# Quantum Information Science

## at the SQMS Center

H. Padamsee & A. Grasselli

The Superconducting Quantum Materials and Systems Center is one of the five U.S. Department of Energy National Quantum Information Science Research Centers. Led by Fermi National Accelerator Laboratory, SQMS is a collaboration of over 30 partner institutions—national labs, academia and industry—working together to bring transformational advances in the field of quantum information science. The center leverages Fermilab's expertise in building complex particle accelerators to engineer multiqubit quantum processor platforms based on state-of-the-art qubits and superconducting technologies. Working hand in hand with embedded industry partners, SQMS is building quantum computers and new quantum sensors, which will open unprecedented scientific opportunities. For more information, please visit https://sqmscenter.fnal.gov.

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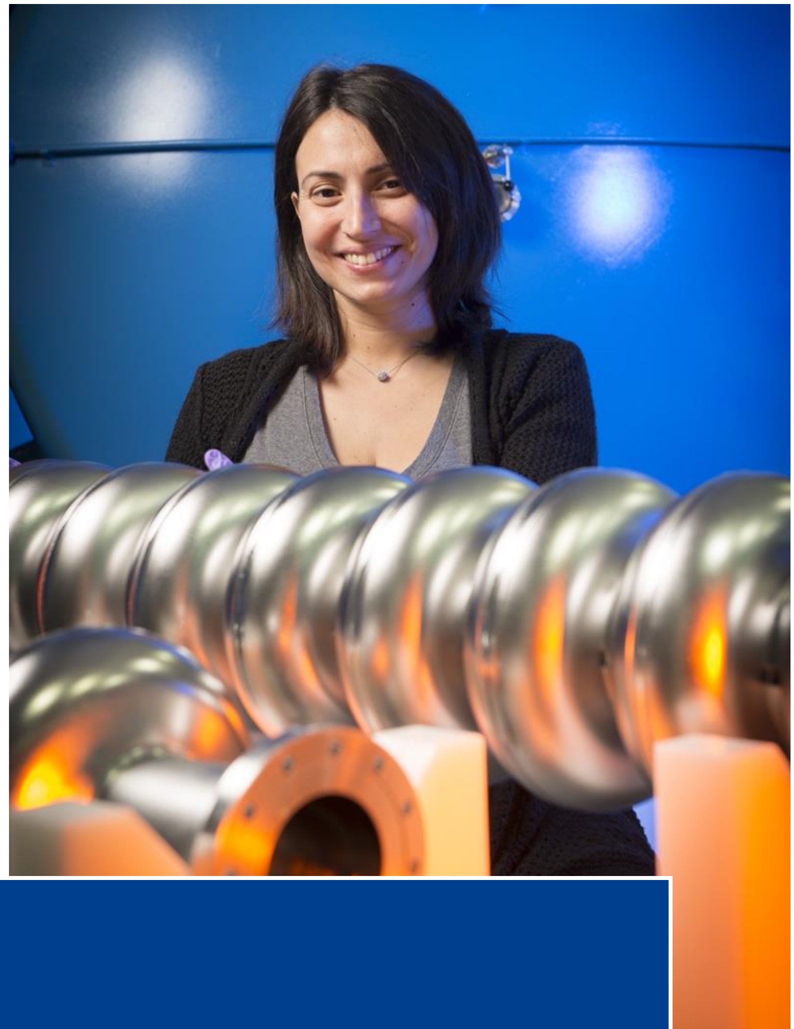

# From the SQMS Director

Dear Reader,

Thank you for reading our booklet. This resource aims to provide information regarding the fascinating world of quantum information science (QIS) and the Superconducting Quantum Material and Systems Center (SQMS), including those who bring it to you. We hope that you enjoy it.

Here, we summarize the status and potential applications with an emphasis on superconducting radiofrequency (SRF) technology of quantum computing and sensing. SRF-based quantum technology opens a pathway to transformative advances from SQMS. Newcomers to the field may also benefit from some of the introductory material.

Thanks to Hasan Padamsee for his assistance in writing this booklet, as well as Ziwen Huang, Akshay Murthy and Hannah Adams for their editing contributions. Without them, this booklet would not be a reality.

Sincerely,

Anna Grassellino
Director, Superconducting Quantum Materials and Systems Center

# Quantum Information Science
## at the SQMS Center

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# What is quantum computing?

Quantum Computing is a fusion of quantum physics and computer science. It harnesses three fundamental properties of the quantum world—superposition, entanglement, and interference—to create a new computational paradigm. Each of these key concepts is explained on a separate page.

A conventional computer typically performs calculations in series, one after another, until it has completed the task. For example, if such a computer must figure its way out of a maze, it will try every single branch in turn, ruling them all out individually until it finds the right choice that leads to the exit. A quantum computer can examine every path of the maze at once. Quantum computers consider many calculations in parallel, arriving at the most probable correct answer in much less time.

Using *superposition* and *entanglement,* the amount of information a quantum computer can encode exponentially increases with the number of qubits *(see next page).* Quantum parallelism allows the solving of problems that grow exponentially more difficult with the number of possibilities. This means the quantum computer is well-suited to solve complex organization problems and/or maze problems exponentially faster than a classical computer.

# Impact of Quantum Computers

Quantum computers will let us carry out tasks that we could not even dream of with classical computers, even the best supercomputer.

Conventional computers have doubled power and processing speed nearly every two years for decades. Despite these steady increases, they will still be unable to solve specific problems. For example, the computation time to find the prime factors for very large integers grows exponentially with the number of digits. The most complex factoring problem that can be solved today is about 200 digits, which can be done in a few months by a network of powerful computers working together. A 500-digit problem would take longer than the age of the universe! Now, a quantum computer with eight perfect *qubits* (a qubit is the quantum parallel of an "on-off bit" of the classical computer — *see page 5*) could solve the 200-digit problem in a tenth of a second and the 500-digit problem in two seconds!

Other equally complex problems for classical computers include accurately modeling the structure and dynamics of molecules like lithium hydride for car batteries or iron sulfide for fertilizer enzymes. Molecular problems grow exponentially more computationally expensive as the number of electrons increases. Yet, these are still small molecules. Pharmaceutical compounds contain 50 to 80 atoms. And the cellular proteins with which drugs interact contain thousands of atoms.

Simulating the interaction between atoms and molecules will help design new drugs and new materials. Pharmaceutical companies can analyze and compare compounds to create new medicines. The automobile industry anticipates using quantum computers to simulate the optimal chemical compositions for battery compounds in electric cars. Airlines can calculate fuel-efficient paths for aircraft from many possible paths. Cities can calculate optimal routes for buses and taxis to minimize congestion.

Breakthroughs in quantum computing will open new paths to pursue fundamental physics questions. Fermilab researchers are developing ways to use quantum computers to simulate some of the most basic interactions that hold our universe together.

# What Role Will Quantum Computers Play?

Quantum Computers are expected to have broad implications on various fields and disciplines, ranging from fundamental explorations of our universe to business, finance, medicine, materials, data security, space exploration, climate forecasts, global climate change and many more.

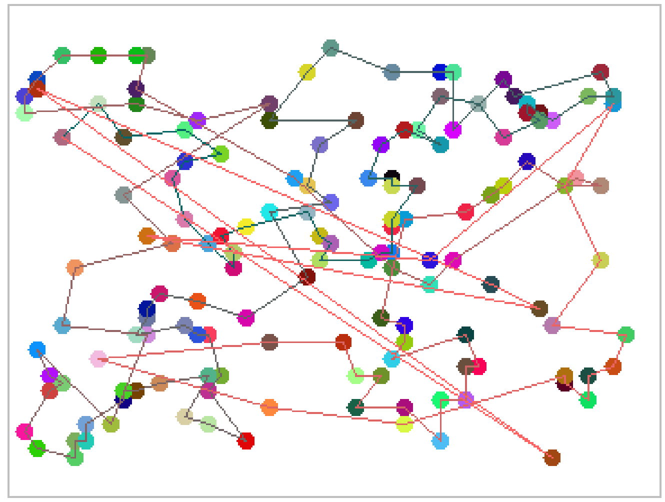
However, there exist many types of problems for which quantum computing could be more effective. For the typical user, quantum computing will not run web browsers or stream the latest episode on Netflix. It is unlikely that there will ever be a quantum chip in a laptop or smartphone. Classical computers will still be useful in the quantum computing world.

Using a classical machine will still be the easiest and most economical solution for tackling most problems. For classical computers, leading chip manufacturers keep churning out conventional chips with *billions* of transistors each. At this stage, quantum computer institutions struggle to build a quantum computer chip with more than a thousand qubits. Yet, while quantum computers are still at the starting gate, this field is advancing rapidly, and researchers are paving the way for exciting capabilities.

The quantum computing revolution is expected to arrive over the next decade with machines that promise to offer computing possibilities even the most capable of today's—and tomorrow's—supercomputers.

# Limits of Classical Computers


*IBM Summit Supercomputer at Oakridge National Lab*



*Traveling salesman problem*

### The Power of Classical Computers

Classical computers include everything from today's smartwatches to supercomputers occupying entire buildings. These computers store data as strings of binary digits (bits), either a 1 or a 0. Every app, website, and digital photograph is ultimately made up of millions of 0's and 1's in some combination. Everything from tweets and emails to songs and videos on streaming services are long strings of such binary digits.

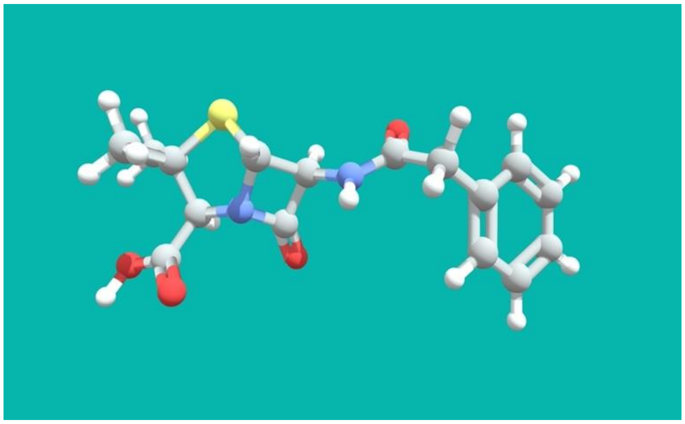
As Moore's law describes, over decades of development, digital computers got faster, smaller, and more powerful at an accelerating pace, doubling in power every 18-24 months. Today, a typical computer chip holds about twenty billion ($20x10^9$) bits as transistors, while the latest smartphone chip holds about six billion bits. Digital computers are considered universal because they can, in principle, solve any computational problem (although they possibly require an impractically long time). Digital computers are also truly reliable at the bit level, with fewer than one error in $10^{18}$ operations. The more common sources of error are software and mechanical malfunctions.

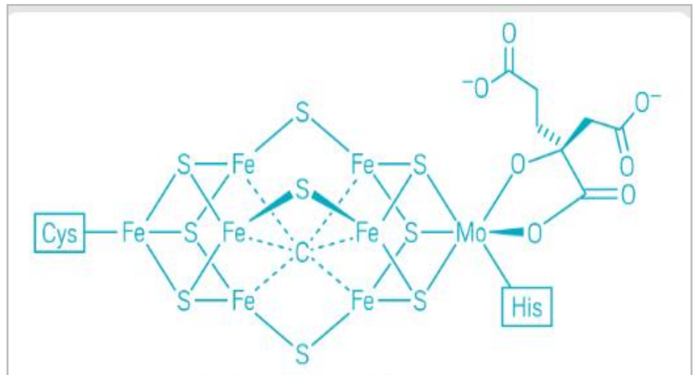
### Computational Limits

A simple illustration of a problem that quickly becomes very difficult for a classical computer is the traveling salesman optimization problem. Consider finding the one travel route that would be the most efficient way to visit many destinations and waste the least time and distance traveling between them. The number of possible paths proliferates with the number of stops. For 5 destinations, there are only 12 possible unique paths. Within microseconds, a classical computer examines every reasonable path, quantifies the distance for that path, and then chooses the shortest one. But for 10 destinations, there are 181,400 paths; for 15 destinations, there are over 43 billion unique paths, which would take many hours. For 20 destinations and their $6x10^{16}$ paths, it would take a computer about a thousand years! By reaching 25 destinations, the best computer would have to run for about 10 billion years, comparable to the universe's age!

Similar problems exist in DNA sequencing, manufacturing, optimizing delivery routes, and supply chains.

# Limits of Classical Computers






Nitrogenase Fe-Mo cofactor

**Quantum Limits for Classical Computers**

More than 50 years of chip innovation have allowed transistors to get progressively smaller so that chips now have transistors with 5 nanometer line spacing — about the size of 16 adjacent oxygen molecules.

Classical computers are also reaching quantum limits in their density and speed. As circuits get progressively smaller, systems of few particles will become subject to Heisenberg's quantum uncertainty principle. Electrons can tunnel through barriers between wires to corrupt signals.

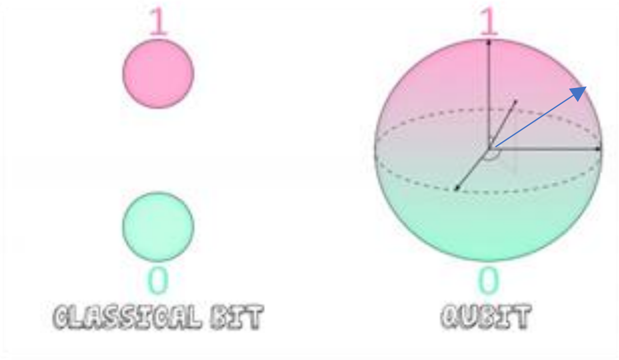
There will also come a power dissipation limit. A room temperature machine with $10^{18}$ gates packed in one cubic cm would have to deal with 3 MW of dissipated power, enough for a small city.

Quantum computers will be well suited to scale with the number of atoms to compute relatively complex molecular structures. Modeling penicillin on a quantum computer would be possible with as few as 286 high-quality (low error) qubits *(see next page).*

As another example, nitrogenase enzymes (produced by bacteria) pull nitrogen from the air to make ammonia for fertilizers to feed the world. A tiny portion of the precious enzyme contains only four atoms of iron and four atoms of sulfur. Simulating the interactions between even this small portion of the enzyme is barely possible with the most powerful classical computer today. But as the number of atoms increases, the interactions grow exponentially, making it too difficult for the classical method.

Today, even the best supercomputers can only analyze the quantum behavior of most basic molecules with just a few atoms. IBM has estimated that complete and accurate modeling of the base-state energy of the penicillin molecule, composed of 41 atoms, would require a classical computer with more transistors than atoms in the observable universe.

# Qubits & Superposition





In analogy with classical computing circuits called "bits," the unit of quantum computing is a "qubit." A bit can be a 1 or a 0 since it is just a switch with two possible configurations, "on" or "off." A classical bit is like a coin: heads (0) or tails (1). A set of n coins can be described as a probabilistic mixture of $2^n$ states, but the set is always in only one.

**Superposition**

A quantum bit or qubit can take on a quantum superposition of an infinite range of values between 1 and 0. As a simple analogy, a qubit behaves like a spinning coin. Each coin can be simultaneously in both states, heads and tails, with each state having a probability (of 50%) when landed. The qubit has a fluid binary identity. If two coins spin simultaneously, they would represent a superposition of four states. Three coins would simultaneously represent eight possible states. Fifty spinning coins would represent $2^{50}$ ($10^{15}$) states, which are more states than possible with today's largest supercomputer today. Three hundred coins would simultaneously represent more states than atoms in the universe.

A qubit is a bit that has a complex number called an amplitude attached to the possibility that it's 0, and a different amplitude attached to the possibility that it's 1.

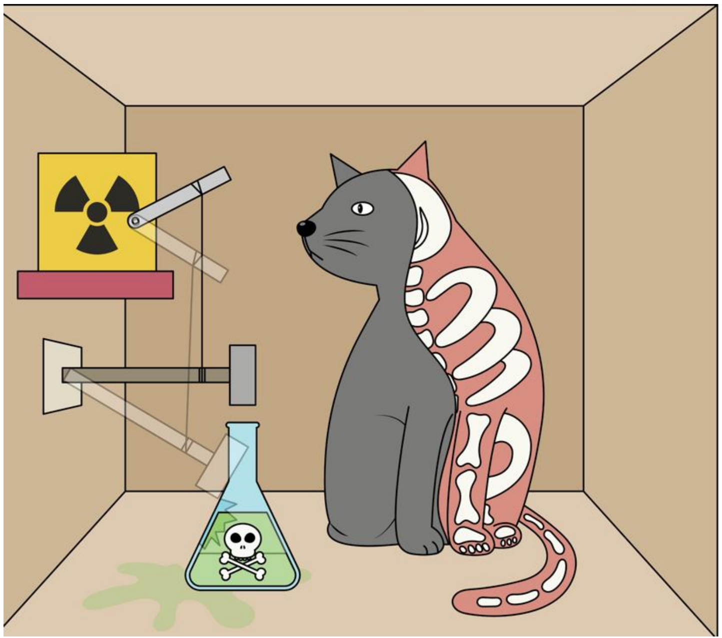
These amplitudes are closely related to probabilities and are represented by the Bloch sphere shown in the figure above.

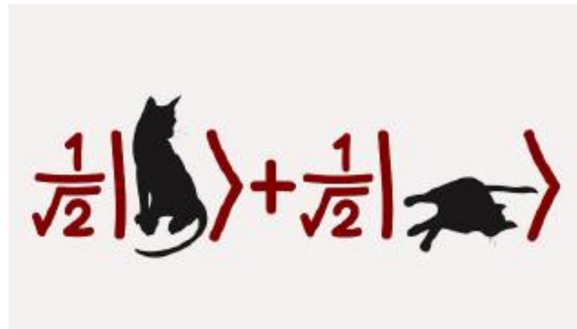
The Bloch sphere provides a convenient way to visualize the superposition state of a single qubit as a Bloch vector inside the sphere, starting at the origin and pointing to any value on the sphere's surface.

