Fermilab

February 7, 2026

Quantum Science & Quantum Computing

Silvia Zorzetti

How the smallest rules of nature can change our world

U.S. DEPARTMENT of ENERGY

Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

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01

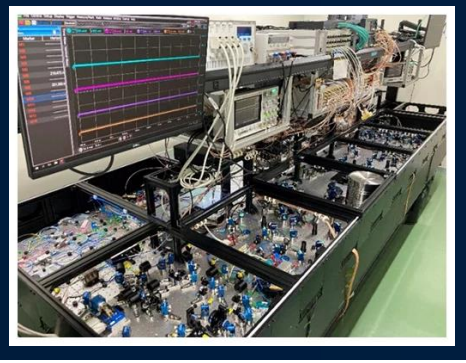
The world is excited about quantum

Why are people excited about Quantum

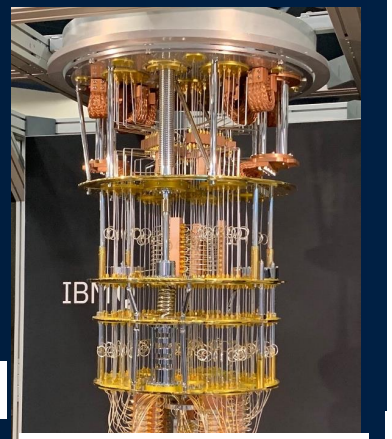
Quantum science helps us:

- Understand how Nature works at the smallest scales
- Build new technologies that were impossible before
- Ask and answer new kinds of questions
- Bring together physics, math, computer science, and engineering

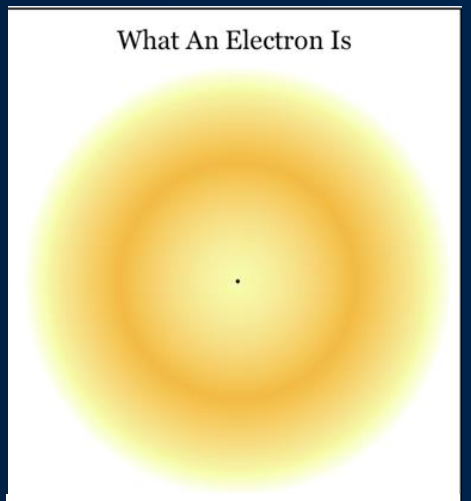
Source: Fermilab



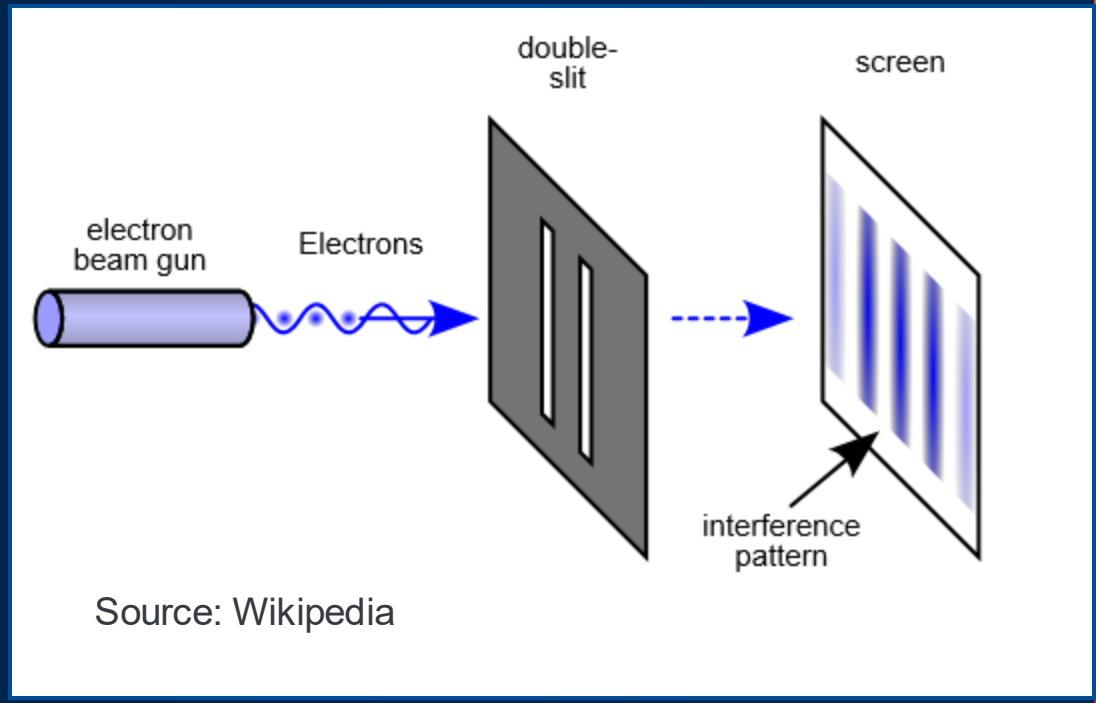
Source: thequantuminsider.com



Source: IBM



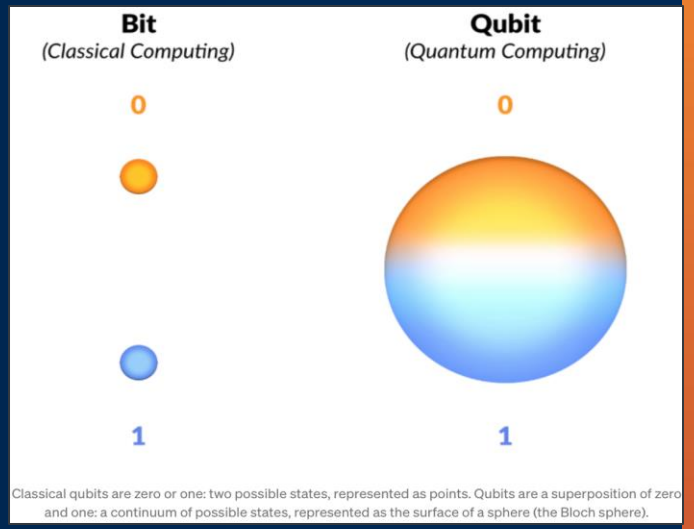
faculty.wcas.northwestern.edu/infocom/The%20Website/plates/Plate%201.html

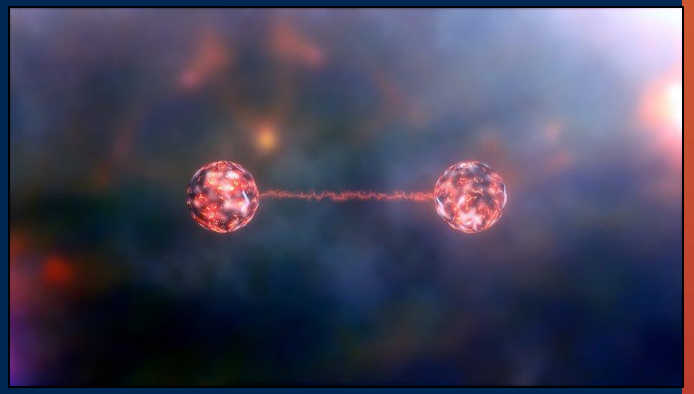


Source: Wikipedia

Quantum Information Science

- A growing field in science and technology that combines and draws from the disciplines of physics, mathematics, computer science, and engineering.
- The goal is to understand how some fundamental laws of quantum physics—superposition, entanglement—can be exploited to drastically improve the acquisition, transmission, and processing of information and data.
- The exciting scientific opportunities offered by QIS are attracting the interest of a growing community of scientists and technologists, fostering unprecedented interactions beyond traditional disciplinary boundaries.





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Quantum science is confusing

… and physicists seem to be ok with that!

- “I think I can safely say that nobody really understands quantum mechanics,” observed the physicist and Nobel laureate Richard Feynman.
- Quantum mechanics has a reputation for being especially mysterious.
- What’s surprising is that physicists seem to be O.K. with not understanding the most important theory they have.

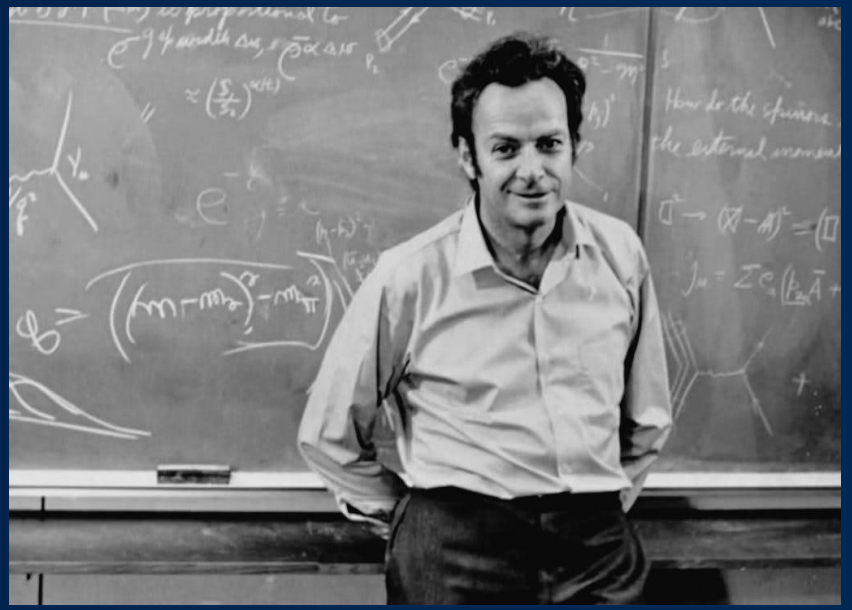
The New York Times | https://www.nytimes.com/2019/09/07/opinion/sunday/quantum-physics.html

Even Physicists Don’t Understand Quantum Mechanics

Worse, they don’t seem to want to understand it.

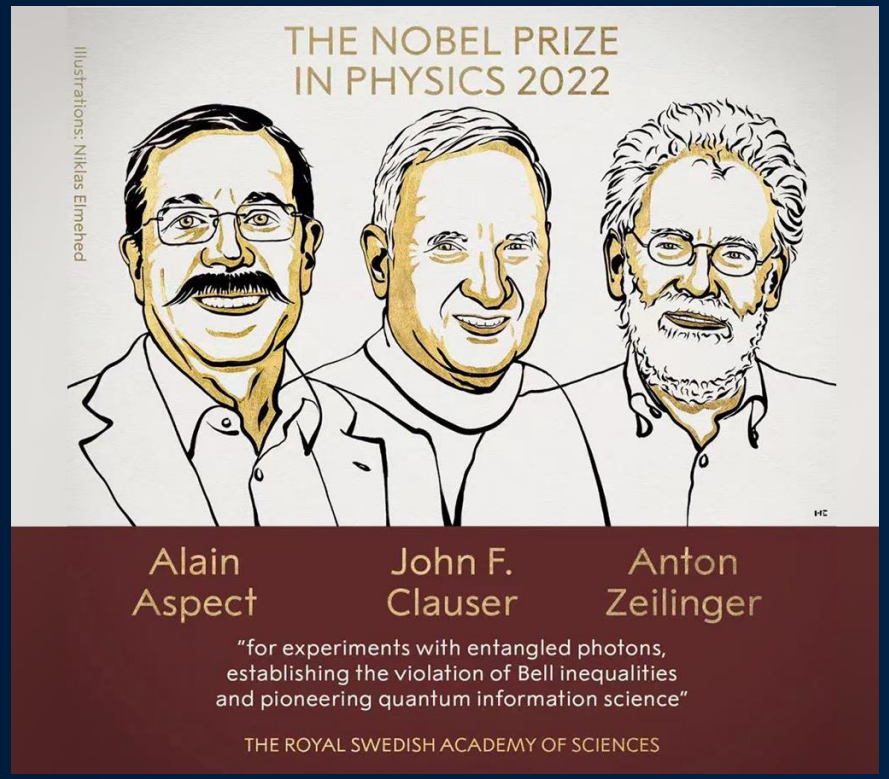
Sept. 7, 2019

By Sean Carroll
Dr. Carroll is a physicist.

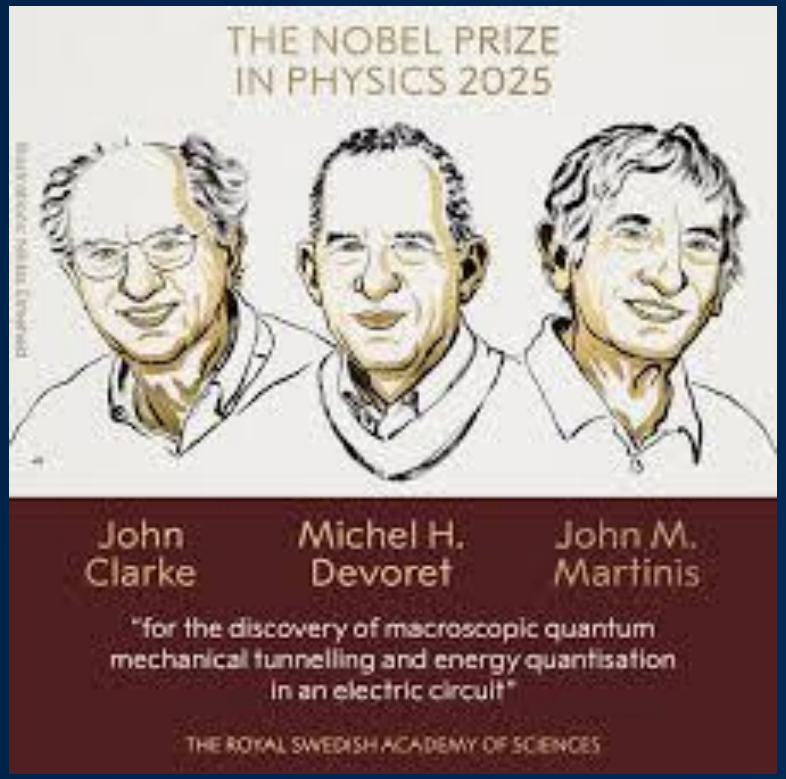


The world is excited about QIS

- Nobel prize in physics 2022



- Nobel prize in physics 2025



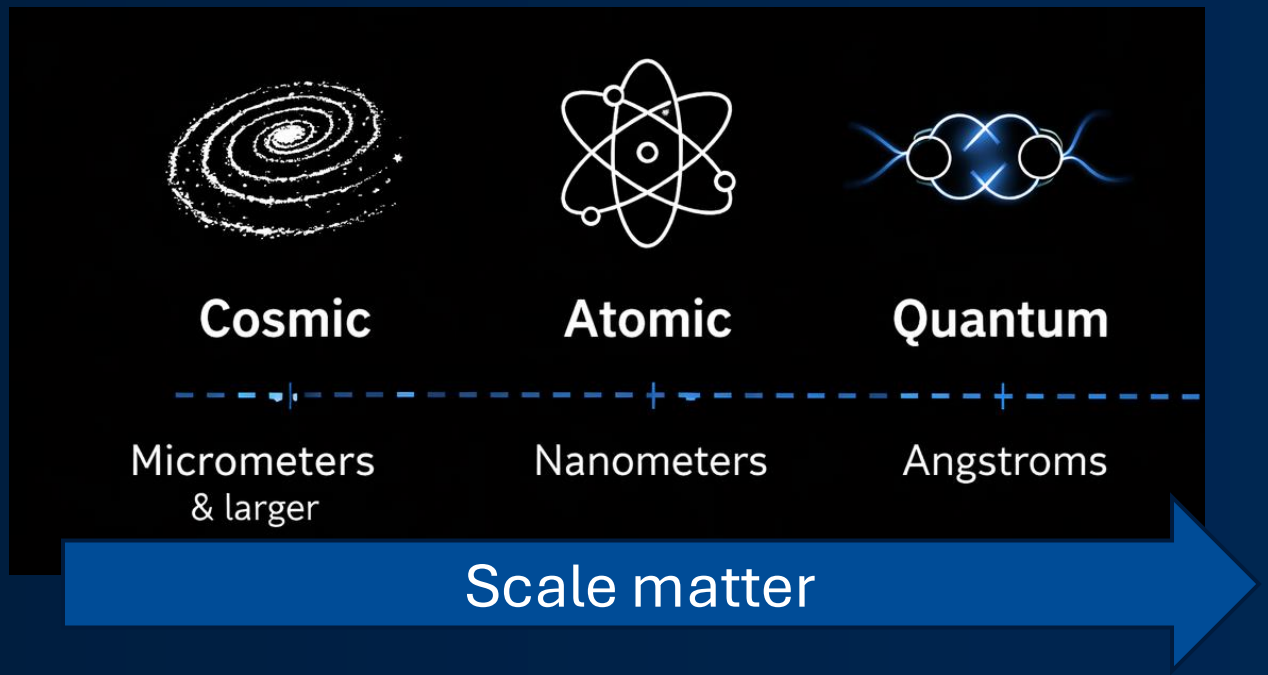
The world we see vs. the quantum world

Everyday world

- Objects have clear positions
- Things behave predictably
- Classical physics works well

