DA VINCI DIALOGUES

# SÉMINAIRE DEEP TECH

**9-10 AVRIL 2024**

**CHÂTEAU LOUISE DE LA VALLIÈRE**
REUGNY, INDRE-ET-LOIRE


## À LA DÉCOUVERTE DES TECHNOLOGIES QUANTIQUES

**Olivier Ezratty**

# à la découverte des technologies quantiques

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⟨ auteur | … ⟩

Tours, 10 avril 2024

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14 May 2018
Alain Aspect
Fanny Bouton
at OVHcloud since June 2020

# sciences used with quantum technologies

**physics**

electromagnetism
quantum physics
quantum matter
thermodynamics
fluids mechanics
photonics

**engineering**

materials design
electronics engineering
cryogenics

**mathematics**

linear algebra
groups theory
analysis
complexity theories

**computer science**

information theory
algorithms design
programming
classical computing
telecommunications
machine learning

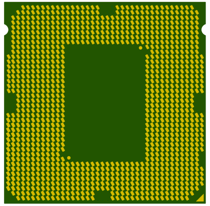
**human sciences**

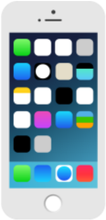
philosophy
epistemology
sociology
technology ethics
economics of innovation
R&D policy making
geopolitics
startups ecosystem

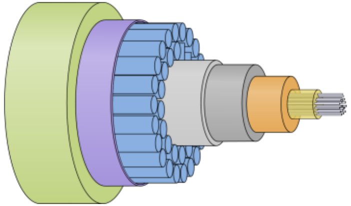
# 1st and 2nd quantum revolutions

## first quantum revolution

manipulating
**groups of quantum particles**
photons, electrons and atoms interactions





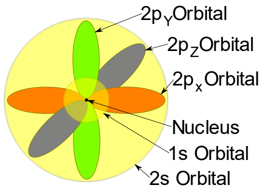


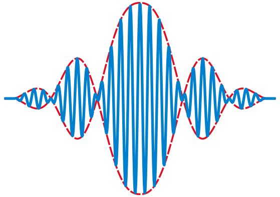
**transistors, lasers, fiber optics, GPS**
**photovoltaic cells, atom clocks**
**medical imaging, digital photography and video**
**LEDs, LCD TV quantum dots**

1947-*

## second quantum revolution

manipulating
**superposition** and **entanglement**
and/or **individual particles**

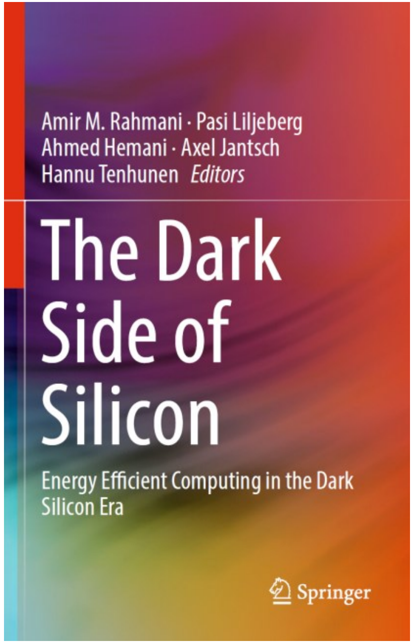


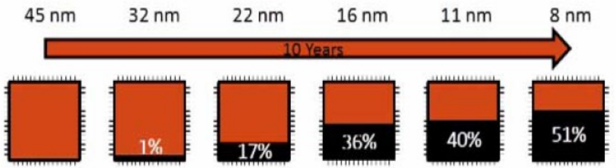



**quantum computing**
**quantum telecommunications**
**quantum cryptography**
**quantum sensing**

1982-*

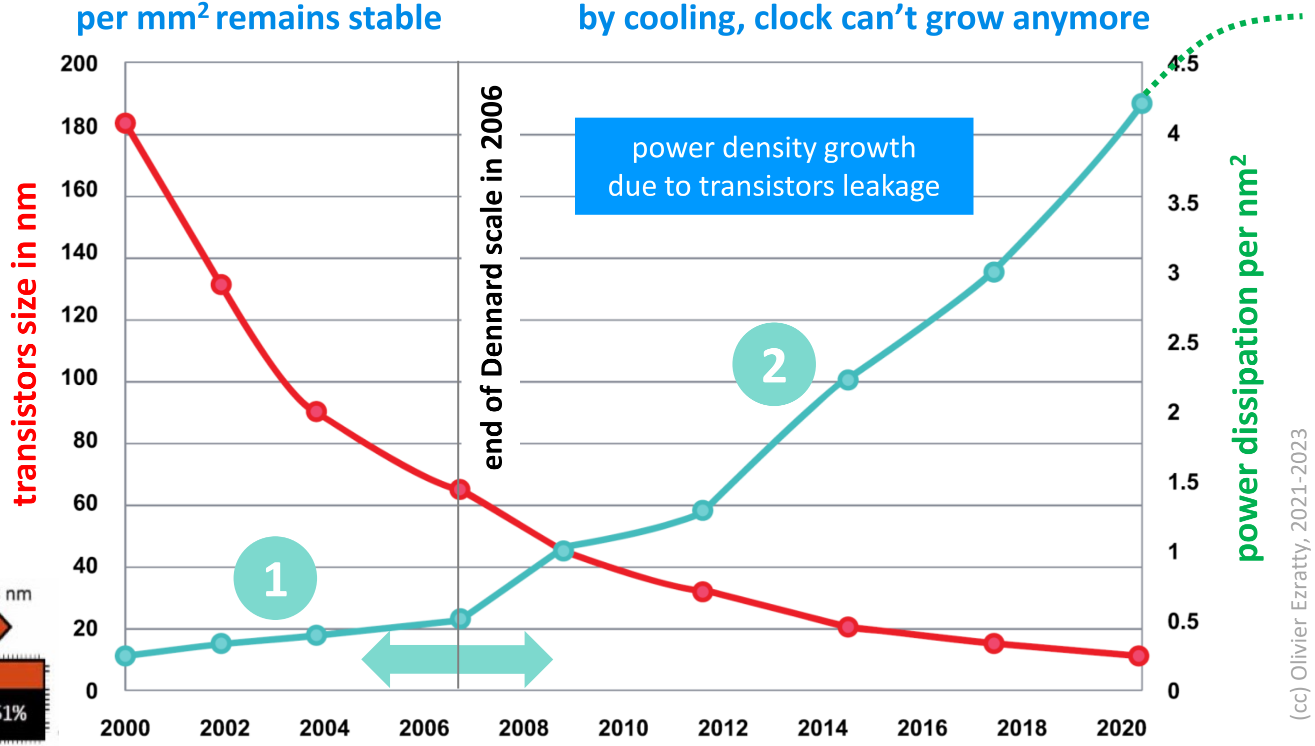
# end of Dennard scale in 2006




transistors density increases + clock but power consumption per mm² remains stable

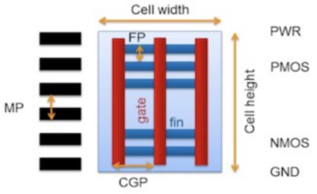
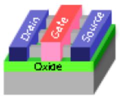
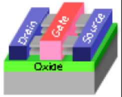
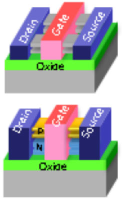
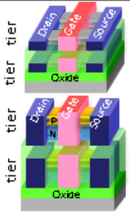
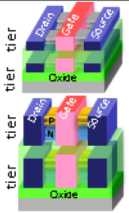
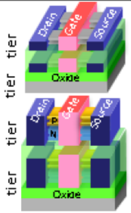
since 2006, this power density increases and can't easily be absorbed by cooling, clock can't grow anymore



International Roadmap for Devices and Systems 2022 update “More Moore”, 2022 (39 pages).

## Table MM-7 Device Architecture and Ground Rules Roadmap for Logic Devices.

*Note: GxxMxx/Tx notation refers to Gxx: contacted gate pitch, Mxx: tightest metal pitch in nm, Tx: number of tiers. This notation illustrates the technology pitch scaling capability. On top of pitch scaling there are other elements such as cell height, number of stacked devices, DTCO constructs, 3D integration, etc. that define the target area scaling (gates/mm²).*

| YEAR OF PRODUCTION | 2022 | 2025 | 2028 | 2031 | 2034 | 2037 |
|---|---|---|---|---|---|---|
| | G48M24 | G45M20 | G42M16 | G40M16/T2 | G38M16/T4 | G38M16/T6 |
| Logic industry "Node Range" Labeling | "3nm" | "2nm" | "1.5nm" | "1.0nm eq" | "0.7nm eq" | "0.5nm eq" |
| Fine-pitch 3D integration scheme | Stacking | Stacking | Stacking | 3DVLSI | 3DVLSI | 3DVLSI |
| Logic device structure options | finFET LGAA | LGAA | LGAA CFET-SRAM | LGAA-3D CFET-SRAM | LGAA-3D CFET-SRAM | LGAA-3D CFET-SRAM |
| Platform device for logic | finFET | LGAA | LGAA CFET-SRAM | LGAA-3D CFET-SRAM-3D | LGAA-3D CFET-SRAM-3D | LGAA-3D CFET-SRAM-3D |
|  |  |  |  |  |  |  |
| LOGIC DEVICE GROUND RULES | | | | | | |
| Mx pitch (nm) | 32 | 24 | 20 | 16 | 16 | 16 |
| M1 pitch (nm) | 32 | 23 | 21 | 20 | 19 | 19 |
| M0 pitch (nm) | 24 | 20 | 16 | 16 | 16 | 16 |
| Gate pitch (nm) | 48 | 45 | 42 | 40 | 38 | 38 |
| Lg: Gate Length - HP (nm) | 16 | 14 | 12 | 12 | 12 | 12 |
| Lg: Gate Length - HD (nm) | 18 | 14 | 12 | 12 | 12 | 12 |
| Channel overlap ratio - two-sided | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| Spacer width (nm) | 6 | 6 | 5 | 5 | 4 | 4 |
| Spacer k value | 3.5 | 3.3 | 3.0 | 3.0 | 2.7 | 2.7 |
| Contact CD (nm) - finFET, LGAA | 20 | 19 | 20 | 18 | 18 | 18 |
| Device architecture key ground rules | | | | | | |
| Device lateral pitch (nm) | 24 | 26 | 24 | 24 | 23 | 23 |
| Device height (nm) | 48 | 52 | 48 | 64 | 60 | 56 |
| FinFET Fin width (nm) | 5.0 | | | | | |
| Footprint drive efficiency - finFET | 4.21 | | | | | |
| Lateral GAA vertical pitch (nm) | | 18.0 | 16.0 | 16.0 | 15.0 | 14.0 |
| Lateral GAA (nanosheet) thickness (nm) | | 6.0 | 6.0 | 6.0 | 5.0 | 4.0 |
| Number of vertically stacked nanosheets on one device | | 3 | 3 | 4 | 4 | 4 |
| LGAA width (nm) - HP | | 30 | 30 | 20 | 15 | 15 |
| LGAA width (nm) - HD | | 15 | 10 | 10 | 6 | 6 |
| LGAA width (nm) - SRAM | | 7 | 6 | 6 | 6 | 6 |
| Footprint drive efficiency - lateral GAA - HP | | 4.41 | 4.50 | 5.47 | 5.00 | 4.75 |
| Device effective width (nm) - HP | 101.0 | 216.0 | 216.0 | 208.0 | 160.0 | 152.0 |
| Device effective width (nm) - HD | 101.0 | 126.0 | 96.0 | 128.0 | 88.0 | 80.0 |
| PN seperation width (nm) | 45 | 40 | 20 | 15 | 15 | 10 |



*Acronyms used in the table (in order of appearance): LGAA—lateral gate-all-around-device (GAA), CFET (Complementary Field Effect Transistor), 3DVLSI—fine-pitch 3D logic sequential integration.*