Many physical systems can be used to build a qubit capable of storing quantum information. Consider a particle with spin, such as the electron. Regarding a given axis (e.g., z axis), the spin of the particle can point in two opposite directions, say "up" or "down," and the spin states can be denoted as $|0\rangle$ and $|1\rangle$. By the laws of quantum mechanics, the particle can exist in a superposition of these two states (or as a wave of probability), corresponding to arbitrary orientation.

A quantum computer with n qubits can exist in a superposition of $2^n$ states. Due to superposition, a quantum computer with 100 qubits can represent $2^{100}$ solutions simultaneously. How significant is that number? As a powerful example, an estimate for the number of possible chess game positions is $10^{120}$, which is about $2^{400}$. Thus, a high-quality (error-free) 400-qubit quantum processor would be able to hold all possible chess games!

# Superposition...of Dead and Alive!





*Schrödinger's cat is  Dead and Alive (Coherent Superposition)*

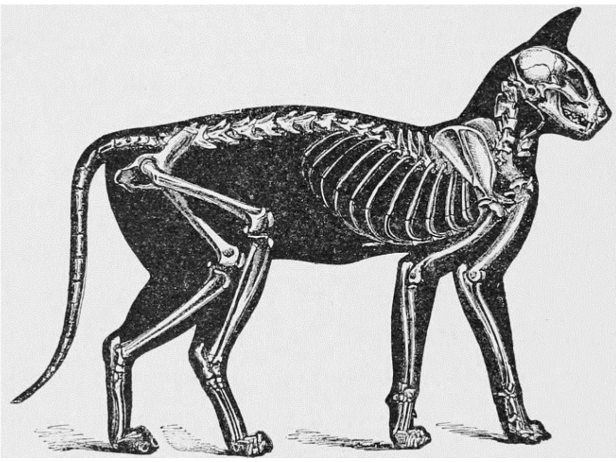
Superposition describes a quantum state where particles or qubits exist in multiple states simultaneously.  Superposition allows quantum computers to look at many different variables at the same time.

Schrödinger's cat is a well-known paradox that illustrates superposition in a dramatic yet paradoxical way—the ability for two opposite quantum states to co-exist simultaneously. The idea is that a cat is placed in a sealed box with a radioactive source coupled to a poison vial that will leak if an atom of the radioactive substance decays. Atomic decay is a quantum process.  Before any measurement, an atom in the box exists in a superposed quantum state of decayed and not decayed.  Therefore, the vial exists in a state of sealed and leaking, while the cat exists in a state of dead and alive!  The quantum state of the atom is only determined when a measurement is made, which means that the cat is only “found to be “dead” or “alive” the moment the box is opened and looked at.

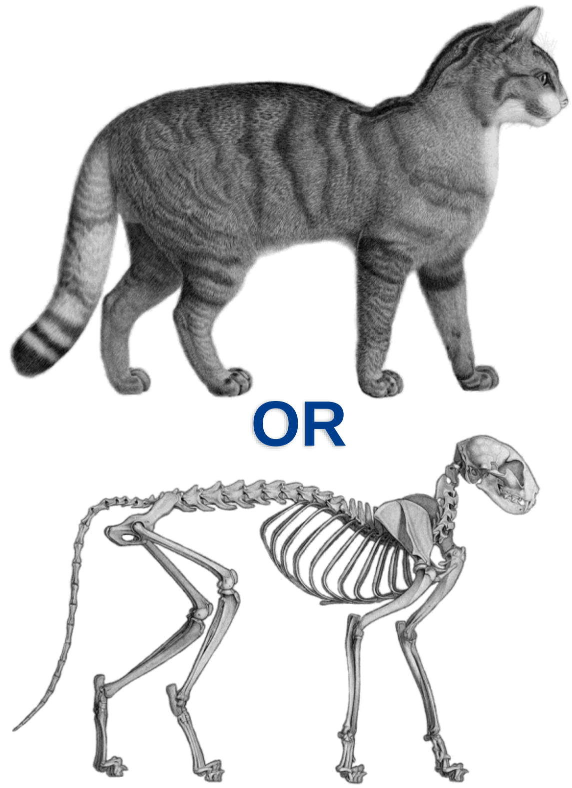
Until someone opens the box, the cat is in an indeterminate state of both alive and dead, a superposition of states.  Opening the box to observe the cat causes it to abruptly change its state randomly, forcing it to be either dead or alive.

In real life, the analogy is ill-conceived because it identifies a macroscopic body (the cat) with quantum properties of a microscopic body (the atom). However, the boundary between classical macroscopic and quantum microscopic behaviors is a grey area and changing towards larger and larger numbers of atoms with progress in quantum technology.

# From Coherence To Decoherence



*From Dead and Alive (Coherent quantum state)*




*To Alive or Dead (Decoherence to classical state)*

**Coherence**

For successful quantum computing, it is necessary to keep qubits in their superposition state for a long time in order to process the information. The longer the time they stay in the superposed state, the higher the coherence. The time a qubit can remain in superposition is called its “coherence time.”

The coherence time of the qubit is a key performance metric. Quantum computation must be completed before decoherence kicks in and scrambles the qubits. The quantum state of superposition is fragile. The slightest disturbance, such as vibration, change in temperature, or interaction with the environment, can cause qubits to tumble out of superposition before their job has been done.

Methods to protect qubits from disturbance include keeping them in vacuum chambers, free from vibration, external electric and magnetic fields, or inside supercooled fridges, called dilution refrigerators, at a very low temperature of 10 millikelvin, a hair above absolute zero.

A central challenge in developing quantum computers is to increase the coherence time to increase the number of computations possible.

Quantum error correction is a way around decoherence but requires more qubits and introduces more complexity. By contrast, the zeros and ones in classical computer memory rarely switch by accident, so little error correction is needed in most classical computers.

# Entanglement

Entanglement is an enigmatic characteristic of the quantum state of two or more particles. When a pair of qubits is entangled, the two members exist in a single, correlated quantum state. Entangled qubits affect each other instantly when measured, no matter how far apart they are, even if they are separated at opposite ends of a galaxy! Changing the state of one of the qubits instantaneously changes the state of the other qubits predictably. Operations and processes applied to one qubit can also affect the entangled qubit. Measuring one member of a pair of entangled qubits directly gives the properties of its partner without having to test it.

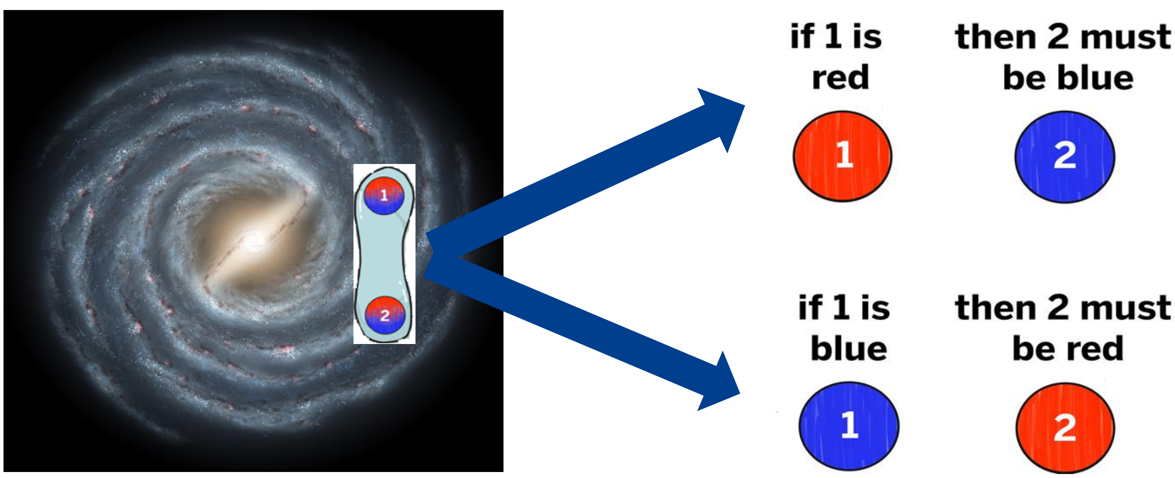
Typically, if you flip two coins, the result of one coin toss has no bearing on the result of the other one. The results of two-coin tosses are entirely independent.

But if two coins were somehow “entangled,” when one comes up heads on landing, the other one will automatically come up tails, even if two coins are physically separated by a vast distance!

The entangled state contains information that the states are correlated. When qubits are entangled, so are their measurements; information in an entangled state is spread between the individual particles. In an entangled quantum book, all the information is stored among multiple pages. You cannot read one page at a time -- to access the information requires the entire book!

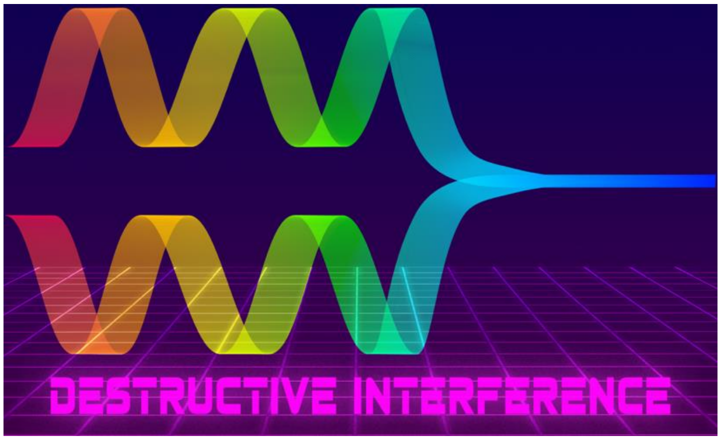
Entanglement greatly enhances computational power and scalability. Entanglement makes it possible to change the state of multiple qubits simultaneously. Using entanglement, qubits work together as multiple qubits with hidden correlations. With each additional qubit entangled, a quantum computer can explore double the number of possible solutions, an exponential increase - impossible with classical machines. Entanglement becomes a computational multiplier. Entanglement is also used for error correction (discussed on page 22).

Like superposition, quantum entanglement is also fragile, subject to decoherence due to the coupling of the quantum system to the environment.

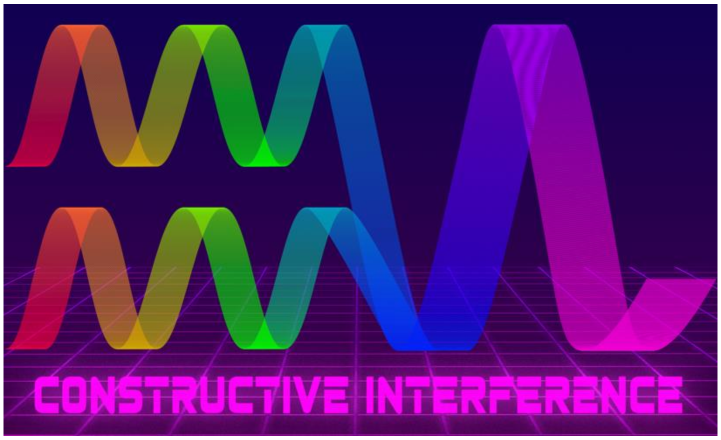



*Two qubits are entangled and subsequently separated very far from each other, even across a galaxy. Both qubits are in a superposed state of red and blue. When qubit 1 is measured to be red, qubit 2 must instantaneously turn out to be blue…Or if qubit 1 is measured to be blue, then qubit 2 must turn out to be red.*

# Interference




*When waves are out of phase, amplitudes cancel (above), when they are in phase the amplitudes add (below).*




As discussed previously, a quantum computer can explore a huge number of possible solutions to a problem. However, we can still only measure a single outcome to the calculation. How can we access the quantum advantage, then? The answer is that when a qubit is measured, the results depend on adding up many different possibilities to obtain the final probable results.

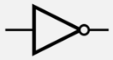
When some contributions to a qubit amplitude are positive and others are negative, the contributions interfere destructively and cancel so that the net amplitude is zero and the corresponding outcome is never observed. Similarly, the contributions can interfere constructively and increase the likelihood of an outcome.

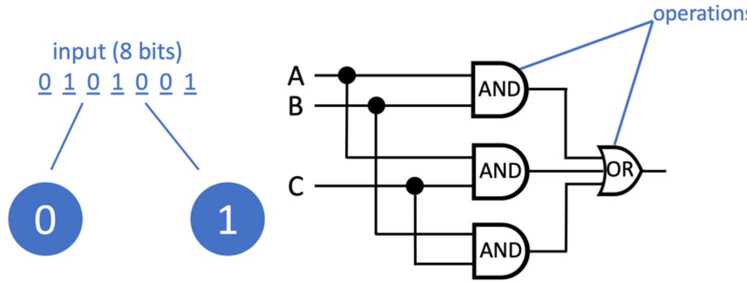
The strategy for programming a quantum computer is to arrange the sequence of gates in a pattern of constructive and destructive interference. The contributions to qubit amplitude reinforce each other for the correct answer.

The trick is to accomplish this without knowing the answer in advance.

When the qubit is finally measured, the act of measurement forces the qubit to “collapse” down to a classical bit with a definite 0 or 1 value.

# How Classical Computers Calculate

| Gate | Description | Symbol | Input | | Output |
|---|---|---|---|---|---|
| NOT | The output is 1 when the input is 0 and 0 when the input is 1. |  | 0 | | 1 |
| | | | 1 | | 0 |
| AND | The output is 1 only when both inputs are 1, otherwise the output is 0 |  | 0 | 0 | 0 |
| | | | 0 | 1 | 0 |
| | | | 1 | 0 | 0 |
| | | | 1 | 1 | 1 |



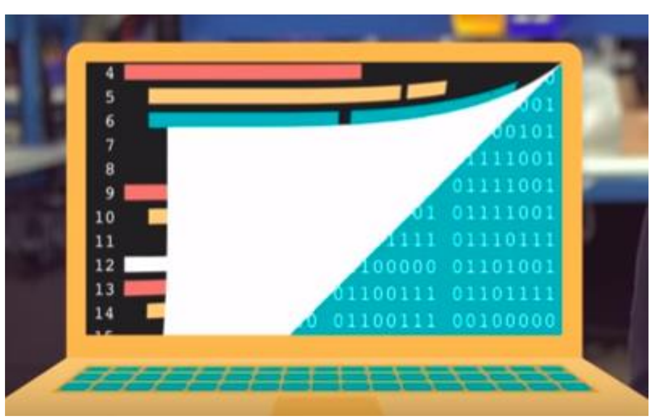

The classical computer accomplishes two main tasks using bits - storage and processing.

Storage: Long strings of ones and zeros store any number, letter, or symbol using the binary code with ones and zeros in memory registers. A string of eight bits (also called a byte) can represent one of 255 different characters (such as A-Z, a-z, 0-9, and common symbols).

Gates: Classical computers calculate with circuits called logic gates made from a transistor. Calculations use a small set of single-bit (left figure) and two-bit gates (right Figure). One example of a single-bit gate is the NOT gate. Here, the output of the gate operation is 1 when the input is 0, and the output is 0 when the input is 1. One example of a two-bit gate is the AND gate. It has output 1 only when both inputs are 1, otherwise, the output is 0.

Several variants of two-bit gates include AND, OR NAND (a combination of NOT and AND), NOR (a combination of NOT and OR), and others. Logic gates compare patterns of bits, stored in registers, and then turn them into new patterns.

Process: Computers process the stored numbers with operations like “add” and “subtract” that are built out of elementary gates. They do more complex calculations by stringing together simple operations into a series of operations called an algorithm. Multiplying is done as a series of additions, for example. In this way, transistor-based logic gate circuits turn patterns of bits stored in memories into new patterns that correspond to the result of operations.



# How Quantum Computers Calculate

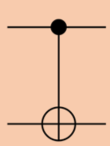
A quantum computer has analogous features to a conventional computer: qubits, registers, quantum gates, and algorithms. But it processes all the states simultaneously using superposition and entanglement to encode an exponentially increasing amount of information with an increasing number of qubits.

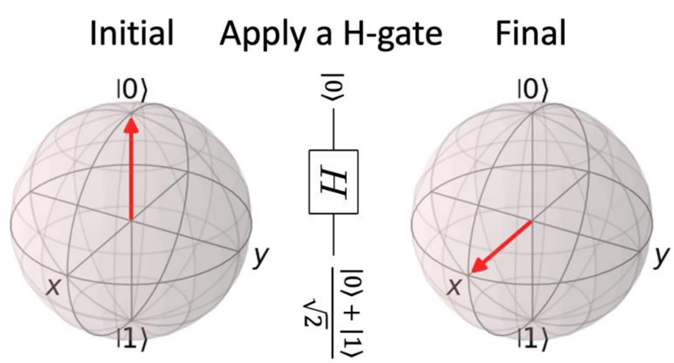
Rather than replicating classical algorithms to accomplish multiplication, quantum computing focuses on tasks such as to hunting large databases for particular items, using Grover's algorithm, factoring large numbers into constituent primes using Shor's algorithm, or simulating chemical bonds and other physical processes with Schrödinger's equation.

Quantum logic is performed by a set of single-qubit and two-qubit gates, as shown in the second figure at the left. Single-qubit operations translate an arbitrary quantum state from one point on the Bloch sphere to another point by rotating the Bloch vector at a certain angle about a particular axis. For example, the Hadamard (H) gate will transform a qubit from the |0> state to a superposition of |0⟩ and |1⟩, which is equivalent to rotating the vector, as shown in the third panel of the Figure on the left.

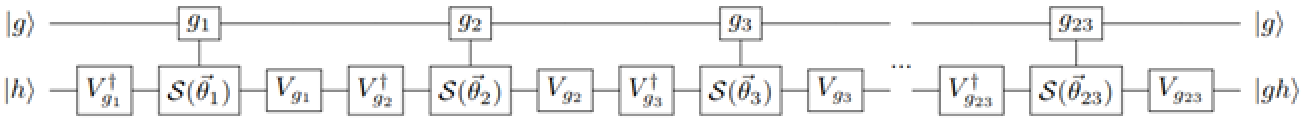
Two-qubit quantum-logic gates are generally "conditional" gates that take two qubits as inputs. Typically, the first qubit is the "control" qubit, and the second is the "target" qubit (lower figure in the second panel). For example, the gate shown (controlled-NOT) flips the state of the target qubit if and only if the control qubit is in the state |1⟩.

