Building Qudit-based Quantum Computing Architecture using SRF Cavities

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SQMS division, Fermilab

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Why Quantum Computing?

Frontier

Image: Wikipedia

1.2×10^{18} calculations / sec

Not efficient for all problems

1. Prime Factorization

7629045585188558 53

HARD

77 ? 01 × 98 ? 53

Shor's factoring algorithm 1994

Image: mit.edu

Build a Quantum Computer

2. Quantum Simulation

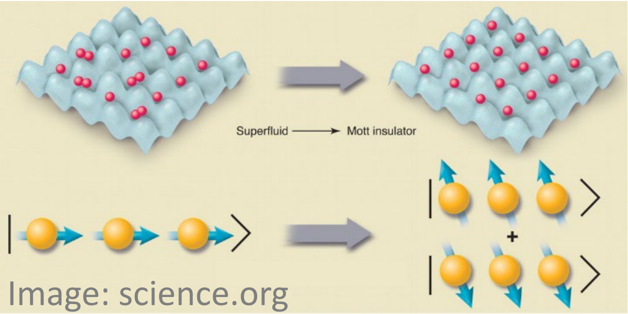


Image: science.org

Simulate one QM system with another

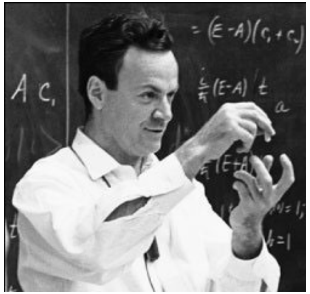
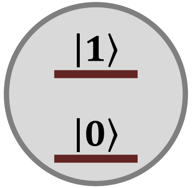
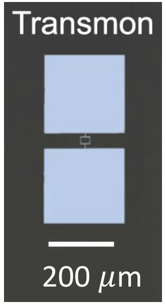


Image: needull.com

Outline

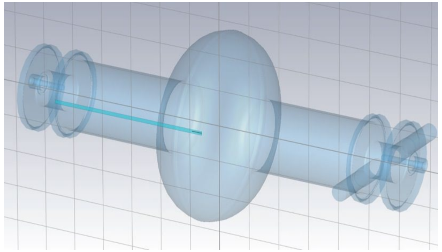
- Basic requirements and challenges



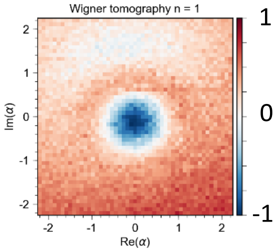


- Introduction to superconducting qubits

- Benefits of 3D SRF cavities

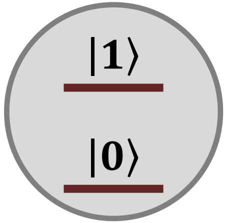


- Gate schemes and measurements

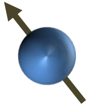


- Current achievements and outlook

Basic Requirements for a Quantum Computer

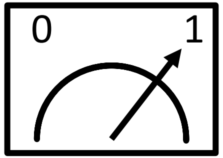


Quantum two level systems

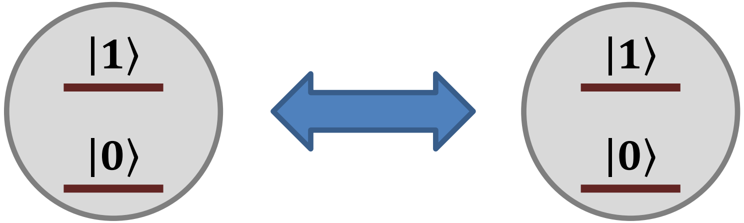


$\alpha|0\rangle + \beta|1\rangle$

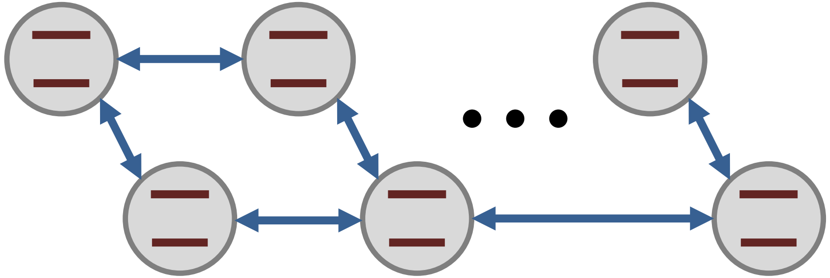
Create arbitrary states



Measure quantum states

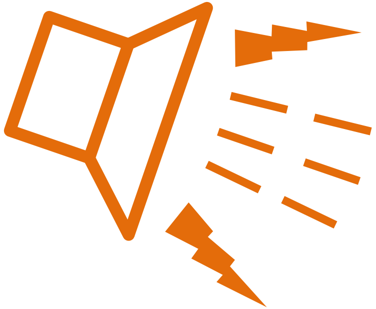


Couple multiple qubits



Scalable architecture

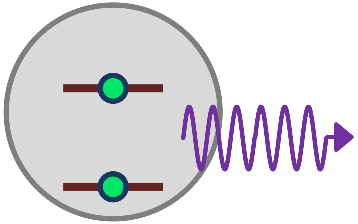
Challenges: Decoherence



Noise

Decoherence

Relaxation (T_1)

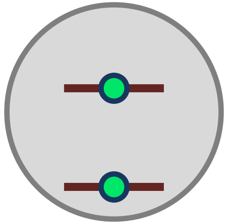


$\alpha|0\rangle + \beta|1\rangle$

↓

$|0\rangle$

Dephasing (T_ϕ)

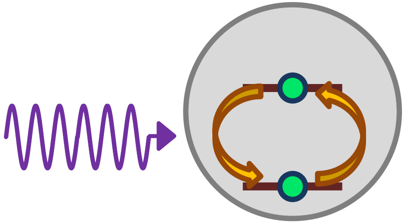


$|0\rangle + e^{i\phi}|1\rangle$

↓

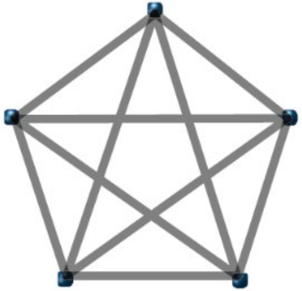
Incoherent mix of $|0\rangle$ and $|1\rangle$

Challenges: Gates and Connectivity



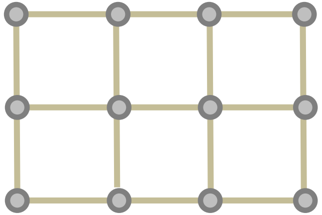
Fast & high-fidelity

$$\frac{\text{Coherence time}}{\text{Gate time}}$$

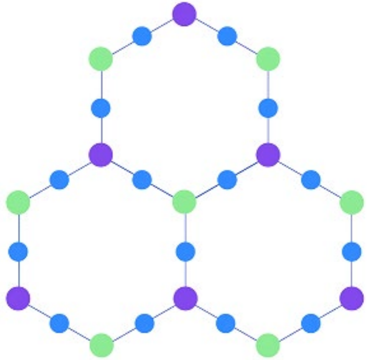


All-to-all

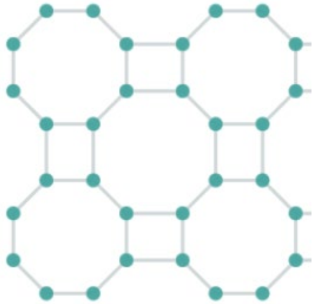
Linear chain



Square lattice



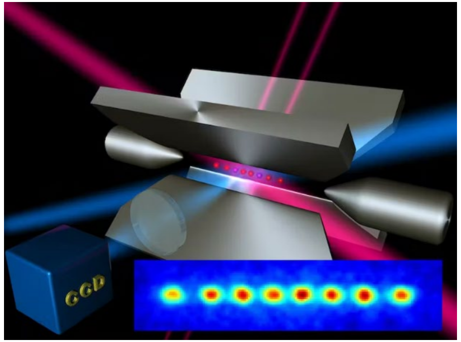
Heavy hexagon



Octagonal

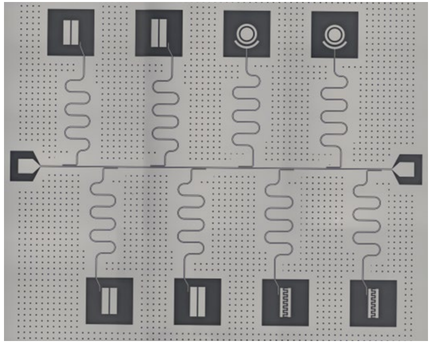
Different Platforms

Trapped ions



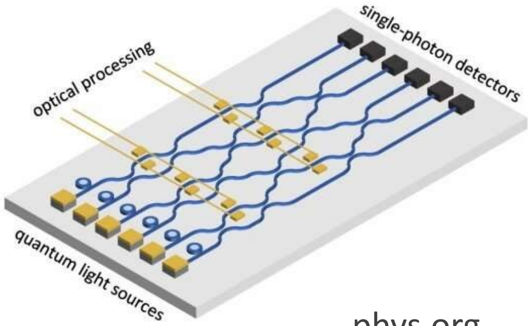
laserfocusworld.com

Superconducting circuits



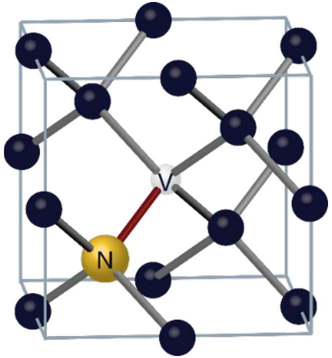
SQMS

Photonic crystals



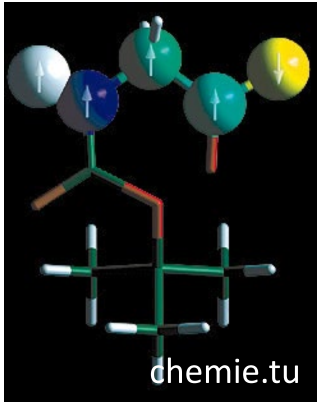
phys.org

NV centers



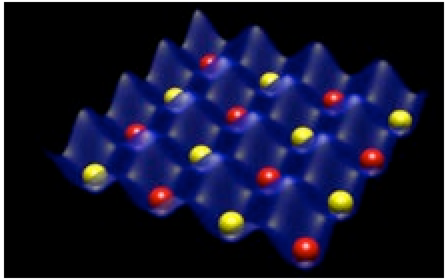
phys.org

NMR



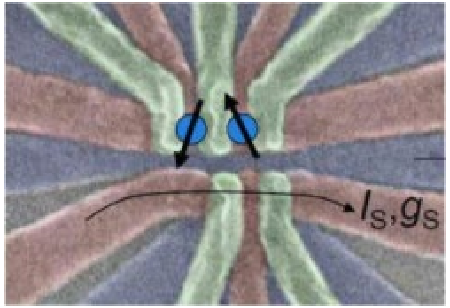
chemie.tu

Neutral atoms



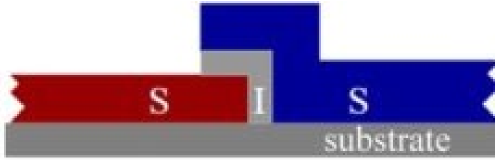
NIST

Quantum dots



sciencemag.org

Superconducting Circuits

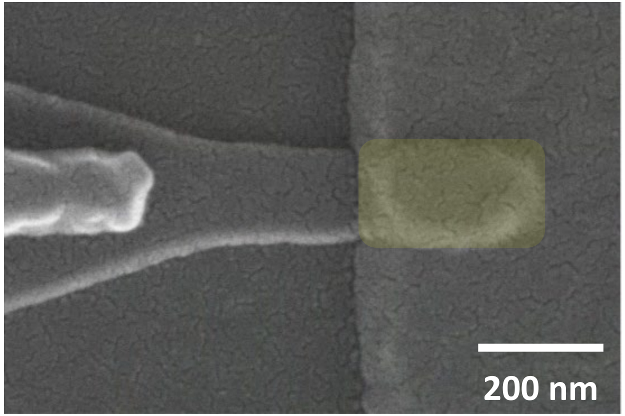


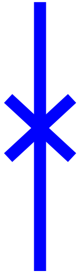
Josephson Junction

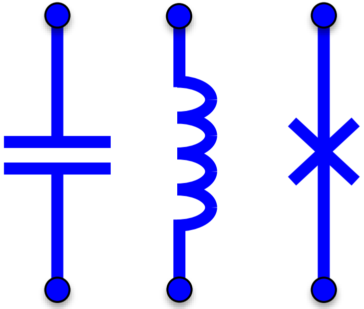
$$I(t) = I_0 \sin\delta(t)$$
$$V(t) = \varphi_0 \dot{\delta}(t)$$

Lossless nonlinear inductor

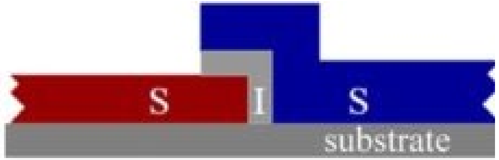
$$L_J(I) = \frac{\varphi_0}{(I_0^2 - I^2)^{1/2}}$$







Transmon Circuit



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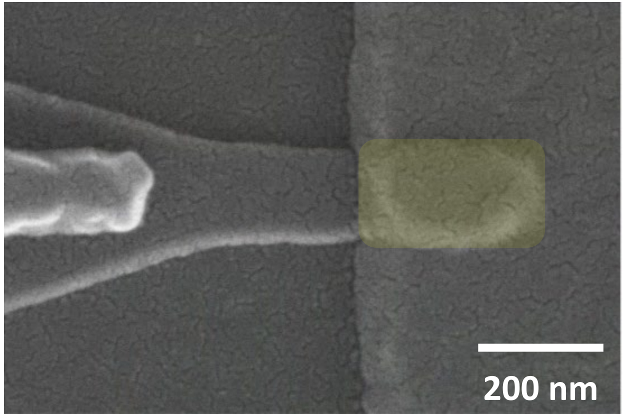

