FROM RESEARCH TO INDUSTRY

Quantum Computing

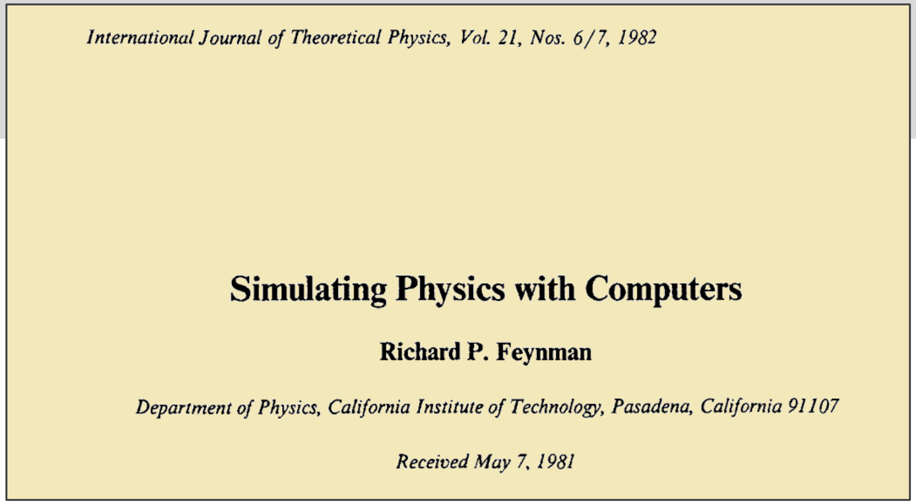
May 5th 2022, Madrid

Philippe Chomaz

Scientific and Program Director of CEA Basic Research

With the help of Florent Staley

Quantum computing

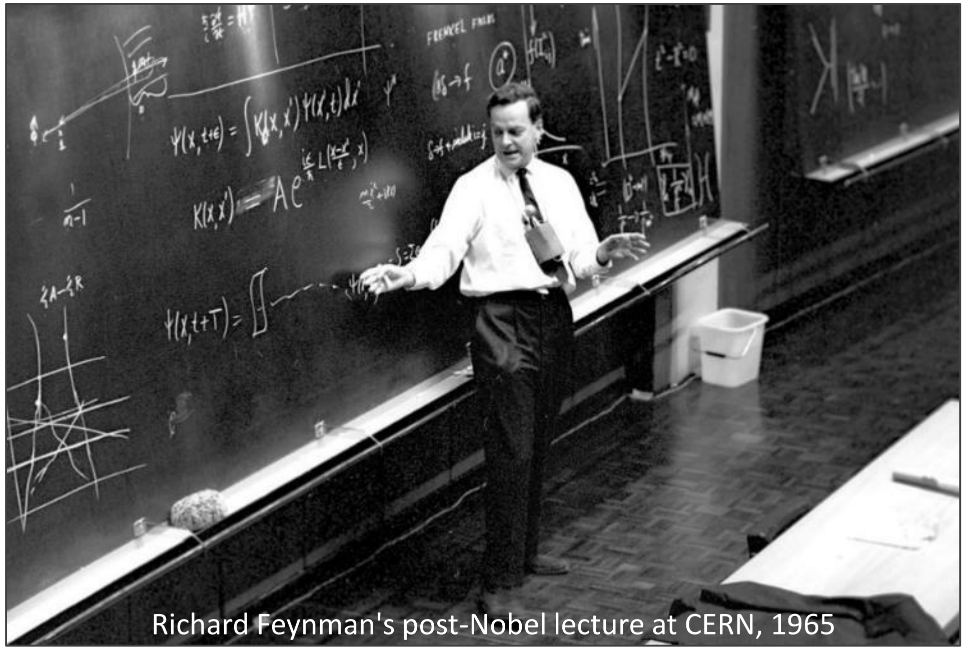

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

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

Received May 7, 1981


Richard Feynman's post-Nobel lecture at CERN, 1965

"Nature isn't classical, dammit !
if you want to make a simulation of Nature,
you'd better make it quantum mechanical"

Richard Feynman at the conference on "*simulating physics with computer*" on May 1981

Quantum Computing is the use of quantum-mechanical phenomena such as superposition and entanglement to perform computation of a new kind.

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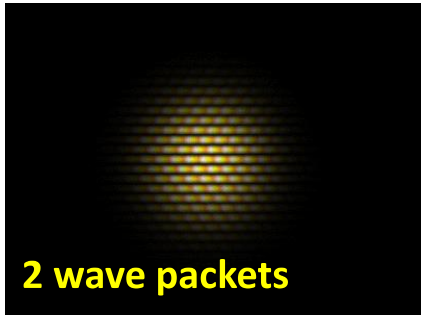
Quantum 1.0 and the Digital Revolution

Quantum Revolutions

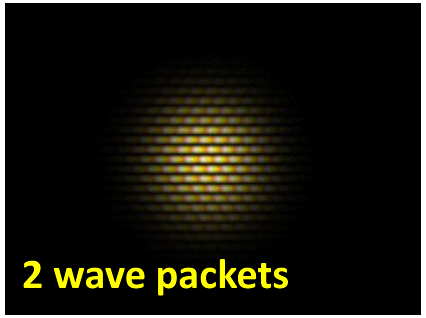
Quantum Revolutions

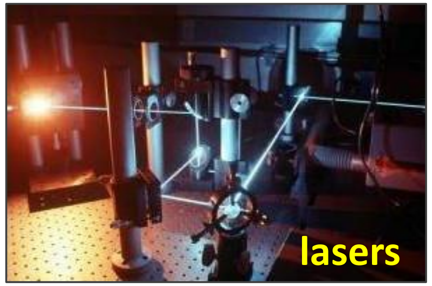


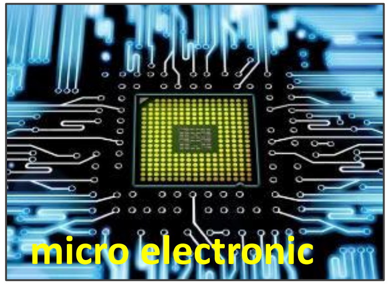
“Invention” of quantum mechanics:

Matter, light and interactions composed of **particles** governed by a **wave** mechanics.

Quantum Revolutions







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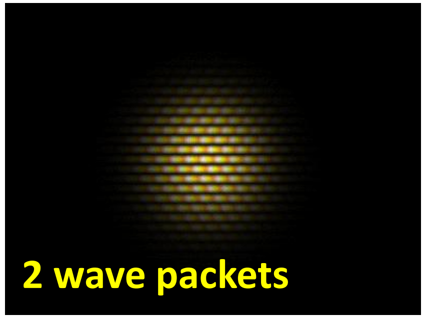
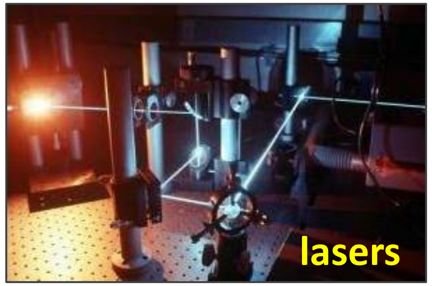
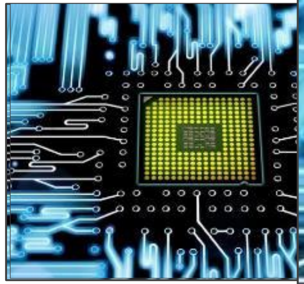
Quantum 1.0 and the digital revolution:

Macroscopic quantum systems of **bosons** or **fermions** with **quantized energies** have revolutionized **information technology**: computing, sensing, communication.

Quantum Revolutions







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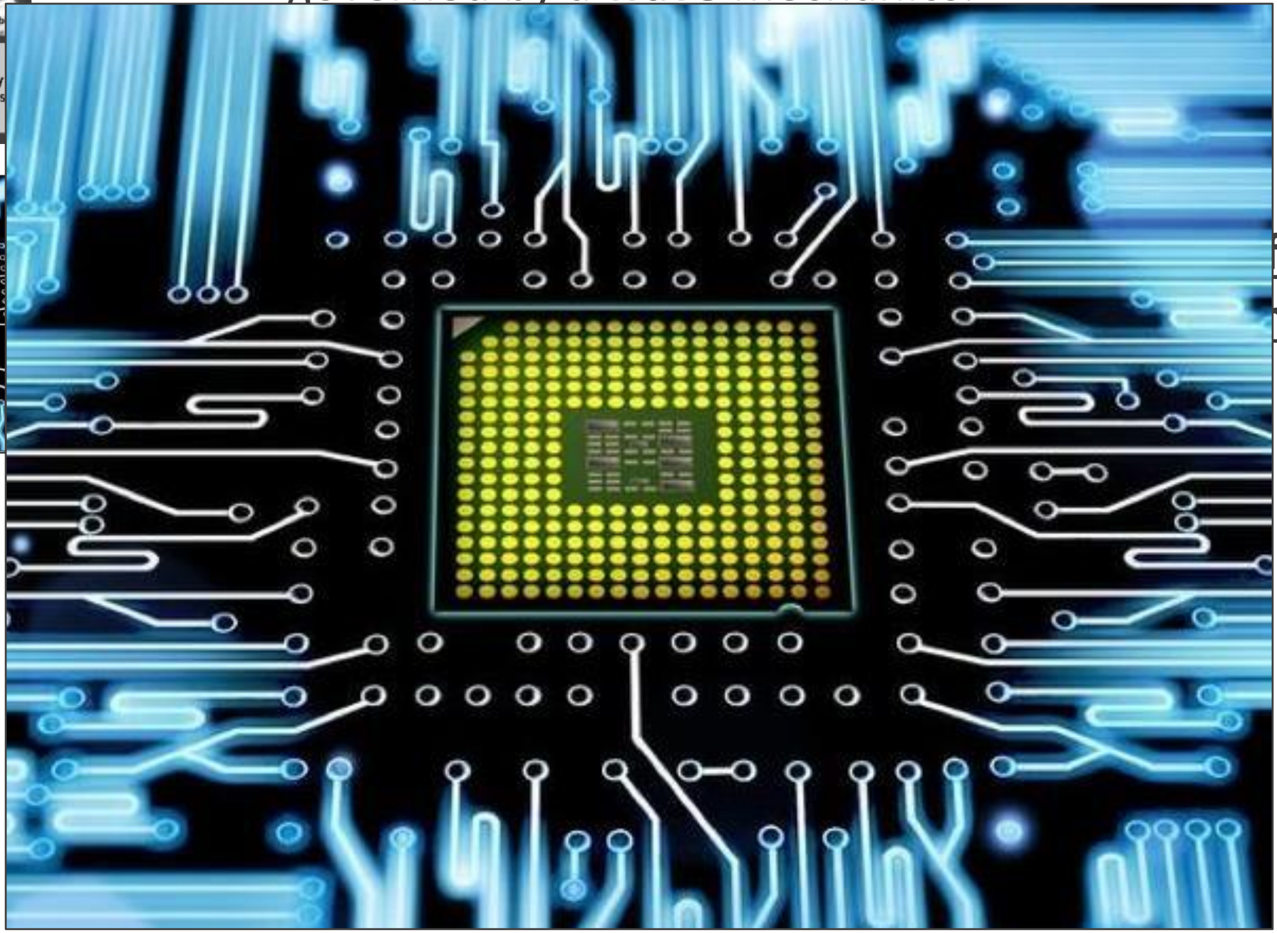
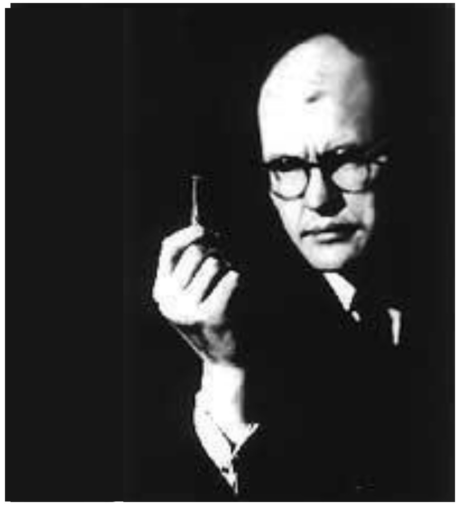


fermions with

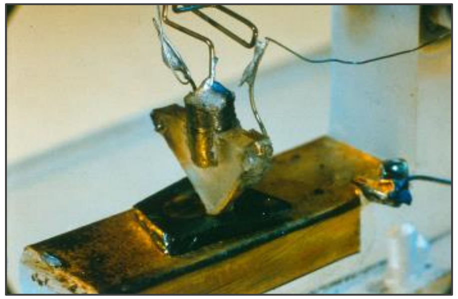
mation technology:

Quantum 1.0: Revolution of information treatment

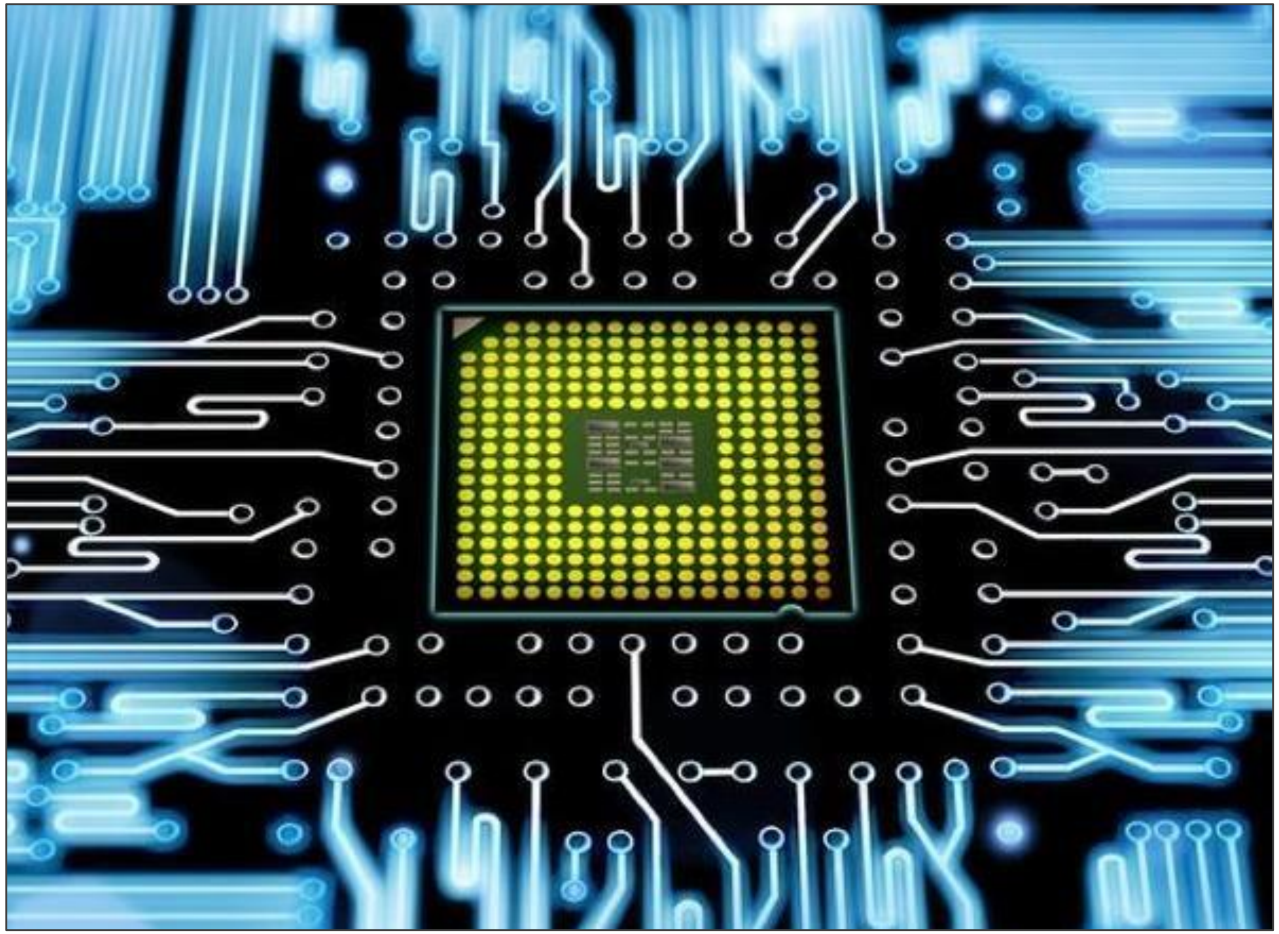
- Electronic et photonic
- the revolution in information and communication technologies



1959 Jack S. Kilby handling the first integrated circuit

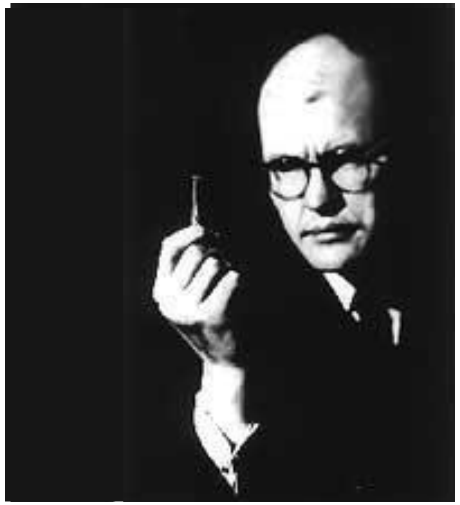


1947 First Transistor at Bell Laboratories



Quantum 1.0: Revolution of information treatment

Classical computers



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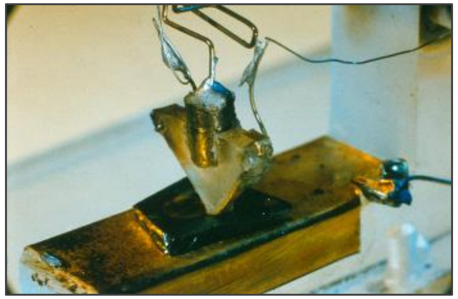

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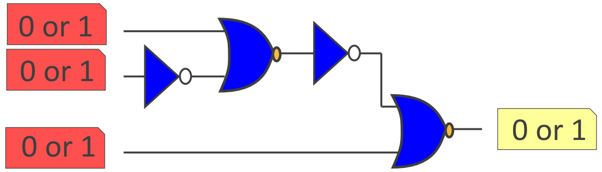
Elementary information:

Bit: 0 or 1

Processed with logic gates (transistors)

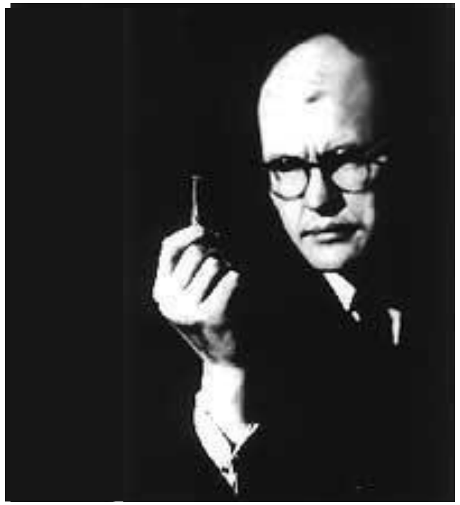


NOT and a single 2 bit gate (as **XOR**) are enough => **Universal Turing Machine**

Quantum 1.0: Revolution of information treatment

Classical computers

Are reaching the limit of one atom per bit



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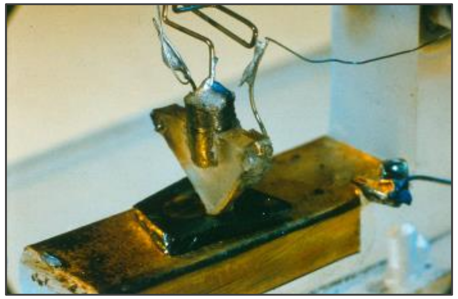

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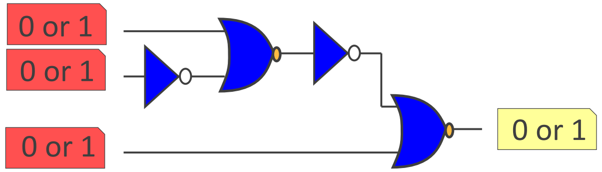

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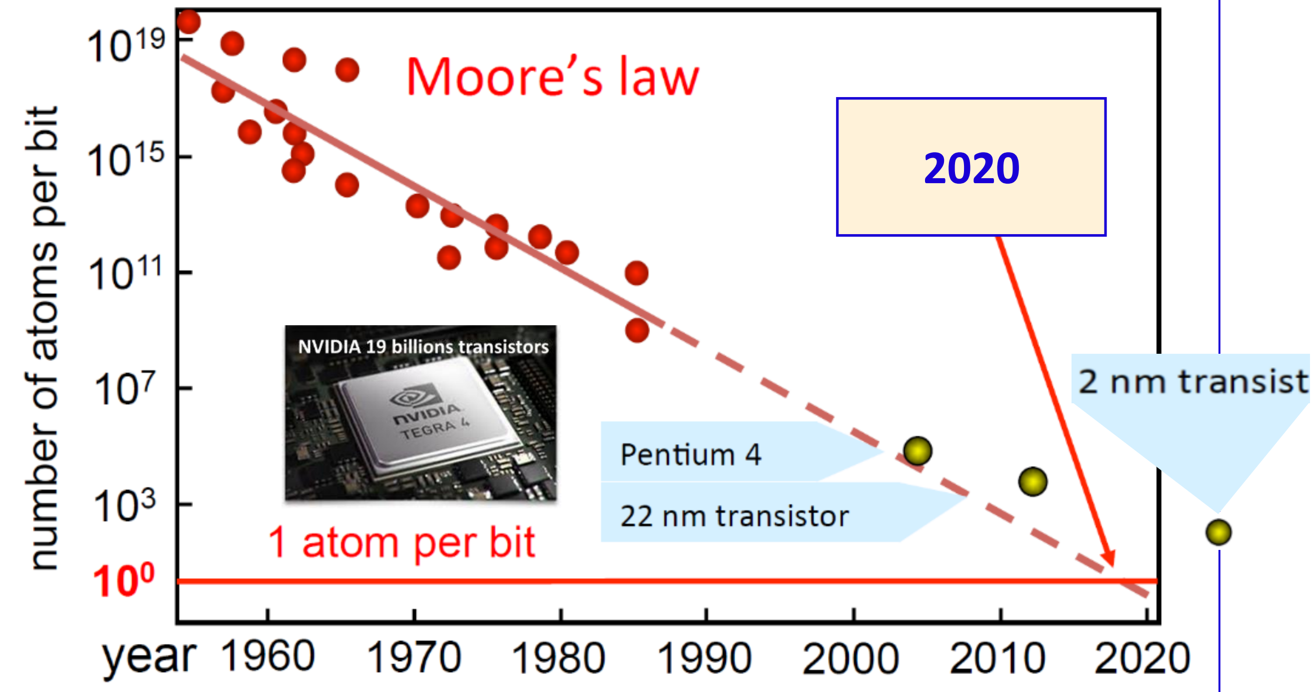
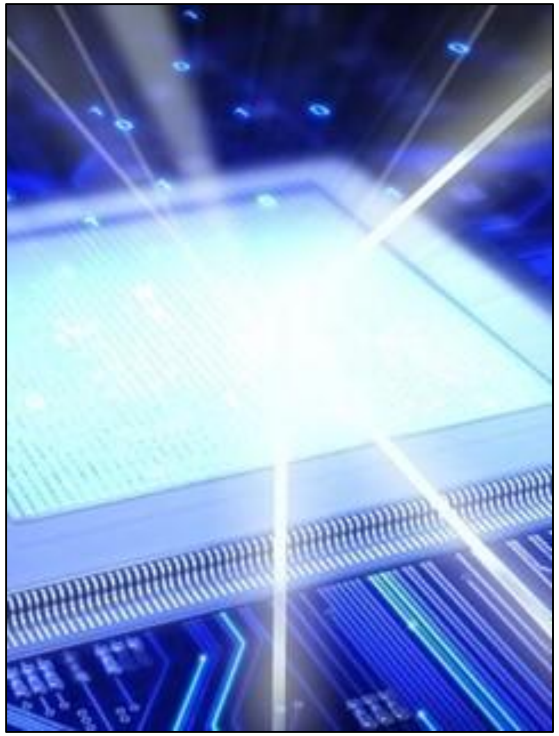


2

Quantum 2.0 and the disruption of information technology

Quantique 2.0 : Mastering individual quantum “objects”

- **Quantique 1.0: Reaching its end**
  Manipulating macroscopic quantum systems
  ie with many quantum “objects”



Germanium laser

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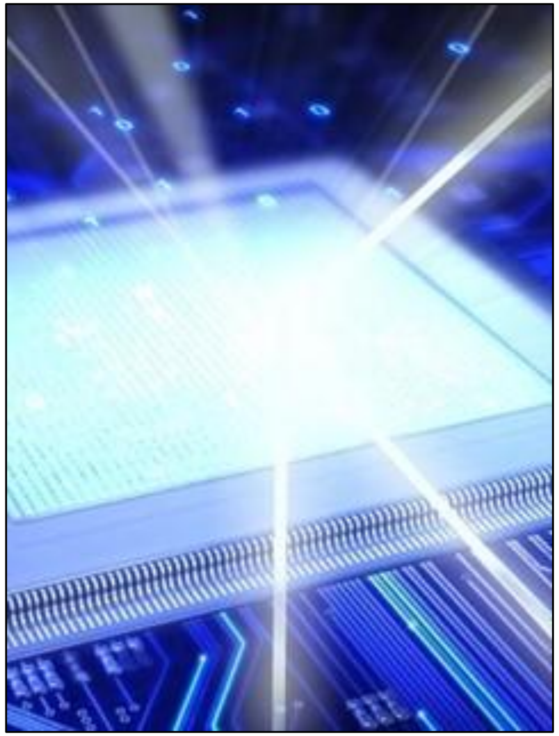

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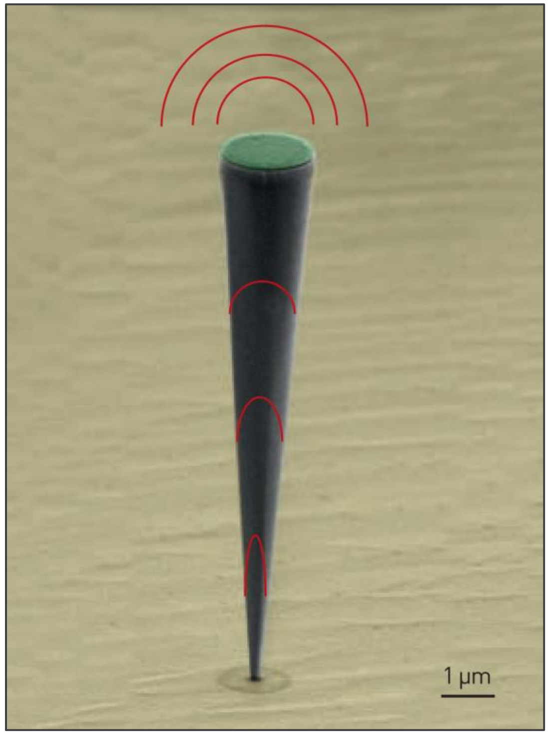

