Mitigating Phonon-mediated Quasiparticle Poisoning of Superconducting Qubits

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Radiation Impact on Superconducting Qubits
Fermilab
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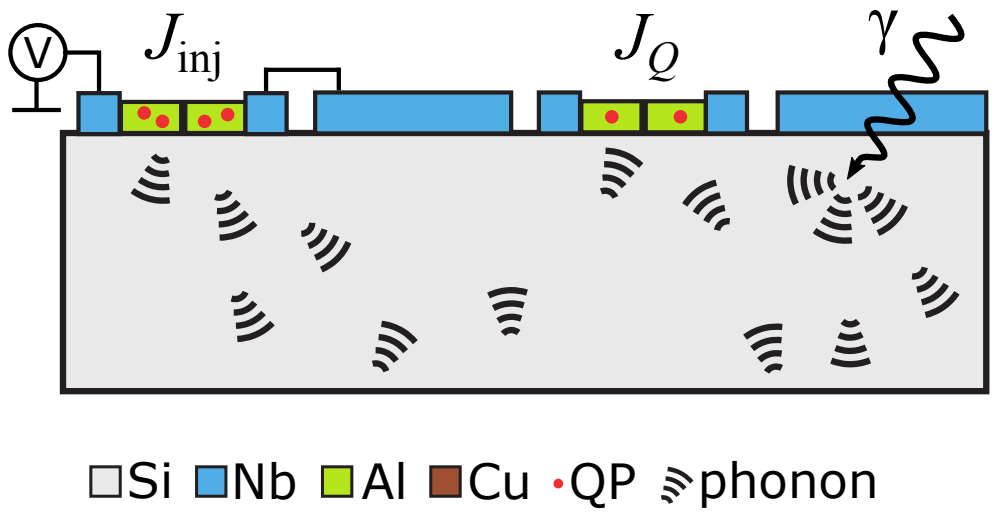
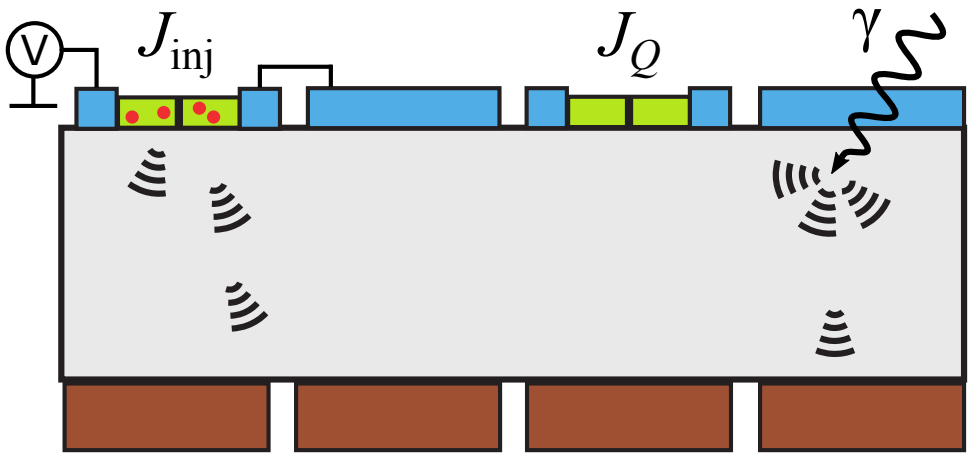
Mitigating & characterizing phonon-mediated QP poisoning

- Qubit arrays with & without back-side metallization for down-converting phonon energy

- Generate QP poisoning from:
  - *Direct phonon injection with on-chip tunnel junctions*
  - *Background radioactivity in lab*
  - *Active gamma irradiation with ^{60}Co source*

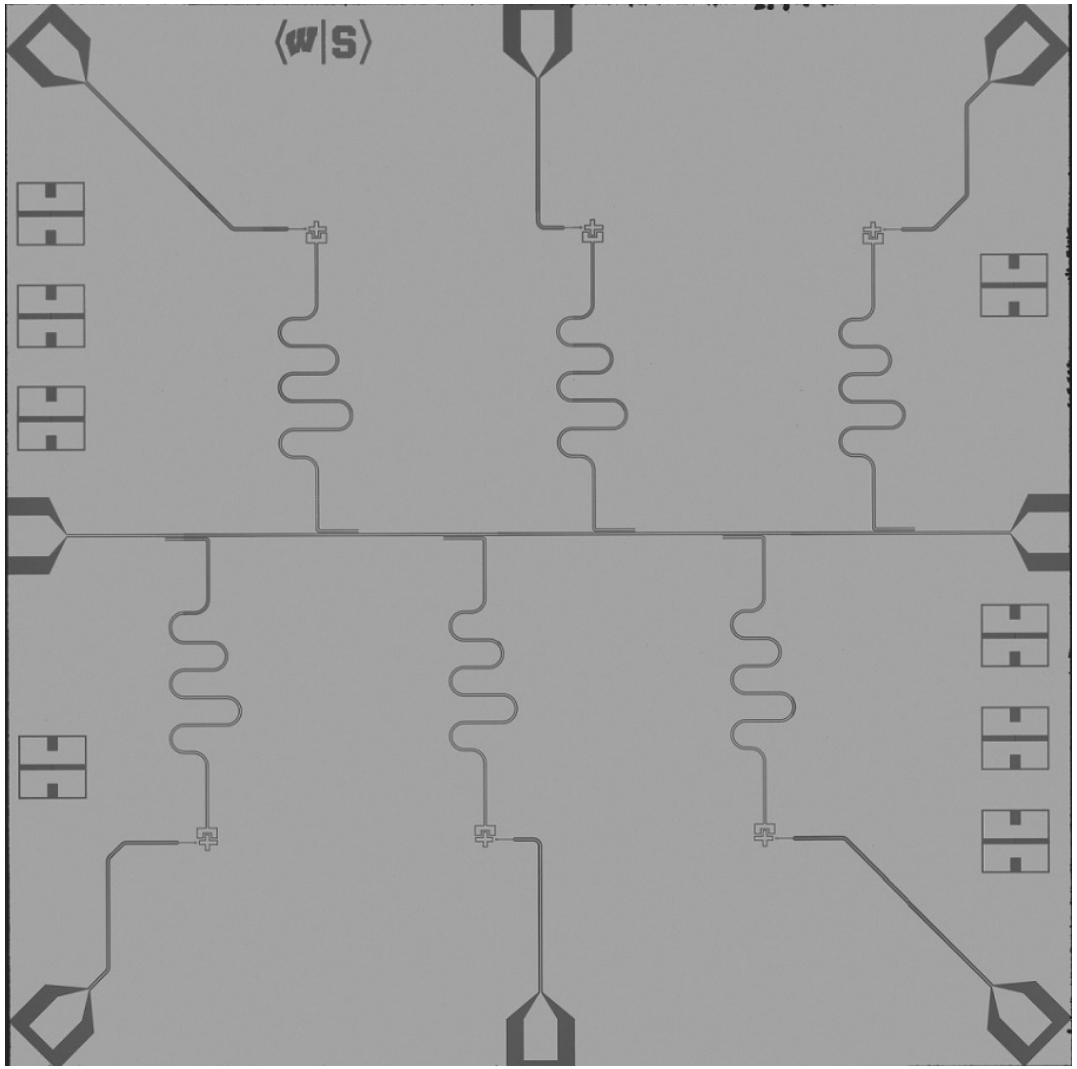
- Characterize QP poisoning through:
  - *Transient reductions in T_1*
  - *QP charge-parity switching rate*
  - *Offset-charge shifts**

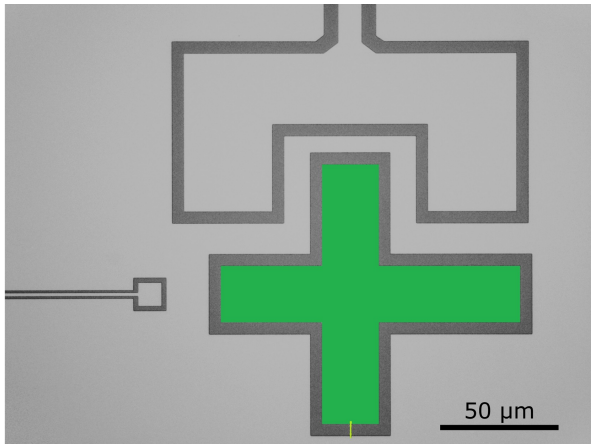




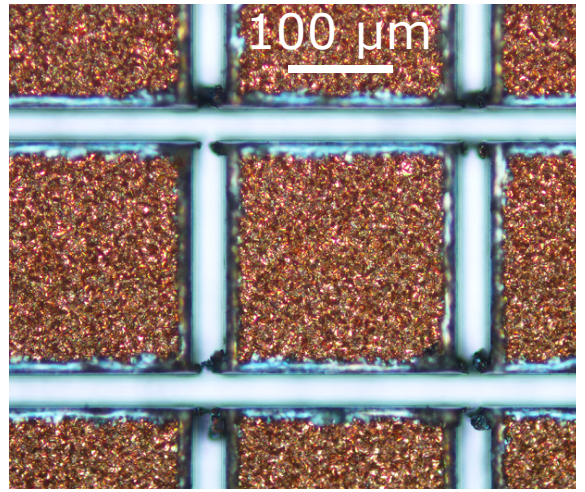
Martinis, npj Quantum **7**, 1 (2021)

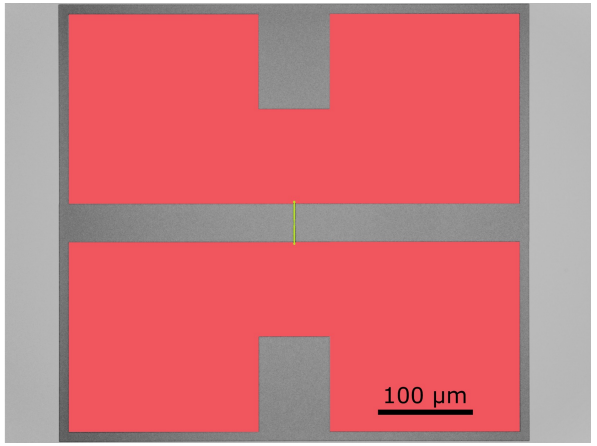
Controlled study of phonon-mediated QP poisoning





