Qudit-based quantum computing with SRF cavities at Fermilab

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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

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1. Prime Factorization

7629045585188558 53

HARD

? × ?

Shor's factoring algorithm 1994

Image: mit.edu

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2. Quantum Simulation

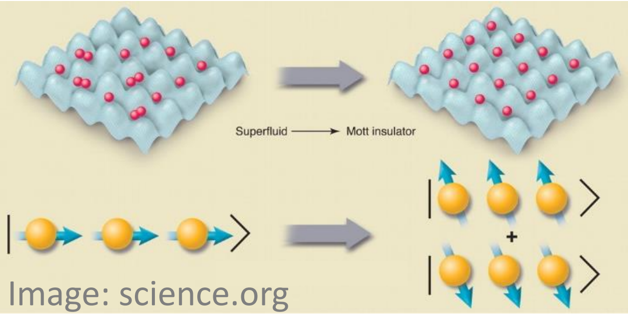

Image: science.org

Simulate one QM system with another

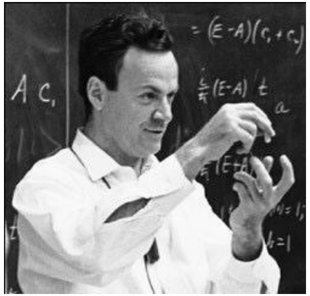

Image: needull.com

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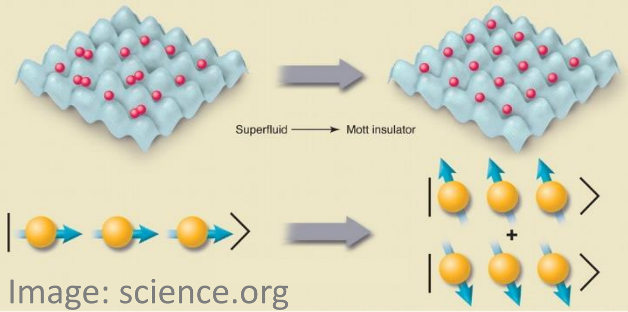
Build a Quantum Computer

2. Quantum Simulation



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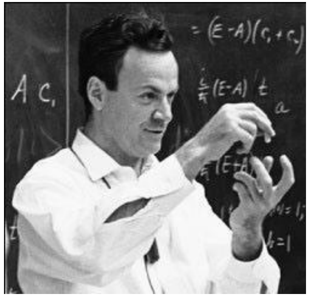
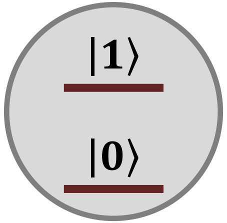
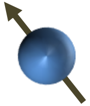


Image: needull.com

Basic Requirements for a Quantum Computer

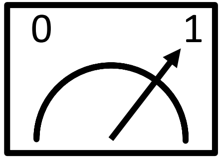


Quantum two level systems

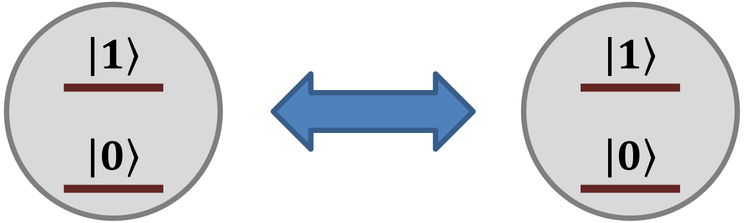


$\alpha|0\rangle + \beta|1\rangle$

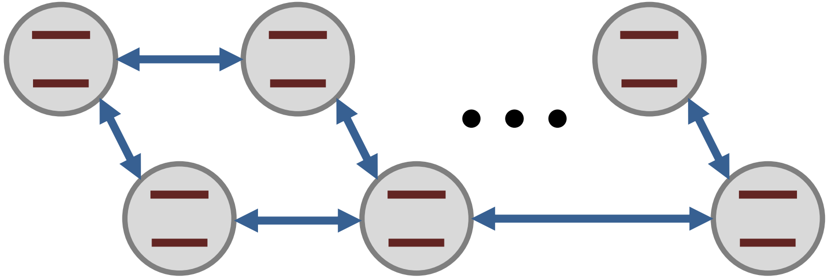
Create arbitrary states



Measure quantum states



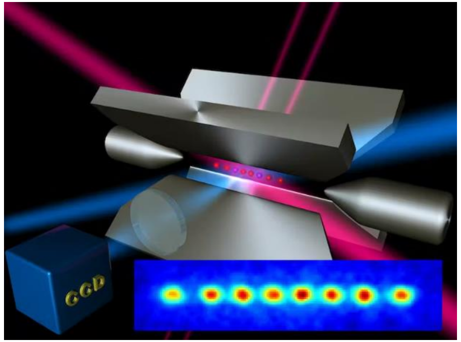
Couple multiple qubits



Scalable architecture

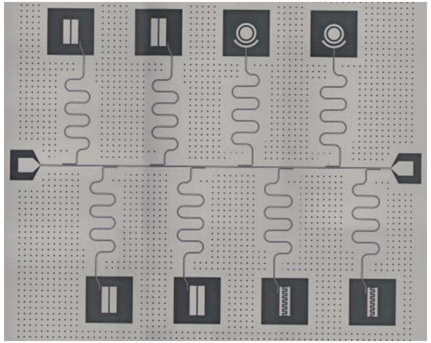
Different Platforms

Trapped ions



laserfocusworld.com

Superconducting circuits



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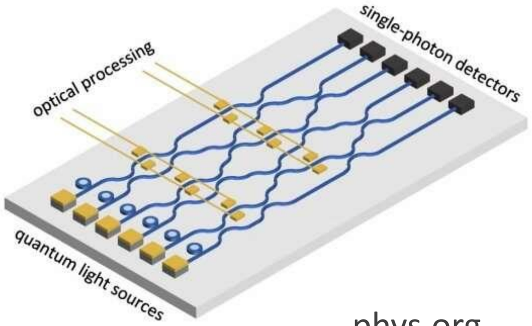
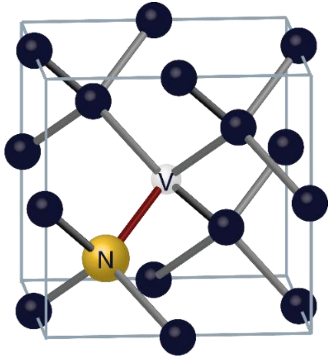
Photonic crystals



phys.org

NV centers



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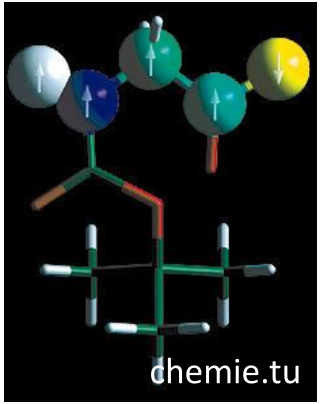
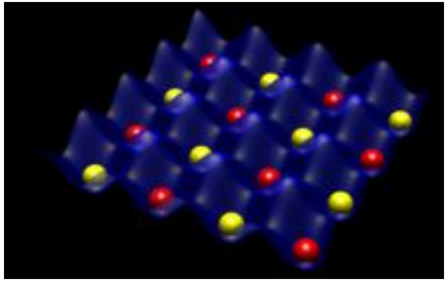
NMR

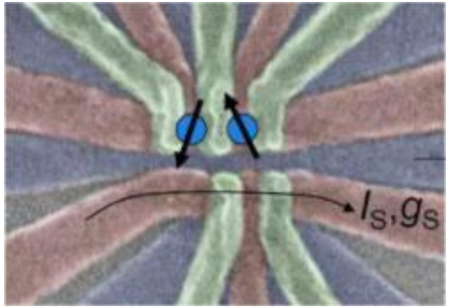


Neutral atoms



NIST

Quantum dots



sciencemag.org

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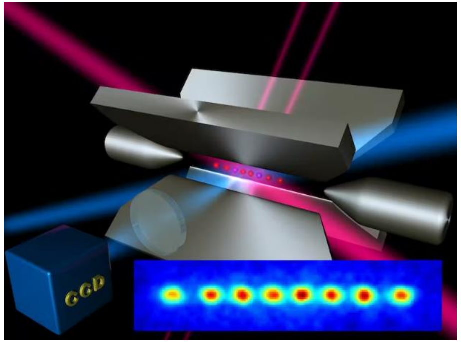

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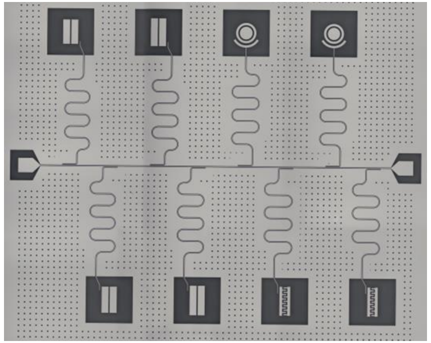

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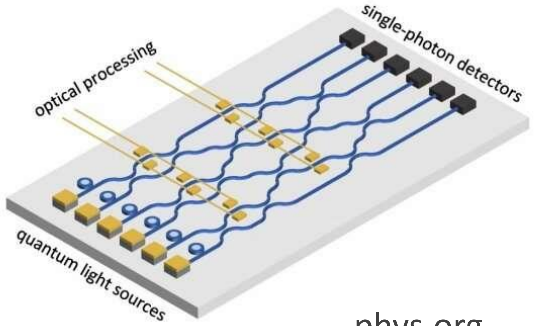

phys.org

Organization	Year	Qubits
IonQ	2022	32
Quantinuum	2023	32
Alpine Quantum Technologies	2022	20

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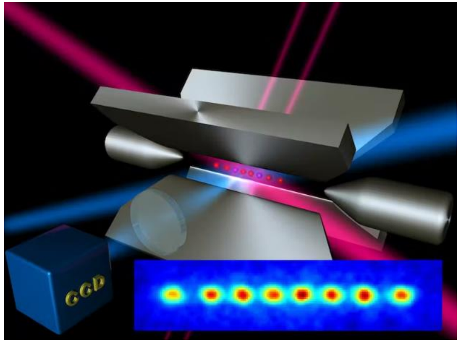

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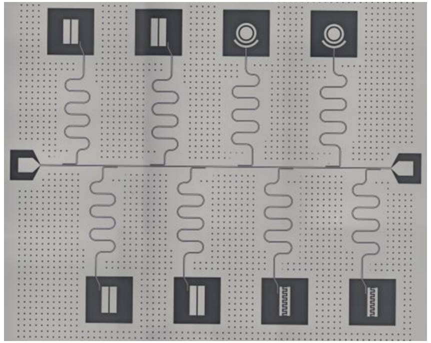

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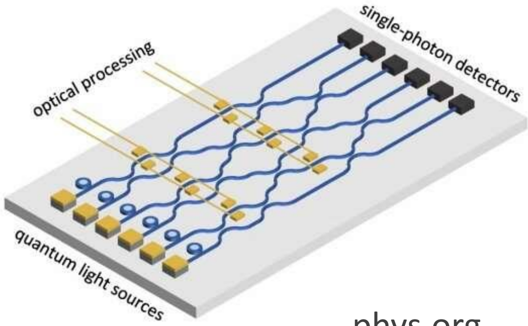

