



Advances in SRF cavity architectures for quantum computing

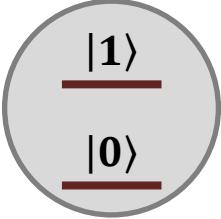
Tanay Roy

SQMS division, Fermilab

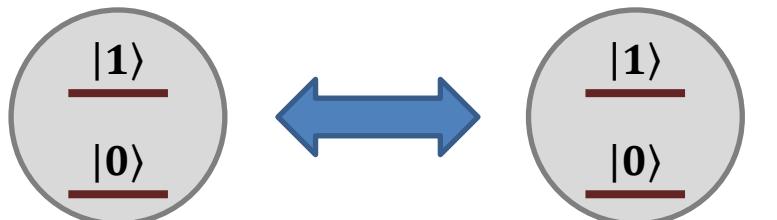
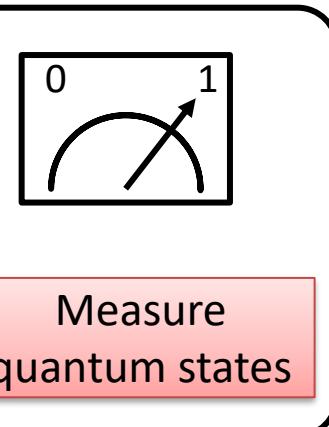
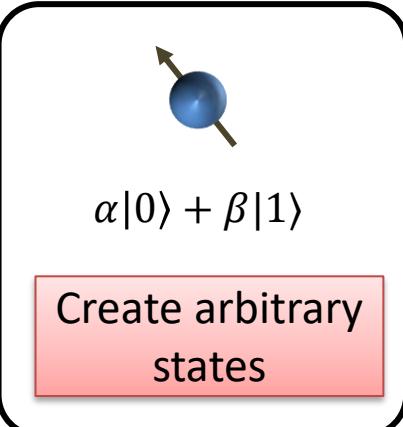
Quantum Technologies for Fundamental Physics Workshop, Erice, Italy
3 Sep 2023

Report number: FERMILAB-SLIDES-23-283-SQMS

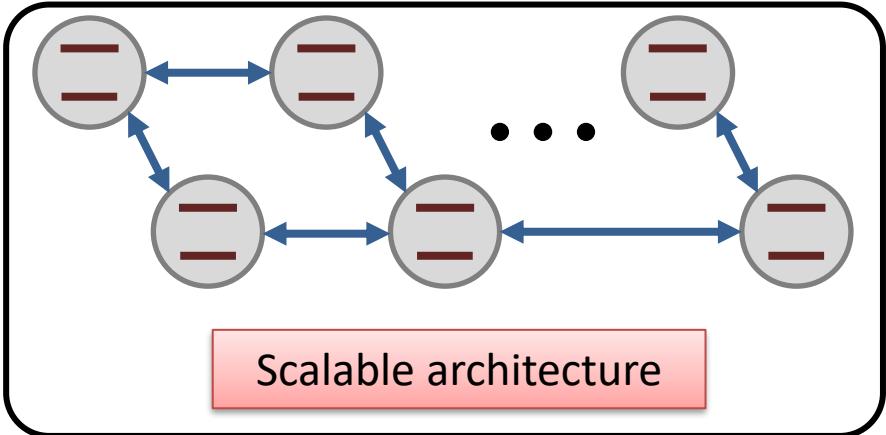
Basic Requirements for a Quantum Computer



Quantum two
level systems



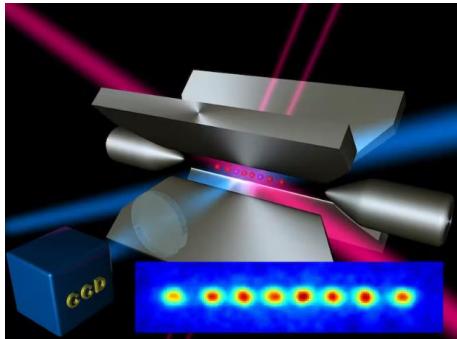
Couple multiple qubits



Scalable architecture

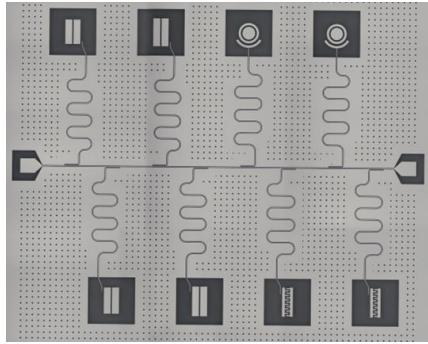
Different Platforms

Trapped ions



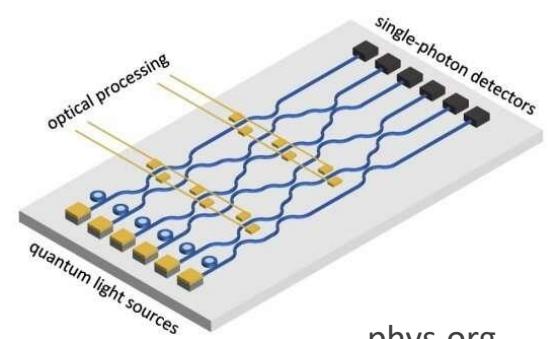
laserfocusworld.com

Superconducting circuits



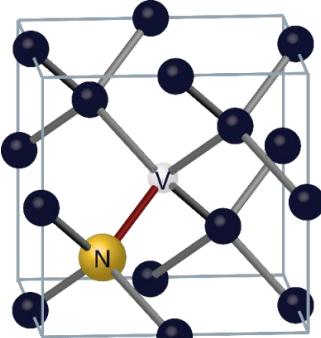
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Photonic crystals



