Advances in SRF cavity architectures for quantum computing

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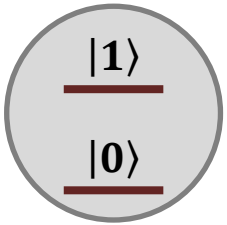
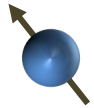
Basic Requirements for a Quantum Computer

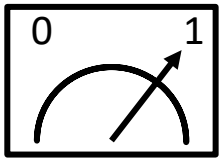


Quantum two level systems

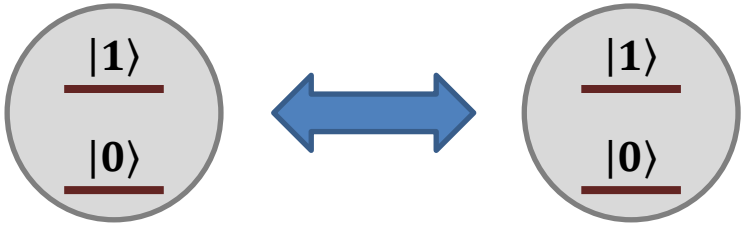


$\alpha|0\rangle + \beta|1\rangle$

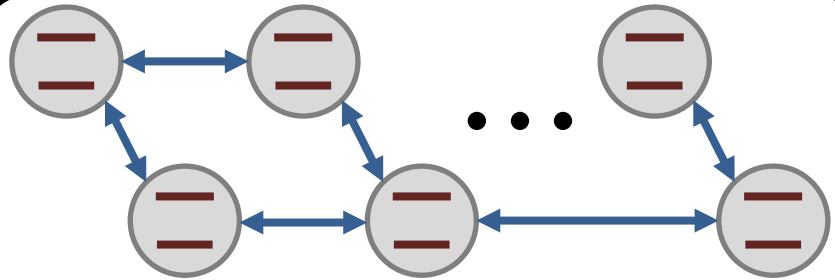
Create arbitrary states



Measure quantum states



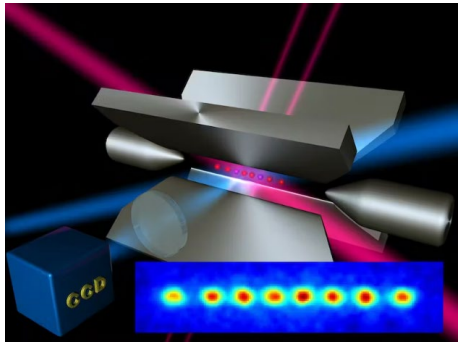
Couple multiple qubits



Scalable architecture

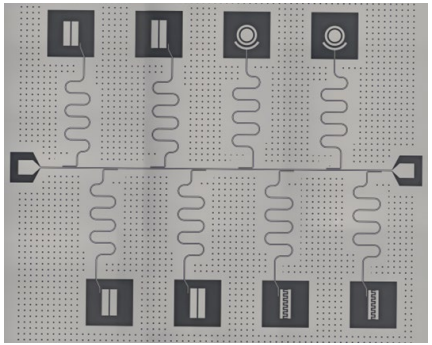
Different Platforms

Trapped ions



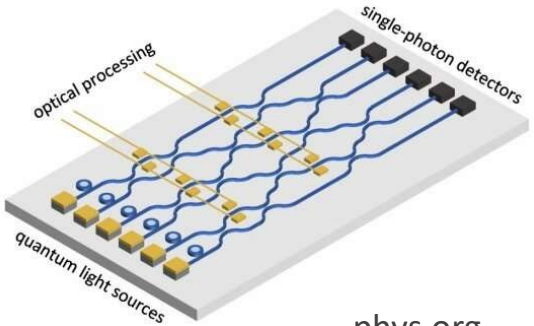
laserfocusworld.com

Superconducting circuits



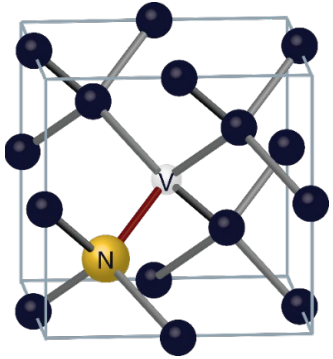
SQMS

Photonic crystals



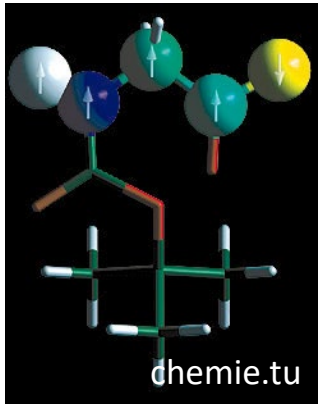
phys.org

NV centers

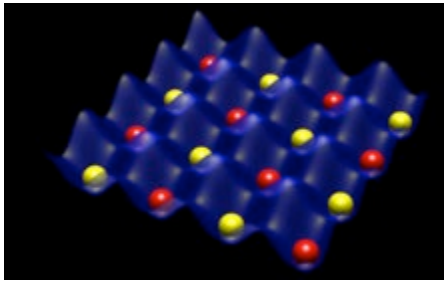


phys.org

NMR

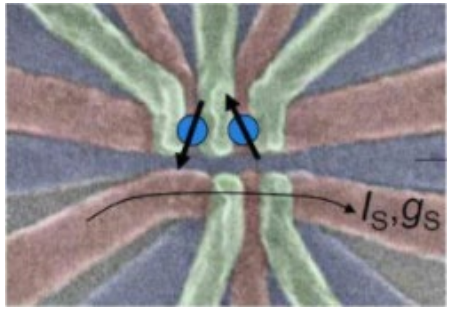


Neutral atoms



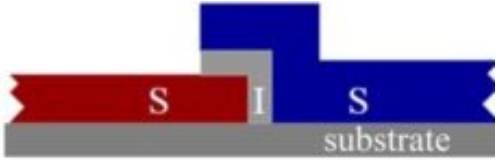
NIST

Quantum dots

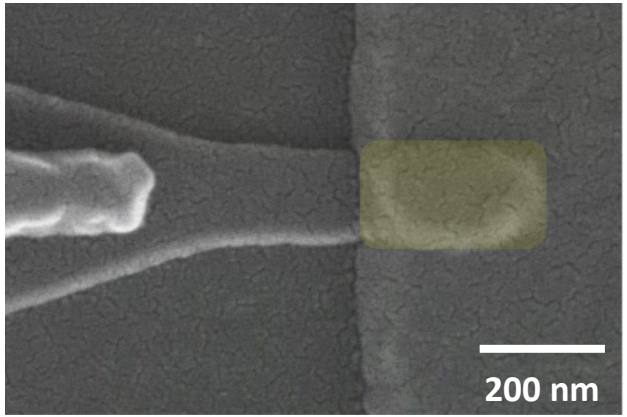


sciencemag.org

Superconducting Circuits



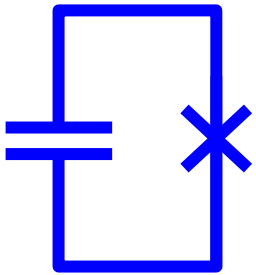
Josephson Junction

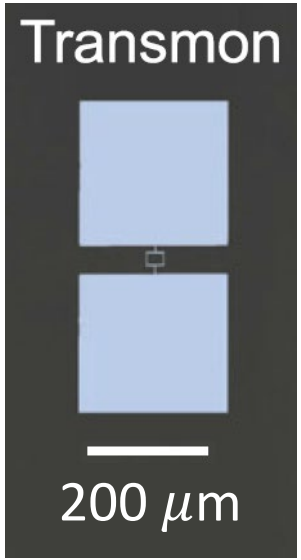


Lossless nonlinear inductor

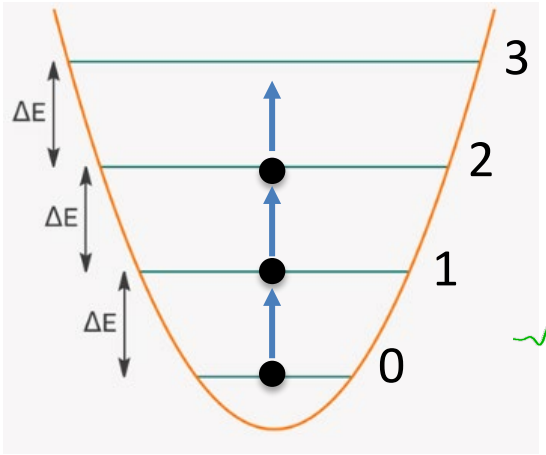
$$L_J(I) = \frac{\varphi_0}{(I_0^2 - I^2)^{1/2}}$$

