UNIVERZA V LJUBLJANI | FMF Fakulteta za matematiko in fiziko

Jožef Stefan Institute, Ljubljana, Slovenia

quantum computing

state of the art, challenges, and opportunities

olivier ezratty

⟨ author | … ⟩

Ljubljana, April 15th, 2024

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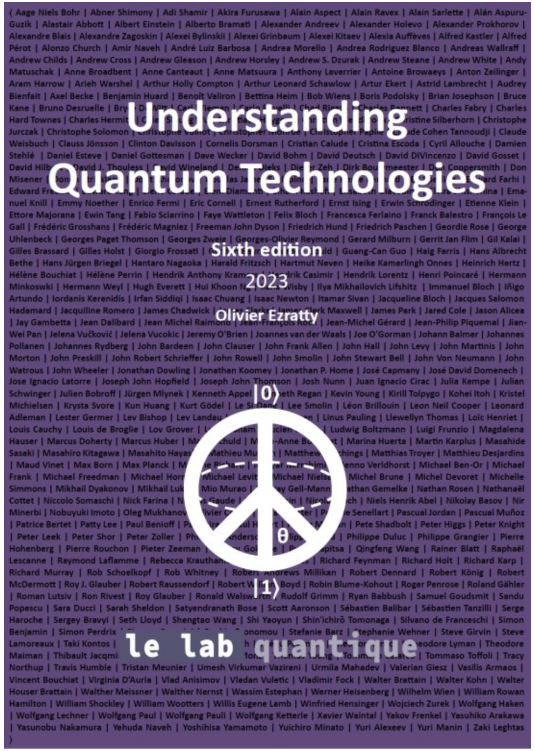

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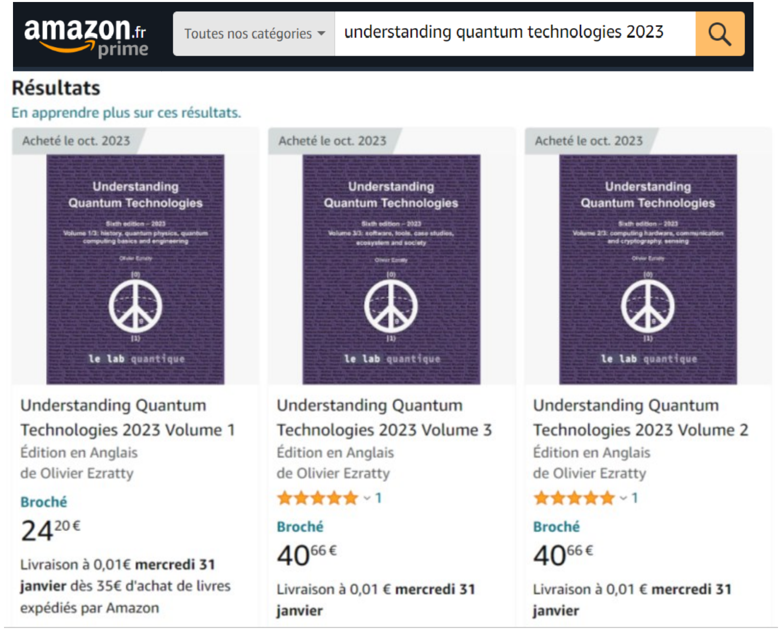
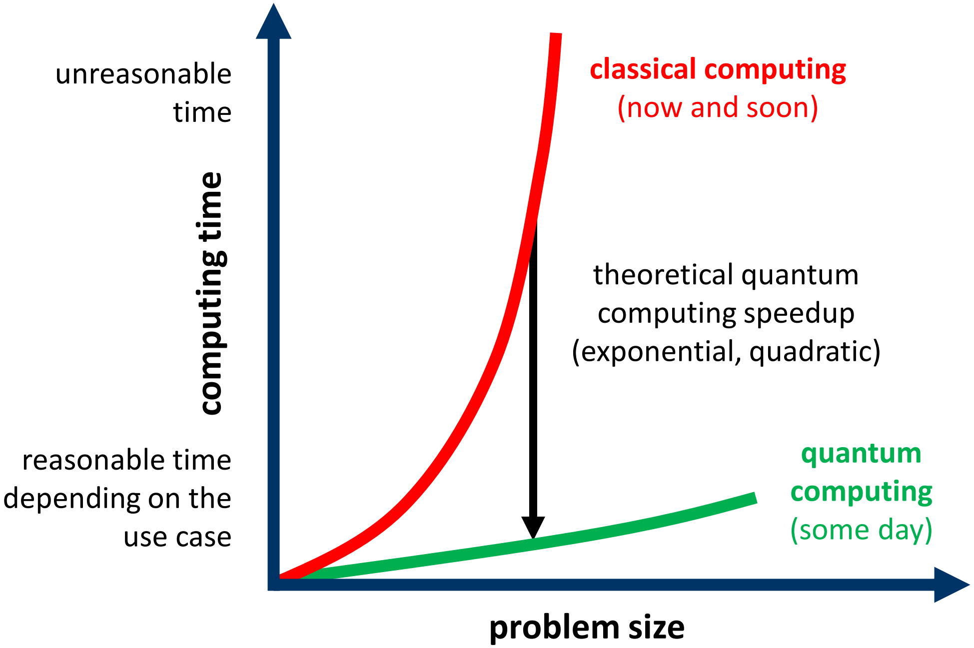


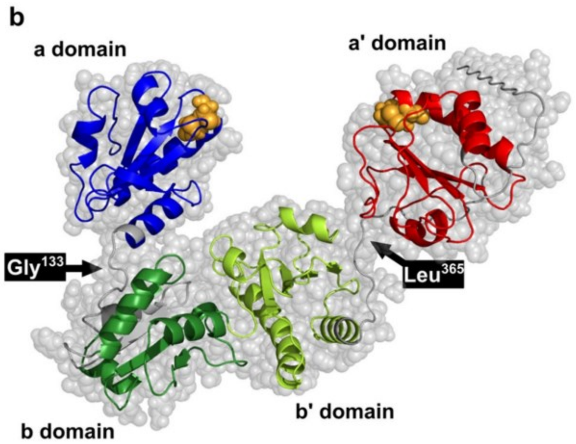
Amazon paperback edition in 3 volumes

quantum computing *promise*



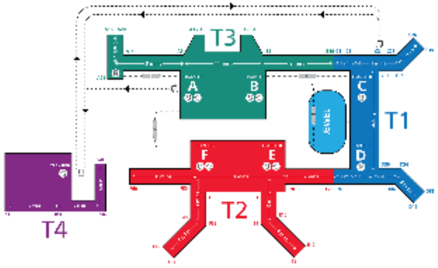
solving intractable / exponential problems in **reasonable** time

typical difficult problems



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

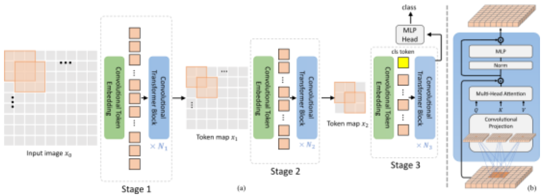
solving Schrodinger's wave equation to simulate quantum matter



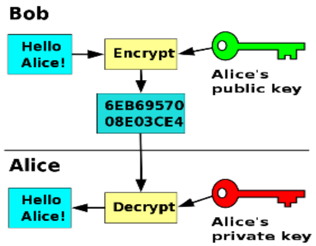
combinatorial optimizations

$$\frac{\partial^2 u_1}{\partial x_1^2} + \frac{\partial^2 u_2}{\partial x_2 \partial x_1} + \frac{\partial^2 u_3}{\partial x_3 \partial x_1} + \frac{\partial^2 u_1}{\partial x_1^2} + \frac{\partial^2 u_1}{\partial x_2^2} + \frac{\partial^2 u_1}{\partial x_3^2} + f_1 = 0$$
$$\frac{\partial^2 u_1}{\partial x_1 \partial x_2} + \frac{\partial^2 u_2}{\partial x_2^2} + \frac{\partial^2 u_3}{\partial x_3 \partial x_2} + \frac{\partial^2 u_2}{\partial x_1^2} + \frac{\partial^2 u_2}{\partial x_2^2} + \frac{\partial^2 u_2}{\partial x_3^2} + f_2 = 0$$
$$\frac{\partial^2 u_1}{\partial x_1 \partial x_3} + \frac{\partial^2 u_2}{\partial x_2 \partial x_3} + \frac{\partial^2 u_3}{\partial x_3^2} + \frac{\partial^2 u_3}{\partial x_1^2} + \frac{\partial^2 u_3}{\partial x_2^2} + \frac{\partial^2 u_3}{\partial x_3^2} + f_3 = 0$$

solving partial derivative equations



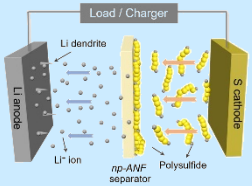
machine learning and deep learning



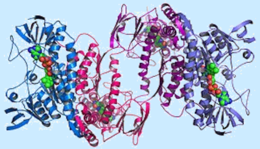
breaking asymmetric cryptography keys

quantum computing usage categories

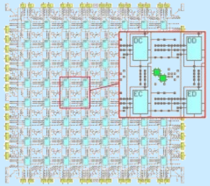
research



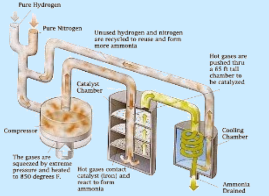
batteries



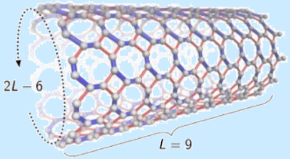
drugs



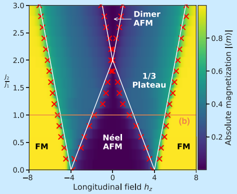
semiconductors



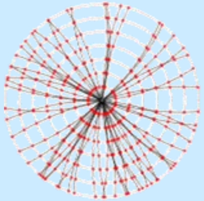
fertilizers production



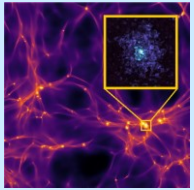
materials design



condensed matter physics



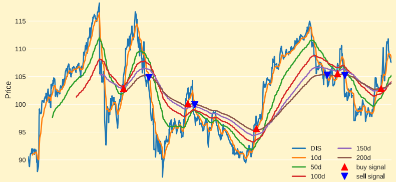
high-energy particle physics



astrophysics

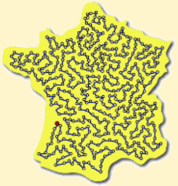
operations

transportation

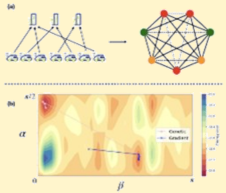


financial services

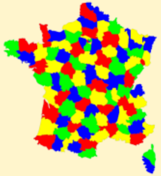
logistics



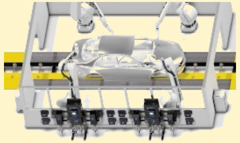
delivery



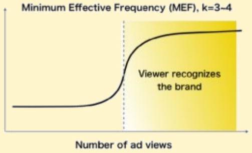
energy utilities



telecoms



manufacturing



marketing

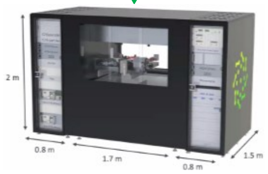
quantum & classical computing paradigms

classical computers		**analog** quantum computers		**digital** quantum computers	
quantum inspired classical algorithms running on classical computer, inspired by quantum algorithms.	**quantum emulators** running quantum computers code on classical computers, for training, debugging and testing	quantum **annealing computers**	analog **quantum simulators**	**gate-based** **NISQ** (Noisy Intermediate Scale Quantum) no error correction with a few noisy qubits	**gate-based** **FTQC** (Fault-Tolerant Quantum Computers) error correction and fault tolerance
classical algorithms improvements	quantum algorithms debug and testing	optimization problems and quantum physics simulation		general purpose quantum computing, adds search and integer factoring	
MULTIVERSE COMPUTING, ZAPATA AI	EVIDEN, IBM, FUJITSU, Google, Microsoft, aws, PASQAL, C12, QUANDELA, ALICE & BOB	D-Wave The Quantum Computing Company™	PASQAL, QuEra	IBM, rigetti, PsiQuantum, Google, IQM, ALICE & BOB, OQC, Microsoft, QUANTINUUM, IONQ, QUANDELA, XANADU	

digital vs analog quantum computing

	« digital quantum computing »	« analog quantum computing »	
problems		combinatorial problems (CSP, Max cut, SAT, TSP)	some mathematical **problem** with data inputs and desired output.
algorithms	QAOA	combinatorial optimization algorithms	**algorithm** to solve the given problem, which are mostly hybrid and/or variational.
problem reformulation		QUBO and Ising model formulations	with analog quantum computing, the quantum part of the algorithm may map to a generic QUBO or Ising **model formulation.**
quantum toolbox		craph &/or Hamiltonian preparation / BQM problems + embedding	QUBO/Ising model may itself map to a generic problem formulation like **BQM** in the case of D-Wave annealers.
quantum computer	gate-based	simulators / annealers	the reformulated problem is **directly solved** by the (analog) quantum computer, in an hybrid manner along with a classical computer.

