QIS at Fermilab and Workforce development efforts

Silvia Zorzetti, QIS Ecosystem Leader at the DOE SQMS Research Center
Sandra Charles, Chief Equity, Diversity, Inclusion, and Accessibility Officer
Anna Grassellino, SQMS Director
Jens Koch, SQMS Deputy Director

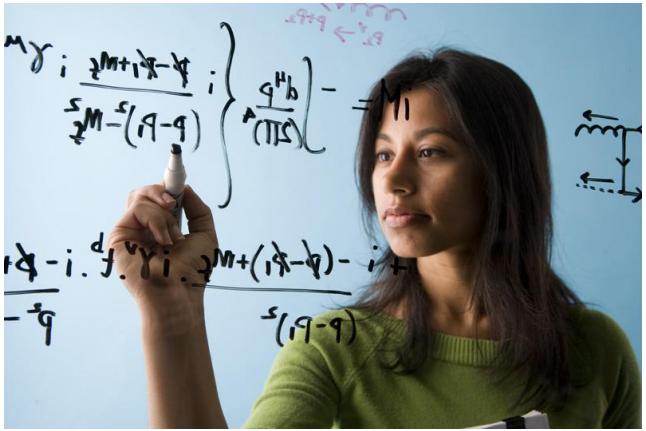
Fermilab at a Glance

- America's particle physics and accelerator laboratory
- Operates the largest US particle accelerator complex
- ~1,900 staff and ~$600M/year budget
- 6,800 acres of federal land
- Facilities used by 4,000 scientists from >50 countries

As we move into the next 50 years, our vision remains to solve the mysteries of matter, energy, space, and time for the benefit of all.

Fermilab Science Mission – P5 science drivers

- Higgs boson
- Neutrinos
- Dark matter
- Dark energy and inflation
- Exploring the unknown



Fermilab is delivering on the DOE/SC discovery science mission: Major particle physics breakthroughs from Fermilab experiments, major technology breakthroughs from Fermilab research

Fermilab

Quantum computing and sensing at Fermilab

HEP for QIS

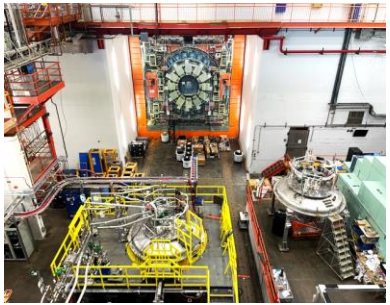
Technology expertise and infrastructure for the development of new quantum devices and for the challenges of scaling up quantum systems

QIS for HEP

Tackle HEP challenges, such as dark matter detection, quantum computing advantage for field simulations

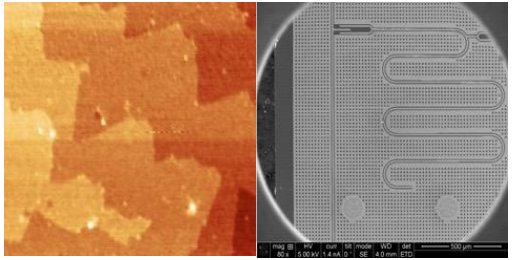
Superconducting technology

SRF cavities with long coherence time



Cryogenics

Control electronics



Materials and devices

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

National Quantum Initiative Act (2018)

10 yr plan to accelerate the development of **quantum information science & technology applications.**


H. R. 6227

One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen

An Act

To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

" **Department of Energy (DOE)** shall carry out a **basic research program** in QIS;

DOE Office of Science shall establish and operate **NQI Science Research Centers** to conduct basic research to accelerate scientific breakthroughs in quantum information science and technology. "

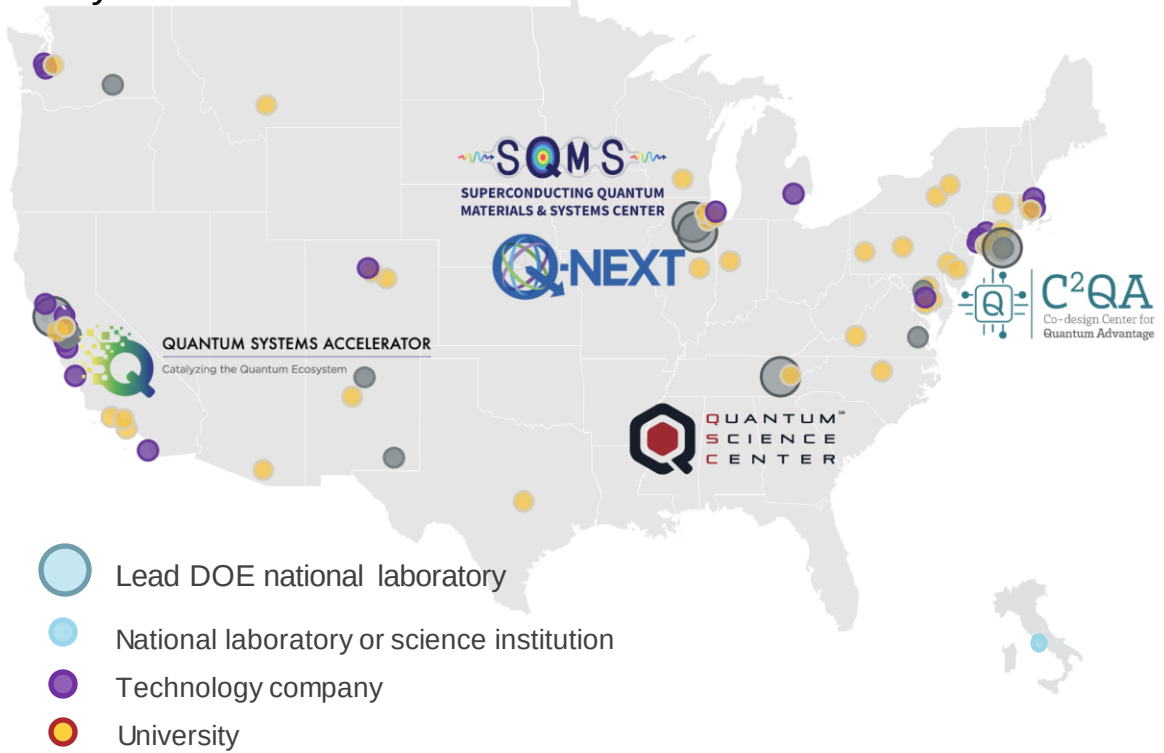
" Quantum information science is the use of the laws of quantum physics for the storage, transmission, manipulation, or measurement of information."

Partnerships across academia, industry and 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



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30 Partner Institutions

>500 Collaborators

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

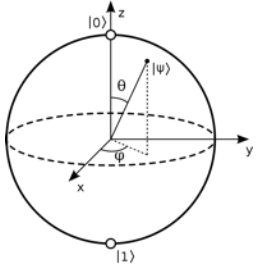
Fermilab
Northwestern University
rigetti
AMES NATIONAL LABORATORY
Creating Materials & Energy Solutions
NASA Ames Research Center
NIST
COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT
FORMFACTOR™
Goldman Sachs
ILLINOIS INSTITUTE OF TECHNOLOGY
INFN
Jefferson Lab
JOHNS HOPKINS UNIVERSITY
LOCKHEED 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®
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

Quantum vs. classical

Qubit in quantum computing

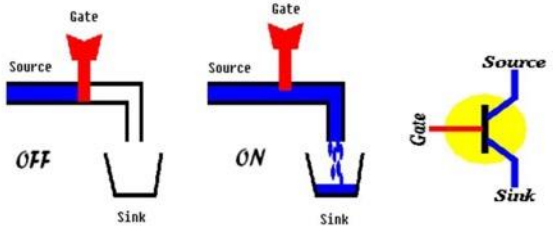
Infinite number of states through superposition

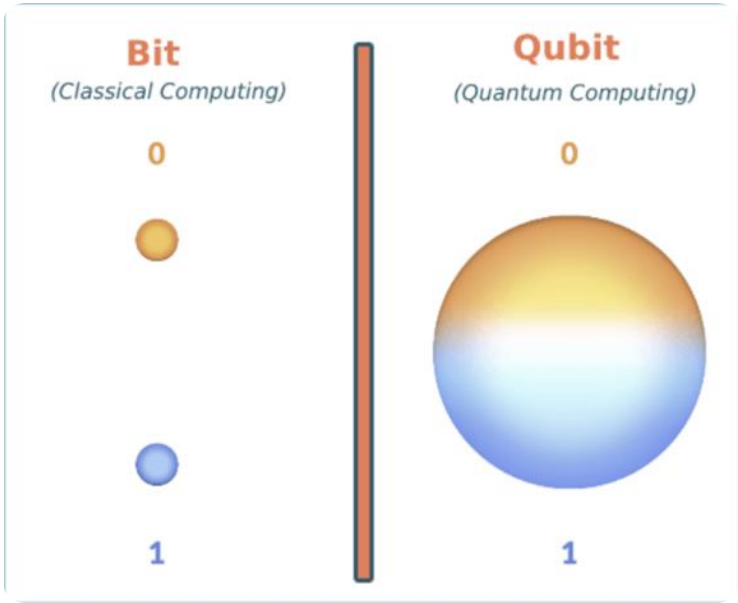


Transistor in classical computing

About 11.8 billion transistors in an iPhone

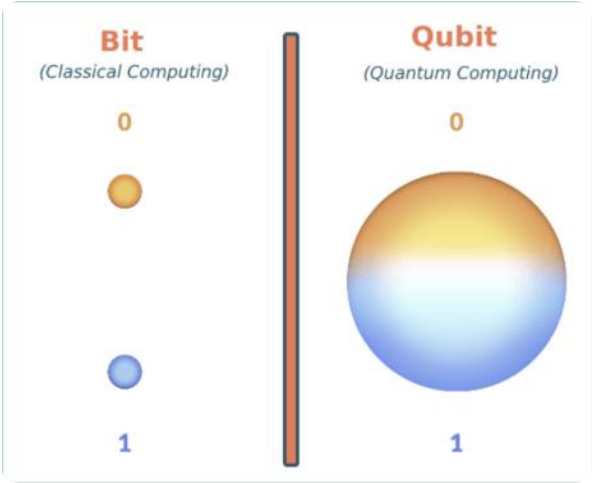
- Gate on, Water flow: 1
- Gate off, Water not flow: 0





