Phonon-Only Events and Correlated Quasiparticle Poisoning

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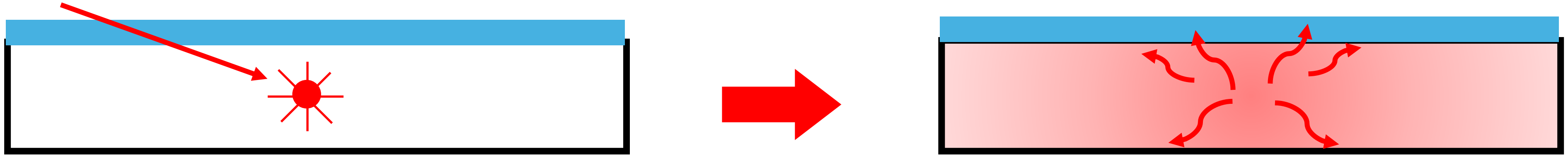
Phonon-mediated quasiparticle poisoning from radiation impacts

γ-ray, muon impact deposits ~100 keV – 1 MeV

rate ~ 1/(10 s) for $(8\text{ mm})^2$ chip



1. Generation of electron-hole pairs in Si, ***offset charge jumps***
2. e-h recombination and radiation of high-energy phonons
3. ***Pair-breaking phonons*** travel throughout chip
4. Phonons impacting superconductor break pairs, quasiparticles recombine and emit 2Δ phonons back into Si

→ Correlated pair-breaking & ***quasiparticle*** generation across the chip

Vepsäläinen *et al*., Nature **584**, 551 (2020)

McEwen *et al*., Nature Physics **18**, 107 (2021)

Wilen *et al*., Nature **594**, 7863 (2021)

Martinis, npj Quantum **7**, 1 (2021)

Cardani *et al*., Nature Comm. **12**, 1 (2021)

Iaia, Ku *et al*., Nature Comm. 13, 6425 (2022)

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

⋮

Signatures of phonon-mediated QP poisoning from particle impacts

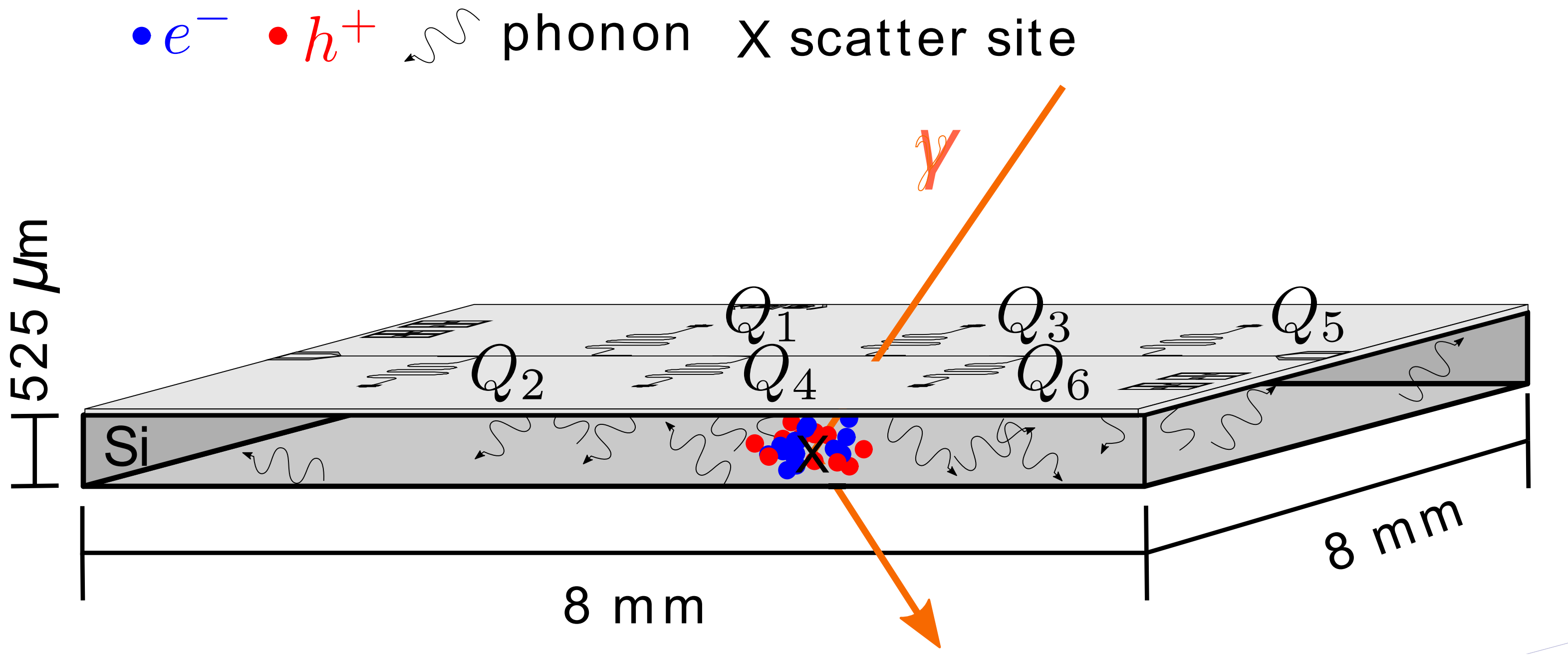
- Impact produces many electron-hole pairs that spread before trapping

Shifts in local charge environment for qubits near impact site

- Motion and recombination of *e-* and *h+* radiates high-energy phonons; enhanced pair-breaking

Enhanced relaxation rates for qubits

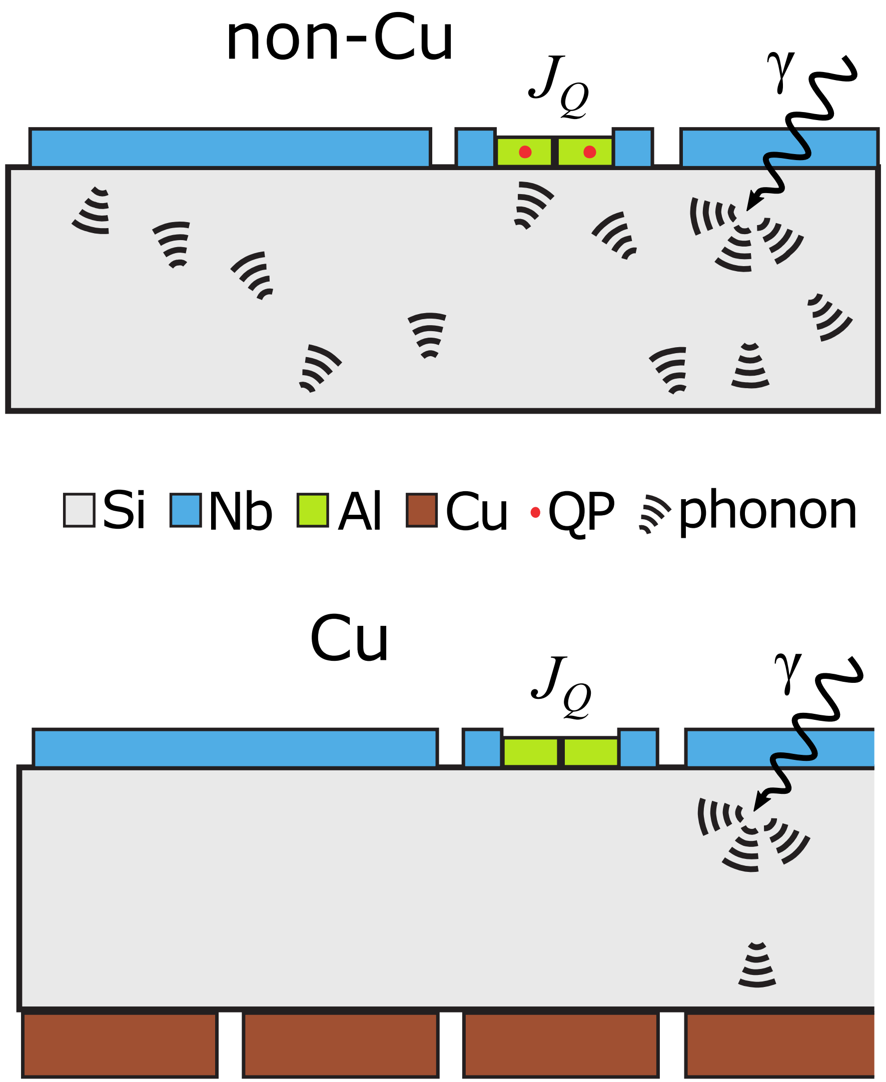
Elevated QP charge-parity switching rates on qubits



Mitigating phonon-mediated QP poisoning

Possible mitigation strategies:

- SC gap-engineering to suppress tunneling of excess QPs
- Phonon downconversion…



Normal metal structures on back side of chip:

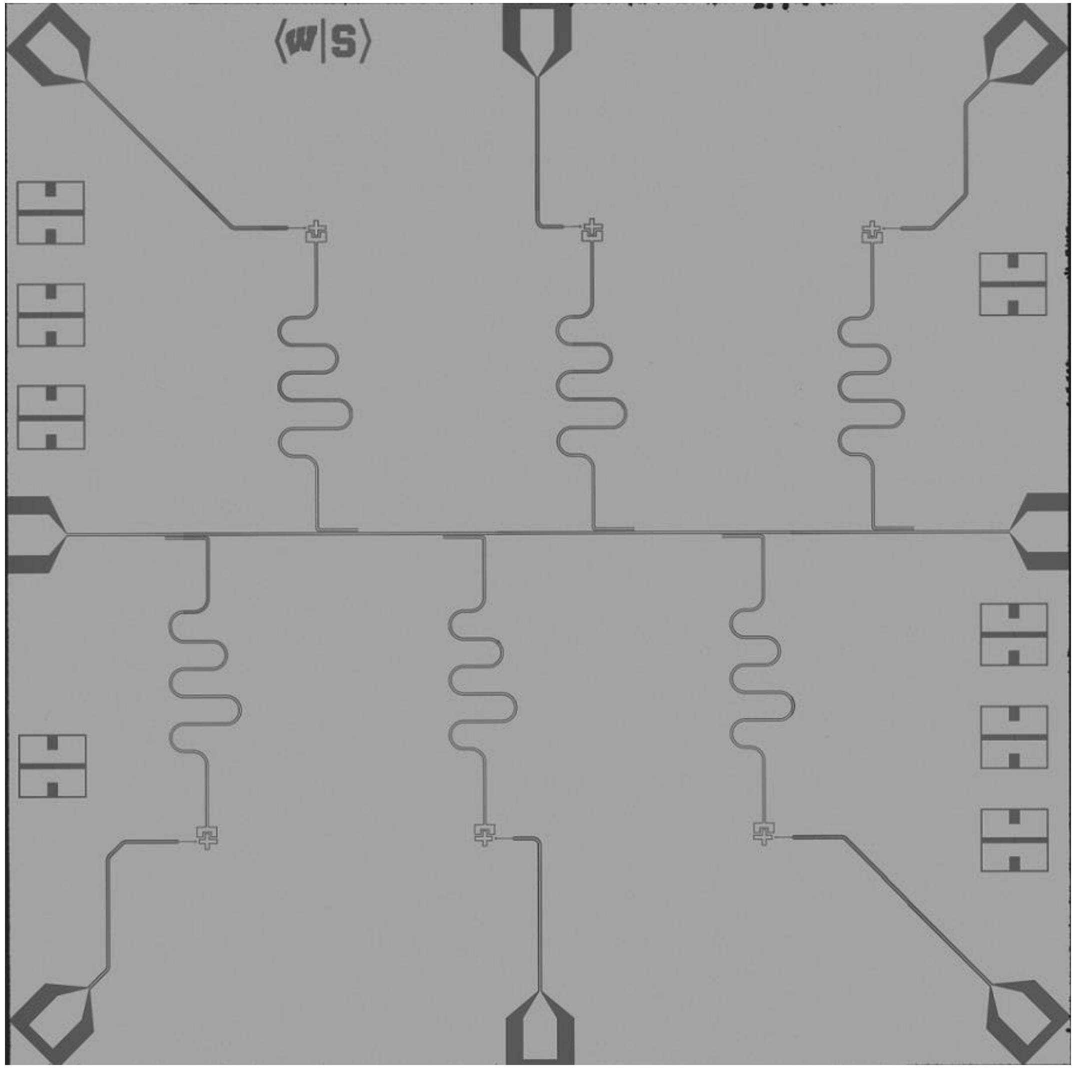
- Inelastic electron-phonon scattering
- Low e-ph interaction rate at low temperatures
- Need large metallic volume

