Building a quantum computing architecture using 3D superconducting cavities

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ASET Colloquium, TIFR Mumbai

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Five DOE National Quantum Centers

The centers bring together multidisciplinary collaborations of more than 1,500 experts, including 600 students and postdocs, across over 115 academic, industry, national labs institutions in more than 23 states and DC.

- Lead DOE national laboratory
- National laboratory or science institution
- Technology company
- University

SQMS

Superconducting Quantum Materials & Systems Center

A DOE National QIS Research Center

36
Partner Institutions

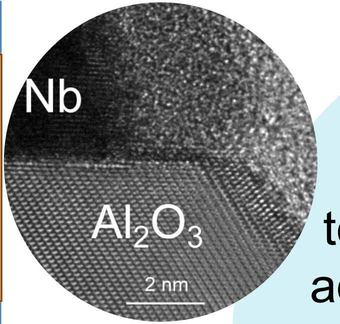
550+
Collaborators

SQMS brings together hundreds of experts from more than 30 DOE national labs, academia, industry and other federal and international entities to bring transformational advances in QIS

Advance QIS building on accelerator expertise

Abate qubit losses

Fundamental science of materials and nanostructures to advance superconducting qubit coherence



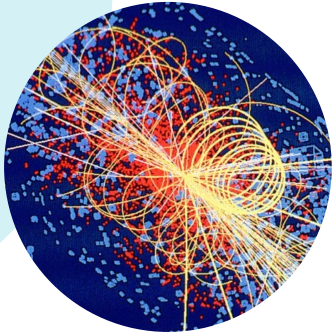
High coherence quantum systems

Record coherence microwave cavity devices and quantum interconnects for high fidelity scaling of quantum computers and sensors

SQMS Mission:
to bring transformational advances in development and deployment of high coherence superconducting quantum systems.

Efficient cryogenic scaling

Large scale low temperature cryogenic technology, distribution systems for scaling efficiently to large quantum systems



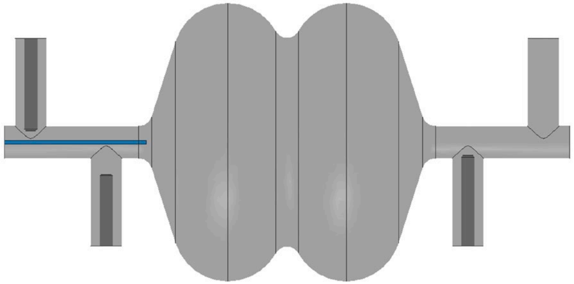
Simulation and sensing

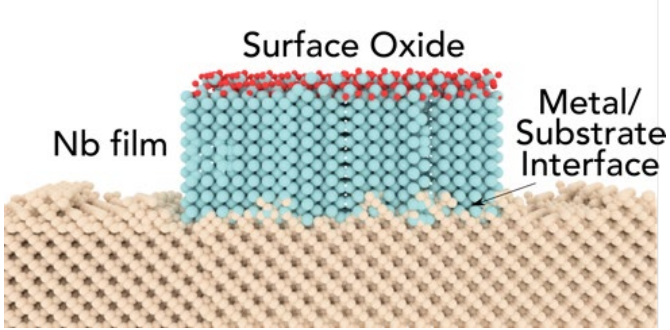
Theory and simulation to solve high energy and condensed matter physics problems on quantum platforms

SQMS brings decades of DOE investments in accelerator facilities and technologies in a ***government-industry-academia*** *strategic partnership framework for broad impacts*

Talk Outline

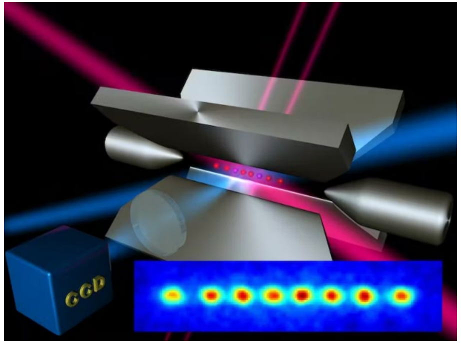
- Introduction to SQMS Center goals
- Development of a bosonic QPU
  - Integration of a single-cell cavity
  - Development of two-mode system
  - Error-resilient state preparation & entanglement
- Strategies for improvement and scaling up
  - Mitigate TLS losses in surface oxide
  - Improve coherence of ancilla transmons
  - Building larger systems





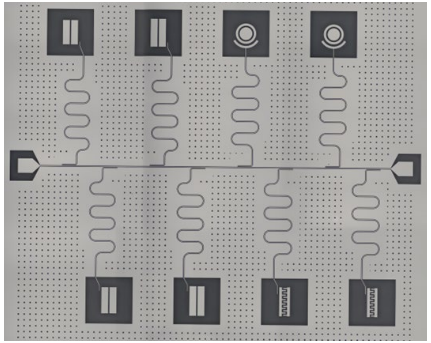
Different Platforms

Trapped ions



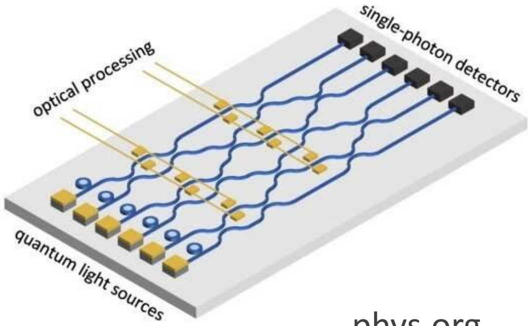
laserfocusworld.com

Superconducting circuits



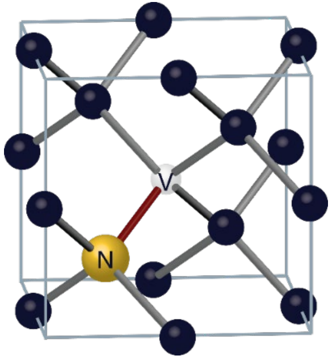
SQMS

Photonic crystals



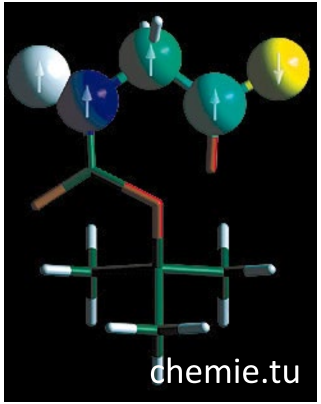
phys.org

NV centers



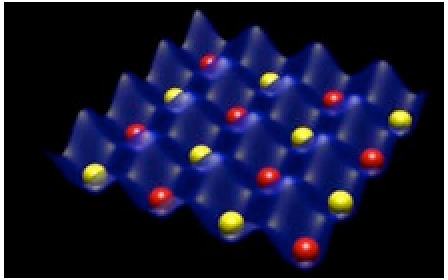
phys.org

NMR



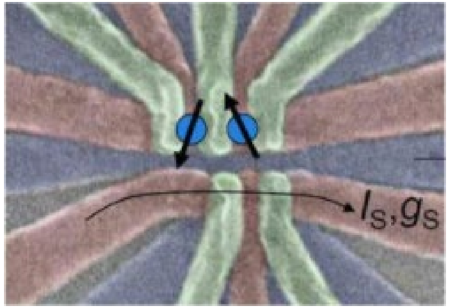
chemie.tu

Neutral atoms



NIST

Quantum dots



sciencemag.org

Physics Nobel Prize 2025

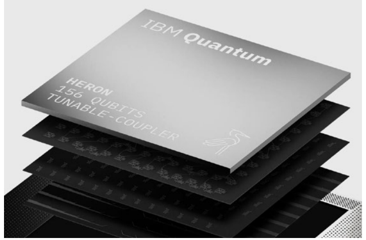
Scientific background

John Clarke	Michel H. Devoret	John M. Martinis

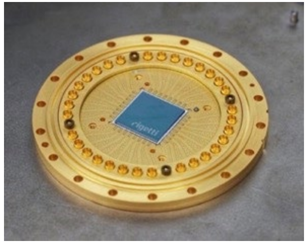
"FOR THE DISCOVERY OF MACROSCOPIC QUANTUM MECHANICAL TUNNELLING AND QUANTISATION IN AN ELECTRICAL CIRCUIT"

Superconducting platforms

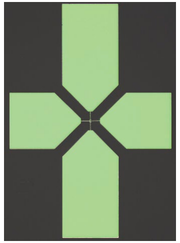
Two-dimensional (2D)



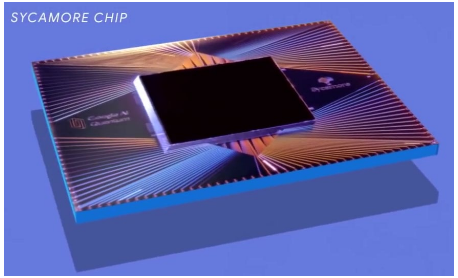
IBM



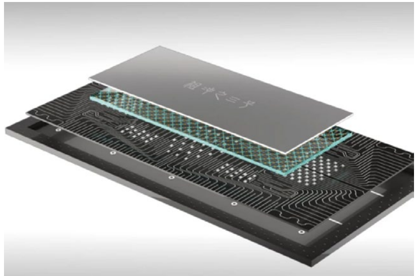
Rigetti



TIFR

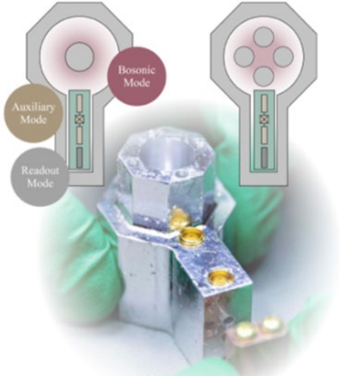


Google

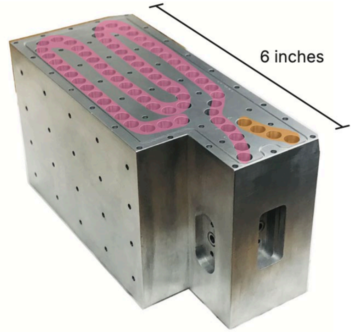


USTC, China

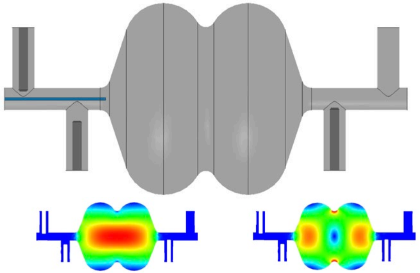
Three-dimensional (3D)



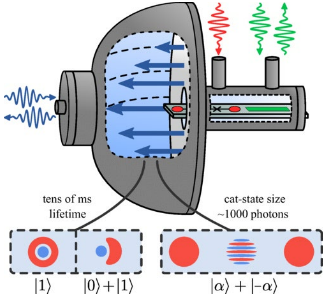
Nord Quantique



Rutgers University

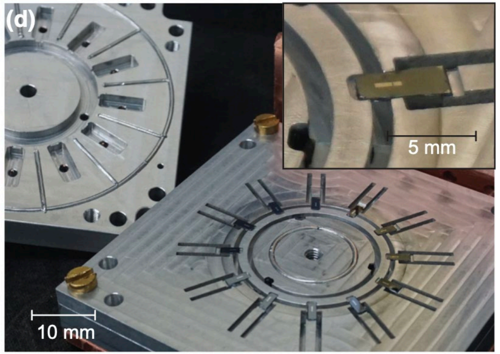


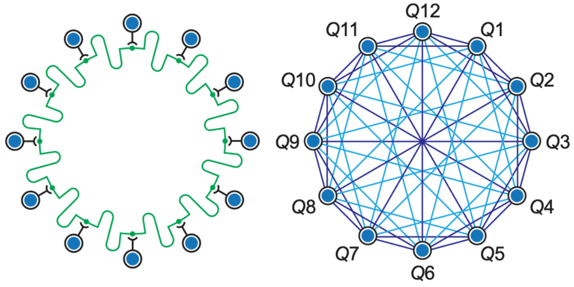
SQMS



Weizmann Inst.

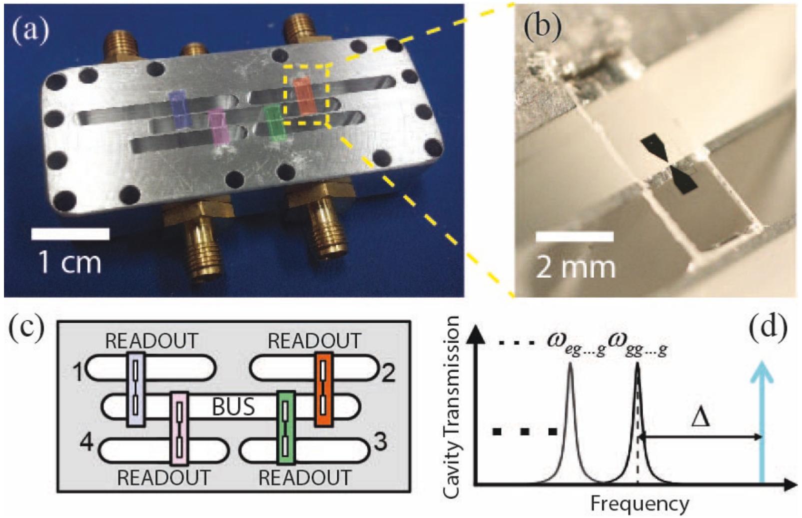
Superconducting platforms





TIFR

PRAppl. 16, 024018 (2021)



IBM

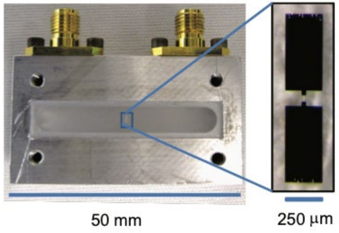
PRL 117, 250502 (2016)

Information stored in 2D circuits

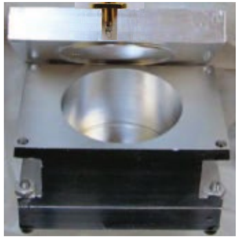
Hybrid 2D-3D or Semi 3D

Geometry optimization

Pillbox	Cylindrical	Stub	Flute	Elliptical

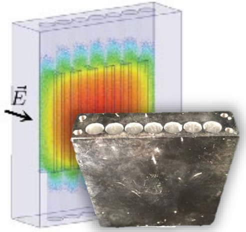


PRL **107,** 240501

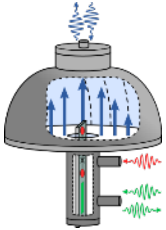


APL **116,** 154002

APL **102,** 192604

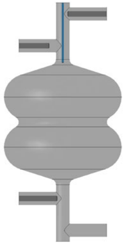


PRL **127,** 107701



PRX Quantum **4,** 030336

Phys. Rev. App. **13,** 034032



arxiv: 2506.03286

Vacuum is lossless

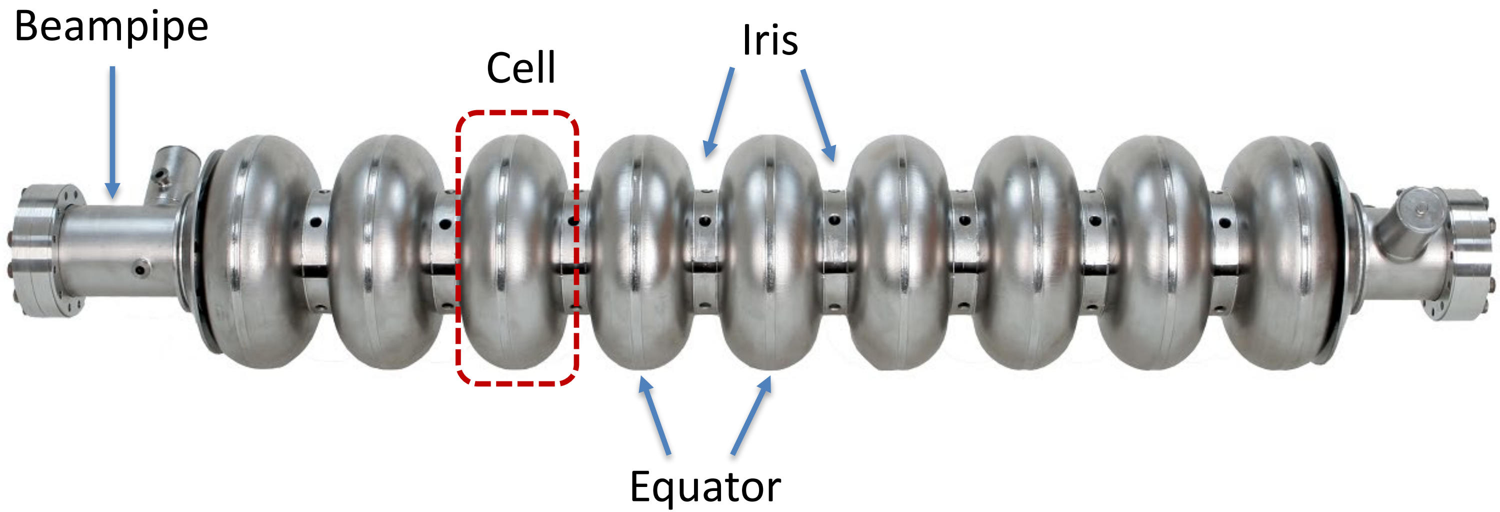
Major loss source: surface

Minimize surface to volume ratio

} Spherical cavity

Practical geometry: Elliptical

Particle accelerator cavities



9-cell TESLA cavity

TESLA: TeV-Energy Superconducting Linear Accelerator

1.3 GHz

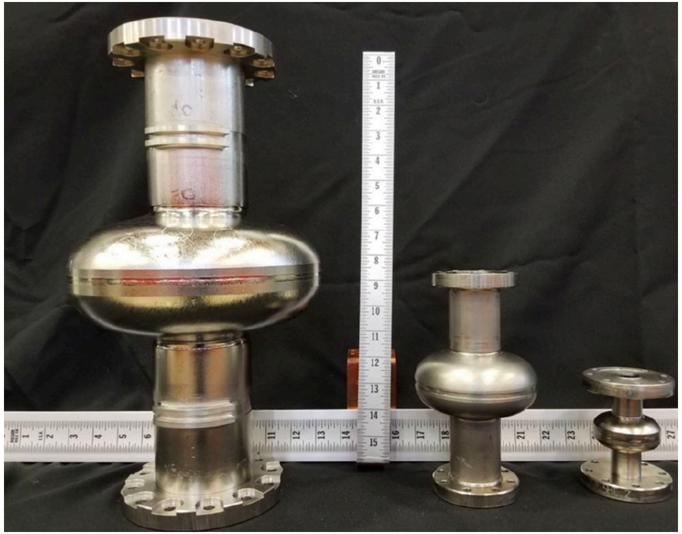
Pure Niobium

At ~1.5K: $Q_0 > 10^{10}$

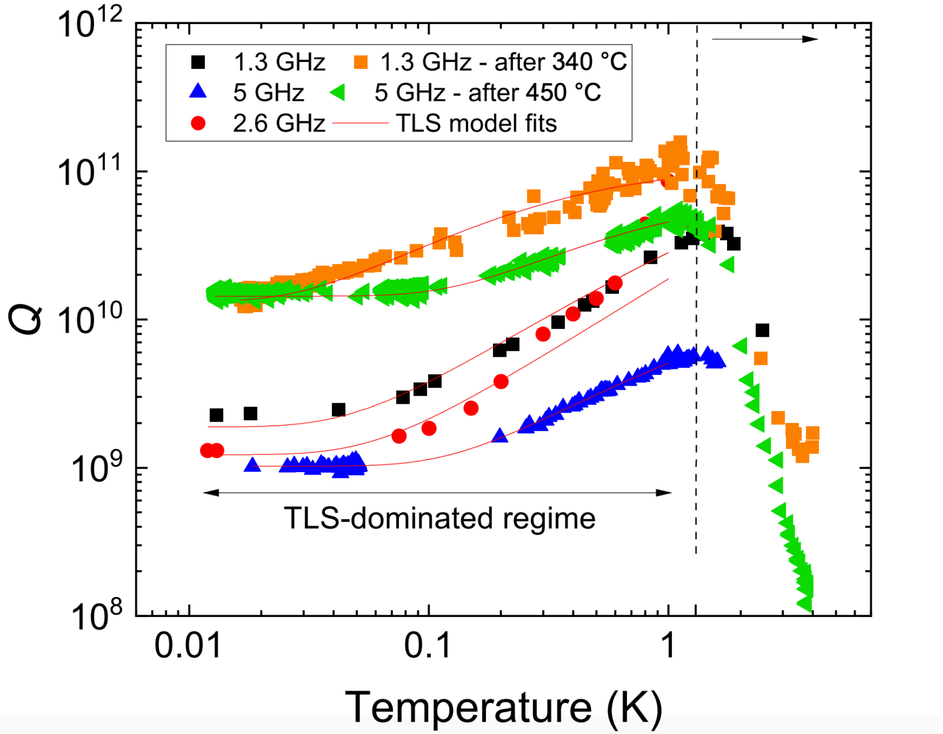
Good for quantum applications?