- Nb groundplane
- Al/AlOx/Al junctions
- Charge-sensitive transmons

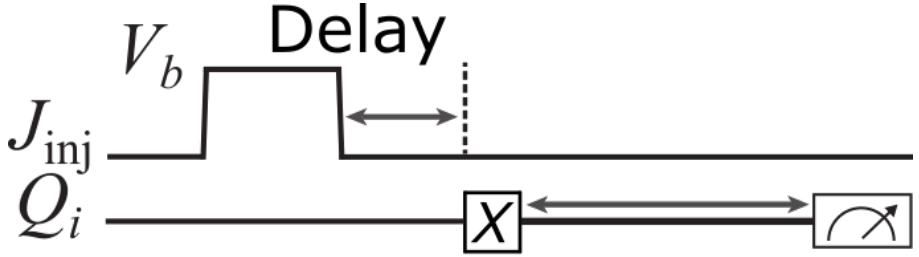




- Electroplated Cu
- Thickness: 1 μm, 10 μm

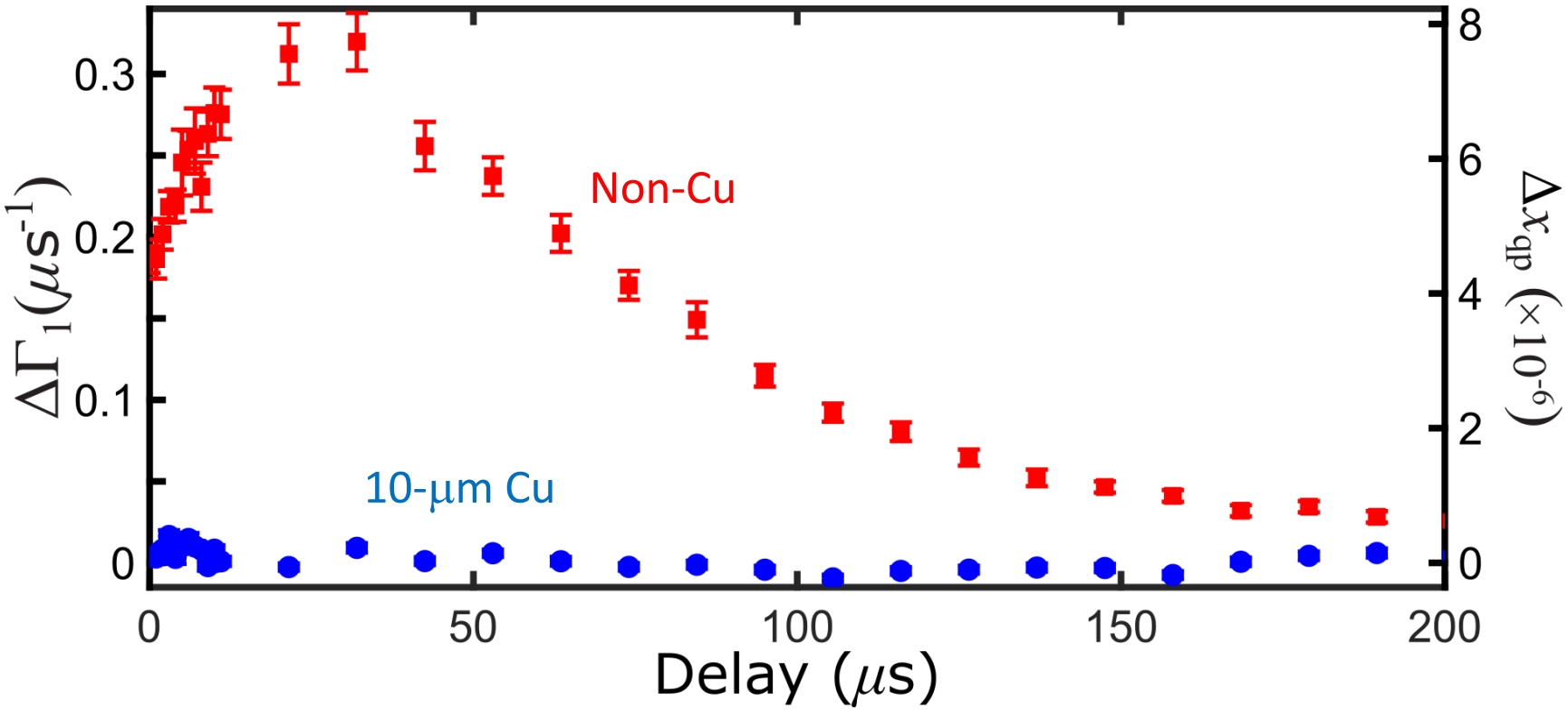
CNF Cornell NanoScale Science and Technology Facility

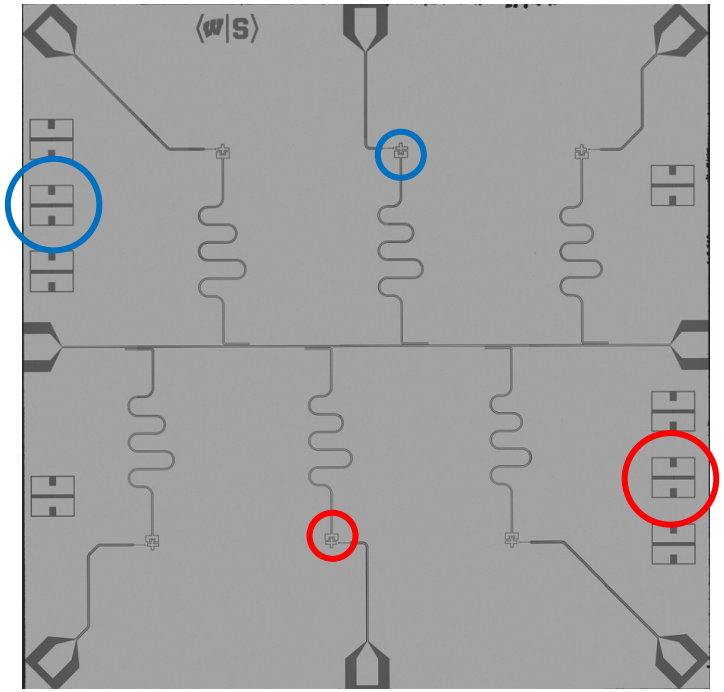
Enhanced qubit relaxation from controlled phonon injection



$$\Delta\Gamma_1 = \frac{1}{T_1} - \frac{1}{T_1^b}$$

$$x_{qp} = \frac{\pi}{\sqrt{2\Delta\omega_{01}/\hbar}}\Delta\Gamma_1$$

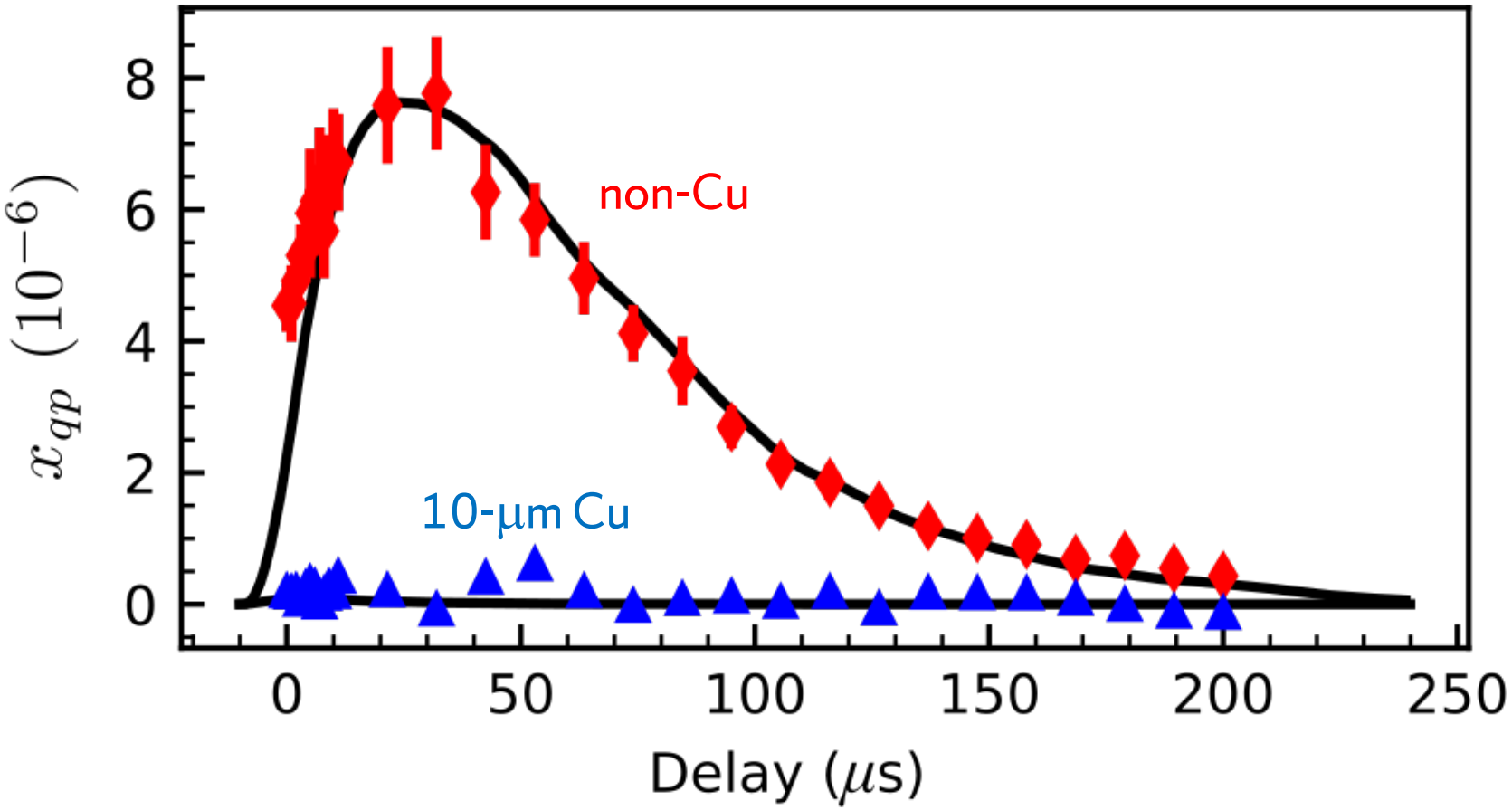




Iaia, Ku *et al.*, Nature Comm. 13, 6425 (2022)

