

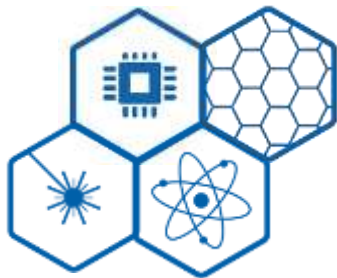
# QUANTUM TECHNOLOGIES

**Dra. Gemma Rius**

Investigadora Ramón y Cajal

**Instituto de Microelectrónica de Barcelona**

IMB-CNM-CSIC



*10/09/2024*

# On QUANTUM TECHNOLOGIES

1<sup>st</sup>. Towards QTech

2<sup>nd</sup>. QTech for HEP

# Institute of Microelectronics of Barcelona IMB-CNM-CSIC



## IMB-CNM-CSIC. Research Axes

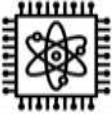
**Physics Frontiers  
&  
Civil Security**

**Energy  
&  
Mobility**

**Health  
&  
Environment**

**Advanced Processes for  
Micro & Nano systems**

**8 Research Groups**



# IMB-CNM-CSIC. Capability

- ✓ **Integrated Clean Room for Micro/Nano fab @ IMB as key facility**



## Main Clean Room @ IMB-CNM-CSIC

- 1,500 m<sup>2</sup>
- Class 100-10,000
- CMOS processing technology
- Microsystems processing
- Nanolithography & Nanofabrication

## Back-End Clean Room

- 40 m<sup>2</sup>
- Class 1000-10,000
- Chip packaging
- Hybrid circuit assembly

## 10 Specialized Areas or Labs

- Graphene Tech, SIAM, RadLab, PDS-Thermal, Rapid Prototyping, Printed-Electronics...



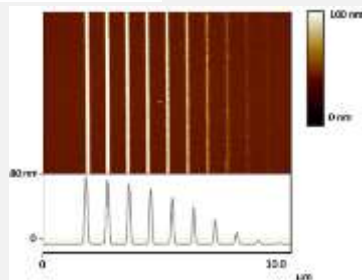
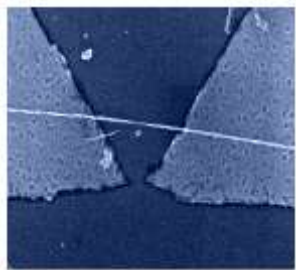
# Onset of Nanofabrication @ IMB-CNM-CSIC



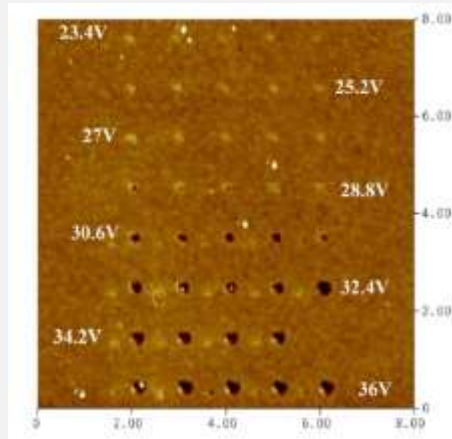
- *Setup Electron Beam Lithography.*
- *Implementation EBL 2002-2008*

## Nanopatterning

### Electron Beam



### Scanning Probe



Nanotechnology 2005

### Ion Beam



JVST B 2012, NIMS B 2014, ...

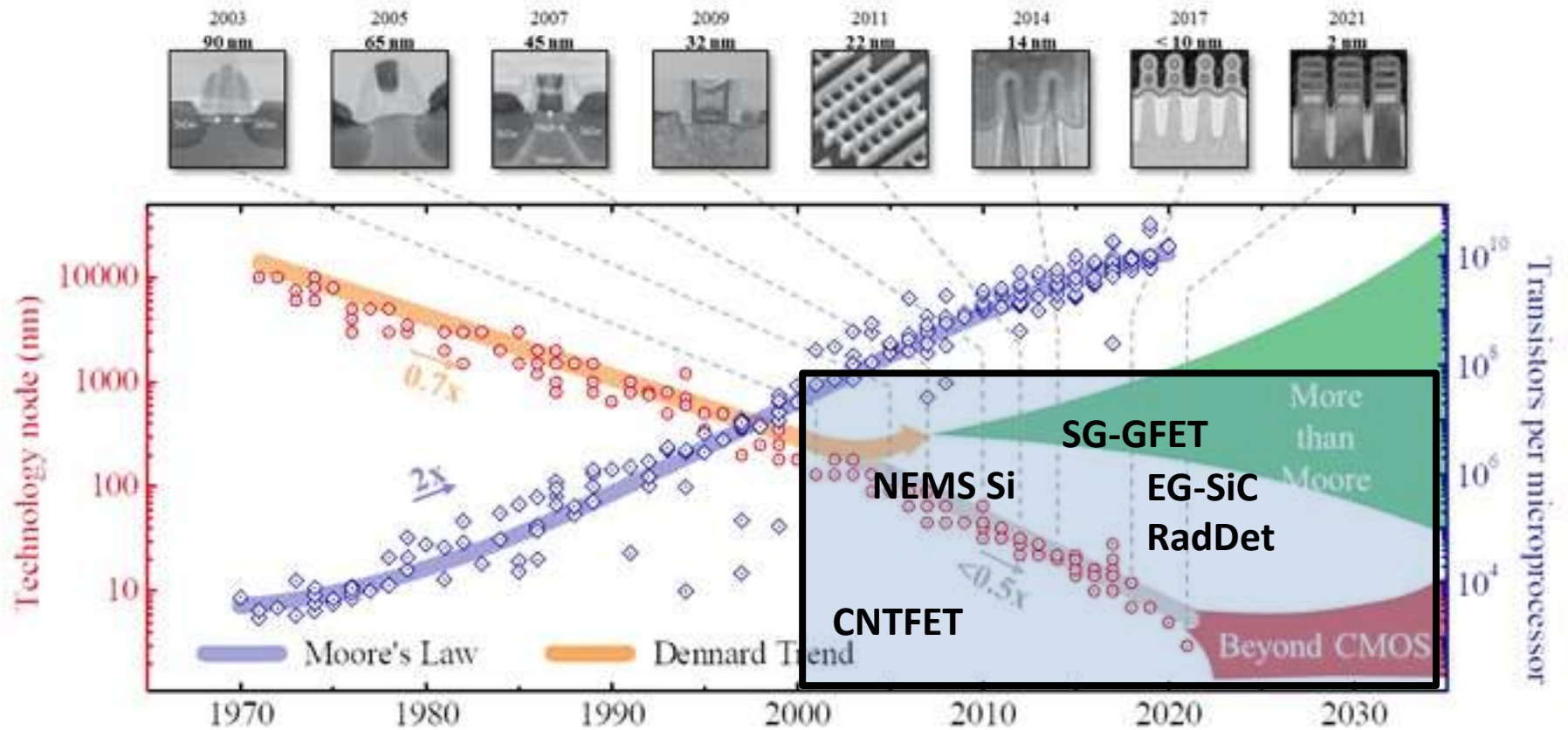
## Advanced Characterization

FE-SEM

AFM

FIB

# Introduction



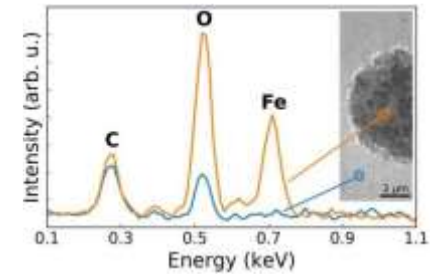
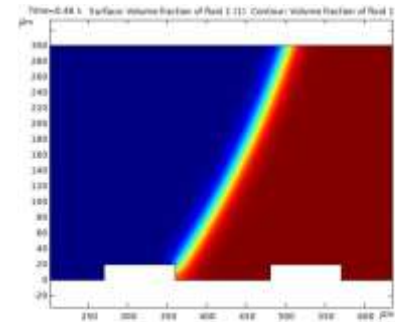
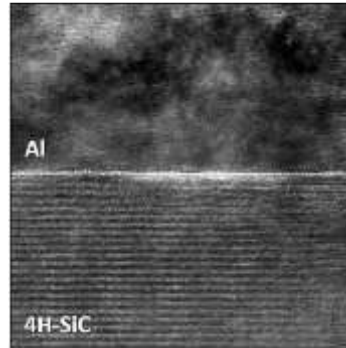
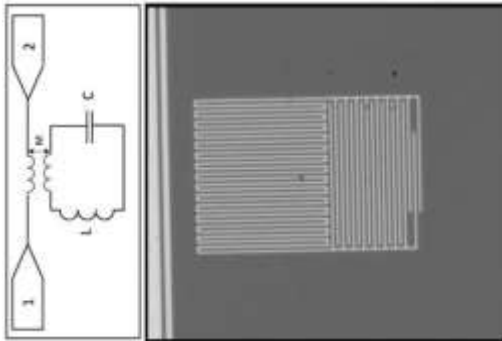
# Fabrication and Integration of Emerging Electronic Devices and Nanomaterials

1. Fabrication of staple Superconducting Devices and Circuits

2. Exploring Hybrid Devices based on 2D Materials and Superconductors

3. Miniaturization of Devices for Unconventional Environments or Applications

4. *Micro-Nano Fabrication of Novel Emerging Devices*



**QUANTUM TECHNOLOGIES**

TRL 1 - 5

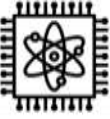
**HARSH Appl.**

TRL 1 - 7

**Emerging ICT**

TRL 1 - 4





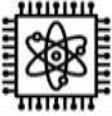
## 2nd Quantum Revolution

**First Quantum revolution** was a revolution in **atomic and subatomic physics**, as the new principles governing the physical reality.

**Second Quantum revolution** is about **controlling individual quantum systems**, to take these rules and use them to develop new technologies .

Examples of outcomes that could deliver Quantum Technologies in coming decades include knowledge, devices and applications related to,

- quantum information technology
- quantum electromechanical systems
- coherent quantum electronics
- quantum optics
- condensed matter technology



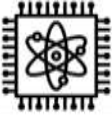
## Quoting Feynman



*“Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.”*

*“What I want to talk about is the problem of manipulating and controlling things on a small scale. (...)*

*Why cannot we write the entire 24 volumes of the Encyclopedia Britannica on the head of a pin?”*



# Nanotechnology

**Nanotechnology**, stands for both Nanoscience and Nanotechnology

On the ability to understand & control **matter at the nanoscale** (1-100nm)

Matter can exhibit unusual physical, chemical, and biological properties at the nanoscale, **differing in important ways from the properties of bulk materials, single atoms, and molecules.**

**Disruptive.** It leads to ongoing (r)evolutions in technology and industry

With the aim to benefit society in widespread applications.

# 10<sup>-9</sup>

# Nanotechnology



**Miniaturization**

**Matter**

**Knowledge**

Nanofabrication

Nanomaterials

Applications

Characterization

Simulation

Feynman 1959

Taniguchi 1972  
Nanotechnology

ALD 1974

Binnig&Rohrer 1981 STM  
Q-Dots @ Bell Labs

Molecular Electronics  
Fullerenes

Iijima 1991 CNTs

Novoselov&Geim  
2004 Graphene

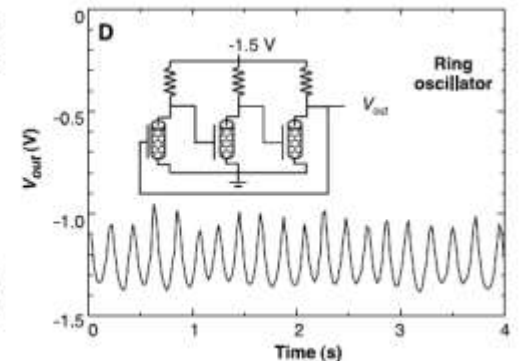
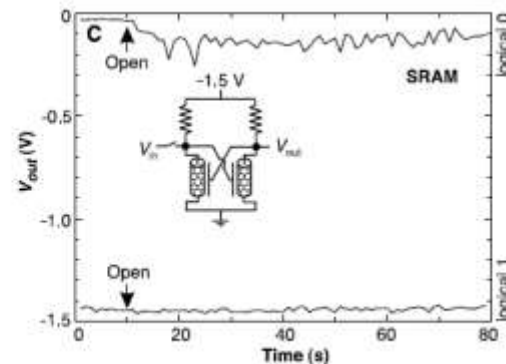
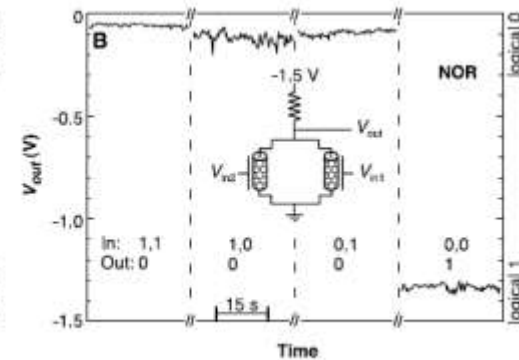
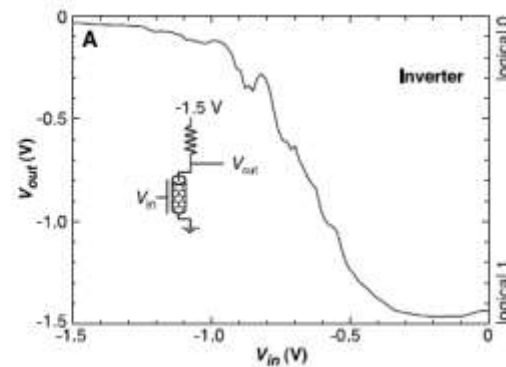
# Disruption in Nanotechnology Advanced Materials based Electronics



## Logic Circuits with Carbon Nanotube Transistors

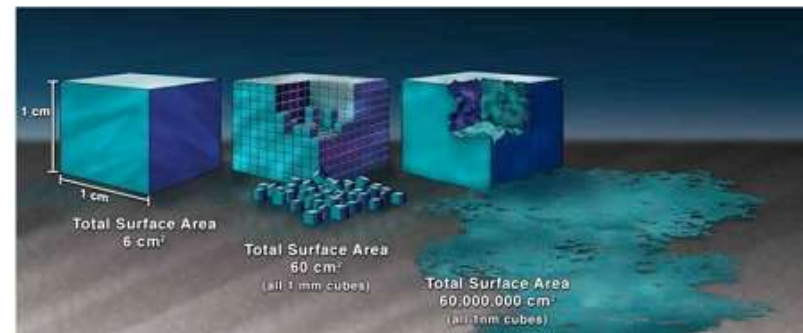
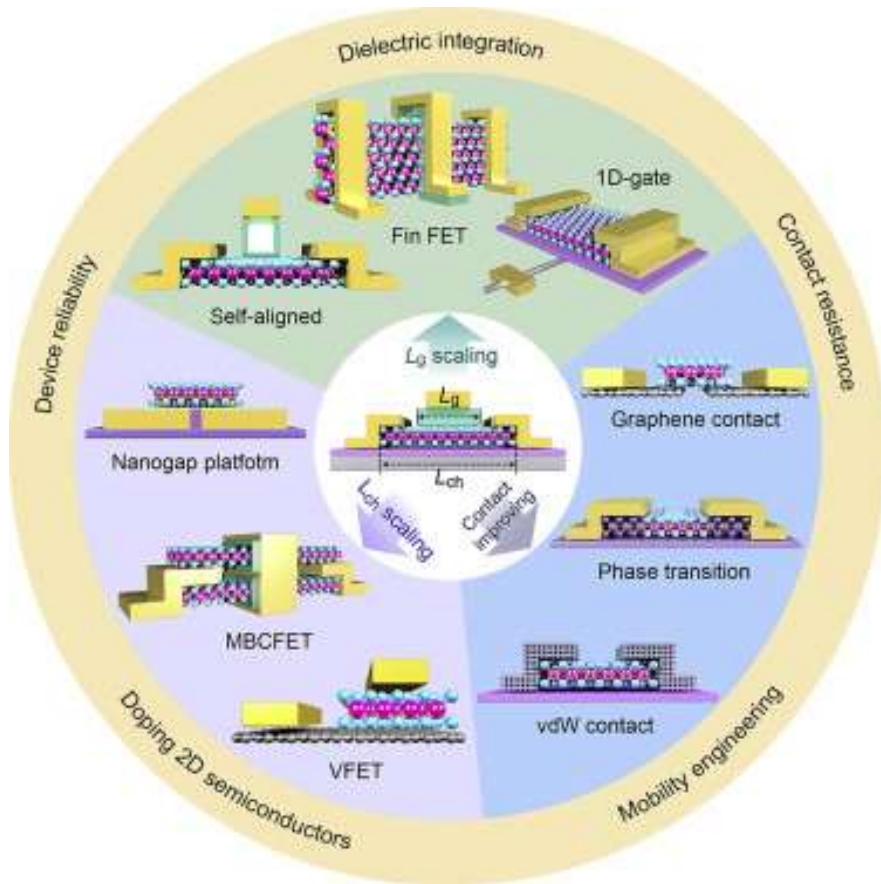
Adrian Bachtold,\* Peter Hadley, Takeshi Nakanishi, Cees Dekker†

We demonstrate logic circuits with field-effect transistors based on single carbon nanotubes. Our device layout features local gates that provide excellent capacitive coupling between the gate and nanotube, enabling strong electrostatic doping of the nanotube from *p*-doping to *n*-doping and the study of the nonconventional long-range screening of charge along the one-dimensional nanotubes. The transistors show favorable device characteristics such as high gain ( $>10$ ), a large on-off ratio ( $>10^5$ ), and room-temperature operation. Importantly, the local-gate layout allows for integration of multiple devices on a single chip. Indeed, we demonstrate one-, two-, and three-transistor circuits that exhibit a range of digital logic operations, such as an inverter, a logic NOR, a static random-access memory cell, and an ac ring oscillator.