Quantum world

- Particles act like waves
- Outcomes are probabilistic
- Quantum physics is needed



From quantum mechanics to quantum computing

02

Quantum mechanics

The atom

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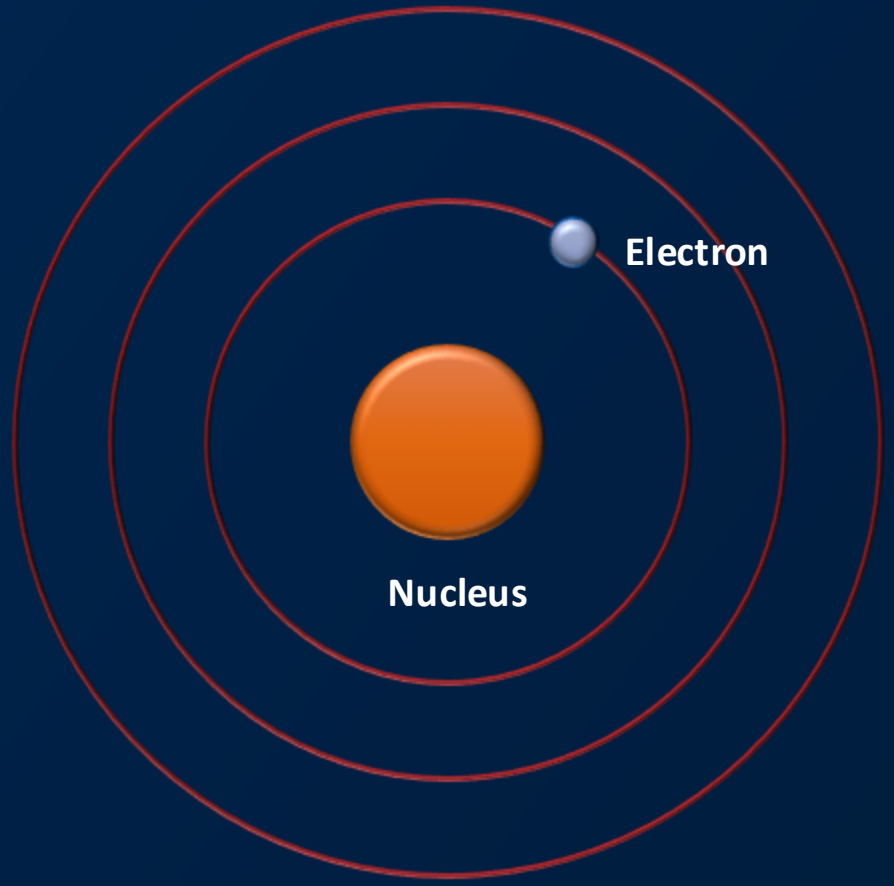
The atom



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The atom

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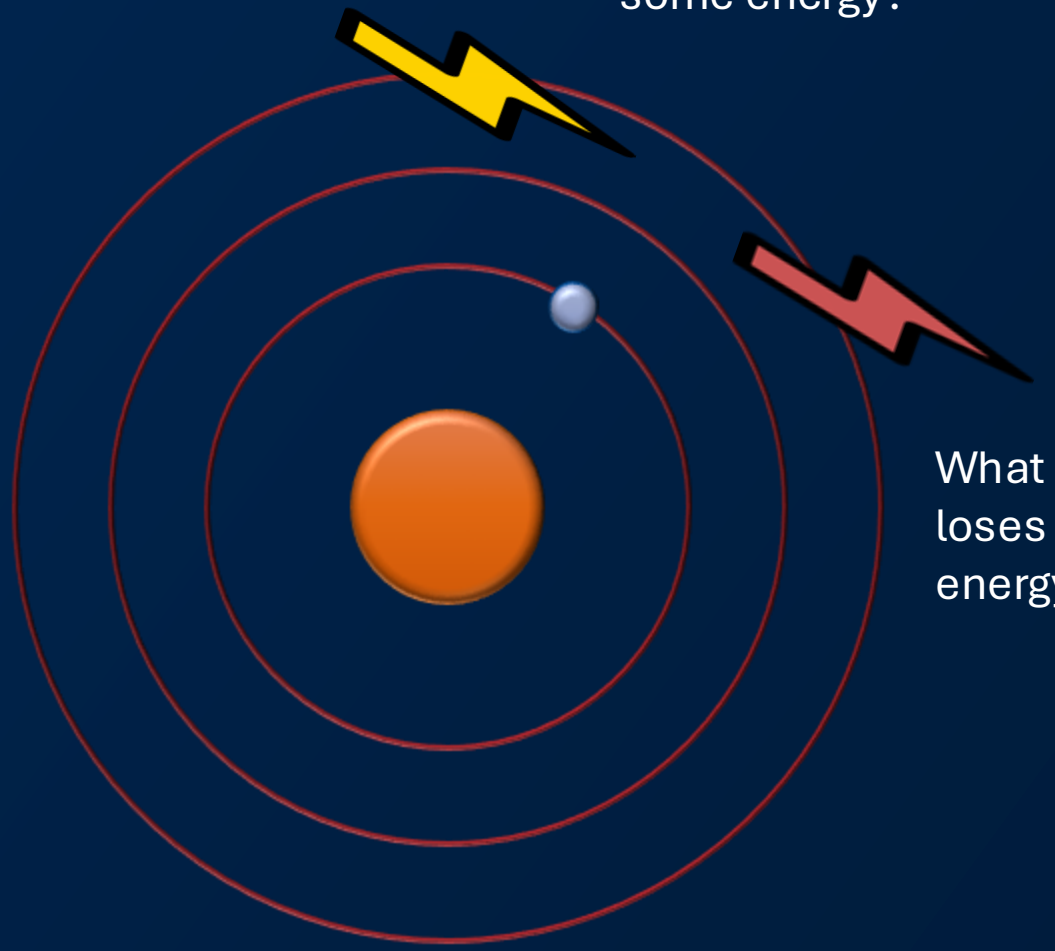
The atom

What happens if the atom is excited with some energy?



What if it loses energy?

Energy quanta

$$\Delta E = E_2 - E_1 = hf$$

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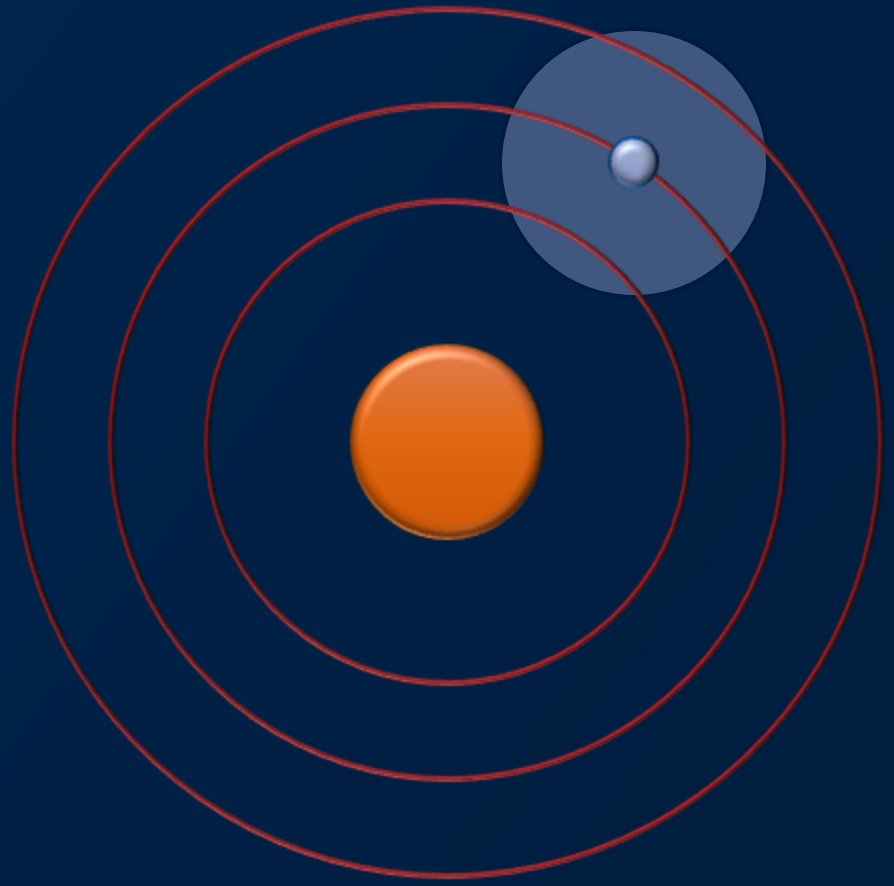
Heisenberg's Uncertainty Principle

The electron’s position is only known with some uncertainty



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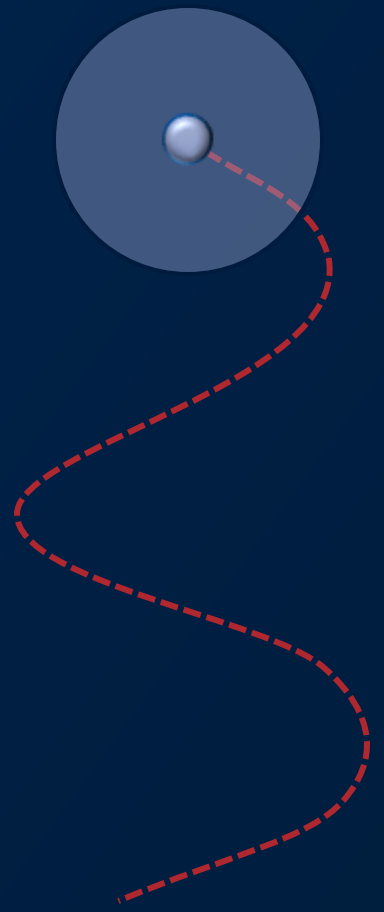
Heisenberg's Uncertainty Principle

Velocity and position cannot be known at the same time with infinite precision



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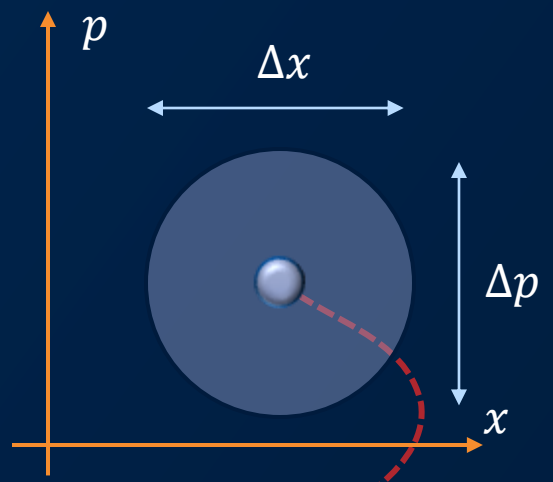
Heisenberg's Uncertainty Principle

Position

Momentum (velocity)

$$\Delta x \, \Delta p \geq \frac{\hbar}{2}$$

A very small number



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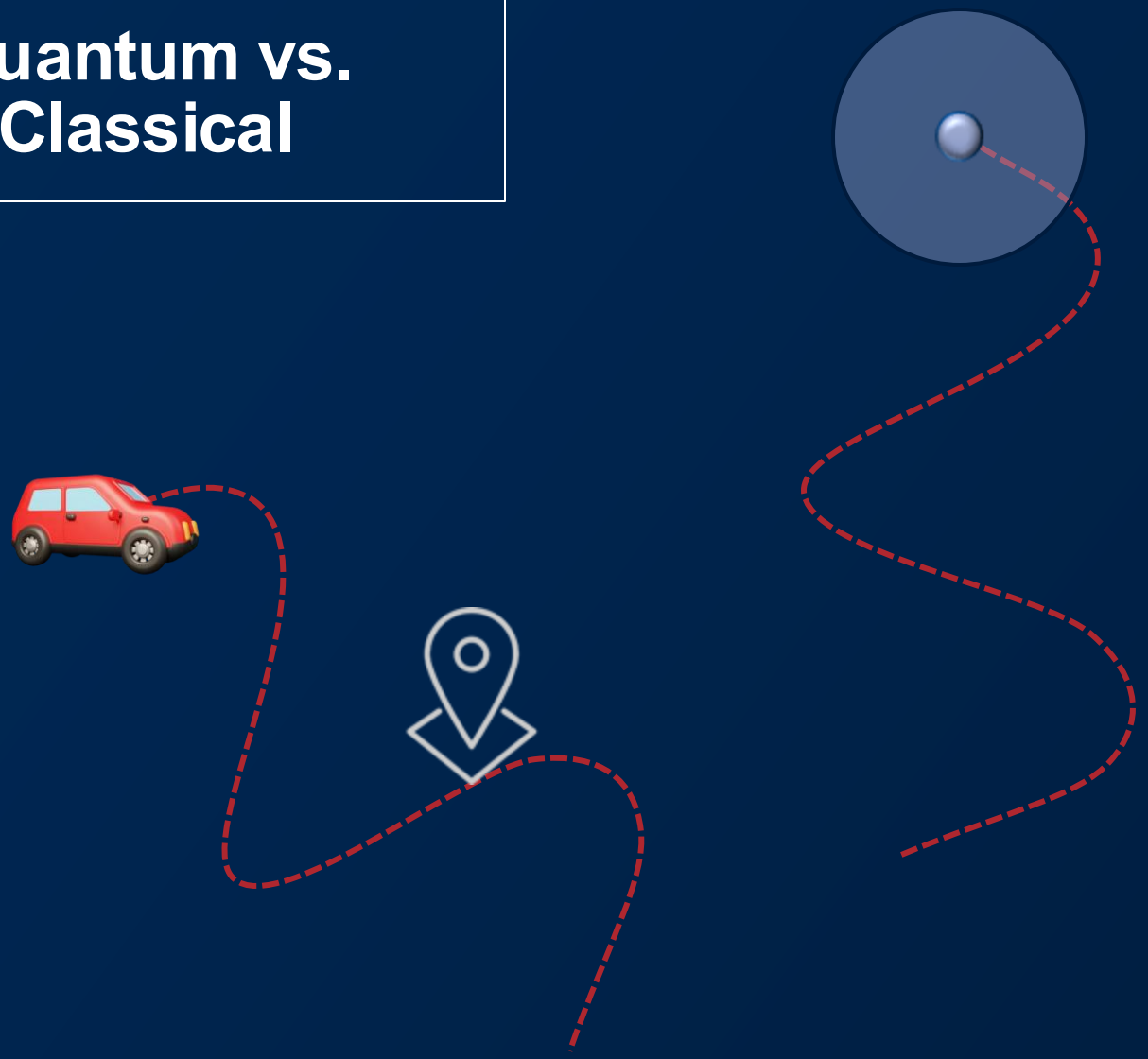
Quantum vs. Classical



What happens to macroscopic objects?