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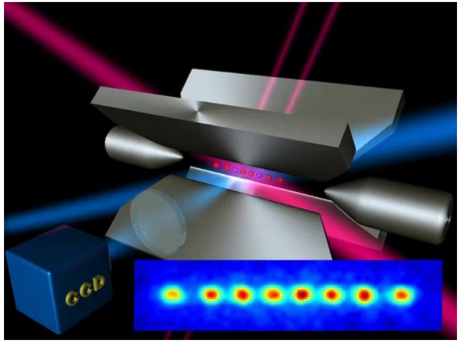
Organization	Year	Qubits
IBM	2022	433
Rigetti	2022	80
Google	2023	72

Organization	Year	Qubits
USTC	2023	176
Fujitsu	2022	36
Baidu	2022	10

Different Platforms

Trapped ions



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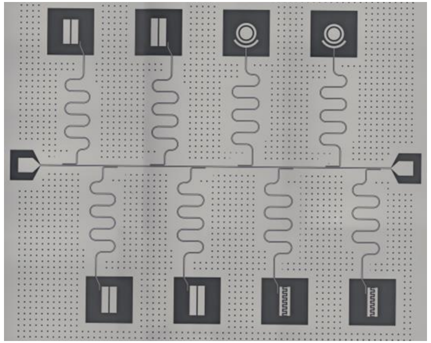

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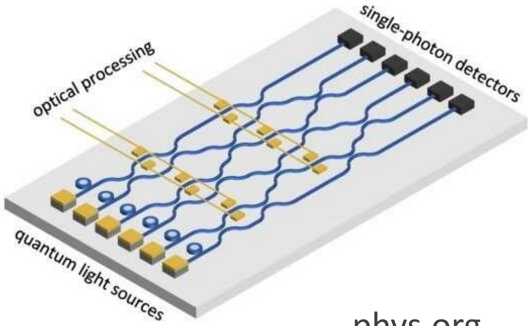


phys.org

XANADU

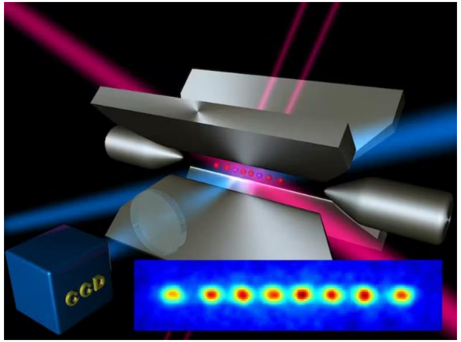
QUANDELA

QUIX QUANTUM

Organization	Year	Qubits
Xanadu	2022	216
Quandela	2023	12
QuiX	2022	20

Different Platforms

Trapped ions



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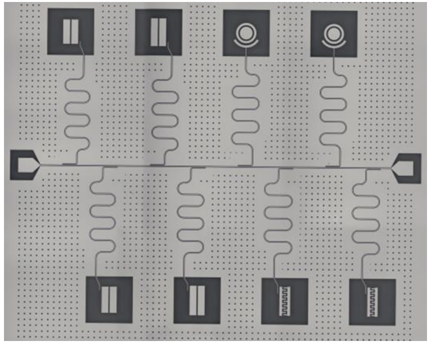

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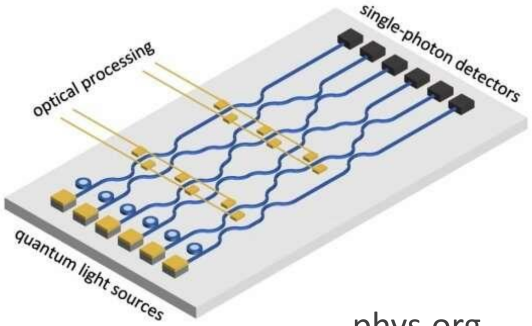


phys.org

|QuEra⟩ Computing Inc.

intel

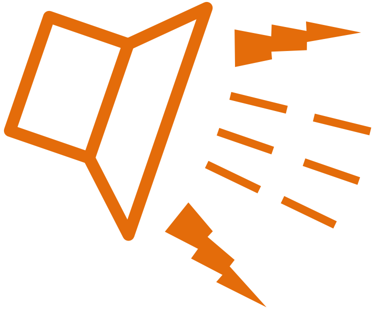
SPINQ

Organization	Platform	Year	Qubits
QuEra	Neutral atoms	2022	256
Intel	Quantum dot	2022	12
SpinQ	NMR	2022	3
EeroQ	Electron-on-helium		

Wikipedia The Free Encyclopedia

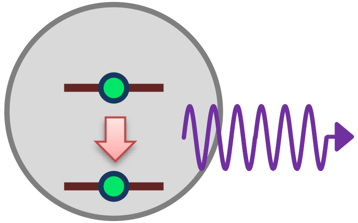
EeroQ Quantum Hardware

Challenges: Decoherence



Noise

Relaxation (T_1)

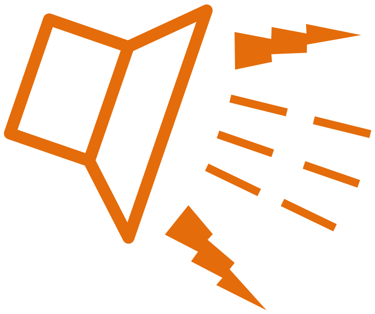


$$\alpha|0\rangle + \beta|1\rangle$$

$$\Downarrow$$

$$|0\rangle$$

Challenges: Decoherence



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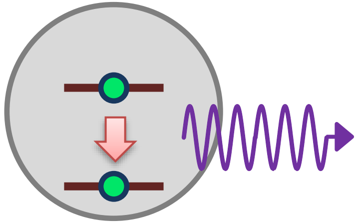
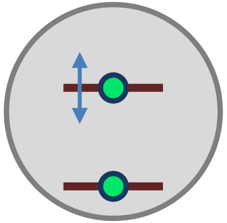


$\alpha|0\rangle + \beta|1\rangle$

$|0\rangle$

Dephasing (T_ϕ)

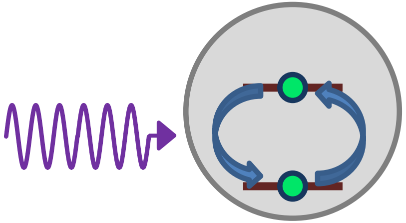


$|0\rangle + e^{i\phi}|1\rangle$

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

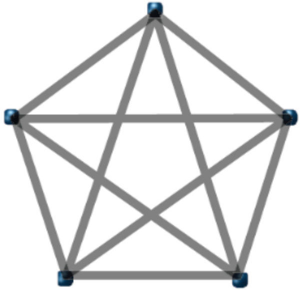
Long coherence

Challenges: Gates and Connectivity



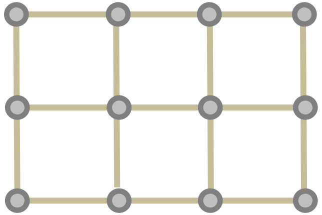
Fast & high-fidelity

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

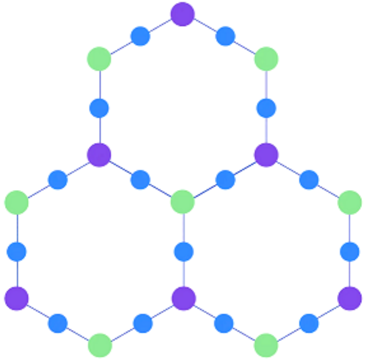


All-to-all

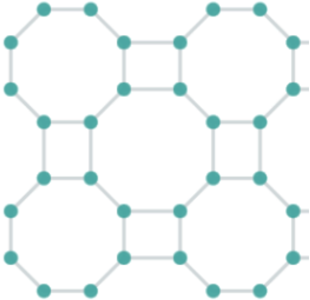
Linear chain



Square lattice

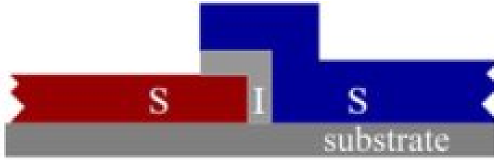


Heavy hexagon



Octagonal

Superconducting Circuits

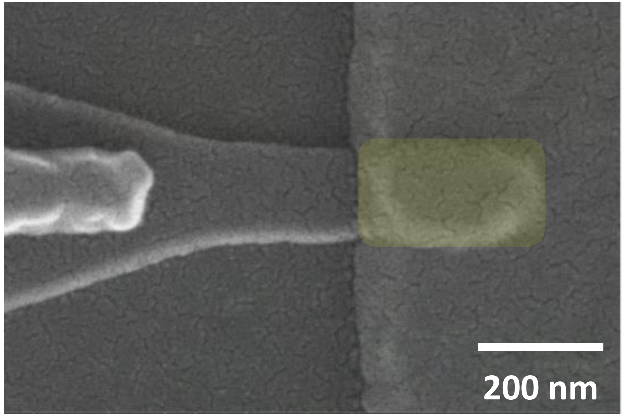


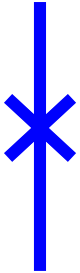
Josephson Junction

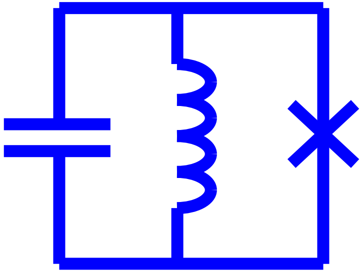
$$I(t) = I_0 \sin \delta(t)$$
$$V(t) = \varphi_0 \dot{\delta}(t)$$

Lossless nonlinear inductor

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







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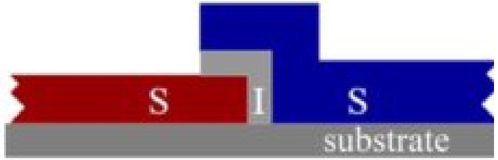

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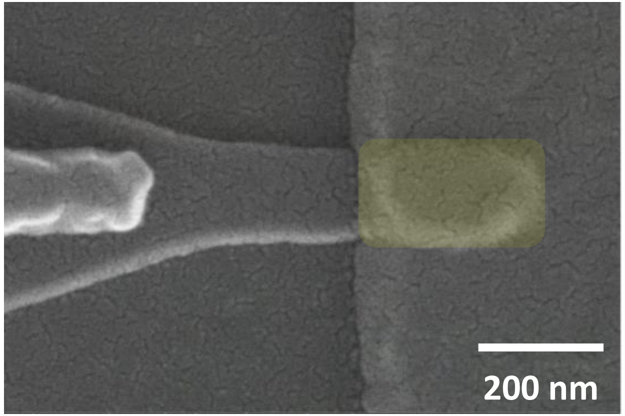
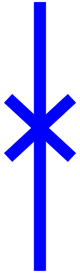
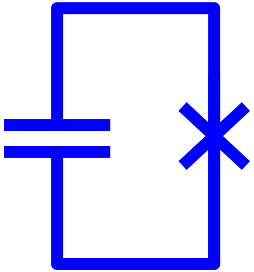
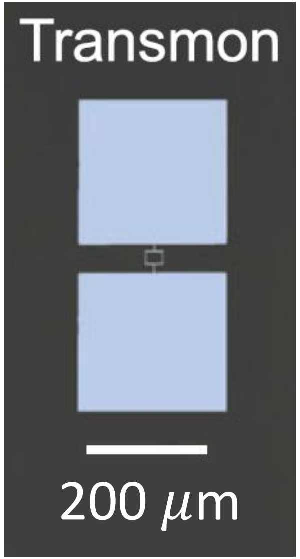


