Superconducting Quantum Materials and Systems Center

Anna Grassellino, SQMS Center Director

GGI Summer School

July 27th 2022

(Bill Passed Dec 2018)

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.

National Quantum Initiative Act

This bill directs the President to implement a National Quantum Initiative Program to, among other things, establish the goals and priorities for a 10-year plan to accelerate the development of quantum information science and technology applications.

The bill defines "quantum information science“ as the storage, transmission, manipulation, or measurement of information that is encoded in systems that can only be described by the laws of quantum physics.

The National Science and Technology Council shall establish a Subcommittee on Quantum Information Science, including membership from the National Institute of Standards and Technology (NIST) and the National Aeronautics and Space Administration (NASA), to guide program activities.

The President must establish a National Quantum Initiative Advisory Committee to advise the President and subcommittee on quantum information science and technology research and development.

NIST shall carry out specified quantum science activities and convene a workshop to discuss the development of a quantum information science and technology industry.

The National Science Foundation shall: carry out a basic research and education program on quantum information science and engineering, and award grants for the establishment of Multidisciplinary Centers for Quantum Research and Education.

The Department of Energy (DOE) shall carry out a basic research program on quantum information science. The Office of Science of DOE shall establish and operate National Quantum Information Science Research Centers to conduct basic research to accelerate scientific breakthroughs in quantum information science and technology.

U.S. National Quantum Initiative

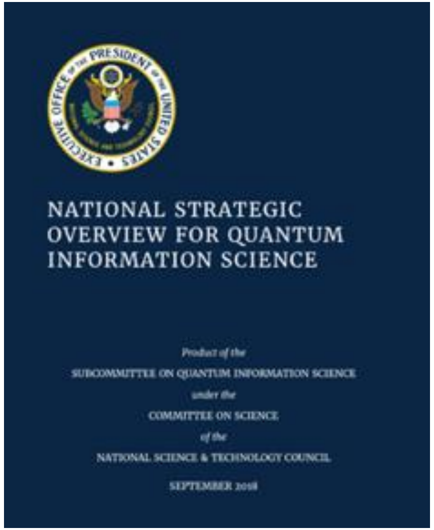
https://www.quantum.gov

https://science.osti.gov/Initiatives/QIS/QIS-Centers

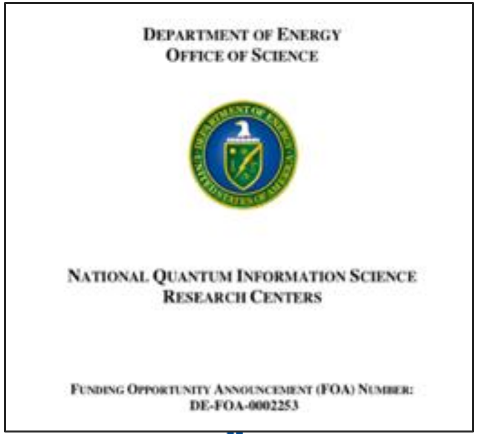
In 2019 Congress mandated the creation of **five Dept. of Energy national quantum centers** (initiative across Office of Science)

$575M over five years , renewable for another five years, to develop quantum computers, quantum sensors, and quantum communications

- Goal is transformational advances in quantum science and technology
- Create a quantum economy
- Work in coordination with other agencies
- DOE Centers first five years funded through 2025, with potential renewal up to 2030


NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL
SEPTEMBER 2018


DEPARTMENT OF ENERGY
OFFICE OF SCIENCE

NATIONAL QUANTUM INFORMATION SCIENCE RESEARCH CENTERS

FUNDING OPPORTUNITY ANNOUNCEMENT (FOA) NUMBER:
DE-FOA-0002253

Fermilab

SQMS

Led by FNAL, $115M
Awarded August 2020

Superconducting Quantum Materials and Systems Center

A DOE National Quantum Information Science Research Center

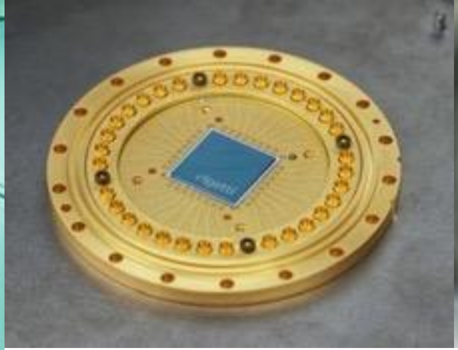
23 Institutions
> 350 Researchers
> 100 students/postdocs

Fermilab · rigetti · Northwestern University · Ames Laboratory (Creating Materials & Energy Solutions, U.S. Department of Energy) · NASA Ames Research Center

NIST · INFN Istituto Nazionale di Fisica Nucleare · Stanford University · University of Illinois Urbana-Champaign · Rutgers · Università di Pisa

University of Colorado Boulder · Illinois Institute of Technology · Johns Hopkins University · Temple University · Colorado School of Mines · The University of Arizona

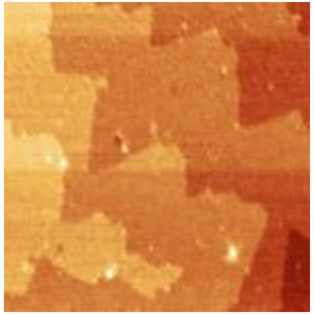
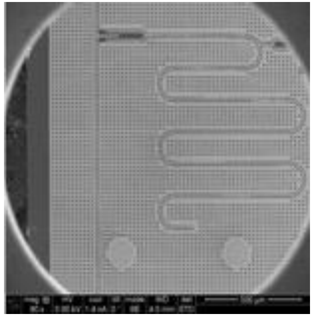
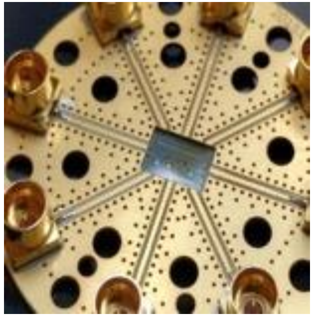
University of Minnesota · NYU · Goldman Sachs · Lockheed Martin · JANIS · Unitary Fund

