Forum TERATEC

# Key points from the rapport of Académie des Technologies


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***Quantum Energy Initiative co-founder***


# calcul quantique tolérant aux fautes

*points clés du rapport de l'Académie des Technologies*

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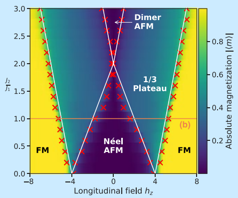
Forum Teratec, Vincennes, 21 mai 2025

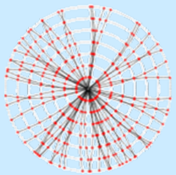
# algorithms requirements for a quantum advantage

# from science to industry applications

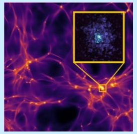
## fundamental research




condensed matter physics

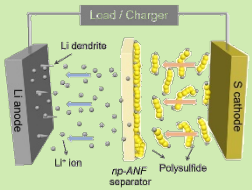


high-energy particle physics



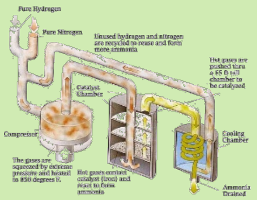
astrophysics

## applied research

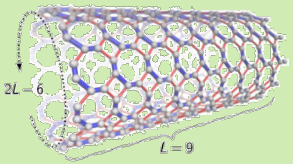



batteries

drugs

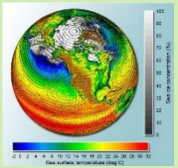



fertilizer production




material design

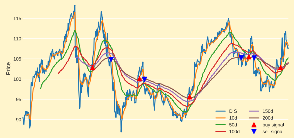
semiconductors



climate modeling

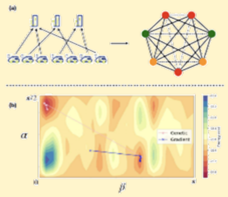
## business operations

transportation

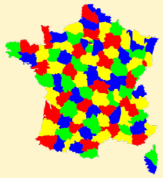


financial services

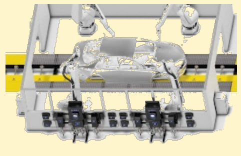
logistics and retail



energy utilities

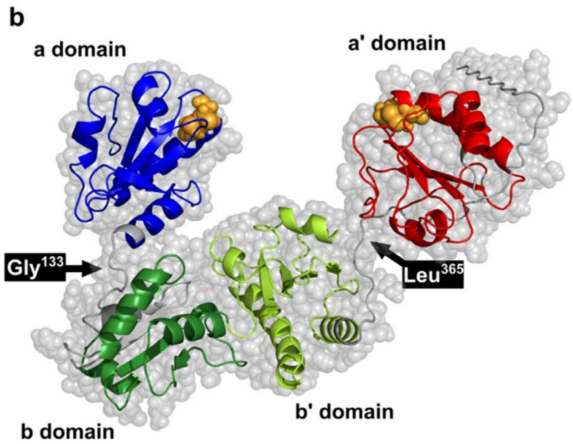


telecoms



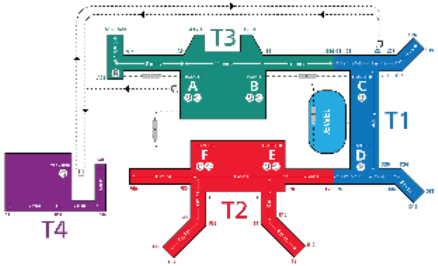
manufacturing

# typical difficult problems

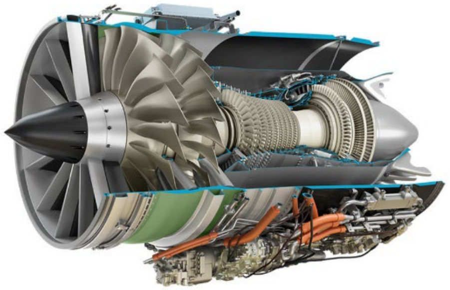



$$i\hbar \frac{\partial \Psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2 \Psi(x,t)}{\partial x^2} + V(x)\Psi(x,t)$$

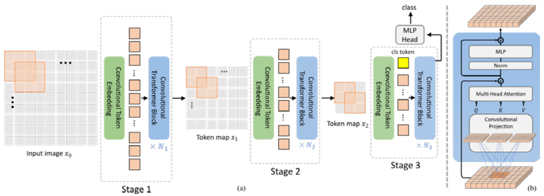
solving Schrodinger's wave equation to simulate quantum systems




