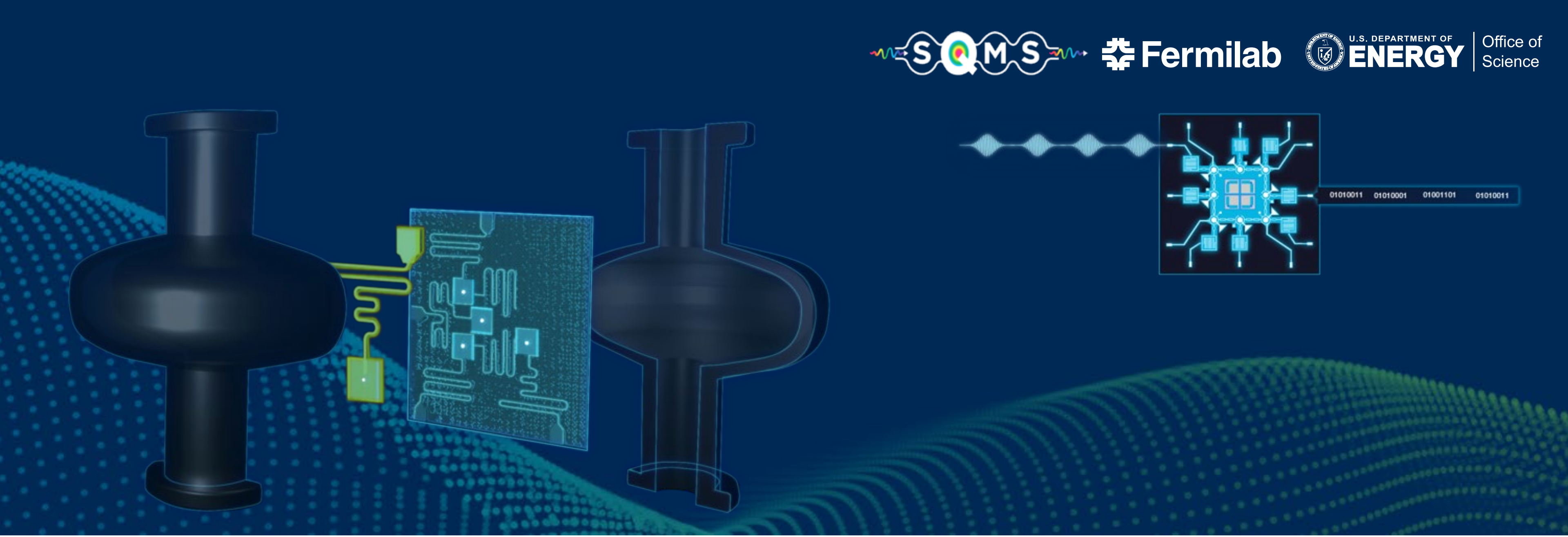
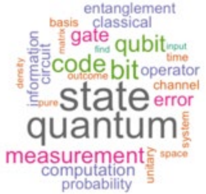


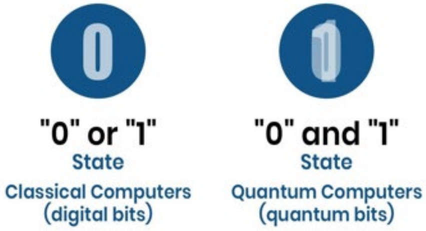
Superconducting Quantum Materials and Systems Center: Advancing the Field of Quantum Information Science

Akshay Murthy
Deputy Head, Qubits and Materials Department, SQMS division, Fermilab



