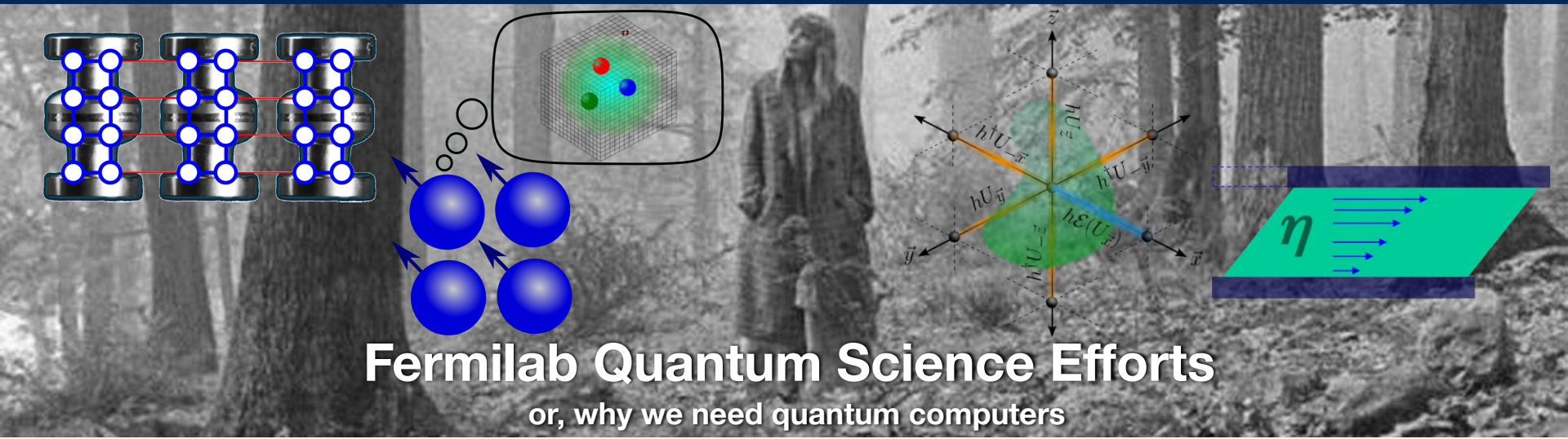
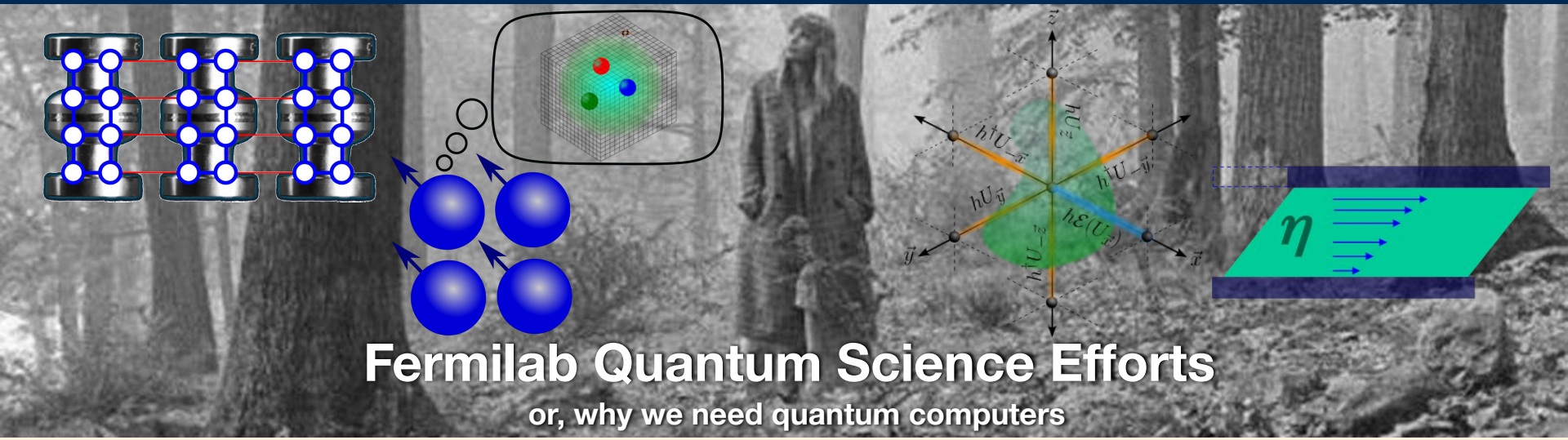