Uncertainty in macroscopic systems is infinitesimal.

In our world, classical mechanics is still valid!

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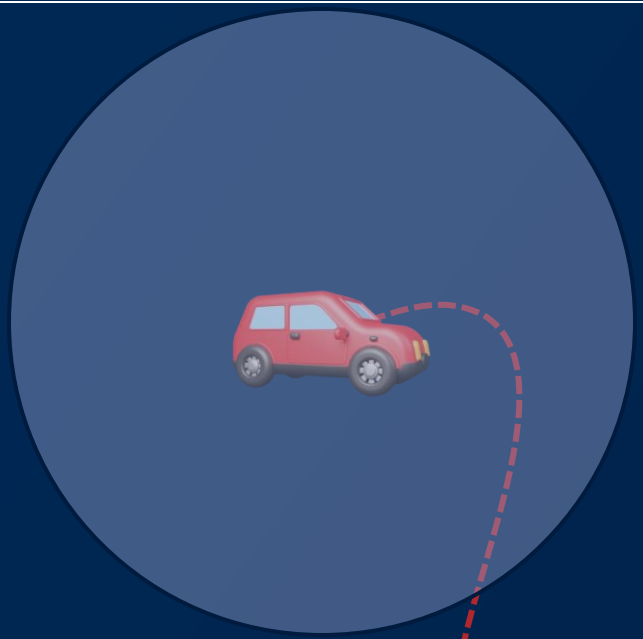
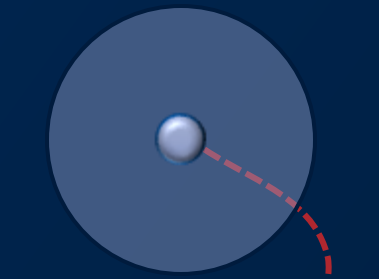
Heisenberg's Uncertainty Principle



The uncertainty is a very small number



What happens to macroscopic objects?

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Quantum vs. Classical

A baseball with a mass of 150 g (about 5 onces) is moving at a velocity of 40 m/s (90 mph).

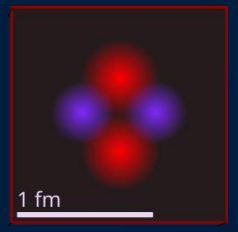
If the uncertainty in the velocity is 0.1 m/s, the minimum uncertainty in position is?

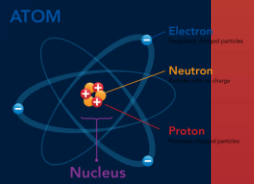
Δx ? ? ?

$\Delta x \geq 3.515\ 10^{-29} m$

Let's apply the uncertainty principle to a baseball ball

This is:
24 orders of magnitude smaller than a hair
20 orders of magnitude smaller than a virus
19 orders of magnitude smaller than an atom
11 orders of magnitude smaller than an electron





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Quantum vs. Classical

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If the uncertainty in the velocity is 0.1 m/s, the minimum uncertainty in position is?

Let's apply the uncertainty principle to a baseball ball

$\Delta x\ \Delta p \geq \frac{\hbar}{2} = \frac{h}{4\pi}$: Uncertainty principle

$h = 6.626\ 10^{-34} m^2 kg/s$: Plank constant

The uncertainty in momentum can be written as:
$\Delta p = m\Delta v$:
Δv - the uncertainty in velocity
m - the mass of the particle

In your case, you're dealing with a **150-g** baseball that has an uncertainty in velocity of 0.1 m/s, which means that the uncertainty in momentum will be

$$\Delta p = 15\ 10^{-3} m\ kg/s$$
$$\Delta x \geq h 4\pi \Delta p$$
$$\Delta x \geq 3.515\ 10^{-29} m$$

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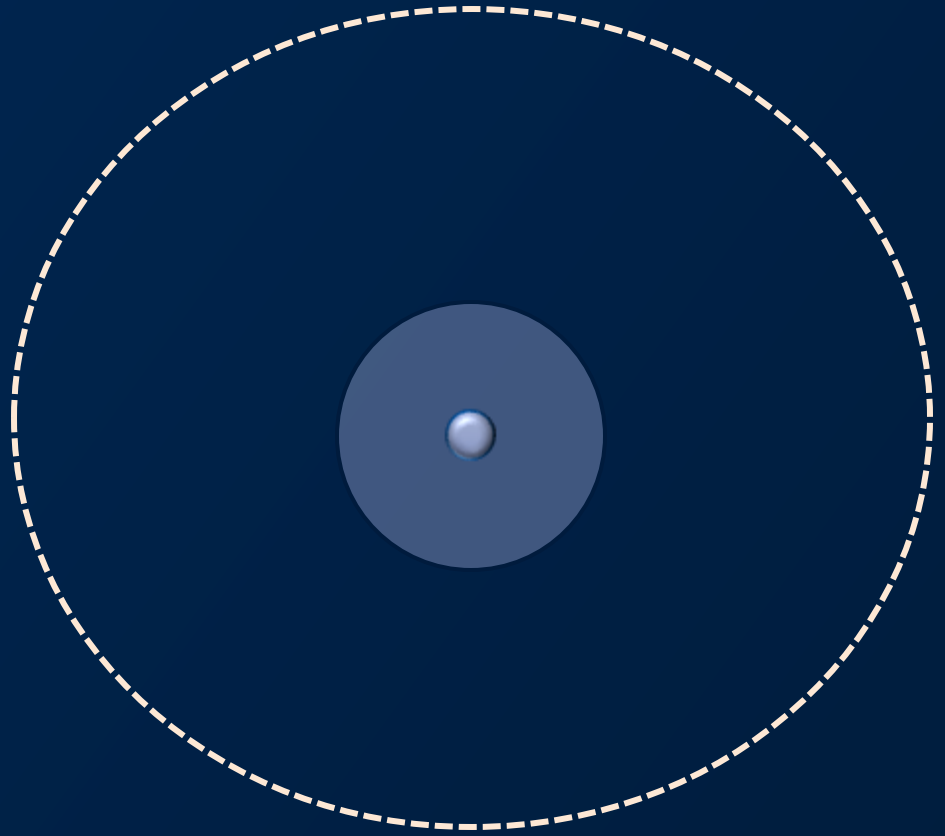
The wave function

God doesn't play dice



$$\mathcal{P}(\boldsymbol{r}, t)dV = |\Psi(\boldsymbol{r}, t)|^2 dV$$

The physical state of a particle is determined by the probability of being within a certain volume.

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03

What makes quantum mechanics spooky

Superposition

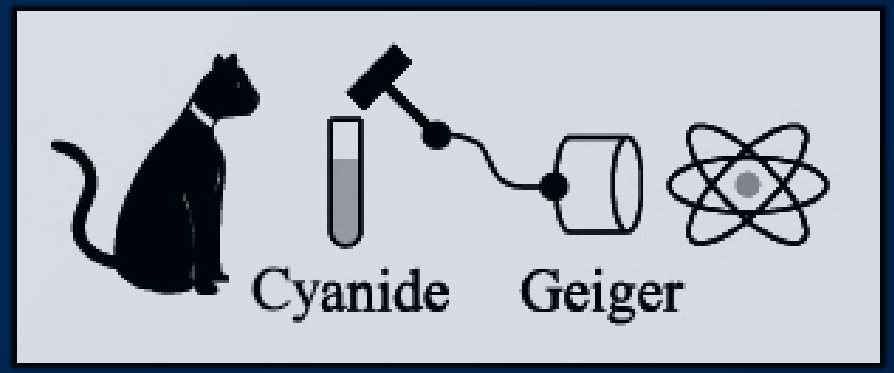
Schrodinger's cat

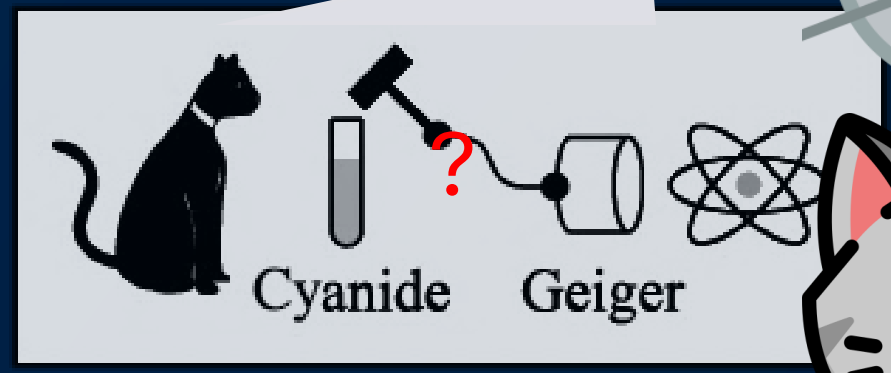
Question: Is the cat alive or dead?

Answer: The cat is in both states→ **SUPERPOSITION**

Instrument: Make a measurement

The measurement is: open the lead of the box
The measurement can trigger or not the radioactive mechanism → It alters the outcome





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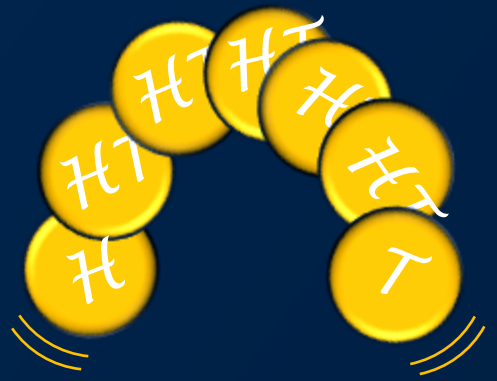
Superposition



When flipping a coin and measuring the result, the outcome is always Heads or Tails. The probability of each state is 50%

What is the probability?

50/50 HT

In quantum computing, it is possible to create a superposition state with percentages different from 50/50

What happens while the coin fluctuates?

It is in superposition of HT

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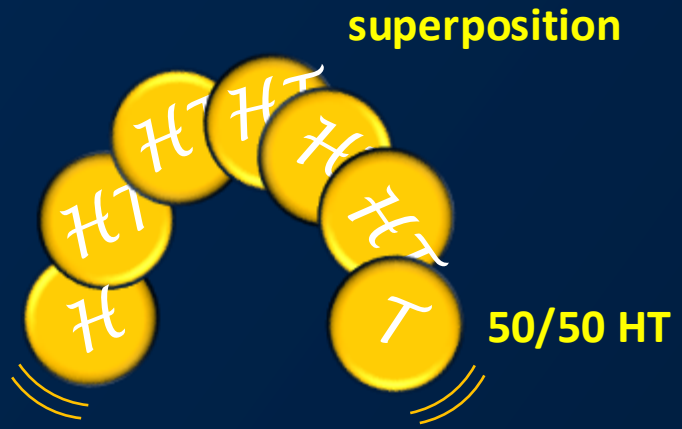
Superposition



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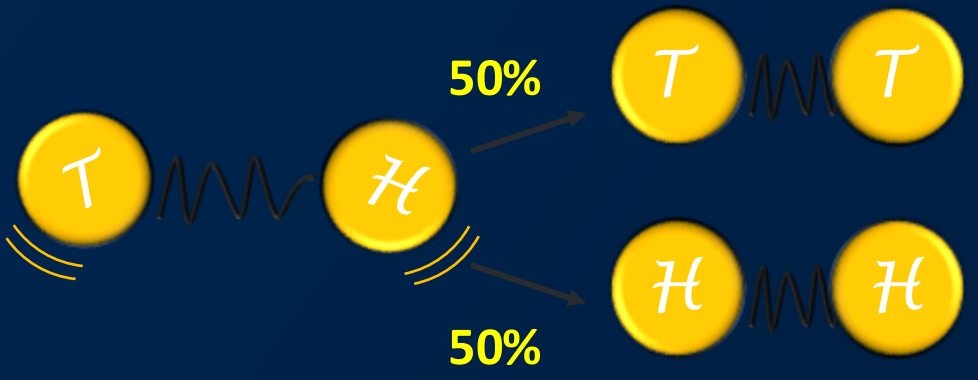
Quantum Entanglement



The possible results would be:
TT, TC, CT, CC (25% probability each).

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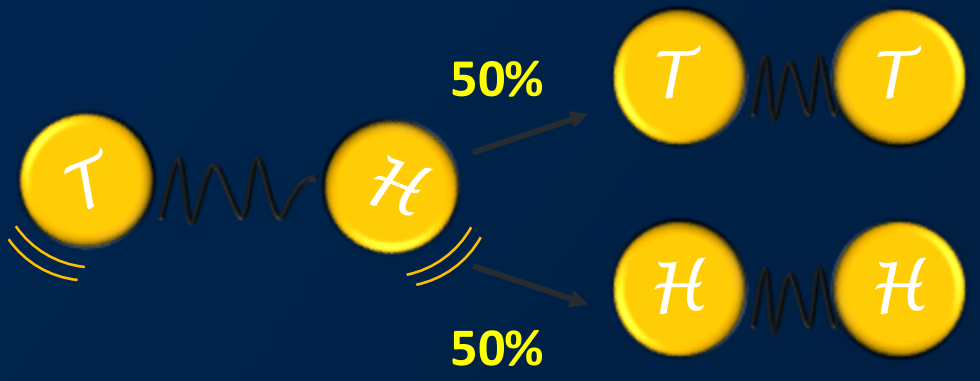
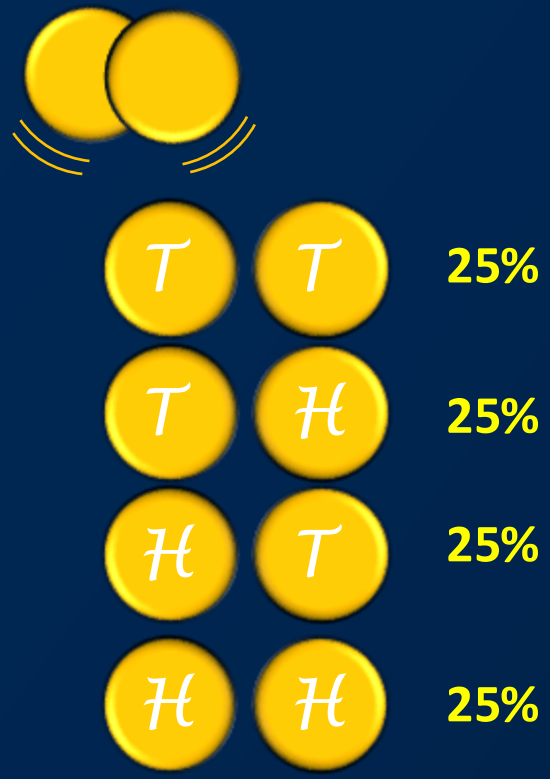
Superposition





The possible results would be:
TT, TC, CT, CC (25% probability each).

Quantum Entanglement:
A correlation is created between the outcomes of the coins.