Modeling and fitting of phonon injection measurements

- Adjust phonon loss probability at chip edges and QP trapping rate for best fit

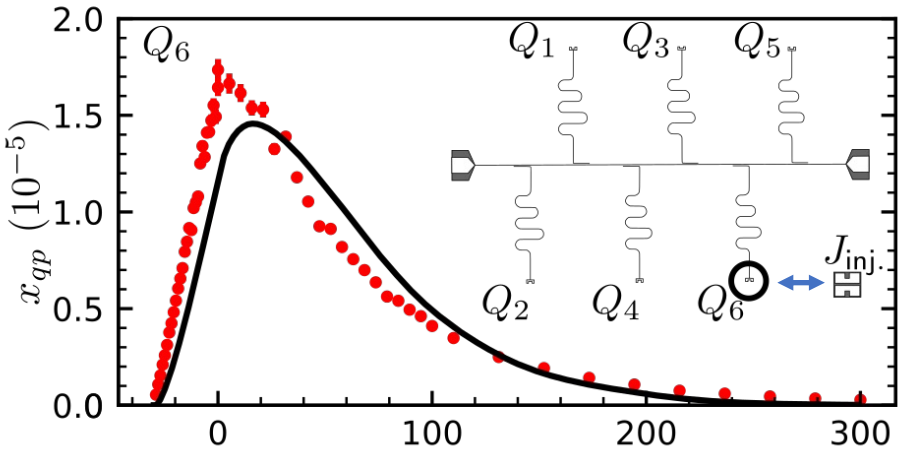


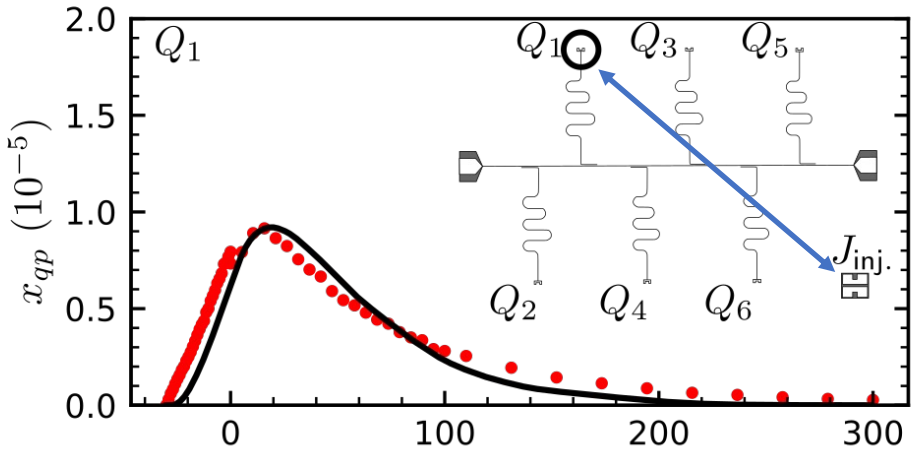
2.5% phonon boundary absorption $s = 4.5 \times 10^{-2}\ \mu\mathrm{s}^{-1}$

Yelton *et al.*, arXiv:2402.15471

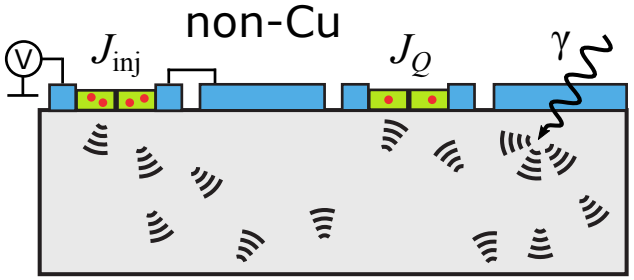
QP poisoning with phonon injection: spatial variation

