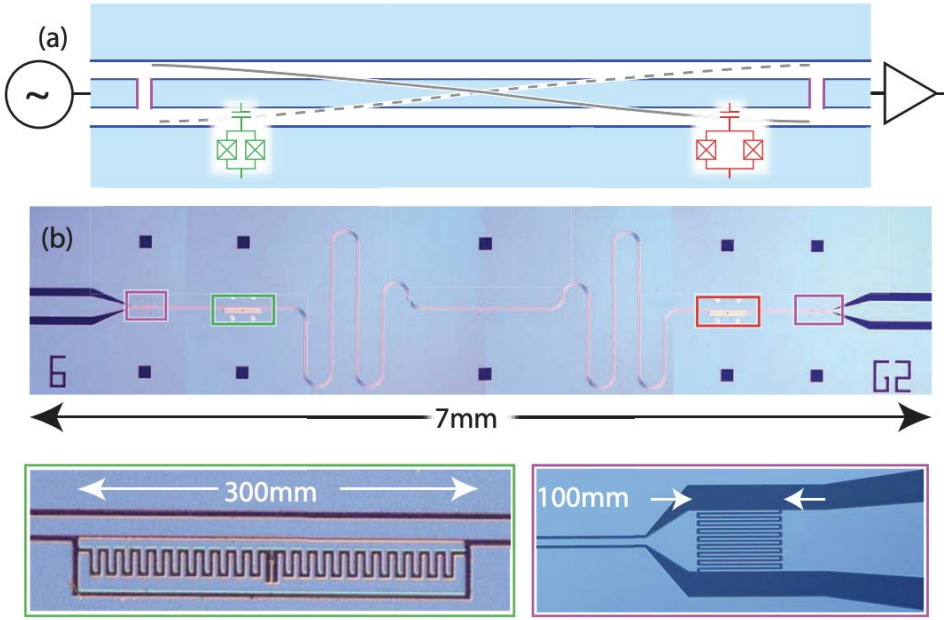
Quantum communication with itinerant surface acoustic wave phonons

Joe Kitzman
Quic- 2/15/2022

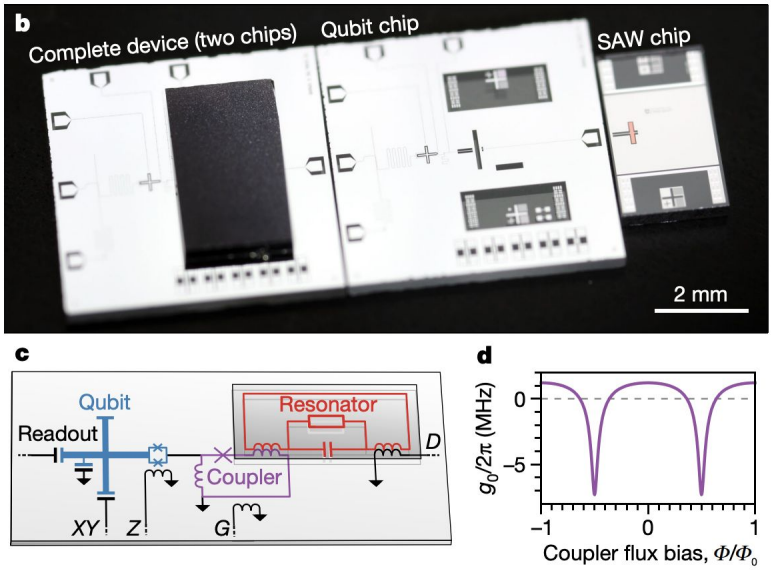
Traditional Two Qubit Entanglement



$$H_{\text{eff}} = \frac{\hbar\omega^{(1)}}{2}\sigma_z^{(1)} + \frac{\hbar\omega^{(2)}}{2}\sigma_z^{(2)} + \hbar\left(\omega_C + \chi^{(1)}\sigma_z^{(1)} + \chi^{(2)}\sigma_z^{(2)}\right)a^\dagger a + \hbar J\left(\sigma_-^{(1)}\sigma_+^{(2)} + \sigma_-^{(2)}\sigma_+^{(1)}\right).$$

Why Use Acoustics?

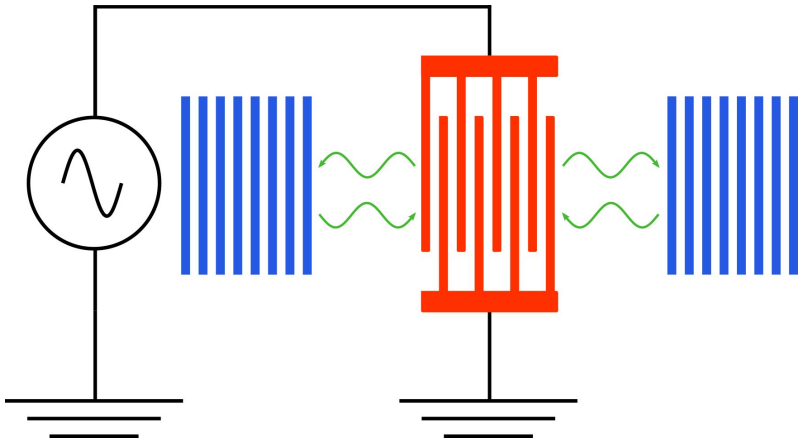
- Separation of scale of signals!
- Engineer large couplings
- Small spatial footprint
- Classically understood very well!

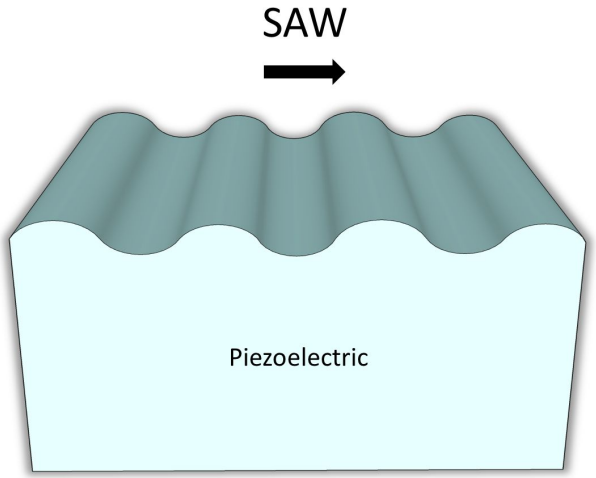


Surface Acoustic Waves (SAWs)

