



quantum computing

state of the art, challenges, and opportunities

olivier e兹atty

`(author | ...)`

Ljubljana, April 15th, 2024

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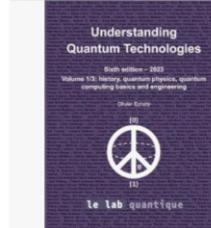
understanding quantum technologies 2023



Résultats

En apprendre plus sur ces résultats.

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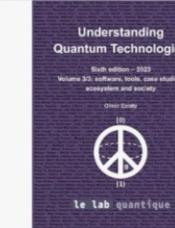
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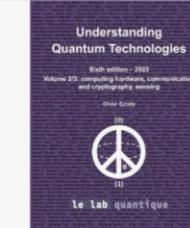
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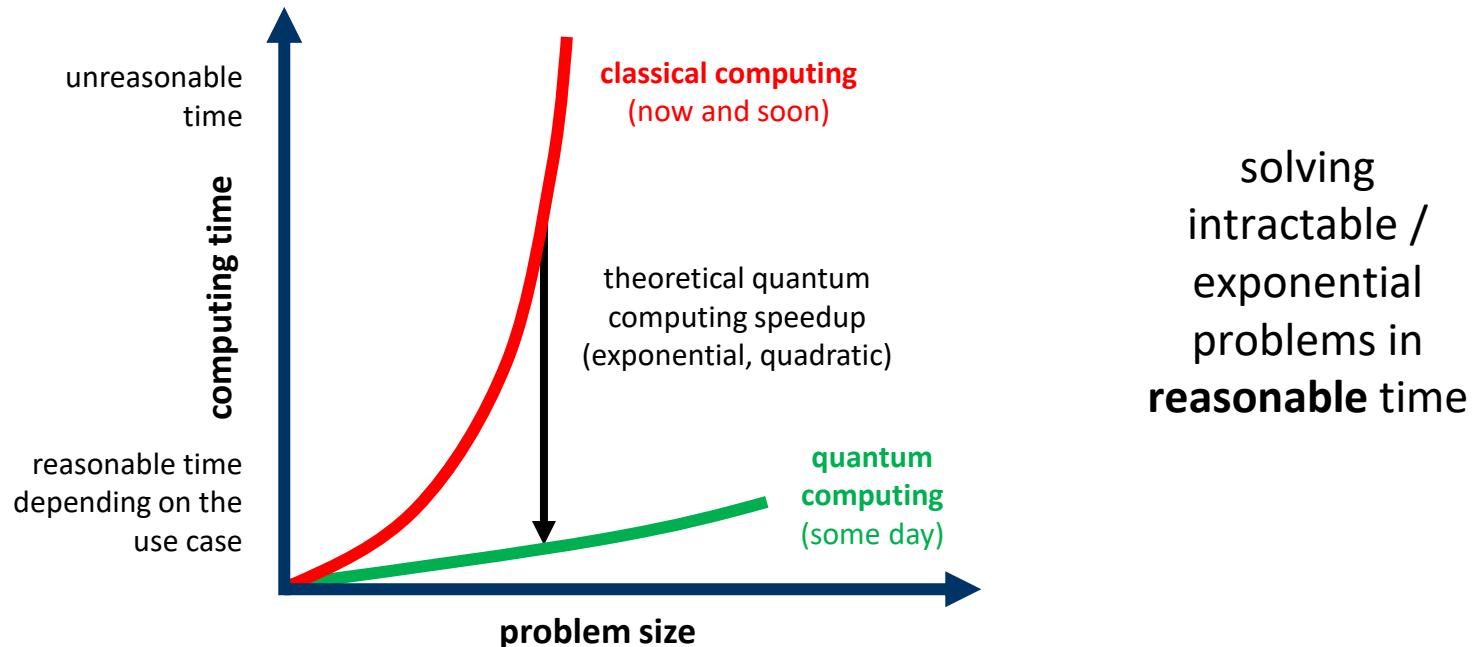
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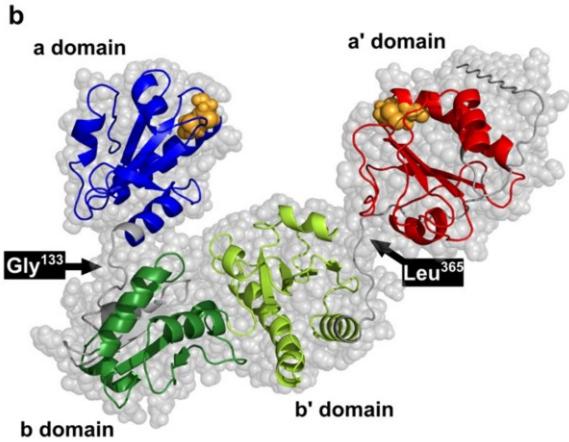
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quantum computing *promise*

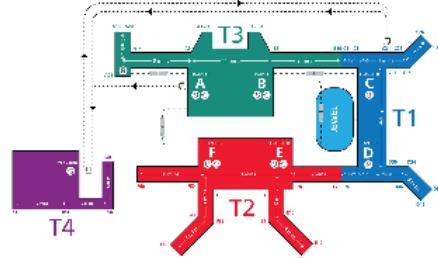


typical difficult problems

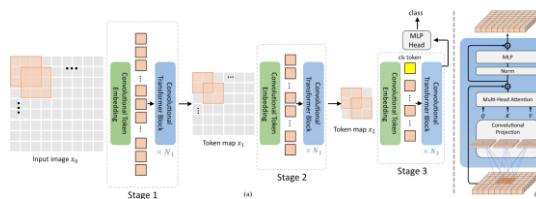


$$ih \frac{\partial \Psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \Psi(x,t)}{\partial x^2} + V(x)\Psi(x,t)$$

solving Schrodinger's wave equation
to simulate quantum matter



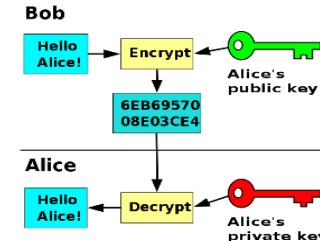
combinatorial optimizations



machine learning
and deep learning

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

solving partial derivative equations



breaking asymmetric
cryptography keys

quantum computing usage categories

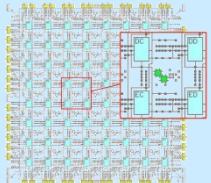
research



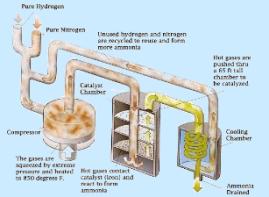
batteries



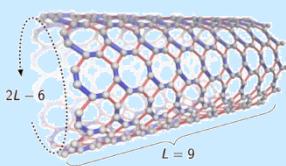
drugs



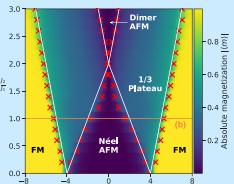
semiconductors



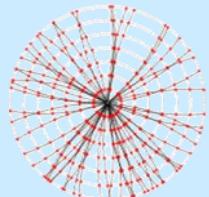
fertilizers production



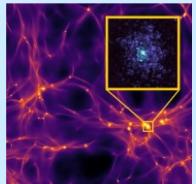
materials design



condensed matter physics

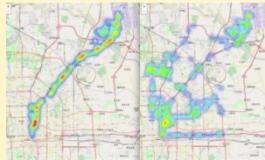


high-energy particle physics

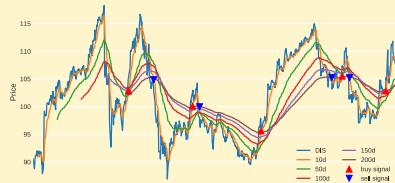


astrophysics

operations



transportation



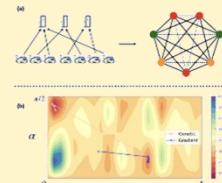
financial services



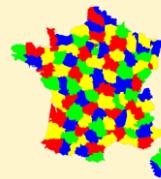
logistics



delivery



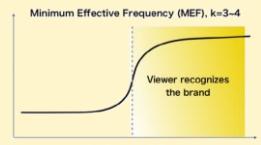
energy utilities



telecoms



manufacturing



marketing

quantum & classical computing paradigms

classical computers

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

analog quantum simulators

optimization problems and quantum physics simulation



digital quantum computers

gate-based

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

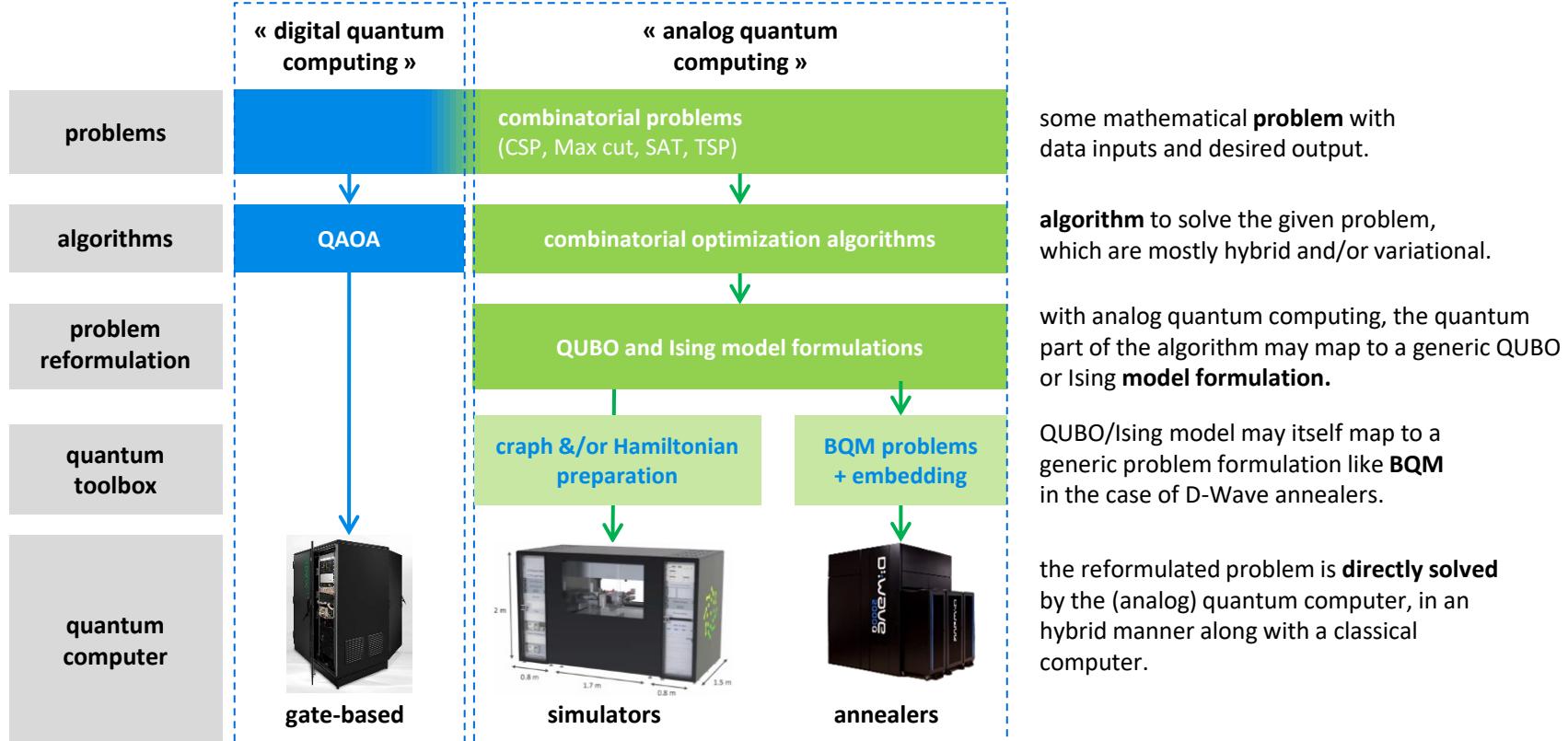
general purpose quantum computing,
adds search and integer factoring