In quantum computing, if there is an entangled state, the result is 50% TT and 50% CC

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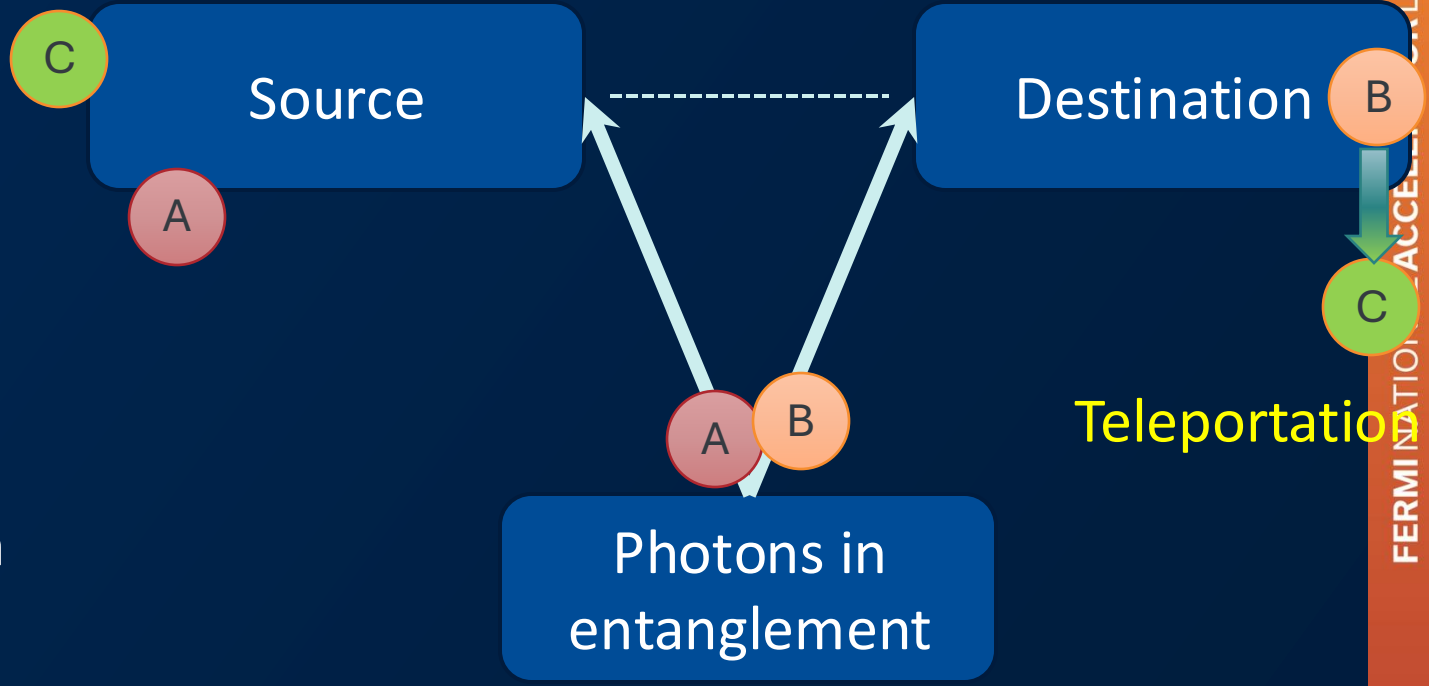
Teleportation



Algorithms for distributing information over secure channels are based on the following:

- Cryptography (prime numbers)
- Teleportation of information

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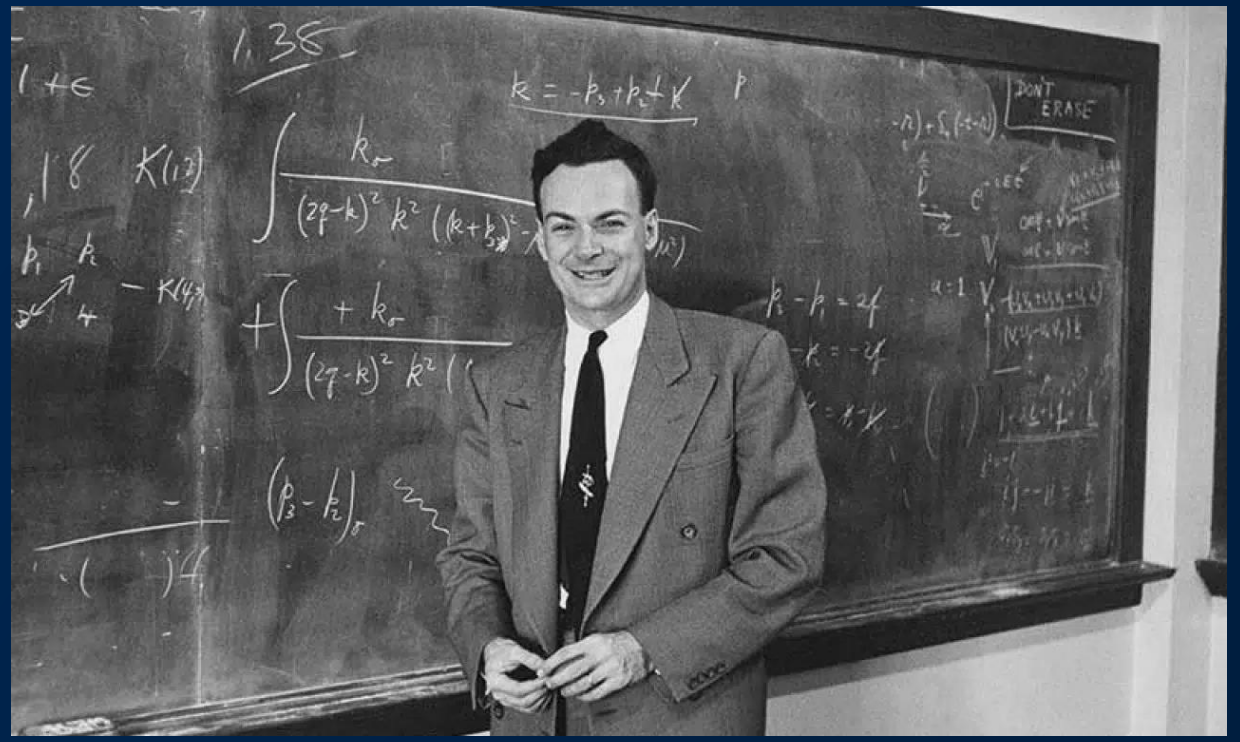
Teleportation

- The spacecraft Enterprise (Star Trek) was equipped with a transporter.
- Teleportation, in reality, is only possible for quantum information.

04

Quantum computing and applications

Quantum computers to simulate nature



Simulating Physics with Computers

Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

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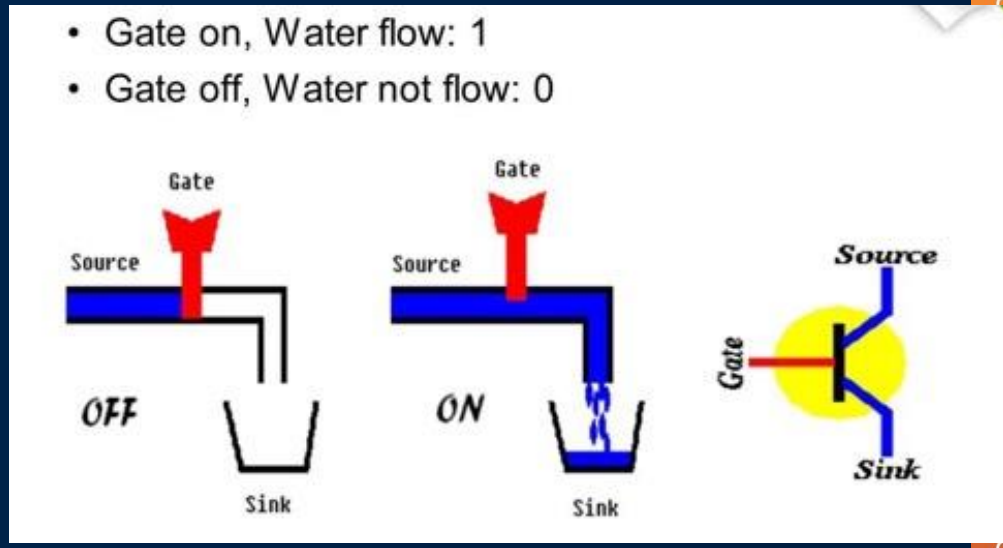
Quantum vs. Classical

Transistor

Logic unit
about 11.8 billions of transistors in a smartphone



Classical computing is based on strings of bits

`01110101011010101000100011……0100101`

The number bits can be huge, but it will still be truncate

Truncating introduces an errors

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Quantum vs. Classical

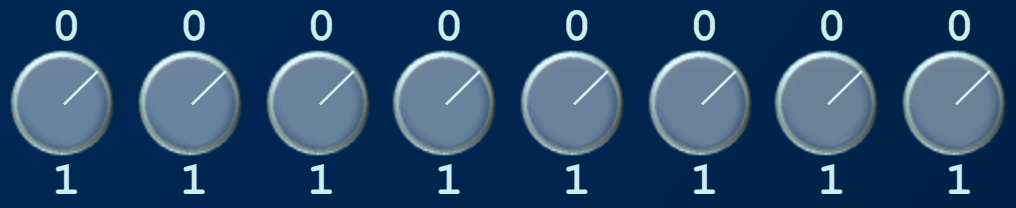
In digital classical systems, truncating introduces an error

Nature is based on an infinite number of states

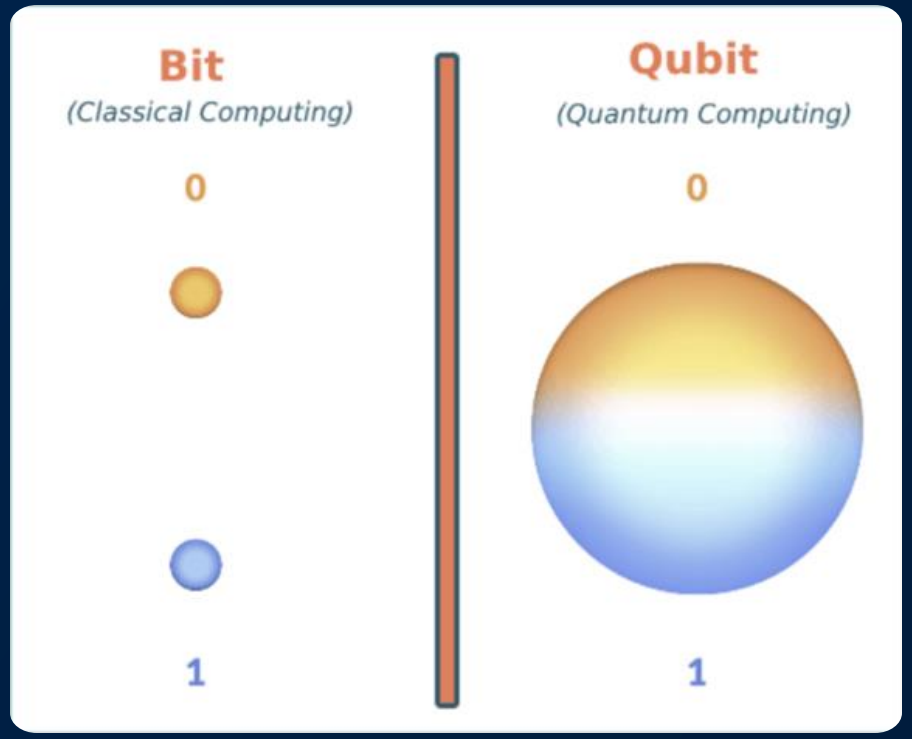
Through quantum computing, it is possible to reduce the error in simulating Nature. This is achieved by leveraging superposition and entanglement.

String of bits

01110101011010101000100011



String of QuBit



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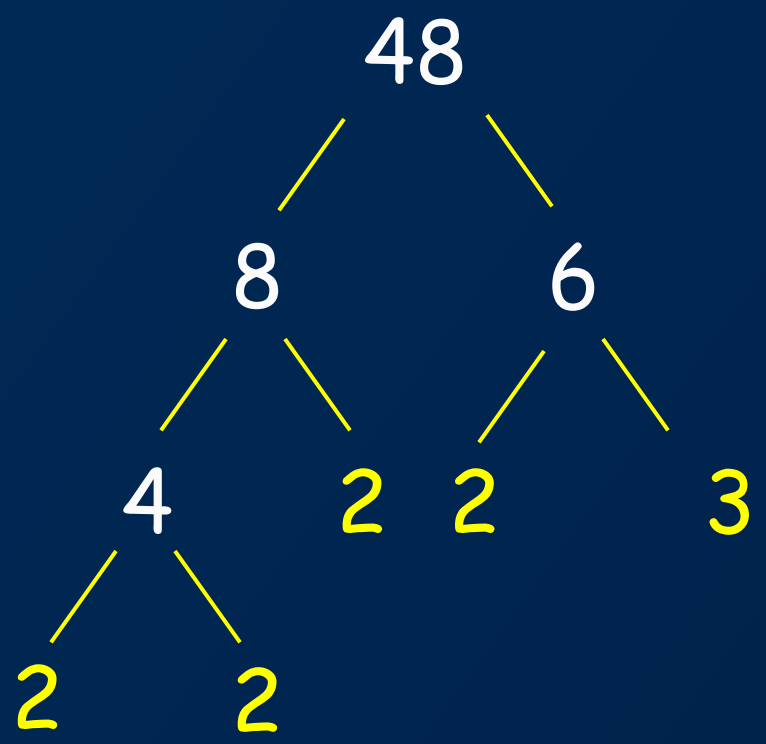
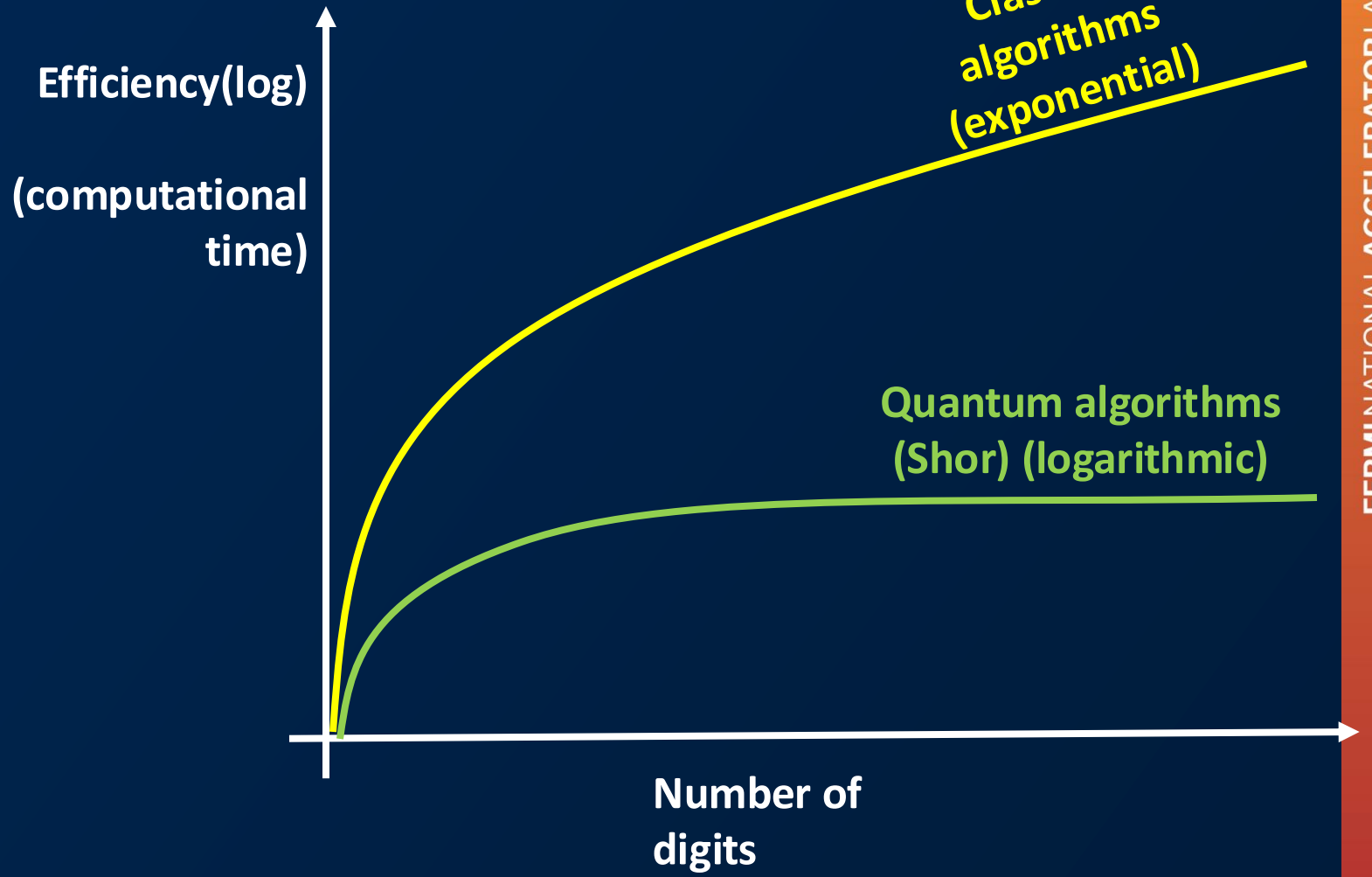
Prime number factorization