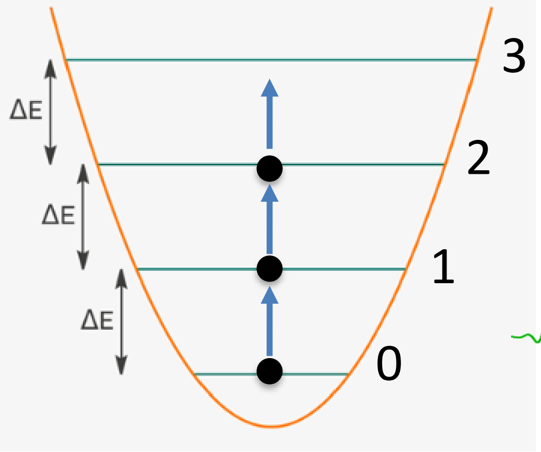


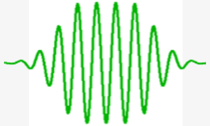


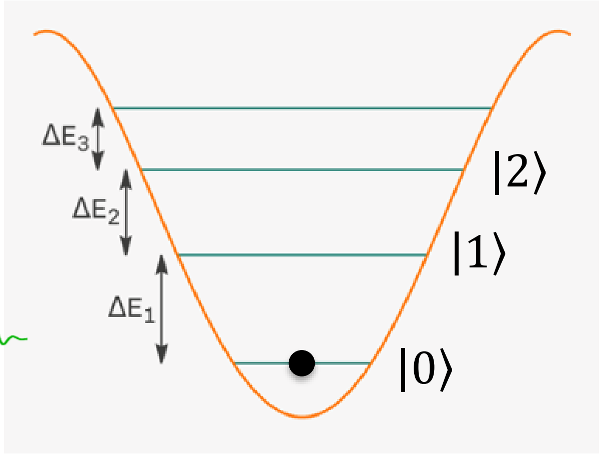
Transmon



Transmon: Anharmonic Oscillator

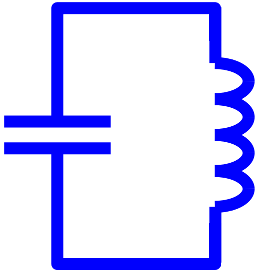


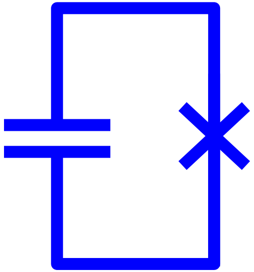




Harmonic Oscillator

Anharmonic Oscillator





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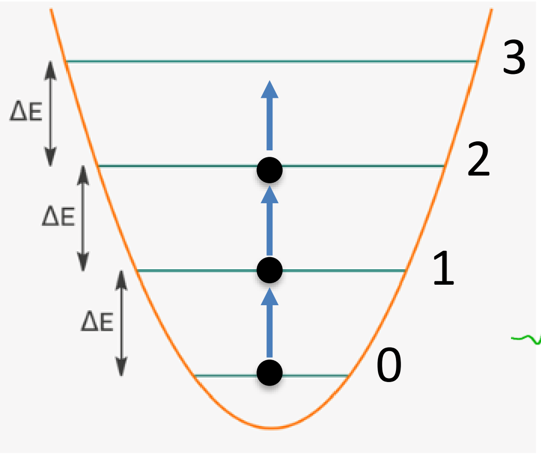

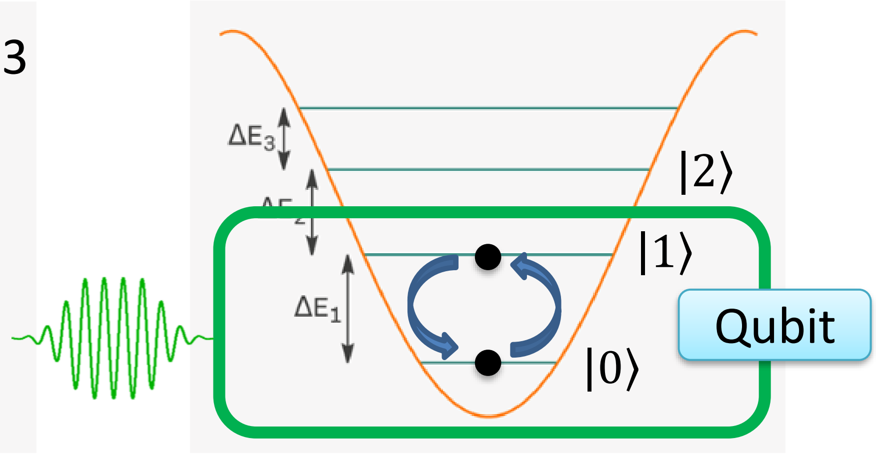

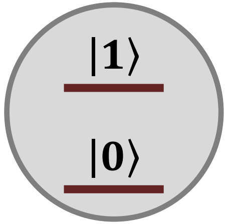

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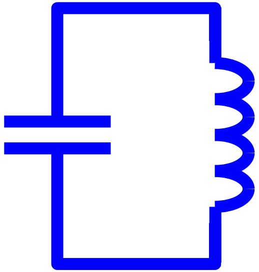
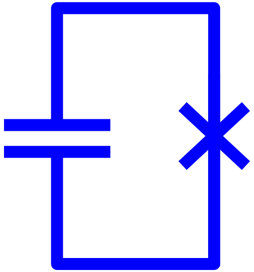




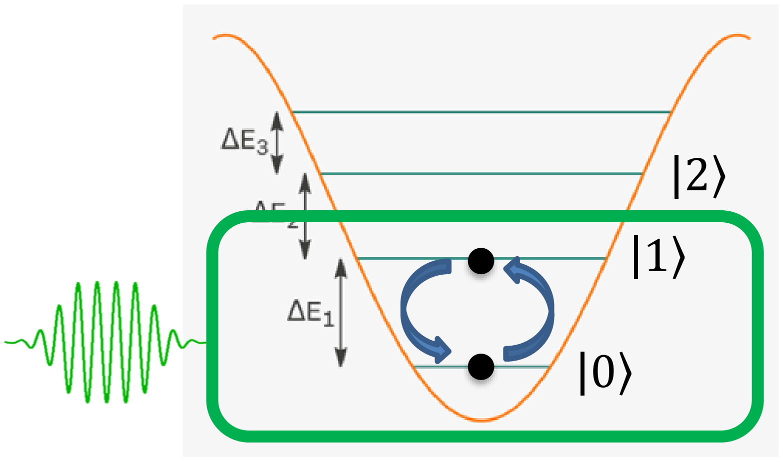
Operating Temperature

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

$\sim$ 5 GHz

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

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



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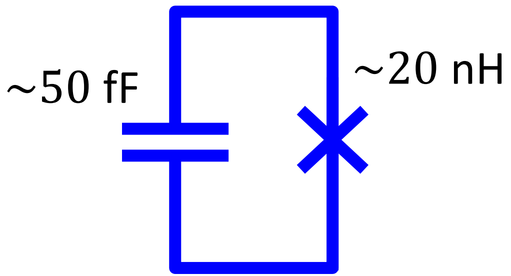

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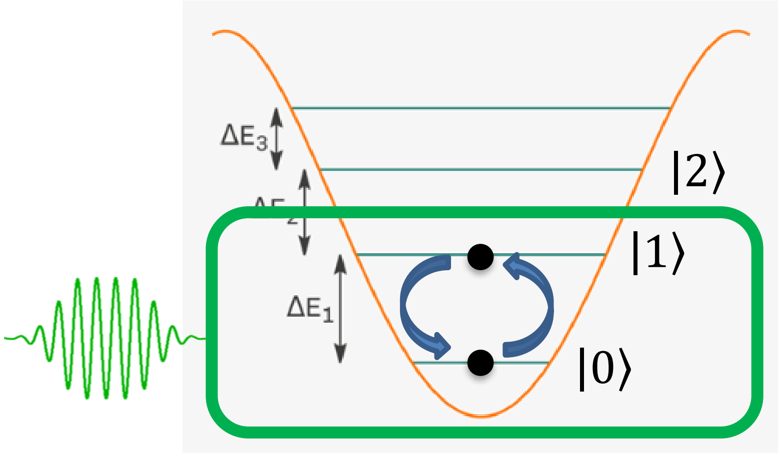

