HEP Strategy and Vision for QIS

HEPAP December 2024

Zachary Goff-Eldredge
Program Manager, QIS

National Quantum Initiative

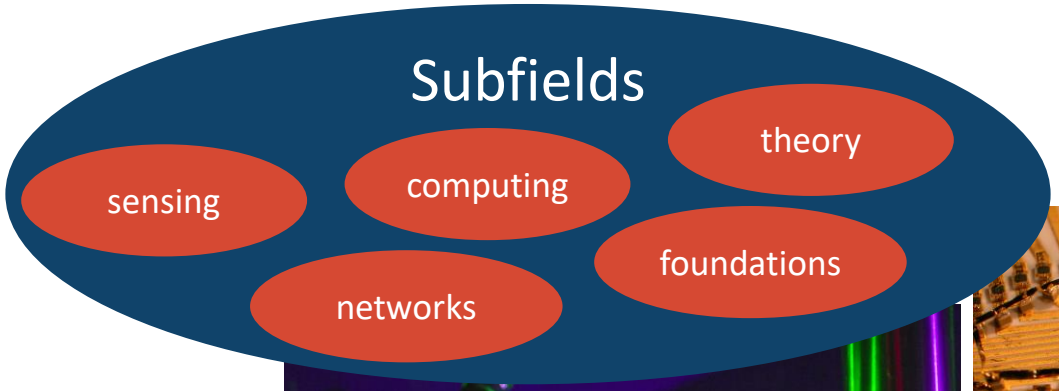
- National Quantum Initiative Act (2018)
  - Established the National Quantum Initiative (NQI)
  - NQI is a whole-of-government quantum thrust
  - Authorizes research at NIST, NSF, DOE
- Created interagency coordinating bodies:
  - National Science and Technology Council Subcommittee on QIS
  - National Science and Technology Council Subcommittee on Economic/Security Implications of QIS
  - National Quantum Coordination Office
  - NQI Advisory Committee
- NQI encompasses 23 agencies, $2.6B in investments, 14 major research centers, >150 companies
- HEP QIS program collaborates with NQI activities

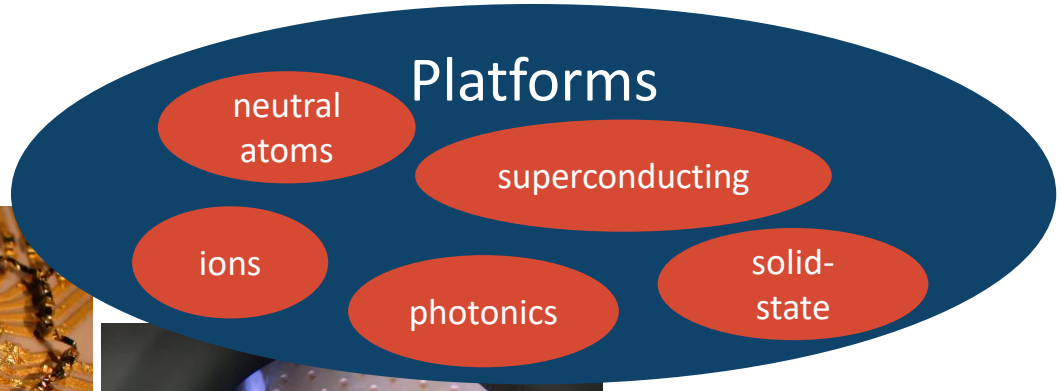
Quantum Information Science

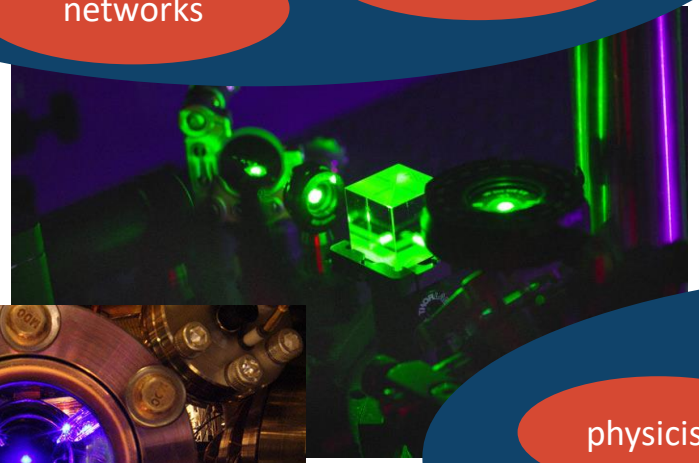
Quantum information science (QIS): *technologies for computation, information processing, and detection that elude classical limitations through the use of quantum effects.* (2023 P5 Report)