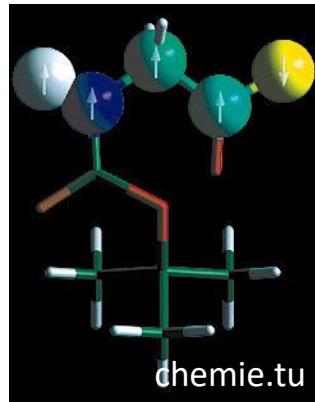
phys.org

NV centers



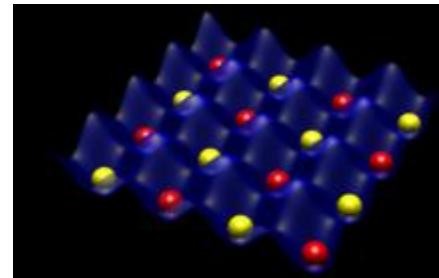
phys.org

NMR



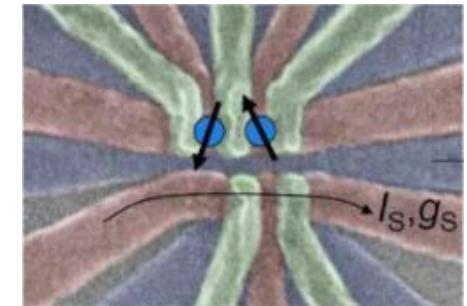
chemie.tu

Neutral atoms



NIST

Quantum dots

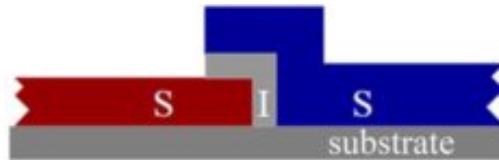


sciencemag.org

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SUPERCONDUCTING QUANTUM
MATERIALS & SYSTEMS CENTER

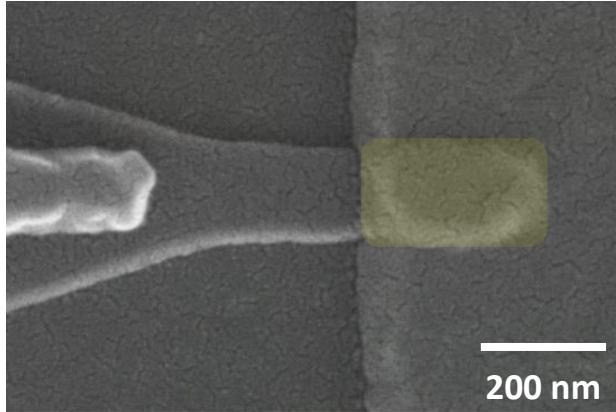
Superconducting Circuits



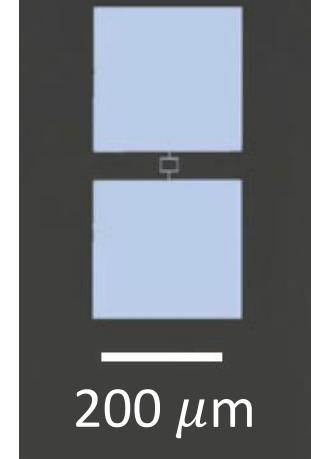
Josephson Junction

Lossless nonlinear inductor

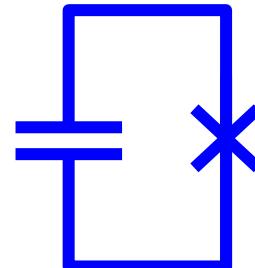
$$L_J(I) = \frac{\varphi_0}{(I_0^2 - I^2)^{1/2}}$$



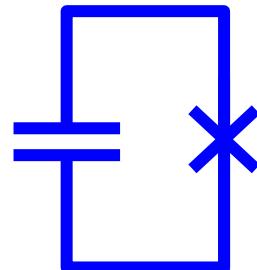
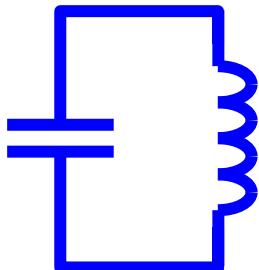
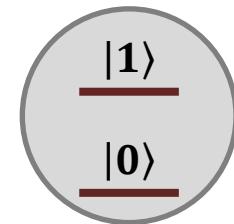
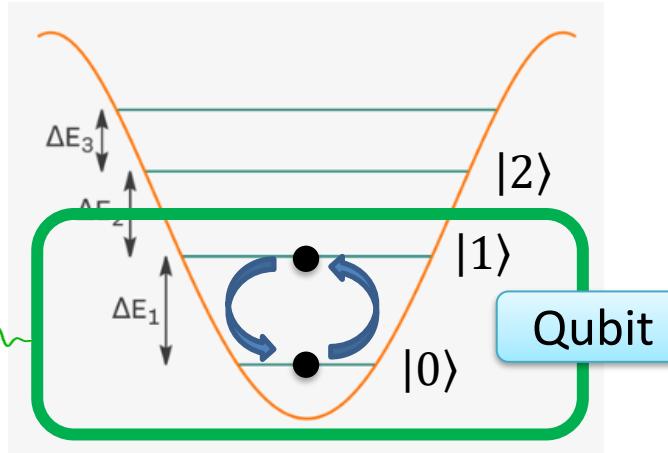
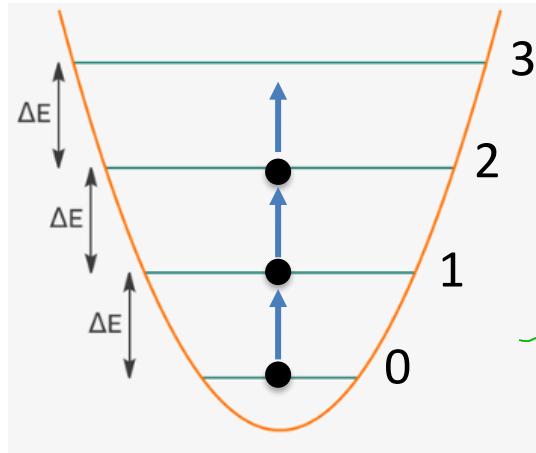
Transmon