48 = 3 x 2 x 2 x 2 x 2



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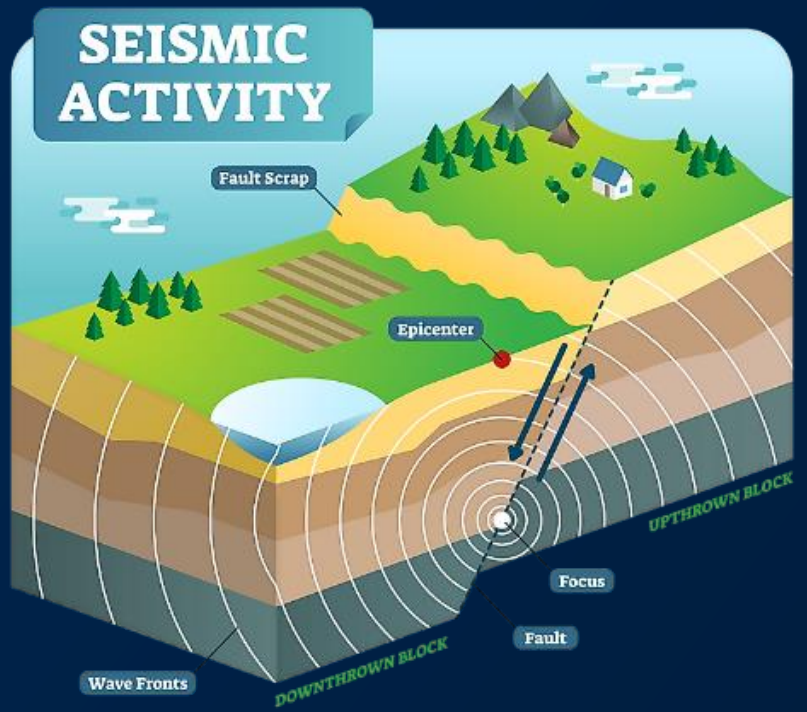
Quantum computing and sensing



Quantum sensors are used to detect very weak signals, such as those underwater and underground.

Sensor networks: increase the sensitiviy of single sensors through entanglement

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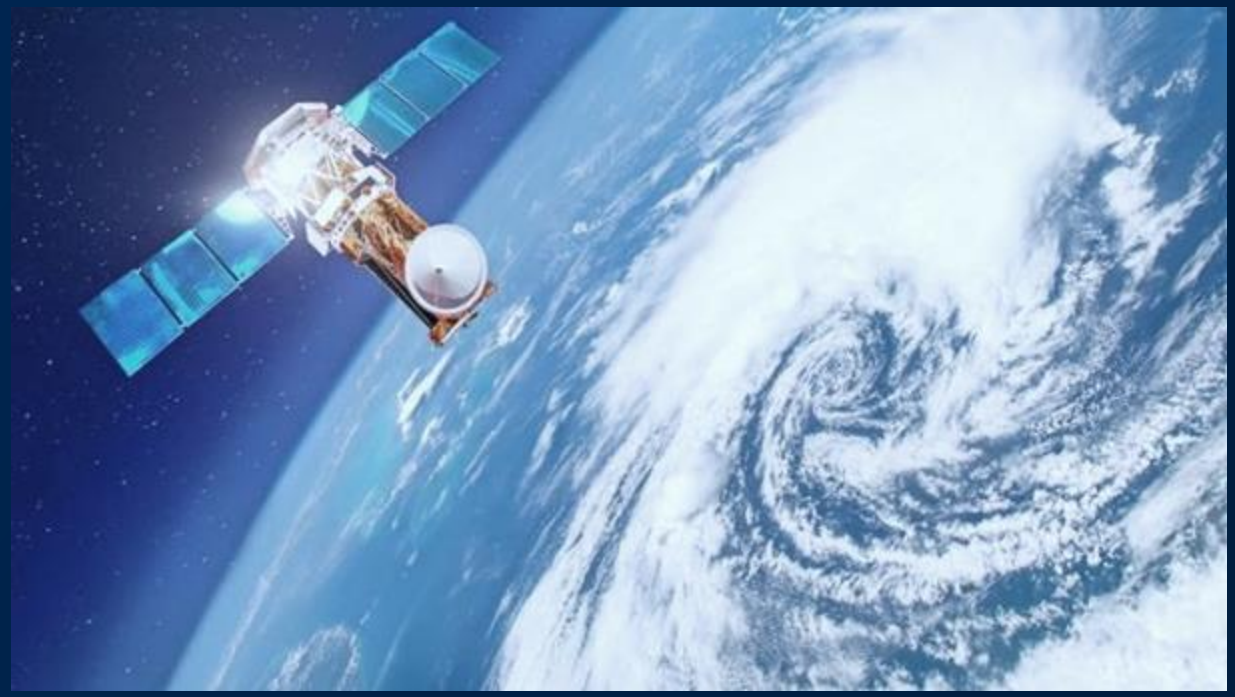
Quantum computing and sensing



Quatum algorithms can solve very complex models, such as weather forecasting, with very high efficiency and at a reduced time

All matematical models with high number of variables may benefits from quantum computing algorithms

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Quantum computing and sensing

Protein synthesis is an example for which high computational power is needed

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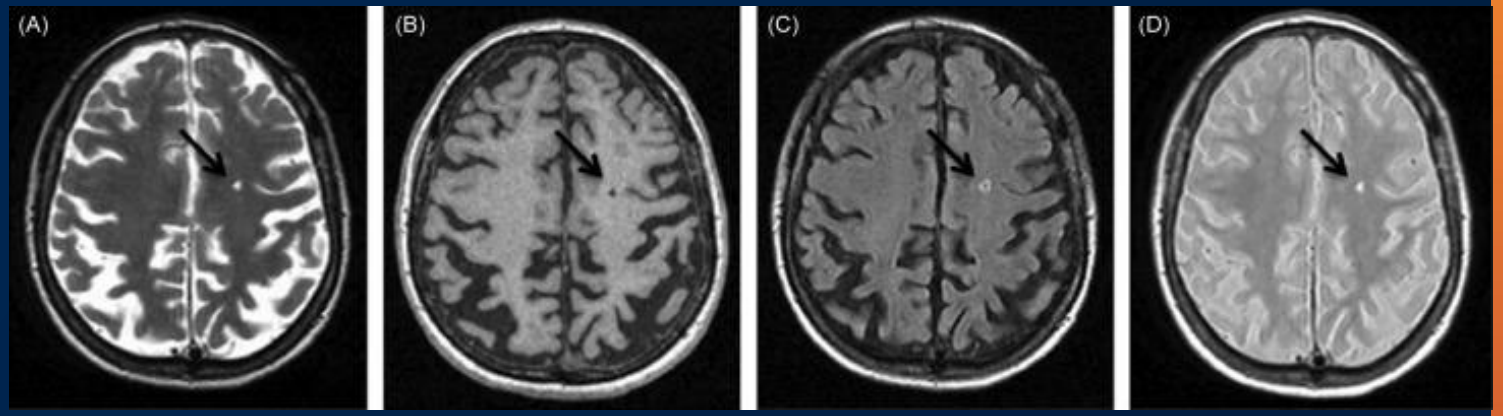
Quantum computing and sensing



Analysis of biomedical data and imaging, such as Magnetic Resonance signals.

We are exploring using quantum algorithms to increase the imaging resolution and potentially increase the chances of diagnosis.

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Quantum computing and sensing

Optimizing traffic routes. Pilot programs have been launched in Lisbon and Barcelona

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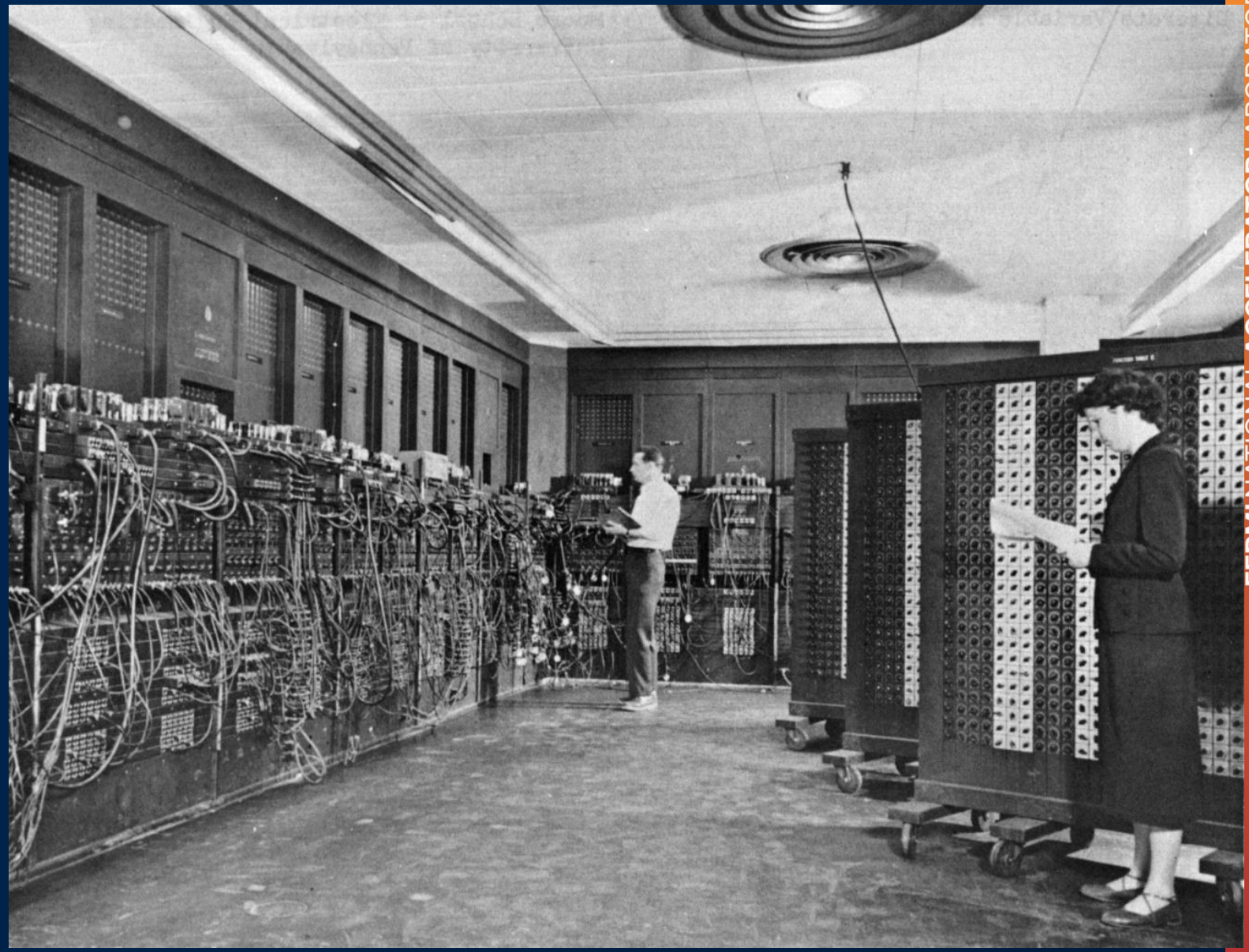
05

Hardware platforms

Classical computers

ENIAC filled a 20 by 40-foot room, weighed 30 tons, and used more than 18,000 vacuum tubes.

Transistor



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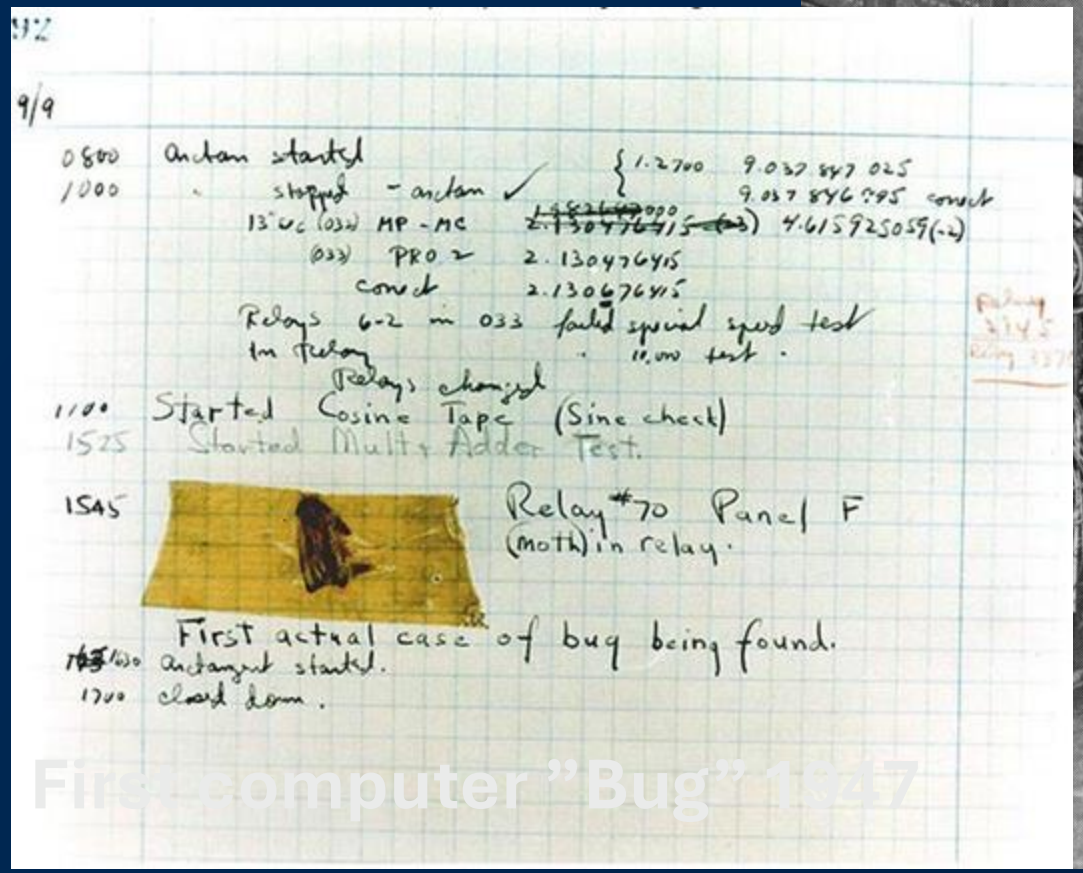
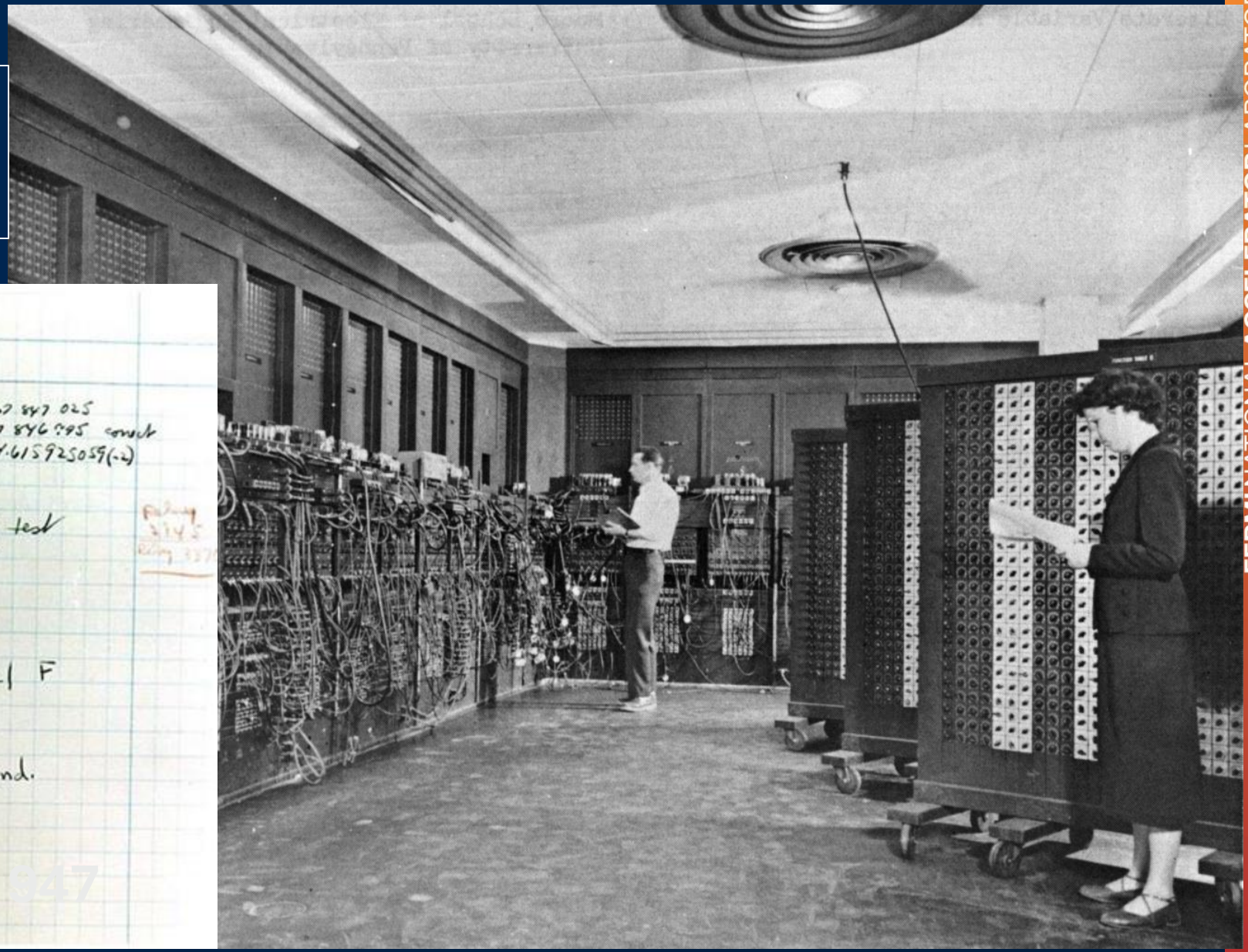
Classical computers

