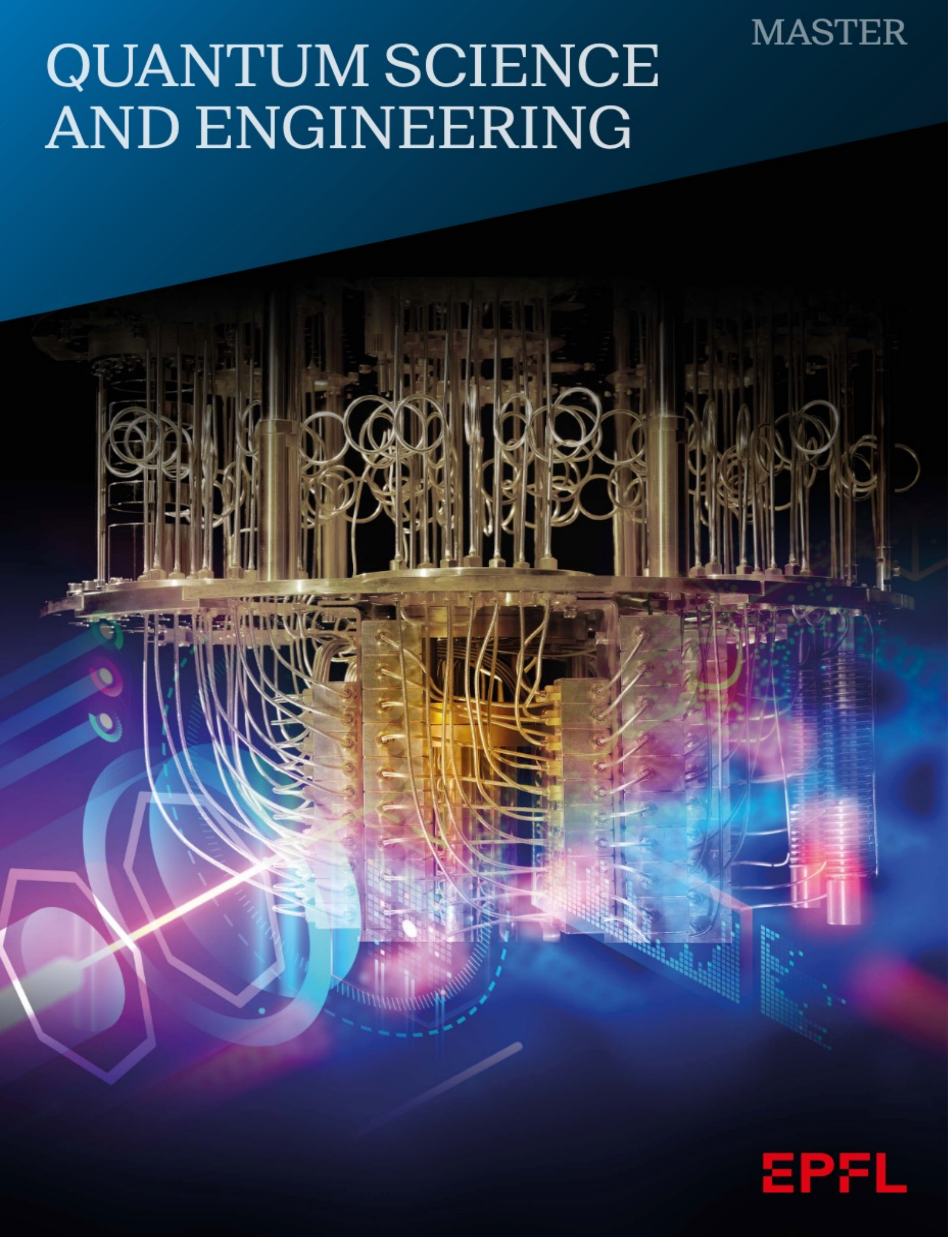
EPFL

Master in Quantum Science and Engineering

Nicolas Macris

journées des masters spécialisés
EPFL, 28 Février 2024

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

Director: Prof. Nicolas Macris (IC)

Co-directors: Prof. Edoardo Charbon (STI) and Prof. Giuseppe Carleo (SB)

Section deputy: Hind Klinke
Administrative assistant: Emilie Thévoz

Web sites: SSIQ and go.epfl.ch/master-quantum-science

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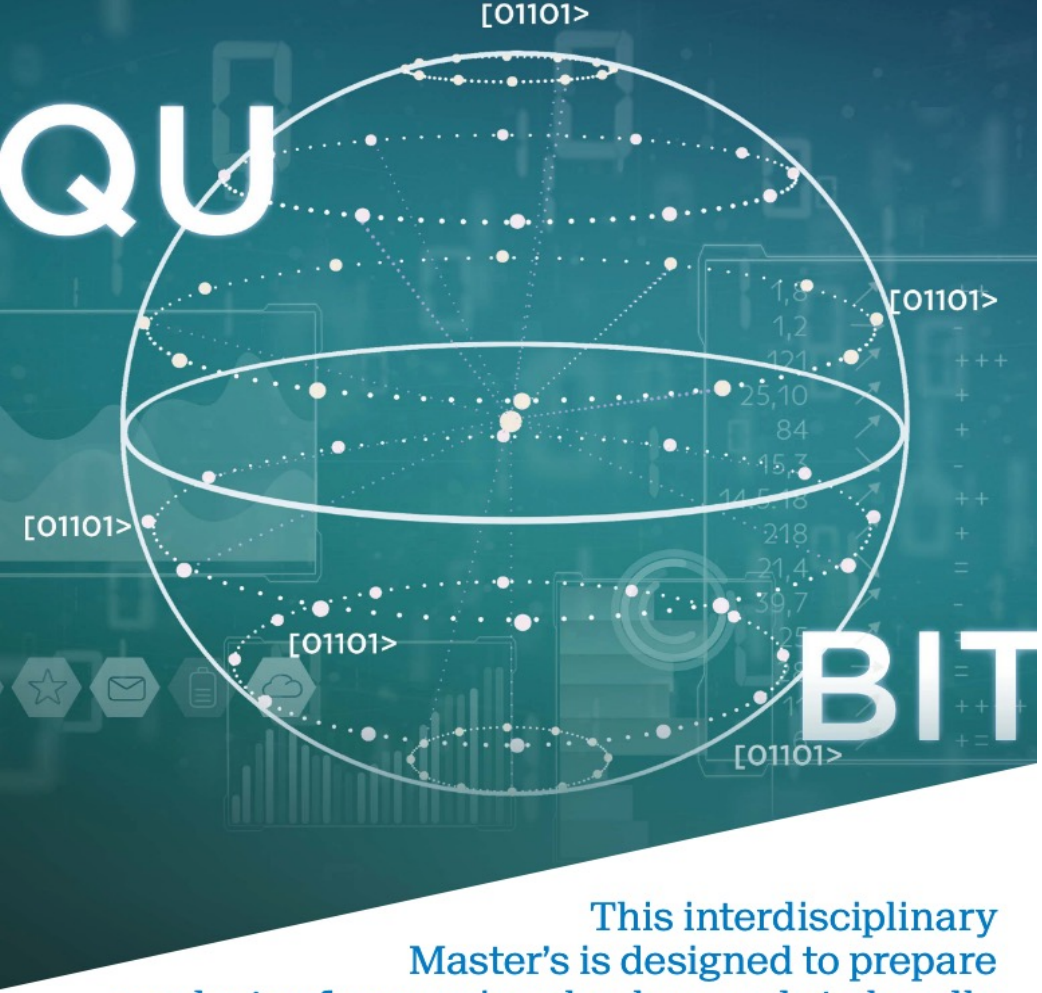


This interdisciplinary Master's is designed to prepare graduates from various backgrounds to handle the new paradigm shift brought by Quantum science and technology in the way we treat data, communicate, measure and compute. Thanks to their broad vision of diverse aspects of the field, they will have 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 to take part in the "second quantum revolution"

engineers that understand and use the quantum paradigm shifts in:

- Computation and algorithmics
- Information processing
- Simulation
- 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 must apply until 31 March

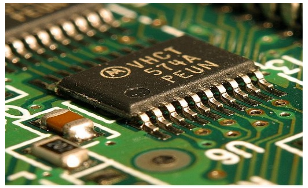
  (minimal admission condition GPA 4.5)

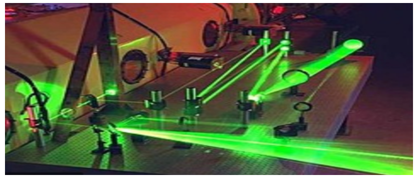
The second quantum revolution: what is it about ?

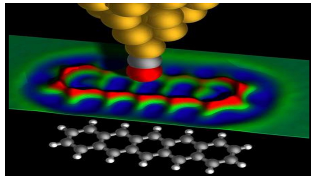
Laws of quantum physics known since the 1930's have led to our modern understanding of the atomic nature of matter and all solid state phenomena and photonics and much more…

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,…

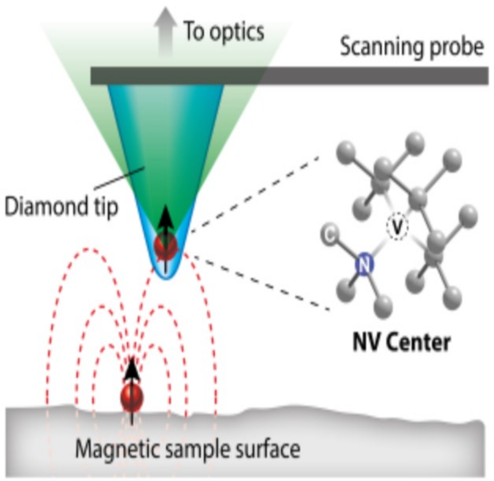
- **Sensing and Metrology:** photon detectors and counters, gravimeters, accelerometers, cold atom interferometers, magnetometry, atomic and optical clocks,…

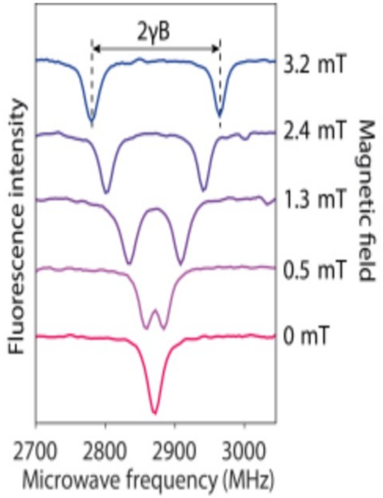
- **Computation:** quantum algorithms, optimization, quantum machine learning, sampling, complexity theory,…

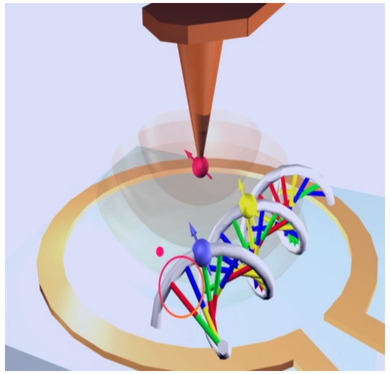
- **Simulation:** dynamics of physical systems, low temperature phases of matter, quantum chemistry, material science, better drug discovery,…

A few examples: from sensing and metrology

Magnetometry with Nitrogen Vacancy centers in diamond

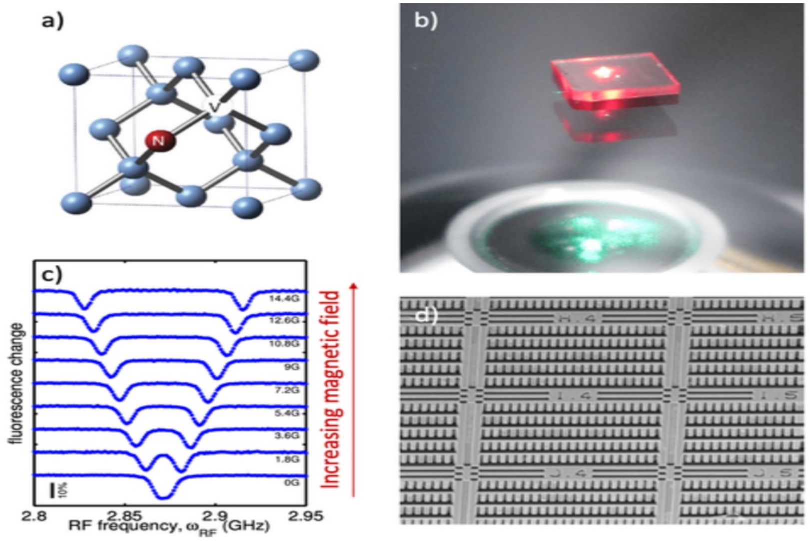




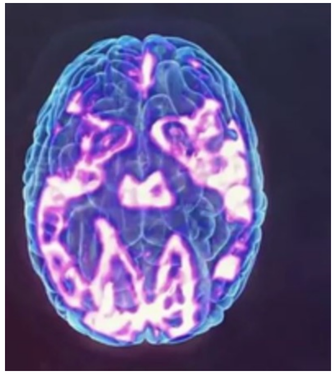


Sensing biomolecules

(source Qzabre)