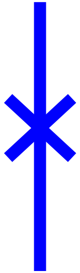

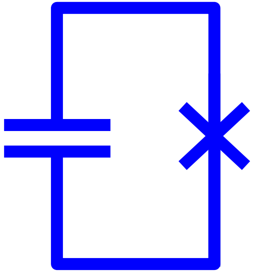

Transmon

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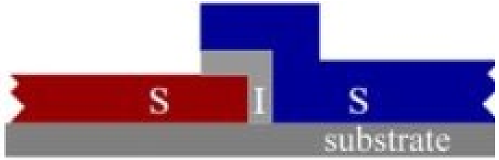

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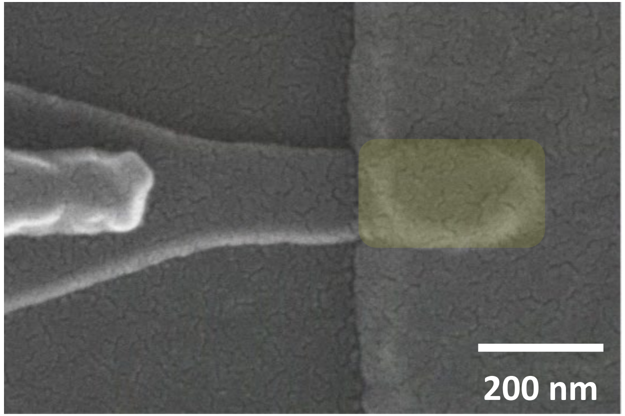
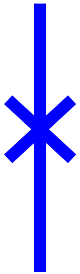
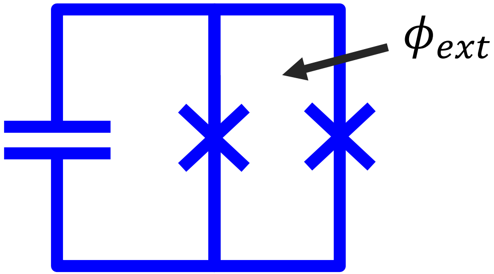
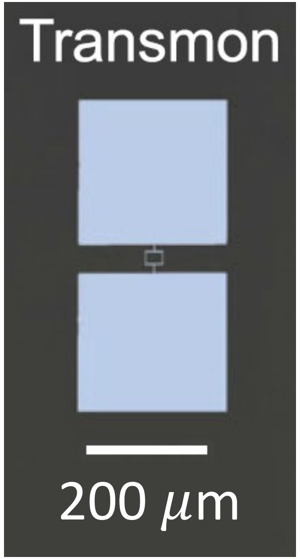


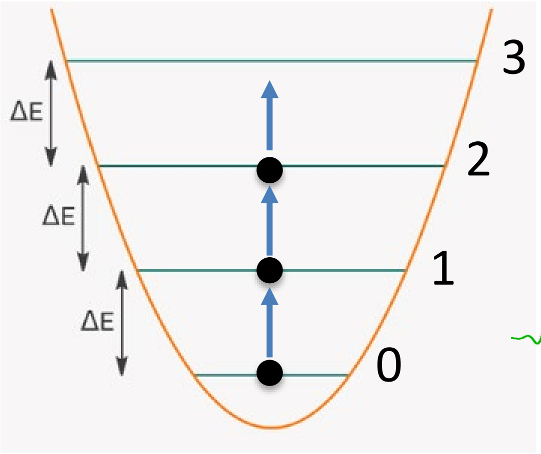


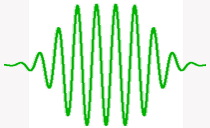


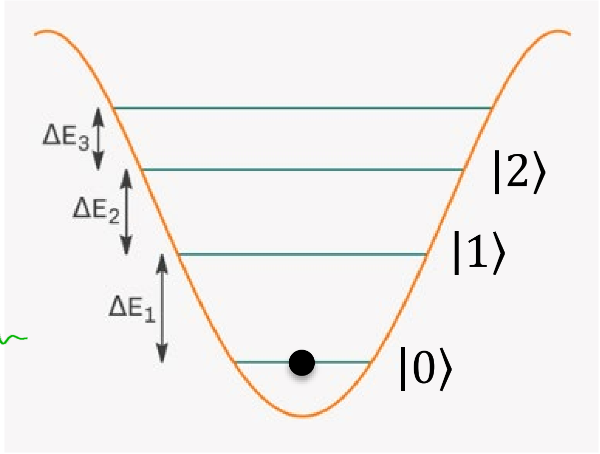
Tunable Transmon



Transmon: Anharmonic Oscillator

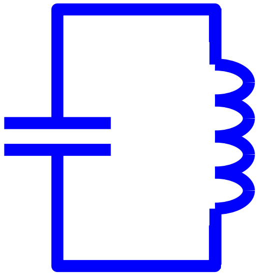


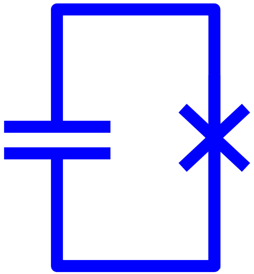




Harmonic Oscillator

Anharmonic Oscillator





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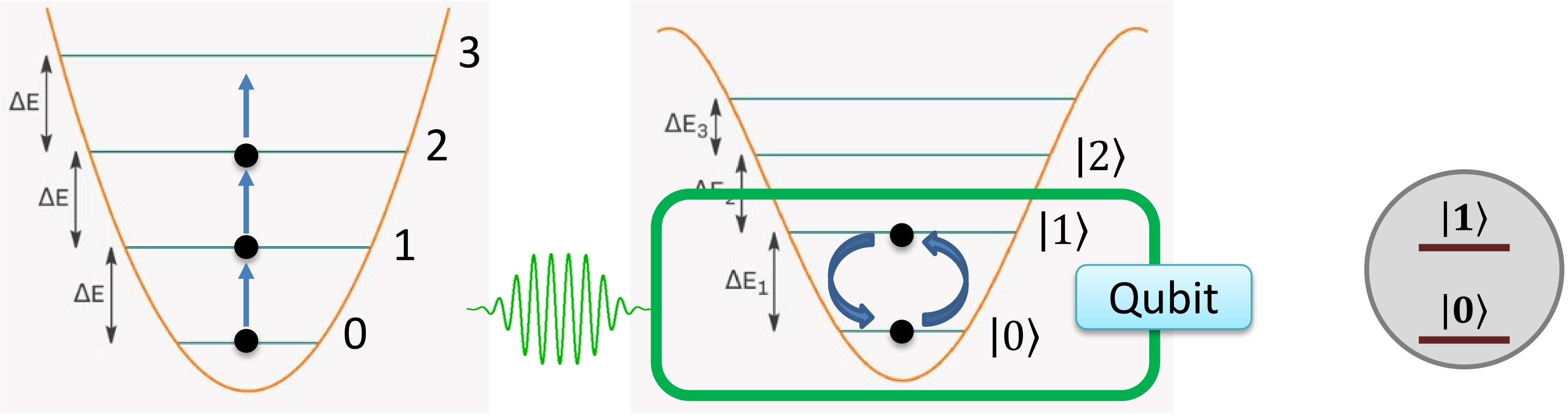

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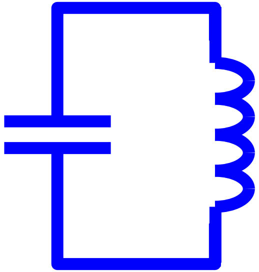
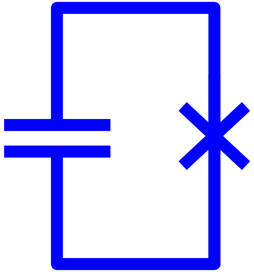




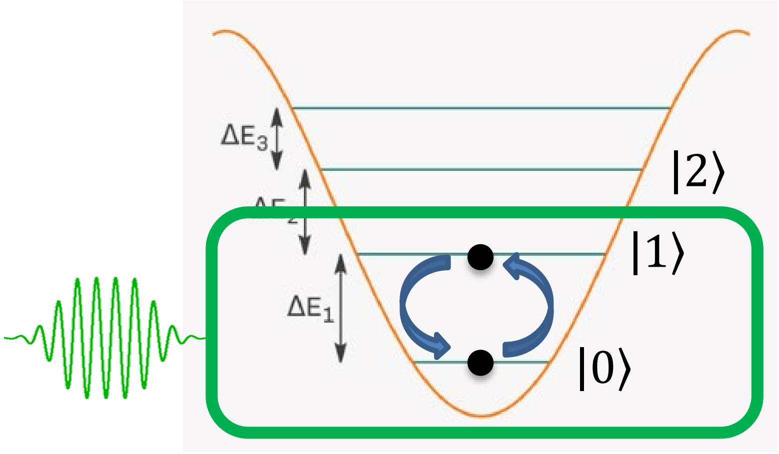
Operating Temperature

$$f_{01} \approx \frac{1}{2\pi\sqrt{L_J C}}$$

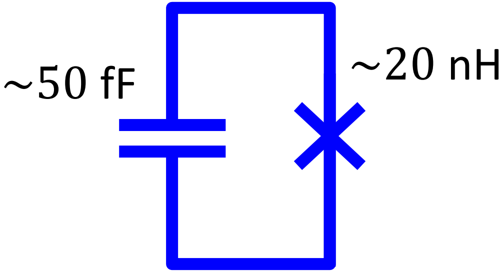
$\sim$ 5 GHz

$$k_B\, T \ll h\, f_{01}$$

20 mK $\sim$ 240 mK



Anharmonic Oscillator



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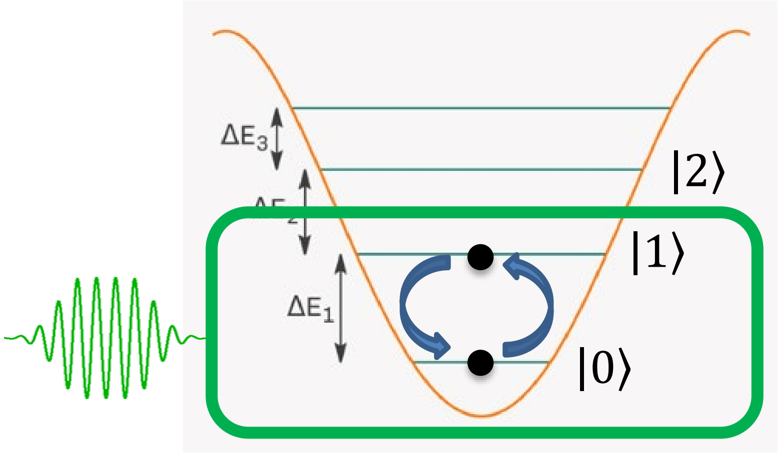

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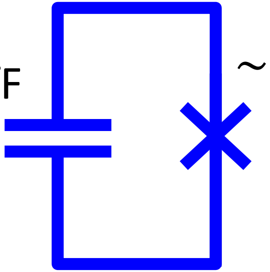
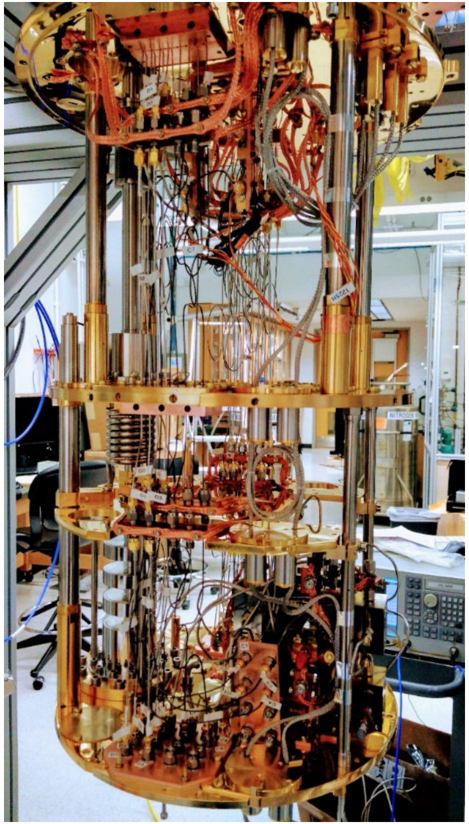
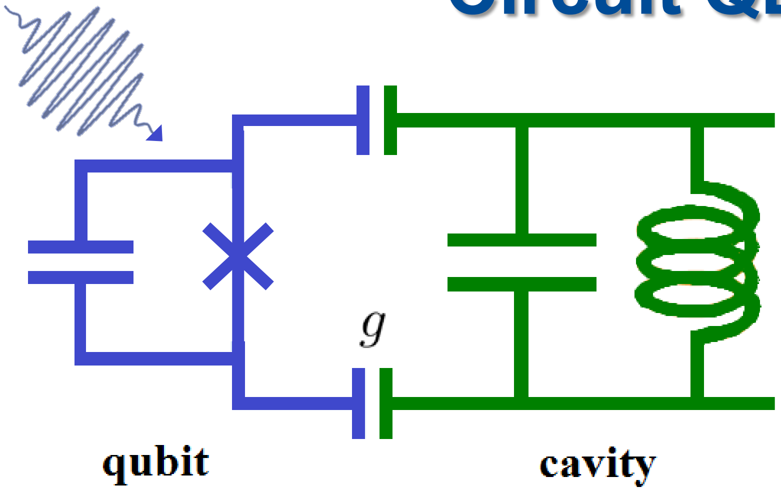
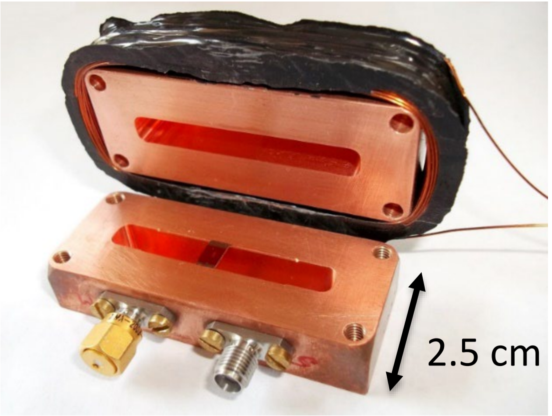