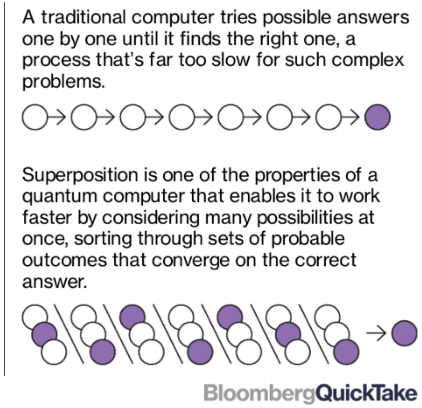
Quantum computing

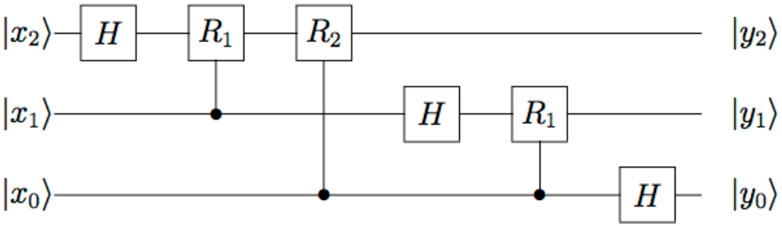
- Build computer which uses "qubits" instead of bits
  - **superposition:** the ability for a system to exist in separate states simultaneously
  - **entanglement:** shared interactions between multiple particles within a group
- A quantum computer can provide potentially computational capacity for dramatic speedups in several very high impact areas, such as:
  - Finding large prime number multipliers
  - Searching databases
  - Simulating and predicting molecules behavior and interactions
  - Modeling financial markets
  - Simulating particle collisions



Exponential speedup

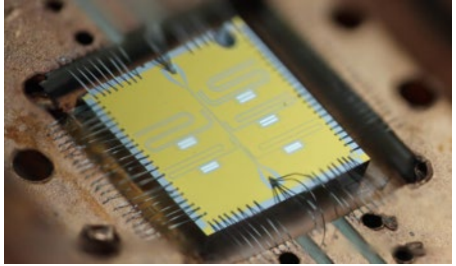
- The discrete Fourier transform is an example of a calculation that a quantum computer can do **exponentially faster** than any classical computer:
- For n qubits we need ~ n^2 gate operations, whereas a conventional Fast Fourier Transform requires ~ $n*2^n$ operations
- In 1994, Peter Shor showed that **factorization of a product of large prime numbers** can be done this way.
- Major impact on **RSA encryption**



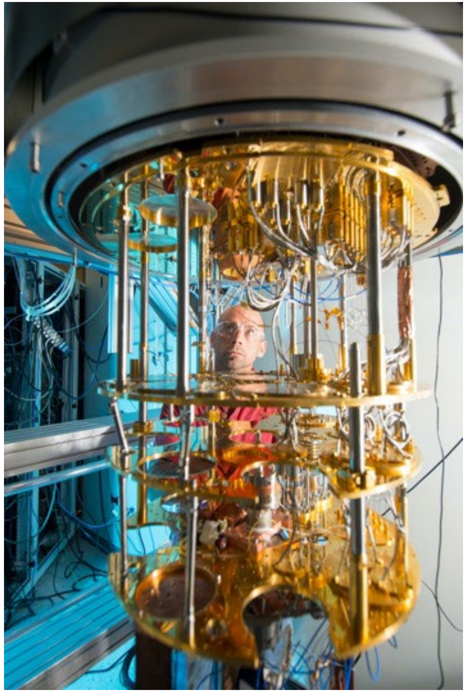


Challenges of building quantum computers

- 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

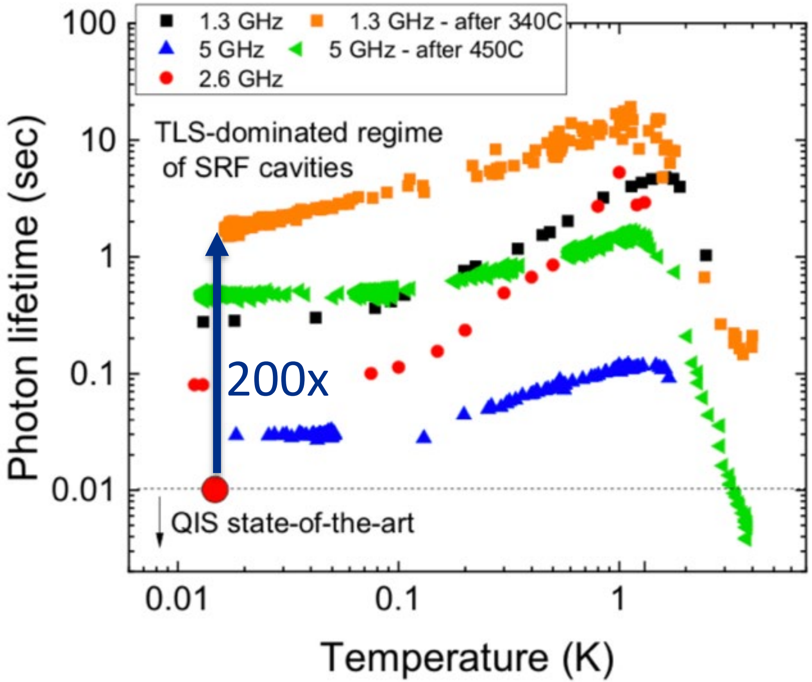


	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies 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%

