



quantum computing

science, technology, use cases



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Aristote, Ecole Polytechnique, Palaiseau, 10 octobre 2025

agenda

1. quantum computing 101
2. quantum computing hardware
3. quantum computing software
4. using quantum computers
5. quantum computing ecosystem

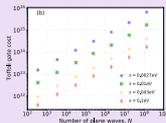
potential quantum computing benefits



- or
- **computing faster than classical systems.**
 - **solving problems inaccessible to classical computers.**



- **reducing required training data**, particularly for machine learning tasks.



- **improving results quality:** chemical accuracy, better heuristics, etc.

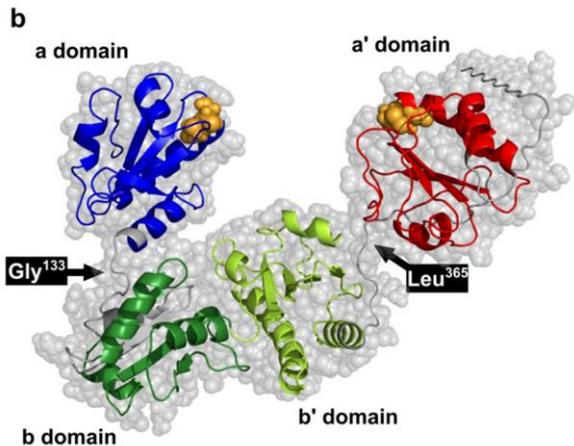


- or
- **energy advantage (NISQ).**
 - **energy acceptability (FTQC).**



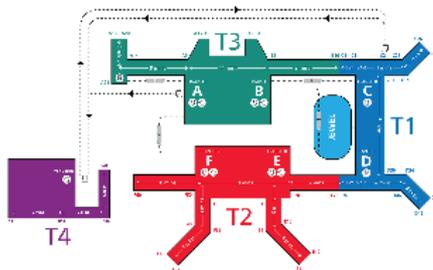
- **usefulness:** which depends on the stakeholder (fundamental research, governments, industry).

typical difficult problems

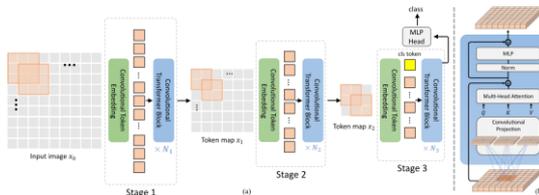


$$i\hbar \frac{\partial \Psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi(x,t)}{\partial x^2} + V(x)\Psi(x,t)$$

solving Schrodinger's wave equation
to simulate quantum systems



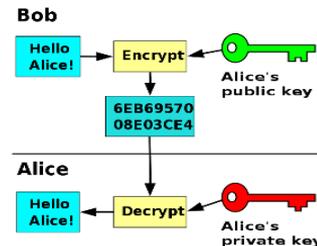
combinatorial optimizations



machine learning
and deep learning



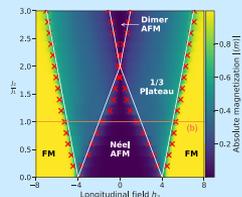
solving partial differential equations



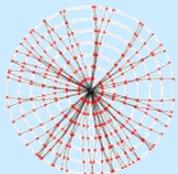
breaking asymmetric
cryptography keys

from science to industry applications

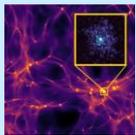
fundamental research



condensed matter physics

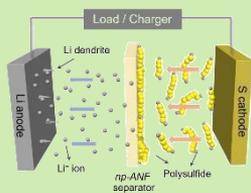


high-energy particle physics



astrophysics

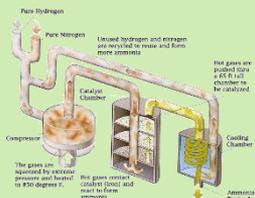
applied research



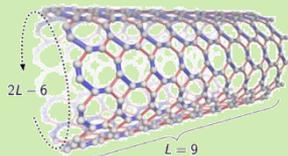
batteries



drugs



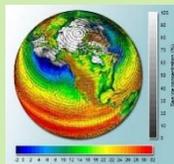
fertilizer production



material design

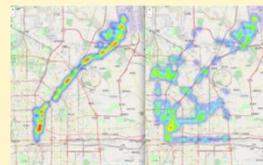


semiconductors



climate modeling

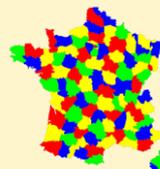
business operations



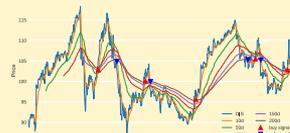
transportation



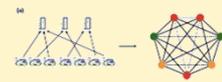
logistics and retail



telecoms



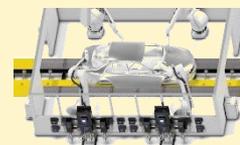
financial services



energy utilities



manufacturing



what is a qubit?

mathematically

basic unit of quantum information

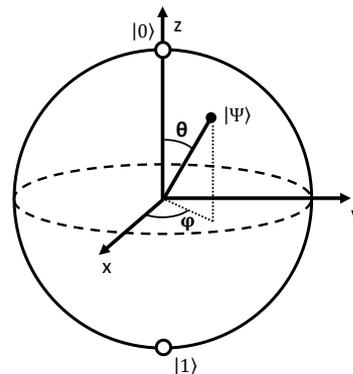
vector in a 2-dimension complex numbers Hilbert space

complex numbers amplitudes

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

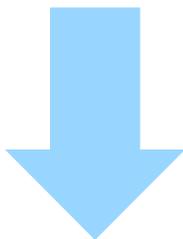
$$|\alpha|^2 + |\beta|^2 = 1$$

probabilities and Born normalization constraint

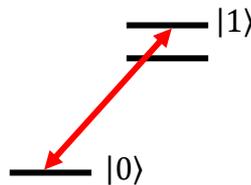


Bloch sphere representation with amplitude and phase

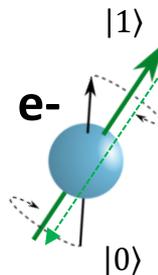
physically



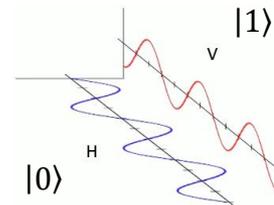
two-level state controllable quantum object



separable atom energy level

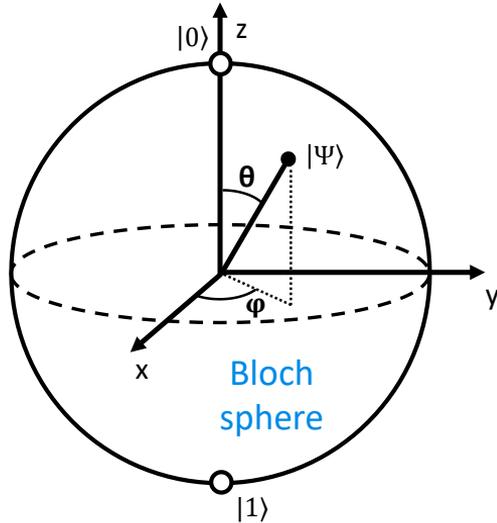


electron or nucleus spin orientation



photon mode (polarization, number, frequency)

qubits mathematical operations



two-level quantum object,
handling the equivalent of
two floating point numbers

complex
amplitudes

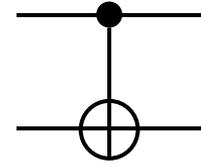
$$\begin{bmatrix} \alpha_1 \\ \dots \\ \dots \\ \dots \\ \dots \\ \alpha_{2^N} \end{bmatrix}$$

combinations
of 0s and 1s

$$\begin{aligned} &|00 \dots 00\rangle \\ &|10 \dots 01\rangle \\ &|11 \dots 11\rangle \end{aligned}$$

