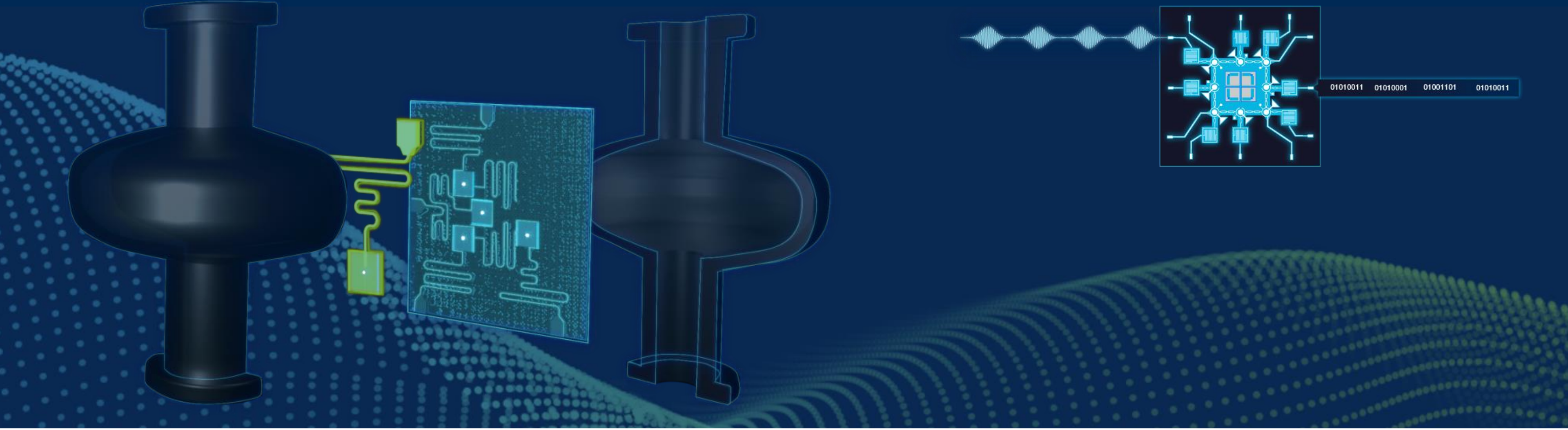
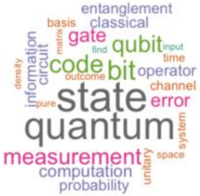


Superconducting Quantum Materials and Systems: A new National Quantum Information Science Center

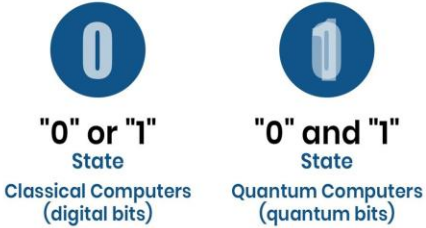
Anna Grassellino

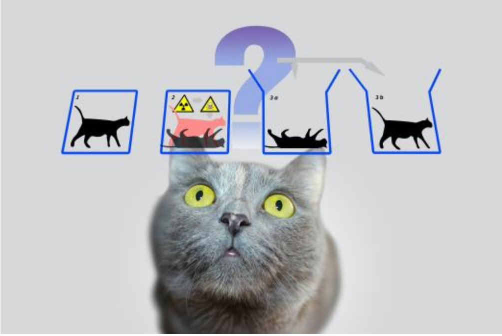
SQMS Center Director, Fermilab



Quantum computing

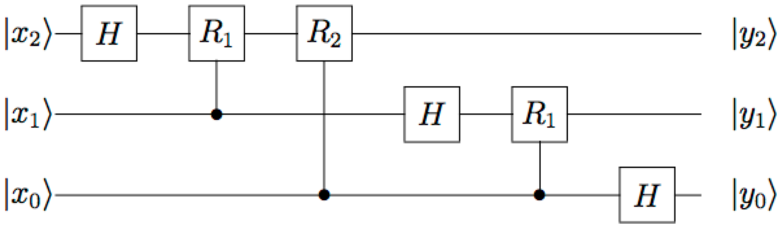
- Basic idea is to build a computer which uses “qubits” instead of bits
  – Utilize very special quantum mechanics principles: two states of the quantum system (|0>, |1>), which can be also prepared in any “**superposition**”
  – Also utilize “**entanglement**” between the qubits
- A quantum computer can provide potentially computational capacity for dramatic speedups in several very high impact areas, such as:
    - Finding large prime number multipliers, database search, simulating and predicting molecules behavior and interactions, modeling financial markets, simulating particle collisions etc





Exponential speedup

- The discrete Fourier transform is an example of a calculation that a quantum computer can do **exponentially faster** than any classical computer:
- For n qubits we need ~ n^2 gate operations, whereas a conventional Fast Fourier Transform requires ~ $n2^n$ operations
- In 1994 Peter Shor showed that **factorization of a product of large prime numbers** can be done this way.
- Thus a quantum computer can do at least one important calculation **exponentially faster than a classical computer**
- This will eventually be the doom of **RSA encryption**



How long before quantum computers destroy the world economy?