**G38M16/T6**

**« 0.5 nm node»**

**6 tiers**

**metal pitch = 16 nm**

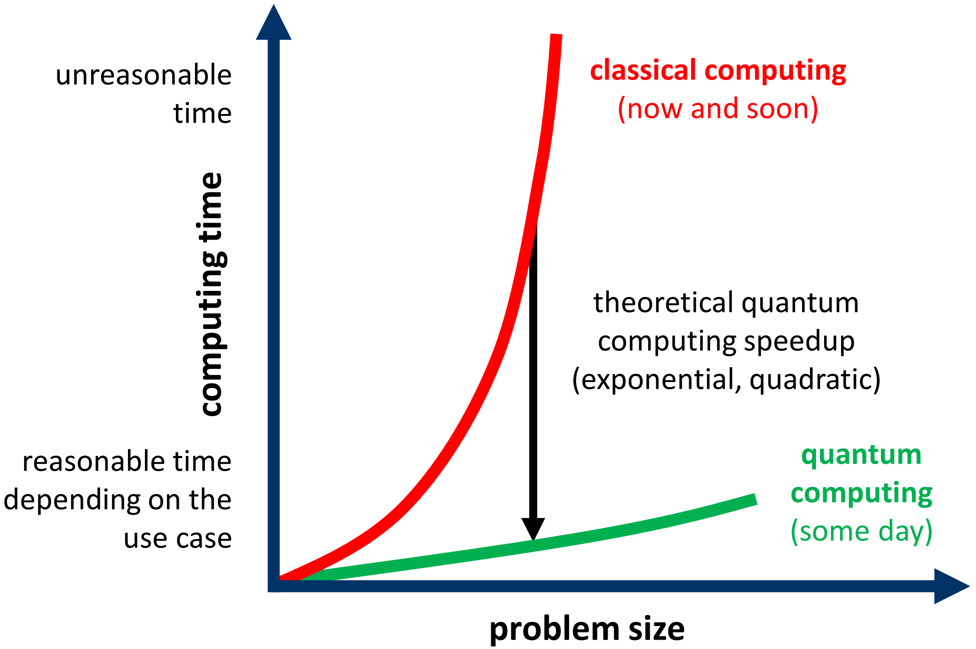
**gate pitch = 38 nm**

**4 nm thick nanosheet**

**4 nanosheets**

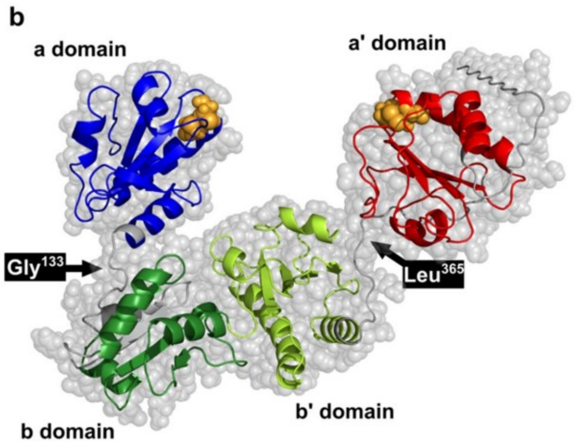
**total size is increasing!**

# quantum computing *promise*



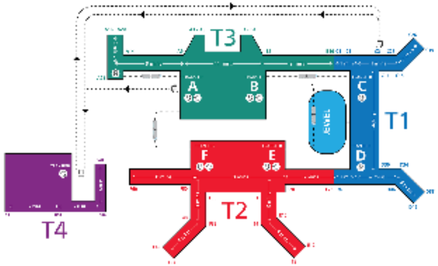

solving intractable / exponential problems in **reasonable** time

# typical exponential problems




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

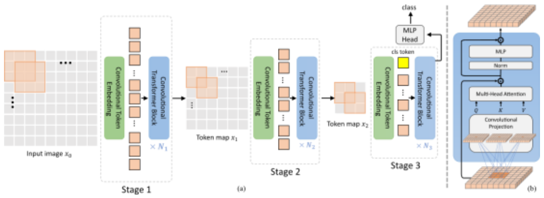
**solving Schrodinger's wave equation to simulate quantum matter**



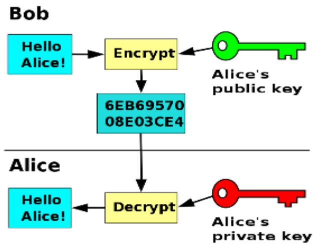

**combinatorial optimizations**

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

**solving partial derivative equations**



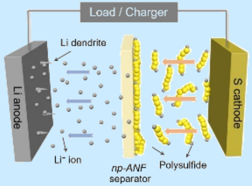

**machine learning and deep learning**



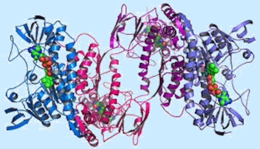

**breaking asymmetric cryptography keys**

# quantum computing usage categories

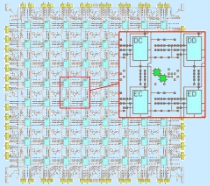
## research



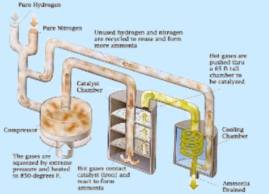

batteries



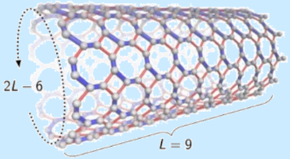
drugs



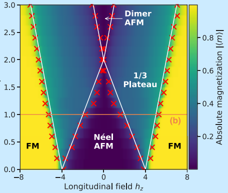
semiconductors



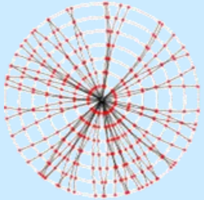

fertilizers production



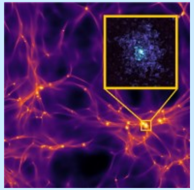

materials design




condensed matter physics



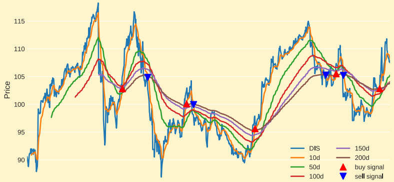
high-energy particle physics



astrophysics

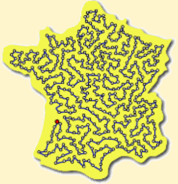
## operations

transportation

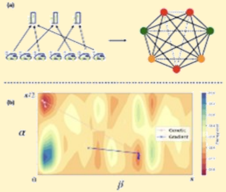



financial services

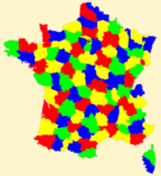
logistics



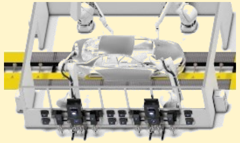
delivery



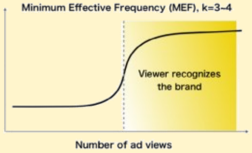
energy utilities



telecoms



manufacturing




marketing

# what is a qubit?

mathematically

**basic unit of quantum information**

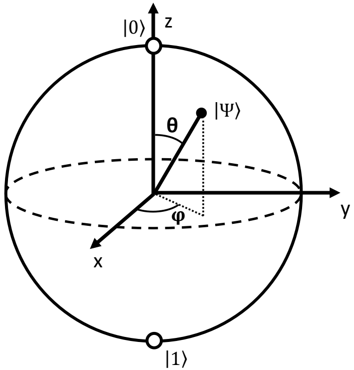
vector in a 2-dimension
complex numbers Hilbert space

complex numbers
amplitudes

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|\alpha|^2 + |\beta|^2 = 1$$

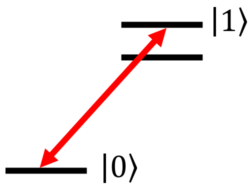
probabilities and Born
normalization constraint



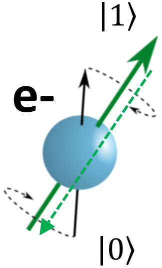

Bloch sphere representation
with amplitude and phase

physically

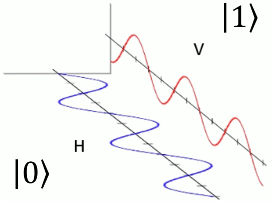
**two-level state controllable**
**quantum object**




separable
atom energy
level



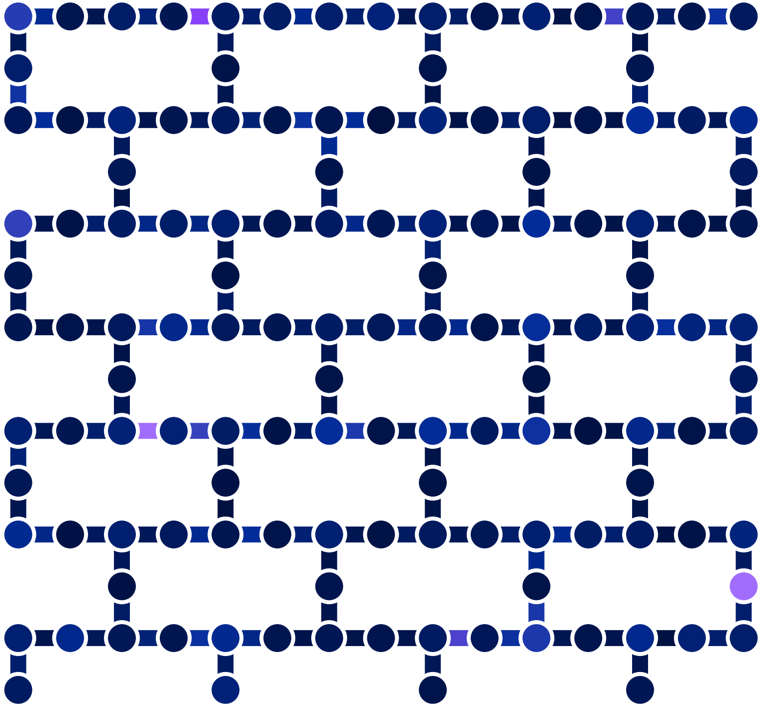

electron or
nucleus spin
orientation




photon mode
(polarization,
number, frequency)

N qubits handle the equivalent of **$2^{N+1}$ real numbers** during computation

it benefits from **quantum parallelism** brought by superposition, engtanglement and interferences

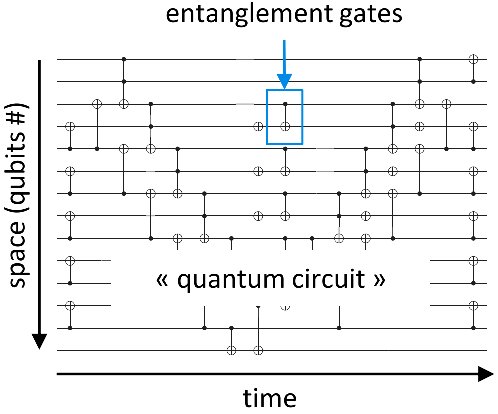


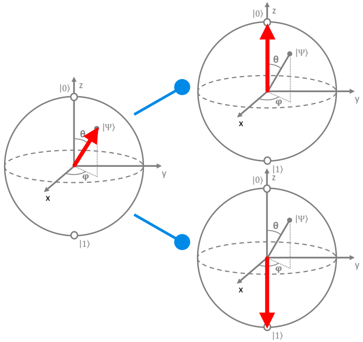
layout of a 133-qubit processor from IBM

# from computing to measurement

complex amplitudes | of all combinations of 0 and 1

$$\begin{bmatrix} \alpha_1 \\ \cdots \\ \cdots \\ \cdots \\ \cdots \\ \alpha_{2^N} \end{bmatrix} \quad \begin{matrix} |00\ldots00\rangle \\ \vdots \\ |01\ldots11\rangle \\ \vdots \\ |11\ldots11\rangle \end{matrix}$$



**010…011**
(N 0s and 1s)



**N qubits registers**
information in $2^N$ superposed states

**quantum gates**
act on qubits and on all the register amplitudes

**measurement**
ends superposition and entanglement

**outputs**
N probabilistic classical bits

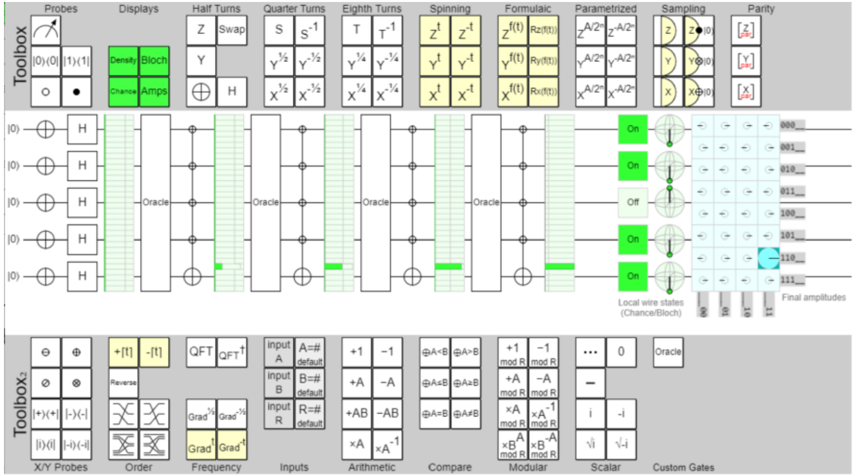
**large internal data space**
but slow I/Os

**speedups brought by algorithms design and entanglement**

**probabilistic outcomes in most cases**

# a new programming model

**visual quantum circuits design**




**https://algassert.com/quirk**

online open source tool to learn, program and emulate up to 16 « perfect » qubits

**scripted Python code**

```
# Initialize counting qubits
# in state |+>
for q in range(n_count):
    qc.h(q)

# And auxiliary register in state |1>
qc.x(3+n_count)

# Do controlled-U operations
for q in range(n_count):
    qc.append(c_amod15(a, 2**q),
             [q] + [i+n_count for i in range(4)])

# Do inverse-QFT
qc.append(qft_dagger(n_count), range(n_count))

# Measure circuit
qc.measure(range(n_count), range(n_count))
qc.draw(fold=-1)  # -1 means 'do not fold'
```

