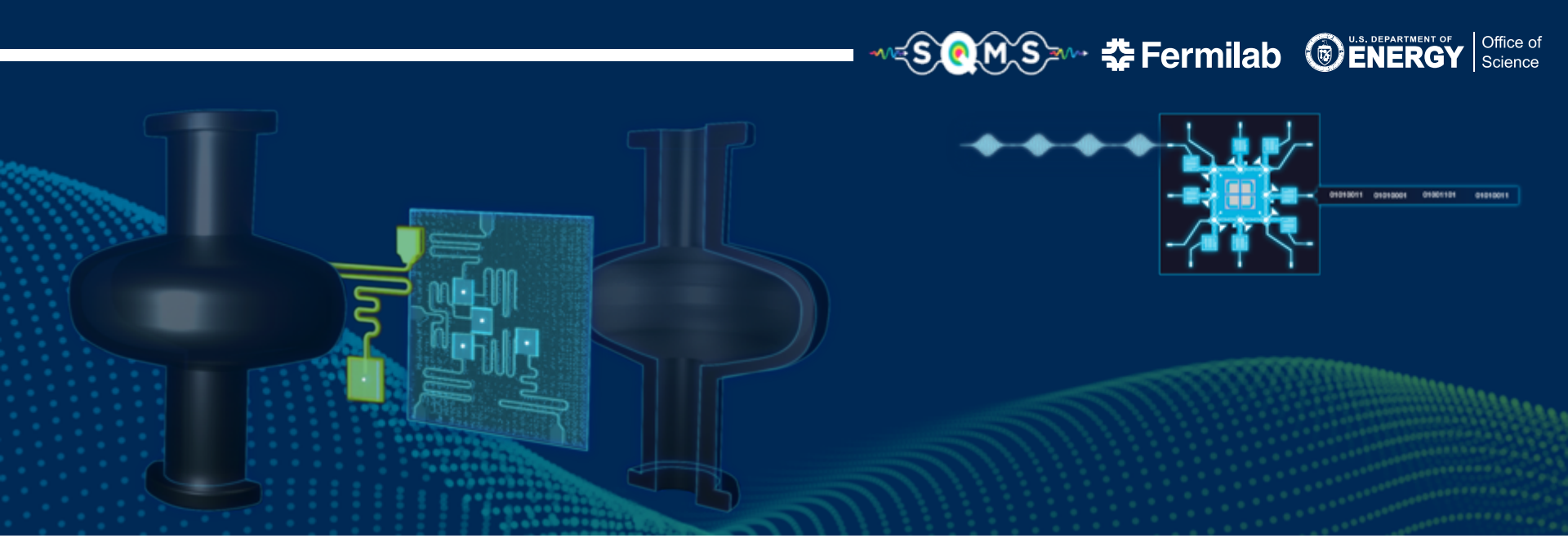


Status of the SQMS Center led by Fermilab

Fermilab PAC Meeting, December 7th 2020

Anna Grassellino

SQMS Director and Deputy Director

National Quantum Initiative

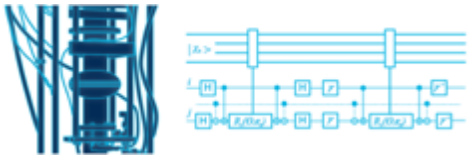
In 2019 Congress mandated the creation of five Dept. of Energy national quantum centers ($625M over five years)

Develop quantum computers, quantum sensors, and quantum communications

Goal is transformational advances in quantum science and technology

Create a quantum economy

Anna Grassellino - SQMS



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

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

SQMS Collaboration and Mission

SUPERCONDUCTING QUANTUM
MATERIALS & SYSTEMS CENTER

August 2020: Fermilab is awarded one of the five National Centers

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 the **major cross-cutting challenge** of understanding and eliminating the decoherence mechanisms in superconducting 2D and 3D devices, with the final goal of enabling construction and deployment of superior quantum systems for **computing and sensing**.”

Fermilab

NASA Ames Research Center

Northwestern University

ARIZONA

rigetti

LOCKHEED MARTIN

INFN Istituto Nazionale di Fisica Nucleare

JANIS

ILLINOIS INSTITUTE OF TECHNOLOGY

AMES LABORATORY Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY

COLORADO SCHOOL OF MINES

JOHNS HOPKINS UNIVERSITY

NIST

Goldman Sachs

SQMS

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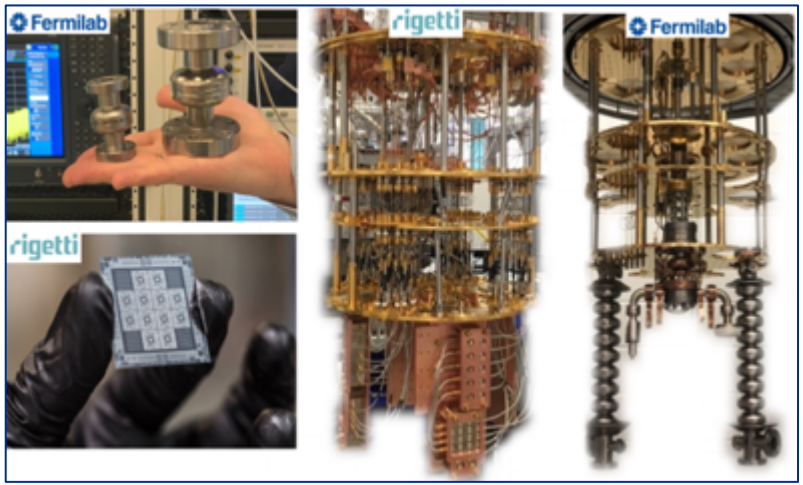
SQMS key expertise towards QIS revolutionary goals

