FERMILAB-SLIDES-23-157-SQMS-TD

SQMS Center – Recent Achievements & Looking Ahead

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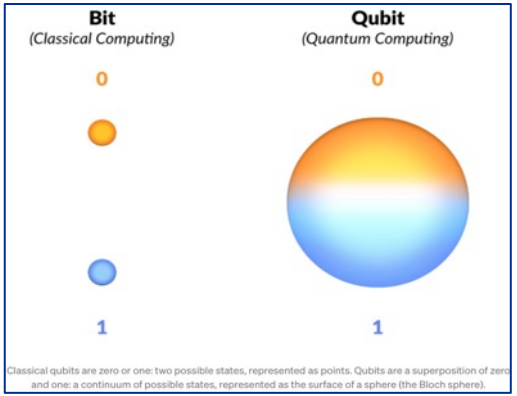
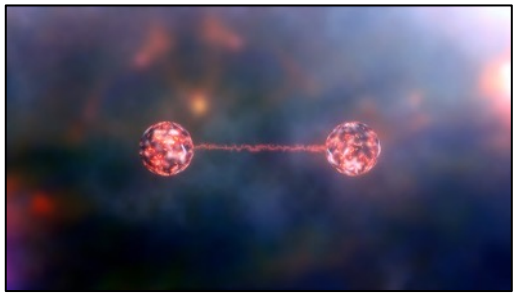
Fermilab Users Meeting 2023

June 30th, 2023

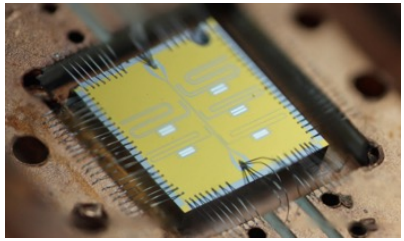
Quantum Information Science

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

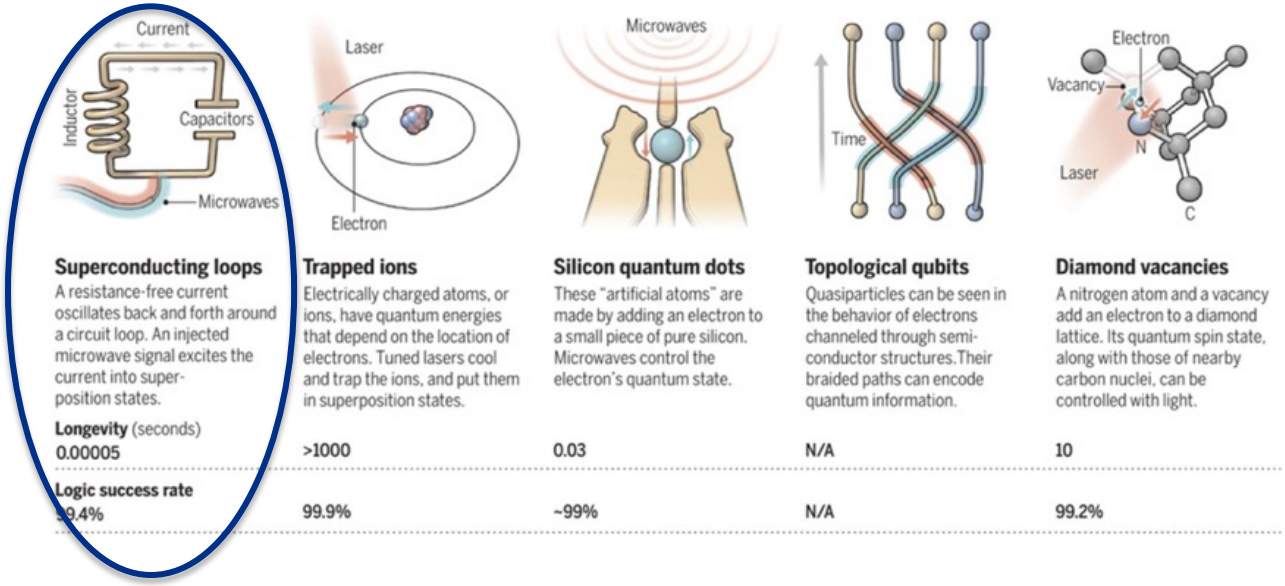




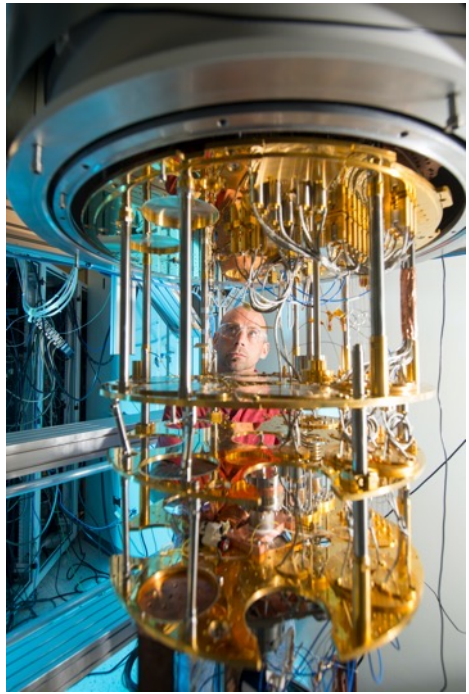
Challenges of building quantum computers



- 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 super-position 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 semi-conductor 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%



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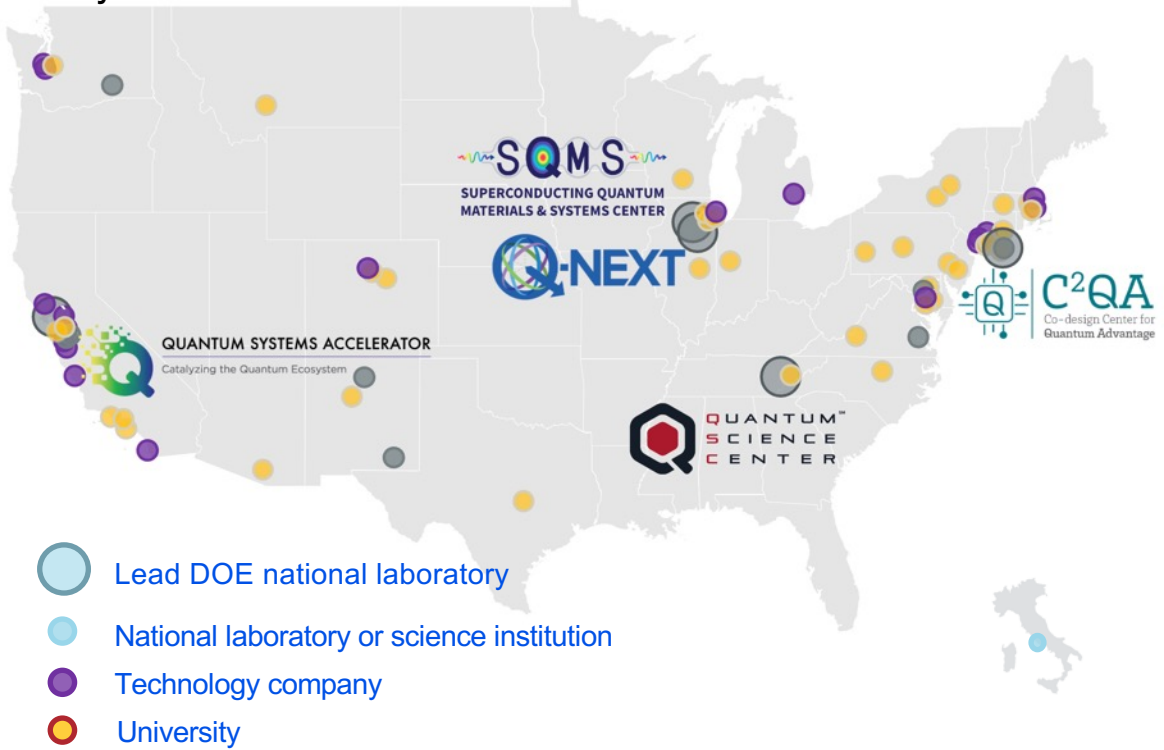
Partnerships across academia, industry & national labs