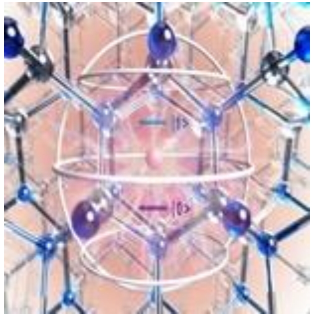
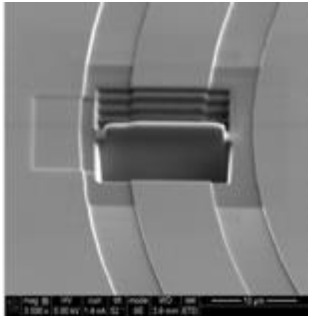


SQMS Mission Statement: “bring together the power of national labs, industry and academia to achieve transformational advances in the major cross-cutting challenge of understanding and eliminating **quantum decoherence** in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior quantum systems for computing and sensing."

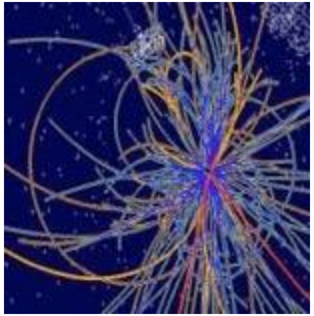
SQMS Roadmap: from material discovery to quantum advantage

Materials Discovery → High Coherence Devices → Systems Integration → New quantum computing and sensing platforms → Quantum Advantage



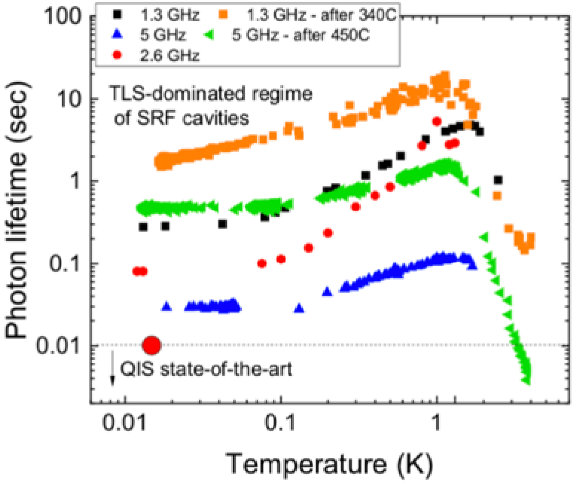


Potential for physics discovery lays at every step of the chain

Foundational Technological Strengths: SRF

- **The "perfect photon box"** – Einstein's dream closer than ever to reality
- Fermilab SRF group has demonstrated the world's record photon lifetime in quantum regime **with coherence up to 2 seconds**

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



Probing a quantum field in a photon box

J M Raimond[1], T Meunier[1], P Bertet[1], S Gleyzes[1], P Maioli[1], A Auffeves[1], G Nogues[1], M Brune[1] and S Haroche[1,2]

[1] Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, F-75231 Paris Cedex 05, France
[2] Collège de France, 11 place Marcelin Berthelot, F-75231 Paris Cedex 05, France

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Received 5 November 2004, in final form 8 December 2004
Published 25 April 2005
Online at stacks.iop.org/JPhysB/38/S535

Abstract
Einstein often performed thought experiments with 'photon boxes', storing fields for unlimited times. This is yet but a dream. We can nevertheless store quantum microwave fields in superconducting cavities for billions of periods. Using circular Rydberg atoms, it is possible to probe in a very detailed way the quantum state of these trapped fields. Cavity quantum electrodynamics tools can be used for a direct determination of the Husimi Q and Wigner quasi-probability distributions. They provide a very direct insight into the classical or non-classical nature of the field.

PHYSICAL REVIEW APPLIED **13**, 034032 (2020)

Three-Dimensional Superconducting Resonators at $T < 20$ mK with Photon Lifetimes up to $\tau = 2$ s

A. Romanenko,* R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Belomestnykh, S. Posen, and A. Grassellino
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

(Received 23 December 2019; accepted 14 February 2020; published 12 March 2020)

Fermilab

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

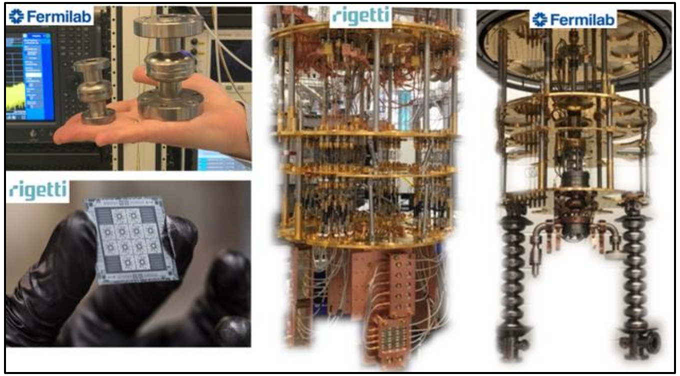
Novel QPU architectures

- Long coherence allows going from qubit to "qudit" 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

Foundational Technological Strengths: 2D devices nanofabrication

- Expertise in engineering performance of superconducting microwave devices, knowledge driven, based on material and SC physics characterization and understanding
- SQMS adds a new group with core expertise to Fermilab portfolio – superconducting 2D devices design, nanofabrication and test


