QUANTUM TECHNOLOGY CONFERENCE QT4HEP 20-24 January 2025
CERN Main Auditorium

quantum computing roadmaps

towards fault-tolerance

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CERN QT4HEP Conference, Geneva, January 22nd, 2025

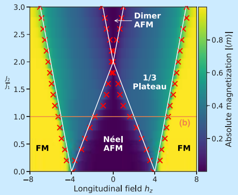
LRE
LABORATOIRE DE RECHERCHE DE L'EPITA

what is this talk about?

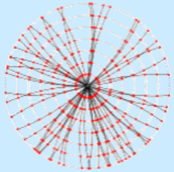
1. defining **practical quantum advantage**.
2. **segmenting** quantum computing use cases and algorithms.
3. providing quantum algorithms **resource estimates**.
4. uncovering hardware **scalability challenges**.
5. updating **qubit modalities** advances and vendor roadmaps.

from science to industry applications

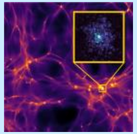
fundamental research



condensed matter physics

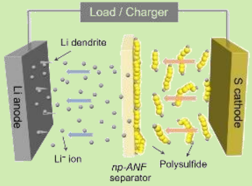


high-energy particle physics

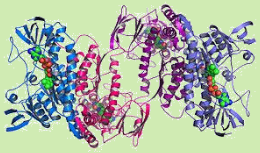


astrophysics

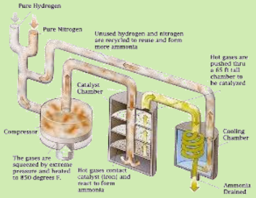
applied research



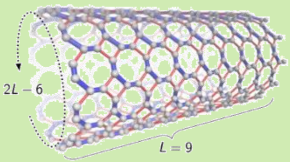
batteries



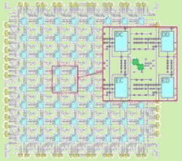
drugs



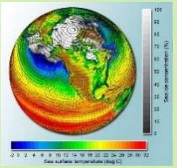
fertilizer production



material design

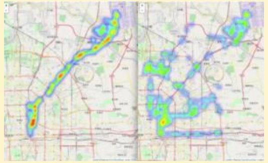


semiconductors

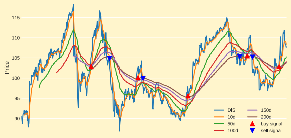


climate modeling

business operations

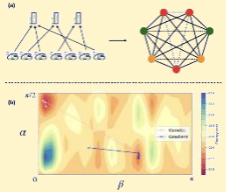


transportation

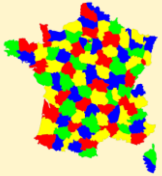


financial services

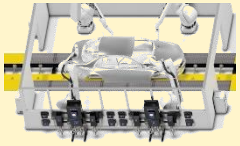
logistics and retail



energy utilities



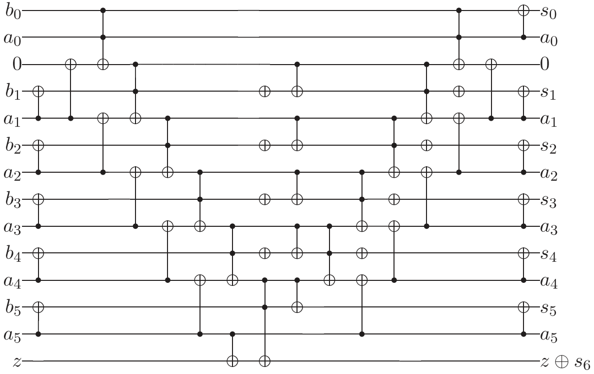
telecoms



manufacturing

main quantum computing paradigms

gates-based quantum computers

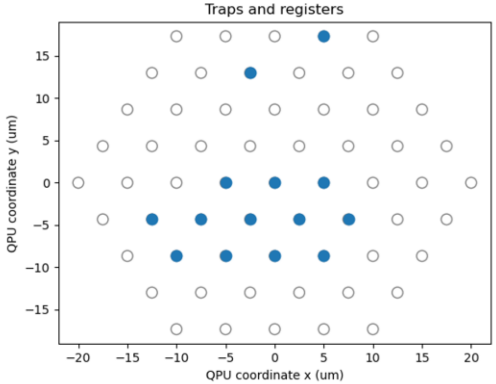


The ripple-carry adder for $n = 6$.

problem solved with an algorithm containing a series of quantum gates, implementing any unitary transformation

IBM QUANDELA

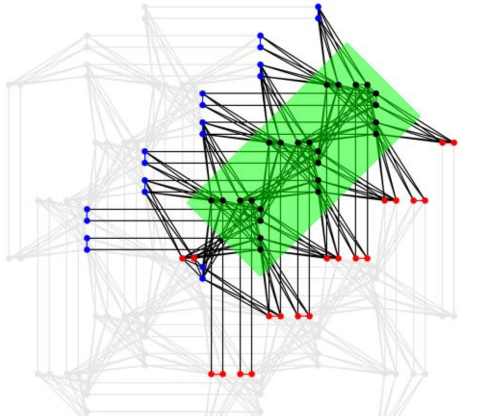
analog quantum simulators



problem embedded in a graph to solve Ising or QUBO problems, using dynamic qubit positioning but no or poor local qubit control

Pasqal QuEra

quantum annealers



problem embedded in a BQM model to solve Ising or QUBO problems, using static qubit connectivity and local control

D-Wave The Quantum Computing Company™

typical target Hamiltonians per paradigm

gates-based quantum computing

Heisenberg model (VQE)

spin dynamics, quantum magnetism, superconductivity.

$$H = \sum_{\langle i,j\rangle} \left(J_x S_i^x S_j^x + J_y S_i^y S_j^y + J_z S_i^z S_j^z\right) + \sum_i h_i S_i^z$$

electronic structure model (VQE, QPE)

encoded into qubit gates using Jordan–Wigner and Bravyi–Kitaev transforms, also applicable with HEP.

$$H = \sum_{p,q} h_{pq} a_p^\dagger a_q + \frac{1}{2} \sum_{p,q,r,s} g_{pqrs} a_p^\dagger a_q^\dagger a_r a_s$$

Fermi-Hubbard model (VQE, QPE)

strongly correlated systems in condensed matter physics, magnetism, Mott insulators, high T_c superc.

$$H = -t \sum_{\langle i,j\rangle,\sigma} \left(\hat{c}_{i,\sigma}^\dagger \hat{c}_{j,\sigma} + \text{h.c.}\right) + U \sum_i \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$

create unitary U based on H so that $||U - e^{-iHt}|| < \epsilon$ (error rate), and find eigenvalue or eigenstate of H of interest

analog quantum **simulation**

XX Ising models

quantum transport, superfluid-Mott insulator transitions, topological phases...

$$H = \sum_{i<j}^{N} J_{ij}\, \hat{\sigma}_i^x \hat{\sigma}_j^x$$

XY Ising models

non-trivial topological effects, real-time quench dynamics...

$$H = \sum_{i<j}^{N} J_{ij} \left(\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y\right)$$

XXZ Ising models

ferromagnetic, antiferromagnetic, spin-liquid states, U(1) LGT simulations...

$$H = \frac{1}{2} \sum_{i\neq j} J_{ij}^x (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + J_{ij}^z \sigma_i^z \sigma_j^z$$

find σ_i^x, σ_i^y, and/or σ_i^z minimizing a cost function that is the minimum eigenvalue of H

quantum **annealing**

Ising Hamiltonian

spin–spin interactions, quantum magnetism, $\mathbb{Z}_2$ and $U(1)$ lattice models.