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



Fermilab

28 Partner Institutions

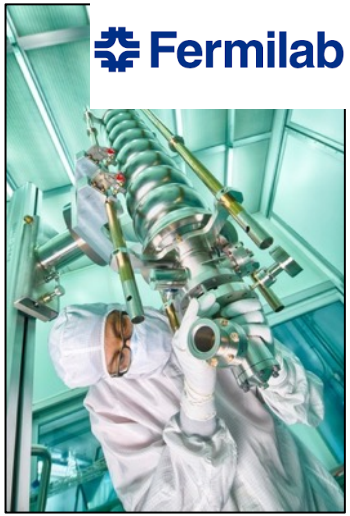
>450 Collaborators

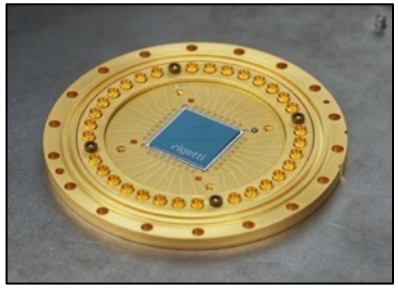
A DOE National Quantum Information Science Research Center, led by Fermilab

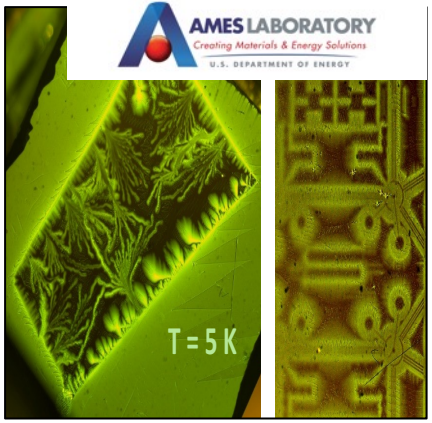
Fermilab
Northwestern University
rigetti
AMES NATIONAL LABORATORY
NASA Ames Research Center
NIST
COLORADO SCHOOL OF MINES EARTH • ENERGY • ENVIRONMENT
FORMFACTOR™
Goldman Sachs
ILLINOIS INSTITUTE OF TECHNOLOGY
INFN
Jefferson Lab
JOHNS HOPKINS UNIVERSITY
LOCKHEED MARTIN
LSU
NPL National Physical Laboratory
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®
IN SUPREMÆ DIGNITATIS 1343 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 Cross-Cutting Challenge





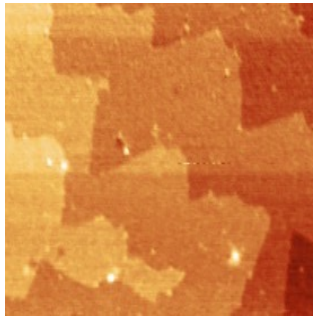


SQMS Mission

"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."

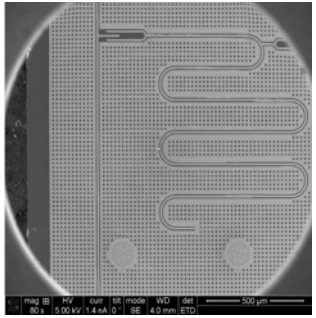
SQMS Goals: Science & Technology Innovation Chain

Materials



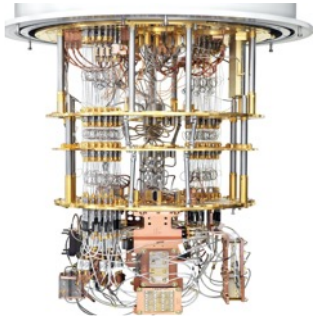
Developing a full understanding of sources of decoherence via a systematic, fundamental science approach

High-coherence devices



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

Systems integration

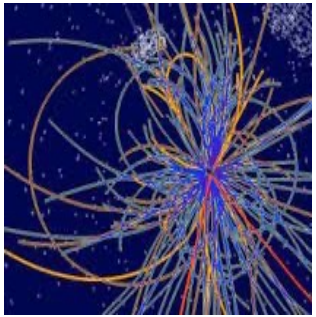


Preserving device high performance through the process of integrating into more complex systems

New platforms for quantum computing & sensing

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

Quantum advantage



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

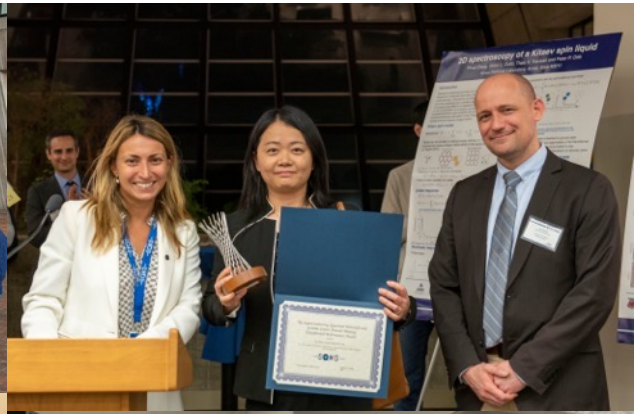
SQMS bridges the gap between ideas and large-scale realizations via the unique center-wide, multidisciplinary coordinated approaches

Fermilab

SQMS facilities: fleet of new quantum testbeds

Fermilab

Growing an Ecosystem and a Diverse Quantum Workforce



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

A. Romanenko

J. Rondinelli

J.. Sauls

Theory

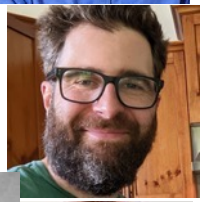
First-principles Materials
Superconductivity
Disorder and Dynamics

Characterization

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

M. Hersam

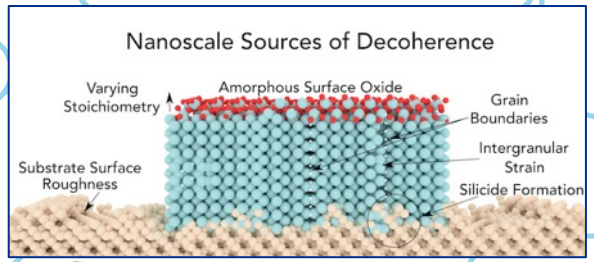
J. Mutus



M. Iavarone

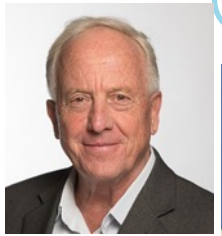
Spectroscopies

Magneto-Optical
Scanning Tunneling
Point Contact Tunneling



V. Chandrasekhar

Y. Krasnikova



J. Zasadzinski

M. Kramer

Transport

London Penetration
NMR/muSR
Microwave
TeraHertz

R. Prozorov

J. Wang

Fermilab ILLINOIS TECH LSU Northwestern University rigetti AMES LABORATORY 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