non-Cu, 30-μs injection pulse

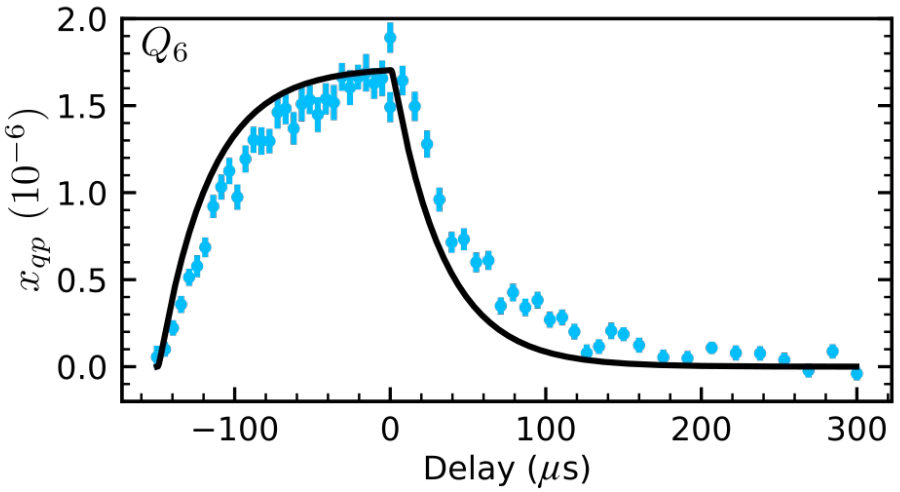


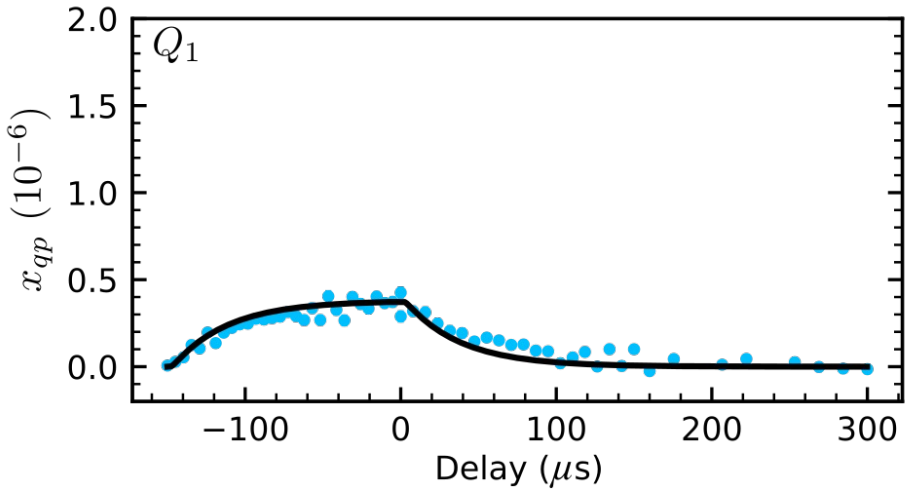


$s = 5 \times 10^{-2}\ \mu\mathrm{s}^{-1}$

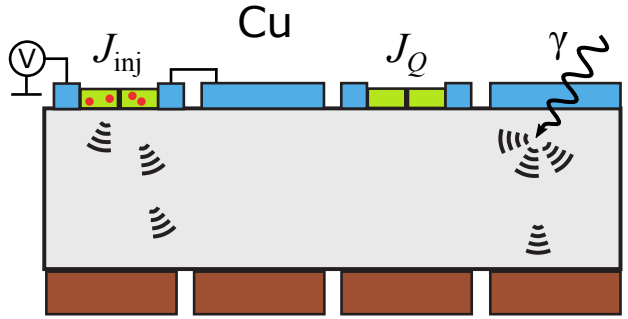


1-μm Cu, 150-μs injection pulse





$s = 4 \times 10^{-2}\ \mu\mathrm{s}^{-1}$

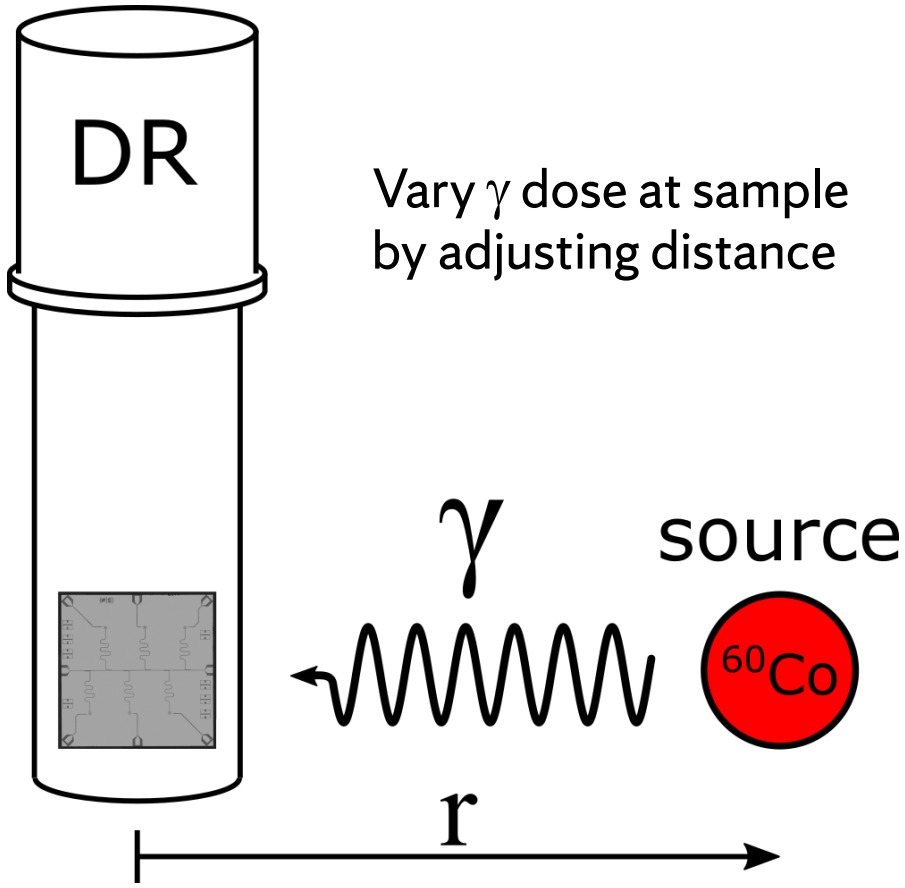


2.5% phonon boundary absorption

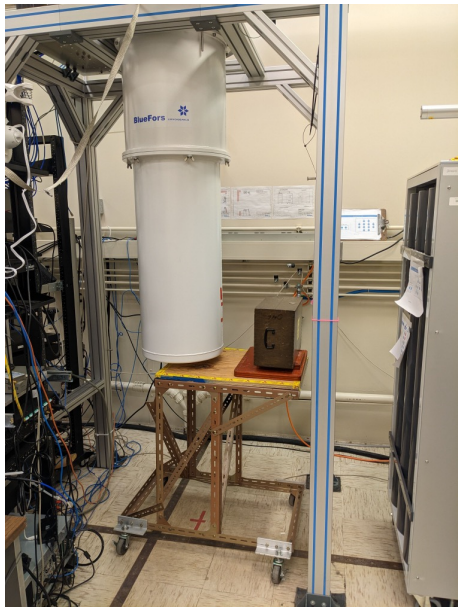
Yelton *et al.*, arXiv:2402.15471

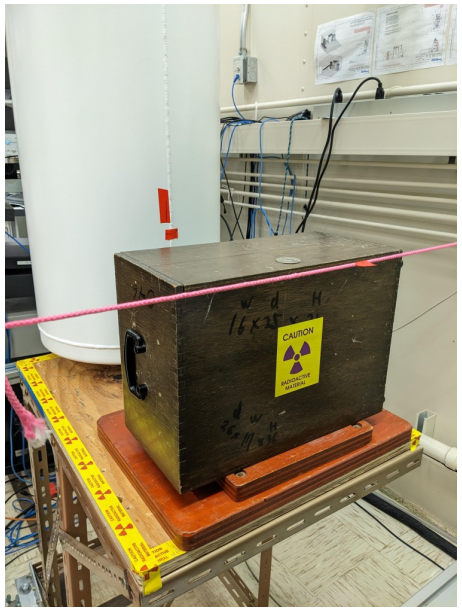
QP poisoning from active γ irradiation

^{60}Co source outside DR
- half life ~ 5 years

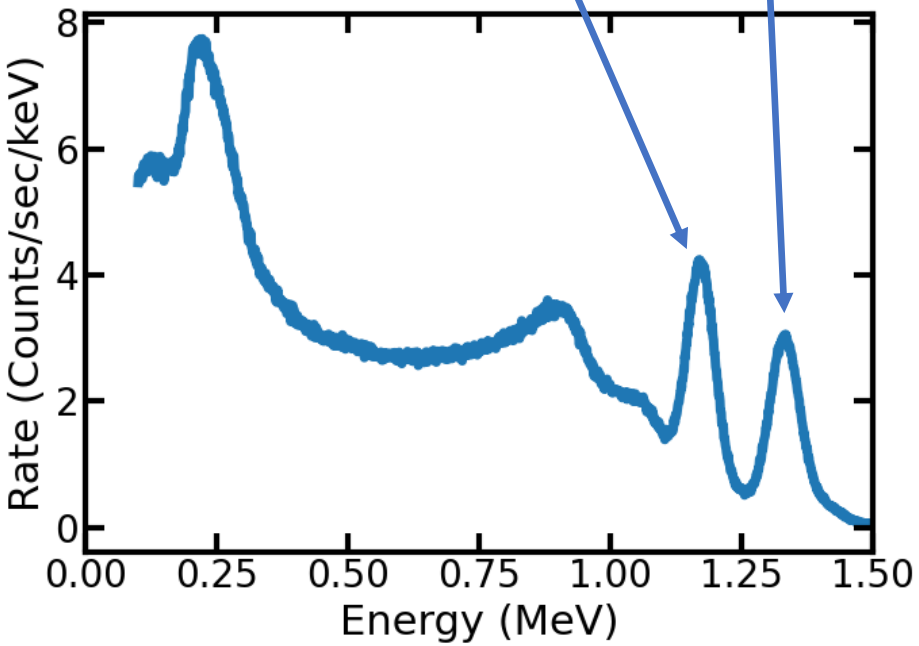


Vary γ dose at sample by adjusting distance



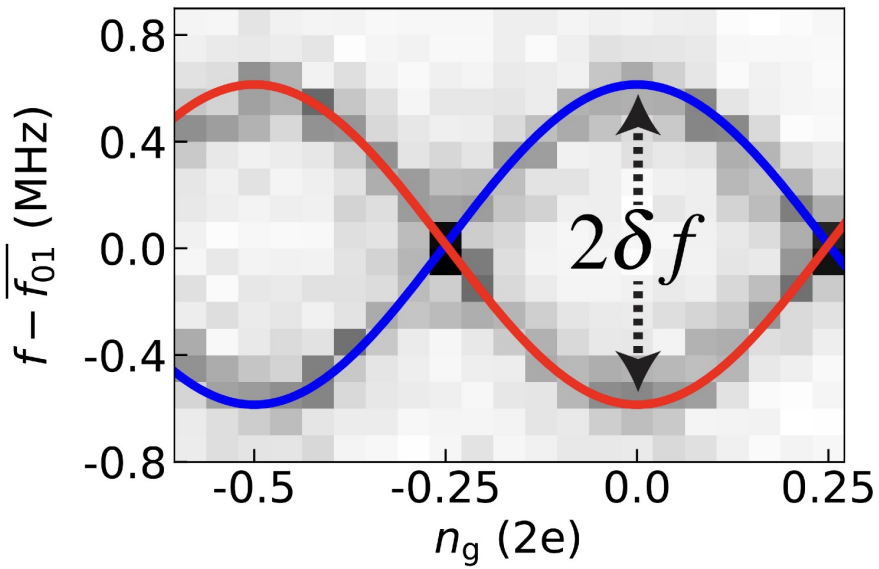


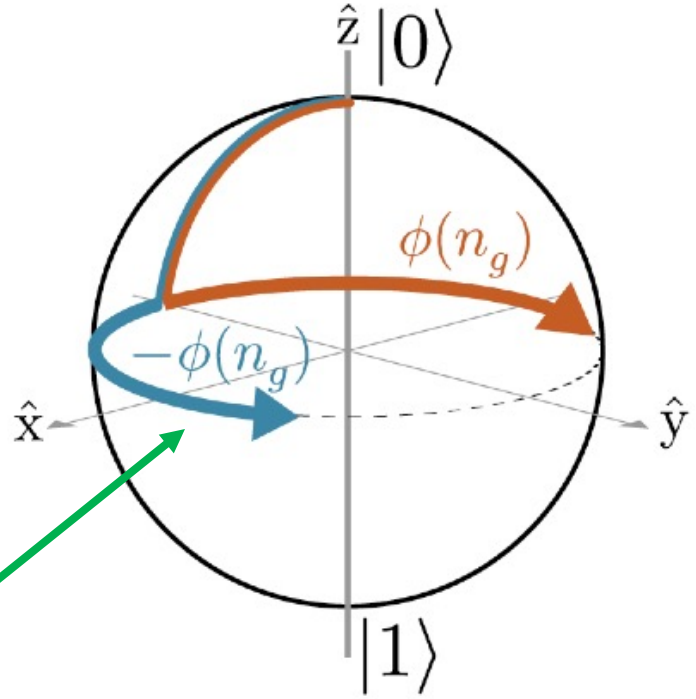
emission of two γ-rays at 1.17 and 1.33 MeV

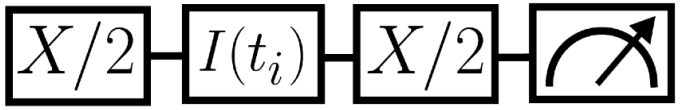


Larson *et al.*, in preparation (2024)

Monitoring Offset-charge Jumps



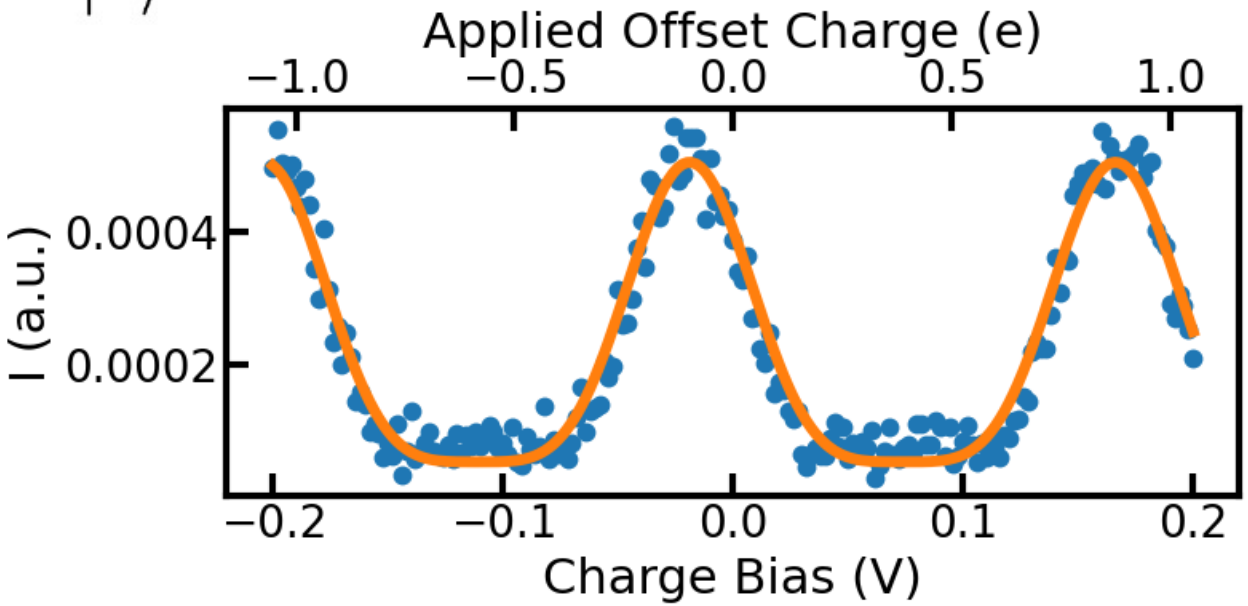




$$t_i = 1/2\delta f$$

Acquisition & fitting time for charge tomography scan ~0.2 s

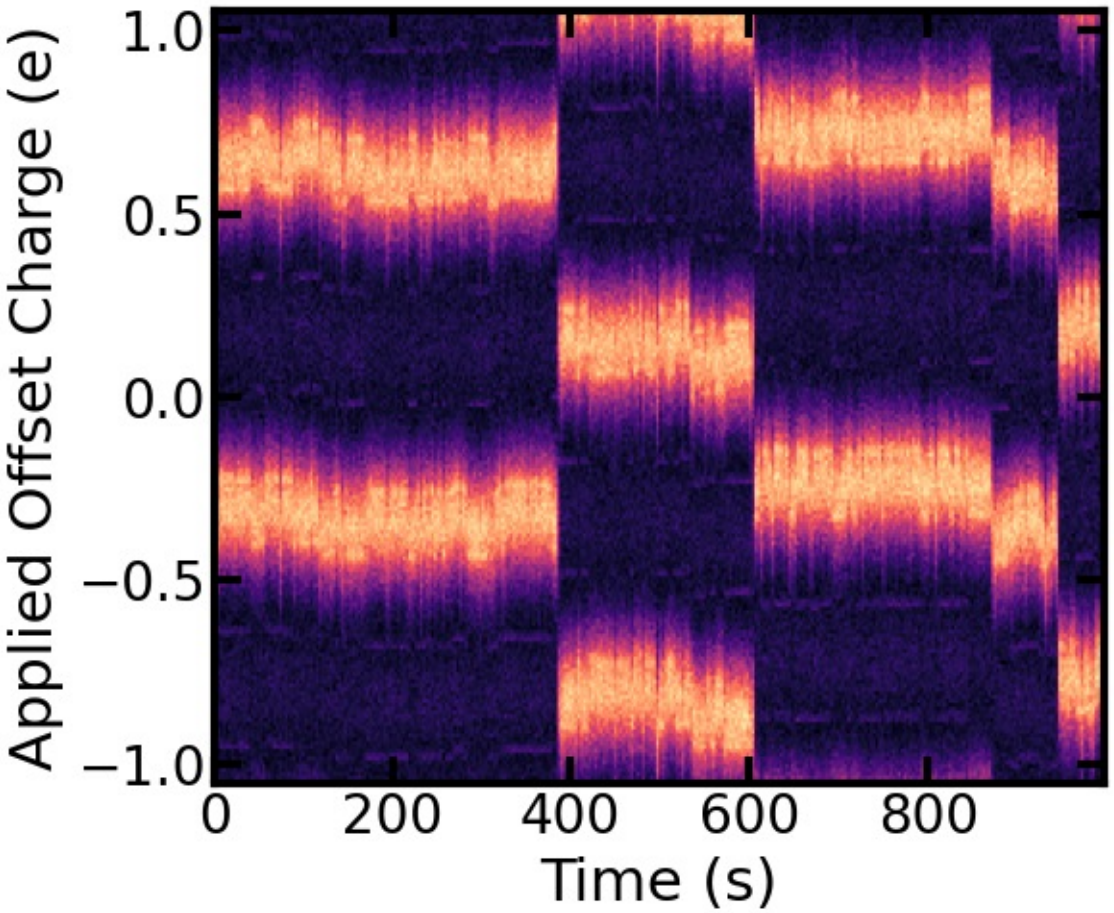
$$\phi(n_g) = t_i \Delta\omega_{10} \cos(2\pi n_g)$$



