QUANTUM COMPUTING

An overview on the latest QC technologies and future strategies

Gabriella Bettonte, PhD
g.bettonte@cineca.it

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The quantum hype

https://www.elsevier.com/solutions/scopus/research-and-development/quantum-computing-report

Financial Times, Sep 22, https://www.ft.com/content/46b79149-81bd-47d2-98a8-0f60f4cf501a

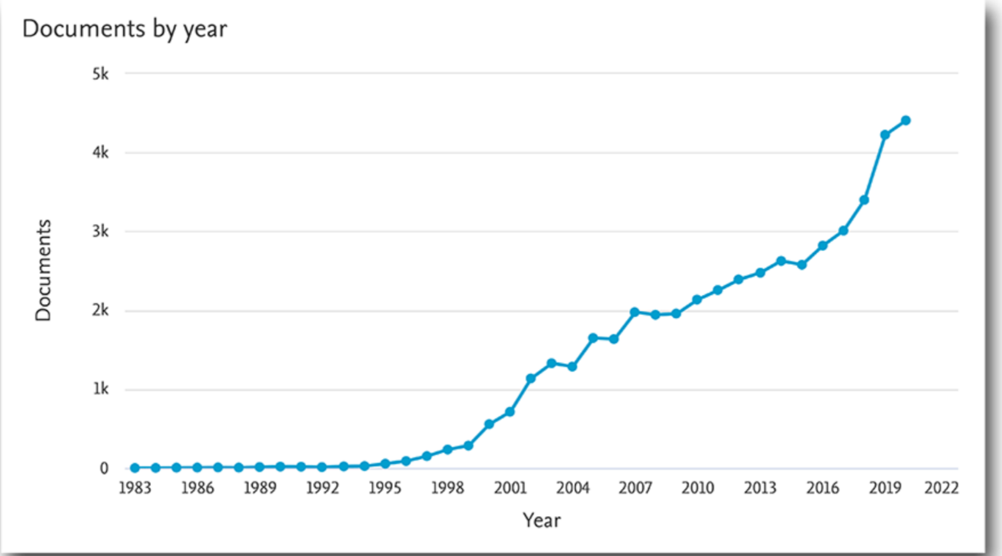
Separating quantum hype from quantum reality

Are the sceptics too sceptical?

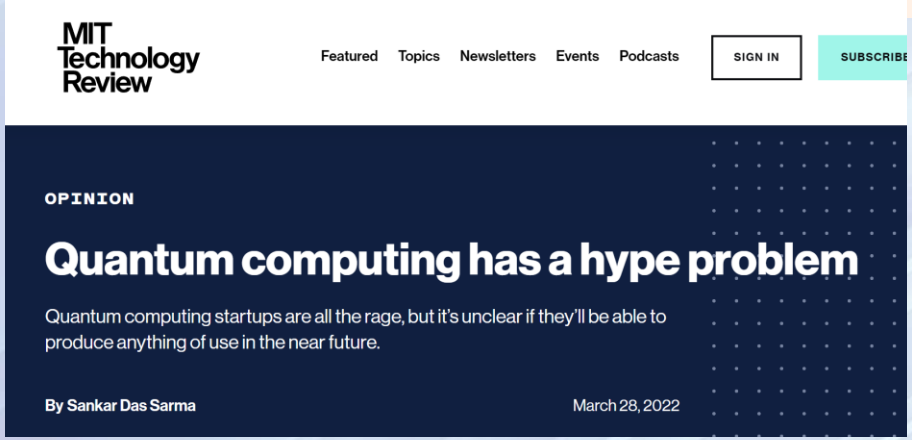
Baidu is the latest company to unveil a prototype quantum computer, © REUTERS

Simon Benjamin SEPTEMBER 2 2022

Publication rate on quantum computing has steeply increased



https://www.technologyreview.com/2022/03/28/1048355/quantum-computing-has-a-hype-problem/



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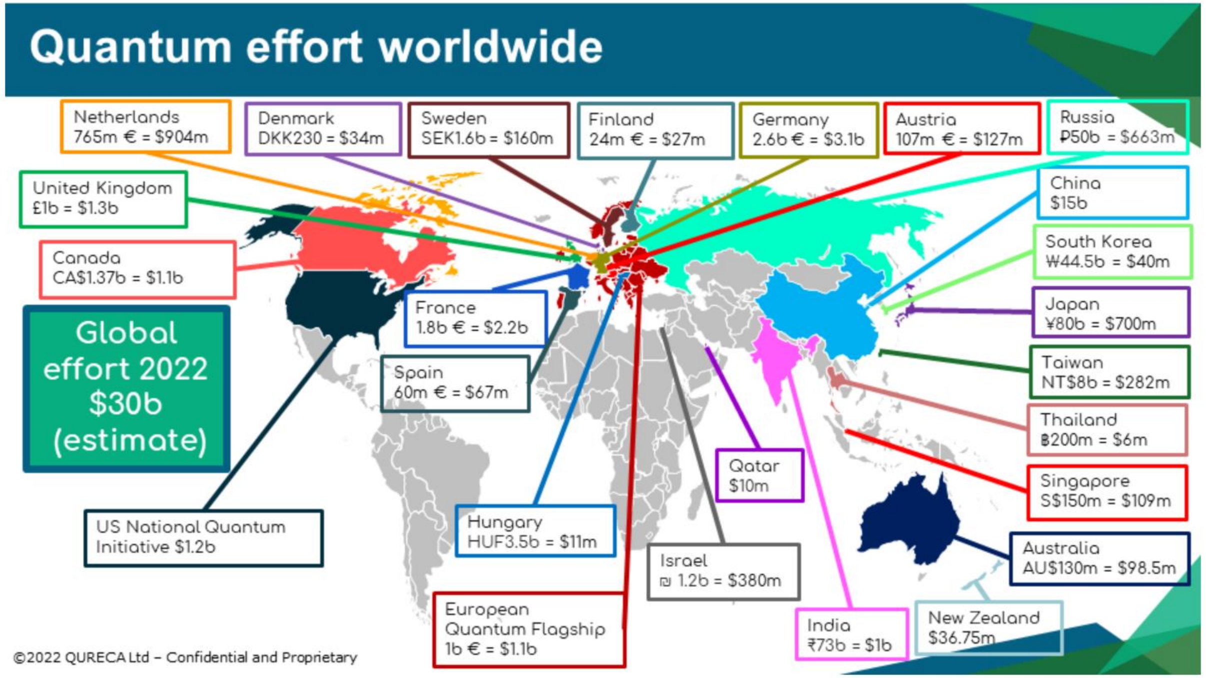
OPINION

Quantum computing has a hype problem

Quantum computing startups are all the rage, but it's unclear if they'll be able to produce anything of use in the near future.

