SQMS Center – Recent Achievements & Looking Ahead

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Fermilab Users Meeting 2023

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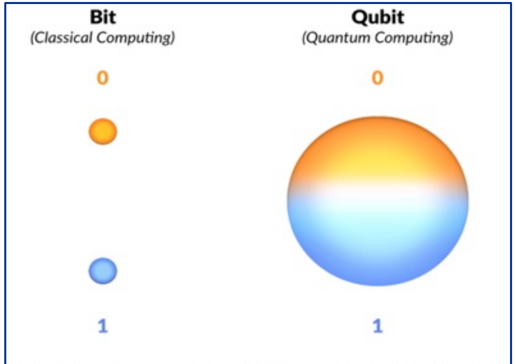
FERMILAB-SLIDES-23-157-SQMS-TD

Quantum Information Science

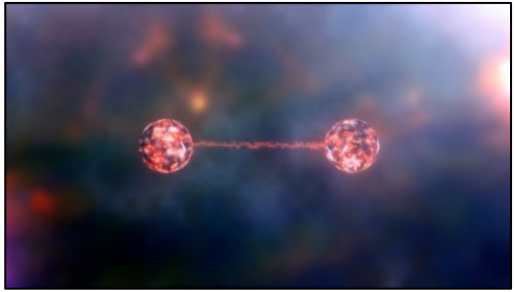
- Growing field of science and technology, combining physics, mathematics, computer science, and engineering

- **<u>Goal</u>**: understand and apply **fundamental laws of quantum physics** – **superposition, entanglement** – to acquire, transmit, and process information

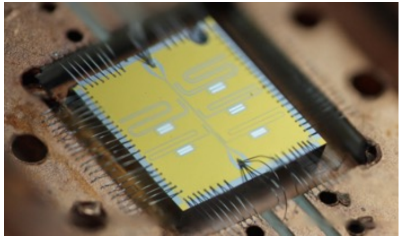
- QIS opportunities are attracting interest of scientists and technologists and promoting unprecedented interactions across traditional disciplinary boundaries



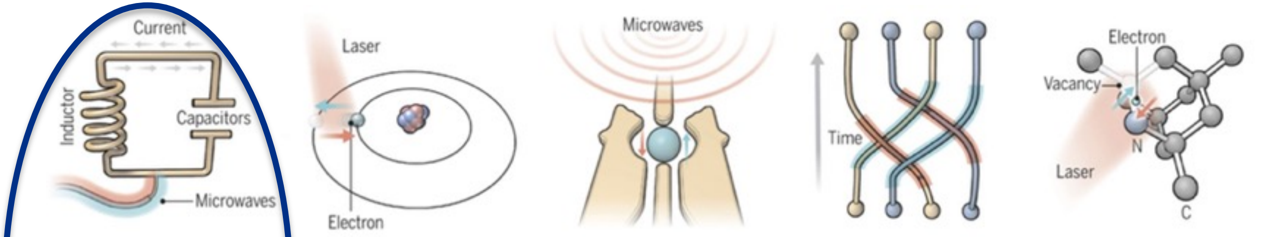
Classical qubits are zero or one: two possible states, represented as points. Qubits are a superposition of zero and one: a continuum of possible states, represented as the surface of a sphere (the Bloch sphere).



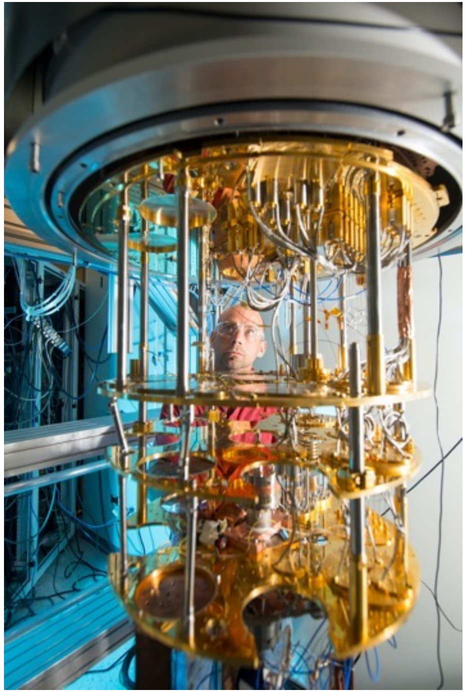
Challenges of building quantum computers



- Requires qubit that can be manipulated without being confused with other possible states of the system
- Maintain the **quantum coherence** of superposition long enough to perform gate operations



Superconducting loops	**Trapped ions**	**Silicon quantum dots**	**Topological qubits**	**Diamond vacancies**
A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds) 0.00005	>1000	0.03	N/A	10
Logic success rate 99.4%	99.9%	~99%	N/A	99.2%

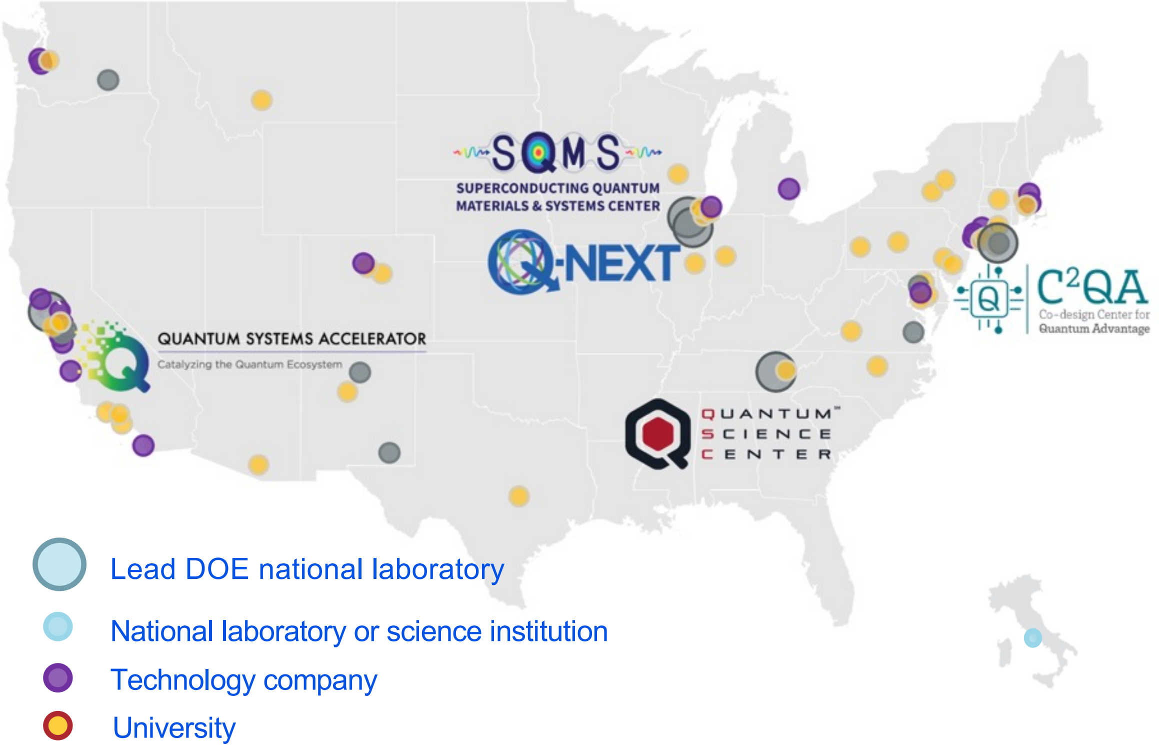


Partnerships across academia, industry & national labs

The DOE centers bring together multidisciplinary collaborations of **1,200** experts, including **600** students and postdocs, across **80** academic, industry and national science institutions in **21** states and DC.

Through institutional partnerships, the centers unite unique capabilities, expertise and facilities.

