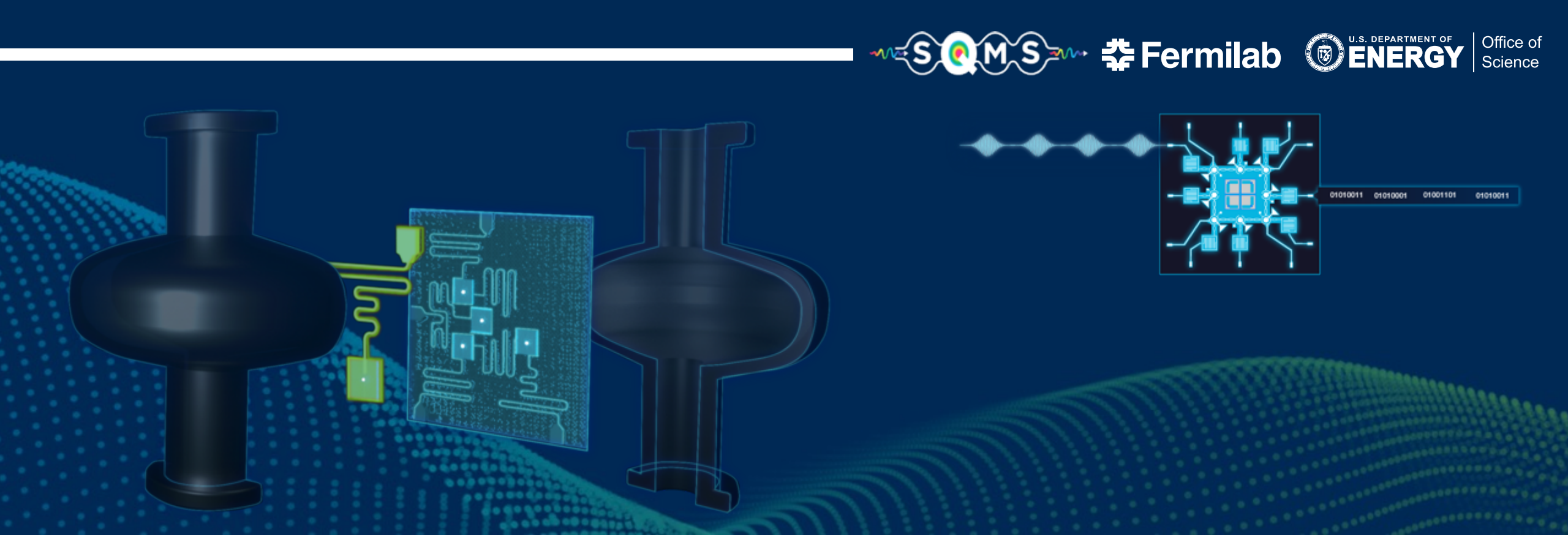



# Superconducting Quantum Materials and Systems Center

Anna Grassellino, SQMS Center Director

PAC

June 6th, 2021

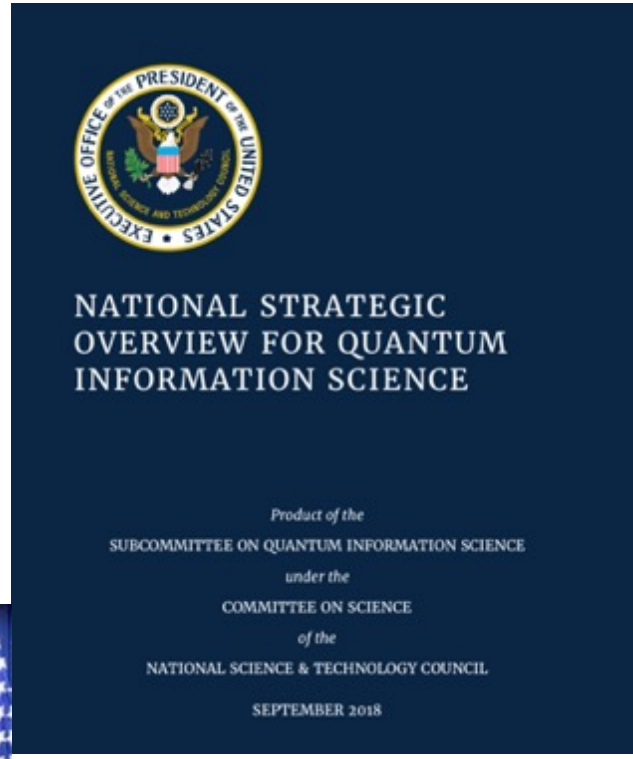
# U.S. National Quantum Initiative

In 2019 Congress mandated the creation of **five Dept. of Energy national quantum centers**

$625M over five years to develop quantum computers, quantum sensors, and quantum communications

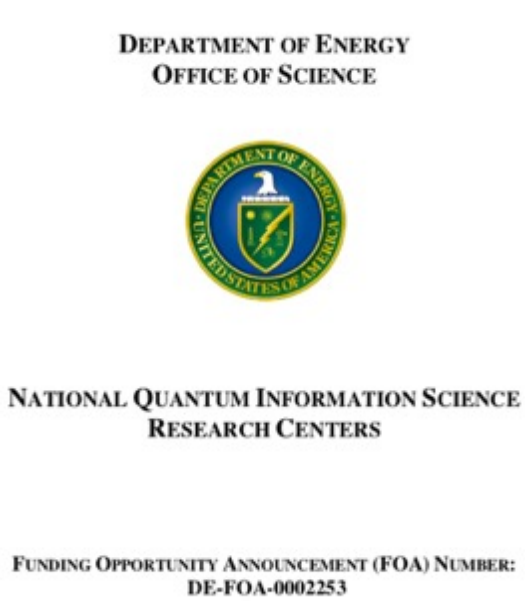
Goal is transformational advances in quantum science and technology

Create a quantum economy


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

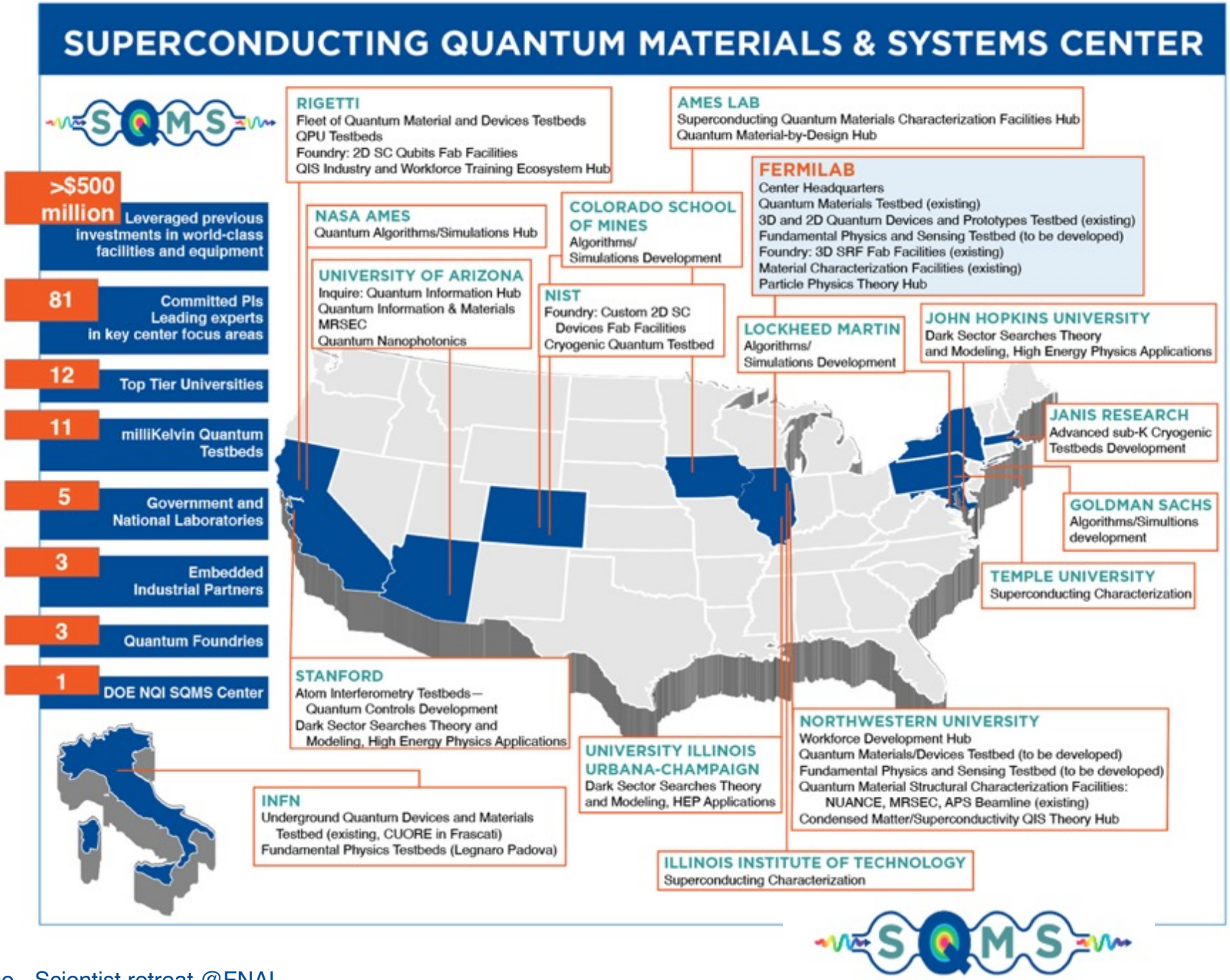
# August 2020: Fermilab will lead a DOE National Quantum Center

"With the **Superconducting Quantum Materials and Systems** Center (SQMS), we bring the power of DOE laboratories, together with industry, academia and other federal entities, to "achieve transformational advances in quantum technologies for computing and sensing"

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
LOCKHEED MARTIN
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
University of Colorado Boulder
THE UNIVERSITY OF ARIZONA
Stanford University
Goldman Sachs
COLORADO SCHOOL OF MINES
JOHNS HOPKINS UNIVERSITY
ILLINOIS INSTITUTE OF TECHNOLOGY
JANIS
Unitary Fund

More than 200 collaborators!