# Novel Nanomaterials Applications in Emerging Devices

Two dimensional semiconducting materials for ultimately scaled transistors (2022)



# Technology Trends of this and next Decade

**Technology trends and underlying technologies**

**Industry-agnostic trends**

**1** **Next-level process automation...**  
Industrial IoT<sup>1</sup>  
Robots/cobots<sup>2</sup>/RPA<sup>3</sup>

**2** **Future of connectivity**  
5G and IoT connectivity

**3** **Distributed infrastructure**  
Cloud and edge computing

**4** **Next-generation computing**  
Quantum computing  
Neuromorphic chips (ASICs<sup>4</sup>)

**5** **Applied AI**  
Computer vision, natural-language processing, and speech technology

**6** **Future of programming**  
Software 2.0

**7** **Trust architecture**  
Zero-trust security  
Blockchain

**Industry-specific trends**

**8** **Bio Revolution**  
Biomolecules/"-omics"/ biosystems  
Biomachines/biocomputing/augmentation

**9** **Next-generation materials**  
Nanomaterials, graphene and 2-D materials, molybdenum disulfide nanoparticles

**10** **Future of clean technologies**  
Nuclear fusion  
Smart distribution/metering  
Battery/battery storage  
Carbon-neutral energy generation

McKinsey & Co (2021)

<https://www.weforum.org/agenda/2021/10/technology-trends-top-10-mckinsey/>

## *Ubiquitous Microelectronics*

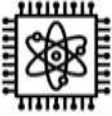
### Semiconductors are the foundations of any modern technology

Chips are embedded in a wide range of products: automotive, computers, medical devices, etc.

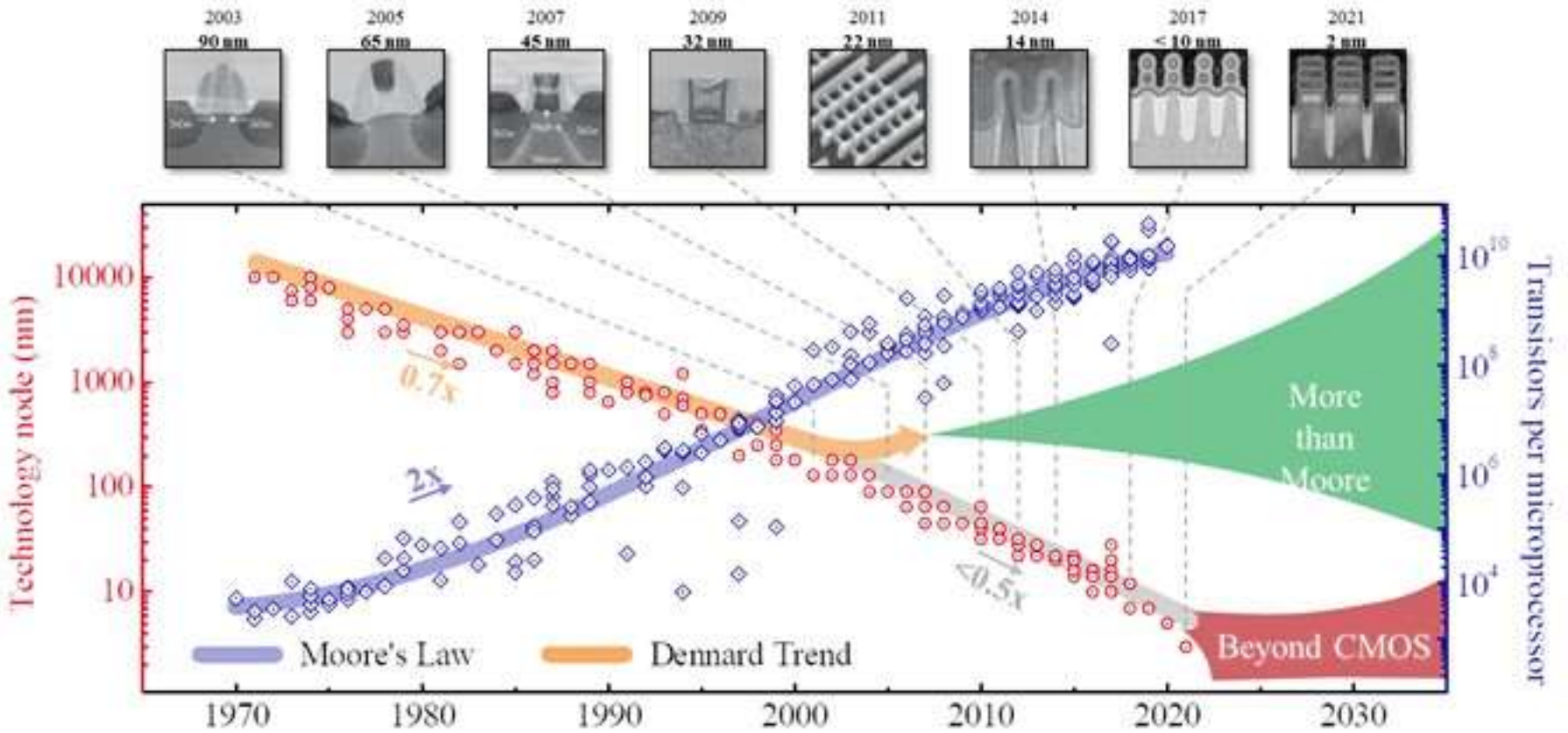
“**Microelectronics** (...) refers to integrated electronic devices and systems generally **manufactured using semiconductor-based materials and related processing**.

Such devices and systems include **analog and digital electronics, power electronics, optics and photonics, and micromechanics, for memory, processing, sensing, and communications.**”

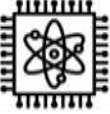




# ICT & Microelectronics Hardware Nanotechnologies



**Microelectronics Evolution - Much more than geometrical down scaling**



## Nano to Quantum

**Quantum Technology** allows us to organise and control the components of a complex system governed by the **laws of quantum physics**, instead of exploiting classical physics as in conventional technology.

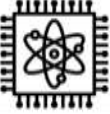
Two essential drivers in quantum technology:

- **Miniaturization**, as the dominant trend in last decades: to build devices on a smaller and smaller scale.

Ultimately this will deliver devices at length scales of nanometres and action scales approaching Planck's constant.

At that point design must be based on quantum principles.

- **Principles of quantum mechanics**: the promise of a vastly improved performance over what can be achieved within a classical framework.



## Quantum Principles

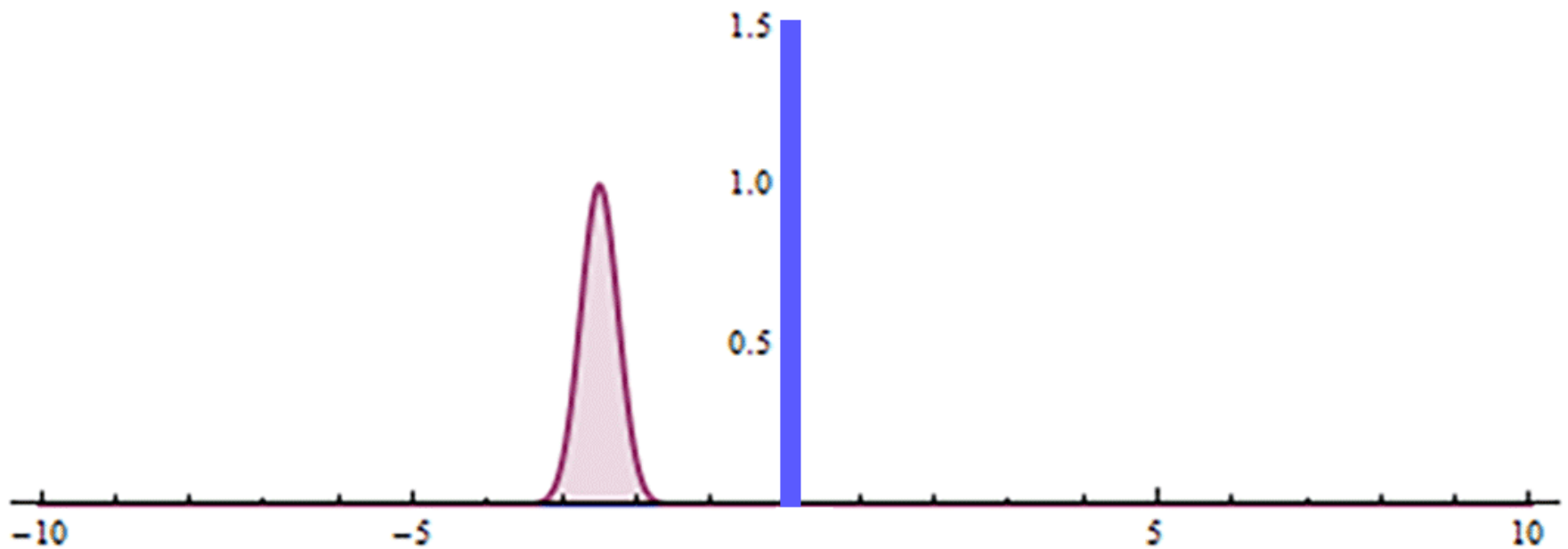
**Goal:** to deliver **useful devices and processes** that are based on **quantum principles**

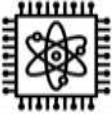
- **Quantisation or quantum size effect** - the allowed energies of a tightly confined system of particles are restricted to a discrete set.
- **Uncertainty principle** - for every perfectly specified quantum state there is always at least one measurement, the results of which are completely certain, and simultaneously at least one measurement for which the results are largely random.
- **Quantum superposition** - if an event can be realized in two or more indistinguishable ways, the state of the system is a superposition of each way simultaneously.
- **Tunneling** - the ability of a particle to be found in spatial regions from which classical mechanics would exclude it.
- **Entanglement** - the superposition principle applied to certain nonlocal correlations, if a correlation can be realized in two or more indistinguishable ways, the state of the system is a superposition of all such correlations simultaneously.
- **Decoherence** - what happens to quantum superpositions when an attempt is made to distinguish previously indistinguishable ways an event can be realized. It renders superpositions of probability amplitudes into superpositions of classical probabilities. Decoherence has no analogue in classical physics

---

# Quantum Tunneling

When a wave packet strikes a barrier, part of it reflects and part tunnels through.





# Quantum Matter (or Materials)

IOP Publishing

*J. Phys. Mater.* 3 (2020) 042006<https://doi.org/10.1088/2515-7639/abb74e>

Journal of Physics: Materials



## ROADMAP

## The 2021 quantum materials roadmap

## OPEN ACCESS

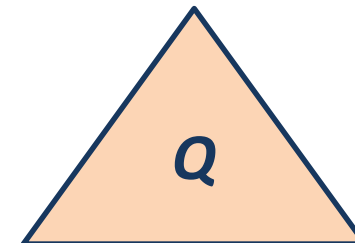
RECEIVED  
18 May 2020REVISED  
5 August 2020ACCEPTED FOR PUBLICATION  
10 September 2020

PUBLISHED

Feliciano Giustino<sup>1,2</sup>, Jin Hong Lee<sup>1</sup>, Felix Trier<sup>3</sup>, Manuel Bibes<sup>4</sup>,  
 Stephen M Winter<sup>5</sup>, Roser Valenti<sup>6</sup>, Young-Woo Son<sup>3</sup>, Louis Taillefer<sup>7</sup>, Christoph Heil<sup>8</sup>,  
 Adriana I Figueroa<sup>9</sup>, Bernard Plaças<sup>10</sup>, QuanSheng Wu<sup>11</sup>, Oleg V Yazyev<sup>11</sup>, Erik P A M Bakkers<sup>12</sup>,  
 Jesper Nygård<sup>13</sup>, Pol Forn-Díaz<sup>14,15</sup>, Silvano De Franceschi<sup>16</sup>, J W McIver<sup>17</sup>, L E F Foa Torres<sup>18</sup>,  
 Tony Low<sup>19</sup>, Anshuman Kumar<sup>20</sup>, Regina Galceran<sup>21</sup>, Sergio O Valenzuela<sup>22</sup>, Marius V Costache<sup>23</sup>,  
 Aurélien Manchon<sup>24</sup>, Eun-Ah Kim<sup>25</sup>, Gabriel R Schleder<sup>24,26</sup>, Adalberto Fazzio<sup>24,25</sup> and  
 Stephan Roche<sup>1,21</sup>

1. Introduction
2. Complex oxides
3. Quantum spin liquids
4. Twisted 2D layered crystals
5. Cuprate superconductors
6. Ultrathin layered superconductors
7. Topological insulators
8. Topological semimetals
9. Quantum materials for topological devices based on Majorana modes
10. Superconductor and semiconductor qubits
11. Non-equilibrium phenomena in quantum materials
12. 2D hyperbolic materials
13. Spin torque materials
14. Magnetic skyrmions
15. Machine learning using experimental quantum materials data
16. Machine learning and DFT simulations of quantum materials

Properties



Structure

Processing

# THE MAP OF QUANTUM COMPUTING

### CLASSICAL COMPUTERS

1 STATE AT A TIME

BITS ARE INDEPENDENT OF EACH OTHER

### CLASSICAL VS. QUANTUM

#### QUANTUM COMPUTERS

SUPERPOSITION  
ENTANGLEMENT  
INTERFERENCE

MANY STATES AT A TIME

QUBITS ARE IN A COMBINED STATE TOGETHER

### INTERFERENCE

QUBIT REALITY DESCRIBED BY QUANTUM WAVEFUNCTION

CONSTRUCTIVE INTERFERENCE

DESTRUCTIVE INTERFERENCE

OVERALL WAVEFUNCTION

PROBABILITY DISTRIBUTION

ON MEASUREMENT GET ONE ANSWER OUT

### SUPERPOSITION

MEASUREMENT

50% 0

50% 1

### ENTANGLEMENT

PROBABILITY DISTRIBUTION

35% 00 11 25% 01 10

### ONE MAIN MODEL OF CLASSICAL COMPUTING

BITS

NOT GATE

NOR GATES

0 → 1

1 → 0

### WHAT TO BUILD QUBITS FROM?

FUNDAMENTAL PARTICLE

ATOMIST

ELECTRONIST

PHOTONIST

NEED A 2-LEVEL QUANTUM SYSTEM

1

0

TO ENCODE THE ENERGY STATES

WAVE QUANTUM SYSTEMS

### GATE MODEL

QUBITS ENTANGLED WITH EACH OTHER

OR CIRCUIT MODEL QUANTUM COMPUTING

ALGORITHM IS A SERIES OF GATE OPERATIONS

SINGLE QUBIT GATES

MEASUREMENT

TWO-QUBIT GATES

### MEASUREMENT BASED

USE ONE-BIT QUANTUM COMPUTING

# MODEL QUANTUM COMPUTING

### ADIABATIC QUANTUM COMPUTING

MAXIMUM ENERGY STATE IS THE ANSWER TO YOUR PROBLEM

ENERGY LANDSCAPE

CORRECT ANSWER

EQUIVALENT TO GATE MODEL

### QUANTUM ANNEALING

ALSO ENERGY MINIMIZATION BUT NOT UNIVERSAL

SPECIAL PURPOSE PURPOSE

### TOPOLOGICAL QUANTUM COMPUTING

MAKES A ZERO BACK SCATTERING PARTICLES (MAJORANA)

MADE OF ELEMENTS THAT ARE PHYSICALLY SEPARATED

PROTECTED BY AN ENERGY GAP

QUANTUM DOT

QUANTUM DOT EXAMPLE: ELECTRON HOLE

A HOLE IN A SEA OF ELECTRONS HAS PARTICLE-LIKE PROPERTIES

# QUANTUM ALGORITHMS

MULTIPLICATION 7177 x 3001

21538177

EASY! EFFICIENT CLASSICAL ALGORITHM

FACTORIZATION 21538177

7177 x 3001

HARD! NO EFFICIENT CLASSICAL ALGORITHM

USED FOR ENCRYPTION

21538177

SHOR'S ALGORITHM

7177 3001

EFFICIENT QUANTUM ALGORITHM

# POTENTIAL APPLICATIONS OF QUANTUM COMPUTERS

### QUANTUM SIMULATION

IS FASTER THAN PHYSICALLY MAKING AND TESTING THEM

BARELY PRODUCTIVE MANY DIFFERENT MATERIALS

WANT TO SIMULATE LARGE QUANTUM SYSTEMS ON A SUPERCOMPUTER IS DIFFICULT

SIMULATING AS FEW AS 30 PARTICLES ON A SUPERCOMPUTER IS DIFFICULT

IMPROVING BATTERIES

DRUG DEVELOPMENT

CHEMICAL REACTIONS

ELECTRONIC PROPERTIES

MATERIAL PROPERTIES

BETTER CATALYST FOR FERTILIZER PRODUCTION

MATERIALS FOR AEROSPACE

NEW CHEMICALS

IMPROVING SOLAR PANELS

FABRICATE CATALYST

CURRENTLY 3% OF GLOBAL CO2 EMISSIONS

FINANCIAL MODELING

WEATHER FORECASTING

# COMPLEXITY THEORY

HOW MUCH HARDER IS IT TO SOLVE THE PROBLEM AS THE PROBLEM GETS LARGER?

NP-COMPLETE

NP

BQP

P

EFFICIENT FOR CLASSICAL COMPUTER

# CLASSICAL COMPUTERS

ANY VERY COMPLEX PROBLEM

NEEDS A LOT OF CLASSICAL COMPUTING POWER

WILL BE SOLVED BY QUANTUM COMPUTING

QUANTUM COMPUTING

QUANTUM COMPUTING

QUANTUM COMPUTING

QUANTUM COMPUTING

# QUANTUM COMPLEXITY THEORY

PROBLEM: FACTORISE A NUMBER WITH N DIGITS

N=8

21538177

SHOR'S ALGORITHM

IS POLYNOMIAL log(N)

HOW MUCH HARDER IS IT TO FACTORISE A NUMBER WITH N-DIGIT?