combinatorial optimizations



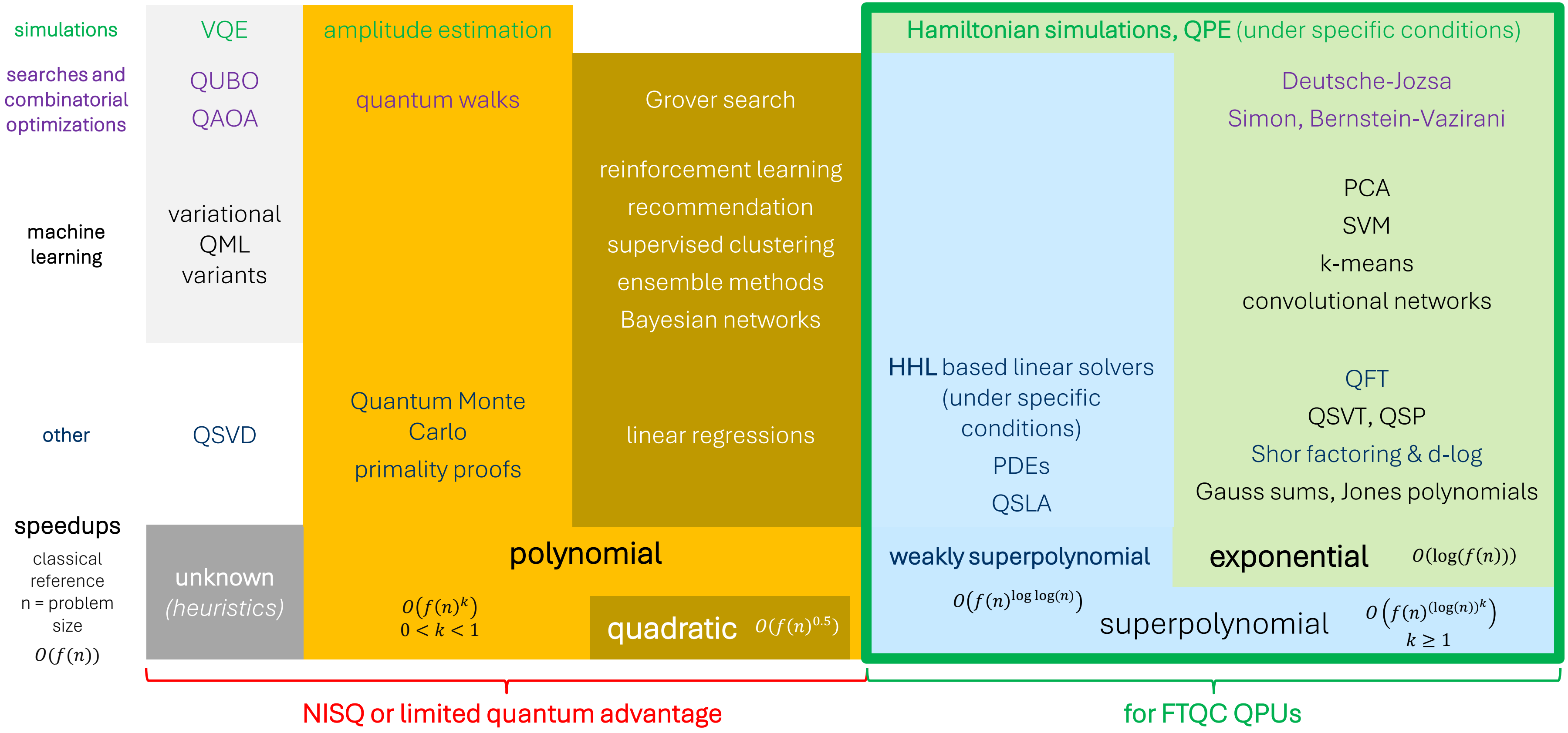
solving partial differential equations




machine learning and deep learning

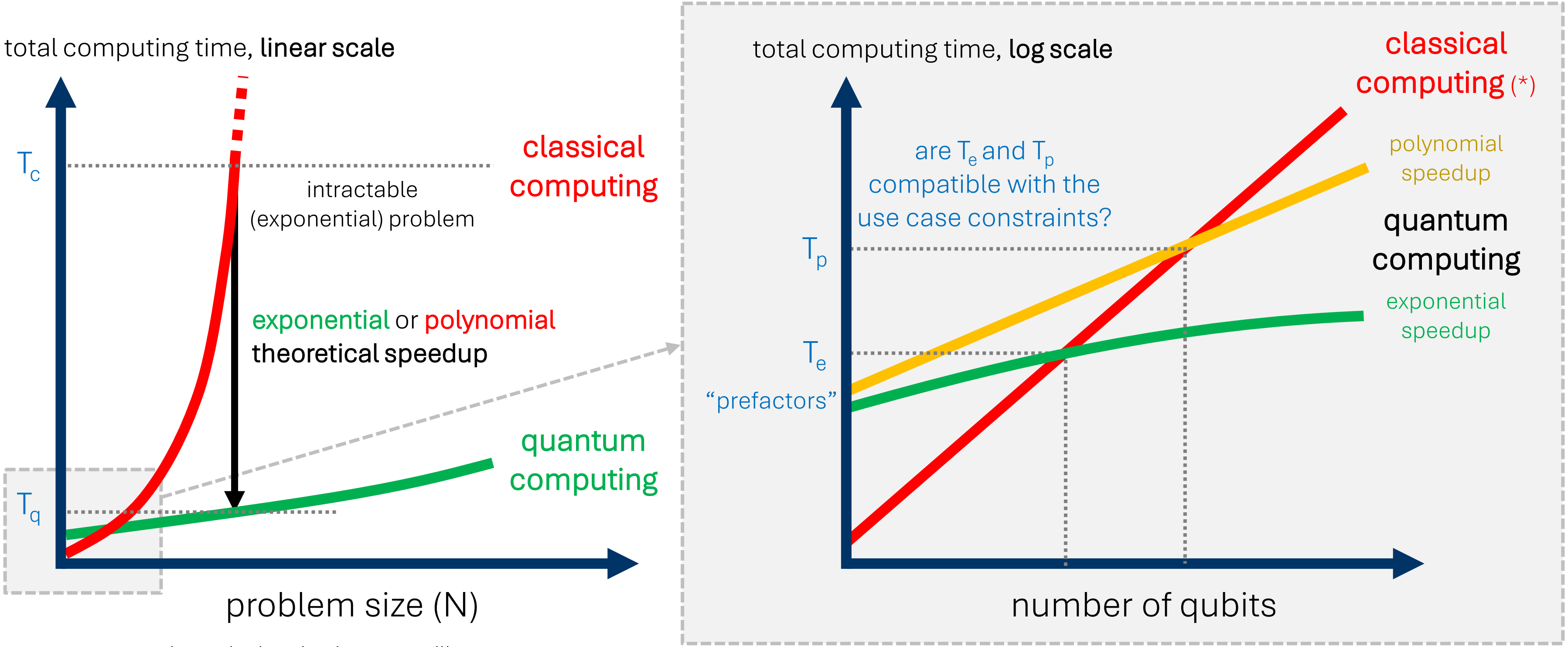

breaking asymmetric cryptography keys

# potential quantum speedups




Understanding Quantum Technologies by Olivier Ezratty, as of April 2025.