IBM Qiskit, Google Cirq, Eviden Qaptiva

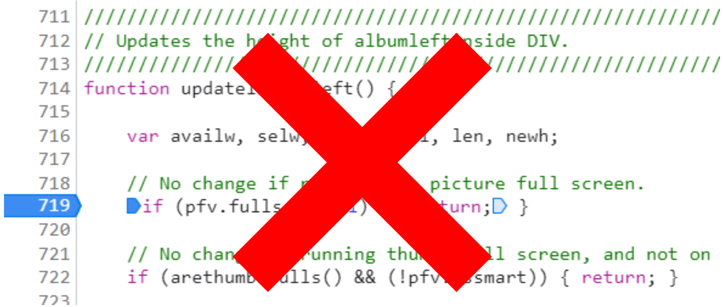
# some key differences

$$f(\lambda x) = \lambda f(x) \ for \ all \ \lambda, x \in \mathbb{R}$$
$$f(x+y) = f(x) + f(y) \ for \ all \ x, y \in \mathbb{R}$$

$$\langle \Psi_1 | \Psi_2 \rangle = [\overline{\alpha_1}, \overline{\beta_1}] \times \begin{bmatrix} \alpha_2 \\ \beta_2 \end{bmatrix} = \overline{\alpha_1}\alpha_2 + \overline{\beta_1}\beta_2$$

$$|\Psi_2\rangle\langle\Psi_1| = \begin{bmatrix} \alpha_2 \\ \beta_2 \end{bmatrix} \times [\overline{\alpha_1}, \overline{\beta_1}] = \begin{bmatrix} \alpha_2\overline{\alpha_1} & \alpha_2\overline{\beta_1} \\ \beta_2\overline{\alpha_1} & \beta_2\bar{\beta}_1 \end{bmatrix}$$

need to understand
**linear algebra**

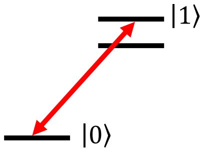



**breakpoints**
become endpoints

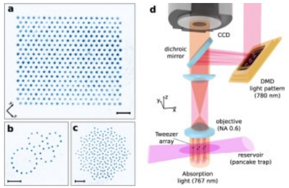
**uncopiable data**, but transferable

# main qubit types

## atoms and ions



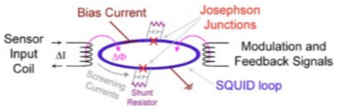

**quantum states:** atom energy level



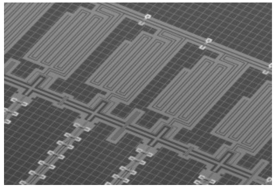

**physical aspect**

**interactions:** laser pulses and/or microwaves

## superconducting

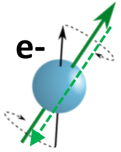



**quantum states:** loop phase or energy

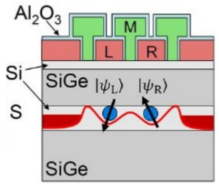


**physical aspect**

## electron spins



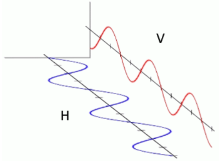

**quantum states:** electron spin orientation



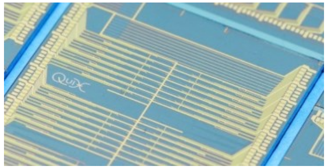

**physical aspect**

**interactions (superconducting and electron spins):** microwave pulses and/or DC current

## photons




**quantum states:** photo polarization (or other property)



**physical aspect**

**interactions:** interferometers, polarizing beam splitters, ...

# quantum & classical computing paradigms

## classical computers

**quantum inspired**
classical algorithms running on classical computer, inspired by quantum algorithms.

classical algorithms improvements

MULTIVERSE COMPUTING, ZAPATA AI

**quantum emulators**
running quantum computers code on classical computers, for training, debugging and testing

quantum algorithms debug and testing

EVIDEN, IBM, FUJITSU, Google, Microsoft, aws, PASQAL, C12, QUANDELA, ALICE & BOB

## analog quantum computers

quantum **annealing computers**

analog **quantum simulators**

optimization problems and quantum physics simulation

D-Wave The Quantum Computing Company™, PASQAL, QuEra

## digital quantum computers

**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

general purpose quantum computing, adds search and integer factoring

IBM, rigetti, PsiQuantum, Google, IQM, ALICE & BOB, OQC, QUANTINUUM, IONQ, Microsoft, QUANDELA, XANADU

**émulateur quantique** (langa[…]

*Domaine :* Informatique/Info[…]

*Définition :* Dispositif qui util[…] […]ter un algorithme quantique conçu pour un ordinateur q[…]

*Note :* La durée d'exécution […] […]nulation quantique croissent exponentiellement avec l[…] […]npliquer le recours à des superordinateurs classiques[…]

*Voir aussi :* algorithme quant[…]

*Équivalent étranger :* quantu[…]

RÉPUBLIQUE FRANÇAISE

JOURNAL OFFICIEL

LOIS ET DÉCRETS

Mardi 20 décembre 2022 / N° 294

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LOIS

1 LOI n° 2022-1587 du 19 décembre 2022 visant à lutter contre la fraude au compte personnel de formation et à interdire le démarchage de ses titulaires

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2 Arrêté du 4 novembre 2022 établissant la liste des membres du Conseil supérieur des gens de mer

3 Arrêté du 15 décembre 2022 relatif à l'approbation de la modification du cahier des charges de l'appel à projets « Innovations en biothérapies et bioproduction »

4 Avenant n° 2 du 19 décembre 2022 relatif à la convention du 13 février 2017 portant avenant n° 4 à la convention du 20 octobre 2010 entre l'Etat et l'Agence nationale pour la rénovation urbaine (ANRU) relative au programme d'investissements d'avenir (actions : « Internats d'excellence et égalité des chances » et « Internats de la réussite »)

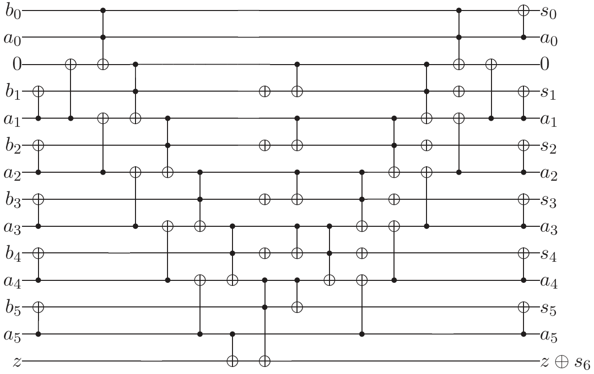
ministère de l'économie, des finances et de la souveraineté industrielle et numérique

5 Arrêté du 2 décembre 2022 portant abrogation de l'arrêté du 21 octobre 2022 pris en application des articles L. 562-3 et suivants du code monétaire et financier

6 Arrêté du 13 décembre 2022 relatif à la classification des engagements d'assurance consécutifs aux atteintes aux systèmes d'information et de communication

# quantum computing paradigms

## **gates-based** quantum computers

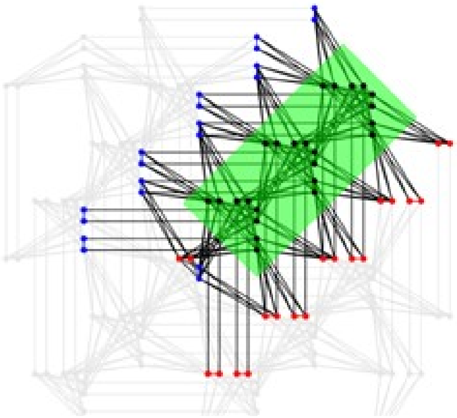



The ripple-carry adder for $n = 6$.

sequential programming of quantum gates, can implement any algorithm and Hamiltonian transformation

IBM QUANDELA

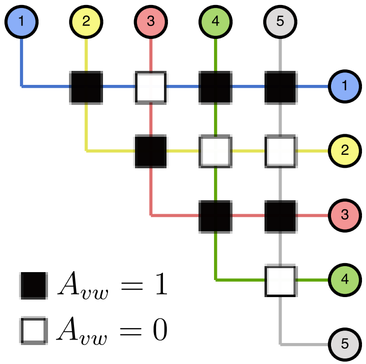
## quantum **annealers**



finding a ground state of an Ising model, optimization problems are mapped to Ising models (QUBO)

D-Wave The Quantum Computing Company™

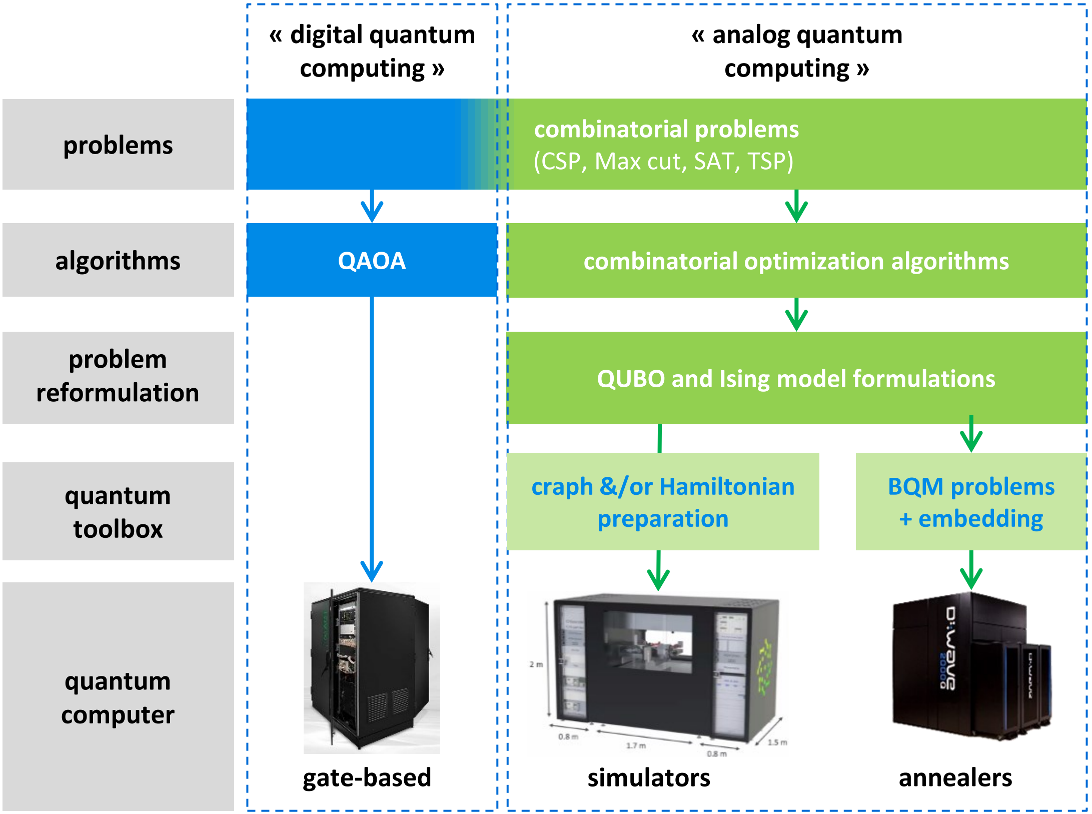
## quantum **simulators**




finding a ground state of an Ising model or XY quantum simulation model (with more degrees of liberty)

PASQAL |QuEra> COMPUTING INC.

# analog quantum computing




some mathematical **problem** with data inputs and desired output.

**algorithm** to solve the given problem, which are mostly hybrid and/or variational.

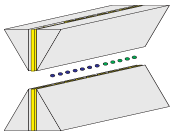
with analog quantum computing, the quantum part of the algorithm may map itself to a generic QUBO or Ising **model formulation.**

QUBO/Ising model may itself map to a generic problem formulation like **BQM** in the case of D-Wave annealers.

the reformulated problem is **directly solved** by the (analog) quantum computer, in an hybrid manner along with a classical computer.

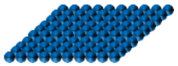
# QPUs vendors per qubit type

| atoms | | electron *superconducting loops & controlled spin* | | | | | photons |
|---|---|---|---|---|---|---|---|
| trapped ions | cold atoms | annealing | super-conducting | silicon | vacancies | topological | photons |



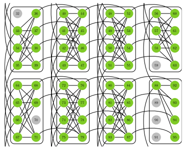
**trapped ions**

Quantinuum, IonQ, AQT, UQ, oxford ionics, eleQtron, Foxconn, Quantum Art, Crystal Quantum Computing, NEQxT, Qudora Technologies



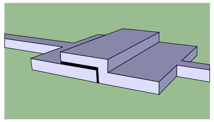
**cold atoms**

Pasqal, QuEra, Infleqtion, atom computing, planqc, QuANTier, NanoQT (Nanofiber Quantum Technologies)



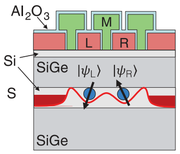
**annealing**

D-Wave (The Quantum Computing Company™), Qilimanjaro Quantum Tech, NEC



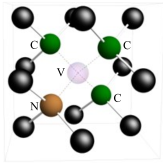
**super-conducting**

IBM, rigetti, amazon, Google, qci, Nord Quantique, OQC, IQM, Alice & Bob, Origin Quantum, Anyon, Atlantic Quantum, bleximo, Fujitsu



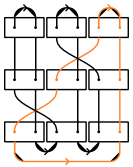

**silicon**

intel, quobly, Quantum Motion, Silicon Quantum Computing, diraq, EeroQ, equal1.labs, C12, ARQUE, QπAI, Archer