Fermilab Quantum Science Efforts

or, why we need quantum computers

Hank Lamm
Theory Division
SQMS Center
FQI

August 6, 2024



Fermilab Quantum Science Efforts

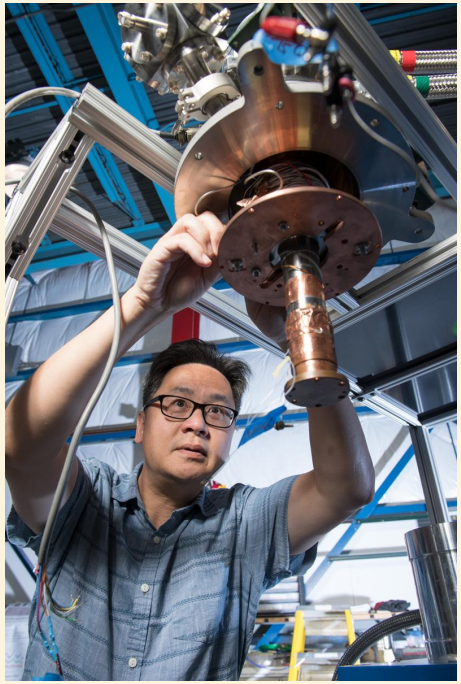
or, why we need quantum computers

Hank Lamm
Theory Division
SQMS Center
FQI

August 6, 2024

We are motivated by quantum utility

quan·tum u·til·i·ty (n): the leveraging of quantum physics phenomena to address problems more efficiently or outside the range of classical phenomena



Examples:

High-sensitivty dark matter searches

Simulations of particle collisions

Hopefully by the end, I will convince you…

There is so much **exciting work** to do,
and **not** enough people at present for it

Who am I?

Physics/Mech&Nuke Eng Undergrad at KANSAS STATE UNIVERSITY

Nuclear Theory Postdoc at UNIVERSITY OF MARYLAND

Physics PhD at Arizona State University

Fermilab

HEP Theory Postdoc -> Associate Scientist at

Why am I here?


Fermilab
Home | About | Science | Jobs | Contact | Phone Book
Newsroom | DUNE at LBNF | Come visit us | Resources for
Fermilab is America's particle physics and accelerator laboratory
We bring the world together to solve the mysteries of matter, energy, space and time.

Long history here of experimental physics

In 1977, the **bottom quark** was found here, & in 1995 the **top quark**.

Long history here of experimental physics

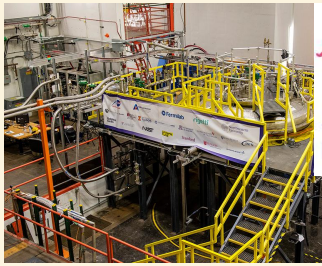
Today, we are studying **dark matter and neutrinos** with experiments including quantum sensors.

Long history here of computational physics

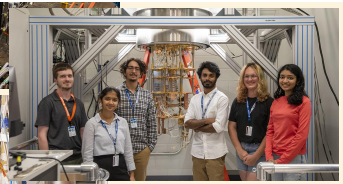
Long history here of computational physics