MIT Technology Review　Topics　Maga

Computing

How a quantum computer could break 2048-bit RSA encryption in 8 hours

A new study shows that quantum technology will catch up with today's encryption standards much sooner than expected. That should worry anybody who needs to store data securely for 25 years or so.

by **Emerging Technology from the arXiv**　May 30, 2019

Many people worry that quantum computers will be able to crack certain codes used to send secure messages. The codes in question encrypt data using "trapdoor" mathematical functions that work easily in one direction but not in the other. That makes encrypting data easy but decoding it hugely difficult without the help of a special key.

These encryption systems have never been unbreakable. Instead, their security is based on the huge amount of time it would take for a classical computer to do the job. Modern encryption methods are specifically designed so that decoding them would take so long they are practically unbreakable.

How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits

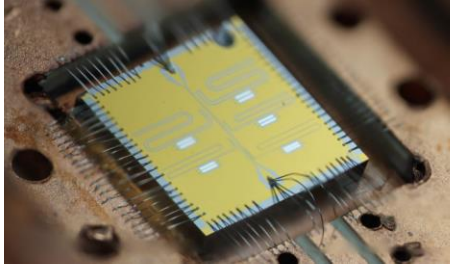
Craig Gidney[1,*] and Martin Ekerå[2]

[1] *Google Inc., Santa Barbara, California 93117, USA*
[2] *KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden*
Swedish NCSA, Swedish Armed Forces, SE-107 85 Stockholm, Sweden

(Dated: May 24, 2019)

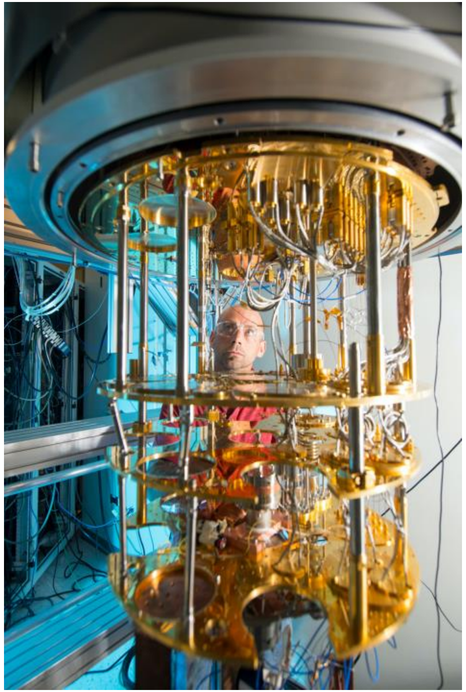
We significantly reduce the cost of factoring integers and computing discrete logarithms over finite fields on a quantum computer by combining techniques from Griffiths-Niu 1996, Zalka 2006, Fowler 2012, Ekerå-Håstad 2017, Ekerå 2017, Ekerå 2018, Gidney-Fowler 2019, Gidney 2019. We estimate the approximate cost of our construction using plausible physical assumptions for large-scale superconducting qubit platforms: a planar grid of qubits with nearest-neighbor connectivity, a characteristic physical gate error rate of 10^{-3}, a surface code cycle time of 1 microsecond, and a reaction time of 10 microseconds. We account for factors that are normally ignored such as noise, the need to make repeated attempts, and the spacetime layout of the computation. When factoring 2048 bit RSA integers, our construction's spacetime volume is a hundredfold less than comparable estimates from earlier works (Fowler et al. 2012, Gheorghiu et al. 2019). In the abstract circuit model (which ignores overheads from distillation, routing, and error correction) our construction uses $3n + 0.002n \lg n$ logical qubits, $0.3n^3 + 0.0005n^3 \lg n$ Toffolis, and $500n^2 + n^2 \lg n$ measurement depth to factor n-bit RSA integers. We quantify the cryptographic implications of our work, both for RSA and for schemes based on the DLP in finite fields.

Challenges of building quantum computers



Need a qubit that you can manipulate and not confuse with other possible states of the system

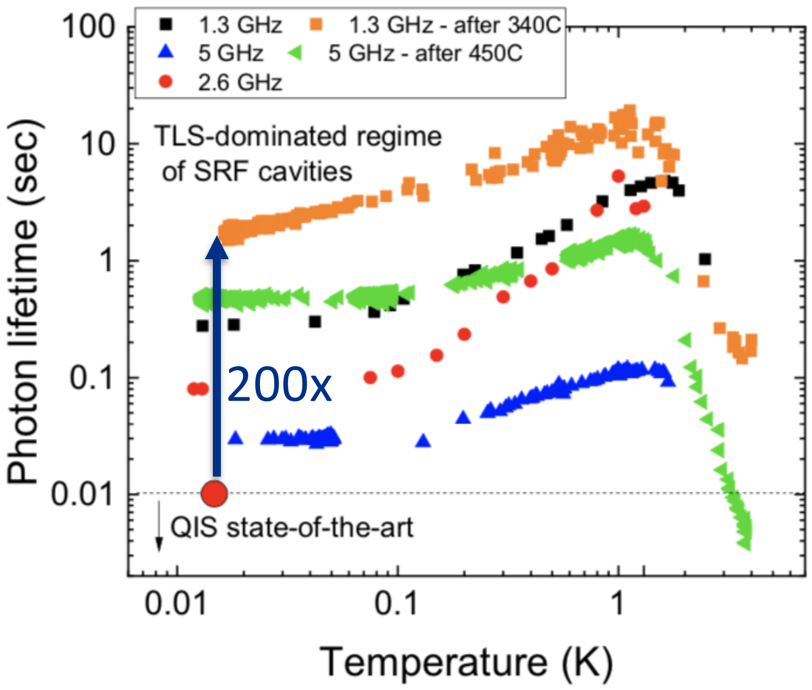
Maintain the **quantum coherence** of superpositions long enough to perform a large number of gate operations