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

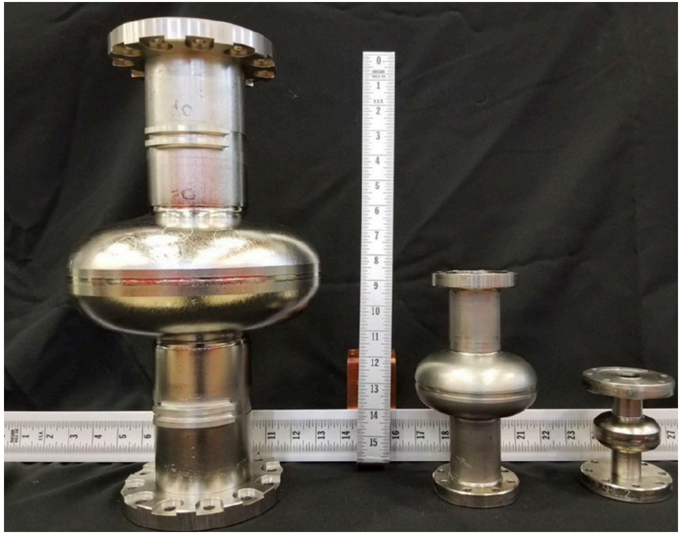
Q_0 of single-cell TESLA cavities



A. Romanenko et al., PRApplied **13**, 034032 (2020)



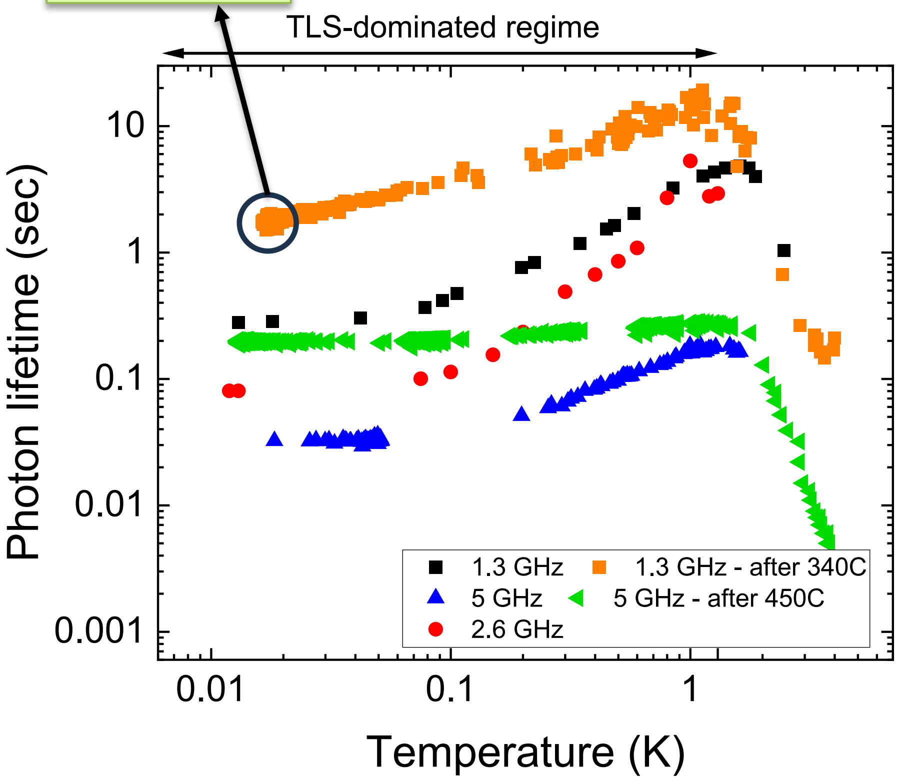
Q_0 of single-cell TESLA cavities



A. Romanenko et al., PRApplied **13**, 034032 (2020)

Explore TESLA-style cavities

$T_1 > 1$ sec



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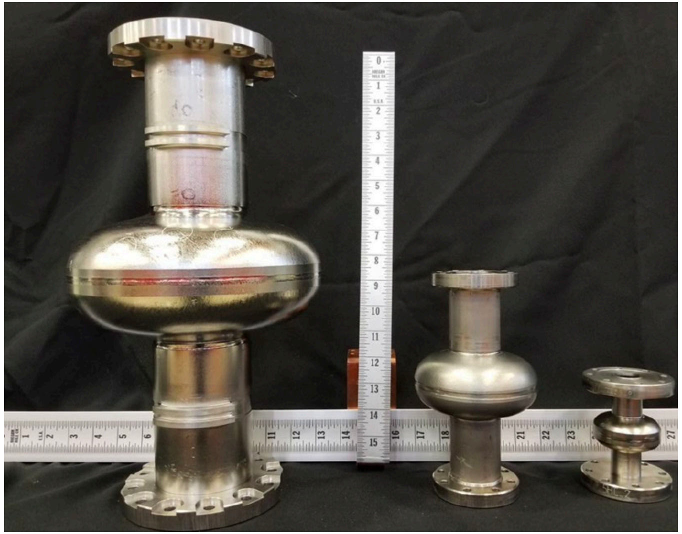
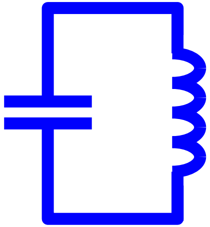
Energy eigenstates

Harmonic oscillators

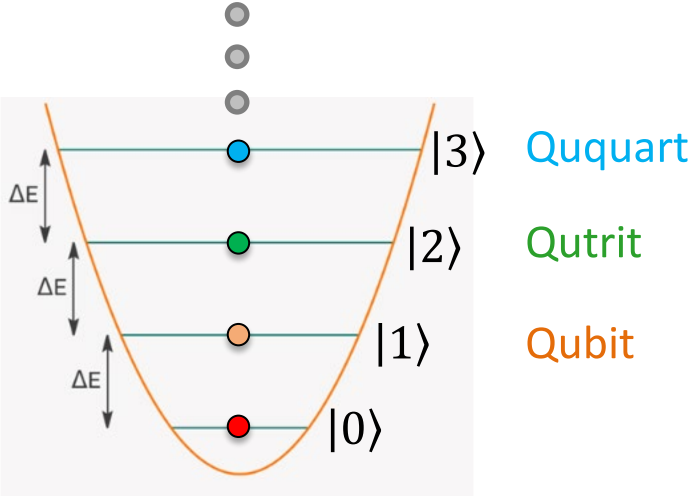


A. Romanenko et al., PRApplied **13**, 034032 (2020)



Explore TESLA-style cavities

Qudit

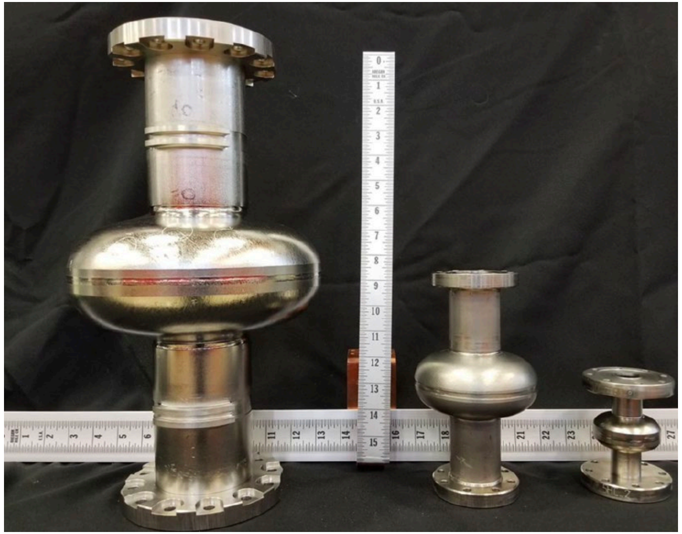


Quantum d-level system

Needs nonlinear ancillary components

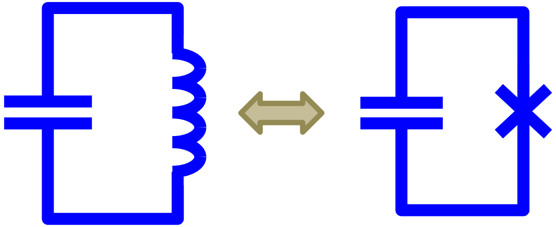
Energy eigenstates

Harmonic oscillators

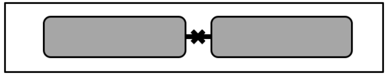


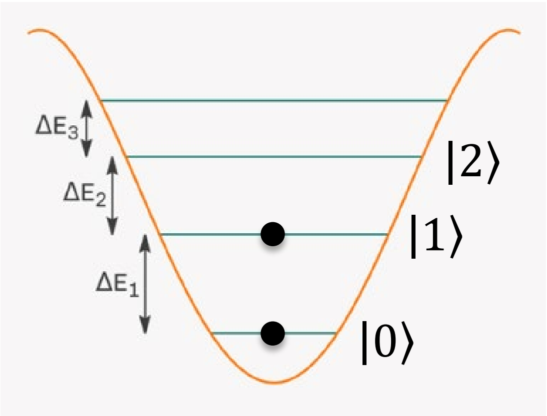
A. Romanenko et al., PRApplied **13**, 034032 (2020)

Explore TESLA-style cavities



Transmon

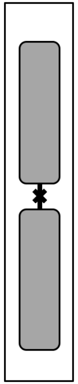


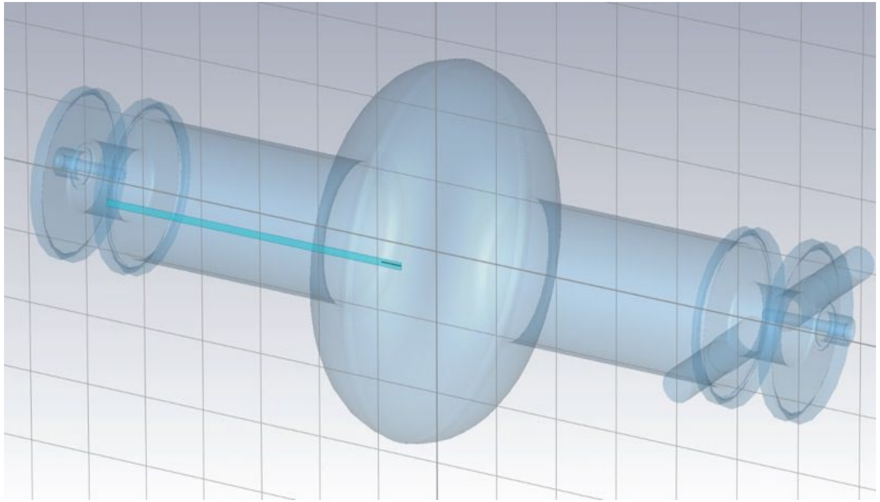


J. Koch et al., PRA **76**, 042319 (2007)

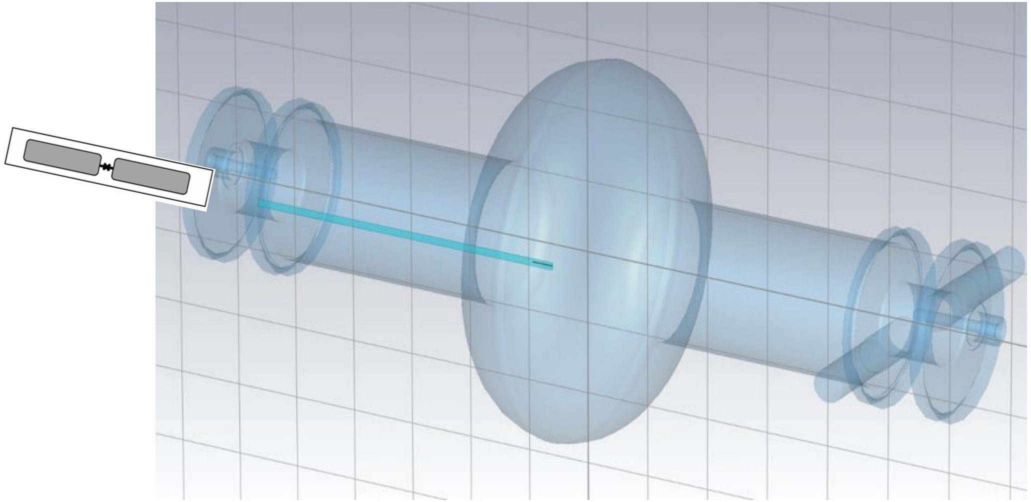
Needs nonlinear ancillary components

Incorporating transmon into TESLA cavity

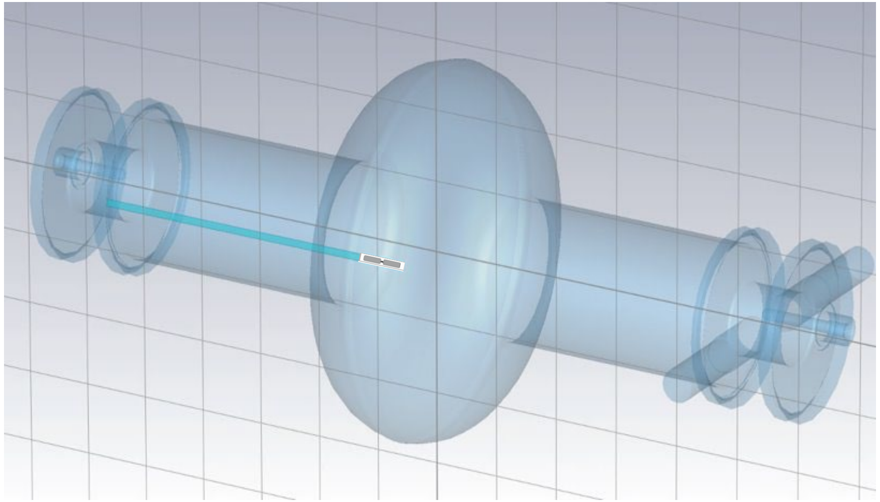


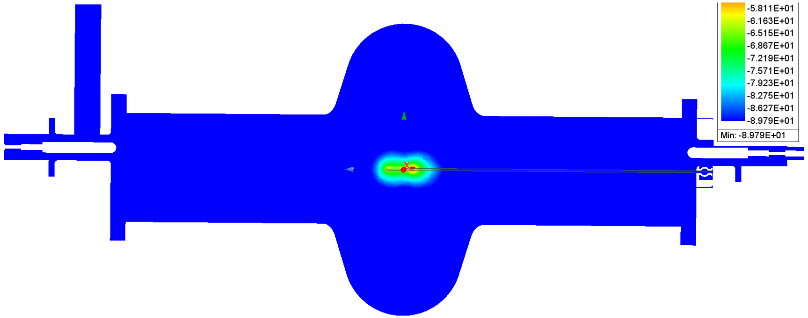


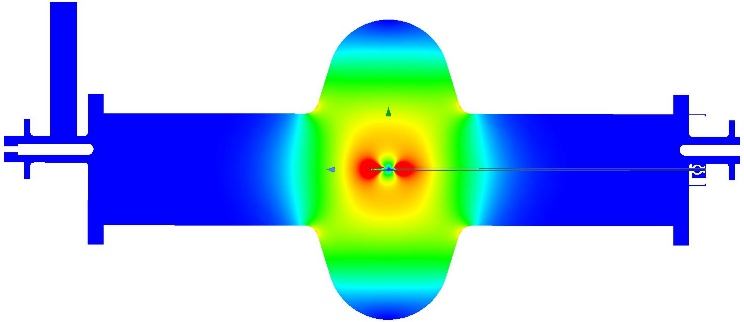
Incorporating transmon into TESLA cavity



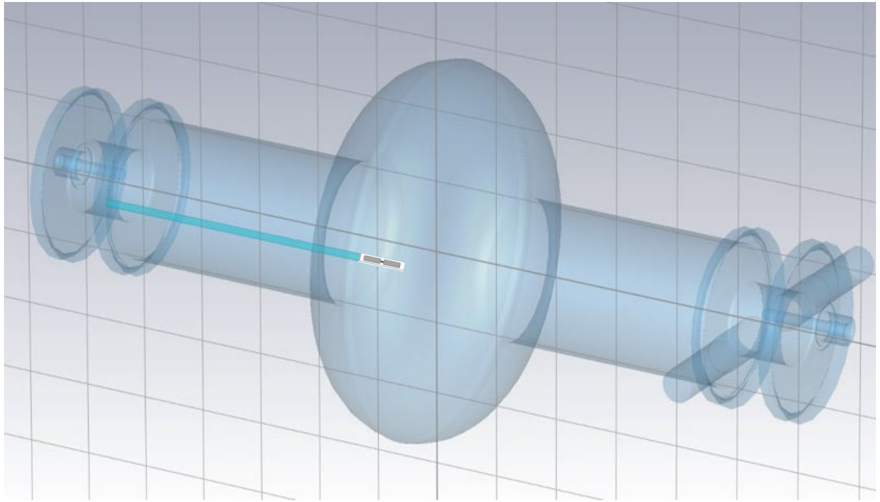
Incorporating transmon into TESLA cavity

