Advances in SRF qubit architectures for quantum computing

Tanay Roy

SQMS division, Fermilab

30 June 2023

Why Quantum Computing?

Frontier

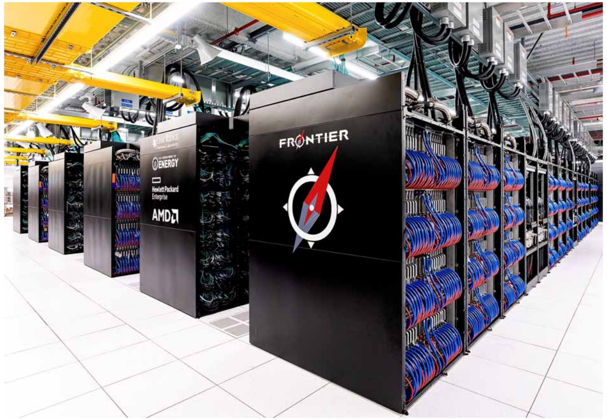

Image: Wikipedia

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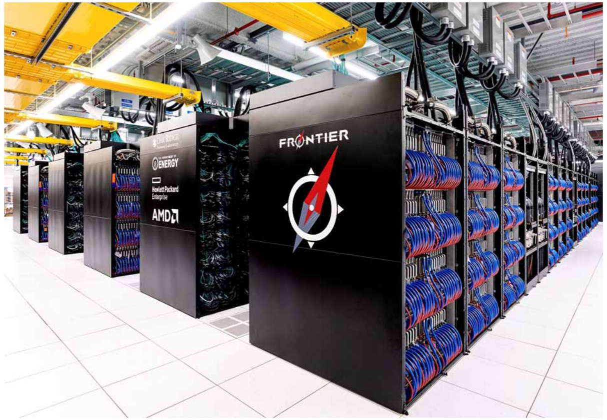

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$$1.2 \times 10^{18} \, calculations\,/sec$$

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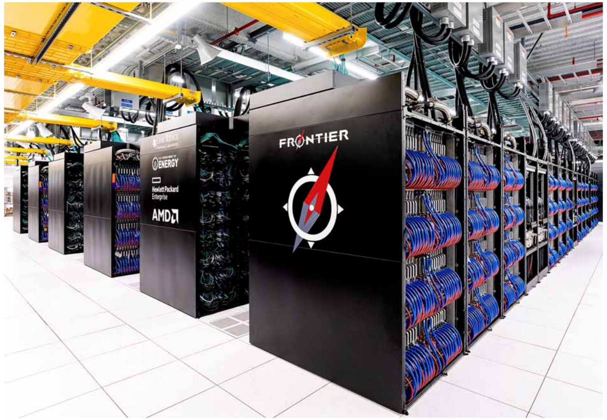

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Not efficient for all problems

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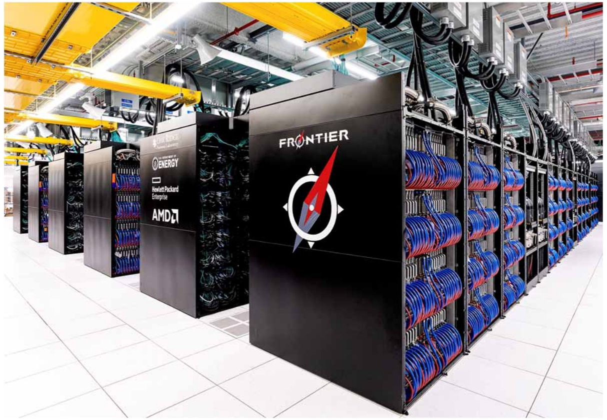

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1. Prime Factorization

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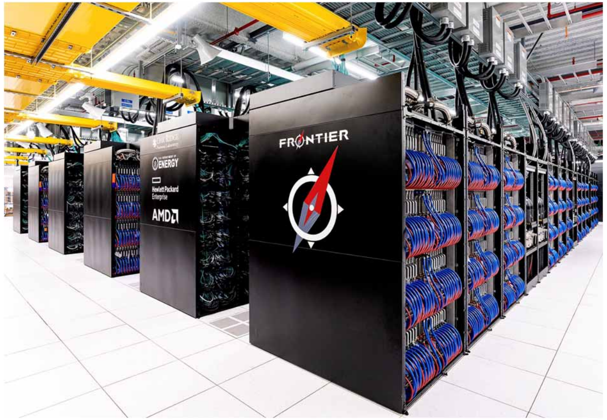

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1. Prime Factorization

762904558518855853

? × ?

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Why Quantum Computing?

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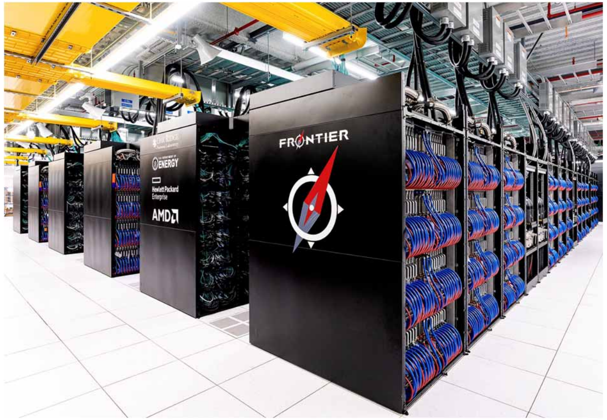

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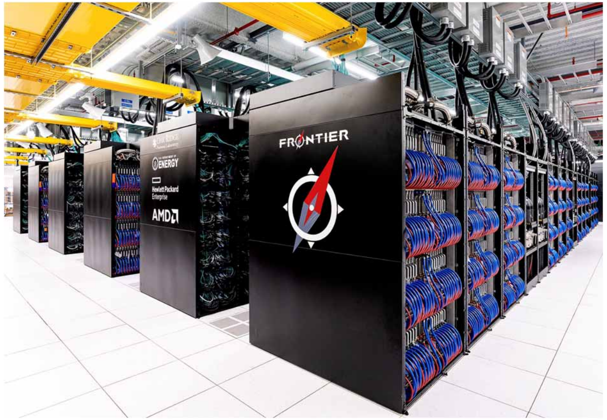

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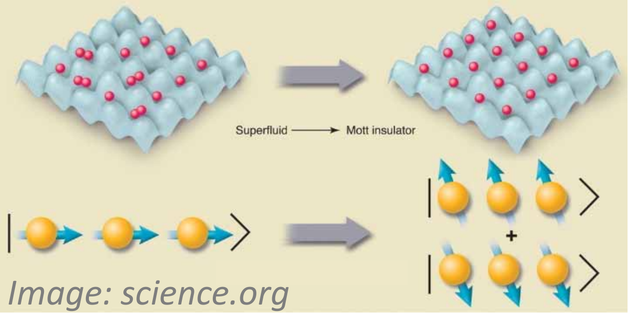
2. Quantum Simulation



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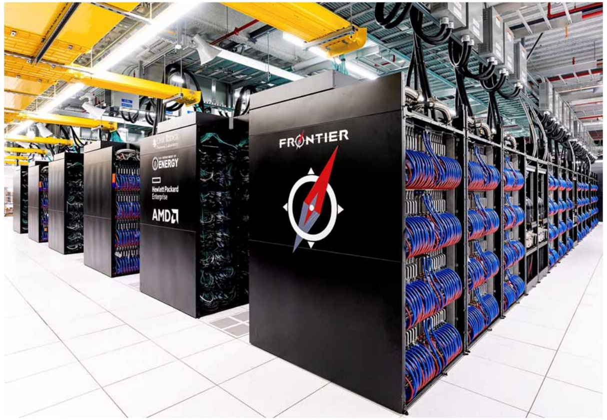

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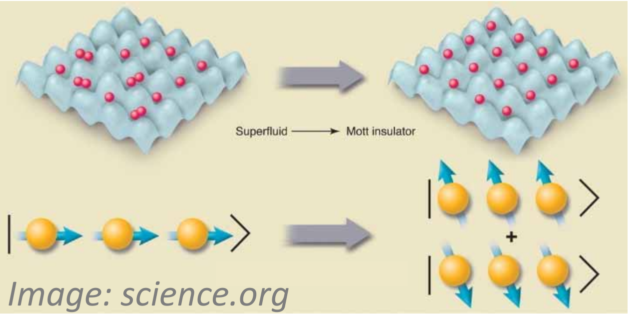

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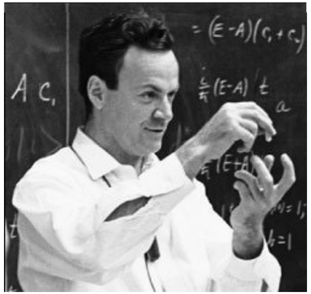
Simulate one QM system with another



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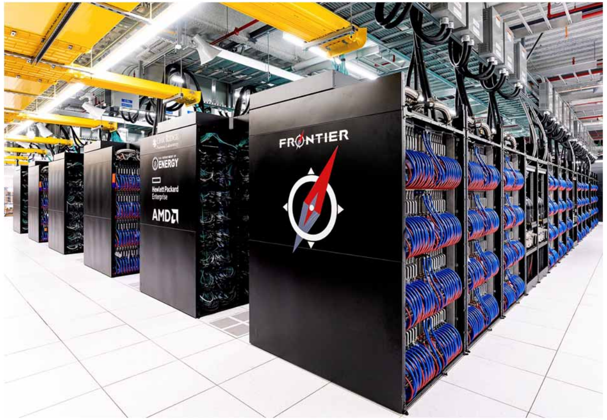

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Shor's factoring algorithm 1994

Image: mit.edu

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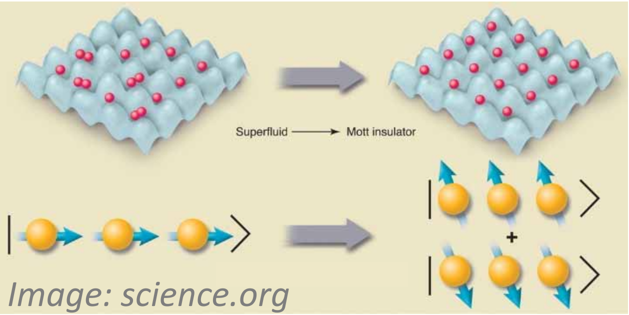

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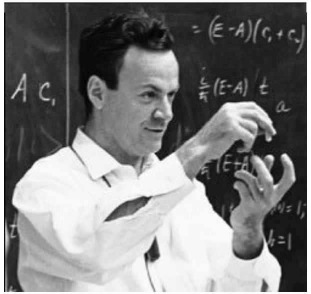

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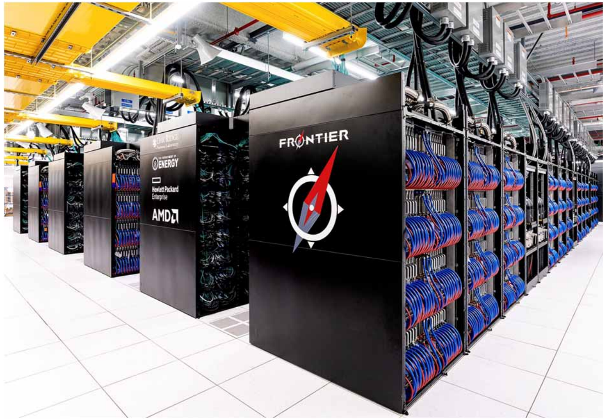

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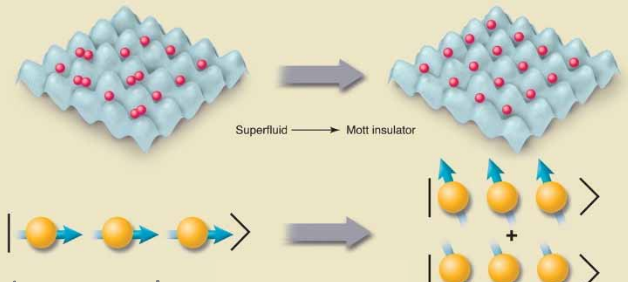
Build a Quantum Computer

2. Quantum Simulation



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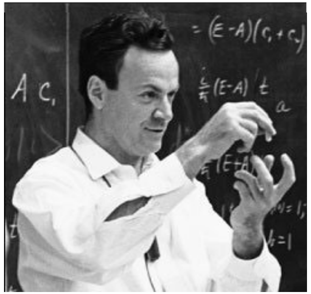

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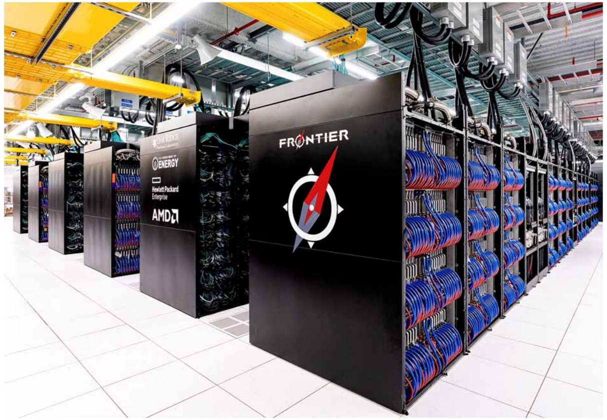

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HARD

776531401 × 982451653

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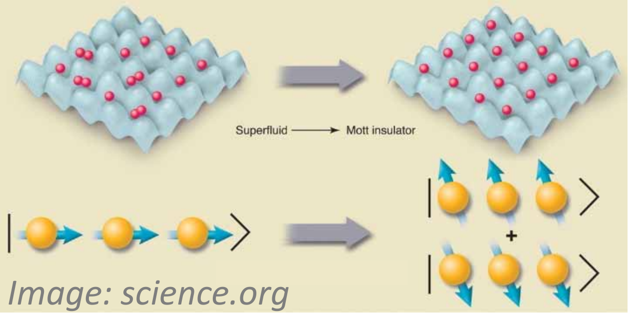

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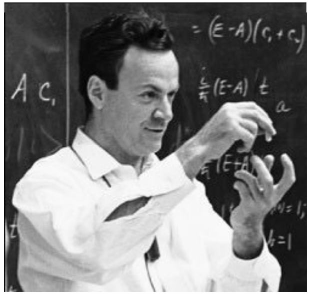

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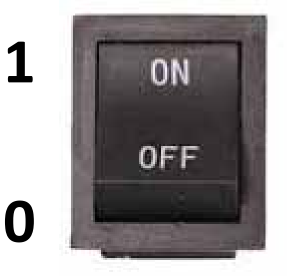
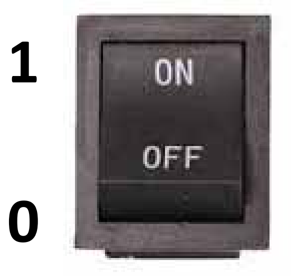
Fundamental Unit

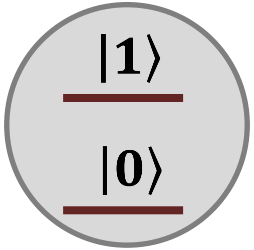
Fundamental Unit



Classical bit:
"0" or "1"

Fundamental Unit





Quantum bit
Qubit

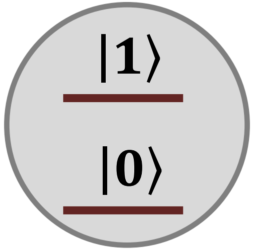
Classical bit:
"0" or "1"

Quantum bit:
"0" and "1"

Fundamental Unit

1

0



Quantum bit

Qubit

Classical bit:
"0" or "1"

Quantum bit:
"0" and "1"

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

Fundamental Unit

1

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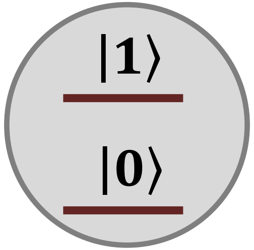

Quantum bit

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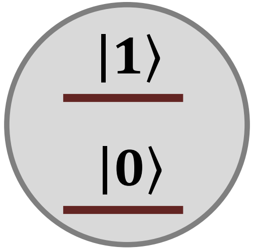
Superposition: $|\mathbf{0}\rangle \pm |\mathbf{1}\rangle$

Entanglement

Fundamental Unit

1

0



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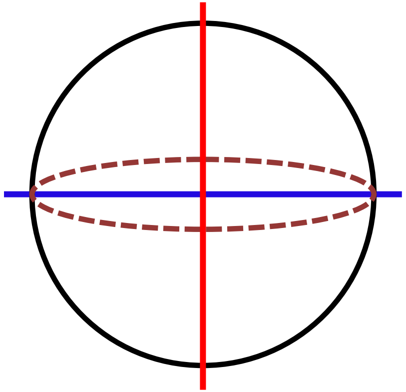
Superposition: $|0\rangle \pm |1\rangle$

Superior

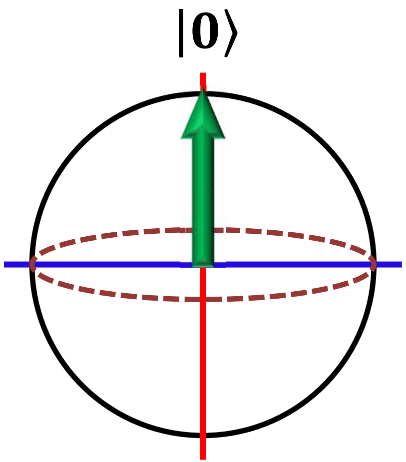
Entanglement

Qubit Visualization



Bloch sphere

Qubit Visualization



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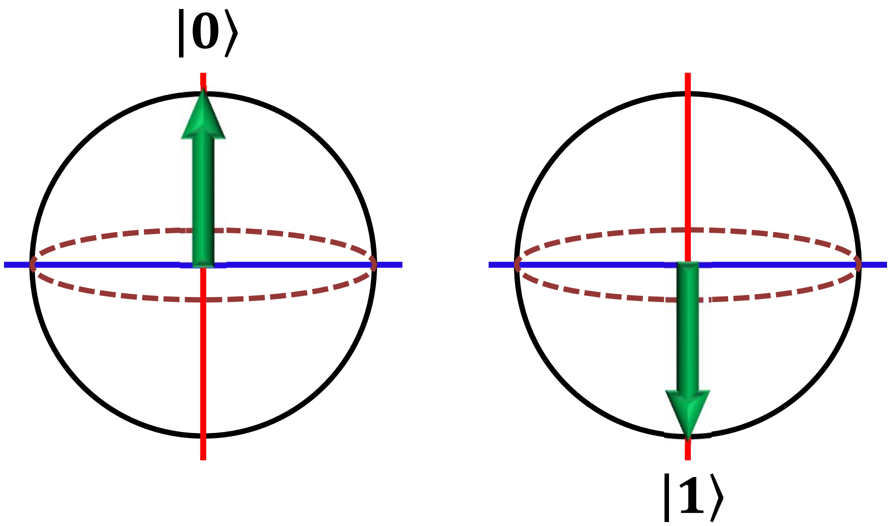

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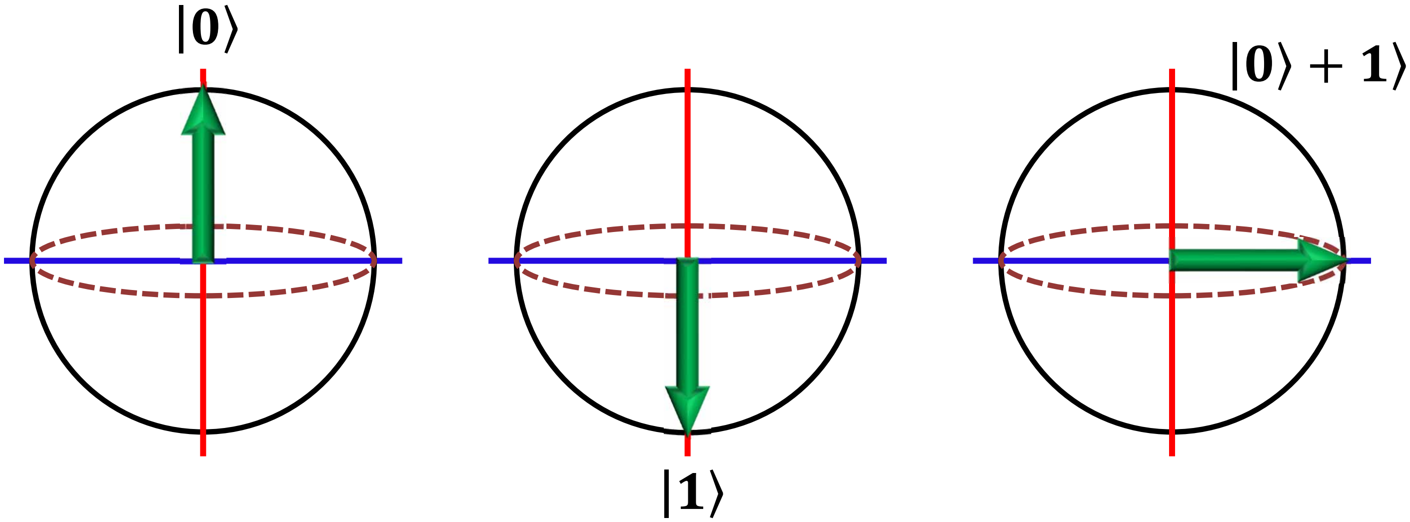

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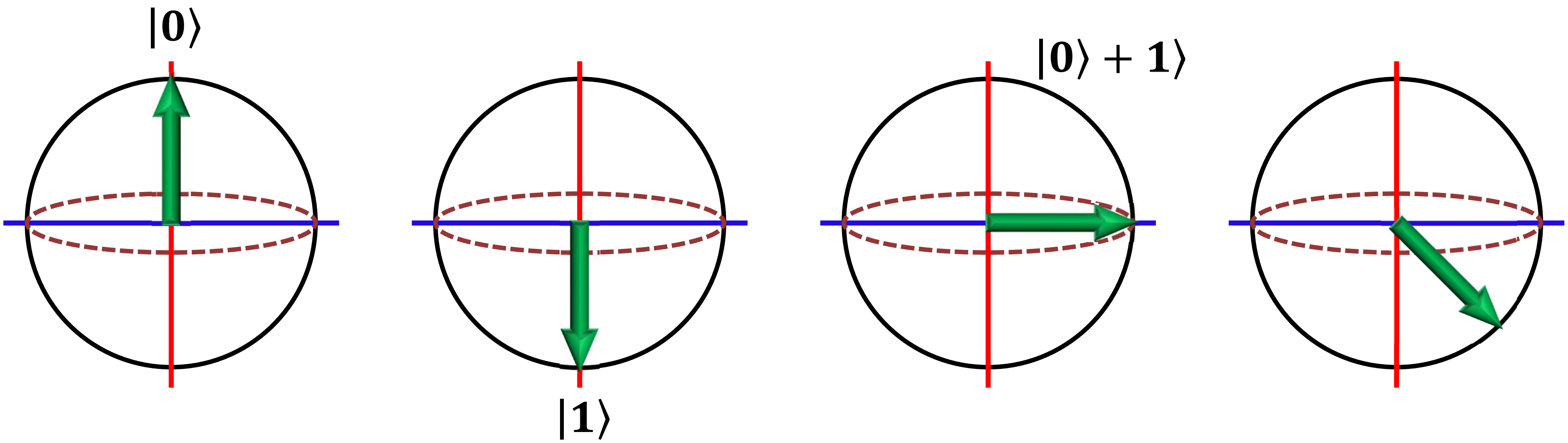

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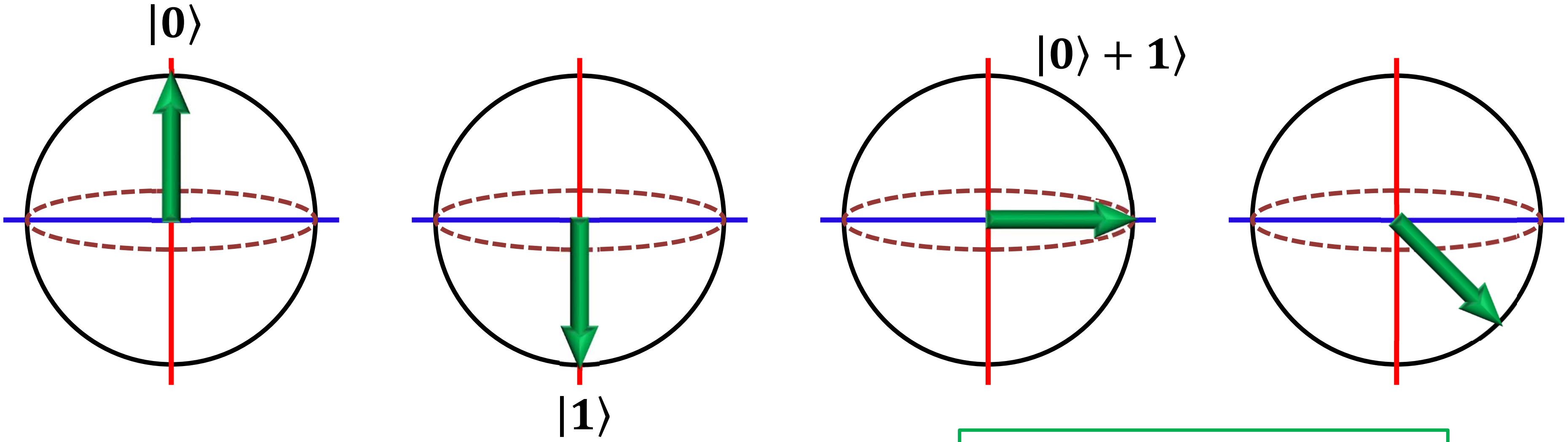
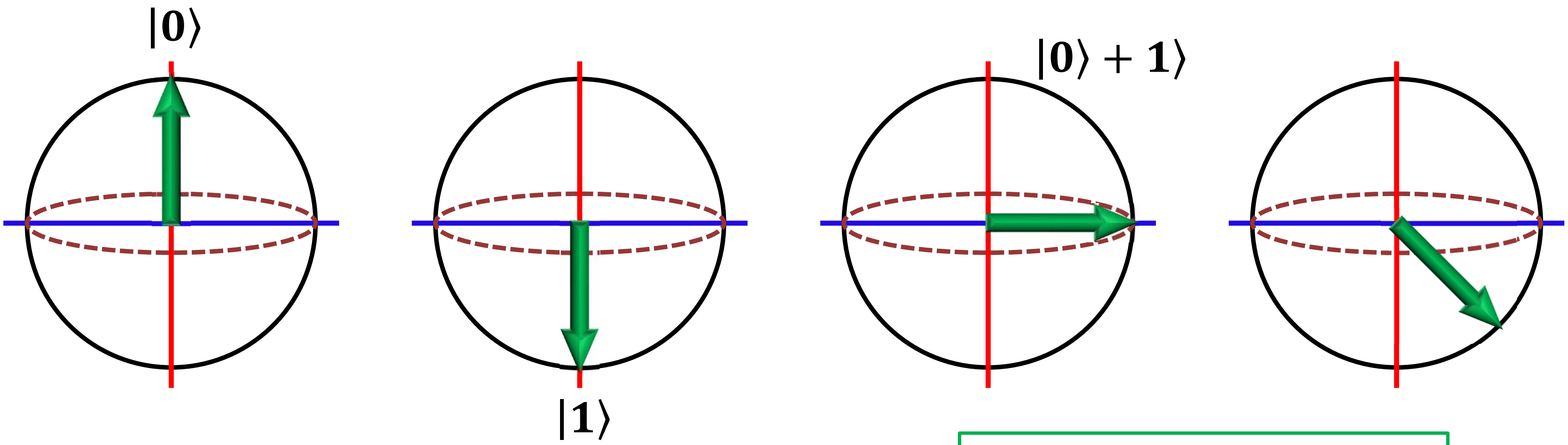


Bloch sphere

Superposition states

Qubit Visualization



Bloch sphere

Superposition states

General state: $\boldsymbol{\alpha}|\mathbf{0}\rangle + \boldsymbol{\beta}|\mathbf{1}\rangle$