Christensen *et al.*, Phys. Rev. B **100**, 140503 (2019)

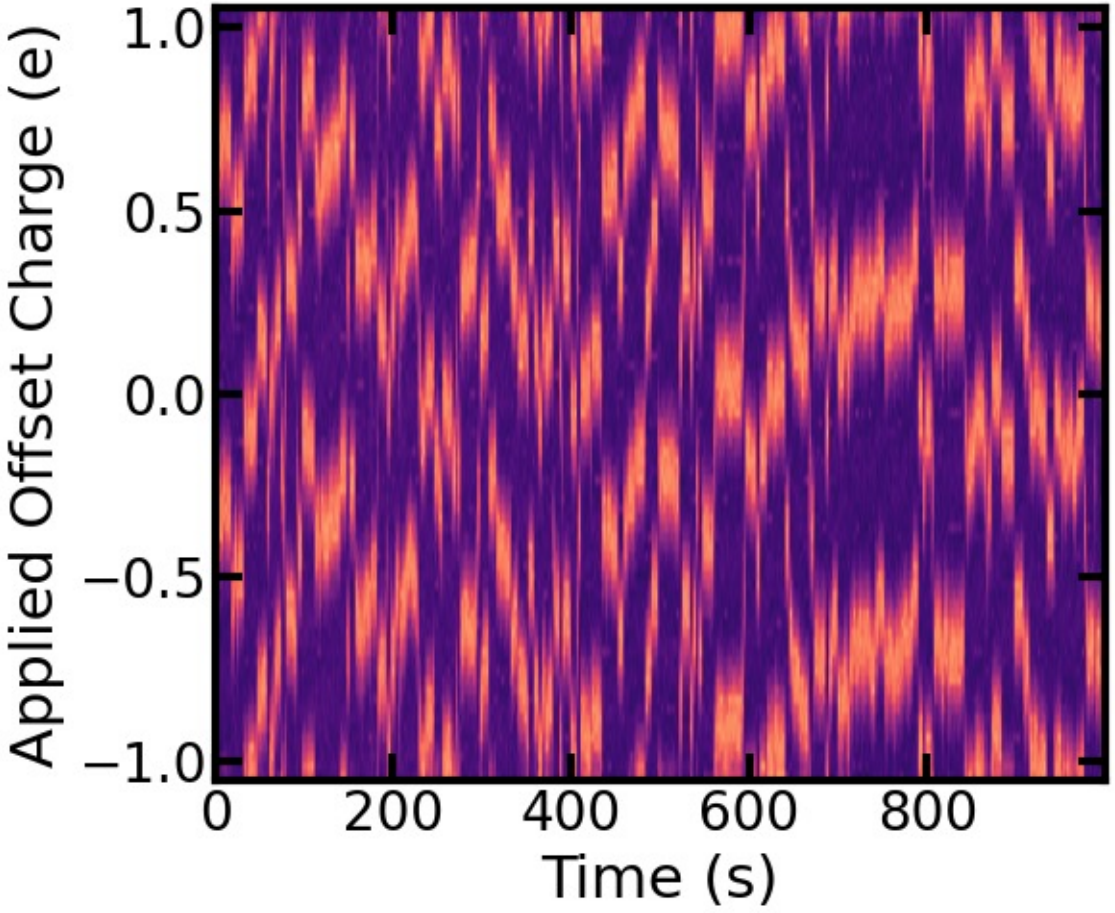
Repeated measurements of offset charge

No ^{60}Co source



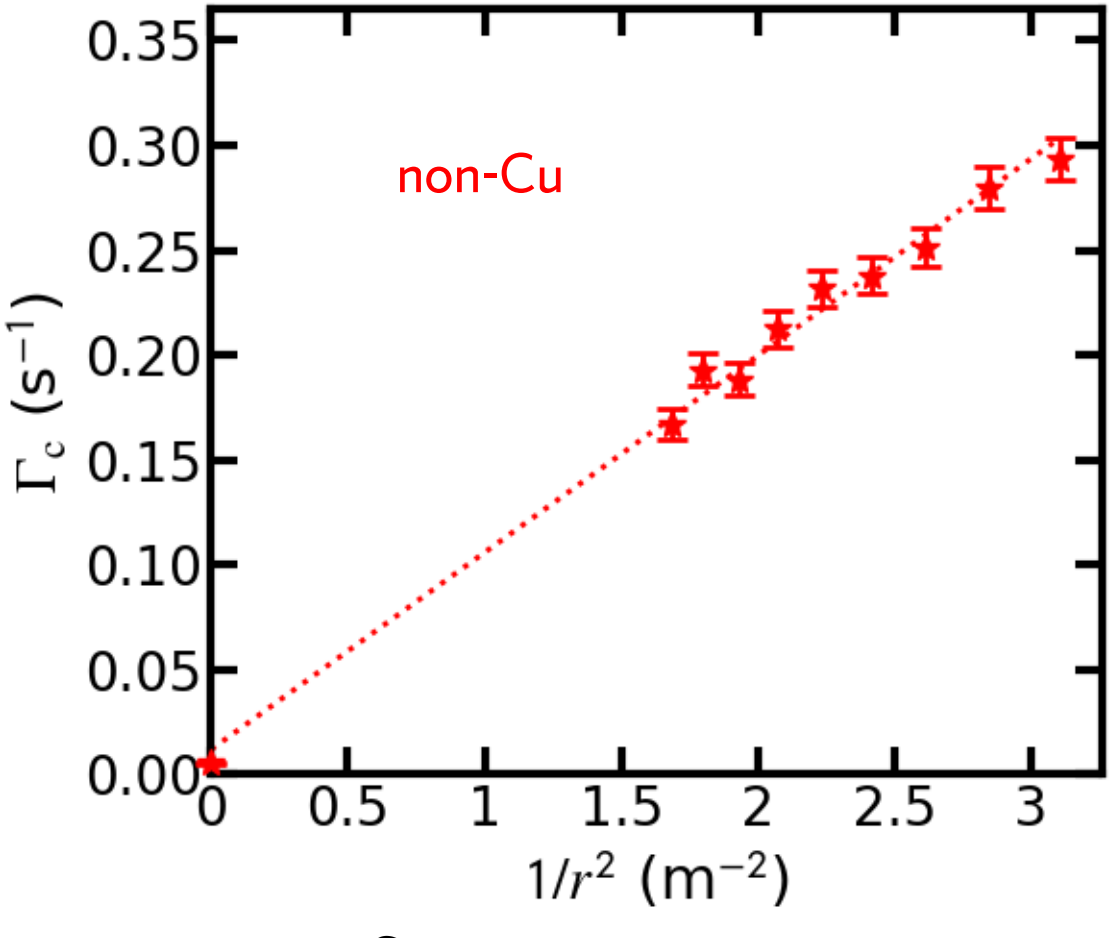
Run charge tomography
scan every 3 s for 1000 s

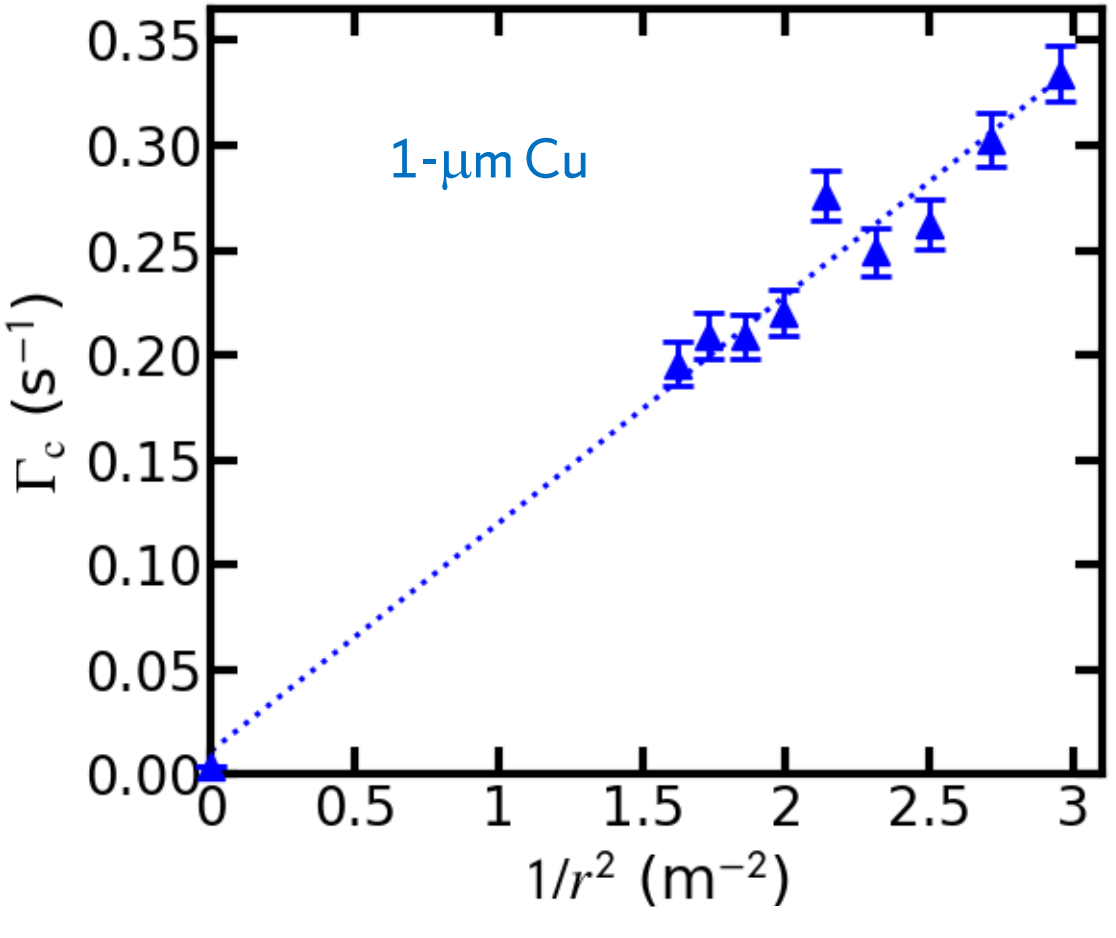
^{60}Co source at 79 cm

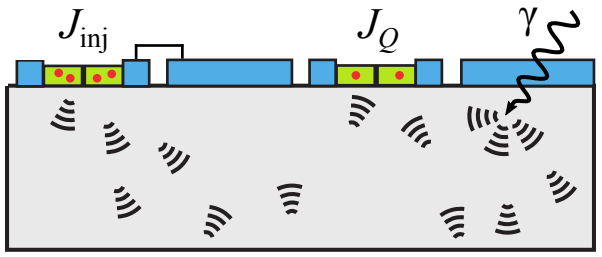


Run charge tomography
scan every 0.2 s for 1000 s

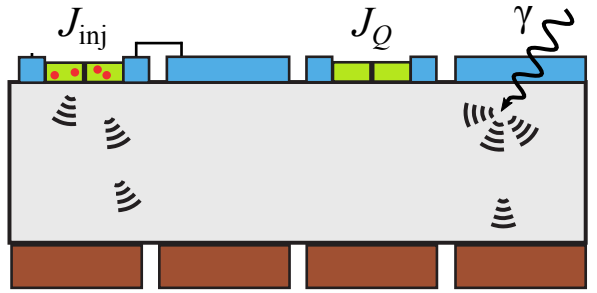
Offset-charge jump rate for different γ doses