Industry use cases

Radio frequency superconductivity

Condensed Matter Physics



Material Science

Particle Physics

Cryogenics

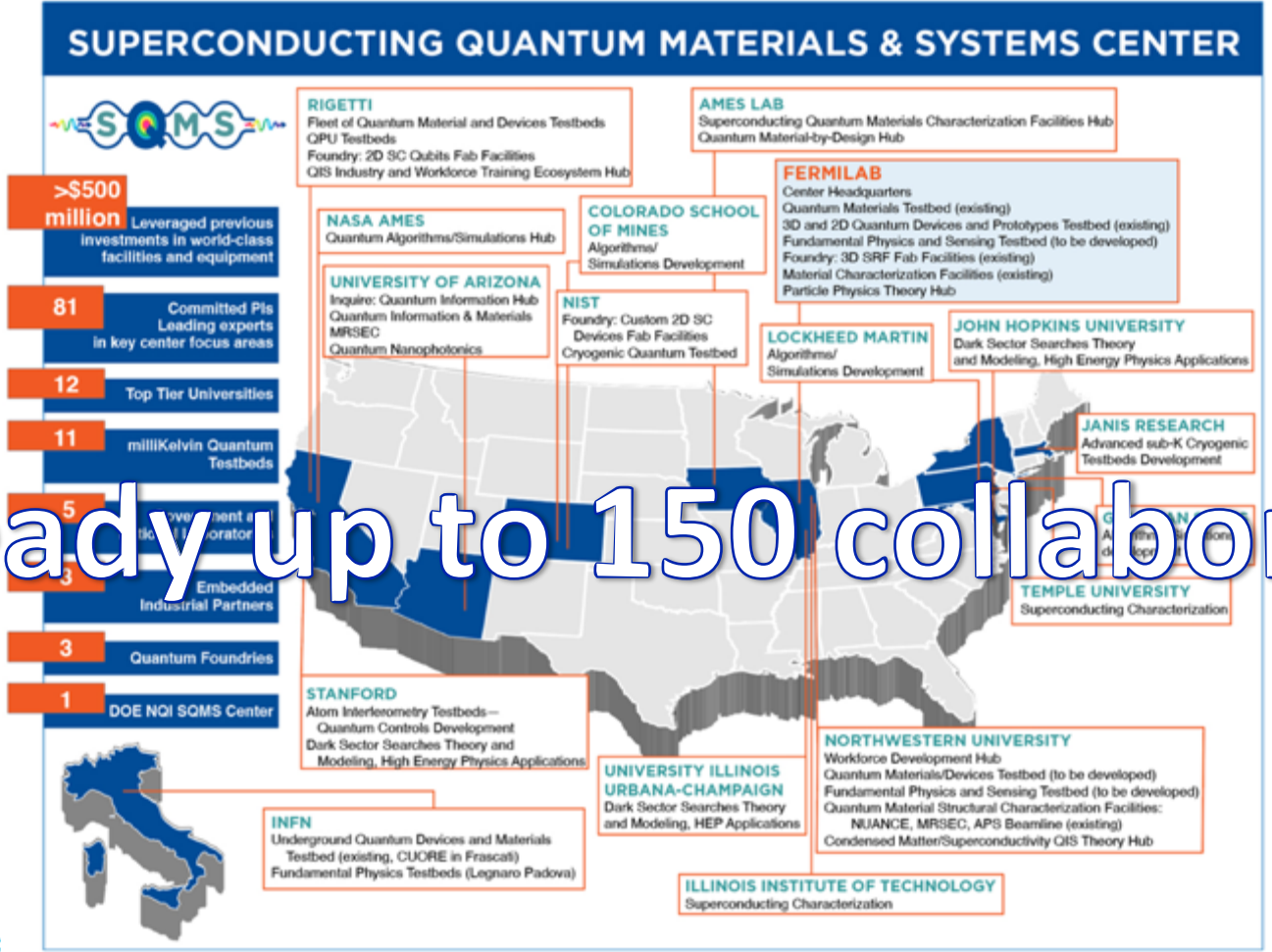
Computational Science

Scale up and integration

Controls and electronics

Superconducting qubits

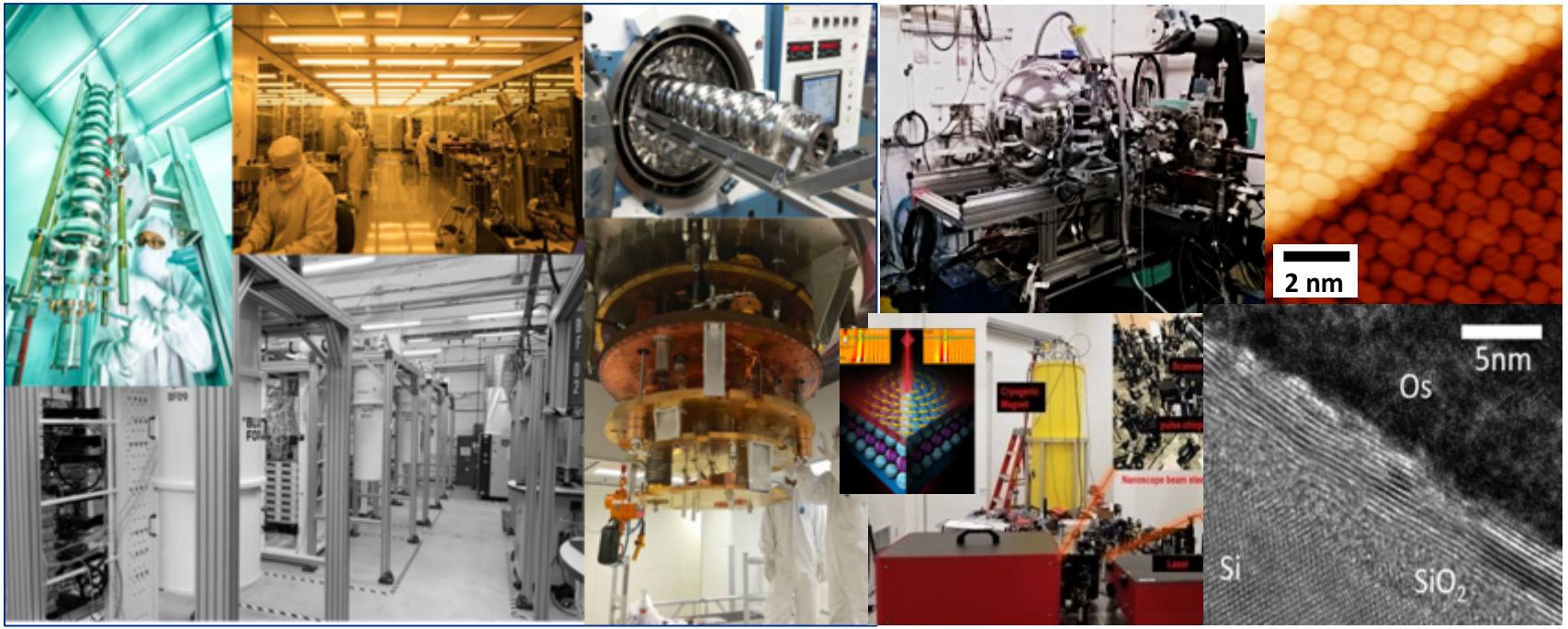
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



Already up to 150 collaborators

SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

SQMS leverages unique national facilities



From world unique superconducting 2D and 3D foundries, to material science and superconducting characterization tools, to milliKelvin testbeds, which will be taken beyond the state of the art with SQMS investments

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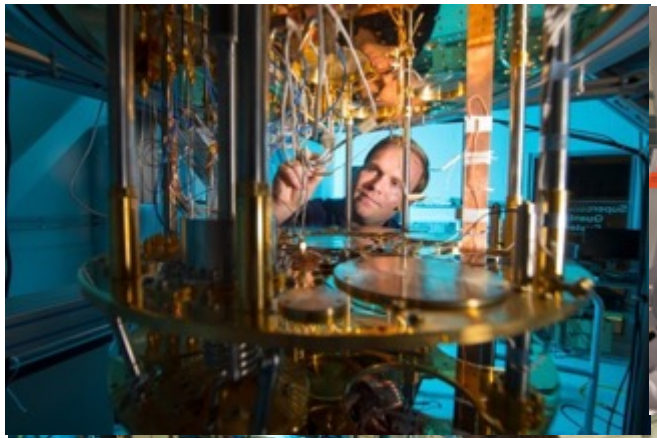
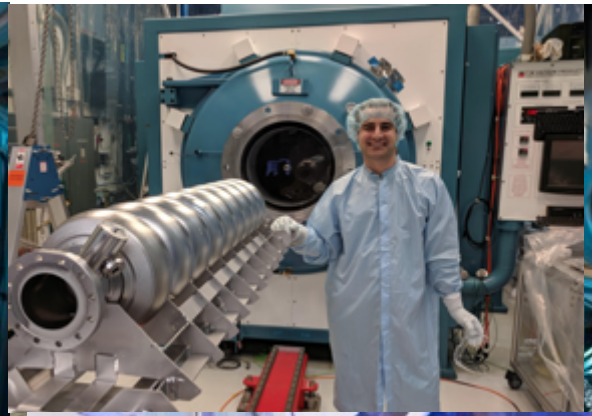
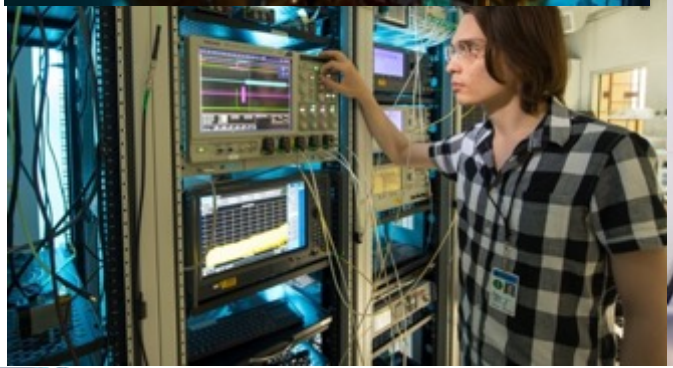
Example of Fermilab facilities

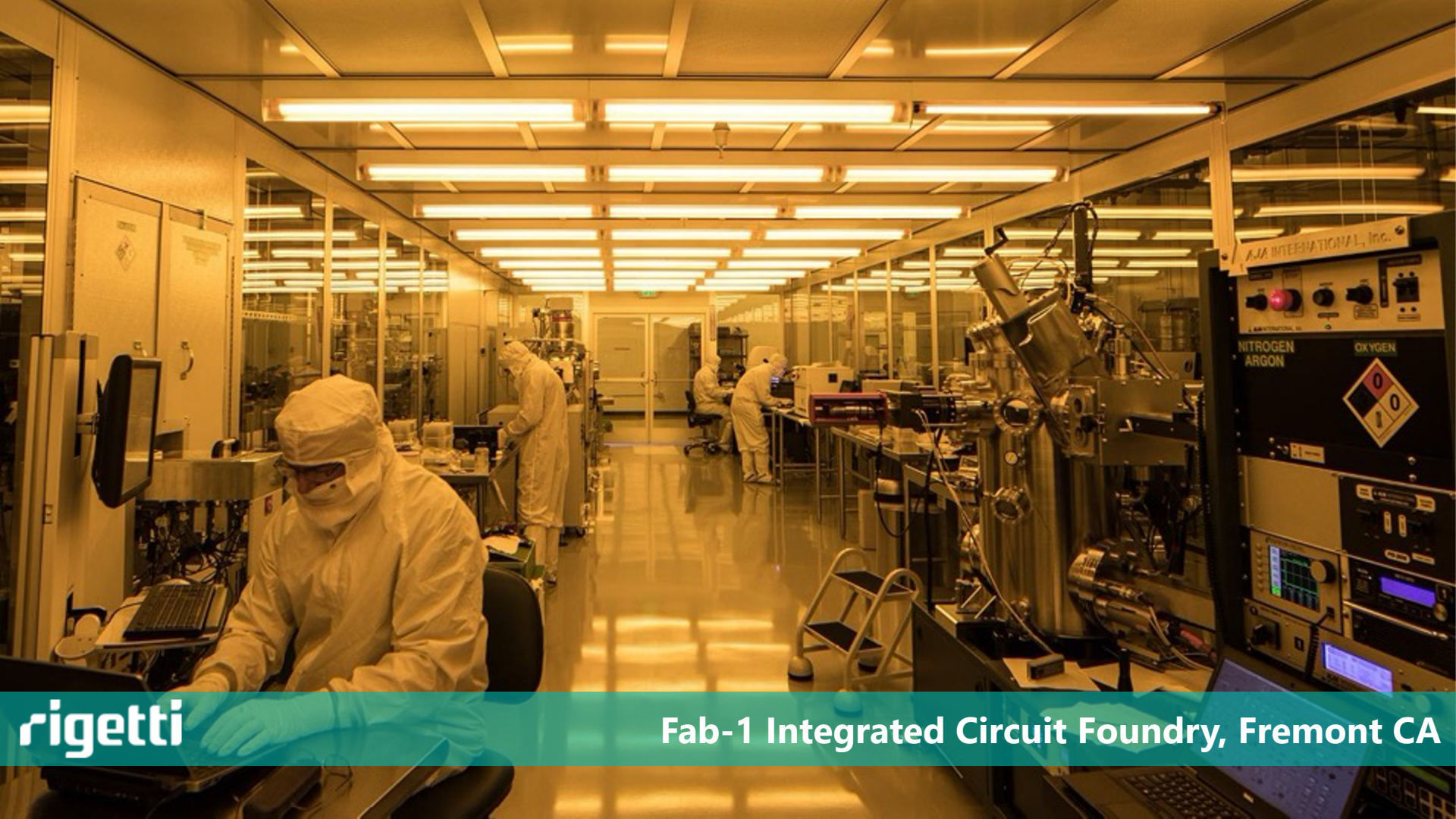
DOE HEP QuantiSED, GARD and BES investments