**"We have the ambitious goal of building the first quantum computer at Fermilab"**

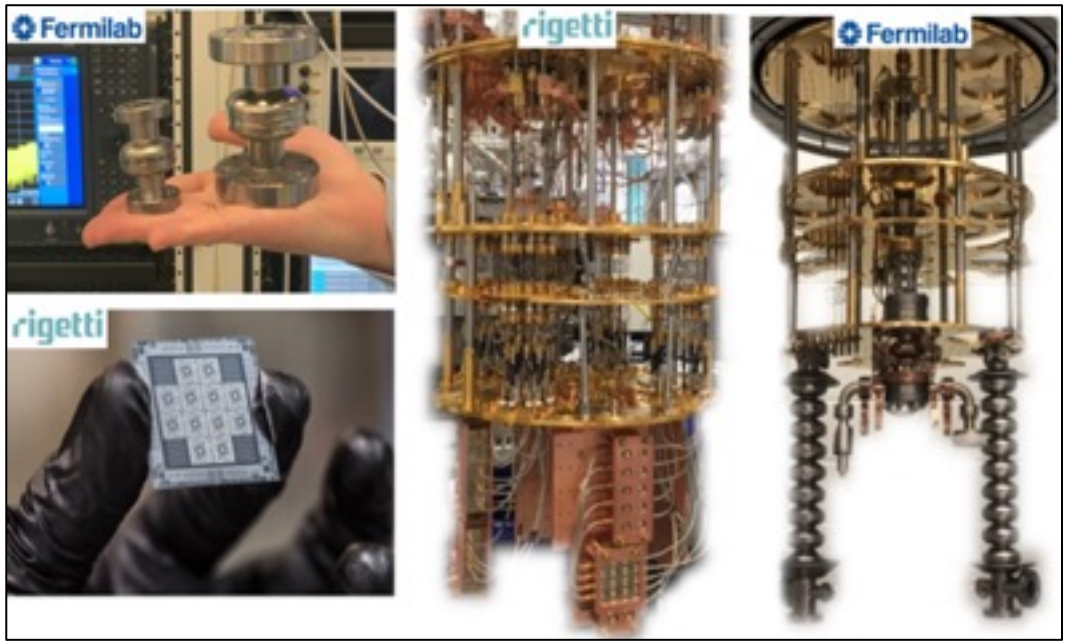


# Quantum Information Science: a multidisciplinary endeavor

Industry use cases

Radio frequency superconductivity

Condensed Matter Physics




Material Science

Particle Physics

Computational Science

Cryogenics

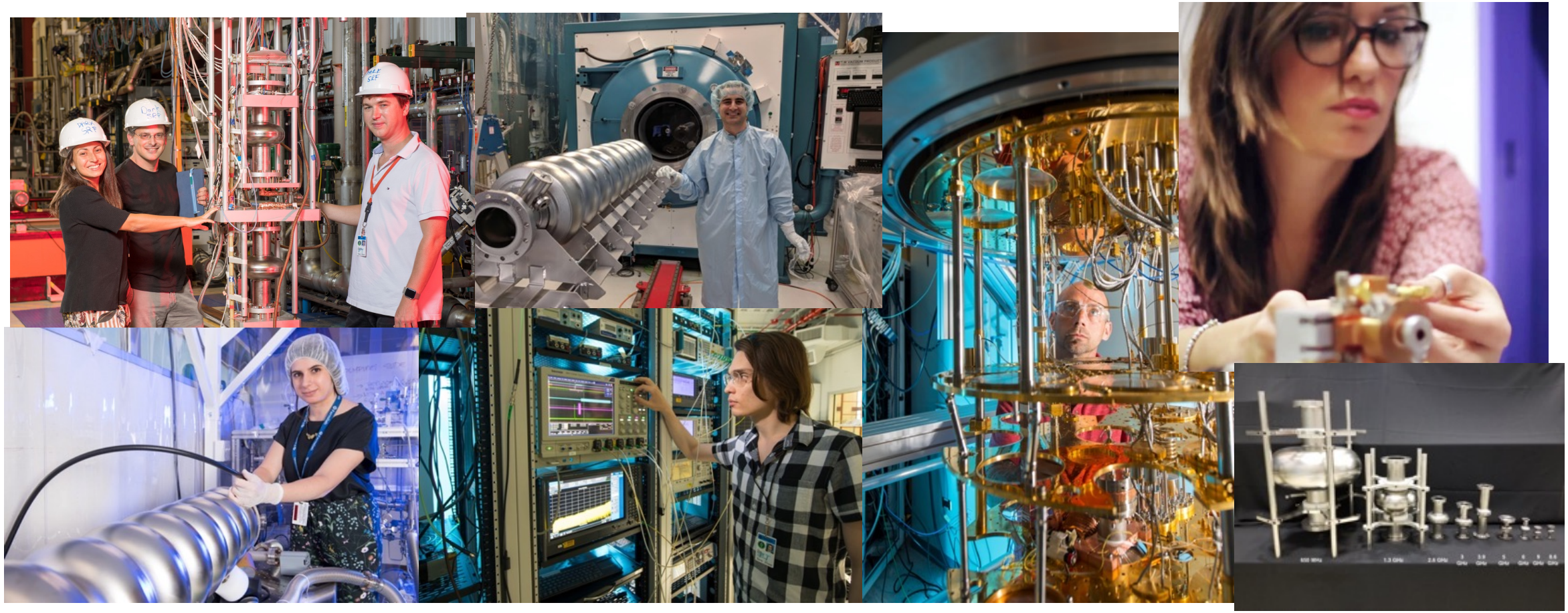
Scale up and integration

Controls and electronics

Superconducting qubits

Strong programmatic focus; Materials, Devices, physics/sensing and algorithms groups; Ecosystem and workforce development; all groups meeting weekly and dozens of sub-groups meeting multiple times a week

# SQMS strengths at Fermilab



SQMS builds upon several Fermilab unique strengths, among which decades of investments in SRF technology and cryogenics, the newer superconducting quantum labs, and particle physics as a science driver and end user of QIS technologies

# SQMS leverages unique national and international facilities

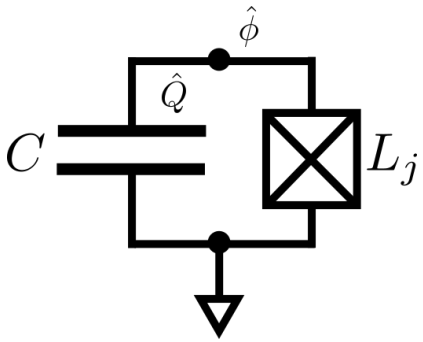
Rigetti superconducting fab facilities in Fremont, California

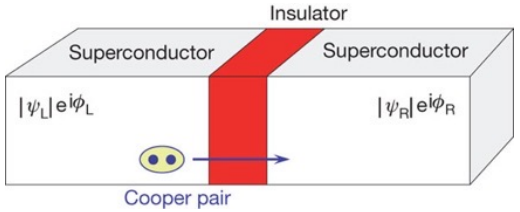
INFN CUORE underground cryostat at Gran Sasso, Italy

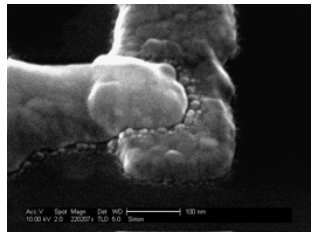
From unique superconducting 2D and 3D foundries, to material science and superconducting characterization tools, to above and underground milliKelvin testbeds, SQMS brings together the key facilities and world class experts to make transformational advances in quantum information science

# Pushing the coherence of Superconducting Qubits, 2D and 3D

## 1. LC circuit with Josephson junction



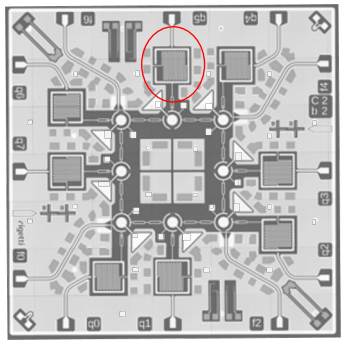
"Transmon" qubits

J. Koch et al, Phys. Rev. **A** 76, 042319 (2007)

+

## 2. Resonators (cavities)

2D



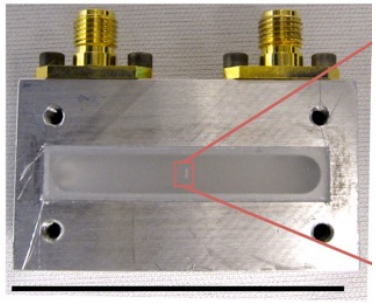
Rigetti 8-qubit processor

$Q \sim 10^5$

$T_{coherence} \sim 0.000001$ s

M. Reagor et al, Science Advances, Vol.4, no. 2, (2018)

3D




3D transmon

$Q \sim 10^8$

$T_{coherence} \sim 0.001$ s

H. Paik et al, Phys. Rev. Lett. 107, 240501 (2011)

Fermilab SRF resonators

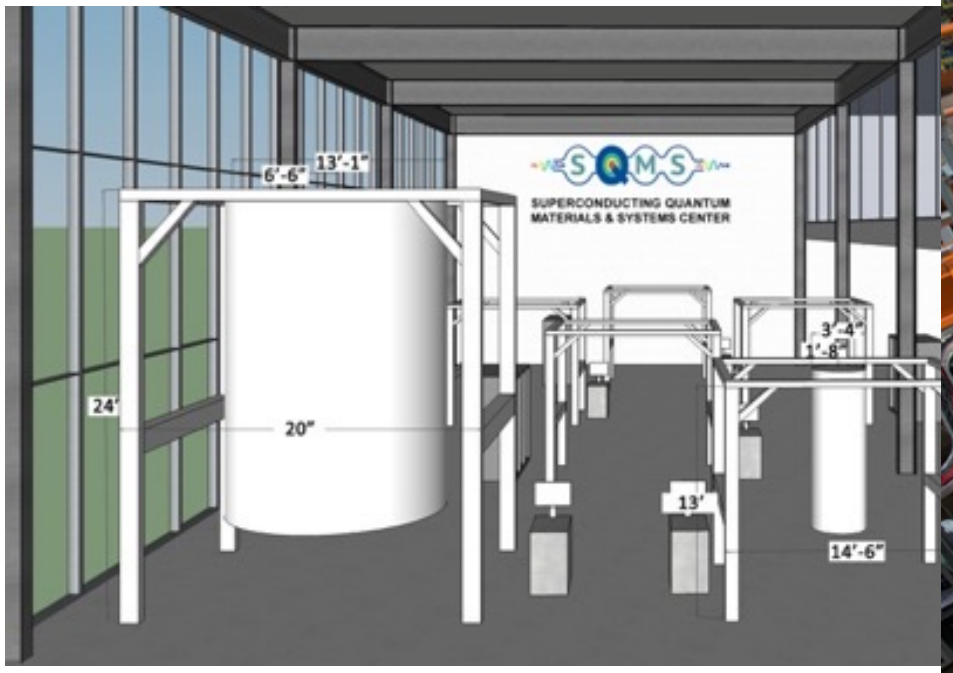
**$Q > 10^{10}$**

**$T_{coherence} > 2$ s**

A. Romanenko et al, Phys. Rev. Appl. 13, 134052 (2020)

SQMS, by improving the **coherence** of both key components, and of the system combined, will bring transformational advances in the fundamental QIS building blocks, leading to quantum computing scalability and quantum sensing potential for discovery