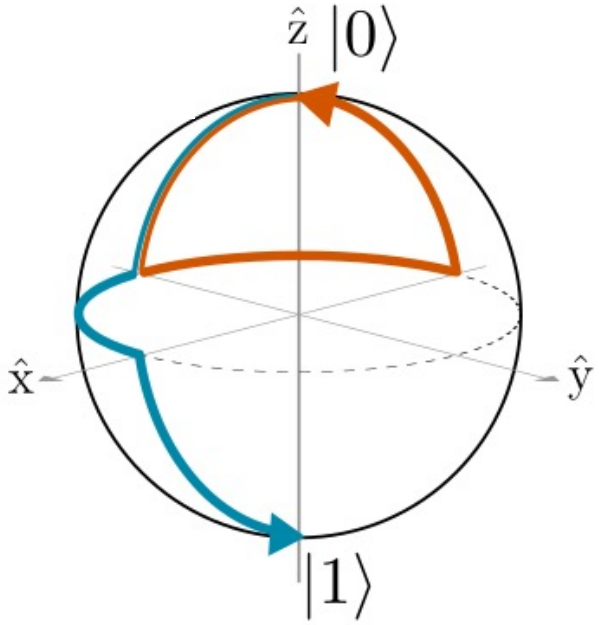




Rate of offset-charge jumps comparable for both chips



Direct measurement of QP poisoning via charge parity



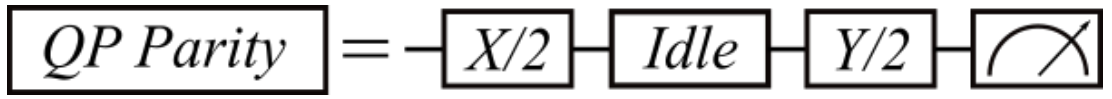
Riste *et al.*, Nat. Comm. **4**, 1913 (2013)

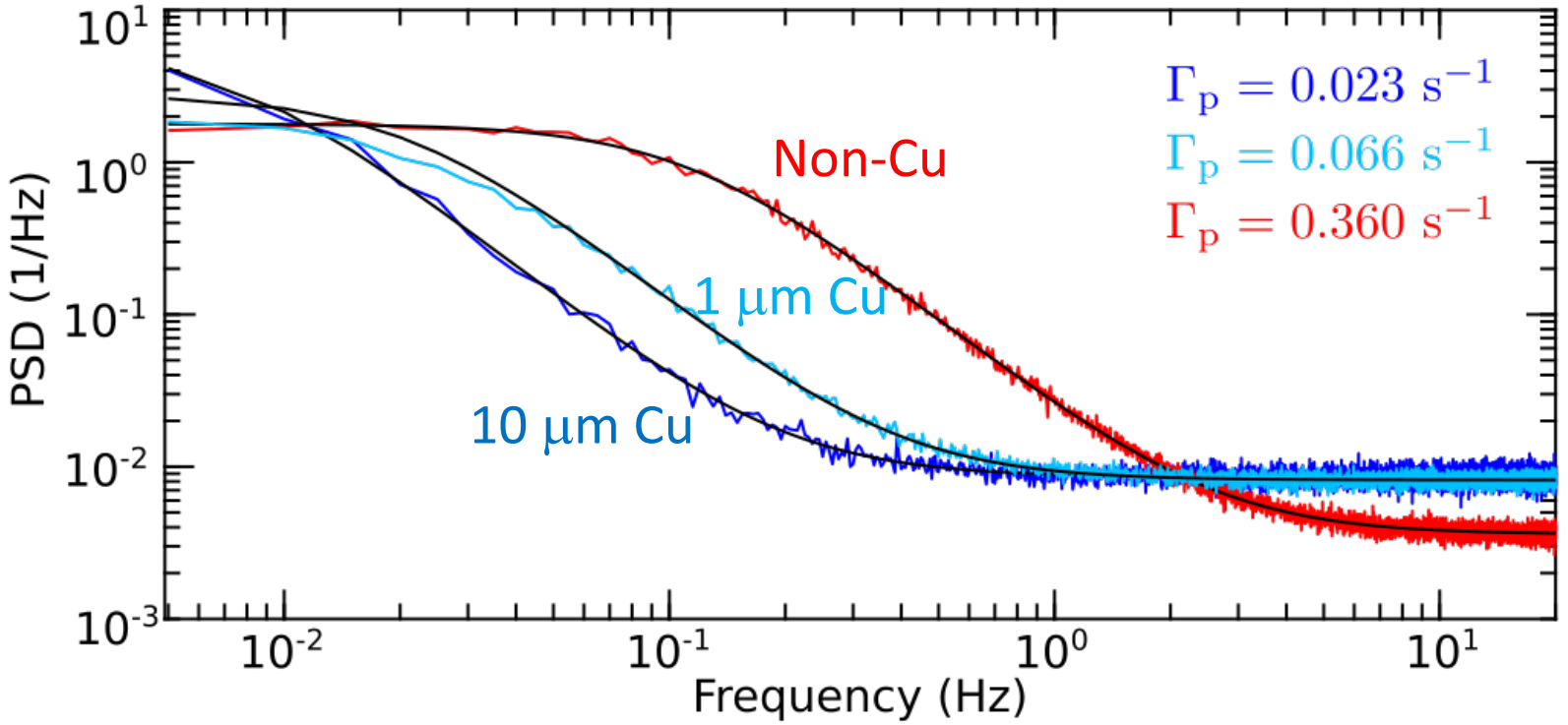
$$S_p(f) = \frac{4F^2\Gamma_p}{(2\Gamma_p)^2 + (2\pi f)^2} + \left(1 - F^2\right)\Delta t$$

Kurter *et al.*, npj Quantum **8**, 1 (2022)

Pan *et al.*, Nature Comm. **13**, 7196 (2022)