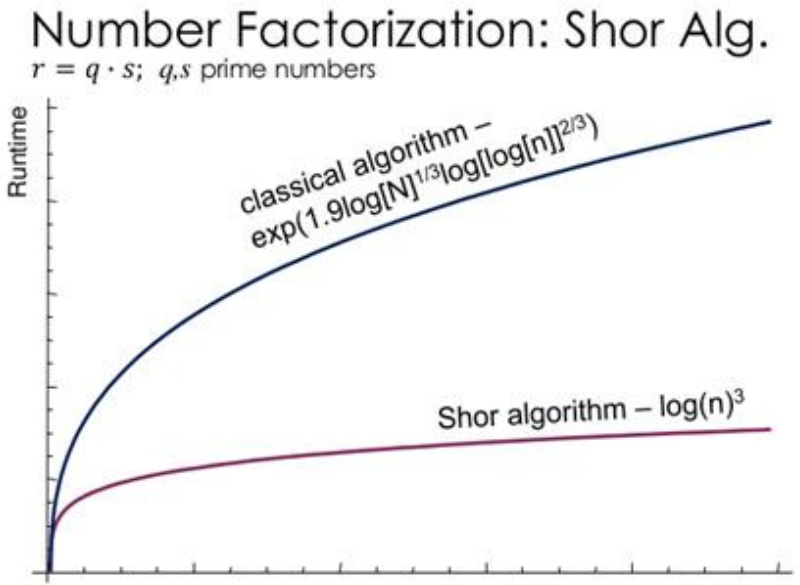
Quantum computing's method of parallel calculation will be successful in analyzing very complex system that requires very high computational power

Classic vs Quantum

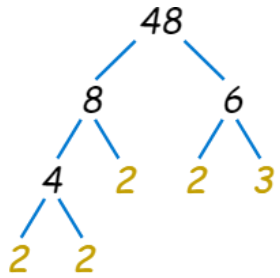


Parallel calculation through **superposition**

Computational efficiency



Number factorization



$48 = 2 \times 2 \times 2 \times 2 \times 3$

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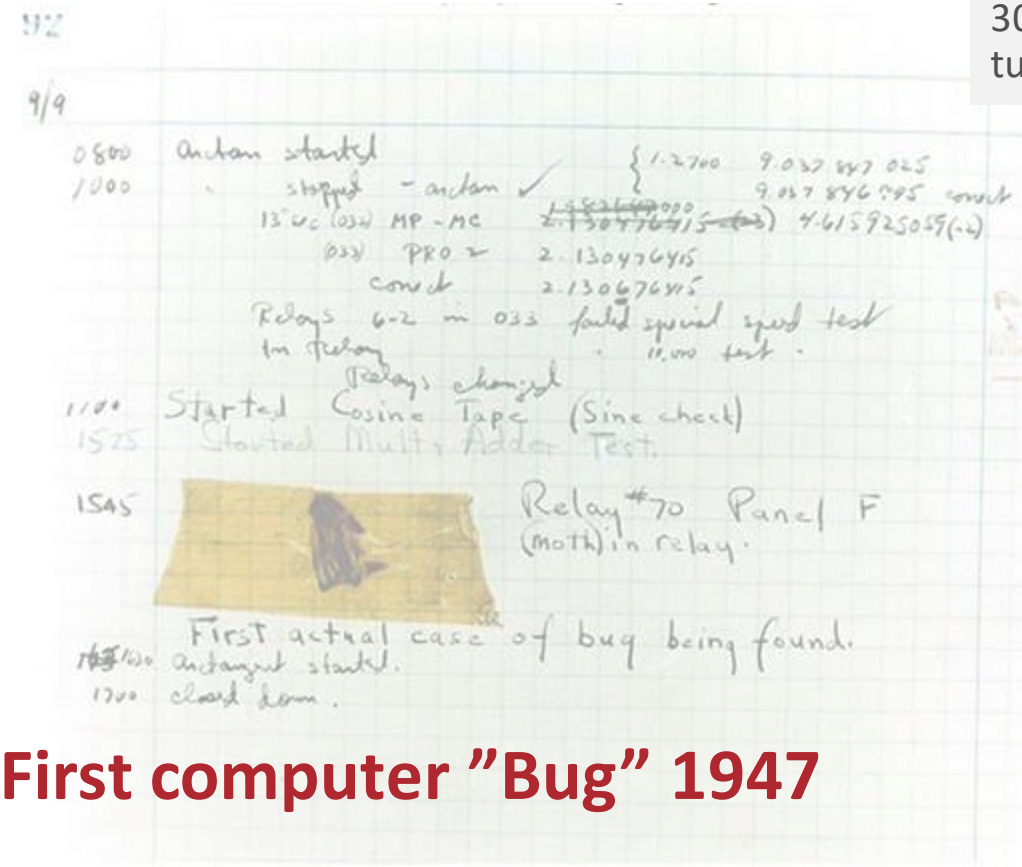
The first calculators

ENIAC filled a 20 by 40-foot room, weighed 30 tons, and used more than 18,000 vacuum tubes.



First computer ”Bug” 1947

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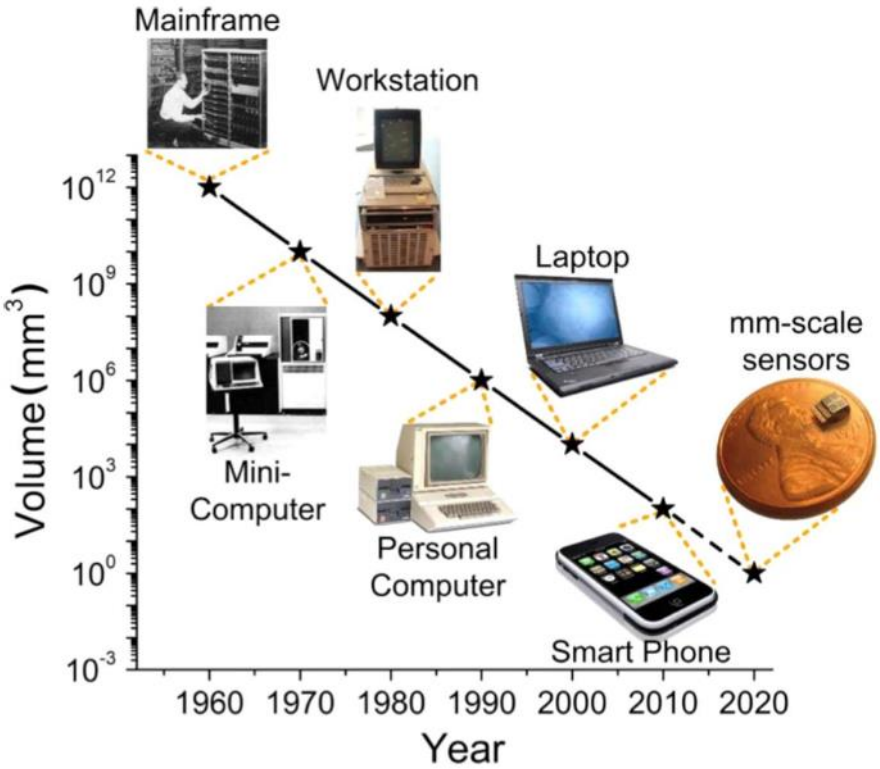
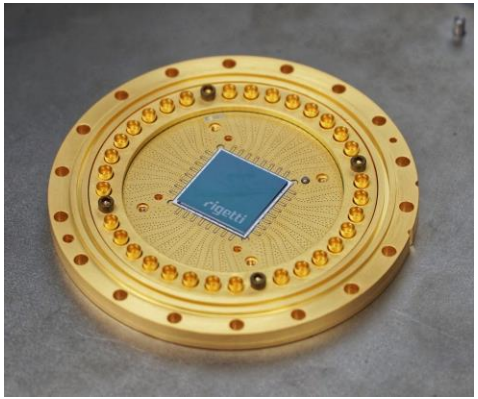
Scaling



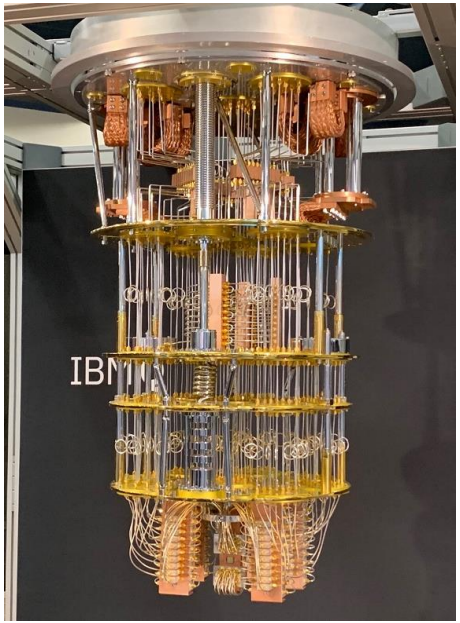
ENIAC filled a 20 by 40-foot room, weighed 30 tons, and used more than 18,000 vacuum tubes.