Single photon source

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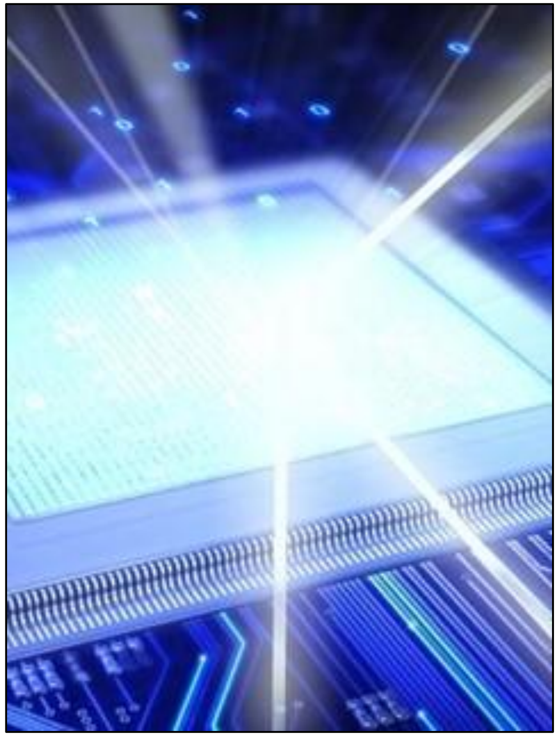
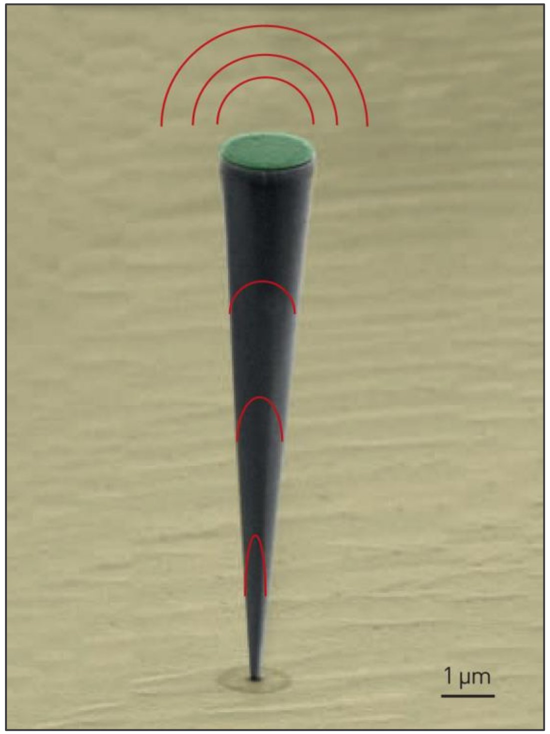


Germanium laser

- **Same quantum degrees of freedom**
  but
  going from a **macroscopic ensemble**
  to **individual states**

- **Huge paradigm shift**
  for the accessible space of possibilities
  => access to the **huge** space of quantum states
  (Hilbert/Fock space)

  => access the "strangest" quantum phenomena
  - **Superposition**
  - **Non-locality**
  - **Entanglement**



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Superposition & Entanglement

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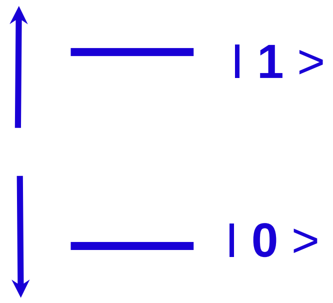
- **Superposition of states :**
  - Example of an object with 2 states : **quantum bit or Qubit**



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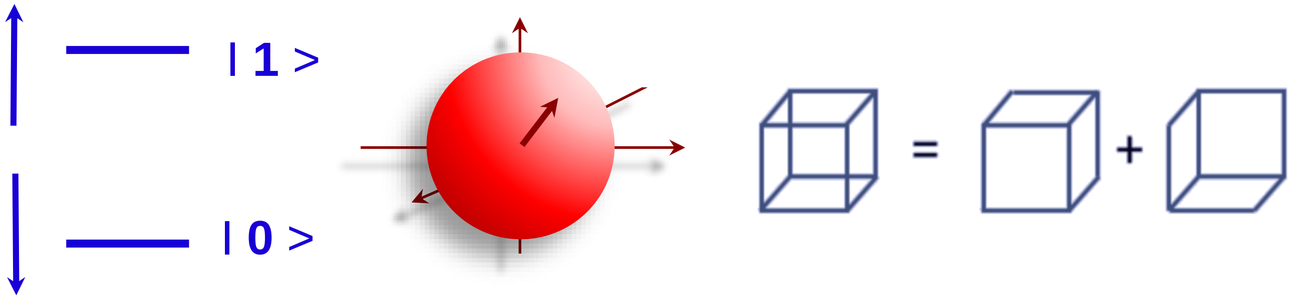

An infinity of states "simultaneously" 0 and 1 : $| \text{state} \rangle = \alpha | \mathbf{0} \rangle + \beta | \mathbf{1} \rangle$

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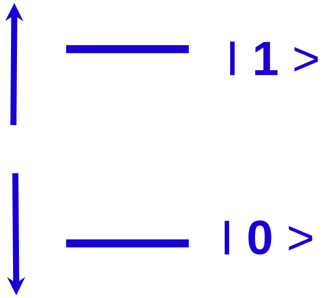

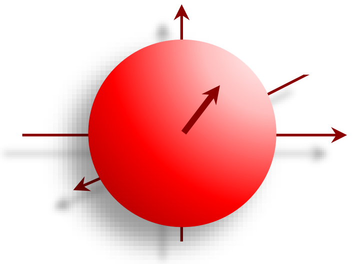

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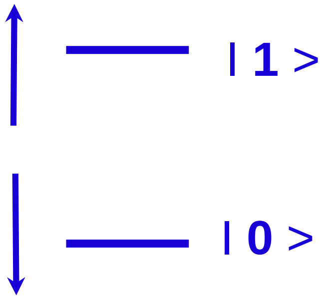

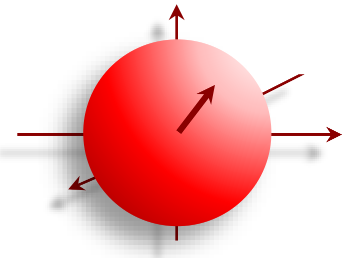

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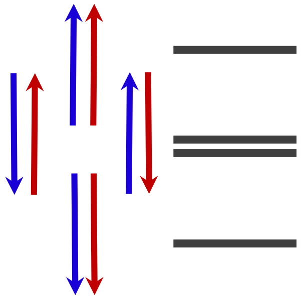

$|11\rangle = |1\rangle * |1\rangle$

$|10\rangle = |1\rangle * |0\rangle$

$|01\rangle = |0\rangle * |1\rangle$

$|00\rangle = |0\rangle * |0\rangle$

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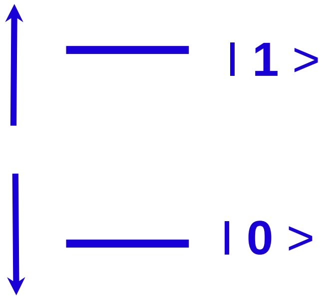

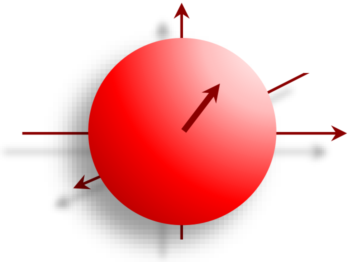

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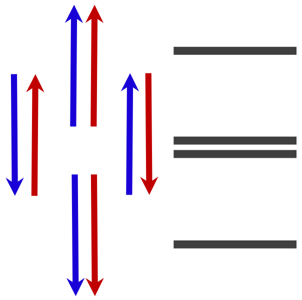

I11> = I1>∗I1>

I10> = I1>∗I0>

I01> = I0>∗I1>

I00> = I0>∗I0>

N “objects” => 2^N dimensions space, ex 2 qubits : I state > = α I00> + β I01> + γ I10> + δ I11>

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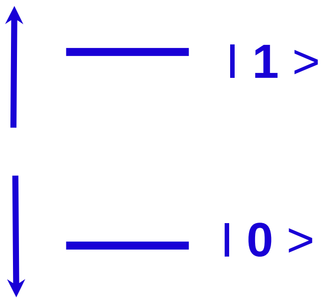

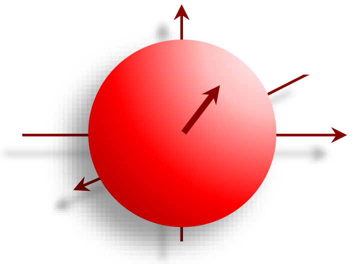

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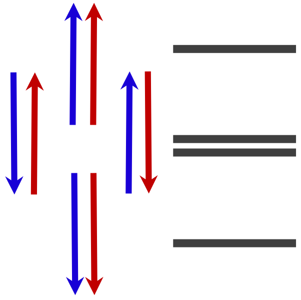

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Coupled quantum objects cannot be thought individually

Example : I00> + I11> $\neq$ (α_A I0> + β_A I1>) ∗ (α_B I0> + β_B I1>)

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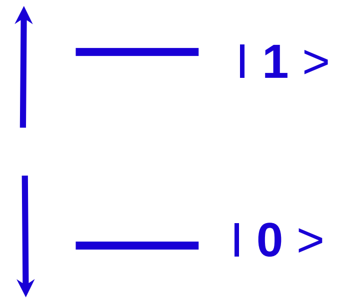

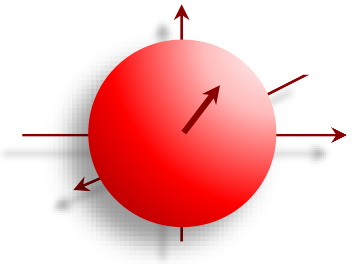

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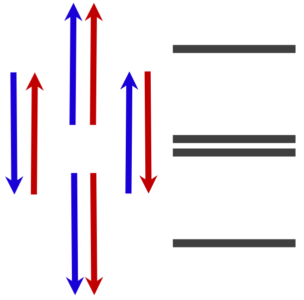

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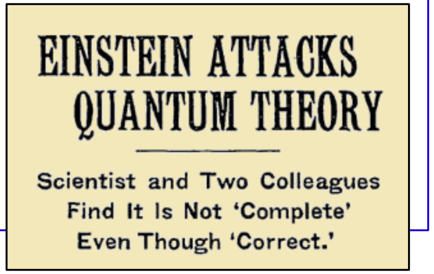
N “objects” => 2^N dimensions space, ex 2 qubits : $| \text{state} \rangle = \alpha |00\rangle + \beta |01\rangle + \gamma |10\rangle + \delta |11\rangle$

Coupled quantum objects cannot be thought individually => they are entangled

$\Rightarrow$ **access to the huge space with 2^N dimensions of entangled states**

$\Rightarrow$ **2^N evolution of all the solutions « at the same time »**


EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues Find It Is Not ‘Complete’ Even Though ‘Correct.’

Quantique 2.0: the promise disruptions for ICT

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Mastering individual quantum "objects": ultimate sensitivity

QUANTUM
Sensing
metrology

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Entangling distant "objects": inviolable and disruptive communications

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QUANTUM Communication

Massive entanglement: unprecedented massive computing capabilities

QUANTUM Computing

QUANTUM Simulation

Quantique 2.0: Major difficulties

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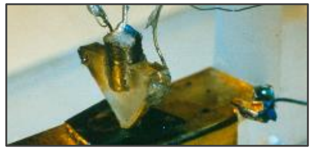
- **Fabrication challenges:**
  - Even more difficult then the 1st quantum revolution



1947, 1st Transistor

1971, 2 300 transistors.

2020, 54 milliard transistors

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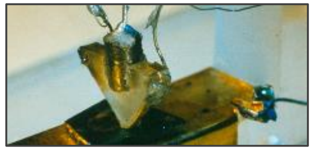

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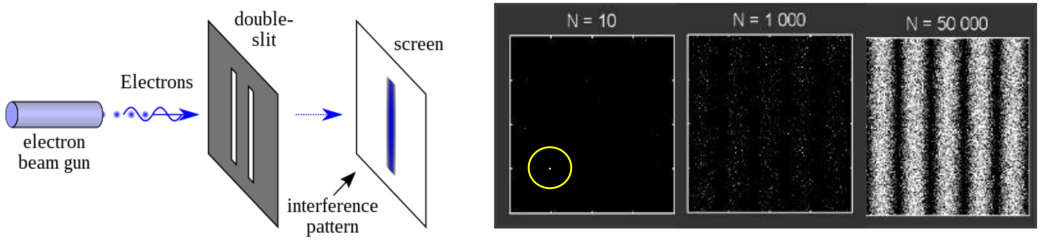
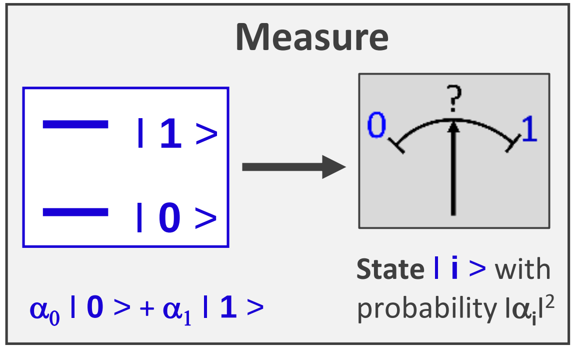


Example. Electron waves and probabilistic measure on screen



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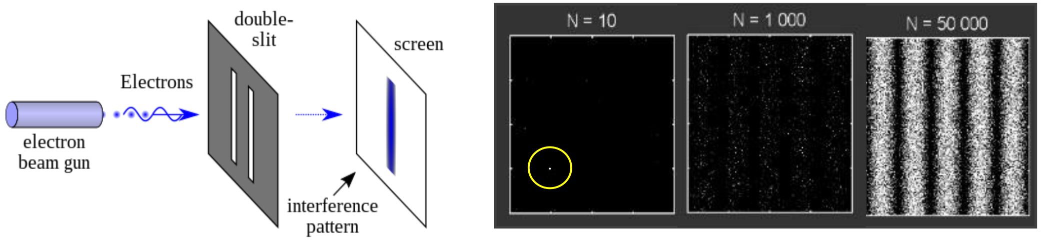

