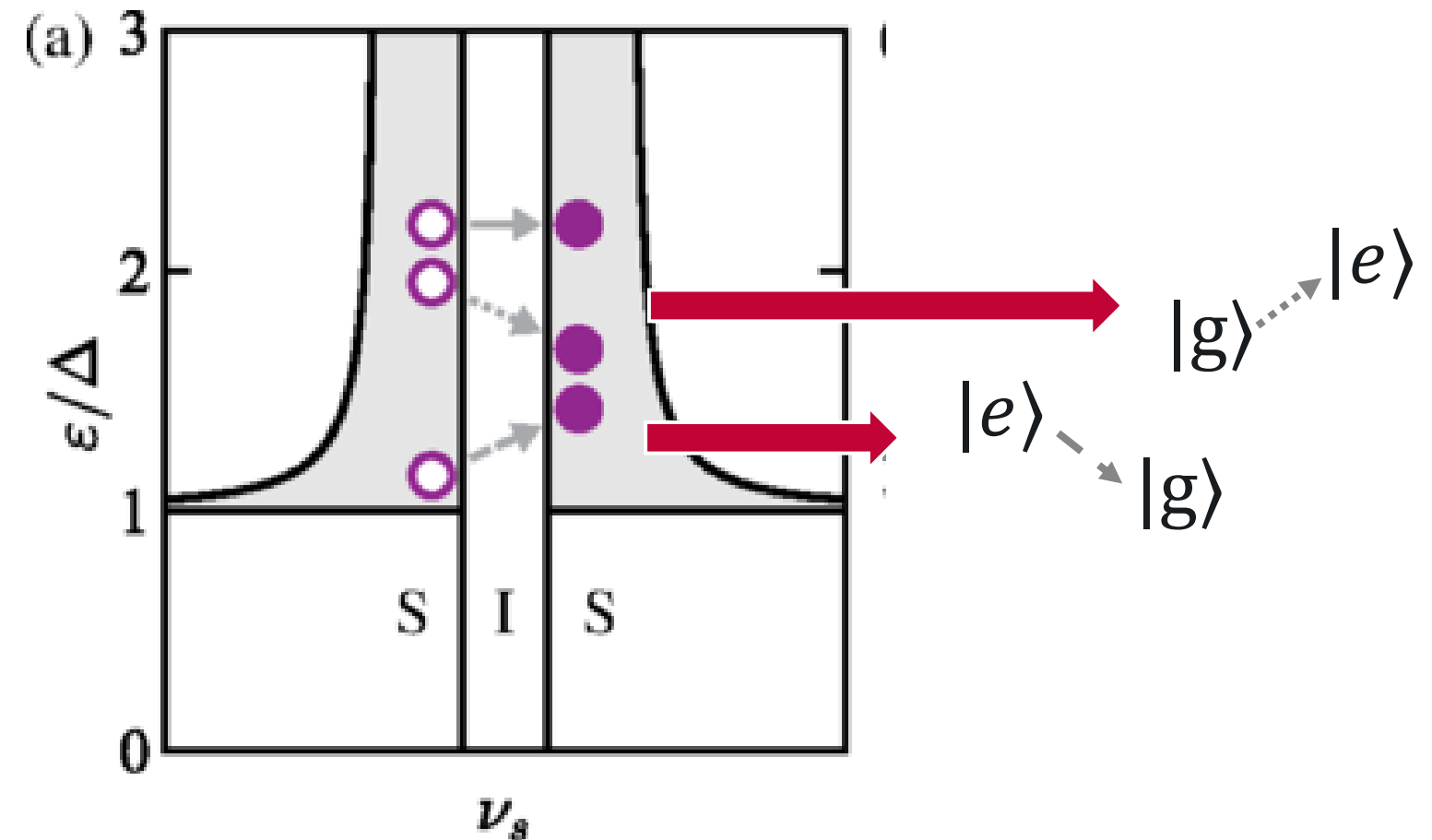


- “hot” QPs last $\sim \mu\text{s}$, cold QPs last $\sim \text{ms}$
- Lattice defects, charge trapping last hours (indefinitely)

Radiation-induced qubit error mechanisms

Quasiparticle tunneling

- Relaxation: QP steals energy from qubit, causes $|1\rangle \rightarrow |0\rangle$
- Excitation: QP gives energy to qubit, causes $|0\rangle \rightarrow |1\rangle$ (less common)
- Gate errors: QP absorbs photons from drive signal

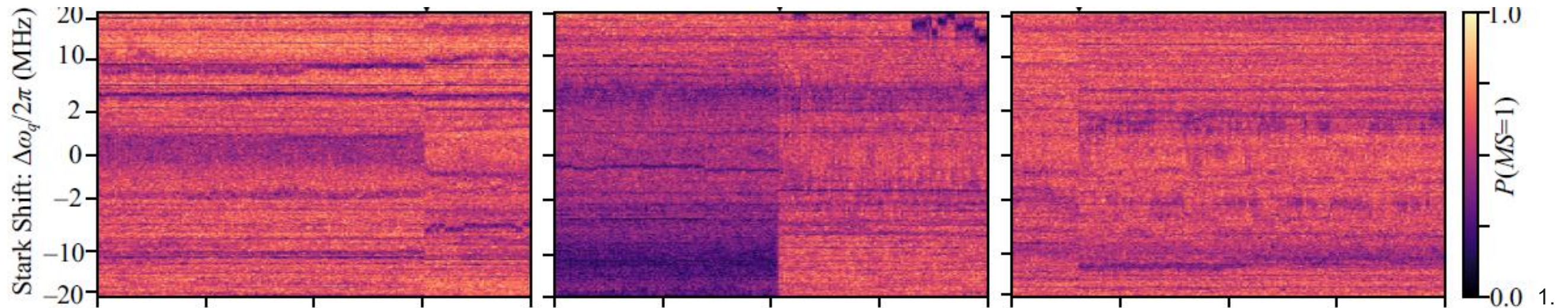


Adapted from Serniak, K. *et al.* Hot Nonequilibrium Quasiparticles in Transmon Qubits. *Phys. Rev. Lett.* **121**, 157701 (2018).

Radiation-induced qubit error mechanisms

Two Level Systems (TLS) coupling

- Qubit coupling to local environment changed by charge trap modifications
- QPs shift qubit frequency and increase linewidth, coupling to different TLS

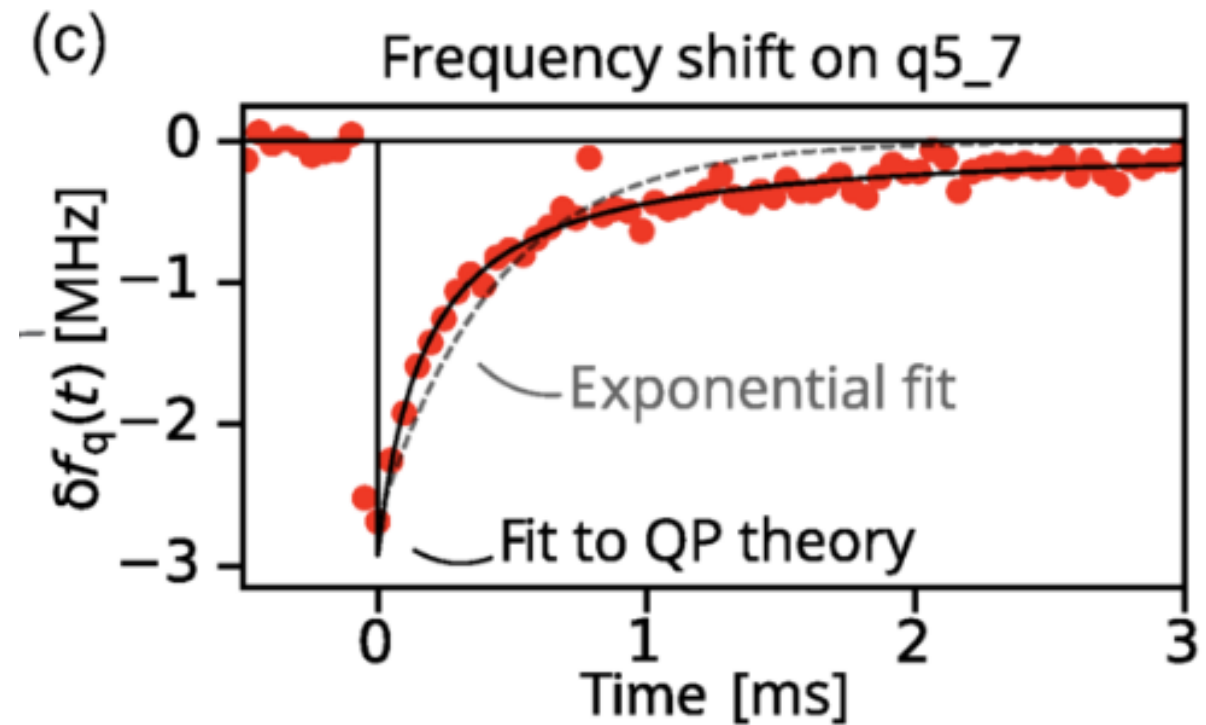
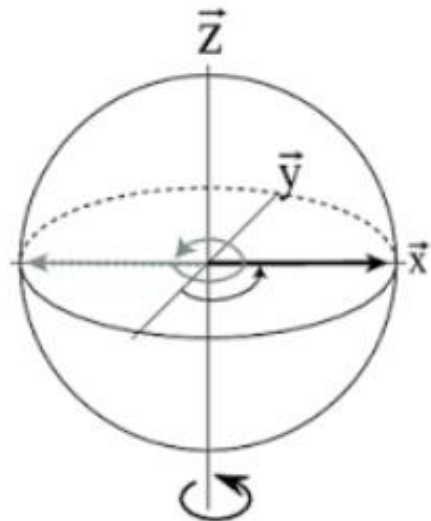


Thorbeck, T., Eddins, A., Lauer, I., McClure, D. T. & Carroll, M. Two-Level-System Dynamics in a Superconducting Qubit Due to Background Ionizing Radiation. *PRX Quantum* 4, 020356 (2023).

Radiation-induced qubit error mechanisms

QP induced frequency shift

- Phase precession offset $|0\rangle + e^{i(\delta\omega)t}|1\rangle$
- State preparation errors (drive with wrong frequency)

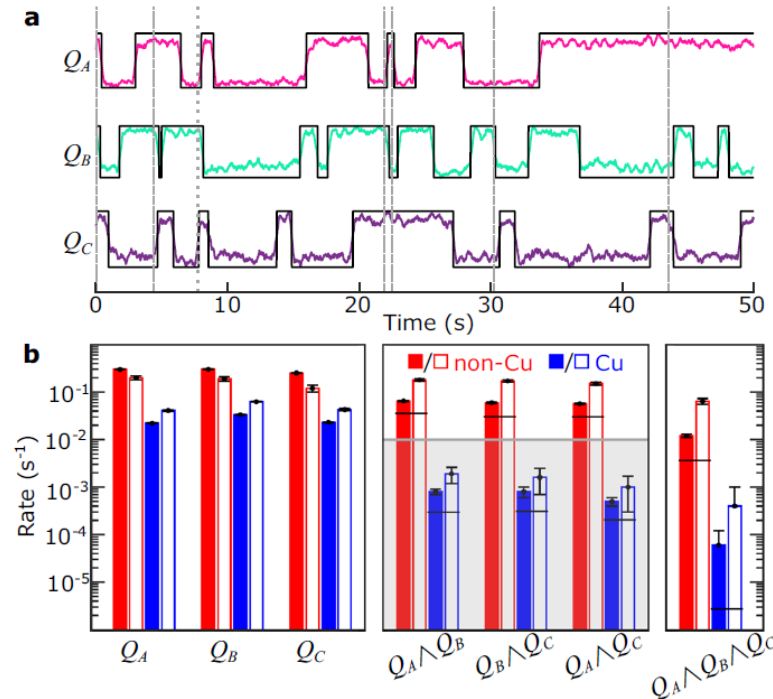
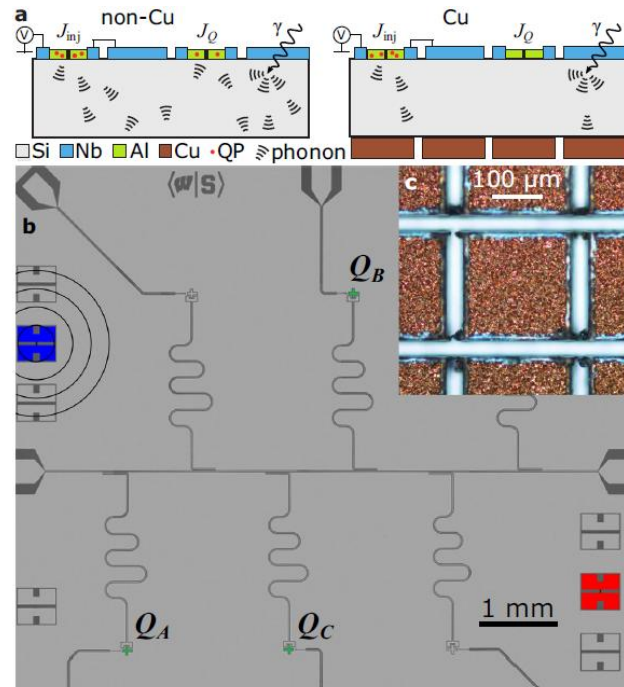


Kurilovich, V. D. *et al.* Correlated Phase Error Bursts in a Gap-Engineered Superconducting Qubit Array. *Phys. Rev. X* **16**, 021025 (2026).