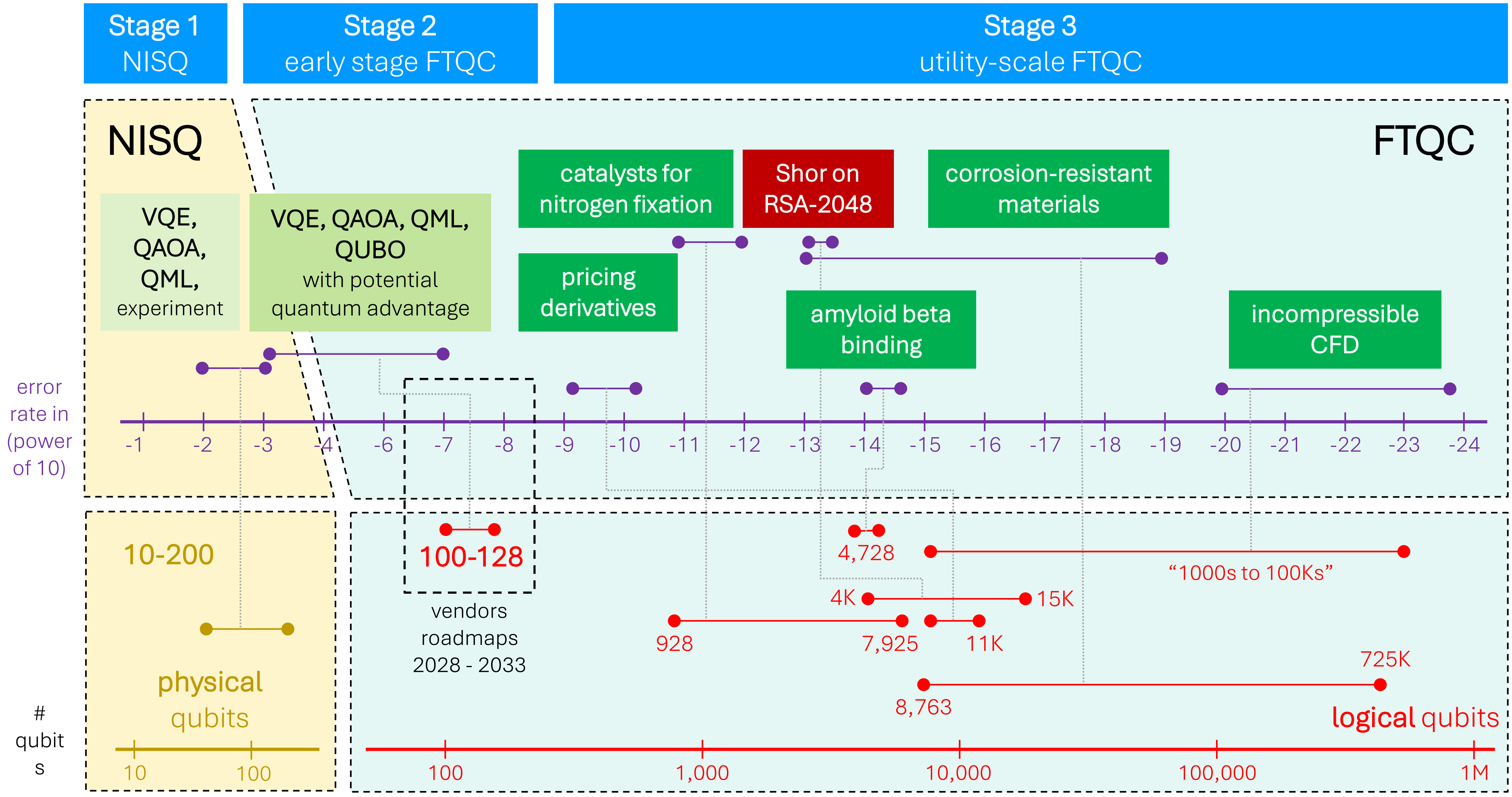
# theoretical vs practical speedups




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

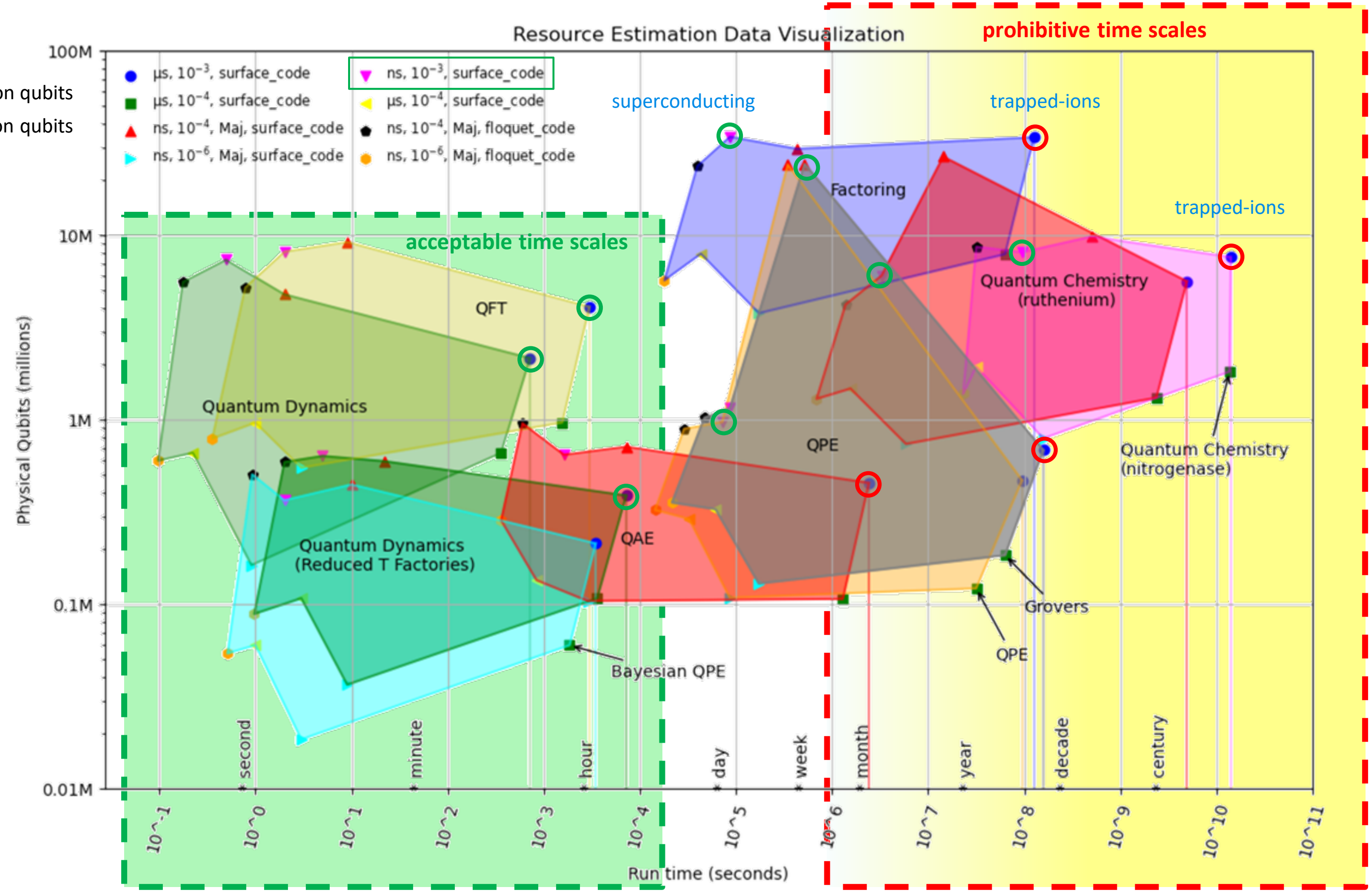
inspired by Opening the Black Box inside Grover's Algorithm by E. Miles Stoudenmire and Xavier Waintal, PRX, November 2024.

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


Stage 1
NISQ
Stage 2
early stage FTQC
Stage 3
utility-scale FTQC
NISQ
FTQC
VQE, QAOA, QML, experiment
VQE, QAOA, QML, QUBO with potential quantum advantage
catalysts for nitrogen fixation
Shor on RSA-2048
corrosion-resistant materials
pricing derivatives
amyloid beta binding
incompressible CFD
error rate in (power of 10)
-1
-2
-3
-4
-6
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
10-200
physical qubits
100-128
vendors roadmaps 2028 - 2033
4,728
"1000s to 100Ks"
4K
15K
928
7,925
11K
725K
8,763
logical qubits
# qubits
10
100
100
1,000
10,000
100,000
1M

**µs gate times**: trapped ion qubits

**ns gate times**: superconducting and silicon qubits

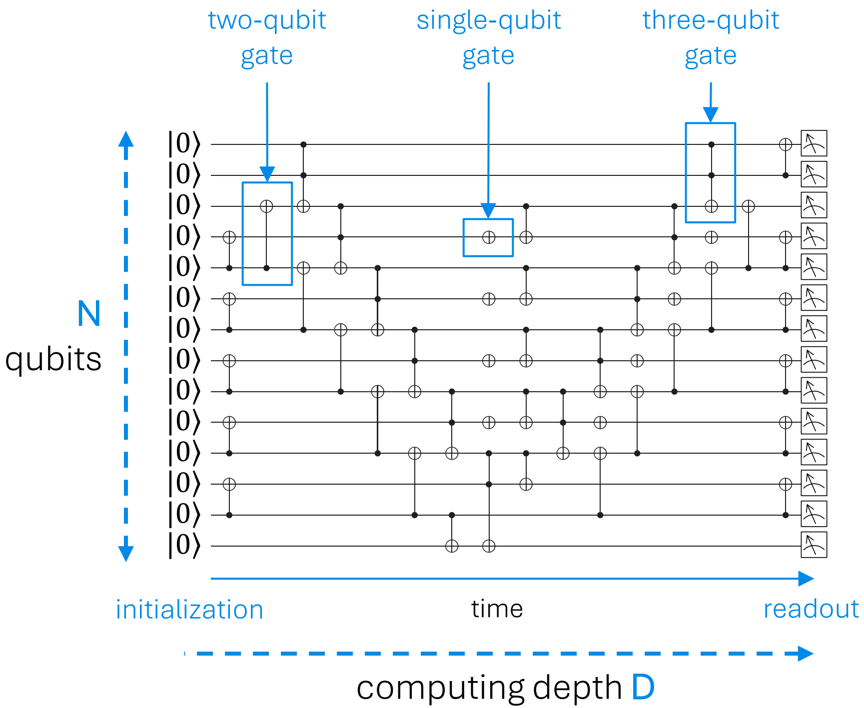



several scenarios are used with different physical qubit error rates and gate times. The realistic ones are with 99.9% fidelities and µs readout cycle times.

[The GQI Quantum Resource Estimator Playbook - Quantum Computing Report](#) by Doug Finke, Quantum Computing Report, August 2024.

# quantum error correction

# raw algorithm fidelities requirements




desired error rate $< \frac{\mathbf{1}}{\mathbf{N} \times \mathbf{P}}$

# logical qubits and FTQC

## physical qubit

error rates ≈0.1%

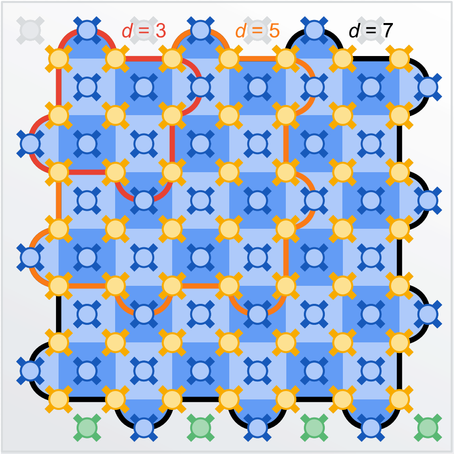
+

## error correction code

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

## logical qubits

error rate ≈$10^{-4}$ to ≈$10^{-18}$

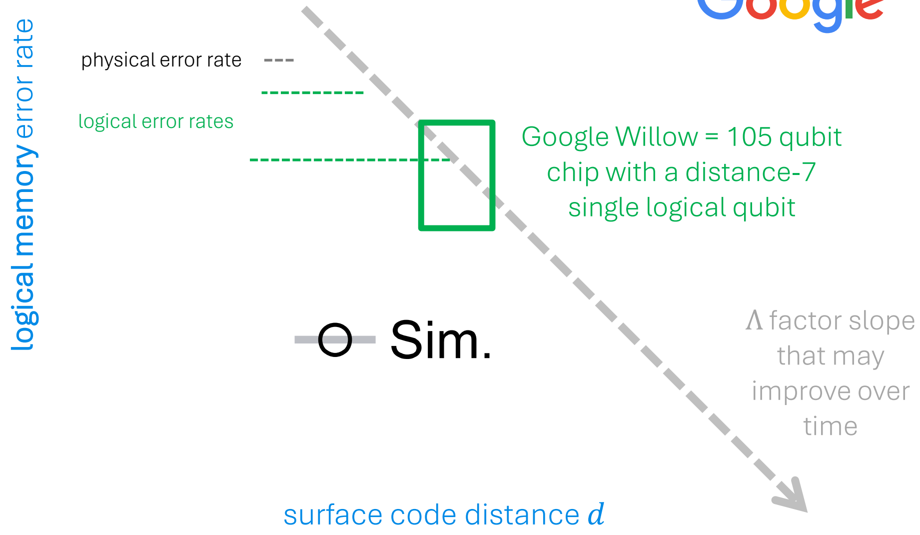



tens to thousands physical qubits per logical qubits

## fault tolerance (FTQC)

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

# beyond the first breakeven logical qubits




number $n_q$ of physical qubits per logical qubit

$$n_q = 2d^2 - 1$$

$$\boldsymbol{d} = 2\,\frac{\ln(p_L/A)}{\ln(p/p_{thr})} - 1$$

$$\boldsymbol{N_{phys}} = 2d^2 - 1 \qquad \Lambda = \varepsilon_d/\varepsilon_{d+2} \approx p_{thr}/p$$

| | | |
|---|---|---|
| $d$ | = | surface code distance |
| $N_{phys}$ | = | number of physical qubits |
| $N_{phys}$-opt | = | number of physical qubits with optimization |
| $N_{phys}$-total | = | number of physical qubits with FTQC |
| $p$ | = | physical error rate |
| A | = | between 0.03 and 0.1 |
| $p_{thr}$ | = | threshold error rate |
| $p_L$ | = | target logical error rate |
| $\Lambda$ (lambda) | = | error reduction factor when growing d by 2 |

| $p_L$ | $10^{-6}$ | $10^{-7}$ | $10^{-8}$ | $10^{-9}$ | $10^{-10}$ | $10^{-11}$ | $10^{-12}$ | $10^{-13}$ |
|---|---|---|---|---|---|---|---|---|
| d | 27 | 33 | 39 | 45 | 51 | 57 | 63 | 69 |
| $N_{phys}$ | 1,483 | 2,211 | 3,082 | 4,099 | 5,260 | 6,565 | 8,015 | 9,609 |
| $N_{phys}$-opt | 742 | 1,106 | 1,542 | 2,050 | 2,630 | 3,283 | 4,008 | 4,805 |
| $N_{phys}$-total | 1,457 | N/A | N/A | N/A | N/A | N/A | N/A | N/A |