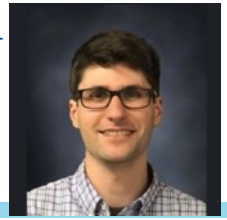
Francesco Crisa',
Fermilab

Shaojiang Zhu
Fermilab

Lin Zhou
Ames National Lab

Pete Hopkins,
NIST

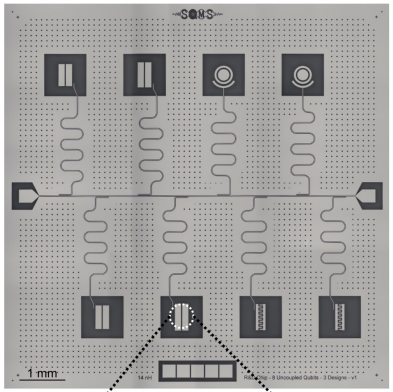
Florent Lecoq,
NIST

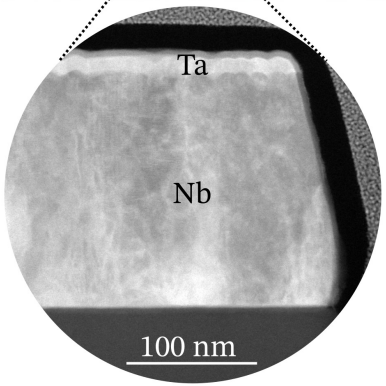


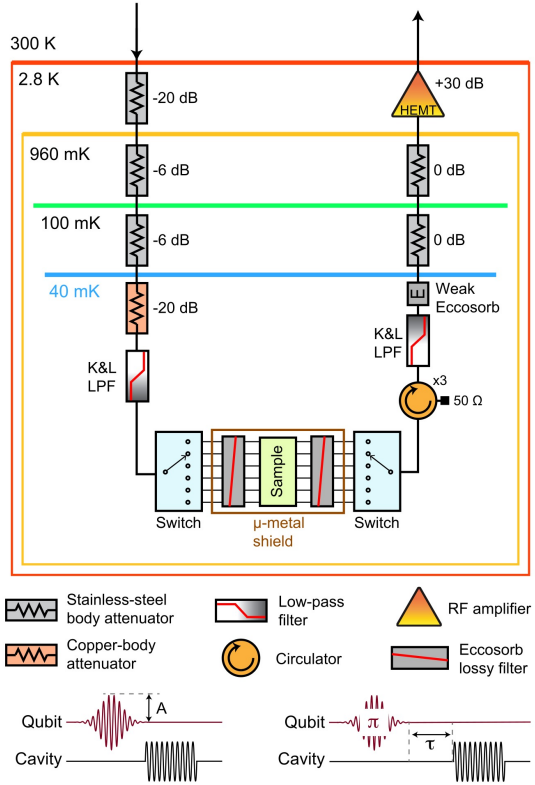
Nik Zhelev, NU

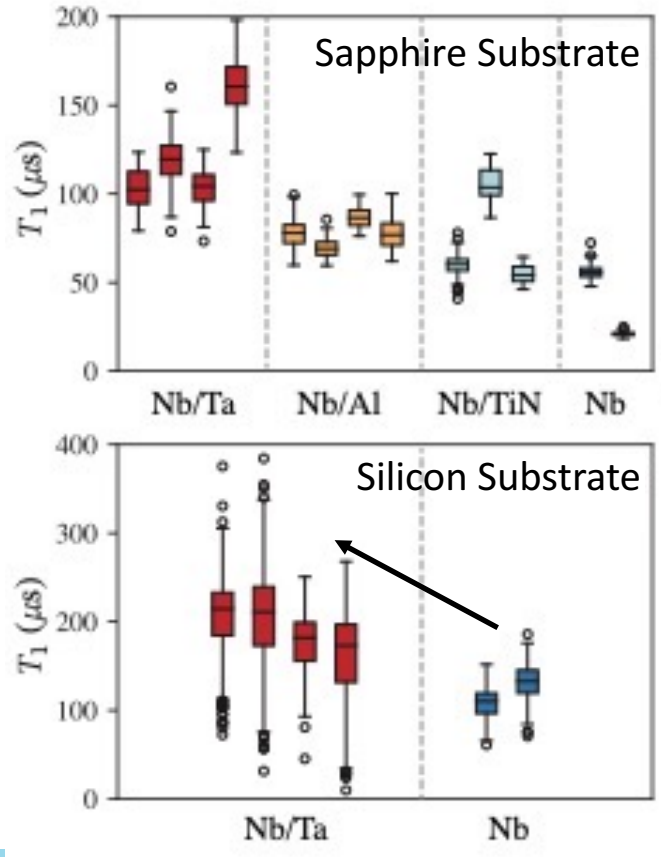
Yuvraj Mohan
Rigetti Computing

Milestone: Advanced coherence in encapsulated qubits

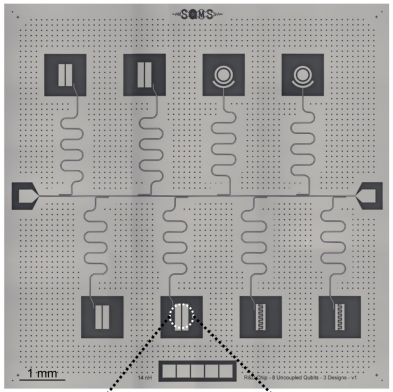


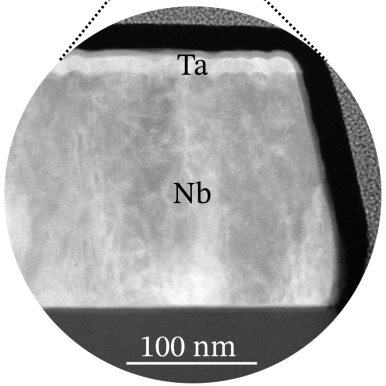