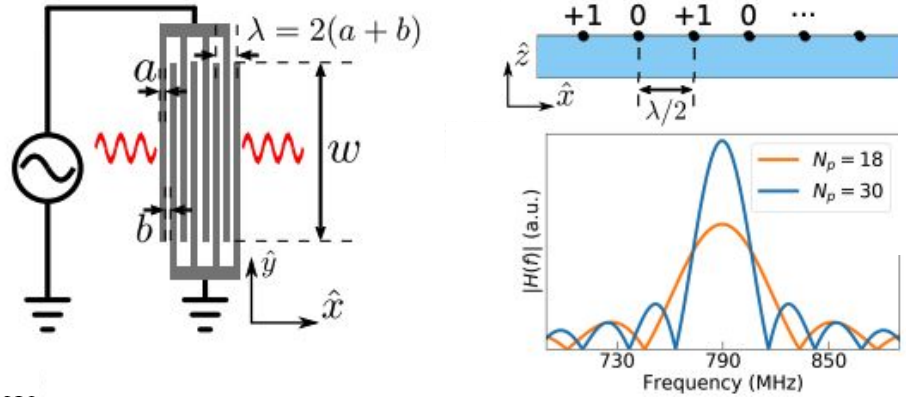
- SAW: elastic wave propagating on a surface
- Piezoelectric substrate: **co-propagating electric field**

v = 4000 m/s
f = 4GHz
λ = 1 μm





Modeling of a SAW Device



Model finger structures as delta functions

Transfer function:

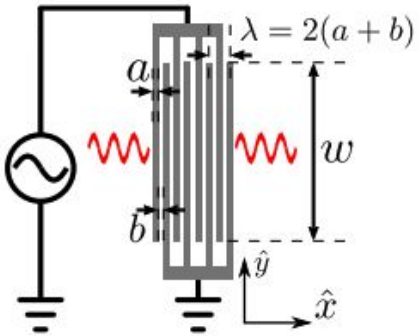
$$H(f) \approx N_p \left| \frac{\sin\left(N_p \pi (f - f_0)/f_0\right)}{N_p \pi (f - f_0)/f_0} \right|$$

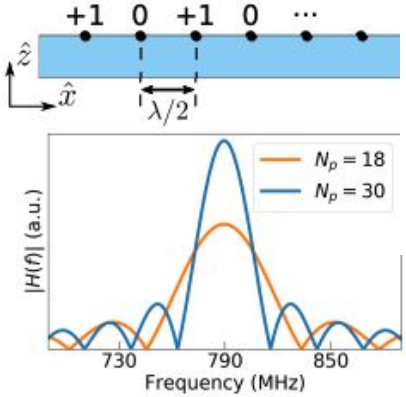
N_p - number of finger pairs
f_0 - center frequency

Frequency response depends on number of finger pairs and center frequency

J.R. Lane (2021). Integrating Superconducting Qubits With Quantum Fluids and Surface Acoustic Wave Devices

Modeling of a SAW Device





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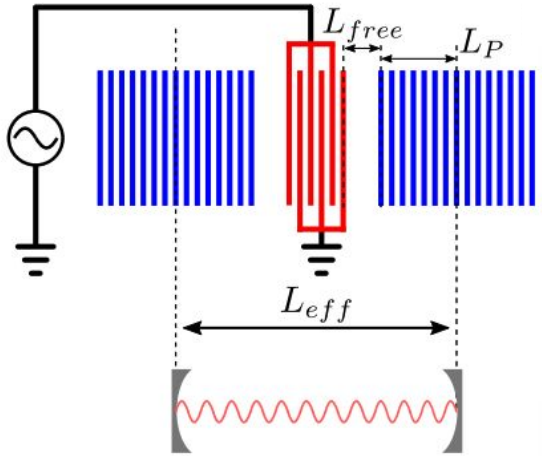
Here we have totally ignored any reflections

J.R. Lane (2021). Integrating Superconducting Qubits With Quantum Fluids and Surface Acoustic Wave Devices

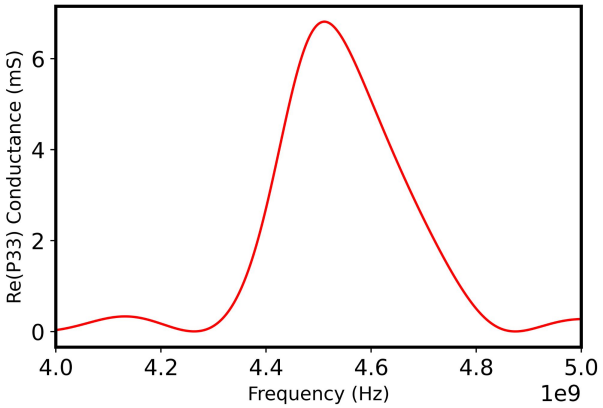
Modeling of a SAW Device

- Resonant structures require reflections
- Describe the dynamics of SAWs via the *P-matrix*
- Allows us to cascade independent elements into a single structure

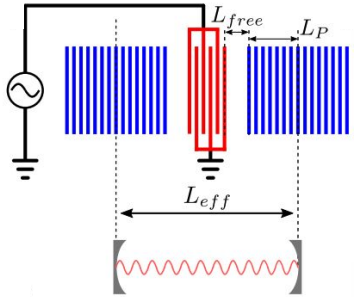


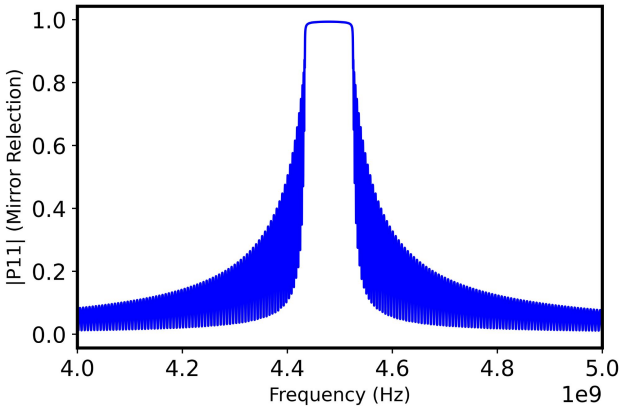
$$\begin{pmatrix} A_{L,out} \\ A_{R,out} \\ I \end{pmatrix} = \begin{pmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{pmatrix} \begin{pmatrix} A_{L,in} \\ A_{R,in} \\ V \end{pmatrix}$$

