FERMILAB-SLIDES-23-030-SQMS

Advances in quantum computing and sensing using SRF technology

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SQMS division, Fermilab

15 April 2023

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SQMS

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>450 Collaborators

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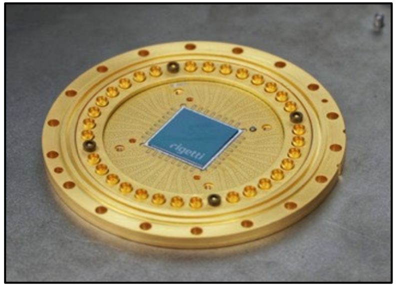
IQC Institute for Quantum Computing

A rich ecosystem, multi-institutional and multidisciplinary collaboration leveraging investments at DOE national labs, academia, industry and several other federal and international entities

SQMS Mission



SQMS Mission

“bring together the power of national labs, industry and academia to achieve transformational advances in the QIS **major cross-cutting challenge** of **understanding** and **eliminating** the **decoherence** mechanisms in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior quantum systems for computing and sensing."

SQMS Center Research

SRF high Q devices

FNAL

Superconducting qubits

Rigetti, NIST, NU, FNAL, INFN, Colorado Boulder, Rutgers, NPL, RHUL

Theory and Applied Superconductivity

FNAL, NU, Temple, IIT, LSU

Material Science

Ames Lab, NU, FNAL

Enabling thrust: Quantum Technology

Focus Area 1
Materials for 2D and 3D Quantum Devices

Focus Area 2
Devices Integration, Prototypes and QPU

Scale up and integration

FNAL, Rigetti

Cryogenics

FNAL, NU, Royal Holloway, Form Factor

Controls and electronics

Rigetti, NIST, NU, FNAL

Co-design Cycle

Application thrust: Quantum Science

Focus Area 3
Quantum Physics and Sensing

Focus Area 4
Algorithms, Simulations and Benchmarking

Particle Physics

FNAL, UIUC, Stanford, INFN, John Hopkins

Computational Science, QIS Theory

NASA Ames, Colorado Mines, Rigetti, NU, Arizona

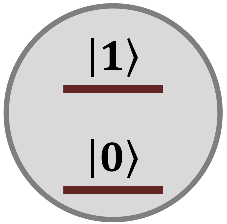
Condensed Matter Physics

Ames Lab, NU, NASA Ames, LSU

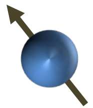
Industry use cases

Goldman Sachs, Lockheed Martin, Rigetti, NYU

Basic Requirements

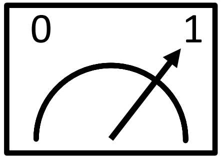


Quantum two level systems

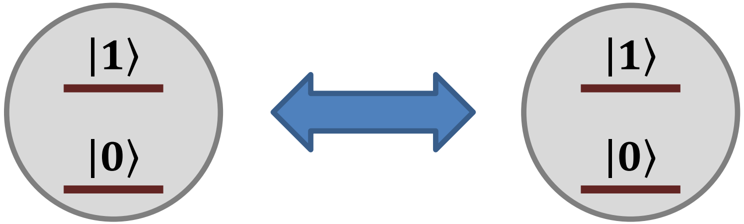


$\alpha|0\rangle + \beta|1\rangle$

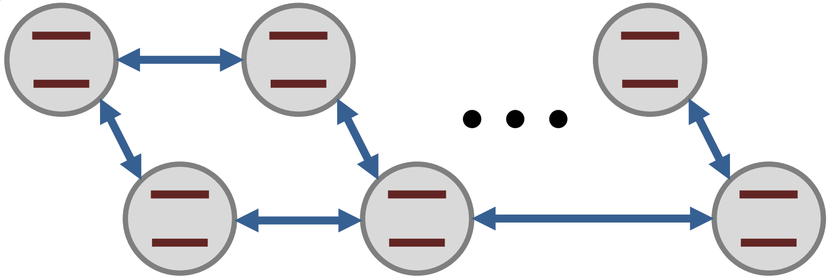
Create arbitrary states



Measure quantum states



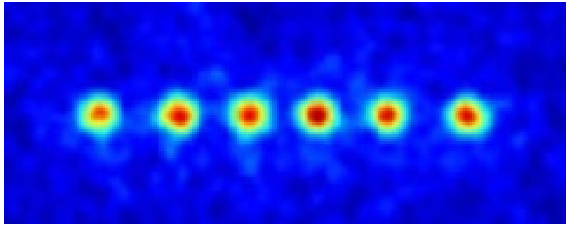
Couple multiple qubits



Scalable architecture

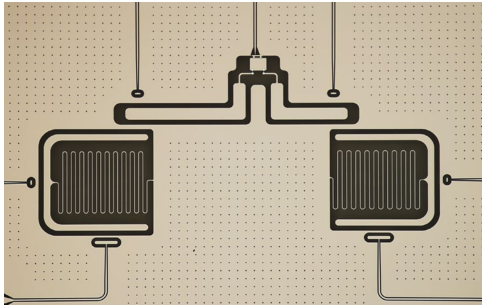
Qubit Implementations

Ion traps



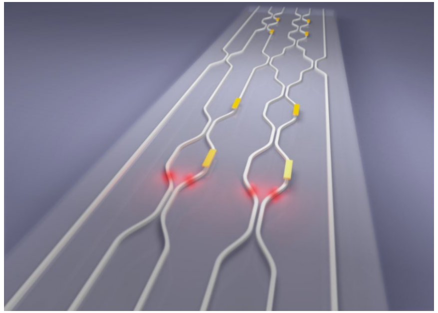
quantumoptics.at

Superconducting qubits



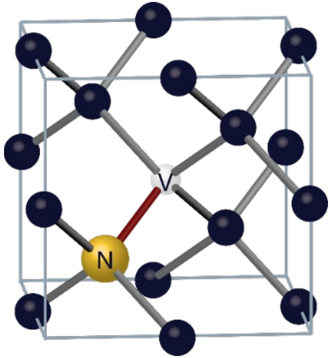
Schuster lab

Photonic crystals



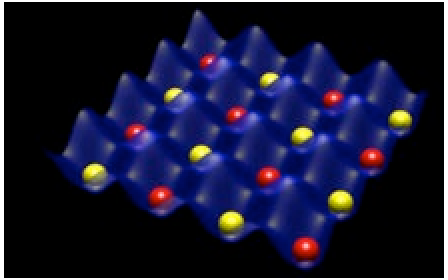
phys.org

NV centers



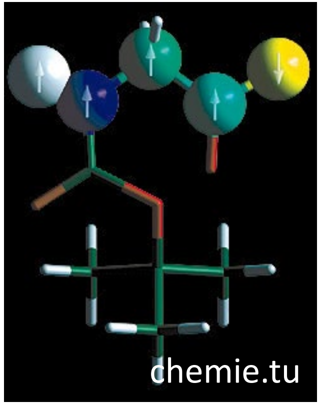
phys.org

Neutral atoms

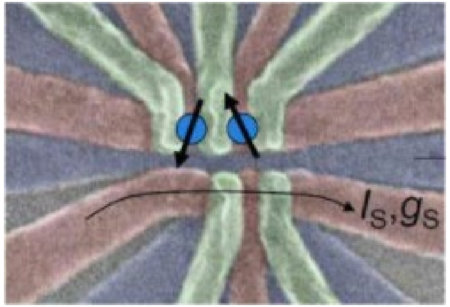


NIST

NMR

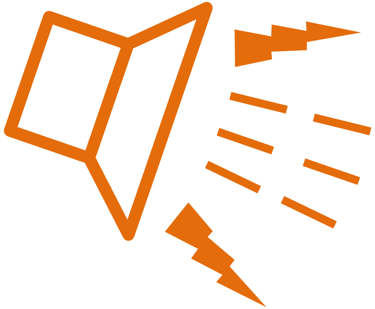


Quantum dots



sciencemag.org

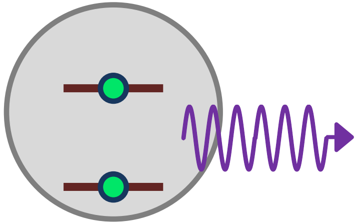
Limited Coherence



Noise

Decoherence

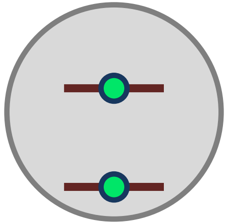
Relaxation (T_1)



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

$|0\rangle$

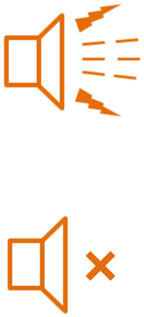
Dephasing (T_ϕ)

