# état de l'art quantique

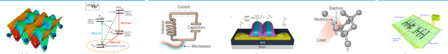
## ce qui s'est passé dans l'année écoulée

**olivier ezratty**

olivier@oezratty.net www.oezratty.net

Journée Thématique Panorama des Technologies Quantiques pour les applications civiles et militaires,
Lyon, 5 octobre 2023

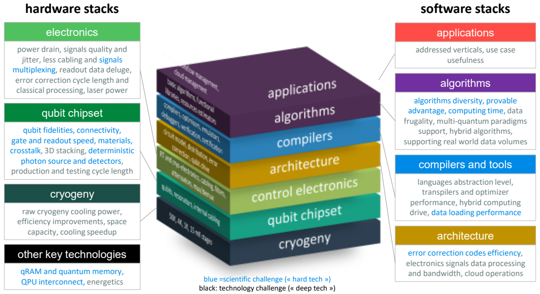
# agenda



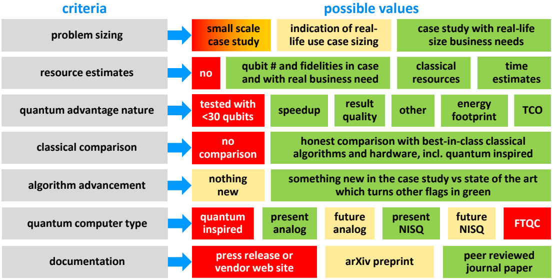
| | atoms | | electrons superconducting & spins | | | photons |
|---|---|---|---|---|---|---|
| | cold atoms | trapped ions | superconducting | silicon | NV centers | photons |
| qubit size | about 1 µm space between atoms | about 1 µm space between atoms | $(100\mu)^2$ | $(100nm)^2$ | $<(100nm)^2$ | 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<br>4K for vacuum pump | <1mK<br>4K cryostat | 15mK<br>dilution cryostat | 100mK-1K<br>dilution cryostat | 4K to RT | RT<br>4K-10K cryostats for photons gen. & det. |
| operational qubits | 256 (QuEra)<br>100 (Pasqal) | 32 (IonQ and Quantinuum) | 433 (IBM)<br>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!

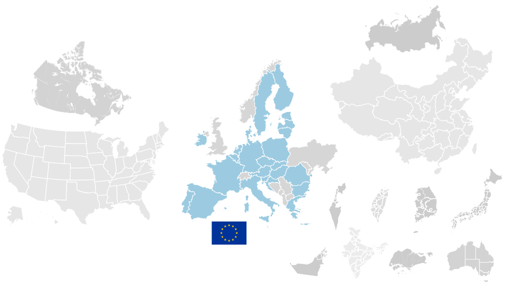
## actualité des qubits




## enjeu de la scalabilité




## analyse des études de cas



## géopolitique


## scène entrepreneuriale

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Quantum Physics

[Submitted on 4 Oct 2023]

# Quantum algorithms: A survey of applications and end-to-end complexities

Alexander M. Dalzell, Sam McArdle, Mario Berta, Przemyslaw Bienias, Chi-Fang Chen, András Gilyén, Connor T. Hann, Michael J. Kastoryano, Emil T. Khabiboulline, Aleksander Kubica, Grant Salton, Samson Wang, Fernando G. S. L. Brandão

The anticipated applications of quantum computers span across science and industry, ranging from quantum chemistry and many-body physics to optimization, finance, and machine learning. Proposed quantum solutions in these areas typically combine multiple quantum algorithmic primitives into an overall quantum algorithm, which must then incorporate the methods of quantum error correction and fault tolerance to be implemented correctly on quantum hardware. As such, it can be difficult to assess how much a particular application benefits from quantum computing, as the various approaches are often sensitive to intricate technical details about the underlying primitives and their complexities. Here we present a survey of several potential application areas of quantum algorithms and their underlying algorithmic primitives, carefully considering technical caveats and subtleties. We outline the challenges and opportunities in each area in an "end-to-end" fashion by clearly defining the problem being solved alongside the input-output model, instantiating all "oracles," and spelling out all hidden costs. We also compare quantum solutions against state-of-the-art classical methods and complexity-theoretic limitations to evaluate possible quantum speedups.

The survey is written in a modular, wiki-like fashion to facilitate navigation of the content. Each primitive and application area is discussed in a standalone section, with its own bibliography of references and embedded hyperlinks that direct to other relevant sections. This structure mirrors that of complex quantum algorithms that involve several layers of abstraction, and it enables rapid evaluation of how end-to-end complexities are impacted when subroutines are altered.

Comments: Survey document with wiki-like modular structure. 337 pages, including bibliography and sub-bibliographies. Comments welcome

Subjects: **Quantum Physics (quant-ph)**

Cite as: arXiv:2310.03011 **[quant-ph]**

(or arXiv:2310.03011v1 **[quant-ph]** for this version)

https://doi.org/10.48550/arXiv.2310.03011

# Quantum algorithms:

## A survey of applications and end-to-end complexities

Alexander M. Dalzell*[1], Sam McArdle*[1], Mario Berta[1,2,3], Przemyslaw Bienias[1], Chi-Fang Chen[1,4], András Gilyén[5], Connor T. Hann[1], Michael J. Kastoryano[1,6], Emil T. Khabiboulline[1,7], Aleksander Kubica[1], Grant Salton[1,4,8], Samson Wang[1,3] and Fernando G. S. L. Brandão[1,4]

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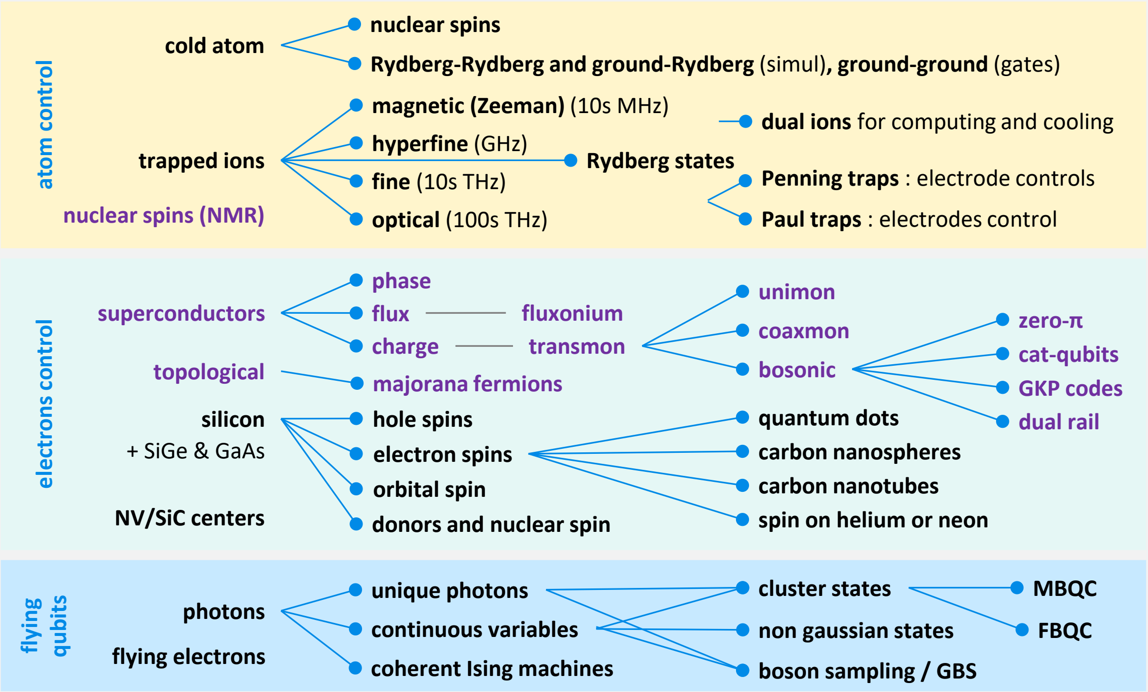
[2] *Institute for Quantum Information, RWTH Aachen University, Aachen, Germany*
[3] *Imperial College London, London, UK*
[4] *Institute for Quantum Information and Matter, Caltech, Pasadena, CA, USA*
[5] *Alfréd Rényi Institute of Mathematics, Budapest, Hungary*
[6] *IT University of Copenhagen, Copenhagen, Denmark*
[7] *Department of Physics, Harvard University, Cambridge, MA, USA*
[8] *Amazon Quantum Solutions Lab, Seattle, WA, USA*



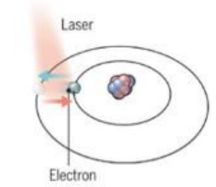
**Abstract**

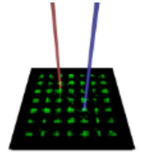
The anticipated applications of quantum computers span across science and industry, ranging from quantum chemistry and many-body physics to optimization, finance, and machine learning. Proposed quantum solutions in these areas typically combine multiple quantum algorithmic primitives into an overall quantum algorithm, which must then incorporate the methods of quantum error correction and fault tolerance to be implemented correctly on quantum hardware. As such, it can be difficult to assess how much a particular application benefits from quantum computing, as the various approaches are often sensitive to intricate technical details about the underlying primitives and their complexities. Here we present a survey of several potential application areas of quantum algorithms and their underlying algorithmic primitives, carefully considering technical caveats and subtleties. We outline the challenges and opportunities in each area in an "end-to-end" fashion by clearly defining the problem being solved alongside the input-output model, instantiating all "oracles," and spelling out all hidden costs. We also compare quantum solutions against state-of-

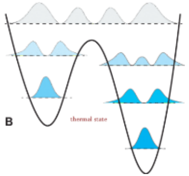
# actualité des qubits

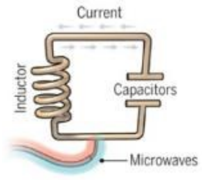


| atoms | electron *superconducting loops & controlled spin* | photons |
|---|---|---|

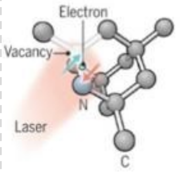


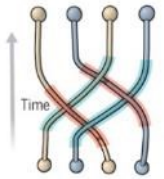



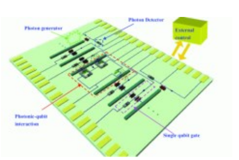








## vendors

**trapped ions**: Quantinuum, IonQ, AQT, Universal Quantum, Oxford Ionics, eleQtron, Foxconn, Quantum Art, Crystal Quantum Computing, NextQ, Qudora Technologies

**cold atoms**: Pasqal, QuEra, Infleqtion, Atom Computing, planqc, QuANTier, NanoQT

**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, Origin Quantum 本源量子, 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, XeedQ, Quantum Transistors

**topological**: Microsoft

**photons**: PsiQuantum, Quandela, ORCA Computing, Xanadu, Duality Quantum Photonics, QuiX Quantum, BardeenQ, QBoson, QCi, photonicsQ, Quanfluence, Tundra Systems Global Ltd.

