QUANTUM TECHNOLOGIES

(1/2)

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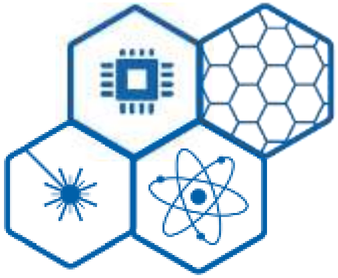


13/09/2023

2 Sessions
on
QUANTUM TECHNOLOGIES

1st. Towards QTech
2nd. QTech for HEP

Institute of Microelectronics of Barcelona
IMB-CNM-CSIC

Centre Nacional de Microelectrònica IMB

IMB-CNM-CSIC. Research Axes

Physics Frontiers & Civil Security

Energy & Mobility

Health & Environment

Advanced Processes for Micro & Nano systems

8 Research Groups

Centre Nacional de Microelectrònica

IMB

IMB-CNM-CSIC. Capability

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

Main Clean Room @ IMB-CNM-CSIC

- 1,500 m^2
- Class 100-10,000
- CMOS processing technology
- Microsystems processing
- Nanolithography & Nanofabrication

Back-End Clean Room

- 40 m^2
- Class 1000-10,000
- Chip packaging
- Hybrid circuit assembly

10 Specialized Areas or Labs

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

www.imb-cnm.csic.es/index.php/en

✓ **Other Servicios Científico-Técnicos, available on Campus UAB**

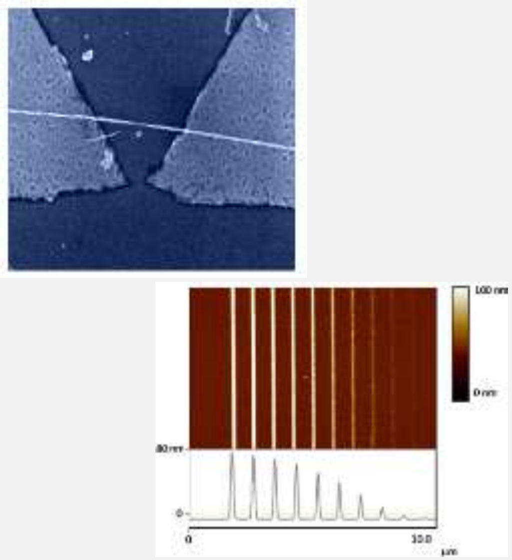
(XRD, XPS, HR-TEM, PPMS o MPMS…)

Onset of Nanofabrication @ IMB-CNM-CSIC

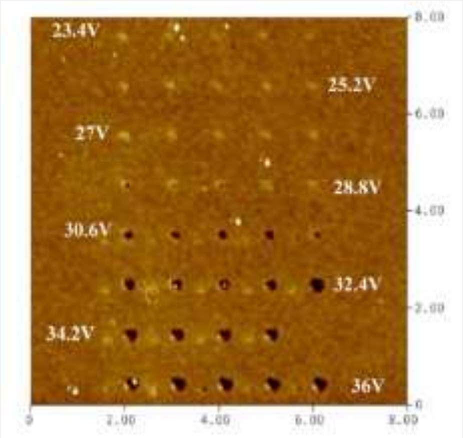
- ***Setup Electron Beam Lithography.***
- ***Implementation EBL 2002-2008***

Nanopatterning

Electron Beam

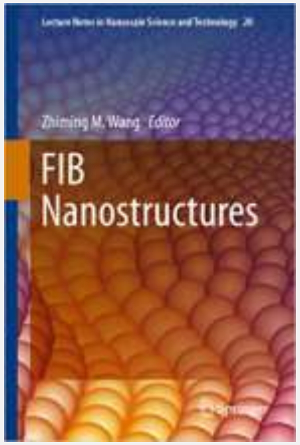


Scanning Probe



Nanotechnology **2005**

Ion Beam


Lecture Notes in Nanoscale Science and Technology 20

Zhiming M. Wang Editor

FIB Nanostructures

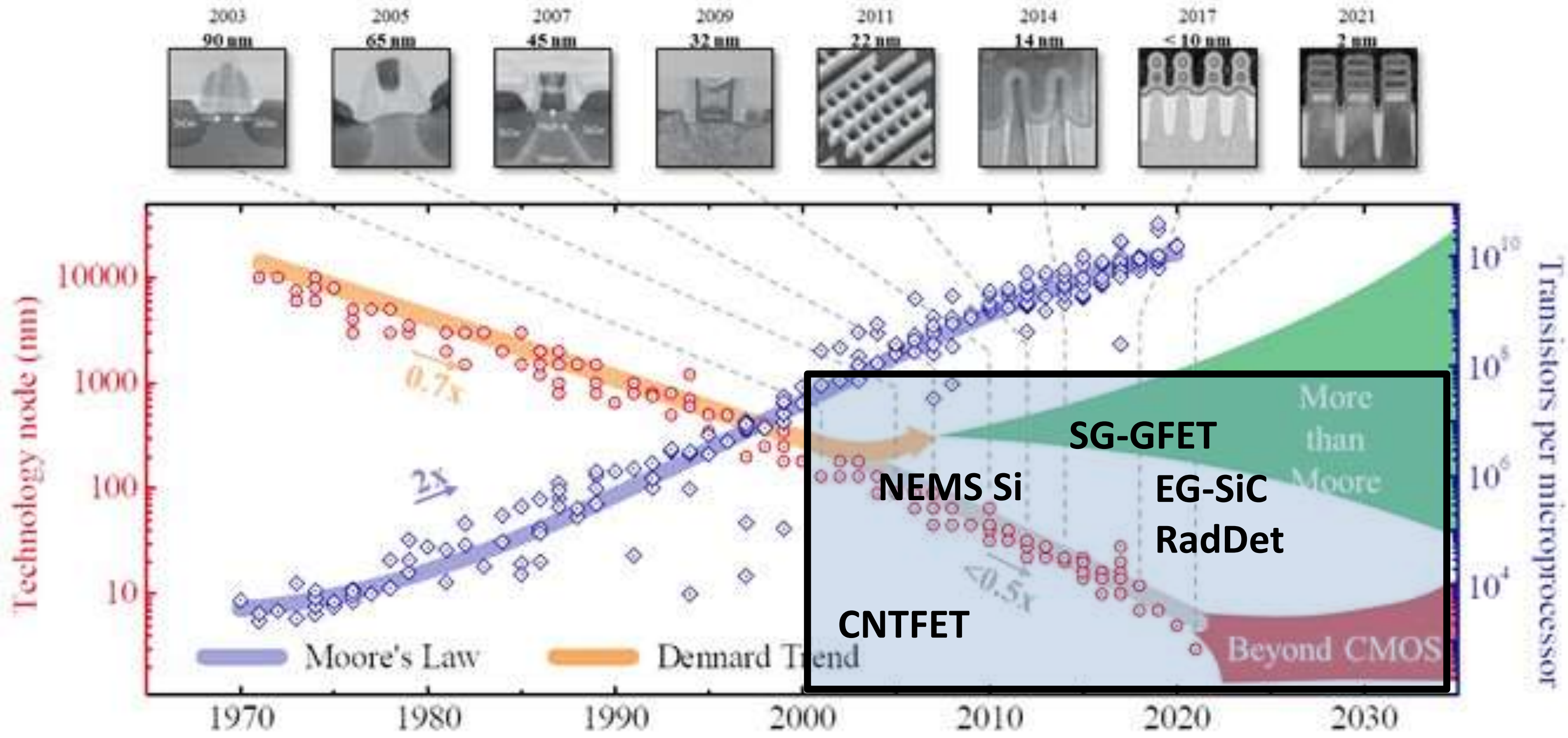
Springer

JVST B **2012**, NIMS B **2014, …**

Advanced Characterization

FE-SEM	AFM	FIB

Introduction



APPLIED PHYSICS & ELECTRONICS Nanomecánicos, FET, SG-FET, diodos, electrodos…

MICRO/NANOTECHNOLOGIES Nanopatterning, procesos, fabricación e integración…

NANO/QUANTUM MATERIALS 1D&2D Carbons, thin films, superconductores

HARSH & QUANTUM Techs

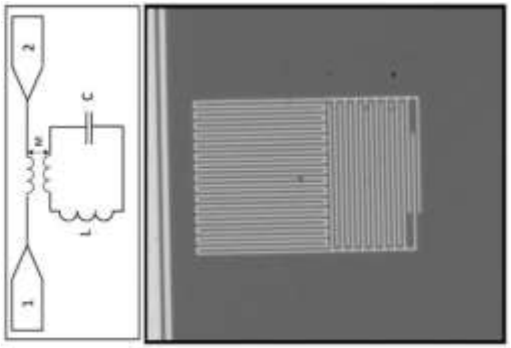
Fabrication and Integration of Emerging Electronic Devices and Nanomaterials

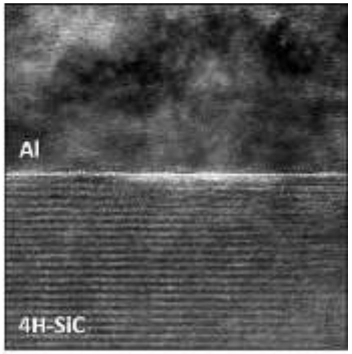
1. Fabrication of staple Superconducting Devices and Circuits

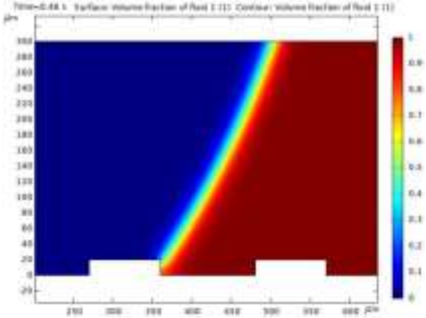
2. Exploring Hybrid Devices based on 2D Materials and Superconductors

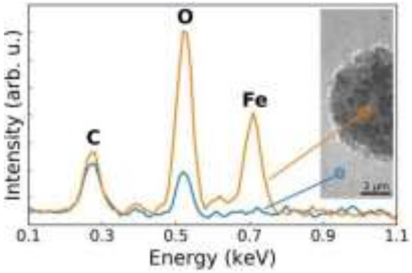
3. Miniaturization of Devices for Unconventional Environments or Applications

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









QUANTUM TECHNOLOGIES	*HARSH Appl.*	*Emerging ICT*
TRL 1 - 5	TRL 1 - 7	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 Brittanica 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.

$$\mathbf{10^{-9}}$$

Nanotechnology

Miniaturization

Matter

Knowledge

Nanofabrication

Nanomaterials

Applications

Simulation

Caracterization

Feynman 1959

Taniguchi 1972 Nanotechnology

ALD 1974

Bining&Rohrer 1981 STM

Q-Dots @ Bell Labs

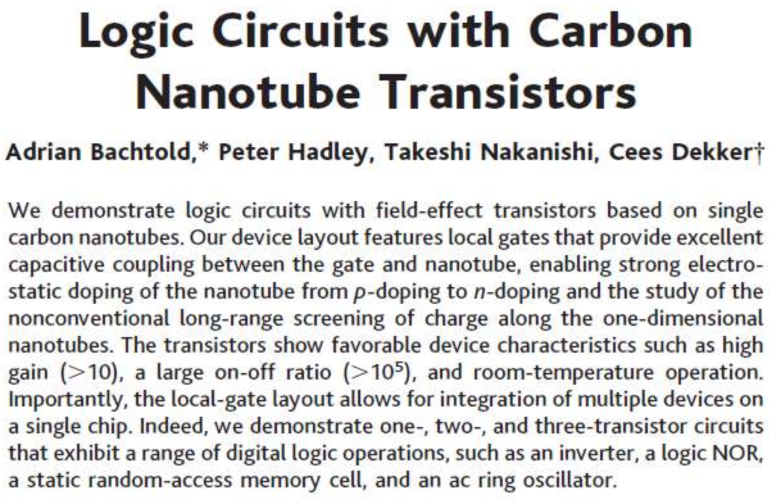
Molecular Electronics

Fullerenes

Ijima 1991 CNTs

Novoselov&Geim 2004 Graphene

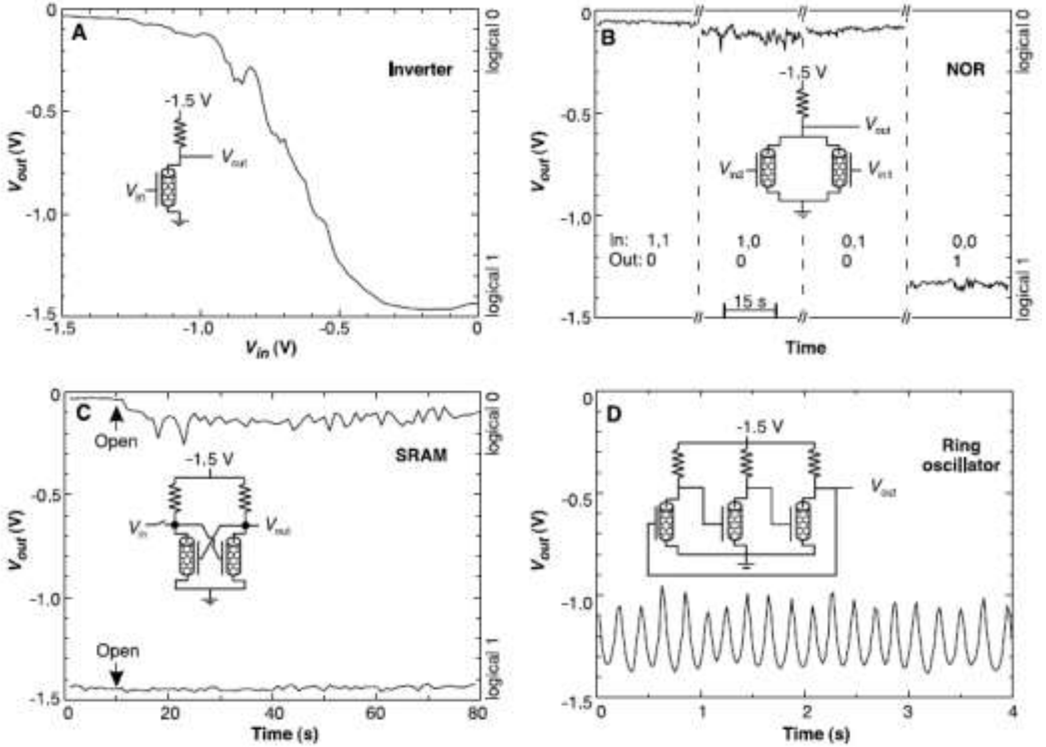
Disruption in Nanotechnology
Advanced Materials based Electronics



Logic Circuits with Carbon Nanotube Transistors

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

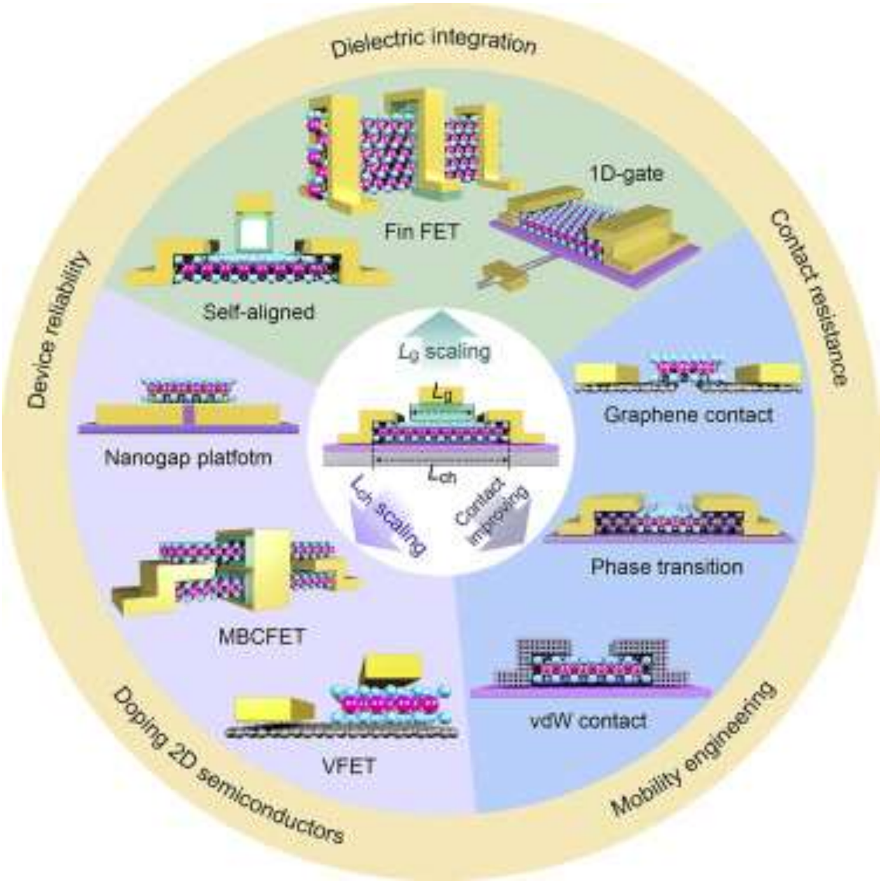
We demonstrate logic circuits with field-effect transistors based on single carbon nanotubes. Our device layout features local gates that provide excellent capacitive coupling between the gate and nanotube, enabling strong electrostatic doping of the nanotube from *p*-doping to *n*-doping and the study 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.