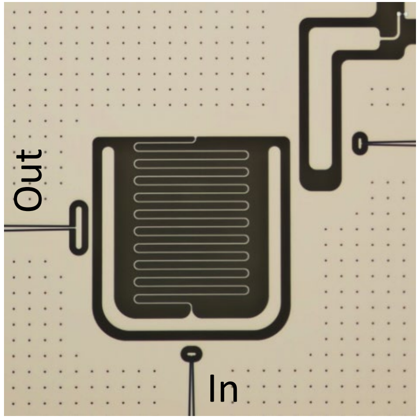


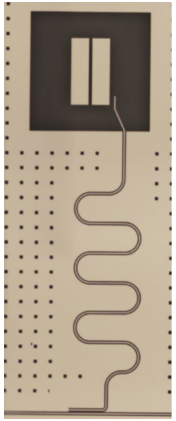
Dilution fridge ~ 10 mK

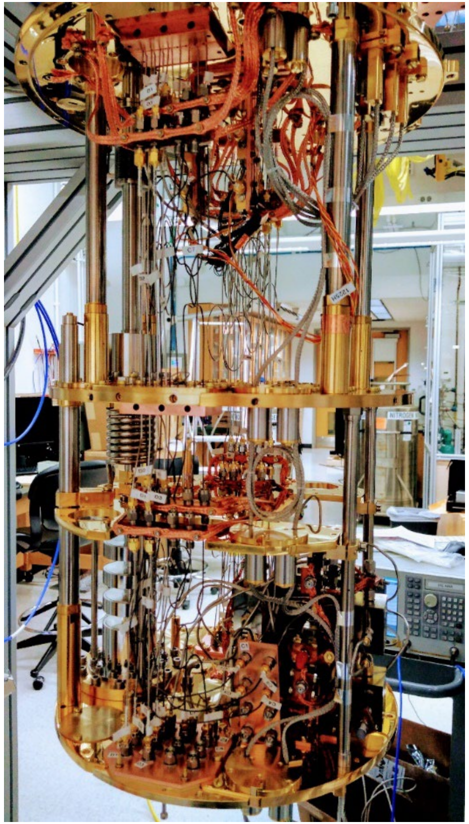
Circuit QED Architecture







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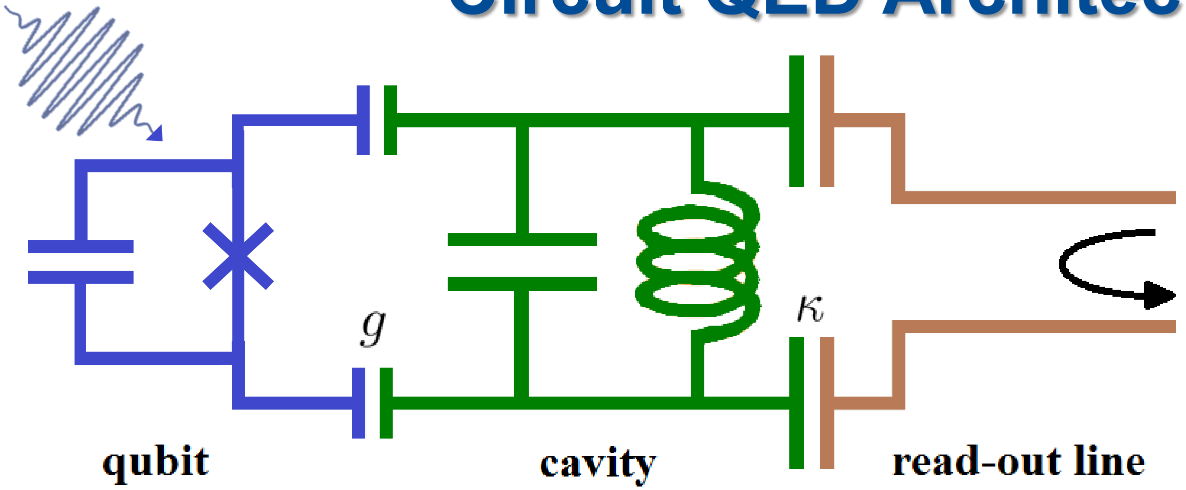


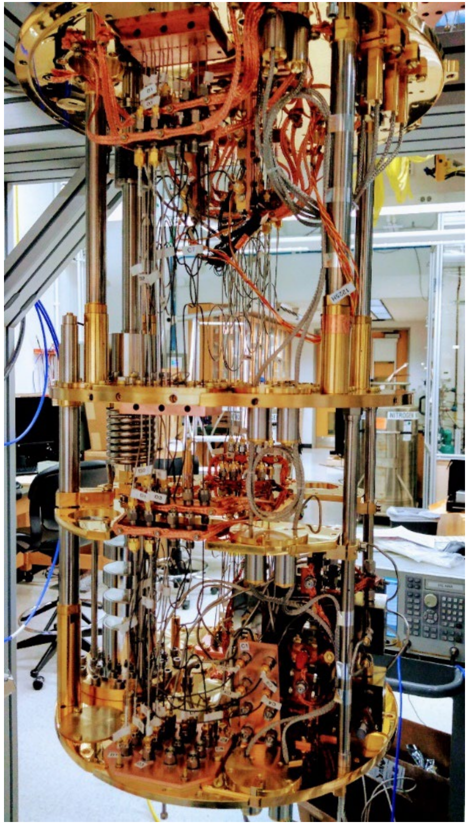
$$H = \frac{\omega_q}{2}\sigma_z + \omega_c a^\dagger a + g(a^\dagger \sigma_- + a\sigma_+)$$

$$\approx \frac{\omega_q}{2}\sigma_z + \omega_c a^\dagger a + \frac{\chi}{2}(a^\dagger a)\sigma_z$$

$$= \frac{\omega_q}{2}\sigma_z + \left(\omega_c + \frac{\chi}{2}\sigma_z\right) a^\dagger a$$

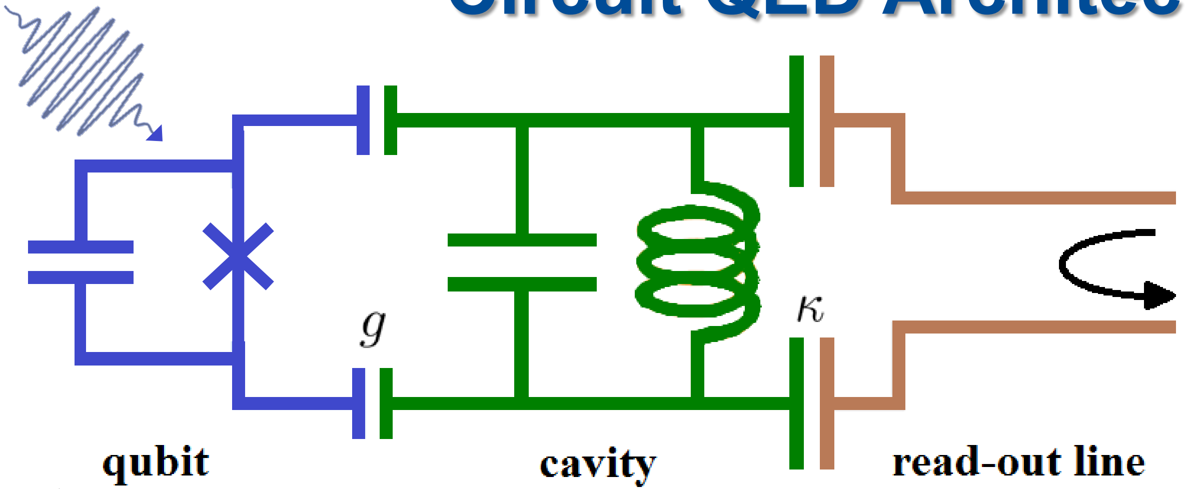
$$\Delta = \omega_q - \omega_c$$

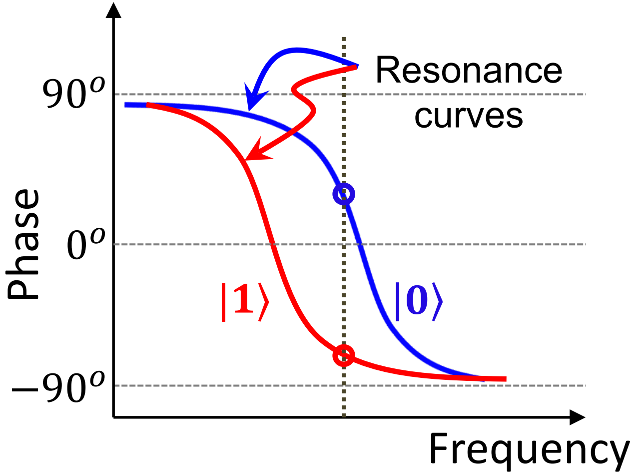
$$g \ll \Delta, \chi = 2g^2/\Delta$$

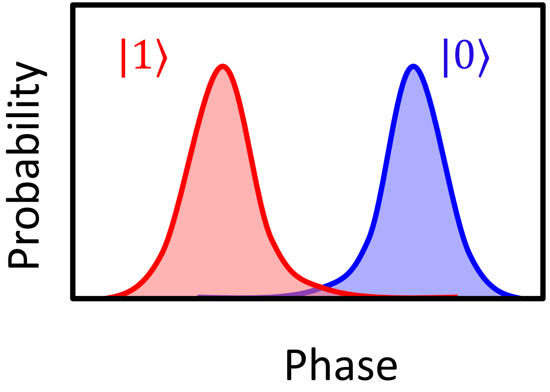


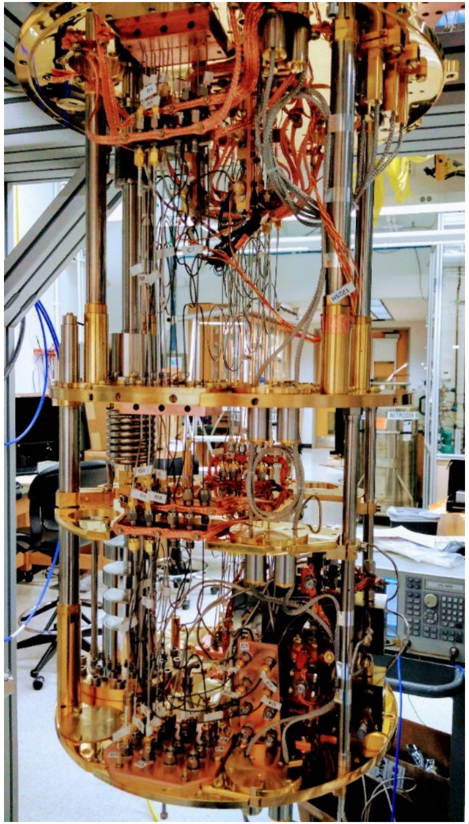
Dilution fridge ~ 10 mK

Circuit QED Architecture





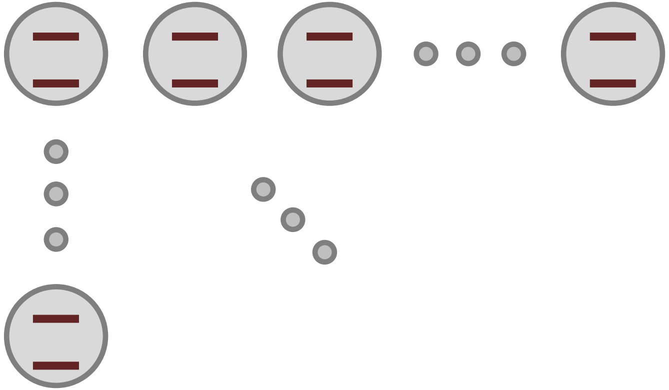




Dilution fridge ~ 10 mK

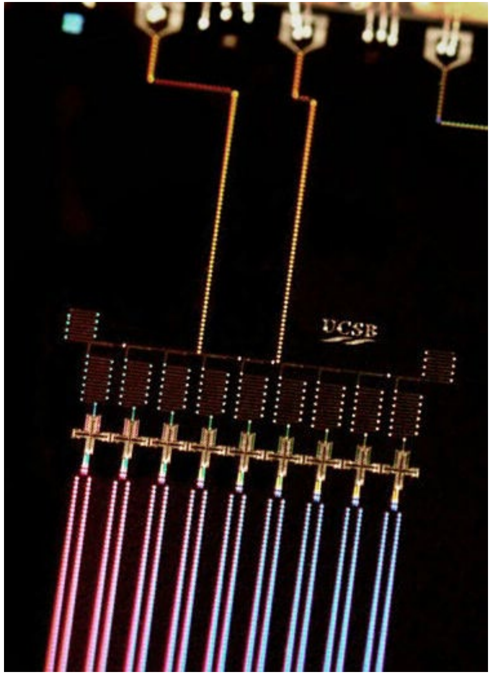
Traditional Multi-qubit Architecture

Linear or planar geometry

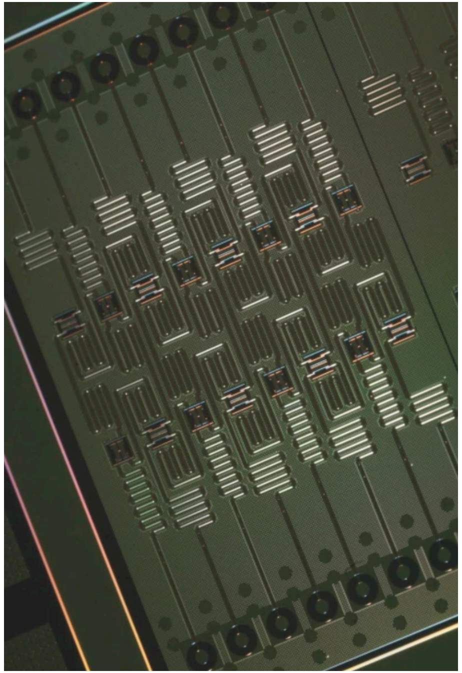


Computational space: 2^N

Can we do **better**?