ANYTHING WITH A 2<sup>N</sup> TIME COMPLEXITY IS HARD

SCALING OF FACTORISATION IS 2<sup>N</sup>

BEST CLASSICAL ALGORITHM IS EXPONENTIAL

IF YOU HAVE A QUANTUM COMPUTER

PROBLEM: FIND THE NUMBER 43

00 16 39 28 68 72 01

QUANTUM SPEEDUP OVER CLASSICAL

1,000,000

DO NOT HAVE TO WORRY ABOUT YOUR BANK ACCOUNT YET

BUT NEED UPDATES OF 1 MILLION QUANTS

DO NOT THINK YET OUR COMPUTERS ARE SAFE FOR NOW

POST-QUANTUM SECURITY

QUANTUM SECURITY

WEATHER FORECASTING

CYBERSECURITY

# PHYSICAL REALISATIONS

### SUPERCONDUCTING QUANTUM COMPUTERS

TRANSMON QUBIT

2-LEVEL SYSTEM

FREQUENCY OF CHARGE OSCILLATION

COOPER PAIR

FLUX QUBIT

OR MAGNETIC FLUX

OR SUPERCONDUCTING PHASE

### QUANTUM DOT QUANTUM COMPUTERS

ALSO CALLED SPIN QUANTUM COMPUTERS

QUANTUM DOT ELECTRONICS

2-LEVEL SYSTEM

SPIN OR CHARGE

CONTROL WITH BACKGATES OR VOLTAGES OR MAGNETIC FIELDS

MADE OF SILICON

GALLIUM ARSENIDE

SILICON CARBIDE

OR DIAMOND

### LINEAR OPTICAL QUANTUM COMPUTERS

LINEAR OPTICAL ELEMENTS

MIRRORS

WAVEPLATES

INTERFEROMETERS

2-LEVEL SYSTEM

PATH

OR PHOTONS

CONTROLLED WITH VOLTAGES

### TRAPPED ION QUANTUM COMPUTERS

CONTROL WITH MICROWAVES OR LASERS

IONIZED ATOMS TRAPPED IN MAGNETIC FIELD

2-LEVEL SYSTEM

EMBED LEVELS OF THE ION

### COLOUR CENTRE QUANTUM COMPUTERS

2-LEVEL SYSTEM

LINE OF THE ROOM

CONTROL WITH MICROWAVES OR LASERS

### NEUTRAL ATOMS IN OPTICAL LATTICES

CONTROL WITH LASERS

TRAPPED ATOMS

COOLED TO MILLICELSI OF A KELVIN

OPTICAL LATTICE

CAN ALSO BE USED TO MAKE PERSI QUANTUM SIMULATORS

2-LEVEL SYSTEM

EMBED LEVELS OF THE ATOM

A 10 THOUSAND ATOM QUANTUM SIMULATOR HAS BEEN MADE

### OTHER APPROACHES

ELECTRON ON HELIUM QUANTUM

CAVITY QUANTUM ELECTRODYNAMICS

MAGNETIC MOLECULES

NUCLEAR MAGNETIC RESONANCE

MOLECULAR SPINS

**Dra. Gemma Rius**

Investigadora Ramón y Cajal

**Instituto de Microelectrónica de Barcelona**

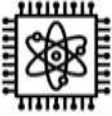
IMB-CNM-CSIC

# On QUANTUM TECHNOLOGIES

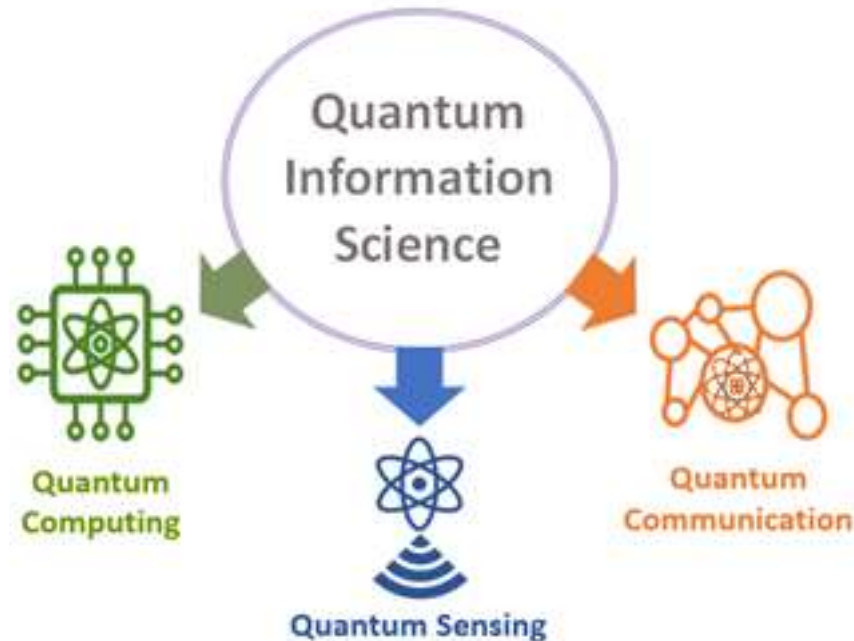
1<sup>st</sup>. Towards QTech

2<sup>nd</sup>. QTech for HEP





**Quantum information science (QIS)** is an emerging field that harnesses the power of **quantum mechanics and information sciences** to build innovative technologies, including quantum sensors, networks, and computers that are capable of new speed, precision, and functionality

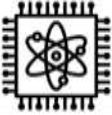


**Quantum computing.** Rather than relying on bits (value of 1 or 0), quantum computing uses qubits, which can exist in a probabilistic mix of both values simultaneously. Quantum computers, while not a substitute for classical computers, have the promise to be extraordinarily powerful at solving some problems in science, including certain simulations, optimization, and ML tasks.

**Analog quantum simulation.** It is believed that quantum systems would be especially apt at simulating actual physical quantum behavior, whether in material or chemical systems.

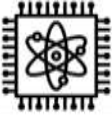
**Quantum communication.** Quantum information systems hold out the possibility of extremely secure encryption—a major attraction in an age where cybersecurity is constantly at risk.

**Quantum sensing and microscopy.** Sensors based on quantum effects could be exquisitely sensitive and could aid in understanding everything from biological systems to the nature of DM.

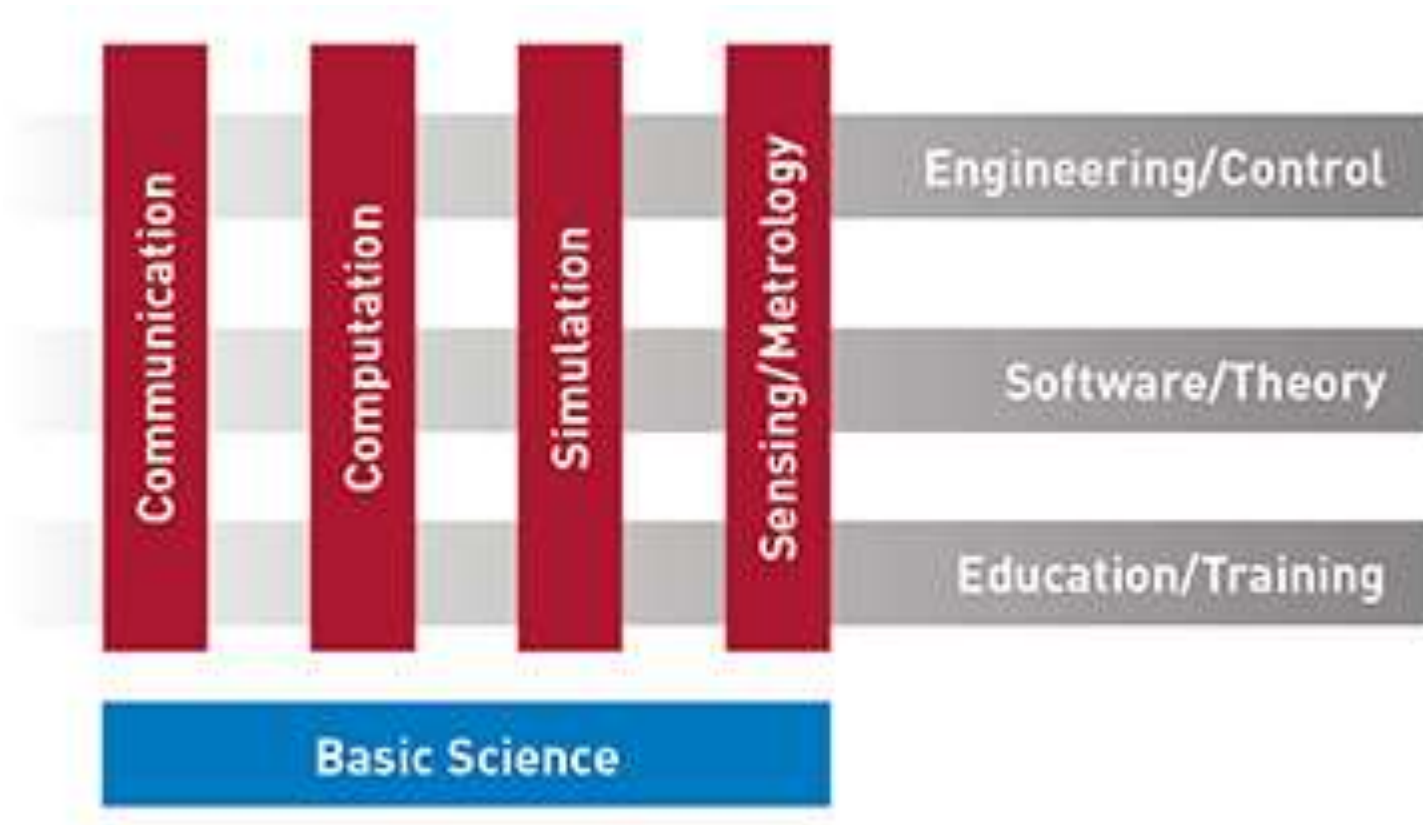


## QUANTUM FRONTIERS IN BRIEF

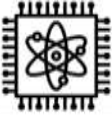
- 1. Expanding Opportunities for Quantum Technologies to Benefit Society** a. Elucidating Fundamental Capabilities of Quantum Technologies b. Engaging QIS Researchers with Domain Specialists and End-Users
- 2. Building the Discipline of Quantum Engineering** a. Integrating Quantum Hardware, Software, and Support Technology b. Exploring System-level Architectures, Abstractions, and Testing c. Enabling Modular Systems
- 3. Targeting Materials Science for Quantum Technologies** a. Using Materials Science to Improve Device Performance b. Pursuing New Approaches to Materials Design, Fabrication, and Characterization
- 4. Exploring Quantum Mechanics through Quantum Simulations** a. Developing Quantum Simulation Applications b. Implementing Algorithms on Available Devices and Exploring Their Performance
- 5. Harnessing Quantum Information Technology for Precision Measurements** a. Deploying Quantum Technology for Improved Accuracy and Precision b. Creating New Modalities and Applications for Quantum Sensing In Situ and In Vivo c. Using Entanglement and Quantum Computers to Improve Measurements
- 6. Generating and Distributing Quantum Entanglement for New Applications** a. Developing Foundational Components for Quantum Networks b. Enabling Quantum State Transduction c. Integrating Quantum Networking Systems d. Exploring Quantum Networking Algorithms, Applications, Protocols, and Approaches
- 7. Characterizing and Mitigating Quantum Errors** a. Characterizing and Controlling Multi-qubit Systems b. Approaching the Fault-tolerant Domain c. Using Current Devices to Expand the Limits of Performance for Qubit Performance
- 8. Understanding the Universe through Quantum Information** a. Exploring Mathematical Foundations of Computation and Information b. Expanding the Limits of Physical Theory c. Testing the Standard Model of Particle Physics



# Quantum - Europe

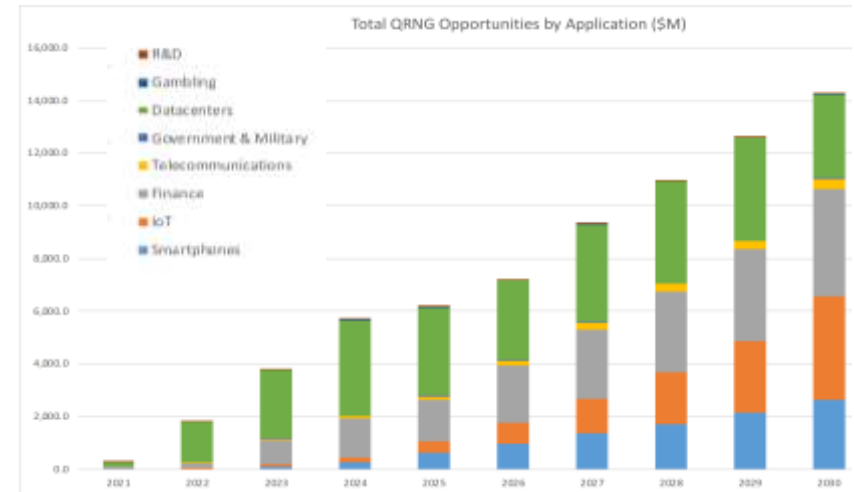


**Quantum Initiatives – CHIPS Act, QuIC, ISO and more**

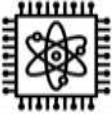


❖ **Quantum communication** is about transferring quantum information from one place to another.

- **Quantum states** encode quantum information
- Quantum communication implies transmission of quantum information and the **distribution of quantum resources**, such as entanglement.
- **Quantum Key Distribution (QKD)** is a major focus: a way to establish a confidential key between distributed partners.



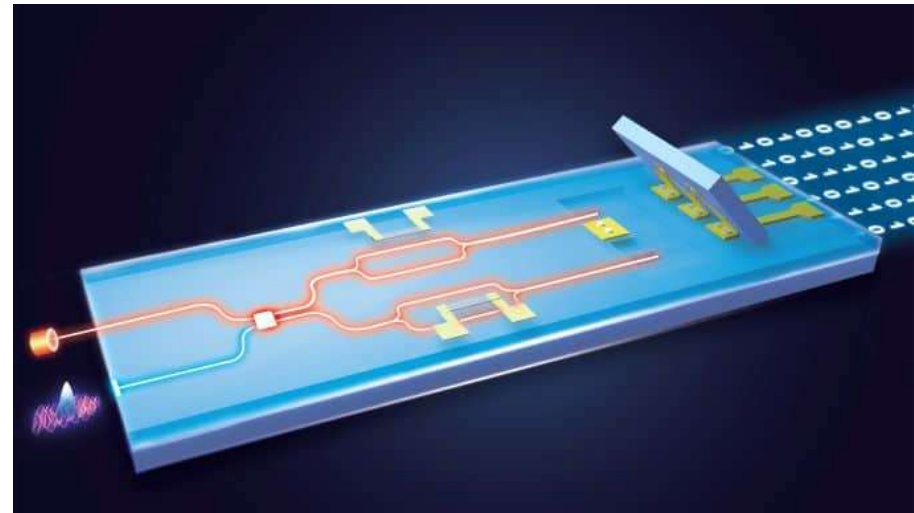
- Covers aspects from basic physics to practical current applications very relevant to society
- **Cybersecurity.** In our information based society, as well as emerging problems associated with long term secure storage (e.g. for health records and infrastructure), QKD is considered most desirable solution
- Secure operation of applications involving the Internet of Things and Cloud Networking, or related to e.g. banking.
- Q. Comm technologies are considered strategical assets at **National level**



- ❖ **QKD systems** are now available as compact and autonomous systems, becoming a growing commercial market.

Low-cost devices for access networks and even hand-held devices, exploiting **integrated photonic technologies**

The archetypal **QRNG** involves a photon impinging on a beamsplitter followed by two detectors associated to the bit values 0 and 1. Whether the photon is reflected or transmitted at the beamsplitter is a fundamentally random process and as there is only one photon at a time, only one detector will register this random outcome.

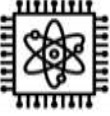


**Long-term goal:** Quantum-based security over many-node networks running in various places worldwide

- long-distance communication (100s-1000s km)
- higher bit rates

**Requires:** quantum and conventional cryptography, quantum repeater technologies, i.e. quantum memories

To deliver practical, autonomous, systems capable of performing continuous secure key distribution  
> 100 Mbps rates



❖ **Quantum computers** have the potential to perform calculations in fundamentally different ways from classical computers

- **Qubit.** Physical device as most basic memory block of a quantum computer
- Quantum versions of the classical bits (transistors) used in today's computers and smartphones.

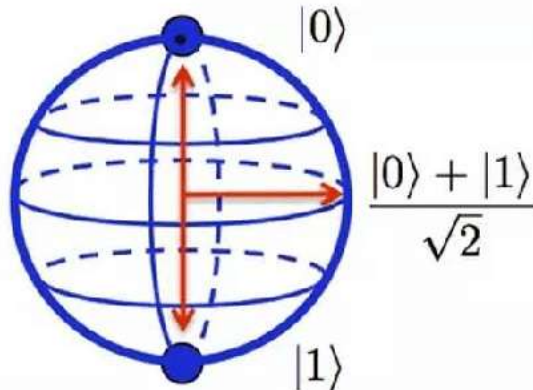
- Both bits and qubits have the same role: to physically record the data that each computer is processing
- The bit or qubit must be modified to reflect the change in information as it is altered throughout computation.

- Quantum computers store information in quantum states (superpositions and entanglement states)
- Qubits must be able to physically represent these quantum states.
- Quantum events only occur (and last) in the most severe circumstances.