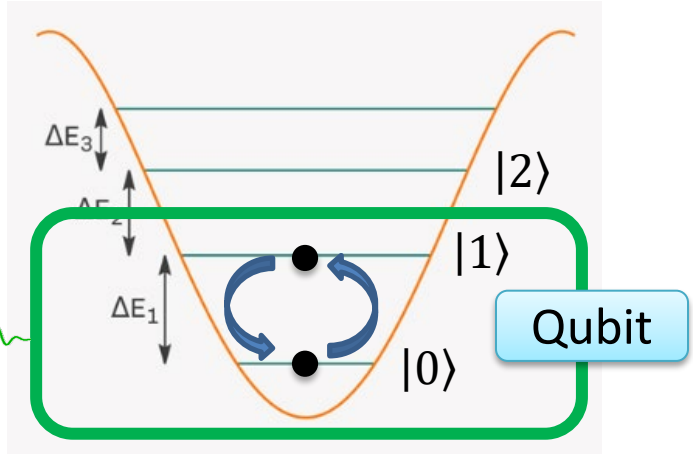
Transmon

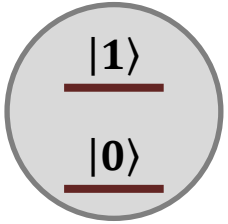




Transmon: Anharmonic Oscillator

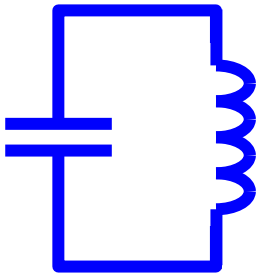


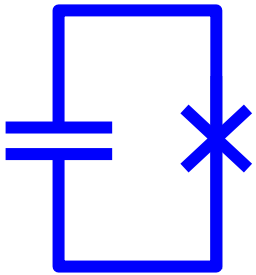




Harmonic Oscillator

Anharmonic Oscillator





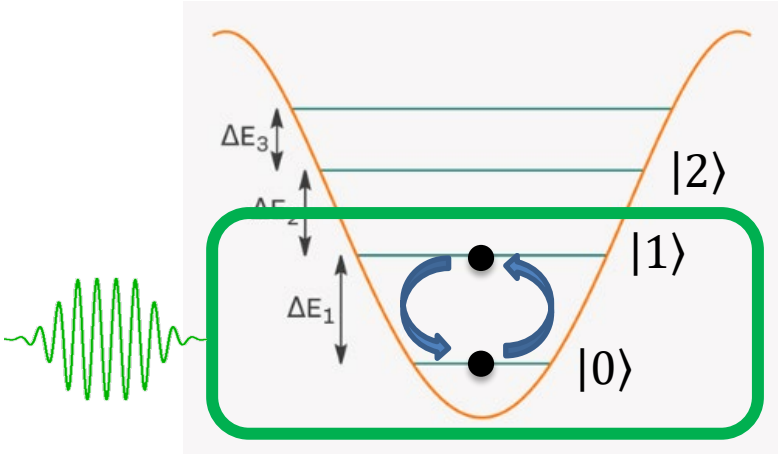
Operating Temperature

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

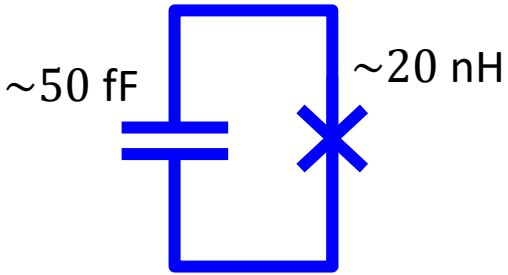
$\sim$ 5 GHz

