Phonon-only quasiparticle poisoning in superconducting qubits

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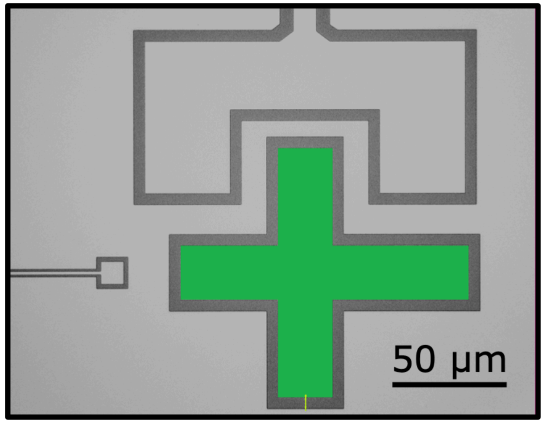
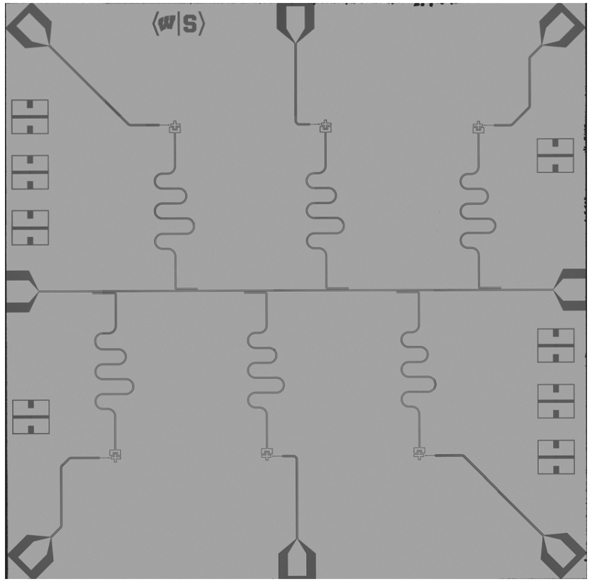
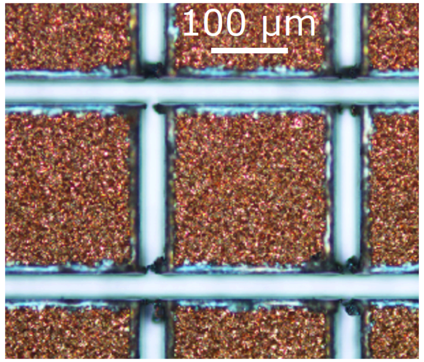
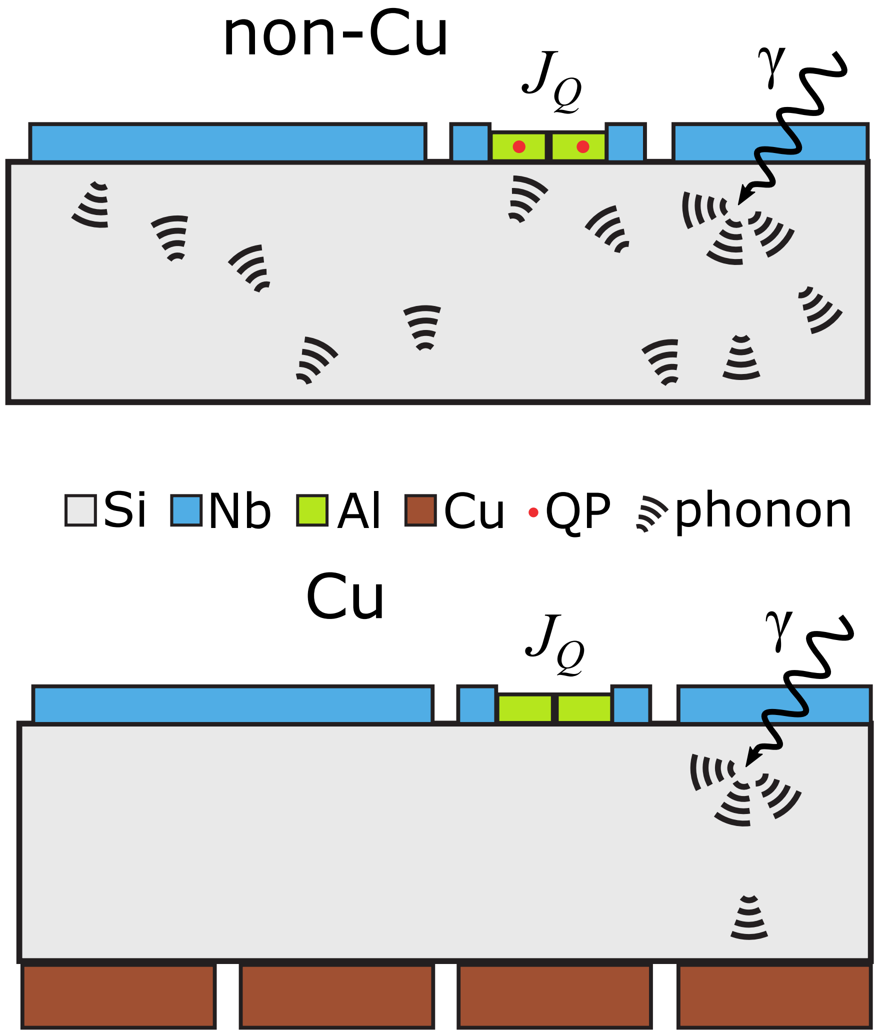
Mitigating phonon-mediated QP poisoning

- Array of six charge-sensitive transmons (E_J/E_C~20-25)
- Nb ground plane device one with 10-μm thick Cu islands and one without







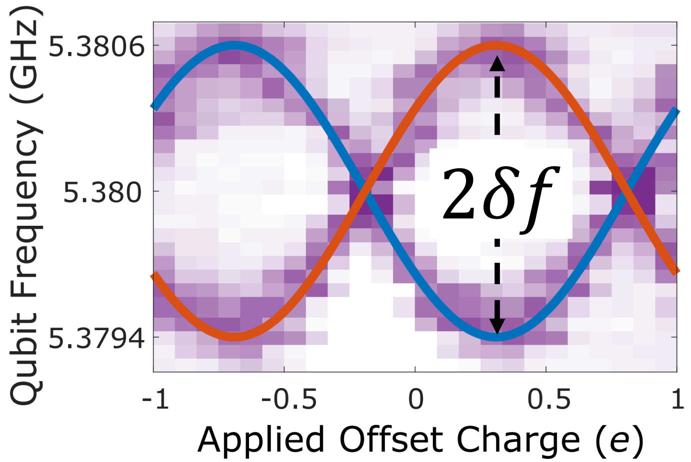


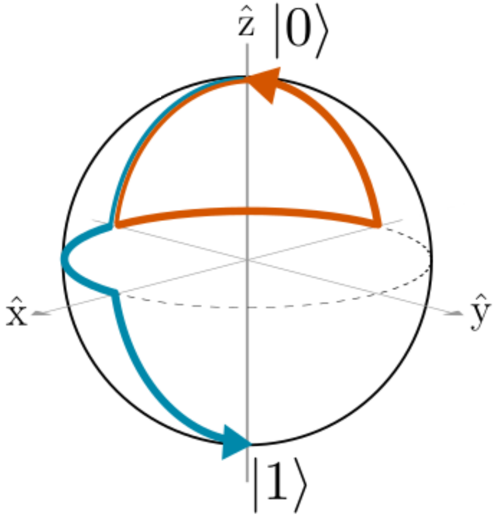
CNF
Cornell NanoScale
Science and Technology Facility

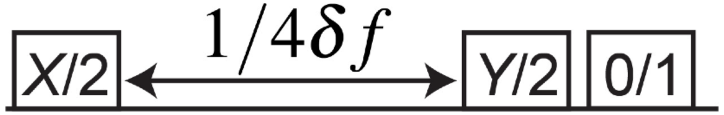
Martinis, npj Quantum Inf. 7, 90 (2021)

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

Monitoring quasiparticle poisoning







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

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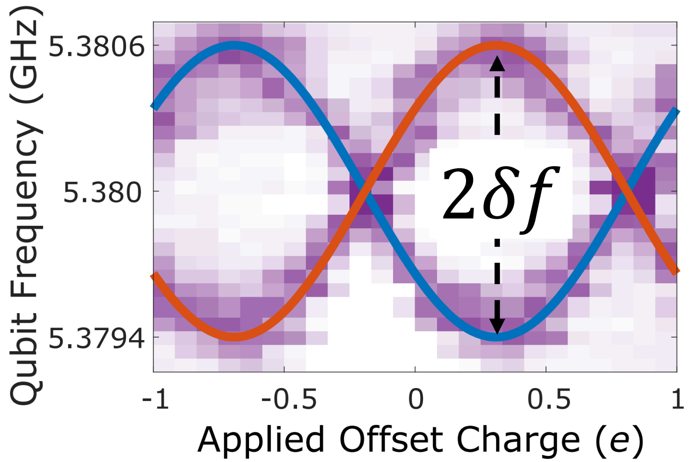
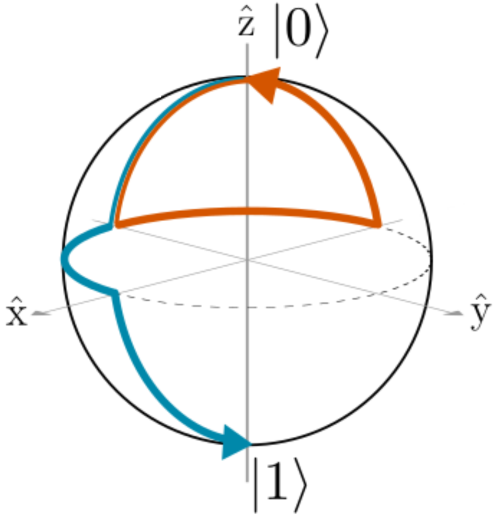
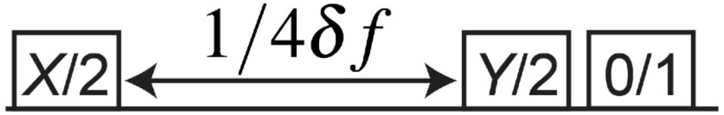






Repeat QP parity sequence at fixed period

↓

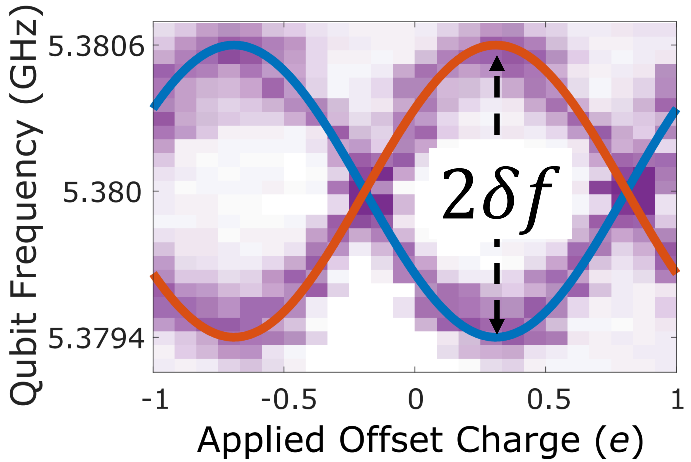
001100010…111001

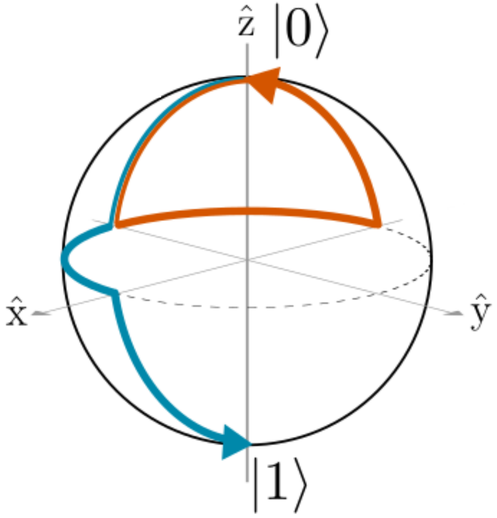
Riste *et al.*, Nat. Comm. 4, 1913 (2013)

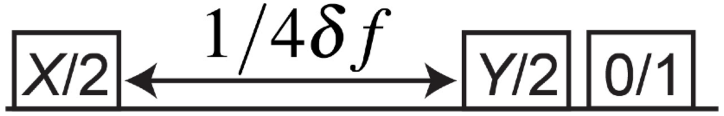
Christensen *et al.*, Phys. Rev. B 100, 140503 (2019)

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

Quasiparticle poisoning limited by phonons







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

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

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

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

Connolly, Kurilovich *et al.*, Phys. Rev. Lett. 132, 217001 (2024)

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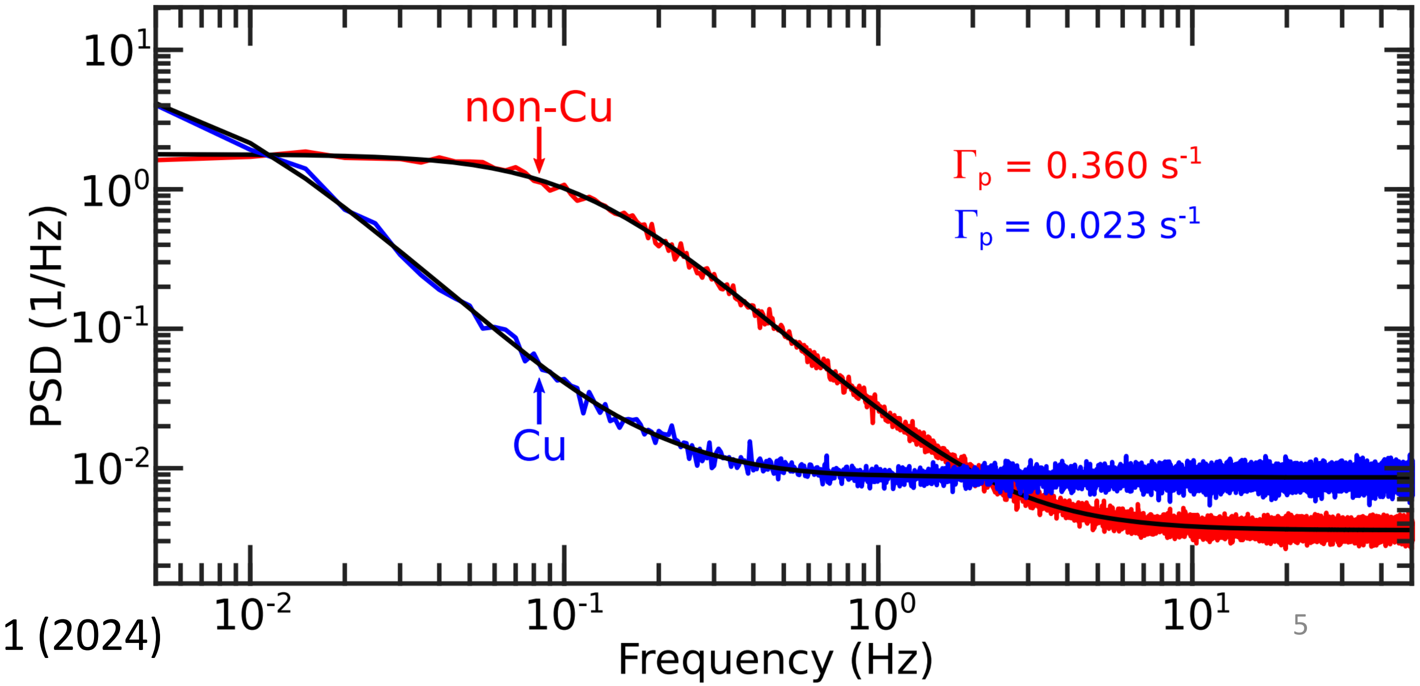

