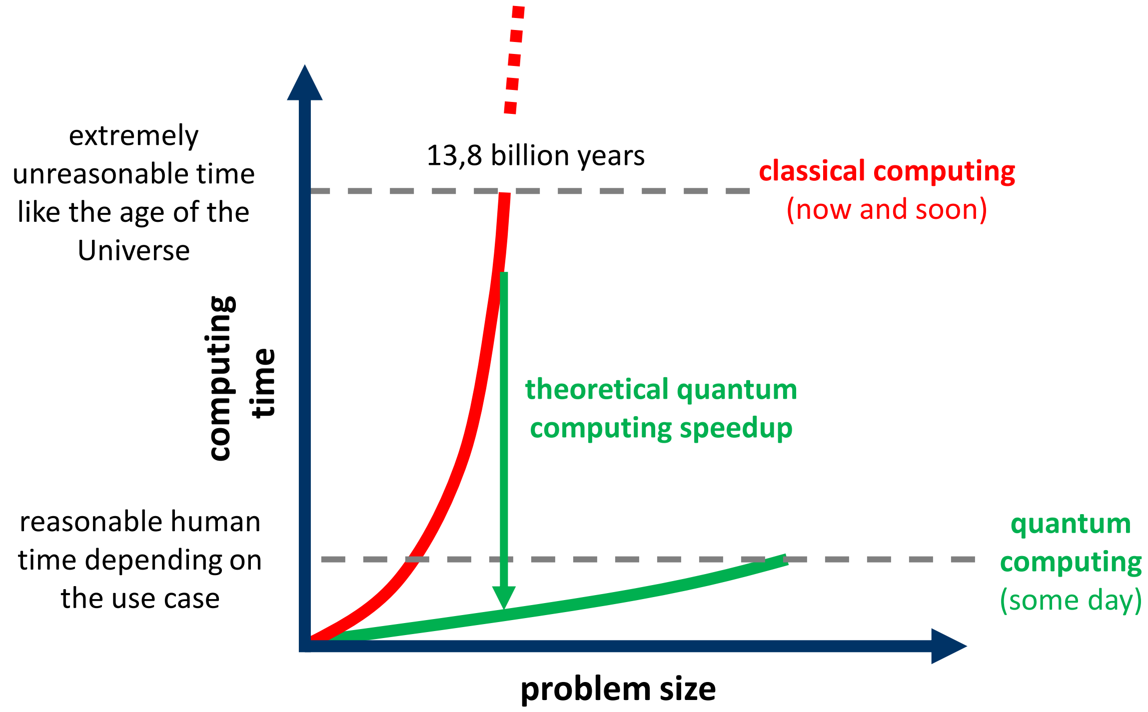
quantum computing
challenges and opportunities

olivier ezratty
olivier@oezratty.net www.oezratty.net

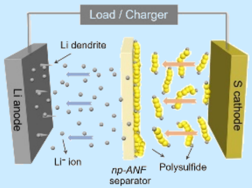
DTU, Kongens Lyngby, December 6th, 2023

the quantum computing promise

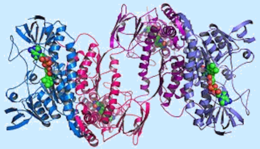


quantum computing use case categories

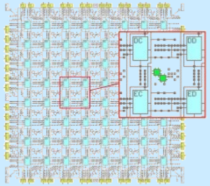
research



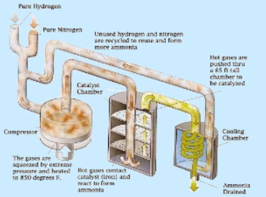
batteries



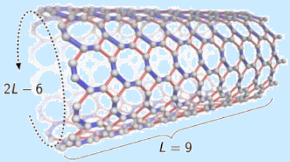
drugs



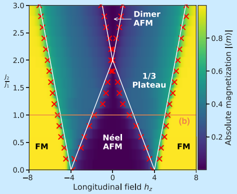
semiconductors



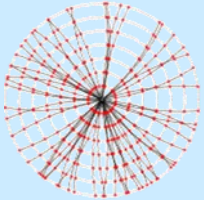
fertilizers production



materials design

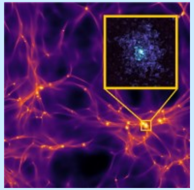


condensed matter physics



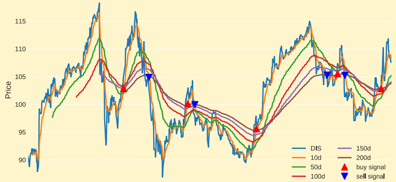
high-energy particle physics

astrophysics



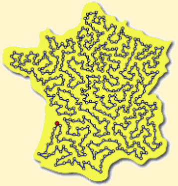
operations

transportation

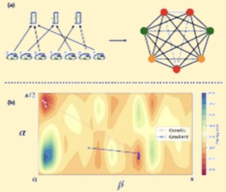


financial services

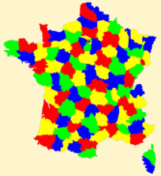
logistics



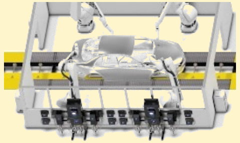
delivery



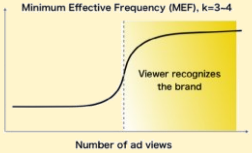
energy utilities



telecoms



manufacturing



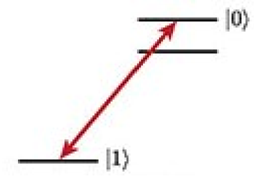
marketing

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	**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	
Microsoft, Multiverse Computing, Zapata AI	Eviden, IBM, Fujitsu, Google, Microsoft, aws	D-Wave The Quantum Computing Company™	Pasqal, QuEra Computing Inc.	IBM, rigetti, PsiQuantum, Google, IQM, Alice & Bob, OQC, Quantinuum, IonQ, Microsoft, Quandela, Xanadu	

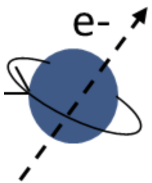
qubit types genealogy

qubit type: collective quantum object
qubit type: individual quantum object



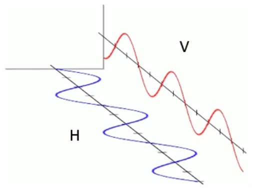
atom control

- **cold atom**
  - **nuclear spins**
  - **Rydberg-Rydberg and ground-Rydberg** (simul), **ground-ground** (gates)
- **trapped ions**
  - **magnetic (Zeeman)** (10s MHz)
  - **hyperfine** (GHz)
  - **Rydberg states**
  - **fine** (10s THz)
  - **optical** (100s THz)
  - **dual ions** for computing and cooling
  - **Penning traps** : electrode controls
  - **Paul traps** : electrodes control
- **nuclear spins (NMR)**



electrons control

- **superconductors**
  - **phase**
  - **flux** — **fluxonium**
  - **charge** — **transmon**
    - **unimon**
    - **coaxmon**
    - **bosonic**
      - **zero-π**
      - **cat-qubits**
      - **GKP codes**
      - **dual rail**
- **topological**
  - **majorana fermions**
- **silicon** + SiGe & GaAs
  - **hole spins**
  - **electron spins**
    - **quantum dots**
    - **carbon nanospheres**
    - **carbon nanotubes**
    - **spin on helium or neon**
  - **orbital spin**
  - **donors and nuclear spin**
- **NV/SiC centers**



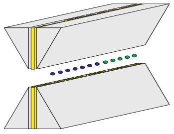
flying qubits

- **photons**
  - **unique photons**
  - **continuous variables**
  - **coherent Ising machines**
    - **cluster states**
      - **MBQC**
      - **FBQC**
    - **non gaussian states**
    - **boson sampling / GBS**
- **flying electrons**