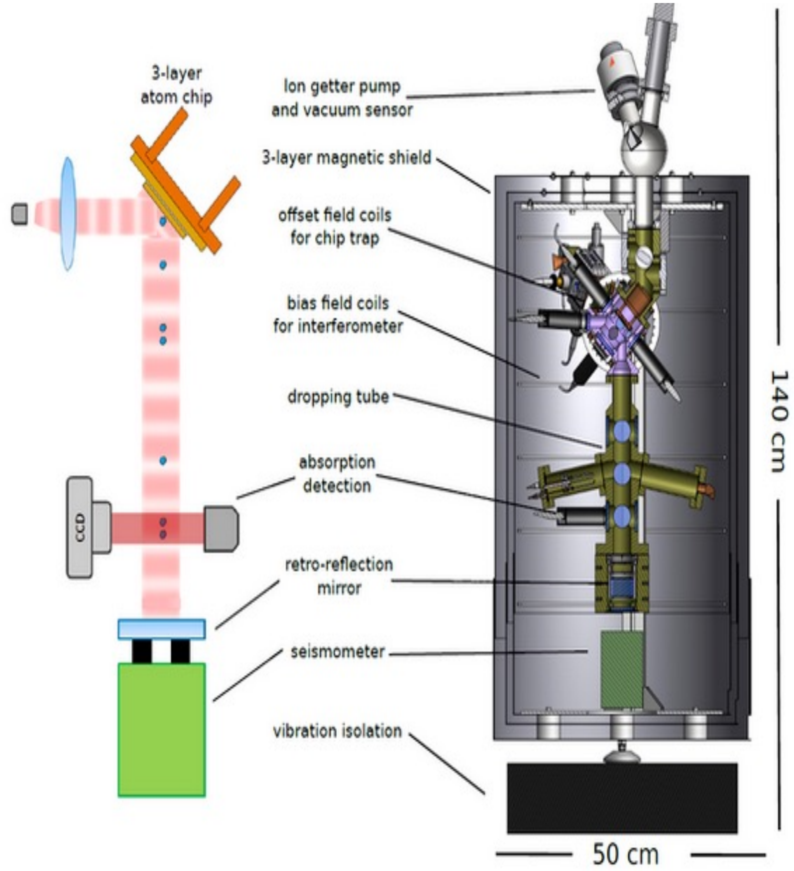
(Source: Qnami)

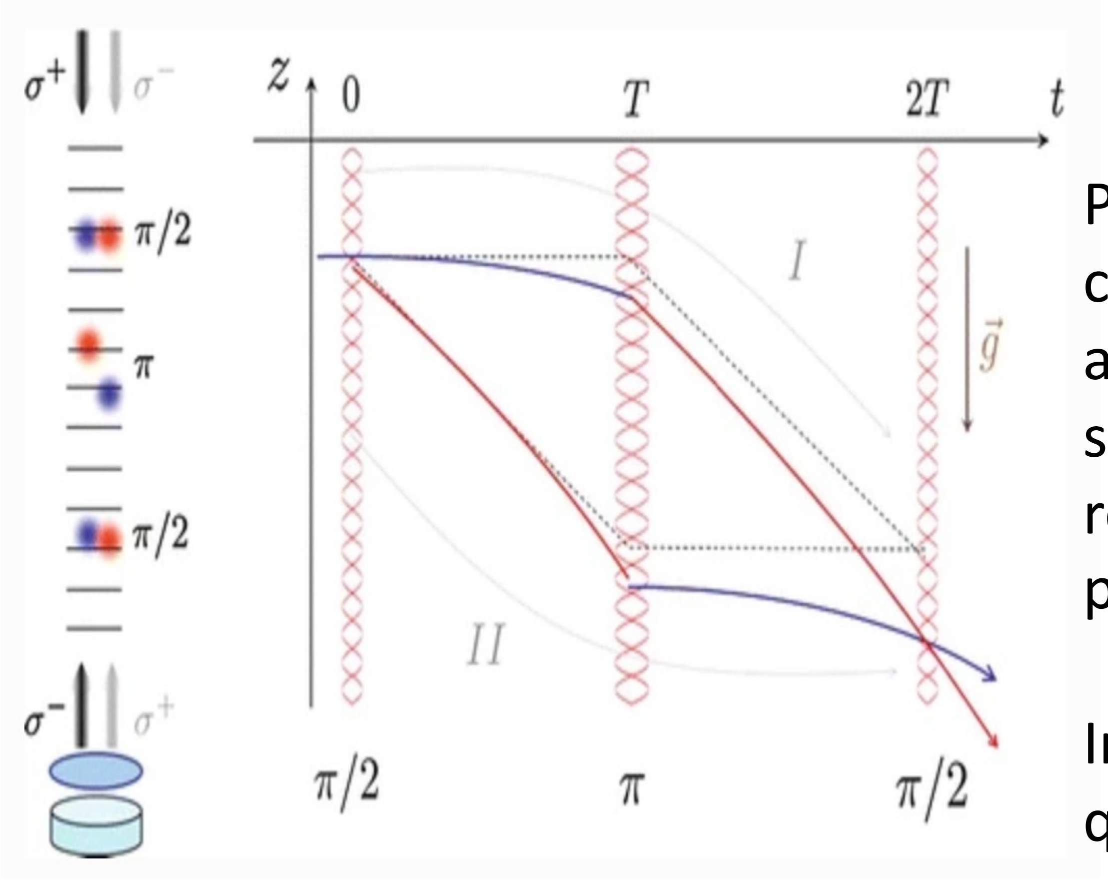


Measurement of very weak magnetic fields

Examples: from sensing and metrology

Cold atom interferometry:

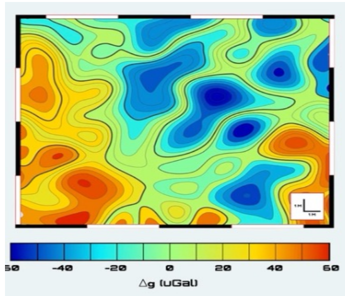




Path of falling cloud of cold atoms is separated and reunited by light pulses.

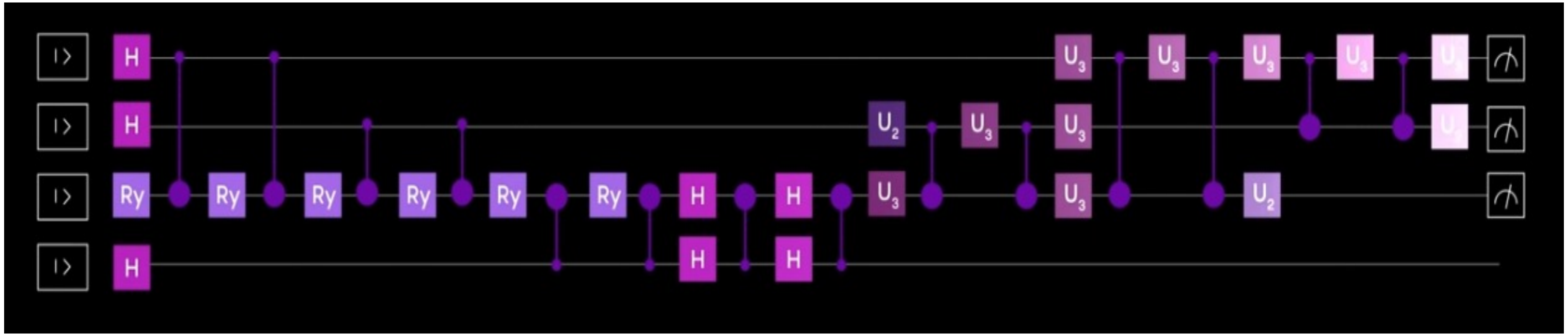
Interference of quantum waves gives information on gravity field.

Applications to measurement of weak gravitational fields, accelerometers.
May also lead to tests of gravitation at small distances and for weak fields.

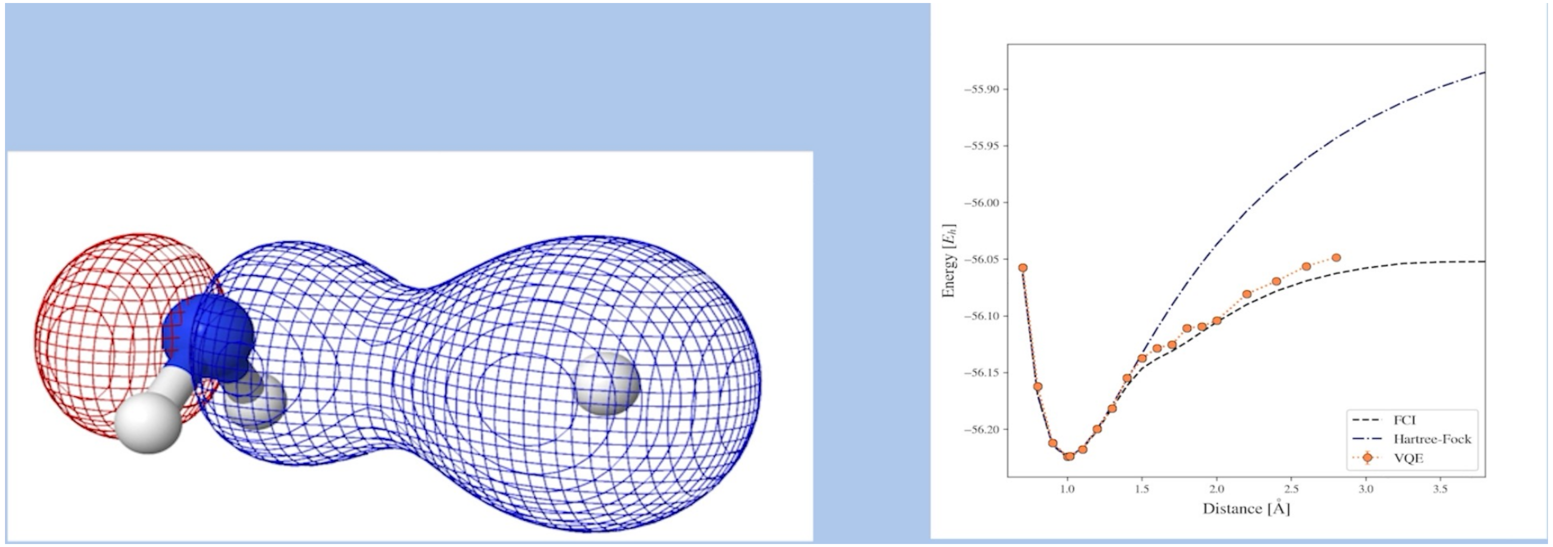


Examples: from computation and simulation

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



Sequence of QUBIT GATES: time flows left to right

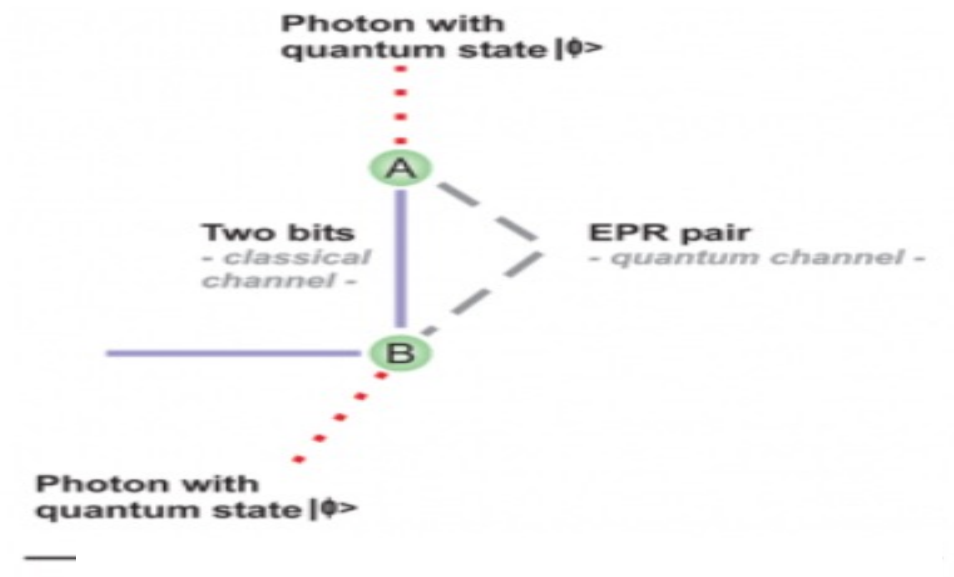


Simulation of physical systems

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

Examples: from quantum communications

Quantum Teleportation



Initial state:

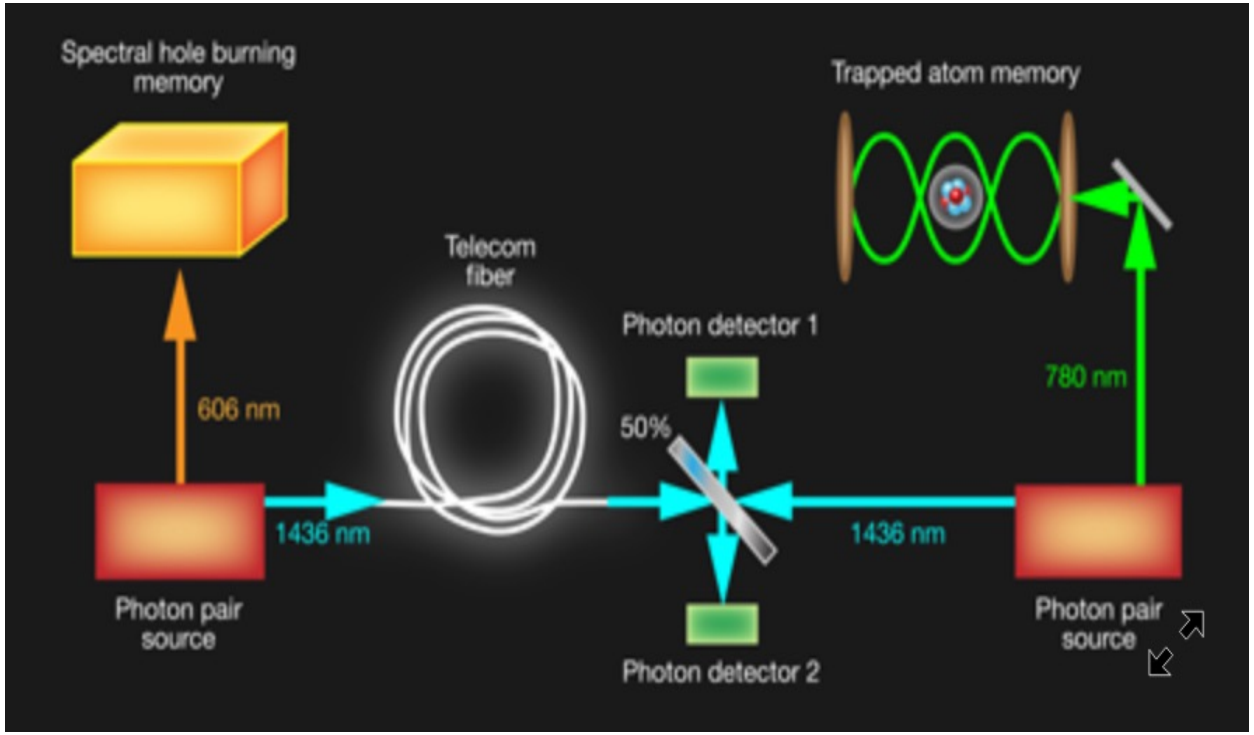
$$|\Phi\rangle_A \otimes |\mathrm{EPR}\rangle_{AB} = |\Phi\rangle_A \otimes \frac{|00\rangle_{AB} + |11\rangle_{AB}}{\sqrt{2}}$$

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).