Model of a SAW Resonator



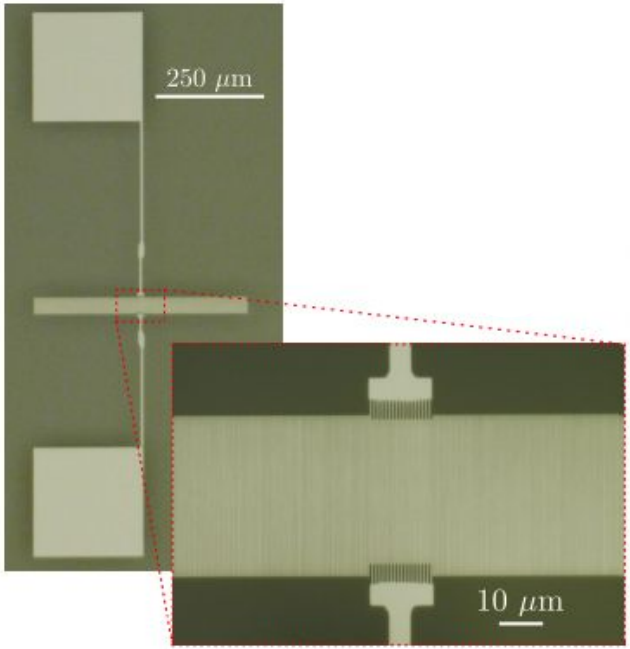
IDT Response

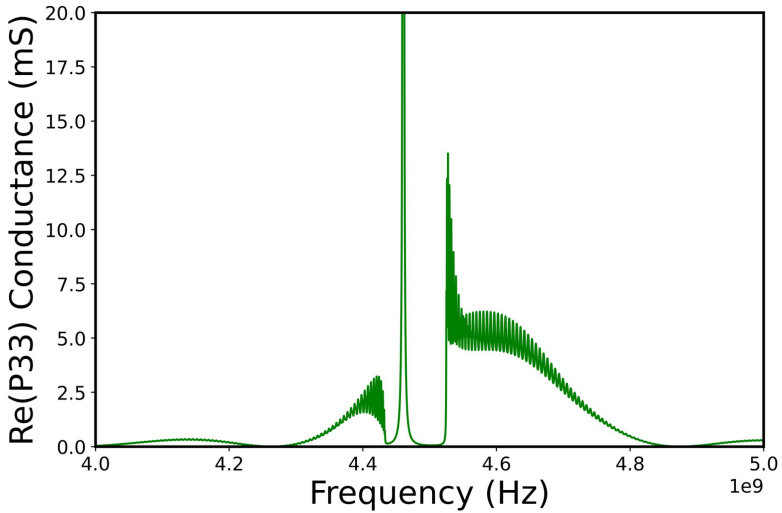




Mirror Reflectivity

Model of a SAW Resonator



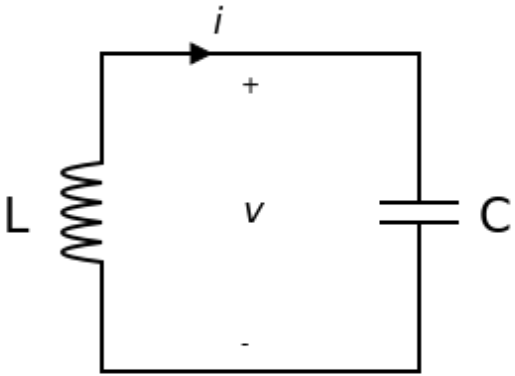


Resonator Response

Superconducting qubits: a brief intro

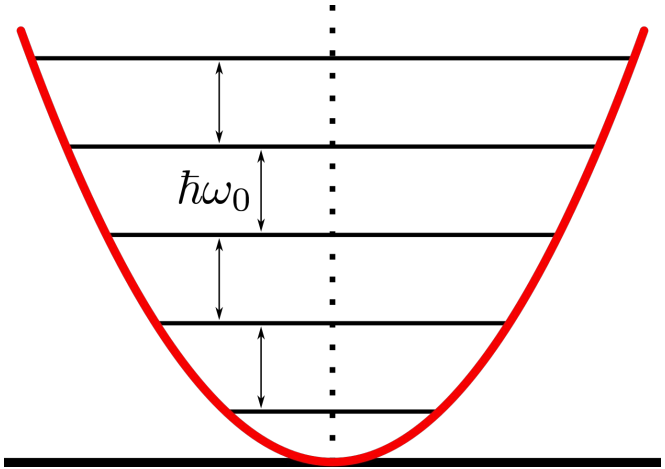
How do we make a coherent quantum system from a circuit?

Well resolved energy levels → narrow linewidth → low loss → **superconductors**



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

$$\omega_0 = (LC)^{-1/2}$$



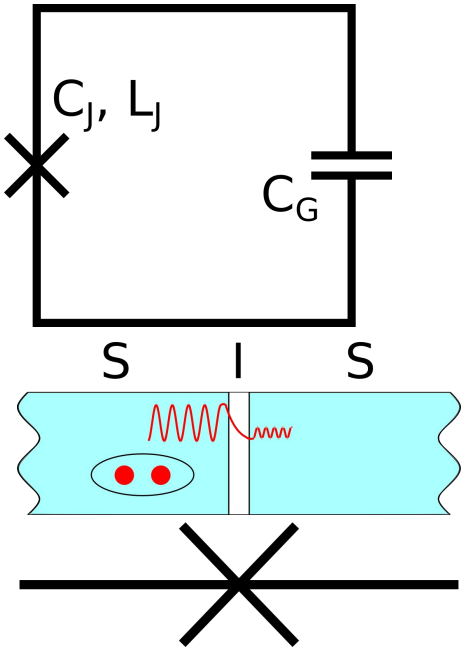
$$\hbar\omega_0 \ll 2\Delta$$

$$\omega_0/2\pi \approx 5 - 10 \text{ GHz}$$

$$\hbar\omega_0 \gg k_b T \approx 250 - 500 \text{ mK}$$

Superconducting qubits: a brief intro

Introduce anharmonicity via a **Josephson junction**



Acts as a nonlinear inductor!

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

Quantum numbers: Cooper pair number and phase

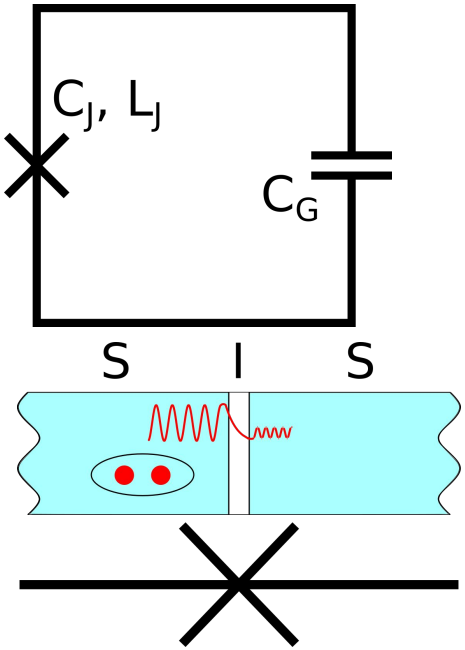
$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J \cos\hat{\phi}$$