$$H = \sum_i h_i \sigma_i^z + \sum_{i<j} J_{ij} \sigma_i^z \sigma_j^z$$

QUBO formulation

optimization problems, graph partitioning, route planning

$$H = \sum_i a_i x_i + \sum_{i,j} b_{ij} x_i x_j$$

MaxCut problems

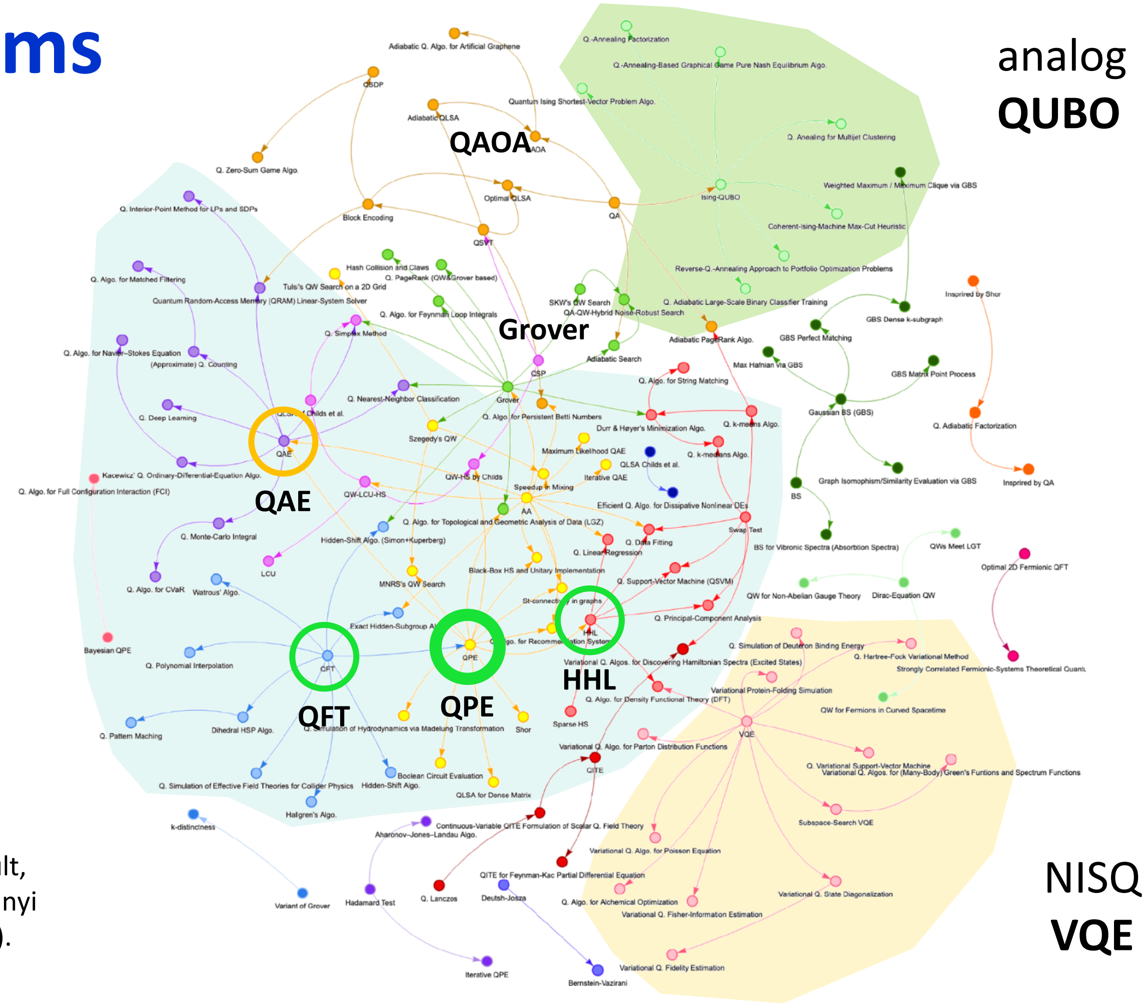
solving various graph problems.

$$H = \sum_{\langle i,j\rangle} w_{ij} \left(\frac{1 - \sigma_i^z \sigma_j^z}{2}\right)$$

find σ_i^z minimizing a cost function that is the minimum eigenvalue of H

quantum algorithms interdependency clusters

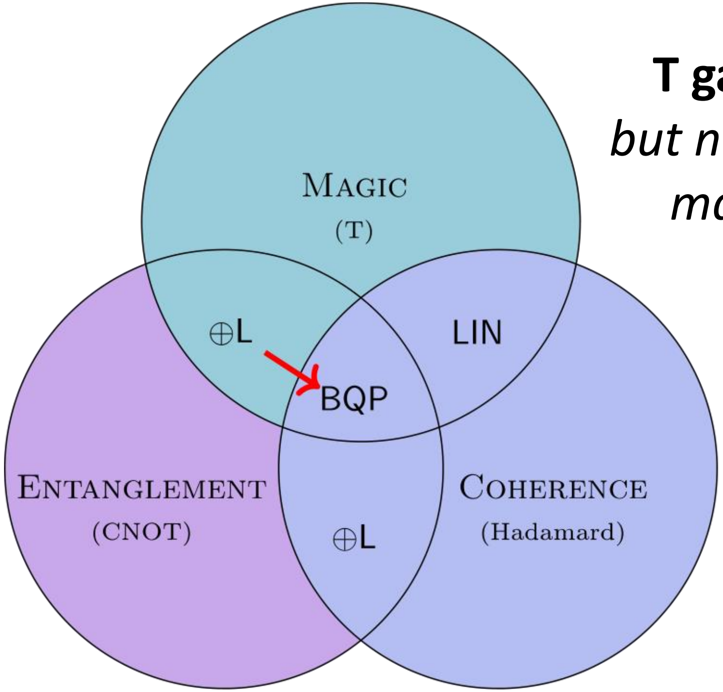
FTQC
QPE & QFT based



QUANTINUUM

A typology of quantum algorithms by Pablo Arnault, Pablo Arrighi, Steven Herbert, Evi Kasnetsi, and Tianyi Li, Inria, Quantinuum, arXiv, July 2024 (60 pages).

what is a valuable quantum algorithm?