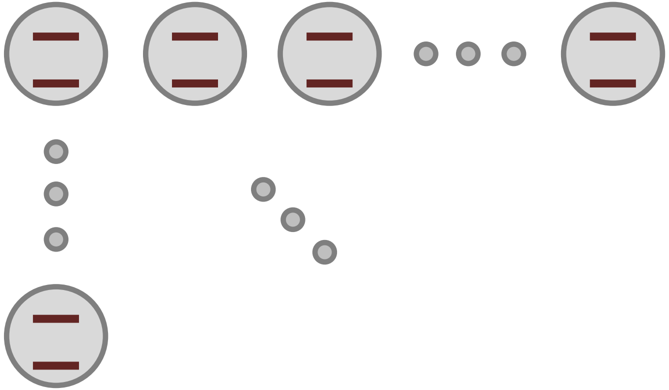
UCSB, Nature 519 (7541)



IBM

Traditional Multi-qubit Architecture

Linear or planar geometry

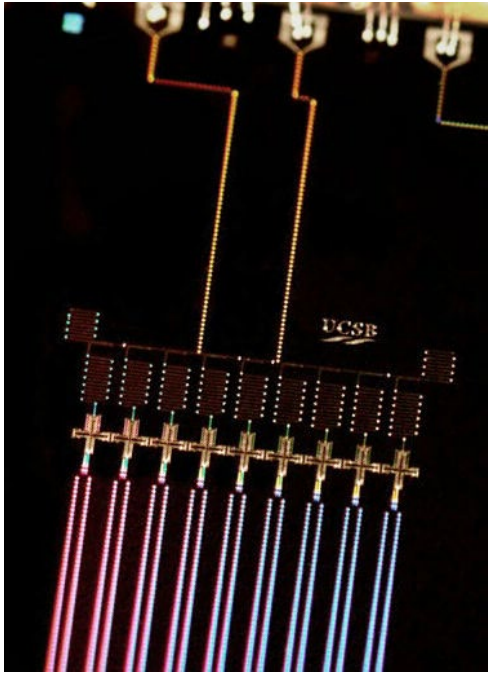


Computational space: 2^N

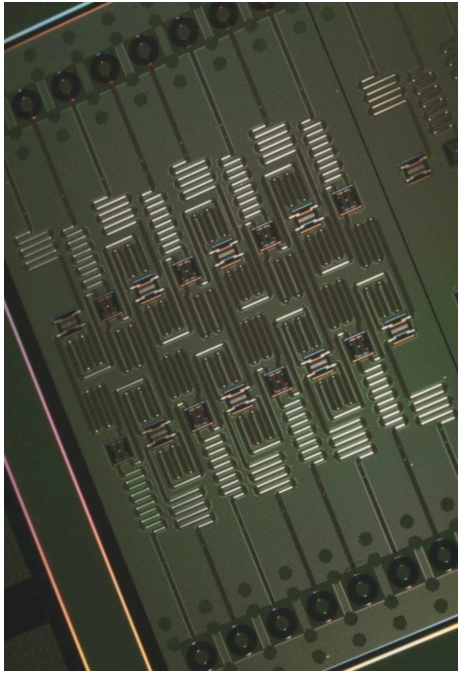
Can we do better?

Scaling: $d^N, d > 2$

Qudit



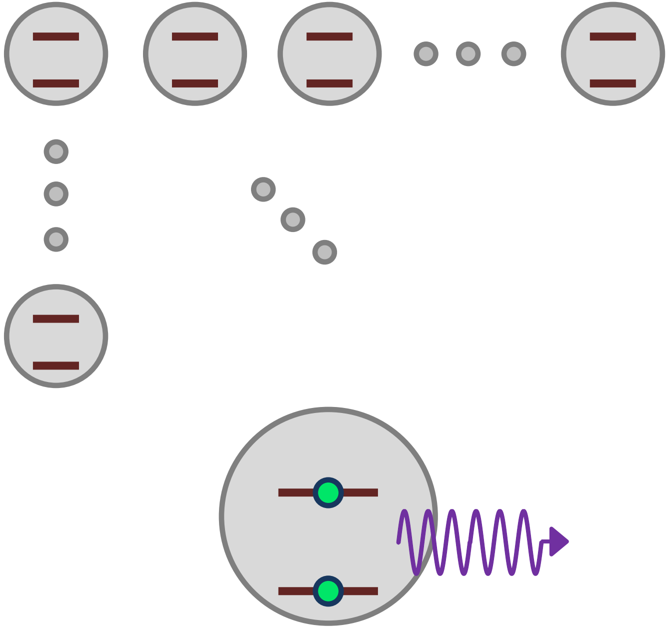
UCSB, Nature 519 (7541)

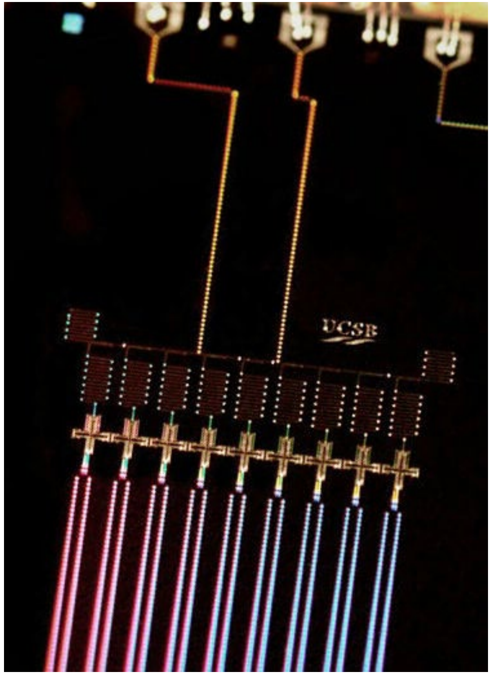


IBM

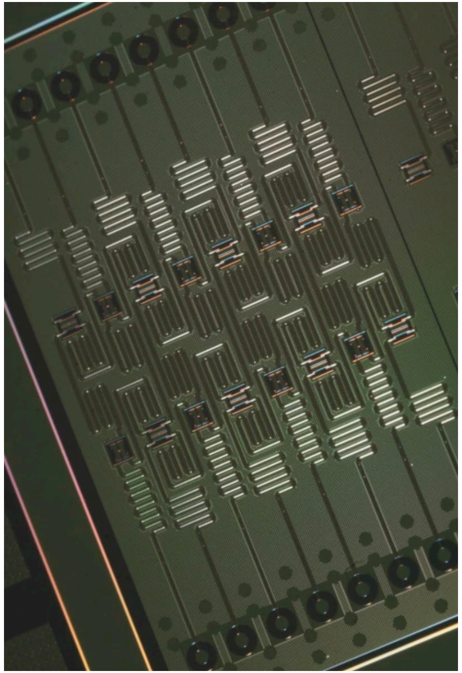
Problem of Relaxation

Linear or planar geometry





UCSB, Nature 519 (7541)



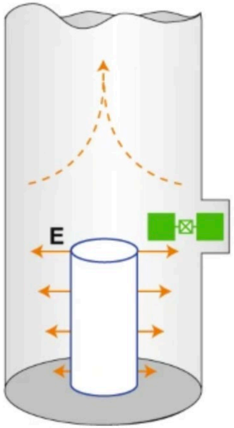
IBM

$T_1 \sim 100\ \mu s$

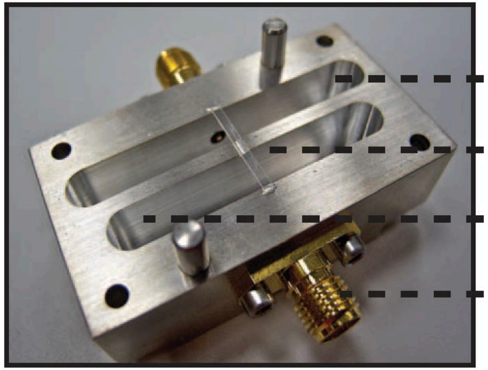
Q: a few 10^6

Can we do **better**?

Zoo of Cavities

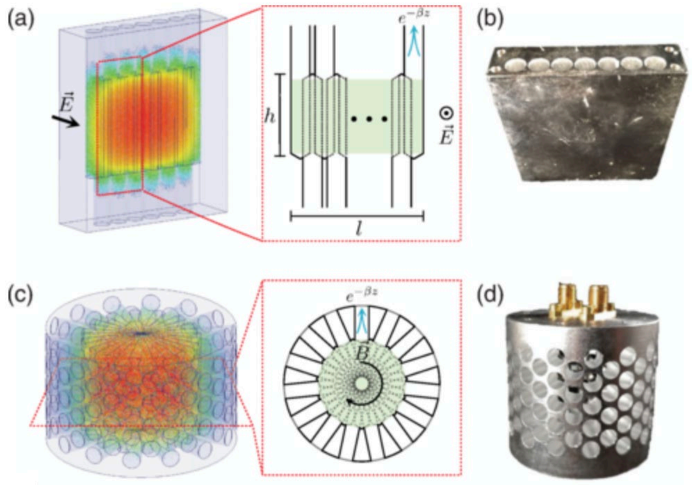


Nat. Phys. 16, 247



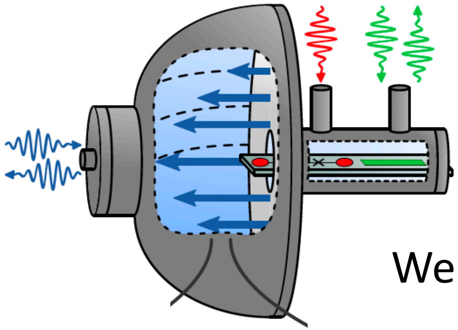
Science 342, 6158

Yale, U. Pittsburgh



PRL 127, 107701

U. Chicago, Rutgers

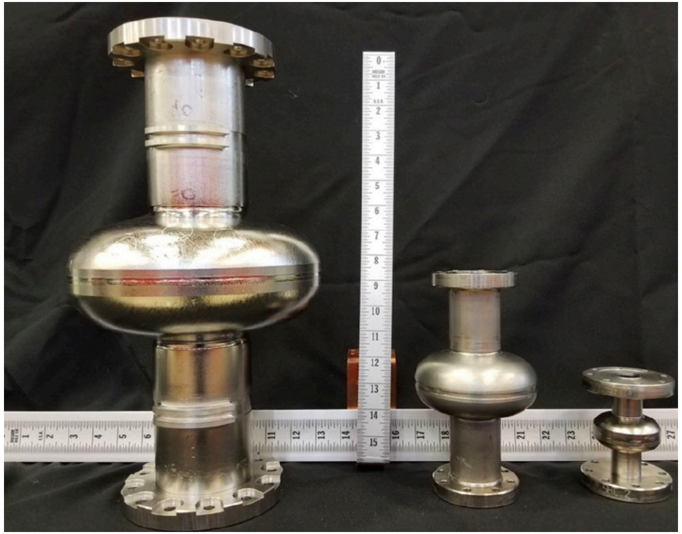


Weizmann

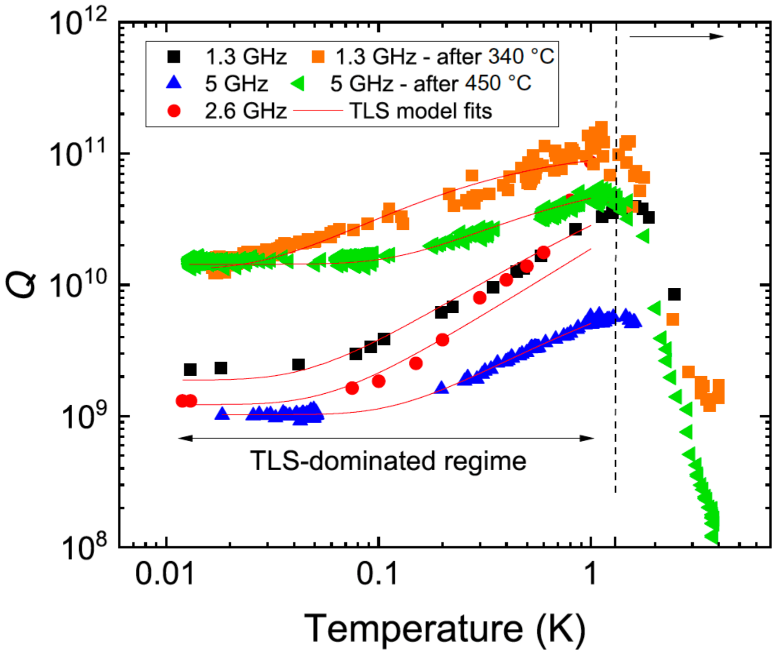
PRX Quant. 4, 030336

Under exploration

High-Q 3D SRF Cavities



Romanenko et al. PRApplied 13, 034032

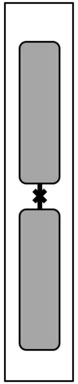


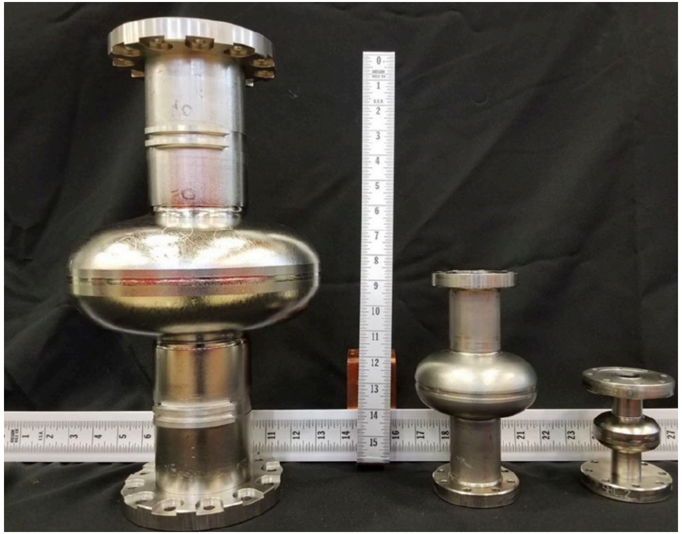
1.3 GHz SRF: $Q > 10^{11}$ at 1 K ⟹ $T_1 > 2$ s