Bluefors Dilution refrigerators, full multi-qubit measurements capabilities, new material deposition furnaces and plasma systems

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



rigetti

Fab-1 Integrated Circuit Foundry, Fremont CA

The road to SQMS main goals

- We have given ourselves the concrete and focused goal of delivering tangible unique QIS platforms
  - **Quantum Computing and Sensing Prototypes of unprecedented capabilities and reach for science and industry applications**
- The path to these concrete goals can be put on a timeline, thanks to relative level of maturity of the QIS technological platforms we have chosen
- It will require all the strengths of our multidisciplinary collaboration working in **co-design**
- Still, the road will be rich of new unexpected findings and failures, which should not discourage us but force us to think, learn and choose new routes
- Ultimately, surprising intermediate results may very well be the main discoveries produced by the SQMS collaboration

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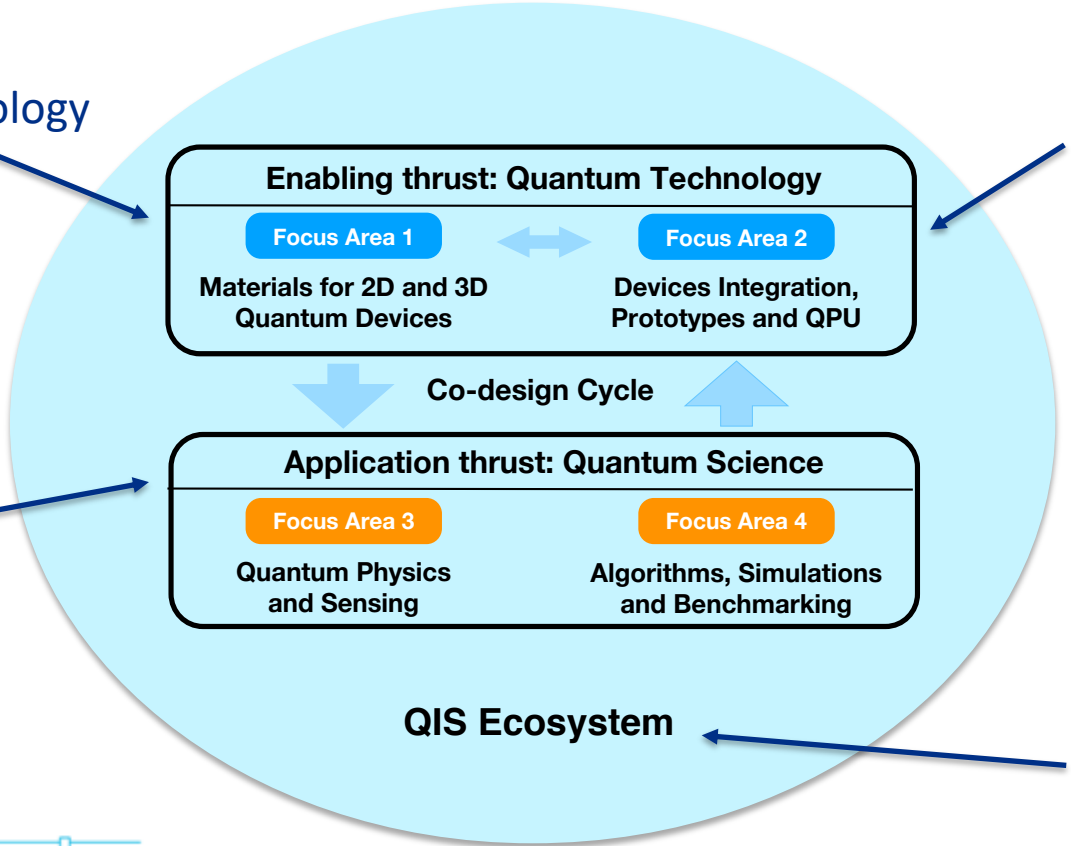
SQMS Center Thrusts and Focus Areas

Qubit Technology

Scale up capabilities and plans



Science Applications drivers

Ecosystem plans

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Appendix 13 Project Timetable

- The SQMS Project timetable (extracts below) provides specific milestones and deliverables associated with the different Center activities for near, intermediate and long-term goals
- Some activities are higher risk than others, and several risk mitigation strategies have been embedded in the Center plan in the form of parallel R&D routes

Focus Area	Major Activity	Deliverables and Benchmarks	Center Year				
			1	2	3	4	5
Materials for 2D and 3D Quantum Devices	(1) Infrastructure & Testbeds *Impacts:(2),(3),(4),(5),*	Infrastructure upgrades to enable low (T~1.5K) and ultralow (T<=100mK) temperature characterization stations at partner institutions **Risk mitigation: risk reduction via creation of additional testing bandwidth to evaluate new ideas*	■				
		SRF cavity-based testbed available for characterizing dielectrics in quantum regime at Fermilab	■	■	■	■	■
		SRF cavity-based testbed available for characterizing dielectrics in the quantum regime at Northwestern and NIST/UColorado		■	■	■	■
	(2) Advanced Materials Studies *Impacts:(4),(5)* *Drives: (1)*	Initial exploration of dominant quasiparticle sources including underground measurements (INFN) of the 2D Rigetti transmon **Risk mitigation: by testing the same devices in different testbeds by different experimenters, environments and techniques that maximize performance can be identified*	■	■			

Devices Integration, Prototypes and QPUs	(6) 3D QPU *Impacts: (15),(16),(17),(18)* *Drives: (2),(3),(4),(5)*	High coherence SRF cavity integration with high coherence transmon qubit demonstrating quantum operation	■				
		First 3D basic prototypes available on HEPCloud		■			
		SRF-Alpha is available on HEPCloud **Risk mitigation: SRF-Alpha prototype lessons learned help inform SQMS-3D development*			■		
		Compare the cavity-transmon systems with different number of cells, select optimum number of levels to control in the cavity, number of cells **Risk mitigation: explore different cavity structures to optimize control and performance*			■		
		SQMS-3D construction begins				■	
		Deploy the SQMS-3D QPU with >200 effective all-to-all connected qubits					■
	(7) 2D QPU Development	Rigetti's Aspen backend QPU integrated into HEPCloud	■				

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SQMS technology goals

- World's longest coherence SRF cavities and Rigetti transmons will be for the first time integrated to make the best possible QPU building blocks
- Unprecedented scale materials science investigation for decoherence-causing defects understanding and mitigation
  - Unique, fast turn-around industry manufacturing capabilities, world's best material science facilities and superconductivity expertise
  - Study the parts of actual measured cavities and qubits
- Create National and International platforms for cross-checked measurements and qubit performance benchmarking
- Scale up to a quantum computer prototype

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

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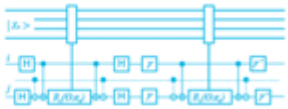
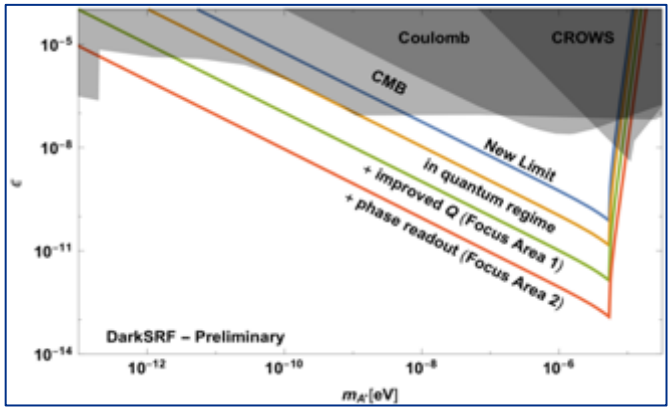
SQMS science goals

- World's best cavities and qubits will be employed in innovative new particle search schemes or particle properties measurements
  - Leading to transformational advances in sensitivity of several experiments
- Quantum computer prototypes taking advantage of extended coherence and all to all connectivity of 3D architectures, will enable new HEP and condensed matter simulations
- Exploration of macroscopic to microscopic boundary with creation of very large cat states in high Q SC cavities
- Physics of interfaces, fundamental material science and superconductivity advancements