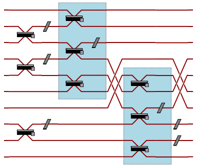

**vacancies**

Quantum Brilliance, SaxonQ, Turing, photonic, NTT, XEED, Quantum Transistors



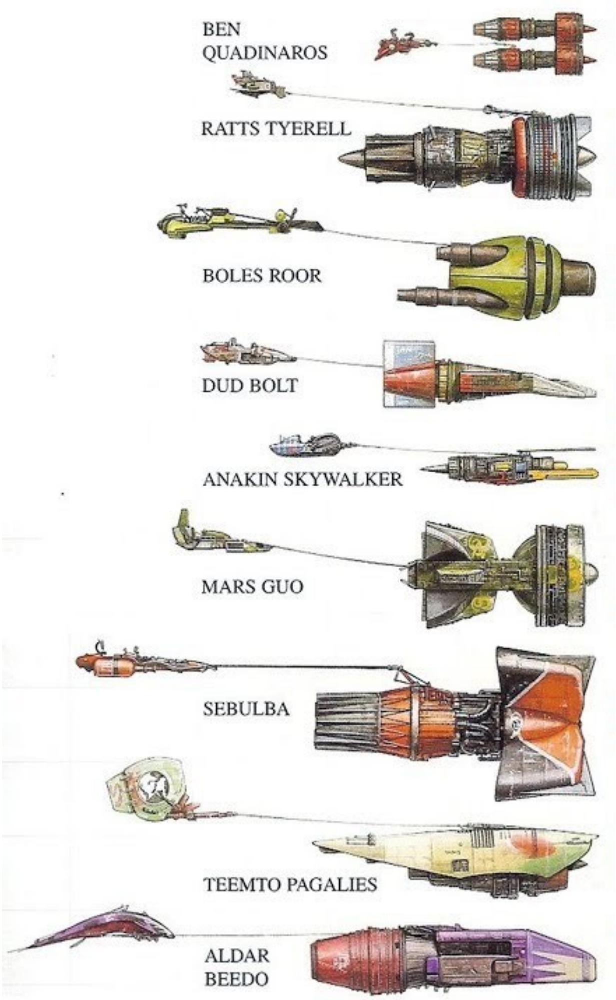
**topological**

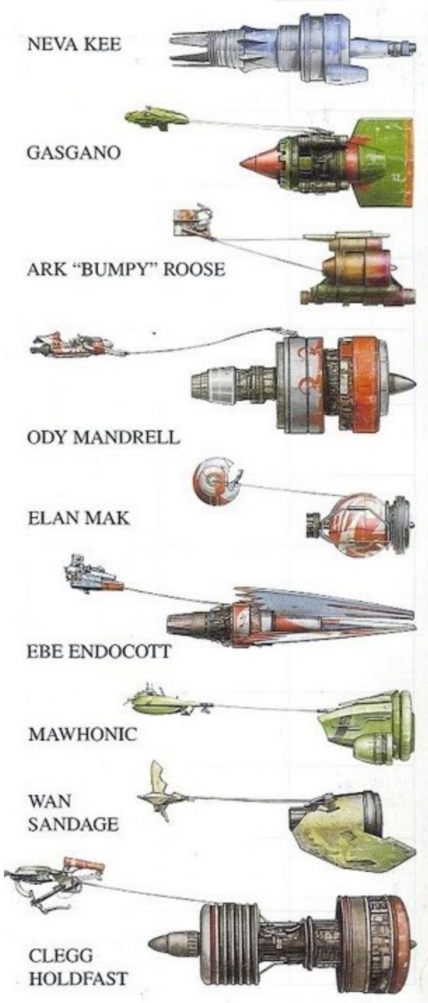
Microsoft, Quoherent, Quantum Gravity Research



**photons**

PsiQuantum, Quandela, Orca Computing, Xanadu, Duality Quantum Photonics, QuiX Quantum, BardeenQ Labs, TuBoson, QCi, photonicsQ, Quanfluence, Tundrasys

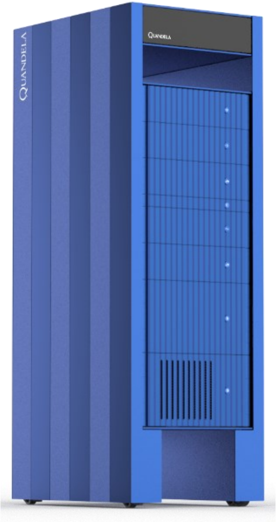

BEN QUADINAROS
RATTS TYERELL
BOLES ROOR
DUD BOLT
ANAKIN SKYWALKER
MARS GUO
SEBULBA
TEEMTO PAGALIES
ALDAR BEEDO


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

# France QPU startups

| atomes | | électrons | | | photons |
|---|---|---|---|---|---|
| ions piégés | atomes froids | qubits de chats | silicium | nanotubes de carbone | photons |
| CRYSTAL QUANTUM COMPUTING | PASQAL | ALICE & BOB | quobly | C12 | QUANDELA |
| **2021** | **2019**<br>140 M€ | **2020**<br>30 M€ | **2022**<br>19 M€ | **2020**<br>10 M€ | **2017**<br>70 M€ |
| cnrs, Université Paris Cité | cnrs, INSTITUT d'OPTIQUE GRADUATE SCHOOL | cea, cnrs, Lab PHYS ENS de LYON, MINES ParisTech, Inria | cea, cnrs, NÉEL institut | cnrs, LPENS LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE | cnrs, cea, C2N, université PARIS-SACLAY |