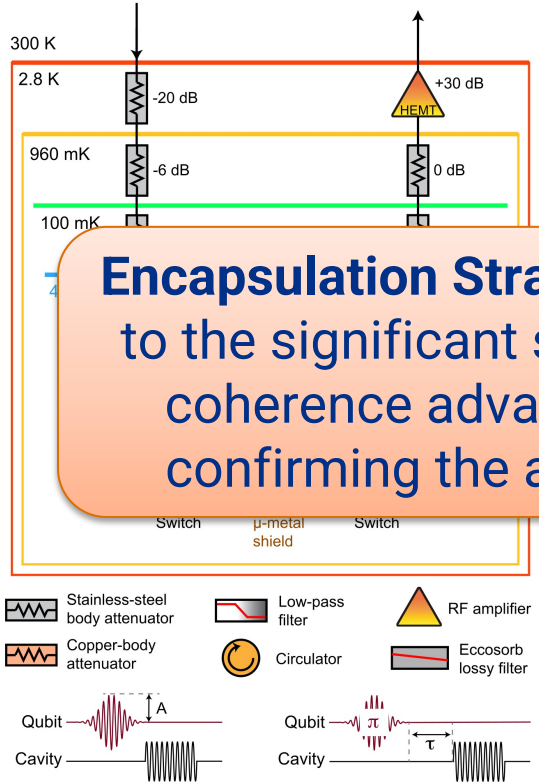




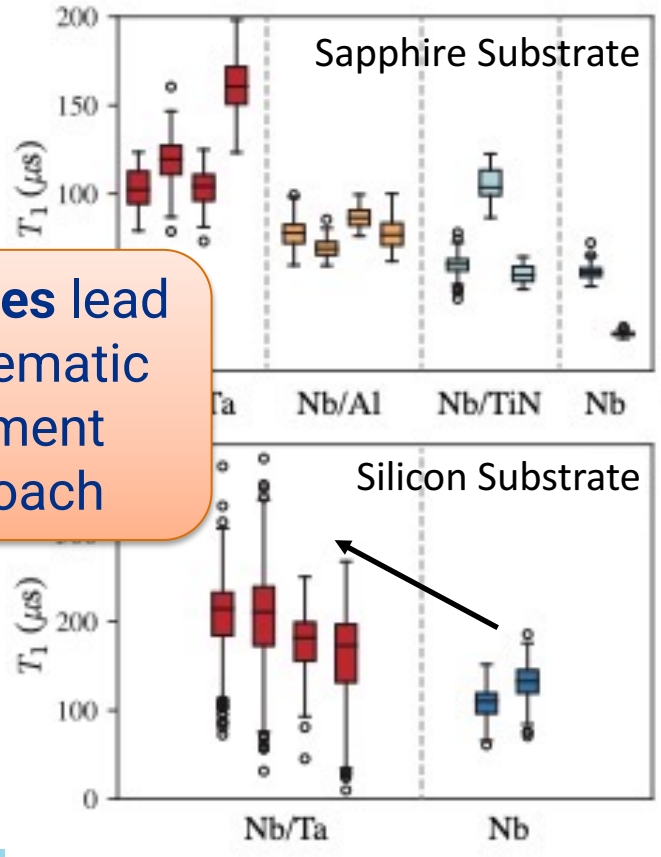
Milestone: Advanced coherence in encapsulated qubits







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



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

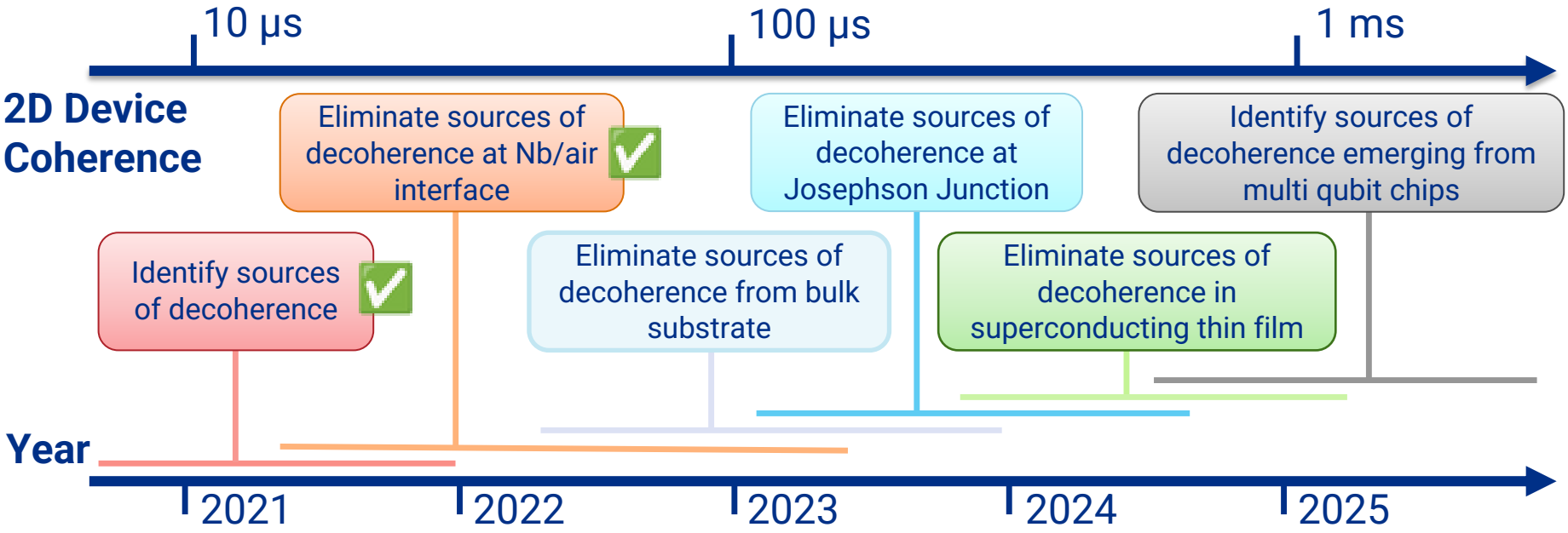
SQMS Best T_1:

⟷ Nb/Si -> 451 us

⟷ Nb/sapphire -> 198 us

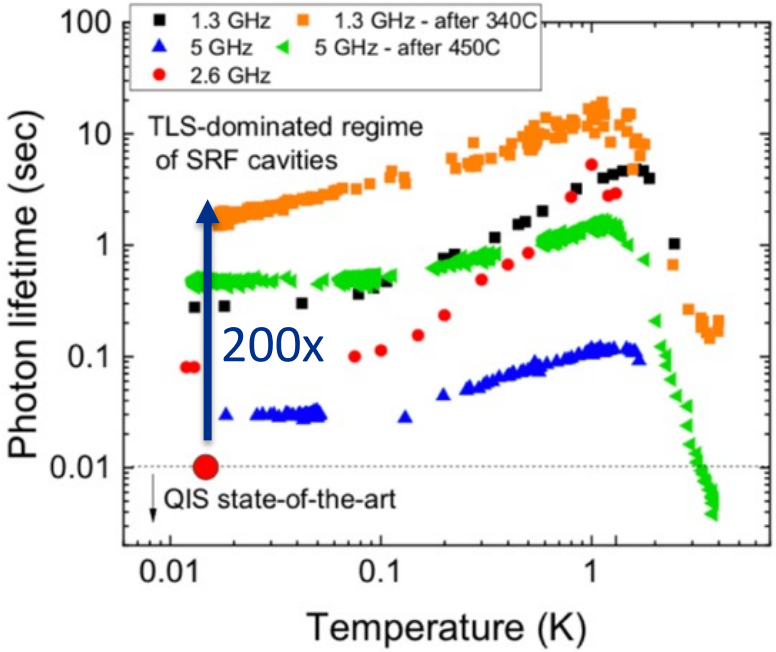
SQMS 2D qubits are now at the forefront of the national and world-wide efforts