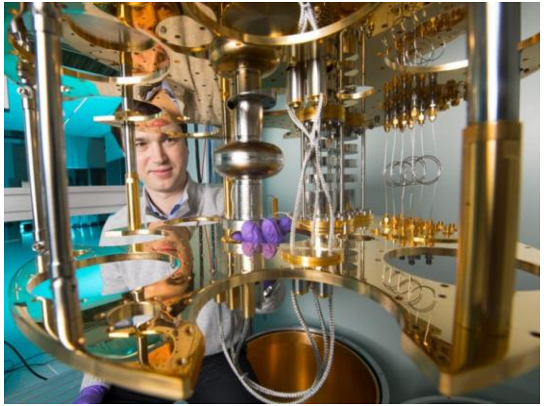
Examples of qubits:

- Photons in superposition of two polarizations or time bins
- Electron spin, nuclear spin, atomic spin, ion states
- Ground state and excited state of a nonlinear oscillator, e.g. a superconducting Josephson Junction LC circuit
- **SRF cavities: Fermilab has demonstrated WORLD record coherence times! As such we hold promise to potentially build the most advanced quantum computer ever built**
- **Coherence of Seconds (fermilab) versus microseconds (IBM, Google…)**

Fermilab superconducting cavities:
highest coherence quantum resonators ever demonstrated



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



- Technology originally developed for particle accelerators
- Powerful methodology of combining fab and test with materials analysis, to develop the fundamental understanding of device performance

Quantum Supremacy

Google paper in 2019 reported how their 53-qubit superconducting Sycamore quantum processor outperformed Summit, the world's largest supercomputer

25 years after Peter Shor got everybody's attention, we finally have quantum technology that is more than proof-of-principle

Now we need to demonstrate that quantum processors can perform even more complex computations: requires transformational improvement of the 'building blocks'

How long before quantum tech has positive economic impact?

According to a recent study by the Boston Consulting Group, we are almost there

This is the Quantum 2.0 revolution

EXHIBIT 2 | The Expected Phases of Quantum Computing Maturity

	NISQ era 3–5 years	Broad quantum advantage 10+ years	Full-scale fault tolerance 20+ years
Technical achievement	Error mitigation	Error correction	Modular architecture
Example of business impact	Material simulations that reduce expensive and time-consuming trial-and-error lab testing	Near-real-time risk assessment for financial services firms (e.g., quant hedge funds)	De novo drug design with large biologics that have minimal off-target effects
Estimated impact (operating income)	**$2 billion–$5 billion**	**$25 billion–$50 billion**	**$450 billion–$850 billion**

Source: BCG analysis.