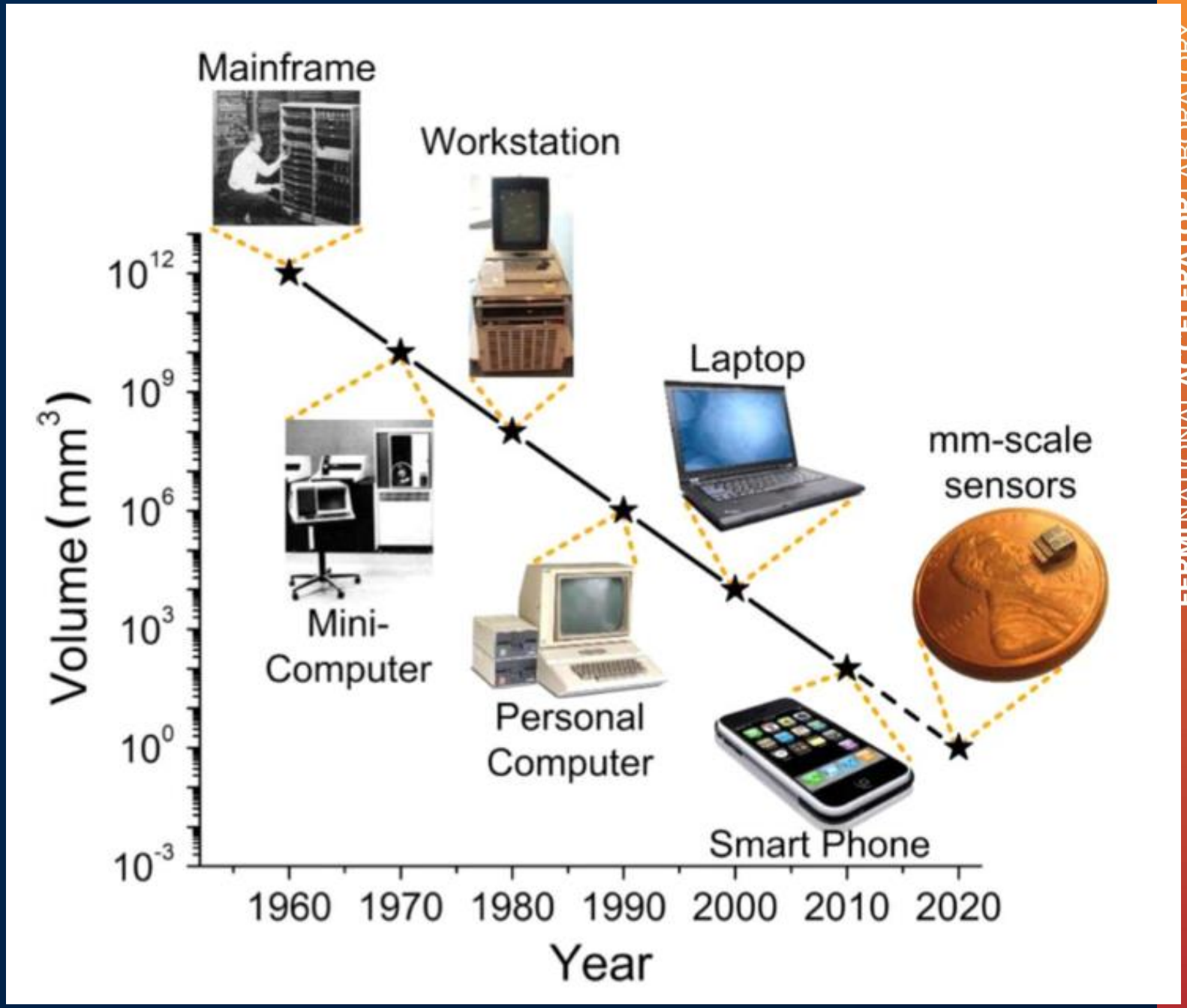


First computer "Bug" 1947



FERMI NATIONAL ACCELERATOR LABORATORY

Classical computers



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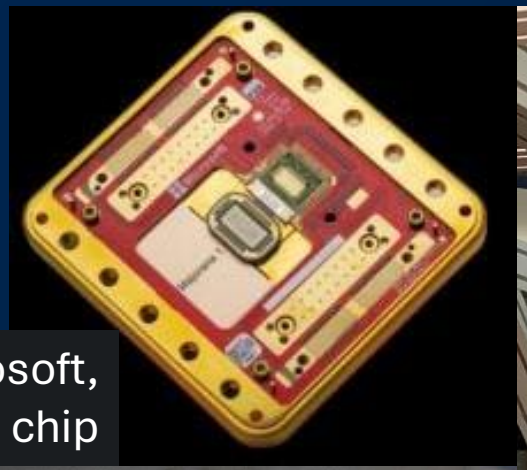
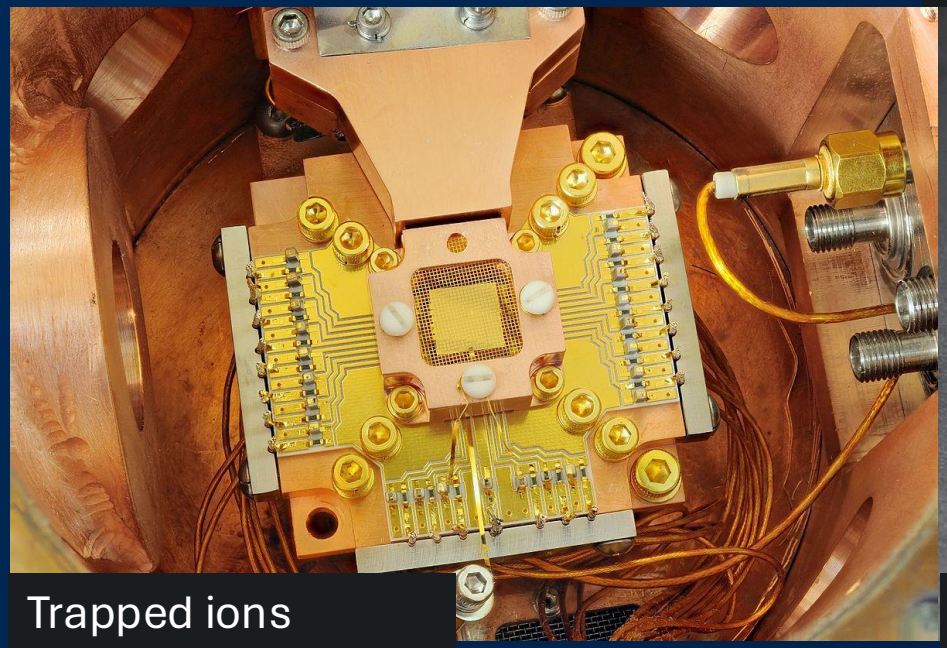
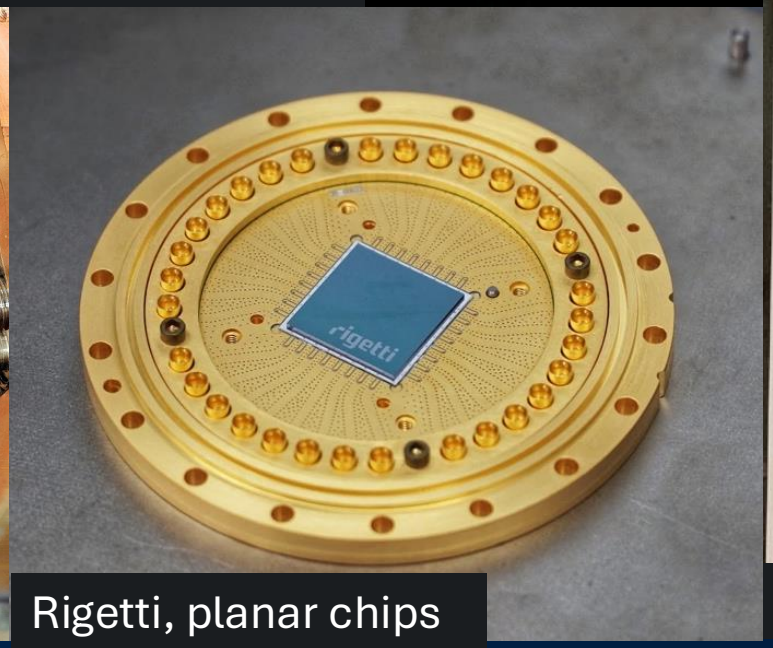
Quantum Computers