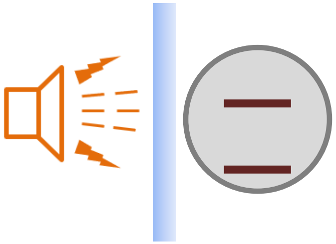


$|0\rangle + e^{i\phi}\,|1\rangle$

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

Protection from Noise





① Reduce noise sources

- Materials
- Fabrication
- EM environment engineering

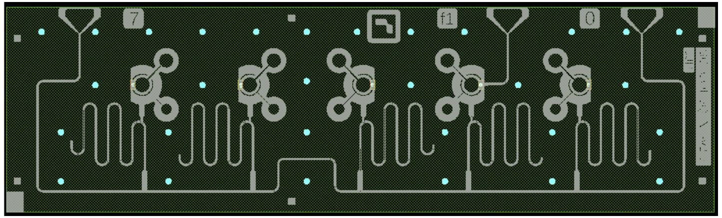
② Intrinsic noise protection

- Hamiltonian insensitive to noise

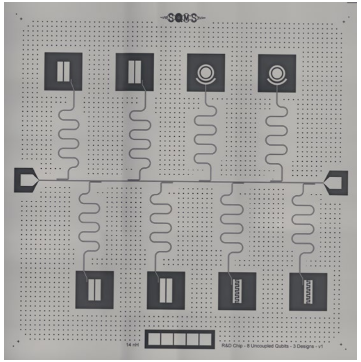
③ Quantum error correction

- Detect and correct error
- Feedback based
- Autonomous

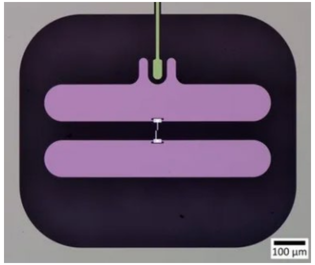
Focus Area 1: Understanding Materials



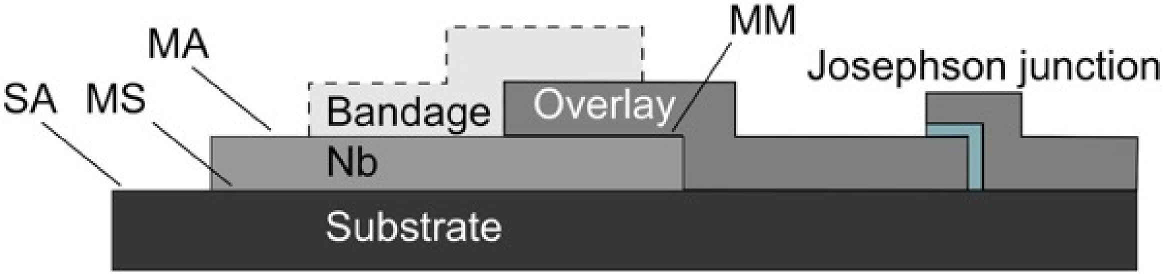
Rigetti



SQMS



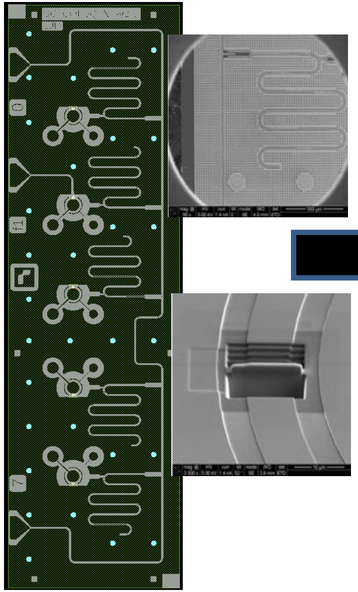
Houck lab



Systematic study of loss sources

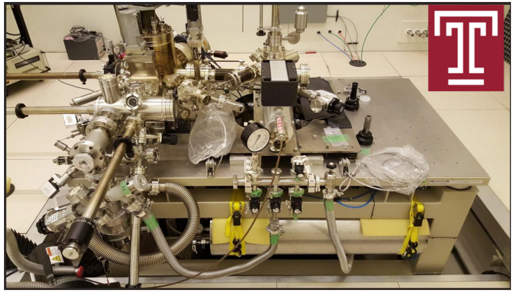
1. Koch, J. *et al.* Physical Review A **76**, 042319 (2007)
2. Wenner, J. *et al.* Applied Physics Letters **99**, 113513 (2011)
3. Wang et al. Appl. Phys. Lett. 107, 162601 (2015)
4. Calusine, G. *et al.* Applied Physics Letters **112**, 062601 (2018)

