Superconducting Circuits for Quantum Computing and Quantum Sensing

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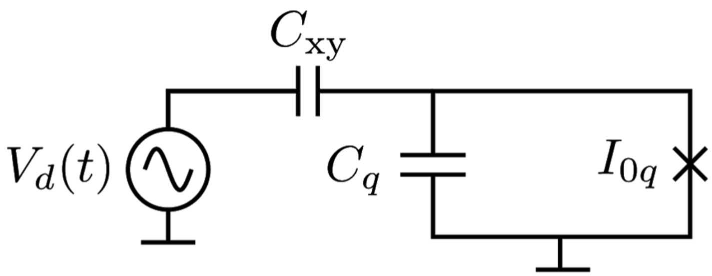
ICEPP Workshop
March 9, 2022

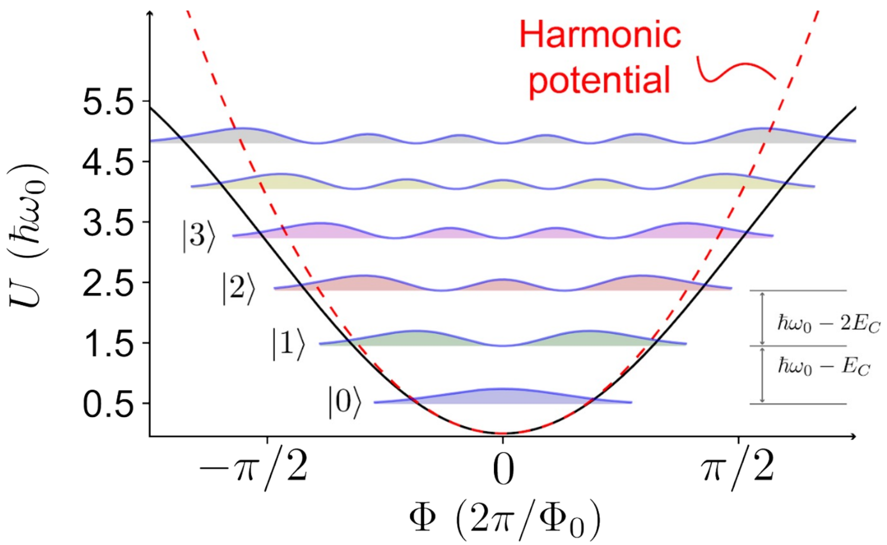
Outline

- Introduction to SC qubits
- Requirements for fault tolerance
- Correlated errors from particle impacts; mitigation
- Photon-assisted QP poisoning
- Qubit-based sensors for dark matter detection

Transmon qubit



$$\hat{H} = \frac{\hat{Q}^2}{2C_\Sigma} - E_J \cos\left(\frac{2\pi\hat{\Phi}}{\Phi_0}\right)$$

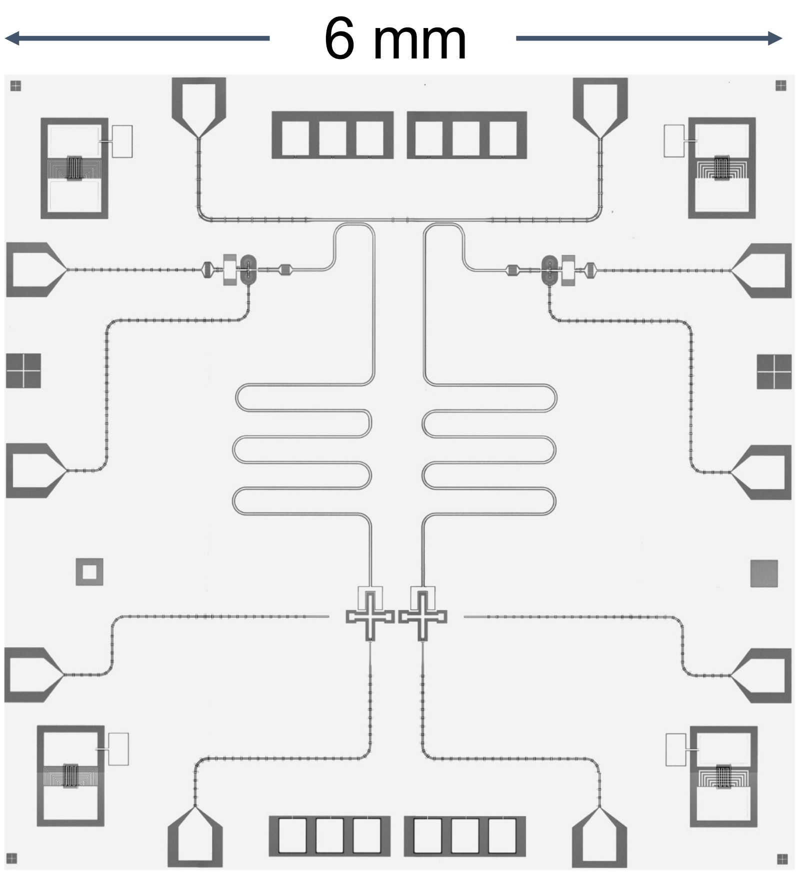


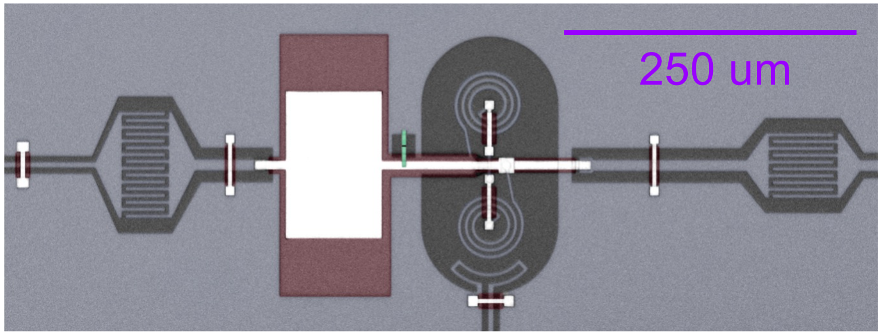
$$E_J = I_{0q}\Phi_0/2\pi$$

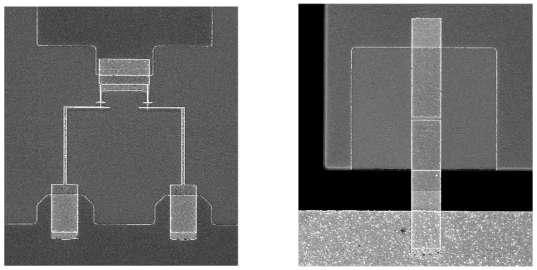
$$E_C = e^2/2C_\Sigma$$

$$\omega_0 = \sqrt{8E_JE_C}/\hbar$$

Chip layout

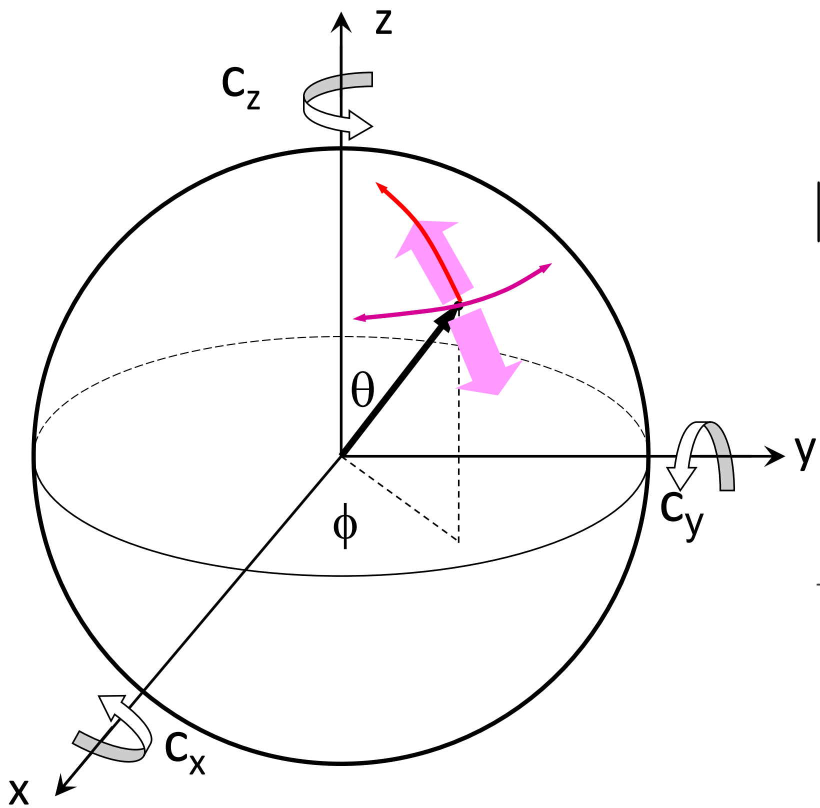






Opremcak *et al*., PRX 11, 011027 (2021)