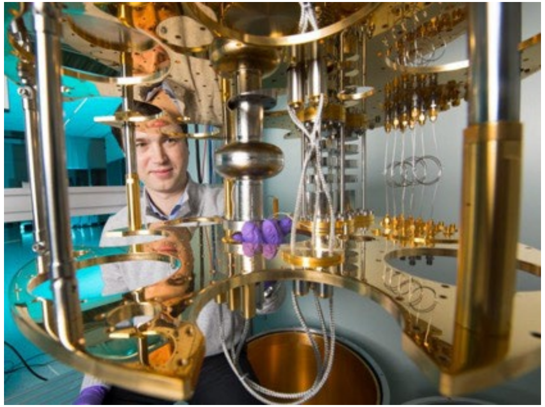


Fermilab

Fermilab superconducting cavities: Highest coherence quantum resonators ever demonstrated

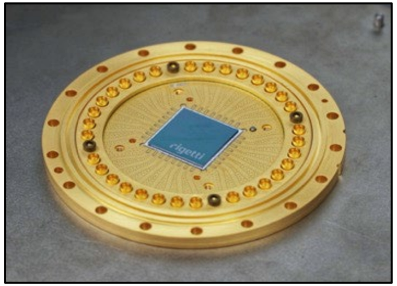


A. Romanenko *et al*, Phys. Rev. Applied **13**, 034032 (2020)



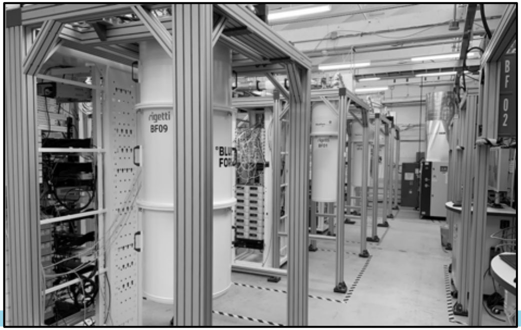
- Technology originally developed for particle accelerators
- Powerful methodology of combining fab and test with materials analysis, to develop the fundamental understanding of device performance

SQMS: Major Cross-Cutting Challenge

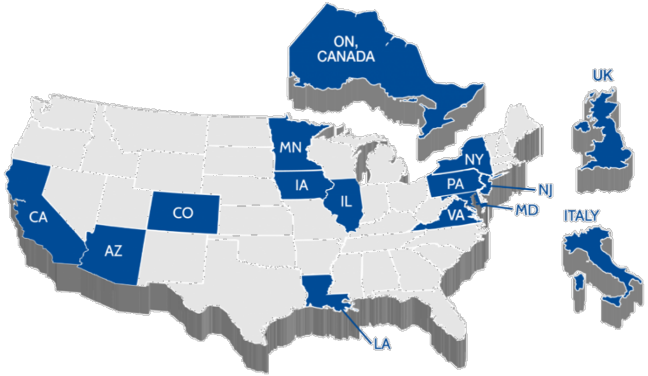


<u>SQMS Mission</u>

“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 Institutions



Regional: Chicagoland concentration

National: Institutions in 12 US states

International: Partners in Canada, UK, and Italy

Host institution

Fermilab

Core partners

AMES NATIONAL LABORATORY

NASA Ames Research Center

NIST

Northwestern University

rigetti

Contributing partners

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

SQMS Center Research: multidisciplinary, integrated, synergistic approach

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

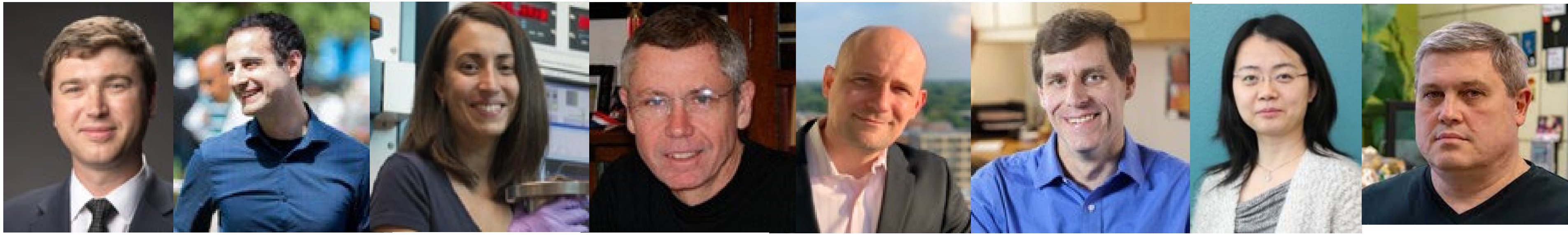
Computational Science, QIS Theory
NASA Ames, Colorado Mines, Rigetti, NU, Arizona