Quantum computers

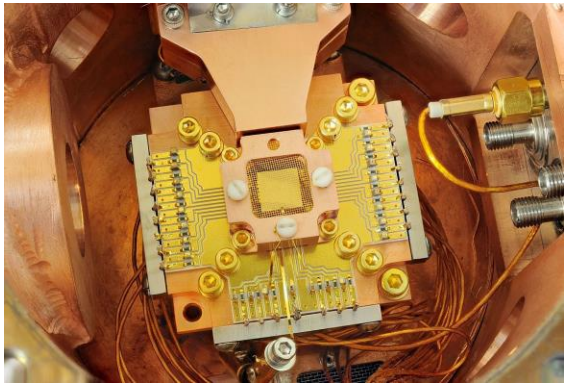


Rigetti planar chip

Quantum algorithm, Qiskit



IBM hardware



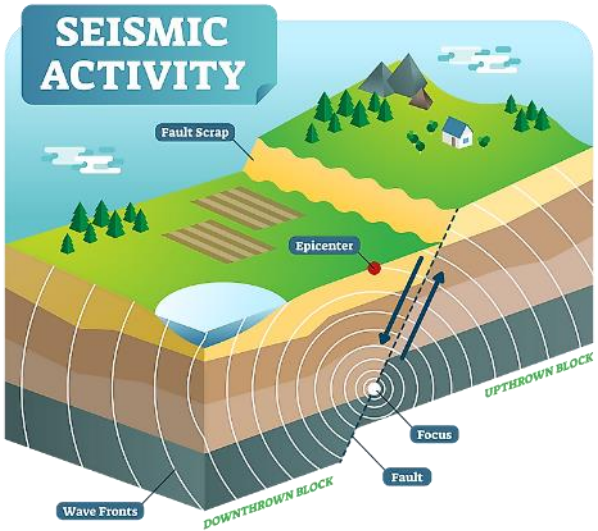
3D quantum computers, Fermilab

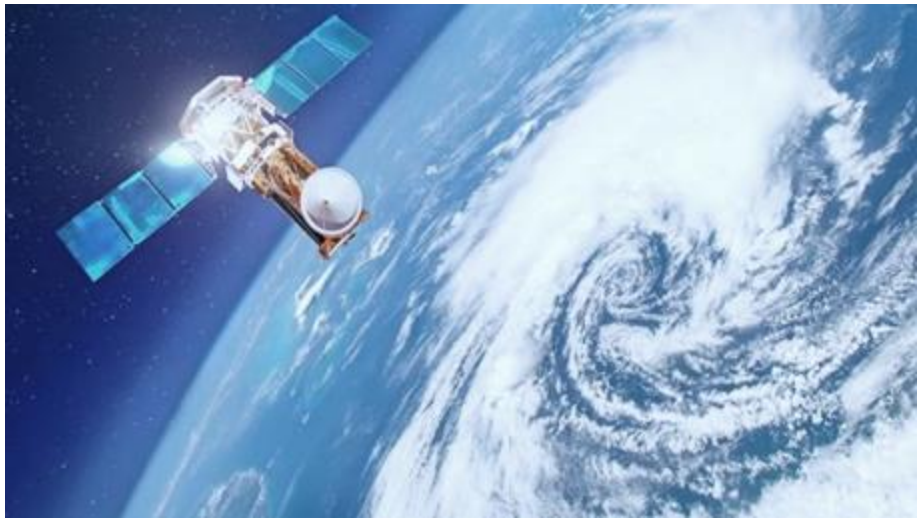
Trapped ion quantum computers, e.g. IonQ

Quantum advantage

Quantum sensors, weather and events forecasting

Solve **algorithms** to resolve complex models to predict the weather more efficiently and assess weather patterns

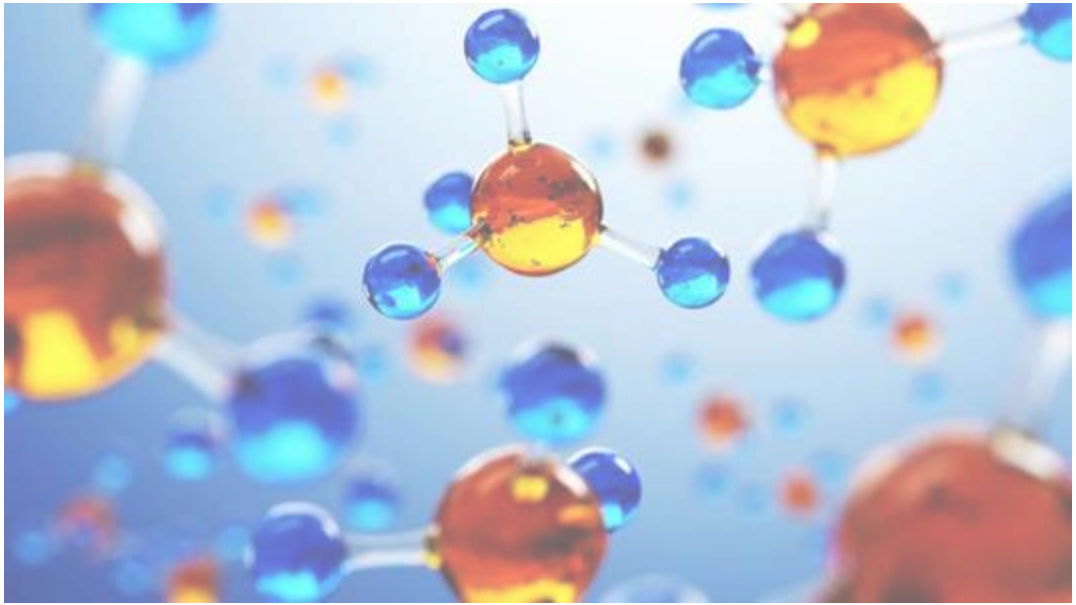




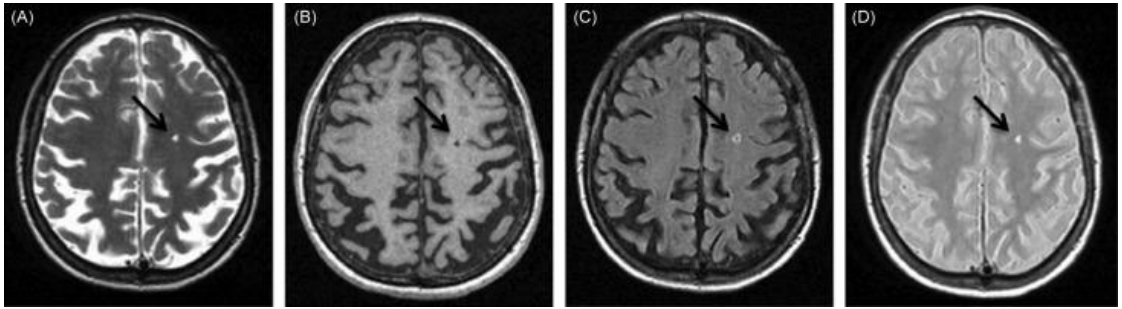
Use **very sensitive quantum sensors** to detect weak signals underwater or underground, in environments with a high level of interference, analyze seismic and volcanic activities

Chemistry and medicine

- Reduce the number of clinical testing
- Synthetize proteins, that are computationally hard to simulate



- Analyze medical data in a faster and more efficient way to reduce the diagnostic time



Magnetic Resonance Imaging analysis

Traffic management

- Optimize routes and traffic
- Predicts future traffic volumes, demand for transport and the duration of each journey. This helps to avoid traffic jams and shorten waiting times.