Single-qubit Gate and Measurement

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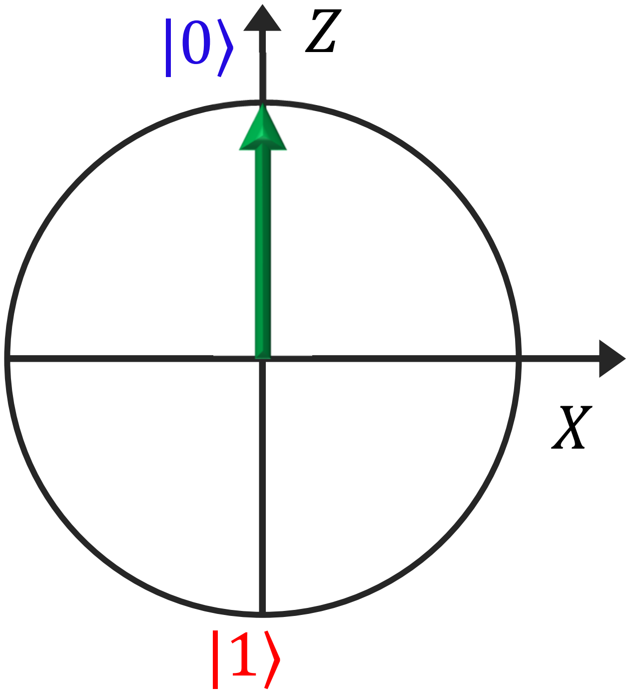
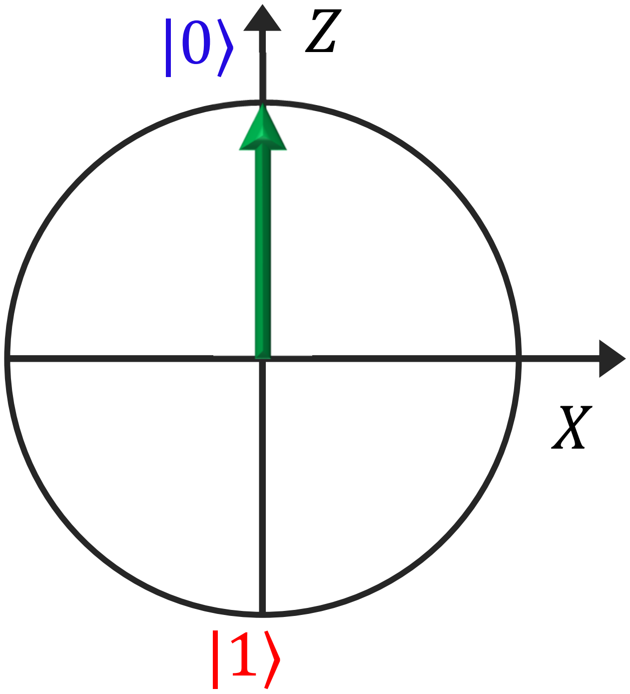


Rabi Oscillation

Single-qubit Gate and Measurement



Rabi Oscillation

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

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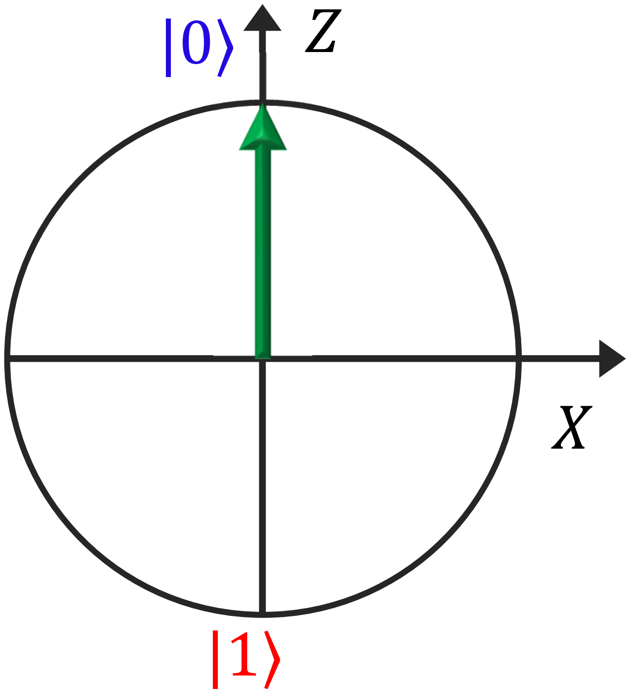

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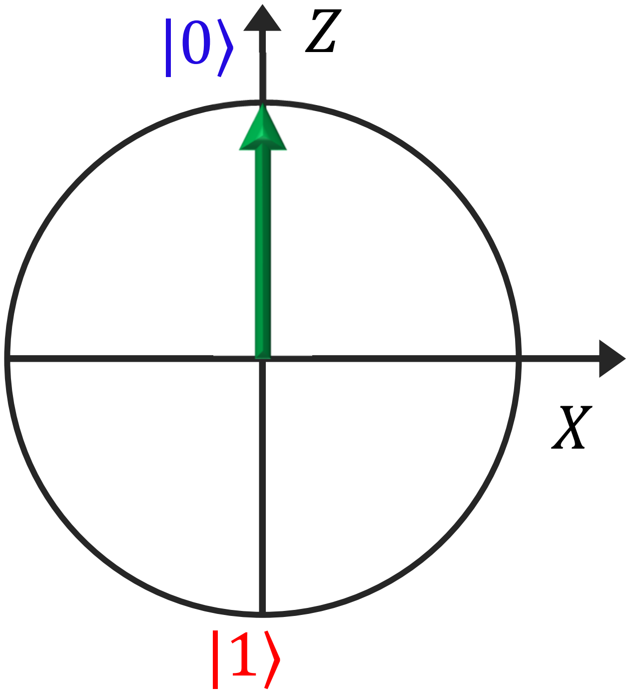
Measure

Single-qubit Gate and Measurement



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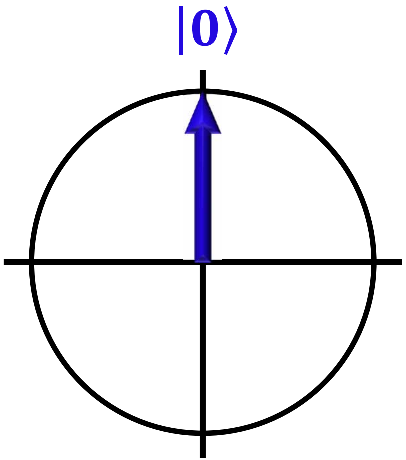

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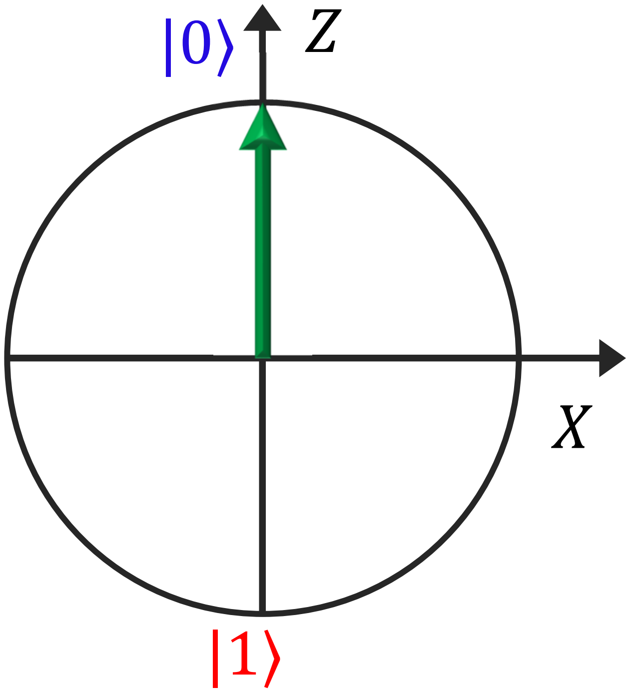

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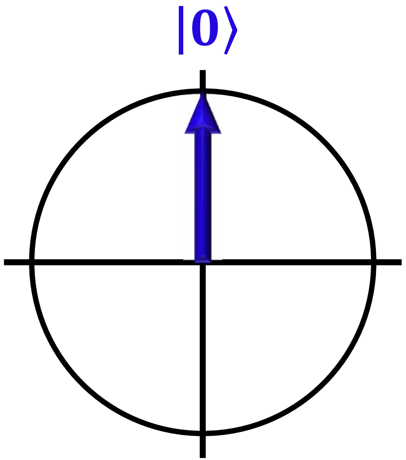
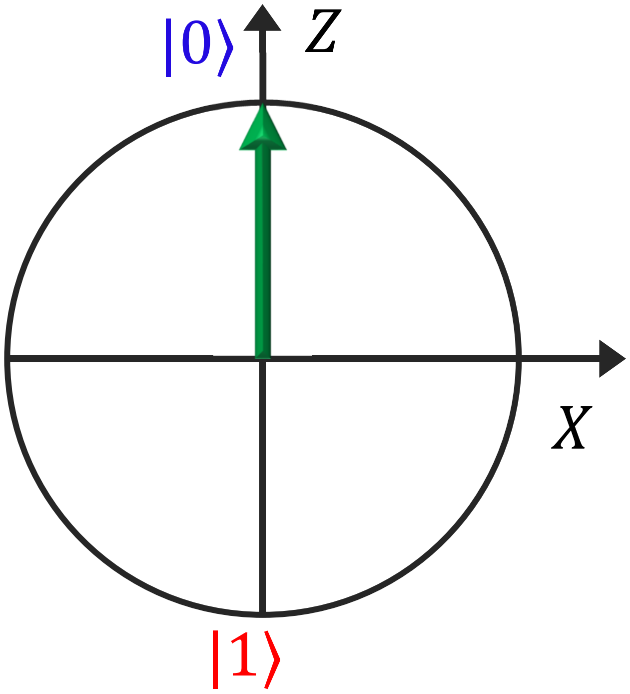


$P(0) = |\alpha|^2$

Single-qubit Gate and Measurement



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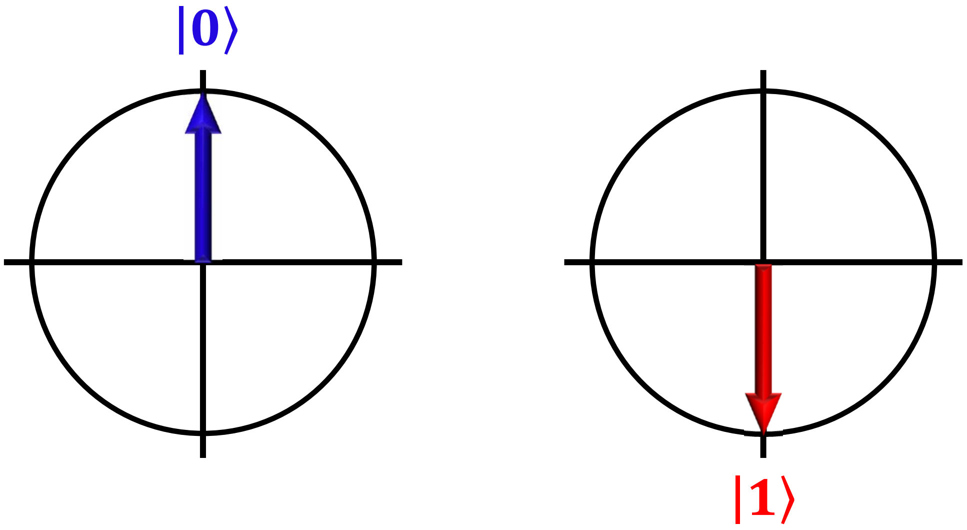

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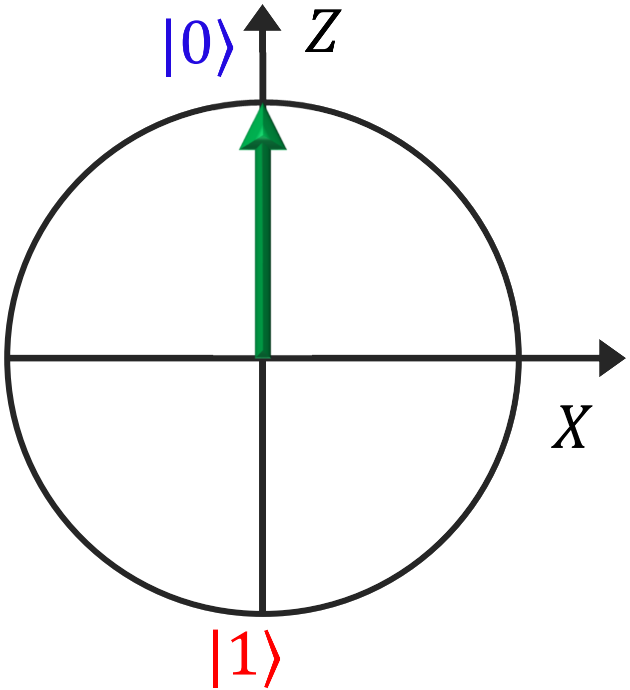

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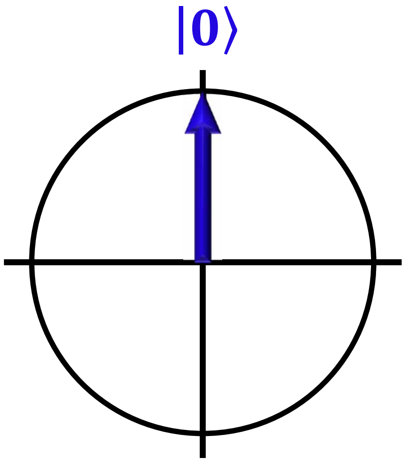

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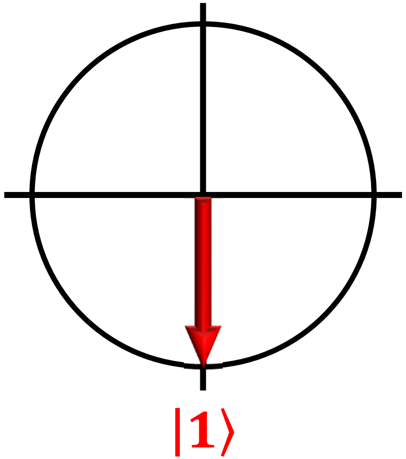
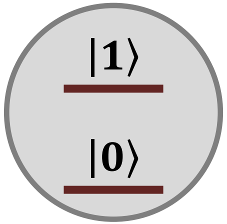


$P(1) = |\beta|^2$

Basic Requirements for a Quantum Computer



Quantum two level systems

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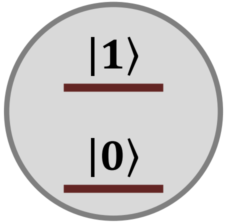

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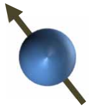

$$\alpha|0\rangle + \beta|1\rangle$$

Create arbitrary states

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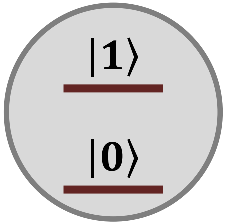

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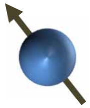

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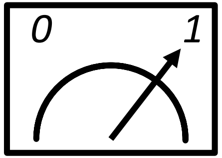

Measure quantum states

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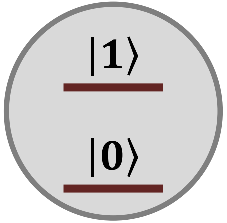

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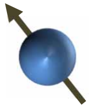

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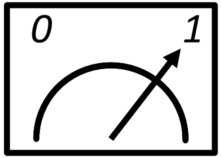

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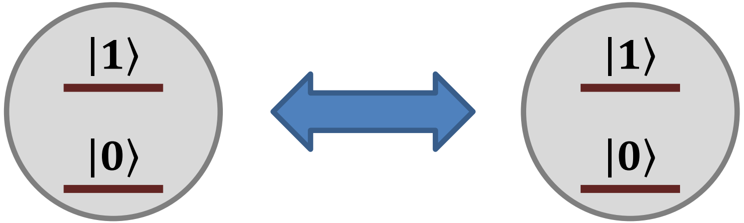

Couple multiple qubits

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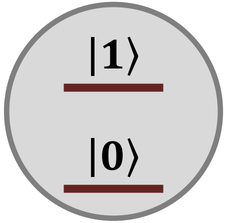

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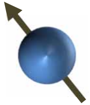

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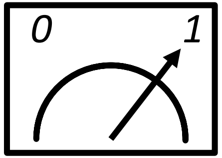

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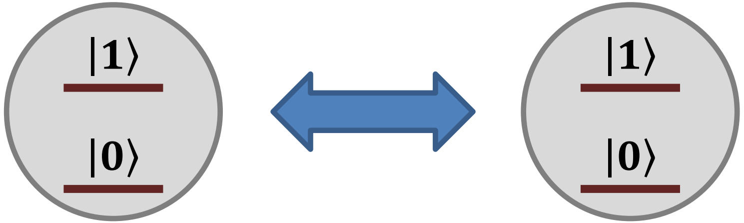

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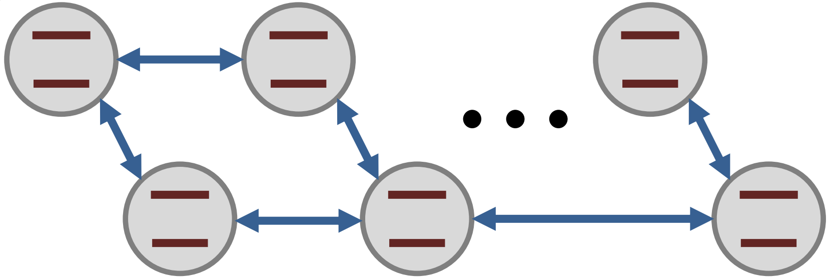
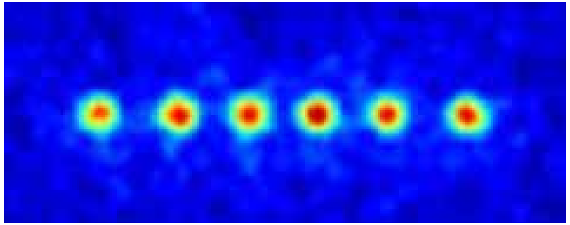


Scalable architecture

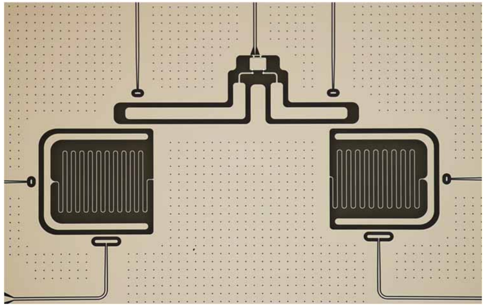
Different Platforms

Ion trap



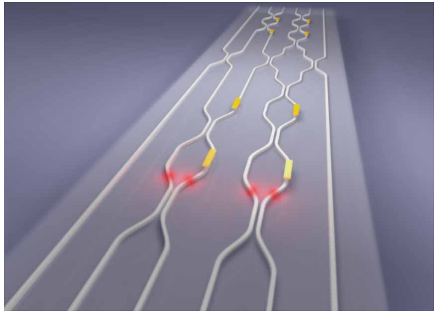
quantumoptics.at

Superconducting circuits



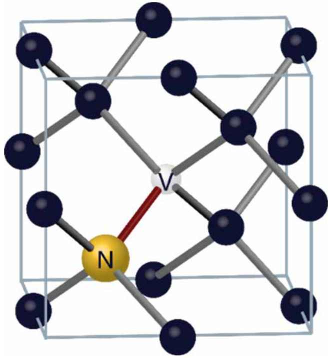
Schuster lab

Photonic crystals



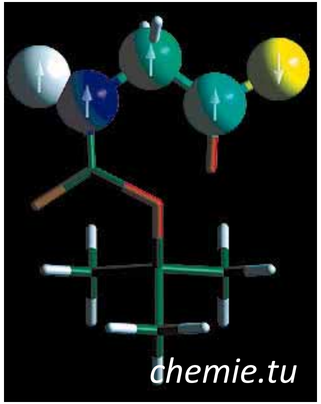
phys.org

NV centers



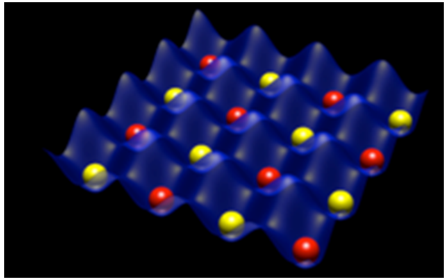
phys.org

NMR



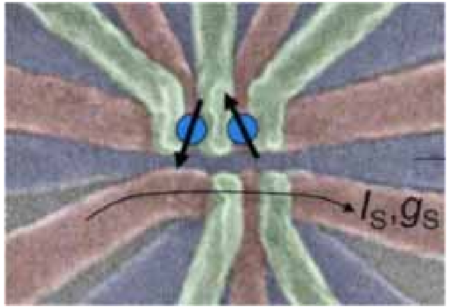
chemie.tu

Neutral atoms



NIST

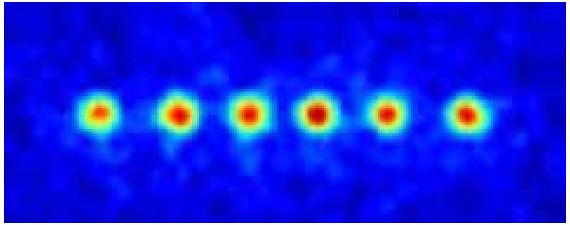
Quantum dots



sciencemag.org

Different Platforms

Ion trap



quantumoptics.at

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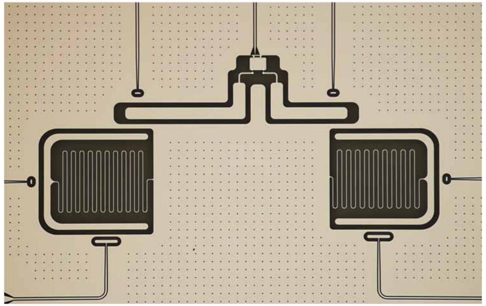

Schuster lab

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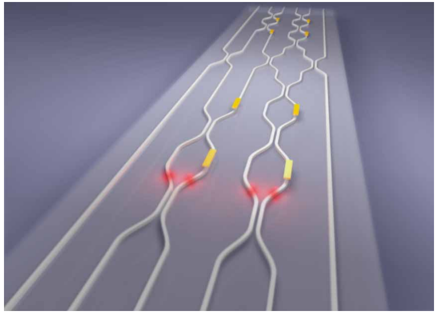

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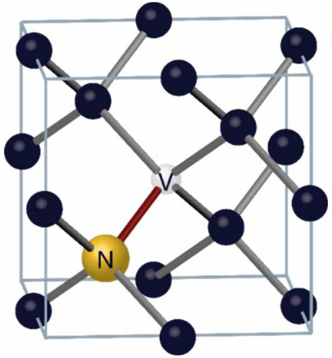
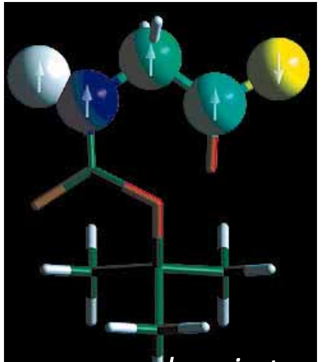


phys.org

NMR



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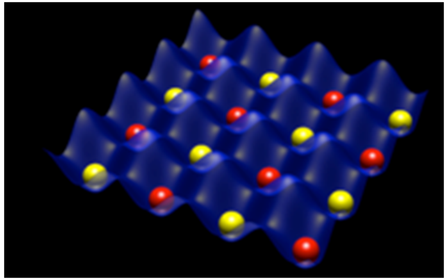

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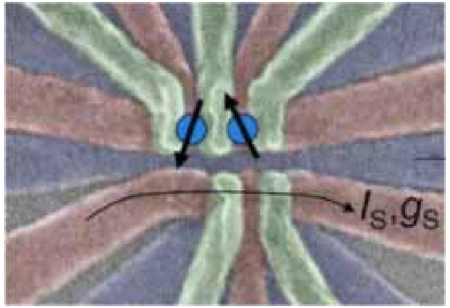
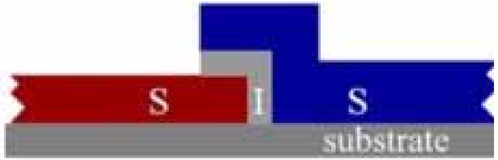
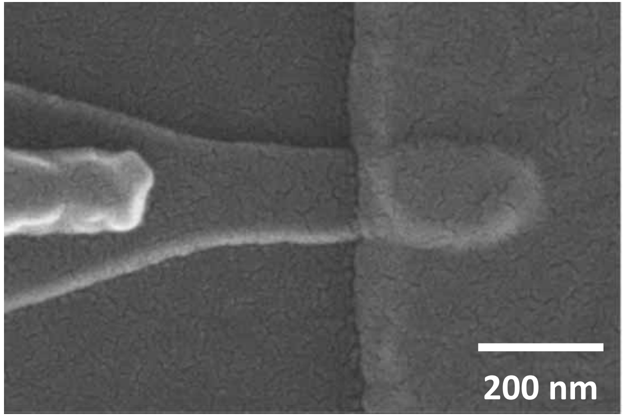


sciencemag.org

Superconducting Circuits



Josephson Junction



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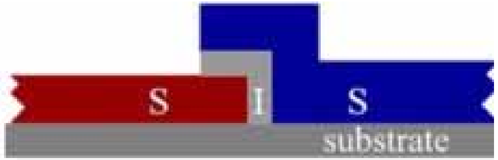

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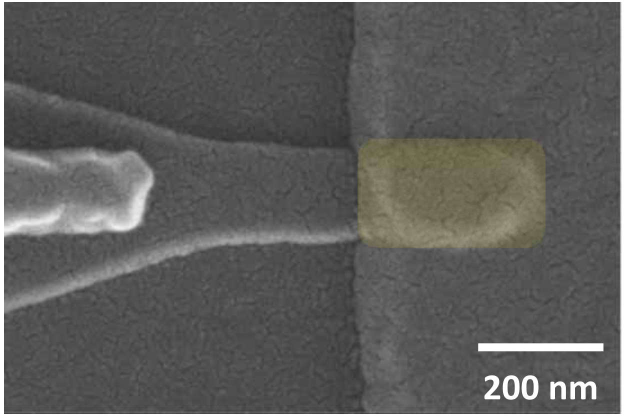

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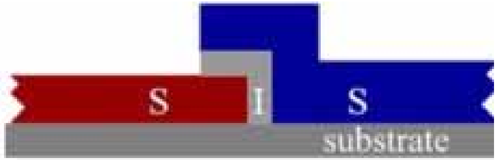

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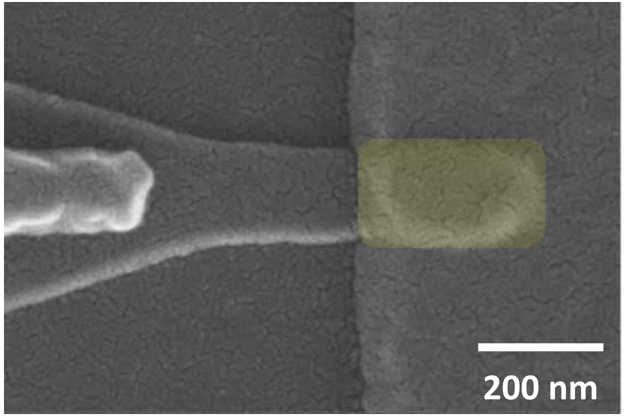
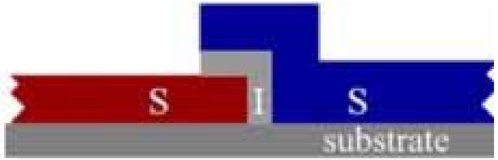