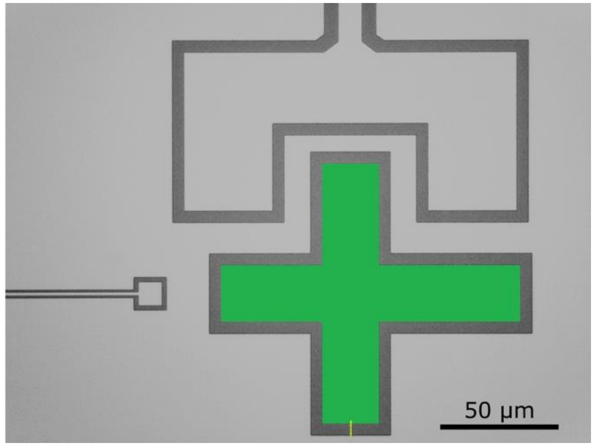
Martinis, npj Quantum **7**, 1 (2021)

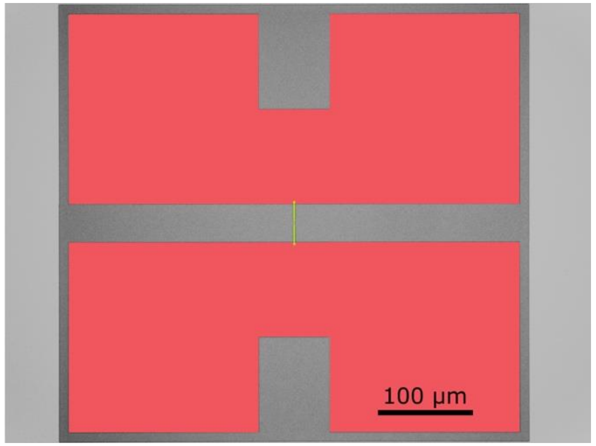
Alternatively, could use low-gap superconductor…

Henriques *et al.*, APL **115**, 212601 (2019)   Karatsu *et al.*, APL **114**, 032601 (2019)

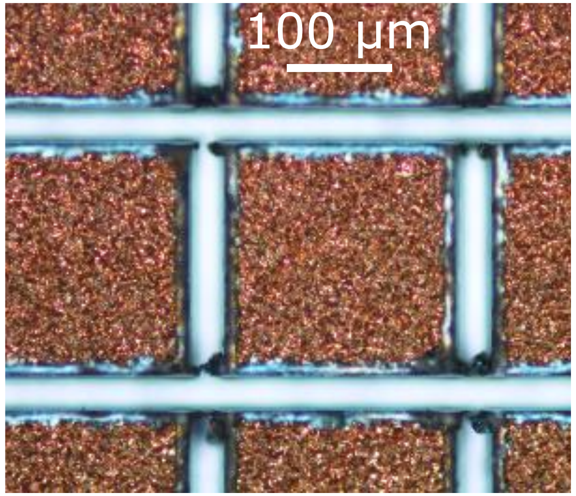
Device layout for studying phonon-mediated QP poisoning







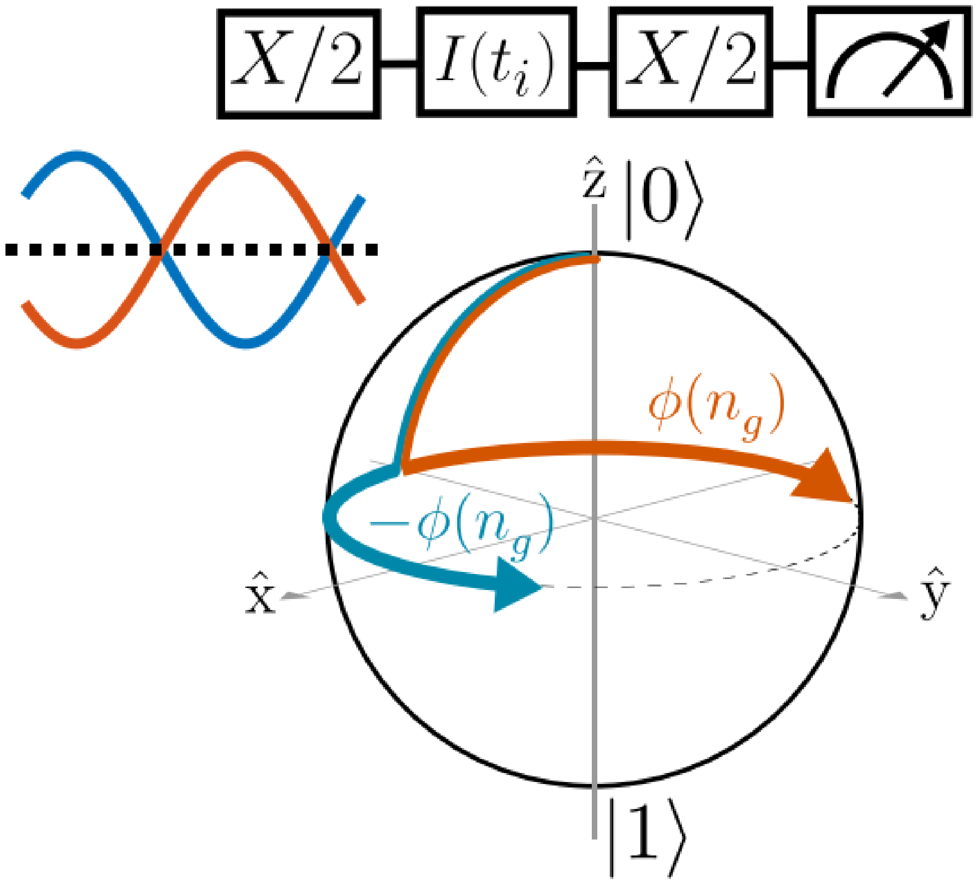
- Nb groundplane (or Al)
- Al/AlOx/Al junctions
- Charge-sensitive transmons



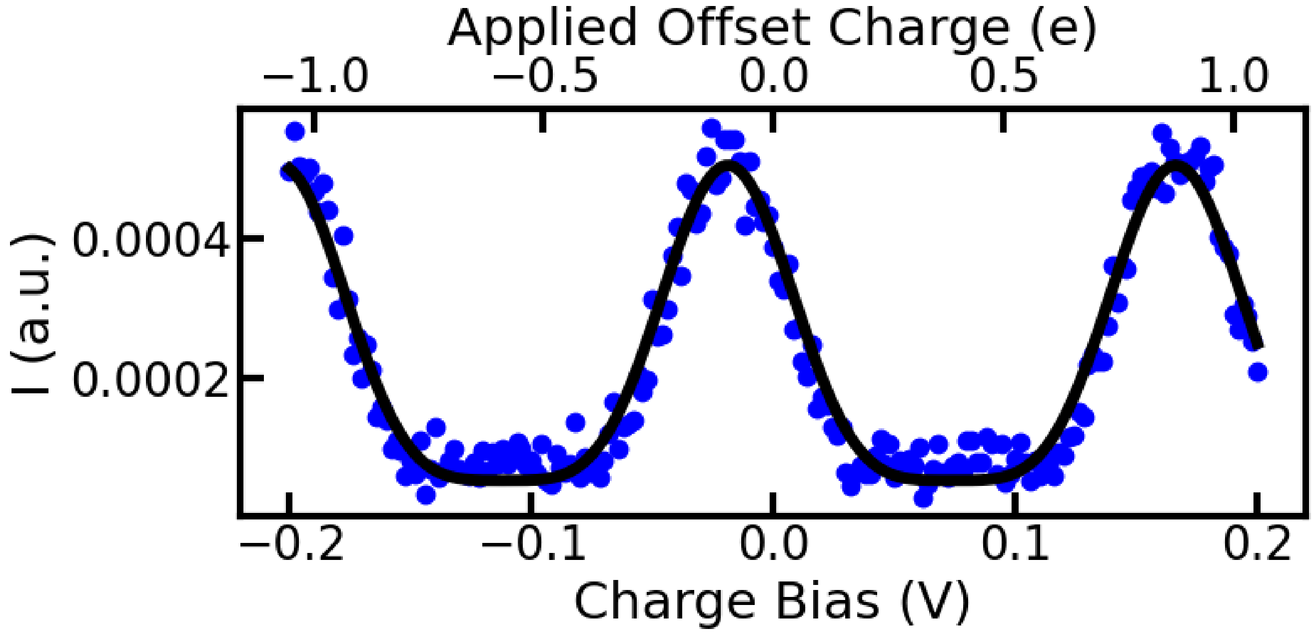
- Electroplated Cu
- Thickness: 1 μm, 10 μm

CNF Cornell NanoScale Science and Technology Facility

Using qubits as sensors of charge environment



$$\phi(n_g) = t_{idle}\,\Delta\omega_{10}\cos(2\pi n_g)$$



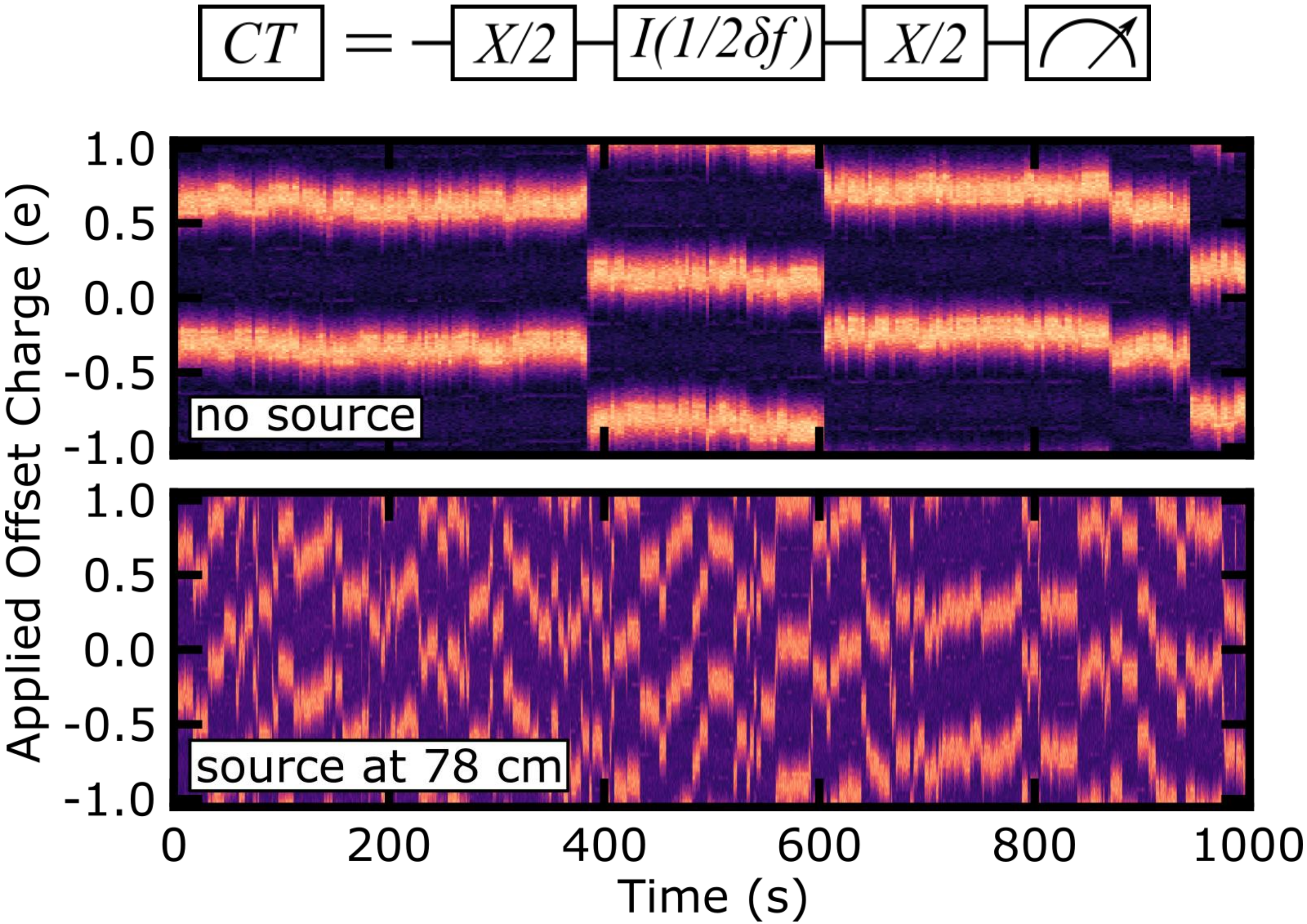
$$P_1 = \frac{1}{2}[d + \nu\cos(\pi\cos 2\pi n_g)]$$