Two paths forward

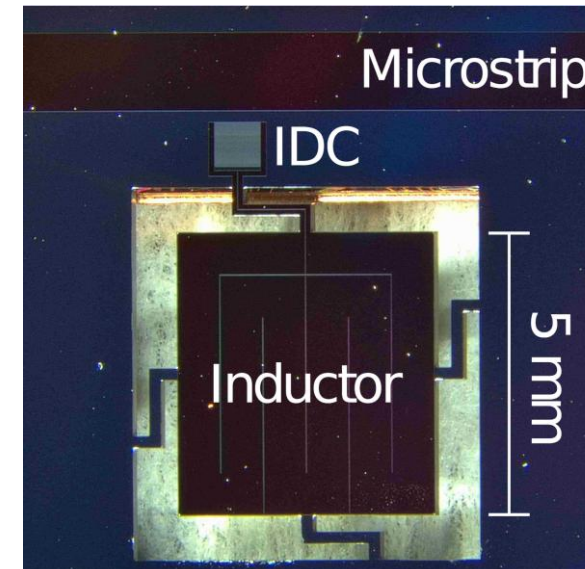
- Make qubits less sensitive, especially to correlated errors
- Reduce the radiation environment with shielding and material considerations

Phonon Protection



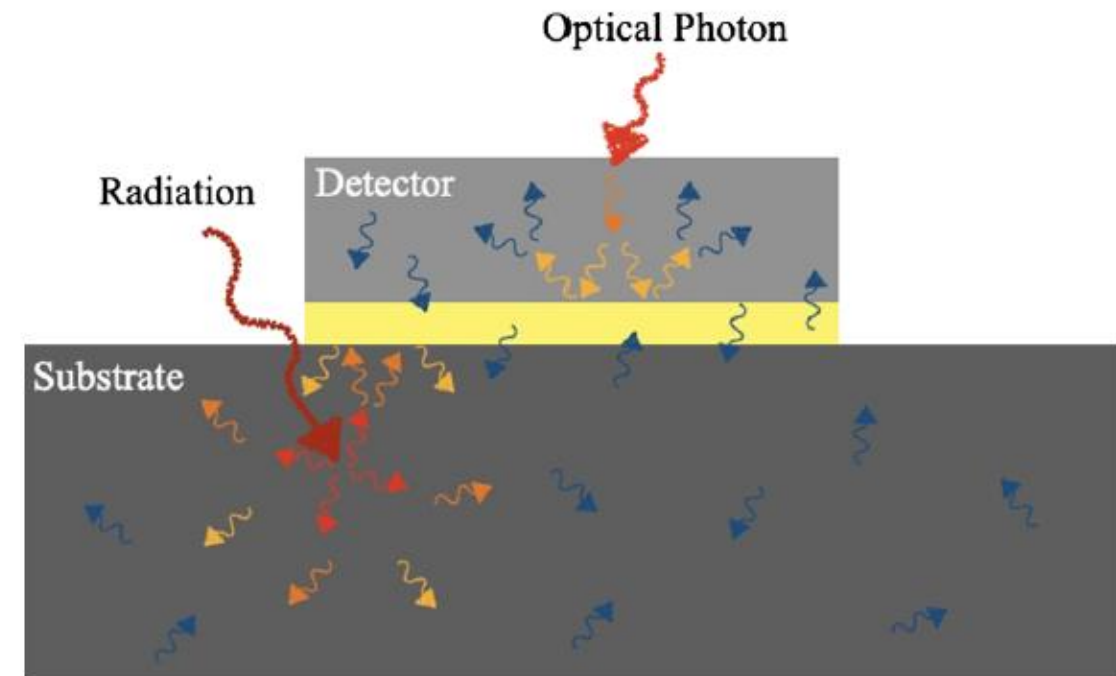
Normal metal on backside rapidly cools phonons to below superconducting gap

Iaia et al. "Phonon downconversion to suppress correlated errors in superconducting qubits." Nature Communications **13**, 6425 (2022)



Physically isolate the active elements from the rest of the substrate

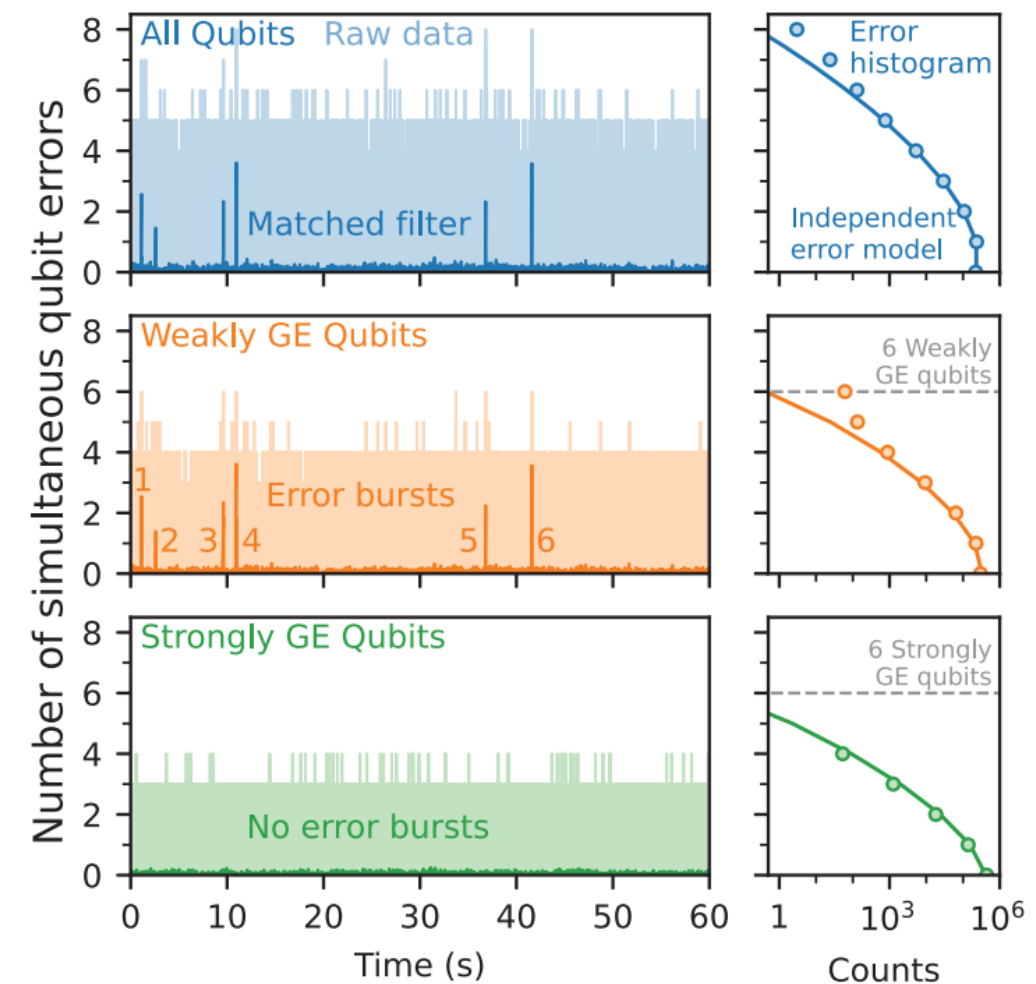
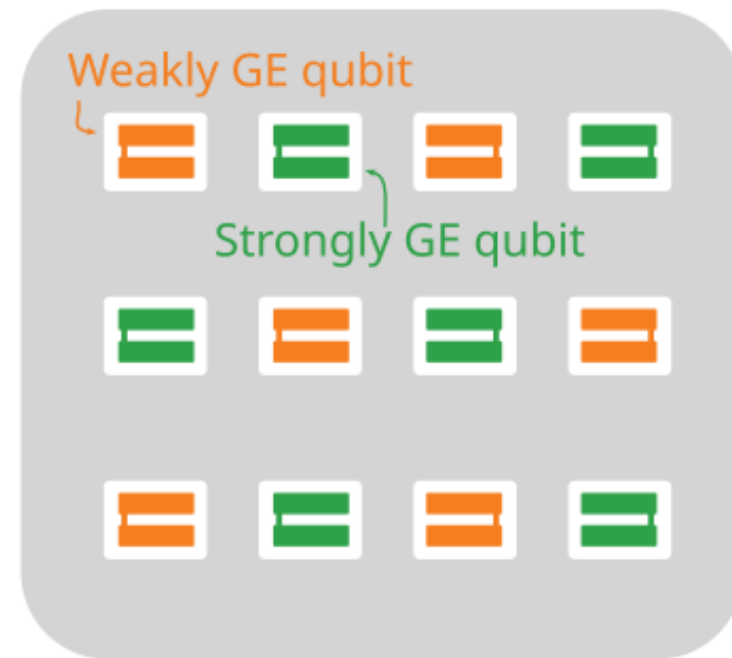
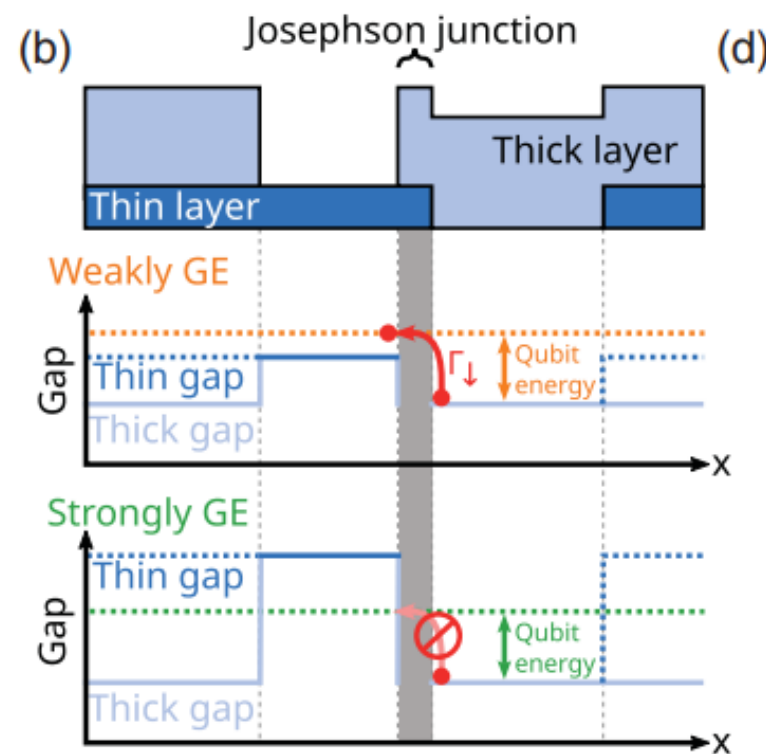
Fowler et al. "Spectroscopic Measurements and Models of Energy Deposition in the Substrate of Quantum Circuits by Natural Ionizing Radiation". PRX Quantum **5** 040323 (2024)



Zobrist et al. "Membraneless Phonon Trapping and Resolution Enhancement in Optical Microwave Kinetic Inductance Detectors". Phys. Rev. Lett. **129**, 017701 (2022)