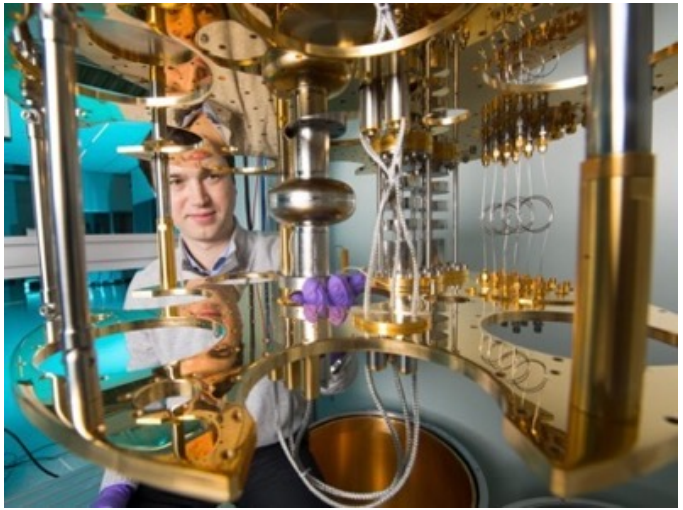
Near-term Goals: 2D Qubit Materials Roadmap



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

Fermilab

SQMS 3D SRF approach

Novel QPU architectures

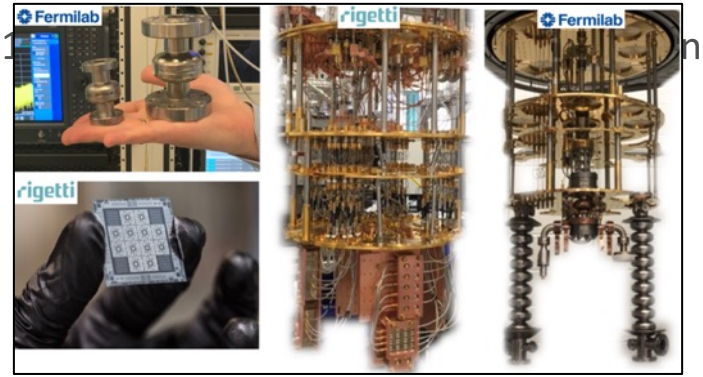
- Long coherence allows going from qubit to "qu**d**it" approach (use **d** energy levels instead of traditional 2)

~~All-to-all qubit connectivity~~

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

Scalability

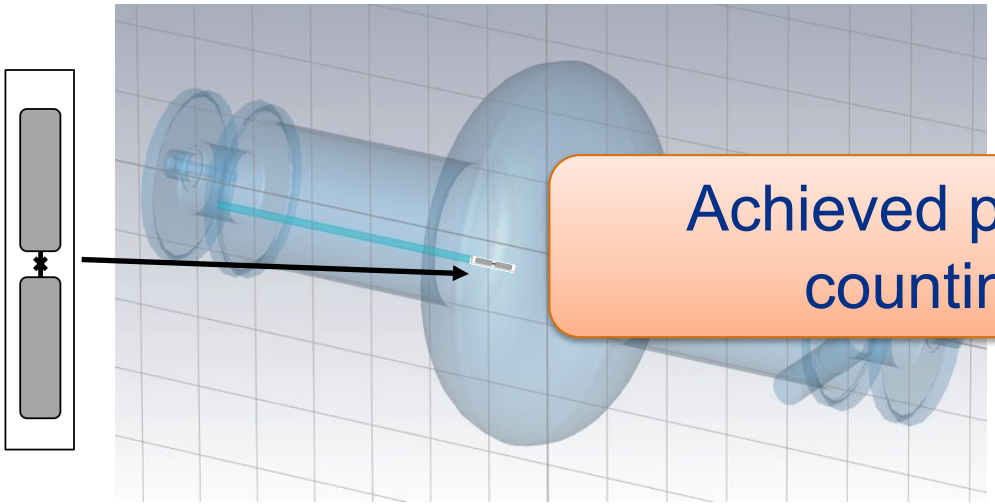
- > 1 nes



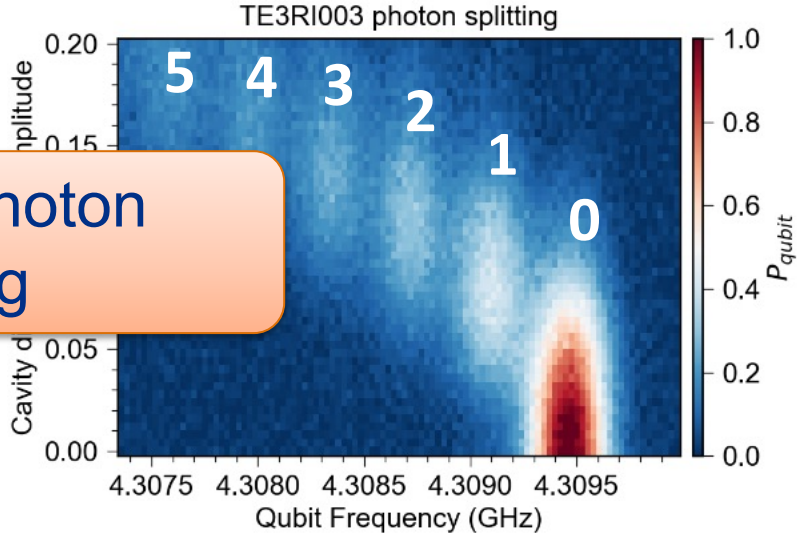
Science

- 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



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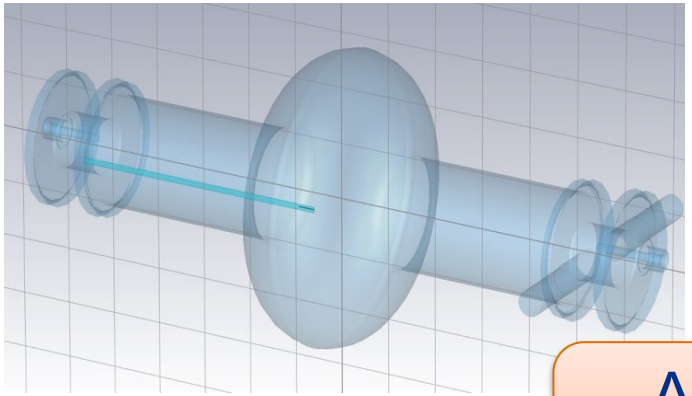
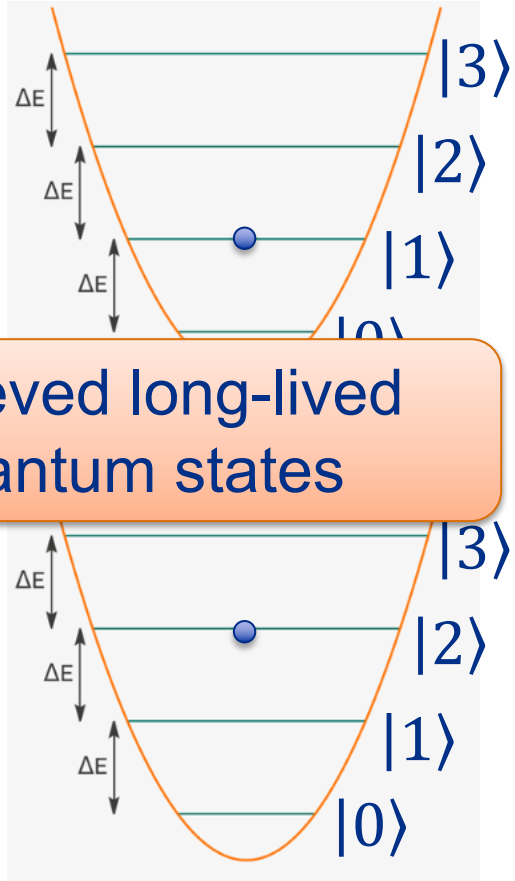
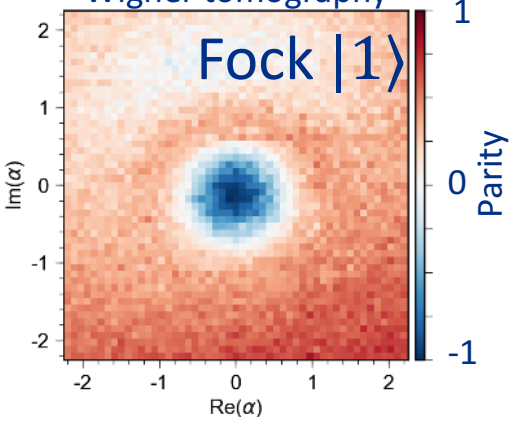
Milestone: Incorporated Transmon into SRF Cavity

