Correlated Charge Noise and Relaxation Errors In Superconducting Qubits

Joe Kitzman - 2/1/2021

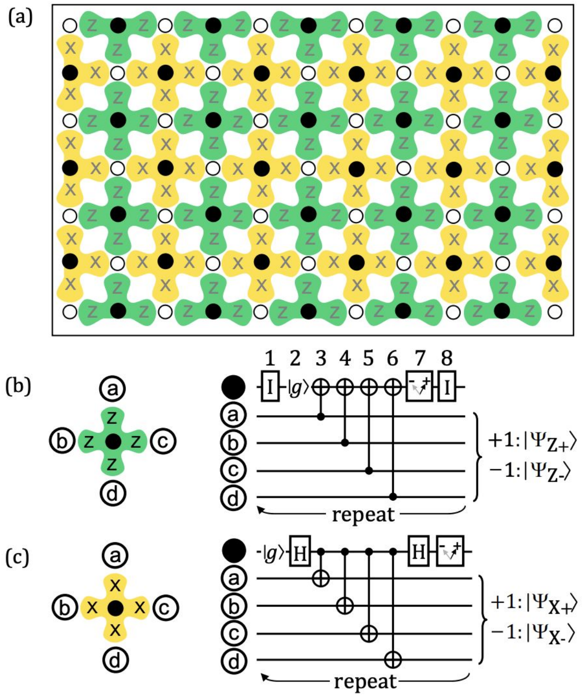
https://arxiv.org/abs/2012.06029
https://arxiv.org/abs/1905.13712

Overview

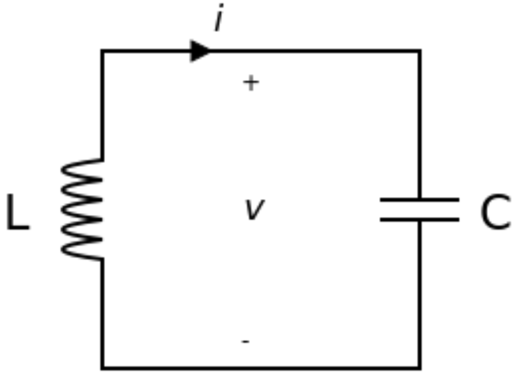
- Surface Code
- Introduction to superconducting qubits
- Offset Charge Sensitive (OCS) qubits
- Detecting charge events (paper)

Error Correction With Surface Code

- 2D array of qubits
- Only n.n. Interactions
- Measure errors (X & Z) via stabilizing qubits
- An error here is *localized*



Introduction to Quantum Circuits



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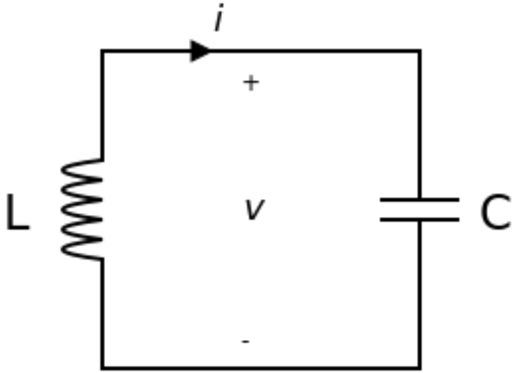

$$E = \frac{1}{2}LI^2 + \frac{1}{2}CV^2$$

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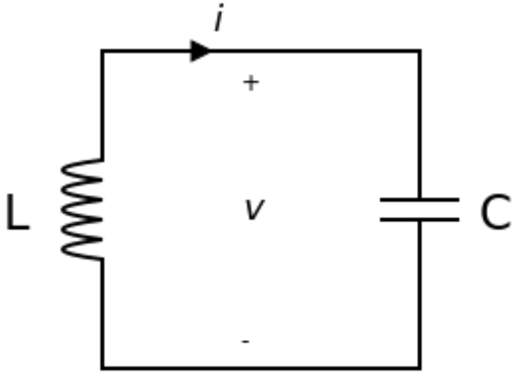

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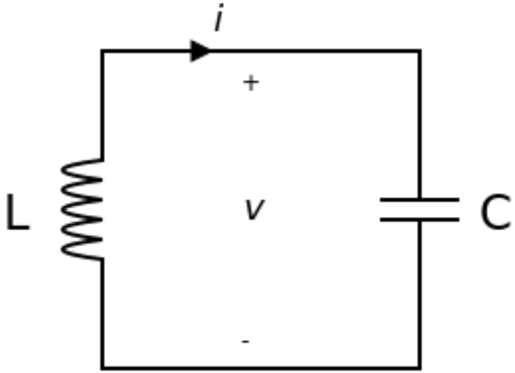

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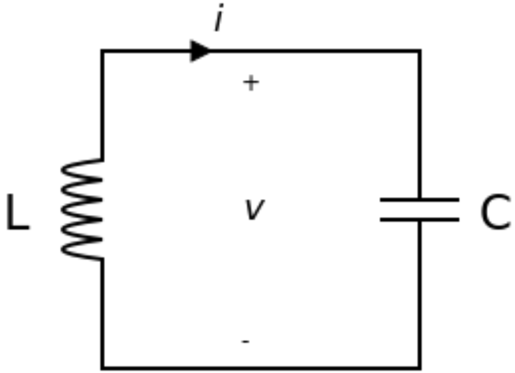

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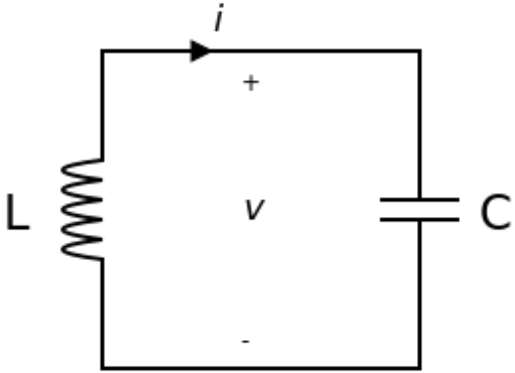