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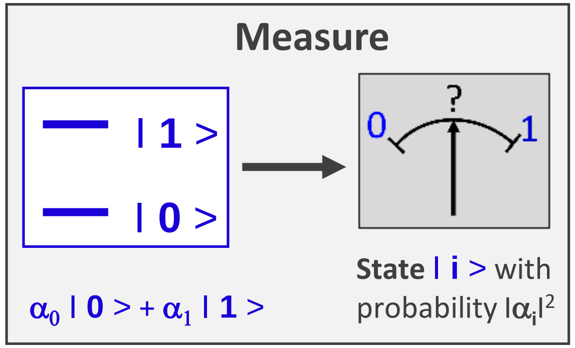
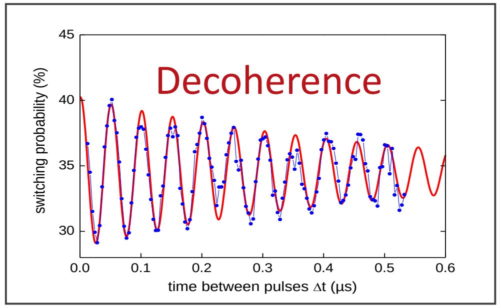
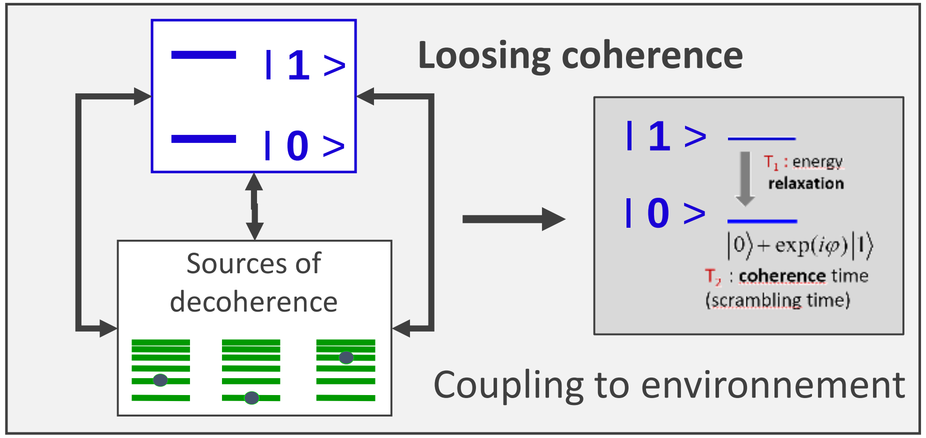


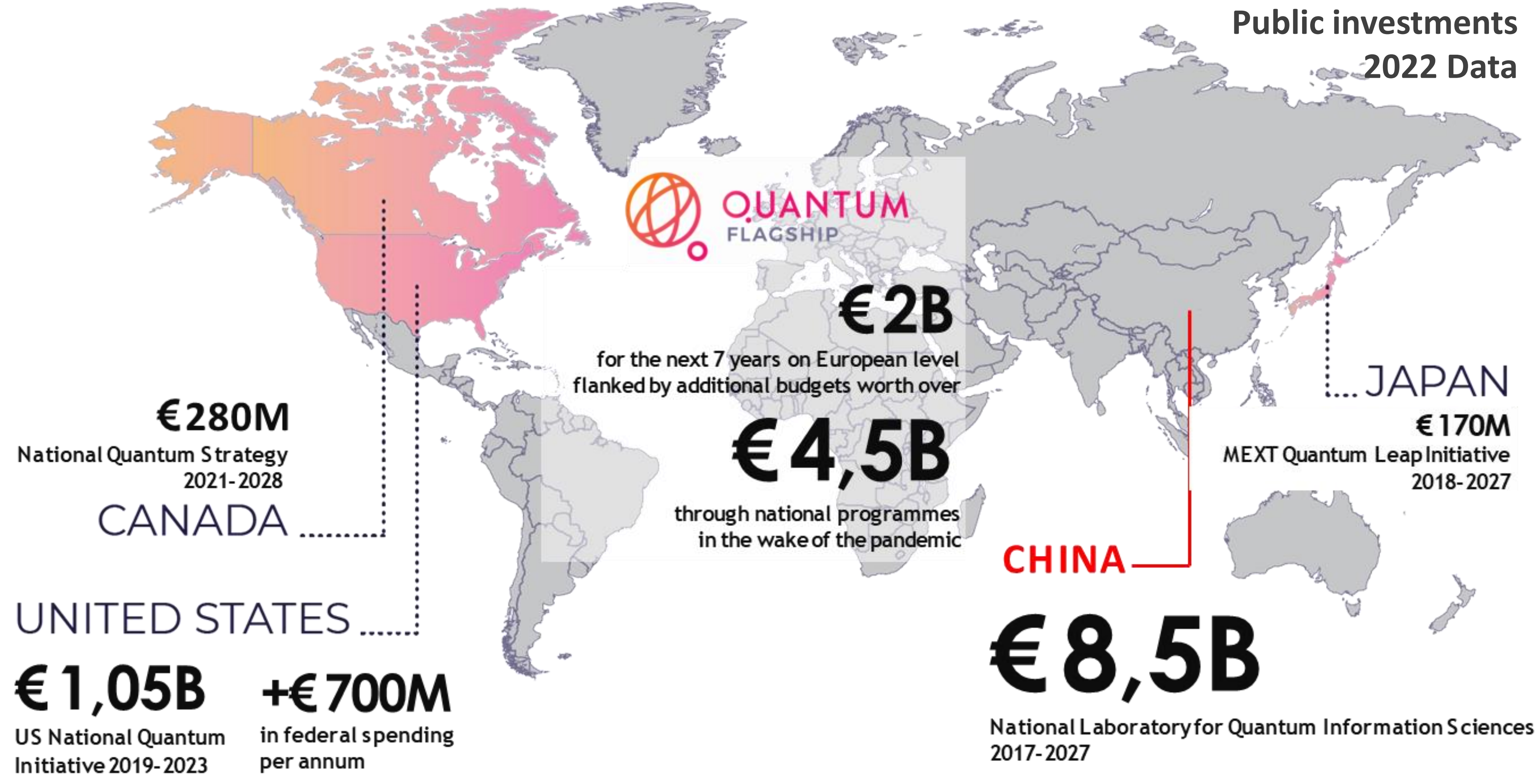
- **Coupling to environment is destroying coherence: Superposition & entanglement**
  - **Error correction codes needed** => thousands of physical qubits to protect a single logical qubit
  - **Or new robust qubits** protected from decoherence





2022 International competition and collaboration

Public investments
2022 Data



3 Quantum computing for nuclear, particle and astro physics

Different quantum computing strategies

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- **Quantum annealing**

  $|\psi> \;=>\; |\psi_0>$

  <u>Looking for ground states</u>

  - adiabatic optimization
  - exploring many paths
  - using tunnel effects

Different quantum computing strategies

- **Quantum annealing**

  $|\psi\rangle \Rightarrow |\psi_0\rangle$

  <u>**Looking for ground states**</u>

  - adiabatic optimization
  - exploring many paths
  - using tunnel effects

- **Quantum simulation**

  $|\psi(t)\rangle = \hat{U}(0,t)\ |\psi(0)\rangle$

  <u>**Quantum evolution**</u>

  - analogue computing

Different quantum computing strategies

▶ **Quantum annealing**

$|\psi\rangle \Rightarrow |\psi_0\rangle$

<u>Looking for ground states</u>

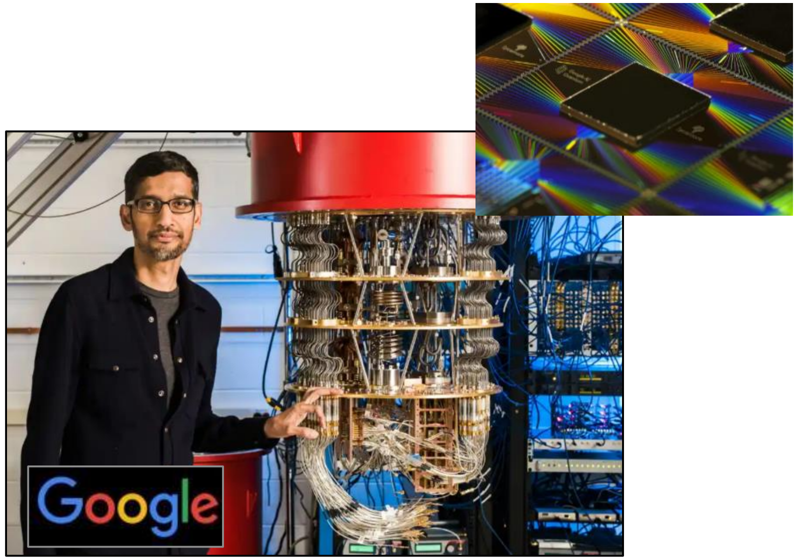
- adiabatic optimization
- exploring many paths
- using tunnel effects

▶ **Quantum simulation**

$|\psi(t)\rangle = \hat{U}(0,t)\ |\psi(0)\rangle$

<u>Quantum evolution</u>

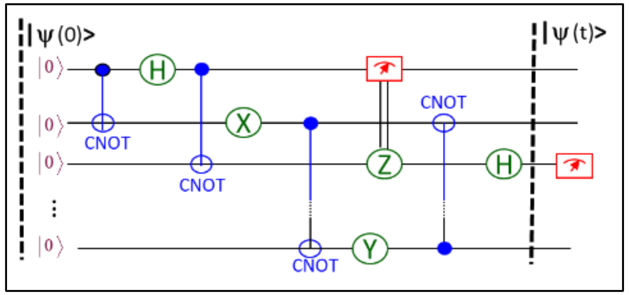
- analogue computing



▶ **Quantum digital computing**

$|\psi(N\Delta t)\rangle = \hat{U}_N(\Delta t) \ldots \hat{U}_1(\Delta t)|\psi(0)\rangle$

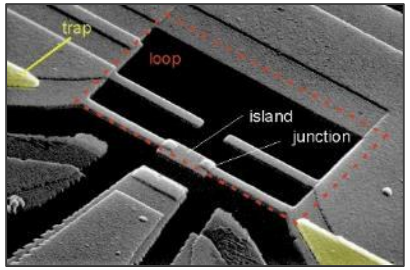
<u>Gate based evolution</u>



Many possible technologies/degrees of freedom

Many possible technologies/degrees of freedom

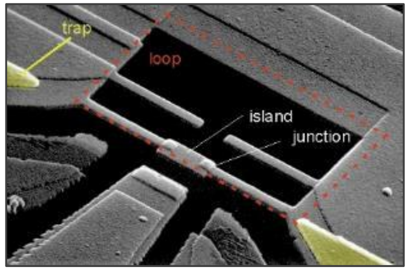
Quantum “objects”/degrees of freedom



- **Electrons pairs / superconducting curent**
  - Quantronium - transmon

Many possible technologies/degrees of freedom

Quantum “objects”/degrees of freedom



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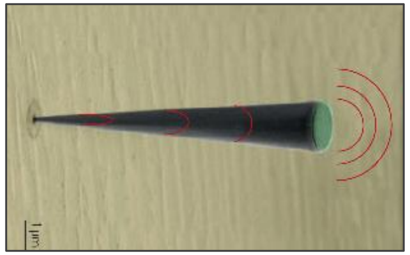
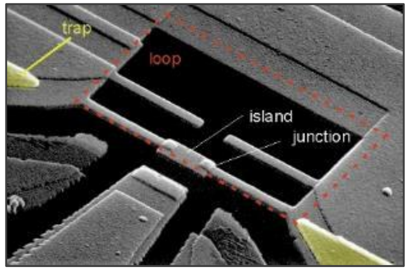


- Photons

Many possible technologies/degrees of freedom

Quantum “objects”/degrees of freedom



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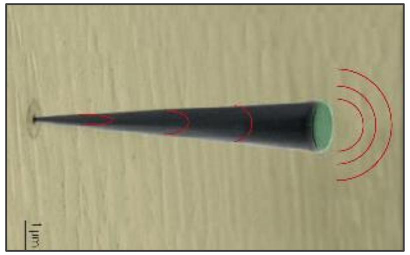

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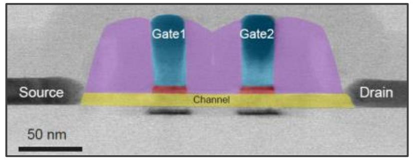
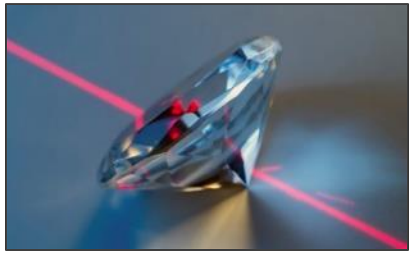
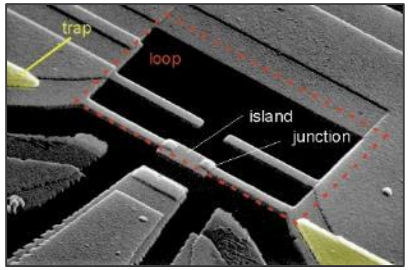




- **Spin**
  - Electrons or holes in semiconductors (AsGa, Si, Ge, …)
  - NV centers in diamond (Nitrogen vacancy)

Many possible technologies/degrees of freedom

Quantum "objects"/degrees of freedom



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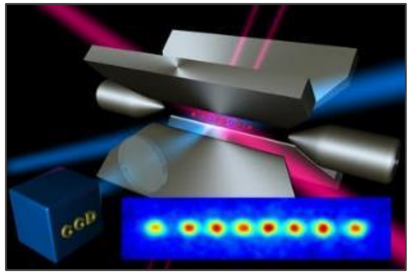
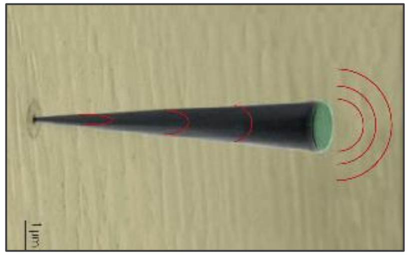


- Ions



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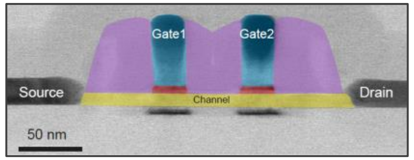