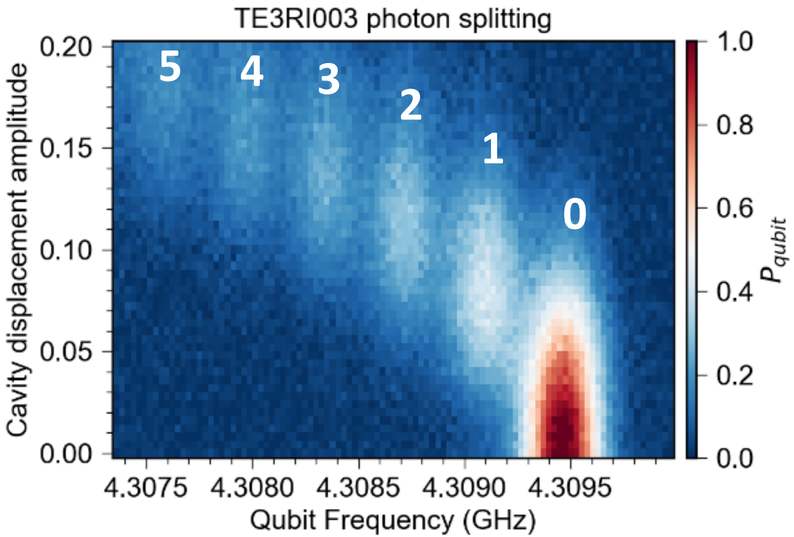






Incorporating transmon into TESLA cavity

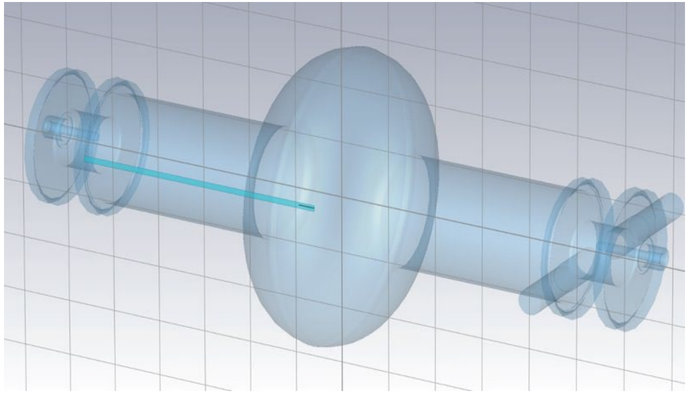




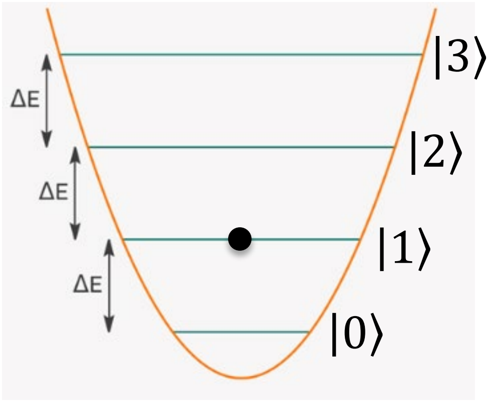
Qubit spectroscopy with coherent states

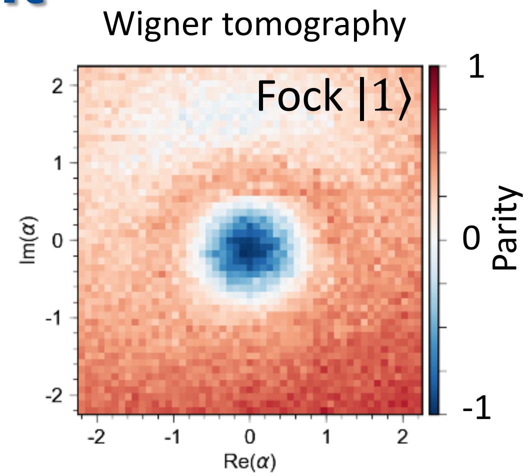
Achieved photon counting

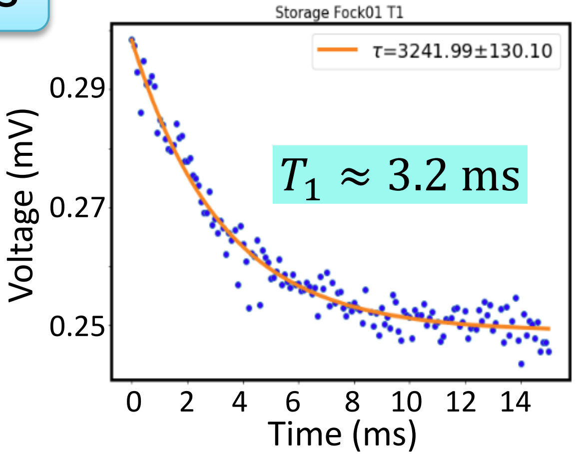
Coherence measurement

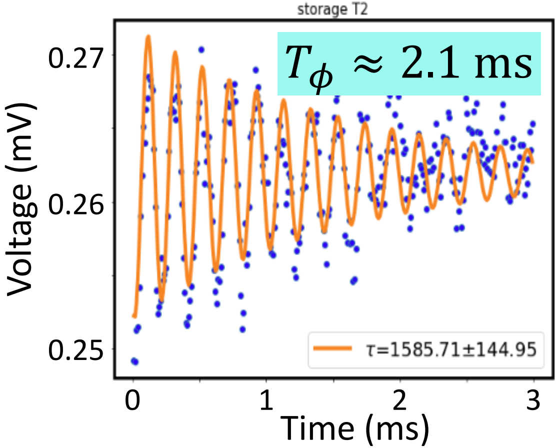


Prepare quantum states

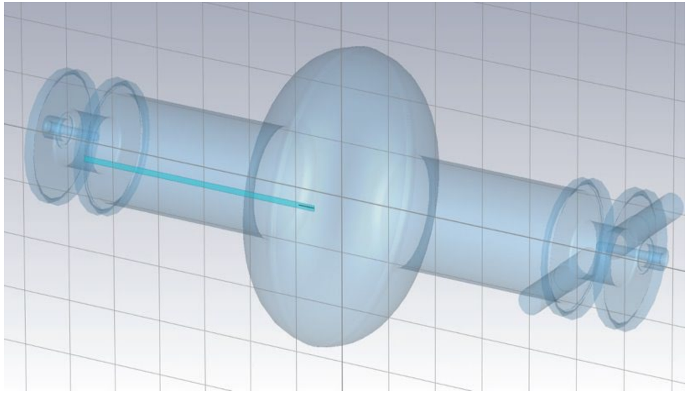








Fock state preparation



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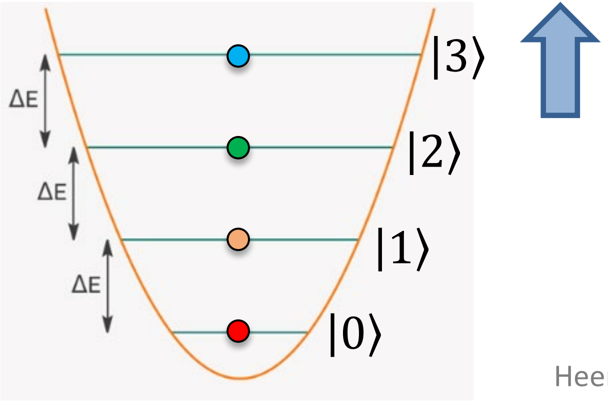
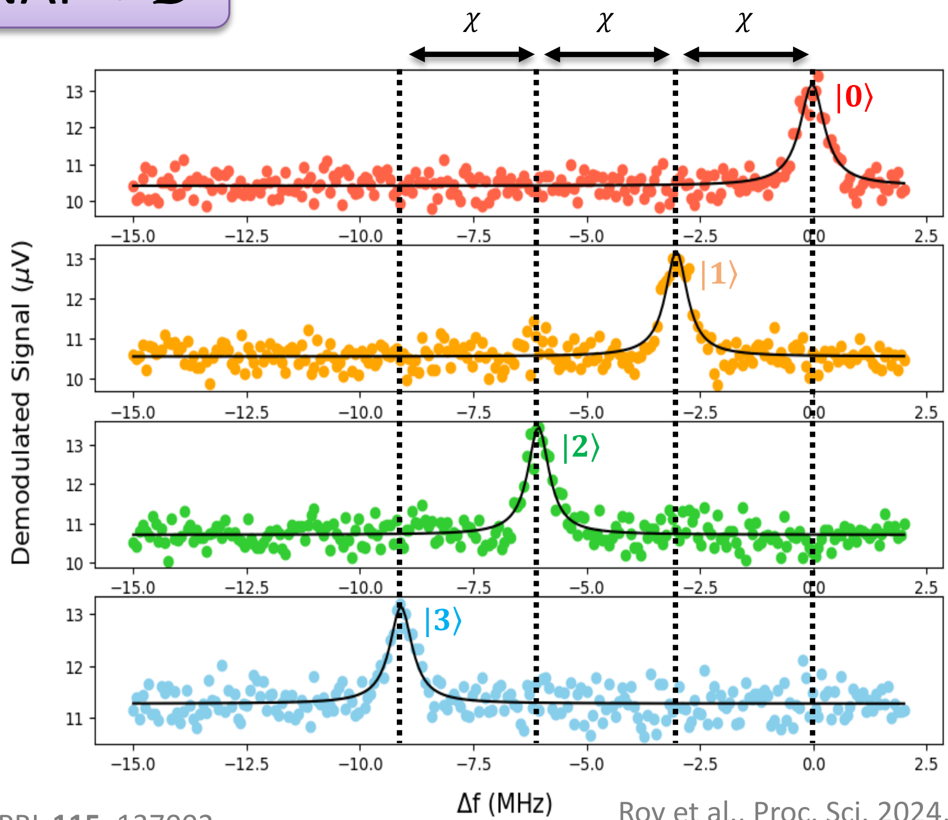


SNAP + $\mathcal{D}$

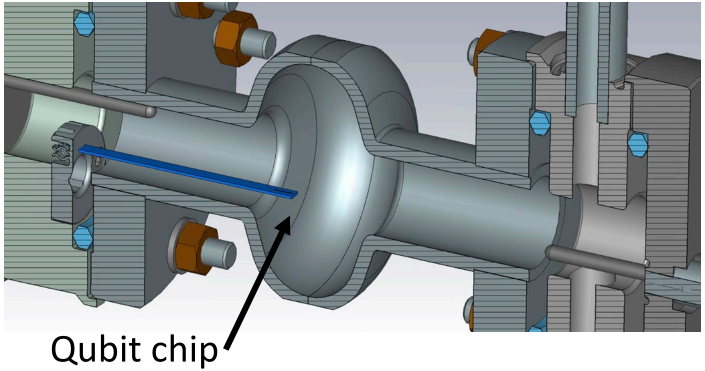
Qubit spectroscopy



Heeres et al., PRL **115**, 137002

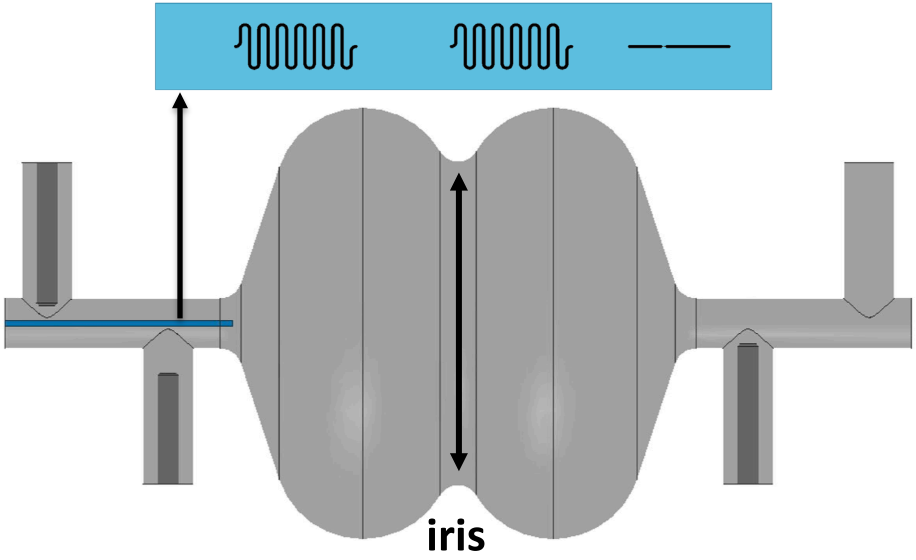
Roy et al., Proc. Sci. 2024, 127

Flaws of the single-cell cavity



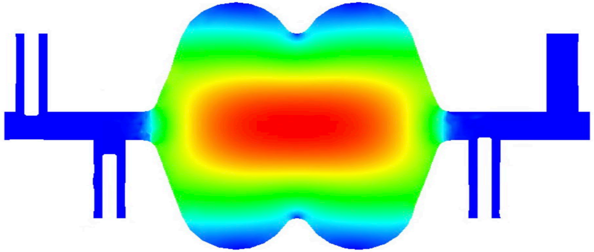
1. Cavity T_1 reduction (30 ms → 3 ms)
2. High qubit thermal population (8%), contributing to low cavity T_2
3. High cavity thermal population (10%)
4. Slow readout (16 us) with low fidelity (50%)
5. Cavity-readout cross-Kerr (0.1 MHz)

New 2-cell design

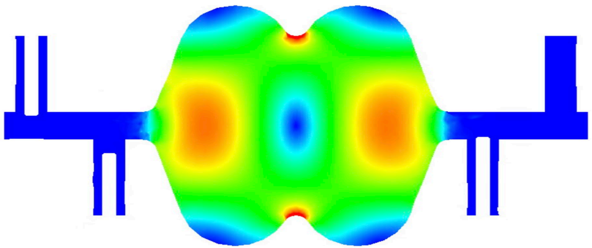


- Preserved Tesla geometry
- Reduced beampipe diameter
- Retracted chip from cavity center
- Two cells with large “iris” form two normal modes
- On-chip readout and Purcell filter enabling individual control and fast readout

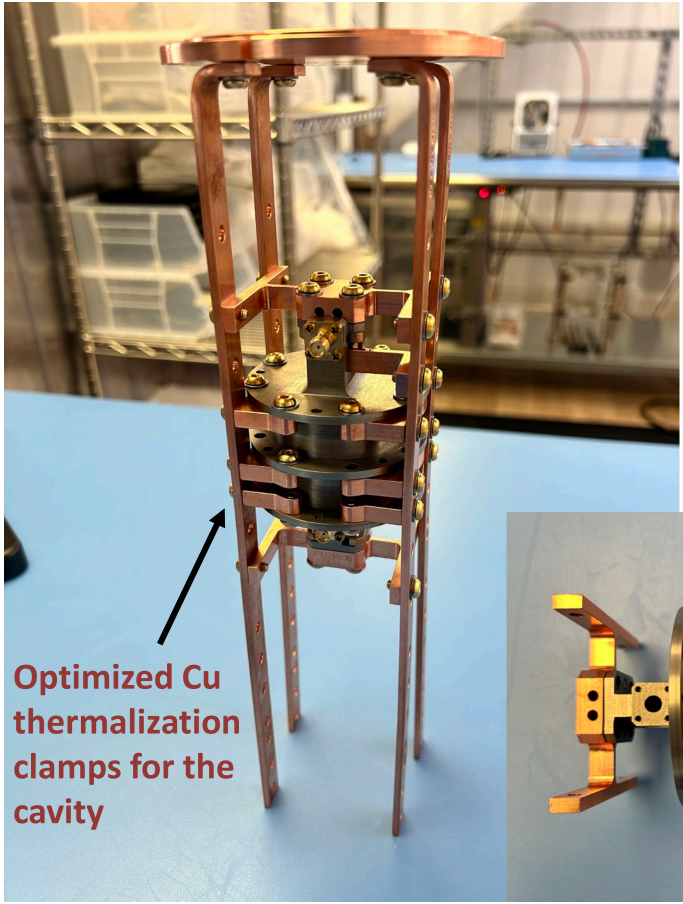
Alice (5.8 GHz)

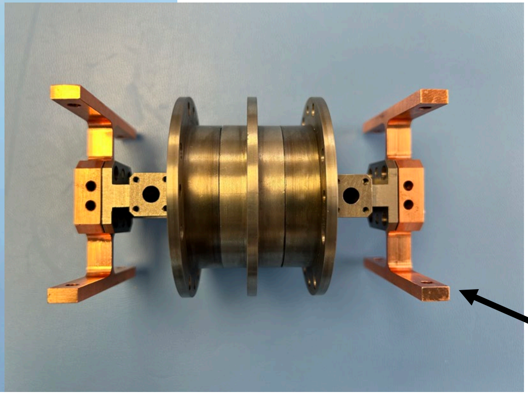


Bob (6.9 GHz)



New 2-cell design

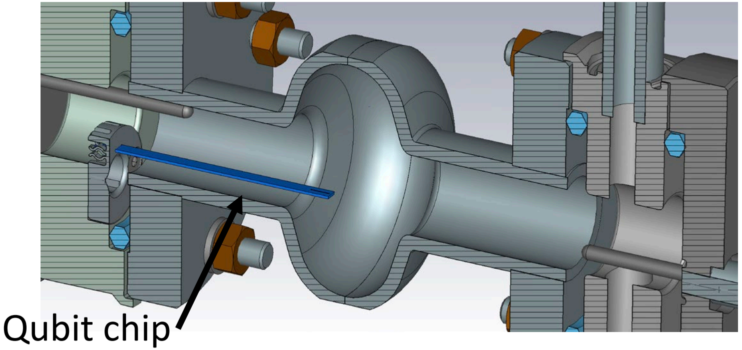




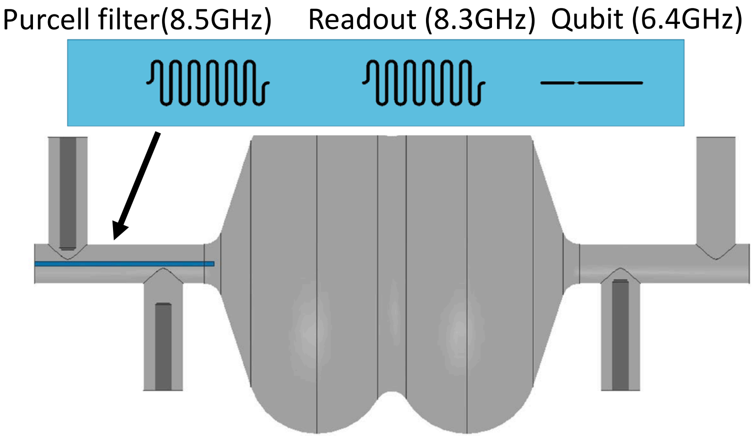
- Preserved Tesla geometry
- Reduced beampipe diameter
- Retracted chip from cavity center
- Two cells with large “iris” form two normal modes
- On-chip readout and Purcell filter enabling individual control and fast readout
- Optimized qubit chip/cavity clamp

Optimized Cu clamp for the qubit chip

Improvements

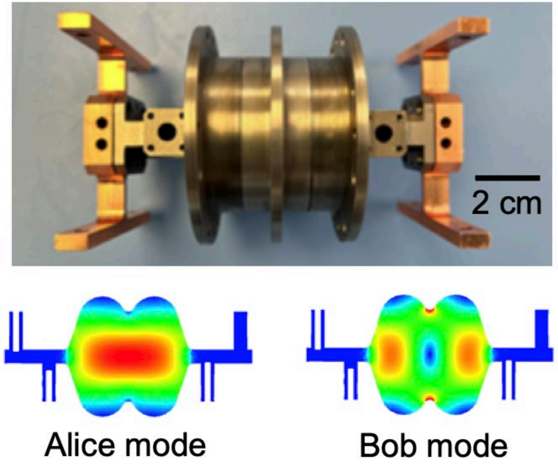


1. Cavity T_1 reduction (30 ms $\rightarrow$ 3 ms)
2. High qubit thermal population (8%), contributing to low cavity T_2
3. High cavity thermal population (10%)
4. Slow readout (16 μs) with low fidelity (50%)
5. Cavity-readout cross-Kerr (0.1 MHz)



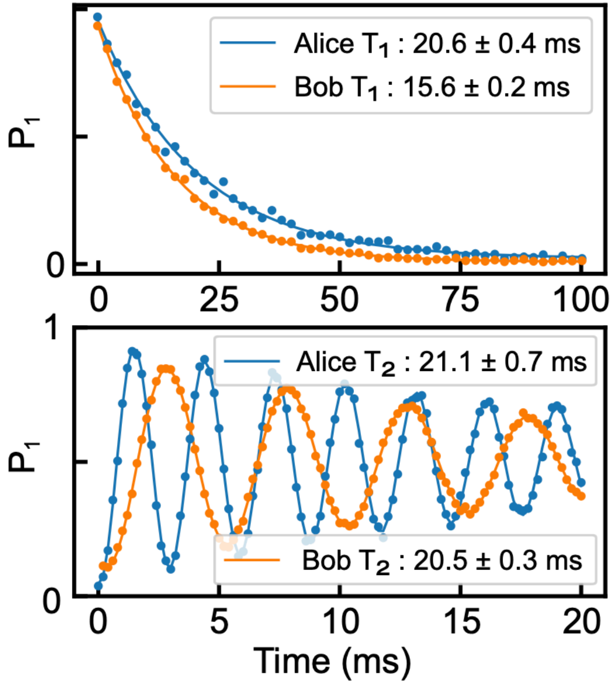
1. Cavity T_1 preservation (25 ms $\rightarrow$ 21 ms)
2. Low qubit thermal population (< 1%), helpful for high cavity T_2
3. Low cavity thermal population (< 0.5%)
4. Fast readout (2 μs) with high fidelity (98%)
5. Cavity-readout cross-Kerr ($\ll$ 0.1MHz)

Multiqudit platform

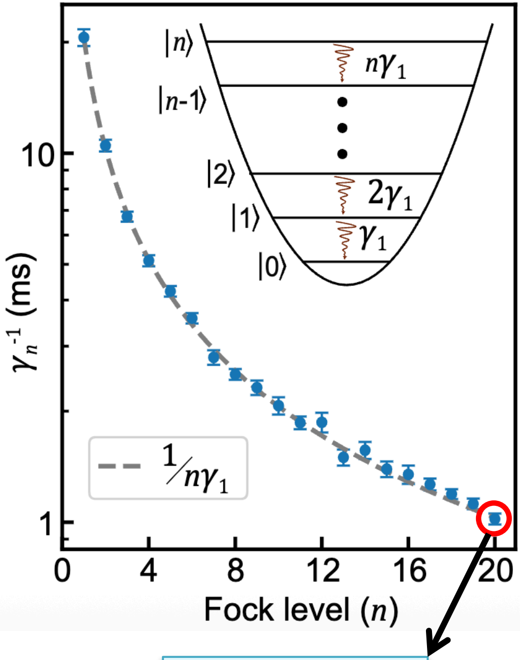


Transmon
T_1: 150 μs, T_2: 40 μs

Two high-coherence qudits with $d = 20$



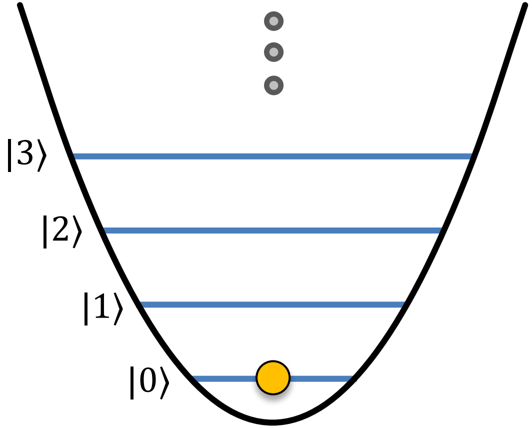
Large single-photon $T_1^{(1)}$ and $T_2^{(1)}$ in a 2-mode system