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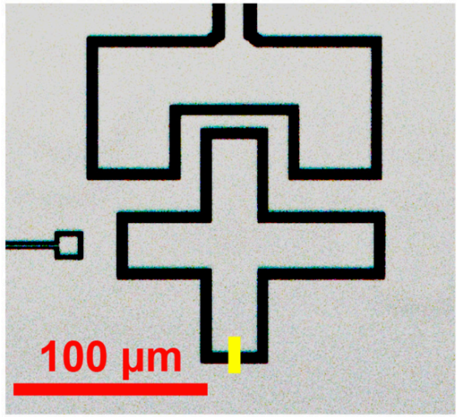
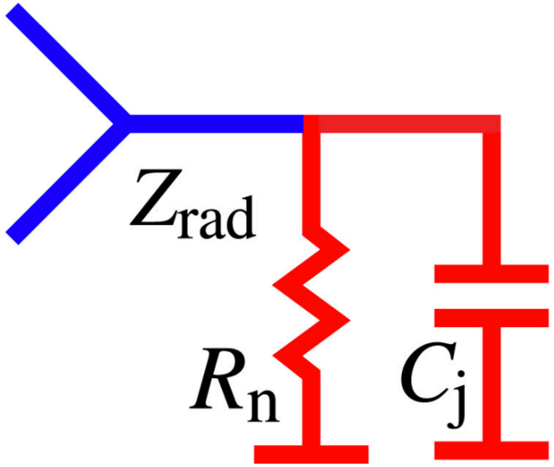
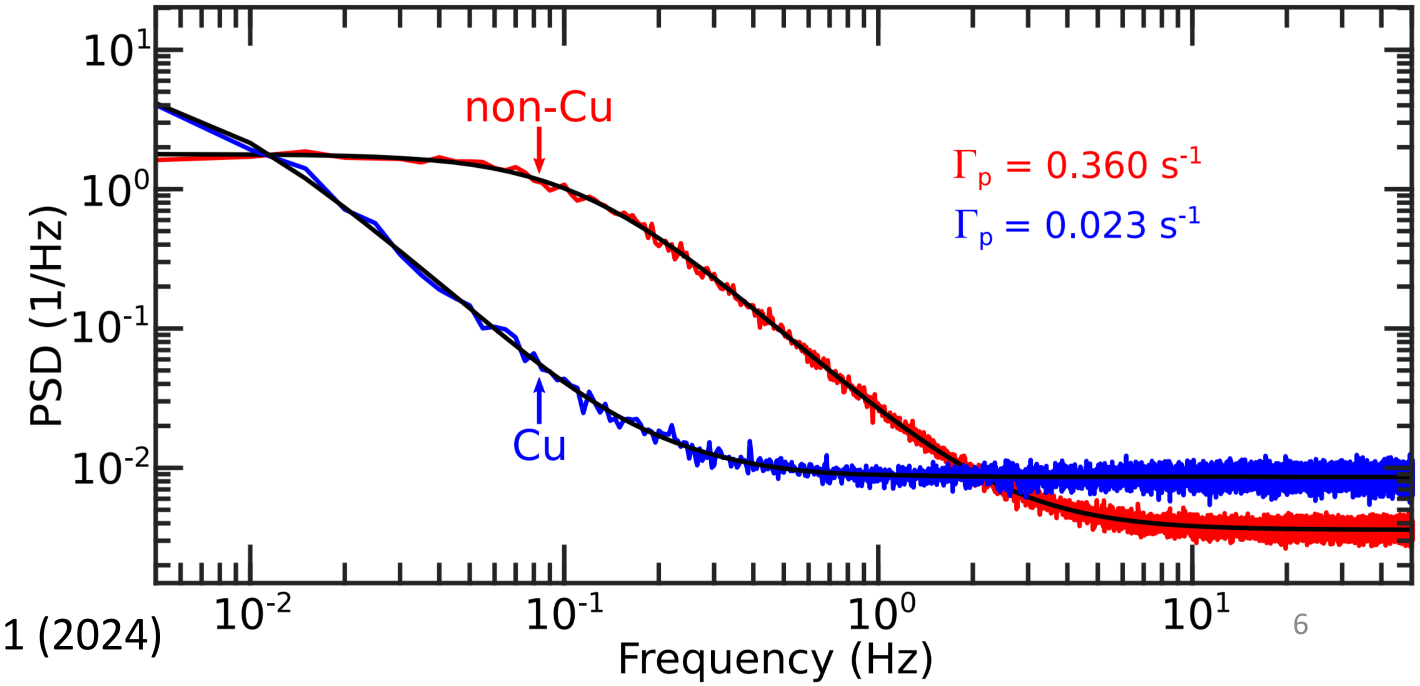




- Low QP parity switching rates
- Shielding from stray light
- Compact qubit footprint (antenna resonance of ~270 GHz)

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

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



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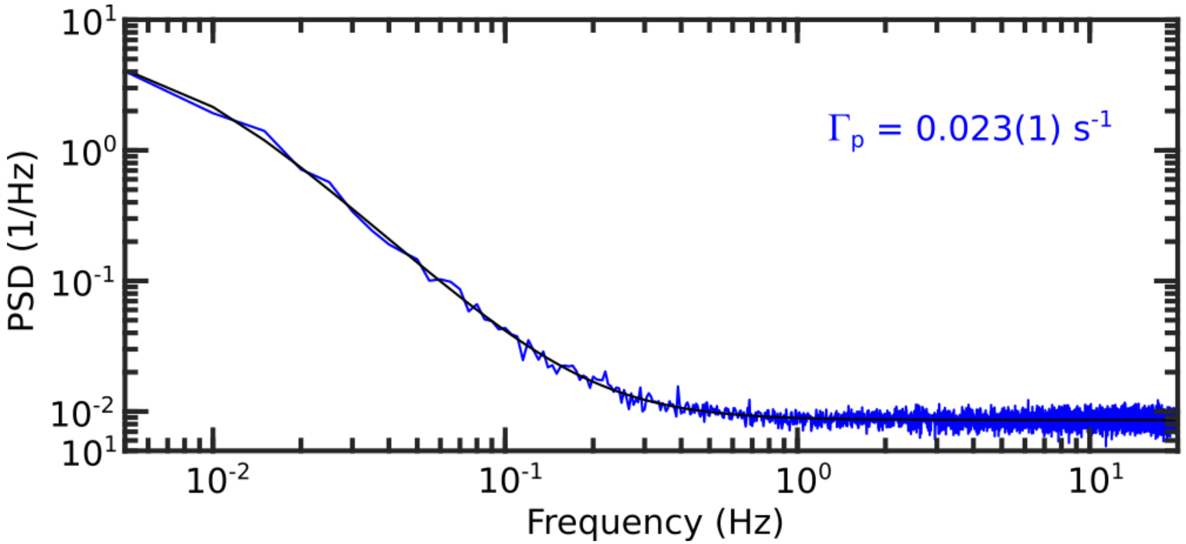
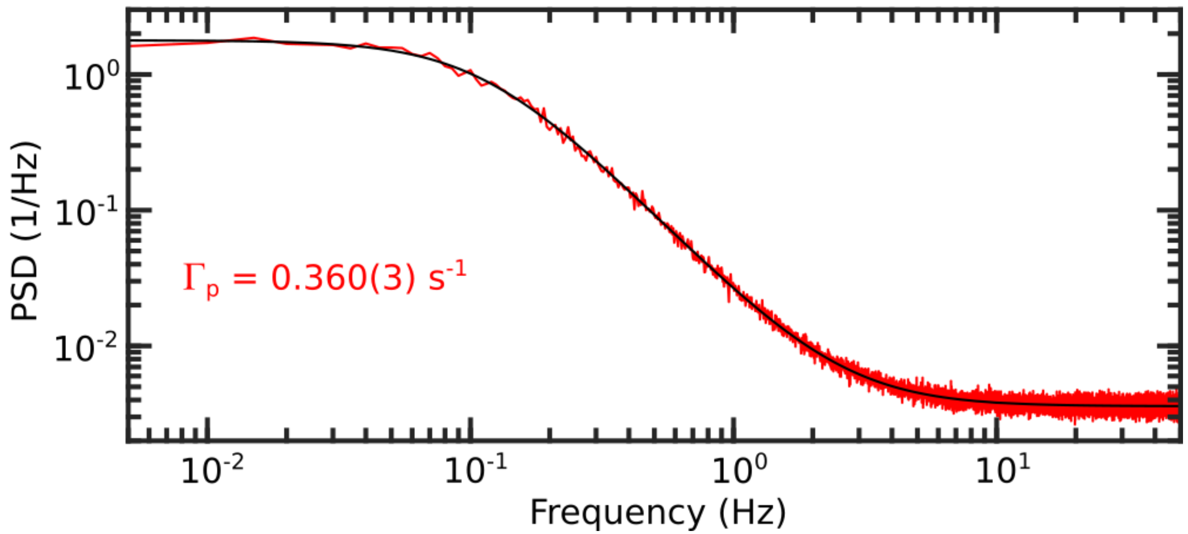
Iaia, Ku *et al.*, Nat. Comm. 13, 6425 (2022)

Connolly, Kurilovich *et al.*, Phys. Rev. Lett. 132, 217001 (2024)

Parity switching rates after ~5 month cooldown



10 μm-Cu



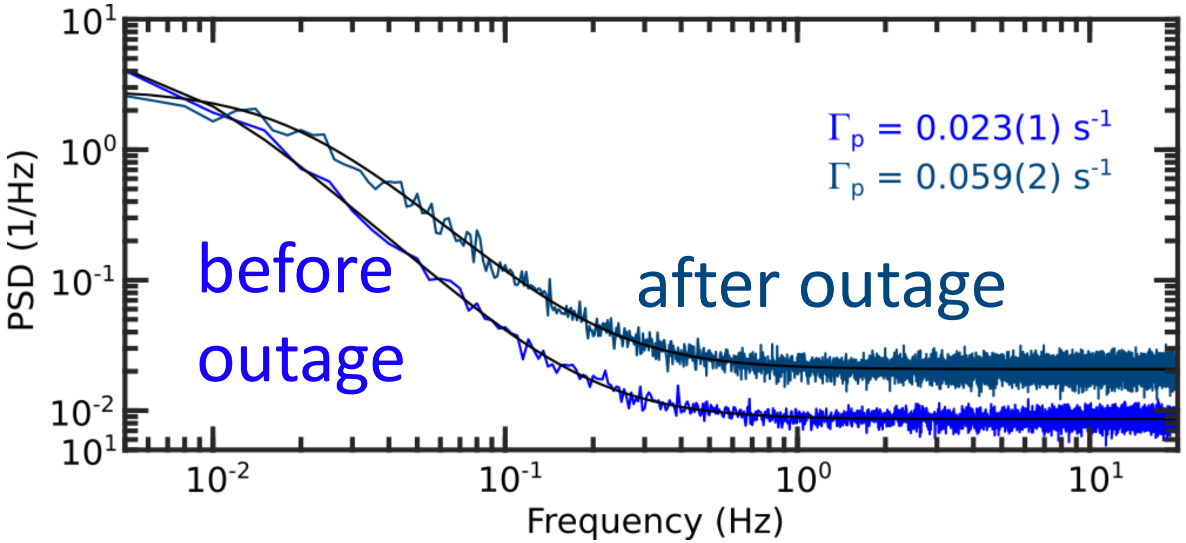
non-Cu

- Measurements were taken during a 5-month long cooldown

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

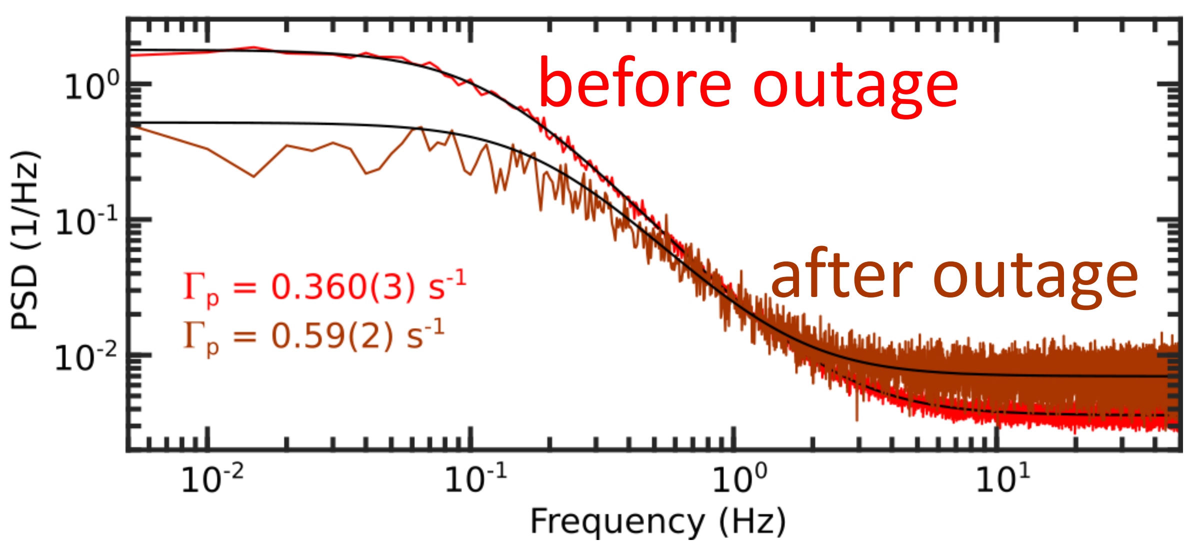
Parity switching rates after a few weeks

