EPFL

Master in Quantum Science and Engineering

Nicolas Macris

Masters days
EPFL, 26 & 27 Février 2025

École
polytechnique
fédérale
de Lausanne

A cross-faculty master program!
of the three schools
Basic Sciences, Engineering, and
Computer and Communication Sciences

Section de Science et Ingénierie Quantiques

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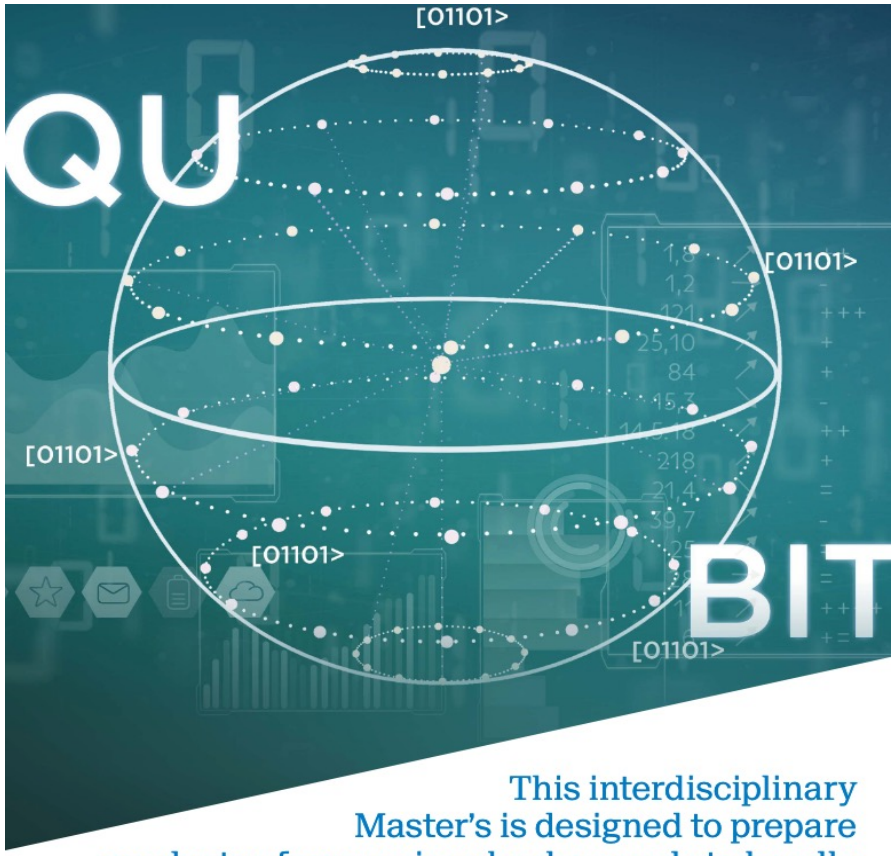


This interdisciplinary Master's is designed to prepare graduates from various backgrounds to handle the new paradigm shift brought by Quantum science and technology in the way we treat data, communicate, measure and compute. Thanks to their broad vision of diverse aspects of the field, they will have the ability to thrive in this new technology frontier which has the disruptive potential to revolutionize our society.

This program aims to train a new generation of quantum proficient engineers & physicists to take part in the "second quantum revolution"

Engineers and physicists that understand and use the quantum paradigm shifts in:

- Computation (algorithmics, optimization)
- Information processing (communications, cryptography)
- Simulation (physics, chemistry, material science)
- Metrology and sensing

Diploma and title awarded:

MSc Science et ingénierie quantiques - MSc Quantum science and engineering

Ingénieur en science quantique (ing. quant. dipl. EPF)

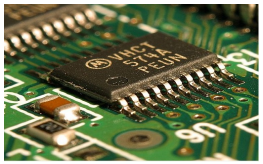
- Consecutive master for physicists and chemists EPFL
- Other sections you must apply until 31 March

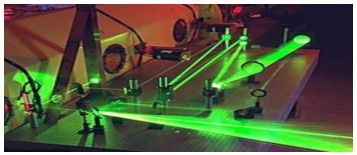
The second quantum revolution: what is it about ?

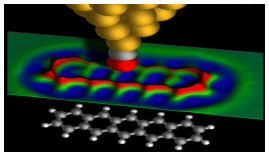
Laws of quantum physics known since the 1930's have led to our modern understanding of the atomic nature of matter, and all solid state phenomena, and photonics and much more…

Major role in modern technology of integrated circuits, lasers nanotechnology, microscopy, imaging,…

This has completely reshaped our world







These devices process information/signals classically → 0111000111001010 → classical bits

But one can use quantum laws at their heart to process information in radically new ways
(*Pionners of the 80's*: *Benioff, Landauer, Wiesner, Feynman, Deutsch, Bennett,…*)

The concept of quantum bit – the QUBIT – is the new unit of information: $a|0\rangle + b|1\rangle$

It behaves radically differently than classical bits and offers new computational resources !

QSE leads to paradigm shifts and applications many areas:

- **Information Processing:** quantum communication (e.g. teleportation), cryptography, quantum networks, distributed information, error correction, memories, random number generators,…

- **Sensing and Metrology:** photon detectors and counters, gravimeters, accelerometers, cold atom interferometers, magnetometry, atomic and optical clocks,…

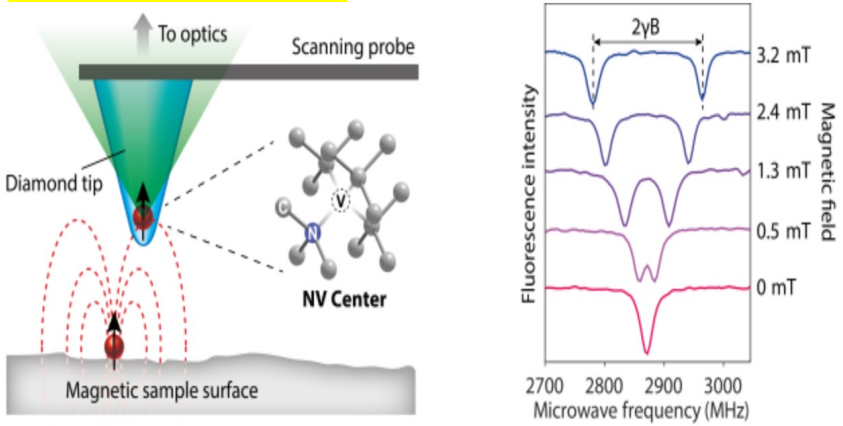
- **Computation:** quantum algorithms, optimization, quantum machine learning, sampling, complexity theory,…

- **Simulation:** dynamics of physical systems, low temperature phases of matter, quantum chemistry, material science, drug discovery, climate,…

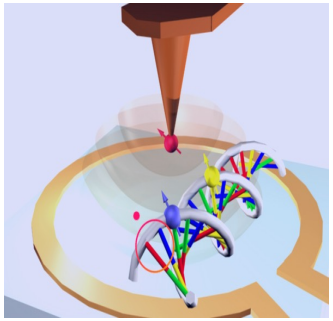
All this impacts science, engineering, and our society!

A few examples: from sensing and metrology

Magnetometry with Nitrogen Vacancy centers in diamond

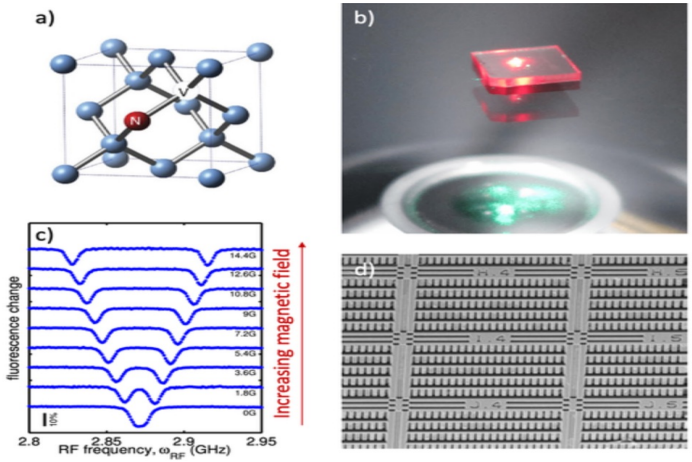


(source Qzabre)



Sensing Biomolecules with applications in

- biology,
- medtech industry,…



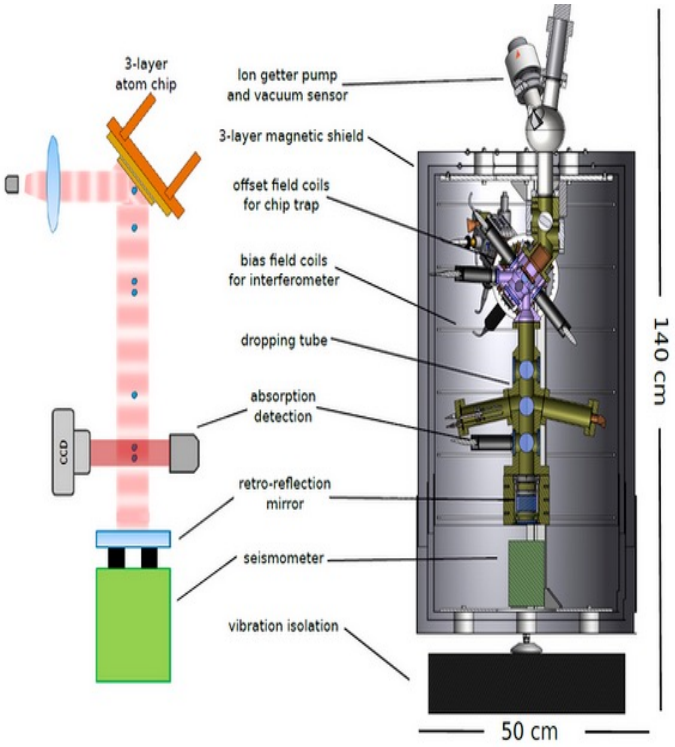
(Source: Qnami)

Measurement of very weak magnetic fields.

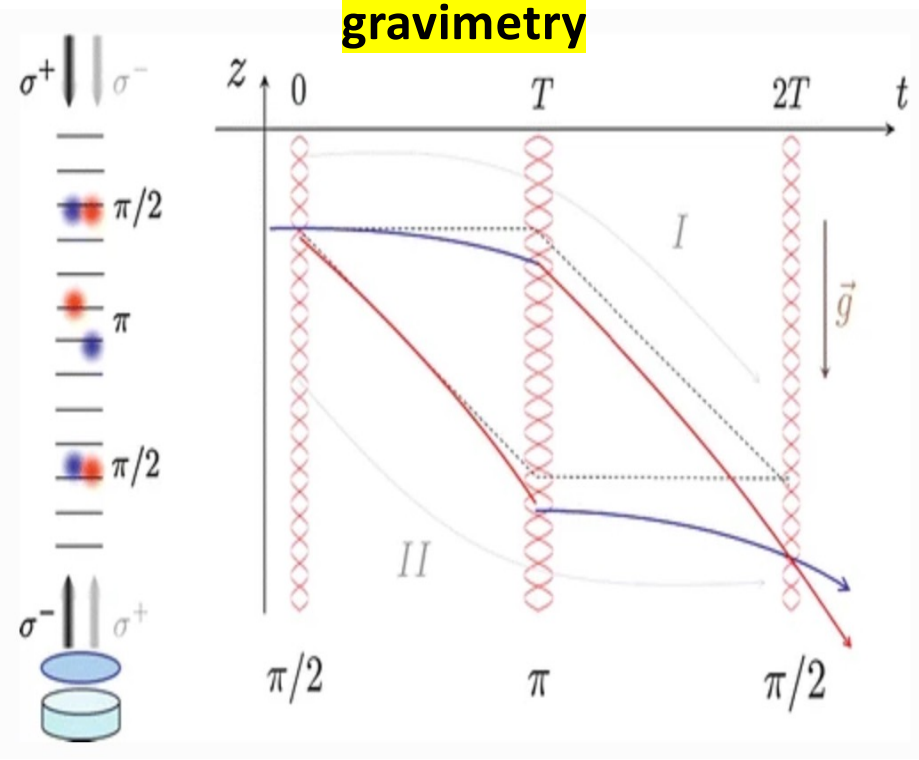
Impacts medical imaging – e.g. for

- brain,
- Magneto-cardiograms

Examples: from sensing and metrology



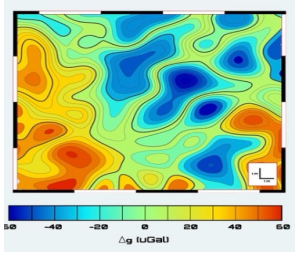
Cold atom interferometry for gravimetry



Path of falling cloud of cold atoms is separated and reunited by light pulses.