ALICE & BOB

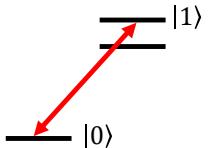


digital vs analog quantum computing



main qubit types

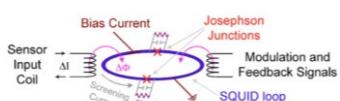
atoms and ions



quantum states

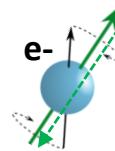
atom energy level

superconducting



loop phase or energy

electron spins



electron spin orientation

photons

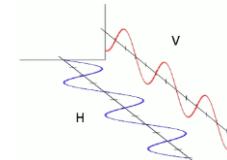
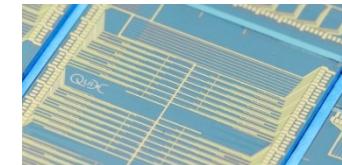
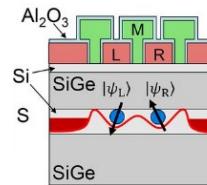
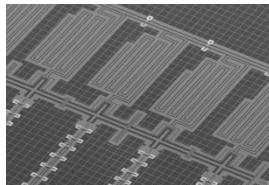
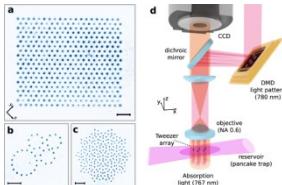


photo polarization (or other property)

physical aspect



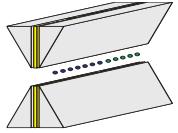
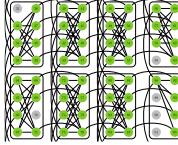
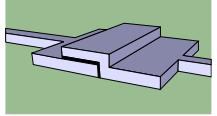
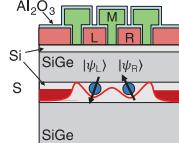
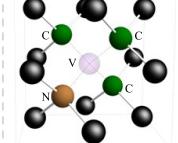
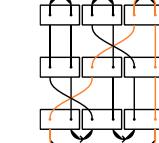
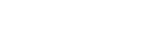
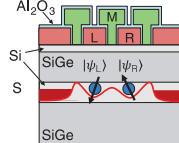
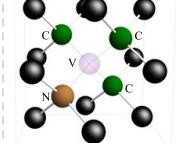
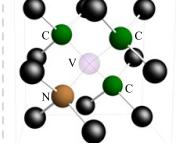
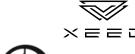
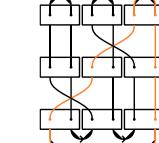
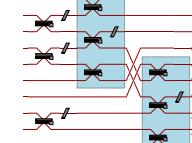
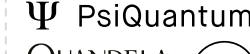
interactions

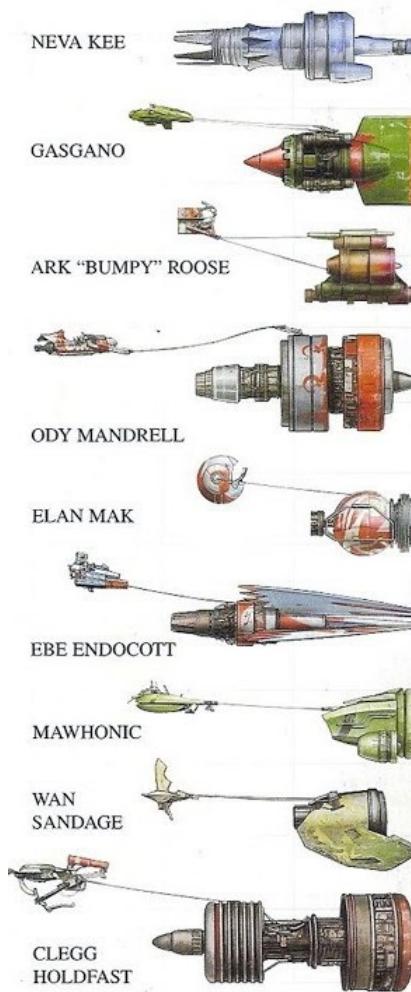
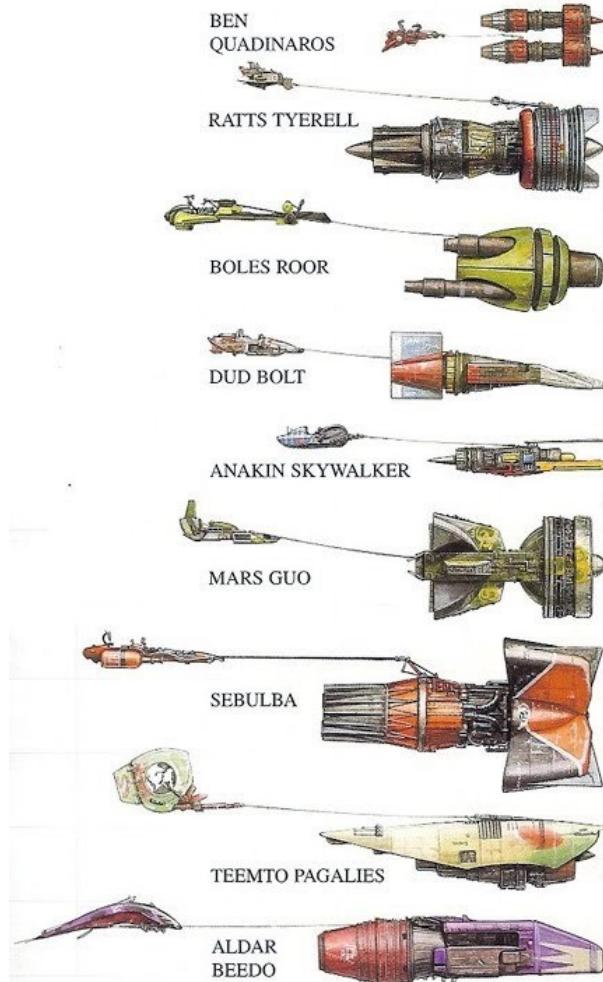
laser pulses and/or microwaves

microwave pulses and/or DC current

interferometers, polarizing beam splitters, ...

QPUs vendors per qubit type

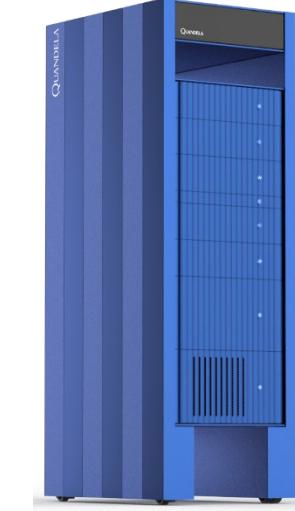
atoms	electron superconducting loops & controlled spin					photons
						
trapped ions	cold atoms	annealing	super-conducting	silicon	vacancies	topological
 QUANTINUUM  IONQ OQAT oxford ionics 	 PASQAL  iQuEra  Infleqtion  atom computing  planqc  QUANTier  NanoQT <small>Nanofiber Quantum Technologies</small>	 D-WAVE <small>The Quantum Computing Company™</small>  rigetti  amazon  Google  qci  Nord Quantique  OQC  IQM  ALICE & BOB  ORIGIN QUANTUM  ANYON  ATLANTIC QUANTUM  bleximo  FUJITSU	 	  QUANTUM BRILLIANCE  SaxonQ  TURING  quantum motion  diraq  EeroQ  equali.labs  C12  ARQUE  Quantum Transistors  π AI  ARCHER	  Microsoft  QUOHERENT  QUANTUM GRAVITY RESEARCH  DUALITY QUANTUM PHOTONICS  BardeenQ LABS  Wboson  QCI photronics  Q QUANFLUENCE  TUNDRA-355 EMSG GBL	  Ψ PsiQuantum  QUANDELA  ORCA COMPUTING  XANADU  QUIX QUANTUM  BardeenQ LABS  Wboson  QCI photronics  Q QUANFLUENCE  TUNDRA-355 EMSG GBL