By Sankar Das Sarma March 28, 2022



Overview of public funding in quantum technologies.

https://qureca.com/overview-on-quantum-initiatives-worldwide-update-2022/

Quantum computing in a nutshell

Qubit: a basic unit of quantum information. Each qubit have two pure state vectors $|0\rangle$ and $|1\rangle$. Any state of a qubit is a lineat combination of the two pure states: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$, where $\alpha, \beta \in \mathbb{C}$ and $|\alpha|^2 + |\beta|^2 = 1$

Operators: $|\phi_{t+1}\rangle = U|\phi_t\rangle$

- Unitary $U^\dagger U = UU^\dagger = I$, with I identity matrix and $U^\dagger$ is the conjugate transposed of U
- Reversibile

To describe a **quantum machine**:

- the number of available qubits
- the error rate (or noise) and the decoherence time
- the architecture and the qubits connection
- Gate-based model vs Quantum annealing

Quantum computing timeline

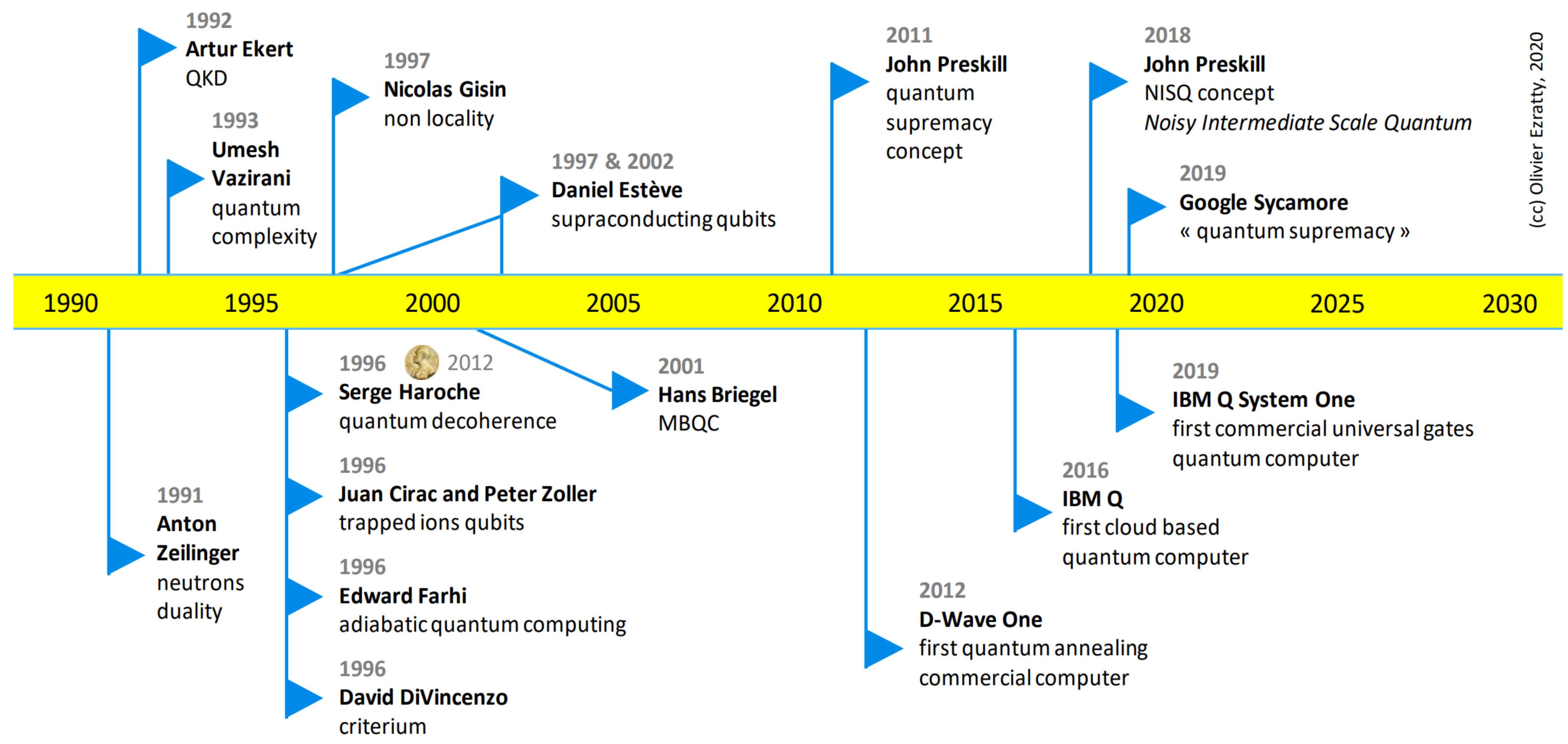


Figure 55: quantum computing key events timeline from 1990 to 2020. (cc) Olivier Ezratty, 2020.

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QC: a very multi-disciplinary subject

physics
- electromagnetism
- quantum physics
- quantum matter
- thermodynamics
- fluids mechanics
- photonics

engineering
- materials design
- electronics engineering
- cryogenics

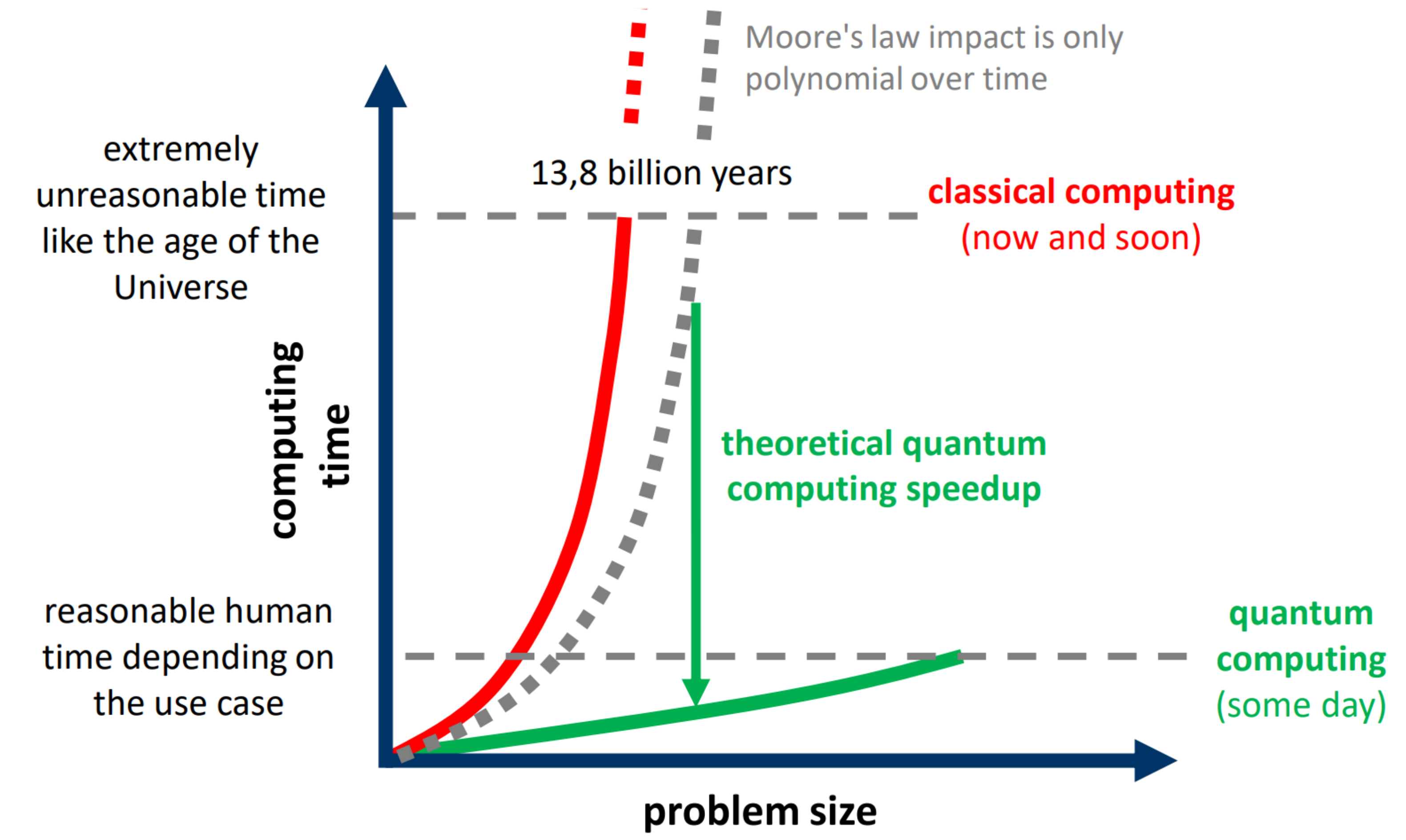
mathematics
- linear algebra
- groups theory
- analysis
- complexity theories

computer science
- information theory
- algorithms design
- programming
- classical computing
- telecommunications

human sciences
- philosophy
- epistemology
- sociology
- technology ethics
- economics of innovation
- R&D policy making
- geopolitics
- startups ecosystem

Figure 3: the many scientific domains to explore when being interested in quantum technologies. That's why you'll love this book if you are a curious person. (cc) Olivier Ezratty, 2021-2022.