● 0

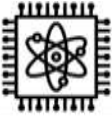
● 1

Classical bit

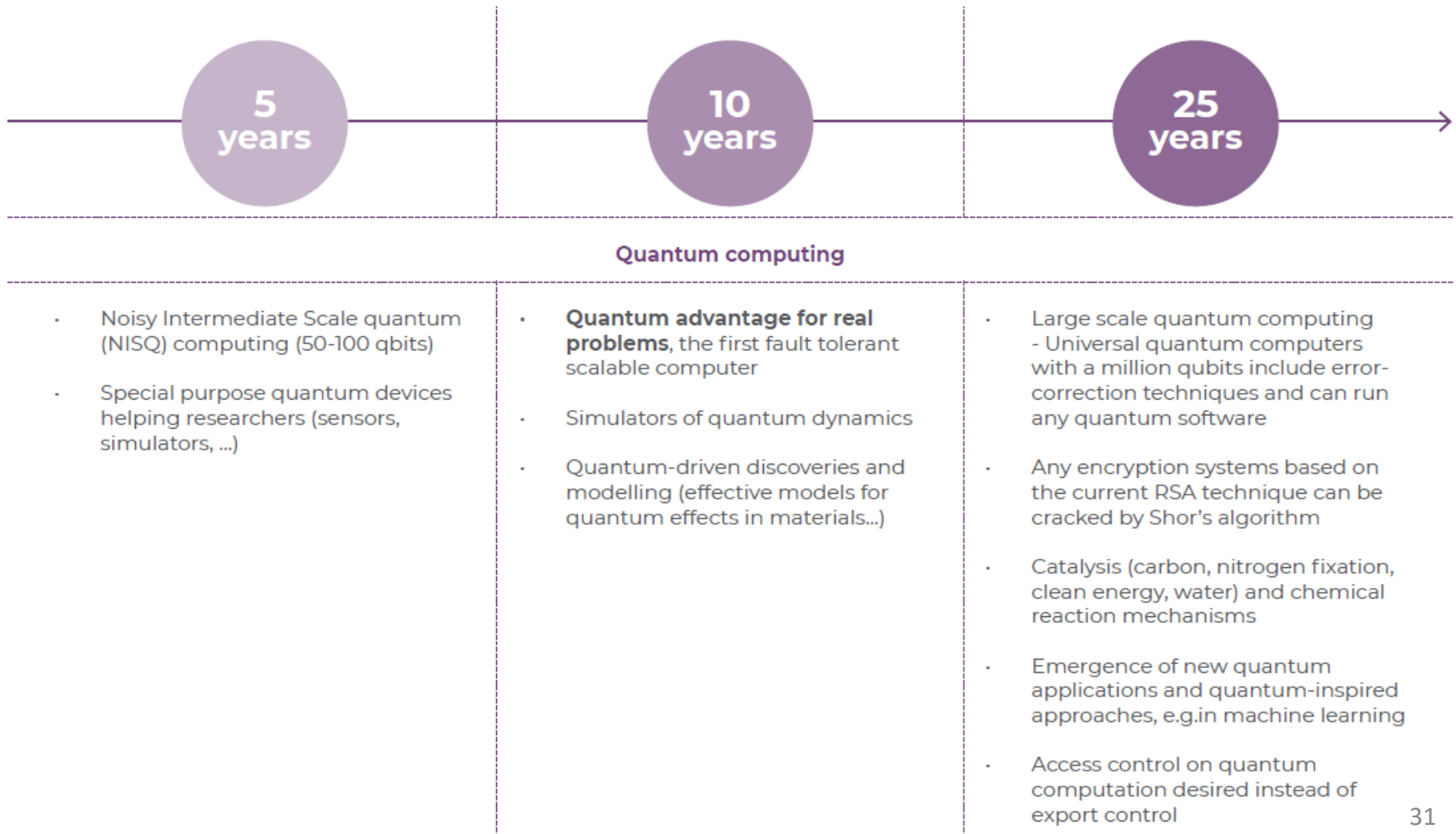


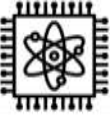
Qubit

✓ Probabilistic



- Quantum computing is not a general-purpose technology
- Quantum computing cannot be used to solve all of existing (business) challenges





## ➤ One of the current challenges of Quantum Computing is identifying Use Cases

Quantum computing use cases are getting real—what you need to know

**Industry, key segment for quantum computing**

● Low ● Medium ● High

**Economic value**

~2025-30    ~2030-35

### Global energy and materials

Oil and gas	●	●
Sustainable energy	●	●
Chemicals	●	●

### Pharmaceuticals and medical products

Pharmaceuticals	●	●
-----------------	---	---

### Advanced industries

Automotive	●	●
Aerospace and defense	●	●
Advanced electronics	●	●
Semiconductors	●	●

### Financial industry

Financial services	●	●
--------------------	---	---

### Telecom, media, and technology

Telecom	●	●
Media	●	●

### Travel, transport, and logistics

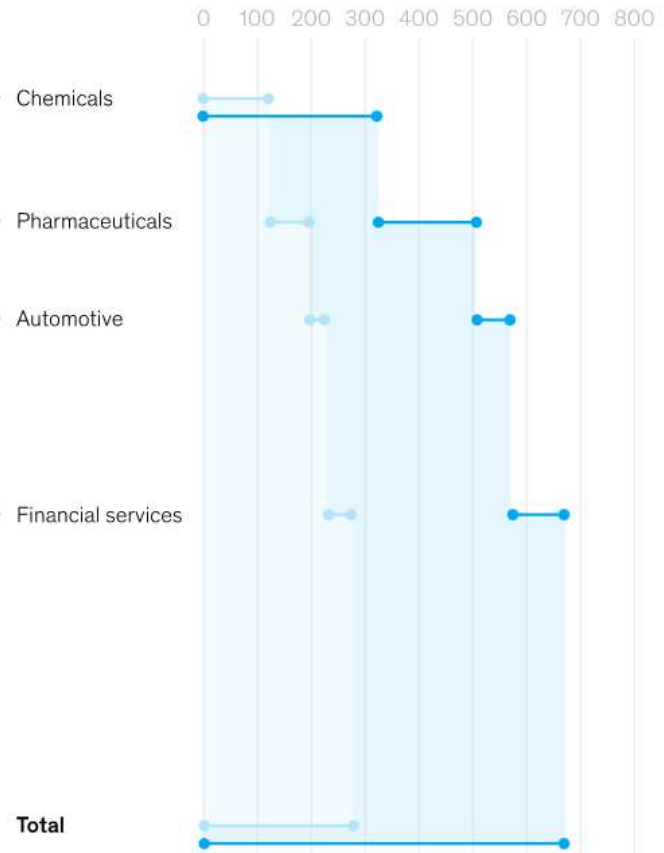
Logistics	●	●
-----------	---	---

### Insurance

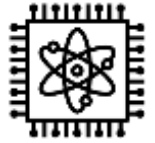
	●	●
--	---	---

**Value at stake with incremental impact of quantum computing by 2035, \$ billion**

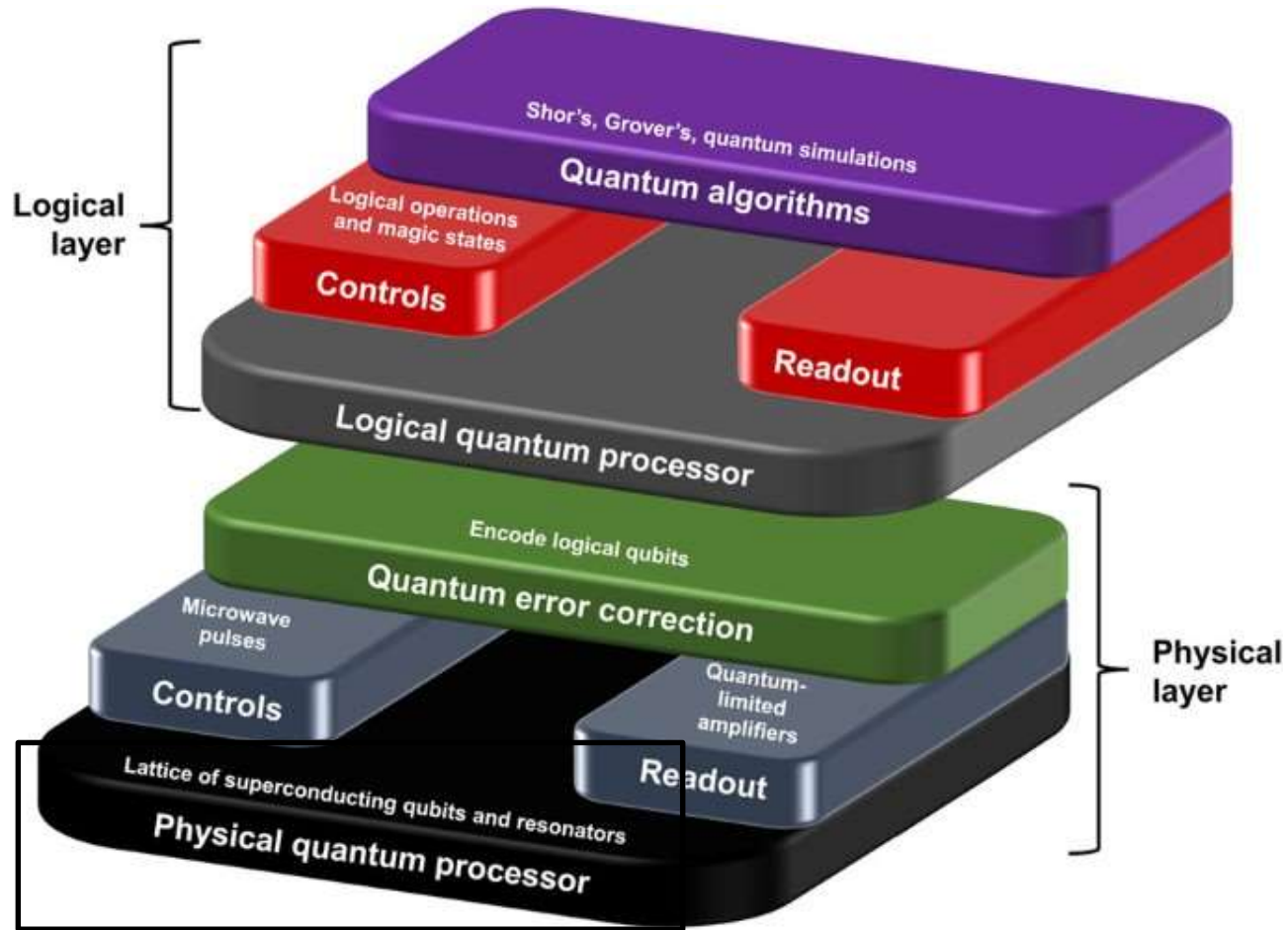
● Lower estimate  
● Upper estimate



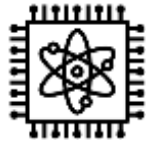




# Quantum Computer



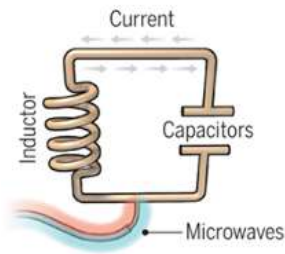
➤ Converging Quantum Physics, Materials Science, Micro/Nanotechnologies, ...



# Quantum Devices

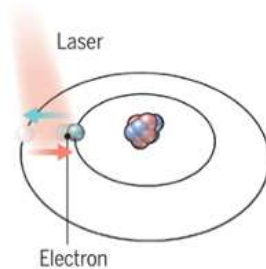
## A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.



### Superconducting loops

A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.



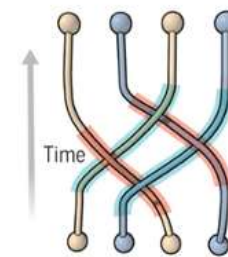
### Trapped ions

Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.



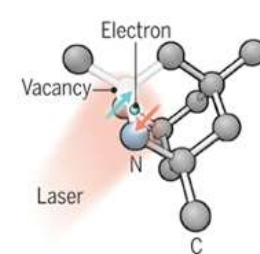
### Silicon quantum dots

These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.



### Topological qubits

Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.

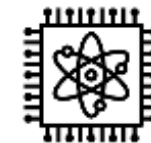


### Diamond vacancies

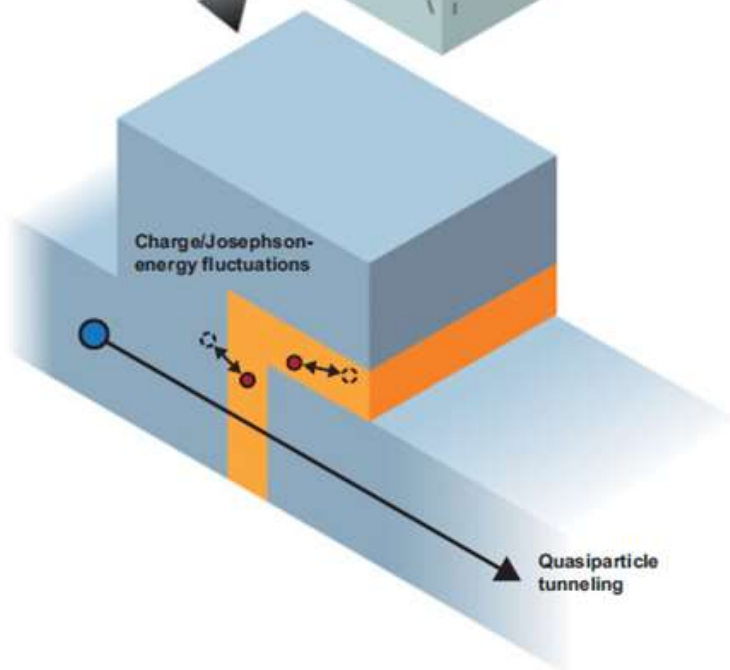
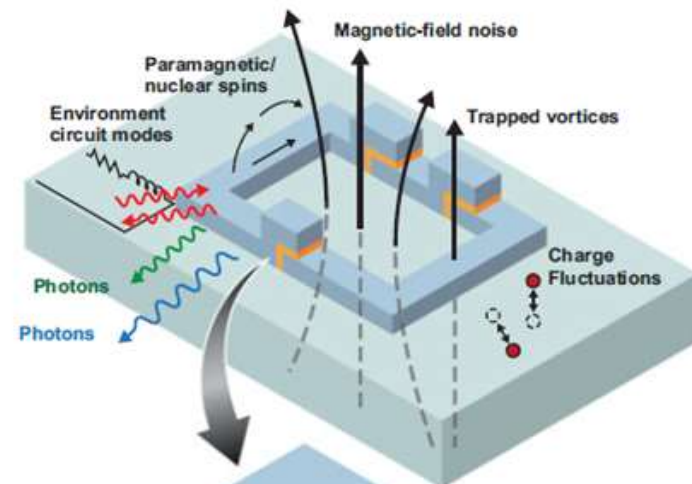
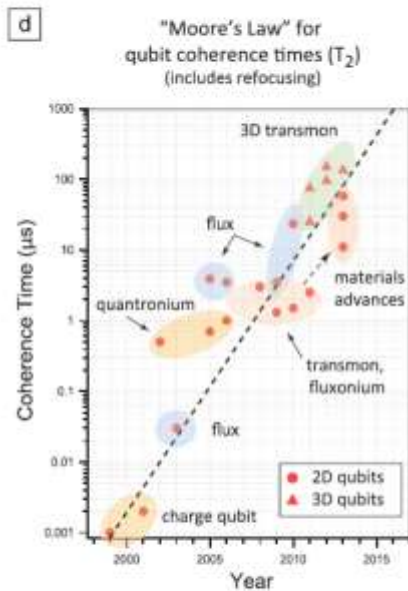
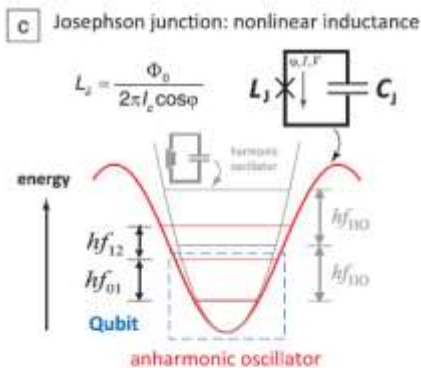
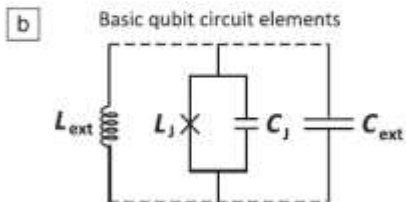
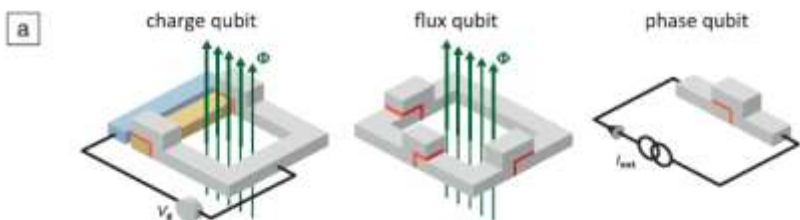
A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

<b>Longevity</b> (seconds)	0.00005	>1000	0.03	N/A	10
<b>Logic success rate</b>	99.4%	99.9%	~99%	N/A	99.2%
<b>Number entangled</b>	9	14	2	N/A	6
<b>Company support</b>	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
<b>Pros</b>	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
<b>Cons</b>	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

**Note:** Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

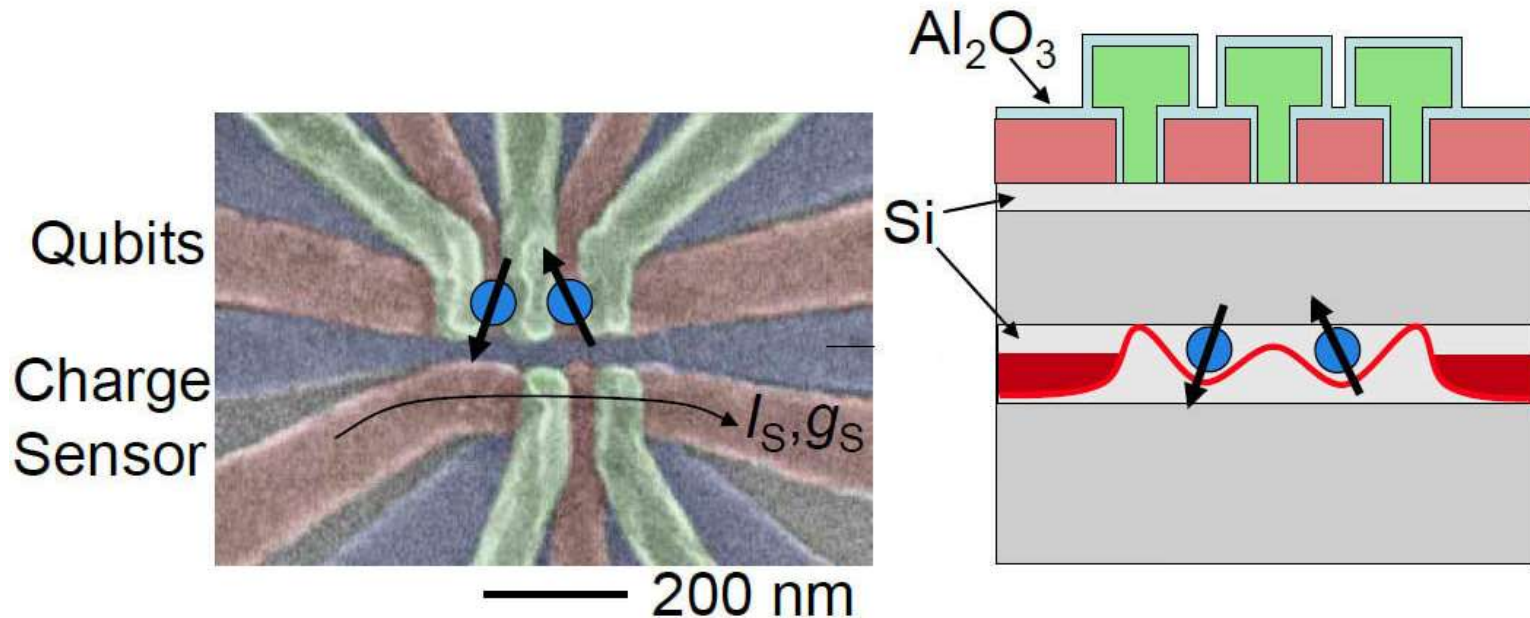
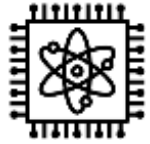


# Superconducting Qubits





## Silicon Qubits

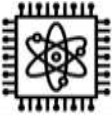


To construct the **two-qubit gate**, layered tiny Al wires onto a highly ordered silicon crystal are used. The wires deliver voltages that trap two single electrons, separated by an energy barrier, in a well-like structure called a **double quantum dot**.