Transmon



Transmon: Anharmonic Oscillator



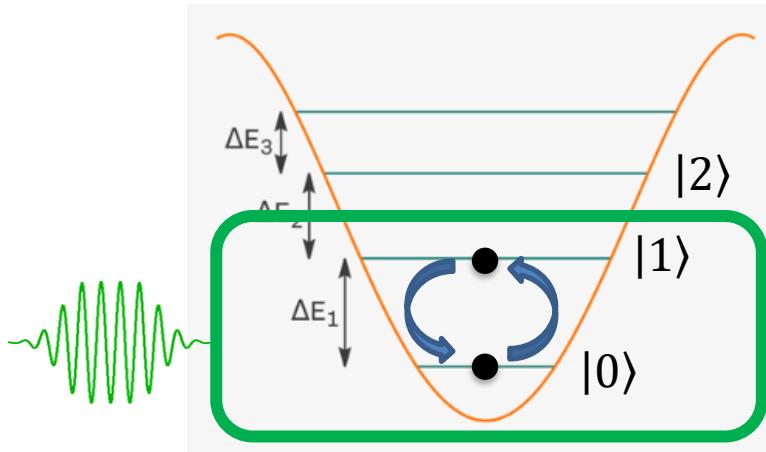
Operating Temperature

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

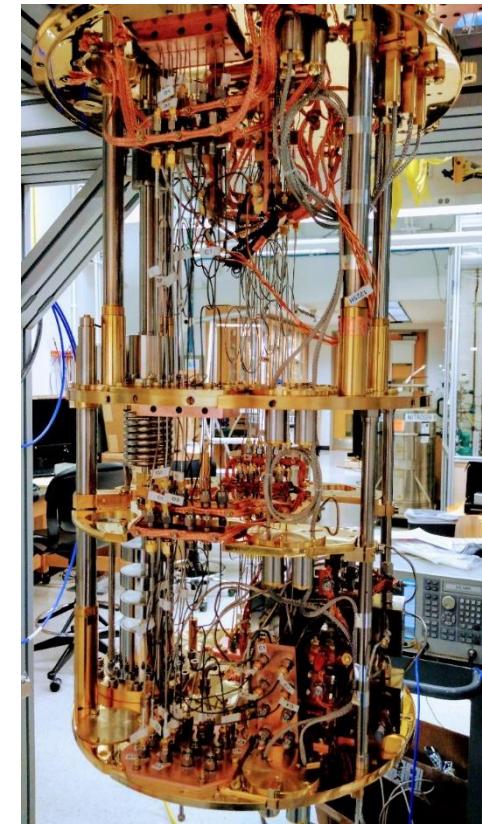
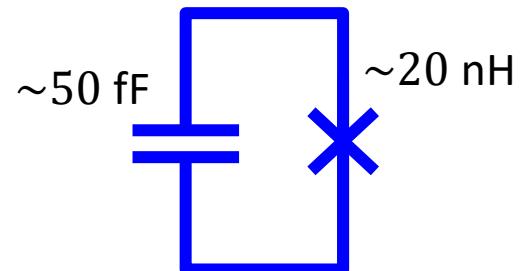
$\sim 5 \text{ GHz}$

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

20 mK $\sim 240 \text{ mK}$



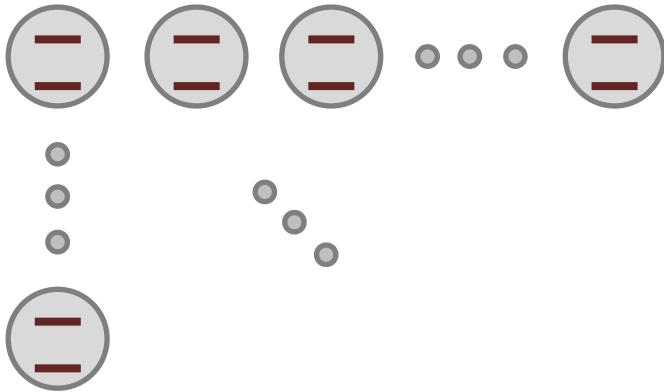
Anharmonic Oscillator



Dilution fridge $\sim 10 \text{ mK}$

Traditional Multi-qubit Architecture

Linear or planar geometry

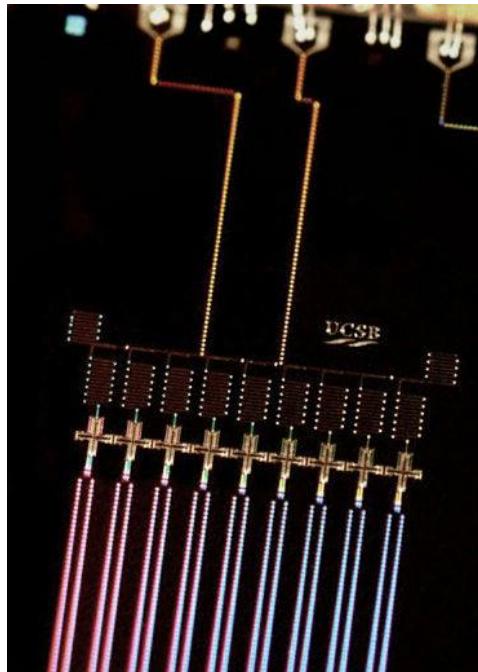


Computational space: 2^N

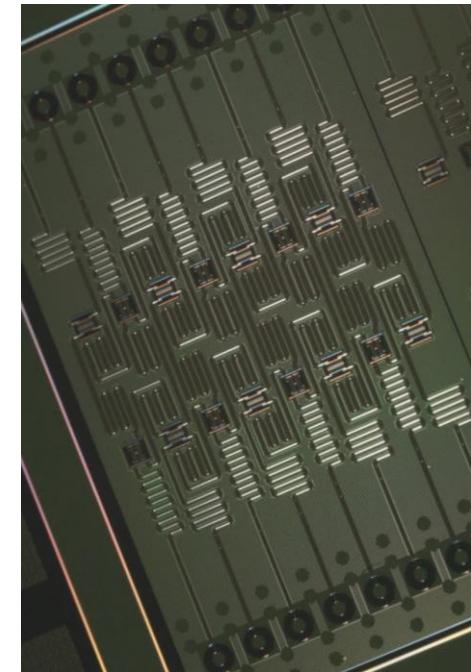
Can we do **better?**

Scaling: d^N , $d > 2$

Qudit



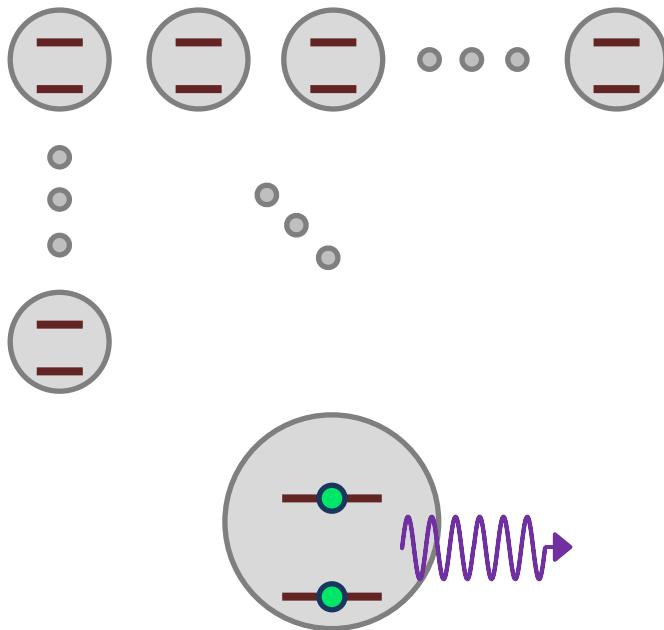
UCSB, Nature 519 (7541)