5 GHz SRF: $Q > 10^{10}$ at 10 mK ⟹ $T_1 > 300$ ms

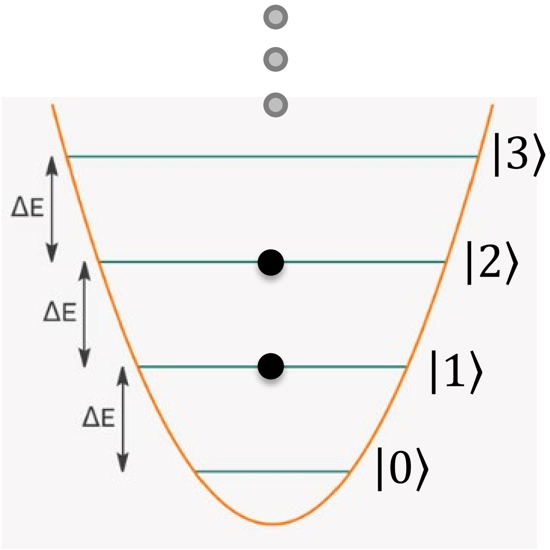
>1000 times better than transmons

High-Q 3D Cavities as Qudits





Romanenko et al. PRApplied 13, 034032



$T_1^{|1\rangle} > 300$ ms

$T_1^{|2\rangle} > 150$ ms

$T_1^{|n\rangle} > T_1^{|1\rangle}/n$

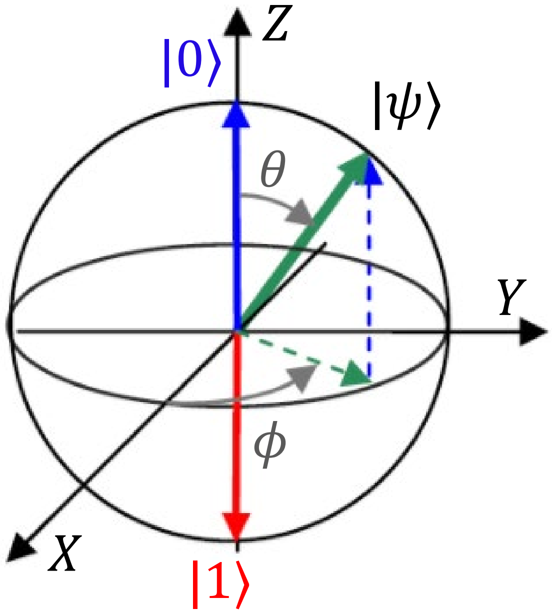
$T_1^{|10\rangle} > 30$ ms

Qudit

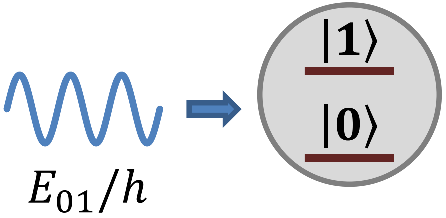
Still much better than transmon qubits

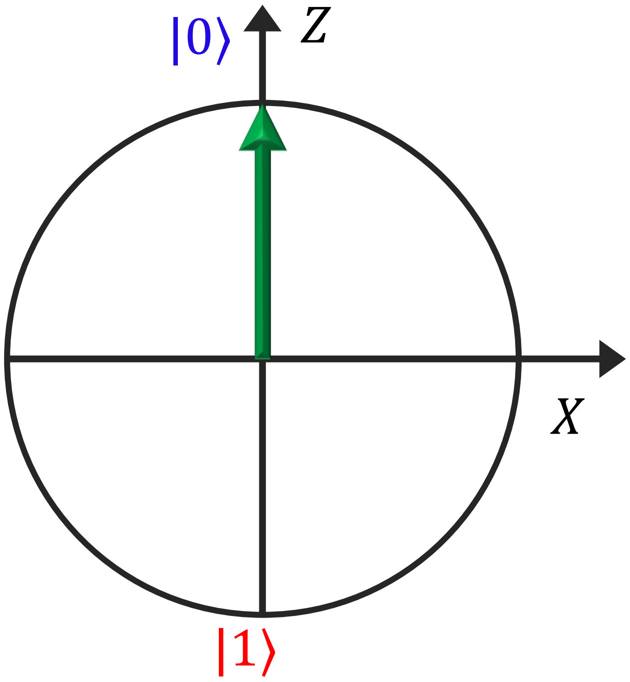
Qubit Visualization

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \quad = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$



Bloch Sphere

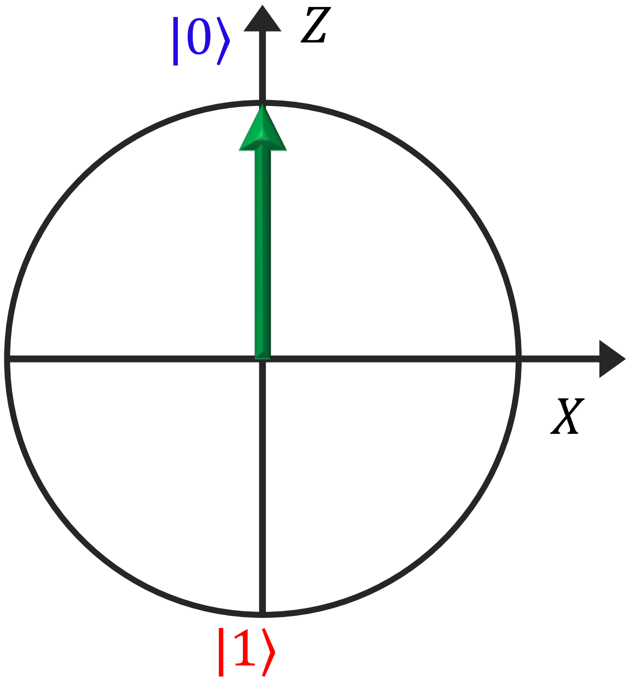




Rabi Oscillation

Single-Qubit Gates

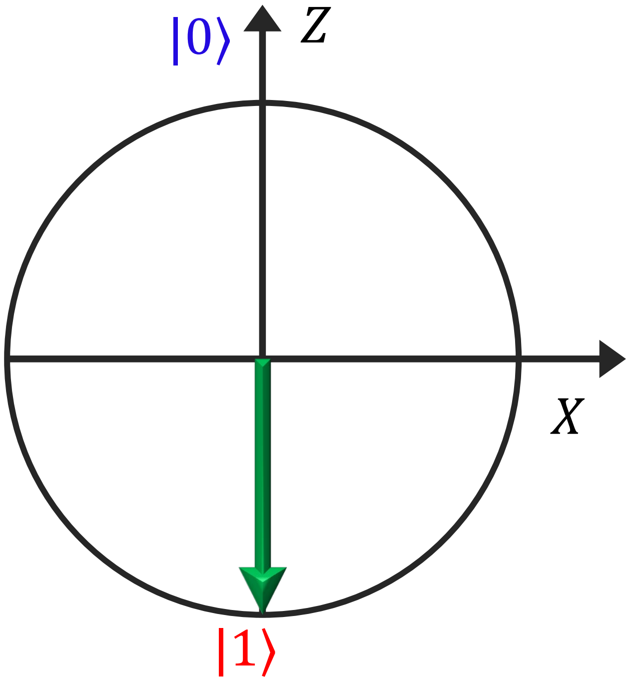
$\pi/2$ pulse: $|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$



Single-Qubit Gates

$\pi/2$ pulse: $|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$

$|1\rangle \rightarrow (|0\rangle - |1\rangle)/\sqrt{2}$



Single-Qubit Gates

$\pi/2$ pulse: $|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$

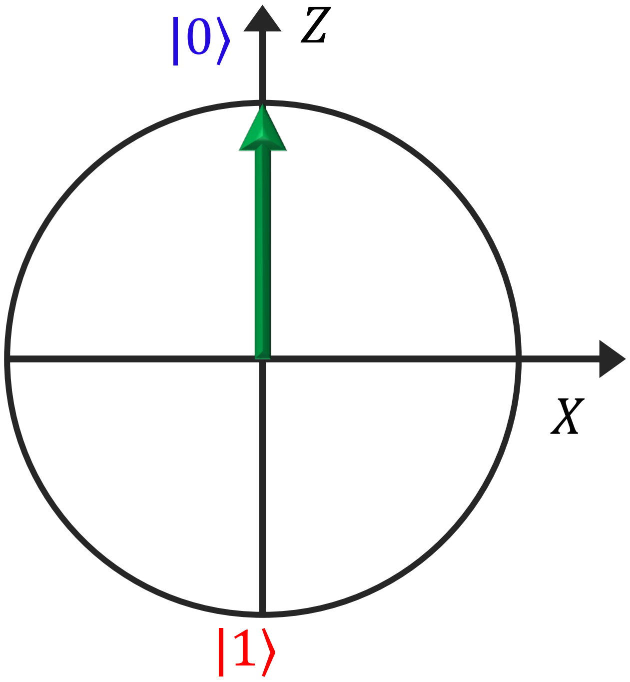
$|1\rangle \rightarrow (|0\rangle - |1\rangle)/\sqrt{2}$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

π pulse: $|0\rangle \rightarrow |1\rangle$

$|1\rangle \rightarrow |0\rangle$

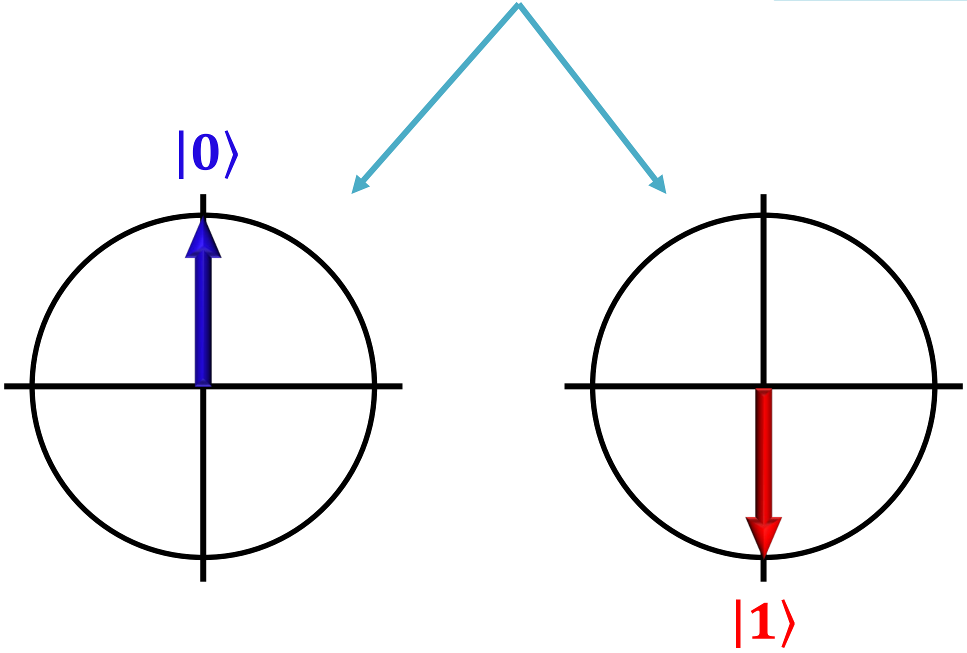
$$X = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$



Single-Qubit Measurement

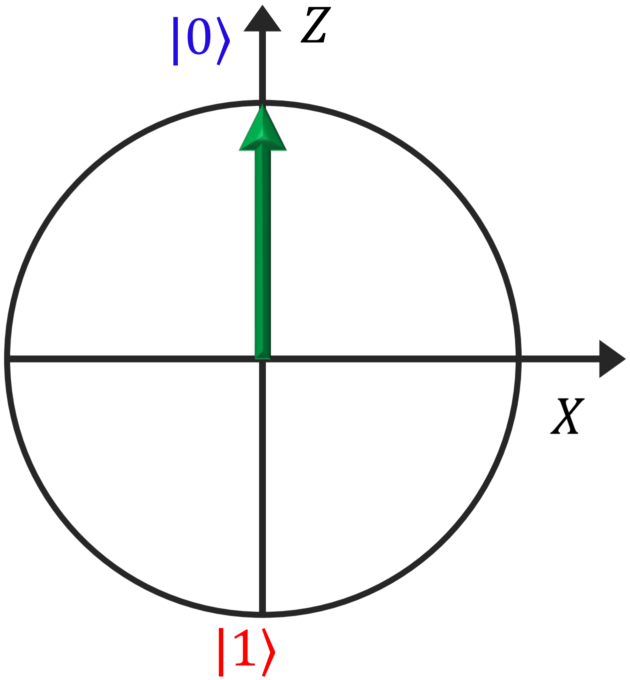
$\alpha|0\rangle + \beta|1\rangle$

Measure



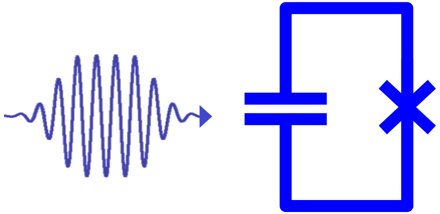
$P(0) = |\alpha|^2$

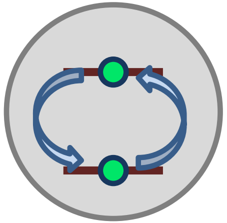
$P(1) = |\beta|^2$



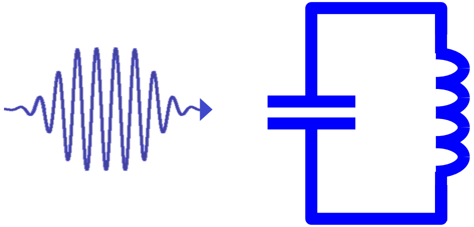
Transmon vs. Cavity Drive

Qubit: $\alpha|0\rangle + \beta|1\rangle$

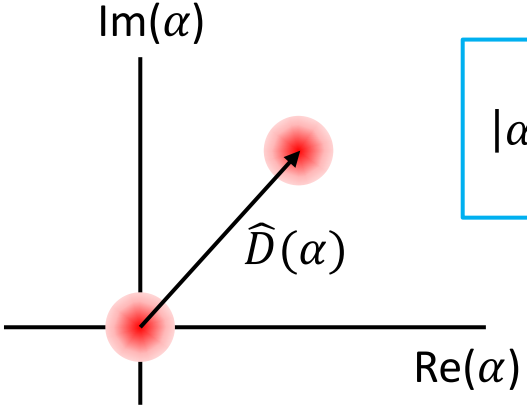




Qudit: $\alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle$



Coherent state



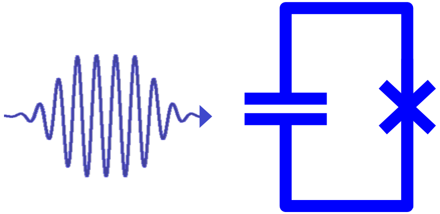
$$|\alpha\rangle = c \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