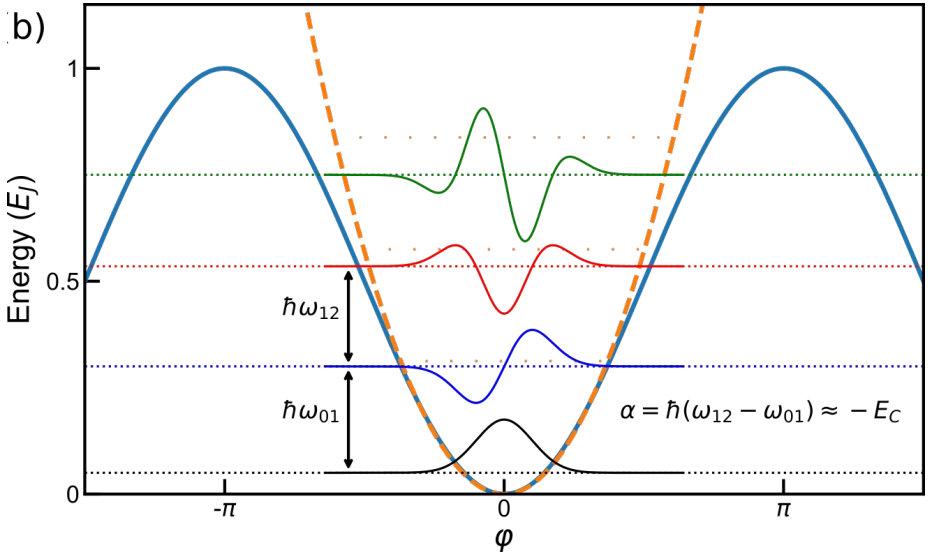
Charging and Josephson energies set by fabrication

$$E_C = e^2/2C_\Sigma, E_J = \hbar I_0/2e$$

Superconducting qubits: a brief intro

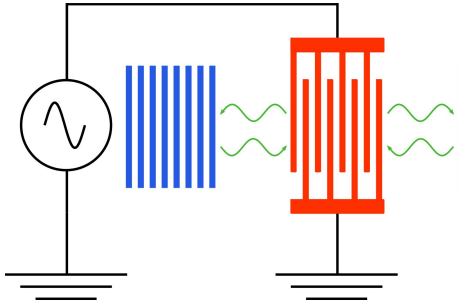
Introduce anharmonicity via a **Josephson junction**

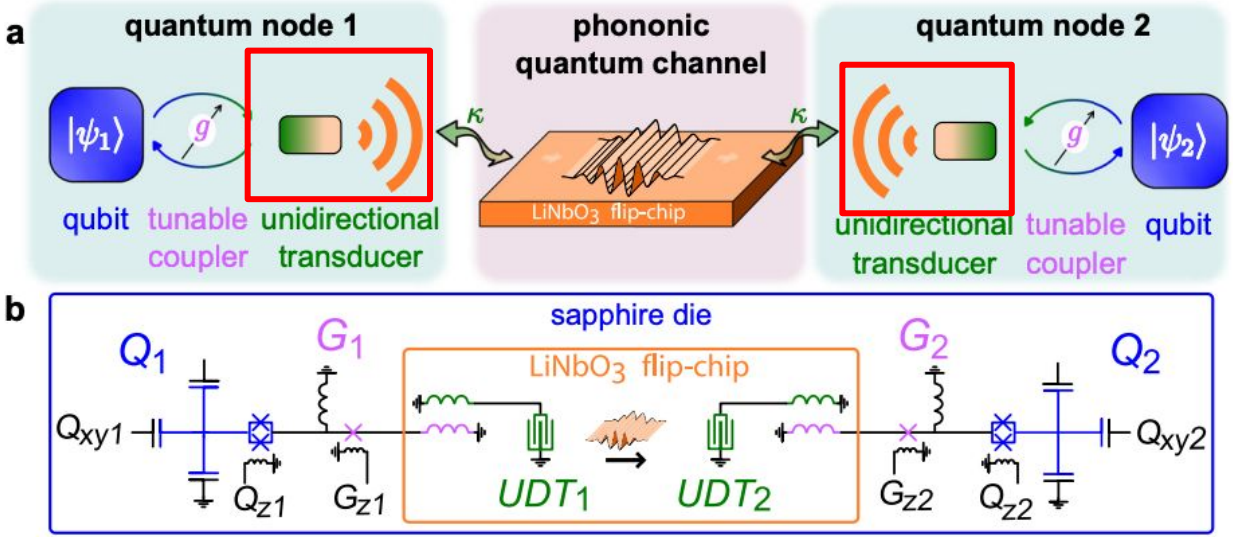




$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J \cos\hat{\phi}$$

Goal of our Experiments

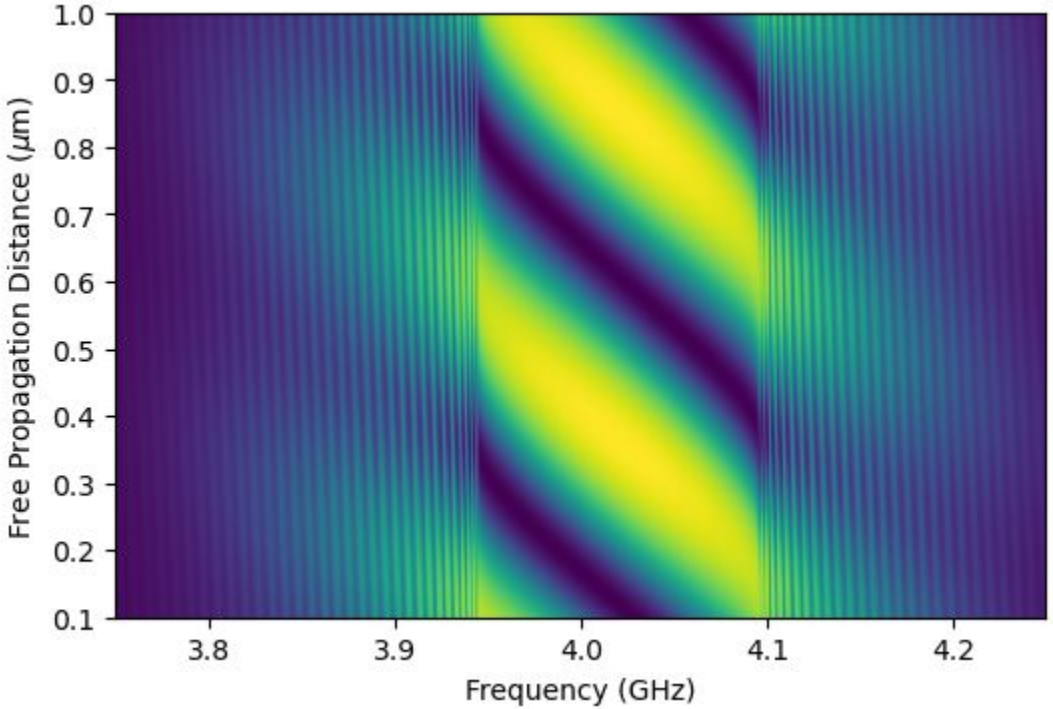




Time of flight ~500ns

Equivalent to 100m cable!