In 1989, ACPMAPS was about **2000x less powerful** than your phone

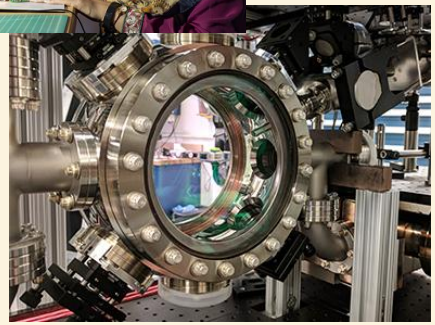
Overview of *(some of)* the Efforts



SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



QUANTUM SCIENCE CENTER



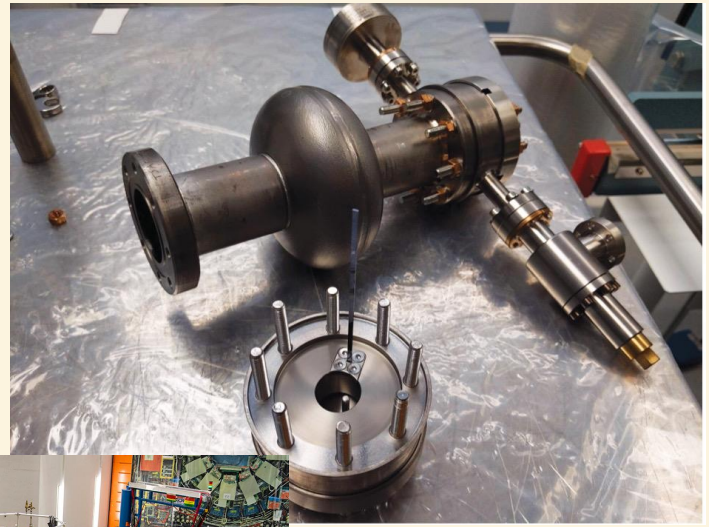
- **Superconducting Quantum Materials and Systems Center (SQMS)**
  - *Materials, Devices, Physics and Sensing, Algorithms*
  - Building quantum information platforms for sensing & computing
- **Fermilab Quantum Institute (FQI)**
  - *Networking, Sensing, Algorithms, Applications, Electronics*
  - Advancing the capabilities of computer networks & electronics
  - Affiliated with Quantum Science Center
- **Quantum Theory Department**
  - *Theoretical efforts in HEP Simulations & Sensing*
  - Quantum Computing Internship for Physics Undergraduates

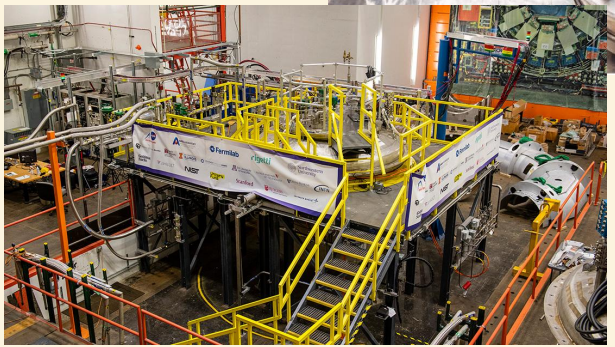
SQMS at a glance

Goal: Understanding and mitigating the physical processes that cause decoherence and limit the performance of superconducting qubits is critical to realizing next-generation quantum computers and sensors.

SQMS takes a materials science-based approach to tackle this challenge. The Center has built a broad coalition of experts studying quantum devices at the frontier of coherence, using advanced characterization tools, including DOE accelerator-based user facilities.

Leveraging Fermilab's unique expertise in building particle accelerators and cryogenics systems, the SQMS Center aims to bring critical capabilities to the QIS, to scale up quantum systems.