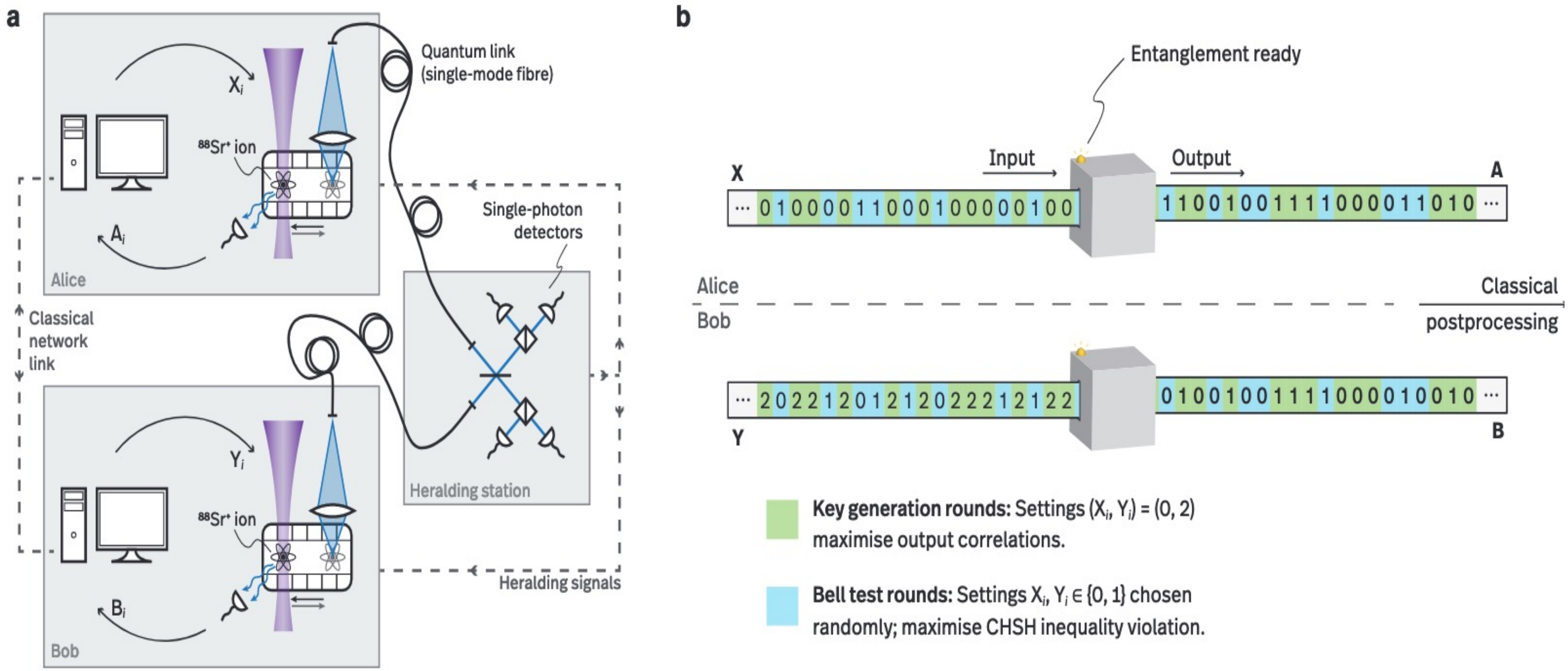
Entangled distributed storage



source:ICFO

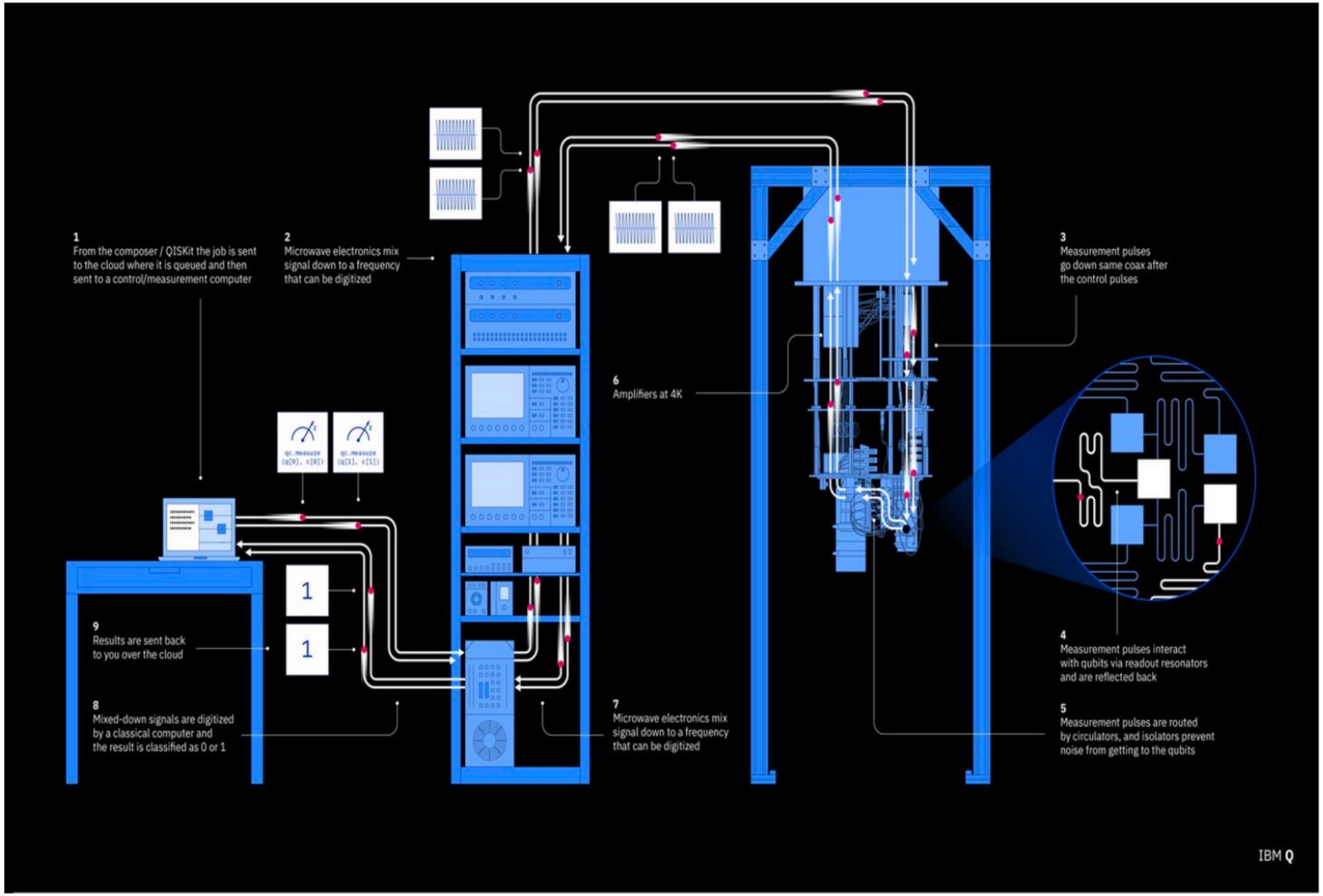
Examples: from quantum communication

Quantum Key Distribution for cryptography



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

Intense efforts are being displayed to develop quantum computing hardware technologies…

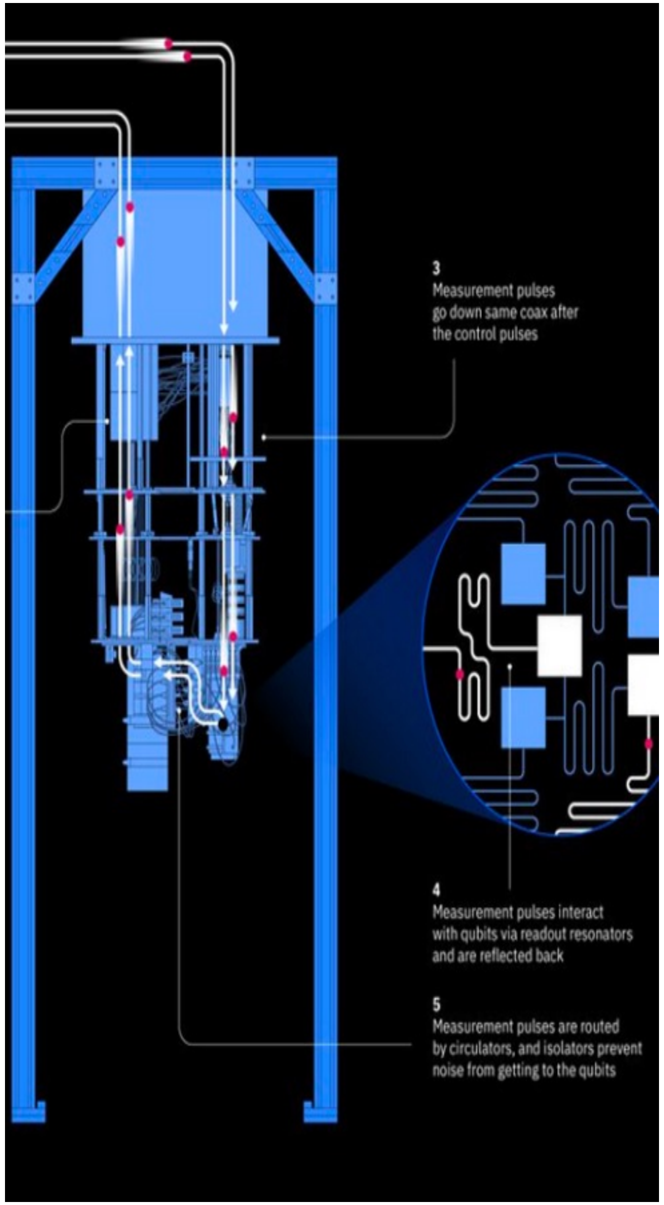


Flow chart illustrating how IBM's quantum computer works. Source: IBM. (Click image to enlarge.)

NISQ devices are small Noisy Intermediate Scale Quantum devices allowing computing with 10's to 400's qubits.

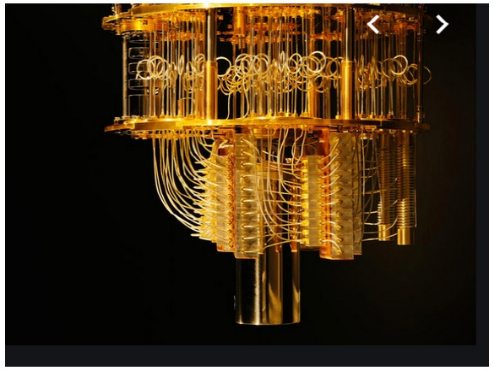
Stack of advanced classical and quantum electronic technologies operating from room temperature down to a few milli-Kelvins.

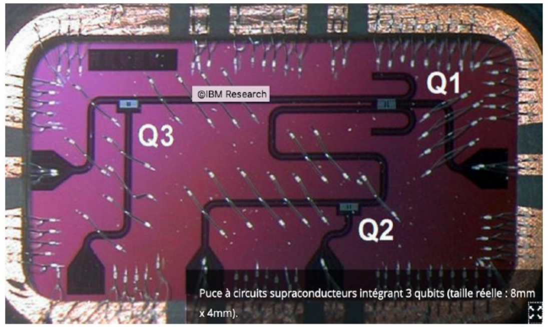
Dilution fridge

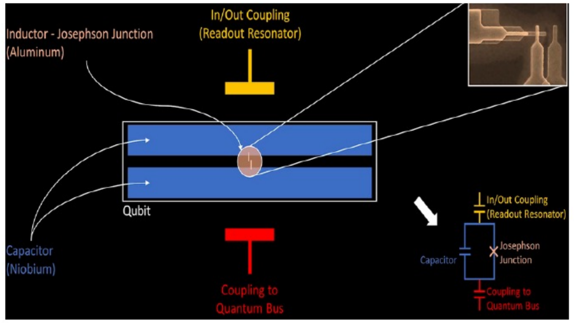


(source: IBM Q)