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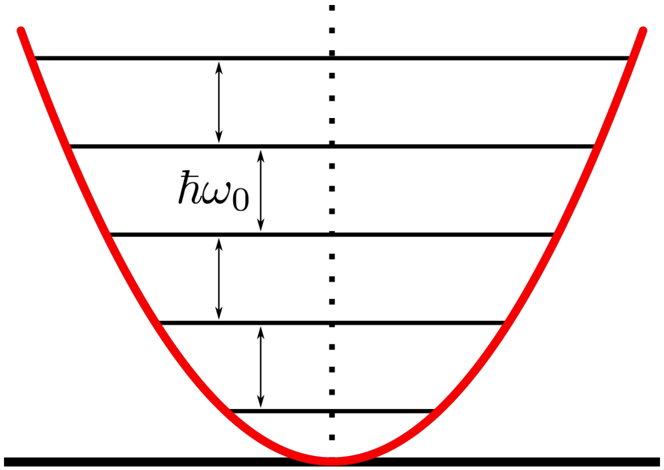
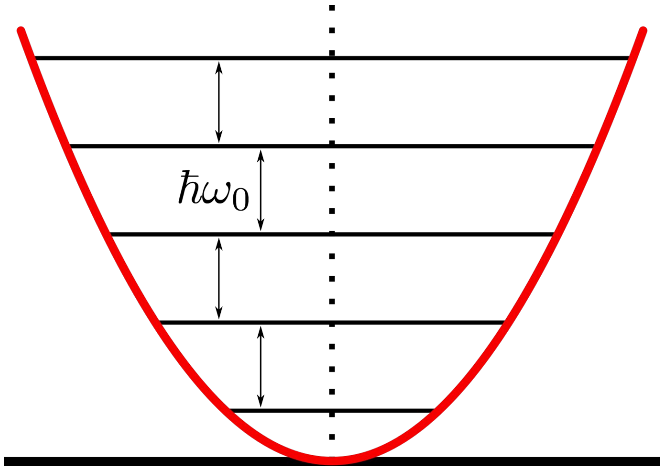


Introduction to Quantum Circuits

STOP

Why does this circuit make a bad qubit?

$$\hat{H} = \hbar\omega_0(\hat{a}^\dagger\hat{a} + 1/2)\ ,\ \omega_0 = (LC)^{-1/2}$$



Introduction to Quantum Circuits

We need some sort of non-linear circuit element!

Introduction to Quantum Circuits

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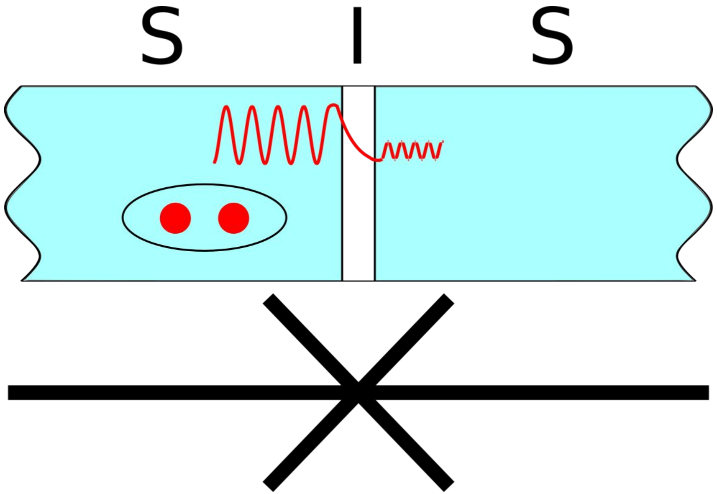
Fortunately, the **Josephson junction** is a superconducting, non-linear circuit element



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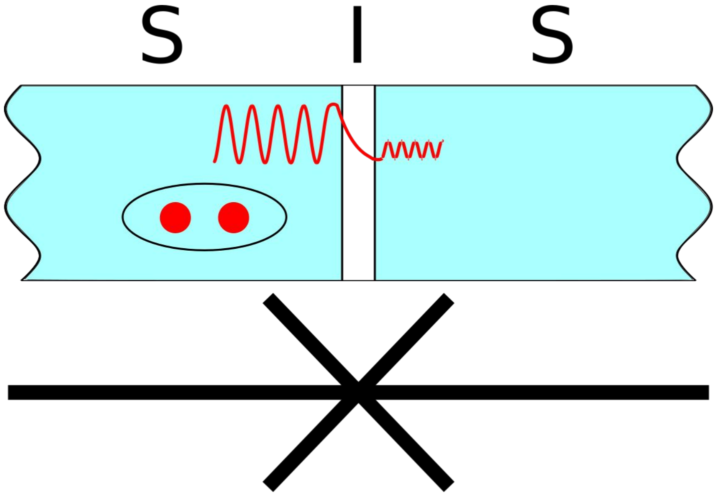


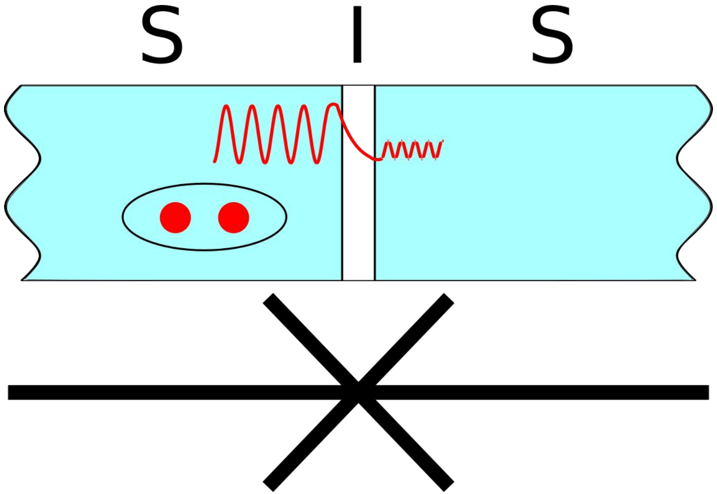
$$I = I_c \sin\varphi$$

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

I_C = critical current of the Junction

Φ_0 = superconducting flux quantum = h/2e

Introduction to Quantum Circuits



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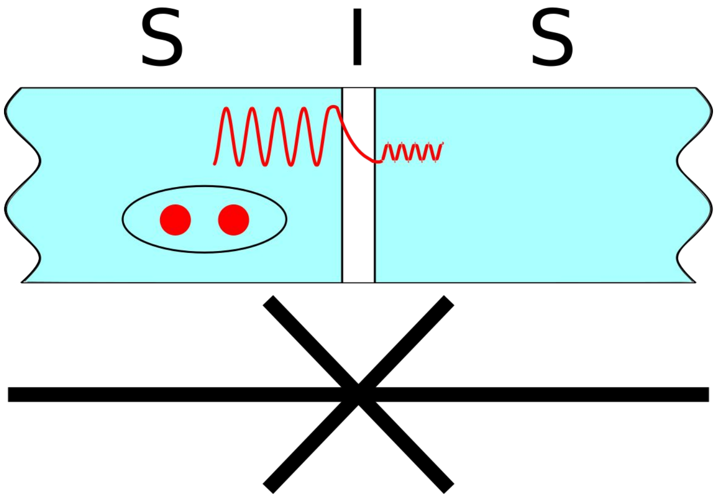
Introduction to Quantum Circuits

