Advances in SRF qubit architectures for quantum computing

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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

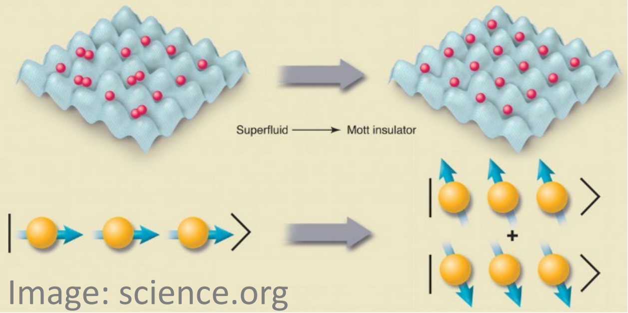


Image: science.org

Simulate one QM system with another

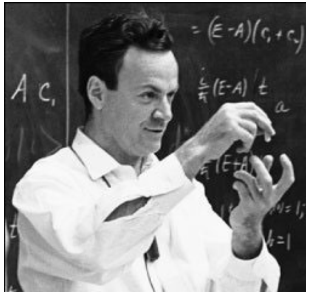


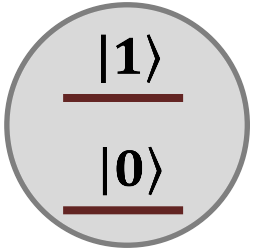
Image: needull.com

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Fundamental Unit

1

0



Quantum bit

Qubit

Classical bit:
"0" or "1"

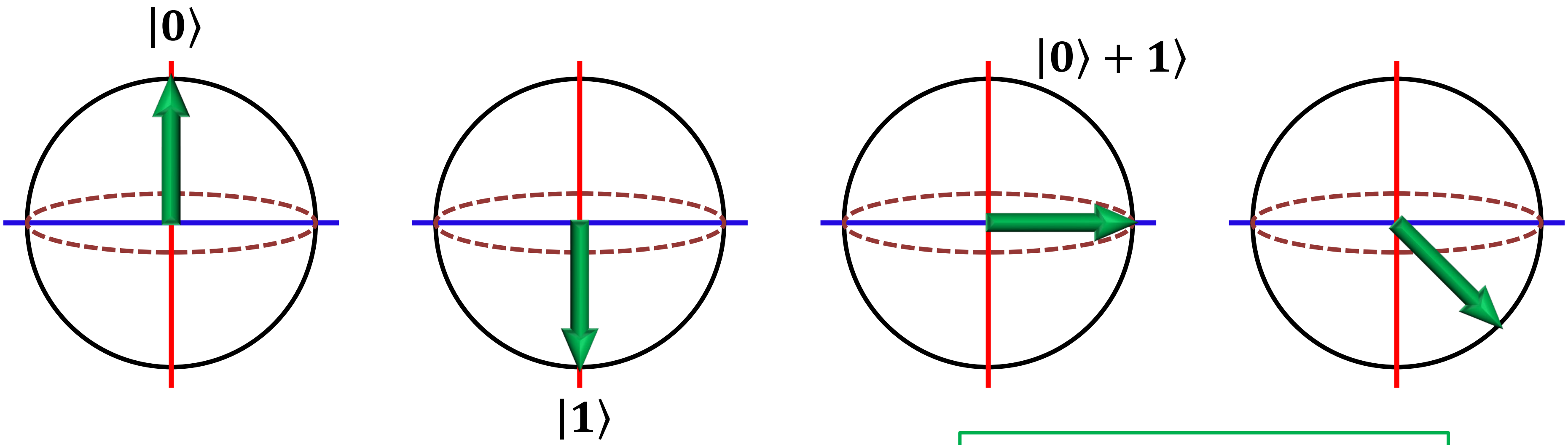
Quantum bit:
"0" *and* "1"

Superior

Superposition: $|\mathbf{0}\rangle \pm |\mathbf{1}\rangle$

Entanglement

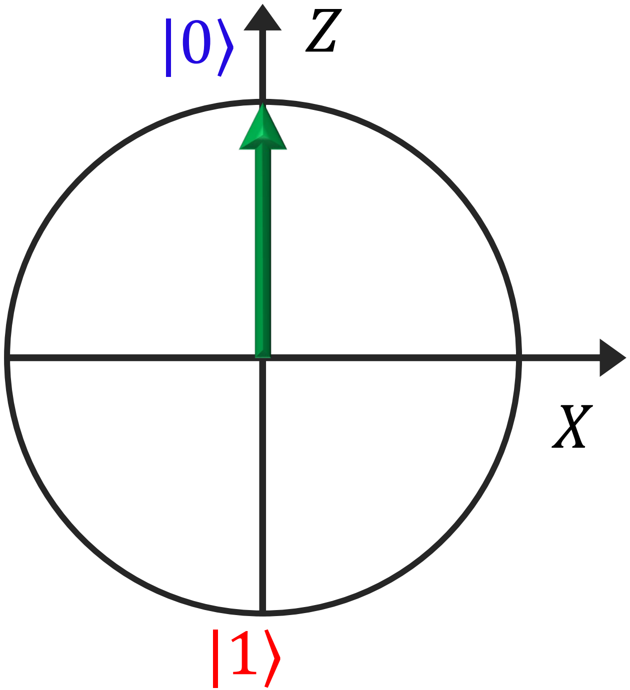
Qubit Visualization



Superposition states

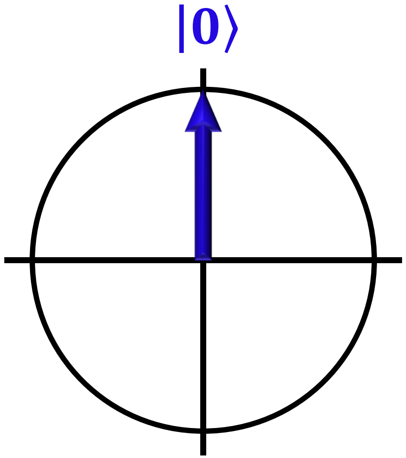
General state: $\alpha|0\rangle + \beta|1\rangle$