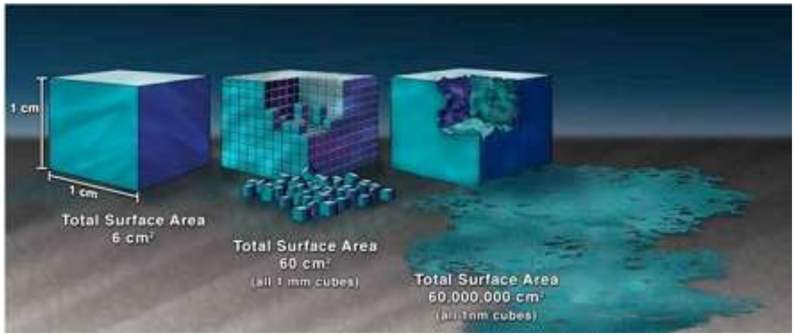


SCIENCE VOL 294 9 NOVEMBER 2001

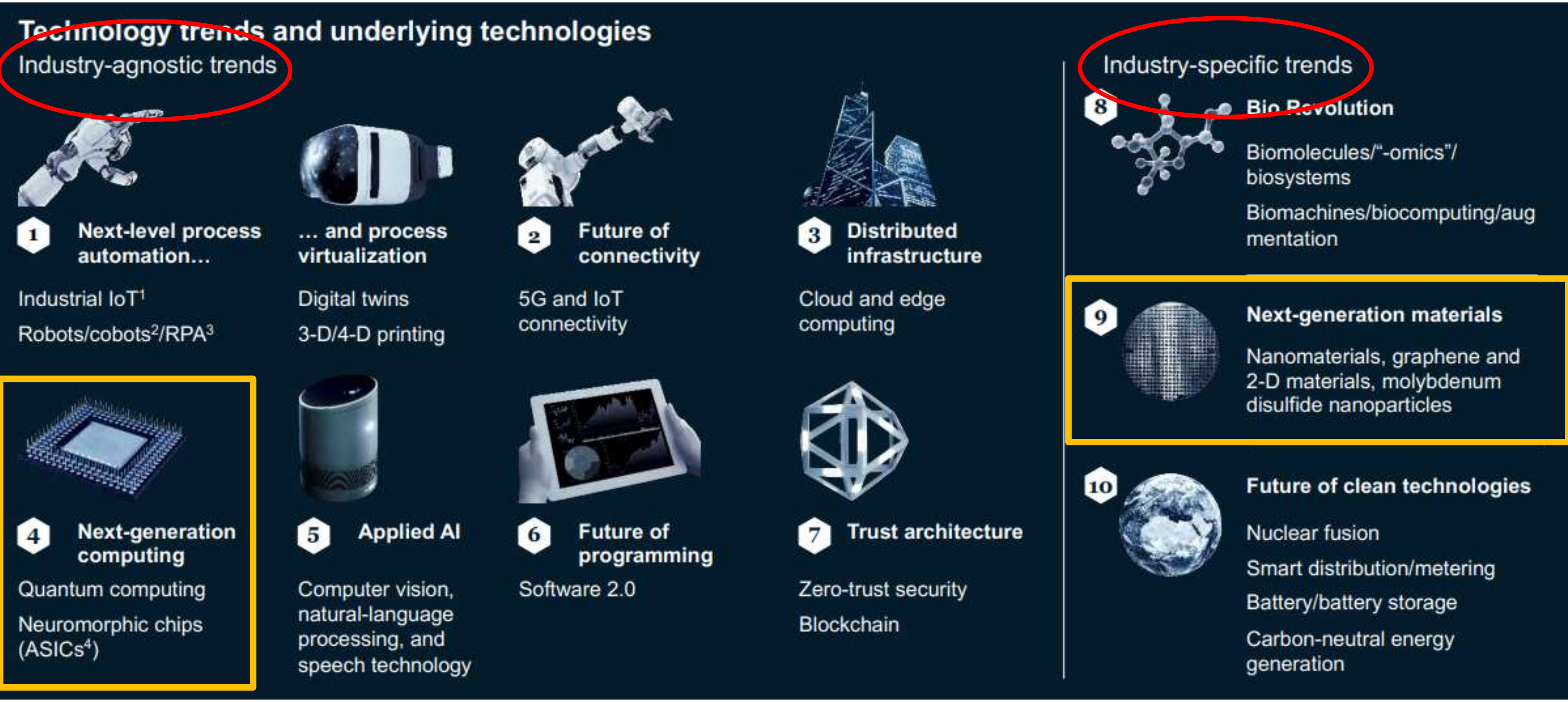
Novel Nanomaterials
Applications in Emerging Devices

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[1]

Robots/cobots[2]/RPA[3]

… and process virtualization

Digital twins

3-D/4-D printing

2 Future of connectivity

5G and IoT connectivity

3 Distributed infrastructure

Cloud and edge computing

4 Next-generation computing

Quantum computing

Neuromorphic chips (ASICs[4])

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/

Ubiquitious Microelectronics

Semiconductors are the foundations of any modern technology

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

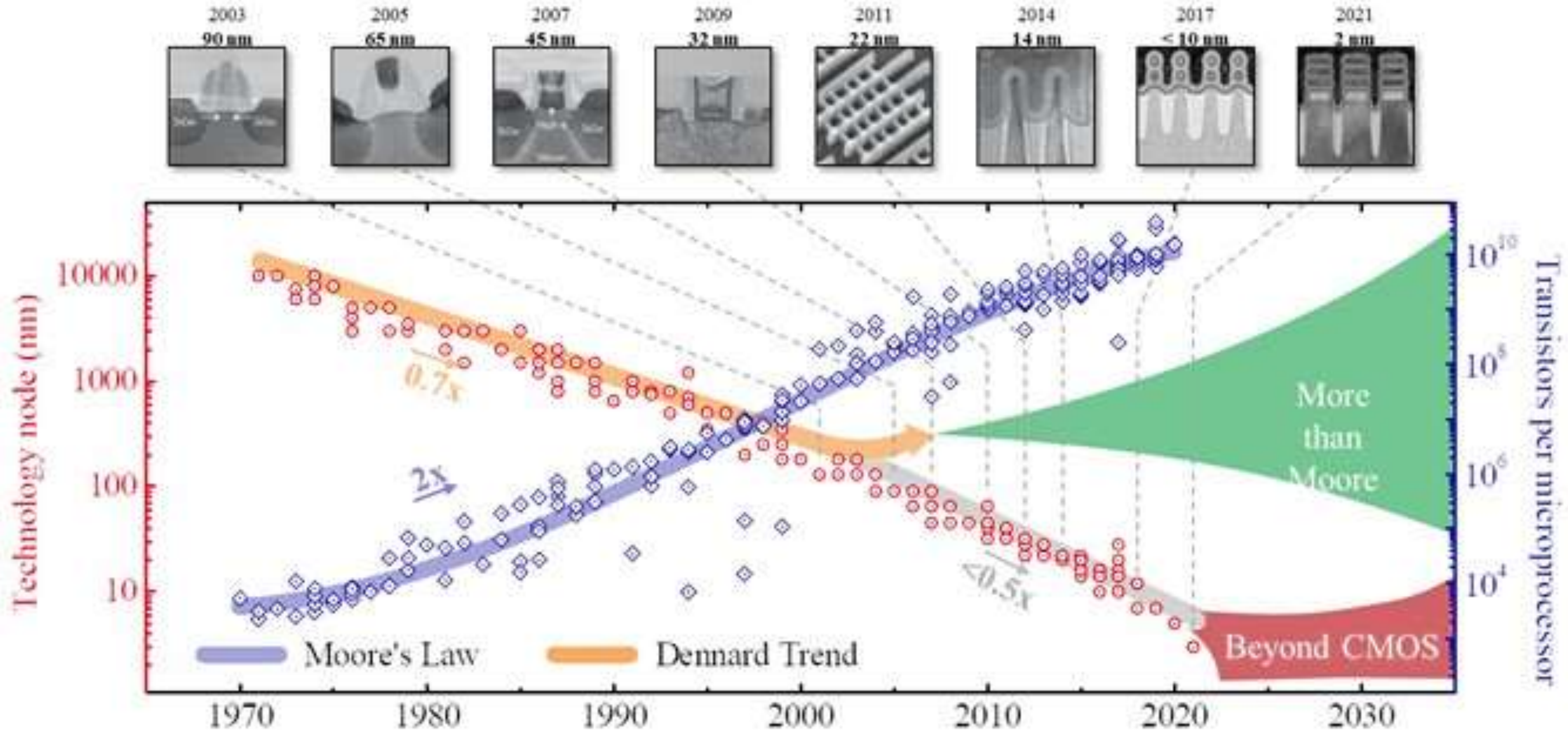
“**Microelectronics** (…) refers to integrated electronic devices and systems generally **manufactured using semiconductor-based materials and related processing**.

Such devices and systems include **analog and digital electronics, power electronics, optics and photonics, and micromechanics,**

for **memory, processing, sensing, and communications**.”

NIST (2019) https://nvlpubs.nist.gov/nistpubs/CHIPS/NIST.CHIPS.1000.pdf

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.

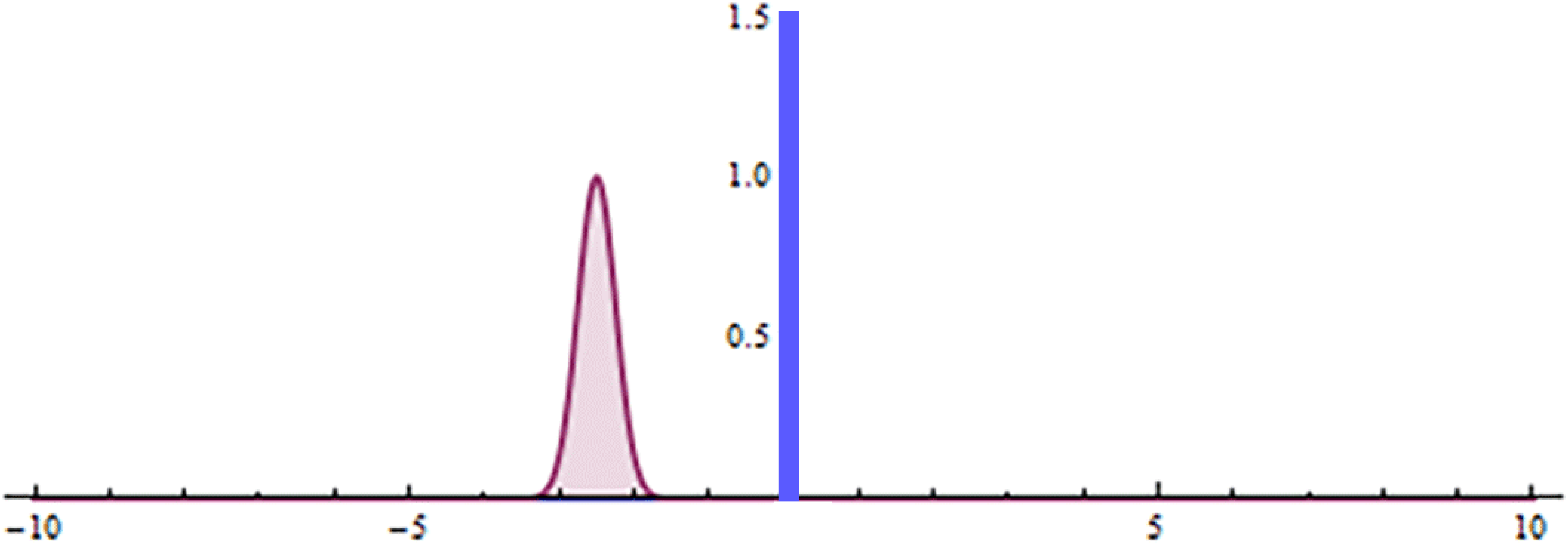
Quantum Principles

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

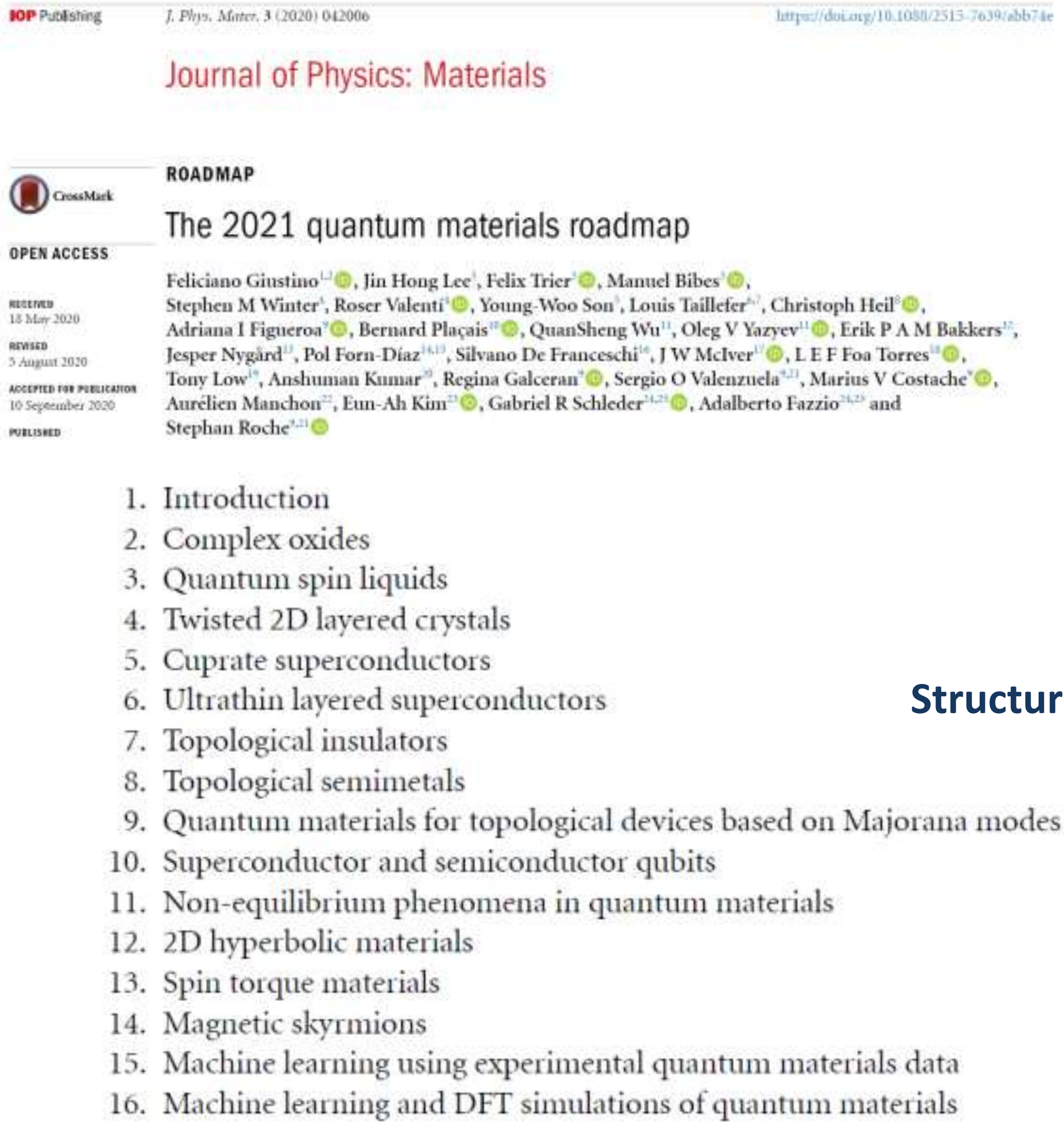
- **Quantisation or quantum size effect** - the allowed energies of a tightly confined system of particles are restricted to a discrete set.
- **Uncertainty principle -** for every perfectly specified quantum state there is always at least one measurement, the results of which are completely certain, 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)



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Journal of Physics: Materials