Physical / Superconductivity Characterization

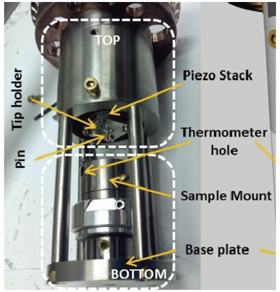


Study the ‘good vs bad’ performing qubit fragments

PPMS- AFM/MFM

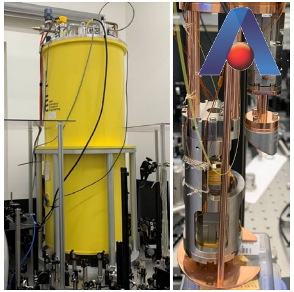


STM

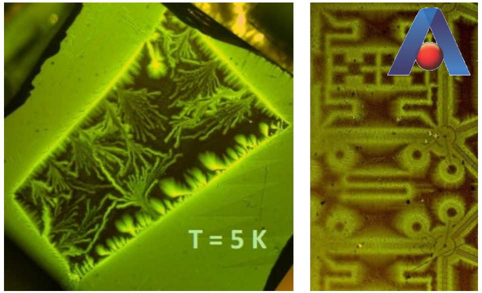


ILLINOIS INSTITUTE OF TECHNOLOGY

Point-Contact Tunneling



THz Spectroscopy



Magneto-optical

TRIUMF

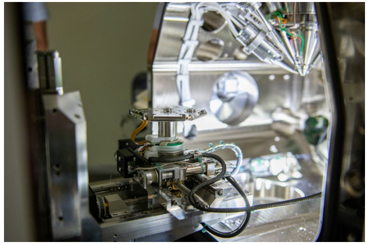
PAUL SCHERRER INSTITUT

PSI

β-NMR/μSR

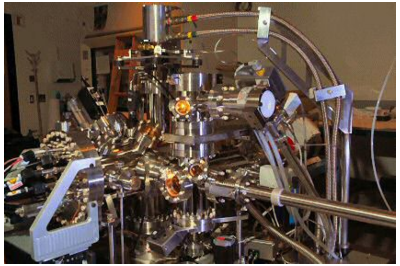
Structural / Chemical Characterization

Electron Microscopy



XRR/XRD

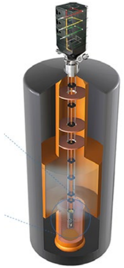
APT



TOF-SIMS

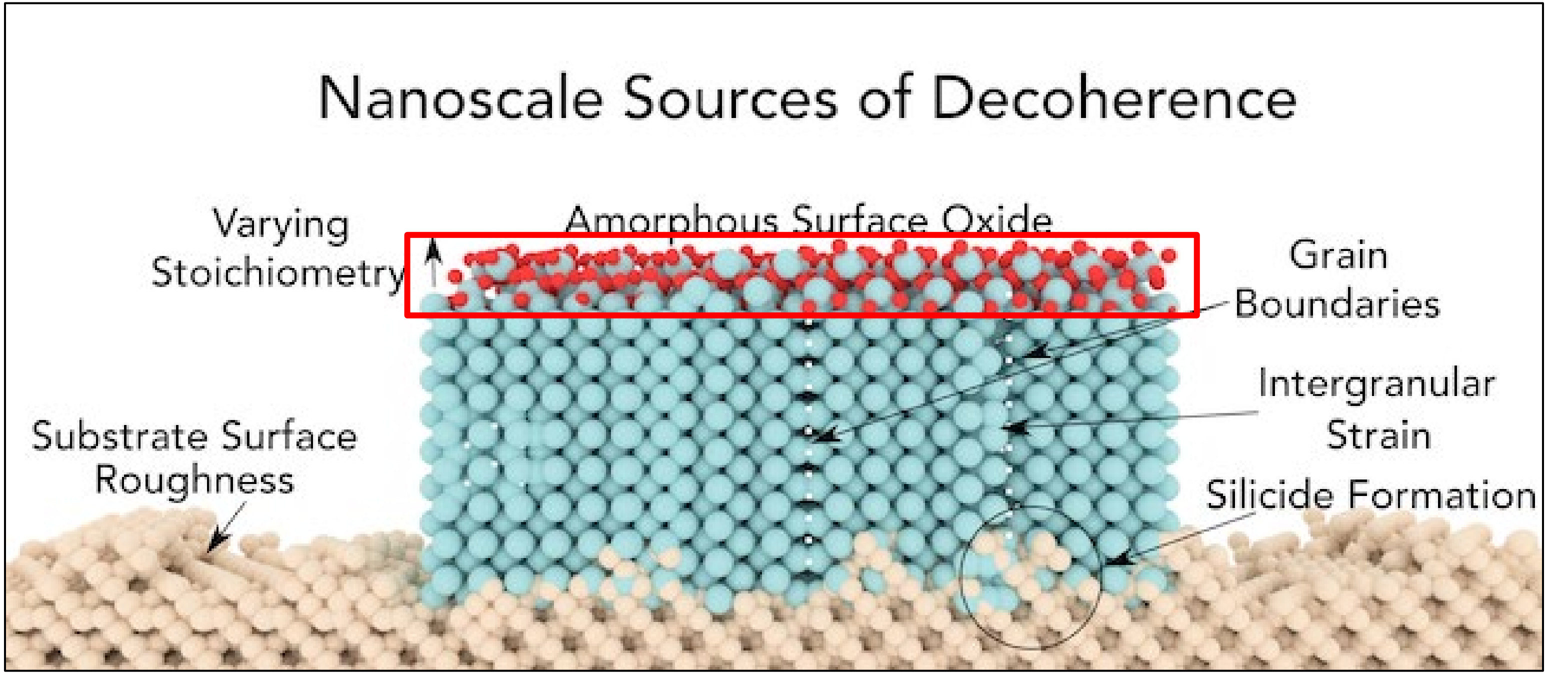
XPS

AFM/MFM



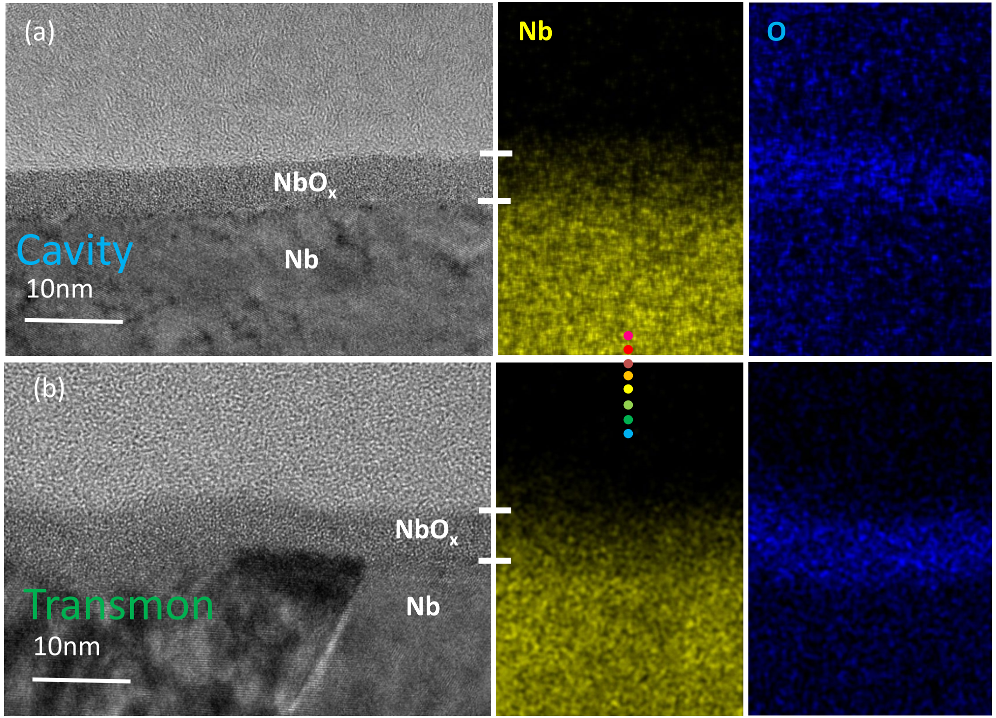
Raman

Metal-air Interface



Presence of Niobium Oxide

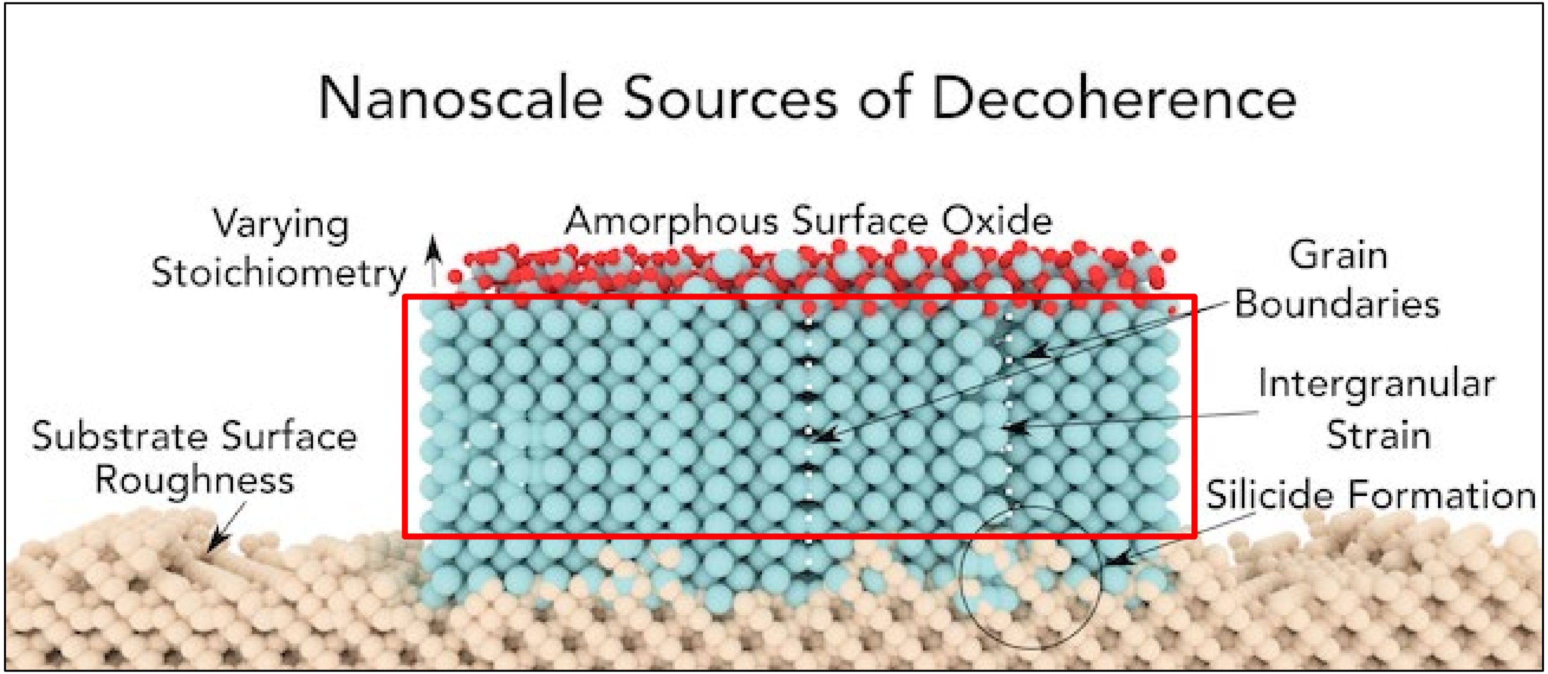
- Multi-institute study of 2D qubit fragments confirming
  - Thickness
  - Composition
  - Mostly amorphous structure - Nb_2O_5
  - Is almost identical to SRF cavities



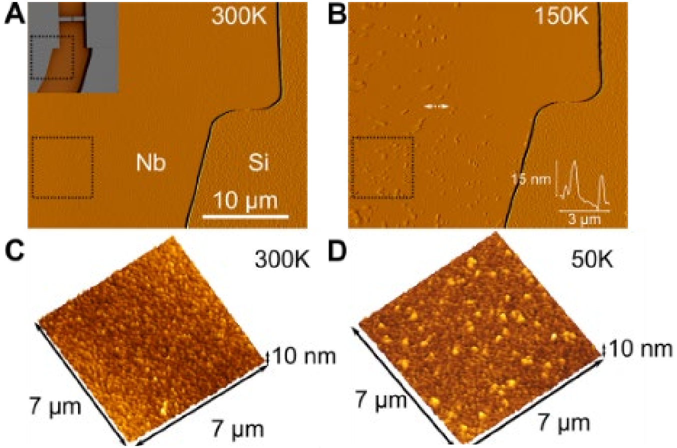
X. Fang et al., *Materials Research Letters*, **11**, 2, 108-116, (2023)

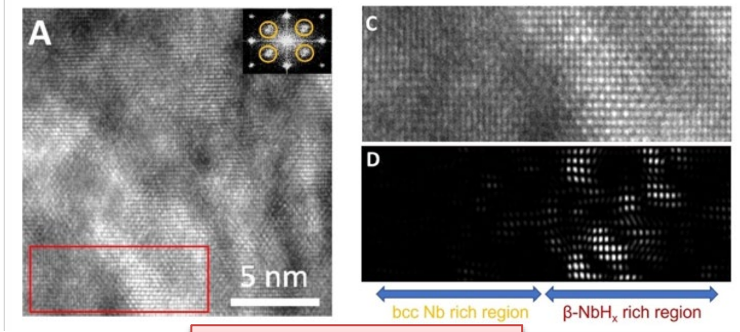
A. A. Murthy et al., *ACS Nano* **16**, 10, 17257−17262 (2022).