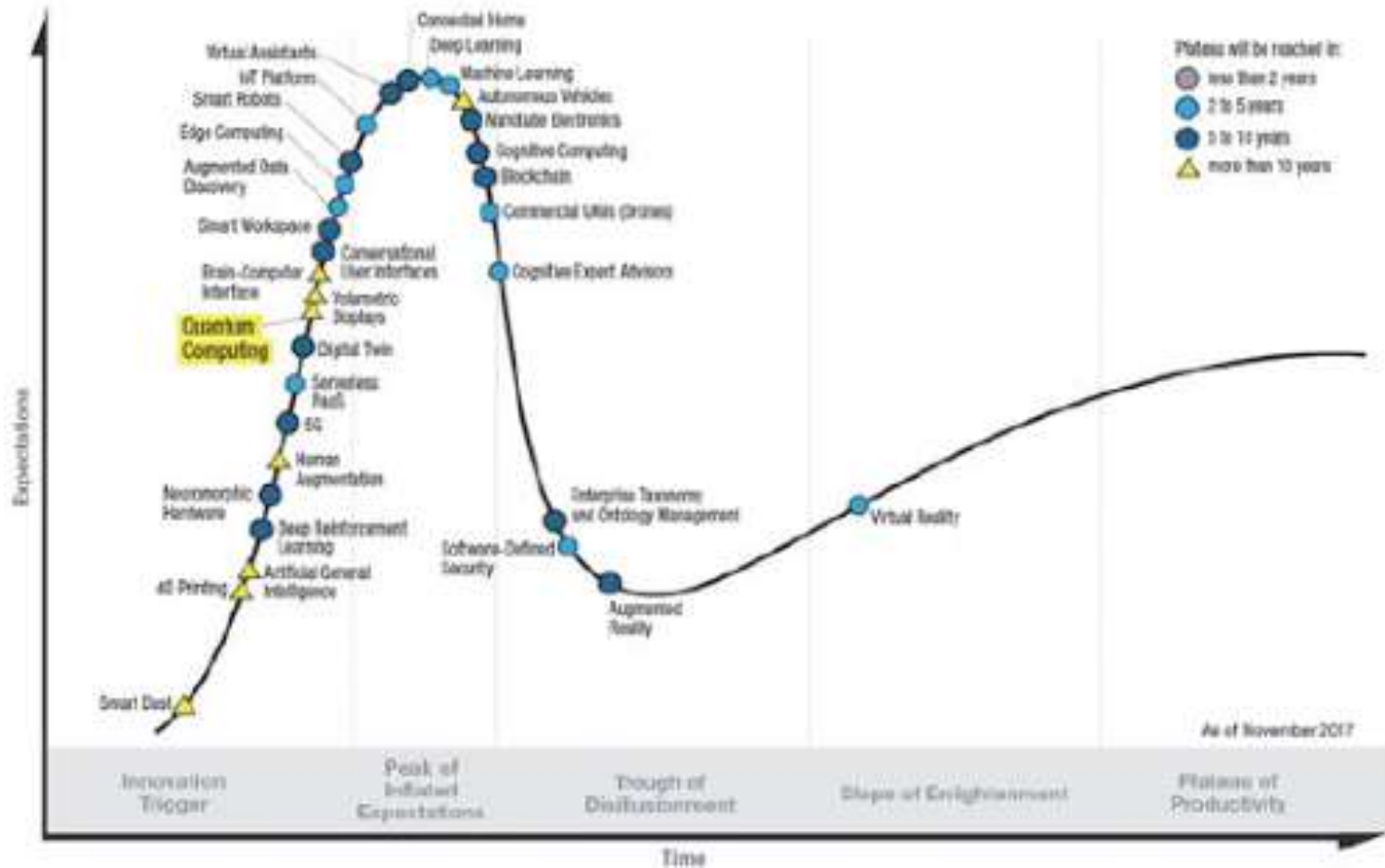
By temporarily lowering the energy barrier, the researchers allow the electrons to share quantum information, creating a special quantum state called **entanglement**.

These **trapped and entangled electrons** are now ready for use as qubits

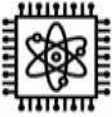
While a conventional bit can represent a 0 or a 1, each qubit can be simultaneously a 0 and a 1, now an exponential **number of possible permutations can be compared instantaneously**.



# Quantum Computing Hype

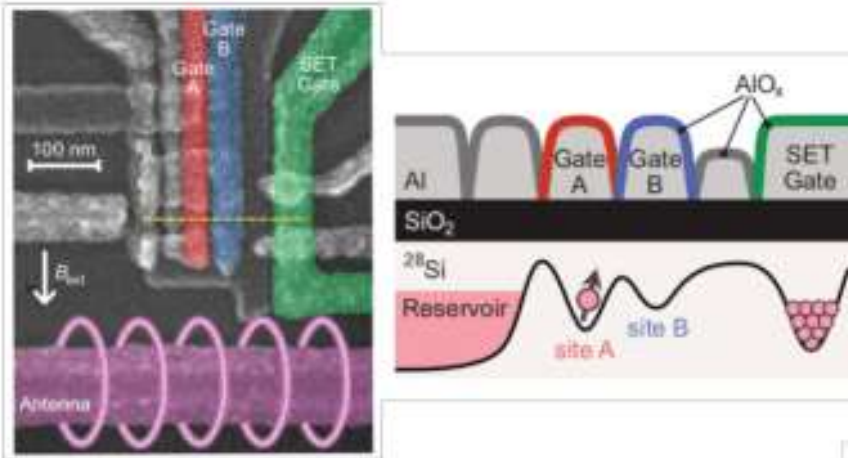


Quantum computing has been classified as an emerging technology since 2005

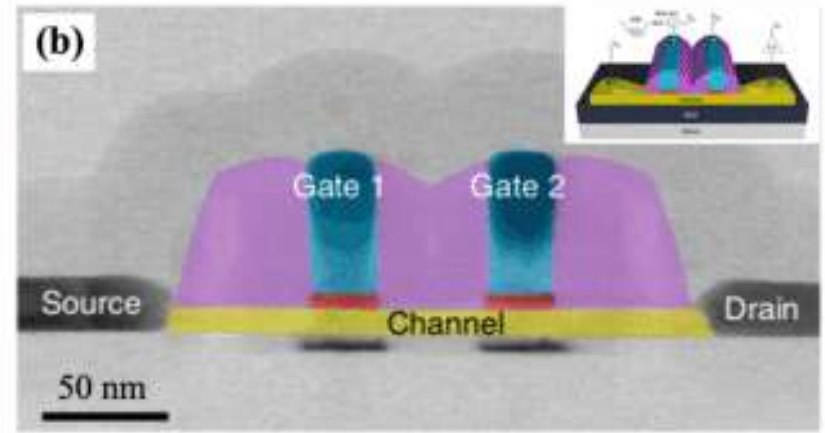


# Quantum Computing Hype

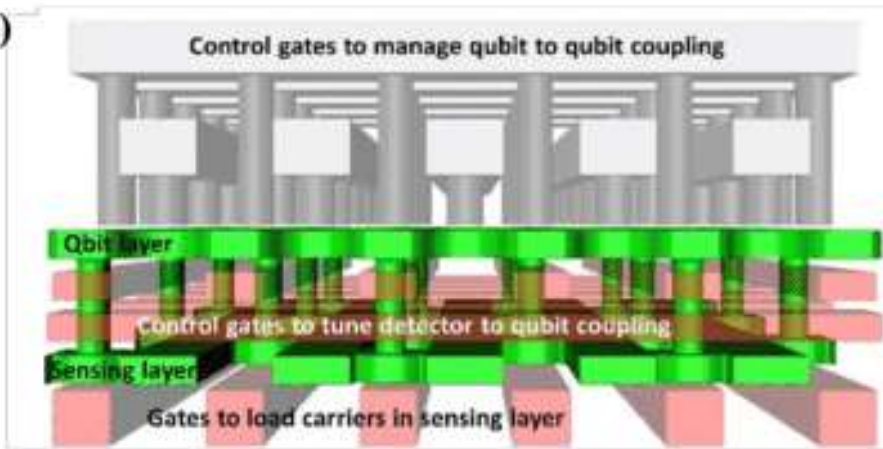
(a)



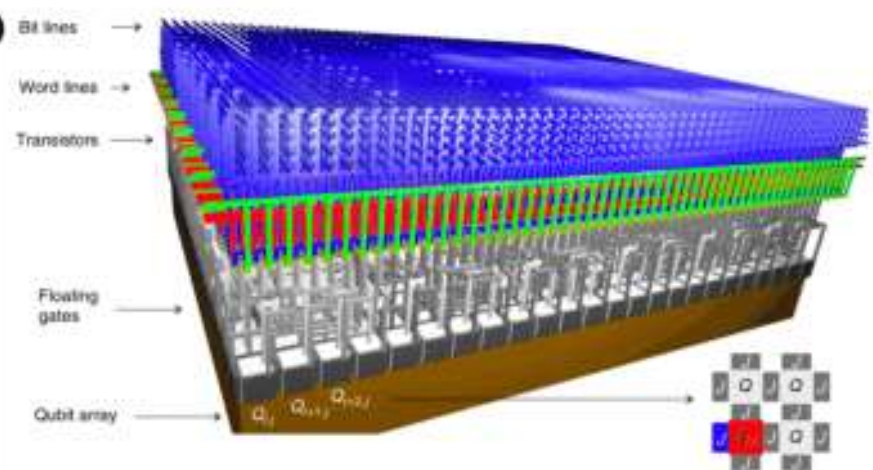
(b)



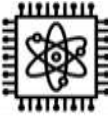
(c)



(d)



Quantum computing has been classified as an emerging technology since 2005

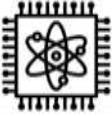


# Yet, an Innovation Trigger

Quantum as a Service (QaaS) Capability Available

Quantum Systems, Software and Services					Classical	Software and Services
Quantum Annealing Systems	Superconducting Gate Quantum Computing	Trapped Ion Quantum Computing	Photonic	Neutral Atom	Simulated Quantum Computing	
D-Wave	IBM	CQC (Honeywell)	Xanadu	Pasqal	IBM	Zapata Computing QC Ware 1QBit Riverlane
NEC*	Rigetti Computing	IonQ	PsiQuantum <sup>a</sup>	<ul style="list-style-type: none"> <li>Atom Computing <sup>a</sup></li> <li>Wuhan Institute of Physics and Mathematics (WIPM) of CAS</li> </ul>	Amazon	Rigetti Computing (QxBranh)
	Google	Alpine Quantum Technologies	Chinese Academy of Science (CAS) (Hefei National Laboratory for Physical Sciences at the Microscale [HFNL])		Microsoft	IBM
	<ul style="list-style-type: none"> <li>Amazon <sup>a</sup></li> <li>Fujitsu <sup>a</sup></li> <li>IQM <sup>a</sup></li> <li>QCI <sup>a</sup></li> <li>Oxford Quantum <sup>a</sup> Circuits <sup>a</sup></li> <li>Qilimanjaro <sup>a</sup></li> </ul>	Oxford Ionics			<ul style="list-style-type: none"> <li>Atos</li> <li>NVIDIA</li> </ul>	Amazon Microsoft Multiverse Classiq Google
					<b>Quantum Inspired Computing</b> Fujitsu Digital Annealer Microsoft	

<sup>a</sup> Prototype/Embryonic Indigenous Quantum Computing Capability



# Quantum Sensing

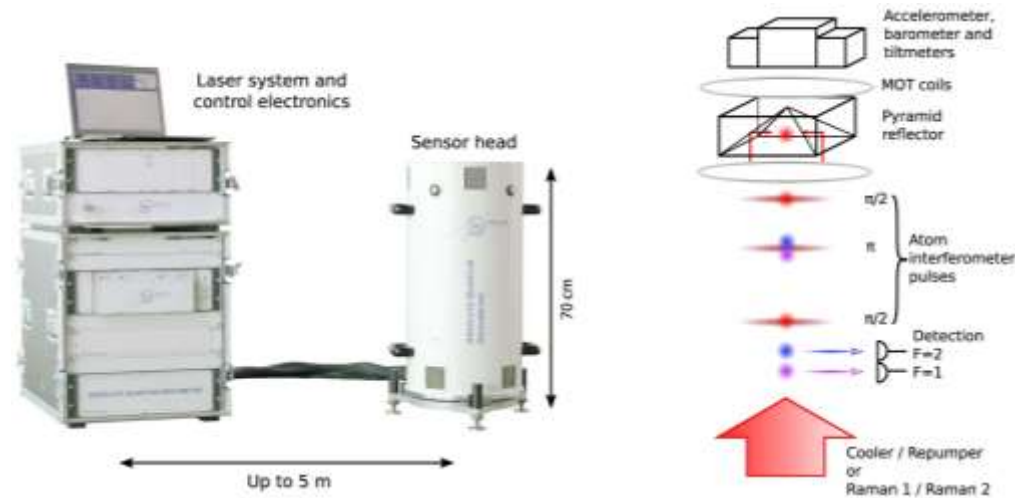
New modes of measurement, sensing, and imaging that offer unprecedented levels of precision, spatial and temporal resolution, stability, ultra-sensitivity...

**Key:** operation relying on quantum phenomena, such as coherence and entanglement

- ✓ Time and frequency standards,
- ✓ Light-based calibration,
- ✓ Gravimetry,
- ✓ Magnetometry
- ✓ Accelerometry
- ✓ New medical diagnostic tools,...

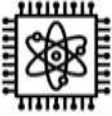
➤ Extend the reach of quantum sensing and metrology into other fields of science to **uncover novel natural phenomena**, e.g. biology, fundamental physics, high-energy physics, quantum gravity.

**Atom interferometry** provides top-level performance in terms of sensitivity, long-term stability and accuracy



Portable system that measured the absolute gravitational acceleration continuously with a long-term stability below  $10 \text{ nm}\cdot\text{s}^{-2}$



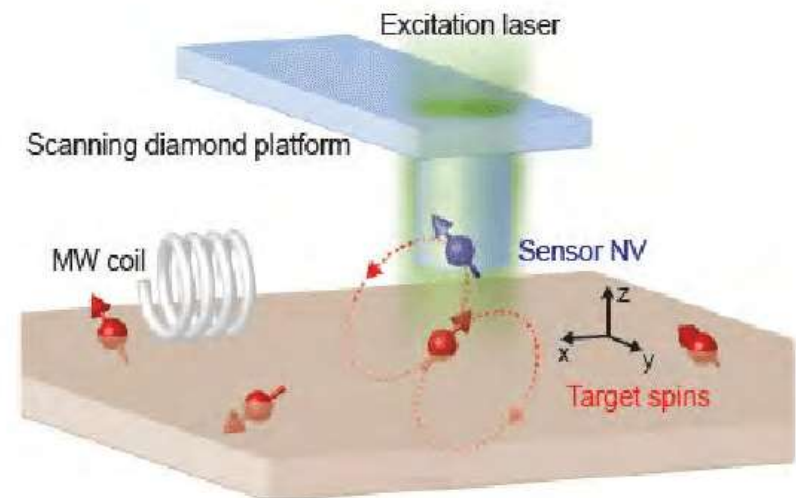


## Quantum-enhanced strategies

- ❖ Original techniques are needed to make quantum-enhanced metrology and sensing
- ❖ Deployable in **non-laboratory environments**.
- ❖ Wide range of prospective applications, each with certain specificity/ies
- ❖ Broad range of physical platforms to be considered:
  - trapped ions,
  - ultra-cold atoms,
  - room-temperature atomic vapors,
  - artificial systems, such as quantum dots or defect centers,
  - all-optical set-ups with e.g. on nonlinear optical interactions.
- ❖ Theoretical analysis of noise or losses mechanisms is needed

1. **Novel sources of non-classical radiation** and methods to **engineer quantum states of matter** for quantum-enhanced operation
2. Develop **detection schemes** that are optimized with respect to **extracting relevant information from physical systems**

Optimization criteria selected for specific applications. These techniques may find applications in other photonic technologies, e.g. increasing transmission rates in optical communication...