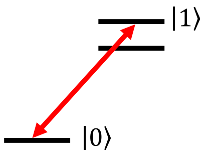
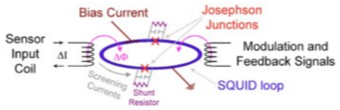
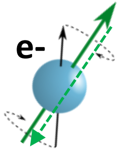
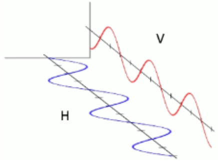
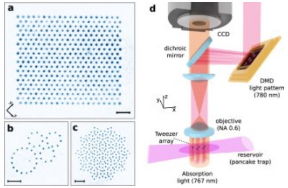
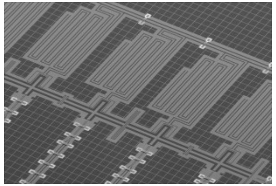
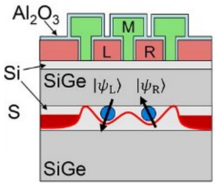
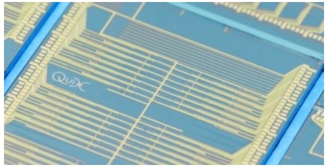
gate-based



simulators

annealers

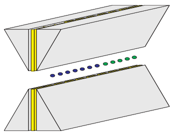
main qubit types

	atoms and ions	superconducting	electron spins	photons
				
quantum states	atom energy level	loop phase or energy	electron spin orientation	photo polarization (or other property)
physical aspect				
interactions	laser pulses and/or microwaves	microwave pulses and/or DC current		interferometers, polarizing beam splitters, ...

QPUs vendors per qubit type

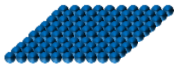
atoms

trapped ions



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

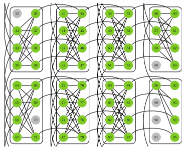
cold atoms



- PASQAL
- QuEra
- Infleqtion
- atom computing
- planqc
- QUANTier
- NanoQT Nanofiber Quantum Technologies

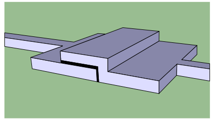
electron *superconducting loops & controlled spin*

annealing



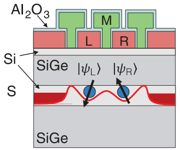
- D-Wave The Quantum Computing Company™
- QILIMANJARO QUANTUM TECH
- NEC

super-conducting



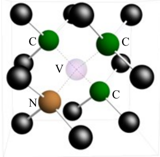
- IBM
- rigetti
- amazon
- Google
- qci
- Nord Quantique
- OQC
- IQM
- ALICE & BOB
- 本源量子 ORIGIN QUANTUM
- ANYON
- ATLANTIC QUANTUM
- bleximo
- FUJITSU

silicon



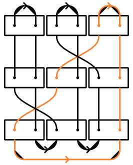
- intel
- quobly
- QUANTUM MOTION
- Silicon Quantum Computing
- diraq
- EeroQ
- equal1.labs
- C12
- ARQUE
- QπAI
- ARCHER

vacancies



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

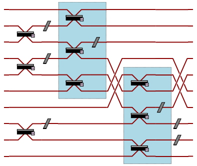
topological



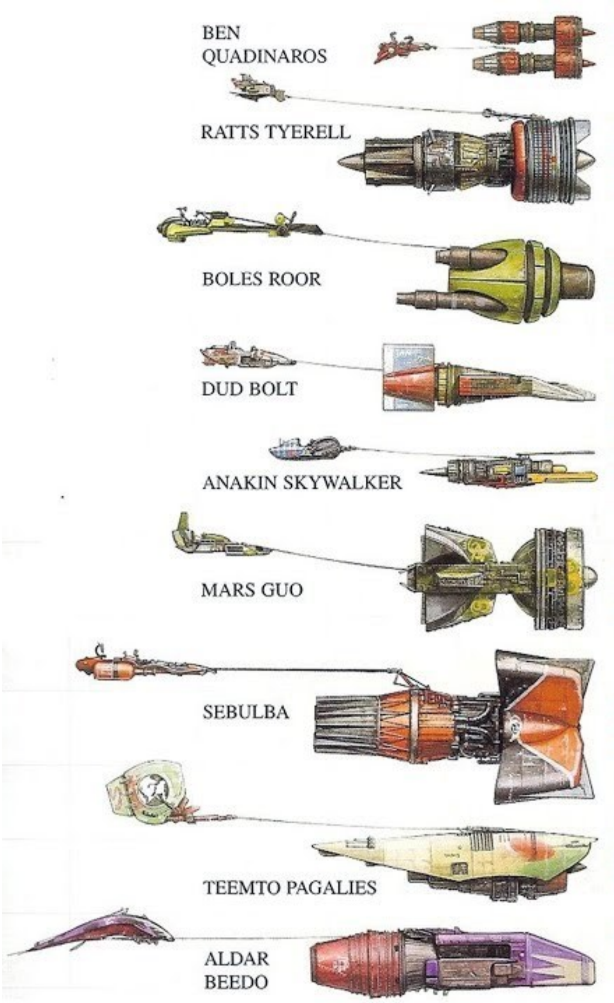
- Microsoft
- QUOHERENT
- QUANTUM GRAVITY RESEARCH

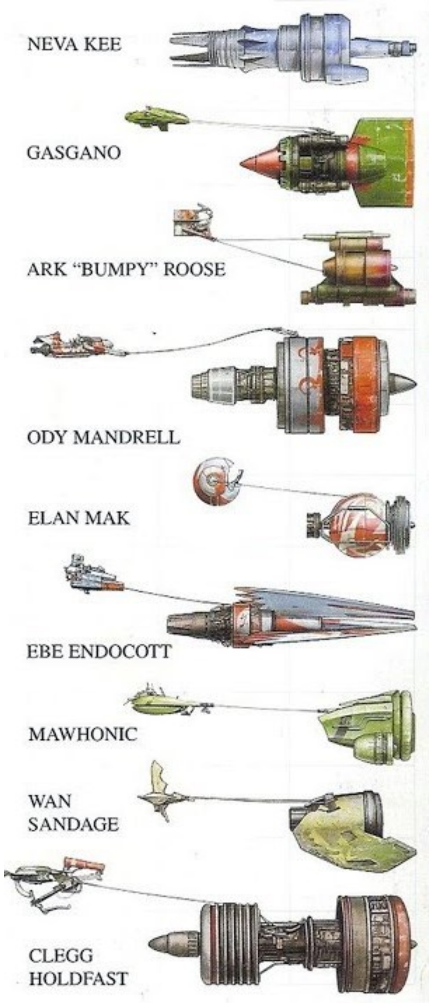
photons

photons

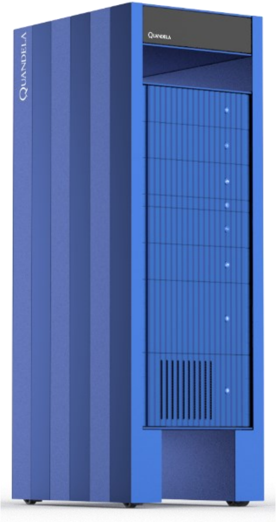


- PsiQuantum
- QUANDELA
- ORCA COMPUTING
- XANADU
- DUALITY QUANTUM PHOTONICS
- QUIX QUANTUM
- BardeenQ LABS
- QBoson
- QCi
- photonicsQ
- QUANFLUENCE
- TUNDRASYSTEMS GLOBAL LTD