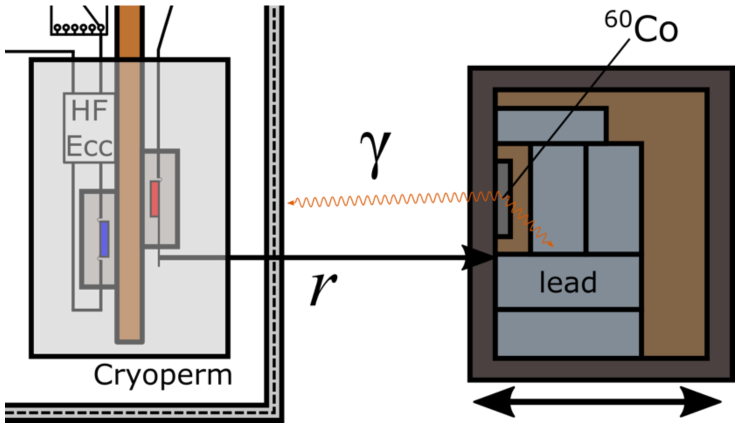
$$n_g = n_g^{\text{ext}} + \delta n_g$$

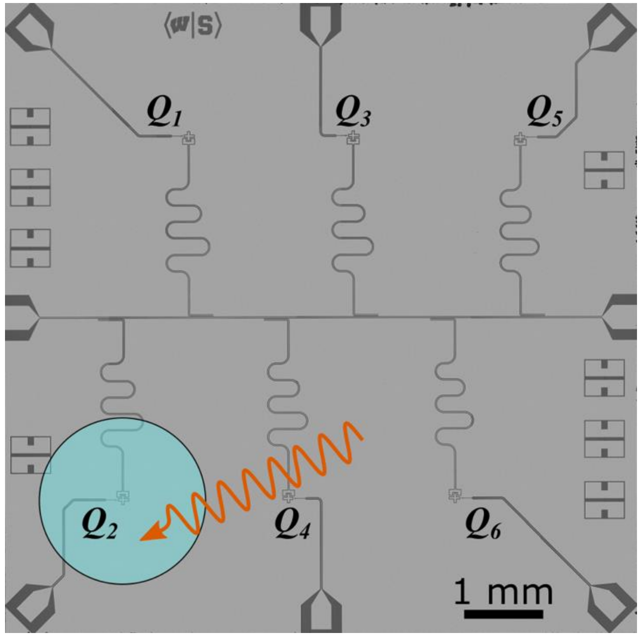
environmental

Christensen et al., Phys. Rev. B **100**, 14 (2019)

Dependence of offset-charge jump rate on γ dose

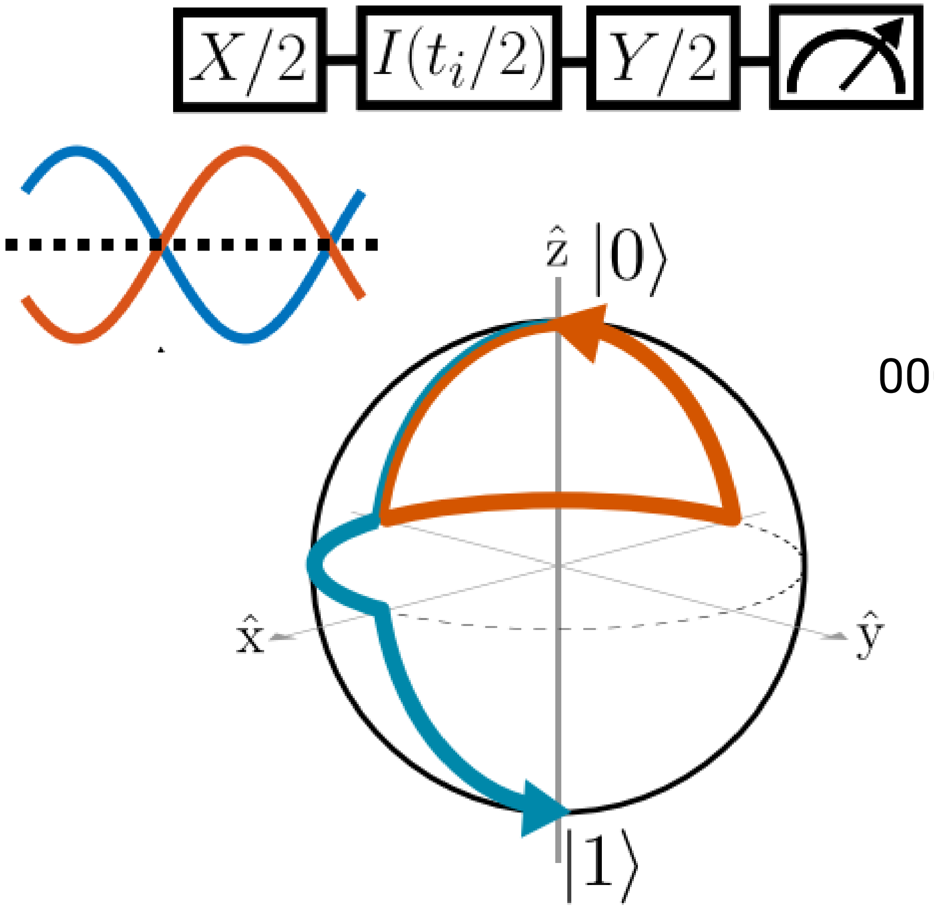


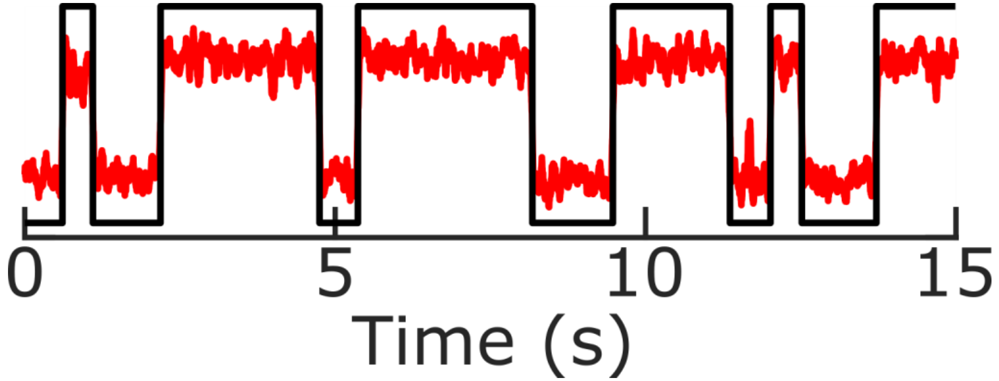




Larson *et al.*, PRX Quantum 6, 030339 (2025)

Sensing QP poisoning with charge-parity switching





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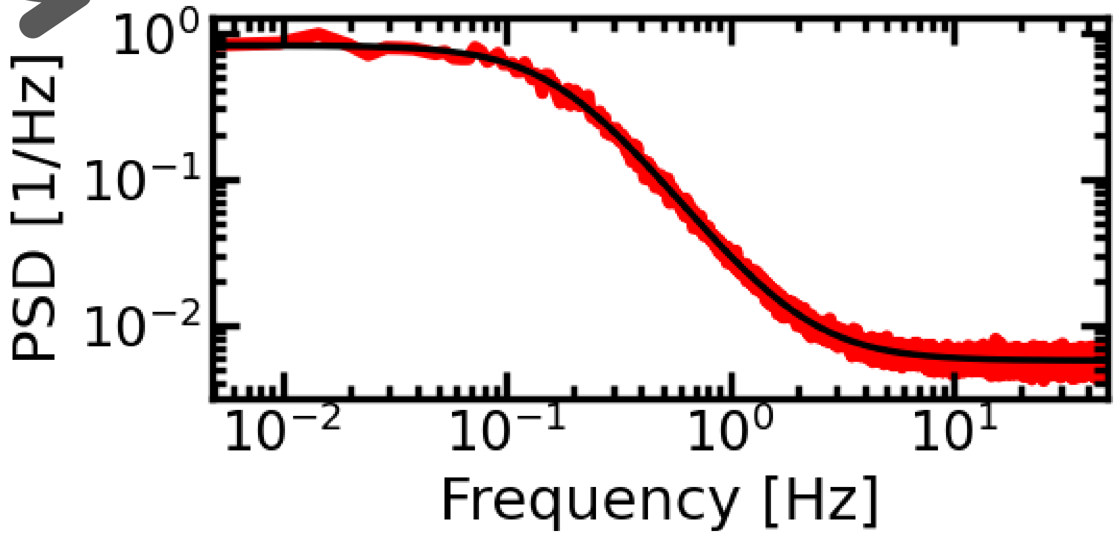
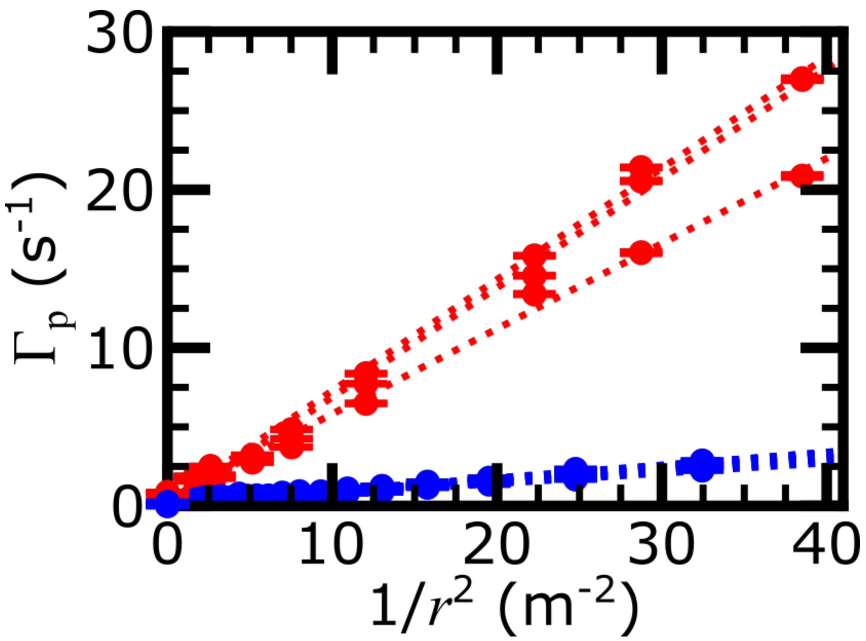
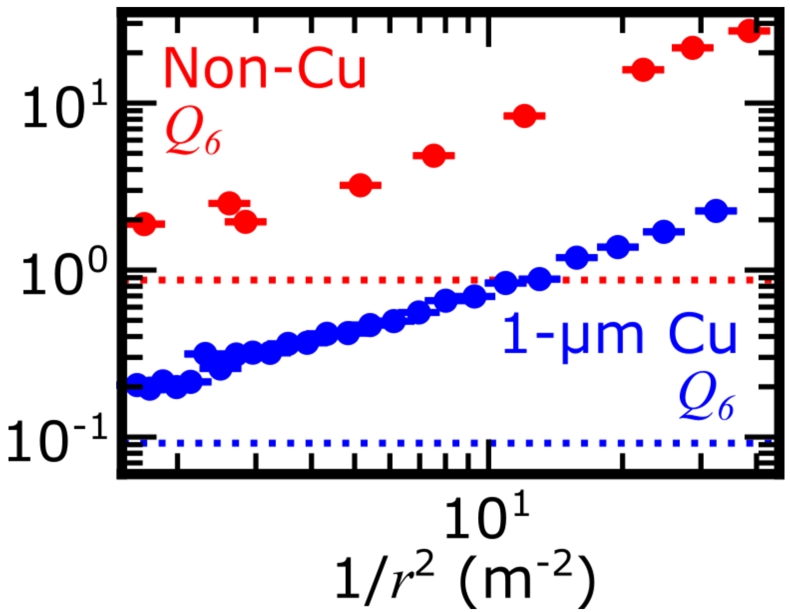
$$S_p(f) = \frac{4F^2\Gamma_p}{(2\Gamma_p)^2+(2\pi f)^2} + (1-F^2)\Delta t$$

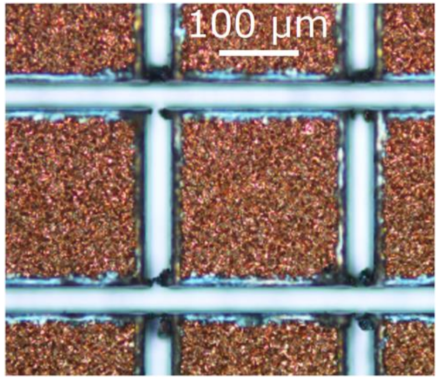


Christensen et al., Phys. Rev. B **100**, 14 (2019)
Riste et al., Nature Comm. **4**, 1913 (2013)