QPUs vendors per qubit type

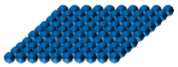
atoms | **electron** *superconducting loops & controlled spin* | **photons**

trapped ions



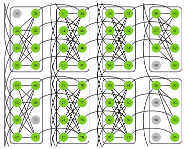
Quantinuum, IONQ, AQT, UQ, oxford ionics, eleQtron, FOXCONN, Quantum Art, CRYSTAL QUANTUM COMPUTING, NEQXT, QUDORA TECHNOLOGIES

cold atoms



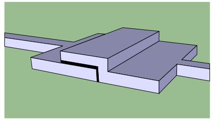
PASQAL, QuEra, Infleqtion, atom computing, planqc, QUANTier, NanoQT Nanofiber Quantum Technologies

annealing



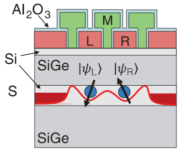
D-Wave The Quantum Computing Company™, QILIMANJARO QUANTUM TECH, NEC

super-conducting



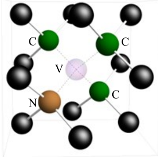
IBM, rigetti, amazon, Google, qci, Nord Quantique, OQC, IQM, ALICE & BOB, Alibaba, Baidu 百度, 本源量子 ORIGIN QUANTUM, ANYON, ATLANTIC QUANTUM, bleximo, FUJITSU

silicon



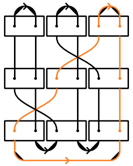
intel, quobly, QUANTUM MOTION, Silicon Quantum Computing, diraq, EeroQ, SemiQon, equal1.labs, C12, ARQUE, QπAI, ARCHER

vacancies



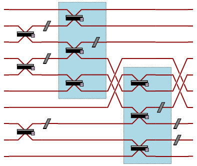
QUANTUM BRILLIANCE, SaxonQ, TURING, photonic, NTT, XEED, Quantum Transistors

topological



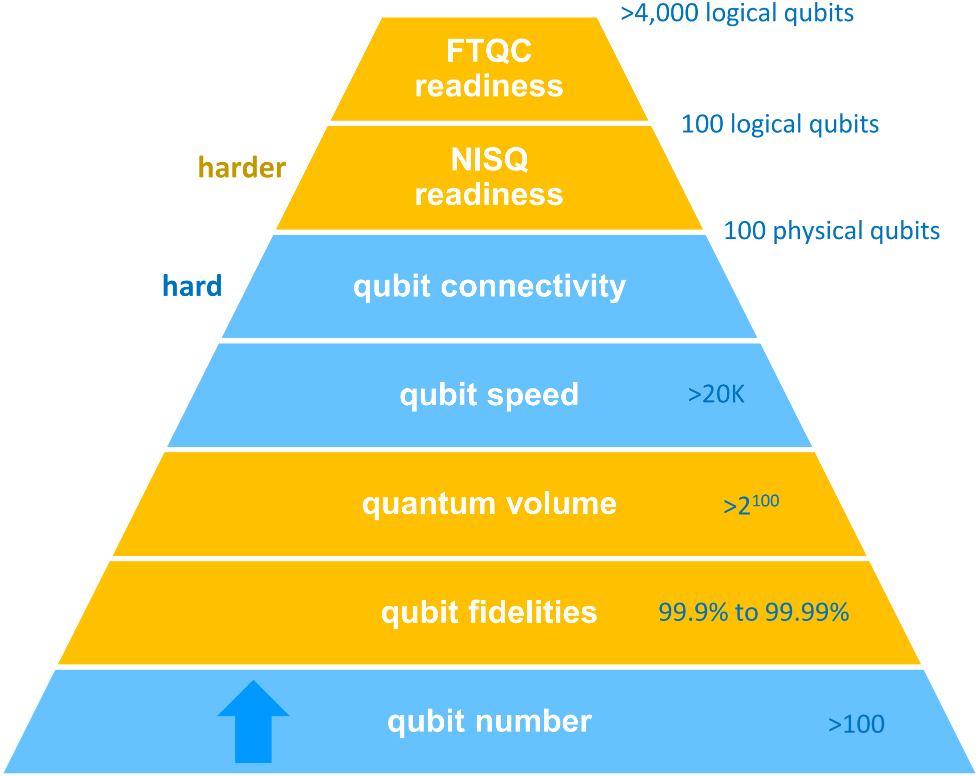
Microsoft, QUOHERENT, QUANTUM GRAVITY RESEARCH

photons



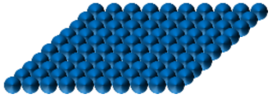
PsiQuantum, QUANDELA, ORCA COMPUTING, XANADU, DUALITY QUANTUM PHOTONICS, QUIX QUANTUM, BardeenQ LABS, Boson, QCi, photonicsQ, QUANFLUENCE, TUNDRA

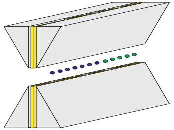
qubit Maslow pyramid

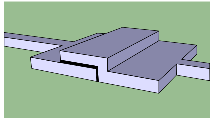


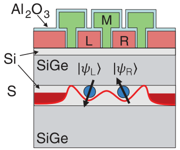
- **level 7** — requires a lot of qubits with fidelities >99.9%
- **level 6** — requires >100 qubits with excellent fidelities > 99.99%
- **level 5** — conditions algorithm depth and quantum error correction overhead
- **level 4** — conditions computing time
- **level 3** — combines qubit number, fidelities and ability to execute algorithms
- **level 2** — needed to execute deep algorithms and/or enable quantum error correction
- **level 1** — conditions the speed up, computing space and potential quantum advantage

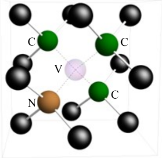
NISQ: noisy intermediate scale quantum
FTQC: fault-tolerant quantum computing

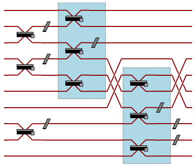












	atoms		**electrons** superconducting & spins			**photons**
	cold atoms	**trapped ions**	**superconducting**	**silicon**	**NV centers**	**photons**
qubit size	about 1 µm space between atoms	about 1 µm space between atoms	$(100\mu)^2$	$(100nm)^2$	$<(100nm)^2$	nanophotonics waveguides lengths, MZI, PBS, etc
best two qubits gates fidelities	99.5%	99.94%	99.68% (IBM Egret 33 qubits)	>99% (SiGe)	99.2%	98%
best readout fidelity	95%	99.99%	99.4%	99% (SiGe)	98%	50%
best gate time	≈1 ns	0.1 to 4 µs	20 ns to 300 ns	≈5 µs	10-700 ns	<1 ns
best T_1	> 1 s	0,2s-10mn	100-400µs	20-120µs	2.4 ms	∞ & time of flight
qubits temperature	< 1mK 4K for vacuum pump	<1mK 4K cryostat	15mK dilution cryostat	100mK-1K dilution cryostat	4K to RT	RT 4K-10K cryostats for photons gen. & det.
operational qubits	1,180 (Atom Computing)	32 (IonQ and Quantinuum)	433 (IBM) 176 (China)	12 (Intel) in SiGe	5 (Quantum Brilliance)-10	216 modes GBS (Xanadu)
scalability	up to 10,000	<100	1000s	millions	100s	100s-1M

these are the best figures of merit, but it doesn't mean a single system in a column has them all!

all qubit types have their challenges

quantum annealing

- mature **development tools** offering.
- large number of **software startups**, particularly in Japan and Canada.
- quantum annealers are available in the **cloud** by D-Wave and Amazon Web Services.
- the greatest number of well documented **case studies** in many industries although still at the proof of concept stage.
- most universal qubits gates algorithms can be have an equivalent on quantum annealing.

- **all algorithms are hybrid**, requiring some preparation on classical computers.
- only **one operational commercial vendor**, D-Wave.
- computing **high error rate.**
- **most commercial applications** are still at the pilot stage and not production-grade scale, but they are closer than gate-based use cases.
- no **generic operational proof** of quantum advantage.

superconducting qubits

- **key technology** in public research and with commercial vendors (IBM, Google, Rigetti, Intel, Amazon, OQC, IQM, etc).
- **record of 433 programmable qubits** with IBM.
- constant progress in **noise reduction**, particularly with the cat-qubits variation which could enable a record low ratio of physical/logical qubits.
- many existing **enabling technologies**: cryostats, cabling, amplifiers, logic, sensors.
- **potentially scalable technology** and deployable in 2D geometries.

- **qubit coherence time usually < 300 µs.**
- **cryogeny constrained technology at <15 mK.**
- **heterogeneous qubits requiring calibration and complex micro-wave frequency maps.**
- **qubit coupling limited to neighbor qubits in 2D structures (as compared with trapped ions).**
- **cabling complexity and many passive and active electronic components to control qubits with micro-waves.**
- **qubits size and uneasy miniaturization.**
- **qubit fidelities are average with most vendors.**

silicon spin qubits

- **good scalability potential** to reach millions of qubits, thanks to their size of 100x100 nm.
- **works at around 100 mK - 1K** => larger cooling budget for control electronics vs superconducting qubits.
- **relatively good qubits fidelity** reaching 99.6% for two qubits gates in labs for a small number of qubits.
- adapted to **2D architectures** usable with surface codes or color codes QEC.
- can leverage existing semiconductor **fabs**.
- good quantum **gates speed**.

- **active research in the field started later than with other qubit technologies and spread over several technologies** (full Si, SiGe, atom spin donors).
- **less funded startup scene.**
- **qubits variability to confirm.**
- **high fabs costs and long test cycles** (18 months average).
- **so far, only 4 to 15 entangled qubits (QuTech, UNSW, Princeton, University of Tokyo).**
- **scalability remains to be demonstrated.**

qubits NV centers

- **works at 4K**, with simple cryogeny without dilution and helium 3.
- can also potentially work at **ambiant temperature**, with some limitations on entanglement.
- long **coherence time** > 1 ms.
- **strong and stable diamond structure.**
- can also help create **quantum memory** for other qubits types, like superconducting qubits.
- possible to integrate it with **optical quantum telecommunications**.

