INTRODUCTION TO SUPERCONDUCTING QUBITS AND QUANTUM EXPERIENCE:
A 5-QUBIT QUANTUM PROCESSOR IN THE CLOUD

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OUTLINE

TODAY

- **Superconducting Josephson junction qubit: an artificial atom**
- **Circuit Quantum electrodynamics: Interaction between microwave light and artificial atoms**

TOMORROW

- **Quantum Experience: A 5-qubit in the cloud**

INTRODUCTION TO

SUPERCONDUCTING JOSEPHSON JUNCTION QUBIT

QUANTUM INFORMATION SYSTEMS

micro

coupling
with environment

- PHOTONS
- NUCLEAR SPINS
- IONS
- ATOMS
- MOLECULES
- QUANTUM DOTS
- SUPERCONDUCTING CIRCUITS

MACRO

QUANTUM INFORMATION SYSTEMS

micro

coupling
with environment

- PHOTONS
- NUCLEAR SPINS
- IONS
- ATOMS
- MOLECULES
- QUANTUM DOTS
- SUPERCONDUCTING CIRCUITS

MACRO

Circuits are quantized!!

- FIRST DEMONSTRATION BY DEVORET, MARTINIS, CLARKE (1985)
- engineered hamiltonian with "LEGO" blocks:
  capacitors, inductors and Josephson junctions

A.J. Leggett, 1982

ATOM → SUPERCONDUCTING CIRCUIT; ELECTRON DEGREES OF FREEDOM → MACROSCOPIC CURRENTS AND VOLTAGES

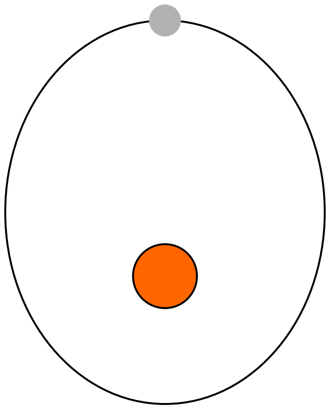
SIMPLEST EXAMPLE: SUPERCONDUCTING **LC** OSCILLATOR CIRCUIT

Sub-mm dimensions ➡ L ~ nH, C ~ pF, $\omega_r/2\pi$ ~ GHz ➡ Lumped elements

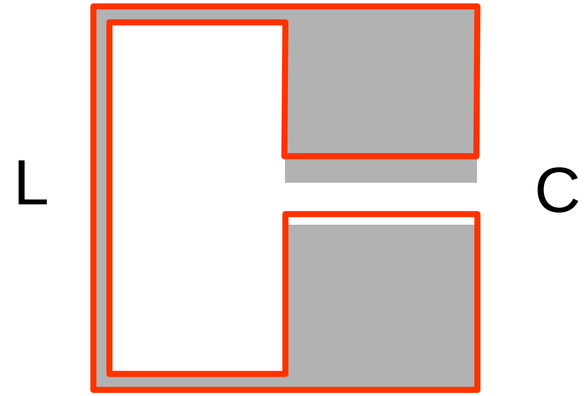
ELECTRONIC FLUID SLOSHES BACK AND FORTH
FROM ONE PLATE TO THE OTHER, NO INTERNAL DISSIPATION

DEGREE OF FREEDOM IN ATOM vs CIRCUIT

Rydberg atom



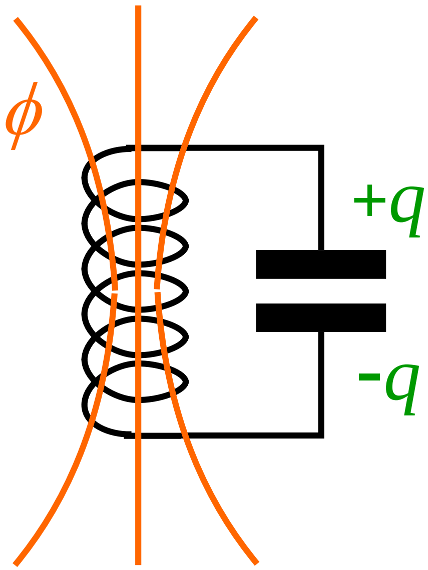
Superconducting LC oscillator

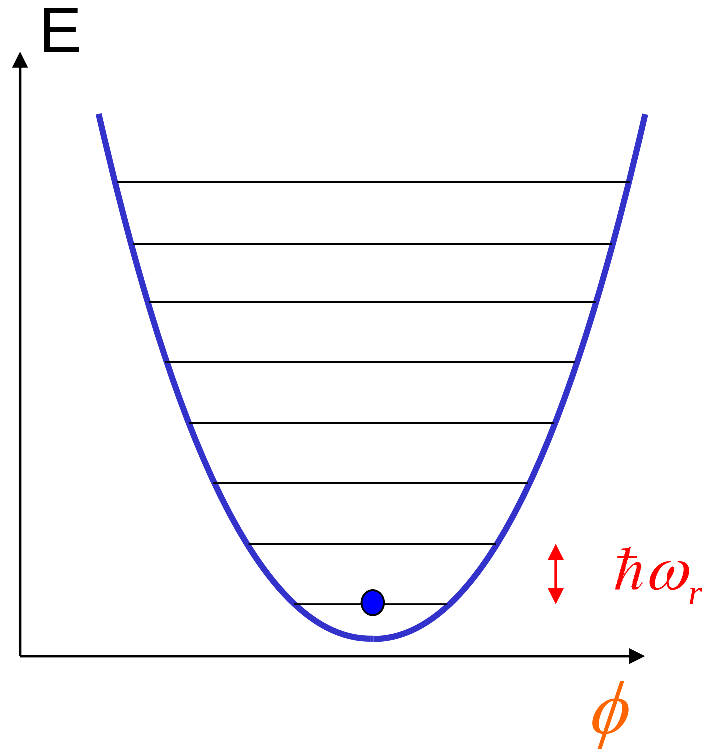


velocity of electron → voltage (charge) across capacitor

force on electron → current (flux) through inductor

LC OSCILLATOR AS A QUANTUM CIRCUIT





$$\left[\hat{\phi},\hat{q}\right]=i\hbar$$

$$\hbar\omega_r >> k_B T$$

5-10 GHz

10mK

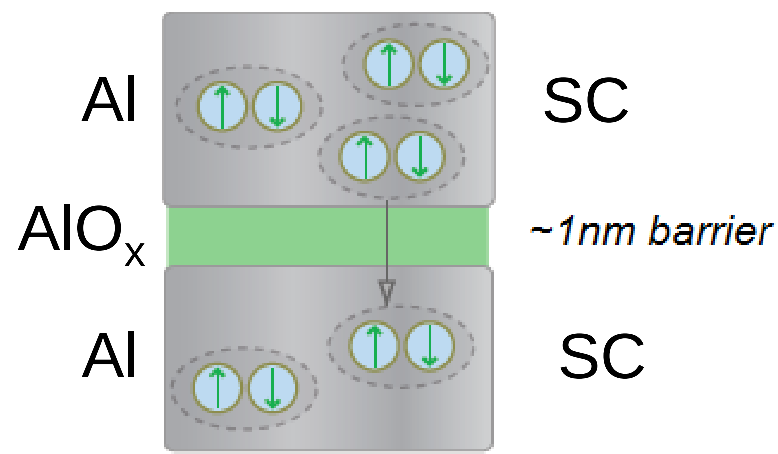
SUPERCONDUCTING JOSEPHSON JUNCTION QUBIT