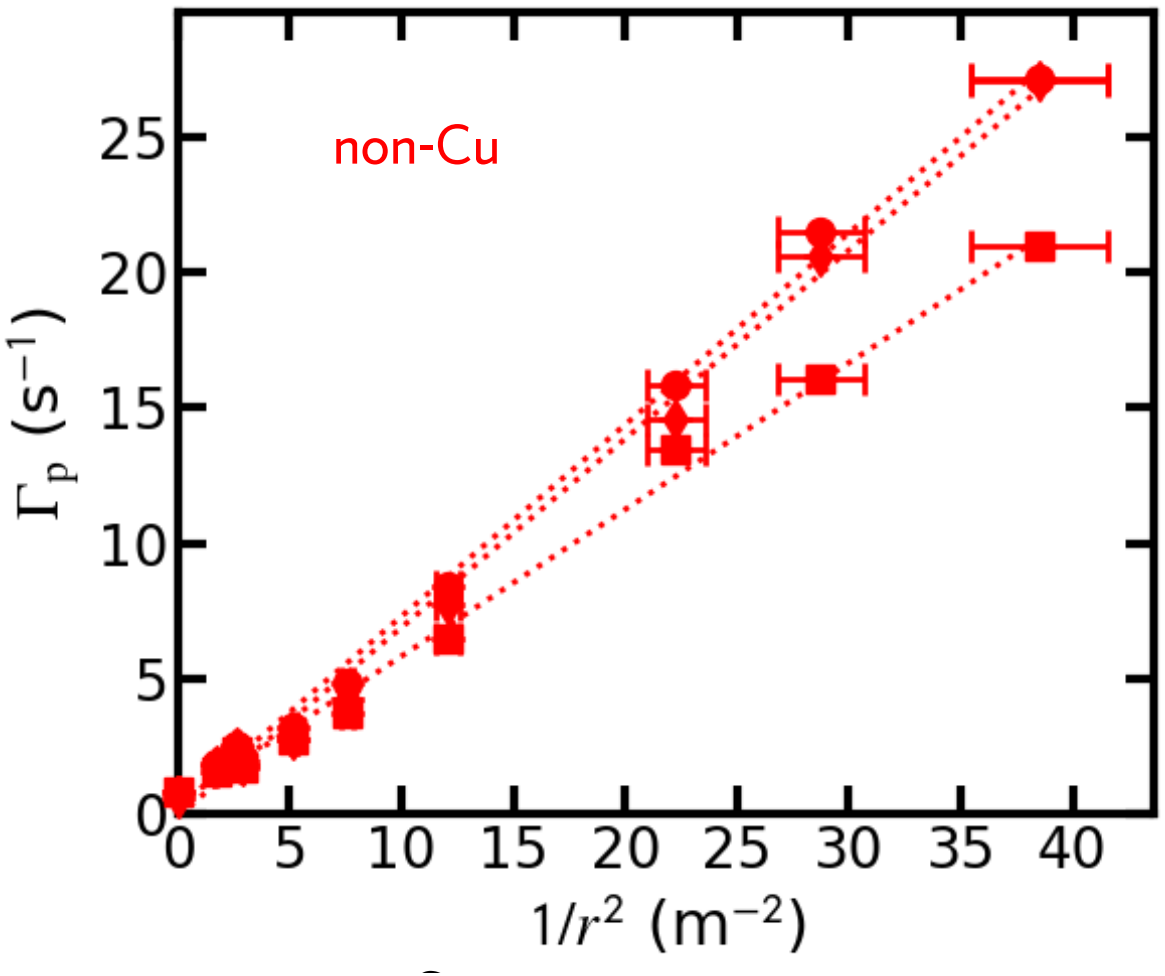
Connolly *et al.*, arXiv:2302.12330

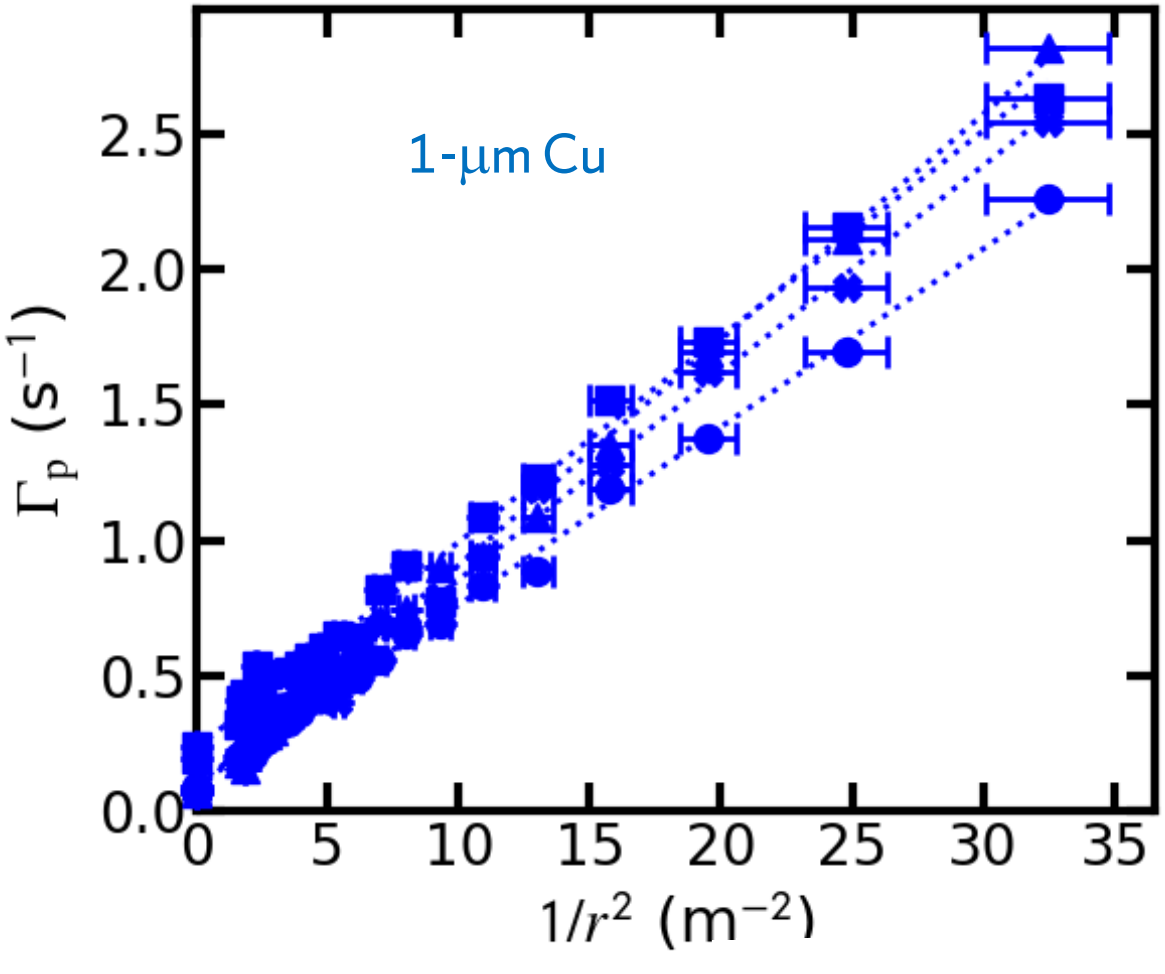


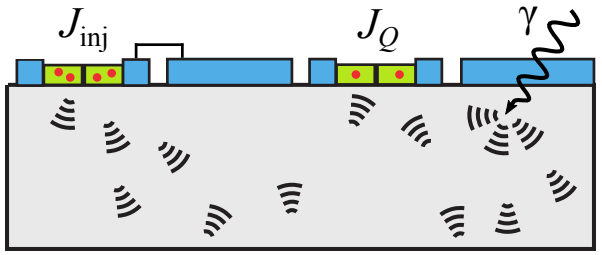


- Low QP parity switching rates
- Effective shielding from stray light and compact qubit footprint

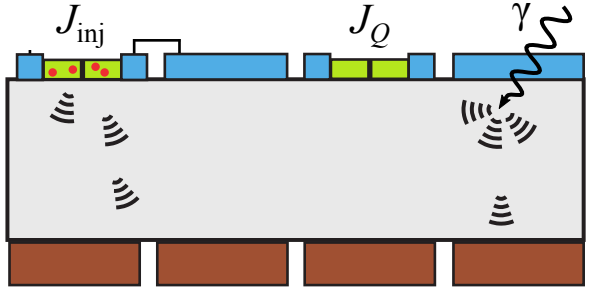
QP charge-parity switching for different γ doses





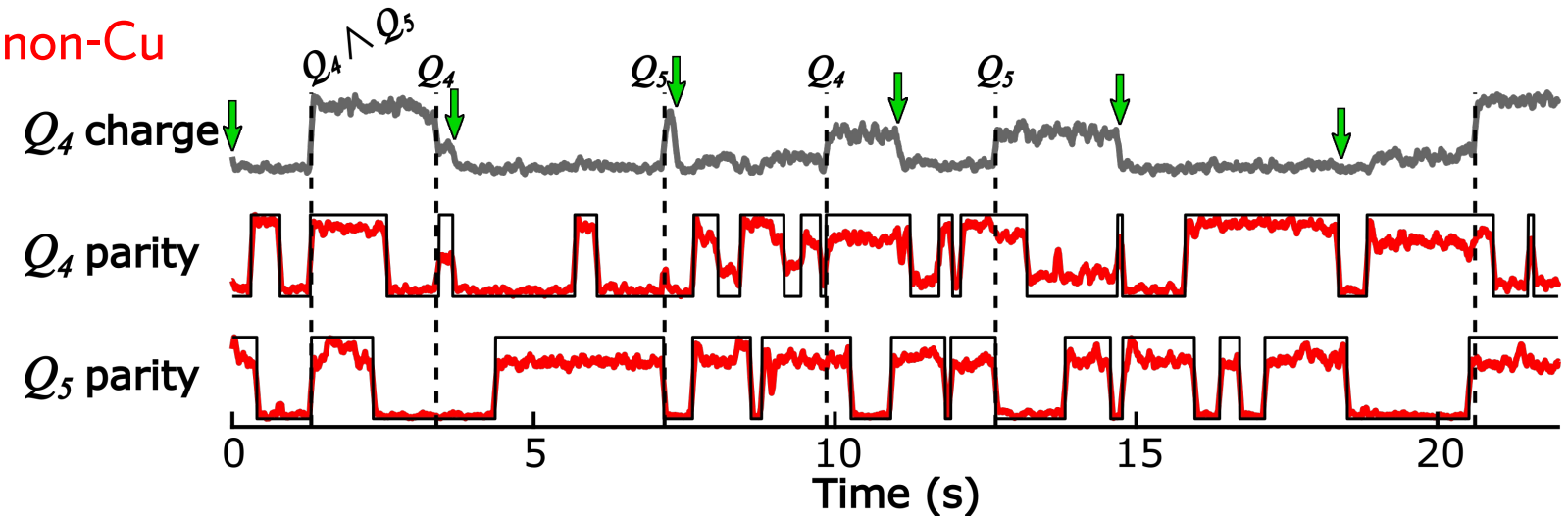


Rate of QP poisoning
~10x higher for device
with no phonon mitigation



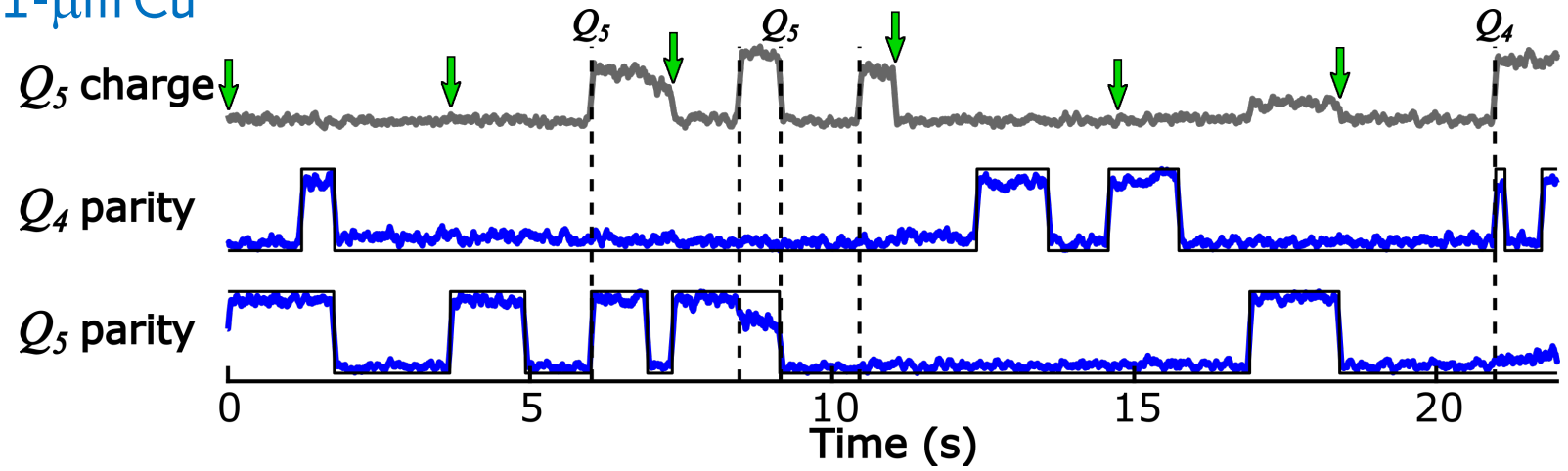
Correlations: offset-charge shifts & QP charge-parity switching (preliminary)

non-Cu



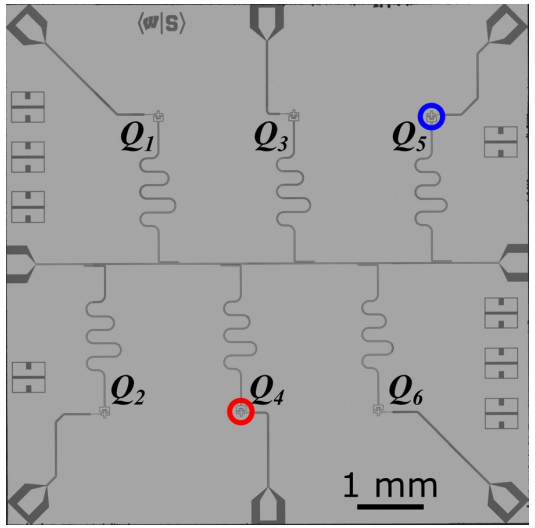
= periodic stabilization of offset charge