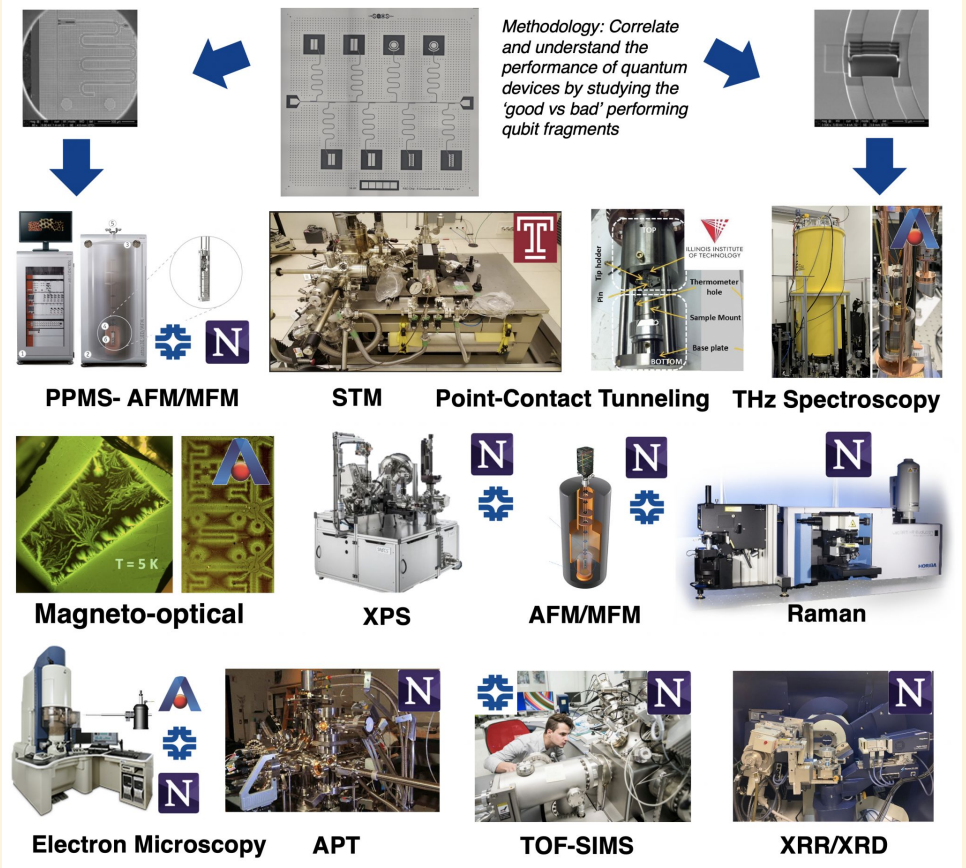


Colossus: Future's world's largest dilution refrigerator

SQMS : Materials for high coherence

- Presently, experimental quantum devices are far from theoretical limits

- **Goal:** Systematically understand and improve the coherence of devices



SQMS : 3D SRF-cavity based QPU

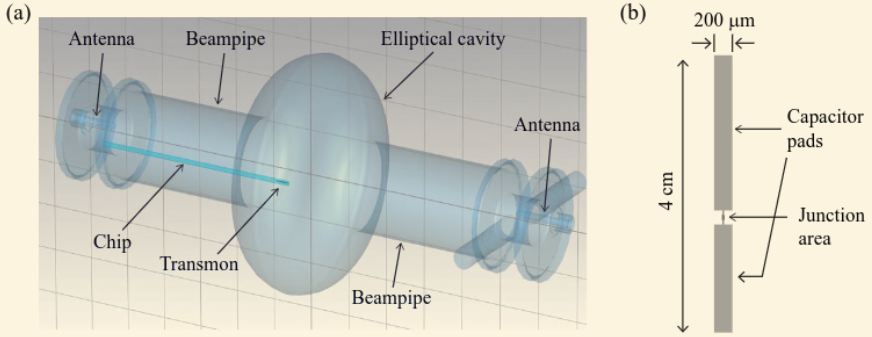
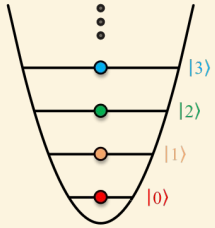
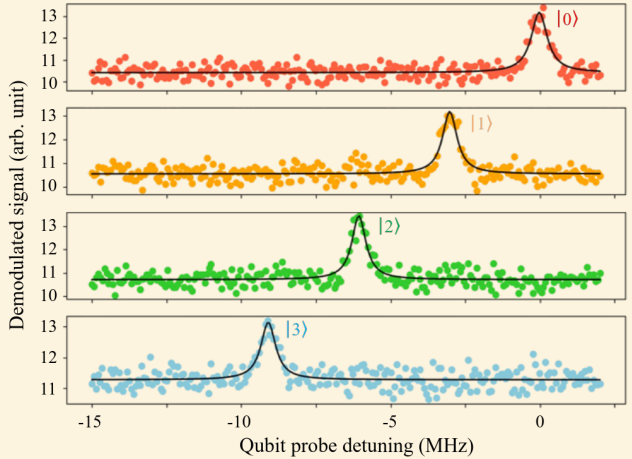


Figure 6: The transmon-cavity system. (a) The SRF cavity is made using Niobium. A transmon qubit is inserted through the beampipe so that it can strongly interact with the high-Q TM_{01} mode. The antennas are used to deliver and collect RF signals. The readout of the transmon is performed using the TM_{11} mode. (b) Typical geometry of the transmon (not to scale) consisting of two capacitor pads and a Josephson junction. The transmon is fabricated on a silicon or sapphire substrate.