IBM

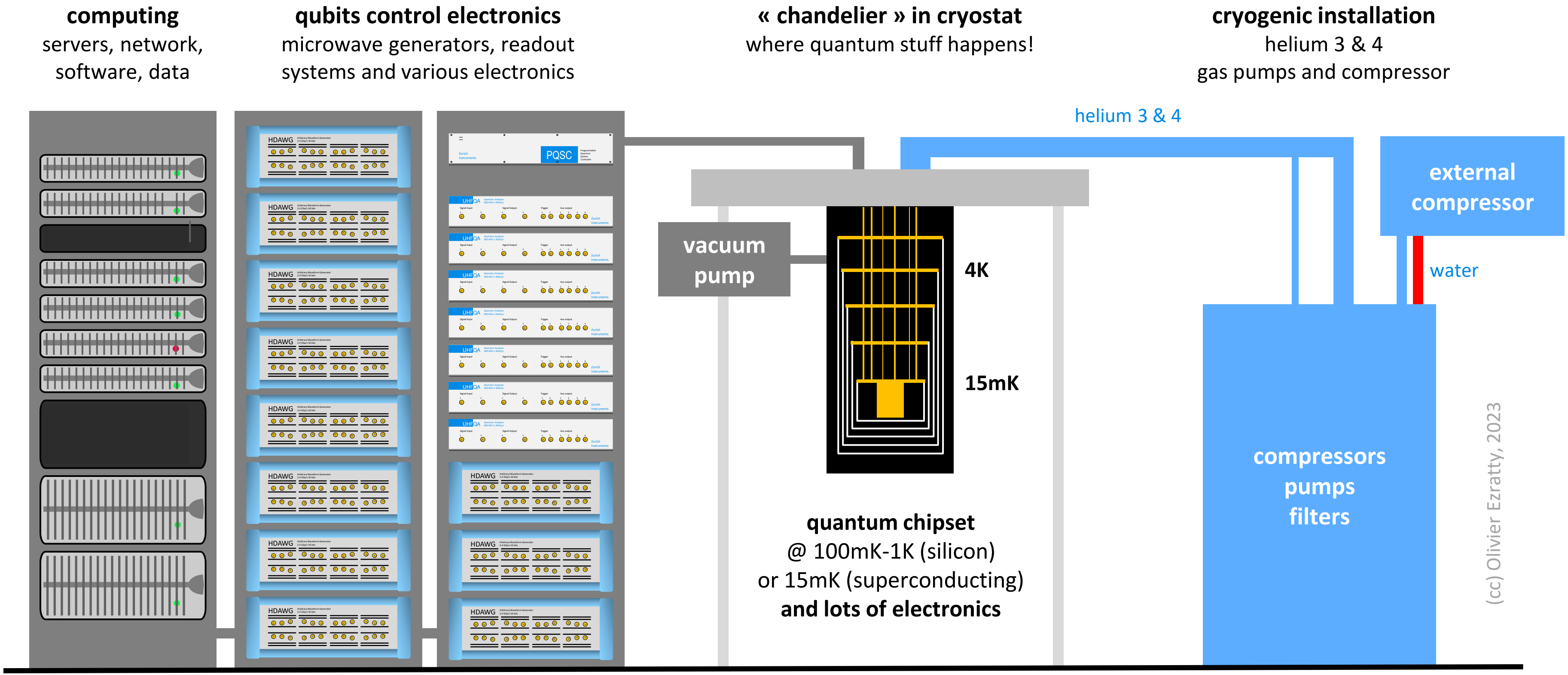

QUANDELA

IONQ



PASQAL

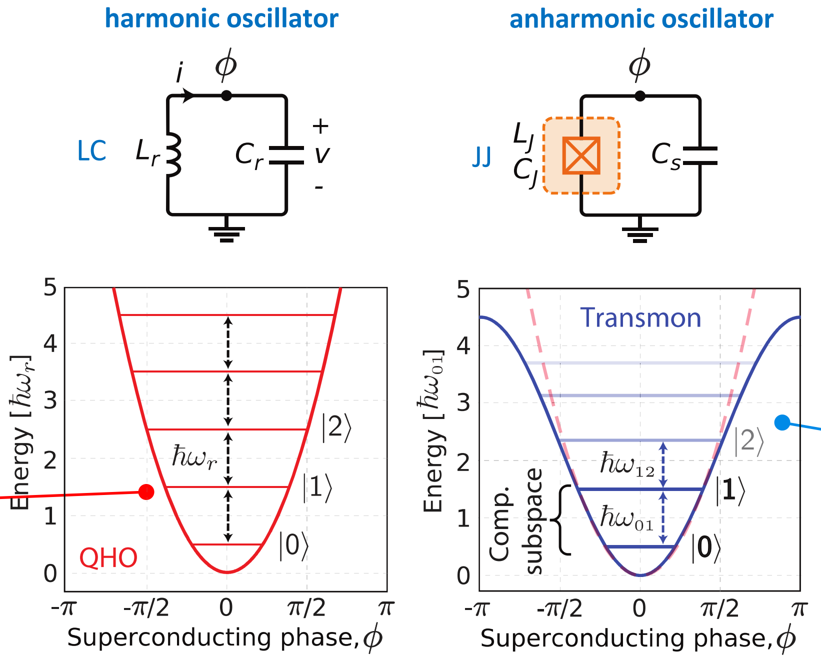
# inside a typical quantum computer



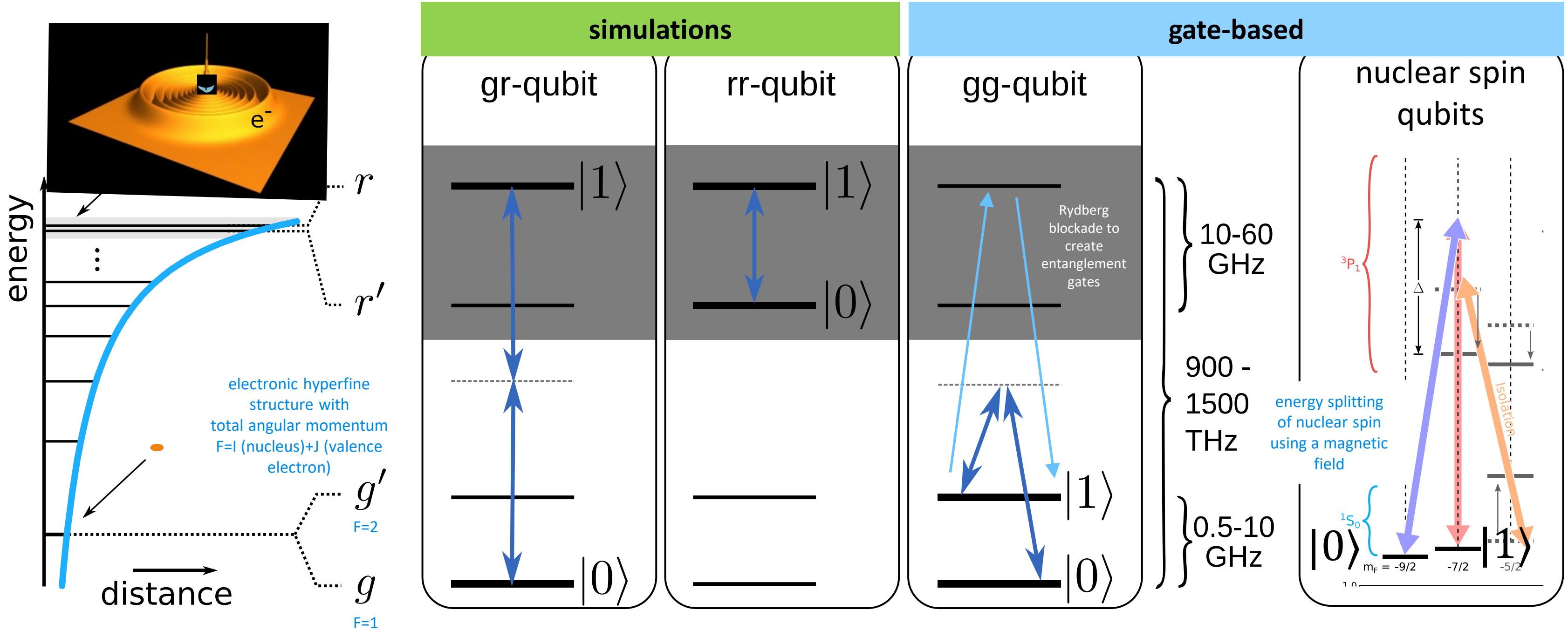

for superconducting or electron spin qubits

# superconducting qubits

$$H = 4E_C n^2 + \frac{1}{2}E_L\phi^2$$




$$H = 4E_C n^2 + E_L cos(\phi)$$

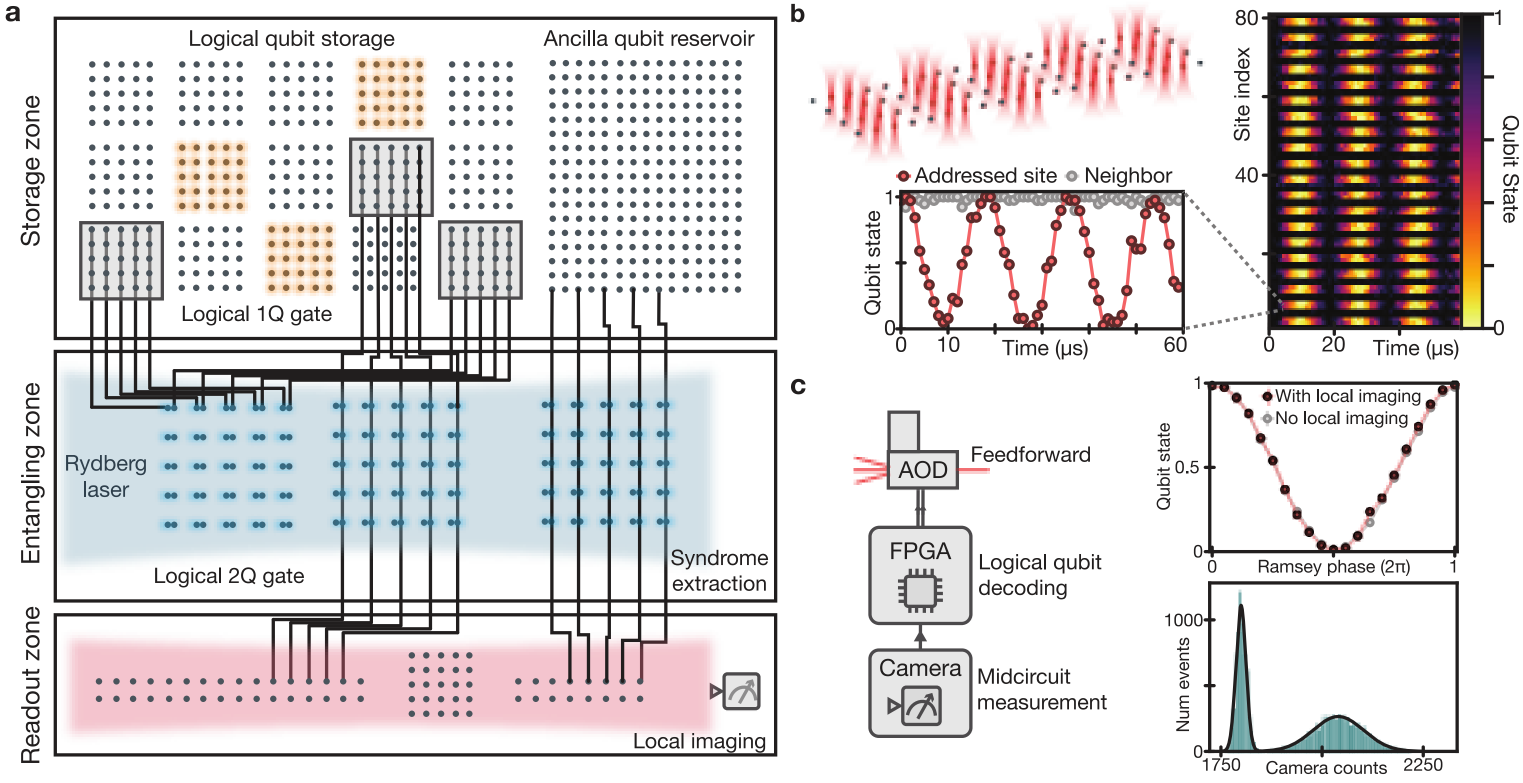



| | | | | |
|---|---|---|---|---|
| **qubit type** | **ground-Rydberg** | **Rydberg-Rydberg** | **ground-ground** | **nuclear spin** |
| **transitions** | **UV laser or visible/IR lasers** | **microwaves** | **microwaves and optical lasers** | **two optical photons Raman transition** |
| $T_2^*$ | **2 to 100 µs** | **22 µs** | **3.5 ms** | **42 s** |
| **vendors** | Caltech, PASQAL (1), QuEra (1) | PASQAL (1) | Infleqtion, PASQAL (2), QuEra (2) | atom computing |

(1): in quantum simulation mode
(2): in gate-base mode

schema source: Quantum simulation and computing with Rydberg-interacting qubits by Manuel Agustin Morgado and Shannon Whitlock, December 2020 and additions by Olivier Ezratty, 2022.

# Harvard / QuEra logical qubits




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

# 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.

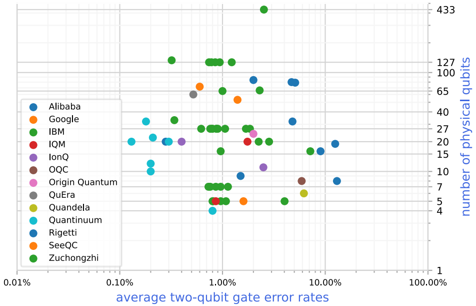
- **topological qubits programming is different and requires an additional software layer.**
- **rather few laboratories involved in this path.**
- **no startup was launched in this field. Microsoft is the only potential vendor. IBM is investigating the field in Zurich.**
- **works at low cryogenic temperatures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

## photons qubits

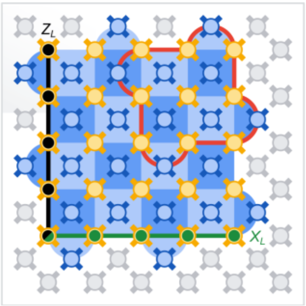
- **stable qubits** with absence of decoherence.
- qubits processing at **ambiant temperature.**
- **emerging nano-photonic** manufacturing techniques enabling scalability.
- **easier to scale-out** with inter-qubits communications and quantum telecommunications.
- **MBQC/FBQC** circumventing the fixed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

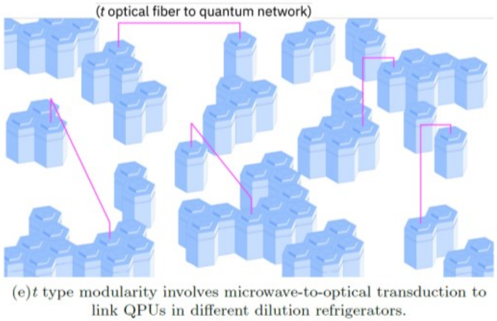
# key hardware challenges



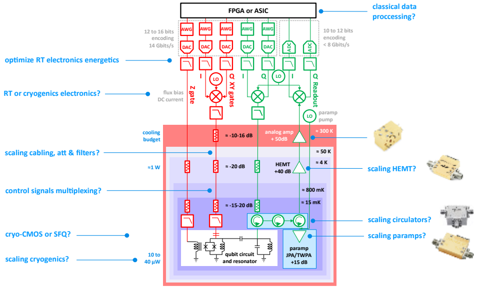

qubits fidelities



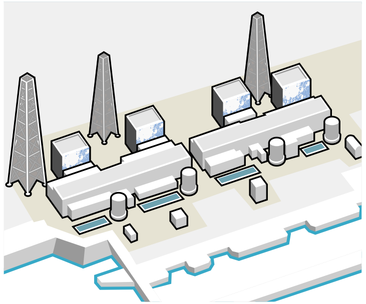

errors mitigation and correction



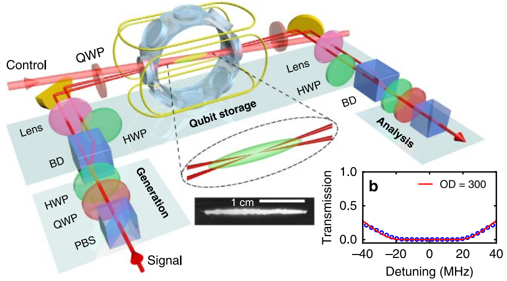

quantum interconnect




enabling technologies scalability

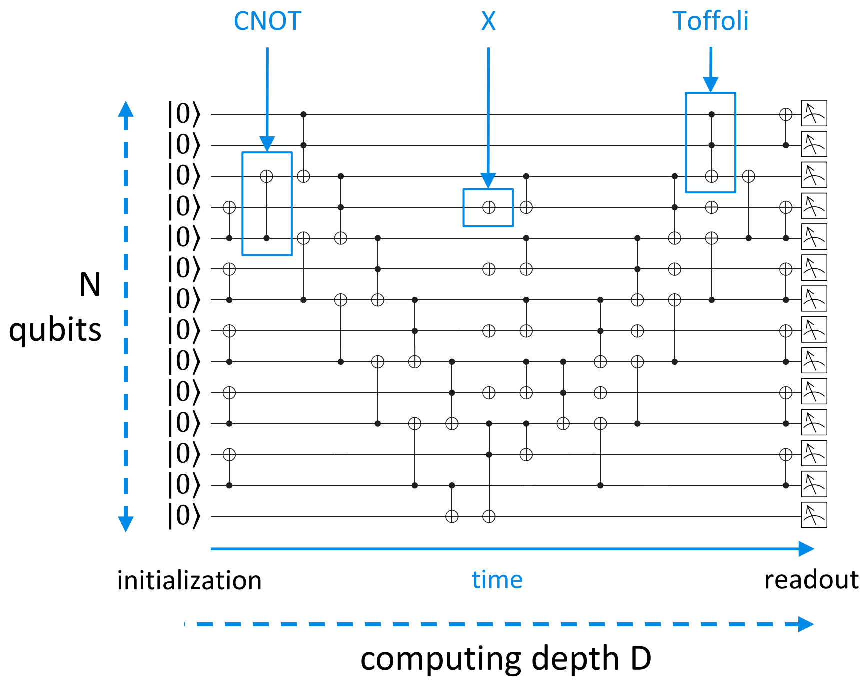


energy consumption




quantum memory

# raw algorithm fidelities requirements




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

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

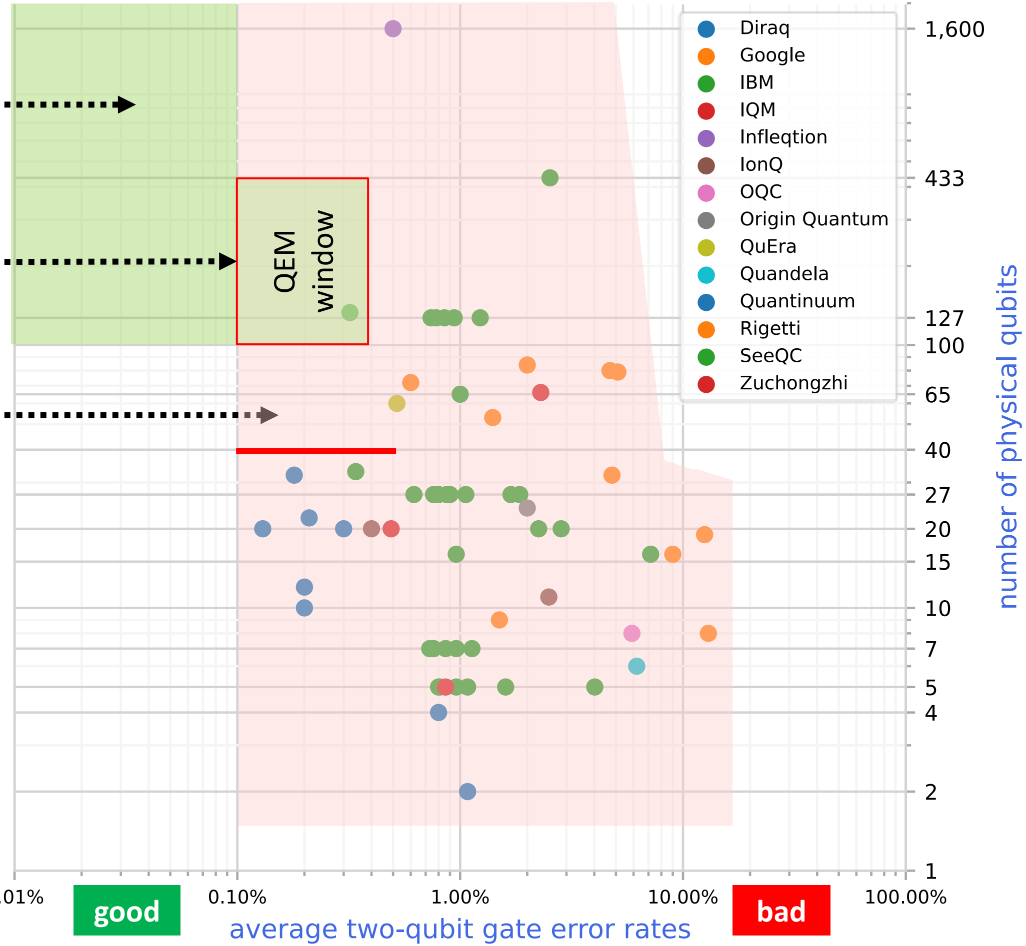
**qubit errors quickly kills quantum computing accuracy**

**useful NISQ* requirements**

with quantum error mitigation

**state of the art**

easy to emulate classically, too noisy to be useful




* NISQ = noisy intermediate scale quantum computers.