10K qubit chips → QPU interconnect

Quantum error correction below the surface code threshold by Rajeev Acharya, Frank Arute, Michel Devoret, Edward Farhi, Craig Gidney, William D. Oliver, Pedram Roushan et al, Google, arXiv, August 2024.

extra qubits are needed to perform syndrome extraction, interconnect logical qubits, and support operations like state injection and distillation

# alternative approaches

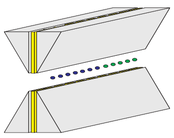
1. **qLDPC** instead of surface codes, needs better qubit non-local connectivity or 1D correction.
2. **intrinsic physical error correction** (fluxonium, zero-pi, ...).
3. **biased error qubits** (cat-qubits).
4. **symmetric self-corrected qubits** (GKP qubits).
5. **qubits replacing Pauli errors by erasure errors** (dual-rail).
6. **measurement based paradigms** (photons, FBQC, MZMs).

# qubit technologies

# QPUs vendors per qubit type

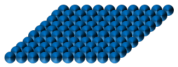
| atoms | | electrons *controlled spin and microwave cavities* | | | | | photons |
|---|---|---|---|---|---|---|---|
| trapped ions | cold atoms | annealing | superconducting | silicon | vacancies | topological | photons |

### trapped ions



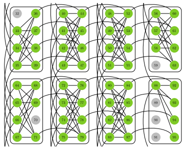
- Quantinuum
- IONQ
- AQT
- oxford ionics
- eleQtron
- FOXCONN
- Quantum Art
- CRYSTAL QUANTUM COMPUTING
- NEQXT
- QUDORA TECHNOLOGIES
- ZuriQ
- HYQ Co

### cold atoms



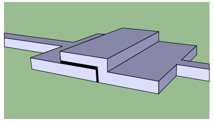
- Pasqal
- QuEra
- Infleqtion
- atom computing
- planqc
- QUANTier
- NanoQT (Nanofiber Quantum Technologies)
- Atom Quantum Labs

### annealing



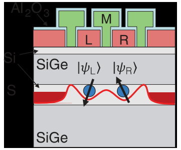
- D-Wave (The Quantum Computing Company™)
- QILIMANJARO QUANTUM-TECH
- NEC

### superconducting



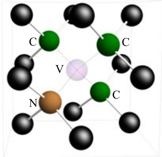
- IBM
- rigetti
- amazon
- Google
- qci
- Nord Quantique
- OQC
- IQM
- ALICE & BOB
- 本源量子 ORIGIN QUANTUM
- ANYON
- ATLANTIC QUANTUM
- FUJITSU
- QOLAB
- Peak Quantum (Jumpstarting Quantum Computing)
- QuamCore
- Z-Axis Quantum

### silicon



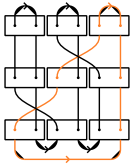

- intel
- quobly
- QUANTUM MOTION
- Silicon Quantum Computing
- diraq
- EeroQ
- equal1.labs
- C12
- ARQUE
- QπAI
- ARCHER
- Groove Quantum

### vacancies



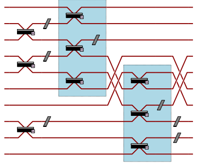

- QUANTUM BRILLIANCE
- SaxonQ
- TURING
- photonic
- Quantum Transistors
- SQUTEC
- XEED
- FUJITSU
- NTT

### topological



- Microsoft
- QUOHERENT
- QUANTUM GRAVITY RESEARCH
- NOKIA

### photons



- PsiQuantum
- QUANDELA
- ORCA COMPUTING
- XANADU
- DUALITY QUANTUM PHOTONICS
- QUIX QUANTUM
- BardeenQ LABS
- QBoson
- QCi
- photonicsQ
- QUANFLUENCE
- TUNDRASYSTEMS GLOBAL
- aegiq

Understanding Quantum Technologies
by Olivier Ezratty.

# nobody's perfect!

## superconducting qubits key takeaways

### highlights
- **key technology** in the academic world and with the largest and well funded commercial vendors community including large players like IBM, Google, IQM and Rigetti.
- **record of 156 programmable qubits** with 99.7% two qubit gates fidelities (IBM Heron r2, 2024).
- **noise reduction** constant progress in regular transmons with tunable couplers and with bosonic qubits which could enable a record low ratio of physical/logical qubits.
- **first break-even logical qubits**: Google in August 2023.
- **enabling technologies** are abundant with cryostats, cabling, analog electronics, amplifiers, and sensors.
- **quantum error mitigation** and **quantum error correction** known techniques to enable NISQ applications and future FTQC designs.

### challenges
- **qubits variability**: requires calibration and complex micro-wave frequency maps and need to contain crosstalk.
- **qubit connectivity**: limited to neighbor qubits in 2D structures.
- **qubit coherence time**: usually < 300 µs with some lab records >1ms.
- **cryogeny**: constrained technology at <15 mK, but not a scientific obstacle per se, more an engineering one. Yield can be improved.
- **logical qubits**: are not yet under break even. They are currently worse than physical qubits in most experiments.
- **cabling clutter**: complexity and many passive and active electronic components to control qubits with micro-waves and other signals.
- **qubits size**: uneasy miniaturization limits qubit # per chips and requires QPU interconnect solutions.
- **qubit fidelities**: have a hard time reaching 99.9%, needed for QEC.

### variations
- **bosonic qubits**: cat-qubits, GKP, dual rail with self-correction and lower QEC overhead. They are less mature but promising.
- **fluxonium qubits**: with better fidelities but a more complicated designs and few involved vendors.
- **qutrits**: with larger Hilbert space, which are exotic in the commercial world.
- **Andreev spin qubits**: localized excitation of the BCS condensate that natively has only two levels, using a nanowire.
- **hybrid quantum analog-digital** architectures: to solve specific problems, not generic.

### path to scalability
- **materials**: improve elements purity, identify other promising ones.
- **EDA**: full stack electronic design automation tools.
- **manufacturing**: industrialization, 300 mm wafers epixaxial deposition.
- **qubit mid-range coupling**: to enable lower overhead qLDPC QEC.
- **interconnect**: using transduction and photonic gate teleportation.
- **signals multiplexing or SFQ control electronics**: to reduce cabling overhead and cryogenic requirements.
- **QEC syndrome detection** speed improvements using ASICs.
- **cryostats**: larger and more efficient.

## quantum dots spin qubits key takeaways

### highlights
- **qubits fidelity**: reaching 99.5% for two-qubit gates in labs for a small number of qubits (RIKEN, 2022).
- **simpler qubit drive** than with superconducting qubits.
- **good quantum gates times**: 75 ns for two-qubit gates.
- **operating temperature**: around 100 mK - 1K => larger cooling budget for control electronics vs superconducting qubits.
- **2D architectures**: usable with surface codes or color codes QEC.
- **manufacturing**: can leverage existing semiconductor fabs.
- **cryo-CMOS developments**: for scalable qubit drive.
- **scalability potential**: could reach millions of qubits, thanks to their size of 100x100 nm.

### challenges
- **research in the field**: started later than with other qubit technologies and spread over several technologies (full Si, SiGe, atom spin donors).
- **lesser funded startups**: and Intel relatively modest investment.
- **qubit addressing** and **unsettled qubit drive** techniques (ESR, …).
- **high fabs costs and long test cycles**: 18 months average.
- **only 4 to 15 entangled qubits** (QuTech, UNSW, Princeton, University of Tokyo).
- **long-distance coupling** between qubits.
- **high qubits variability**: requires calibration.
- **charge noise and other sources of noise** to address, and scalability that remains to be demonstrated.