- **room–temperature operations need some fact-check.**
- **not demonstrated at scale so far.**
- **qubits controls complexity with lasers and microwaves => not easy to scale.**
- **NV centers applications are more centered on quantum magnetometry and sensing than computing.**
- **high-complexity of NV centers circuits manufacturing.**

trapped ions qubits

- **identical ions** => no calibration required like with superconducting/electron spin qubits.
- **good qubits stability.**
- **excellent qubit gate fidelities** and high ratio between coherence time and gate time => supports deep algorihms in number of gate cycles.
- **entanglement** possible between all qubits on 1D architecture which speeds up computing, avoiding SWAP gates.
- requires some cryogeny at **4K to 10K** => simpler.
- **easy to entangle ions with photons** for long distance communications.

- **unproven scalability options beyond 50 qubits** (ions shuttling, 2D architectures, photon interconnect, micro-Penning traps).
- **two-qubit gate times increasing with ion distance in 1D and 2D settings.**
- **relatively slow computing due to long quantum gate times which may be problematic for deep algorithms.**

neutral atoms qubits

- long qubit **coherence time and fast gates**.
- **operational systems** with 100-300 atoms.
- **identical atoms**, that are controlled with the same laser and micro-wave frequencies (but dual-elements architectures are investigated).
- works in both **simulation** and **gate-based** paradigms.
- no need for specific **integrated circuits**.
- uses **standard apparatus**.
- low **energy consumption**.

- **adapted to quantum simulations more than to universal gates computing.**
- **crosstalk between qubits that can be mitigated with two-elements atom architectures.**
- **not yet operational QND (quantum non demolition) measurement that is required for QEC and FTQC.**
- **slow operations (1 Hz simulation cycle).**
- **hard to implement with gate-based model.**
- **losing atoms during computing.**

Majorana fermions

- **theorically very stable qubits** with low level of required error correction.
- **long coherence time and gates speed** enabling processing complex and deep algorithms.
- **potential qubits scalability**, built with technologies close to electron spin qubits.
- some researches in the topological matter field could be fruitful with no Majorana fermions.

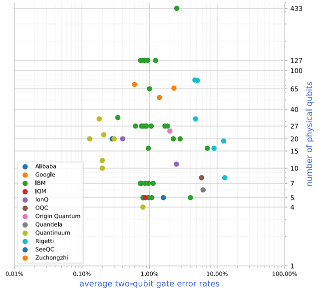
- **topological qubits programming is different and requires an additional software layer.**
- **rather few laboratories involved in this path.**
- **no startup was launched in this field. Microsoft is the only potential vendor. IBM is investigating the field in Zurich.**
- **works at low cryogenic temperatures like superconducting qubits < 20mK.**
- **no Majorana fermion qubit demonstrated yet.**

photons qubits

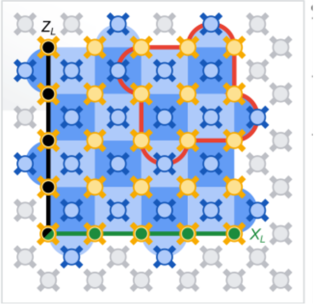
- **stable qubits** with absence of decoherence.
- qubits processing at **ambiant temperature.**
- **emerging nano-photonic** manufacturing techniques enabling scalability.
- **easier to scale-out** with inter-qubits communications and quantum telecommunications.
- **MBQC/FBQC** circumventing the fixed gates depth computing capacity.

- **need to cool photon sources and detectors, but at relatively reasonable temperatures between 2K and 10K, requiring lighweight cryogenic systems.**
- **boson sampling based quantum advantage starts to being programmable but a practical quantum advantage remains to be proven.**
- **not yet scalable in number of operations due to probabilistic character of quantum gates and the efficiency of photon sources in most paradigms.**

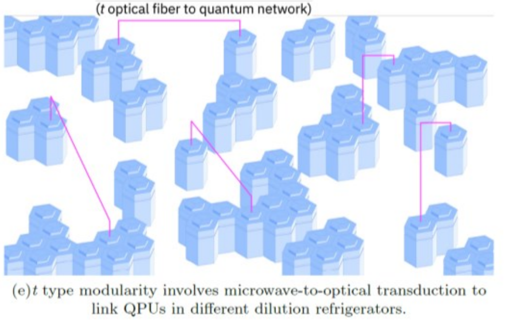
key scientific and engineering challenges



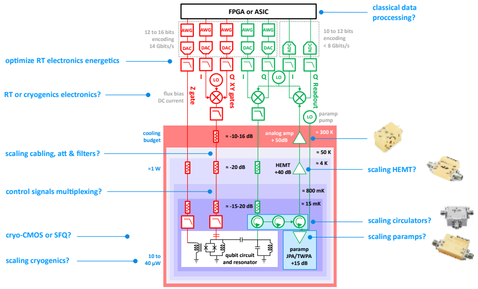
improve qubits fidelities



errors mitigation and correction



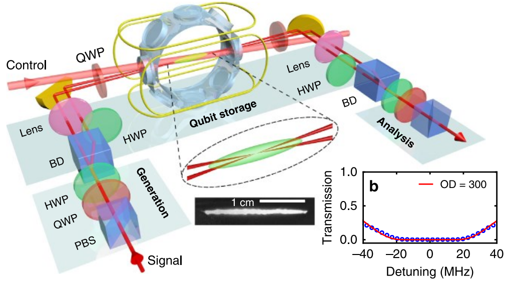
quantum interconnect



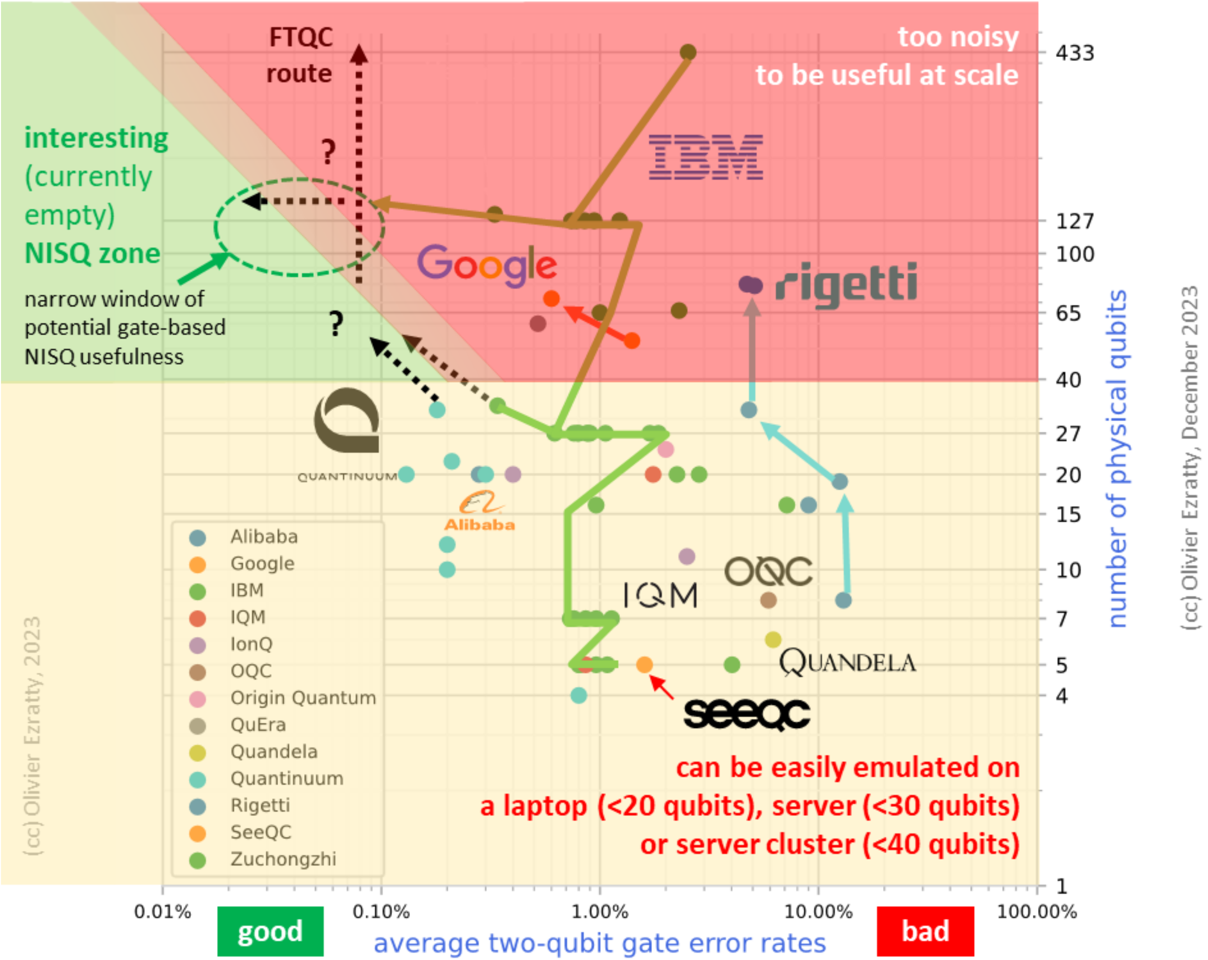
electronics, cabling and/or cryogeny scalability