$$L_J = \frac{\Phi_0}{2\pi\sqrt{{I_0}^2 - I^2}}$$

Josephson junction acts like a
non-linear inductor



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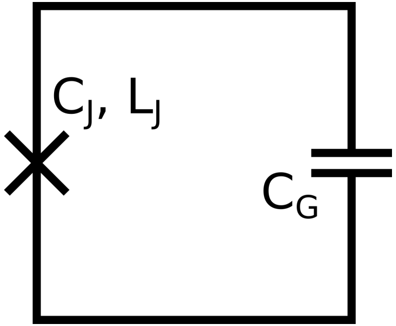
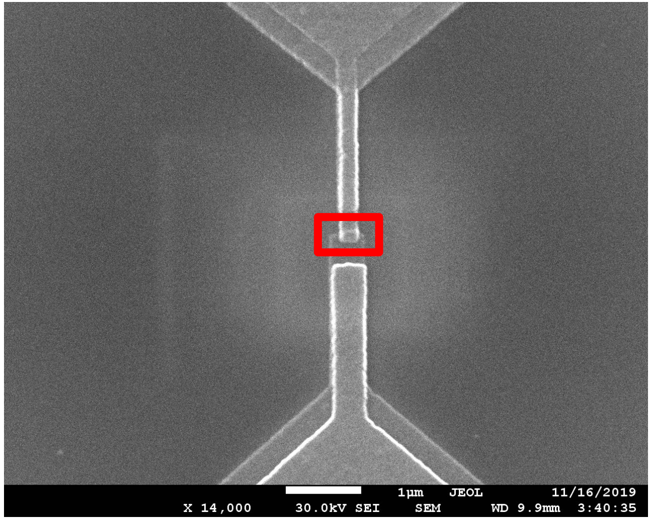


$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J \cos\hat{\varphi}$$

$$E_C = e^2/2C_\Sigma, C_\Sigma = C_J + C_G$$

$$E_J = \frac{\hbar I_c}{2e}$$



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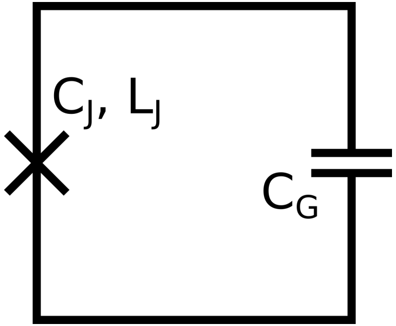

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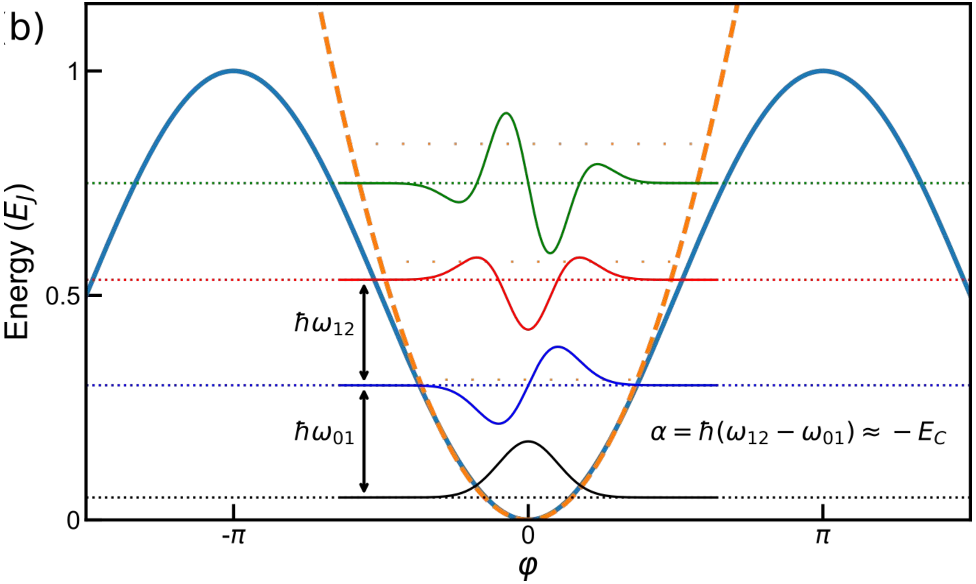
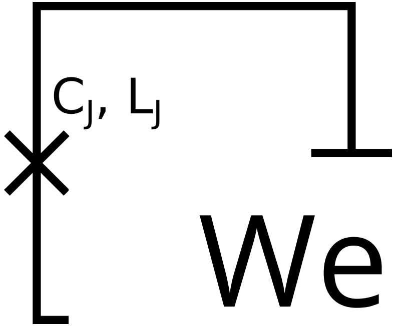


Introduction to Quantum Circuits



We did it!

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

$$E_C = e^2/2C_\Sigma, C_\Sigma = C_J + C_G$$

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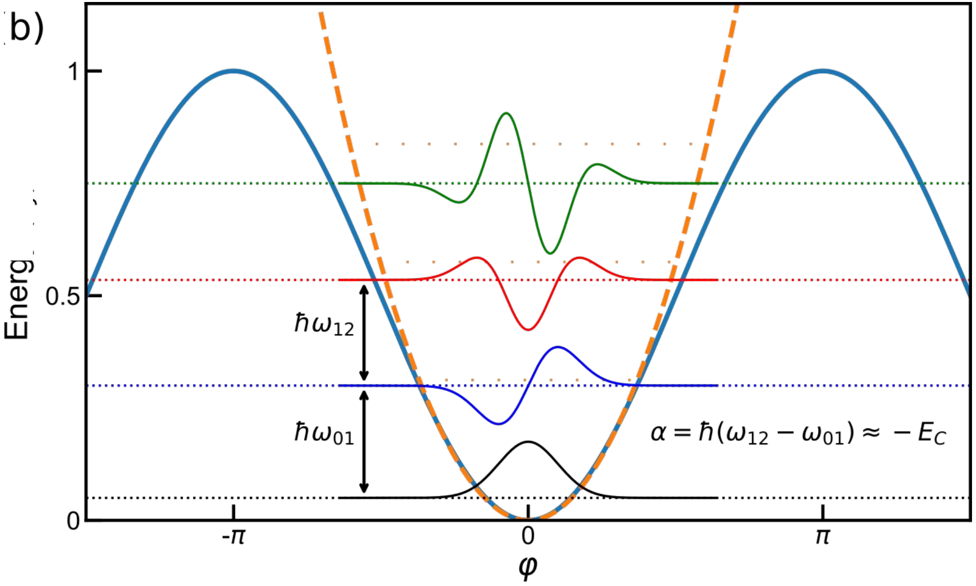
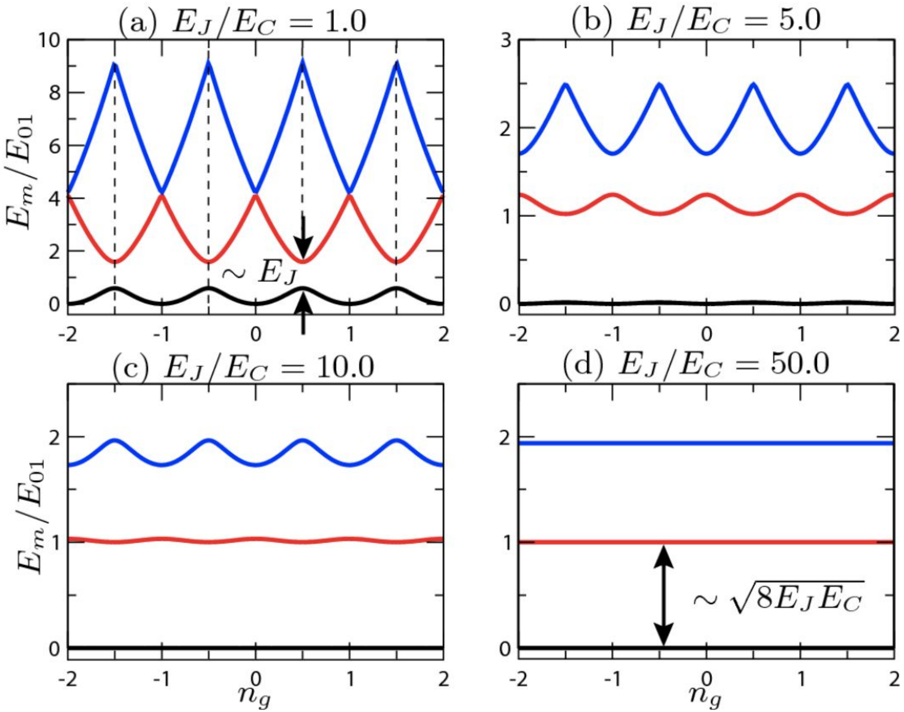