Another type of transformation is a phase-shift operation that changes the phase of multiple qubits. Phase changes introduce a new dimension to quantum computation.

| | | | Input | Output |
|---|---|---|---|---|
| X gate | Rotates the qubit state by 180° about the X-axis |  | $\|0\rangle$<br>$\|1\rangle$ | $\|1\rangle$<br>$\|0\rangle$ |
| | | | Input | Output |
| Controlled -NOT gate | Apply an X-gate to the target qubit if the control qubit is in state $\|1\rangle$ |  | $\|00\rangle$<br>$\|01\rangle$<br>$\|10\rangle$<br>$\|11\rangle$ | $\|00\rangle$<br>$\|01\rangle$<br>$\|11\rangle$<br>$\|10\rangle$ |



# How Quantum Computers Calculate



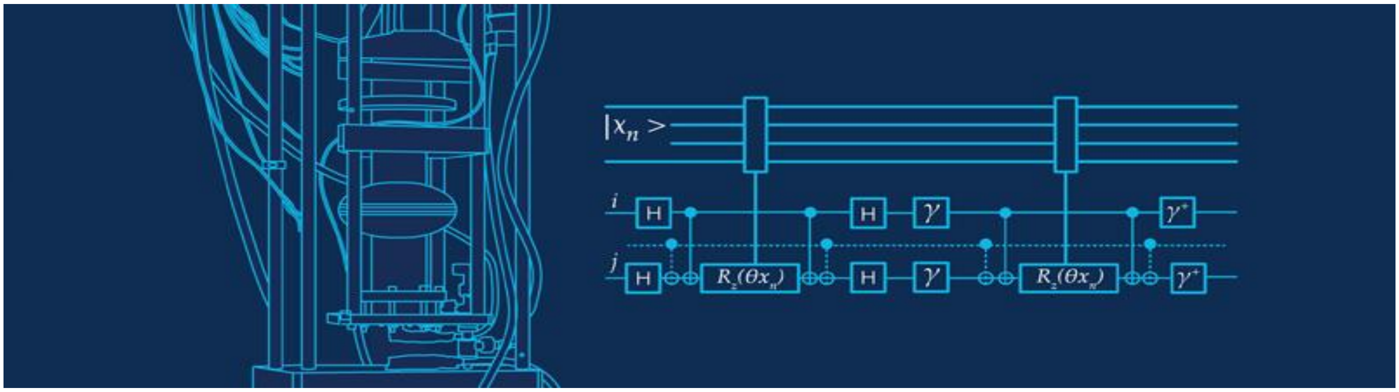

Every computation is a clever arrangement of gates. A program is written as a diagram with a sequence of quantum gates and phase operations.

A quantum computation starts by putting the qubits in a succession of superposed states, or it entangles qubits; then the states are modified by gate operations and phase-shifts, so they assume another state; then modified again; and so on. Interference amplifies some answers and suppresses other answers. The final step of measurement applies interference to consolidate the superposition into fewer outcomes, "collapsing" the superposition into one of the possible final states—which gives the answer to the problem.

The probability of getting one or the other result is related to the state of the qubit, just as a coin is more likely to land on heads if it is tipping towards heads when it is measured, i.e. when it lands. The entire calculation must take place before the natural decoherence of the superposed state.

Quantum entanglement adds a new dimension. It is the quantum computer's special sauce. Qubits can be entangled using quantum logic gates. For example, the Controlled-NOT gate (previous page), runs on two qubits. It flips the second qubit if the first qubit is 1,  By entanglement, multiple qubits can be linked, letting quantum computers explore lots of possible solutions to a problem at once. With each additional qubit entangled, a quantum computer can explore double the number of possible solutions.

Entanglement is also used for error correction (see page 22).




*Graphic provided by the SQMS Center*

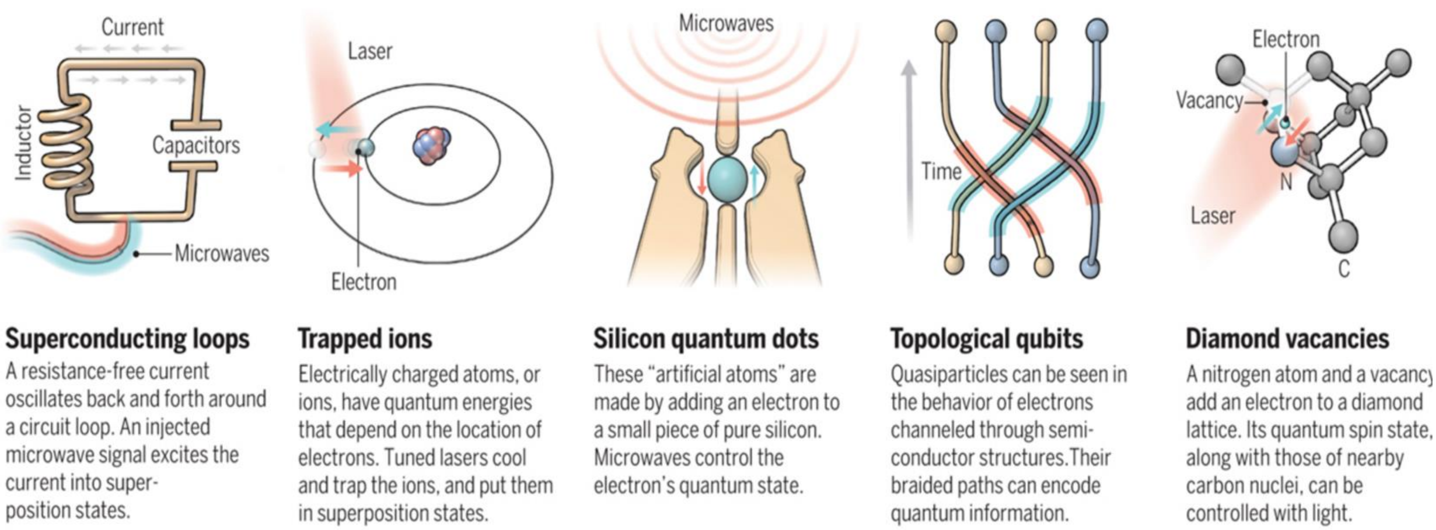
# Qubits Realization

Any physical system with two distinguishable basis states for 0 and 1 can be used for a qubit. Many types of qubits are under development. To mention a few, laser-trapped ion systems, semiconductor quantum dots, superconducting circuit-based systems (next page), and diamond nitrogen-vacancy centers.

In the conceptually simplest case, a qubit uses two energy levels of an atom. Thus, the atom interacts with light at certain frequencies to activate the transitions between the ground and excited states. But the coupling between the atom and the interacting light is normally very weak. An optical cavity with mirrors enhances the interaction. Photons bouncing between the mirrors pass by the atom multiple times. A single atom can induce large enough changes in the electromagnetic fields of the optical cavity light waves to allow measurements.

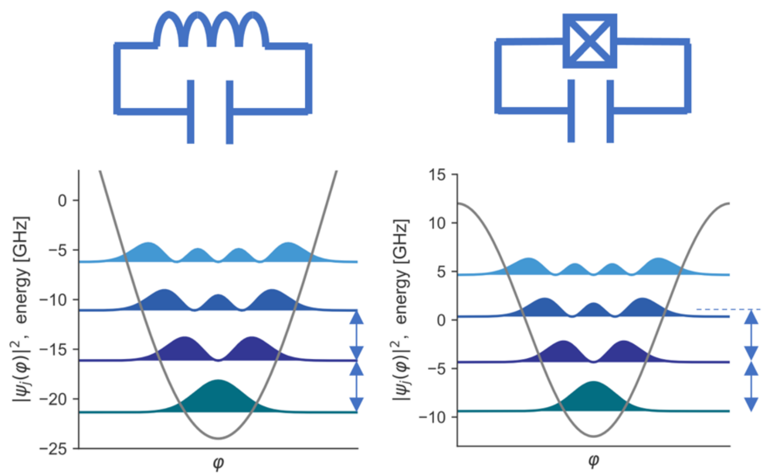
Each qubit type has particular advantages and disadvantages. Two qubit types that have been heavily developed are the ion-based and the superconducting circuit-based systems. Trapped ions have a longer coherence time compared to the circuit but the gate operation time is faster in the superconducting circuit.

The core elements of the trapped ion qubits are single ions (charged atoms) trapped in electric fields. The energy levels of their intrinsic spin form the qubit. Such a system uses laser pulses to change the energy level of laser-cooled ions.




https://www.science.org/content/article/scientists-are-close-building-quantum-computer-can-beat-conventional-one

# Superconducting Circuit Qubits




The strong interaction between an optical cavity with atoms (described on the previous page) can be translated to microwave photons and resonant electrical circuits, or to microwave cavities. This analog carries the name “circuit quantum electrodynamics” or circuit QED (cQED). QED is the quantum theory of electrodynamics covering the interaction of light with matter.

In circuit QED, qubits derive from an electrical circuit that behaves exactly like the optical cavity-atom system. In the 2D version, the ”cavity” is a harmonic oscillator circuit consisting of inductors and capacitors where the energy oscillates between the capacitor and the inductor. The qubit transition frequency depends on the capacitances and inductances in the circuit. The inductors are made from superconducting elements for high - quality factor (Q, a metric of how well they resonate), leading eventually to high coherence qubits.

However, the 2D harmonic oscillator circuit by itself cannot be used to provide qubit states. All the different states form a ladder with equal spacing so that photons would drive the system from one state to the next higher energy state, or all the states up the ladder without control.

To operate as a qubit, two adjacent resonant energy levels must be made uneven so they can be distinguished. An additional circuit element is needed to make this change. With uneven levels, the control signals can only make changes between chosen quantum states, the lowest energy levels serve as the two states of the qubit, |0⟩ and |1⟩.

That change to the circuit is made by substituting the inductor with a Josephson junction (see next page) to create what is known as a transmon qubit. The junction behaves like a non-linear inductor due to the Josephson effect. With a Josephson junction, the energy transitions of the different states will be different.

The Josephson junction makes the step between the two levels unique. Microwaves at a frequency of several GHz transfer the circuit from a “ground” state to the ”first excited state” (|0⟩ to |1⟩) without accidentally energizing other states. The superconducting circuit-based qubit with the transmon is called an “artificial atom” because it behaves like an atom with two quantum energy levels.

The transmon-based superconducting qubit has been one of the most widely deployed versions for implementing quantum computers.

# Superconducting Qubit Controls

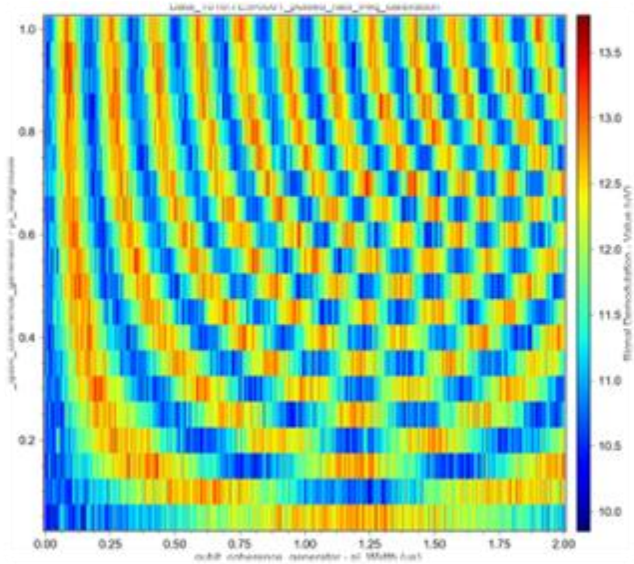
When the drive frequency (e.g. 4 – 6 GHz) is resonant with the fundamental transition frequency of the transmon, the transmon undergoes a Rabi oscillation—sequential stimulated absorption and emission of photons.

By using different pulse lengths, Rabi oscillations provide essential tools to prepare arbitrary quantum states of the transmon qubit. The pulse duration controls the angle of rotation of the qubit state around the Bloch sphere. Different pulses form different quantum gates. To make a measurement, the electronic system sends a microwave signal to the qubit and analyzes the signal it reflects back. The amplitude and phase of the reflected signal depend on the qubit state.

Superconducting qubits fabricated using advanced solid-state technology offer fast gate speeds. By using superconducting materials, losses due to electrical resistance are greatly reduced, preserving long coherence times.

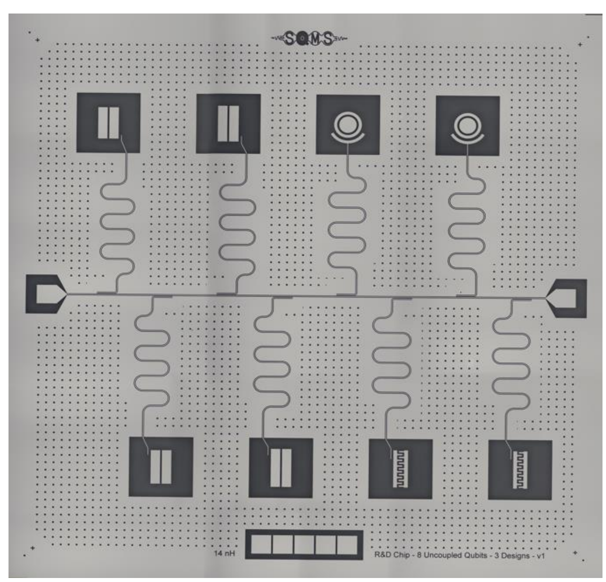
Compared with the qubits based on other quantum systems, superconducting qubits based on the semiconductor microfabrication process and advanced chip-making technologies have high designability and scalability.

It is easier to couple multiple qubits together as well as to control and operate the qubits with microwaves. The disadvantages are the short coherence times (< millisecond) and the need for dilution refrigerators to provide ultra-low temperatures.



*Rabi Oscillations*

Transmon circuits are scaling up to many tens of qubits. A superconducting quantum bus around the qubits controls their interactions to entangle multiple qubits so qubits work together to form a large-scale quantum processor. Corporations such as IBM, Google, Rigetti, Alibaba, Quantum Circuits, and others, with experience in large-scale semiconductor systems, use the superconducting qubit.



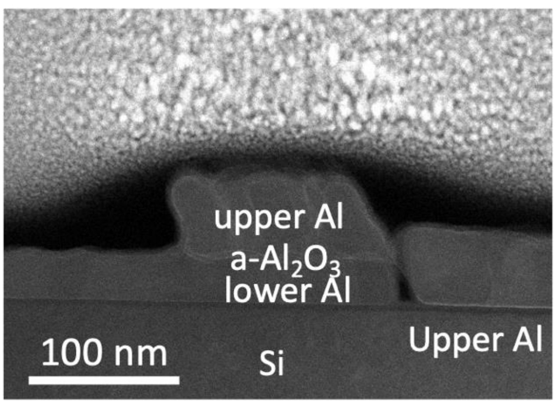

*SQMS Superconducting Qubits*

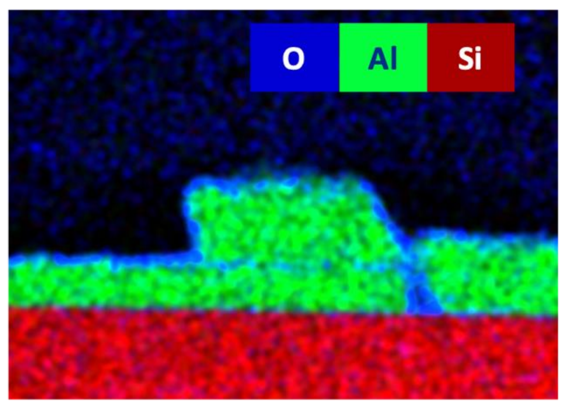
# Josephson Junctions & Transmons

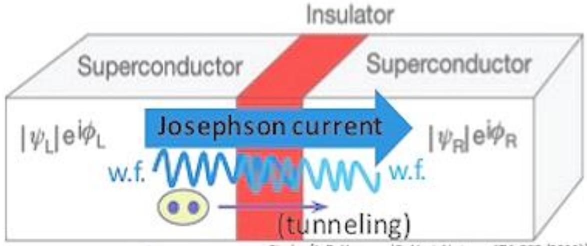
As a Ph.D. student, Brian Josephson showed how two superconducting islands coupled with a thin oxide layer led to the desired new circuit element for creating unequally spaced energy levels. If classical physics were applied, the oxide layer would act as a barrier to prevent the flow of current between the islands. But in the quantum world operating at the junction, super-current carrying Cooper pairs tunnel through from one superconducting island to the other. The supercurrent can flow across the barrier until a critical current is reached. The Josephson effect is due to the overlapping wave functions of the two superconductors.

Josephson derived the relationship between the tunneling current and the voltage difference to show that the junction behaves as a non-linear inductor to provide the needed non-uniformly spaced energy levels for the harmonic oscillator.

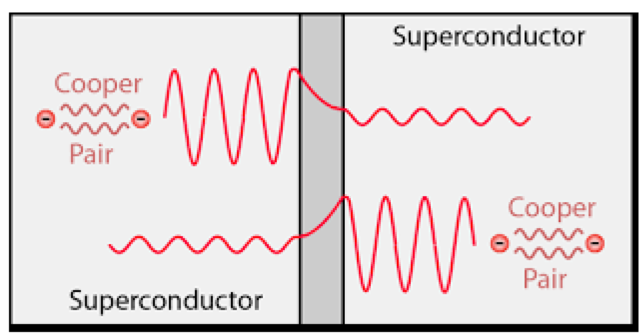
The circuit behaves like an artificial atom embedded into a resonating structure and couples to the modes of the resonator with the dipole antenna. GHz frequency microwaves transfer the circuit from a "ground state" to the "first excited state" to operate as a qubit.