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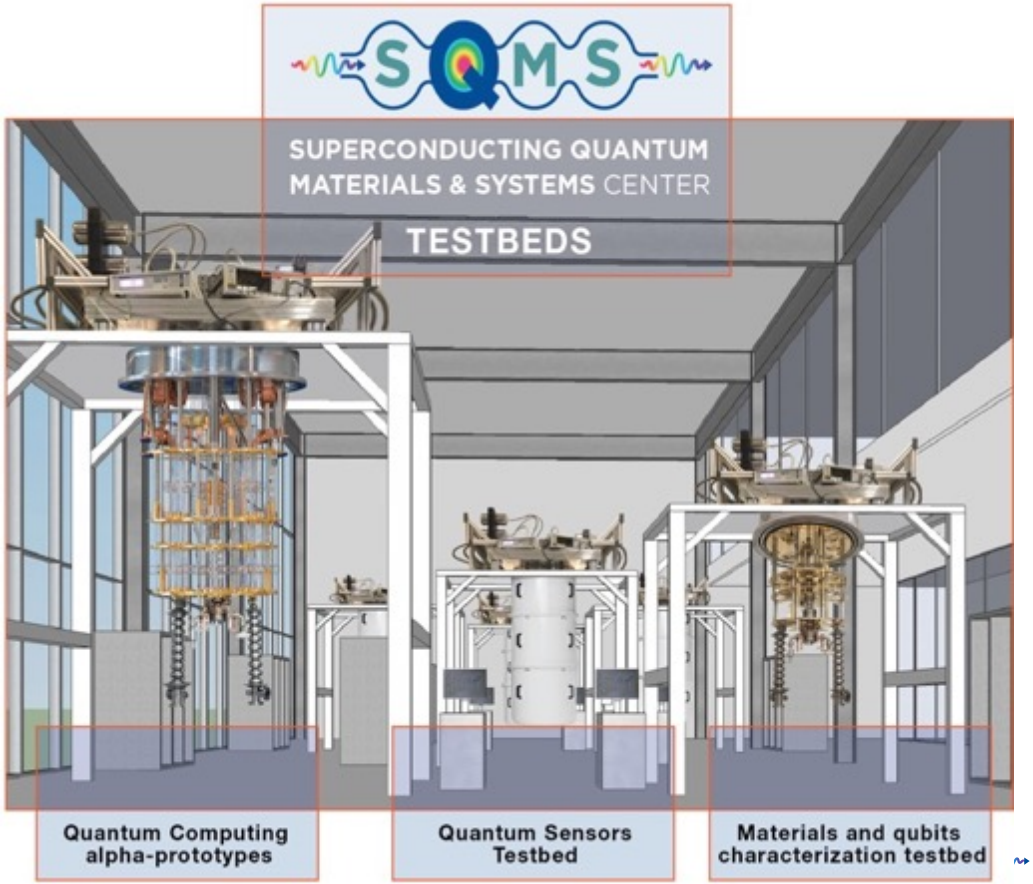
SQMS Five Year Vision – Unique QIS National Facilities

- New quantum computing, sensing and materials platforms allowing:
  - Qubits measurements in the most sensitive environments
  - New particle searches/sensing experiments
  - Computing/simulations on advanced quantum computer prototypes
  - Training the next generation of diverse quantum workforce



SQMS Year One Technical Goals and Ongoing Activities

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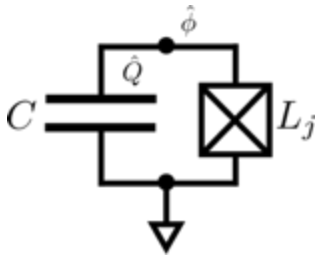
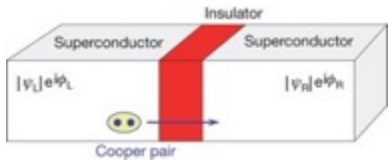
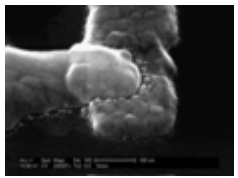
MATERIALS & SYSTEMS CENTER

Superconducting Qubits SQMS goals

1. LC circuit with Josephson junction







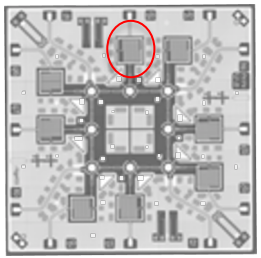
"Transmon" qubits

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

+

2. Resonators (cavities)

2D



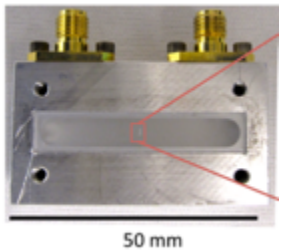
Rigetti 8-qubit processor

$Q \sim 10^5$

$T_{coherence} \sim 0.000001$ 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

$Q > 10^{10}$

$T_{coherence} > 1$ 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

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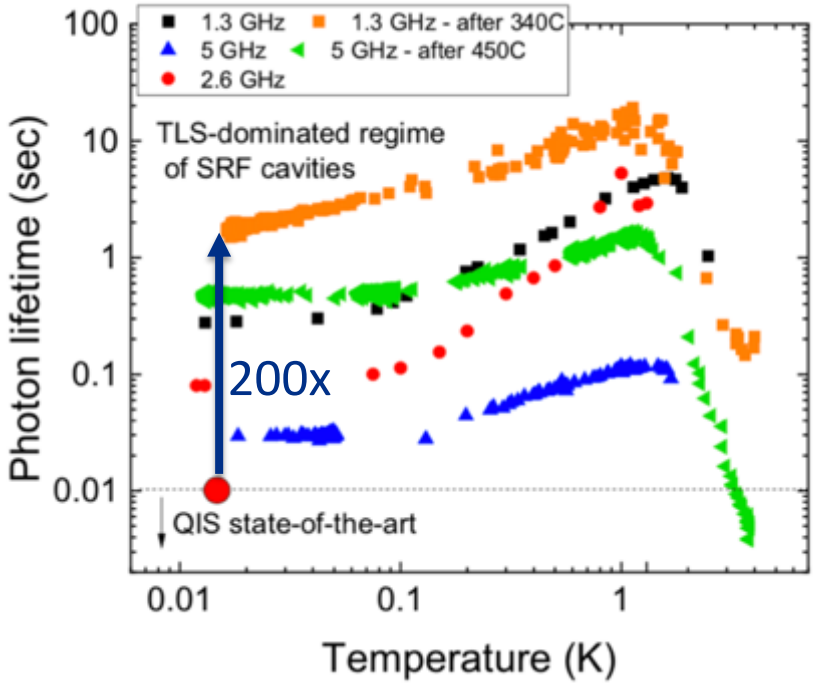
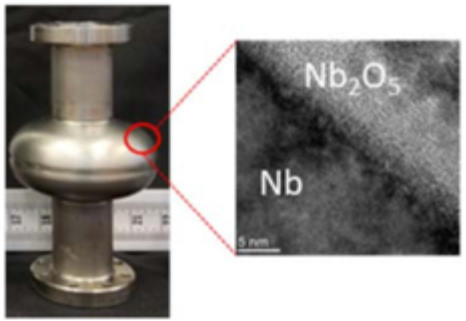
Fermilab SRF resonators in quantum regime for 3D: highest coherence quantum resonators ever demonstrated





- Results achieved with the powerful methodology of combining device fab and test with materials analysis, to advance technology by developing the fundamental understanding of device performance
- Enormous advantage starting point for SQMS

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

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First time integration of SRF cavities with Rigetti qubits

- First time integration of the Fermilab high Q SRF cavity with the Rigetti 2D transmon leads to integrated system photon lifetimes > 32 milliseconds
- Successful integration of the SRF cavity with transmon qubit without degrading the ultrahigh Q of the cavity is a **cornerstone** on the path to the high coherence QPU

Details

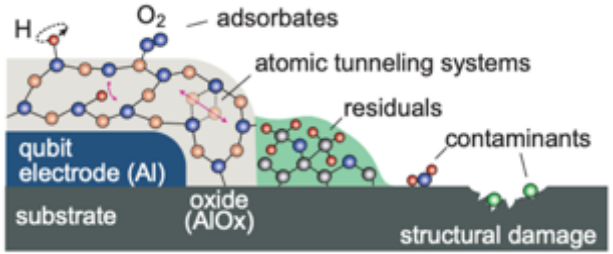
- *High coherence 3D SRF cavities with photon lifetimes of >100 ms used for integration*
- Fermilab redesigned transmon was manufactured by Rigetti and used for integration
- Integrated system achieved tau > 32 ms photon lifetime

Rigetti Transmon at the silicon rod to be integrated with the Fermilab SRF niobium cavity

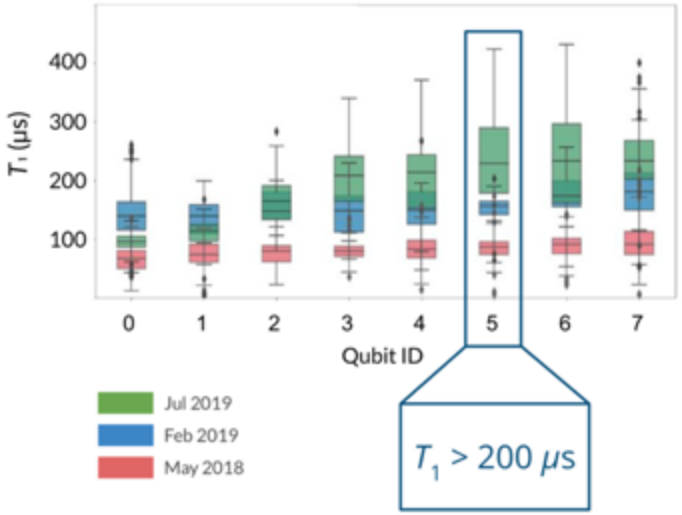
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

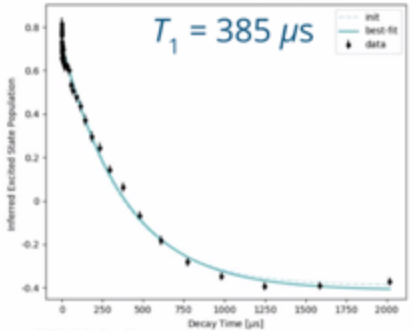
Rigetti's 2D qubits at the forefront of coherence: materials studies