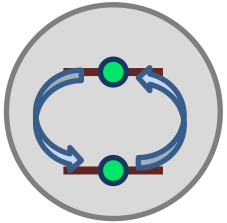
Classical

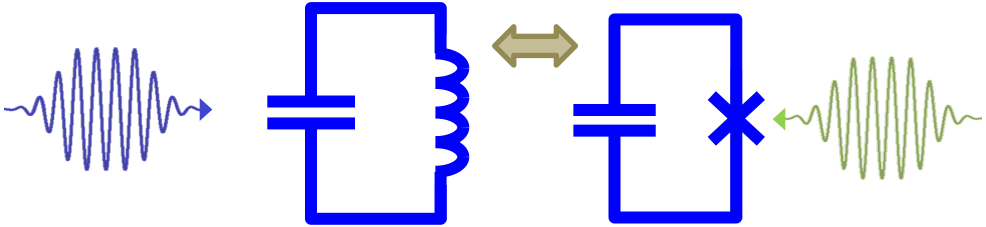
Transmon vs. Cavity Drive

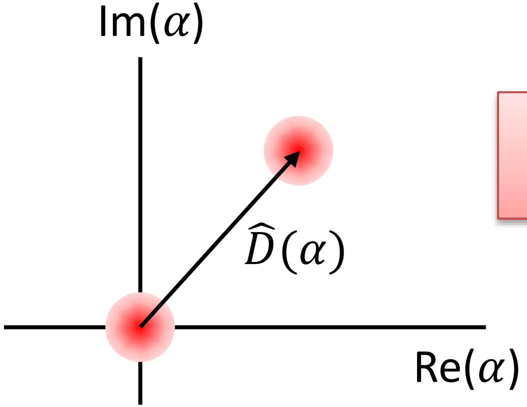
Qubit: $\alpha|0\rangle + \beta|1\rangle$

Qudit: $\alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle$









Quantum states?

Qudit Operation

$|0\rangle$ $\xrightarrow{\mathcal{D}(\alpha = 1)}$ $\alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle$

$|1\rangle \to e^{i\pi}|1\rangle$

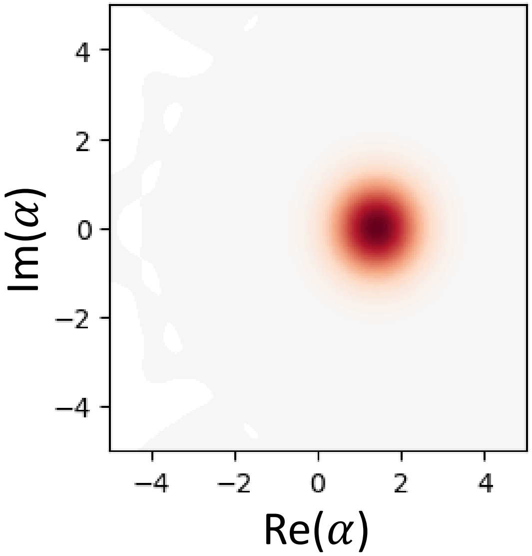
Quantum state

$\alpha_0|0\rangle - \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle$

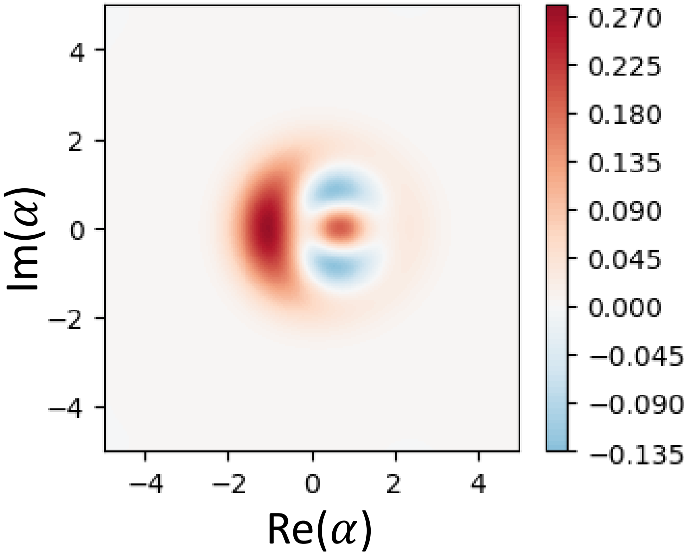
$|n\rangle \to e^{i\theta}|n\rangle$

Selective number-dependent arbitrary phase (SNAP) gate

PRL 115, 137002 (2015)

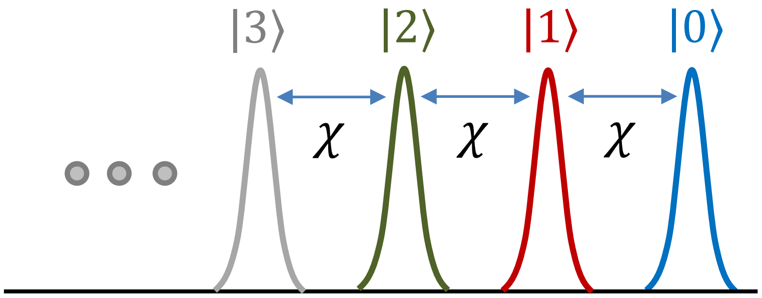


$|1\rangle \to e^{i\pi}|1\rangle$

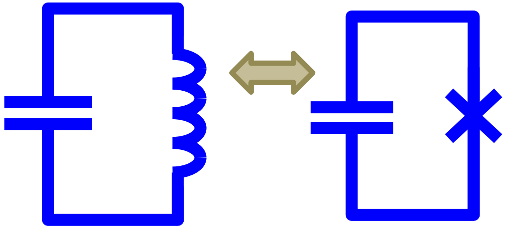


Qubit Frequency Dependence

$$H = \omega_c a^\dagger a + \left(\omega_q + \chi a^\dagger a\right)\frac{\sigma_z}{2}$$



$\chi > \gamma$



$$\omega_q'(|0\rangle_c) = \omega_q$$

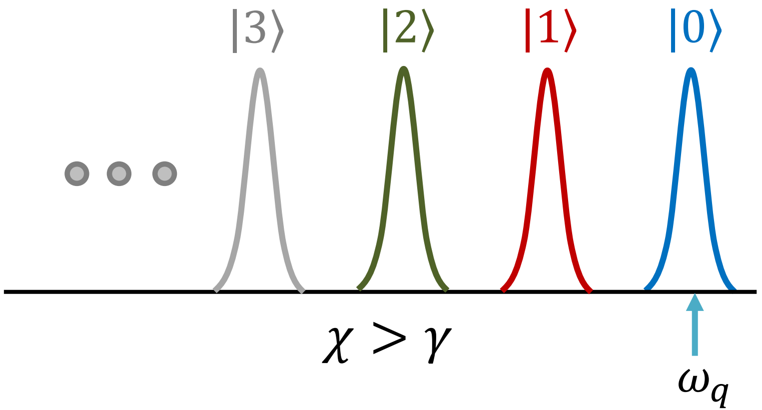
$$\omega_q'(|1\rangle_c) = \omega_q + \chi$$

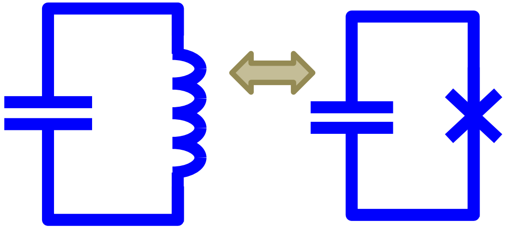
⋮

$$\omega_q'(|n\rangle_c) = \omega_q + n\chi$$

Visualization of SNAP

Selective number-dependent arbitrary phase pulse





$$(|0\rangle + |1\rangle + |2\rangle + \cdots)_c |0\rangle_q$$

$$= |0\rangle|0\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots$$

$\downarrow$ $\cos \omega_q t$ (π pulse)

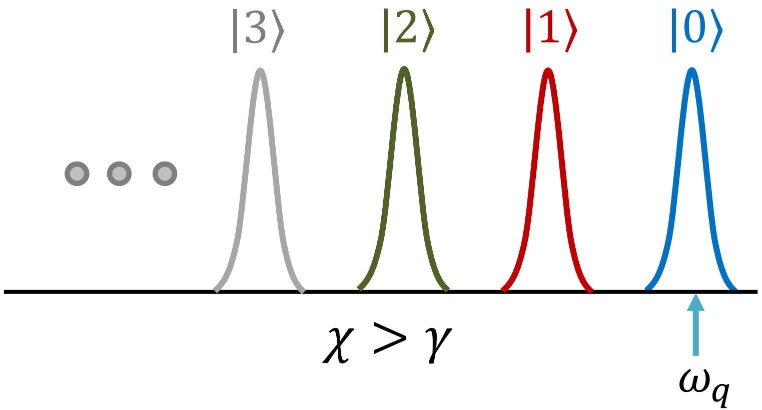
$$|0\rangle|1\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots$$

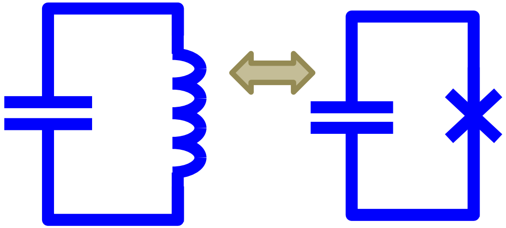
$\downarrow$ $\cos \omega_q t$ (π pulse)

$$-|0\rangle|0\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots$$

Visualization of SNAP

Selective number-dependent arbitrary phase pulse





$$(|0\rangle + |1\rangle + |2\rangle + \cdots)_c|0\rangle_q$$

$$= |0\rangle|0\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots$$

$\downarrow$ $\cos \omega_q t$ (π pulse)

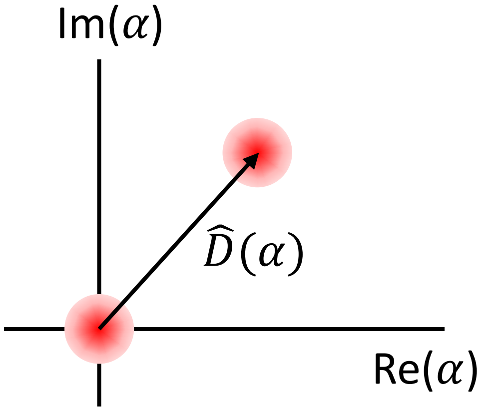
$$|0\rangle|1\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots$$

$\downarrow$ $\cos(\omega_q t + \theta')$

$$e^{i\theta}|0\rangle|0\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots$$

$$= (e^{i\theta}|0\rangle + |1\rangle + |2\rangle + \cdots)|0\rangle$$

Universal Gate Set



Qudit: $\alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle$

SNAP gate

Qudit: $\alpha_0 e^{i\theta_0}|0\rangle + \alpha_1 e^{i\theta_1}|1\rangle + \cdots + \alpha_d e^{i\theta_d}|d\rangle$