Radiation Resistant Qubits: Gap Engineering

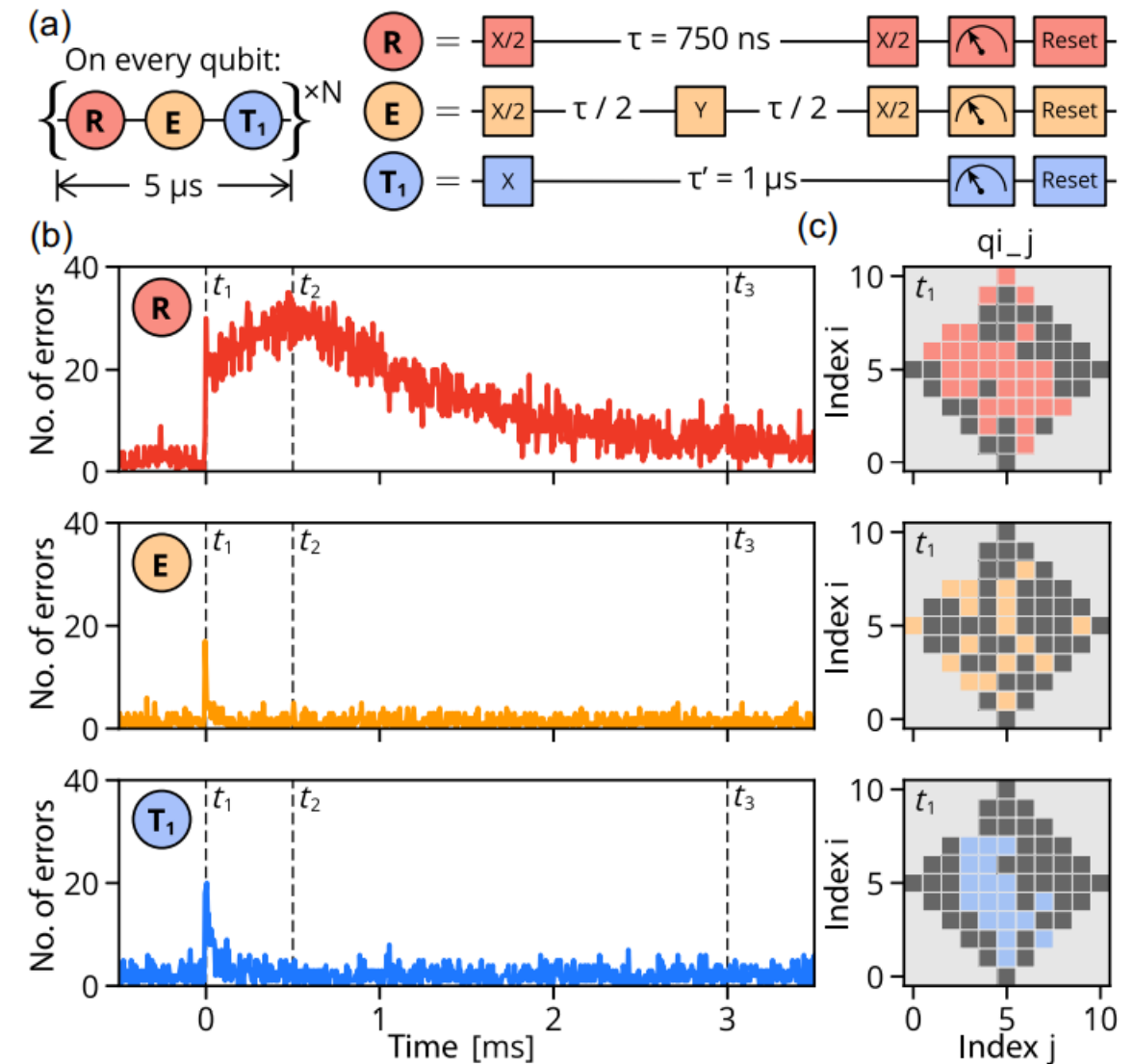
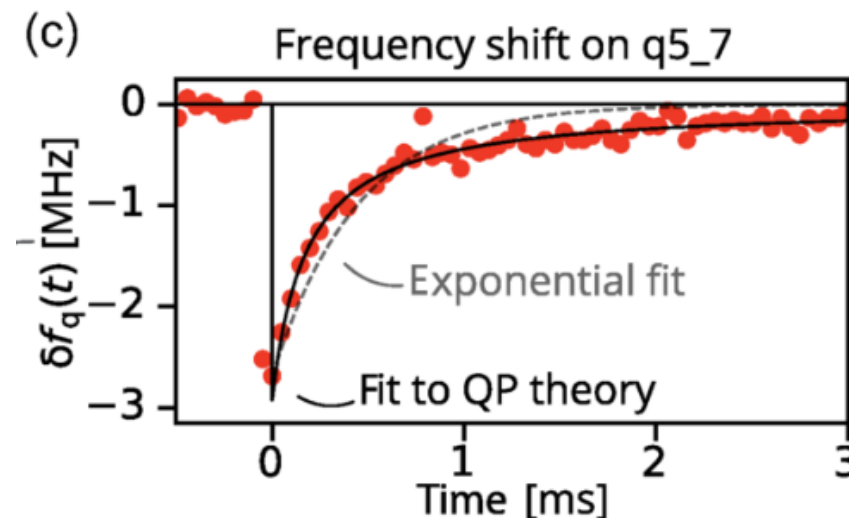
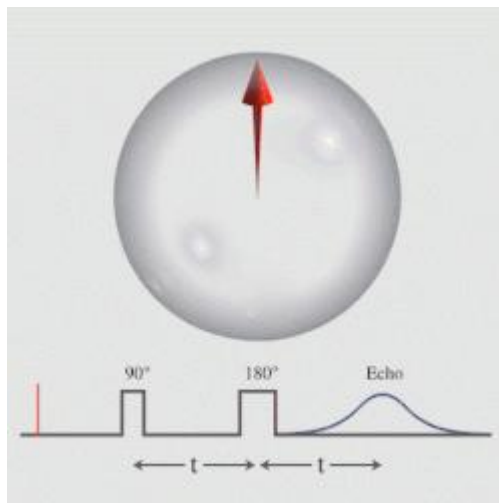
- Asymmetric Josephson junctions raise the barrier above the qubit excitation energy. Significantly reduces quasiparticle poisoning



McEwen et al. "Resisting High-Energy Impact Events through Gap Engineering in Superconducting Qubit Arrays". Phys. Rev. Lett. **133**, 240601 (2024)

Latest results shed more light on gap engineering

- Sample much more rapidly
- Add Ramsey and spin echo sequence to detect phase errors
- Phase drift not affected by gap engineering threshold
- Spin echo improvement over Ramsey indicates the phase drift is “quasi-static”

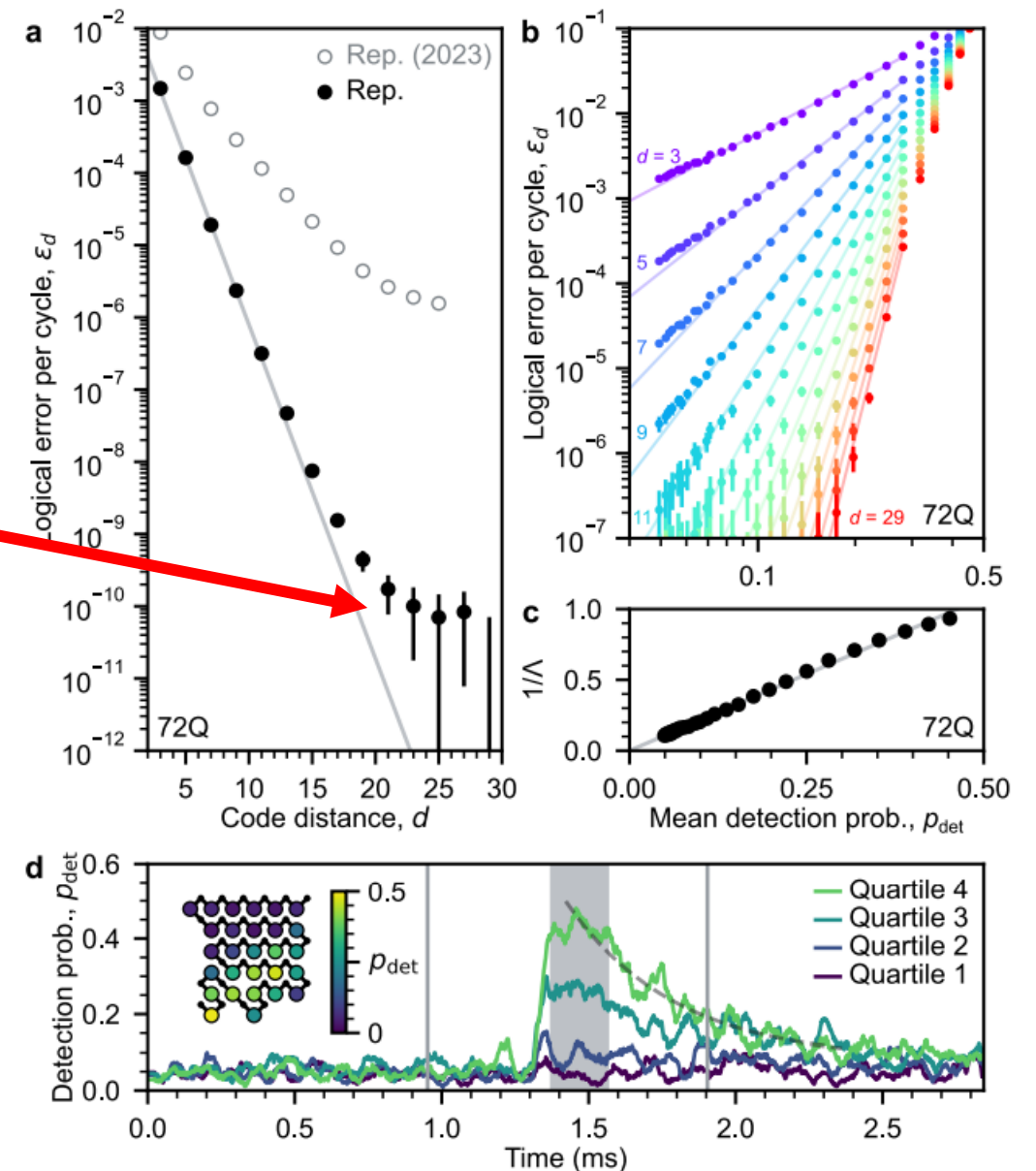


Kurilovich, V. D. *et al.* Correlated Phase Error Bursts in a Gap-Engineered Superconducting Qubit Array. *Phys. Rev. X* **16**, 021025 (2026).

Surpassing the Logical Error Correction Limit

- Beyond break-even error correction achieved using gap-engineered qubits
- Still observe large correlated error bursts, but with frequency $\sim 1/\text{hour}$ (vs $1/10\text{s}$)
- What sets this new floor, and can we overcome it?

Quantum Error Correction Below the Surface Code Threshold.
Google Quantum AI and Collaboration. Nature **638**, pages 920–926
(2025)