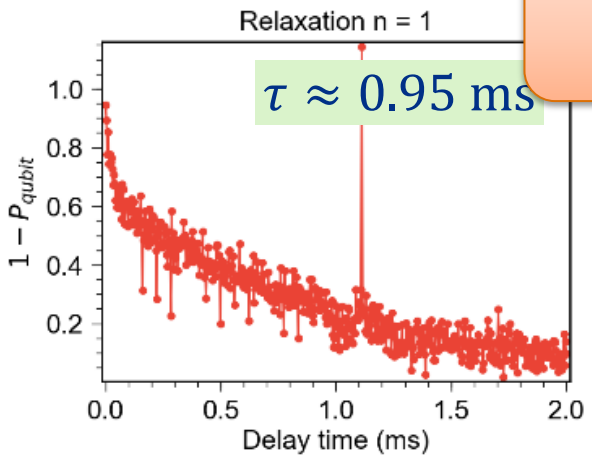


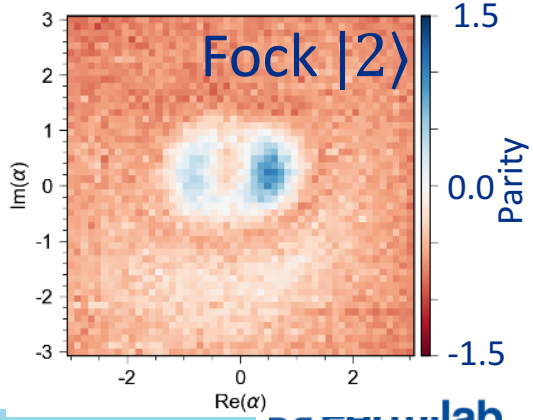


Wigner tomography



Achieved long-lived quantum states





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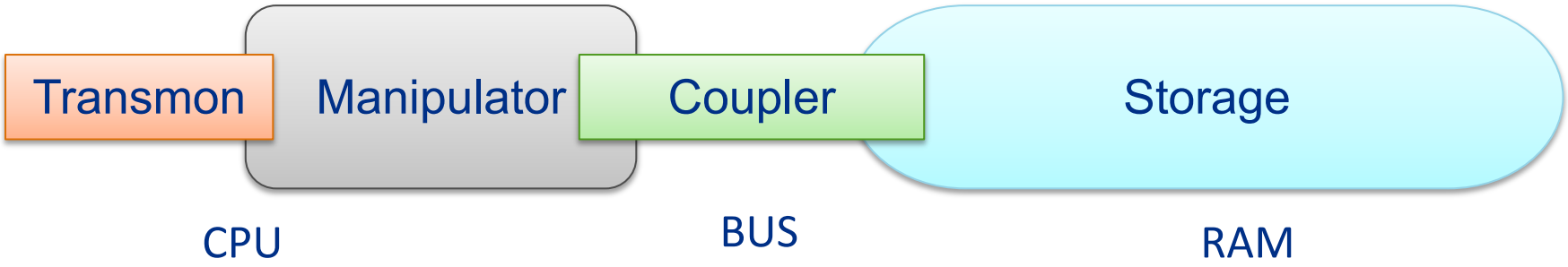
Near-Term Goals: Design Multiqubit Architecture

Crosstalk issues

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

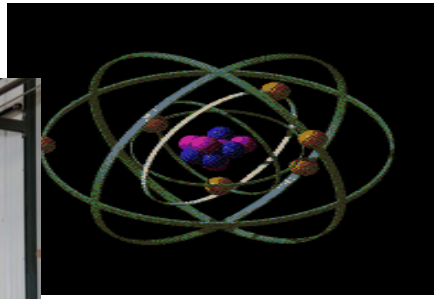
All-to-all coupling



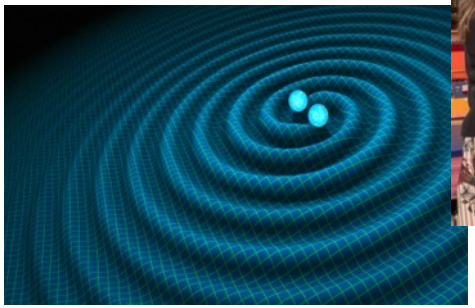
Quantum Sensing: Exploring Fundamental Physics