#QEI
the quantum energy initiative

energy consumption containment or advantage



data loading and quantum memory

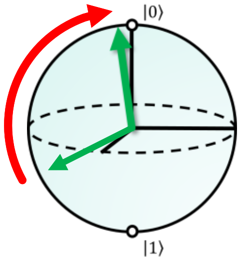
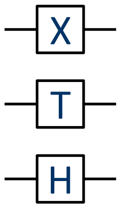
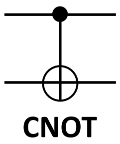
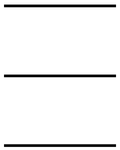
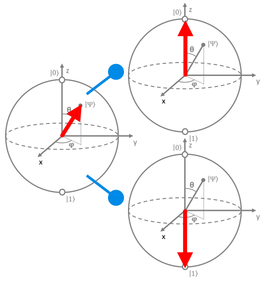

FTQC route
too noisy to be useful at scale
interesting (currently empty) NISQ zone
narrow window of potential gate-based NISQ usefulness
?
?
IBM
Google
rigetti
QUANTINUUM
Alibaba
IQM
OQC
QUANDELA
seeqc
Alibaba
Google
IBM
IQM
IonQ
OQC
Origin Quantum
QuEra
Quandela
Quantinuum
Rigetti
SeeQC
Zuchongzhi
can be easily emulated on a laptop (<20 qubits), server (<30 qubits) or server cluster (<40 qubits)
433
127
100
65
40
27
20
15
10
7
5
4
1
number of physical qubits
0.01%
0.10%
1.00%
10.00%
100.00%
good
average two-qubit gate error rates
bad
(cc) Olivier Ezratty, 2023
(cc) Olivier Ezratty, December 2023

qubit operations generating errors

when

qubit operations when errors are generated

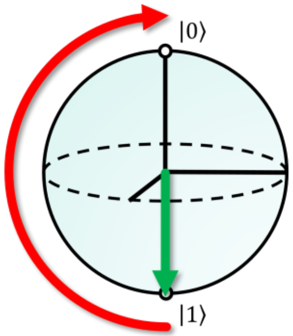
SPAM errors

initialization	1 qubit gate	2 qubit gate	idle qubit	readout
				
qubit initialization, preparation or reset does not create a perfect $\|0\rangle$	error created while applying a single qubit gate	error created while applying a two qubit gate	error created while doing nothing	error while reading out the qubit state, impacts QEC and final results

qubit errors types

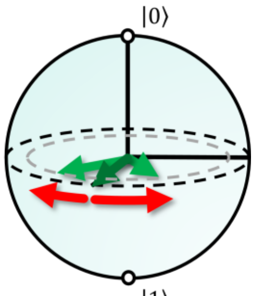
what
computational effects of errors on qubits

flip



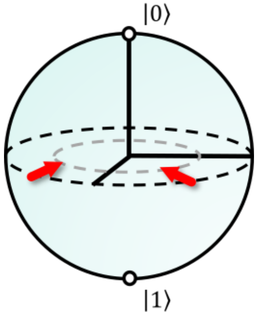
amplitude error, moving the qubit toward $|0\rangle$

phase



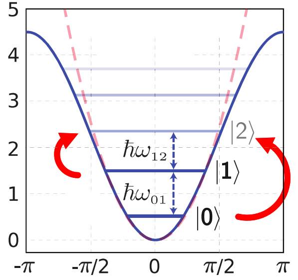
phase error, changing the phase of the qubit

depolarizing



qubit progressively turning into a mixed state, a maximally mixed state corresponding to an **erasure error**

leakage



qubit getting out of its two level basis states (e.g., with superconducting qubits)