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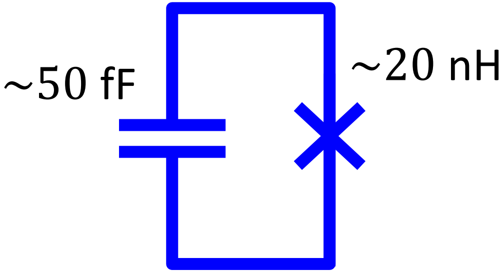
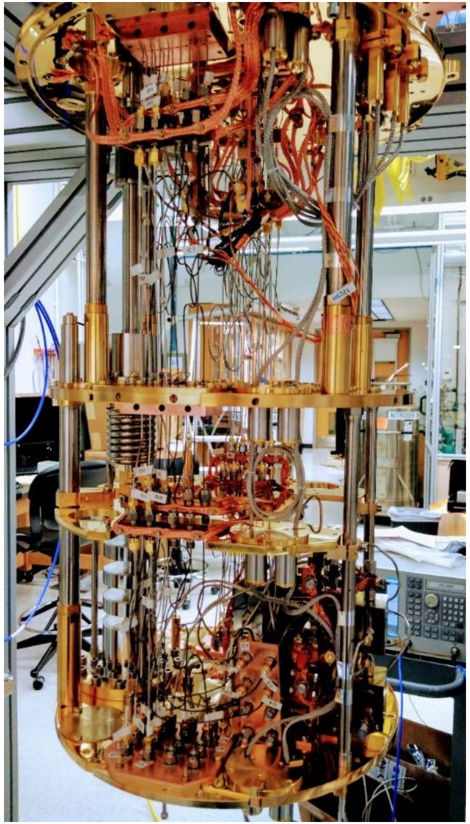
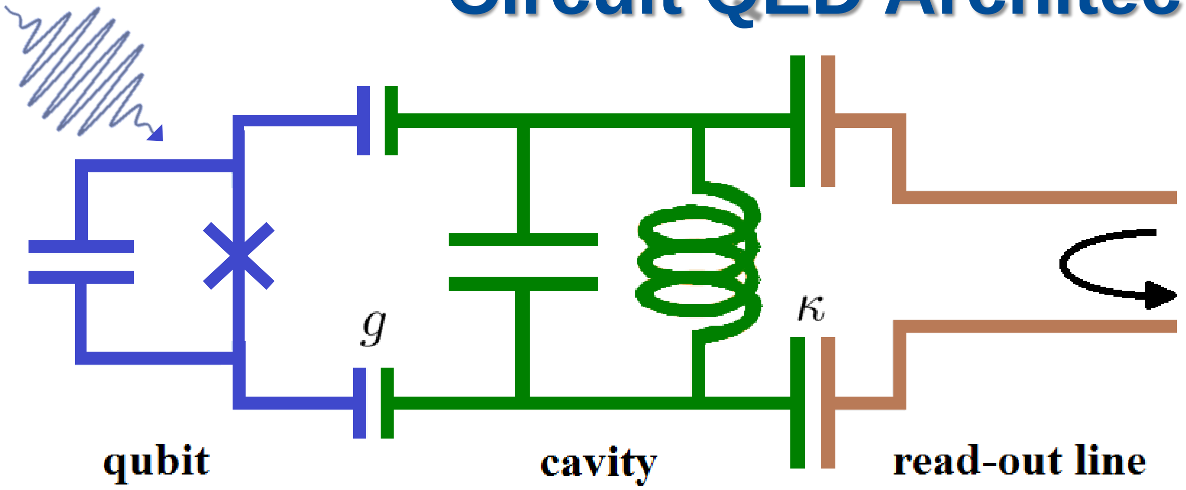
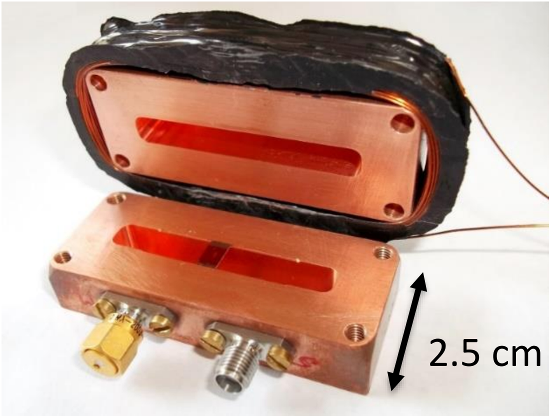


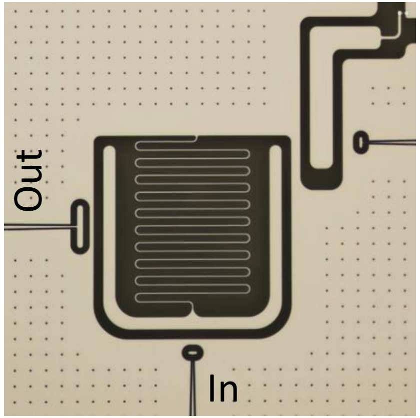


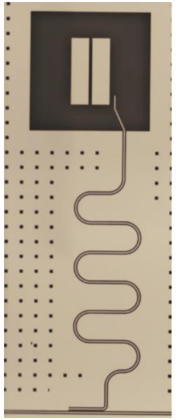
Dilution fridge ~ 10 mK

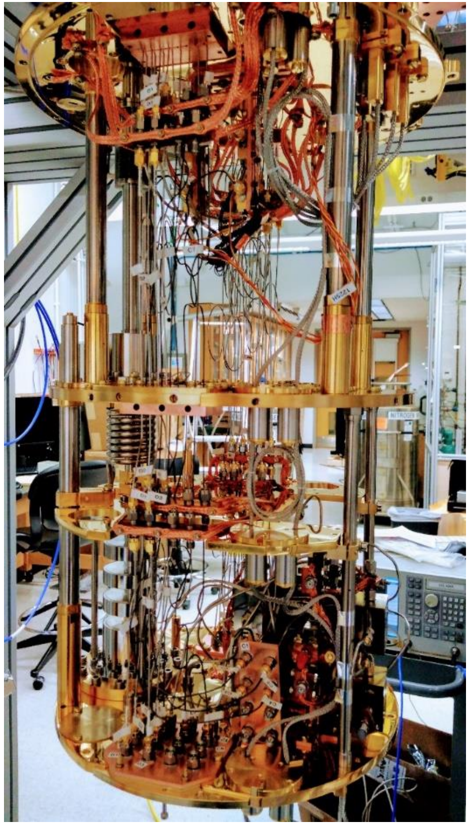
Circuit QED Architecture





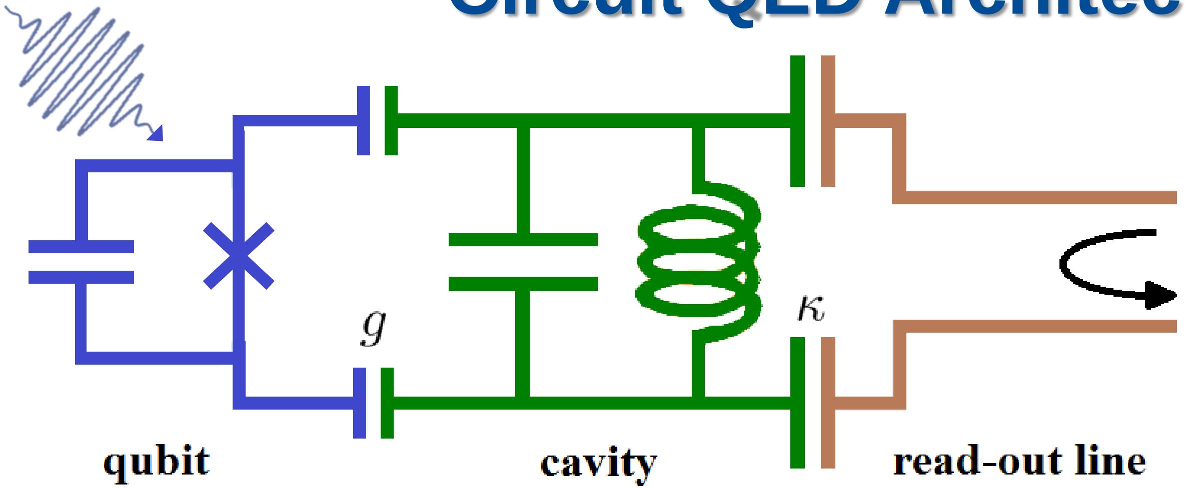






Dilution fridge ~ 10 mK

Circuit QED Architecture



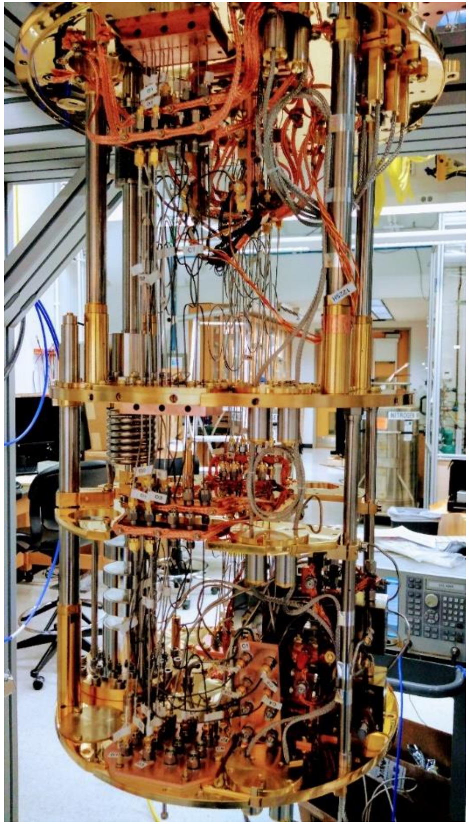
$$H = \frac{\omega_q}{2}\sigma_z + \omega_c a^\dagger a + g(a^\dagger \sigma_- + a\sigma_+)$$

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

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

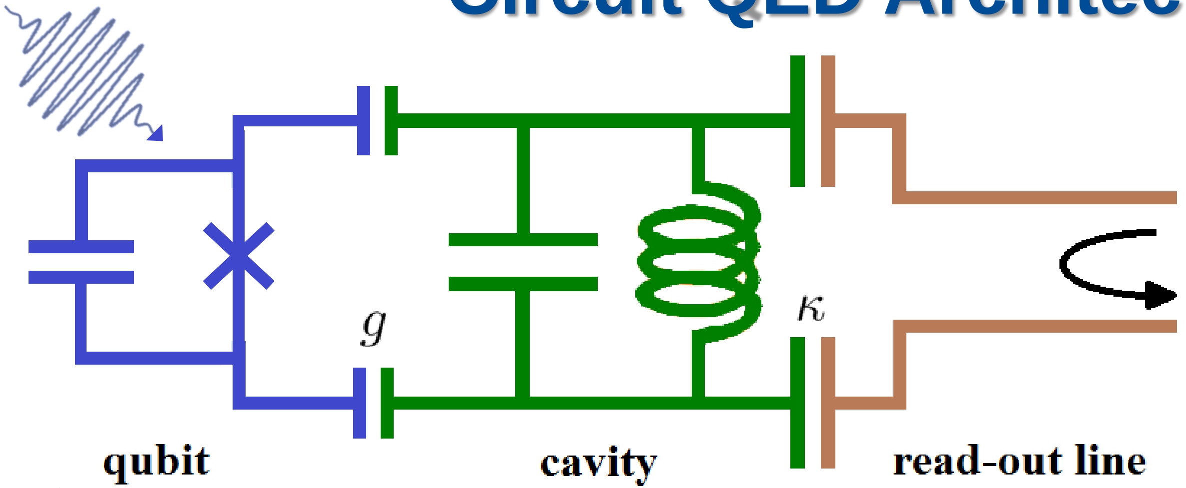
$$g \ll \Delta, \chi = 2g^2/\Delta$$

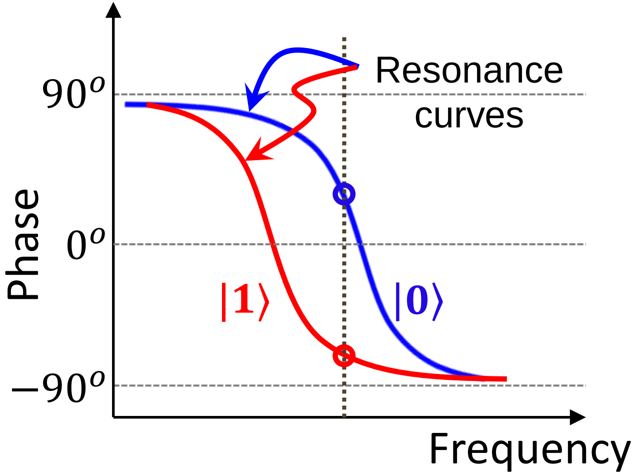
$$= \frac{\omega_q}{2}\sigma_z + \left(\omega_c + \frac{\chi}{2}\sigma_z\right) a^\dagger a$$