- Leveraging our expertise in high-Q cavities, cryogenics, and HEP computational science
- **Goal:** Develop a **qudit-**based quantum computer system

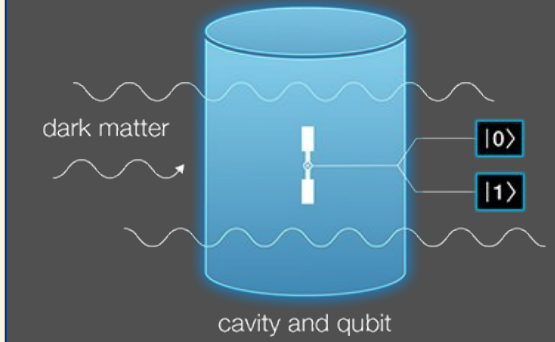


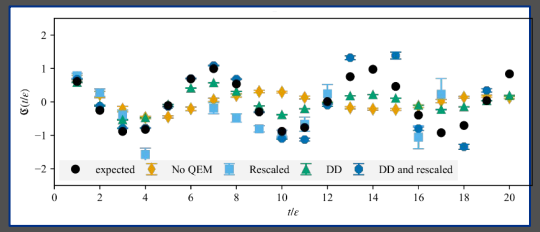


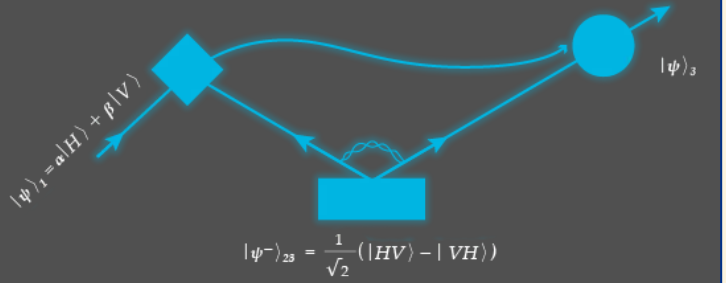
Qudit-based quantum computing with SRF cavities at Fermilab
Roy, Kim, Romanenko, Grassellino - PoS LATTICE2023 (2024) 127
Gentle review of specific hardware and state-of-the-art results

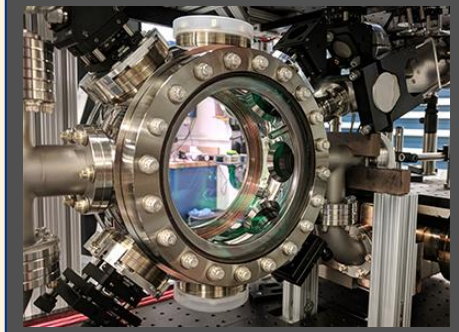
FQI in an instance

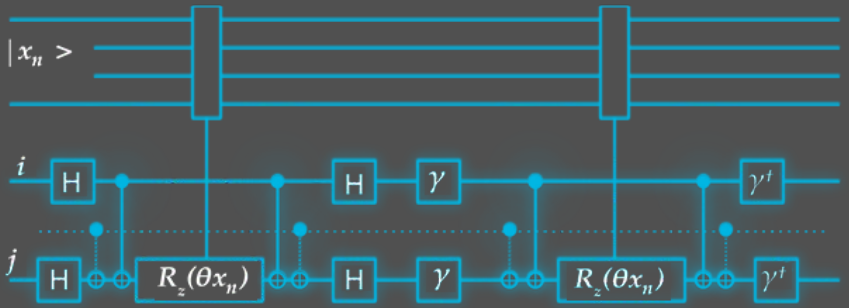
Goal: Pursue high-impact QIS research and development while advancing high-energy physics applications in the areas of networking, sensing, and algorithms

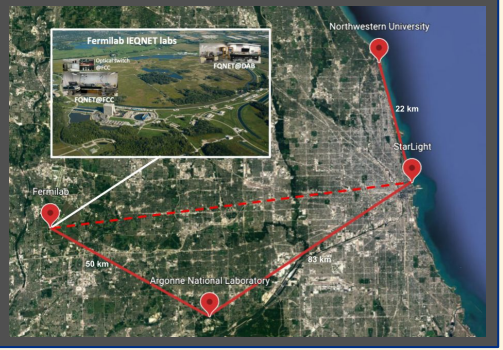












FQI : Illinois-Express Quantum Network (IEQNET)