BEN
QUADINAROS
RATTS TYERELL
BOLES ROOR
DUD BOLT
ANAKIN SKYWALKER
MARS GUO
SEBULBA
TEEMTO PAGALIES
ALDAR
BEEDO


NEVA KEE
GASGANO
ARK "BUMPY" ROOSE
ODY MANDRELL
ELAN MAK
EBE ENDOCOTT
MAWHONIC
WAN
SANDAGE
CLEGG
HOLDFAST

IBM

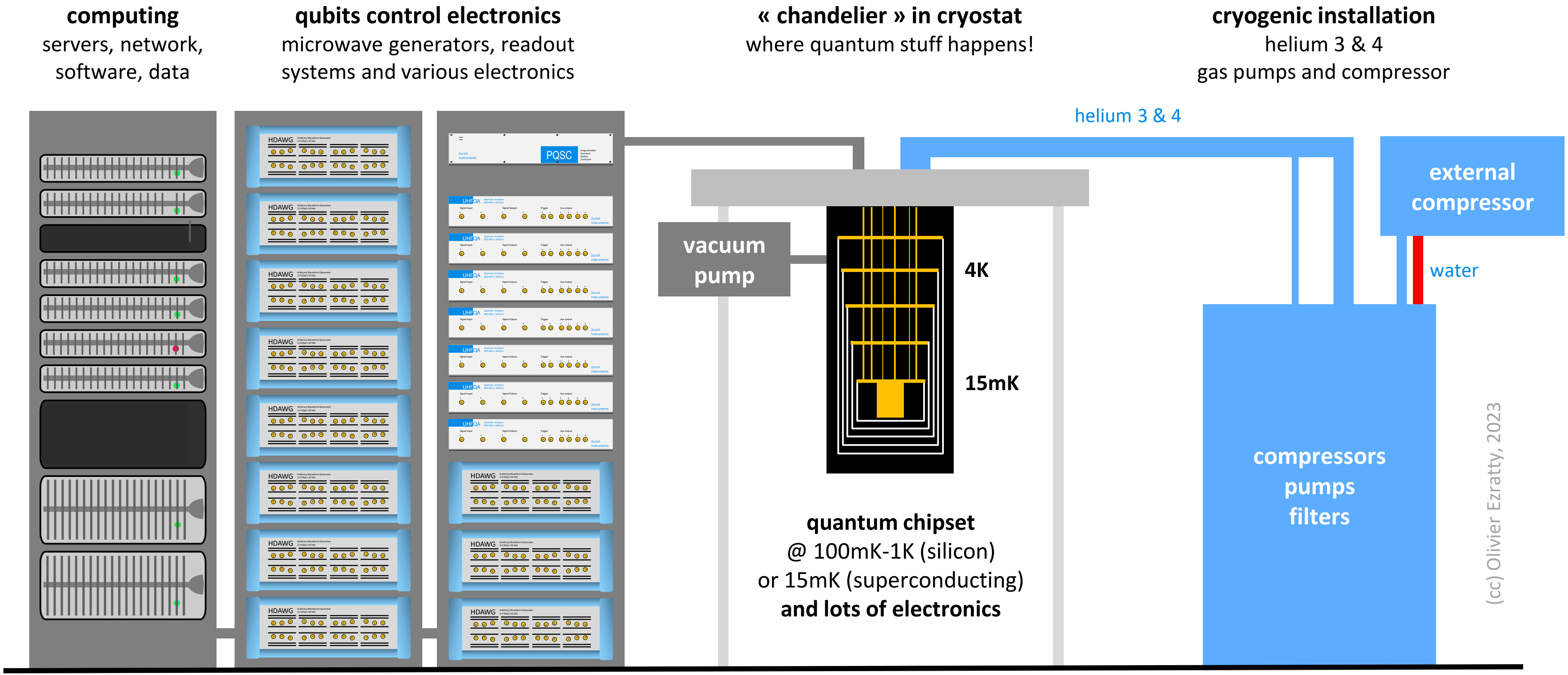


QUANDELA

IONQ

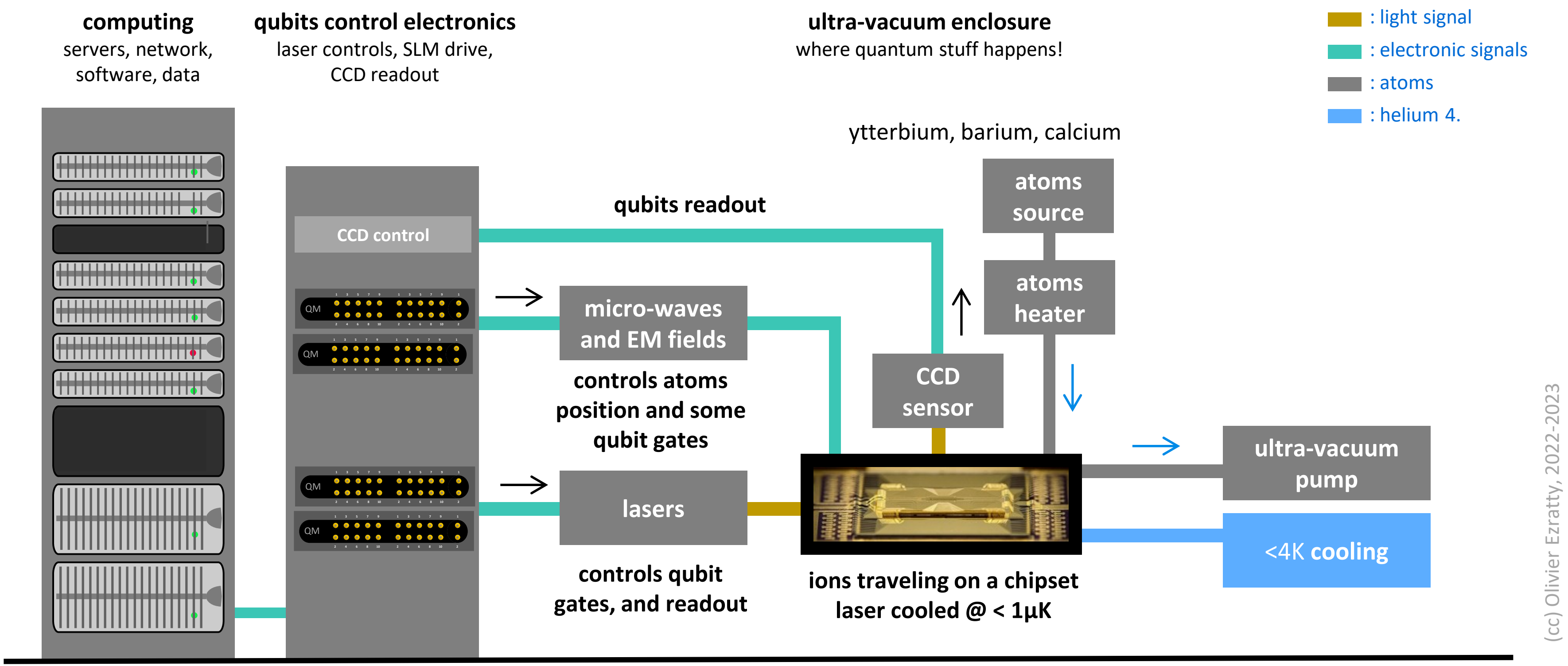
PASQAL

inside a typical quantum computer



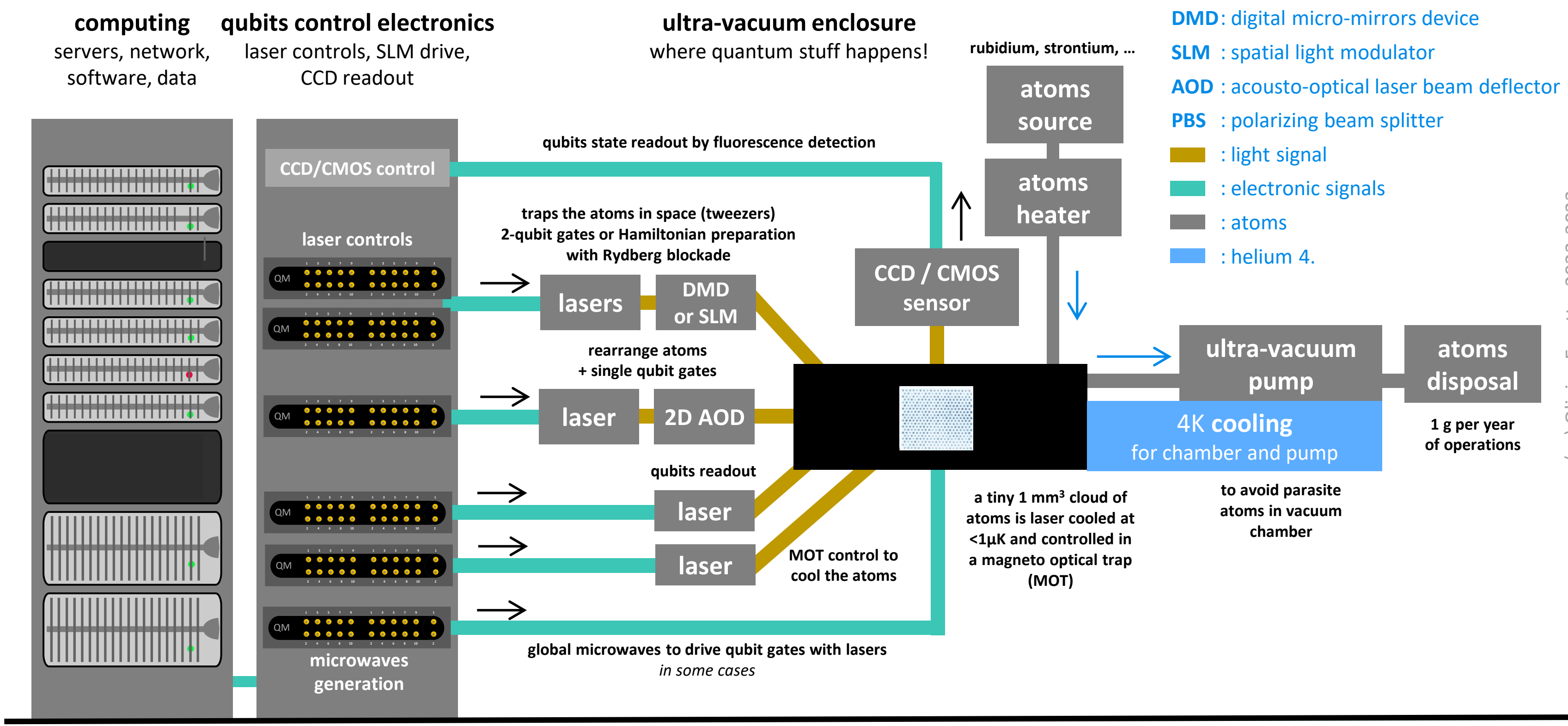
for superconducting or electron spin qubits