18 days



10 μm-Cu

23 days

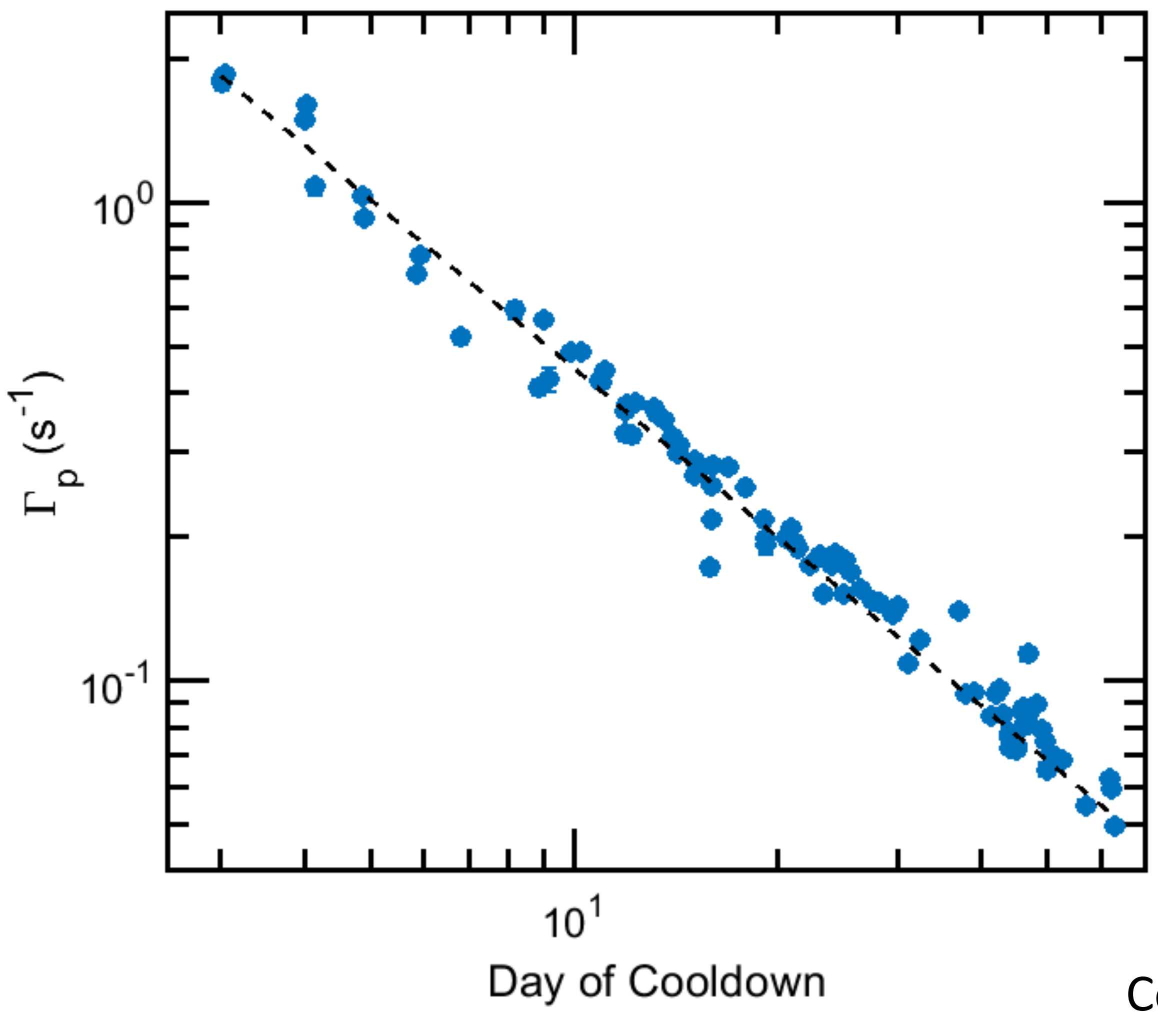


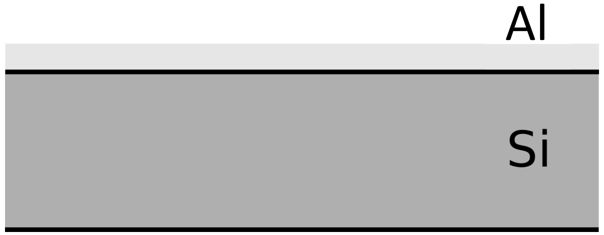
non-Cu

- Measurements were taken during a 5-month long cooldown
- Unexpected power outage required us to warm-up
- The characteristic parity switching rates were elevated for both devices after cooling back down

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

Γ_p during cooldown of Al ground plane device





$$\Gamma_p \propto t^{-\alpha}$$

$$\alpha = 1.2$$

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

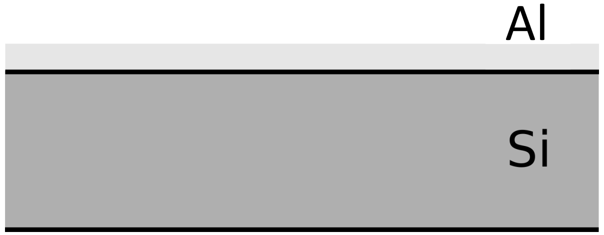
Compare to Mannila *et al.*, Nat. Phys. 18 145-148 (2022)

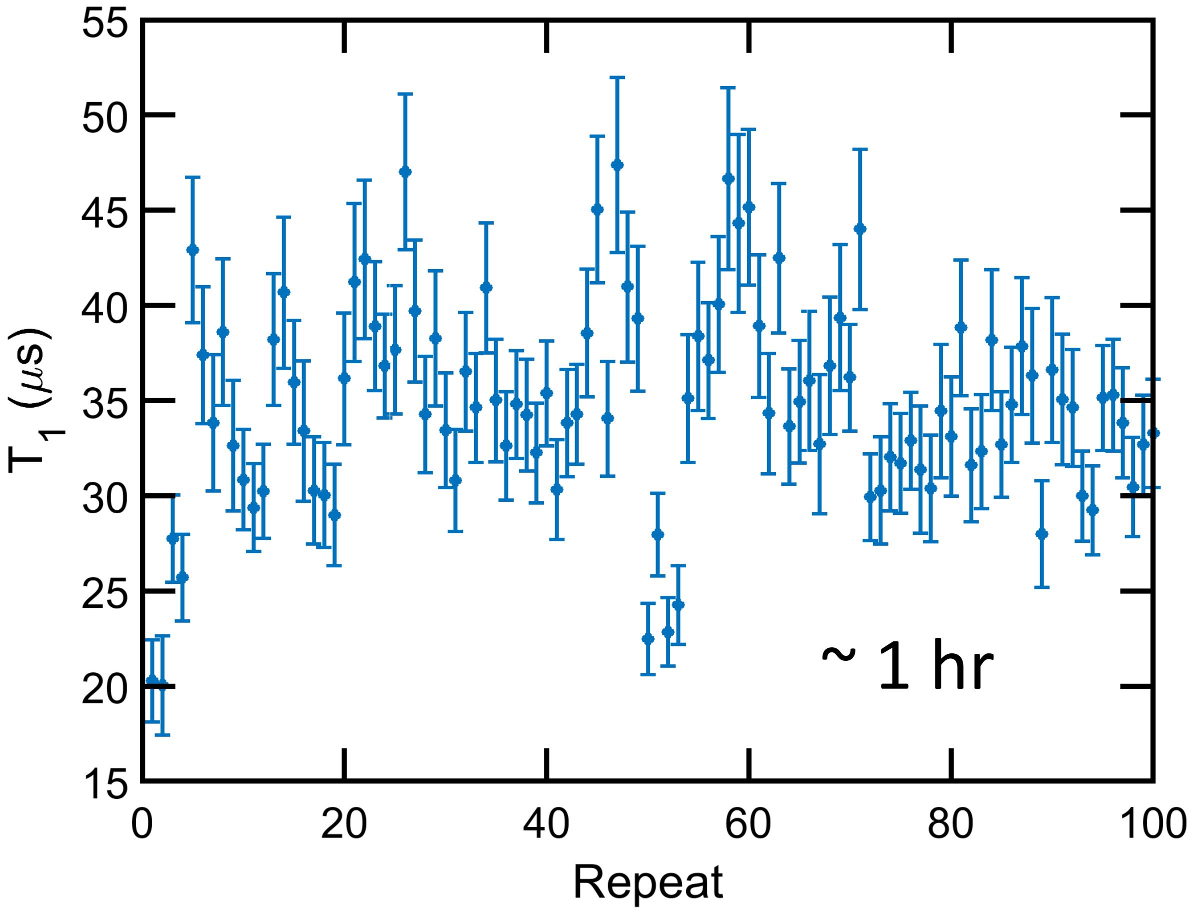
Romani, arXiv:2406.15425

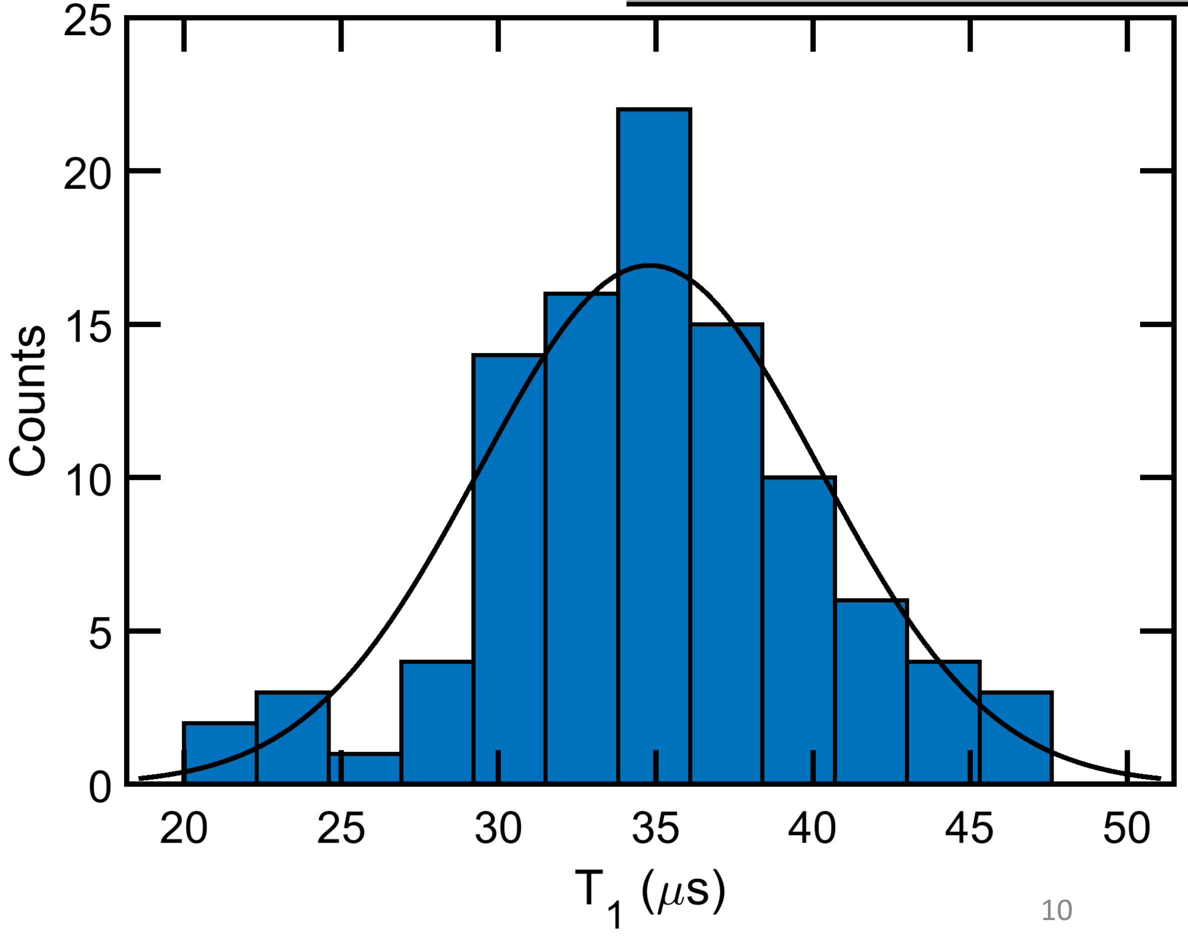
Dodge, Yelton *et al.*, in preparation (2024)

Repeated measures of qubit T_1

- Typical fluctuations in qubit T_1 for repeated measurements

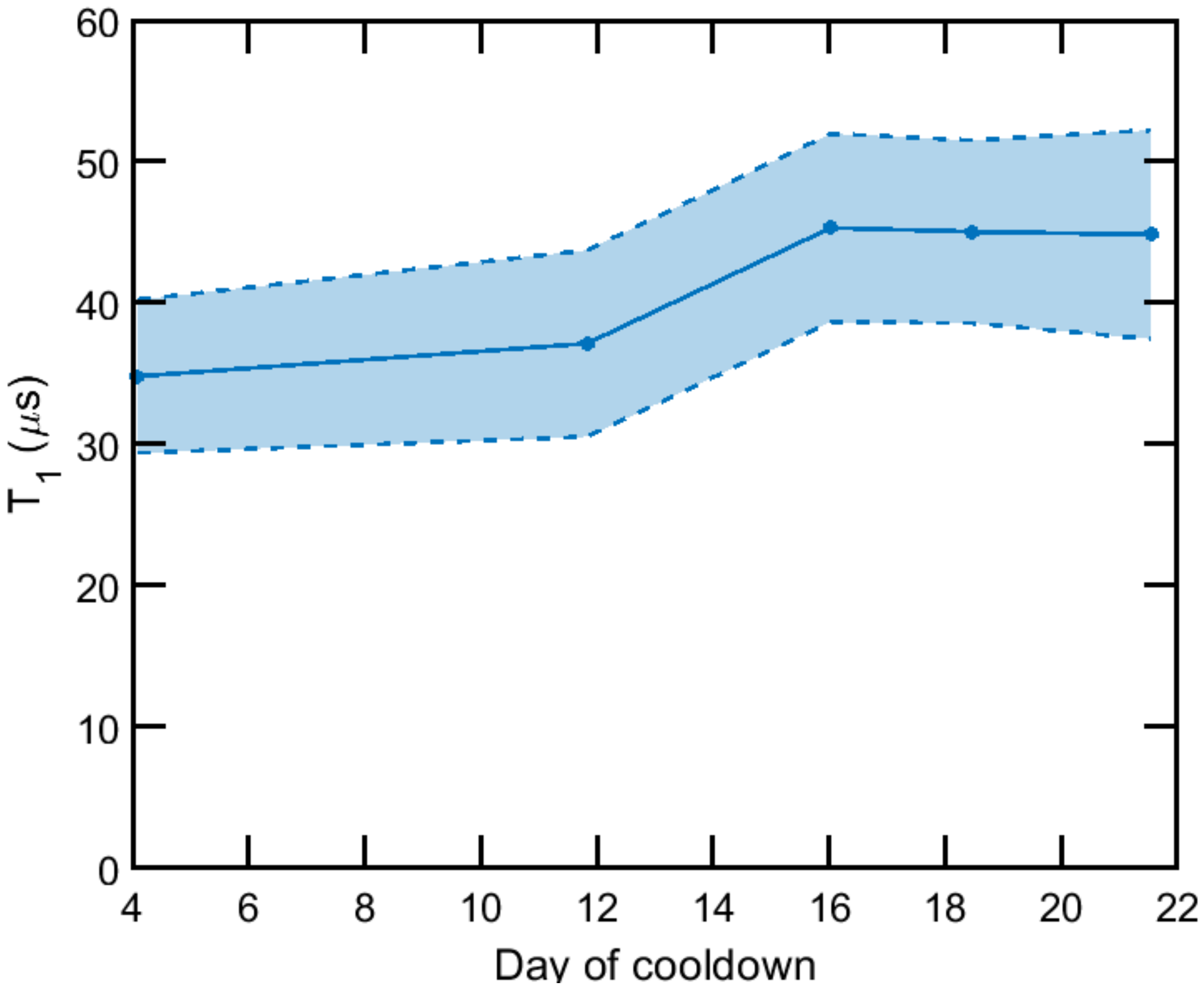


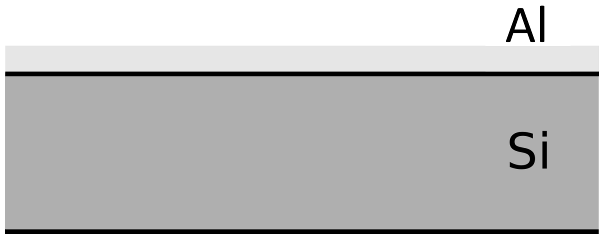


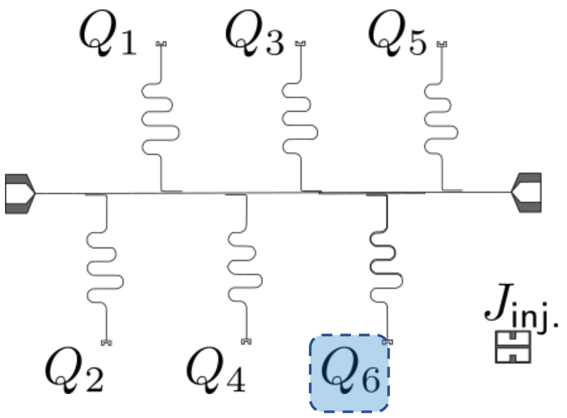


Dodge, Yelton *et al.*, in preparation (2024)