Lossless nonlinear inductor

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

Superconducting Circuits



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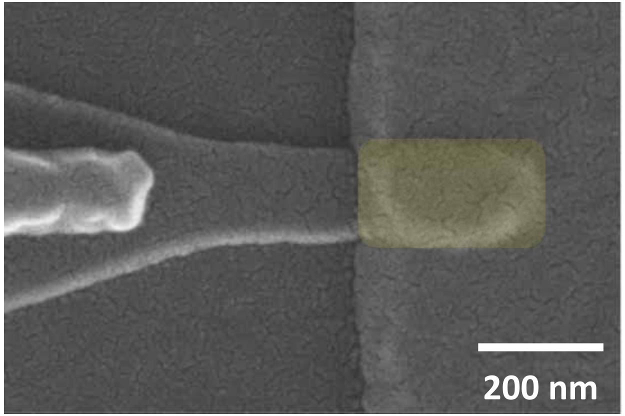

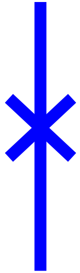

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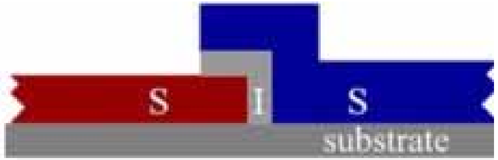

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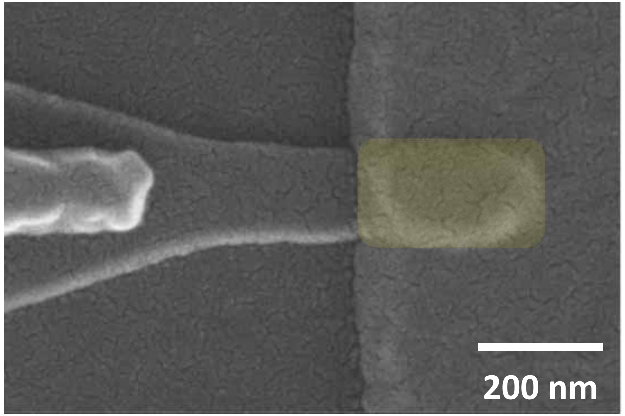

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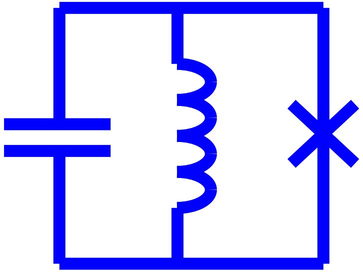

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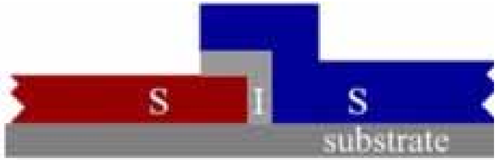

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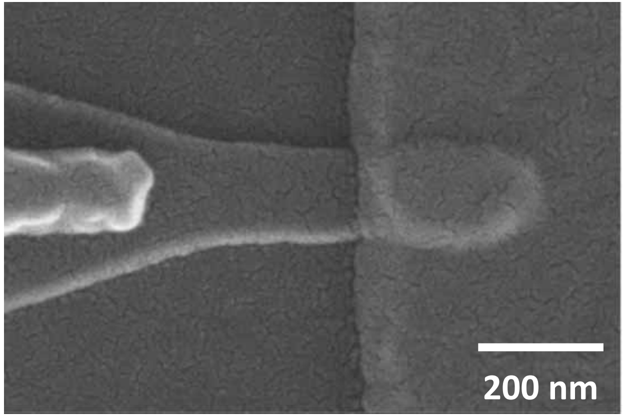

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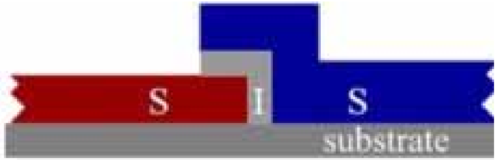

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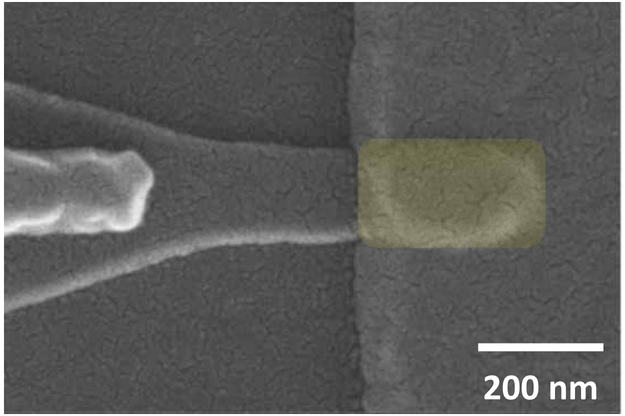

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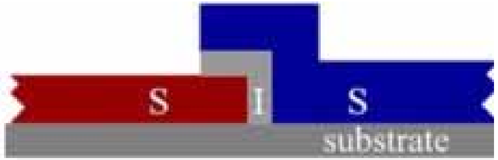

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$$I(t) = I_0 \sin \delta(t)$$
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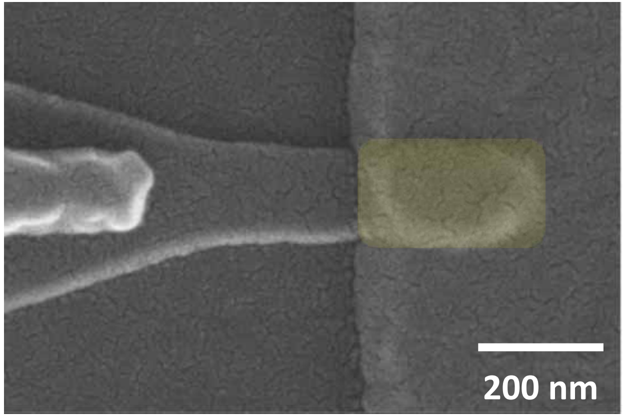

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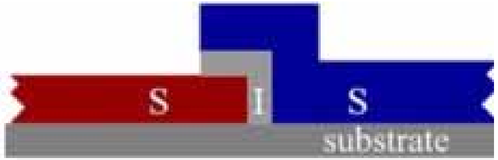

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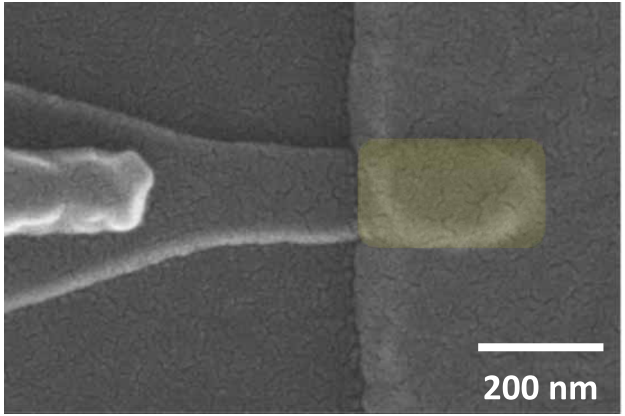

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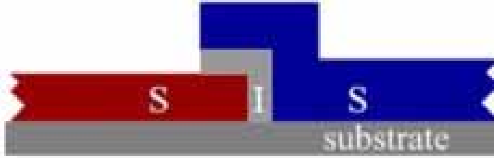
Superconducting Circuits



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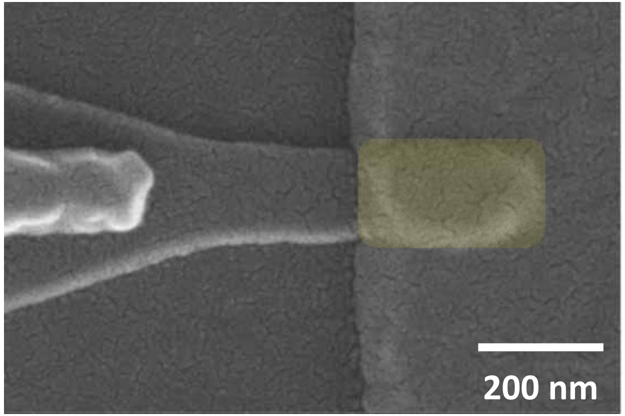

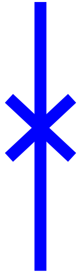

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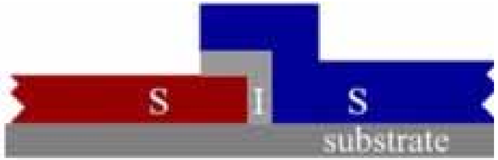

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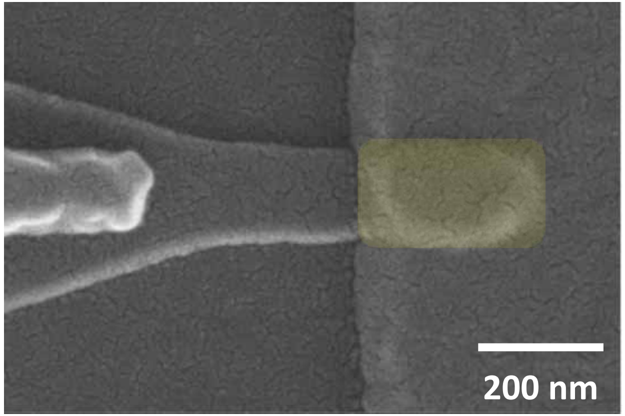

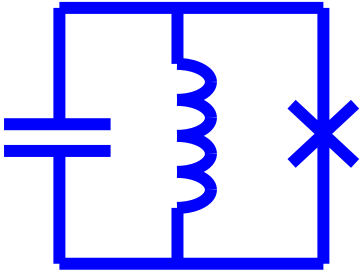

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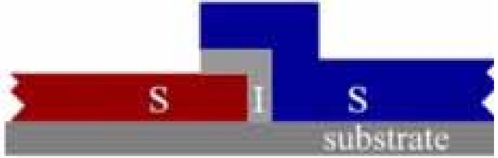

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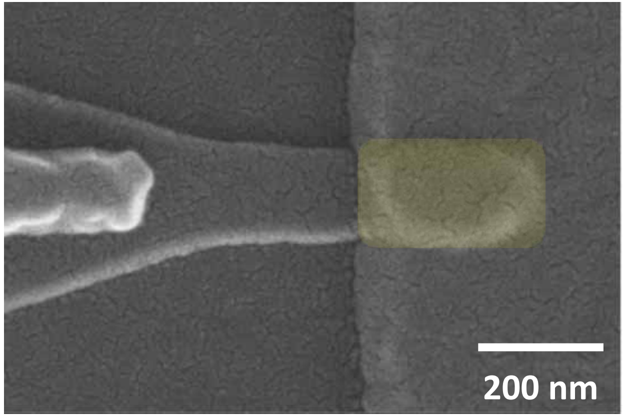

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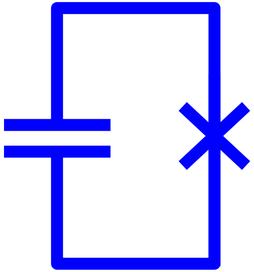
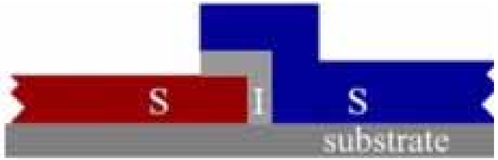


Transmon

Superconducting Circuits



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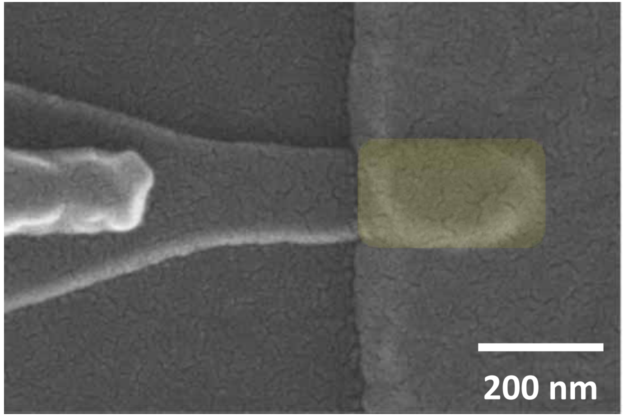

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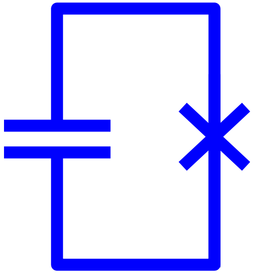

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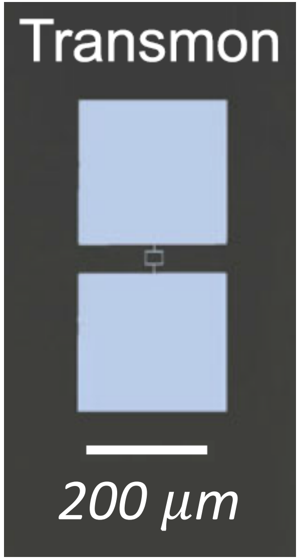
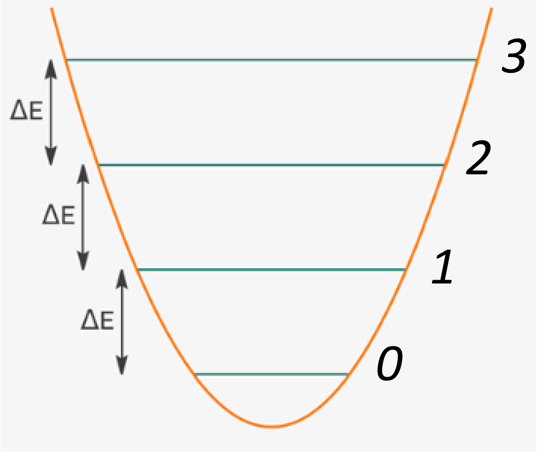
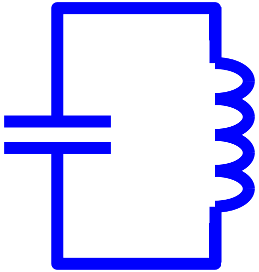


Transmon: Anharmonic Oscillator



Harmonic Oscillator



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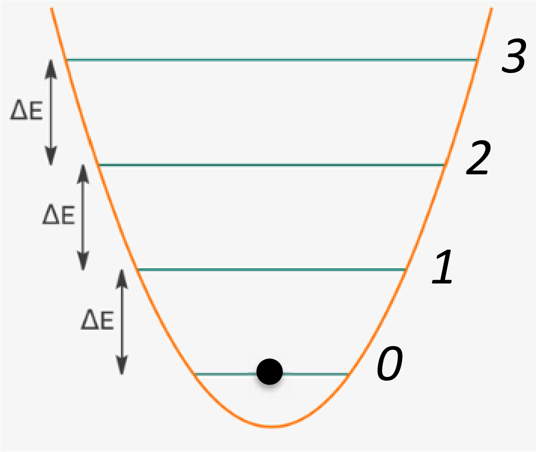

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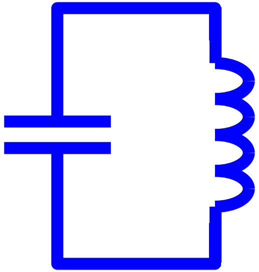

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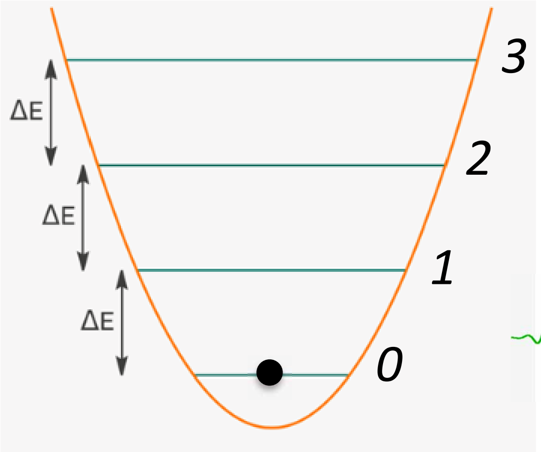

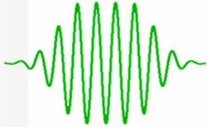

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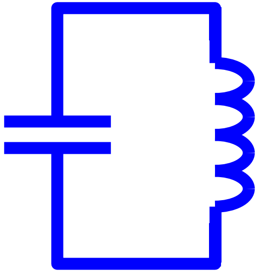

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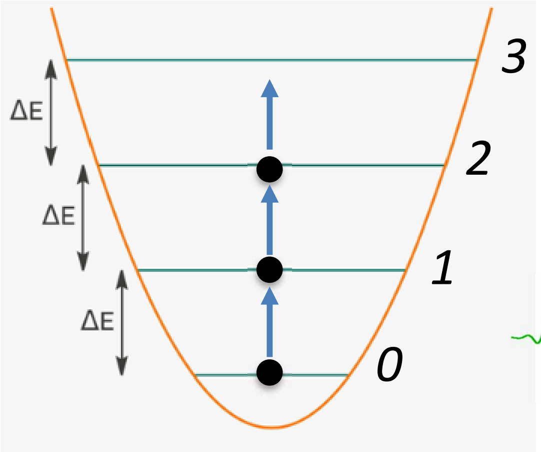

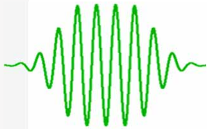

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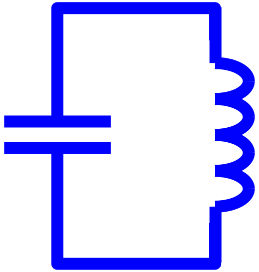

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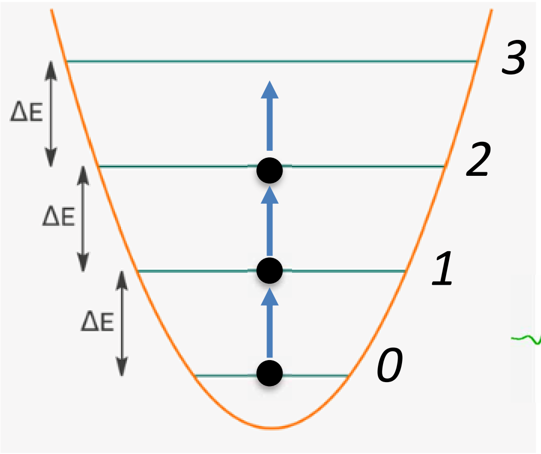

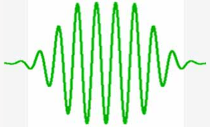

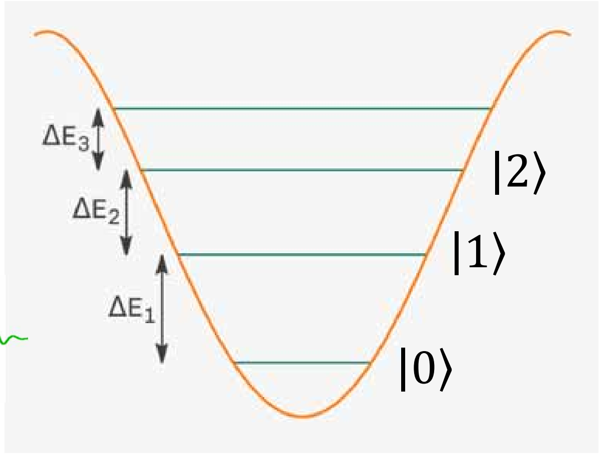

Harmonic Oscillator

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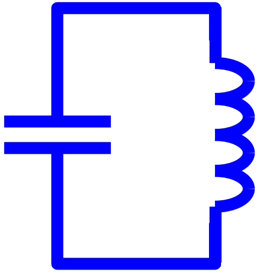

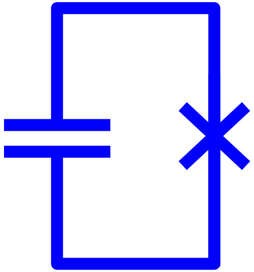

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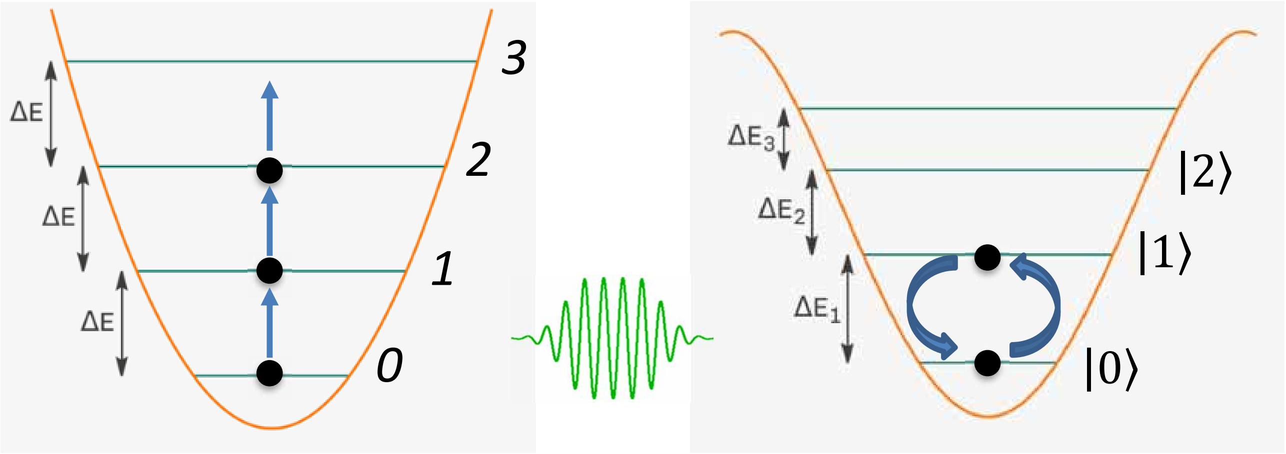

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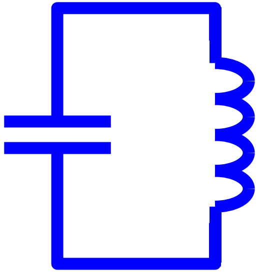

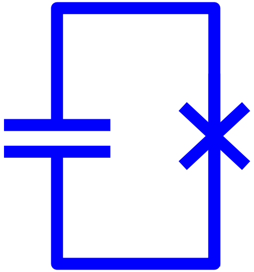

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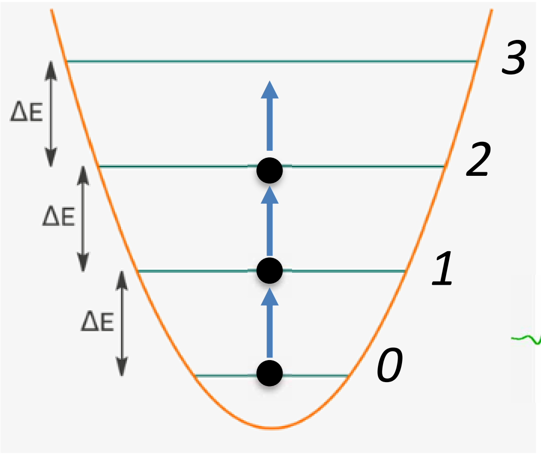

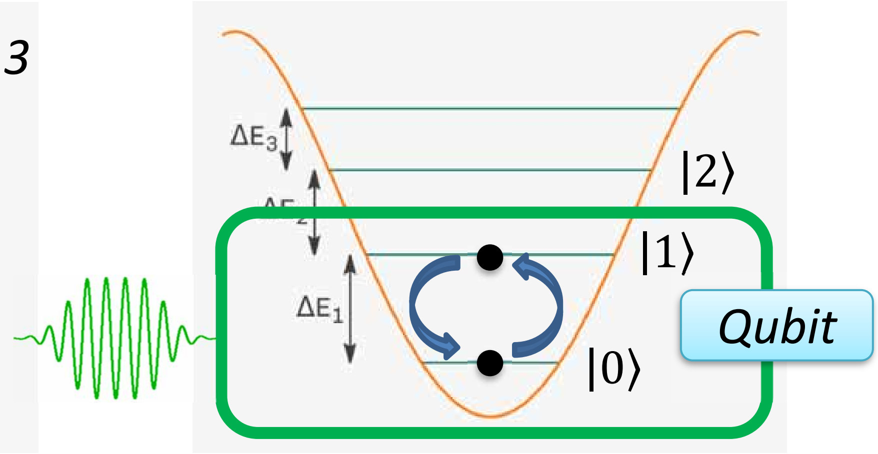

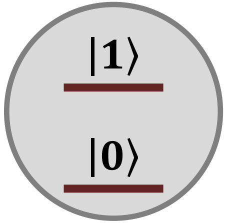

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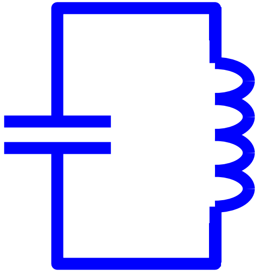
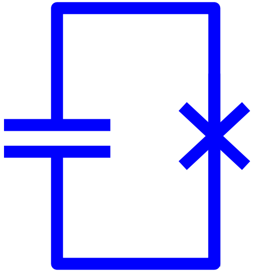
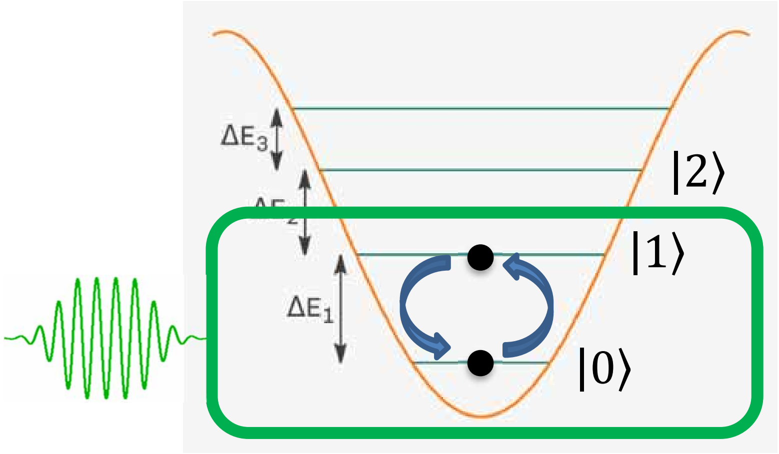