inside a trapped ions QC

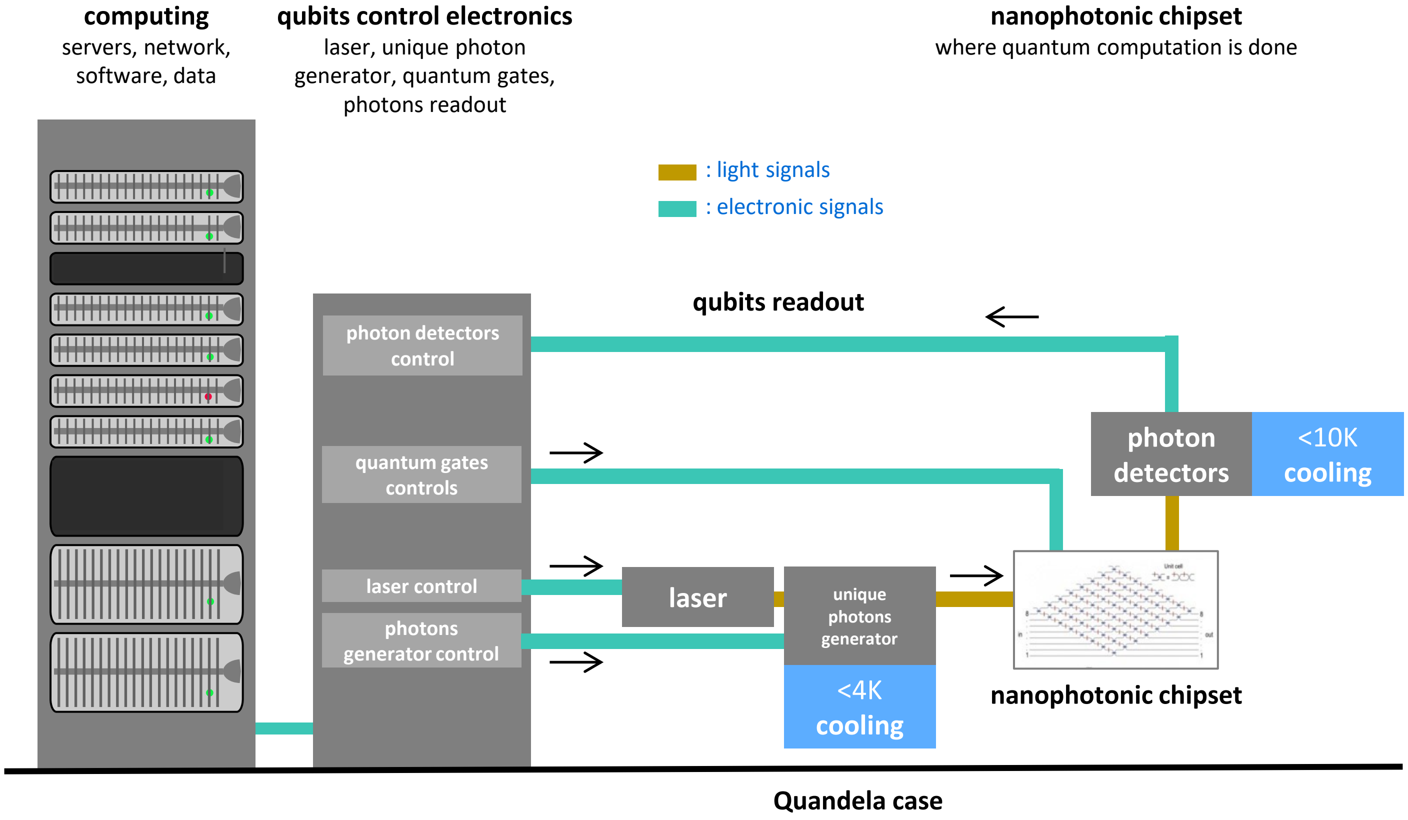


IonQ trapped ions case

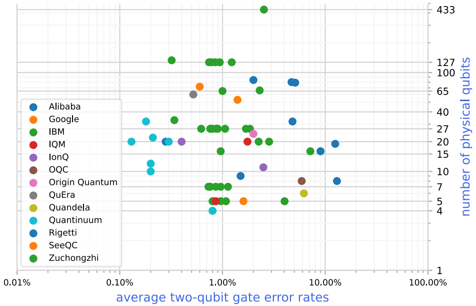
with a neutral atoms quantum computer



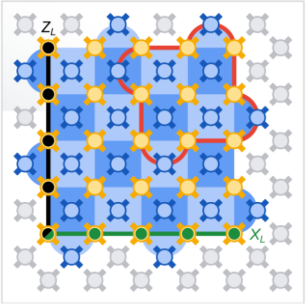
with a photon qubits quantum computer



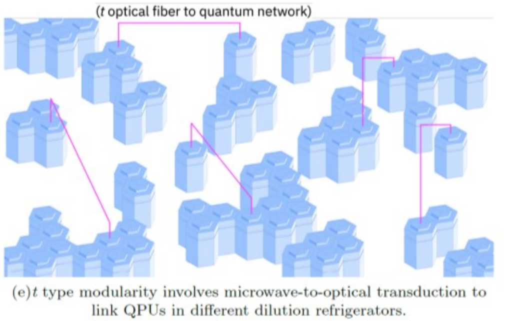
key QPU challenges



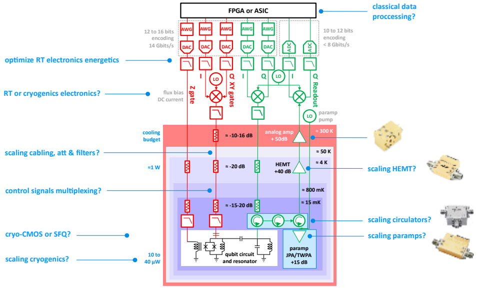
qubits fidelities



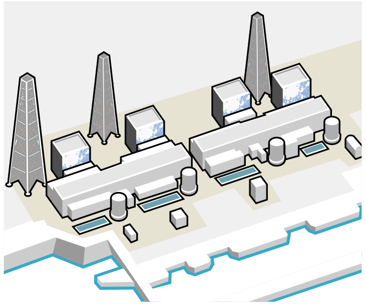
errors mitigation and correction



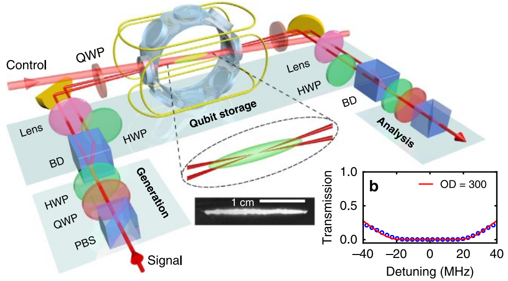
quantum interconnect



enabling technologies scalability

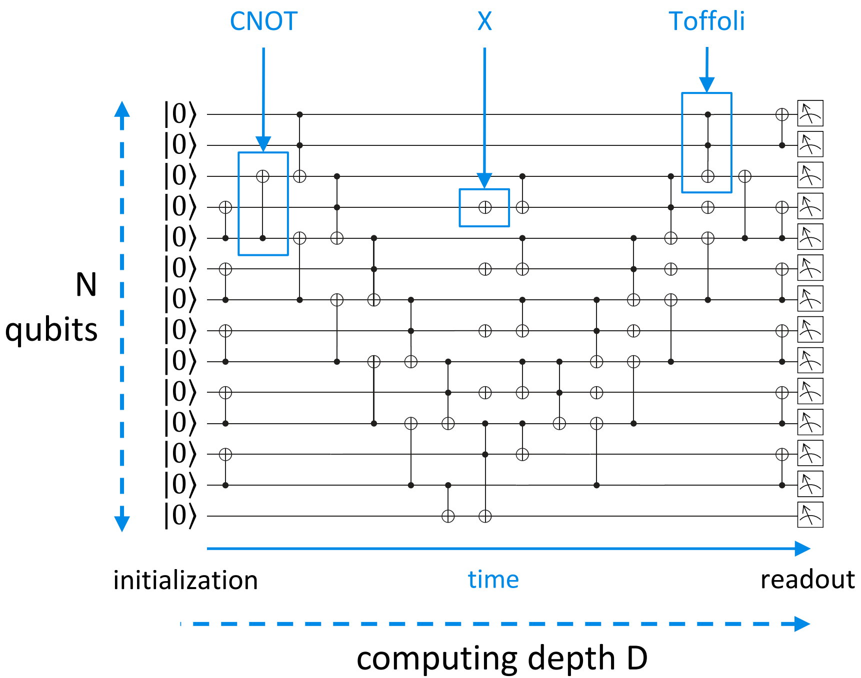


energy consumption



quantum memory

raw algorithm fidelities requirements



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

N qubits	D depth	required error rate (%)	required fidelity (%)	available fidelity (%)
50	100	0.02000%	99.98%	**99.30%**
133	300	0.00251%	99.9975%	**99.6%**
433	1000	0.00023%	99.9998%	**98%**
1121	2000	0.00004%	99.99996%	N/A

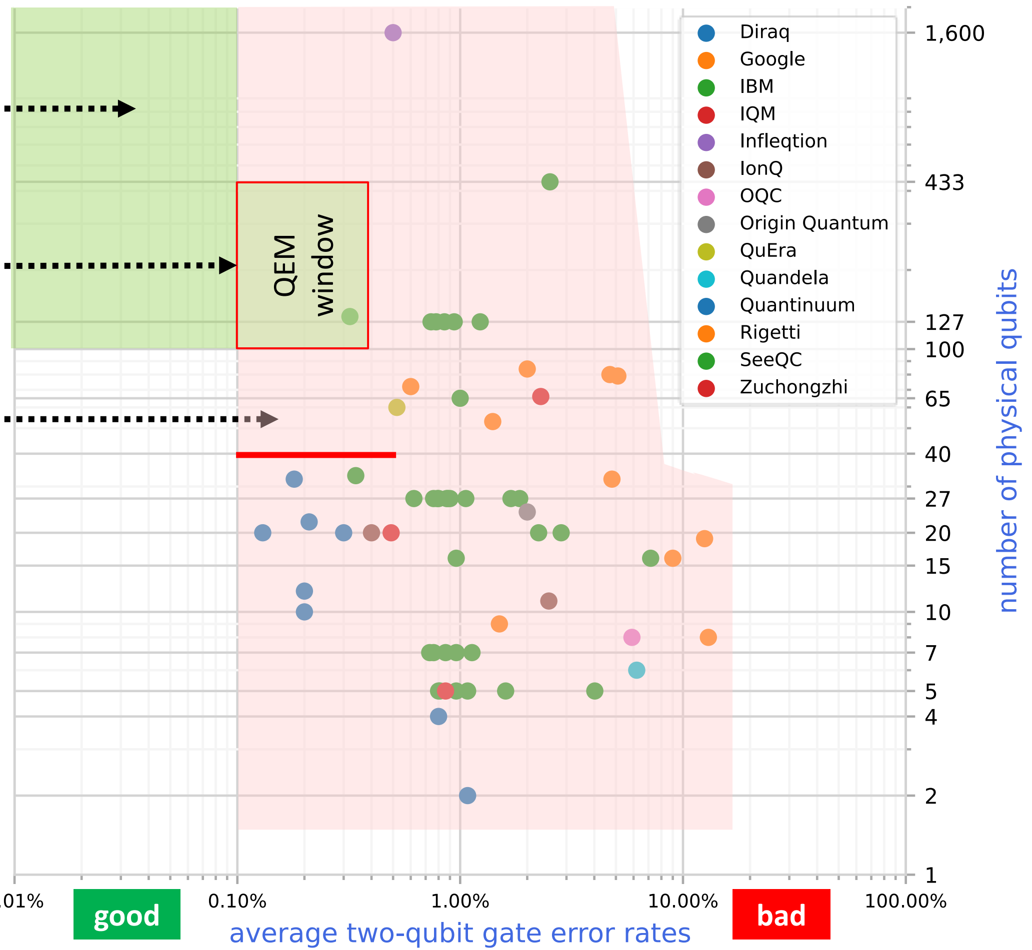
but… QEC cost discrepancy between Clifford and non-Clifford gates

useful NISQ* requirements

with quantum error mitigation

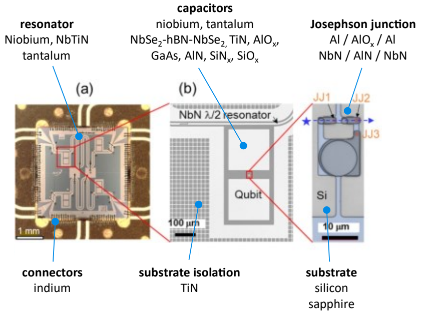
state of the art

easy to emulate classically, too noisy to be useful

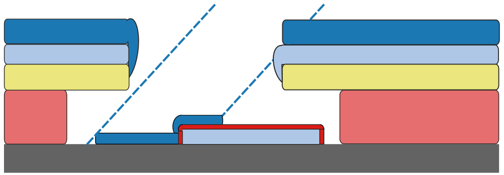


* NISQ = noisy intermediate scale quantum computers.

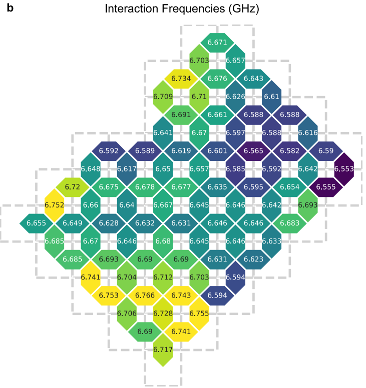
how to improve qubit fidelities? *



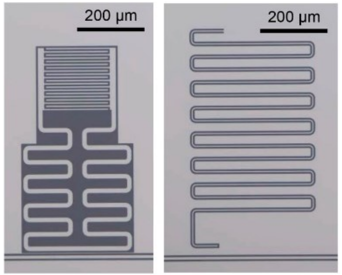
materials



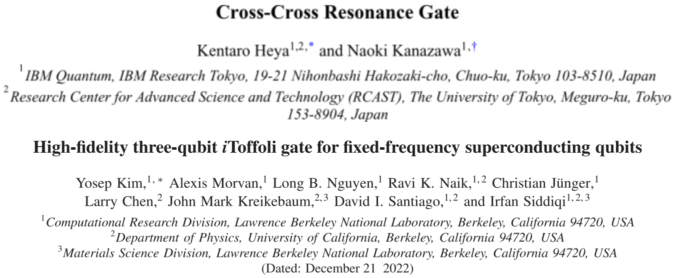
manufacturing



reduce crosstalk



tune qubit parameters



Cross-Cross Resonance Gate

Kentaro Heya[1,2,*] and Naoki Kanazawa[1,†]

[1] *IBM Quantum, IBM Research Tokyo, 19-21 Nihonbashi Hakozaki-cho, Chuo-ku, Tokyo 103-8510, Japan*
[2] *Research Center for Advanced Science and Technology (RCAST), The University of Tokyo, Meguro-ku, Tokyo 153-8904, Japan*

High-fidelity three-qubit *i*Toffoli gate for fixed-frequency superconducting qubits

Yosep Kim,[1,*] Alexis Morvan,[1] Long B. Nguyen,[1] Ravi K. Naik,[1,2] Christian Jünger,[1] Larry Chen,[2] John Mark Kreikebaum,[2,3] David I. Santiago,[1,2] and Irfan Siddiqi[1,2,3]

[1] *Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2] *Department of Physics, University of California, Berkeley, California 94720, USA*
[3] *Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Dated: December 21 2022)

use different primary gates

improve control signals quality

* using here the example of superconducting qubits

logical qubits and FTQC

physical qubit

error rates ≈0.1%

+

error correction code

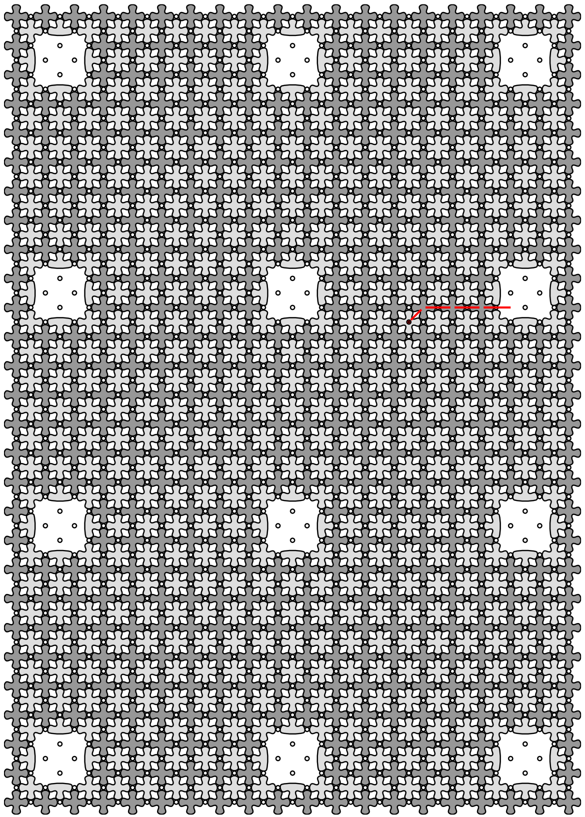
threshold, physical qubits overhead, connectivity requirements, syndrome decoding and scale

logical qubit

error rate $<10^{-8}$ to $<10^{-15}$

fault tolerance

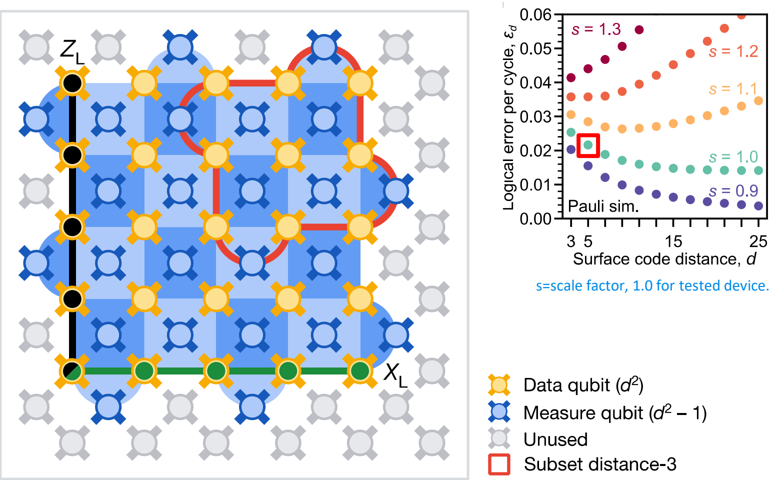
avoid error propagation and amplification
implement a universal gate set
fault-tolerant results readout



tens to thousands qubits

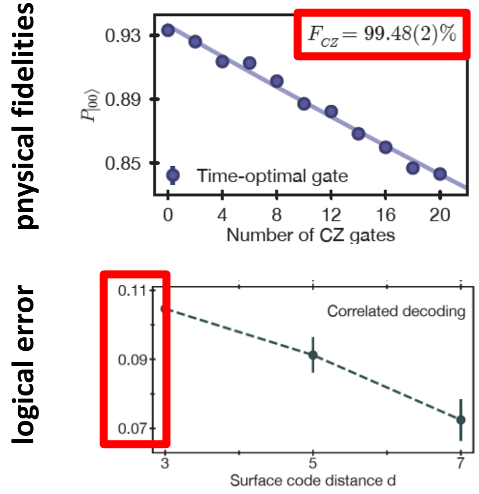
https://arxiv.org/abs/1202.2639

existing logical qubits *above* break-even



Sycamore 72-qubit processor
single distance-5 logical qubit – July 2022

it slightly outperforms a distance-3 logical qubit but with providing a higher error rate (2.1%) than the underlying physical qubits (0.7%).