- Answering fundamental open questions in QIS
- Leveraging DOE user facilities for advanced materials analysis and device fabrication
- Training a new and diverse quantum workforce
- Technology transfer – rapid cycle from discovery to commercialization
- Accelerating scaling up and production
- Developing national standards



SQMS

28 Partner Institutions

>450 Collaborators

A DOE National Quantum Information Science Research Center, led by Fermilab

Fermilab

Northwestern University

rigetti

AMES NATIONAL LABORATORY Creating Materials & Energy Solutions

NASA Ames Research Center

NIST

COLORADO SCHOOL OF MINES EARTH • ENERGY • ENVIRONMENT

FORMFACTOR™

Goldman Sachs

ILLINOIS INSTITUTE OF TECHNOLOGY

INFN

Jefferson Lab

JOHNS HOPKINS UNIVERSITY

LOCKHEED MARTIN

LSU

NPL National Physical Laboratory

NYU

ROYAL HOLLOWAY UNIVERSITY OF LONDON

RUTGERS THE STATE UNIVERSITY OF NEW JERSEY

Stanford

Temple University

Unitary Fund

THE UNIVERSITY OF ARIZONA

University of Colorado Boulder

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

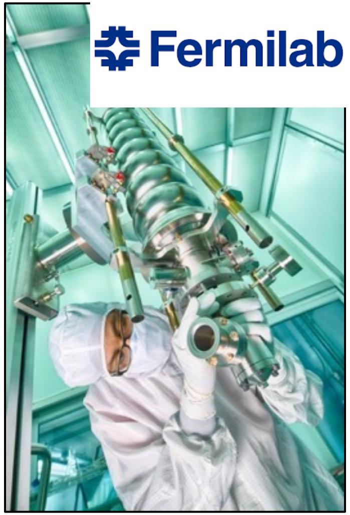
UNIVERSITY OF MINNESOTA Driven to Discover®

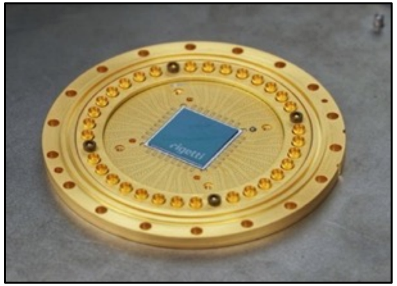
UNIVERSITÀ DI PISA

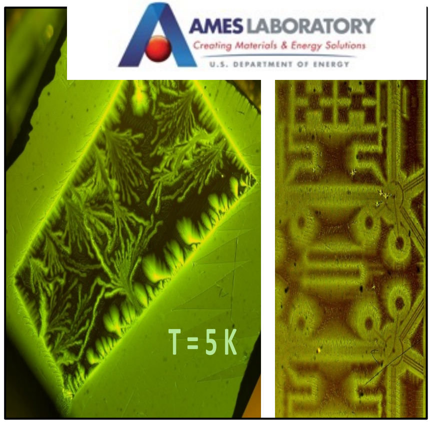
UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

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

Mission: Attacking QIS Cross-Cutting Challenges







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 Goals: Science & Technology Innovation Chain

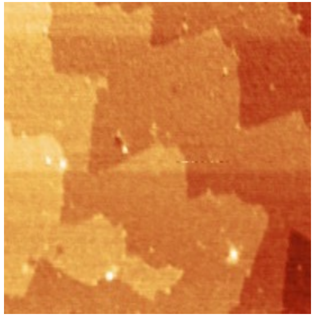
Materials

High-coherence devices

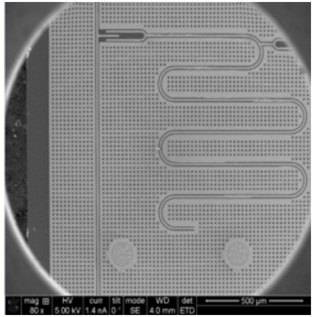
Systems integration

New platforms for quantum computing & sensing

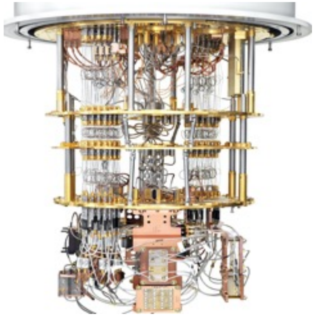
Quantum advantage



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

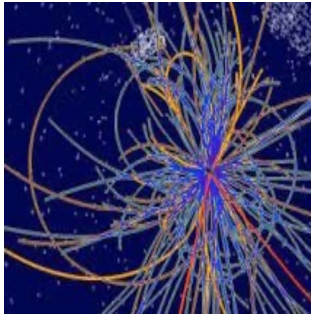


Demonstrating devices with systematically and consistently higher coherence at different SQMS partners



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

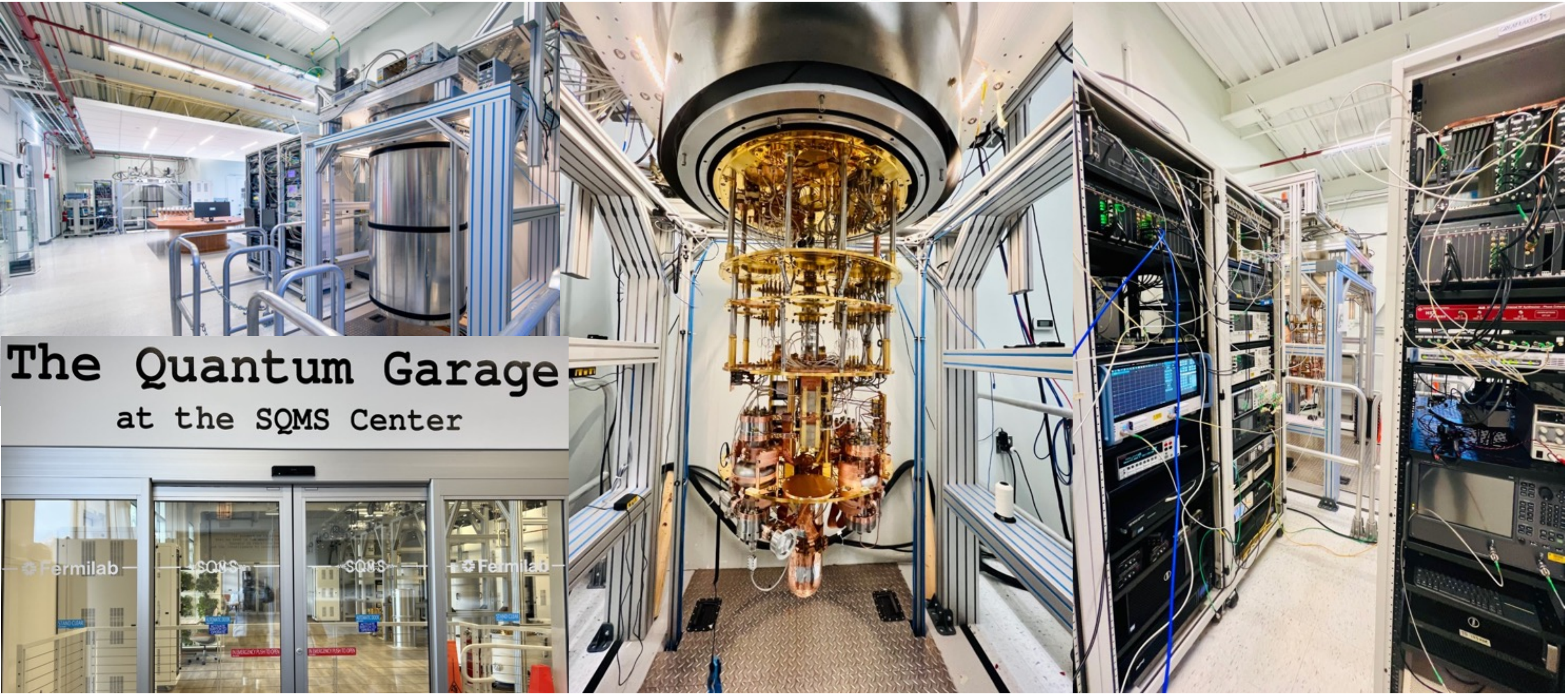
Deploying quantum computing and sensing facilities of innovative architectures and improved performance



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

SQMS bridges the gap between ideas and large-scale realizations via the unique center-wide, multidisciplinary coordinated approaches

SQMS facilities: Fleet of new quantum testbeds



Growing an Ecosystem and a Diverse Quantum Workforce

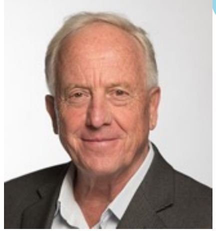
SQMS theorists and experimentalist ‘co-design’ to target decoherence

A. Romanenko

J. Rondinelli

J.. Sauls

M. Iavarone



J. Zasadzinski

M. Kramer

Theory

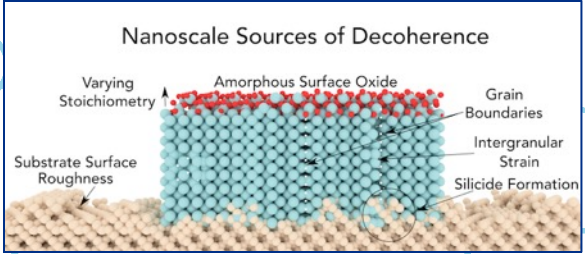
First-principles Materials
Superconductivity
Disorder and Dynamics