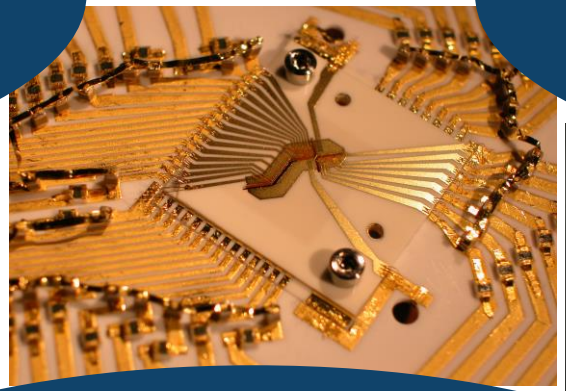
Fermilab SQMS

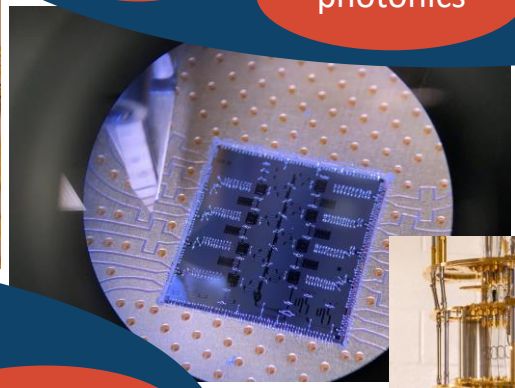
QIS Means Many Approaches

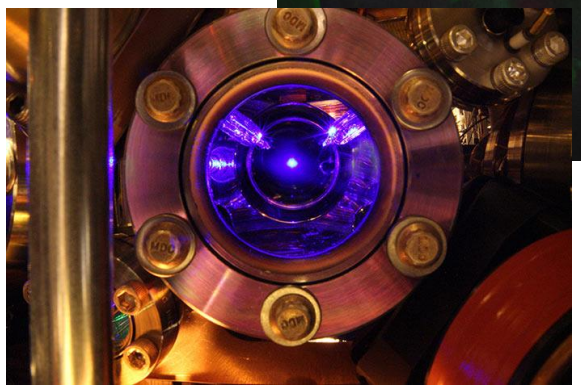


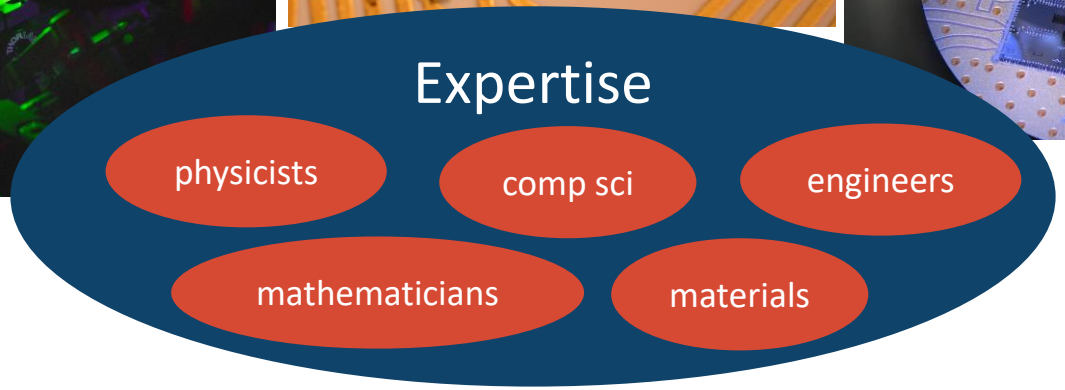








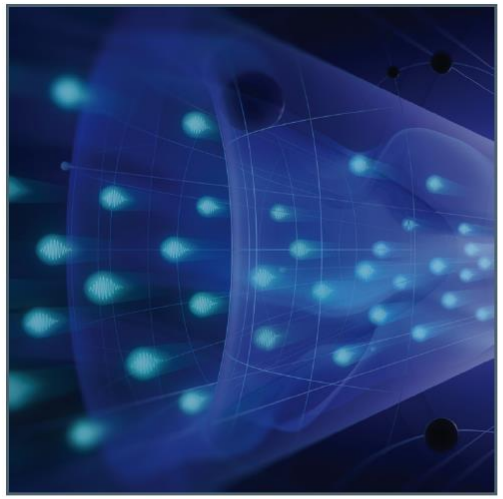




All images from quantum.gov image gallery

QIS is Relevant Across P5 Themes and Frontiers

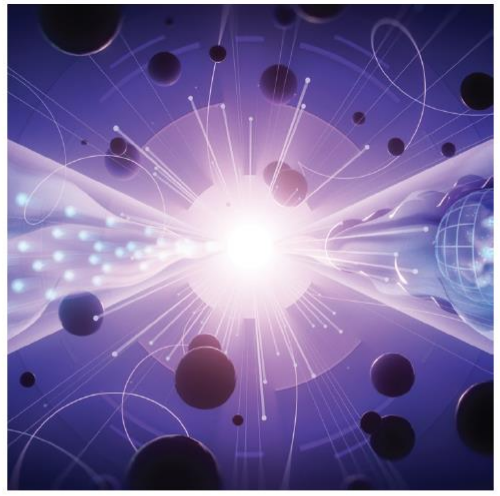
Energy
Intensity
Cosmic
Theory



Decipher the Quantum Realm

Elucidate the Mysteries of Neutrinos

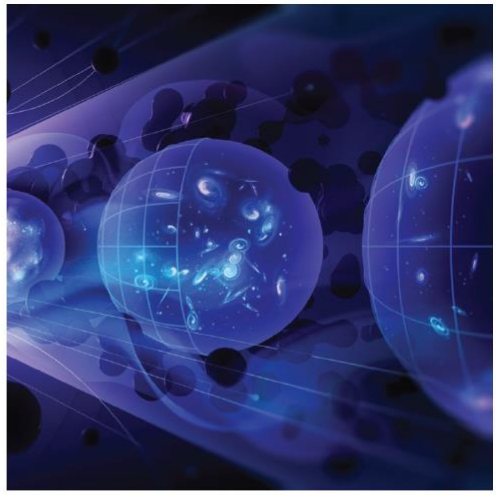
Reveal the Secrets of the Higgs Boson



Explore New Paradigms in Physics

Search for Direct Evidence of New Particles

Pursue Quantum Imprints of New Phenomena



Illuminate the Hidden Universe

Determine the Nature of Dark Matter

Understand What Drives Cosmic Evolution

Particle detection (E, I, C)

Light dark matter (C)

Quantum gravity (C, T)

Quantum simulation (E, I, C, T)

Quantum data analysis (E, I)

Detector R&D (E, I, C)

Entanglement signatures (E, T)

Accelerator R&D (E, I)

Building a HEP QIS Vision: Three Specific Goals

Challenge: from the broad interest in QIS expressed in P5 recommendations to specific program goals.

Seize the NQI Opportunity

"A coordinated effort that […] leverages nation… …ntum infor… …s all aspec… …(p17)

"unique intersection of particle physics and quantum science positions the field as a vital contributor to the National Quantum Initiative" (p99)

"resources for national initiatives in AI/ML, quantum computing, and microelectronics should be leveraged and incorporated" (p95)