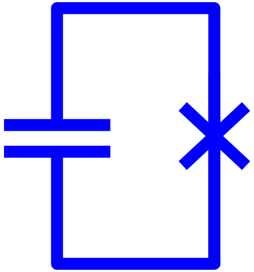


Operating Temperature

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

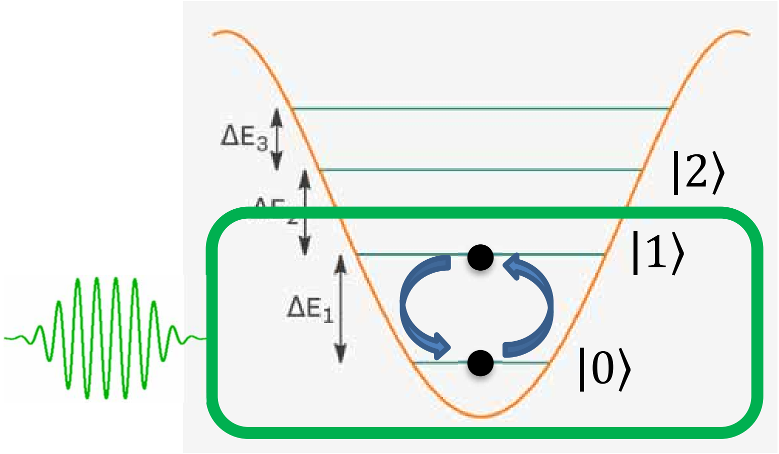


Anharmonic Oscillator

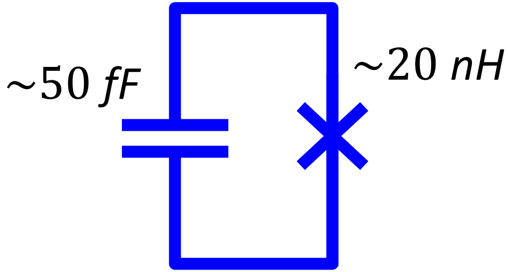


Operating Temperature

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



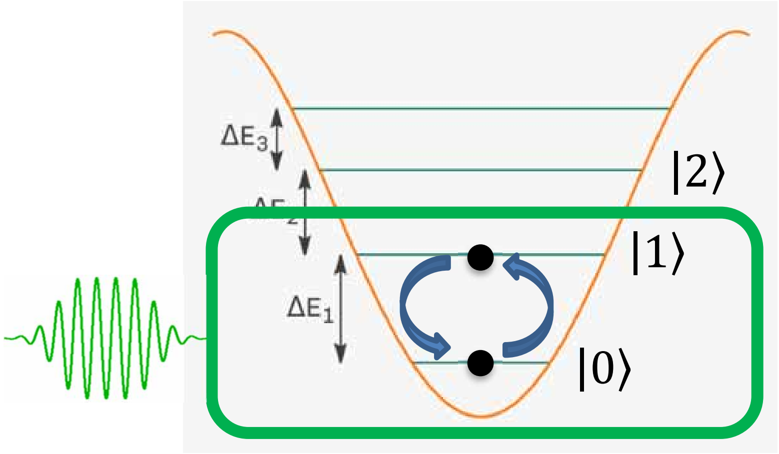
Anharmonic Oscillator



Operating Temperature

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

$\sim$ *5 GHz*



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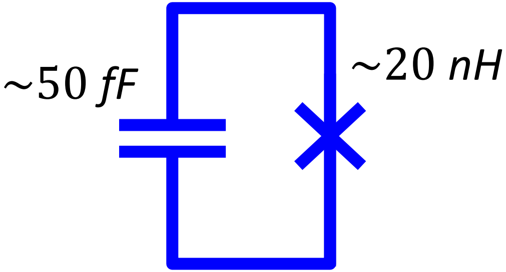
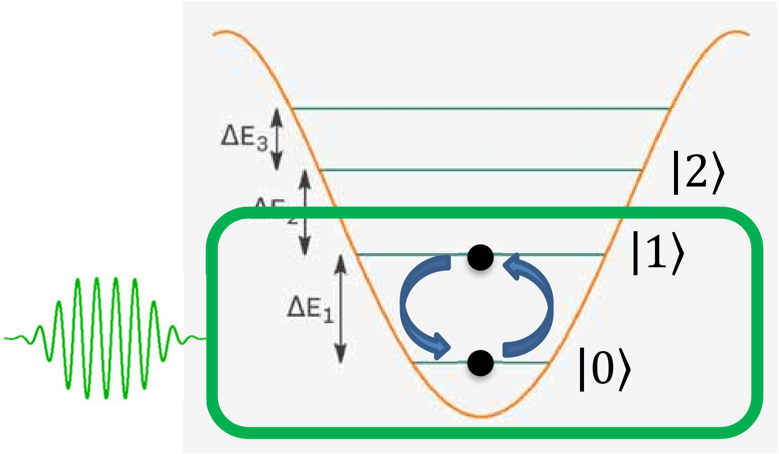


Operating Temperature

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

$\sim$ *5 GHz*

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



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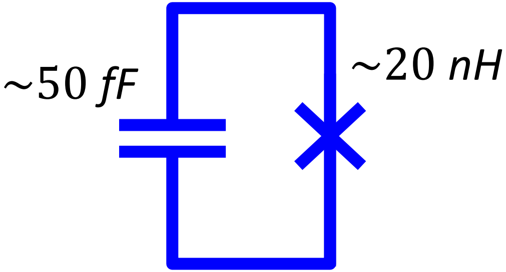


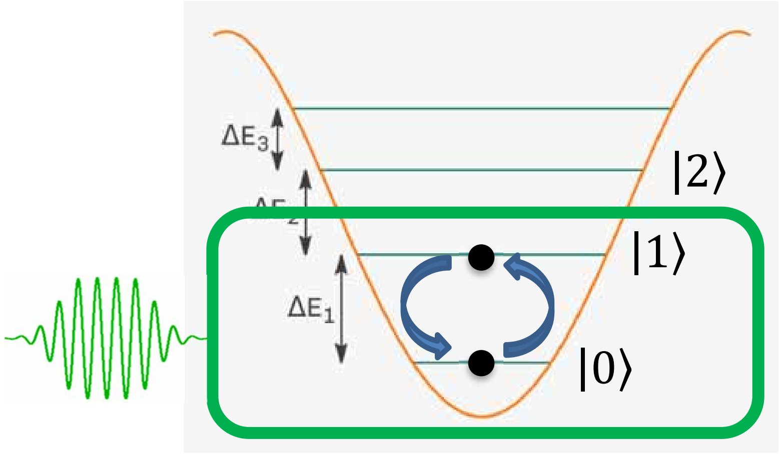
Operating Temperature

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

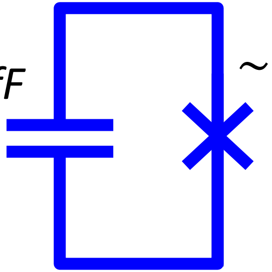
$\sim$ *5 GHz*

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

$\sim$ *240 mK*



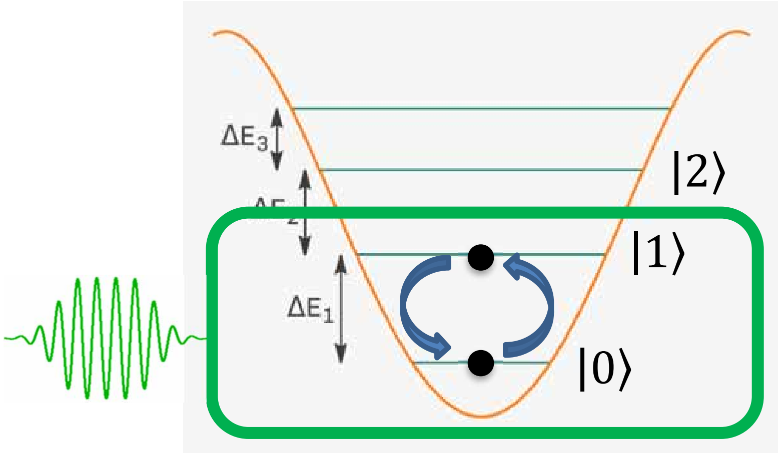
Anharmonic Oscillator



Operating Temperature

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

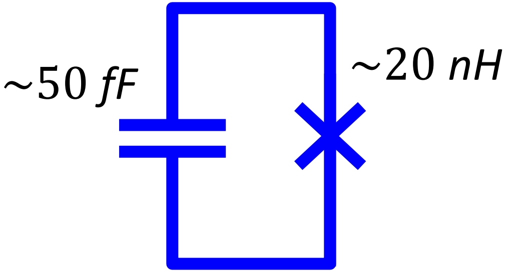
$\sim$ *5 GHz*



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

20 mK $\quad$ $\sim$ *240 mK*

Anharmonic Oscillator



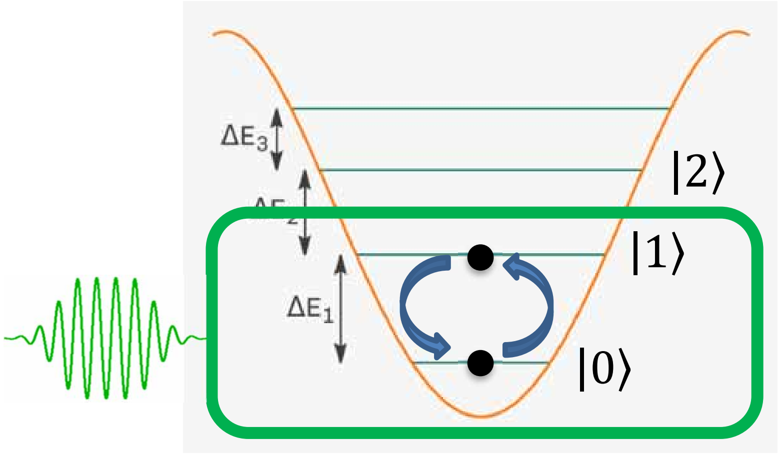
Operating Temperature

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

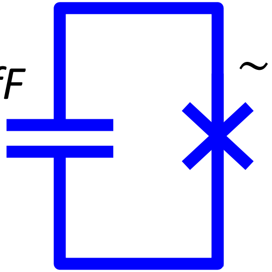
$\sim$ *5 GHz*

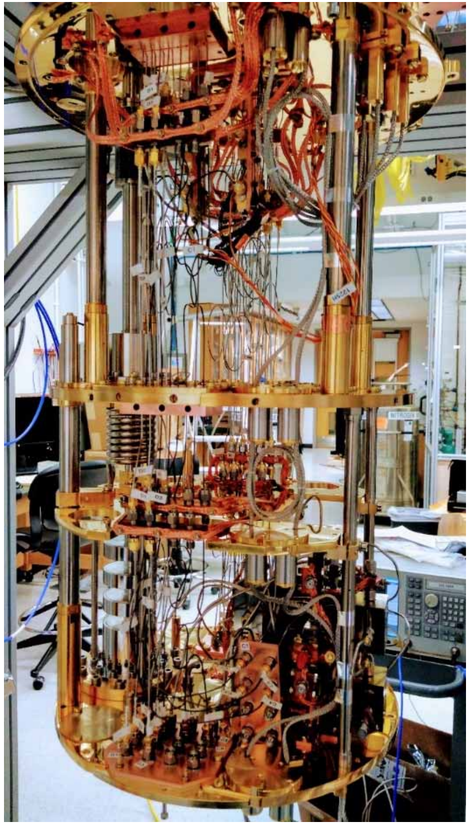
$$\boxed{k_B\, T \ll h\, f_{01}}$$

20 mK $\sim$ *240 mK*



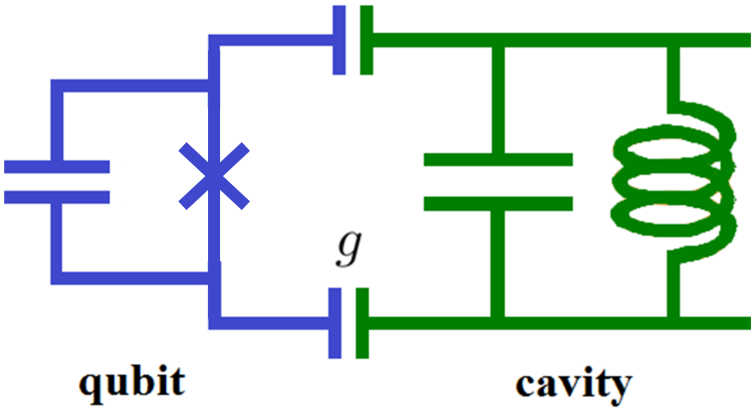
Anharmonic Oscillator

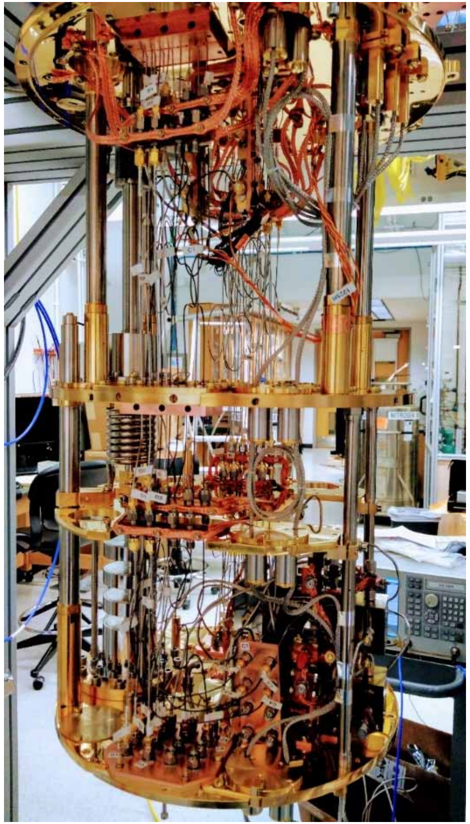




Dilution fridge ~ 10 mK

Circuit QED Architecture





Dilution fridge ~ 10 mK

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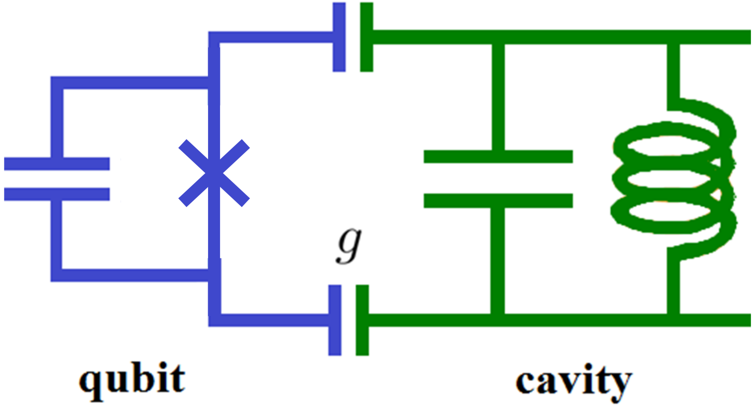

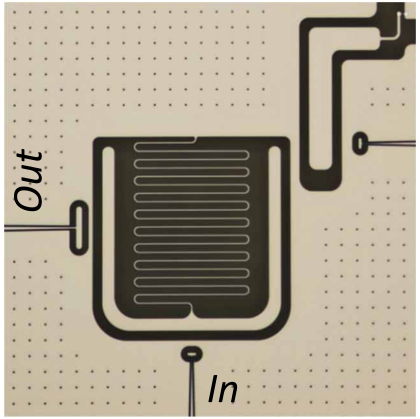

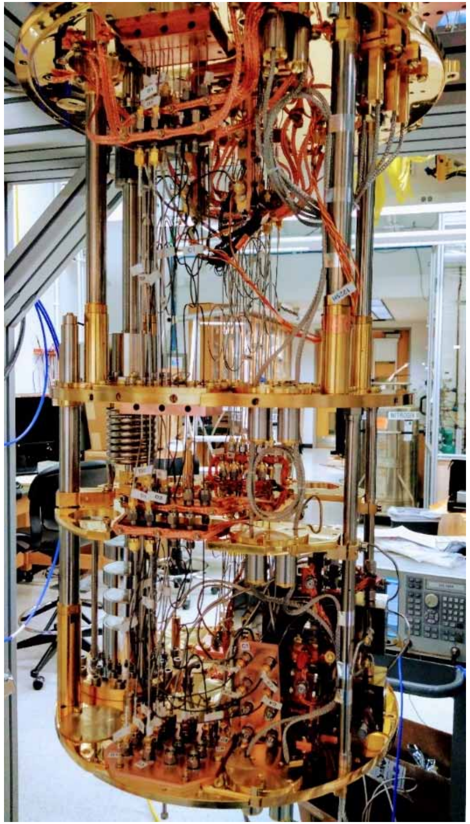

Dilution fridge ~ 10 mK

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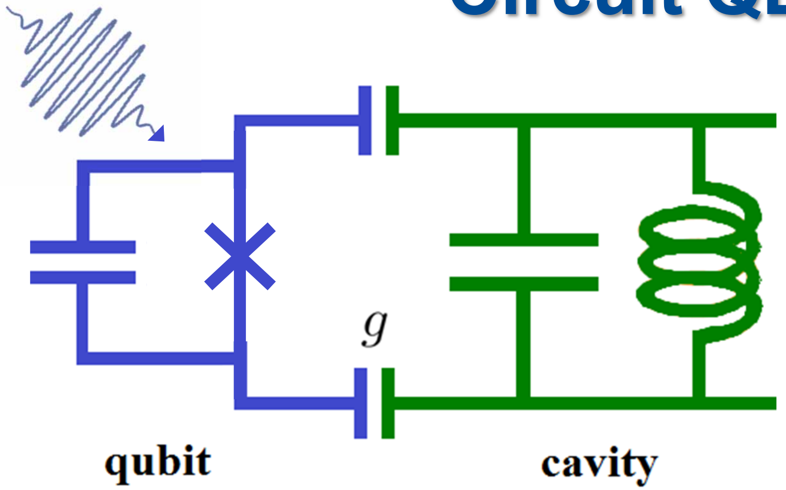

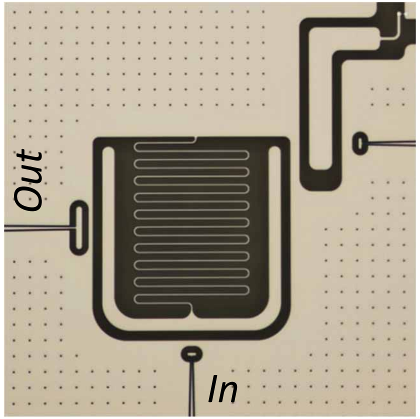

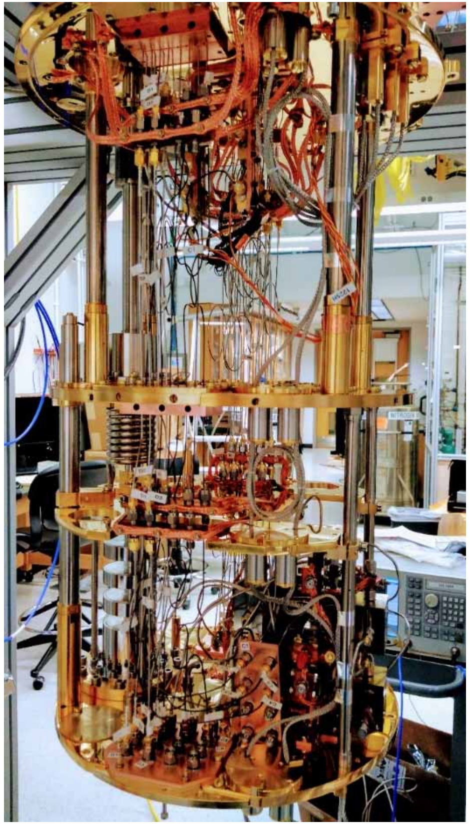

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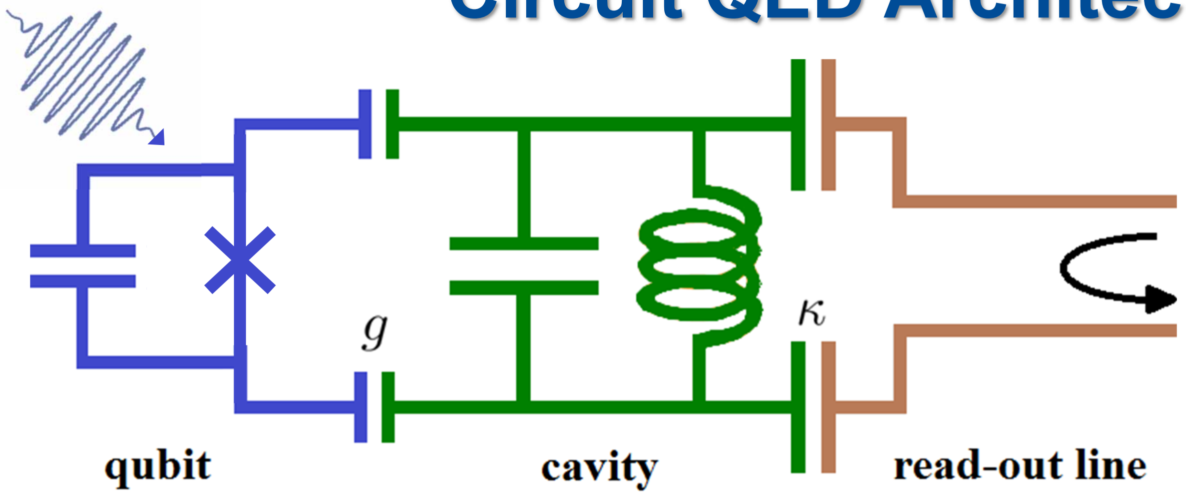
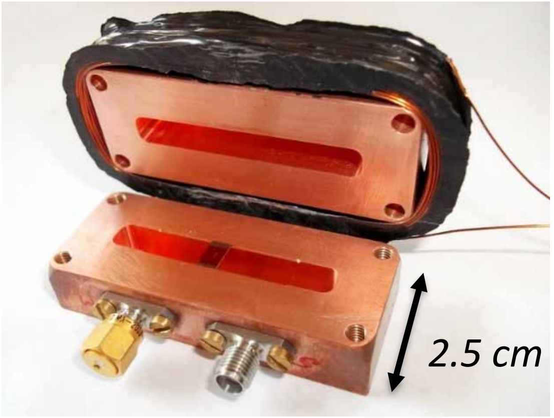
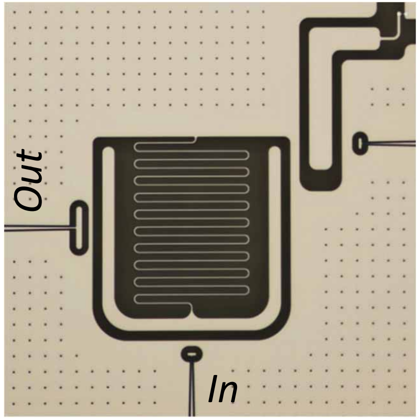
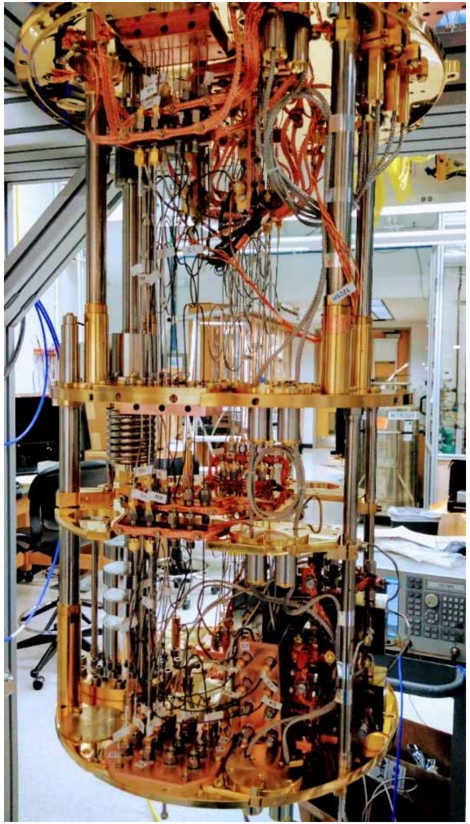