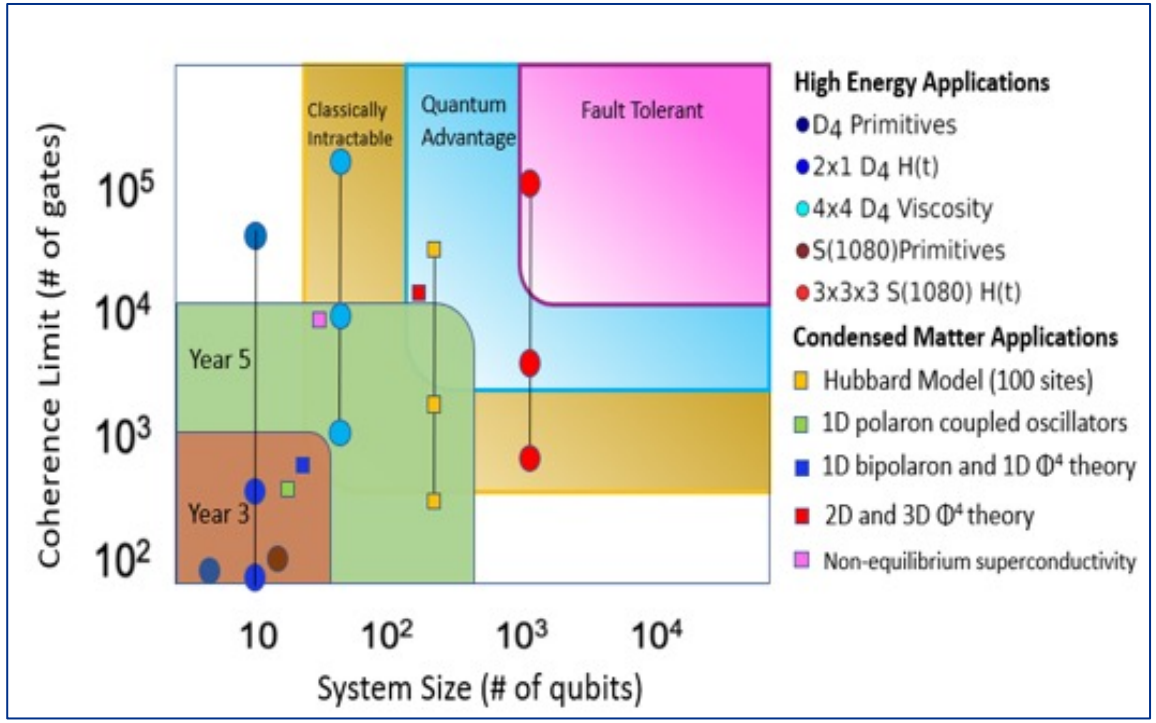
# Scale up, integration capabilities and plans for the first quantum computer at Fermilab

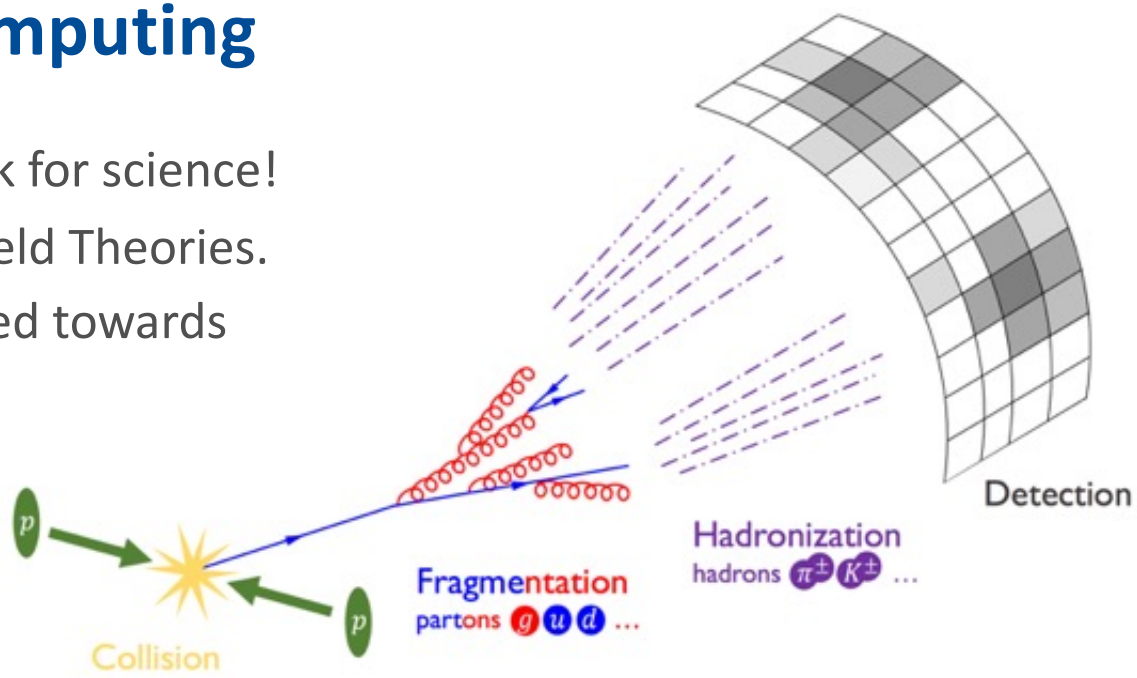


We plan to build the largest dilution fridge ever constructed, to host hundreds of qubits, to be hosted in the IARC building

# Science and Discovery with SQMS - Computing

- We are excited to put SQMS quantum computer to work for science!
- High connectivity is well-suited to simulate Quantum Field Theories.
- Ladders of simulations (progression of toy-models) aimed towards ambitious science goals.




**HEP:**

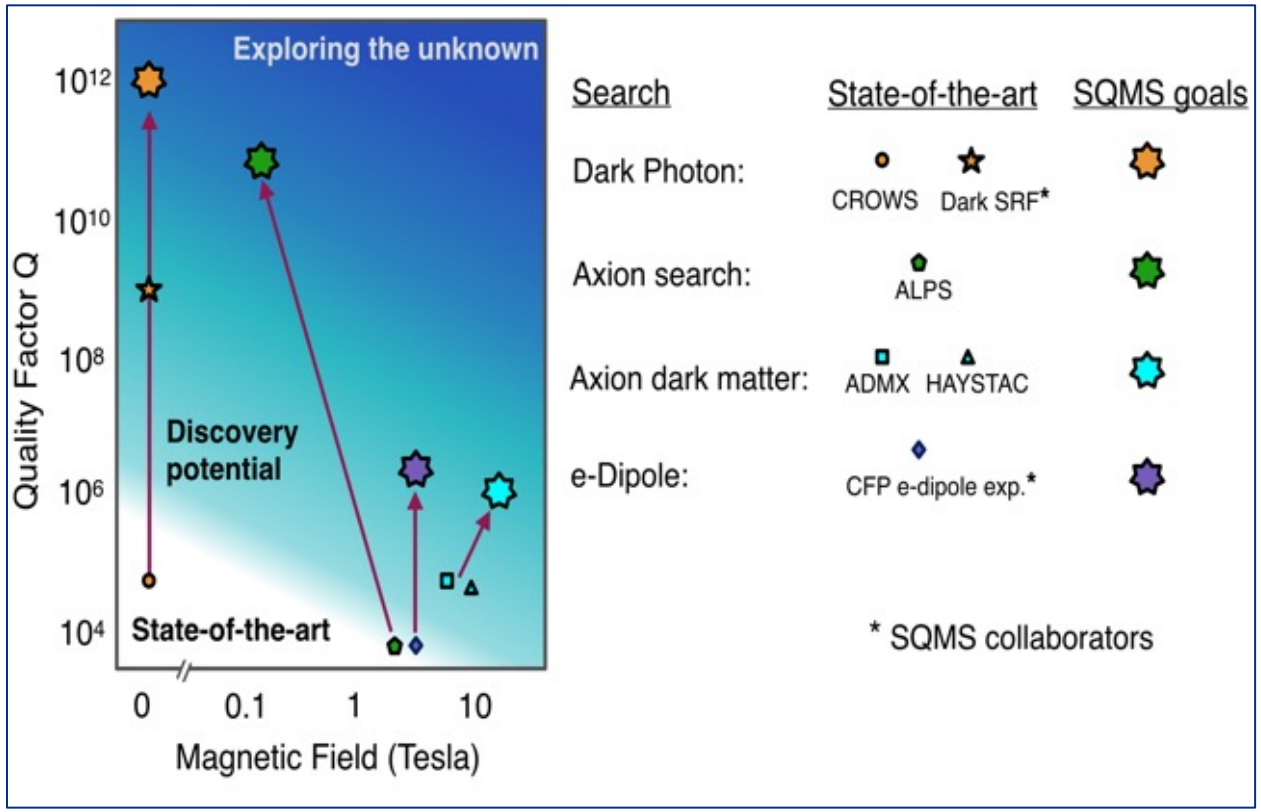
**QCD dynamics: least understood parts of LHC collisions and early Universe (Hadronization, viscosity of gluon plasma)**

**Condensed matter:**

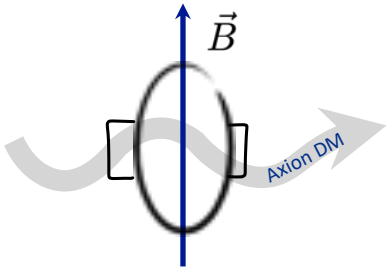
Many body states with high entanglement (aided by connectivity), many body localization. polaron system dynamics.

# Science and Discovery with SQMS Technology - Sensing

- We are excited to use SQMS technology for direct exploration:
  - *Are there new long range forces?*
  - *What is the Dark Matter (DM)?*
  - *Can we probe single electrons more precisely?*




- High coherence also allows to pick up fainter signals, search for elusive particles.




e.g. Axion DM Search -
High Q in high B field (FNAL+INFN)

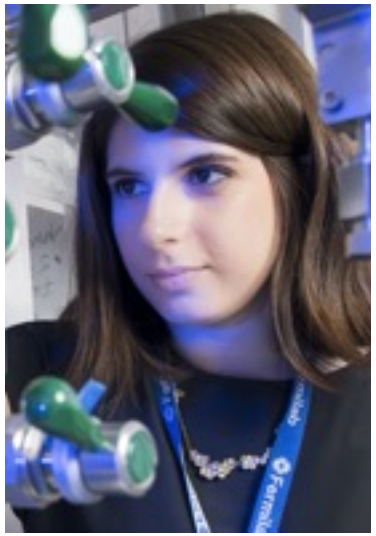
**Orders of magnitude in sensitivity to new physics!**

## Sensing

- Our goal is to use SQMS technology to address some of the questions that keep us up at night”
  - *Are there new long range interactions?*
  - *What is the dark matter that dominates the mass of galaxies?*
  - *What are the properties of fundamental particles?*
  - *Can we detect gravitational waves in new ways?*

- Lead team: Caterina Braggio (INFN), Gerald Gabrielse (NWU), Roni Harnik (Fermilab), Yoni Kahn (UIUC), Sam Posen (Fermilab)