A Small Amount of COM- UDT *and* IDT



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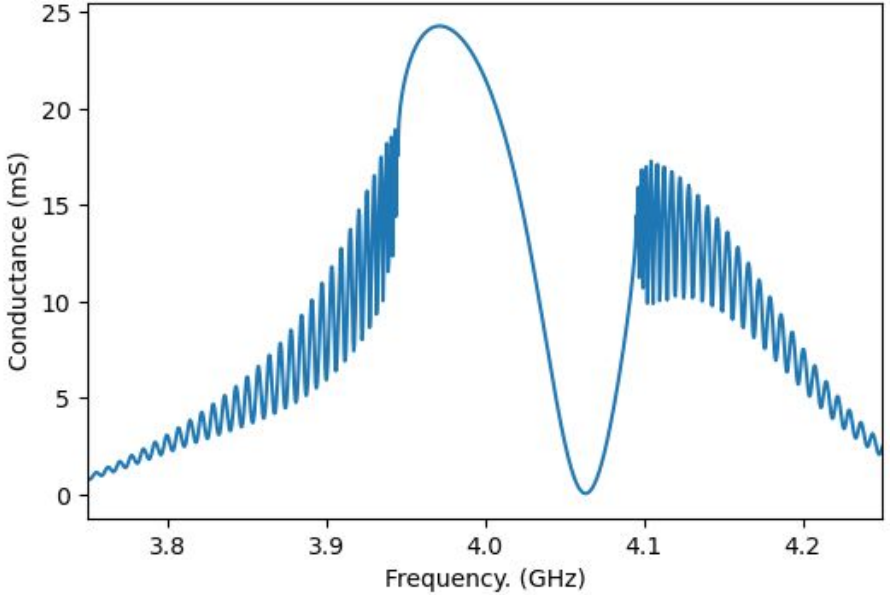
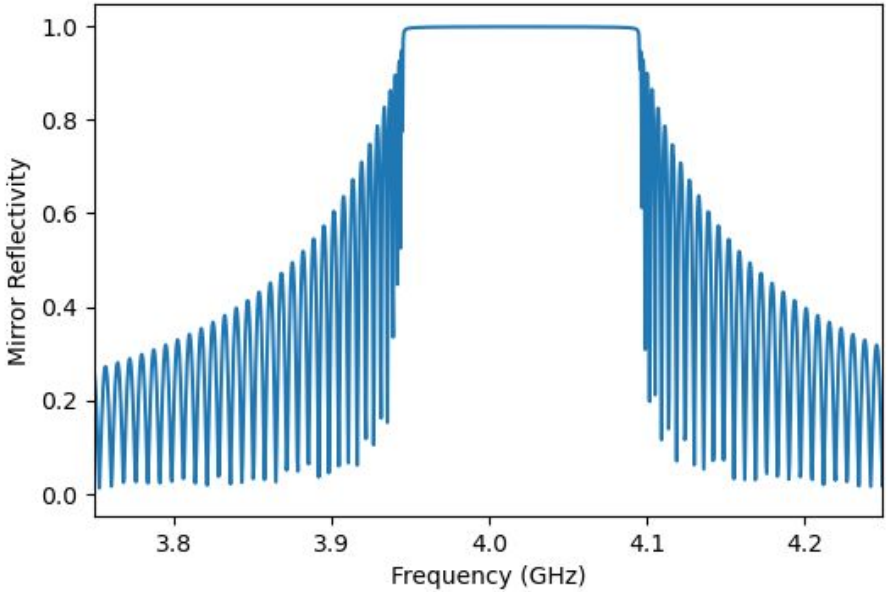
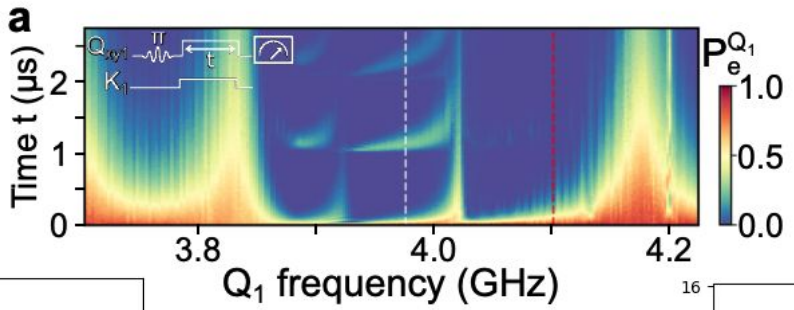
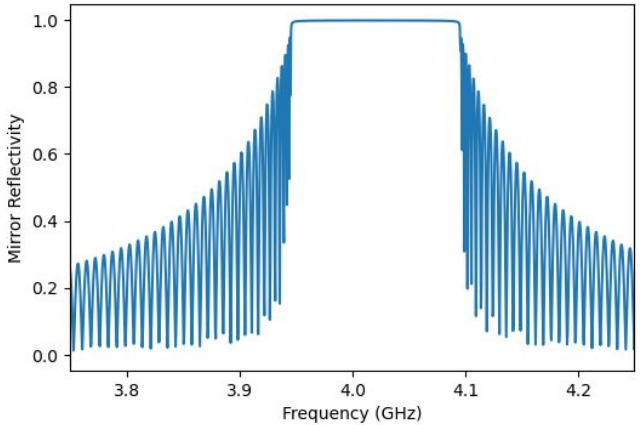
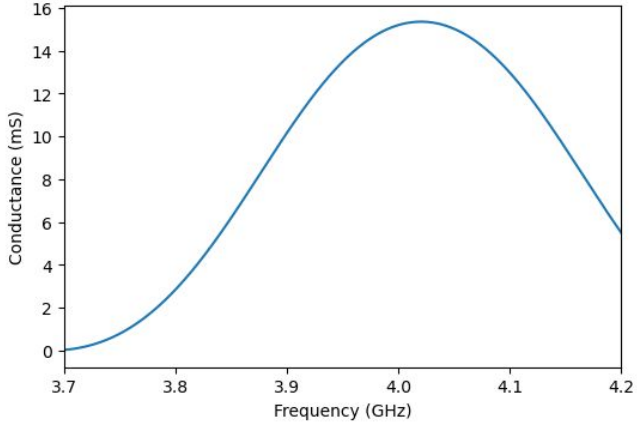




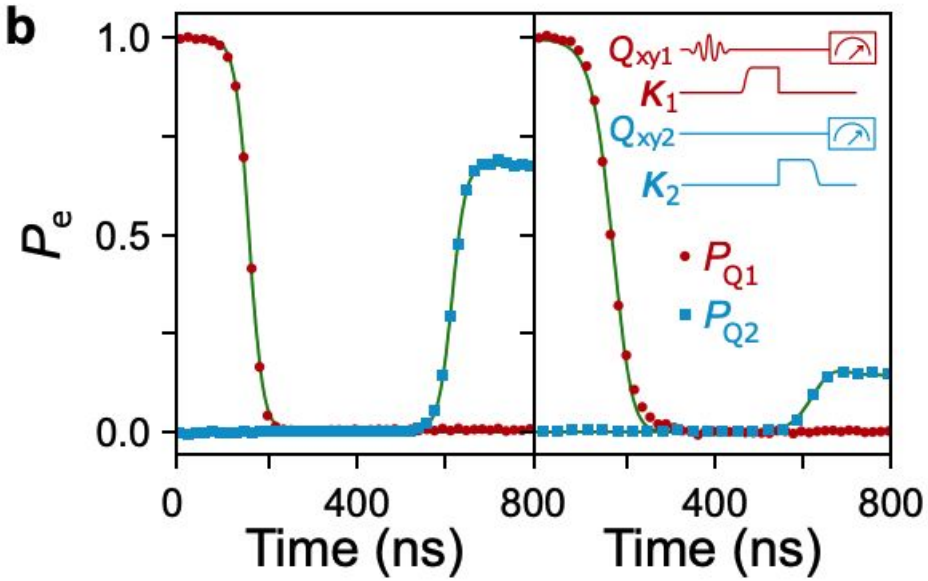
Characterizing the Qubit(s)







Quantum Time of Flight



Load excitations into Q1, transfer into Q2 via itinerant phonons! (both UDT and IDT variations)

~4.5 increase in signal!