Harvard-MIT-QuEra 48 logical qubits – December 2023

logical 2-qubit gate error rates at 7% with distance-7 surface code while physical qubit error rate is 0.5%.

sources: Suppressing quantum errors by scaling a surface code logical qubit by Rajeev Acharya et al, Google AI, Nature, July 2022-February 2023 (44 pages) and Logical quantum processor based on reconfigurable atom arrays by Dolev Bluvstein, Mikhail D. Lukin et al, December 2023 (32 pages)..

Microsoft-Quantinuum logical qubits

Demonstration of logical qubits and repeated error correction with better-than-physical error rates

M. P. da Silva,[1] C. Ryan-Anderson,[2] J. M. Bello-Rivas,[1] A. Chernoguzov,[2] J. M. Dreiling,[2] C. Foltz,[2] J. P. Gaebler,[2] T. M. Gatterman,[2] D. Hayes,[2] N. Hewitt,[2] J. Johansen,[2] D. Lucchetti,[2] M. Mills,[2] S. A. Moses,[2] B. Neyenhuis,[2] A. Paz,[1] J. Pino,[2] P. Siegfried,[2] J. Strabley,[2] S. J. Wernli,[1] R. P. Stutz,[2] and K. M. Svore[1]

[1] *Microsoft Azure Quantum*
[2] *Quantinuum*

(Dated: April 2, 2024)

The promise of quantum computers hinges on the ability to scale to large system sizes, e.g., to run quantum computations consisting of more than 100 million operations fault-tolerantly. This in turn requires suppressing errors to levels inversely proportional to the size of the computation. As a step towards this ambitious goal, we present experiments on a trapped-ion QCCD processor where, through the use of fault-tolerant encoding and error correction, we are able to suppress logical error rates to levels below the physical error rates. In particular, we entangled logical qubit states encoded in the $[[7,1,3]]$ code with error rates $9.8\times$ to $500\times$ lower than at the physical level, and entangled logical qubit states encoded in a $[[12,2,4]]$ code with error rates $4.7\times$ to $800\times$ lower than at the physical level, depending on the judicious use of post-selection. Moreover, we demonstrate repeated error correction with the $[[12,2,4]]$ code, with logical error rates below physical circuit baselines corresponding to repeated CNOTs, and show evidence that the error rate per error correction cycle, which consists of over 100 physical CNOTs, approaches the error rate of two physical CNOTs. These results signify an important transition from noisy intermediate scale quantum computing to reliable quantum computing, and demonstrate advanced capabilities toward large-scale fault-tolerant quantum computing.

https://arxiv.org/abs/2404.02280

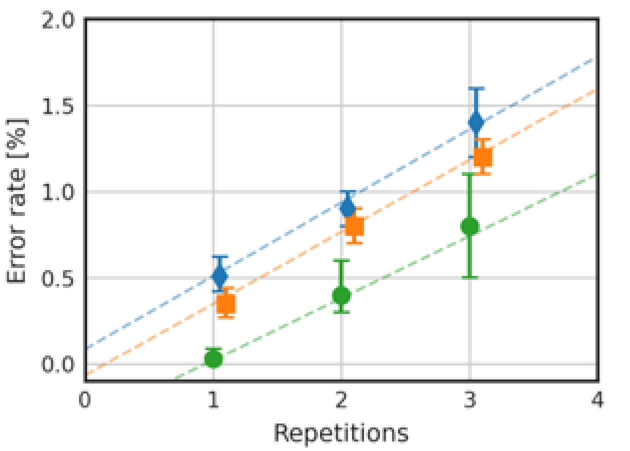


FIG. 7. Observed error rate for circuits with 1 to 3 rounds of error correction with the $[[12,2,4]]$ Carbon code (green circles) and physical baselines (blue diamond for pairs of 1-bit teleportations, and orange squares for pairs of CNOTs). Results are offset along the x-axis for clarity. Linear fits are obtained by maximum-likelihood estimation (see Appendix A for details).

claim: logical qubit with x800 improvement vs physical qubit

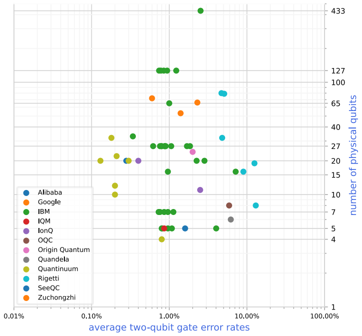
reality: x800 improvement only for the first gate cycle!

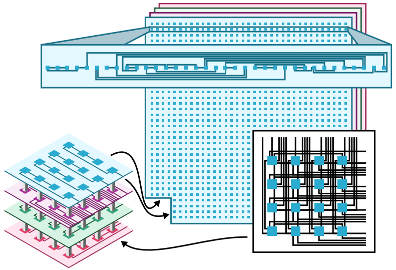
Craig Gidney's comment on Scott Aaronson's blog

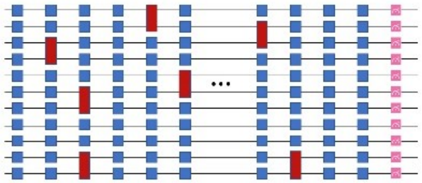
https://scottaaronson.blog/?p=7916#comment-1973425

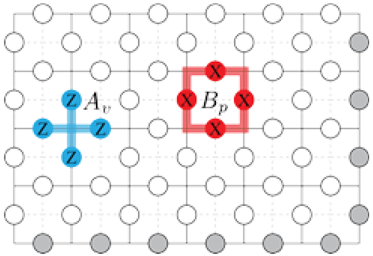
qubits for FTQC?

>99.9%









physical qubits fidelities

physical qubits connectivity

algorithm breadth and depth

n_T = # of T gates in algorithm

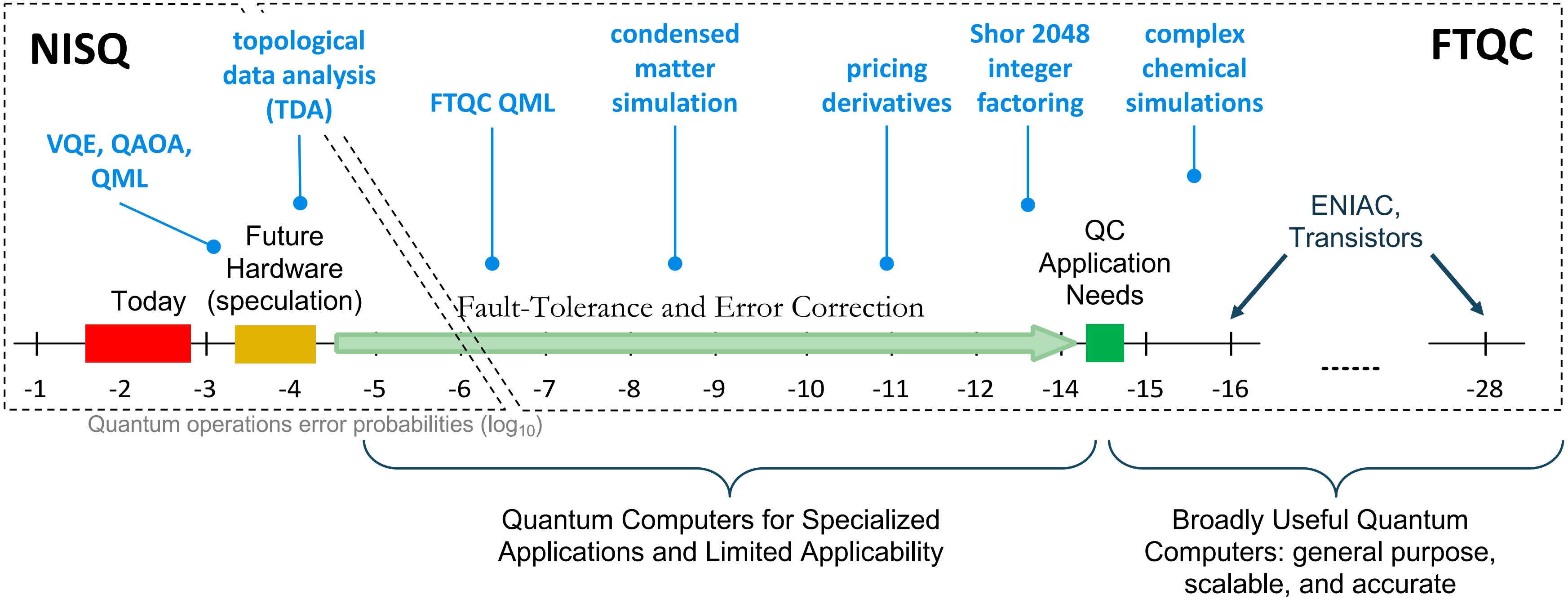
logical qubit error rate $< \frac{1}{n_T}$

error correction code

physical qubits / logical qubit

dynamically adjusted against the algorithm size

logical qubits requirements



source: How about quantum computing? by Bert de Jong, DoE Berkeley Labs, June 2019 (47 slides) + Olivier Ezratty additions, 2021-2024.

Li-Ion battery chemical simulation

needs…

6,652 logical qubits

10^{-12} error rate

computing times in months/years

VOLKSWAGEN

XANADU

source: Simulating key properties of lithium-ion batteries with a fault-tolerant quantum computer by Alain Delgado et al, April-September 2022 (31 pages).

PHYSICAL REVIEW A **106**, 032428 (2022)

Simulating key properties of lithium-ion batteries with a fault-tolerant quantum computer

Alain Delgado,[1,*] Pablo A. M. Casares,[2,*] Roberto dos Reis,[1,3] Modjtaba Shokrian Zini,[1] Roberto Campos,[2,4] Norge Cruz-Hernández,[5] Arne-Christian Voigt,[6] Angus Lowe,[1] Soran Jahangiri,[1] M. A. Martin-Delgado,[2,7] Jonathan E. Mueller,[6] and Juan Miguel Arrazola[1,†]