Deposited Metal

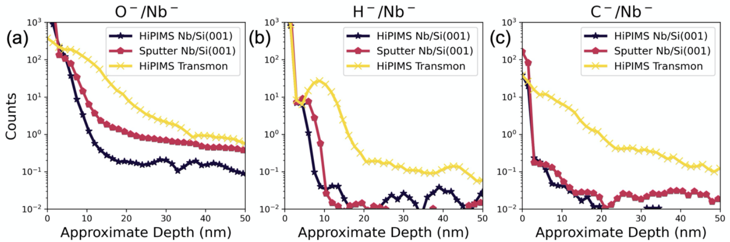


Impurities in Superconducting Films

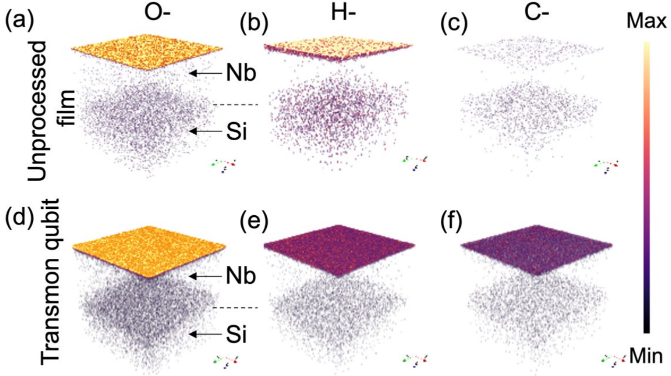




Presence of NbH



Depth Profiles of impurities in Nb film

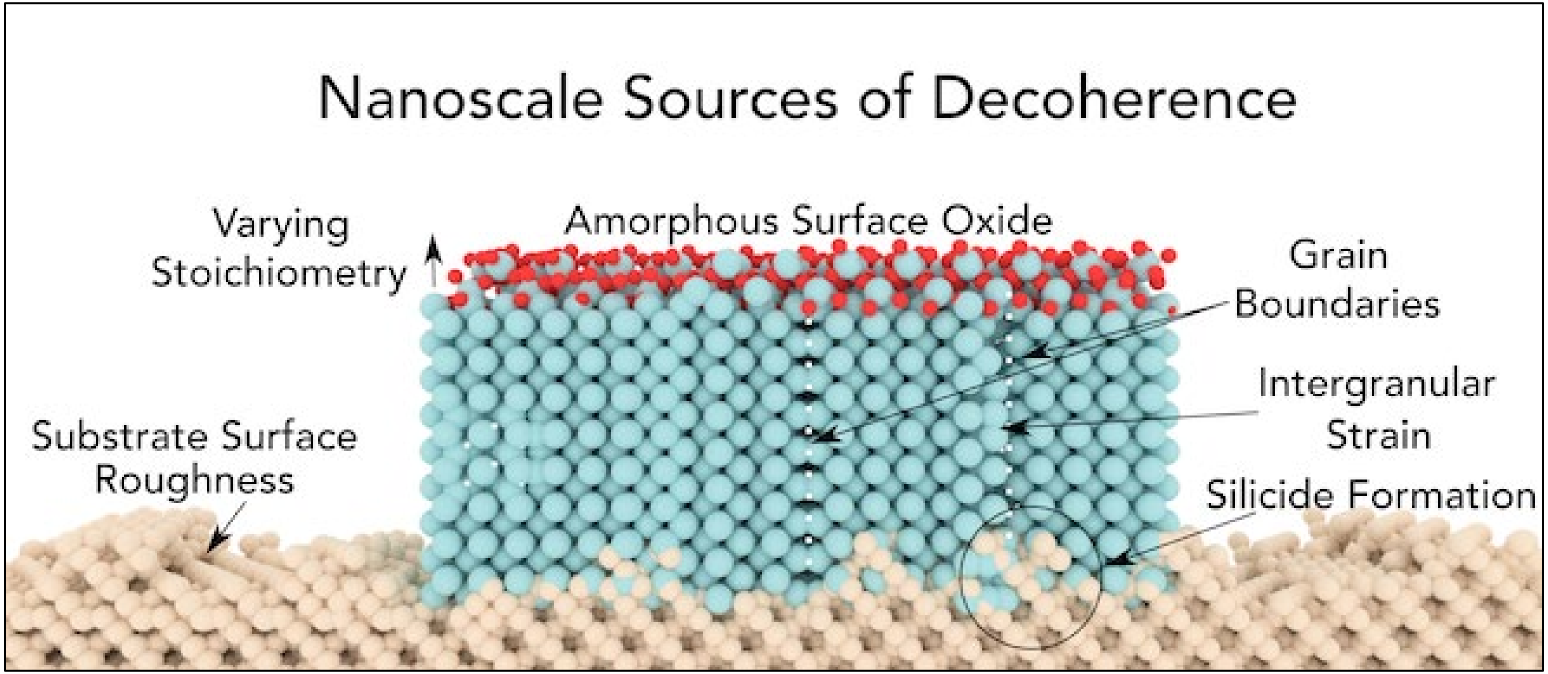


3D representation of impurity concentrations

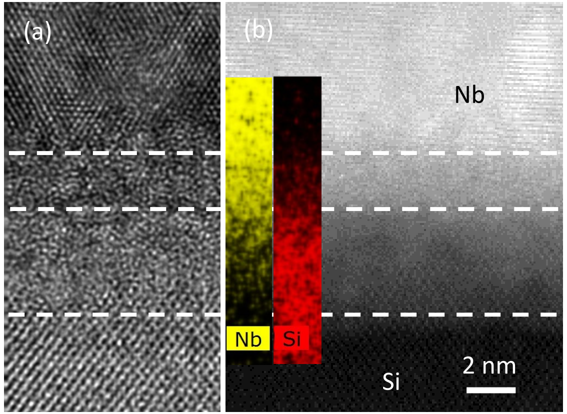
Presence of O^-, H^-, C^-, Cl^-, F^-, Na^+, Mg^+, and Ca^+

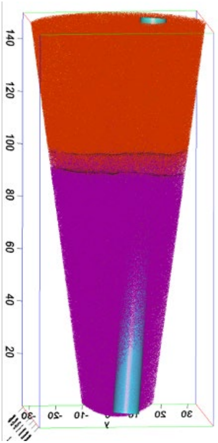
Lee et al. arxiv 2108.10385
Murthy et al. APL **120** (4), 044002 (2022)

Metal-substrate Interface

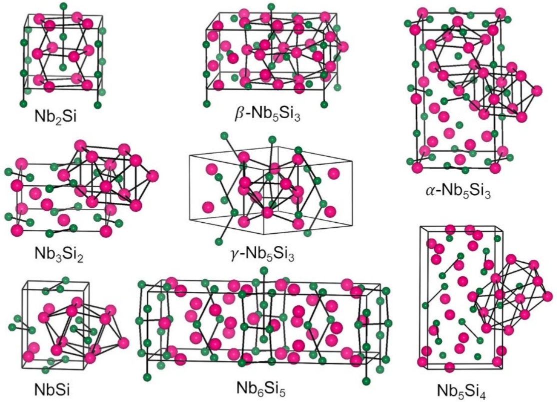


Niobium-Silicon Interface





Presence of Nb_xSi_y



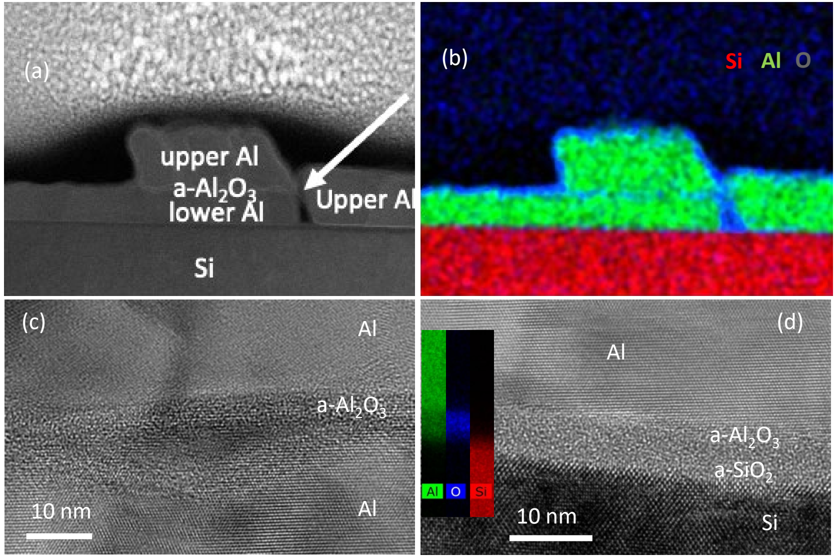
Ongoing effort on understanding lossy silicides

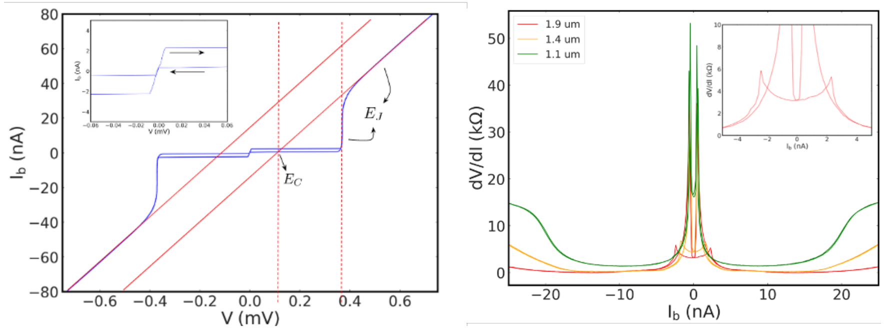
X. Fang et al., *Materials Research Letters*, **11**, 2, 108-116, (2023)
X. Lu et al., *Phys. Rev. Mater.* **6**, 064402 (2022).