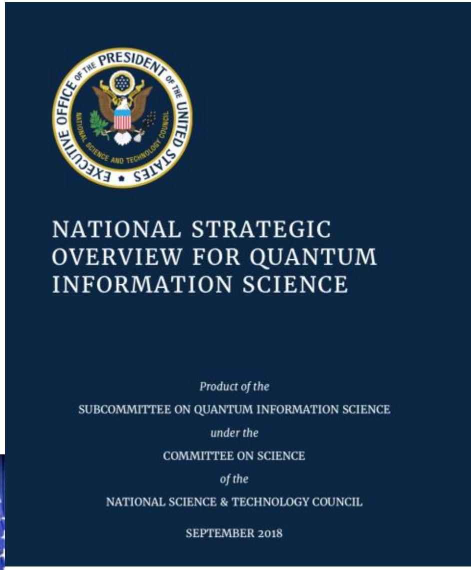
National Quantum Initiative

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

Develop quantum computers, quantum sensors, and quantum communications

Goal is transformational advances in quantum science and technology

Create a quantum economy

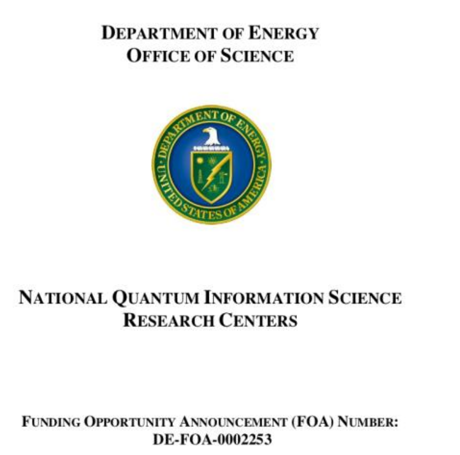


EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

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

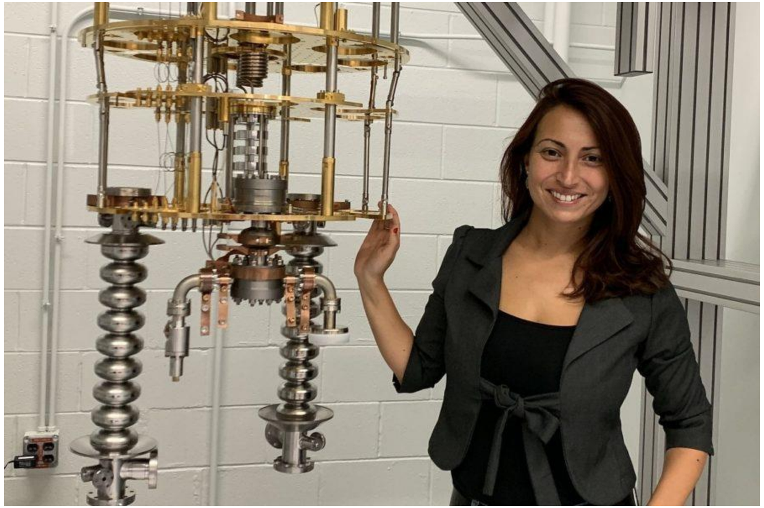
August 2020: Fermilab will lead a DOE National Quantum Center

SQMS

With the **Superconducting Quantum Materials and Systems** Center (SQMS), we propose to 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, Illinois, Stanford, Arizona, CU, Temple, rigetti, Lockheed Martin, INFN Istituto Nazionale di Fisica Nucleare, JANIS, Illinois Institute of Technology, Ames Laboratory, Colorado School of Mines, Johns Hopkins University, NIST, Goldman Sachs

SQMS: a multi-disciplinary collaboration of more than 150 world top scientists



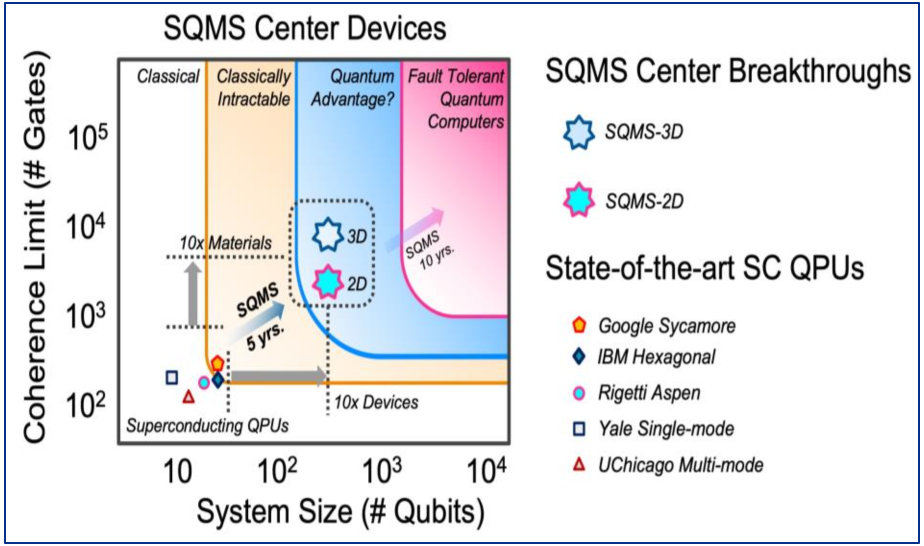
World leaders from materials science, particle physics, and QIS

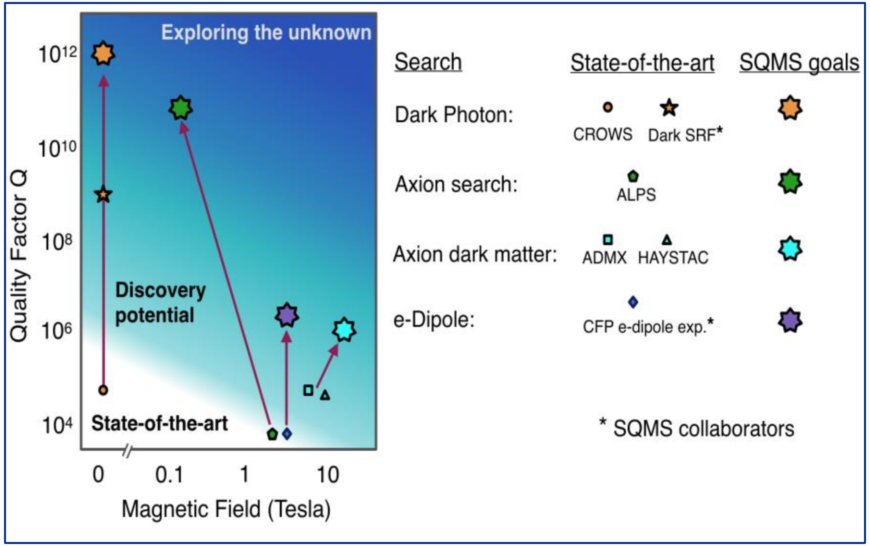
SQMS will leverage substantial investments in DOE facilities and other federal, private and educational investments

- **Three different foundries for 2D and 3D** devices fabrication/integration (Rigetti, NIST, FNAL)
- **Eleven sub-K quantum testbeds** for materials/devices characterization and physics experiments
- **Material and superconducting characterization facilities** -DOE BES investments in AMES material labs, and the extensive Northwestern Material science facilities including: MRSEC and NUANCE. STM capabilities by Temple University and IIT
- **Quantum Computing and HPC platforms** at Rigetti, FNAL and NASA Ames
- World largest **underground** dilution fridge (INFN Gran Sasso)