CrossMark

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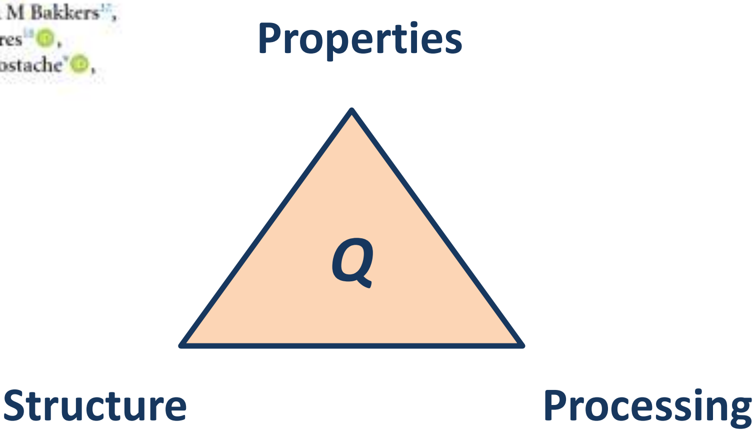
ROADMAP

The 2021 quantum materials roadmap

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

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

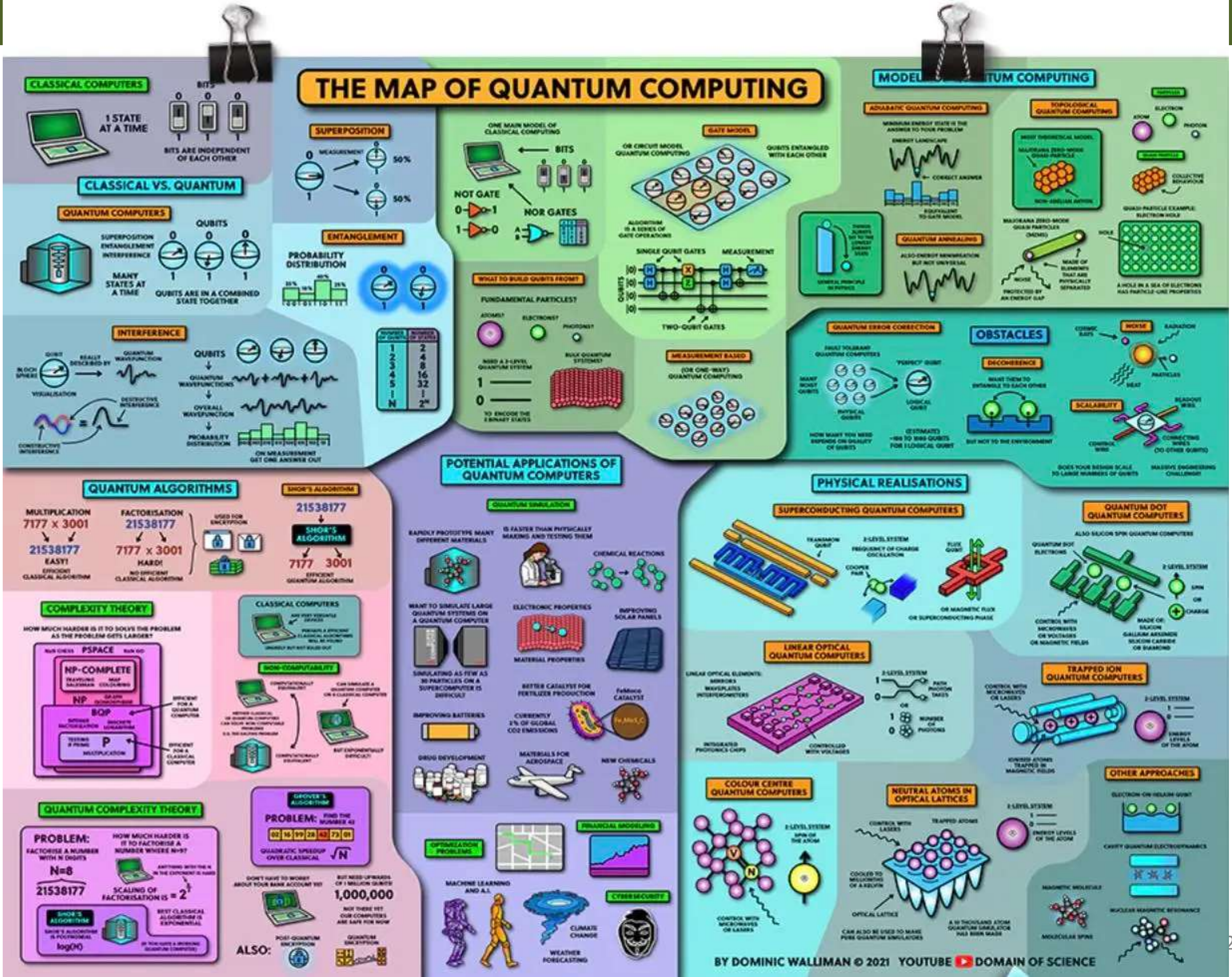


Properties

Q

Structure

Processing


THE MAP OF QUANTUM COMPUTING
CLASSICAL COMPUTERS
1 STATE AT A TIME
BITS
BITS ARE INDEPENDENT OF EACH OTHER
CLASSICAL VS. QUANTUM
QUANTUM COMPUTERS
QUBITS
SUPERPOSITION
ENTANGLEMENT
INTERFERENCE
MANY STATES AT A TIME
QUBITS ARE IN A COMBINED STATE TOGETHER
SUPERPOSITION
50%
50%
ENTANGLEMENT
PROBABILITY DISTRIBUTION
INTERFERENCE
QUBITS
QUANTUM WAVEFUNCTIONS
OVERALL WAVEFUNCTION
PROBABILITY DISTRIBUTION
ON MEASUREMENT GET ONE ANSWER OUT
ONE MAIN MODEL OF CLASSICAL COMPUTING
BITS
NOT GATE
NOR GATES
GATE MODEL
OR CIRCUIT MODEL QUANTUM COMPUTING
QUBITS ENTANGLED WITH EACH OTHER
ALGORITHM IS A SERIES OF GATE OPERATIONS
SINGLE QUBIT GATES
MEASUREMENT
TWO-QUBIT GATES
WHAT TO BUILD QUBITS FROM?
FUNDAMENTAL PARTICLES?
ATOMS?
ELECTRONS?
PHOTONS?
BULK QUANTUM SYSTEMS?
NEED A 2-LEVEL QUANTUM SYSTEM
TO ENCODE THE 2 BINARY STATES
MEASUREMENT BASED
(OR ONE-WAY) QUANTUM COMPUTING
MODELS OF QUANTUM COMPUTING
ADIABATIC QUANTUM COMPUTING
QUANTUM ANNEALING
TOPOLOGICAL QUANTUM COMPUTING
QUANTUM ERROR CORRECTION
OBSTACLES
DECOHERENCE
NOISE
SCALABILITY
POTENTIAL APPLICATIONS OF QUANTUM COMPUTERS
QUANTUM SIMULATION
CHEMICAL REACTIONS
ELECTRONIC PROPERTIES
IMPROVING SOLAR PANELS
MATERIAL PROPERTIES
IMPROVING BATTERIES
BETTER CATALYST FOR FERTILIZER PRODUCTION
DRUG DEVELOPMENT
MATERIALS FOR AEROSPACE
NEW CHEMICALS
OPTIMIZATION PROBLEMS
FINANCIAL MODELING
MACHINE LEARNING AND A.I.
CYBERSECURITY
CLIMATE CHANGE
WEATHER FORECASTING
QUANTUM ALGORITHMS
MULTIPLICATION
7177 x 3001
21538177
EASY!
FACTORISATION
21538177
7177 x 3001
HARD!
SHOR'S ALGORITHM
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SHOR'S ALGORITHM
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COMPLEXITY THEORY
PSPACE
NP-COMPLETE
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CLASSICAL COMPUTERS
NON-COMPUTABILITY
QUANTUM COMPLEXITY THEORY
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GROVER'S ALGORITHM
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ALSO:
PHYSICAL REALISATIONS
SUPERCONDUCTING QUANTUM COMPUTERS
QUANTUM DOT QUANTUM COMPUTERS
LINEAR OPTICAL QUANTUM COMPUTERS
TRAPPED ION QUANTUM COMPUTERS
COLOUR CENTRE QUANTUM COMPUTERS
NEUTRAL ATOMS IN OPTICAL LATTICES
OTHER APPROACHES
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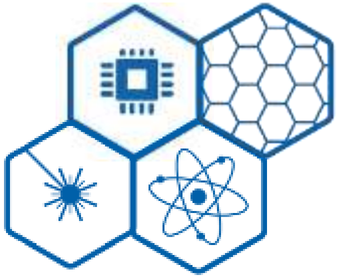

13/09/2023

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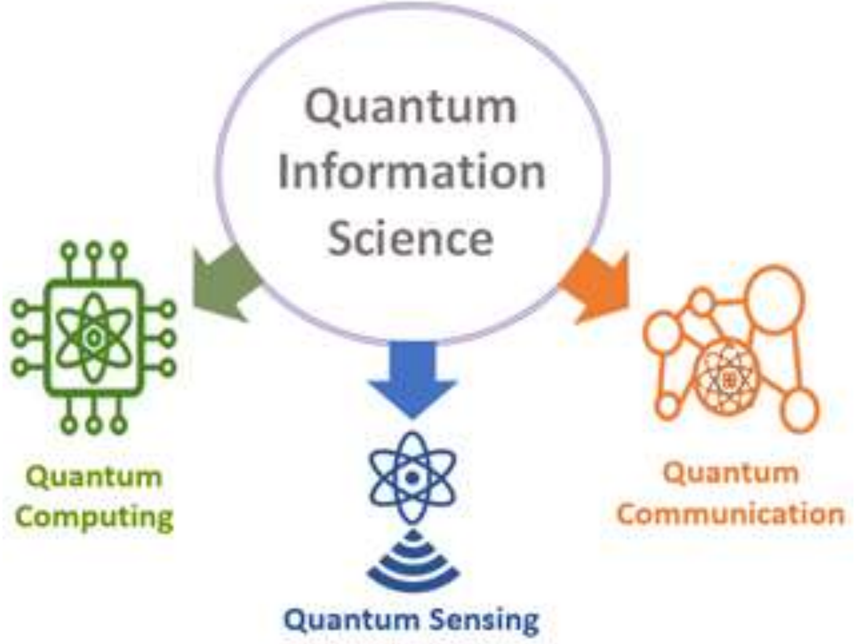
1st. Towards QTech

2nd. QTech for HEP

Quantum Technologies

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, <u>while not a substitute for classical computers,</u> 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 <u>quantum systems would be especially apt at simulating actual physical quantum behavior</u>, whether in material or chemical systems.

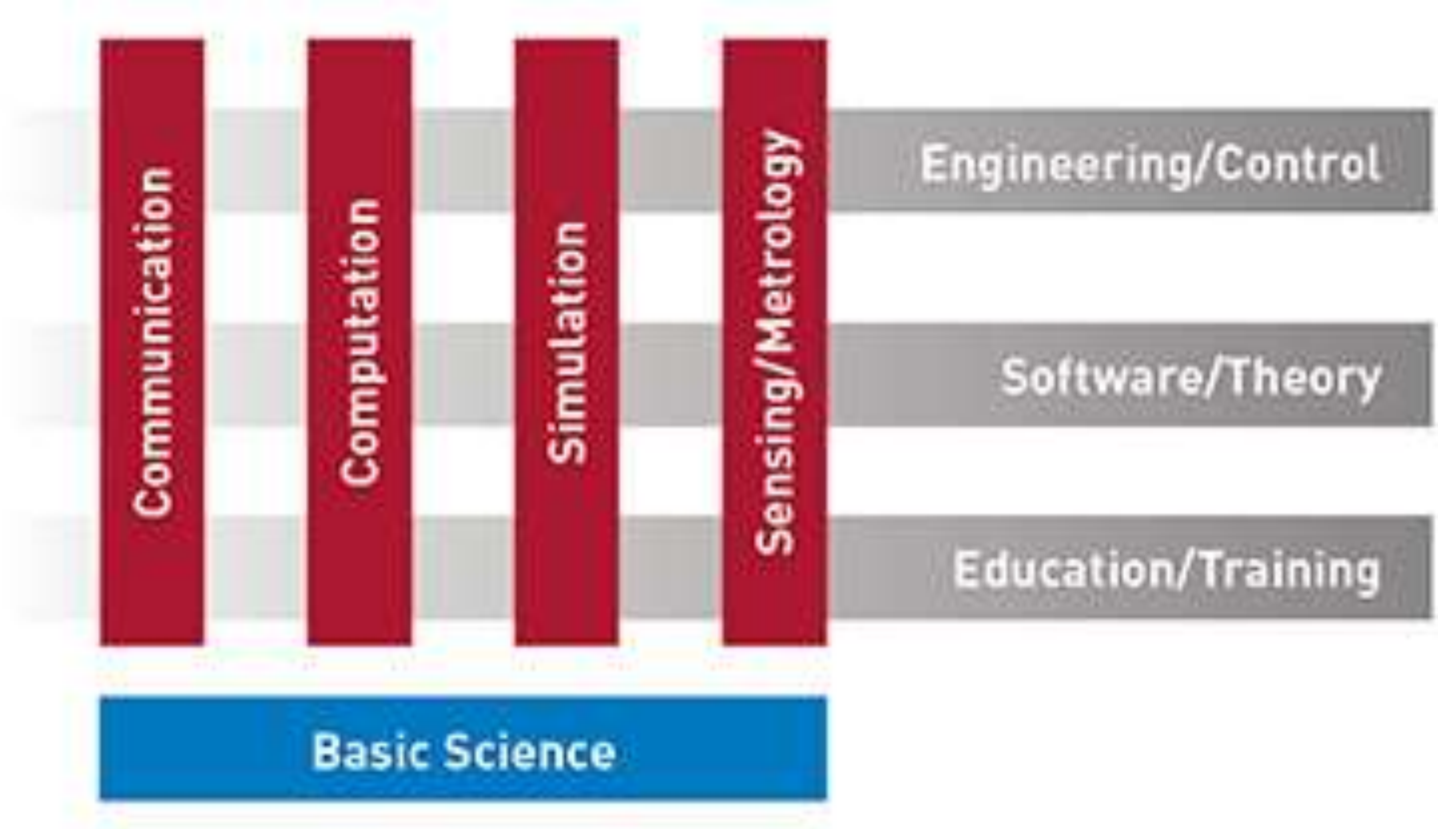
Quantum communication. Quantum information systems hold out the possibility of <u>extremely secure encryption</u>—a major attraction in an age where cybersecurity is constantly at risk.

Quantum sensing and microscopy. Sensors based on quantum effects could be exquisitely sensitive and could <u>aid in understanding everything</u> 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



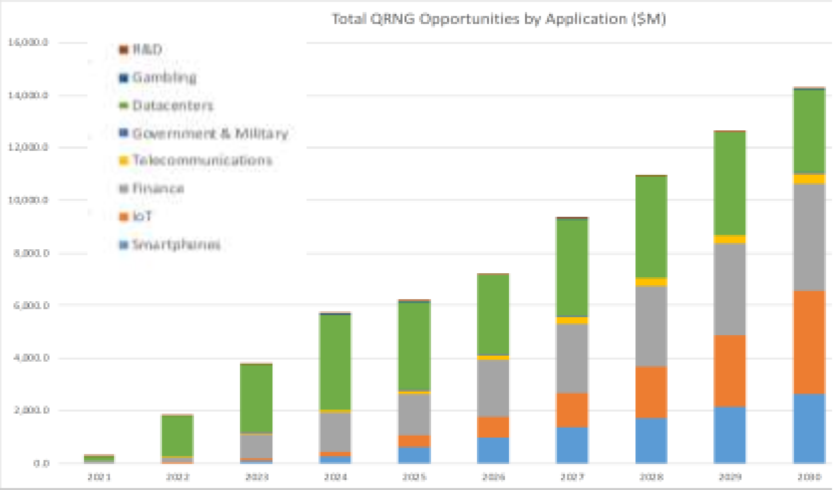
FET FLAGSHIPS

QUANTUM FLAGSHIP

Quantum Communication

❖ **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.

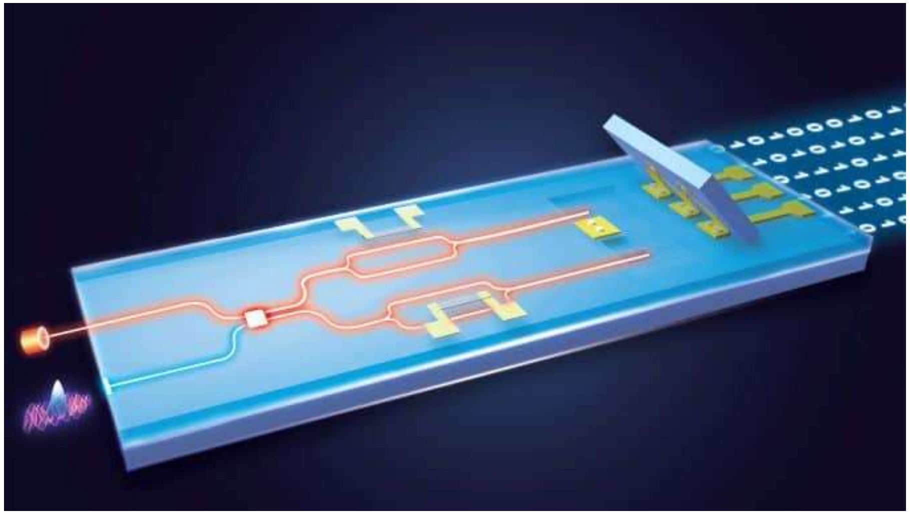


- Covers aspects from basic physics to practical current applications very relevant to society
- **Cybersecurity**. In our information based society, as well as emerging problems associated with long term secure storage (e.g. for health records and infrastructure), QKD is considered most desirable solution
- 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.