IBM

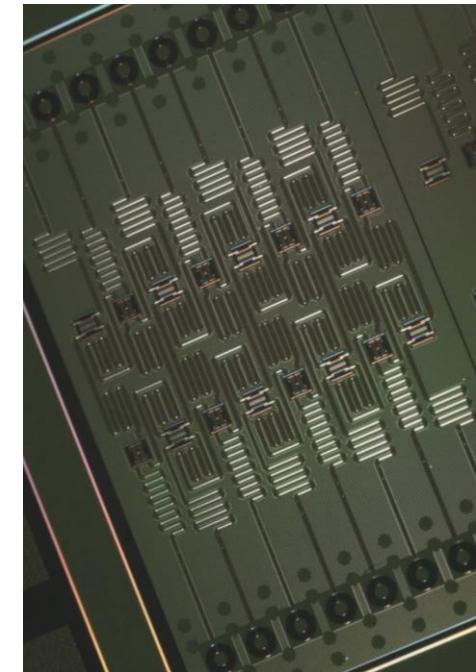
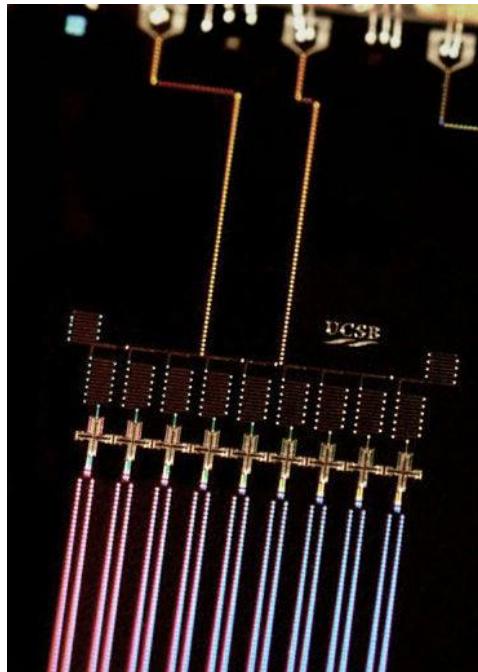
Problem of Relaxation

Linear or planar geometry



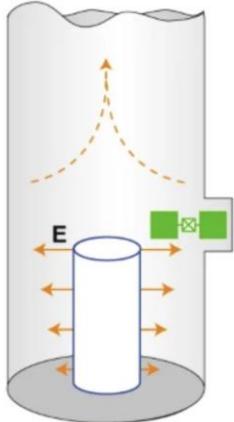
$$T_1 \sim 100 \mu\text{s}$$

Q: a few 10^6

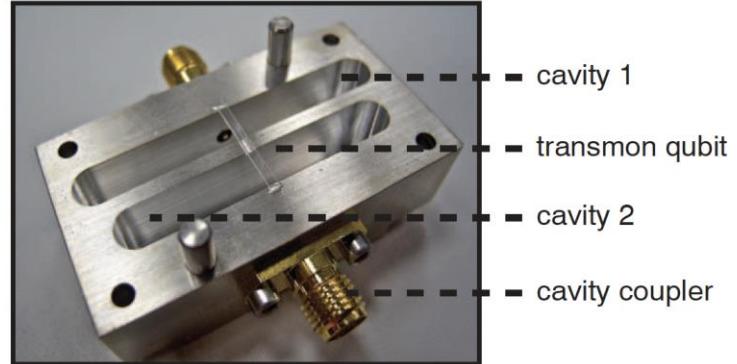


Can we do **better**?