"pursue synergies with other disciplines outside of particle physics, as well as close collaborations with industry. Recent examples of this [include] quantum sensors" (p82)

Unite the QIS-HEP Cutting Edges

"Particle physics pr… gr… qu… sc…

"particle physics-… …d … …s will … after … in quantum computing" (p105)

"We recommend mechanisms to support interactions outside the particle physics program…allow scientists and engineers working with quantum sensors, whatever their specific field, to tackle the most interesting and challenging problems" (p82-83)

"particle physics has long used cutting-edge quantum sensing techniques…an ideal testing ground for these technologies" (p99)

Open New Horizons

"[low-mass dark matter] detection techniques are inherently quantum in nature" (p50)

"explore the potential of quantum simula… …ex and previc… …lems"

"direct-detection technologies, particularly in quantum sensing [have] enabled discernment of the most minute signals" (p50)

"use the profound connections between quantum information theory and quantum gravity" (p99)

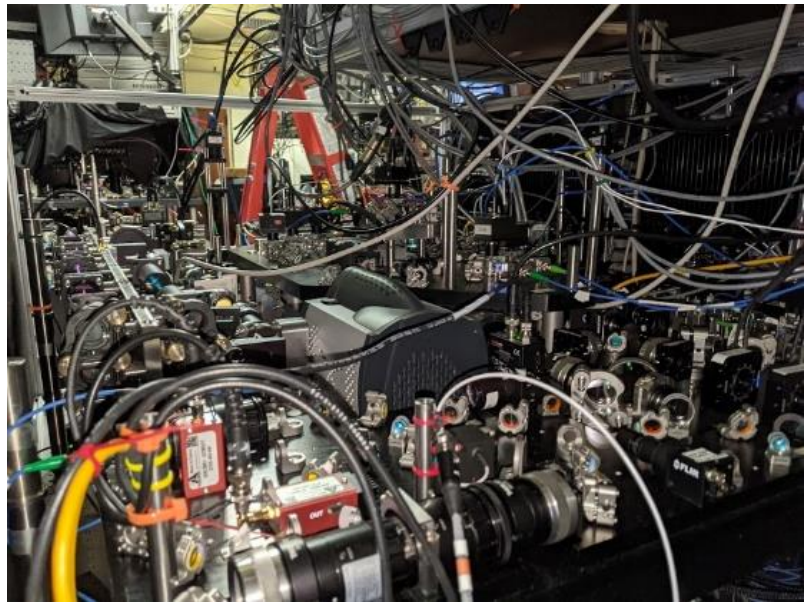
"Quantum sensors are being deployed in all areas of particle physics…continue strong support for a broad range of quantum sensors" (p82)

QIS Organization at OHEP

Fermilab

Fermilab's **Superconducting Quantum Materials and Systems (SQMS)** center is our coupling to the NQI, pursuing foundational quantum information science and technology development in global partnerships with academia, industry, and government.