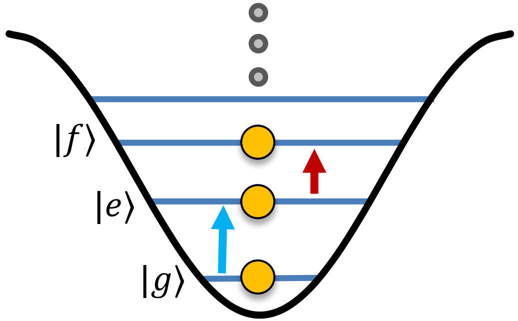
$T_1^{(20)} > 1$ ms

Verified 1/n dependence

Climbing Fock ladder

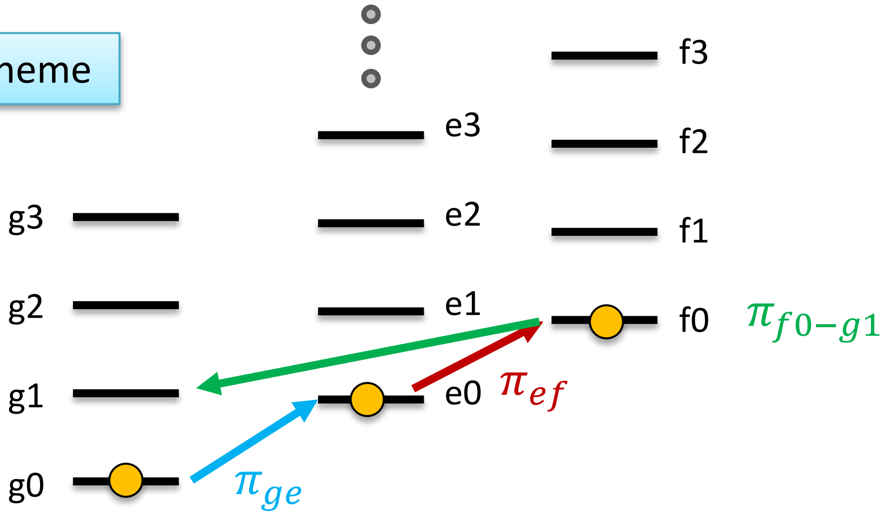


Cavity

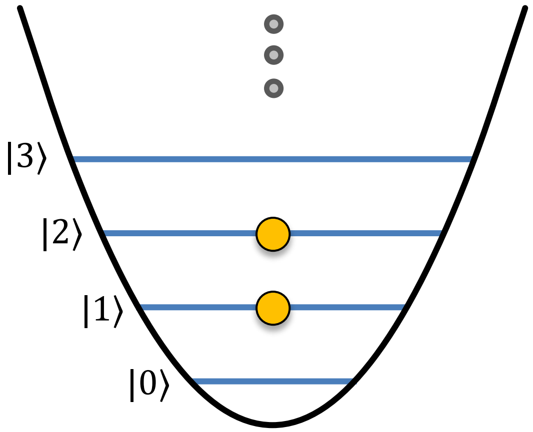


Transmon

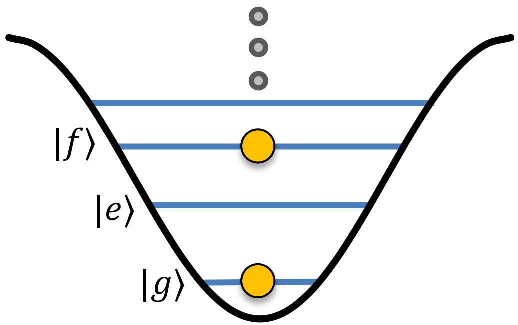
Sideband scheme



Climbing Fock ladder

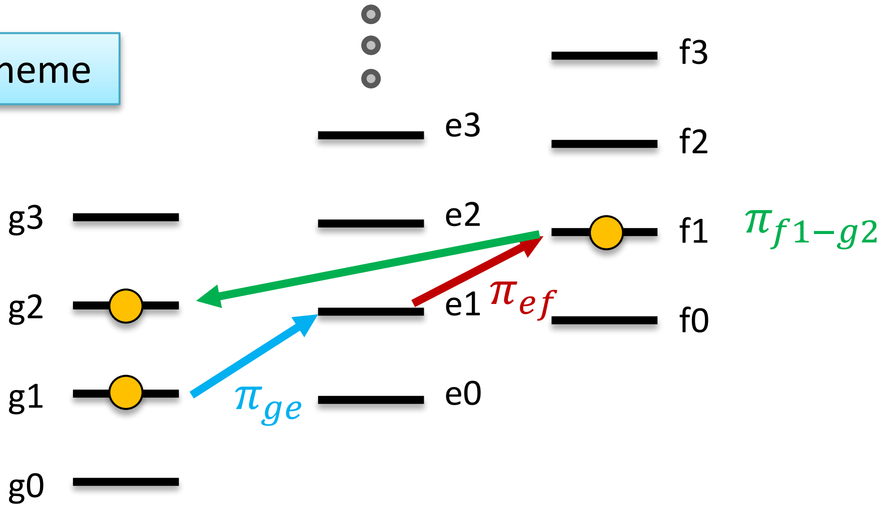


Cavity



Transmon

Sideband scheme

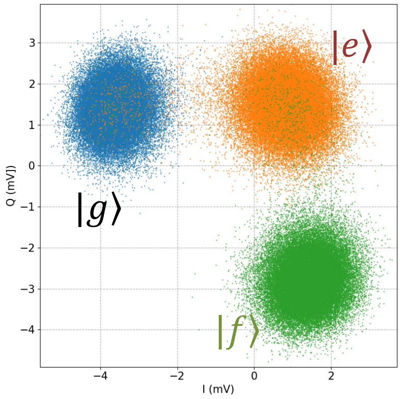


Transmon decay, dephasing

Cavity decay

Fixable in real-time

Sideband feedforward protocol

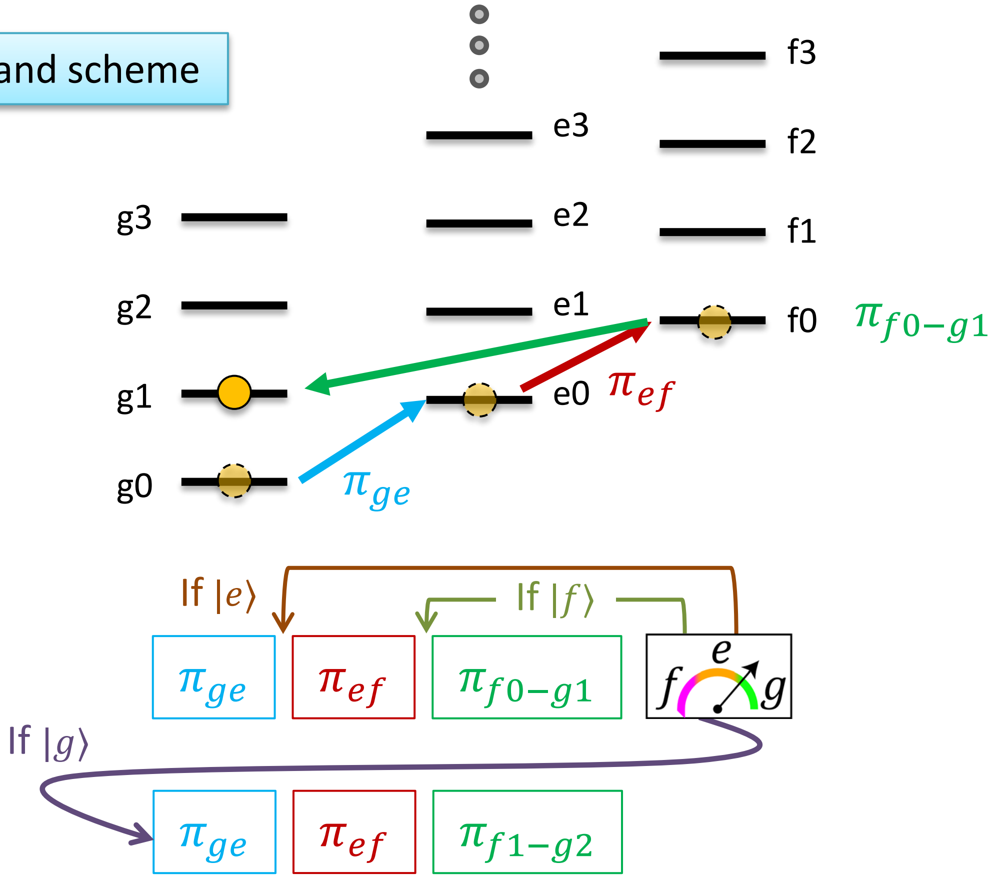


3-state readout $\mathcal{F} = 0.987$

Fix transmon errors in realtime

Sideband Feedforward protocol (SFP)

Sideband scheme



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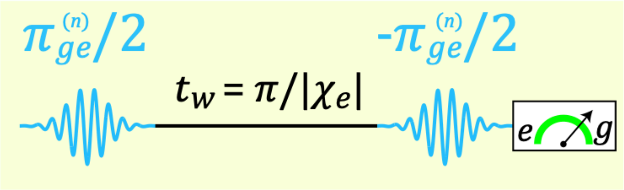
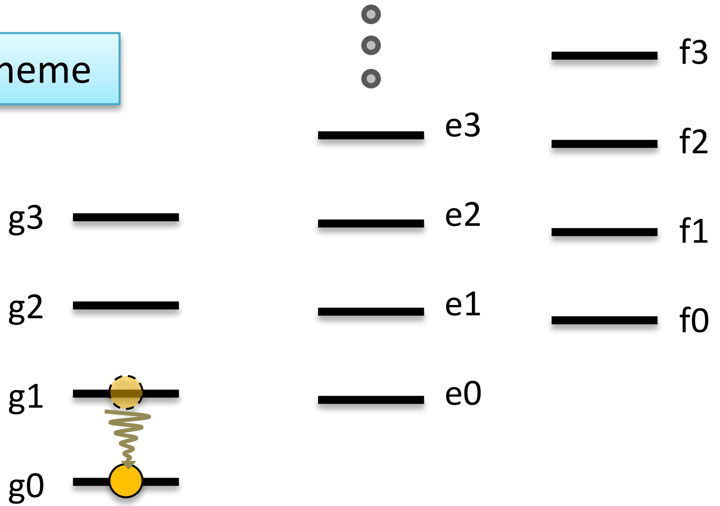
Parity filter

Sideband scheme

Parity filter (PF)

Π =



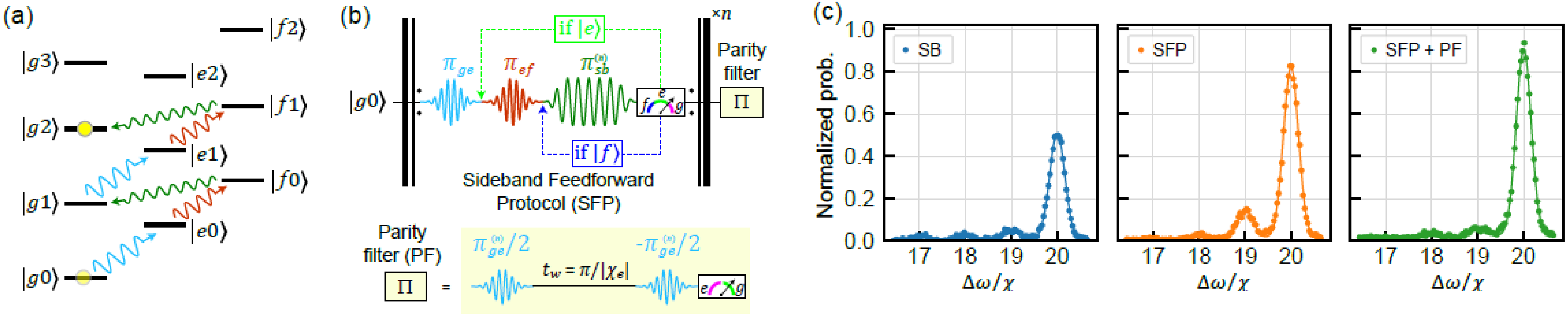


$|g\rangle \rightarrow$ no cavity decay
$|e\rangle \rightarrow$ single-photon decay

Fix cavity decay through post-selection

π_{ge} π_{ef} π_{f0-g1} Π Parity filter

Fault-tolerant Fock state preparation

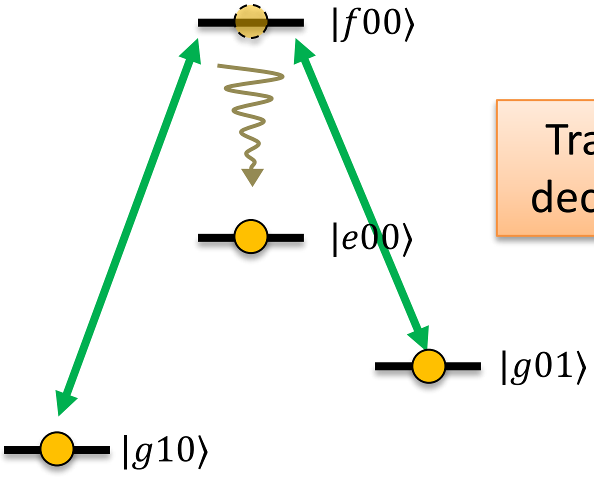


- Fock preparation using $|f, n\rangle \leftrightarrow |g, n+1\rangle$ sideband interactions
- Realtime error correction of ancilla errors
- Parity filter for detecting cavity decay

Fock $|20\rangle$ with $\mathcal{F} > 95\%$
Record preparation fidelity

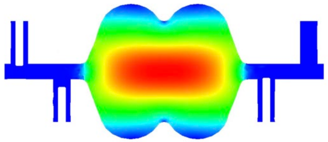
Kim & Roy et al., arxiv:2506.03286

Two-mode entanglement

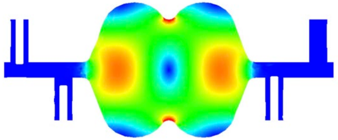


Transmon decay error

On-resonance sideband drives

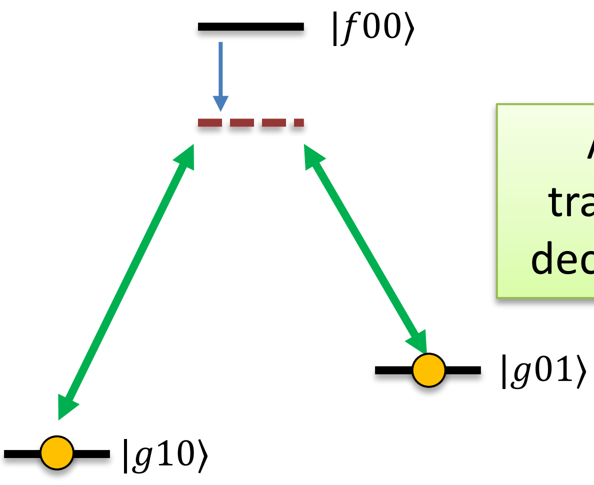


Alice (5.8 GHz)



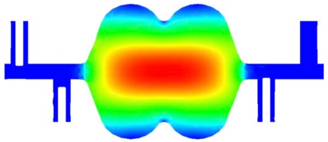
Bob (6.9 GHz)

Two-mode entanglement

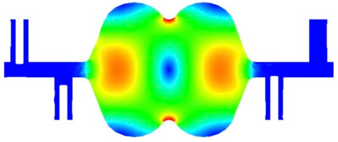


Avoid transmon decay error

Off-resonance sideband drives



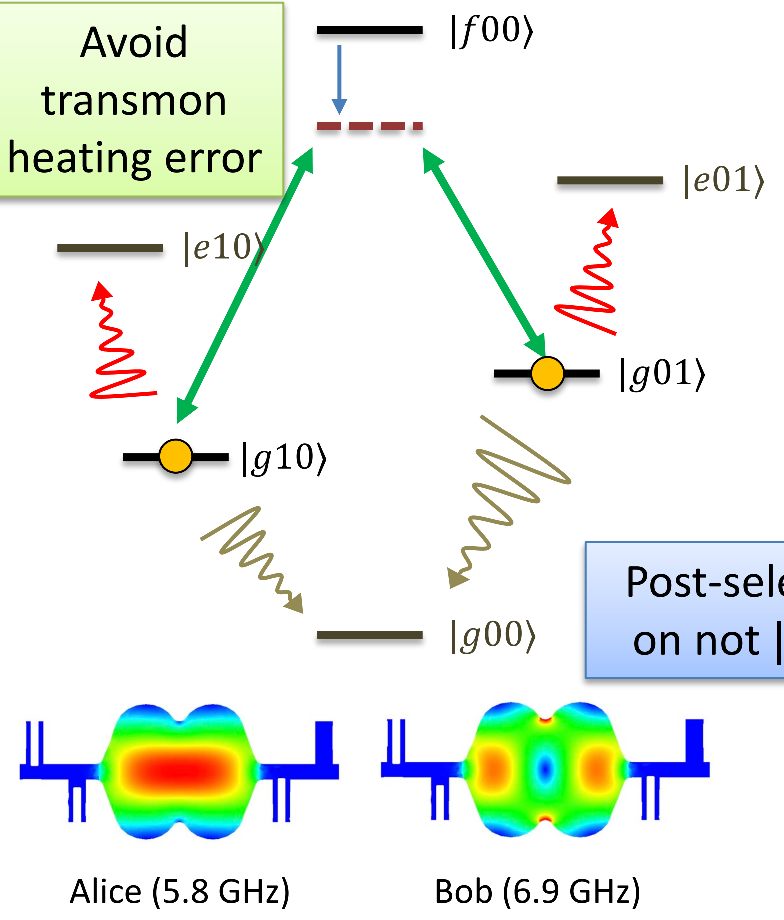
Alice (5.8 GHz)



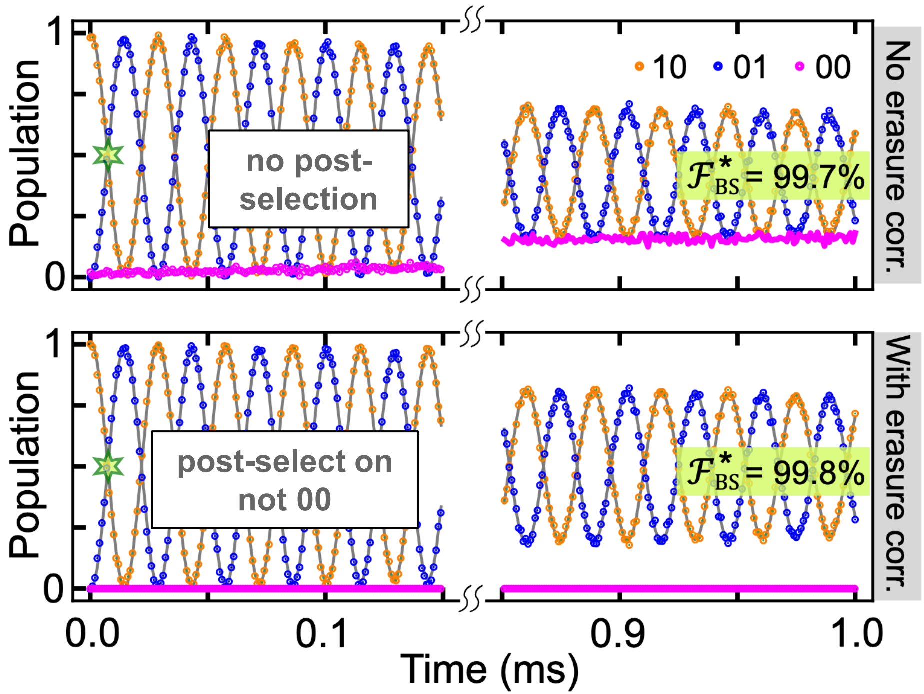
Bob (6.9 GHz)

Two-mode entanglement

Avoid transmon heating error



Post-select on not |e⟩



High-fidelity swap operations

Kim & Roy et al., arxiv:2506.03286

Two-mode entanglement

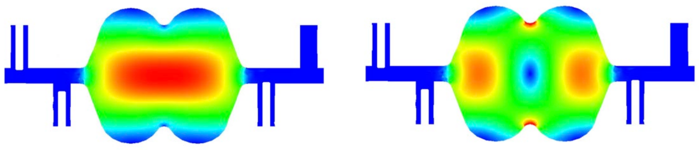
Bell state

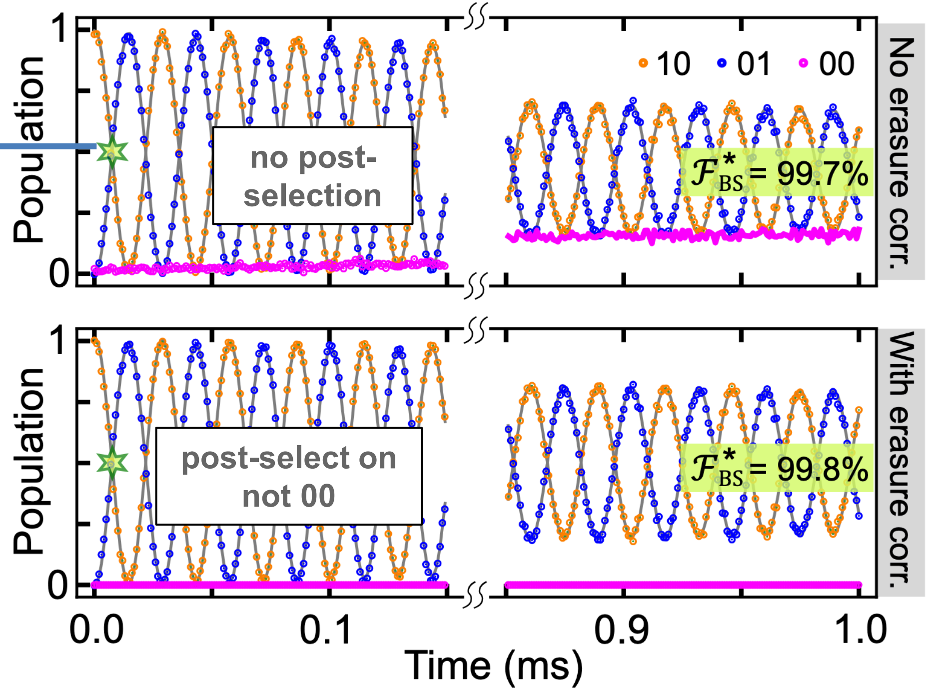
$$|\psi\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

Beamsplitter operation connects higher levels

Generates two-qudit entanglement

Enables universal two-qudit QPU



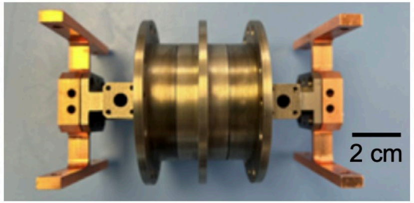


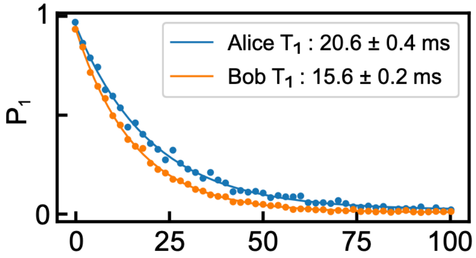
High-fidelity swap operations

Kim & Roy et al., arxiv:2506.03286

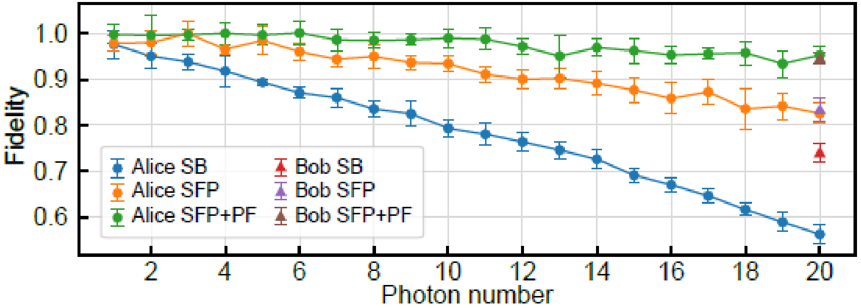
Summary of part 1

Two-mode system with high coherence

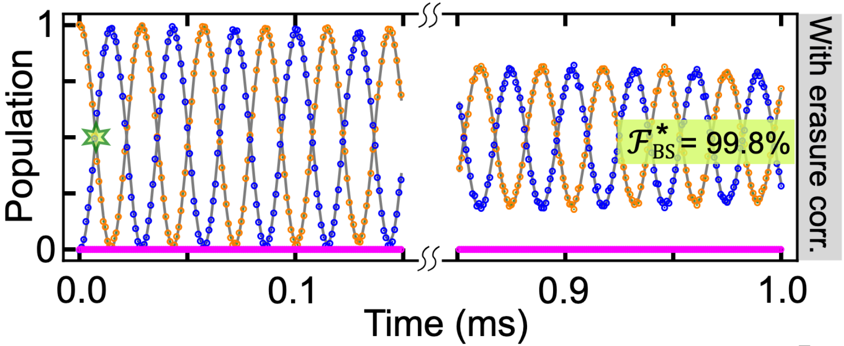




Error-resilient large Fock state preparation



High-fidelity swap operations



Next steps

- Single-qudit gates
- Qudit entangling operations
- Universal two-qudit system

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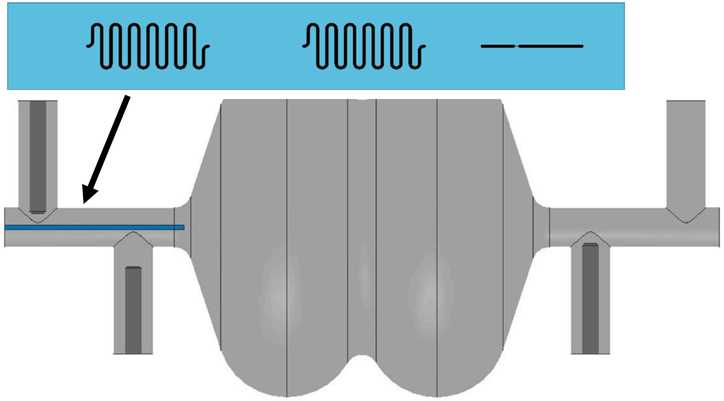
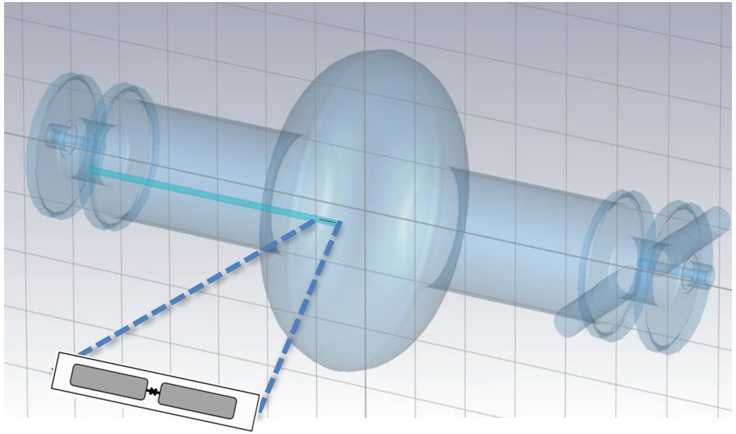
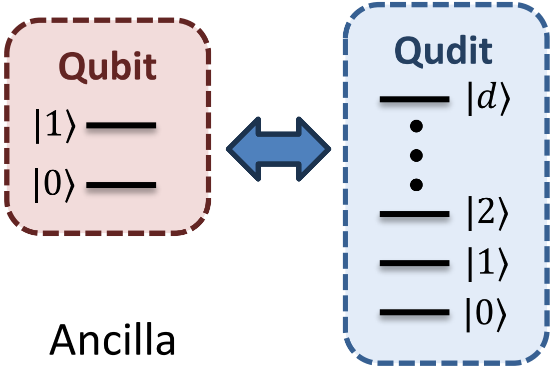
Further improvement strategies