N qubits handle the
equivalent of $2^{N+1} - 1$
floating point numbers

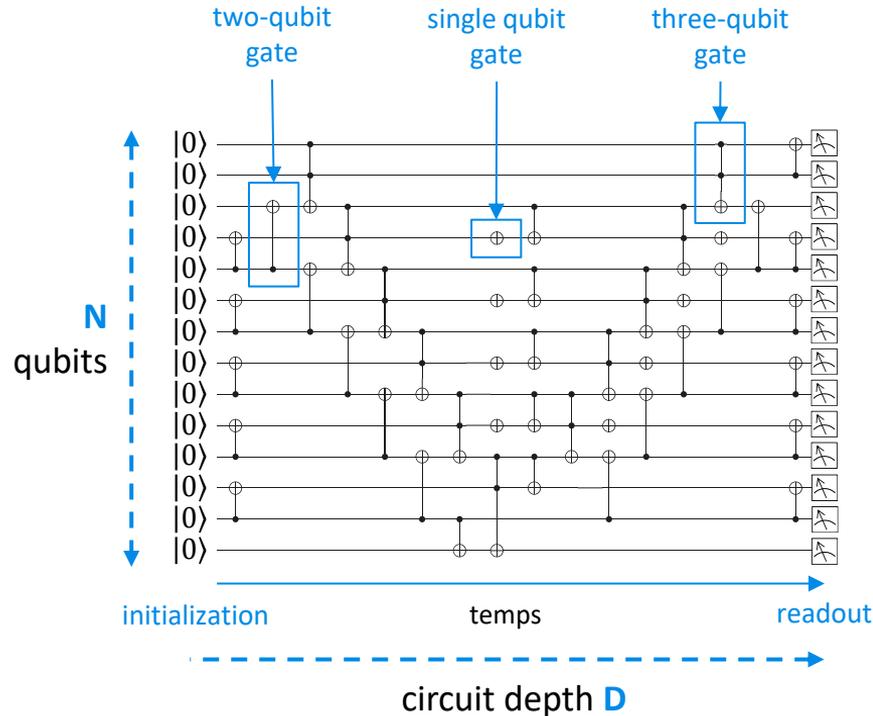
CNOT gate



$$\begin{bmatrix} \alpha_{00} \\ \alpha_{01} \\ \alpha_{10} \\ \alpha_{11} \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix} = \begin{bmatrix} \alpha_{00} \\ \alpha_{01} \\ \alpha_{11} \\ \alpha_{10} \end{bmatrix}$$

entanglement creates links between
qubits and brings computing power
under certain circumstances

what is a quantum algorithm?



quantum algorithm: decomposes a solution to solve some mathematical problem into a quantum circuit.

quantum circuit: series of operations (gates) acting on a quantum memory, on individual qubits (superposition) or with connecting them (entanglement in most cases).

matrix computing: operating on a memory space of dimension 2^{N+1} real numbers.

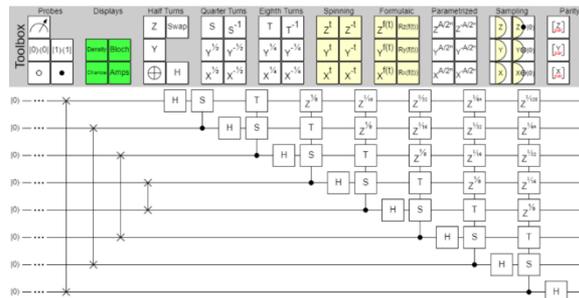
mecanism: exploit various techniques to yield a value of interest in a series of classical bits.

classical computing: used to prepare the circuit, encode data, and extract useful result from multiple circuit runs.

key differences

$$\langle \Psi_1 | \Psi_2 \rangle = [\overline{\alpha_1}, \overline{\beta_1}] \times \begin{bmatrix} \alpha_2 \\ \beta_2 \end{bmatrix} = \overline{\alpha_1} \alpha_2 + \overline{\beta_1} \beta_2$$

$$|\Psi_2\rangle\langle\Psi_1| = \begin{bmatrix} \alpha_2 \\ \beta_2 \end{bmatrix} \times [\overline{\alpha_1}, \overline{\beta_1}] = \begin{bmatrix} \alpha_2 \overline{\alpha_1} & \alpha_2 \overline{\beta_1} \\ \beta_2 \overline{\alpha_1} & \beta_2 \overline{\beta_1} \end{bmatrix}$$



```
# Initialize counting qubits
# in state |1>
for q in range(n_count):
    qc.h(q)

# And auxiliary register in state |1>
qc.x(3+n_count)

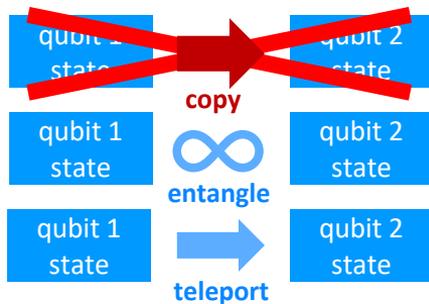
# Do controlled-U operations
for q in range(n_count):
    qc.append(c_amod15(a, 2**q),
              [q] + [i+n_count for i in range(4)])

# Do inverse-QFT
qc.append(qft_dagger(n_count), range(n_count))

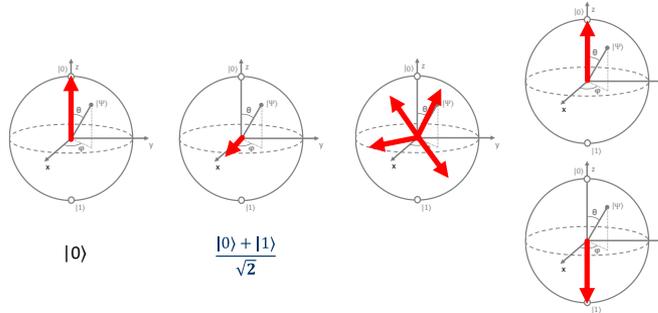
# Measure circuit
qc.measure(range(n_count), range(n_count))
qc.draw(fold=-1) # -1 means 'do not fold'
```

need to (re-)learn linear algebra

visual or Python scripted « circuits » programming



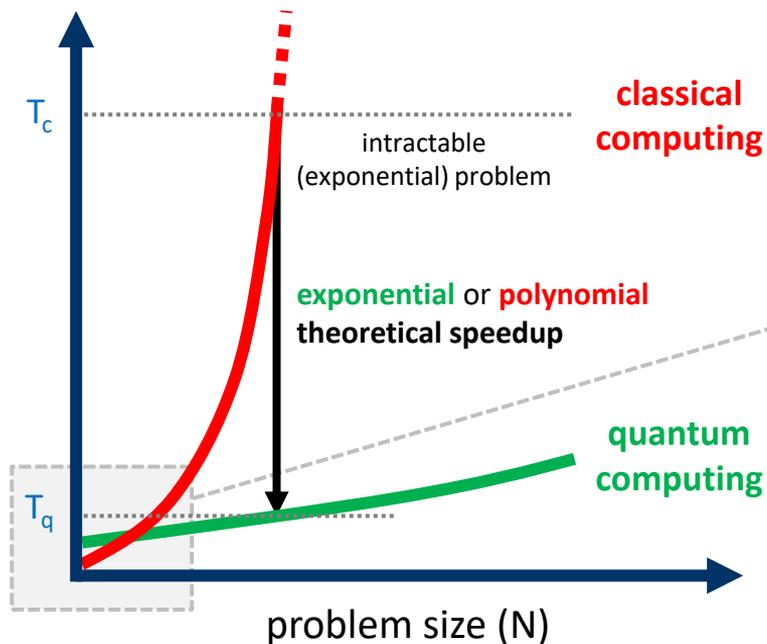
uncopiable data,
but transferable



probabilistic results, and repeated computing to
generate a deterministic outcome