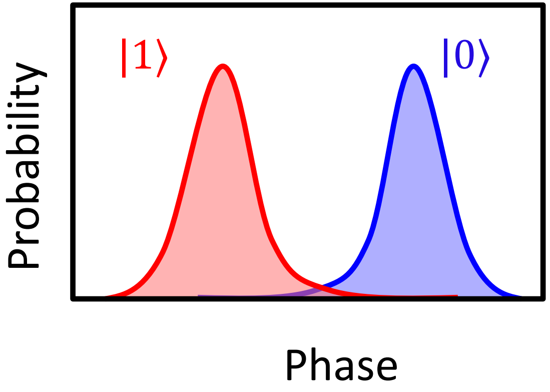


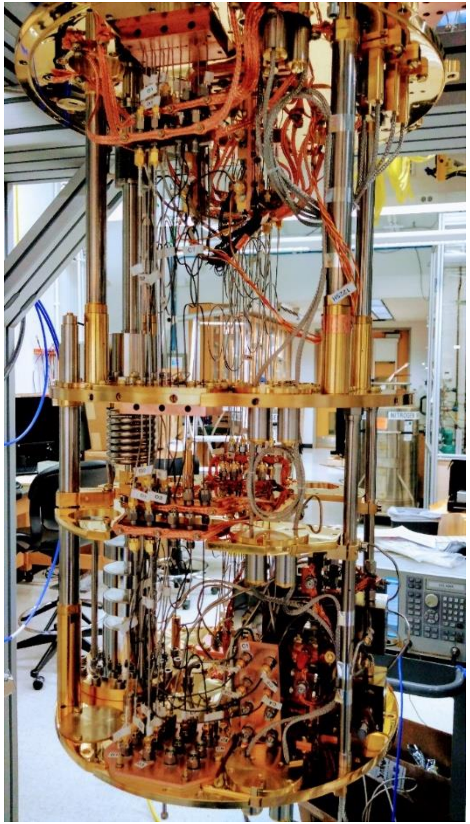
Dilution fridge ~ 10 mK

Circuit QED Architecture





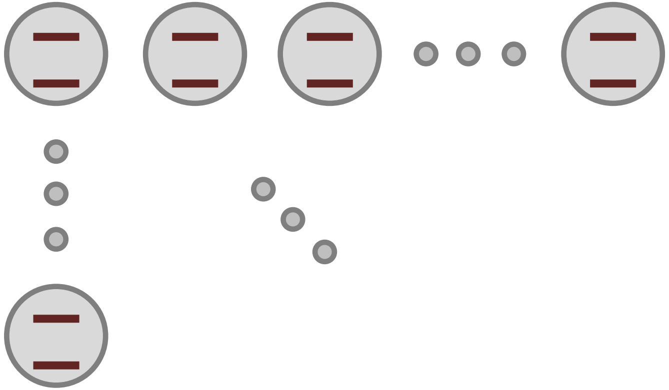




Dilution fridge ~ 10 mK

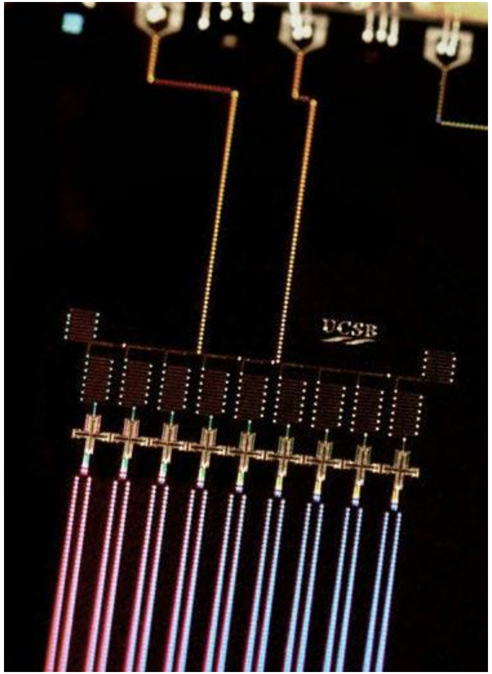
Traditional Multi-qubit Architecture

Linear or planar geometry

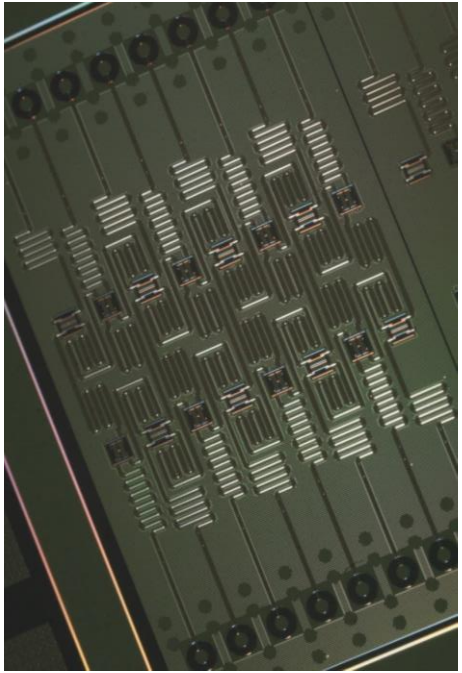


Computational space: 2^N

Can we do better?



UCSB, Nature 519 (7541)



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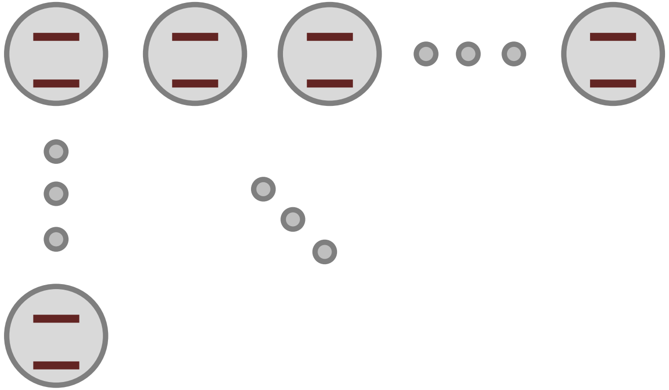
Traditional Multi-qubit Architecture

Linear or planar geometry

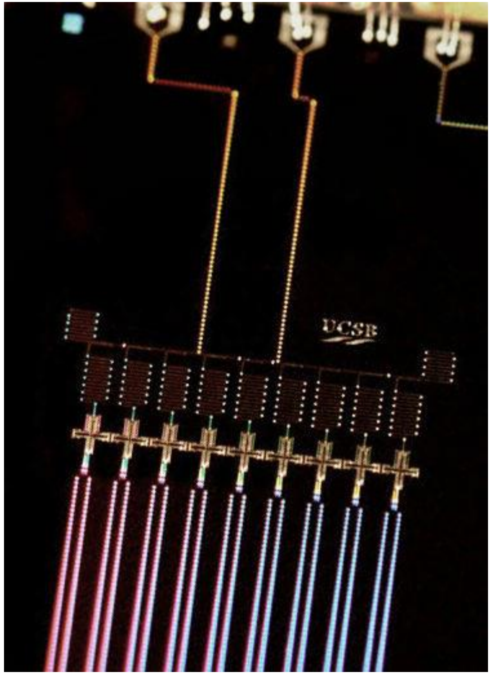


Computational space: 2^N

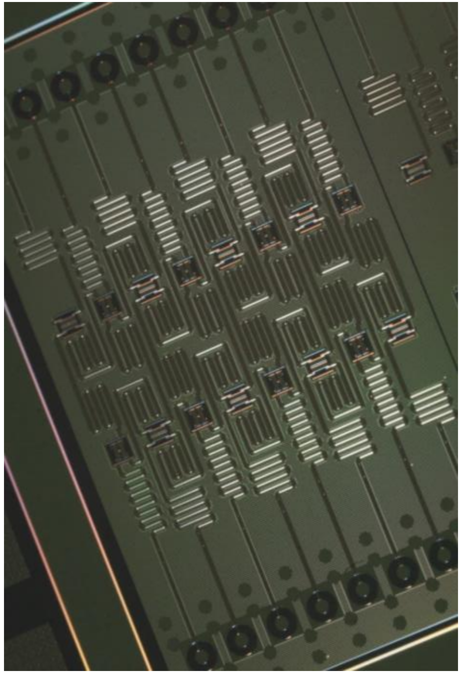
Can we do better?

Scaling: $d^N, d > 2$

Qudit



UCSB, Nature 519 (7541)



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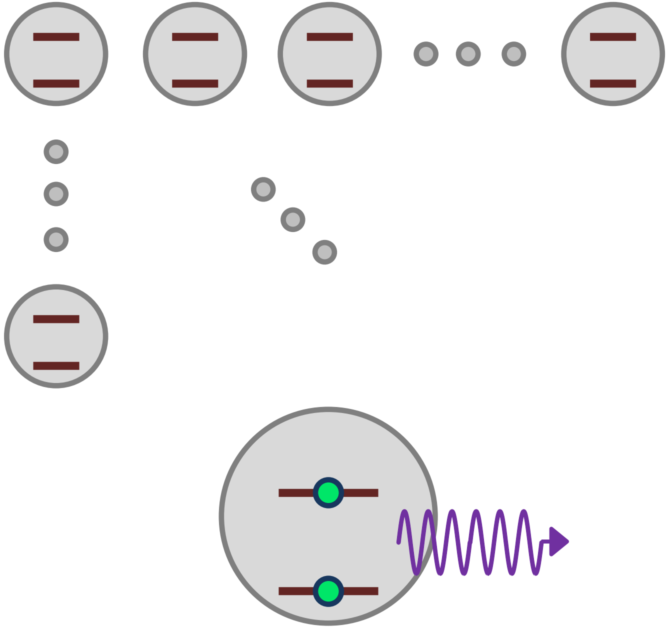
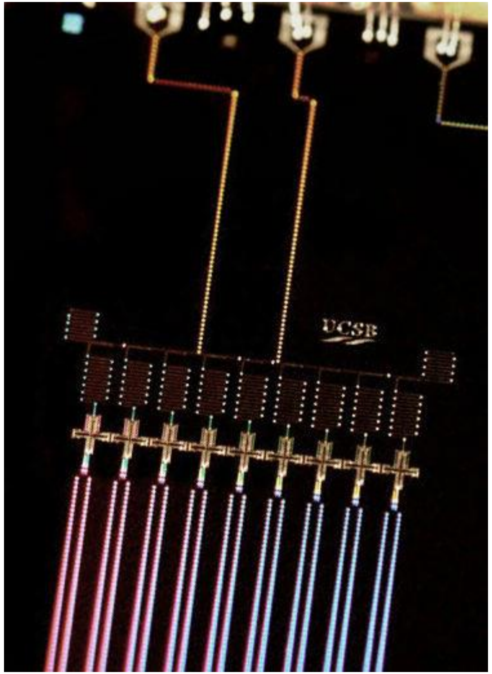
Problem of Relaxation