## Selection from QUANTUM FRONTIERS IN BRIEF

- ✓ **Exploring Quantum Mechanics through Quantum Simulations**
  - a. Developing Quantum Simulation Applications
  - b. Implementing Algorithms on Available Devices and Exploring Their Performance
- ✓ **Harnessing Quantum Information Technology for Precision Measurements**
  - a. Deploying Quantum Technology for Improved Accuracy and Precision
  - b. Creating New Modalities and Applications for Quantum Sensing In Situ and In Vivo
  - c. Using Entanglement and Quantum Computers to Improve Measurements
- ✓ **Understanding the Universe through Quantum Information**
  - a. Exploring Mathematical Foundations of Computation and Information
  - b. Expanding the Limits of Physical Theory
  - c. Testing the Standard Model of Particle Physics

***“Not only is the Universe stranger than we think,  
it is stranger than we can think.”***

**Werner Heisenberg**

## Quantum Computing Solutions for High-Energy Physics – QuantERA project

Investigate and assess the potential of quantum computation for experimental particle physics challenges.

Specifically, quantum algorithms as a solution to the increasingly challenging, and soon intractable, problem of analyzing and simulating events from large experiments in particle-physics.

1. **To develop quantum algorithms for event selection and event reconstruction**
2. **To use them to perform proof-of-principle analysis of real data from CERN**
3. **Benchmarking the potential advantage of this novel quantum-enhanced processing**

### **Deliverables:**

- Development of software libraries to simulate particle physics' objects (elementary particles, composite particles, jets...)
- Using them as building blocks to develop the quantum simulation of scattering processes
- Proof-of-principle scattering quantum simulation

By combining classical and freely-available quantum processors - benchmarking against CERN classical simulations to characterize a quantum advantage threshold for HEP processes.

## Vision and Synergies of Q Technologies - HEP

1. Connecting quantum information, quantum field theory, gravity, ...
2. Tradition of HEP theory as asset and contribution
3. Quantum Computing intrinsically fitting HEP fundamental physics problems
4. Quantum Metrology bridging theory and sensing
5. HEP as early adopter of new technologies

**Single qubit  $\neq$  computer,**

but

It can be an **ideal sensor**

Learn from previous success:

**HEP-Microelectronics**

- Solid State detectors
- DAQs

## Quantum Computing

- High profile problems (banking, logistics, drug design, etc.)
- Numerical simulations for large entangled systems
- Compute quantities not traditionally accessible numerically
- New challenges for young scientists, technologists and engineers

## Quantum Computing & HEP

- ✓ HEP provides complementary problems to high profile problems
- ✓ HEP provides data to be addressed quantum computationally
- ✓ QC enables insights for phenomena in quantum field theory,
- ✓ Prediction or classification of events, duality of QG..
- ✓ Alternative approaches or tools for more innovative HEP
- ✓ Rethinking of formulae or algorithms

**Both theoretical & experimental aspects of HEP  
Quantum Computing as game changer for HEP**

## Some hints on current Quantum Computing & HEP

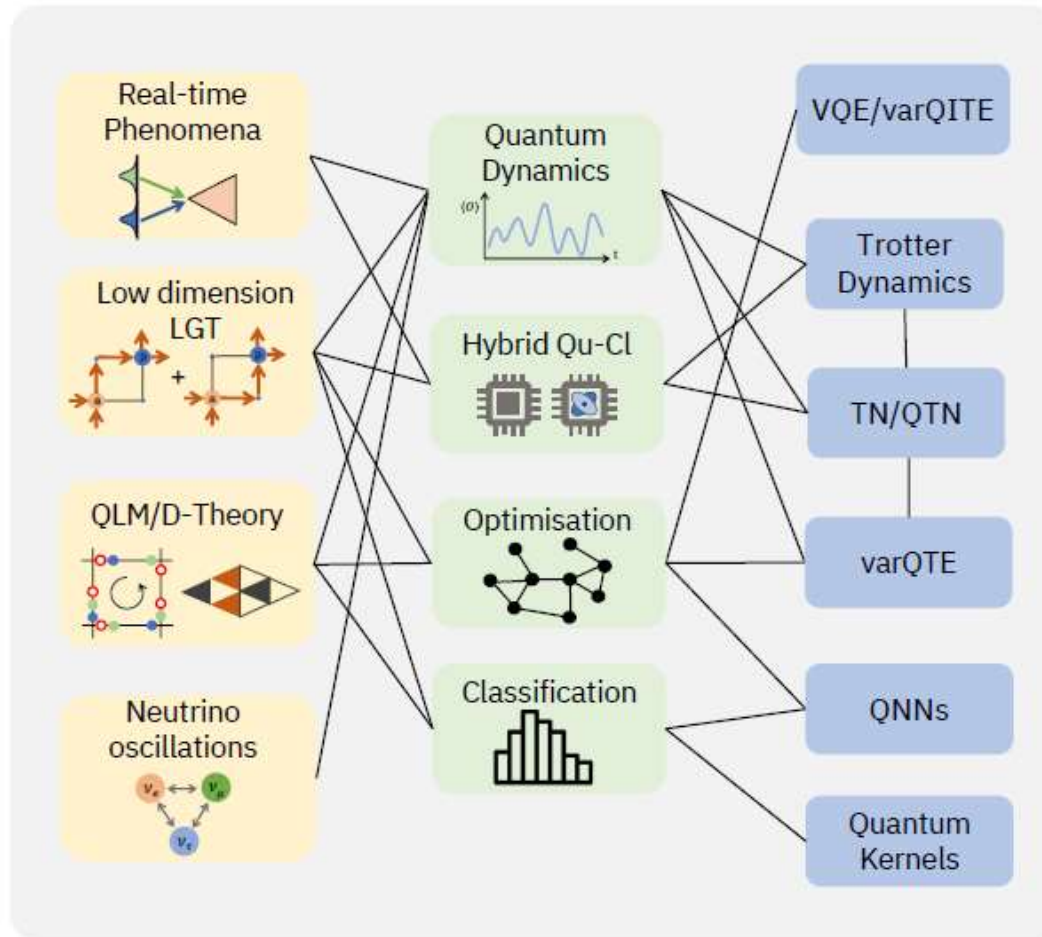
- ✓ Both theoretical & experimental aspects of HEP
- ✓ Quantum Computing as game changer for HEP

### ❖ Near-Mid Term:

Classes of problems and corresponding algorithms, tractable with NISQ devices, such as open/cloud IBM's processors

1. Quantum Computing for HEP Theoretical Modelling
2. Quantum Computing in HEP Experiments

# 1. Quantum Computing for HEP Theoretical Modelling



**VQE:** Variational Eigensolver  
**varQITE:** variational Imaginary Time evolution  
**TN:** Tensor Networks  
**QTN:** Quantum Tensor Networks inspired from classical TN  
**varQTE:** variational Quantum Real Time evolution  
**QNN:** Quantum Neural Networks

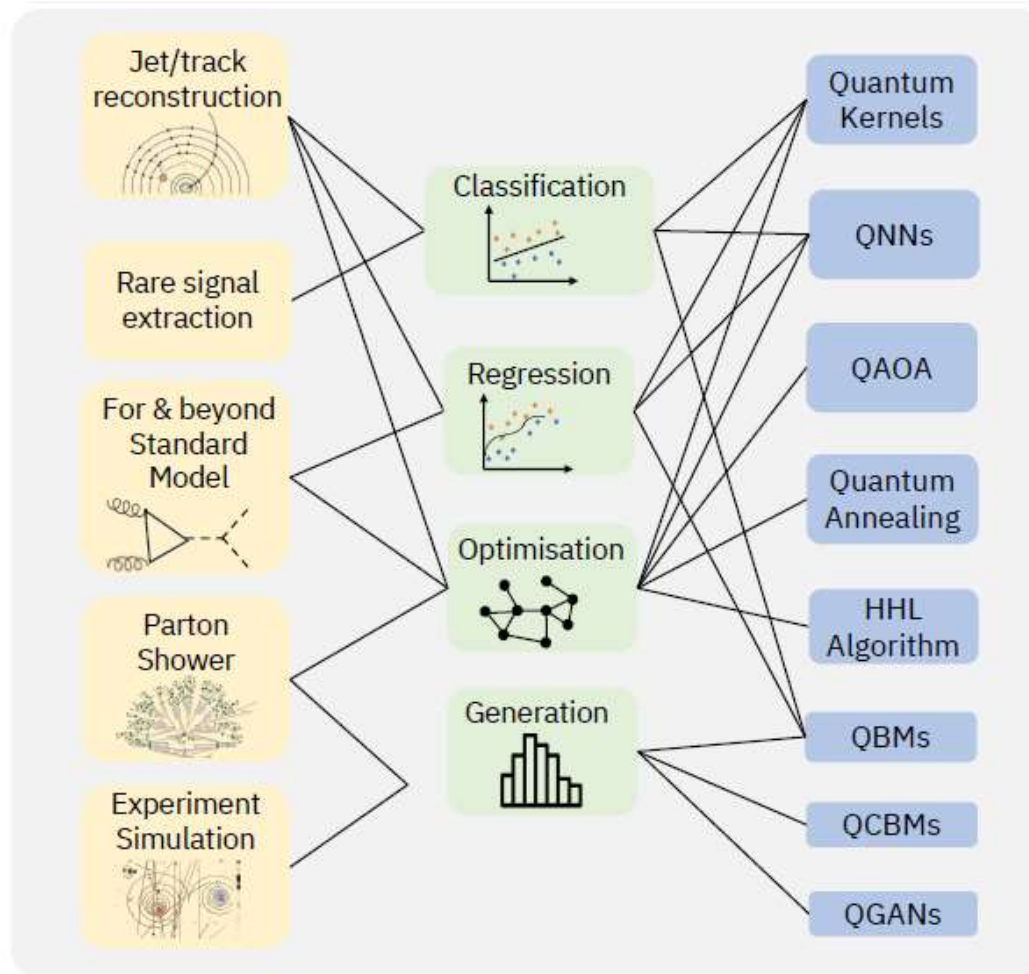
*Theoretical  
Physical  
Problem*

*Computing  
Approach*

*Quantum  
Algorithm*

## 2. Quantum Computing in HEP Experiments

*Large amount of complex, highly-structured data*



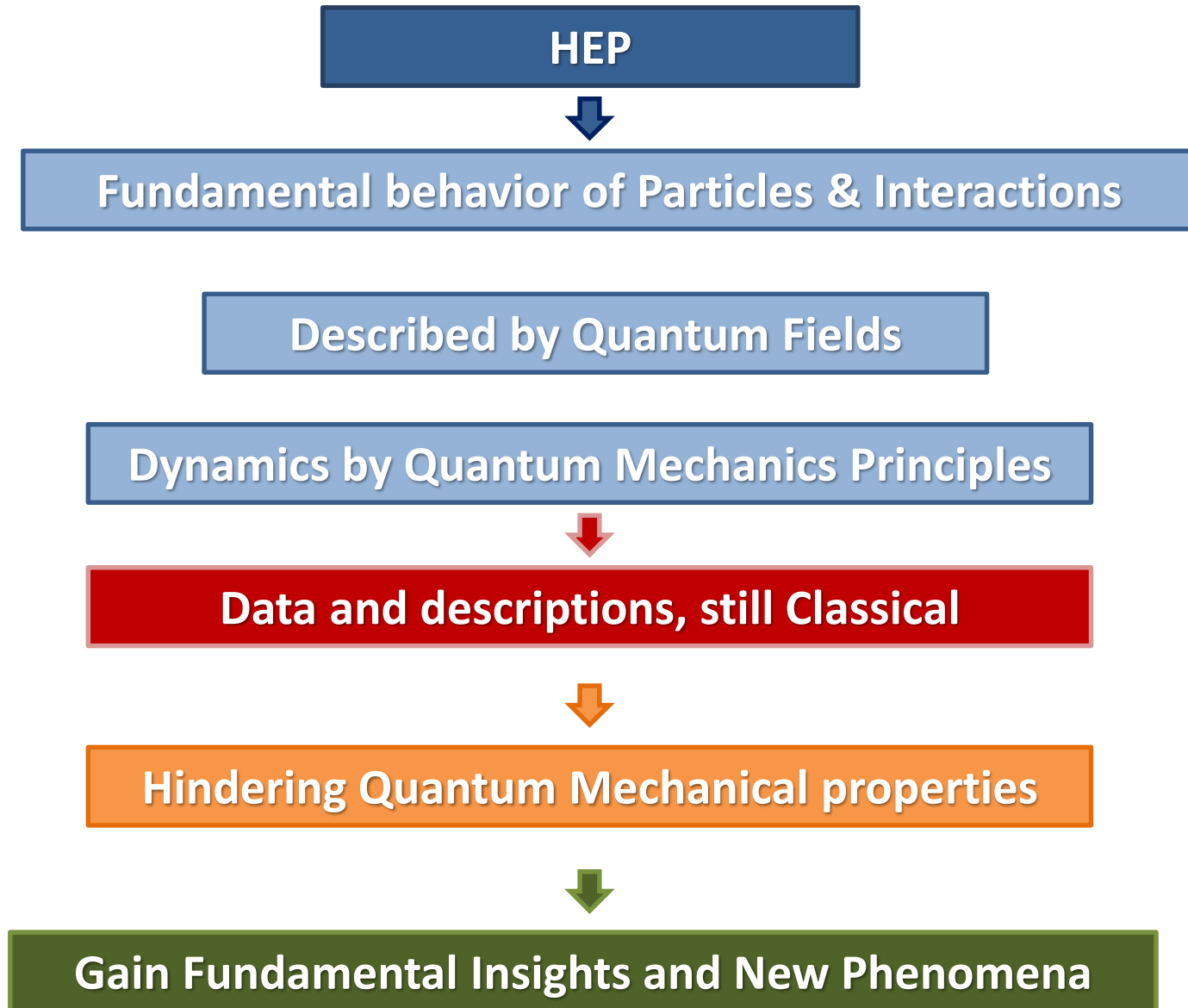
- QNN:** Quantum Neural Networks
- QAOA:** Quantum Approximate Optimization Algorithms
- HHL Algorithm:** Quantum algorithm for linear systems of equations
- QBM:** Quantum Boltzman Machines
- QCBM:** Quantum Circuit Born Machine
- QGAN:** Quantum Generative Adversarial Networks

**Experimental Challenges**

**Analysis Approach**

**Quantum Algorithm**





## Quantum Sensing

- Important applications in fields such as physics, chemistry, biology, medicine or data storage and processing
- **Variety of measurement approaches** include, high-precision spectroscopy and microscopy, positioning systems, clocks, gravitational, electrical and magnetic field sensors, to optical resolution beyond the wavelength limit.
- Physical platforms often common with Q Communication or Computing
- **Quantum-enhanced precision** beyond standard quantum limits relies on generating, manipulating and measuring **non-classical single-particle or collective many-body quantum states**

## Quantum Sensing & HEP

- ✓ QC (and QCom) builds qubits and entanglement, then they decohere, not by Q fluctuations, but noise, TLS, 1/f, materials imperfections...
- ✓ QS (and QCom) enables quantum sensors for super small energies and no noise, then background low energy processes arise, not linked for instance to DM
- ✓ HEP sensors typically use **quantum effects in materials + classical signal amplification**
- ✓ If target measurable is smaller than bandgap or ionization, it will remain hidden
- ✓ One trend is to apply superconducting qubits, as they are sensitive to those extremely small energies, such as for rare events in astroparticle physics
- ✓ Direct detection of DM or neutrinoless double beta decay
- ✓ Foundations theory and quantum metrology based on HEP can be applied beyond

## Quantum Calorimeters 4 HEP

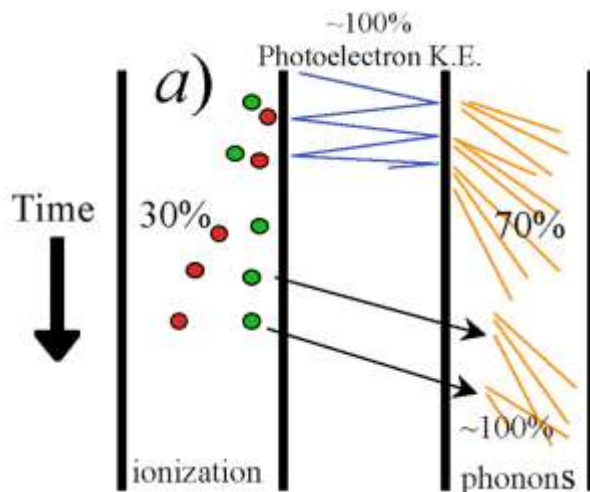
Thermal detection of radiation, or more general the calorimetric detection of energetic particles, is old strategy within physics.

It is based on the **first law of thermodynamics**: energy conservation.