## labs (*)

**trapped ions**: IQST, University of Maryland, MIT, KIT Karlsruher Institut für Technologie, IQOQI, universität innsbruck, Sandia National Laboratories, JGU Johannes Gutenberg Universität Mainz, NIST, Harvard University, US University of Sussex

**cold atoms**: cnrs, Institut d'Optique Graduate School, Harvard University, Caltech, Jülich Forschungszentrum, PennState, EPFL, The Ohio State University

**annealing**: NEDO, Stanford University, MIT, KIT Karlsruher Institut für Technologie, MCQST, ETH zürich

(*) non exhaustive inventory, missing Chinese labs among others

**super-conducting**: cea, cnrs, MIT, Inria, UCSB, QuTech, UMass Amherst, MCQST, ETH zürich, Universität des Saarlandes, Berkeley University of California, Yale, Caltech, 東京大学 The University of Tokyo

**silicon**: cea, cnrs, University of Bristol, QuTech, University of Oxford, UNSW Sydney, Yale, HRL Laboratories, ETH zürich, The University of Wisconsin Madison, EPFL, RIKEN, Princeton University

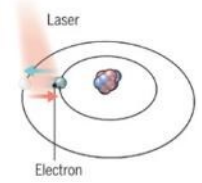
**vacancies**: cea, cnrs, MIT, University of Maryland, TU Delft, Harvard University, Universität Stuttgart, The University of Chicago

**topological**: cea, cnrs, University of Maryland, UCSB, TU Delft, QuTech, Niels Bohr Institutet, The University of Sydney

**photons**: cnrs, University of Bristol, University of Oxford, Sapienza Università di Roma, Università degli Studi di Milano, universität wien, 東京大学 The University of Tokyo

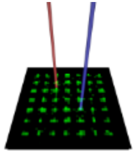
# new vendors since october 2022

## atoms




**trapped ions**

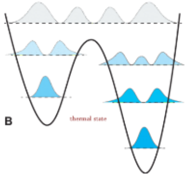
- Quantum Art
- NEQXT
- QUDORA TECHNOLOGIES



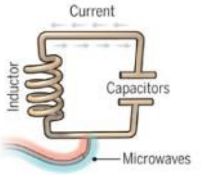
**cold atoms**

- QUANTier
- NanoQT

## electron *superconducting loops & controlled spin*



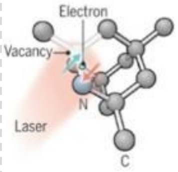

**annealing**




**super-conducting**

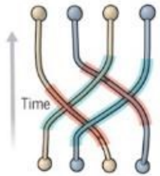

**silicon**

- quobly
- SemiQon™
- ARQUE



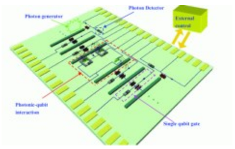

**vacancies**

- SaxonQ
- NTT
- Quantum Transistors



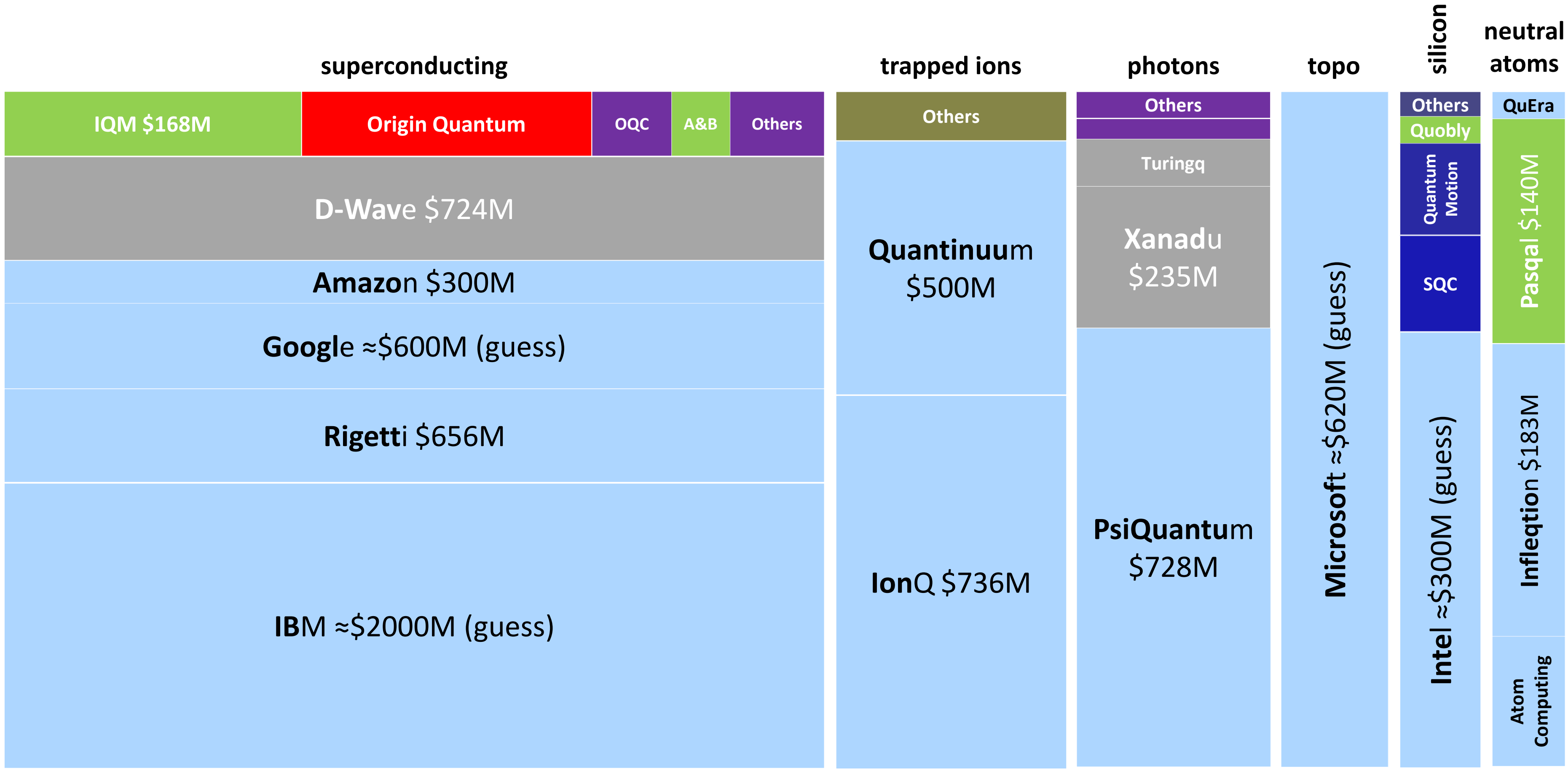

**topological**

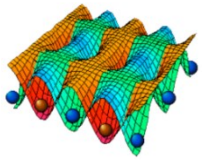
## photons

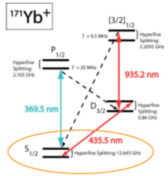


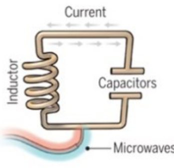
**photons**

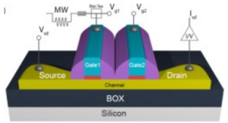
- photonicsQ
- QUANFLUENCE

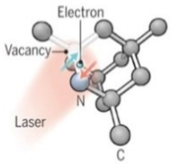

superconducting
IQM $168M
Origin Quantum
OQC
A&B
Others
D-Wave $724M
Amazon $300M
Google ≈$600M (guess)
Rigetti $656M
IBM ≈$2000M (guess)
trapped ions
Others
Quantinuum $500M
IonQ $736M
photons
Others
Turingq
Xanadu $235M
PsiQuantum $728M
topo
Microsoft ≈$620M (guess)
silicon
Others
Quobly
Quantum Motion
SQC
Intel ≈$300M (guess)
neutral atoms
QuEra
Pasqal $140M
Infleqtion $183M
Atom Computing

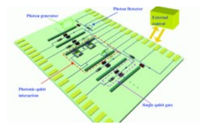




| | **atoms** | | **electrons** superconducting & spins | | | **photons** |
|---|---|---|---|---|---|---|
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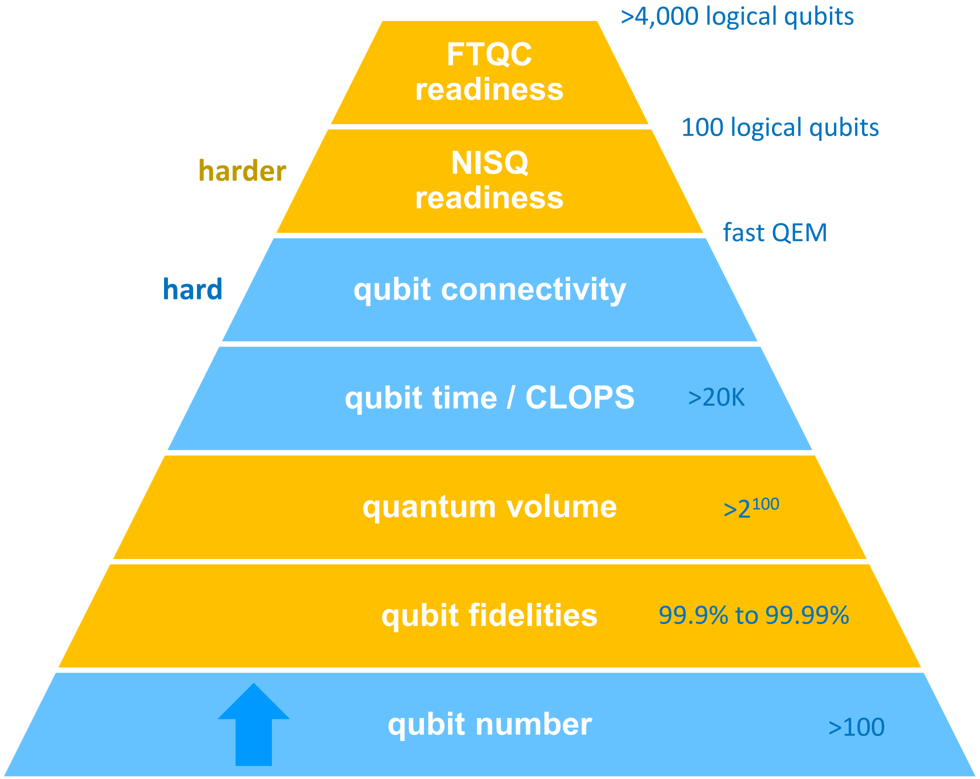
 RT = room temperature.