2 levels

d >2 levels

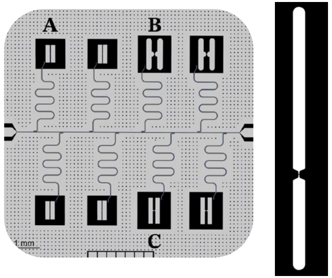


Ancilla transmon

Bosonic modes

To increase coherence of the joint system:

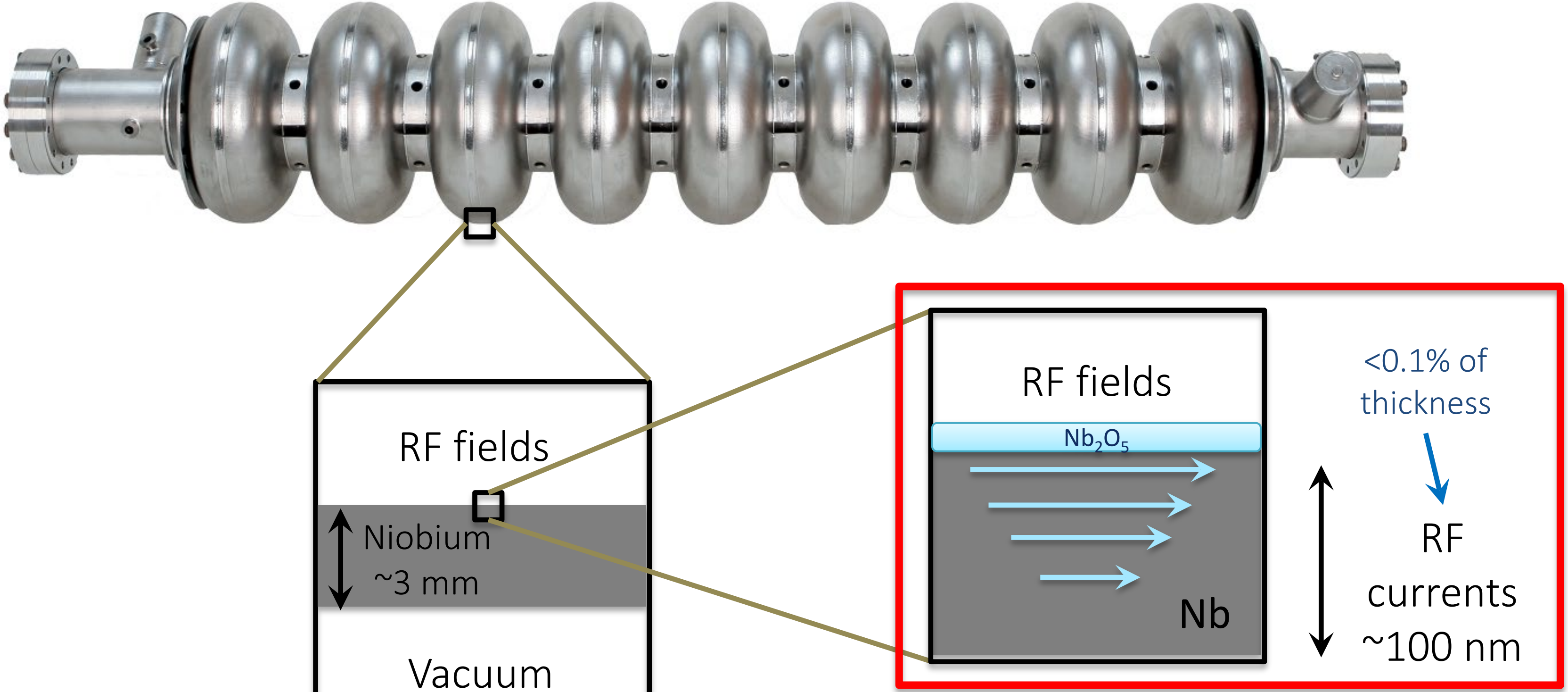
Improve cavity Q



Improve transmon Q

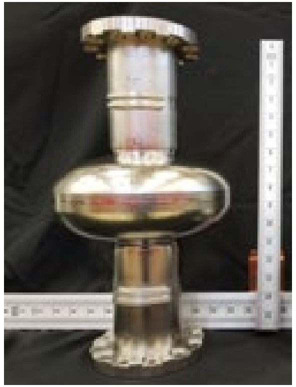
Cavity improvement strategies

Surface contribution

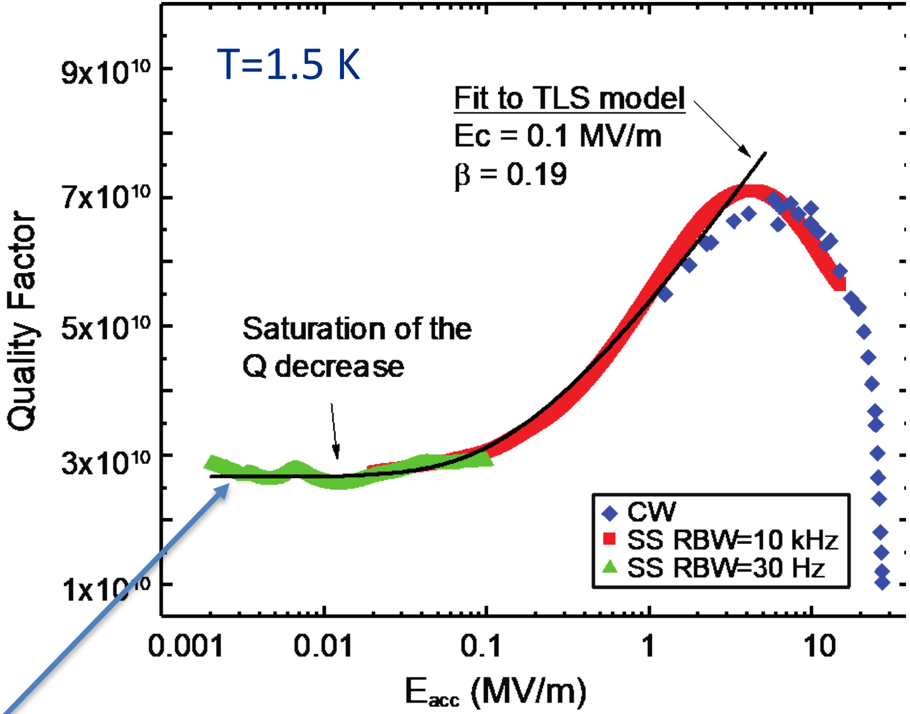


Characterization and nano-engineering the surface layer is crucial to performance

TLS signature



1.3 GHz



Measured down to <N> ~ 1000 photons

Low field Q saturates at **3×10^{10}**

Field dependence

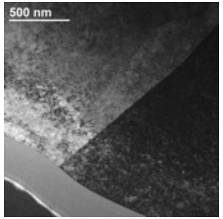
$$\frac{1}{Q} = \frac{F\delta_{\mathrm{TLS}}(T)}{\left(1 + \left(\frac{E_{\mathrm{acc}}}{E_{\mathrm{c}}(T)}\right)^2\right)^{\beta}} + \frac{1}{Q_{\mathrm{qp}}}$$

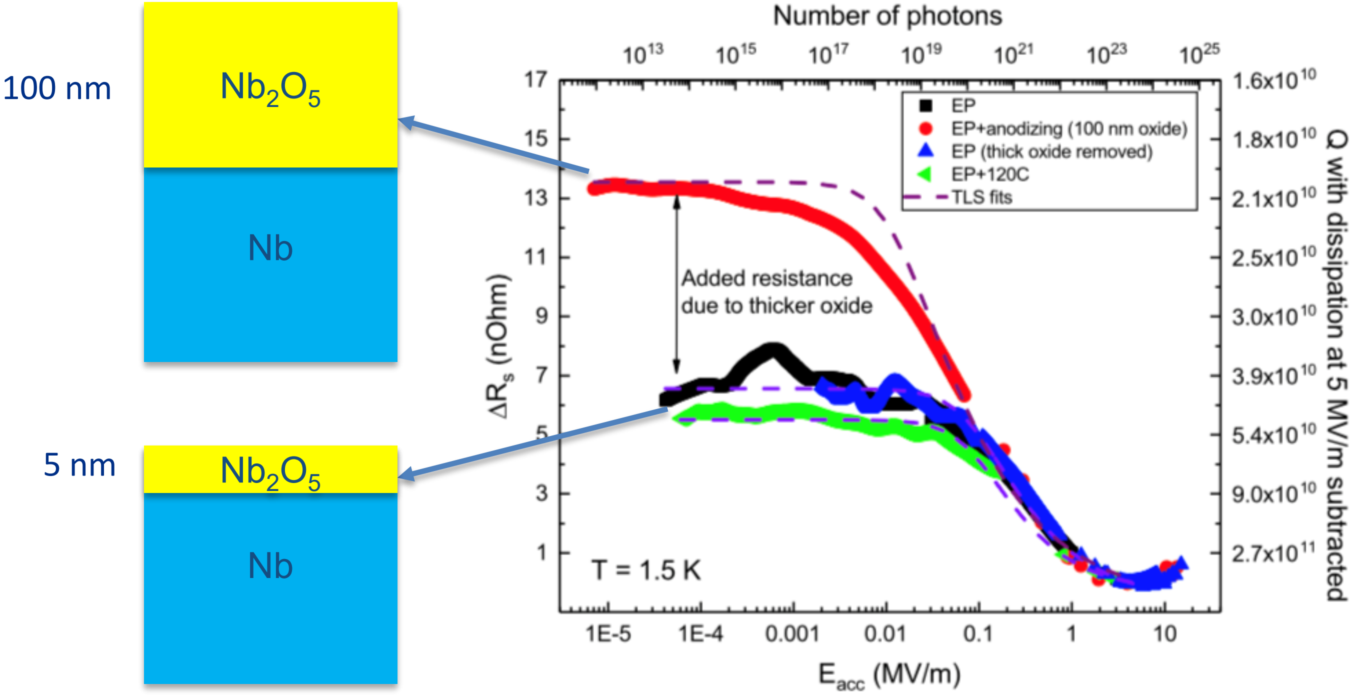
Loss is TLS dominated

TLS location?

A. Romanenko and D. I. Schuster, Phys . Rev. Lett. **119**, 264801 (2017)

TLSs in the natural niobium oxide





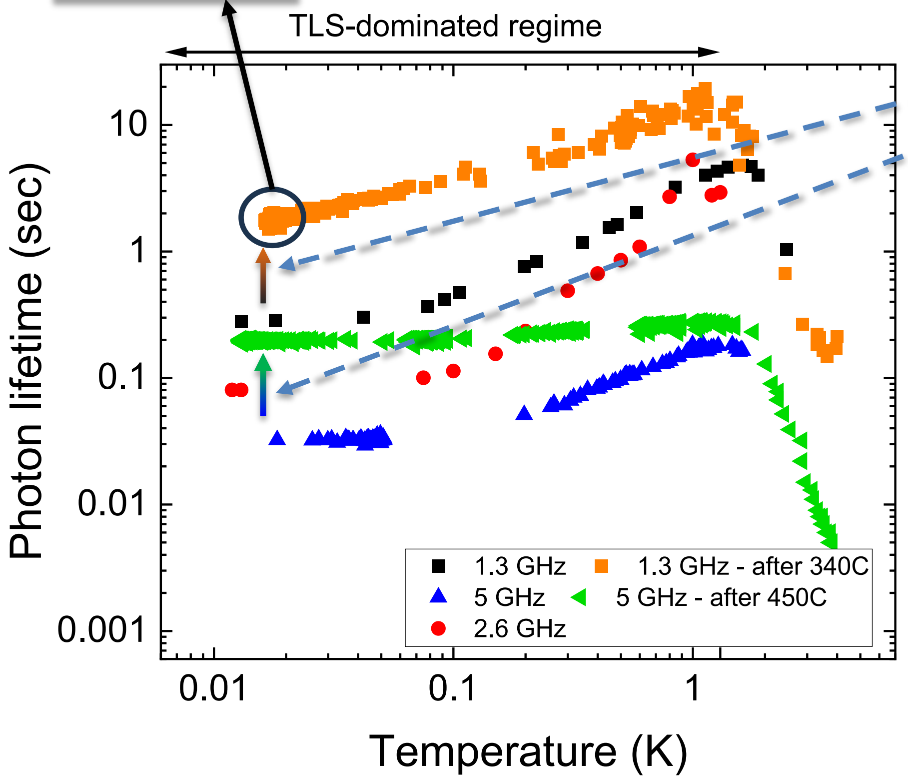
Surface oxide hosts TLSs

How to mitigate?