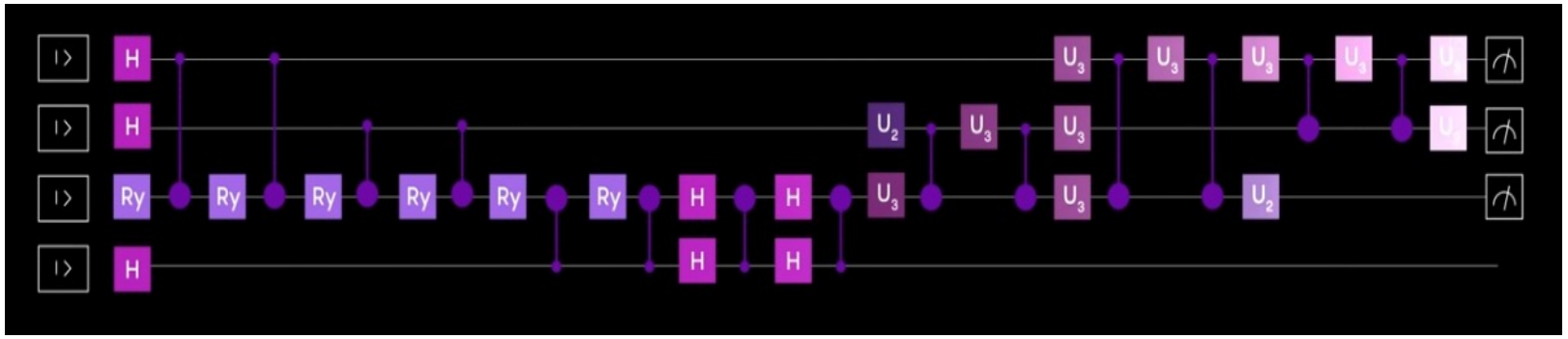
Interference of quantum waves gives information on gravity field.

- Applications to measurement of weak gravitational fields, accelerometers → e.g underground resource exploration.
- Fundamental physics tests in gravitation research.

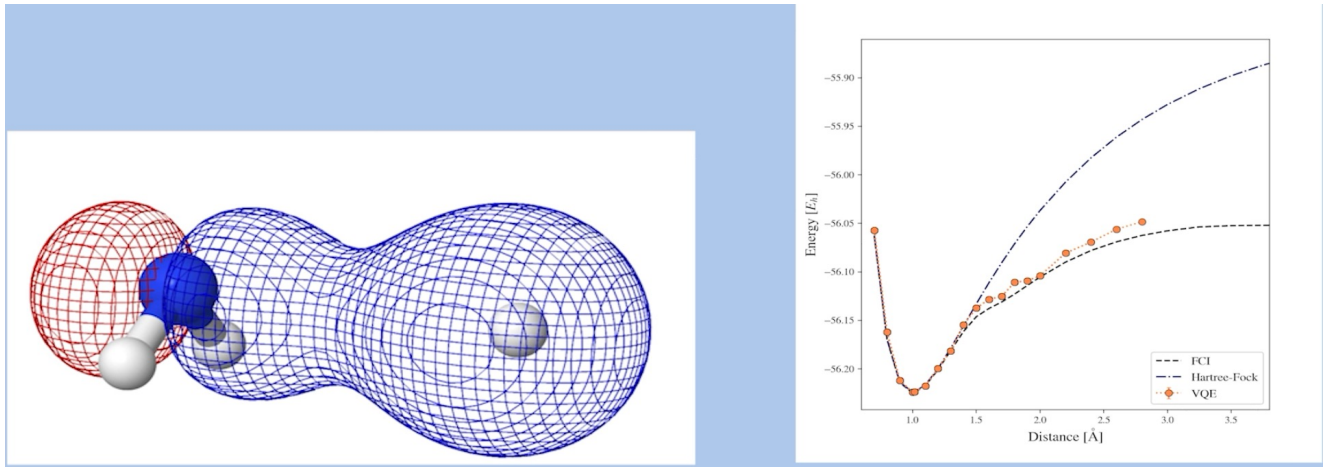


Examples: from computation and simulation

Quantum algorithms and circuits for computation (factoring, algebra, optimization, ML,…)



Sequence of QUBIT GATES: time flows left to right

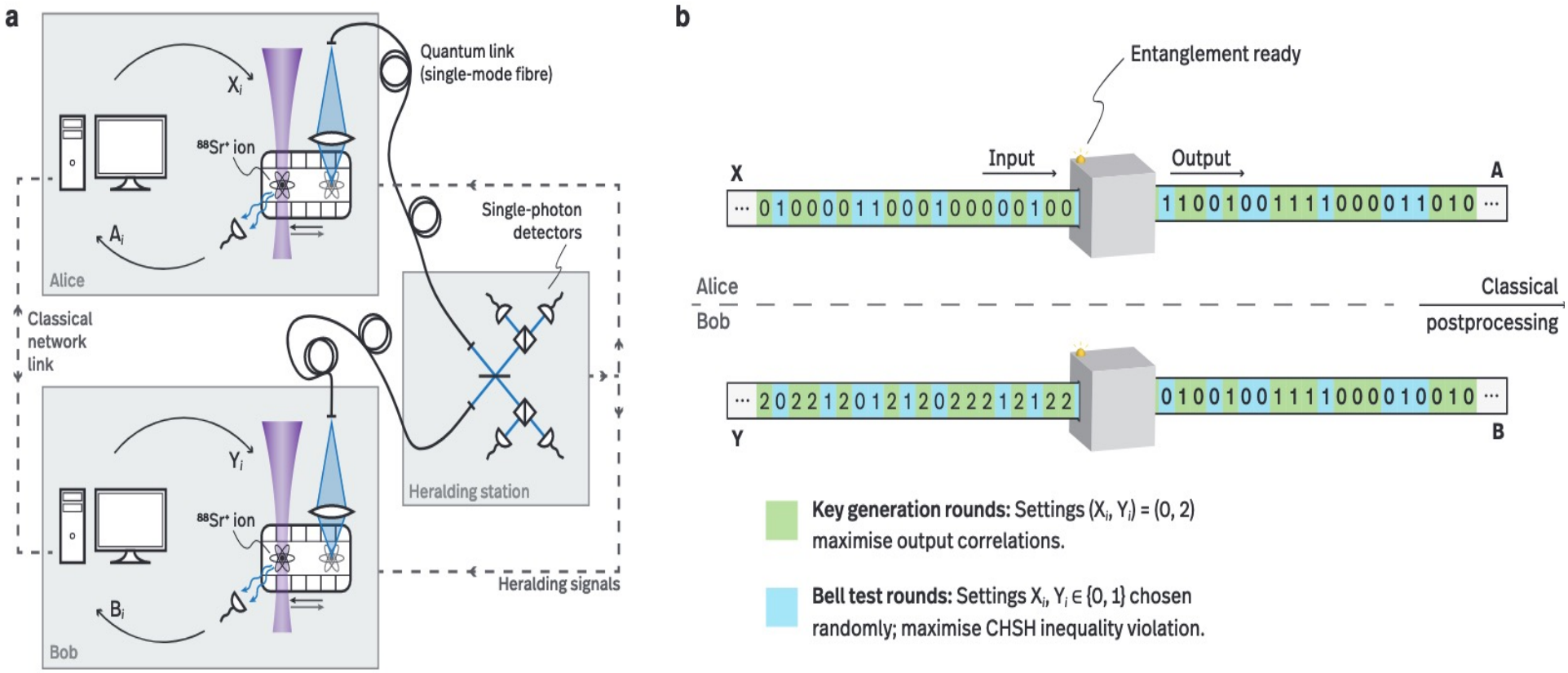


Simulation of physical systems

e.g., for quantum chemistry. Here the ammonia molecule NH_3

Examples: from quantum communication

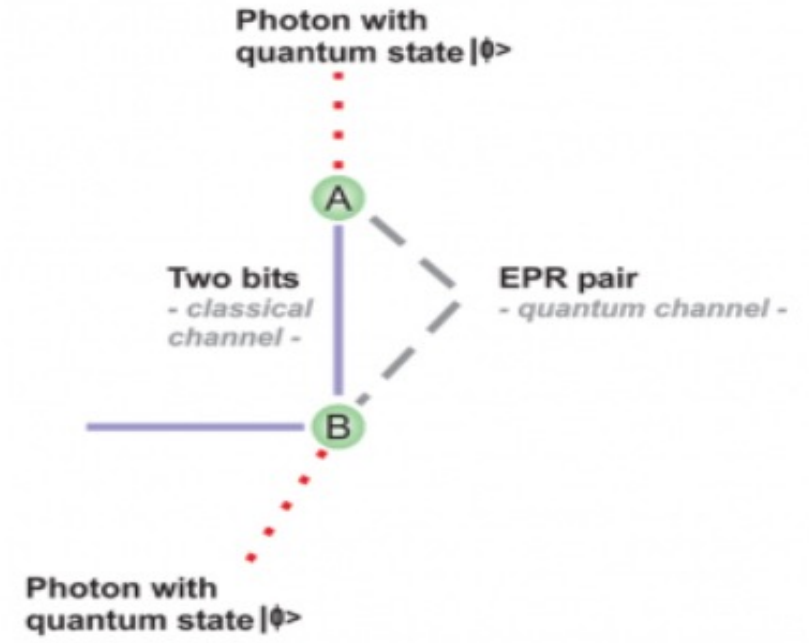
Quantum Secret Key Distribution for cryptography



Ref: Nadlinger et al, Nature 607, 682-686 (2022)

Examples: from quantum communications

Quantum Teleportation: a fundamental protocol using entanglement as a quantum resource,



Initial state:

$$|\Phi\rangle_A \otimes |\mathrm{EPR}\rangle_{AB} = |\Phi\rangle_A \otimes \frac{|00\rangle_{AB} + |11\rangle_{AB}}{\sqrt{2}}$$