Pilot program in Beijing, Barcelona and Lisbon

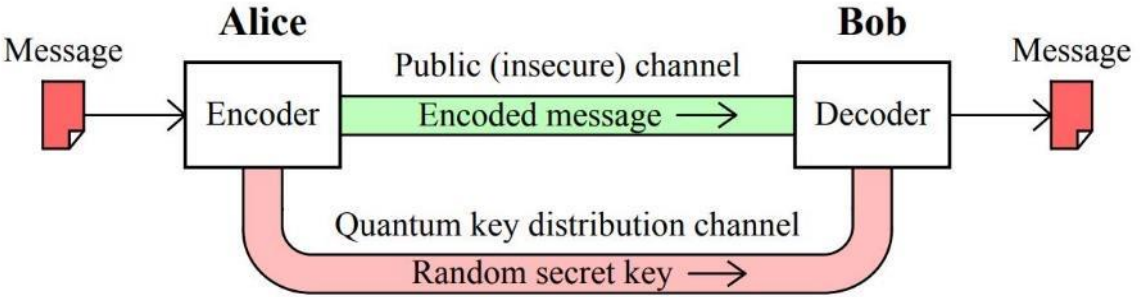
https://www.volkswagenag.com/en/news/stories/2018/11/intelligent-traffic-control-with-quantum-computers.html

Quantum cryptography

Secure the communication through quantum key distribution

Secret sharing, secure computation, and secure direct communications

Identify the authenticity through readout



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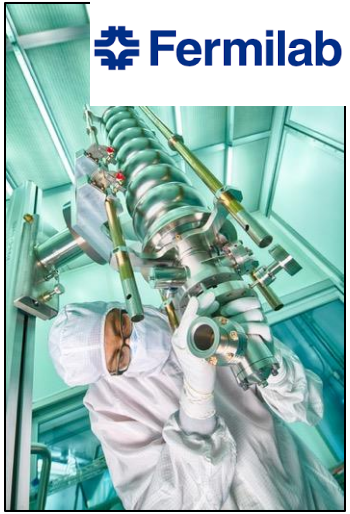
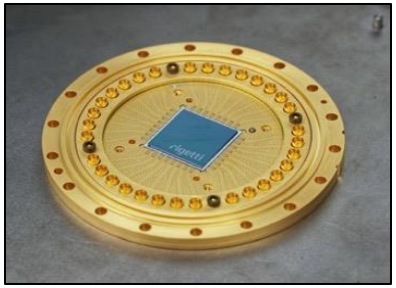
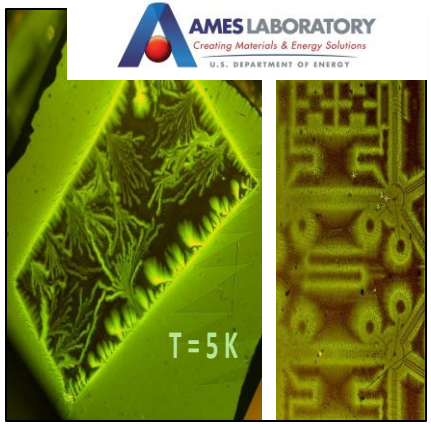
SQMS

Mission: Attacking the Decoherence 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."

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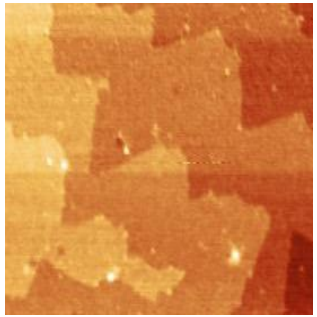
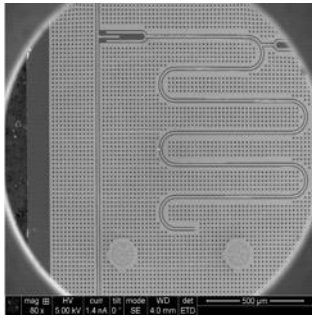
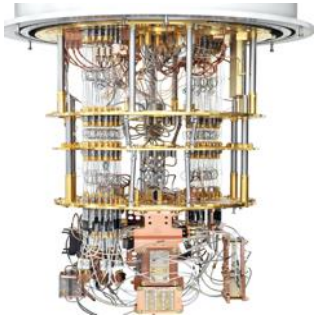
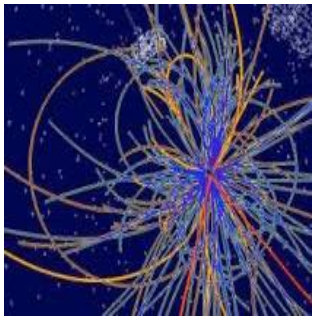
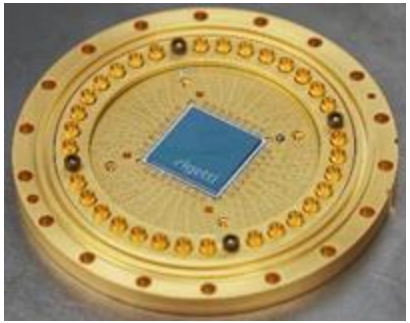
SQMS Goals and Science & Technology Innovation Chain

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

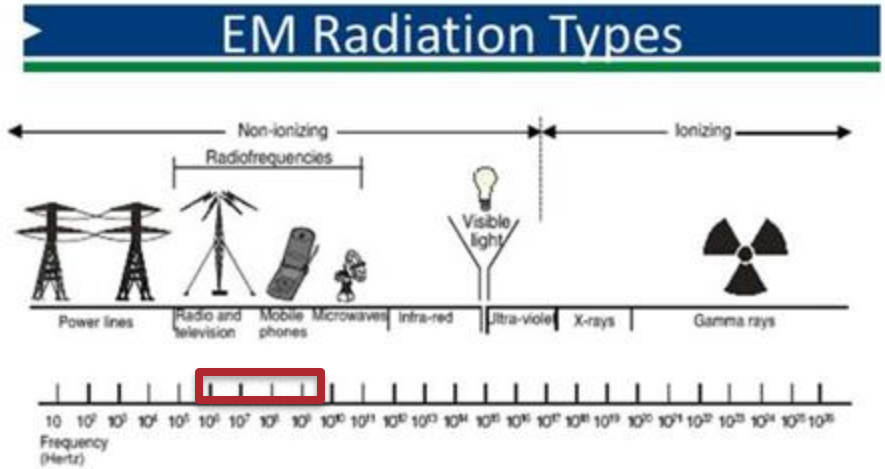
SQMS bridges the gap between ideas and large-scale realizations via the unique center-wide, multidisciplinary coordinated approaches