T gates
but not too many

maximally entangled states

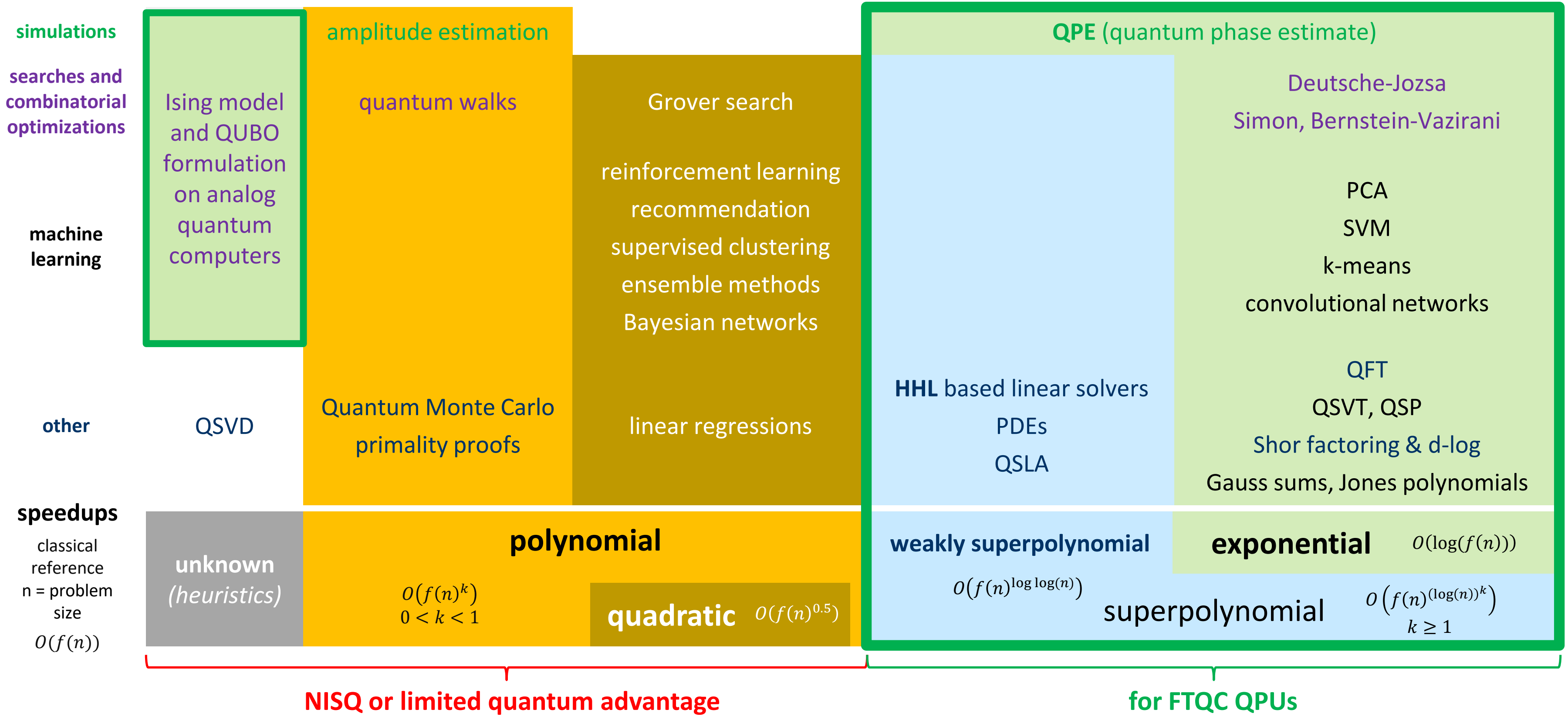
not too deep

chart source: On the role of coherence for quantum computational advantage by Hugo Thomas, **Pierre-Emmanuel Emeriau**, Elham Kashefi, Harold Ollivier, and Ulysse Chabaud, Quandela, LIP6, Inria, University of Edinburgh, arXiv, October 2024 (20 pages).

and…

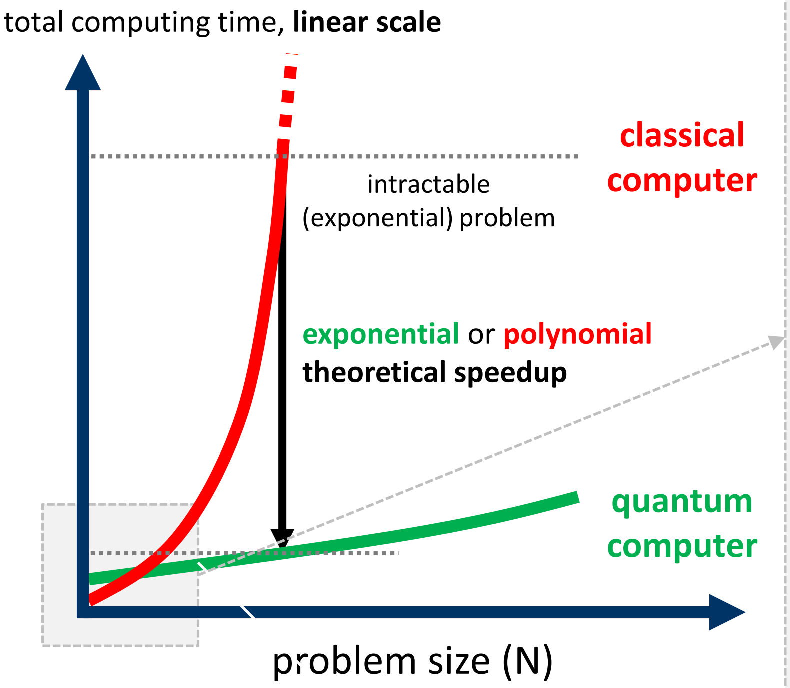
- **usefulness**: bringing some scientific or business value and genericity.
- **speedup**: practical vs best-in-class classical algorithms on reasonable time scales.
- **quality**: better accuracy or heuristics.
- **data**: not too much data in, not too many samplings out, avoid use of classical oracle.

potential quantum speedups

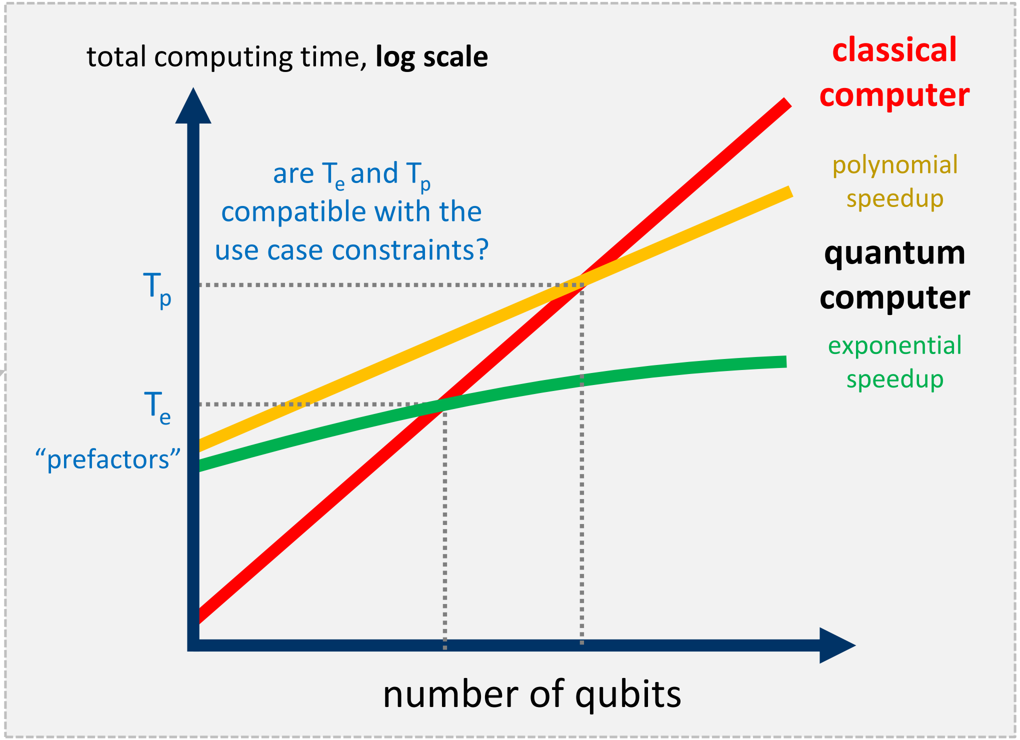


Understanding Quantum Technologies by Olivier Ezratty, as of November 2024.

theoretical vs practical speedup



the typical way to illustrate quantum computing theoretical speedups.



Opening the Black Box inside Grover's Algorithm, E. Miles Stoudenmire and Xavier Waintal, PRX, November 2024.

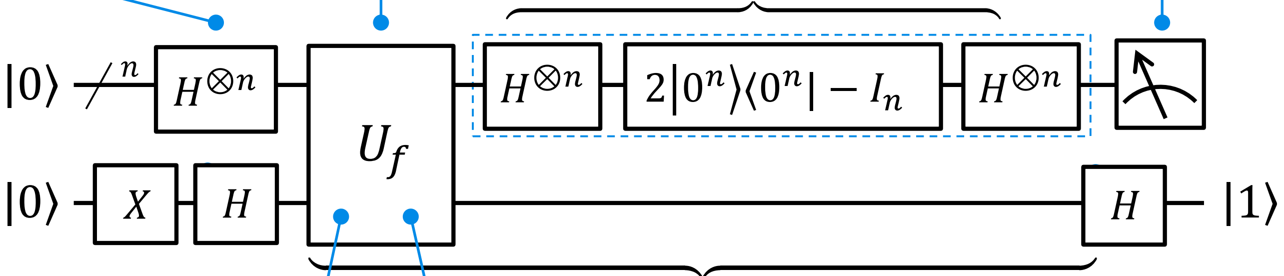
how **oracle based algorithms** work

creates a superposition of N=2^n computational states

U quantum oracle function flips the sign/phase of found computational state **x**