UW-Madison

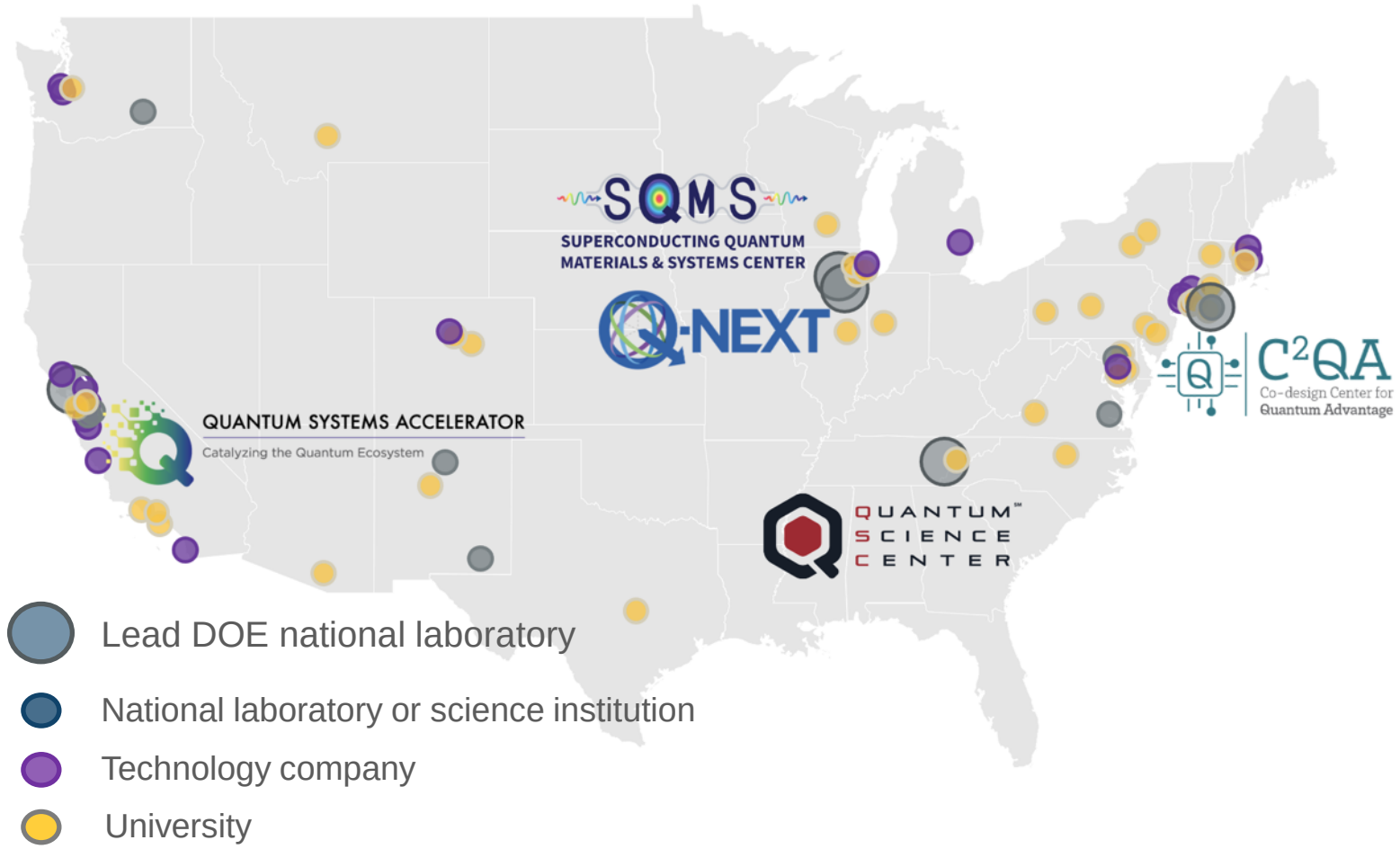


Our **Quantum Information Science Enabled Discovery (QuantISED)** program has funded dozens of research groups at universities and laboratories across the country since 2018 to advance theory and experiment of QIS in pursuit of HEP science goals.

Together, these programs define a robust portfolio with deep roots in both QIS and HEP communities enabling next-generation discoveries

DOE NQISRCs

- **N**ational **Q**uantum **I**nformation **S**cience **R**esearch **C**enters
  - Five centers operated by DOE
  - Each hosted at a different lab
  - Each center has unique scope and capabilities
- Authorized under NQI Act of 2018
- Began initial five-year program in 2020



BERKELEY LAB · Fermilab · Brookhaven National Laboratory · Argonne NATIONAL LABORATORY · OAK RIDGE National Laboratory

SQMS

SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Anna Grassellino, Director

A DOE National QIS Research Center

35
Partner Institutions

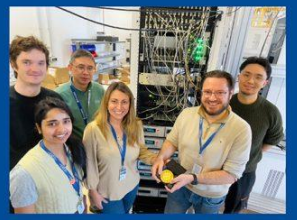
450+
Collaborators

Fermilab · Northwestern University · rigetti · AMES National Laboratory · NASA Ames Research Center · NIST · Colorado School of Mines · Coppin State University · FormFactor · Goldman Sachs · IBM · Illinois Institute of Technology · INFN · Jefferson Lab · Johns Hopkins University · Lockheed Martin · Lawrence Livermore National Laboratory · LSU · NPL National Physical Laboratory · NYU · Royal Holloway University of London · Rutgers The State University of New Jersey · Spelman College · Stanford · Temple University · Unitary Fund · The University of Arizona · University of Colorado Boulder · University of Illinois Chicago · University of Illinois Urbana-Champaign · University of Michigan · University of Minnesota Driven to Discover · Università di Pisa · USC University of Southern California · University of Waterloo · IQC Institute for Quantum Computing