- Qubit (two level system) requires nonlinearity.
- No loss

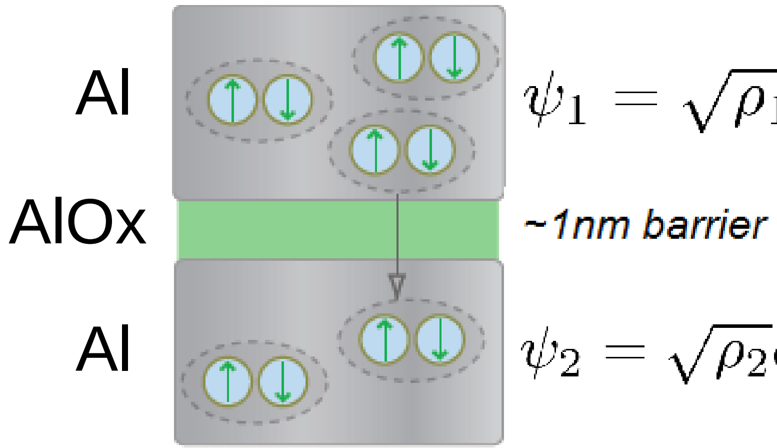
<u>Superconducting Josephson Junction</u>

- <u>Josephson junction provides a nonlinear element.</u>
- Conducts electricity without resistance (no loss).

- Couple two superconductors via oxide layer
- Oxide layer acts as tunneling barrier



JOSEPHSON JUNCTIONS – FEYNMAN'S MODEL



$$\psi_1 = \sqrt{\rho_1} e^{i\gamma_1}$$

$$\psi_2 = \sqrt{\rho_2} e^{i\gamma_2}$$

$\rho_{1(2)}$ density of electrons on either side of the SC

$\gamma_{1(2)}$ phase of the SC

Equations of motion from a toy model

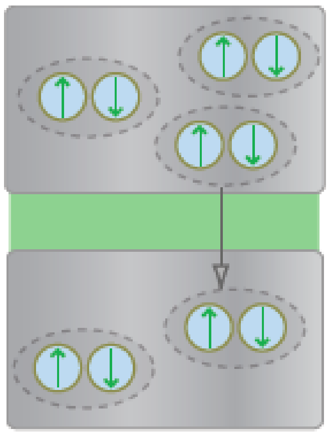
$$i\hbar \frac{\partial}{\partial t} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} = \begin{pmatrix} 2eV & K \\ K & 0 \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

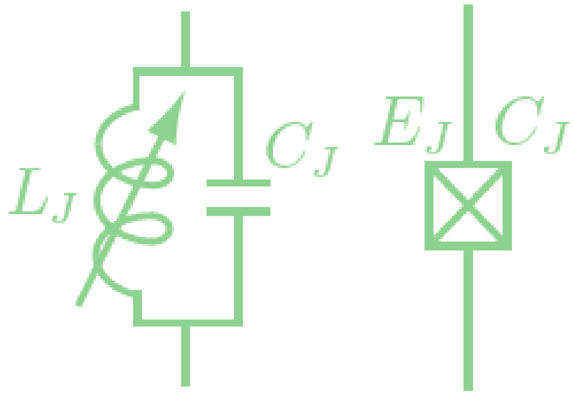
K – tunneling energy
2eV – energy across the junction

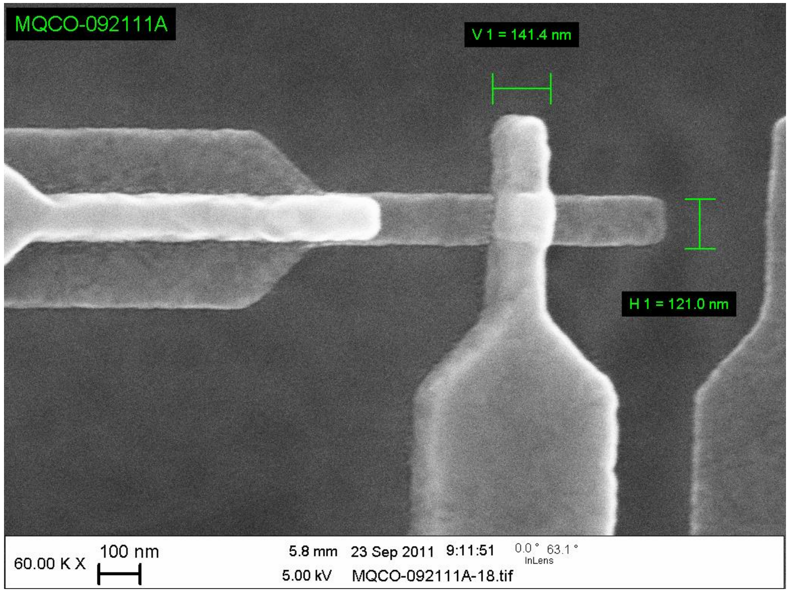
$$\dot{\gamma} = \frac{2eV}{\hbar} - \frac{2K\rho}{\hbar\rho_0\sqrt{1-\rho^2/\rho_0^2}}\cos(\gamma) \approx \frac{V}{\varphi_0}$$ *AC-Josephson effect*

$$I = \dot{\rho} = \frac{2K\rho_0}{\hbar}\sqrt{1-\rho^2/\rho_0^2}\sin(\gamma) \approx I_c \sin(\gamma)$$ *DC-Josephson effect*

THE JOSEPHSON JUNCTION HAMILTONIAN







Energy stored in the capacitor $$U_K = \frac{1}{2}CV^2 = \frac{1}{2}C\left(\frac{\hbar}{2e}\right)^2 \dot{\varphi}^2$$

Energy stored in the inductor $$U_P = \int IVdt = -E_J \cos\varphi$$

$$\boxed{[\hat{\varphi}, \hat{n}] = i}$$

What is the conjugate momentum P_j for φ?

$$p_\varphi = \frac{\partial L}{\partial \dot{\varphi}} = C\left(\frac{\hbar}{2e}\right)^2 \dot{\varphi} = \frac{\hbar}{2e}CV = \frac{\hbar}{2e}(2en) = \hbar n$$