Mustafa Bal
Associate Scientist


Akshay Murthy
Associate Scientist


Arpita Mitra
Postdoc


David Van Zanten
Associate Scientist


Francesco Crisa',
PhD student

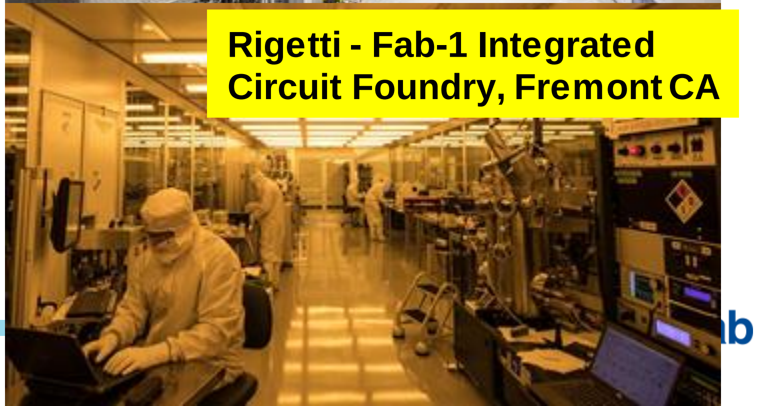

Ivan Nekrashevich
Associate Scientist


Yulia Krasnikova
Associate Scientist


Shaojiang Zhu
Associate Scientist

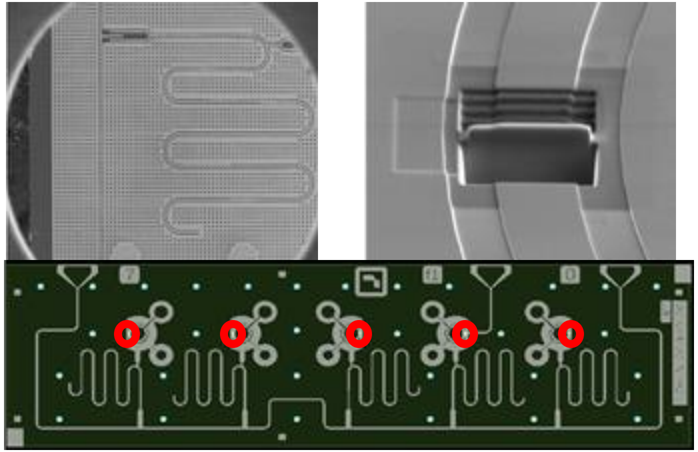

Xinyuan You
Postdoc


Ziwen Huang
Postdoc



Foundational Strenghts: QIS materials and devices characterization

Dissecting and studying fragments of microwave performance characterized devices



Device Layout

- Leveraging DOE and SQMS academic partners user facilities capabilities
- Extending beyond-the-state-of-the-art via focused SQMS investments in upgrades e.g. for milliKelvin characterization

Cryogenic TEM, AFM, MFM

AMES LABORATORY | SENSITIVE INSTRUMENT FACILITY

Cryo XRD, XRR

Cryogenic TOF-SIMS

Atom Probe Tomography

FNAL Material Science Lab

THz spectroscopy

Magneto Optical Imaging

betaNMR, muSR

NUANCE Northwestern University Atomic and Nanoscale Characterization Experimental Center

ANL Advanced Photon Source

Northwestern | MRSEC MATERIALS RESEARCH SCIENCE AND ENGINEERING CENTER

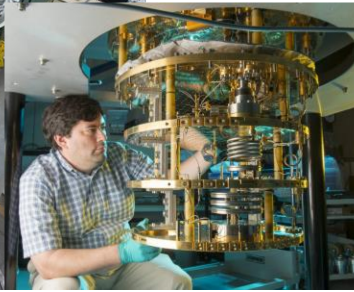
TRIUMF

Foundational Strengths: large accelerators, R&D to large scale integration

FNAL expertise and facilities critical for success in scale up of 3D QIS technologies

- Vacuum systems
- Superconducting Materials
- Microwave SC devices
- Cryogenics
- High precision frequency control
- LLRF, controls
- Magnetic shielding

M. Hollister



Fermilab SQMS is constructing a world record sized DR capable of hosting thousands of qubits

Modern accelerators are like quantum computers and sensors: large and complex high coherence (Q) superconducting microwave systems controlled with the highest precision

Scientific and Technological Goals – quantum computing

Develop and deploy a prototype quantum computer at Fermilab

Based on our own SRF technology for QIS

Explore and demonstrate advantage for HEP (and more)

1. FROM ELEMENTS TO STRUCTURE AND FROM STRUCTURE TO ELEMENTS

An unfamiliar computer from far away stands at the center of
ibition hall. Some of the onlookers marvel at its unprecedented pc
iers gather in animated knots trying, but so far in vain, to make ou
ilosophy, its logic, and its architecture. The central idea of the new d

"Computer science and basic physics mark two of the frontiers of the civilization of this age. One seeks to build complexity out of simplicity. The other tries to unravel complexity into simplicity. No one, it has been said, is better at taking a puzzle apart than the person who put it together and no one is better at putting a puzzle together than the one who took it apart"

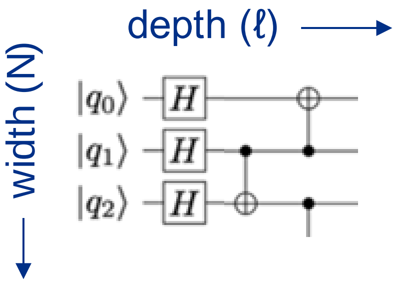
SQMS processors performance goals compared to leading systems →

Processor metrics	Leading systems	Center prototypes (3 yr)		Center device goals (5 yr)	
		2D-Alpha (estimate)	SRF-Alpha (estimate)	SQMS-2D (estimate)	SQMS-3D (estimate)
Number of qubits	53	128	>100	256	>200
Connectivity graph (qubit:neighbors)	1:4	1:3	1:10	1:3	1:200
Qubit T_1 lifetime, μs (median)	70	200	400,000	400	1,000,000
Gate time, ns (median)	20	50	2000	40	100
Coherence/gate time ratio	1,000	4,000	20,000	10,000	10,000,000
Single qubit gate fidelity (%)	99.85	99.6	99.5	99.95	99.95
Two qubit gate fidelity (%)	99.65	99.2	99.5	99.9%	99.95
Achievable circuit depth (1/error)	300	100	200	1,000	2,000

SQMS key goals and estimated performance parameters.