qubit errors sources

where
physical sources or errors

control

signals jitter

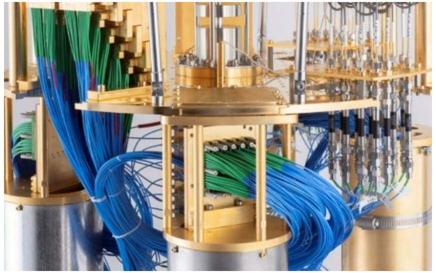
calibration

many body interactions

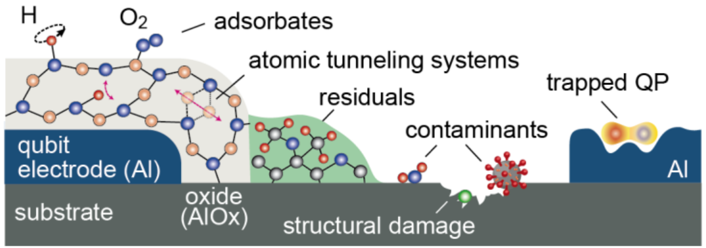
thermal noise

back-action

electromagnetic noise

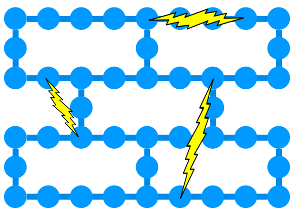


material defects

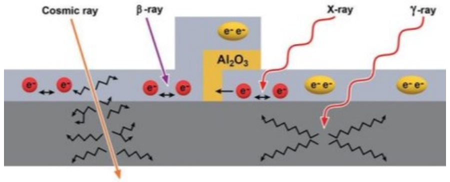


crosstalk

photon loss

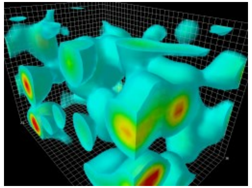


cosmic rays

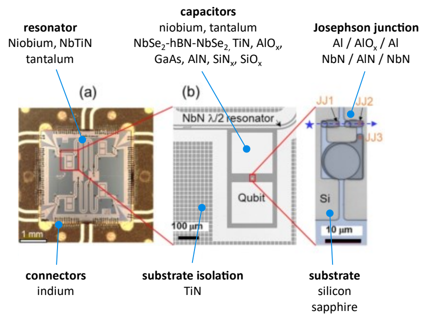


gravity

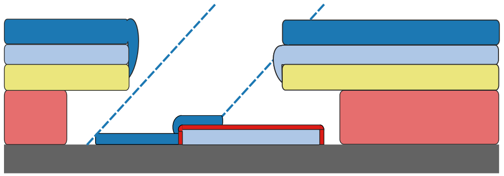
vacuum quantum fluctuations



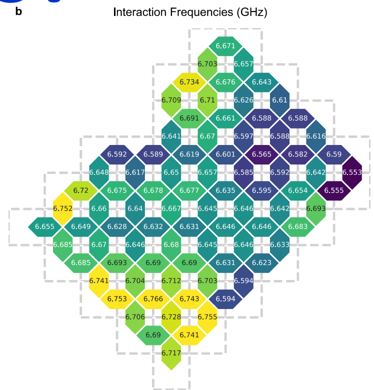
how to improve qubit fidelities? *



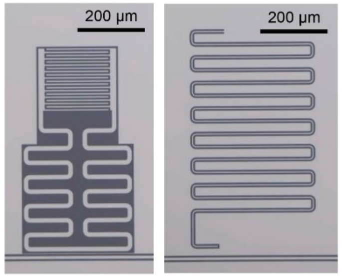
materials



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

physical qubit

error rates ≈0.1%

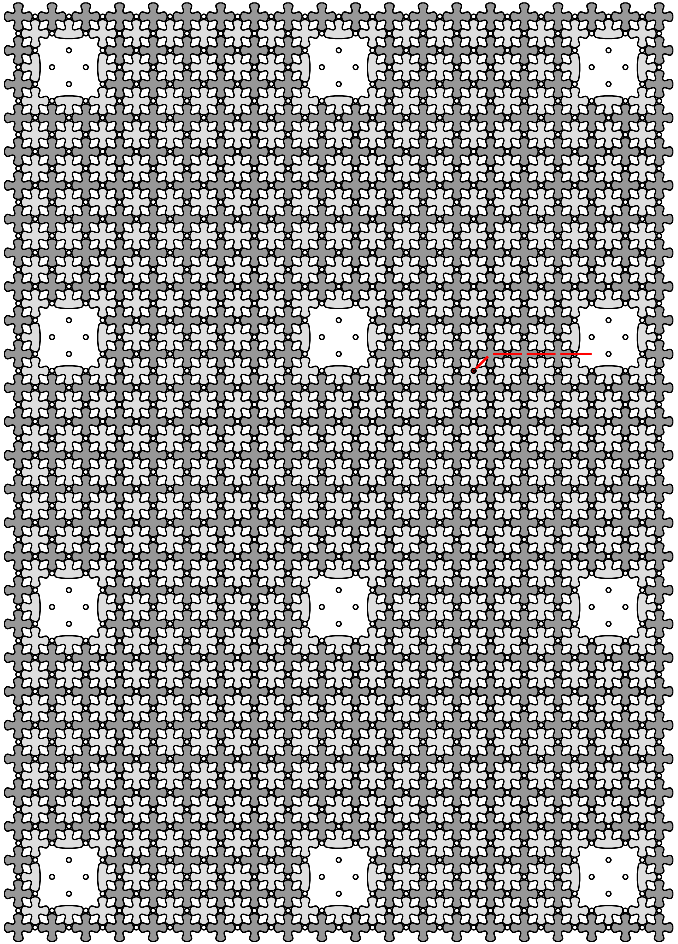
logical qubit

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

implementing error correction codes

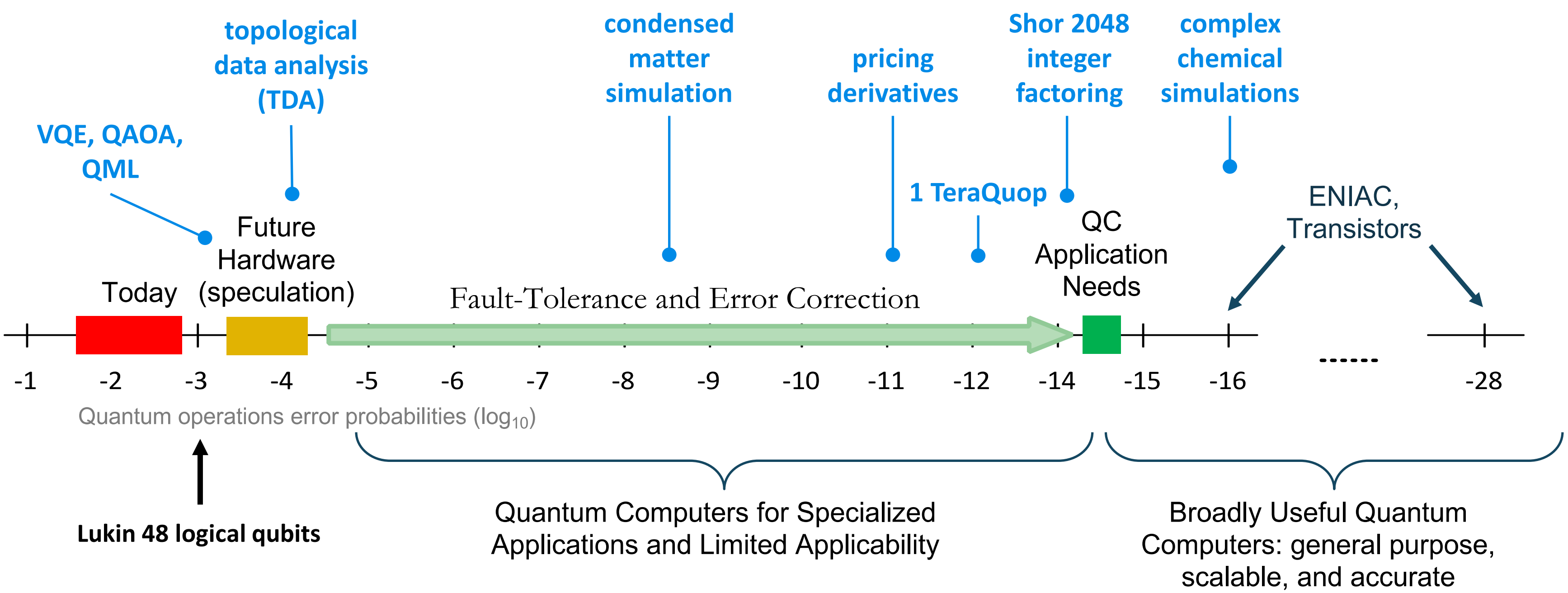
made of thousands of physical qubits depending on physical qubit fidelities, connectivity, algorithm size, etc.

+ fault-tolerant features: transversal error correction to avoid errors spreading but works only with Clifford group gates, (costly) magic state distillation for T gates errors corrections, etc.



https://arxiv.org/abs/1202.2639

from NISQ to FTQC



The Harvard Gazette

SCIENCE

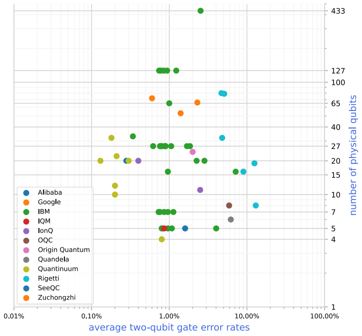
Researchers create first logical quantum processor

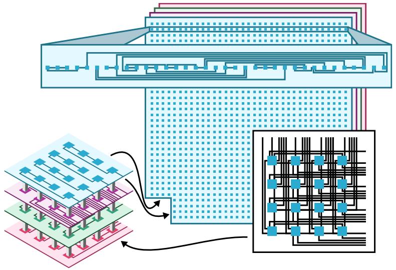
Dec 8th, 2023

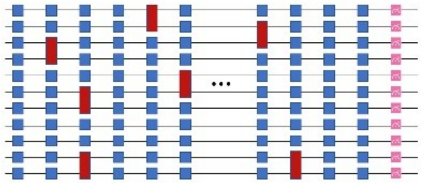
source: How about quantum computing? by Bert de Jong, DoE Berkeley Labs, June 2019 (47 slides) + Olivier Ezratty additions.

qubits for FTQC?