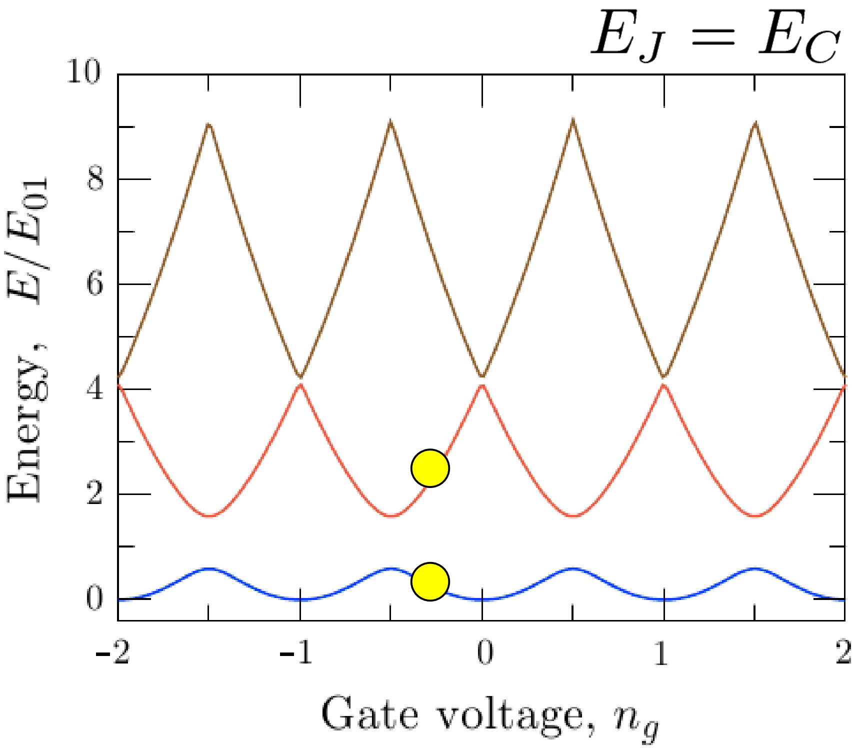
Josephson Hamiltonian

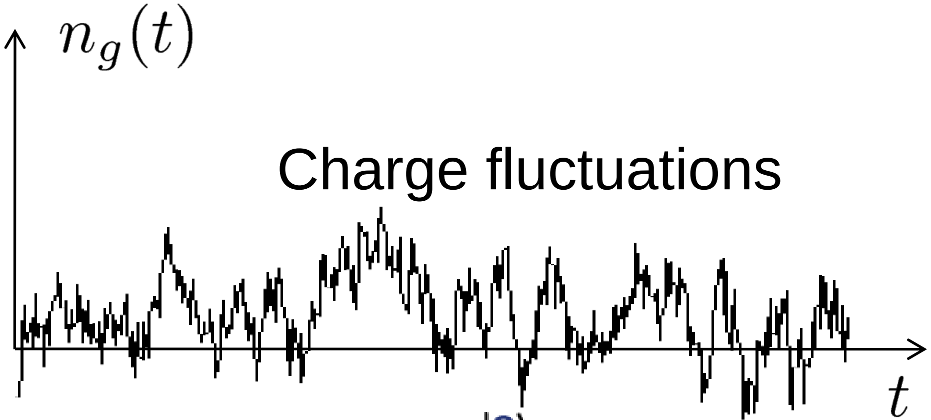
$$\boxed{\hat{H} = E_C(\hat{n} - \frac{q_{ext}}{2e})^2 - E_J \cos\hat{\varphi}}$$