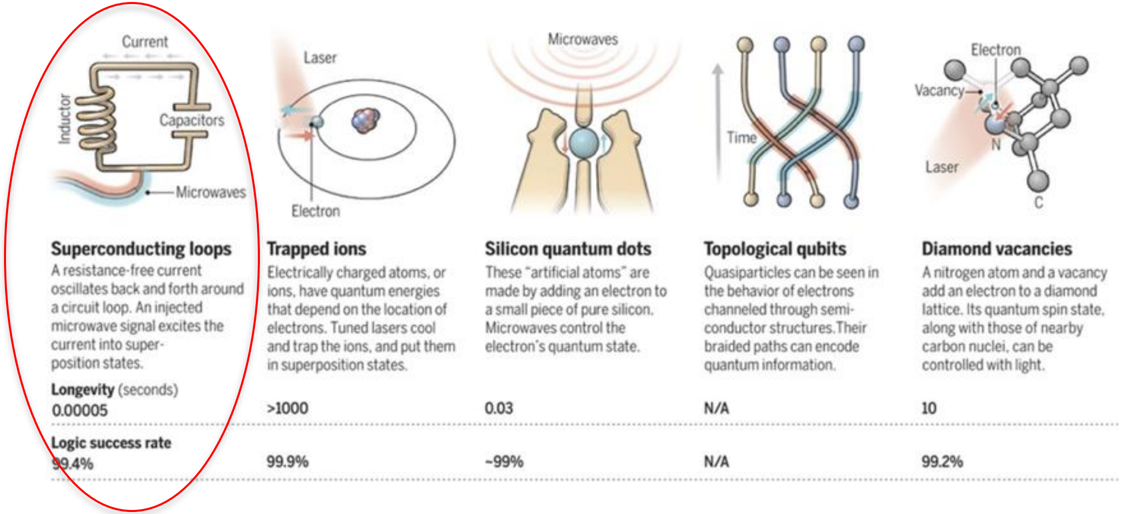
SQMS Center main goals: 3D and 2D superconducting technologies

- Build a quantum computer prototype entering the quantum advantage era
- Build quantum sensors and new sensing schemes leading into the physics discovery potential and exploring the unknown regions
- SRF cavities as enabling technology for computing and sensing goals





Betting on a qubit: superconducting microwave technologies



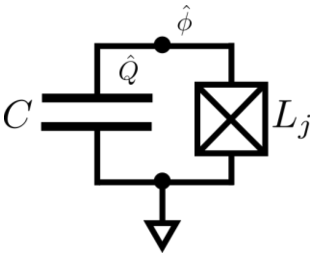
"The tech giants, IBM, Google, and Intel, all have staked out their quantum computing claims with superconducting qubits. Rigetti Computing, a recent but impressive California start-up, also uses superconducting qubits"

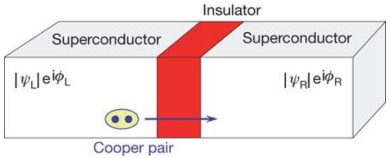
Qubit technologies overview. From: Forbes, [*Quantum Computer Battle Royale: Upstart Ions Versus Old Guard Superconductors*]

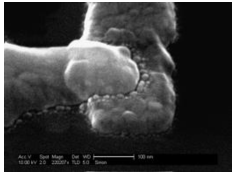
The U.S. is currently in a leading position in quantum systems based on superconducting microwave technologies; but to realize these technologies at their full potential, substantial efforts must still be devoted to enable orders of magnitude in device performance improvements.

Superconducting qubits have two main components

1. LC circuit with Josephson junction







"Transmon" qubits

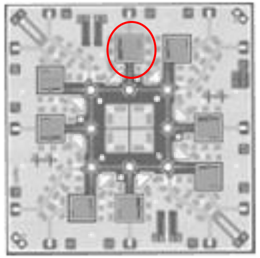
J. Koch et al, Phys. Rev. **A** 76, 042319 (2007)