Zoo of Cavities

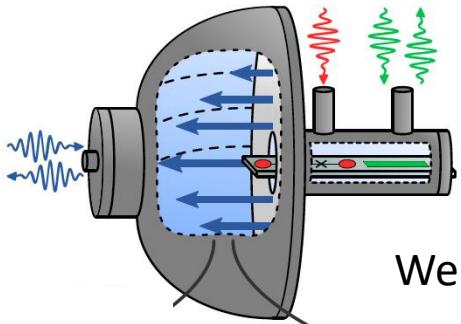


Nat. Phys. 16, 247



Science 342, 6158

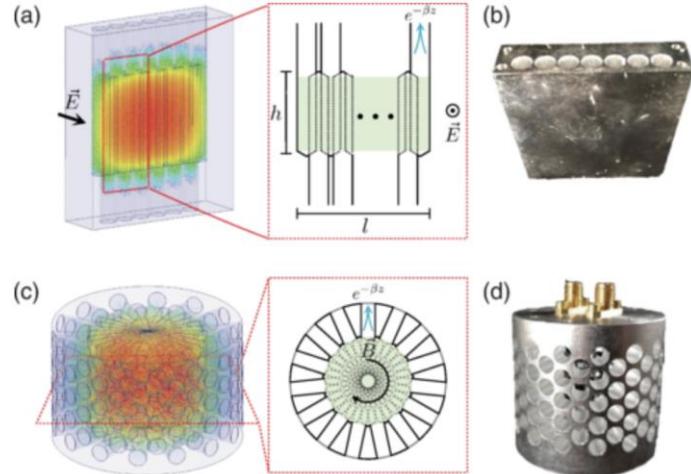
Yale, U. Pittsburgh



Weizmann

arXiv:2302.06442

Under
exploration



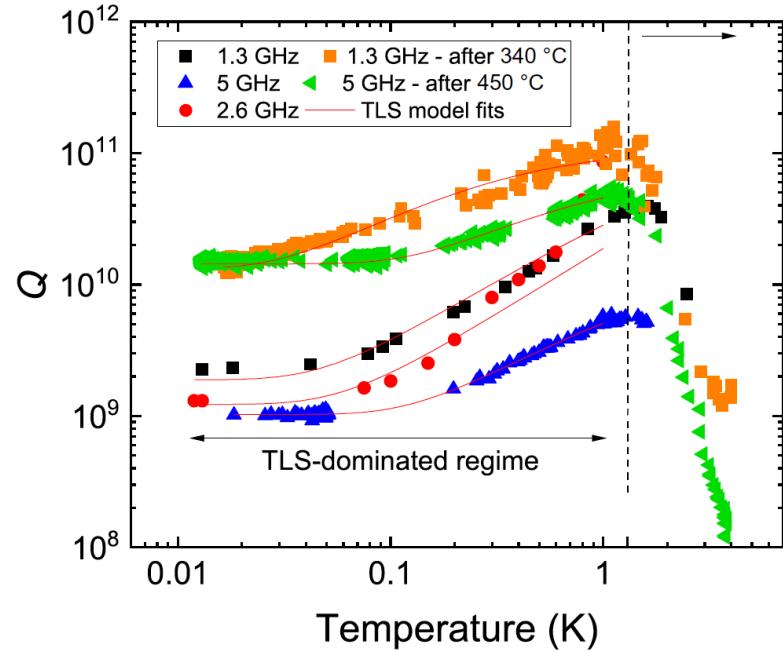
PRL 127, 107701

U. Chicago, Rutgers

High-Q 3D SRF Cavities



Romanenko et al. PRApplied 13, 034032

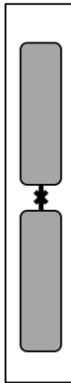


$$1.3 \text{ GHz SRF: } Q > 10^{11} \text{ at } 1 \text{ K} \quad \xrightarrow{\hspace{1cm}} \quad T_1 > 2 \text{ s}$$

$$5 \text{ GHz SRF: } Q > 10^{10} \text{ at } 10 \text{ mK} \quad \xrightarrow{\hspace{1cm}} \quad T_1 > 300 \text{ ms}$$

>1000 times better than transmons

High-Q 3D Cavities as Qudits



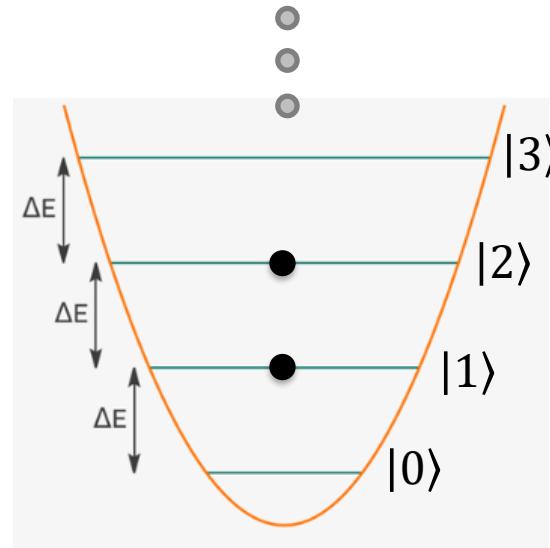
Romanenko et al. PRApplied 13, 034032

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

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

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

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

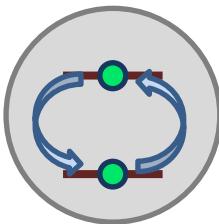
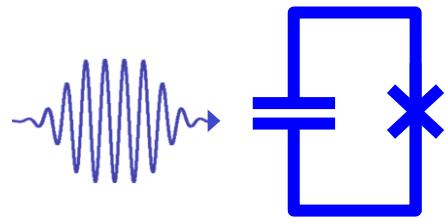


Qudit

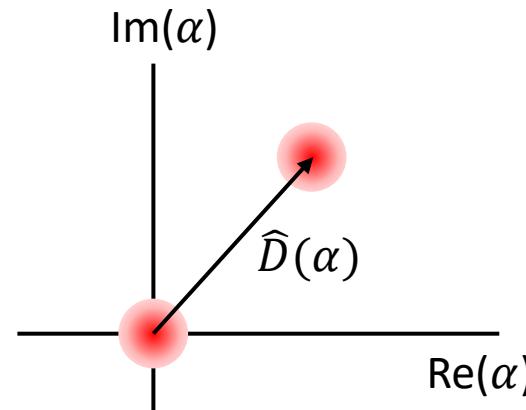
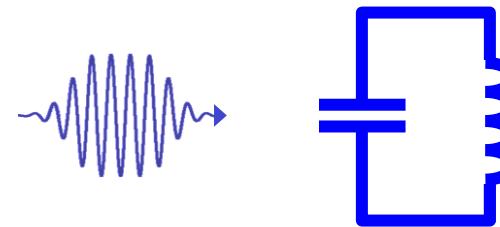
Still much better than transmon qubits