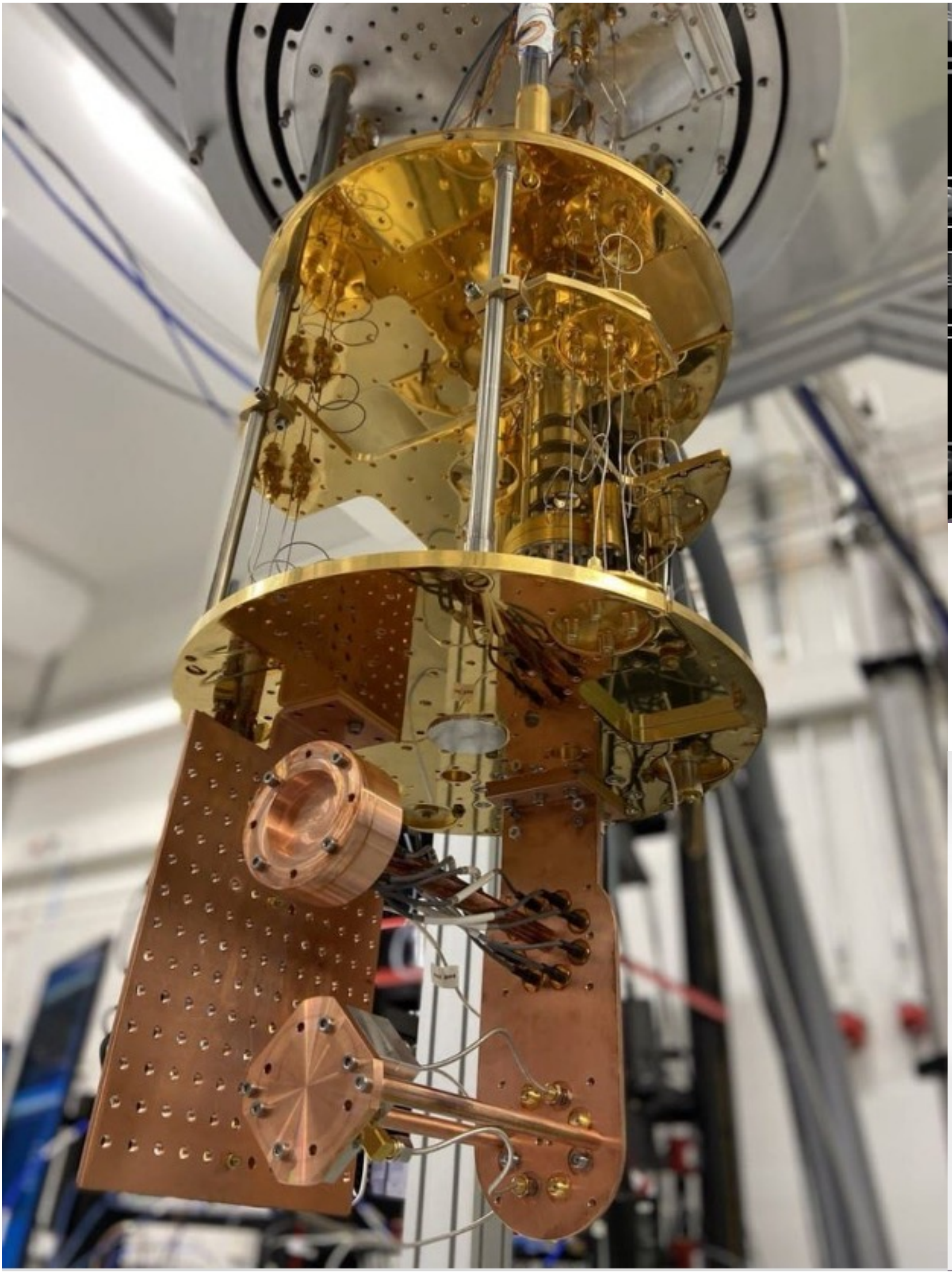
Opening the dilution fridge…

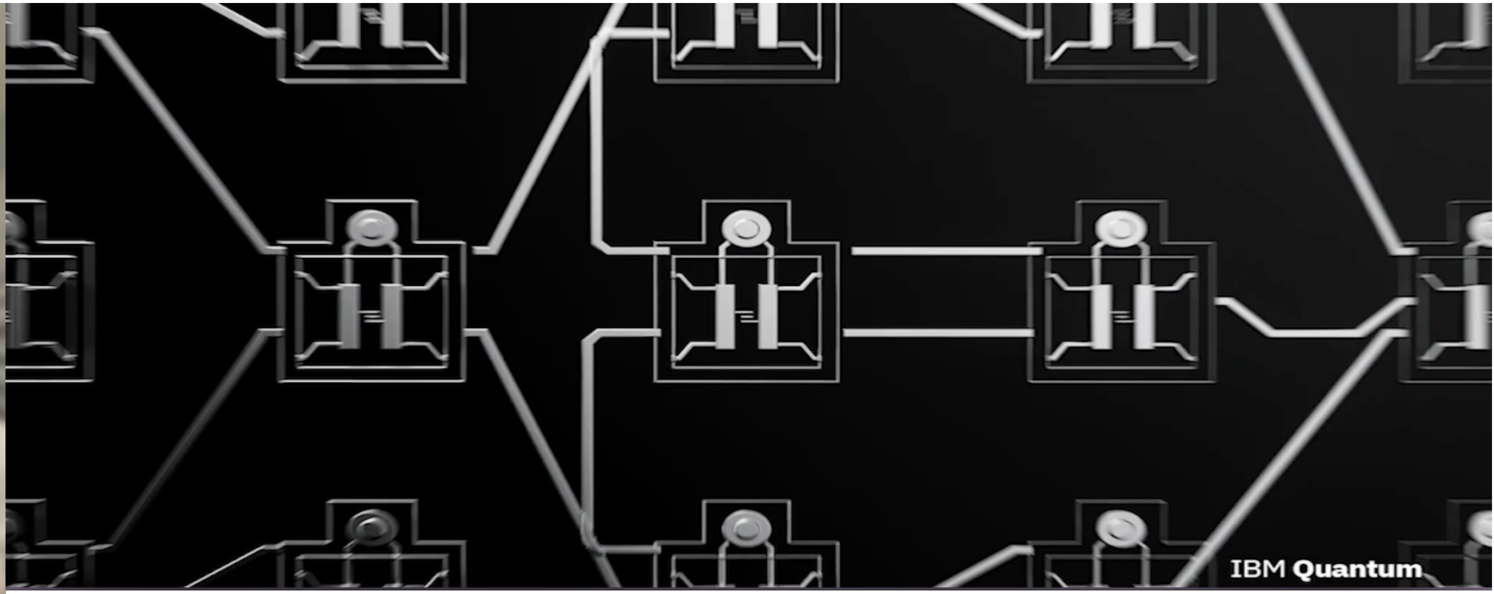




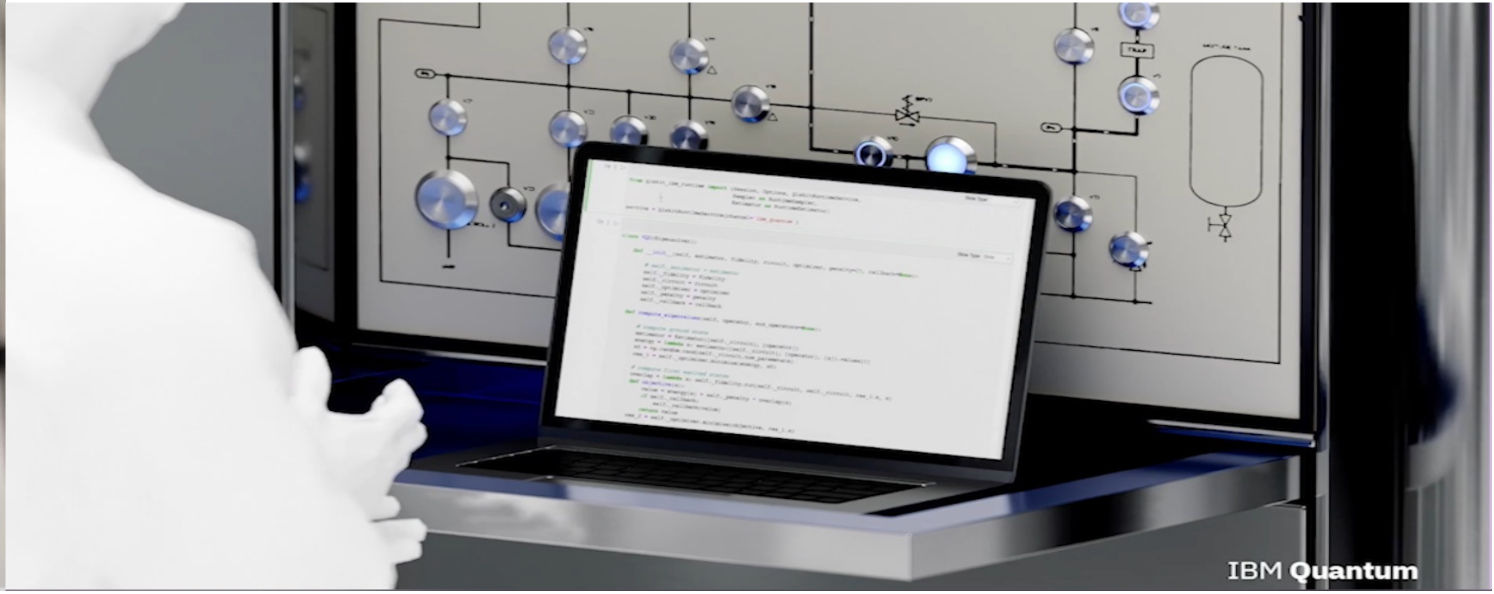


superconducting qubit platforms

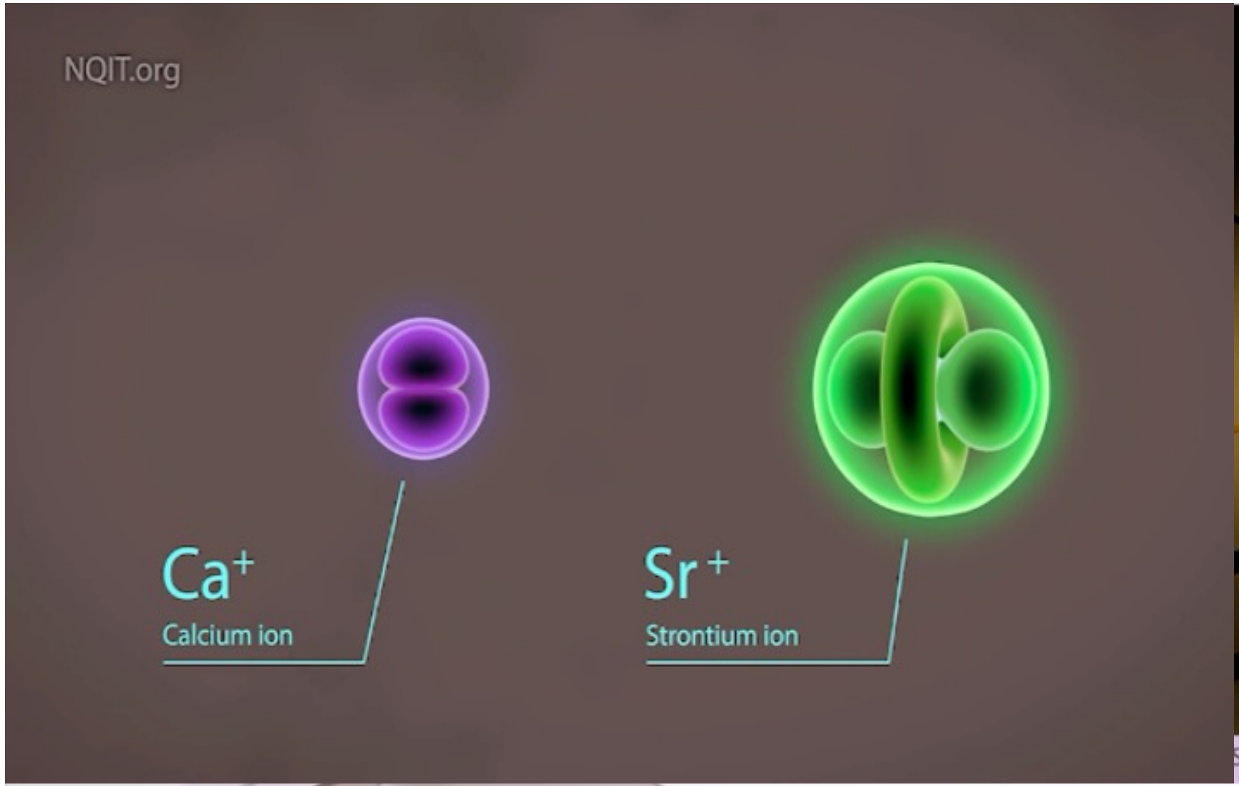


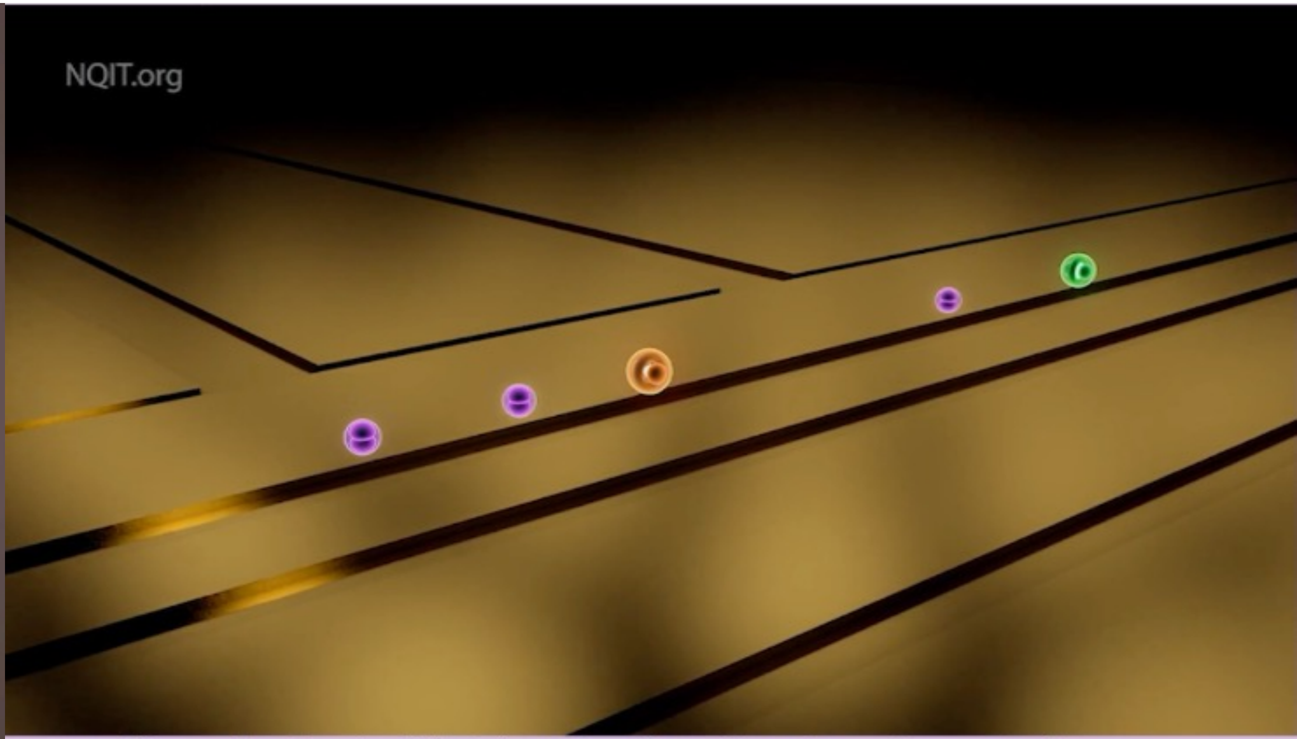


Superconducting QUBIT NISQ devices for computing

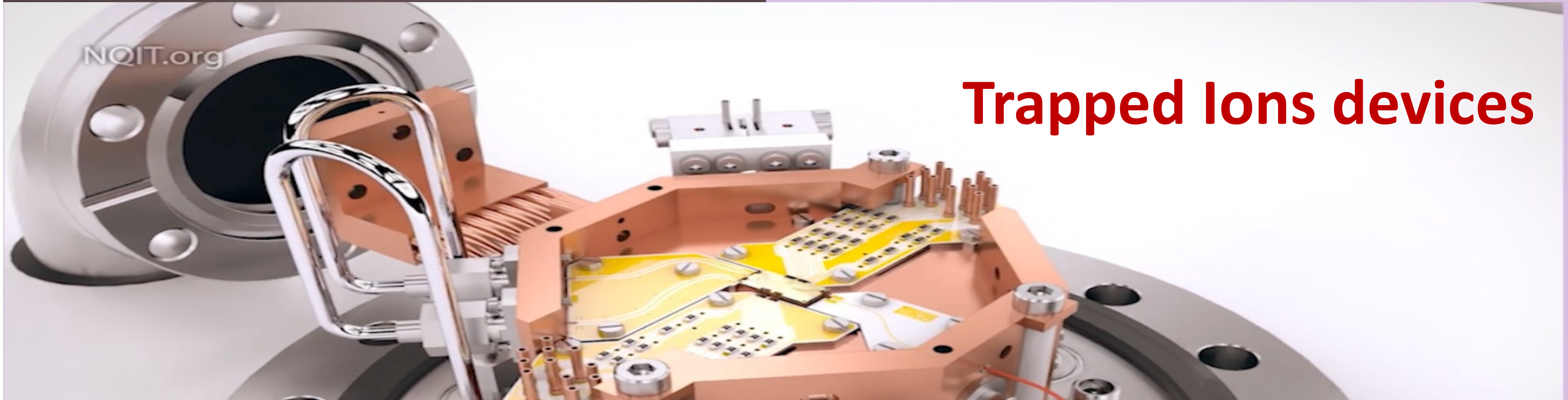


Trapped Ions devices

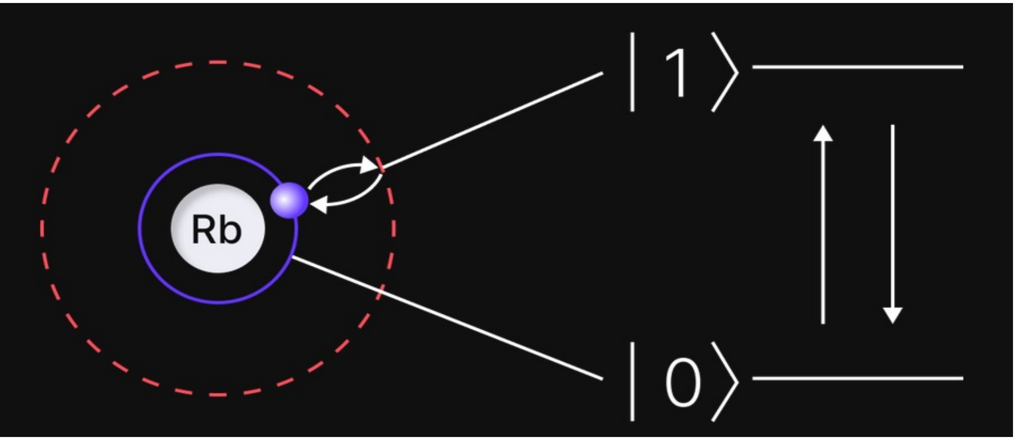