Grover diffusion operator series of gates amplifying x and attenuating other states

index response readout: solution index **x** with n bits



repeated $O(\sqrt{N})$ *times*

oracle sign inversion on one computational base value, x

classical preparation of a quantum circuit

or

qRAM accessing classical data

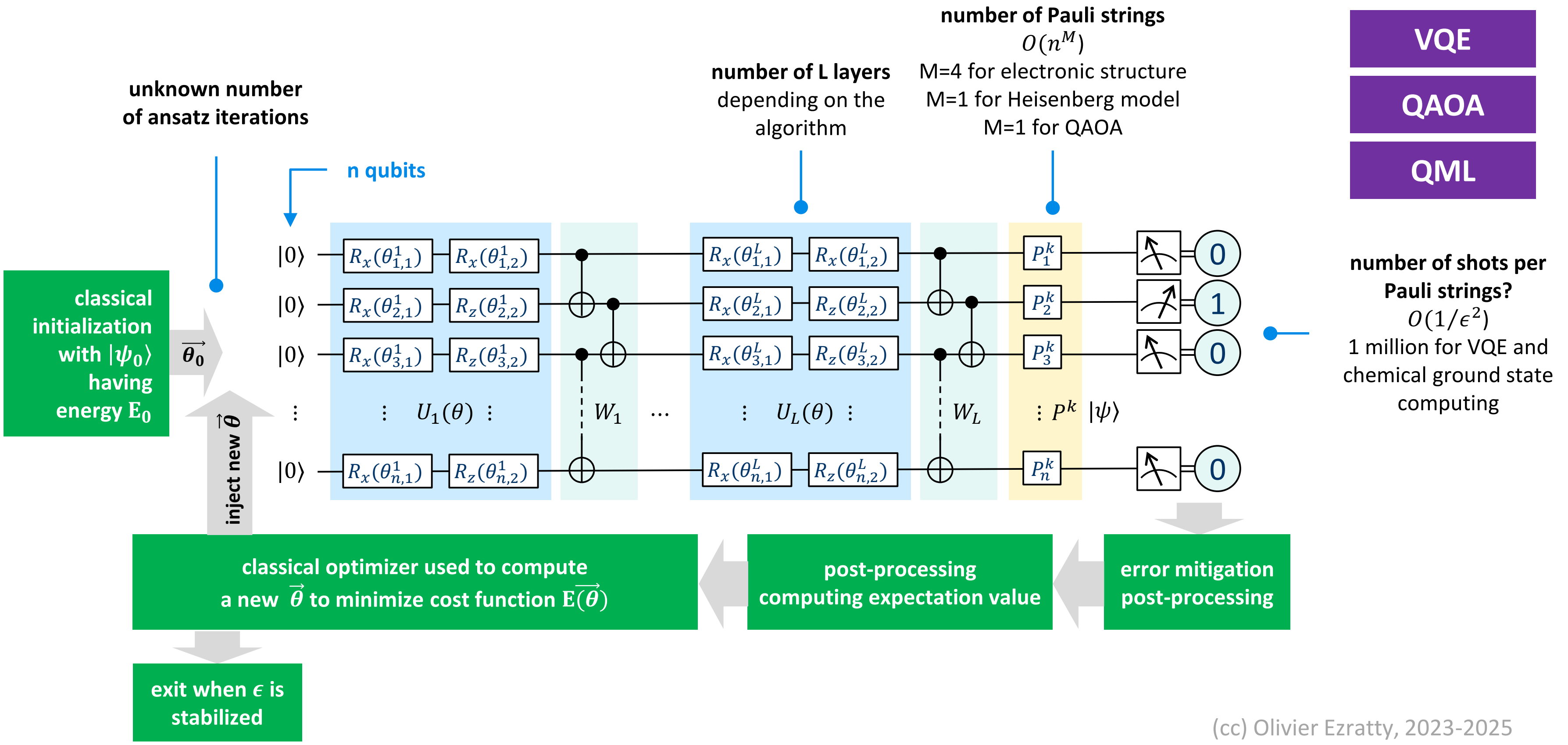
Grover

Simon

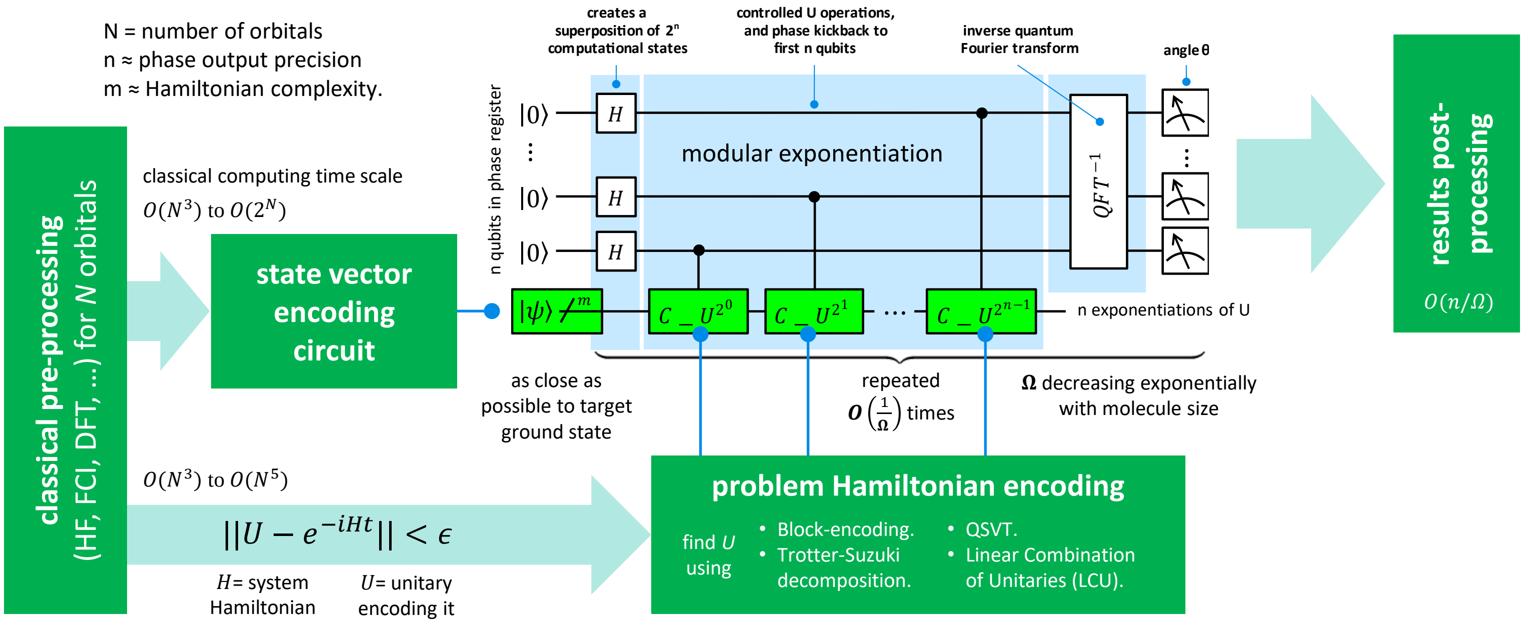
Bernstein-Vazirani

example with the Grover algorithm

how **variational algorithms** work

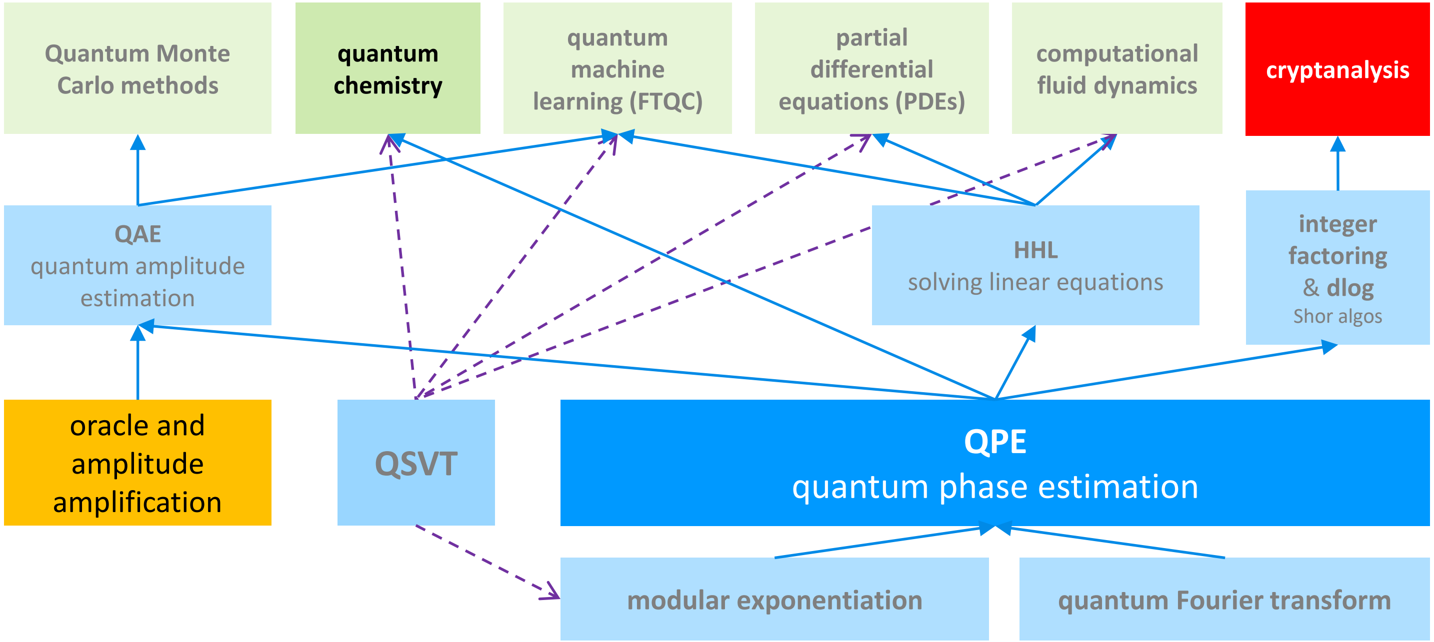


how **Quantum Phase Estimation** works



inspired by Quantum chemistry, classical heuristics, and quantum advantage by Garnet Kin-Lic Chan, arXiv, July 2024 & On the feasibility of performing quantum chemistry calculations on quantum computers by Thibaud Louvet, Thomas Ayral, and Xavier Waintal, arXiv, June 2023-October 2024.