[1]*Xanadu, Toronto, Ontario, M5G 2C8, Canada*
[2]*Departamento de Física Teórica, Universidad Complutense de Madrid, 28040 Madrid, Spain*
[3]*Department of Materials Science and Engineering, Northwestern University, Evanston, Illinois 60208, USA*
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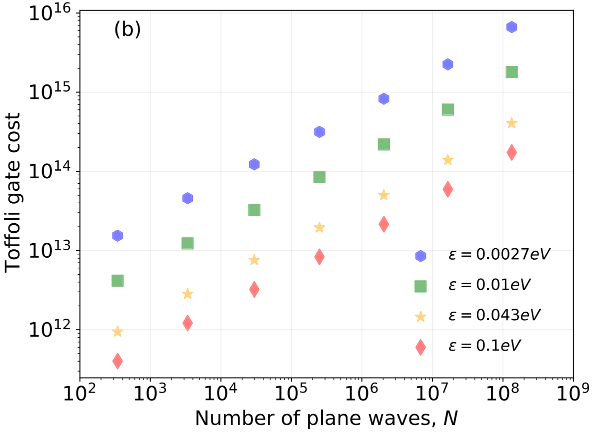
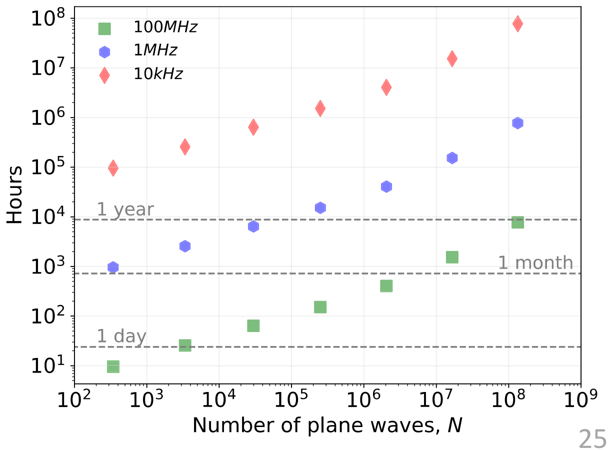
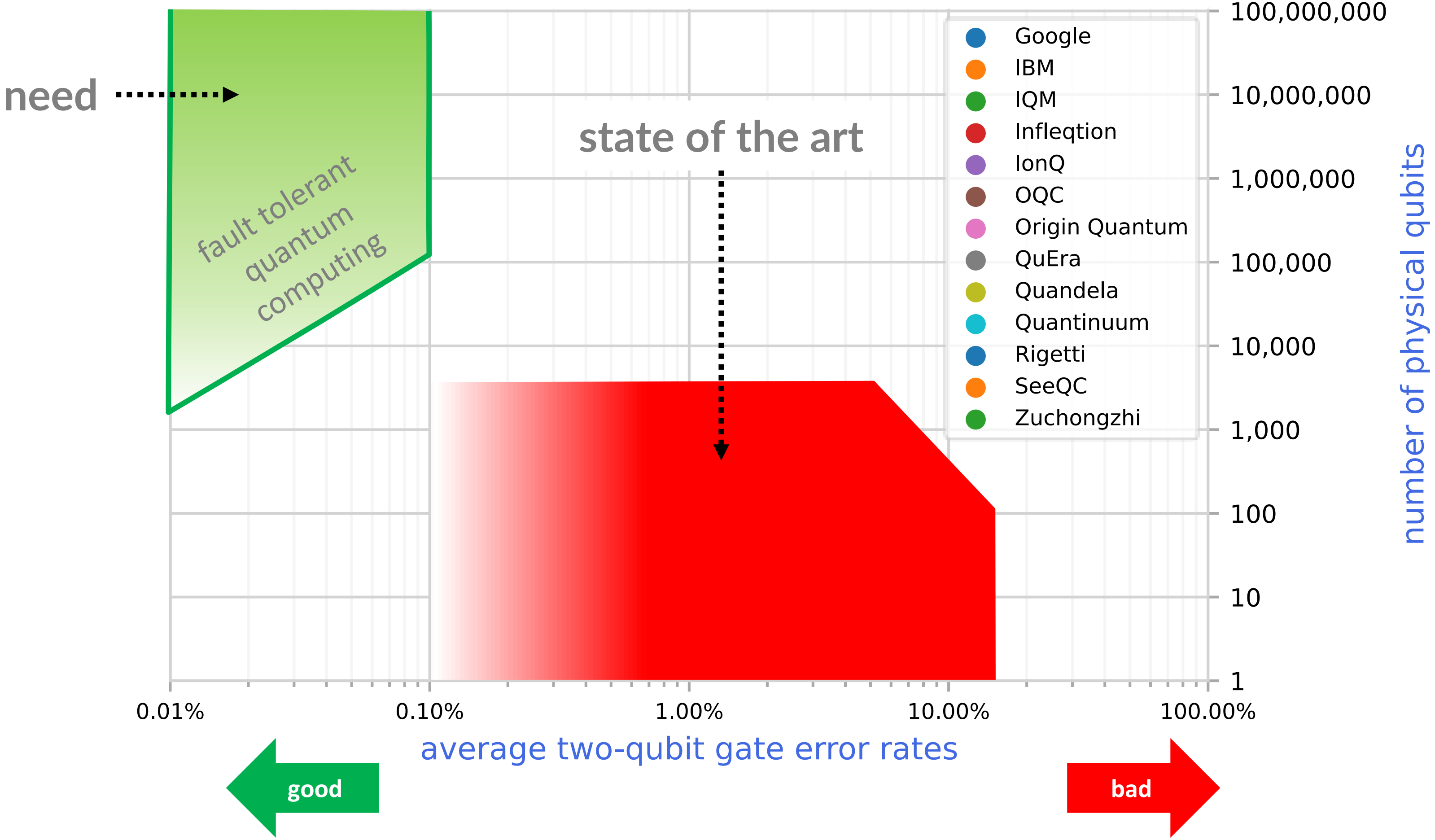
[5]*Departamento de Física Aplicada I, Escuela Politécnica Superior, Universidad de Sevilla, Seville, E-41011, Spain*
[6]*Volkswagen AG, Berliner Ring 2, 38440 Wolfsburg, Germany*
[7]*CCS-Center for Computational Simulation, Universidad Politécnica de Madrid, 28040 Madrid, Spain*

(Received 27 April 2022; revised 14 July 2022; accepted 10 August 2022; published 26 September 2022)







need
state of the art
fault tolerant quantum computing
Google
IBM
IQM
Infleqtion
IonQ
OQC
Origin Quantum
QuEra
Quandela
Quantinuum
Rigetti
SeeQC
Zuchongzhi
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
number of physical qubits
0.01%
0.10%
1.00%
10.00%
100.00%
average two-qubit gate error rates
good
bad

some hardware scalability challenges and trade-offs

the superconducting qubit case

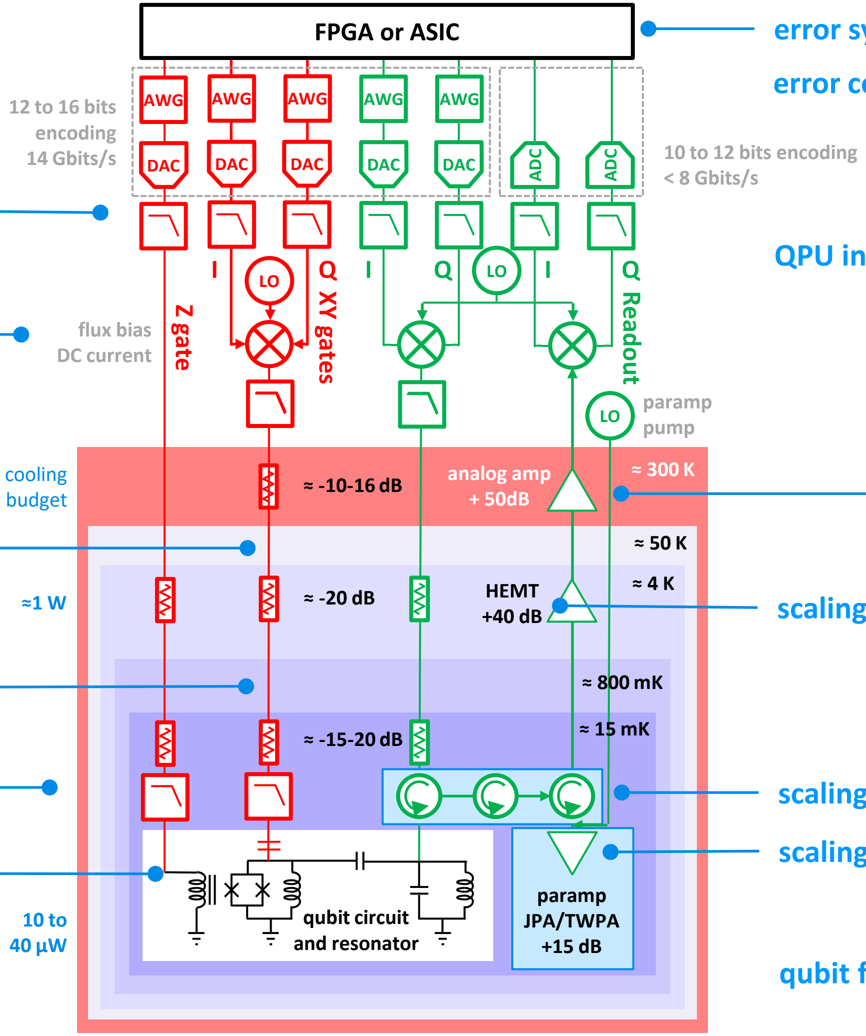
error syndrome decoding

error correction codes

optimize RT electronics energetics

QPU interconnect

RT *or* cryogenics electronics?



scaling cabling, att & filters

scaling HEMTs

control signals multiplexing

cryo-CMOS *or* SFQ electronics?

at which temperature?

scaling circulators

scaling paramps

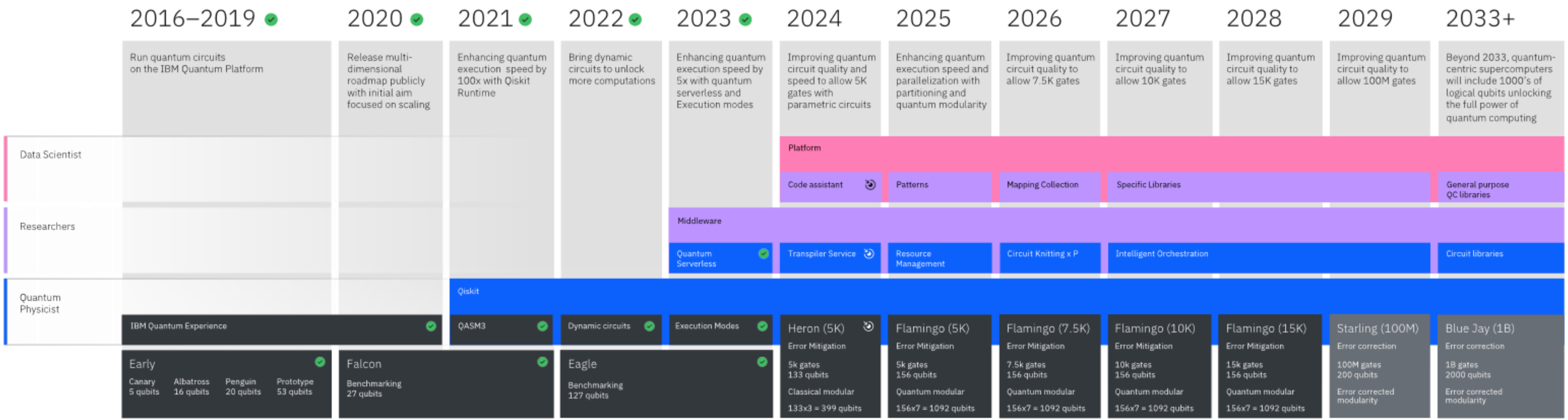
long range qubit connectivity

scaling cryogenics

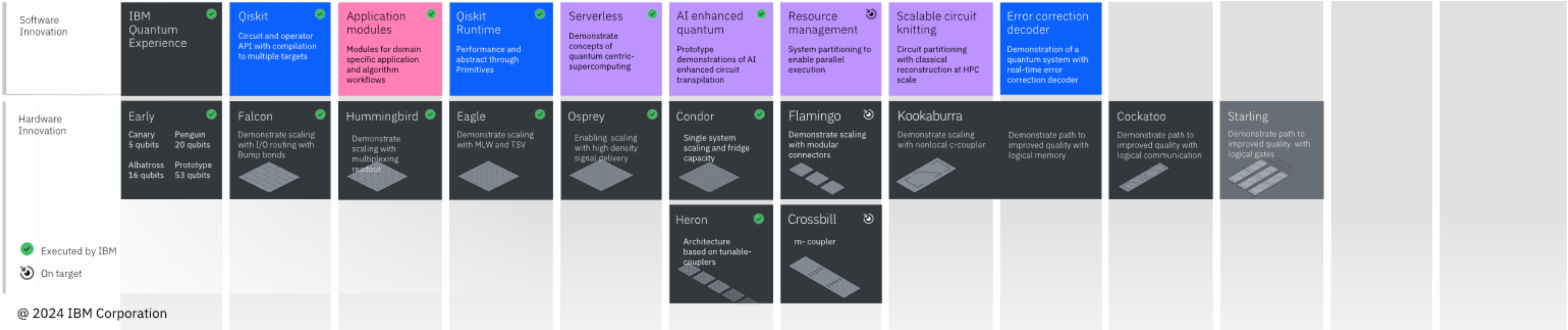
qubit fidelities improvement

Development Roadmap

IBM **Quantum**



Innovation Roadmap



IBM Quantum System 2 with three Heron 133-qubit QPUs

Unlocking True Commercial Advantage

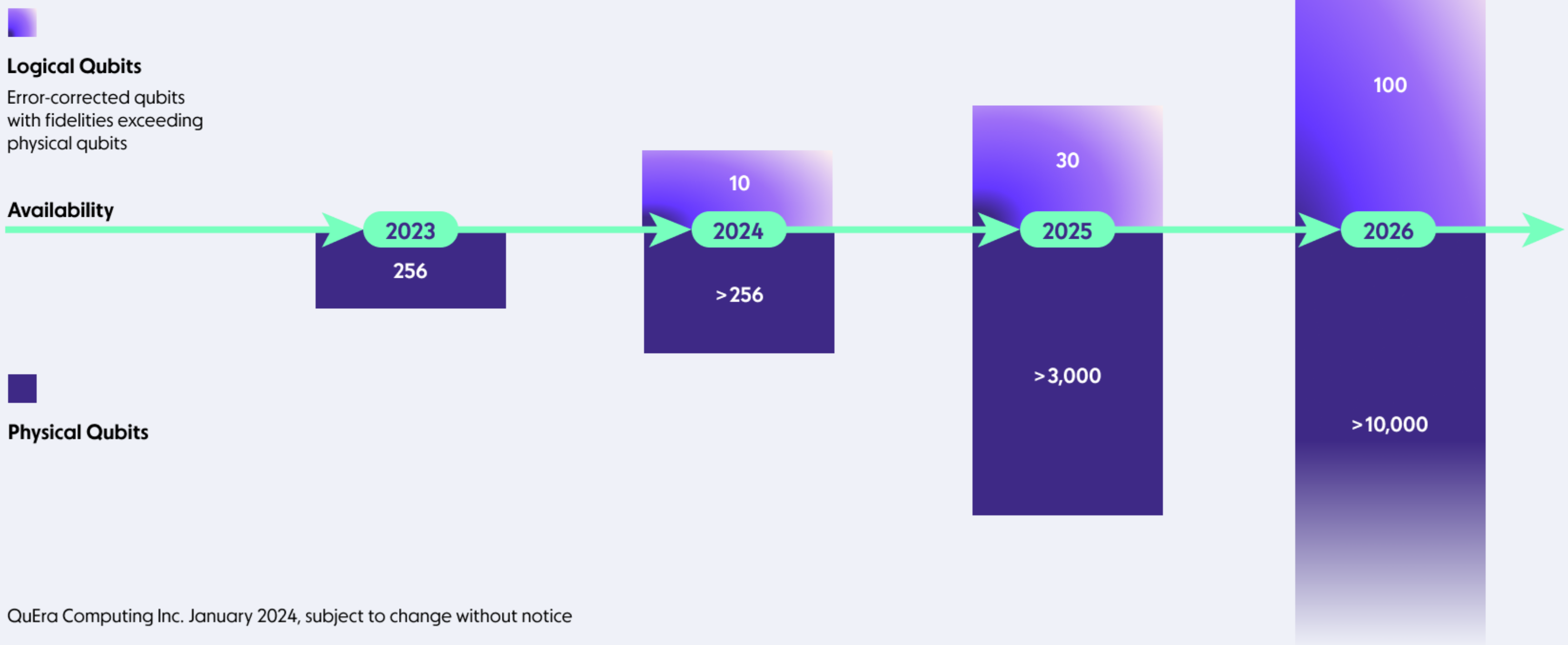
Designing data center ready solutions at scale