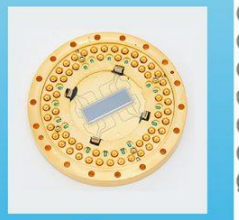
SQMS brings together hundreds of experts from more than 30 DOE national labs, academia, industry and other federal and international entities to bring transformational advances in QIS

From 1-10 high coherence qubits prototype **(3D)**

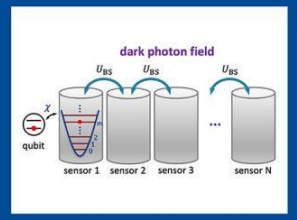
9 qubit – QPU commissioned at Fermilab **(2D)**



Mid scale QPU prototypes at Fermilab



High-Q Quantum Interconnects

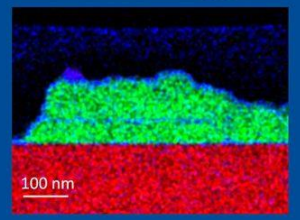


Larger scale quantum computing/sensing platforms

2020

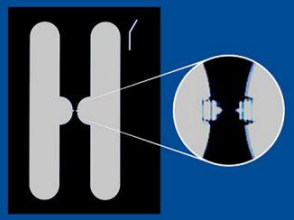
2025

2030



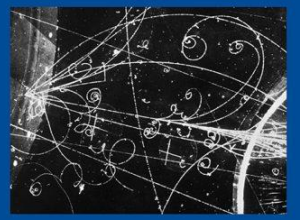
Materials Research for high coherence qubits **(2D)**