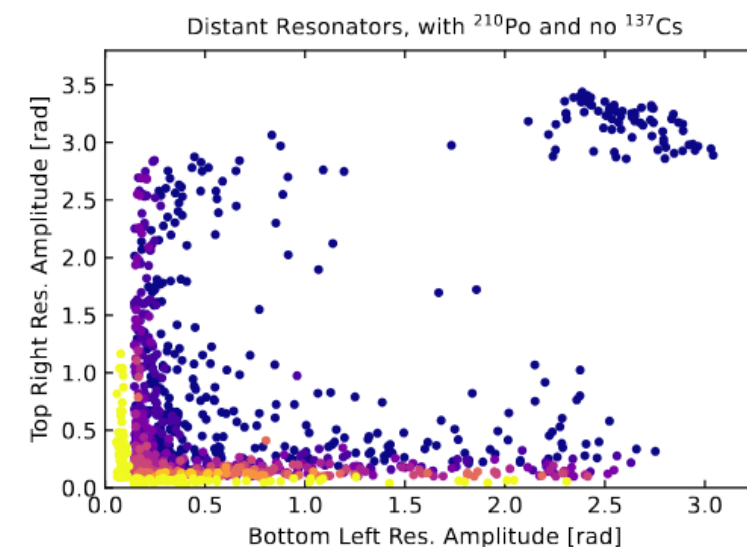
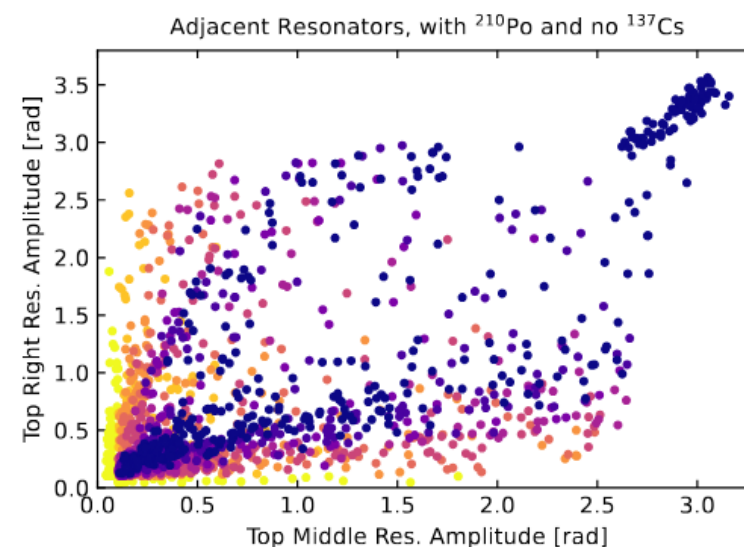
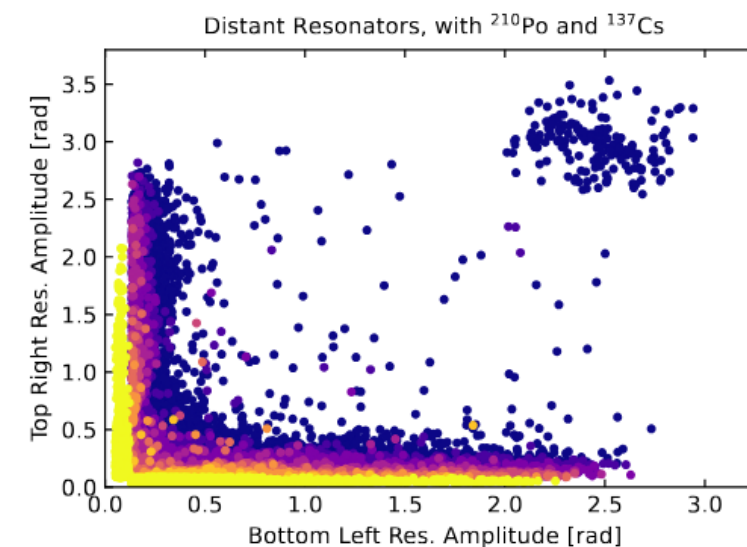
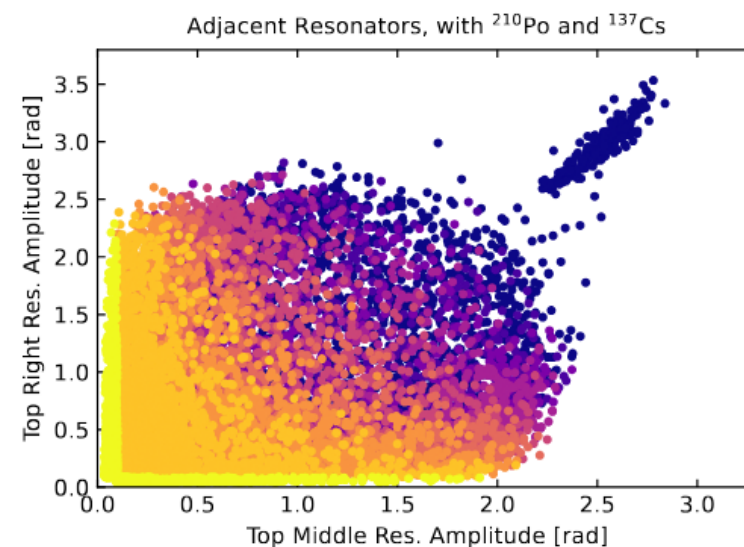
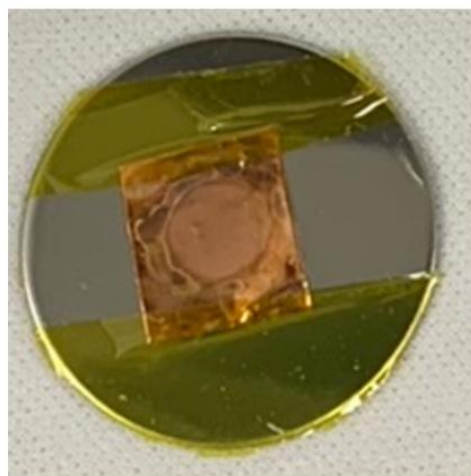
Modeling and Measuring Ionizing Radiation

- First Google “Catastrophic” paper saw correlated errors $\sim 1/10$ s
- Gap engineered floor $\sim 1/\text{hour}$
- Spoiler: Rates are consistent with raising the effective sensitivity threshold from $\sim \text{keV}$ to MeV scales
- Until qubits are completely “rad hard”, how best to reduce the radiation environment?
- Spoiler: We probably need to go underground

High energy impacts (^{210}Po alphas) spread across the whole device

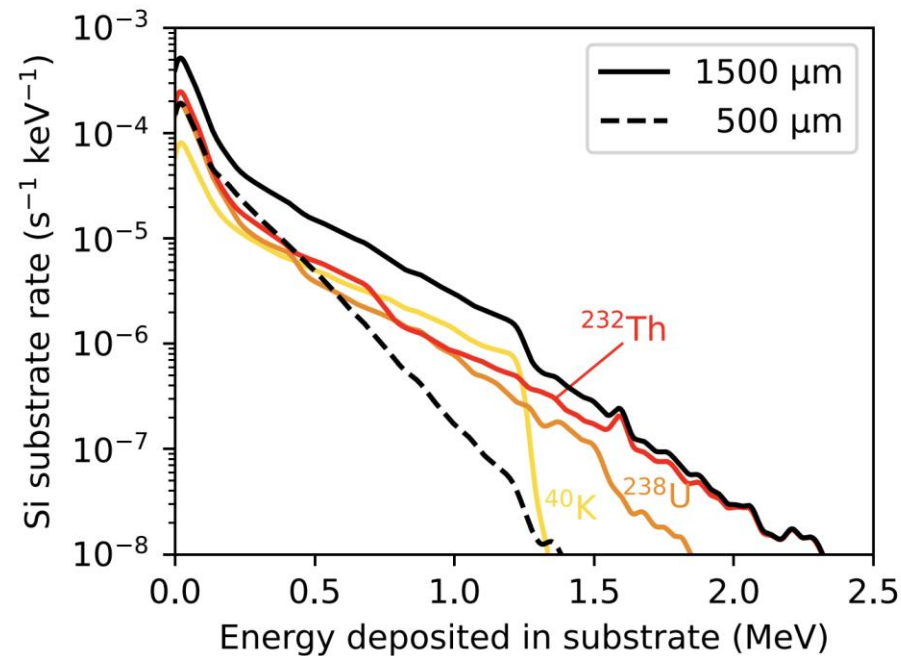


1 cm



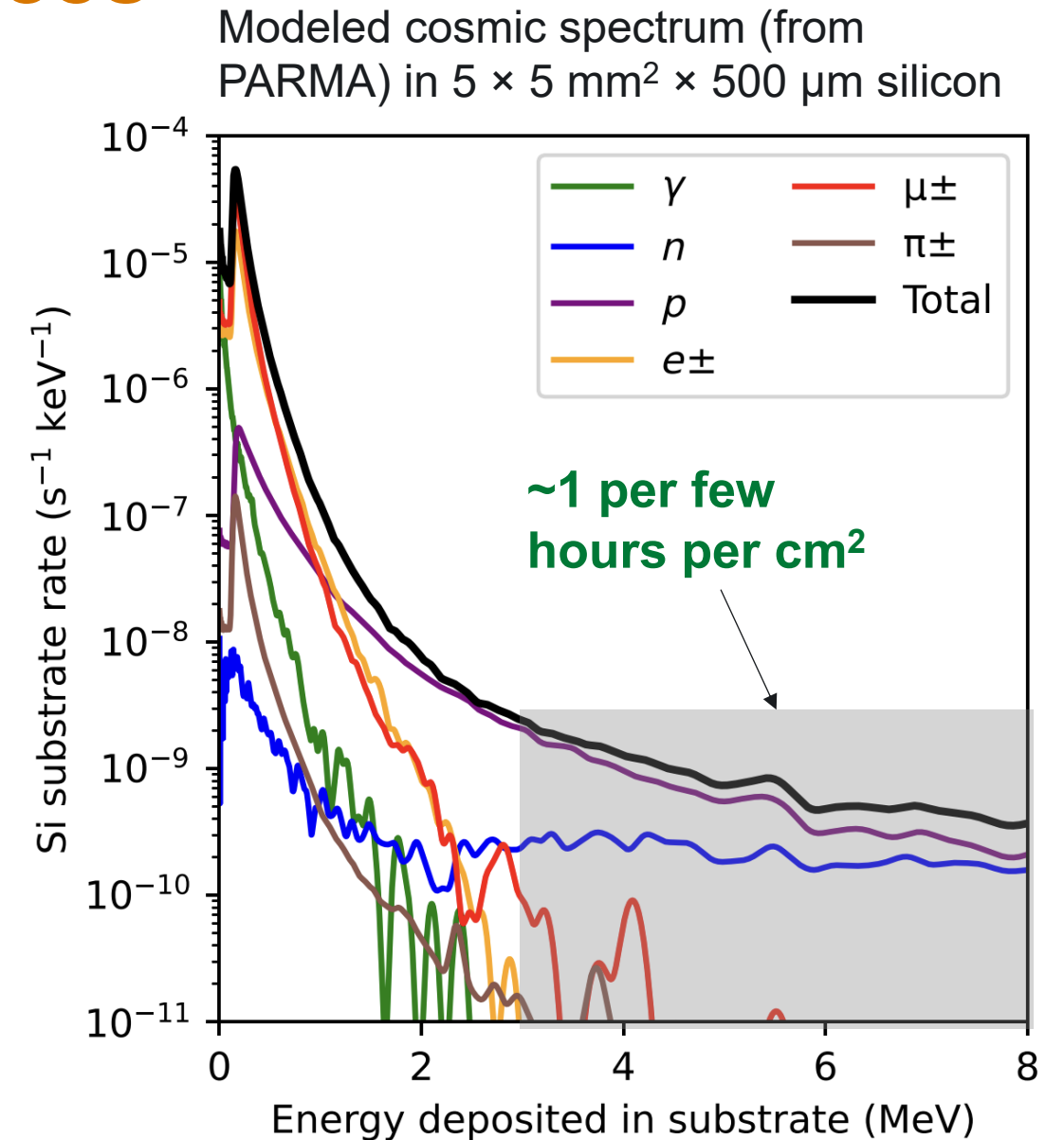
Energy Spectra in Superconducting Devices from Environmental Sources

- Modeling predicts rare (~ 1 per few hours per cm^2) cosmic ray proton and neutron events with $E_{\text{dep}} \gtrsim 3 \text{ MeV}$



Modeled gamma spectrum in $5 \times 5 \text{ mm}^2$ silicon

Fowler, J. W. *et al.* Spectroscopic Measurements and Models of Energy Deposition in the Substrate of Quantum Circuits by Natural Ionizing Radiation. *PRX Quantum* **5**, 040323 (2024).