# 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 |

# superconducting qubits

**433 qubits**
May 2023

**quantum utility**
June 2023

**QLDPC**
August 2023

| Exp. | 1 amp. | 1 million noisy samples | | |
|---|---|---|---|---|
| | FLOPs | FLOPs | XEB fid. | Time |
| SYC-53 [9] | $6.44 \cdot 10^{17}$ | $2.60 \cdot 10^{17}$ | $2.24 \cdot 10^{-3}$ | 6.18 s |
| ZCZ-56 [10] | $6.24 \cdot 10^{19}$ | $6.40 \cdot 10^{19}$ | $6.62 \cdot 10^{-4}$ | 25.3 min |
| ZCZ-60 [11] | $1.32 \cdot 10^{21}$ | $1.41 \cdot 10^{23}$ | $3.66 \cdot 10^{-4}$ | 38.7 days |
| **This work** | $4.74 \cdot 10^{23}$ | $6.27 \cdot 10^{25}$ | $1.68 \cdot 10^{-3}$ | 47.2 yr |

Google

**new Sycamore supremacy**
June 2023

rigetti

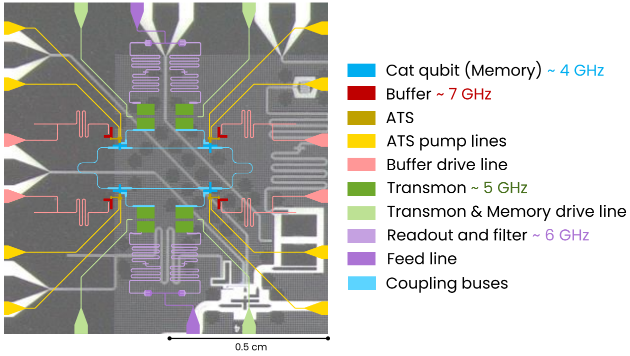
**27% layoffs and new CEO,**
February 2023
**fab deal with AFRL**
April 2023

ATLANTIC QUANTUM

**AFRL 1.25M€ funding**
April 2023

ALICE & BOB

**first 4 sampled qubits**



Article

# Evidence for the utility of quantum computing before fault tolerance

https://doi.org/10.1038/s41586-023-06096-3

Received: 24 February 2023

Accepted: 18 April 2023

Published online: 14 June 2023

Open access

Check for updates

Youngseok Kim[1,6]✉, Andrew Eddins[2,6]✉, Sajant Anand[3], Ken Xuan Wei[1], Ewout van den Berg[1], Sami Rosenblatt[1], Hasan Nayfeh[1], Yantao Wu[3,4], Michael Zaletel[3,5], Kristan Temme[1] & Abhinav Kandala[1]✉

Quantum computing promises to offer substantial speed-ups over its classical counterpart for certain problems. However, the greatest impediment to realizing its full potential is noise that is inherent to these systems. The widely accepted solution to this challenge is the implementation of fault-tolerant quantum circuits, which is out of reach for current processors. Here we report experiments on a noisy 127-qubit processor and demonstrate the measurement of accurate expectation values for circuit volumes at a scale beyond brute-force classical computation. We argue that this represents evidence for the utility of quantum computing in a pre-fault-tolerant era. These experimental results are enabled by advances in the coherence and calibration of a superconducting processor at this scale and the ability to characterize[1] and controllably manipulate noise across such a large device. We establish the accuracy of the measured expectation values by comparing them with the output of exactly verifiable circuits. In the regime of strong entanglement, the quantum computer provides correct results for which leading classical approximations such as pure-state-based 1D (matrix product states, MPS) and 2D (isometric tensor network states, isoTNS) tensor network methods[2,3] break down. These experiments demonstrate a foundational tool for the realization of near-term quantum applications[4,5].

https://www.nature.com/articles/s41586-023-06096-3

- **127 qubits Kyiv model with 1% CNOT error rate. 4h and 9.5h execution times on QPU (including 5 mn in the QPU) and 8-32h on single CPU with MPS version.**
- **using a ZNE quantum error mitigation.**
- **found a quantum advantage with an Ising model problem.**
- **compared it with MPS-based classical algorithm running on a single CPU classical system.**
- **Response #1:** « *Efficient tensor network simulation of IBM's kicked Ising experiment* » by Joseph Tindall, Matt Fishman, Miles Stoudenmire and Dries Sels, June 2023 (9 pages). 2 mn on single CPU. https://arxiv.org/abs/2306.14887
- **Response #2:** « *Fast classical simulation of evidence for the utility of quantum computing before fault tolerance* », Caltech. 2 mn on a laptop single core. https://arxiv.org/abs/2306.16372
- **Response #3:** « *Effective quantum volume, fidelity and computational cost of noisy quantum processing experiments* », Google AI. 1s per data point on a Nvidia A100 GPU. https://arxiv.org/abs/2306.15970

**Jay Gambetta** @jaygambetta · Sep 28

While I like what you have done with another approximate classical method you are confusing the difference between simulating the circuit and simulating the processor and I disagree that you can make any conclusions about the processor.

> **Roman Orus** @OrusRoman · Sep 28
>
> We just did some tensor network simulations of large quantum processors arxiv.org/abs/2309.15642

4 · 26 · 7,739

**Roman Orus** @OrusRoman · Sep 28

Hi Jay, sorry for the confusion, I actually agree with you. The simulation is restricted to the actual experiment of the kicked Ising model. The hard instances to simulate with TNs are either long time evolutions or other quantum circuits that generate large entanglement.

1 · 13 · 1,005

**Jay Gambetta** @jaygambetta · Sep 29

Awesome then I think it is on us to make sure we are clear between simulating a circuit and a processor as it will lead to confusion for others not in the field. I would love to see the classical simulator community finding example 100q circuits where their methods breakdown

1 · 4 · 589

**Olivier Ezratty** @olivez · Sep 29

It looks like one challenge is to run QEM corrected quantum circuits with large (maximally) entangled states, in order to bring some quantum advantage beyond tensor network capabilities. Thoughts on the Bar-Ilan U. paper in arxiv.org/abs/2308.01339?

> arxiv.org
>
> Dissipative mean-field theory of IBM utility experi...
>
> In spite of remarkable recent advances, quantum computers have not yet found any useful ...

1 · 1 · 158

**Jay Gambetta**
@jaygambetta

Hi Olivier, nice to hear from you again. Rigorous QEM methods such as PEC have error bounds that only depend on the noise and not on the entanglement in the circuit.

6:44 PM · Sep 29, 2023 · **67** Views

1 · 1

Post your reply

Reply

**Jay Gambetta** @jaygambetta · 17h

Regarding the paper, its easy to see that this simulation doesn't capture the experiment even for the simplest cases where the exact result is known, and even there the experiment does a better job.

1 · 1 · 74

**Jay Gambetta** @jaygambetta · 17h

Im not surprised that the the classical simulation isn't shown for the most complex observables that the experiment measured.

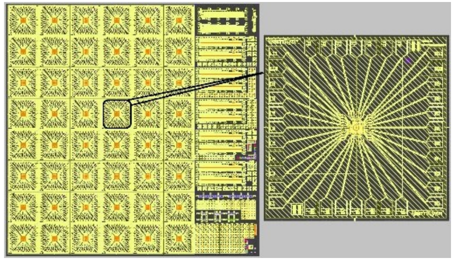
1 · 73

# spin qubits

**created in November 2022**

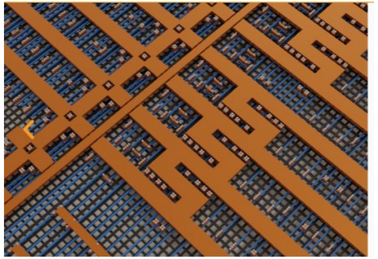
raised 19.5 M€ in July 2023

EIC grant of 2.5 M€ in July 2023



**created in 2023, Sweden**

integrated qubits and cryo-CMOS control on same chip



**first chip "tape out" with 2,432 qubits**

**electron spin on superfluid helium**

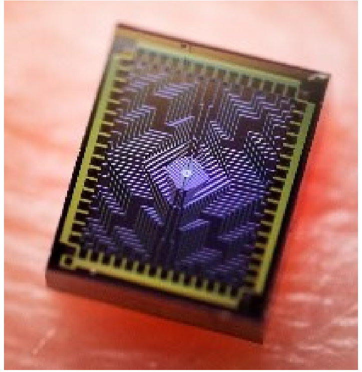
June 2023

**Callisto emulator on OVHcloud**

June 2023

**Tunnel Falls**
**12 qubits**

June 2023



# trapped ions qubits

IONQ

**29 « algorithmic qubits » with the Forte 32 qubit QPU**

**Tempo 64 qubits announced for 2025**

September 2023

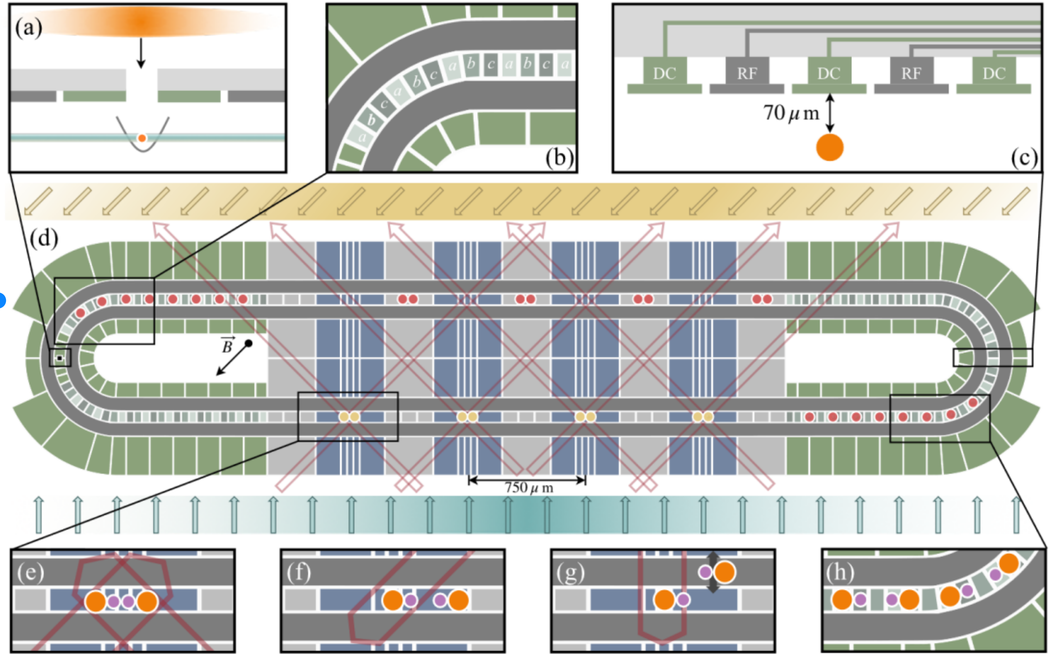
QUANTINUUM

**32 « racetrack » qubit QPU**

May 2023

**$2^{19}$ QV record**

June 2023




Universal Quantum

**65 M€ deal with DLR in Germany**

November 2022

# cold atoms

PASQAL

**raised 100M€**

December 2022

**CACIB case study with Multiverse**

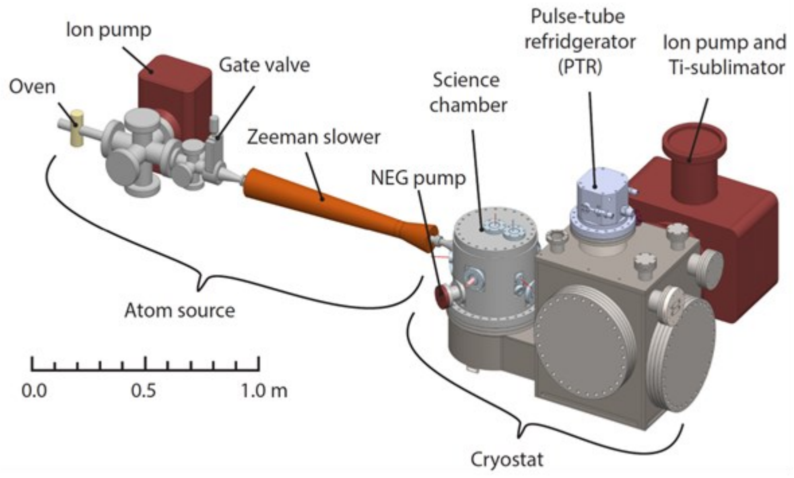
December 2022

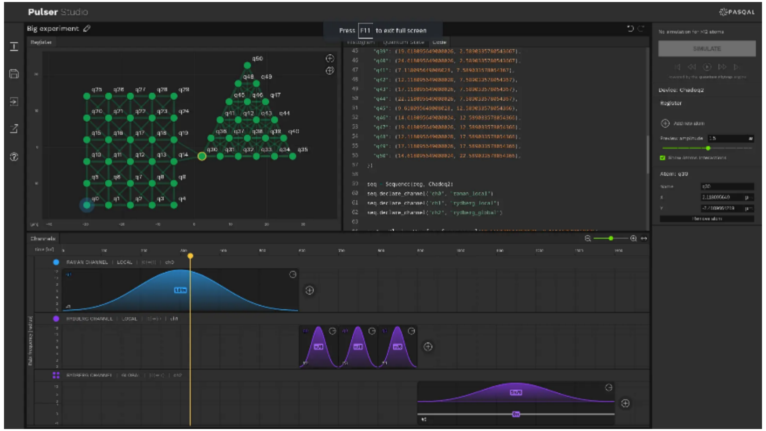
**preparing next generation QPU with >300 atoms**