New quantum testbeds and foundries commissioned



Commercial transmon qubit improvement in coherence > 10 **(2D)**

Large scale, efficient ultra low T cryogenics



Solving complex problems in HEP, CMP, medicine, climate, national security

SQMS Center 10 year roadmap

Complete

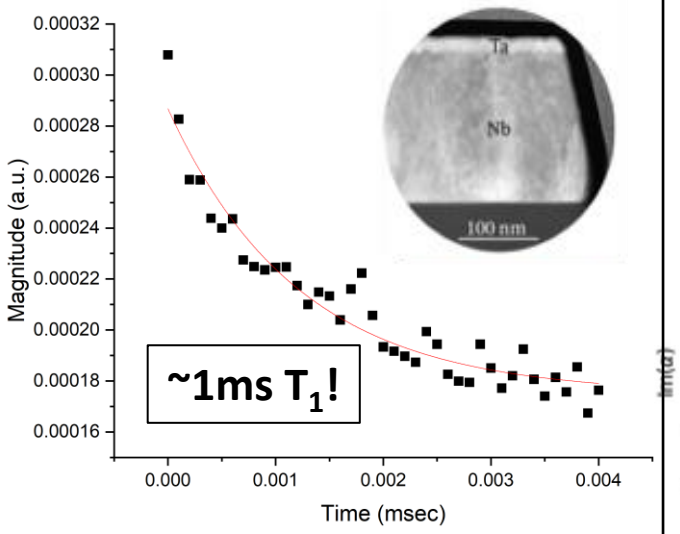
In-progress

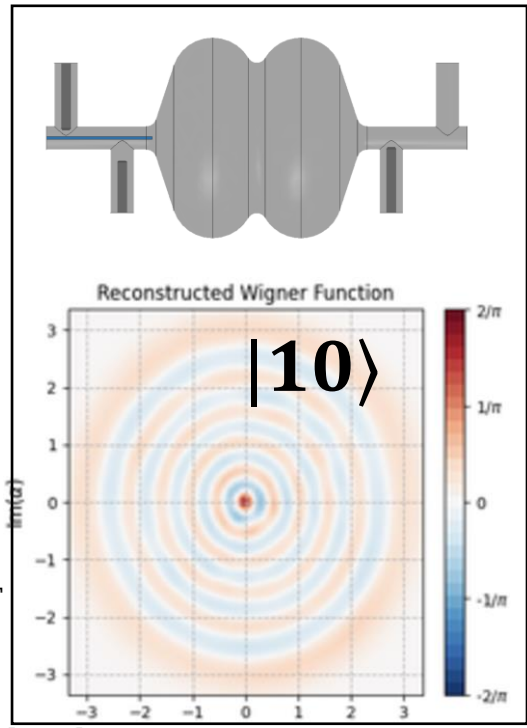
Future tech

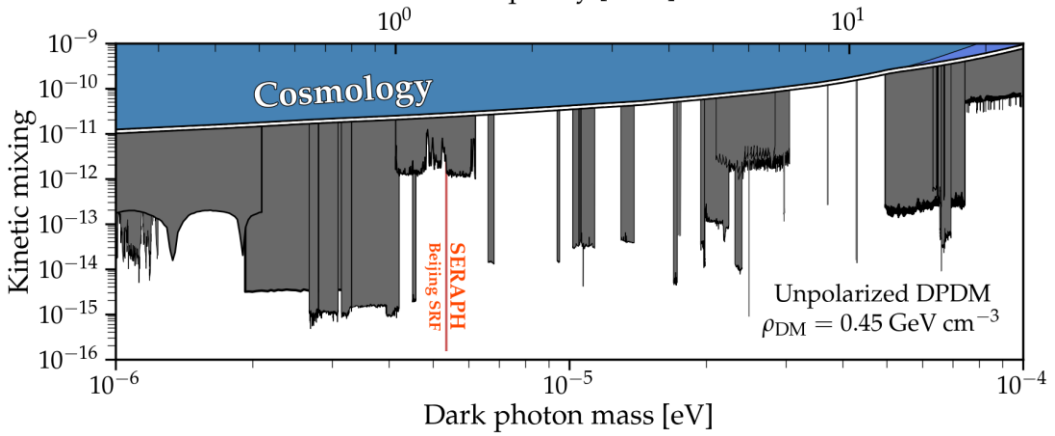
All images from SQMS

SQMS Successes

- Scientific successes
  - Understanding and mitigating decoherence in superconducting qubits – reaching ~1ms lifetimes!
  - Creation of first-of-a-kind SRF cavity systems for quantum information storage and processing – high-fidelity preparation of high-n Fock states
  - New experiments using SRF cavities to look for dark photon dark matter
- New facilities and capacity
  - "Quantum garage" has five dedicated dilution refrigerators
  - At Fermilab and elsewhere, built out equipment for fabrication, characterization, and materials analysis
- Ecosystem (People and Workforce)
  - Supported >200 students and postdocs
  - Hosted 2023 QIS Summer School with 150 participants, taught by 40 experts from the 5 NQISRCs







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SQMS

AT A GLANCE

SUPERCONDUCTING QUANTUM MATERIALS AND SYSTEMS CENTER

BY THE NUMBERS

Hosted by DOE's Fermi National Accelerator Laboratory, SQMS's mission is to develop beyond-the-state-of-the-art quantum computers and sensors applying technologies developed for the world's most advanced particle accelerators.

RESEARCH SPANS

35 ACADEMIC, NATIONAL LABORATORY, AND INDUSTRIAL INSTITUTIONS

MORE THAN **550** COLLABORATORS ACROSS THE U.S. AND AROUND THE GLOBE

BUILT ON 3 PILLARS

- DEMONSTRATION OF WORLD-RECORD ACCELERATOR CAVITY LIFETIMES IN THE QUANTUM REGIME
- ABILITY TO SCALE UP TO LARGE & COMPLEX MACHINES
- CONTINUE THE LEGACY OF ANSWERING FUNDAMENTAL QUESTIONS IN PHYSICS WHILE ADVANCING NEW TECHNOLOGIES

195 NEW HIRES (TO-DATE, CENTER-WIDE)

OVER **200** STUDENTS & POSTDOCS ADVANCING SQMS GOALS AND MISSION

OVER **350** COMPANIES ENGAGED WITH SQMS (MEMBERS + VENDORS)