Dependence of QP charge-parity switching rate on γ dose

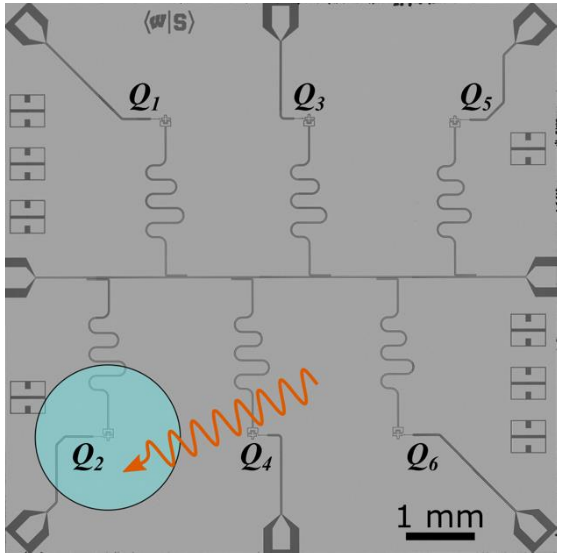


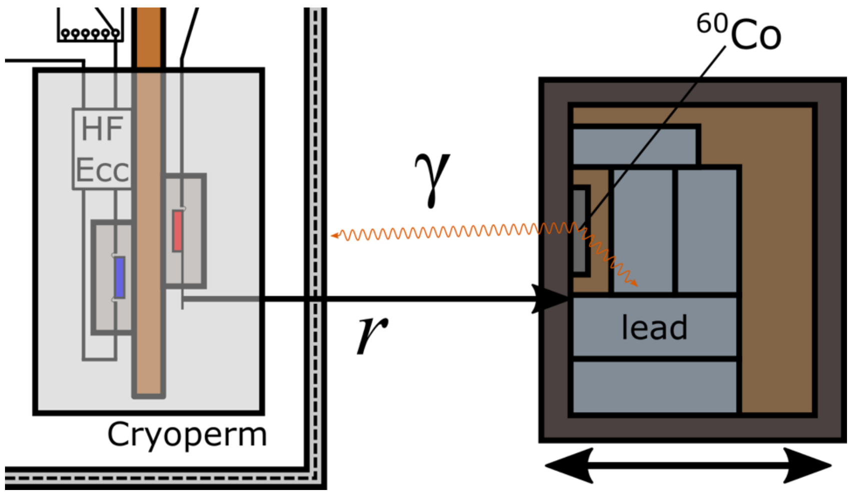




- QP charge-parity switching rates proportional to *1/r²*
- Rates suppressed by ~10x with 1-μm Cu islands

Larson *et al.*, PRX Quantum 6, 030339 (2025)





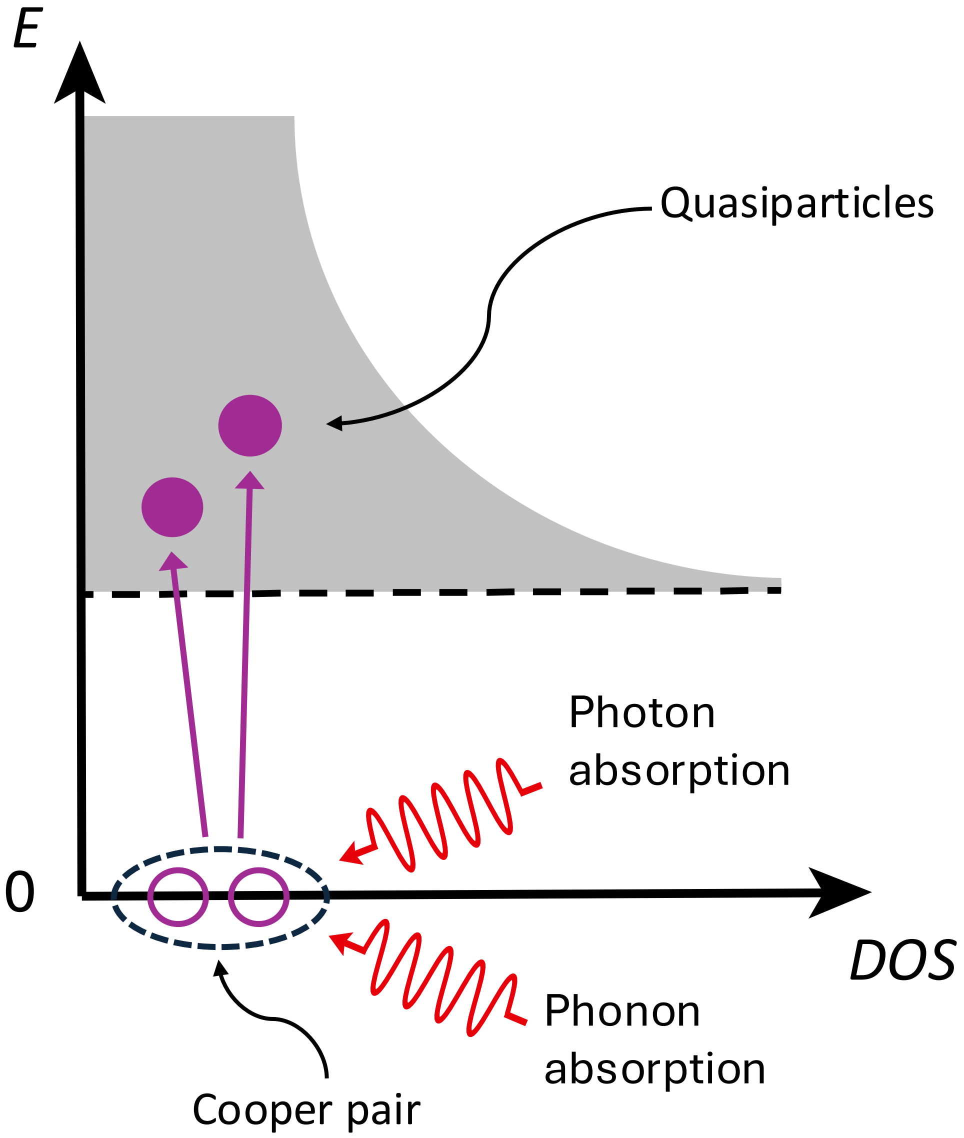
Generation of nonequilibrium QP in qubits

Deposition of pair-breaking energy generates QPs near qubit junction

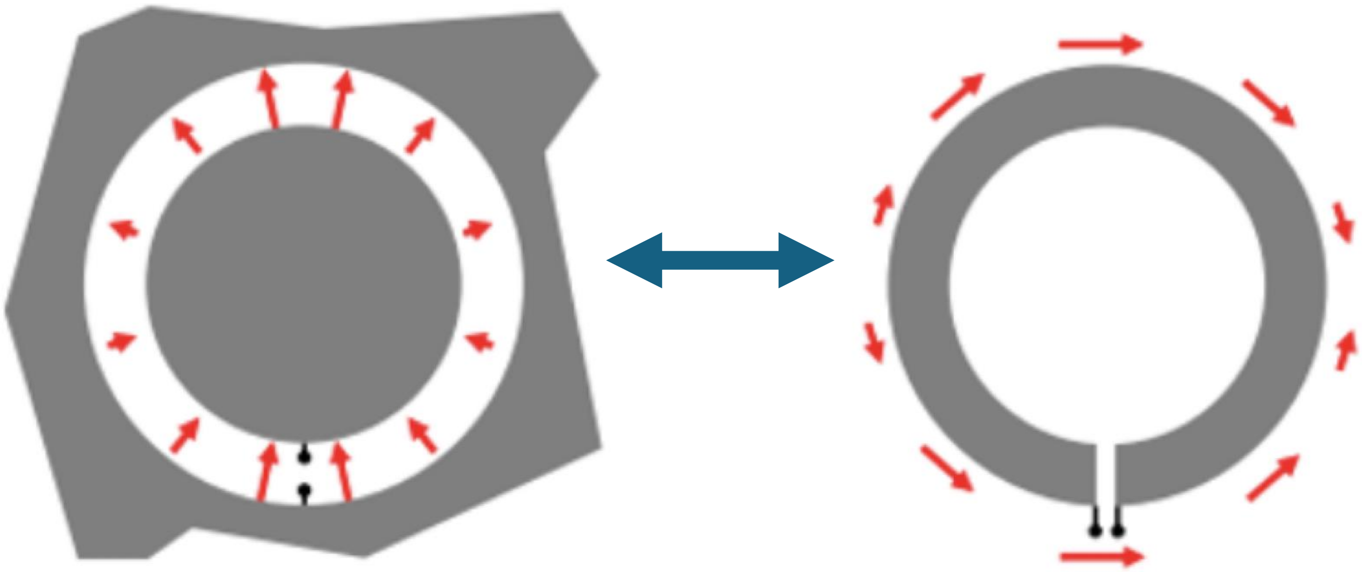
- Impact of ***phonons*** near junction electrodes, e.g., following radiation impact

- Absorption of pair-breaking ***photons***

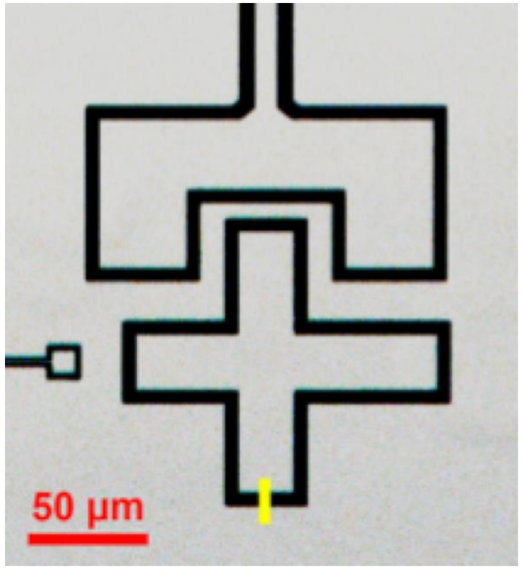
Mechanism for photon absorption and coupling to qubit junction…?



Spurious Antenna Modes of Superconducting Qubits



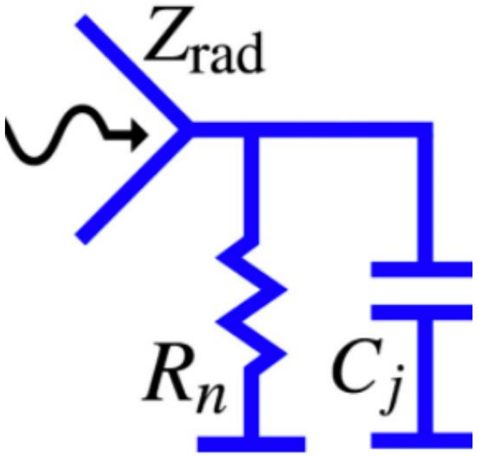
Babinet's Principle



Coupling efficiency:

$$e_c = 1 - |\Gamma|^2$$

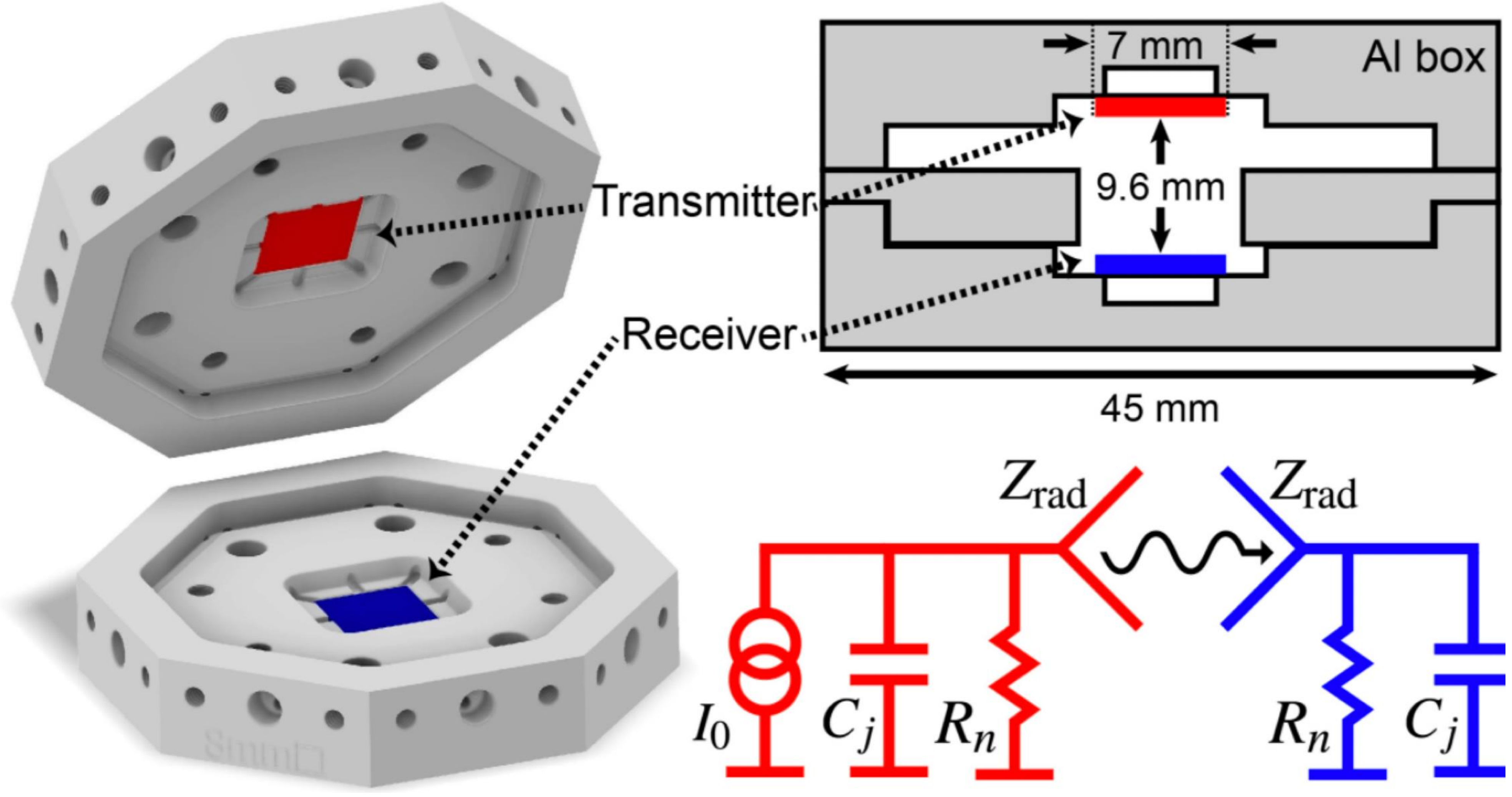
$$\Gamma = \frac{Z_{\mathrm{rad}} - Z_J^*}{Z_{\mathrm{rad}} + Z_J^*}$$