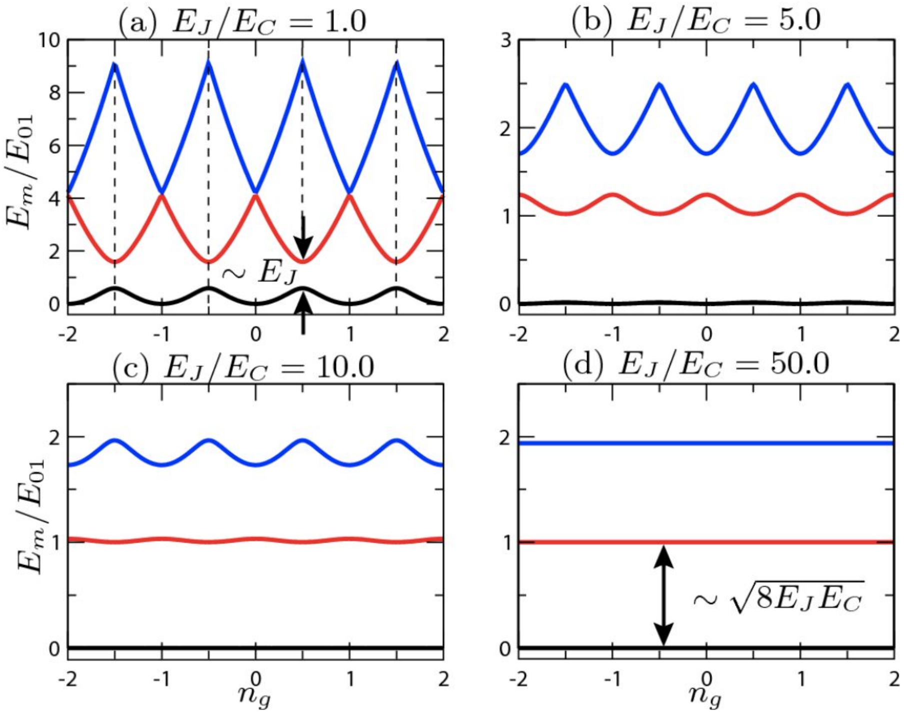
Introduction to Quantum Circuits: the Transmon



What if we wanted to use the qubit as a **charge sensor**??

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

Introduction to Quantum Circuits: the Transmon



What if we wanted to use the qubit as a **charge sensor**??

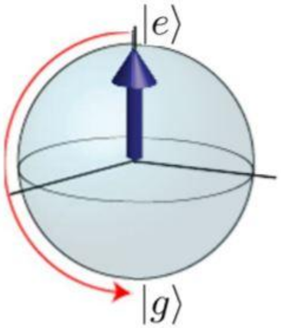
Small deviations from the transmon limit make the qubit frequency a slowly varying function of offset charge (Ej/Ec ~ 25)

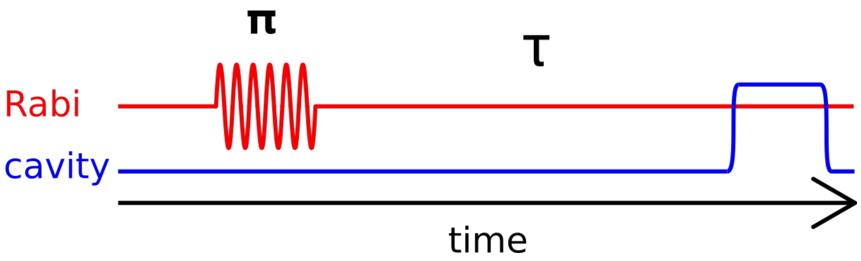
$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J \cos\hat{\varphi}$$