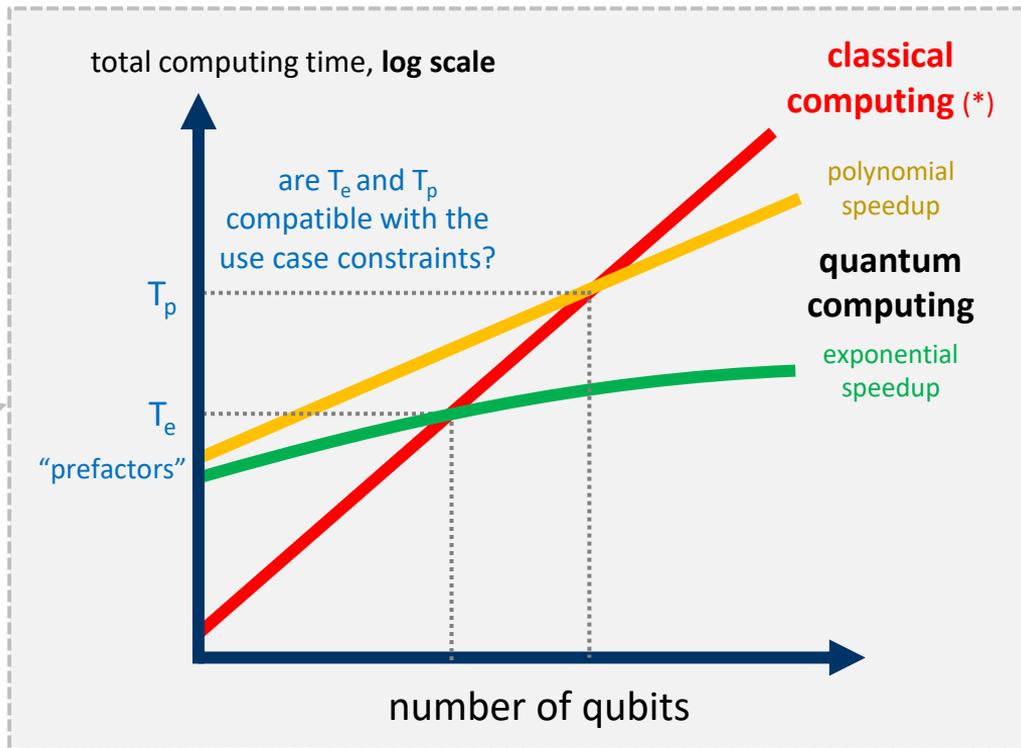
theoretical vs practical speedups

total computing time, linear scale



the typical and naive way to illustrate quantum computing theoretical speedups.

total computing time, log scale

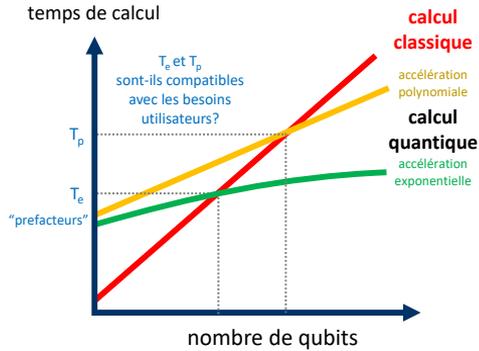


inspired by [Opening the Black Box inside Grover's Algorithm](#)

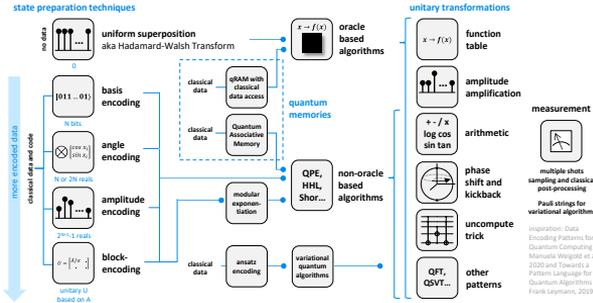
by E. Miles Stoudenmire and Xavier Waintal, PRX, November 2024.

(*) for a fair comparison, the classical computer can be as expensive and/or energy hungry as the QPU.

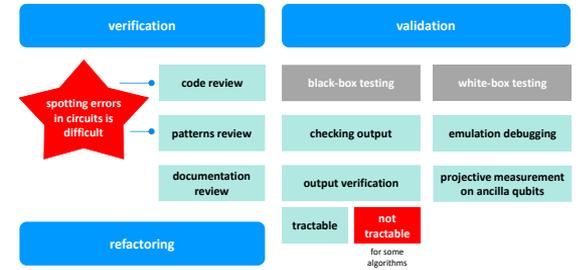
software challenges



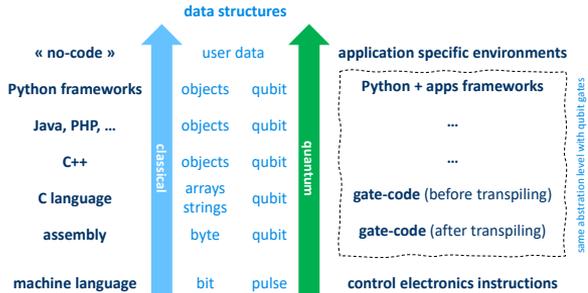
algorithms



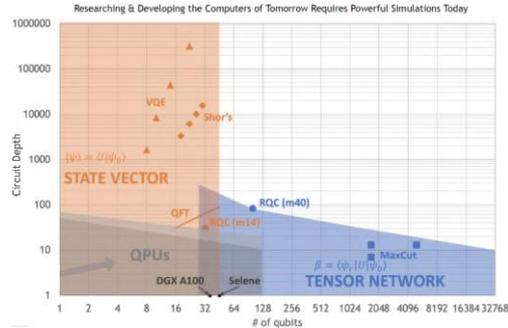
data loading



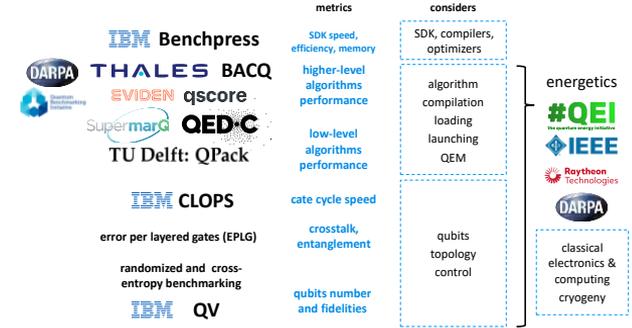
software engineering



abstraction level



tensor networks competition



benchmarking

EU AI+QT white paper



As international competition escalates, a new white paper published today calls on the EU to invest in combining quantum computing and artificial intelligence to generate economic benefits and strengthen Europe's position as a prominent global player in emerging deep technologies.

Published today by a group of interdisciplinary scientists and global industry experts, the new paper shows that for Europe to remain competitive and at the cutting edge of deep-tech innovation, it must actively fund the convergence of AI and quantum computing.

Called "Artificial Intelligence and Quantum Computing White Paper", the new paper highlights the need for a carefully orchestrated funding strategy that spans fundamental research, talent cultivation, and technology transfer incentives to ensure a robust pathway from visionary lab-scale projects to

<https://arxiv.org/abs/2505.23860>



Quantum computing and artificial intelligence: status and perspective

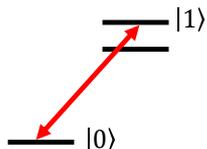
Giovanni Acampora,¹ Andris Ambainis,² Leonardo Banchi,^{3,4} Pallavi Bhardwaj,⁵ Daniele Binosi,^{6,7} Tommaso Calarco,^{6,8} Vedran Dunjko,⁹ Jens Eisert,¹⁰ Olivier Ezratty,^{11,12} Paul Erker,^{13,14} Elies Gil-Fuster,^{10,15} Martin Gärtner,¹⁶ Mats Granath,¹⁷ Anton Frisk Kockum,¹⁸ Iordanis Kerenidis,¹⁹ Matthias Klusch,²⁰ Richard Kueg,²¹ Mario Krenn,²² Antonio Macaluso,²⁰ Sabrina Maniscalco,²³ Kristel Michielsen,⁸ Gorka Muñoz-Gil,²⁴ Hendrik Poulsen Nautrup,²⁴ Roman Orus,²⁵ Jörg Schmiedmayer,¹³ Philipp Slusallek,^{26,20} and Frank K Wilhelm^{26,8}

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²⁶Saarland University, D-66123 Saarbrücken, Germany
 (Dated: April 22, 2025)

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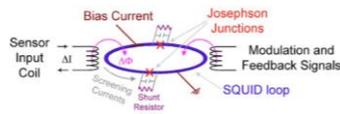
main qubit types

atoms and ions



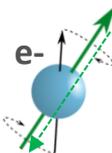
atom energy level

superconducting



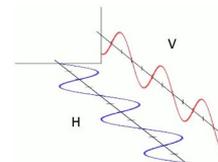
anharmonic oscillator
current phase and energy

electron spins



electron spin orientation

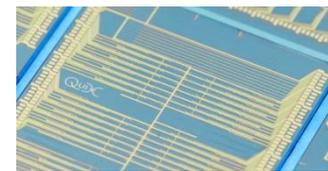
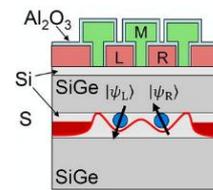
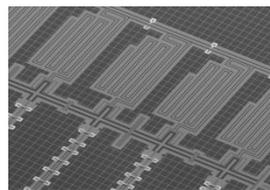
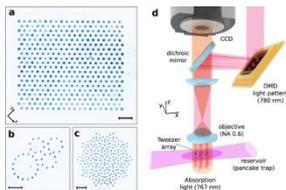
photons



photon polarization,
or other property

quantum states

physical aspect



interactions

readout

laser pulses,
and/or microwaves

laser illumination and
fluorescence detection

microwave pulses,
and/or DC current

reflectometry of microwave pulses
on an oscillator

interferometers, polarizing
beam splitters, ...