Transmon vs. Cavity Drive

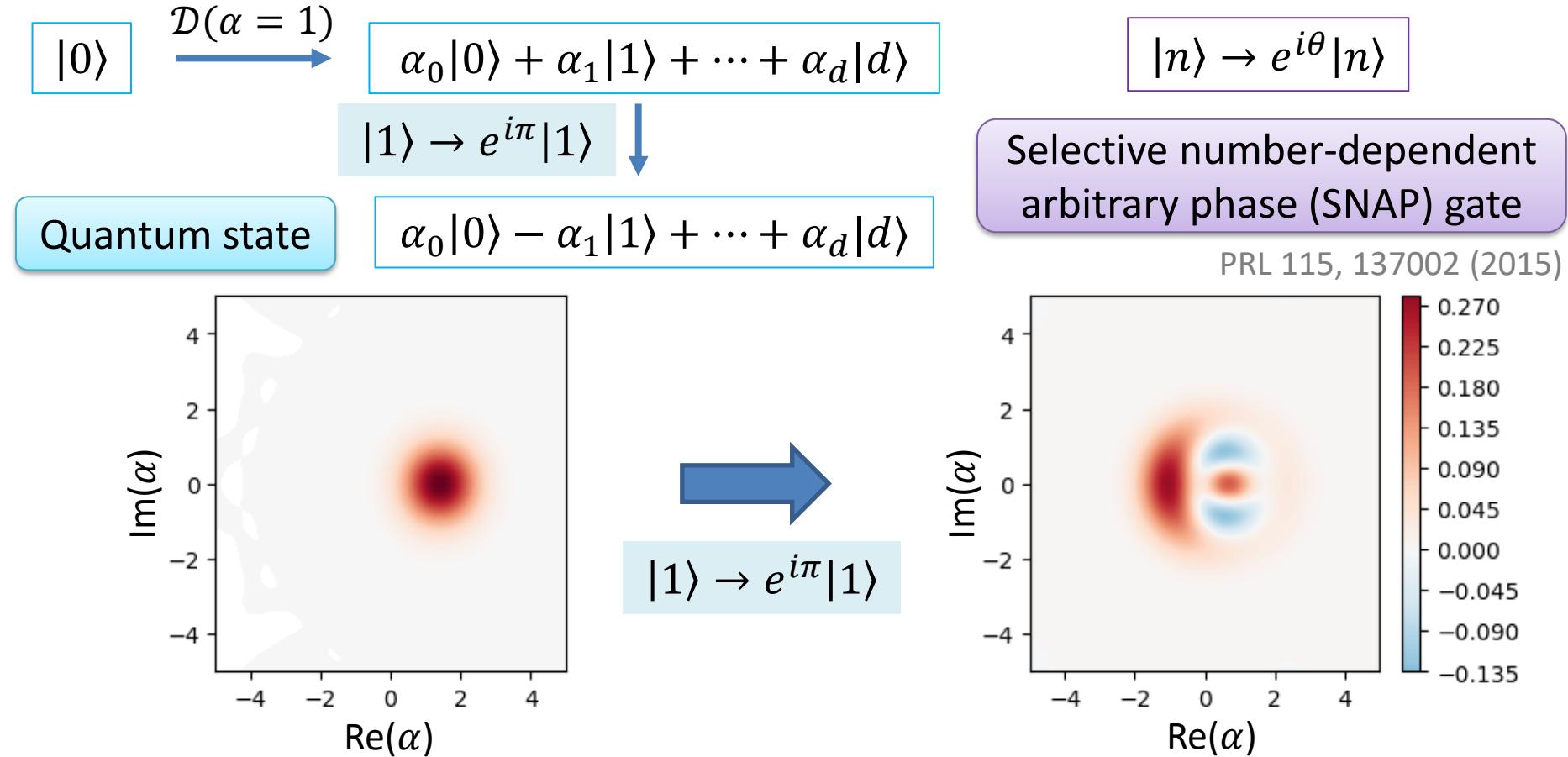
Qubit: $\alpha|0\rangle + \beta|1\rangle$



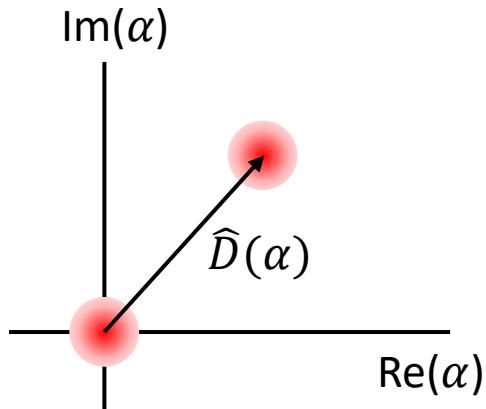
Qudit: $\alpha_0|0\rangle + \alpha_1|1\rangle + \cdots + \alpha_d|d\rangle$



Qudit Operation



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

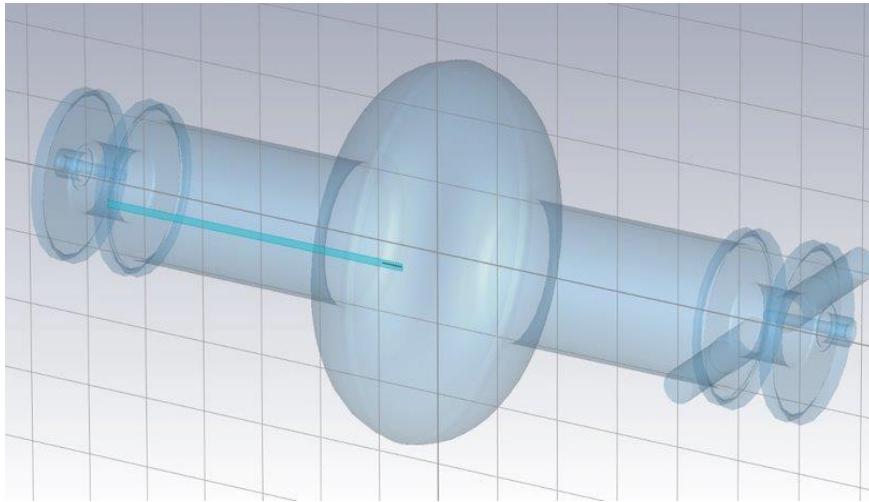
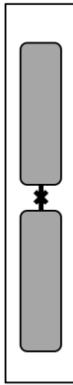


Universal control

Unconditional operation on cavity

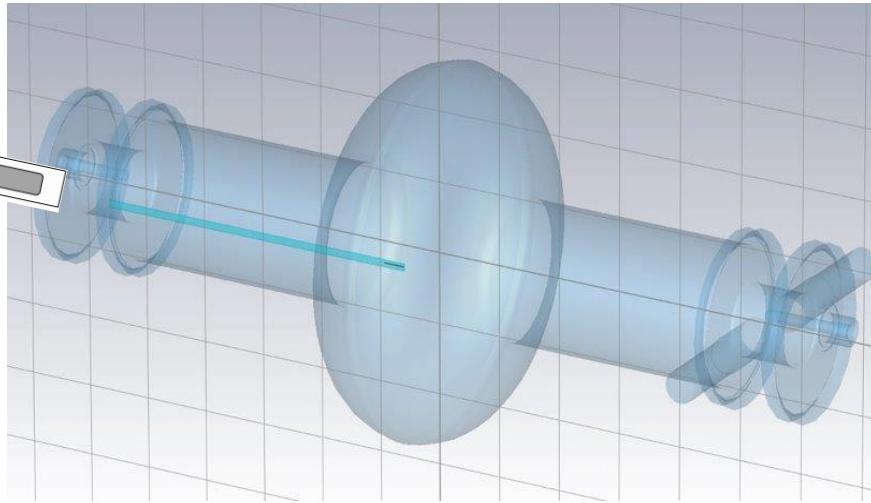
Conditional operation on cavity enabled by a transmon