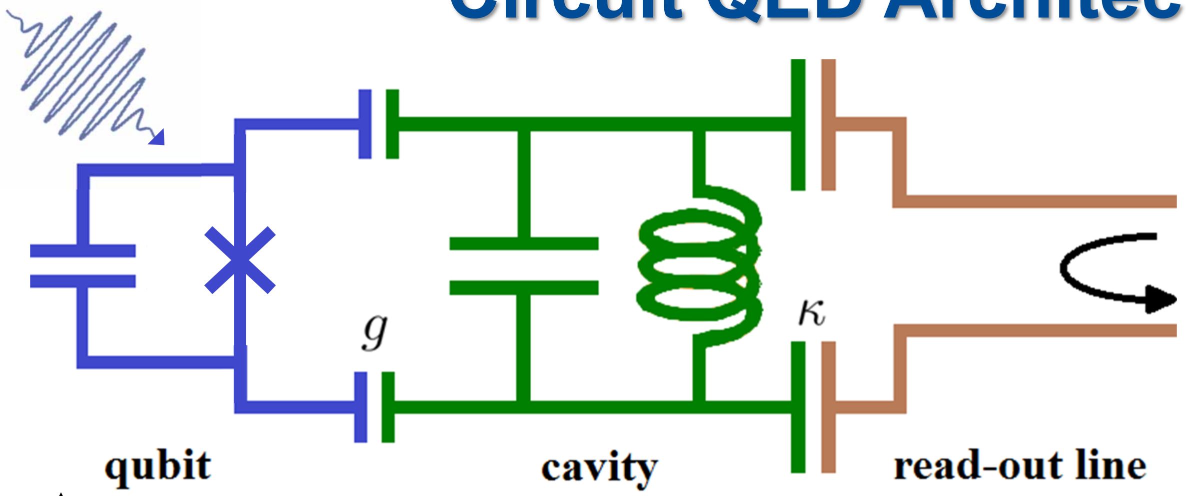


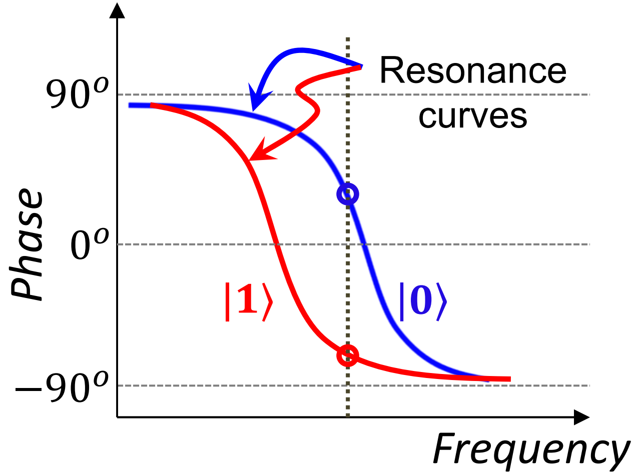


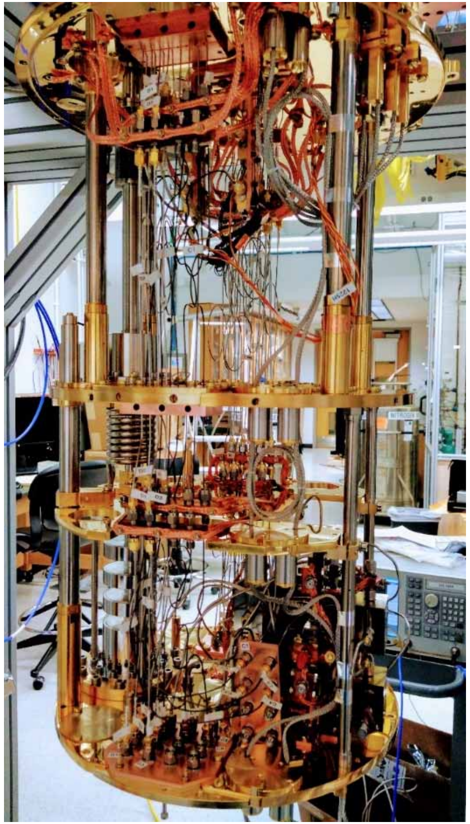


Dilution fridge ~ 10 mK

Circuit QED Architecture

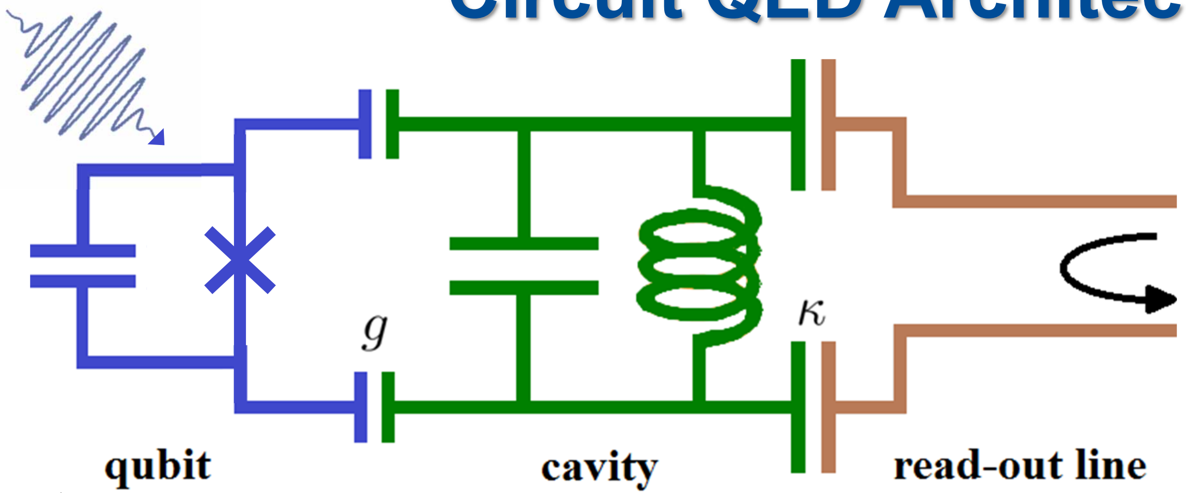


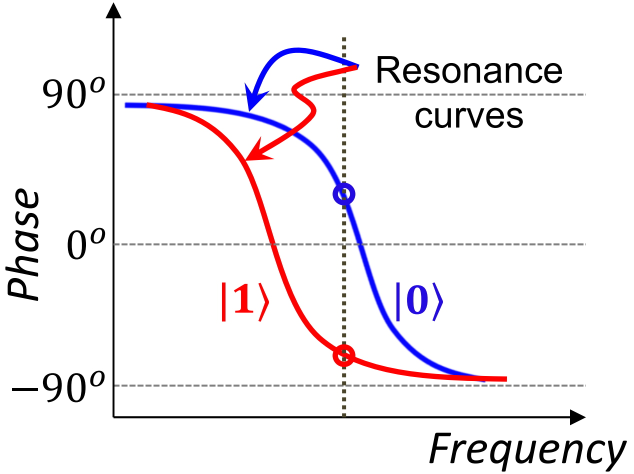


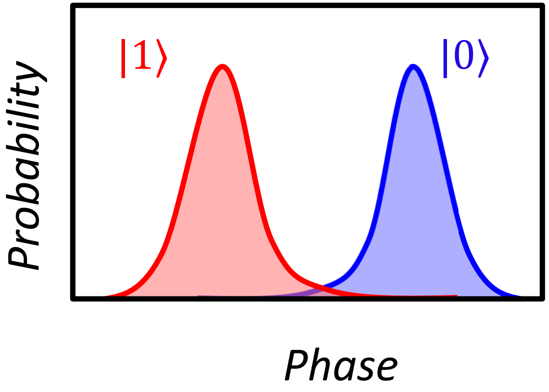


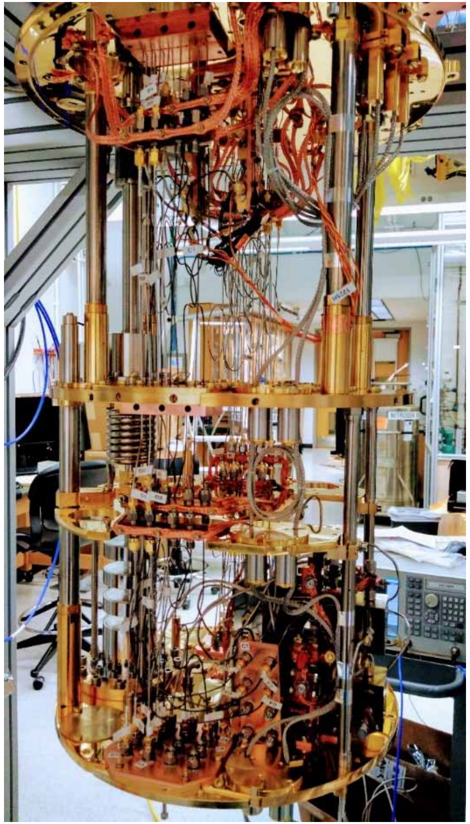
Dilution fridge ~ 10 mK

Circuit QED Architecture





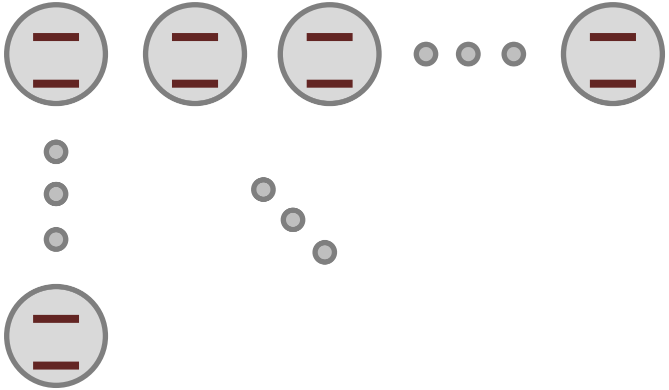




Dilution fridge ~ 10 mK

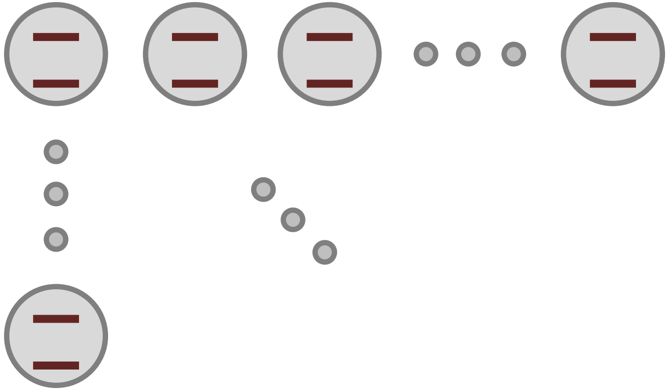
Traditional Multi-qubit Architecture

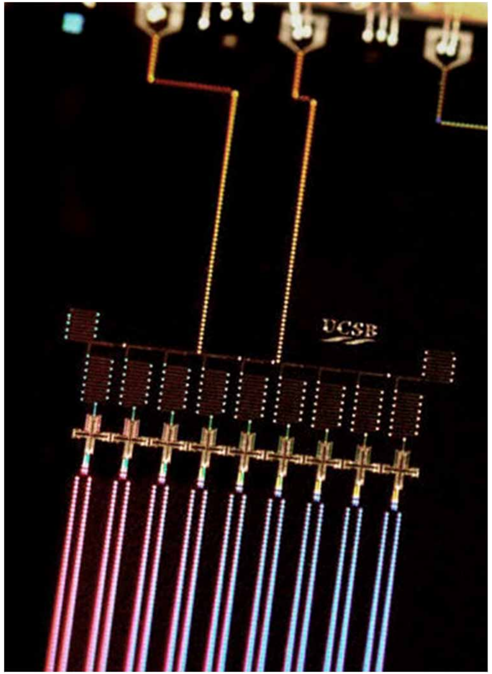
Linear or planar geometry



Traditional Multi-qubit Architecture

Linear or planar geometry





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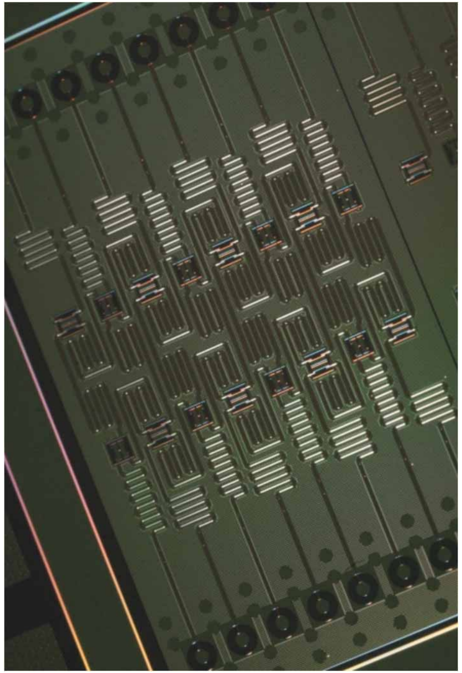

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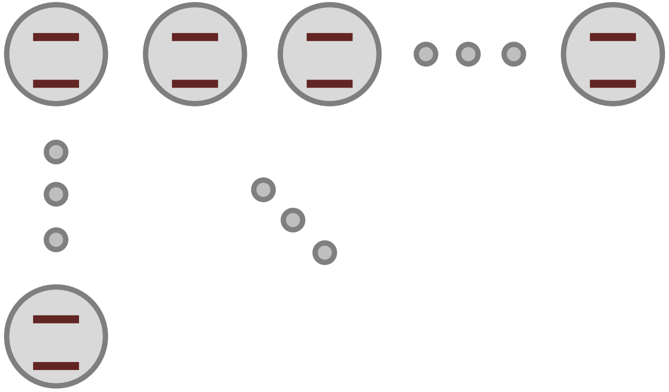
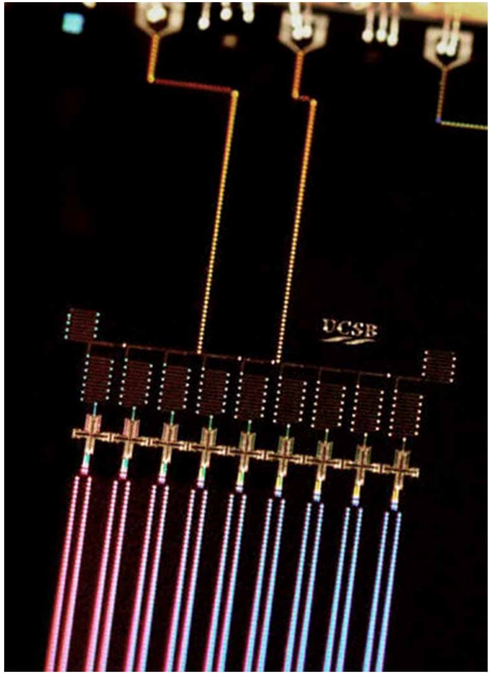
Linear or planar geometry



Computational space: 2^N



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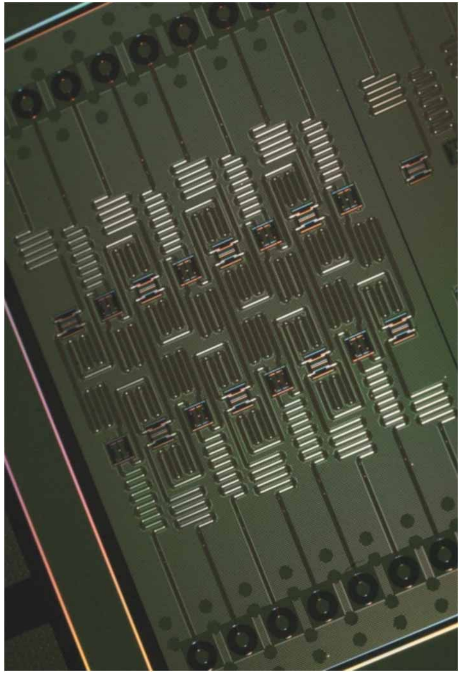

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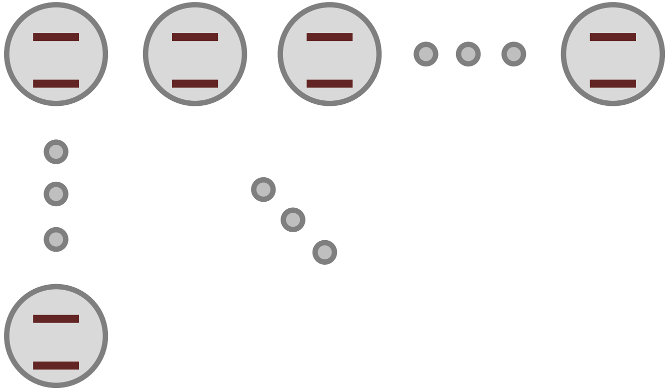
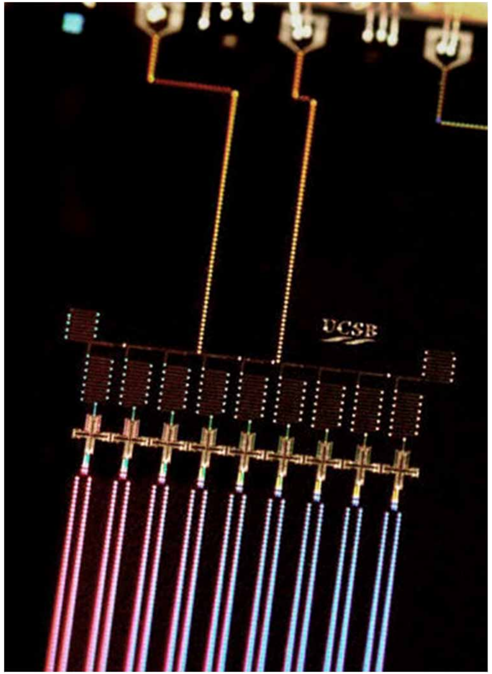
Traditional Multi-qubit Architecture

Linear or planar geometry



Computational space: 2^N

Can we do **better***?*



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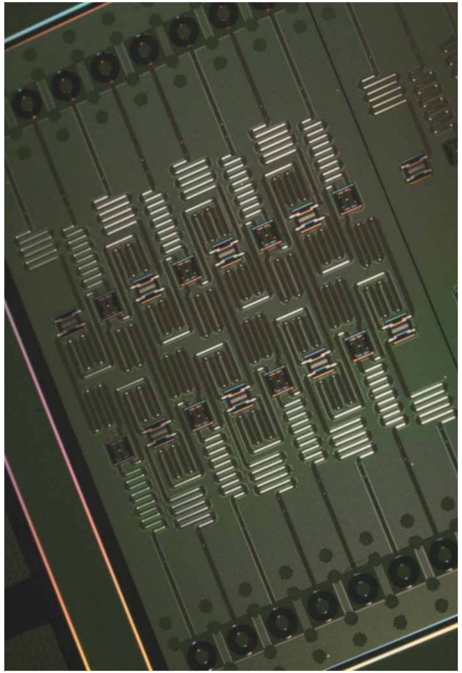

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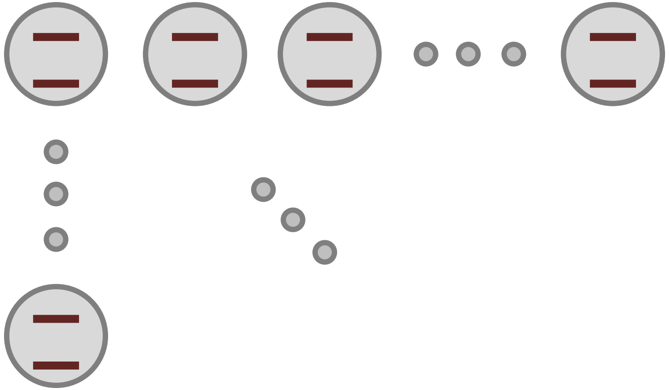
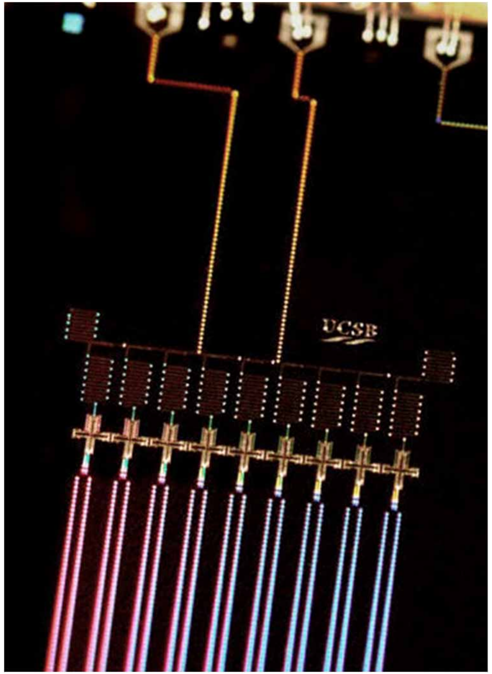
Linear or planar geometry



Computational space: 2^N

Can we do **better**?

Scaling: d^N, $d > 2$



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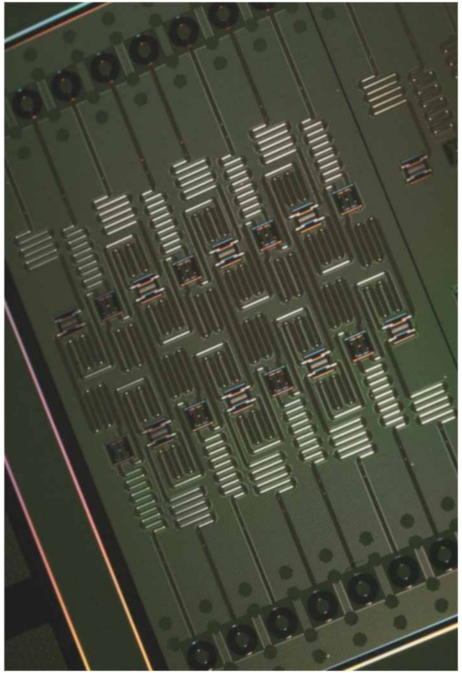

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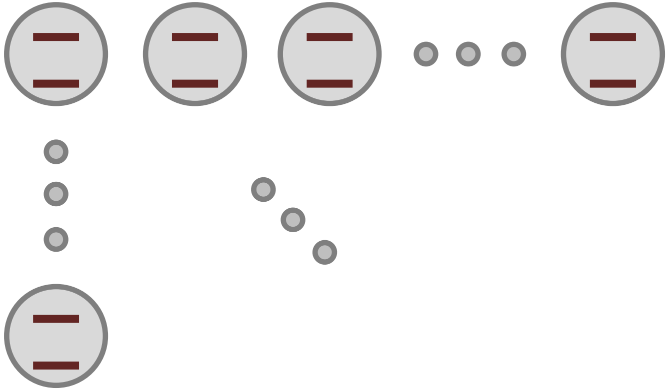
Traditional Multi-qubit Architecture

Linear or planar geometry

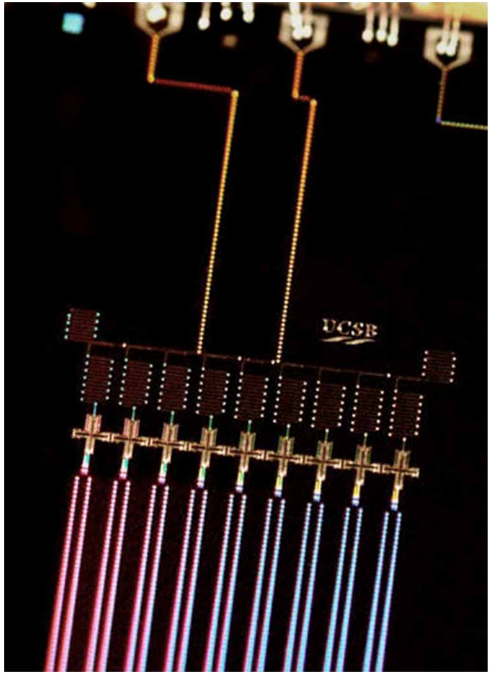


Computational space: 2^N

Can we do **better**?

Scaling: d^N, $d > 2$

Qudit



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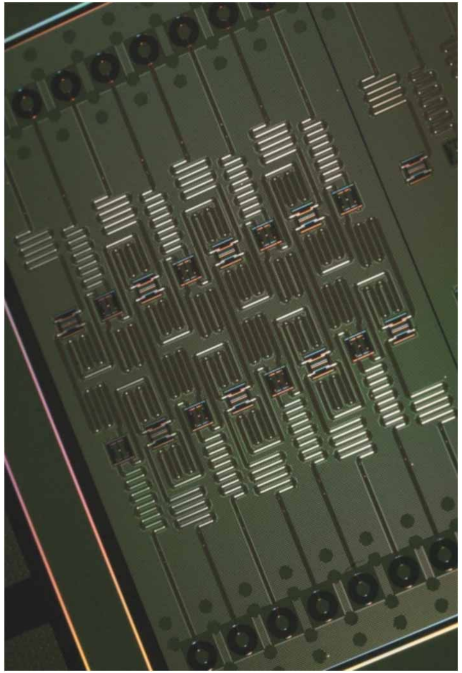

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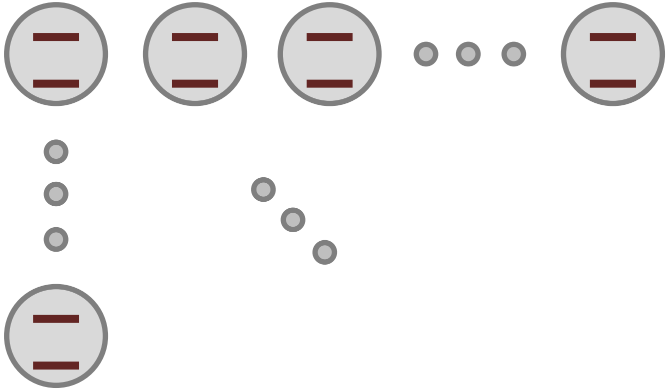
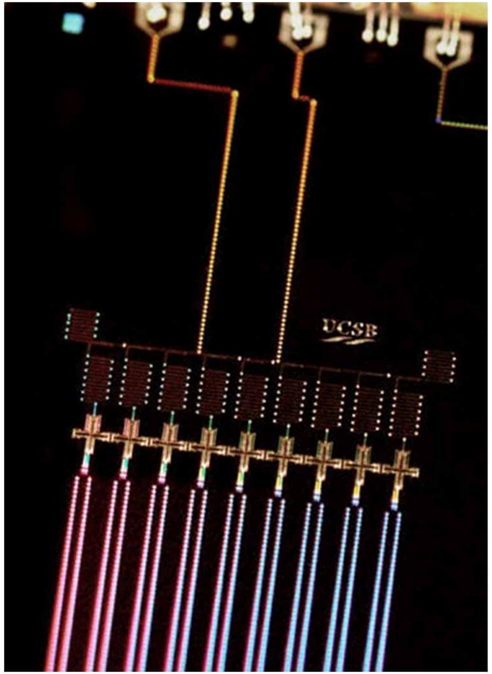
Problem of Relaxation

Linear or planar geometry





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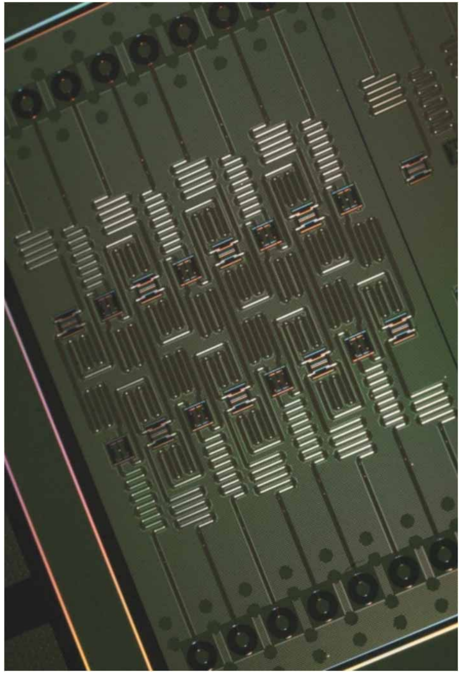

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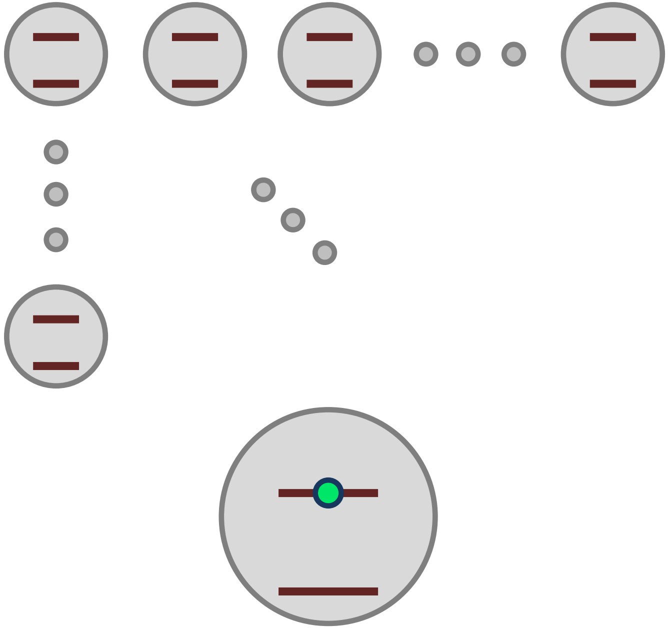

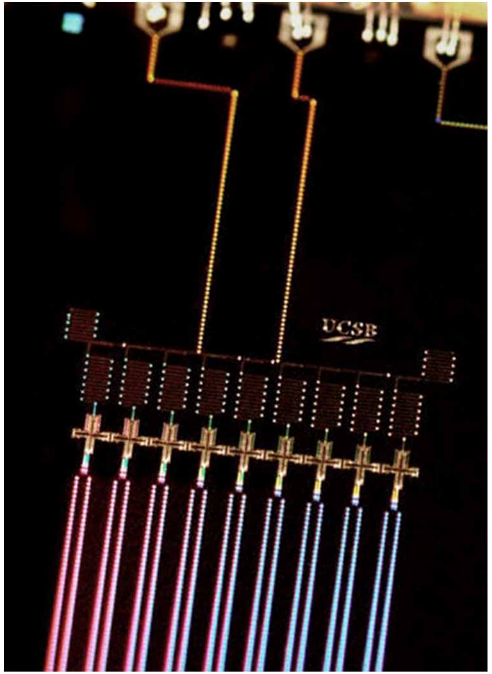

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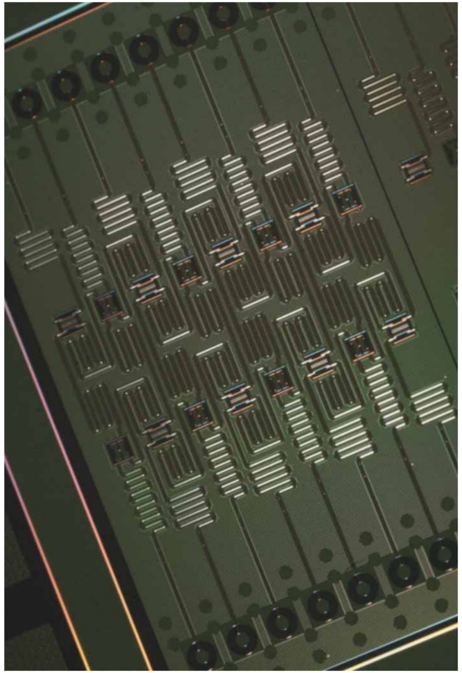

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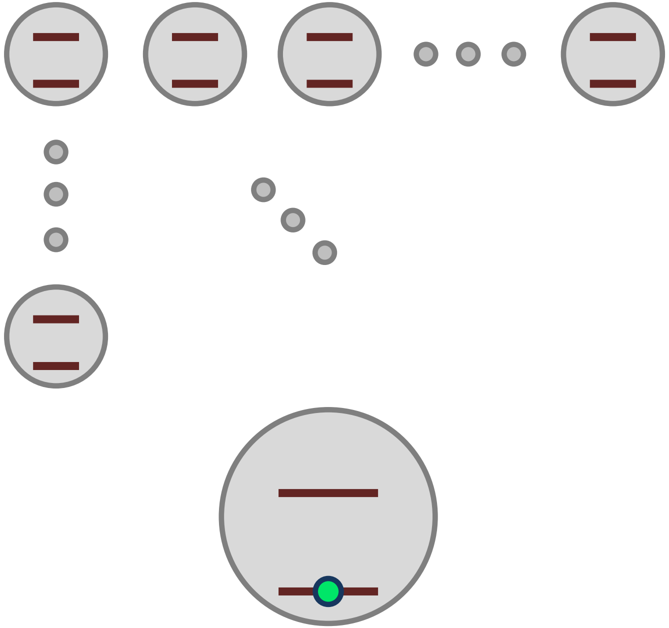