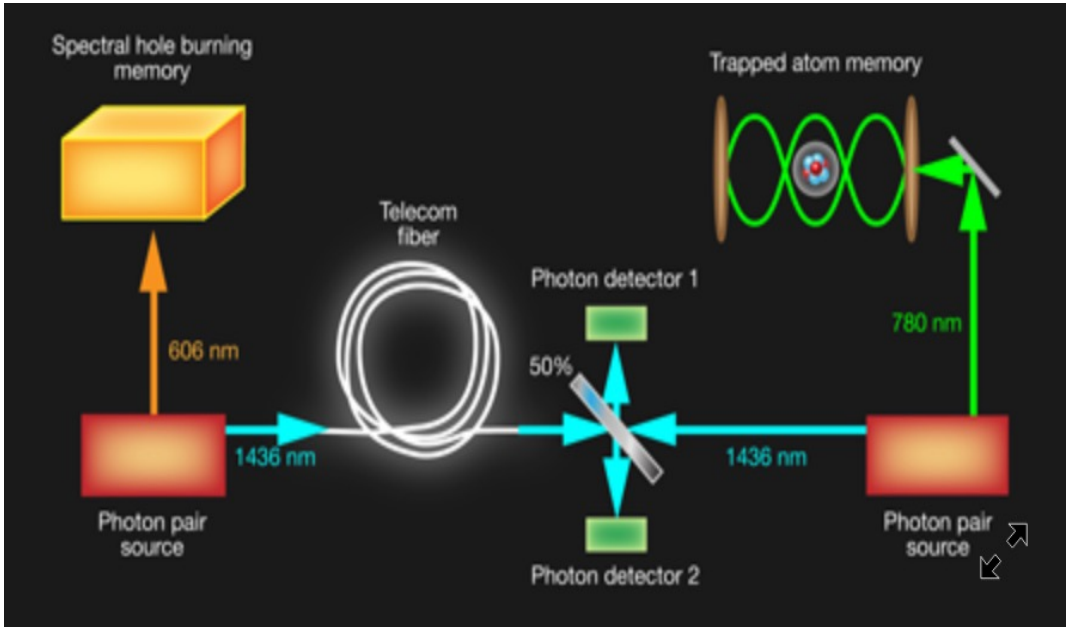
Final state after teleportation protocol:

$$|\widetilde{\mathrm{EPR}}\rangle_A \otimes |\Phi\rangle_B$$

Quantum state $|\Phi\rangle$ has been *teleported* from Alice to Bob (two classical bits are needed).

With many applications, for example to:

distributed storage



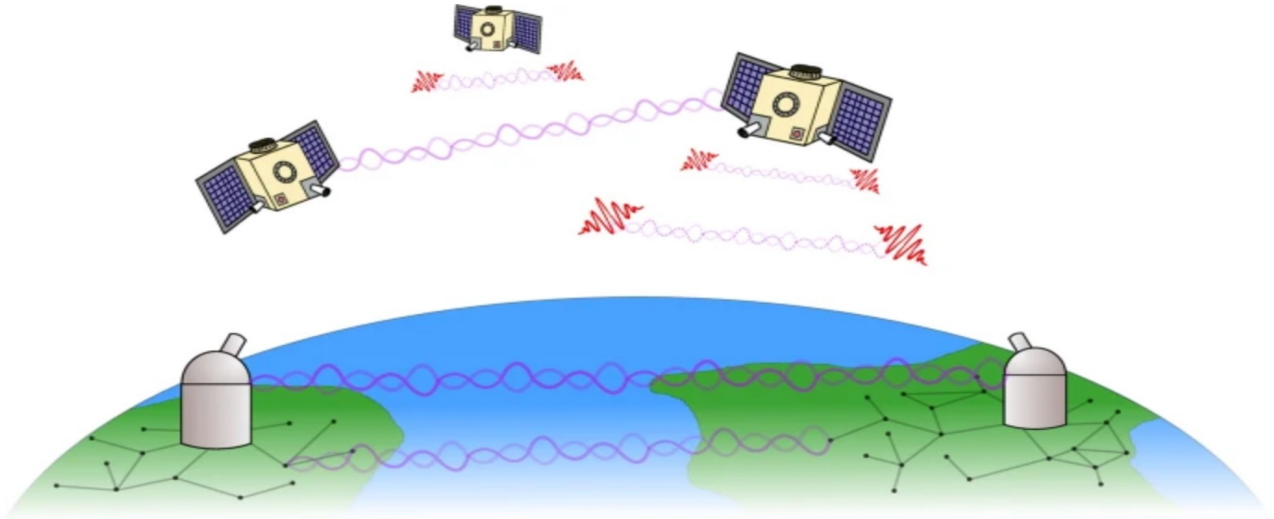
source:ICFO

Spooky action at a global distance: analysis of space-based entanglement distribution for the quantum internet

Sumeet Khatri, Anthony J. Brady, Renée A. Desporte, Manon P. Bart & Jonathan P. Dowling

npj Quantum Information **7**, Article number: 4 (2021) | Cite this article

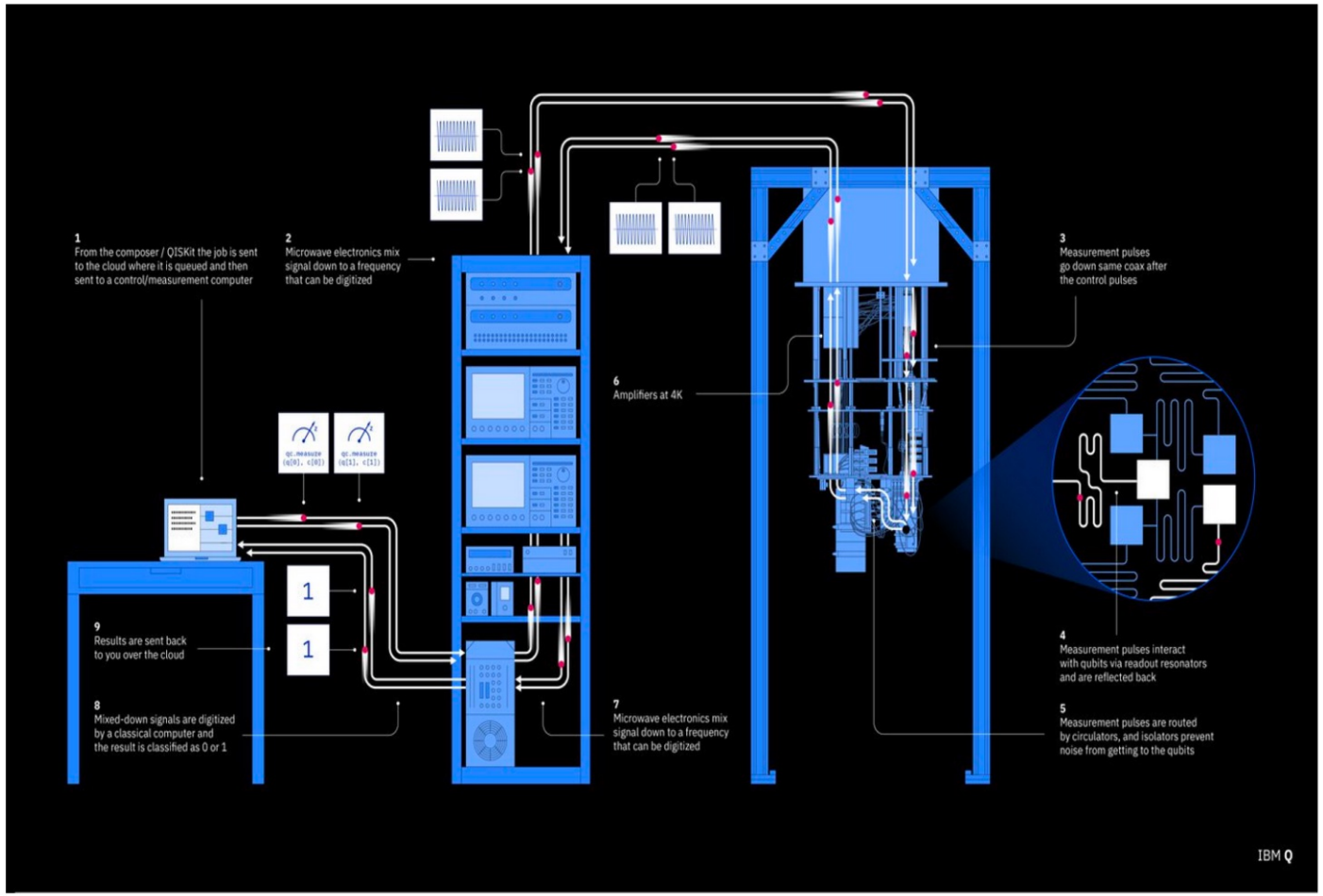
Fig. 1: A hybrid global quantum communications network.



A satellite constellation distributes entangled photon pairs (red wave packets; entanglement depicted by wavy lines) to distant ground stations (observatories) that host multimode quantum memories for storage[114,115,116]. These stations act as hubs that connect to local nodes (black dots) via fiber-optic or atmospheric links. Using these nearest-neighbor entangled links, via entanglement swapping, two distant nodes can share entanglement. Note that this architecture can support inter-satellite entanglement links as well, which is useful for exploring fundamental physics[60], and for forming an international time standard[55].

Hardware:

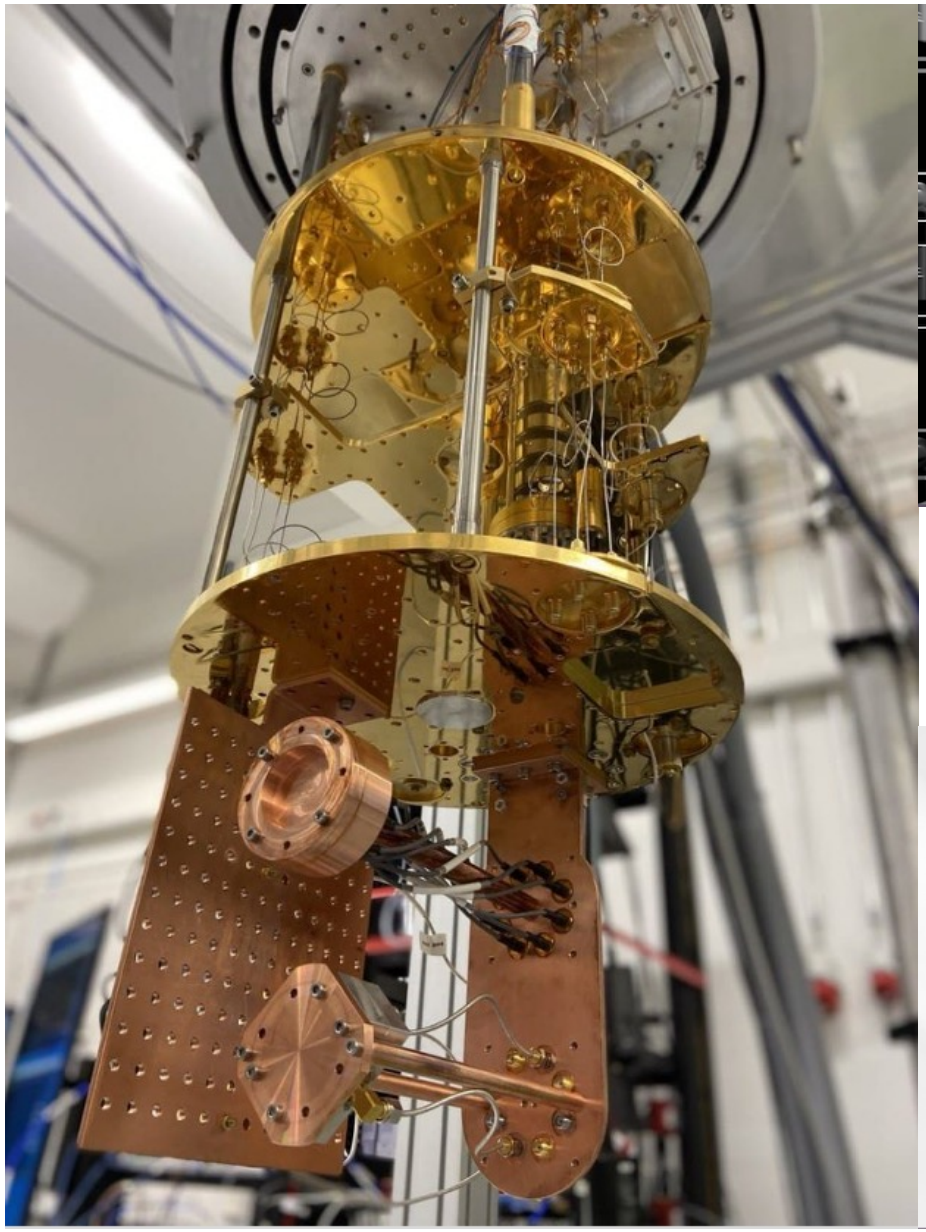
Intense efforts are being displayed to develop quantum computing and bring it to the user