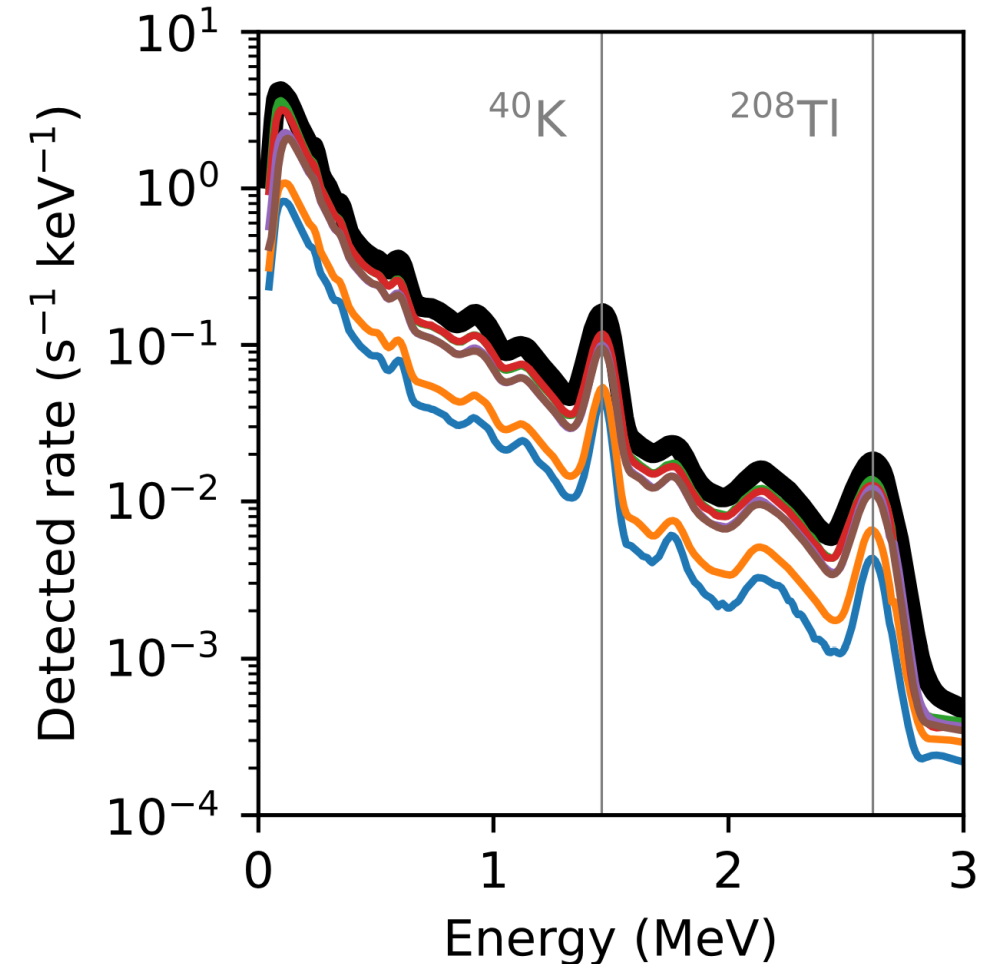
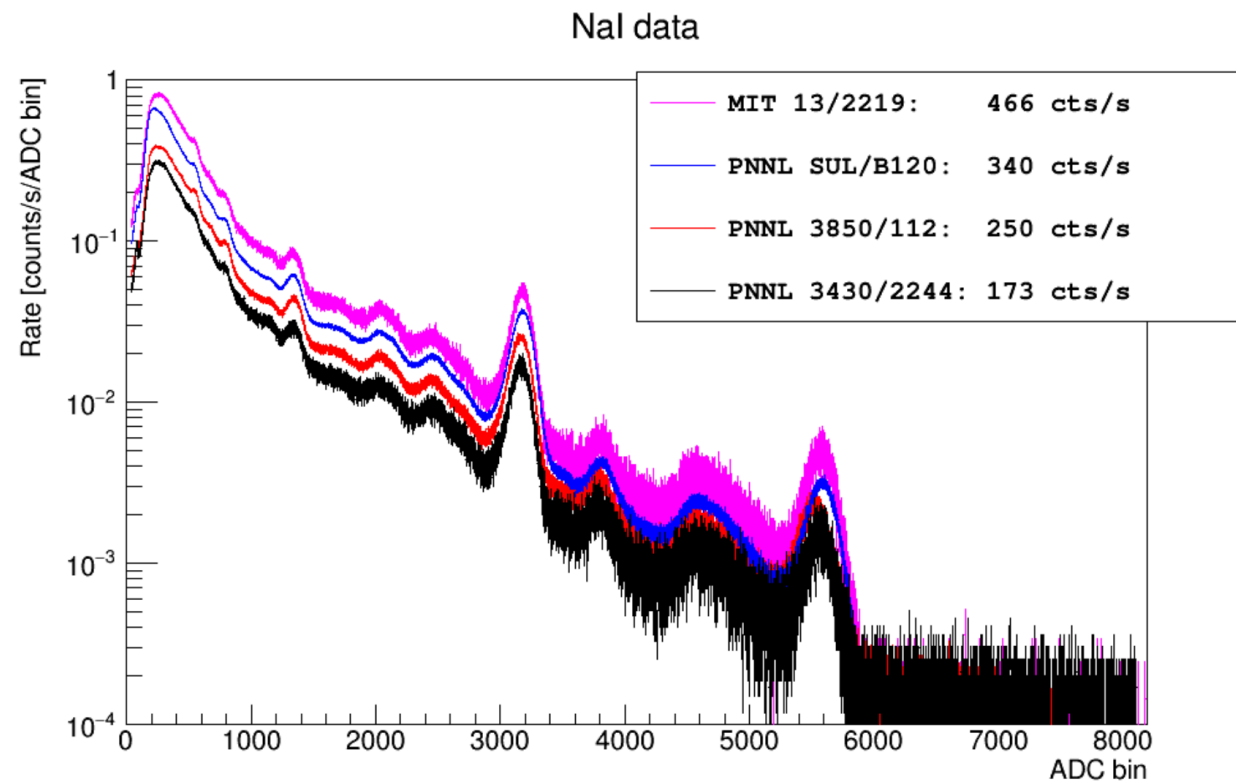


[Fowler *et al.*, PRX Quantum 5 040323 \(2024\)](#)

Common Gamma Backgrounds

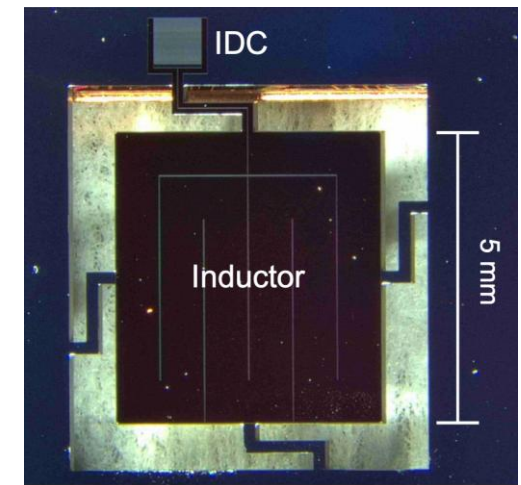


- Environmental gamma and muon rates measured in multiple buildings, laboratories, and institutions with same instrument
- All within factor of ~ 5

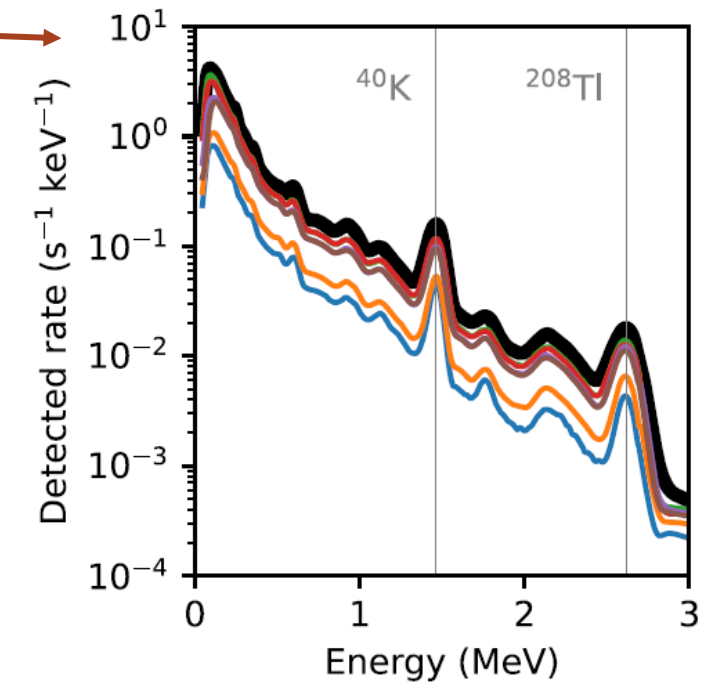
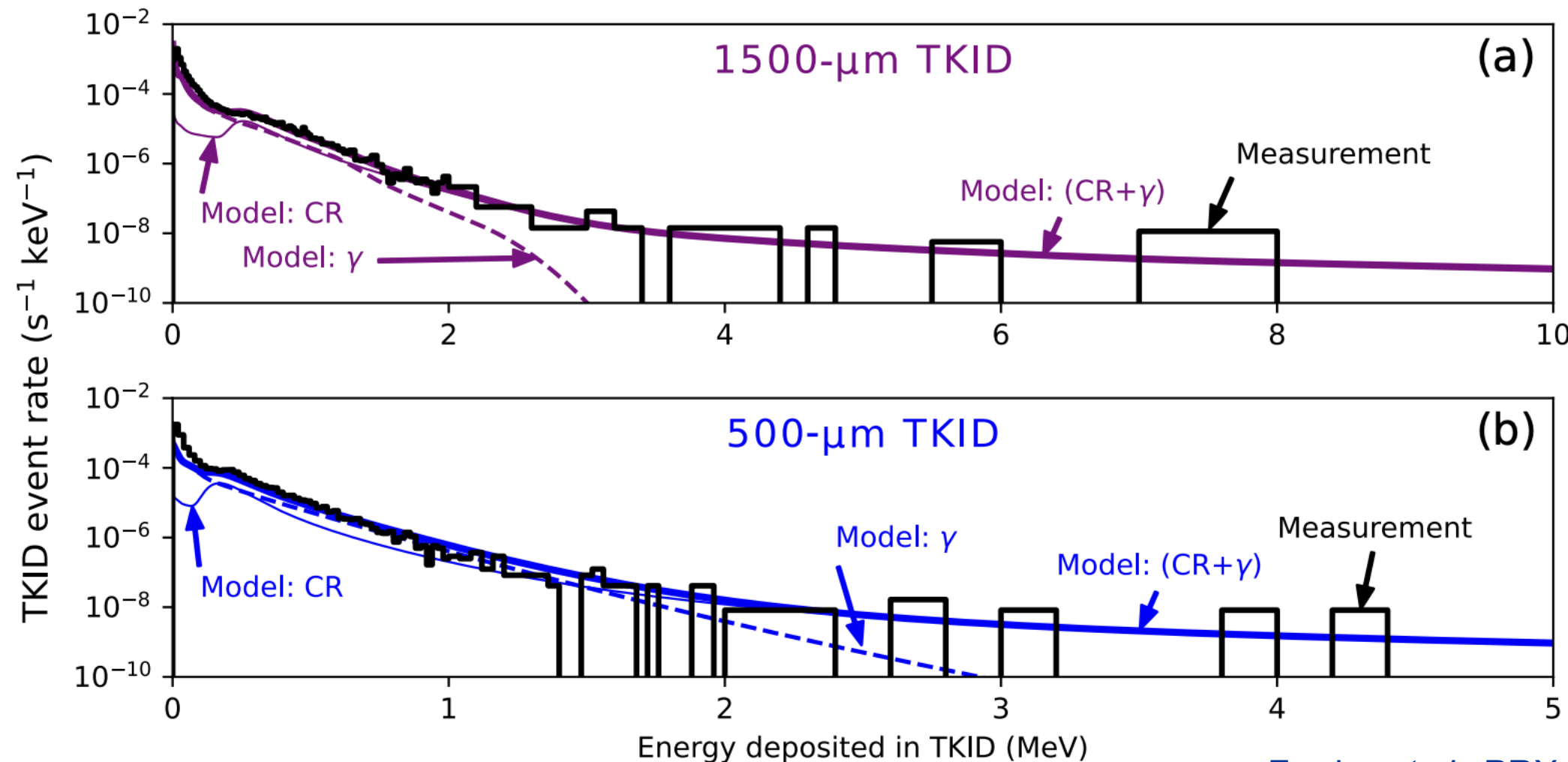


Measured Energy Spectra in QIS Devices

Thermal Kinetic Inductance Device (TKID)