Charging Energy

Josephson Energy

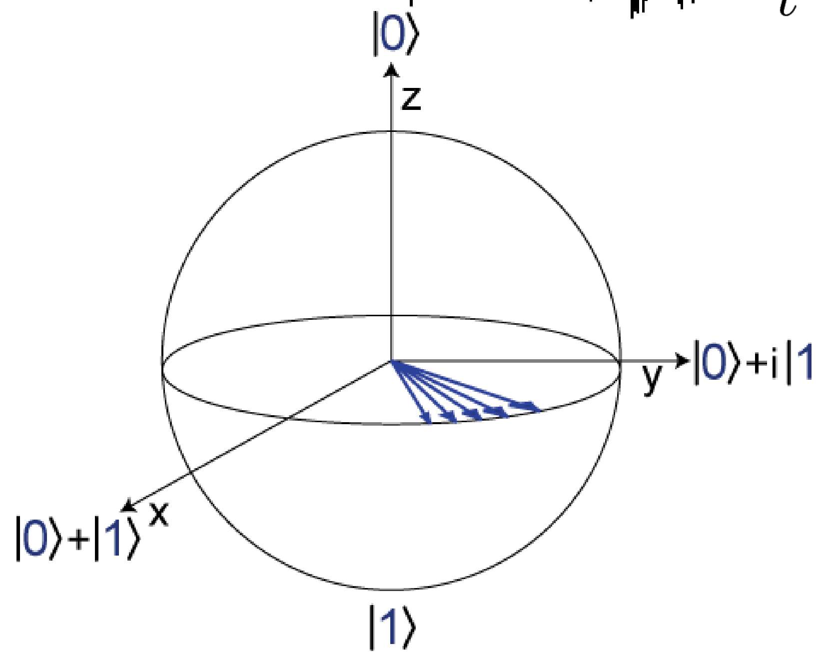
THE CHARGE LIMIT





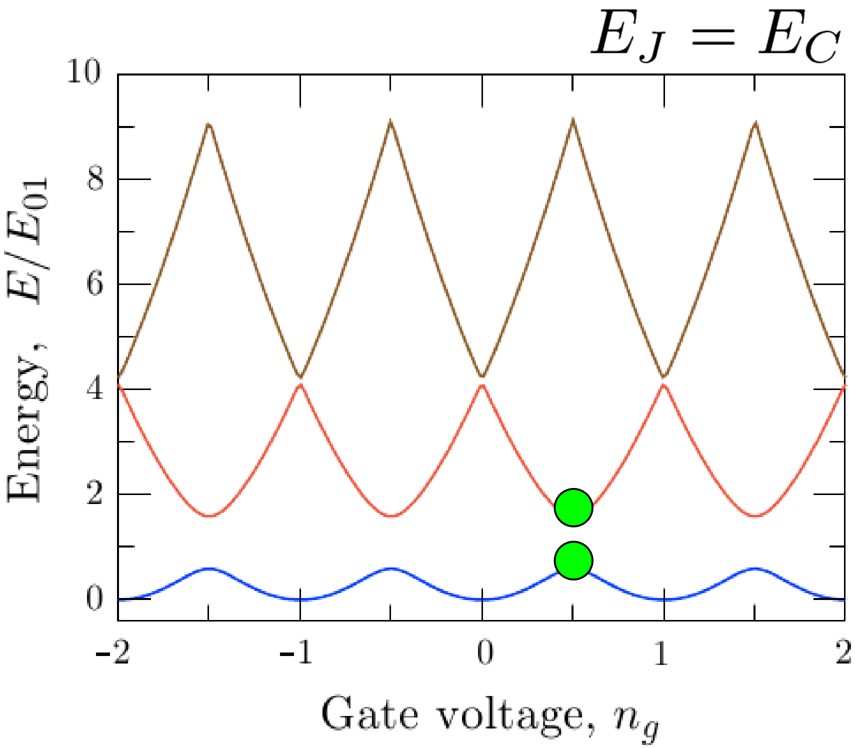
First experiment in 1999

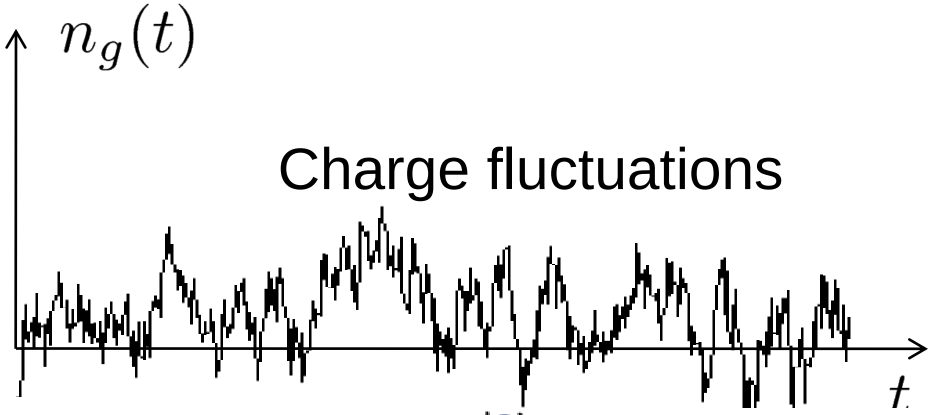
$$T_2 \approx 1 \text{ ns}$$

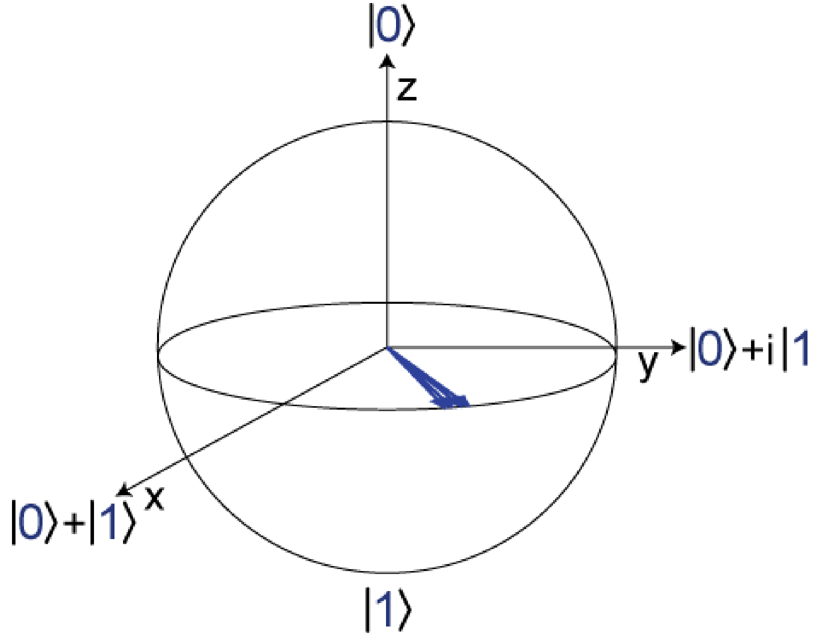


FIRST coherent manipulation of SC qubit by Nakamura et. al. *Nature* **398**, 786 (1999)

THE CHARGE LIMIT







First experiment in 1999

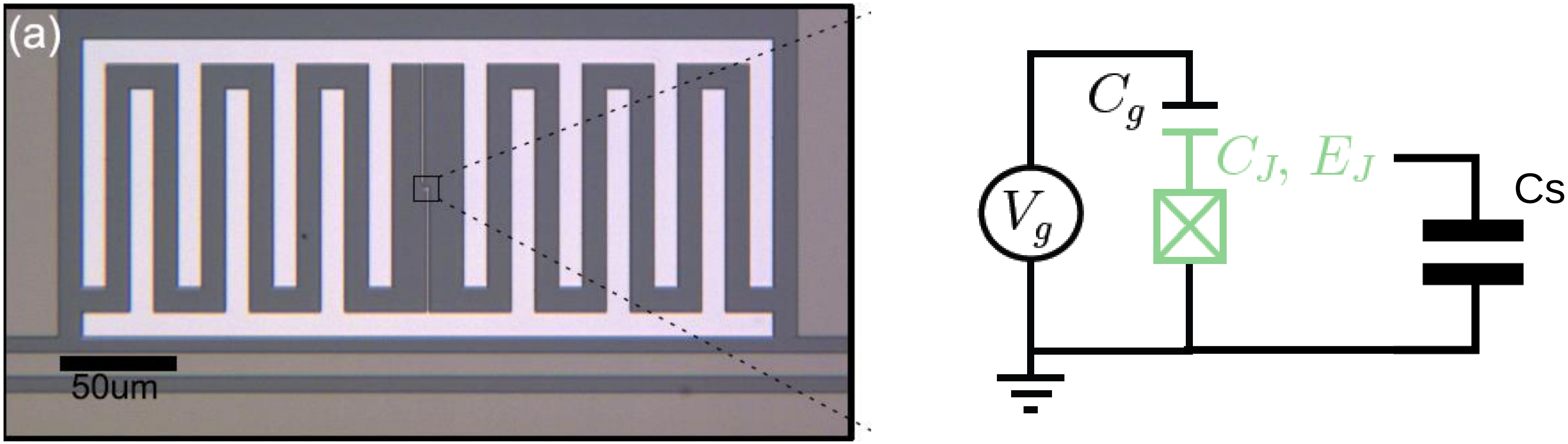
$$T_2 \approx 1 \text{ ns}$$

Sweet spot operation in 2002

$$T_2 = 500 \text{ ns}$$

FIRST BREAKTHROUGH IN COHERENCE by Vion et. al. *Science* **296**, 886 (2002)

THE TRANSMON



The transmon = <u>Capacitively-shunted Josephson junction qubit</u>

$$H = 4E_C(n - n_g)^2 - E_J \cos(\gamma)$$

where $E_C = \dfrac{e^2}{2C_\Sigma}$ and $n_g = \dfrac{C_g V_g}{2e}$

- *Engineering an artificial atom* with a capacitor and an inductor (JJ critical current).
- Depending on E_J/E_c, the transmon dynamics varies.

Koch et. al. PRA **76**, 04319 (2007)