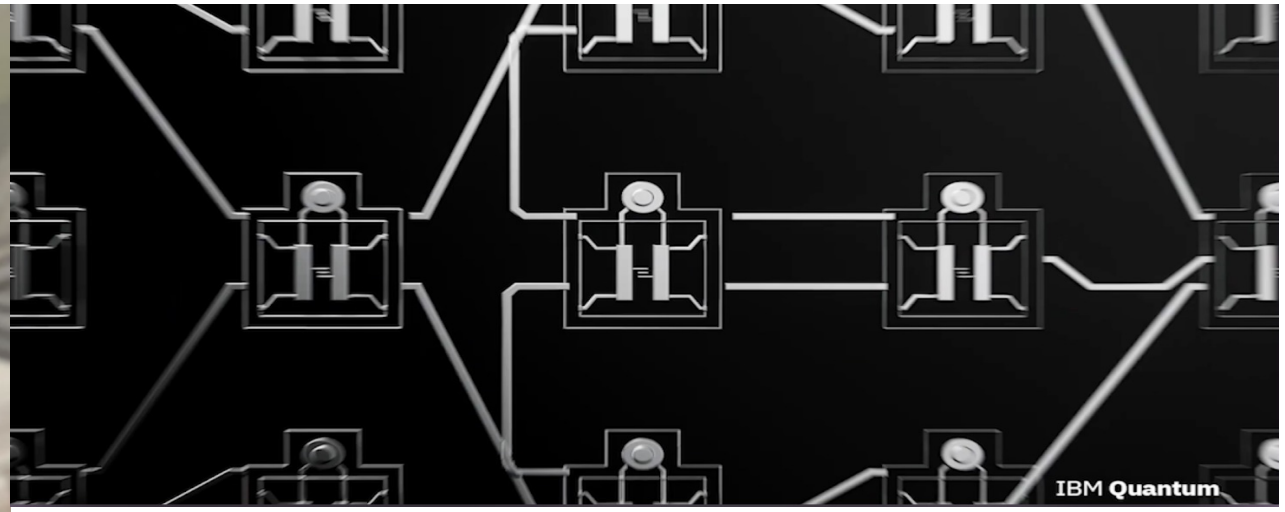


Flow chart illustrating how IBM's quantum computer works. Source: IBM. (Click image to enlarge.)

NISQ devices are small Noisy Intermediate Scale Quantum devices allowing computing with qubits.

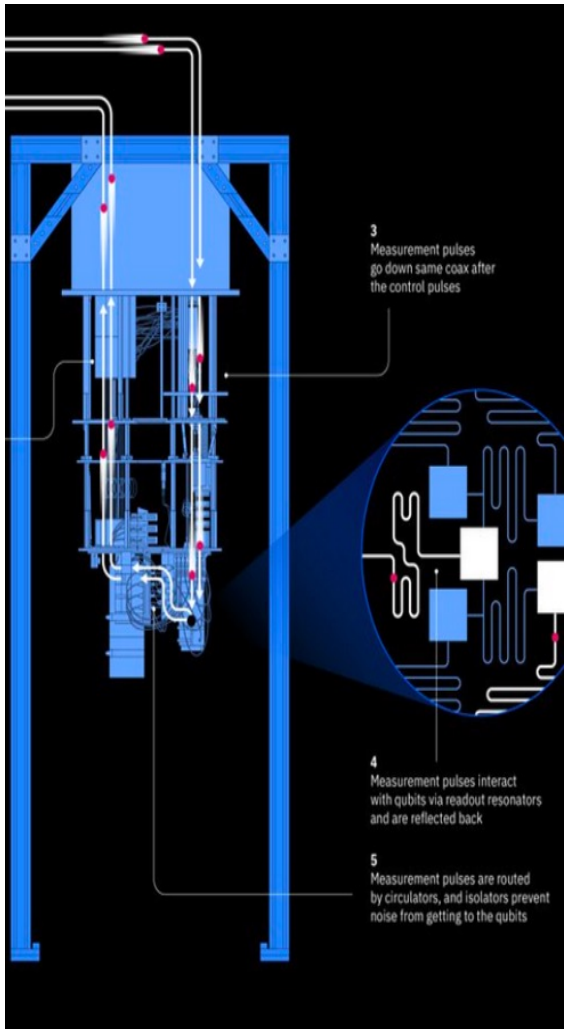
Stack of advanced classical and quantum electronic technologies operating from room temperature down to a few milli-Kelvins.





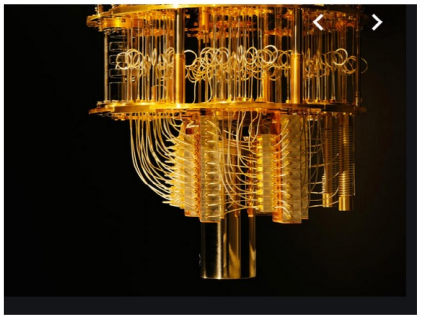
Superconducting QUBIT NISQ devices for computing

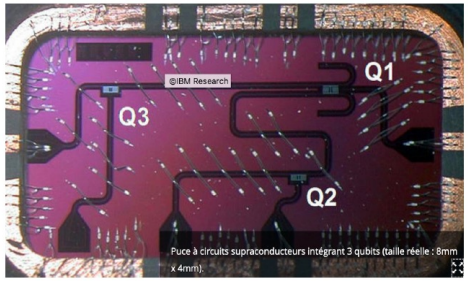
Dilution fridge

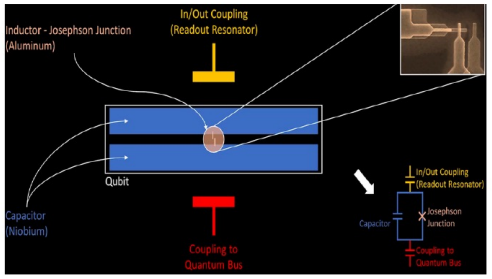


(source: IBM Q)