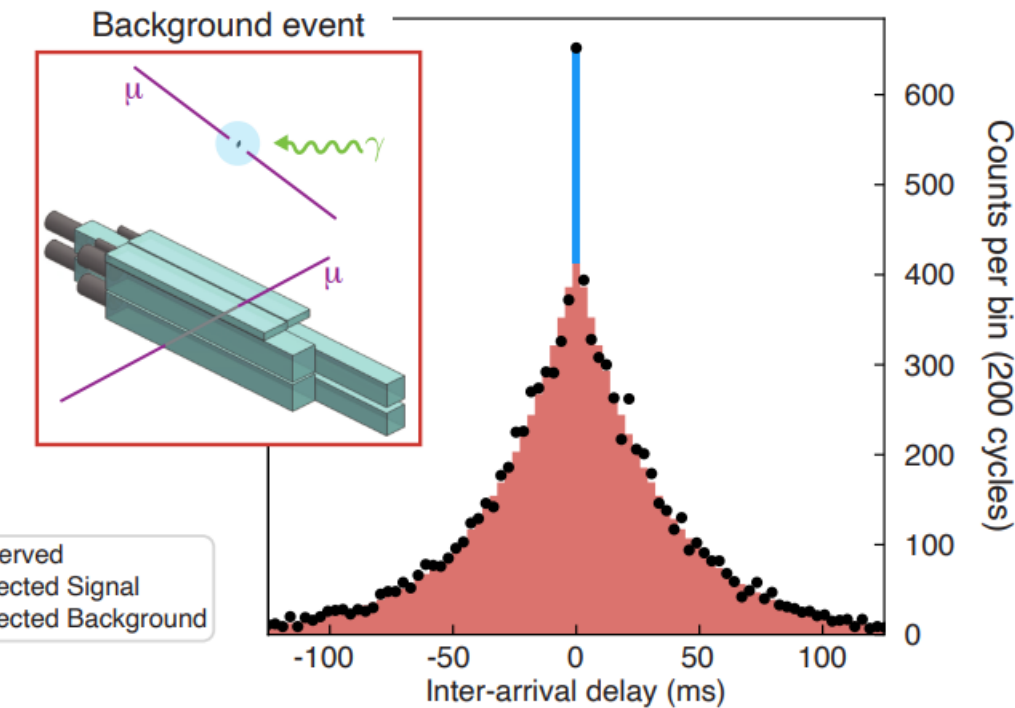
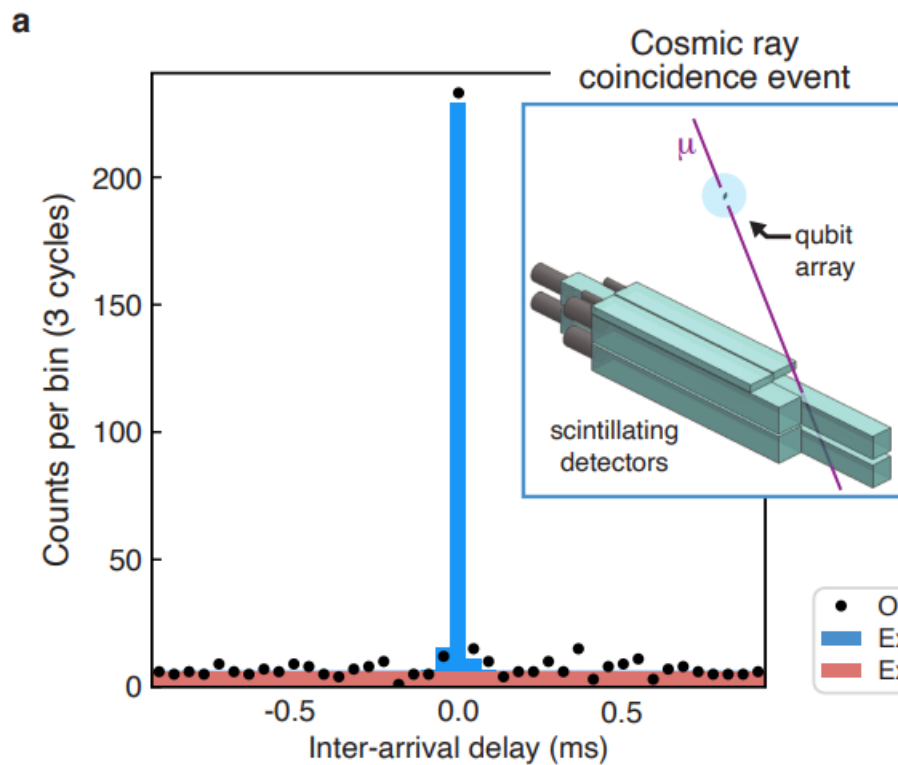
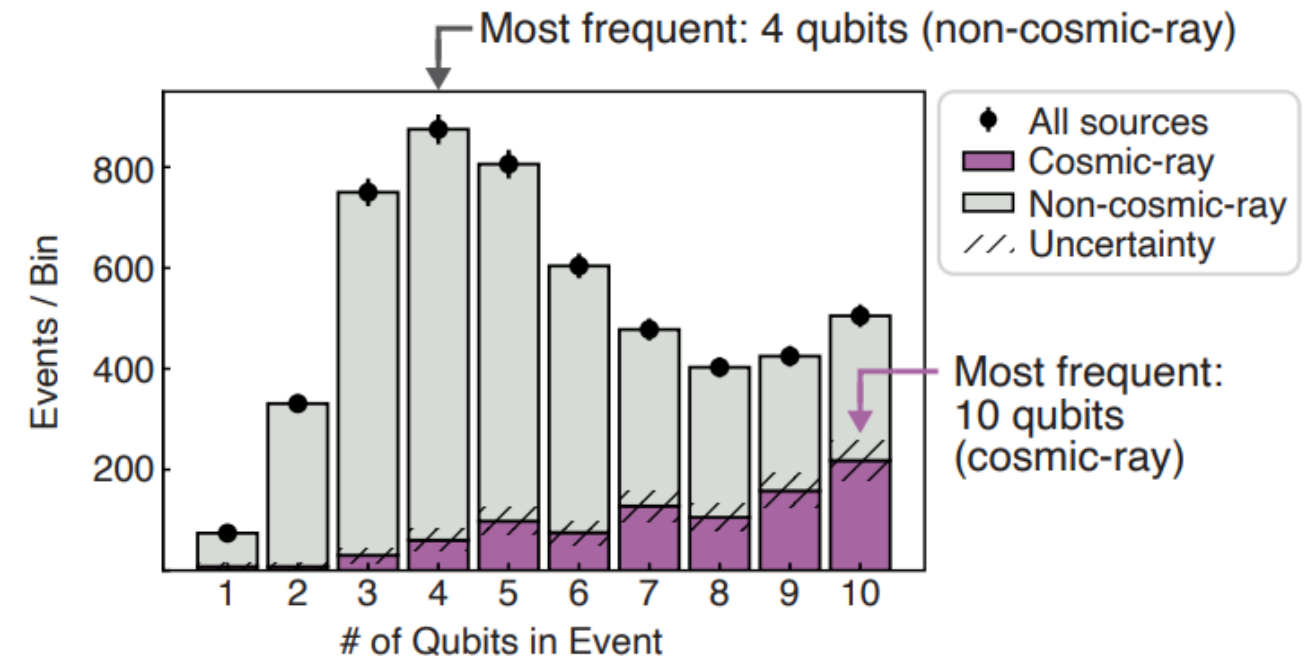
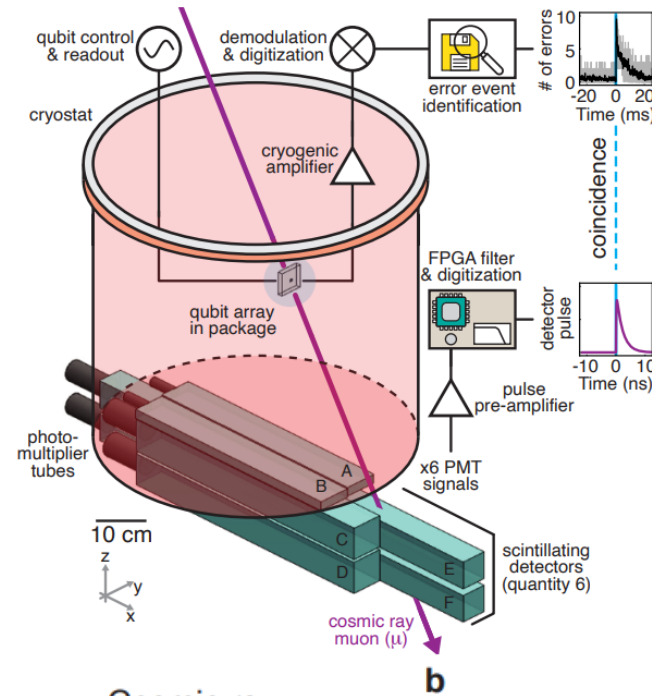
- Excellent agreement w/data taken on TKID validates the background model
- There is no fitting!** Model is simply matched to the room background measured by separate NaI detector



Multiple labs across the country measured with same NaI, all have same gamma flux within ~ 5

Fowler *et al.*, PRX Quantum **5** 040323 (2024)

Errors and cosmic ray muons

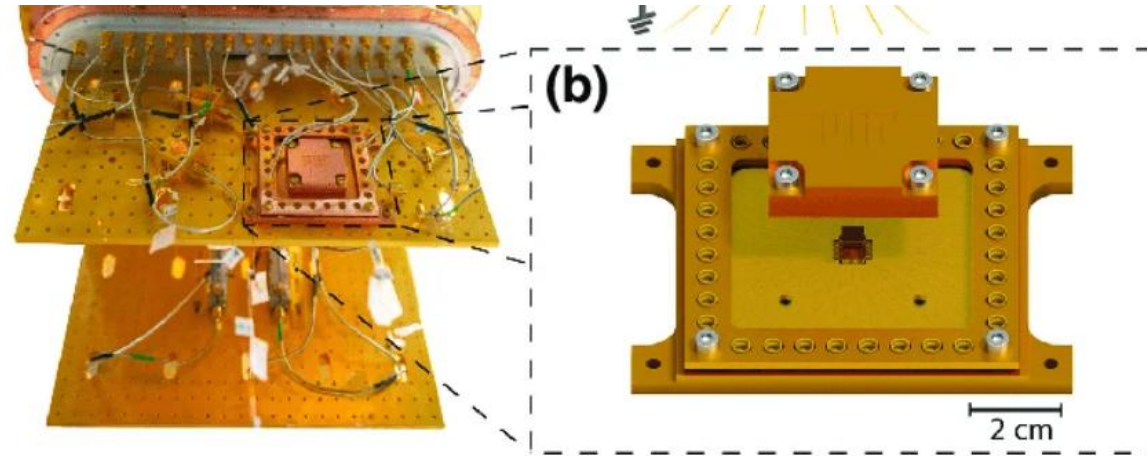
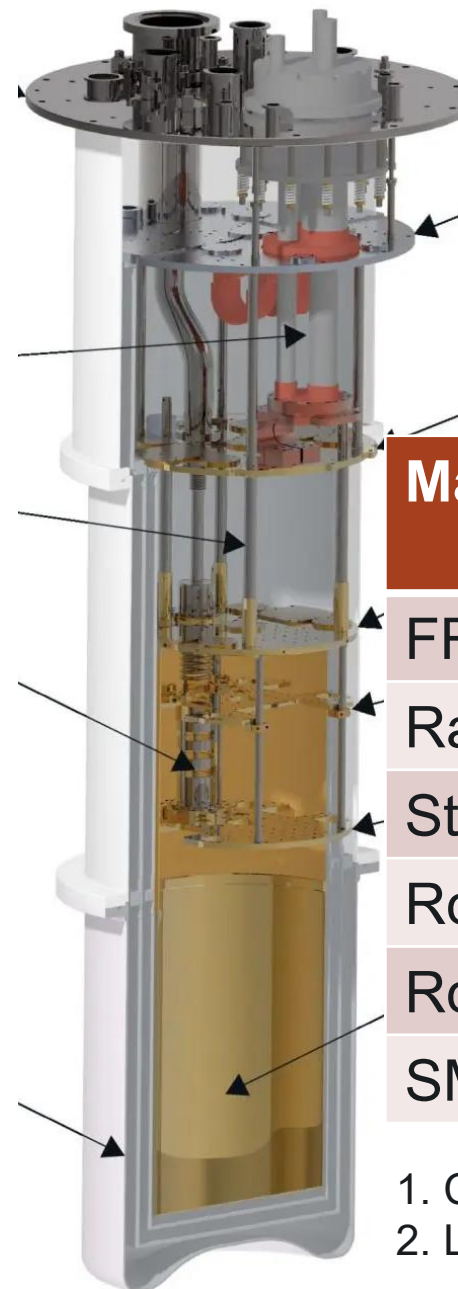


• Observed
 ■ Expected Signal
 ■ Expected Background

Harrington et al. "Synchronous Detection of Cosmic Rays and Correlated Errors in Superconducting Qubit Arrays". arXiv:2402.03208

Xue-Gang Li et al. "Direct evidence for cosmic-ray-induced correlated errors in superconducting qubit array." arXiv:2402.04245