Superconducting radio-frequency (SRF) technology

Transmission lines

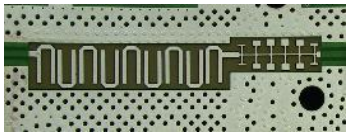


Transmission lines radiating electro-magnetic (EM) fields

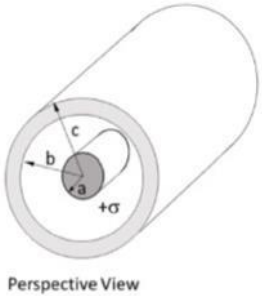


MHz – GHz for many applications in quantum and particle accelerators

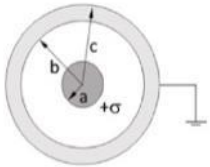
Different types of transmission lines



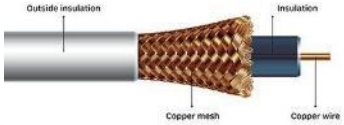
Coaxial cable



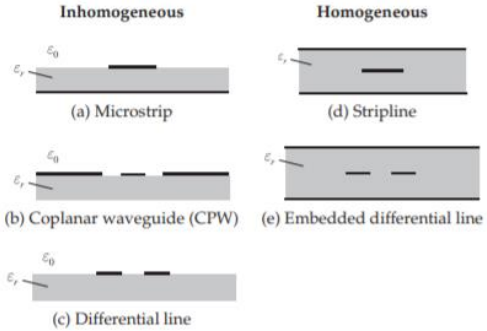
Perspective View



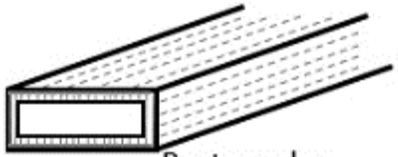
Front View



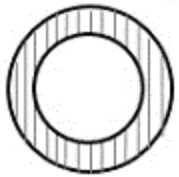
Planar transmission lines



Waveguides

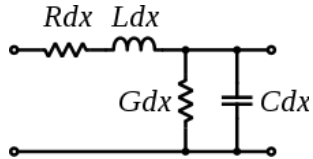


Rectangular waveguide



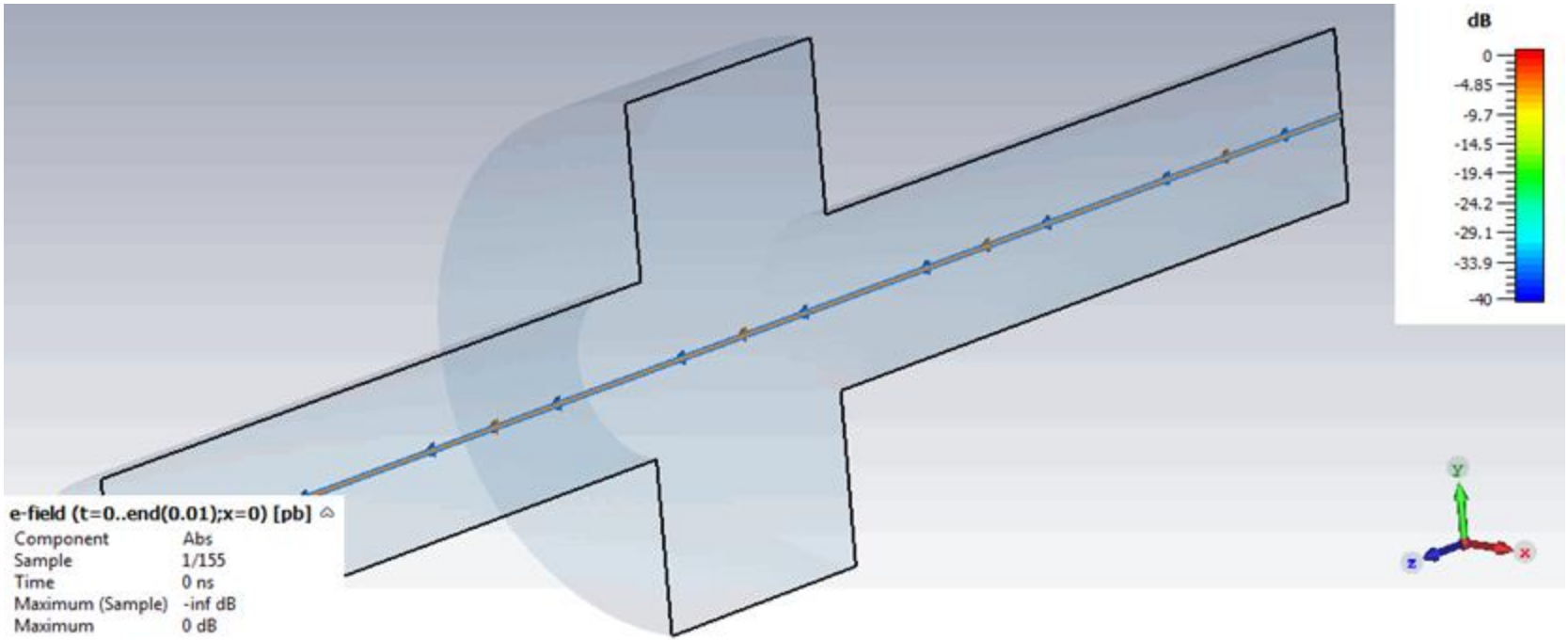
Circular waveguide

Telegrapher's equations



- Characteristic impedance of line $Z_0 = \sqrt{\frac{L}{C}}$
- Velocity Factor $v_f = \frac{1}{\sqrt{\varepsilon_r \mu_r}}$
- Medium properties: C, L, $\boldsymbol{\varepsilon}$, $\boldsymbol{\mu}$

Resonant cavity



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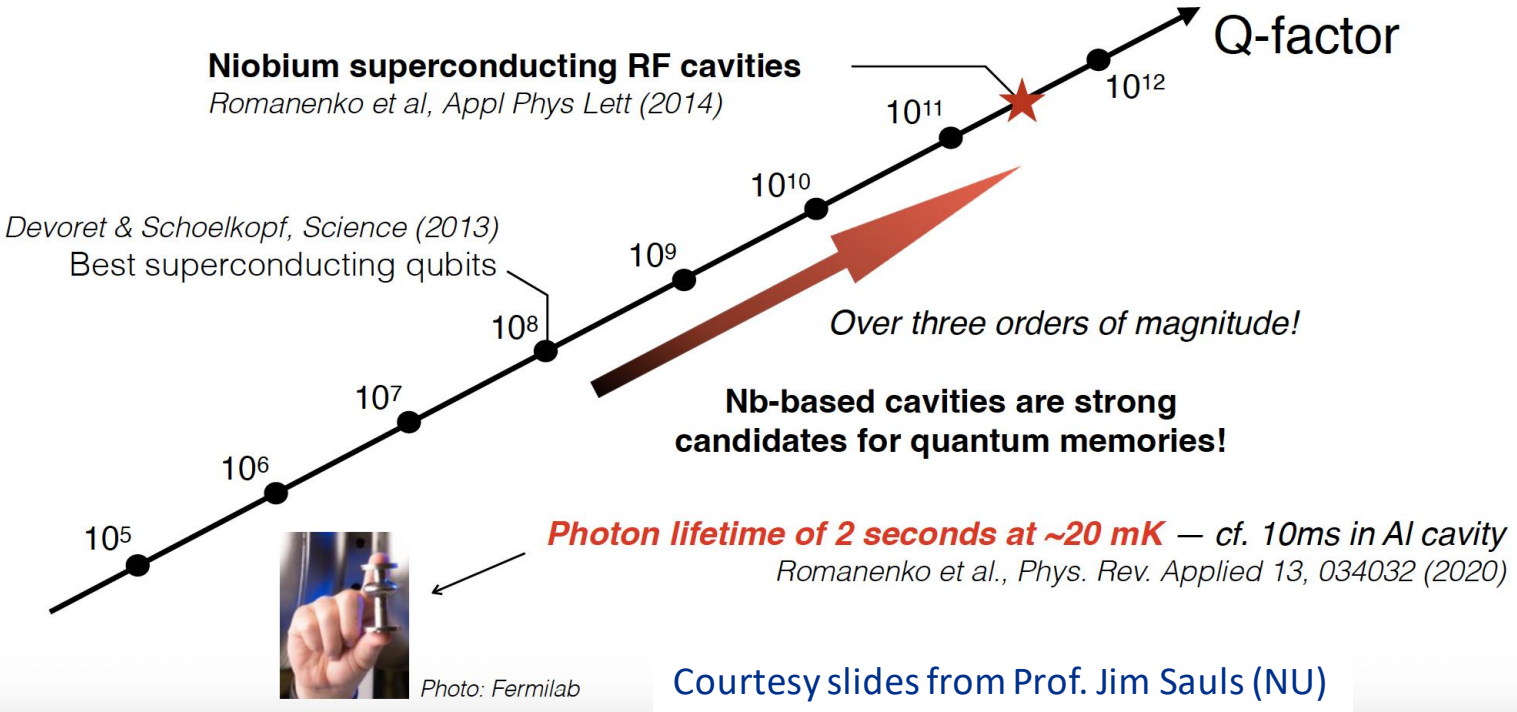
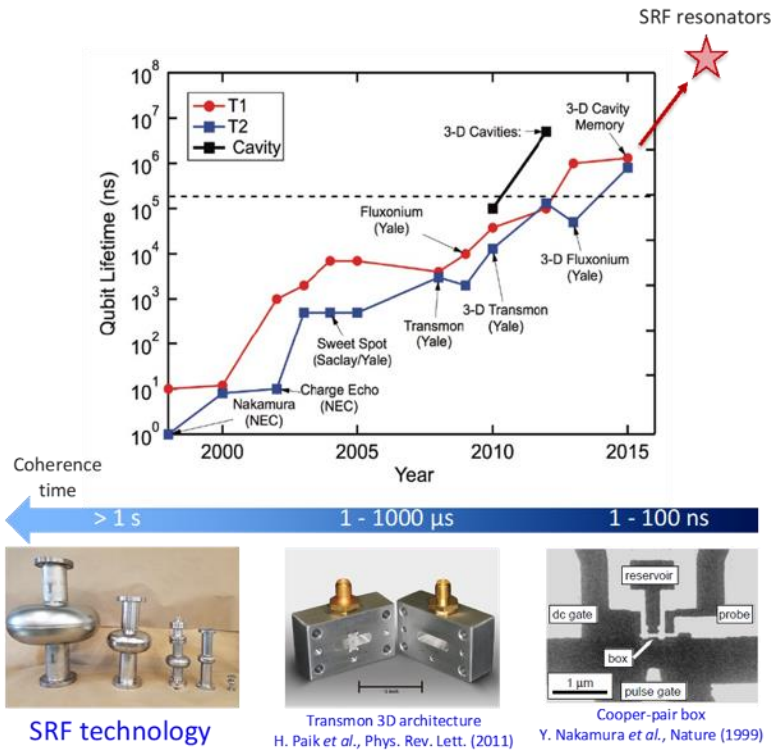
Improved photon lifetimes by a factor of 1,000

In the quantum regime



Courtesy slides from Prof. Jim Sauls (NU)