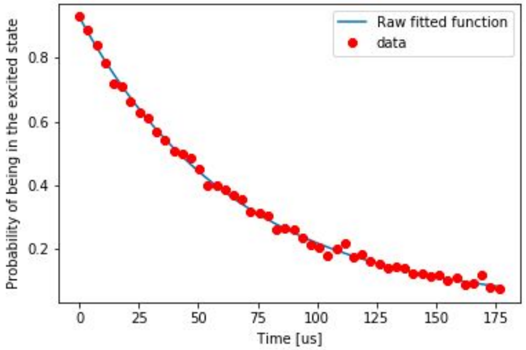
Qubit Energy Relaxation

- Fermi's Golden Rule: $P_e \sim e^{-\frac{t}{\tau}}$

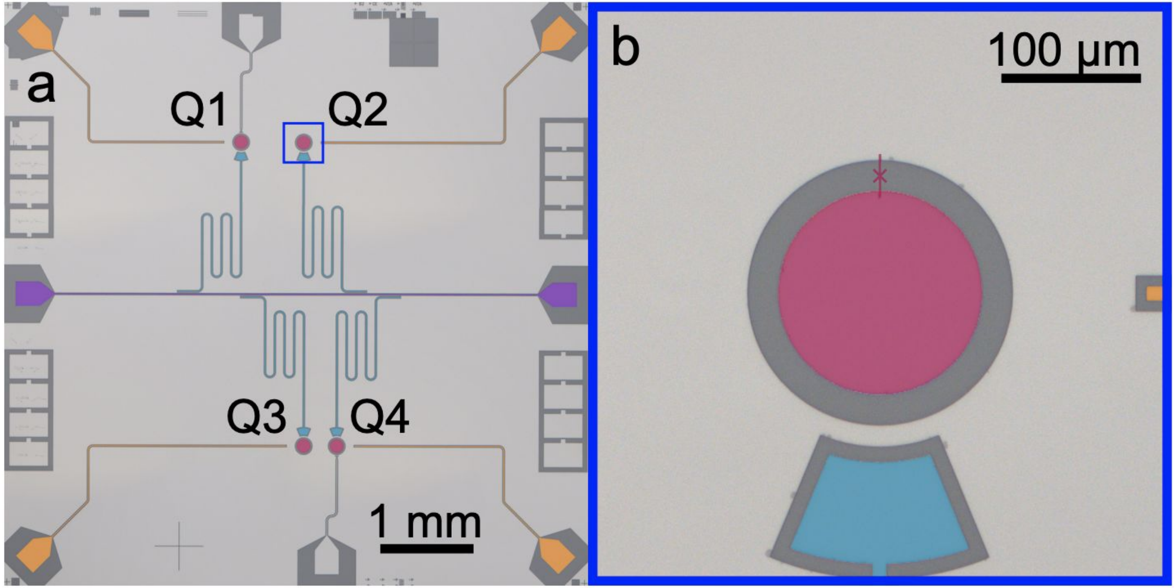
  Microwave pulse sequence to measure:







Offset Charge Sensitive Transmon



Transmon - junction and capacitive shunt

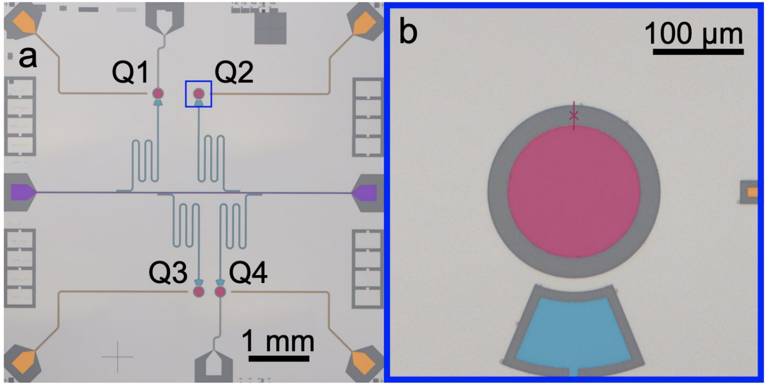
Capacitively coupled 2D resonator

Local charge gate line

Common feedline

Offset Charge Sensitive Transmon

- Spatial separation is relevant here!
  - Q34 ~ 340um
  - Q12 ~ 640um
  - Q24 ~ 3000um
- Reference - Sycamore
  - 53 functional qubits on 1cm x 1cm chip
- Charge correlations?

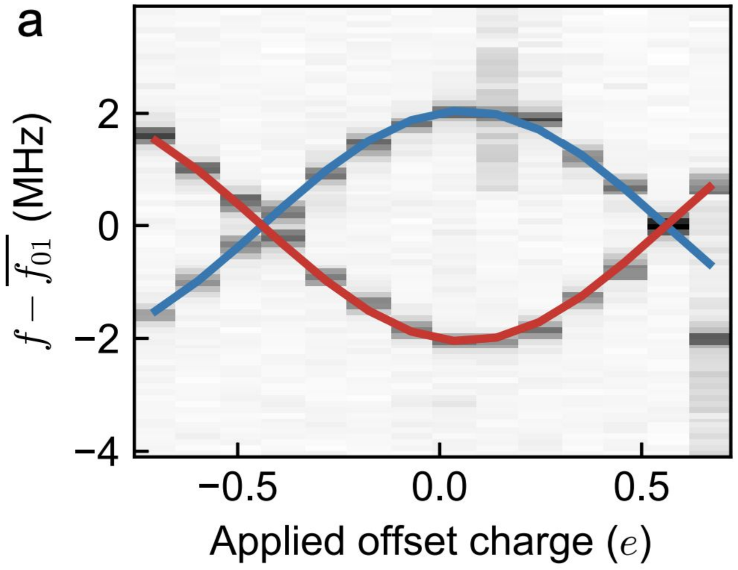


Qubits as a Charge Sensor

- Single quasiparticle tunneling produces two parity bands

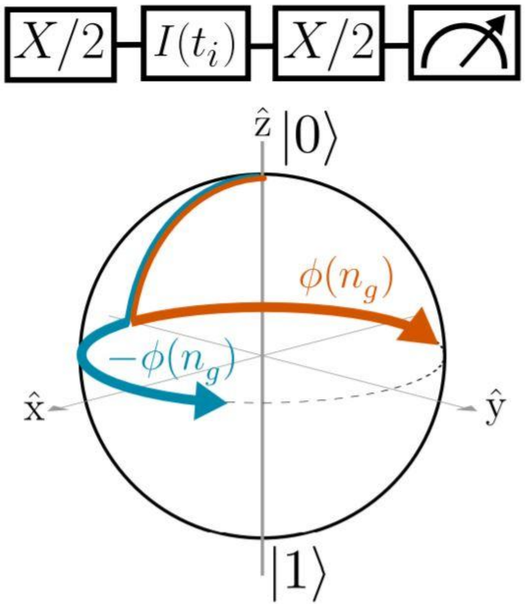
$$\omega_{10}(n_g) = \overline{\omega_{10}} + \Delta\omega_{10}\cos(2\pi n_g)$$