Materials in the superconducting qubit environment



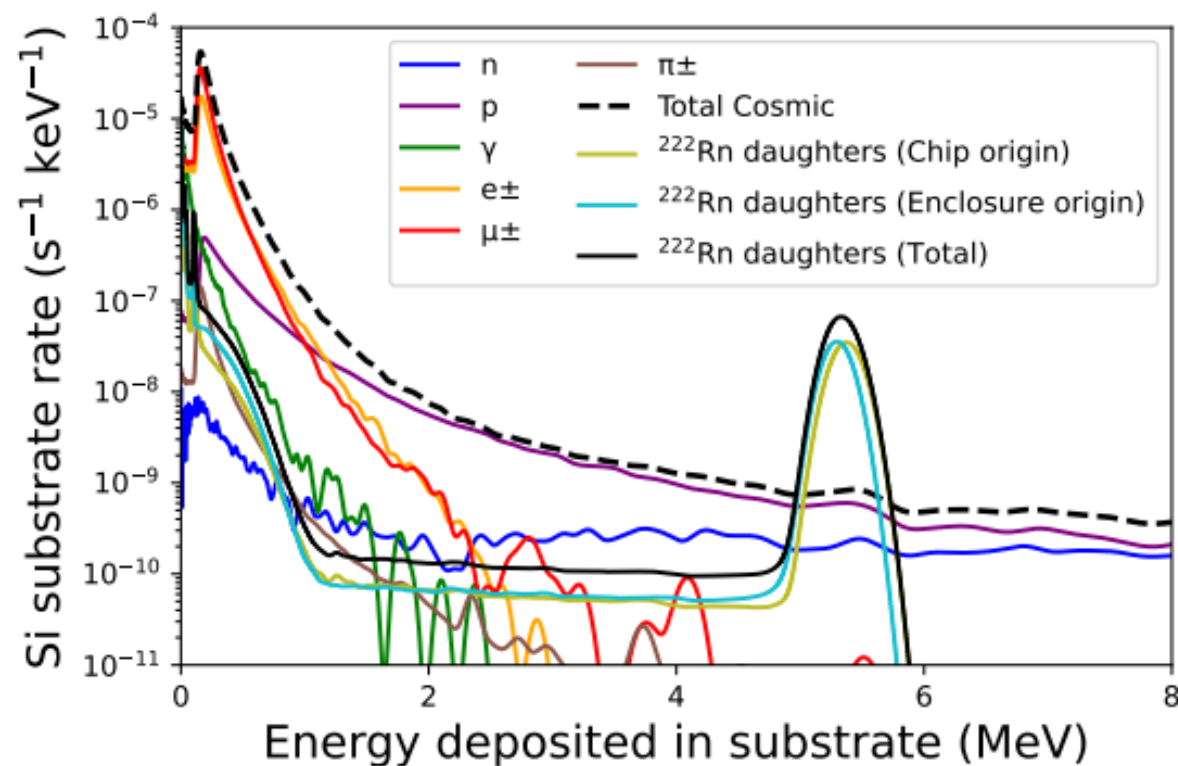
Materials of concern; close and hot

Material	U238 (mBq/kg)	Th232 (mBq/kg)	K40 (mBq/kg)
FR4 PCB	11500 +- 400	18000 +- 1000	12000 +- 1000
Radial cryogenic switch	1340 +- 60	1880 +- 100	2200 +- 300
Stycast conductive epoxy	9400 +- 900	53 +- 4	290 +- 40
Rogers TMM10 PCB	25400 +- 800	5500 +- 300	17300 +- 900
Rogers RO4350B PCB	11200 +- 400	15100 +- 900	9100 +- 800
SMA connector	25000 +- 2000	2240 +- 140	

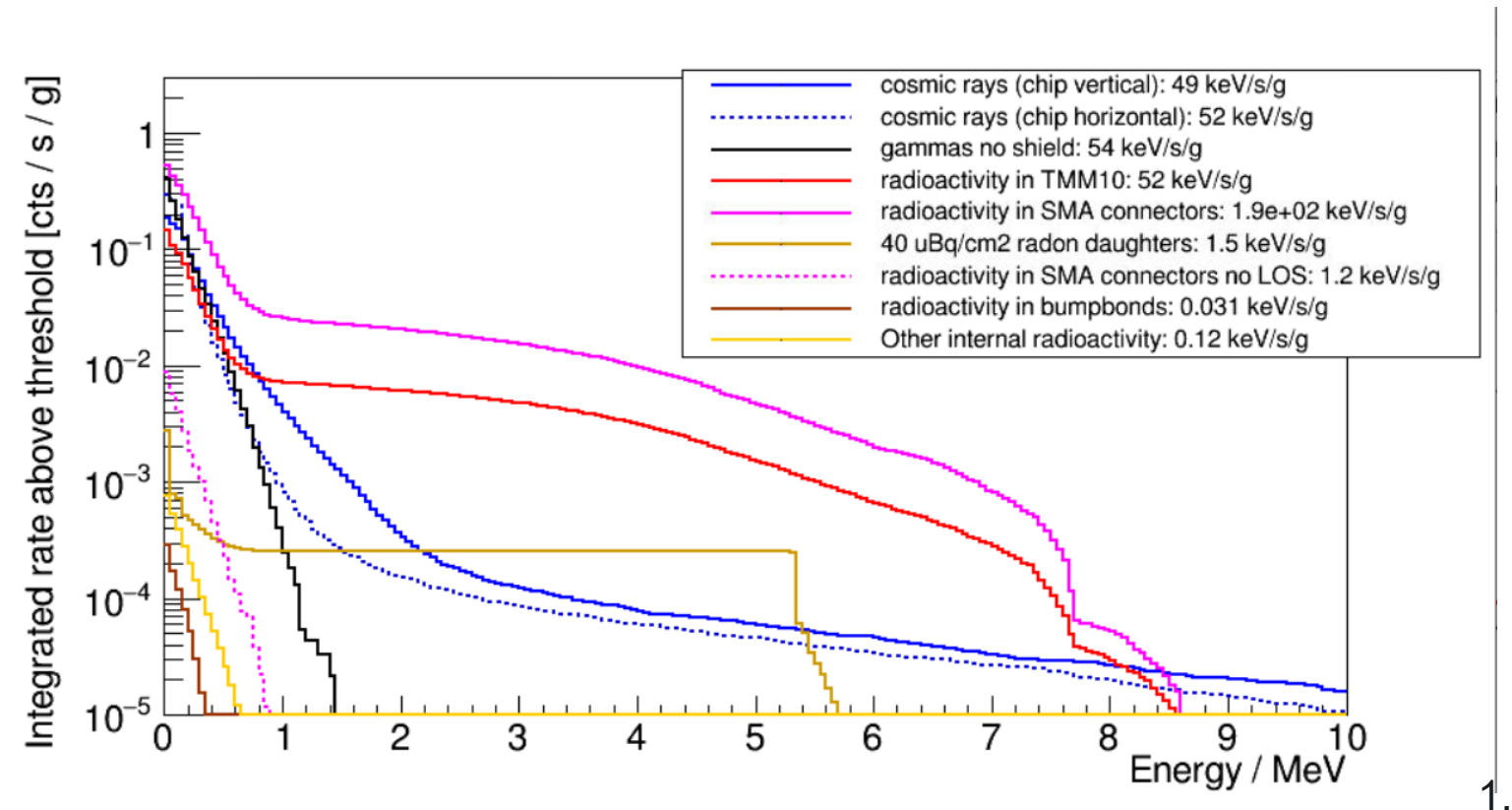
1. Cardani, L. *et al.* Disentangling the sources of ionizing radiation in superconducting qubits. *Eur. Phys. J. C* **83**, 94 (2023).
2. Loer, B. *et al.* Abatement of ionizing radiation for superconducting quantum devices. *J. Inst.* **19**, P09001 (2024).

Alphas

- Alphas from material contamination and radon on line-of-sight surfaces can dominate the high energy background budget



Poudel, S. S. *et al.* Accelerating Surface Radiation Content to Investigate the Impact of Radon Progeny on Superconducting Qubits [arXiv.2606.00473](https://arxiv.org/abs/2606.00473) (2026).



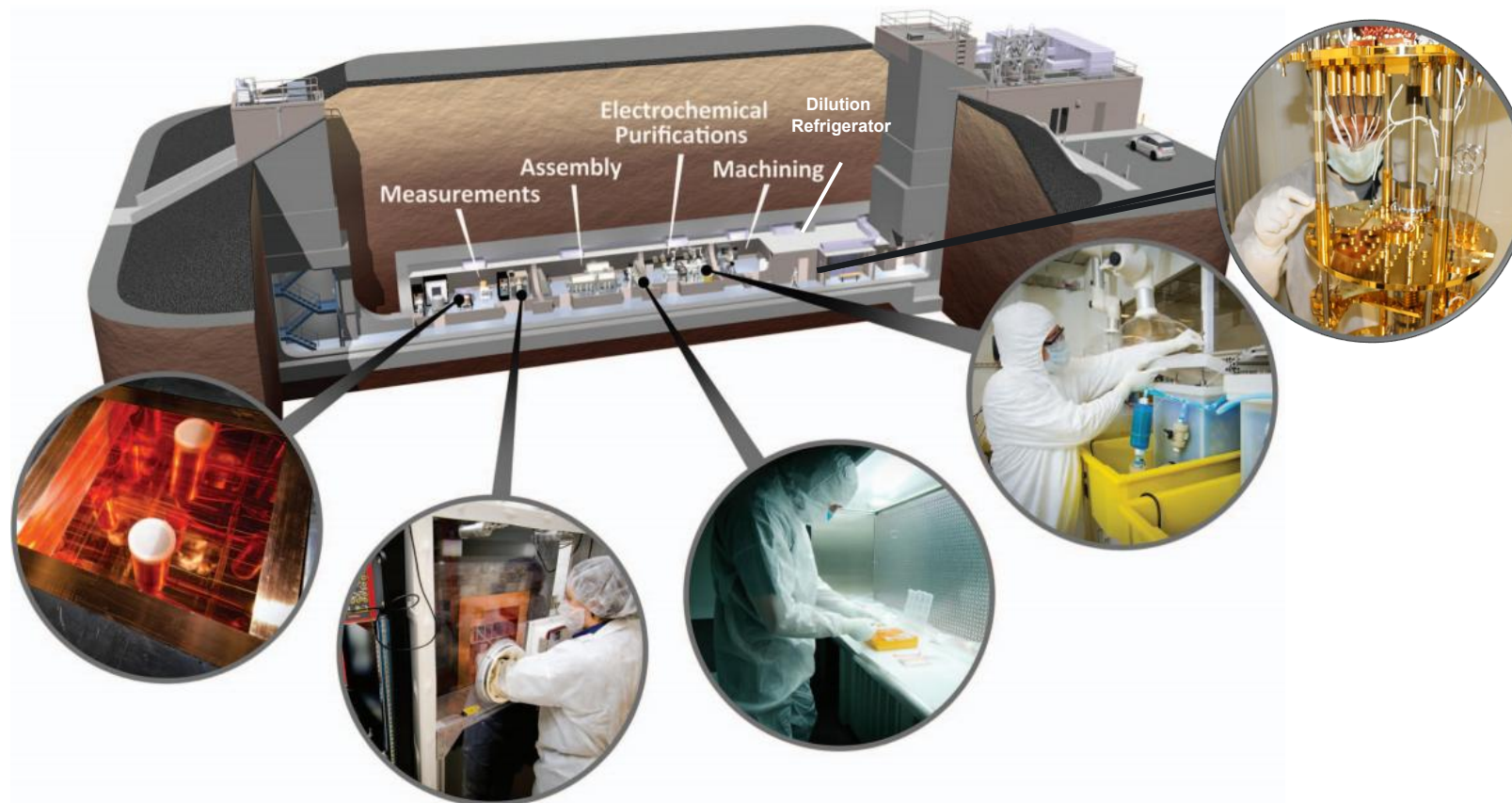
Adapted from Loer, B. *et al.* Abatement of ionizing radiation for superconducting quantum devices. *J. Inst.* **19**, P09001 (2024).

Key Takeaways

- Three dominant sources of ionizing radiation events:
 - Cosmic ray secondaries
 - Ambient gammas
 - Line-of-sight “dirty” components (ceramic PCBs, BeCu coax connectors)
- If devices are sensitive to low energy impacts, these sources contribute roughly equally
- If there is a significant threshold effect (e.g. from gap engineering), line-of-sight alphas are the biggest concern, followed by cosmic rays (hadronic component), and gammas are very subdominant
- Careful attention to radioactivity in the fridge is probably only necessary for components very close to the active devices
- Feasible that remaining correlated errors not suppressed by gap engineering are cosmic ray neutrons and protons. These are attenuated ***much*** more efficiently than muons with overburden!