# qubit errors sources

**where**
physical sources or errors

control

signals jitter

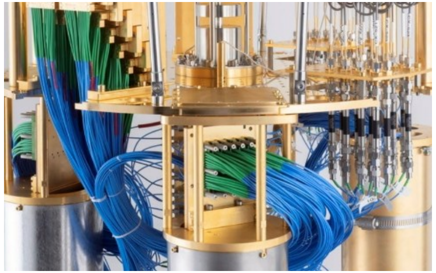
calibration

many body interactions

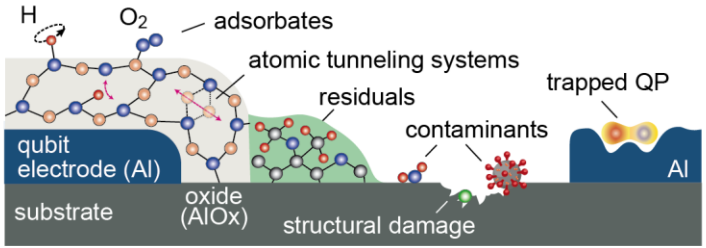
thermal noise

back-action

electromagnetic noise

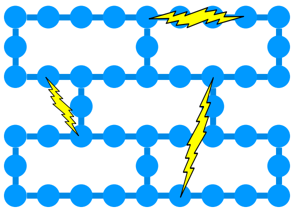


material defects

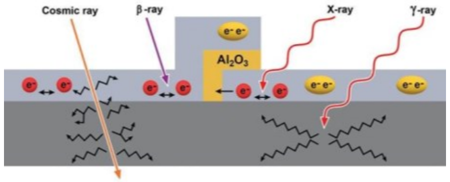



crosstalk

photon loss

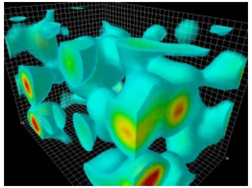


cosmic rays

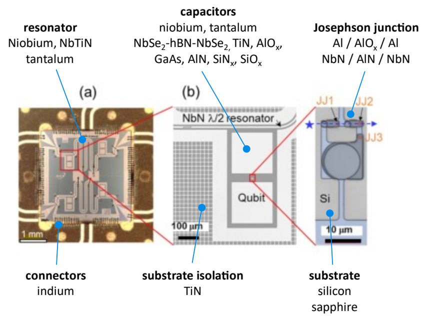



gravity

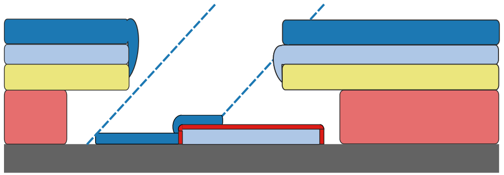
vacuum quantum fluctuations



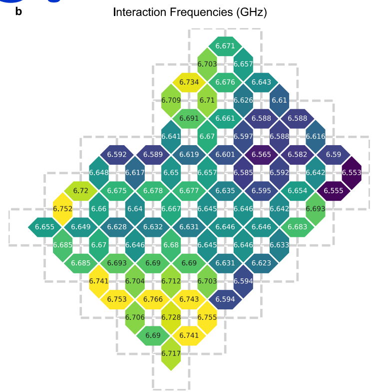
# how to improve qubit fidelities? *



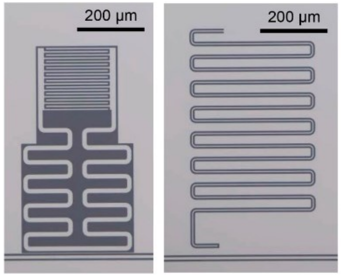

## materials



## 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 and FTQC

**physical qubit**

error rates ≈0.1%

+

**error correction code**

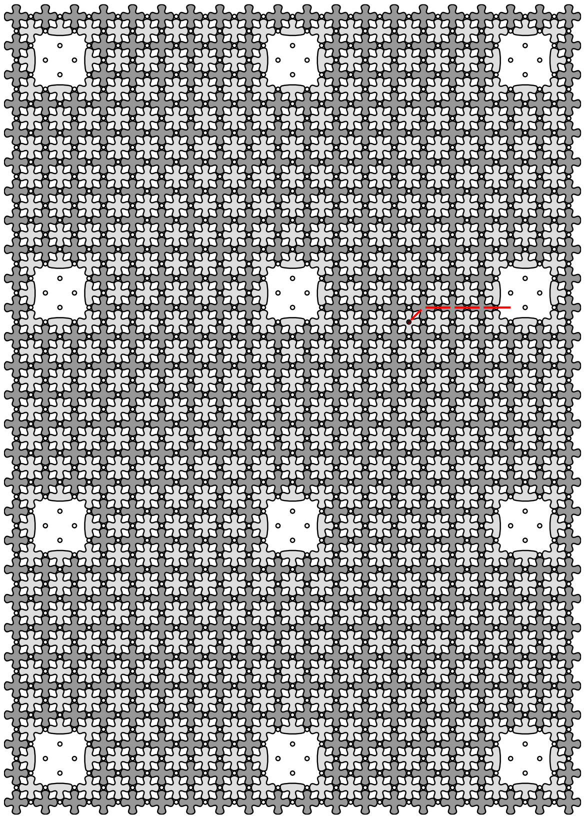
threshold, physical qubits overhead, connectivity requirements, syndrome decoding and scale

**logical qubit**

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

**fault tolerance**

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



tens to thousands qubits

https://arxiv.org/abs/1202.2639

# Microsoft-Quantinuum logical qubits

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

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

[1] *Microsoft Azure Quantum*
[2] *Quantinuum*
(Dated: April 2, 2024)

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

https://arxiv.org/abs/2404.02280

**claim**: logical qubit with x800 improvement vs physical qubit

**reality**: x800 improvement only for the first gate cycle!

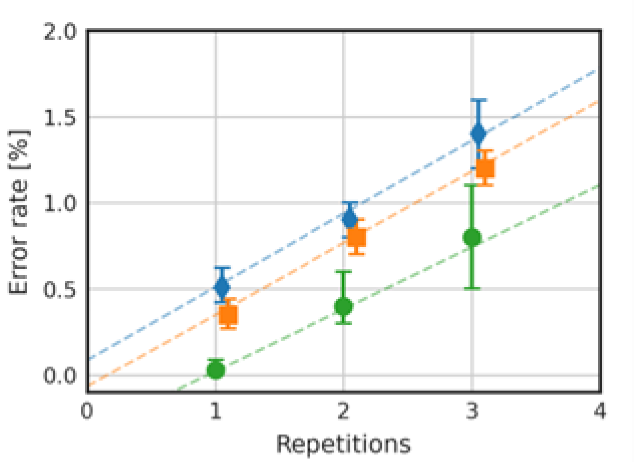
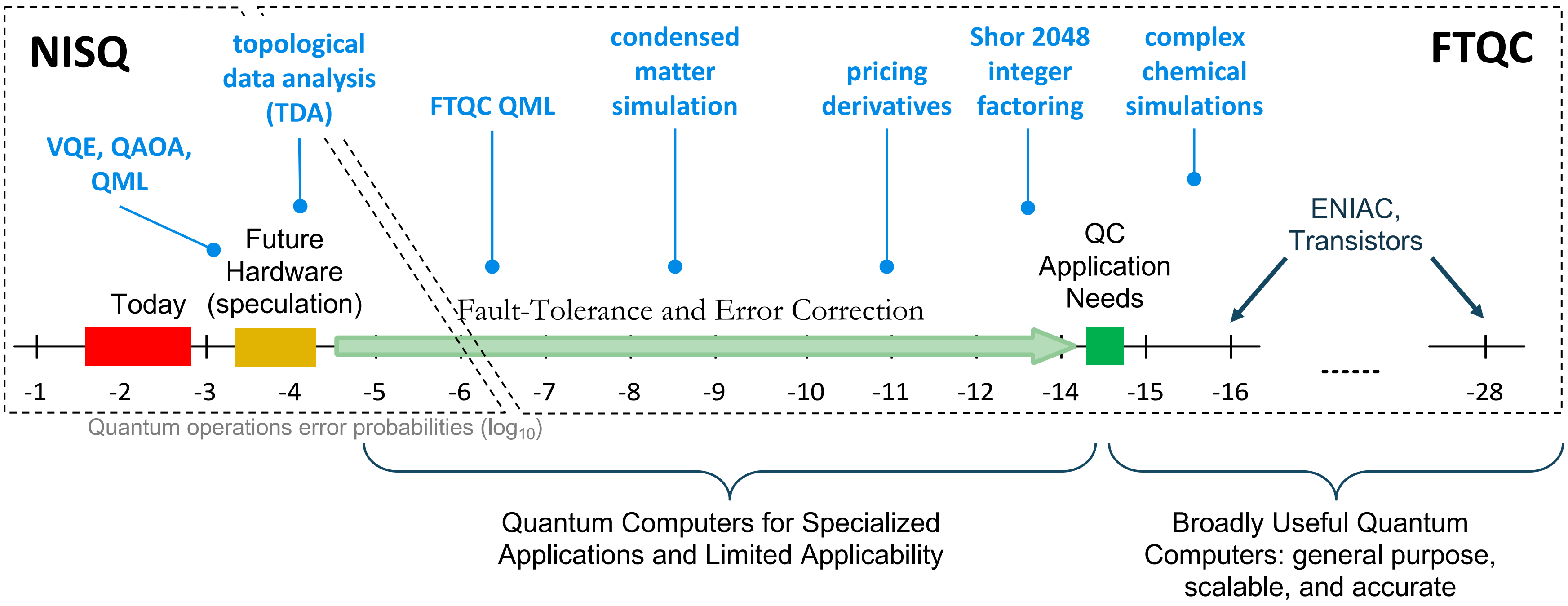



FIG. 7. Observed error rate for circuits with 1 to 3 rounds of error correction with the [[12, 2, 4]] Carbon code (green circles) and physical baselines (blue diamond for pairs of 1-bit teleportations, and orange squares for pairs of CNOTs). Results are offset along the x-axis for clarity. Linear fits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