A. Romanenko and D. I. Schuster, Phys . Rev. Lett. **119**, 264801 (2017)

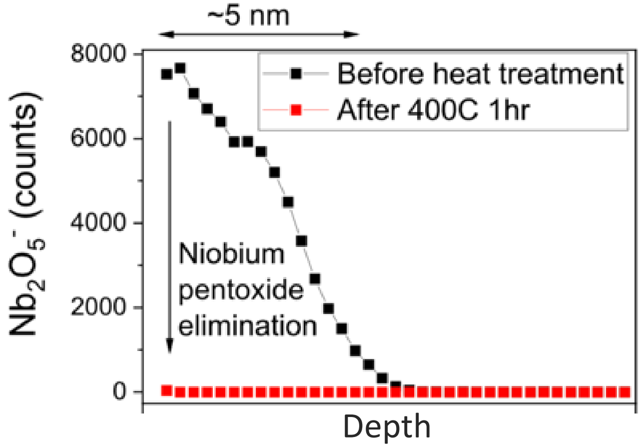
Ultra high Q at mK temperatures

$T_1 > 1$ sec



340-450°C vacuum baking for ~4 hours

Nb_2O_5 hosting TLSs was dissolved

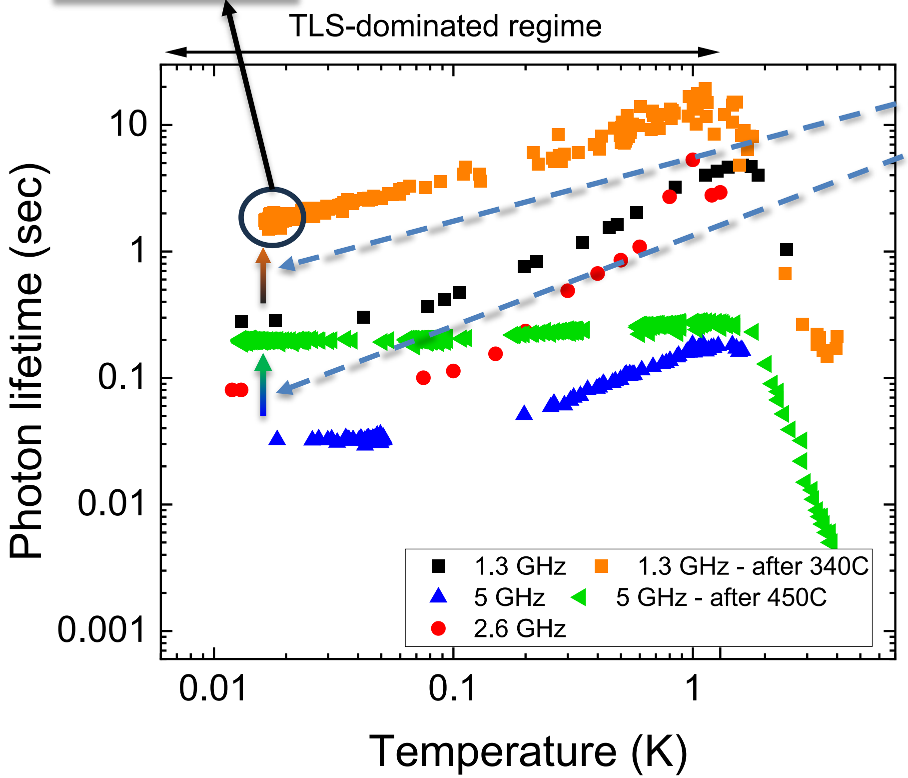


TOF-SIMS data on cavity cutouts

A. Romanenko et al.
Phys. Rev. Appl. **13**, 034032 (2020)

Ultra high Q at mK temperatures

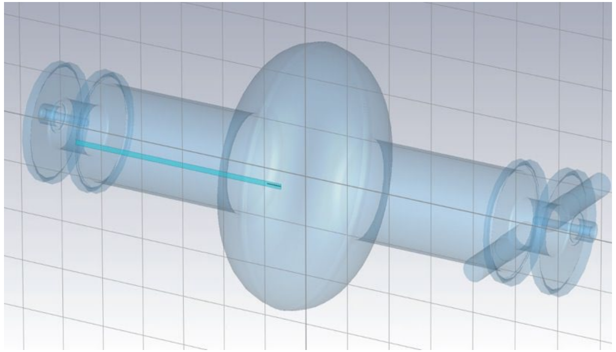
$T_1 > 1$ sec



340-450°C vacuum baking for ~4 hours

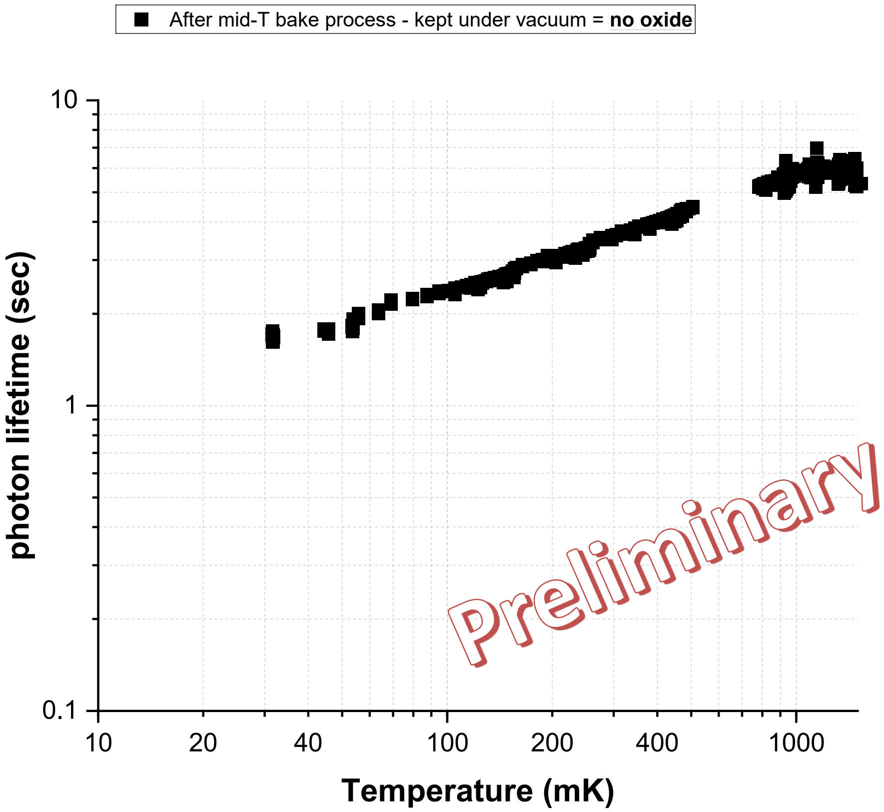
Nb_2O_5 hosting TLSs was dissolved

Challenging for QPU

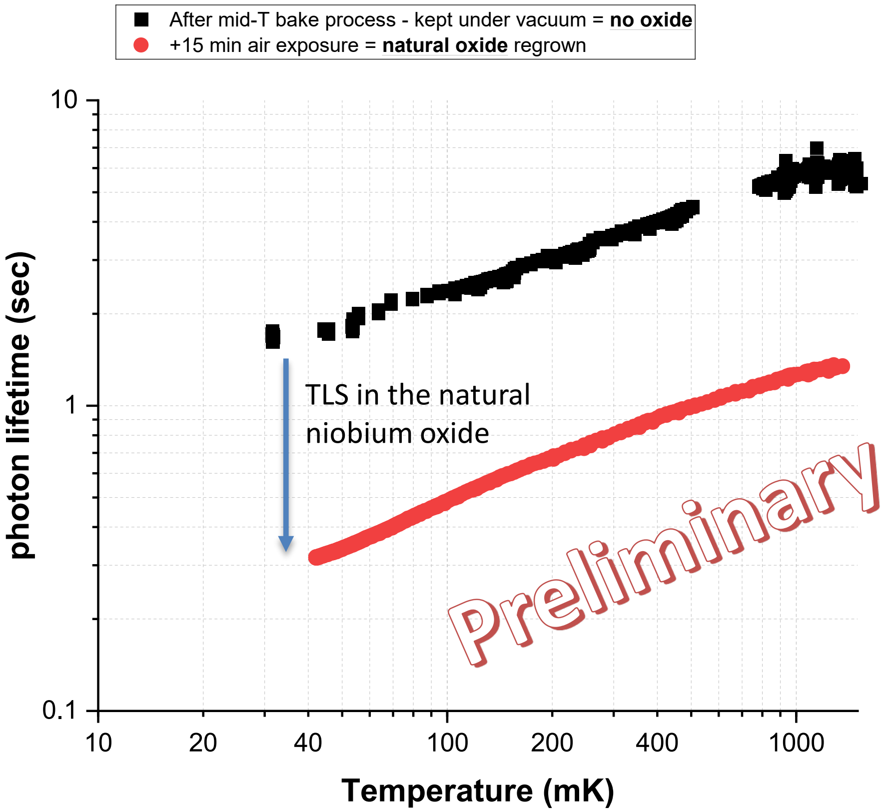


A. Romanenko et al.
Phys. Rev. Appl. **13**, 034032 (2020)

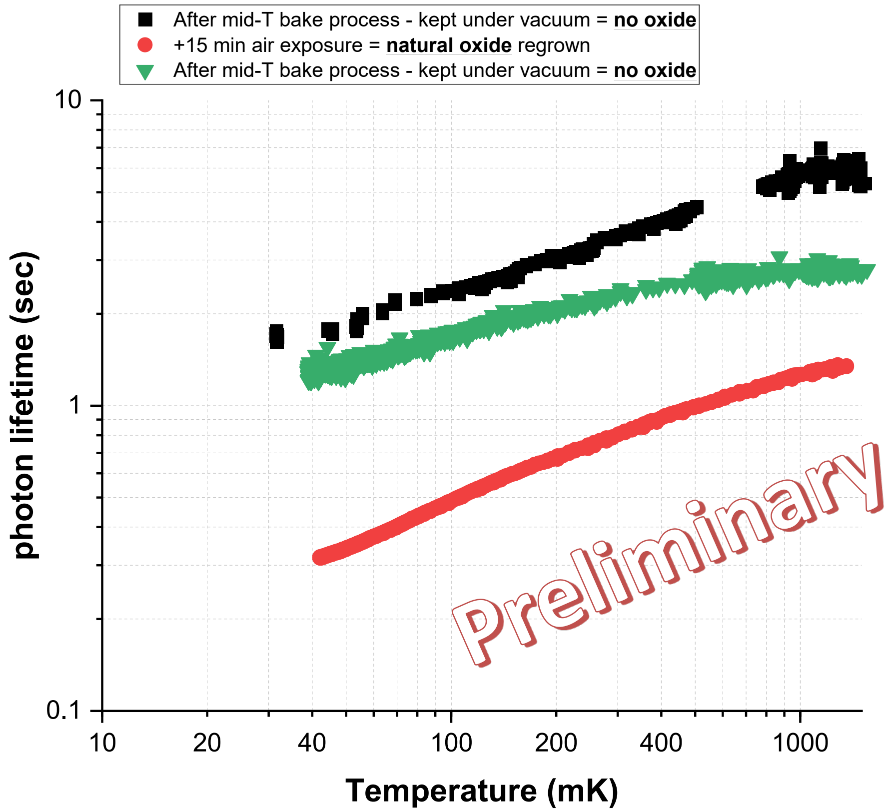
Regrowing Niobium Oxide with less loss



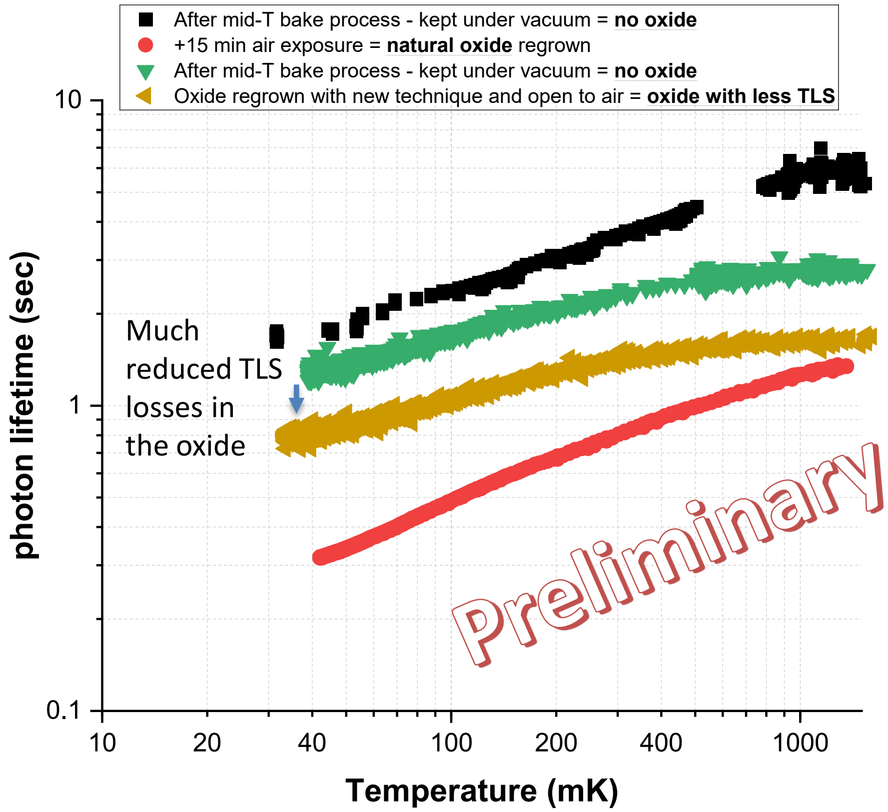
Regrowing Niobium Oxide with less loss



Regrowing Niobium Oxide with less loss



Regrowing Niobium Oxide with less loss



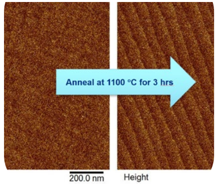
Easily integrable with 3D transmons

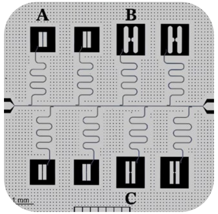
Proof-of principle demonstration of growing niobium oxide with much lower TLS losses

Transmon improvement strategies

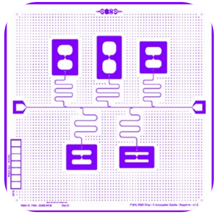
Directions for T_1 improvement

Improved Dielectric Substrate Losses
- Sapphire Annealing



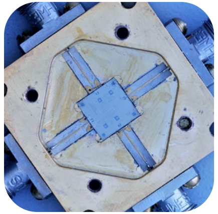


Optimization SC Base Metal Layer
- Nb, Ta, Re
- Nb Encapsulation
- High T Deposition

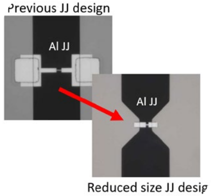


Optimization of qubit T_1

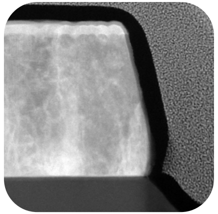
Optimization of Qubit Package
- Package Limitations



Optimization of Qubit Design
- Reduced EPR



Optimization of JJ
- Reduced JJ Footprint



Improved Fab Processing
- Substrate Preparation
- Etching
- JJ Processing

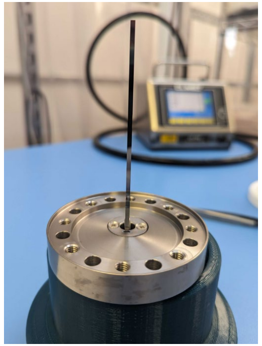
Substrate improvement strategies

RF characterization of dielectric materials

Ultra high-Q 3D Nb resonators with $Q\sim10^9$ enable ppb precision

Q degrades after sample is inserted → allows extraction of $\tan\delta$

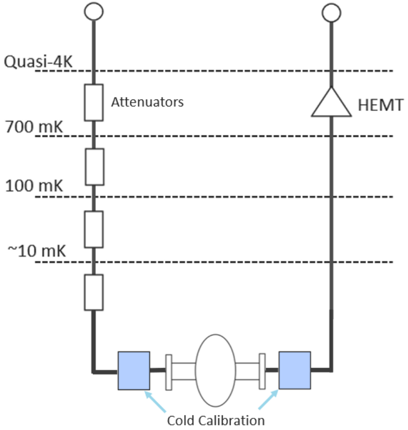
Sample prepared and installed at cavity flange



Sample installed into cavity

Cavity sealed and evacuated

Installation into DR and RF tested



Goal: compare different samples and pinpoint sources of dissipation

Temperature dependence of substrate loss

Unannealed HEMEX Sapphire

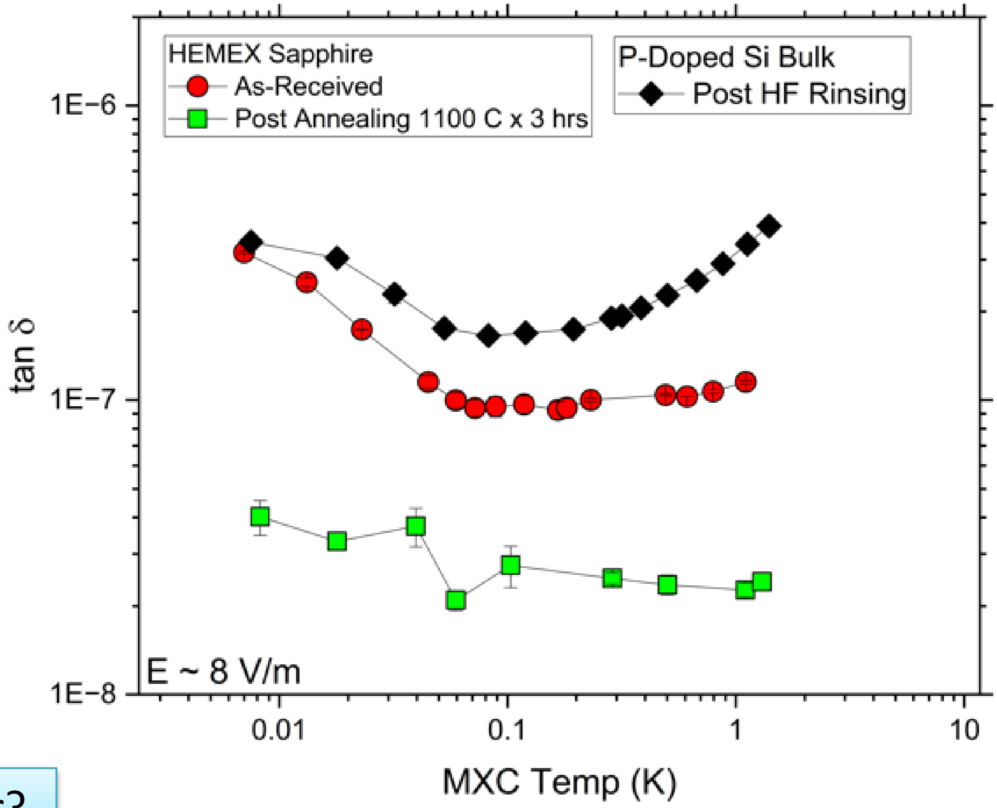
- Slight decrease with temperature
- Estimate tanδ ~ 3e-7

Annealed HEMEX Sapphire

- Slight decrease with temperature
- Tanδ ~ 4e-8

Silicon

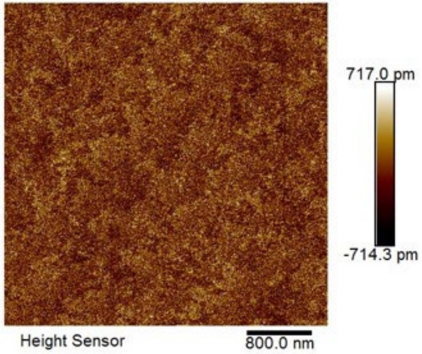
- Tanδ ~ 3e-7 – 3e-6 depending on resistivity



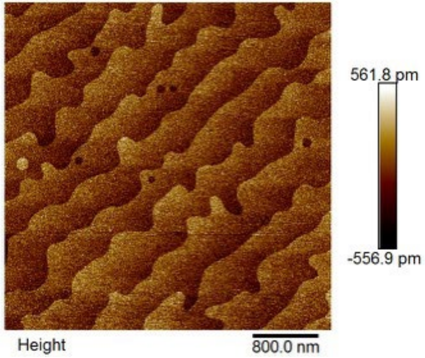
Why is annealed HEMEX sapphire better?

Potential material origin

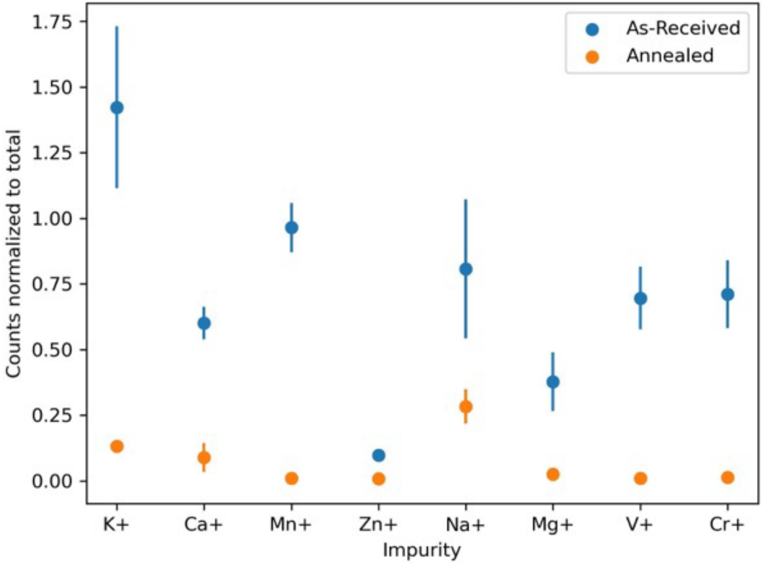
Unannealed Sapphire



Annealed Sapphire



Average Impurity Concentration in Bulk

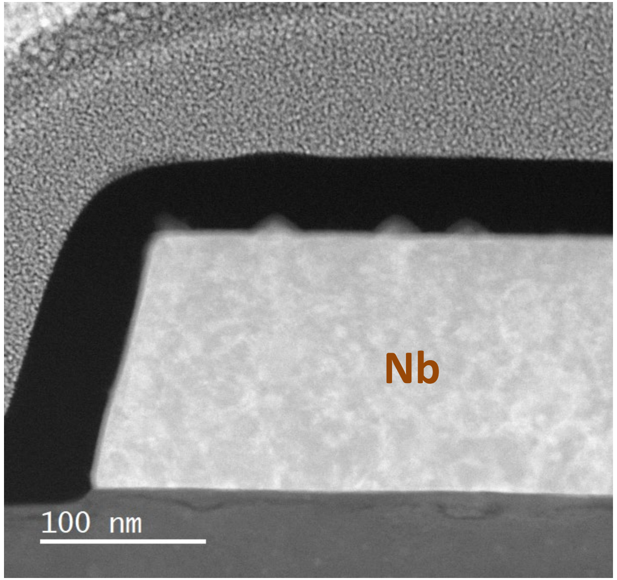


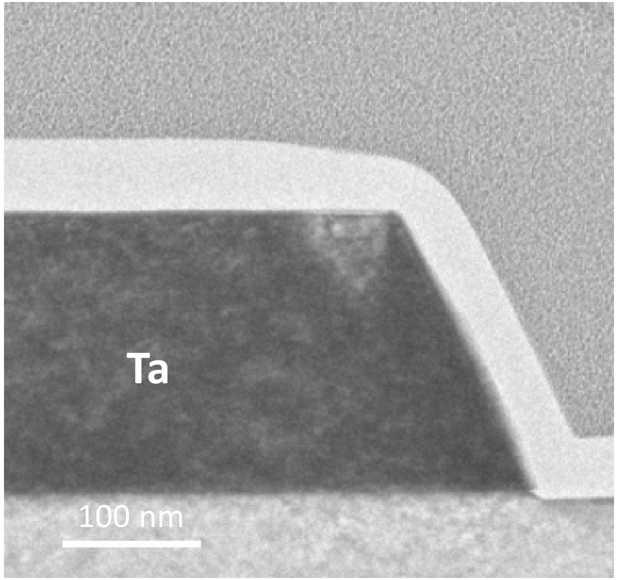
Creates atomically flat, terraced surfaces

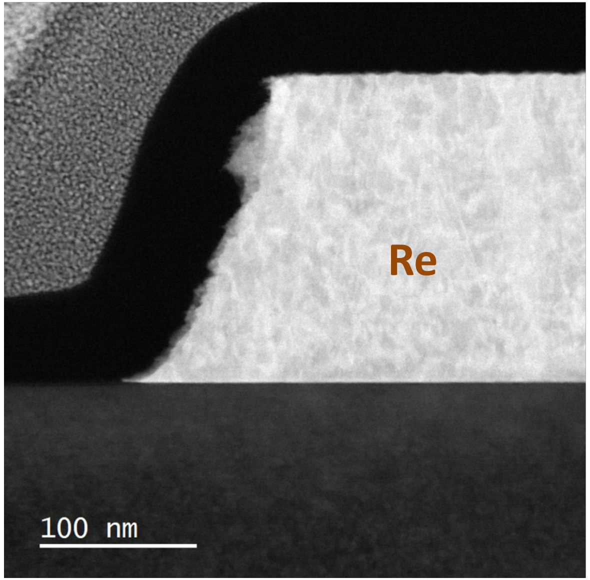
Decreases paramagnetic impurity concentrations in the **bulk material → Less TLS loss**

Exploration of base layer

Superconducting base layer exploration







- Tc ~ 9.3 K
- ~ 5nm Surface Oxide
- T1 avg ~ 0.4 msec
- T1 max ~ 0.6 msec

- Tc ~ 4.2 K
- ~ 5nm Surface Oxide
- T1 avg ~ 0.3 msec
- T1 max ~ 0.45 msec

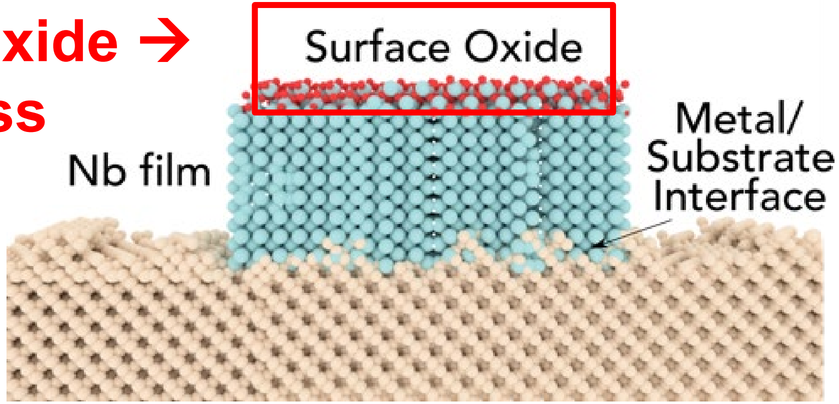
- Tc ~ 1.7 K
- < 1nm Surface Oxide
- T1 avg ~ 0.25 msec
- T1 max ~0.4 msec

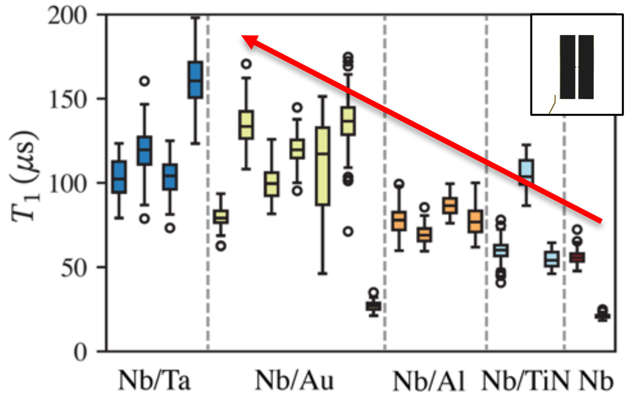
Suppression of Niobium Oxide growth

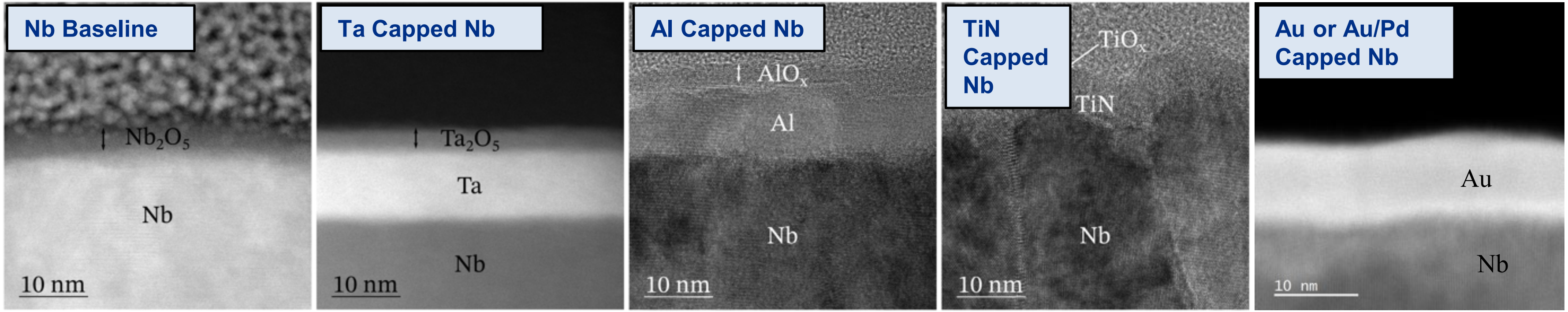
Surface encapsulation to abate oxide loss