Characterization

Cryo SEM, TEM
TOF-SIMS
Light sources
XRR, XRD, APT
SRF cavities

Spectroscopies

Magneto-Optical
Scanning Tunneling
Point Contact Tunneling



Transport

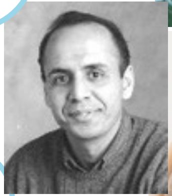
London Penetration
NMR/muSR
Microwave
TeraHertz

R. Prozorov

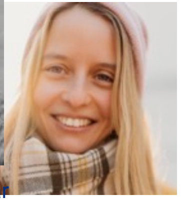
J. Wang

M. Hersam

J. Mutus



V. Chandrasekhar



Y. Krasnikova

Fermilab ILLINOIS TECH LSU Northwestern University rigetti AMES LABORATORY Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY TEMPLE UNIVERSITY

Fermilab

SQMS National Qubit Nanofabrication Taskforce

- SQMS coordinated study/process flow across **FNAL-UChicago, NIST, Rigetti, Northwestern** foundries to address material losses
- Demonstrate reproducibility of improved qubit coherence


Mustafa Bal
Fermilab


Akshay Murthy
Fermilab


Ella Lachman
Rigetti Computing

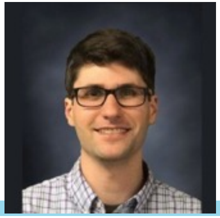

Francesco Crisa',
Fermilab


Shaojiang Zhu
Fermilab


Lin Zhou
Ames National Lab

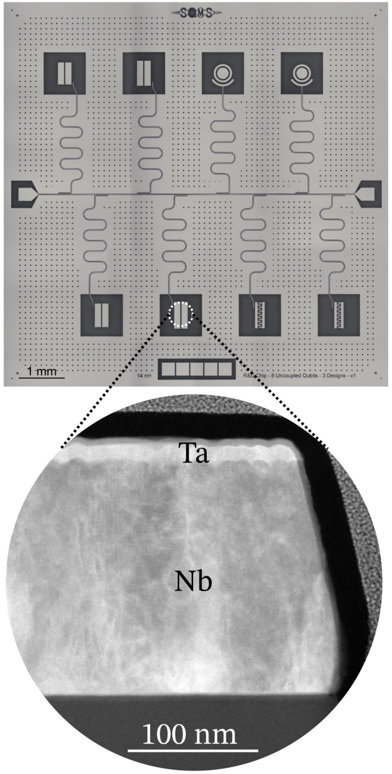

Pete Hopkins,
NIST

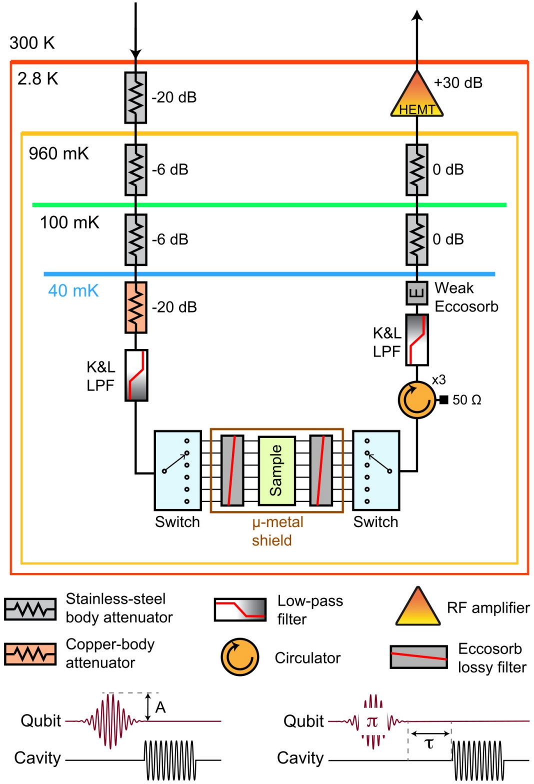

Florent Lecoq,
NIST

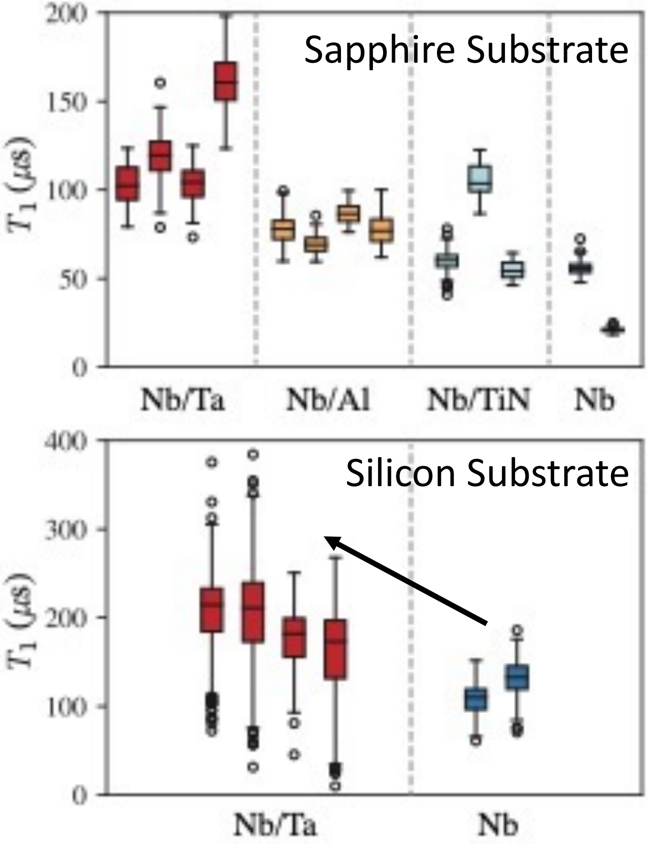

Nik Zhelev, NU


Yuvraj Mohan
Rigetti Computing

Milestone: Advanced coherence in encapsulated qubits

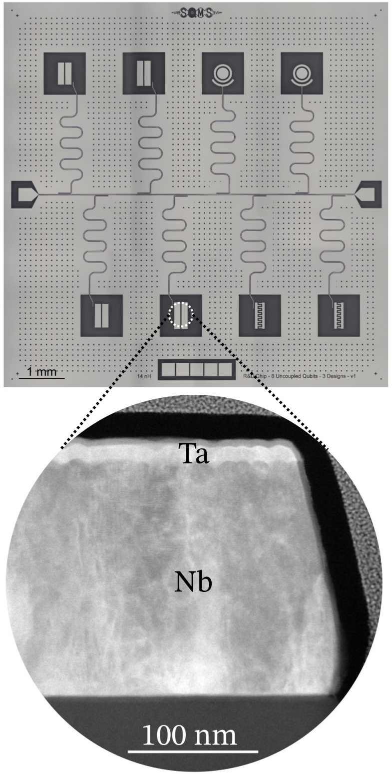