### variations
- **SiGe qubits**: spins or holes, more complicated to manufacture but better gate fidelities.
- **donor spins**: phosphorus atom nucleus, more complicated to scale.
- **carbon nanotubes** : with better spin stability but harder to manufacture and drive, with only one startup (C12).
- **spin on superfluid** helium or neon with only one startup in the domain (EeroQ).

### path to scalability
- **materials purity improvements**: isotopic and element impurities.
- **manufacturing**: improvements, faster cycling and characterization.
- **full-stack EDA** for digital simulation.
- **long range qubit coupling within chips**: to enable efficient qLDPC QEC.
- **SFQ electronics** for qubit drive.
- **cryo-CMOS integration with qubits**: for better integration.
- **inter-QPU connectivity**: electron spin shuttling, hole-microwave photons coupling, color centers.

## trapped ions qubits key takeaways

### highlights
- **first two-qubit gate fidelities reaching 99.9%** (Quantinuum, Oxford Ionics).
- **first logical qubits** above break-even.
- **high ratio between coherence time and gate time**: supports deep algorithms in number of gate cycles.
- **low qubits variability** given the ions are all the same.
- **entanglement** possible between all qubits on 1D architecture which speeds up computing, avoiding SWAP gates.
- requires some cryogeny at **4K to 10K**.
- **QPU interconnect** can directly use photon entangled resources.

### challenges
- **unproven scalability options beyond 60 qubits** (ions shuttling, 2D architectures, photon interconnect, micro-Penning traps).
- **slow computing**: due to long quantum gate times and ions shuttling which may be problematic for deep algorithms in a FTQC regime despite better qubit many-to-many connectivity at small scale.
- **two-qubit gate times** increase with ion distance in some laser-driven 1D and 2D settings.
- **many-to-many connectivity** demonstrated only at small scale.
- **control signals variability**: microwave, lasers, etc.
- **ions heating phenomenon**: it is not yet explained yet and really contained.

### variations
- **microwave/DC drive** instead of laser drive.
- **connectivity**: many-to-many within zones and ions shuttling between zones.
- **dual species** like ytterbium + barium for computing and cooling.
- **Rydberg ion** qubits for avoiding phonon and heating effect.
- **hybrid** neutral atoms-ions platforms.

### path to scalability
- **2D QCCD** and ions shuttling.
- **QCCD tiling** (Universal Quantum).
- **multi modules** ion traps with intermodules ions shuttling.
- **multi-layer ion traps** to enable long-range microwave based entanglement.
- **photonic interconnect** to entangle qubits from different QPUs.

## neutral atoms qubits key takeaways

### highlights
- **operational systems** with 100-300 atoms in simulation mode and not far from a provable quantum advantage.
- long qubit **coherence time and fast gates**.
- **identical atoms**, that are controlled with the same laser and micro-wave frequencies.
- **first logical qubits** thanks to movable atoms.
- works in both **simulation** and **gate-based** paradigms.
- no need for specific **integrated circuits**.
- uses **standard apparatus**: lasers, optics, controls, cryogenics.
- low **energy consumption**.

### challenges
- **crosstalk between qubits**: can be mitigated with two-elements atom architectures.
- **slow operations**: 1 Hz simulation cycle.
- **harder to implement with gate-based model**: need a stable universal gate set with support for error correction.
- **need to move atoms around**: to enable many-to-many two-qubit gates and reducing QEC overhead, enabling qLDPC, but with risk of losing the atoms on the way.
- **implement full QND measurement**: needed for error correction.
- **losing atoms during computing while disconnecting the tweezers.**

### variations
- **dual species qubits**: to improve QND measurement.
- **nucleus spin qubits**: with longer coherence times, in seconds.
- **circular Rydberg atoms**: more stable.
- **fermionic computing**: better for chemical simulations.
- **bosonic codes (cat-codes, GKP) with atom qubits**: better QEC.
- **hybrid gate-based and analog**: for specific case studies.
- **atoms trapped on nanophotonic circuits**: enabling interactions.
- **hybrid neutral atoms and ions**: getting the best of both worlds.
- **atom ensembles**: studied particularly in China.

### path to scalability
- **powerful lasers**: needed to control >300 atoms, with stabilized power, fiber lasers.
- **atoms positioning**: large scale SLM+AOD to trap up to 10K atoms.
- **QND measurement**: using dual species and/or atoms shuttling.
- **faster operations and duty cycle**: better and more powerful lasers, fast classical controls (FPGA, ASIC).
- **implement full universal gate set**: T gate & magic state distillation.
- **QPU interconnect**: photon based, including for memories, can also use nanophotonic circuit traps.

## photon qubits key takeaways

### highlights
- **stable qubits** with absence of decoherence.
- **ambient temperature for processing.**
- **emerging nano-photonic** manufacturing techniques enabling scalability.
- **easier to scale-out** with inter-qubits communications and quantum telecommunications.
- **MBQC/FBQC** circumventing the fixed gates depth computing capacity and difficulty to create multiple qubit gates.
- **boson sampling-based quantum advantage**: starts to being programmable but a practical quantum advantage remains to be proven.

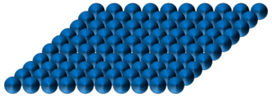
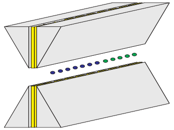
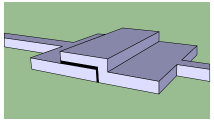
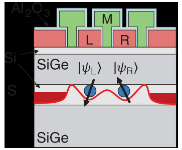
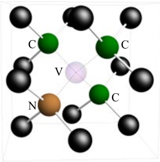
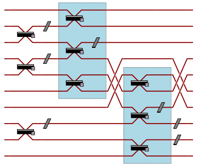
### challenges
- **need to cool photon sources and detectors**: but at relatively reasonable temperatures between 2K and 10K, requiring lighweight cryogenic systems (unless also cooling the whole photonic circuit).
- **not yet scalable in number of operations**: due to probabilistic character of quantum gates and the efficiency of photon sources in most paradigms.
- **non-deterministic** cluster states and two-photon interactions.
- needs **delay lines** and **optical switches**.
- **heat generated by phasers**: increasing cooling budget.
- **photon detectors efficiency** is too low, at 89% with PsiQuantum.
- **photon losses** must be contained in nanophotonic circuits.

### variations
- **encoding**: direct variables qubits (DV), continous variables (CV) qubits, multimode photon encoding.
- **MBQC** (measurement based quantum computing) and **FBQC** (fusion-based quantum computing).
- **BS/GBS**: programmable Boson sampling and Gaussian boson sampling.
- **hybrid approaches**: spin-optical quantum computing (SPOQC) with quantum dots spin qubits (Quandela), hybrid atom-photon qubits.
- **classical photonic models**: coherent Ising models, photonic waveguide arrays and interferometric systems.

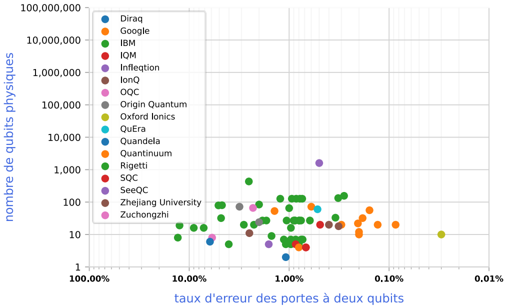
### path to scalability
- **efficiency**: improve photon sources efficiency, determinism and indistinguishability, improve photon detectors efficiency (SNSPD and PNRD).
- **cluster states**: generate large cluster states, with or without heralding.
- **interactions**: improve fusion efficiency in FBQC.
- **losses**: large-scale and low-losses optical switches and wave guides, reduce photon losses in nanophotonic circuits thanks to higher precision manufacturing and new materials.
- **energy**: create low-heating phasers to minimize power consumption.
- **nanophotonics**: heterogeneous nanophotonic circuits (III-V + silicon).
- **classical control speed**: particularly with FBQC models.

not covered in the report:
- NV centers/SiC qubits.
- topological qubits.