Josephson Junction Features

- $Al/Al_2O_3/Al$ interface is wavy
- Amorphous AlO_x and amorphous SiO_x layer at Al/Si interface
- Junction fabrication scheme can introduce defects

- Noise-optimized dc transport measurements to determine qubit JJ critical parameters
- Switching current much less than expected critical current





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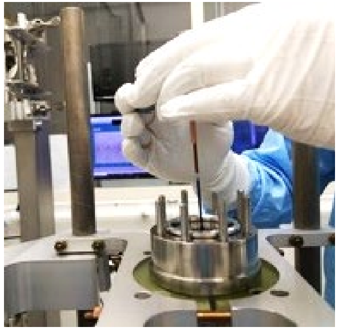
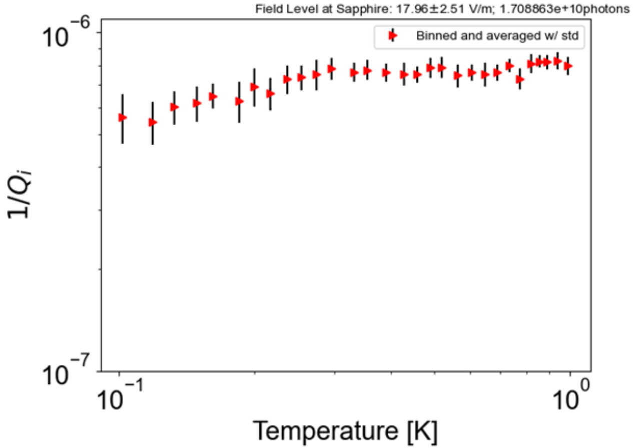
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Substrates Testing

Example: Silicon sample mounted on the cavity flange



SRF Cavity with sample inside



Sapphire is better than Si, evaluating several vendors

Examining every aspect of device materials

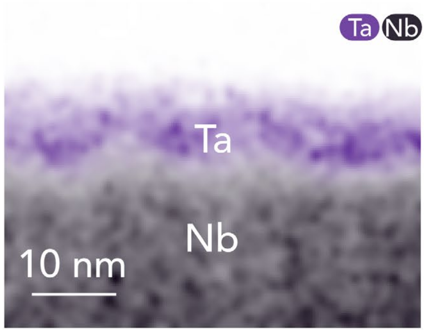
Publication in preparation

Mitigation of Lossy Oxides

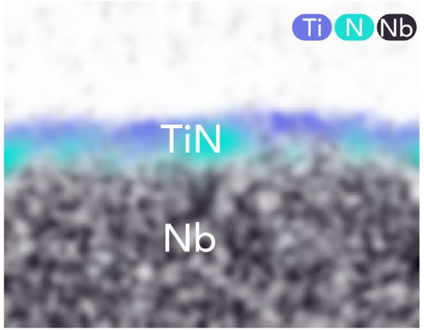
Introduce encapsulating layer

- Thin (~5-10 nm) => small contribution to conductive losses
- But TLS-hosting dissipative surface Nb2O5 is absent => improved coherence

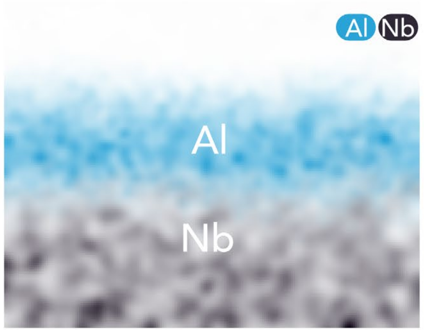
Method 1

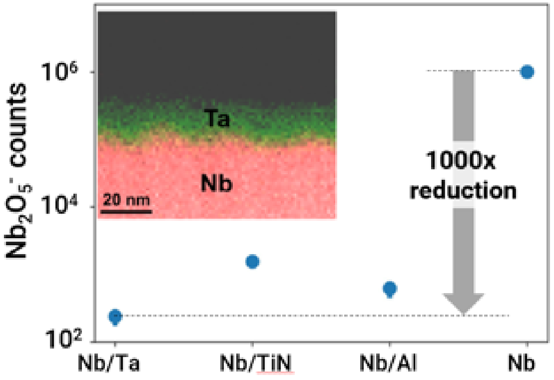


Method 2



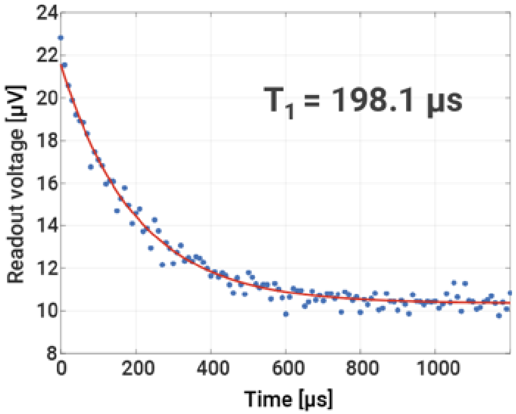
Method 3

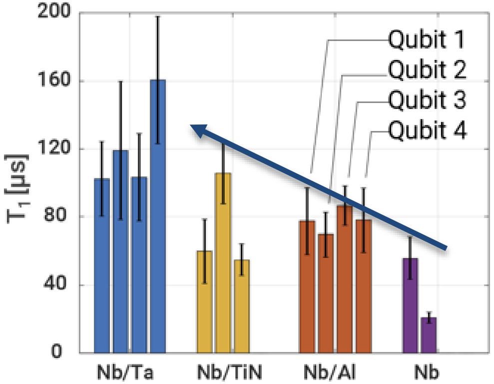




Improved Performance

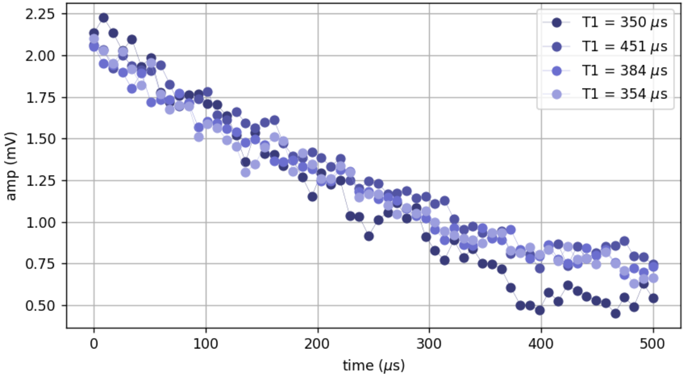
FNAL:

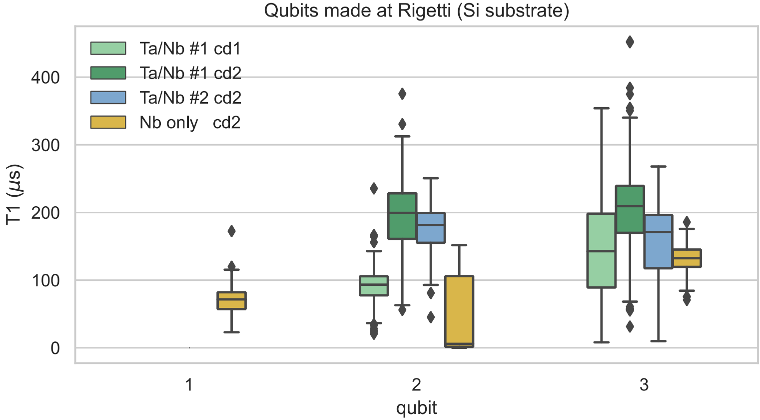




T_1 improved by 3-5x

Rigetti:





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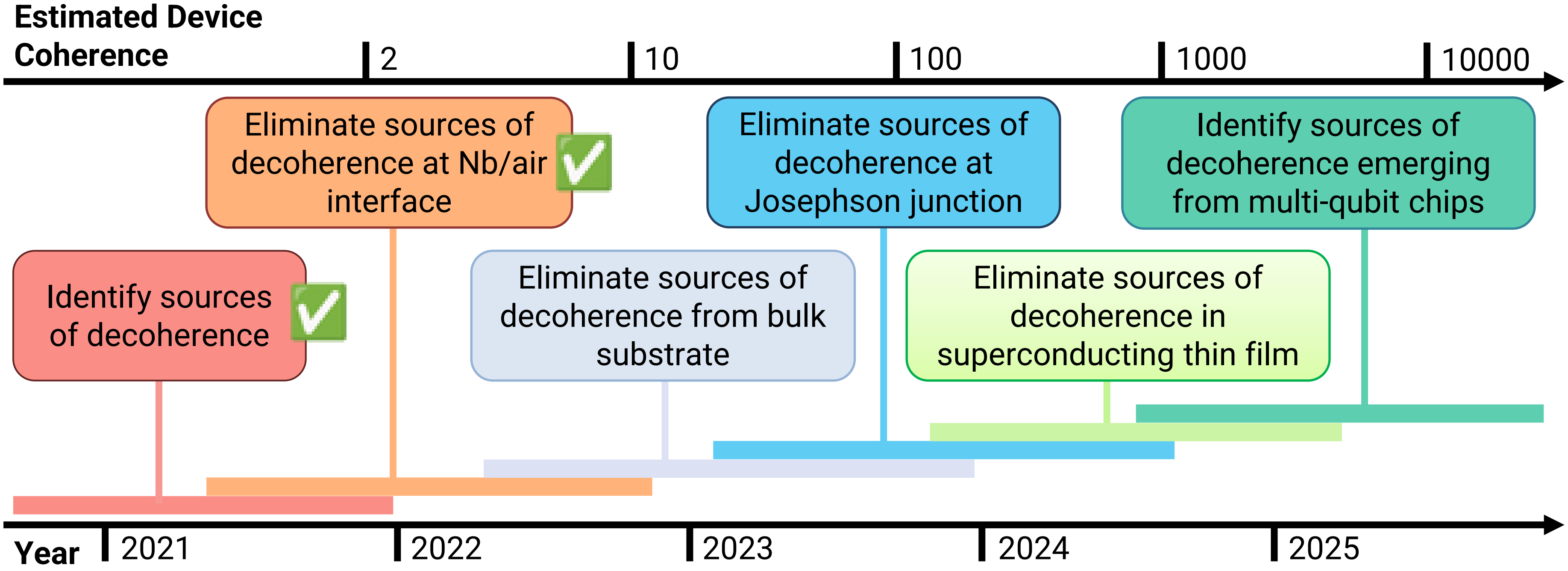
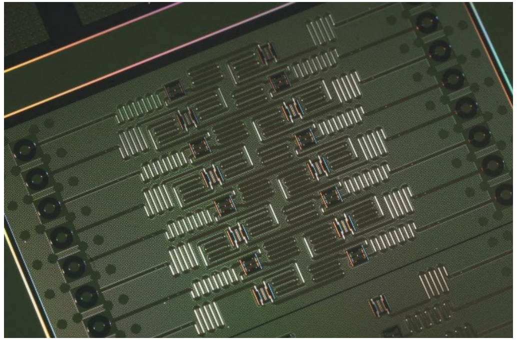
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