Bloch sphere representation



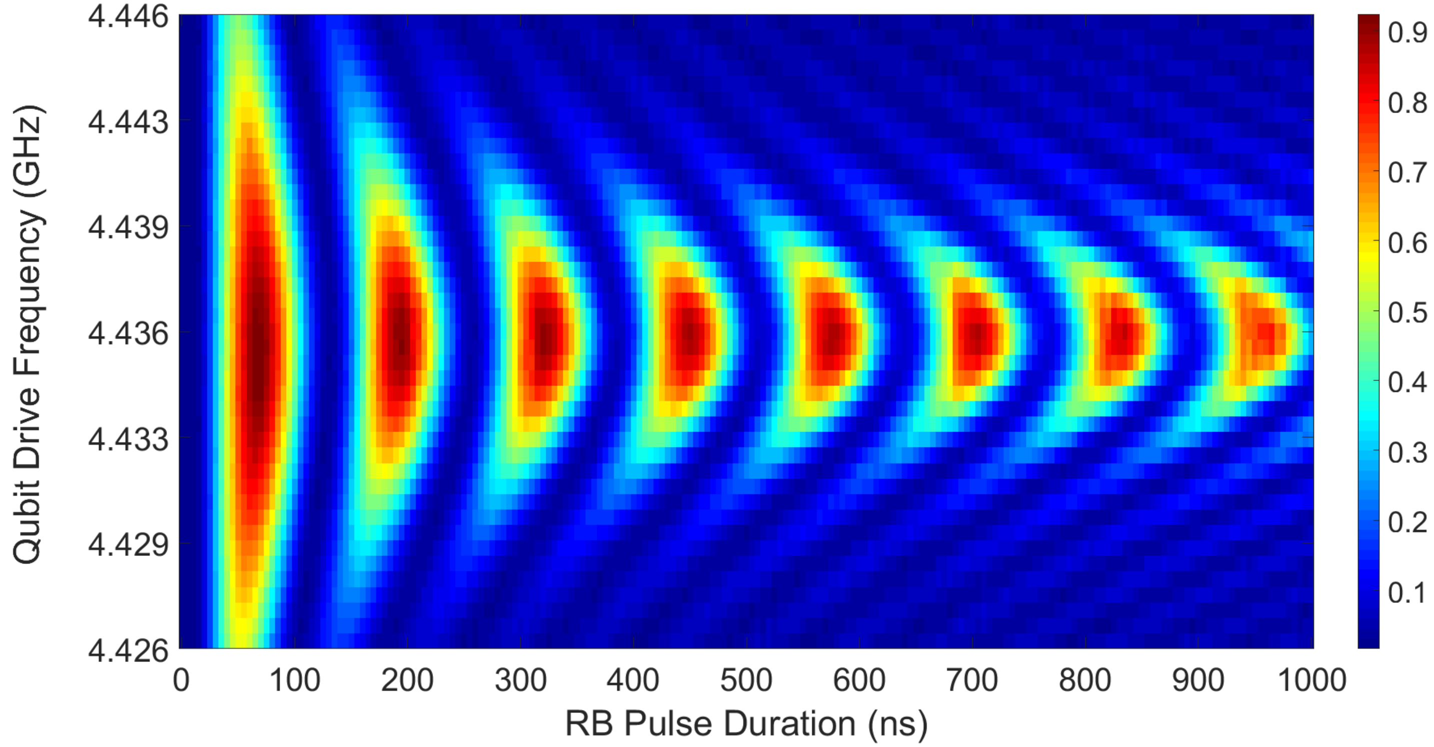
$$|\Psi\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\phi}\sin\frac{\theta}{2}\,|1\rangle$$

$$\hat{H} = \frac{\hat{Q}^2}{2C_\Sigma} - E_J\cos\left(\frac{2\pi\hat{\Phi}}{\Phi_0}\right) + \frac{C_{\mathrm{xy}}}{C_\Sigma}V_d(t)\hat{Q}$$

controlled dynamically

Qubit Rabi oscillations

Opremcak *et al.*,
Science **361**, 1239 (2018)



Towards fault-tolerant QC

The challenge:

- Pauli X and Z don't commute
(impossible to
simultaneously monitor
bit and phase flips
using naïve approach)

However:

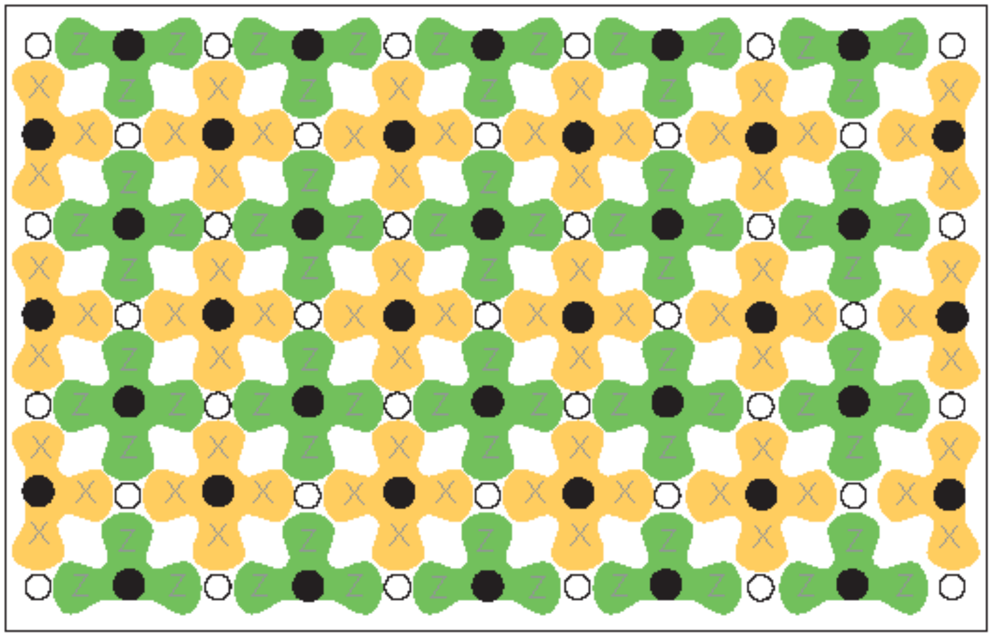
- Multiqubit parity operators (e.g., XXXX, ZZZZ) do commute!

possible in principle to uniquely identify errors in multiqubit arrays

Towards fault-tolerant QC

Two-dimensional surface code

Fowler et al., PRA 86, 032324 (2012)



single QB gates: 99.9%
entangling gates: 99%
measurement: 90%

(generally target one order of magnitude lower infidelity)

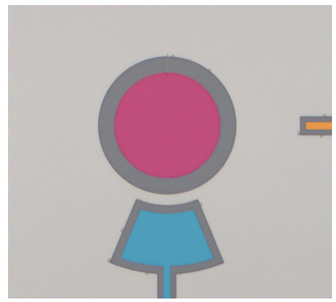
Assumption: NO correlated errors

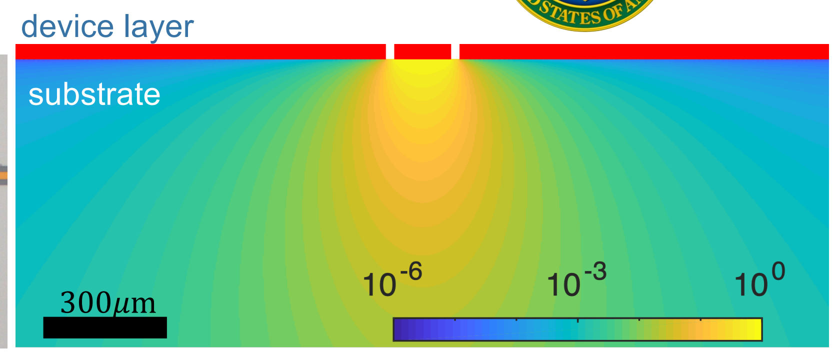
Correlated errors in SC multiqubit circuits

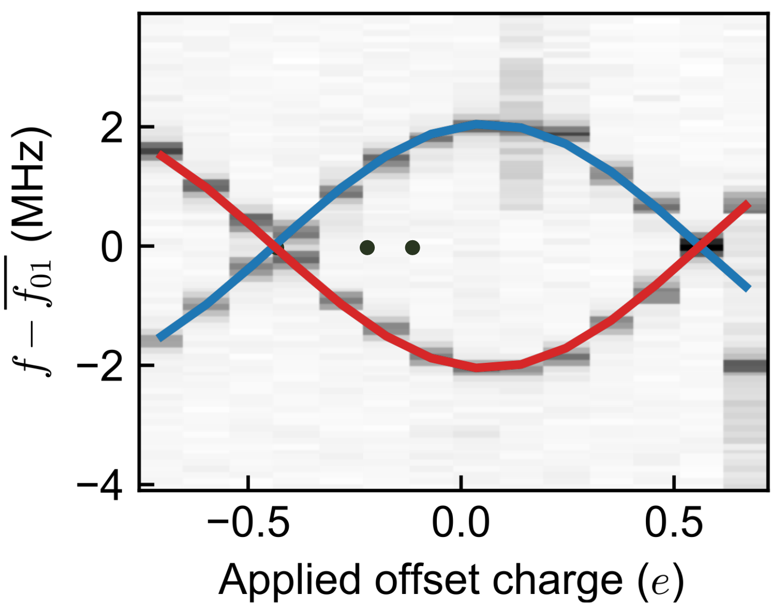
(prior DOE project)

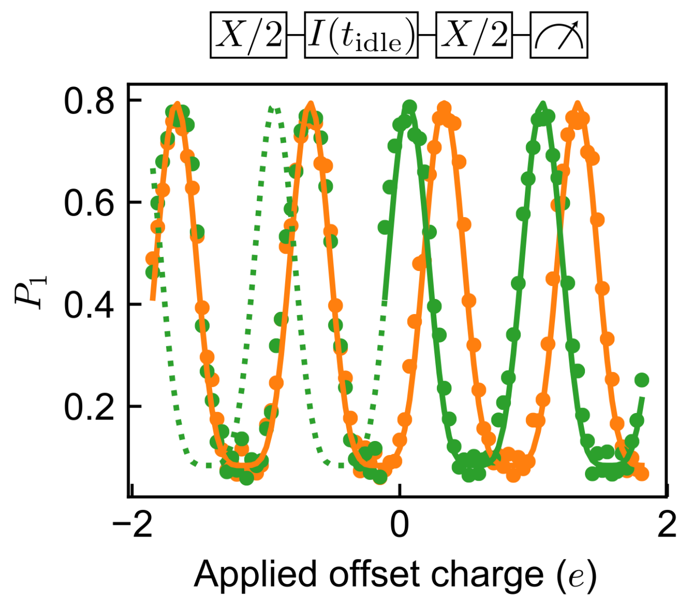
Wilen *et al.*, Nature **594**, 7863 (2021)