>99.9%

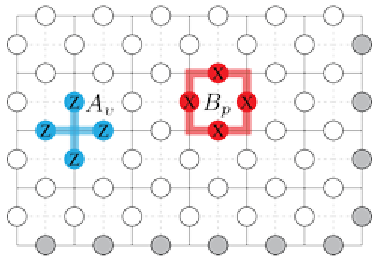






algorithm breadth and depth

n_T = # of T gates in algorithm



physical qubits fidelities

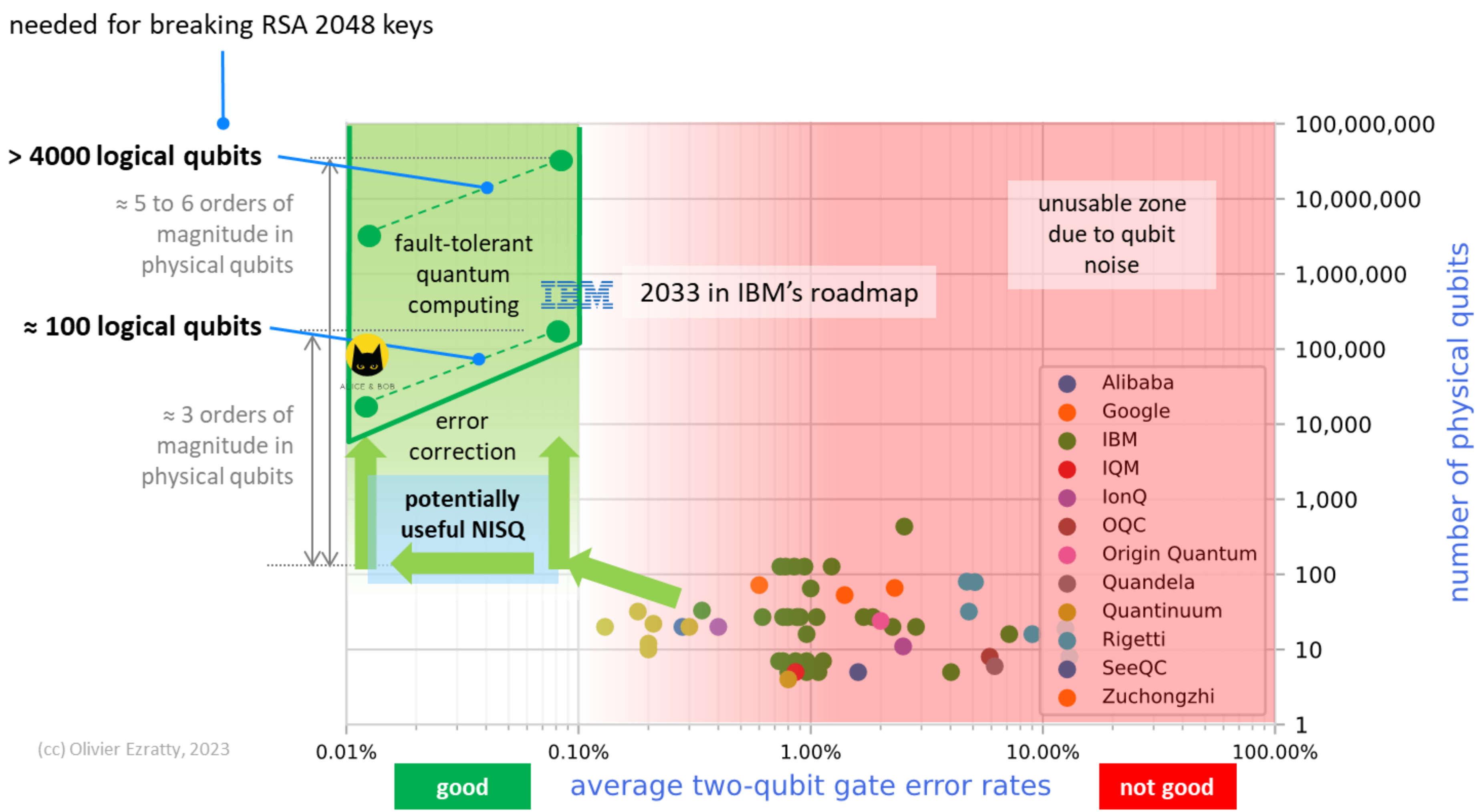
physical qubits connectivity

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

error correction code

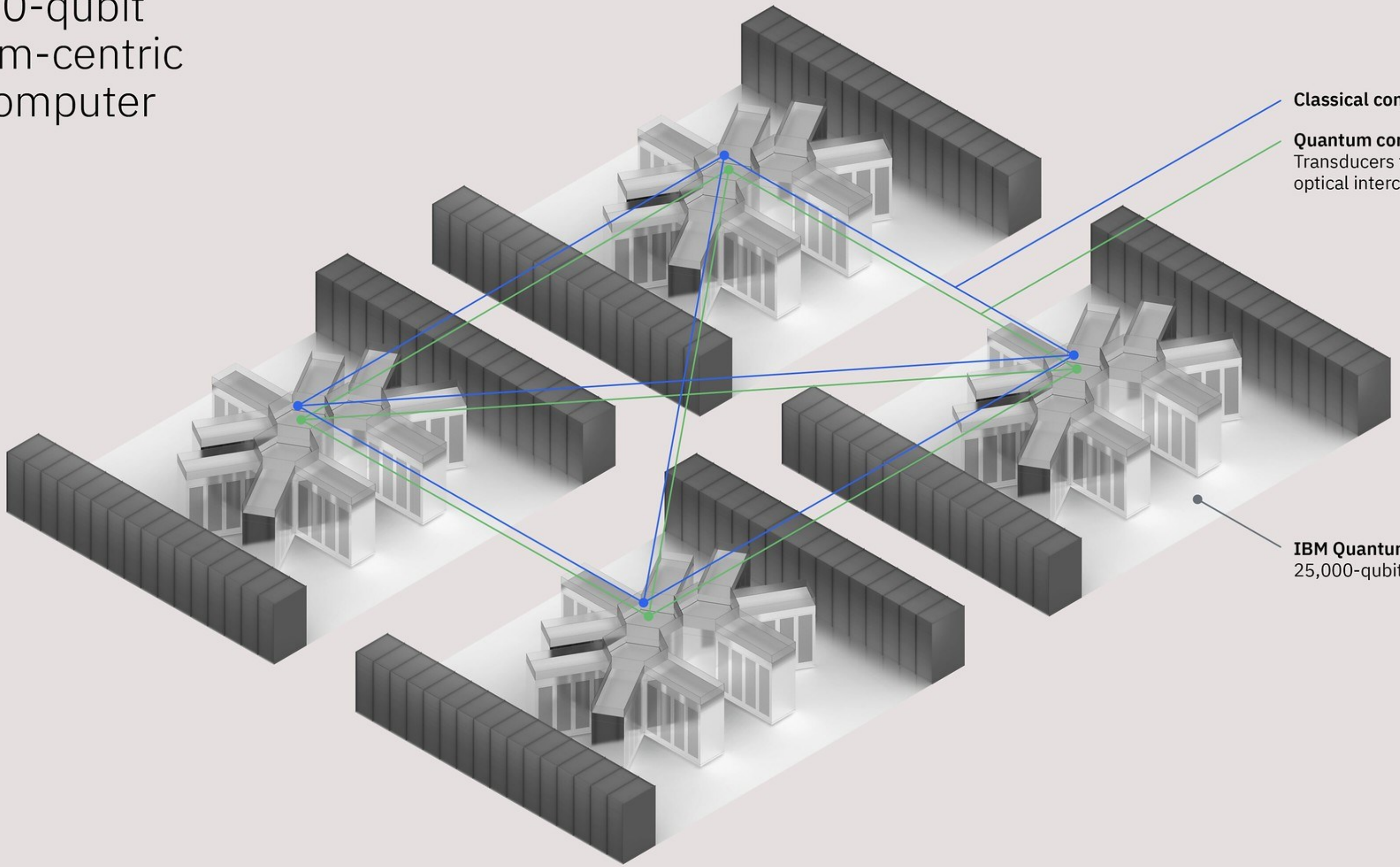
physical qubits / logical qubit

dynamically adjusted against the algorithm size



needed for breaking RSA 2048 keys
> 4000 logical qubits
≈ 5 to 6 orders of magnitude in physical qubits
≈ 100 logical qubits
≈ 3 orders of magnitude in physical qubits
fault-tolerant quantum computing
error correction
potentially useful NISQ
IBM
2033 in IBM's roadmap
ALICE & BOB
unusable zone due to qubit noise
Alibaba
Google
IBM
IQM
IonQ
OQC
Origin Quantum
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%
good
average two-qubit gate error rates
not good
(cc) Olivier Ezratty, 2023

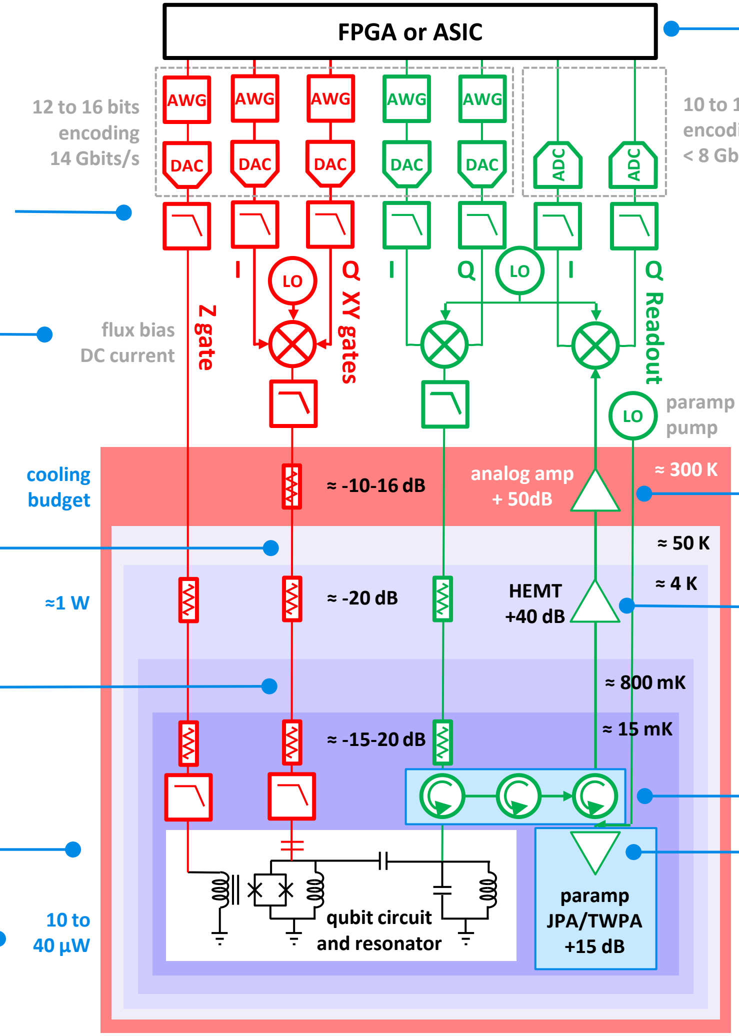
100,000-qubit quantum-centric supercomputer
—
2033



IBM **Quantum**

energetic related hardware engineering 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?

scaling cryogenics?

classical data proccessing?

scaling HEMT?

scaling circulators?

scaling paramps?