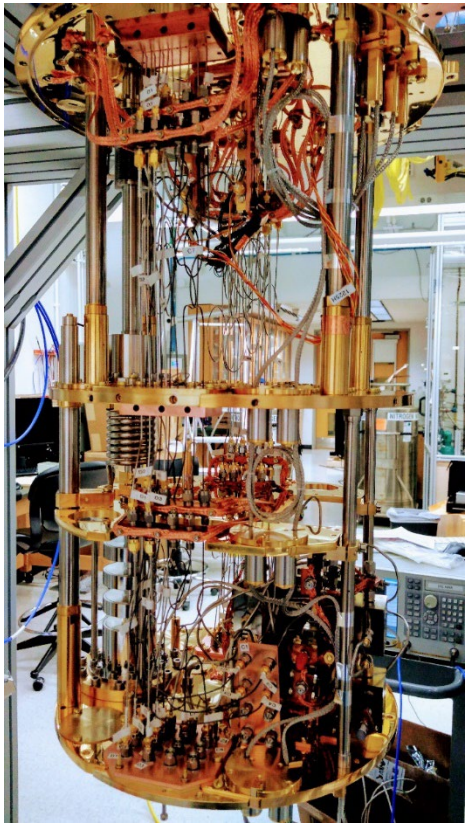
$$k_B T \ll h f_{01}$$

20 mK $\sim$ 240 mK



Anharmonic Oscillator

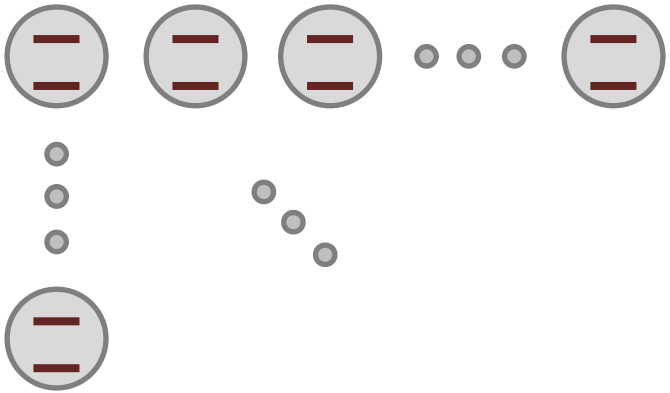




Dilution fridge ~ 10 mK

Traditional Multi-qubit Architecture

Linear or planar geometry

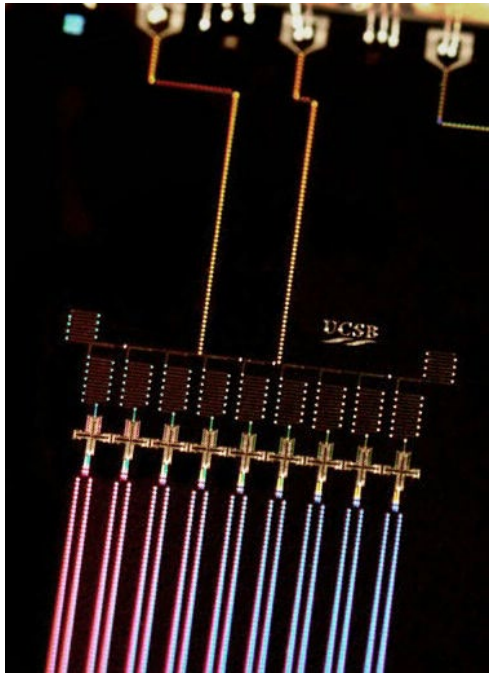


Computational space: 2^N

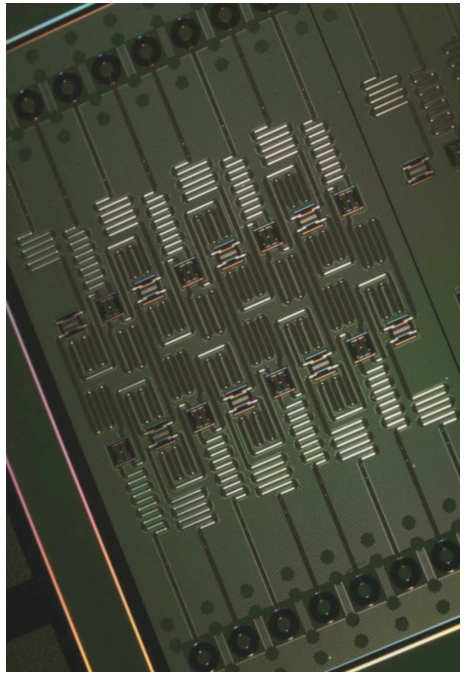
Can we do **better**?

Scaling: d^N, $d > 2$

Qudit



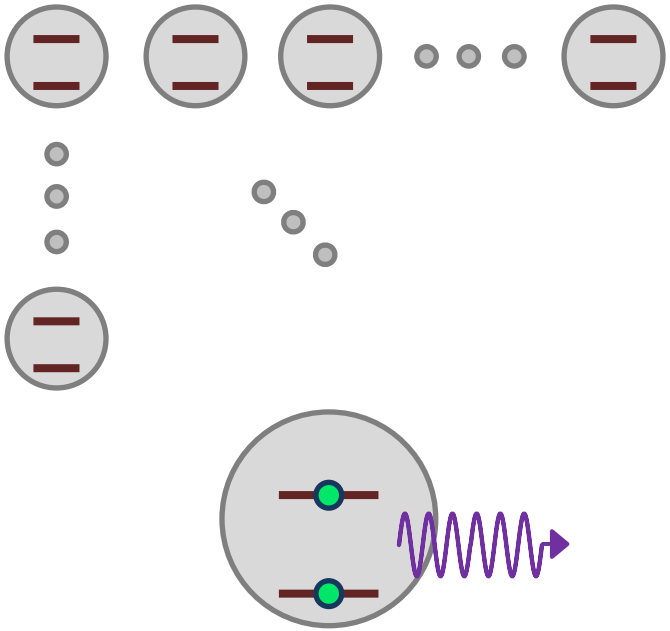
UCSB, Nature 519 (7541)