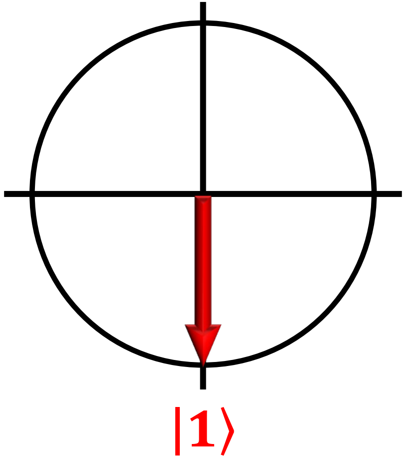
Single-qubit Gate and Measurement



Rabi Oscillation

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



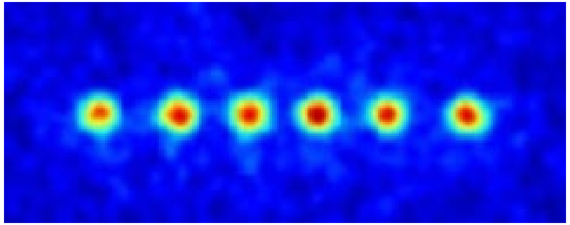


P(0) = $|\alpha|^2$

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

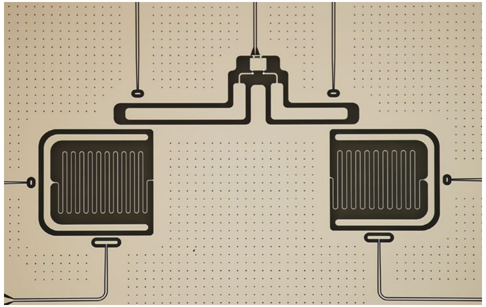
Different Platforms

Ion trap



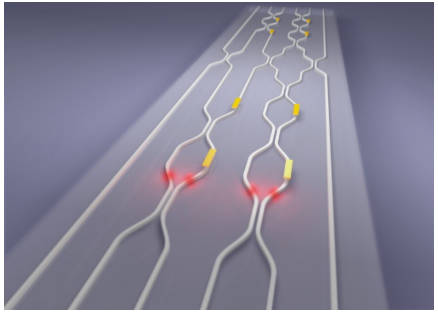
quantumoptics.at

Superconducting circuits



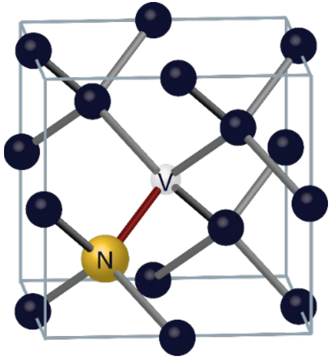
Schuster lab

Photonic crystals



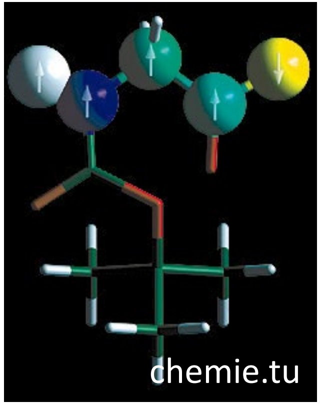
phys.org

NV centers

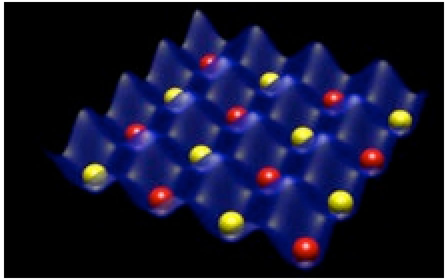


phys.org

NMR

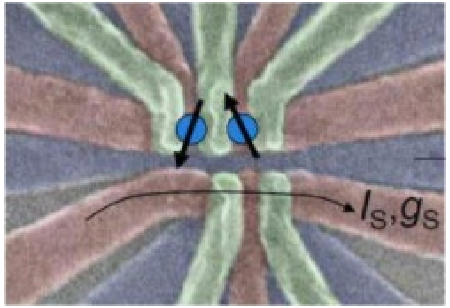


Neutral atoms



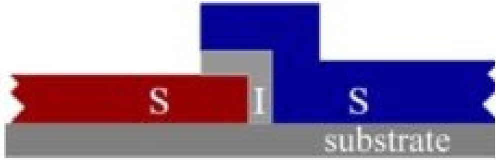
NIST

Quantum dots



sciencemag.org

Superconducting Circuits

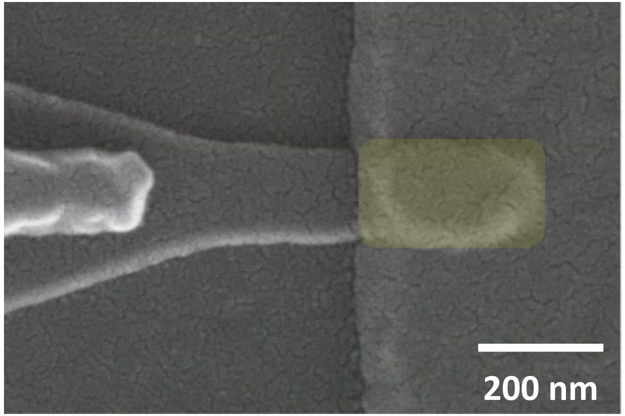


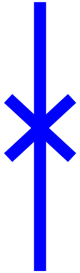
Josephson Junction

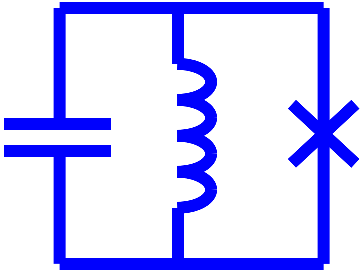
$$I(t) = I_0 \sin\delta(t)$$
$$V(t) = \varphi_0 \dot{\delta}(t)$$

Lossless nonlinear inductor

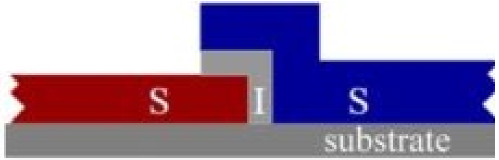
$$L_J(I) = \frac{\varphi_0}{(I_0^2 - I^2)^{1/2}}$$







Superconducting Circuits



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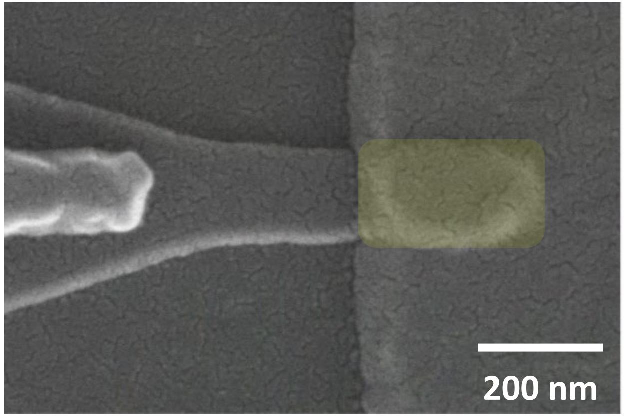
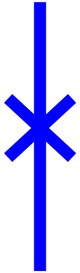
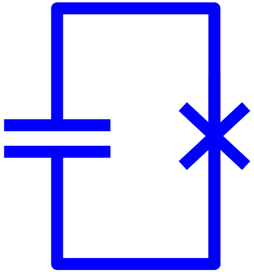
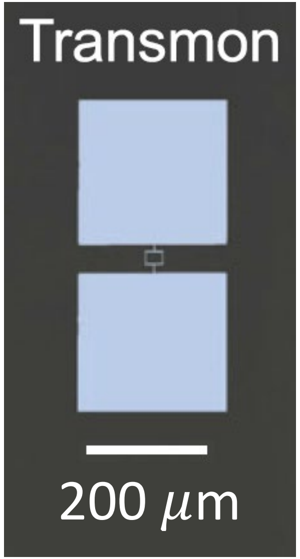