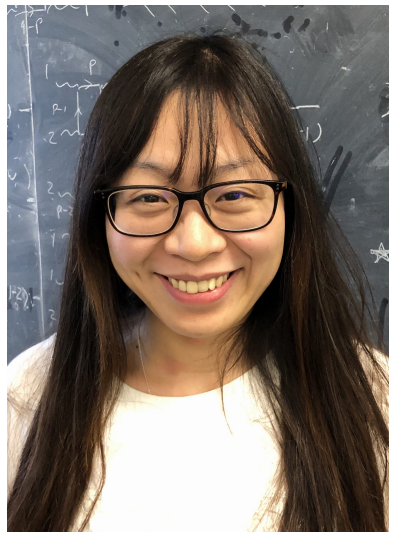
# Recent Hires in SQMS Physics/Sensing



**Bianca Giaccone**
(previously IIT/Fermilab)
**Associate Scientist @ Fermilab**
Superconducting microwave devices, quantum physics/sensing

**Raphael Cervantes**
(previously U Washington/ ADMX)
**Postdoc at Fermilab**
Quantum Physics/Sensing

**Asher Berlin**
(previously NYU)
**Associate Scientist @ Fermilab Theory**
BSM, Dark matter and GW detection with SRF



**Christina Gao**
(previously UC Davis)
**Postdoc, Joint Fermilab-UIUC**
Theory - axion searches

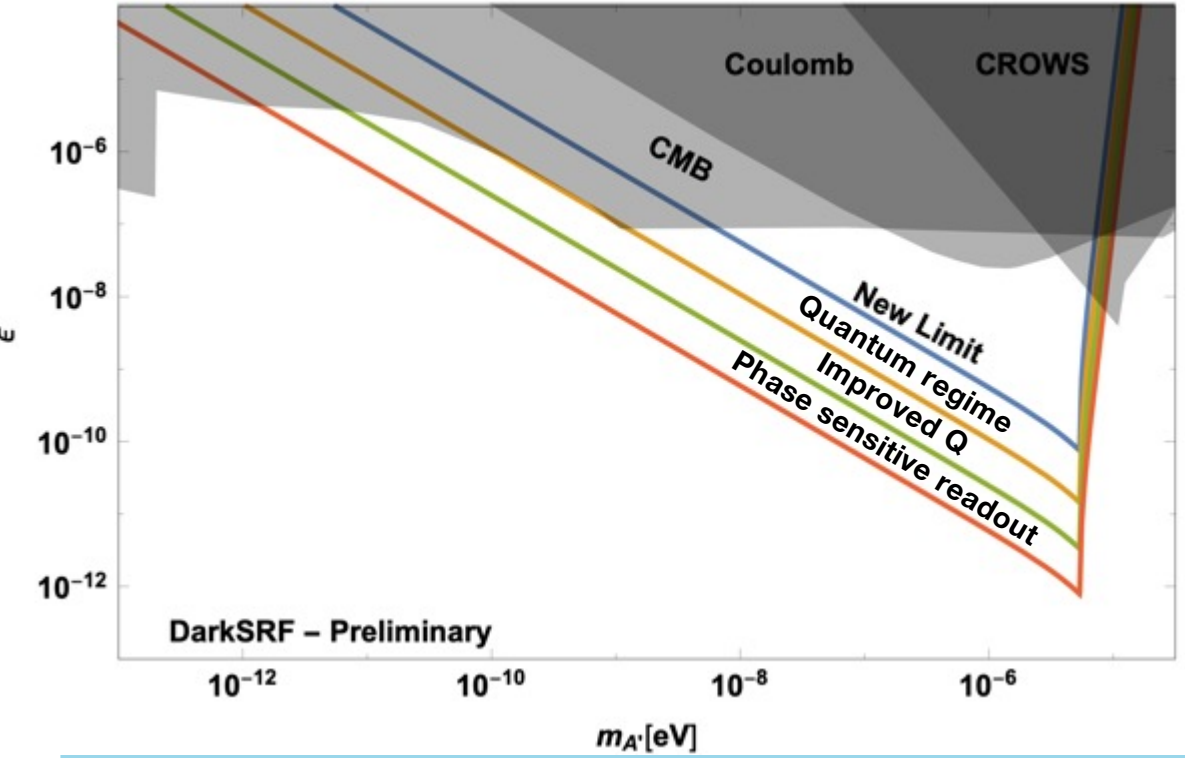
**Michael Wentzel**
**PhD Student @ UIUC**
Multimode cavity axion search and GW sensitivity

**Jan Schütte-Engel**
(previously Hamburg U.)
**Postdoc @ UIUC**
Axion and GW searches with SRF cavities

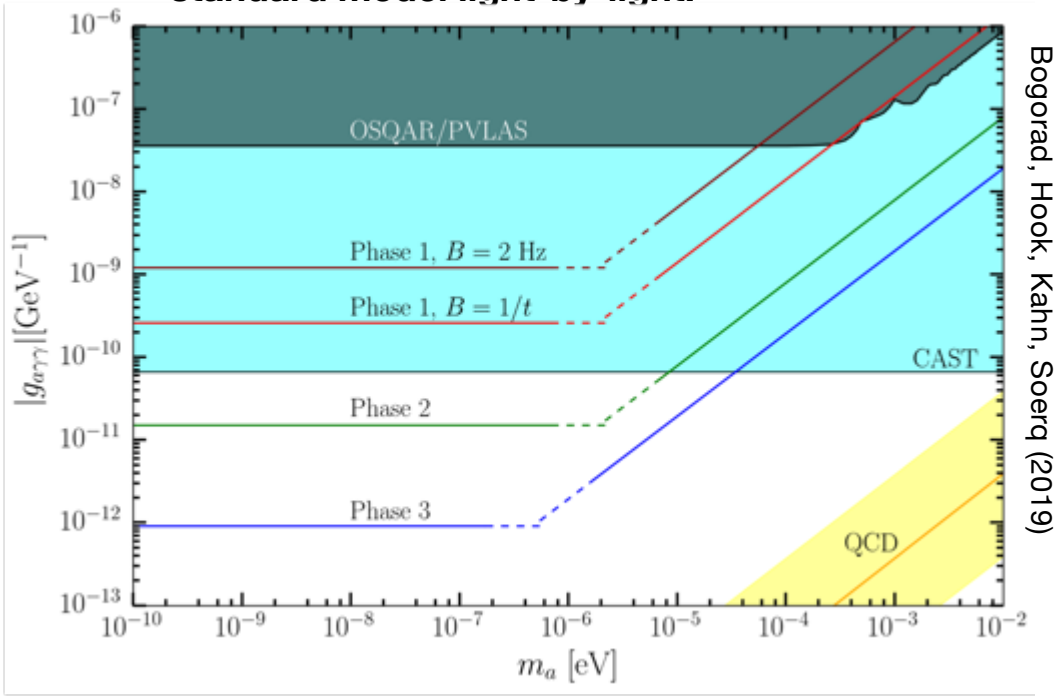
# SQMS progress - sensing

- SQMS is working to enable new searches for dark matter and other new physics.
- High coherence systems can be leveraged in search of new particles interacting with light (axions/dark photons), probing particle properties (electron g-2). Examples:

**Dark photon search progression:**



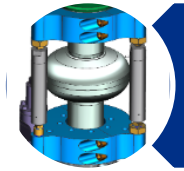
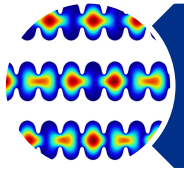
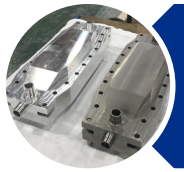
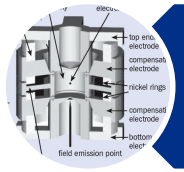
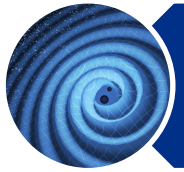

**New approaches to axion searches and standard model light-by-light:**




Bogorad, Hook, Kahn, Soerq (2019)

Requires beyond state of art Q's degree of linearity.

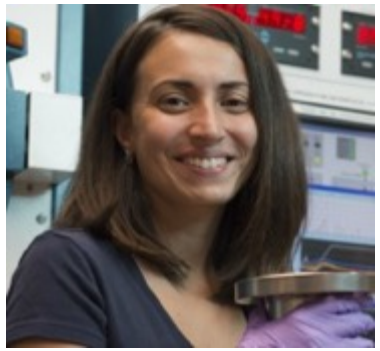
# Physics and Sensing Roadmap, based on Appendix 13

| | 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 | | 1-cavity multimode design | | 1-cavity 1st test |
| | | 2-cavity multimode design | | 2-cavity multimode 1st test | |
|  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- $\mu/\mu_B$ measurements | |
|  Other QIS Sensing Schemes | | Theory study of QIS for dark radiation detection | | | |
| | | Evaluate SRF cavities for gravitational wave detection | | | |

# Center Management Goals & Progress

# SQMS Top Leadership Team

Dr. Anna Grassellino (FNAL)
Center Director



Prof. James Sauls (Northwestern University)
Center Deputy Director

Dr. Matt Reagor (Rigetti)
Chief Technology Officer

Dr Eleanor Rieffel (NASA Ames)
Chief Research Scientist

Dr Matt Kramer (Ames Lab)
Chief Engineer

Rich Stanek (FNAL)
Interim COO

Dr Alexander Romanenko (FNAL)
Technology Thrust Leader

Dr Roni Harnik (FNAL)
Science Thrust Leader

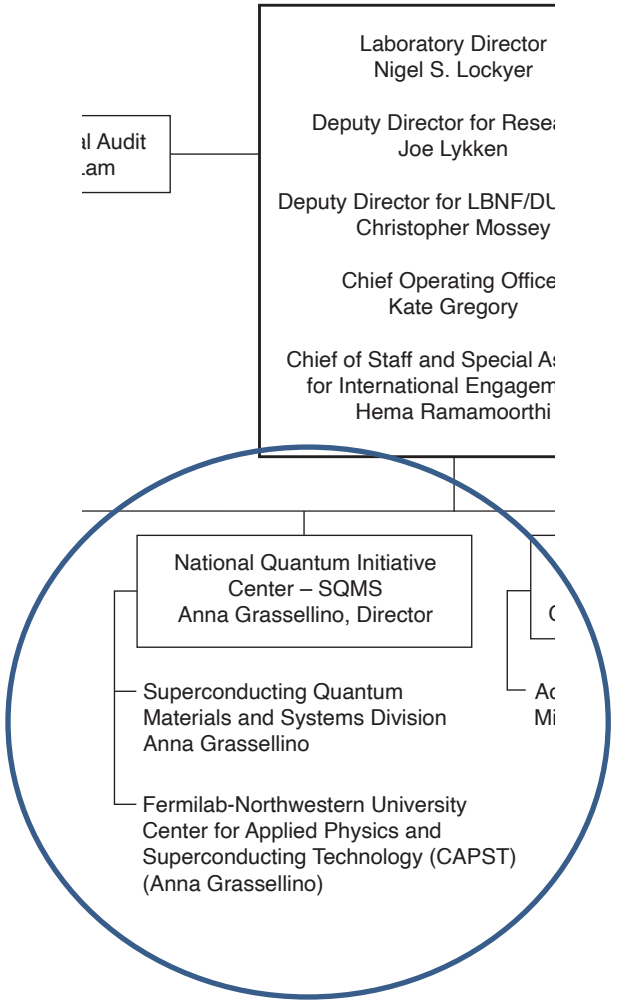
Mandy Birch (Rigetti)
Ecosystem Leader

# SQMS Direct DOE Program Managers

Dr. Altaf Carim (DOE HEP)