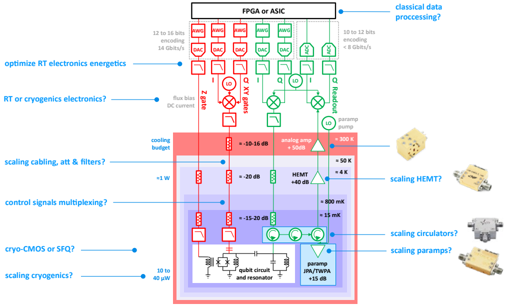
# nobody's perfect indeed!

| | atoms | | electrons *controlled spin and microwave cavities* | | | photons |
|---|---|---|---|---|---|---|
| |  |  |  |  |  |  |
| | cold atoms | trapped ions | superconducting | silicon | NV centers | photons |
| operations fidelities | | | | | | |
| gate times | with no shuttling | | | | | |
| qubit connectivity | with shuttling | | | | | |
| cooling needed | 4K | 4K | 15 mK | ≈500 mK | TBD | 1.8 to 4K |
| qubit size | | | | | | |
| scalability | | with tiled chips | | | | |

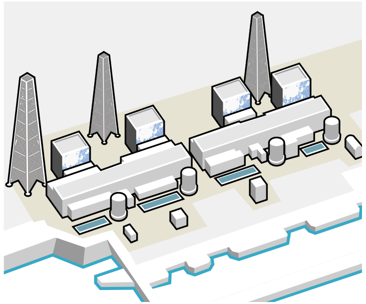
# hardware challenges



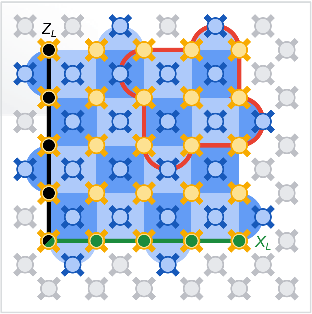

qubit quality



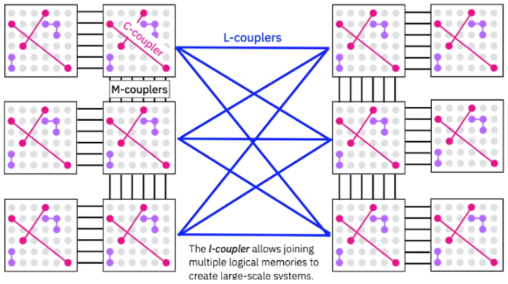

electronics, cabling, cryogeny



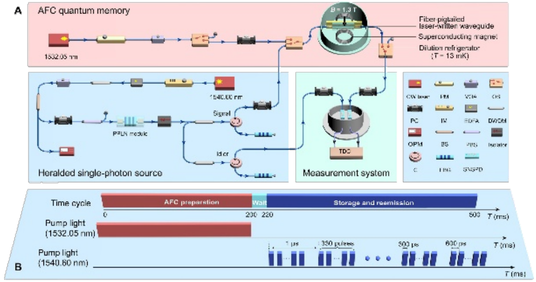
cost and power/energy



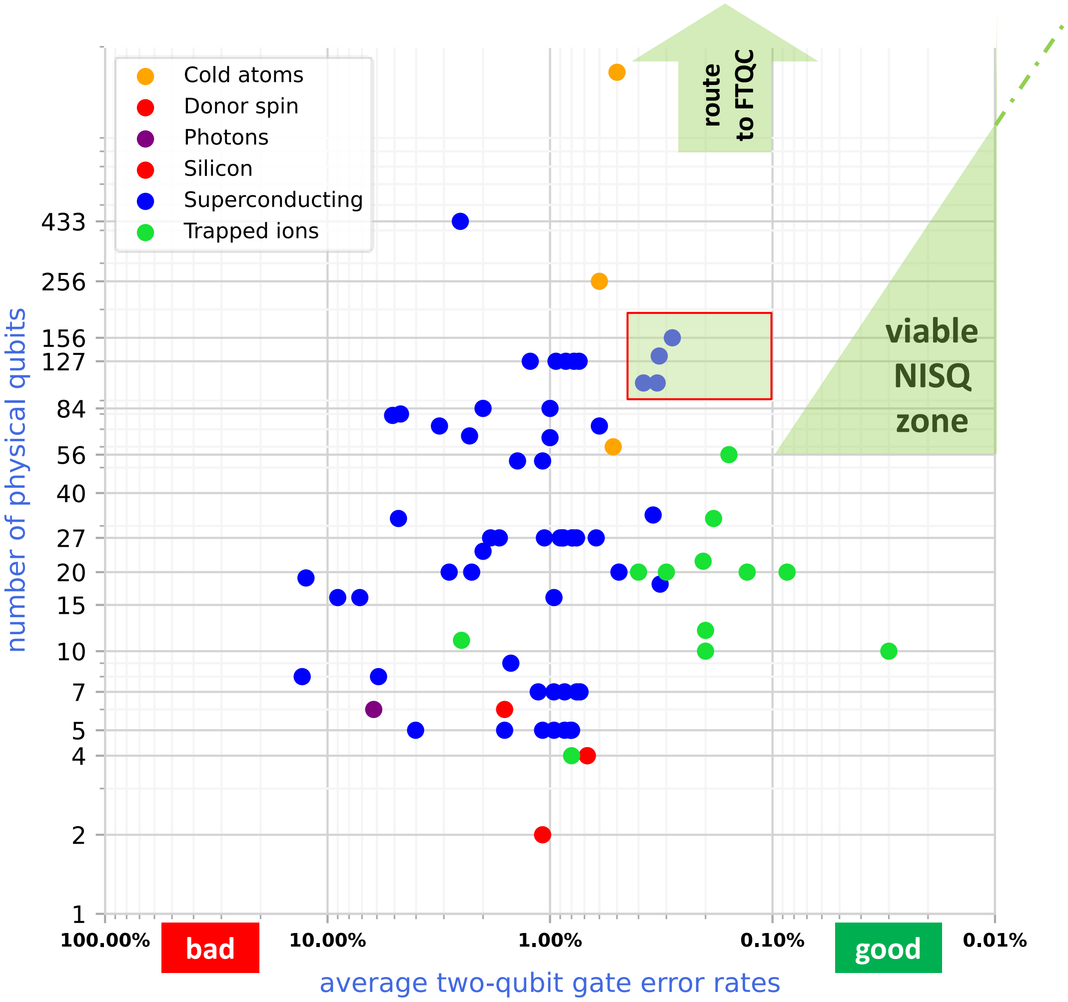

error correction



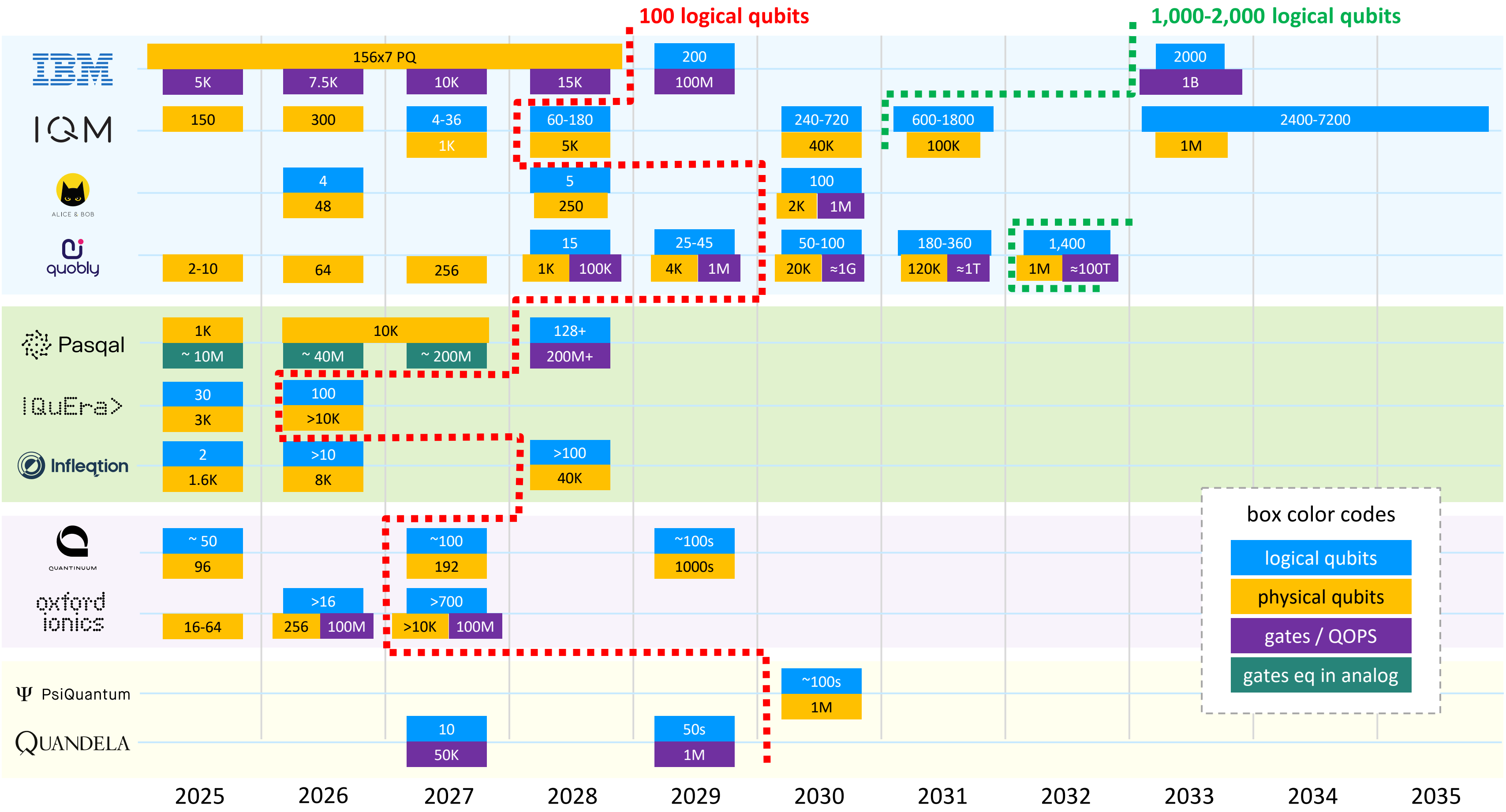

interconnection




quantum memory