Why Quantum Computing?

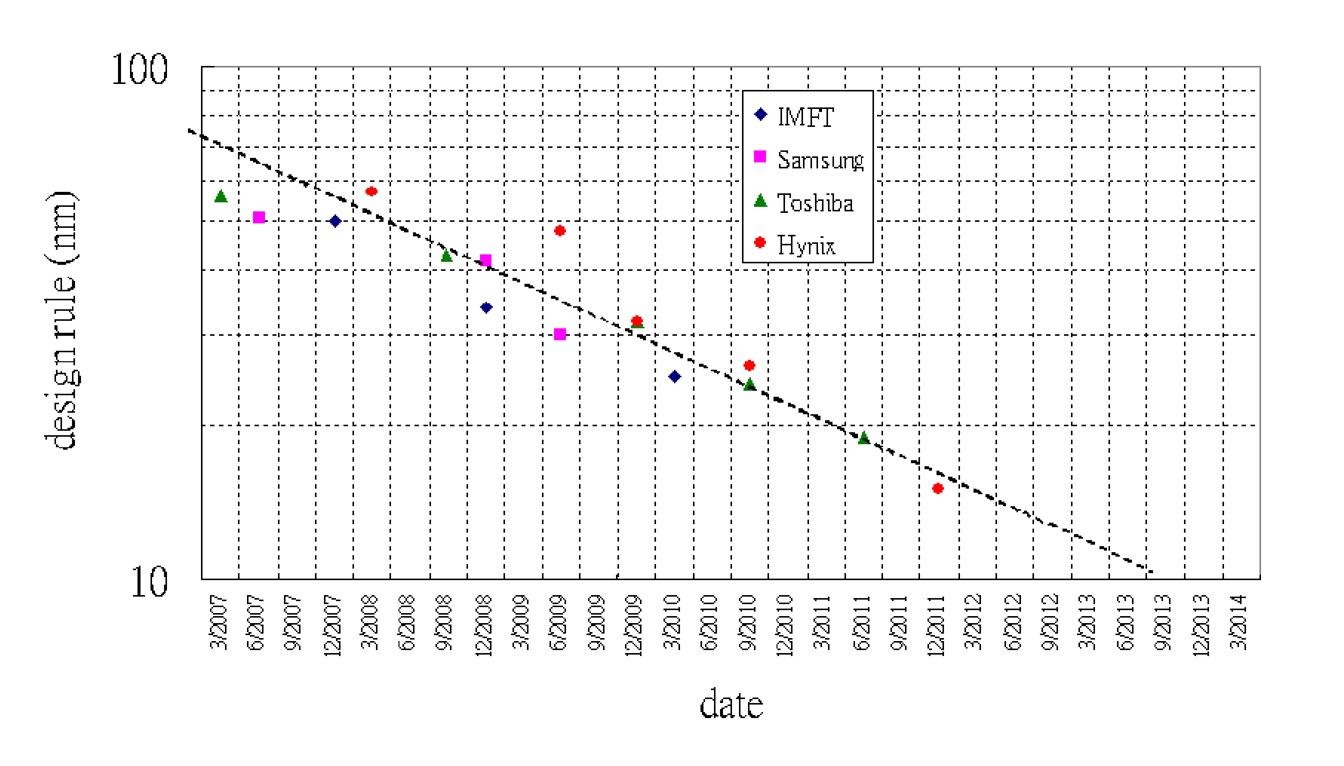


solving intractable / exponential problems in reasonable time

Figure 6: simplified view of the quantum computing theoretical promise. Before delivering this promise, quantum computers may bring other benefits like producing better and more accurate results and/or doing this with a smaller energy footprint. (cc) Olivier Ezratty, 2022.

Why Quantum Computing?

Moore's Law predicted successfully that the size of transistors would halve every two years, but now it seems to have reached its limit.



transistors are approaching a size s.t. the laws of quantum mechanics impact their functioning

Reference: [EETimes article on NAND scaling, 3/22/2010]

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Potential applications of QC

ISSUES:

1. Quantum computers enable substantial **speed-up** to a small set of computational problems.
2. For other problems, quantum computers **do not seem** to perform better than classical computers
3. Decoherence: unwanted interaction between a quantum computer and its environment (nearby electric fields, warm objects...) → solution: quantum error correction.

The three main areas that the quantum computing revolution **may** impact are:

- cryptography,
- optimization,
- simulation of quantum systems

Quantum Computing is different

QUANTIZED COLUMNS

What Makes Quantum Computing So Hard to Explain?

22

To understand what quantum computers can do — and what they can't — avoid falling for overly simple explanations.

"Quantum computers aren't the next generation of supercomputers – **they're something else entirely.**"
Scott Aaronson

→ we need to understand the fundamental physics that drives the theory of quantum computing.

Quantum vs Classical

For small *problems* solving it with a quantum computer will be **slower** and **more expensive** than solving it classically → only as *the problem size* grows the quantum speedup appears

The difficulty is not so much proving that a quantum computer can do something quickly, but convincingly arguing that a classical computer can't!

conjectured quantum speedups have repeatedly gone away when classical algorithms were found with similar performance:

Quantum Recommendation Systems

Iordanis Kerenidis * Anupam Prakash †

September 23, 2016

Abstract

A recommendation system uses the past purchases or ratings of n products by a group of m users, in order to provide personalized recommendations to individual users. The information is

A quantum-inspired classical algorithm for recommendation systems

Ewin Tang

May 22, 2018

Abstract

A recommendation system, which suggests products to users based

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Quantum computers

There is not just one category of quantum computers, but many!