single/multiple
photon detectors

various forms of light-matter interactions

quantum & classical computing paradigms

classical computers

quantum inspired
 classical algorithms running on classical computer, inspired by quantum algorithms.

classical algorithms improvements



quantum emulators
 running quantum computers code on classical computers, for training, debugging and testing

quantum algorithms debug and testing



analog quantum computers

quantum annealing computers

optimization problems and quantum physics simulation



analog quantum simulators

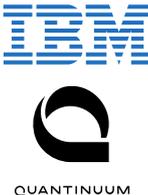


digital quantum computers

gate-based

NISQ (Noisy Intermediate Scale Quantum)
 no error correction with a few noisy qubits

general purpose quantum computing, adds search and integer factoring

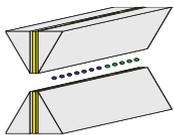


FTQC (Fault-Tolerant Quantum Computers)
 error correction and fault tolerance

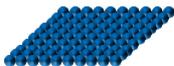


>80 QPUs industry vendors!

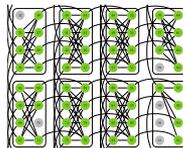
atoms



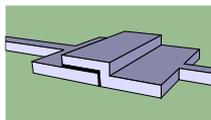
trapped ions



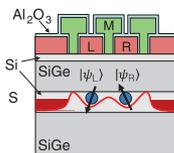
cold atoms



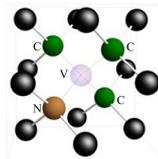
annealing



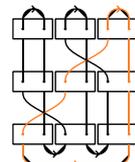
superconducting



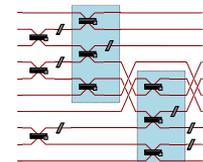
silicon



vacancies



topological



photons

electrons controlled spin and microwave cavities

1

4

2

3

5

6

7

8

9

10

12

13

14

15

16

IBM



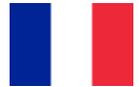
QUANDELA

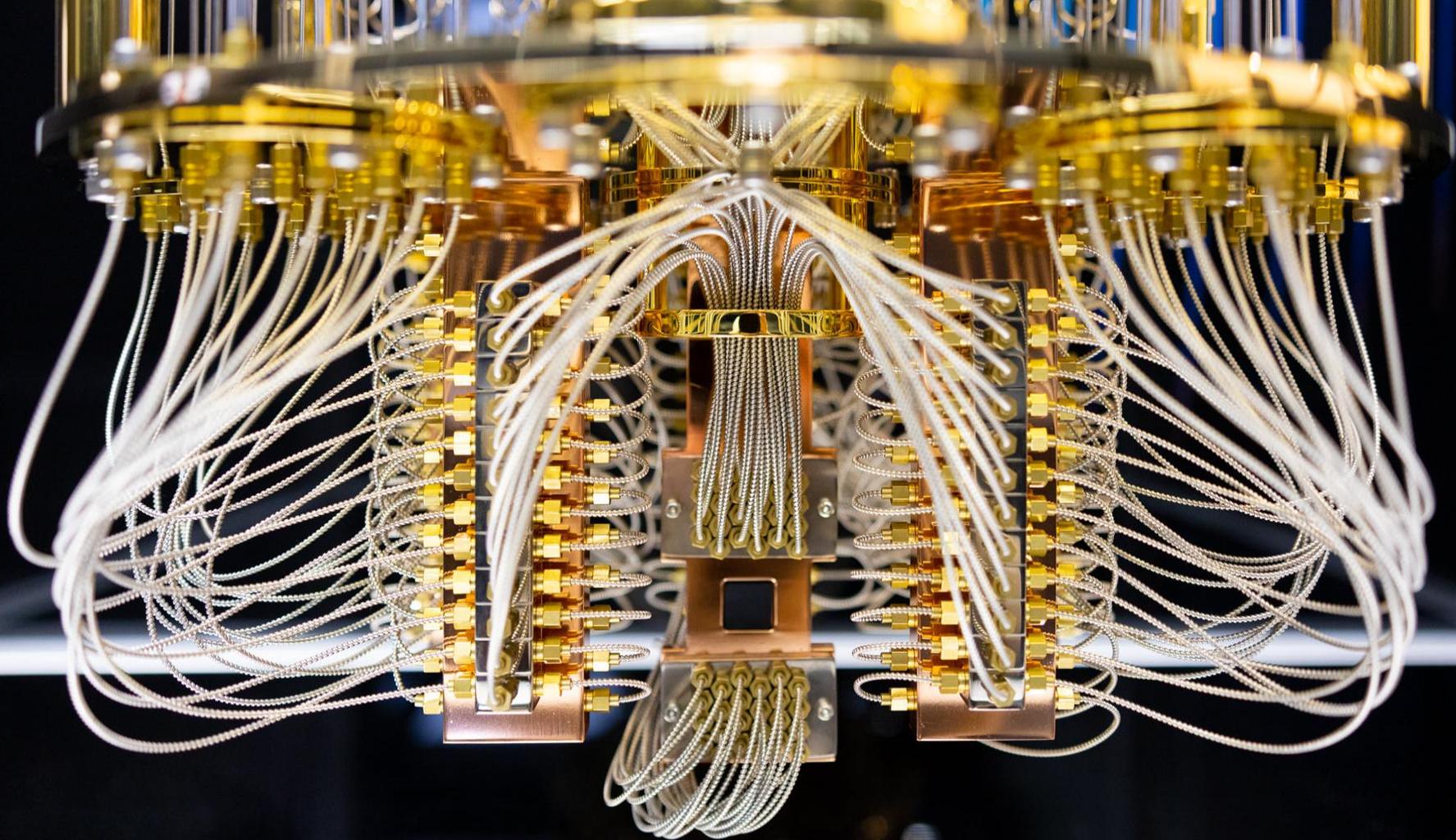


IONQ



Pasqal





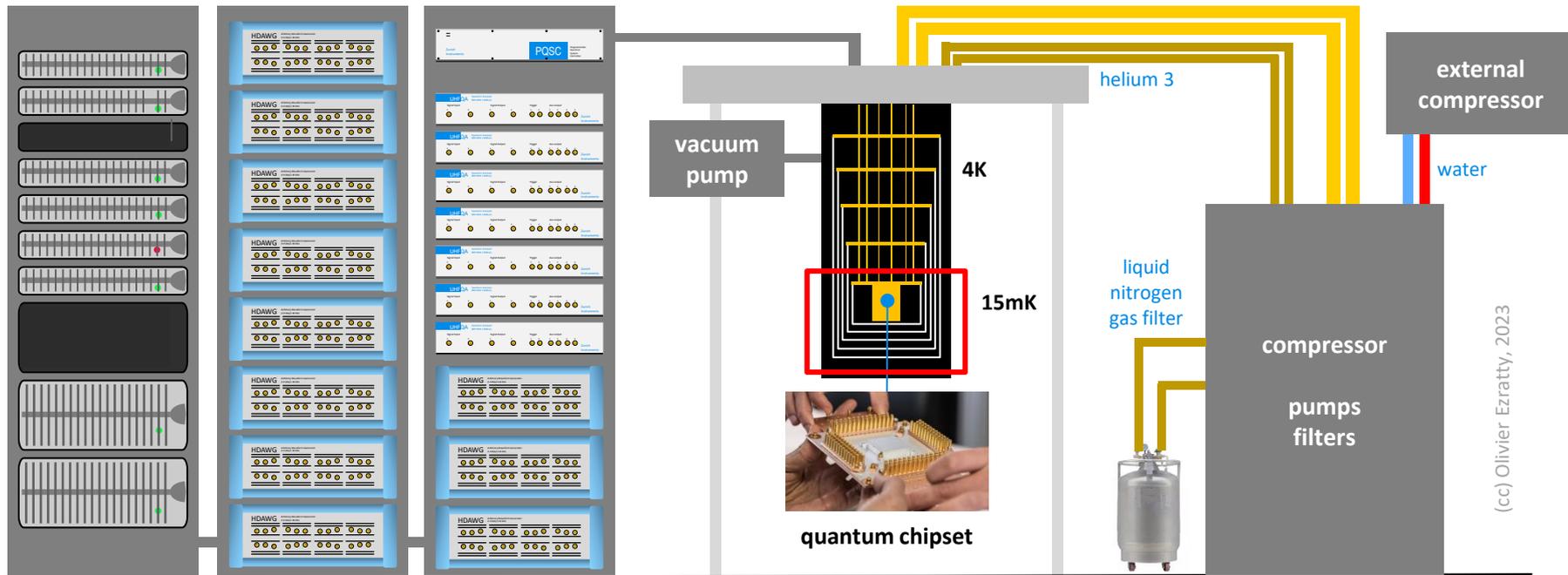
inside a typical quantum computer

computing
servers, network,
software, data

qubits control electronics
microwave generators, readout
systems and various electronics

« chandelier » in cryostat
where quantum stuff happens!