	2024 Error Detection	2026 Error Correction	2028 Commercial Advantage
Logical Performance	Dual-species crosstalk-free measurement	Logical circuit depth > 1,000 Universal quantum gate set	Logical circuit depth > 1 million.
Logical Qubits	2	>10	>100
Logical Operations Rate		10,000/sec	100,000/sec
Physical qubits	1,600	8,000	40,000
Fidelity 2Q (CZ):	99.50%	99.90%	99.95%
Fidelity Local 1Q:	99.90%	99.95%	99.95%
Fidelity Global 1Q:	99.99%	99.99%	99.99%
Software	Tooling (QCVV) for verifying fault-tolerant properties	Optimized compilation of fault-tolerant circuits	Exponential speedup demonstration
Enabling technologies	Optimized laser pulse modulation	Advanced photonic beam steering	Realtime atom reloading

|QuEra> Computing Inc.

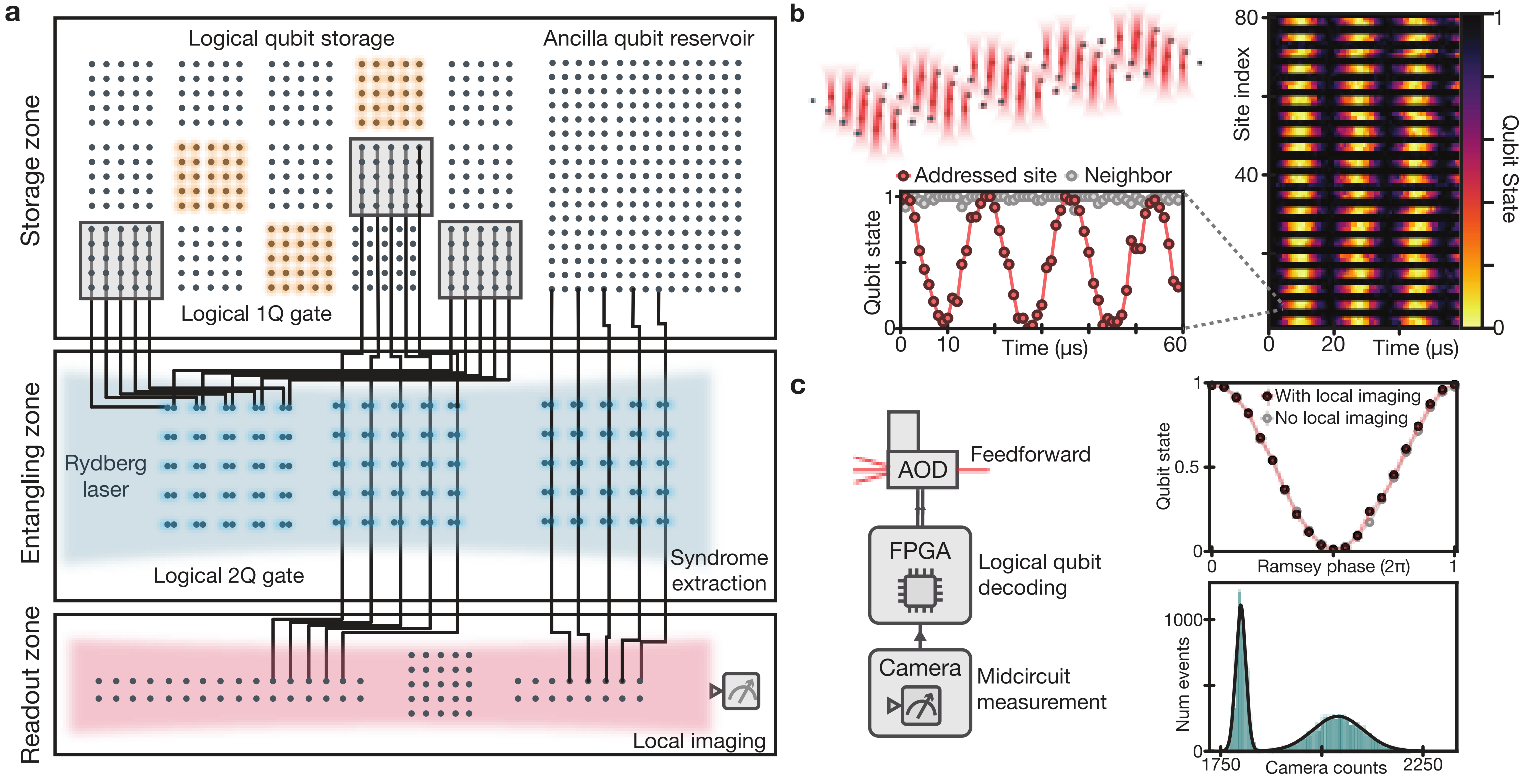
Error-Corrected Quantum Computing Roadmap

System	Aquila	2nd generation	3rd generation	4th generation
Customer Impact	Quantum simulation, optimization and machine learning	Explore QEC, NISQ algorithms with hundreds of qubits	Prototype applications	Practical quantum advantage
QEC Capabilities	N/A	Transversal gates Logical qubit simulator	Non-Clifford gates	Deep logical circuits



QuEra Computing Inc. January 2024, subject to change without notice

Harvard / QuEra logical qubits



source: Logical quantum processor based on reconfigurable atom arrays by Dolev Bluvstein, Mikhail D. Lukin et al, December 2023 (32 pages)..

Public Roadmap

PASQAL

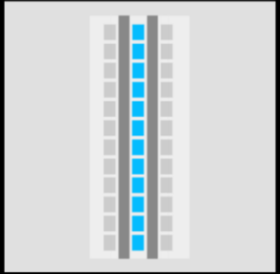
	2022 - 2023	2024 - 2025	2026 - 2027	2028+
Technology — PASQAL & affiliated ecosystem				
HARDWARE PLATFORM				
Max qubits	200	1,000	10,000	
Addressability	Z add	Z+X add; Addressable 1Q and 2Q gates		
Base repetition rate	1 Hz	3 Hz	10 Hz	100 Hz
FTQC Program		Atom shuttling; Ultra High-Fidelity Gates	Scalable logical qubits architecture	
HARDWARE ACCELERATED LIBRARIES				
Quantum Matter & Quantum AI	Algorithm Blueprint	Algorithm Development	Production	
Products				
QUANTUM PROCESSORS				
Generation	**Orion Alpha** ~3M gates	**Orion Beta** ~5M gates On premise delivery; **Orion Gamma** ~10M gates On premise delivery	**Vela** ~40M gates; **Pegasus** ~200M gates	**Centaurus FTQC QPU** 128+ Logical qubits 200M+ gates
Total hours of QPU for users	500	5-10,000; 20-30,000	60-70,000; 200-250,000	500-550,000
Factories	France	Canada; Factory 3		
COMMUNITY				
Platform		Learn; Interact	Collaborate	
Open-source Software Stack	Pulser	Qadence; Solvers & Emulators		

HONEYWELL QUANTUM SOLUTIONS
GENERATIONAL ROADMAP

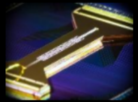
Noisy Intermediate-Scale Quantum (NISQ) Era — 2030

2020 — Fault-Tolerant Quantum Computing

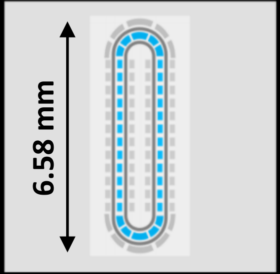
Model H1



Linear



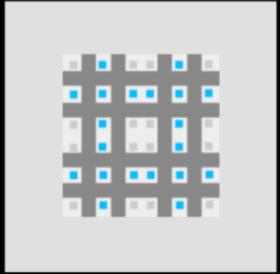
Model H2



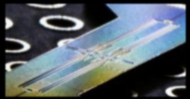
Racetrack

Multi-layer fab demonstrated

Model H3

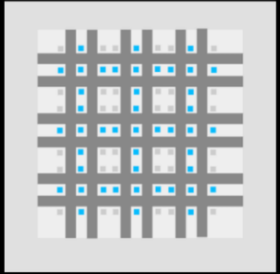


Grid

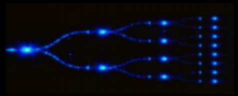


Junction transport demonstrated

Model H4

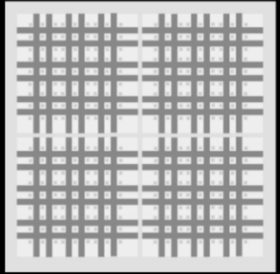


Integrated Optics

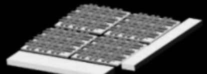


Photonic devices designed and tested

Model H5



Large Scale

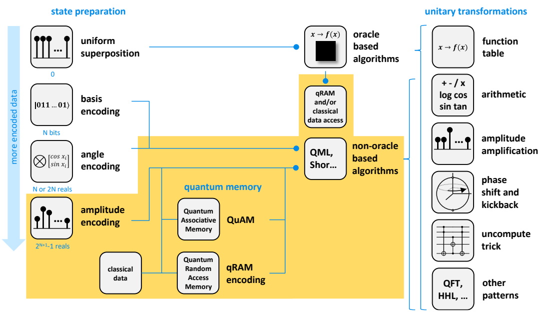


Ion-trap tiling strategy developed

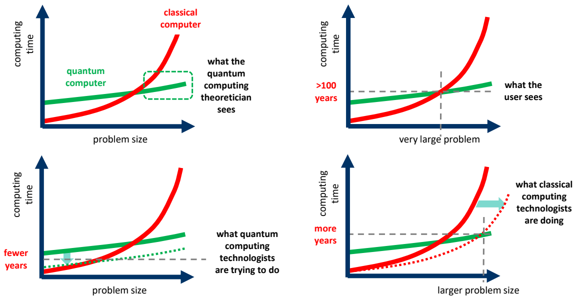
- 10 → 40 Qubits
- 2Q Fidelity: ≥99.5%
- All-to-all connectivity
- Conditional quantum logic
- Mid-circuit measurement
- Qubit reuse

- Massive scaling of physical qubits and computing power
- Ion trap fabrication in Honeywell's foundry
- Key enabling technologies already demonstrated for generational upgrades