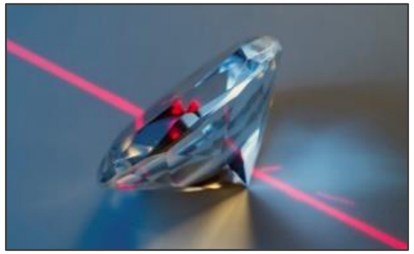

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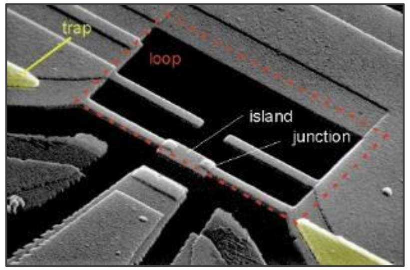

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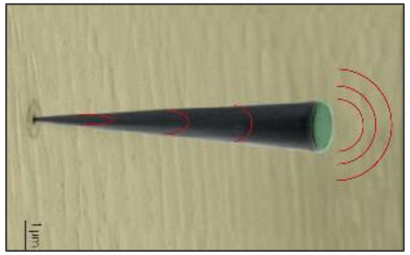

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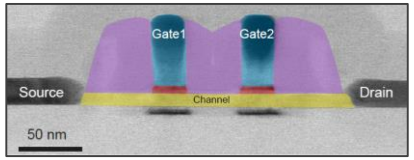

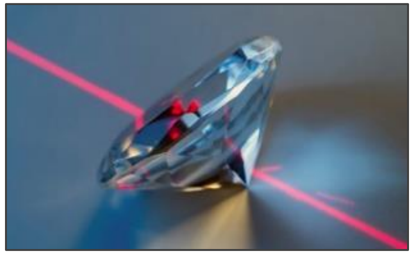

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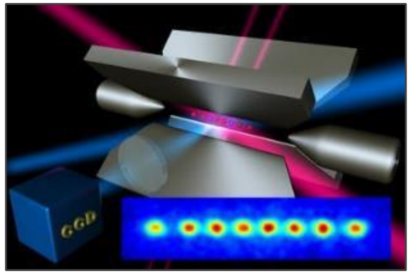

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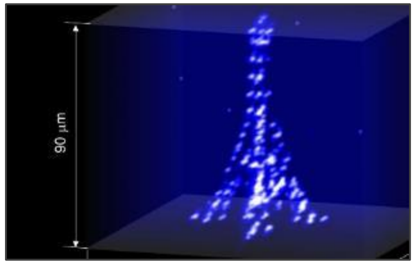
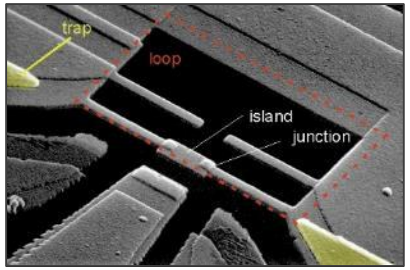


- Atoms
- Molecules

Many possible technologies/degrees of freedom

Quantum “objects”/degrees of freedom



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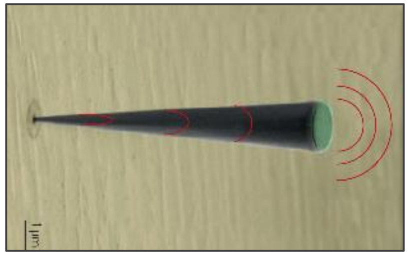

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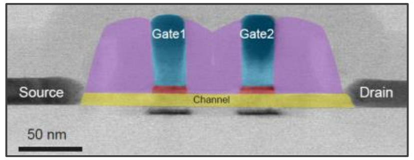

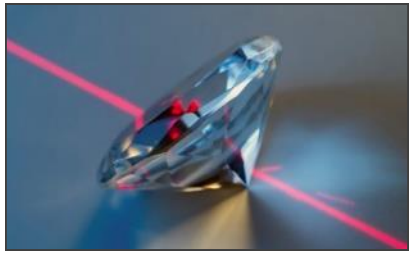

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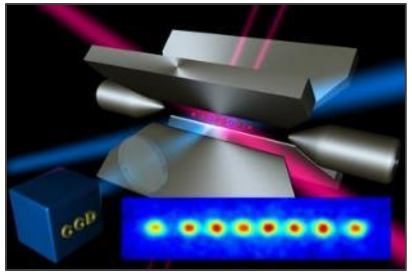

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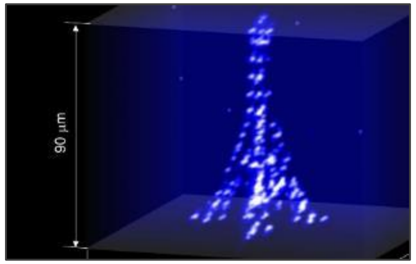
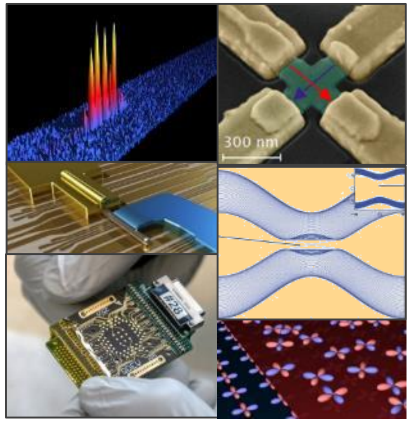


- **Atoms**
- **Molecules**



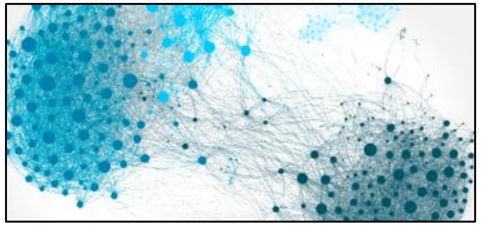
- **New quantum degrees of freedom / quantum materials**

  Flying qubits, surface states, leviton, pseudospin, Skyrmions, spin-orbite, 2D systems, topological materials, Majorana fermions, anti/multi-ferroïc …

Main classes of quantum algorithms

Main classes of quantum algorithms

- **Search**
  based on Deutsch-Jozsa, Simon and Grover's algorithms
  - Polynomial acceleration



Exploring graphs and data bases

Main classes of quantum algorithms

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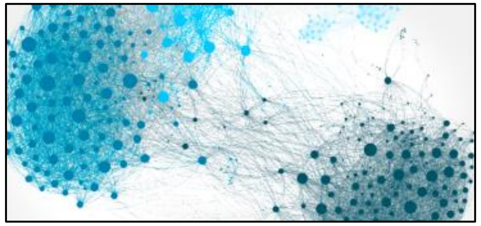

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- **Quantum Fourier transforms (QFT)**
  such as Shor's algorithm for factorization (&Bitcoin)
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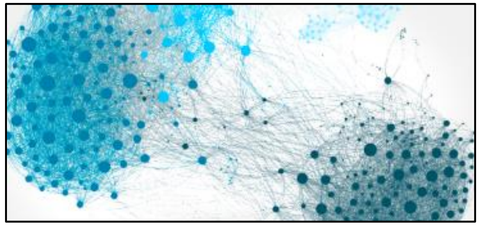

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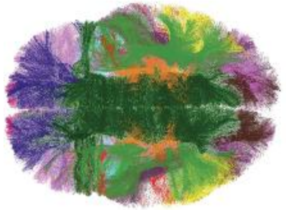

Image processing

Market evolution

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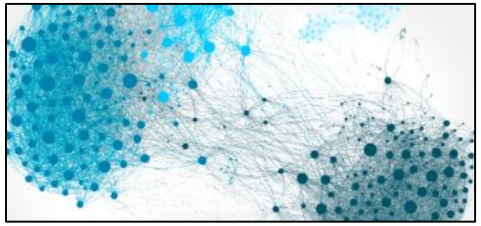

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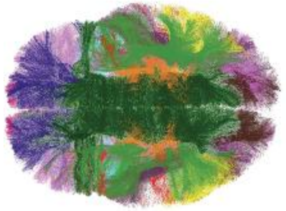
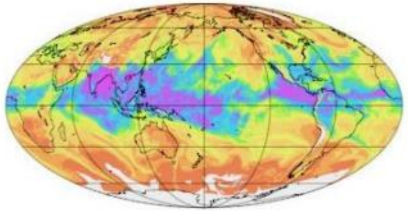


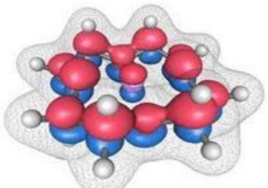
Image processing

Market evolution

- **Quantum simulation and variational approach**
  Quantum many body problems
  Resolution of linear differential equations (HHL)
  - Exponential acceleration



Weather broadcast



Molecules

Quantum algorithms for nuclear, particle and astroparticle

- **Search**
  based on Deutsch-Jozsa, Simon and Grover's algorithms
  - Polynomial acceleration
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  - Exponential acceleration

- **Data mining**
  pattern recognition, Graph analysis
- **Signal treatment**
  frequency decomposition
- **Image and data analysis**
  Advance treatment (AI, statistical analysis)
- **Theory and simulation**
  Many-body problem and field theory,

First quantum calculation of a deuteron

Dumitrescu, McCaskey, Hagen, Jansen, Morris, TP, Pooser, Dean, Lougovski, Phys. Rev. Lett. 120, 210501 (2018)

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PHYSICAL REVIEW LETTERS 120, 210501 (2018)

Editors' Suggestion | Featured in Physics

Cloud Quantum Computing of an Atomic Nucleus

E. F. Dumitrescu,[1] A. J. McCaskey,[2] G. Hagen,[3,4] G. R. Jansen,[5,3] T. D. Morris,[4,3] T. Papenbrock,[4,3,*] R. C. Pooser,[1,4] D. J. Dean,[3] and P. Lougovski[1,*]

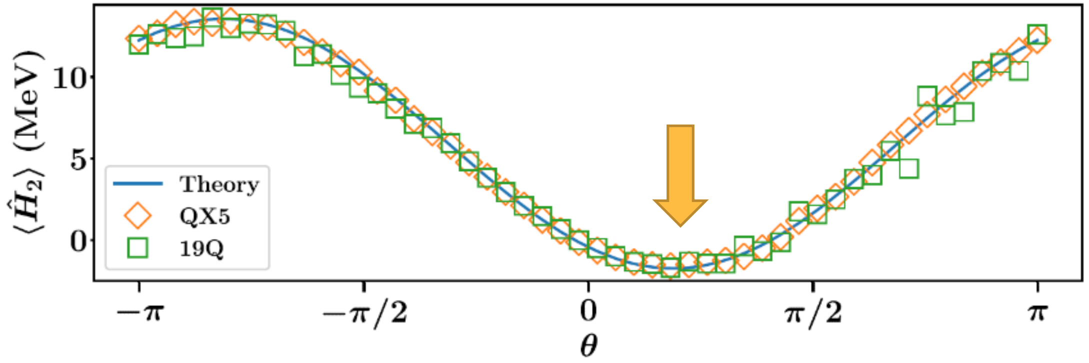
[1]*Computational Sciences and Engineering Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[2]*Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[3]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[4]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[5]*National Center for Computational Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

(Received 12 January 2018; published 23 May 2018)

We report a quantum simulation of the deuteron binding energy on quantum processors accessed via cloud servers. We use a Hamiltonian from pionless effective field theory at leading order. We design a low-depth version of the unitary coupled-cluster ansatz, use the variational quantum eigensolver algorithm, and compute the binding energy to within a few percent. Our work is the first step towards scalable nuclear structure computations on a quantum processor via the cloud, and it sheds light on how to map scientific computing applications onto nascent quantum devices.

Unitary operator entangling 2 (and 3) orbitals

$$U(\theta) \equiv e^{\theta(a_0^\dagger a_1 - a_1^\dagger a_0)}$$



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https://quantum.cern.ch

CERN
Quantum Technology
Initiative

Strategy and Roadmap

v. 0.4-Rev3

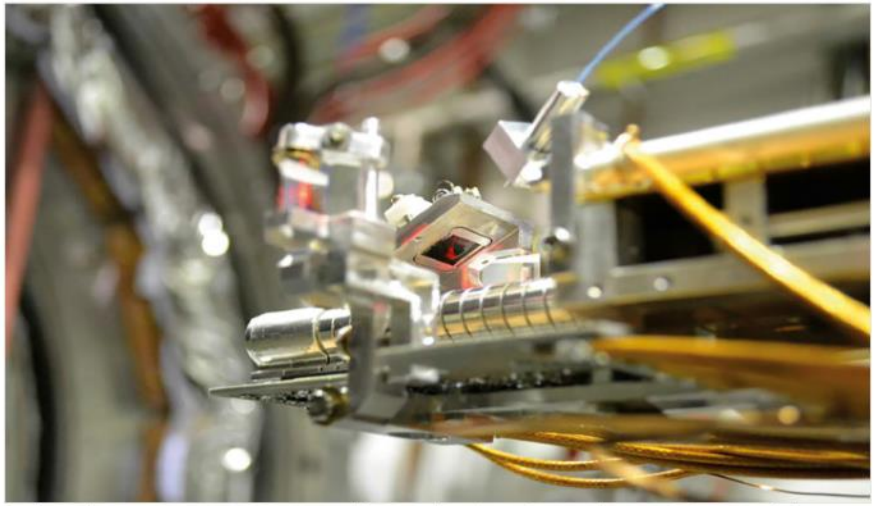
15 September 2021

QUANTUM TECHNOLOGY INITIATIVE

CERNCOURIER

25 September 2020

CERN's new quantum technology initiative has the potential to enrich and expand its challenging research programme, says Alberto Di Meglio.