Condensed Matter Physics
Ames Lab, NU, NASA Ames, LSU

Industry use cases
Goldman Sachs, Lockheed Martin, Rigetti, NYU

Multidisciplinary Leadership World's Top Experts in Key Areas for QIS

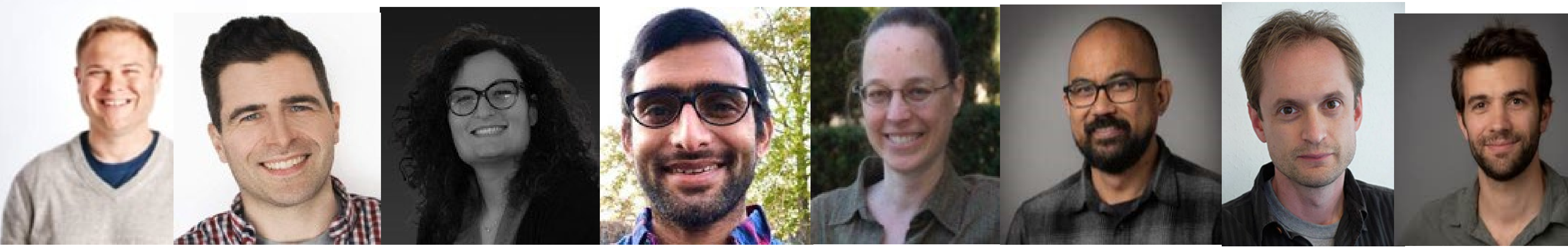
Strategy: aligning leadership with expertise as key to reach SQMS goals



Fermilab:
3D High-Q SRF cavities and materials

Northwestern:
Superconductivity Theory, QIS theory, MatSci

Ames Lab:
MatSci, Superconductivity



Rigetti:
Devices and Materials

INFN:
Radiation on SC Qubits

Rutgers:
3D QIS architectures

NASA:
Algorithms, QIS theory

NIST:
QIS Devices

Hiring of Diverse Talent Across SQMS

Developing the next generation of scientists, engineers, and technicians

131 **new hires**

>20% **URM or women**

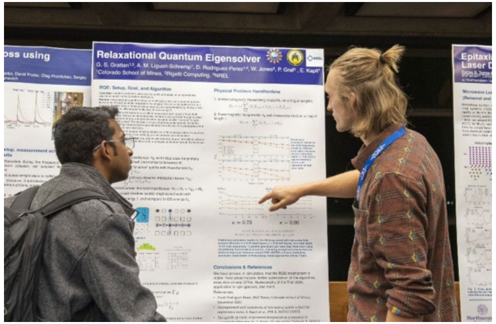
Workforce Development

- Hire, train, mentor and support researchers and staff to accomplish SQMS mission

- Create welcoming environment and foster collaborative community among SQMS participants

- Prepare young SQMS participants for career paths in QIS

- Actively steer QIS towards increased representation and equitable inclusion of all participants



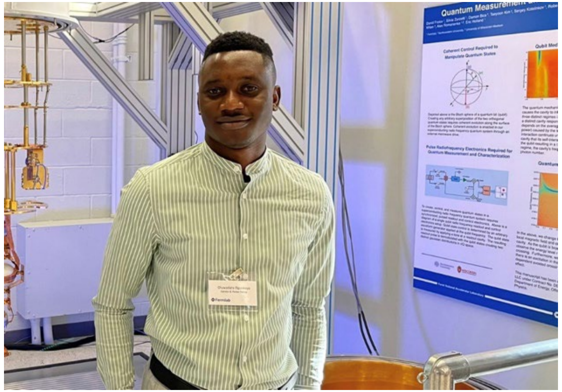
Carolyn B. Parker Fellowship

dedicated to increasing representation and inclusion of groups historically and contemporarily underrepresented in STEM

Carolyn B. Parker

first African American woman to earn a postgraduate degree in physics (1951)