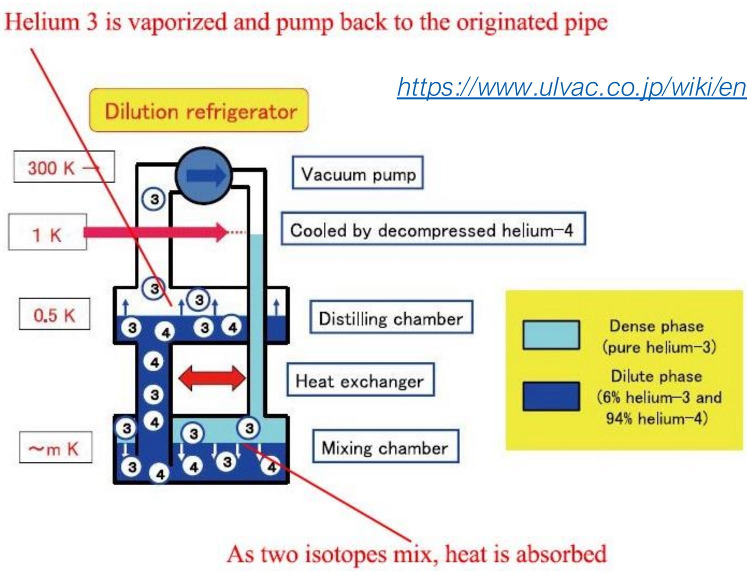




https://phys.org/news/2019-03-breakthrough-quantum-tunnelling.html



# Helium-3 Dilution Refrigerators




Many types of disturbances can knock a qubit out of its delicate state of superposition, causing decoherence. To minimize decoherence, quantum computers must be isolated from all forms of thermal and electrical interference. Qubits must be chilled close to 10 — 20 millikelvin above absolute zero, colder than outer space. This is done by using a mixture of Helium-4 and another isotope, Helium-3. Naturally occurring He-3 is extremely rare. But it can be manufactured, as it is a radioactive decay product of tritium ($^3$H), an isotope of hydrogen produced in nuclear reactors. The two isotopes behave differently below 2.17 K. The He-4 atoms are bosons that fall into a superfluid condensate with zero viscosity. He-3 atoms are fermions that stay in the liquid state with normal viscosity.

The dilution refrigerator uses mixtures of He-4 and He-3 in a system of pipes and chambers. Inside a mixing chamber near the bottom of the refrigerator, there is a physical separation between two phases, one with a high and one with a low concentration of He-3 due to the different mass densities of the two isotopes.

A small number of He-3 atoms move into the He-4 superfluid liquid, almost as into a vacuum. The transition from the concentrated to the dilute phase is equivalent to an evaporation process, with cooling, where energy is taken from the thermal energy of the environment, which consequently cools down. The quantum processor sits at the cold bottom inside a light-tight and magnetic-field shield to isolate the qubits from environmental disturbances.

Cooling continues until the equilibrium concentration of about 6% of He-3 atoms is reached. However, the He-3 concentration can be artificially decreased by connecting the dilute phase to an upper distilling chamber where a turbomolecular pump is connected to reduce the concentration of 3He. After evaporating from the still, the He-3 is cleaned in a liquid nitrogen cold trap, compressed, and liquefied on its way back to the dilution unit, where it is re-inserted into the He-3-rich phase. So, the cooling process continues in a cycle.

# Errors and Corrections

**Decoherence and Errors**

Quantum computers are highly error-prone because of qubit decoherence. Errors in a quantum computation will ruin the entire algorithm. Many types of small disturbances can knock a qubit out of its delicate state of superposition

**Classical Error Detection and Correction**

In classical computers, the probability of an error in any given operation is usually less than 1 part in $10^{18}$. The zeros and ones in classical computer memory so rarely switch by accident that little error correction is needed.

Nevertheless, error-correcting codes are possible by just copying the information many times to ensure correct representations Errors can be corrected, for example, using the majority rule: A desired bit, whether 1 or 0, is first triplicated as 111 or 000. Later, even if one of the three bits has been corrupted, the other two "outvote" it, and allow recovery of the original data.

**Quantum Error Detection and Correction**

Quantum error correction faces many challenges. Looking at a quantum state destroys the information contained within, making it impossible to copy a quantum state. The "no-cloning" feature forbids the duplication of a qubit and any data back up. A quantum state has to survive on its own from start to finish during an algorithm.

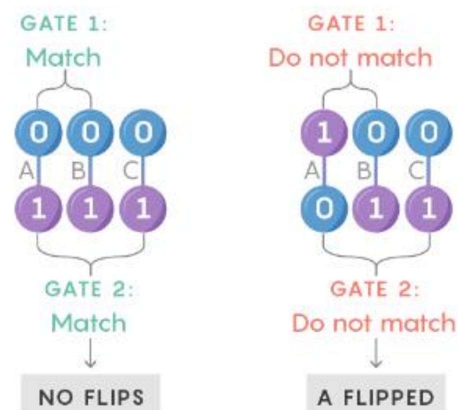
Even though it is impossible to measure the state of a qubit, it is still possible to measure relationships between entangled qubits without measuring the values stored by the qubits themselves.

The method resembles the “majority rule” method for classical computing.

The strategy for error detection and correction is to add additional qubits and gates, as with classical computers.

Instead of using a single qubit of data, we can use three entangled physical qubits with correlated states. It is possible to determine whether the first and second qubit maintain their correlation and whether the second and third qubit have the same relation, without determining what that state is or destroying it. These two measurements suffice to determine whether one of the three qubits was flipped, and which of the three it is, without providing any information about what the actual values are. If one of the qubits disagrees with the other two, it can be reset to its proper value by performing an appropriate gate operation to flip the state, even without knowing its value. Beyond adding qubits, there are other methods of error correction discussed later.

For quantum processing, gate error is the precision of applying a quantum gate. Currently, the best two-qubit quantum gates have an error rate of around 0.5%, meaning one error for every 200 operations. Quantum computing researchers are working towards an error rate of $10^{-3}$ in about $10^3$ qubits.




*From Quanta Magazine*

# Logical Qubits

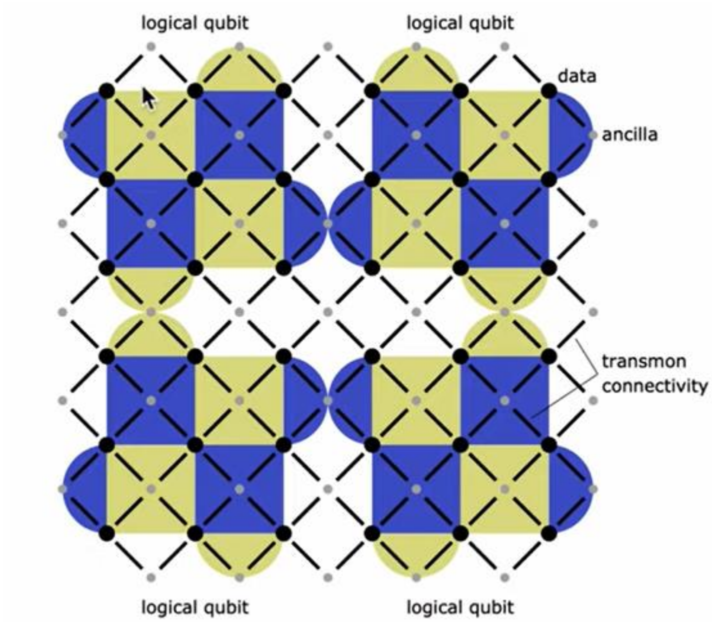
It will be many years before we have quantum computers that will be broadly useful. The primary reason is that the number of qubits available today is relatively small and developers struggle with high error rates. Quantum error correction is what will ultimately enable quantum computers to scale successfully beyond a couple of hundred qubits.

Error-corrected machines will achieve true quantum advantage, outperforming classical computers. Quantum Error Correction can eventually be used to define fault-tolerant logical qubits. A logical qubit comprises multiple interconnected qubits that work together as a single qubit, which is more stable and less prone to error. As discussed on the previous page, adding more qubits reduces errors, while smart quantum algorithms compensate for errors.

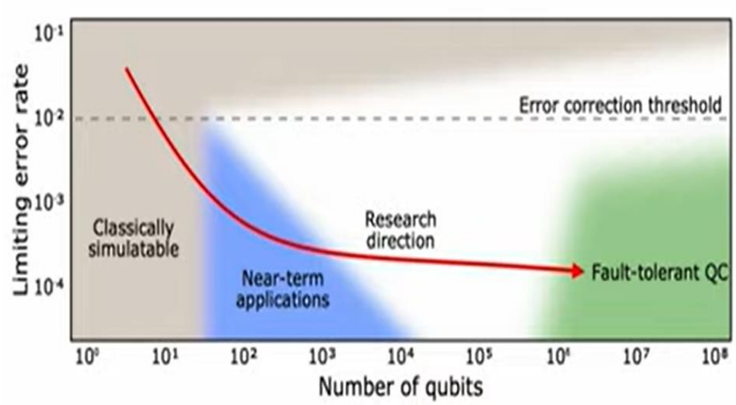
However, it will likely take many hundred standard qubits to create a single, reliable "logical" qubit, depending on the underlying coherence of each physical qubit. 200 physical qubits per logical qubit could dramatically reduce the error rate to 1 in $10^{15}$, comparable to present classical computers.

Reliable quantum simulations will need about 100-150 logical qubits. 200 logical qubits would open the door to quantum chemistry, and 5,000 logical qubits would open transformative application possibilities. It will take 4000 logical qubits to break RSA encryption used widely today with a 2048-bit key.

This could be less, depending on the cleverness of the algorithms used. If heavy error correction is required with a 1:1000 logical-to-physical ratio, then this factoring could not be accomplished until about the year 2040.

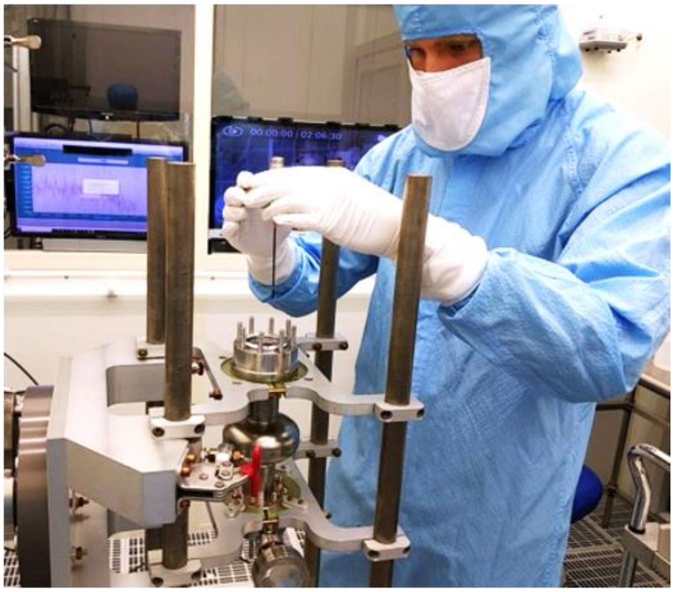



*Nine qubits (dots) represent a single logical qubit*

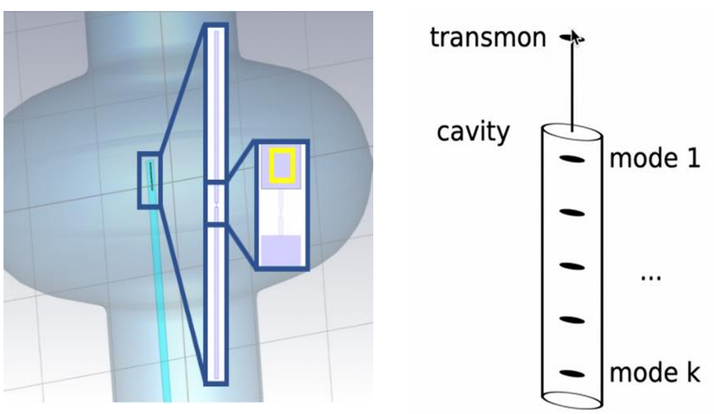



*How the limiting error rate needs to improve along with the number of qubits for a quantum computer to progress from the present stage of 100s qubits to a future stage of fault-tolerant quantum computing.*

# Superconducting Cavity Qubits



*Superconducting cavity qubit. The Josephson junction is inserted from the beam tube via a sapphire rod to couple to the electric fields of the SRF cavity to induce a strong coupling between the charge in the junction and the electric field of the wave.*




*Expanded color detail shows the transmon (right). A single transmon controls and processes many qubits through the modes of the cavity.*

The alternative to massive error correction is to dramatically increase the coherence time of qubits. SRF cavity-based qubits, which store information in photons trapped in a cavity, offer this exciting possibility. Fermilab is a world leader in SRF cavity technology, and the FNAL SRF niobium cavities routinely achieve very high-quality factors Q from $10^{10}$ to $>10^{11}$, which can lead to dramatic increases in coherence time. These Q values are much higher than typical values ($10^8$) reported with 2D superconducting circuits with best coherence times that approach one millisecond.

In a 3D cavity, the increased volume occupied by the electromagnetic fields for similar surface currents allows for higher Q's. Therefore, niobium SRF cavities provide a promising approach for 3D circuit QED architecture for quantum computing or for quantum memory, with the potential of a thousand-fold increase in the photon lifetime and qubit coherence. The enclosing superconducting cavity also serves as an effective shield for the embedded Josephson junction-based transmon. Cavity QED using superconducting transmon circuits is an extension of circuit QED.

The cavity provides the possibility to encode several qubits inside each of the cavity-transmon modules using qubits stored in cavity modes. The transmon can load, store, and interact with one mode at a time. This approach allows for a substantial decrease in the required number of microwave channels for system and control manipulations.

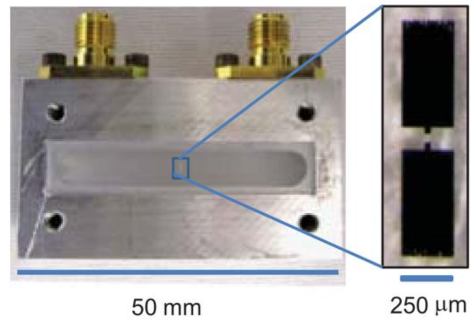
# Superconducting Cavity Qubits

Scientists at Yale invented cavity QED with a superconducting circuit Josephson junction. A superconducting qubit strongly interacts with photons in a microwave cavity. The Aluminum superconducting cavity has two antennas that can be used to feed signals via connectors into the cavity and allow for transmission.
Niobium SRF cavities provide a promising approach for 3D circuit QED architecture for quantum computing or quantum memory, with the potential of a thousand-fold increase in the photon lifetime and, therefore, cavity-stored quantum state coherence times. The enclosing superconducting cavity serves as an effective shield for the embedded Josephson junction-based transmon.

By minimizing losses that result from the native oxide on Nb through optimized annealing, scientists at Fermilab have demonstrated record coherence niobium cavities with photon lifetimes of up to 2 seconds. Operating at resonant frequencies 1.3, 2.6, and 5 GHz, at temperatures of about 10 mK and field levels down to a few photons, we have successfully demonstrated a reduction in two-level systems losses up to 200x beyond the present state-of-the-art.

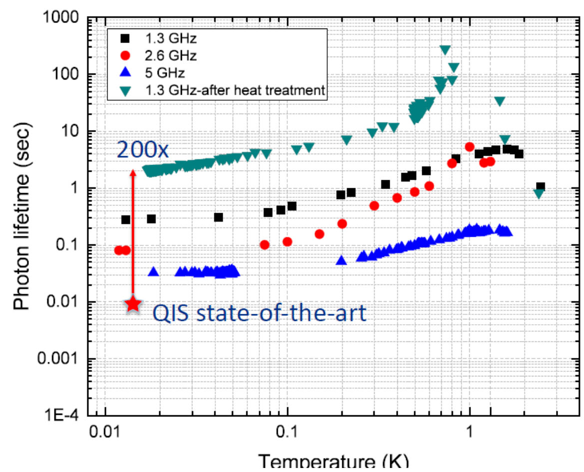
With enormous coherence times available with SRF cavities, the absence |0⟩ or presence |1⟩ of microwave photons in specific cavity quantum states can provide “error-free” cavity-based logical qubits.

It’s on these foundational results and the exciting prospects of revolutionizing quantum computing platforms with SRF technology that we built the vision for the SQMS Center.

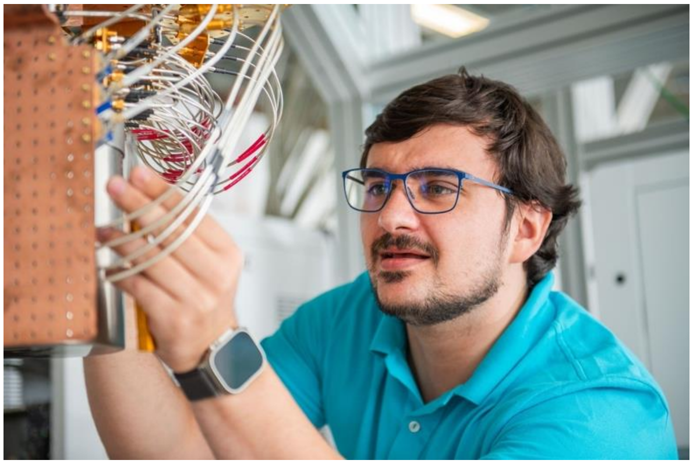


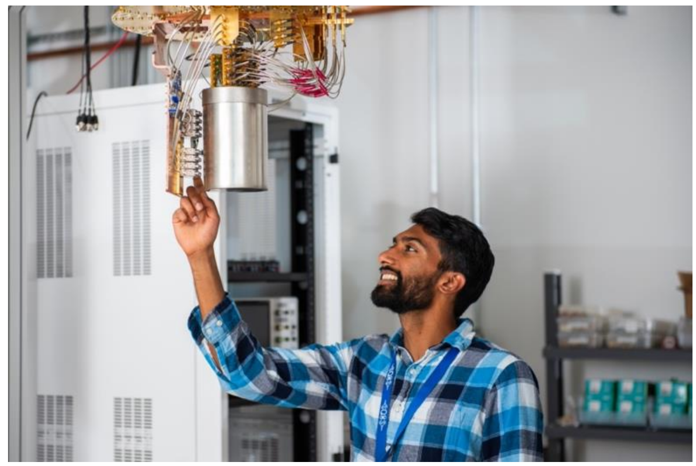

*Hanhee Paik et al., 2011*

*Single - cell cavities measured for Q at low temperatures. From left to right, the frequencies are 1.3, 2.6 and 5 GHz.*




*Photon lifetimes with Fermilab Nb cavities after reducing TLS losses with 340 C vacuum baking. Even prior to baking , record lifetimes can be achieved.*






# A Department of Energy National Quantum Information Science Research Center

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Fermilab

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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# The SQMS Center

The Superconducting Quantum Materials and Systems Center, led by Fermi National Accelerator Laboratory, is one of the five National Quantum Information Science Research Centers funded by the U.S. Department of Energy, as part of a national initiative to bring revolutionary advances in quantum technology and quantum science.