SQMS Quantum Computing 10-year Roadmap - technology

Quantum algorithms:



Ultimate limits to depth:

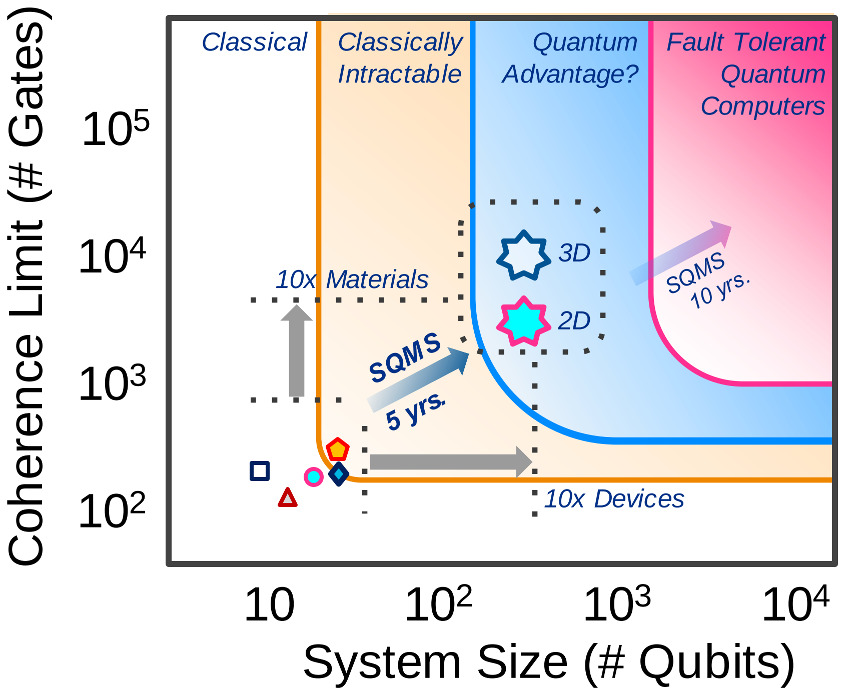
max(ℓ) ∝ T_1 / t_{gate}

For SC qubits, typical:

t_{gate} = [20-1000] ns

max(N*ℓ) ~ 10^4

Superconducting Qubits



SQMS Consequences:

- SQMS-3D
- SQMS-2D

Leading US testbeds:

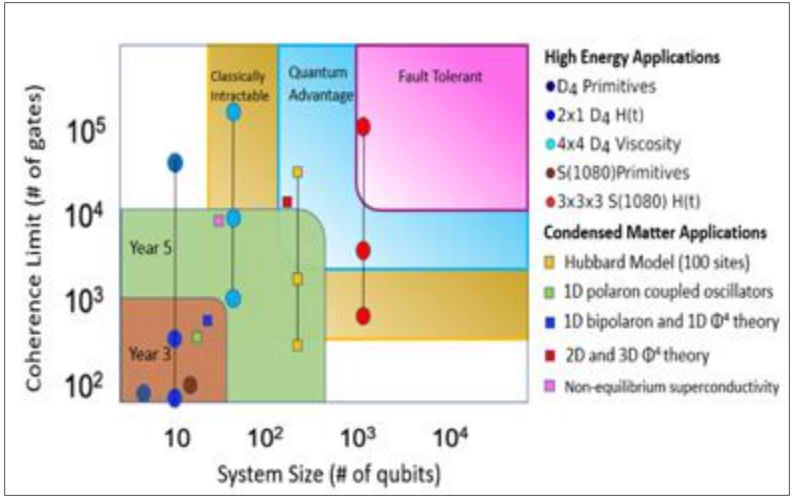
- *Google Sycamore*
- *IBM Hexagonal*
- *Rigetti Aspen*
- *Yale Single-mode*
- *UChicago Multi-mode*

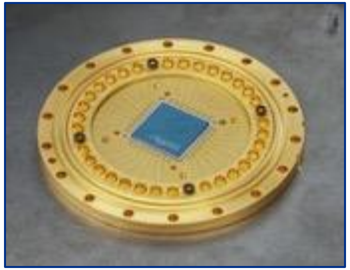
SQMS Quantum Computing Roadmap - science

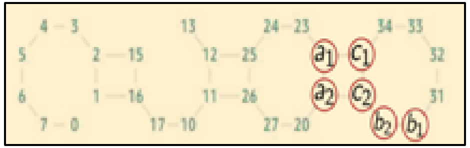
Goal: Investigate and develop quantum algorithms and simulations enabled by the groundbreaking SQMS 3D and 2D prototypes through co-design principles

Deliverables/metrics: simulations of the dynamics of theories approximating QCD, simulate LHC physics, plasma early universe conditions, quantum materials far from equilibrium, intermediate electron/phonon SC…

SQMS computational and simulation science goals mapped to prototypes







Qubits considered for a D4 gauge field theory test simulation on the Rigetti hardware.

Fermilab

Scientific and Technological Goals – quantum sensing

Develop and deploy new quantum sensors at Fermilab

Push superconducting sensors at the frontier of coherence and frequency control technologies

From technology R&D to experimental prototypes, informing future large experiments

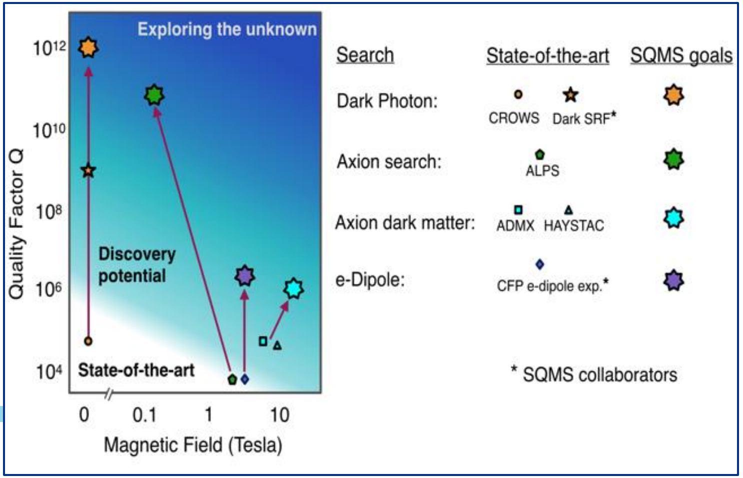
THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

The European Committee for Future Accelerators Detector R&D Roadmap Process Group