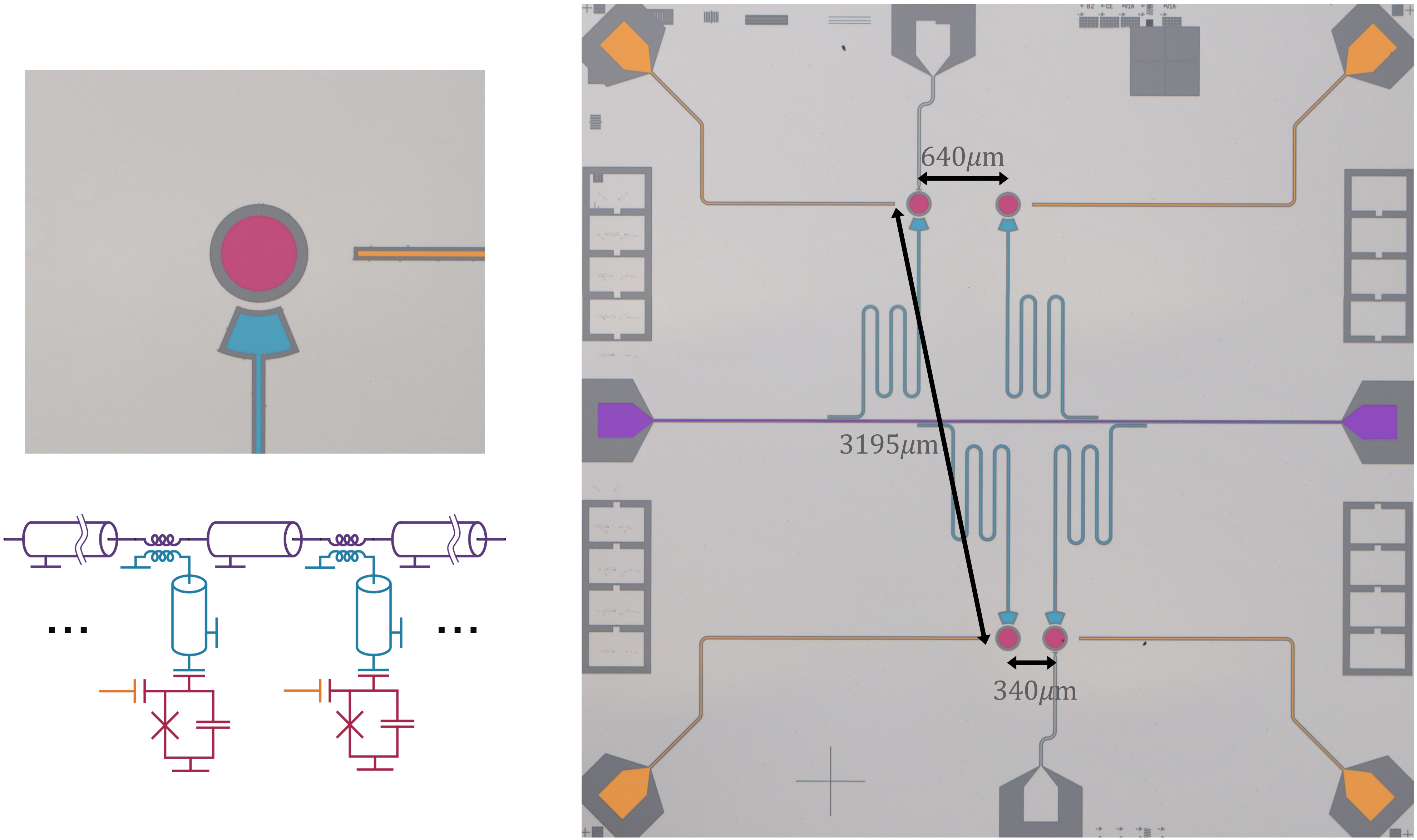
- Qubit as electrometer
- $E_J/E_C \sim 25$
- Ramsey-based charge tomography









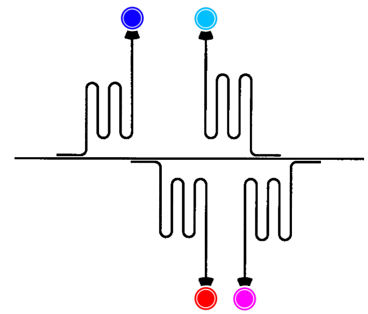


640μm
3195μm
340μm

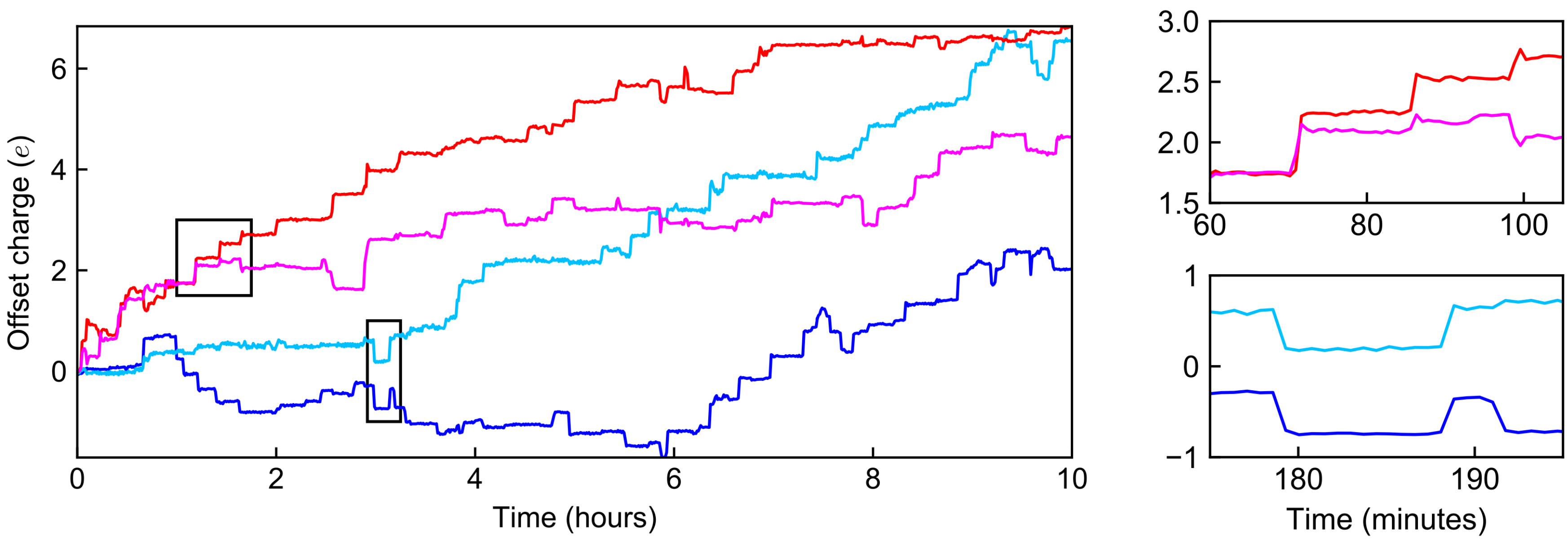
Correlated charge fluctuations

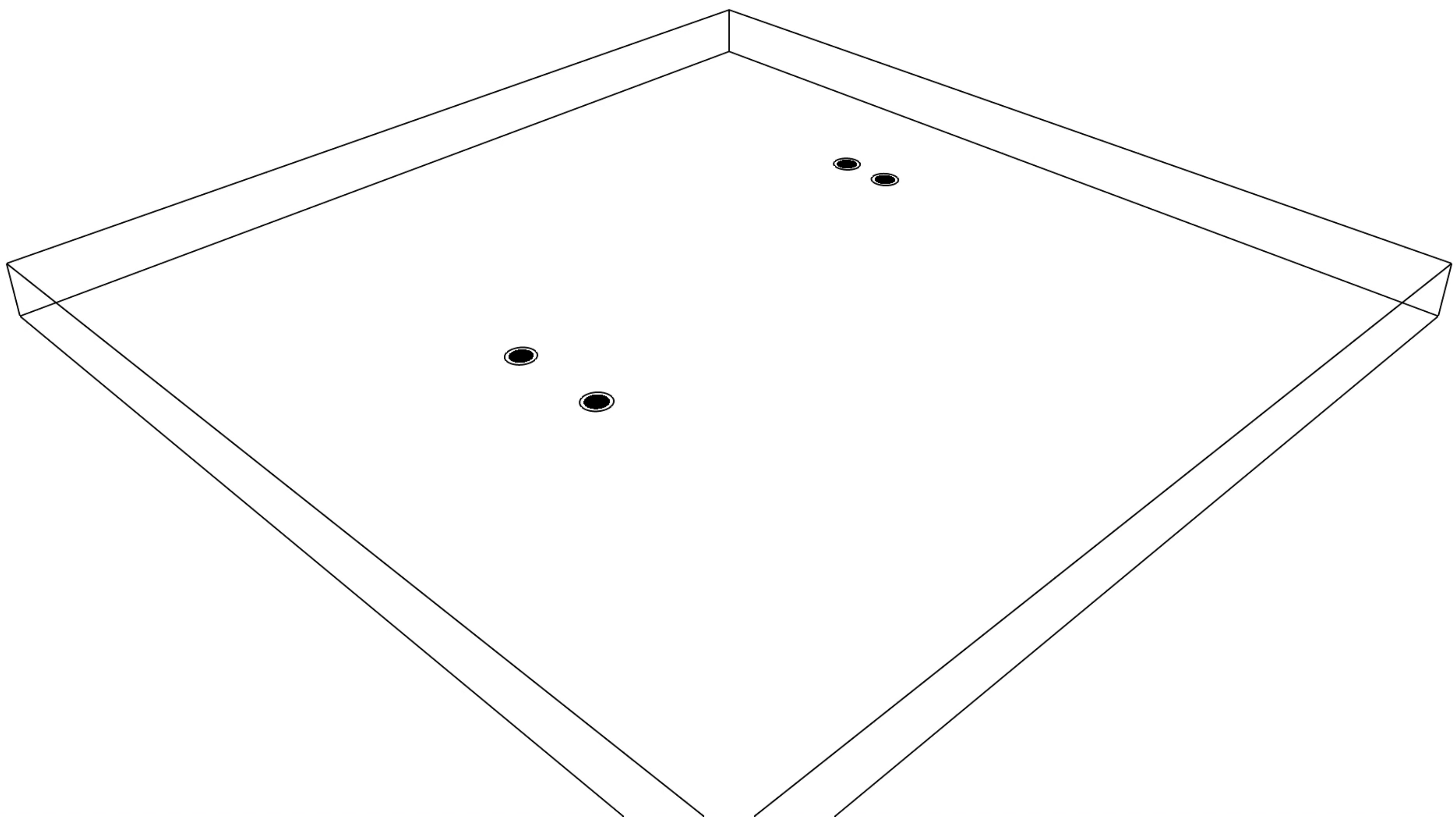
- Large discrete jumps

Riste et al., Nat. Comm. **4**, 1913 (2013).
Serniak et al., PRL **121**, 157701 (2018).
Christensen et al., PRB **100**, 140503 (R)(2019).