The SQMS mission is to enable the deployment of beyond-the-state-of-the-art quantum computers and sensors applying technologies developed by the Department of Energy for the world's most advanced particle accelerators.

SQMS brings together more than 500 experts from over 30 partner institutions —national laboratories, academia and industry—in a mission-driven, multidisciplinary collaboration that integrates deep expertise in quantum information science, material science, applied and theoretical superconductivity, computational science, particle and condensed matter physics, cryogenics, microwave devices and controls engineering, industry applications and more.

Integrating world experts in these areas from the U.S., U.K., Italy and Canada, the SQMS Center has become one of the world's largest hubs for the advancement of quantum technologies.

# SQMS Research Areas

Our research focuses on attacking the major cross-cutting challenge in the field of QIS of extending the lifetime of quantum states. This lifetime, known as coherence time, is the length of time that a qubit can effectively store and process information.

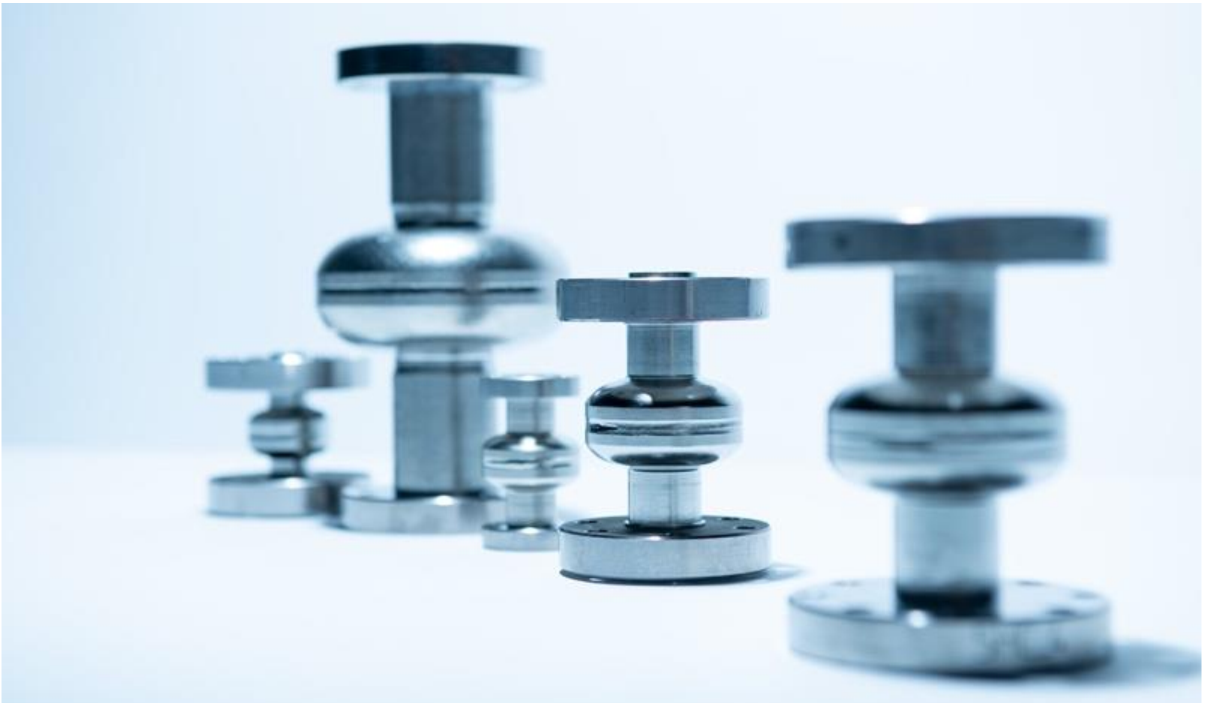
Understanding and mitigating the physical processes that cause decoherence and limit the performance of superconducting qubits is critical to realizing next-generation quantum computers and sensors. Decoherence makes performing precise calculations with few to no errors a non-trivial task. This phenomenon is an obstacle researchers need to overcome to make quantum computers a viable technology.

The SQMS Center is taking a materials science-based approach to tackle this challenge. The Center has built a first-of-its-kind, broad coalition of experts studying quantum devices at the frontier of coherence, using the world's most advanced characterization tools, including DOE accelerator-based user facilities.

Leveraging Fermilab's unique expertise in building particle accelerators and cryogenics systems, the SQMS Center aims at bringing critical technological capabilities to the QIS field, to successfully scale up complex quantum systems.

The Center brings together a coalition of hardware and applied researchers working in co-design, exploring early-stage applications of quantum technologies.

In alignment with Fermilab's core mission in particle physics, the Center has already demonstrated the first applications of quantum sensors as detectors for new particles with world-leading sensitivity.



## Understanding Quantum Decoherence

SQMS researchers use a broad array of specialized material characterization techniques to study dissected cavities and qubits of varying performance levels. Scientists apply these techniques to gain insight into the nanoscale and atomic-scale mechanisms limiting quantum coherence to advance the performance of quantum devices.

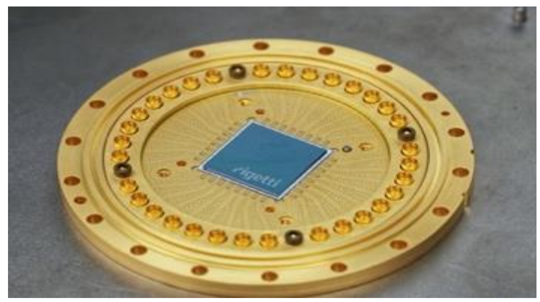
## Ultra High-Q SRF Cavities

The SQMS Center is exploring the use of its world-record quality-factor SRF cavities as building blocks of quantum computing platforms that promise orders of magnitude in performance improvements and scalability over the current state-of-the-art commercial platforms. We are also exploring SRF-based quantum memories and transducers.

## Superconducting Qubits and Processors

SQMS is on a mission to bring dramatic performance improvement to superconducting devices. Working hand in hand with quantum industry leaders, we have created a national nanofabrication taskforce that leverages several foundries and has demonstrated systematic performance improvements with newly developed fabrication processes.

## Algorithms, Simulations and Benchmarking




Researchers are tailoring algorithms to efficiently process information on the SQMS SRF QPUs and exploring the use of commercial quantum platforms and benchmarking computational capabilities of different hardware. Applications range from fundamental physics simulations for high-energy and condensed-matter physics to finance to MRI.

## Quantum Sensing for Fundamental Physics

The exquisite sensitivity of the Center's high-coherence devices offers new platforms with reach into unexplored regimes. Researchers focus on search for particles beyond the Standard Model, dark matter candidates, gravitational waves, measurements of fundamental properties at the precision frontier and tests of quantum mechanics.

## Scaling up milli-Kelvin Cryogenics

SQMS is developing the world's largest and highest cooling power dilution fridge, capitalizing upon Fermilab's unique facilities and expertise in cryogenics. Engineers are also developing critical technologies to enable scaling up to future large quantum computing data centers.

# SQMS Center Research:
## multidisciplinary, integrated, synergistic approach

**Superconducting qubits**

*Rigetti, NIST, NU, FNAL, INFN, Colorado Boulder, Rutgers, NPL, RHUL*

**Theory and Applied Superconductivity**

*FNAL, NU, Temple, IIT, LSU*

**Controls and electronics**

*Rigetti, NIST, NU, FNAL*

**Scale up and integration**

*FNAL, Rigetti*

**Materials Science**

*Ames Lab, NU, FNAL*

**SRF high Q devices**

*FNAL*

**Cryogenics**

*FNAL, NU, Royal Holloway, Form Factor*

**Enabling thrust: Quantum Technology**

- **Focus Area 1** — Materials for 2D and 3D Quantum Devices
- **Focus Area 2** — Devices Integration, Prototypes and QPU

**Co-design Cycle**

**Application thrust: Quantum Science**

- **Focus Area 3** — Quantum Physics and Sensing
- **Focus Area 4** — Algorithms, Simulations and Benchmarking

**Particle Physics**

*FNAL, UIUC, Stanford, INFN, John Hopkins*

**Computational Science, QIS Theory**

*NASA Ames, Colorado Mines, Rigetti, NU, Arizona*

**Condensed Matter Physics**

*Ames Lab, NU, NASA Ames, LSU*

**Industry use cases**

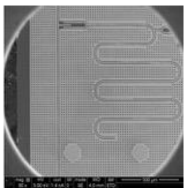
*Goldman Sachs, Lockheed Martin, Rigetti, NYU*

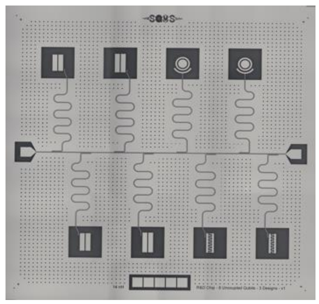
# SQMS Technology Thrust

### Focus Area 1: Materials for 2D and 3D quantum devices

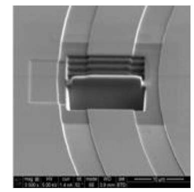
Goals: Understand and mitigate the key limiting mechanisms of coherence in superconducting qubits, such as losses in two-level systems in oxides, non-thermal quasiparticles, and the bulk substrate.

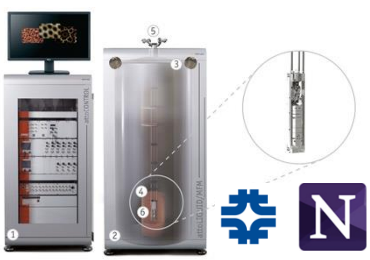
- Demonstrate a jump of at least an order of magnitude in coherence times with superconducting 2D transmons with coherence up to milliseconds, along with a decrease in performance spread to enable the high coherence multiqubit processors.
- Demonstrate SRF cavities with coherence times up to tens of seconds.



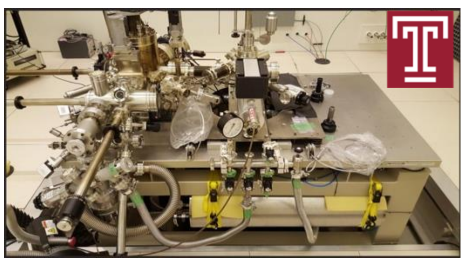



*Methodology: Correlate and understand the performance of quantum devices by studying the 'good vs bad' performing qubit fragments*

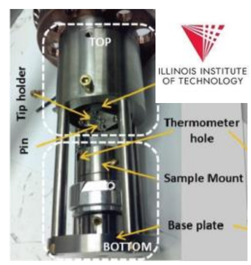




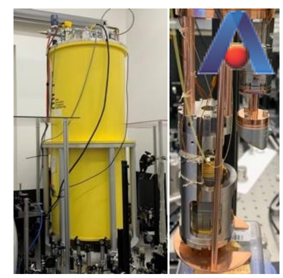
**PPMS- AFM/MFM**



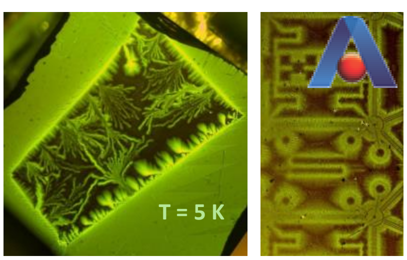
**STM**



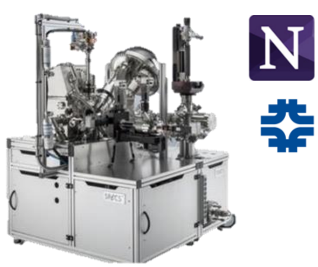

**Point-Contact Tunneling**



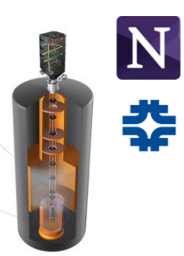
**THz Spectroscopy**




**Magneto-optical**



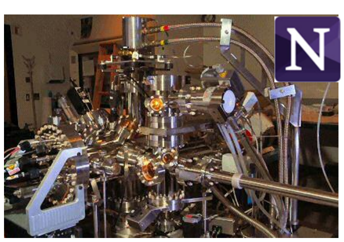
**XPS**



**AFM/MFM**


**Raman**

**Electron Microscopy**



**APT**

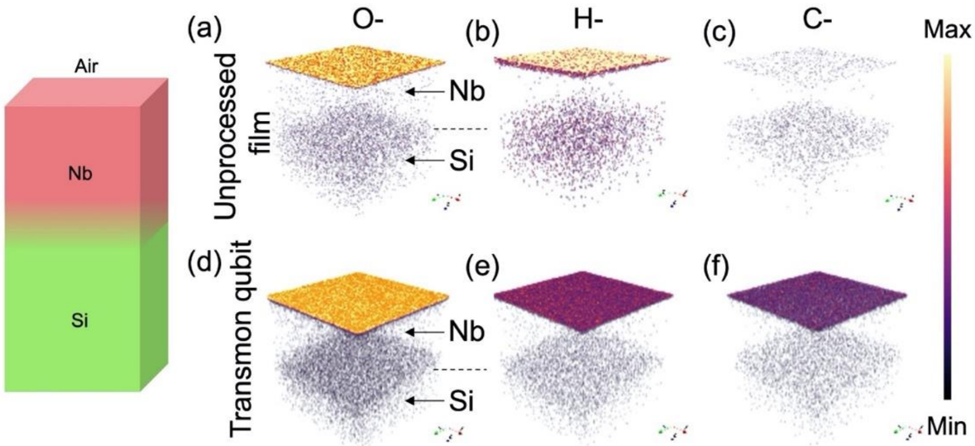
**TOF-SIMS**

**XRR/XRD**

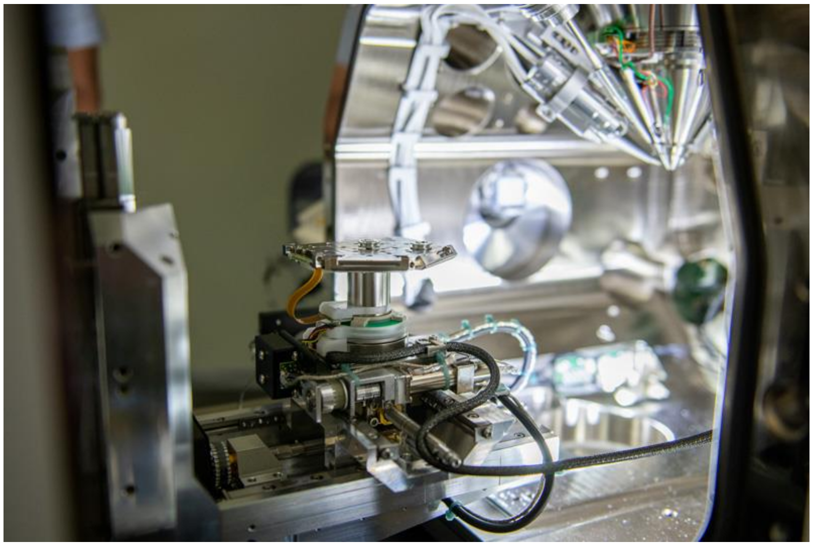
# SQMS Technology Thrust

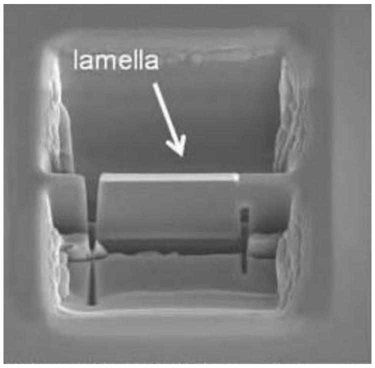
## Focus Area 1: Materials for 2D and 3D quantum devices

The SQMS collaboration has launched the largest systematic investigation into the origin of decoherence in materials. By studying performance differences of state-of-the-art qubits with the world's most advanced characterization techniques, together with superconducting and materials modeling efforts, the Center is building a hierarchy of loss mechanisms that informs how to fabricate the next generation of high-coherence qubits and processors. Some examples of advancements are given below.




Through a three-dimensional analysis of the qubit at the atomic level, SQMS scientists used for the first time TOF-SIMS to reveal impurities such as oxygen, hydrogen, carbon, chlorine, fluorine, sodium, magnesium and calcium. TOF-SIMS, or time-of-flight secondary ion mass spectrometer, fires ions at a qubit and chips away at it. The ions are analyzed with part per million accuracies. With the employment of this technique and of electron microscopy, for the first time applied at cryogenic temperatures, we have identified new features such as nano-hydride formation as one of the factors that contribute to short coherence times.