Unconditional operation on cavity → Cavity drive

\+

SNAP ← Conditional operation on cavity enabled by a transmon

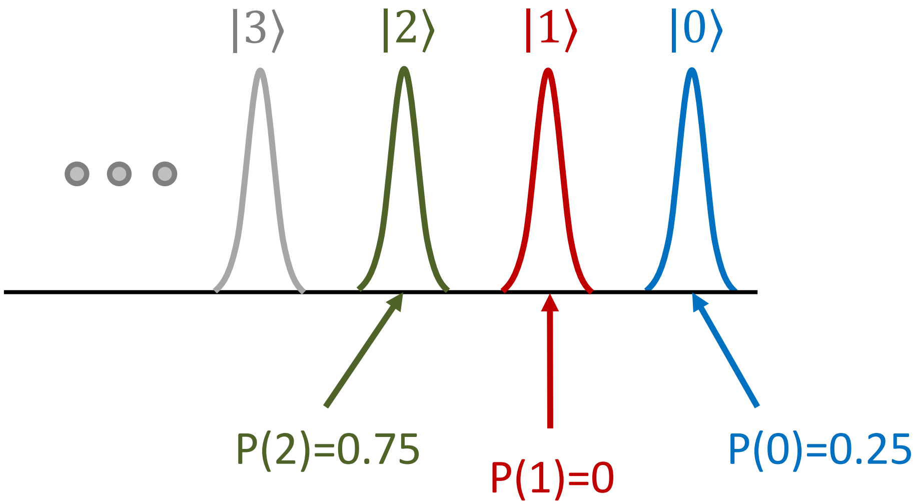
Universal control

Qudit Measurement

$$|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle$$

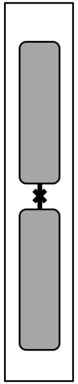
Ask the transmon if there are n photons

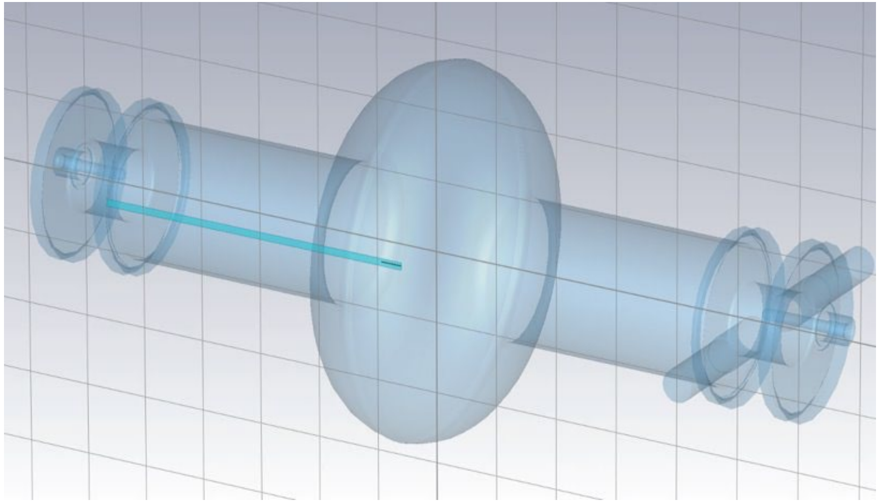
Transmon jumps to $|1\rangle$ if yes



$$|\psi\rangle = \sqrt{\frac{1}{4}}|0\rangle + \sqrt{\frac{3}{4}}|2\rangle$$

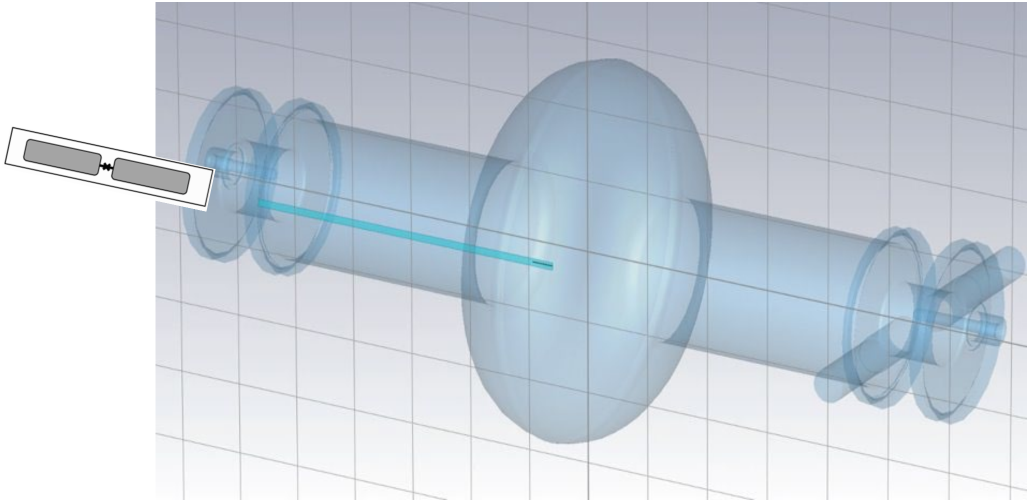
First Milestone





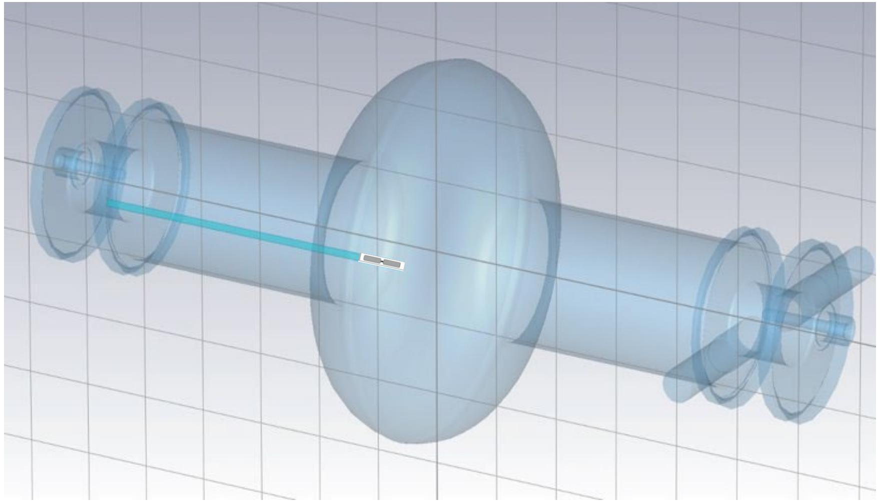
Incorporate Transmon into a TESLA cavity

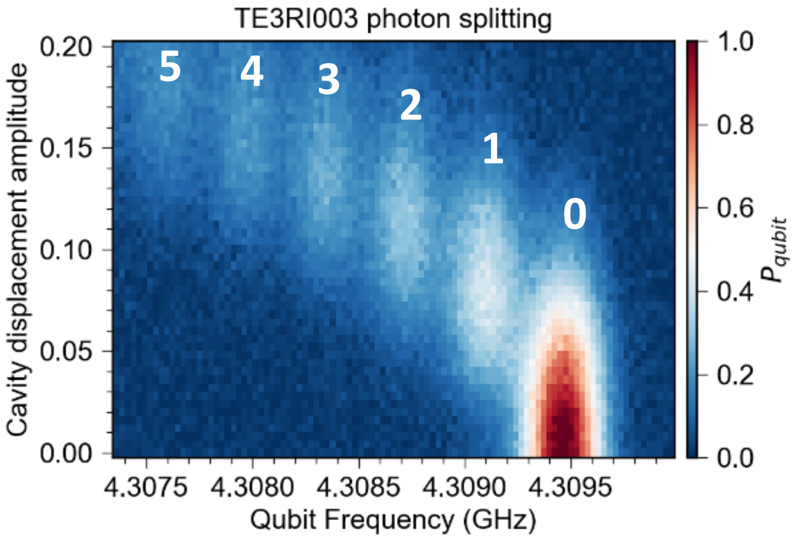
First Milestone



Incorporate Transmon into a TESLA cavity

First Milestone

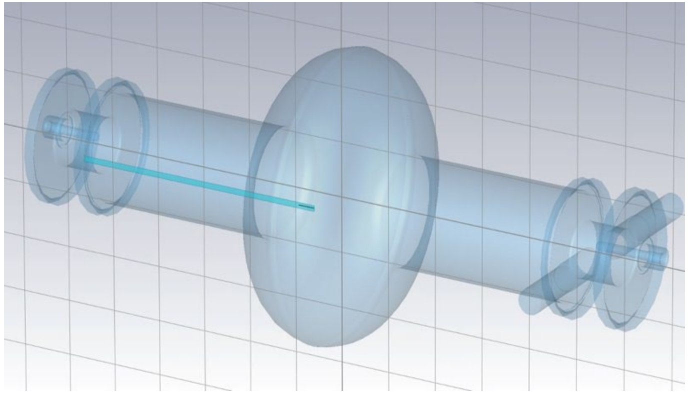




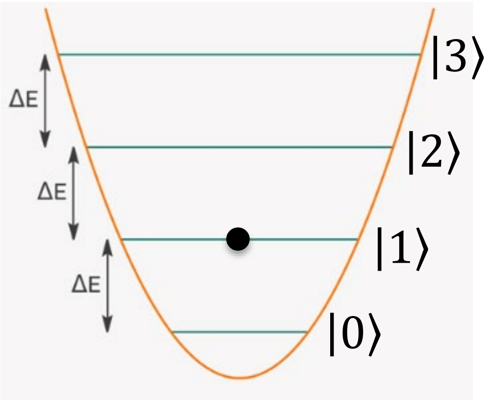
Incorporate Transmon into a TESLA cavity