1-μm Cu



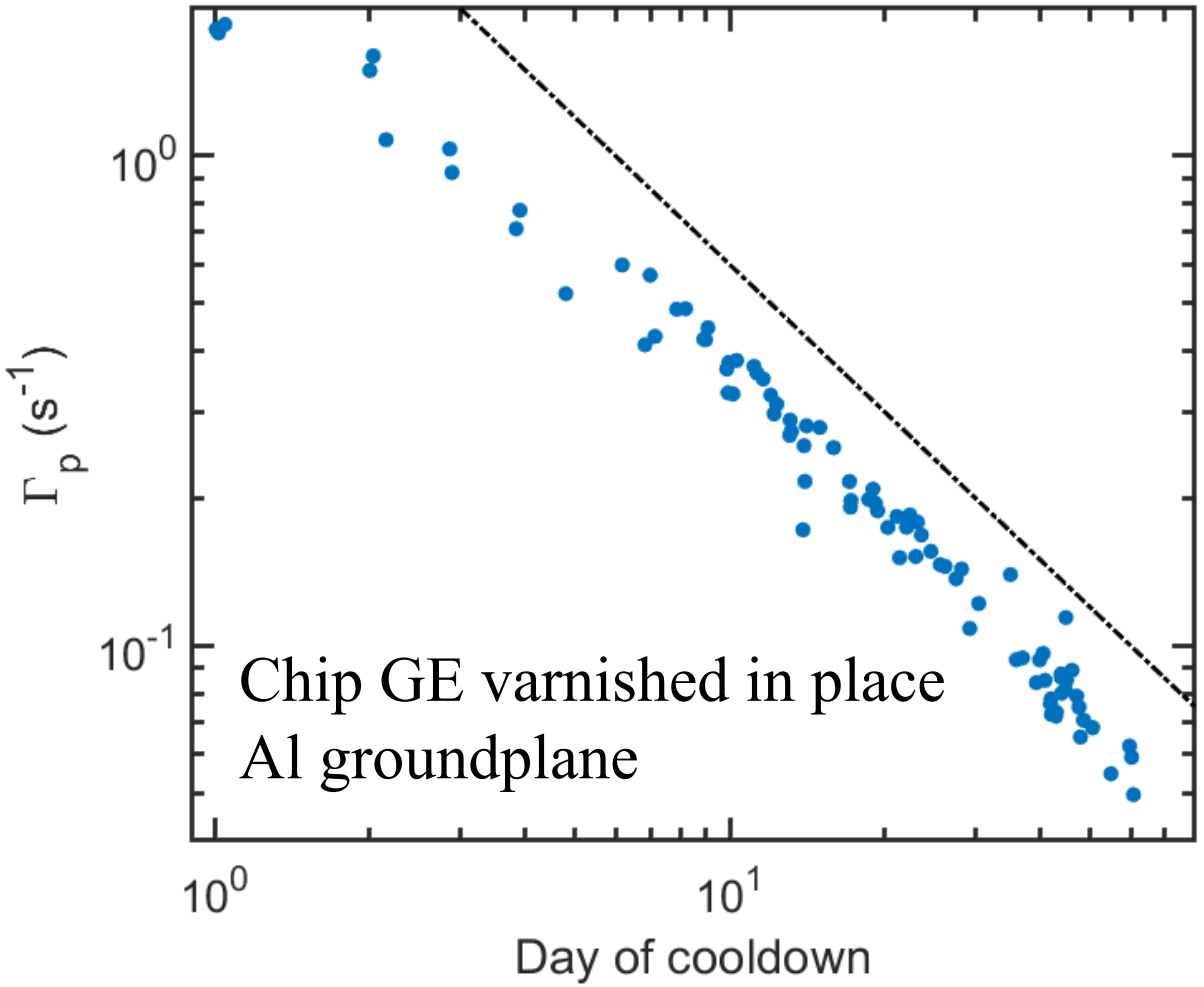
Larson *et al.*, in preparation (2024)

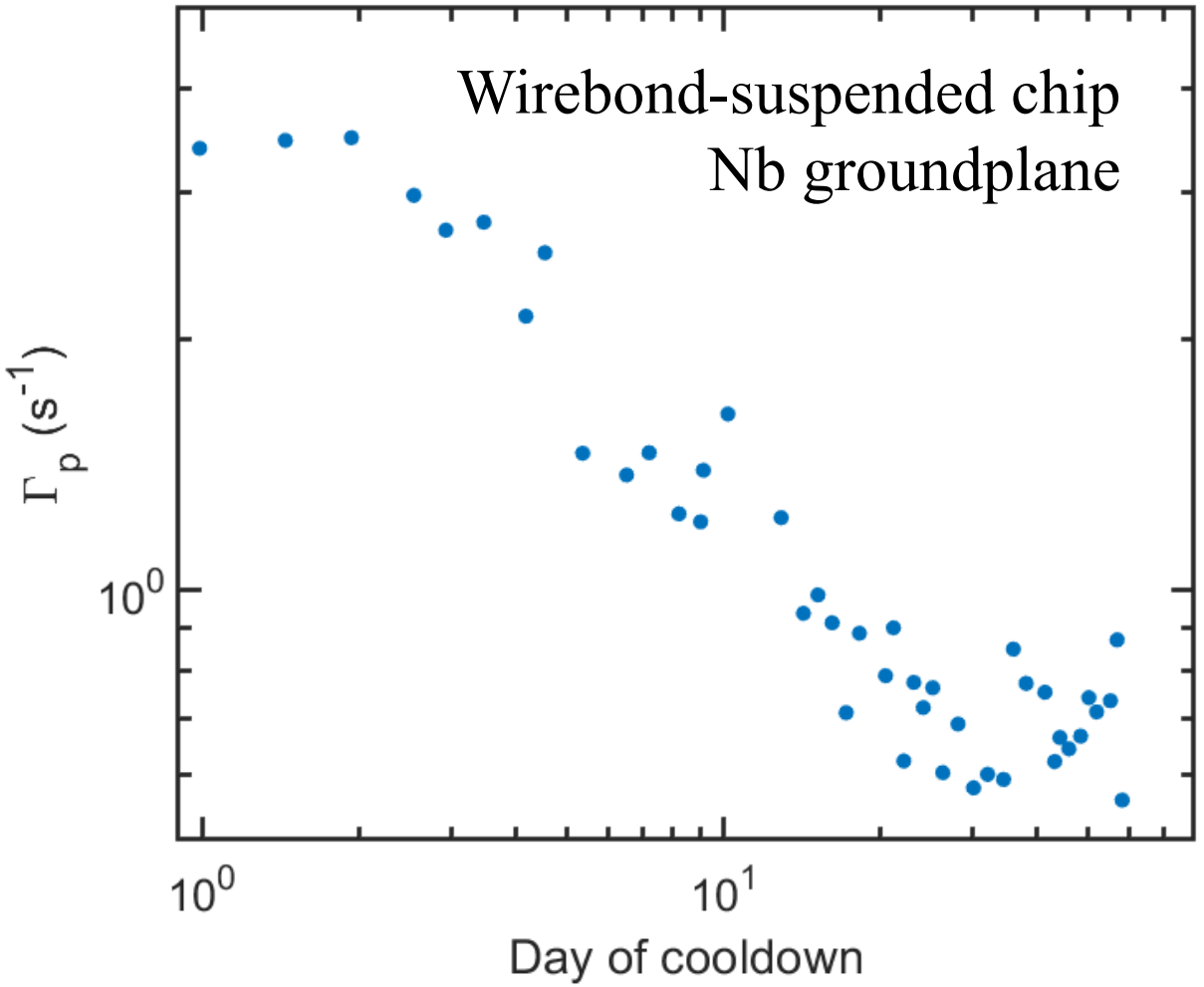
- Strong correlation for QP parity switching & offset charge shift on same qubit
- Significant correlation for all other qubits



- Strong correlation for QP parity switching & offset charge shift on same qubit
- Significant correlation for neighboring qubit but weak for all others

QP parity switching rate versus cooldown time (preliminary)



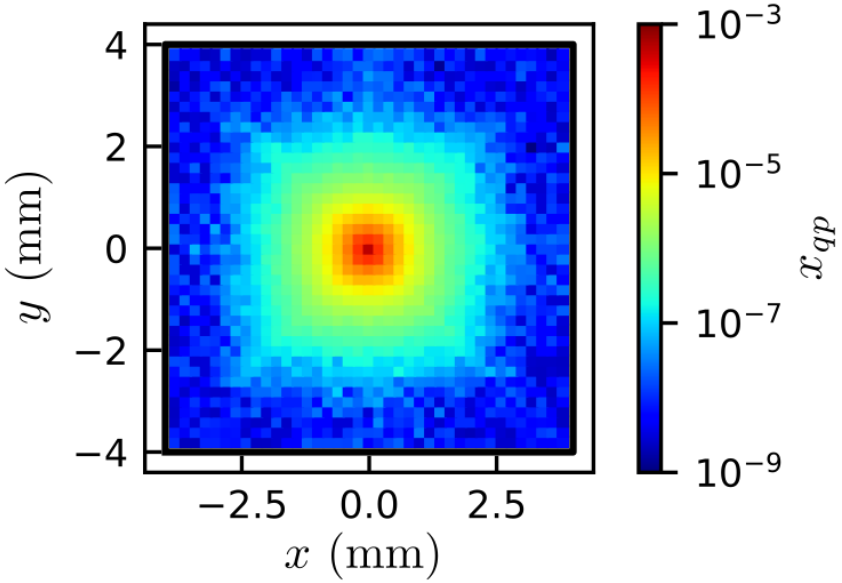


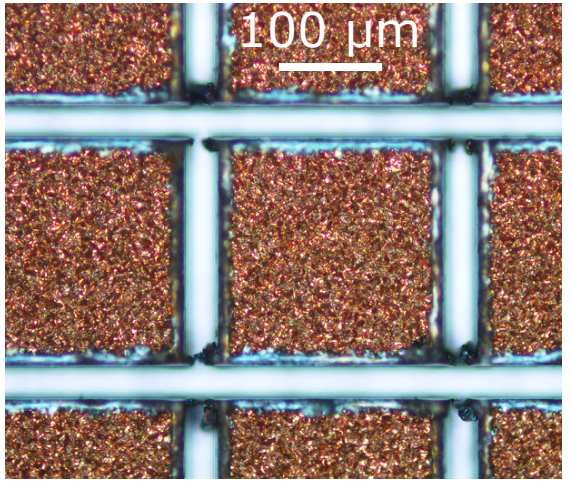
- Power-law relaxation of stress releases phonon bursts
- Stresses in SC films? Si substrate?

Dodge *et al.*, in preparation (2024)

Conclusions & Ongoing Work

- Phonon downconversion in normal metal reservoirs effective for suppressing simultaneous quasiparticle poisoning
- Numerical modeling of phonon and QP dynamics effective for evaluating strategies for mitigating phonon-mediated QP poisoning
- Direct phonon injection with tunnel junctions & active γ irradiation provides direct test of phonon-mediated poisoning
- Correlations between offset-charge shifts and QP parity switching for analyzing poisoning footprint
- Need effective IR shielding for low background QP parity switching rates; study source of power-law phonon-only events





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

Yelton *et al.*, arXiv:2402.15471

Larson *et al.*, in preparation (2024)

Dodge *et al.*, in preparation (2024)

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