Dark Matter

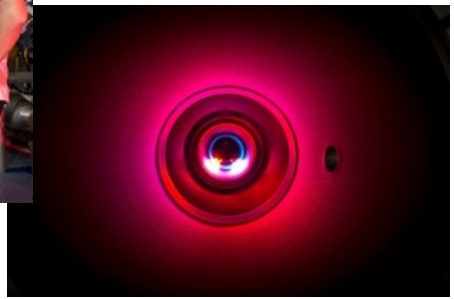
Fermilab DarkSRF experiment



Precision Measurements



Gravitational Waves



Quantum Physics

Fermilab

The Sensing Team

Fermilab

Northwestern University

University of Minnesota
Driven to Discover®

The University of Arizona

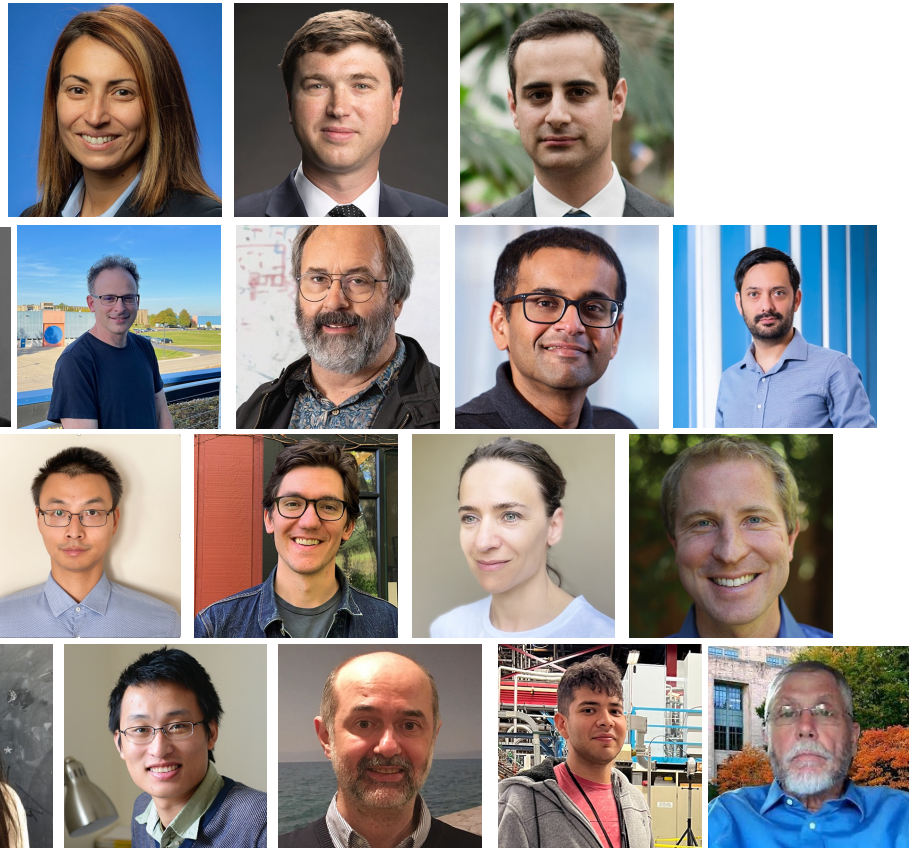
LSU

Johns Hopkins University

University of Illinois Urbana-Champaign

INFN

Stanford



Theorists and experimentalists working closely. Experts in HEP, materials, SRF, sensing, QIS, RF engineering.

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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

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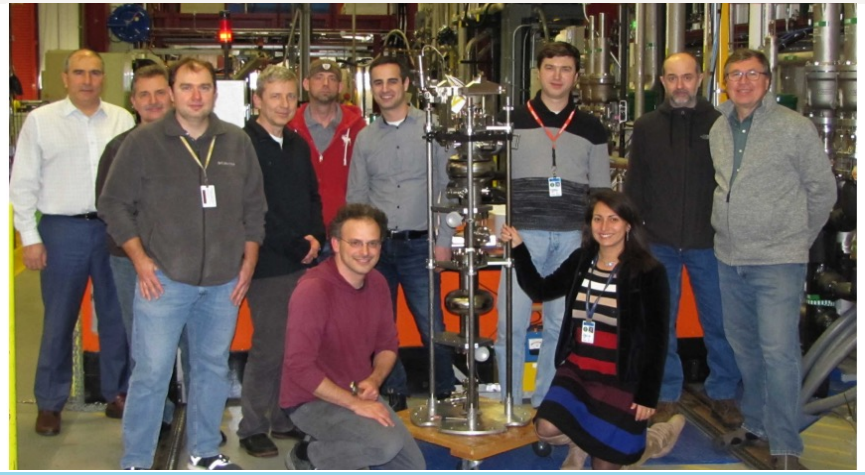

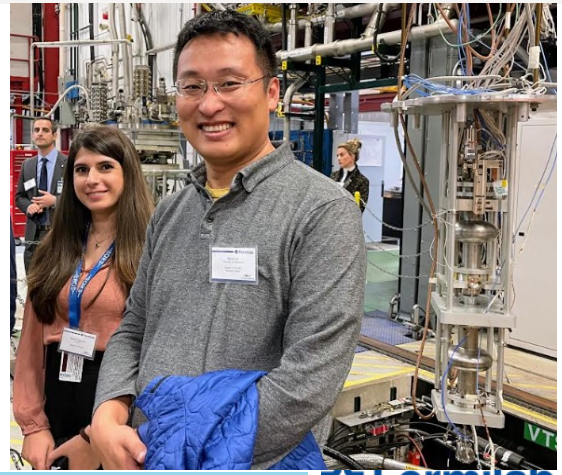

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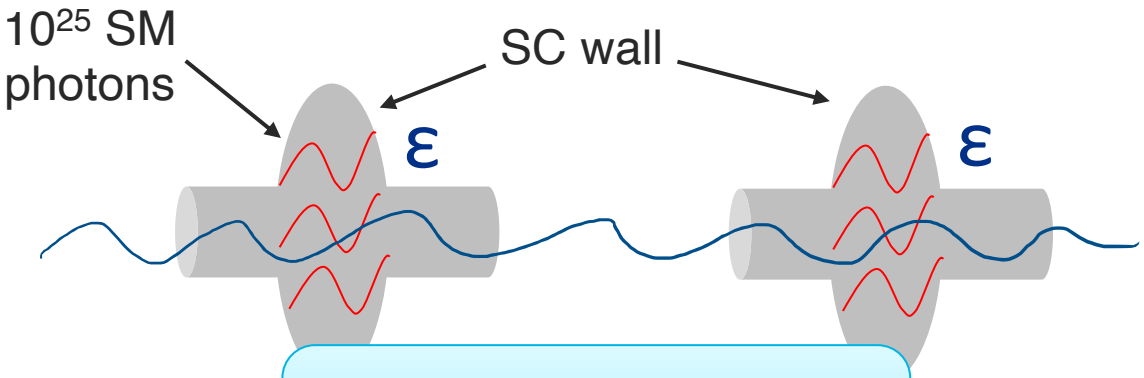
Dark SRF: ”Light shining through wall” Experiment