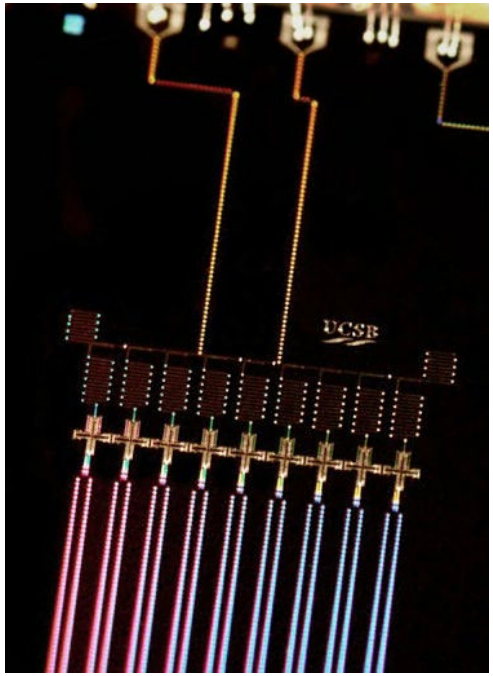


IBM

Problem of Relaxation

Linear or planar geometry





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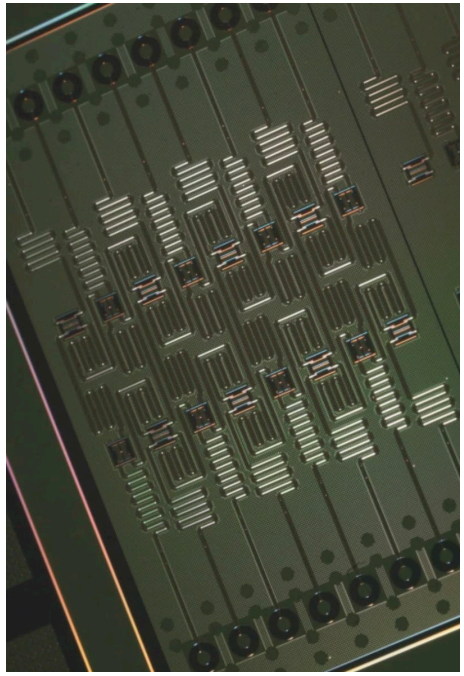


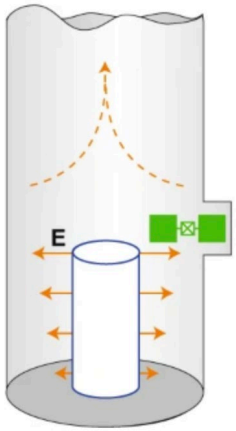
IBM

$T_1 \sim 100\ \mu s$

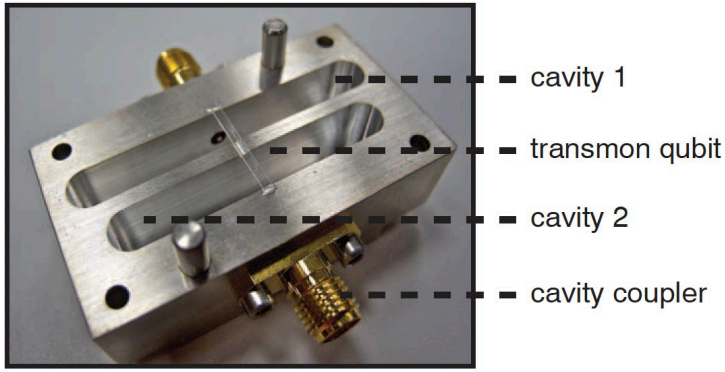
Q: a few 10^6

Can we do **better**?