Both individual qubits and full processor chips foundry



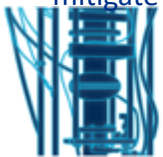
Material Science studies to understand and mitigate qubit decoherence





Continuous improvement in relaxation times

- For 3D architecture we will be able to 'cherry pick' best qubits for integration
- To fully advance also 2D, hundreds of state-of-the-art qubits with measured coherences will be used for studies via material and surface science techniques to understand origins of decoherence and spread
- Enabled by the unique BES and other material science facilities, plus some investments in upgrading equipment to beyond state-of-the-art capabilities



SQMS
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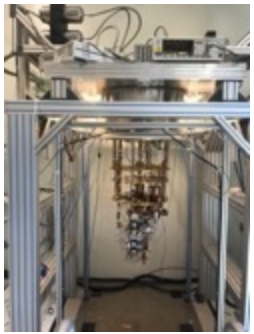
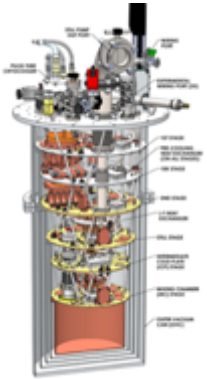
First Systematic Cross-institutional benchmarking study of qubit performance: “round robin” experiment

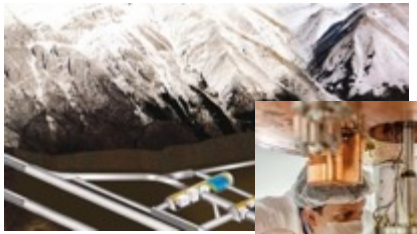
Fermilab



Rigetti



INFN/Gran Sasso



Northwestern

SQMS cryogenic testbed
To be established in Year 1

UColorado/NIST

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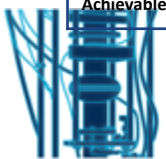
Scale up and integration plans

- One of our main goals is to go beyond proof of principle - single qubits level demonstrations, with the objective to build a **quantum computer prototype** with beyond state-of-the-art performance
  - DOE unique expertise and facilities for **building** large complex SRF and cryogenics systems plus industry scale up capabilities
  - Broad multidisciplinary collaboration covering all key aspects, working in co-design: e.g. Rigetti's routine expertise in building quantum computers (full stack), NASA Ames and NU QIS theory, DOE devices integration…
  - Unique cryogenics expertise and resources at FNAL with industry to build the world largest dilution fridge with the goal to host very large number of qubits

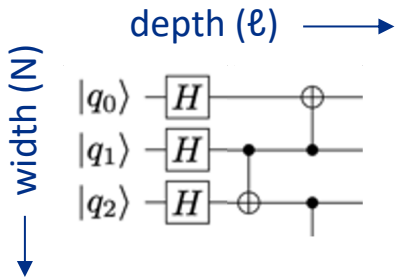
Processor Metrics	Leading Systems	Center Prototypes (3 yr)		Center Device Goals (5 yr)	
		2D-Alpha (estimate)	SRF-Alpha (estimate)	SQMS-2D (estimate)	SQMS-3D (estimate)
Number of qubits	53	128	>100	256	>200
Connectivity graph (qubit:neighbors)	1:4	1:3	1:10	1:3	1:200
Qubit T_1 lifetime, us (median)	70	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



SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Quantum Computing SQMS Roadmap

Quantum algorithms:



Ultimate limits to depth:

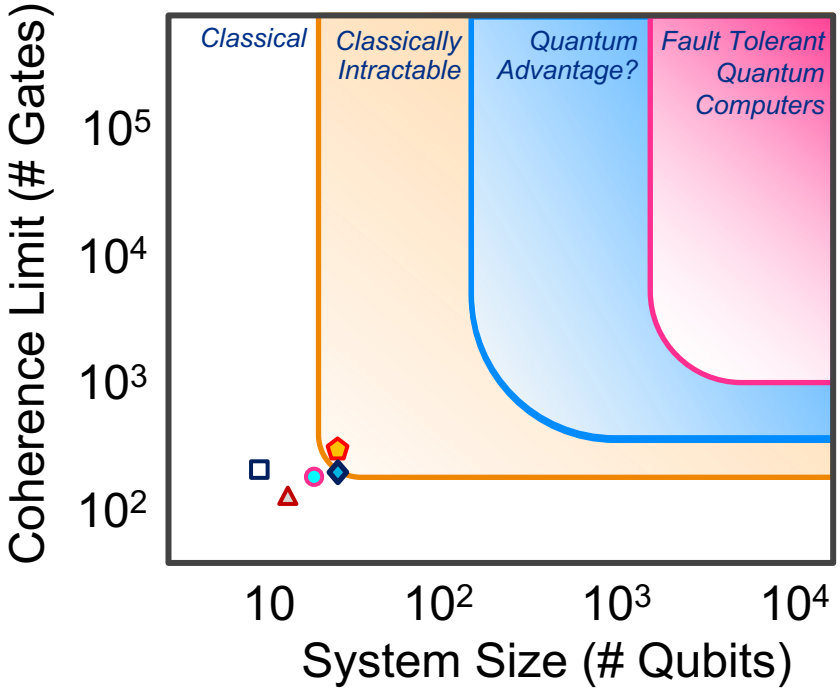
$\max(\ell) \propto T_1 / t_{gate}$

For SC qubits, typical:

t_{gate} = [20-1000] ns

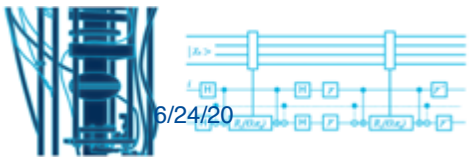
$\max(N*\ell) \sim 10^4$

Superconducting Qubits



Leading US testbeds:

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



SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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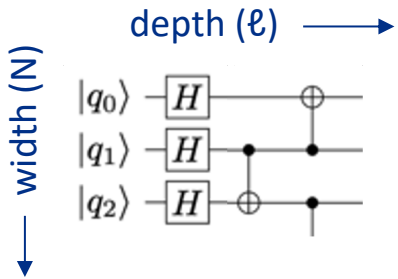

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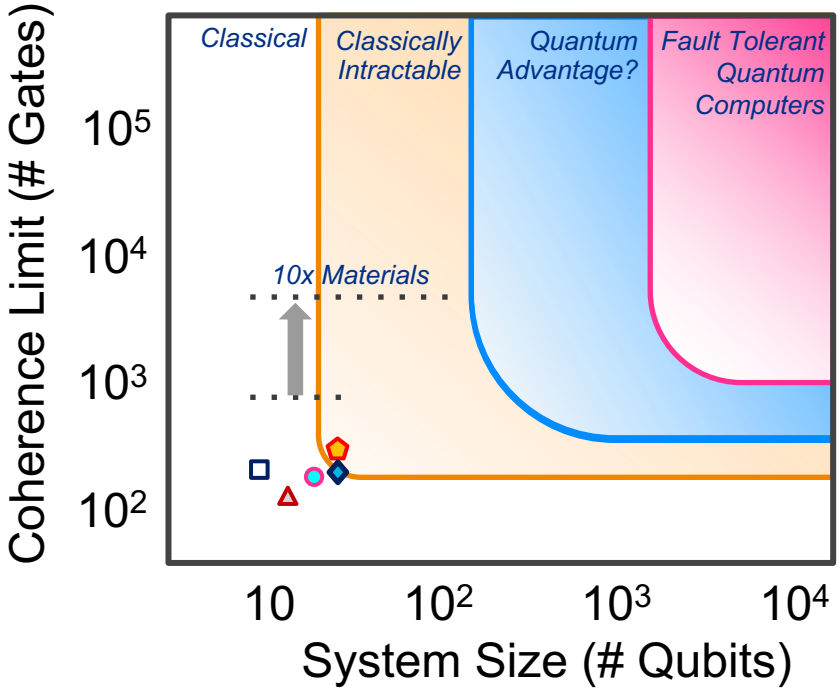

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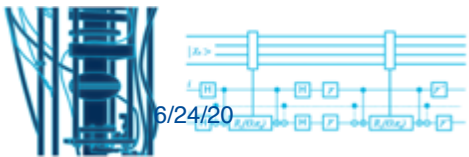

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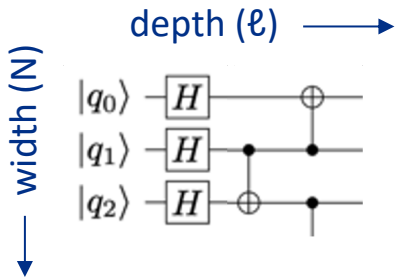
Quantum Computing SQMS Roadmap

Quantum algorithms:



Ultimate limits to depth:

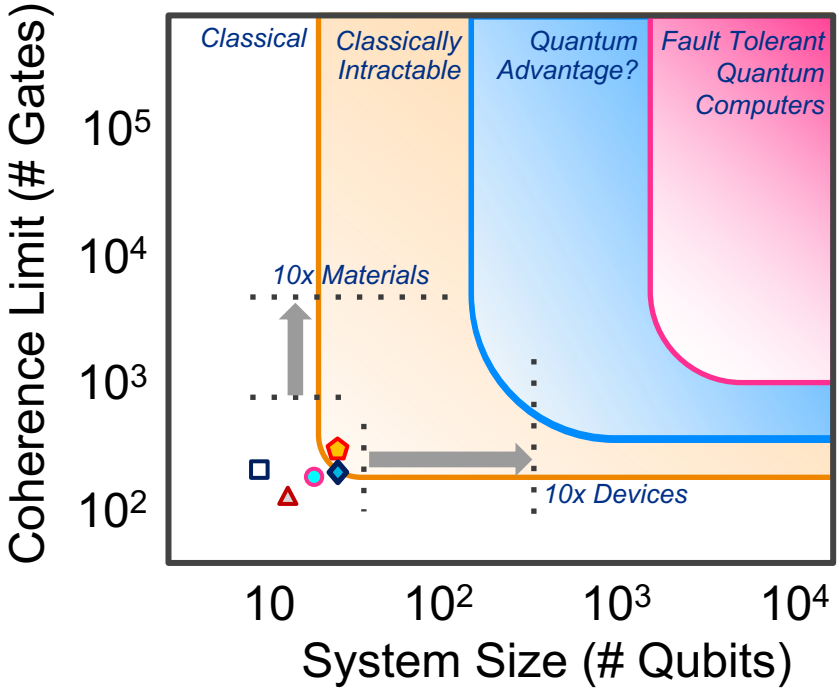
$\max(\ell) \propto T_1 / t_{gate}$

For SC qubits, typical:

t_{gate} = [20-1000] ns

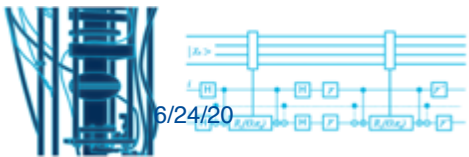
$\max(N*\ell) \sim 10^4$

Superconducting Qubits



Leading US testbeds:

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



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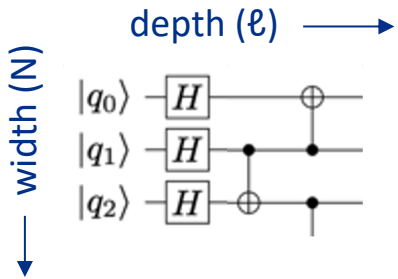

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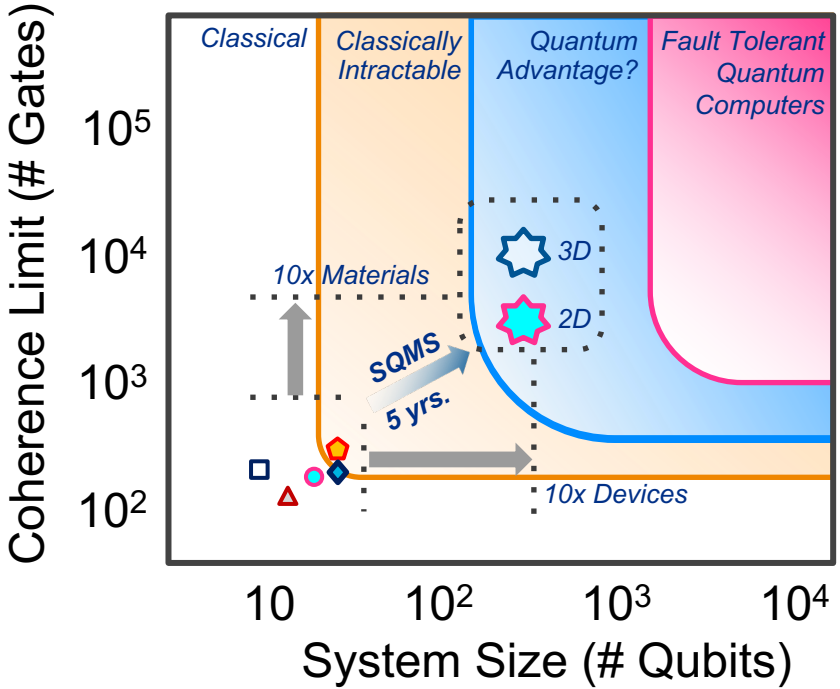

SQMS Consequences:

- SQMS-3D
- SQMS-2D

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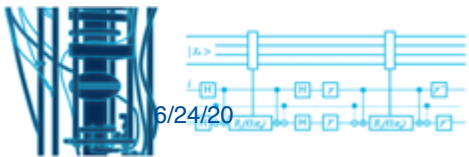

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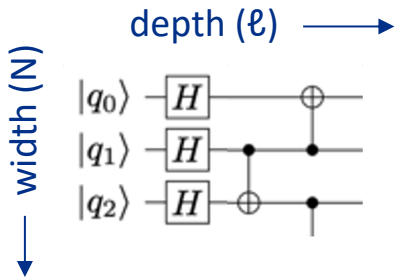

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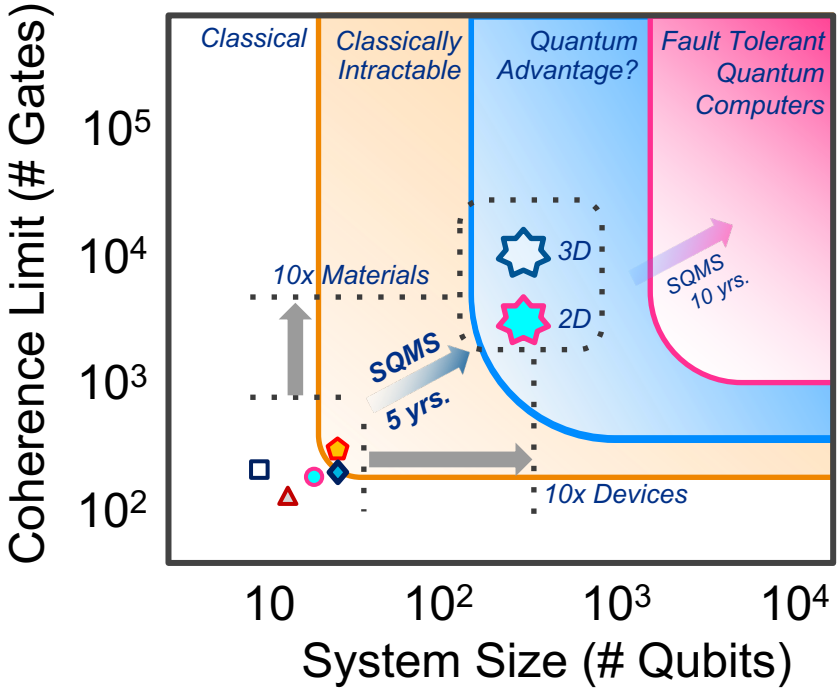

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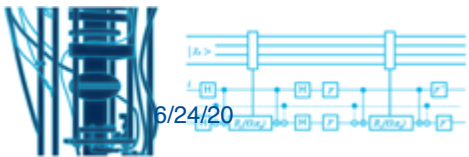

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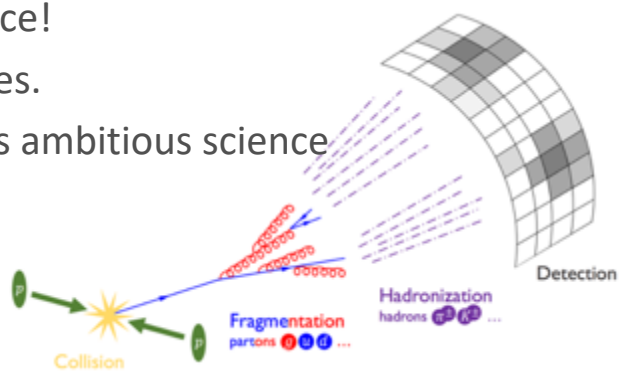
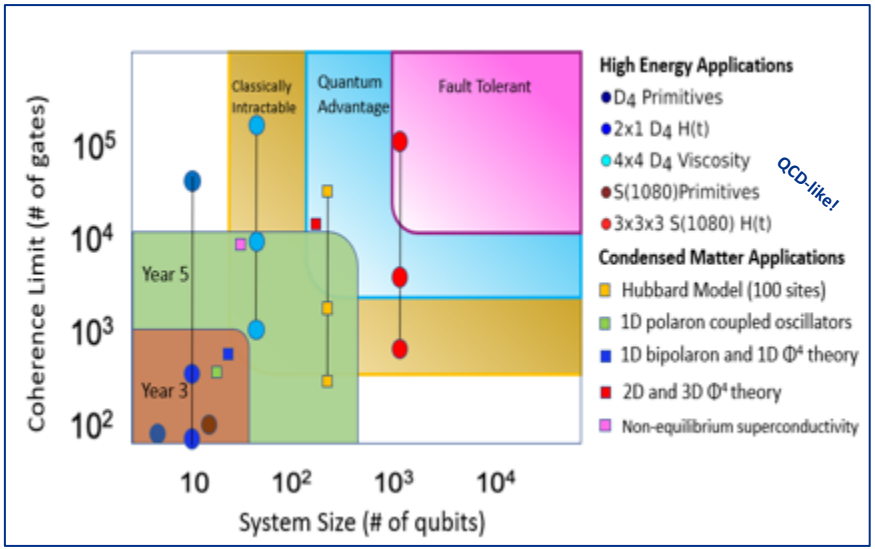
Science applications - Computing

- 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.