2023-2024

**Pulser Studio**

January 2023



# photon qubits

QUANDELA

**OVHcloud QPU acquisition**

March 2023

**new fab in Palaiseau**

June 2023

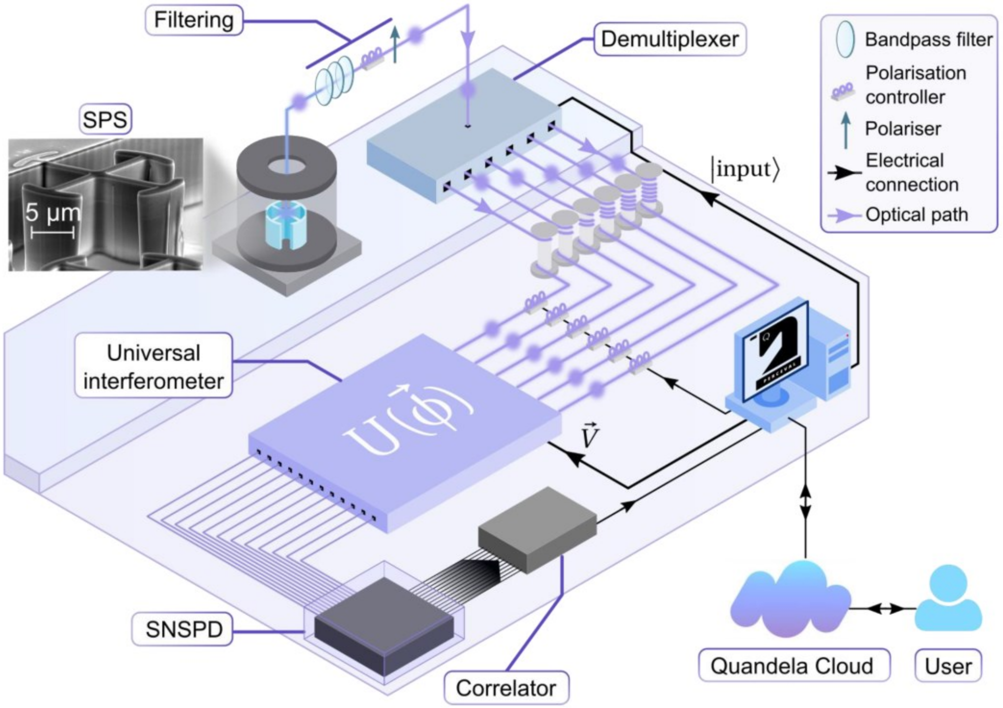
**Quandela Ascella 6 qubit system**
(KLM path-encoding mode)

**progress on photonic cluster state development (C2N)**

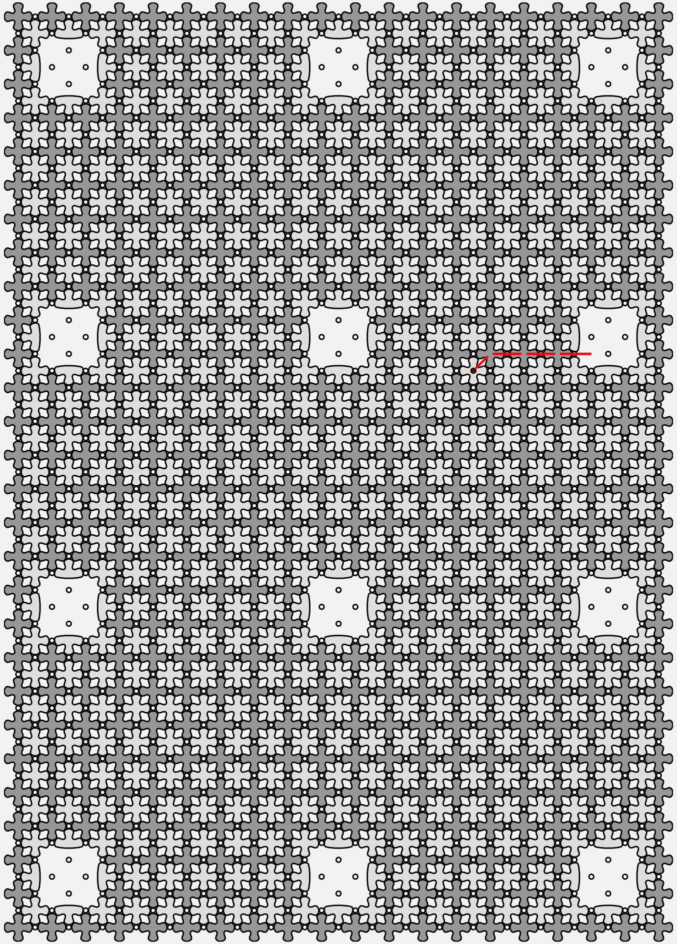
Ψ PsiQuantum

**AFRL 22.5M€ funding**

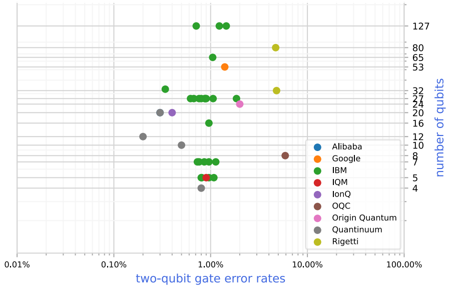
October 2022



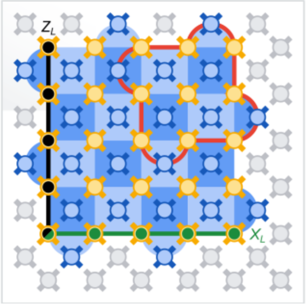
# enjeux de la scalabilité



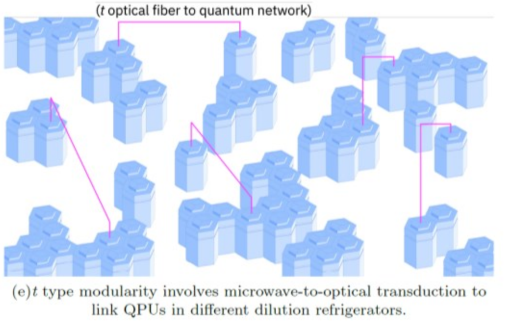
# key scientific and engineering challenges



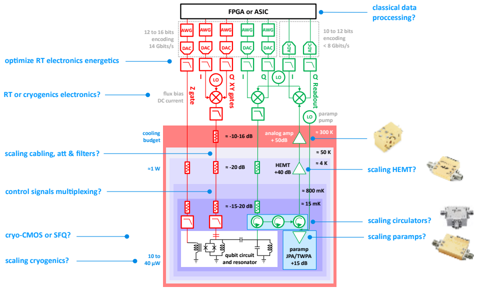

**improve qubits fidelities**




**errors mitigation and correction**




**quantum interconnect**

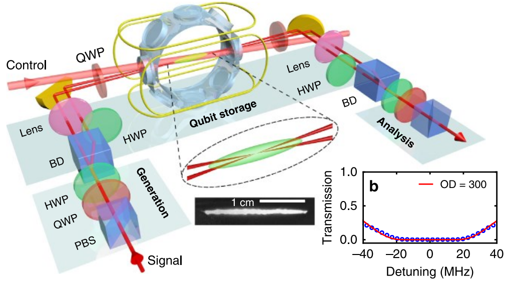



**electronics, cabling and/or cryogeny scalability**

# #QEI

**the quantum energy initiative**

**energy consumption containment or advantage**




**data loading and quantum memory**

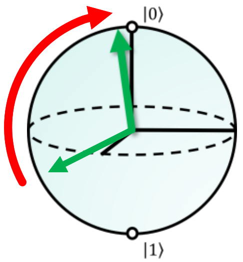
# qubit operations generating errors

**when**

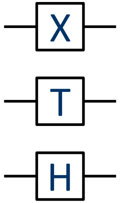
qubit operations when errors are generated

SPAM errors

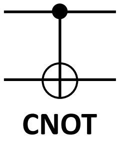
| initialization | 1 qubit gate | 2 qubit gate | idle qubit | readout |
|---|---|---|---|---|



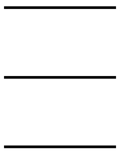

qubit initialization, preparation or reset does not create a perfect $|0\rangle$



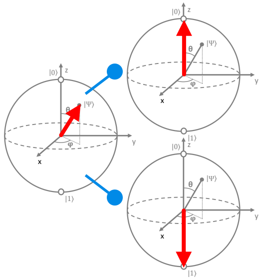

error created while applying a single qubit gate




error created while applying a two qubit gate



error created while doing nothing

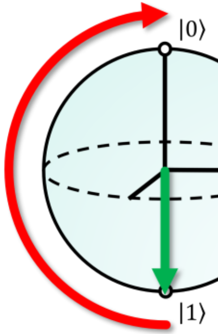


error while reading out the qubit state, impacts QEC and final results

# qubit errors types

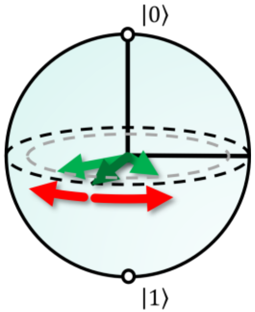
**what**
computational effects of errors on qubits