Qubit T_1 during cooldown







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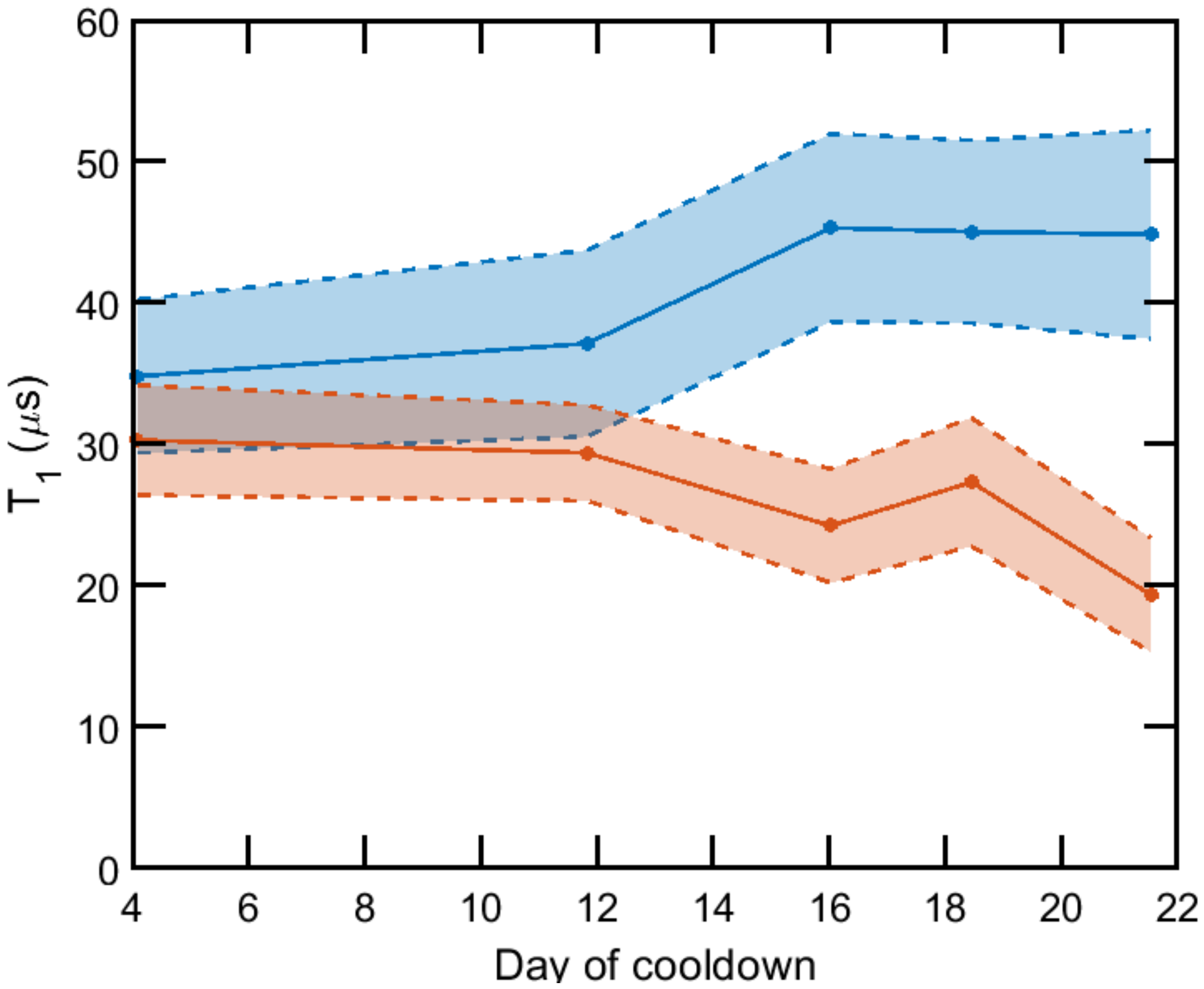

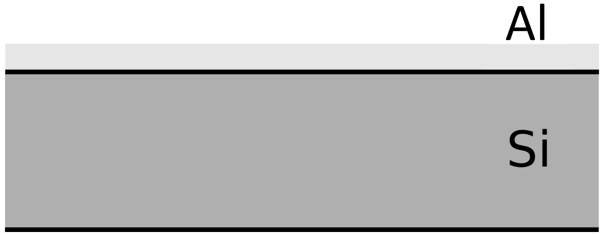

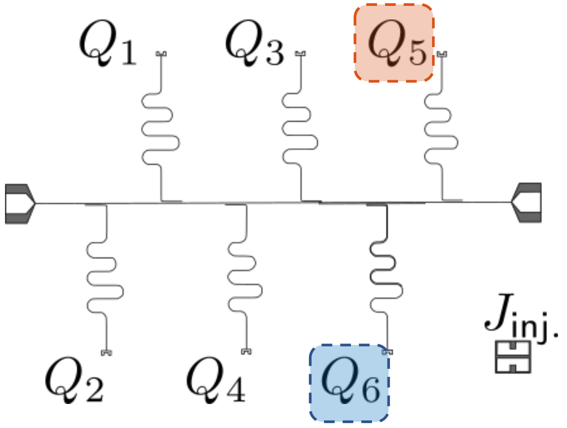

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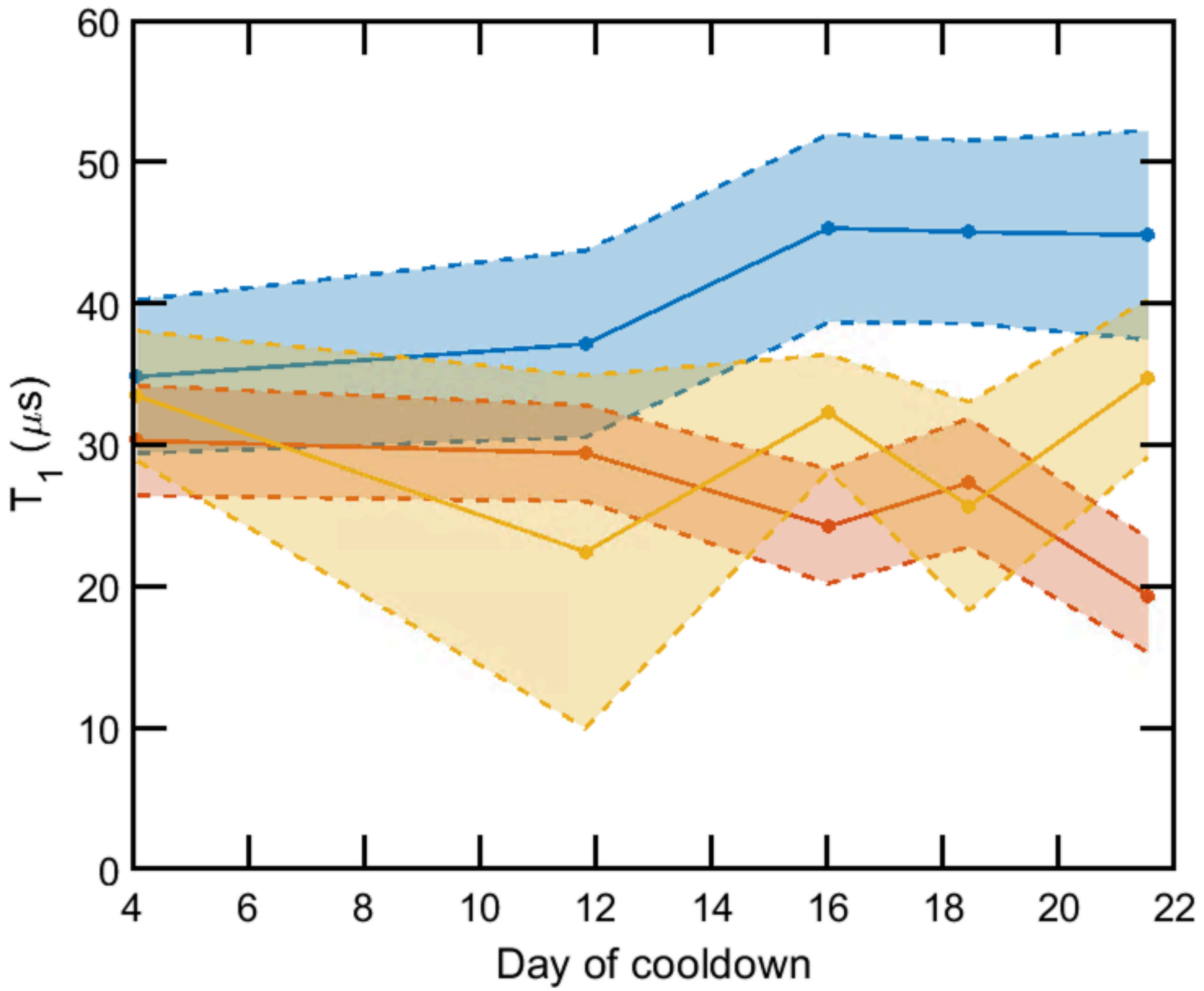
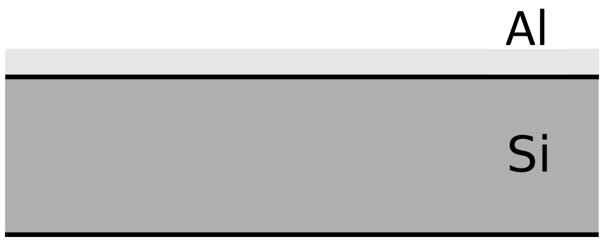
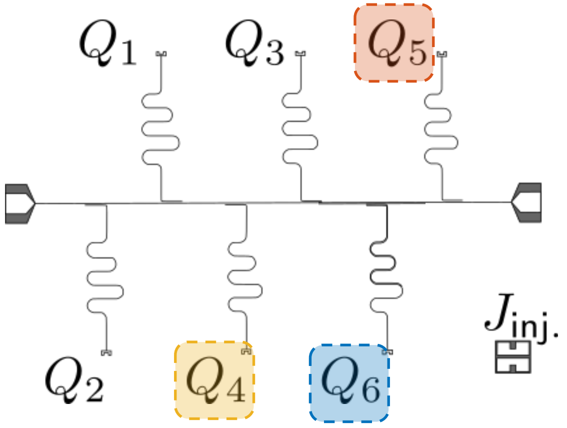




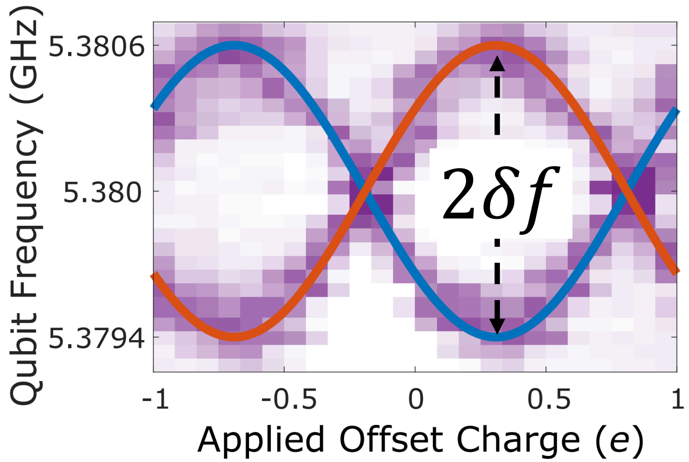
Do not observe power law time dependence

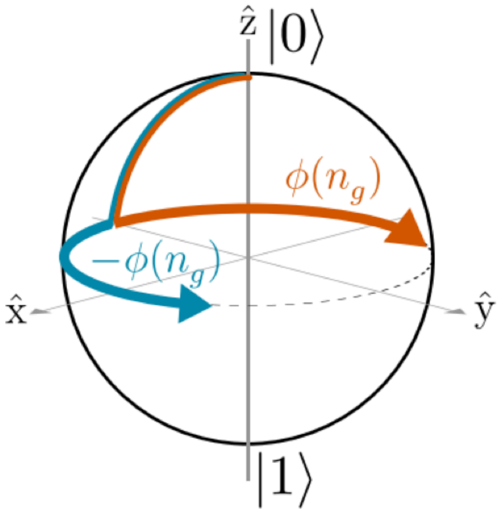


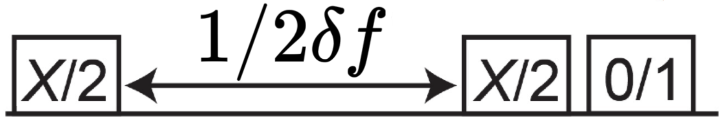
Occasional drop-outs in T1 due to TLS

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

Offset charge jumps to tag impact events



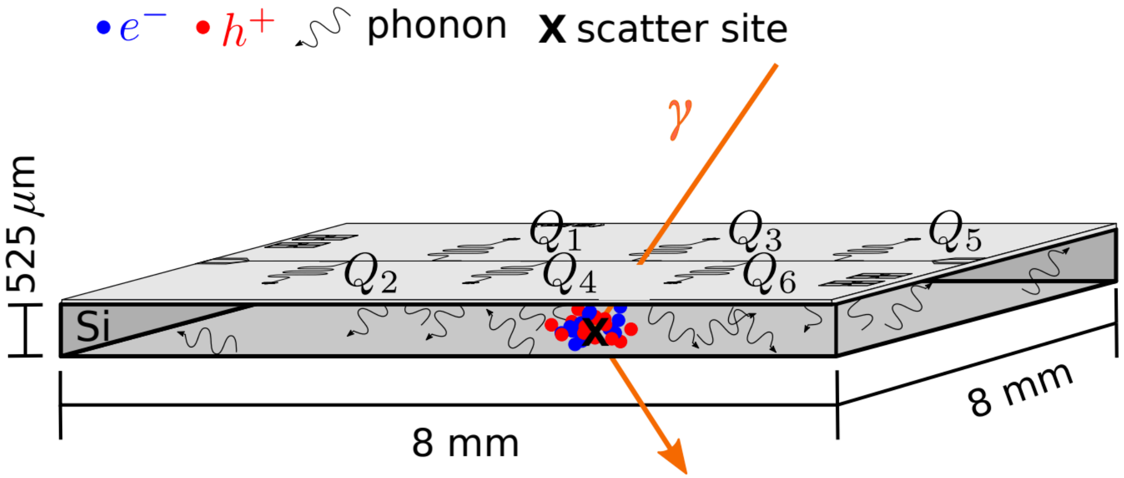




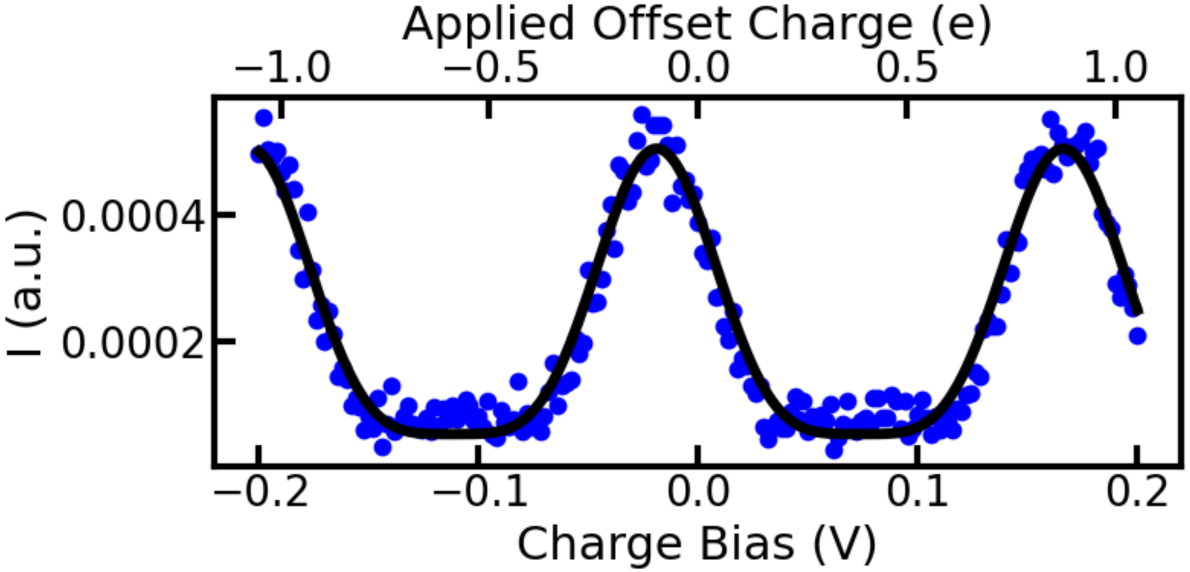
$$P_1 = \frac{1}{2}[d + \nu \cos(\pi \cos(2\pi n_g))]$$