*e.g. Lamm et al, PRD **100**, 114501 (2019),*

Iadecola et al. PRB 98, 174201 (2018)





HEP:

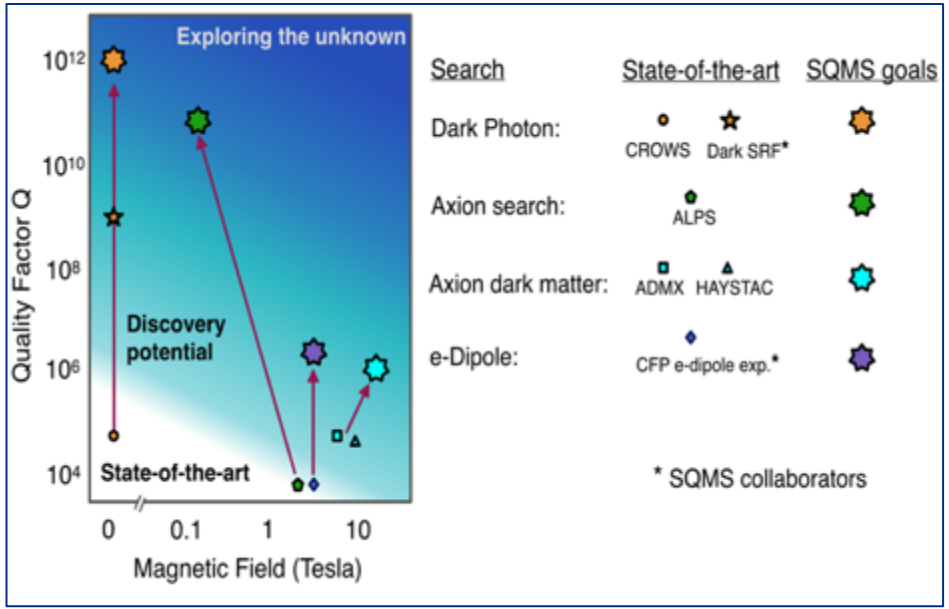
QCD dynamics: least understood parts of LHC collisions and early Universe (Hadronization, viscosity of gluon plasma).

Condensed matter:

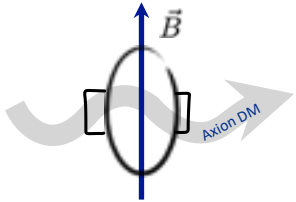
Many body states with high entanglement (aided by connectivity), many body localization. polaron system dynamics.

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!

Co-design work ongoing in quantum sensing

- Axion-like particle search: Several concepts proposed by SQMS physicists.

2 modes ··· Static B field – signal mode

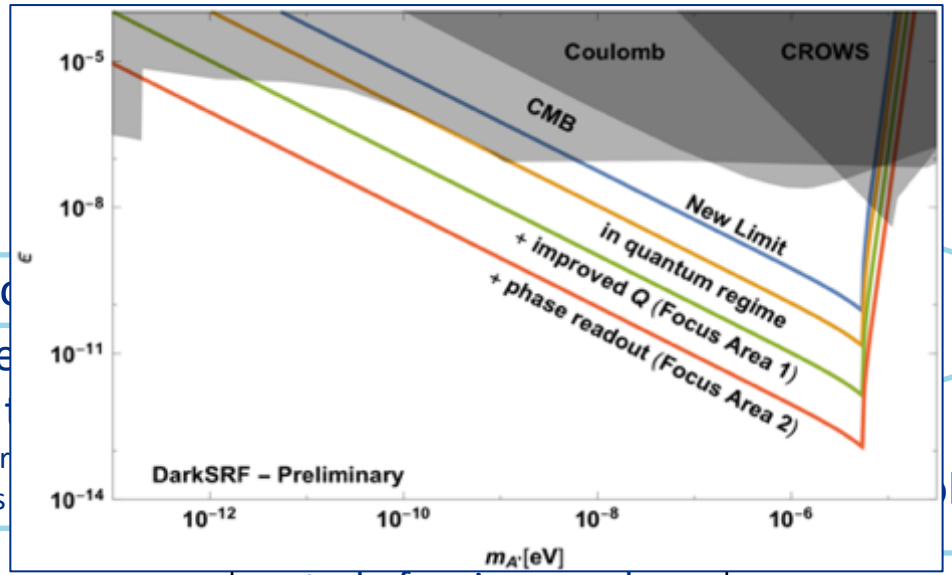
2 modes ··· spectator mode + signal mode

2 modes ···· signal mode

***JHU**: Rajendran et al Phys.Rev.D 100 (2019)*

***FNAL**:* Harnik and Gao (in prep)

***UIUC**: Kahn et al. Phys. Rev. Lett.* 123 (2019)



Proto

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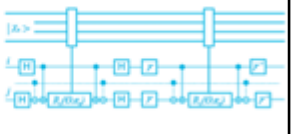

control of various modes are pushed to improve, QIS for computing will benefit

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Ecosystem Thrust Overview

Connecting the SQMS's work to advancing national goals

Task Force

Workforce Development

- Supporting your work
  - Partnerships for complementary expertise
  - Pilot programs that leverage our test beds & infrastructure
- Transitioning your work into practice
  - Knowledge and technology transfer
  - Creating economic and security value
- Industry readiness
  - Workforce development
  - Enabling technologies industrial base

Economic Competitiveness

Security

Sustained Leadership in QIS

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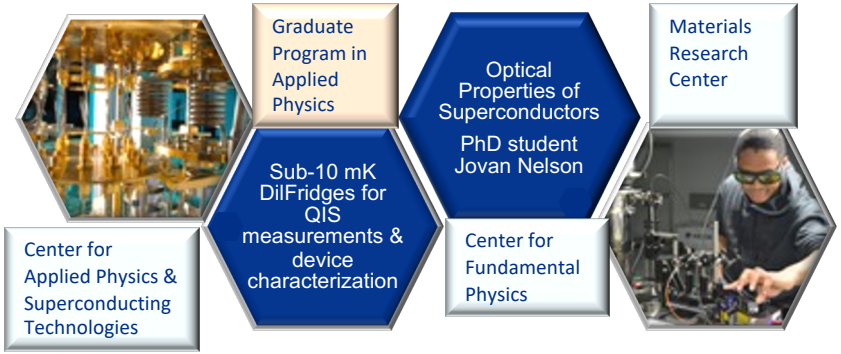
SQMS Educational initiatives and QIS workforce development

Michelle Driscoll - SQMS workforce development lead, Northwestern

Jens Koch – director of graduate studies in Applied Physics, Northwestern

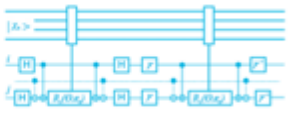
Training a workforce of quantum scientists, engineers & technicians



- Cross-disciplinary Education, Training, & Recruitment
- Center-wide Graduate & Postdoctoral Fellowships
- Women for the Quantum Workforce
- Undergraduate Internship Programs
- QIS Curricular Development – BS, MS, PhD
- Summer Schools -

QIS Curriculum developed/selected by WDC

- Existing ULT & New facilities for QIS testbed will support research in QIS measurements, materials & device characterization
- Training a new workforce of quantum scientists, engineers and technicians
- Hands-on access to device testing and fabrication
- Enhanced undergraduate & PhD QIS education & training – upgraded laboratories



Jim Sauls

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SQMS Management Highlights and Progress

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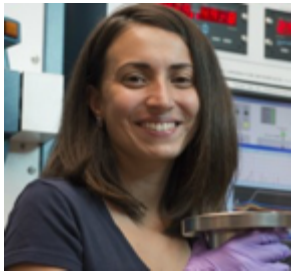
SQMS Top Leadership



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

Dr Alexander Romanenko (FNAL)
Technology Thrust Leader

Dr Roni Harnik
(FNAL)
Science Thrust
Leader

Dr Mandy Birch
(Rigetti)
Ecosystem Leader

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SQMS Advisory Board

Prof. Maria Spiropulu (Caltech)

Prof. Hasan Padamsee (Cornell)

Dr. Alex King (Iowa State)

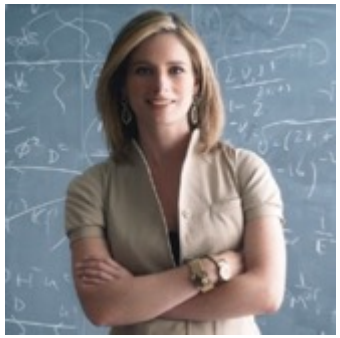
Prof. Sir Peter Knight (Imperial College London)

Dr. Patricia Dehmer (DOE Office of Science, retired)

Prof. John Martinis (UC Santa Barbara)

Dr Celia Merzbackher (QED-C)

Dr Josh Mutus (Google)



Prof. Lisa Randall (Harvard)

Dr Jeremy Glick (Goldman Sachs)

Dr. Hanhee Paik (IBM)

Prof. Joh Saunders (Royal Holloway)

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SQMS Direct DOE Program Managers

Dr. Altaf Carim (DOE HEP)

Dr. Athena Safa Sefat (DOE BES)

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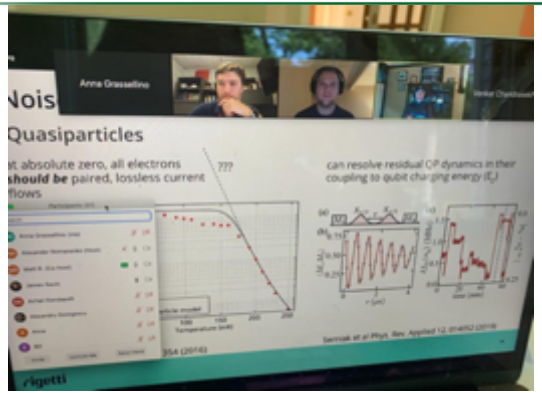
SQMS Center Spotlight on Management Progress