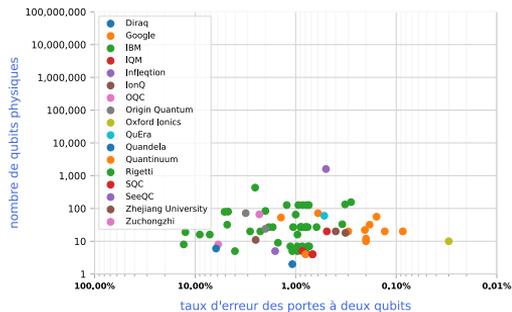
cryogenic installation
helium 3 & 4
gas pumps and compressor



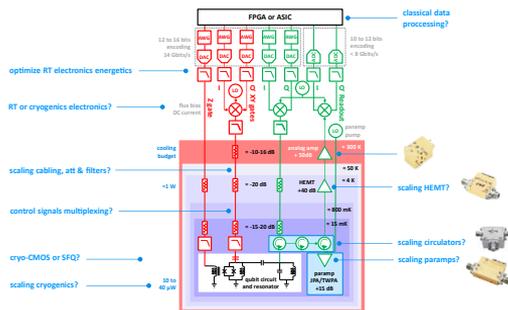
for superconducting or electron spin qubits

(cc) Olivier Ezratty, 2023

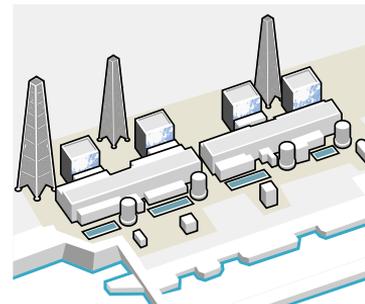
hardware challenges



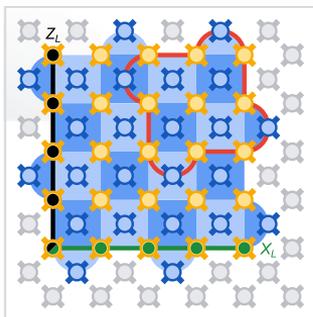
qubit quality



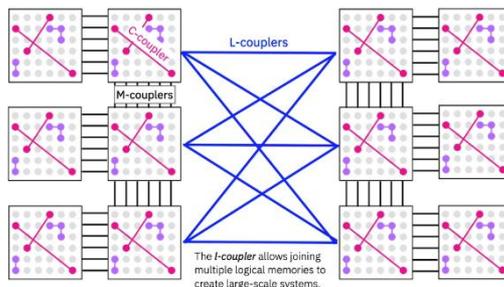
electronics, cabling, cryogeny



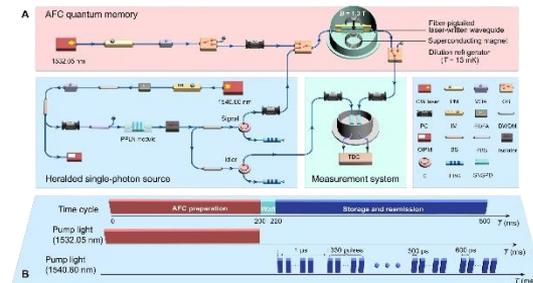
cost and power/energy



error correction

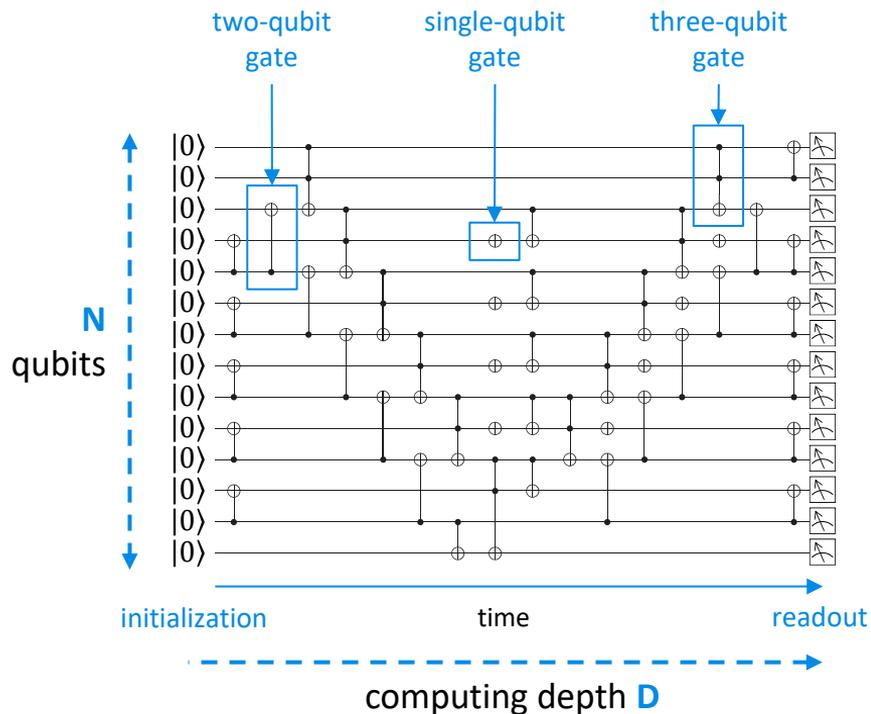


interconnection



quantum memory

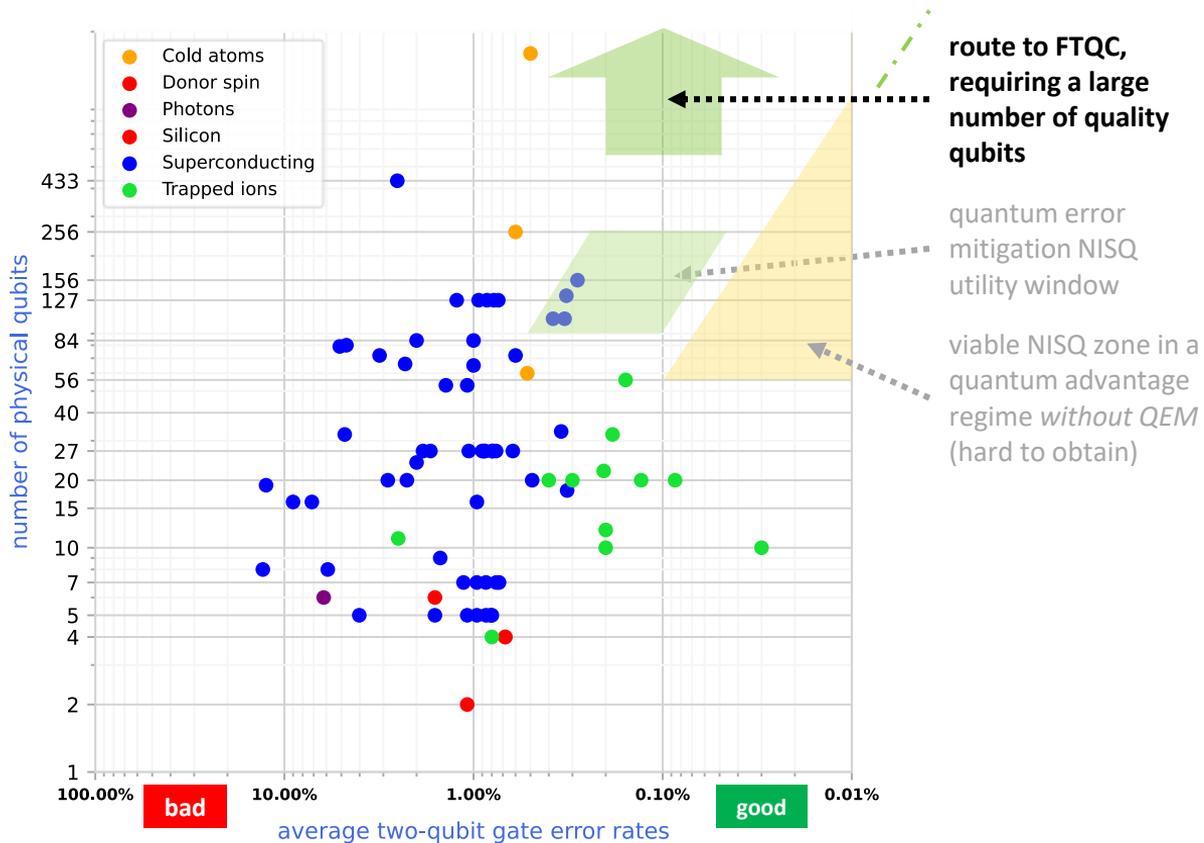
raw algorithm fidelities requirements

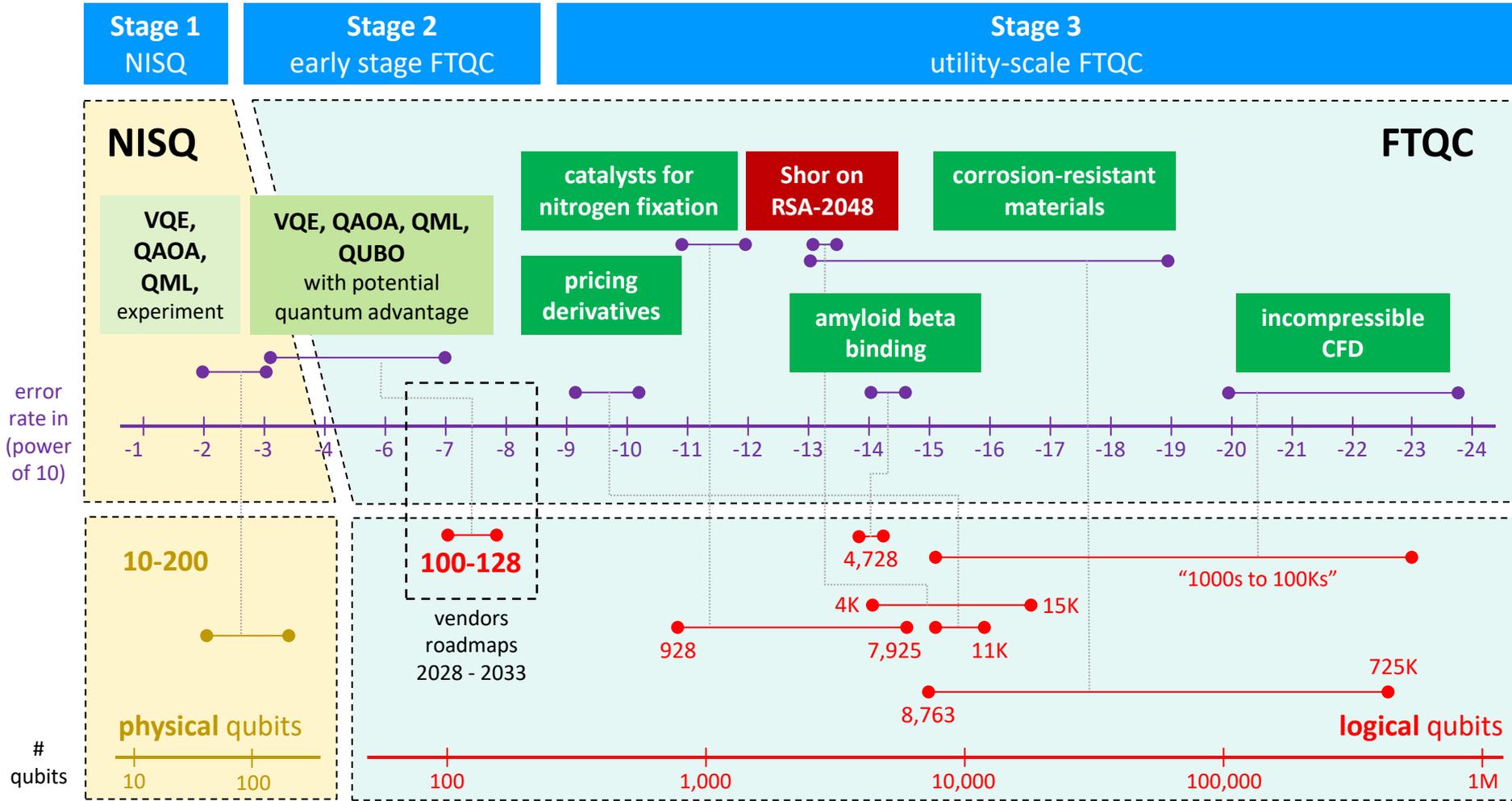


$$\text{desired error rate} < \frac{1}{N \times D}$$

each operation in blue adds errors that accumulates during computing and damage results quality.

the qubit fidelities challenge