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

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



Yelton *et al.*, accepted by PRB (2024)



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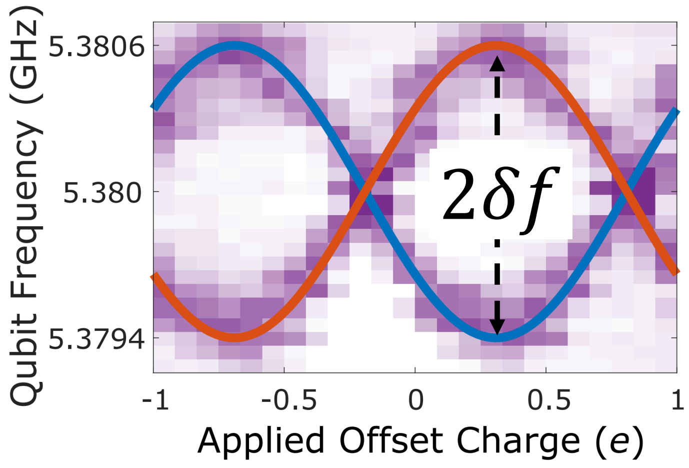

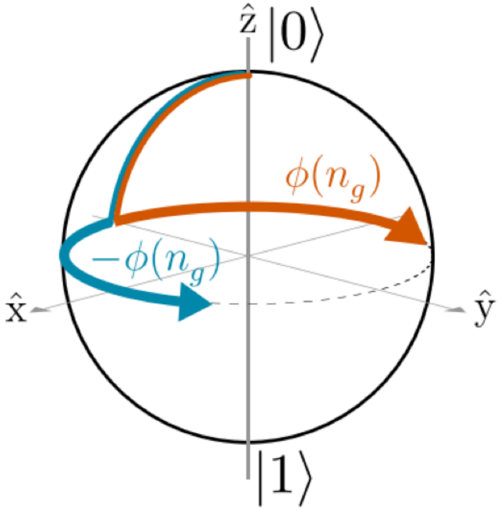

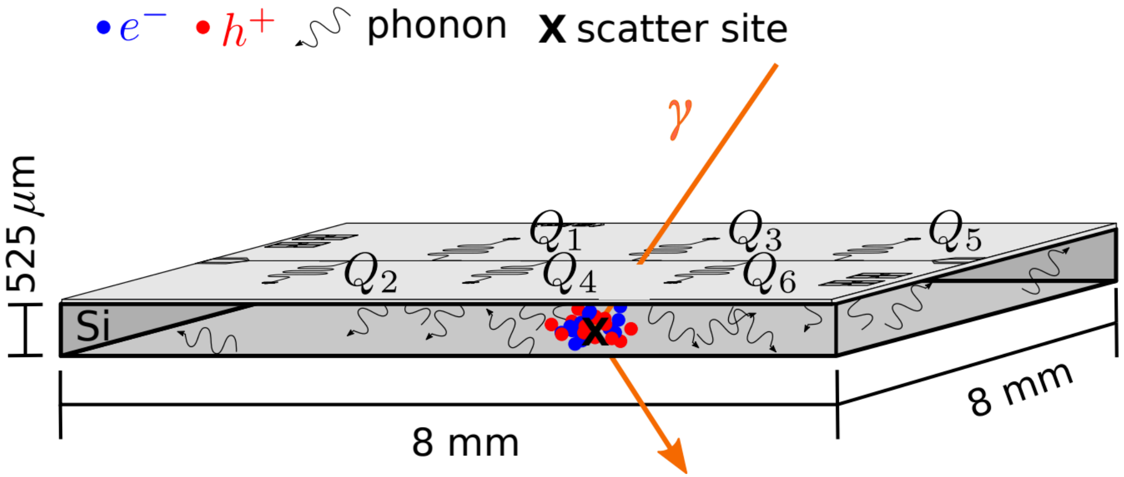

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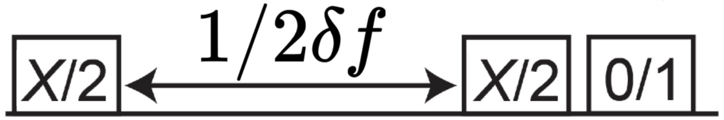

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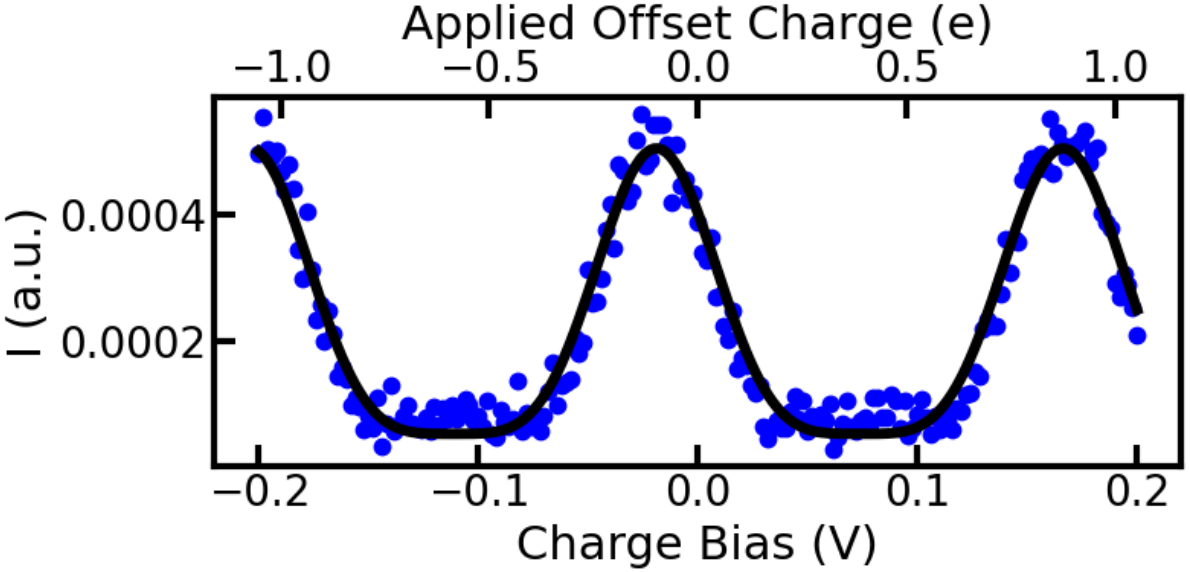

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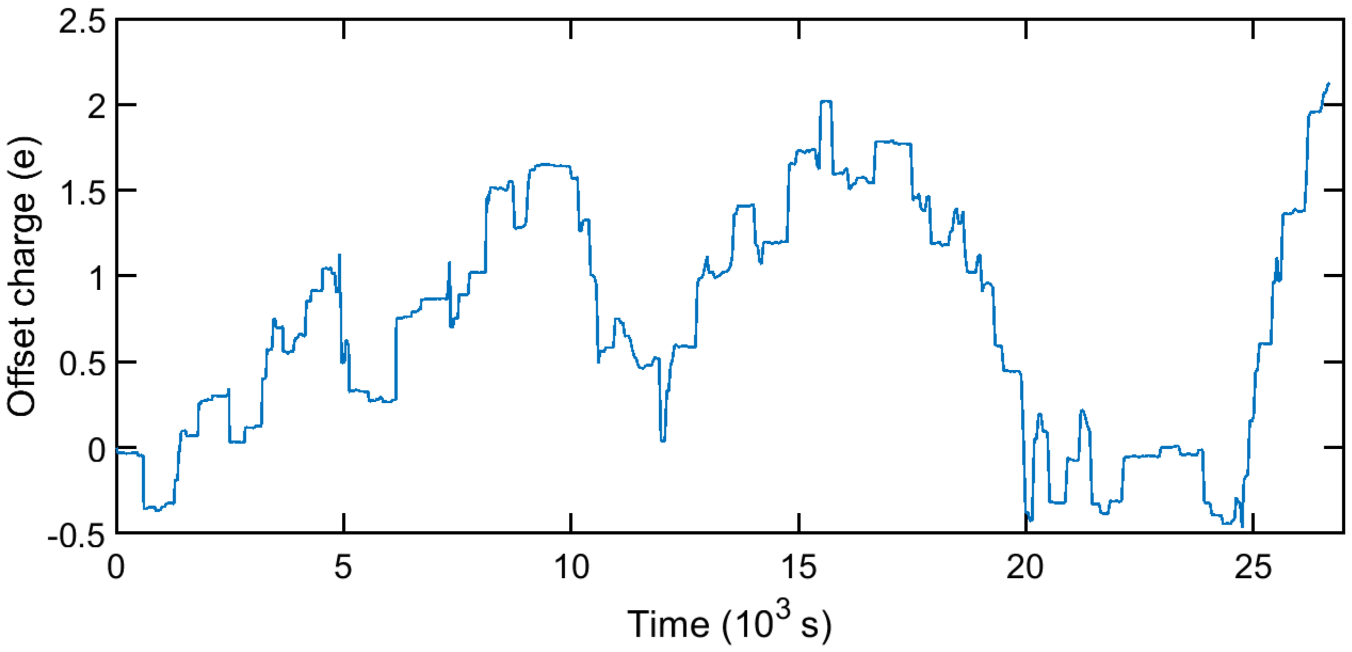
Dodge, Yelton *et al.*, in preparation (2024)

Tracking rate of large offset charge jumps



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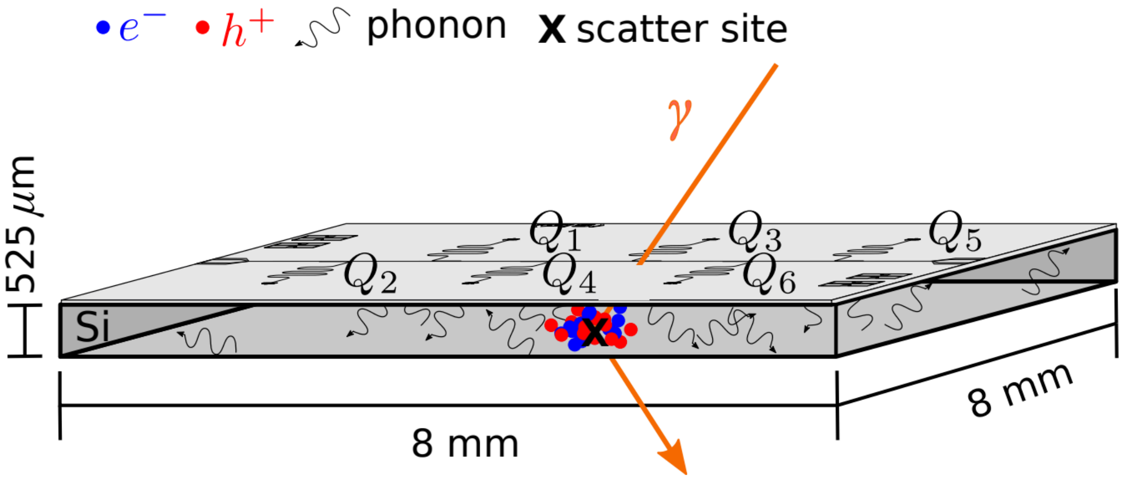


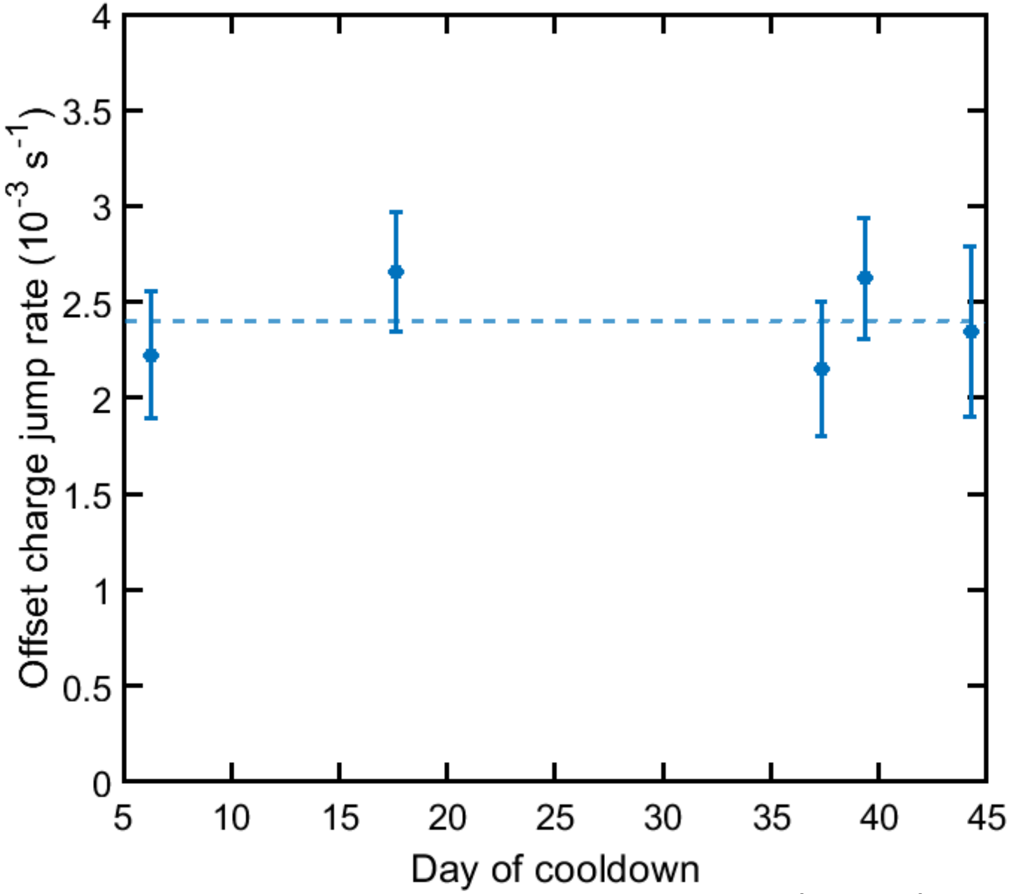
Yelton *et al.*, accepted by PRB (2024)

- Repeatedly measure charge tomography sequence and fit to extract offset charge versus time
- Count the rate of large offset charge jumps > 0.1e