SQMS focus area all PIs biweekly meetings involve about 35-40 participants per each focus area

SQMS focus area lead team biweekly meetings involve about 7-10 leaders

Progress/Achievement in Management/QIS Ecosystem

SQMS Center weekly Thrust/Focus Areas meetings structure finalized and meetings ongoing

Significance and Impact

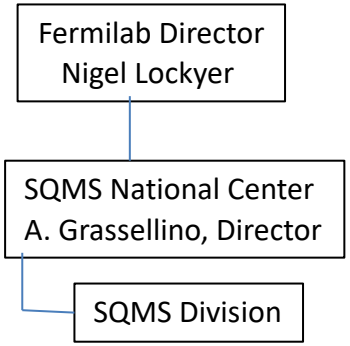
Meetings with thematic focus and weekly periodicity are key for setting the pace and for communication for the collaboration work

Details

- Each Focus Area weekly meetings, alternating:
  - All Focus area PIs biweekly
  - Lead Teams biweekly
- Currently serving to introduce the foundational work and sharpen the experimental work and means towards appendix 13 goals and deliverables
- Lead teams prioritizing the work ready to go for year one, and setting agenda for broad all PI meetings
- SQMS internal website setup for exchanging materials

SQMS Center Spotlight on Management Progress

Fermilab Technology Campus and lab space available for building large quantum computing, material and sensing testbeds



Caption: SQMS organization at Fermilab

Progress/Achievement in Management Structure

SQMS Center organizational setup at Fermilab successfully completed

Significance and Impact

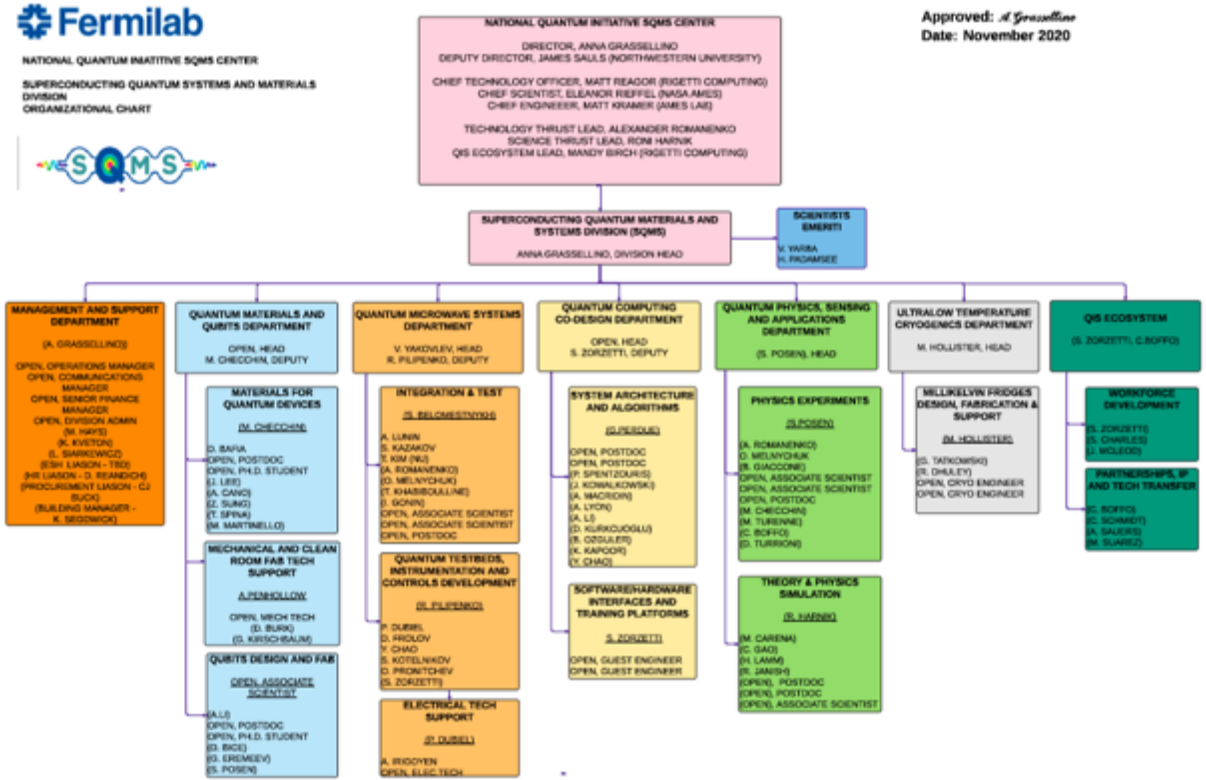
Well defined and high visibility organization at the host national lab will be instrumental for the SQMS center success

Details

- SQMS Center reports directly to the Fermilab Director Nigel Lockyer
- SQMS will also be a division with direct hiring capability of key personnel
- 20 new scientific and technical hires approved, posting in process
- Fermilab Director has announced the SQMS Center and division creation as a high priority organization as LBNF and PIP-2
- Lab will provide some support for key support functions
- Will reside in technology campus with new dedicated office and lab space sponsored by Fermilab (ongoing)
- Space for big computing, sensing and materials testbeds will also include the IARC high bay area (ongoing)
- Procurement defined subcontract award process and timeline

SQMS new division at FNAL

- Several top FNAL experts in RF and SRF, cryogenics, electronics and controls, who have been through few years of QIS learning curve thanks to our HEP QuantiSED program
- Science applications (algorithms/simulation for physics, and sensing experiments) foundational part of FNAL mission
- Will inject new strategic hires from QIS which mixed with experts from key technology and science areas will form the winning team
- Develop new expertise and capabilities at FNAL (eg qubits fabrication..)



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SQMS FNAL job openings

We have twenty job openings in the area of materials and devices for QIS, physics/sensing, algorithms and support staff for the new SQMS Center (postdocs, associate scientists, engineers, technicians, managers…)

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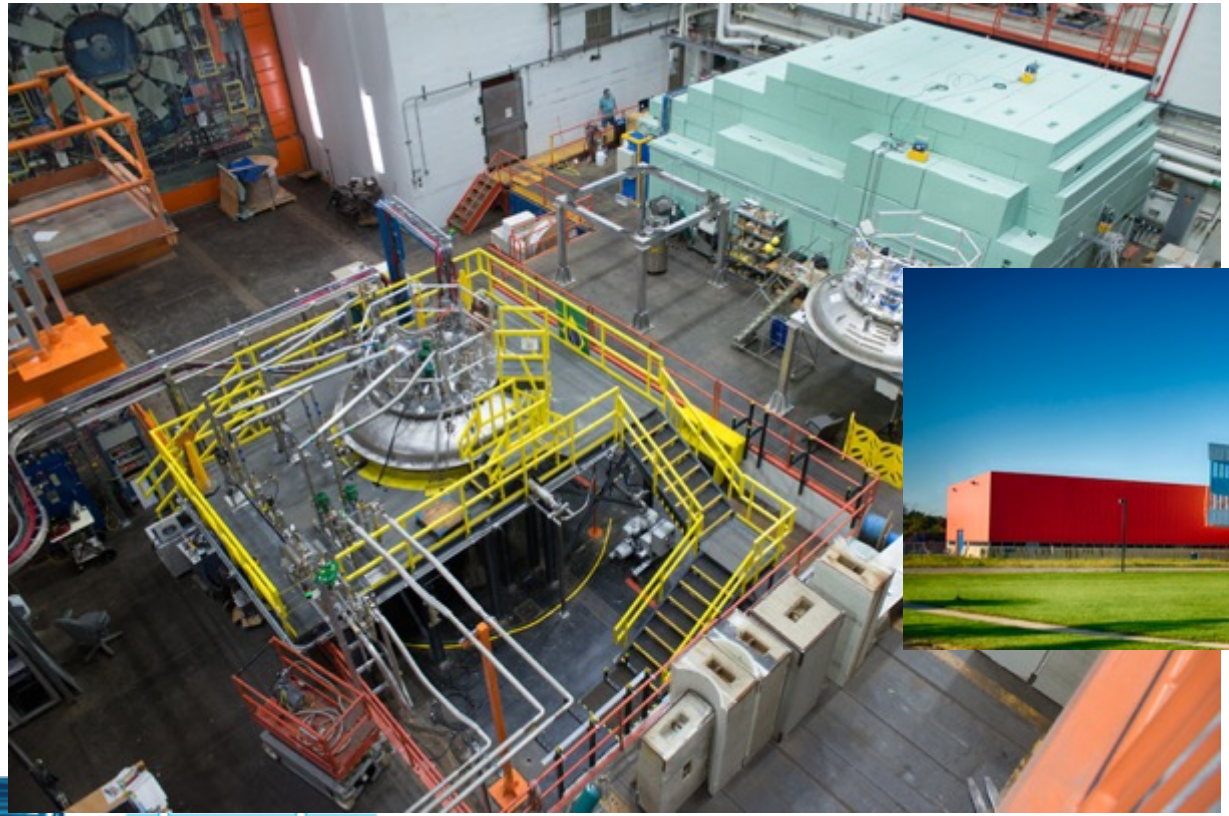
5-year quantum computing and sensing national facilities – potential home at FNAL



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Conclusions

- Unique collaboration gathering multidisciplinary top talent and facilities towards very ambitious quantum computing and sensing goals

- We will have a very focused mission: building together something revolutionary

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