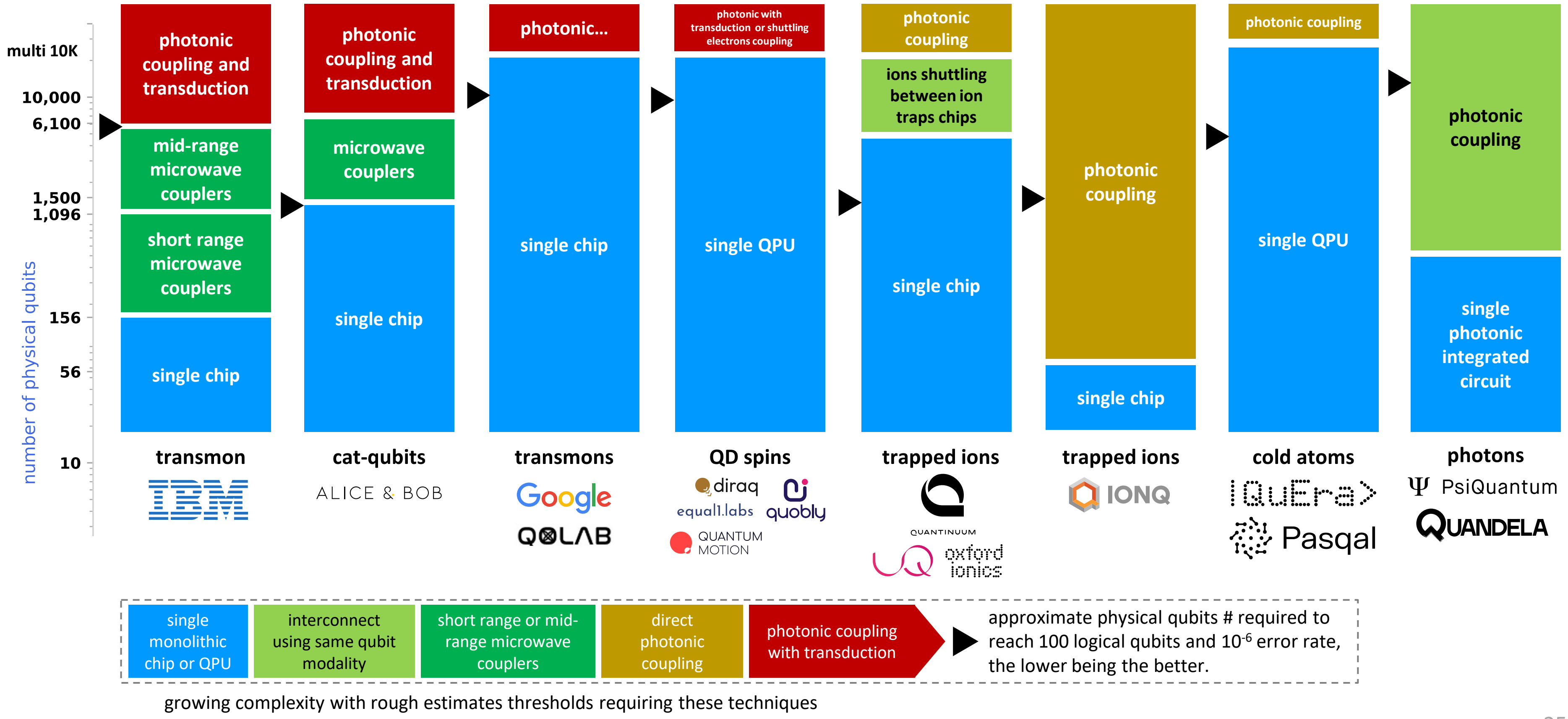


Cold atoms
Donor spin
Photons
Silicon
Superconducting
Trapped ions
route to FTQC
viable NISQ zone
number of physical qubits
433
256
156
127
84
56
40
27
20
15
10
7
5
4
2
1
100.00%
bad
10.00%
1.00%
0.10%
good
0.01%
average two-qubit gate error rates

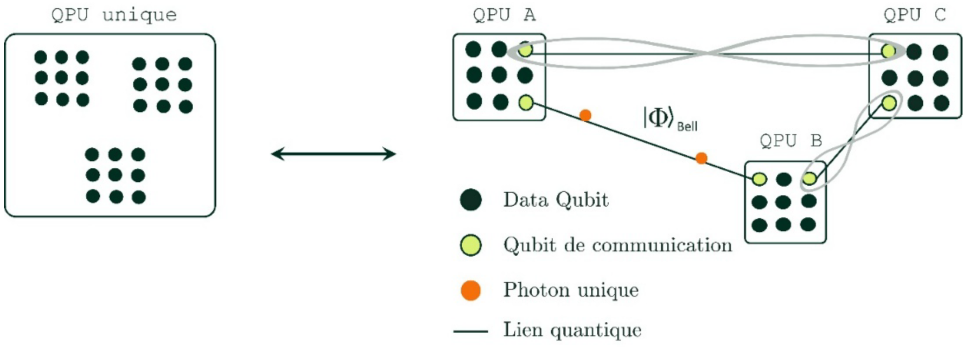

100 logical qubits
1,000-2,000 logical qubits
IBM
156x7 PQ
5K
7.5K
10K
15K
200
100M
2000
1B
IQM
150
300
4-36
1K
60-180
5K
240-720
40K
600-1800
100K
2400-7200
1M
ALICE & BOB
4
48
5
250
100
2K
1M
quobly
2-10
64
256
15
1K
100K
25-45
4K
1M
50-100
20K
≈1G
180-360
120K
≈1T
1,400
1M
≈100T
Pasqal
1K
~ 10M
10K
~ 40M
~ 200M
128+
200M+
|QuEra>
30
3K
100
>10K
Infleqtion
2
1.6K
>10
8K
>100
40K
QUANTINUUM
~ 50
96
~100
192
~100s
1000s
oxford ionics
16-64
>16
256
100M
>700
>10K
100M
PsiQuantum
~100s
1M
QUANDELA
10
50K
50s
1M
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
box color codes
logical qubits
physical qubits
gates / QOPS
gates eq in analog