Rafferty *et al*., arXiv:2103.06803

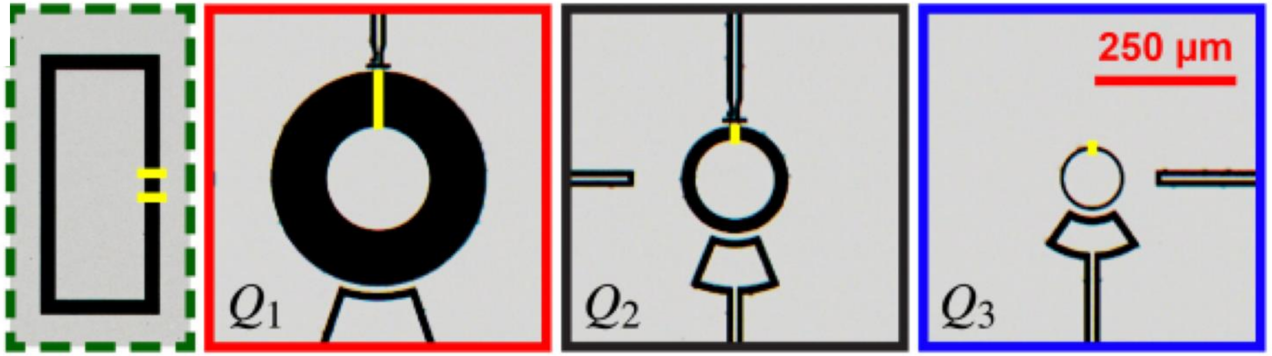
Houzet *et al*., Phys. Rev. Lett. 2019

Measuring Photon-mediated Quasiparticle Poisoning

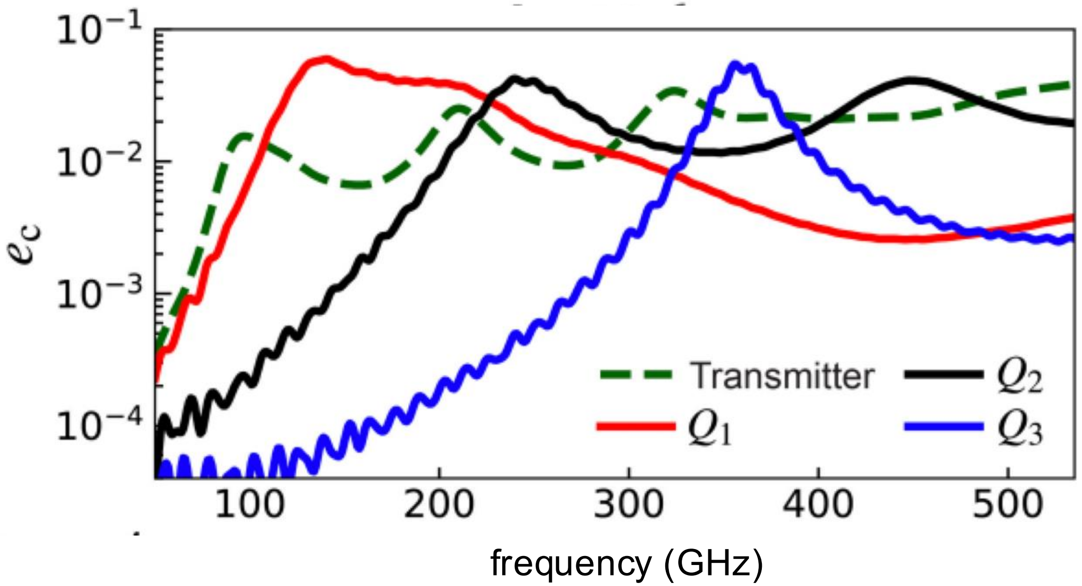


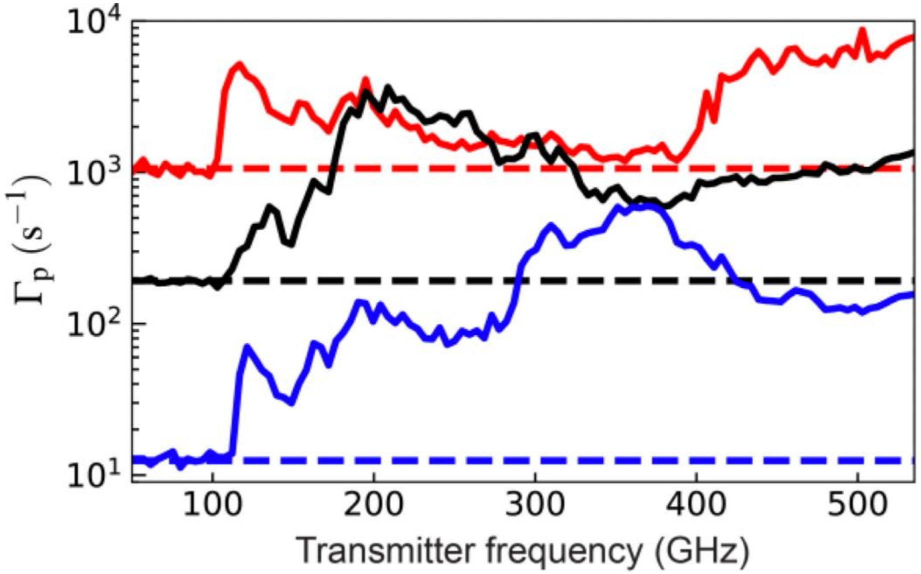
Liu *et al.*, Phys. Rev. Lett. 132, 017001 (2024)

Photon-mediated Quasiparticle Poisoning



Liu *et al*., Phys. Rev. Lett. 132, 017001 (2024)





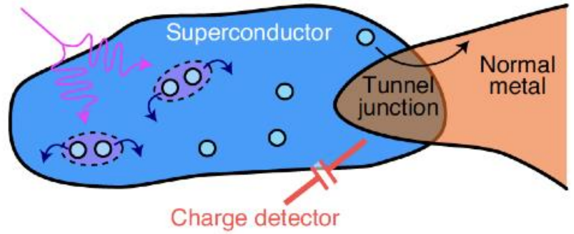
Mitigating photon-mediated QP poisoning:

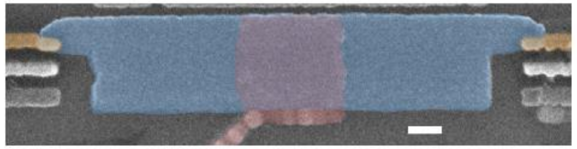
- More compact shunt capacitor designs for higher frequency antenna modes
- Further improvements to filtering, shielding, thermalization to reduce effective blackbody temperature of photons in qubit environment

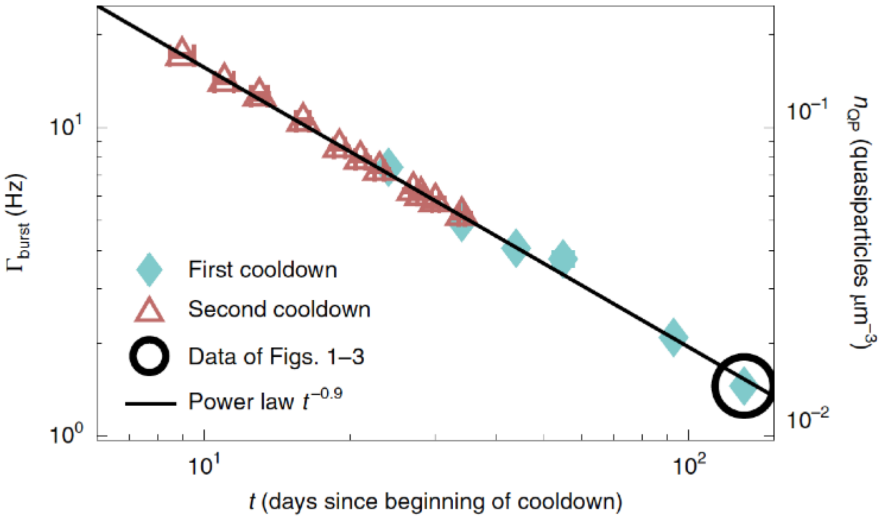
Correlated QP poisoning from phonon-only events

- Slow decrease in QP poisoning rates & low-energy excess events observed in TES detectors and mesoscopic SC devices

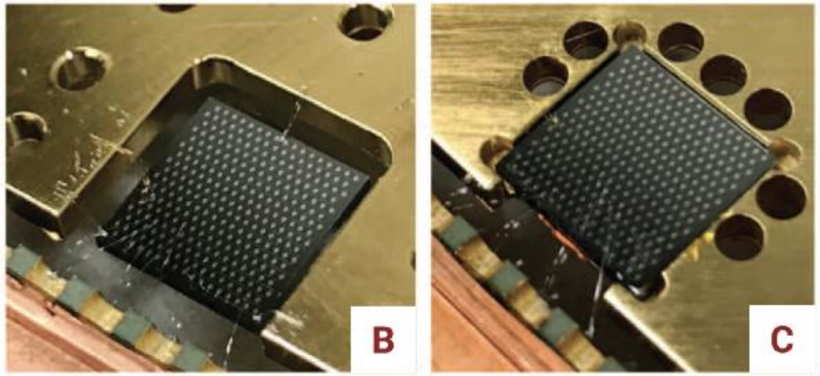
Mannila et al., Nature Phys 18, 145 (2022)