Zoo of Cavities

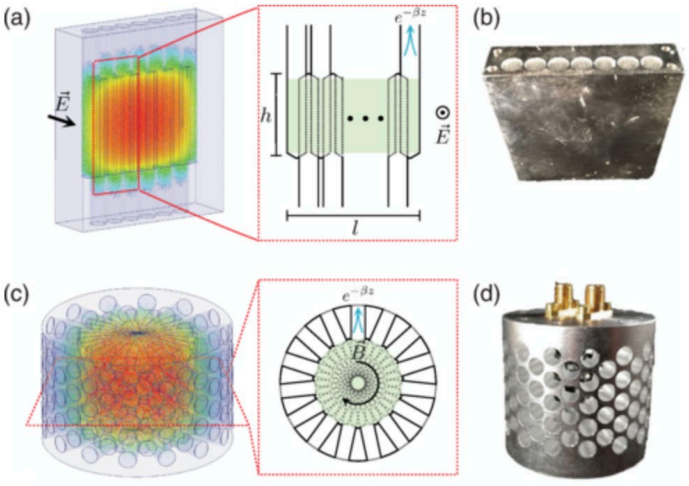


Nat. Phys. 16, 247



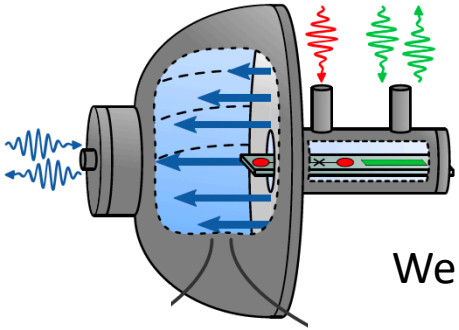
Science 342, 6158

Yale, U. Pittsburgh



PRL 127, 107701

U. Chicago, Rutgers

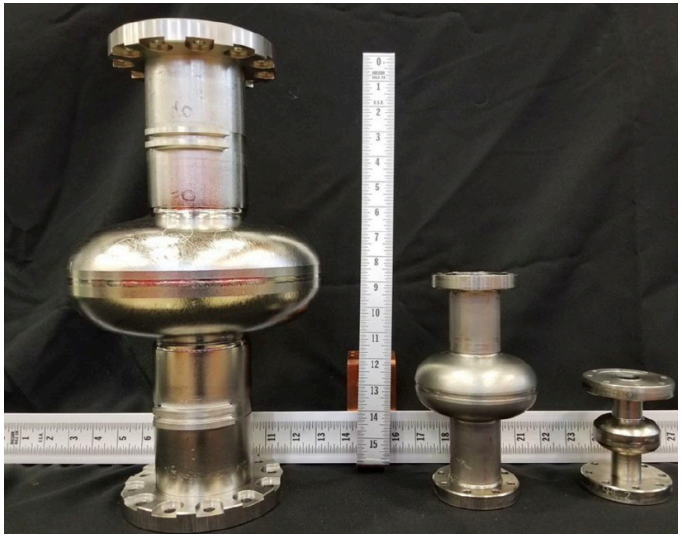


Weizmann

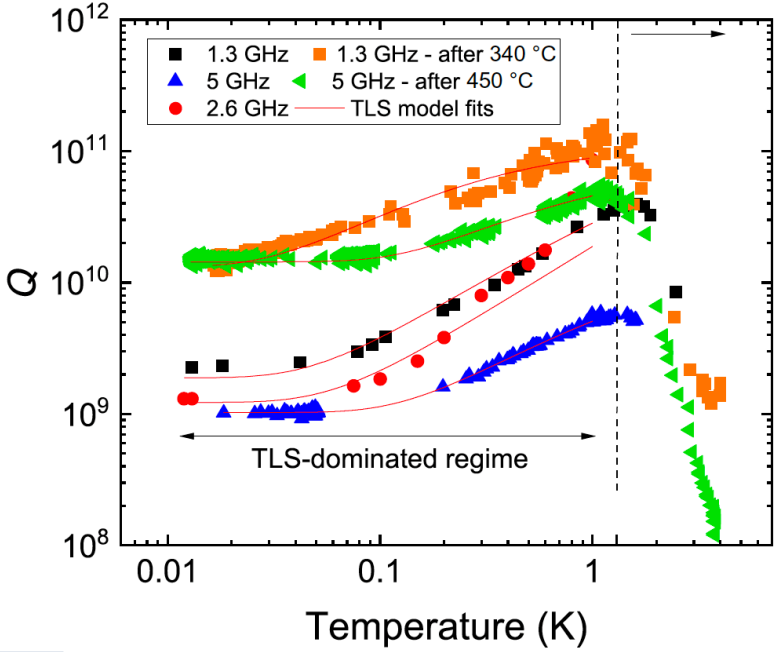
arXiv:2302.06442

Under exploration

High-Q 3D SRF Cavities



Romanenko et al. PRApplied 13, 034032

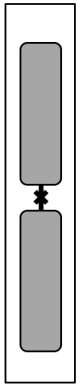


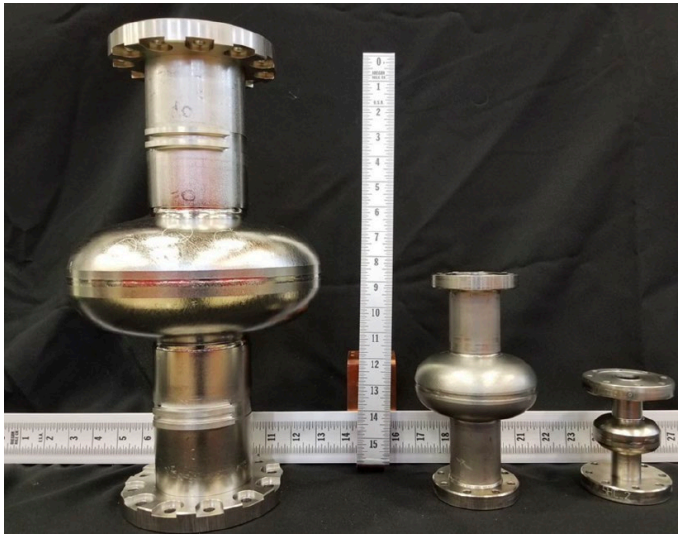
1.3 GHz SRF: $Q > 10^{11}$ at 1 K ⟹ $T_1 > 2$ s