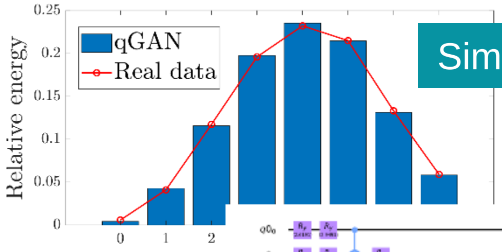
QT inroads CERN's AEGIS experiment is able to explore the multi-particle entangled nature of photons from positronium annihilation, and is one of several examples of existing CERN research with relevance to quantum technologies. Credit: CERN-PHOTO-201604-080-2

- **A strong quantum initiative @ CERN**

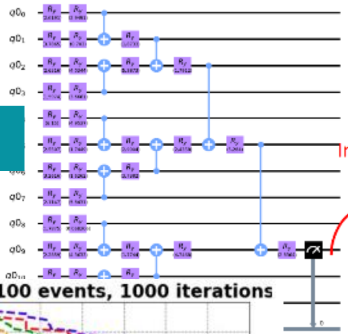
Areas of Research

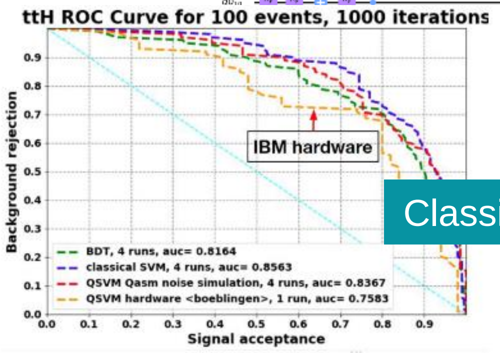
Computing

Simulation



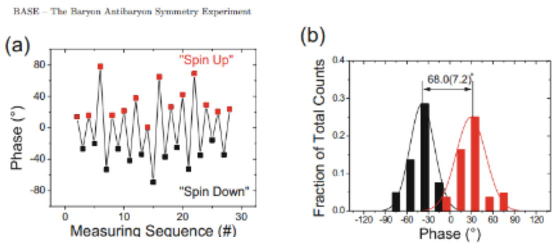
Reconstruction





Classification

Sensing

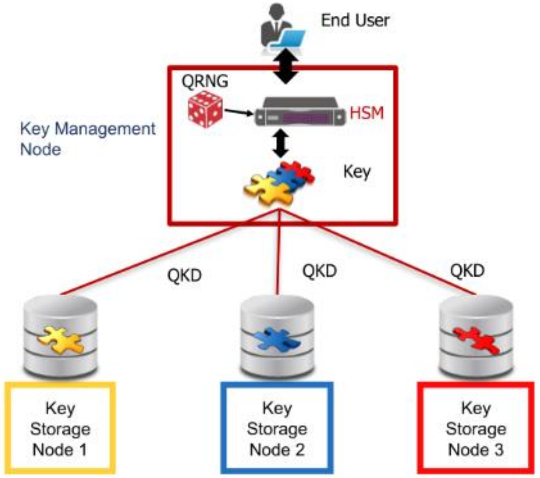


https://doi.org/10.1140/epjst/e2015-02607-4

Low-energy experiments, quantum states measurements, nano-technologies

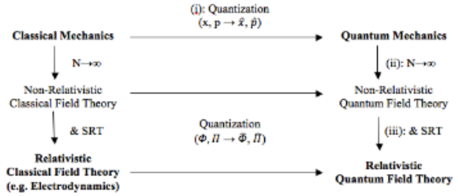
Future HEP Detectors

Communications

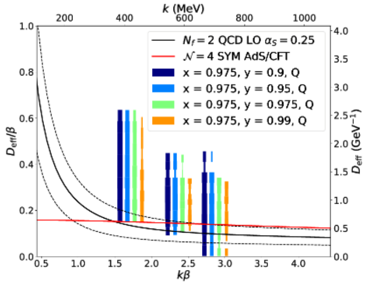


QKD infrastructures Quantum Internet

Theory



Quantum Field Theory

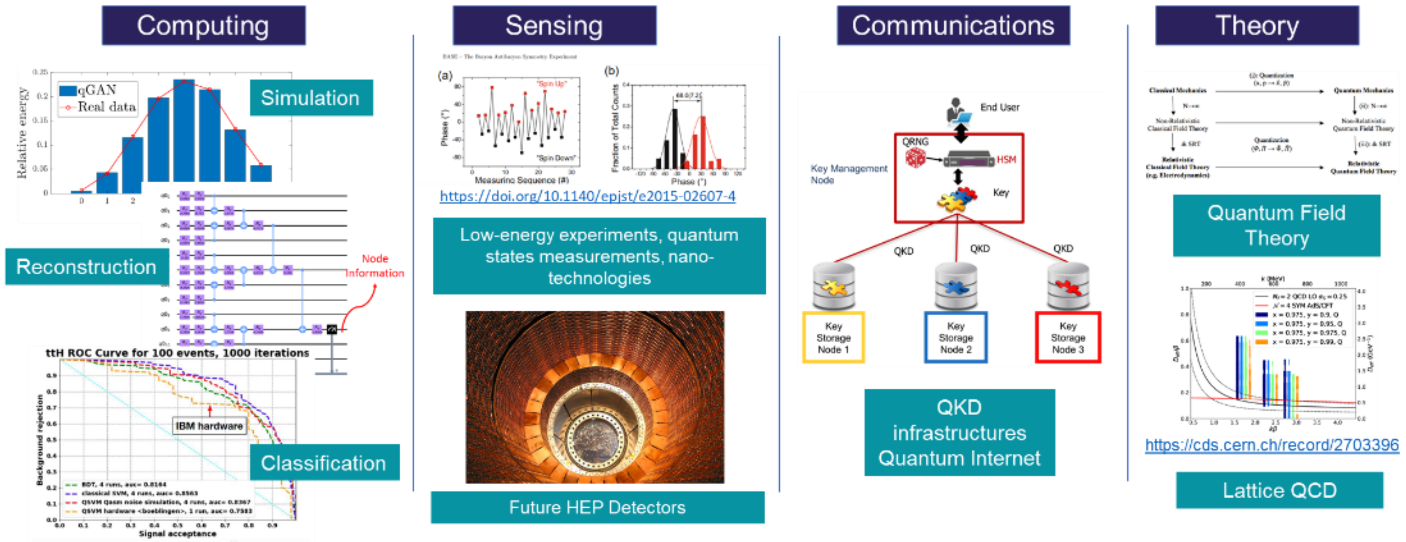


https://cds.cern.ch/record/2703396

Lattice QCD

Scientific Publications (2021)

- **More than 20 projects in all four quantum areas**
- **18 papers**
  - 8 on peer-reviewed journals
- **More than 20 talks and presentations at conferences and workshops**



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  four quantun
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CERN-TH-2021-188

Efficient Representation for Simulating U(1) Gauge Theories on Digital Quantum Computers at All Values of the Coupling

Christian W. Bauer[1,*] and Dorota M. Grabowska[2,†]
[1] Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[2] Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland

(Dated: November 17, 2021)
arXiv:2111.08015v1 [hep-ph] 15 Nov 2021

We derive a representation for a lattice U(1) gauge theory with exponential convergence in the number of states used to represent each lattice site that is applicable at all values of the coupling. At large coupling, this representation is equivalent to the Kogut-Susskind electric representation, which is known to provide a good description in this region. At small coupling, our approach adjusts the maximum magnetic field that is represented in the digitization as in this regime the low-lying eigenstates become strongly peaked around zero magnetic field. Additionally, we choose a representation of the electric component of the Hamiltonian that gives minimal violation of the canonical commutation relation when acting upon low-lying eigenstates, motivated by the Nyquist–Shannon sampling theorem. For (2+1) dimensions with 4 lattice sites the expectation value of the plaquette operator can be calculated with only 7 states per lattice site with per-mille level accuracy for all values of the coupling constant.

The Standard Model of Particle Physics, encapsulating the vast majority of our understanding of the fundamental nature of our Universe, is at its core a gauge theory. Much of the richness of its phenomenology can be traced back to the complicated interplay of its various gauged interactions. While massive theoretical and algorithmic developments in classical computing have allowed us to probe many of these aspects, there remain a plethora of open questions that do not seem amenable to these methods. With a fundamentally different computational strategy, quantum computers hold the promise to simulate the dynamics of quantum field theories from first principles, allowing access to ab-initio predictions of observables that are inaccessible using existing techniques on classical computers. In order to harness the full potential of quantum computers, an efficient implementation of the Hamiltonian of gauge theories on quantum processors is a mandatory first step. This is no simple task due to the redundancies inherent to any gauge theory, as well as the finite number of degrees of freedom inherent to both ... For a review of various approaches, see [1–7].

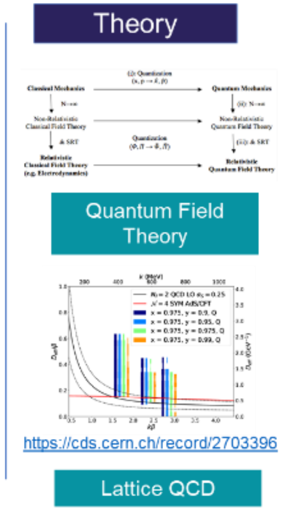
On a poset of quantum exact promise pr...

A report on teaching a series of online lec... computing from CERN

Quantum machine learning in high energy phy...

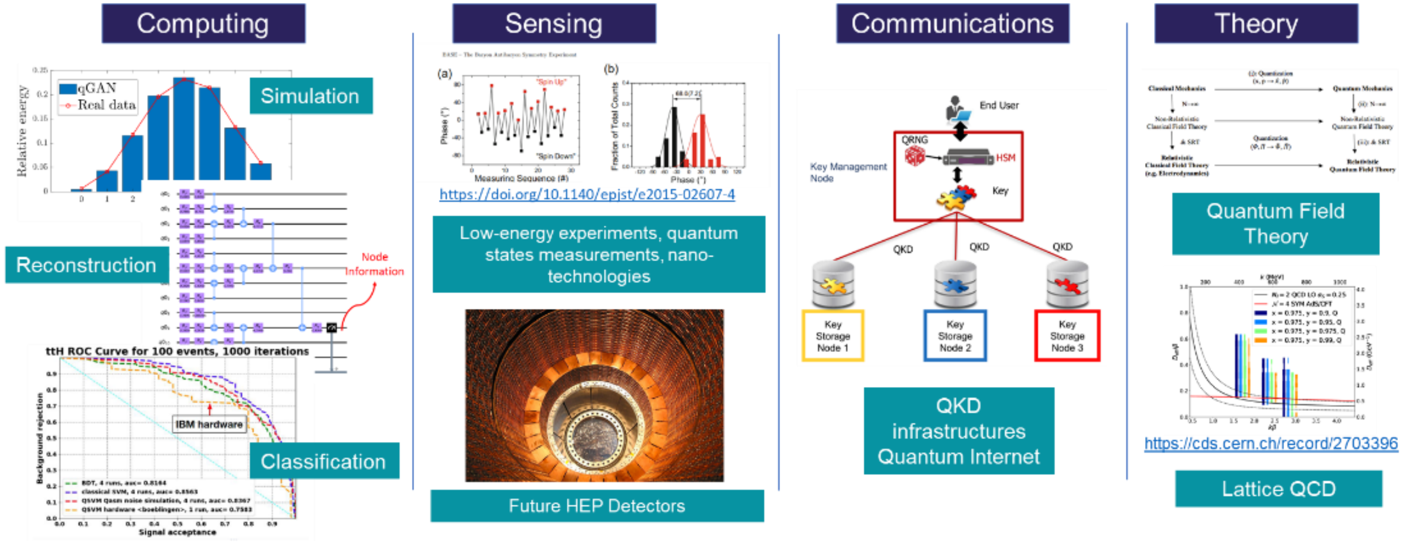
PHYSICAL REVIEW RESEARCH

Application of quantum machine learning using the quantum kernel algorithm on high energy physics analysis at the LHC



Scientific Publications (2021)

- **More than 20 projects in all four quantum areas**
- **18 papers**
  - 8 on peer-reviewed journals
- **More than 20 talks and presentations at conferences and workshops**



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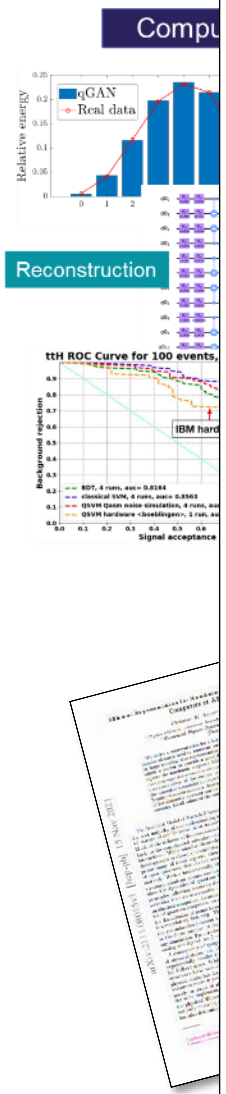