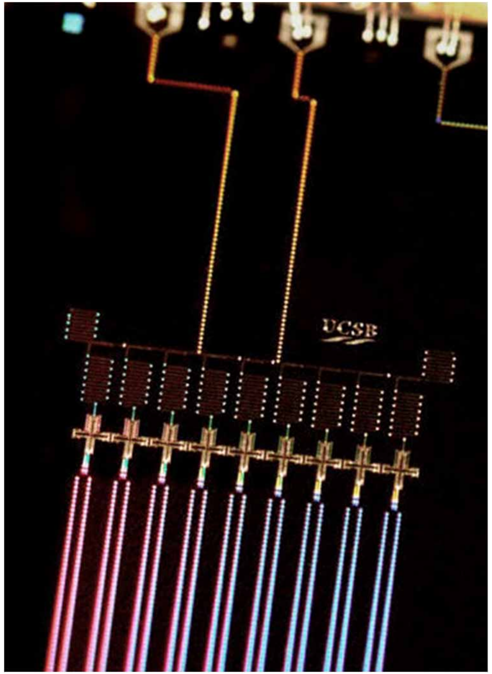

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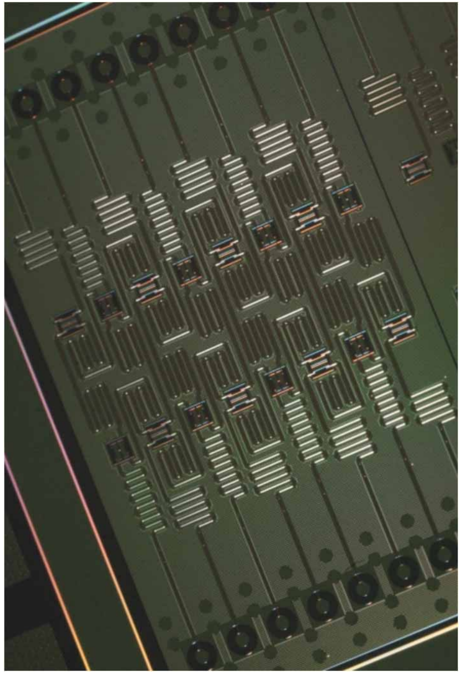

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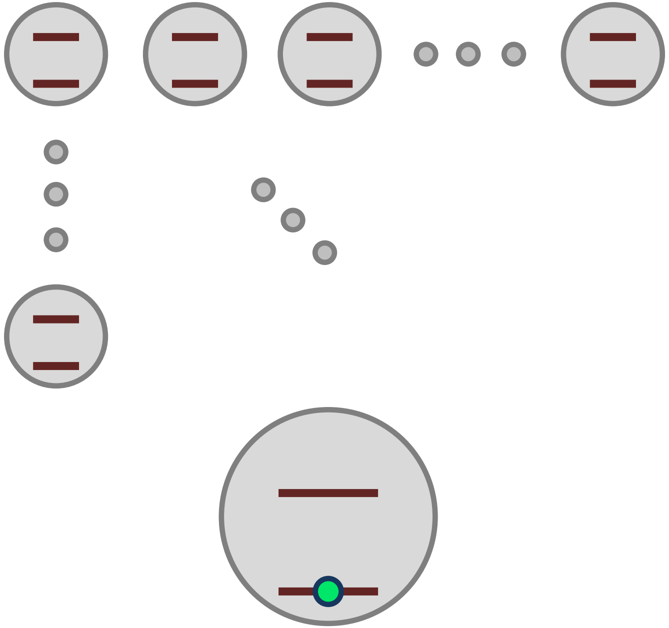
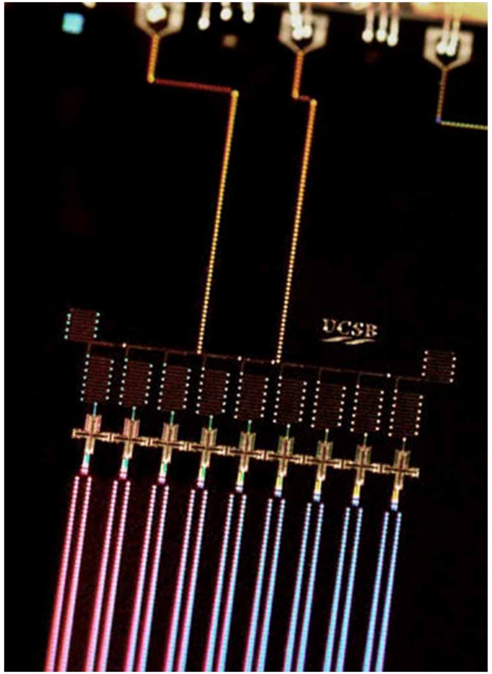
Linear or planar geometry



$T_1 \sim 100\ \mu s$



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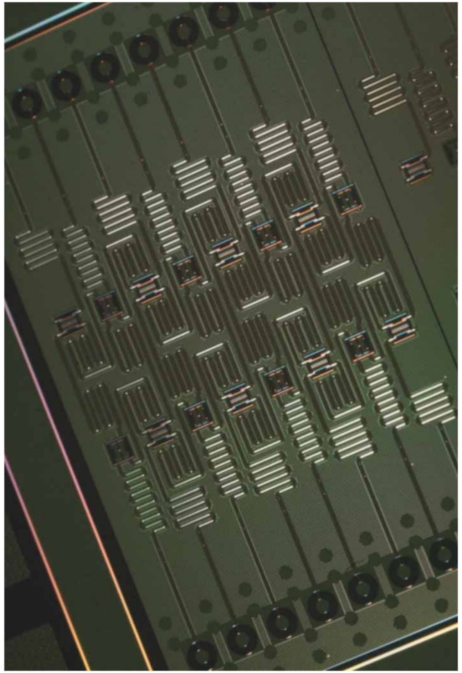

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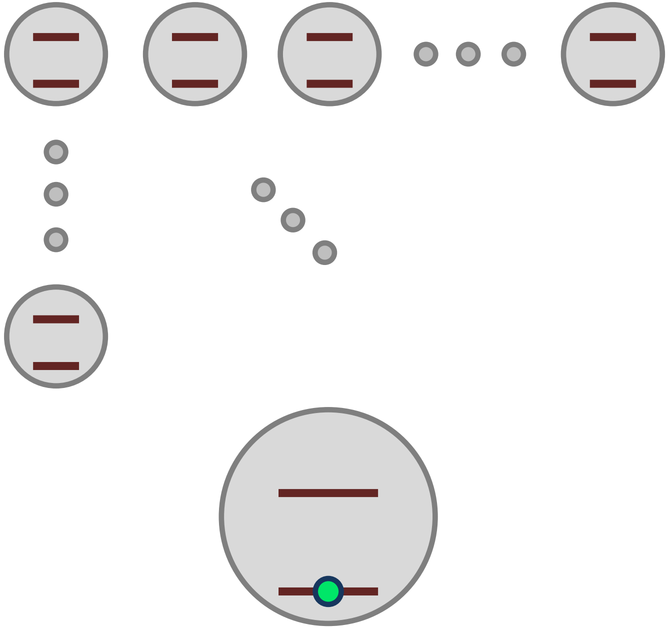
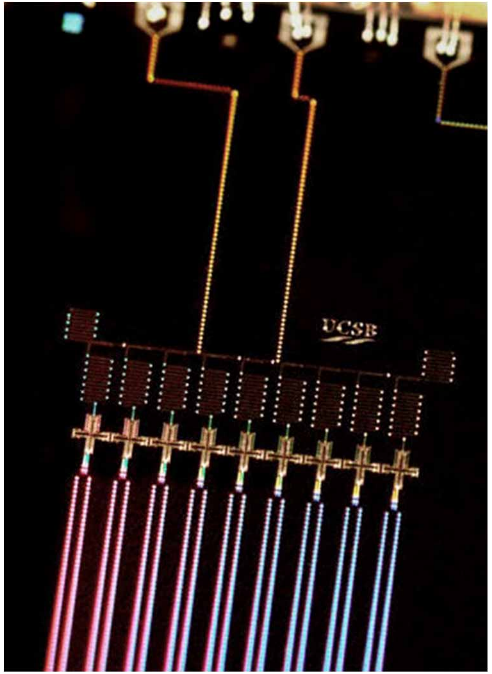
Linear or planar geometry





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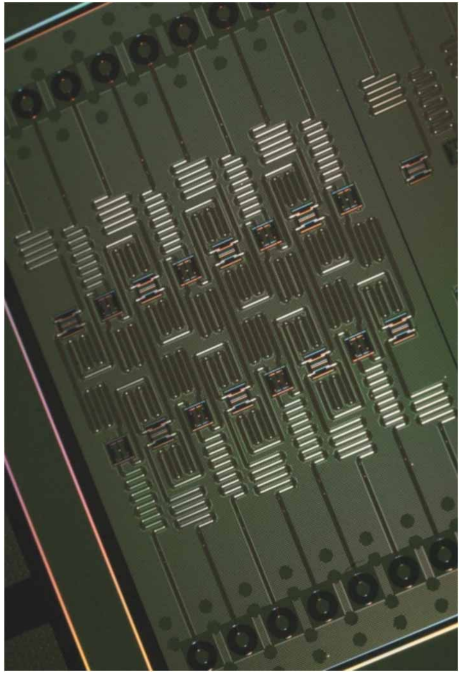

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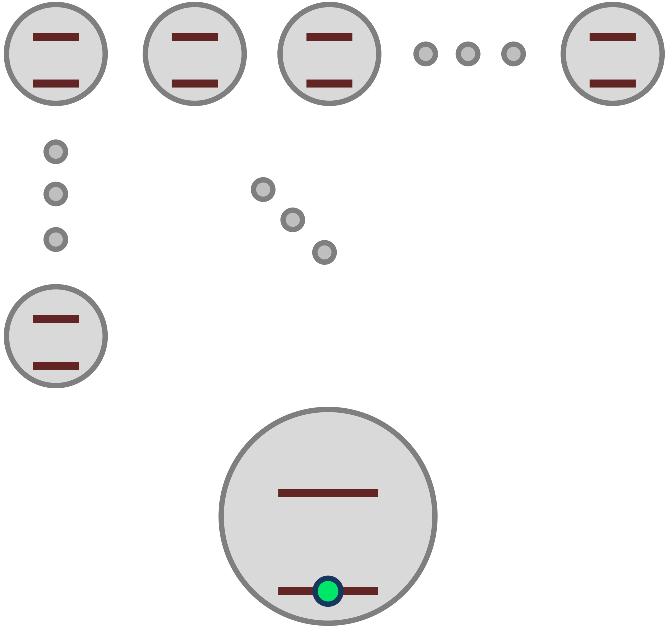
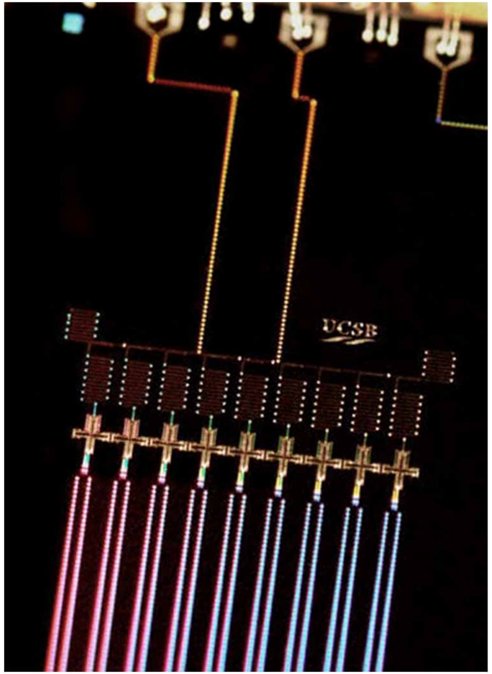
$T_1 \sim 100\ \mu s$

Q: a few 10^6

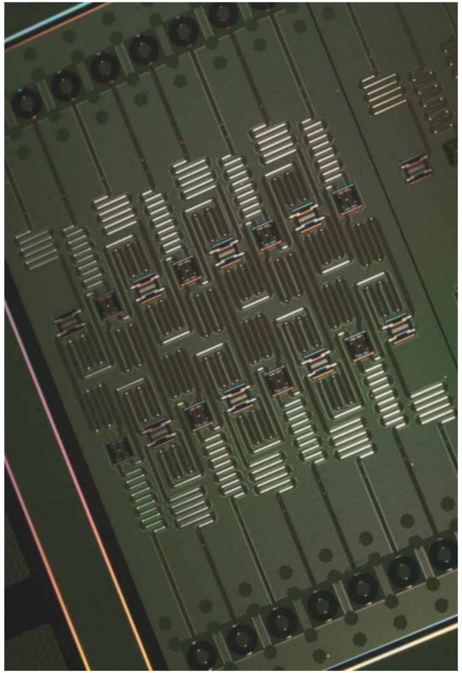
Problem of Relaxation

Linear or planar geometry





UCSB, Nature 519 (7541)



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

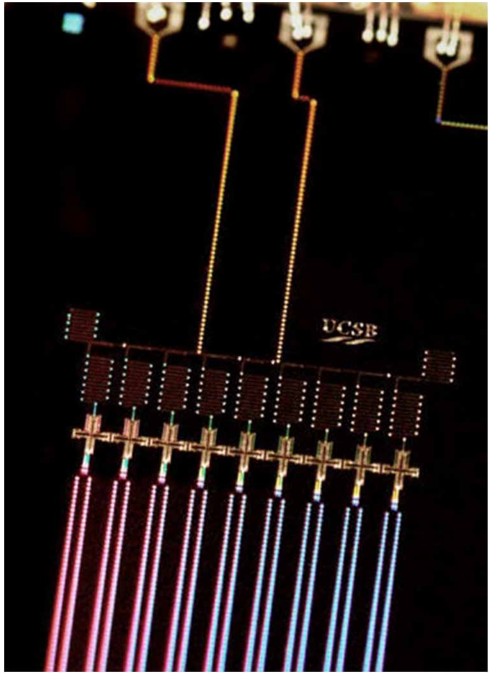
Can we do **better***?*

Traditional Architecture

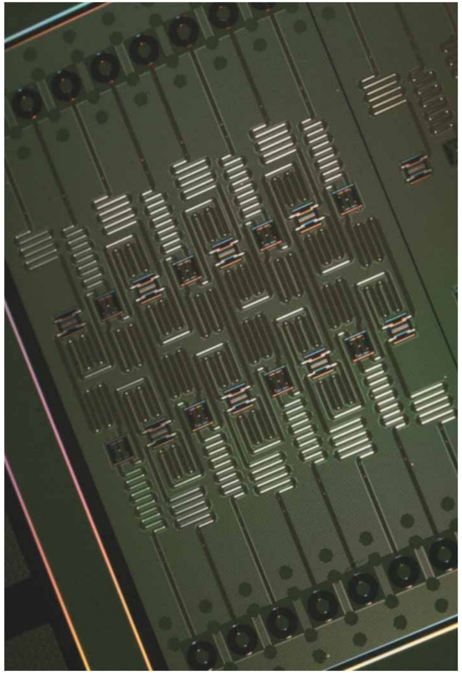
Linear or planar geometry

Q — C — Q — C — Q — C ○ ○ ○

Scaling: 2^N



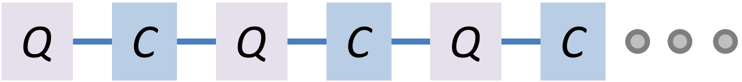
UCSB, Nature 519 (7541)



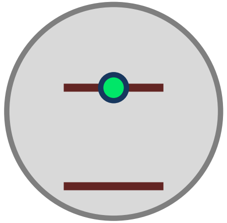
IBM

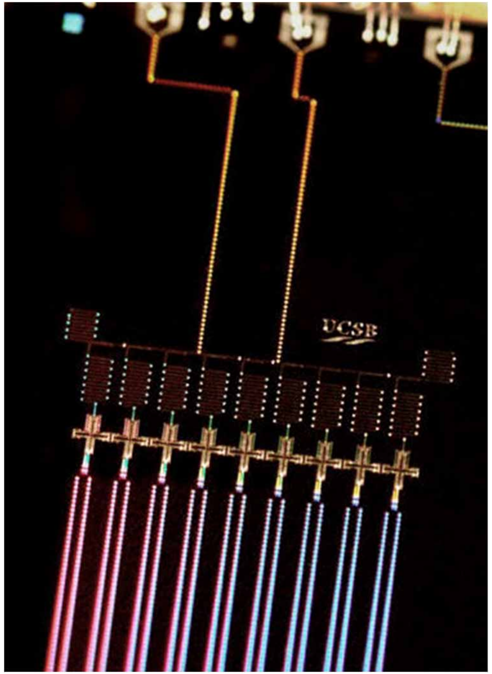
Traditional Architecture

Linear or planar geometry



Scaling: 2^N





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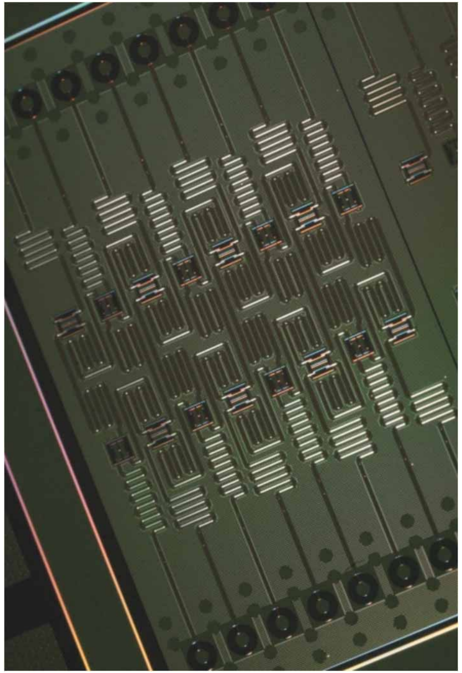

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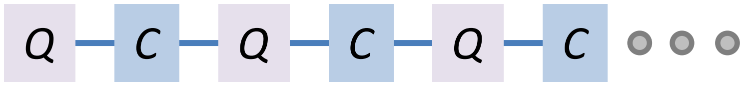
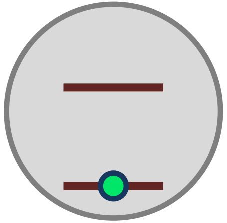
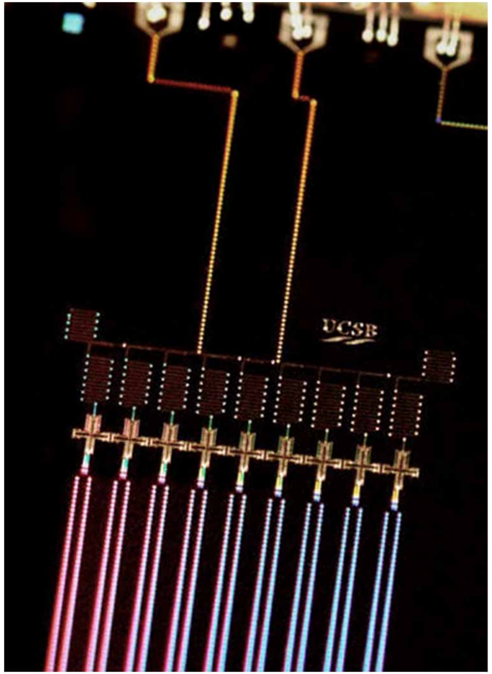


Scaling: 2^N





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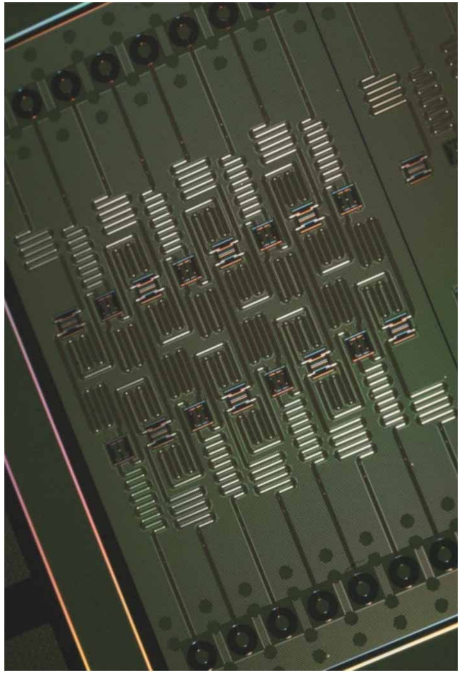

IBM

Traditional Architecture

Linear or planar geometry

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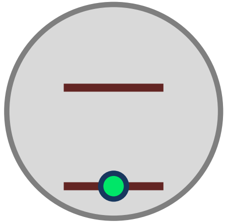
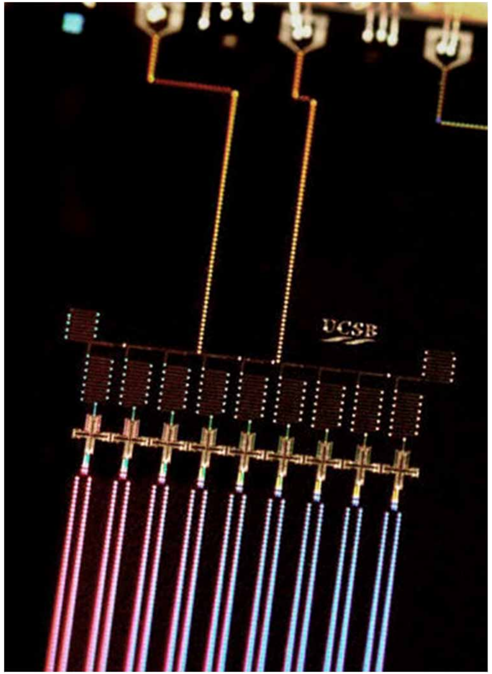
Scaling: 2^N



$\mathrm{T}_1 \sim 100\ \mu s$



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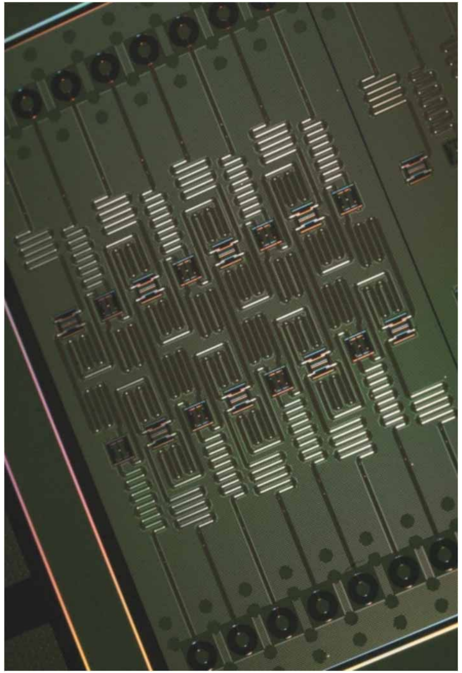

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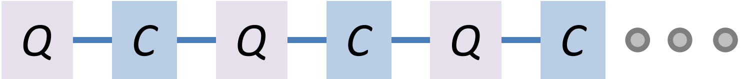
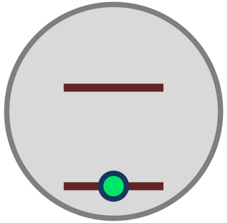


Scaling: 2^N



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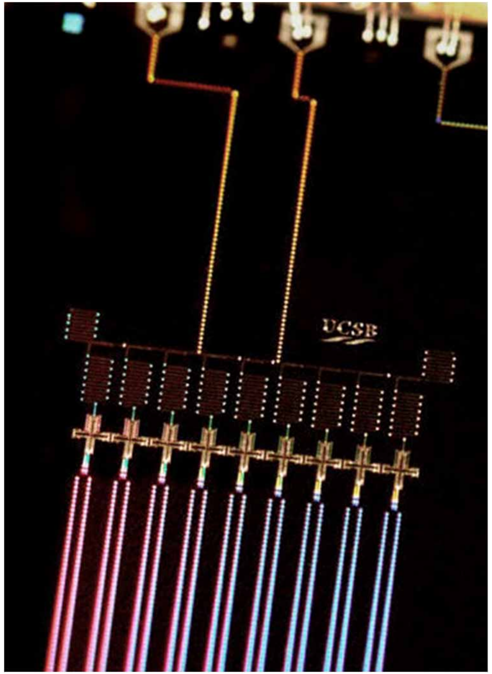

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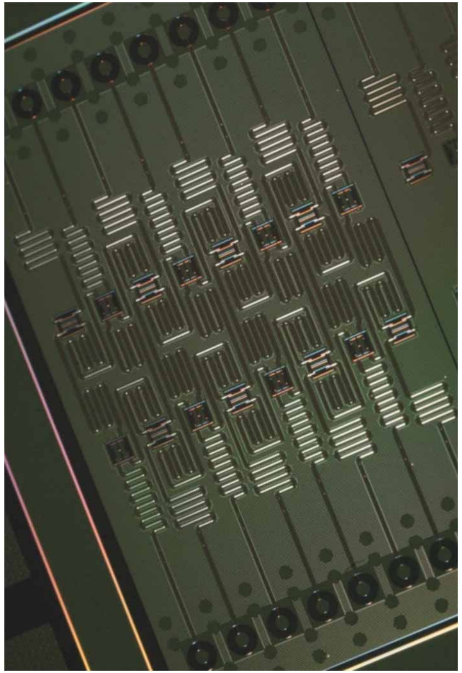

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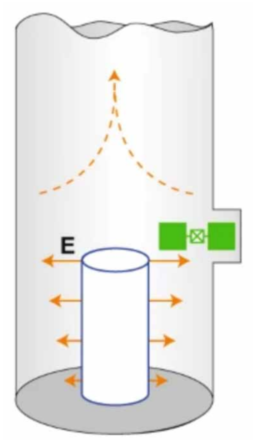
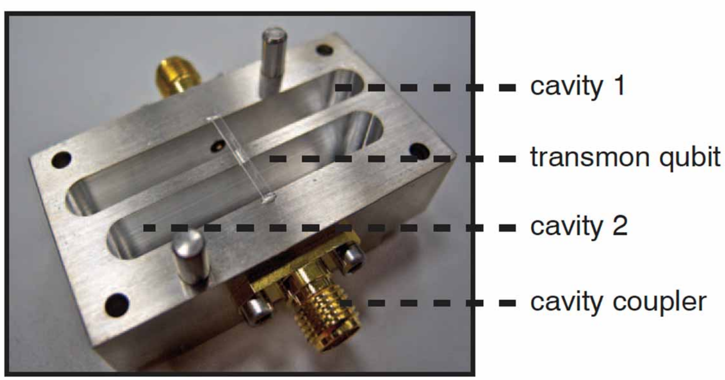
Q: a few 10^6