FROM A CHARGE REGIME TO A "TRANSMON" REGIME

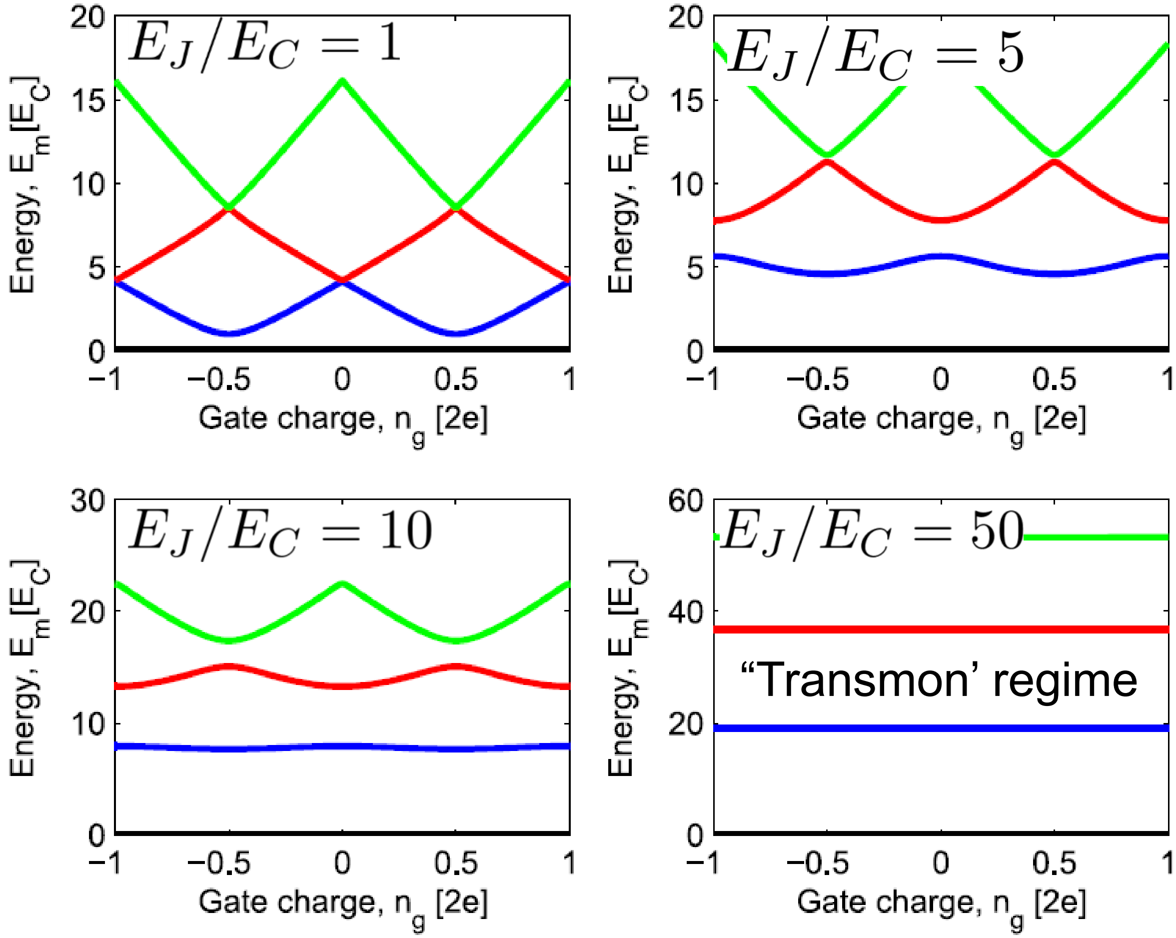
Increasing E_J/E_C

- Charge dispersion becomes flat

$$\epsilon_m = E_{m0}(n_g = 1/2) - E_{m0}(n_g = 0)$$

- anharmonicity decreases

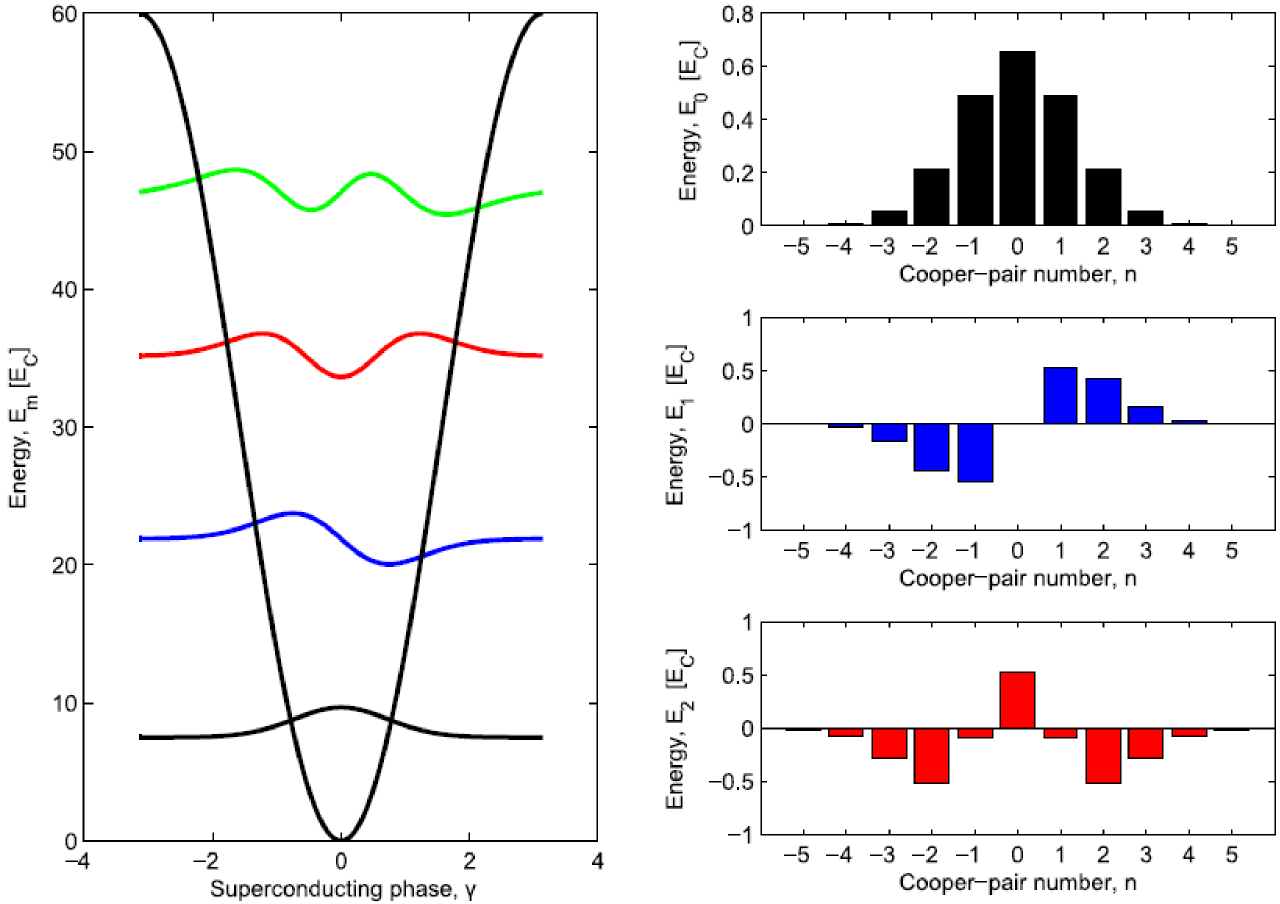
$$\delta = \omega_{12} - \omega_{01}$$



Nowadays (2016), T_2 ~ 50000 ns (50 μs) to 200000 ns (200 μs).

Koch et. al. PRA **76**, 04319 (2007)

EIGENFUNCTIONS OF THE TRANSMON



Eigen functions similar to a harmonic oscillator – suggest a good basis is the harmonic oscillators eigenfunctions

LARGE E_J/E_C HAMILTONIAN

Expanding the cosine to 4th order gives

$$\hat{H}_{\mathrm{tr}} \approx \frac{\hat{Q}^2}{2\bar{C}_\Sigma} + \frac{\hat{\Phi}^2}{2L_J} - \frac{E_C\hat{\Phi}^4}{3Z_{\mathrm{tr}}^2\hbar^2} + \mathcal{O}(\hat{\Phi}^6)$$

where $Z_{\mathrm{tr}} = \sqrt{L_J/\bar{C}_\Sigma} = (\hbar/e^2)\sqrt{E_C/2E_J}$

Defining dimensionless variables $\hat{x} = \sqrt{1/\hbar Z_{\mathrm{tr}}}\hat{\Phi}$ and $\hat{y} = \sqrt{Z_{\mathrm{tr}}/\hbar}\hat{Q}$

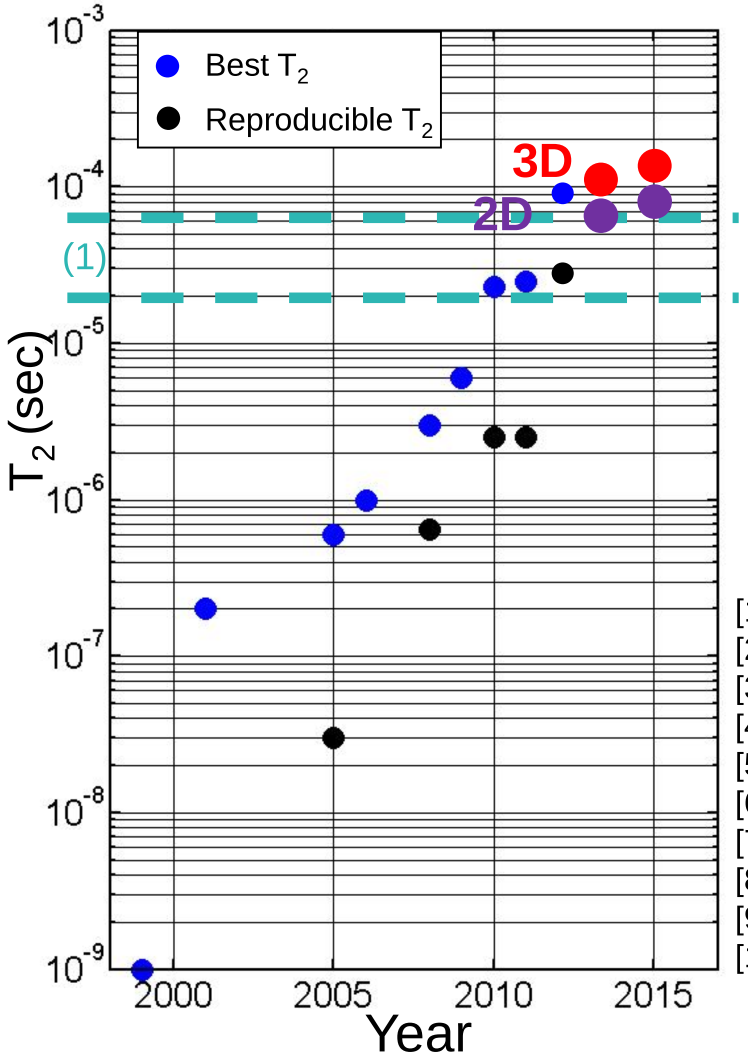
$$\hat{H}_{\mathrm{tr}} = \frac{\hbar\omega_0}{2}(\hat{y}^2 + \hat{x}^2) - \frac{E_C\hat{x}^4}{3}$$