- Correlated jumps in neighboring qubits



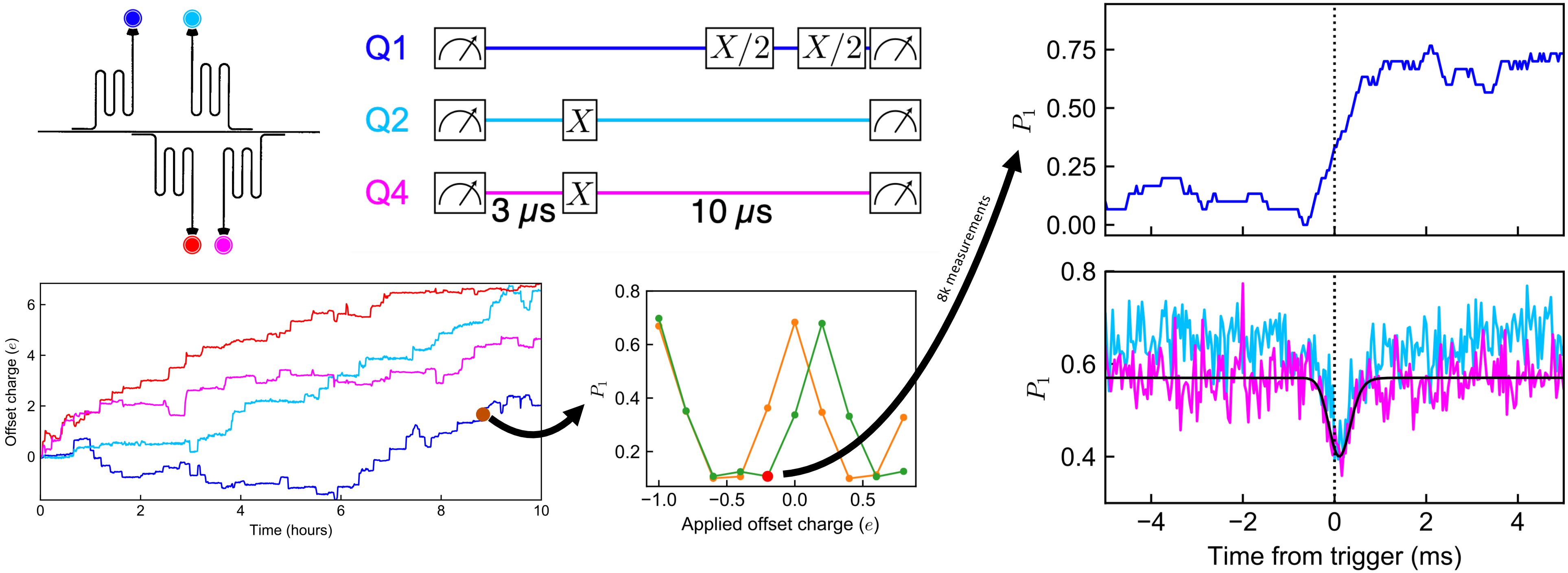


Correlated relaxation errors

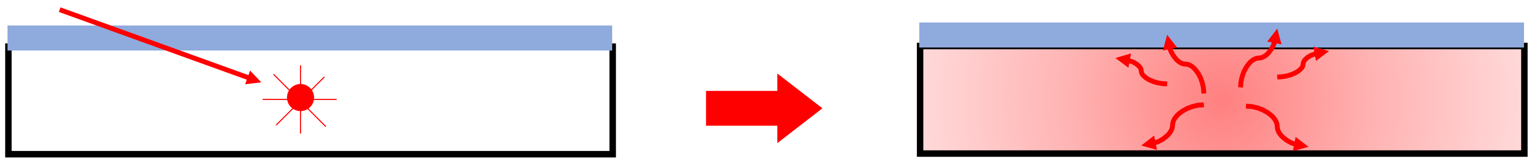
- Use jumps in Ramsey measurement as trigger
- Seen across distances > 3 mm

recovery timescale

$\tau = 130 \pm 40\mu s$



Phonon-mediated quasiparticle poisoning



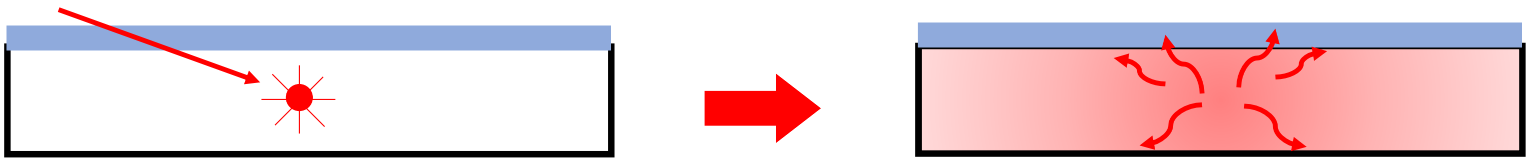
- 95% of deposited energy coupled to phonon reservoir
  [CDMS: e.g., Shutt et al., PRL 69, 3531 (1992)]

- Weak acoustic coupling to environment
- Few relaxation channels below SC gap edge
- Correlated pair-breaking across the chip

Possible mitigation strategies:

- Superconducting gap engineering
- Backside normal metallization
- Micromachining to suppress phonon transport
- Shielding to suppress absorption of HE particles

Phonon-mediated quasiparticle poisoning



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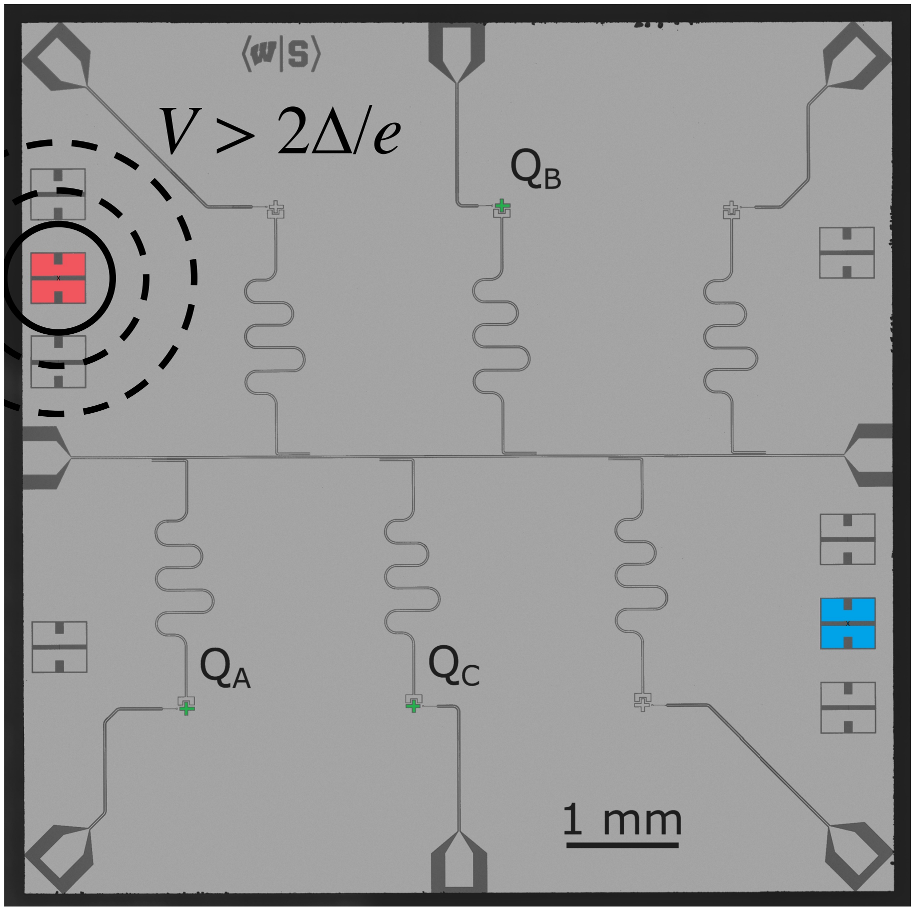
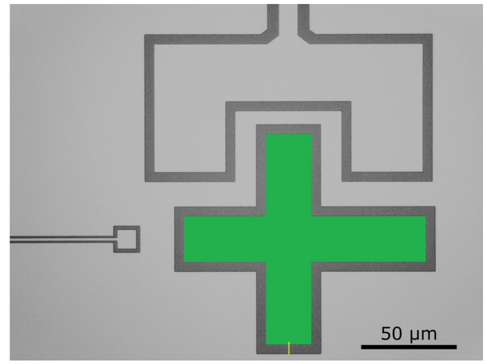
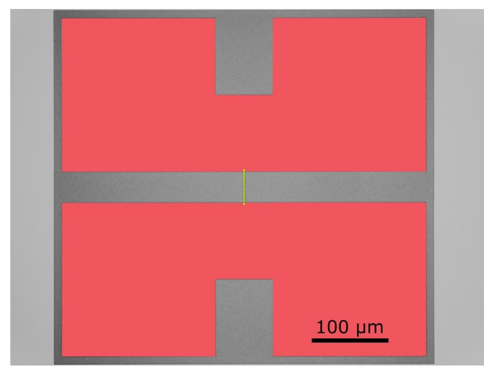
Controlled study of phonon-mediated QP poisoning

(With B. Plourde group, Syracuse U.)