Dr. Oluwadara Ogunkoya



SQMS Facilities Space at Fermilab

- SQMS headquarters and facilities are co-located alongside SRF fab and test facilities, material science labs
- 40+ office spaces allocated in the technology complex for SQMS personnel and visitors
- SQMS has two laboratory space for QIS experiments, QCL1 and QCL2 (APS-TD), and material labs
- A third 6000 sq ft lab space has been assigned to SQMS in IARC

SQMS Center is located in FNAL Technology Campus, in APS-TD buildings and the IARC building

SQMS Office and Collaboration Space

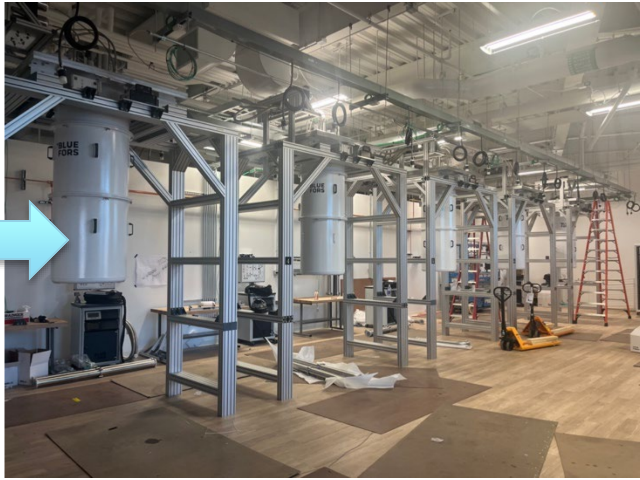
SQMS Center Headquarters

Fermilab

New Quantum Computing Labs at FNAL: *“The Quantum Garage”*

2021

2022



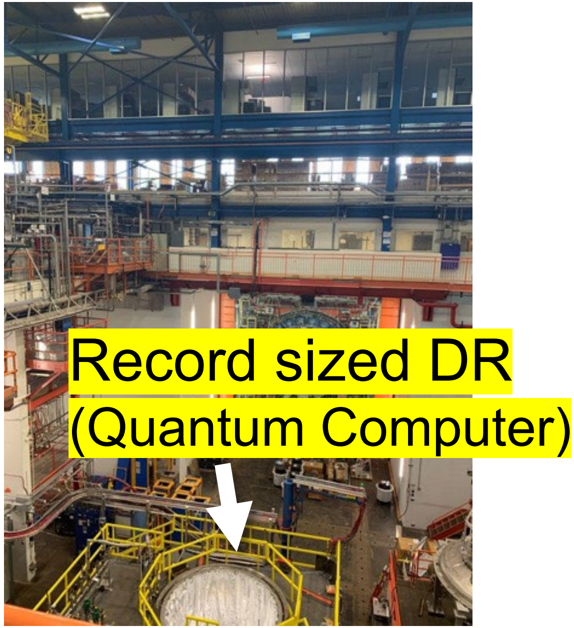
2023

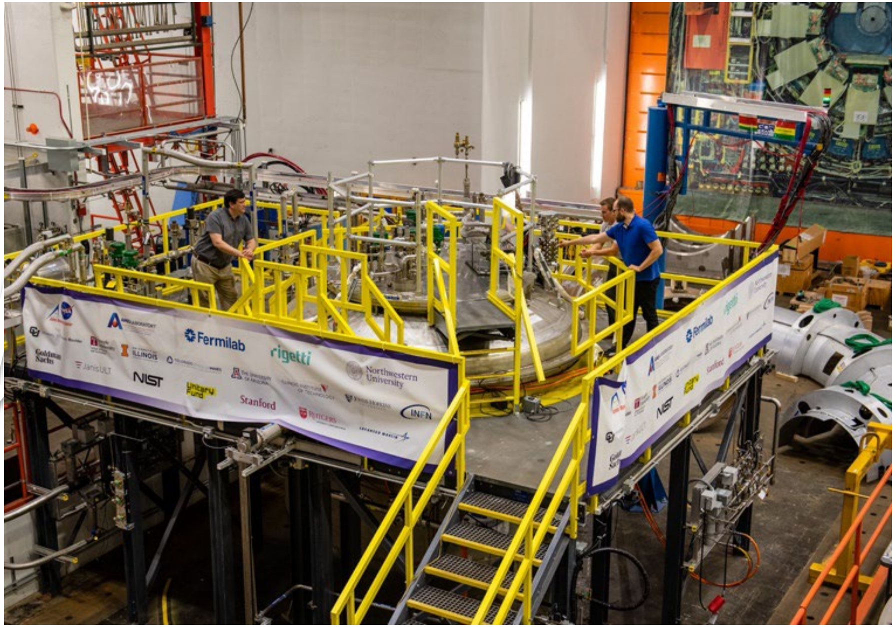
- The new quantum testbeds lab at FNAL will be fully commissioned in March 2023
- It hosts 5 dilution fridges, clean room facilities for cavities and qubits
- Full renovation from garage to finished lab space, all components procured and received