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

Large offset charge jump rates during cooldown

Large offset charge jump rate is constant during cooldown



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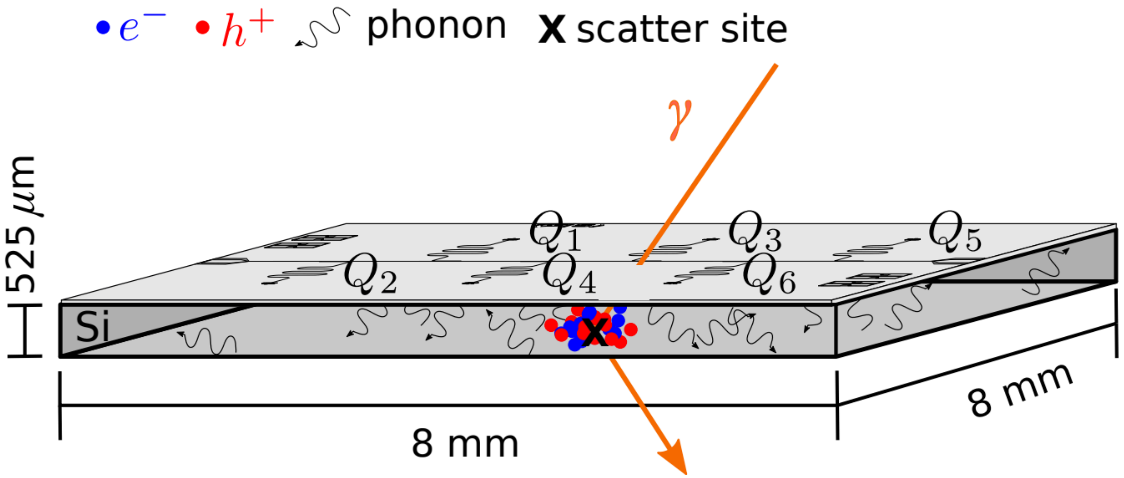

Yelton *et al.*, accepted by PRB (2024)

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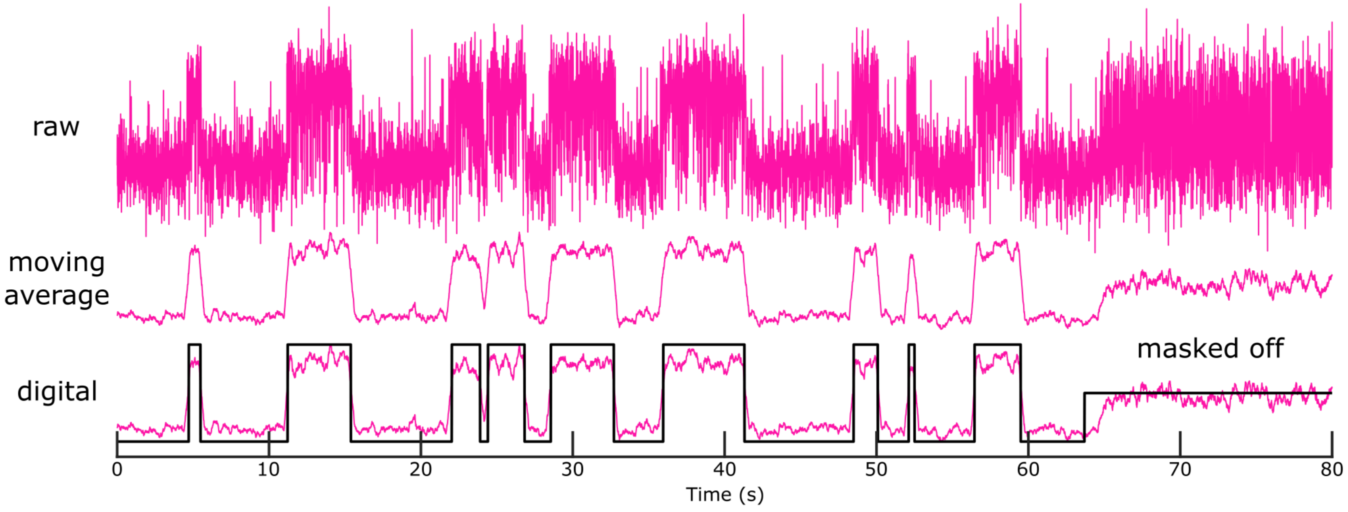
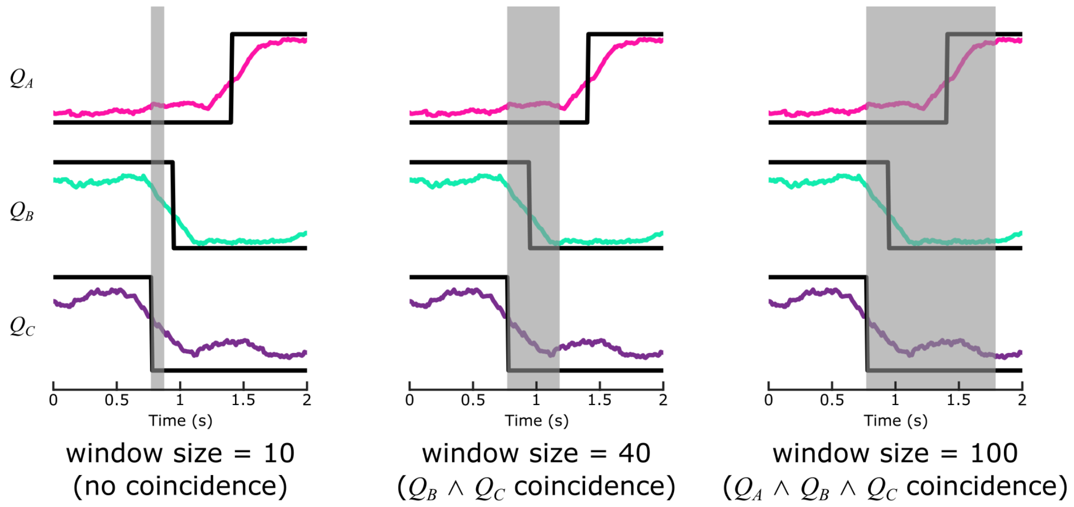
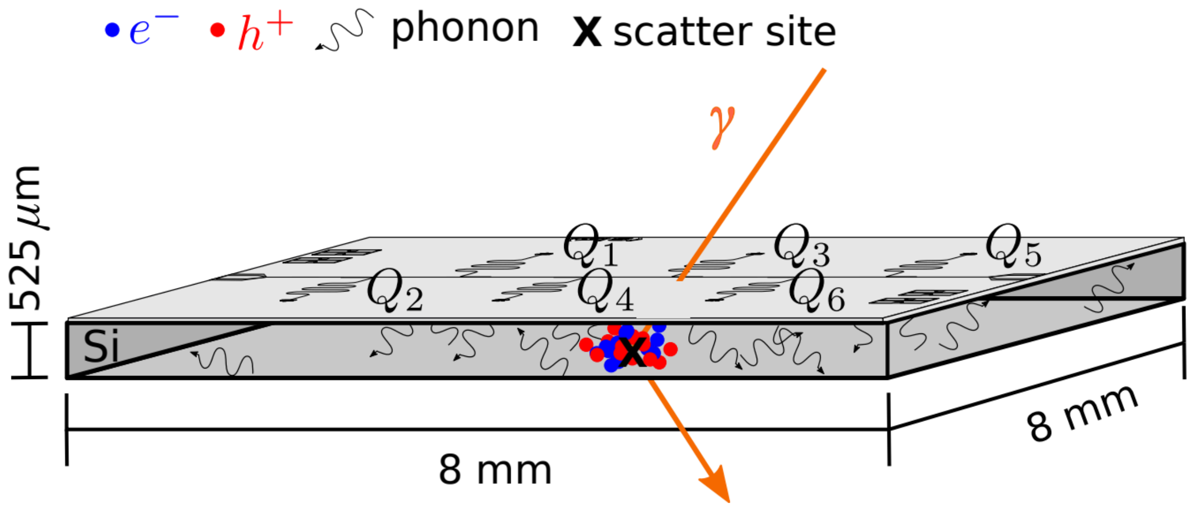
Correlated QP parity switches coincide with phonon bursts





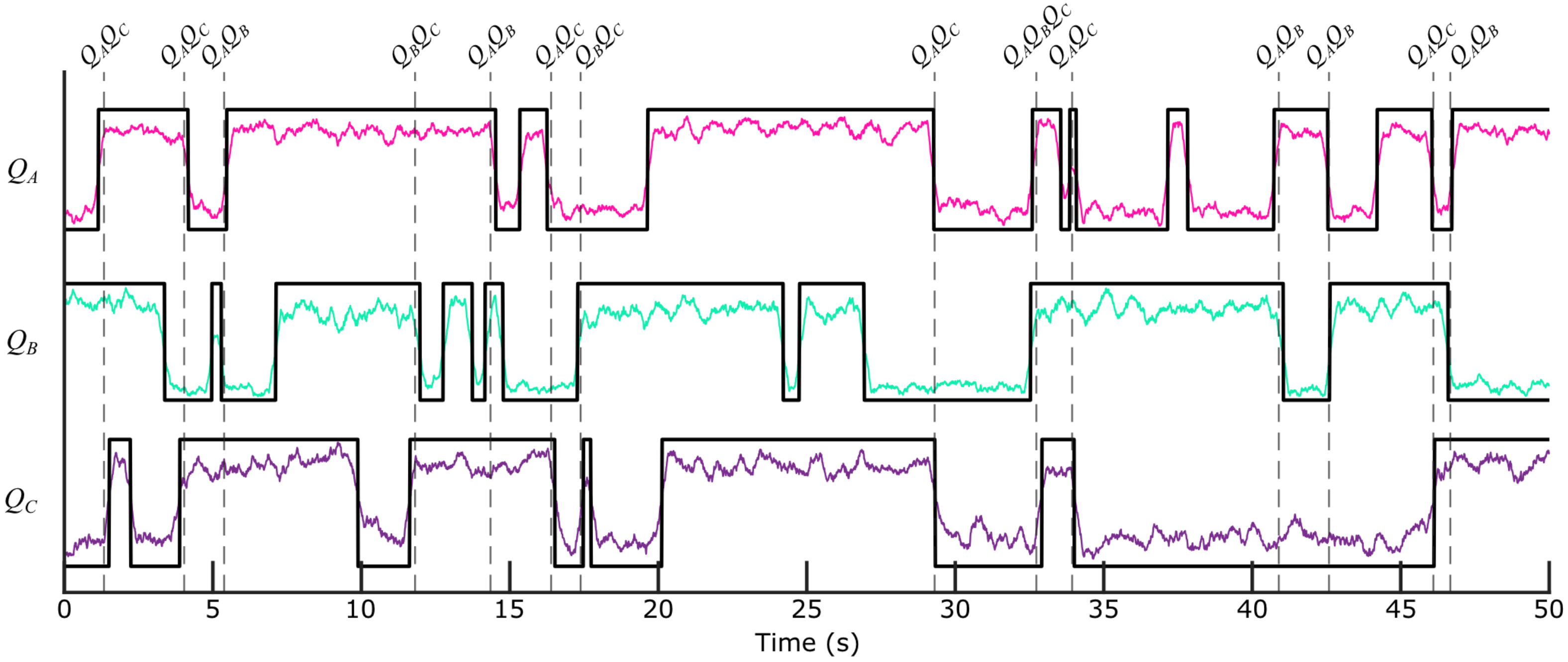
Iaia, Ku *et al.*, Nat. Comm.13, 6425 (2022)



- Use HMM to digitize raw parity switching data
- Coincident parity switching events coincide with rising/falling edges on a moving window

Correlated QP parity switches coincide with phonon bursts

- Example time traces of three qubits on the non-Cu device
- Use these coincident events to get two- and three-fold event rates



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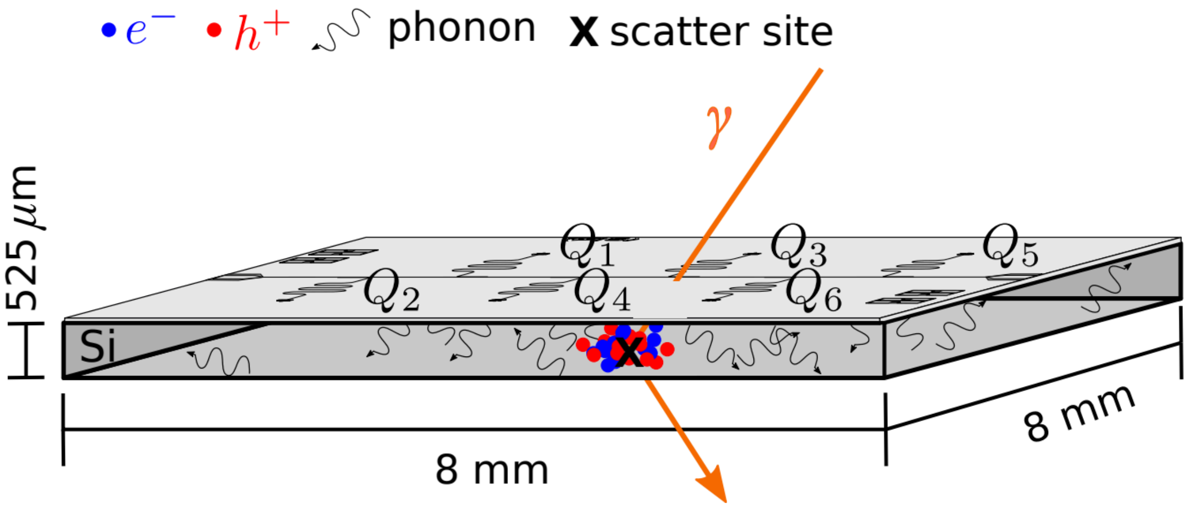

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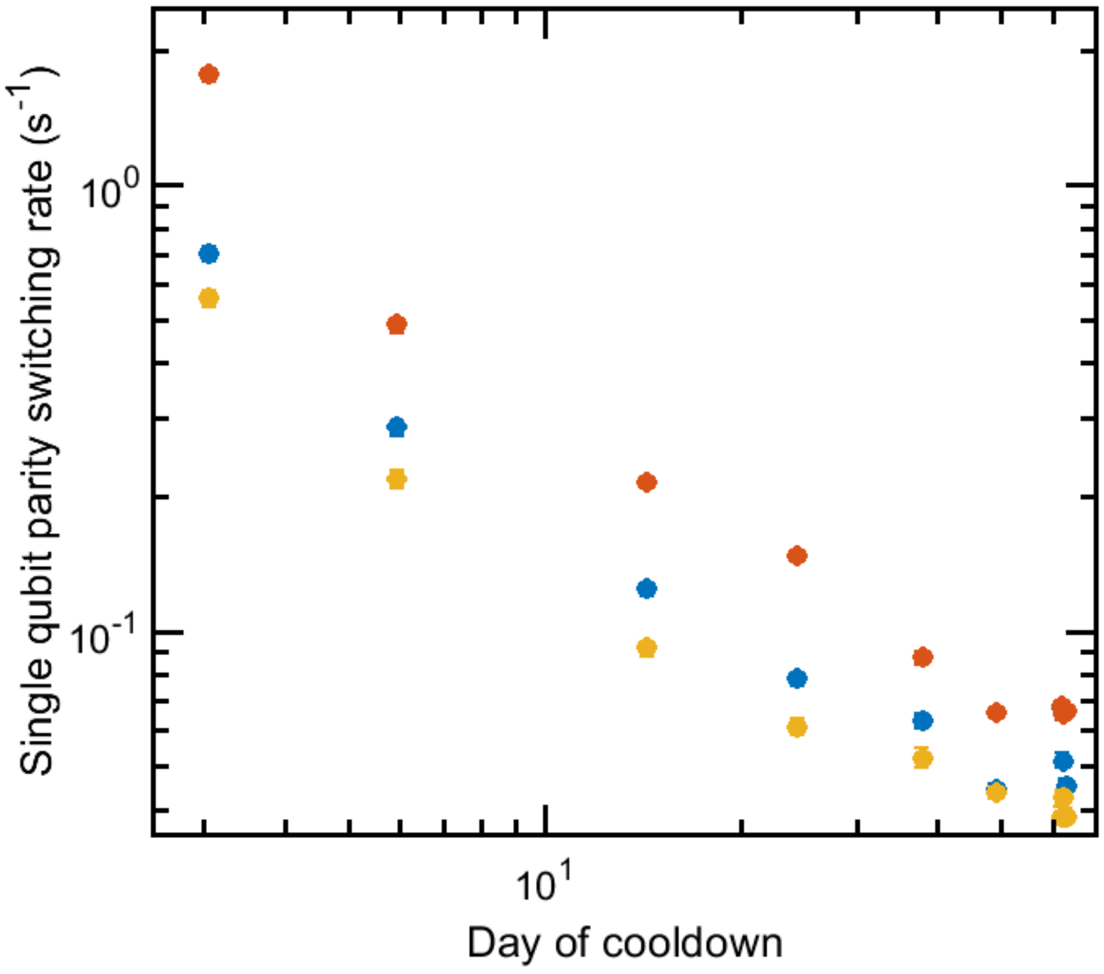
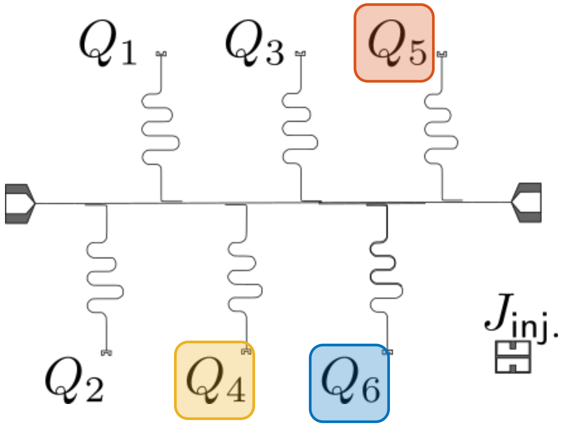
Single qubit QP parity switching rate during cooldown