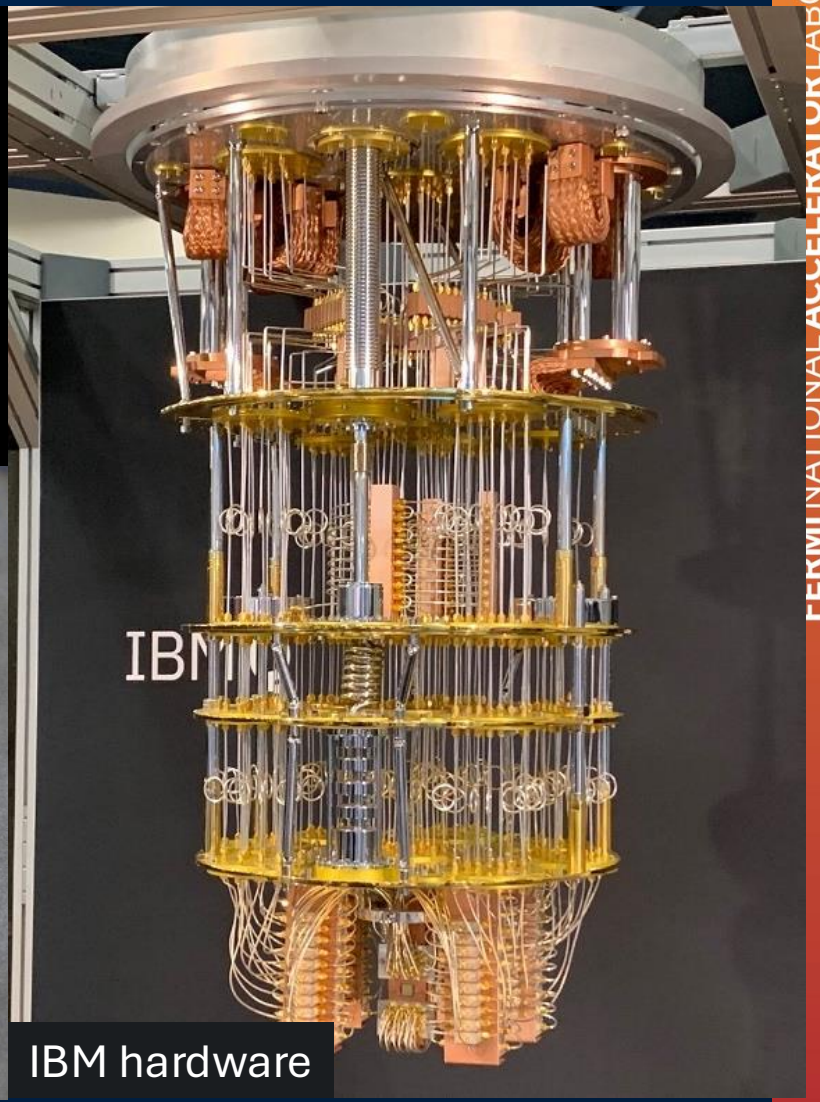
Microsoft,
Majorana chip



Trapped ions



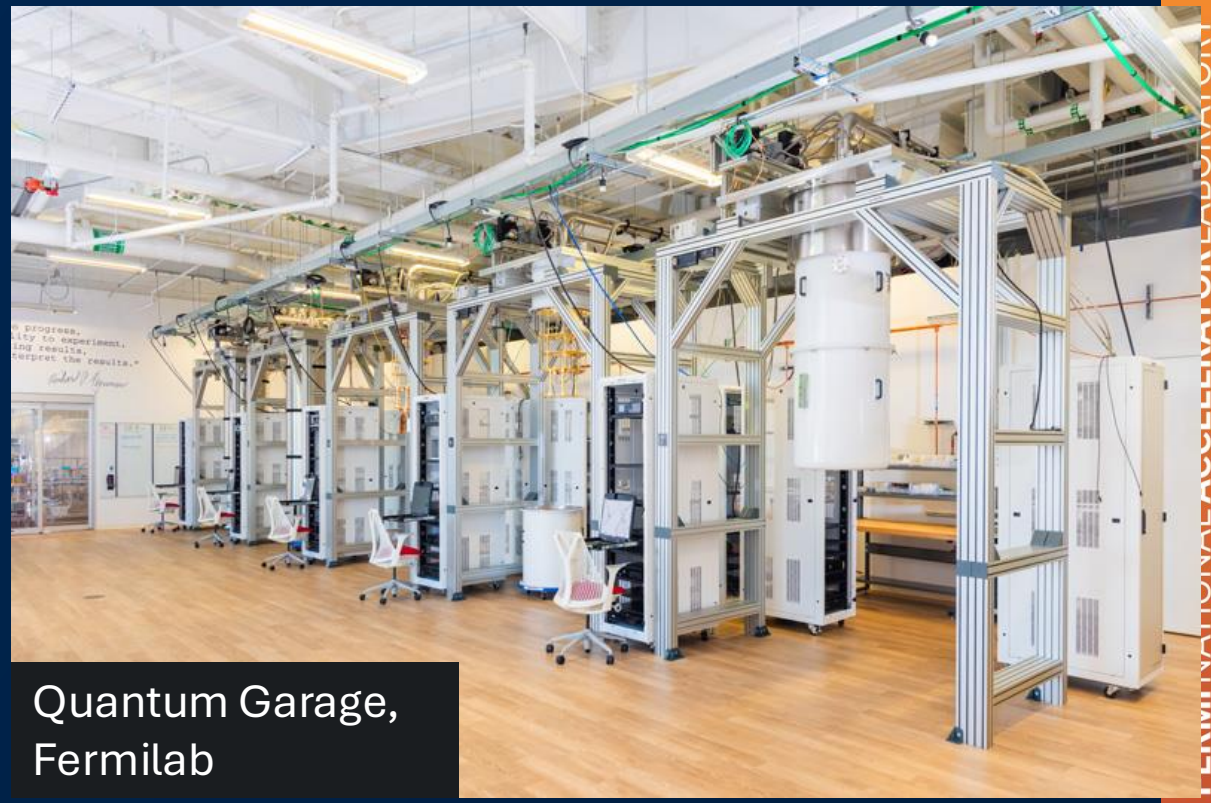
Rigetti, planar chips



IBM hardware

FERMI NATIONAL ACCELERATOR LABORATORY

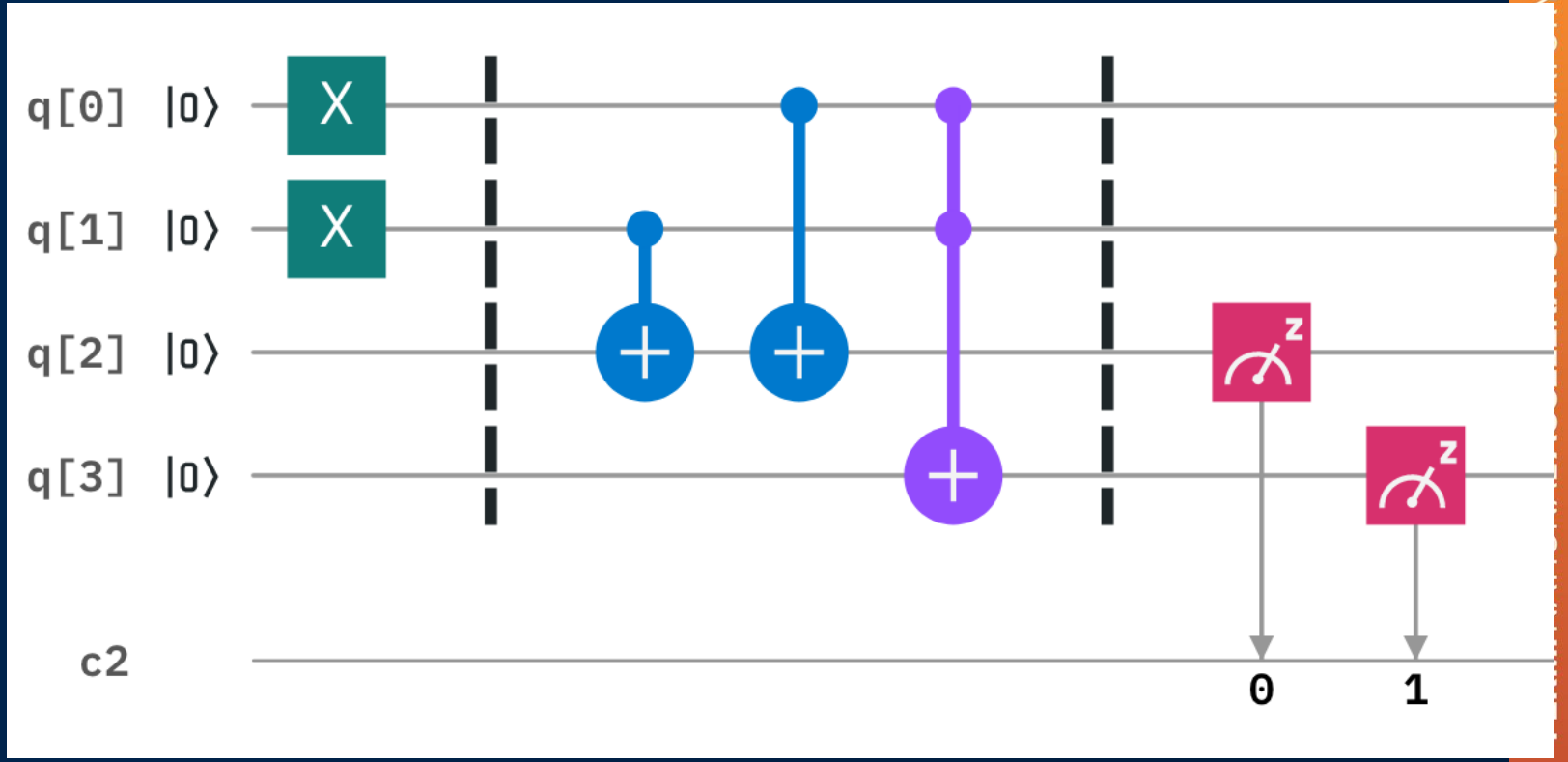
Quantum Computers

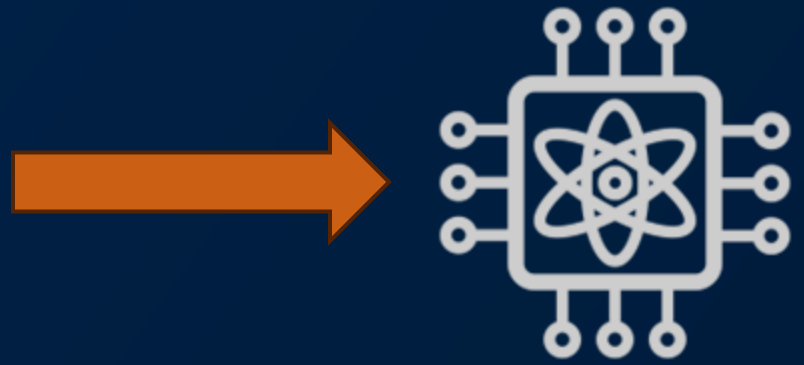


Quantum Garage, Fermilab

3D quantum computers, Fermilab

Quantum algorithms





Cloud

Quantum Processing Units

06

Fermilab and the SQMS Quantum Center

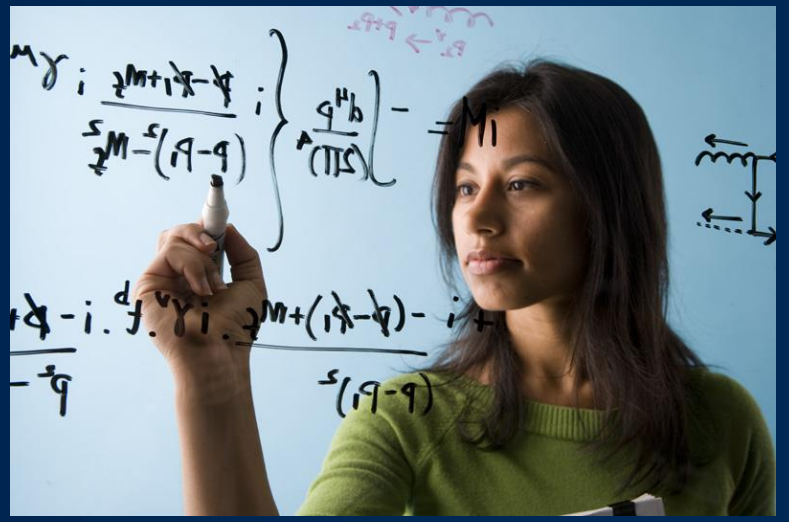
Fermilab

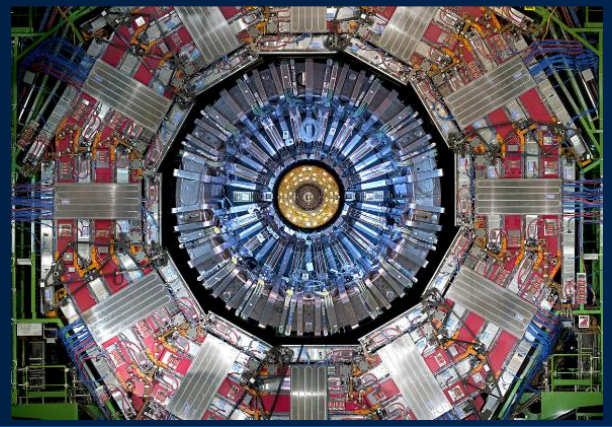
- America's particle physics and accelerator laboratory
- Operates the largest US particle accelerator complex
- ~1,900 staff and ~$600M/year budget
- 6,800 acres of federal land
- Facilities used by 4,000 scientists from >50 countries

As we move into the next 50 years, our vision remains to solve the mysteries of matter, energy, space, and time for the benefit of all.

Fermilab Science Mission

- Higgs boson
- Neutrinos
- Dark matter
- Dark energy and inflation
- Exploring the unknown



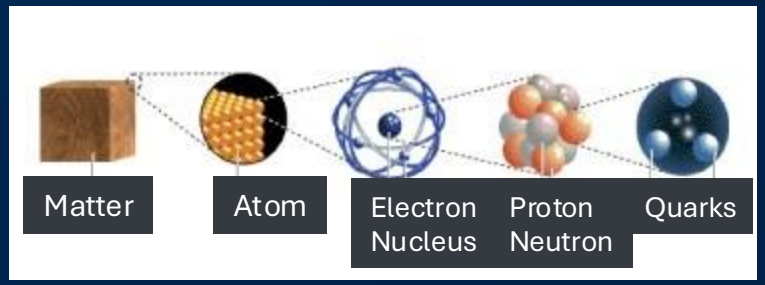


Fermilab is delivering on the DOE/SC discovery science mission: Major particle physics breakthroughs from Fermilab experiments, major technology breakthroughs from Fermilab research

FERMI NATIONAL ACCELERATOR LABORATORY

What is an accelerator

- It is big **microscope** used to study the smallest particles that make up the matter



- Study the origin of the universe

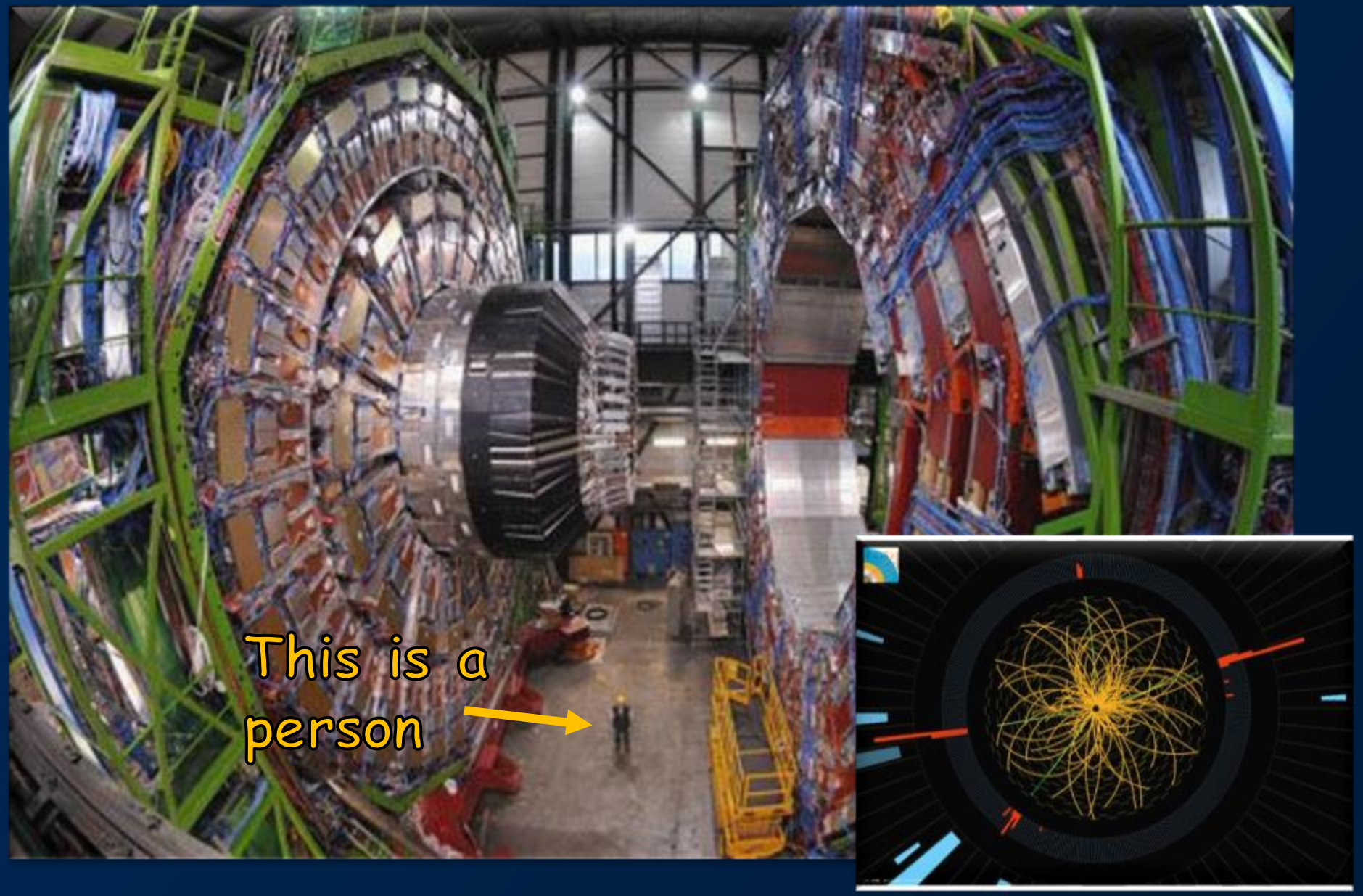
Big Bang

A first collision from which everything started

Speed of Light

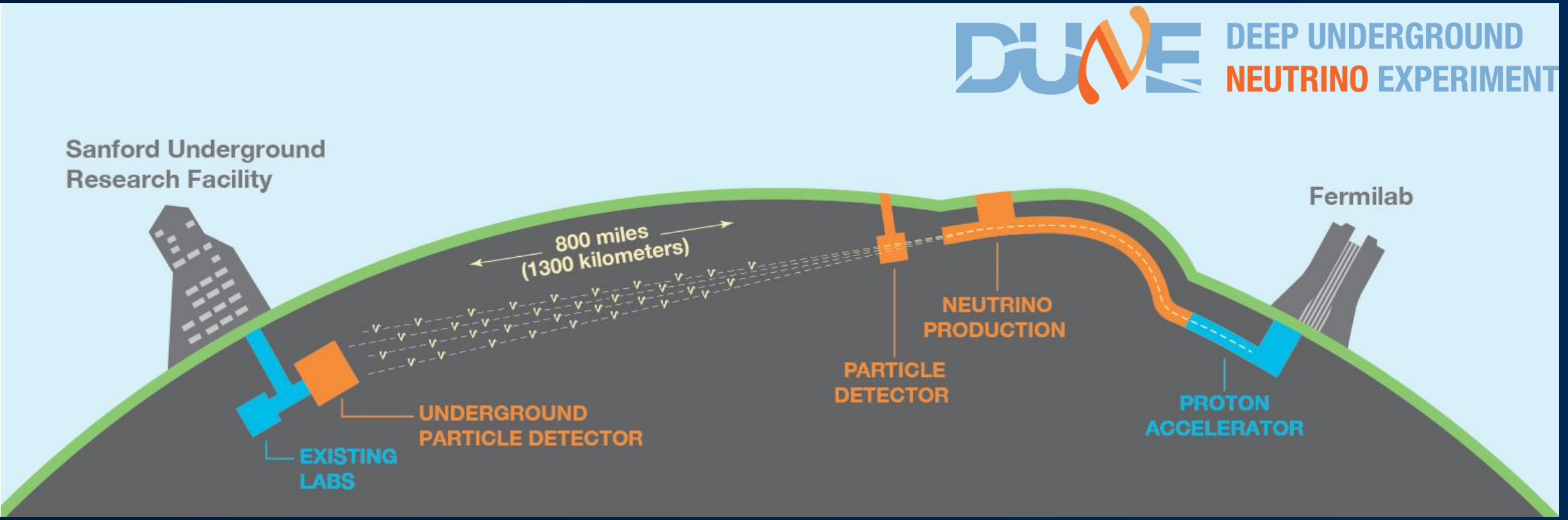
FERMI NATIONAL ACCELERATOR LABORATORY

Understanding the size of an experiment – CMS (CERN)