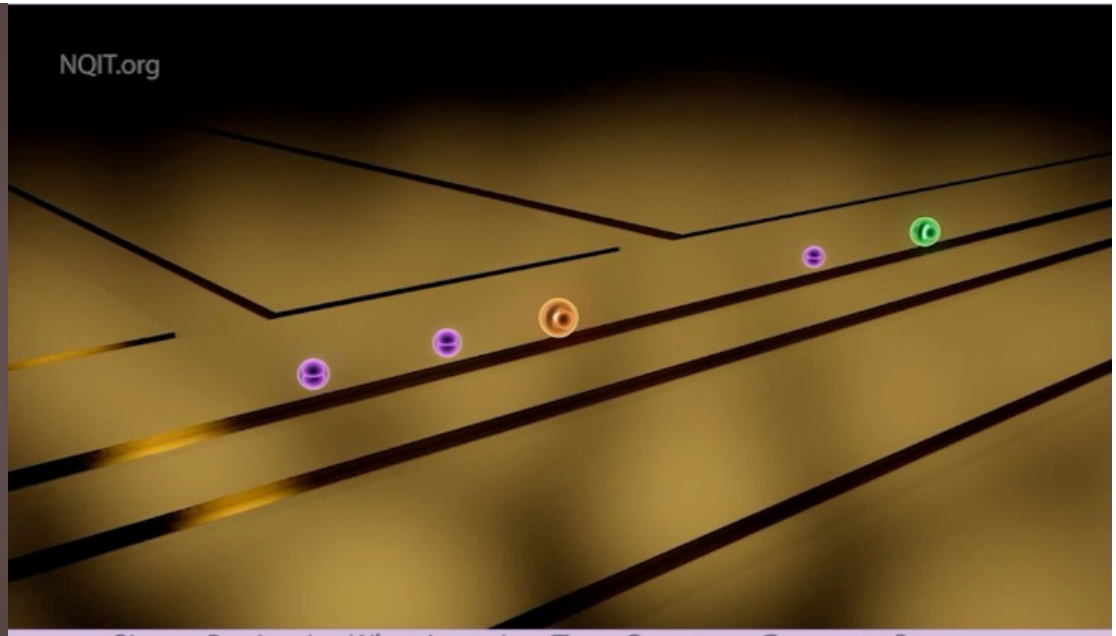
Opening the dilution fridge…



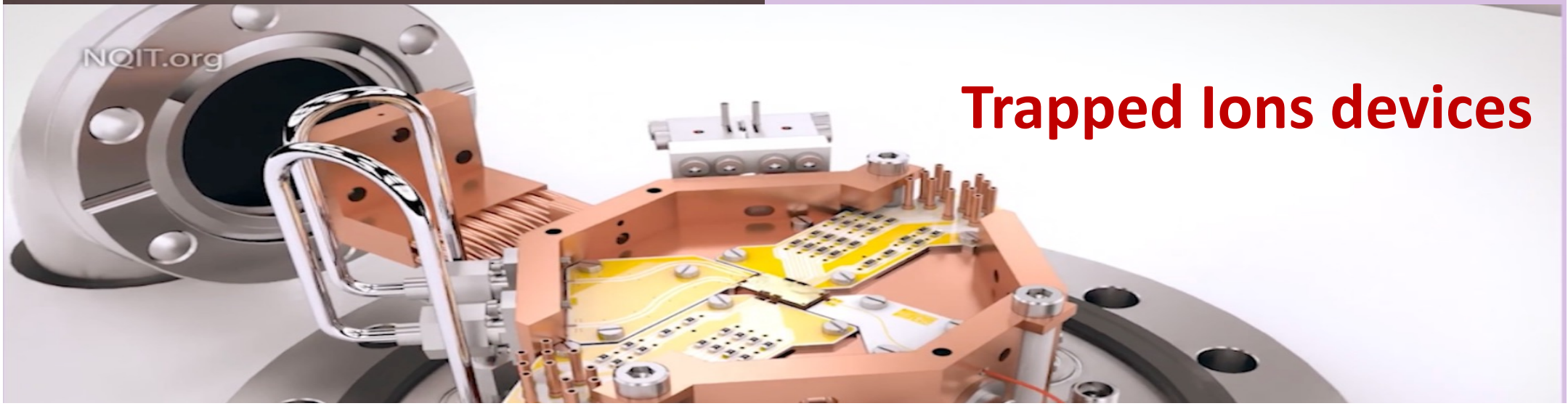




superconducting qubit platforms

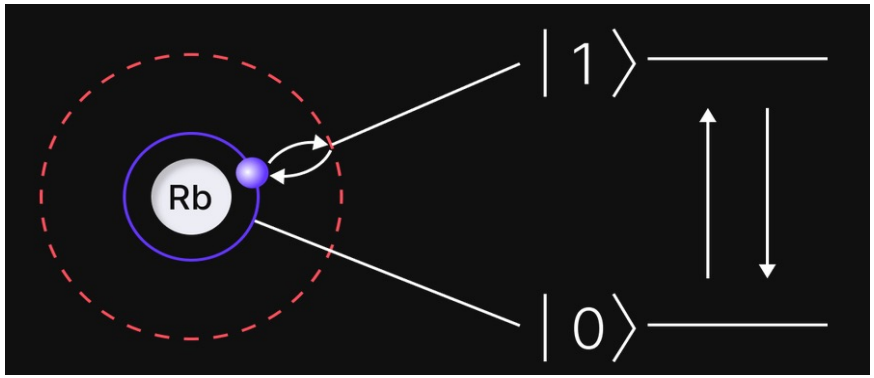


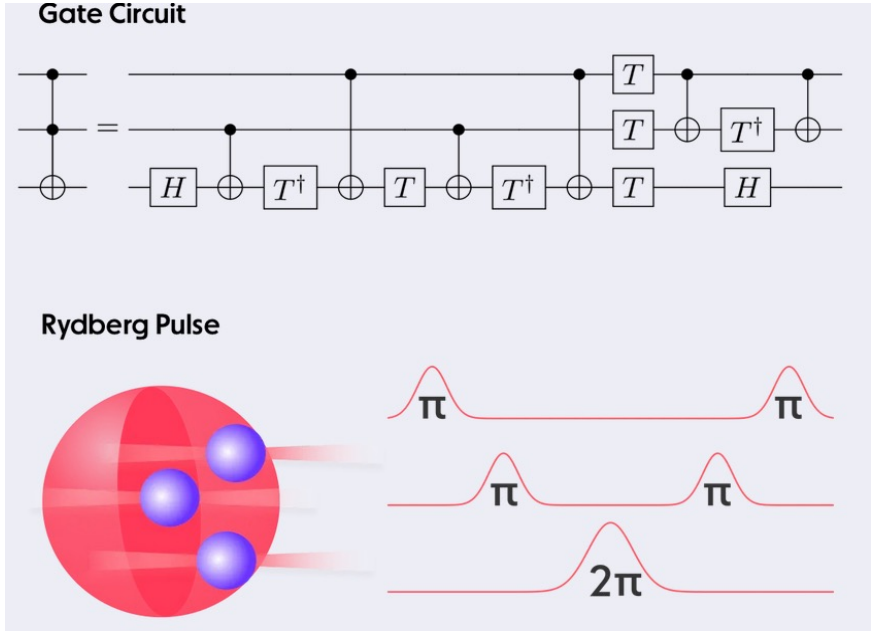
source: Simon Benjamin, What is an Ion Trap Quantum Computer?

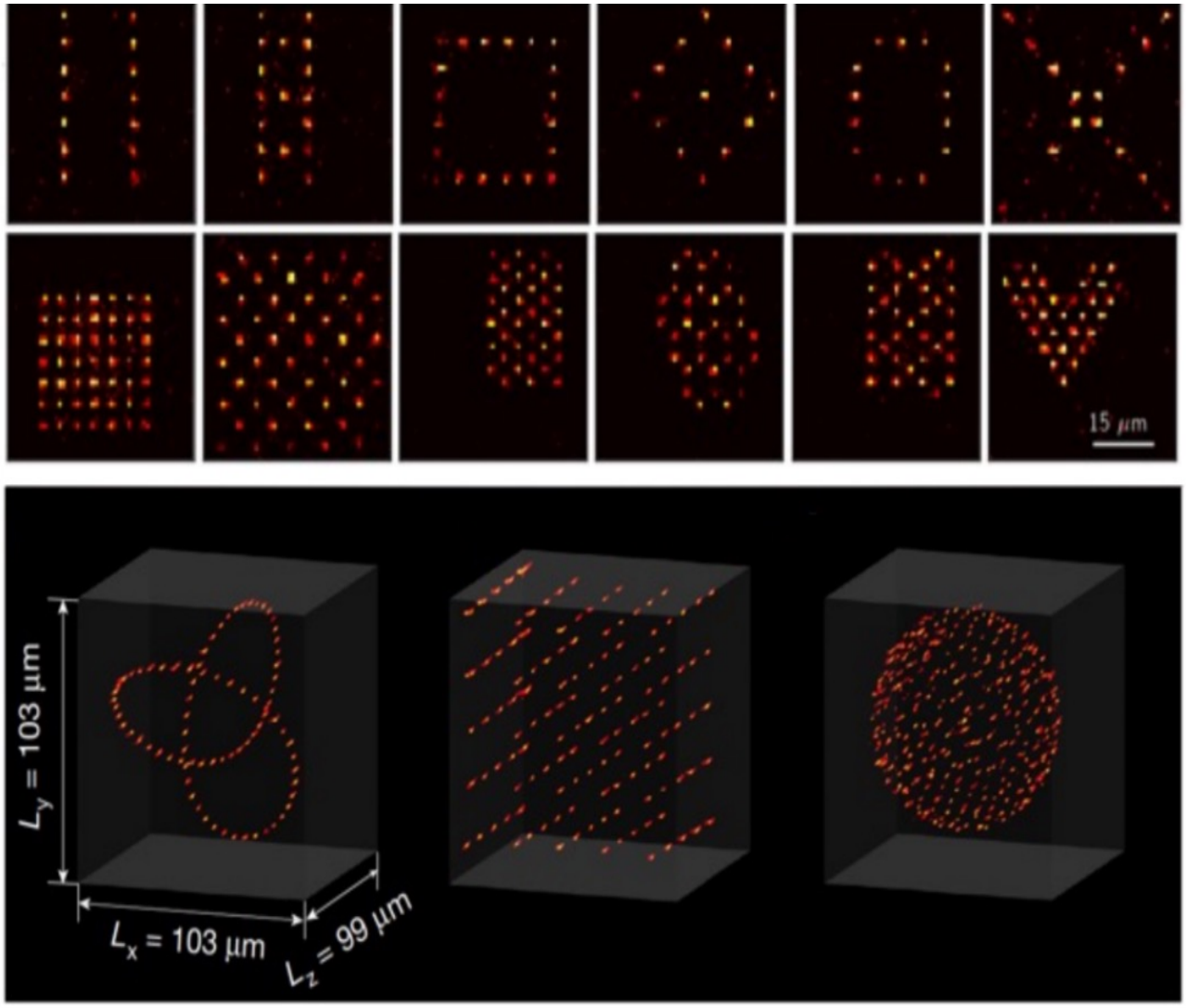


Trapped Ions devices

Rydberg atom computing

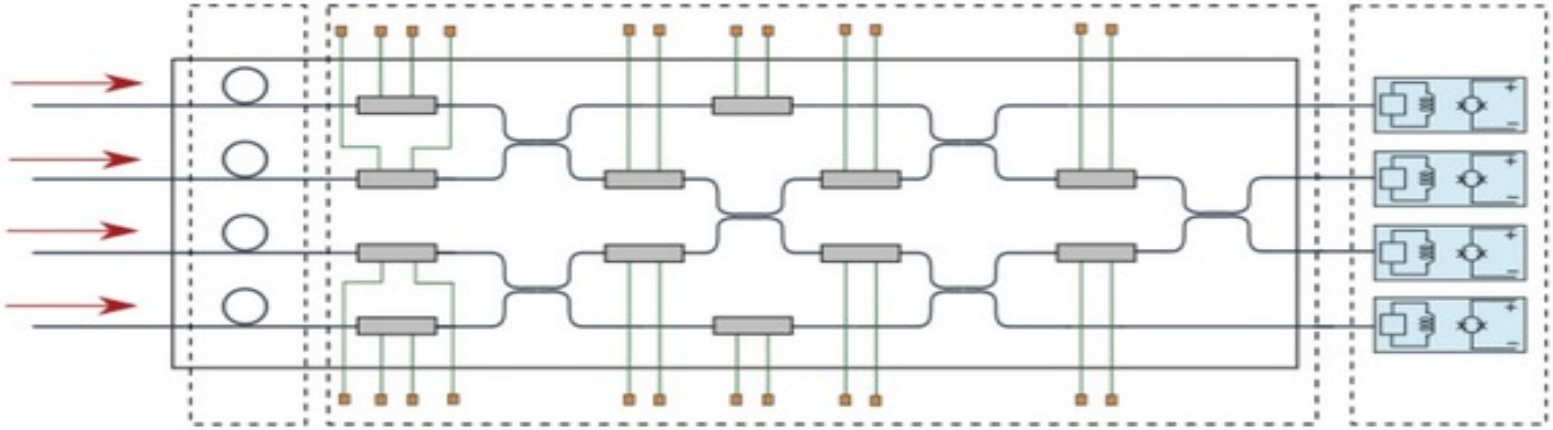


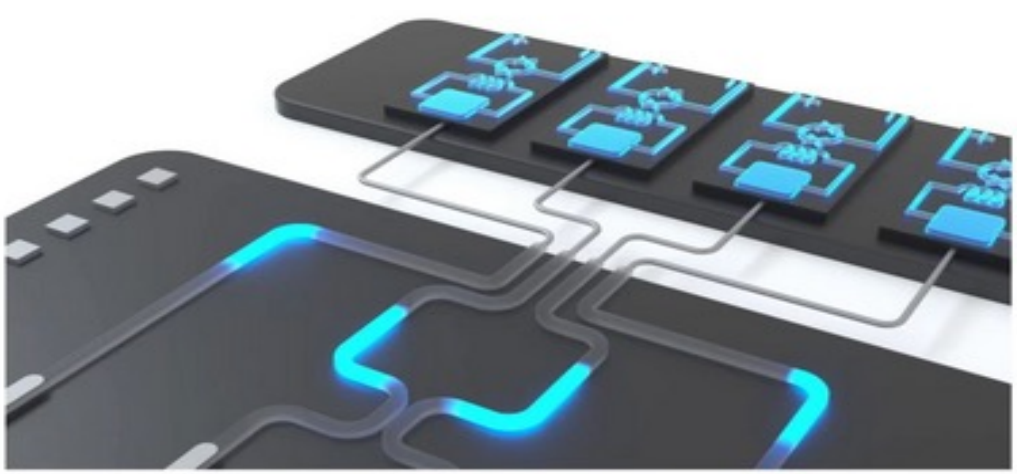


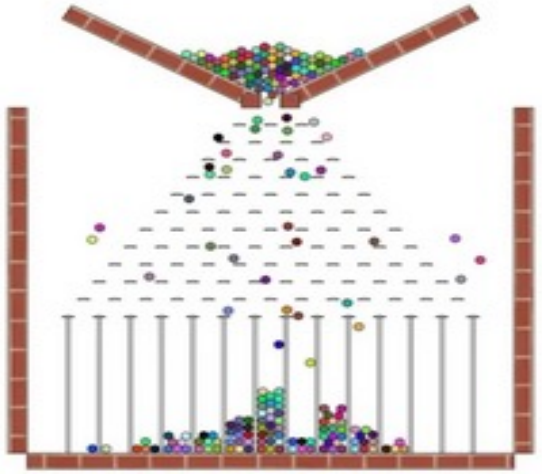


Examples of neutral atom arrays in 2D and 3D, extracted from Barredo, D. et al. (2018). Nature, 561(7721):79–82.