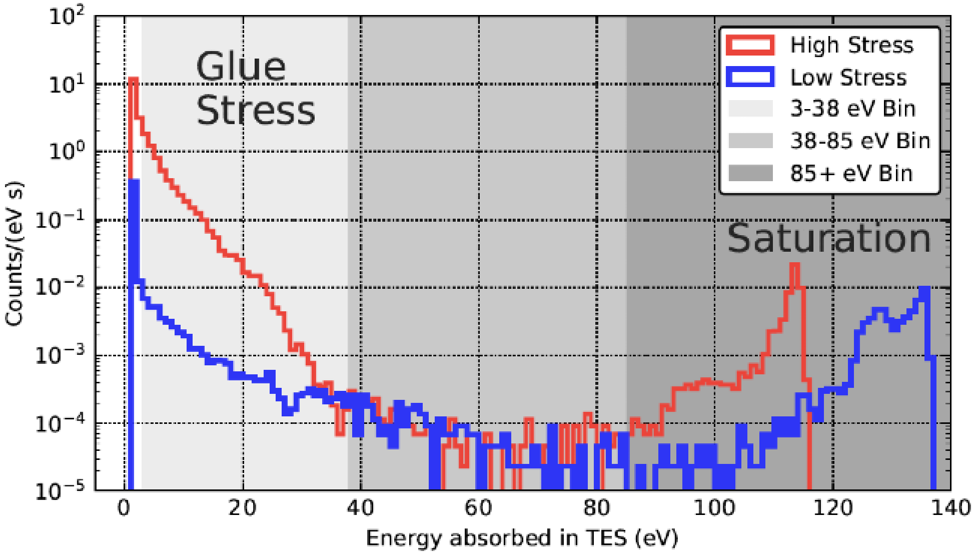






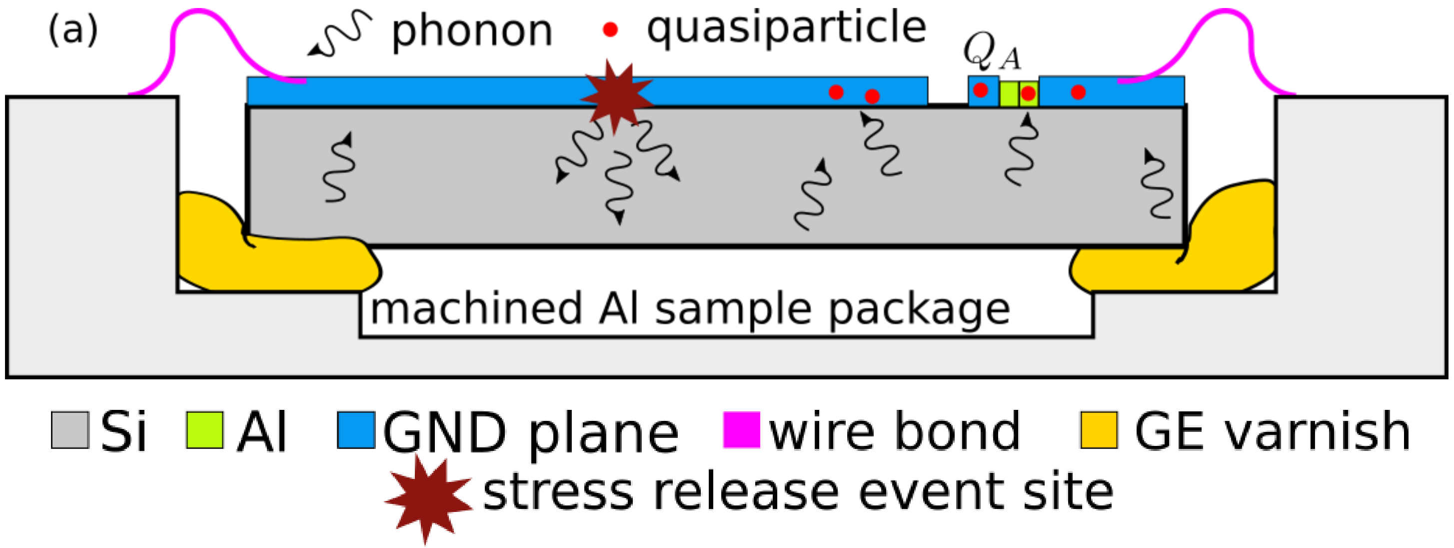
Anthony-Petersen et al., Nature Comm 15, 6444 (2024)

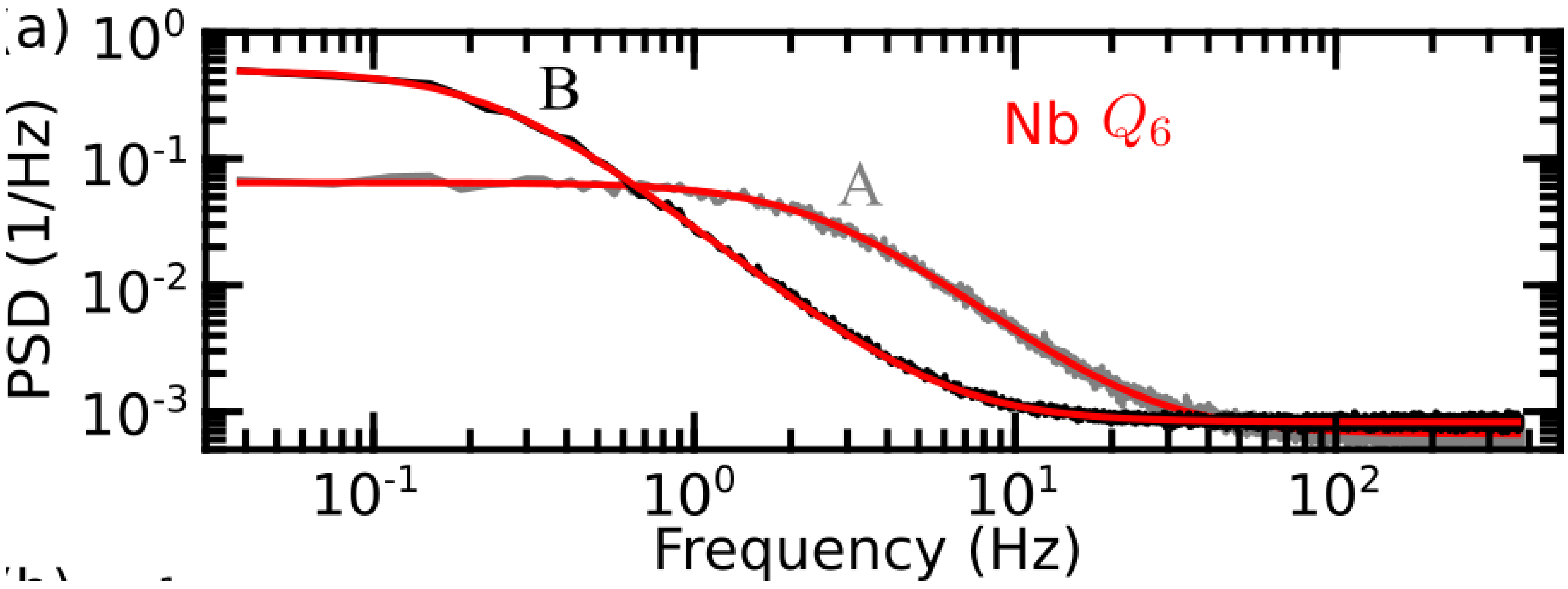




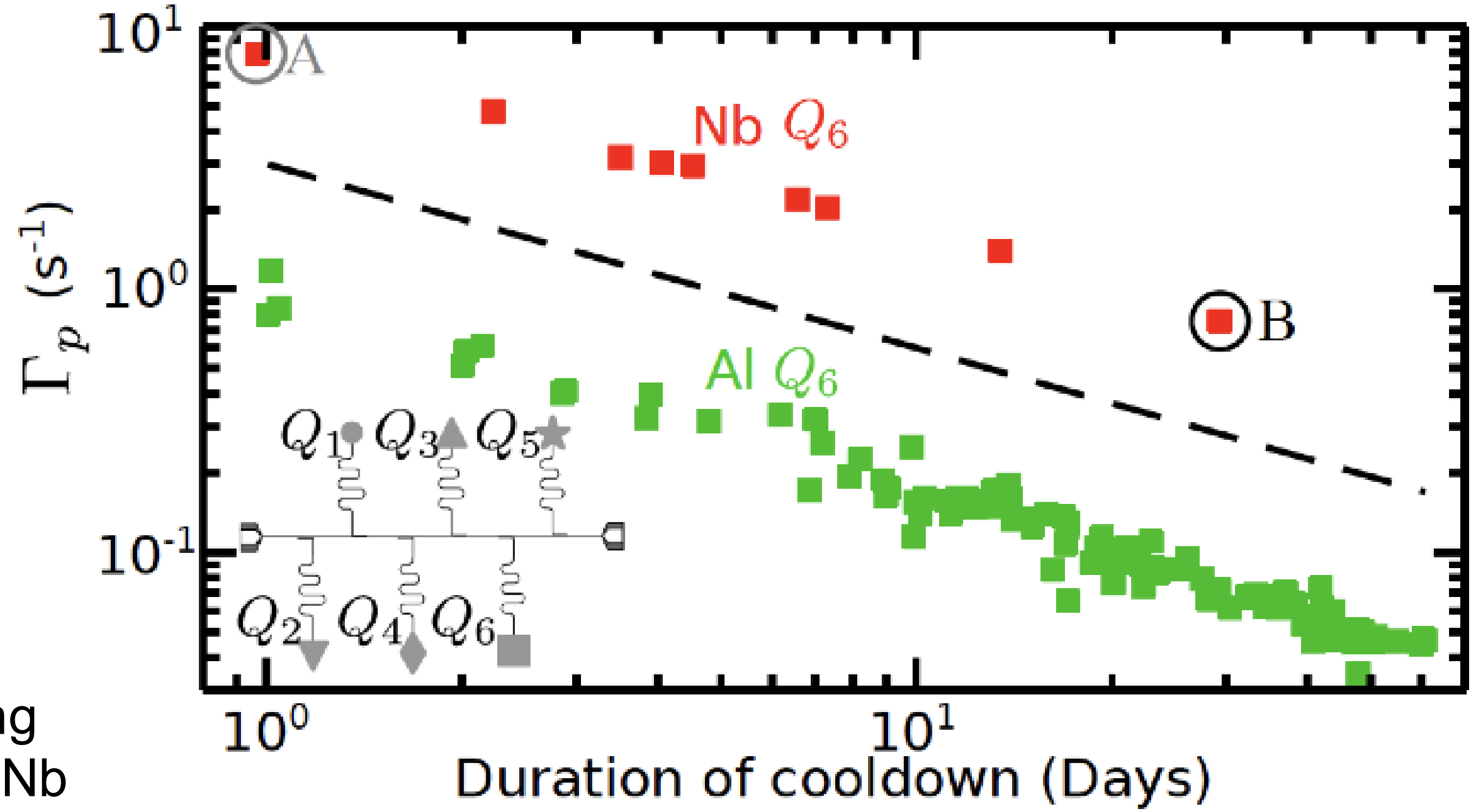
Correlated QP poisoning from phonon-only events

Yelton *et al.*, Phys. Rev. Lett. 135, 123601 (2025)