First Milestone



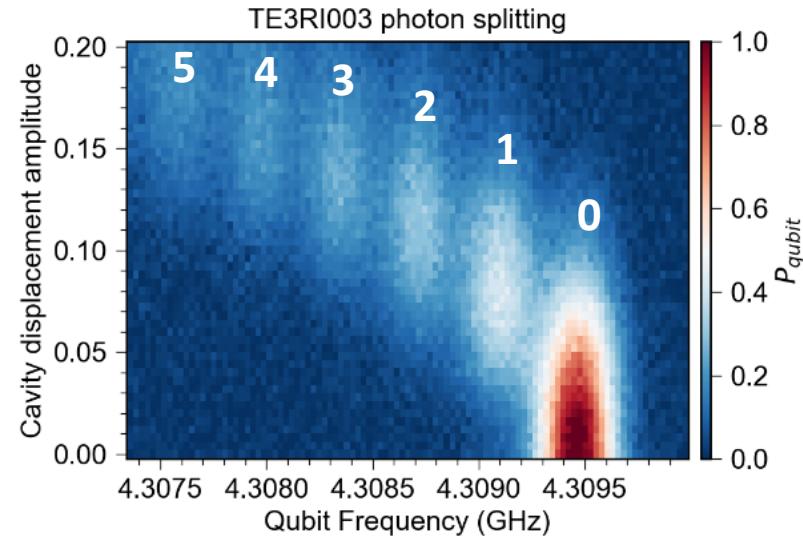
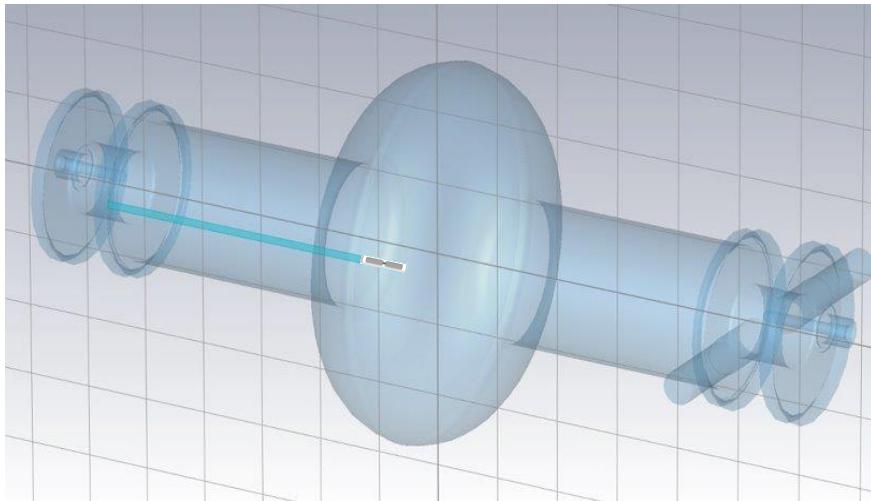
Incorporate Transmon into a
TESLA cavity

First Milestone



Incorporate Transmon into a
TESLA cavity

First Milestone

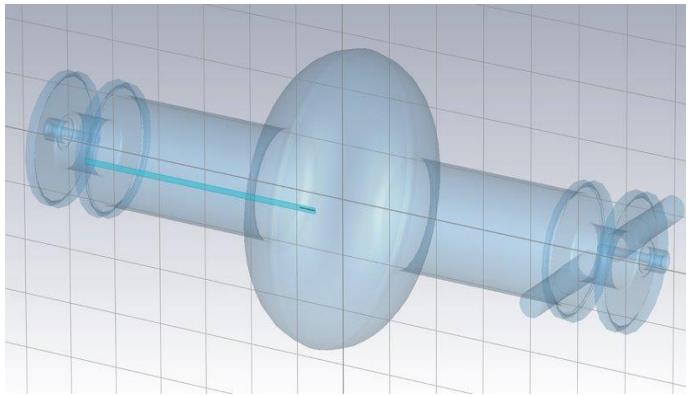


Incorporate Transmon into a
TESLA cavity

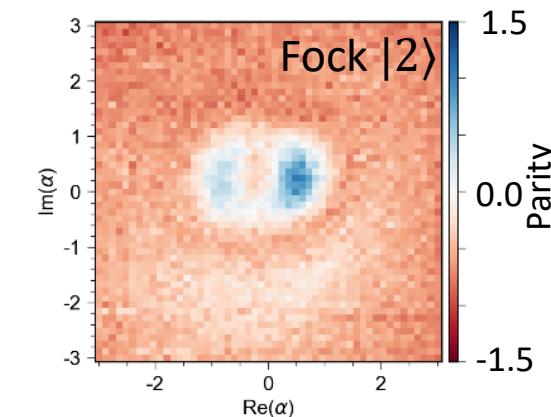
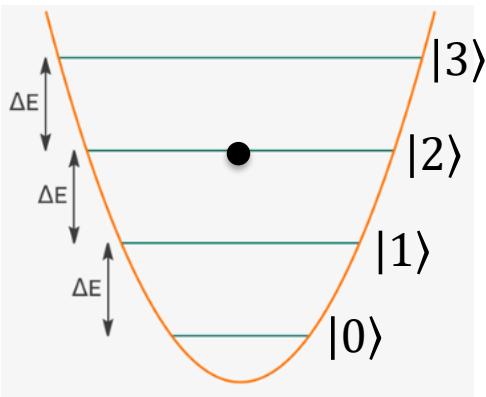
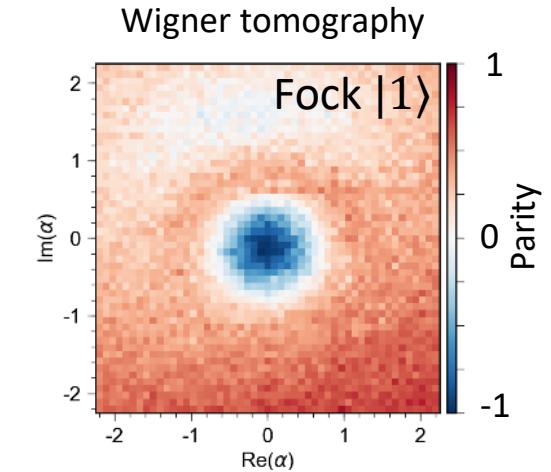
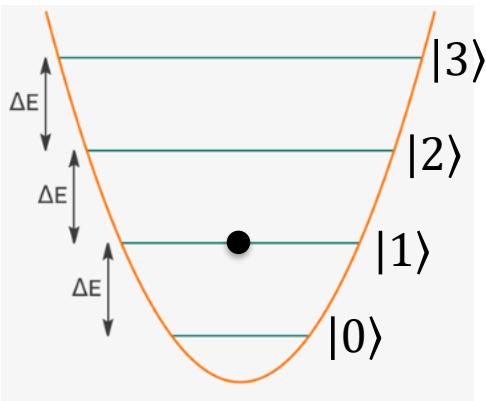
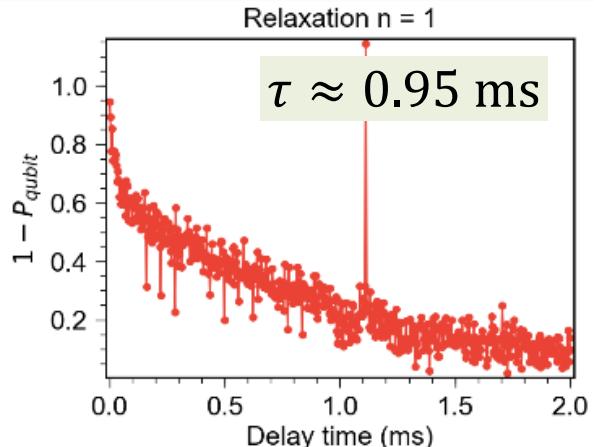
Achieved photon counting