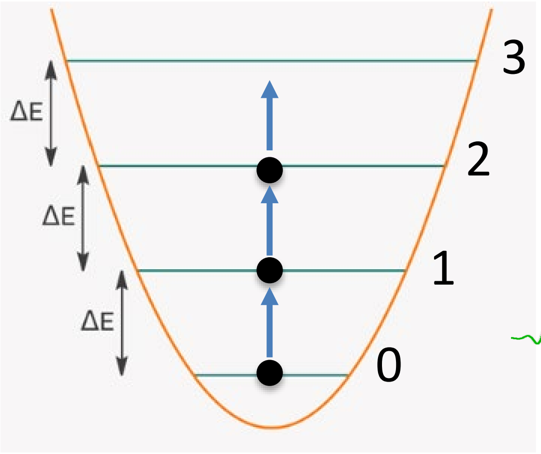


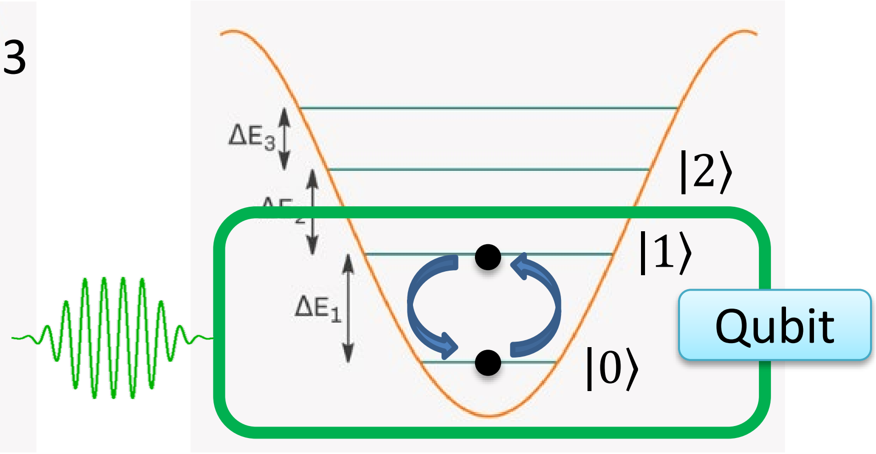


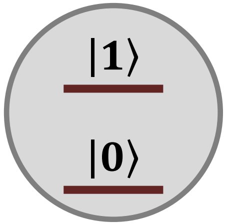
Transmon



Transmon: Anharmonic Oscillator

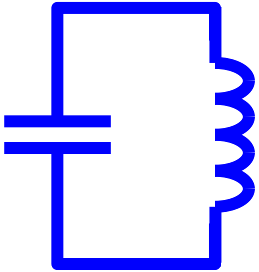


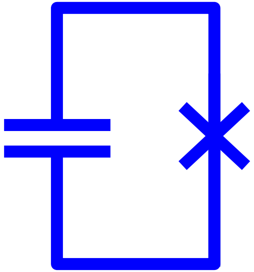




Harmonic Oscillator

Anharmonic Oscillator





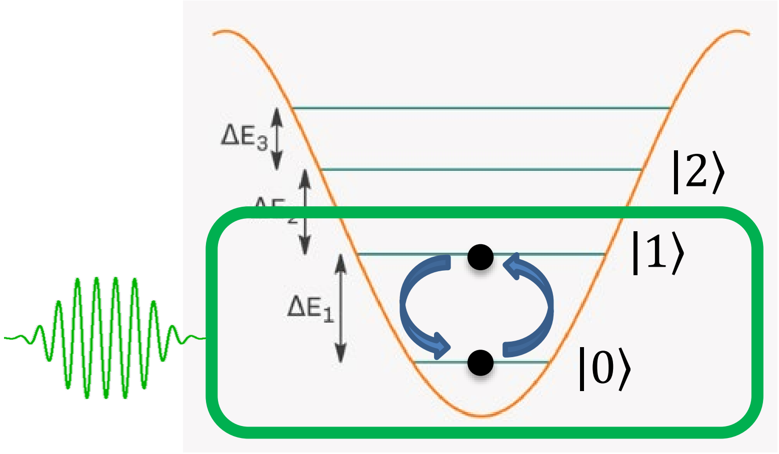
Operating Temperature

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

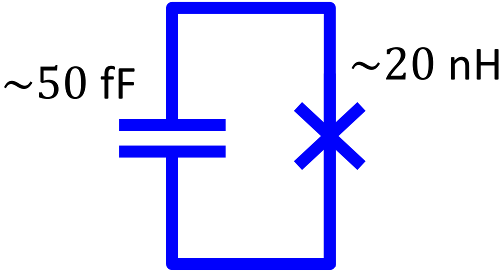