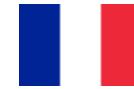
IBM



IONQ



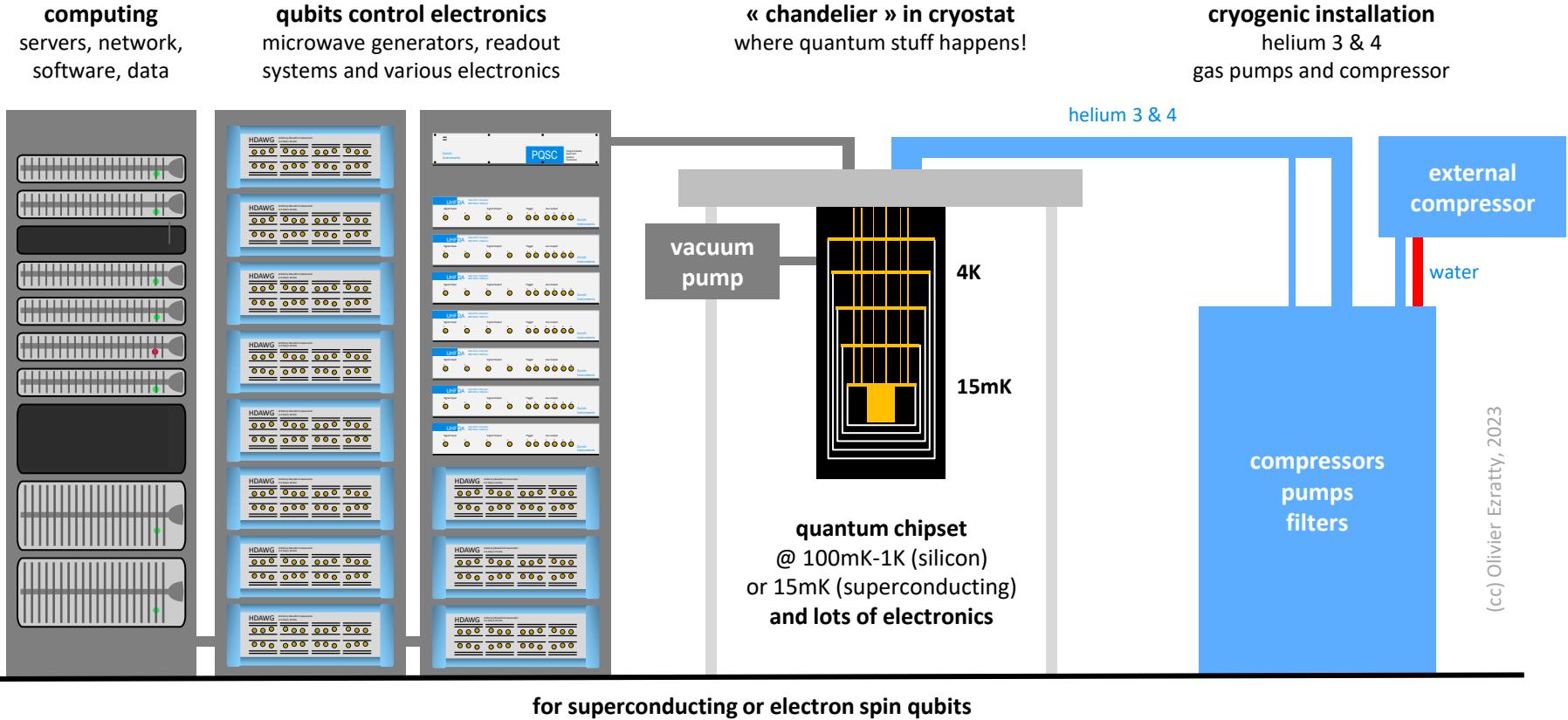
QUANDELA



PASQAL

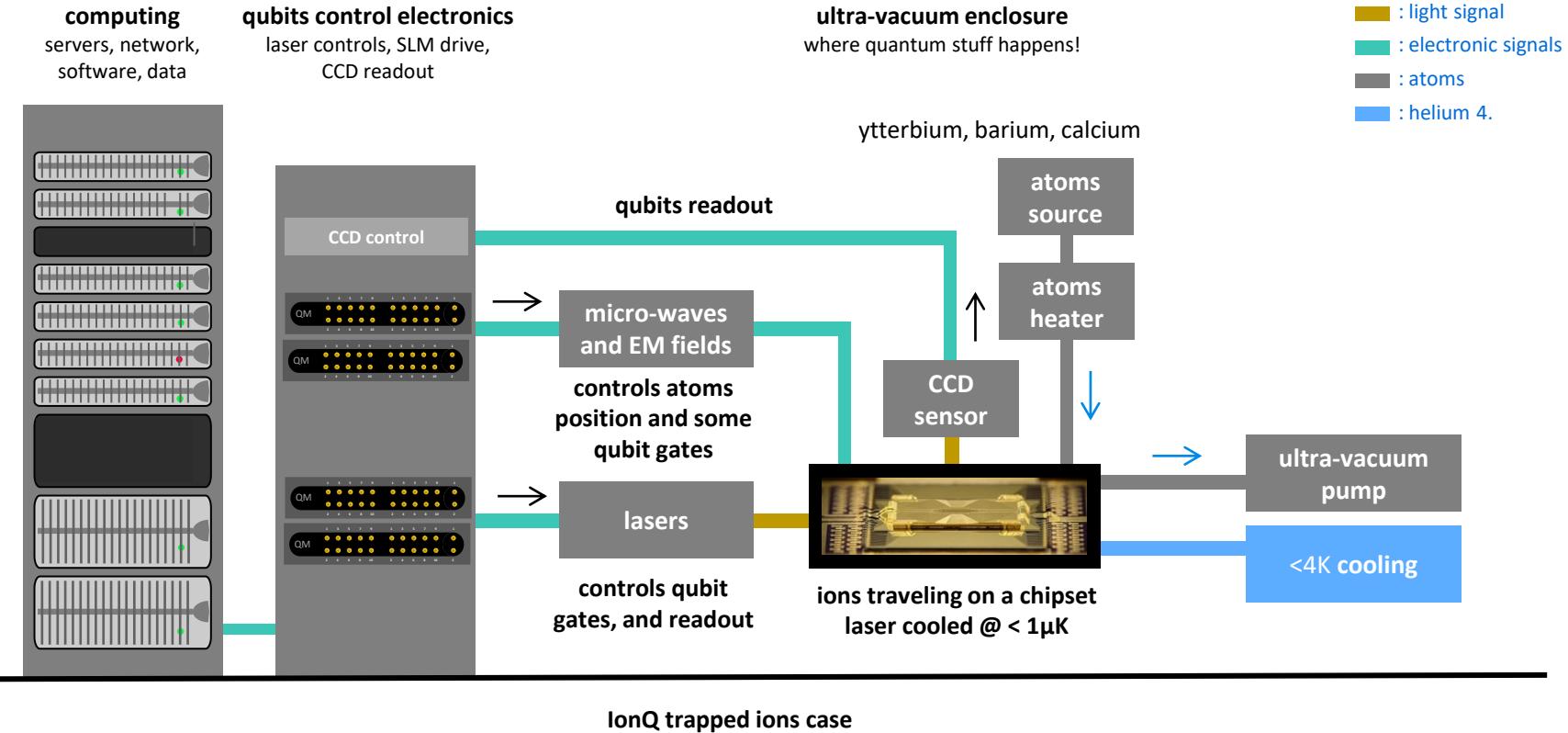


inside a typical quantum computer

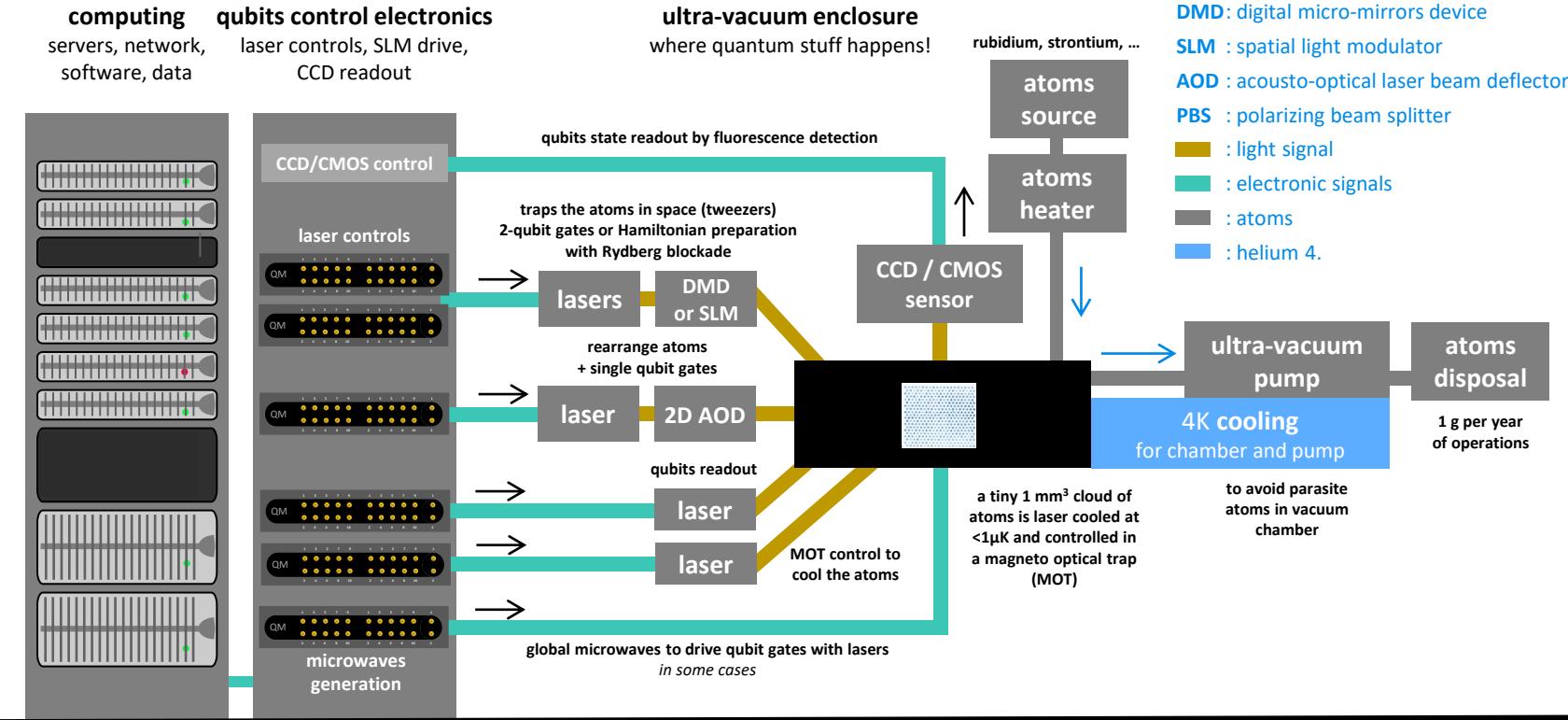


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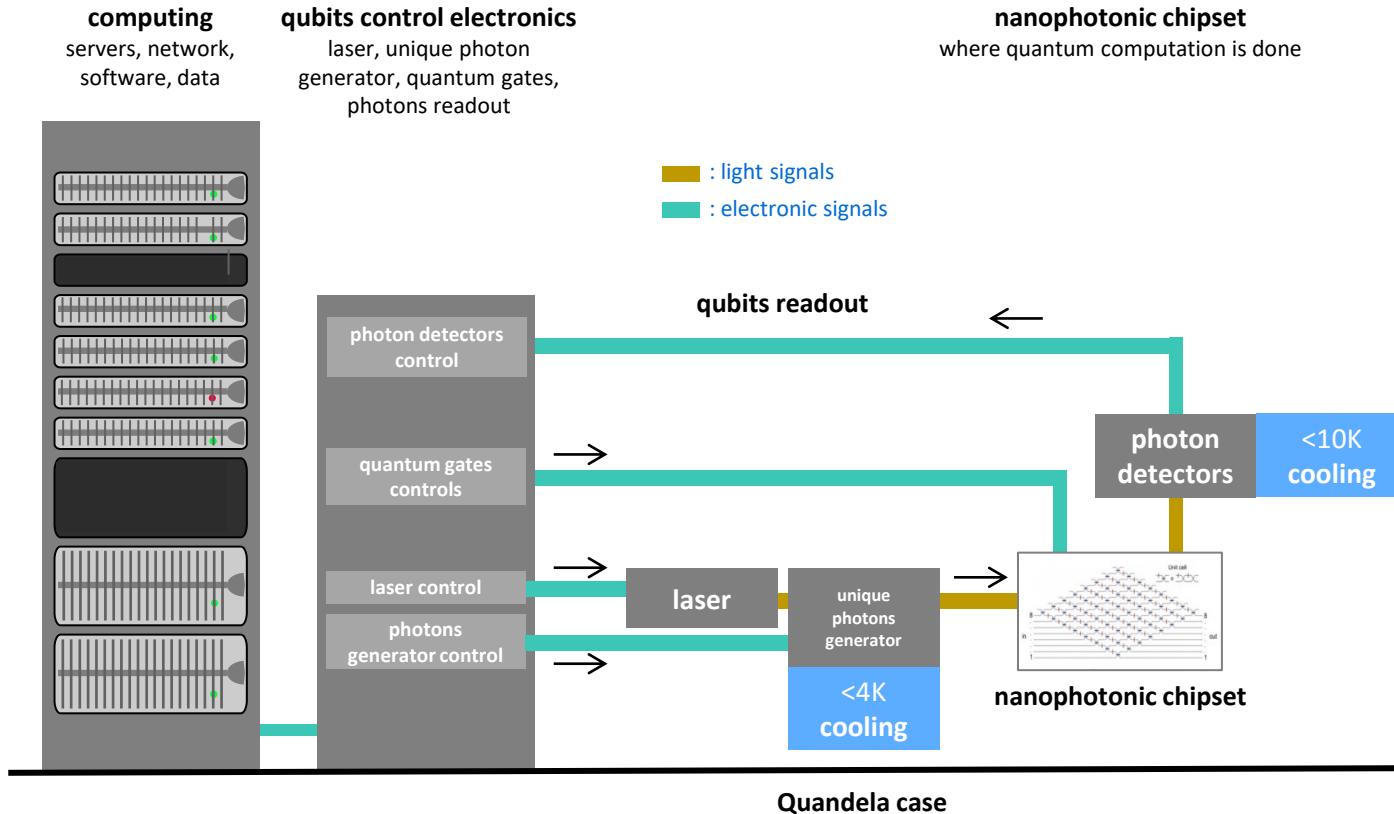
inside a trapped ions QC