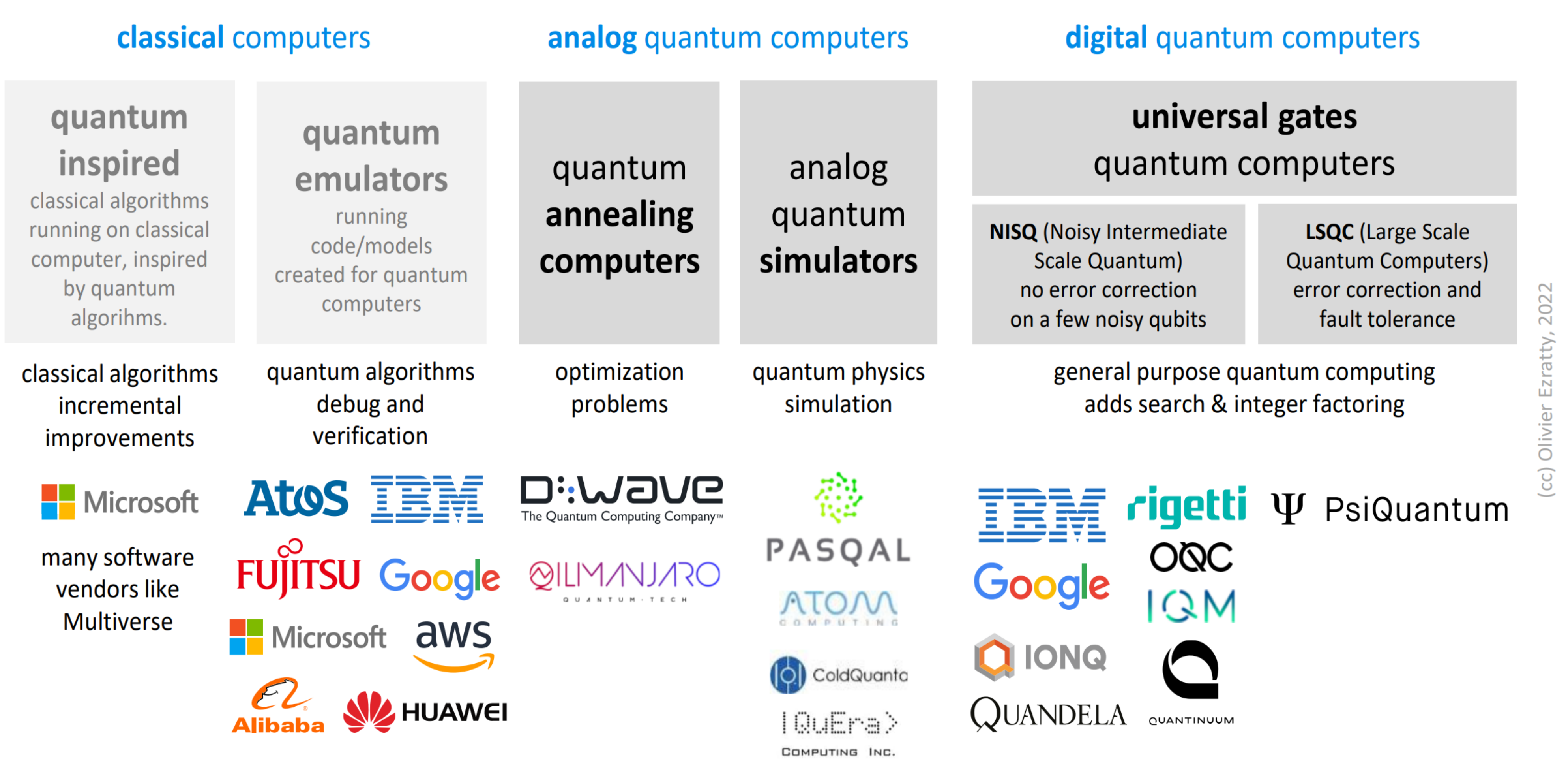

Figure 203: the different computing paradigms with quantum systems, hybrid systems and classical systems. (cc) Olivier Ezratty, 2022.

Quantum computing hardware

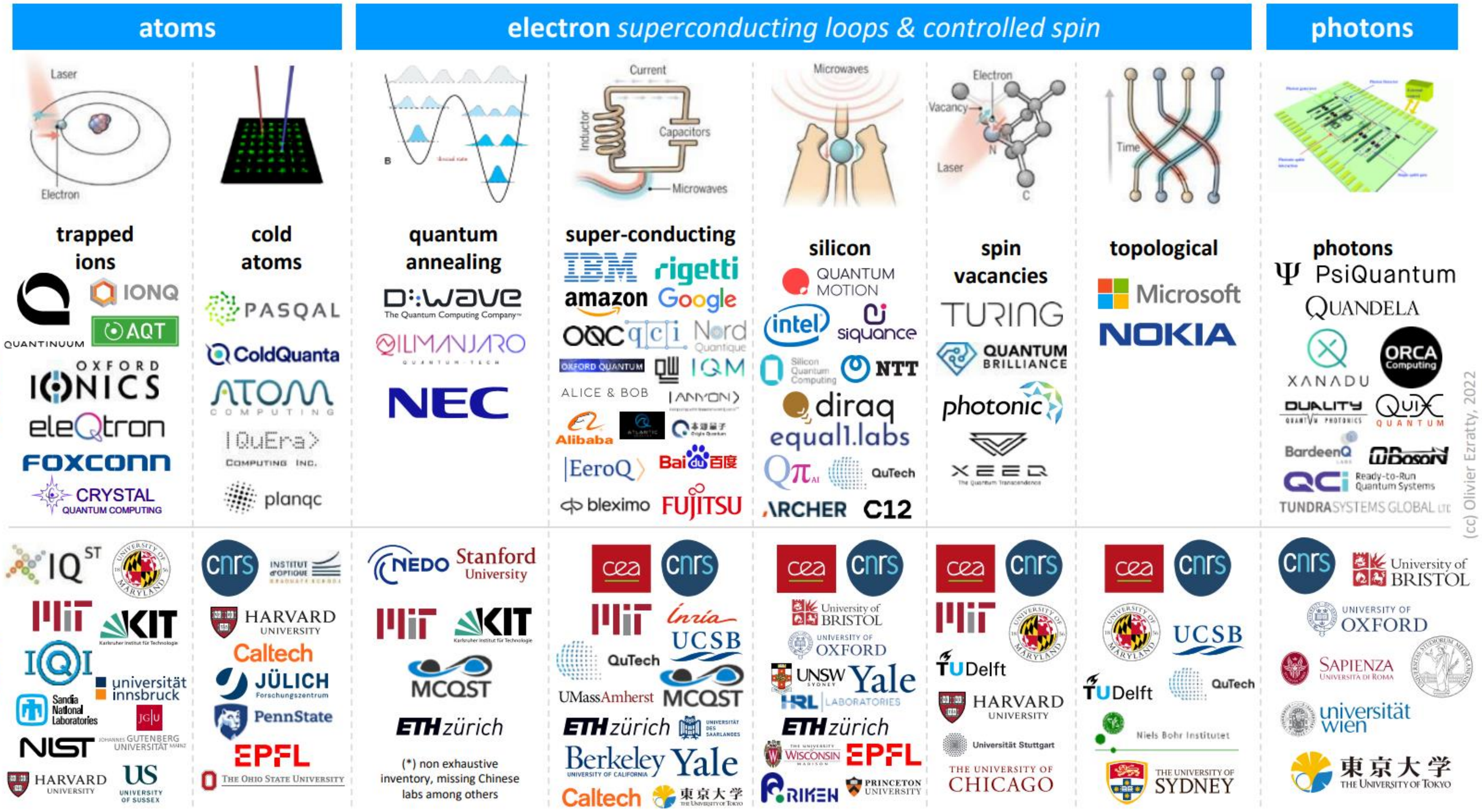

Figure 263: a map of key research lab and industry vendors in quantum computing hardware per qubit type. (cc) Olivier Ezratty, 2022. Qubits drawing source: Scientists are close to building a quantum computer that can beat a conventional one by Gabriel Popkin in Science Mag, December 2016. I consolidated the logos lists since 2018. It's incomplete for the research labs at the bottom but rather exhaustive for the vendors at the top.