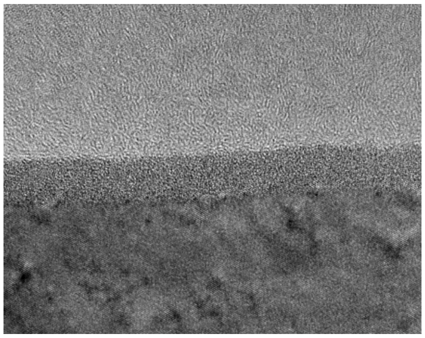


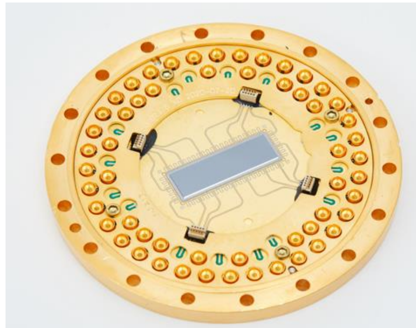


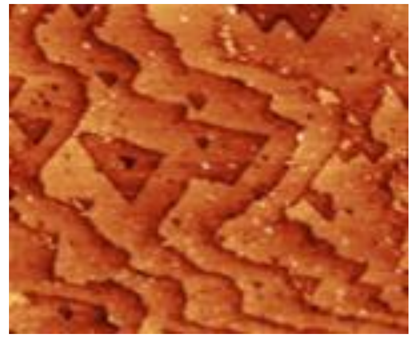

*The focused ion beam instrument is used to look at the surface of superconducting qubit devices after preparing thin lamellas of specific regions of the device for transmission electron microscopy analysis.*

# SQMS Technology Thrust

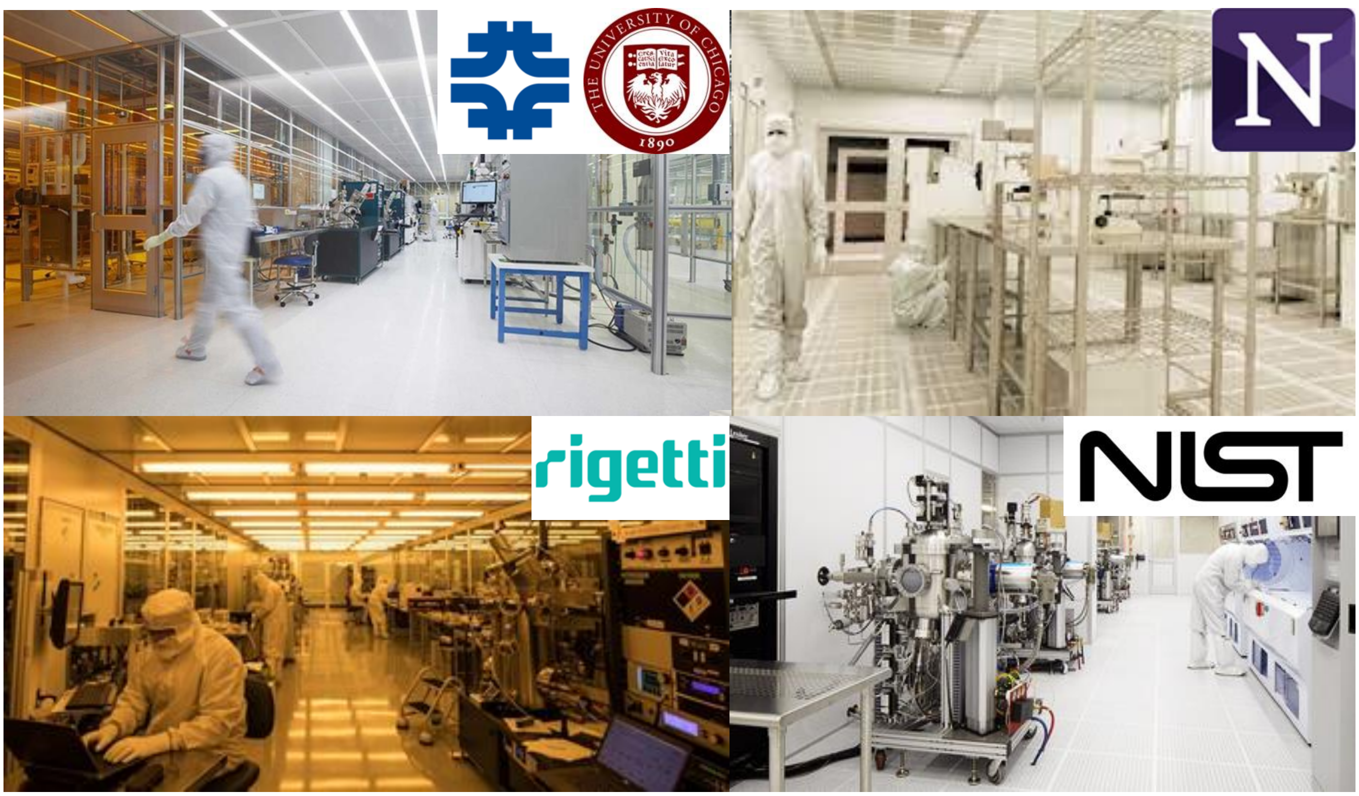
## Focus Area 1: Materials for 2D and 3D quantum devices







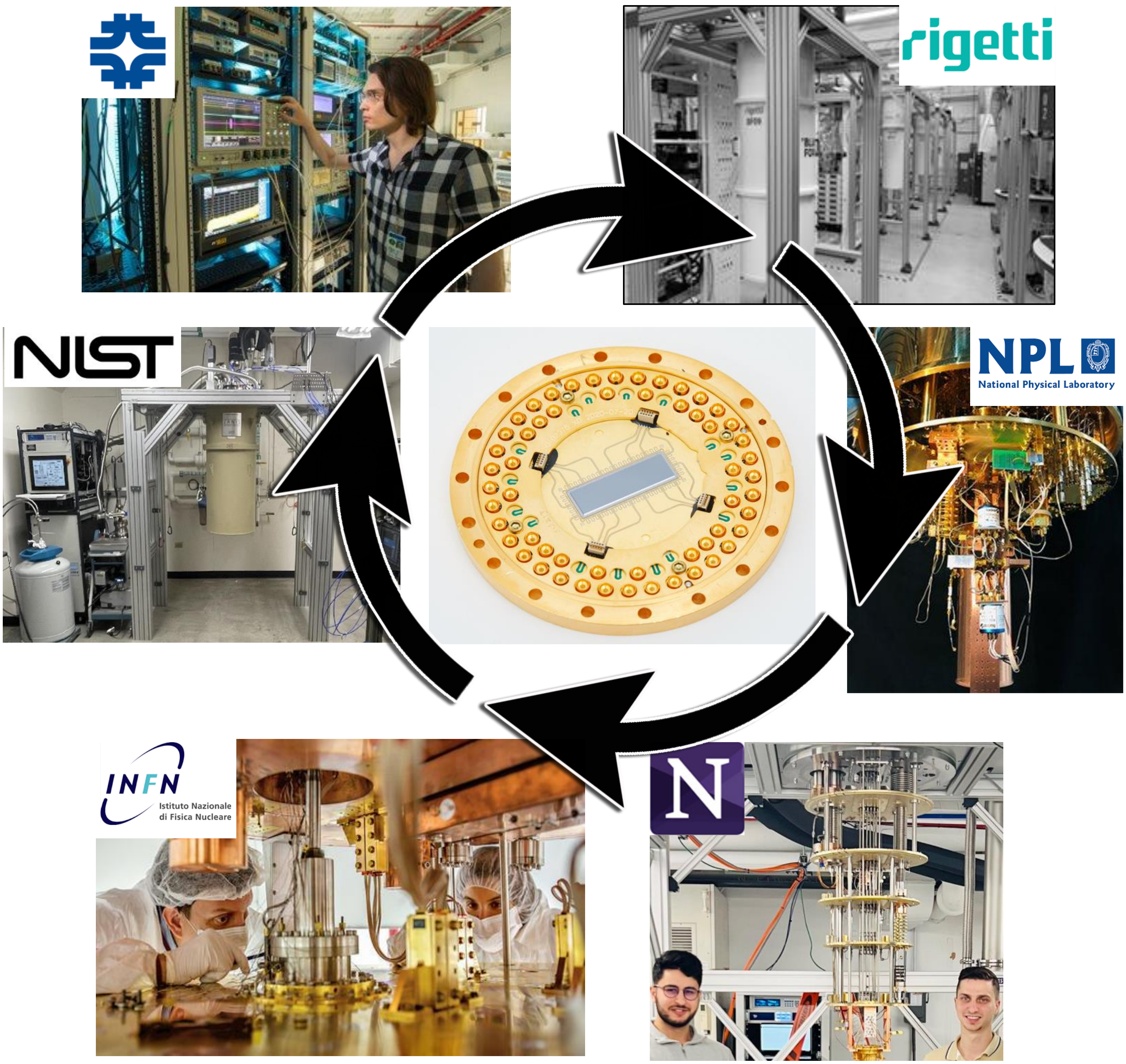
The knowledge advances in sources of decoherence coming from the materials efforts guide the development of new processes for quantum device fabrication. SQMS has established the first national Nanofabrication Taskforce, bringing together qubits fabrication experts from Fermilab, NIST, Northwestern, and Rigetti, making devices with new common processes, and verifying the reproducibility of results across four different state-of-the-art foundries. The first results include newly developed innovative fab techniques, such as niobium surface encapsulation and silicon surface passivation, which have systematically improved transmon qubits' performance.



# SQMS Technology Thrust

## Focus Area 1: Materials for 2D and 3D quantum devices

SQMS has launched the Round Robin experiment, the first international qubit chips exchange to study and compare the performance of the same qubits at different test sites around the world. The collaboration has worked in the first two years to streamline test setups, control systems, qubit fixtures, and packaging and measurement protocols. The underground INFN facility allows for comparison to above ground for possible effects of environmental radiation. Combining measurements with advanced diagnostics, we are shedding new light on the origin of decoherence and performance variations, intrinsic and extrinsic.



# SQMS Technology Thrust

## Focus Area 2: Devices Integration, Prototypes and QPUs

Goals: Pursue device integration and quantum control development for 2D and 3D superconducting architectures to develop quantum computer prototypes with transformational performance in coherence and control.

Build and deploy:

- Quantum computer prototypes based on 3D and 2D architectures

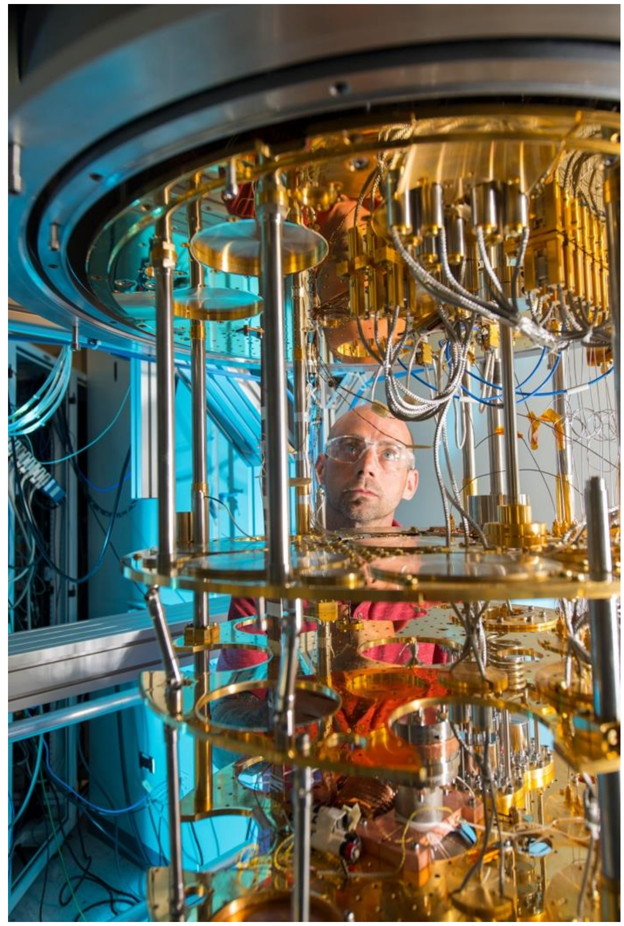
- Build and deploy a 2-meter-diameter dilution fridge to host both the 3D and 2D quantum processors.

In this focus area, we use the advances in coherence reached in the materials focus area for both 2D and 3D devices and work to translate those into quantum processor architectures with ultimately higher performance than the state of the art.

Advances in 2D transmon qubits feed into work hand in hand with our industry partner Rigetti Computing, with whom we are co-designing a new processor that takes advantage of these new fab processes.

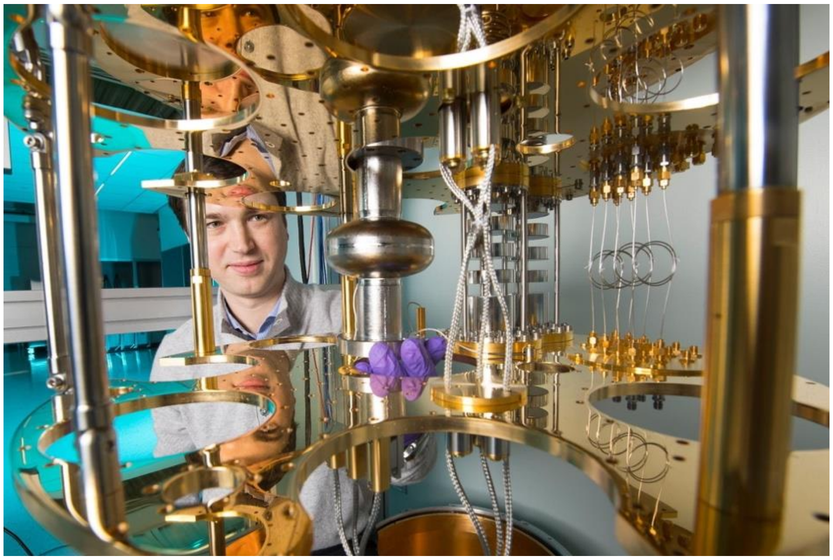
At the same time, these advances are critical to ensure the 2D qubit ancillas we use for our 3D SRF based processors are the best possible, enabling to take full advantage of the 3D SRF high coherence cavities.

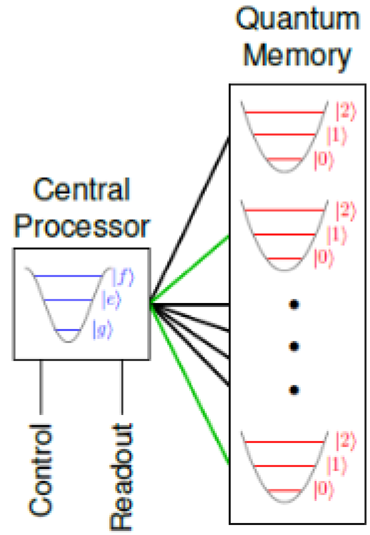
In the next few pages, we zoom in on the details and advantages of 3D cavity-based architectures.



*Colossus: SQMS is developing the world's largest and highest cooling power dilution fridge, capitalizing upon Fermilab's unique facilities and expertise in cryogenics.*

# Single-cell Cavity Qubits






Cavity QED using superconducting cavities is an extension of circuit QED. One challenge in circuit QED is the realization of architectures with high qubit connectivity for the rapidly rising numbers of qubits. Classical computer architectures typically address this challenge using a central processor that randomly accesses a large memory. The two elements often comprise distinct physical systems. A quantum analog realizes a random-access quantum information processor using cQED as processor and quantum memories based on cavity modes.

Quantum behavior in cavities is most obvious in cavity modes excited with specific numbers of energy quanta. But cavity-mode based quantum memory qubits are incapable of logic operations on their own. A single logic-capable processor qubit, such as the transmon, supports many cavity mode-based memory qubits.

This architecture allows control of many highly coherent qubits with minimal electronic overhead to expand the capability to build larger systems. The cavity exhibits a frequency shift dependent on the qubit state.

This interaction between the qubit and the cavity allows for the exchange of coherent quantum information, as well as enabling entanglement between the two. It is also possible to create large entangled states of this memory using cavity QED with superconducting circuits.

In principle, it is possible to encode with a single transmon up to 14 qubits inside each of the cavity-transmon modules, substantially decreasing the required number of microwave channels for system control and manipulation for a large number of qubits.

Here, the very long (seconds) coherence time in SRF cavity modes will ultimately allow the creation, control, and manipulation of up to $2^{14}$ (16,000) microwave photon energy levels, limited by residual nonlinearities and photon loss. Instead of using quantum states in the transmon (coherence times in the milliseconds), we can use quantum states in the resonator, which have higher Q's and higher coherence times.

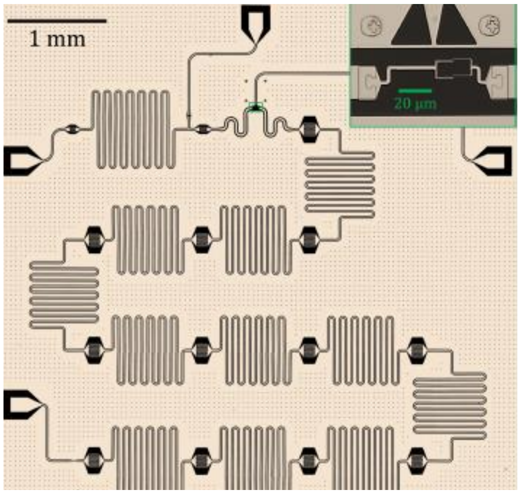
# Multi-cell Cavity Qubits

Multimode cavity QED using superconducting circuits and multi-cell cavities can be used as quantum memories to store larger numbers of qubits. This approach has been pioneered and successfully demonstrated by several leading groups, most notably Yale University to create high-quality factor resonators with tens of modes with their quantum state being controlled by a single Josephson junction circuit. The multiplexed approach can realize a powerful medium-sized quantum processor in the near term.

Yale researchers demonstrated a quantum processor based on controlling 11 coupled 3D cavities with a single transmon. A universal set of quantum gates on 38 arbitrary pairs of modes has been performed and multimode entangled states have been prepared, all using only two control lines. Long-lived quantum memories comprised of bulk, SRF cavities are a particularly enticing architecture toward demonstrating quantum advantage in the near term.

Based on this success, a processor can be implemented, for example, with a 9-cell cavity as memory demonstrating universal operations, with a Josephson junction transmon circuit serving as the central processor. The quantum memory is the multimode cavity, using the modes of the 9-cell coupled niobium superconducting resonator. Replacing a system of many two-level qubits with a 9-cell cavity will drastically reduce the hardware cost and complexity requiring fewer components.

However, introducing higher dimensional system with nine modes raises the issue of how to realize complete control over the system, with more complex gates and longer gate times.