Already in 1984, **novel low temperature particle detectors** were proposed for several applications in nuclear physics, astronomy, and astrophysics.  
 ... and continue to be investigated nowadays

$$\Delta U = Q - W$$

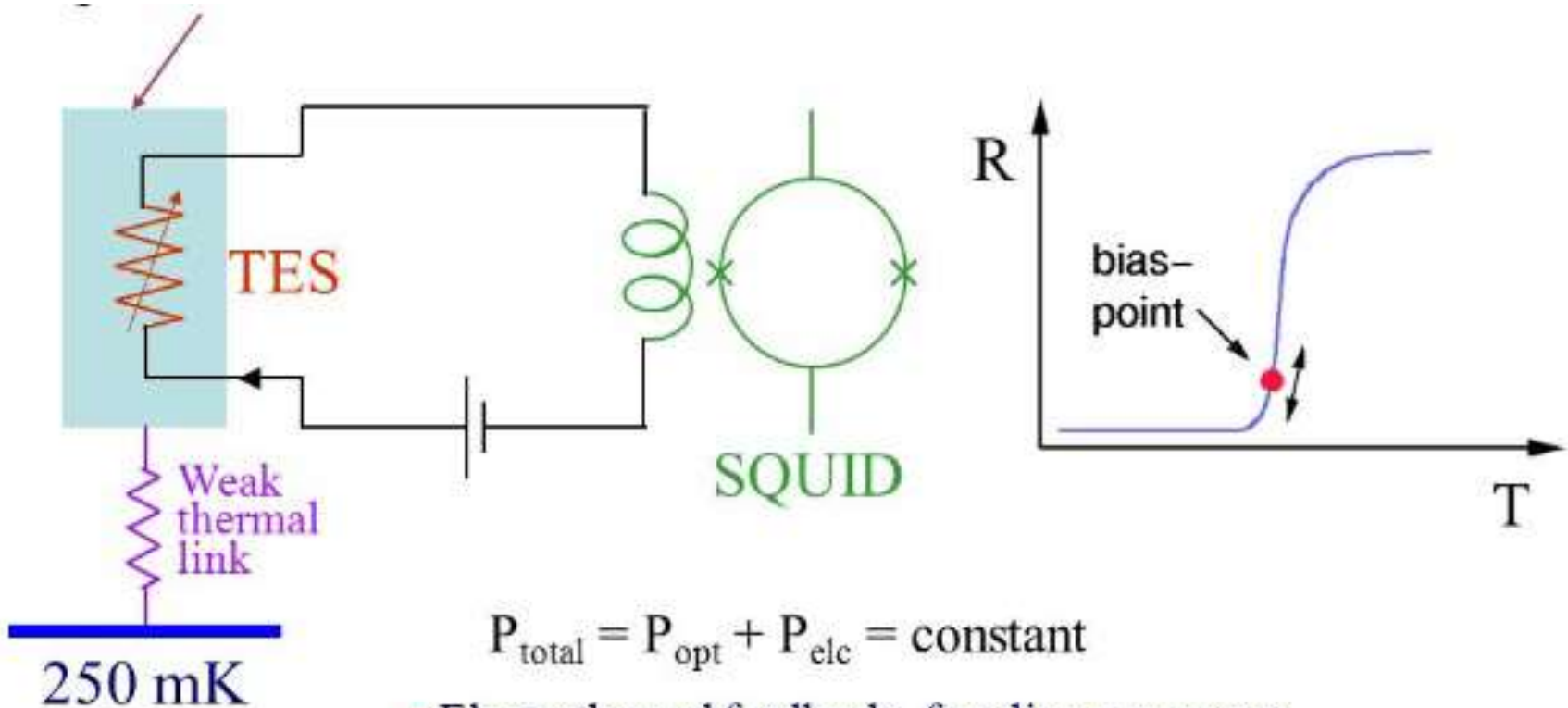
$\Delta U$  = change in internal energy  
 Q = heat added  
 W = work done by the system



- ❖ Calorimetric detectors can be based on devices such as, semiconductor thermistors, metallic magnetic calorimeters, superconducting transition edge sensors

## Superconducting Sensors for Rare Events

### ❖ Transition Edge Sensors



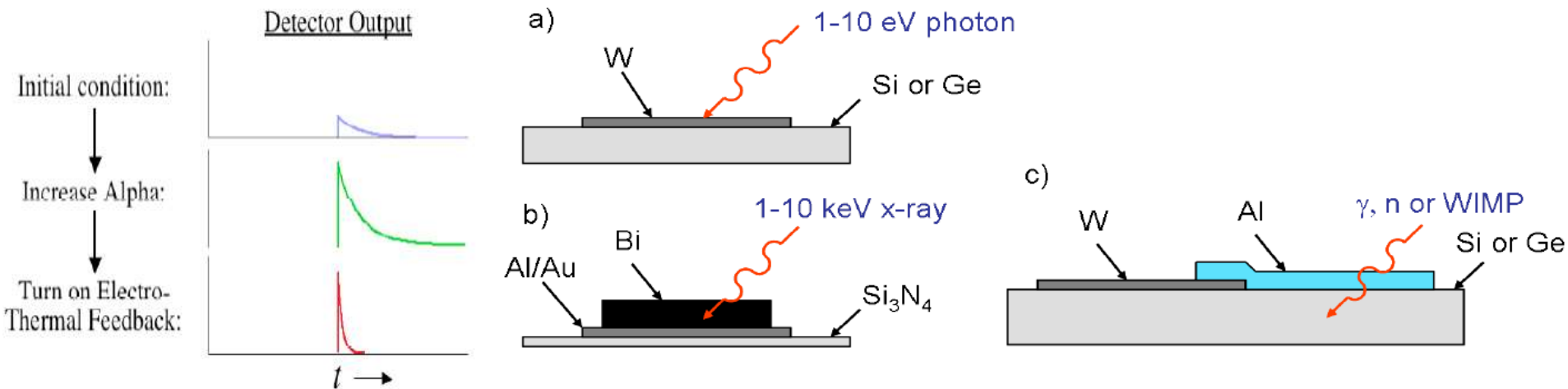
$$P_{\text{total}} = P_{\text{opt}} + P_{\text{elc}} = \text{constant}$$

- Electrothermal feedback: fast, linear response
- Low power dissipation ( $\sim 1$  nW)
- Sensitivity limited by fluctuations in the photon arrival rate

# Superconducting Sensors for Rare Events

## ❖ Transition Edge Sensors

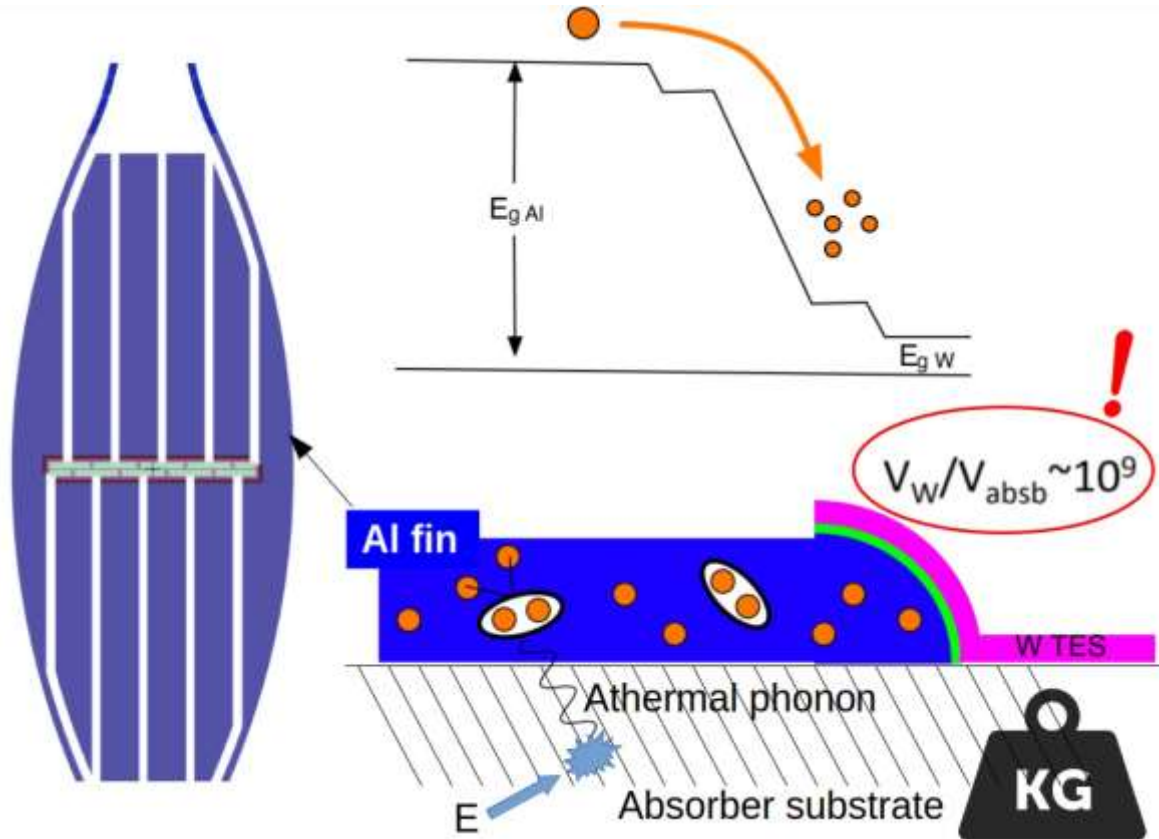
Several different advances, types or designs of TES detectors have been developed,



- (a) Detection of optical photons. The particles are directly absorbed in the TES film
- (b) Detection of X-rays. The TES film is deposited on a  $\text{Si}_3\text{N}_4$  membrane and an absorber in electrical contact with the TES film is attached.
- (c) DM detectors. The incoming particles are scattered in large mass absorbers and the resulting high frequency phonons generate quasiparticles in a superconducting film which diffuse to the TES film.

## Superconducting Sensors for Rare Events

### ❖ Transition Edge Sensors for meV DM



Ideally it allows to decouple the target mass from the TES mass  
The bigger the better for DM interactions vs the smaller the better for noise minimization

An energy blip produces phonons with energy  $>$  thermal energy. These live a while, before they thermalize

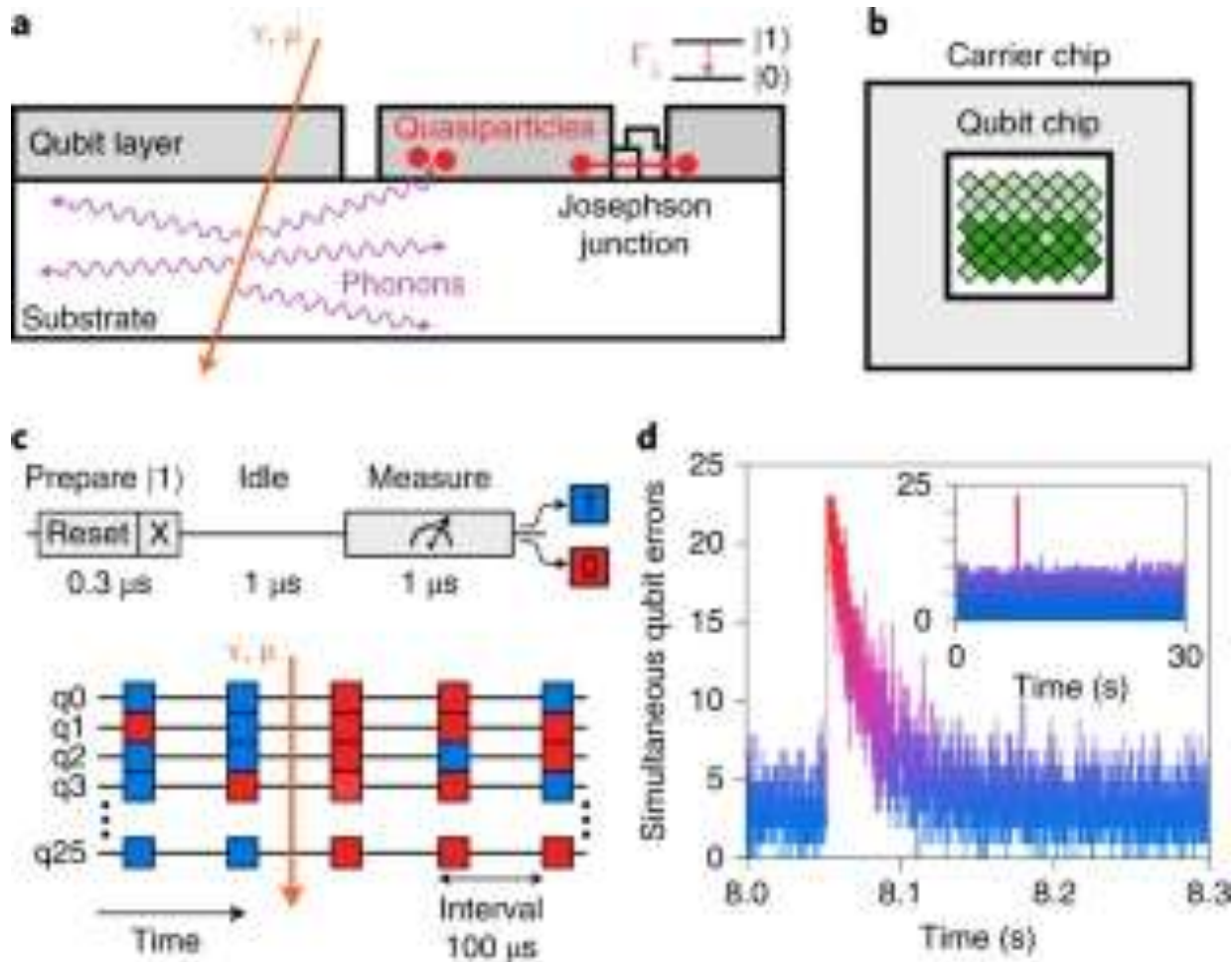
Cooper pairs are sensitive / absorb phonons and break them. Generate quasiparticles\*

Quasiparticles diffuse and reach the TES, they get trapped there and raise the TES temperature

\*In qubits, for quantum computing this is bad: quasiparticle poisoning

## Superconducting Sensors for Rare Events

- ❖ Error bursts from cosmic rays in large arrays of superconducting qubits



## Superconducting Sensors for Rare Events

TES detectors are dissipative devices.

- Not possible to enhance measurements with coherence strategies

### Crystal Defects: A Portal To Dark Matter Detection

Fedja Kadribasic, Nader Mirabolfathi

*Department of Physics and Astronomy, Texas A&M University, College Station, TX, USA*

Kai Nordlund and Flyura Djurabekova

*Helsinki Institute of Physics and Department of Physics, PB 43, University of Helsinki, Finland*

(Dated: February 12, 2020)

PHYSICAL REVIEW LETTERS **124**, 201801 (2020)

---

### Detecting Light Dark Matter with Magnons

Tanner Trickle<sup>1,2,3</sup>, Zhengkang Zhang<sup>3,1,2</sup> and Kathryn M. Zurek<sup>3,2,1</sup>

<sup>1</sup>*Department of Physics, University of California, Berkeley, California 94720, USA*

<sup>2</sup>*Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

<sup>3</sup>*Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, California 91125, USA*

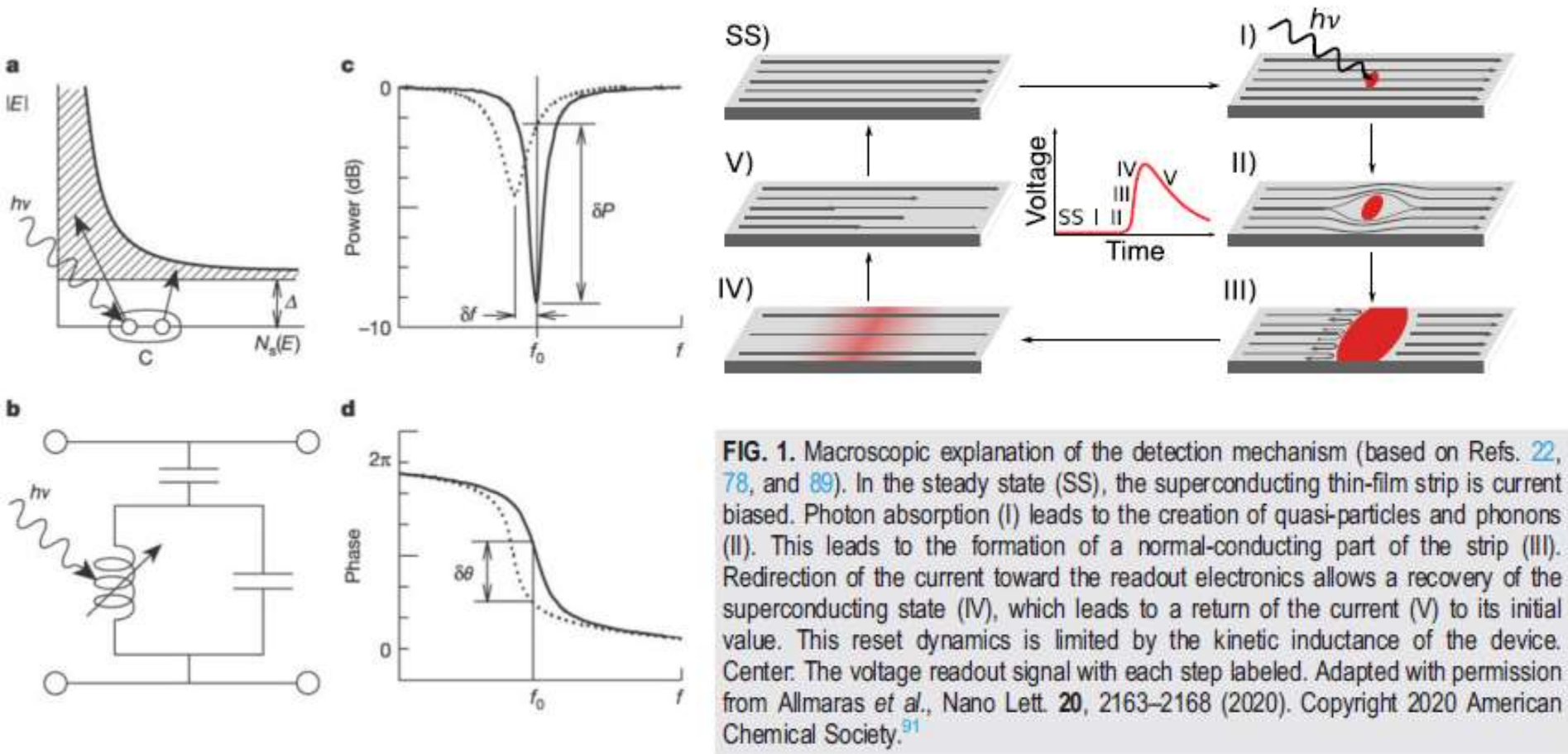
Non dispersive detectors include,

- Opto-mechanical resonators as phonon detectors (resonant)
- He quantum evaporation and detection with spin system (spin-spin coupling)
- Microwave kinetic inductance detectors (MKIDs) (dispersive)
- Superconducting Nanowire Single Photon Detectors