+

2. Resonators (cavities)

2D

3D

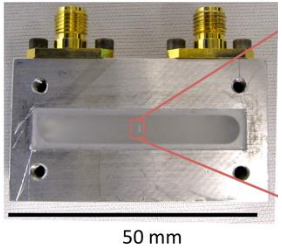


Rigetti 8-qubit processor

Q ~ 10^5

$T_{coherence}$ ~ 0.000001 s

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



3D transmon

Q ~ 10^8

$T_{coherence}$ ~ 0.001 s

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

Fermilab SRF resonators

Q > 10^{10}

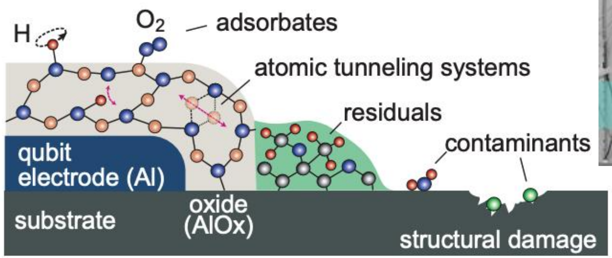
$T_{coherence}$ > 1 s

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

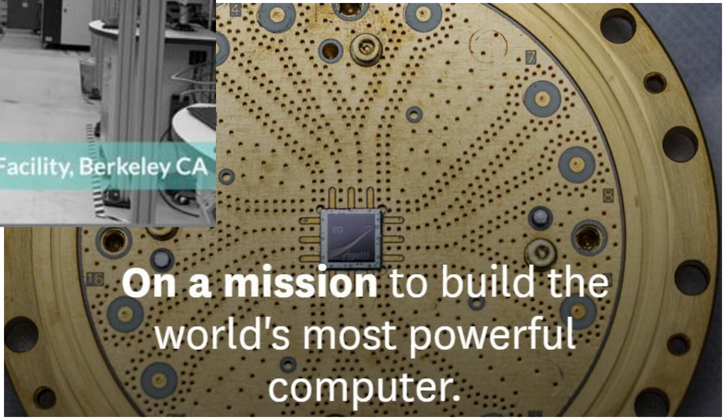
The main challenge is improving the **coherence** of both key components while also **scaling up** to larger combined systems

Rigetti qubits at the forefront of coherence

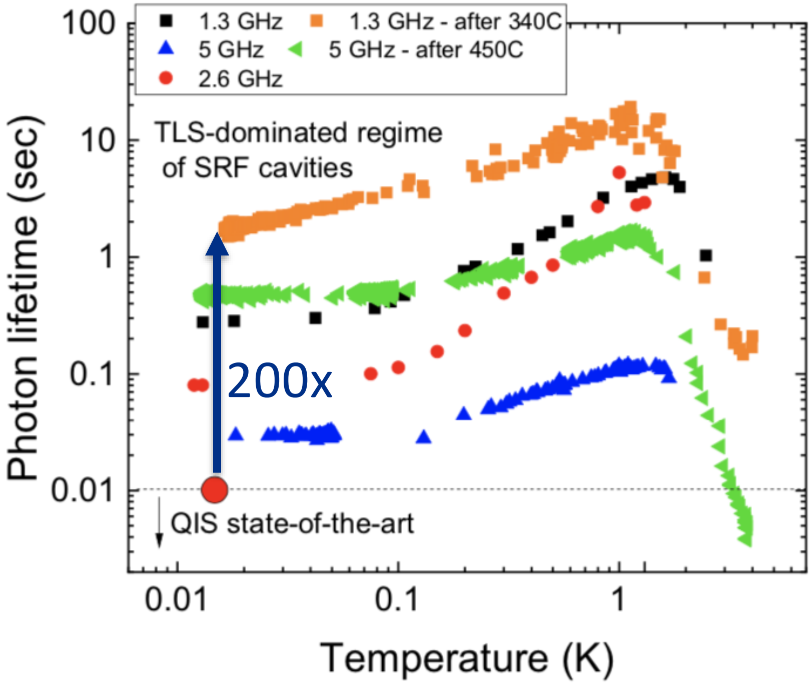
Rigetti qubit foundry



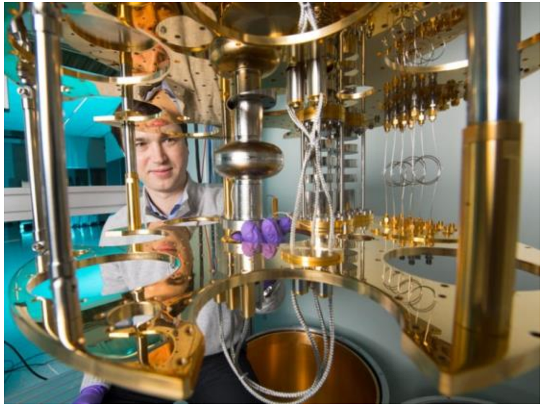
Material science studies to understand and mitigate qubit decoherence



Fermilab superconducting cavities: highest coherence quantum resonators ever demonstrated



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

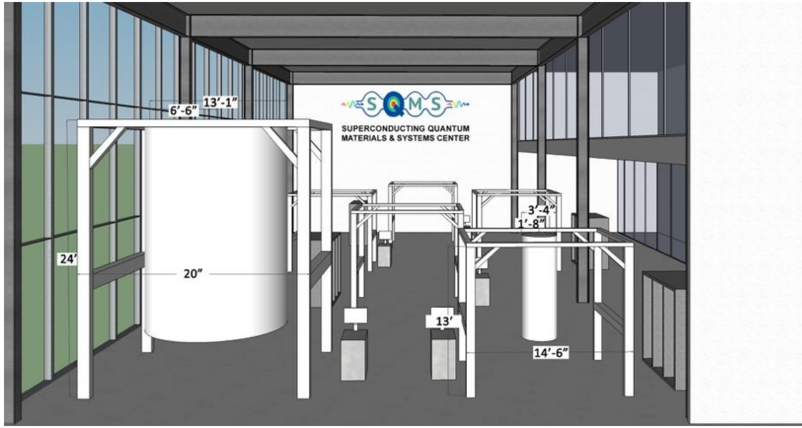


- Technology originally developed for particle accelerators
- Powerful methodology of combining fab and test with materials analysis, to develop the fundamental understanding of device performance

Quantum Computer Prototypes: scale up, integration capabilities and plans

- One of the SQMS 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



Modern accelerators are like quantum computers: large and complex high coherence (Q) 3D superconducting microwave systems