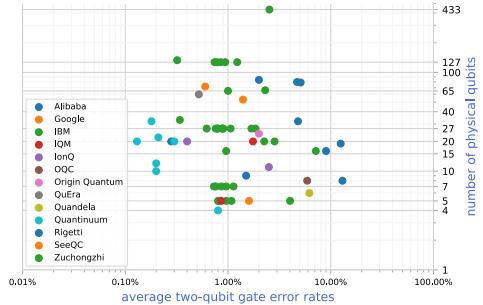
with a neutral atoms quantum computer



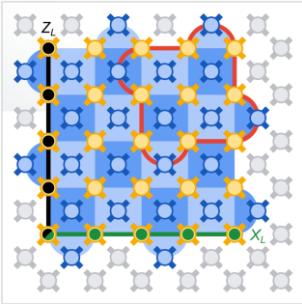
with a photon qubits quantum computer



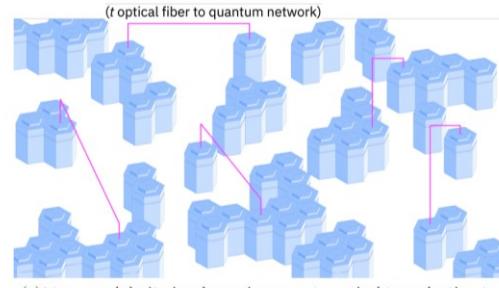
key QPU challenges



qubits fidelities

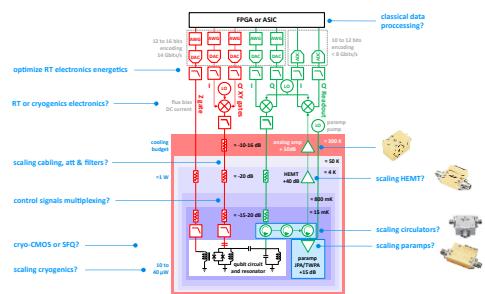


errors mitigation and correction

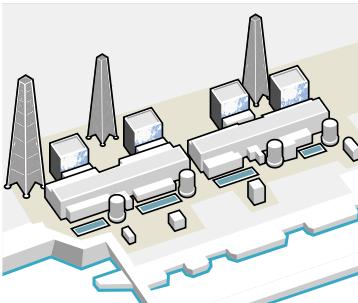


(e) t type modularity involves microwave-to-optical transduction to link QPUs in different dilution refrigerators.

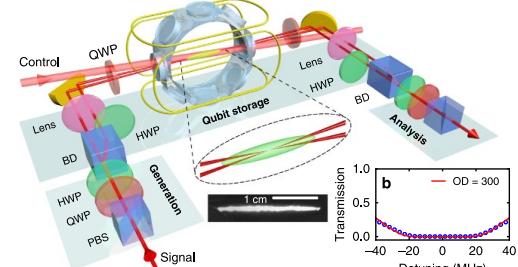
quantum interconnect



enabling technologies scalability

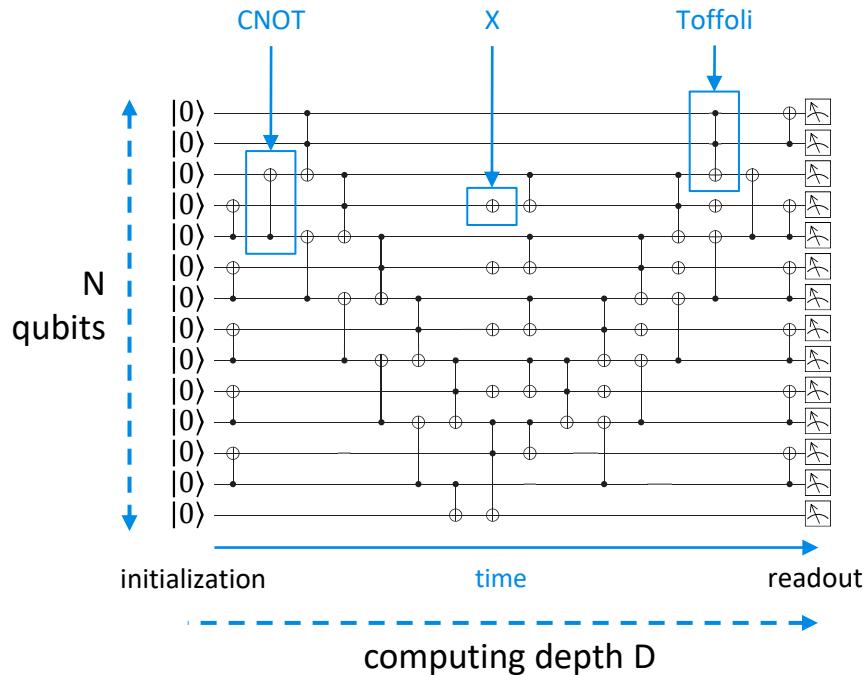


energy consumption



quantum memory

raw algorithm fidelities requirements



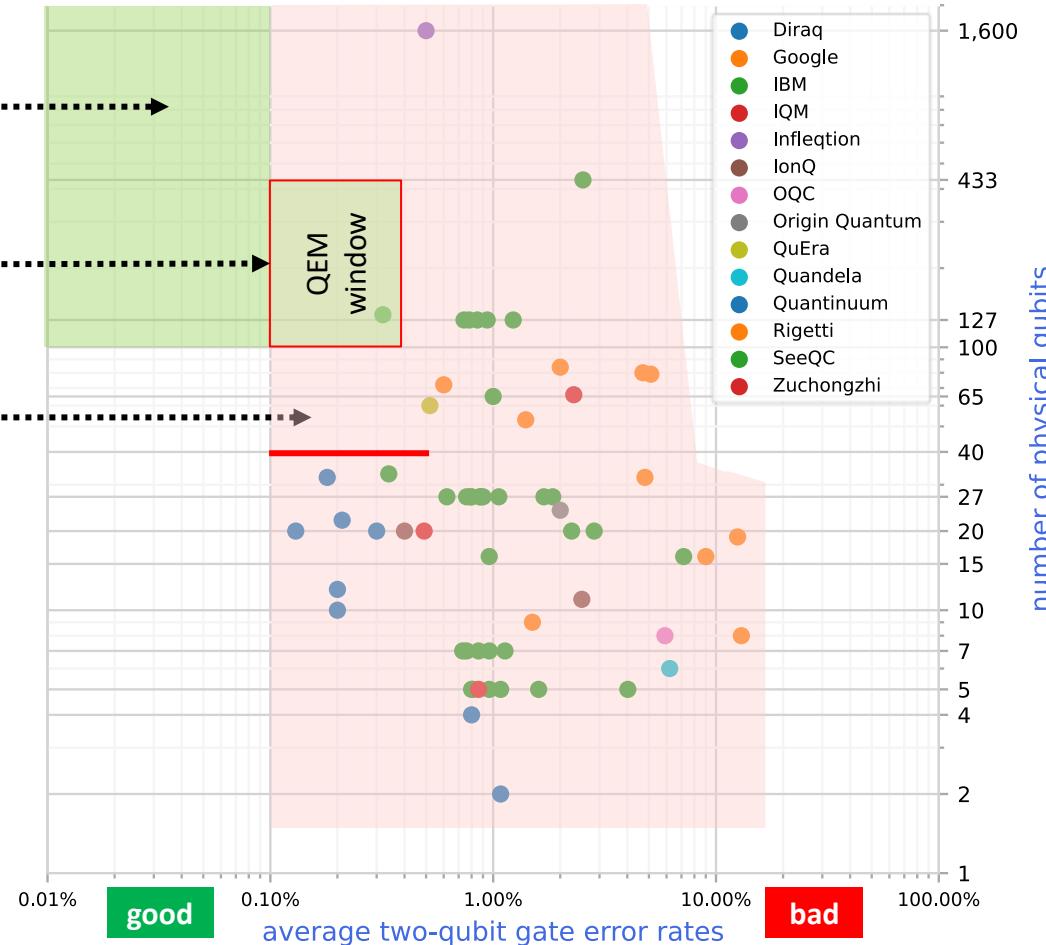
$$\text{desired error rate} < \frac{1}{N \times D}$$

N qubits	D depth	required		available fidelity (%)
		error rate (%)	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

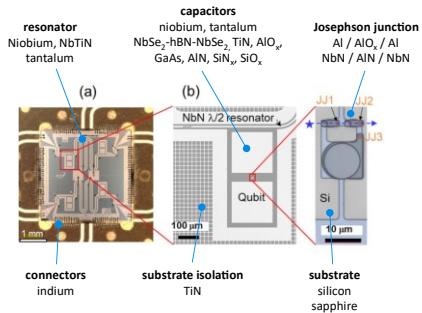
useful NISQ*
requirements
with quantum
error mitigation

state of the art
easy to emulate classically,
too noisy to be useful

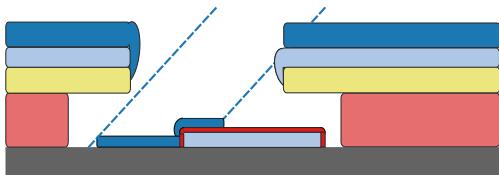


* NISQ = noisy intermediate
scale quantum computers.

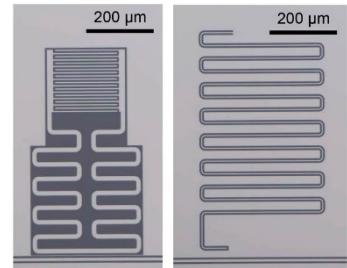
how to improve qubit fidelities? *



materials

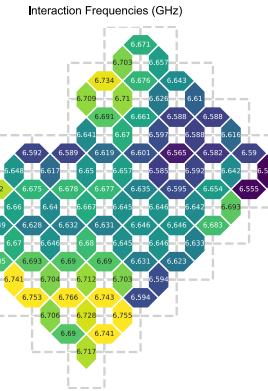


manufacturing



tune qubit parameters

use different primary gates



reduce crosstalk



improve control signals quality

* using here the example of superconducting qubits

logical qubits and FTQC

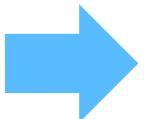
physical qubit

error rates $\approx 0.1\%$

+

error correction code

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

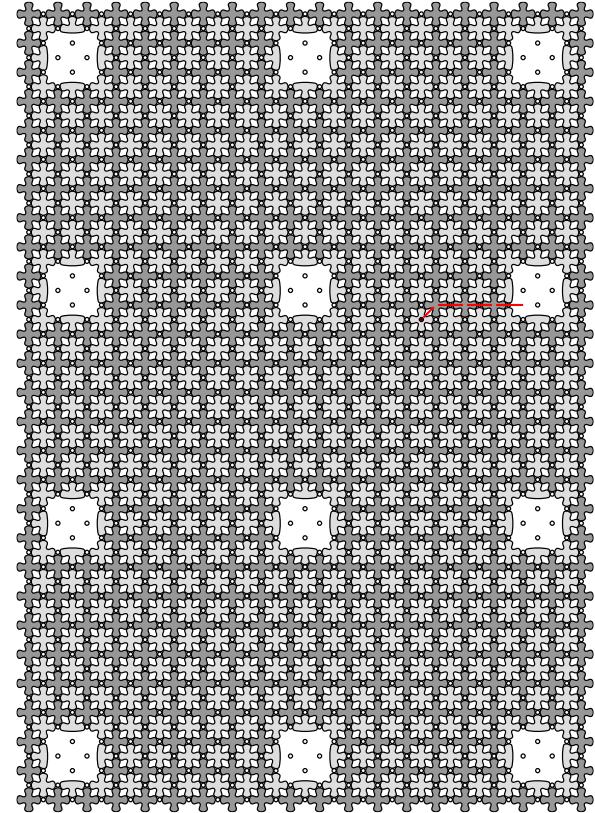


logical qubit

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

fault tolerance

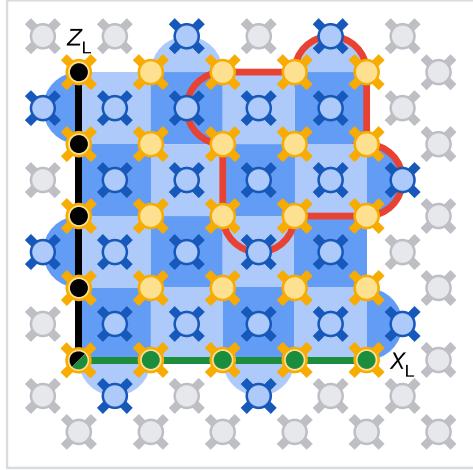
avoid error propagation and amplification
implement a universal gate set
fault-tolerant results readout