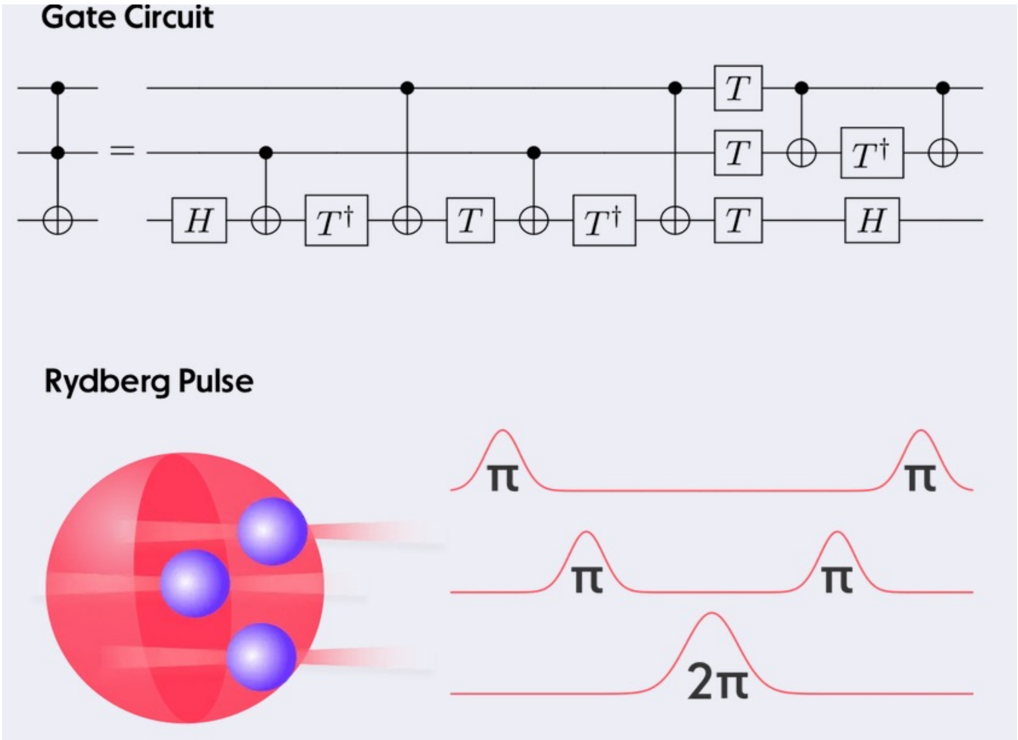


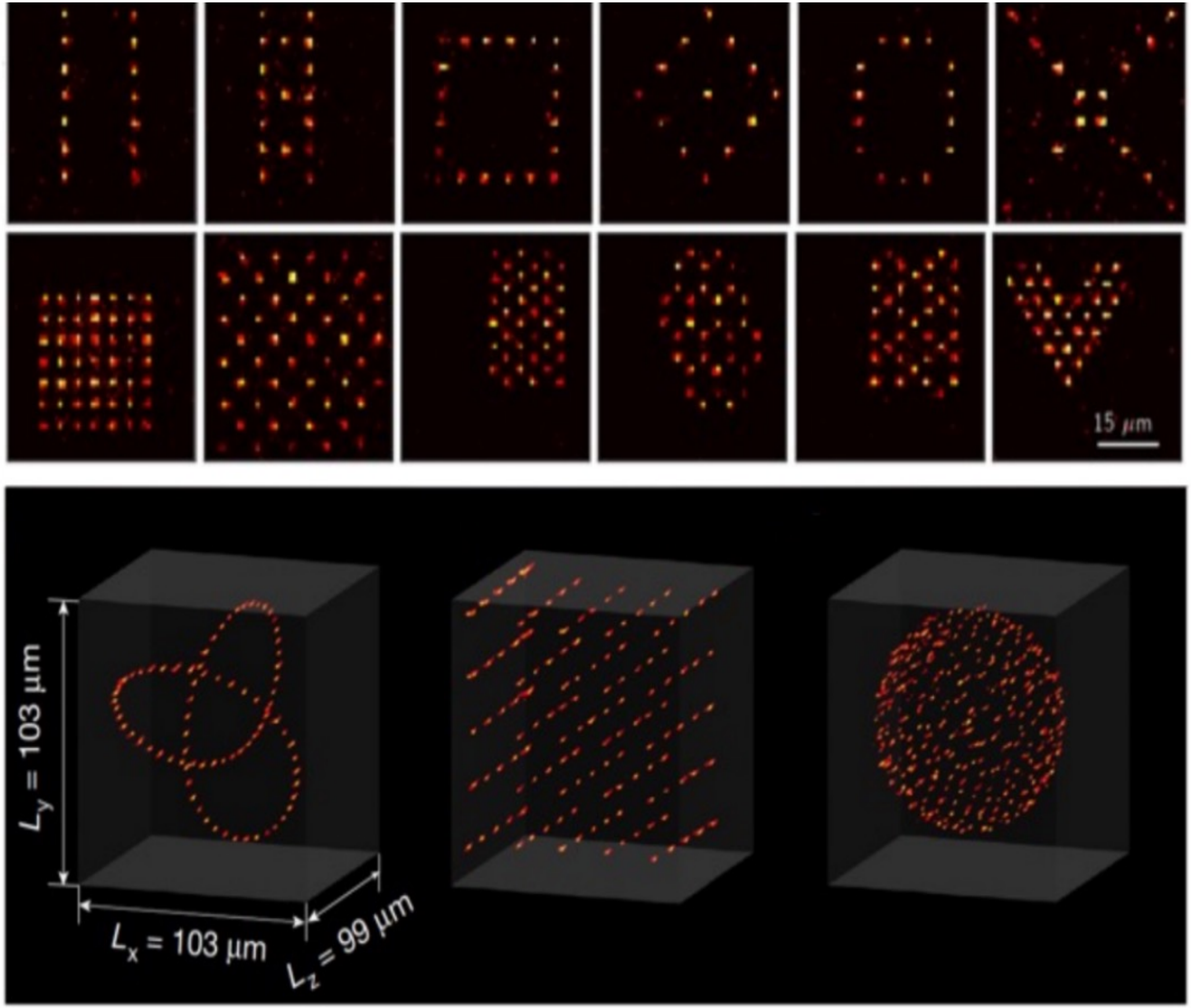
source: Simon Benjamin, What is an Ion Trap Quantum Computer?



Rydberg atom computing

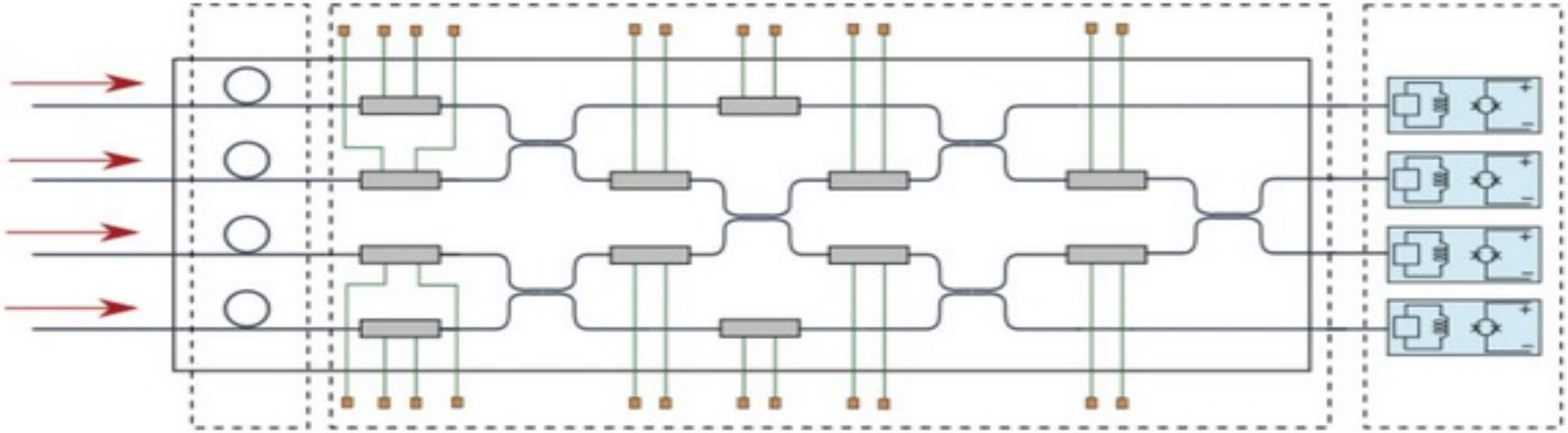


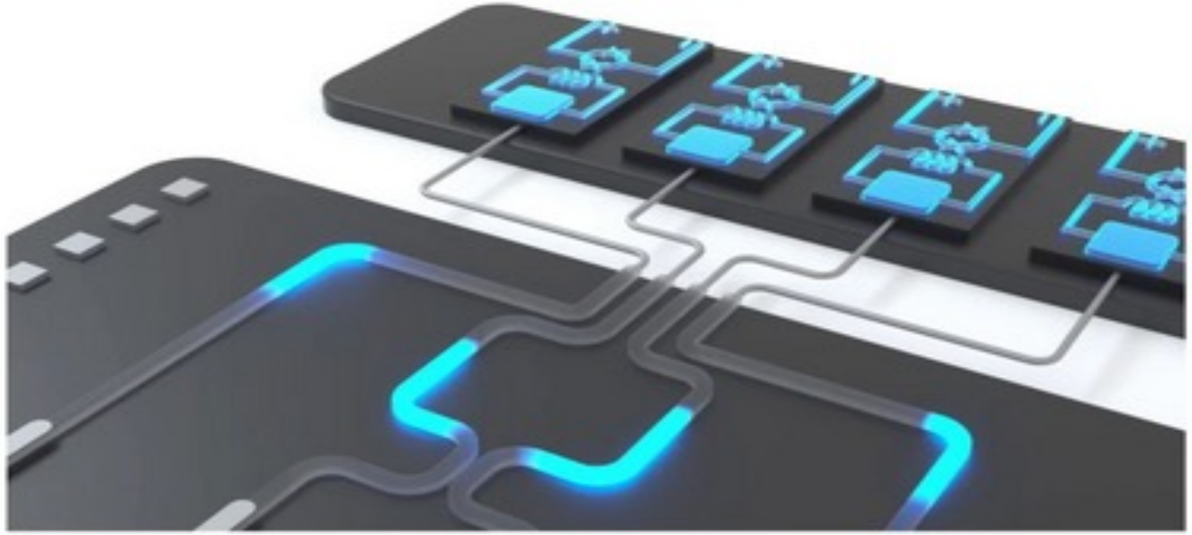


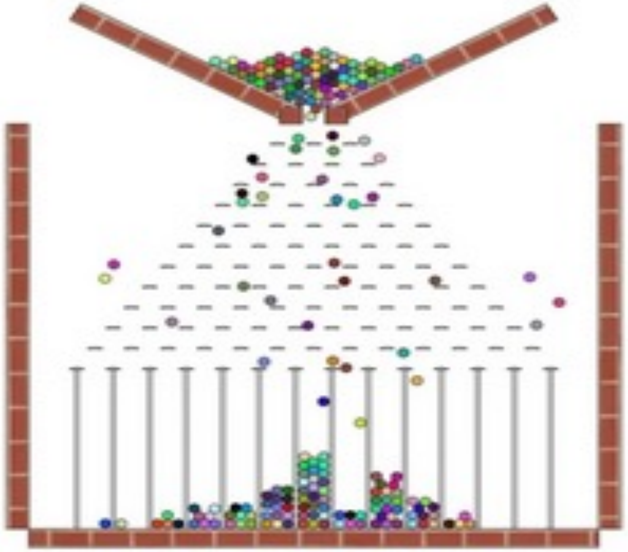


Examples of neutral atom arrays in 2D and 3D, extracted from Barredo, D. et al. (2018). Nature, 561(7721):79–82.