*The circuit comprises an array of 11 co-planar waveguide (CPW) half-wave resonators, capacitively coupled to each other. The top end of the array is capacitively coupled to a tunable transmon qubit. The inset shows the tunable transmon.*

*RK Naik et al. "Random access quantum information processors using multimode circuit quantum electrodynamics" Nature Communications 8.1 (2017), p. 1904.*

As a possible example for the future, the very long coherence in SRF cavities offer transformational advances, ultimately allowing creation, control, and manipulation up to $2^{14}$ (about 16,000) microwave photon energy levels in each cavity mode (limited by residual nonlinearities and photon loss), which in turn corresponds to 14 qubits for a cavity mode.

This translates to 126 qubits (9x14) for a single mode in the 9-cell SRF cavity. By using two high Q cavities, the corresponding number of cavity qubits could be 2x126=252.

The convolution of a high number of qubits together with dramatically higher quality coherence will result in computers for the quantum advantage era.

# Cat States and Error Correction

Any quantum superposition of two macroscopically distinct states is referred to as a cat state. For example, consider the interaction between an optical cavity containing a single trapped atom that is in a superposition of two states (“spin up” and “spin down”). When the light pulse in the optical cavity interacts strongly with the atom, the light pulse is brought into a superposition state as well. The light pulse becomes entangled with the atom just as the hypothetical “cat” is entangled with the radioactive atom in Schrödinger's paradox setup.

Consider two quantum cat-states connected via entanglement, for example, via a two-cavity quantum system. Here, the role of each “cat” is played by the light waves, and “life” and “death” roughly correlate to the directions of the electromagnetic field.

Cat states can be used as states of an encoded qubit. The “0” is the electromagnetic wave field at a certain phase (the “living cat”), and the “1” is the field at the opposite phase (the “dead cat”). The atom and light field can both change each other’s state during gate operations.

Yale scientists demonstrated a two-mode cat state of electromagnetic fields in two microwave cavities bridged by a superconducting artificial atom (Josephson junction), which can also be viewed as an entangled pair of single-cavity cat states.

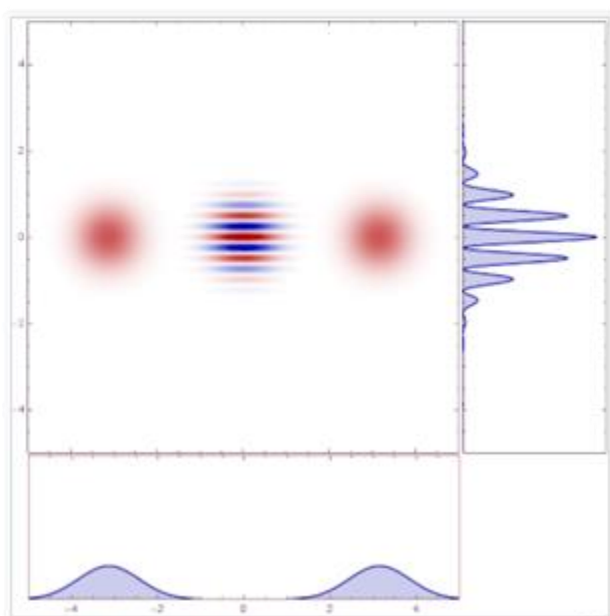
Cat states provide an attractive approach for redundantly encoding quantum information for error correction with minimal overhead. Qubits based on cat states, or bosonic qubits, can be controlled by fewer error-prone ancilla qubits (extra measurement qubits) due to the inherent symmetry of the multi-photon state.

Error-corrected ancilla-enabled gates are an important step towards fully fault-tolerant processing of bosonic qubits.

One key technique is the ability to measure whether the cat state has an even or odd number of photons, i.e to measure the odd or even parity of the cat state, without measuring the photon number. For example, photon loss is an error that flips parity, which results in an observable shift of the qubit frequency. So, it is possible to detect this error without perturbing the encoded information.

Yale scientists have successfully harnessed and manipulated 100 microwave photons into Schrödinger cat states, which could serve as entangled qubits.

With a 9-cell SRF cavity and advanced transmon qubits, it should be possible in principle to generate unprecedently large microwave cat states which can provide a large number of entangled qubits for error-free quantum computing.



Wigner function of a Schrödinger cat state

# Qudits

Qudits are quantum entities in which the number of possible states is D, which can be 3, 4, 5…as long as D is greater than two (as for qubits). A qudit is a generalization of the qubit to D-dimensional space. When D = 3 the quantum entities are called qutrits, with three states; with D = 4 there are four states and the quantum objects are ququarts, and so on.

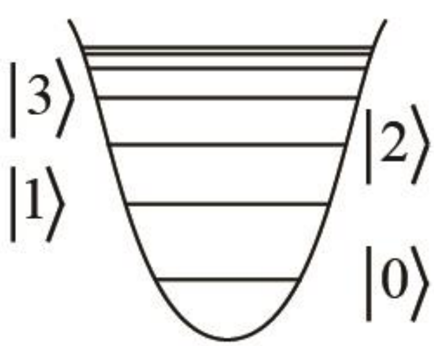
For every added state, the processing ability of a single qudit increases, so you need fewer qudits than qubits to encode and process the same amount of information.

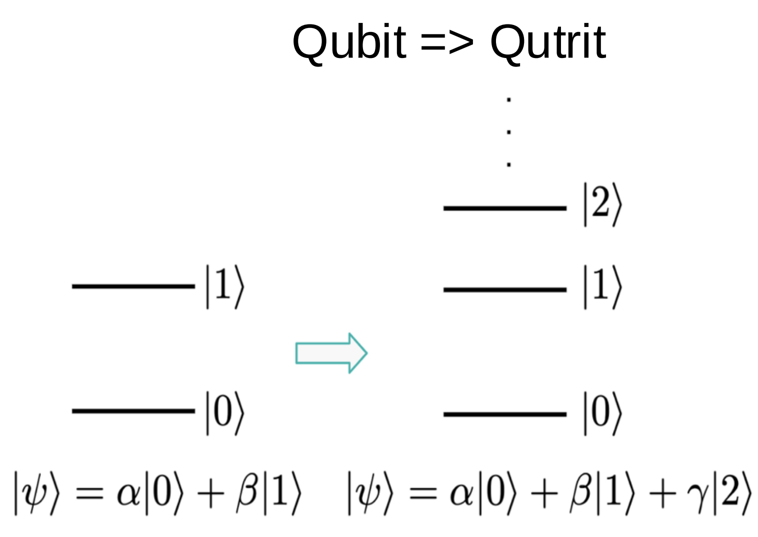
As a specific example, the qutrit is based on a 3-state quantum system, such as the 3 energy levels of an atom, or 3 photon wavelengths in the three modes of a three-cell superconducting cavity. The basis for the qutrit is 0, 1, 2, instead of 0 and 1 for a qubit. The qutrit offers a more efficient way to represent data than the binary qubits. For example, with qutrits, the number 65 can be written as $2.3^3 + 1.3^2 + 0.3^1 + 2.3^0$, as 2102, instead of the longer 1000001 = $1.2^0 + 0.2^1 + 0.2^2 + 0.2^3 + 0.2^4 + 0.2^5 + 1.2^6$ in the binary system.

Qudits offer computing power exponentially more than qubits. Since a qubit exists as a superposition of two states a pair of qubits can perform four operations. Adding a third qubit increases to eight operations. Multilevel qudits provide the potential to simplify computational tasks as well as the circuitry required to realize the quantum computer.

Instead of working with a large number of qubits to reach high processing capabilities, it may turn out more feasible to maintain a smaller number of qudits, with each holding a greater range of values to optimize computations.

Qudits also offer a dramatic reduction in the number of the required microwave channels to only one input per hundred effective qubits. However, it is more difficult to manipulate qudits than qubits.



# SQMS Science Thrust

## Focus Area 3: Quantum Sensing for Fundamental Physics

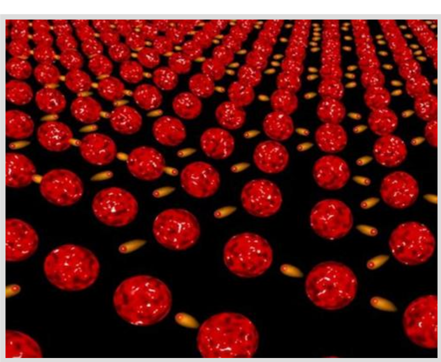
Goals: Explore quantum technology advancements for fundamental physics :

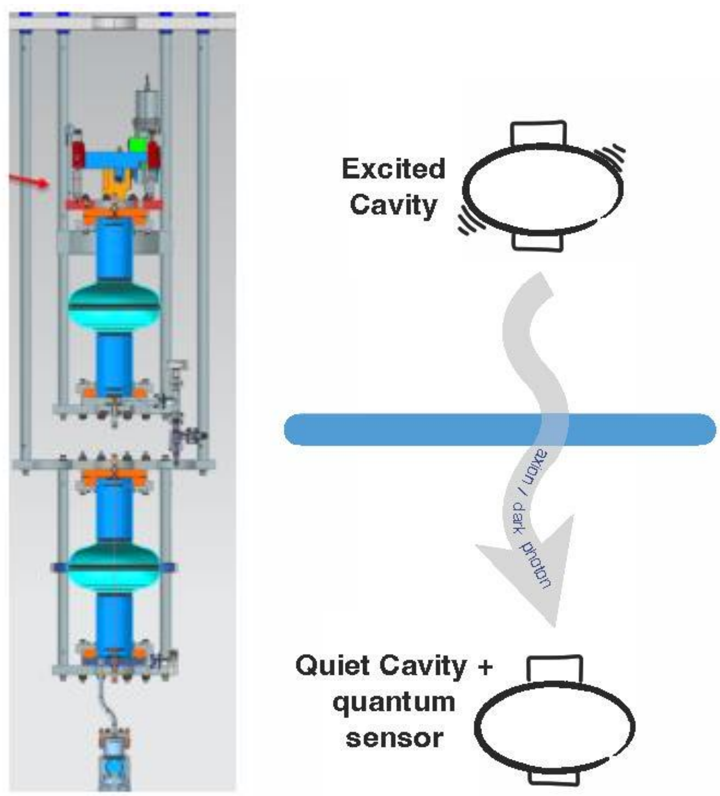
- Are there new interactions and particles?
- What makes up the invisible Dark Matter in our Universe?
- What are the limits of quantum entanglement and the emergent properties of complex entangled states?
- Can we detect high-frequency gravitational waves?

Use the science drivers to push the development of sophisticated quantum devices and control techniques.

Demonstrate quantum advantage for fundamental science problems by:

- Pushing the exclusion boundary for axion or dark photon searches by more than one order of magnitude from the current state of the art;
- Push beyond the limits of quantum entanglement, building record-size cat states to explore the quantum-classical boundary.






*One candidate for dark matter is the dark photon. Its fascinating property (if it exists) is that it can go through walls! In the Fermilab Dark SRF experiment, researchers use superconducting resonators, hunting for signals of dark photons, trying to coax them out of their hiding place. We are combining qubit sensors in these experiments to increase the sensitivity of detection to record levels.*

# Dark Matter And Dark Photons

**Dark Matter**

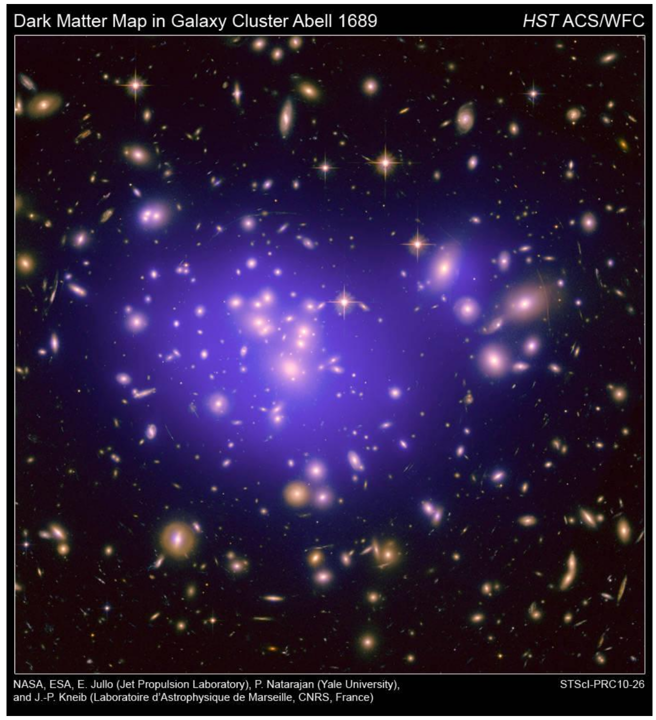
According to Newton's law of gravity, the velocity that a planet needs to maintain to remain in a stable orbit depends on the total mass that resides in the center of its orbital motion. In 1930, Fritz Zwicky made the remarkable observation that galaxies in the Coma cluster orbit much faster than their combined mass can explain. Zwicky postulated the existence of a new form of invisible matter, which he named Dark Matter.

This strange form of matter does not produce any visible or other types of radiation to be detectable. Support for the existence of Dark Matter comes from astronomical observations that clusters of galaxies bend light more than expected. Dark Matter was abundantly produced during the Big Bang. As Dark Matter cooled, it began gravitational clumping, so galaxies started to form. Thus, Dark Matter is essential for a galaxy's existence.

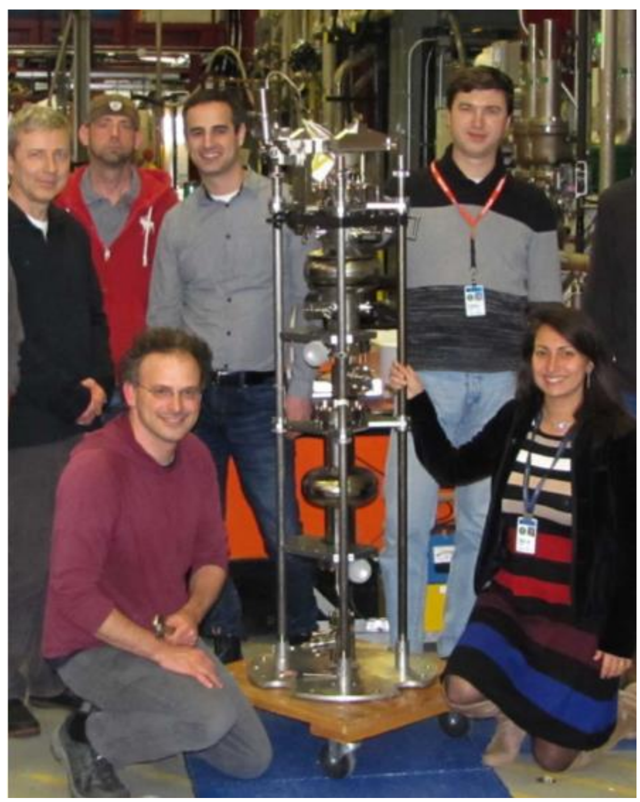
Dark Matter constitutes 23% of all the matter and energy in nature, as compared to 5% of ordinary, familiar matter. But its constituents are completely unknown and undetected, remaining one of the dominant mysteries of science today.

**Dark Photons?**

There are various theoretical candidates for dark matter particles under exploration with special experiments. One candidate is the dark photon. Its fascinating property (if it exists) is that it can go through walls! It is the invisible counterpart to photons. In the Fermilab Dark SRF experiment, researchers are using a pair of superconducting resonators, hunting for signals of dark photons, and have already established world-record sensitivity in a certain mass range. With qubit sensors, these experiments are further increasing the sensitivity of detection, leading to discovery potential.




*NASA's Hubble Space Telescope shows an immense cluster of galaxies located 2.2 billion light-years away. The cluster's gravitation warps light. Dark matter cannot be photographed, but its model distribution is shown in the blue overlay.*



# SQMS For Ultimate Quantum Sensing

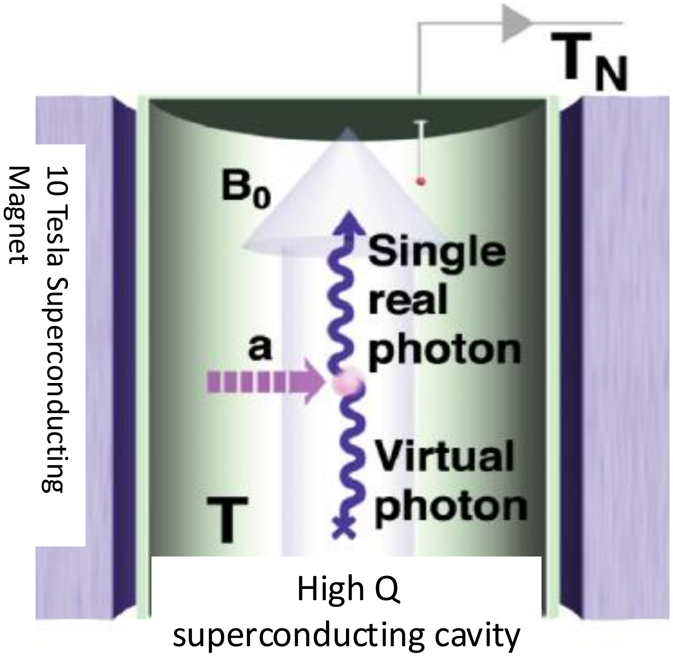
Another candidate for Dark Matter is the Axion, named after a laundry detergent to clean up a key problem in high-energy physics! It is a hypothetical particle with a mass 100 billion times less than that of the electron.

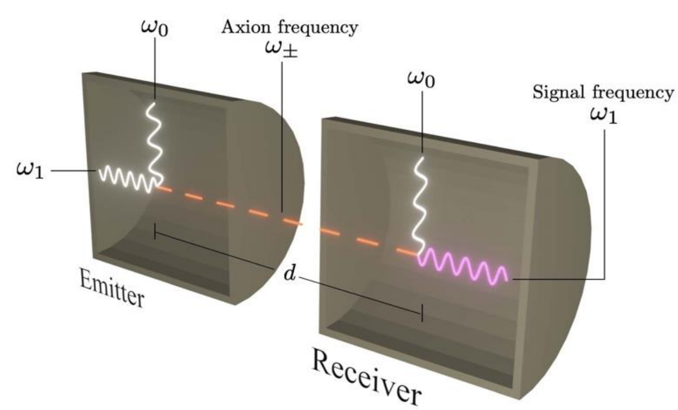
Axions were postulated to explain why Charge-Parity (CP) violation is not observed in strong interactions, although it should be – according to the Standard Model. It also plays a role in cosmology. Even though their mass could be in the range of micro-eV if axions exist, there could be so many of them in the Universe, that they contribute a large proportion of the overall mass of dark matter in the universe, and therefore 23% of all matter. By saturating a region with a very strong electromagnetic field, the axion may decay into two photons, which could be detected by quantum sensors that have the capability to detect single photons.