the road to scalability per qubit type

	superconducting	neutral atoms	trapped ions	silicon spins	photons
challenges	• noise and crosstalk ↗ with # of qubits. • electronics energetic cost. • scaling cabling, circulators. • scaling cryostats.	• atom controls beyond 1000 qubits. • harder to implement gate-based QC. • SLM resolution.	• entanglement beyond 30 qubits. • overall scaling beyond 40 qubits. • slow gate speed.	• controlled electrostatic potential. • error correction. • qubits entanglement. • fab cycle time.	• photon sources power. • photon statistics. • creating large cluster states of entangled photons.
solutions	• materials improvement. • 3D chipset stacking. • cryo-CMOS or SFQ. • microwave signals multiplexing. • scale-out with photons. • more powerful cryostats, JJ circulators.	• scale-out with atoms/photon conversion. • more powerful lasers and SLMs. • various atoms controls (microwaves, lasers).	• ions shuttling. • switched to baryum (IonQ). • Rydberg states ions (Crystal Quantum Computing). • QPU photonic interconnect.	• material and interfaces improvement. • integrated cryoelectronics. • more powerful cryostats. • more efficient fabs (GF).	• bright and deterministic photon sources (Quandela). • deterministic sources of cluster states. • MBQC. • integrated nanophotonics.
caveats	• photonic interconnect overhead and statistics. • energetic cost of microwave multiplexing. • SFQ backaction on qubits.	• gate control precision. • losing the atom while computing. • potential applicability limited to mid-scale simulations.	• photonic interconnect viability. • photonic interconnect statistics and impact on speedups.	• scalability potential is capital intensive. • two-qubit gates fidelities improving slowly.	• photon statistics. • small cluster states so far.

ions and neutral atoms | **superconducting & spin qubits** | **photons**

classical computing

classical part of quantum algorithms
ansatz preparation, cost function computing, data access, networking, post-processing, QEM (NISQ)

code compiling (or minor embedding in analog modes) and **run-time exécution drive** (including number of shots)

error syndromes detection and QEC drive (FTQC)

classical electronics

room temperature electronics and controls
FPGA, DAC/ADCs, AWG, mixers, tone pulses generation; lasers, SLMs, AODs, CCD and photonic circuits controls

lasers (ions and neutral atoms)

SLMs, AODs
CCD/CMOS sensors

low-temperature electronics
JPA, TWPA, HEMT, cryo-CMOS, SFQ, mux/demux

low-temperature passive electronics losses
cables, attenuators, filters

impacts

lasers (photons)

photon sources and detectors

cooling and vacuum

dilution cryostat – 15mK to 1K

4K compressor for dilution, vacuum chambers, cryopumps, photon sources, photon detectors

4K compressor cooling (water/air)

laser cooling (water/air) (ions and neutral atoms)

laser cooling (photons)

ultra-vacuum pump (ions and neutral atoms)

vacuum pump (superconducting & spin qubits)

hardware stacks

electronics

power drain, signals quality and jitter, less cabling and signals multiplexing, readout data deluge, error correction cycle length and classical processing, laser power

qubit chipset

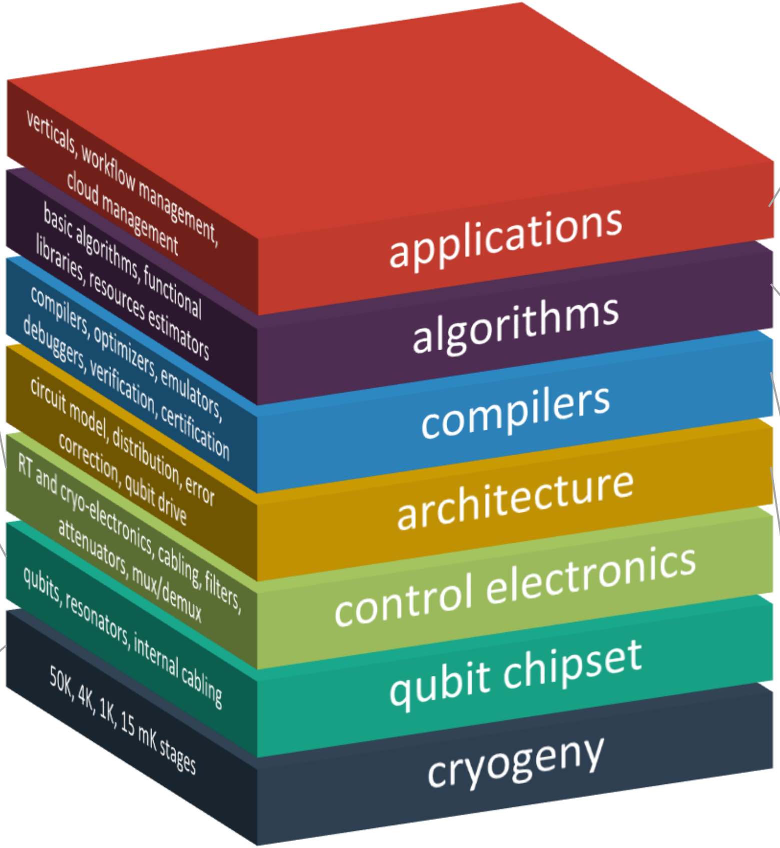
qubit fidelities, connectivity, gate and readout speed, materials, crosstalk, 3D stacking, deterministic photon source and detectors, production and testing cycle length

cryogeny

raw cryogeny cooling power, efficiency improvements, space capacity, cooling speedup

other key technologies

qRAM and quantum memory, QPU interconnect, energetics



blue =scientific challenge (« hard tech »)
black: technology challenge (« deep tech »)

software stacks

applications

addressed verticals, use case usefulness

algorithms

algorithms diversity, provable advantage, computing time, data frugality, multi-quantum paradigms support, hybrid algorithms, supporting real world data volumes

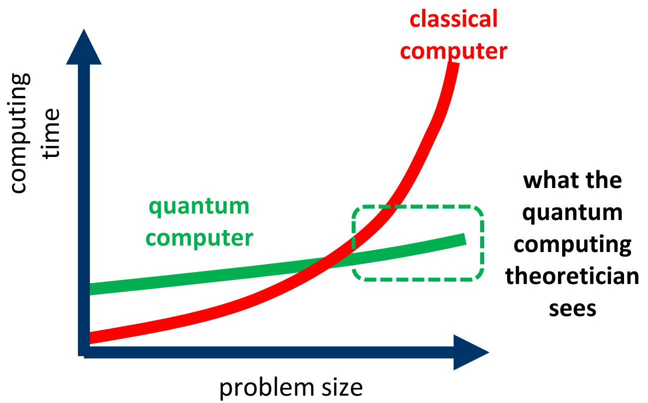
compilers and tools

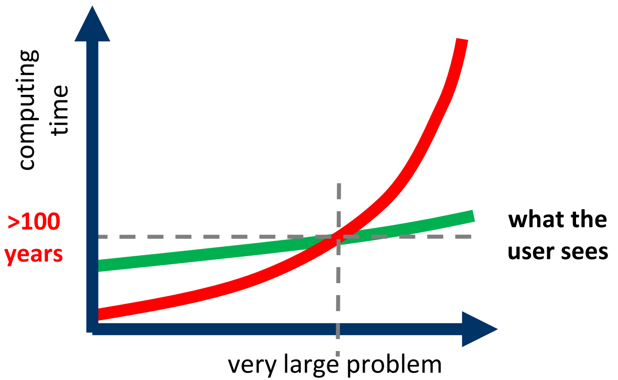
languages abstraction level, transpilers and optimizer performance, hybrid computing drive, data loading performance

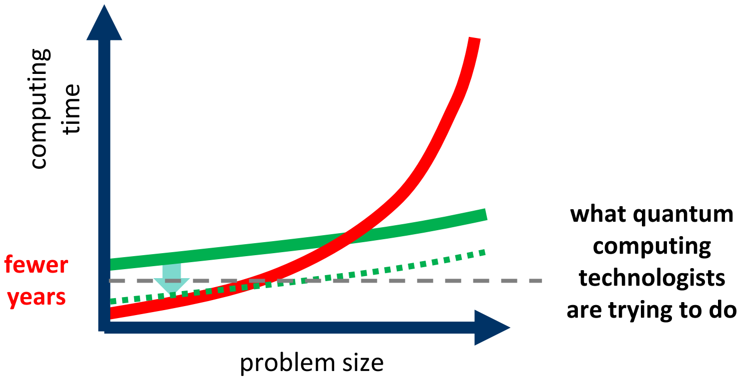
architecture

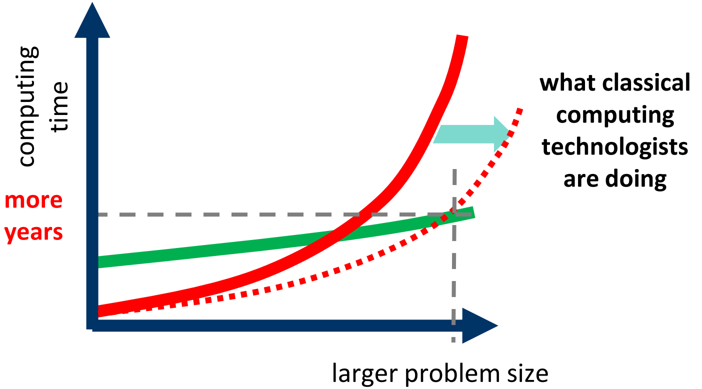
error correction codes efficiency, electronics signals data processing and bandwidth, cloud operations