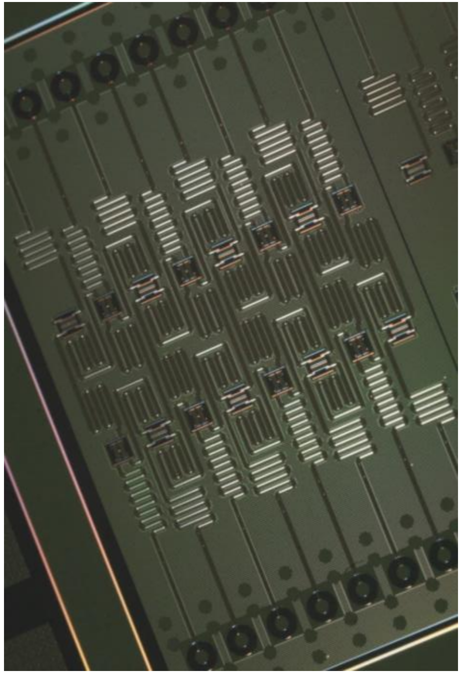
Linear or planar geometry



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



UCSB, Nature 519 (7541)



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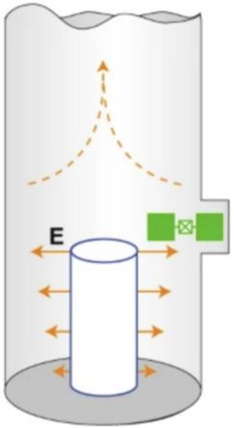
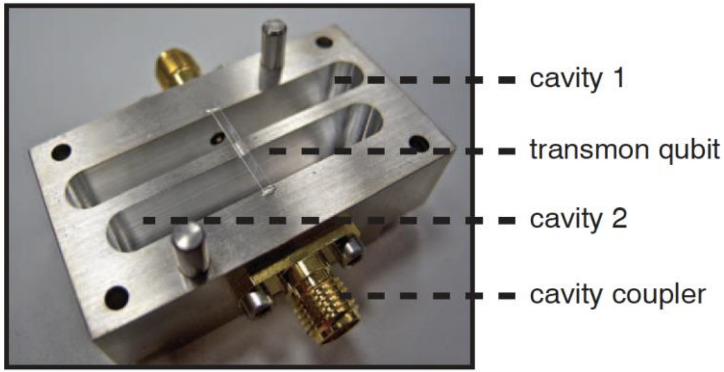
Can we do better?

Zoo of Cavities

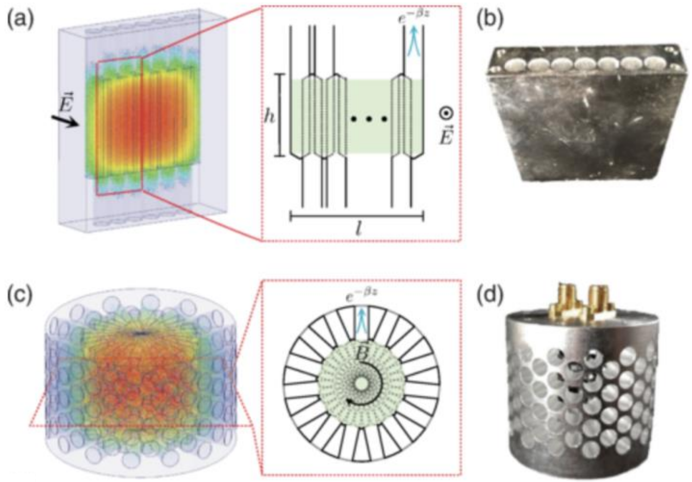


Nat. Phys. 16, 247



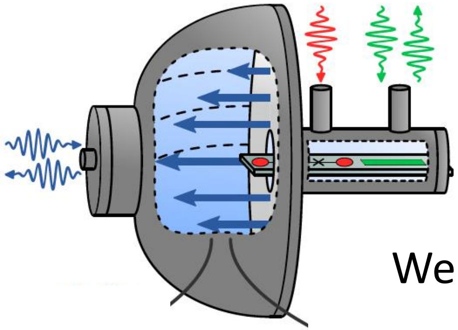
Science 342, 6158

Yale, U. Pittsburgh



PRL 127, 107701

U. Chicago, Rutgers



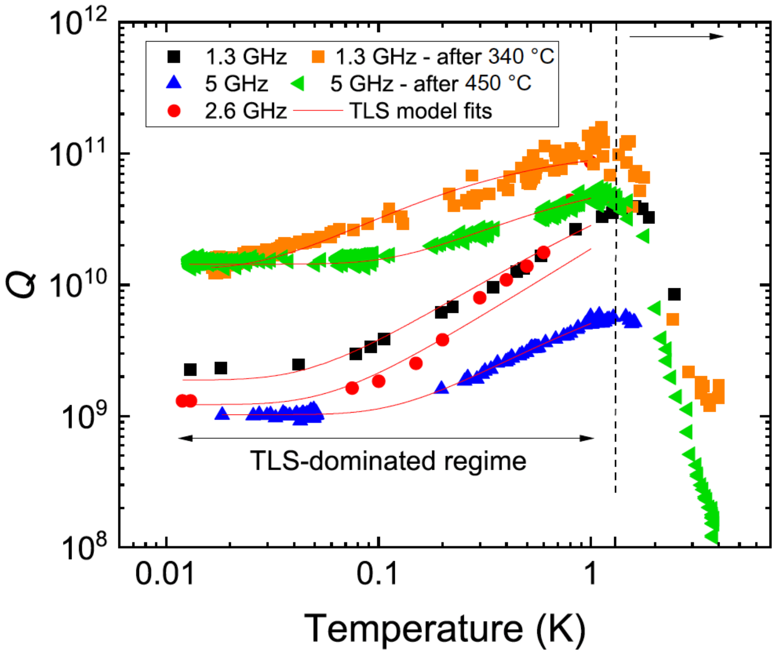
Weizmann

Under exploration

arXiv:2302.06442

High-Q 3D SRF Cavities

Romanenko et al. PRApplied 13, 034032



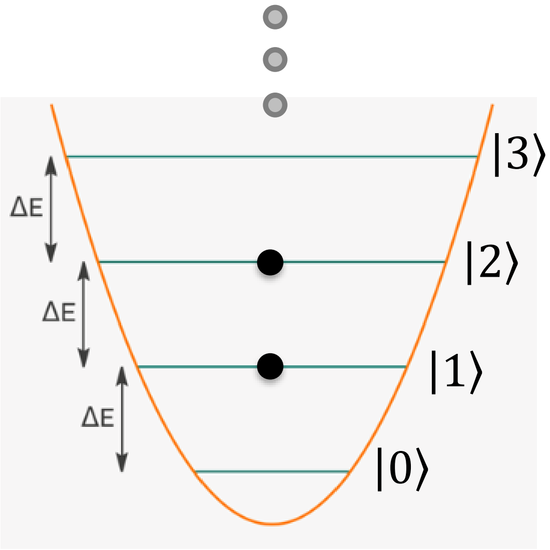
1.3 GHz SRF: $Q > 10^{11}$ at 1 K ⟹ $T_1 > 2$ s

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

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

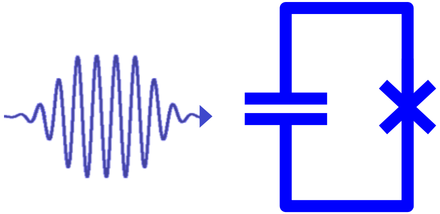
$T_1^{|10\rangle} > 30$ ms

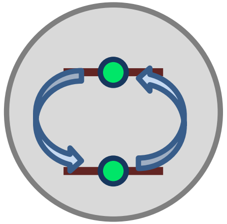
Qudit

Still much better than transmon qubits

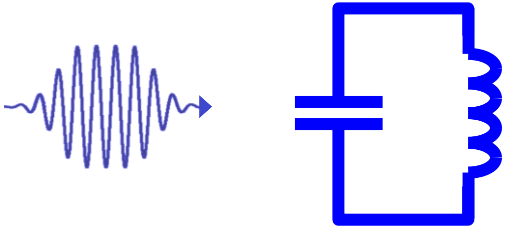
Transmon vs. Cavity Drive

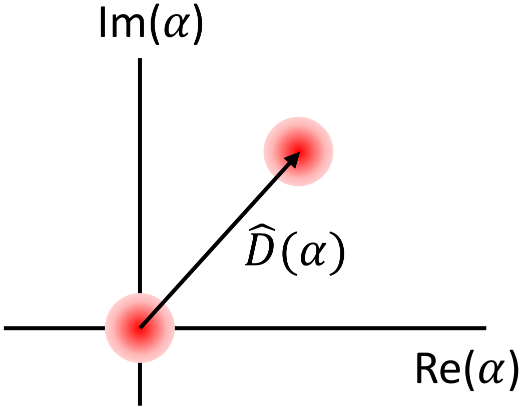
Qubit: $\alpha|0\rangle + \beta|1\rangle$





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





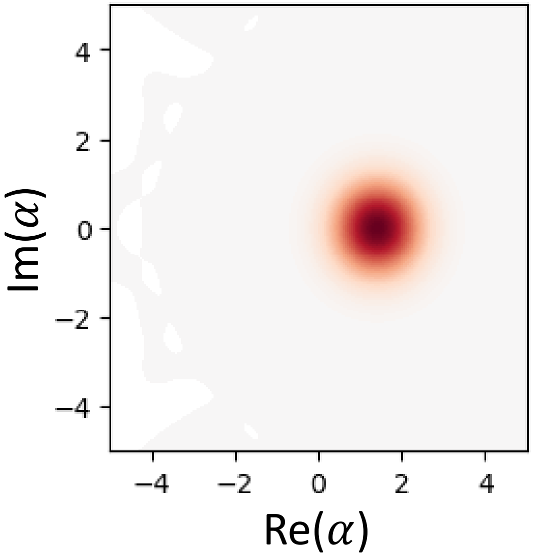
Qudit Operation

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

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

Selective number-dependent arbitrary phase (SNAP) gate

PRL 115, 137002 (2015)