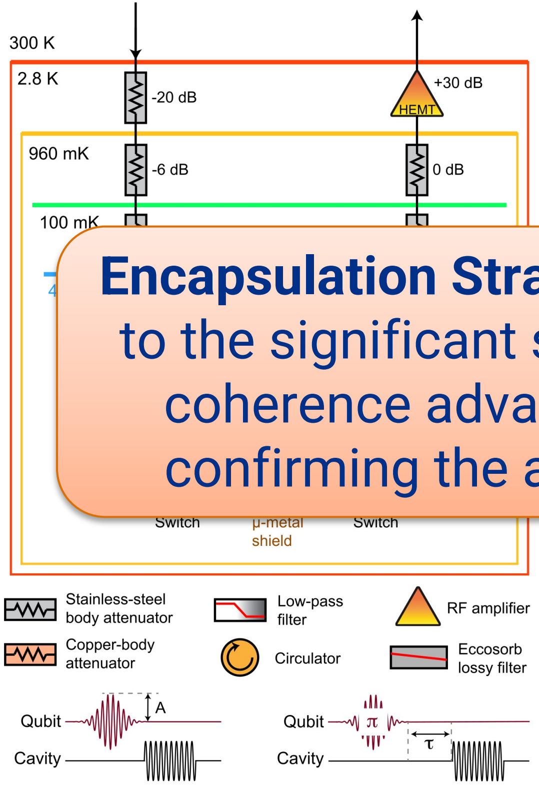


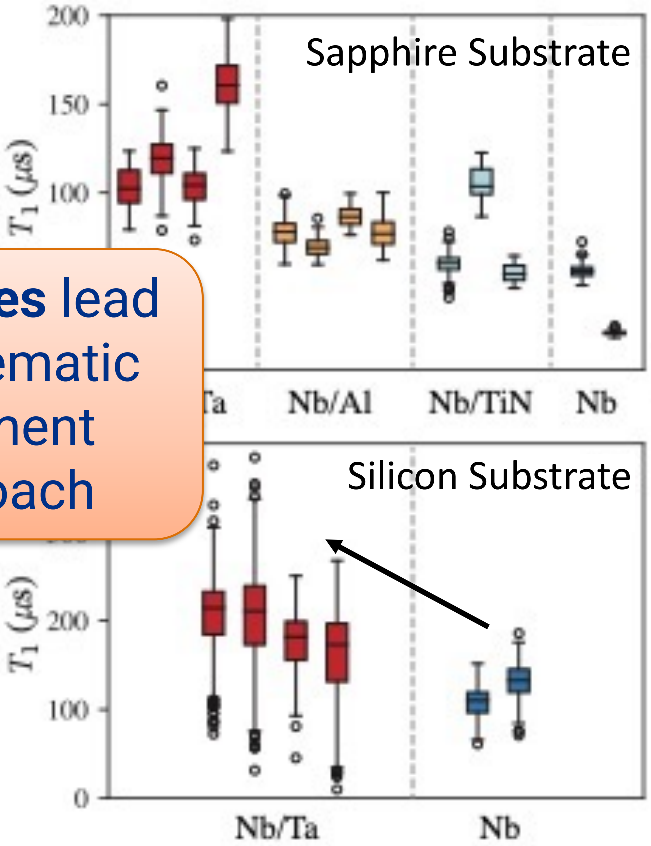


Bal et al., arxiv:2304.13257

Milestone: Advanced coherence in encapsulated qubits





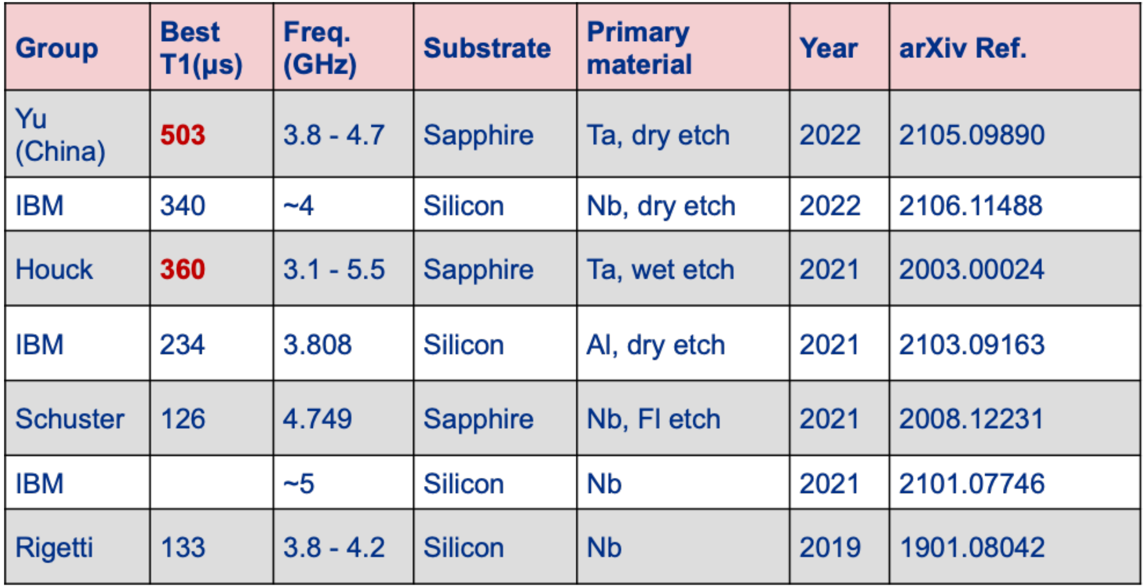


Encapsulation Strategies lead to the significant systematic coherence advancement confirming the approach

Bal et al., arxiv:2304.13257

Significance of the results

World-wide landscape of 2D qubit coherences



Group	Best T1(μs)	Freq. (GHz)	Substrate	Primary material	Year	arXiv Ref.
Yu (China)	**503**	3.8 - 4.7	Sapphire	Ta, dry etch	2022	2105.09890
IBM	340	~4	Silicon	Nb, dry etch	2022	2106.11488
Houck	**360**	3.1 - 5.5	Sapphire	Ta, wet etch	2021	2003.00024
IBM	234	3.808	Silicon	Al, dry etch	2021	2103.09163
Schuster	126	4.749	Sapphire	Nb, Fl etch	2021	2008.12231
IBM		~5	Silicon	Nb	2021	2101.07746
Rigetti	133	3.8 - 4.2	Silicon	Nb	2019	1901.08042

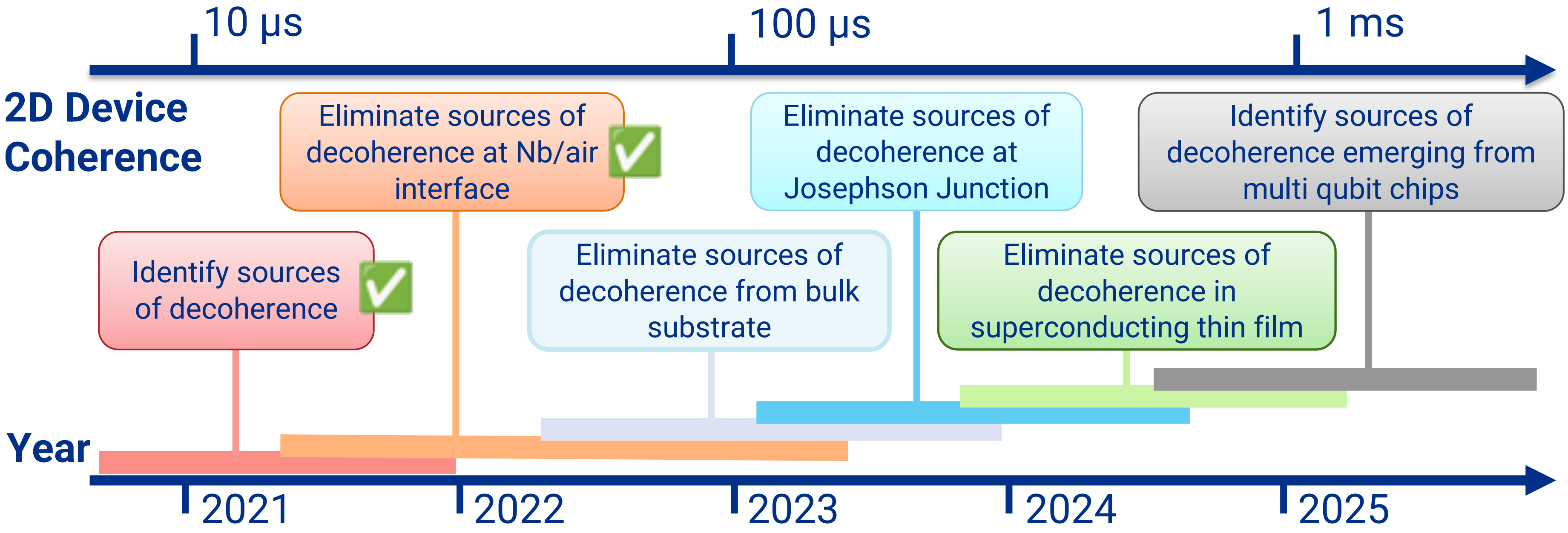
SQMS Best T_1:

Nb/Si → 451 us

Nb/sapphire → 198 us

SQMS 2D qubits are now at the forefront of the national and world-wide efforts

Near-term Goals: 2D Qubit Materials Roadmap



Identify sources of decoherence ✅

Eliminate sources of decoherence at Nb/air interface ✅

Eliminate sources of decoherence from bulk substrate

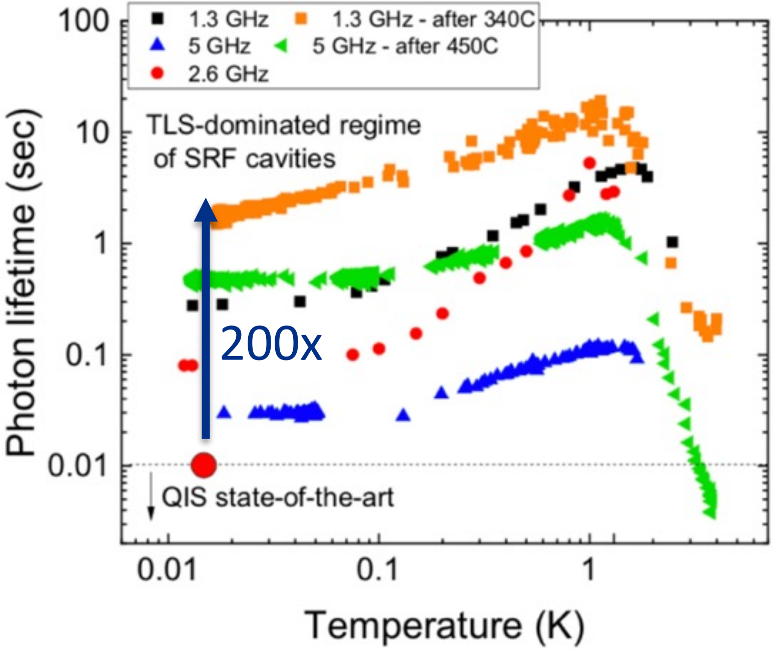
Eliminate sources of decoherence at Josephson Junction