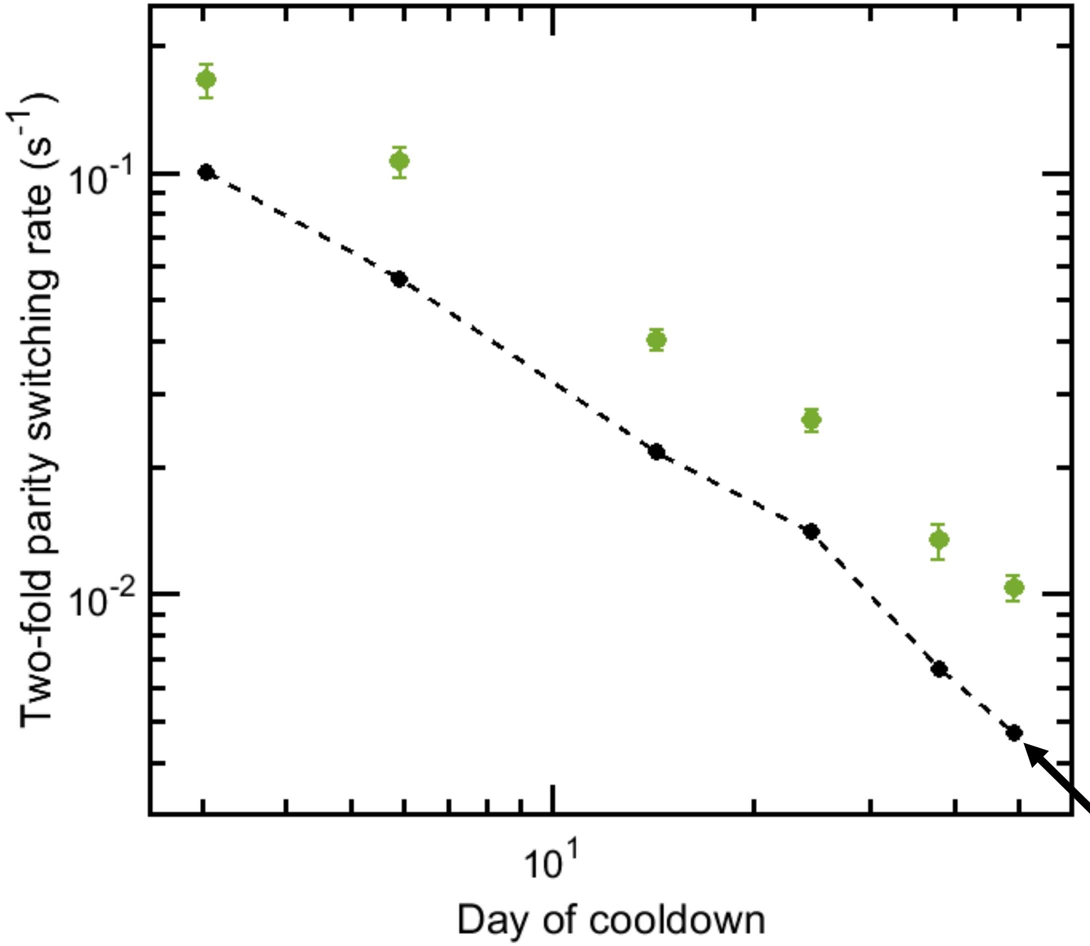


- Single qubit switching rates are consistent with measures of Γ_p during duration of cool down

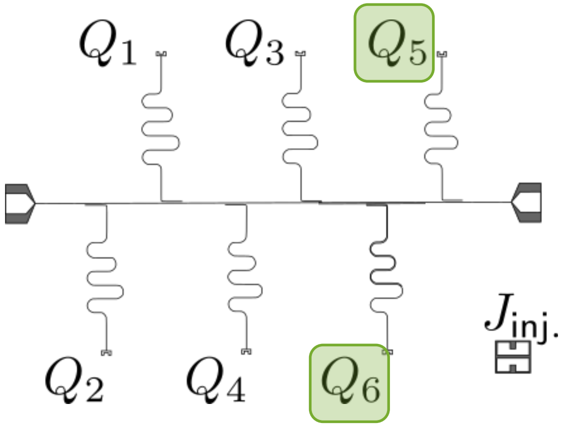


Dodge, Yelton *et al.*, in preparation (2024)

Two-fold qubit QP parity switching rate during cooldown



- Correlated QP parity switching events of a pair of qubits are higher than the random coincident switching background
- Consistent with data after unplanned cooldown in Iaia, Ku *et al.*

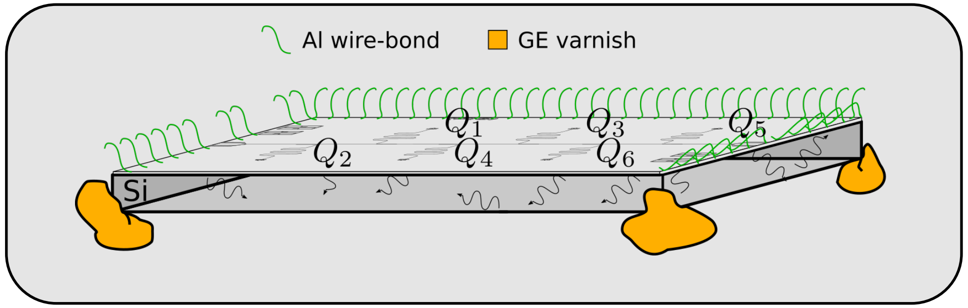


Random two-fold background

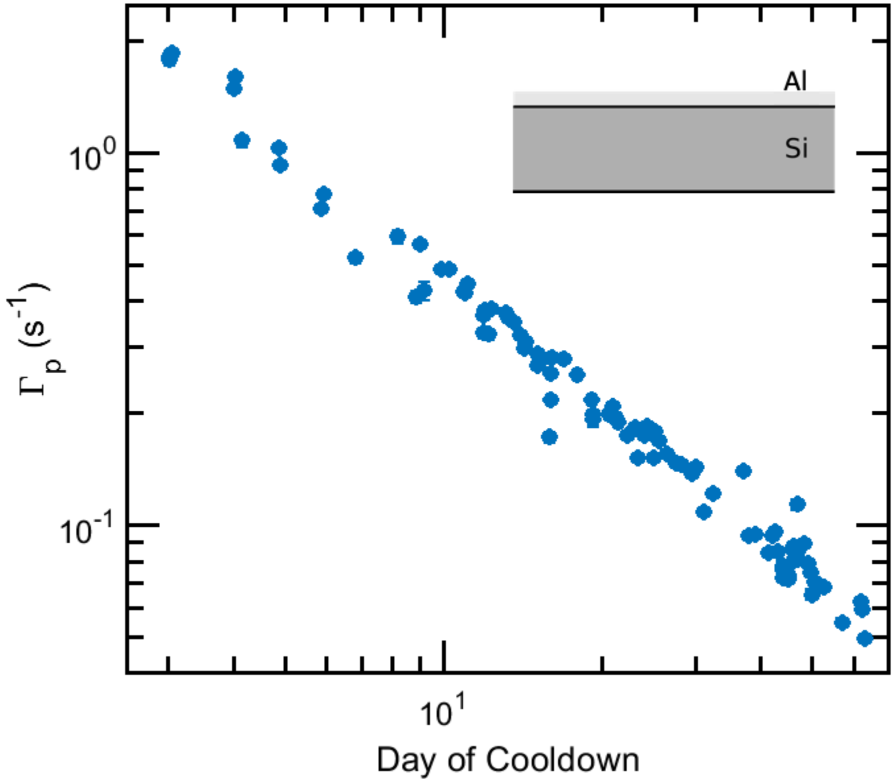
$$(r_{Q_5}\Delta t_{ws})(r_{Q_6}\Delta t_{ws})/\Delta t_{ws}$$

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

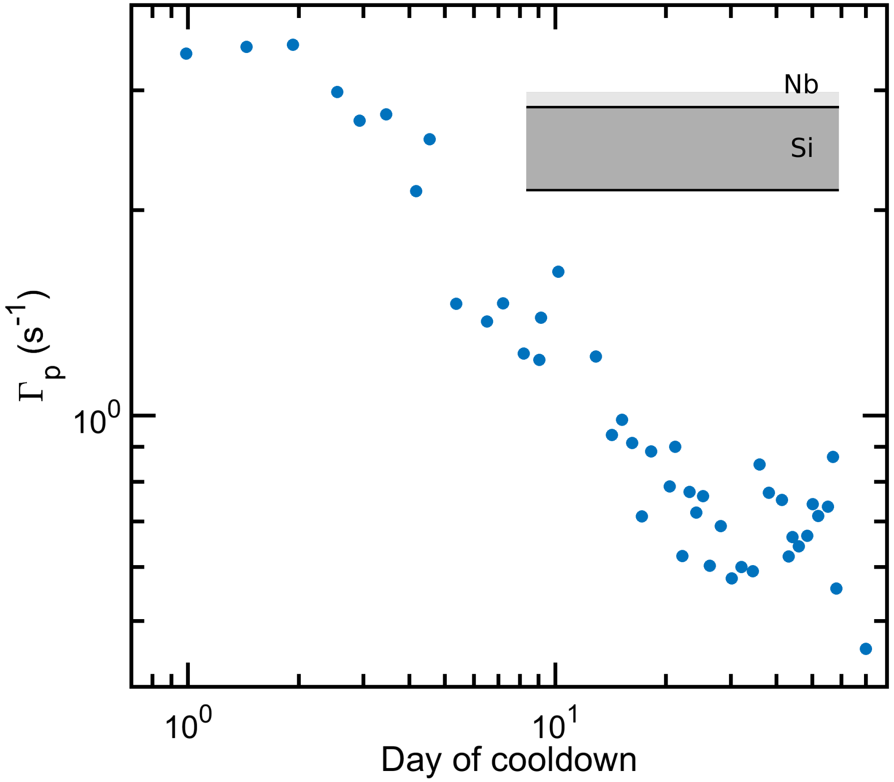
Dependence on sample packaging?



Mounted with GE varnish and Al wire-bonds



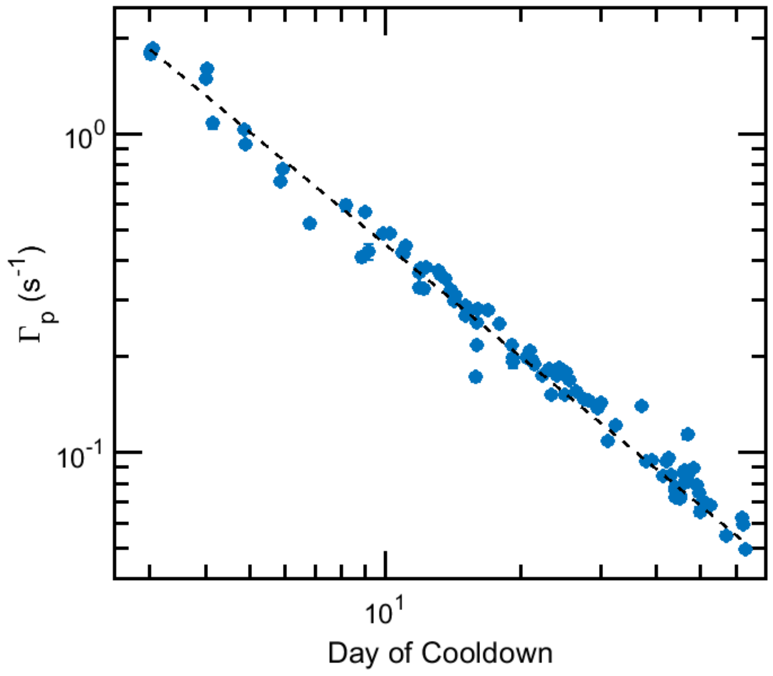
Mounted into package with wire-bonds



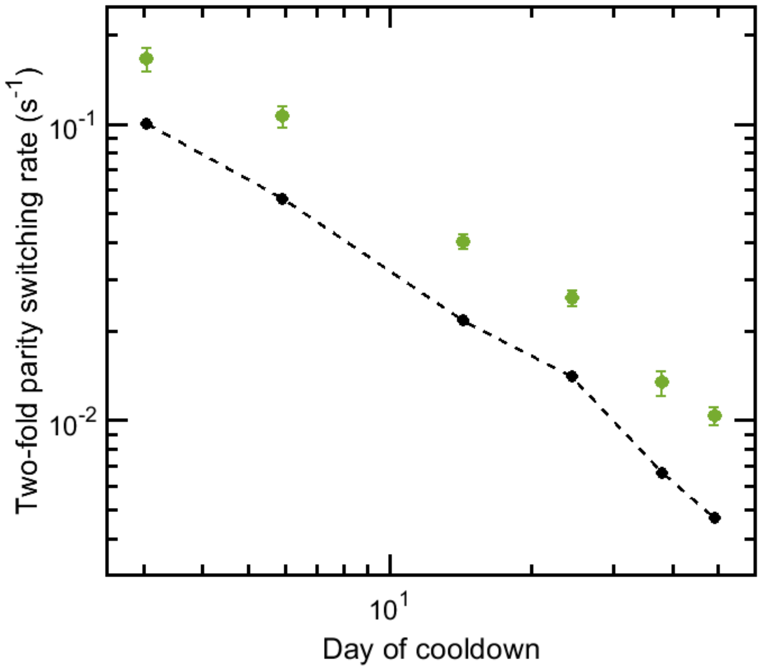
Dodge, Yelton *et al.*, in preparation (2024)

Conclusion

- Power-law dependence of QP parity switching rates versus time of cooldown
- Correlated QP parity switching above random background switching rates during duration of cooldown



Questions?