Chapter 5

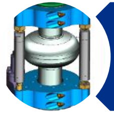
Quantum and Emerging Technologies Detectors

"The unprecedented sensitivity and precision of quantum systems enables the investigation of questions of fundamental concern to particle physics. These include the nature of dark matter, the existence of new forces, the earliest epochs of the universe at T >> 1TeV and the possible dynamics of dark energy, the possible existence of dark radiation and the cosmic neutrino background, the violation of fundamental symmetries, and even the nature of interaction and space-time at scales as high as $M_{Planck} \sim 10^{19}$ GeV"



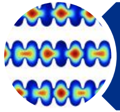
Physics and Sensing 5-year Roadmap

	Year 1	Year 2	Year 3	Year 4	Year 5



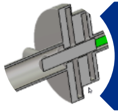
DarkSRF

- Measure in LHe, 1st DarkSRF publication
- Phase sensitive readout
- Implement in DR, quantum regime!
- Improve Q_0 towards 1e12



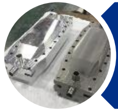
Multimode Cavity Axion Search

- Nonlinearity studies
- 2-cavity multimode design
- 2-cavity 1st test
- 2- and 3- mode 1-cavity design
- 2- and 3- mode 1-cavity 1st test



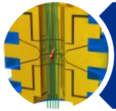
Tunable Dark Photon Search

- Design and fabricate cavity
- Trial runs, feedback
- Study heterodyne vs photon counting
- Data taking runs



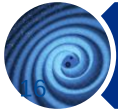
High B-Field Axion Search

- Co-design w/ materials & devices
- Searches w/ best cavities and qubits
- Evaluate Nb_3Sn, NbTi Q_0 in high B
- Evaluate search w/ AC B-field



Single Particle Penning Trap

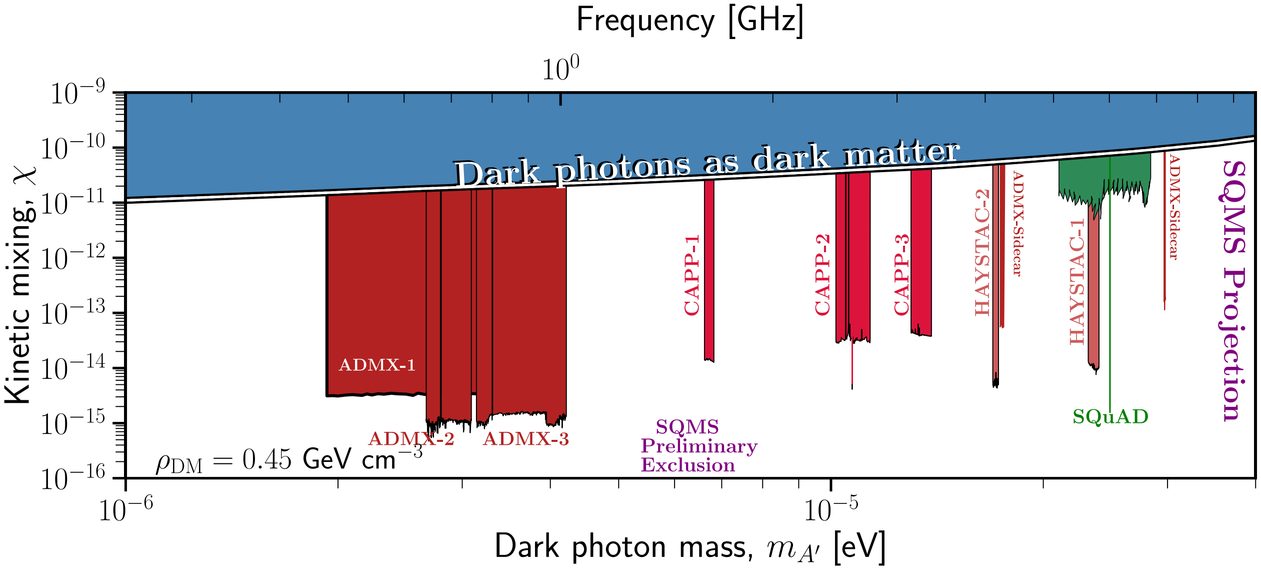
- Design high Q cavity geometry
- Testing optimized cavities/squids
- Prototype cavities & squids
- 1st next gen e- μ/μ_B measurements

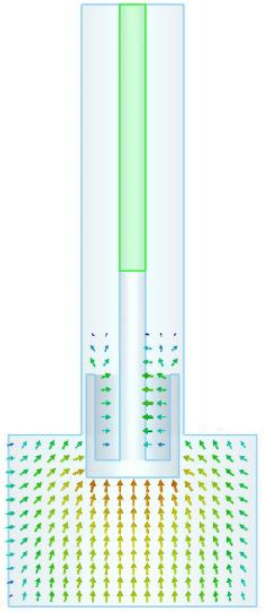


Other Quantum Sensing Schemes

- Theory study of QIS for dark radiation detection, Quantum Sensor Network,
- Evaluate SRF cavities for gravitational wave detection, DM with traps.

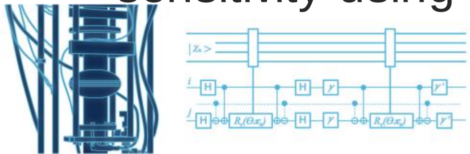
Tunable Cavity Dark Photon Dark Matter Search





Raphael Cervantes, SQMS Postdoc

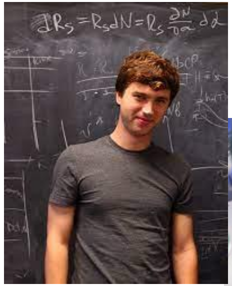
- Dark photon search - similar to axion, but with no magnetic field
- **<u>Just demonstrated the most sensitive experiment for wavelike dark photons.</u>**
- By year 3: First results of 5-8 GHz dark photon search with unprecedented sensitivity using ultra-high Q cavities and superconducting qubits.