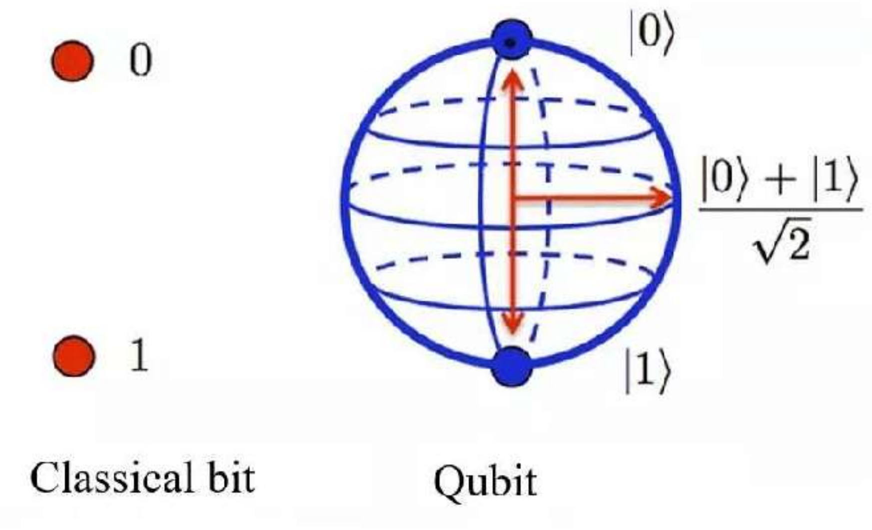
Long-term goal: Quantum-based security over many-node networks running in various places worldwide

- 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



✓ Probabilistic

- **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.

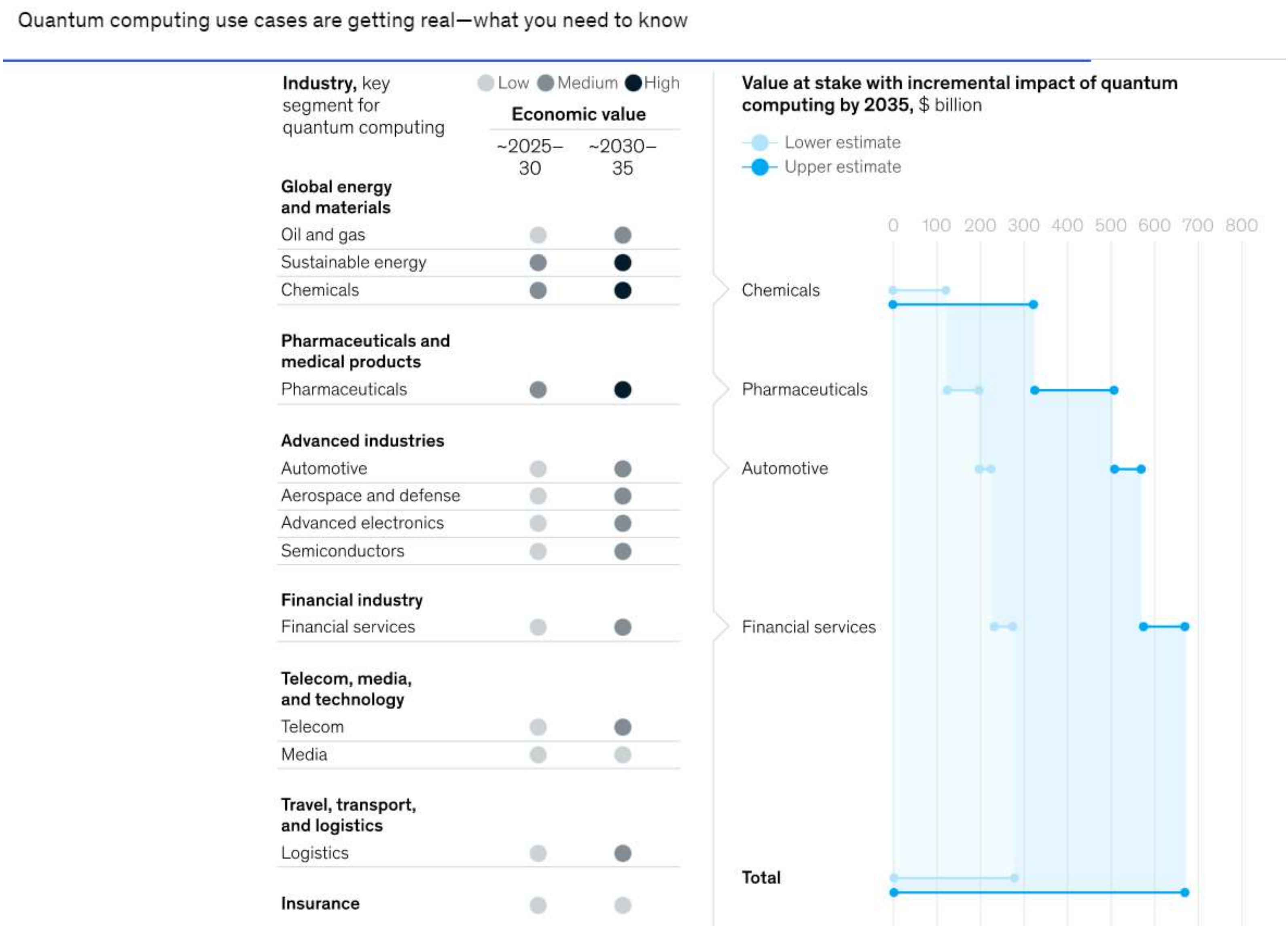
- Quantum computers store information in quantum states (superpositions and entanglement states)
- Qubits must be able to physically represent these quantum states.
- Quantum events only occur (and last) in the most severe circumstances.

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

Quantum computing

5 years	10 years	25 years
· Noisy Intermediate Scale quantum (NISQ) computing (50-100 qbits) · Special purpose quantum devices helping researchers (sensors, simulators, ...)	· **Quantum advantage for real problems**, the first fault tolerant scalable computer · Simulators of quantum dynamics · Quantum-driven discoveries and modelling (effective models for quantum effects in materials...)	· Large scale quantum computing - Universal quantum computers with a million qubits include error-correction techniques and can run any quantum software · Any encryption systems based on the current RSA technique can be cracked by Shor's algorithm · Catalysis (carbon, nitrogen fixation, clean energy, water) and chemical reaction mechanisms · Emergence of new quantum applications and quantum-inspired approaches, e.g.in machine learning · Access control on quantum computation desired instead of export control

- **One of the current challenges of Quantum Computing is identifying Use Cases**



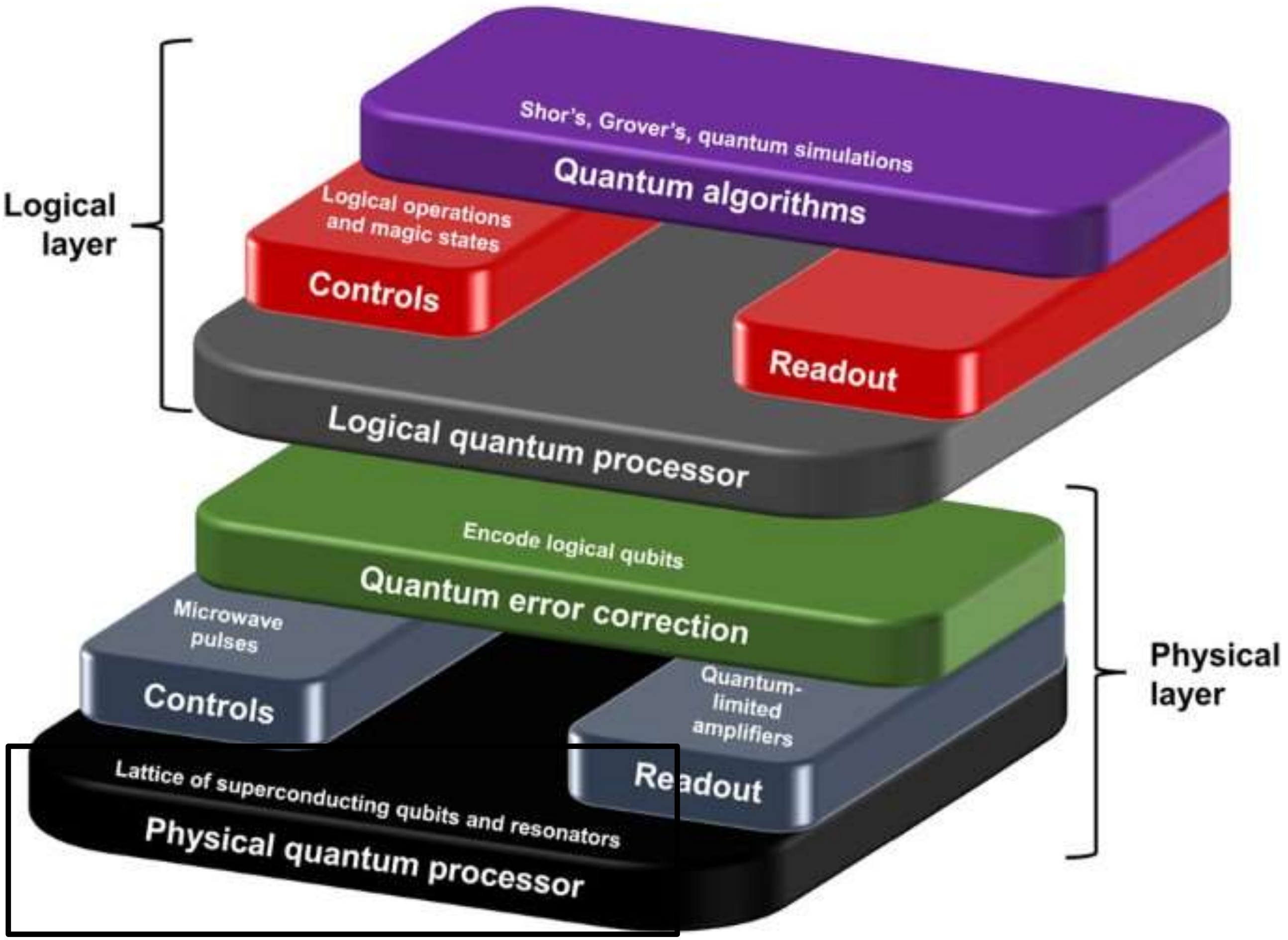
Quantum computing use cases are getting real—what you need to know

○ Low ◐ Medium ● High

Industry, key segment for quantum computing	Economic value ~2025–30	Economic value ~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	○	○

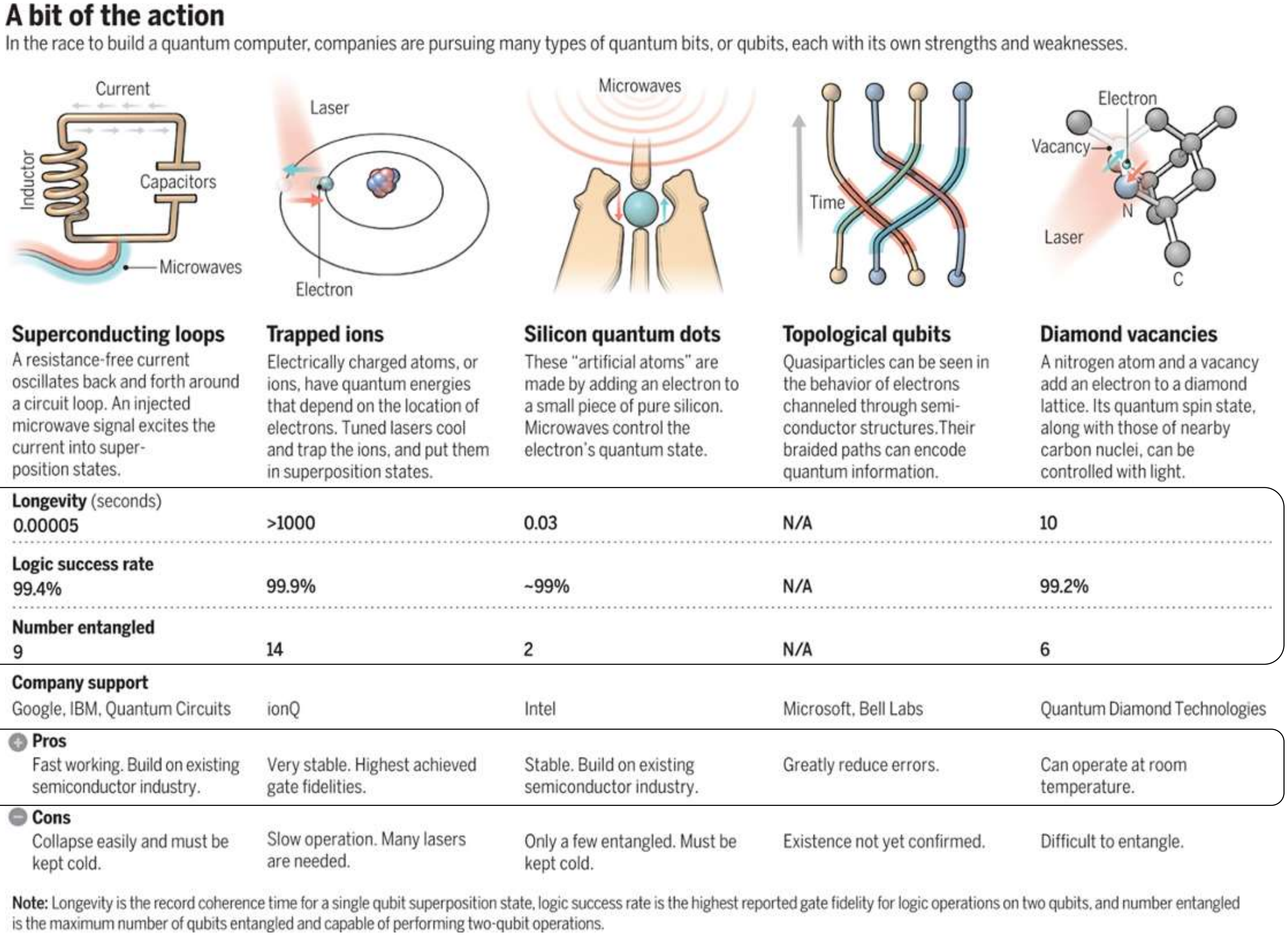
Value at stake with incremental impact of quantum computing by 2035, $ billion

Quantum Computer



- **Converging Quantum Physics, Materials Science, Micro/Nanotechnologies, …**

Quantum Devices



A bit of the action

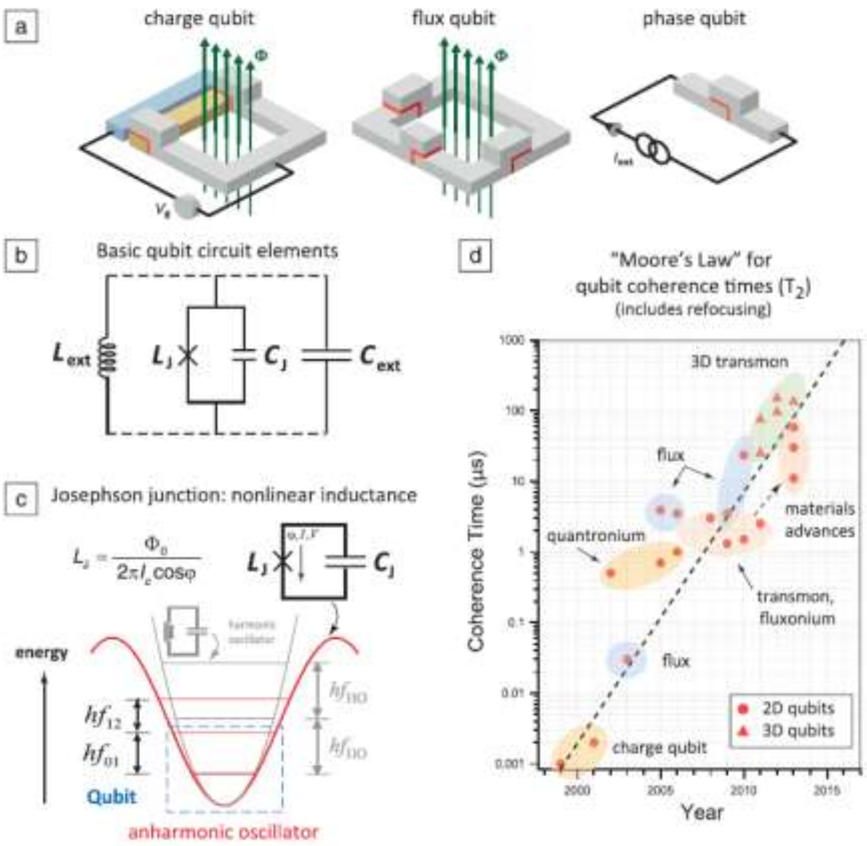
In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