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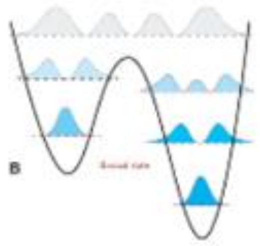
Quantum annealing

Quantum computing paradigm and technology based on the adiabatic theorem



quantum annealing

D-Wave
The Quantum Computing Company

QILIMANJARO
QUANTUM TECH

NEC

quantum annealers

- mature **development tools** offering.
- large number of **software startups**, particularly in Japan and Canada.
- quantum annealers are available in the **cloud** by D-Wave and Amazon Web Services.
- the greatest number of well documented **case studies** in many industries although still at the proof of concept stage.
- most universal qubits gates algorithms can be have an equivalent on quantum annealing.

- only **one operational commercial vendor**, D-Wave.
- computing **high error rate.**
- no **operational proof** of quantum advantage.
- **most commercial applications** are still at the pilot stage and not production-scale grade but this is also the case for all gate-based quantum computers.
- **all algorithms are hybrid**, requiring some preparation on classical computers.

Figure 270: quantum annealers pros and cons. (cc) Olivier Ezratty, 2022.

Superconducting

Superconducting qubits are the most common nowadays

Noisy and do not scale well

superconducting qubits

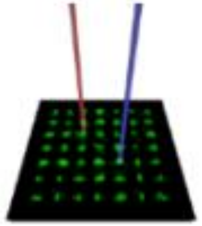
- **key technology** in public research and with commercial vendors (IBM, Google, Rigetti, Intel, Amazon, OQC, IQM, etc).
- **record of 127 programmable qubits** with IBM.
- constant progress in **noise reduction**, particularly with the cat-qubits variation which could enable a record low ratio of physical/logical qubits.
- many existing **enabling technologies**: cryostats, cabling, amplifiers, logic, sensors.
- **potentially scalable technology** and deployable in 2D geometries.

- **qubit coherence time usually** < 300 µs.
- high **qubits noise levels** with most vendors.
- **cryogeny constrained** technology at <15 mK.
- **heterogeneous qubits** requiring calibration and complex micro-wave frequency maps.
- **cabling complexity** and many passive and active electronic components to control qubits with micro-waves.
- **qubit coupling limited** to neighbor qubits in 2D structures (as compared with trapped ions).
- **qubits size** and uneasy miniaturization.

Figure 279: superconducting qubits pros and cons. (cc) Olivier Ezratty, 2022.

Cold atoms

- scale up to a thousand qubits
- potentially also be used in gate-based quantum computing



cold atoms

PASQAL

ColdQuanta

ATOM COMPUTING

|QuEra⟩ COMPUTING INC.

planqc

cold atoms qubits

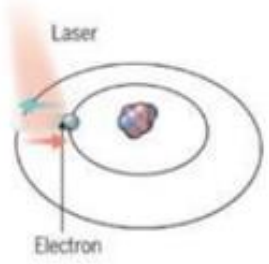
- long qubit **coherence time and fast gates**.
- **operational systems** with 100-300 atoms.
- **identical atoms**, that are controlled with the same laser and micro-wave frequencies (but dual-elements architectures are investigated).
- works in both **simulation** and **gate-based** paradigms, but still with difficulty for gate-based.
- **reuse trapped ions qubits tools** for qubits readout with fluorescence and CCD/CMOS detection.
- no need for specific **integrated circuits**.
- uses **standard apparatus**.
- low **energy consumption**.

- **acceptable quantum gates error rate** although not “best in class”.
- **crosstalk** between qubits that can be mitigated with two-elements systems.
- **adapted to simulation** more than to universale gates computing.
- not yet operational QND (quantum non demolition) measurement that is required for QEC and FTQC.
- control **lasers and optical** not scaling well beyond one thousand qubits with the current state of the art.

Figure 398: pros and cons of cold atoms quantum computers and simulators. (cc) Olivier Ezratty, 2022.

Trapped ions

- best fidelities so far
- hard to scale beyond about 40 qubits



trapped ions

QUANTINUUM
IONQ
AQT
OXFORD IONICS
eleQtron
FOXCONN
CRYSTAL QUANTUM COMPUTING

trapped ions qubits

- **identical ions** => no calibration required like with superconducting/electron spin qubits.
- **good qubits stability** with best in class low error rate.
- **long coherence time** and high ratio between coherence time and gate time => supports deep algorihms in number of gates.
- **entanglement** possible between all qubits on 1D architecture. It speeds up computing.
- works at **4K to 10K** => simpler cryogeny than for superconducting/electron spins.
- **easy to entangle ions with photons** for long distance communications.

- **entanglement** doesn't seem to scale well with a large number of ions.
- **questionnable scalability options** beyond 50 qubits (ions shuttling, 2D architectures, photon interconnect).
- **relatively slow computing** due to slow quantum gates which may be problematic for deep algorithms like Shor integer factoring.

Figure 375: pros and cons of trapped ions qubits. (cc) Olivier Ezratty, 2022.