SQMS theorists and experimentalist ‘co-design’ to develop new experiments

SRF + QIS capabilities enable new particle searches of unprecedented sensitivity and precision

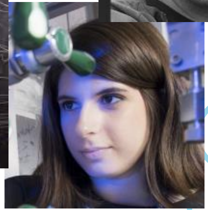
A. Romanenko



R. Harnik

Y. Kahn

B. Giaccone



G. Gabrielse

R. Cervantes

A. Berlin

S. Rajendran

P. Graham

C. Braggio

S. Posen

Theory

Options for mode setups + sensitivity

Prototypes

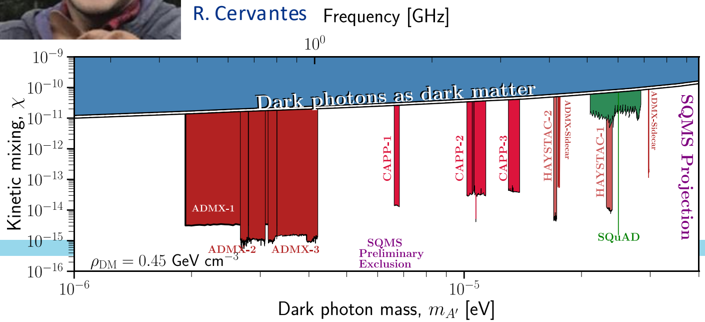
Systems design, testing

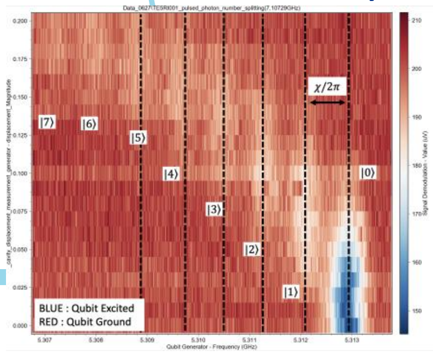
(measure cross-talk, Q for various modes, readout)

co-design

Materials and Devices

Improved Q, sensitivity, controls



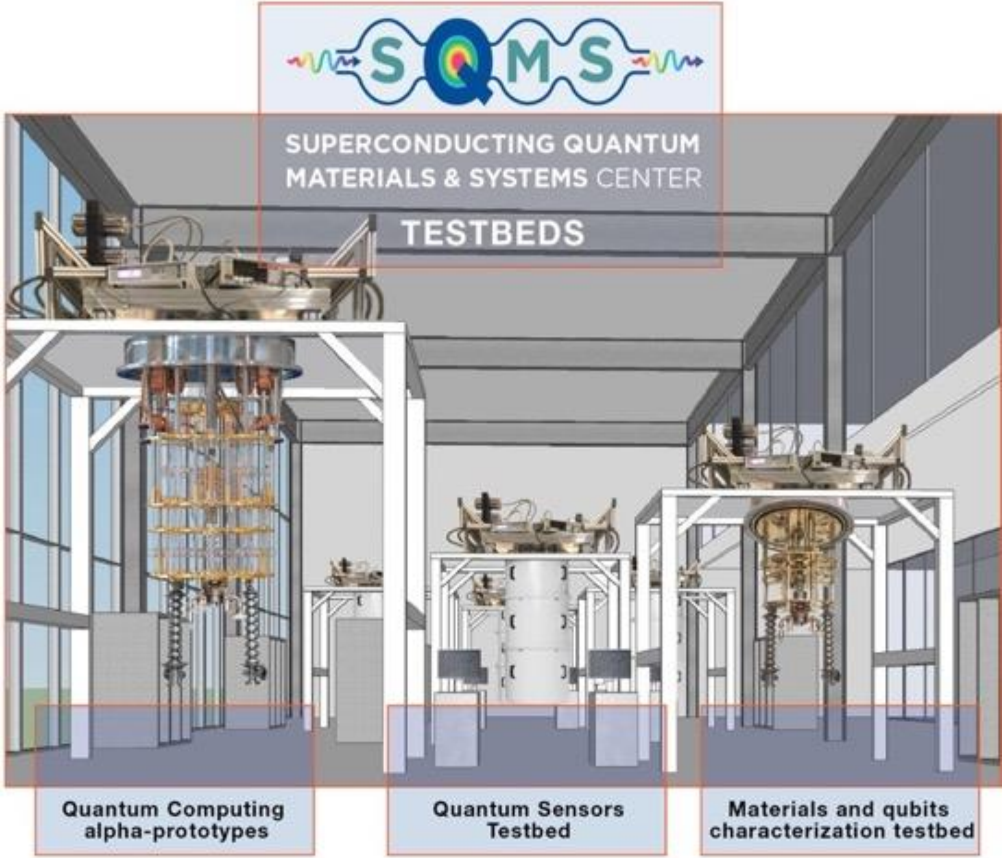


Fermilab

SQMS 5-10 years quantum facilities vision

Developing and delivering tangible, unique platforms/instrumentation for QIS fabrication, computing and sensing:

- Foundries: New high-flexibility nanofabrication tools
- Materials testbeds: Qubits and quantum materials measurements in the most precise and sensitive environments
- Physics Testbeds: Platforms enabling new particle searches/sensing experiments
- Computing Testbeds: 2D and 3D-based quantum computer prototypes