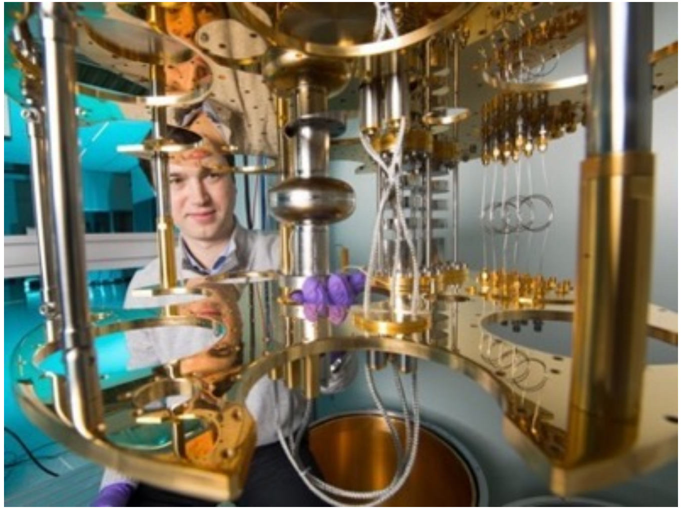
Eliminate sources of decoherence in superconducting thin film

Identify sources of decoherence emerging from multi qubit chips

World record coherence 3D cavities in quantum regime

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





- Technology originally developed for accelerators
- Fermilab is world leader in SRF
- 2 seconds of coherence demonstrated

Foundational Result upon which the SQMS center was built

SQMS 3D SRF approach

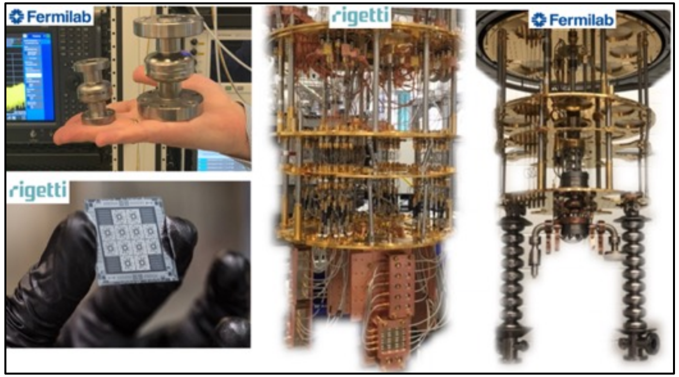
Novel QPU architectures

- Long coherence allows going from qubit to "qudit" approach (use **d** energy levels instead of traditional 2)

ONE nine cell SRF cavity + **ONE** transmon = **SQMS 100+** qubits processor

Scalability

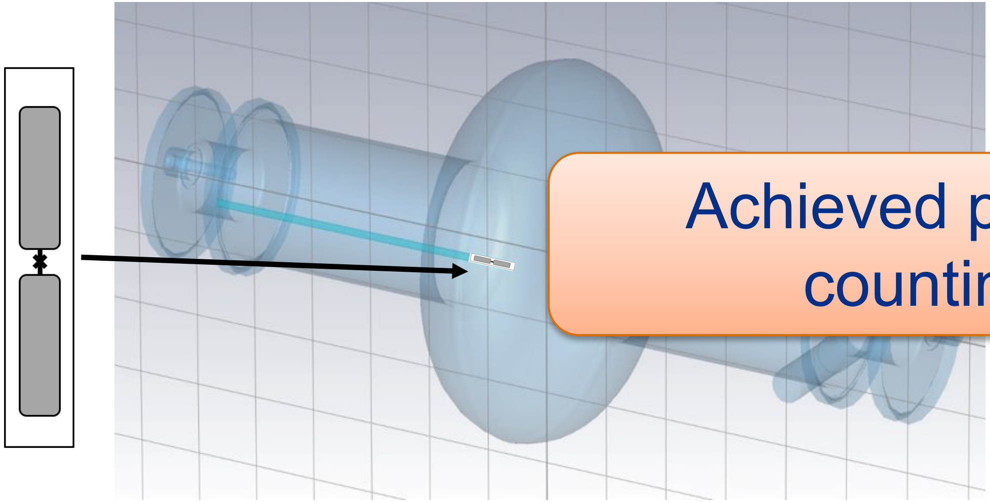
- > 100 qubits with just few input/output lines

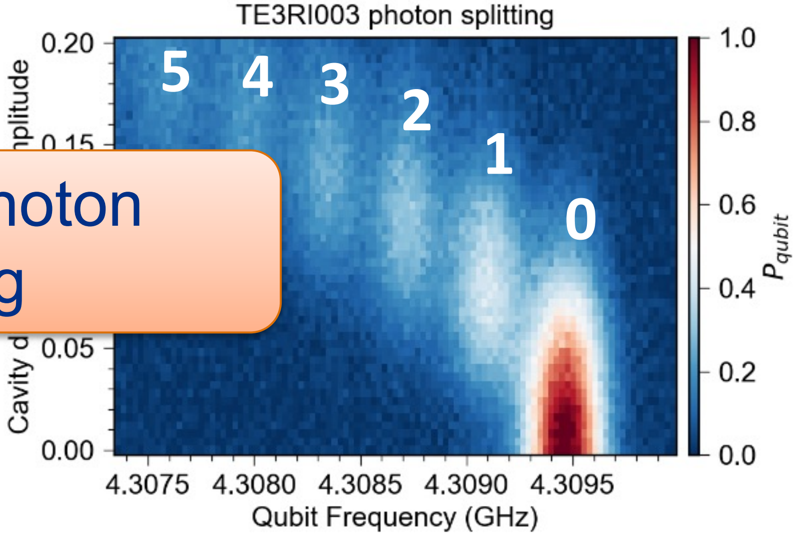


Science

- Directly probing the quantum to classical transition : "Schrodinger cat" states of record large scales
- New physics (dark photon and axion) searches with orders of magnitude improved sensitivity
- Physics simulations enabled by the all-to-all qubit connectivity

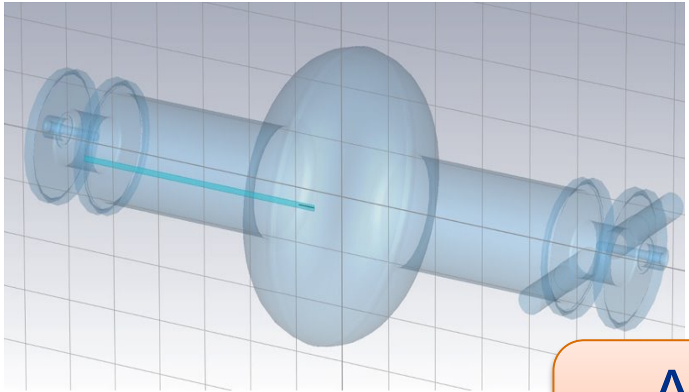
Milestone: Incorporated Transmon into SRF Cavity