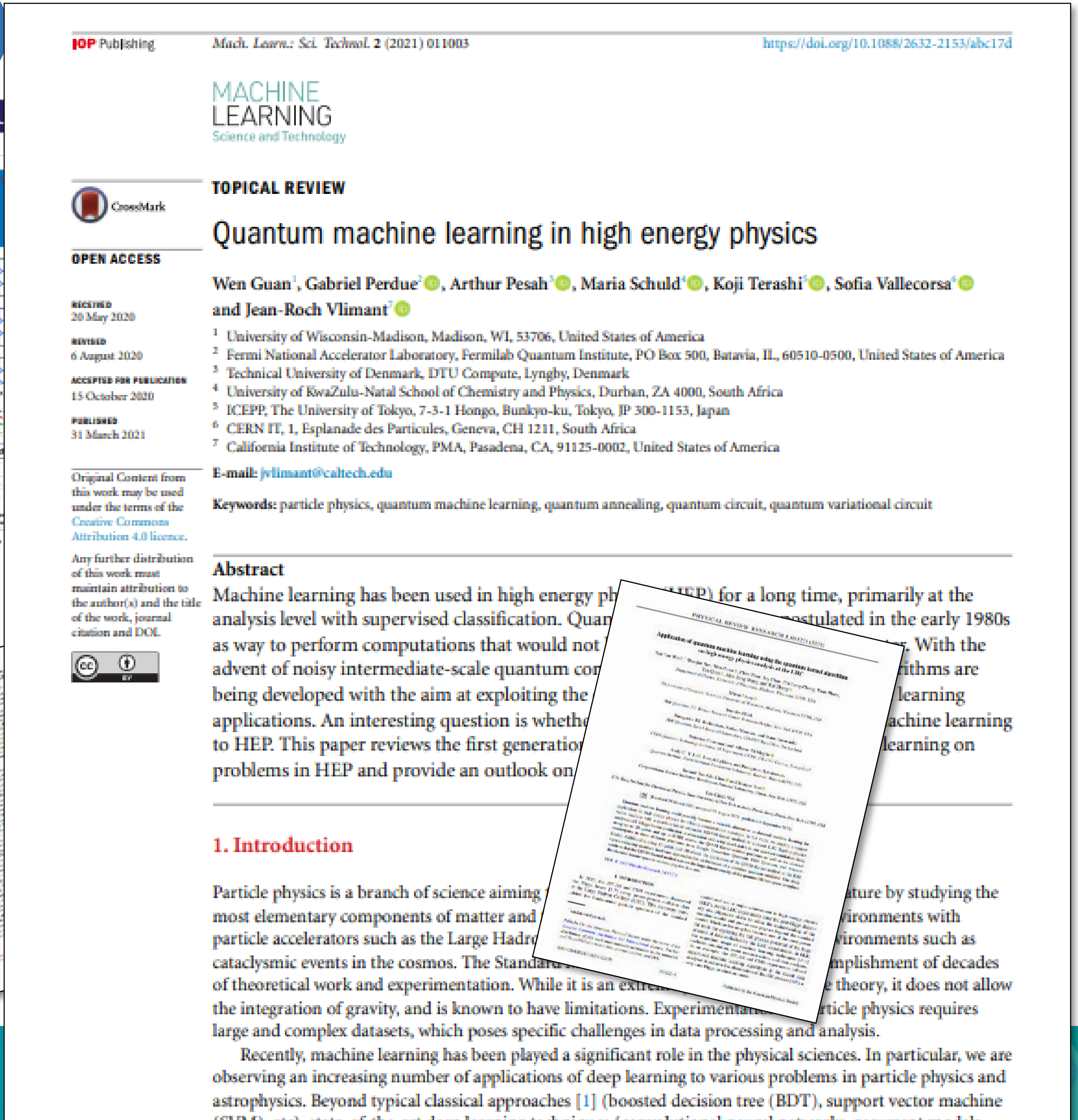

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TOPICAL REVIEW

Quantum machine learning in high energy physics

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Keywords: particle physics, quantum machine learning, quantum annealing, quantum circuit, quantum variational circuit

Abstract

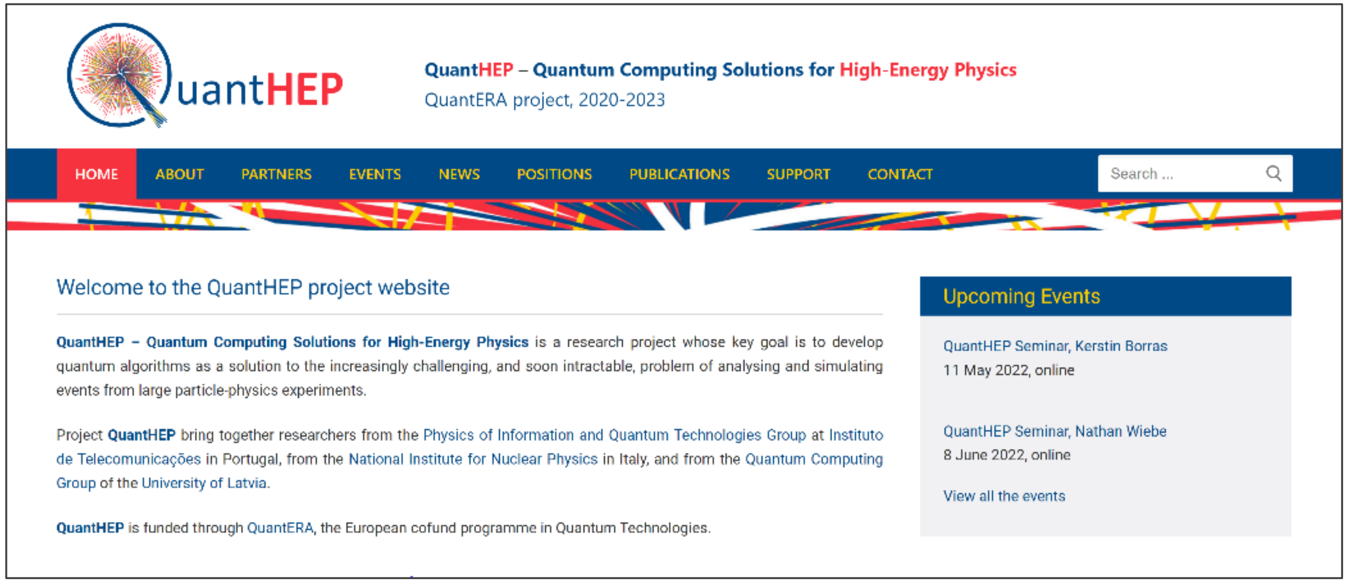
Machine learning has been used in high energy ph... (HEP) for a long time, primarily at the analysis level with supervised classification. Quan... postulated in the early 1980s as way to perform computations that would not ... With the advent of noisy intermediate-scale quantum co... ithms are being developed with the aim at exploiting the ... learning applications. An interesting question is whethe... achine learning to HEP. This paper reviews the first generatio... learning on problems in HEP and provide an outlook on...

1. Introduction

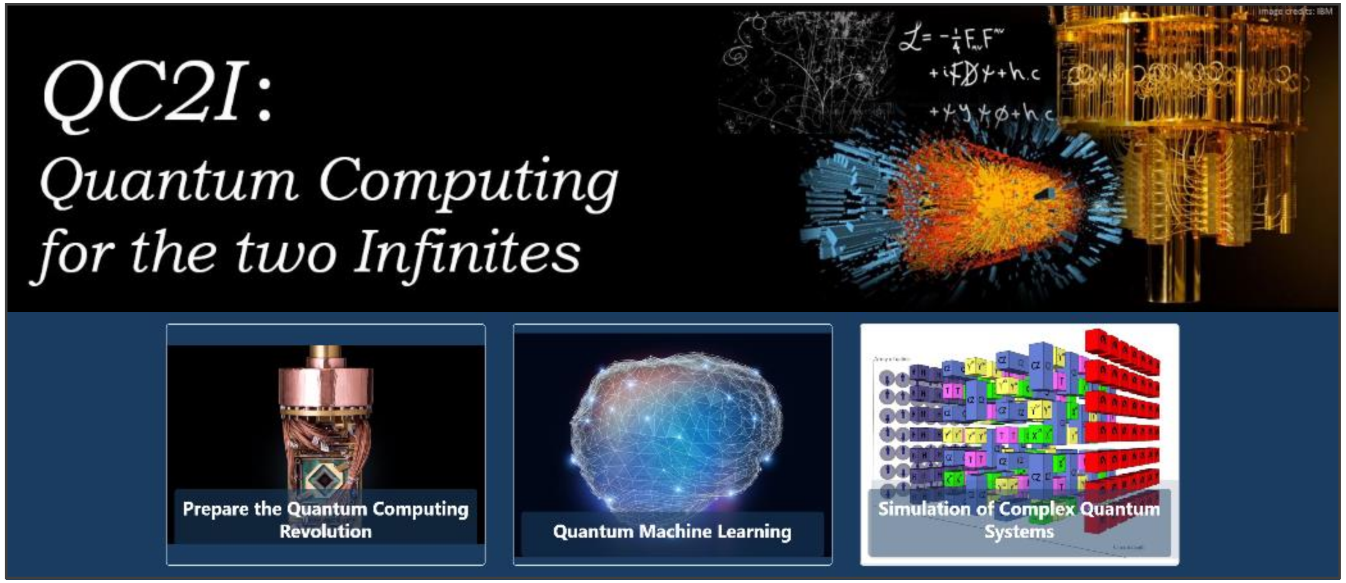
Particle physics is a branch of science aiming ... ture by studying the most elementary components of matter and ... vironments with particle accelerators such as the Large Hadro... vironments such as cataclysmic events in the cosmos. The Standard ... mplishment of decades of theoretical work and experimentation. While it is an extre... e theory, it does not allow the integration of gravity, and is known to have limitations. Experimenta... rticle physics requires large and complex datasets, which poses specific challenges in data processing and analysis.

Recently, machine learning has been played a significant role in the physical sciences. In particular, we are observing an increasing number of applications of deep learning to various problems in particle physics and astrophysics. Beyond typical classical approaches [1] (boosted decision tree (BDT), support vector machine

Many initiatives: 2 examples



- **QuantHEP a QuantERA project in EU**
  - Portugal
  - Italy
  - Latvia



- **QC2I an IN2P3 project in France**
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  - LPC – Clermont-Ferrand
  - LLR – Palaiseau
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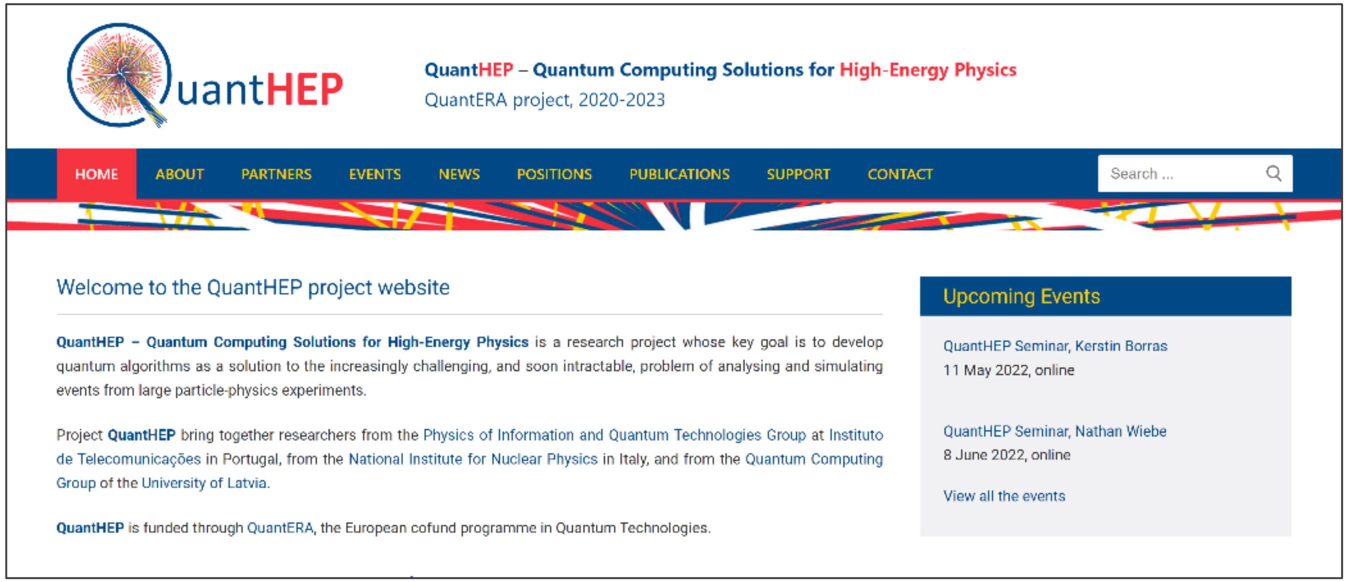