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

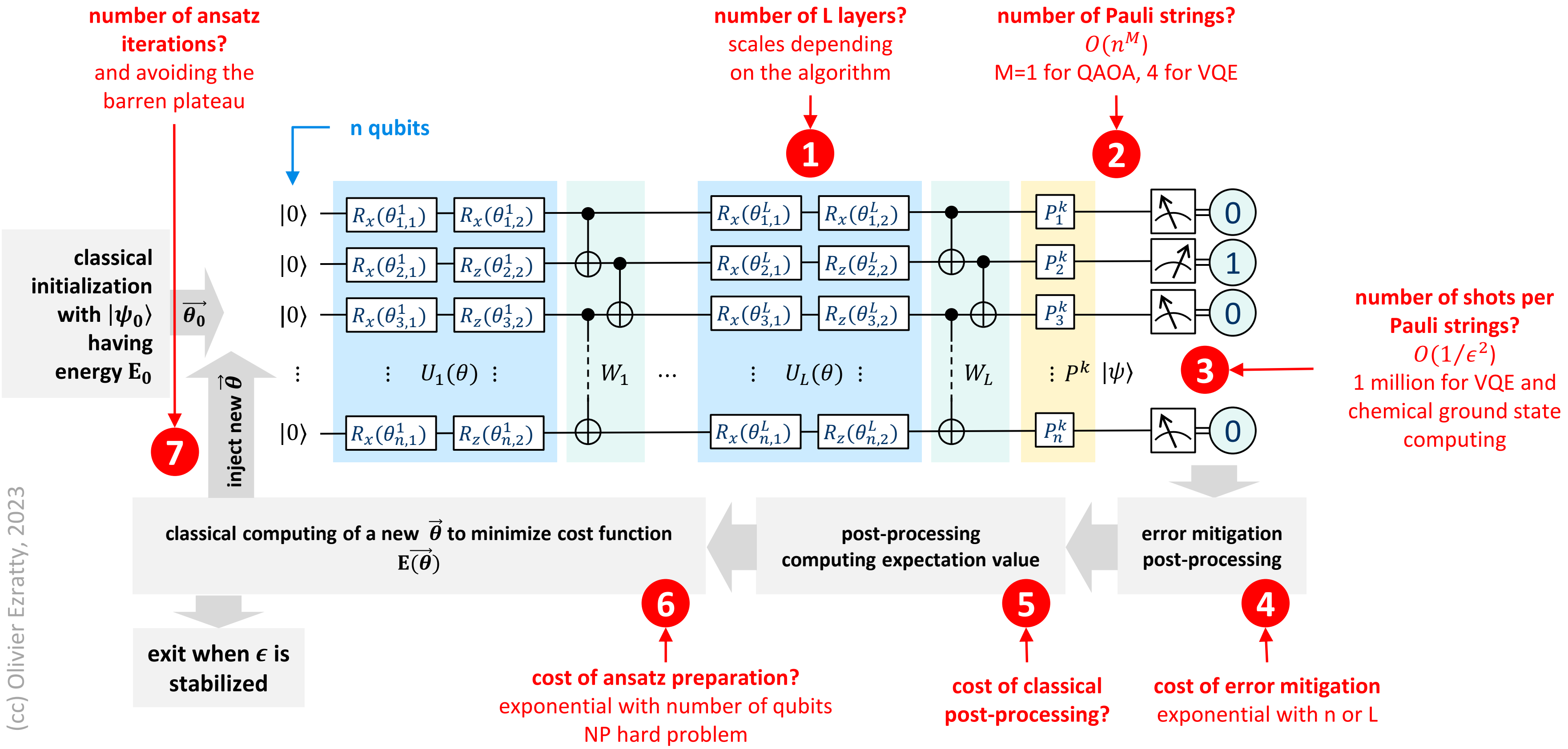
# logical qubits requirements

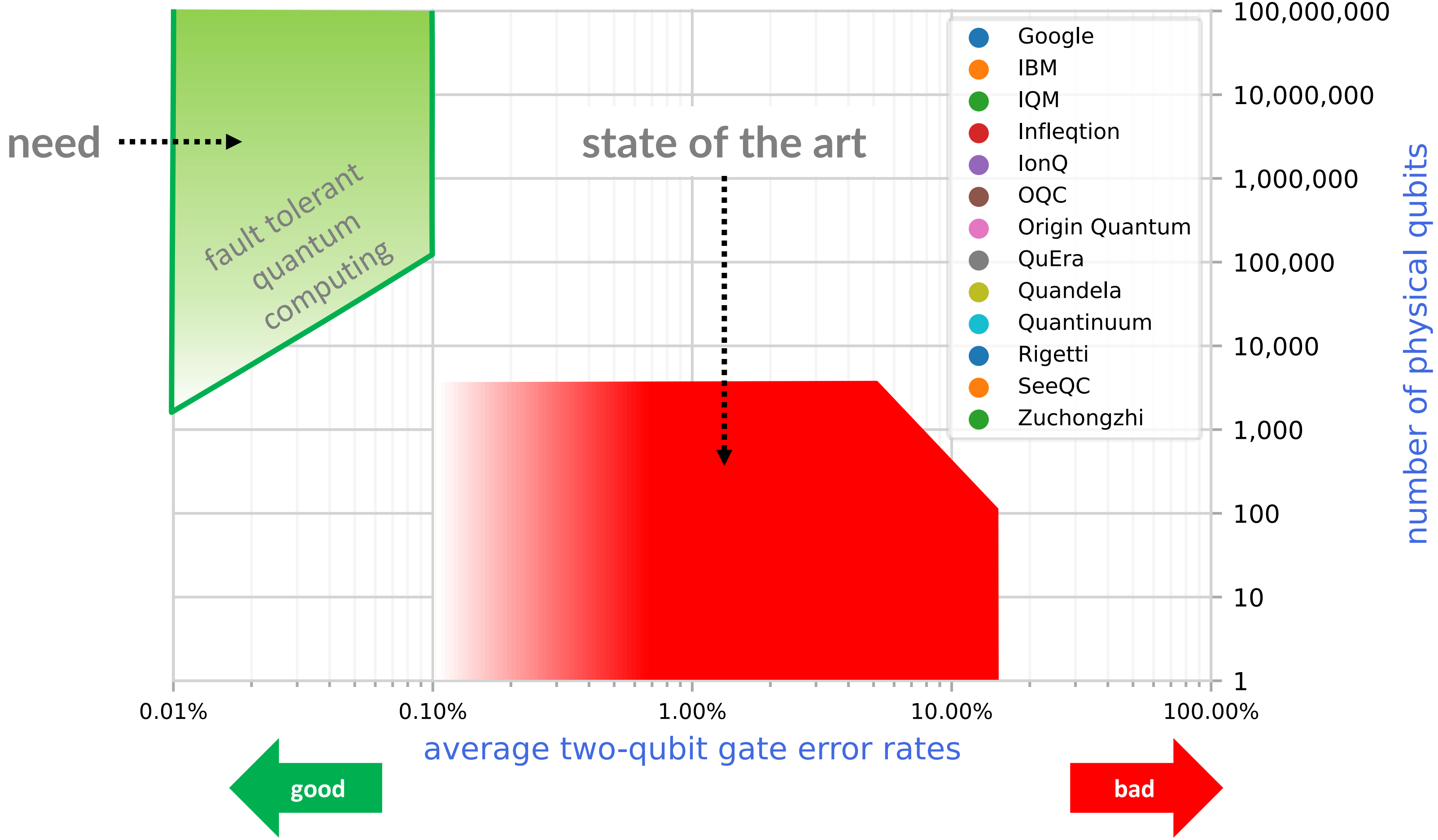



source: How about quantum computing? by Bert de Jong, DoE Berkeley Labs, June 2019 (47 slides) + Olivier Ezratty additions, 2021-2024.

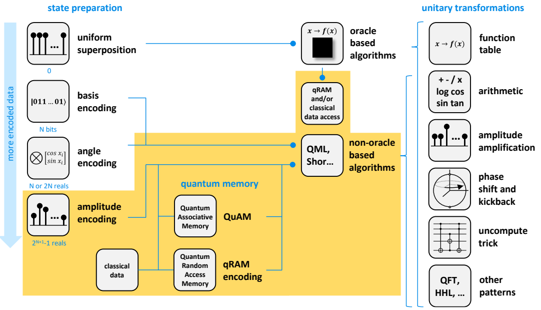
# NISQ VQA process

**VQE for benzene ground state**
72 qubits and 330,816 Pauli strings

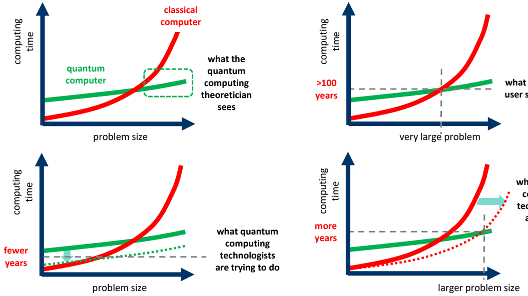



need
state of the art
fault tolerant
quantum
computing
Google
IBM
IQM
Infleqtion
IonQ
OQC
Origin Quantum
QuEra
Quandela
Quantinuum
Rigetti
SeeQC
Zuchongzhi
100,000,000
10,000,000
1,000,000
100,000
10,000
1,000
100
10
1
number of physical qubits
0.01%
0.10%
1.00%
10.00%
100.00%
average two-qubit gate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

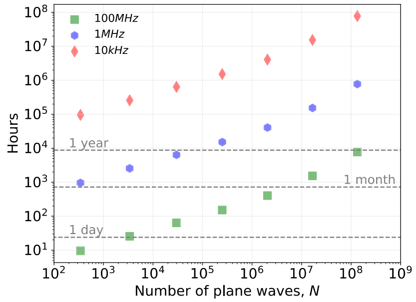
# key software challenges



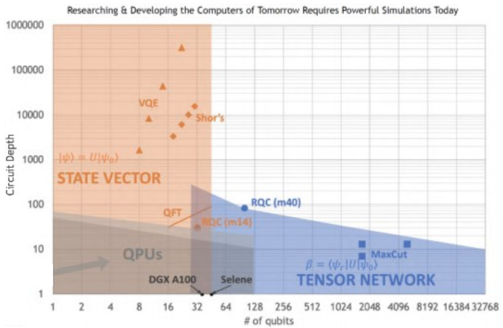

data loading



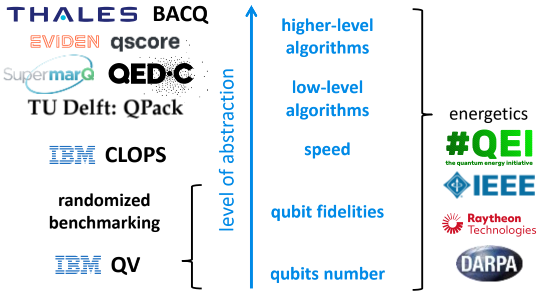

actual speedups



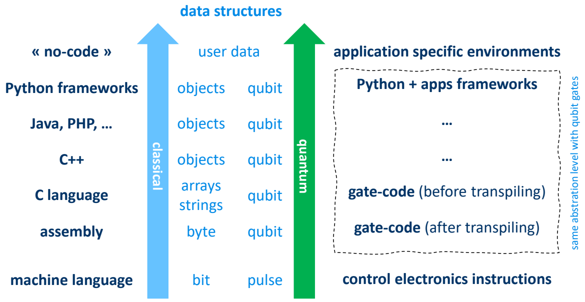

actual computing time




tensor networks competition

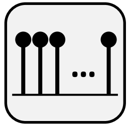



benchmarking



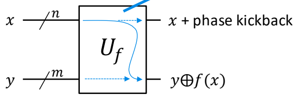

coding abstraction level

# quantum algorithms patterns



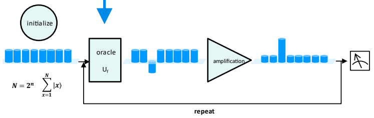
**uniform preparation**

oracle based algorithms, Shor, QPE



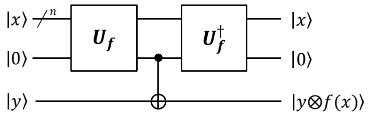

**oracle**

« hidden » function used in search algorithms, may rely on quantum memory



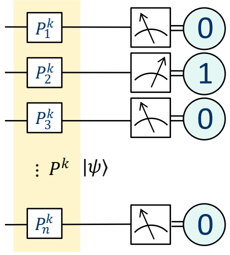

**amplitude amplification**

used in Grover algorithm



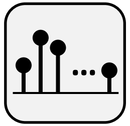

**uncompute trick**

to disentangle ancilla qubit after computing without losing results, used in HHL, U being a QPE




**measurement**

with optional basis change using Pauli strings (in VQA)



**data preparation** *or* **unitary U**

other algorithms

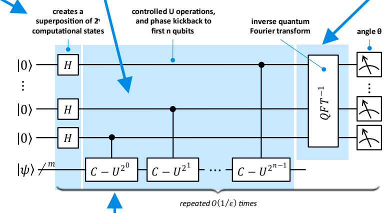
any combination of quantum gates

**period finding**

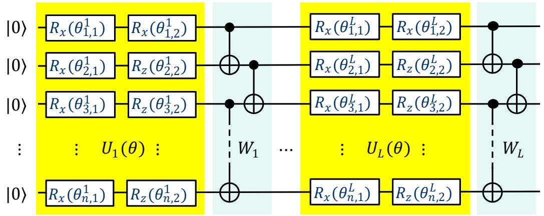
finds the periods of a signal

**QFT**

decomposes or recomposes a signal into/from it components




**phase estimate** (QPE)



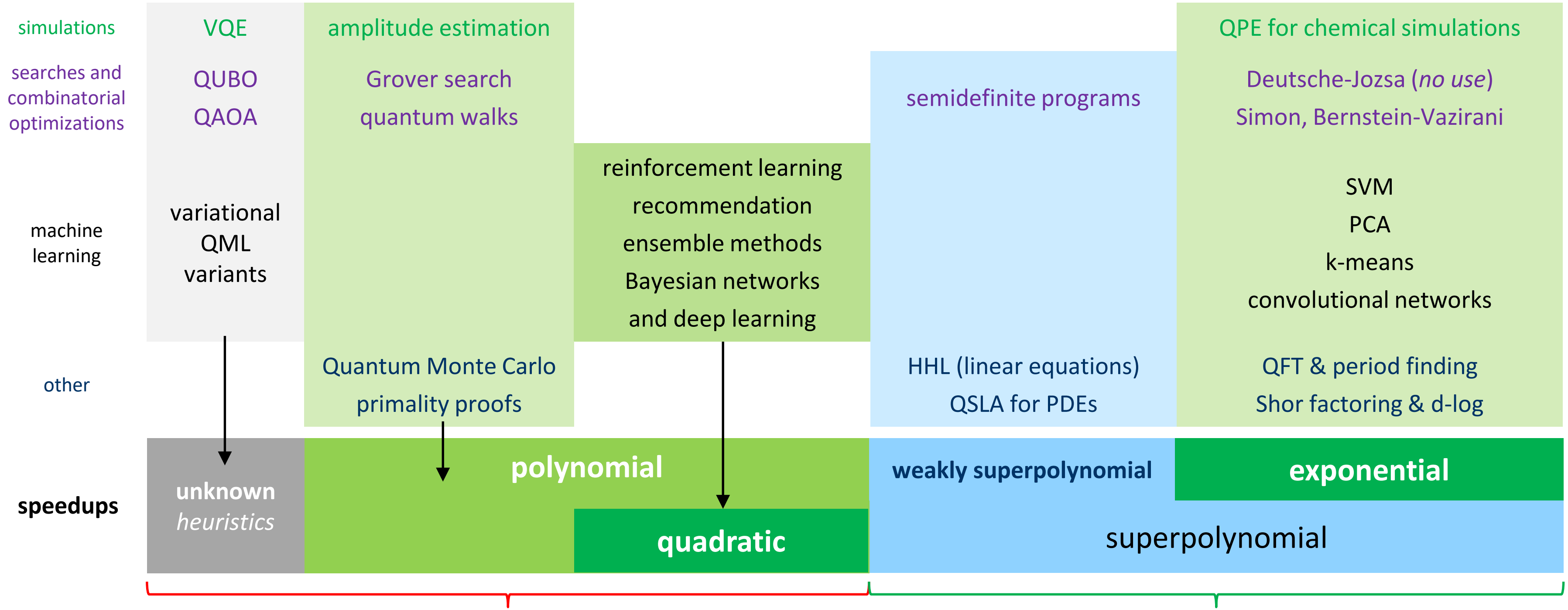

**ansatz**

Hamiltonian injection used in NISQ variational algorithms

# algorithms inputs and outputs

| | algorithm | classical input | quantum input<br>blue for superposed state | quantum output<br>blue for superposed state | classical output | acceleration<br>(# of circuit runs) |
|---|---|---|---|---|---|---|
| FTQC | **Deutsche-Jozsa** | balanced or unbalanced function in oracle | oracle function<br><br>can be entirely quantum using a series of quantum gates (with not much real use case) or access some classical data in superposition using a qRAM (which does not exist yet) | function is balanced if all output qubits are at ground state $\|0\rangle$ | « yes or no » | exponential (O(1)) |
| | **Bernstein-Vazirani** | string encoded in a function | | (integer) secret string in basis encoding | integer | exponential (O(1)) |
| | **Grover** | function returning 1 only for one basis | | searched item index as integer in basis encoding | integer | quadratic (O(1)) |
| | **Simon** | periodic function | | parameters for a linear equation used to find a period, with average of basis encoding | integer representing function period | exponential (O(1)) |
| | **Shor factoring** | semi-prime integer | Hadamard gates and parametrized period finding function with exponentiations | regularly spaced amplitudes starting with 0 | dividing integer found with continuous fraction post-processing | exponential (depends period finding integer) |
| | **Shor dlog** | two integers | | | | |
| | **QFT** | series of values | series of complex amplitudes with amplitude encoding | Fourier coefficients in amplitude encoding, enabling the recovery of the main frequency | main frequency | exponential (O(1)) |
| | **QPE** | Hamiltonian | | phase encoded in bitstring | phase as a real number | exponential (O(1)) |
| | **HHL** | one vector and one matrix | one vector and one matrix amplitude encoding | inverted matrix x entry vector (= one vector) in amplitude encoding | characteristics of the vector to obtain one eigenvalue | exponential (depends) |
| NISQ | **QAOA** | objective function to optimize | cost function parameters encoded in an ansatz function (rotation gates and CNOTs) | probabilistic distribution of Pauli strings | cost function value and objective function params | not proven (many) |
| | **VQE** | problem Hamiltonian | | probabilistic distribution of Pauli strings components of Hamiltonian ground state | cost function evaluation, ansatz update, ground state Hamiltonian | not proven (many due to cost function convergence, Pauli strings # & precision) |
| | **QML classification** | depends (training, inference, model) | object vector to classify encoded in amplitude | prediction result as an integer index in basis encoding | integer representing object position in a reference table | depends (many) |