## flip



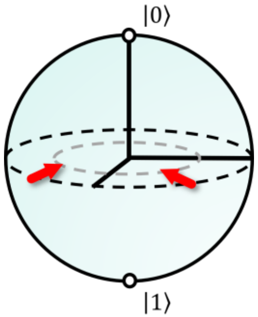

amplitude error, moving the qubit toward |0⟩

## phase



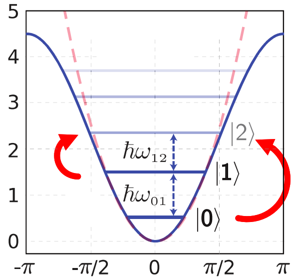

phase error, changing the phase of the qubit

## 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

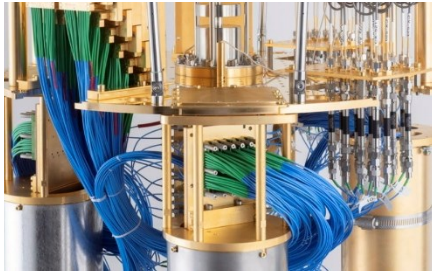
calibration

many body interactions

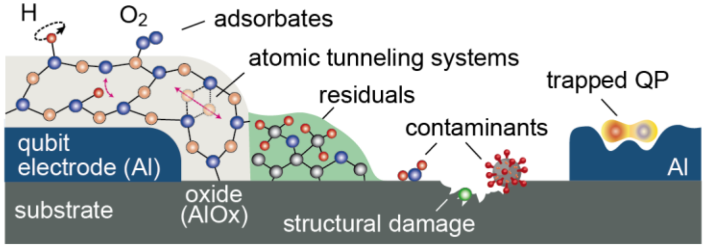
thermal noise

back-action

electromagnetic noise

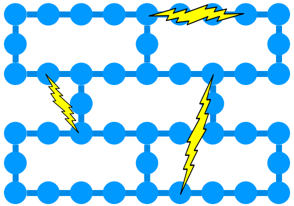


material defects

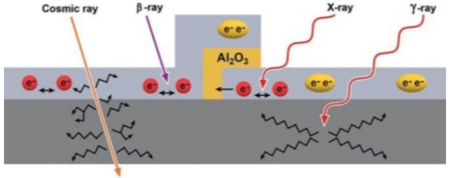



crosstalk

photon loss

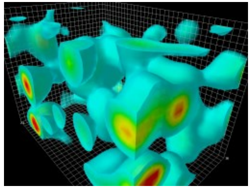


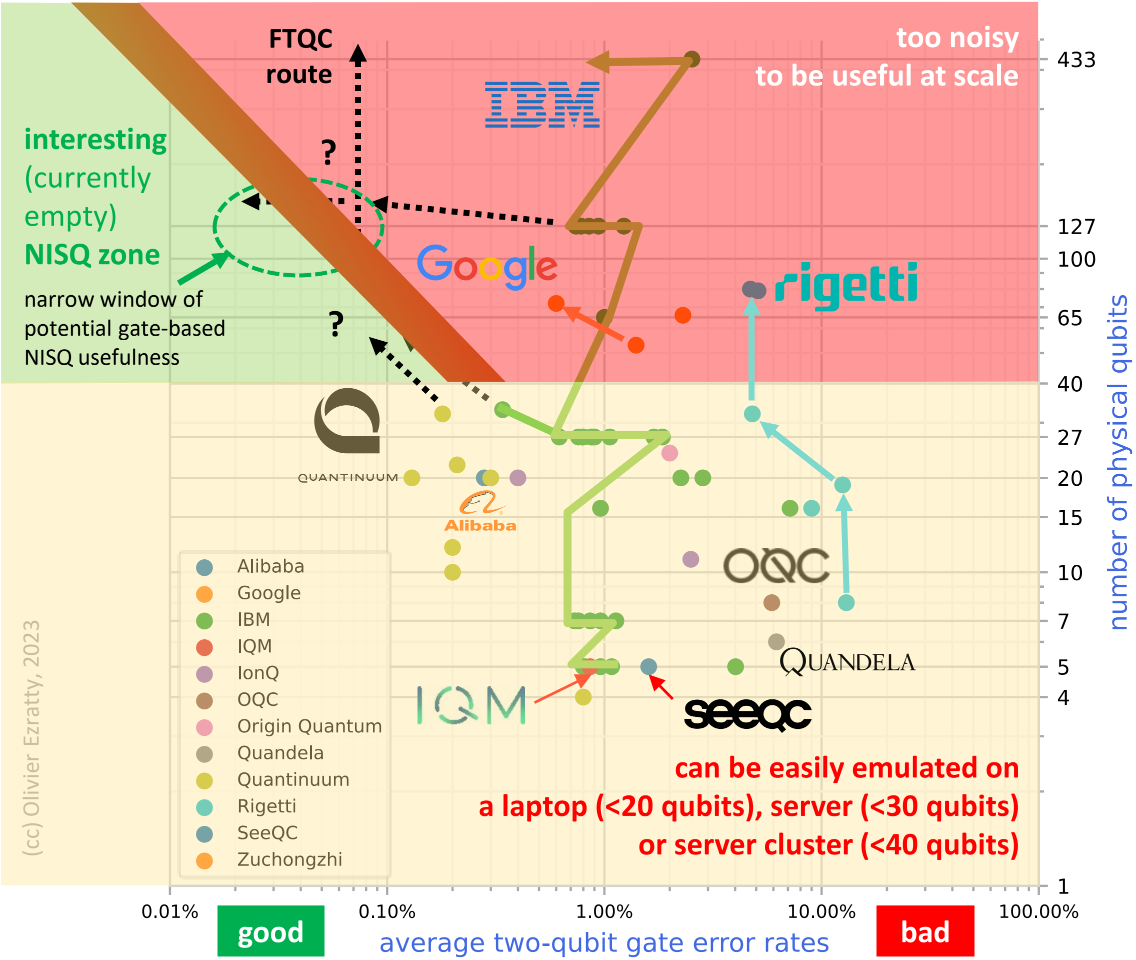
cosmic rays




gravity

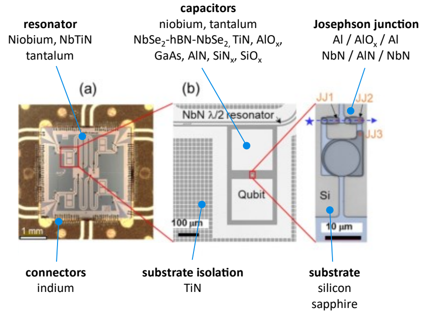
vacuum quantum fluctuations



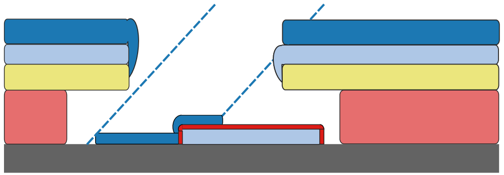


FTQC
route
too noisy
to be useful at scale
interesting
(currently
empty)
NISQ zone
narrow window of
potential gate-based
NISQ usefulness
?
?
433
127
100
65
40
27
20
15
10
7
5
4
1
number of physical qubits
Alibaba
Google
IBM
IQM
IonQ
OQC
Origin Quantum
Quandela
Quantinuum
Rigetti
SeeQC
Zuchongzhi
can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

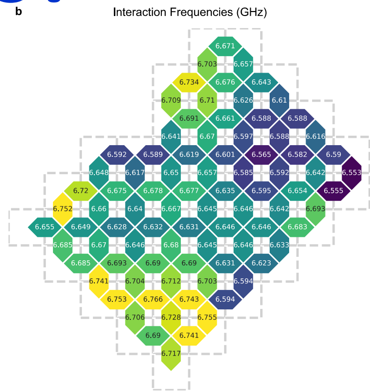
# how to improve qubit fidelities? *



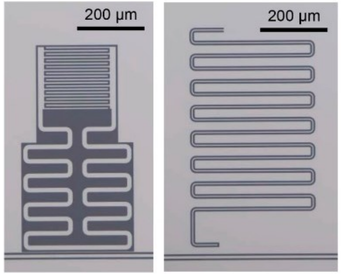

**materials**



**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]

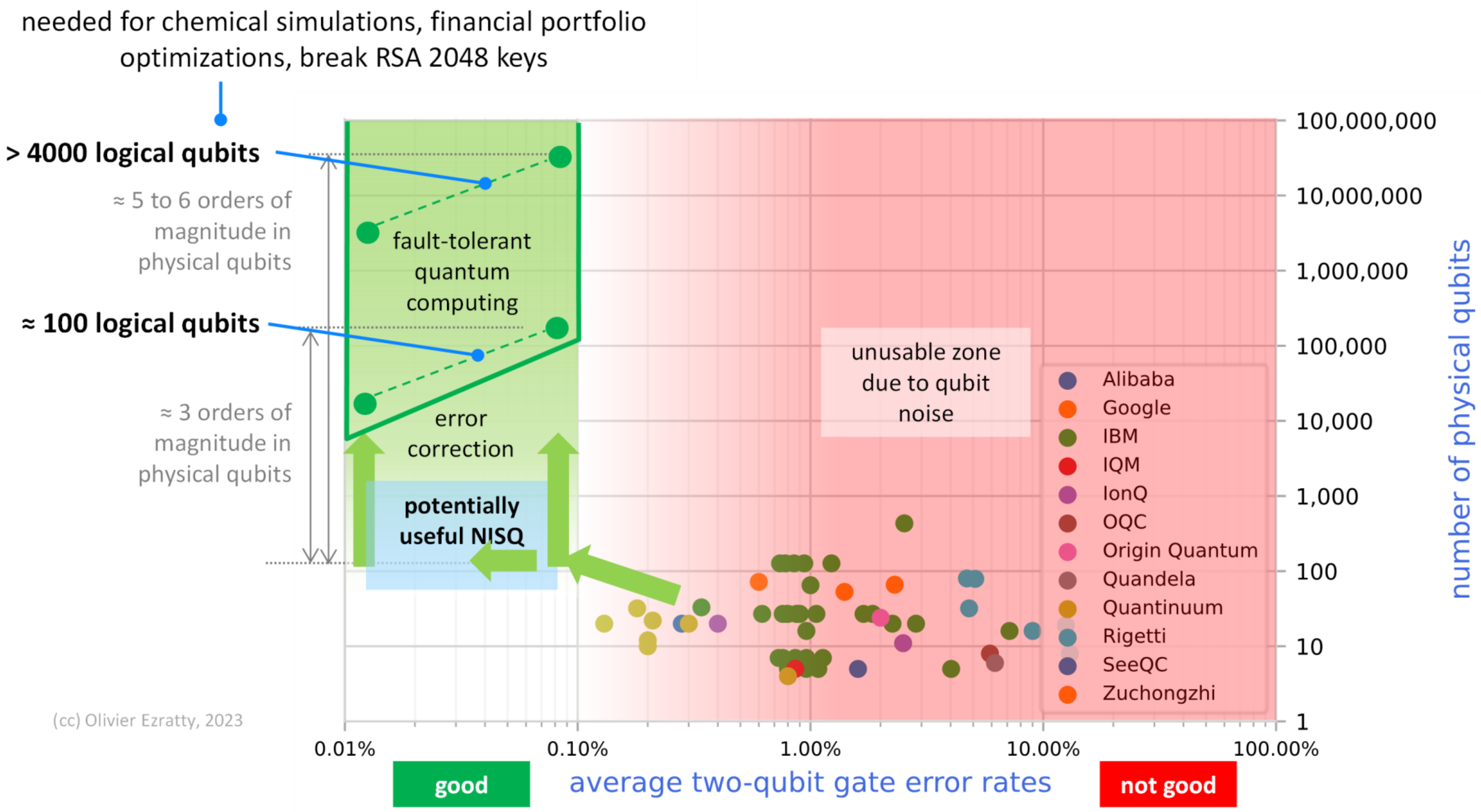
[1] *Computational Research Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2] *Department of Physics, University of California, Berkeley, California 94720, USA*
[3] *Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*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

**use different primary gates**

**improve control signals quality**

* using here the example of superconducting qubits

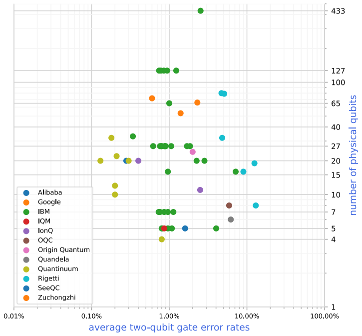
| criteria | **QEM**<br>quantum error mitigation | **QEC**<br>quantum error correction |
| --- | --- | --- |
| **goals** | reduce circuit errors with classical **post-processing** techniques | create longer lifetime **logical qubits** with apparent lower error rates |
| **techniques** | **probabilistic approach**, circuits modifications, several runs, regressions and machine learning | **surface codes**, color codes, LDPC codes, Floquet codes, etc.<br>associated with FTQC |
| **figures of merit** | circuit shots overhead, classical overhead | logical qubit target error rate, physical/logical qubit ratios, classical overhead |
| **overhead** | **more circuit shots**<br>classical post-processing | **more physical qubits**<br>longer circuit execution time |
| **timing** | **short term**<br>NISQ realm | **long-term**<br>FTQC realm |