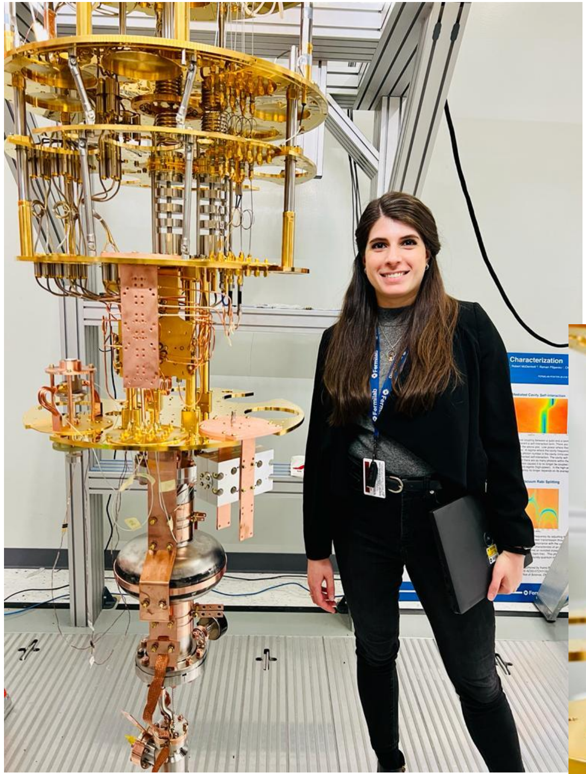
Fermilab

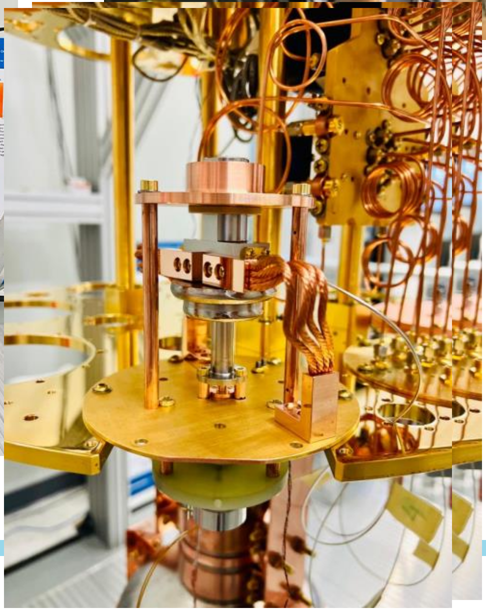
Fermilab Quantum Facilities - 2021

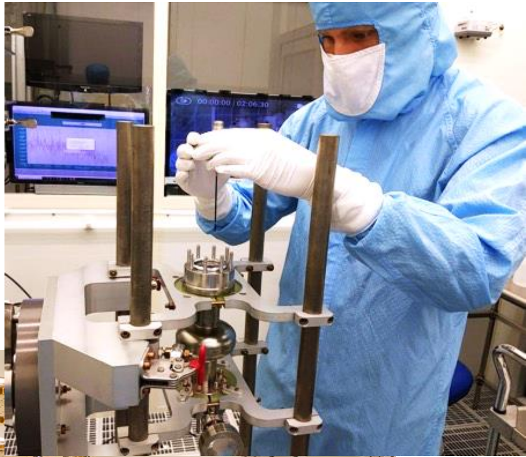
QCL-1 fully commissioned with two DRs, multiqubit controls and readout, piezo controls in DR

Fermilab Quantum Facilities - 2021

QCL-1 fully commissioned with two DRs, multiqubit controls and readout, piezo controls in DR

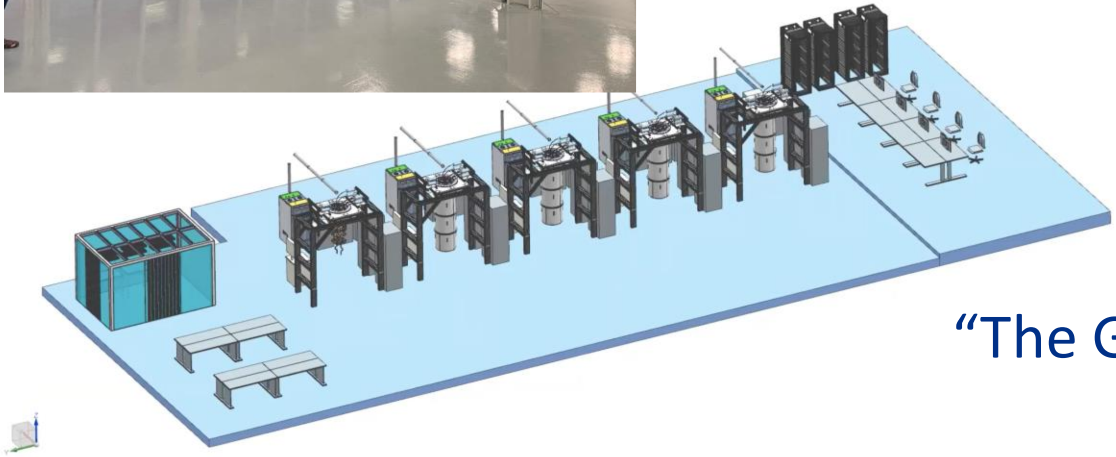






Fermilab Quantum Facilities - 2023

QCL-2 and 3 will deploy an additional fleet of six dilution fridges, one with 9 Tesla magnet, hundreds of new cavities and qubits, controls for QIS experiments, with cavity/qubit preparation clean room area

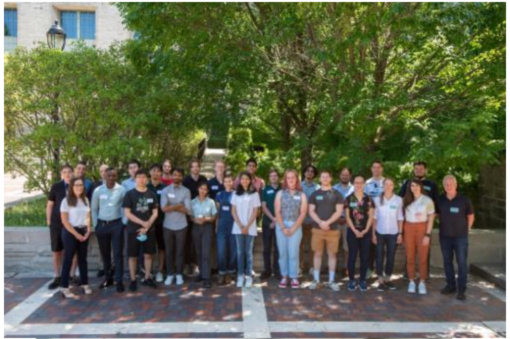


On track with construction and procurement for commissioning in early 2023

“The Garage” @ the SQMS center

Fermilab

Building a diverse quantum workforce: SQMS schools, internships, fellowships



SQMS Summer Internship for undergraduate students

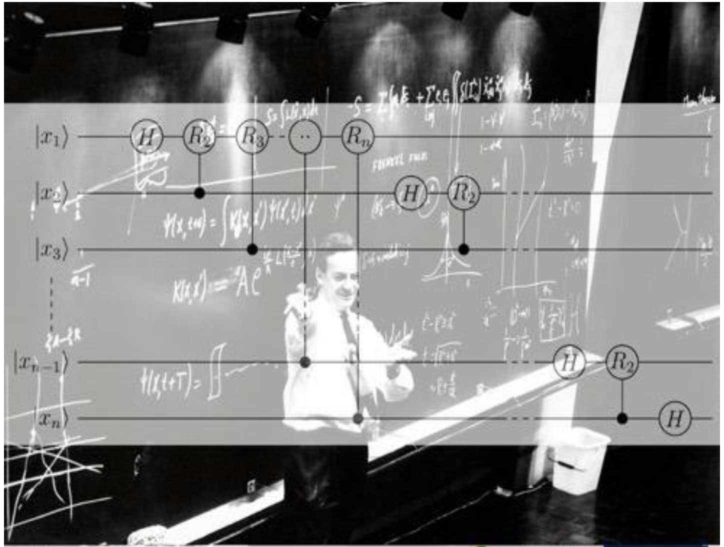
18 students, more than 50% URM and women