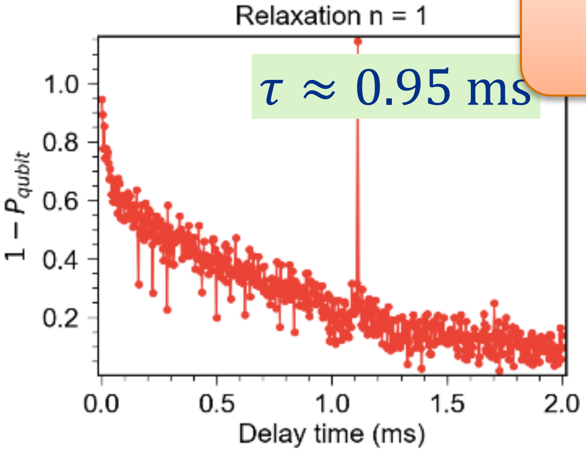




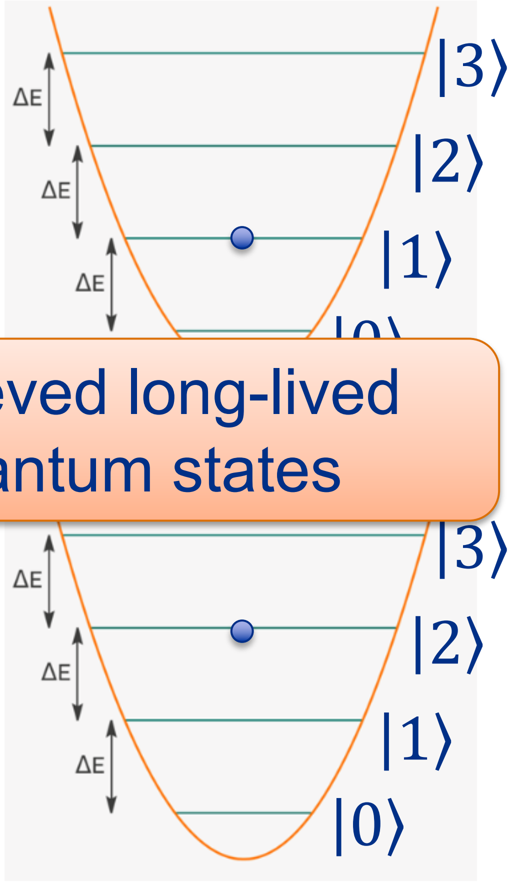
Achieved photon counting

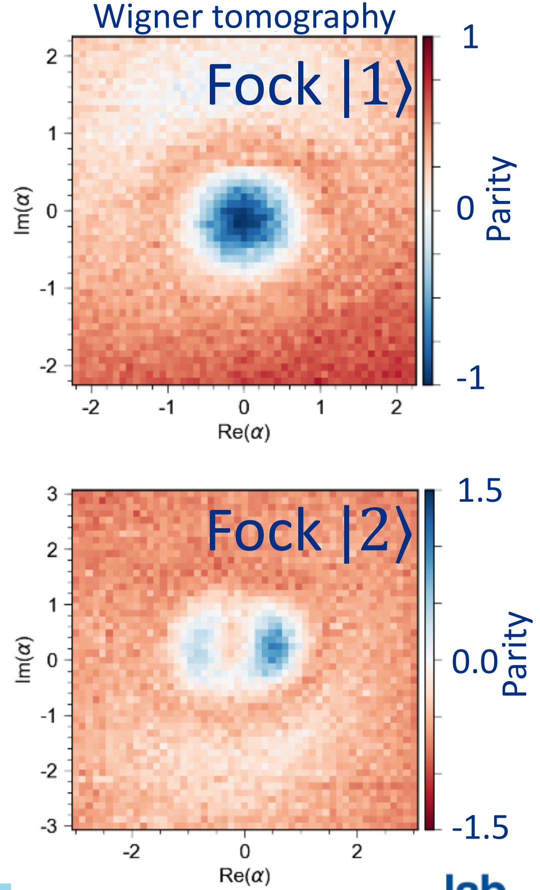
Milestone: Incorporated Transmon into SRF Cavity





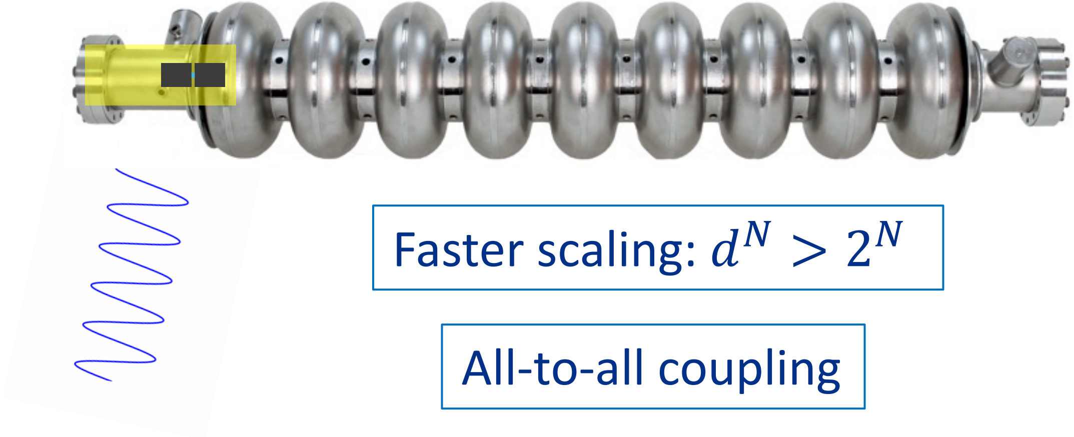
Achieved long-lived quantum states





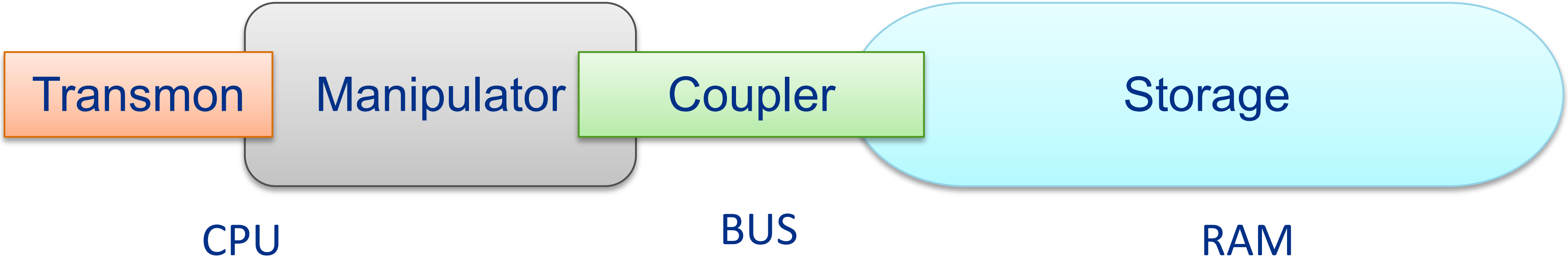
Near-Term Goals: Design Multiqubit Architecture

Crosstalk issues



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

All-to-all coupling


Transmon

Manipulator

Coupler

Storage

CPU

BUS

RAM

Quantum Sensing for Fundamental Physics

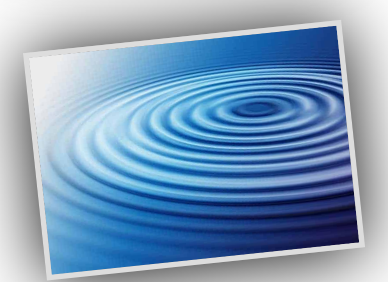
- Quantum sensing: the use of quantum properties of light or matter to enhance sensitivity of measurements.
- Sensing effort is driven by applying our SRF cavities and quantum devices towards physics goals:

Probing Dark sectors:

New light particles: Dark photons and axions.

Either as the dark matter, or as "just" new particle.

A multi-search goal. Our most engaging science goal.



Precision tests:

Tests of the standard model (electron g-2, Euler-Heisenberg)

Tests of quantum mechanics

Gravitational waves:

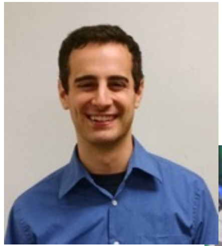
Expanding the frequency for GW detection beyond LIGO/VIRGO

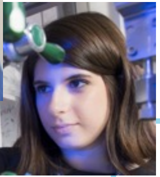
SQMS theorists & experimentalist ‘co-design’ to develop new experiments

SRF + QIS capabilities enable new particle searches of unprecedented sensitivity and precision


R. Harnik


Y. Kahn


S. Posen


B. Giaccone


R. Cervantes


G. Gabrielse

co-design

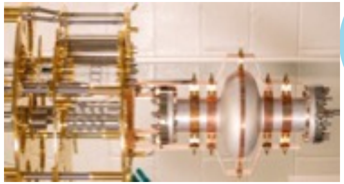
Theory

Options for mode setups + sensitivity

Prototypes

Systems design, testing

(measure cross-talk, Q for various modes, readout)