from theory to practice









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

key takeaways

useful quantum computing may come first from analog QPUs

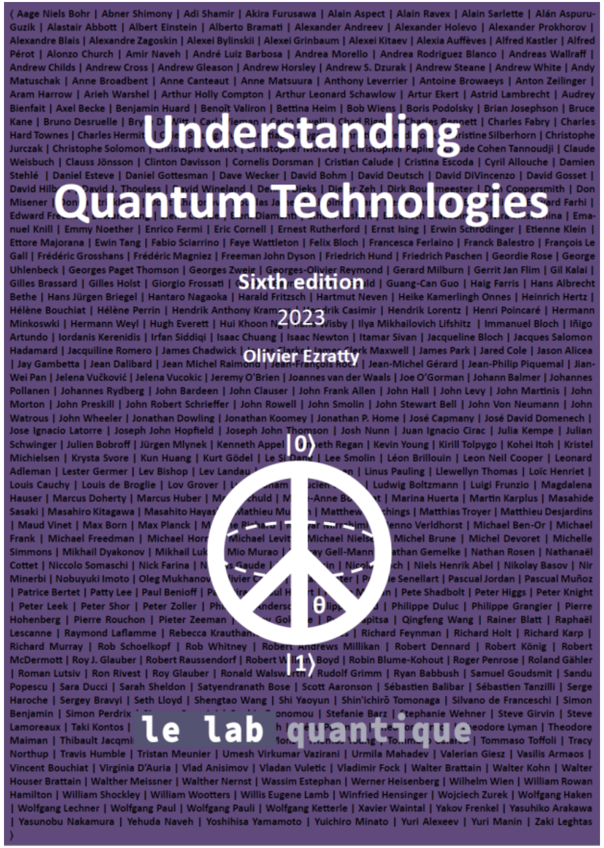
NISQ has a limited potential to deliver business value

the goal post is moving fast with classical computing improvements (GP-GPUs, tensor networks, better heuristics)

FTQC is an enormous scientific and technology challenge

it requires innovative approaches (qubits, hybridization, …)

and many enabling technologies (electronics, lasers, cryogenics)



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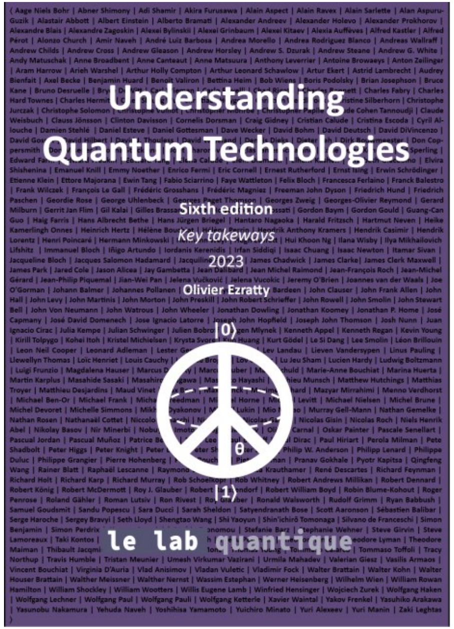

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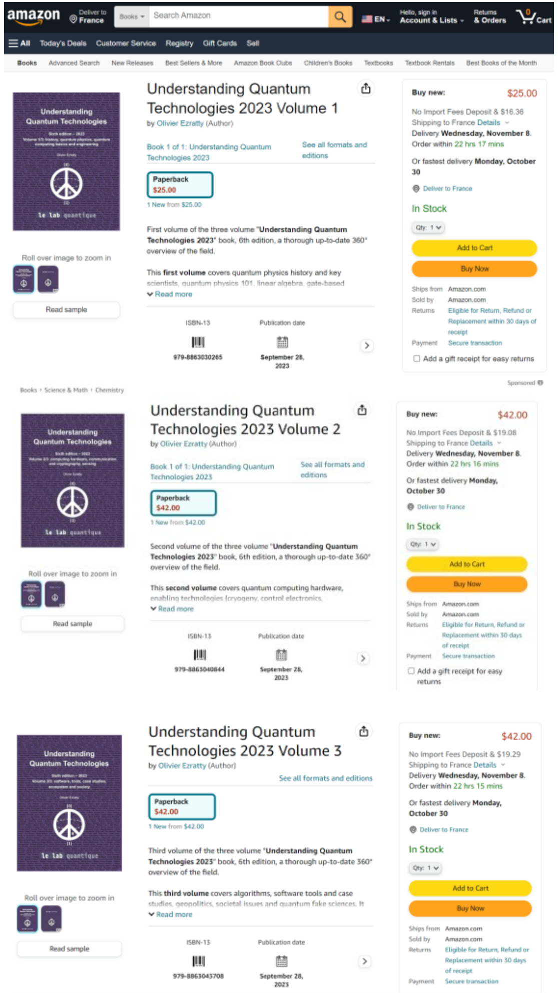

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[Submitted on 23 Jan 2022 (v1), last revised 10 Feb 2022 (this version, v3)]

Mitigating the quantum hype

Olivier Ezratty

We are in the midst of quantum hype with some excessive claims of quantum computing potential, many vendors' and even some research organizations' exaggerations, and a funding frenzy for very low technology readiness level startups. Governments are contributing to this hype with their large quantum initiatives and their technology sovereignty aspirations. Technology hypes are not bad per se since they create emulation, drive innovations and also contribute to attracting new talents. It works as scientists and vendors deliver progress and innovation on a continuous basis after a so-called peak of expectations. It fails with exaggerated overpromises and underdeliveries that last too long. It could cut short research and innovation funding, creating some sort of quantum winter. After looking at the shape and form of technology and science hypes and driving some lessons from past hypes, we investigate the curren
some significant unce
computers, the scient
other technology hyp
on the organization o
other fields like quant
technology readiness
proposals to mitigate
including recommend
quantum science, ve
public education and

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THE EUROPEAN PHYSICAL JOURNAL A

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Review

Perspective on superconducting qubit quantum computing

Olivier Ezratty[a]

EPITA, Paris, France

Received: 12 March 2023 / Accepted: 12 April 2023

Communicated by Denis Lacroix

Cornell University

We gratefully acknowledge support from the Simons Foundation and member institutions.

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Quantum Physics

[Submitted on 27 Mar 2023]

Is there a Moore's law for quantum computing?

Olivier Ezratty

There is a common wisdom according to which many technologies can progress according to some exponential law like the empirical Moore's law that was validated for over half a century with the growth of transistors number in chipsets. As a still in the making technology with a lot of potential promises, quantum computing is supposed to follow the pack and grow inexorably to maturity. The Holy Grail in that domain is a large quantum computer with thousands of errors corrected logical qubits made themselves of thousands, if not more, of physical qubits. These would enable molecular simulations as well as factoring 2048 RSA bit keys among other use cases taken from the intractable classical computing problems book. How far are we from this? Less than 15 years according to many predictions. We will see in this paper that Moore's empirical law cannot easily be translated to an equivalent in quantum computing. Qubits have various figures of merit that won't progress magically thanks to some new manufacturing technique capacity. However, some equivalents of Moore's law may be at play inside and outside the quantum realm like with quantum computers enabling technologies, cryogeny and control electronics. Algorithms, software

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Quantum Physics

[Submitted on 16 May 2023 (v1), last revised 19 May 2023 (this version, v2)]

Where are we heading with NISQ?

Olivier Ezratty

In 2017, John Preskill defined Noisy Intermediate Scale Quantum (NISQ) computers as an intermediate step on the road to large scale error corrected fault-tolerant quantum computers (FTQC). The NISQ regime corresponds to noisy qubit quantum computers with the potential to solve actual problems of some commercial value faster than conventional supercomputers, or consuming less energy. Over five years on, it is a good time to review the situation. While rapid progress is being made with quantum hardware and algorithms, and many recent experimental demonstrations, no one has yet successfully implemented a use case matching the original definition of the NISQ regime. This paper investigates the space, fidelity and time resources of various NISQ algorithms and highlights several contradictions between NISQ requirements and actual as well as future quantum hardware capabilities. It then covers various techniques which could help like qubit fidelities improvements, various breeds of quantum error mitigation methods, analog/digital hybridization, using specific qubit types like multimode photons as well as quantum annealers and analog quantum computers (aka quantum simulators or programmable

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