$$\frac{\Delta\omega_{10}}{2\pi} \approx 2\mathrm{MHz}$$



Mapping of Environmental Charge

b

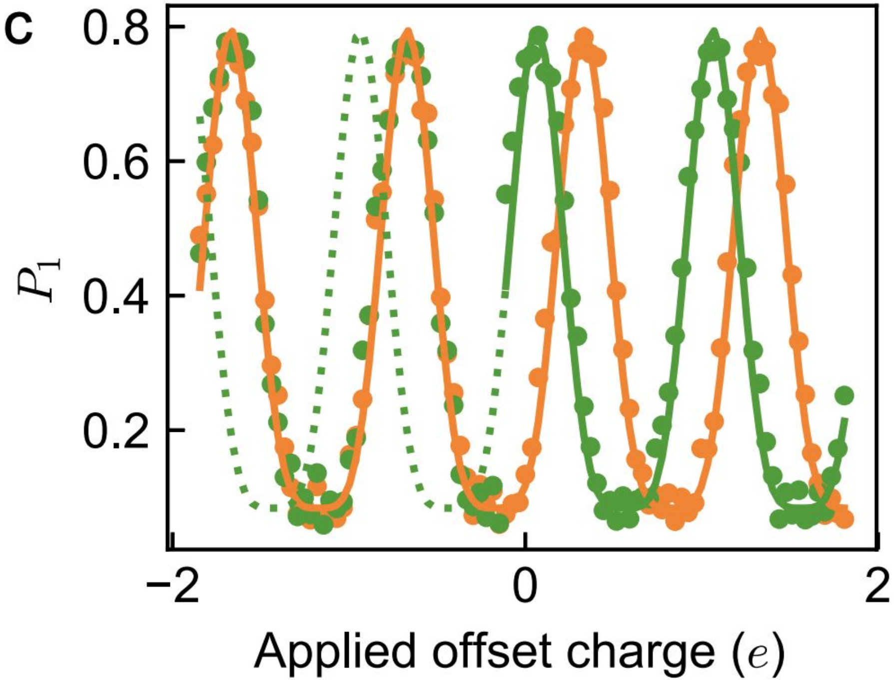


$$\phi(n_g) = t_{idle}\,\Delta\omega_{10}\cos(2\pi n_g)$$

$$P_1 = \frac{1}{2}\left(d + \nu \cdot \cos\left(\pi \cos 2\pi n_g\right)\right)$$

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

Mapping of Environmental Charge



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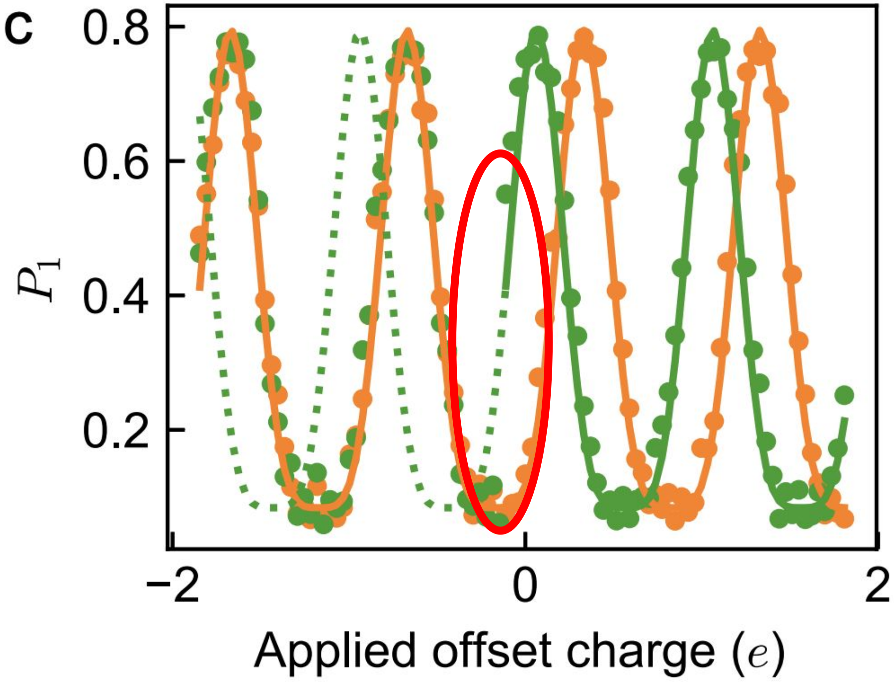
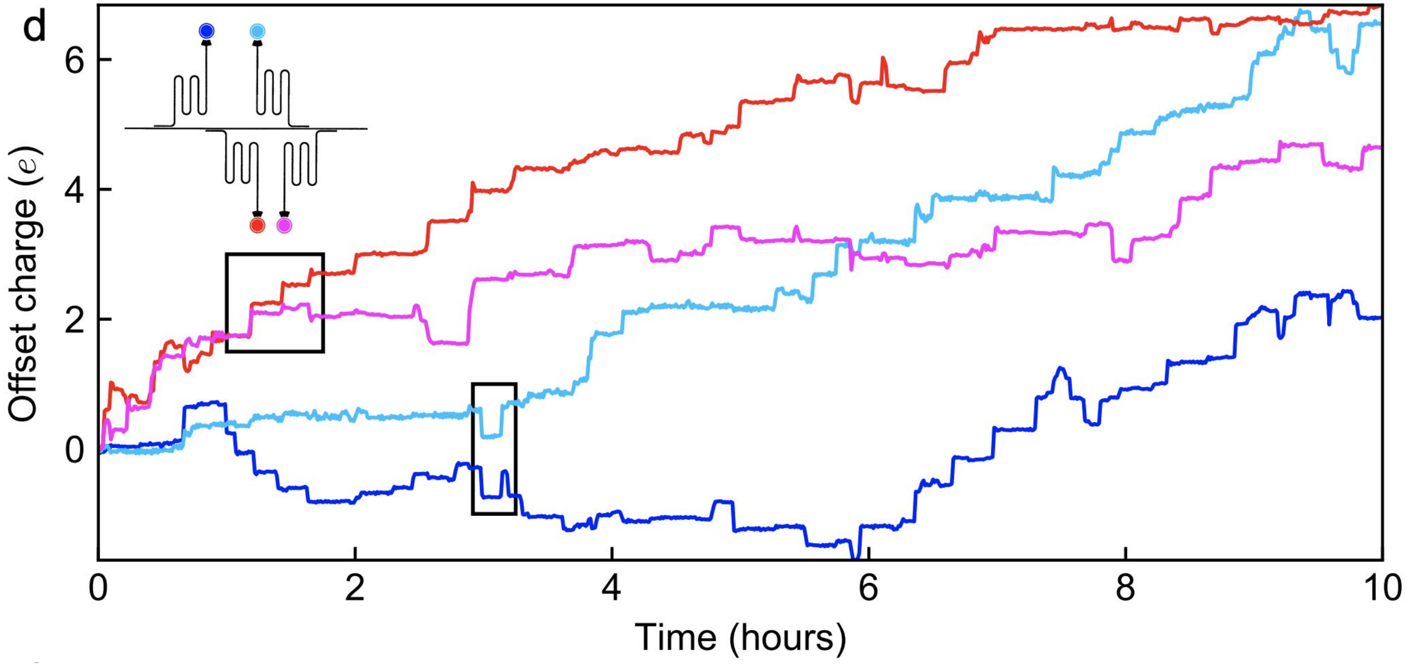


Discrete jump in offset charge!