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

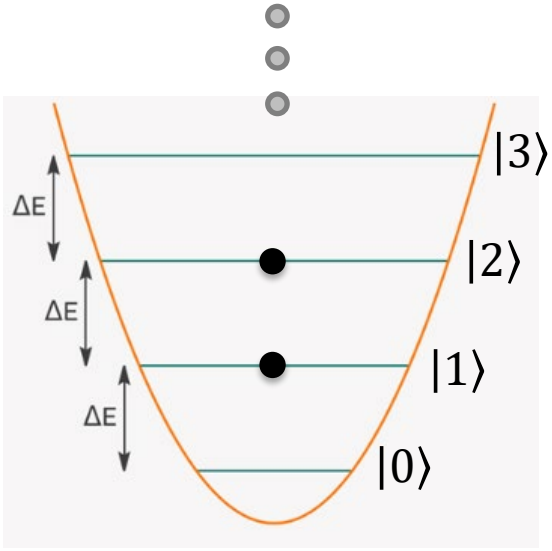
>1000 times better than transmons

High-Q 3D Cavities as Qudits





Romanenko et al. PRApplied 13, 034032



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

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

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

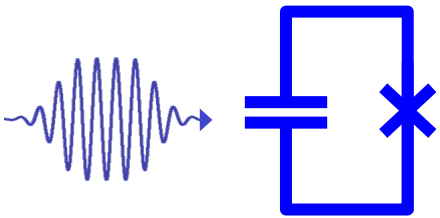
$T_1^{|10\rangle} > 30$ ms

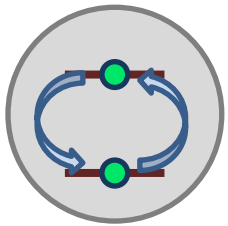
Qudit

Still much better than transmon qubits

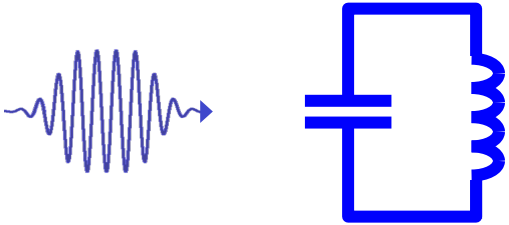
Transmon vs. Cavity Drive

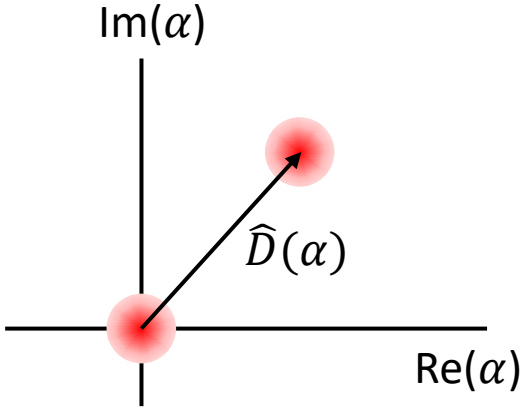
Qubit: $\alpha|0\rangle + \beta|1\rangle$





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





Qudit Operation

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

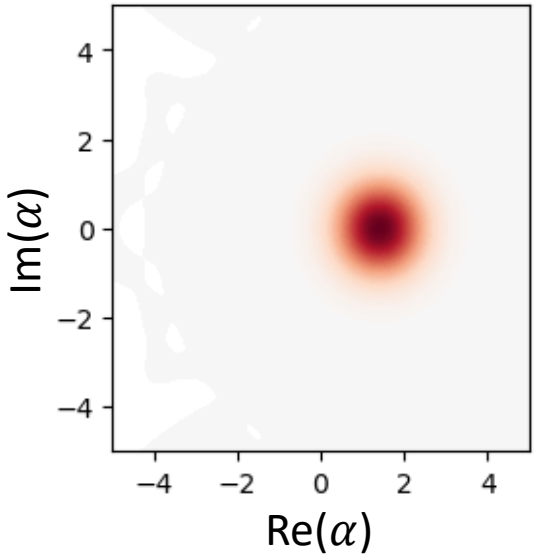
$|n\rangle \rightarrow e^{i\theta}|n\rangle$

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

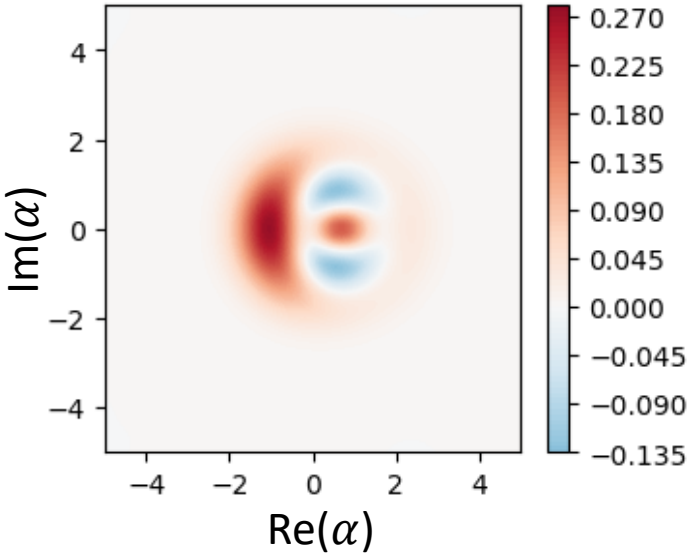
Selective number-dependent arbitrary phase (SNAP) gate

PRL 115, 137002 (2015)

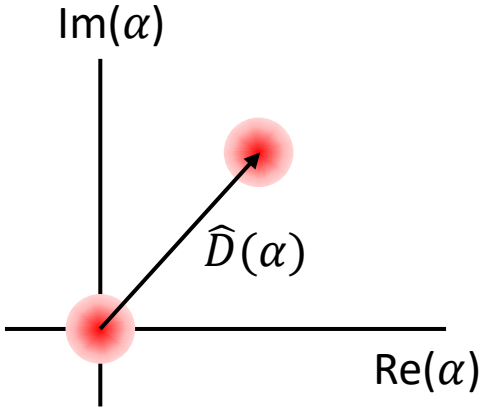
Quantum state $\alpha_0|0\rangle - \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle$



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



Universal Gate Set



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

SNAP gate

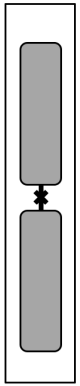
Qudit: $\alpha_0 e^{i\theta_0}|0\rangle + \alpha_1 e^{i\theta_1}|1\rangle + \cdots + \alpha_d e^{i\theta_d}|d\rangle$