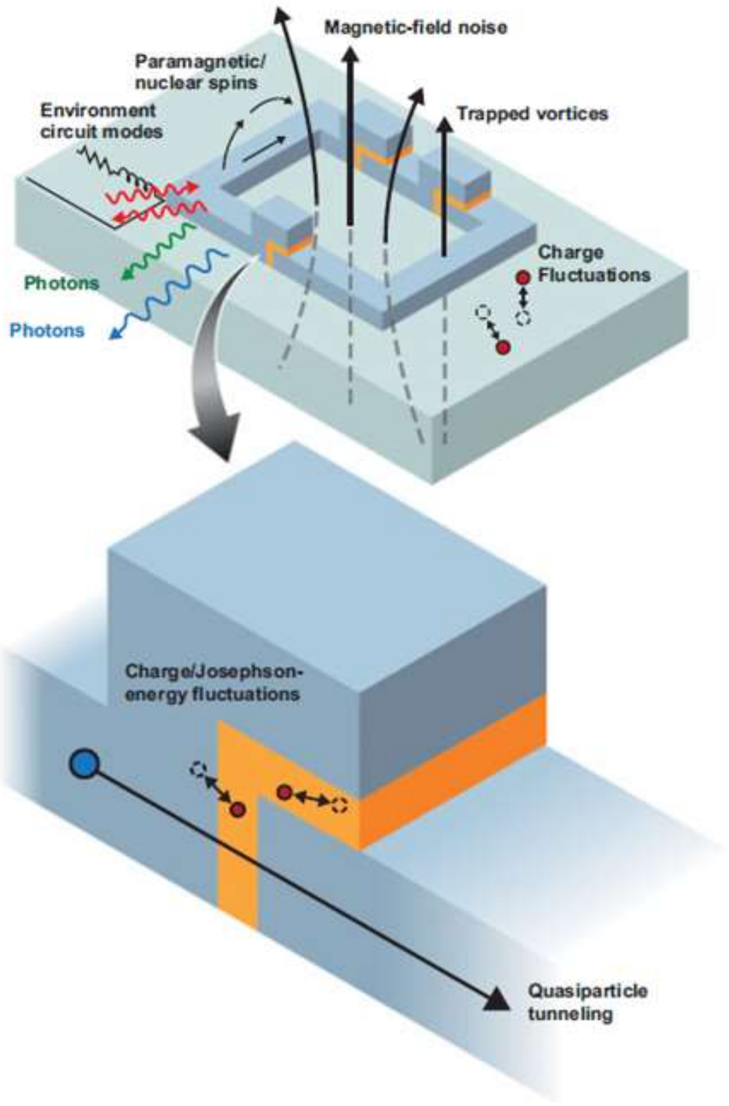
	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	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.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
⊕ **Pros**	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.
⊖ **Cons**	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.

G. Popkin. The Quest for Qubits **Science (2016)** https://www.science.org/doi/10.1126/science.354.6316.1090

Superconducting Qubits





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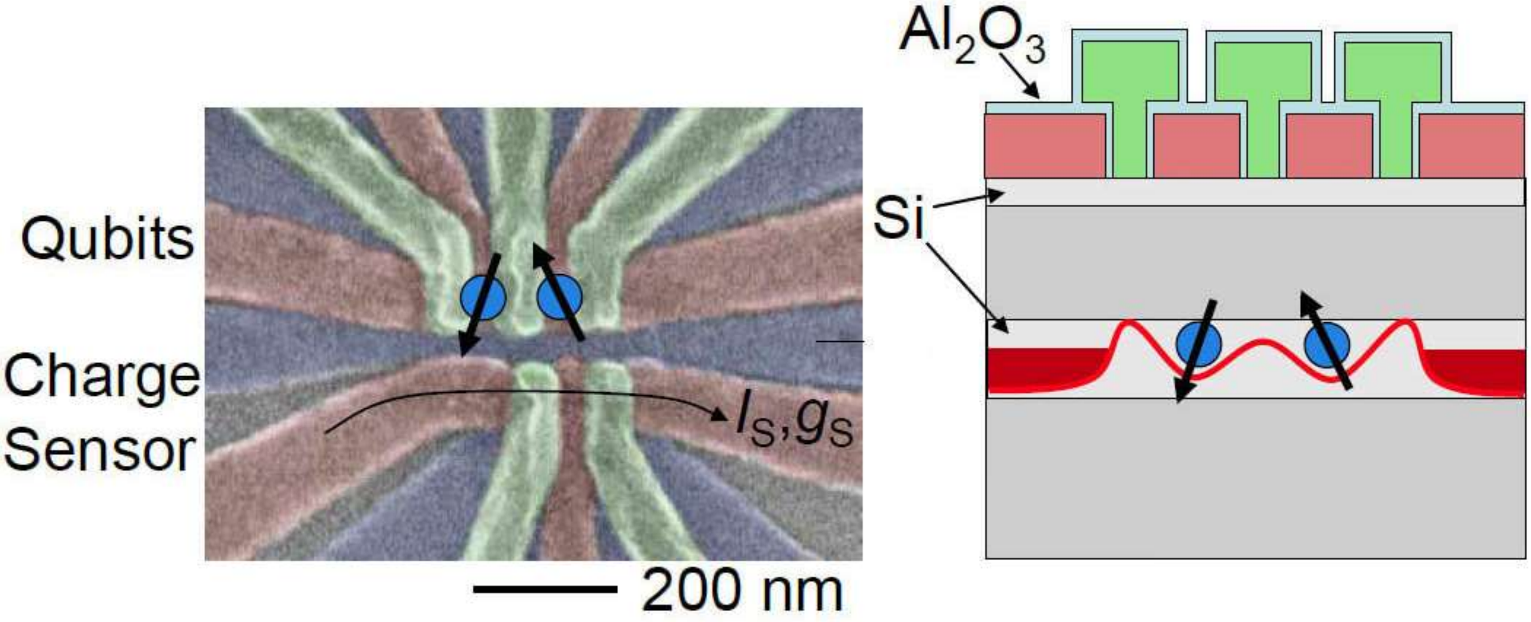
Silicon Qubits



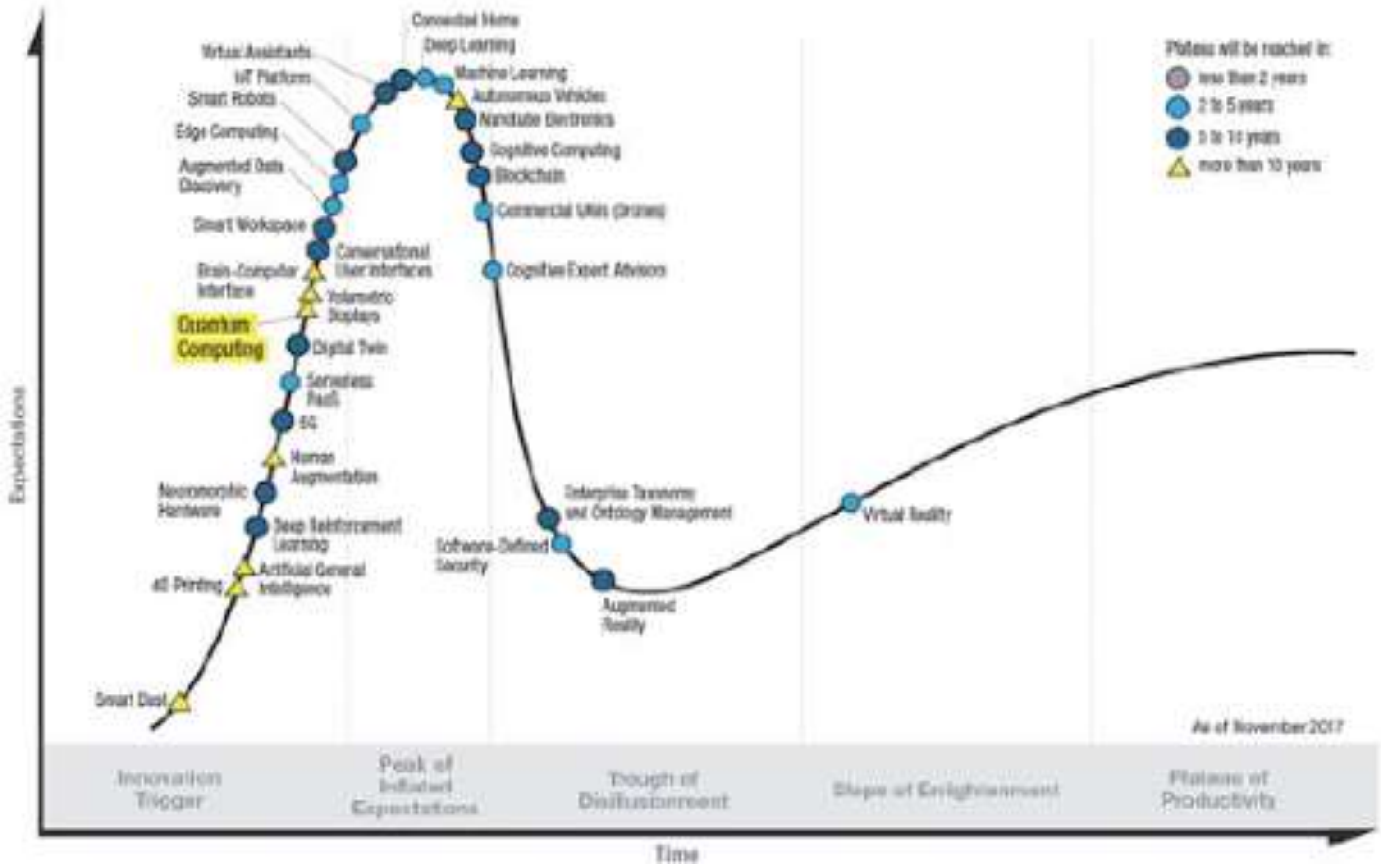
To construct the **two-qubit gate**, layered tiny Al wires onto a highly ordered silicon crystal are used. The wires deliver voltages that trap two single electrons, separated by an energy barrier, in a well-like structure called a **double quantum dot**.

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**

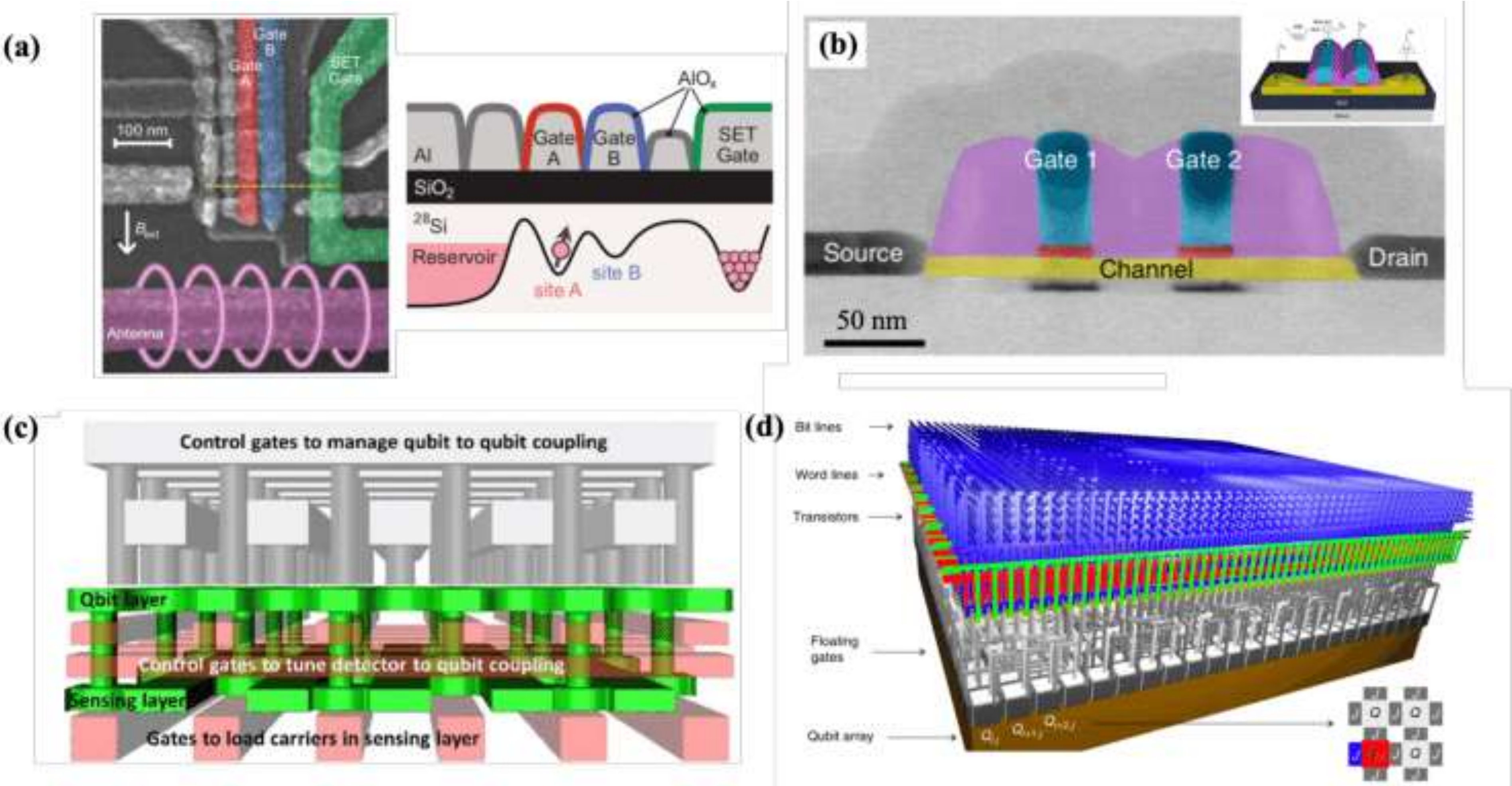
While a conventional bit can represent a 0 or a 1, each qubit can be simultaneously a 0 and a 1, now an exponential **number of possible permutations can be compared instantaneously**.

Quantum Computing Hype



Quantum computing has been classified as an emerging technology since 2005

Quantum Computing Hype



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**	Zapata Computing QC Ware 1QBit Riverlane Rigetti Computing (QxBranch) IBM Amazon Microsoft Multiverse Classiq Google
▨ D-Wave	▨ IBM	▨ CQC (Honeywell)	▨ Xanadu	▨ Pasqal	▨ IBM	
NEC*	▨ Rigetti Computing	▨ IonQ	PsiQuantum [a]	• Atom Computing [a] • Wuhan Institute of Physics and Mathematics (WIPM) of CAS	▨ Amazon	
	▨ Google	Alpine Quantum Technologies	Chinese Academy of Science (CAS) (Hefei National Laboratory for Physical Sciences at the Microscale [HFNL])		▨ Microsoft	
	• Amazon [a] • Fujitsu [a] • IQM [a] • QCI [a] • Oxford Quantum Circuits [a] • Qilimanjaro [a]	Oxford Ionics			• Atos • NVIDIA	
					Quantum Inspired Computing	
					▨ Fujitsu Digital Annealer	
					▨ Microsoft	

[a] Prototype/Embryonic Indigenous Quantum Computing Capability

Quantum Sensing

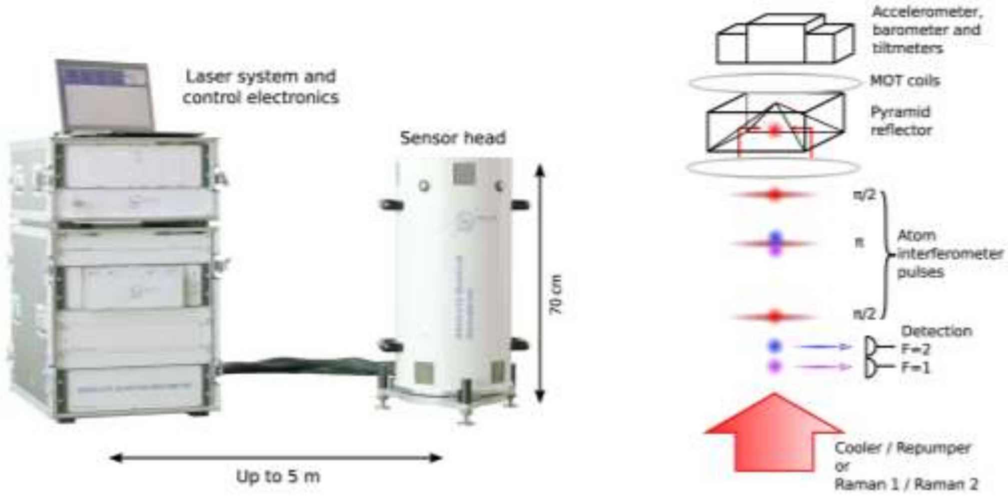
New modes of measurement, sensing, and imaging that offer unprecedented levels of precision, spatial and temporal resolution, stability, ultra-sensitivity...