$\sim$ 5 GHz

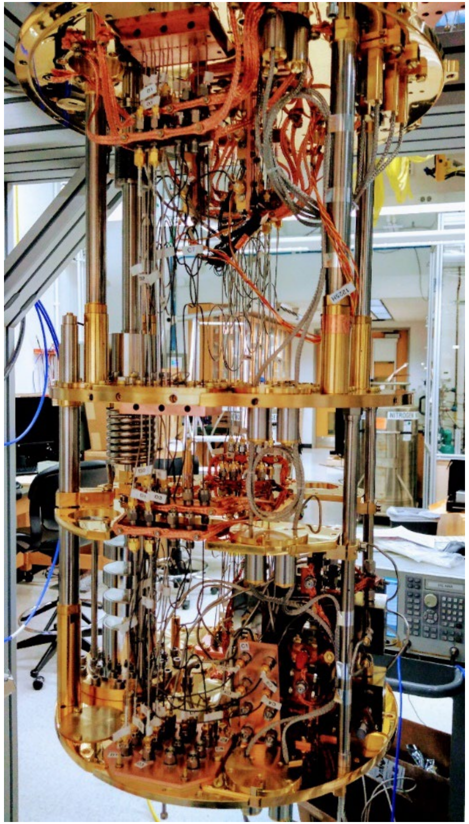
$$\boxed{k_B\, T \ll h\, f_{01}}$$

20 mK $\qquad$ $\sim$ 240 mK



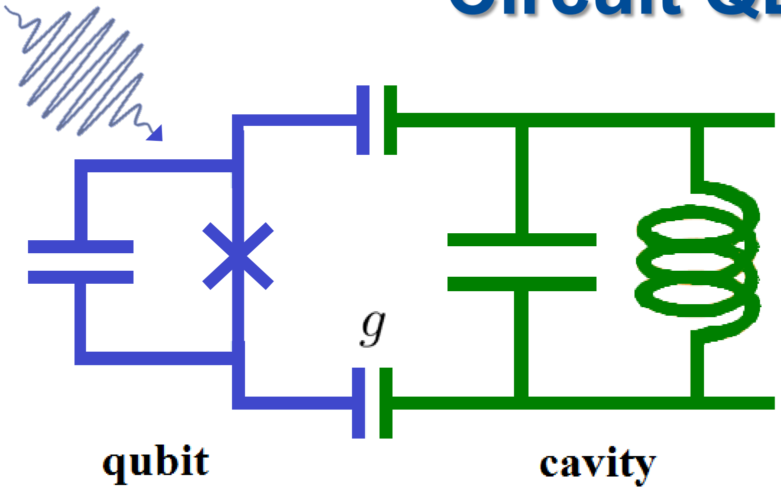
Anharmonic Oscillator

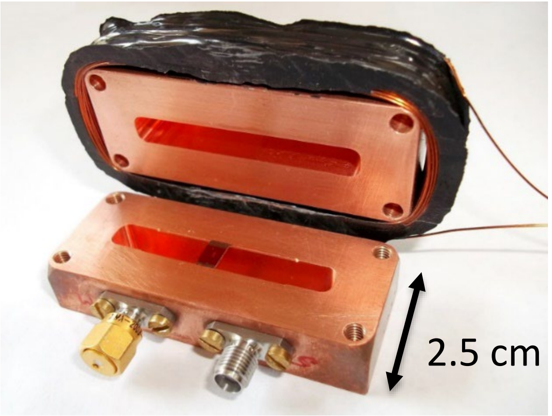


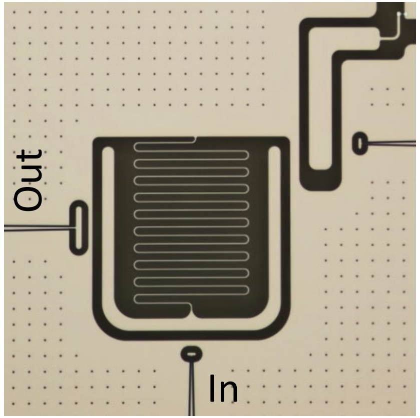


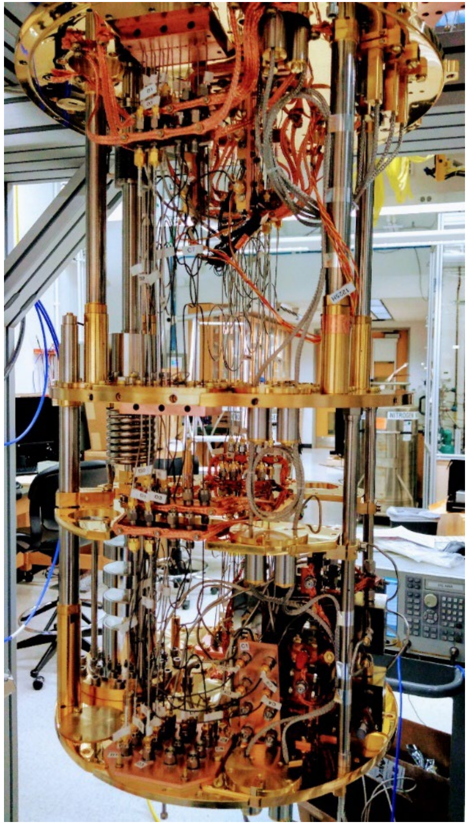
Dilution fridge ~ 10 mK

Circuit QED Architecture



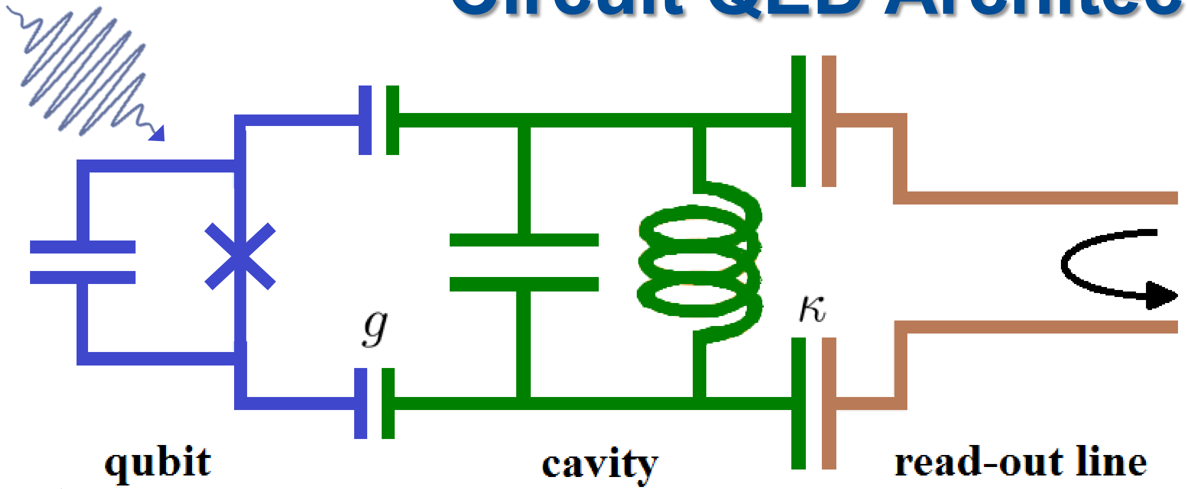


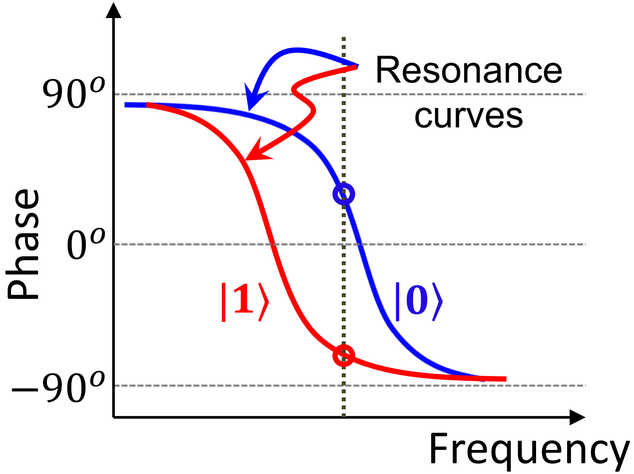


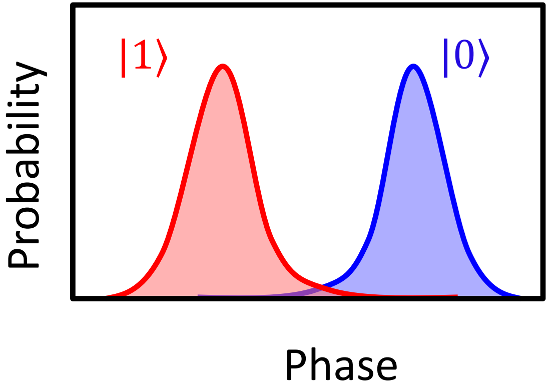