where $\omega_0 = 1/\sqrt{\bar{C}_\Sigma L_J} = \sqrt{8E_CE_J}/\hbar$

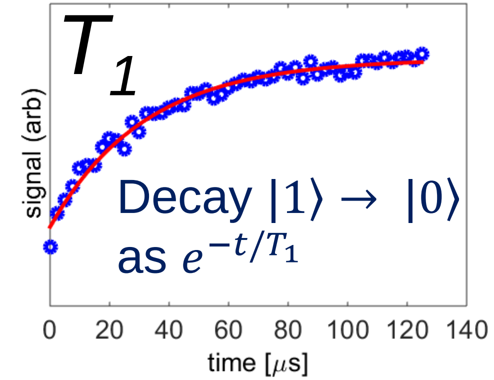
Qubit frequency engineered by E_c and E_j (capacitance and inductance)

This is just a weakly anharmonic oscillator (ω_0 >> Ec)

IMPROVEMENTS IN COHERENCE TIMES



- Understand charge noise e.g. [1]
- 3D transmon [5]
- IR Shielding [6,7],
- Cold cavities & cold qubits [8]
- High Q cavities [9]
- Materials e.g. [2,10]
- Design and geometries [4,10]
- Microwave environment [3]

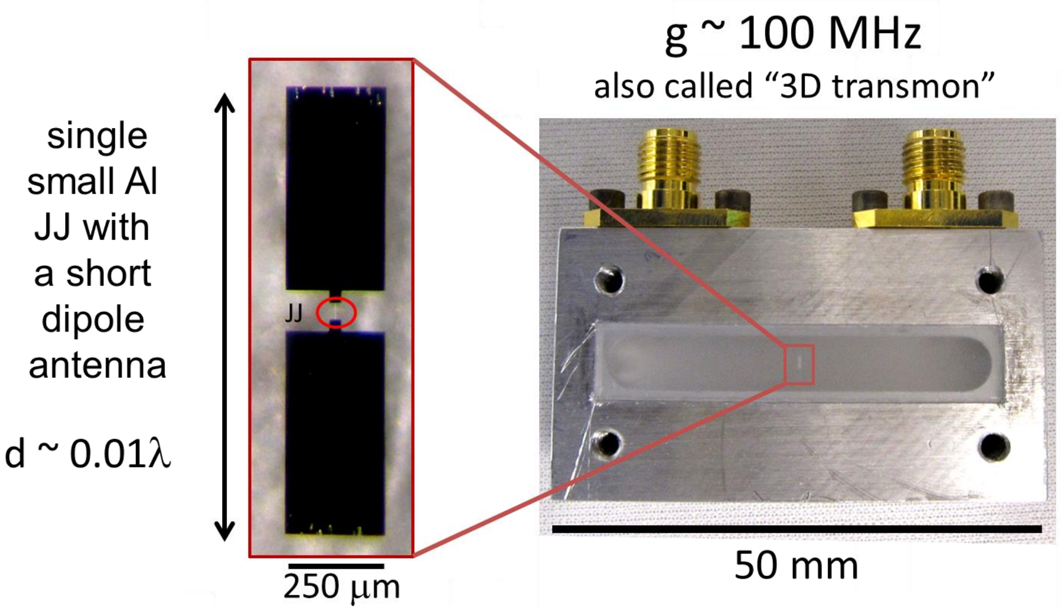


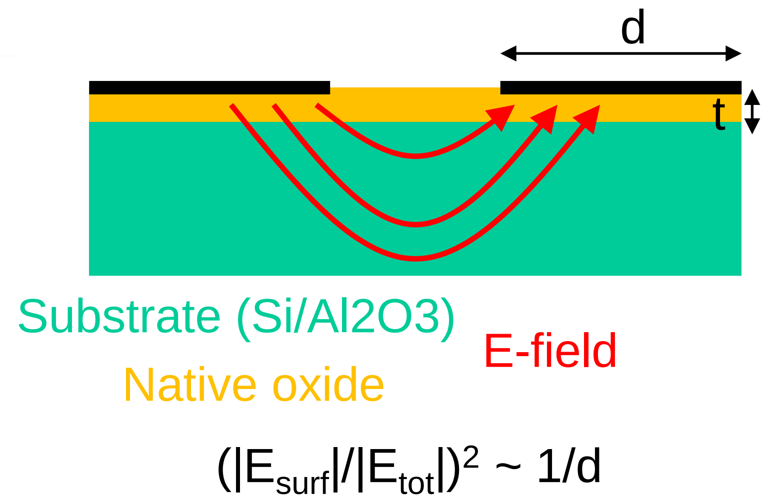
Quality factor of the transmon qubit > 2M routinely achievable

[1] Koch *et. al*. PRA **76**, 04319 (2007)
[2] J. Martinis *et al.,* PRL **95** 210503 (2005)
[3] Houck *et. al*. PRL **101**, 080502 (2008)
[4] K. Geerlings *et al*., APL **100**, 192601 (2012)
[5] H. Paik *et al*., PRL **107**, 240501 (2011)
[6] R. Barends *et al*., APL **99**, 113507 (2011)
[7] A. Corcoles *et al*., APL **99**, 181906 (2011)
[8] C. Rigetti *et al*., PRB **86**, 100506 (2012)
[9] M. Reagor *et al*., APL **102**, 192604 (2013)
[10] J. Chang *et al*. APL **103**, 012602 (2013)

(1) Noise threshold for 2D fault tolerant computation assuming 30-100ns gate time

SUPERCONDUCTING QUBITS IN 3D CAVITIES:
MITIGATING SURFACE LOSSES





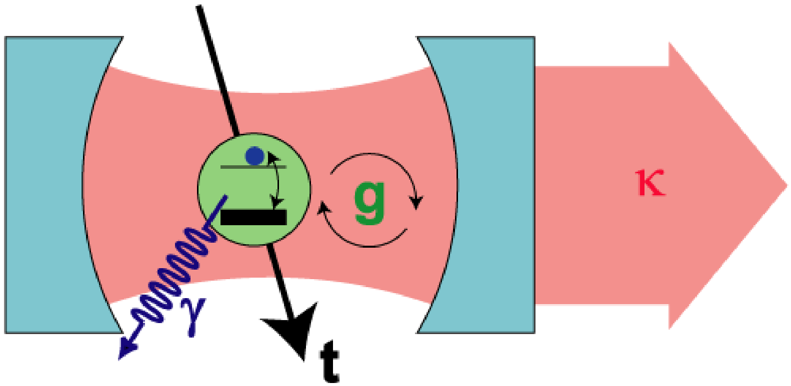
- Big features predicted to have higher Q (less surface contribution)
  - But radiation also increasingly worse
  - flux trapping quickly can be an issue
- Placing a large qubit in a 3D microwave cavity mitigates both surface and radiation losses with decreased surface participation.