Record Size DR and Industry Space

IARC/HAB space hosts the ultra-low-temperature cryogenic developments which include Colossus (world's largest DR) and enabling of cryogenic technologies for future large quantum data centers

SQMS foundries, computing testbeds, collaboration space

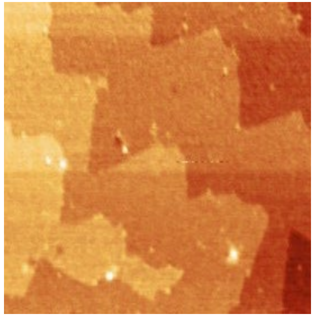




SQMS Science & Technology Innovation Chain

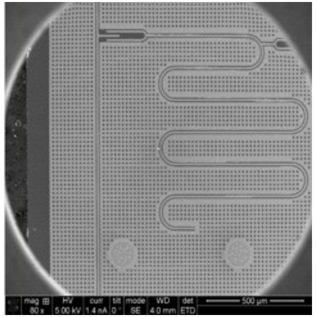
Materials → High-coherence devices → Systems integration → New platforms for quantum computing & sensing → Quantum advantage

Materials



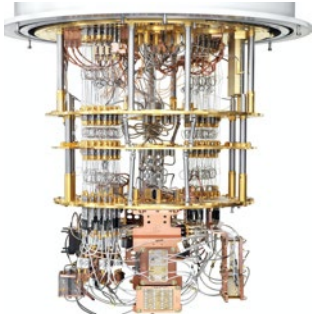
Understand fundamental limits of performance on the atomic level

High-coherence devices



Demonstrating repeatable, high coherence devices

Systems integration

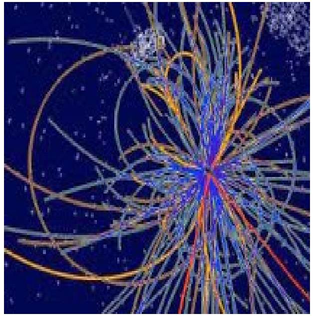


Preserving device performance through the process of integration into more complex systems

New platforms for quantum computing & sensing

Deploying quantum platforms of innovative architectures and improved performance

Quantum advantage

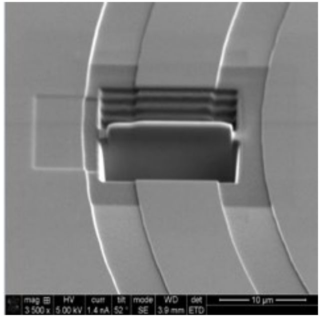


Applying quantum computing and sensing advantage for particle physics and other scientific applications

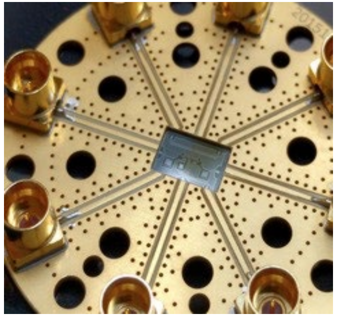
SQMS bridges the gap between ideas and large-scale realizations via unique center-wide coordinated approaches

SQMS Science & Technology Innovation Chain Highlights

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



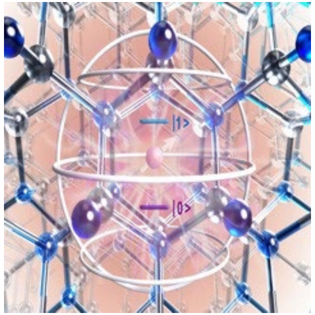
Unprecedented coordinated study has led to understanding of dominant sources of decoherence



Demonstration of superconducting qubits with state-of-the-art coherence times

Integration of qubits + SRF cavities

Launched co-design activities to develop new 2D and 3D QPUs architectural concepts



Demonstrated advantage in quantum sensing for fundamental physics in the area of dark matter search

Excellent progress across the full stack of innovation chain thanks to the strength of center coordinated work

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

SQMS Summary Vision

Building new quantum facilities, capabilities and workforce that will enable new scientific discovery