logical qubits and FTQC

physical qubit

error rates $\approx 0.1\%$

+

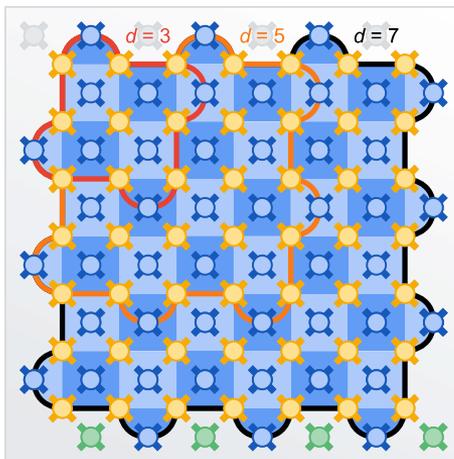
error correction code

threshold, physical qubits overhead, connectivity requirements, syndrome decoding and scale



logical qubits

error rate $\approx 10^{-4}$ to $\approx 10^{-18}$



tens to thousands physical qubits per logical qubits



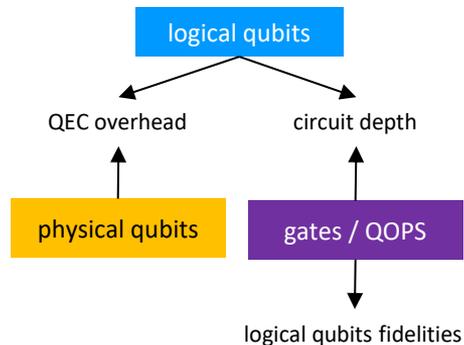
fault tolerance (FTQC)

- implement logical gate correction.
- avoid error propagation and amplification.
- implement a universal gate set.
- fault-tolerant results readout.
- correct correlated errors.

what should we have in FTQC roadmaps?

bare minimum

- # logical qubits.
- supported circuit size / logical error rates.
- # physical qubits.



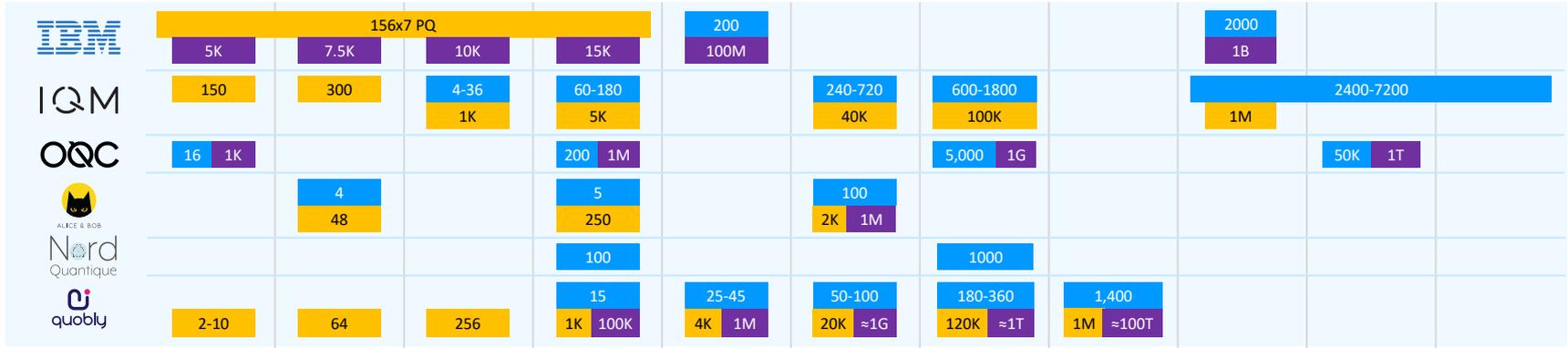
nicer to have

- clock speed and QLOPs/s.
- planned QEC codes and methods.
- processor size & reliance on QPU interconnect.