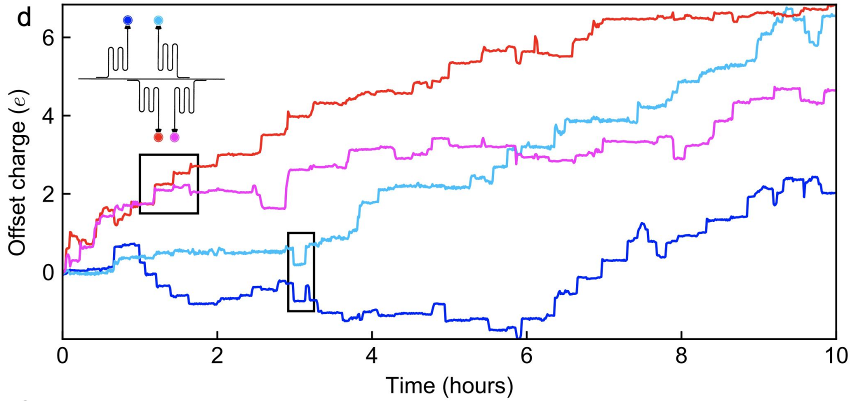
Time Evolution of Offset Charge

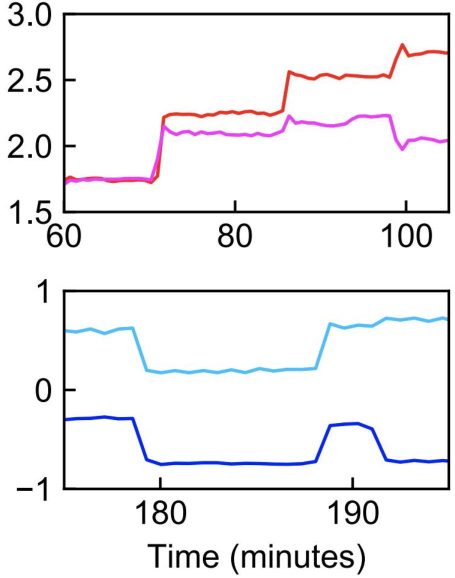
- 3000 Ramsey measurements
  - 10 different gate voltages
  - Cycle time - 44s
- “Large” charge jumps ~ $0.1e < |q| < 0.5e$

Time Evolution of Offset Charge



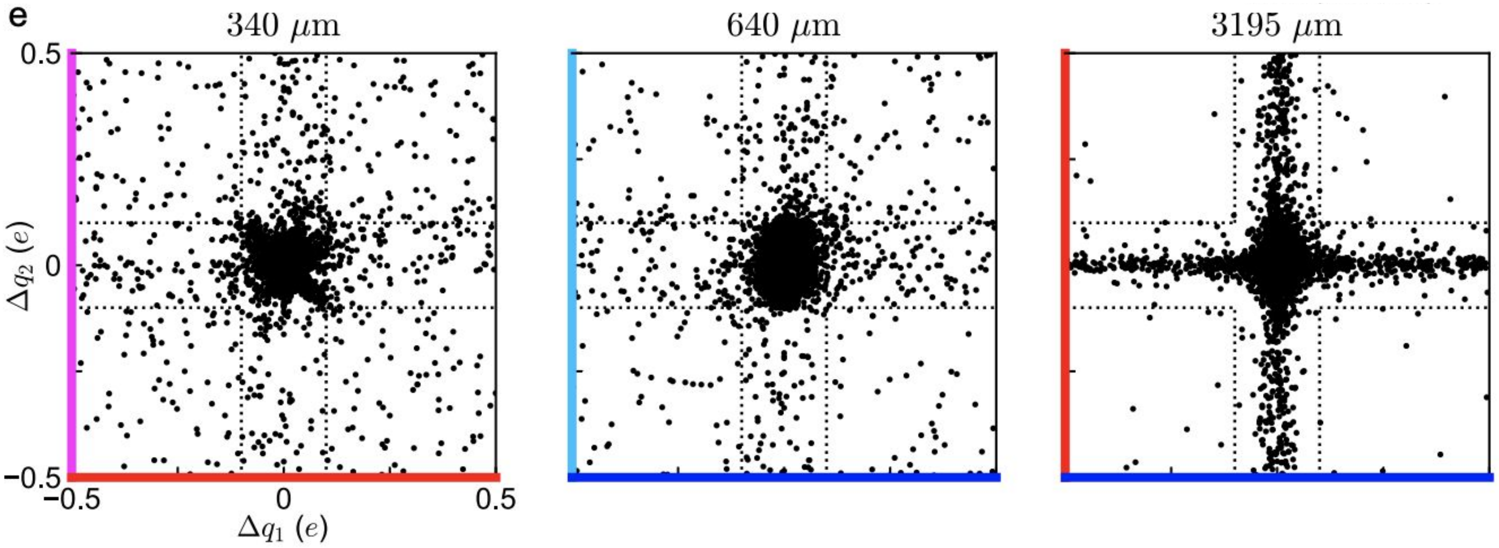
Time Evolution of Offset Charge





T_{jump} ~ 10 min

Correlations in Charge Jumps



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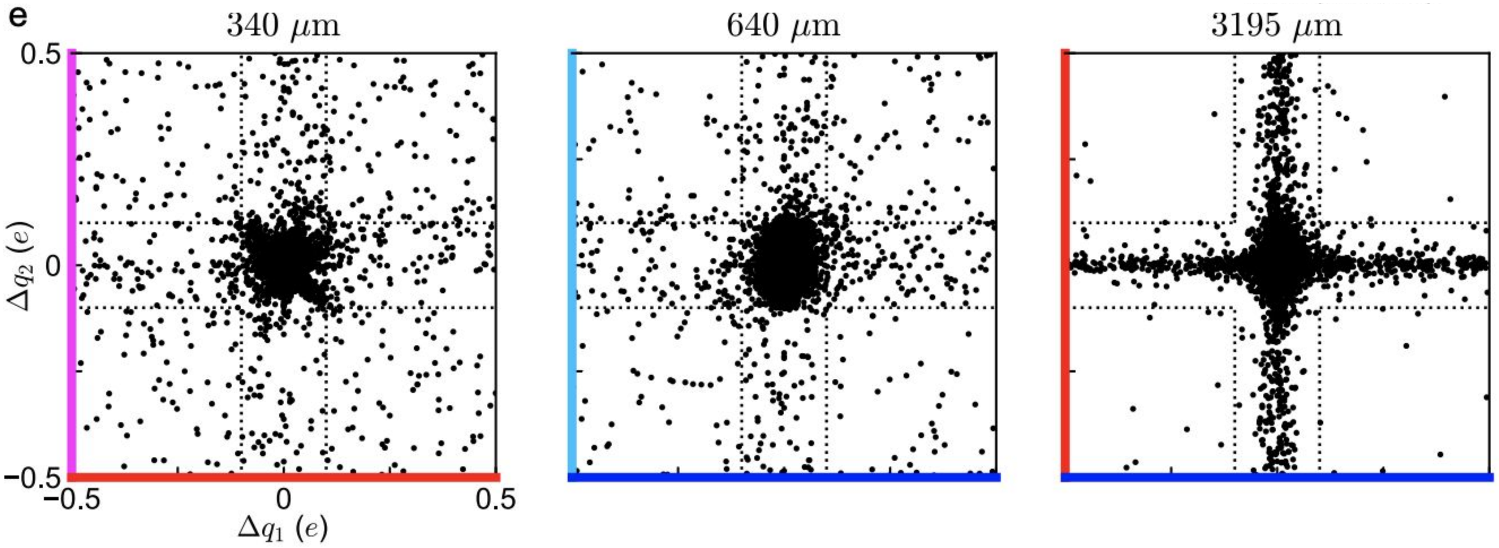