Dr. Athena Safa Sefat (DOE BES)

# New SQMS Division at Fermilab reporting to Fermilab Director



# SQMS Center Spotlight on Management Progress

Josh Mutus, Director of quantum materials at Rigetti Computing, new SQMS leader in materials and round robin experiment

## Progress/Achievement in Management

**More than 50 new hires at the SQMS Center across the various partner institutions – from grad students, to postdocs, scientists, engineers, technicians, support staff and managers.**

## Significance and Impact

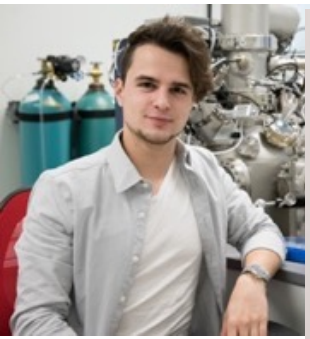
**In addition to internal resources – more than 50 new hires across the SQMS partners, top talent from world's best QIS institutions – will allow SQMS to quickly march towards the goals and deliverables of the Appendix 13 timetable.**

## Details

- FNAL has had a nearly 100% success rate in new hires, with now 22 accepted offers (postdocs, associate scientists, techs, engineers, the SQMS Center financial manager and the SQMS communication manager plus two new graduate students)
- Overall more than 100 people to date at FNAL have been contributing to the SQMS effort, with an average FTE charge of ~24 FTE
- In addition, several student, postdoctoral and scientific hires have been successful at NU, Ames Lab, Rigetti and other partners
- Overall this brings the number of collaborators involved in SQMS activities well above 200

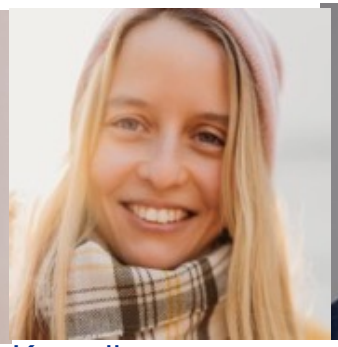
# SQMS new scientific hires at Fermilab (new SQMS division, two theory div)

## Experts from world top groups in quantum materials, devices, quantum computing and sensing

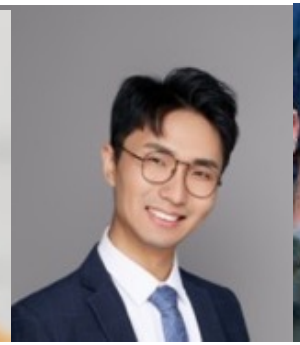


Daniel Bafia (from FNAL) Postdoc

Akshay Murthy (from NU) Postdoc



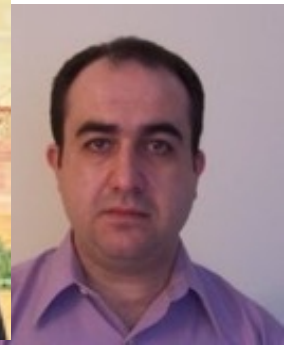
Yulia Krasnikova (from Kapitza Institute) Associate Scientist



Ziwen Huang (from NU) Postdoc

Shaojiang Zhu (from U Wisconsin Madison) Associate Scientist

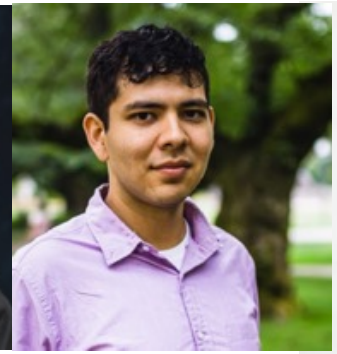
Arpita Mitra (from Penn State) Postdoc



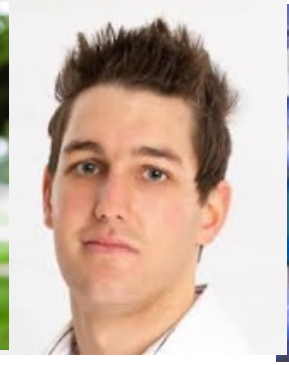
Mustafa Bal (from NIST) Associate Scientist

Ivan Nekrashevich (from Los Alamos) Associate Scientist (offer pending)

Changqing Wang (from Washington University St Louis) Postdoc



Raphael Cervantes (from U of Washington) Postdoc



Nicholas Bornman (from U of Witwatersrand, South Africa) Postdoc

Bianca Giaccone (from FNAL) Associate Scientist

David Van Zanten (from Niels Bohr Institute, Copenhagen), Associate Scientist

Xinyuan You (from NU) Postdoc

Asher Berlin (from NYU, SLAC) Associate Scientist

Hank Lamm (from FNAL) Associate Scientist

{PPD – Theory, Supported by SQMS at 50% each}

# SQMS Center/Division management hires successfully completed

***SQMS Center COO***
**Stefano Lami**
Previously Science Counselor at Embassy of Italy, Washington DC

***SQMS Center Communication Manager***
**Hannah Adams**
Previously Communication Specialist at Goodyear Rubber and Tire Company

***SQMS Center Senior Financial Manager***
**Gilbert Herrera**
Previously Financial Manager at Coca Cola

***SQMS Center Senior Administrative Assistant***
**Laura Siarkevich**
Previously Administrative Assistant for HL-LHC at FNAL

Overall, ~1/3 of the SQMS hires are women or URMs

# Some of the SQMS leaders@ Fermilab from across the lab

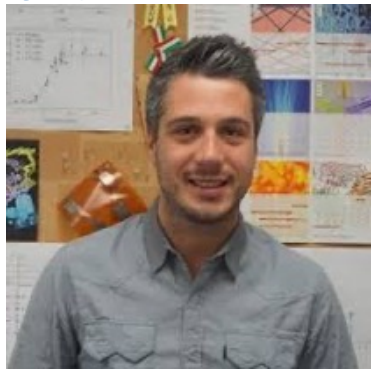
Anna Grassellino
SQMS Center Director,
Division Head

Rich Stanek,
SQMS Center
interim COO

Alexander Romanenko,
SQMS Technology Thrust Leader

Roni Harnik, SQMS Science
Thrust Leader

Sam Posen, SQMS Quantum
Physics/Sensing Focus Area Lead
and Department Head



Mattia Checchin, SQMS quantum
materials and qubits department
deputy head

Slava Yakovlev,
Quantum Microwave
Systems Department Head

Sergey Belomestnykh
Devices Integration
Group Leader

Silvia Zorzetti
Quantum Computing Co-Design
Department Deputy Head,
Workforce Lead

Roman Pilipenko
Quantum Testbeds,
Instrumentation, controls
development group leader

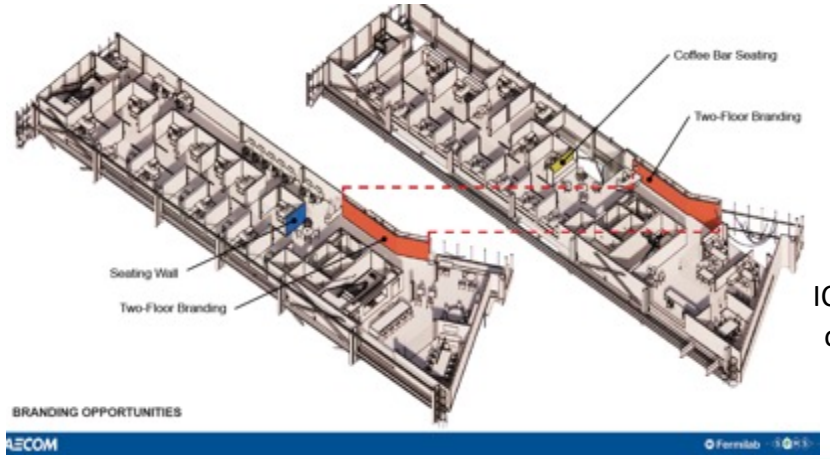
Matt Hollister
Ultra low T cryogenics
Department Head

Gabe Perdue Systems
Architecture and
algorithms group leader

For Center leadership teams please visit: https://sqms.fnal.gov/people/leadership-team/

# SQMS Center Spotlight on Management Progress

New SQMS office space in IARC




ICBA new SQMS office space in design phase

## Progress/Achievement in Management

**FNAL is committed to making the SQMS center a top priority, and to ensure a successful stand-up and growth of the National Quantum Center, FNAL Directorate has assigned to SQMS new offices in IARC, second floor west wing, plus 30 new offices in ICBA, and lab space in IARC/HAB**

## Significance and Impact

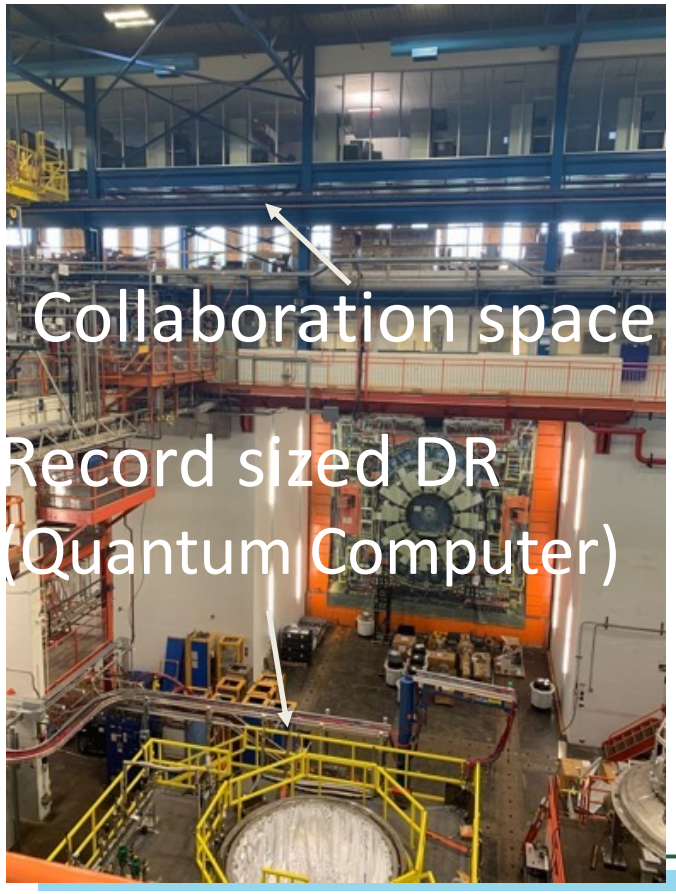
**Office space to co-locate the new hires and the SQMS collaborators near the technical facilities space, will enable SQMS to successfully and smoothly work towards the realization of the science goals**