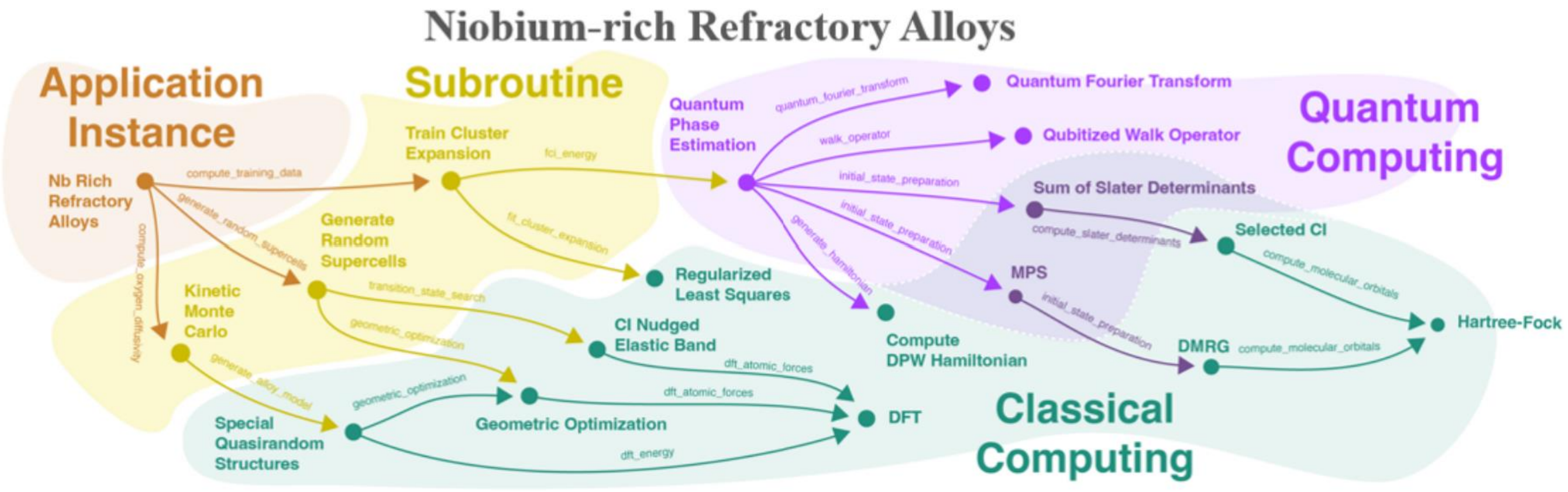
key FTQC quantum algorithms food chain



Why Haven't More Quantum Algorithms Been Found? by Peter Shor, 2003 (4 pages).

Quantum algorithms: A survey of applications and end-to-end complexities by Alexander M. Dalzell, Fernando G. S. L. Brandão et al, AWS, RWTH Aachen University, Imperial College London, Caltech, October 2023 (337 pages).

hybrid software architecture



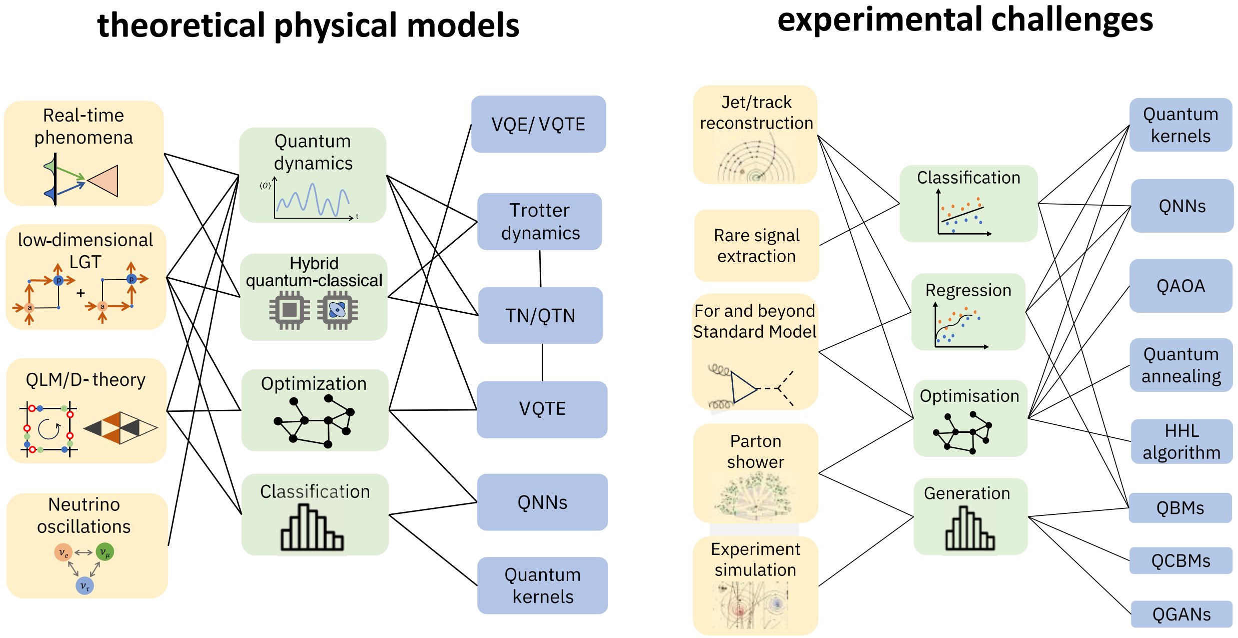
this chart describes not an hybrid classical-quantum algorithm but an hybrid classical-quantum whole architecture, to simulate digitally how niobium-rich refractory alloys could reduce corrosion. Source: [Quantum computing for corrosion-resistant materials and anti-corrosive coatings] design by Nam Nguyen et al, arXiv, June 2024 (52 pages).