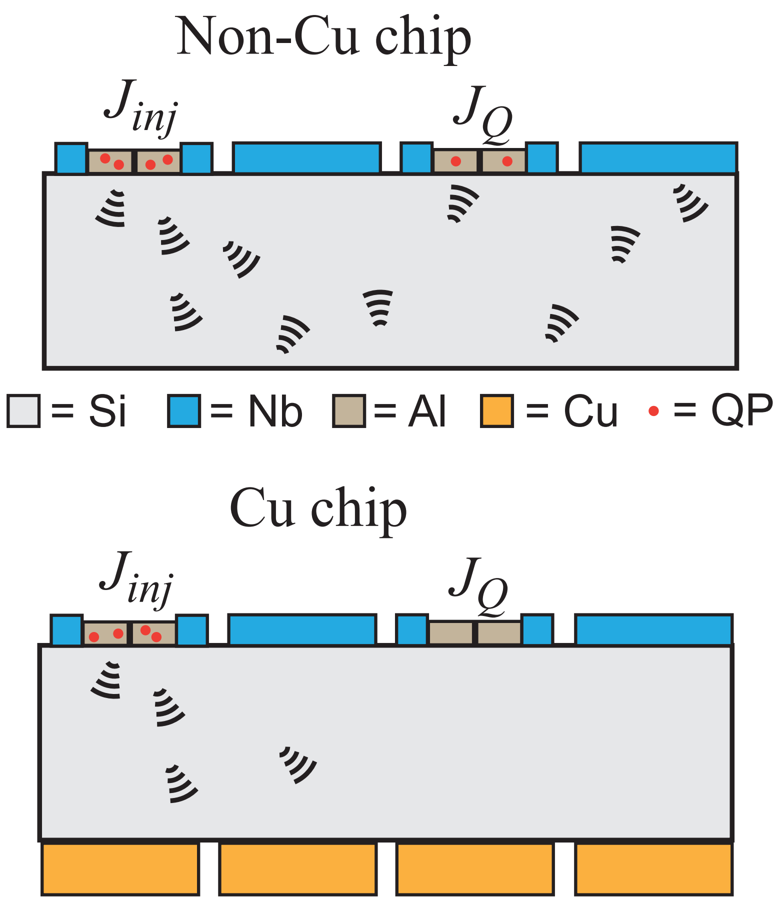
- Nb groundplane, 70 nm
- Al/AlOx/Al JJ, 360 x 150 nm^2
- Cavities: 5.9 - 6.5 GHz
- Qubits: 4.9 - 5.1 GHz
- E_J/E_c ~ 30



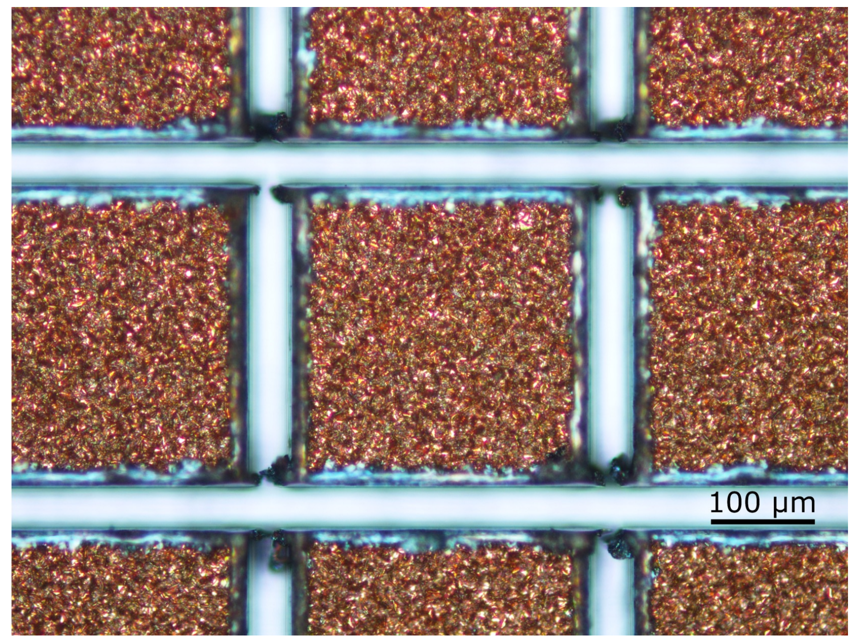
- Injector JJs: 1 μm x 150 nm
- I_c ~ 100 nA
- No galvanic connection to groundplane

Controlled study of phonon-mediated QP poisoning

(With B. Plourde group, Syracuse U.)

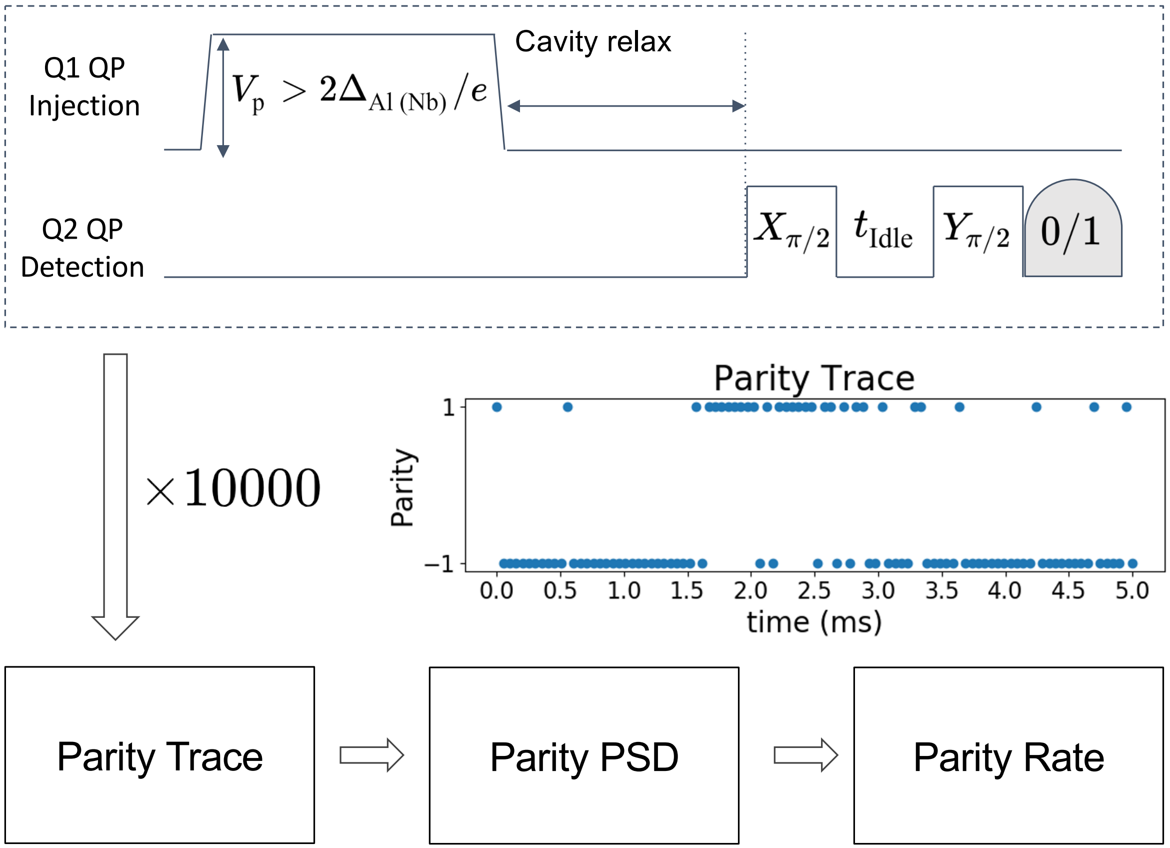


Electroplated Cu
10 μm thick
RRR ~ 42

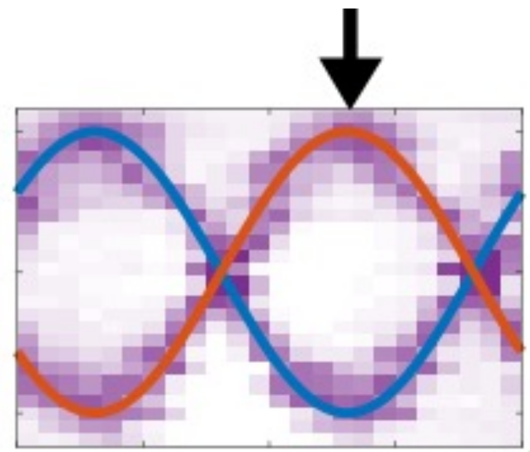


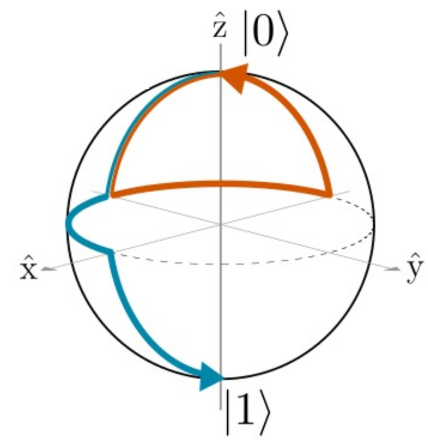
Direct measurement of QP poisoning via charge parity

Riste et al., Nat. Comm. **4**, 1913 (2013)
Serniak et al., PRL **121**, 157701 (2018)