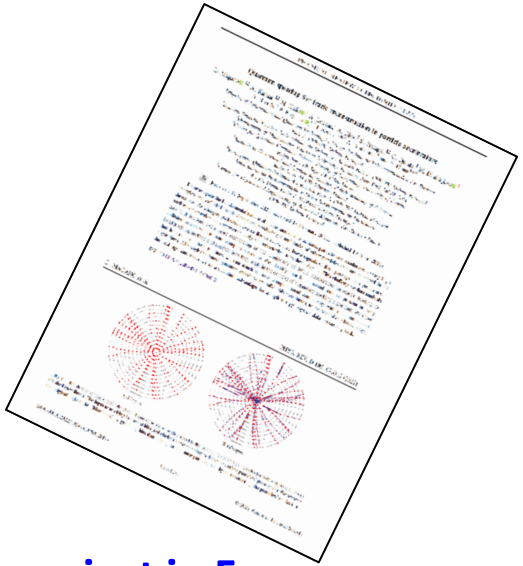

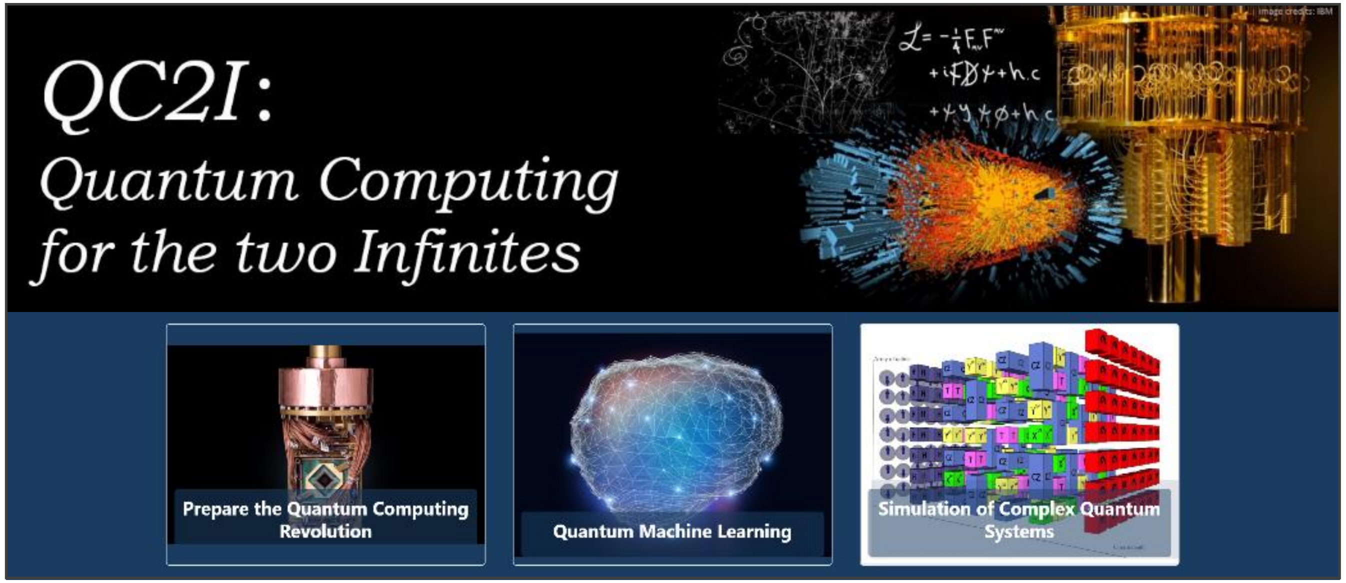

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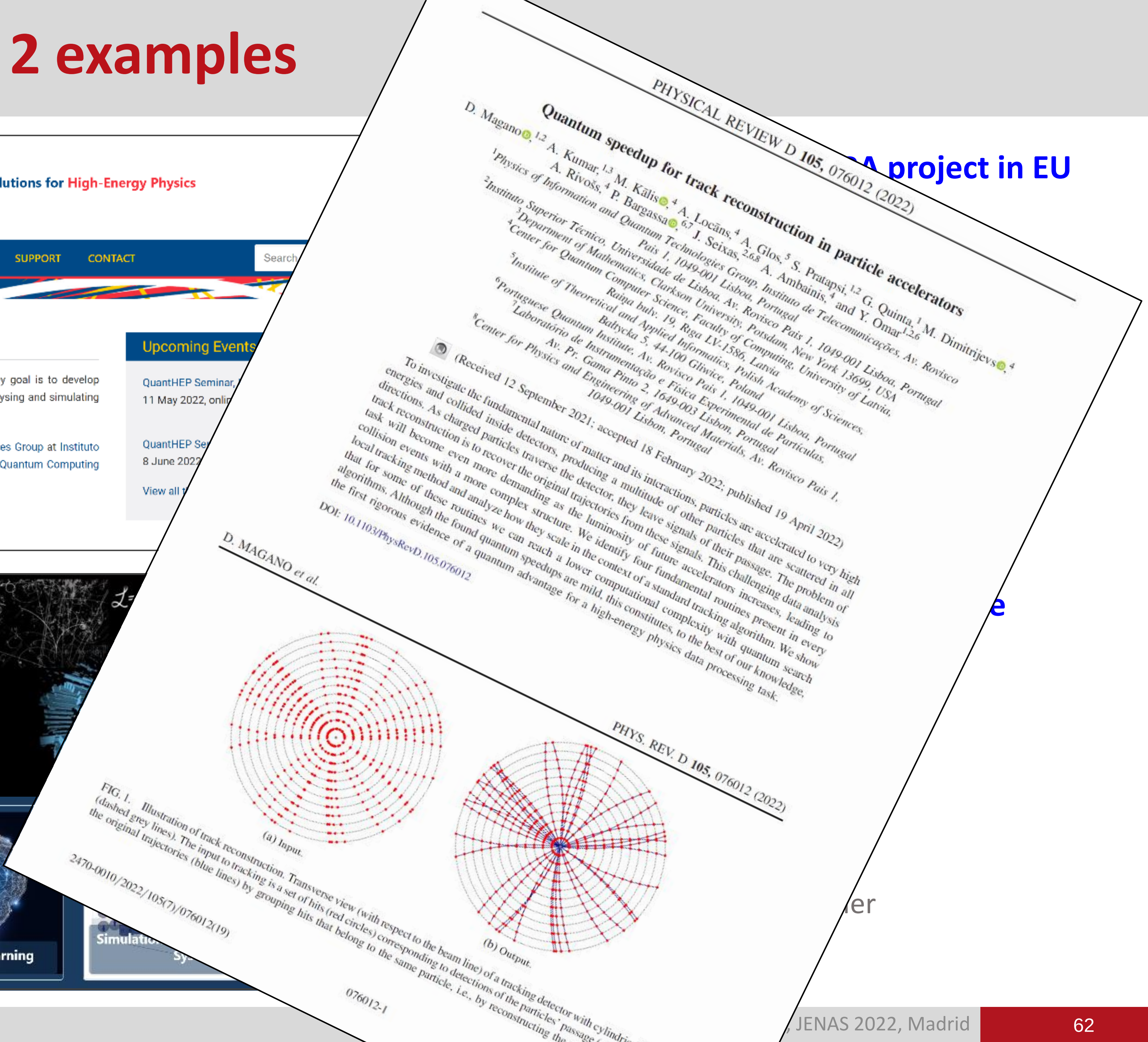
A project in EU



PHYSICAL REVIEW D 105, 076012 (2022)

Quantum speedup for track reconstruction in particle accelerators

D. Magano,[1,2] A. Kumar,[1,3] M. Kālis,[4] A. Locāns,[4] A. Glos,[5] S. Pratapsi,[1,2] G. Quinta,[1] M. Dimitrijevs,[4] A. Rivošs,[4] P. Bargassa,[6,7] J. Seixas,[2,6,8] A. Ambainis,[4] and Y. Omar[1,2,6]

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To investigate the fundamental nature of matter and its interactions, particles are accelerated to very high energies and collided inside detectors, producing a multitude of other particles that are scattered in all directions. As charged particles traverse the detector, they leave signals of their passage. The problem of track reconstruction is to recover the original trajectories from these signals. This challenging data analysis task will become even more demanding as the luminosity of future accelerators increases, leading to collision events with a more complex structure. We identify four fundamental routines present in every local tracking method and analyze how they scale in the context of a standard tracking algorithm. We show that for some of these routines we can reach a lower computational complexity with quantum search algorithms. Although the found quantum speedups are mild, this constitutes, to the best of our knowledge, the first rigorous evidence of a quantum advantage for a high-energy physics data processing task.

DOI: 10.1103/PhysRevD.105.076012

D. MAGANO et al. PHYS. REV. D 105, 076012 (2022)

(a) Input. (b) Output.

FIG. 1. Illustration of track reconstruction. Transverse view (with respect to the beam line) of a tracking detector with cylindri... (dashed grey lines). The input to tracking is a set of hits (red circles) corresponding to detections of the particles' passage... the original trajectories (blue lines) by grouping hits that belong to the same particle, i.e., by reconstructing the...

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Quantum – HPC hybrid platforms

The EuroHPC JU launched its first quantum computing initiative

Published on 1 December 2021

With funding from the European High Performance Computing Joint Undertaking (EuroHPC JU), the project High-Performance Computer and Quantum Simulator hybrid (HPCQS) kicked off today with the objective of integrating quantum simulators in already existing European supercomputers. Hybrid computing, blending the best of quantum and classical HPC technologies will unleash new innovative potential and prepare Europe for the post-exascale era.

<HPC|QS>

HPCQS

- **European initiative to couple Quantum computing/simulation with HPC**
  - Julich in Germany
  - Bruyère le Châtel in France

More than 100 Qubits operational in 2022-2023

French node – national quantum-HPC hybrid platform

- **Hardware: 3 quantum machine in 2022-2023**
  - Analog quantum computers (eg Atoms)
  - Gate-based QPUs (eg superconducting/trapped ions)
  - Early stage innovative QPUs (eg. photonic, carbon nanotubes, cat qubits, self-stabilized architectures)
- **23M€ to develop usage of QPU**

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  - Deployment
    - WP1: QPU integration, HPC integration, cloud access
    - WP2: Software environment
  - Applications
    - WP3: Optimization and machine learning
    - WP4: Simulation of physical systems
  - Exploration
    - WP5: Noise characterization and mitigation
    - WP6: Quantum links for secure computation

Quantum – HPC hybrid platforms

WP4: Simulation of physical systems

- Ab initio calculation of nuclei
- Quantum chemistry
- Entanglement in solid state physics
- Phase transitions in quantum materials
- Partial differential equation

Academia: CEA, CNRS, INRIA, IPP, Paris-Saclay, Sorbonne, UGA
Industry: ATOS, PASQAL, Qubit Pharmaceuticals

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3

Conclusion: a revolution to come

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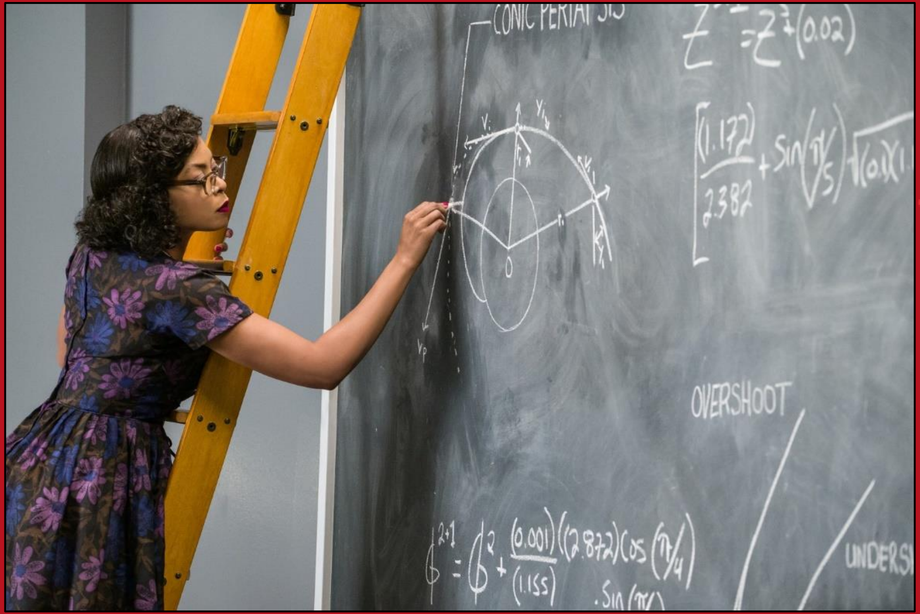
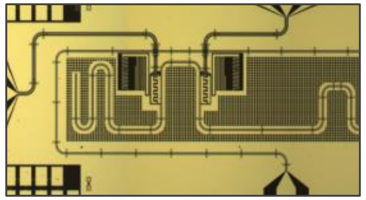
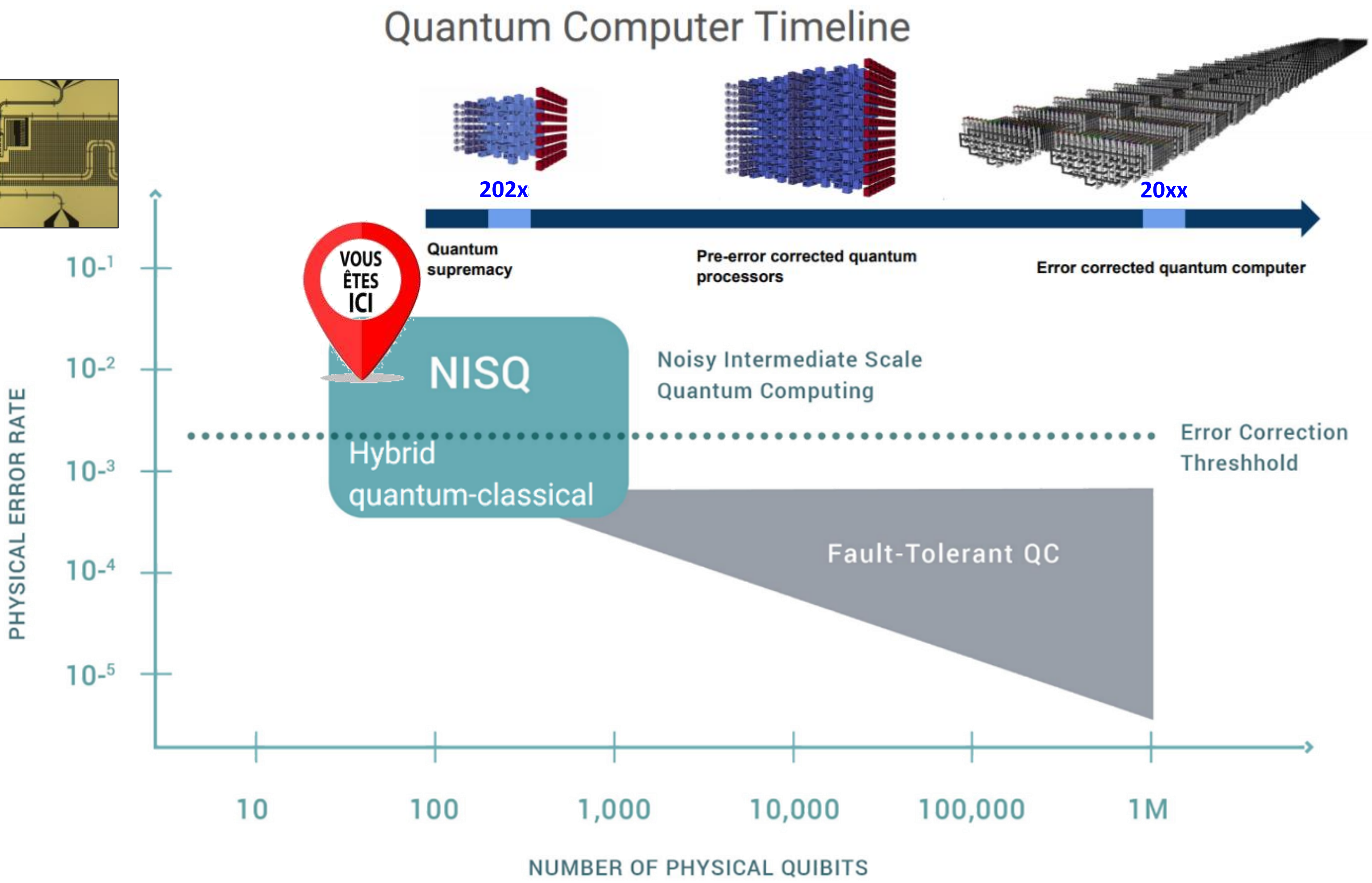


Reduction of quantum errors needed before any applications





FROM RESEARCH TO INDUSTRY

Thank you for your attention