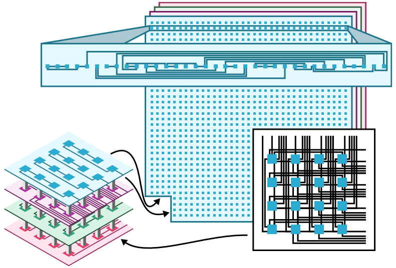


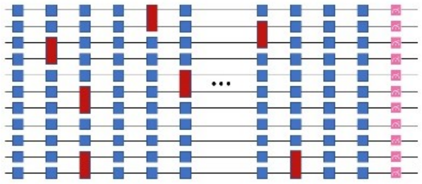
needed for chemical simulations, financial portfolio optimizations, break RSA 2048 keys
> 4000 logical qubits
≈ 5 to 6 orders of magnitude in physical qubits
≈ 100 logical qubits
≈ 3 orders of magnitude in physical qubits
fault-tolerant quantum computing
error correction
potentially useful NISQ
unusable 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

# # qubits for FTQC?

>99.9%



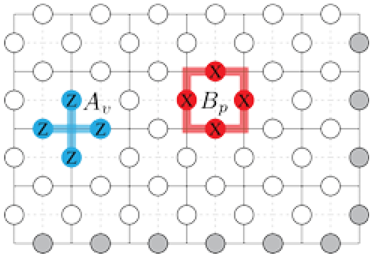





algorithm breadth and depth

$n_T$ = # of T gates in algorithm

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




physical qubits fidelities

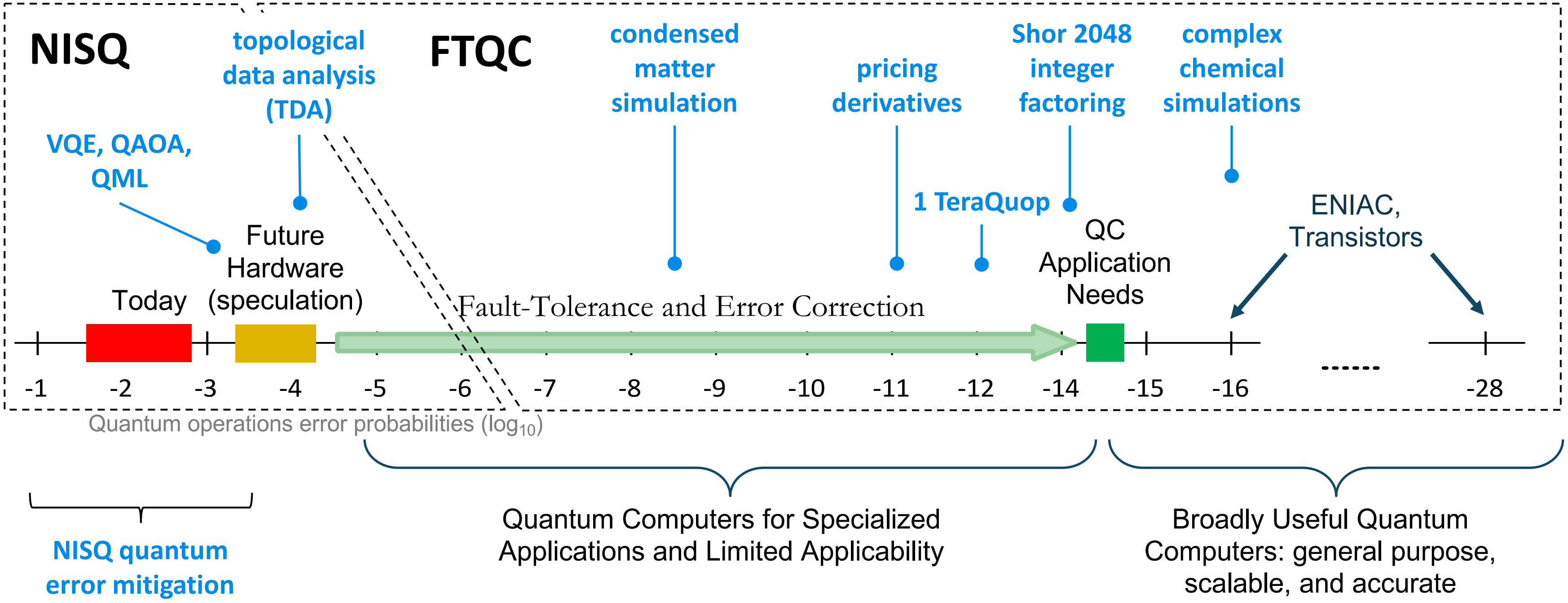
physical qubits connectivity

error correction code

# physical qubits / logical qubit

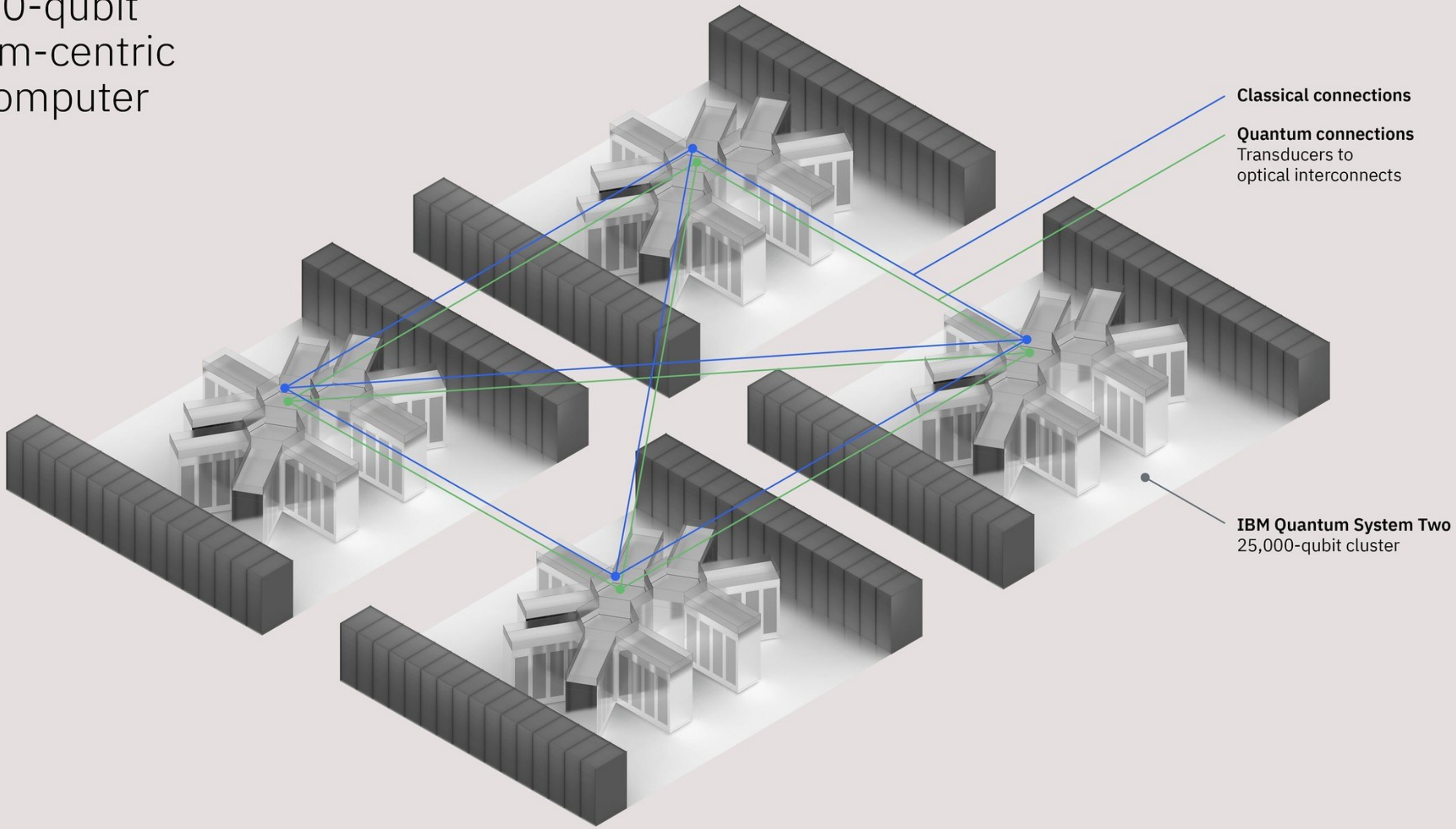
dynamically adjusted against the algorithm size

# from NISQ to FTQC




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

# 100,000-qubit quantum-centric supercomputer
—
2033




IBM **Quantum**

# analyse des études de cas

# assessing QC case studies

**PReQaCAQD**

| criteria | possible values |
| --- | --- |
| problem sizing | small scale case study · indication of real-life use case sizing · case study with real-life size business needs |
| resource estimates | no · qubit # and fidelities in case and with real business need · classical resources · time estimates |
| quantum advantage nature | tested with <30 qubits · speedup · result quality · other · energy footprint · TCO ROI |
| classical comparison | no comparison · honest comparison with best-in-class classical algorithms and hardware, incl. quantum inspired |
| algorithm advancement | nothing new · something new in the case study vs state of the art which turns other flags in green |
| quantum computer type | quantum inspired · present analog · future analog · present NISQ · future NISQ · FTQC |
| documentation | press release or vendor web site · arXiv preprint · peer reviewed journal paper |

THE QUANTUM INSIDER

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# Quantinuum's Quantum Monte Carlo Integration Engine Shows Early Stage Quantum Advantage

Quantum Computing Business, Research · Matt Swayne • September 13, 2023

## A MODULAR ENGINE FOR QUANTUM MONTE CARLO INTEGRATION


ISMAIL YUNUS AKHALWAYA [1,3], ADAM CONNOLLY [1], ROLAND GUICHARD [1,†], STEVEN HERBERT [1,4], CAHIT KARGI [1], ALEXANDRE KRAJENBRINK [1], MICHAEL LUBASCH [2], CONOR MC KEEVER [2], JULIEN SORCI [1], MICHAEL SPRANGER [1], IFAN WILLIAMS [1]

[1] *Quantinuum, Terrington House, 13–15 Hills Road, Cambridge CB2 1NL, United Kingdom*

[2] *Quantinuum, Partnership House, Carlisle Place, London SW1P 1BX, United Kingdom*

[3] *School of Computer Science and Applied Mathematics, University of the Witwatersrand, Johannesburg, South Africa*

[4] *Department of Computer Science and Technology, University of Cambridge, United Kingdom*