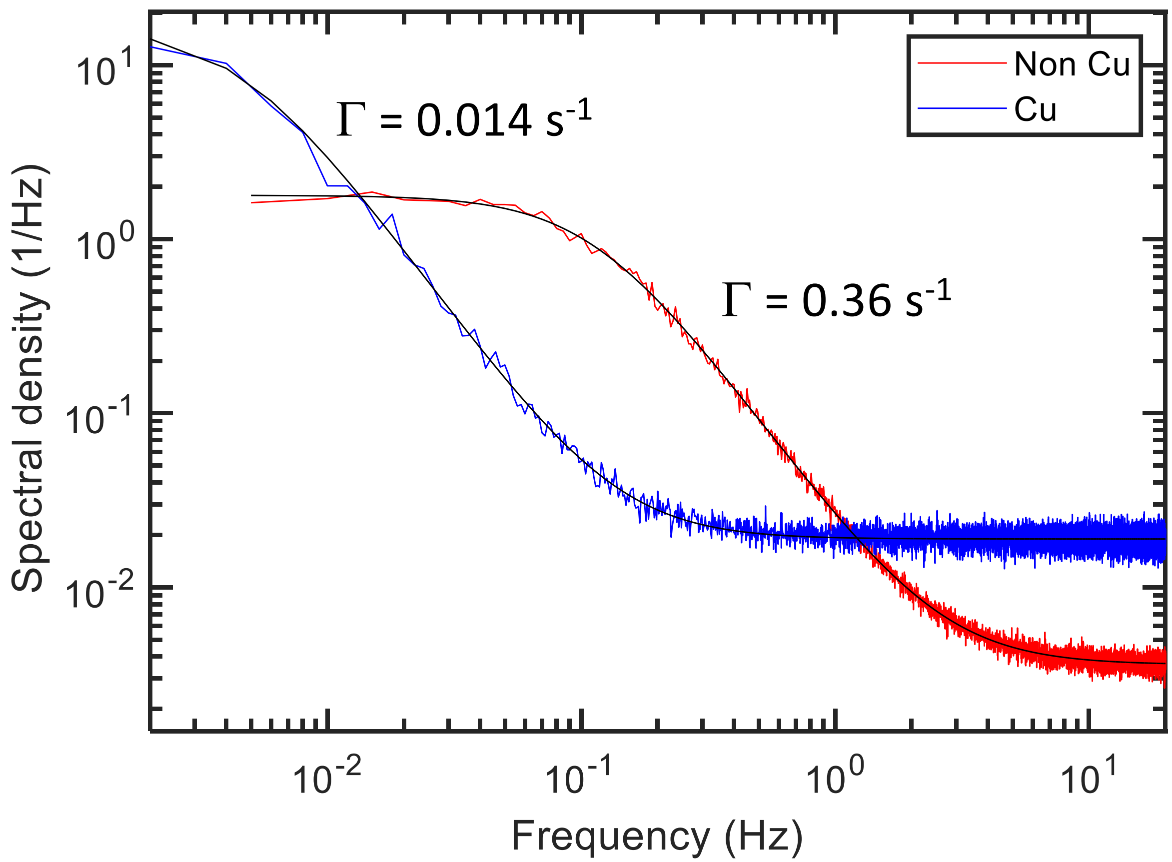
bias at maximum charge dispersion



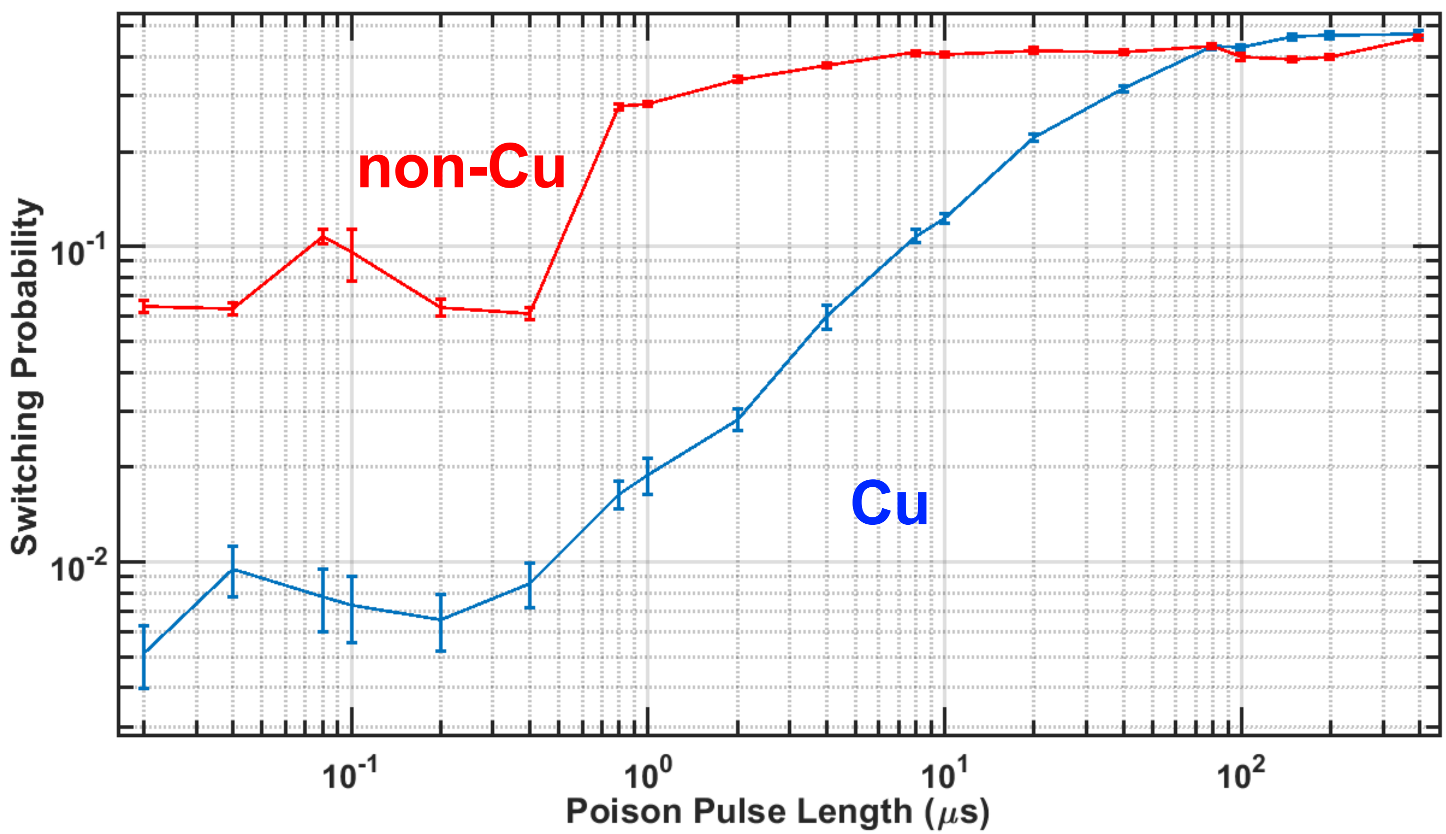


Direct measurement of QP poisoning via charge parity

Baseline:
no QP injection



Simultaneous parity monitoring with phonon injection



No injection: suppression of correlated error from impact events

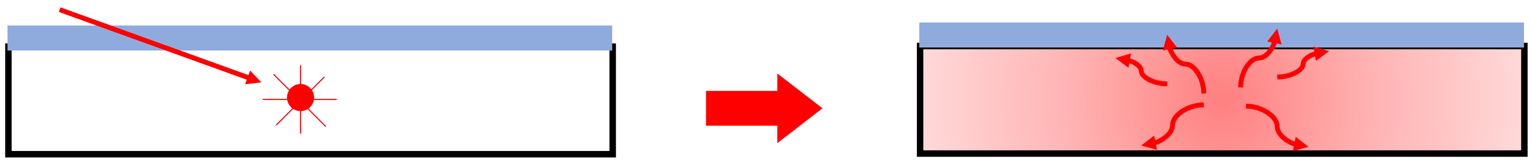
Observed parity switching rates (s^{-1})							
Device	Q_A	Q_B	Q_C	$Q_A \wedge Q_B$	$Q_B \wedge Q_C$	$Q_A \wedge Q_C$	$Q_A \wedge Q_B \wedge Q_C$
Non-Cu	0.309(3)	0.313(4)	0.301(3)	0.073(2)	0.068(2)	0.064(2)	0.0134(9)
Cu	0.0250(4)	0.0344(5)	0.0545(6)	0.0014(1)	0.00357(2)	0.0062(3)	0.00012(6)
spacing	-	-	-	5.3 mm	4.5 mm	2.0 mm	-

Expected random coincident parity switching rates (s^{-1})				
Device	$Q_A \wedge Q_B$	$Q_B \wedge Q_C$	$Q_A \wedge Q_C$	$Q_A \wedge Q_B \wedge Q_C$
Non-Cu	0.039(5)	0.038(5)	0.037(5)	0.005(6)
Cu	0.0003(6)	0.0007(8)	0.0005(7)	0.000007(852)

$(r_A^{\text{obs}}\Delta t)(r_B^{\text{obs}}\Delta t)/\Delta t$ $\qquad$ $(r_A^{\text{obs}}\Delta t)(r_B^{\text{obs}}\Delta t)(r_C^{\text{obs}}\Delta t)/\Delta t$

Extracted poisoning rates (s^{-1})							
Device	Q_A	Q_B	Q_C	$Q_A \wedge Q_B$	$Q_B \wedge Q_C$	$Q_A \wedge Q_C$	$Q_A \wedge Q_B \wedge Q_C$
Non-Cu	0.16(2)	0.16(2)	0.16(1)	0.21(1)	0.19(1)	0.18(1)	0.070(6)
Cu	0.021(2)	0.051(2)	0.072(2)	0.0049(7)	0.013(1)	0.024(1)	0.0002(5)
spacing	-	-	-	5.3 mm	4.5 mm	2.0 mm	-

Are particle impacts the source of nonequilibrium QPs?