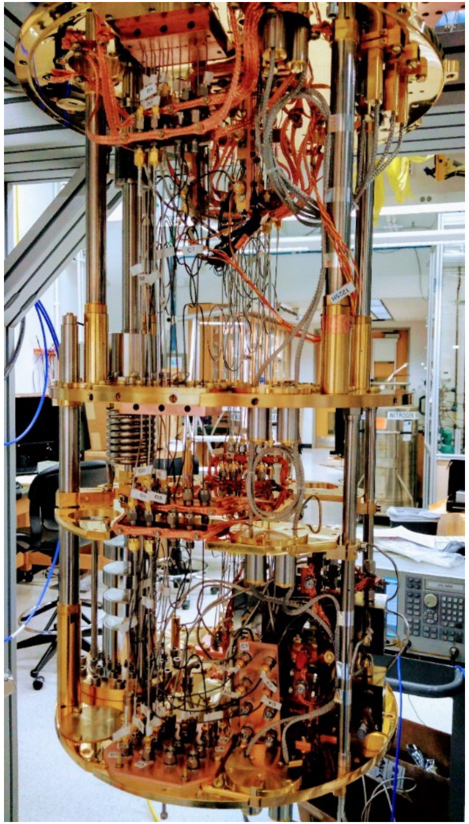
Dilution fridge ~ 10 mK

Circuit QED Architecture





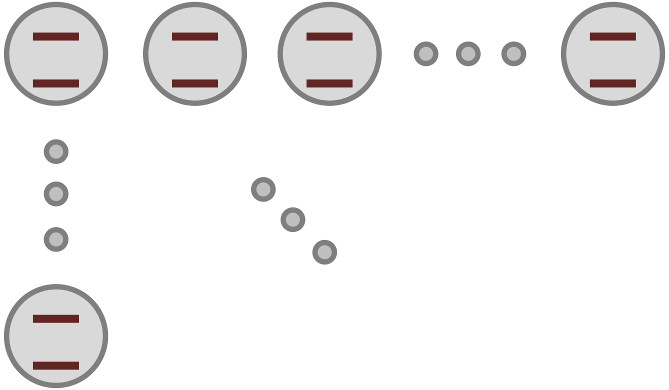




Dilution fridge ~ 10 mK

Traditional Multi-qubit Architecture

Linear or planar geometry

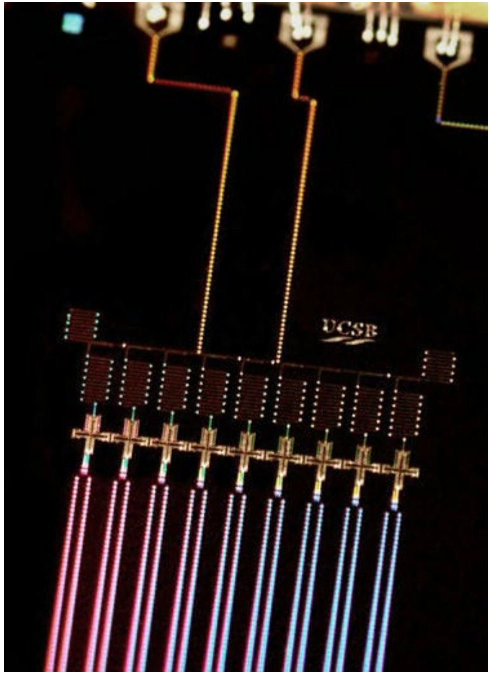


Computational space: 2^N

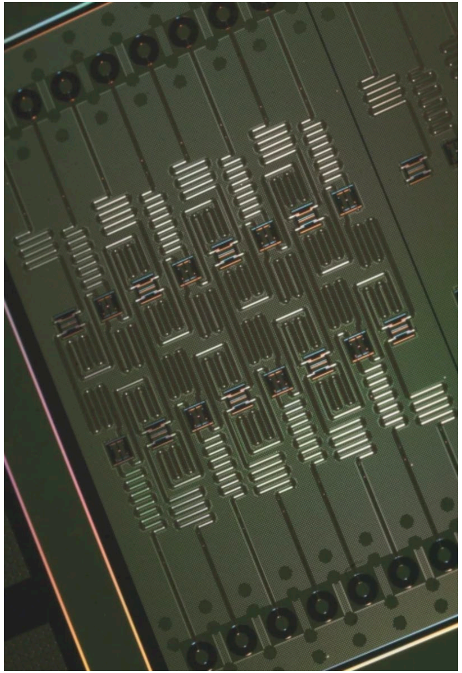
Can we do better?

Scaling: $d^N, d > 2$

Qudit



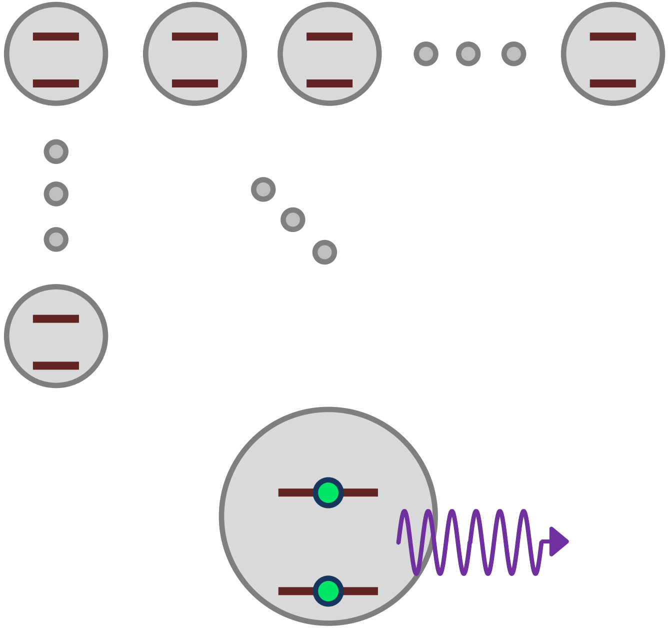
UCSB, Nature 519 (7541)