Quantum State (and Process) Tomography

With qubits we always measure: $\langle \sigma_z \rangle$

How can I reconstruct the density matrix??

Quantum State (and Process) Tomography

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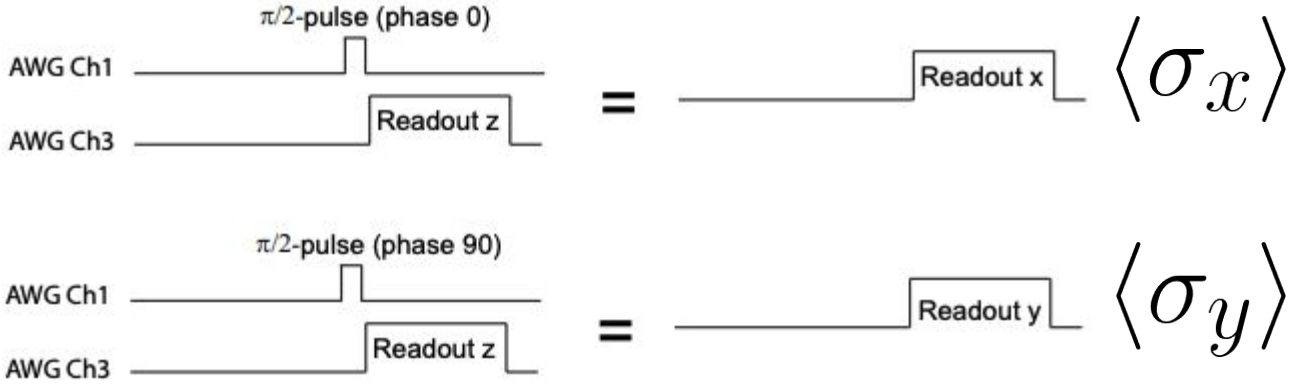
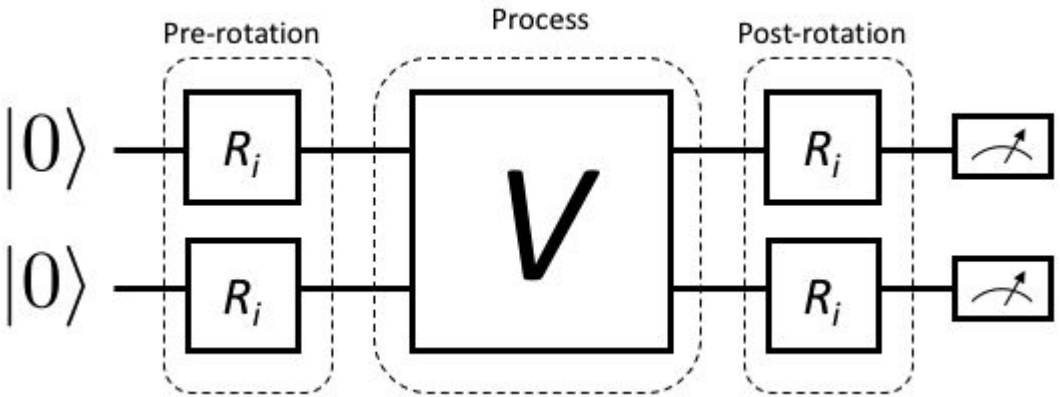
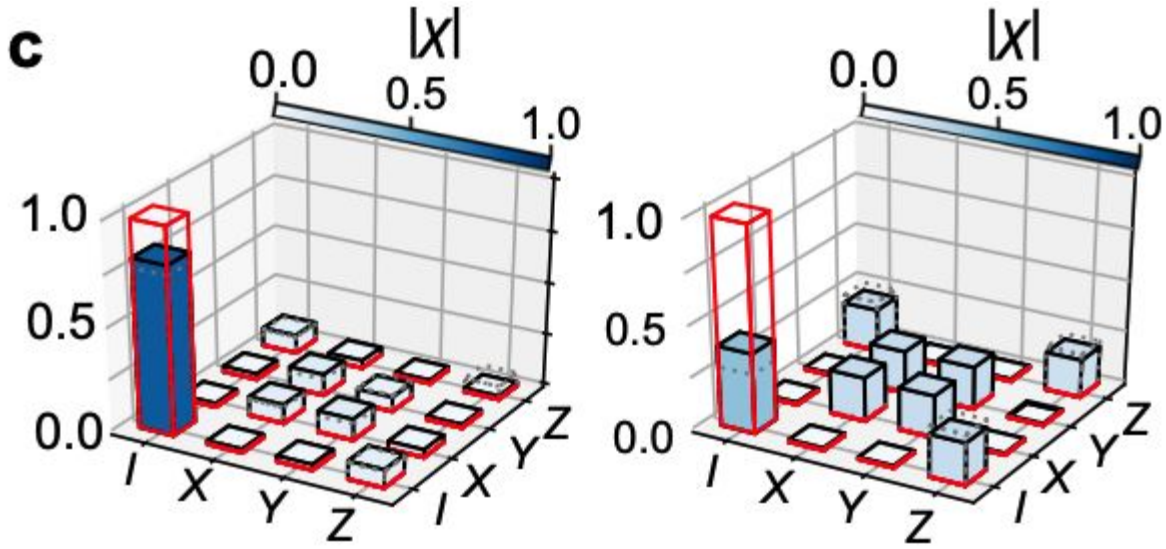


Quantum State (and Process) Tomography

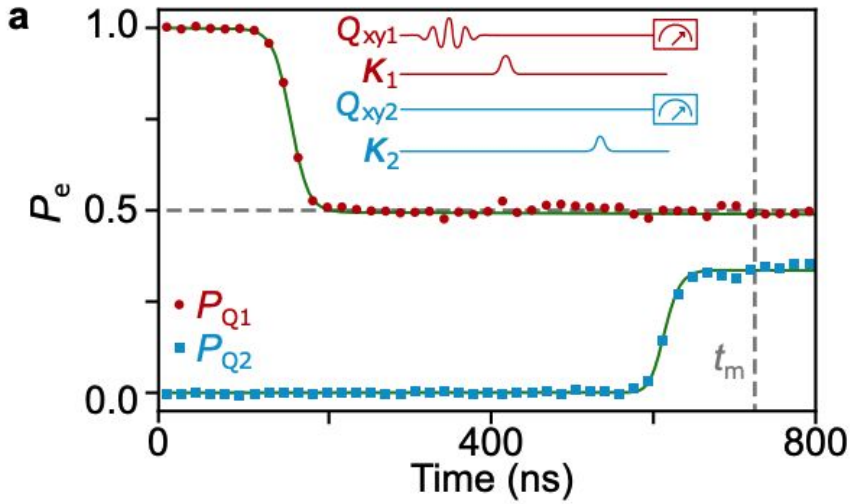


Phonon Mediated Quantum State Transfer



UDT regime much more efficient than IDT regime!