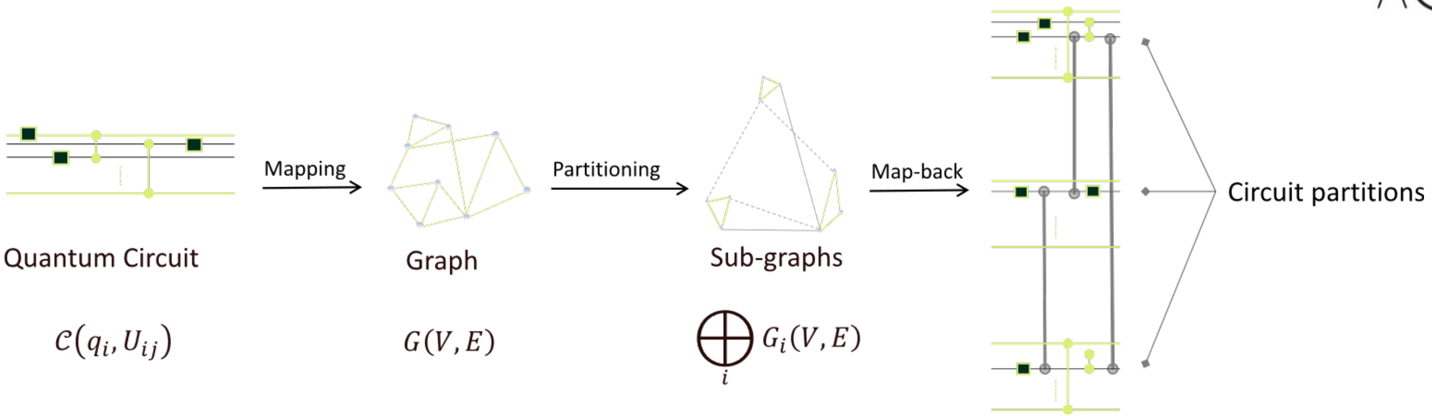
# scaling quantum computers

# multiple QPUs interconnect options

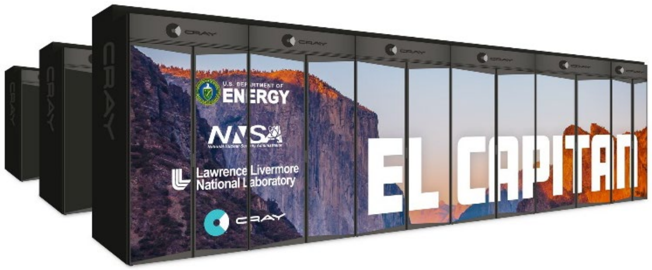


# Distributed Quantum Computing



# HPC integration




**El Capitan**
2.78 FP64 EFLOPs, 40 MW


**Nvidia GB200 NVL72 cluster**
1.4 FP4 EFLOPs, 150 kW

**Nvidia DGX**
72 PFLOPS, 8 GPU, 14 kW

- classical pre-processing and post-processing
- quantum code emulation
- code compilation, real-time quantum error correction

# benchmarking

DARPA
Quantum Benchmarking Initiative

| | metrics |
|---|---|
| IBM Benchpress | SDK speed, efficiency, memory |
| THALES BACQ<br>EVIDEN qscore | higher-level algorithms performance |
| SupermarQ<br>QED-C<br>TU Delft: QPack | low-level algorithms performance |
| IBM CLOPS | gate cycle speed |
| error per layered gates (EPLG) | crosstalk, entanglement |
| randomized and cross-entropy benchmarking<br>IBM QV | qubits number and fidelities |

considers

- SDK, compilers, optimizers
- algorithm, compilation, loading, launching, QEM
- qubits, topology, control

energetics

#QEI the quantum energy initiative
IEEE
Raytheon Technologies
DARPA

classical electronics & computing
cryogeny

metriq
benchmarks repository

# economical discussion

# analogies

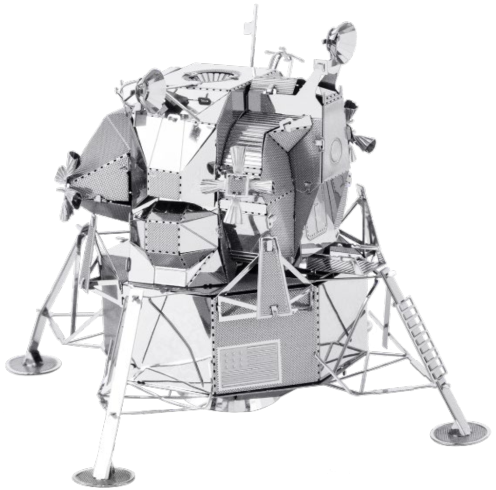
geopolitical context

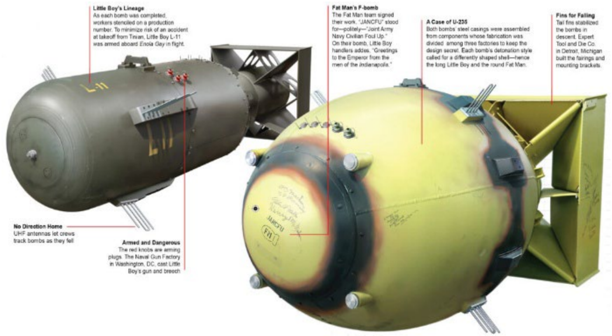
dual-use

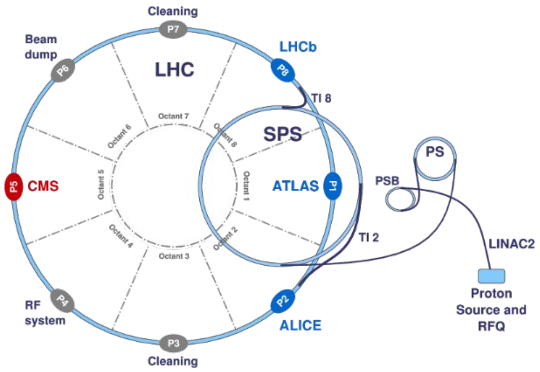
scientific challenges

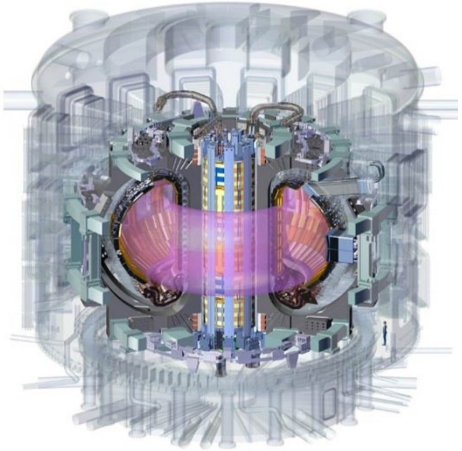
technology challenges

potential market





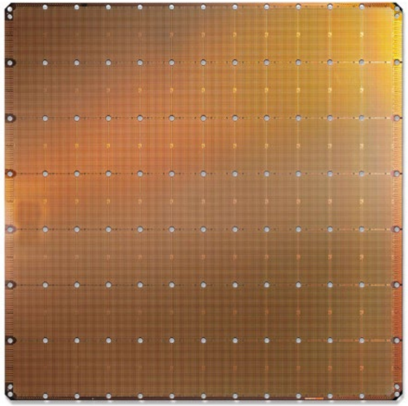
# classical computing is also advancing

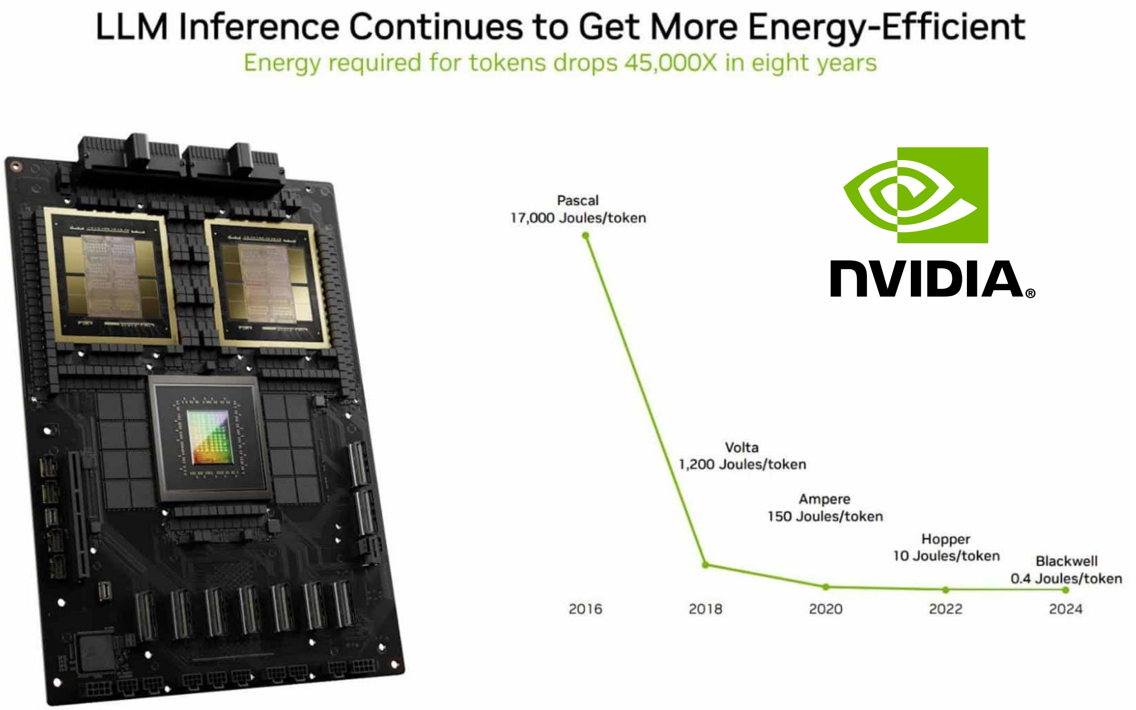
**Nvidia** Blackwell GPU

**tensor networks** (MPS, DMRG)

**classical quantum chemistry**

**wafer-scale chips** (Cerebras)





# discussion

get the slides