Photonic Quantum Computing







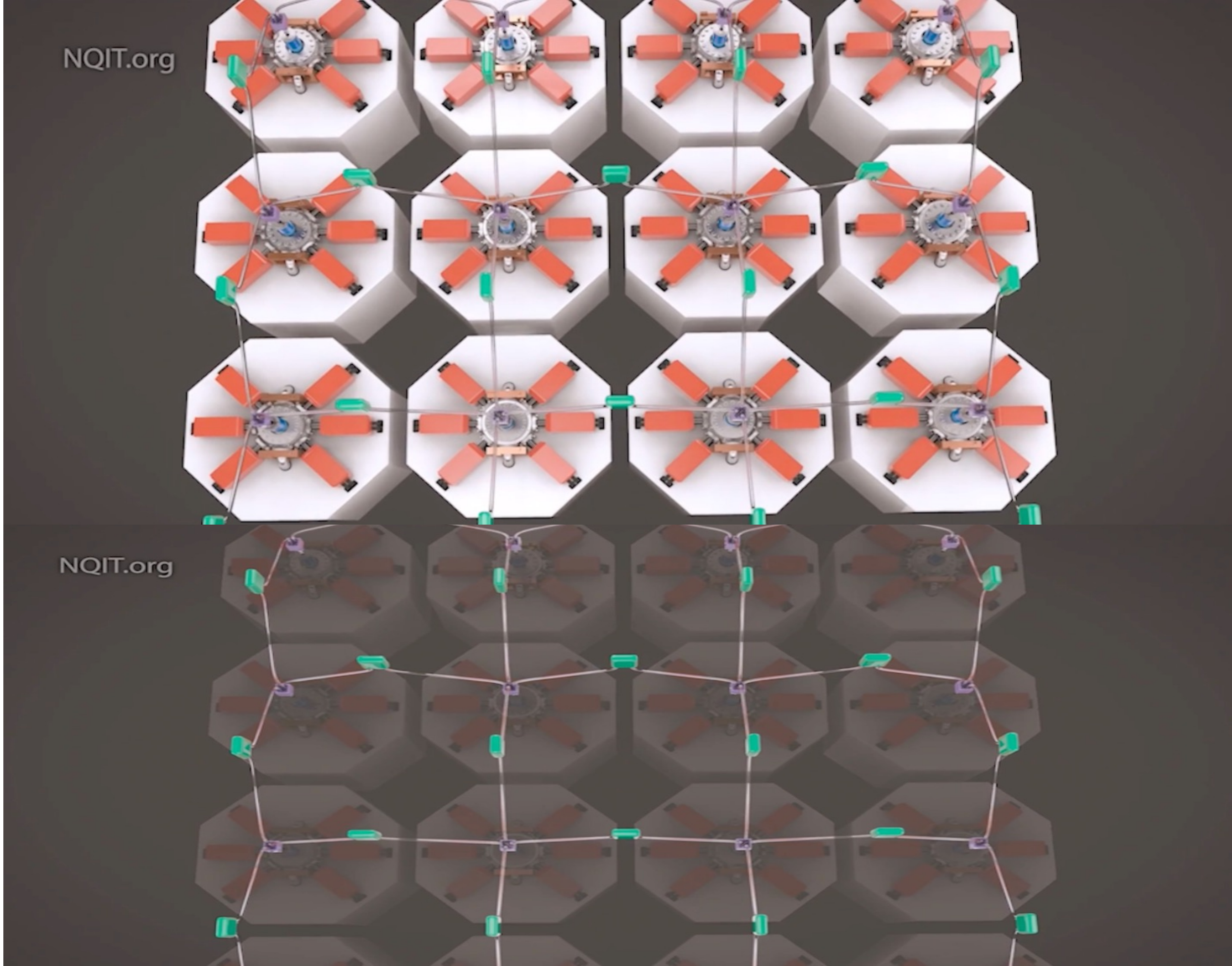
PQC.ai

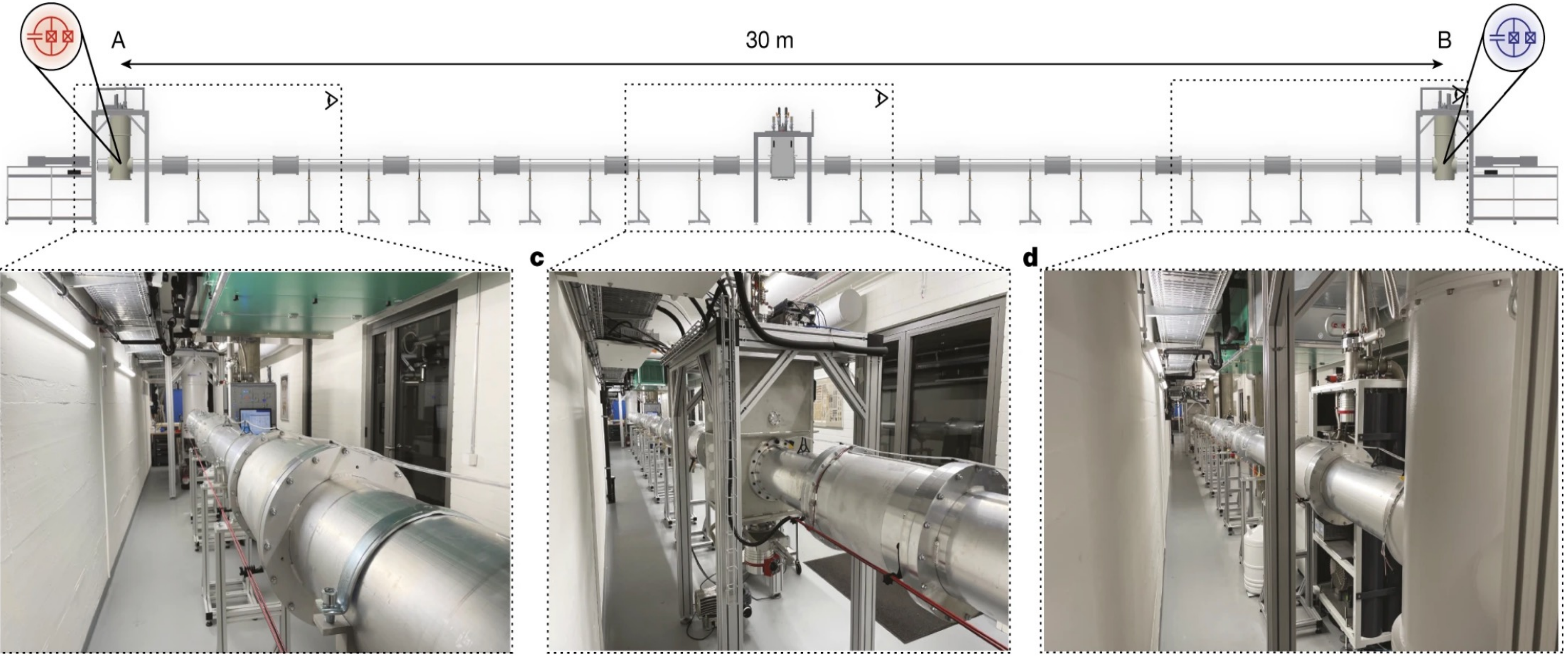
Networks:

Distributed computing

Information distribution and communication

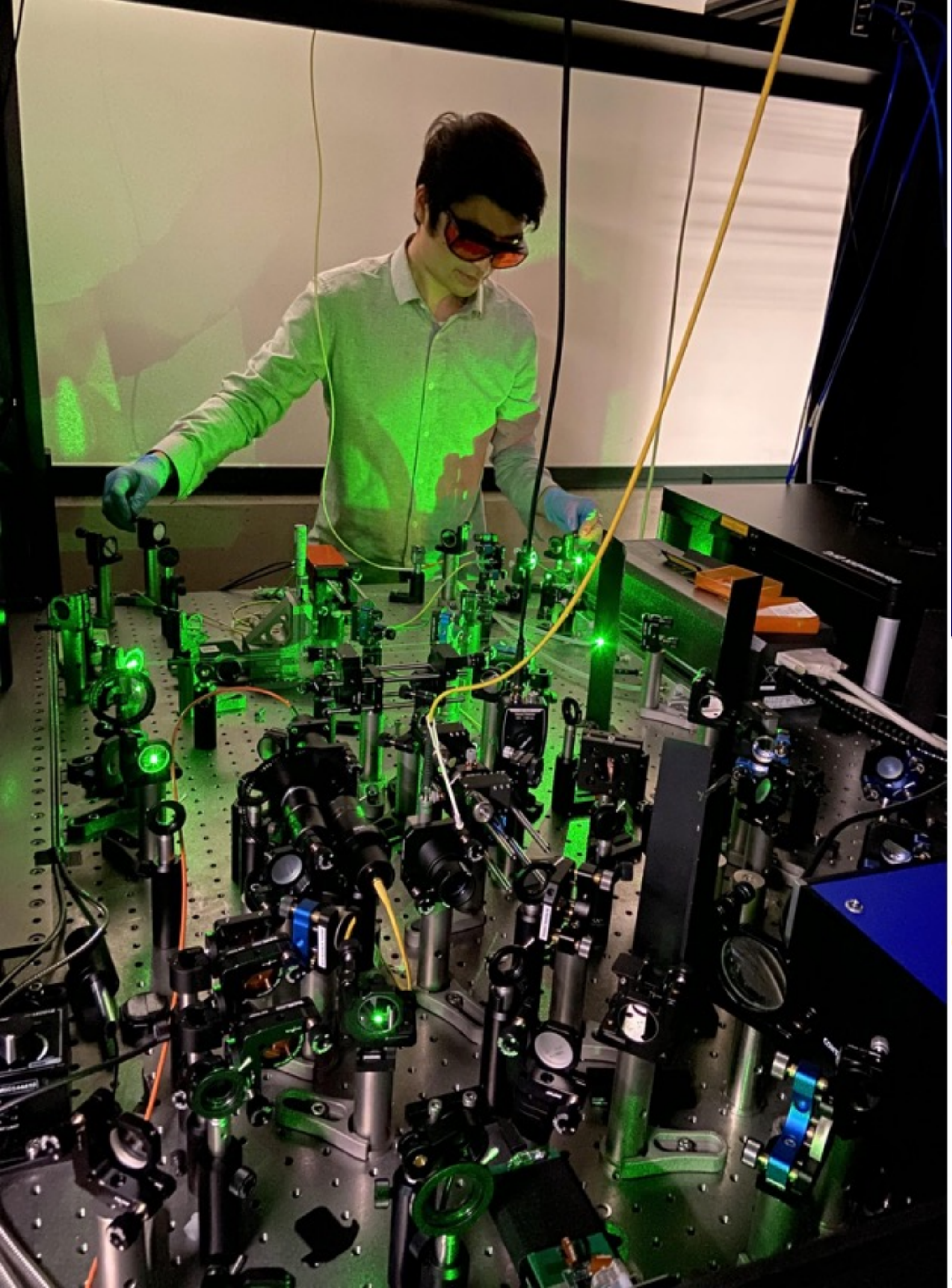
Storage

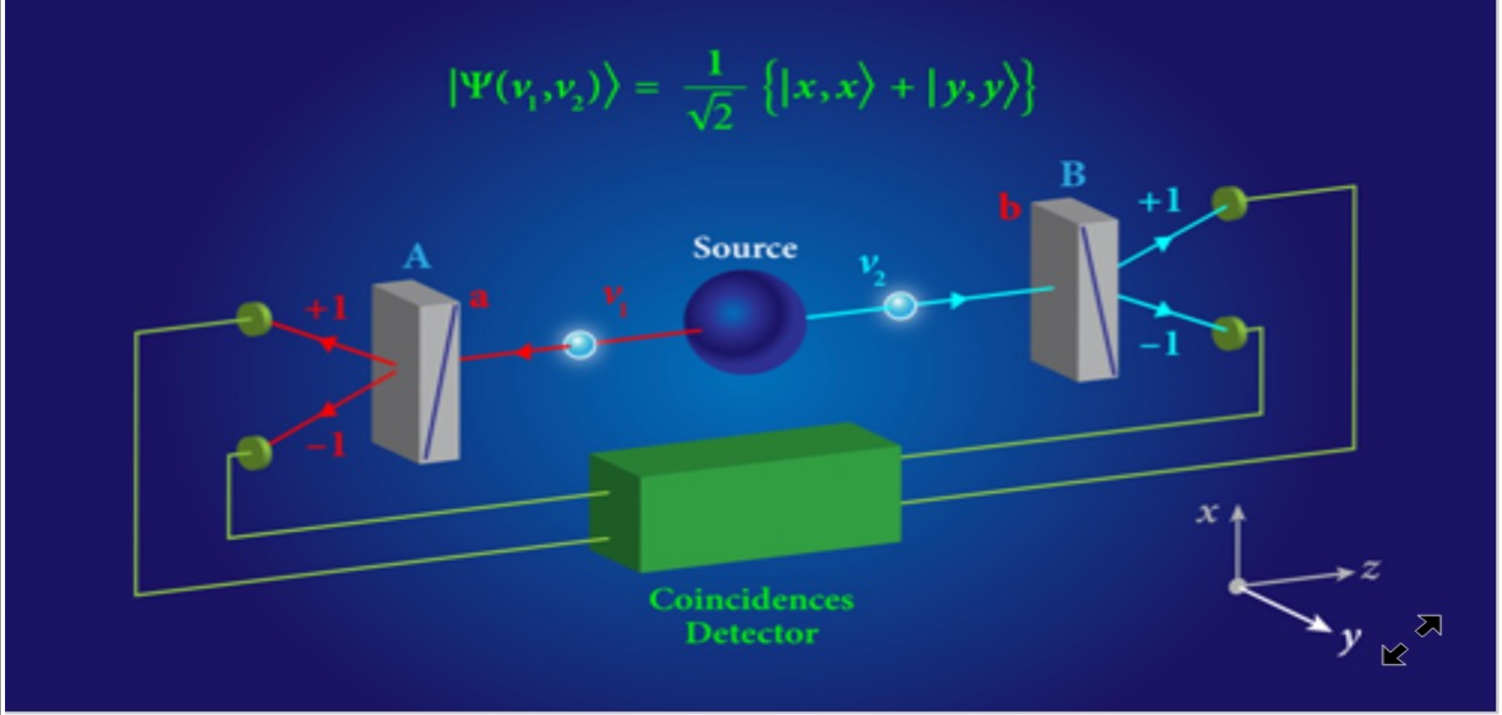


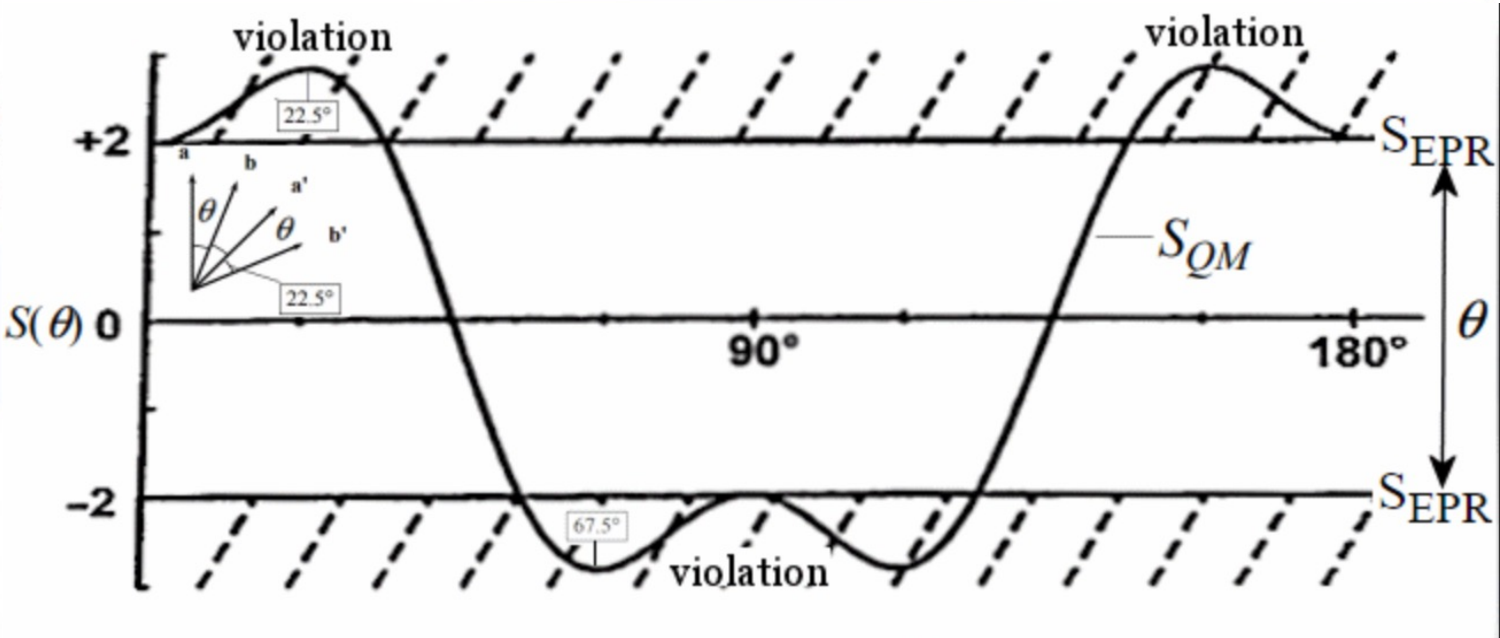


Source: *Nature* **617**, 265–270 (2023)

Loophole-free Bell inequality violation with superconducting circuits.







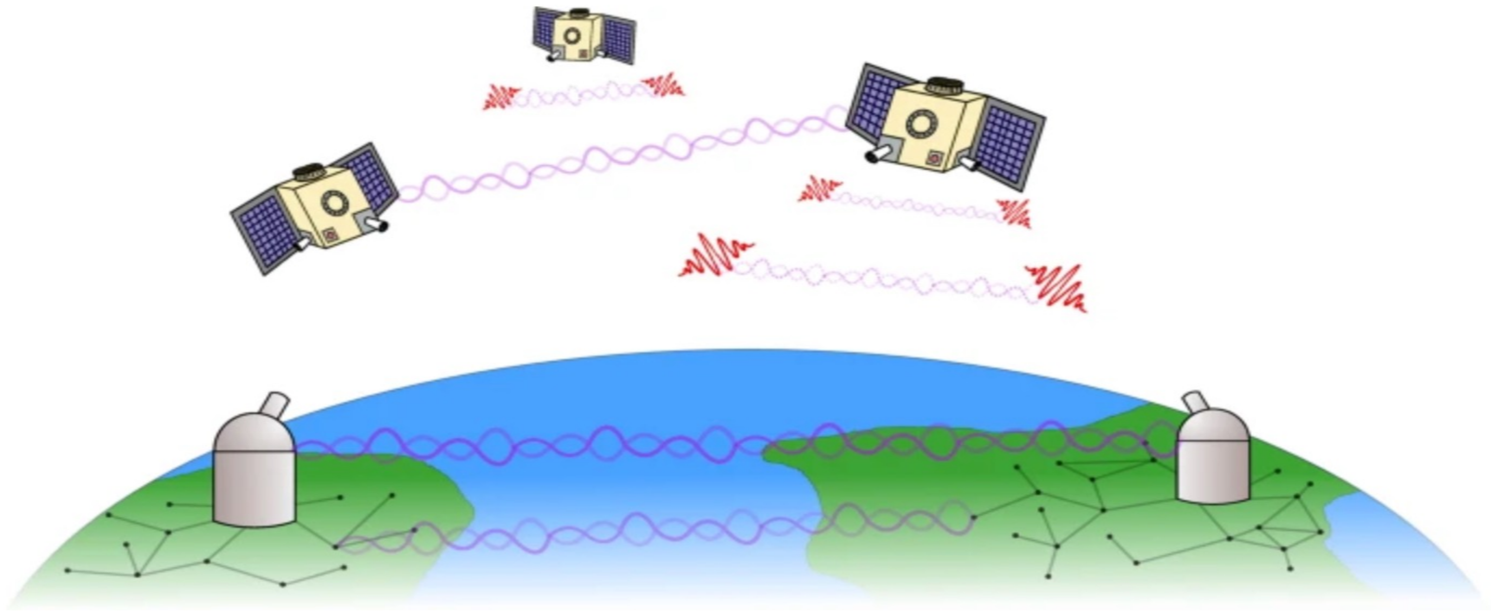
Violation of Bell's Inequality by Quantum Mechanics

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].

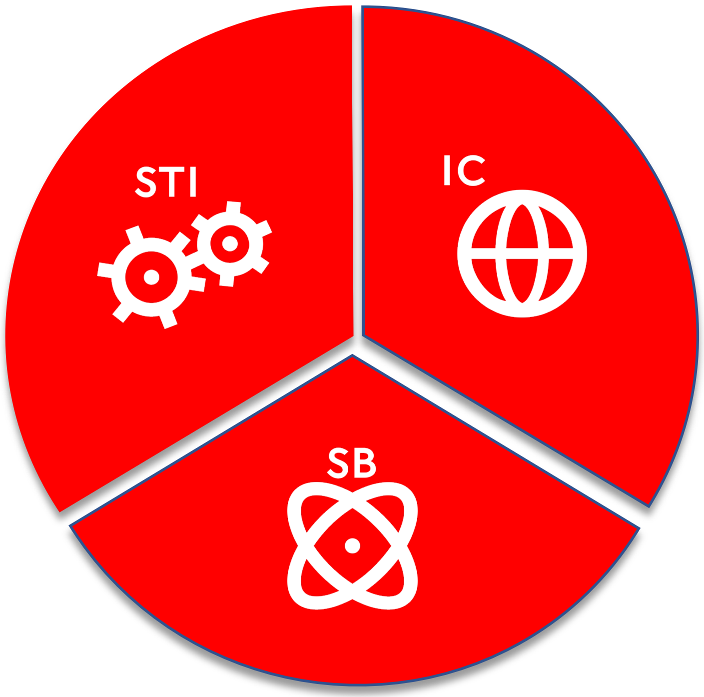
Profiles of a quantum engineers ?

- Skills and knowledge from **Computer Science, Engineering, and Physics / Mathematics / Chemistry**

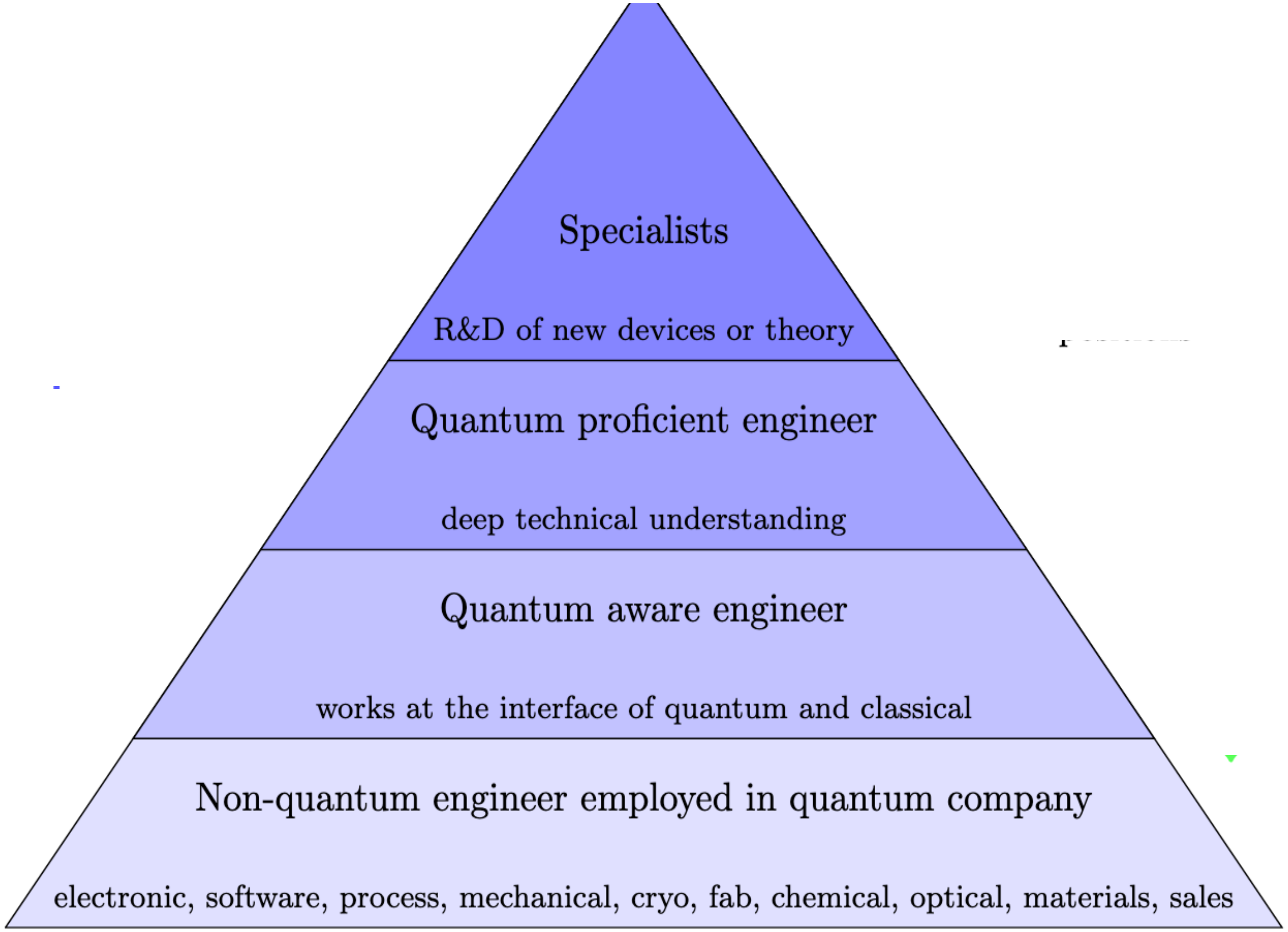
- Few Master's programs worldwide offer such a multidisciplinary educational profile