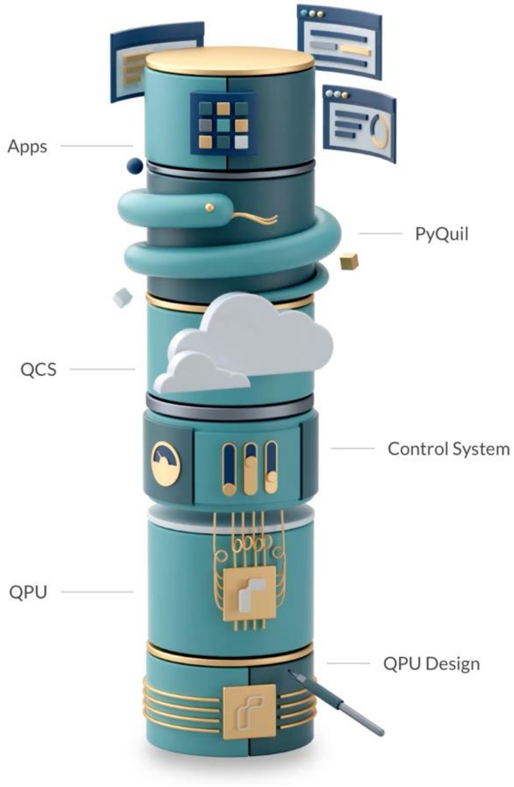
DOE labs expertise and facilities will be critical for success in scale up of 3D QIS technologies

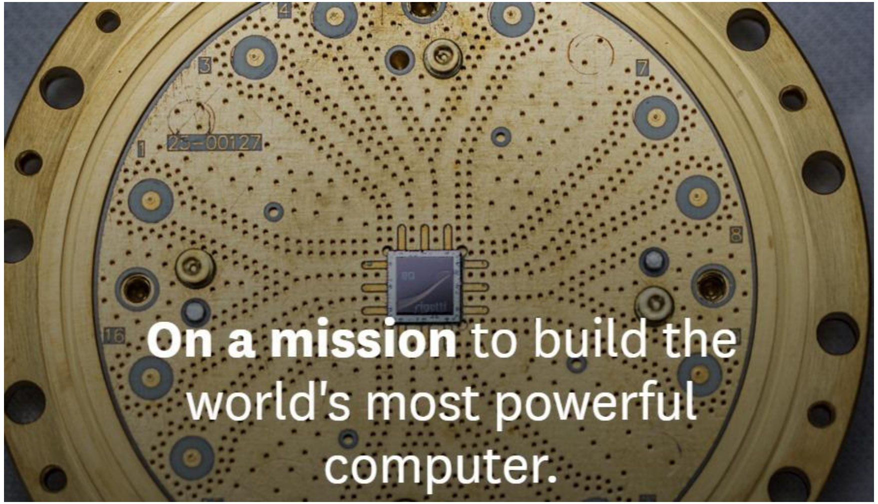
- Vacuum systems
- Superconducting Materials
- Microwave SC devices
- Cryogenics
- Controls
- Magnetic shielding
- Thermal Insulation

Fermilab has demonstrated world record performance cryomodules 3X state of the art quality factors

$Q > 2.7 \times 10^{10}$ @ 2K, 16 MV/m

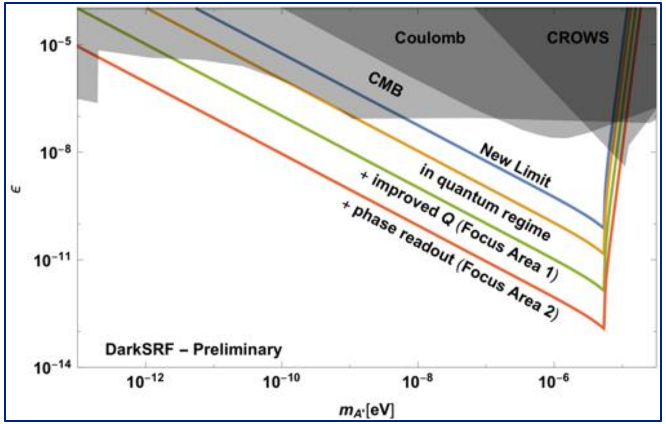
+ Rigetti experience in building full stack quantum computers





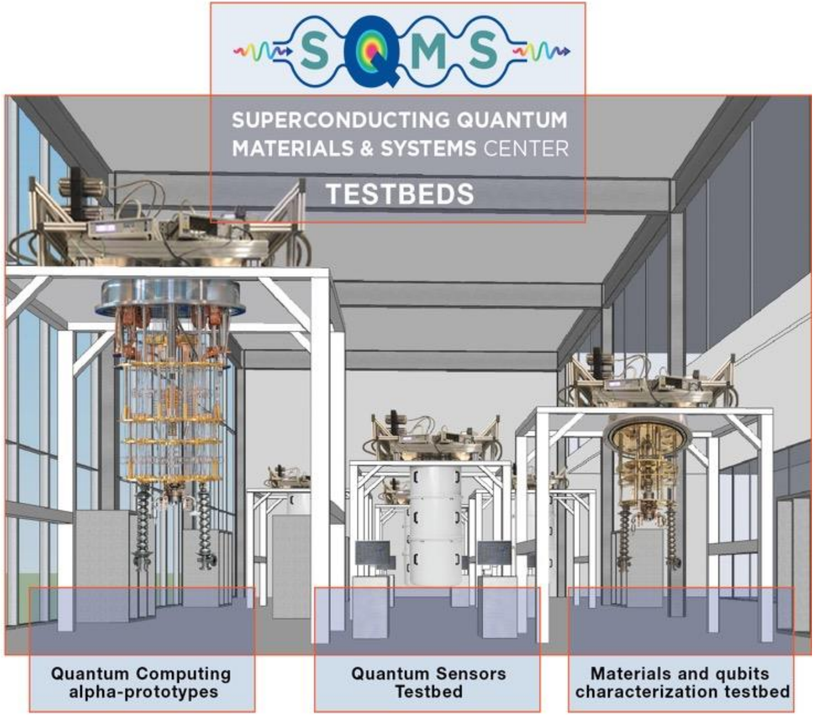
Science drivers boosting technology and vice versa