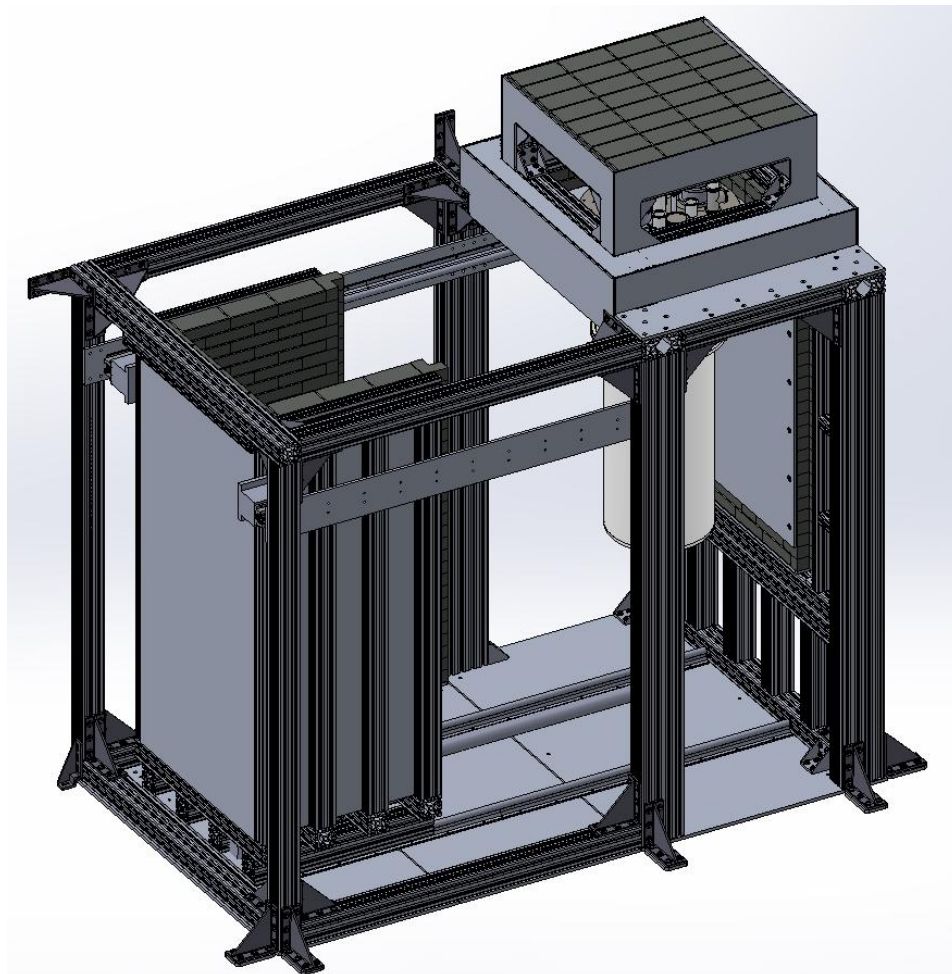
PNNL Shallow Underground Laboratory and Low Background Cryogenic Facility (LBCF)

- SUL houses clean rooms (class 10,000 and 1,000) , world-leading ultra-pure material growth and characterization capability
- 19 m overburden reduces muon flux by 6X, **neutron and proton flux by >100X**
- Bluefors LD-400 dilution fridge with external gamma shield



LBCF Shield Complete!

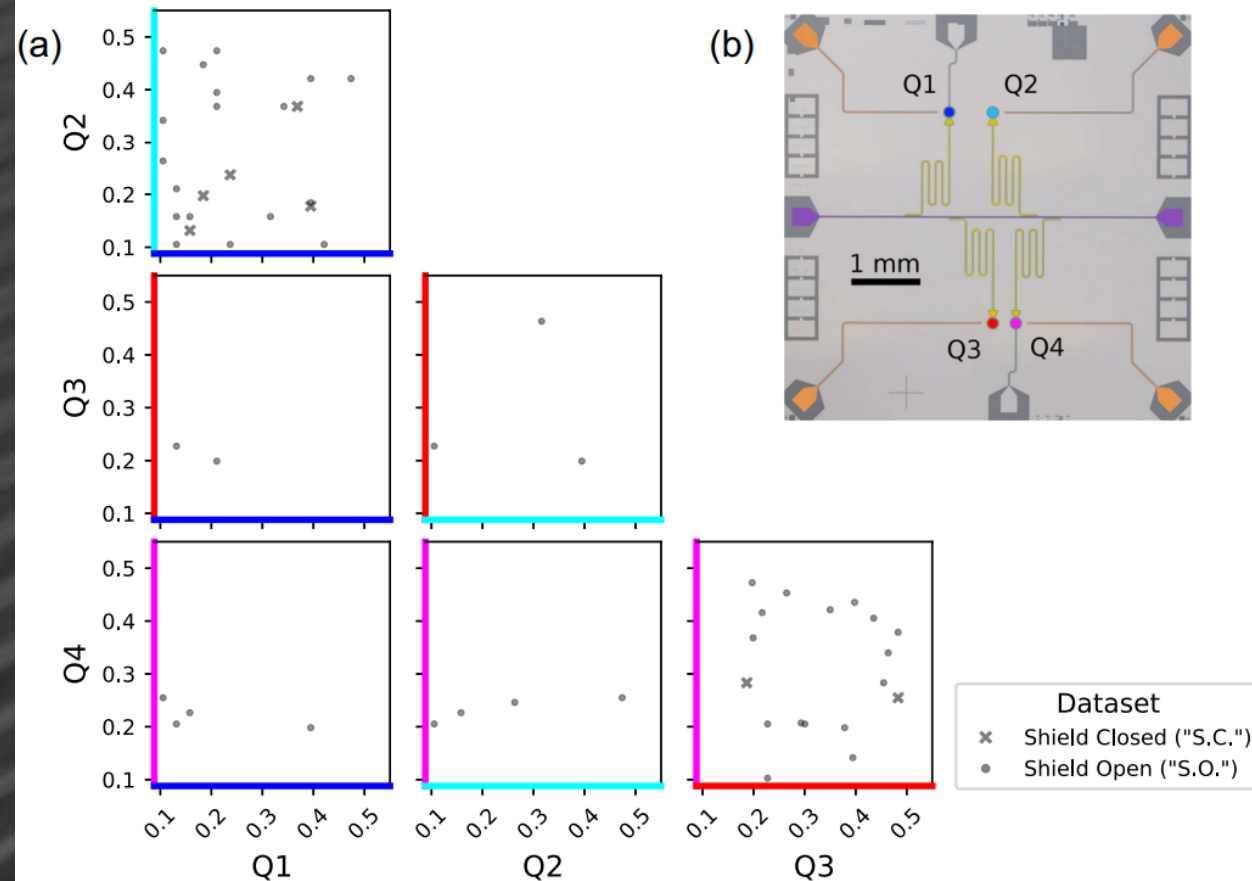
- Reduces gamma rate by ~99% -> dominated by residual cosmic ray muons
- Expected correlated error burst rate for gap engineered qubits ~1/week
- Expect few % improvement in T1 times for state-of-the-art qubits



Qubits already operating underground

Table 2 | Correlated charge jump rates in qubit pairs

	Q1-Q2	Q3-Q4	Q1-Q3	Q1-Q4	Q2-Q3	Q2-Q4	Units
Separation	640	340	3195	3330	3180	3240	μm
Shield open	$0.27^{+0.09}_{-0.07}$	$0.29^{+0.09}_{-0.07}$	$0.03^{+0.04}_{-0.02}$	$0.08^{+0.06}_{-0.04}$	$0.05^{+0.05}_{-0.03}$	$0.08^{+0.06}_{-0.04}$	mHz
Shield closed	$0.10^{+0.07}_{-0.04}$	$0.04^{+0.05}_{-0.03}$	< 0.03	< 0.04	< 0.03	< 0.04	mHz

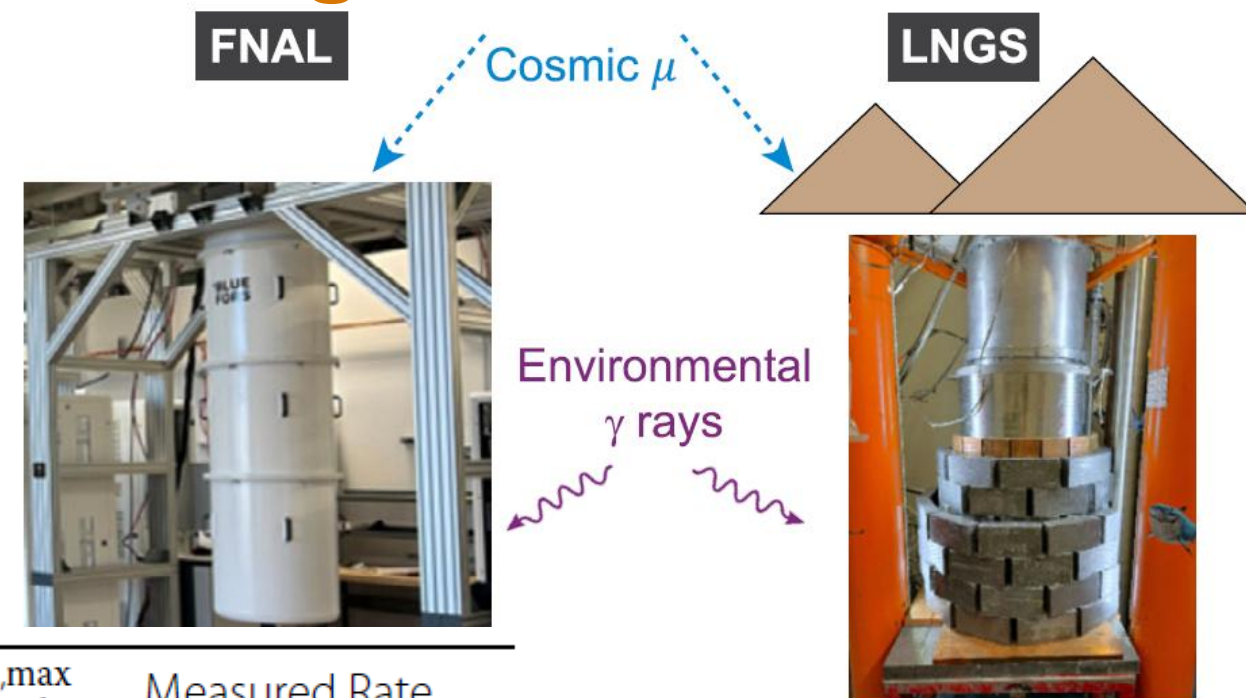


- First device to report correlated tunneling events with offset-charge-sensitive qubits operated in the NEXUS shield in the NuMI tunnel at Fermilab
- Observed rate relative to surface with shield open scales with radiation flux
- Rate drops further with shield closed, but not as much as expected

Bratrud, G. *et al.* Measurement of correlated charge noise in superconducting qubits at an underground facility. *Nat Commun* **16**, 9906 (2025).

Qubits already operating underground

- Single qubit measuring relaxation errors operated at FNAL (surface) and LNGS in a partial
- Measured rate of “pulses” of consecutive errors
- Reduction in good agreement with simulated radiation interaction rate



Datasets	Acquisition Time [min]	Live-time [min]	T_S [μ s]	$P(g)$ [%]	$N_{\text{signal}}^{\text{min}}$	$N_{\text{control}}^{\text{min,max}}$	Measured Rate [events/sec]
LNGS							
Shielded chip	736.7	209.96	73.6	11.8	19	6, 21	$(0.40 \pm 0.18) \times 10^{-3}$
FNAL							
74 μ s - run1	294.4	294.4	73.6	15.1	21	9, 25	$(5.32 \pm 0.55) \times 10^{-3}$
74 μ s - run2	294.4	294.4	73.6	14.5	21	8, 24	$(4.47 \pm 0.50) \times 10^{-3}$
74 μ s - run3	294.4	294.4	73.6	14.2	21	8, 23	$(4.98 \pm 0.53) \times 10^{-3}$
74 μ s - run4	294.4	294.4	73.6	15.0	21	8, 24	$(4.13 \pm 0.48) \times 10^{-3}$

Summary

- Ionizing radiation is not yet a dominant source of single-qubit errors, but becomes more important as coherence times improve
- It is likely the source of remaining correlated error events that currently set the floor of achievable error correction on gap-engineered qubits
- Which sources are the most important depends on energy sensitivity
 - But environmental sources dominant in most cases
- Multiple shielded underground cryogenic quantum facilities are coming online or already active
- It has not yet been demonstrated that underground, shielded systems actually reduce the rate of uncorrectable errors limiting correction codes, especially for gap-engineered qubits

Thank you