Key to Dark Matter detection

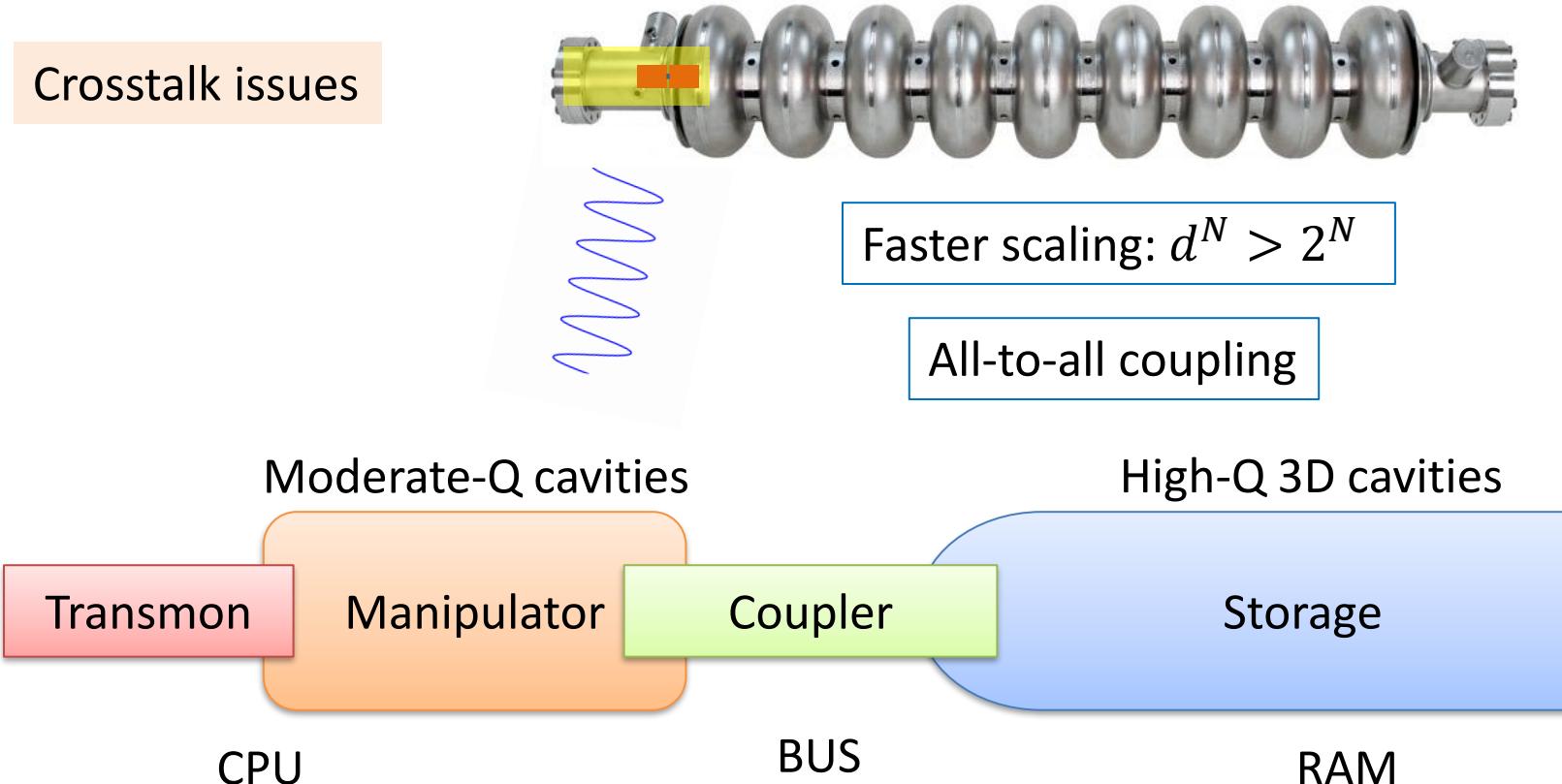
Second Milestone



Prepare quantum states



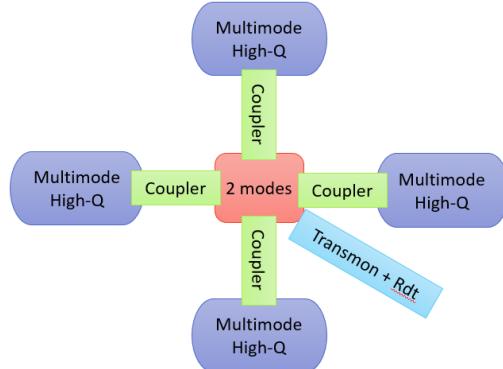
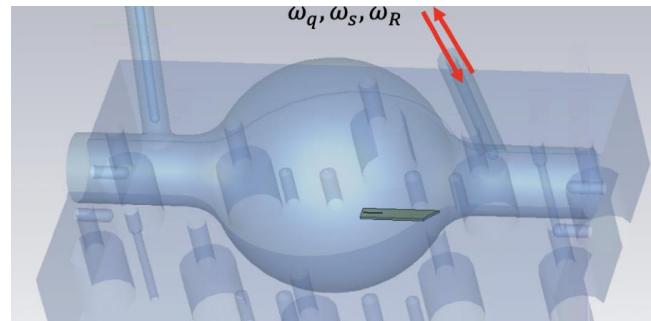
Multqudit Architecture



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

Brand New SQMS Facility at Fermilab



Tanay Roy - Fermilab

Thank You!



Tanay Roy - Fermilab