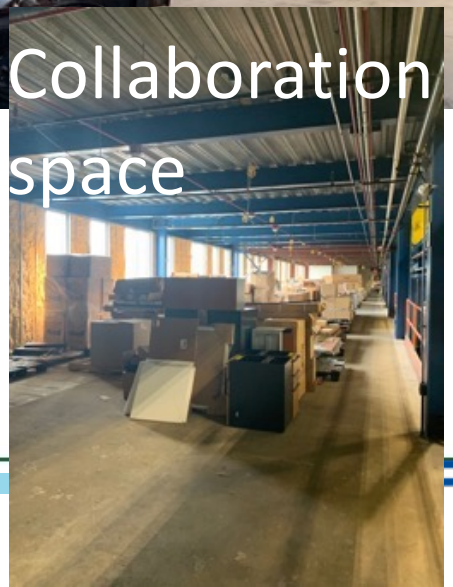
## Details

- New SQMS hires have started populating the new SQMS space in IARC
- This is already accelerating the productivity towards the standup of the SQMS testbeds and facilities in HAB
- FNAL FESS has been working now for few months with a Chicago architectural firm and the SQMS team to finalize the design of the new 30 offices in ICBA
- $3.5M Project funded based on lab commitment of internal overhead funds
- Additional 30 offices will be ready in December-March timeframe
- New: issue with ICBA project, concerns raised from DOE site office on use of overhead funds: substantial problem for SQMS office and lab space

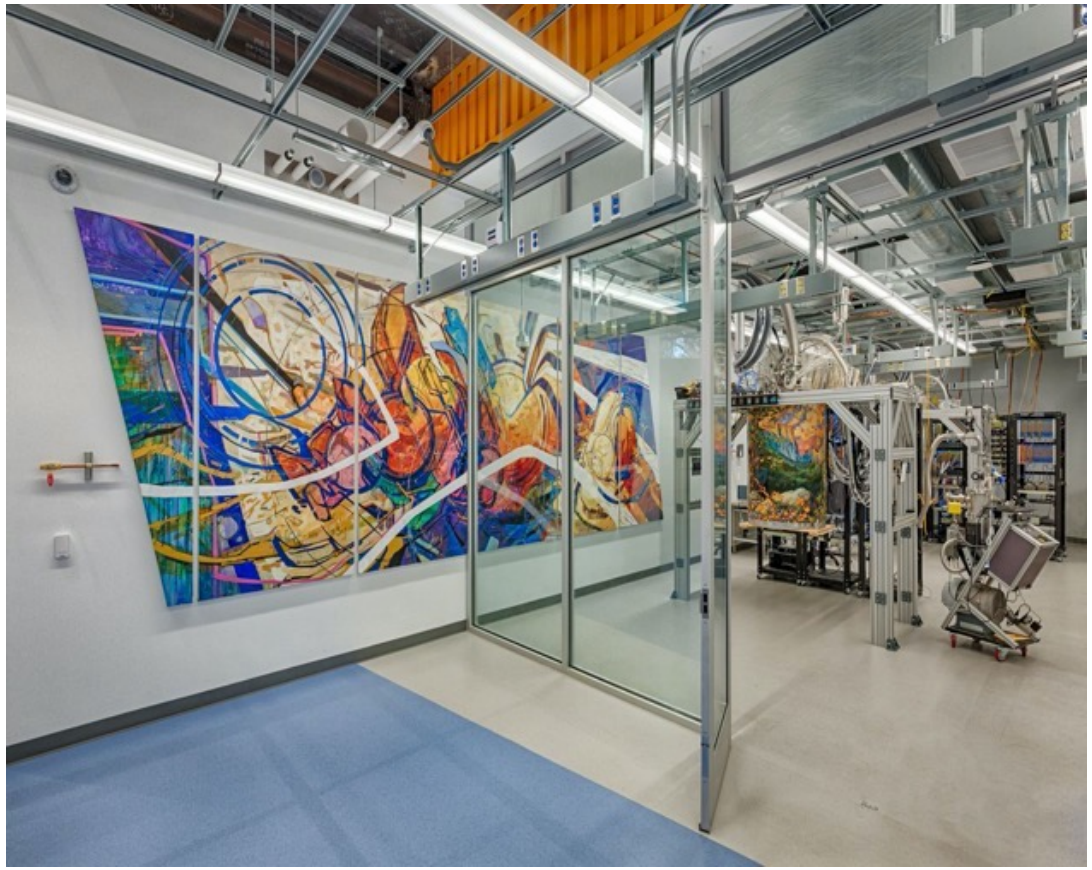
# Conventional Facilities needs to host the SQMS testbeds/foundries

**IARC/HAB space available to SQMS but needs to be finished/outfitted to be ready to receive equipment; vision is to design collaboration space around the facilities for industry, academic partners and users → funding strategy TBD, working on design with FESS**





# Wall Street Journal recent article on similar plans @Google



Google's new Quantum AI campus in Santa Barbara County, Calif., includes a quantum-data center, research labs and chip-fabrication facilities spanning several buildings. Source: Wall Street Journal
https://www.wsj.com/articles/google-aims-for-commercial-grade-quantum-computer-by-2029-11621359156

# SQMS Center Spotlight on Operations Progress

| Partner | Letter Contract | 5 Year Contract | Direct Funded or IAA | Year 1 funding in place |
|---|---|---|---|---|
| Northwestern | Awaiting signature | In Progress | | |
| Rigetti | | In Discussion | | |
| Temple University | | | | |
| Lockheed Martin | | In Progress | | |
| UIUC | | | | |
| IIT | | | | |
| INFN | | | | |
| John Hopkins | | | | |
| NASA Ames | | | | |
| Ames Lab | | | | |
| NIST | | | | |
| | | | | |
| Complete | | | | |
| In Progress | | | | |
| Not Applicable | | | | |

Status of SQMS subcontracts

ATLASSIAN Confluence Jira

Project Management Tools being adopted by SQMS, upon suggestion of the ORNL QSC center

## Progress/Achievement in Management

**Excellent progress in center organizational and operational aspects**

## Significance and Impact

**Successful creation of the new SQMS center and Division reporting to FNAL Director. Progress towards placing subcontracts with some issues, standing up PM tools, and towards the SQMS governance documents**

## Details

- SQMS has developed a set of policies and procedures that will govern Center operations: Joining SQMS, Member Access, Diversity, Inclusivity, Equality, and Code of Conduct, Export Control, Foreign Visitor Policy, Nondisclosure and Intellectual Property, Publications, Press Releases, Funding, Reporting, Safety, Property Management, Committees and Boards
- Standing up Confluence/Jira for SQMS, was successfully used at ORNL/QSC and on Exascale Project – proof of use in similar environment, ability for simplified data entry by PI and various ways to display status. System should be fully operational in approximately 3 months
- Subcontracts moving, main issue currently with determination of type of Rigetti subcontract. Including signed IPMP/NDAs, we are incorporating latest DOE Orders

# SQMS new collaboration opportunities

- Keysight – controls for qubits and 3D QC – only partially in scope
- Amazon AWS – unfunded, scope under discussion
- Rutgers University (S. Chakram) – move scope from FNAL
- University of Wisconsin Madison (R. McDermott) - unfunded
- Universita' di Pisa – unfunded, could be workforce development
- CINECA and CNR (Italy) - unfunded
- TRIUMF – unfunded, jointly applying for beamtime at betaNMR
- Jefferson Lab - applied for NP Quantum Horizon FOA
- University of Waterloo, Center for QC – applied for NP FOA
- Zurich Instrument
- Oxford Instruments
- JP Morgan Chase

# QIS Ecosystem Goals & Progress

# SQMS Center Spotlight on Workforce Development Progress

Training a new generation of quantum diverse talent. Pictured students and fellows are involved in SQMS work at NU and FNAL

## Progress/Achievement in QIS Ecosystem Stewardship

**The SQMS summer undergrad internship program has been launched in April 2021**

## Significance and Impact

**The new SQMS undergraduate summer internship is one of the key component of our workforce development program, aiming at attracting and training the new generation of diverse quantum workforce**

## Details

- **SQMS Undergraduate internship**
  - 15 students accepted: https://internships.fnal.gov/sqms-quantum-undergraduate-internship/ , Program dates: May 31 - August 31, 2021
  - More than 50% accepted students are women and URMS
  - 15 undergraduate/grad students with co-supervisors from two different SQMS partner institutions, to boost inter-center collaboration
  - The students will spend periods of research at FNAL and other SQMS partner institutions, based on the task assignment
  - Program advertised via FNAL Quantum Webinar Series to reach candidates from the National Society of Black Physicists, the National GEM Consortium, and HBCUs

# SQMS Center Spotlight on Workforce Development Progress

Caption: Carolyn Beatrice Parker is the first African-American woman known to have earned a postgraduate degree in physics.

## Progress/Achievement in QIS Ecosystem Stewardship

**The SQMS Parker Postdoctoral Fellowship has been launched in April 2021**

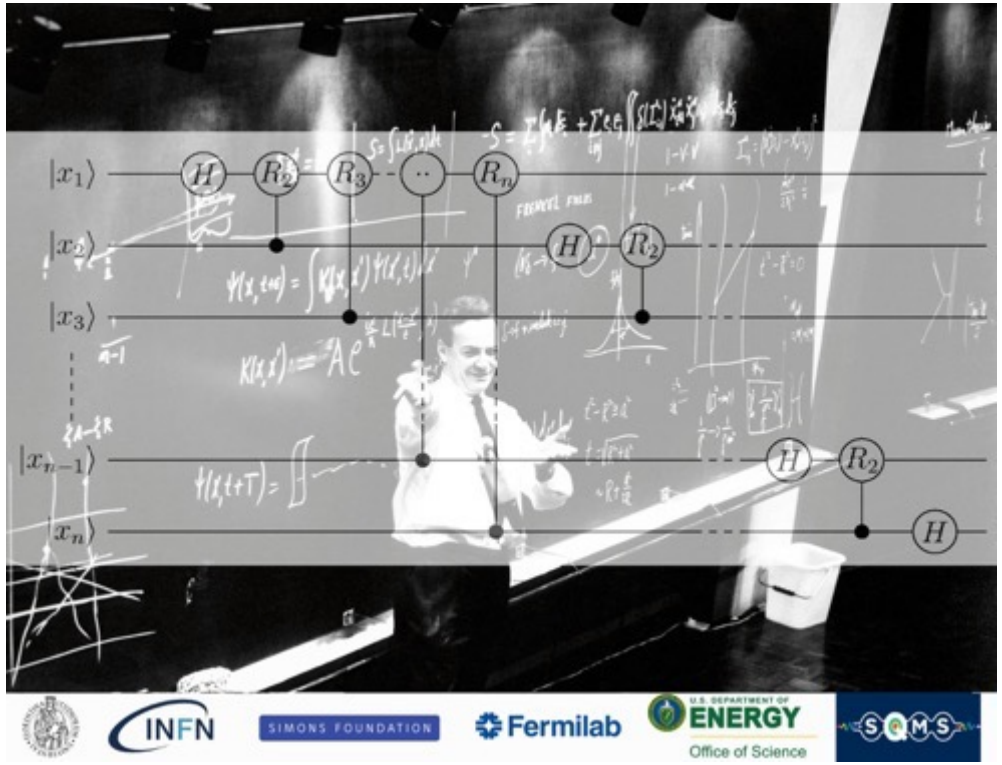
## Significance and Impact

**The new SQMS Parker Postdoctoral Fellowship is one of the key components of our workforce development program, aiming at attracting and training the new generation of diverse quantum workforce**