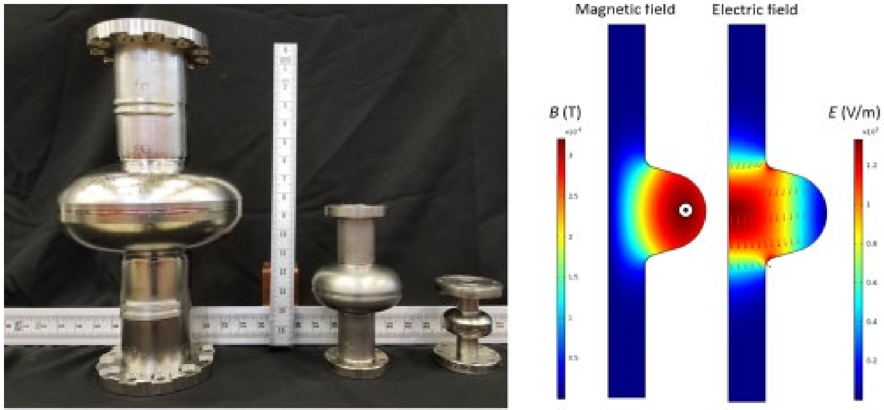
2D Qubit Materials Roadmap

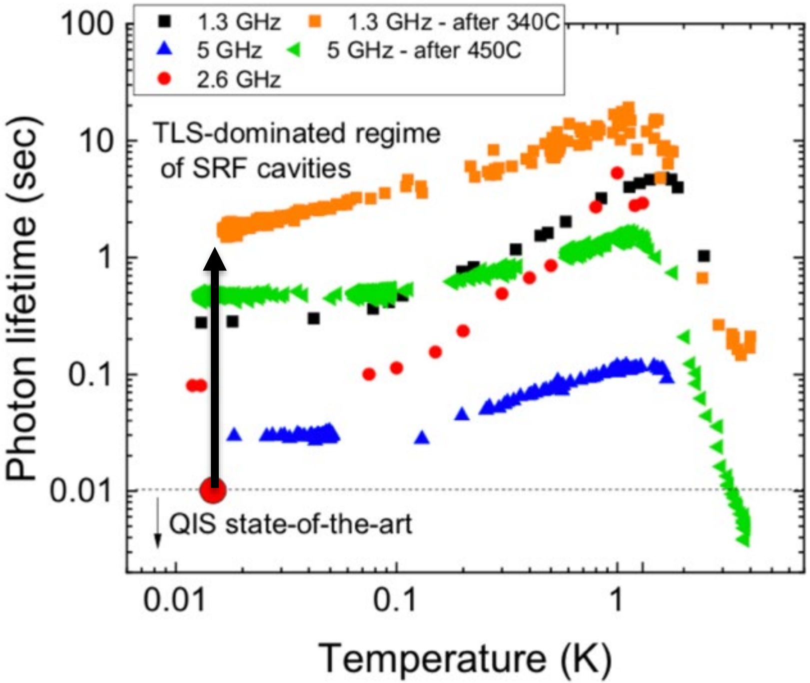


Focus Area 2: 3D QPU Architecture



IBM





Cavity T_1>1 sec

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

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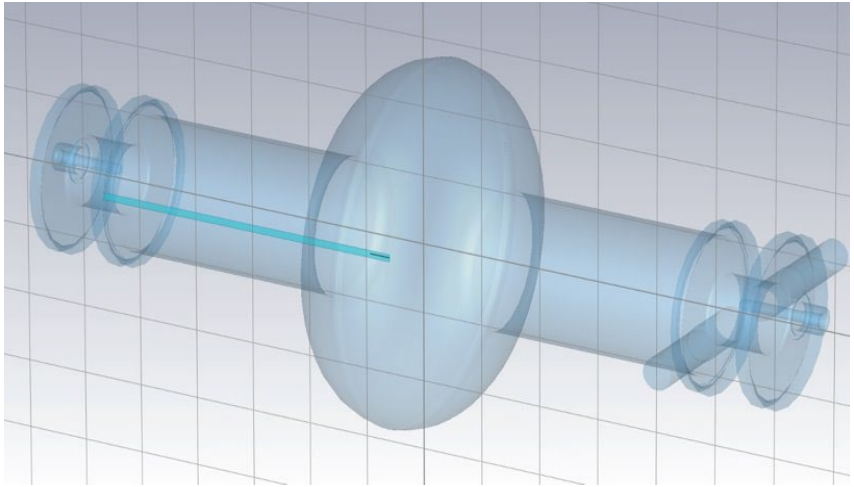
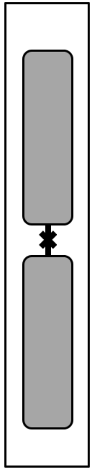
Quantum Control of SRF Cavities



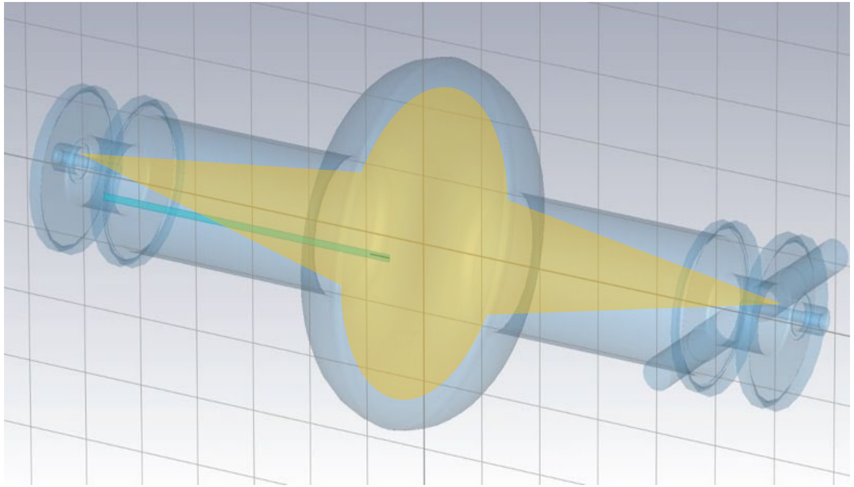


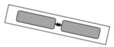
Tanay Roy - Fermilab

Quantum Control of SRF Cavities

3d

EM mode coupled
to transmon

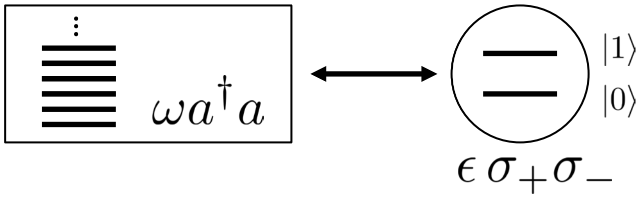




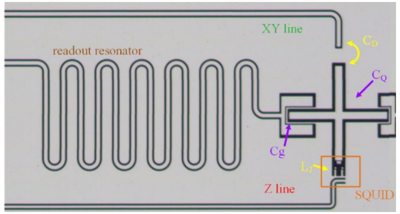
Minimal description:
Jaynes-Cummings model