Materials and Devices

Improved Q, sensitivity, controls

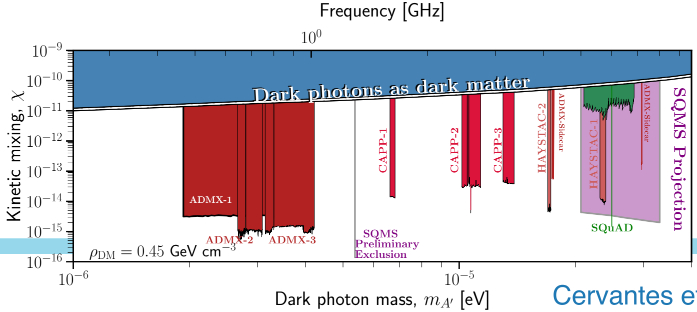

A. Berlin


S. Rajendran

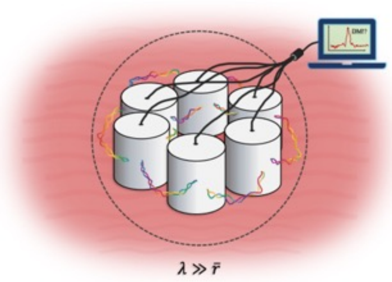

P. Graham


J.. Sauls


C. Braggio



Cervantes et al., arxiv:2208.03183



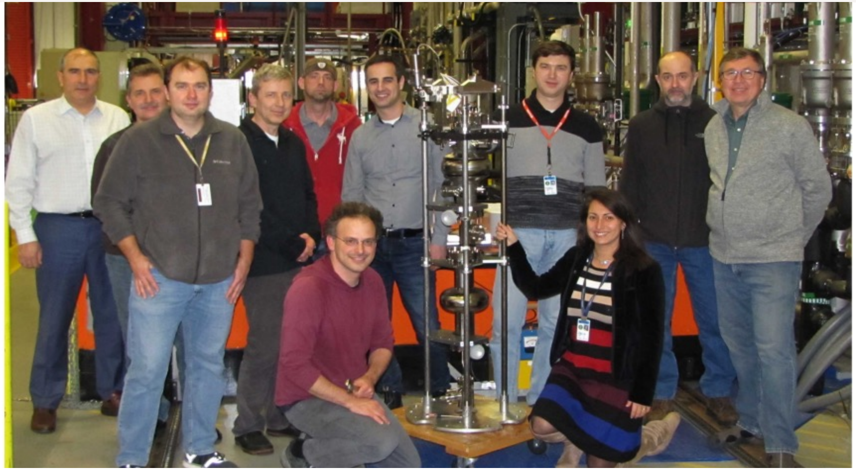
Northwestern University
JOHNS HOPKINS UNIVERSITY
UNIVERSITY OF MINNESOTA Driven to Discover
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
INFN
THE UNIVERSITY OF ARIZONA
LSU
Stanford
Fermilab

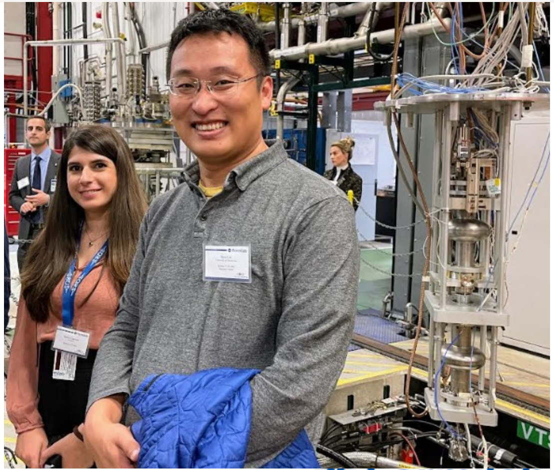
Brady et al PRX Quantum 3 (2022) 3, 030333

Search for Dark Photons with Superconducting Radio Frequency Cavities

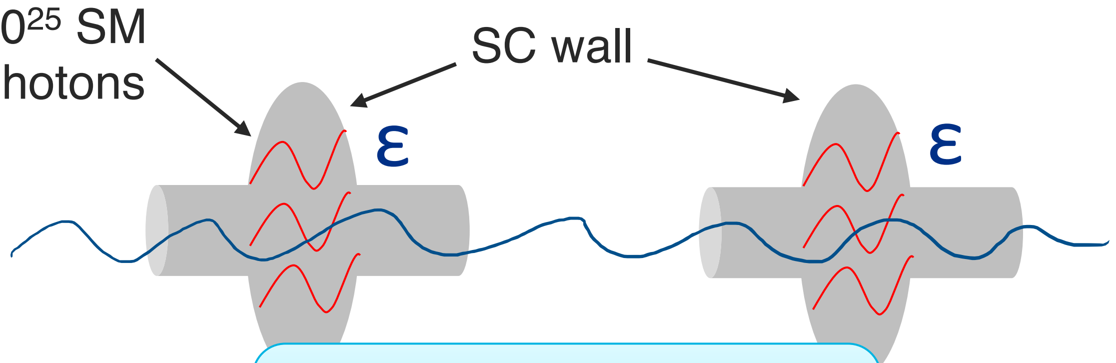
A. Romanenko, R. Harnik, A. Grassellino, R. Pilipenko, Y. Pischalnikov, Z. Liu, O. S. Melnychuk, B. Giaccone, O. Pronitchev, T. Khabiboulline, D. Frolov, S. Posen, S. Belomestnykh, A. Berlin, and A. Hook

Phys. Rev. Lett. **130**, 261801 – Published 26 June 2023





Dark SRF: ”Light shining through wall” Experiment



Emitter

in the acc

regime, high field

avity,

l regime

Necessary to match cavity frequencies!

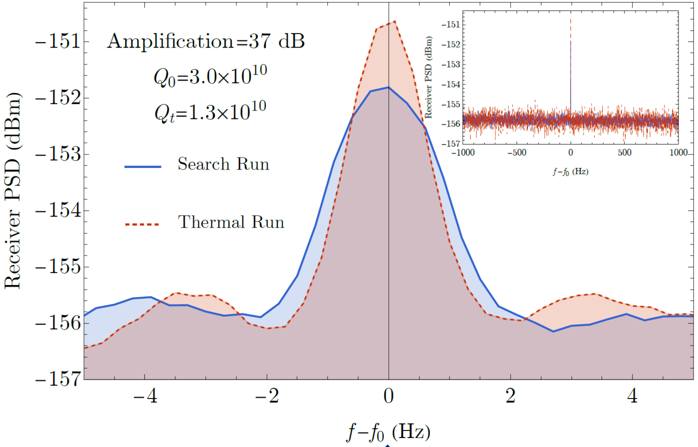
High Q_0: increases number of photons

High Q_0: enhances probability of detecting power excess due to dark photons

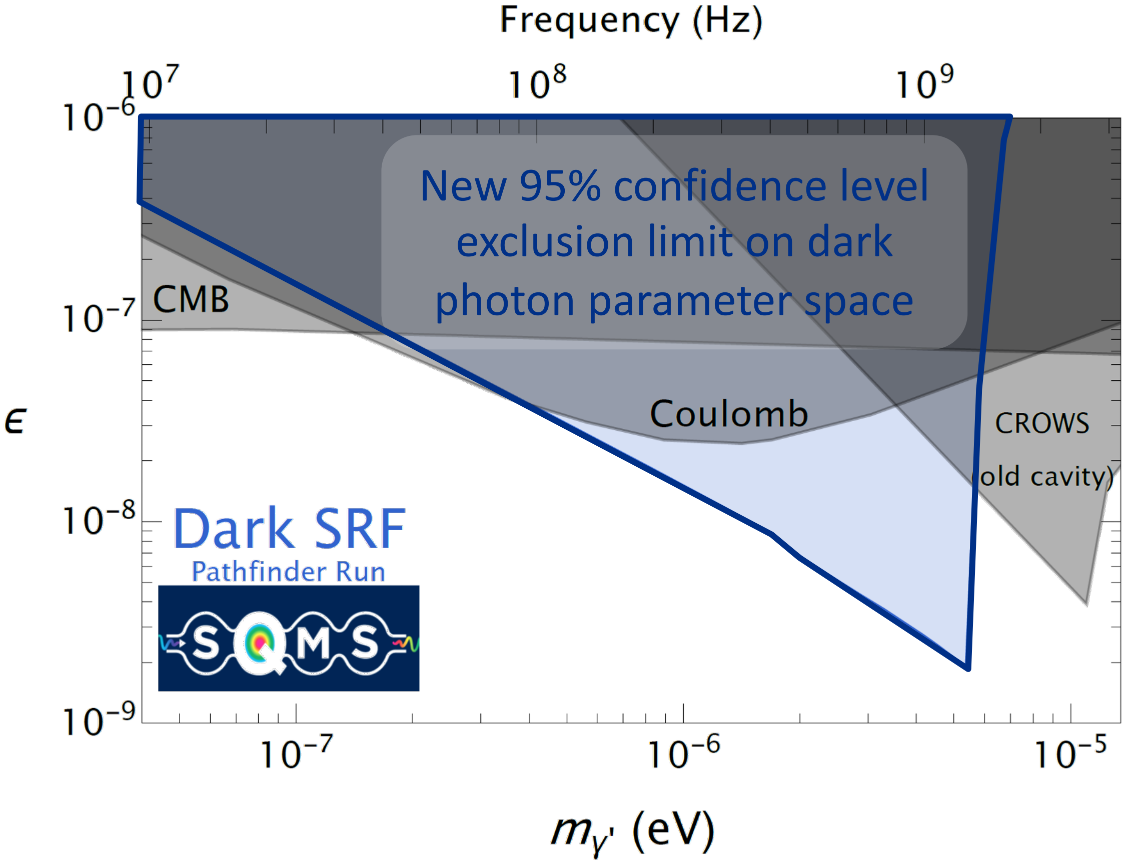
Dark SRF: phase 1 → results

Thermal run vs Search run

Search run conducted at
6.2 MV/m (= 0.6 J stored energy)