Paik et al. PRL, **107,** 240501 (2011)

INTERACTING WITH SUPERCONDUCTING QUBIT

CIRCUIT QUANTUM ELECTRODYNAMICS (cQED)

CAVITY QUANTUM ELECTRODYNAMICS (CQED)



2g = vacuum Rabi freq.

κ = cavity decay rate

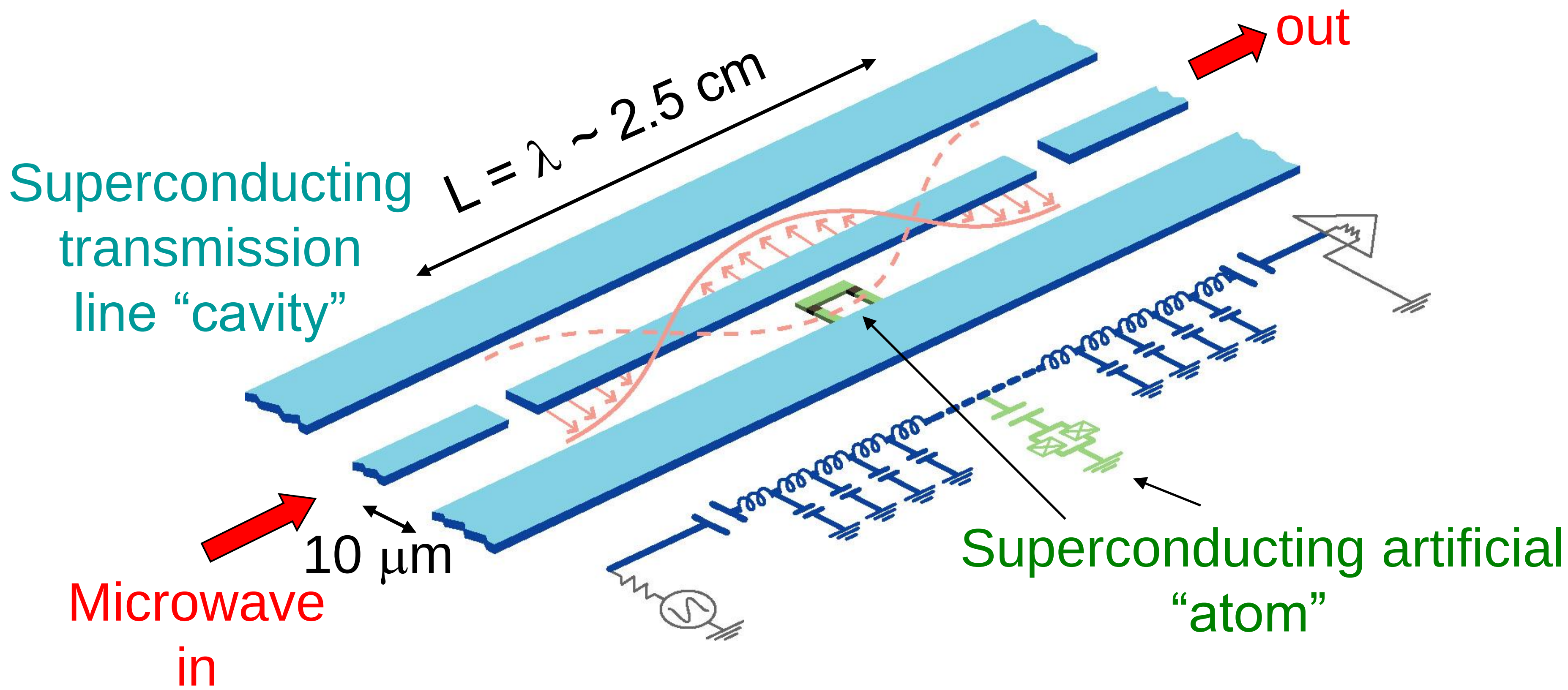
γ = "transverse" decay rate

Jaynes-Cummings Hamiltonian

$$H = \hbar\omega_c a^+ a + \frac{\hbar\omega_q}{2}\hat{\sigma}_z + \hbar g(a\hat{\sigma}^+ + a^+\hat{\sigma}^-)$$

CIRCUIT QUANTUM ELECTRODYNAMICS (cQED)

Theory: Blais et al., Phys. Rev. A **69**, 062320 (2004)



- **Strong coupling achieved**!

THE JAYNES CUMMINGS HAMILTONIAN

The resonator can be represented by a simple harmonic osc.

$$\hat{H}_\mathrm{r} = \hbar\omega_r \hat{a}^\dagger \hat{a} \quad \text{with} \quad \omega_r/2\pi = 6 - 10\ \mathrm{GHz}$$

The voltage is given by $\hat{V}_r = V^0_\mathrm{rms}(\hat{a} + \hat{a}^\dagger)$

$$V^0_\mathrm{rms} = \sqrt{\hbar\omega_r^2 Z_r/2} \approx 3\mu V$$

The interaction with the resonator is described by

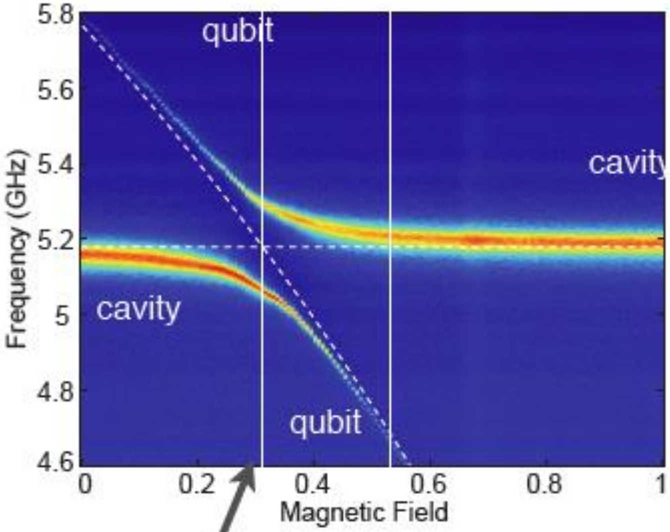
$$\hat{H}_\mathrm{int} = -\frac{C_g \hat{V}_r \hat{Q}}{C_\Sigma} = \hbar g(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

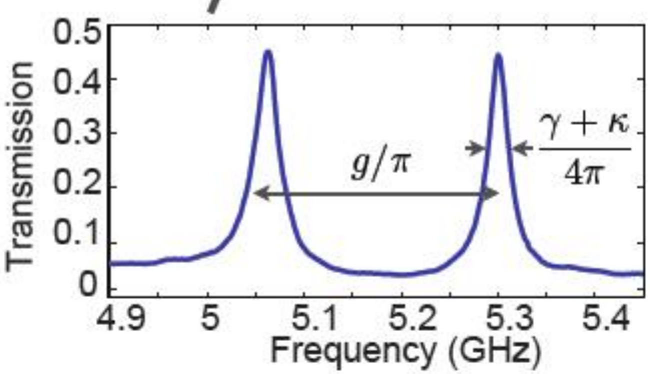
where $g = -\beta\omega_r\sqrt{\frac{Z_r}{4Z_\mathrm{tr}}} = -\beta\omega_r e\sqrt{\frac{Z_r}{\hbar}}\left(\frac{E_J}{8E_C}\right)^{1/4} \approx 10 - 500\ \mathrm{MHz}$