oscillator

qubit



2D

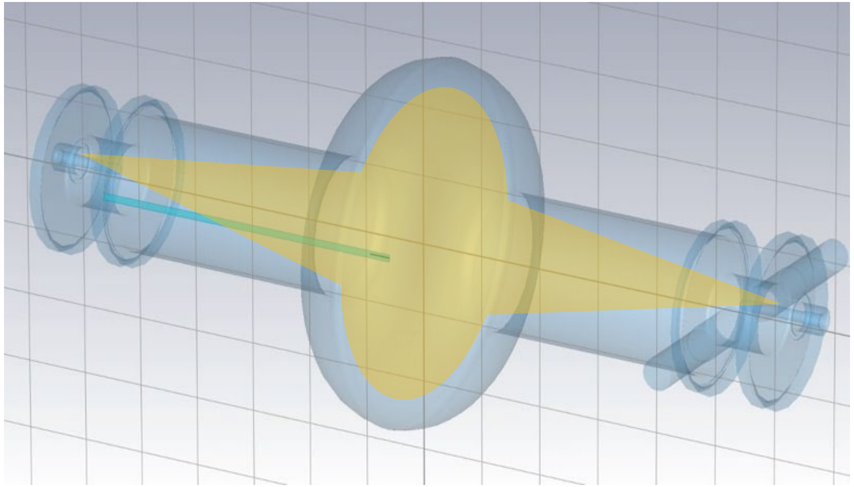


Transmon stores quantum info,
Cavity used for driving & readout

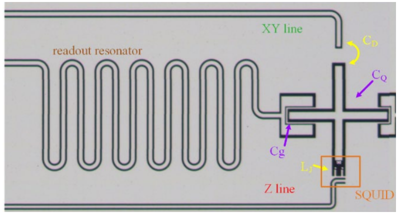
Quantum Control of SRF Cavities

3D

EM mode coupled
to transmon



2D



Minimal description:
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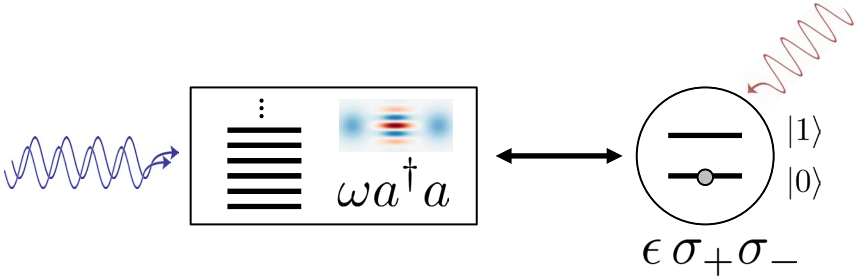
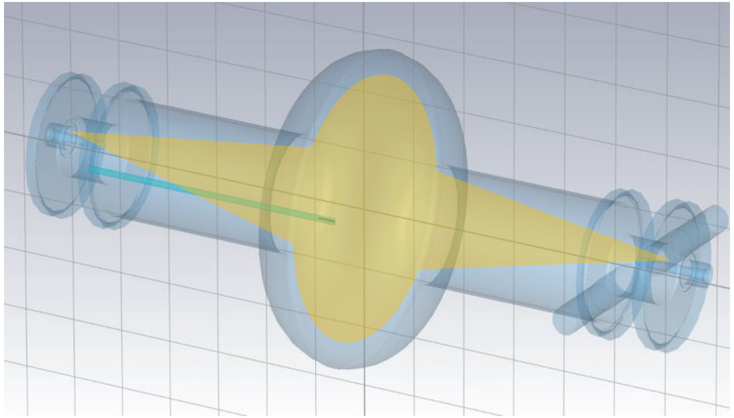


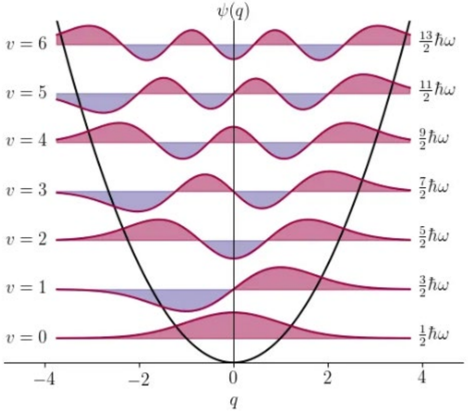
Cavity stores quantum info,
Transmon used for driving & readout