New 3D quantum devices



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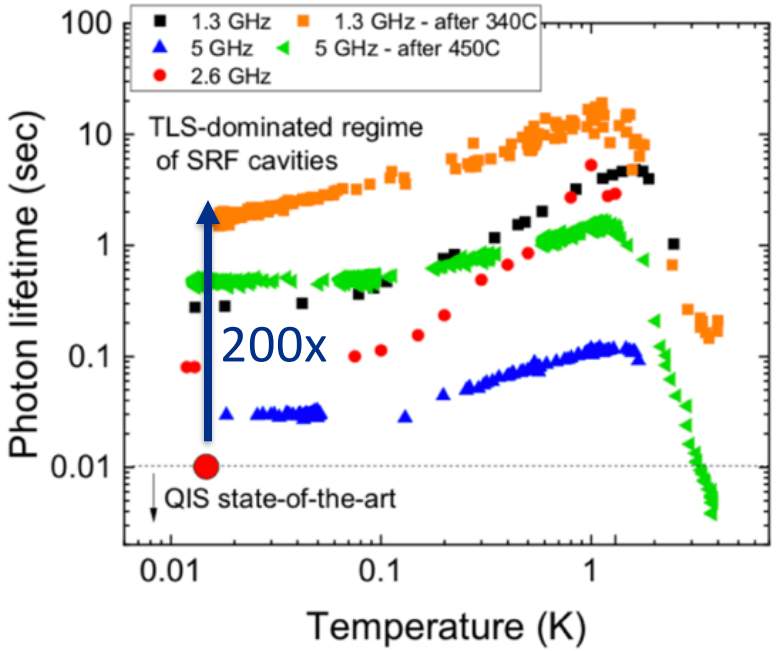
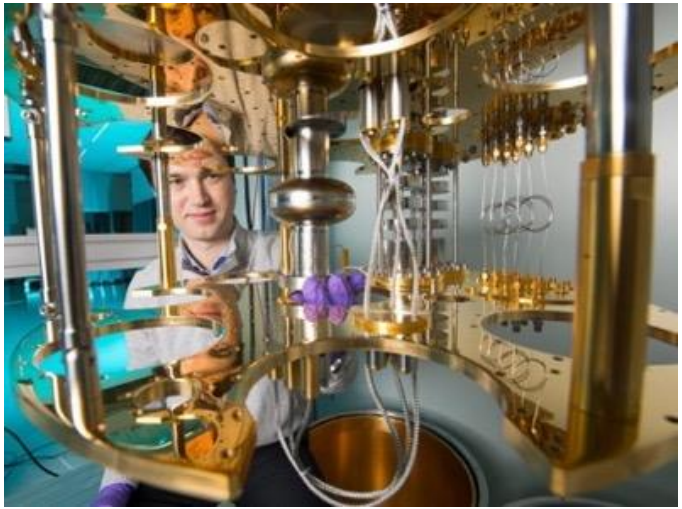
Highlight: world record coherence 3D cavities in quantum regime

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

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SQMS 3D SRF approach – unique benefits of the world's best coherence

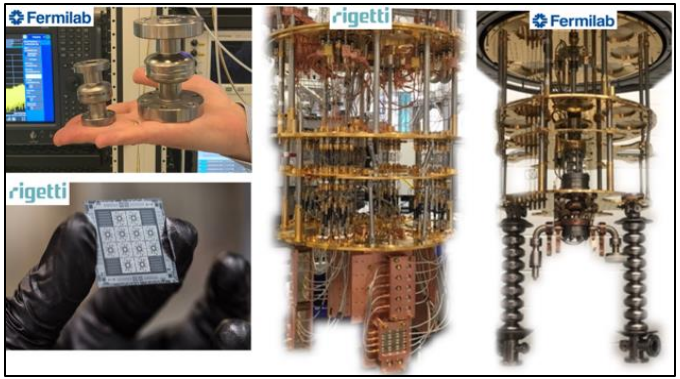
Novel QPU architectures

- 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

- > 100 qubits with just few input/output lines



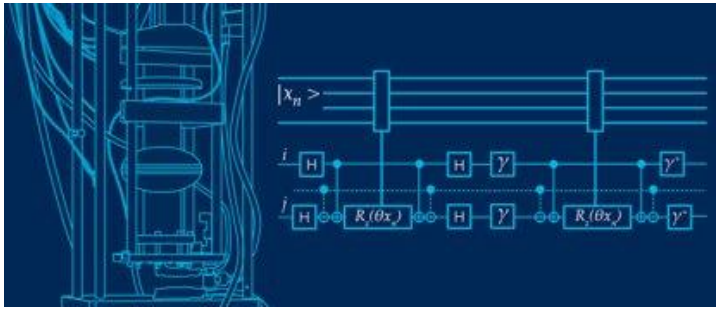
Science

- Directly probing the quantum to classical transition : "Schroedinger 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

Applications – pilot programs

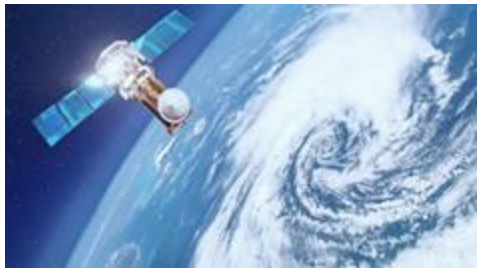
SQMS provides access to unique infrastructure, capabilities, and expertise

Use these capabilities for commercialization and economic growth

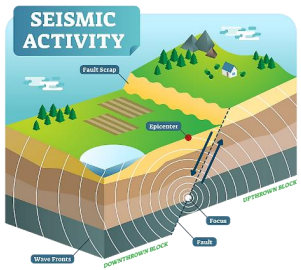


Areas of interest

- Open-source software projects for the QIS ecosystem
- Provide a quantum advantage in real-life applications
- Quantum devices and material

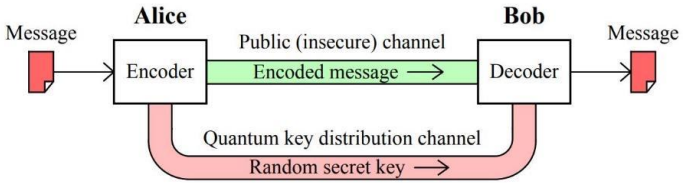


Climate Change



Sensors

SQMS-NYU Langone
Noninvasive estimation of biophysical and electrical properties of biological tissue by using magnetic resonance



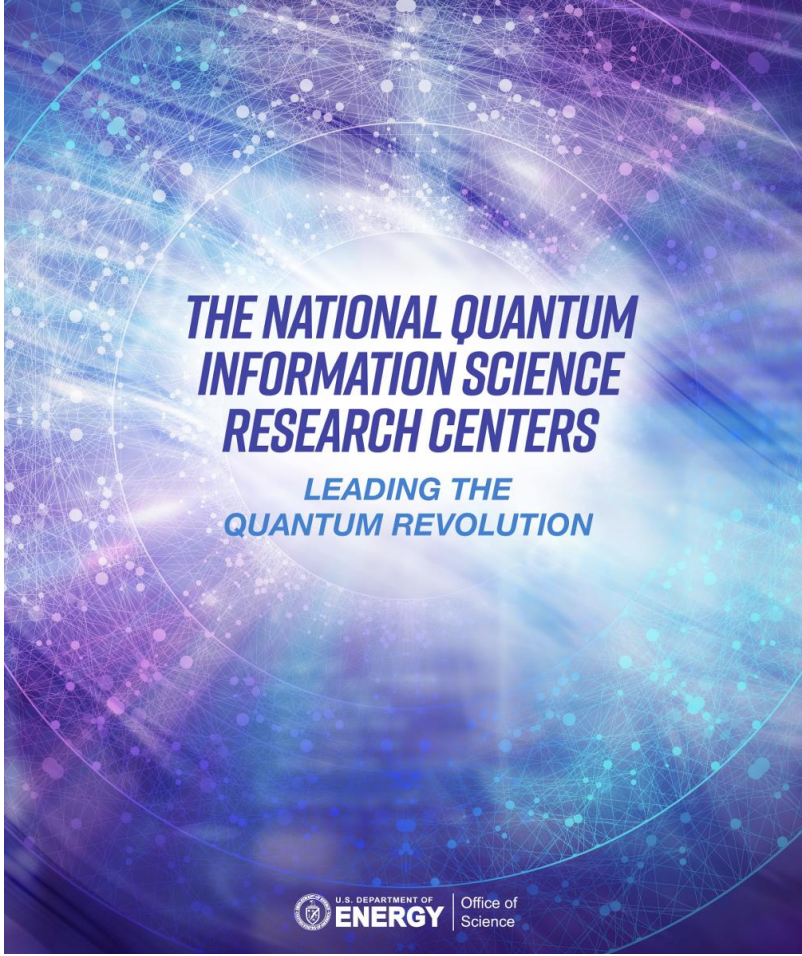
Cryptography

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Workforce development at NQI Research Centers

Mission:

Create and implement programs for training the next generation of scientists and engineers in quantum.