Emitter c 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

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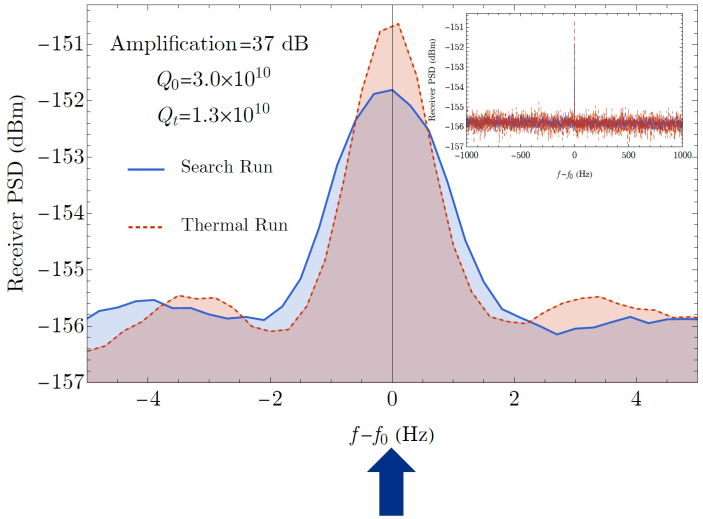
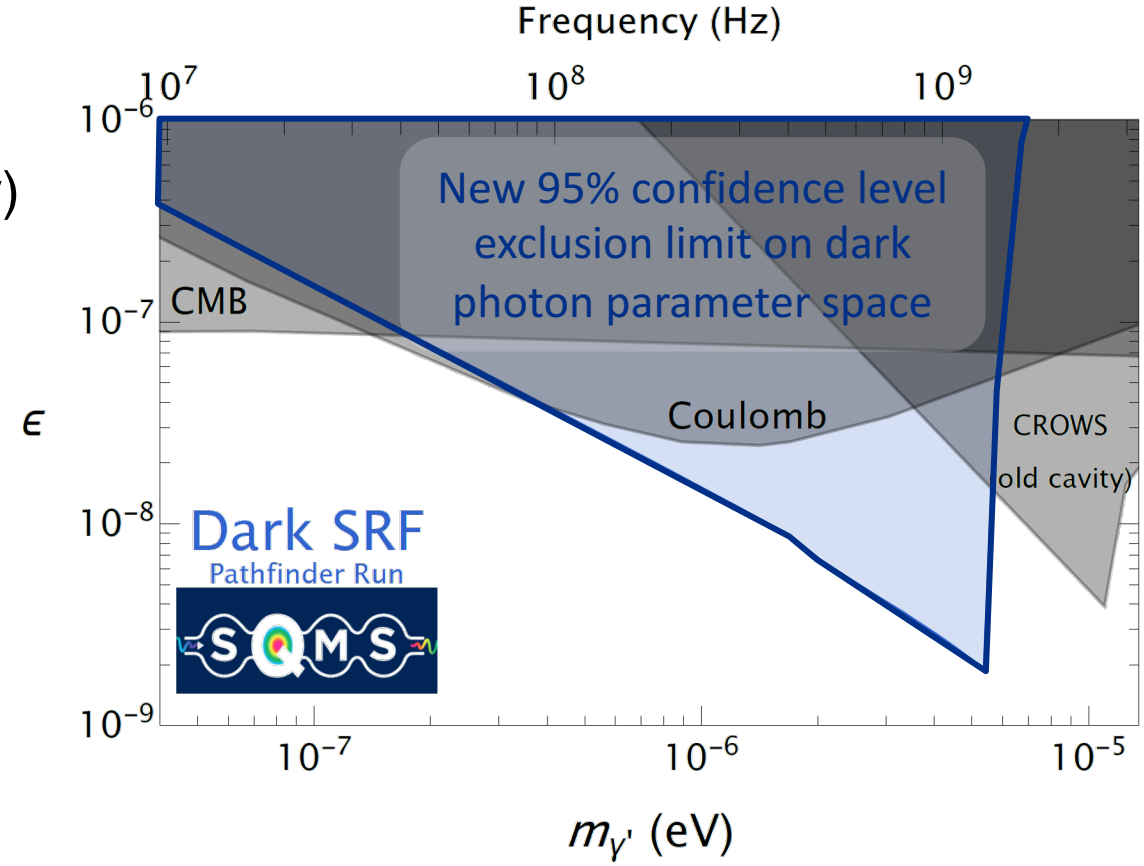
Dark SRF: phase 1 → results

Thermal run vs Search run

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



Both runs consistent to 1σ



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

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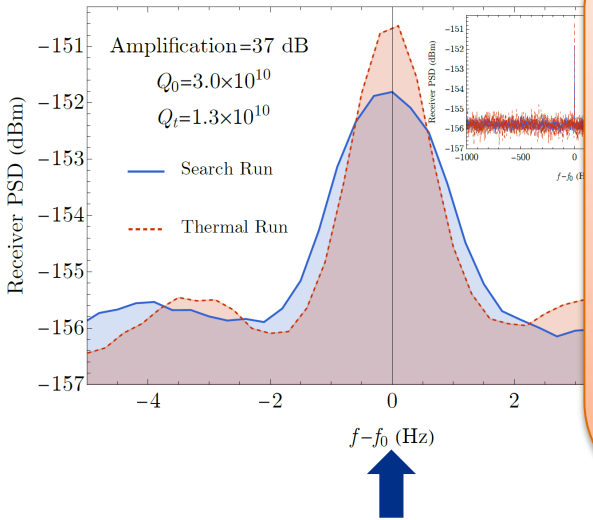
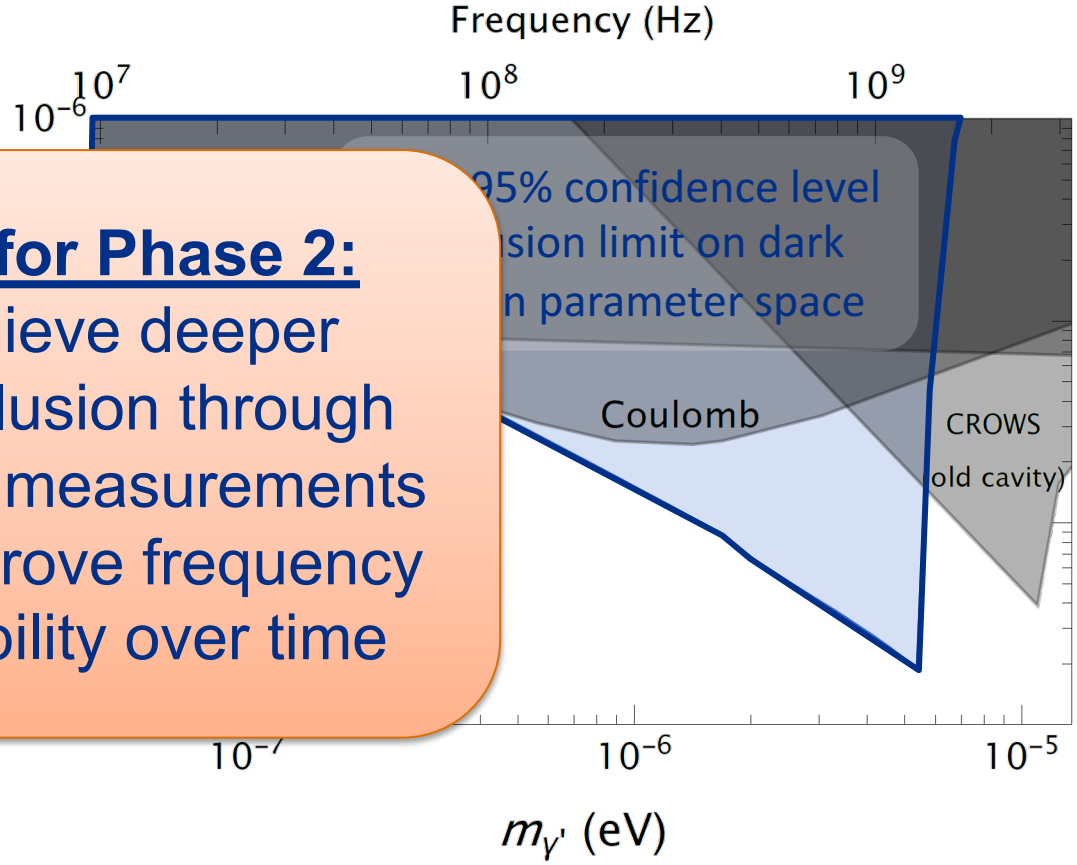


Both runs consistent to 1σ

Goals for Phase 2:

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



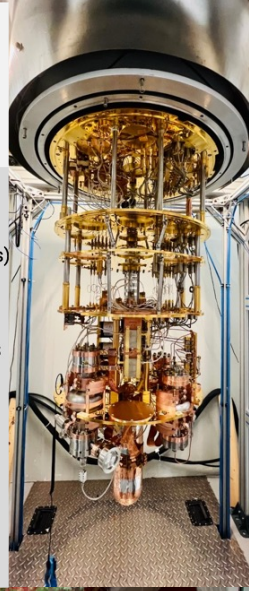
Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

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

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