Quantum algorithms

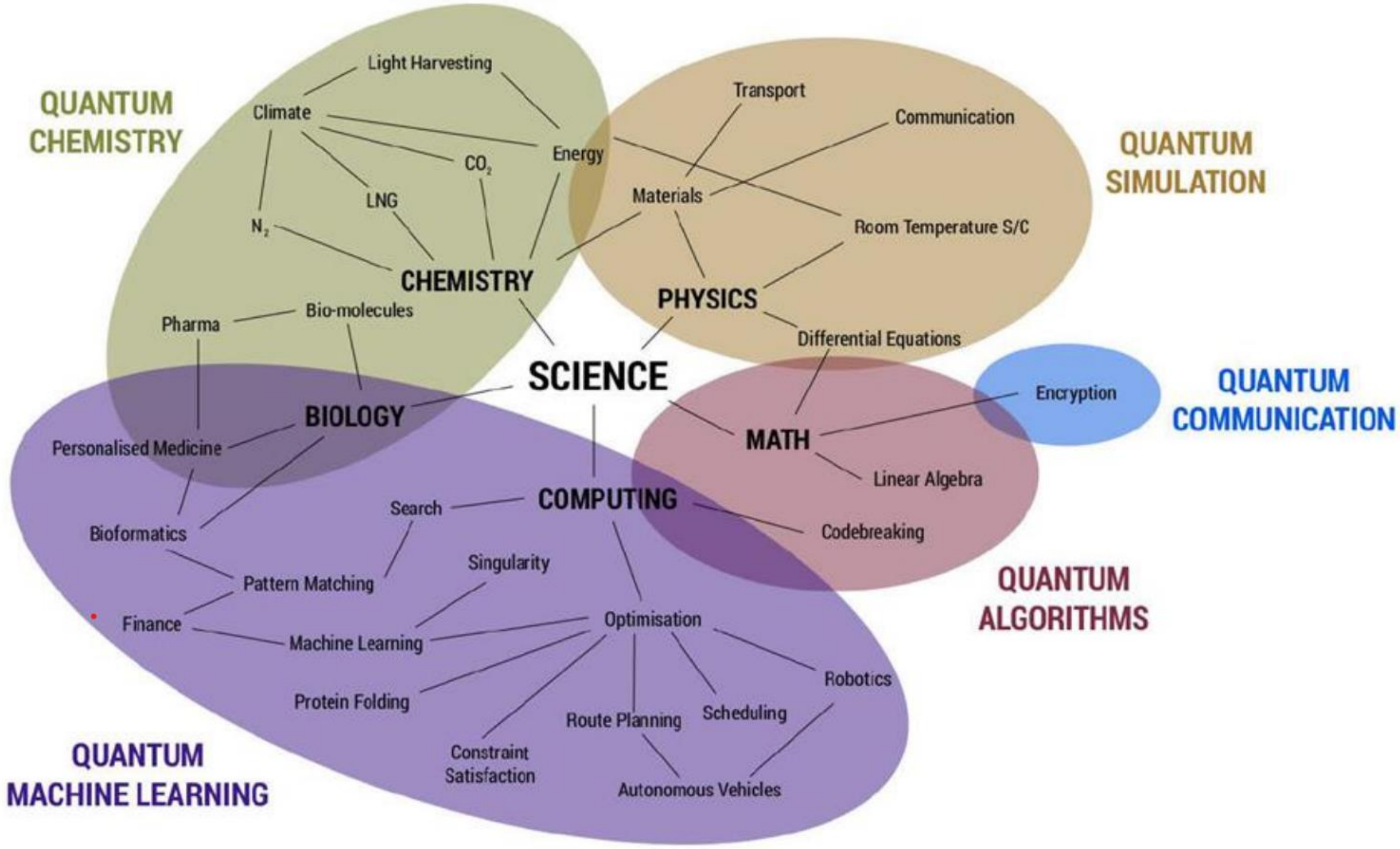
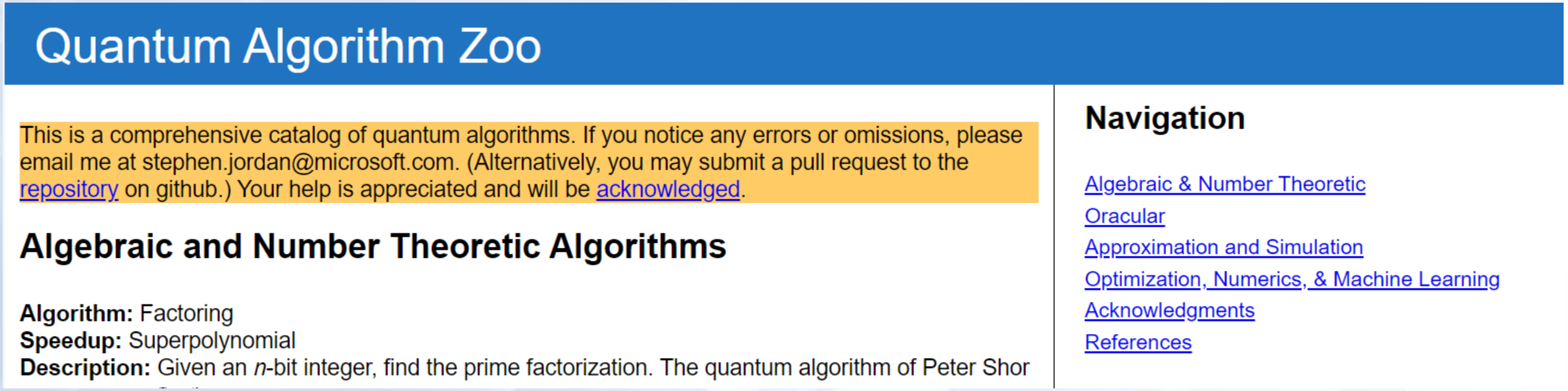


Figure 551: the breadth of science domains covered by quantum algorithms. Source: [Silicon Photonic Quantum Computing](#) by Syrus Ziai, PsiQuantum, 2018 (72 slides).

Quantum algorithms



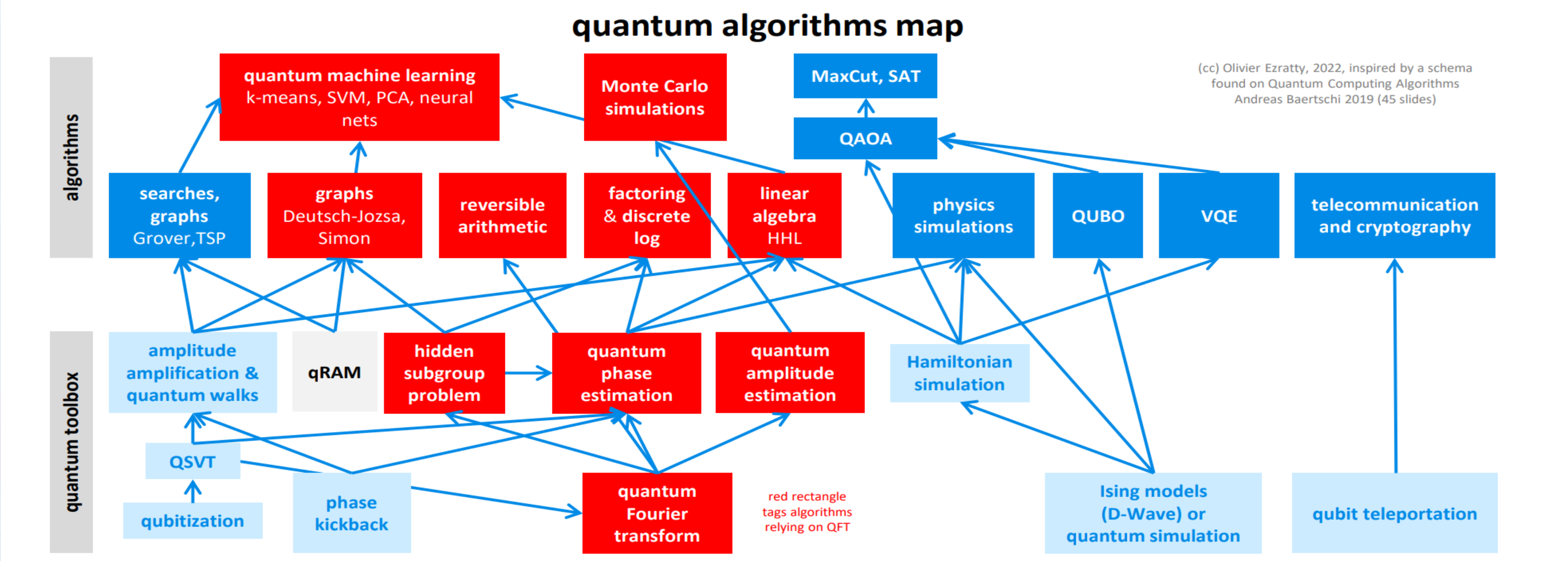


Figure 553: a quantum algorithms map and their interdependencies. One interesting example comes with QSVT which can be used to generate search, phase estimation and Fourier transforms. (cc) Olivier Ezratty, 2022, inspired by a schema found on Quantum Computing Algorithms by Andreas Baertschi, 2019 (45 slides).