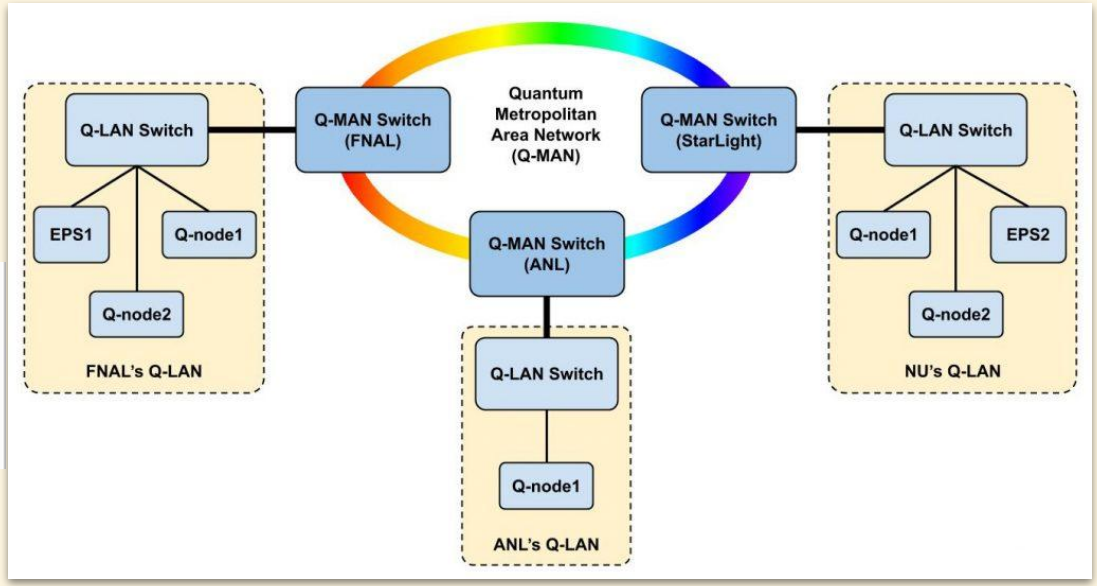
- **Goal:** Develop and demonstrate operation of repeaterless transparent optical **quantum networks** designs in the greater Chicago metropolitan area

Fermilab

Argonne NATIONAL LABORATORY

Northwestern University

Caltech



FQI : QUIET & LOUD

- Deep under the ground is a brand-new research center called **QUIET**, and at the surface sits its twin called **LOUD**

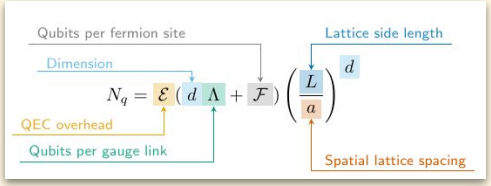
- **Goal:** Study effects of reduced cosmic ray interference and the ambient environment on Earth's surface on quantum sensors and computers

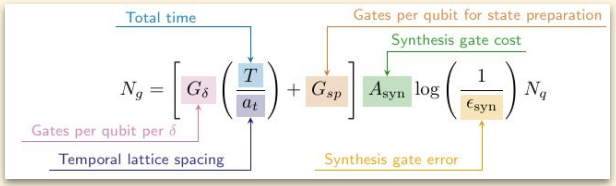
Quantum Theory Department in a quantum

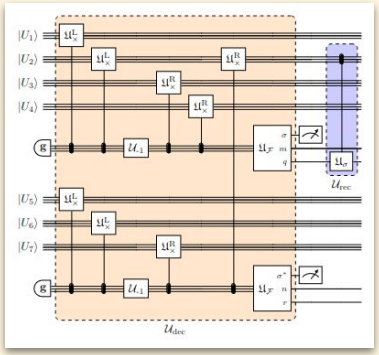
Goal: Research focuses on two main theoretical areas at the HEP-QIS interface, adjacent to experimental developments:

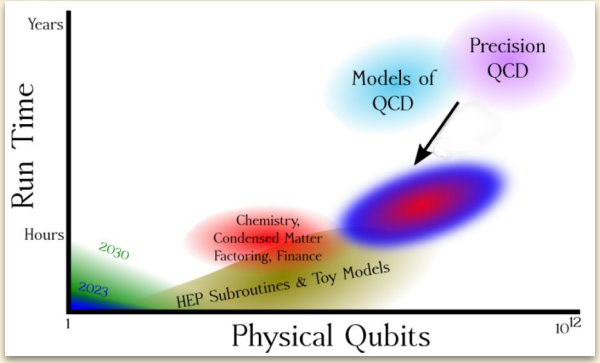
Quantum simulation of quantum field theories for HEP.