- 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

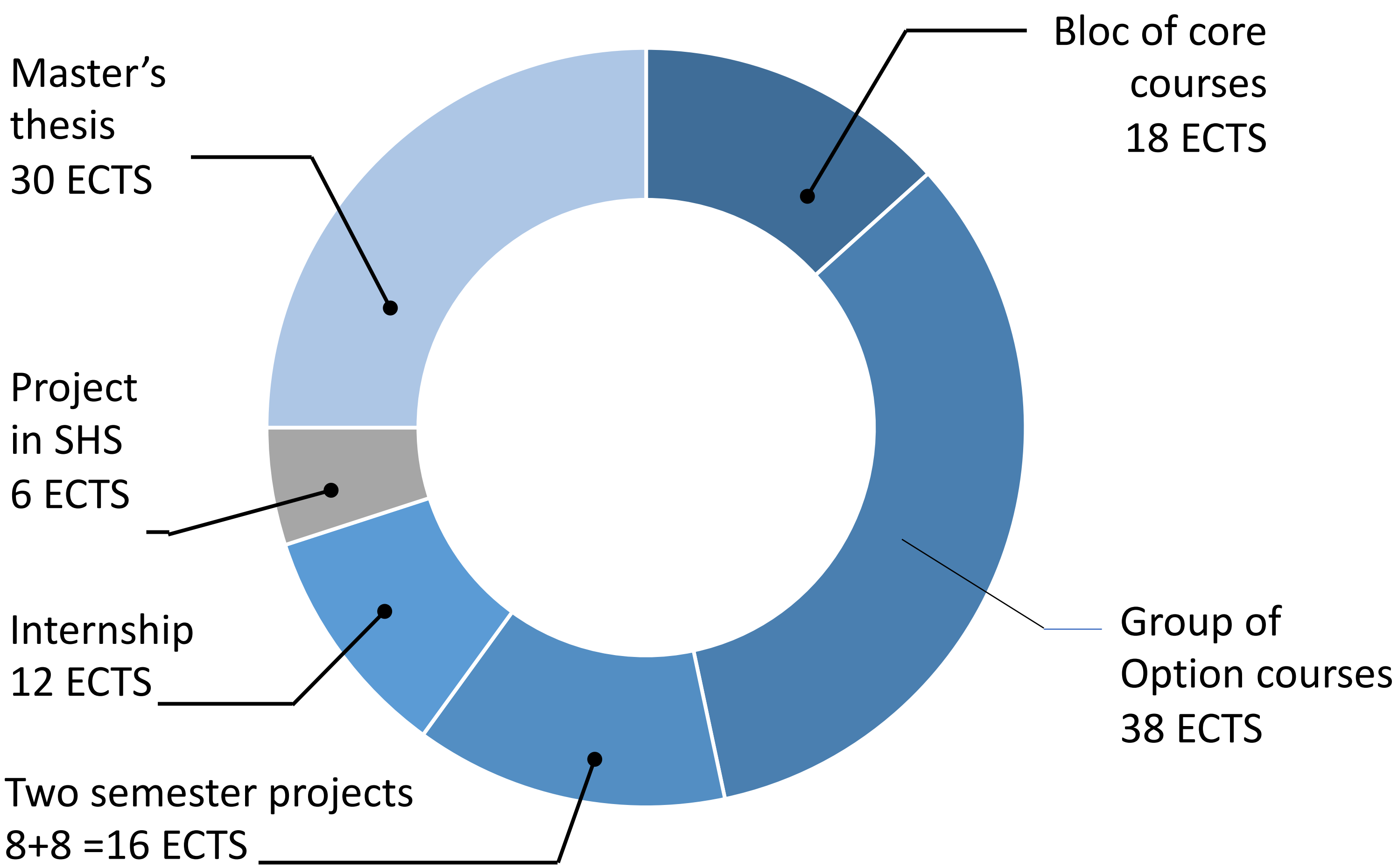


Needs of the industry



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

Basic structure of the master



Choose one specialization:

A: Quantum information and computation

- B: Quantum hardware and engineering

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

Core courses	18	
Quantum Physics for non-physicists (New)	5	-> Should take if didn't have equiv class before
Introduction to Quantum Science, Technology and Applications	5	-> Recommended for all students
Quantum Information Processing	5	-> Two intro classes quant info and computation
Quantum Computation	5	
Solid State Systems for Quantum Information	4	-> Two intro classes for hardware related courses
semiconductors devices I	4	
Quantum and Nanocomputing	6	-> Intro to the "quantum stack"
Computational Complexity	6	-> Theoretical comp science class
Computational quantum physics (New)	4	->Two more advanced classes
Quantum electrodynamics and quantum optics (New)	6	

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,…)

+ <u>3 New classes</u>: Advanced Quantum Physics; 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

- **Big tech companies** IBM, Microsoft, Google, Amazon, Intel, NEC, Righetti, Atos, ……….
- **Medium sized companies and Startups** -> MIRAEX (photonic sensing) QuantumMachines (qubit control systems) QuiX (photonic computing) Qnami , Qzabre (sensing) IDQ (crypto, communications), Pasqal (trapped ion computing), Alice and Bob, SANDBOXAQ (computing, ML), QuEra (neutral atom computing), ……………………………….
- **Research centers** → CSEM, PSI, IBMQ, CERN (Switzerland), ICFO (spain), CQT (singapour), VCQ, ESQ, IQOQI (Austria), Quantum Alliance (Germany), ………………………..
- **Academic research** → PhD in QSE. Many exciting possibilities in Switzerland and worldwide !

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

csem

intel

PAUL SCHERRER INSTITUT PSI

ICFO

amazon

CERN

NEC

QUANTINUUM

Microsoft

Google Quantum AI

rigetti

Baidu Research

IBM Quantum solutions

XANADU

Type	Private
Industry	Quantum Computing
Founded	2016
Founder	Christian Weedbrook, CEO
Headquarters	Toronto, Canada
Website	xanadu.ai

QuEra

HORIZON QUANTUM COMPUTING

accenture

AtoS

PsiQuantum

QUIX QUANTUM

IQM

IONQ

ENTROPICA LABS

SINGLE QUANTUM Excellence in photon detection

QUANTUM MACHINES

Zurich Instruments

RedWave Labs

PicoQuant 25 years

seeqc

ColdQuanta

QUANTUM MOTION

Orange Quantum Systems

Algorithmiq algorithmiq

parityqc

IDQ

QUANTUM DICE

aegiq

CRYPTONEXT SECURITY

Cambridge Quantum

Entangled Networks more than the sum of its parts

ThinkQUANTUM

nu QUANTUM

KETS

Qnami

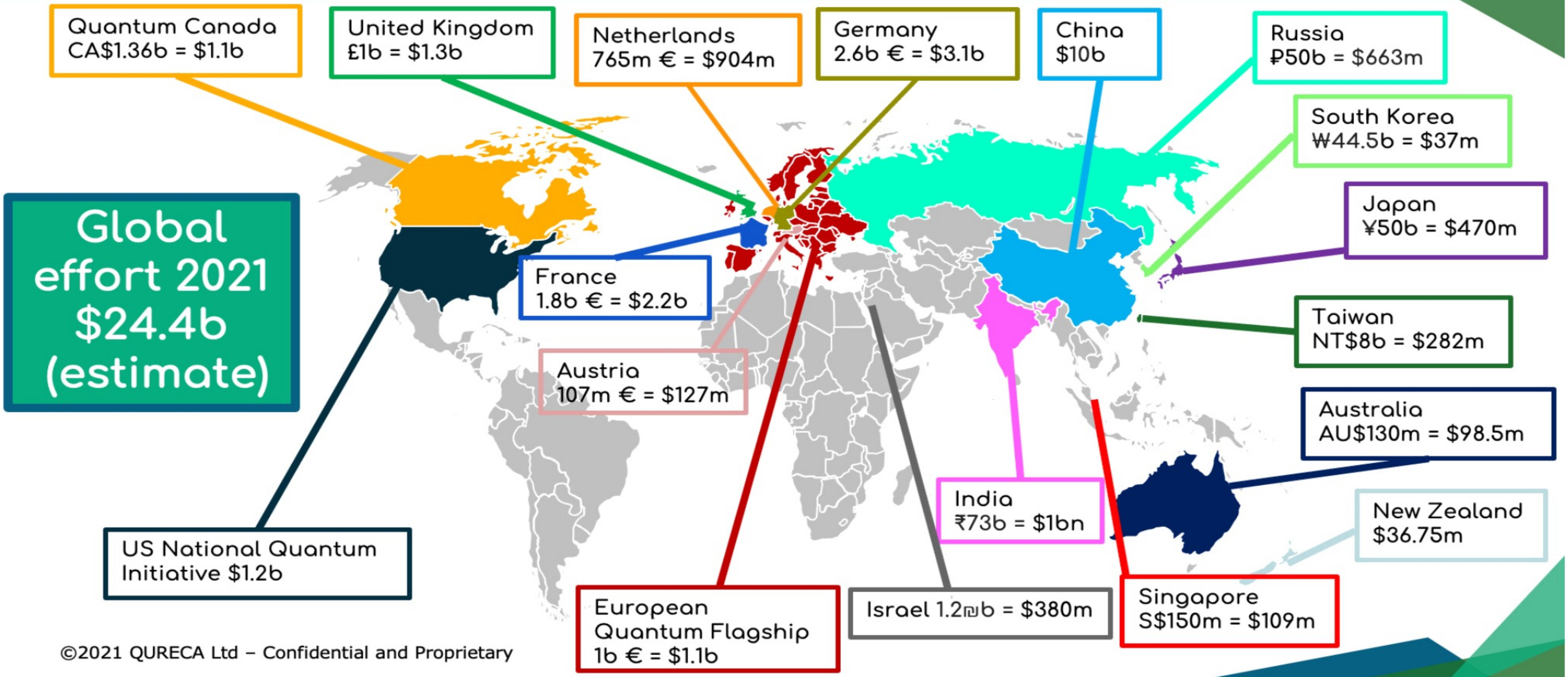
MIRAEX

AQT

VECTOR PHOTONICS

QURECA quantum resources & careers

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/
  Necessary requirement for admission is GPA of 4.5
  (Introductory quantum physics class can be taken in MA1 semester).

- Anybody applying for a bourse d'excellence must submit his application to SIQ by 30 April deadline (note it's a different deadline than above)

- For any info contact siq@epfl.ch

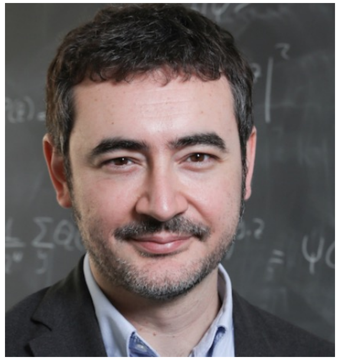
- **For details on the section consult:**

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

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/

Examples of menu for a specialization A on quantum information and computing:

Bloc courses - example 1 - 18 ECTS and average GPA at least 4

- *Quantum Physics for Non-Physicists,* Fall, 5 ECTS
- *Introduction to Quantum Science, Technology and Applications*, Fall 5 ECTS
- *Introduction to Quantum Information Processing* (COM-309), Fall 5 ECTS
- *Introduction to Quantum Computation* (CS-308), Spring 5 ECTS

Bloc courses - example 2 - 18 ECTS average GPA at least 4

- *Introduction to Quantum Science, Technology and Applications*, instructors from various schools, Fall 5 ECTS
- *Introduction to Quantum Computation* (CS-308), Spring 5 ECTS
- *Solid State Systems for Quantum Information* (PHYS-464), Spring 4 ECTS
- *Computational quantum physics* (PHYS-463) Spring, 4 ECTS

Group option courses 38 ECTS (specialization A). Examples:

- *Information Theory and Coding* (COM-404), Fall, 8 ECTS
- *Advanced algorithms* (CS-450), Spring, 8 ECTS **OR** Cryptography and security (COM-401), Fall, 8 ECTS
- *Optimization for machine learning* (CS-439), Fall, 5 ECTS **OR** Machine learning (CS-433), Fall, 8 ECTS
- *Quantum Information Theory, (PHYS-550),* Spring, 4 ECTS
- *Computational Quantum Physics* (PHYS-463), Spring, 4 ECTS
- *Quantum optics and quantum information* (PHYS-454), Spring, 6 ECTS **OR** *Quantum Electrodynamics and Quantum Optics* (PHYS 453) 6 ECTS
- *Computational Methods in Molecular Quantum Mechanics (CH-452*), Fall, 4 ECTS OR *Molecular quantum dynamics* (CH-453) Spring 3 ECTS

OR choose two classes from hardware track, for example:

- *Photonic systems and technology* (EE-440), Spring 4 ECTS
- *Fundamentals of solid state materials* (MSE-423) Fall, 4 ECTS

Example study plan for a specialisation B on quantum hardware engineering:

Bloc courses - example 1 – 18 ECTS and average GPA > 4

- *Introduction to Quantum Science, Technology and Applications*, Fall, 5 ECTS
- *Semiconductors devices I* (EE-557), Fall, 4 ECTS
- *Introduction to Quantum Computation* (CS-308), Spring, 5 ECTS
- *Solid State Systems for Quantum Information* (PHYS-464), Spring, 4 ECTS

Bloc courses - example 2 – 18 ECTS and average GPA > 4

- *Quantum Physics for Non-Physicists*, Fall, 5 ECTS
- *Introduction to Quantum Science, Technology and Applications*, Fall, 5 ECTS
- *Quantum and Nanocomputing* (MICRO-435), Fall, 6 ECTS
- *Solid State Systems for Quantum Information* (PHYS-464), Spring, 4 ECTS

Group option courses 38 ECTS (specialization B). Example 1:

- *Deep Learning,* (EE-559), Spring, 4 ECTS
- *Semiconductor Devices II (EE-567),* Spring*, 4*
- *Photonic systems and technology* (MSE-483), Spring 5 ECTS
- *Metrology* (MICRO-428), Spring, 3 ECTS
- *Metrology practicals* (MICRO-429), Spring, 2 ECTS
- *Fundamentals of Solid-State Materials* (MSE-423), Fall, 4 ECTS
- *Quantum Transport in Mesoscopic Systems* (PHYS-462), Fall, 4 ECTS
- *Nonlinear Optics for Quantum Technologies* (PHYS-470), Fall, 4 ECTS
- *Semiconductor Physics and Light-Matter Interaction* (PHYS-433), Fall, 4 ECTS
- *Nanotechnology* (MICRO-530), Spring 3 ECTS
- *Nanoelectronics* (EE-535), Fall 2 ECTS

Group option courses 38 ECTS (specialization B). Example 2:

- *Advanced Machine Learning* (MICRO 579), Fall 4 ECTS
- *Properties of semiconductors and related nanostructures* (MSE 484), Spring, 5 ECTS
- *Photonic systems and technology* (MSE-483), Spring 5 ECTS
- *Metrology* (MICRO-428), Spring, 3 ECTS
- *Metrology practicals* (MICRO-429), Spring, 2 ECTS
- *Atomistic and Quantum Simulations of Materials* (MSE 468), Spring 4 ECTS
- *Quantum Transport in Mesoscopic Systems* (PHYS-462), Fall, 4 ECTS
- *Photonic systems and technology* (EE 440), Spring 4 ECTS
- *Molecular Quantum Dynamics (CH 453), Spring 3 ECTS*
- *Lab in Nanoelectronics* (EE 490), Fall 4 ECTS