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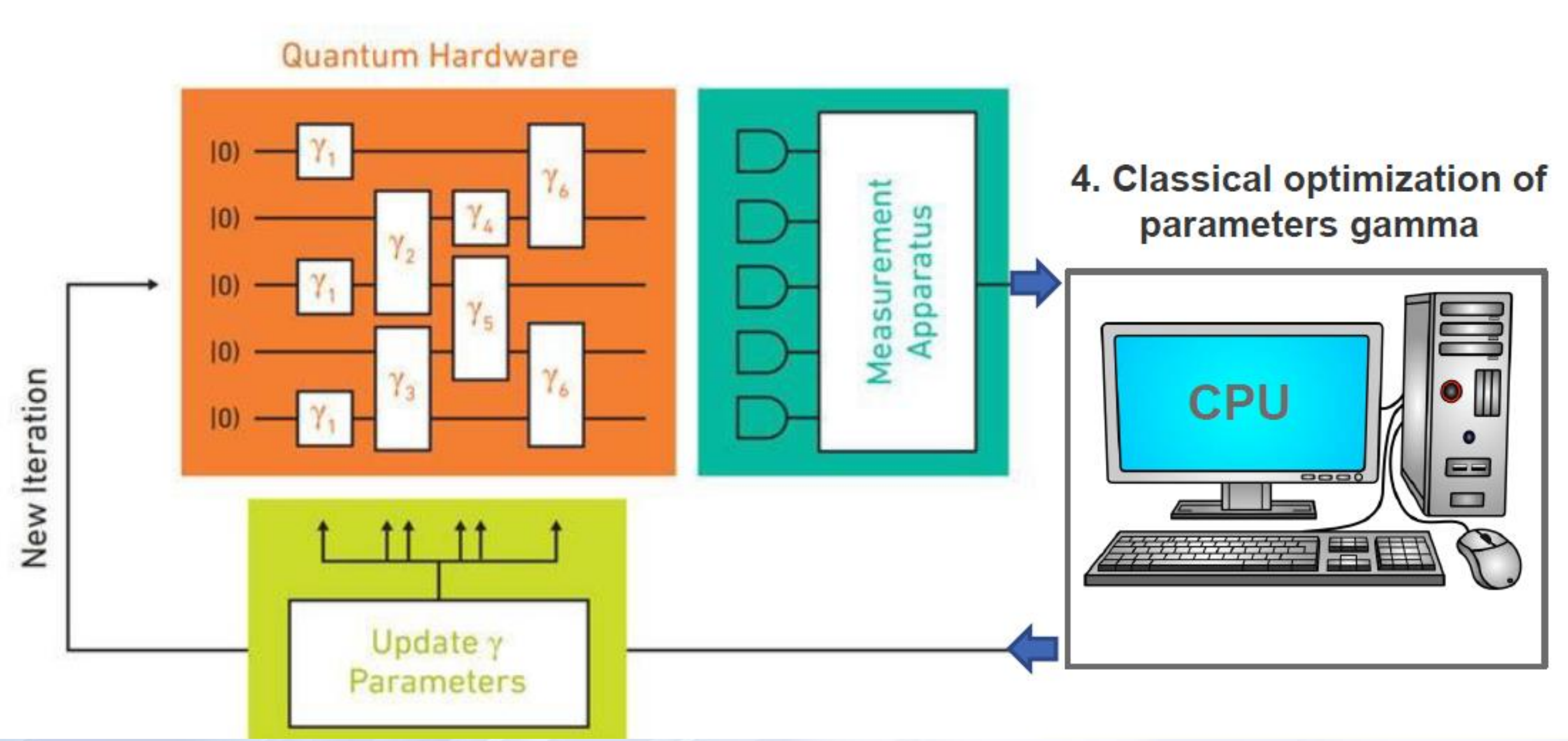
HPC and Quantum computing



Take home message

Quantum computing is not :

- a magical solution.
- a replacement tool to current High-Performance Computers (HPC)

Most of today’s classical computing problems and software are not at all relevant use cases for QC.

As consequence:

- QC will not entirely replace classical legacy technologies.
- QC is a complement to HPC instead of being a replacement technology.

probably we won’t have a quantum desktop, laptop or smartphone to run our usual digital tasks!

Cineca Quantum Computing Lab

Teaching, Outreaching and Dissemination

CINECA ACADEMY

European and National projects

⟨HPC|QS⟩

EURO

Fondazione ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

WCRI - QCSC

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Quantum Computing Resources

Cloud QC

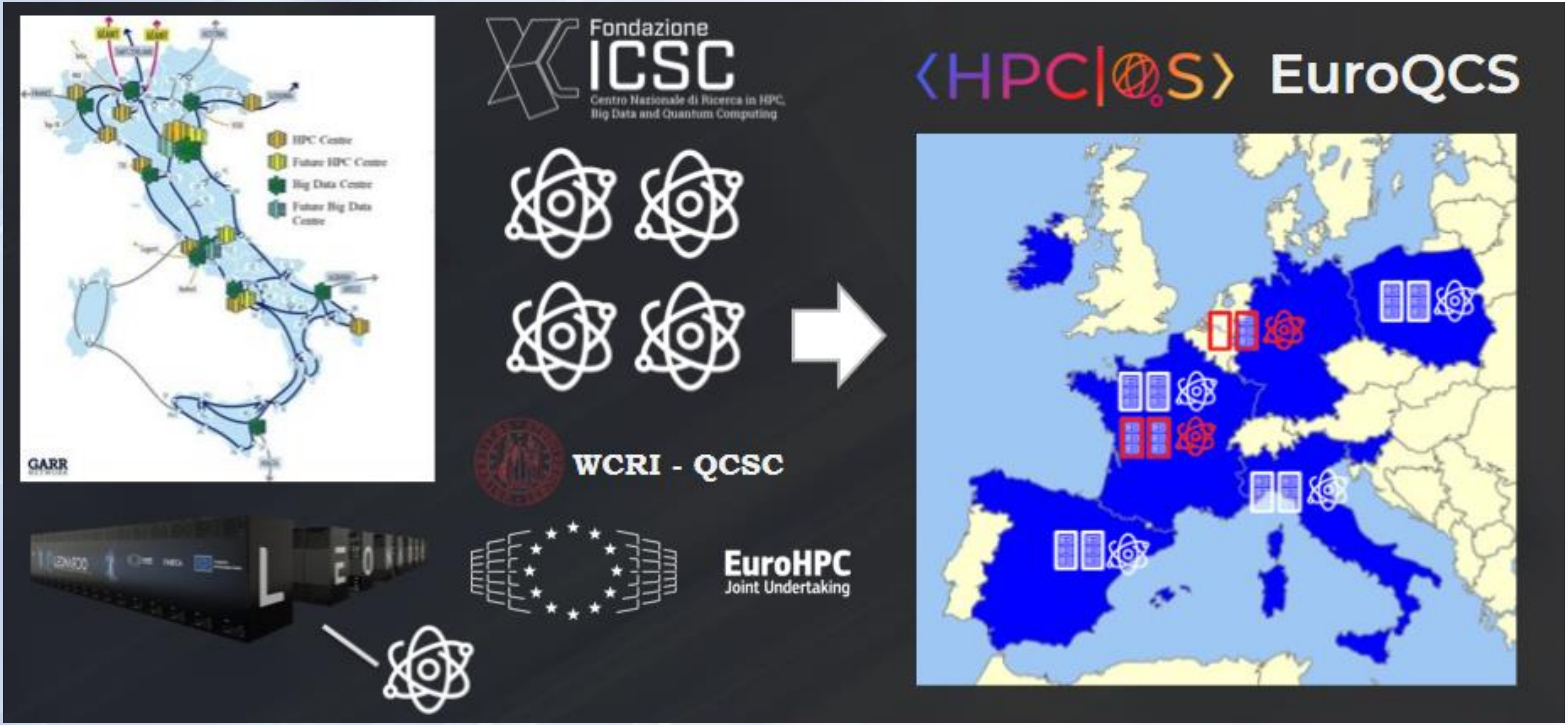
D-Wave — The Quantum Computing Company

?