MORE THAN **500** EXTERNAL STUDENTS TRAINED THROUGH SQMS SCHOOLS AND INTERNSHIPS

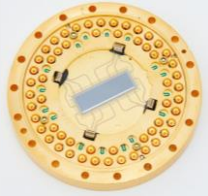
OVER **100** EXPERIMENTS OR INITIATIVES IN QUANTUM RESEARCH

257 PUBLICATIONS (PEER-REVIEWED JOURNALS + ARXIV)

SINCE DEC 2023 **85**

OVER **6 million** MEDIA IMPRESSIONS TO-DATE

$125 million U.S. FEDERAL FUNDING FOR RESEARCH OVER 5-YEAR PERIOD

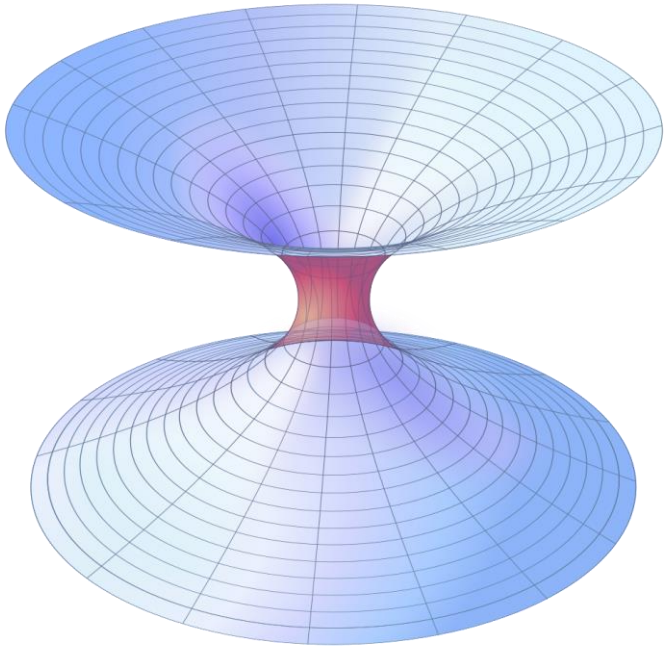


>100,000 SQUARE FEET OF SQMS FACILITY & OFFICE SPACE IN USE

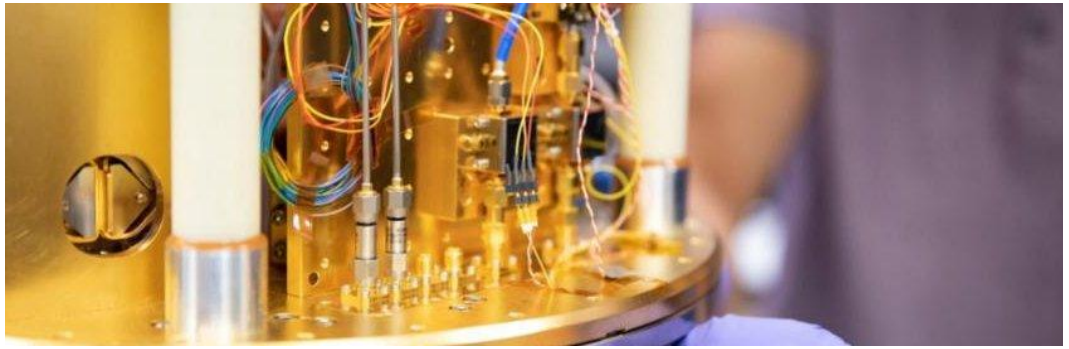
10 NEW FACILITIES / TESTBEDS UNDER DEVELOPMENT OR IN PROCUREMENT

QuantISED

- **Q**uantum **I**nformation **S**cience (QIS) **E**nabled **D**iscovery is our grants program for lab and university projects
- QuantISED 1.0 projects ran in 2018 and 2019, with awards renewed in 2021and 2022
- QuantISED is focused on:
  - QIS for HEP – using quantum information science to accomplish HEP goals
  - HEP for QIS – using HEP techniques and knowledge to advance QIS for societal benefit



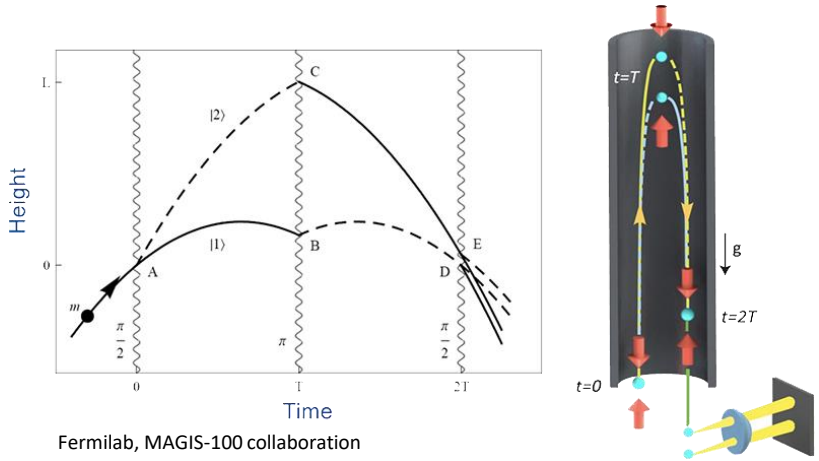
Wikimedia



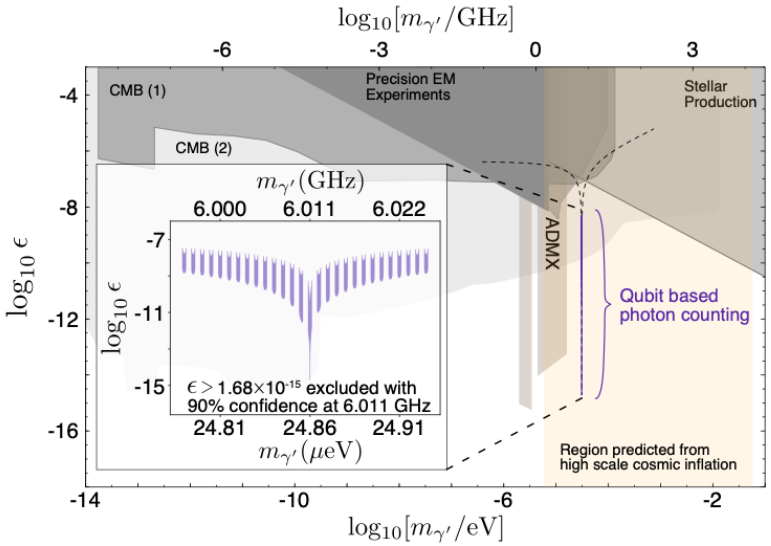
SLAC

QuantISED 1.0 Success Stories

World record search for dark photon dark matter using a superconducting qubit readout to reduce noise nearly 16 dB below SQL