# Superconducting Sensors for Rare Events

## ❖ Microwave kinetic inductance detectors



**FIG. 1.** Macroscopic explanation of the detection mechanism (based on Refs. 22, 78, and 89). In the steady state (SS), the superconducting thin-film strip is current biased. Photon absorption (I) leads to the creation of quasi-particles and phonons (II). This leads to the formation of a normal-conducting part of the strip (III). Redirection of the current toward the readout electronics allows a recovery of the superconducting state (IV), which leads to a return of the current (V) to its initial value. This reset dynamics is limited by the kinetic inductance of the device. Center: The voltage readout signal with each step labeled. Adapted with permission from Allmaras *et al.*, *Nano Lett.* **20**, 2163–2168 (2020). Copyright 2020 American Chemical Society.<sup>91</sup>

# Superconducting Sensors for Rare Events

## ❖ Superconducting Nanowire Single Photon Detectors

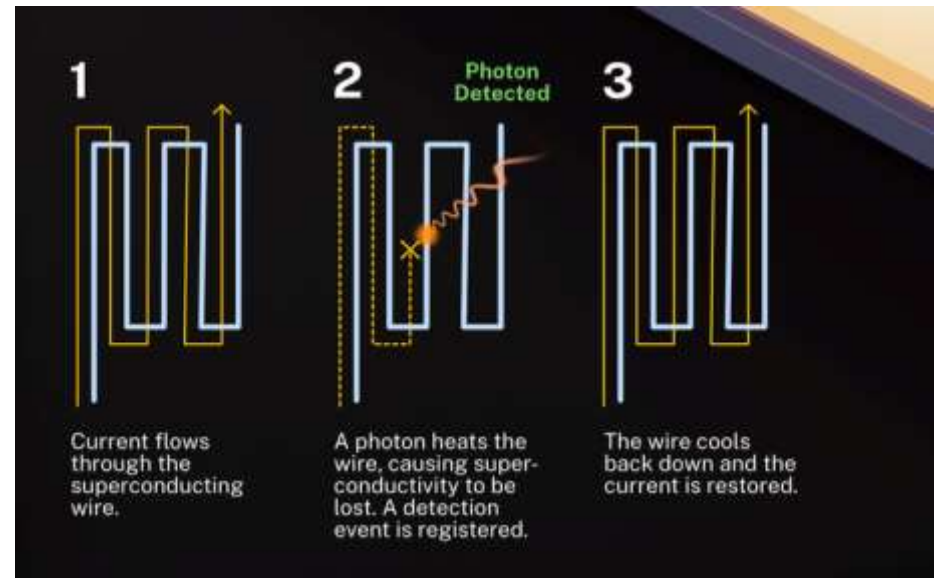
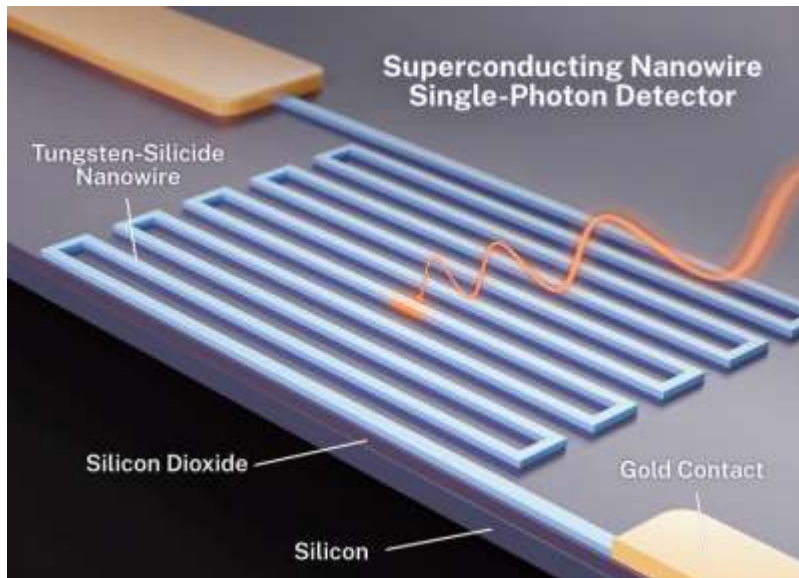


TABLE I. Overview of some SNSPD leading works on different material platforms.

Material	Efficiency/time jitter	Temperature	Wavelength
NbN (Refs. 43 and 45)	92%–98.2%/40–106.1 ps	0.8–2.1 K	1550–1590 nm <sup>a</sup>
NbTiN (Refs. 42 and 46)	92%–99.5%/14.8–34 ps	2.5–2.8 K	1290–1500 nm <sup>b</sup>
WSi (Refs. 41 and 44)	93%–98%/150 ps	120 mK–< 2 K <sup>c</sup>	1550 nm
MoGe (Ref. 106)	20%/69–187 ps	250 mk–2.5 K	1550 nm
MoRe (Ref. 107)	–/–	9.7 K	–
MoSi (Refs. 108–110)	80%–87%/26–76 ps	0.8–1.2 K <sup>d</sup>	1550 nm
NbRe (Ref. 111)	–/35 ps	2.8 K	500–1550 nm
NbTiN (Ref. 76)	15%–82%/30–70 ps	2.5–6.2 K	400–1550 nm
NbSi (Ref. 112)	–/–	300 mK	1100–1900 nm
TaN (Ref. 113)	–/–	0.6–2 K	600–1700 nm
MgB <sub>2</sub> (Refs. 114–116)	–/–	3–5 K	Visible

## More than just measure and collect data...

Challenges in QS for providing data which effectively generates new science including,

- **Precise Modelling of Devices Operation**

E.g. TES is the type of thermometer is most widely used for cryogenic particle detectors, the complex physics associated with operating these devices at the superconducting phase transition is not very well understood

- **Inference, Calculations or Modelling of Physical Parameter of interest**

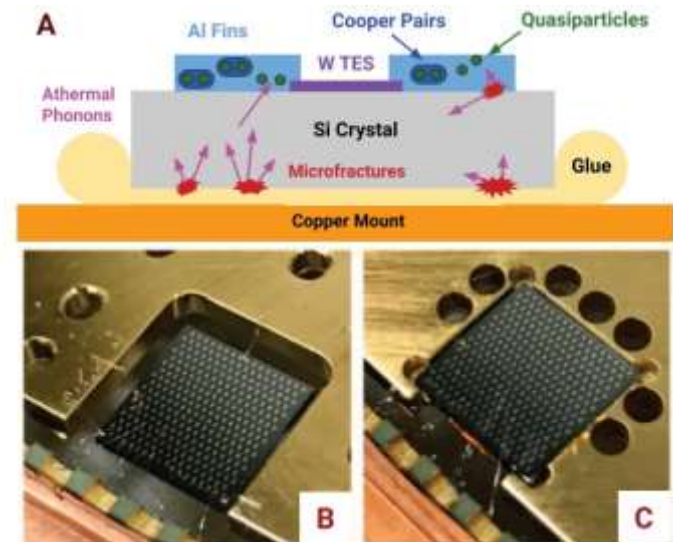
E.g. Correlation of DM in QET direct detection with phononic generation, diffusion, in target

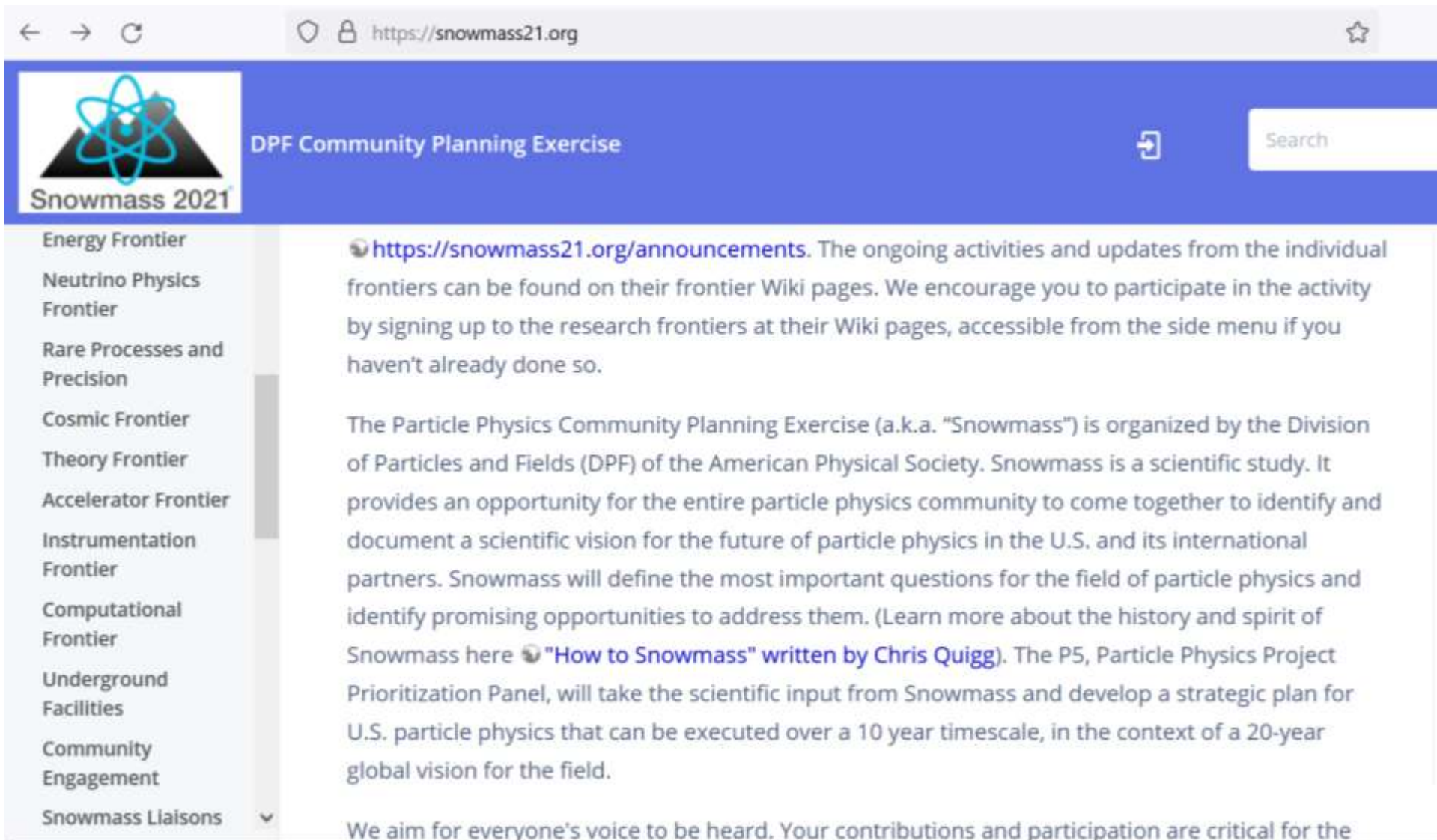
- **Devices ultimate performance, as well as reproducibility or scaling**

E.g. Low reproducibility of W thin films operating practically at a variable numbers in the 10s of mK order.

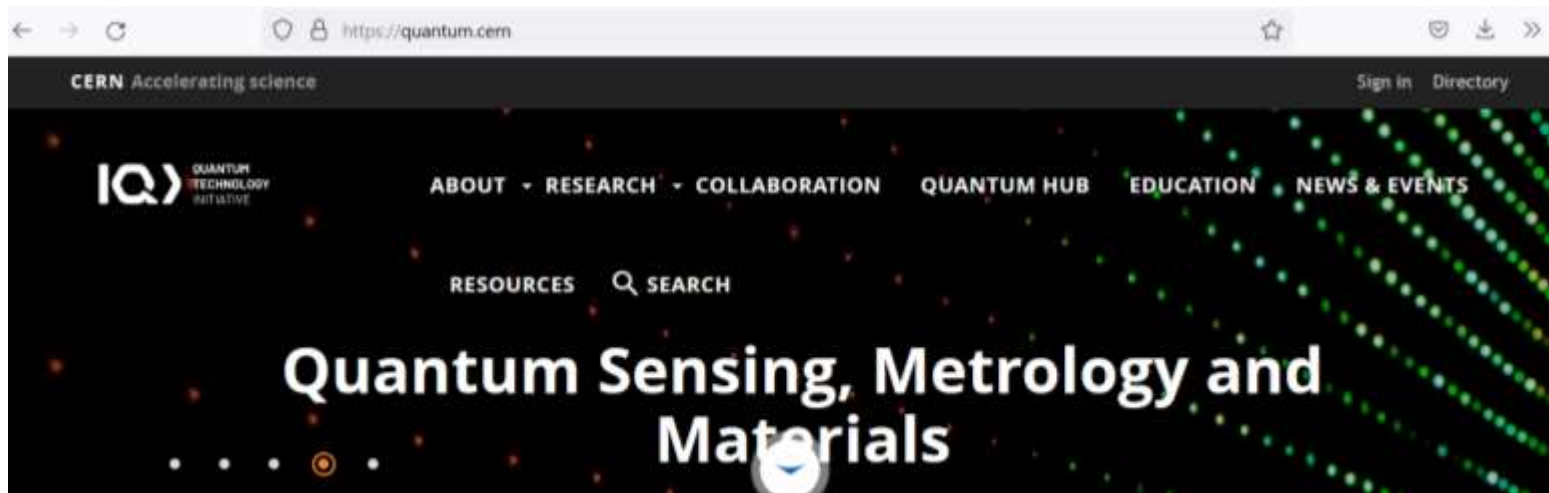
- **Detector implementation in relevant experimental setups for calibration and actual data acquisition**

E.g. Assessment of established methods, such as radioactive sources, to qualify manufactured devices for the application of interest

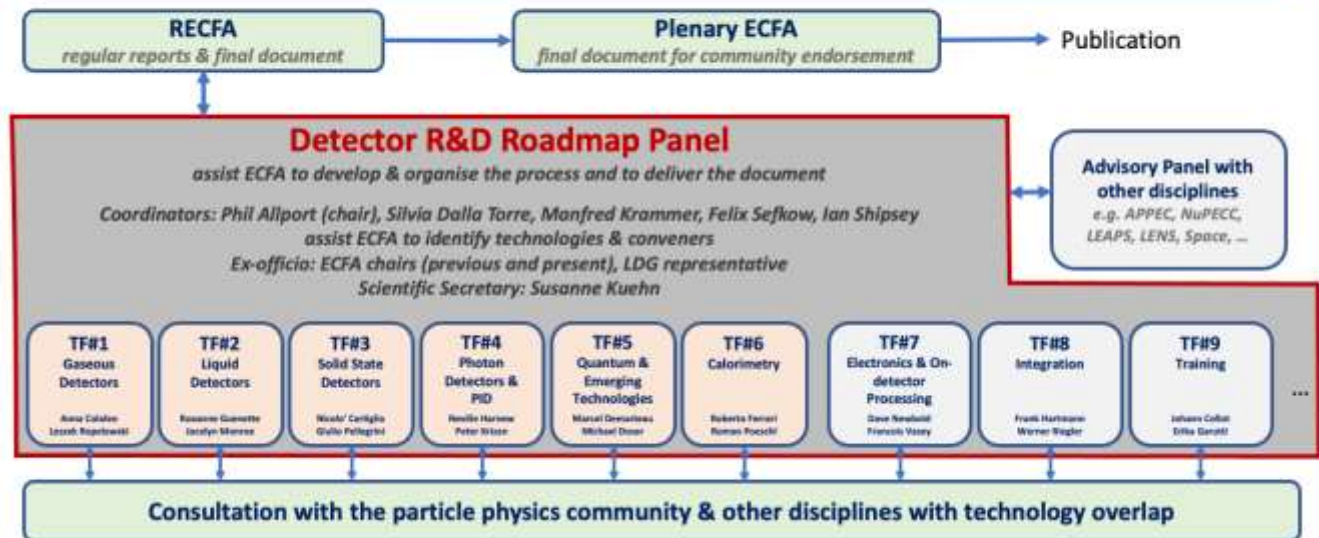




The screenshot shows a web browser window with the URL <https://snowmass21.org>. The page has a blue header with the Snowmass 2021 logo on the left, which includes a stylized atom symbol and the text "Snowmass 2021". To the right of the logo is the text "DPF Community Planning Exercise" and a search bar with the word "Search" inside. Below the header is a vertical navigation menu on the left with the following items: Energy Frontier, Neutrino Physics Frontier, Rare Processes and Precision, Cosmic Frontier, Theory Frontier, Accelerator Frontier, Instrumentation Frontier, Computational Frontier, Underground Facilities, Community Engagement, and Snowmass Liaisons. The main content area on the right contains two paragraphs of text. The first paragraph starts with a globe icon and a link to <https://snowmass21.org/announcements>. The second paragraph describes the DPF Community Planning Exercise (a.k.a. "Snowmass") as a scientific study organized by the Division of Particles and Fields (DPF) of the American Physical Society. It mentions that the study provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. It also mentions that Snowmass will define the most important questions for the field of particle physics and identify promising opportunities to address them. A link to a "How to Snowmass" document by Chris Quigg is provided. The third paragraph starts with "We aim for everyone's voice to be heard. Your contributions and participation are critical for the".



## Organization to structure the consultation with the community



# Quantum Technologies

2813 VIEWS 18 LIKES

[ESA / Enabling & Support / Space Engineering & Technology / Space Optoelectronics](#)

We are already surrounded by quantum technologies. From microprocessors, to digital cameras, to lasers—these technologies rely for their operation on the quantum behaviour of electrons in solids and on the stimulated emission of coherent radiation, respectively. Advances in experimental techniques and equipment over the past few decades have enabled the manipulation of single quantum objects (photons, atoms) to harness more advanced, subtle, aspects of quantum mechanics: superposition and entanglement. Thanks to these properties a new era of Quantum



**European Space Agency**

# Thank you for your attention!

Now, the floor is yours

What are your 'Take home messages?

What are you researching about?

Does Quantum Technology/ies somehow apply? Directly? Implicitly?

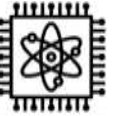
If Yes, share it with us!

If No, or not yet...

Could it be insightful, useful, original?

How could you benchmark your method against the quantum-based?

What skills, collaborations, resources would be needed?



**“Slow is very nice.  
When cycling up a hill, it feels hard.  
Just continue. You’ll get there.”**

Physicist and artist Alexander Lagaaij,  
who has [cycled from the Netherlands to Egypt](#).