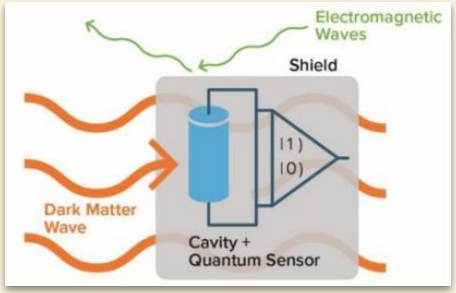
Quantum sensing and small-scale experiments to test fundamental physics.

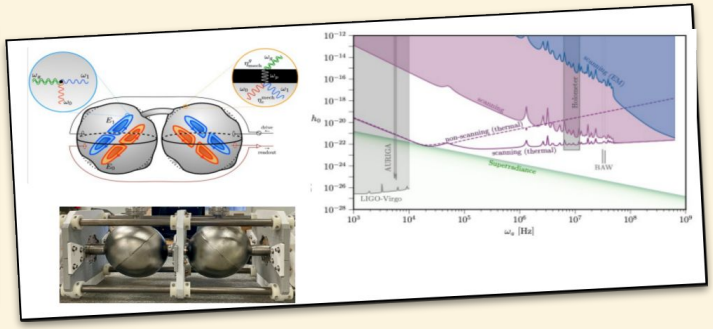










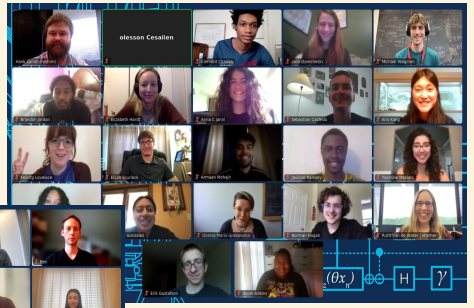


Fermilab Quantum Computing Internship For Physics Undergraduates

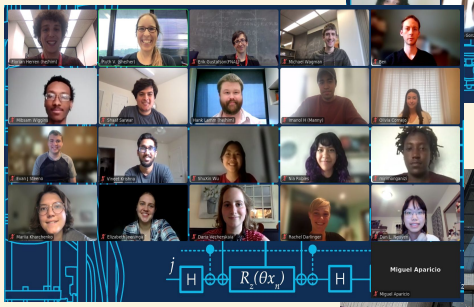
3-week summer school for around 20 students organized and hosted by Fermilab's Theory Division

Expanding opportunities to study quantum science

- Students paid competitive hourly wage
  - –***Essential*** to enable participation by students from all socioeconomic backgrounds.
- Topical lectures by experts in the field
  - –Quantum physics & math, quantum algorithms, error mitigation & correction, quantum hardware. Self-contained and ***accessible to all preparation levels***.
- Hands-on computational laboratories
  - –Python programming exercises on classical and quantum computers reinforce
  - –concepts and build to final project at the cutting edge of quantum research
- Accessible to wide range of undergraduate students
  - –Self-contained program designed for students with only introductory physics,
  - –mathematics, and/or computer science coursework
- Panels and discussions on career opportunities
  - –Discussions on post-graduate education and career opportunities



2021



2022

2023

2024

Fermilab Quantum Computing Internship For Physics Undergraduates

Supporting the next generation of scientists

- Students build long-term connections with instructors and peers
  - Instructors regularly act as professional references, mentors, and collaborators

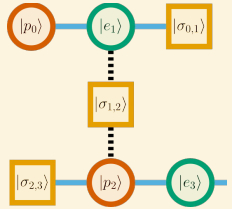
- Opportunities for year-long research internship with Fermilab scientists
  - Four papers with student authors completed with three more in progress

- 11 students pursuing PhD in Physics
  - Others have been accepted into further REUs, national lab jobs