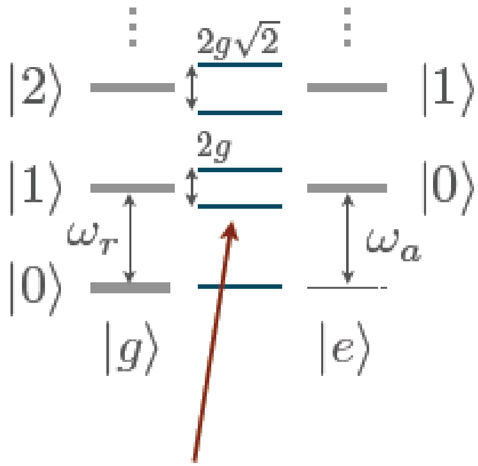
It is possible to reach the strong coupling regime

THE STRONG COUPLING REGIME

$$H_{\mathrm{tot}} = \hbar\omega_r a^\dagger a + \hbar\omega b^\dagger b + \frac{1}{2} b^\dagger b(b^\dagger b - 1) + \hbar g(b^\dagger a + b a^\dagger)$$







$$\frac{|g\ 1\rangle + |e\ 0\rangle}{\sqrt{2}}$$

$g/2\pi = 120$ MHz
$\kappa/2\pi = 45$ MHz
$\gamma/2\pi = 1$ MHz

Wallraff et al. Nature, **431,** 162 (2004)

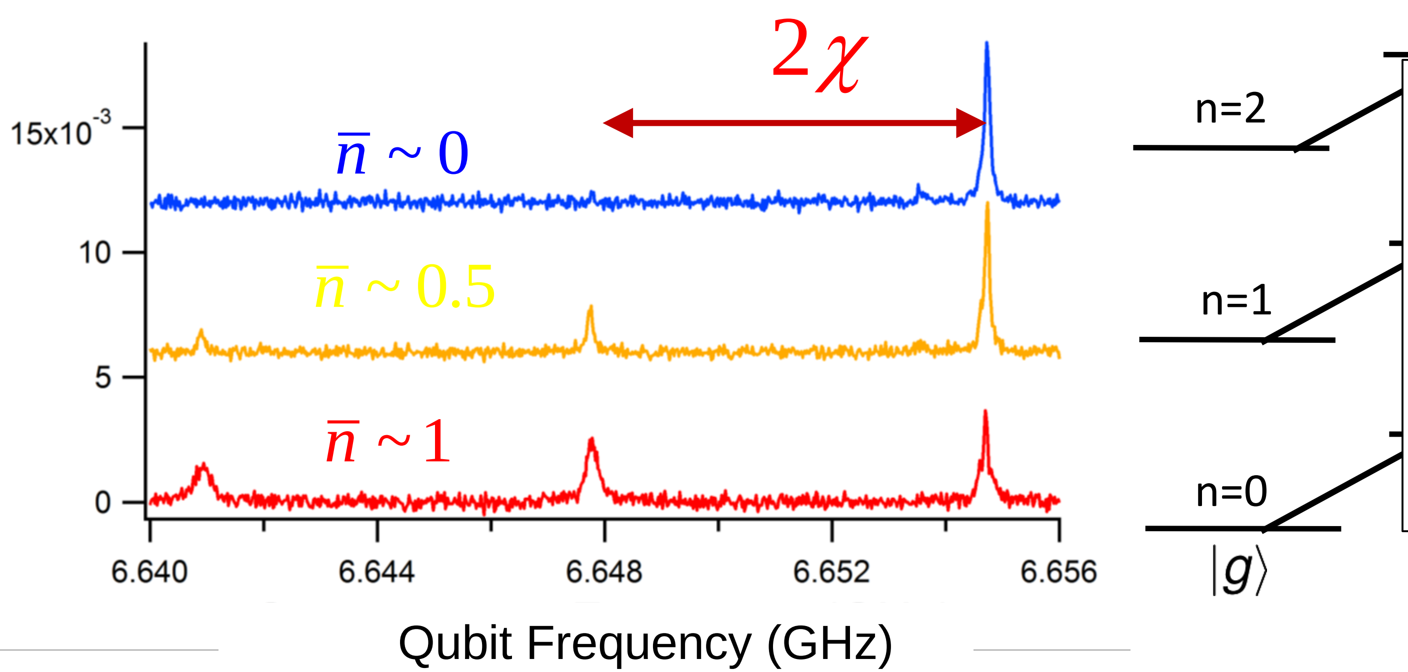
THE (Ultra-Strong) DISPERSIVE LIMIT

Solving to second order after a dispersive approximation

$$|\omega_r - \omega| \gg |g| \qquad H_{\text{tot}}^{D} = \hbar\omega_r a^\dagger a + \hbar\sum_j (\tilde{\omega}_j + \chi_j a^\dagger a)|j\rangle\langle j|$$

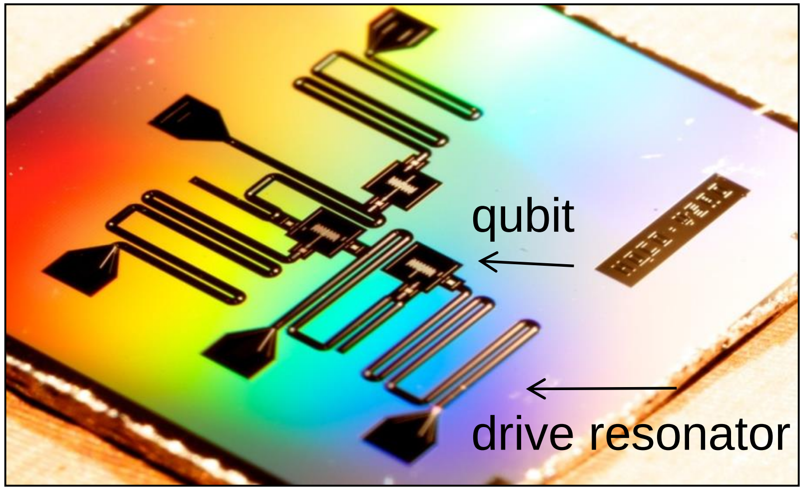
χ is AC Stark shift: a state-dependent qubit or cavity frequency shift

$|g \rightarrow e; n=2\rangle$ $|g \rightarrow e; n=1\rangle$ $|g \rightarrow e; n=0\rangle$



$\chi \gg \kappa, \gamma$
Stark shift per photon now > 1,000 linewidths

MICROWAVE CONTROLS OF TRANSMON:
SINGLE QUBIT GATES



A microwave drive *V is applied to the qubit through a resonator*

Driving Hamiltonian

$$\hat{H}_d = V\hat{Q} = VQ_{ZPF}(\hat{b}+\hat{b}^{+}) = \hbar\Omega(t)(\hat{b}+\hat{b}^{+})$$

$$\Omega(t) = \Omega_x(t)\cos(\omega_d t) + \Omega_y(t)\sin(\omega_d t)$$

After making the rotating wave approximation (driving frame $\Delta = \omega_d - \omega$)

$$\hat{H}^{R}_{\mathrm{tr+dr}} = \frac{\hbar\Delta(t)}{2}\hat{Z} + \frac{\hbar\Omega_x(t)}{2}\hat{X} + \frac{\hbar\Omega_y(t)}{2}\hat{Y}$$

Rotation operator along Pauli matrix *A*

$$R_A(\theta) = \exp\left[-i\hat{A}\frac{\theta}{2}\right] = \hat{I}\cos\left(\frac{\theta}{2}\right) - i\hat{A}\sin\left(\frac{\theta}{2}\right)$$

Complete control in the qubit subspace by using $\Delta(t)$, $\Omega_x(t)$, and $\Omega_y(t)$

TOMORROW

- TWO-QUBIT GATE FOR SC QUBITS: CROSS RESONANCE
- EXPERIMENTAL SET UP
- QUANTUM EXPERIENCE DEMO

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