Generation of Bell State via Phonons



$$|\psi\rangle = |e0g\rangle$$

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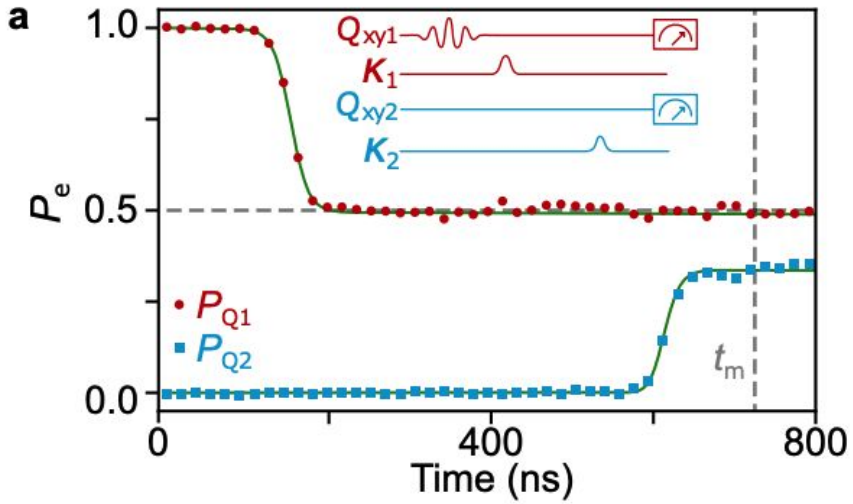
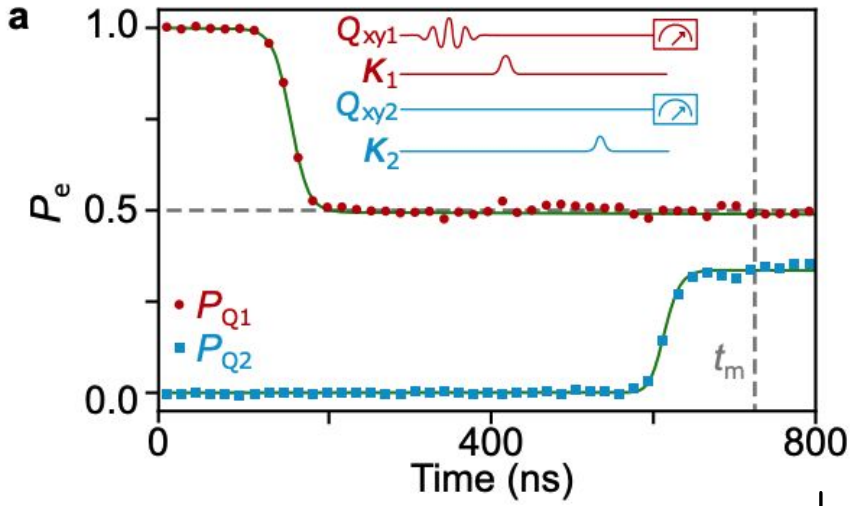


$$|\psi\rangle = \frac{1}{\sqrt{2}}(|e0g\rangle + |g1g\rangle)$$

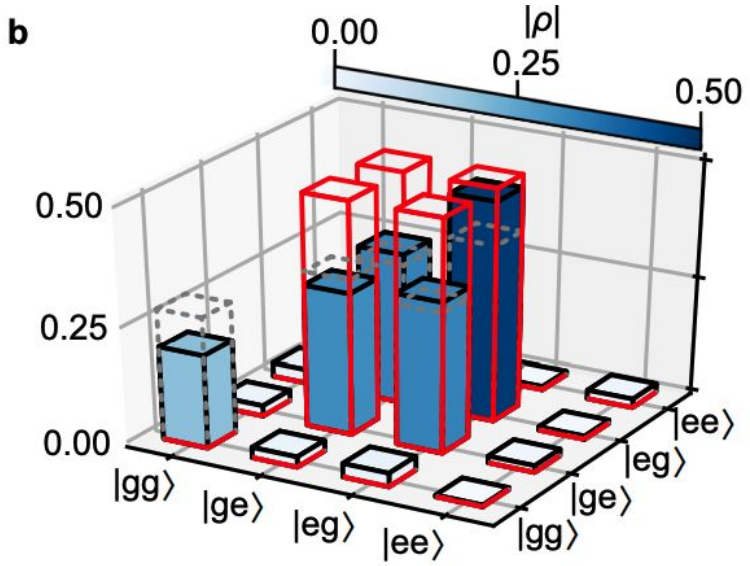
Generation of Bell State via Phonons



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|e0g\rangle + |g0e\rangle\right)$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|eg\rangle + |ge\rangle\right) \otimes |0\rangle$$

Density Matrix Reconstruction of Bell State



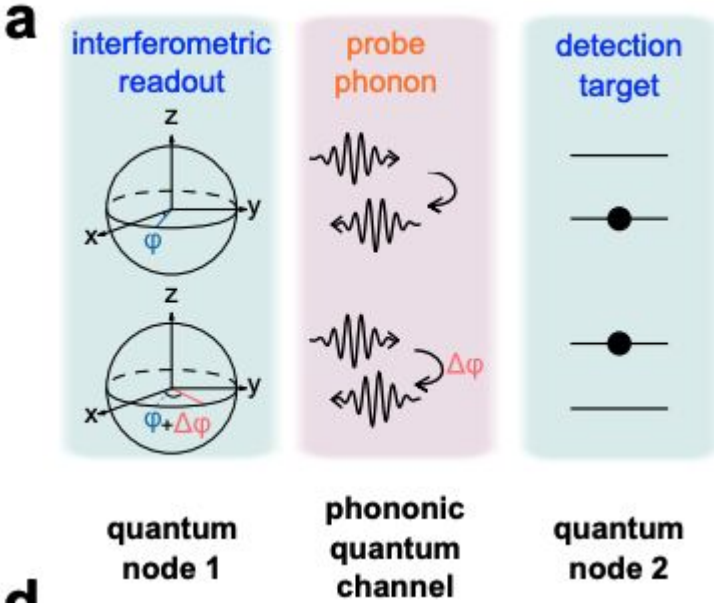
Phonons as a Probe of "Arbitrary" Quantum Systems

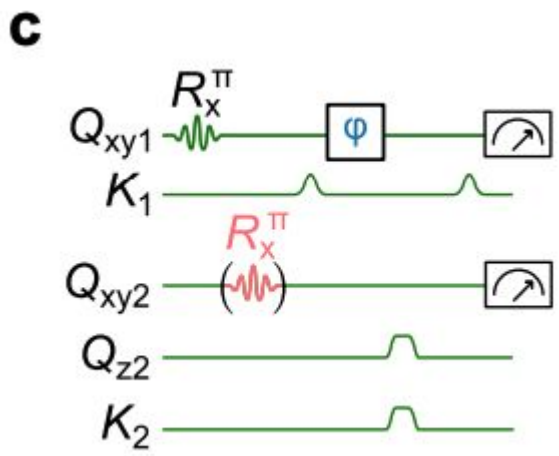
- Goal - learn about another quantum system using a single qubit + phonon
- Use standard cQED as building blocks!

$$\tilde{\omega}_r \simeq \omega_r + \frac{g^2}{\Delta}\langle\sigma_z\rangle$$

We should expect the qubit state to dispersively shift the phonon!