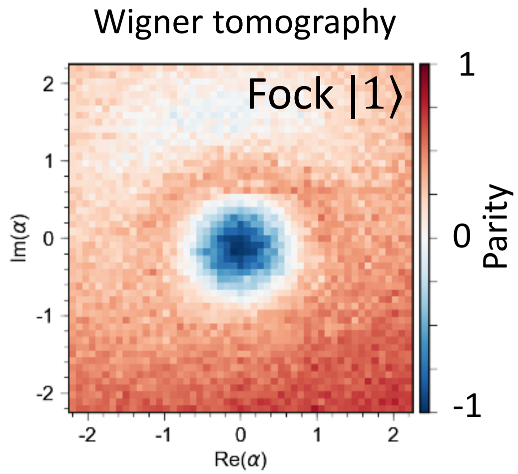
Achieved photon counting

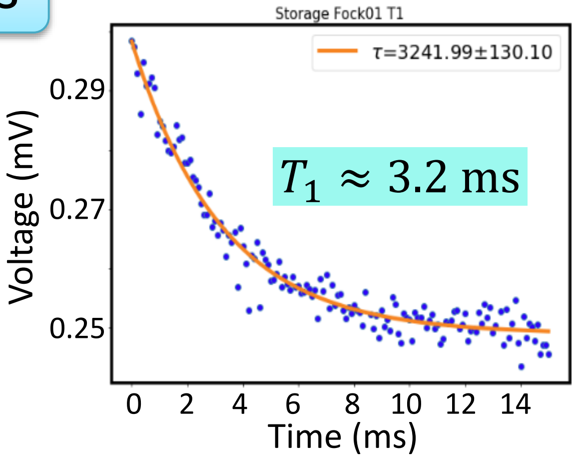
Second Milestone

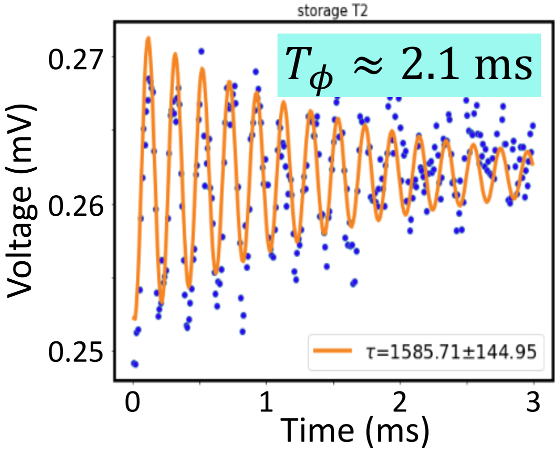


Prepare quantum states



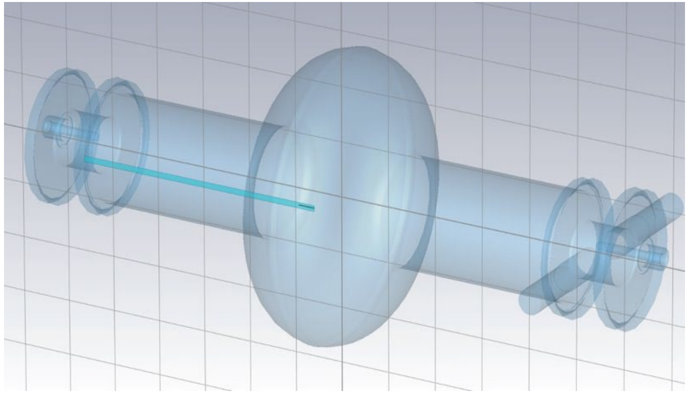




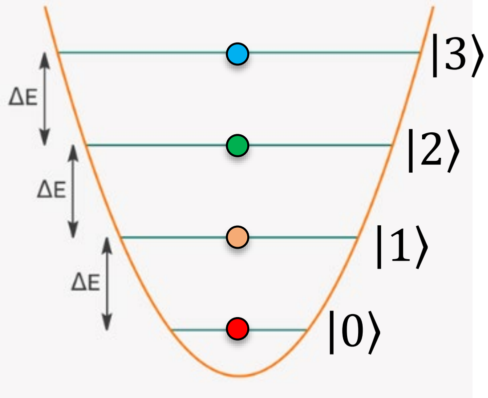


SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

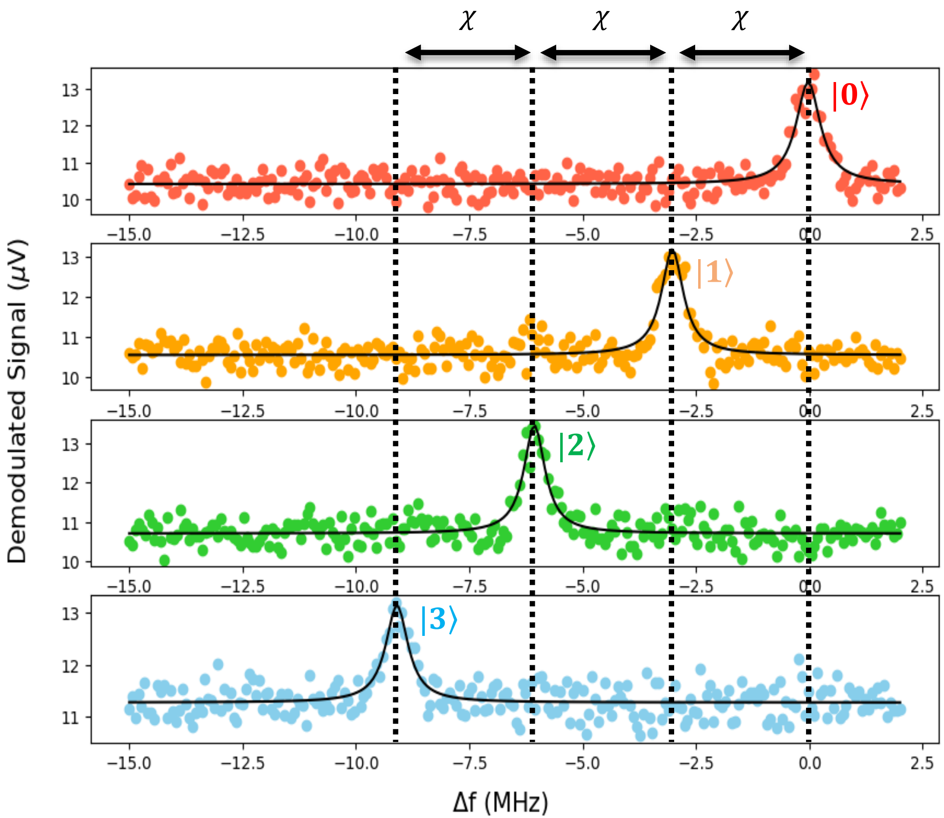
Second Milestone



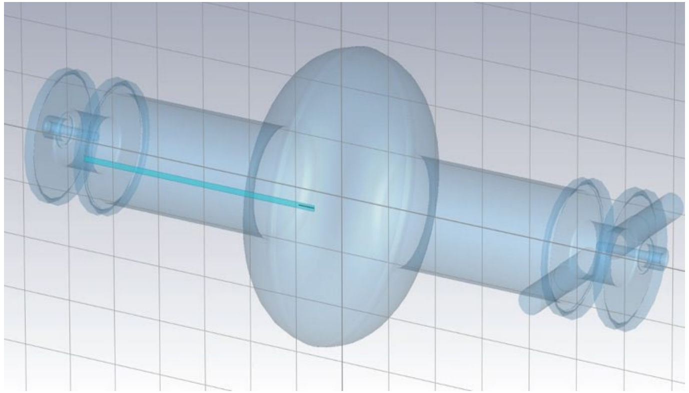
Prepare quantum states

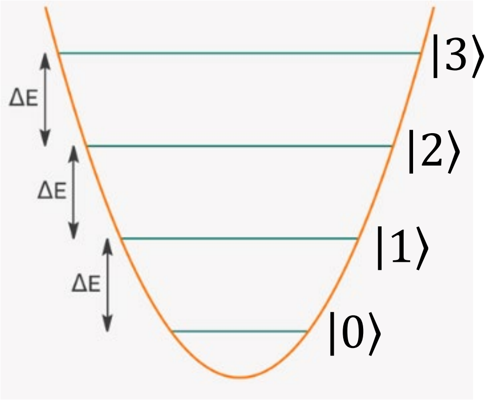


Qubit spectroscopy



Advantages





Longer coherence

- T_1 = 3.2 ms vs. ~100 us
- T_ϕ = 2.0 ms vs <100 us

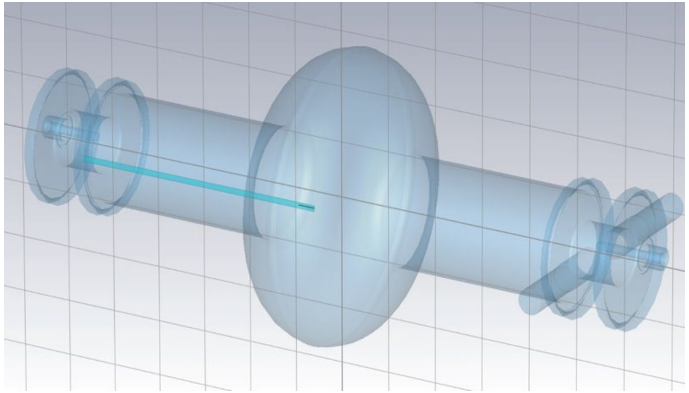
Larger Hilbert Space

- Effectively $\log_2 d$ qubits
- Enables qudit encoding

Efficient control

- One input, one output
- Reduced control hardware

Further Improvements



$T_1 > 50$ ms when no transmon

Substrate

Transmon

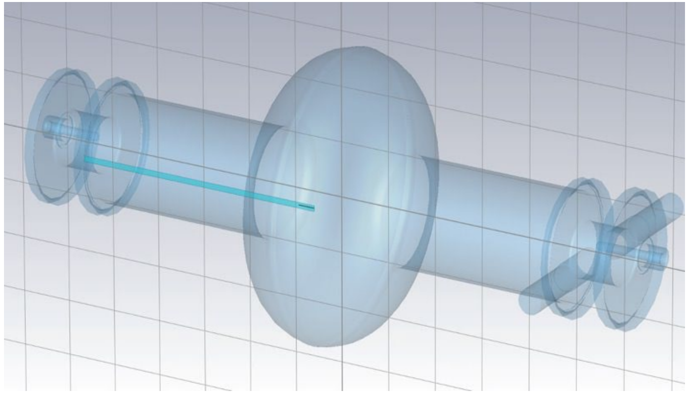
Geometry

Shielding

Find loss sources and eliminate

cite

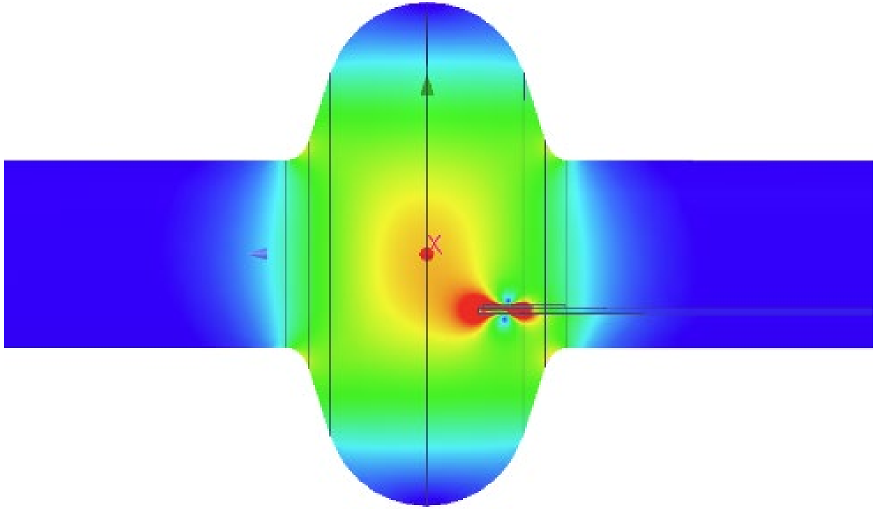
Further Improvements



$T_1 > 50$ ms when no transmon

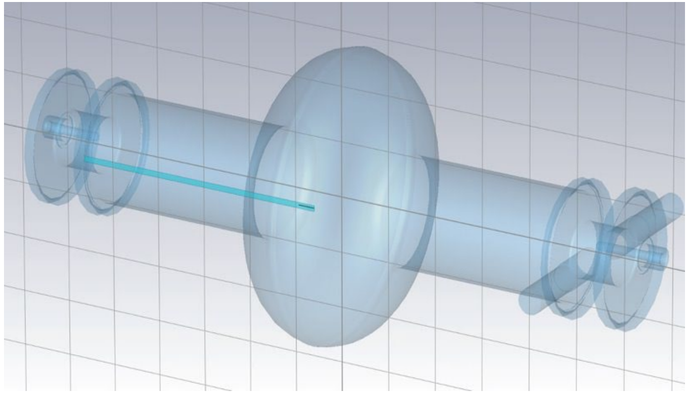
Find loss sources and eliminate

Substrate | Transmon | Geometry | Shielding



- Material: silicon or sapphire
- Manufacturer
- Treatment during fabrication

Further Improvements

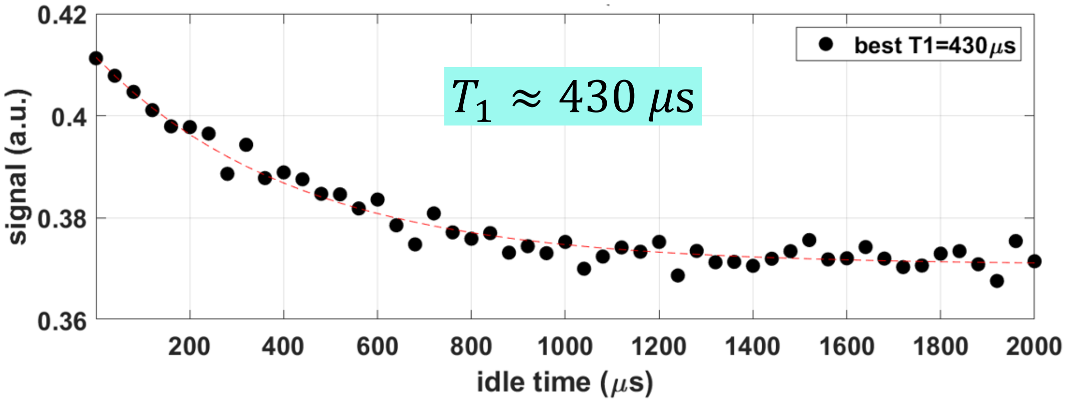


$T_1 > 50$ ms when no transmon

Find loss sources and eliminate

Substrate | **Transmon** | Geometry | Shielding

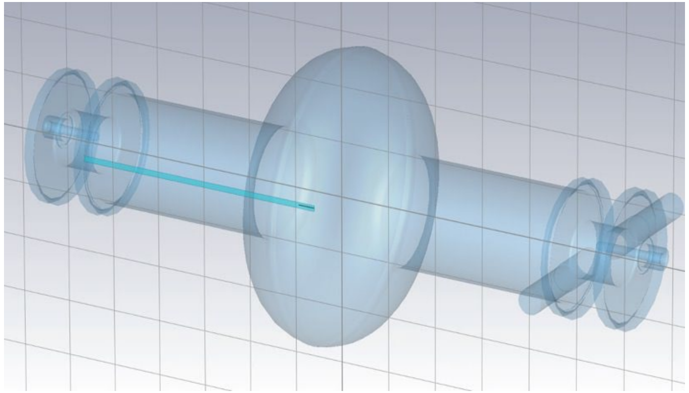
- Qubit sets Purcell limit
- Improve T_1 of transmon



Credit: Shaojiang Zhu

arxiv:2304:13257

Further Improvements

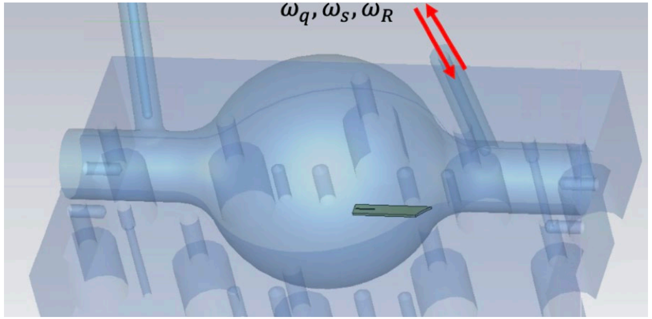


$T_1 > 50$ ms when no transmon

Find loss sources and eliminate

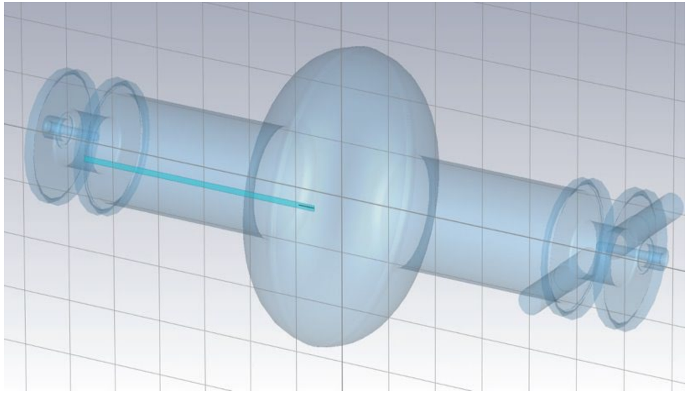
Substrate | Transmon | **Geometry** | Shielding

- Surface loss
- Participation of lossy components



Credit: Taeyoon Kim

Further Improvements



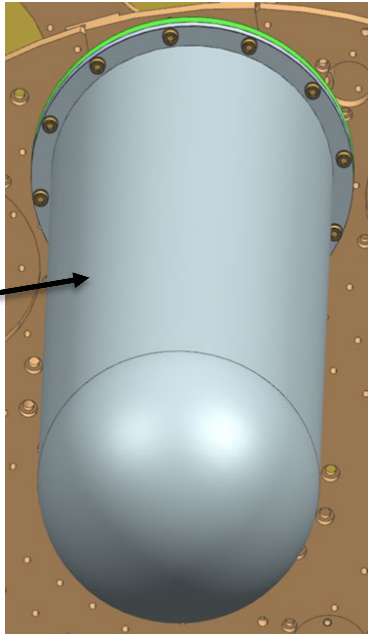
$T_1 > 50$ ms when no transmon

Find loss sources and eliminate

Substrate | Transmon | Geometry | **Shielding**

- Infrared shielding
- Magnetic shielding

Multilayered shield



Credit: Oleg Pronitchev

Multi-qudit Architecture

Crosstalk issues

All-to-all coupling

Faster scaling: $d^N > 2^N$

Moderate-Q cavities

High-Q 3D cavities

Transmon

Manipulator

Coupler

Storage

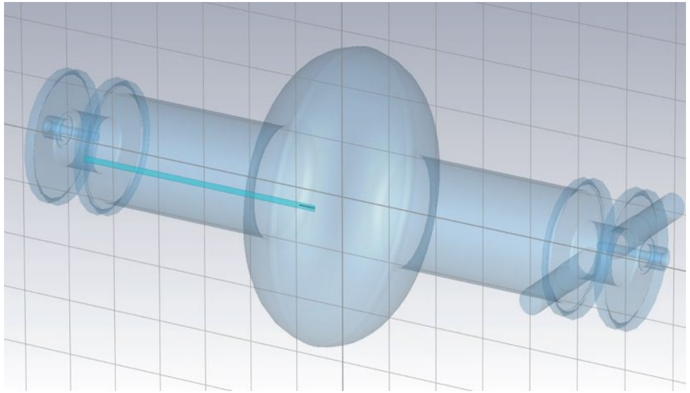
CPU

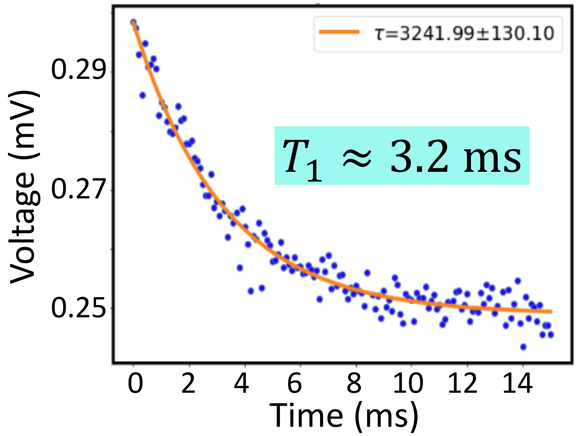
BUS

RAM

Summary

- Achievements
  - Integrated transmon into TESLA
  - Obtained $T_1 \sim 3.2$ ms, $T_\phi \sim 2.1$ ms
  - Prepared several quantum states





- Future directions
  - Implement quantum algorithms
  - Keep improving hardware
  - Scale up

Brand New SQMS Facility at Fermilab

Quantum Garage

Thank You!