Density of QPs in SC devices far exceeds thermal equilibrium value expected from theory (typ. 1 μm^{-3})

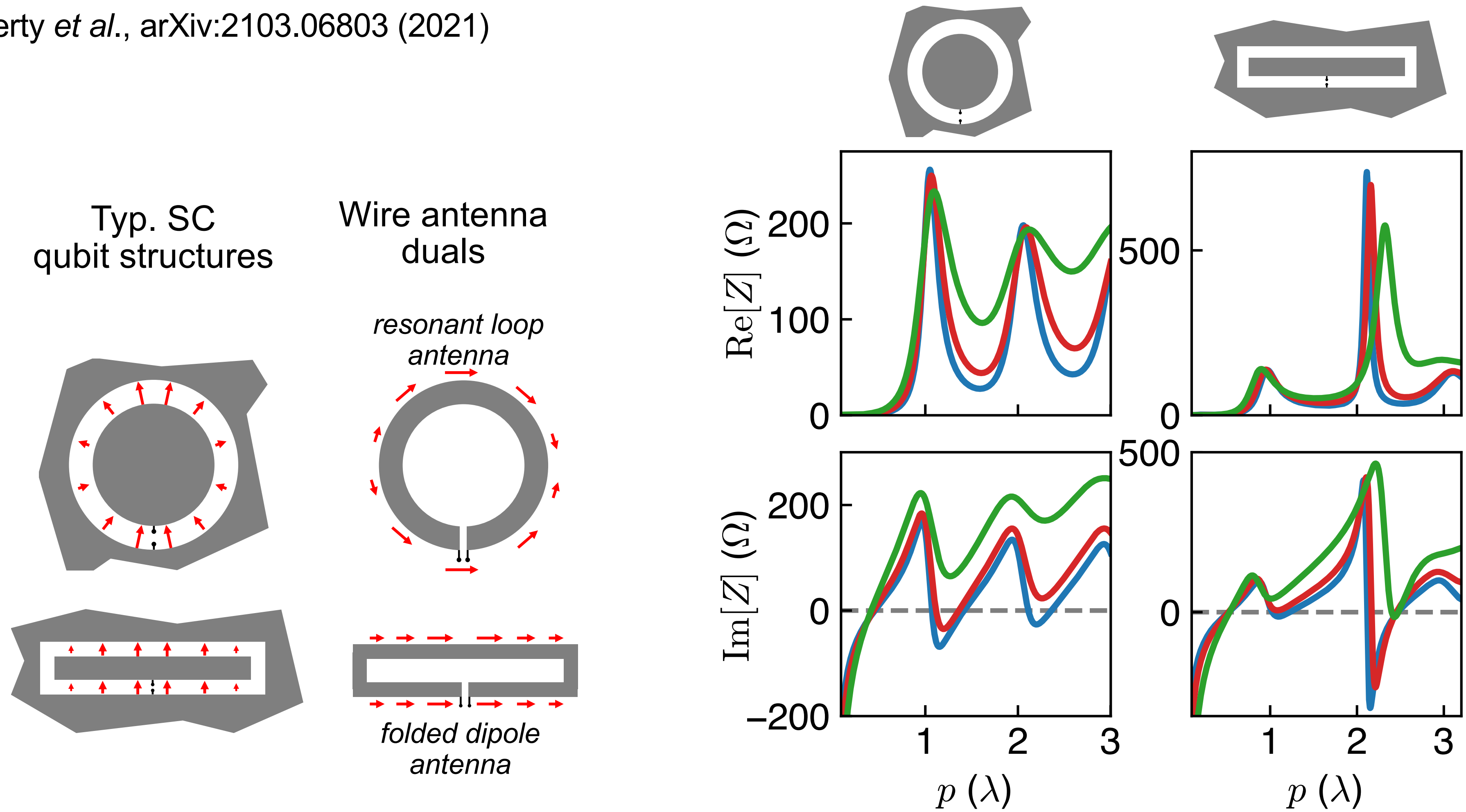
- Poisoning of charge-sensitive devices [cf. Aumentado et al., PRL **92**, 066802 (2004)].
- Enhanced qubit relaxation [Corcoles et al., APL **99**, 181906 (2011)].
- Qubit initialization errors of order 1-3%

MIT/LL group: model for QP poisoning from gamma impacts [Vepsalainen et al., Nature **584**, 551 (2020)]

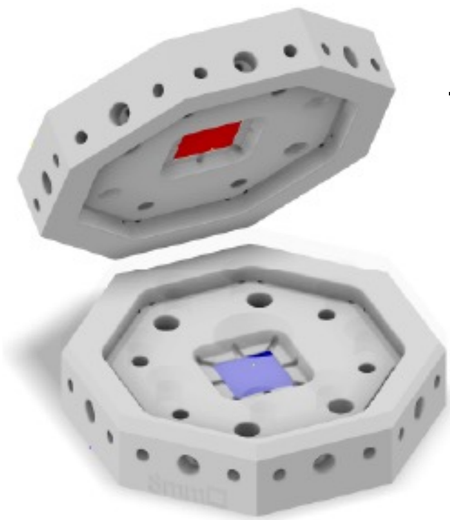
However, event rate too low and escape rate of athermal phonons too high to account for measured QP densities in most devices

Antenna modes of the transmon qubit

Rafferty *et al.*, arXiv:2103.06803 (2021)

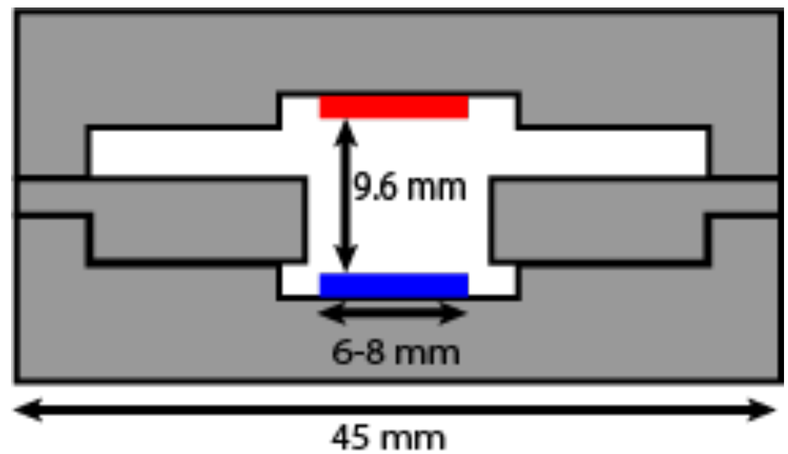


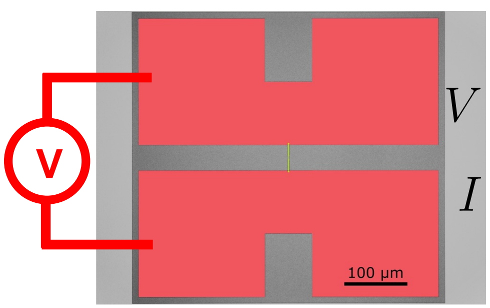
Validation of antenna model



transmitter

receiver



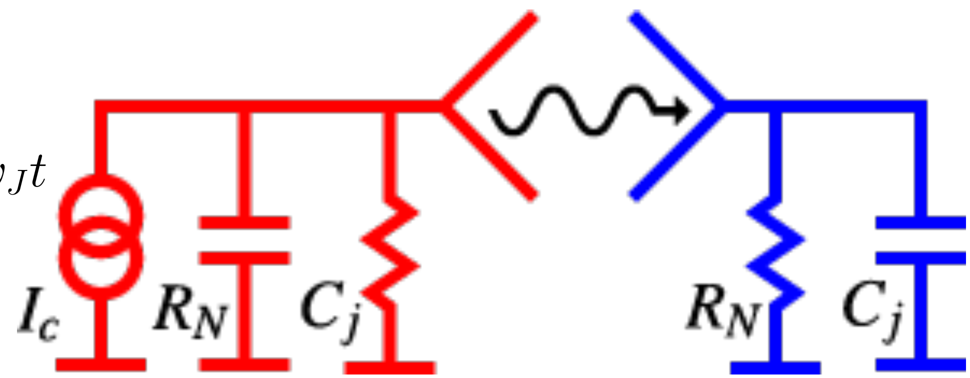


$$V = \frac{\Phi_0}{2\pi}\,\dot{\delta}$$

$$I = I_c \sin\delta$$

$$I = I_c \sin\omega_J t$$

$$f_J = V/\Phi_0$$



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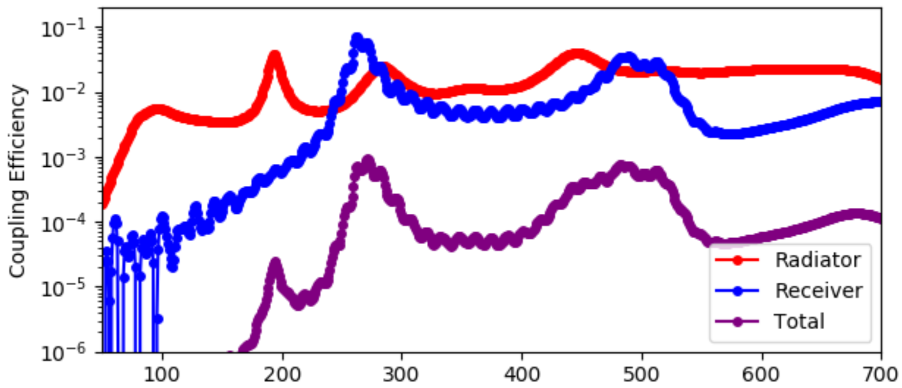
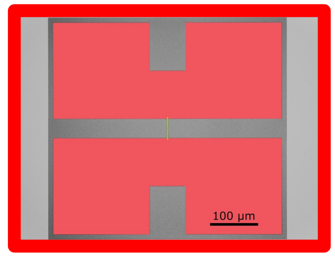
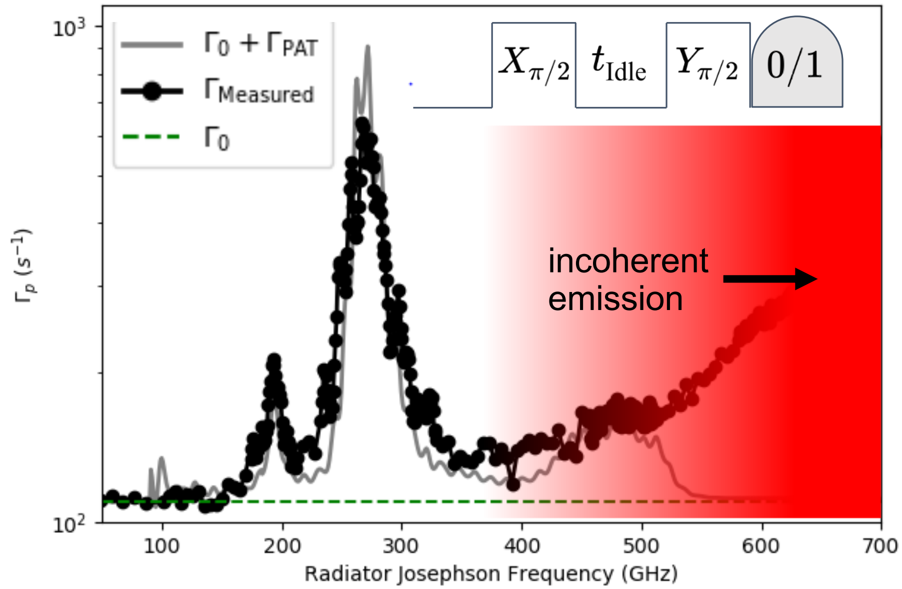
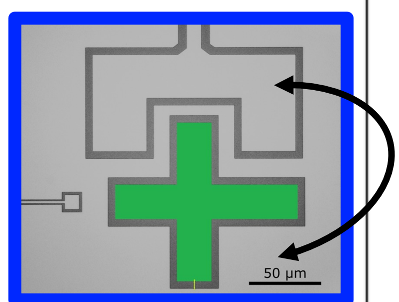
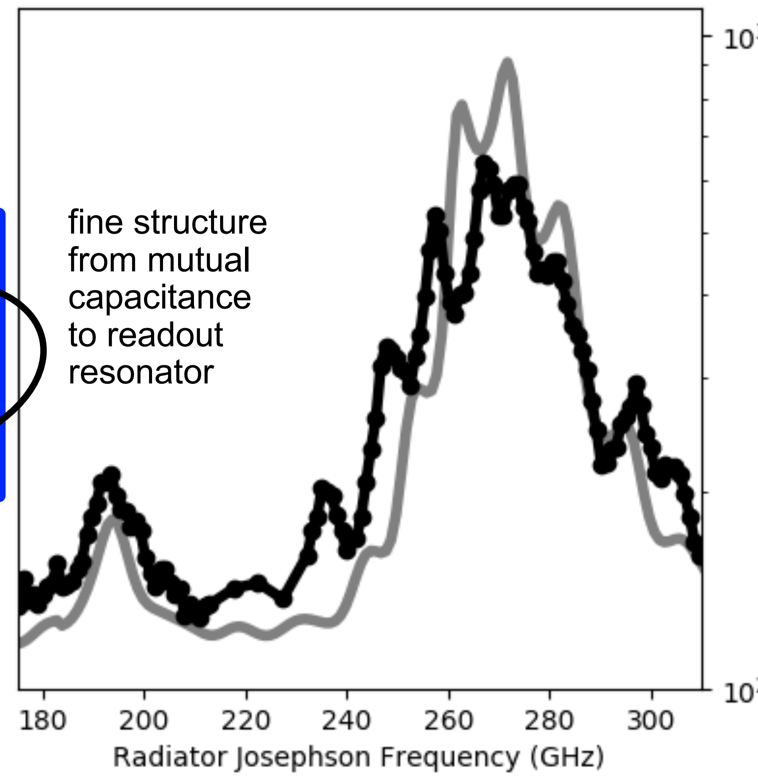