- Center uniqueness: it encompasses from the technology experts to the science end users
- HEP and BES science drivers provide unique motivation and push for technological advancement
- And SQMS technological advancements will open new opportunities for physics discovery, in a synergistic loop
- Examples : search for dark matter, simulations for HEP/BES



QIS Ecosystem and economic returns

- Unique collaboration industry-labs-academia, with industry deeply embedded in the research 'hand in hand'
- Technology development and immediate transfer of prototypes (Rigetti, Janis) will boost US industry competitiveness in QIS
- Industry use cases for algorithms (Goldman Sachs, Lockheed Martin) with large potential economic returns for the US
- Unique facilities for QIS fabrication, computing, sensing will be available to boost the national QIS ecosystem, including workforce development for training the next generation of diverse quantum workforce
- These facilities – foundries or testbeds -can serve the national quantum ecosystem to enable, for example:
  - Qubits measurements in the most sensitive environments
  - New particle searches/sensing experiments
  - Computing/simulations on the new quantum computer prototypes which will be accessible via HEPCloud

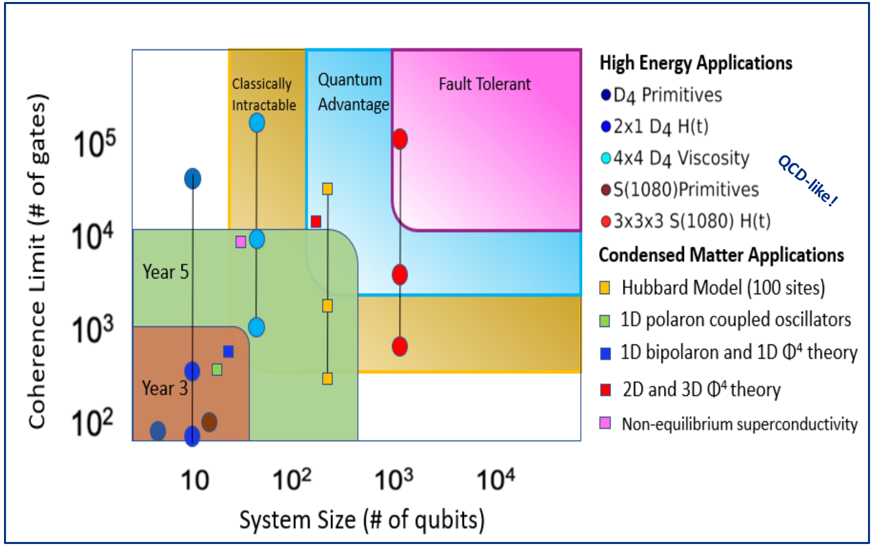


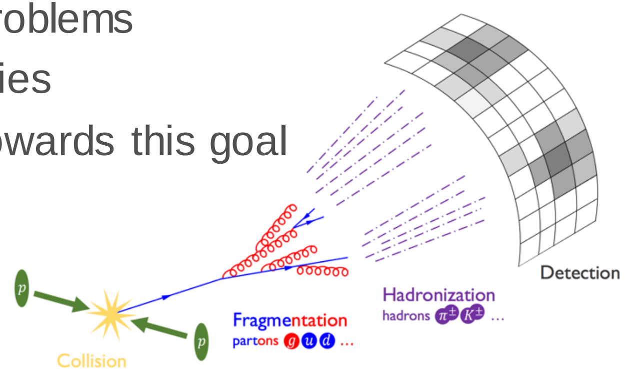
Quantum Advantage for science and discovery

- Feynman said: use quantum computers to solve quantum problems
- Transformational science goal: simulate quantum field theories
- Ladders of simulations (progression of toy-models) aimed towards this goal

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

Iadecola et al. PRB 98, 174201 (2018)





Particle and nuclear physics:

QCD dynamics in LHC collisions

Cosmology:

Early Universe phase transitions

Condensed matter physics:

Many body states with high entanglement, many body localization

SQMS Educational initiatives and QIS workforce development

Michelle Driscoll - SQMS workforce development lead, Northwestern

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

Graduate Program in Applied Physics

Optical Properties of Superconductors

PhD student Jovan Nelson

Materials Research Center

Sub-10 mK DilFridges for QIS measurements & device characterization

Center for Applied Physics & Superconducting Technologies

Center for Fundamental Physics

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

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

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

Questions?