Qudit Operation

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

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

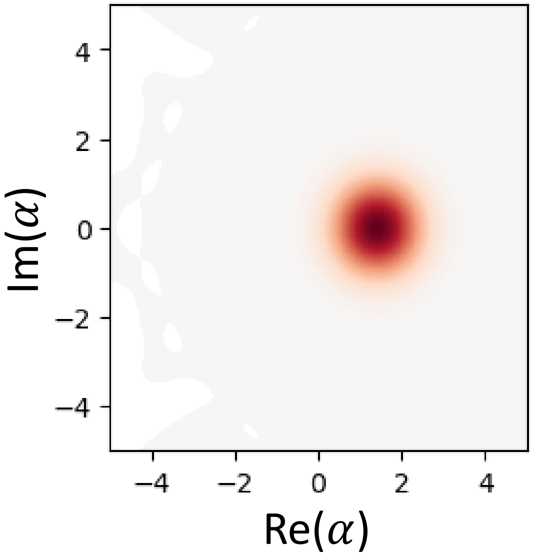
Quantum state

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

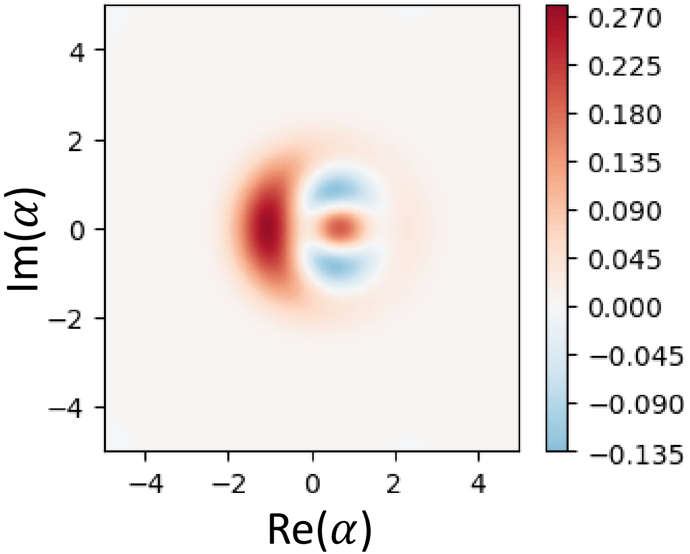
$|n\rangle \rightarrow e^{i\theta}|n\rangle$

Selective number-dependent arbitrary phase (SNAP) gate

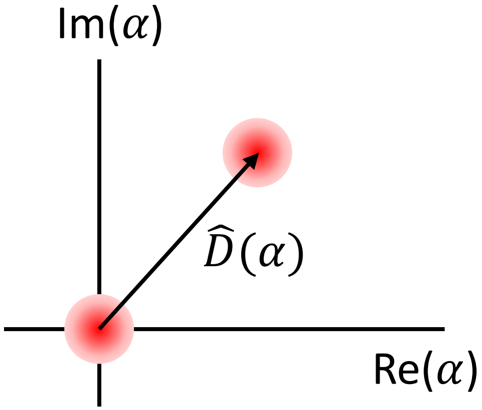
PRL 115, 137002 (2015)



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



Universal Gate Set



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

SNAP gate

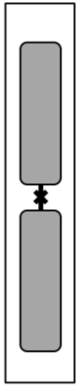
Qudit: $\alpha_0 e^{i\theta_0}|0\rangle + \alpha_1 e^{i\theta_1}|1\rangle + \cdots + \alpha_d e^{i\theta_d}|d\rangle$

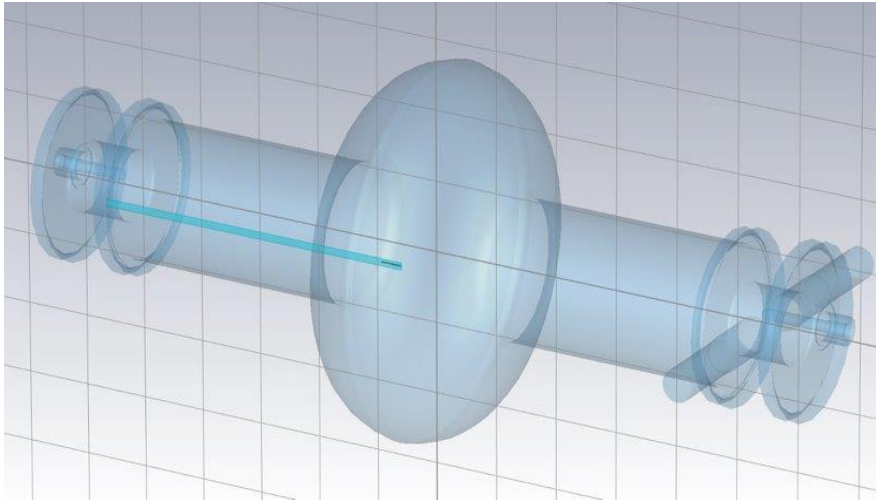
Cavity drive + SNAP → Universal control

Unconditional operation on cavity

Conditional operation on cavity enabled by a transmon

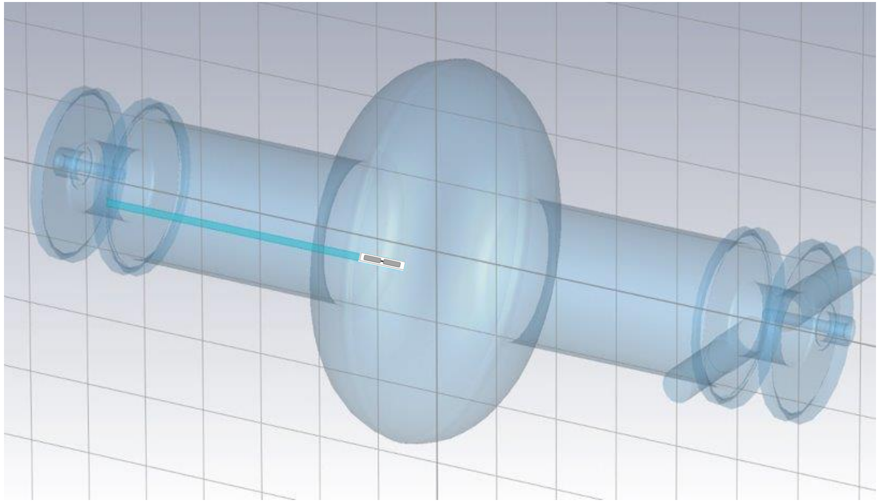
First Milestone





Incorporate Transmon into a TESLA cavity

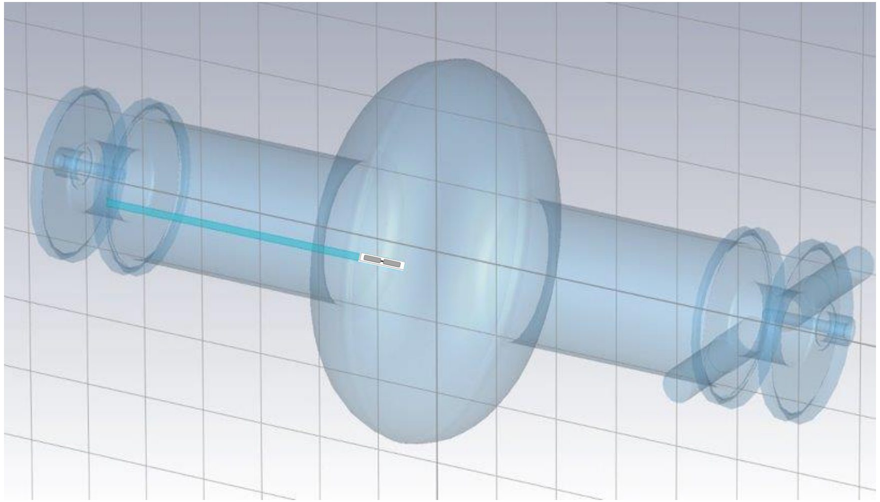
First Milestone

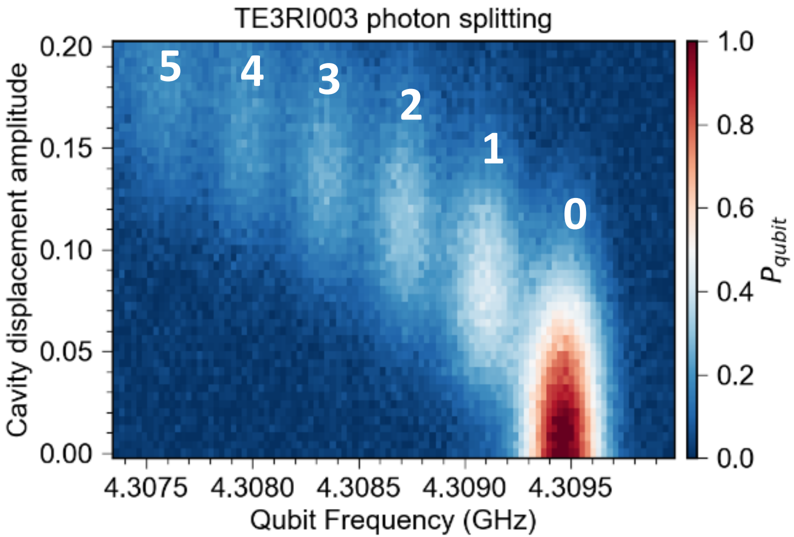


Incorporate Transmon into a TESLA cavity

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

First Milestone

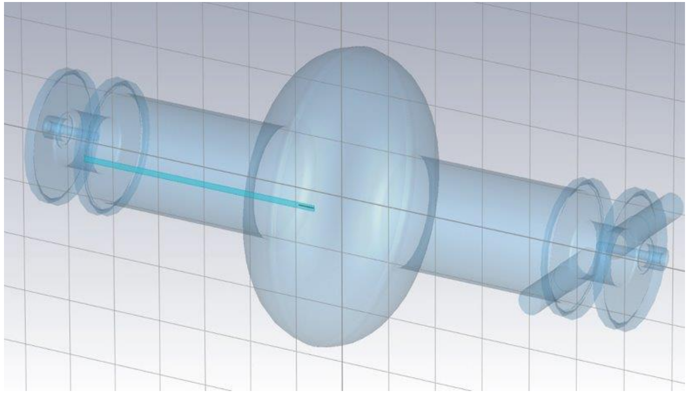




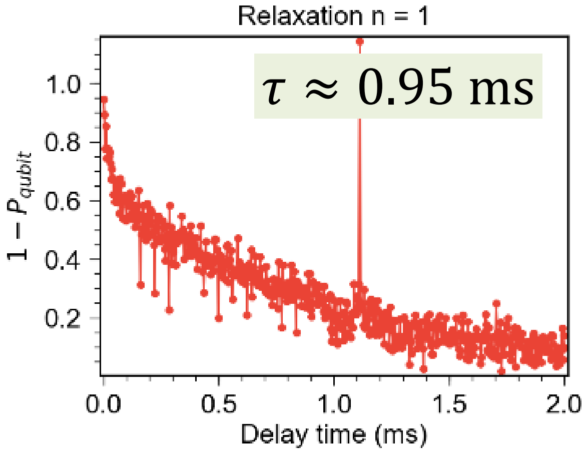
Incorporate Transmon into a TESLA cavity