# potential quantum speedups



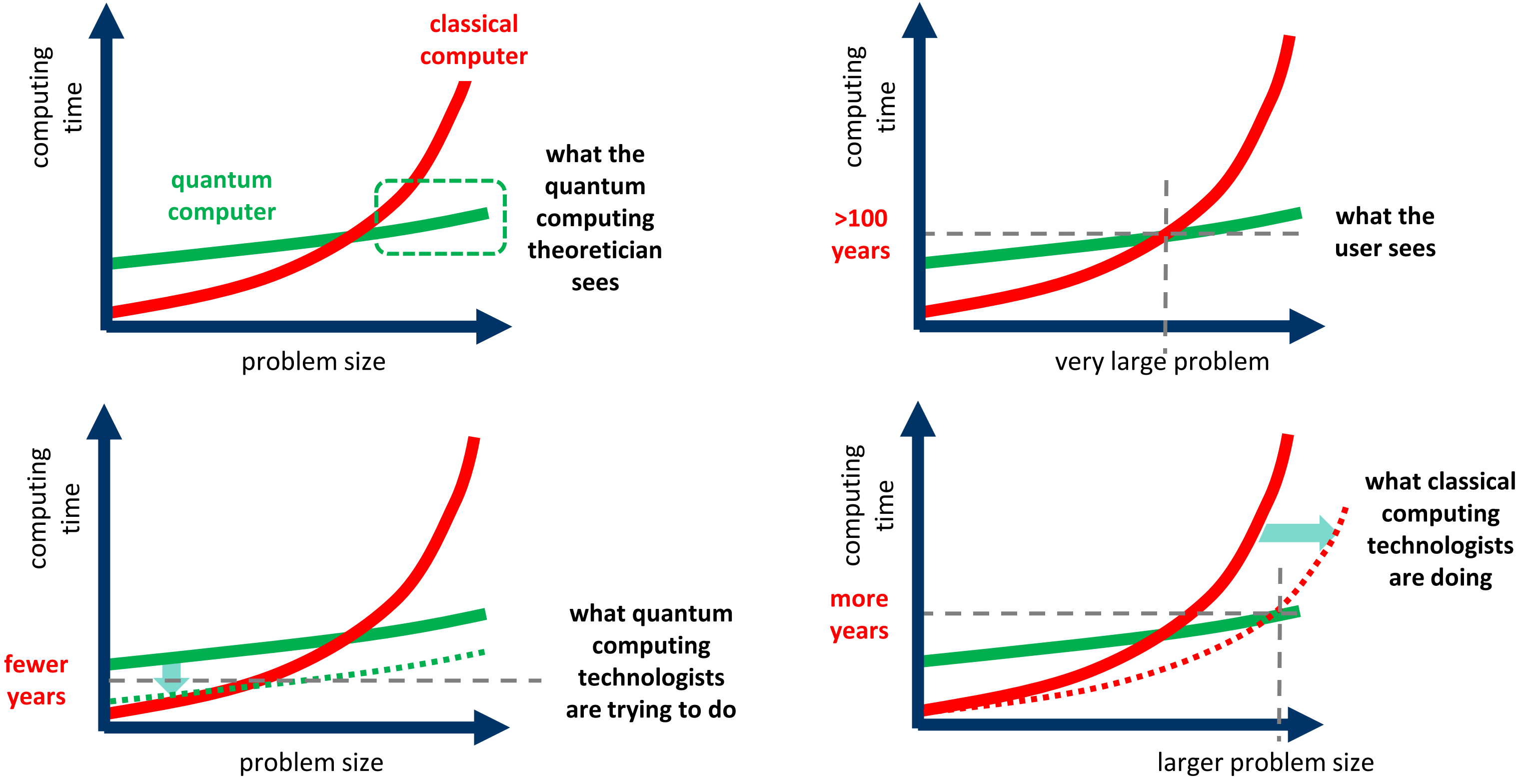

**limited advantage**

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

**requires FTQC QPUs**

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

# a matter of perspective

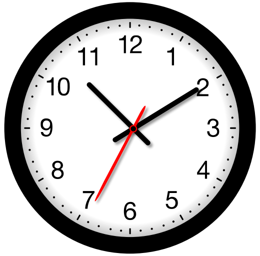


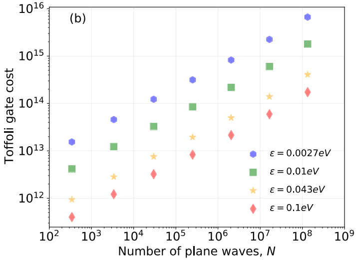

(cc) Olivier Ezratty, 2023, inspired by Disentangling Hype from Practicality: On Realistically Achieving Quantum Advantage by Torsten Hoefler, Thomas Häner, Matthias Troyer, 2023.

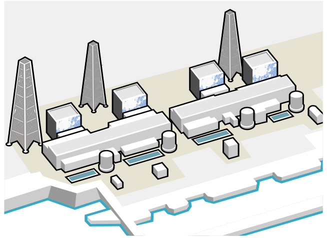
# quantum advantages taxonomy

complex amplitudes | of all combinations of 0 and 1

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



€ $ £

TCO

ROI

## space

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

## speed

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

## quality

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

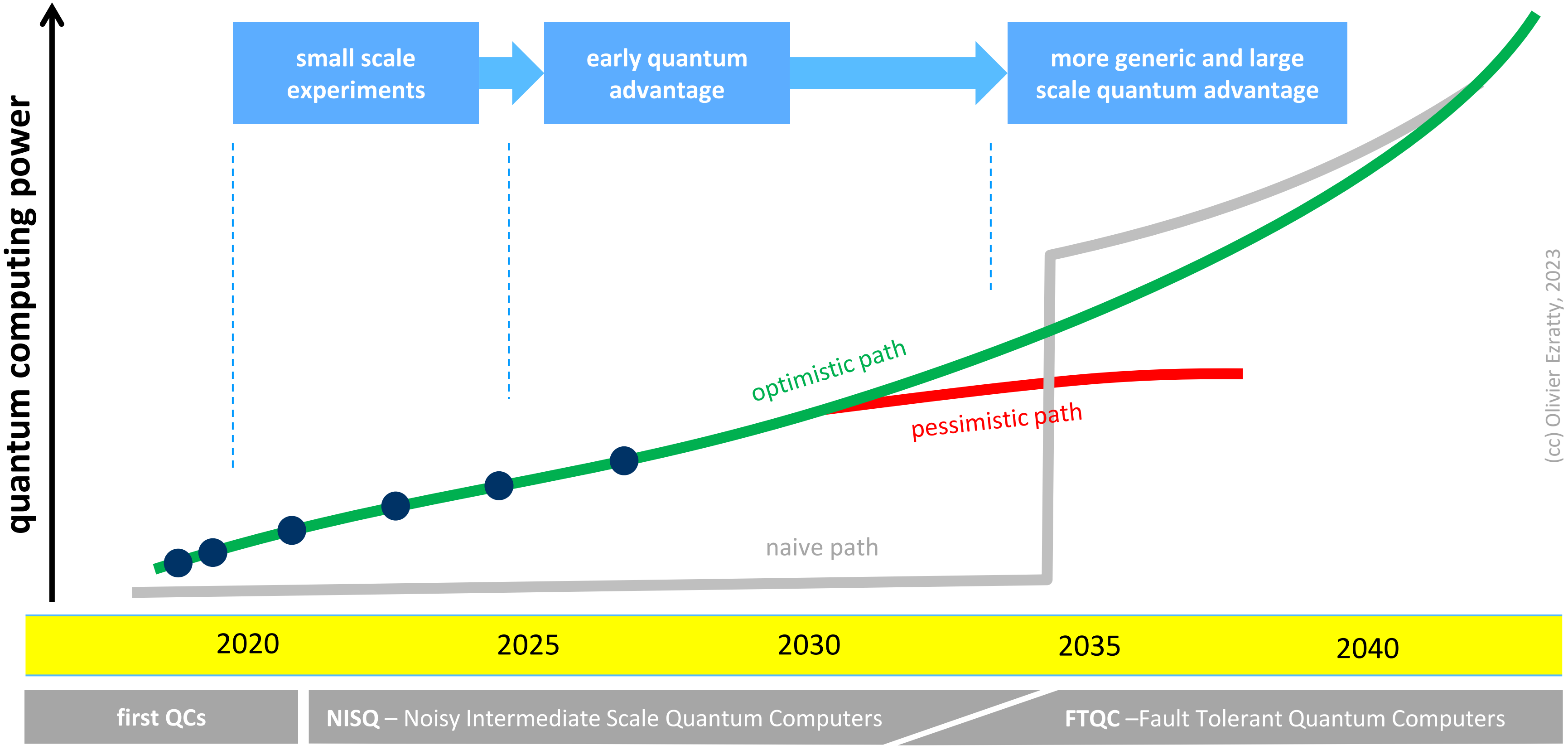
## energetic

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

## cost

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

# a long journey



# quantum computing cloud offerings

| | hybrid computing centers | OVHcloud | IBM | aws | Microsoft | Google |
|---|---|---|---|---|---|---|
| emulation | 40 qubits EVIDEN | EVIDEN<br>QUANDELA | | 34-50 qubits | 30 qubits | 40 qubits |
| quantum computing | hybrid quantum<br>TGCC (Très Grand Centre de calcul du CEA)<br>JÜLICH Forschungszentrum / Jülich Supercomputing Centre<br>LUMI<br>in 2023 | PASQAL<br>100 qubits (simulation)<br>QUANDELA<br>… | IBM<br>5 to 133 qubits | D-Wave<br>5000 qubits (annealing)<br>IONQ<br>32 qubits<br>rigetti<br>80 qubits<br>OQC<br>8 qubits<br>QuEra Computing Inc.<br>XANADU | PASQAL<br>100 qubits (simulation)<br>IONQ<br>32 qubits<br>rigetti<br>80 qubits<br>QUANTINUUM<br>12-32 qubits | IONQ<br>11 qubits |

and also

D-Wave
QCWARE
XANADU
Quantum Inspire - By QuTech

# what is being practically done

## classical computers

**quantum inspired**

- financial services solutions improvements.
- machine learning improvements.

**quantum emulators**

- code learning.
- code debugging.
- designing new algorithms.
- simulating qubit physics.
- simulating error correction codes.

ALPHARAIL, NatWest, Qubit PHARMACEUTICALS

## analog quantum computers

**quantum annealing computers** | **analog quantum simulators**

- solving optimization problems at mid-sized scale, in transportation (Volkswagen, Denso), retail (Ocado, Pattison), job shop scheduling and financial services (Mastercard, CACIB).
- physics simulations (statistical physics, spin glass, ferromagnetism, topological matter, …).
- potential energetic advantage.

CaixaBank, CRÉDIT AGRICOLE CORPORATE & INVESTMENT BANK, Raiffeisen Bank International Member of RBI Group

## digital quantum computers

**gate-based**

**NISQ** (Noisy Intermediate Scale Quantum)

- low-level physics simulations ("IBM quantum utility" with 127 qubits and kicked Ising model).
- creating and testing algorithms at small scale (QML, optimizations, chemical simulations).

eDF, AIRBUS, MBDA MISSILE SYSTEMS, TOTAL

**FTQC** (Fault-Tolerant Quantum Computing)

- large algorithms and resource estimations.
- creating and testing error correction codes (Google, Quantinuum, QuEra, PsiQuantum, …).

HYUNDAI, J.P.Morgan, Goldman Sachs

# why study quantum computing now?

1. **understand** the quantum computing technology and buzz.
2. **become ready** when quantum computing delivers.
3. attract **high-level talent** in your organization.
4. challenge and revisit **legacy classical solutions.**
5. envision **lower energy consumption** in HPC applications.

# 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

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

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

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

**photonics**
- cailabs SHAPING THE LIGHT
- Lytid
- exail
- SPARK LASERS
- LUMIBIRD
- AUREA TECHNOLOGY
- teem PHOTONICS
- SCINTIL PHOTONICS
- GLOphotonics
- QUANDELA

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

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


Hope to see you again
next year!
QuantAlps


ALICE & BOB


quobly


PASQAL

# discussion