tens to thousands qubits

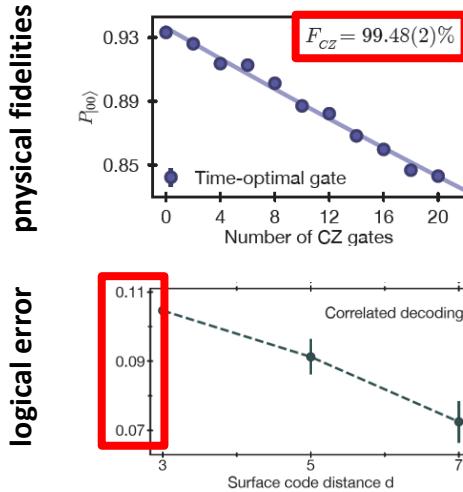
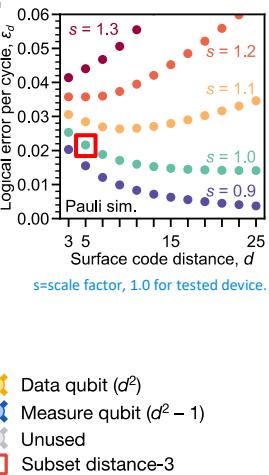
<https://arxiv.org/abs/1202.2639>

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%.

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. Svore¹

¹Microsoft Azure Quantum

²Quantinuum

(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 QCDD 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>

claim: logical qubit with x800 improvement vs physical qubit

reality: x800 improvement only for the first gate cycle!

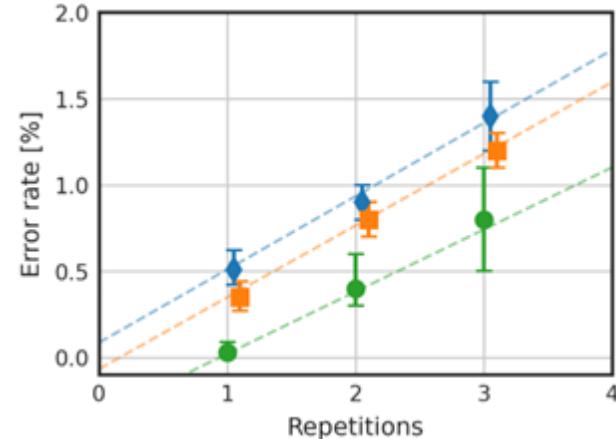


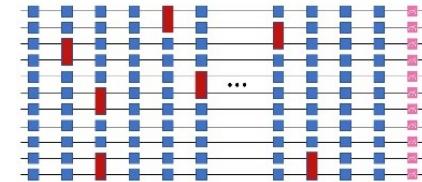
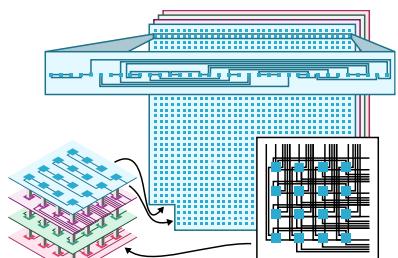
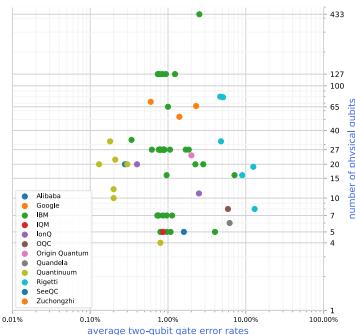
FIG. 7. Observed error rate for circuits with 1 to 3 rounds of error correction with the $[[12, 2, 4]]$ Carbon code (green circles) and physical baselines (blue diamond for pairs of 1-bit teleportations, and orange squares for pairs of CNOTs). Results are offset along the x-axis for clarity. Linear fits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

Craig Gidney's comment on Scott Aaronson's blog

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

qubits for FTQC?

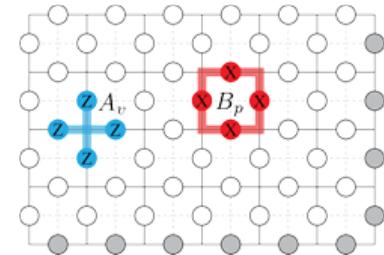
>99.9%



algorithm breadth
and depth

$n_T = \# \text{ of T gates}$
in algorithm

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



error correction
code

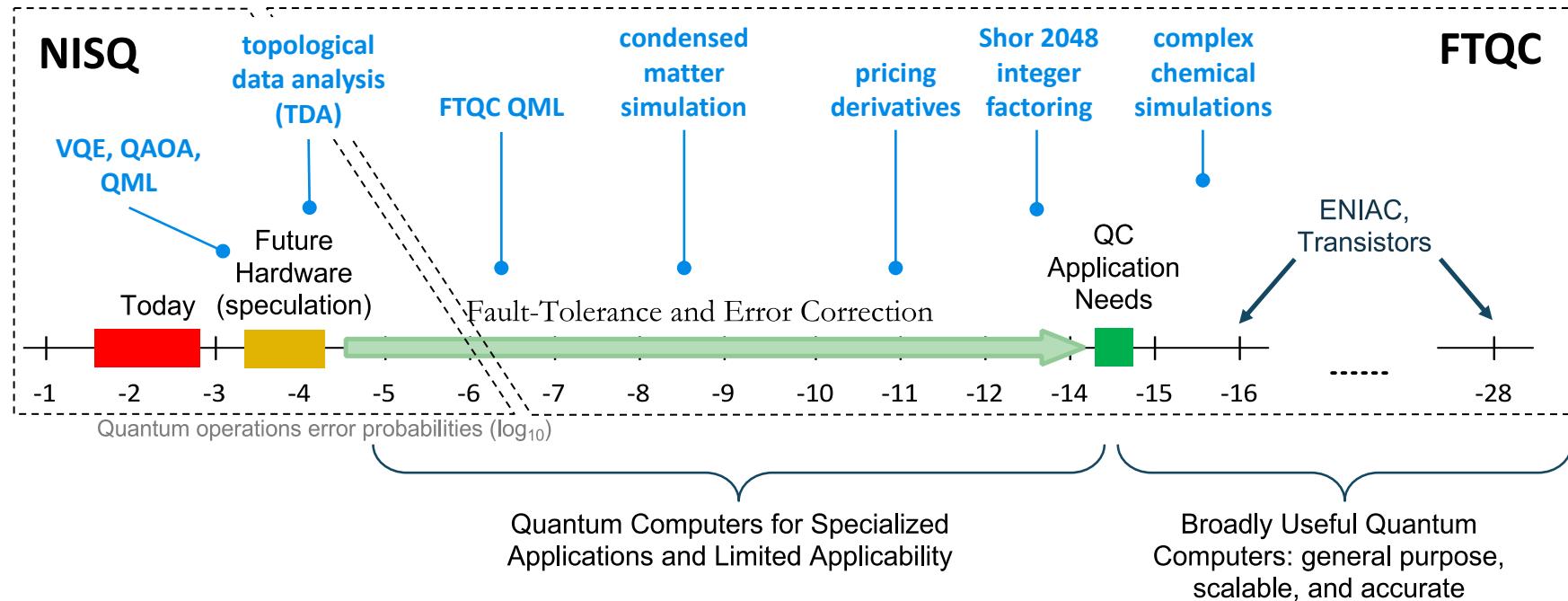
physical qubits
fidelities

physical qubits
connectivity

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

PHYSICAL REVIEW A 106, 032428 (2022)

needs...

6,652 logical qubits

10^{-12} error rate

computing times in months/years

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^{1,2,4}, Norge Cruz-Hernández⁵, Arne-Christian Voigt,⁶, Angus Lowe,¹, Soran Jahangiri¹, M. A. Martin-Delgado^{1,2,7}, Jonathan E. Mueller^{1,6} and Juan Miguel Arrazola^{1,†}

¹Xanadu, Toronto, Ontario, M5G 2C8, Canada

²Departamento de Física Teórica, Universidad Complutense de Madrid, 28040 Madrid, Spain

³Department of Materials Science and Engineering, Northwestern University, Evanston, Illinois 60208, USA

⁴Quasar Science Resources SL, 28231, Las Rozas de Madrid, Spain

⁵Departamento de Física Aplicada I, Escuela Politécnica Superior, Universidad de Sevilla, Seville, E-41011, Spain

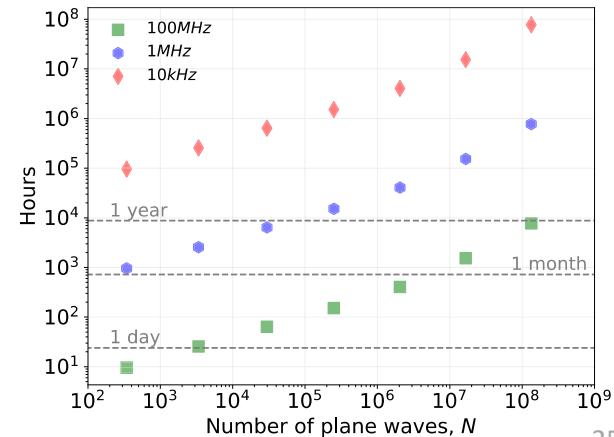
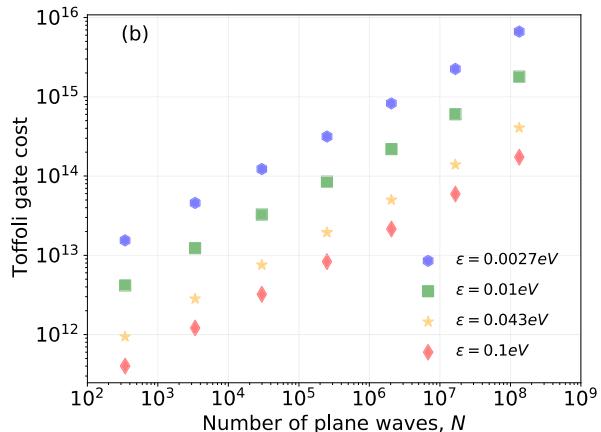
⁶Volkswagen AG, Berliner Ring 2, 38440 Wolfsburg, Germany