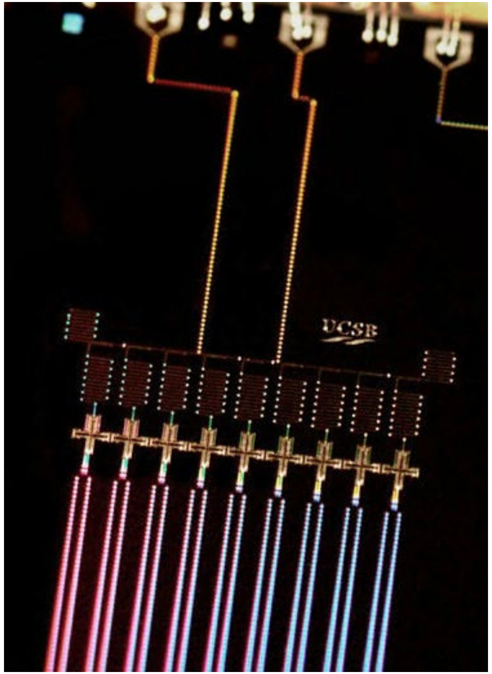
IBM

Problem of Relaxation

Linear or planar geometry



$T_1 \sim 100\ \mu s$ Q: a few 10^6



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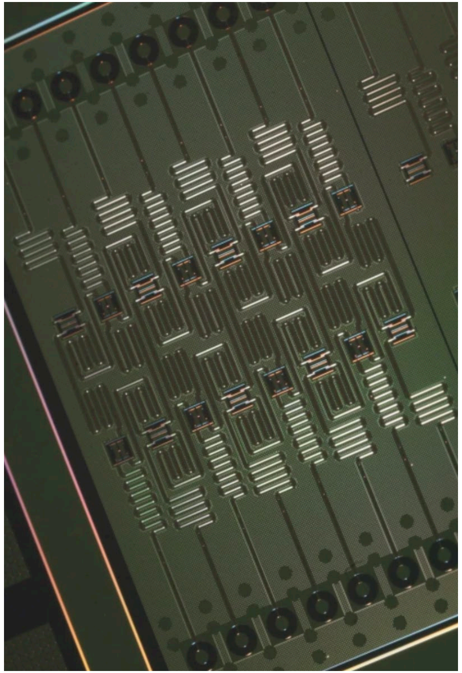
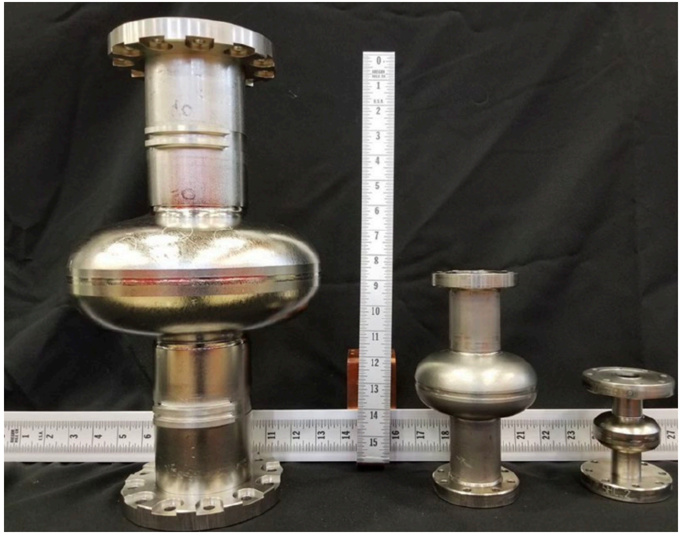


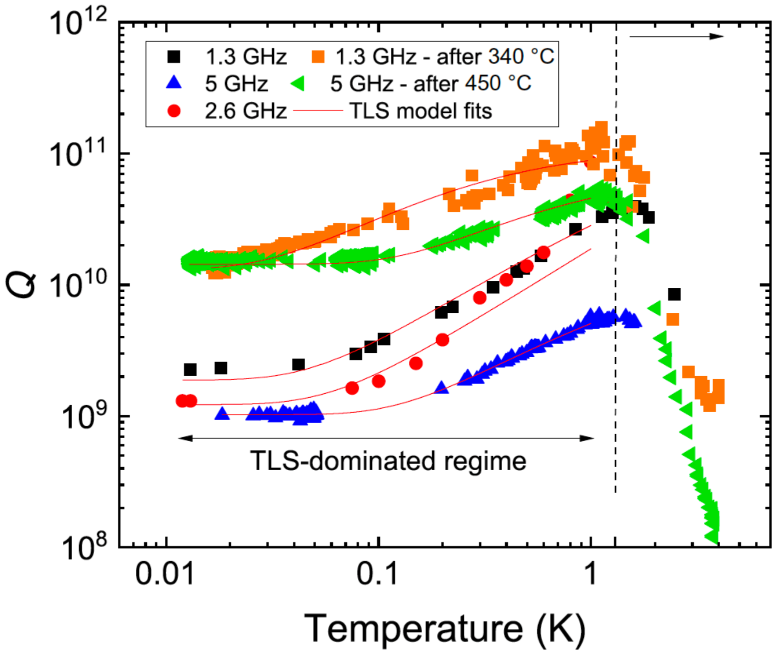
IBM

Can we do better?

High-Q 3D SRF Cavities



Romanenko et al. PRApplied 13, 034032

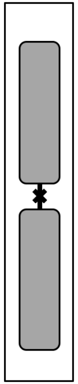


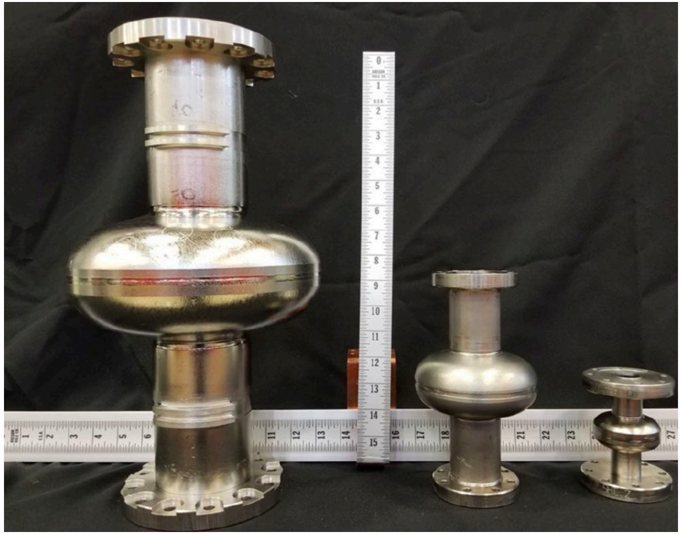
1.3 GHz SRF: $Q > 10^{11}$ at 1 K ⟹ $T_1 > 2$ s

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

>1000 times better than transmons

High-Q 3D Cavities as Qudits





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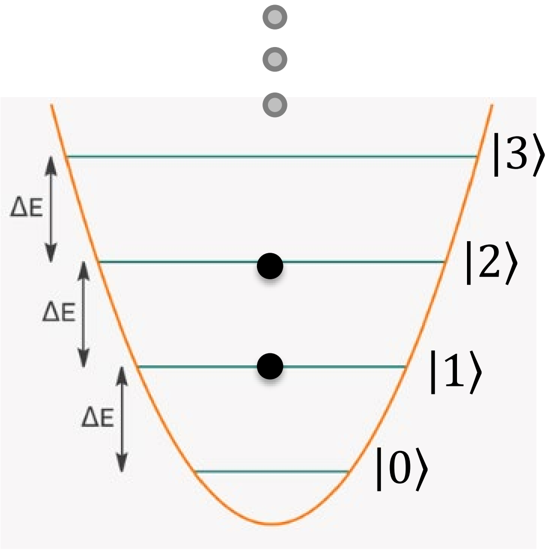


$T_1^{|1\rangle} > 300$ ms

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

$T_1^{|n\rangle} > 300/n$ ms

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

Qudit

Still better than transmon qubits

Qudit States and Gates

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

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

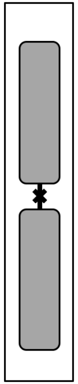
$\Downarrow$ SNAP gate

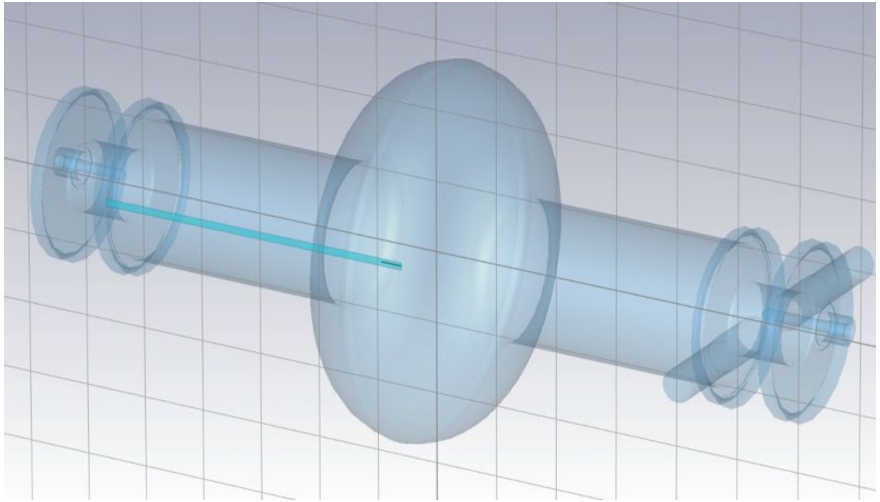
PRL 115, 137002 (2015)