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

- ✓ Time and frequency standards,
- ✓ Light-based calibration,
- ✓ Gravitometry,
- ✓ 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



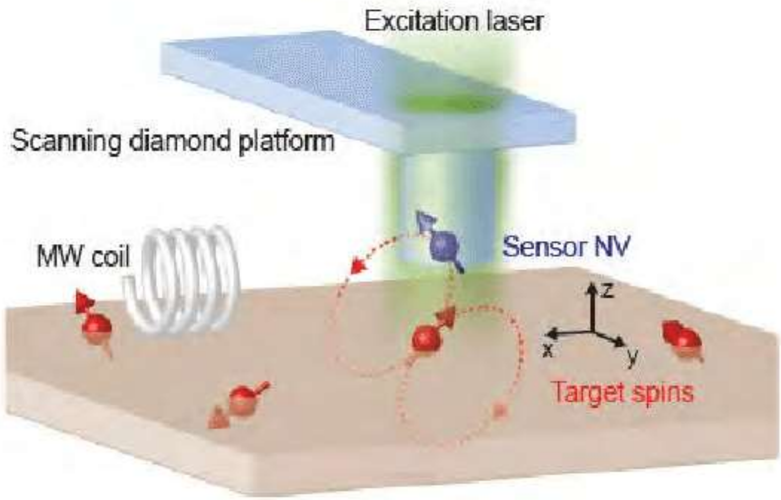
Portable system that measured the absolute gravitational acceleration continuously with a long-term stability below 10 nm.s^{-2}

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 Physic

“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 ≠ 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

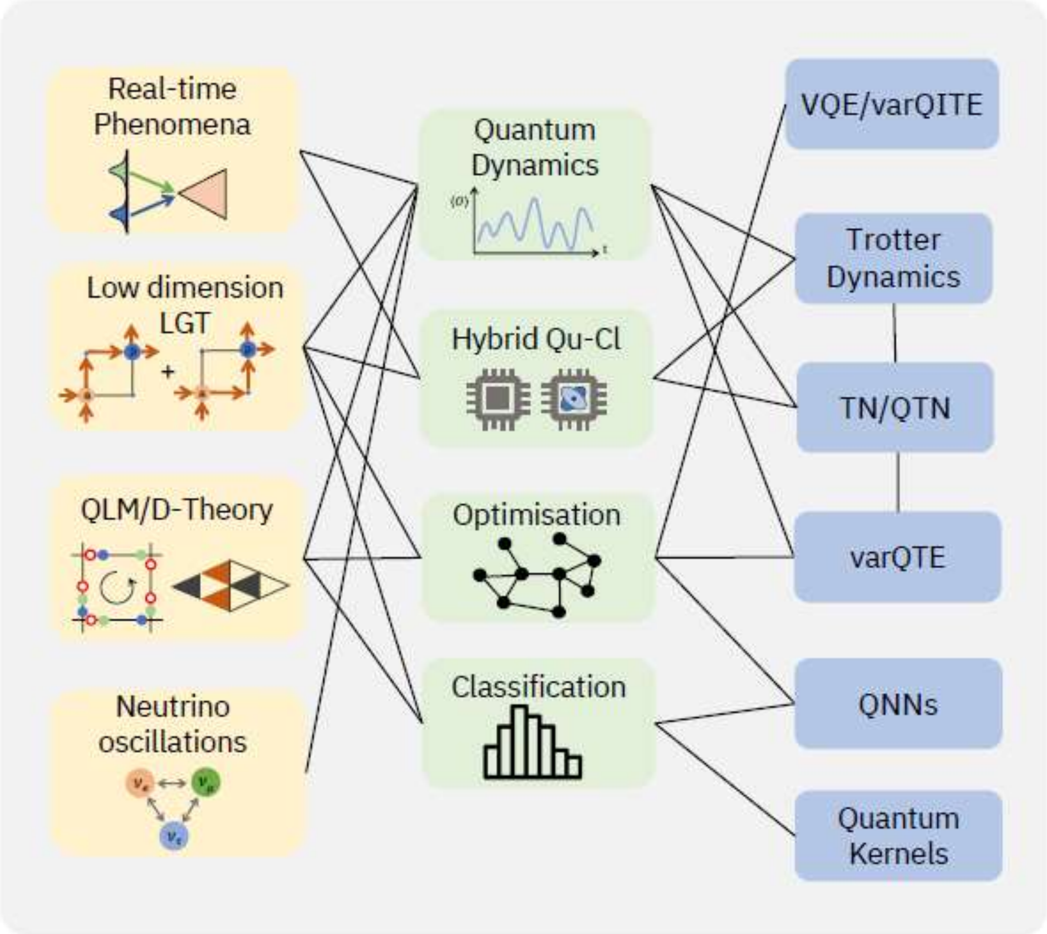
- ✓ **Both theoretical & experimental aspects of HEP**
- ✓ **Quantum Computing as game changer for HEP**

❖ **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



Theoretical Physical Problem

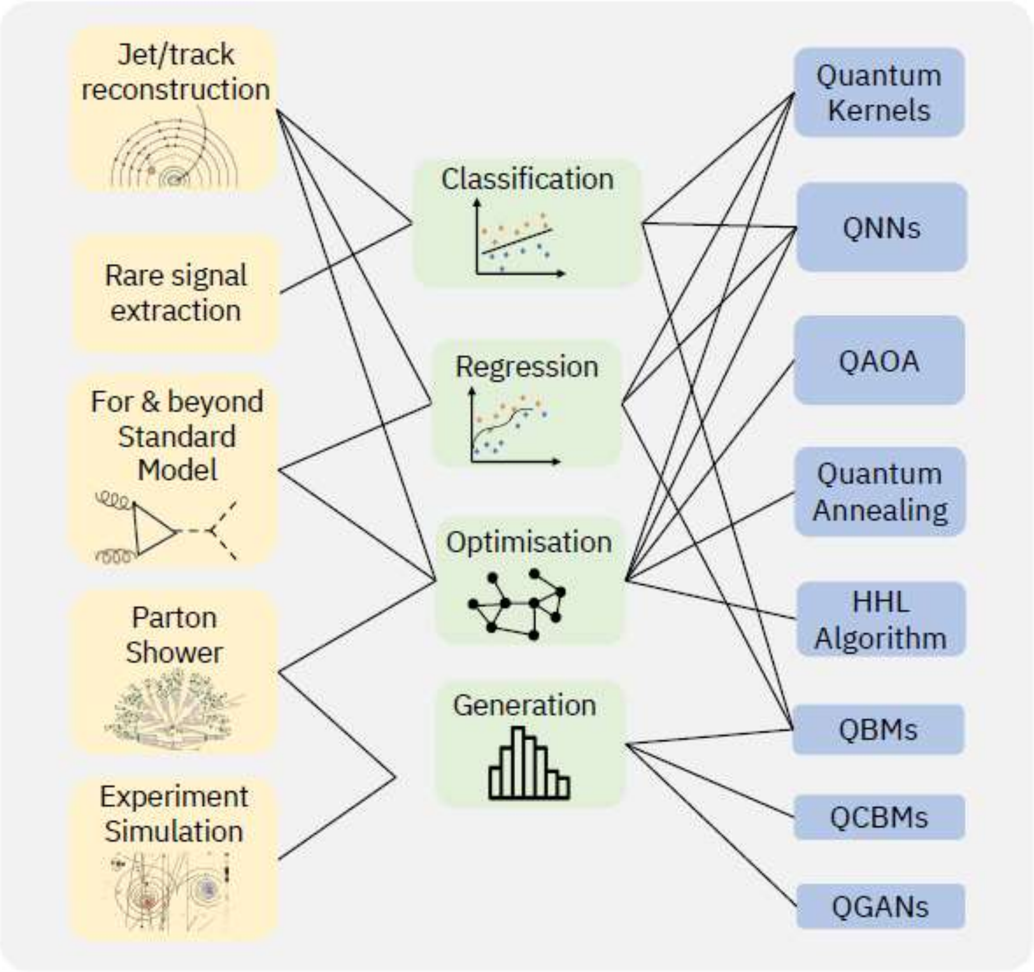
Computing Approach

Quantum Algorithm

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

2. Quantum Computing in HEP Experiments

Large amount of complex, highly-structured data



Experimental Challenges ***Analysis Approach*** ***Quantum Algorithm***

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

QC - HEP

HEP

Fundamental behavior of Particles & Interactions

Described by Quantum Fields

Dynamics by Quantum Mechanics Principles

Data and descriptions, still Classical

Hindering Quantum Mechanical properties

Gain Fundamental Insights and New Phenomena

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 extremelly 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

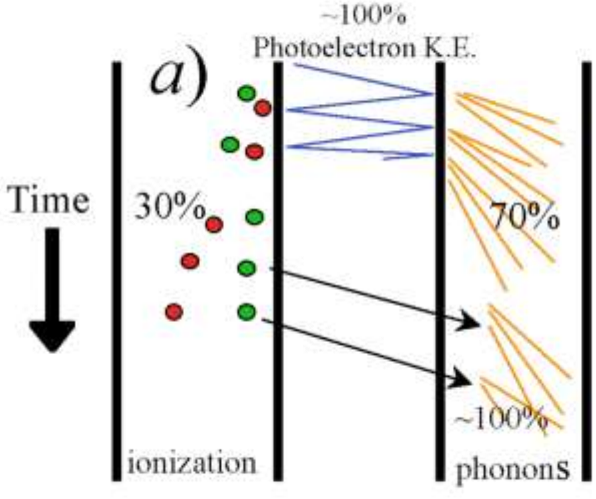
Thermal detection of radiation, or more general the calorimetric detection of energetic particles, is old strategy within physics.

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

$$\Delta U = Q - W$$

ΔU = change in internal energy
Q = heat added
W = work done by the system

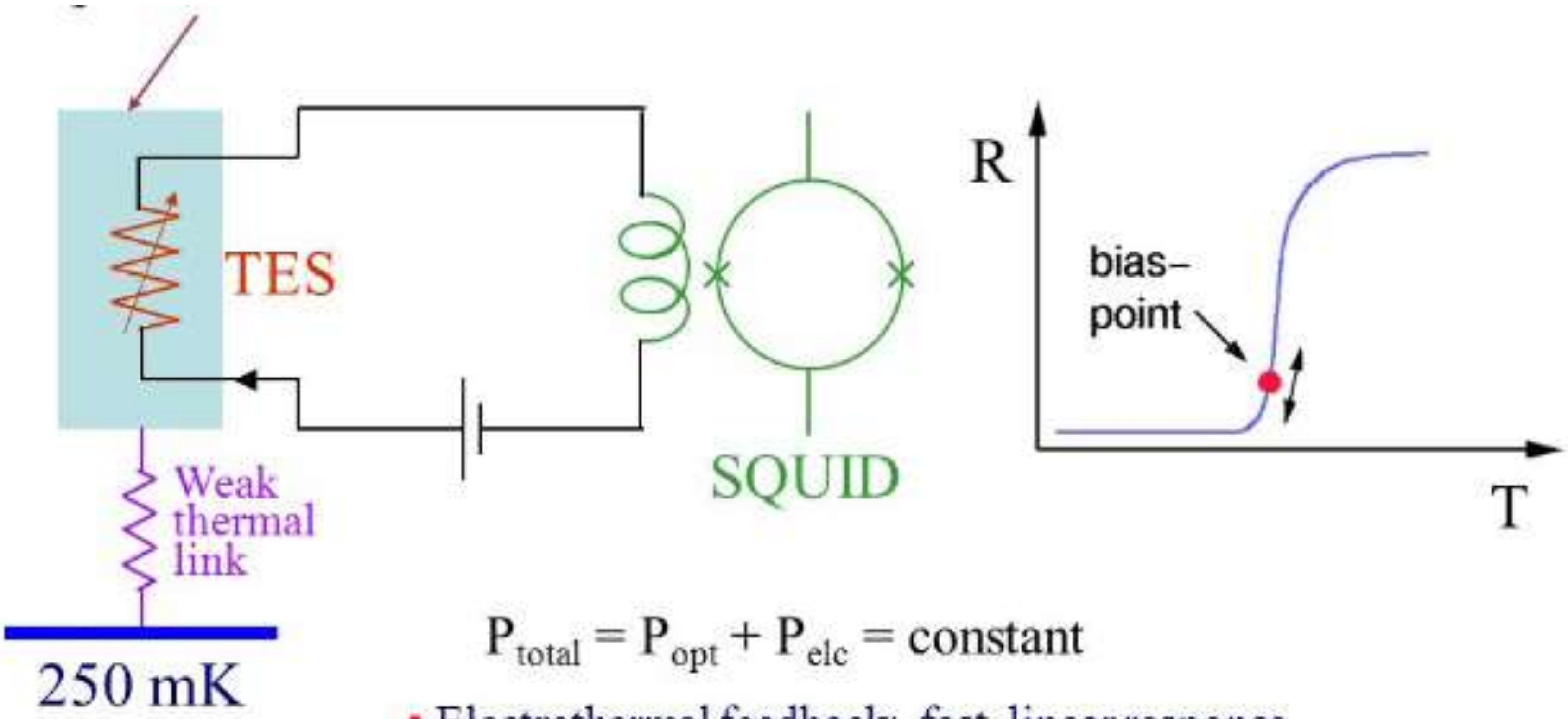
Already in 1984, **novel low temperature particle detectors** were proposed for several applications in nuclear physics, astronomy, and astrophysics.
… and continue to be investigated nowadays



- ❖ 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



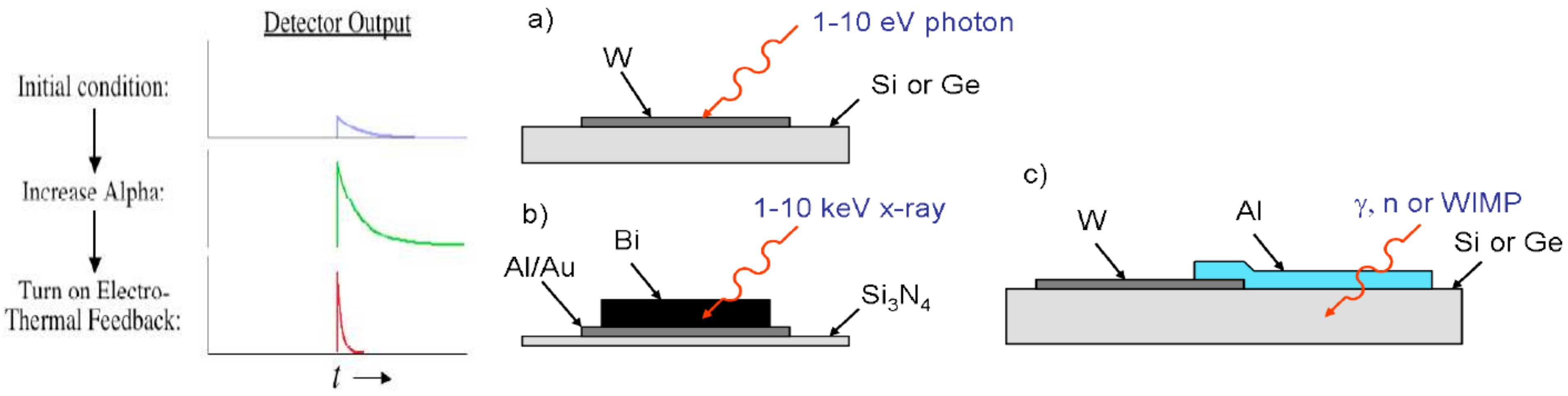
$$P_{\text{total}} = P_{\text{opt}} + P_{\text{elc}} = \text{constant}$$