## Details

- **SQMS Parker Fellowship**
  - Program details available at:
  - https://www.fnal.gov/pub/forphysicists/fellowships/carolyn_parker/index.html
  - Prioritizes the representation and inclusion of historically and contemporarily minoritized individuals underrepresented in STEM
  - One Fellowship will be awarded annually, 3 years postdoctoral appointment
  - Applications will be open in May
  - A center-wide committee has been established
  - To enrich the research experience and enhance scientific collaboration the selected Fellow will spend periods of time conducting research with SQMS partner institutions and organizations

# SQMS Center Spotlight on Workforce Development Progress




Webpage of the GGI summer school on quantum in collaboration with SQMS

## Progress/Achievement in QIS Ecosystem Stewardship

**The Quantum Summer School has been launched – SQMS in collaboration with the INFN Galileo Galilei Institute in Florence, Italy**

## Significance and Impact

**The GGI-SQMS summer school is one of the key components of our workforce development program, aiming at attracting and training the new generation of diverse quantum workforce**

## Details

**GGI-SQMS Summer school:** https://www.ggi.infn.it/showevent.pl?id=402

- The program includes basic concepts in circuit quantum electrodynamics, quantum controls and metrology, along with quantum sensing at the precision frontier.
- Applications closed, program dates: Jun 21 – Jul 02, 2021
- World expert in quantum as lecturers: Alexandre Blais, Caterina Braggio, Elisa Ercolessi, Peter Graham, Jens Koch, Hanhee Paik,
- SQMS Cross-Center organizing committee: Caterina Braggio, Laura Cardani, Roni Harnik, Yonatan Kahn, Raffaele Tripiccione, Paola Verrucchi, Silvia Zorzetti

# Science and Technology Highlights

# Products

- 1 PRL published, 5 papers submitted and on arXiv
- More than 30 papers in preparation for submission
- More than 40 invited talks presented
- Dozens of interviews and articles on major newspapers, scientific magazines, newsletters etc
- Publication policy/procedure still under development

PHYSICAL REVIEW LETTERS **126,** 110402 (2021)

**Four Postulates of Quantum Mechanics Are Three**

Gabriele Carcassi,[1] Lorenzo Maccone,[2] and Christine A. Aidala[1]
[1]*Physics Department, University of Michigan, 450 Church Street, Ann Arbor, Michigan 48109-1040, USA*
[2]*Dip. Fisica and INFN Sez. Pavia, University of Pavia, via Bassi 6, I-27100 Pavia, Italy*

(Received 3 September 2020; revised 2 December 2020; accepted 21 January 2021; published 16 March 2021)

The tensor product postulate of quantum mechanics states that the Hilbert space of a composite system is the tensor product of the components' Hilbert spaces. All current formalizations of quantum mechanics that do not contain this postulate contain some equivalent postulate or assumption (sometimes hidden). Here we give a natural definition of a composite system as a set containing the component systems and show how one can logically derive the tensor product rule from the state postulate and from the measurement postulate. In other words, our Letter reduces by one the number of postulates necessary to quantum mechanics.

DOI: 10.1103/PhysRevLett.126.110402

FERMILAB-PUB-20-256-
November 5, 20

**Axion Searches with Two Superconducting Radio-frequency Cavities**

arXiv:2011.01350v2 [hep-ph] 4 Nov 2020

**Christina Gao*, Roni Harnik†**

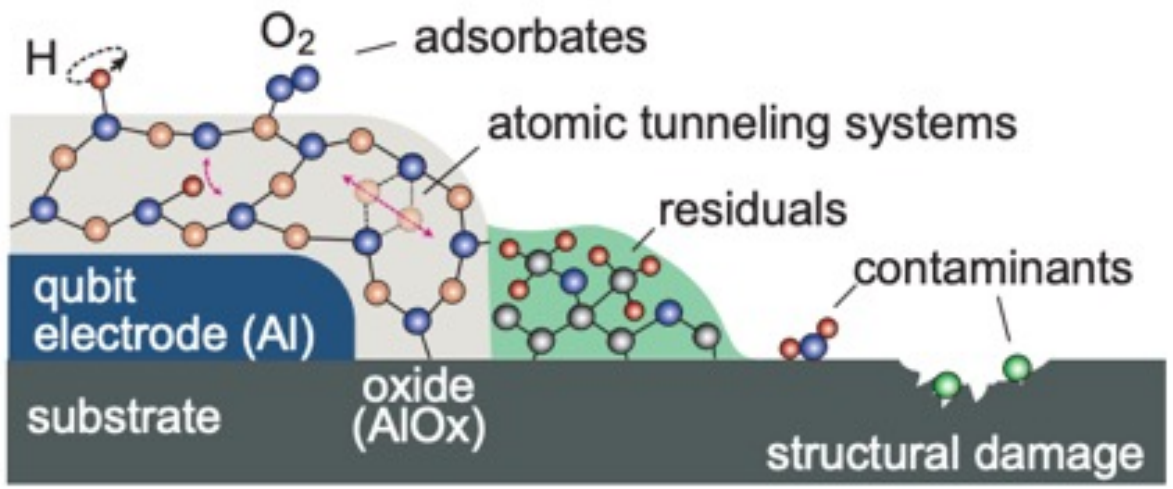
*Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, IL, 6051 USA*

**Abstract**

We propose an experimental setup to search for Axion-like particles (ALPs) using two superconducting radio-frequency cavities. In this light-shining-through-wall setup the axion is sourced by two modes with large fields and nonzero $\vec{E}\cdot\vec{B}$ in an emitter cavity. In a nearby identical cavity only one of these modes, the spectator, is populated while the other is a quiet signal mode. Axions can up-convert off the spectator mode into signal photons. We discuss the physics reach of this setup finding potential to explore new ALP parameter space. Enhanced sensitivity can be achieved if high-level modes can be used, thanks to improved phase matching between the excited modes and the generated axion field. We also discuss the potential leakage noise effects and their mitigation, which is aided by $\mathcal{O}$(GHz) separation between the spectator and signal frequencies.