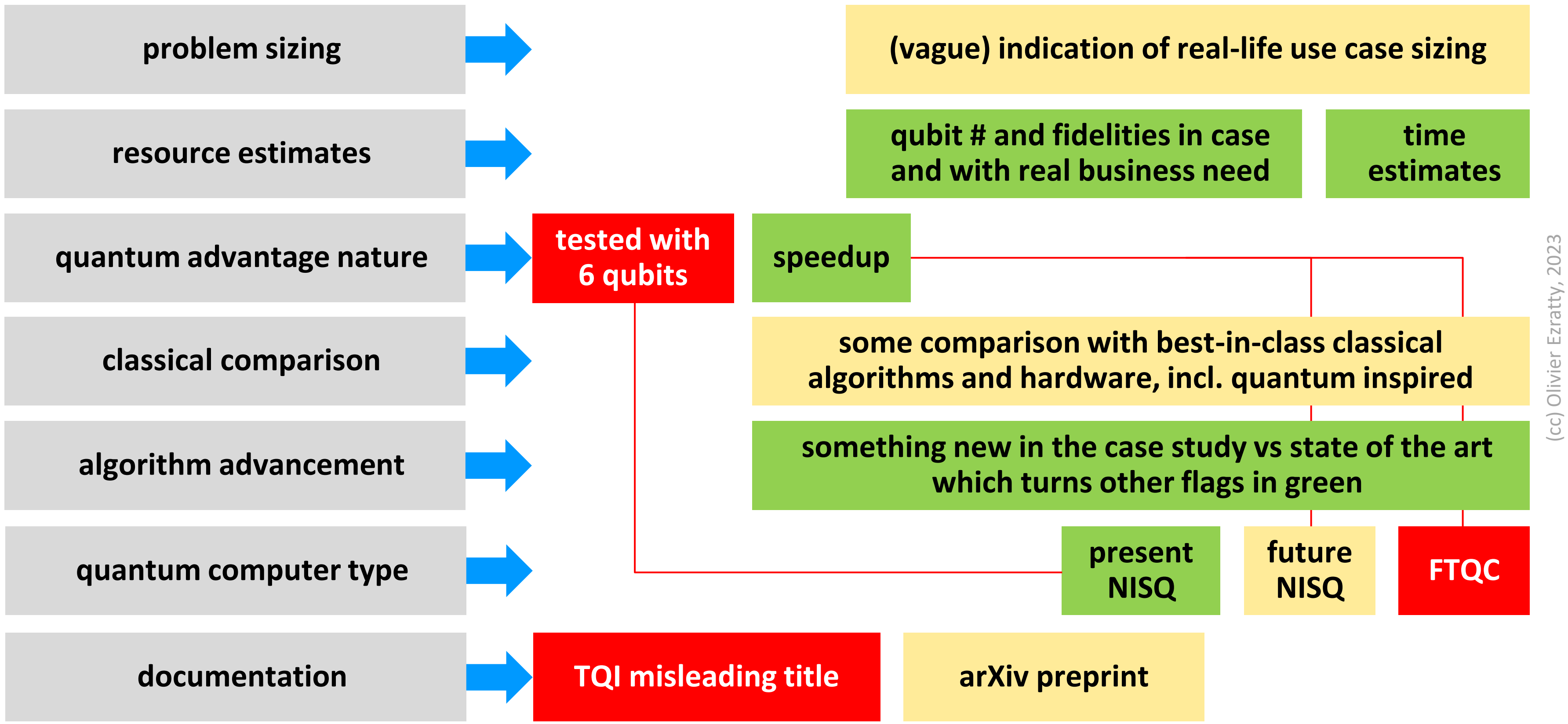
ABSTRACT. We present the Quantum Monte Carlo Integration (QMCI) engine developed by Quantinuum. It is a quantum computational tool for evaluating multi-dimensional integrals that arise in various fields of science and engineering such as finance. This white paper presents a detailed description of the architecture of the QMCI engine, including a variety of distribution-loading methods, a novel quantum amplitude estimation method that improves the statistical robustness of QMCI calculations, and a library of statistical quantities that can be estimated. The QMCI engine is designed with modularity in mind, allowing for the continuous development of new quantum algorithms tailored in particular to financial applications. Additionally, the engine features a resource mode, which provides a precise resource quantification for the quantum circuits generated. The paper also includes extensive benchmarks that showcase the engine's performance, with a focus on the evaluation of various financial instruments.


https://arxiv.org/abs/2308.06081

"The new white paper sets out the areas that stand to benefit from the development of QMCI, beyond finance, including achieving efficiencies in supply chain and logistics, energy production and transmission, and data-intensive fields of science such as solving the high-dimensional integrals in high-energy physics. **It concludes that use cases such as estimation and forecasting can benefit from the new QMCI engine in its current form"**.

**tested with 6 qubits!**

"Accordingly, it is entirely reasonable to speculate that a future quantum computer with **~100 qubits and two-qubit gate fidelity ~99.99% should be capable of running some simple, but not trivial financial QMCI calculations**. However, whilst such a putative future quantum computer may be able to obtain an advantage in sample complexity for a non-trivial financial Monte Carlo integral – which would itself constitute a valuable outcome – **it is doubtful that it would make practical sense to price such an option on a quantum computer**, as we discuss in more detail in Section 12".


problem sizing
resource estimates
quantum advantage nature
classical comparison
algorithm advancement
quantum computer type
documentation
(vague) indication of real-life use case sizing
qubit # and fidelities in case and with real business need
time estimates
tested with 6 qubits
speedup
some comparison with best-in-class classical algorithms and hardware, incl. quantum inspired
something new in the case study vs state of the art which turns other flags in green
present NISQ
future NISQ
FTQC
TQI misleading title
arXiv preprint
(cc) Olivier Ezratty, 2023

# Schnorr schneller than Shor?

FINANCIAL TIMES

US COMPANIES TECH MARKETS CLIMATE OPINION WORK & CAREERS LIFE & ARTS HTSI

Quantum technologies + Add to myFT

## Chinese researchers claim to find way to break encryption using quantum computers

Experts assess whether method outlined in scientific paper could be a sooner-than-expected turning point in the technology

- **hybrid QAOA based algorithm using classical "Schnorr" algorithm.**
- **would require 372 NISQ physical qubits and 1139-1490 gate depth.**
- **QAOA doesn't scale well.**
- **classical and quantum part speedup/time are not provided.**
- **NISQ qubit noise would require some QEC and a much larger number of qubits.**

**Factoring integers with sublinear resources on a superconducting quantum processor**


Bao Yan,[1,2,*] Ziqi Tan,[3,*] Shijie Wei,[4,*] Haocong Jiang,[5] Weilong Wang,[1] Hong Wang,[1] Lan Luo,[1] Qianheng Duan,[1] Yiting Liu,[1] Wenhao Shi,[1] Yangyang Fei,[1] Xiangdong Meng,[1] Yu Han,[1] Zheng Shan,[1] Jiachen Chen,[3] Xuhao Zhu,[3] Chuanyu Zhang,[3] Feitong Jin,[3] Hekang Li,[3] Chao Song,[3] Zhen Wang,[3,†] Zhi Ma,[1,‡] H. Wang,[3] and Gui-Lu Long[2,4,6,7,§]

[1] *State Key Laboratory of Mathematical Engineering and Advanced Computing, Zhengzhou 450001, China*
[2] *State Key Laboratory of Low-Dimensional Quantum Physics and Department of Physics, Tsinghua University, Beijing 100084, China*
[3] *School of Physics, ZJU-Hangzhou Global Scientific and Technological Innovation Center, Interdisciplinary Center for Quantum Information, and Zhejiang Province Key Laboratory of Quantum Technology and Device, Zhejiang University, Hangzhou 310000, China*
[4] *Beijing Academy of Quantum Information Sciences, Beijing 100193, China*
[5] *Institute of Information Technology, Information Engineering University, Zhengzhou 450001, China*
[6] *Beijing National Research Center for Information Science and Technology and School of Information Tsinghua University, Beijing 100084, China*
[7] *Frontier Science Center for Quantum Information, Beijing 100084, China*


https://arxiv.org/abs/2212.12372, December 23rd, 2022


« Happy 40th Birthday Dana!

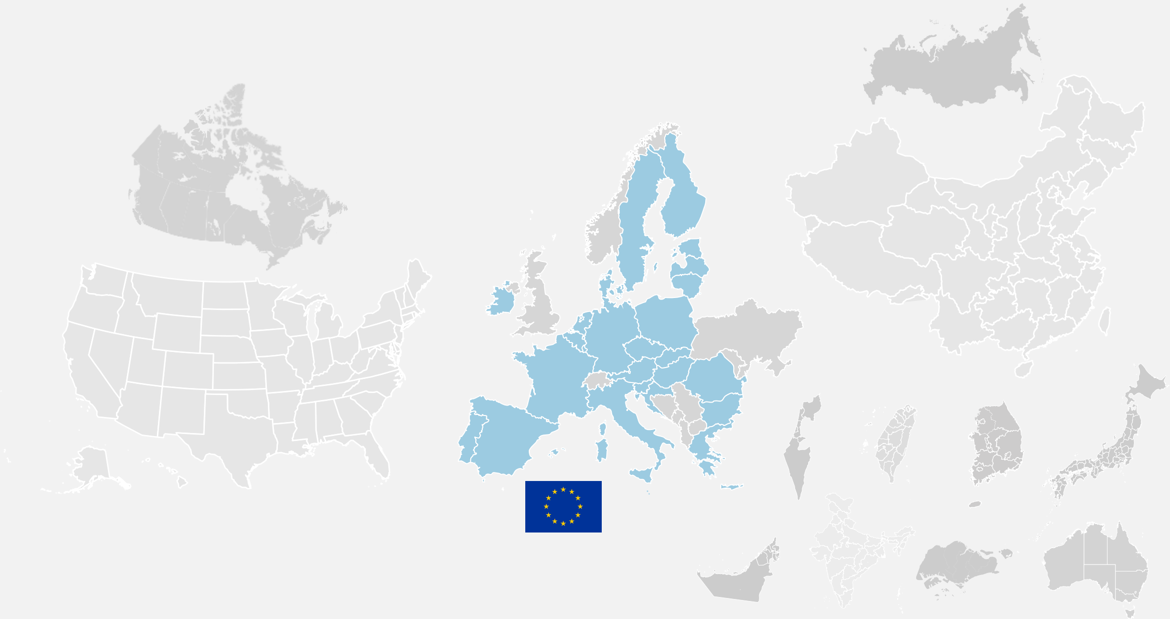
### Cargo Cult Quantum Factoring

For those who don't care to read further, here is my 3-word review:

**No. Just No.**

And here's my slightly longer review:

# géopolitique

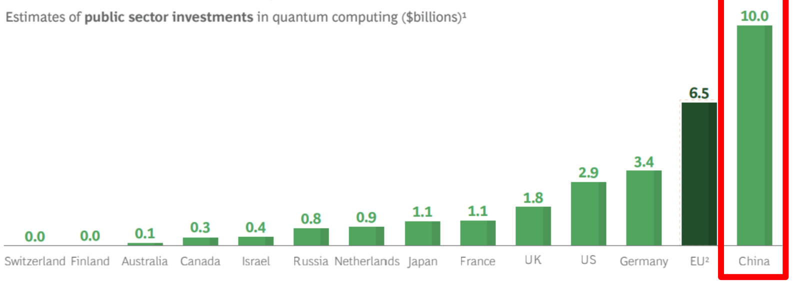


# the China quantum investment hoax

## Exhibit 6 - Ranking Countries by Government Investments in Quantum Computing

China is the front-runner, but the EU is competitive

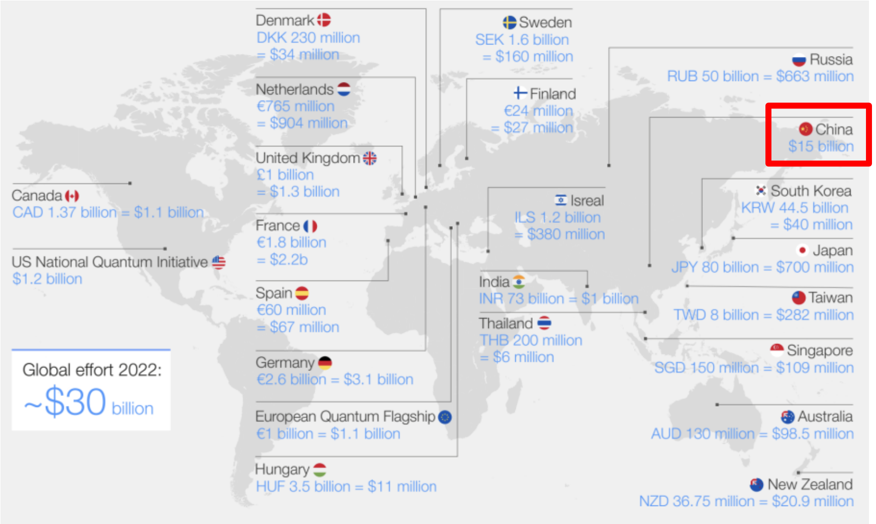
Estimates of **public sector investments** in quantum computing ($billions)[1]




**Sources:** Literature search; BCG analysis.

[1]The data in this exhibit represents public announcements made after 2013; investments may be made for different time horizons.