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

Superconducting Sensors for Rare Events

❖ Transition Edge Sensors

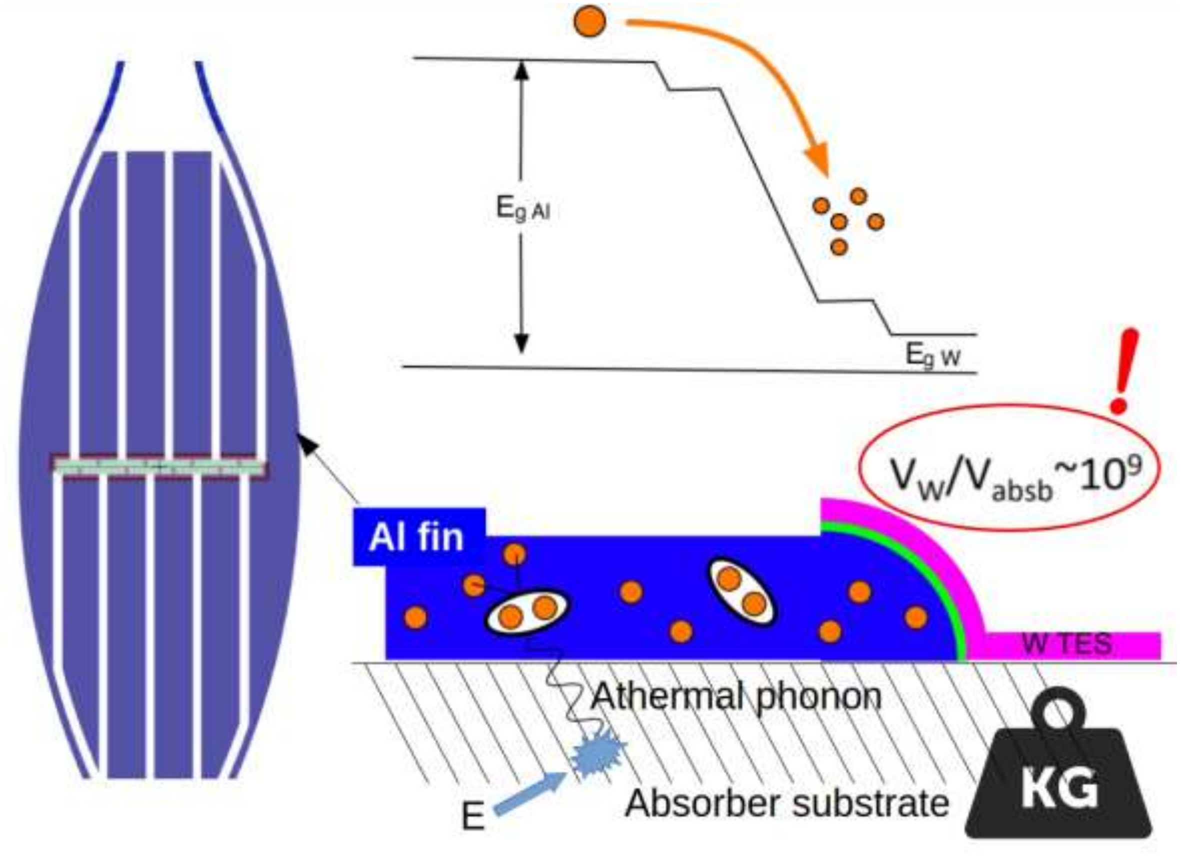
Several different advances, types or designs of TES detectors have been developed,



(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 Si3N4 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

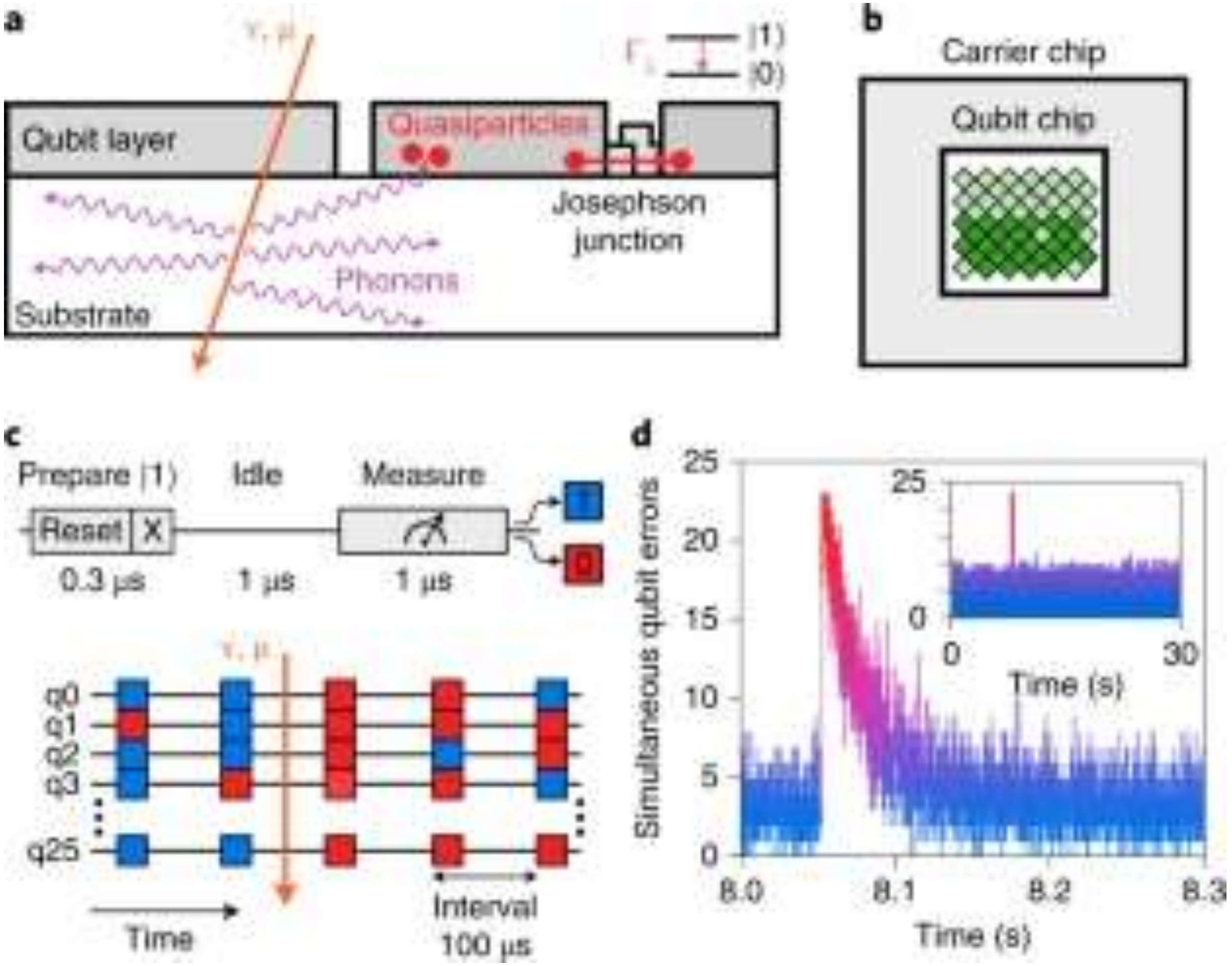
Cooper pairs are sensitive / absorb phonons and break them. Generate quasiparticles*

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

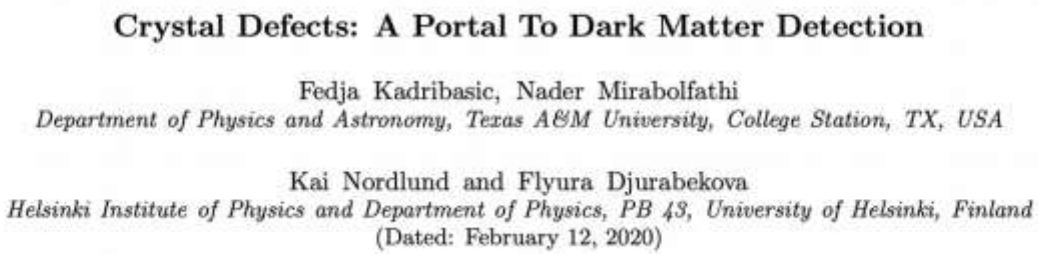
Superconducting Sensors for Rare Events

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



Superconducting Sensors for Rare Events

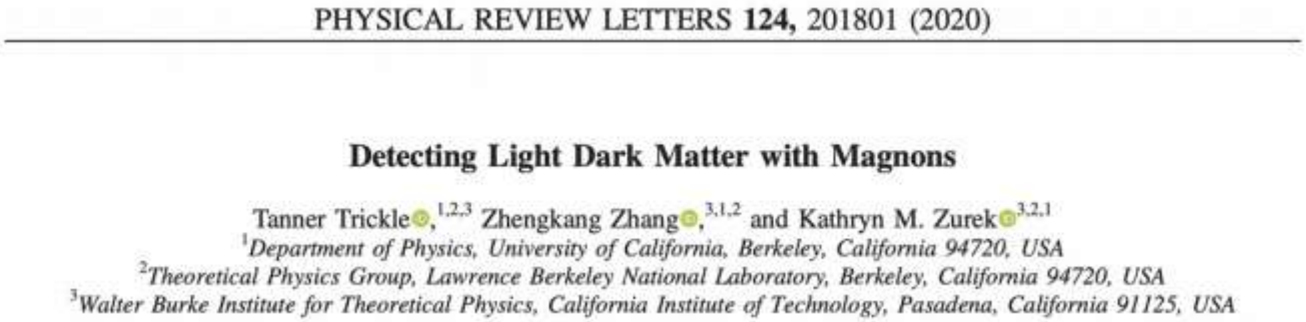
TES detectors are dissipative devices.
- Not possible to enhance measurements with coherence strategies



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,[1,2,3] Zhengkang Zhang,[3,1,2] and Kathryn M. Zurek[3,2,1]
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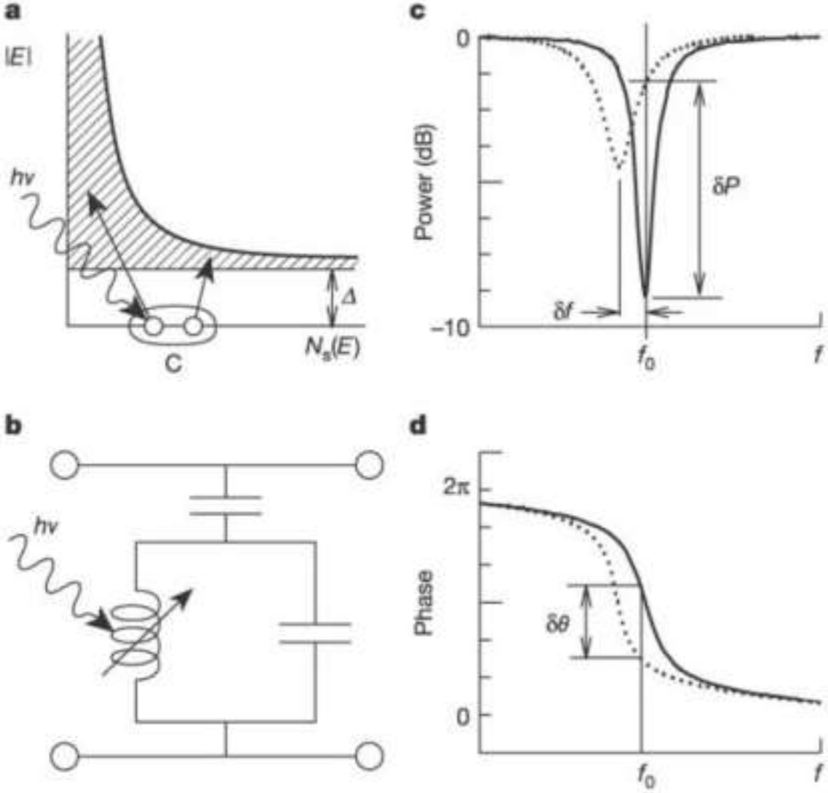
Non dispersive detectors include,
- Opto-mechanical resonators as phonon detectors (resonant)
- He quantum evaporation and detection with spin system (spin-spin coupling)
- Microwave kinetic inductance detectors (MKIDs) (dispersive)
- Superconducting Nanowire Single Photon Detectors

Superconducting Sensors for Rare Events

❖ Microwave kinetic inductance detectors



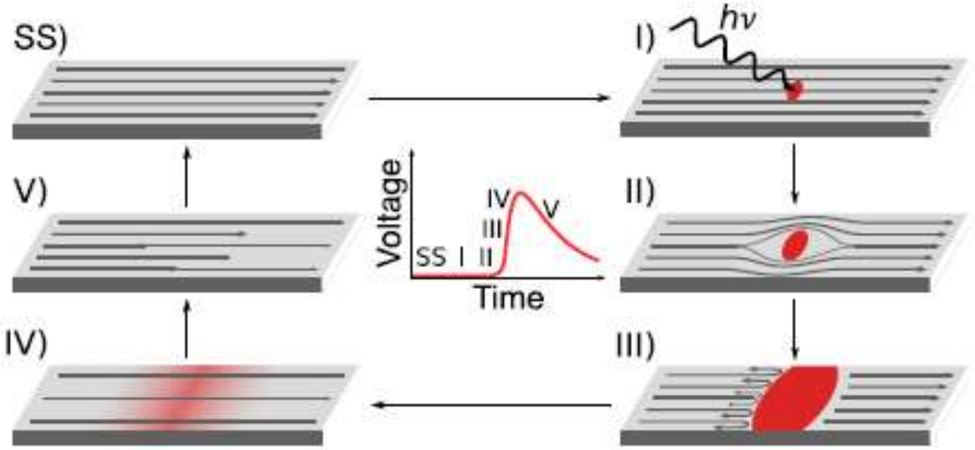
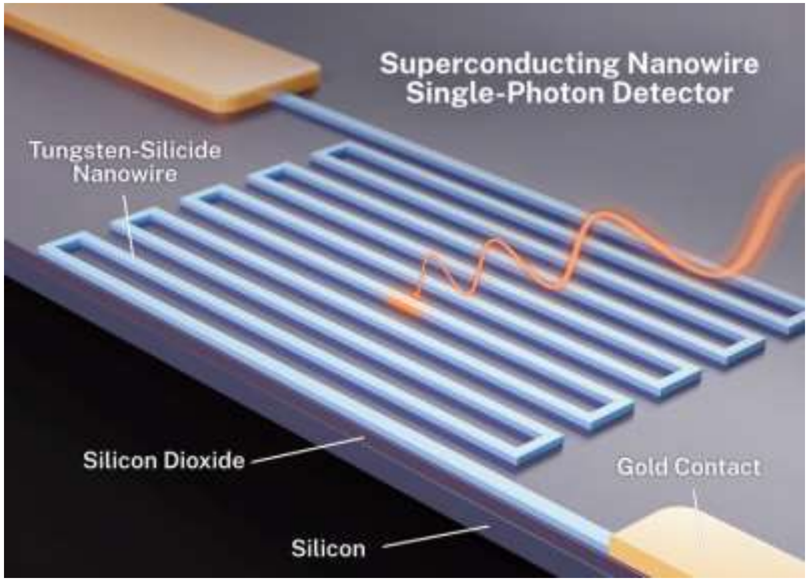
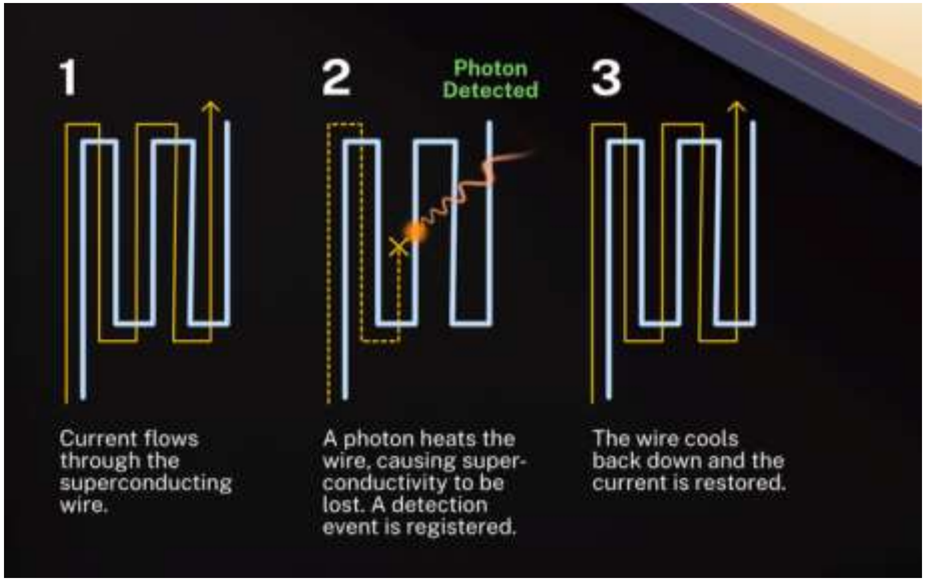


FIG. 1. Macroscopic explanation of the detection mechanism (based on Refs. 22, 78, and 89). In the steady state (SS), the superconducting thin-film strip is current biased. Photon absorption (I) leads to the creation of quasi-particles and phonons (II). This leads to the formation of a normal-conducting 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.[91]

Superconducting Sensors for Rare Events

❖ Superconducting Nanowire Single Photon Detectors





1. Current flows through the superconducting wire.
2. A photon heats the wire, causing superconductivity to be lost. A detection event is registered.
3. The wire cools back down and the current is restored.