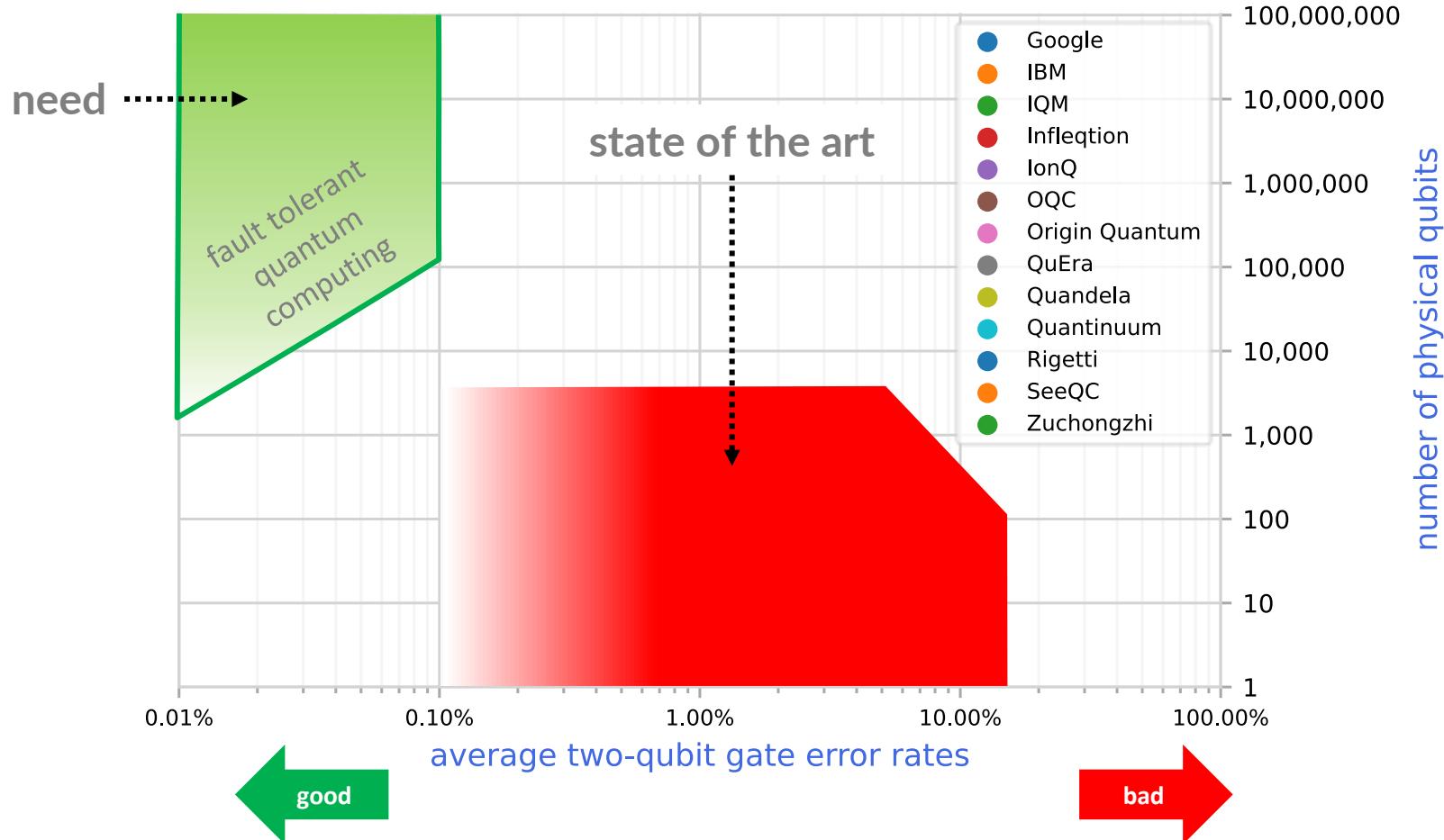
⁷CCS-Center for Computational Simulation, Universidad Politécnica de Madrid, 28040 Madrid, Spain

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



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





some hardware scalability challenges and trade-offs the superconducting qubit case

optimize RT electronics energetics

RT or cryogenics electronics?

scaling cabling, att & filters

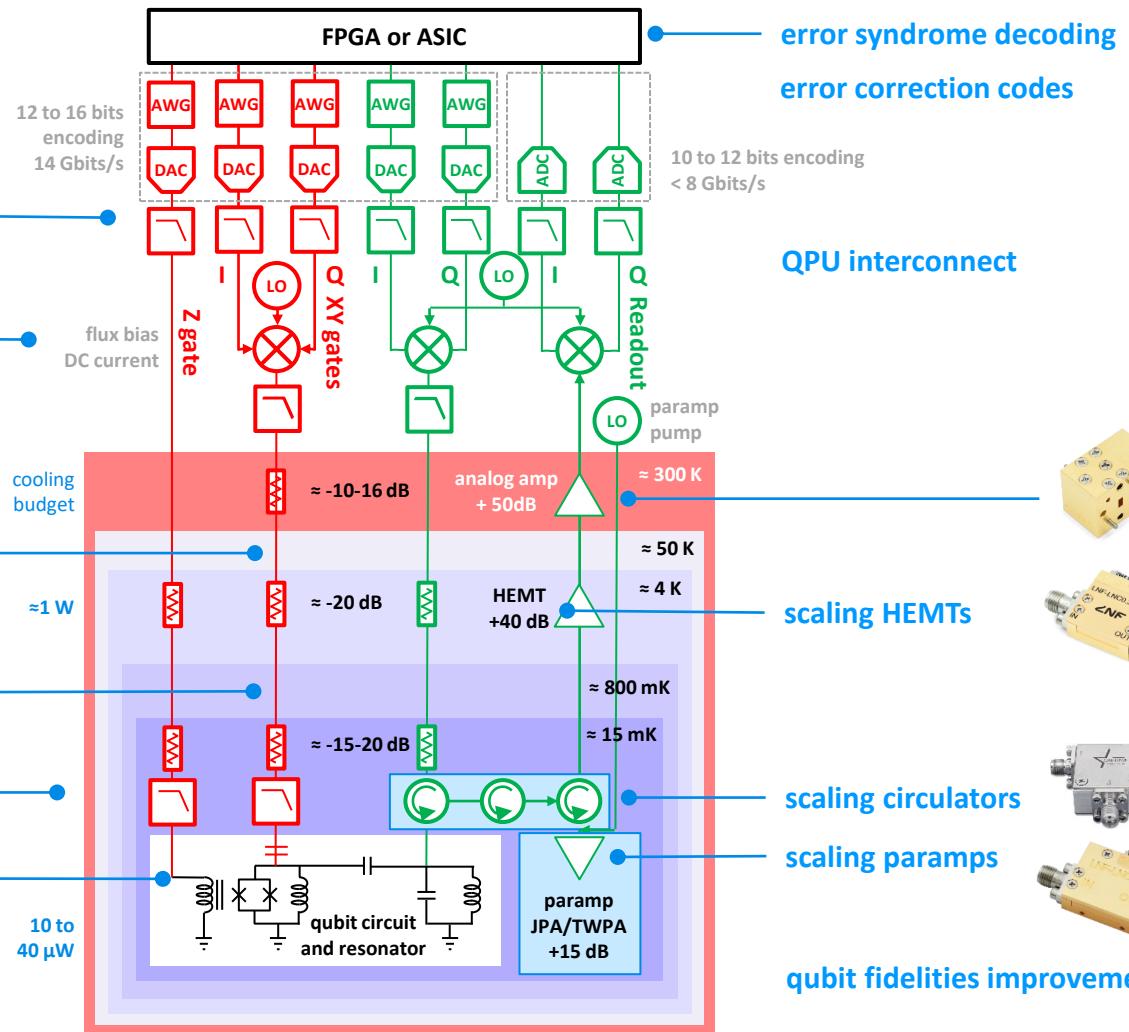
control signals multiplexing

cryo-CMOS or SFQ electronics?

at which temperature?

long range qubit connectivity

scaling cryogenics



Development Roadmap

IBM Quantum

2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
Run quantum circuits on the IBM Quantum Platform	Release multi-dimensional roadmap publicly with initial aim focused on scaling	Enhancing quantum execution speed by 100x with Qiskit Runtime	Bring dynamic circuits to unlock more computations	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving quantum circuit quality to allow 100M gates	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing
Data Scientist					Platform						
Researchers					Code assistant	Patterns	Mapping Collection	Specific Libraries			General purpose QC libraries
Quantum Physicist				Qiskit	Quantum Serverless	Transpiler Service	Resource Management	Circuit Knitting x P	Intelligent Orchestration		Circuit libraries
	IBM Quantum Experience	QASM3	Dynamic circuits	Execution Modes	Heron (5K) Error Mitigation 5k gates 133 qubits Classical modular $133 \times 3 = 399$ qubits	Flamingo (5K) Error Mitigation 5k gates 156 qubits Quantum modular $156 \times 7 = 1092$ qubits	Flamingo (7.5K) Error Mitigation 7.5K gates 156 qubits Quantum modular $156 \times 7 = 1092$ qubits	Flamingo (10K) Error Mitigation 10K gates 156 qubits Quantum modular $156 \times 7 = 1092$ qubits	Flamingo (15K) Error Mitigation 15K gates 156 qubits Quantum modular $156 \times 7 = 1092$ qubits	Starling (100M) Error correction 100M gates 200 qubits Error corrected modularity	Blue Jay (1B) Error correction 1B gates 2000 qubits Error corrected modularity
	Early Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	Falcon Benchmarking 27 qubits	Eagle Benchmarking 127 qubits								

Innovation Roadmap

Software Innovation	IBM Quantum Experience	Qiskit	Application modules	Qiskit Runtime	Serverless	AI enhanced quantum	Resource management	Scalable circuit knitting	Error correction decoder		
Hardware Innovation	Early Canary 5 qubits Albatross 16 qubits	Falcon Demonstrate scaling with I/O routing with bump bonds	Hummingbird Demonstrate scaling with multiplexing readout	Eagle Demonstrate scaling with MLW and TSV	Osprey Enabling scaling with high density signal delivery	Condor Single system scaling and fridge capacity	Flamingo Demonstrate scaling with modular connectors	Kookaburra Demonstrate scaling with nonlocal c-coupler	Cockatoo Demonstrate path to improved quality with logical memory	Starling Demonstrate path to improved quality with logical gates	
 Executed by IBM  On target											
<p>@ 2024 IBM Corporation</p>											