Zoo of Cavities

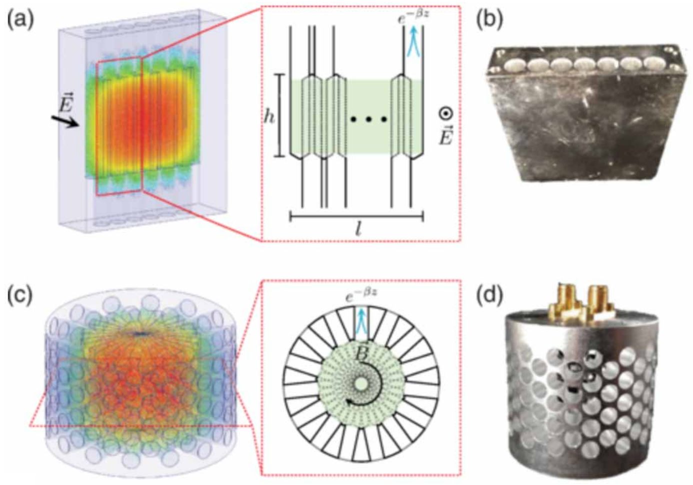


Nat. Phys. 16, 247



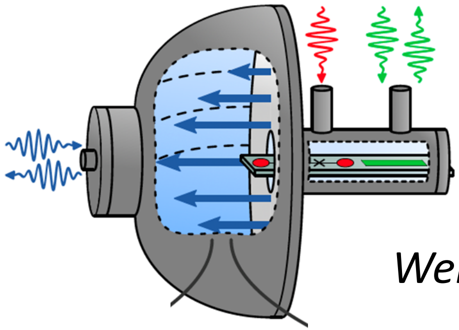
Science 342, 6158

Yale, U. Pittsburgh



PRL 127, 107701

U. Chicago, Rutgers



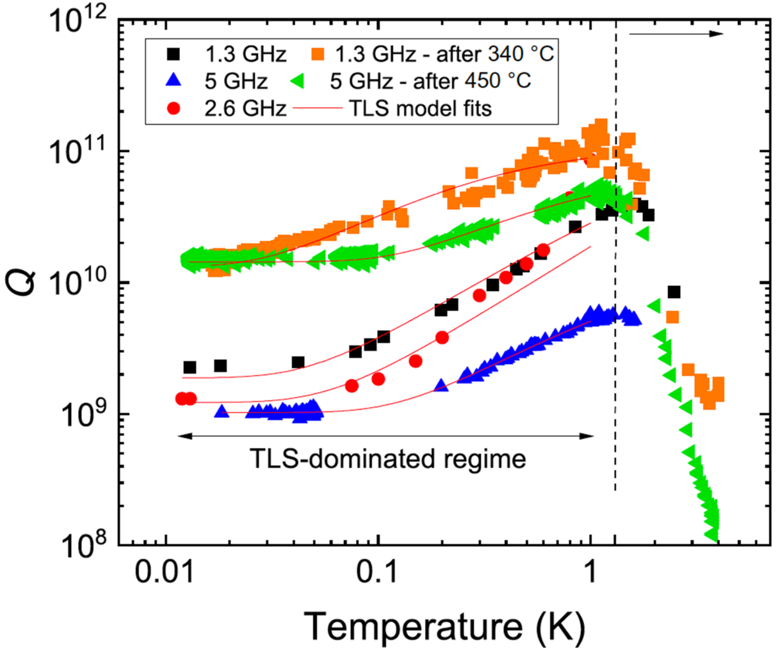
Weizmann

Under exploration

arXiv:2302.06442

High-Q 3D SRF Cavities

Romanenko et al. PRApplied 13, 034032



High-Q 3D SRF Cavities

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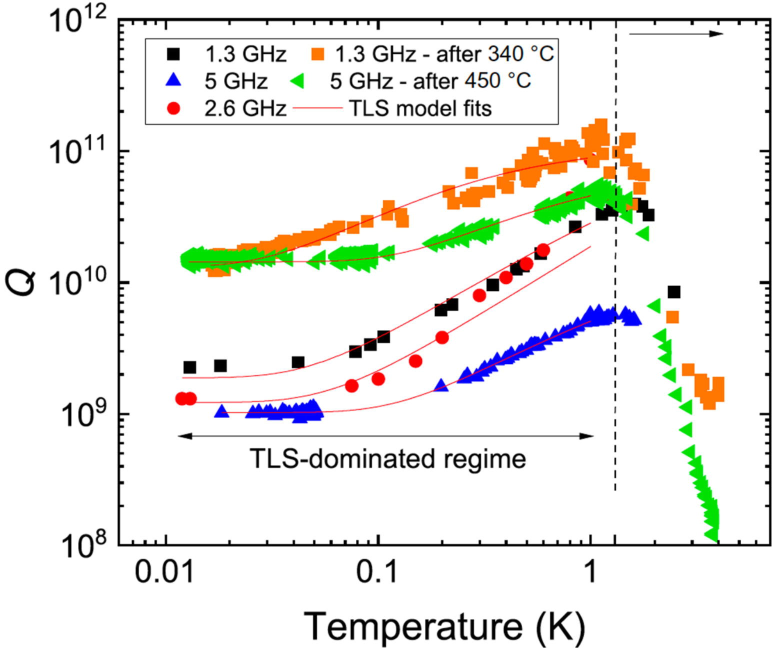
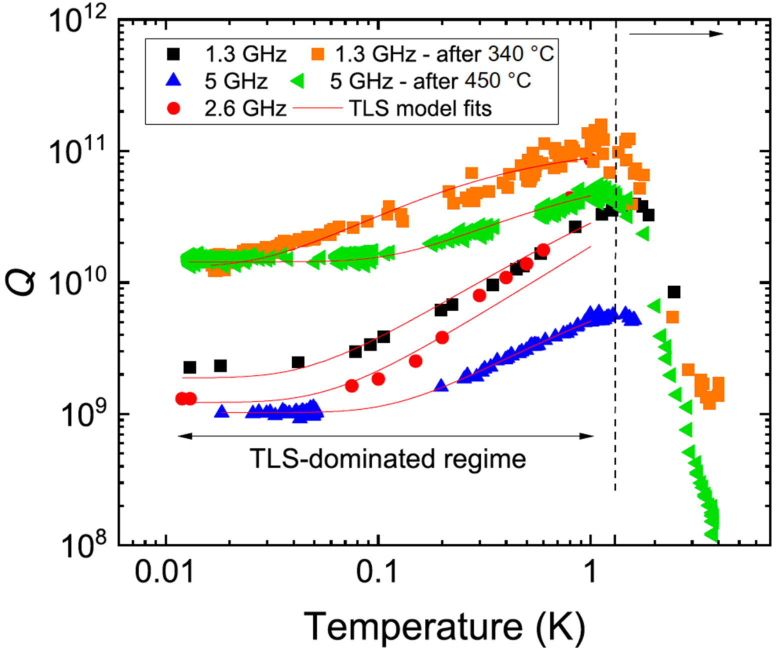


1.3 GHz SRF: $\boxed{Q > 10^{11} \text{ at } 1\ K}$ ⟹ $\boxed{T_1 > 2\ s}$

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

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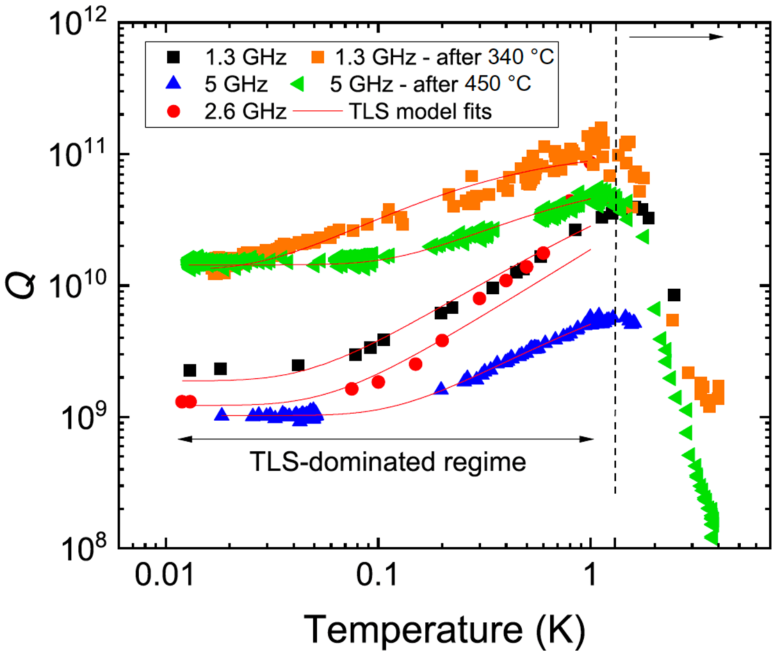
High-Q 3D SRF Cavities

Romanenko et al. PRApplied 13, 034032



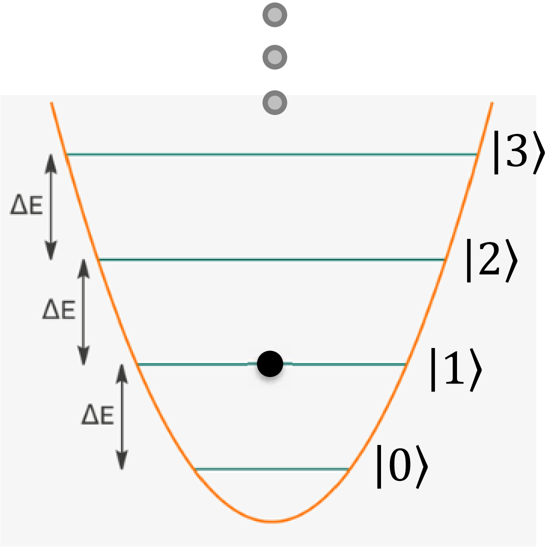
1.3 GHz SRF: $Q > 10^{11}$ *at 1 K* ⇒ $T_1 > 2\ s$

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

>1000 times better than transmons

High-Q 3D Cavities as Qudits

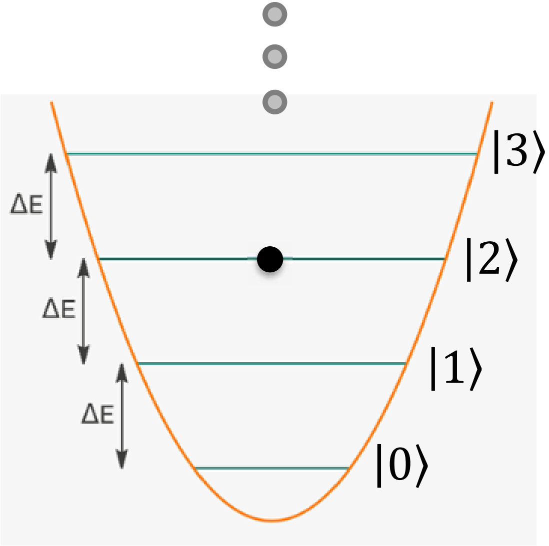
Romanenko et al. PRApplied 13, 034032



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

High-Q 3D Cavities as Qudits

Romanenko et al. PRApplied 13, 034032

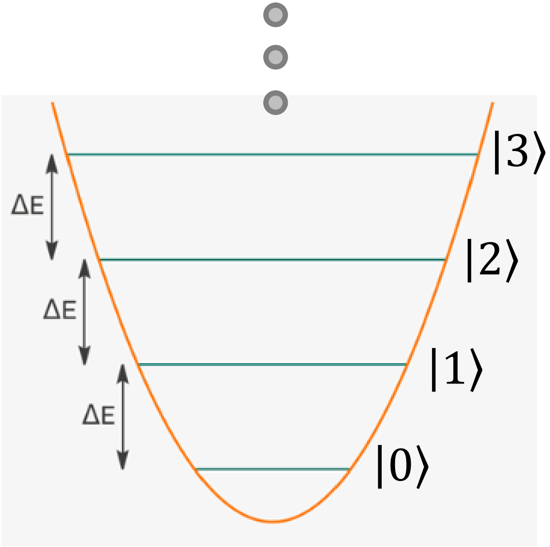


$T_1^{|1\rangle} > 300\ ms$

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

High-Q 3D Cavities as Qudits

Romanenko et al. PRApplied 13, 034032



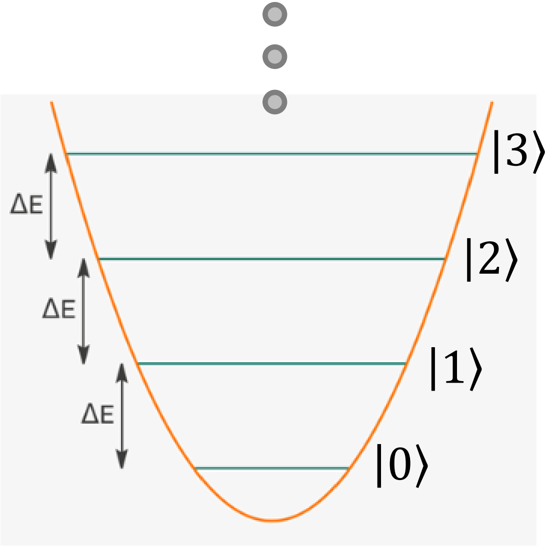
$$\boxed{T_1^{|1\rangle} > 300\ ms}$$

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

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

High-Q 3D Cavities as Qudits

Romanenko et al. PRApplied 13, 034032



$$\mathrm{T}_1^{|1\rangle} > 300\ ms$$

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$$\mathrm{T}_1^{|n\rangle} > \mathrm{T}_1^{|1\rangle}/n$$

$$\mathrm{T}_1^{|10\rangle} > 30\ ms$$

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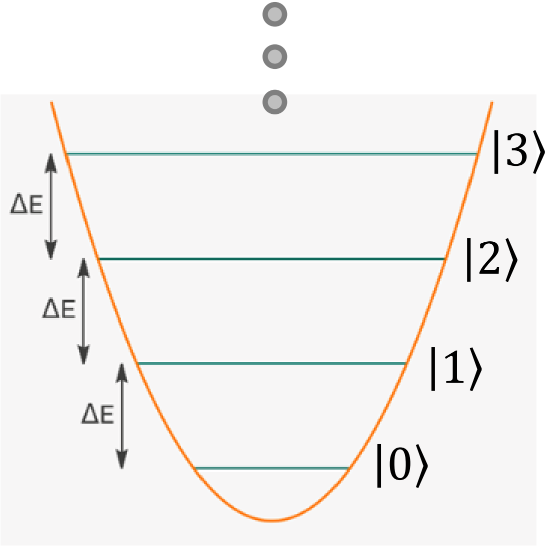

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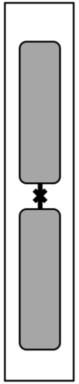
$\mathrm{T}_1^{|2\rangle} > 150\ ms$

$\mathrm{T}_1^{|n\rangle} > \mathrm{T}_1^{|1\rangle}/n$

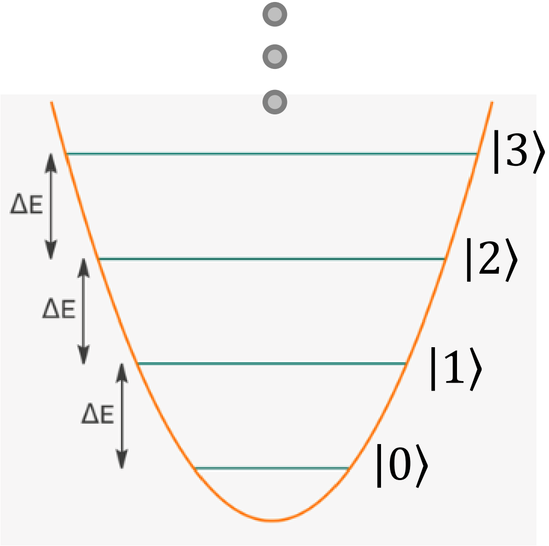
$\mathrm{T}_1^{|10\rangle} > 30\ ms$

Still much better than transmon qubits

High-Q 3D Cavities as Qudits



Romanenko et al. PRApplied 13, 034032



$\mathrm{T}_1^{|1\rangle} > 300\ ms$

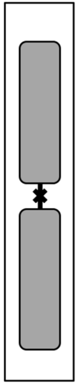
$\mathrm{T}_1^{|2\rangle} > 150\ ms$

$\mathrm{T}_1^{|n\rangle} > \mathrm{T}_1^{|1\rangle}/n$

$\mathrm{T}_1^{|10\rangle} > 30\ ms$

Still much better than transmon qubits

High-Q 3D Cavities as Qudits



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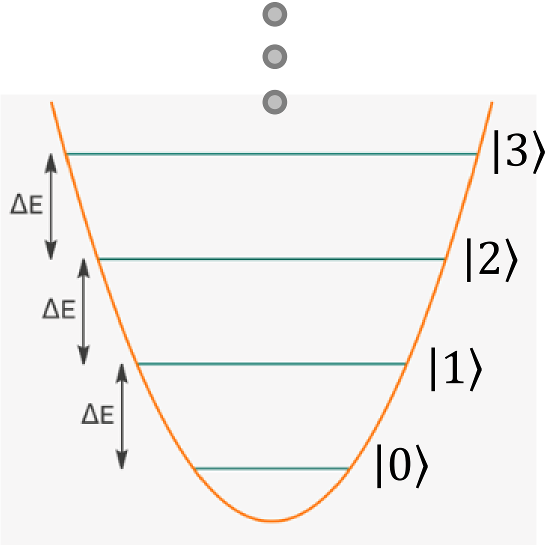


$T_1^{|1\rangle} > 300\ ms$

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

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

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

Qudit

Still much better than transmon qubits

Qudit States and Gates

$\boxed{\textit{Qubit: } \alpha|0\rangle + \beta|1\rangle}$

$\boxed{\textit{Qudit: } \alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle}$

Qudit States and Gates

$\boxed{\text{Qubit: } \alpha|0\rangle + \beta|1\rangle}$

$\boxed{\text{Qudit: } \alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle}$

SNAP gate

PRL 115, 137002 (2015)

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

Qudit States and Gates

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

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

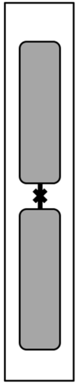
SNAP gate

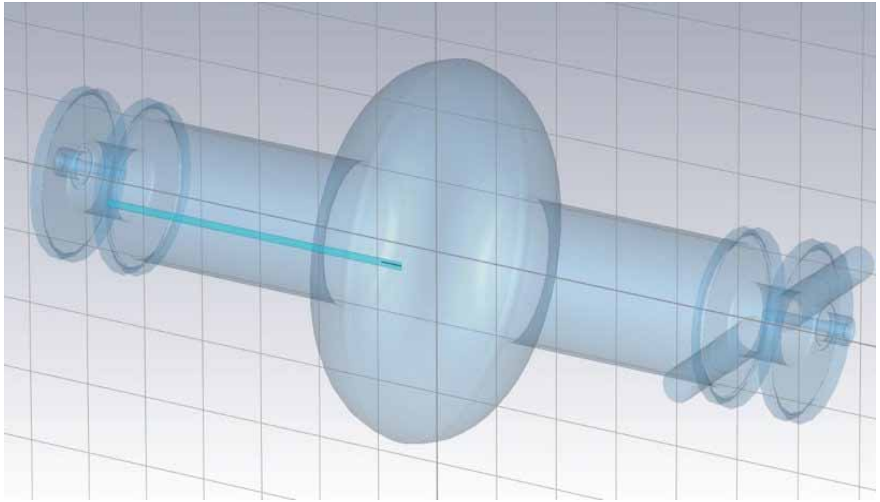
PRL 115, 137002 (2015)

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 → *Universal control*

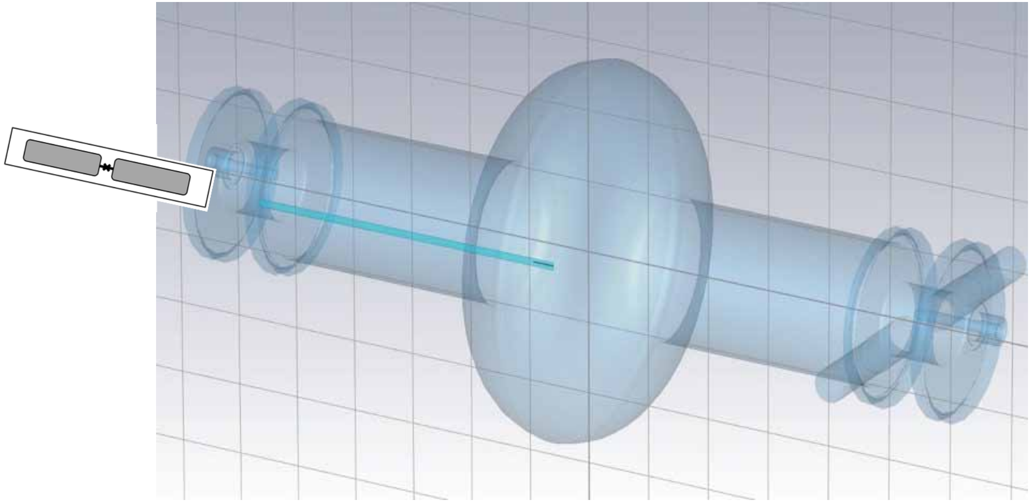
First Milestone





Incorporate Transmon into a TESLA cavity

First Milestone



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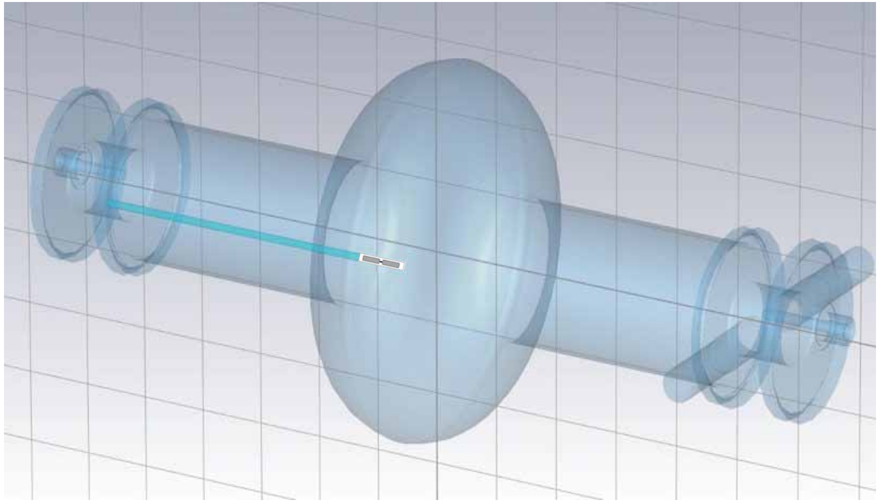

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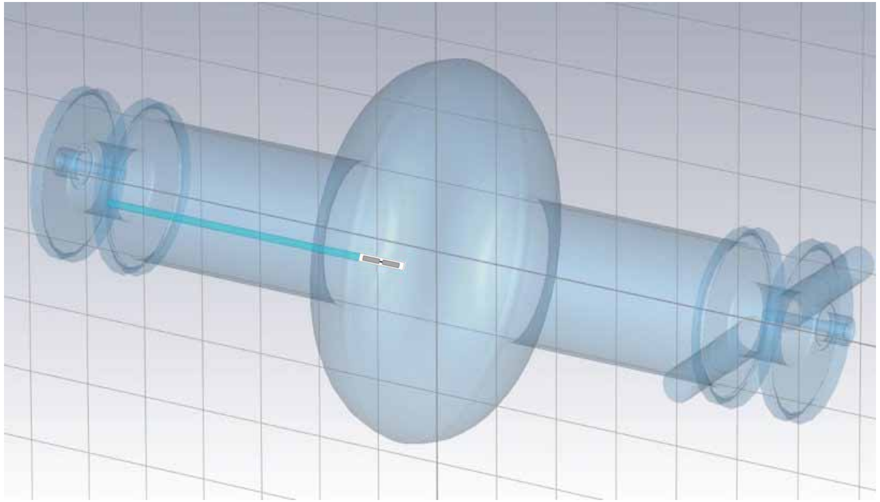

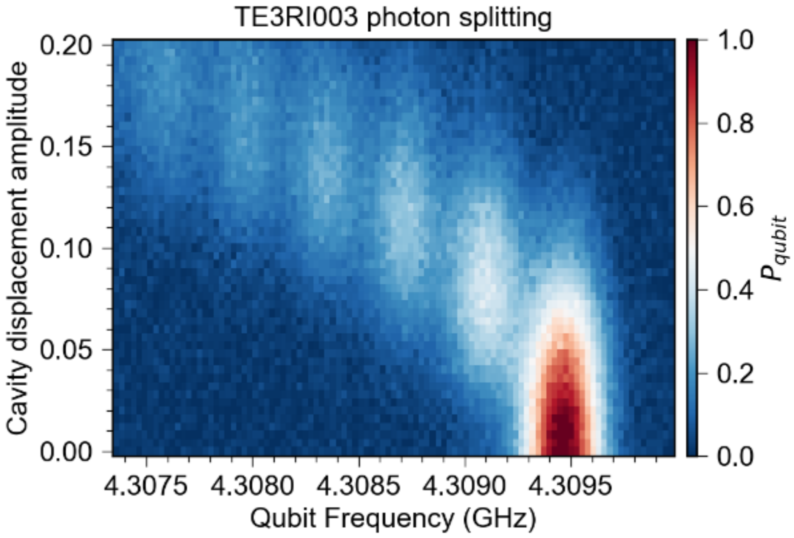

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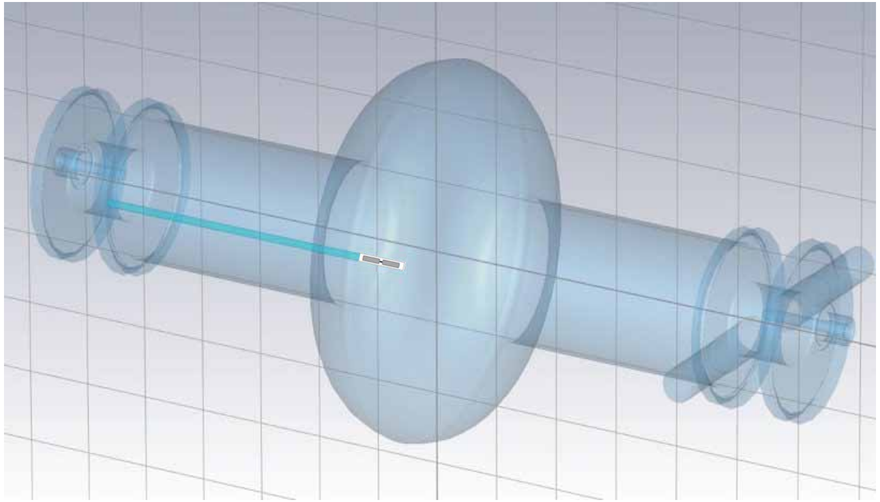

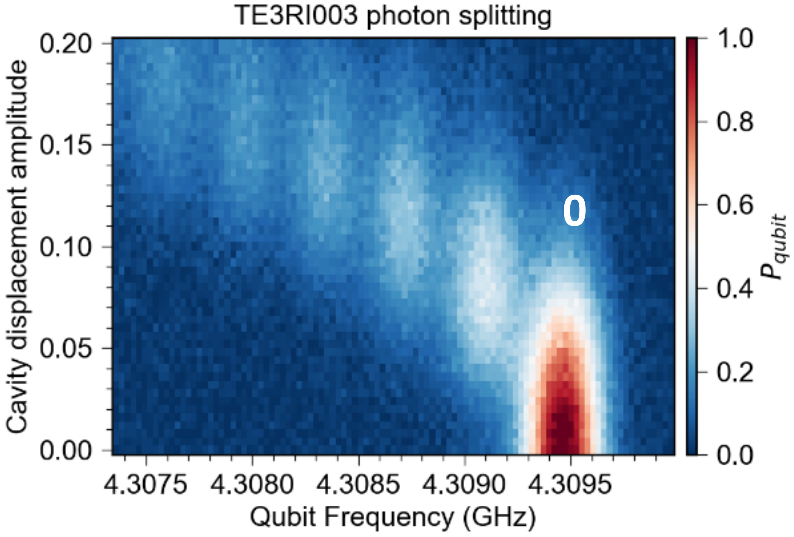

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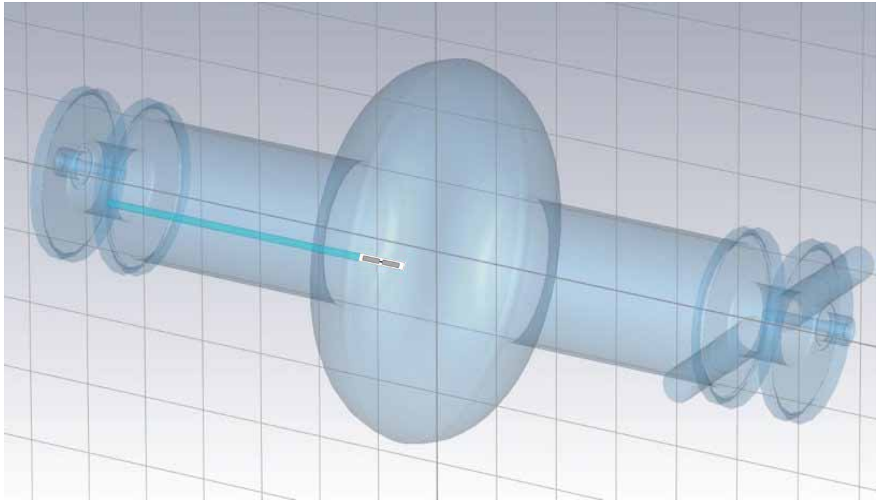