Discovery of axions would re-write the laws of particle physics and cosmology.

A strong superconducting magnet will coax dark matter out of hiding and convert axions into light particles inside a superconducting microwave quantum resonator. Equipped with ultrasensitive, low-noise quantum electronics, a detector can be tuned to different frequencies corresponding to axions of different masses. The expected signal is at $10^{-23}$ watts or less.

SQMS is pushing several experiments in collaboration with INFN and other institutions, with cavities and qubits, that promise leading sensitivity and discovery potential for axion-like particles.




*Microwave cavities in a high magnetic field can also be used as Axion detectors. The Axion-photon conversion is resonantly enhanced when the cavity mode frequency approaches the correct value to couple to the Axion-photon interaction. Both single-cavity as well as multiple-cavity experiments have been proposed.*

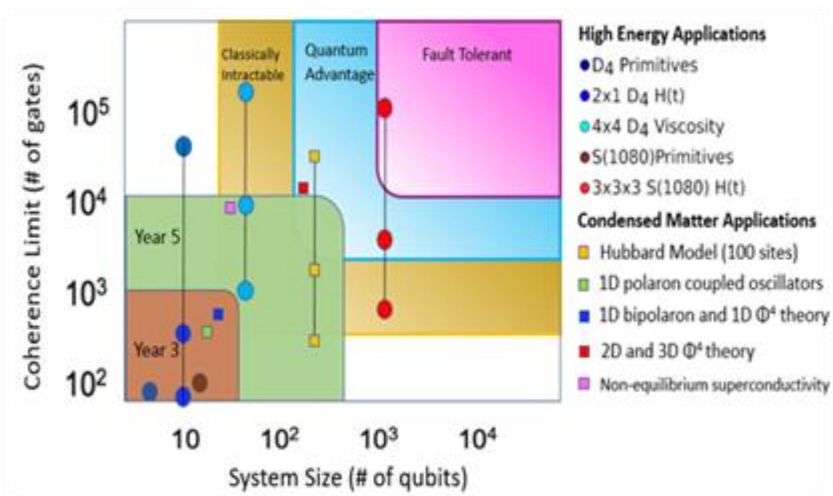
# SQMS Science Thrust

## Focus Area 4: Quantum Algorithms, Simulations and Benchmarking

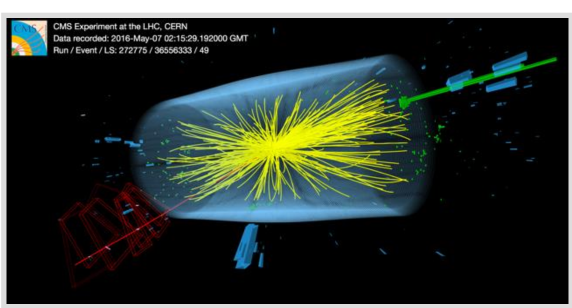
Goals: Investigate and develop quantum algorithms and quantum simulation for:

- Dynamics of theories approximating quantum chromodynamics (QCD) with a goal to simulate LHC physics and the plasma of the early Universe conditions.
- Quantum materials far from equilibrium and intermediate strong electron-phonon superconductivity.
- Development of software libraries that abstract the peculiarities of SRF-based quantum processors.
- Magnetic Resonance Imaging data analysis

- What was the viscosity of the Universe when it was young?
- How does the transition quarks → hadrons (e.g. at LHC) happen in “real-time”?
- What are the phases of complex quantum materials?
- What are the non-equilibrium dynamics of highly entangled systems?

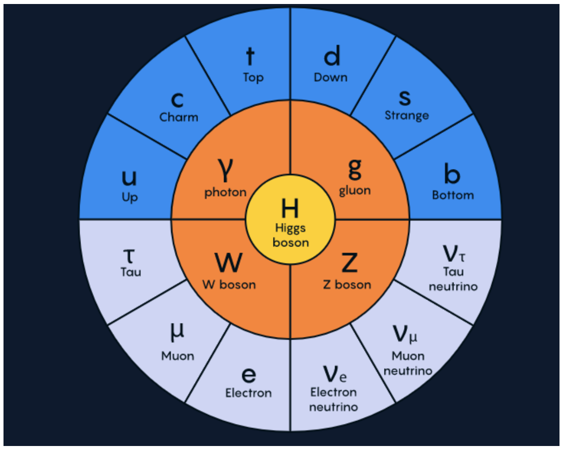



*SQMS simulations and algorithms roadmap*




| | | | $Z_2$ | BT | $S_{1080}$ |
|---|---|---|---|---|---|
| Proof of concept | 2x1 Lattice | 7 links | 7qubits | 35 qubits | 77 qubits |
| | | 1 Trotter step | 28 CNOTs | 70k CNOTs | ~200m CNOTs |
| Nontrivial Physics | 4x4 Lattice | 24 links | 24 qubits | 120 qubits | 264 qubits |
| | | 10 Trotter steps | 96 CNOTs | 220k CNOTs | ~700m CNOTs |
| HEP Applications | $10^3$ Lattice | 3k links | 3k qubits | 15k qubits | 33k qubits |
| | | 10 Trotter steps | 4m CNOTs | ~450m CNOTs | 10t CNOTs |

# SQMS for High Energy Physics




*Standard Model of HEP*

Advanced understanding of nature at the most fundamental level to penetrate the basic features of energy, matter, and space-time. The Standard Model (SM) of particle physics captures current understanding. It is the best answer to the question – what are we made of? Many physicists find the SM contrived, demanding a deeper explanation and a more unified picture.

Some of the dominant open questions are:

- How to include Gravity?
- Are there new interactions and particles, beyond the known forces and matter?
- What makes up the invisible Dark Matter that comprises 23% of the Universe?
- Can the fundamental interactions be completely unified?

Answering such questions will require computers beyond current capabilities. Breakthroughs in quantum computing will open new paths. The goal is to unite powerful analysis techniques with cutting-edge advances in quantum computation to reach unprecedented levels of precision.

At Fermilab simulations will allow physicists to use quantum computing in quantum chromodynamics (QCD), the theory of strongly interacting quarks and gluons, or in the physics beyond the Standard Model. Fermilab's expertise in lattice QCD computations will inform and improve quantum simulation. Fermilab theorists aim to explore and further develop connections between quantum science and quantum field theories, or QFTs, which provide the foundation for particle physics studies. QFTs allow theorists to describe and compute phenomena in a vast range of scale, including examples from the theory of quantum electrodynamics, the effective field theories of the strong and weak interactions at low energies, the gauge theories of the Standard Model of particle physics, and possible extensions beyond the Standard Model.

On the experimental front, computer algorithms will aid in the process of reconstructing particle tracks in detectors that produce billions of particle events per second, as in the Large Hadron Collider at CERN. The data center at CERN stores more than 100 petabytes ($10^{15}$) per year, equivalent to over 3 million Blue-Ray DVD's. Future quantum computers can recognize patterns better and faster than conventional computers, to correctly identify individual particle trajectories.

# SQMS Center Facilities

A variety of new facilities have been built and deployed at the SQMS Center and the Center's partner institutions. These state-of-the-art research facilities are equipped with today's most sophisticated quantum technologies. Moreover, the Center leverages advanced facilities which each partner brings:

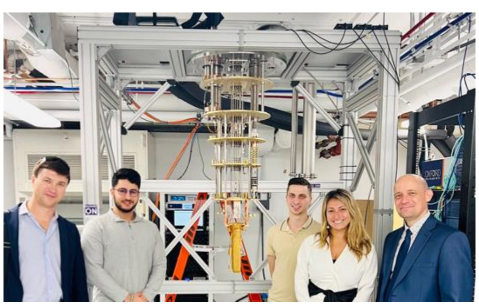
- Millikelvin quantum testbeds – Fermilab, NIST, Colorado Boulder, Rigetti, Northwestern, INFN, NPL
- Qubit foundries – Fermilab, NIST, Northwestern and Rigetti Computing
- Materials characterization tools – Ames Lab, Northwestern, Fermilab, IIT, Temple, NPL

Below, we highlight some of the SQMS flagship facilities built or under construction:

QCL-1 was developed at Fermilab under the leadership of PI Alexander Romanenko. Two state-of-the-art, extra-large dilution fridges serve as testbeds with multi-qubit control capabilities for quantum computing, sensing and communication. Each dilution refrigerator can hold multiple SRF cavities and qubit chips. The large refrigerators have the capacity for meter-long cavities with many cells for multimode operation. One fridge is designed to sustain larger heat loads at the two-kelvin stage for special quantum-sensing physics experiments, such as searches for dark matter.

QCL-2 is the first high-flexibility nanofabrication facility at Fermilab to advance cutting-edge research in high-quality films and materials for next-generation superconducting qubits. Here, researchers will focus on superconducting films and quantum devices with capabilities beyond current state-of-the-art facilities. QCL-2 will offer high-quality film deposition tools, double-angle evaporation tools, imaging and characterization tools, wet-processing benches, and post-processing and packaging tools.

Colossus will be the world's largest cooling dilution refrigerator. Housed within the Heavy Assembly Building on Fermilab's campus, Colossus will contain hundreds to thousands of cavities with varying geometries and will have a cold volume of five cubic meters. This volume is significantly larger than the dilution refrigerators that are currently used for research and development and will have 10 times the cooling capacity. The tank for the dilution refrigerator has tested components at four kelvin and is now being upgraded to hold components at 10 millikelvin. The platform will connect to an existing 4K cryoplant and demonstrate the dry-wet technology, critical to enable scale-up to large quantum computing data centers.



Northwestern QSET: SQMS has commissioned a new quantum computing and sensing testbed at Northwestern University, which will advance research in superconducting qubits and train the next generation of the quantum workforce. Experiments at the Quantum Science, Engineering and Technology (QSET) laboratory aim to pinpoint and overcome performance bottlenecks of quantum devices, such as superconducting qubits, and provide hands-on training of students in superconducting quantum device measurements.

# SQMS Center Facilities: The Quantum Garage

The SQMS Quantum Garage is a new flagship facility developed at Fermilab by the SQMS Center and is among the largest quantum research laboratories nationwide. The newly developed 6000 sqft lab features several newly commissioned, extra-large dilution refrigerators capable of reaching cryogenic temperatures, just a tick above absolute zero, and cleanrooms for qubit and cavities preparation. The fridges host platforms developed by the SQMS collaboration for quantum computing, sensing, metrology and communications. Highlights of the quantum platforms include:

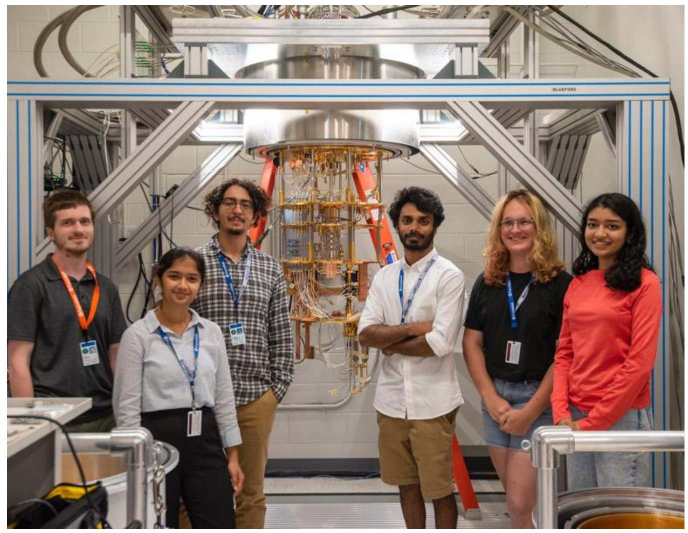
- The first commercial quantum processor deployed on-premise at Fermilab
- Quantum memories and transducers based on novel platforms (constructed with FNAL world-leading accelerator technology)
- Quantum metrology tools for developing materials standards for quantum applications
- Quantum sensors for fundamental physics, with the potential to discover dark matter and new gravitational wave sources
- Training platforms dedicated to providing hands-on education for growing the next-generation quantum-ready workforce

These platforms will enable scientific communities, industries and start-ups to advance quantum technology and science; these new scientific tools will enable applications helping to solve challenges in fundamental science, clean energy, climate change, medicine and national security.  Each of these platforms and experiments involves collaborative efforts of 30 SQMS partners across industry, academia and federal labs including: NIST, NASA Ames, Northwestern University, Rigetti Computing, Ames National Laboratory, the Italian Institute of Nuclear Physics, the U.K. National Physics Laboratory.

# SQMS Workforce Development

SQMS has created a space and a community to train and educate the next generation of researchers to advance the field of quantum information science. This is accomplished by providing work, internships and educational opportunities at the SQMS Center, leveraging partnerships between the multidisciplinary SQMS network.

The SQMS Center has already trained hundreds of students over its first three years. Through new partnerships with minority-serving institutions such as Spelman College, Coppin State University, the University of Illinois at Chicago, and other strategic partners, SQMS will be a key hub for training a diverse workforce of quantum scientists, engineers, and technicians. The Center strives to make quantum information science accessible to everyone.



# Conclusions

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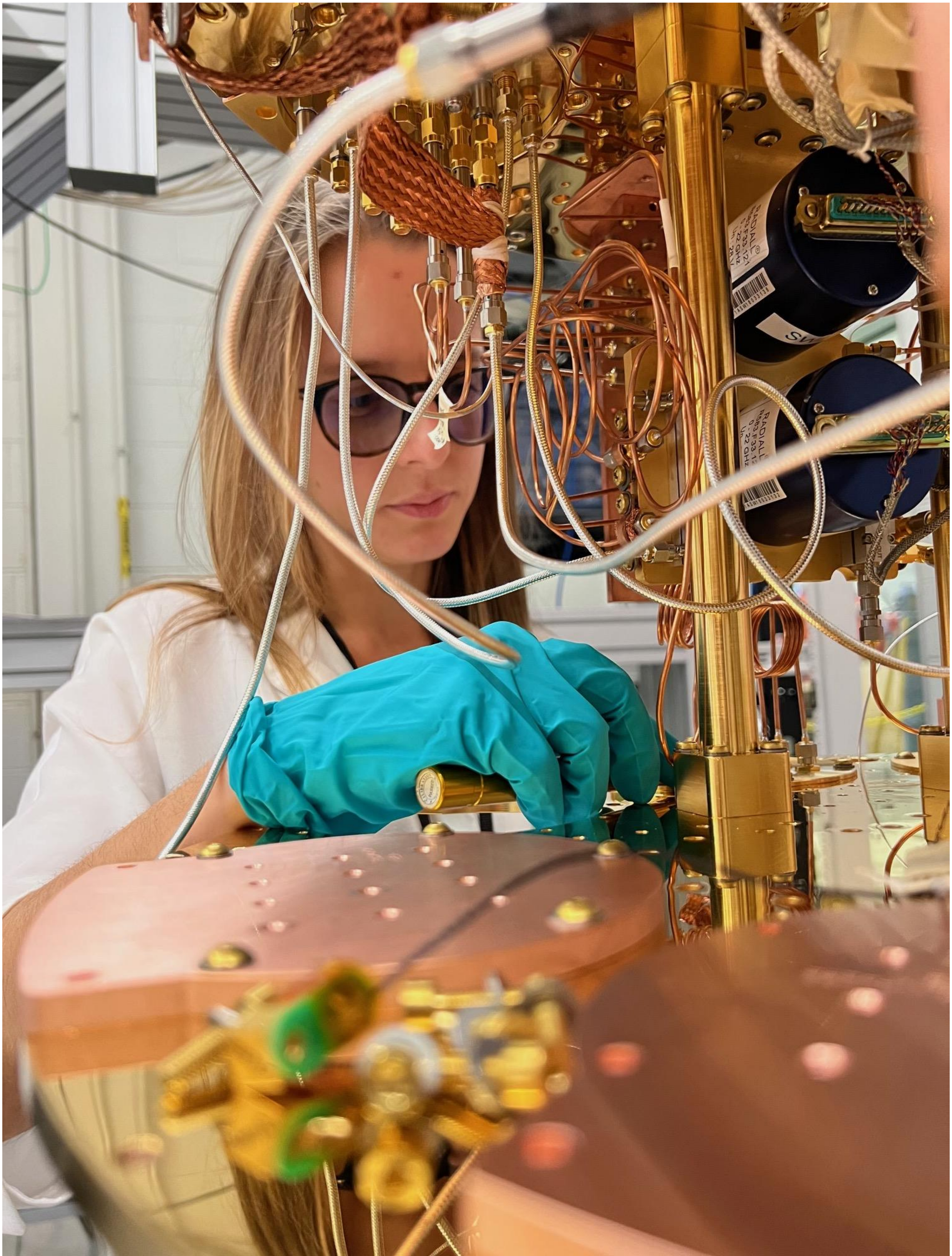
The spark that ignited worldwide interest in quantum computing sprang forth in 1994 with Peter Shor's discovery of a theoretical way to use quantum mechanical resources to unravel a mathematical problem at the heart of electronic commerce and cryptography. Since then, quantum computers have evolved from a tool for researchers to serious number crunching.

Today's quantum processors should be regarded as a stepping-stone to more capable technologies; their primary near-term value is to provide a platform for the development of quantum algorithms and applications that will be useful over the long term.

The quantum information community has taken gigantic strides in understanding the potential applications of a quantum computer and laid the foundational requirements for building one. With anticipated transformational advances over the next decade, quantum computing will become game-changing for every industry and will have a huge impact on the way we do business, invent new medicine and materials, safeguard our data, explore space, understand the universe, and predict weather and climate change.

The SQMS Center will play a key role in ensuring the DOE, the U.S., and the world will successfully harvest the fruits of this quantum revolution.


*Inaugural U.S. Quantum Information Science School, August 2023*



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