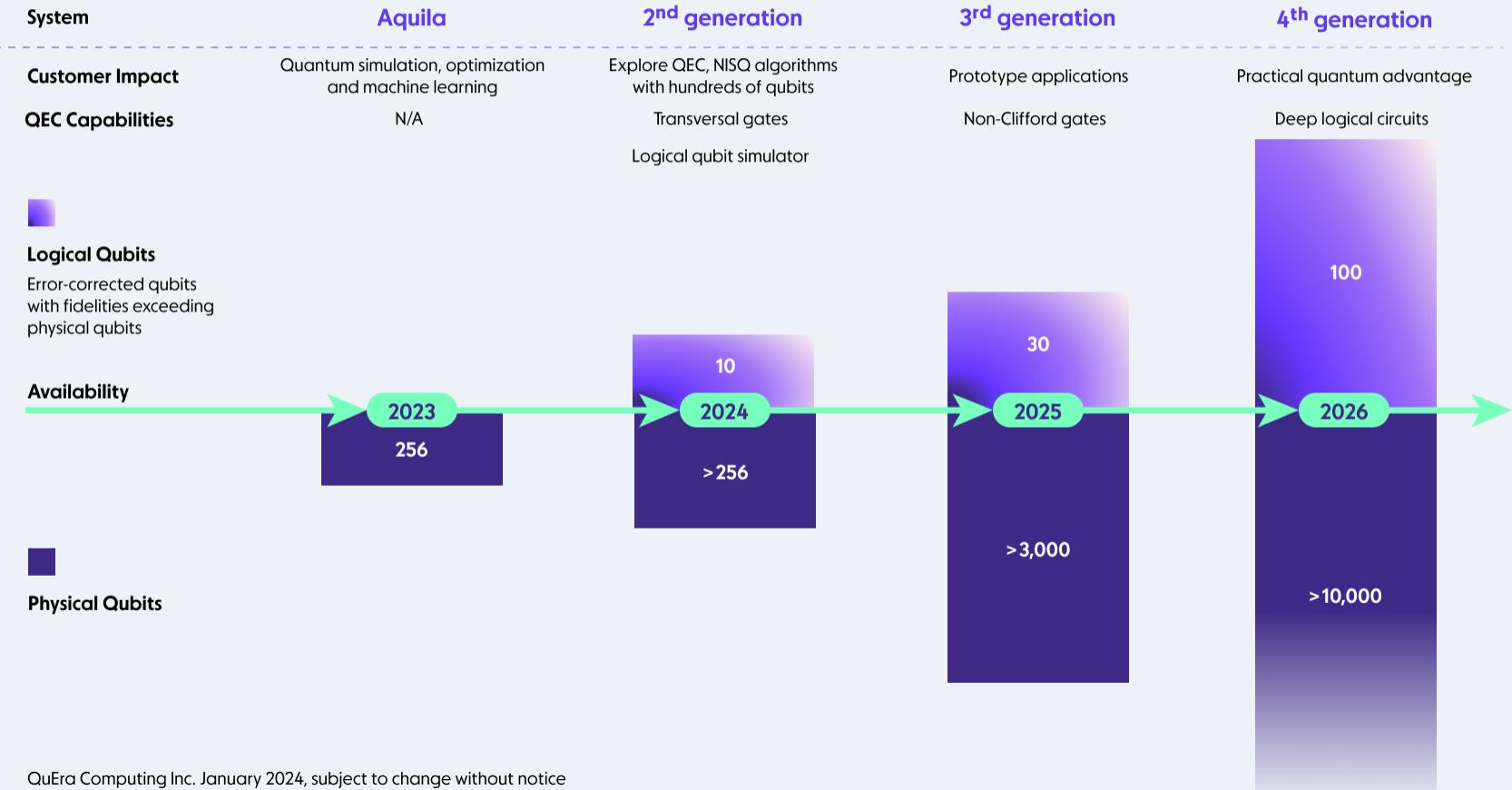
IBM Quantum System 2 with three Heron 133-qubit QPUs

Unlocking True Commercial Advantage

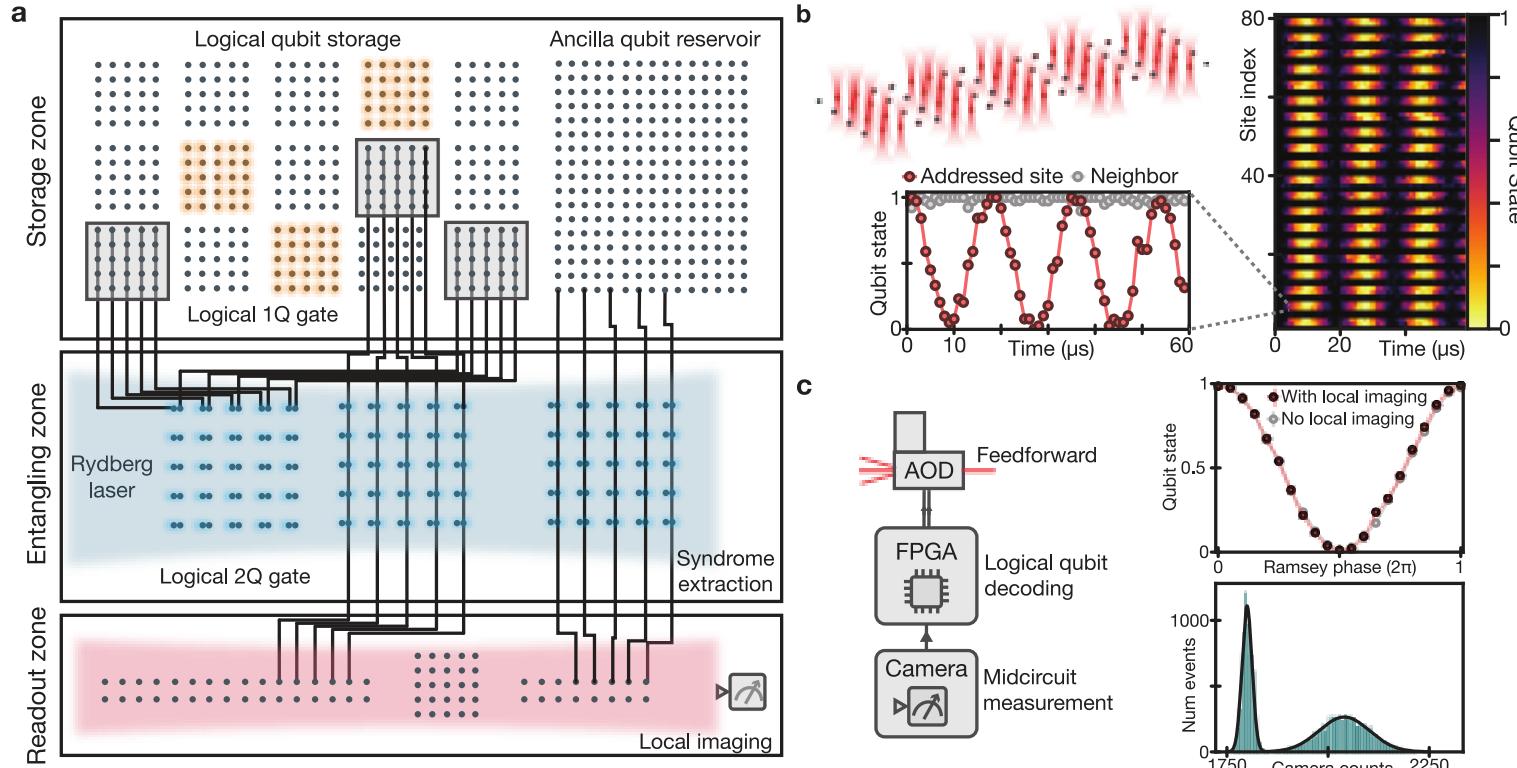
Designing data center ready solutions at scale

	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): Local IQ: Global IQ:	99.50% 99.90% 99.99%	99.90% 99.95% 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

Error-Corrected Quantum Computing Roadmap



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)..

	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

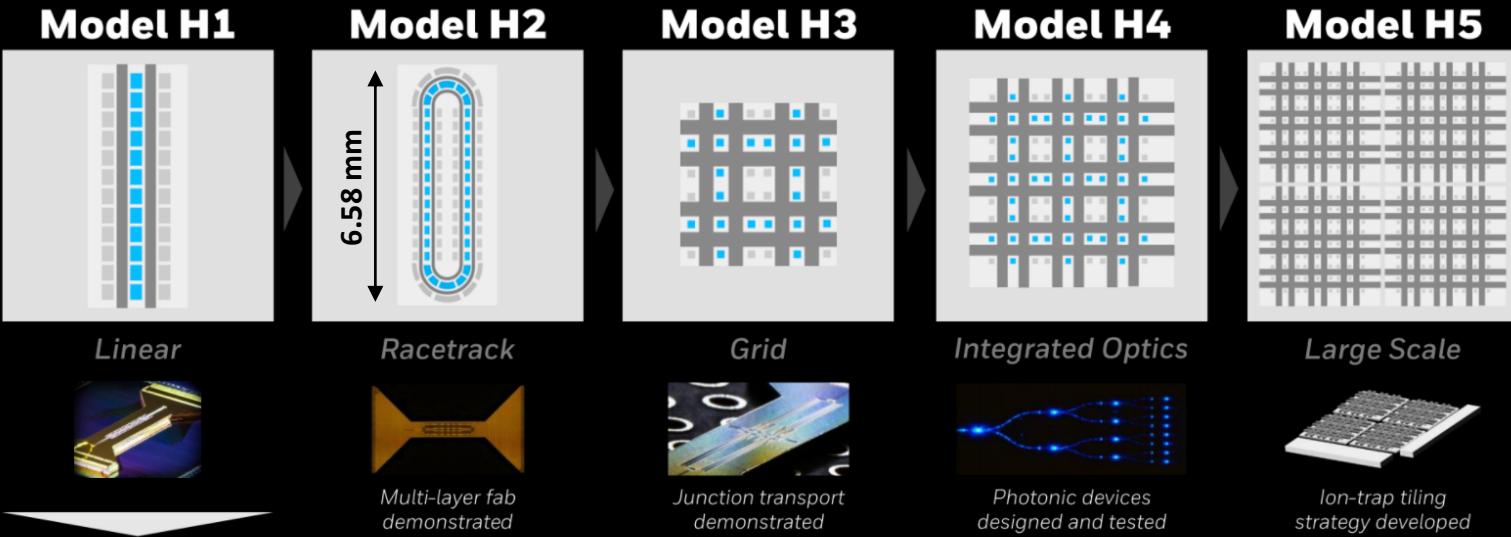
GENERATIONAL ROADMAP

Noisy Intermediate-Scale Quantum (NISQ) Era

2020

2030

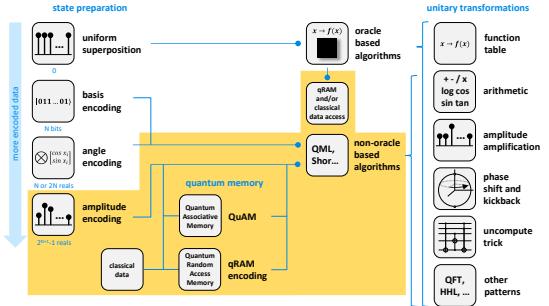
Fault-Tolerant Quantum Computing



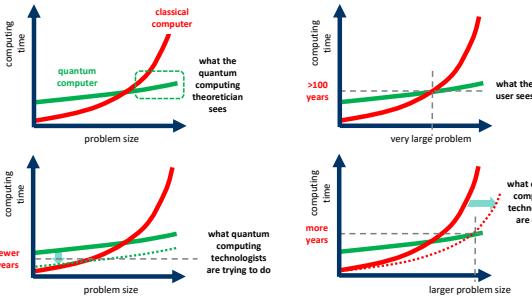
- 10 → 40 Qubits
- 2Q Fidelity: ≥99.5%
- All-to-all connectivity
- Conditional quantum logic
- Mid-circuit measurement
- Qubit reuse