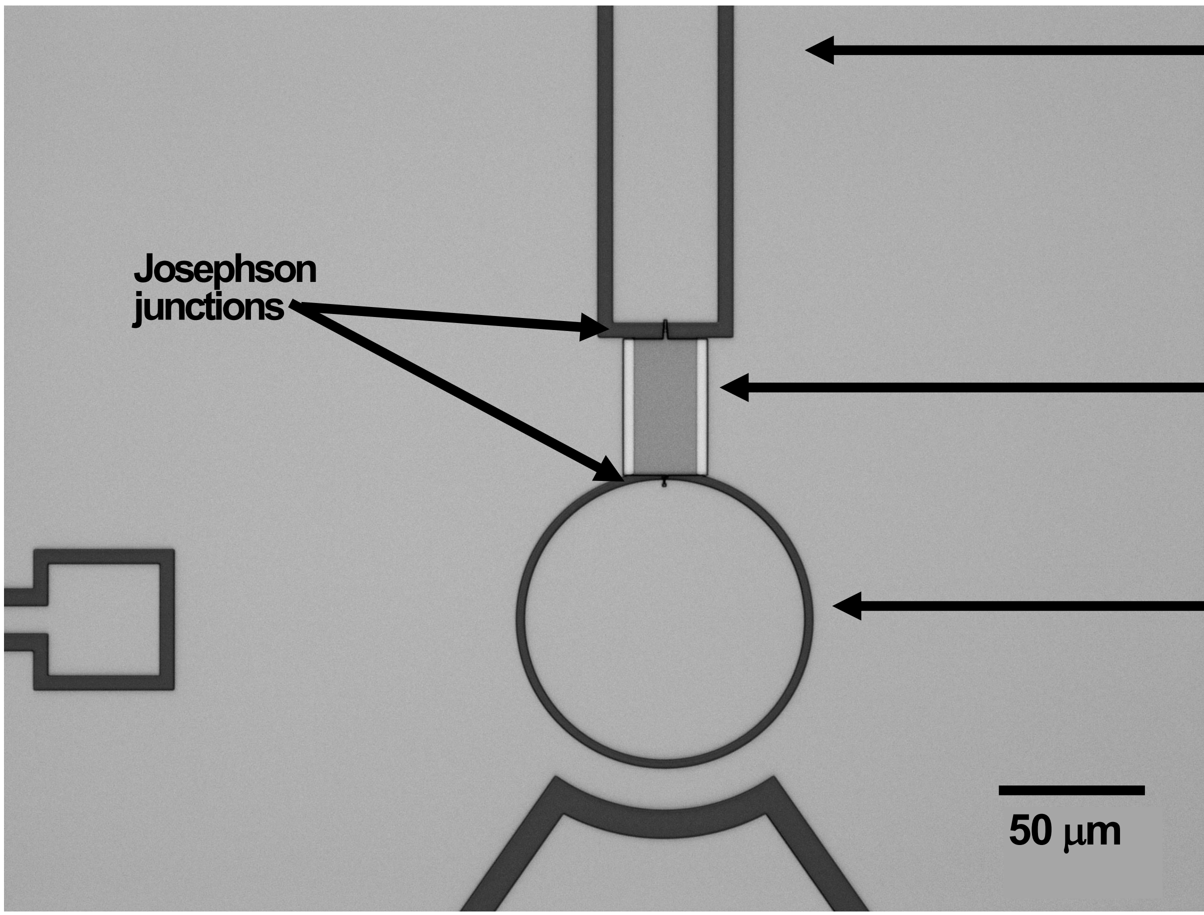




fine structure
from mutual
capacitance
to readout
resonator



Modular detector for axion search



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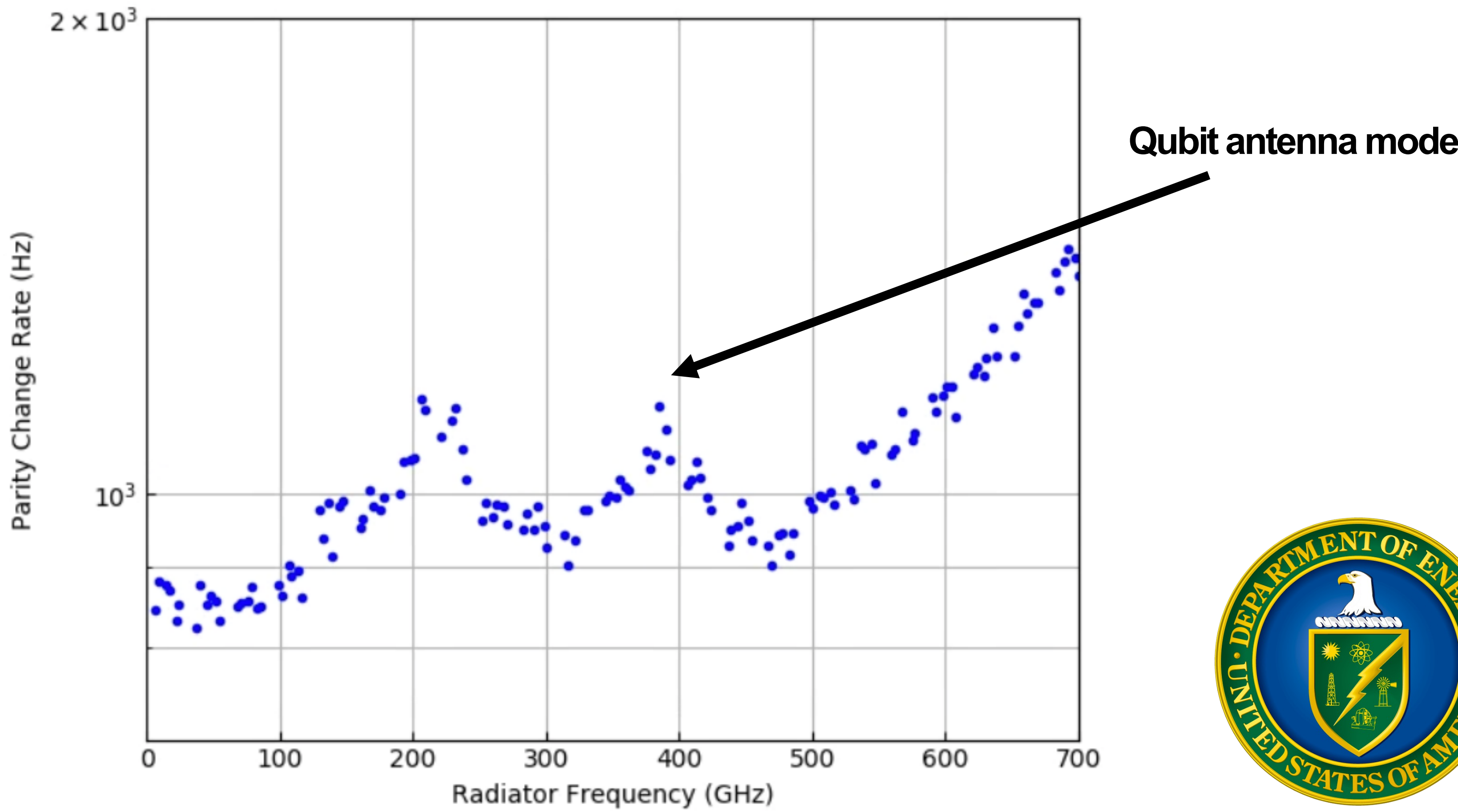

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F. Schlenker (Res. Sci.)
C. D. Wilen (GS)

Conclusion

- Particle impacts give rise to damaging correlated errors on length scales greater than 3 mm: relaxation errors must be mitigated
- Phonon downconversion yields dramatic suppression of correlated parity jumps
- Detailed understanding of photon-assisted QP poisoning
- New class of modular detectors for dark-matter searches