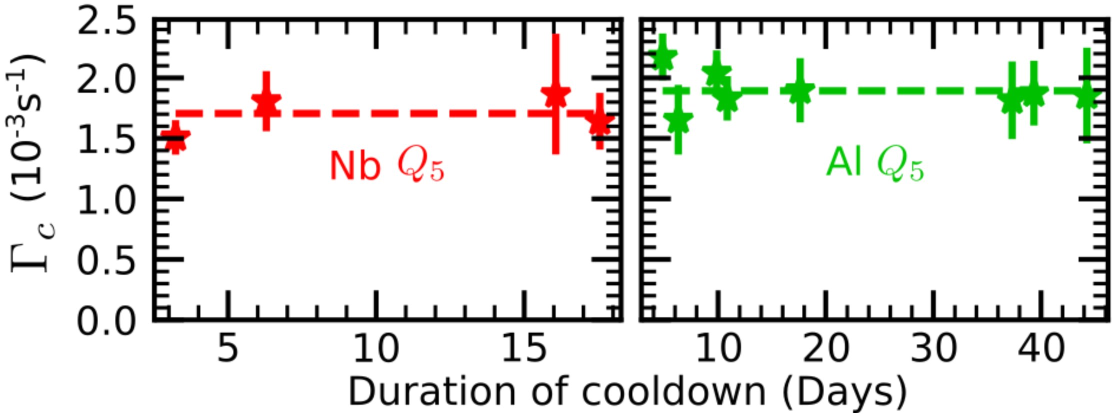




Reduction in charge-parity switching rates over time

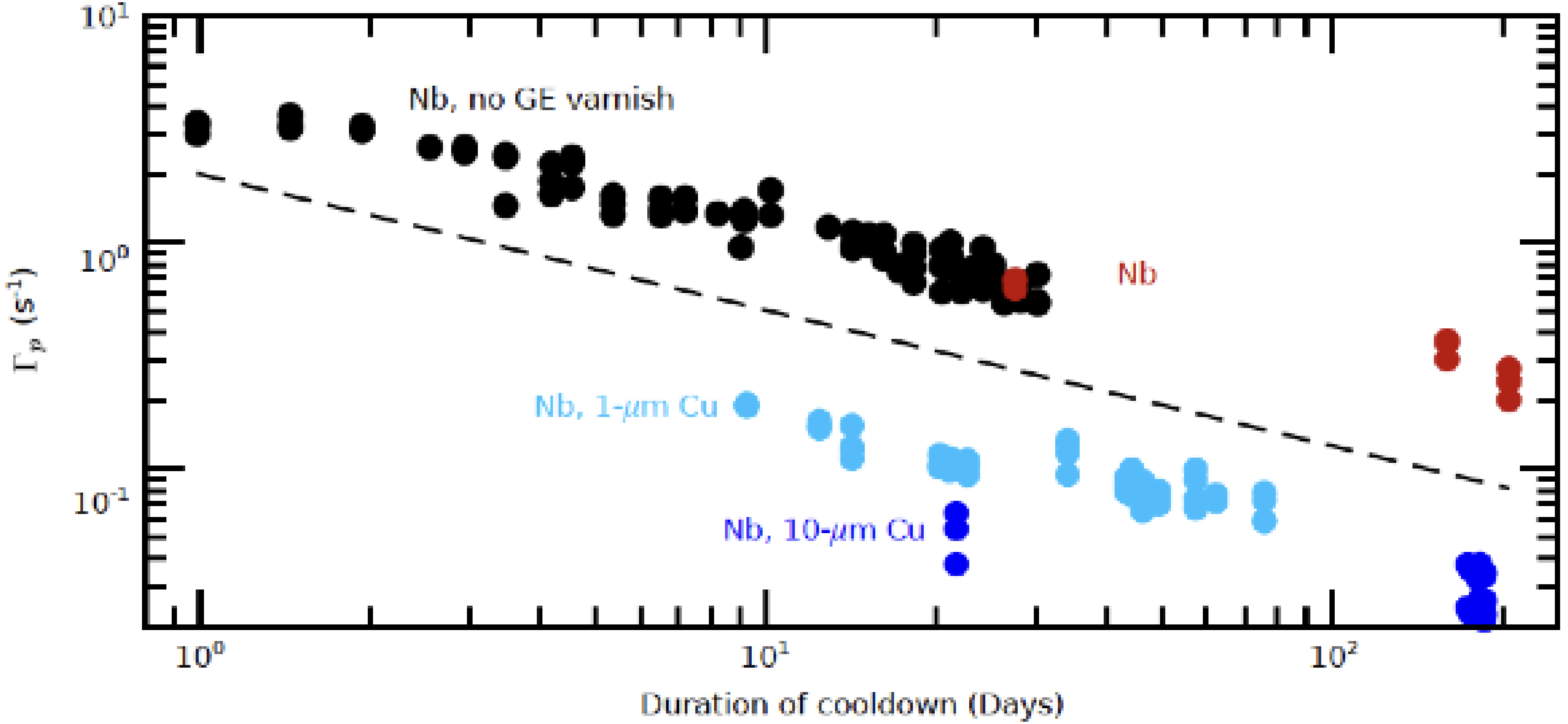


- Lower poisoning rates for Al vs. Nb compatible with phonon-mediated mechanism



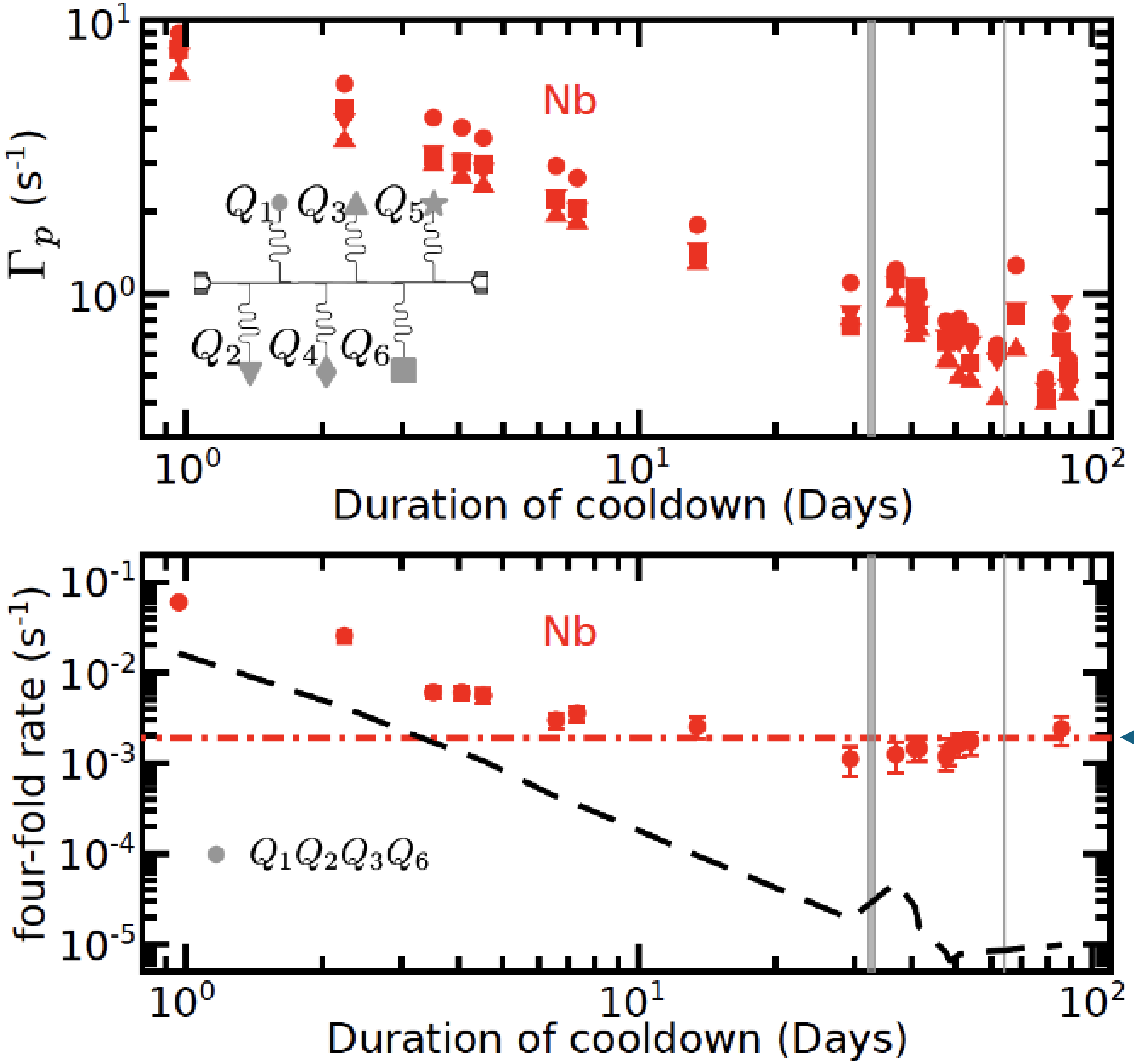
*Offset-charge jump rate constant over course of cooldown

Reduction in charge-parity switching rates over time



- Lower poisoning rates with mitigation of pair-breaking phonons, but all configurations exhibit decreasing poisoning rates with time after start of cooldown

Reduction in *correlated* charge-parity switching rates over time

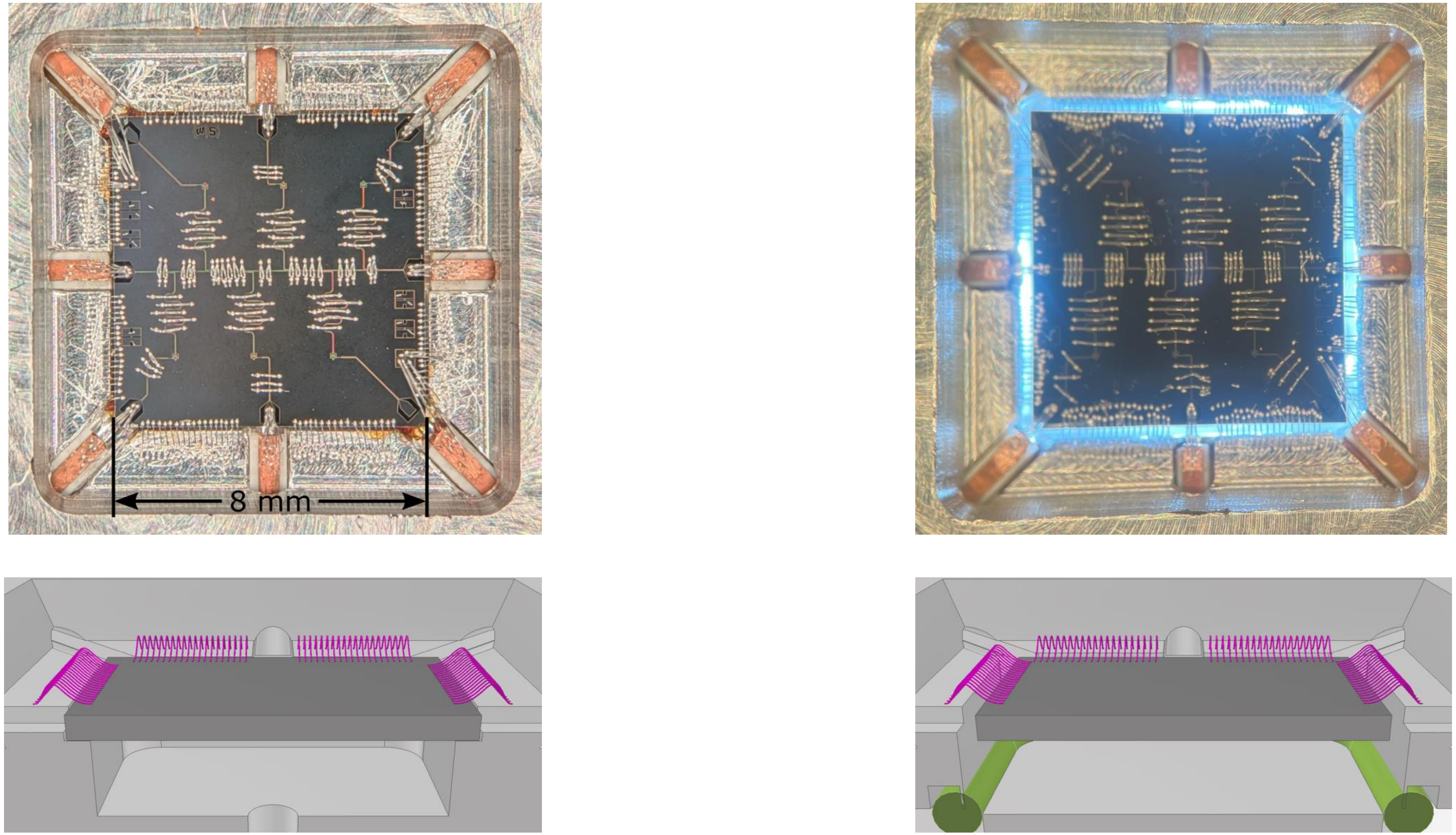


Yelton *et al.*, Phys. Rev. Lett. 135, 123601 (2025)

- Correlations suggest phonon- rather than photon-mediated poisoning

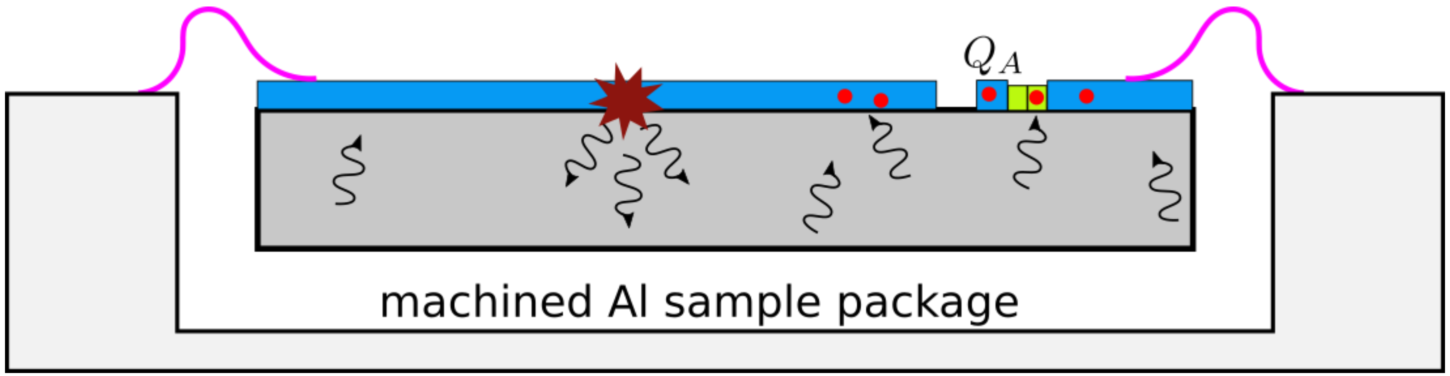
*Expected rate of 4-fold correlated poisoning due to γ impacts with no phonon mitigation = **2 x 10^{-3} s^{-1}**