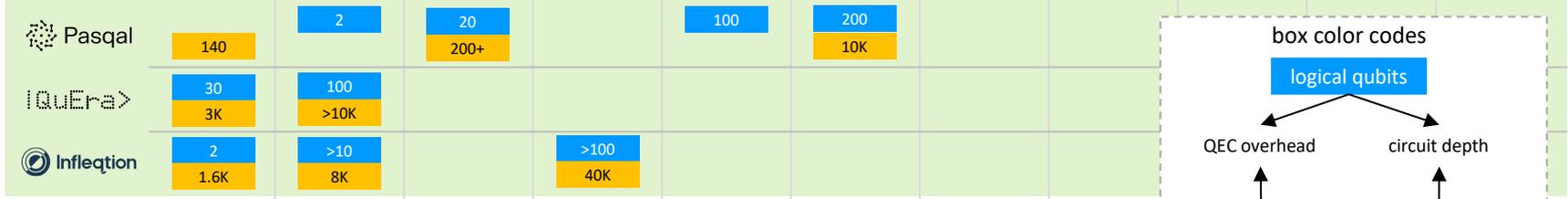
- peak power consumption in W.
- components operating temperature.
- QPU weight and size.
- operational constraints like temperature variability.
- components MTBF.
- capex/opex cost structure.

operational metrics

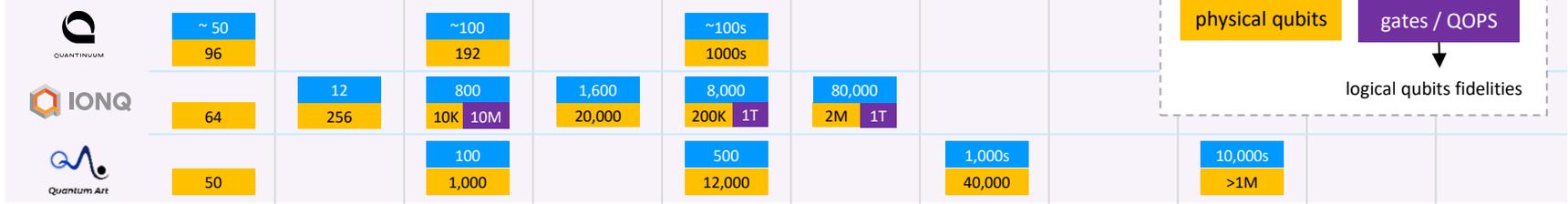
superconductors & spins



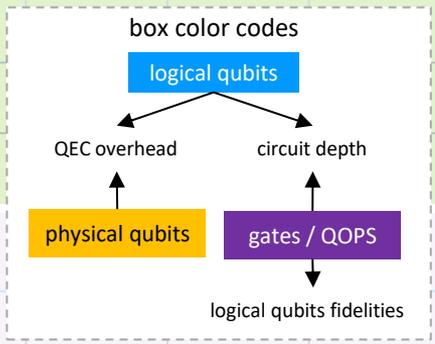
cold atoms



tapped ions

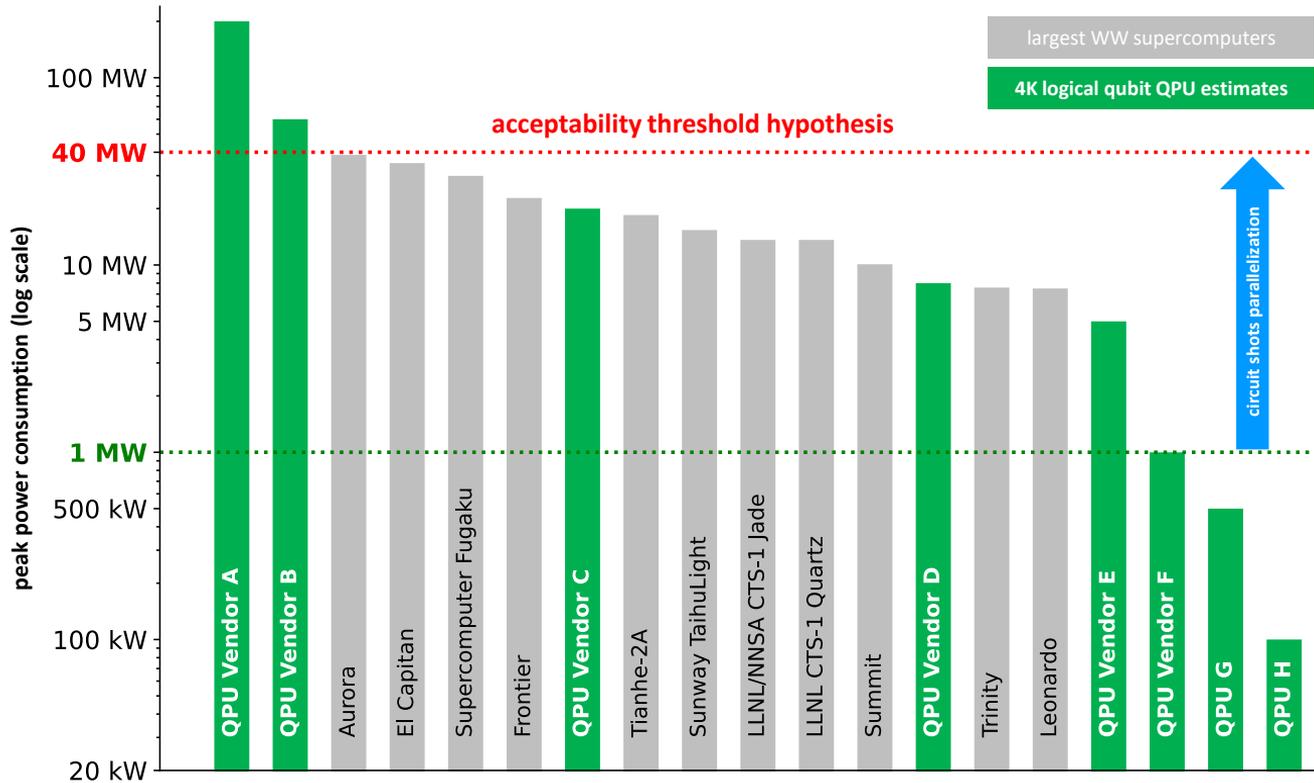


photons



(cc) Olivier Ezratty, October 2025.

QPU vs HPC power scale guesstimates



estimate base power for various QPUs and actual for existing largest HPCs WW.

HPC source: <https://www.top500.org/lists/top500/2024/06/>.

#QEI
the quantum energy initiative



IEEE P3329 Quantum Energy Initiative (QEI) Working Group



<https://www.youtube.com/watch?v=UcPLZeZxG0&t=3048s>

(cc) Olivier Ezratty, 2025.

quantum computing cloud offerings

emulation

quantum computing

hybrid
computing
centers



40 qubits



Qiskit on
your own
hardware

34-50 qubits

30 qubits

40 qubits



Pasqal

100 qubits (analog)



...