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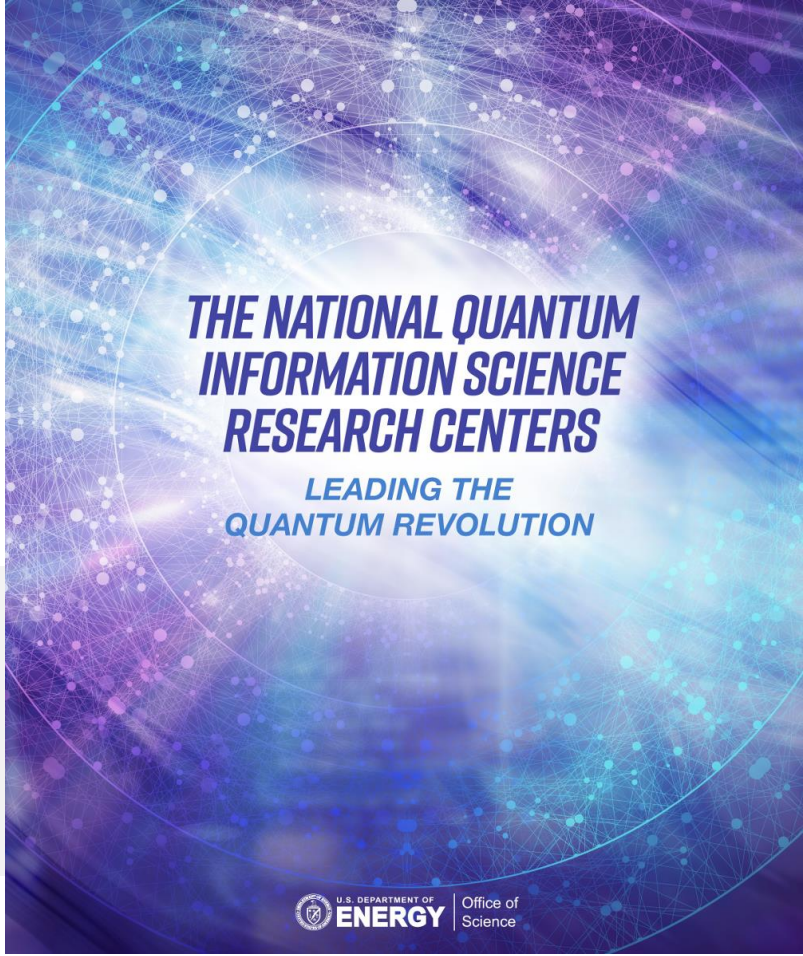
Workforce development at NQI Research Centers

Mission:

Create and implement programs for training the next generation of scientists and engineers in quantum.

DOE is supporting initiatives to address gaps in the workforce through collaboration between national laboratories, academia, and industry to prepare America's next-generation workforce for STEM.



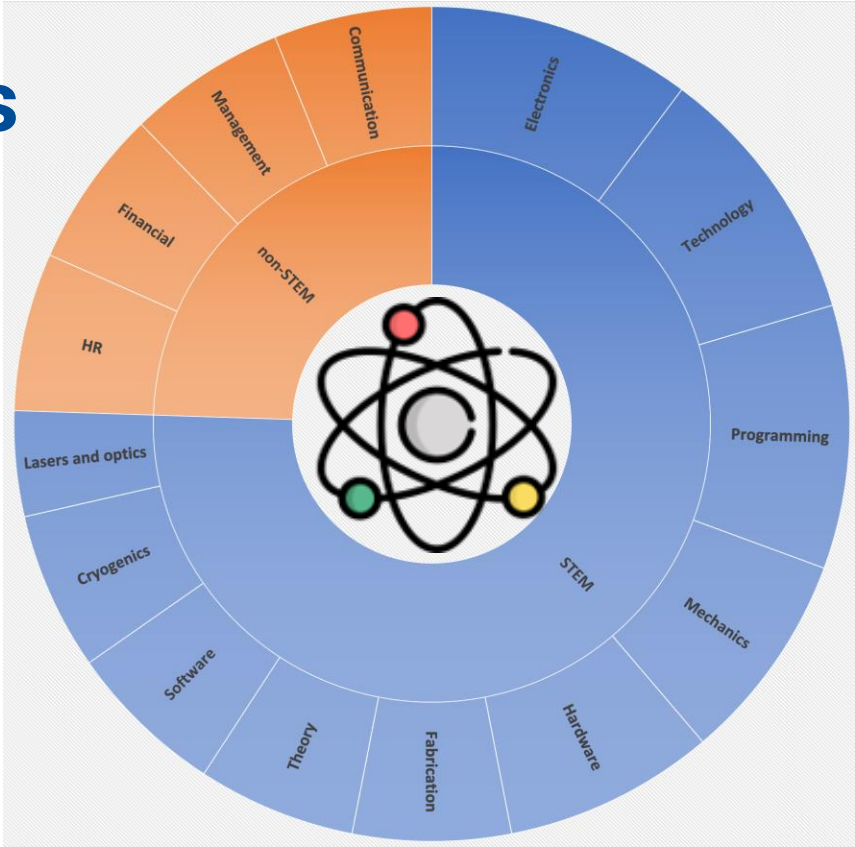
Workforce development at NQI Research Centers

Mission:

Create and implement programs for training the next generation of scientists and engineers in quantum.

Challenges:

- QIS is a multidisciplinary field
- Quantum mechanics, programming and hardware



SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Workforce development at NQI Research Centers

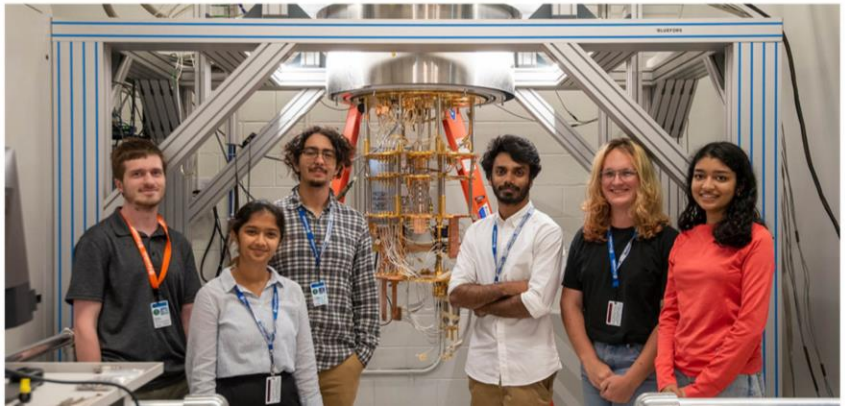
Mission:

Create and implement programs for training the next generation of scientists and engineers in quantum.

Opportunities:

- Cross-functional collaboration between academia, industry, national labs, NQI Research Centers
- Quantum computing as a gateway for a new and diverse workforce in STEM

SQMS engages with more than **400** external students in the first three years of operations



Workforce development at NQI Research Centers

Mission:

Create and implement programs for training the next generation of scientists and engineers in quantum.

Implementation:
Training through research

Workforce development at NQI Research Centers

Mission:

Create and implement programs for training the next generation of scientists and engineers in quantum.

Implementation:

Training through research

Leverage DOE investments

Expose students and early-stage research to state-of-the-art facilities and expertise in a multi-institutional / multi-disciplinary collaboration

Develop and practice research, technical and soft skills (presentation, networking, etc.)

Workforce development at NQI Research Centers

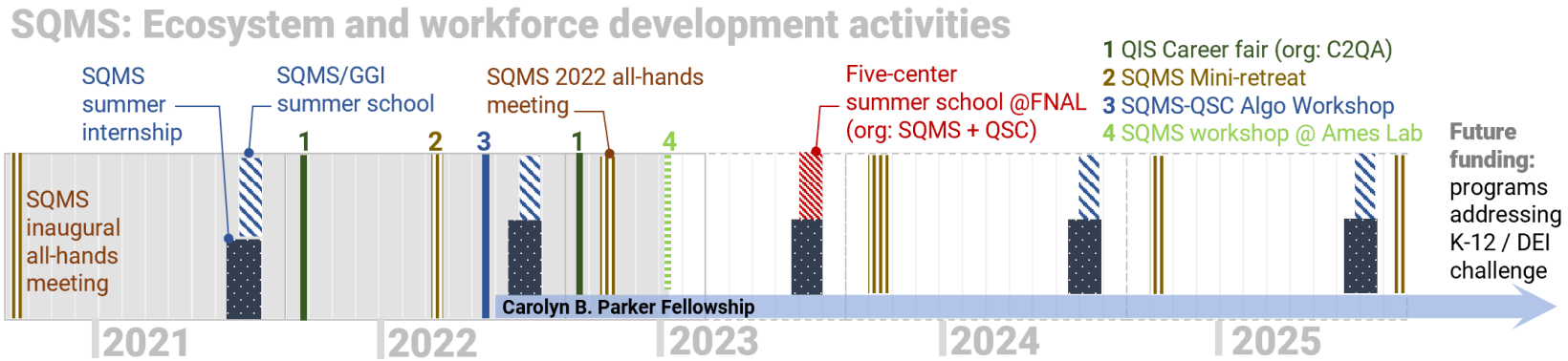
Mission:

Create and implement programs for training the next generation of scientists and engineers in quantum.