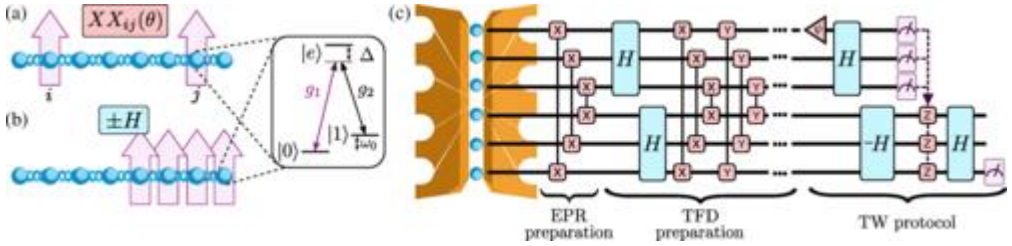
Fermilab, MAGIS-100 collaboration



A. V. Dixit, et al., Phys.Rev.Lett. 126 (2021) 14, 141302

Beginning of the MAGIS-100 project to construct a 100m atom interferometer for probing dark matter, gravitational waves

Discovery of new many-body teleportation techniques and design of implementation for Rydberg, trapped-ion, and SC systems



T. Schuster et al., Phys. Rev. X **12**, 031013

QuantISED 2.0

- QuantISED 2.0 launched May 2024
- Differentiator from QuantISED 1.0 - push beyond demonstration into real discovery science
- Received a very high volume of interest – community (both HEP and QIS) is very interested in pursuing these projects
- Award announcements coming soon!

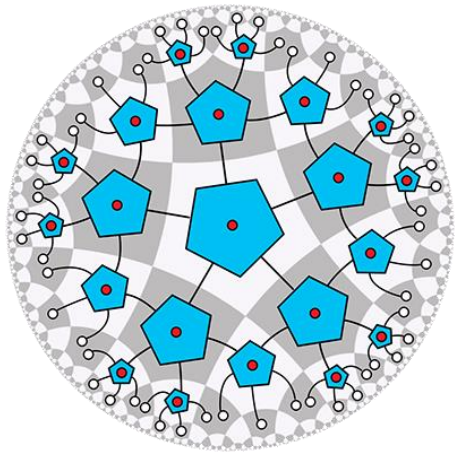
Fermilab

QuantISED 2.0 Topics

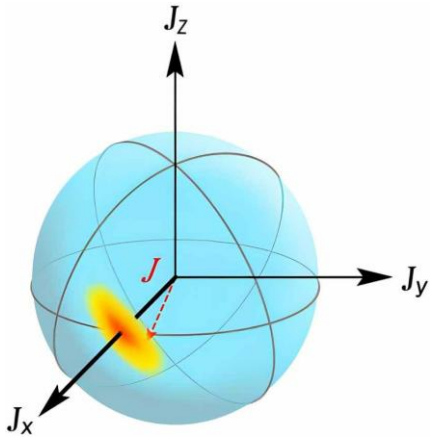
Theory – theoretical research that leverages new methods from QIS to shed light on HEP topics. Quantum gravity, scrambling, holography, simulation, algorithms.

Sensing – creating, manipulating, measuring precise quantum states for metrological advantage; bringing QIS/AMO/condensed matter techniques into HEP space

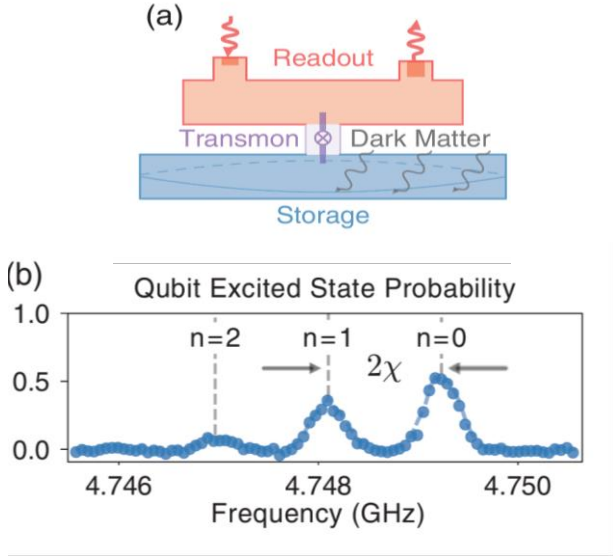
Pathfinders – new experimental concepts with potential of opening new vistas onto fundamental science



Phys. Rev. A 101, 042305 (2020)



New Journal of Physics. 25. 10.1088/1367-2630/acdb90.



Dixit et al., PRL 126 (2021)

Looking Ahead: Realizing Our QIS Vision

Seize the NQI Opportunity	Integrate the potential renewal of NQI into our programs (SQMS and other) and maximize mutual relevance to HEP.
Unite the QIS-HEP Cutting Edges	Use SQMS and other national lab facilities as a base of QIS excellence and a nexus for interdisciplinary collaboration.
Open New Horizons	Build a robust HEP-QIS community by providing opportunities for researchers to collaborate and cross over.
	Launch QuantISED 2.0 proposals – and plan for what's next, through workshops and future funding.

Thank you!

2025:

INTERNATIONAL YEAR OF
Quantum Science
and Technology