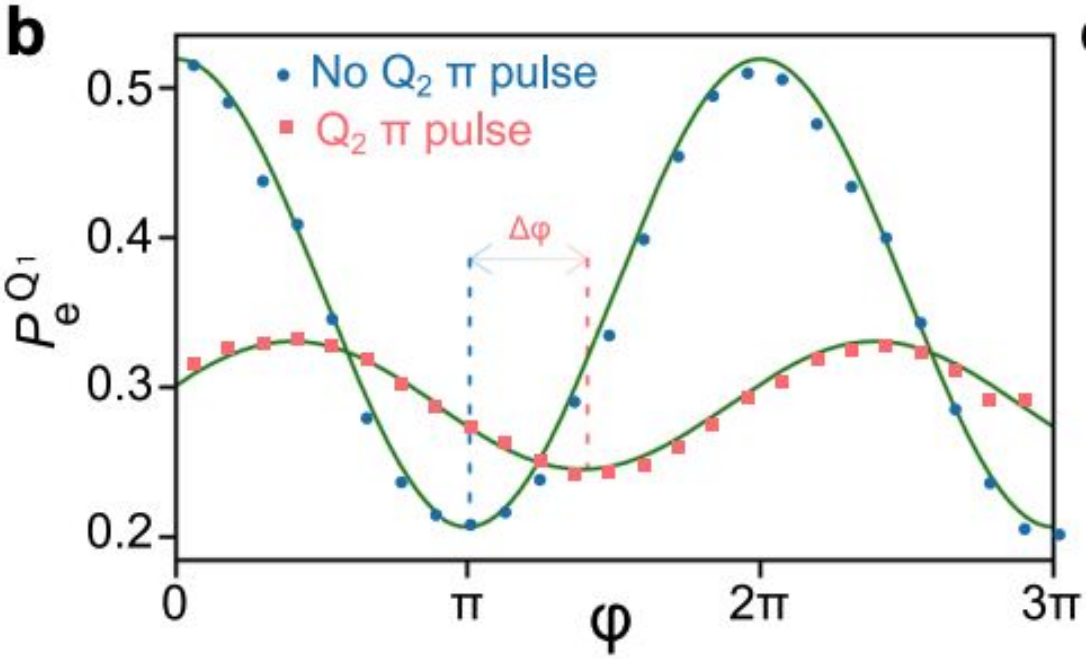
Phonons as a Probe of "Arbitrary" Quantum Systems



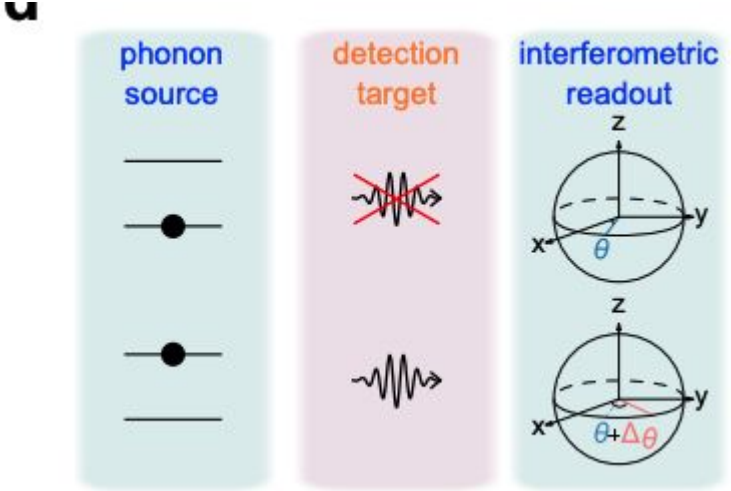


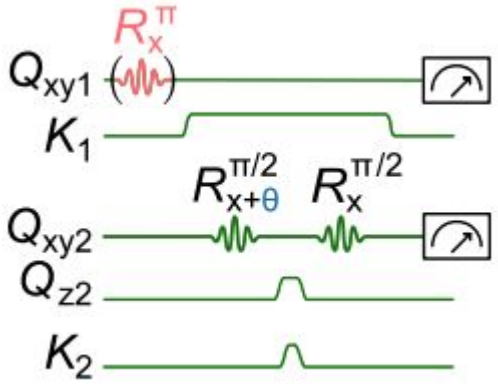
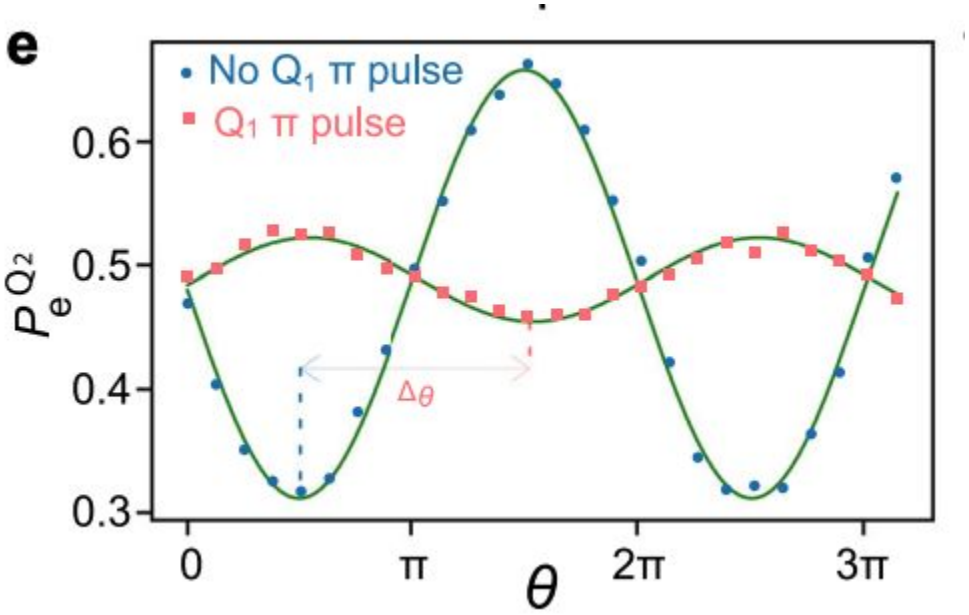
$$\Delta\phi = \chi\Delta t$$

Phonons as a Probe of "Arbitrary" Quantum Systems



Again, but phase sensitive!

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