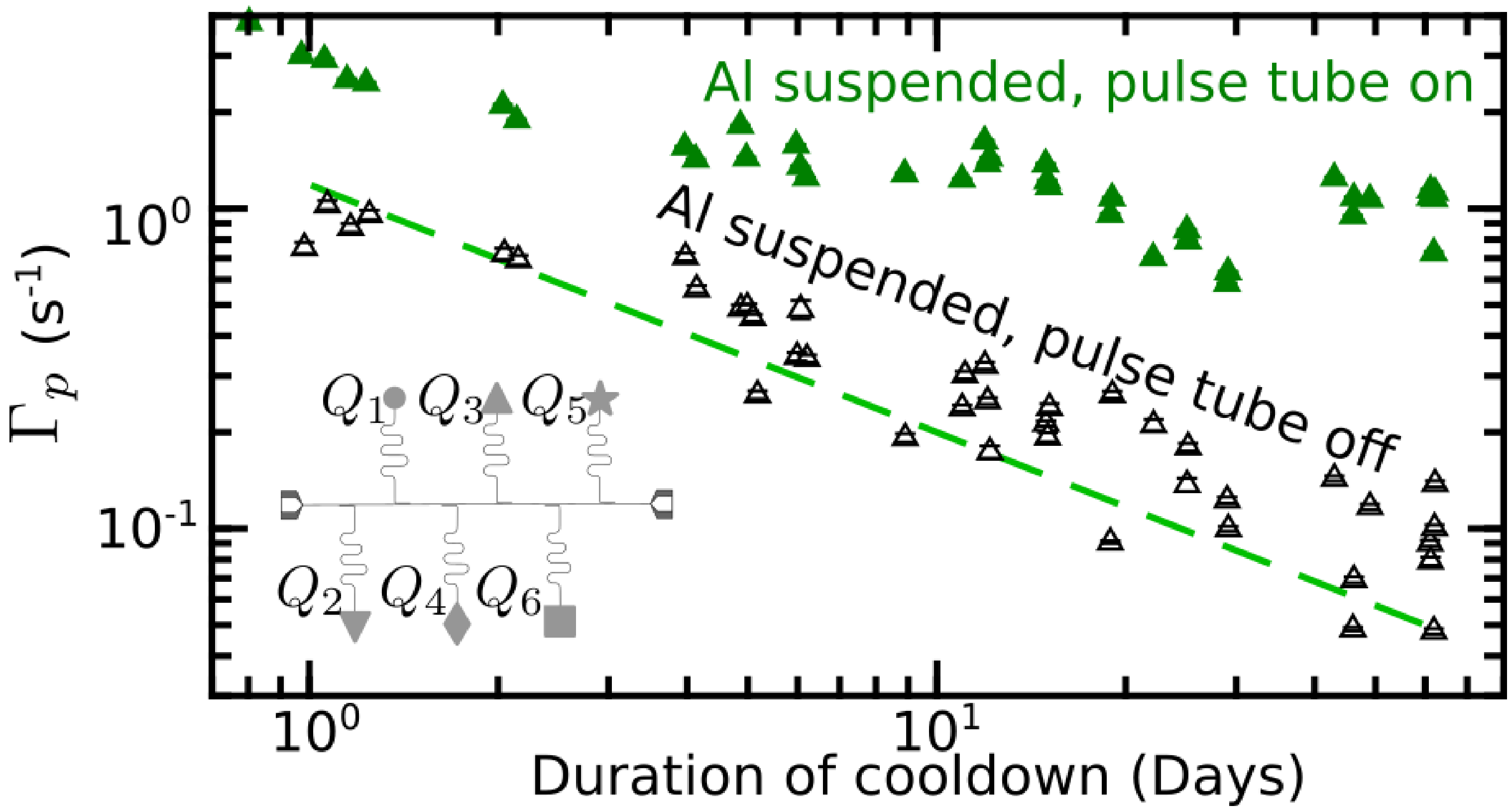
Sample package with wirebond-suspension of chip

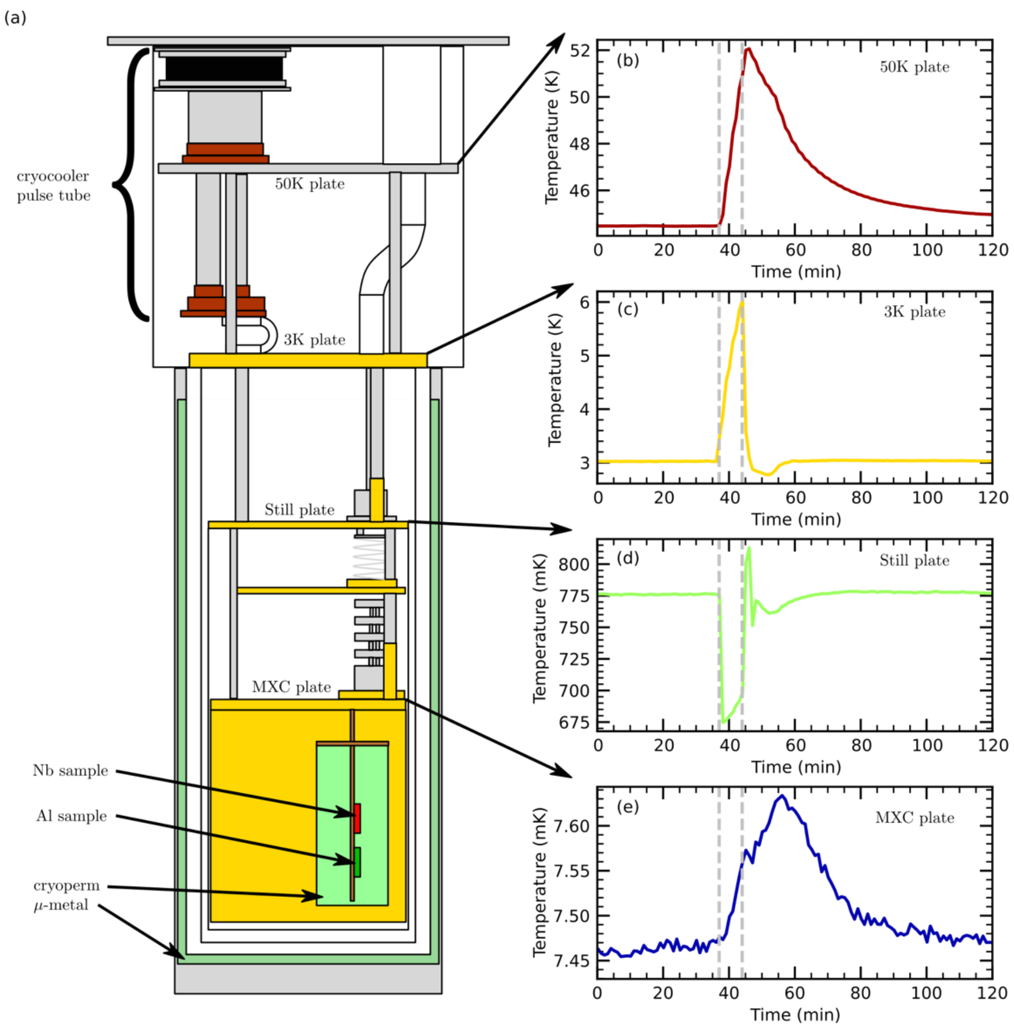


Si (chip) Al (sample box) Al (wire bond) In wire

QP charge-parity switching rates with wirebond-suspension of chip



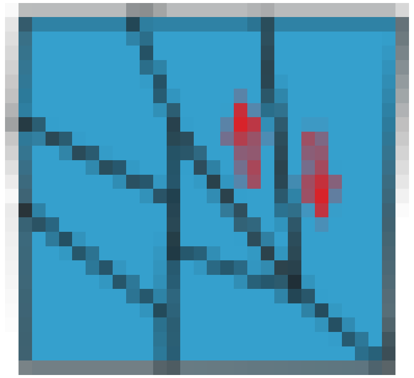




Yelton *et al.*, Phys. Rev. Lett. 135, 123601 (2025)

Potential sources of phonon-only events

Stick-slip relaxation of built-up stresses

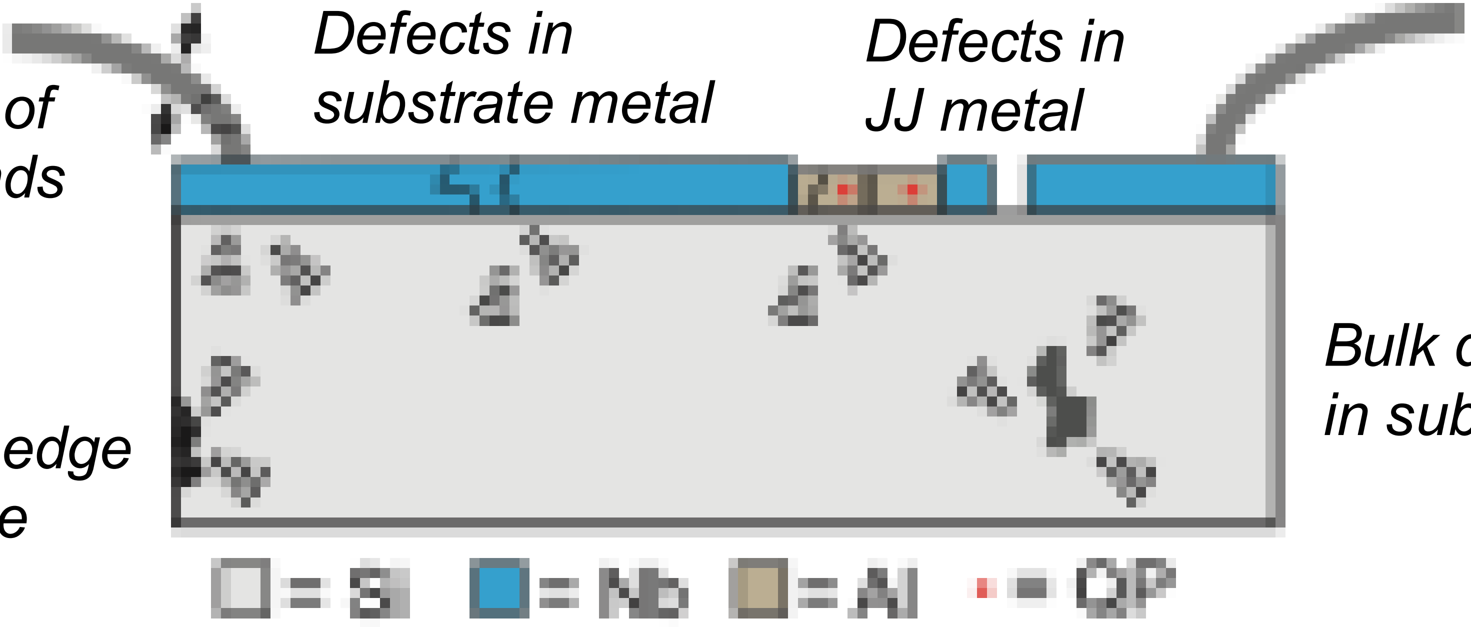


Releases burst of pair-breaking phonons

Flexing of wirebonds

Defects in substrate metal

Defects in JJ metal

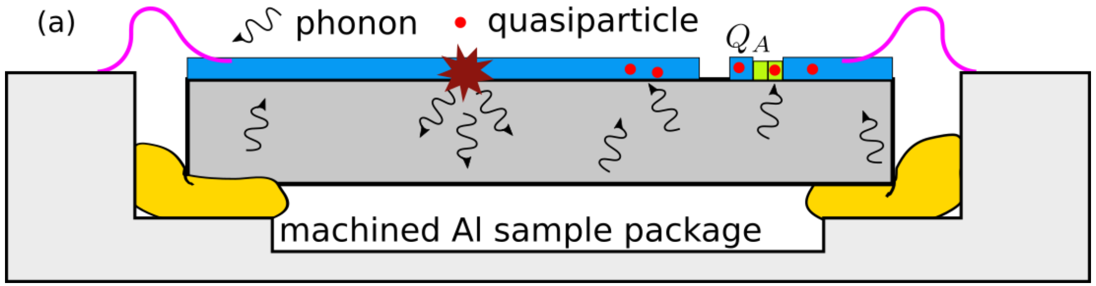


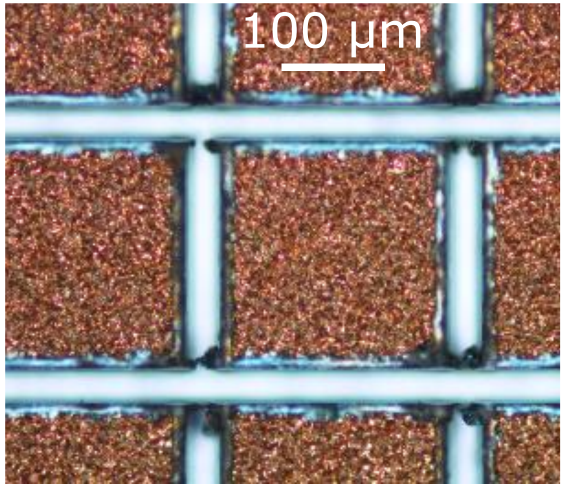
Bulk defects in substrate

Defects at edge of substrate

Conclusions & Ongoing Work

- Compact qubit designs plus extensive IR shielding and filtering can suppress photon-mediated QP poisoning
- Phonon-only events produce QP poisoning without accompanying charge signal
- Releases of built-up mechanical stresses in device produce bursts of pair-breaking phonons
- Rate of phonon bursts decreases gradually with time after start of cooldown





Iaia, Ku *et al.*, Nature Comm. 13, 6425 (2022)

Yelton *et al.*, Phys. Rev. B 110, 024519 (2024)

Larson *et al.*, PRX Quantum 6, 030339 (2025)

Yelton *et al.*, Phys. Rev. Lett. 135, 123601 (2025)

Acknowledgments

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