FERMI NATIONAL ACCELERATOR LABORATORY

An International Experiment for Neutrino Science



Origin of Matter

- Could neutrinos be the reason that the universe is made of matter rather than antimatter? By exploring the phenomenon of neutrino oscillations, DUNE seeks to revolutionize our understanding of neutrinos and their role in the universe.

https://www.dunescience.org/

Quantum computing and sensing at Fermilab

HEP for QIS

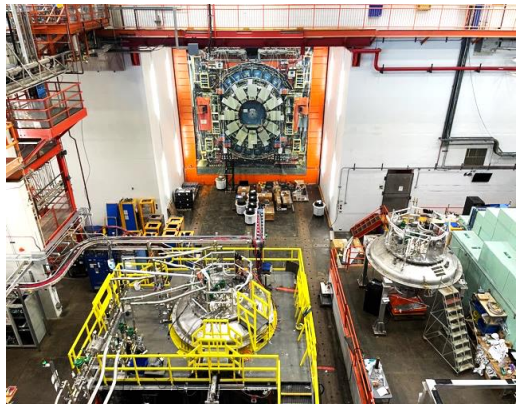
Technology expertise and infrastructure for the development of new quantum devices and for the challenges of scaling up quantum systems

QIS for HEP

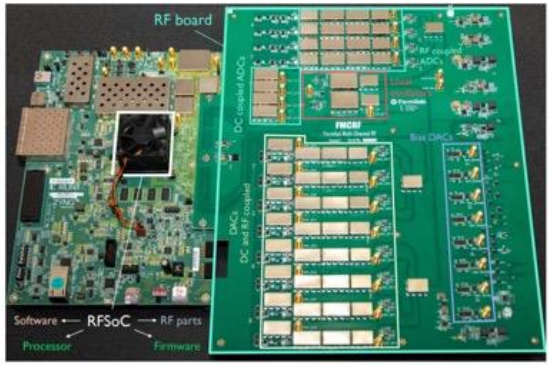
Tackle HEP challenges, such as dark matter detection, quantum computing advantage for field simulations

Superconducting technology

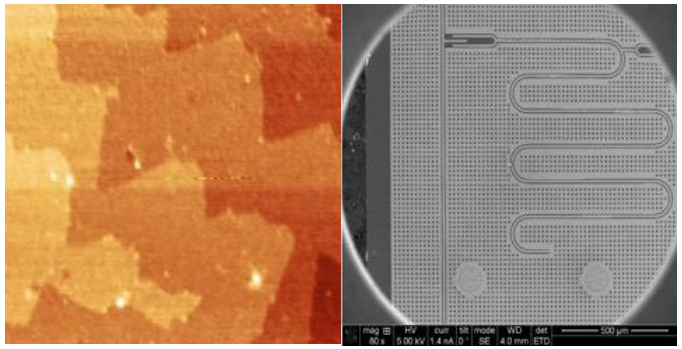
SRF cavities with long coherence time



Cryogenics



Control electronics



Materials and devices

Fermilab

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

A DOE National QIS Research Center

36
Partner Institutions

550+
Collaborators

Fermilab · Northwestern University · rigetti · AMES National Laboratory · NASA Ames Research Center · NIST · Colorado School of Mines · Coppin State University · FormFactor · Goldman Sachs · IBM · Illinois Institute of Technology · INFN · Jefferson Lab · Johns Hopkins University · Lockheed Martin · Lawrence Livermore National Laboratory · LSU · NPL National Physical Laboratory · NYU · Royal Holloway University of London · Rutgers · Spelman College · Stanford · Temple University · Unitary Fund · The University of Arizona · University of Colorado Boulder · University of Illinois Chicago · University of Illinois Urbana-Champaign · University of Michigan · Maybell · University of Minnesota Driven to Discover · Università di Pisa · USC University of Southern California · University of Waterloo · IQC Institute for Quantum Computing

SQMS brings together hundreds of experts from more than 30 DOE national labs, academia, industry and other federal and international entities to bring transformational advances in QIS

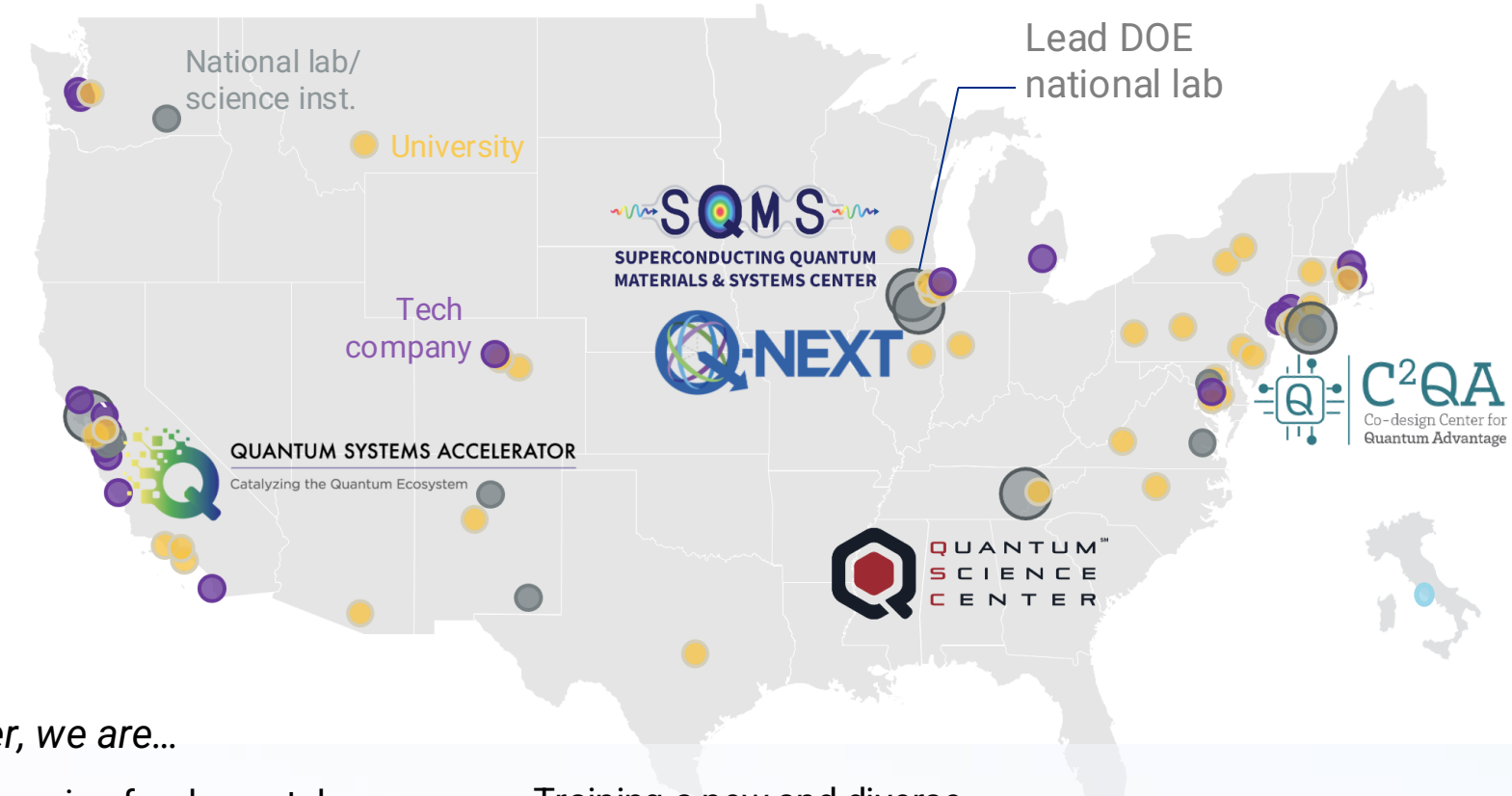
The DOE National QIS Research Centers

Unique institutional partnerships boost joint efforts in academia, industry and national labs

1,200+ experts

600+ students & postdocs

at **80** institutions in in **21** US states & DC



DOE NQISR Centers leverage unique capabilities, expertise and facilities to achieve bold scientific and technological goals.

Together, we are…

- Answering fundamental open questions in QIS
- Leveraging DOE user facilities for advanced materials analysis and device fabrication
- Training a new and diverse quantum workforce
- Fostering technology transfer – rapid cycle from discovery to commercialization
- Accelerating scale-up
- Developing national standards

Fermilab

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Quantum computing and sensing at Fermilab

HEP for QIS

Technology expertise and infrastructure for the development of new quantum devices and for the challenges of scaling up quantum systems

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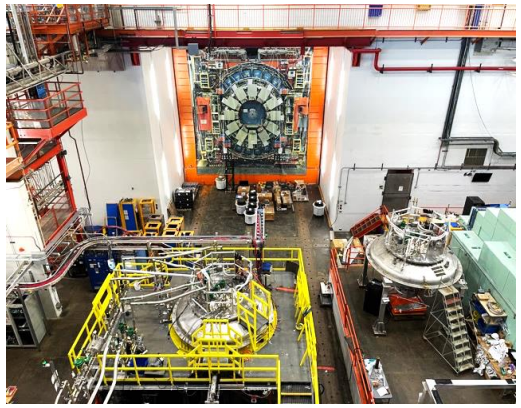

Cryogenics

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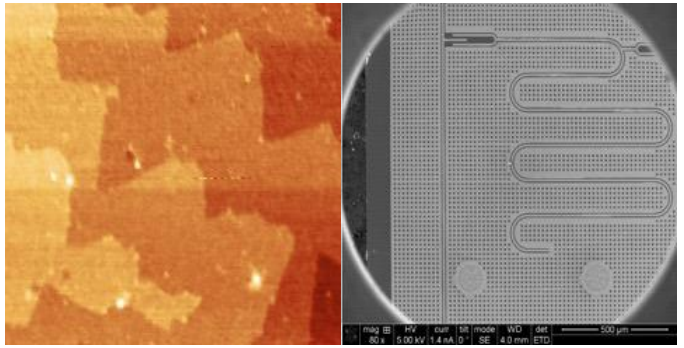


Materials and devices

Fermilab

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

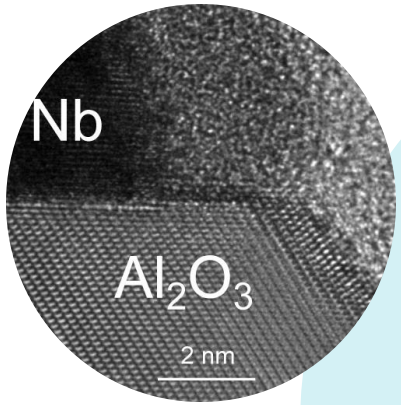
SQMS 1.0: Building on Fermilab's unique accelerator expertise and facilities to advance Quantum Information Science

Abate decoherence sources

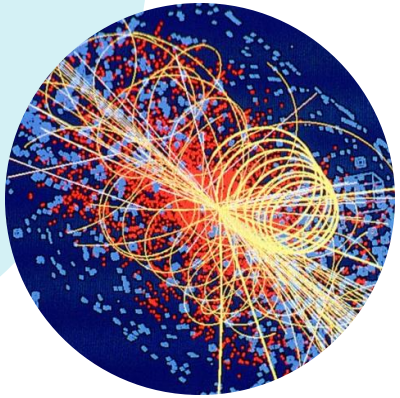
Fundamental science of materials and nanostructures to advance superconducting device performance

High coherence cavity systems

Record coherence microwave cavity devices and quantum interconnects for high fidelity scaling of quantum computers and sensors



SQMS Mission:
to bring transformational advances in development and deployment of high coherence superconducting quantum systems.



Efficient cryogenic scaling

Large scale low temperature cryogenic technology, distribution systems for scaling efficiently to large quantum systems

Simulation and sensing

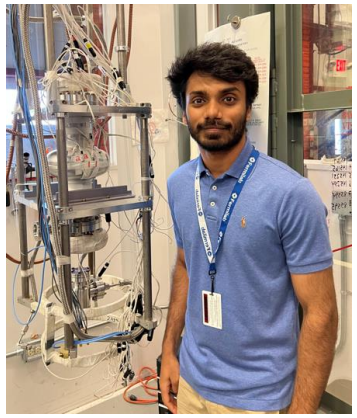
Theory and simulation to solve high energy and condensed matter physics problems on quantum platforms

*SQMS brings decades of DOE investments in accelerator facilities and technologies in a **government-industry-academia** strategic partnership framework for broad impacts*

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Training through research

- Expose interns to cutting-edge facilities and expertise in a multi-institutional/multi-disciplinary collaboration.
- Research projects under the direct supervision of SQMS PIs.
- Develop and practice research, technical, and soft skills (presentations, networking, etc.).
- Interns participate in weekly meetings with SQMS researchers, with progress reports every 3 weeks, a final presentation during the SQMS meeting, and a report on research activities.

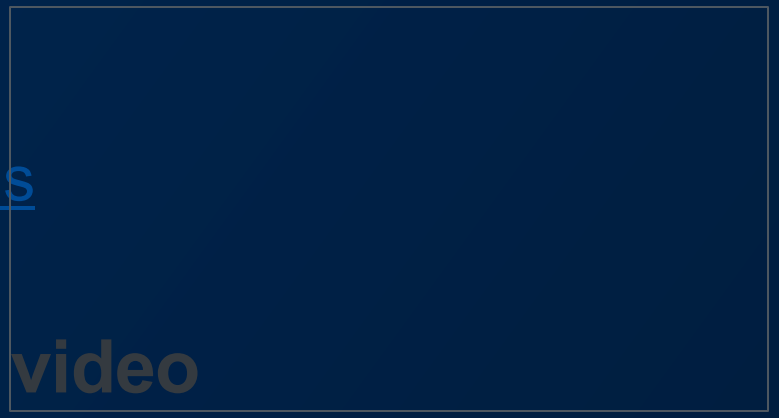


How AI sees a Quantum Computer

THANK YOU FOR YOUR ATTENTION

Fermilab
FermiFORWARD
U.S. DEPARTMENT of ENERGY
FERMI NATIONAL ACCELERATOR LABORATORY

- https://www.youtube.com/watch?v=Sk_0QM_UA4I&t=1s



Hardware platforms

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A DETAILED VIEW