Transmon stores quantum info,
Cavity used for driving & readout

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

New Approach: Qudit

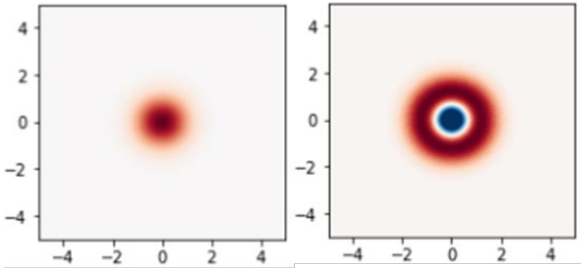


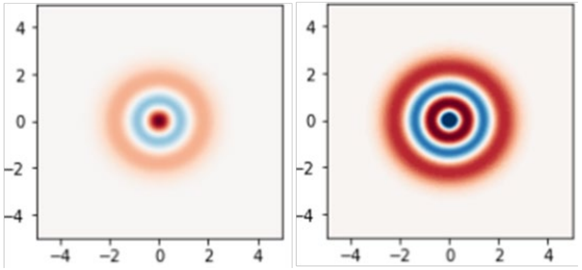


$\log_2 d$ qubits

4-levels: Ququart

2 qubits

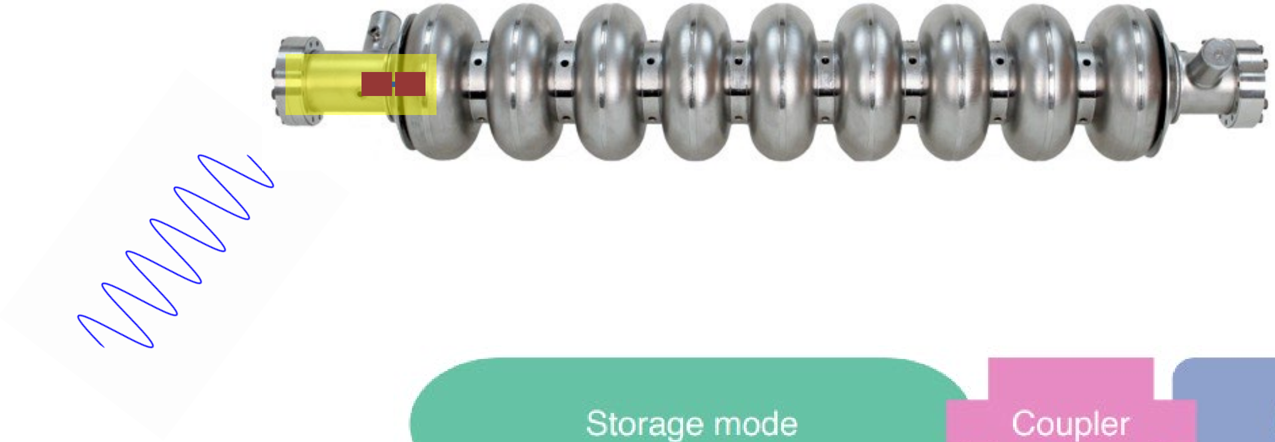




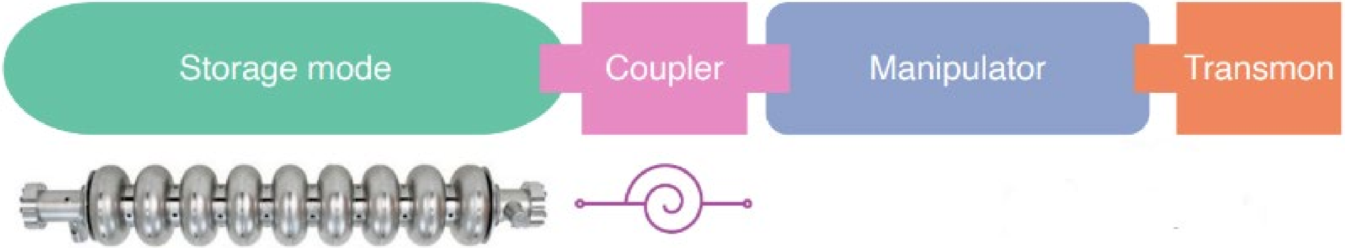
8-levels: Quoct

3 qubits

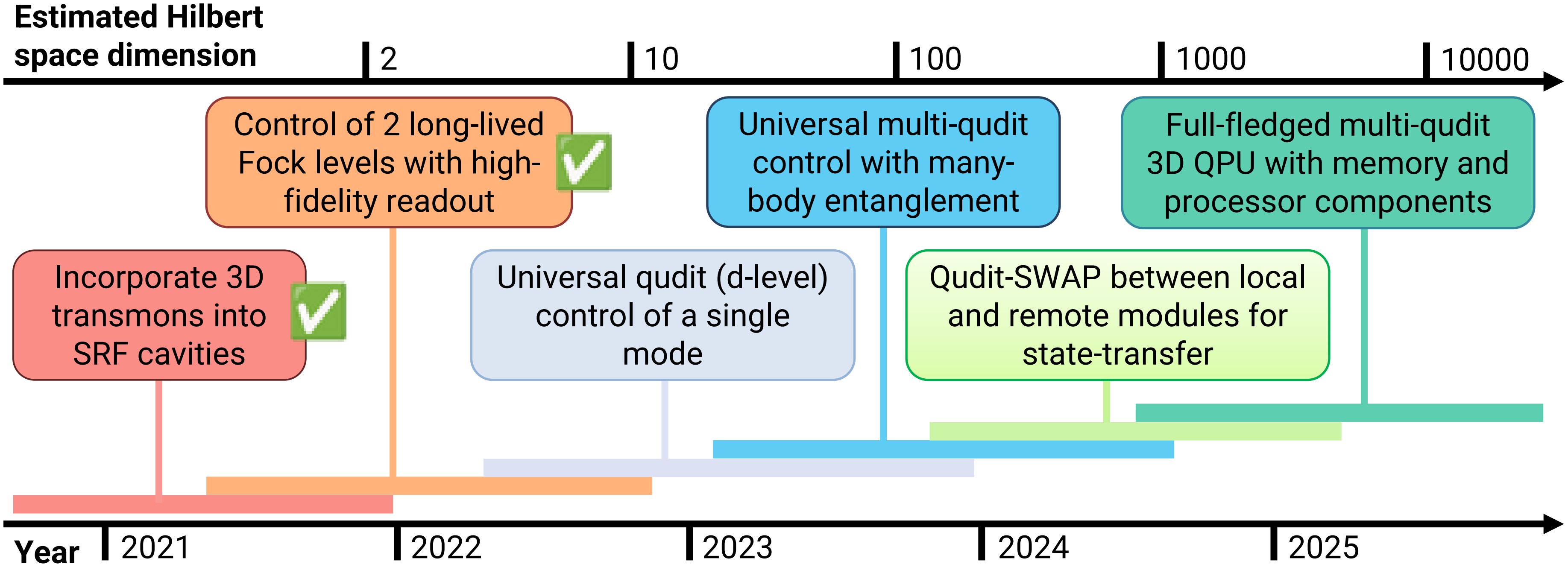
Multi-qudit Architecture



Scaling: d^N

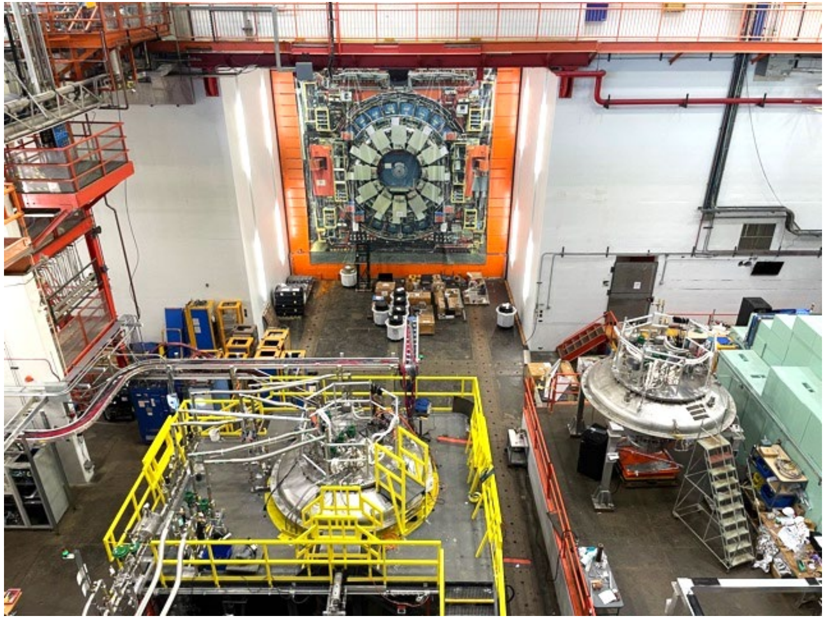


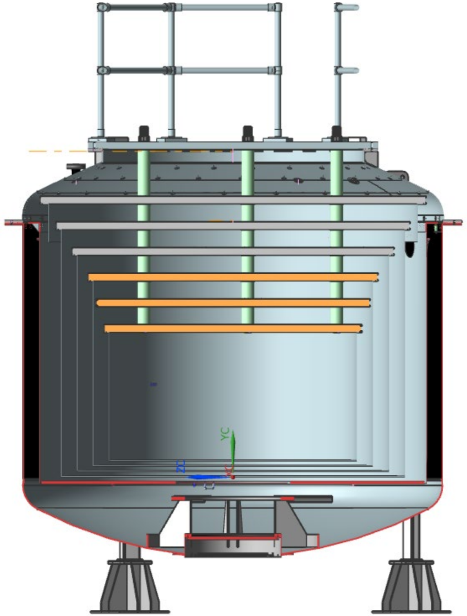
3D QPU Roadmap



Large Cryogenic Facilities

Central liquid
He plant

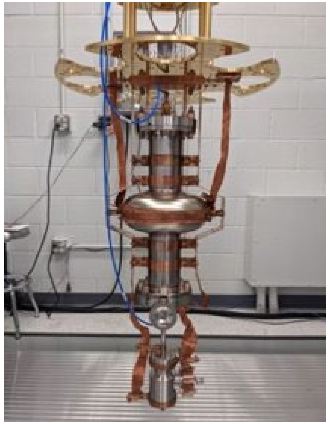


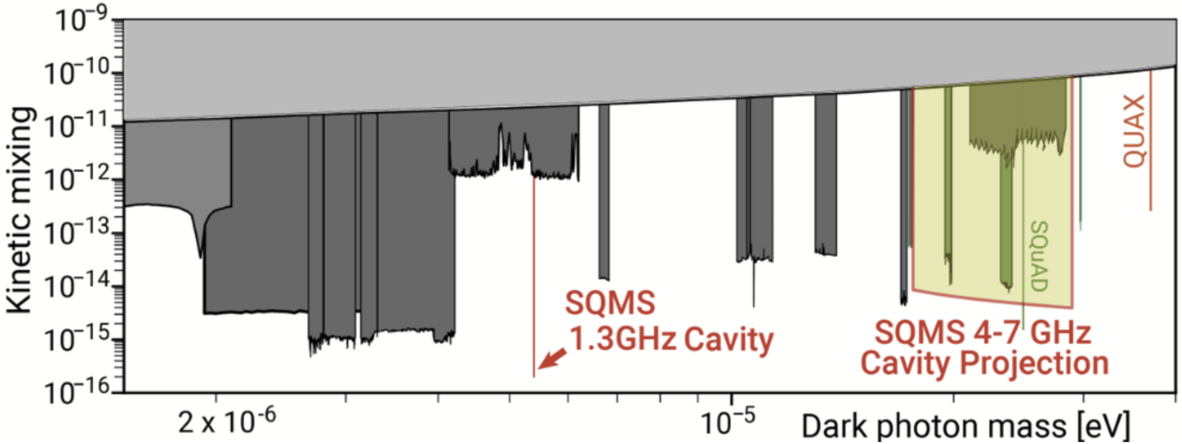


Colossus

Substantial interest from IBM, Rigetti, Form Factor etc.

Ultrahigh Q Cavity for Dark Photon DM Search





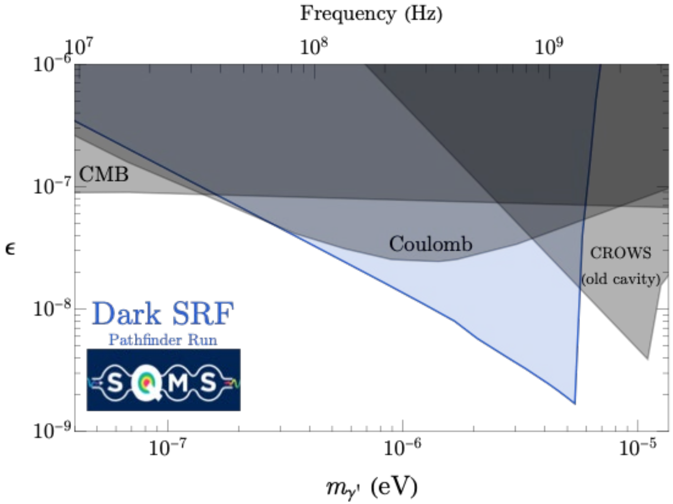
Cervantes et al., arxiv:2208.03183

DPDM search with 1.3 GHz cavity with $Q_L \approx 10^{10}$.
Deepest exclusion to wavelike DPDM by an order of magnitude.

Dark SRF: Cavity-based Dark Photon Search

A "light-shining-through-wall" experiment

Phase 1: Pathfinder run in LHe. Demonstrated enormous potential for SRF based searches.



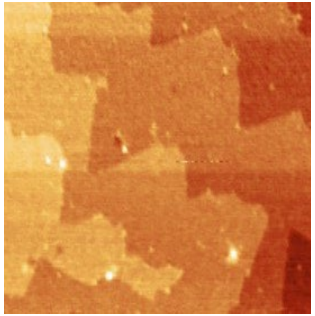
Phase 2: in DR, receiver at ~mk, in quantum regime. Improved frequency stability. Phase sensitive readout.

Will increase the search reach.

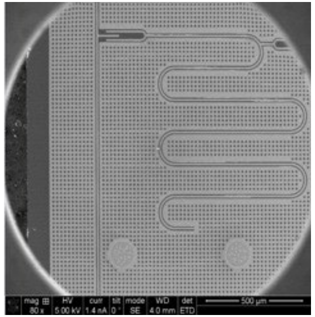
Romanenko et al., arXiv:2301.11512 (2023), in review in PRL.

Summary

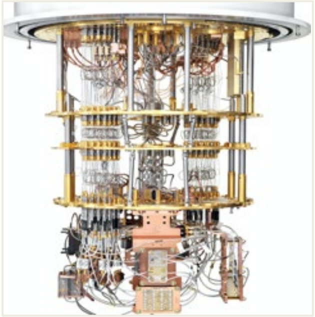
Materials | High-coherence devices | Systems integration | New platforms for quantum computing & sensing | Quantum advantage



Developing a full understanding of sources of decoherence via a systematic, fundamental science approach

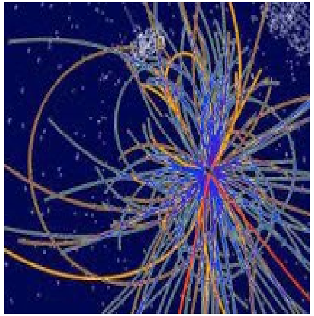


Demonstrating devices with systematically and consistently higher coherence at different SQMS partners



Preserving device high performance through the process of integrating into more complex systems

Deploying quantum platforms of innovative architectures and improved performance



Demonstrating quantum computing and sensing advantage for particle physics and other scientific applications

Additional slides