HEP quantum algorithms

typical problems:

- low-dimensional lattice gauge theory (LGT).
- anomaly detection in collider experiments.
- detector operation algorithms.
- identification and reconstruction algorithms.
- simulation and inference tools.

mix of analog, NISQ and FTQC algorithms.

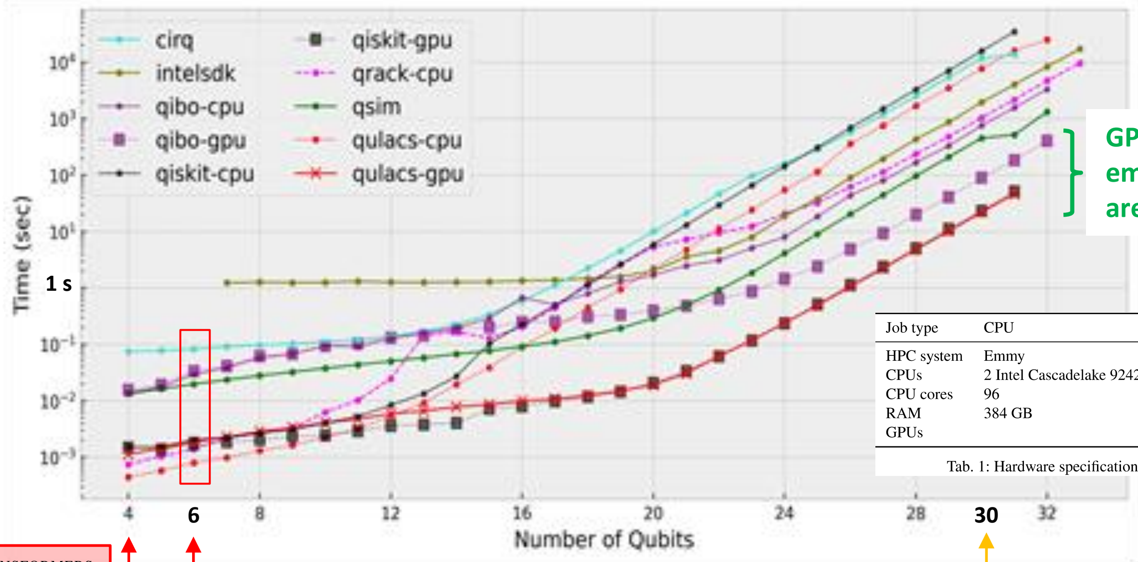


Quantum Computing for High-Energy Physics: State of the Art and Challenges by Alberto Di Meglio et al., PRX Quantum, July 2023-August 2024 (49 pages) focuses on utility-scale NISQ algorithms.

NISQ cases

log times in seconds

for simulating a single quantum volume of the given qubit number for tested emulator on a single classical cluster node



GPU-based emulations are faster

Job type	CPU	CPU with GPU accelerator
HPC system	Emmy	Grete
CPUs	2 Intel Cascadelake 9242	2 AMD Zen3 EPYC 7513
CPU cores	96	64
RAM	384 GB	512 GB
GPUs		4 Nvidia Tesla A100 40GB

Tab. 1: Hardware specifications for single node jobs

A comparison of HPC-based quantum computing simulators using Quantum Volume by Lourens van Niekerk, Christian Boehme et al, arXiv, December 2024.

QUANTUM ATTENTION FOR VISION TRANSFORMERS IN HIGH ENERGY PHYSICS
https://arxiv.org/abs/2411.13520 11/2024

Application of Quantum Machine Learning in a Higgs Physics Study at the CEPC

Abdualazem Fadol [1,5], Qiyu Sha [1,2], Yaquan Fang [1,2], Zhan Li [1,2], Sitian Qian [3], Yuyang Xiao [3], Yu Zhang [4], Chen Zhou [3,*]
[1] Institute of High Energy Physics, 19B Yuquan Road, Shijingshan District, Beijing 100049, China
[2] University of Chinese Academy of Sciences, 19A Yuquan Road, Shijingshan District, Beijing 100049, China
[3] State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University, 209 Chengfu Road, Haidian District, Beijing 100871, China
[4] Qujing Normal University, 222 Sanjiang Road, Qilin District, Qujing 655011, Yunnan Province, China
[5] Spallation Neutron Source Science centre, Dongguan 523803, China
E-mail: *czhouphy@pku.edu.cn

5/2024

https://www.worldscientific.com/doi/full/10.1142/S0217751X24500076

Quantum algorithms for the simulation of QCD processes in the perturbative regime https://arxiv.org/abs/2412.21177

Herschel A. Chawdhry[1] and Mathieu Pellen[2] 12/2024

[1]Department of Physics, Florida State University, 77 Chieftan Way, Tallahassee FL, USA
[2]Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, Freiburg, Germany

Quantum Simulations of Hadron Dynamics in the Schwinger Model using 112 Qubits

Roland C. Farrell[1,*] Marc Illa[1,†] Anthony N. Ciavarella[1,2,‡] and Martin J. Savage[1,§]
[1]InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA.
[2]Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Dated: June 12, 2024)

6/2024 https://arxiv.org/abs/2401.08044

→ 112

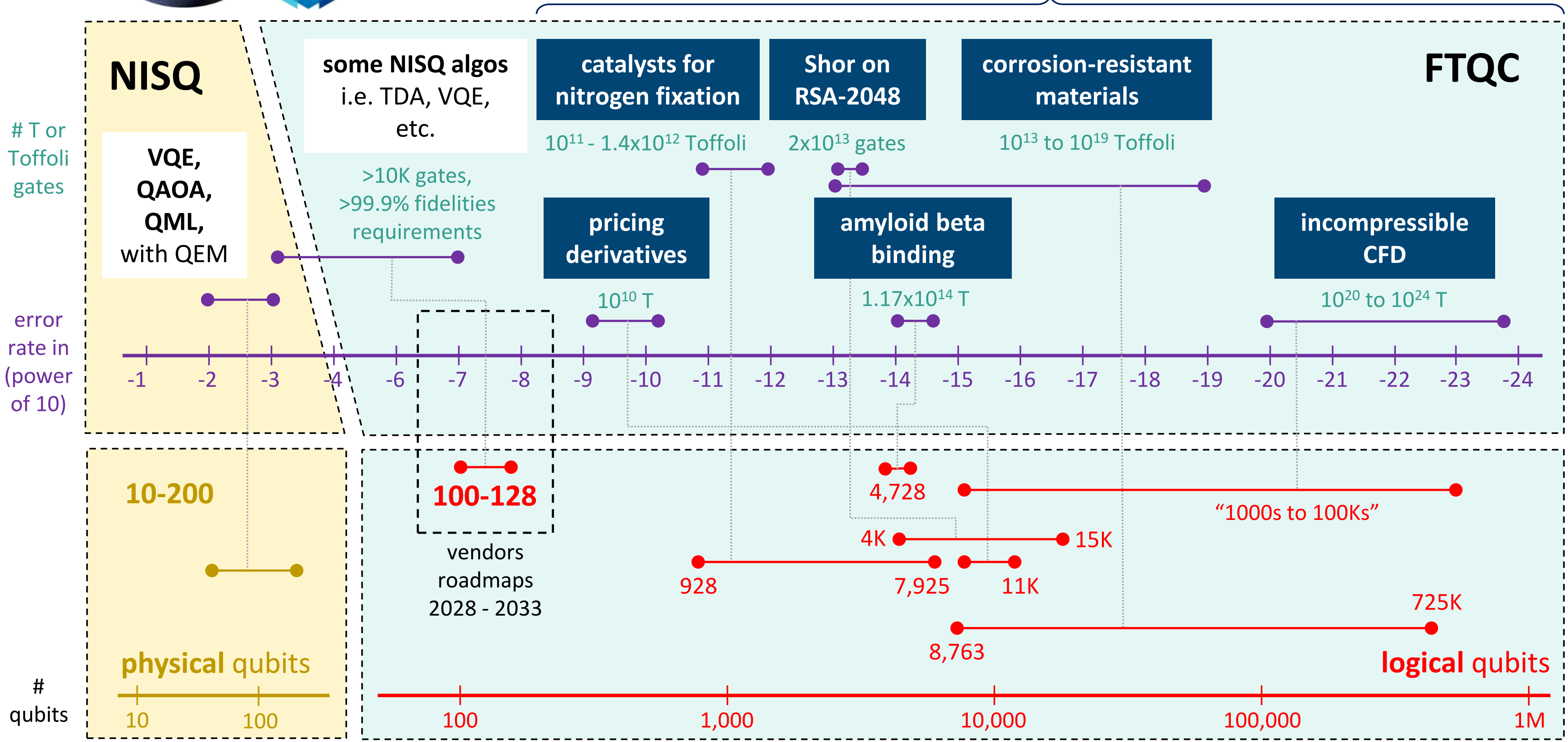
Scalable Quantum Simulations of Scattering in Scalar Field Theory on 120 Qubits