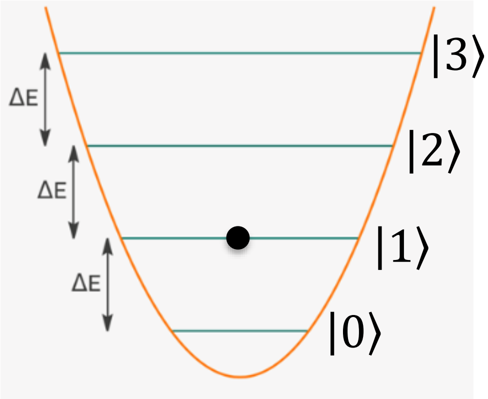
Achieved photon counting

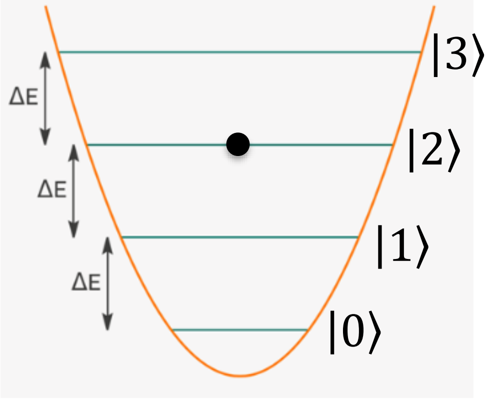
Second Milestone

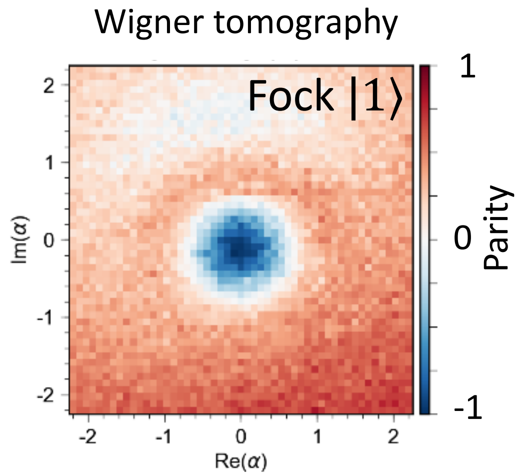


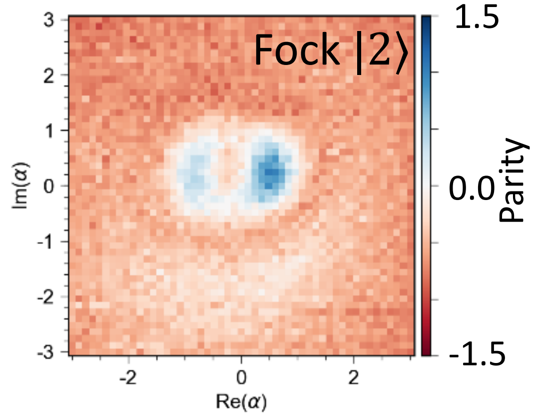
Prepare quantum states





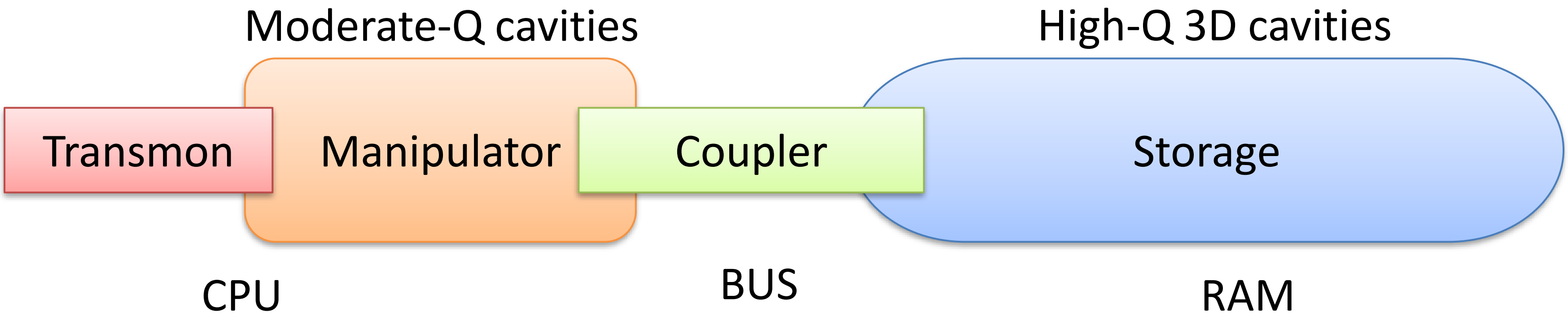






Multi-qudit Architecture

Crosstalk issues

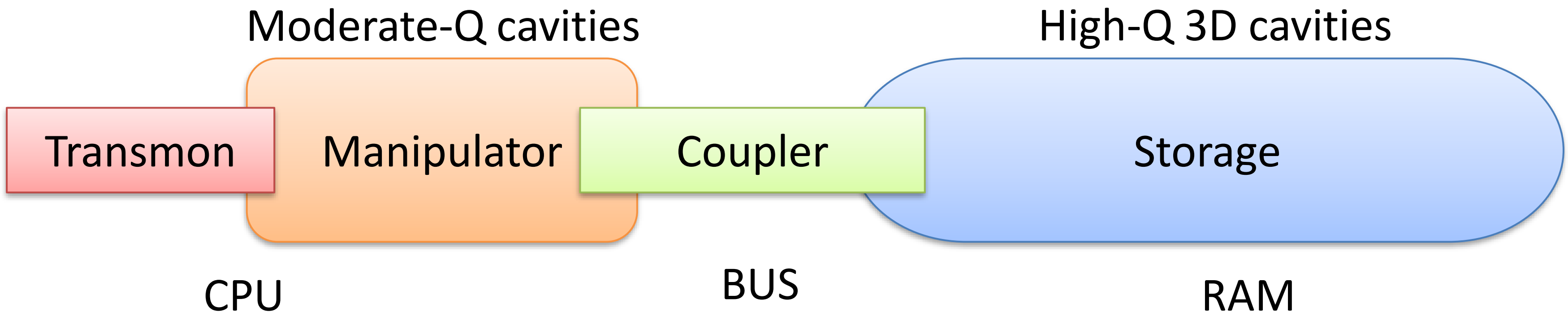


Multi-qudit Architecture

Crosstalk issues

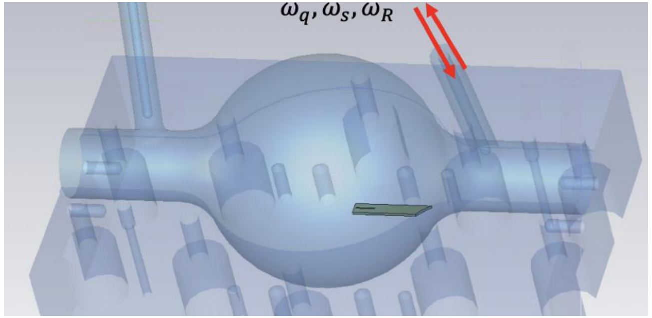
All-to-all coupling

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

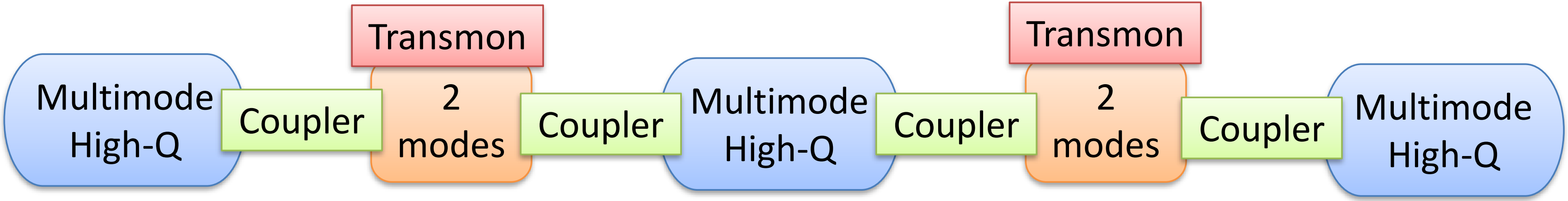


Outlook

- ❖ Improve single-cell devices
  - ➢ Optimize transmon design, placement
  - ➢ Investigate other SRF cavity geometries



- ❖ Scaling up
  - ➢ Develop modular architecture
  - ➢ Connect several modules



Brand New SQMS Facility at Fermilab

Thank You!

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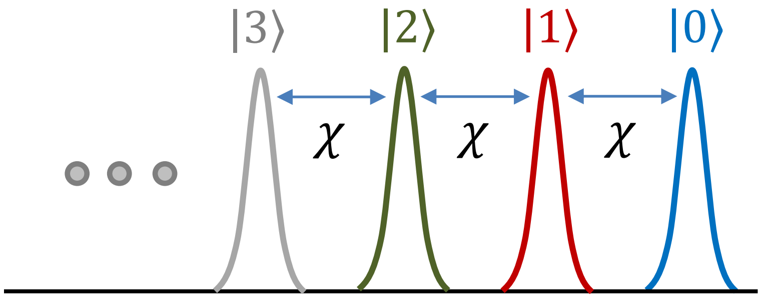
Qubit frequency dependence

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

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

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



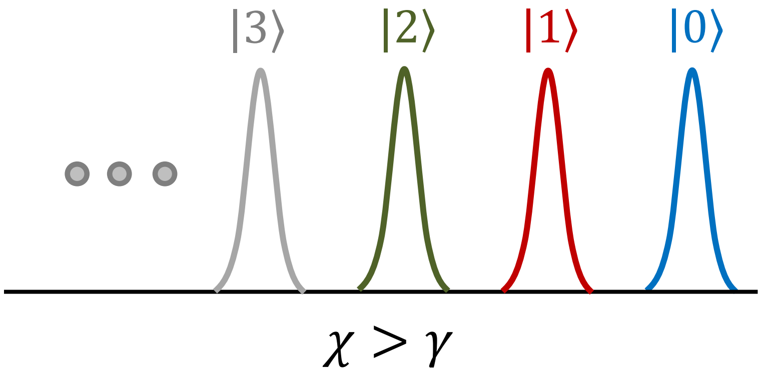
$\chi > \gamma$

SNAP + cavity drive

Universal control

Visualization of SNAP

Selective number-dependent arbitrary phase pulse



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

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

$\downarrow$ $\cos \omega_q t$

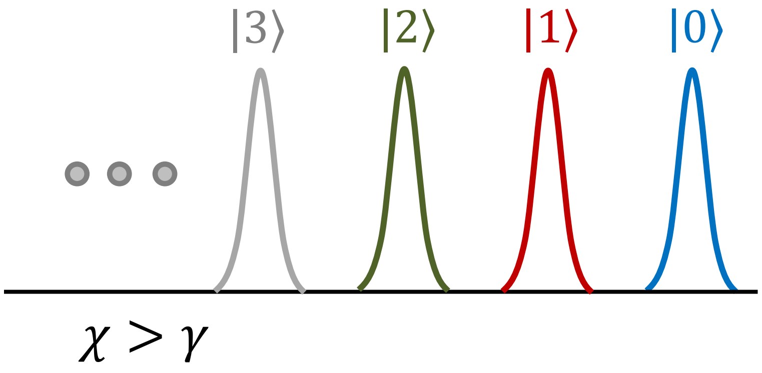
$$|0\rangle|1\rangle + |1\rangle|0\rangle + |2\rangle|0\rangle + \cdots$$

$\downarrow$ $\cos \omega_q t$

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

Visualization of SNAP

Selective number-dependent arbitrary phase pulse



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

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

$\cos \omega_q t$

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

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

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

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