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

SNAP + Cavity drive $\Rightarrow$ Universal control

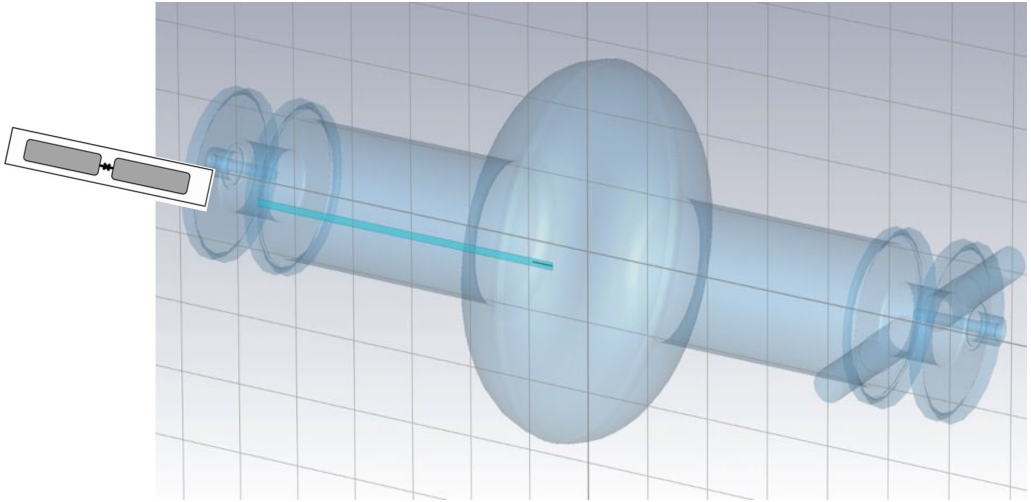
First Milestone





Incorporate Transmon into a TESLA cavity

First Milestone



Incorporate Transmon into a TESLA cavity

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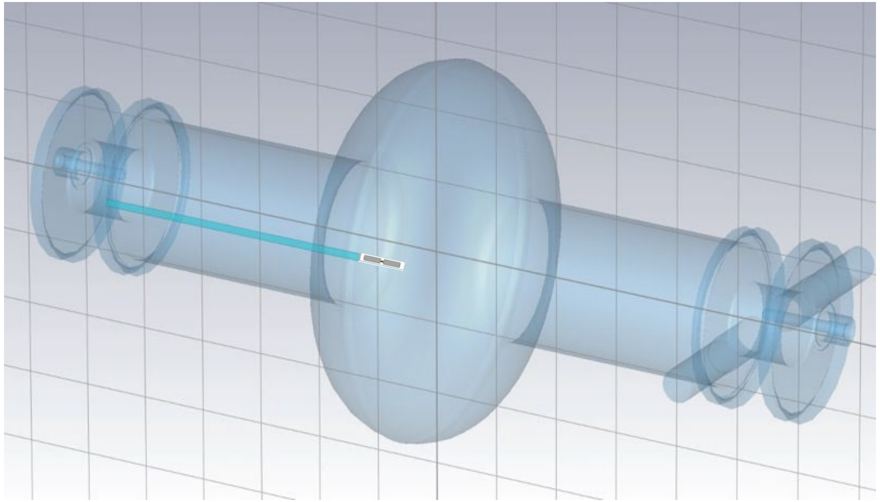
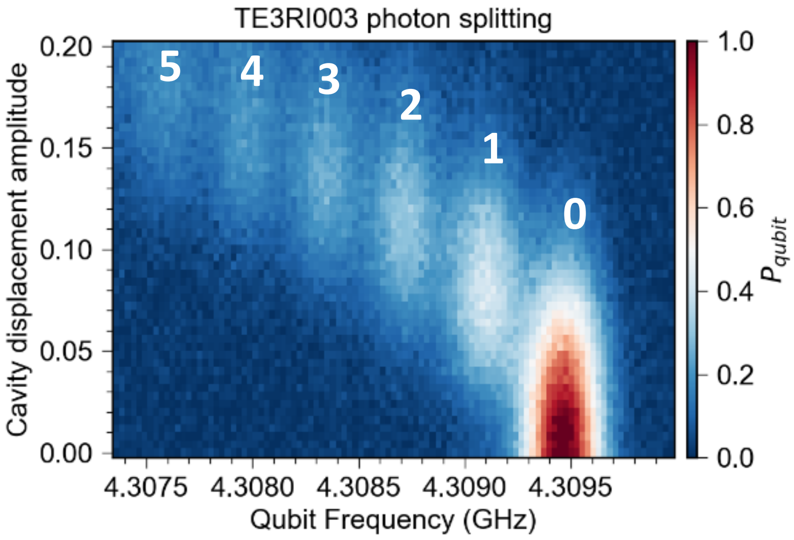
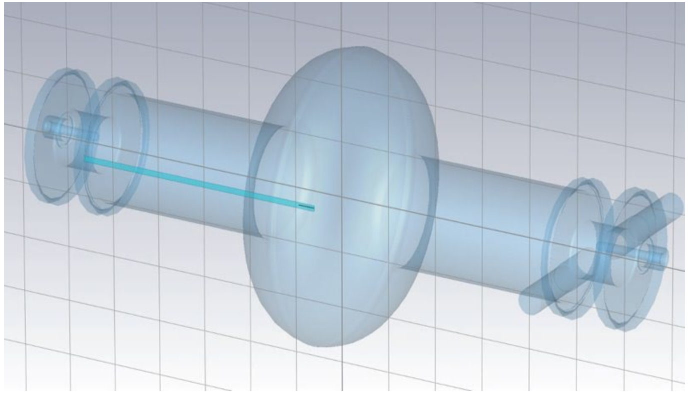




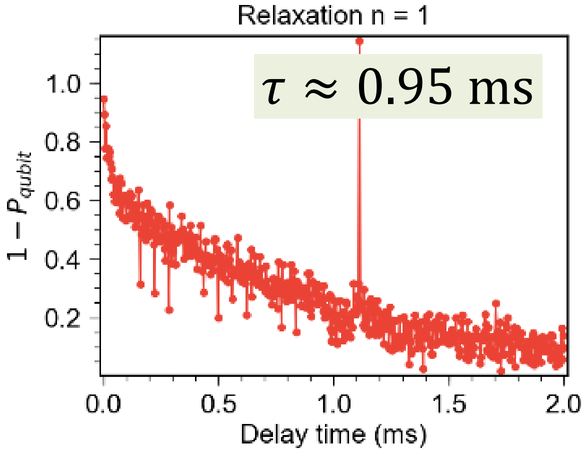
Incorporate Transmon into a TESLA cavity