Photonic Quantum Computing



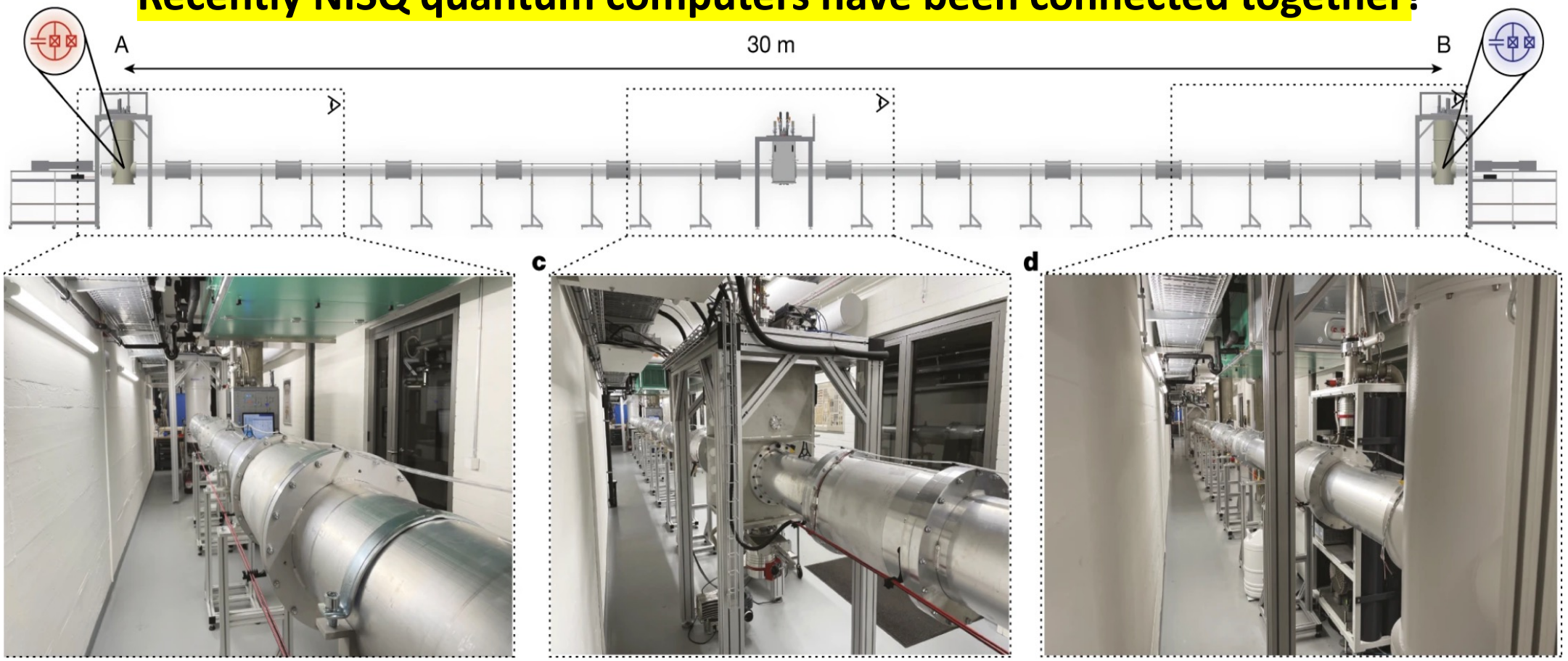




POC.ai

A sampling machine would have immensely important applications

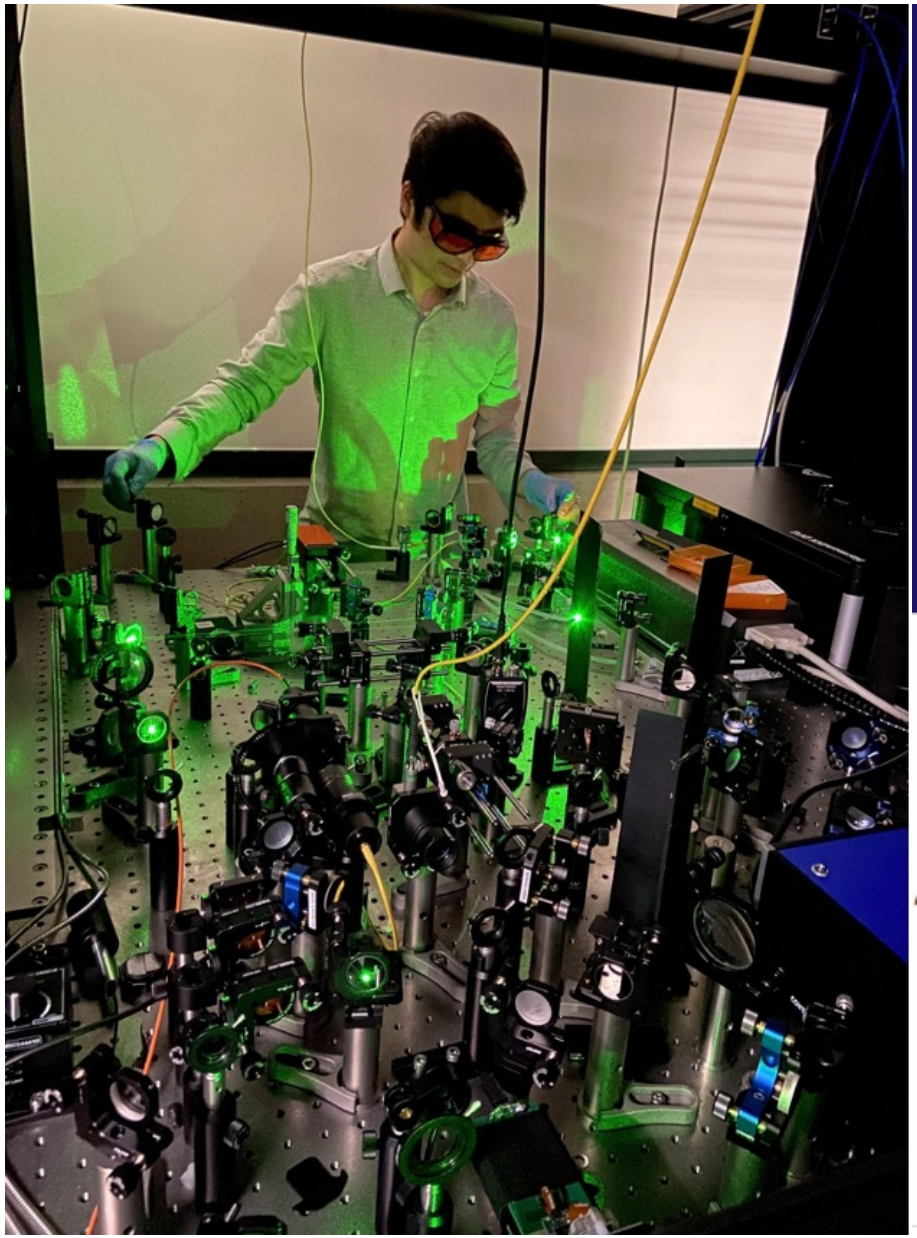
Recently NISQ quantum computers have been connected together!

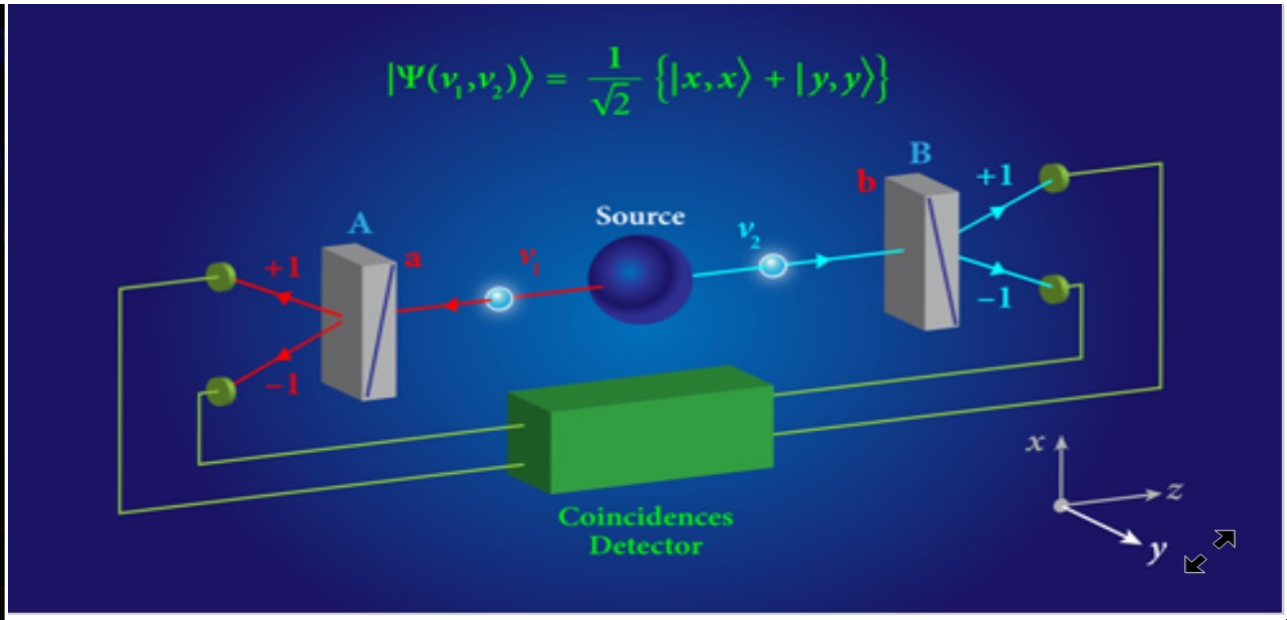


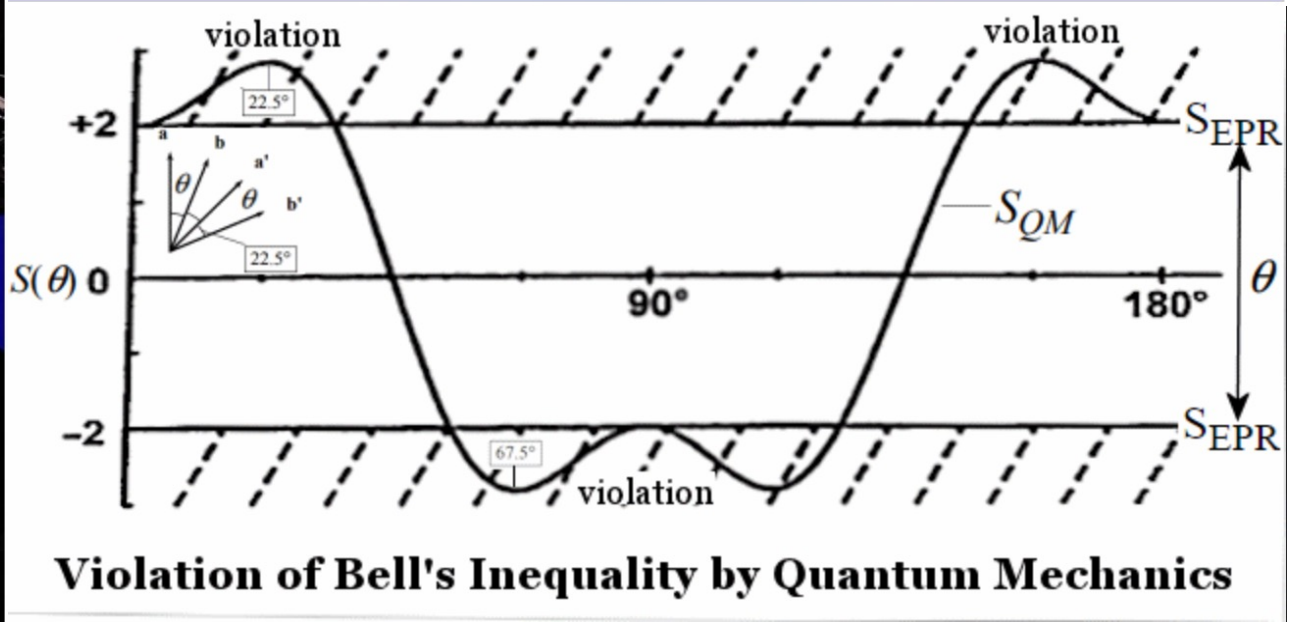
Source: *Nature* **617**, 265–270 (2023)

Loophole-free Bell inequality violation with superconducting circuits.