Both runs consistent to 1σ



New 95% confidence level exclusion limit on dark photon parameter space

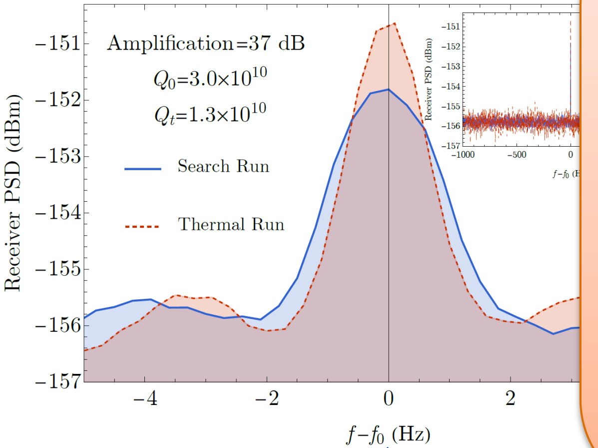
Dark SRF
Pathfinder Run

Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

Dark SRF: phase 1 → results

Thermal run vs Search run

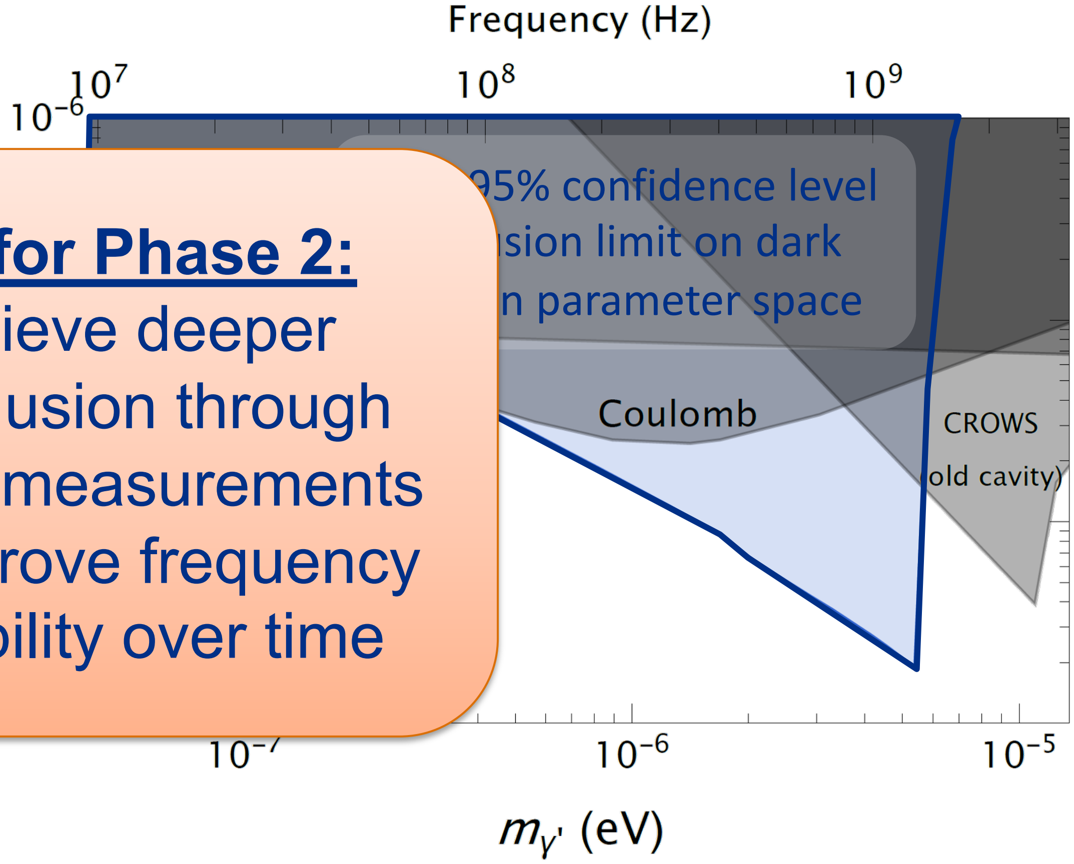
Search run conducted at 6.2 MV/m (= 0.6 J stored



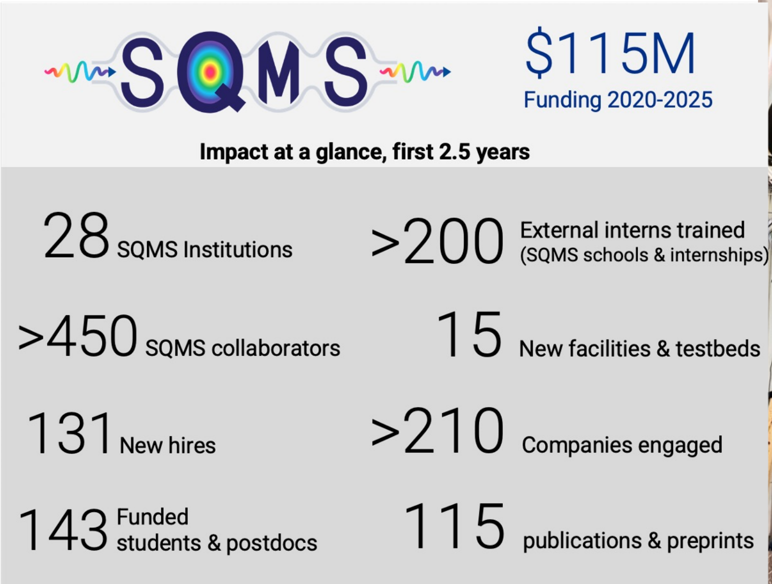
Both runs consistent to 1σ

<u>Goals for Phase 2:</u>

1. Achieve deeper exclusion through DR measurements
2. Improve frequency stability over time



Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)



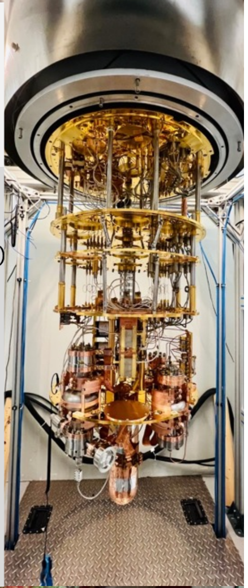
SQMS

$115M

Funding 2020-2025

Impact at a glance, first 2.5 years

28	SQMS Institutions	>200	External interns trained (SQMS schools & internships)
>450	SQMS collaborators	15	New facilities & testbeds
131	New hires	>210	Companies engaged
143	Funded students & postdocs	115	publications & preprints



Summary & Looking Ahead

- Through robust partnerships across the U.S. and abroad as well as extensive investments in quantum infrastructure, the SQMS center has delivered exciting progress across the science + technology innovation chain:

- **Leading edge coherence times in 2D superconducting qubits**
  - Next steps: Targeted removal of additional sources of decoherence
- **Demonstration of long-lived quantum states in cavity-qubit system**
  - Next steps: Design and deployment of multiqubit cavity/qubit architectures
- **Exploring new areas of dark photon parameter space**
  - Next steps: Experimental improvements to achiever deeper exclusion

Appendix

Dark SRF: phase 1 → measurement protocol

1. Excite emitter to desired field and match its frequency to receiver
2. Search for Dark photon for ~30min
3. Verify frequency matching
4. Cross-talk check
5. Thermal background check

Step 1 & 3