Nikita A. Zemlevskiy*
InQubator for Quantum Simulation (IQuS), Department of Physics, University of Washington, Seattle, WA 98195, USA.
(Dated: No b 6, 2024)

11/2024 https://www.arxiv.org/abs/2411.02486

→ 120

most of these solutions are based on variations of QPE

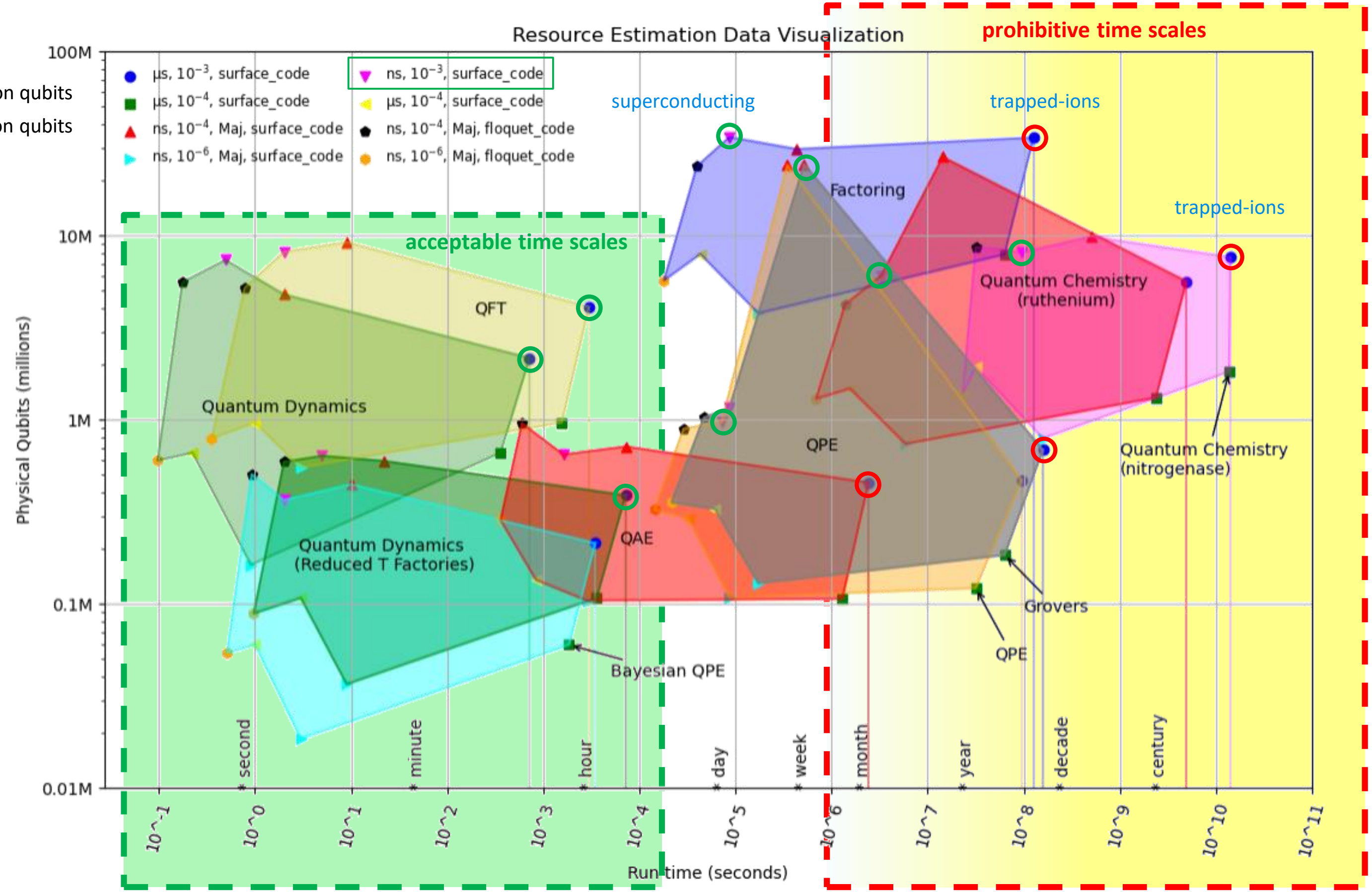


physical qubits and logical qubits are on a similar log scale. What determines the characteristics of logical qubits like the physical per logical qubit count is their target error rate itself dependent on the number of algorithms gates.

Understanding Quantum Technologies
by Olivier Ezratty, as of November 2024.

µs gate times: trapped ion qubits

ns gate times: superconducting and silicon qubits

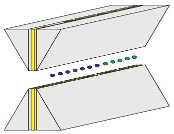


several scenarios are used with different physical qubit error rates and gate times.
The realistic ones are with 99.9% fidelities and µs readout cycle times.

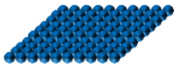
The GQI Quantum Resource Estimator Playbook - Quantum Computing Report
by Doug Finke, Quantum Computing Report, August 2024.

QPUs vendors per qubit type

atoms

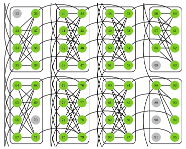
trapped ions


Quantinuum, IonQ, AQT, Oxford Ionics, eleQtron, Foxconn, Quantum Art, Crystal Quantum Computing, NEQXT, Qudora Technologies, HYQ Co

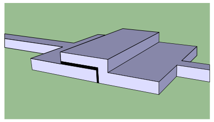
cold atoms


Pasqal, QuEra, Infleqtion, atom computing, planqc, QUANTier, NanoQT (Nanofiber Quantum Technologies), Atom Quantum Labs

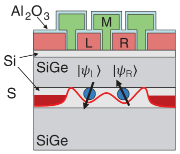
electrons *controlled spin and microwave cavities*

annealing


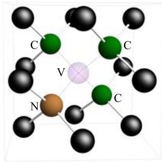
D-Wave (The Quantum Computing Company), Qilimanjaro Quantum-Tech, NEC

superconducting


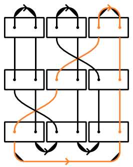
IBM, rigetti, amazon, Google, qci, Nord Quantique, OQC, IQM, Alice & Bob, 本源量子 Origin Quantum, Anyon, Atlantic Quantum, Fujitsu, QoLab, Peak Quantum (Jumpstarting Quantum Computing), Z-Axis Quantum

silicon


intel, quobly, Quantum Motion, Silicon Quantum Computing, diraq, Equal1, SemiQon, equal1.labs, C12, ARQUE, QπAI, ARCHER

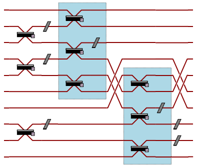
vacancies


Quantum Brilliance, SaxonQ, Turing, photonic, Quantum Transistors, SQutec, XeeD, Fujitsu, NTT

topological


Microsoft, Quoherent, Quantum Gravity Research, Nokia

photons

photons


PsiQuantum, Quandela, ORCA Computing, Xanadu, Duality Quantum Photonics, QuiX Quantum, BardeenQ Labs, QBoson, QCi, photonicsQ, Quanfluence, Tundra Systems Global, aegiq

[Understanding Quantum Technologies](#)
by Olivier Ezratty, as of November 2024.