→ New tests of fundamental physics, and also prospects for distributed computing!



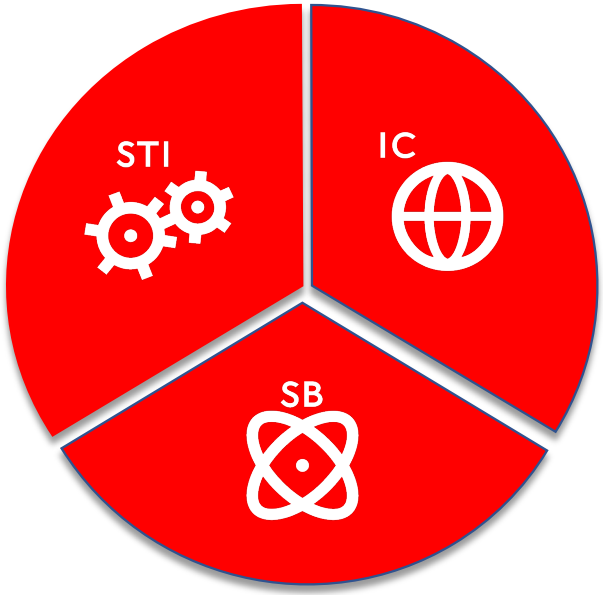




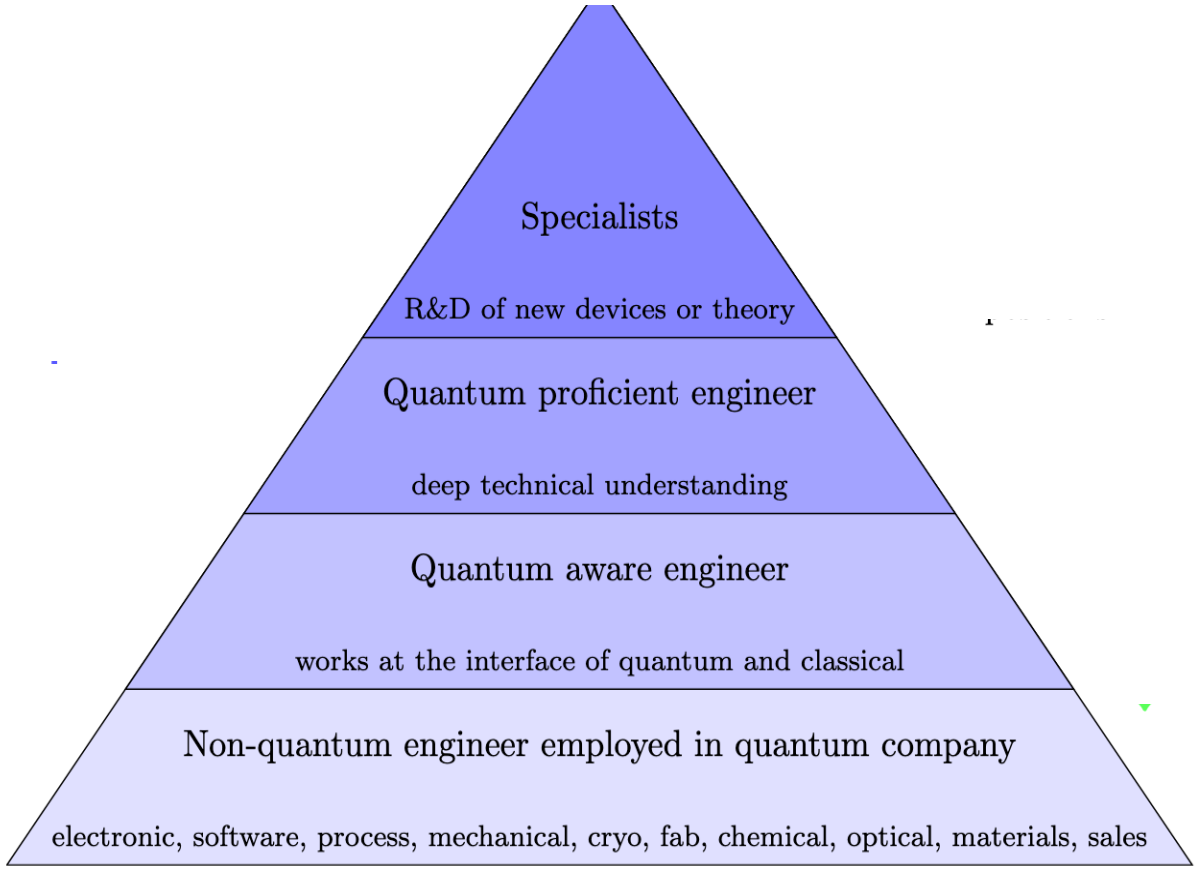
Violation of Bell's Inequality by Quantum Mechanics

Profiles of a quantum engineers ?

- Skills and knowledge from **Computer Science, Engineering, and Physics / Mathematics / Chemistry**
- Few Master's programs worldwide offer such a multidisciplinary educational profile
- At EPFL in **IC, STI, and SB**, there is **a vast portfolio of research and teachings** relevant to the **QSE domain**
- EPFL **Center for Quantum Science and Eng.** fosters research and collab. among teams

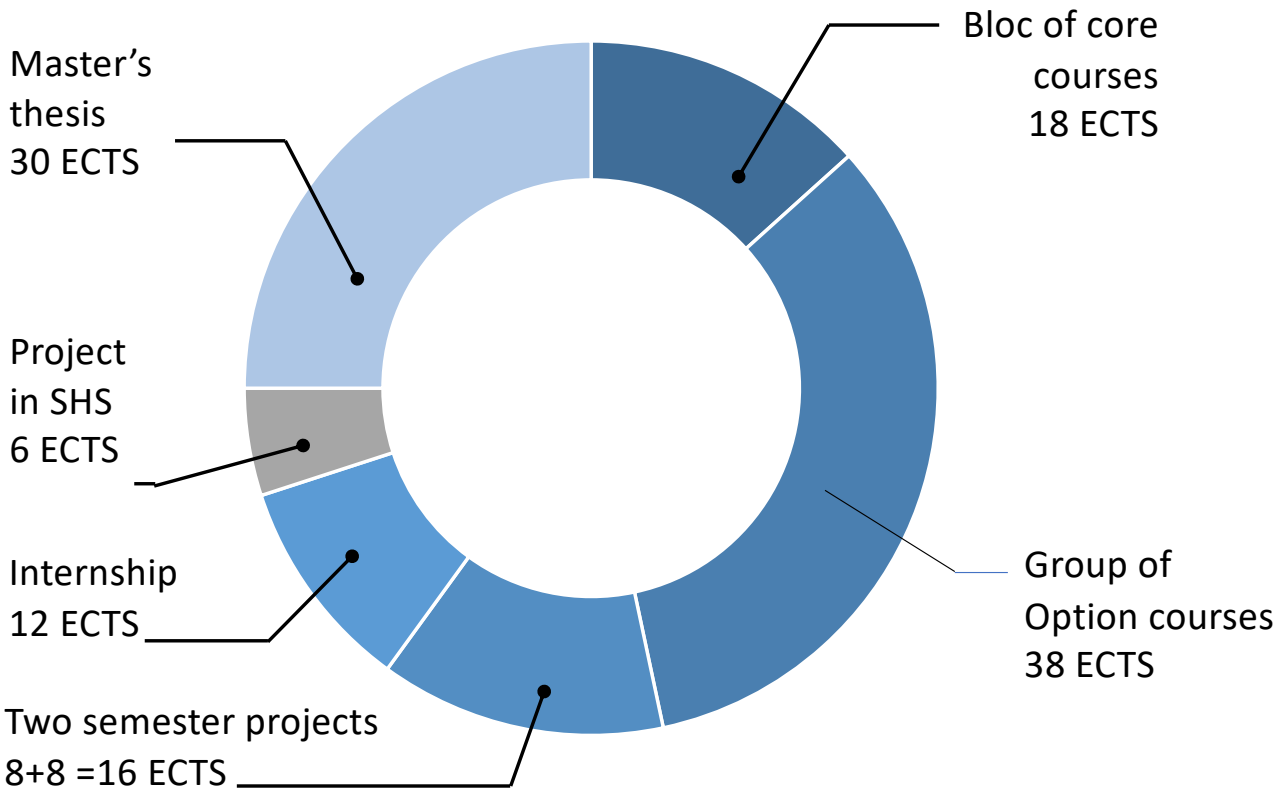


Needs of the industry



Source: *Building a Quantum Engineering Undergraduate Program* by Abraham Asfaw et al arXiv: 2108.01311 [physics.ed-ph]

Basic structure of the master



<u>Choose one specialization</u>:

A: Quantum information and computation

B: Quantum hardware and engineering

At least 30 ECTS in chosen specialization and at most 10 in the other

	Credits
Core courses	**18**
Computational complexity	6
Computational quantum physics	4
Fundamentals of solid-state materials	4
Introduction to quantum computation	5
Introduction to quantum information processing	5
Introduction to quantum science and technology	5
Quantum and nanocomputing	6
Quantum electrodynamics and quantum optics	6
Quantum mechanics for non-physicists	5
Semiconductor devices I	4
Solid state systems for quantum information	4
Introduction to Quantum cryptography New class! New prof!	6

-> Two intro classes quant info and computation

-> Recommended for all students

-> Should take if didn't have equiv class before

-> Two intro classes for hardware related courses

Specialization A: Quantum Information & Computation

Specialization A: Quantum Information and computation	
Information Theory and Coding	8
Foundations of Data Science	8
Computational Complexity	4
Advanced Algorithms	8
Cryptography and security	8
Advanced cryptography	4
Machine Learning	8
Optimization for Machine Learning	5
Artificial Neural Networks	5
Advanced logic synthesis and quantum computing	2
Distributed Algorithms	6
Low Rank Approximation Techniques	5
Machine Learning for Physicists	4
Quantum Information and Quantum Computing	4
Computational Quantum Physics	4
Quantum Transport in Mesoscopic Systems	4
Semiconductor Physics and Light-Matter Interaction	4
Nonlinear Optics for Quantum Technologies	4
Quantum Electrodynamics and Quantum Optics	6
Quantum Optics and Quantum Information	6
Solid State Physics III	6
Statistical Physics IV	6
Advanced Topics in Quantum Science and Technology	4
Statistical mechanics	4
Fundamentals of Solid-State Materials	4
Molecular Dynamics and Monte Carlo Simulations	2
Computational Methods in Molecular Quantum Mechanics	4
Introduction to Electronic Structure Methods	4
Molecular Quantum Dynamics	3