[2]Investments made centrally by the EU (~$1.1 billion) as well as those made by Germany, France, the Netherlands, and Finland.

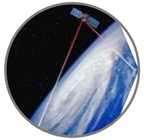



"An Assessment of the U.S. and Chinese Industrial Bases in Quantum Technology" by Edward Parker, Rand Corporation, February 2022 (140 pages) : « *In summary, official reports of the PRC's government investment in quantum R&D in recent years have varied widely, from a low of $84 million per year (Pan's estimate) to a high of at least $3 billion per year (the Anhui Business Daily's reported funding for Pan's laboratory). We are unable to assess from public information which figure is more accurate. By comparison, the U.S. government has spent $450–$710 million per year in recent years; we cannot determine whether the PRC total is higher or lower than this amount.*".

### Overview of the major Chinese government QC programs

- 2006-2010 (Eleven Five-Year Plan) ~1 billion CNY
- 2011-2016 (Twelve Five-Year Plan) ~5 billion CNY
- 2016-present (Thirteen Five-Year Plan) ~2 billion CNY

~4 billion CNY from Anhui , Shanghai, Shandong, etc. Province



Quantum communication

Quantum computation and simulation

Quantum Metrology

China's quantum investments from 2006 to 2021 did not exceed $1.8B. This number is very different from the $10B to $15B investment showcased in various analyst publications. These >$10B numbers are false and based on fuzzy propaganda coming from China and amplified by various US interests. Source: Chinese QC Funding by Xiaobo Zhu, 2017 (35 slides). And… 1 CNY ≈ 0.14 US $.

At the campuses of the University of Science and Technology of China, four competing quantum-computing technologies are being developed in parallel. In a paper published in *Science*, in 2020, a team led by the scientists Lu Chao-Yang and Pan Jian-Wei announced that their processor had solved a computational task millions of times faster than the best super

quan

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then

one i

Lu and I spoke by video earlier this year. He joined the call late and was covered in sweat, having sprinted home from a mandatory COVID test. Lu immediately began debunking claims made by his competitors, and even claims made about his own effort. One widely reported figure stated that China has invested fifteen billion dollars in developing a quantum computer. "I have no idea how that was started," Lu said. "The actual money is maybe twenty-five per cent of that."

ANNALS OF TECHNOLOGY DECEMBER 19, 2022 ISSUE

# THE WORLD-CHANGING RACE TO DEVELOP THE QUANTUM COMPUTER

*Such a device could help address climate change and food scarcity, or break the Internet. Will the U.S. or China get there first?*

By Stephen Witt

December 12, 2022

# industry vendors ecosystem

## computing

- 本源量子 Origin Quantum
- Baidu 百度
- Alibaba
- 图灵量子 TURINGQ
- Boson
- SPINQ 量旋科技
- Tencent

## software

- ARCLIGHT 弧光量子
- 本源量子 Origin Quantum
- KUNFENG 昆峰量子

## telecom and cybersecurity

- 国盾量子 QuantumCTek
- asky
- QUDOOR 启科量子
- 循态量子 XT Quantech
- 量子网络 CAS QUANTUMNET
- HUAWEI
- ZTE
- 中国电信 CHINA TELECOM

## sensing

- 国仪量子 CIQTEK
- Guoyao Quantum Radar Technology

## electronics

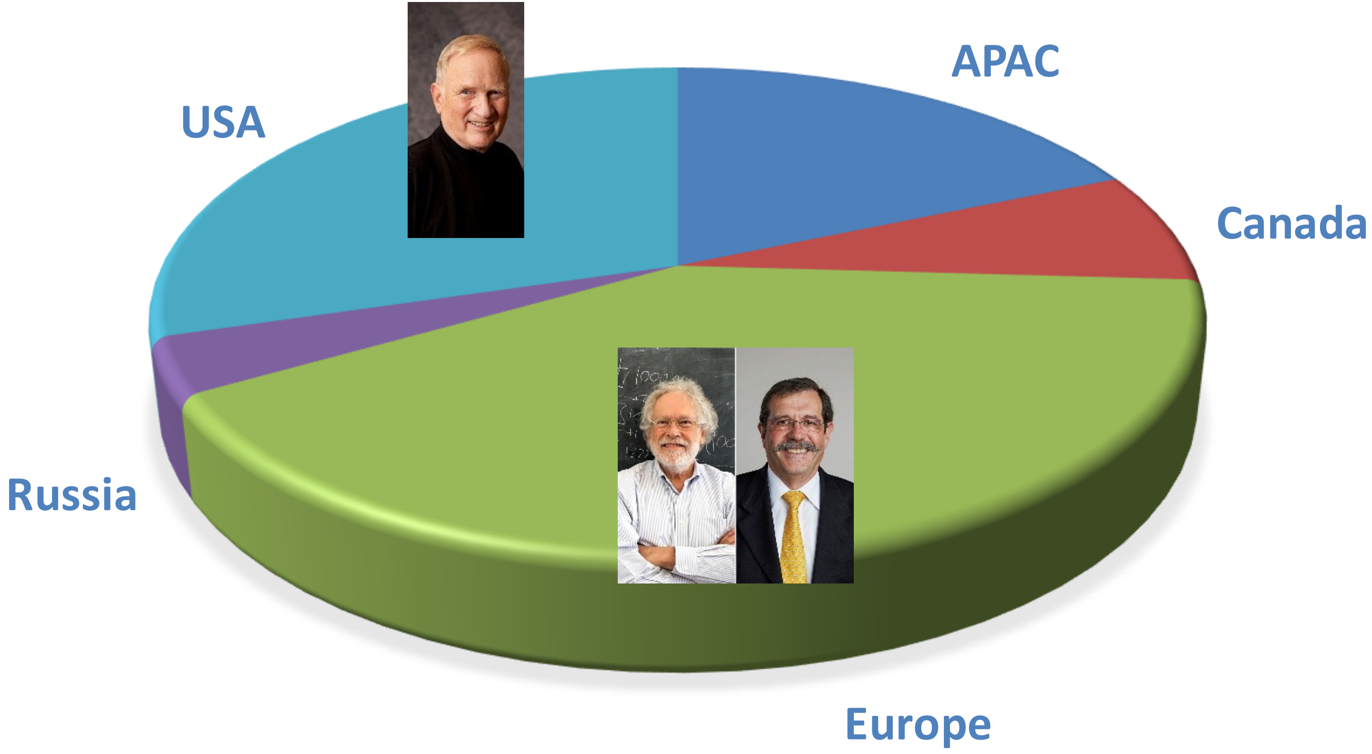
- CIQTEK
- 本源量子 Origin Quantum

## cryogeny

- Shan Lei and Wang Shaoliang project
- 本源量子 Origin Quantum

# Nobel prizes in physics

**share of Nobel prizes in physics since 2004**



# what can be benchmarked in QC?

THALES BACQ

EVIDEN qscore

SupermarQ

QED-C

TU Delft: QPack

IBM CLOPS

randomized benchmarking

IBM QV

level of abstraction

higher-level algorithms

low-level algorithms

speed

qubit fidelities

qubits number

metriq

benchmarks repository

resources energetics

#QEI the quantum energy initiative

IEEE

Raytheon Technologies

DARPA

# industry vendors ecosystem

**computing**
- PASQAL
- ALICE & BOB
- C12
- quobly
- QUANDELA
- CRYSTAL QUANTUM COMPUTING
- EVIDEN an atos business

**software**
- Qubit pharmaceuticals
- EVIDEN an atos business
- QuantFi
- mol|ket⟩
- QPerfect
- QbitSoft Quantum as a Service
- VeriQloud
- ColibrITD
- AQEMIA

**cybersecurity**
- CRYPTONEXT SECURITY
- Crypto Experts
- ravel
- SECURE-IC THE SECURITY SCIENCE COMPANY
- CYFERALL
- QuRISK⟩ ADVISORY

**photonics**
- cailabs SHAPING THE LIGHT
- Lytid
- exail
- SPARK LASERS
- LUMIBIRD
- AUREA TECHNOLOGY
- AZURLIGHT SYSTEMS
- GLOphotonics
- QUANDELA

**sensing**
- THALES
- exail
- wainvam
- Syrlinks
- orolia
- chipiron
- MAG 4He alth

**cryogeny**
- Air Liquide
- CryoConcept
- INNOVATIVE SOLUTIONS ABSOLUT SYSTEM
- MYCRYOFIRM CRYOGENIC SOLUTIONS

**electronics**
- SILENT WAVES
- Vigthor
- Welinq
- Radiall
- ATEM
- SILENTSYS ultralow noise systems

**manufacturing**
- PLASSYS
- RIBER
- SERMA TECHNOLOGIES

**materials**
- orano
- DIAMFAB
- HIQUTE DIAMOND

# industry vendors *today*

**computing**
- quobly
- QUANDELA
- EVIDEN an atos business

**software**
- EVIDEN an atos business

**cybersecurity**
- CRYPTONEXT SECURITY
- QuRISK ADVISORY

**sensing**
- THALES
- chipiron
- MAG4Health

**cryogeny**
- INNOVATIVE SOLUTIONS ABSOLUT SYSTEM

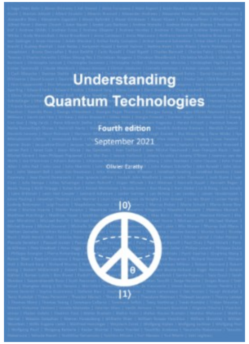
**electronics**
- SILENT WAVES
- Radiall

**photonics**
- QUANDELA

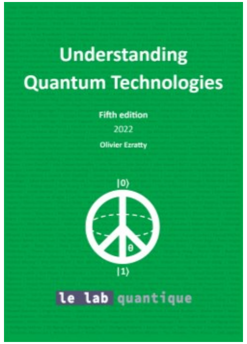
**manufacturing**
- RIBER
- SERMA TECHNOLOGIES

**materials**
- DIAMFAB

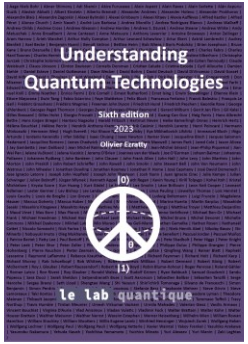
# en savoir plus...




2021, 834 pages
**outdated**




2022, 1132 pages
**outdated**




2023, 1364 pages
**up to date**

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**Decode Quantum** : entretiens du Quantique (62 épisodes)