FERMILAB-PUB-23-171-SQMS-T

Simulating $\mathbb{Z}_2$ lattice gauge theory on a quantum computer

Clement Charles,[1,2] Erik J. Gustafson,[3,4,5] Elizabeth Hardt,[6,7] Florian Herren,[3] Norman Hogan,[8] Henry Lamm,[3] Sara Starecheski,[9,10] Ruth S. Van de Water,[3] and Michael L. Wagman[3]
[1]*Department of Physics, The University of the West Indies, St. Augustine Campus, Trinidad & Tobago*
[2]*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3]*Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[4]*Quantum Artificial Intelligence Laboratory (QuAIL), NASA Ames Research Center, Moffett Field, CA, 94035, USA*
[5]*USRA Research Institute for Advanced Computer Science (RIACS), Mountain View, CA, 94043, USA*
[6]*Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607, USA*
[7]*Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[8]*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA*
[9]*Department of Physics, Sarah Lawrence College, Bronxville, NY 10708, USA*
[10]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
(Dated: May 5, 2023)



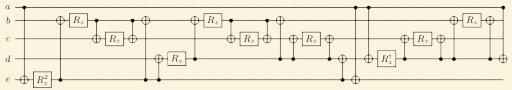
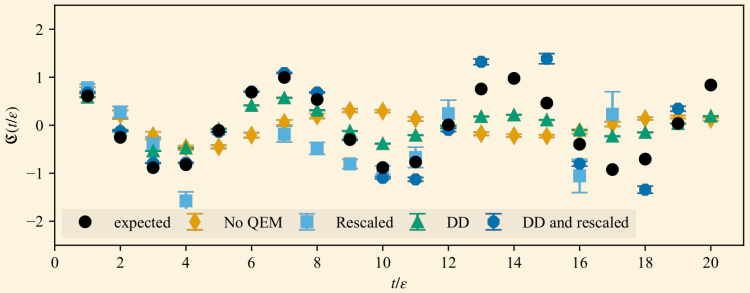


FIG. 4. Trace gate for BT



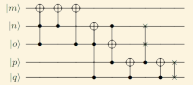


FIG. 2. Inversion Gate for the Binary Tetrahedral Group.

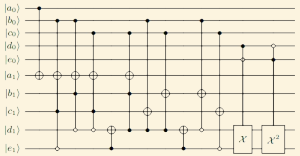


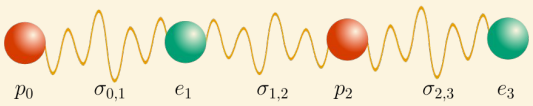
FIG. 3. Multiplication gate

PHYSICAL REVIEW D **106,** 114501 (2022)

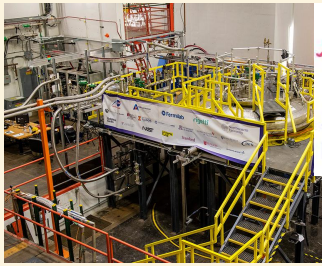
Primitive quantum gates for an $SU(2)$ discrete subgroup: Binary tetrahedral

Erik J. Gustafson,[1,*] Henry Lamm,[1,†] Felicity Lovelace,[2,‡] and Damian Musk[3,§]
[1]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[2]*Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607, USA*
[3]*Stanford University Online High School, Redwood City, California 94063, USA*

(Received 6 September 2022; accepted 9 November 2022; published 8 December 2022)



Overview of *(some of)* the Efforts



SQMS
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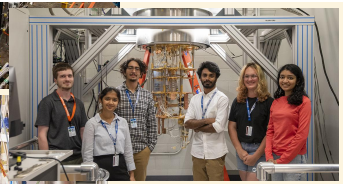
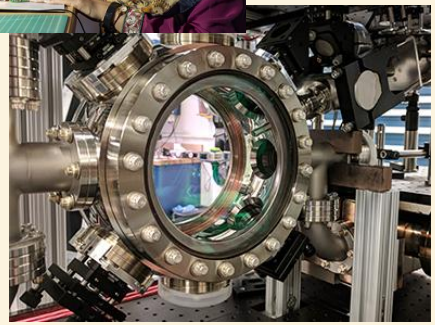


QUANTUM SCIENCE CENTER



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