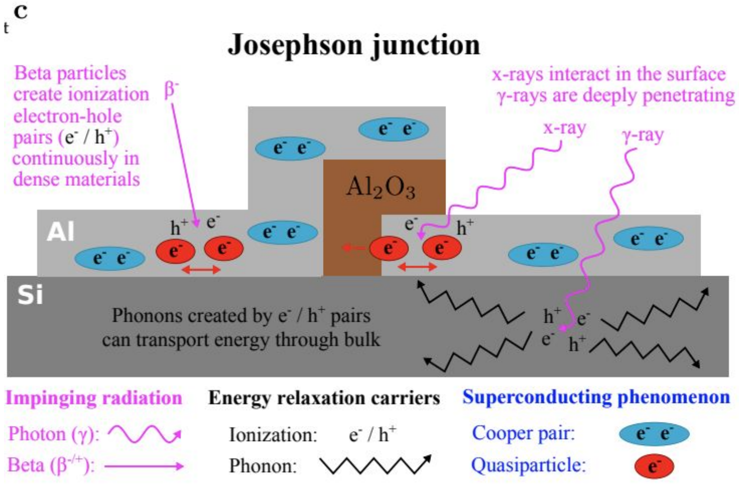
Correlation probabilities: Q34 ~ 54%, Q12, 46%

What Causes Large Charge Jumps?

- Two primary sources (see text for details):
  - ɣ - rays from background radioactivity (40x more likely)
  - Cosmic ray muons
- Worst case scenario:
  - ɣ - rays -> “?” -> (possibly long range) qubit decoherence

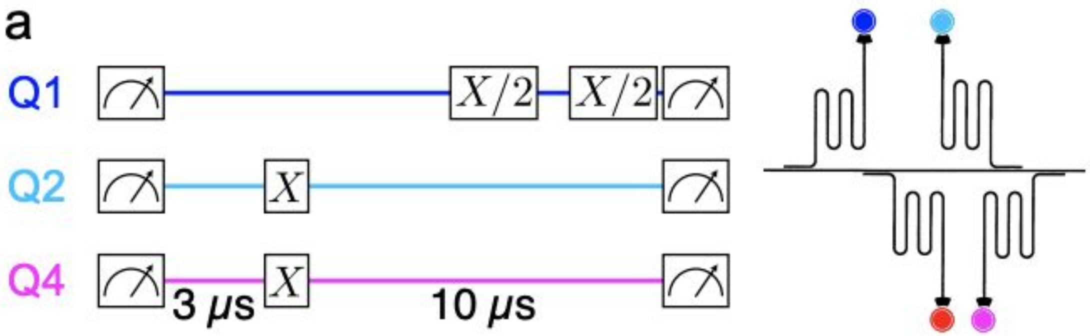
What Causes Large Charge Jumps?

- Energy from charge events is stored in phonon bath of the substrate
- Phonons break Cooper pairs (generating non-equilibrium quasiparticles)
- Non-equilibrium quasiparticles enhance qubit decay
- Timescale ~ 100us



Can We See Enhanced Qubit Decay?

- Q1 “trigger” qubit - measure offset charge (Ramsey sequence)
- Q2 & Q4 - spatially localized T1 probes



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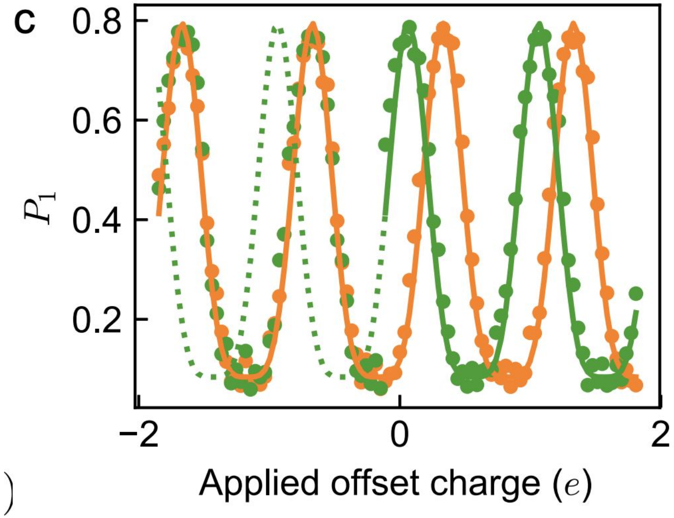

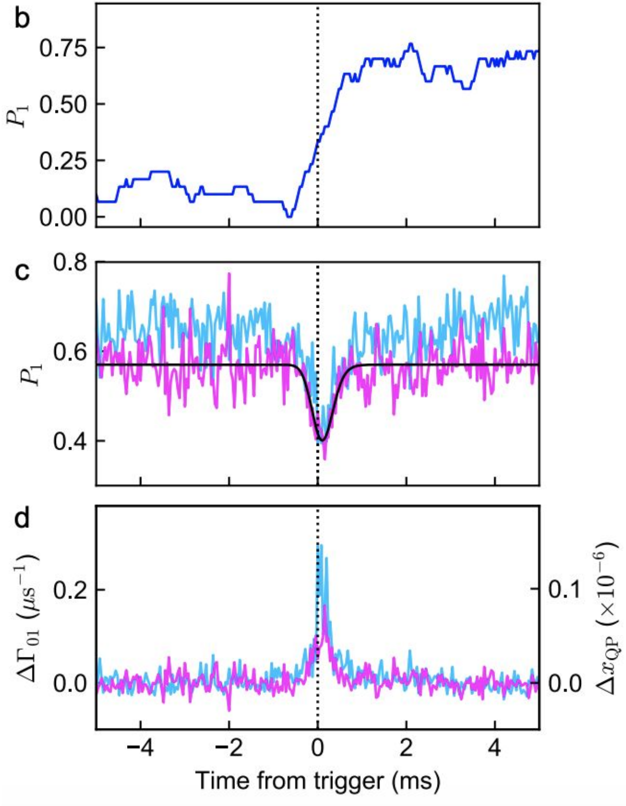

$T_{recovery}$ ~ 130 us

Matches phonon estimate!

Recap

- We learned (hopefully) about superconducting qubits
- Qubits - more than just qubits
- Charge diffusion in the substrates of quantum processors - a real problem!