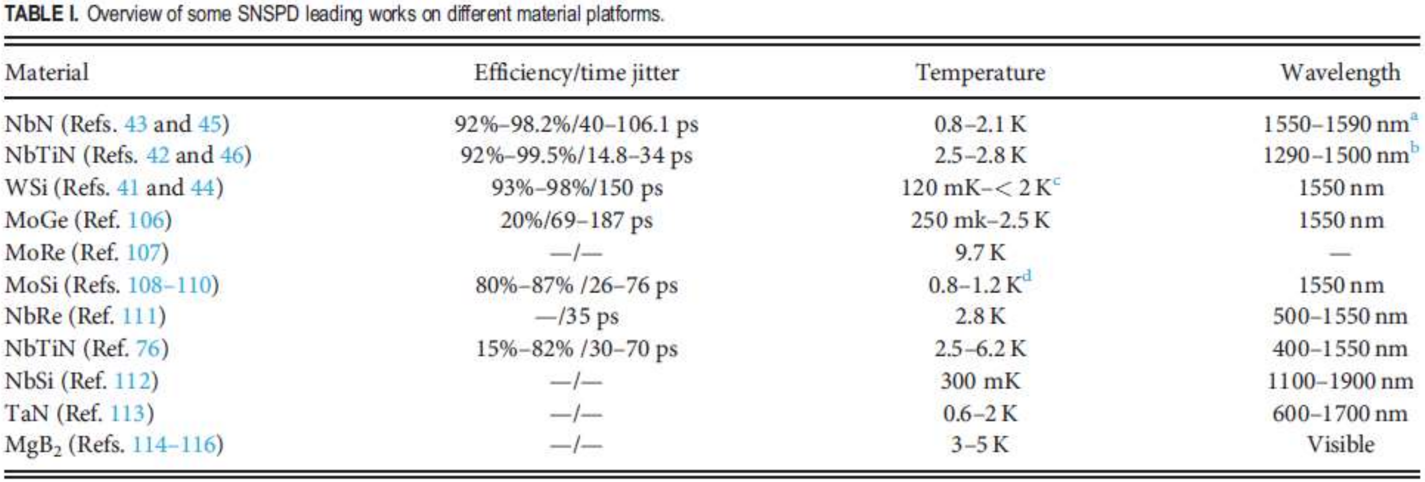
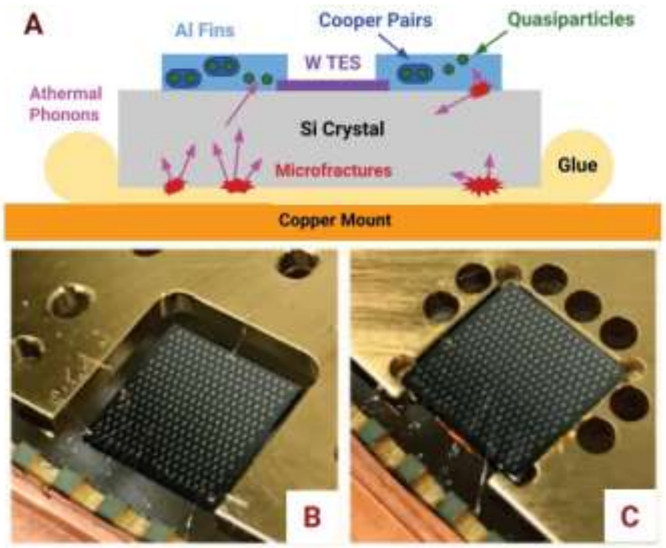


TABLE I. Overview of some SNSPD leading works on different material platforms.

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[a]
NbTiN (Refs. 42 and 46)	92%–99.5%/14.8–34 ps	2.5–2.8 K	1290–1500 nm[b]
WSi (Refs. 41 and 44)	93%–98%/150 ps	120 mK–< 2 K[c]	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[d]	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_2 (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**

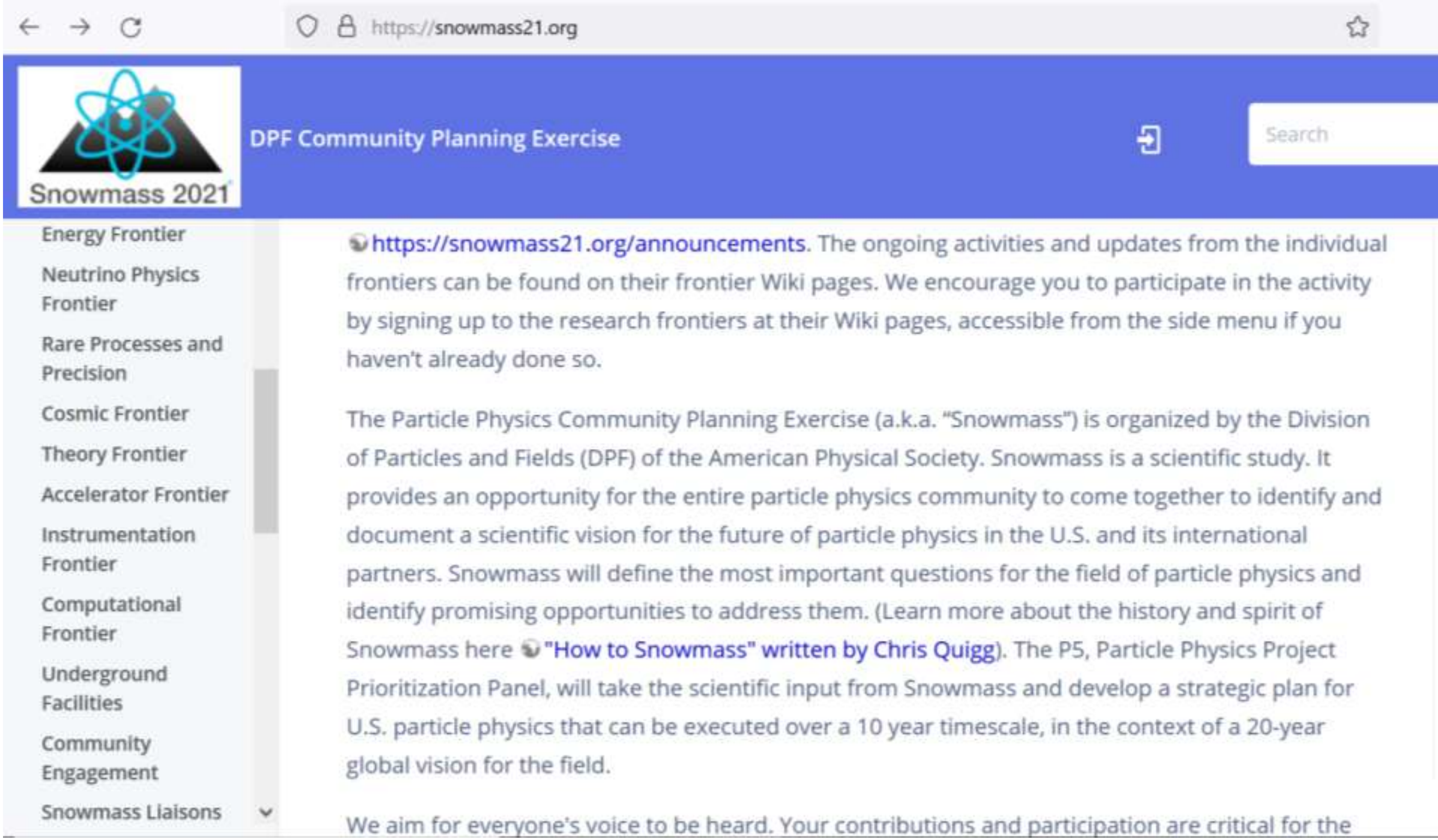
E.g. Correlation of DM in QET direct detection with phononic generation, difusion, in target

- **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 radiactive sources, to qualify manufactured devices for the application of interest

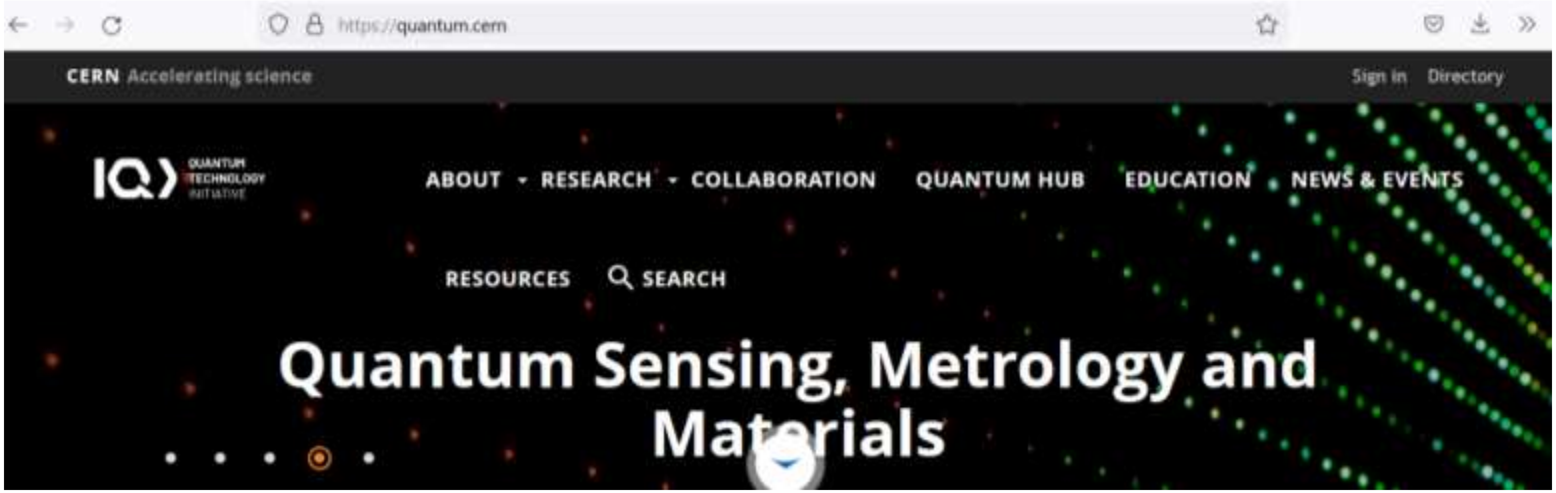


https://snowmass21.org/announcements. The ongoing activities and updates from the individual frontiers can be found on their frontier Wiki pages. We encourage you to participate in the activity by signing up to the research frontiers at their Wiki pages, accessible from the side menu if you haven't already done so.

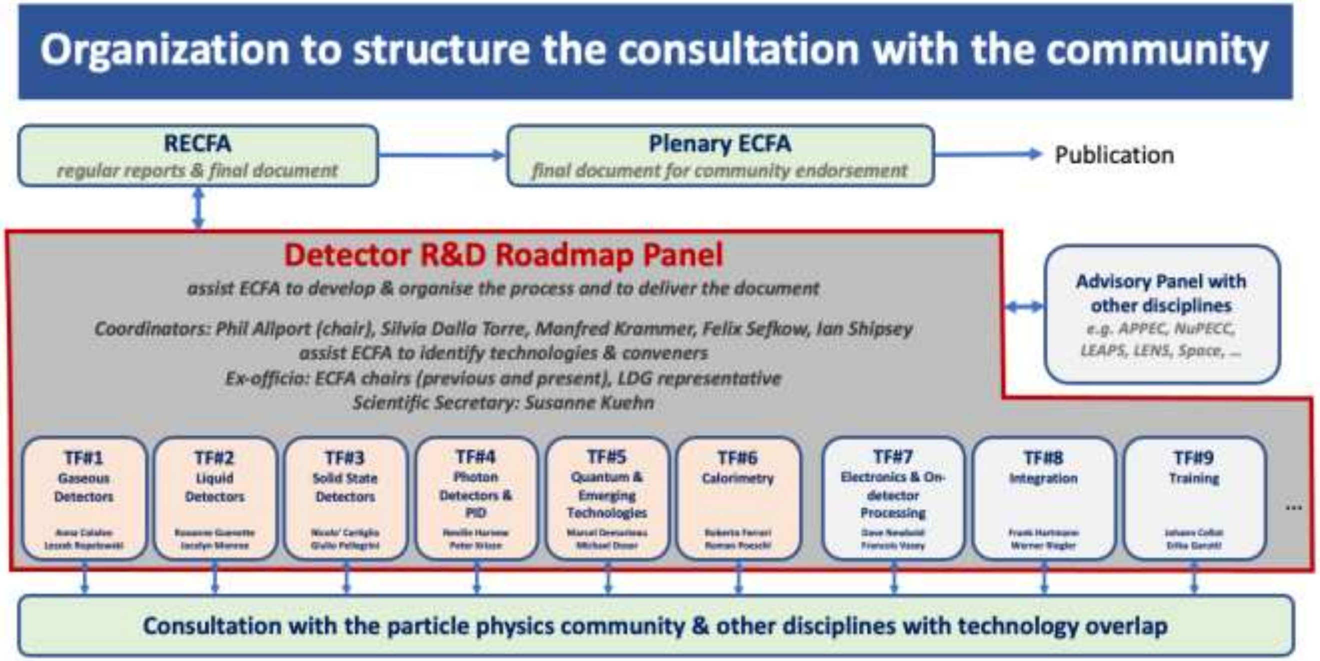
The Particle Physics Community Planning Exercise (a.k.a. "Snowmass") is organized by the Division of Particles and Fields (DPF) of the American Physical Society. Snowmass is a scientific study. It provides an opportunity for the entire particle physics community to come together to identify and document a scientific vision for the future of particle physics in the U.S. and its international partners. Snowmass will define the most important questions for the field of particle physics and identify promising opportunities to address them. (Learn more about the history and spirit of Snowmass here "How to Snowmass" written by Chris Quigg). The P5, Particle Physics Project Prioritization Panel, will take the scientific input from Snowmass and develop a strategic plan for U.S. particle physics that can be executed over a 10 year timescale, in the context of a 20-year global vision for the field.

We aim for everyone's voice to be heard. Your contributions and participation are critical for the

International Initiatives



Quantum Sensing, Metrology and Materials



Organization to structure the consultation with the community

RECFA
regular reports & final document

Plenary ECFA
final document for community endorsement

Publication

Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document

Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chairs (previous and present), LDG representative
Scientific Secretary: Susanne Kuehn

Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, Space, …

- **TF#1** Gaseous Detectors — Anna Colaleo, Leszek Ropelewski
- **TF#2** Liquid Detectors — Roxanne Guenette, Jocelyn Monroe
- **TF#3** Solid State Detectors — Nicolo' Cartiglia, Giulio Pellegrini
- **TF#4** Photon Detectors & PID — Neville Harnew, Peter Krizan
- **TF#5** Quantum & Emerging Technologies — Marcel Demarteau, Michael Doser
- **TF#6** Calorimetry — Roberto Ferrari, Roman Poeschl
- **TF#7** Electronics & On-detector Processing — Dave Newbold, Francois Vasey
- **TF#8** Integration — Frank Hartmann, Werner Riegler
- **TF#9** Training — Johann Collot, Erika Garutti

…

Consultation with the particle physics community & other disciplines with technology overlap

International Initiatives

THE EUROPEAN SPACE AGENCY

esa

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

esa

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?

gemma.rius@csic.es

“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.

Some links to References and Further Reading

www.imb-cnm.csic.es/index.php/en

[quant-ph/0206091] Quantum Technology: The Second Quantum Revolution (arxiv.org)

Quantum computation: Algorithms and Applications - ScienceDirect

Richard P. Feynman Quotes About Quantum Mechanics | A-Z Quotes (azquotes.com)

Nanotechnology: There's Plenty of Room at the Bottom – Richard Feynman

https://www.nano.gov/about-nanotechnology

https://www.cell.com/iscience/fulltext/S2589-0042(22)01432-8

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

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https://nvlpubs.nist.gov/nistpubs/CHIPS/NIST.CHIPS.1000.pdf

NATO Review - Quantum technologies in defence & security

https://www.redbubble.com/i/poster/5-ways-you-use-quantum-technology-every-day-by-DominicWalliman/27438063.LVTDI

https://roughlydaily.com/2022/06/07/if-you-are-confused-by-the-underlying-principles-of-quantum-technology-you-get-it/

National Quantum Initiative

Quantum Information Science (QIS... | U.S. DOE Office of Science(SC) (osti.gov)

Quantum Information Science | Data Science at NIH

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https://physicsworld.com/a/fast-quantum-random-number-generator-fits-on-a-fingertip/

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https://www.nature.com/articles/s41598-018-30608-1

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