Removing oxide → Reduced loss

Encapsulation

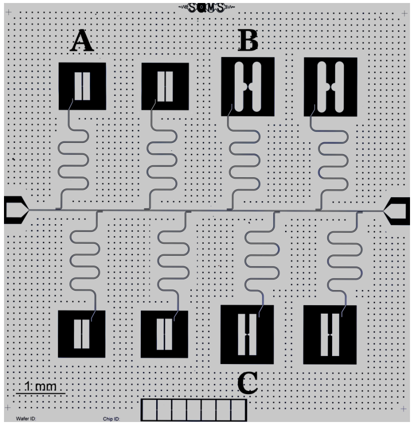


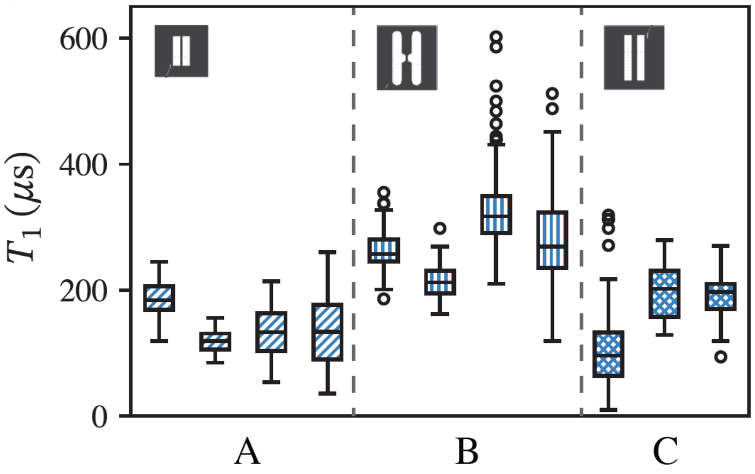


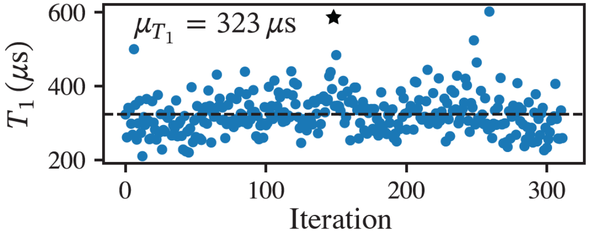


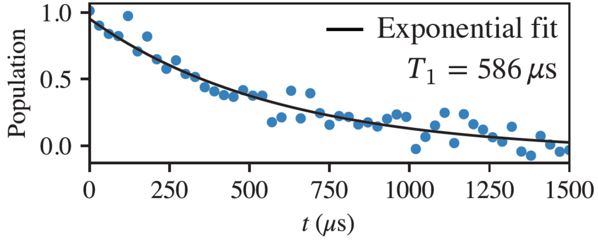
npj Quant. Info. 10, Article no.: 43 (2024)

Exploration of transmon geometry



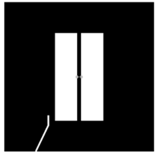






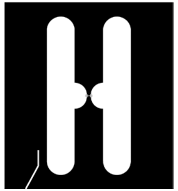
npj Quant. Info. **10**, 43 (2024)

A



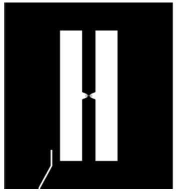
$p_{MA} = 3.1E-5$

B



$p_{MA} = 1.5E-5$

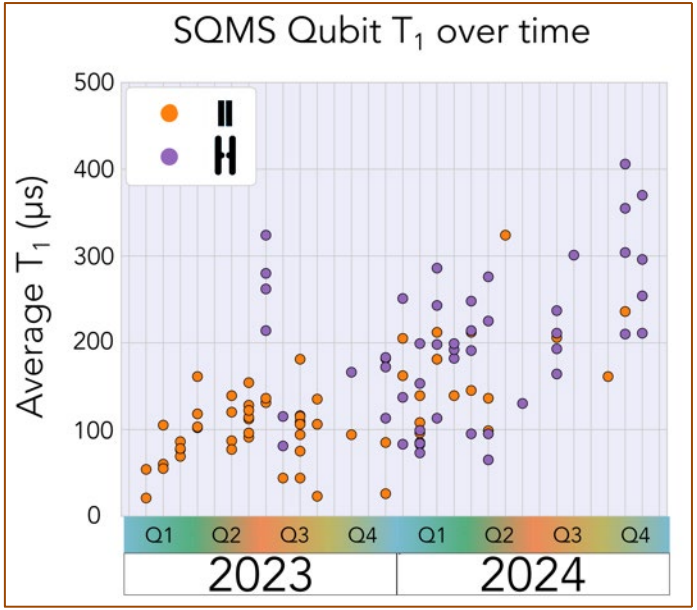
C

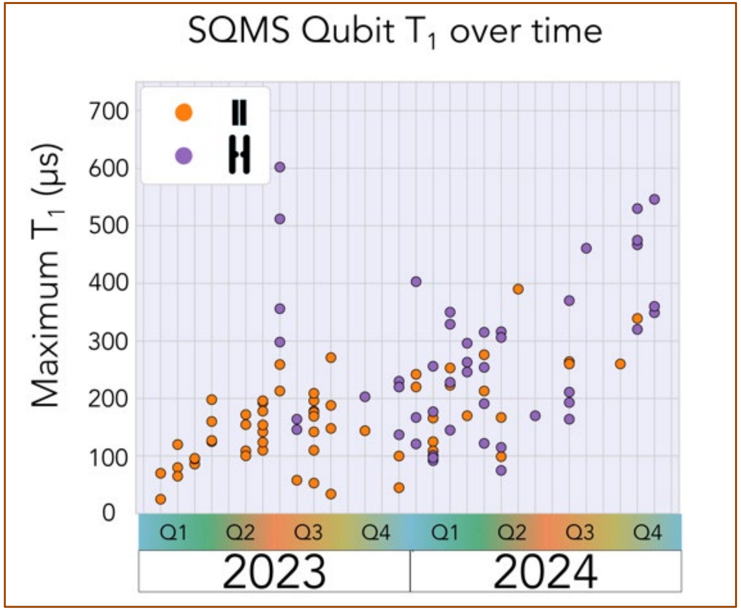


$p_{MA} = 1.7E-5$

- Large paddle factor of 2 improvement
- Average values for larger paddle qubits >0.3 milliseconds
- Best T1's reaching ~ 0.6 milliseconds

Coherence of 2D transmons over time



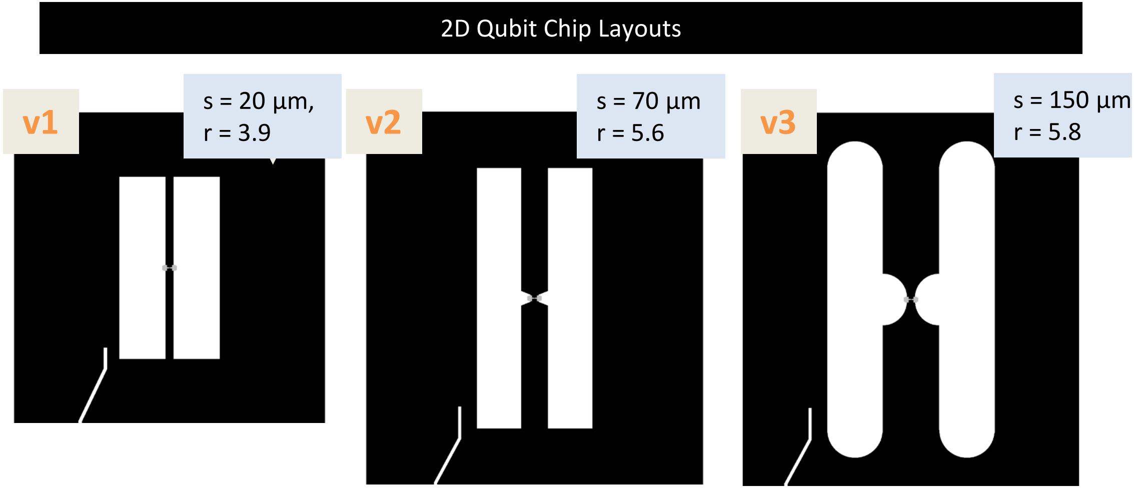


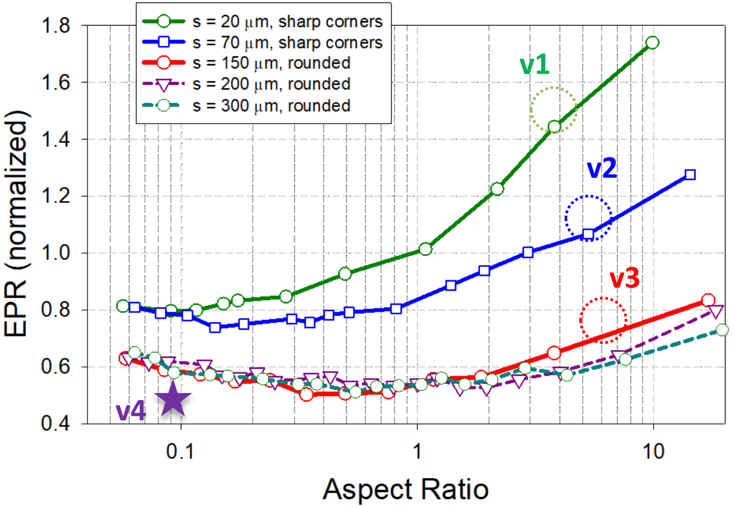
Average $T_1 > 400\ \mu s$

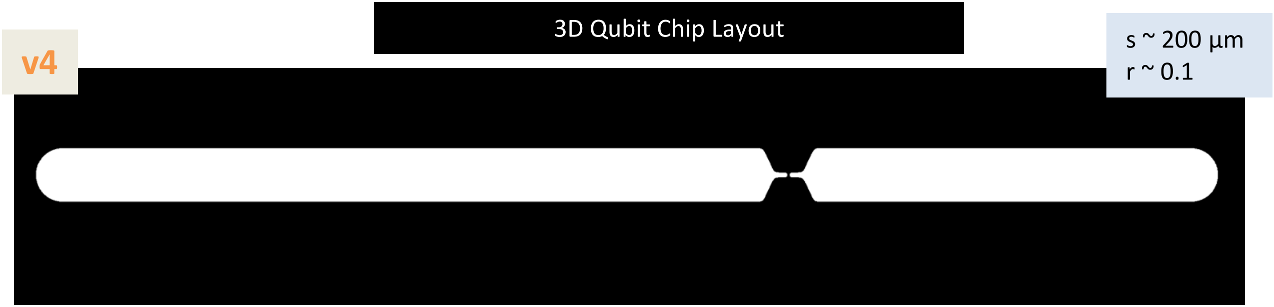
Max $T_1 > 600\ \mu s$

Goal: Average $T_1 > 1$ ms

Geometry optimization for 3D-style transmon



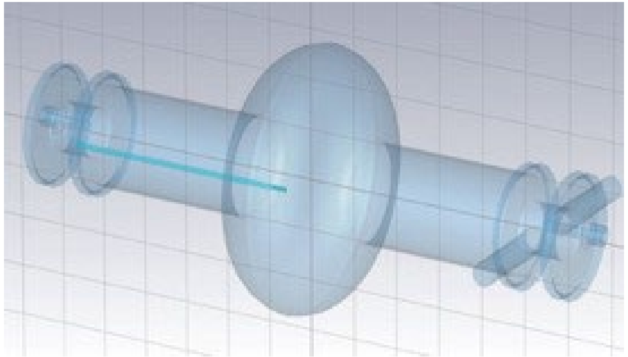




Qubit with arbitrary geometry can be defined by two parameters:

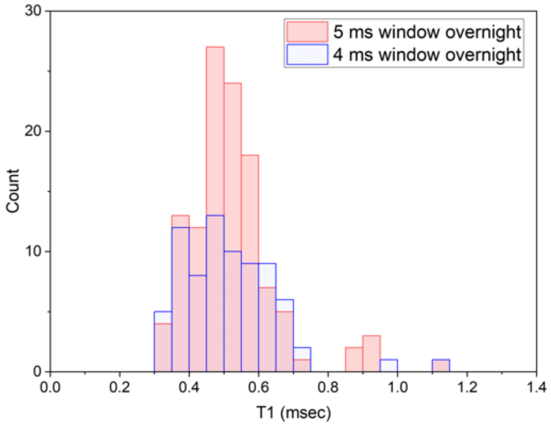
- paddle aspect ratio: $r = l/w$
- paddle to paddle separation: s

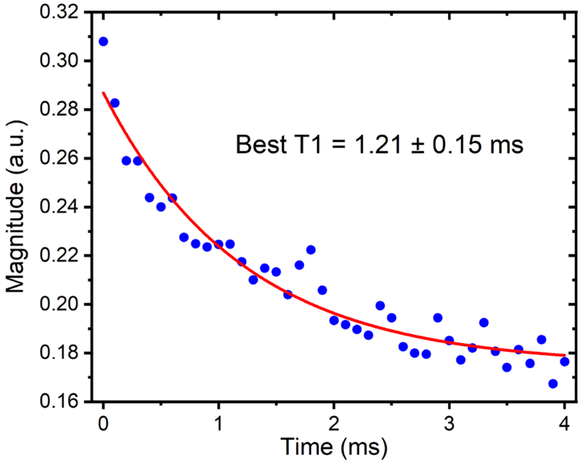
3D style transmon with $T_1 > 1$ ms



Achieved by combining all the advances:

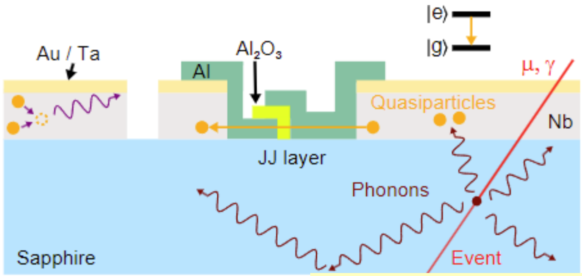
- Nb encapsulated by Ta
- Low loss annealed sapphire substrate
- Reduced junction leads footprint
- Reduced EPR
- 3D SRF cavity = low loss box





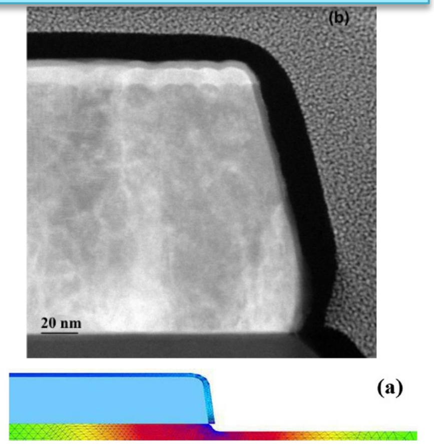
Other studies

Radiation studies

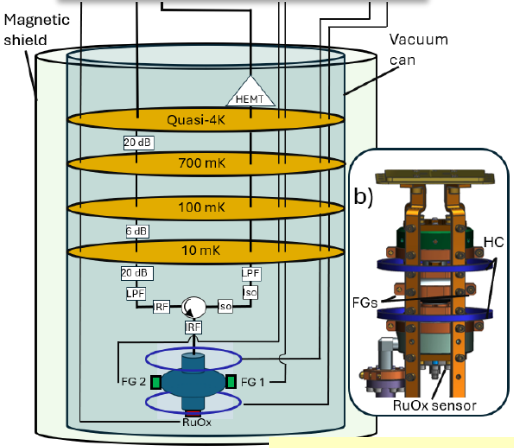


arxiv.:2405.18355

Trenching and sidewall

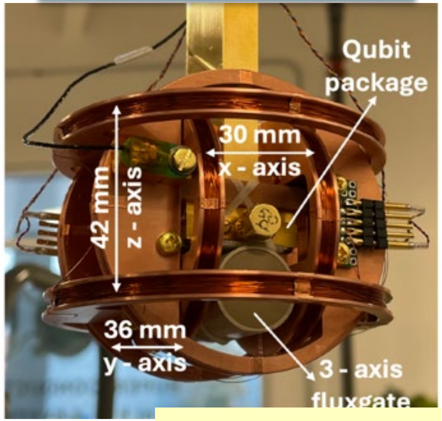


Magnetic vortex



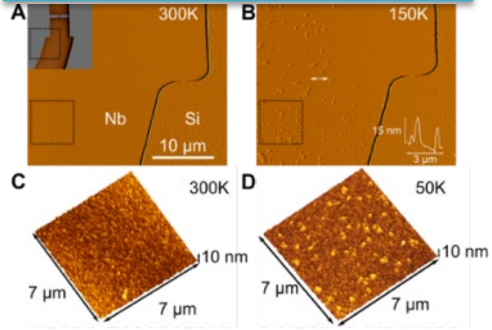
arXiv:2503.14616

Magnetic field



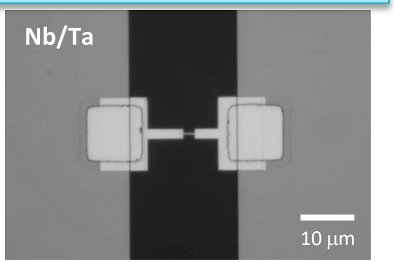
arxiv.:2506.02187

Nanohydrides studies



arxiv:2108.10385, adfm:202401365

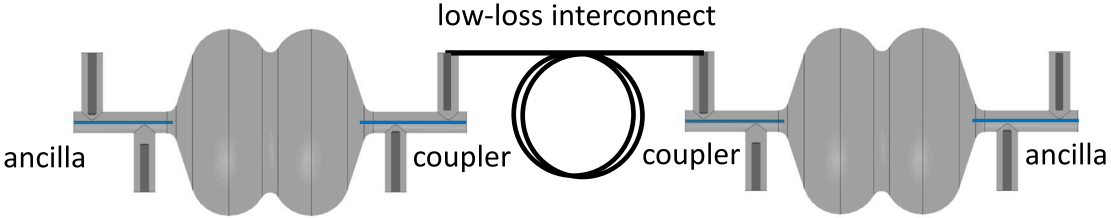
JJ footprint studies



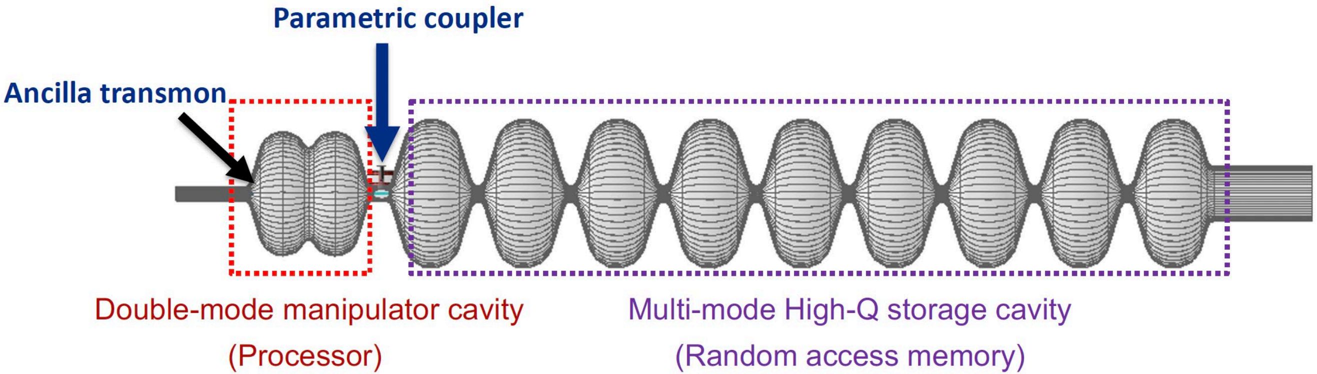
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Scaling up

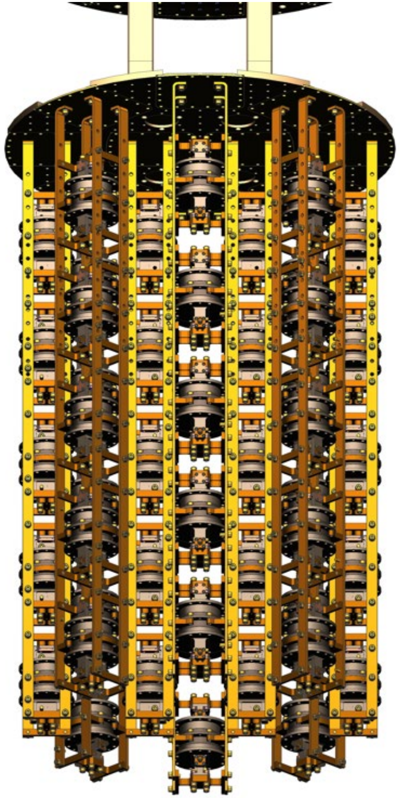
Next steps in 3D architecture



Quantum interconnect



Quantum RAM architecture

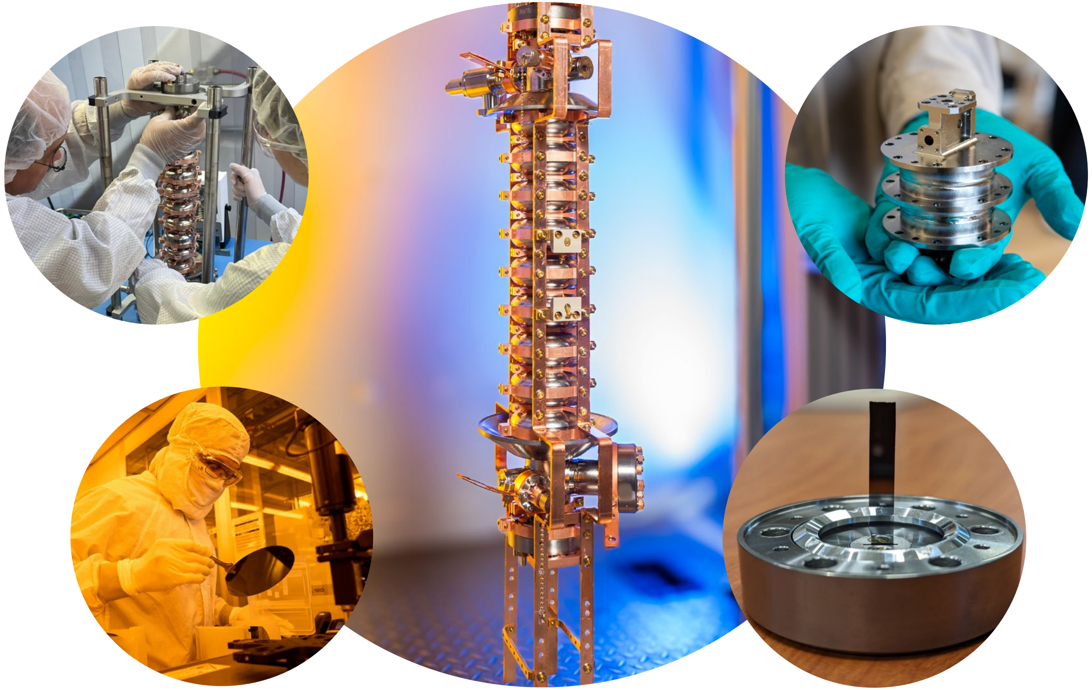


Build a 100-qudit system

Cavity-qudit system for computing and sensing

Ultra high-Q SRF cavities

Multi-qudit QPU



High coherence ancilla components

Quantum sensing & simulation

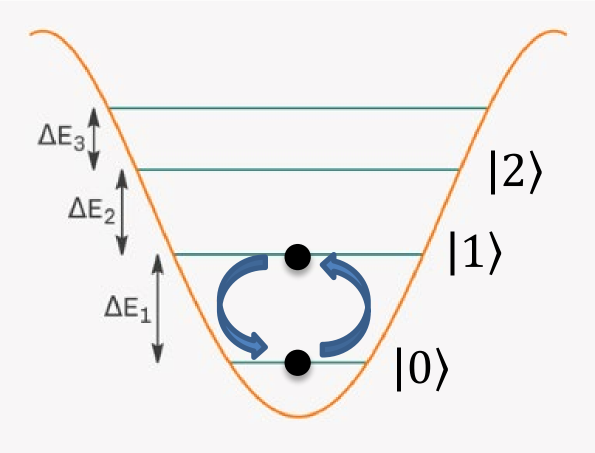
*SQMS cavity-based quantum devices have demonstrated **world-record coherence up to seconds** enabling novel capabilities for storage, manipulation, transfer and sensing of quantum information*

THANK YOU

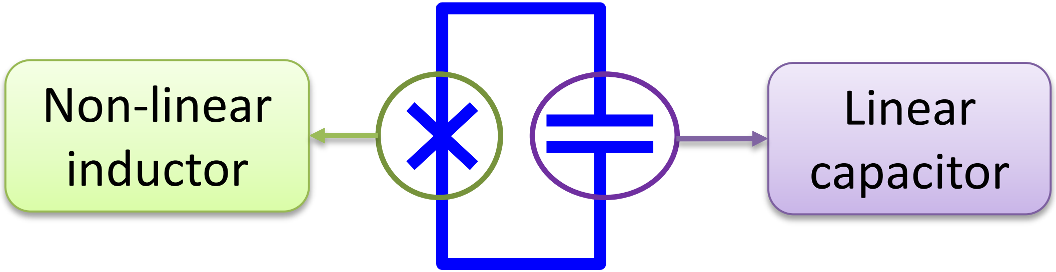
This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359.