Vehicles identified at SQMS:

1. SQMS Summer Internship Program
2. Carolyn B. Parker Fellowship
3. Summer Schools
4. New funding opportunities

SQMS Timeline for Workforce Development



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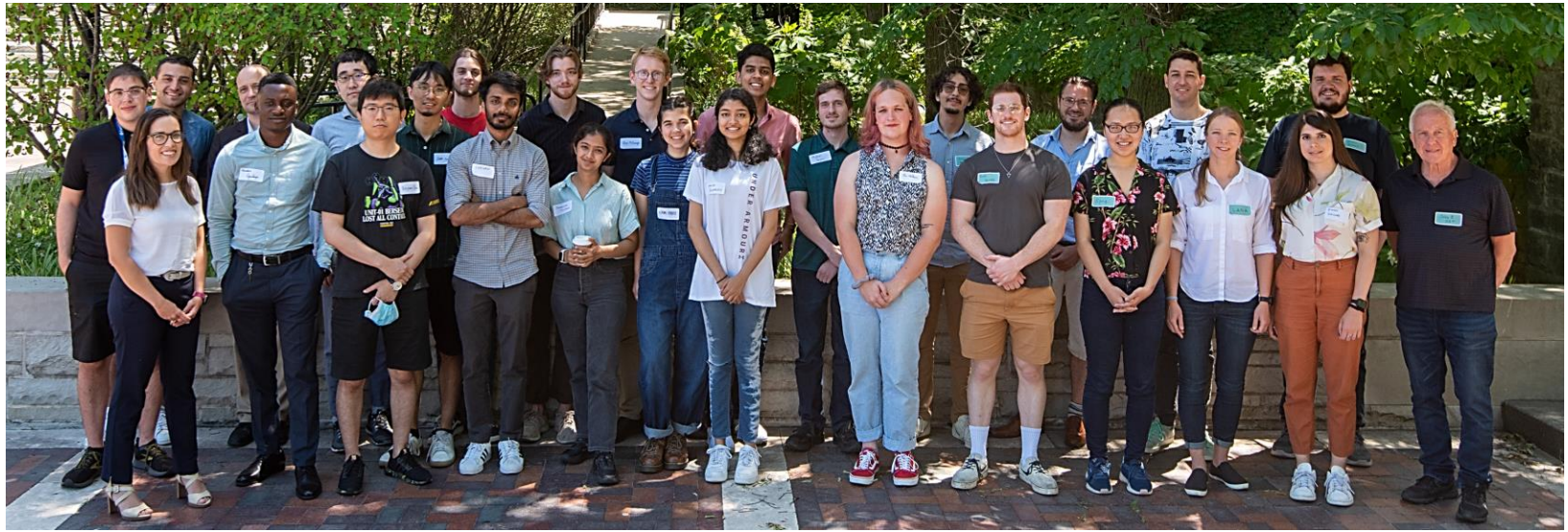


Vehicles identified at SQMS:

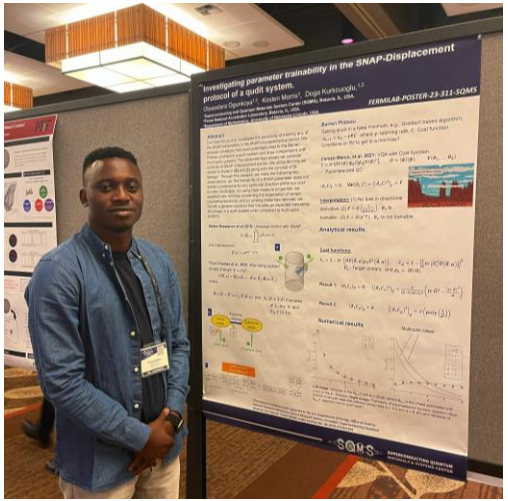
1. SQMS Summer Internship Program
2. Carolyn B. Parker Fellowship
3. Summer Schools
4. New funding opportunities

- 10-week paid internship program
- undergrad interns from across the US
- co-supervised across the center
- dedicated training programs and research activities
- Interim reports and mentoring program
- 50% of interns are female or belong to underrepresented groups in STEM

Carolyn Parker

Parker Fellow

Superconducting Quantum Materials and System Center



Dr. Oluwadara Ogunkoya
1st Parker Fellow

Vehicles identified at SQMS:

1. SQMS Summer Internship Program
2. Carolyn B. Parker Fellowship
3. Summer Schools
4. New funding opportunities

- First fellowship opportunity in QIS to prioritize the representation and inclusion of historically and contemporarily minoritized scholars in STEM.
- Named after the first African American woman to earn a postgraduate degree in physics
- Multi-disciplinary committee to select candidates across with different expertise

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

2023 US QIS Summer School

Vehicles identified at SQMS:

1. SQMS Summer Internship Program
2. Carolyn B. Parker Fellowship
3. Summer Schools
4. New funding opportunities

2023: Largest U.S. school to educate in quantum information science, including lab experience

- > 300 applicants
- 150 participants : students, professionals from labs and industry
- More than 40 instructors, top national experts in QIS from the 5 quantum centers (DOE, academia, industry)

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2023 US QIS Summer School

Hands-on training classes

HEP-RENEW awarded proposal: **Training through research in quantum information science and engineering at the SQMS Center**

Quantum Science focus area of the **RENEW Pathway Summer School** co-organized by Fermilab and Brookhaven national laboratories

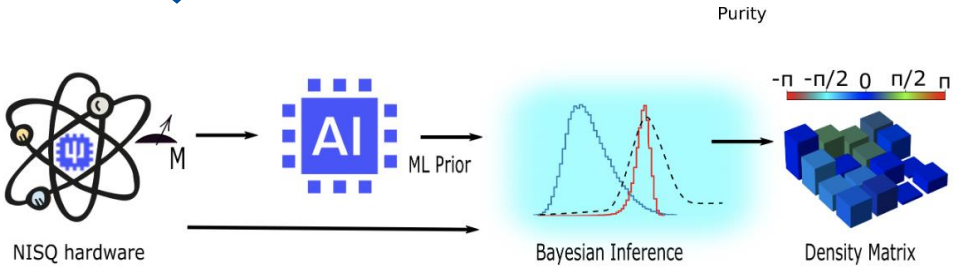
Vehicles identified at SQMS:

1. SQMS Summer Internship Program
2. Carolyn B. Parker Fellowship
3. Summer Schools
4. New funding opportunities

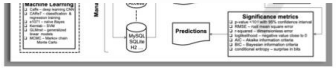
DOE Reaching a New Energy Science Workforce (RENEW)

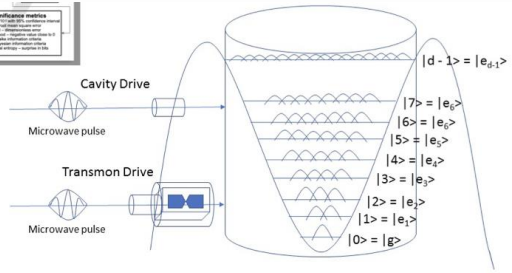
- Leveraging national laboratories and unique facilities while aiming to include more minority serving institutions (MSIs) in particle physics research
- Students and faculty from MSIs to conduct studies at SQMS
- Build the critical infrastructure and next-generation capabilities for quantum computing and sensing

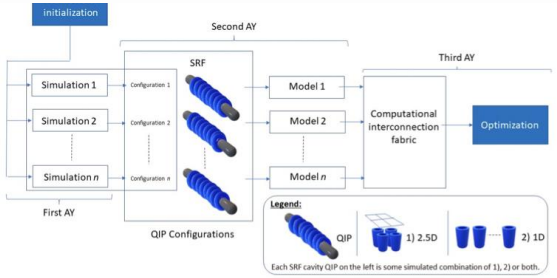
Training through research in quantum information science and engineering at the SQMS Center

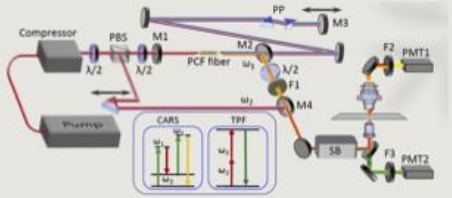


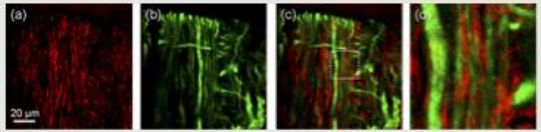
Thomas A. Searles
University of Illinois Chicago
Quantum devices and engineering











Yanhua Zhai
Spelman College
Quantum materials

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Opportunities for ALL at Fermilab

30+ Fellowships & Internships

DOE Internships

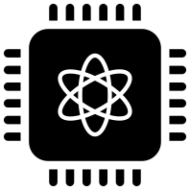
- Minority Education Institutions Student Partnership Program (MEISPP)
- Community College Internship (CCI)
- DOE Omni Technology Alliance Internship Program Summer Undergraduate Laboratory Internship (SULI)
- Visiting Faculty Program (VFP)

Fermilab Programs & Initiatives Flagship

- Programs Graduate Fellowships in Engineering and Science (GEM)
- Summer Internships in Science and Technology (SIST)
- TARGET Program Fermilab Co-Op Program
- VALOR (Veteran Applied Laboratory Occupational Retraining)
- Fermilab Alumni Network –the FAN

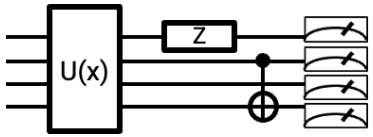
Thank you!

Quantum Information Science



Hardware/ Devices

Physics/ Devices



Algorithms/ Applications

Foundations of Quantum Mechanics

Physics Beyond Standard Model

Dark Matter

Quantum Advantage

Ecosystem

Education

Training

Hands-on research

Industry applications

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Workforce Development in STEM

Recommendations to help physics and astronomy departments develop action plans for systemic change

Success or failure of students in physics is attributed to:

- Sense of belonging → Professional network
- Physics identity → Research project
- Academic and financial support
- Leadership and structures

www.aip.org/diversity-initiatives/team-up-task-force

Carrying out research at DOE national laboratories and at research centers such as SQMS to foster a sense of belonging among staff and students while cultivating a collaborative community

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