Back-up slides

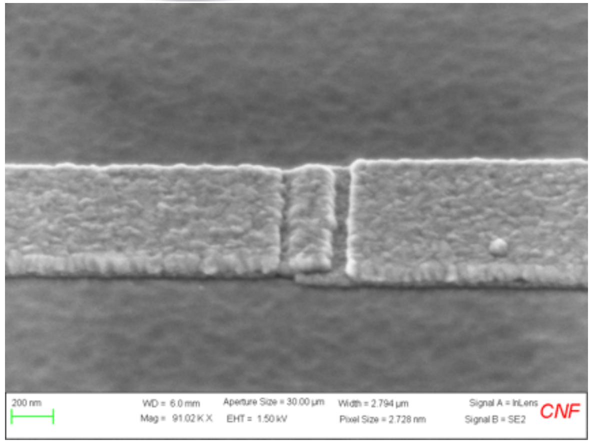
Superconducting qubits

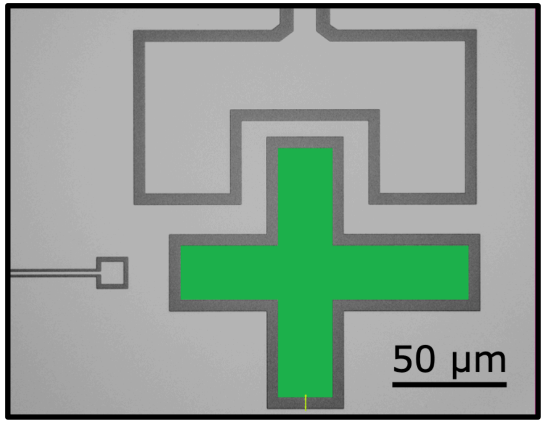
Josephson junctions form a non-linear inductor

$$V = \frac{\Phi_0}{2\pi}\frac{d\phi}{dt}$$

$$I = I_0 \sin\phi$$

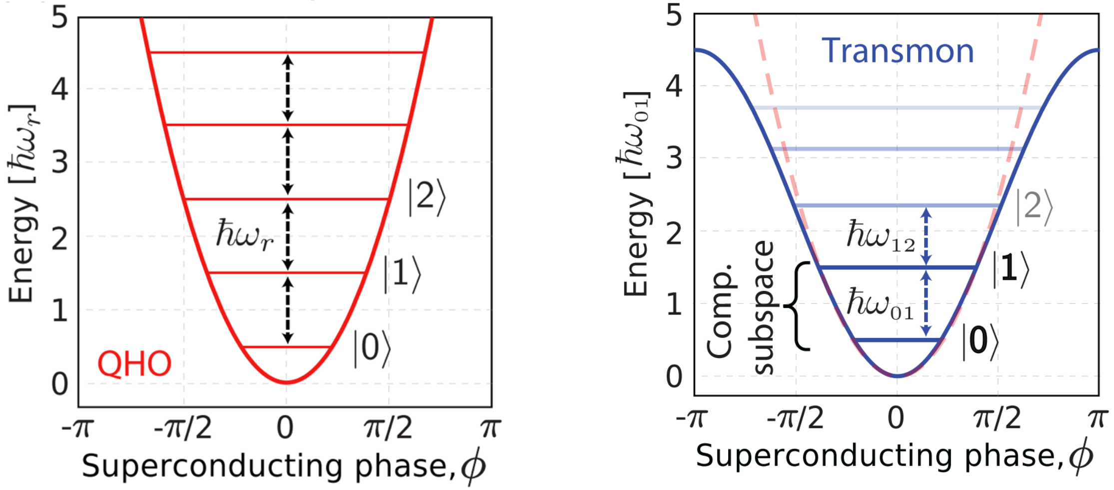
$$\rightarrow L = \frac{\Phi_0}{2\pi I_0 \cos\phi}$$

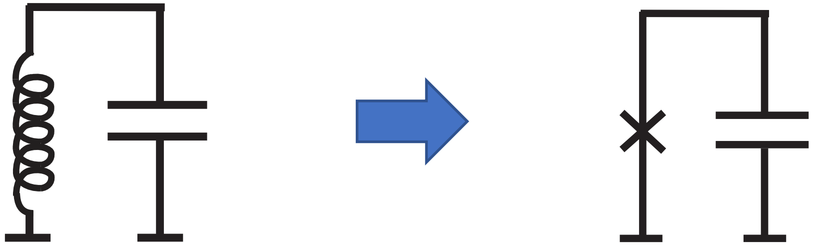


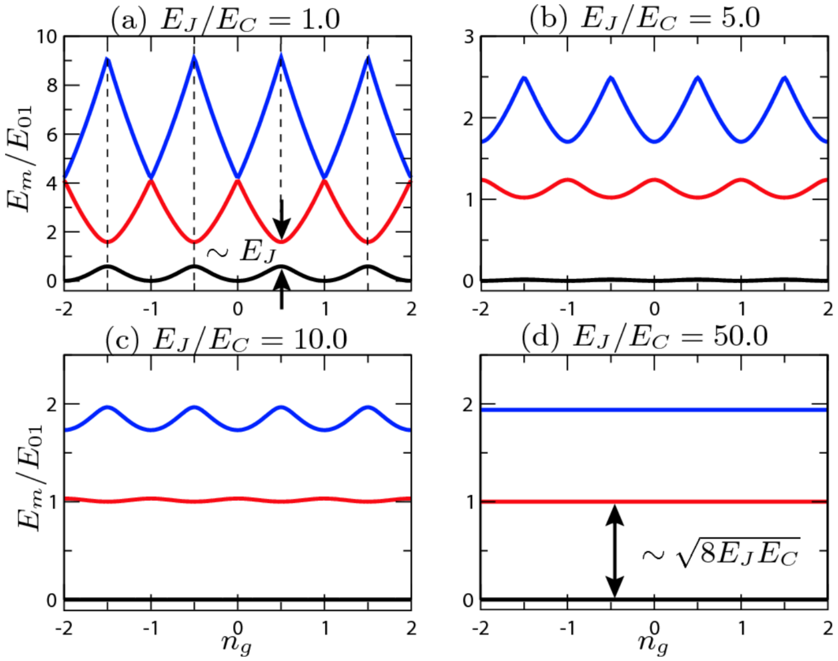


$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos\hat{\phi}$$

Krantz *et al.*, Appl. Phys. Rev. 6, 021318 (2019)

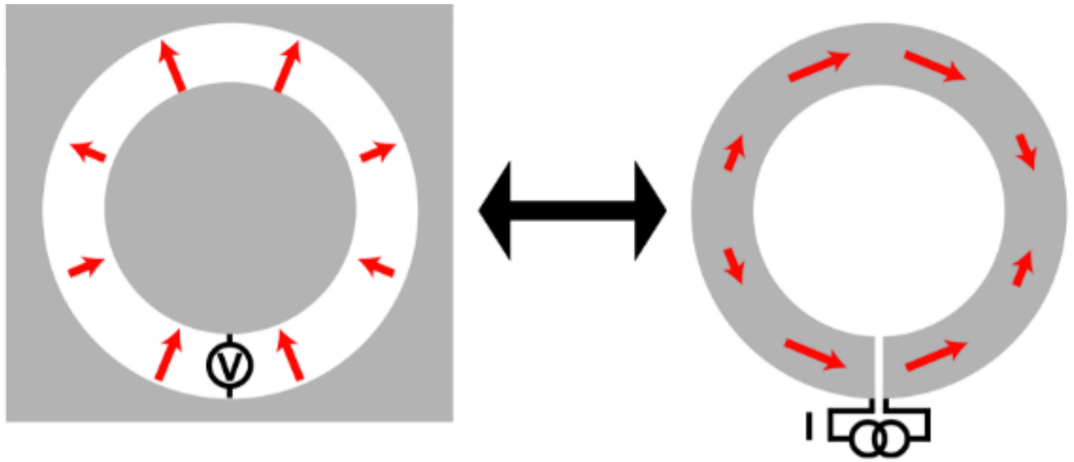


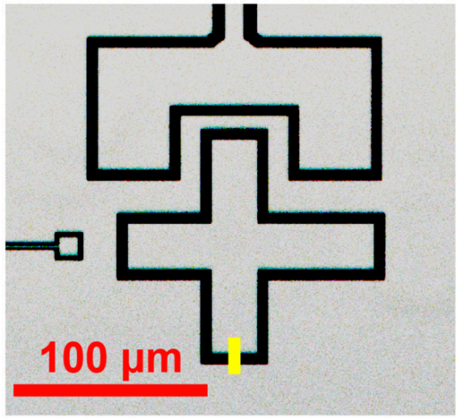


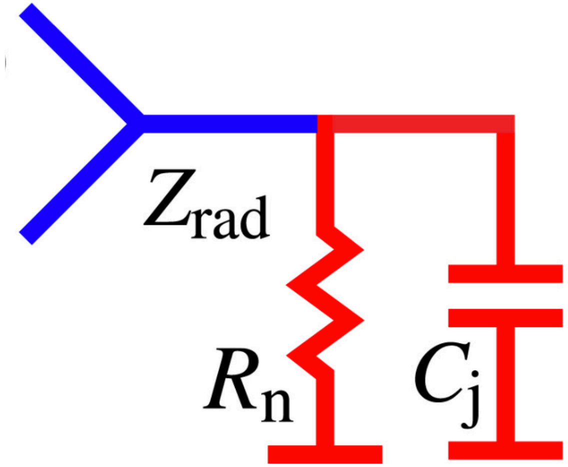


Koch *et al.*, Phys. Rev. A 76, 042319 (2007)

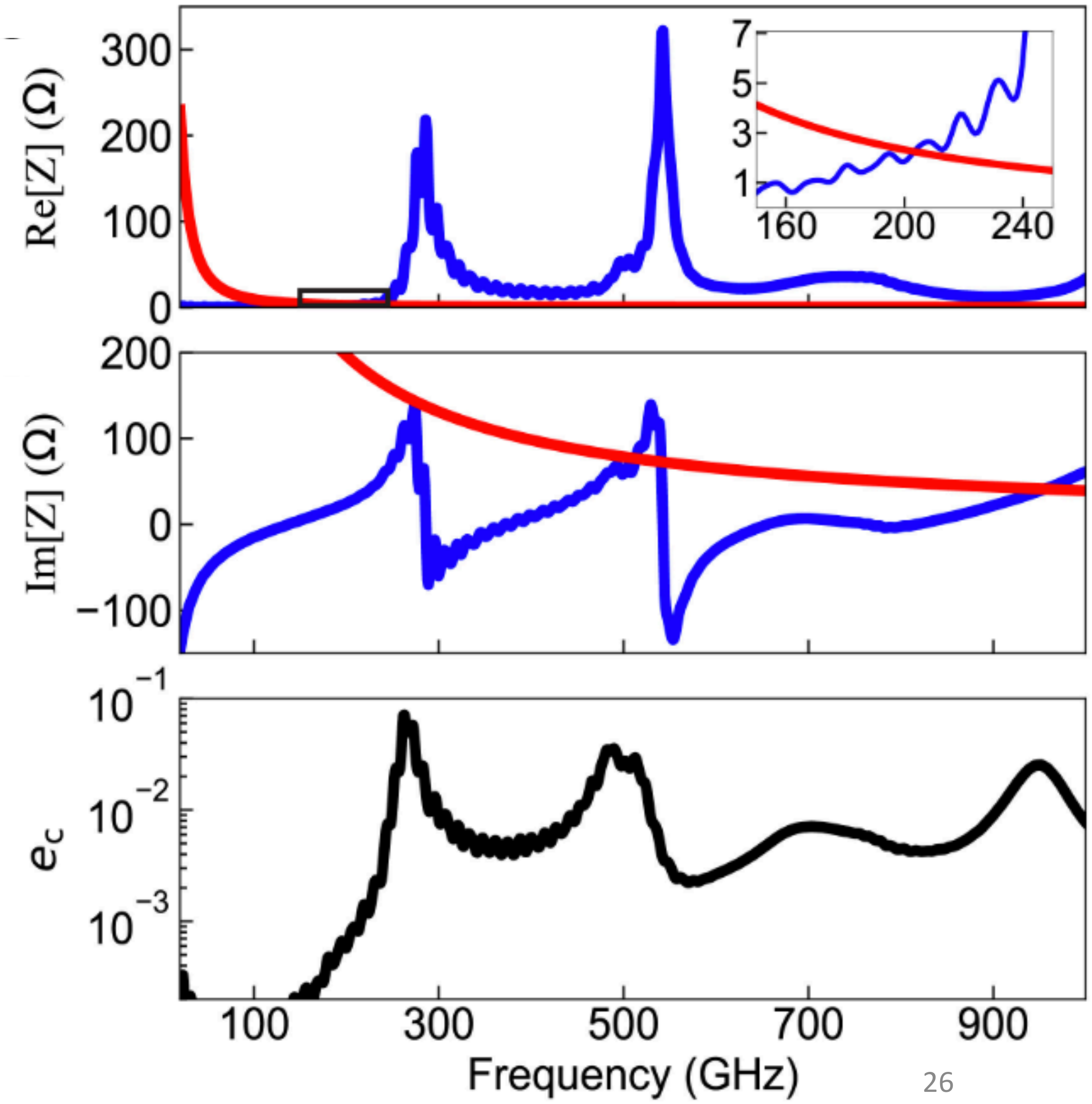
Qubit island antenna resonance







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



Correlated rates before and after unplanned cooldown

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

Observed parity switching rates (s^{-1}) for the non-Cu chip							
Cooldown	Q_A	Q_B	Q_C	$Q_A \wedge Q_B$	$Q_B \wedge Q_C$	$Q_A \wedge Q_C$	$Q_A \wedge Q_B \wedge Q_C$
1	0.299(3)	0.301(4)	0.252(3)	0.065(2)	0.060(2)	0.057(2)	0.012(1)
2	0.505(5)	0.508(4)	0.495(8)	0.170(4)	0.161(6)	0.162(8)	0.042(5)
Extracted poisoning event rates (s^{-1})							
1	0.20(2)	0.19(2)	0.12(2)	0.18(1)	0.17(1)	0.15(1)	0.064(9)
2	0.01(4)	0.02(4)	0.03(5)	0.35(3)	0.31(3)	0.32(4)	0.33(3)
spacing	-	-	-	5.3 mm	4.5 mm	2.0 mm	-

Supplementary Table 4: **Comparison of rates for non-Cu chip between cooldowns.** Observed parity switching rates and extracted poisoning event rates for non-Cu chip on the first and second cooldowns with no poisoning from injector junction.

Observed parity switching rates (s^{-1}) for the Cu chip							
Cooldown	Q_A	Q_B	Q_C	$Q_A \wedge Q_B$	$Q_B \wedge Q_C$	$Q_A \wedge Q_C$	$Q_A \wedge Q_B \wedge Q_C$
1	0.0221(3)	0.0336(5)	0.0230(5)	0.0008(1)	0.0008(2)	0.0005(1)	0.00006(6)
2	0.056(2)	0.053(2)	0.039(1)	0.0051(9)	0.005(1)	0.0047(7)	0.0003(3)
Extracted poisoning event rates (s^{-1})							
1	0.041(1)	0.063(1)	0.043(2)	0.0019(7)	0.0016(9)	0.0010(7)	0.0004(6)
2	0.082(8)	0.07(1)	0.047(8)	0.015(6)	0.017(6)	0.016(5)	0.000(3)*
spacing	-	-	-	5.3 mm	4.5 mm	2.0 mm	-

Supplementary Table 5: **Comparison of rates for Cu chip between cooldowns.** Observed parity switching rates and extracted poisoning event rates for Cu chip on the first and second cooldowns with no poisoning from injector junction. *For the Cu chip on the second cooldown, the solution to the system of equations in Supplementary Eq. (2) results in a small negative value for the three-fold coincidence poisoning event rate that is consistent with zero based on the calculated uncertainty.