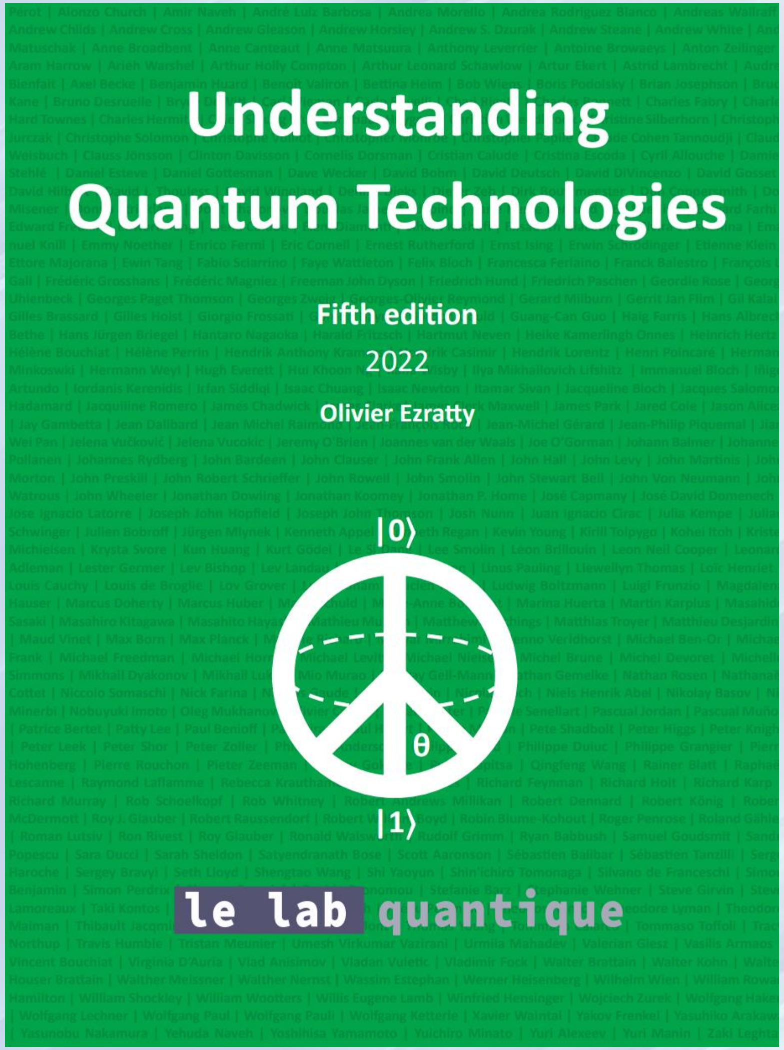
PASQAL

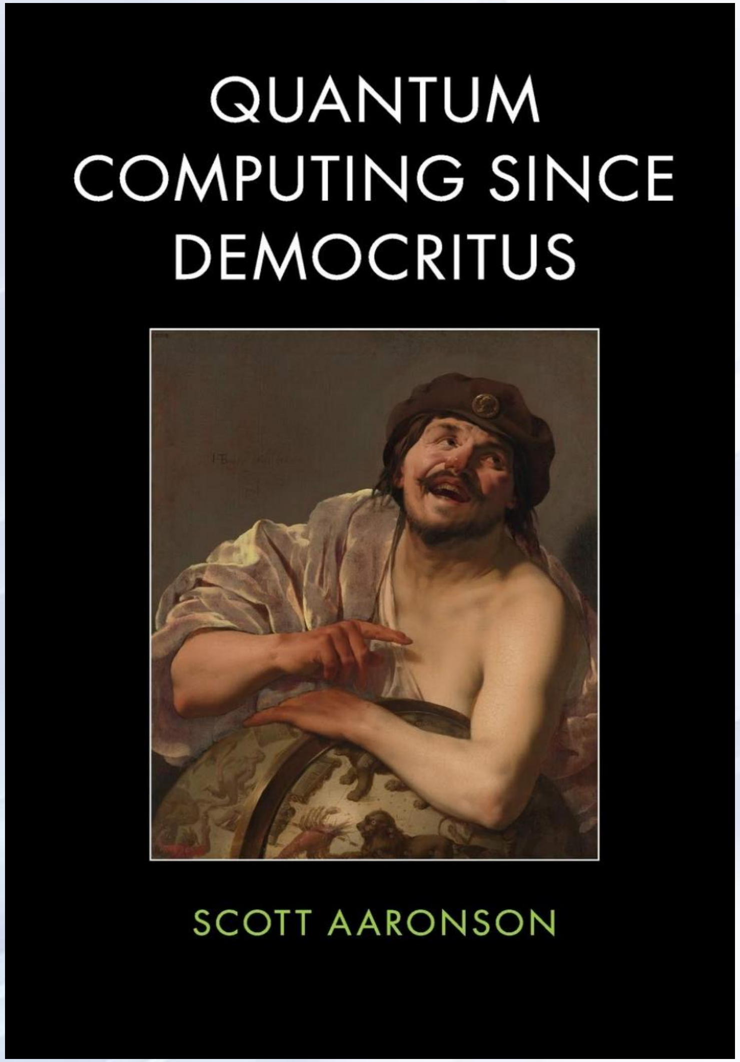
Hybrid HPC-QC System

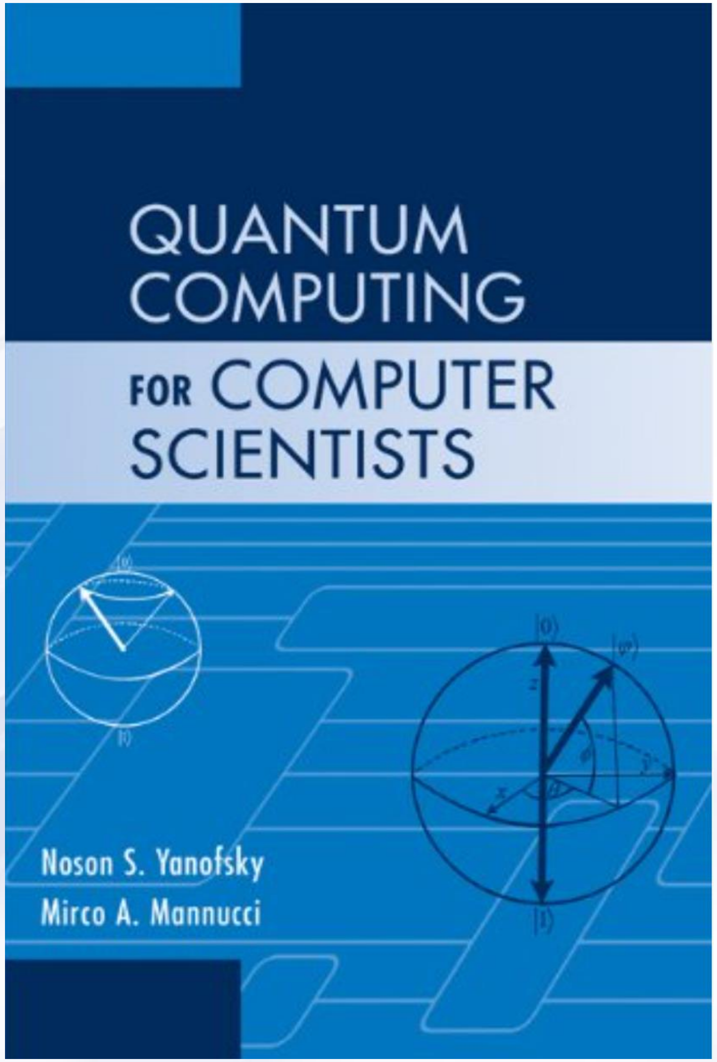
Italian and European QC



Some introduction references







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