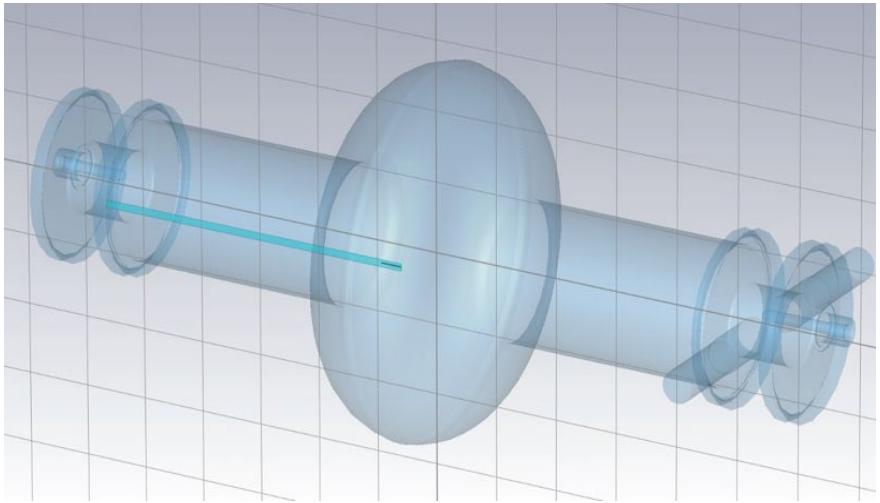
Cavity drive + SNAP ⇒ Universal control

Unconditional operation on cavity

Conditional operation on cavity enabled by a transmon

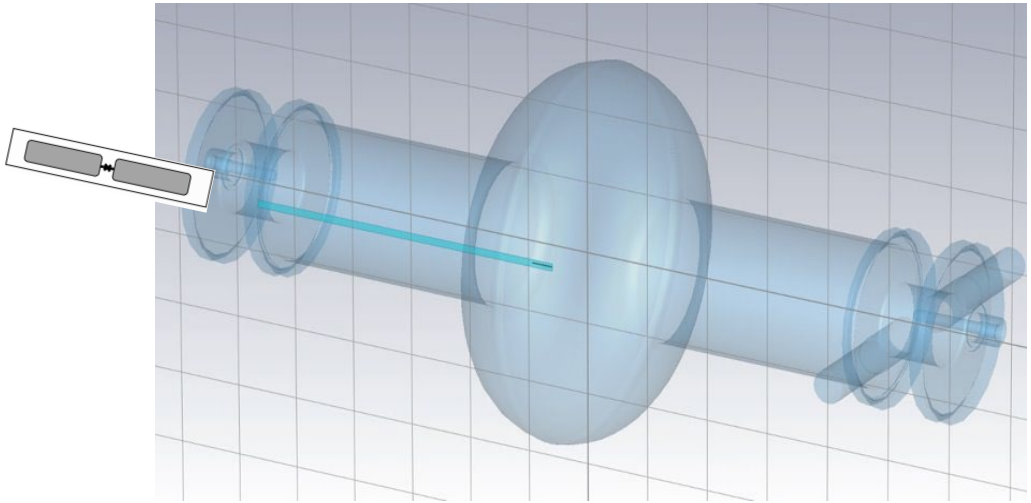
First Milestone





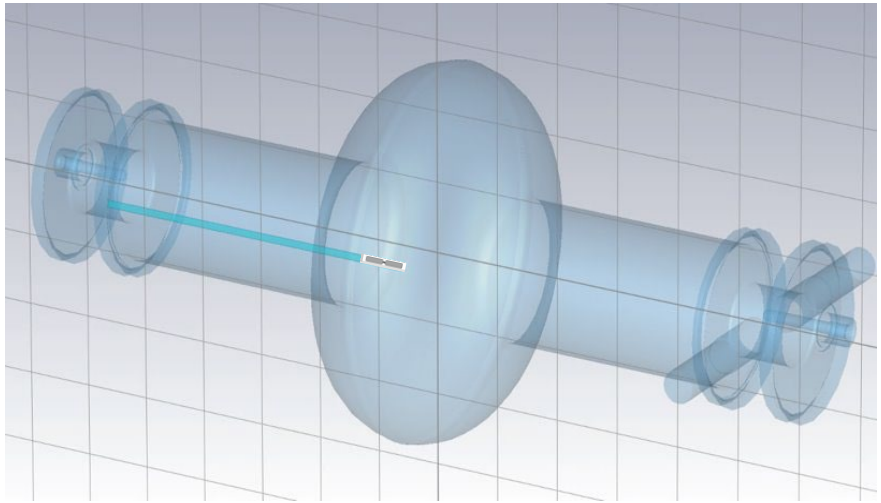
Incorporate Transmon into a TESLA cavity