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

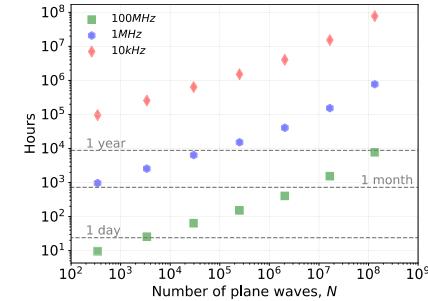
key software challenges



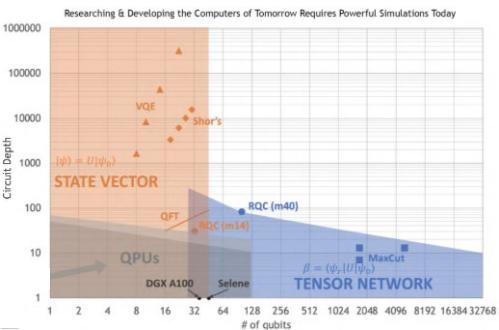
data loading



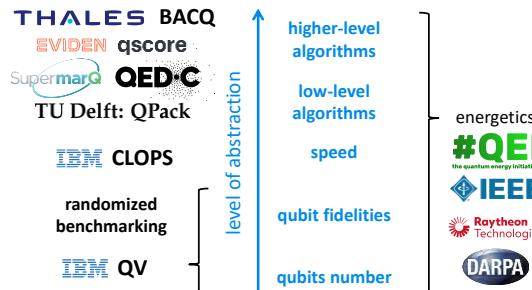
actual speedups



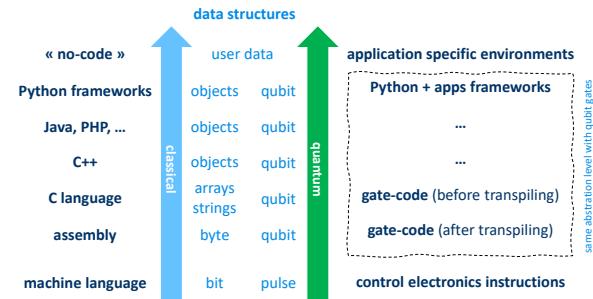
actual computing time



tensor networks competition

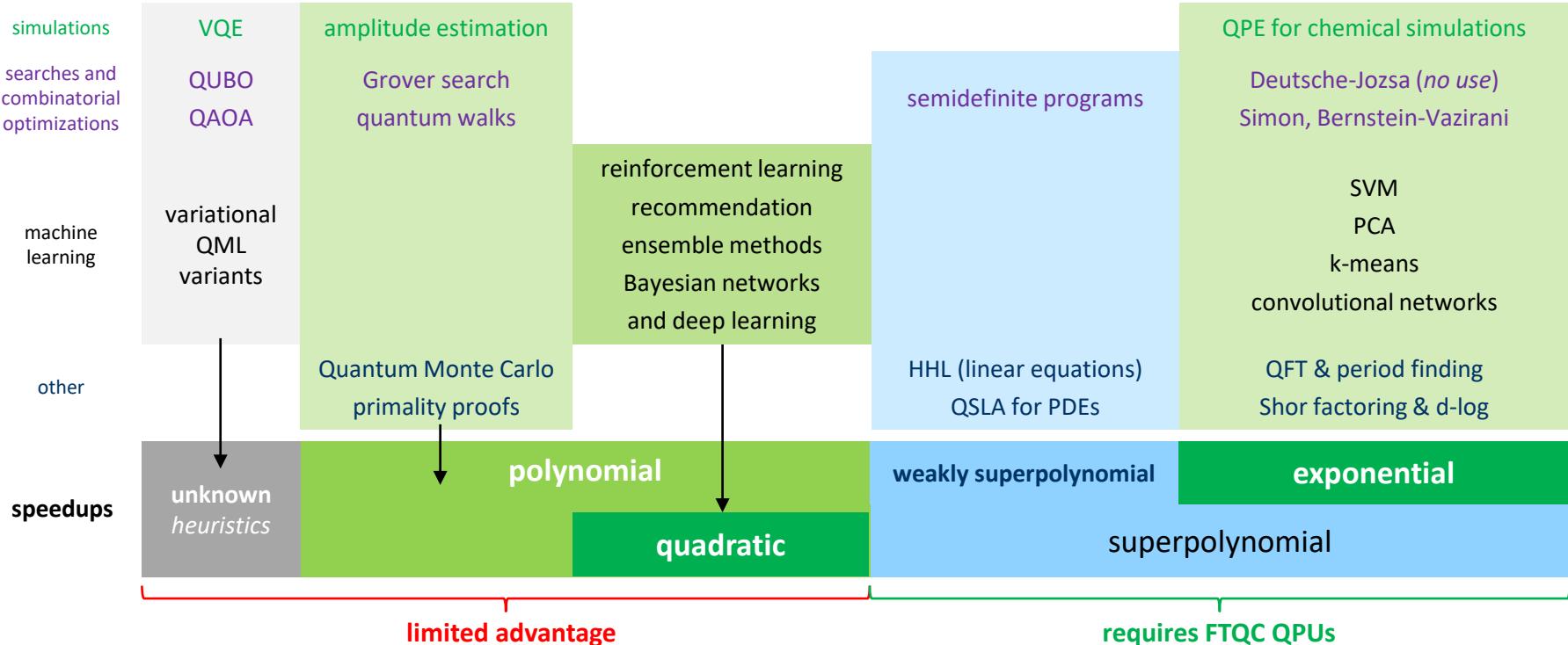


benchmarking



coding abstraction level

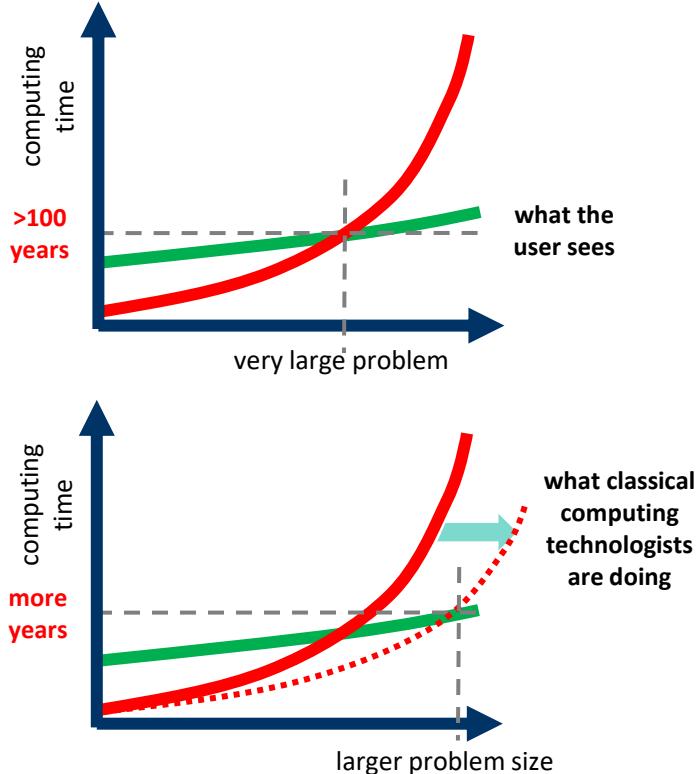
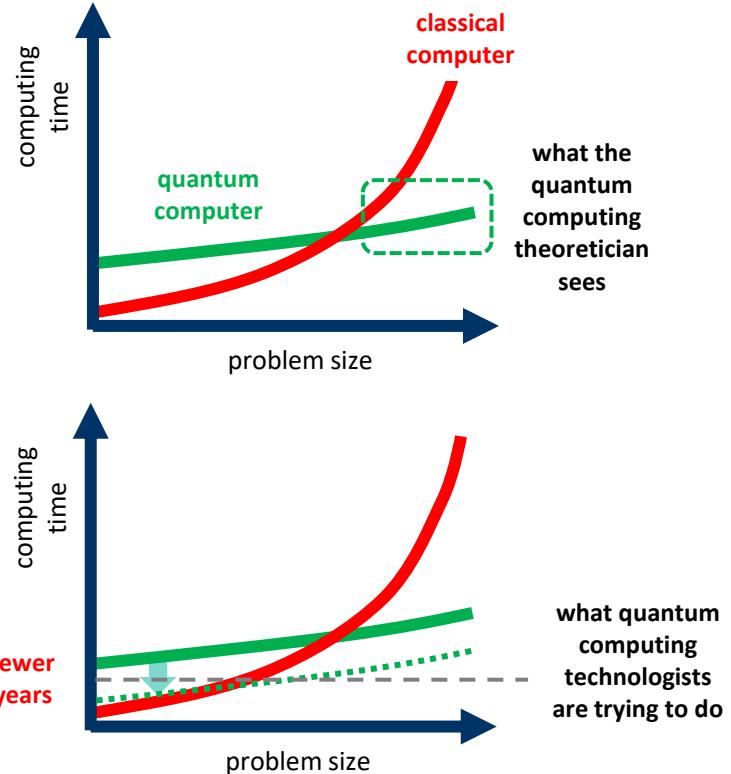
potential quantum speedups



QPU fixed costs make it difficult to exceed classical computing capabilities in reasonable times and problem sizes

and many logical and physical qubits with higher fidelities than today, and preferably monolithic QPUs

a matter of perspective

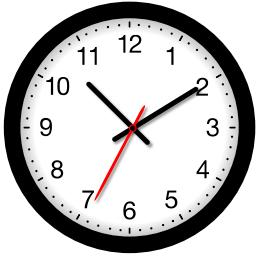


(cc) Olivier Ezratty, 2023; inspired by Disentangling Hype from Practicality: On Realistically Achieving Quantum Advantage by Torsten Hoefler, Thomas Häher, Matthias Troyer, 2023.

quantum advantages taxonomy

complex amplitudes of all combinations of 0 and 1

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

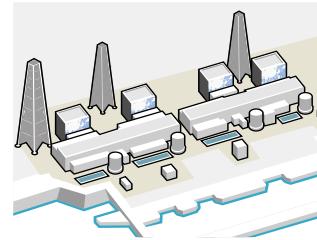
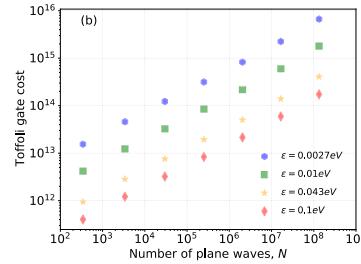


space

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.

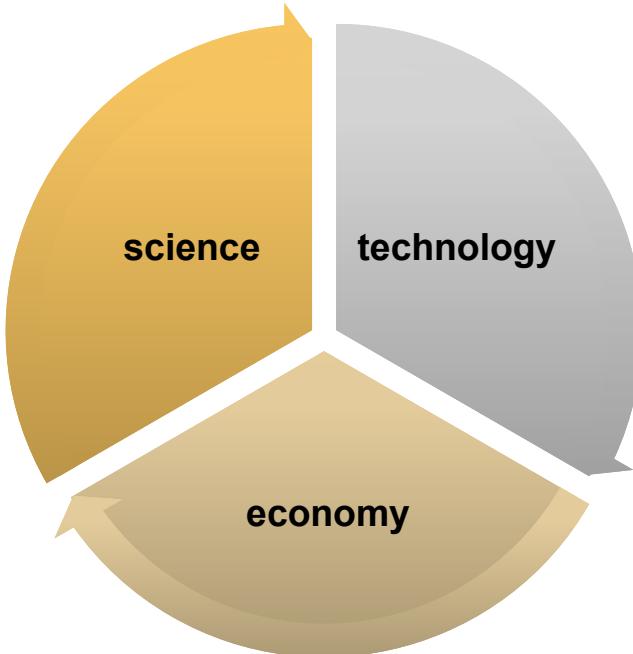
€ \$ £
TCO
ROI

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