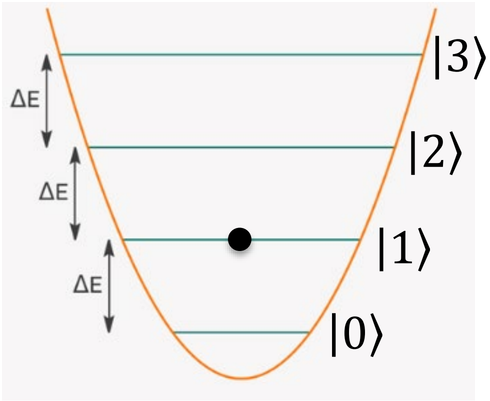
Achieved photon counting

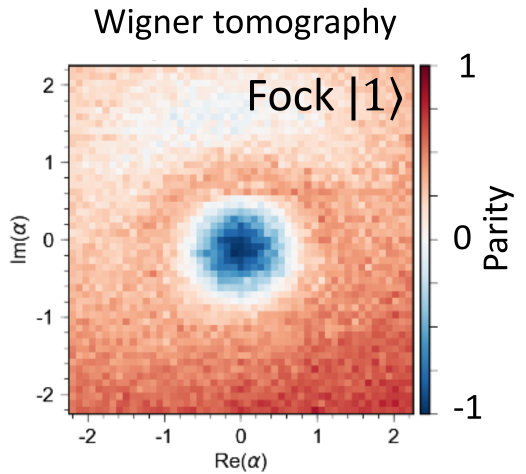
Second Milestone

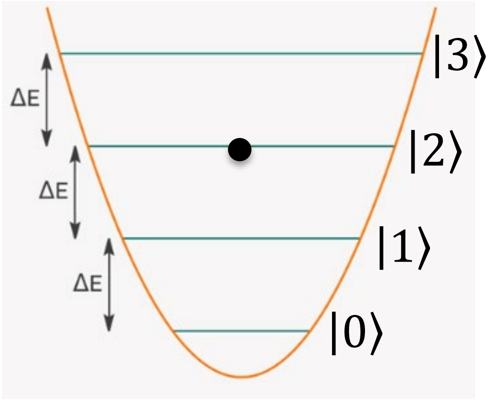


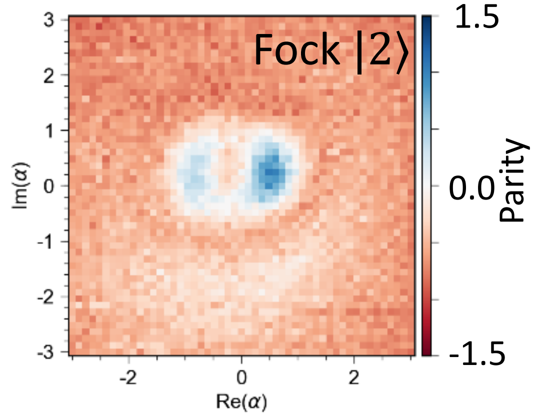
Prepare quantum states





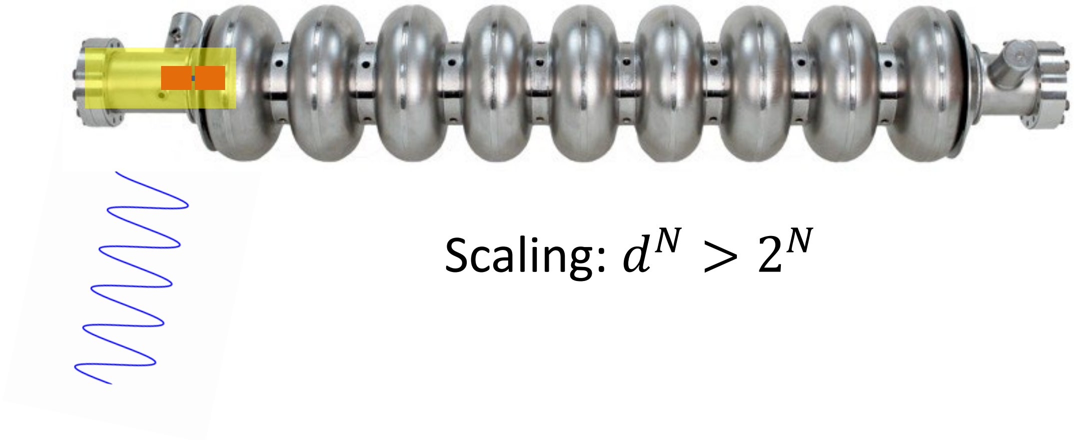






Multqudit Architecture

Crosstalk issues



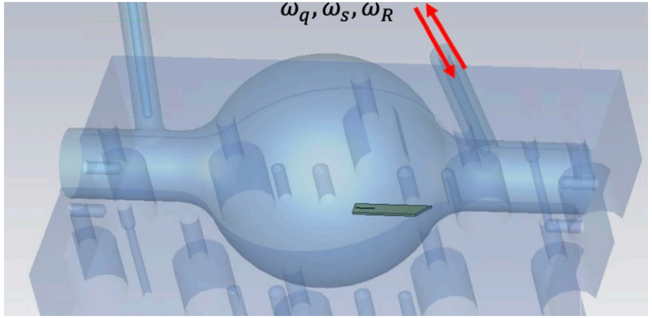
Scaling: $d^N > 2^N$

Transmon | Manipulator | Coupler | Storage

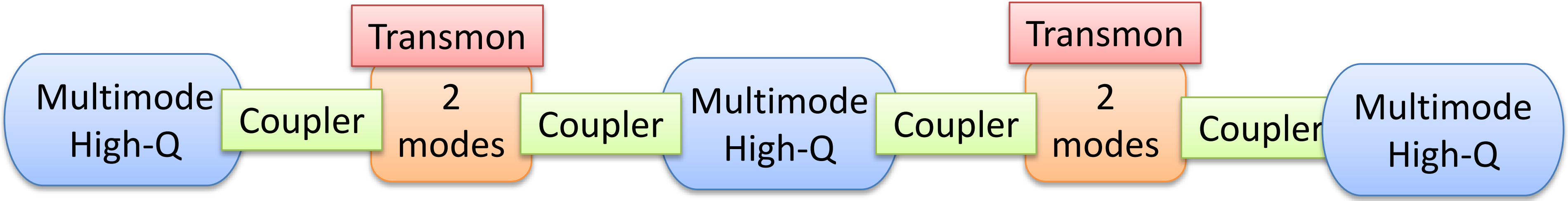
CPU | BUS | RAM

Outlook

- Improve single-cell devices
  - Optimize transmon design, placement
  - Investigate other SRF cavities



- Scaling up
  - Develop modular architecture
  - Connect several modules



Brand New Facility

Thank You!