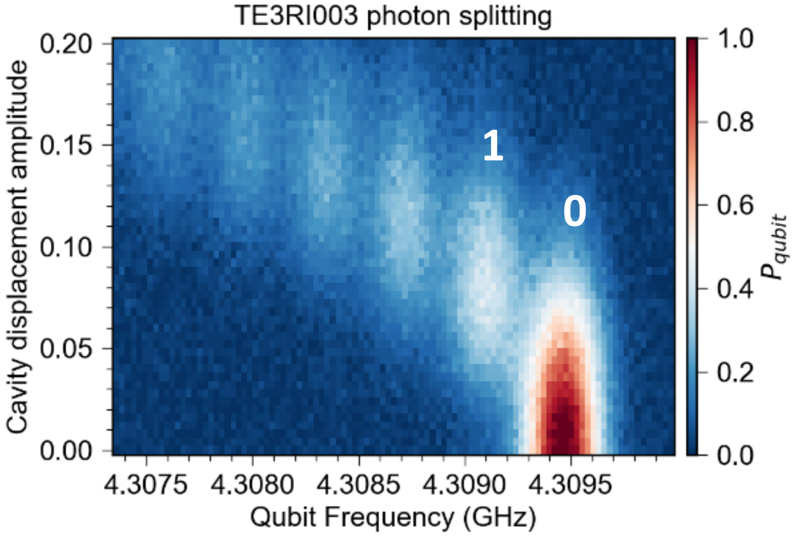

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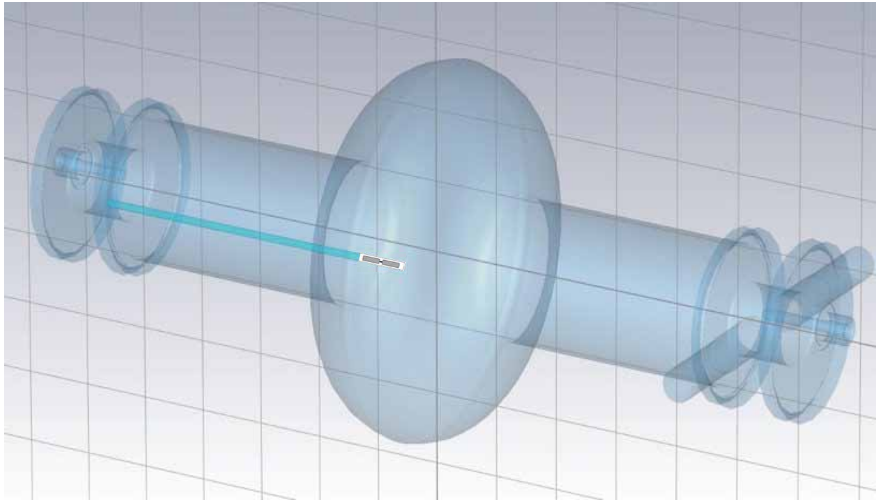
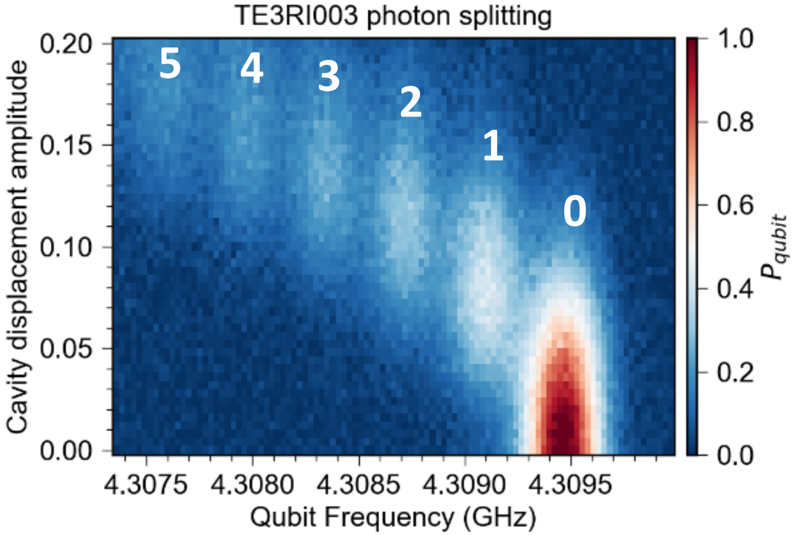
First Milestone





Incorporate Transmon into a TESLA cavity

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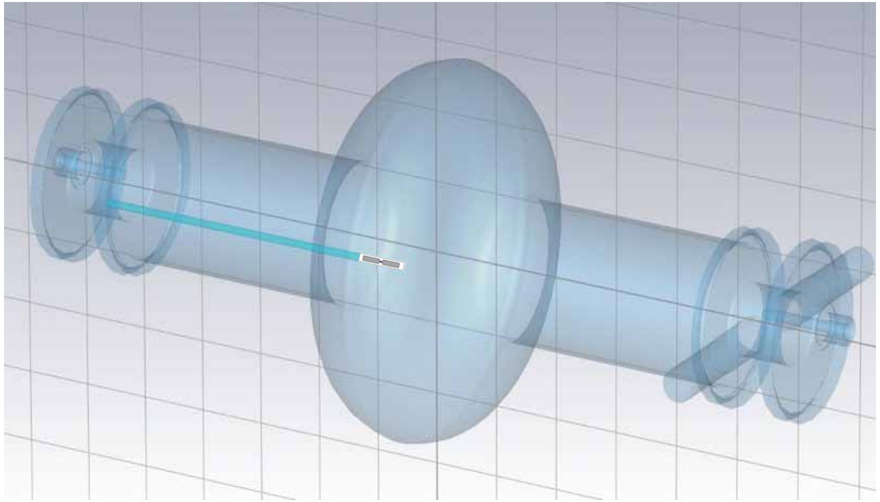
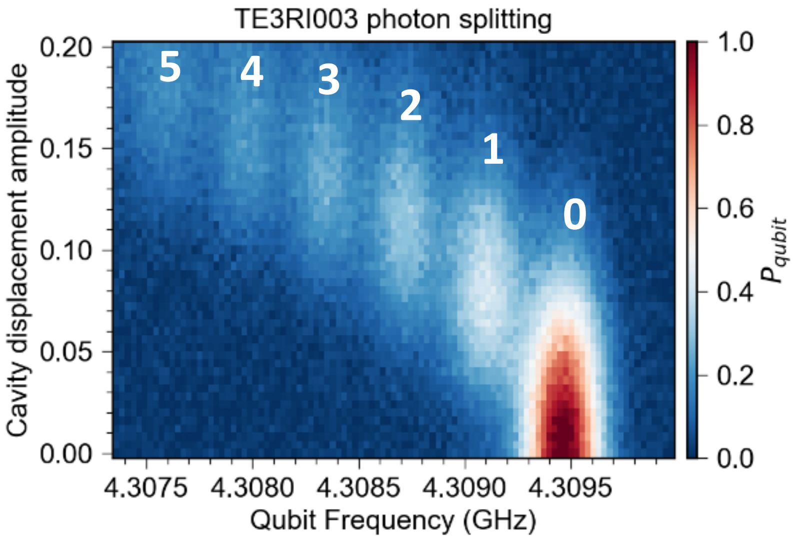
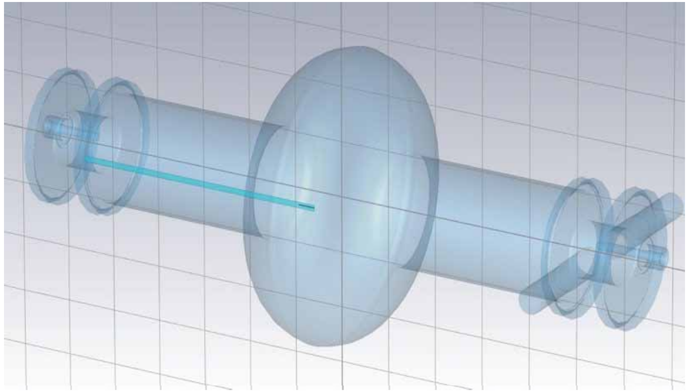




Incorporate Transmon into a TESLA cavity

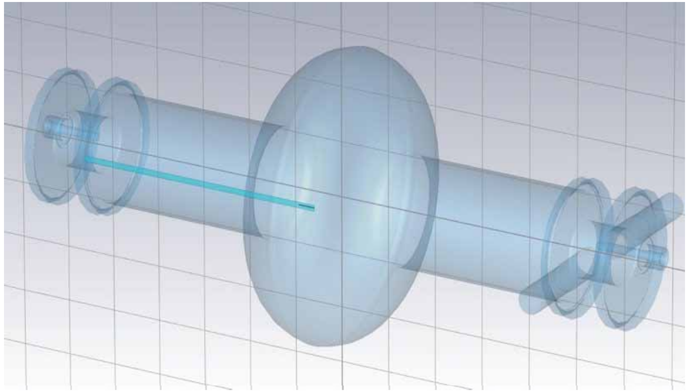
Achieved photon counting

Second Milestone



Prepare quantum states

Second Milestone



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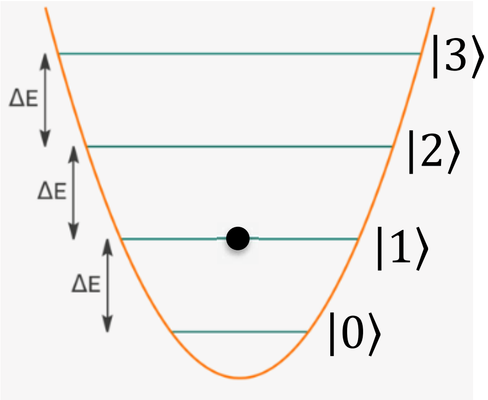
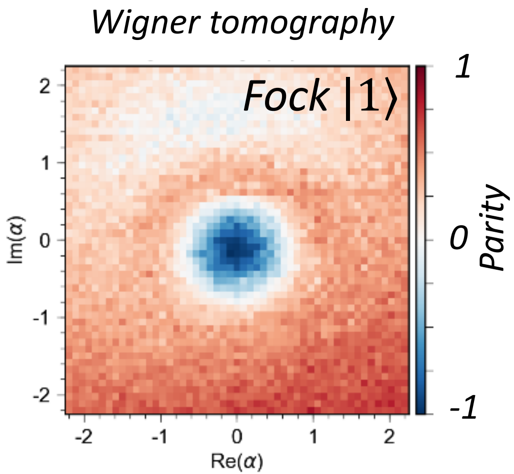
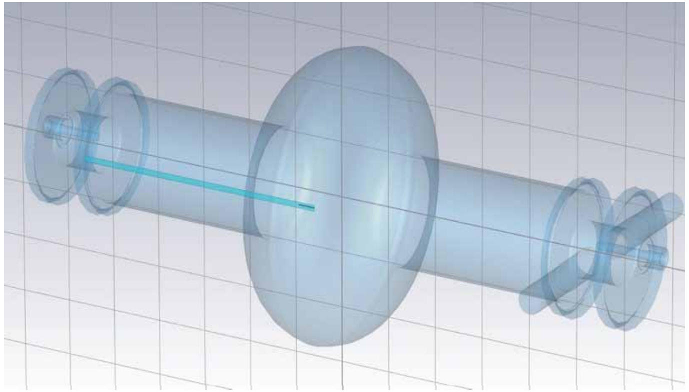




Second Milestone



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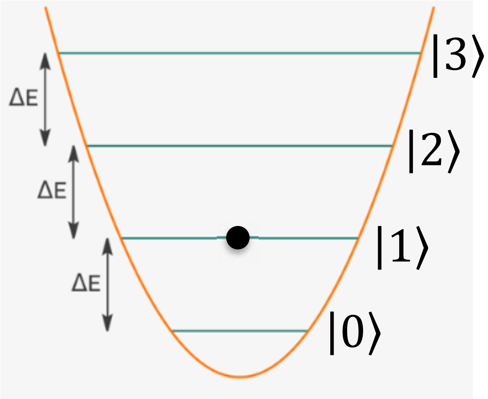

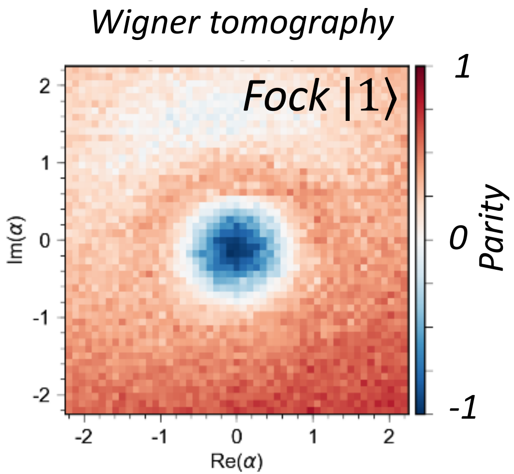

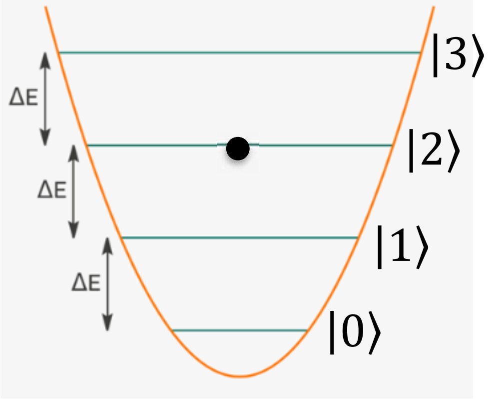

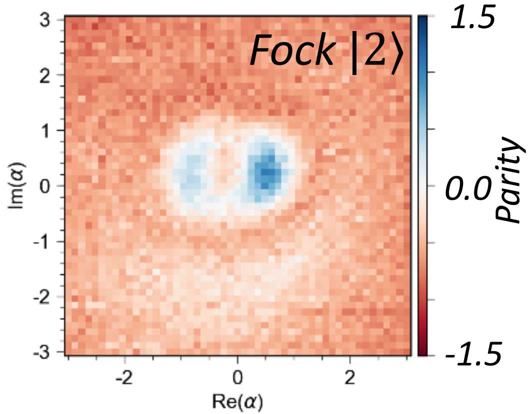

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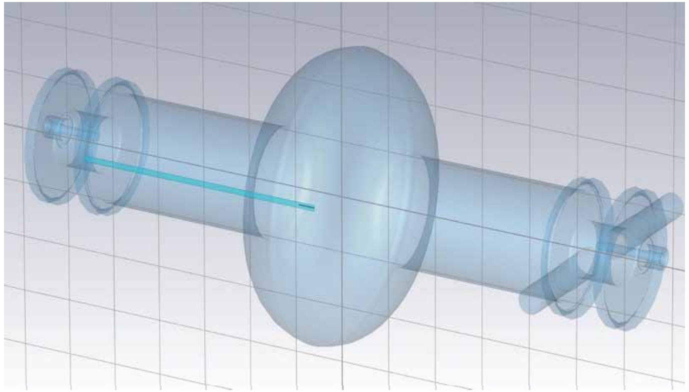
Second Milestone



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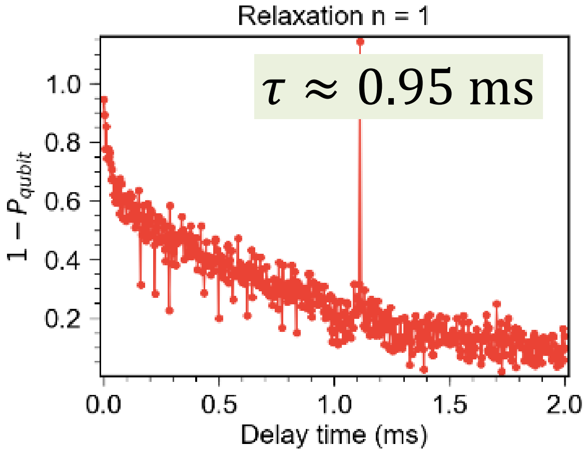
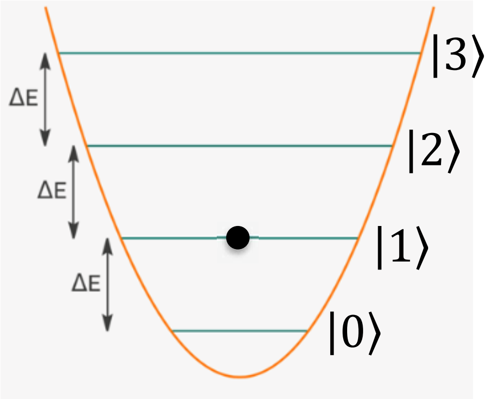
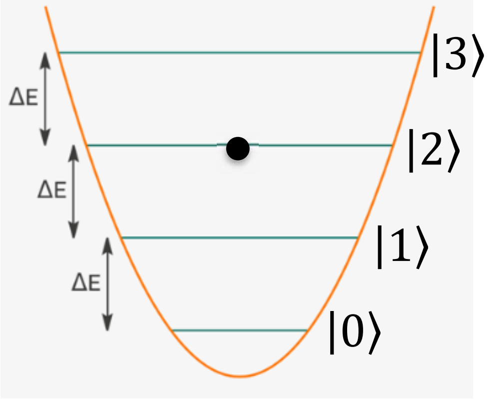
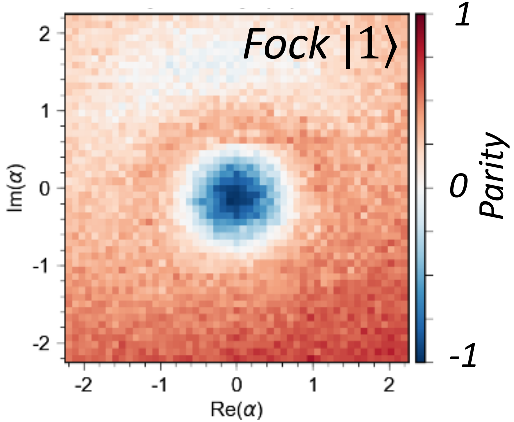
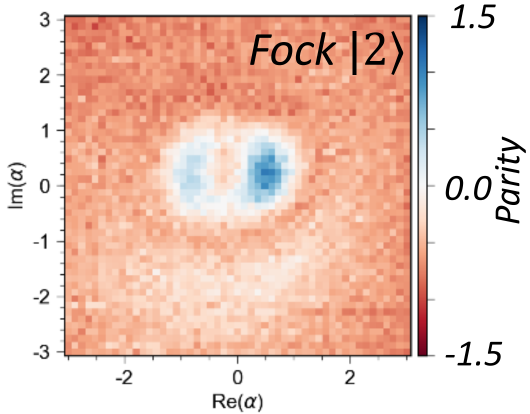






Wigner tomography





Multqudit Architecture

Multqudit Architecture

Crosstalk issues

Multqudit Architecture

Crosstalk issues

Transmon Manipulator Coupler Storage

Multqudit Architecture

Crosstalk issues

Moderate-Q cavities

High-Q 3D cavities

Transmon | Manipulator | Coupler | Storage

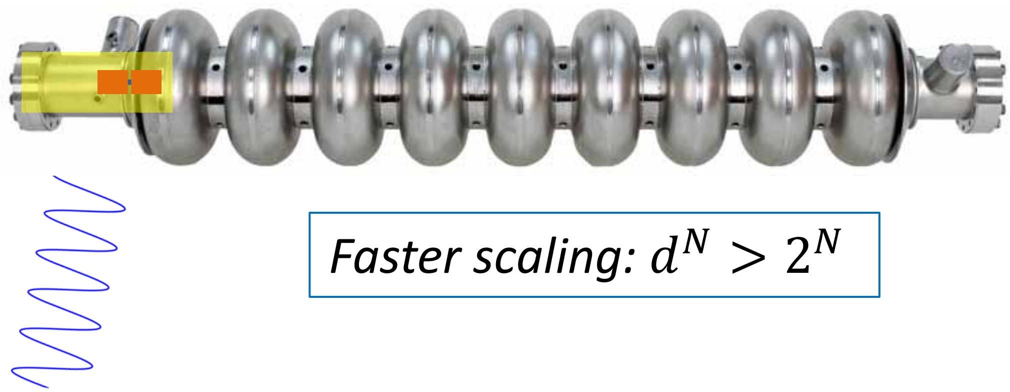
CPU

BUS

RAM

Multqudit Architecture

Crosstalk issues



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

Moderate-Q cavities

High-Q 3D cavities

Transmon

Manipulator

Coupler

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Multqudit Architecture

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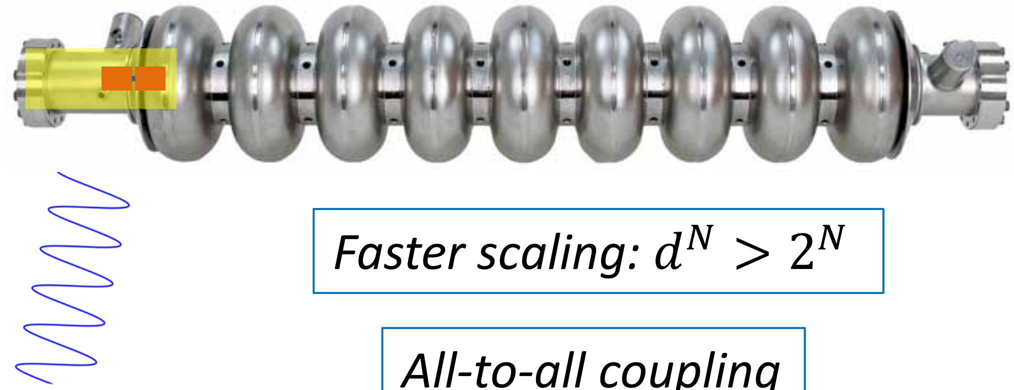

Faster scaling: $d^N > 2^N$

All-to-all coupling

Moderate-Q cavities

High-Q 3D cavities

Transmon | *Manipulator* | *Coupler* | *Storage*

CPU

BUS

RAM

Outlook

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

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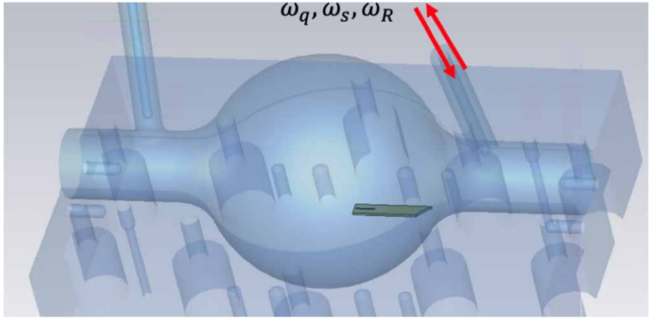

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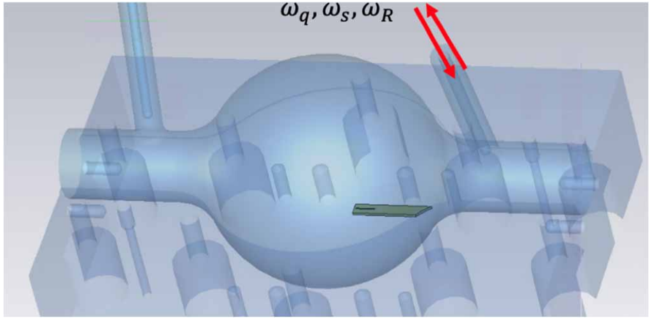
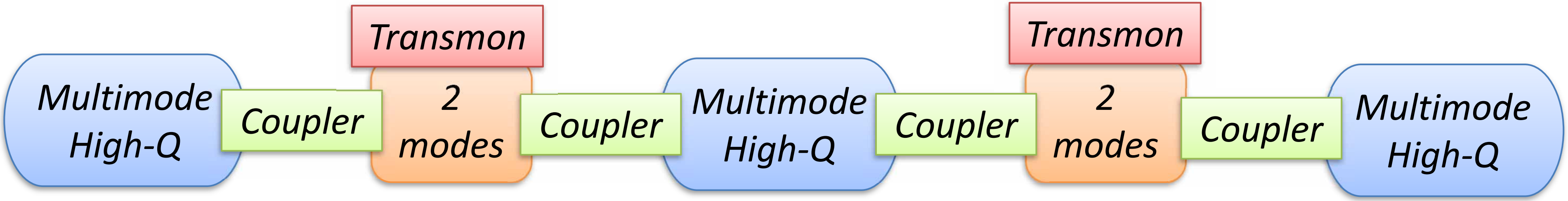
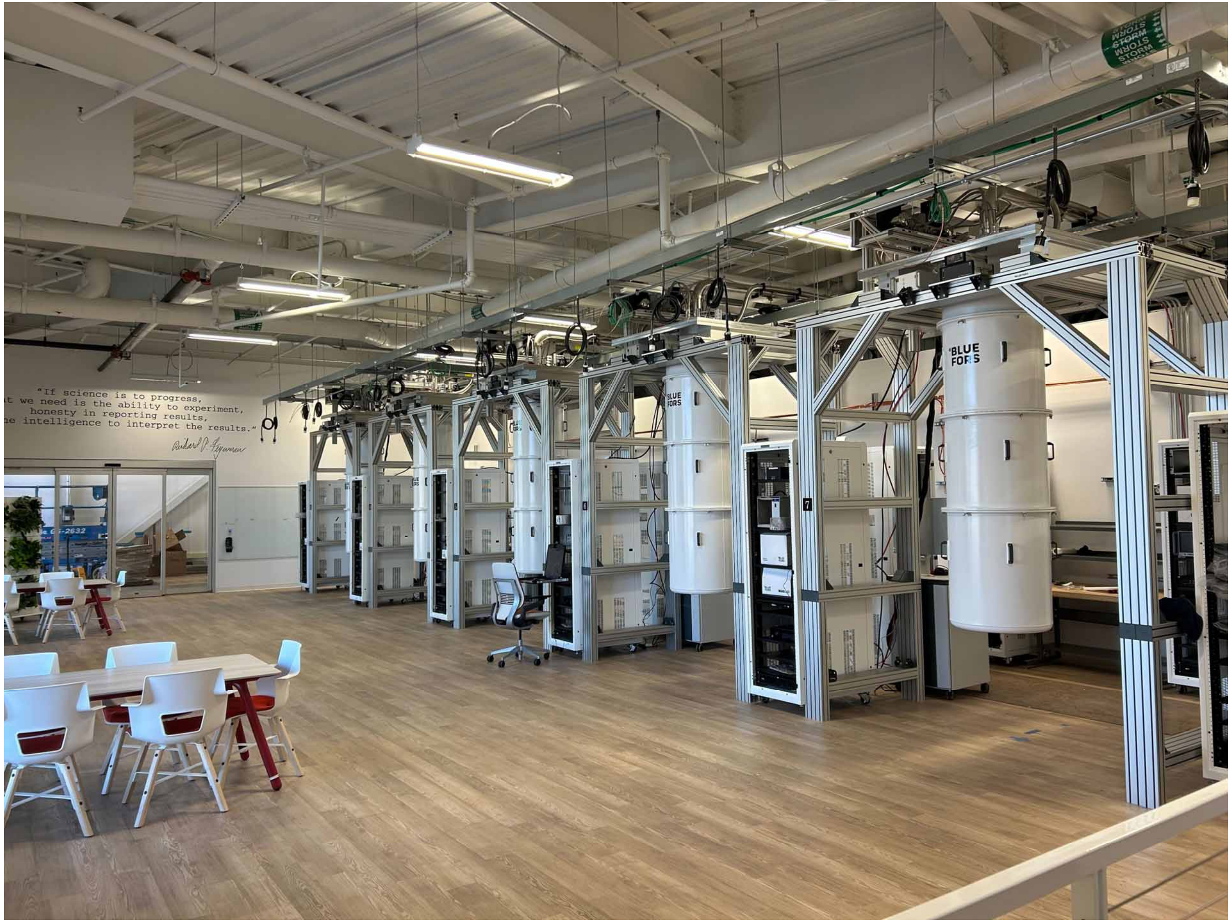


- Scaling up
  - *Develop modular architecture*
  - *Connect several modules*



Brand New SQMS Facility at Fermilab



Thank You!