Specialization B: Quantum hardware & engineering

Specialization B: Quantum hardware and engineering	
Foundations of Data Science	8
Machine Learning	8
Advanced Machine Learning	4
Mathematics of Data: From Theory to Computation	6
Deep Learning	4
Advanced logic synthesis and quantum computing	2
Quantum Information and Quantum Computing	4
Quantum Transport in Mesoscopic Systems	4
Semiconductor Physics and Light-Matter Interaction	4
Nonlinear Optics for Quantum Technologies	4
Quantum Electrodynamics and Quantum Optics	6
Quantum Optics and Quantum Information	6
Statistical Physics IV	6
Advanced Topics in Quantum Science and Technology	4
Statistical mechanics	4
Semiconductor Devices I	4
Semiconductor Devices II	4
Nanoelectronics	2
Lab in Nanoelectronics	4
Photonic systems and technology	4
Fundamentals of Solid-State Materials	4
Superconducting electronics: A materials perspective	3
Introduction to crystal growth by epitaxy	2
Properties of semiconductors and related nanostructures	5
Atomistic and Quantum Simulations of Materials	4
Nanotechnology	3
Metrology	3
Molecular Dynamics and Monte Carlo Simulations	2
Computational Methods in Molecular Quantum Mechanics	4
Introduction to Electronic Structure Methods	4
Molecular Quantum Dynamics	3

Options
38 ECTS

At least 30 ECTS in each specialization
+ 8 possible in other one and/or cours hors-plan

Specializations have overlap

They also contain a strong classical IT component (e.g. ML, optimization, electronics,…)

+ 2 New recent classes: Microwave Engineering in Physics; Topics in sustainability and quantum

WHAT ARE THE PREREQUISITES ?

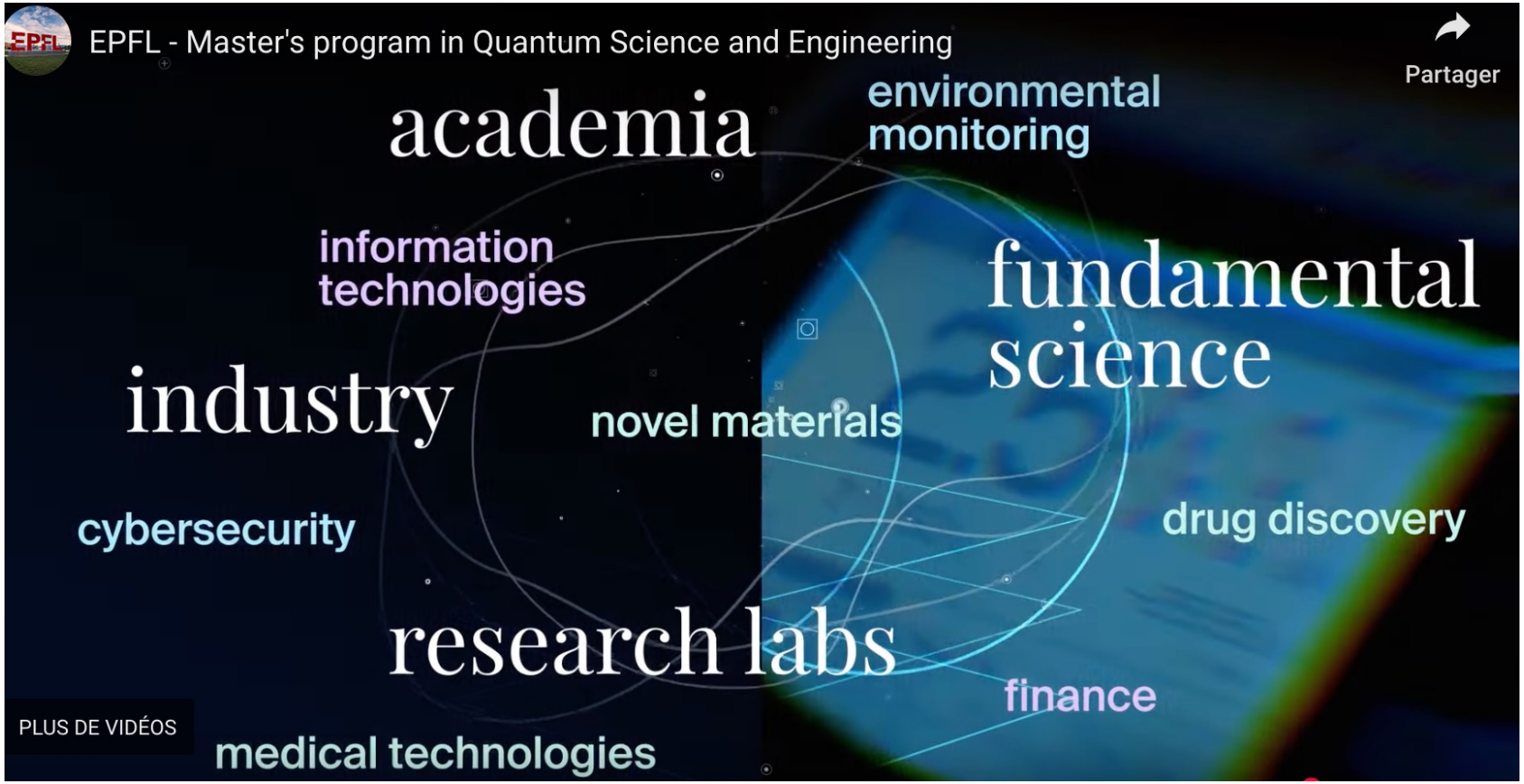
Anybody that did not have a proper Quantum Physics class in 3rd year should follow **"Quantum Physics for Non-Physicists"** in first semester of the master. In the core group.

Non-physicists: we recommend you take a Quantum Physics class in your 3rd year

- **COM, IN, EE**: *"Quantum Physics for Non-Physicists"* (option in fall 5 ECTS)
- **MX, Math**: *can take it as 'hors plan'* (see with your section)
- **MT:** *"La science quantique: une vision singulière"* (option in spring 3 ECTS)
- **Chimie**: classes in module 3 of 3rd year of Bachelor in "Chimie computationnelle"

Preparation is also given by: "*Introduction to Quantum Information Processing"* (COM 309) but does not fully replace a Quantum Physics class.

Job prospects, examples. [A nice read in Quantum Insider]

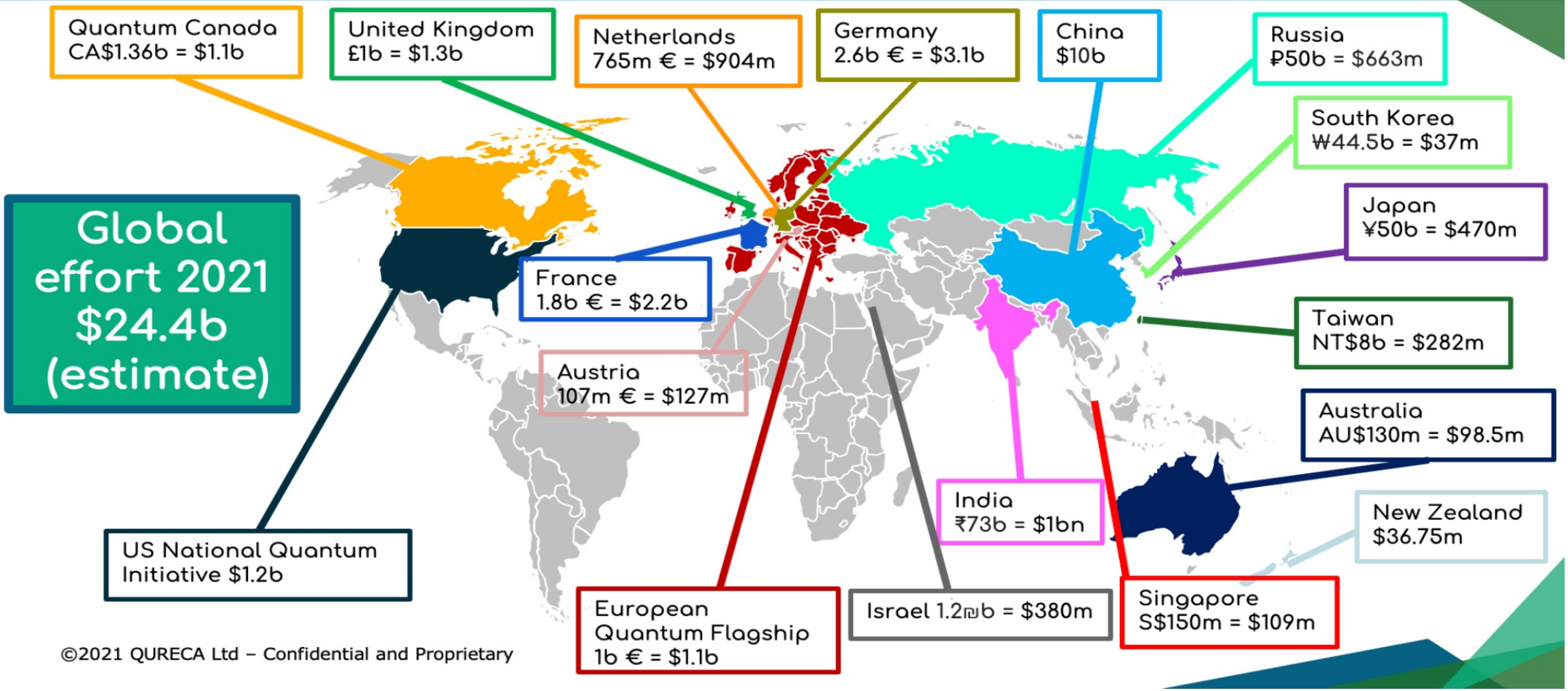


Industry needs engineers at all levels of the 'classical to quantum stack'

The program prepares you well also in the classical IT sector.

Examples of Companies in QSE domain

Quantum effort worldwide



Source: QURECA quantum resources & careers

Important deadlines and informations

- For *Physics and Chemistry* EPFL students the master is *consecutive*

- *Others*: Application **deadline 31st March** on EPFL master's page https://www.epfl.ch/education/master/programs/quantum-science/

- Applications for a bourse d'excellence: refer to general presentation given during master days. For any info contact siq@epfl.ch

- **For details on the section consult:**

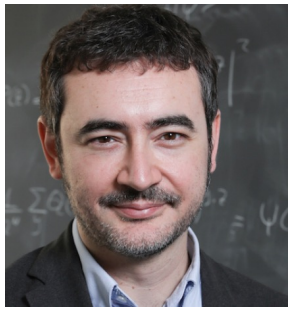
https://www.epfl.ch/schools/sections/quantum-science-and-engineering/

WATCH OUR VIDEO REALIZED IN EPFL LABS WITH OUR CURRENT STUDENTS !

THANK YOU FOR YOUR ATTENTION

WE HOPE TO SEE MANY OF YOU NEXT SEPTEMBER!

Edoardo Charbon (STI)



Giuseppe Carléo (SB)

Nicolas Macris (IC)

Hind Klinke (section deputy)

Emilie Thévoz (section admin)

More info on Section website https://www.epfl.ch/schools/sections/quantum-science-and-engineering/

EPFL website and for applications https://www.epfl.ch/education/master/programs/quantum-science/