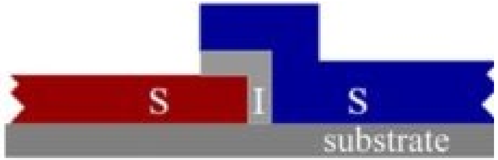
Extra slides

Transmon: Anharmonic Oscillator

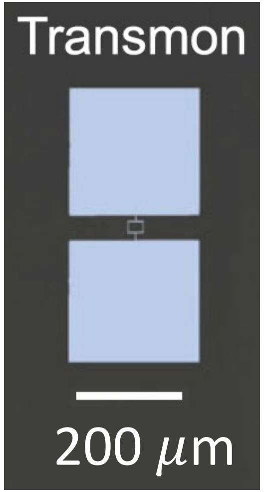


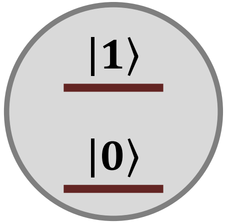
Anharmonic Oscillator





Josephson Junction

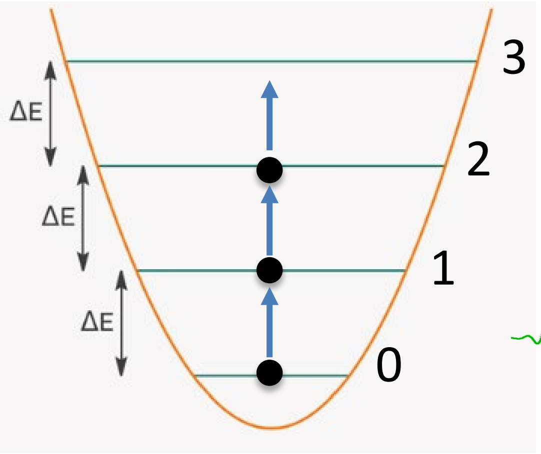


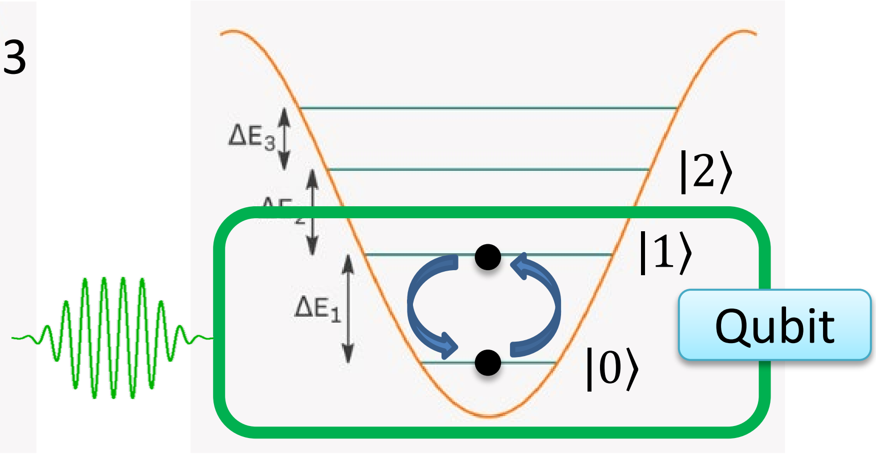


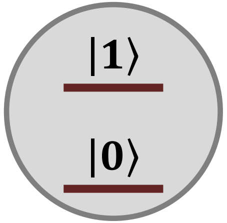
Qubit

Koch *et al.*, PRA 76, 042319

Transmon: Anharmonic Oscillator

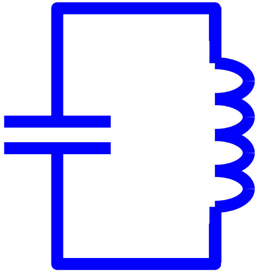


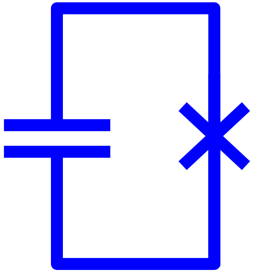




Harmonic Oscillator

Anharmonic Oscillator

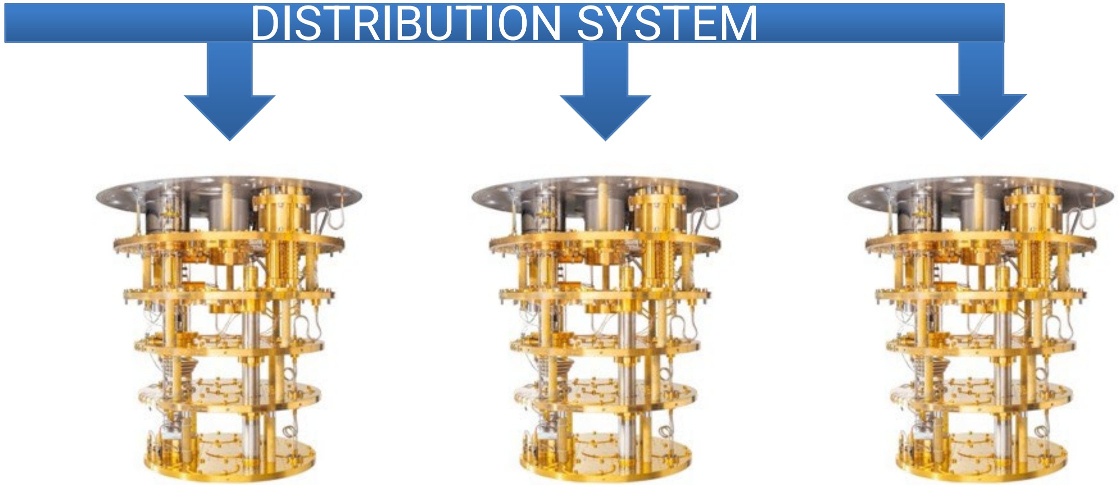




Large scale cryogenics development

- For future large scale quantum data centers, the use of a centralized liquid helium cryogenics plant makes economic sense in terms of energy efficiency.
- SQMS is working with commercial partners and has developed an interface between existing dilution refrigerators and centralized liquid cryogenics plants.

Central liquid helium cryogenics plant



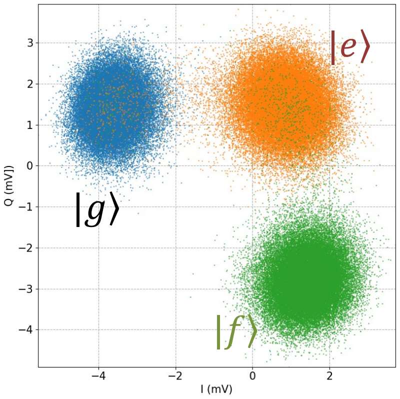
Fermilab

Maybell

IBM

rigetti

Climbing Fock ladder



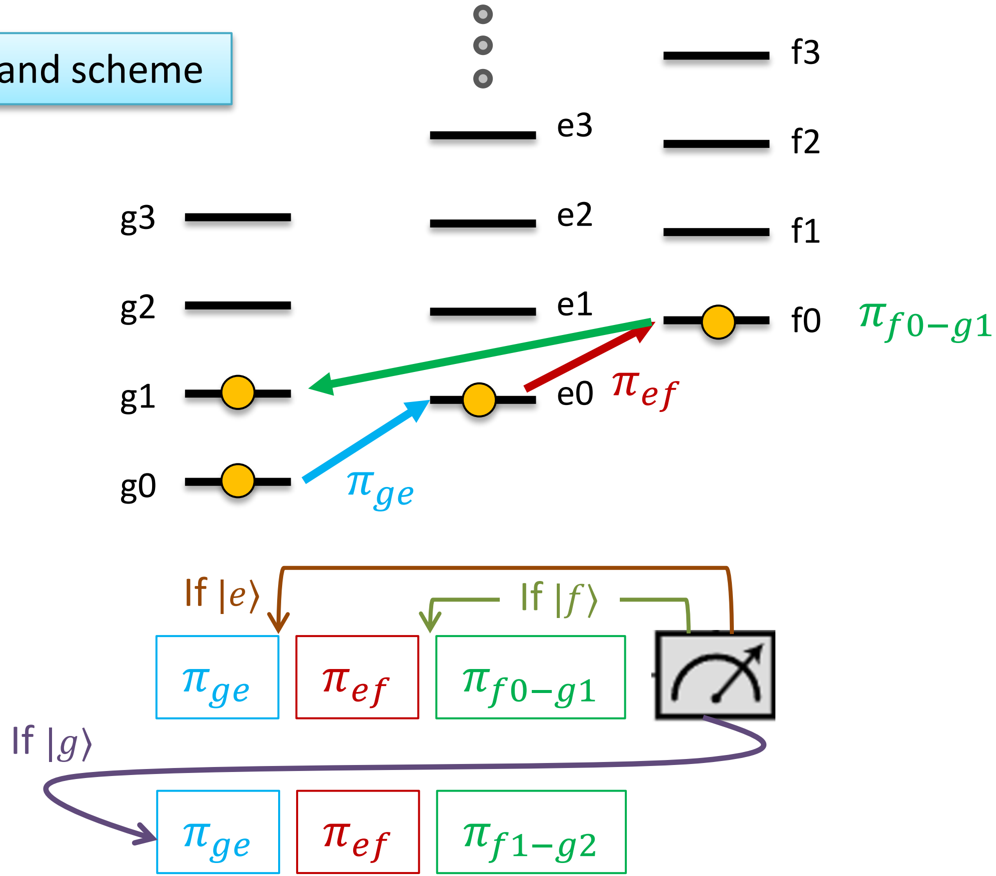
Prepared state / Measured state

	g	e	f
g	0.9978	0.0130	0.0035
e	0.0022	0.9862	0.0190
f	0.0000	0.0008	0.9774

3-state readout $\mathcal{F} = 0.987$

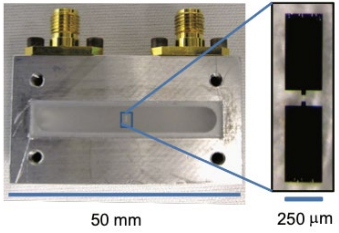
Sideband Feedforward protocol (SFP)

Sideband scheme



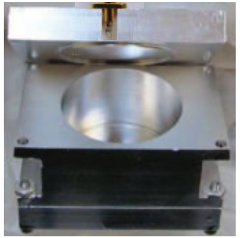
Geometry optimization

Pillbox



PRL **107,** 240501

Cylindrical

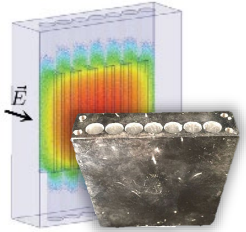


APL **116,** 154002

Stub

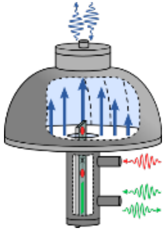
APL **102,** 192604

Flute



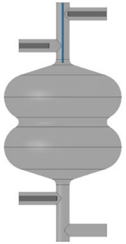
PRL **127,** 107701

Elliptical



PRX Quantum **4,** 030336

Phys. Rev. App. **13,** 034032



arxiv: 2506.03286

Cavity residual surface resistance loss

$$Q_I = \frac{\omega_0}{R_S}\frac{\mu_0 \int_V |H|^2}{\int_S |H|^2} = \frac{G}{R_S}$$

R_S = Surface resistance

Geometry factor [Ω]	
Pillbox:	~200
Cylindrical:	~200
Stub:	~70
Flute:	~70
Mushroom elliptical:	~210
Single-cell elliptical:	~270
Two-cell elliptical:	**~300**

Elliptical geometries show larger G factors

SRF cavity based versatile quantum platform

2 levels

Qubit

$|1\rangle$ —

$|0\rangle$ —

d >2 levels

Qudit

— $|d\rangle$

⋮

— $|2\rangle$

— $|1\rangle$

— $|0\rangle$

Enhanced information density and encodings

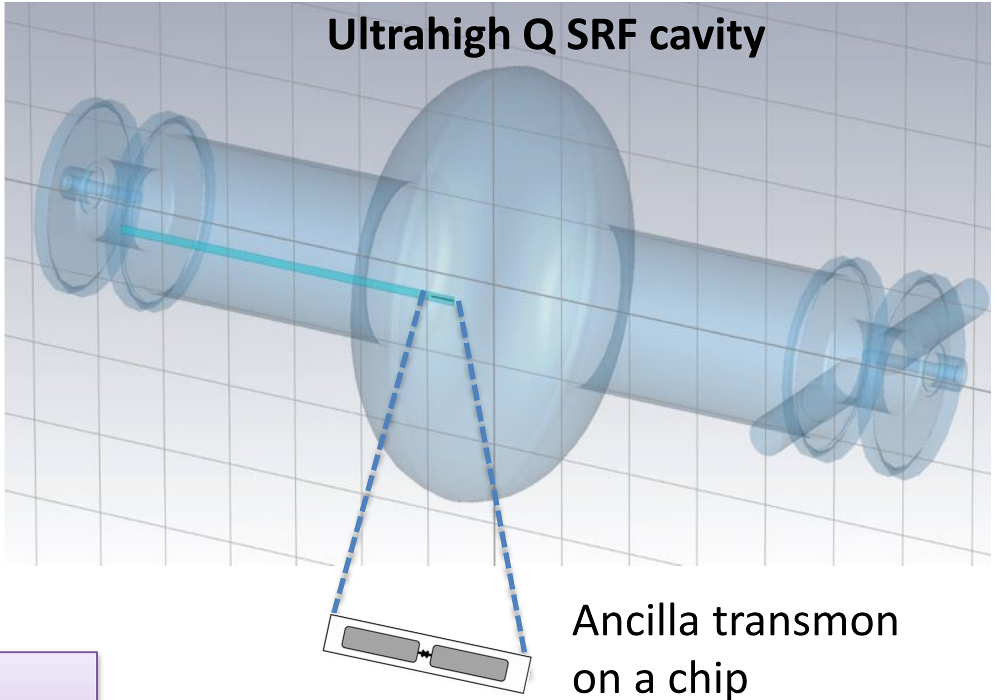
Qudits for computing

Qudits for Sensing

Qudits for Communication

PRL **94,** 230502
Optical Physics **71,** 052318
and others

Chemical reviews 119, **10856**
Frontiers in Physics 8, **589504**
and others

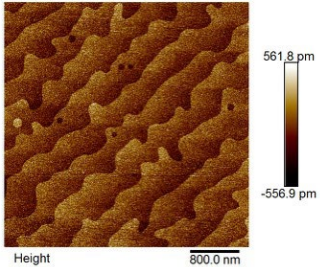


Maximize coherence of the joint system

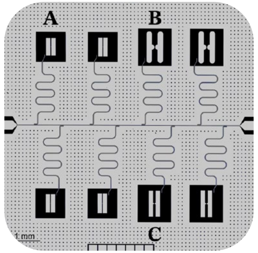
SRF cavity based versatile quantum platform

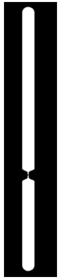
Improve cavity Q

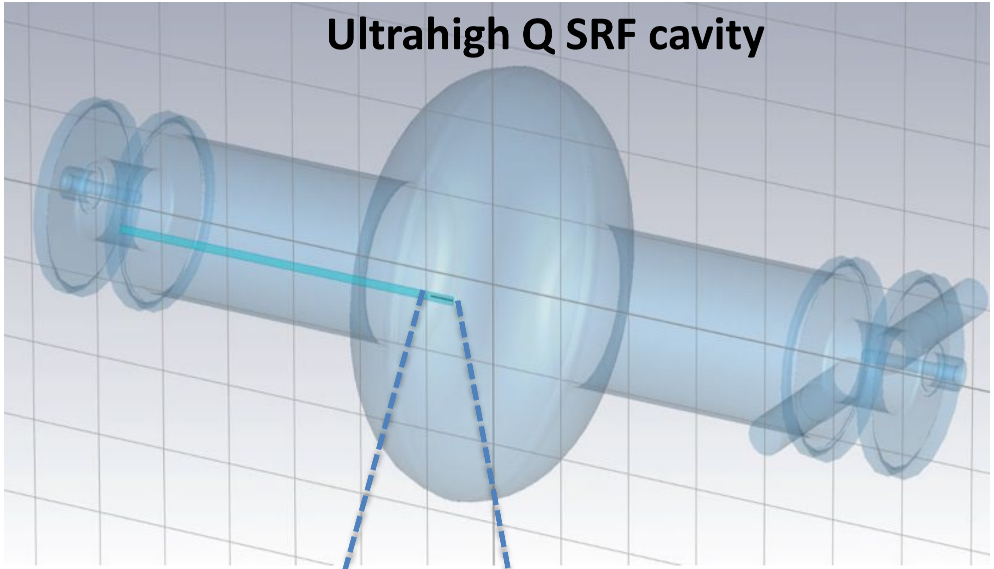
Improve substrate

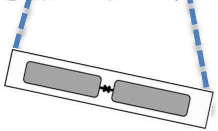


Improve transmon Q







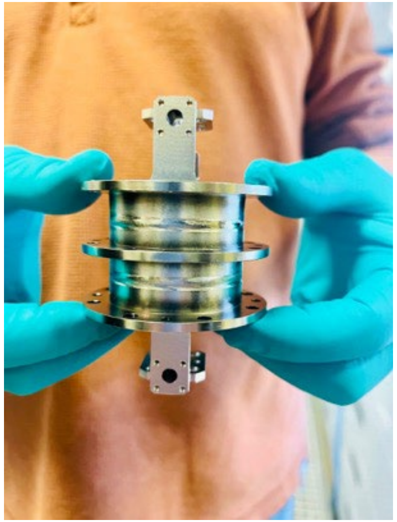


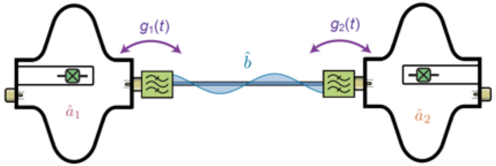
Ancilla transmon on a chip

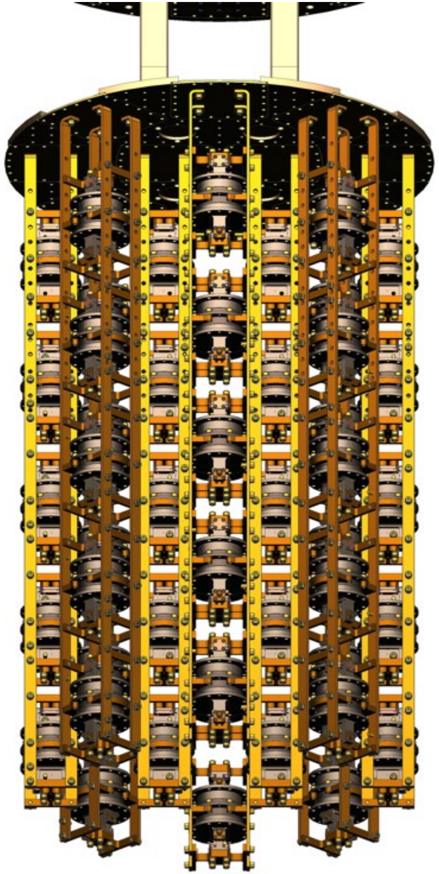
Maximize coherence of the joint system

Next steps in 3D architecture

- This high fidelity qudit unit will serve as building block for our first mid-scale 3D quantum computing platform ~ 100 qudits
- Work will continue in parallel to optimize the unit / building block (more cells, more modes etc)
- Second two cell cavity ready, work on interconnects
- *d* ~ 32, 50 cavities, 2 qudits each > 500 qubit equivalent







Talk Outline