https://internships.fnal.gov/sqms-quantum-undergraduate-internship/

New Carolyn B. Parker postdoctoral fellowship for under-represented minorities

Currently accepting applications

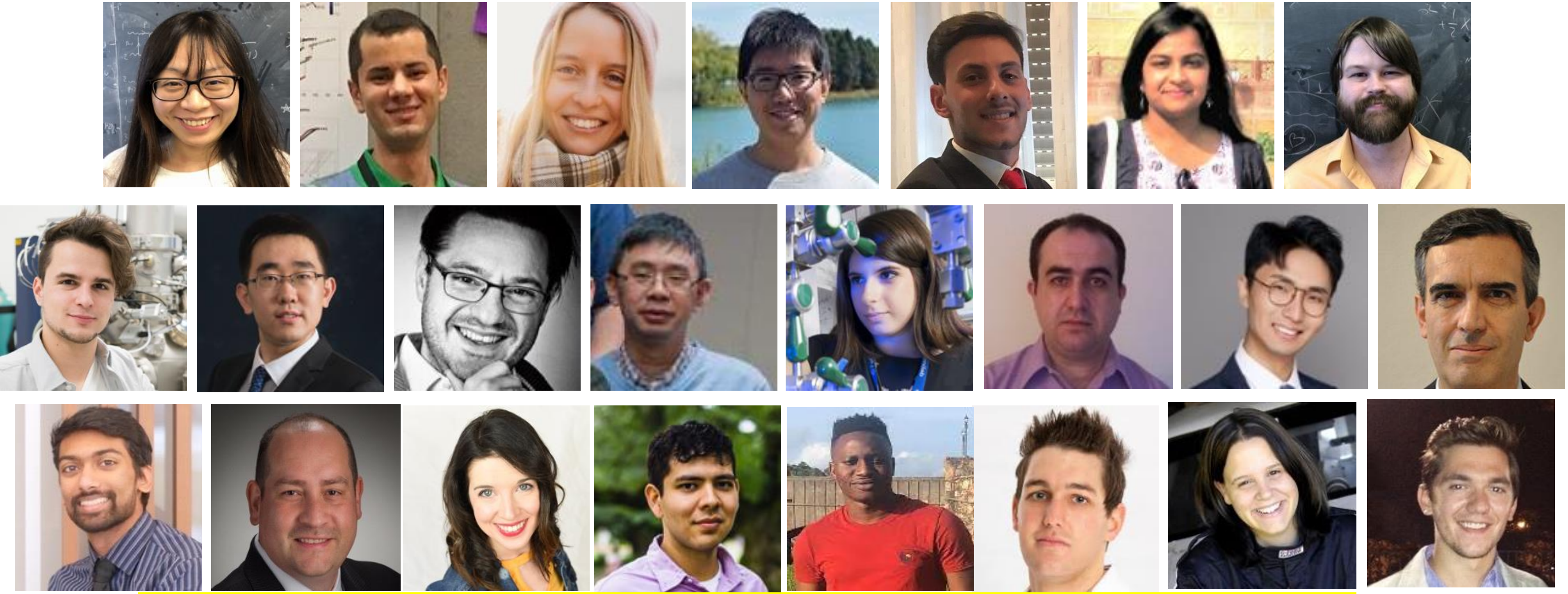
https://news.fnal.gov/2021/05/fermilabs-quantum-center-announces-carolyn-b-parker-fellowship-for-postdocs/



SQMS QIS Summer School hosted by the Galileo Galilei Institute (Florence)

https://www.ggi.infn.it/showevent.pl?id=402

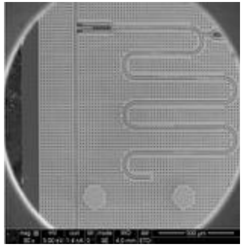
A new diverse quantum workforce: new hires



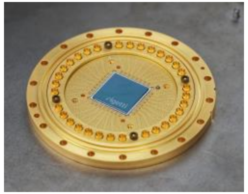
SQMS at Fermilab supports > 100 different employees
Postdocs, Scientists, Engineers, Techs, Management, Communication…
> 400 students and interns and researchers across our partner institutions

SQMS Roadmap: a quantum decade leading to new revolutionary tools

From 1 to 10 high coherence qubits prototype



Transmon qubit improvement in coherence > 10

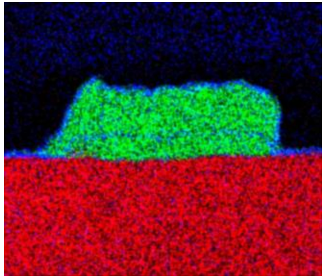


100 qubits Quantum Computer @ Fermilab

Electronics/optimal controls development and scale up

1000 qubits Quantum Computer @ Fermilab

2020-2030: The SQMS Quantum Decade of Technological and Scientific Innovation

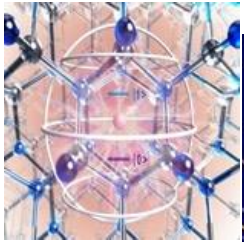


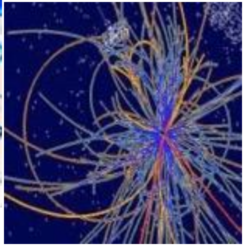
Materials Research for high coherence qubits

New quantum testbeds commissioned

Quantum Sensors for fundamental physics

Colossal fridge commissioned 20mK





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

Grazie!