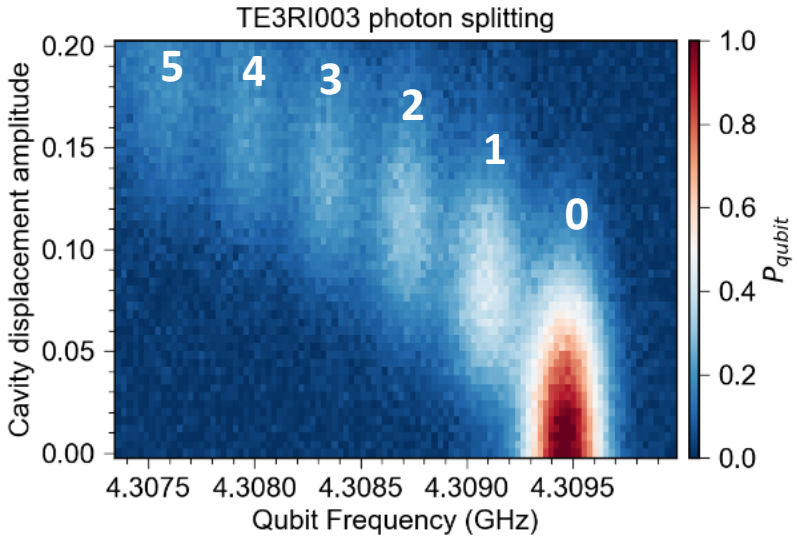
First Milestone



Incorporate Transmon into a TESLA cavity

First Milestone



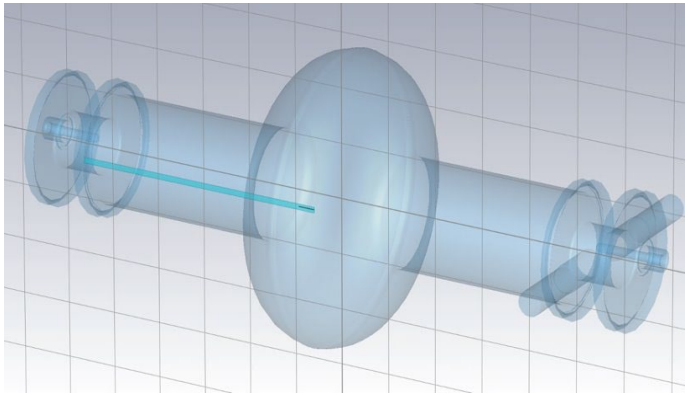


Incorporate Transmon into a TESLA cavity

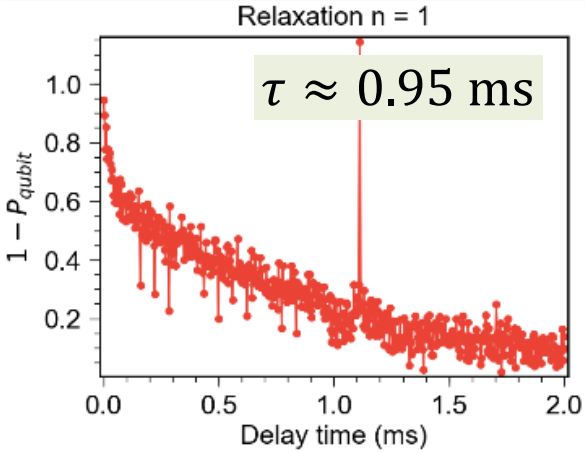
Achieved photon counting

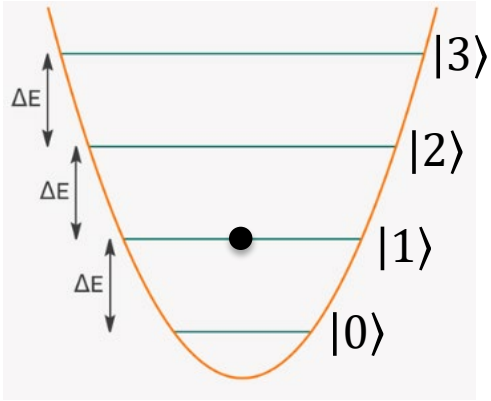
Key to Dark Matter detection

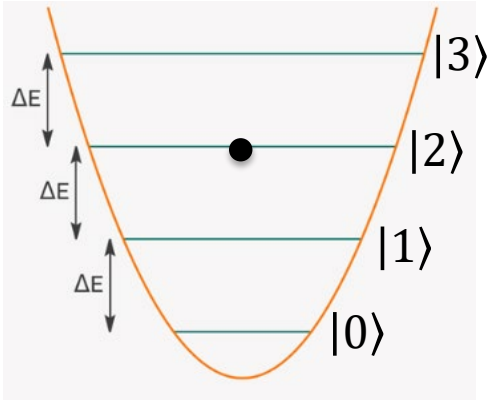
Second Milestone



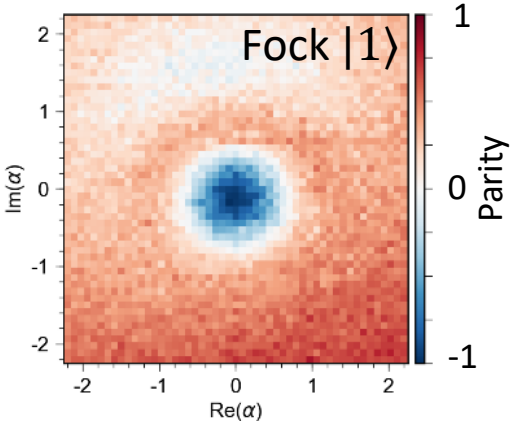
Prepare quantum states

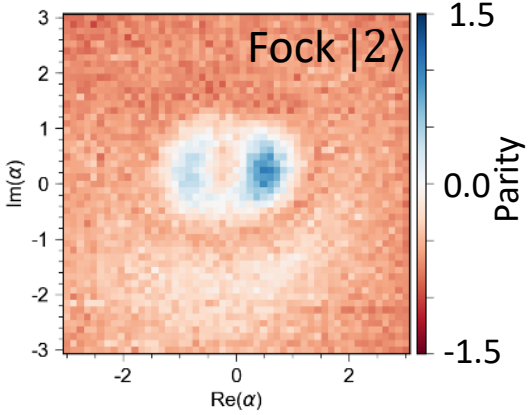






Wigner tomography





Multqudit Architecture

Crosstalk issues

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

All-to-all coupling

Moderate-Q cavities

High-Q 3D cavities

Transmon | Manipulator | Coupler | Storage

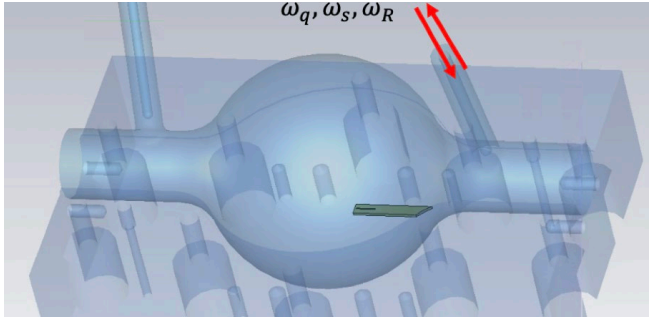
CPU

BUS

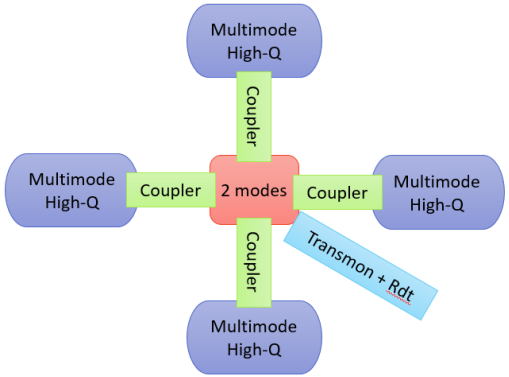
RAM

Outlook

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



- Scaling up
  - Develop modular architecture
  - Connect several modules



Find new applications

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Thank You!