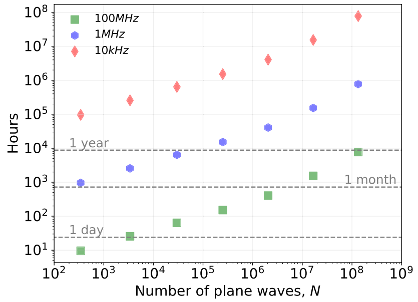
key software challenges



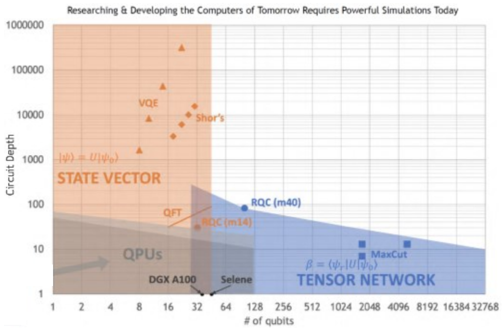
data loading



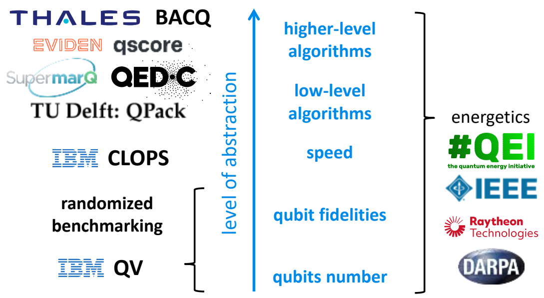
actual speedups



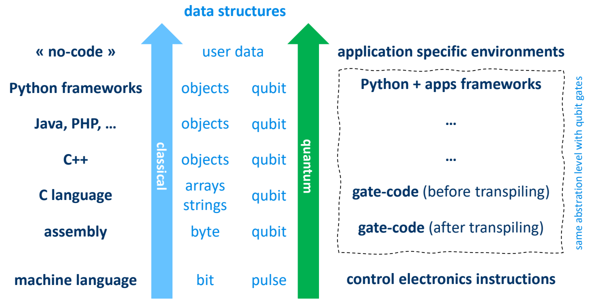
actual computing time



tensor networks competition

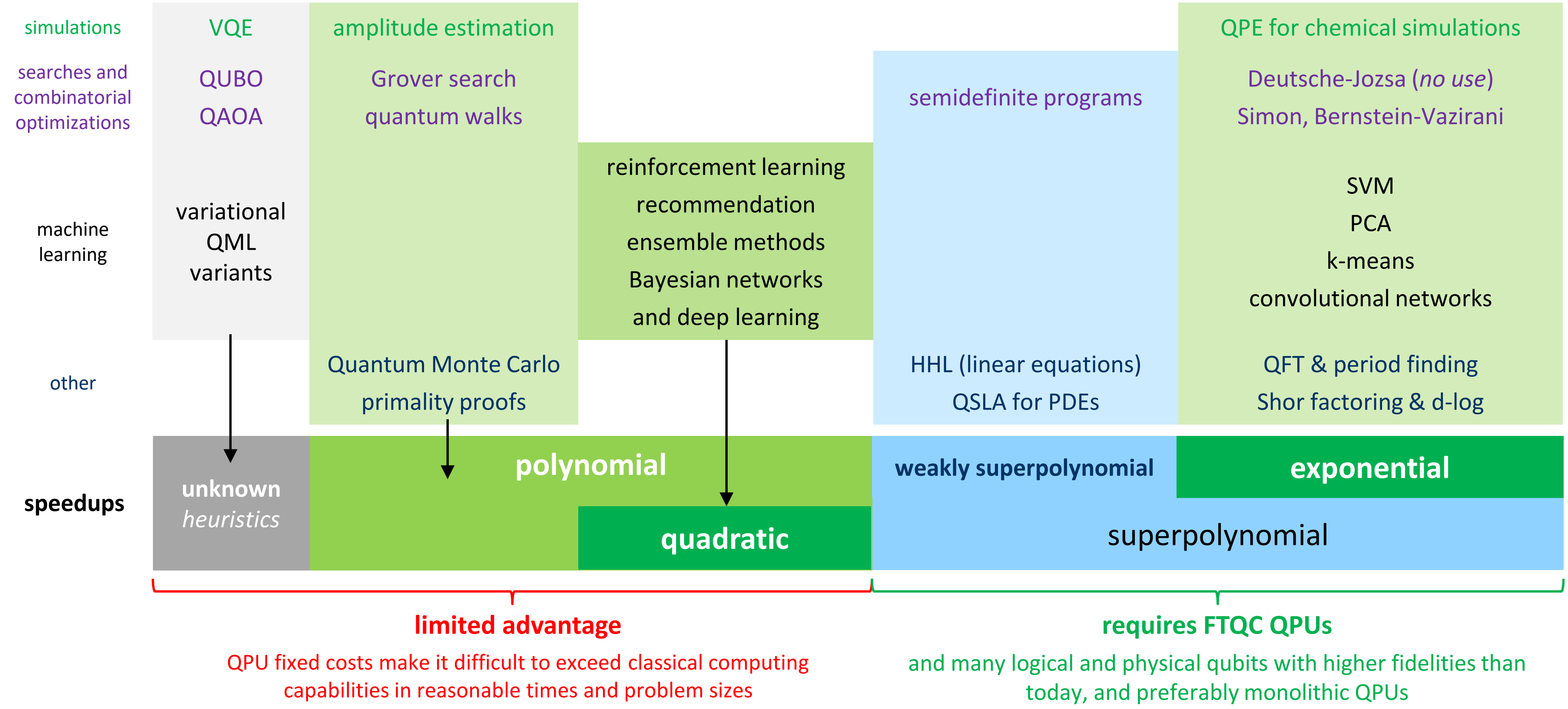


benchmarking

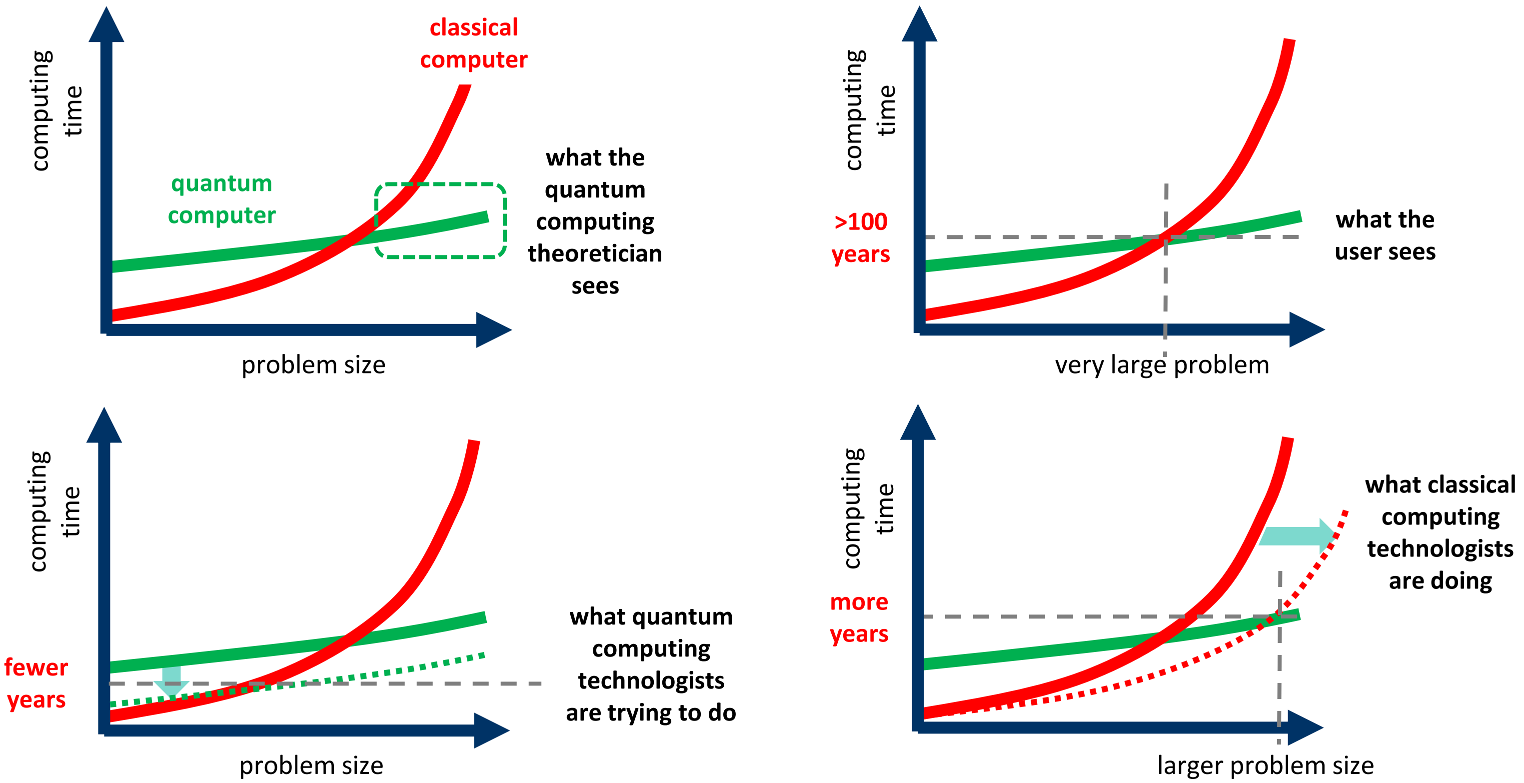


coding abstraction level

potential quantum speedups



a matter of perspective

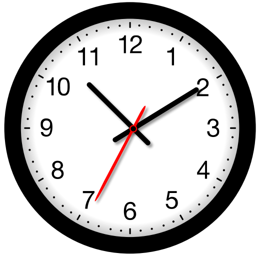


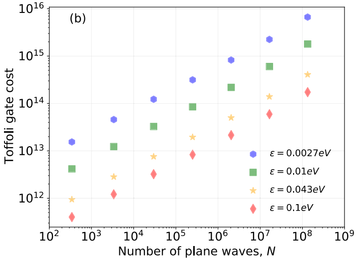
(cc) Olivier Ezratty, 2023, inspired by Disentangling Hype from Practicality: On Realistically Achieving Quantum Advantage by Torsten Hoefler, Thomas Häner, Matthias Troyer, 2023.

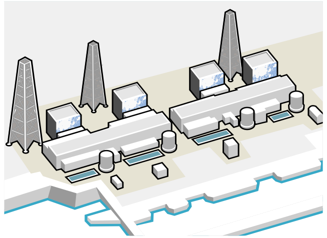
quantum advantages taxonomy

complex amplitudes | of all combinations of 0 and 1

$$\begin{bmatrix} \alpha_1 \\ \dots \\ \dots \\ \dots \\ \dots \\ \alpha_{2^N} \end{bmatrix} \quad \begin{matrix} |00 \dots 00\rangle \\ \\ |01 \dots 11\rangle \\ \\ |11 \dots 11\rangle \end{matrix}$$







€ $ £

TCO

ROI

space

the qubit register data space - scaling in 2^N complex numbers with N qubits - exceeds the memory capacity of classical computers.

speed

a quantum algorithm, including its classical part, runs faster than an equivalent best-in-class classical algorithms running on either the largest supercomputers or a given HPC configuration.

quality

the quality of the results of a quantum algorithm is better for some respect than the best-in-class classical algorithms. e.g: an error rate of a machine learning classification, a chemical simulation accuracy, or a better combinatorial problem solution.

energetic

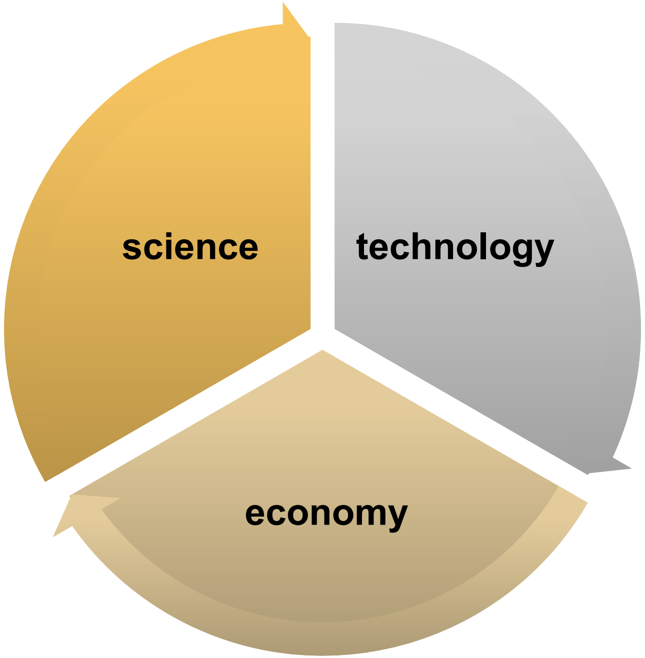
a fully-burdened quantum computer and algorithm configuration consumes less energy than the best-in-class classical equivalent.

cost

the total cost of the quantum solution is lower than the total cost of a best-in-class classical solution.

challenges ahead

- decoherence models
- noise models
- quantum control
- error correction codes
- cluster states creation
- qRAM
- QPU interconnect
- algorithms design
- complexity theory



- control electronics
- manufacturing quality
- cryogeny yield and power
- use cases
- software engineering
- emulators
- cloud infrastructure
- hybrid architectures
- benchmarking

- FPGA->ASIC
- fab investments
- VC, customer and governments investments
- other topics influences (LLMs, …)

discussion

get the slides