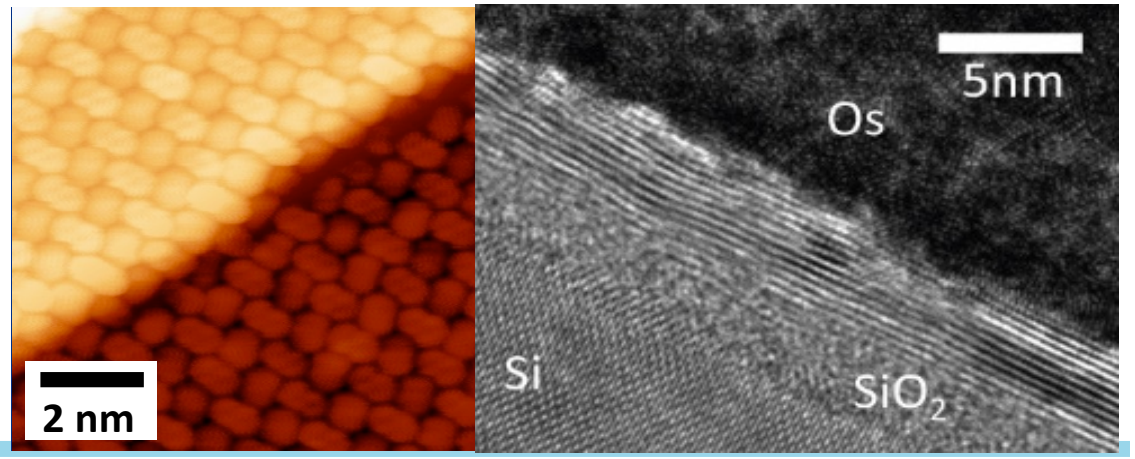
# Backup

# Material science studies of Rigetti's 2D qubits at the forefront of coherence



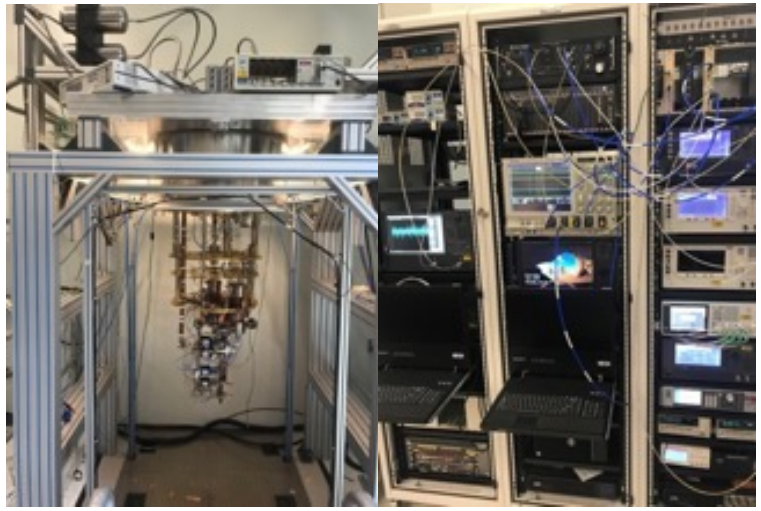

Qubits and processors fabrication

Material Science studies to understand and mitigate qubit decoherence

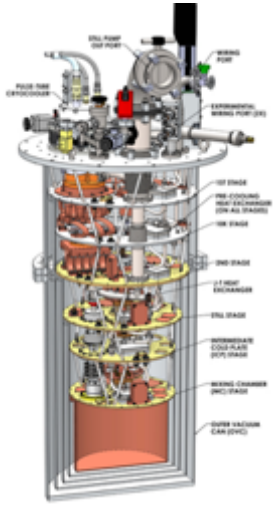


# First Systematic Cross-institutional benchmarking study of qubit performance

## Fermilab

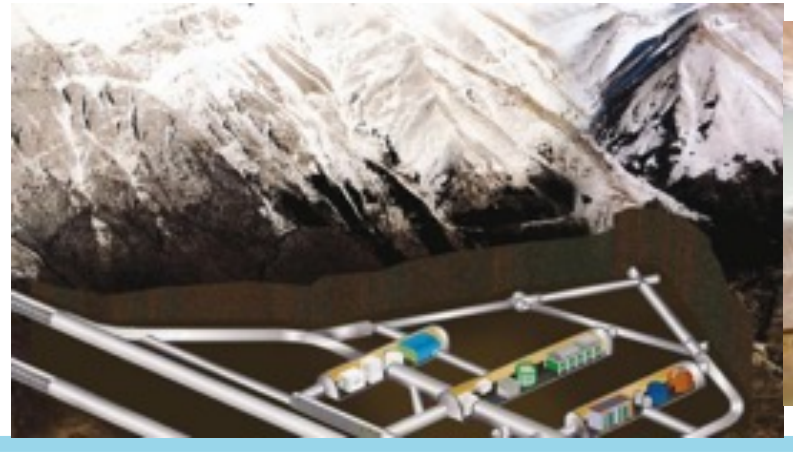


## Rigetti



## NIST

## INFN/Gran Sasso



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

**Novel QPU architectures**

- Long coherence allows going from qubit to "qudit" approach

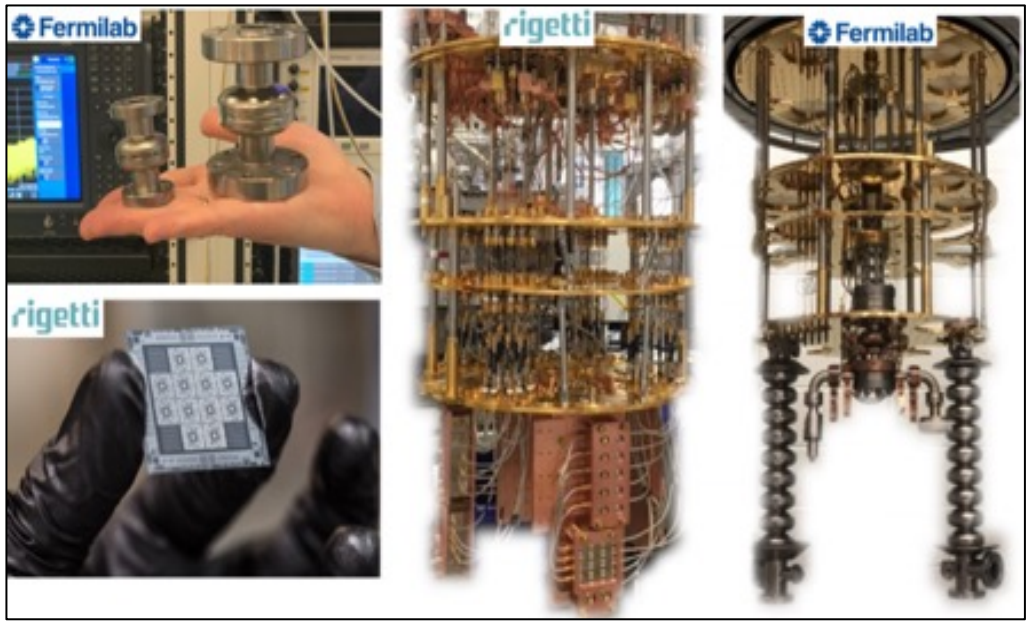
**Scalability**

- > 100 qubits with just few input/output lines

**Science**

- Long coherence and all-to-all connectivity offer new computation/simulation capabilities
- Probing microscopic to macroscopic boundary
- Searching for dark sector particles

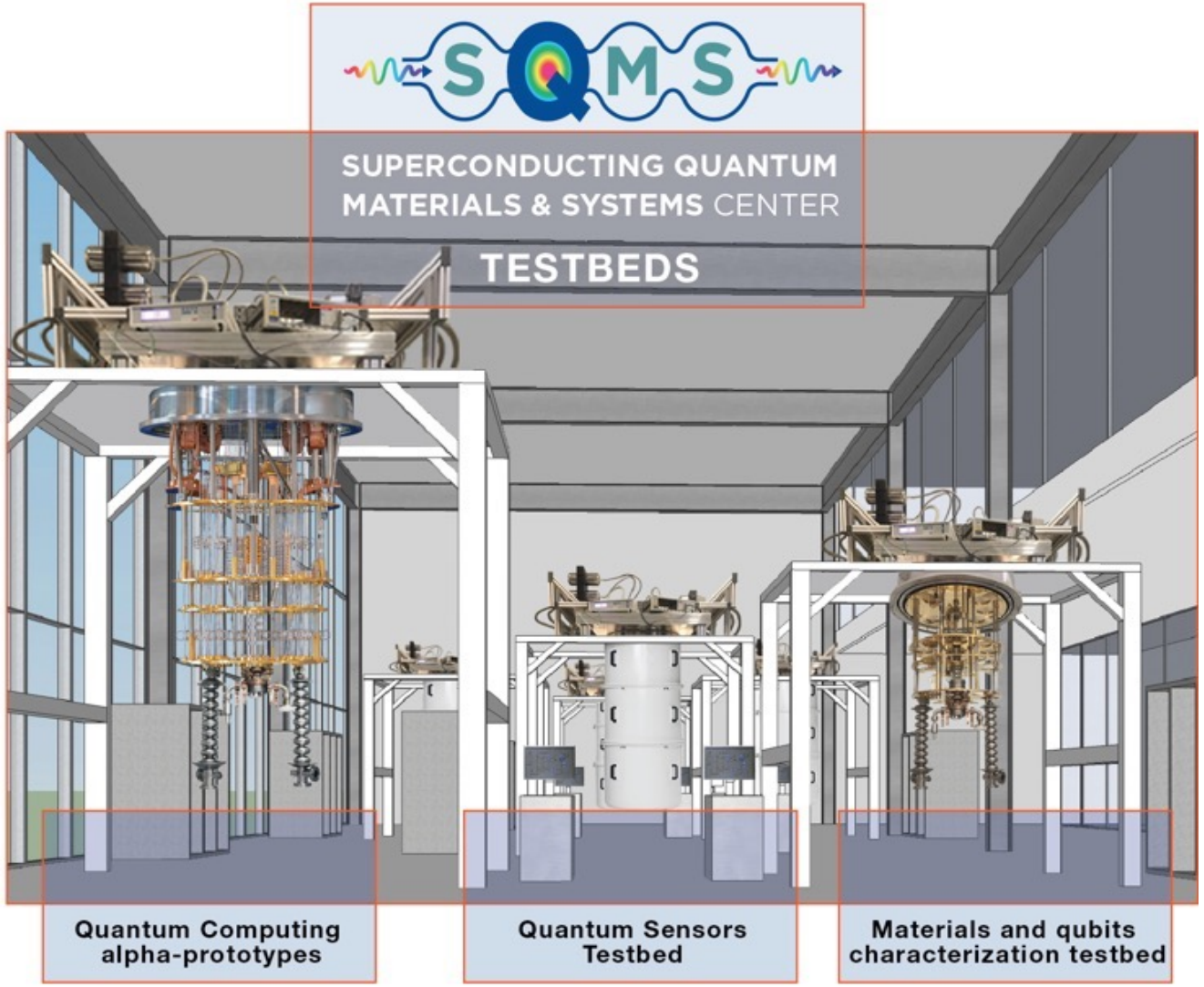
**ONE** nine cell SRF cavity + **ONE** transmon = **SQMS 100+** qubits processor



# SQMS five years vision

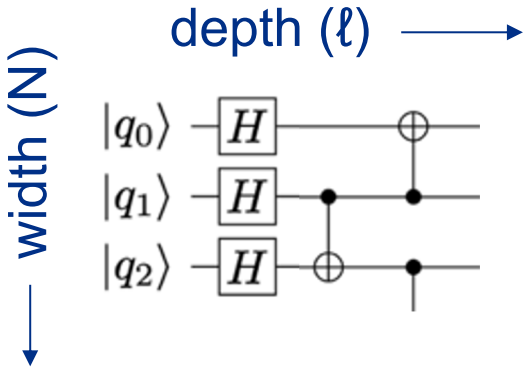
Developing and delivering unique platforms/facilities for QIS fabrication, computing and sensing which will be available to boost the national QIS ecosystem:

- Qubits measurements in the most sensitive environments
- Platforms enabling new particle searches/sensing experiments
- Computing/simulations on the FNAL 3D-based quantum computer



# SQMS Quantum Computing Roadmap

Quantum algorithms:




Ultimate limits to depth:

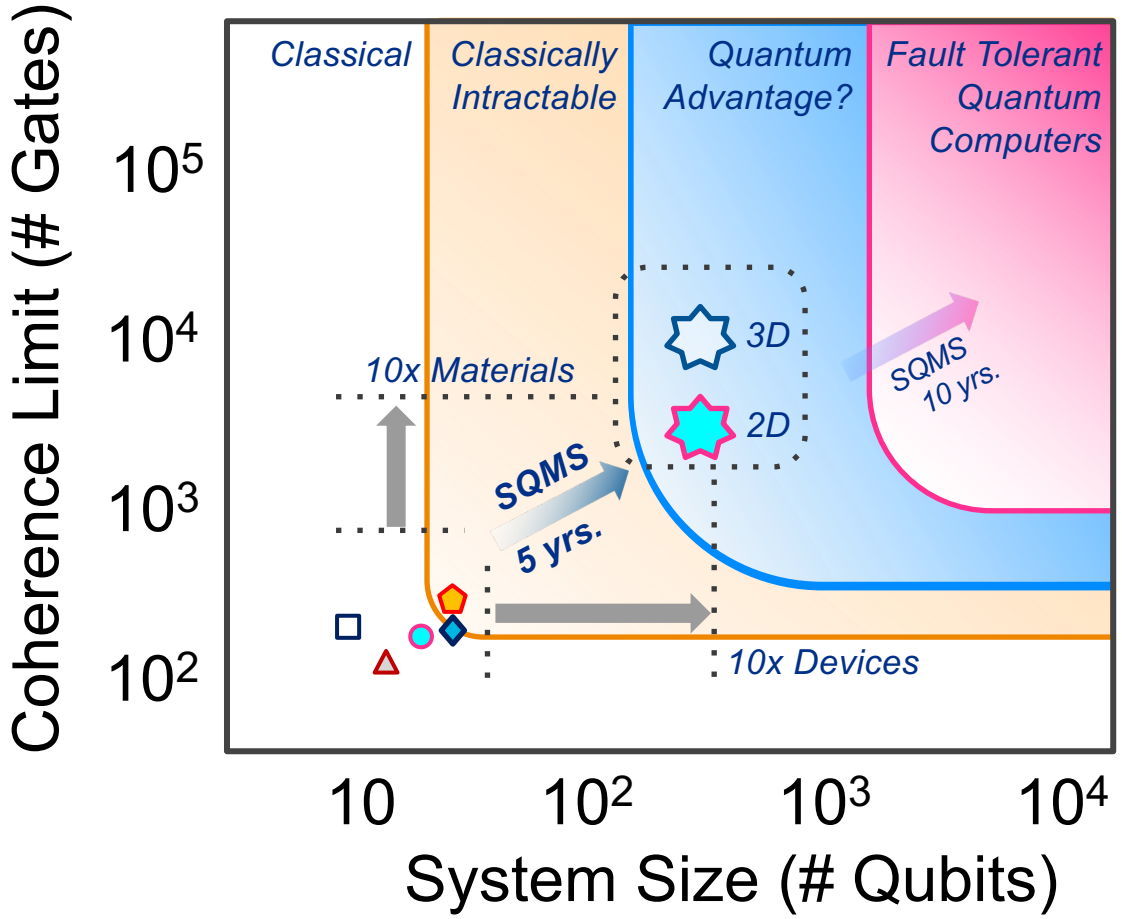
$\max(\ell) \propto T_1 / t_{gate}$

For SC qubits, typical:

$t_{gate}$ = [20-1000] ns

$\max(N^*\ell) \sim 10^4$

## Superconducting Qubits




SQMS Consequences:

- SQMS-3D
- SQMS-2D

Leading US testbeds:

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