127, 133
& 156 qubits



256 qubits (analog)



36 qubits



84 qubits



20 qubits



Pasqal

100 qubits (analog)



25-32 qubits



84 qubits



20 qubits



56 qubits



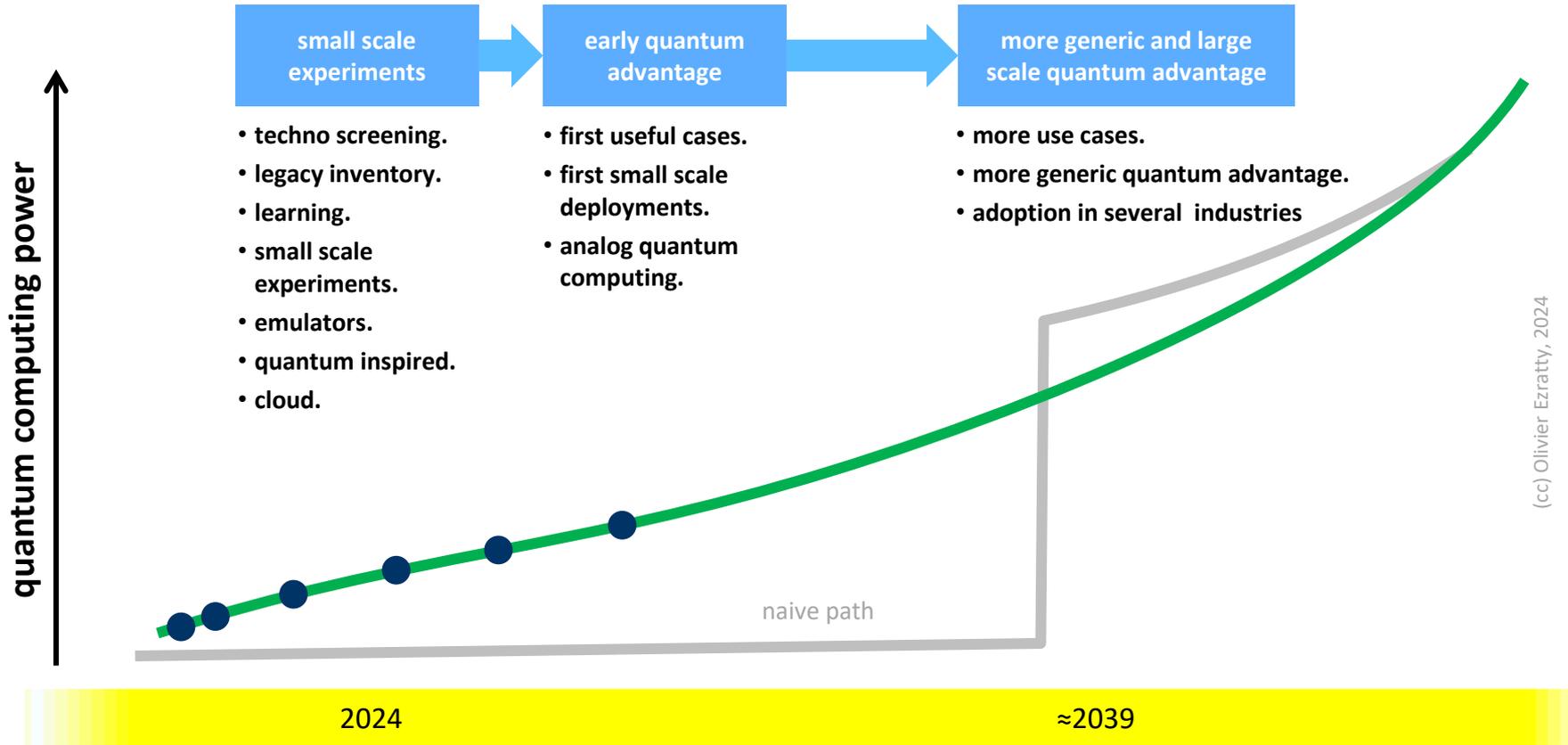
11 qubits



ALICE & BOB

1 cat-qubit

when will « it » be there?





industry vendors ecosystem

computing



software



cybersecurity



sensing



cryogeny



electronics



photonics

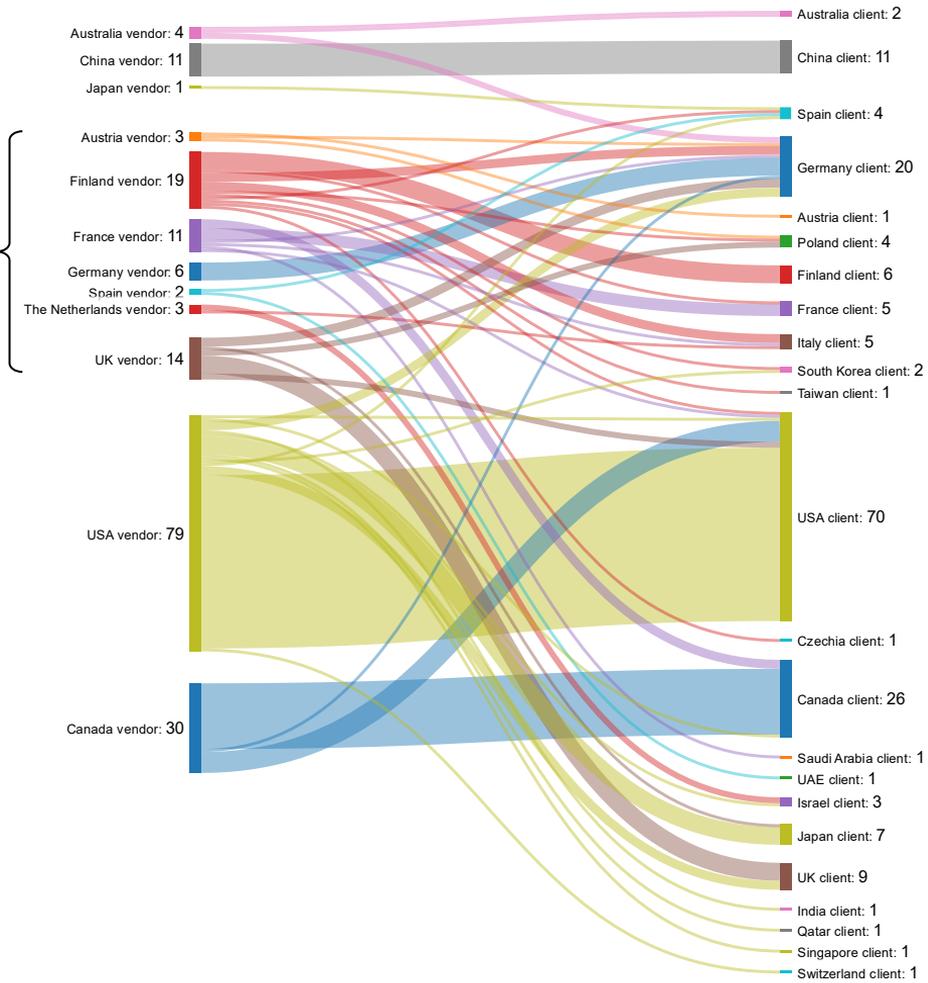


manufacturing



materials





first users in Europe

energy and chemistry



financial services



aerospace and defense



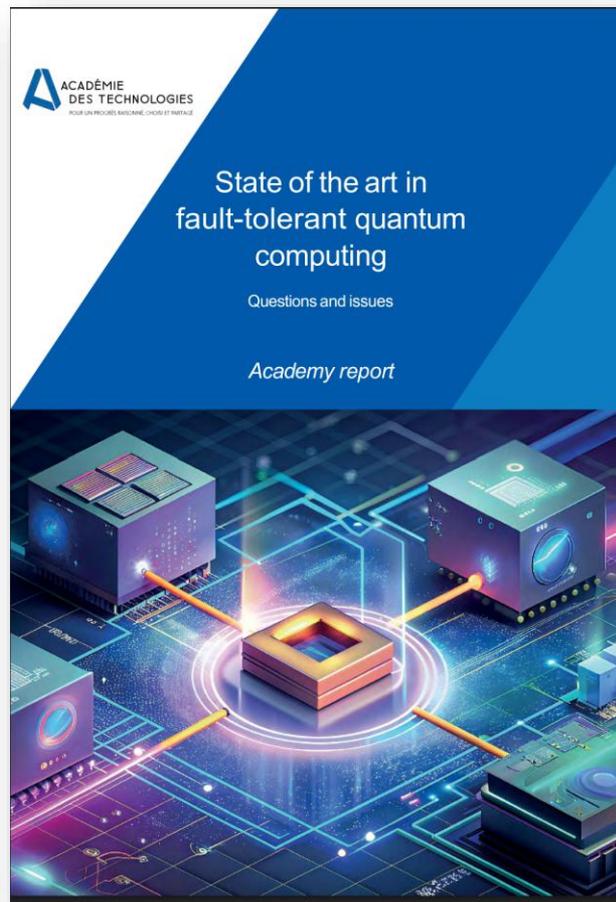
transportation



IT and cloud services







discussion



get the slides!