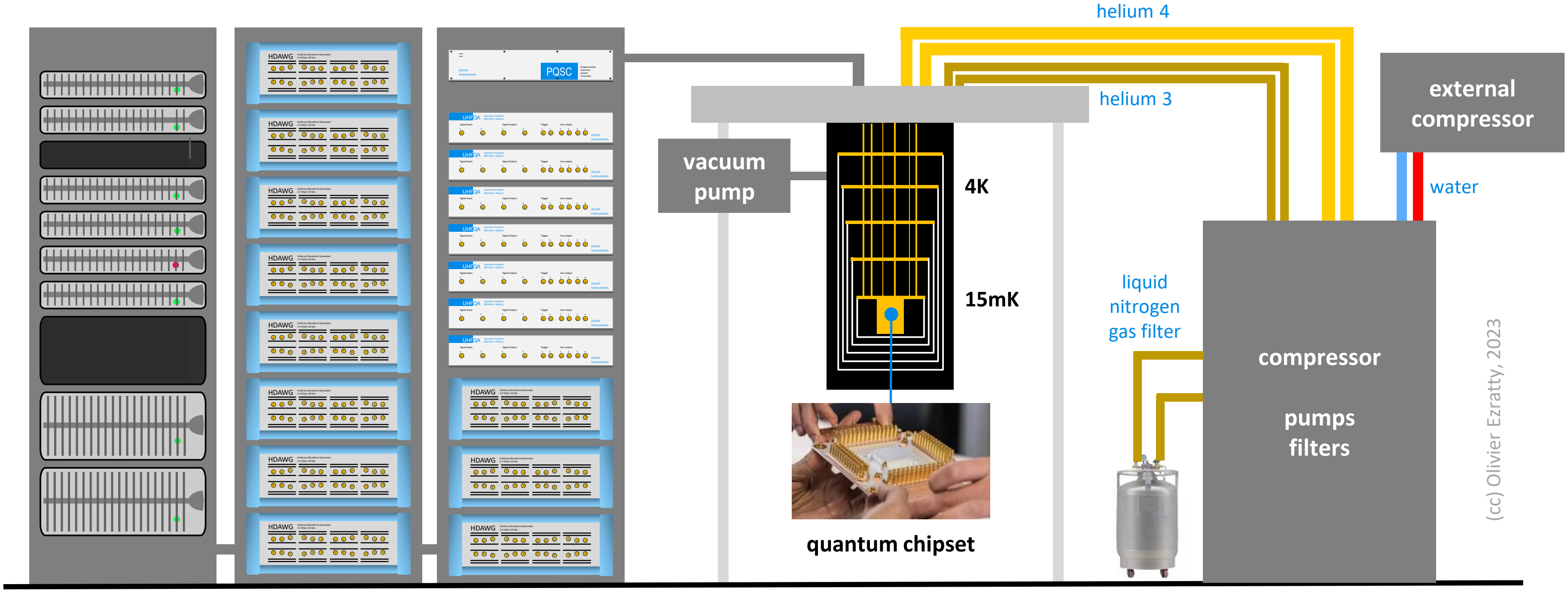
inside a typical quantum computer

computing
servers, network,
software, data

qubits control electronics
microwave generators, readout
systems and various electronics

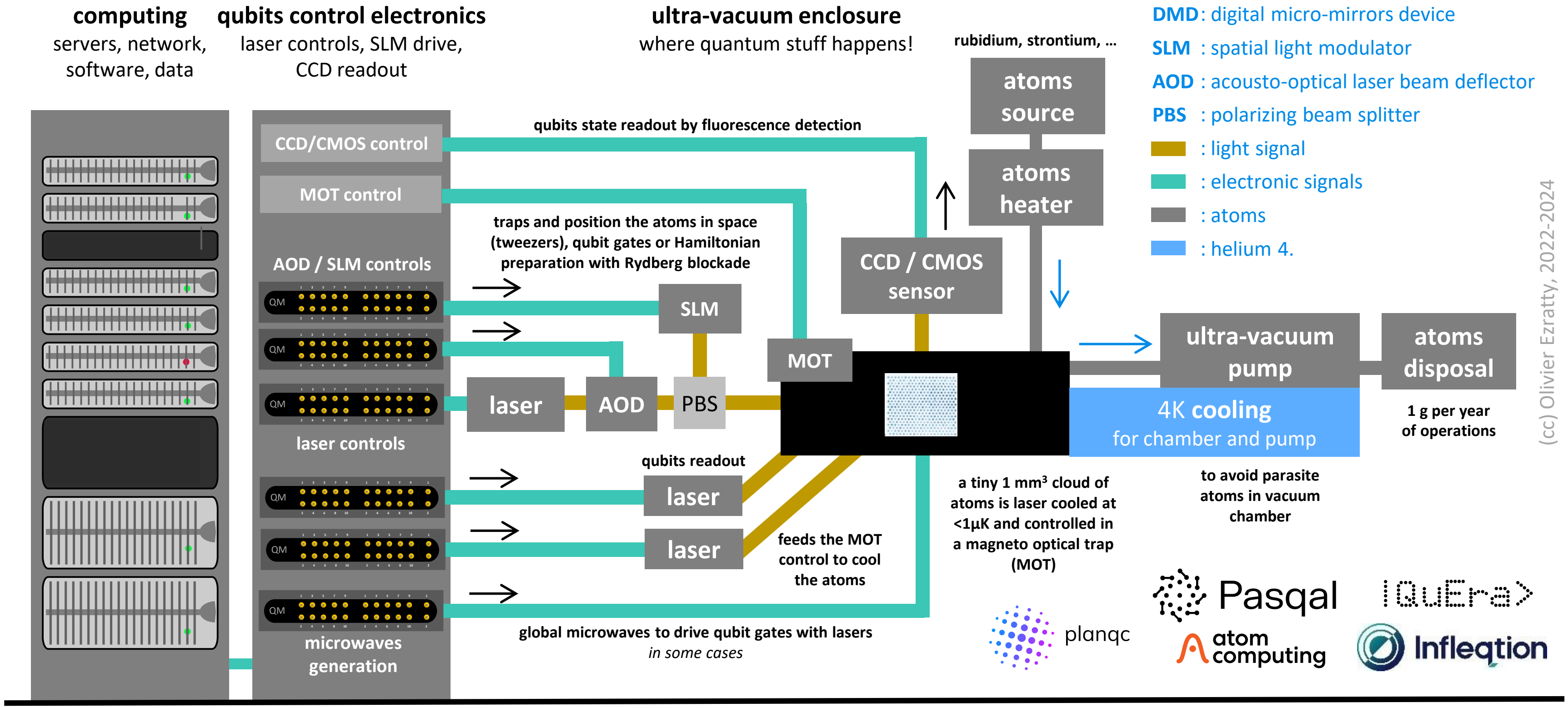
« chandelier » in cryostat
where quantum stuff happens!

cryogenic installation
helium 3 & 4
gas pumps and compressor



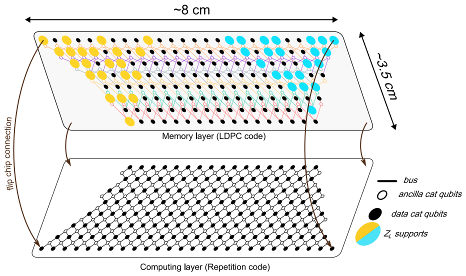
for superconducting or electron spin qubits

with a neutral atoms quantum computer

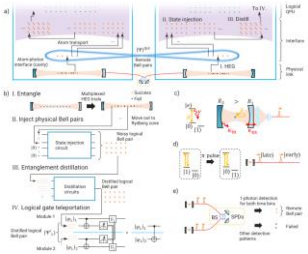


original QPU ideas

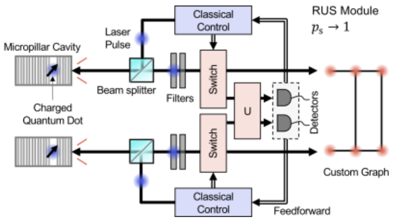
ALICE & BOB
Nord Quantique
amazon



NanoQT
Nanofiber Quantum Technologies



QUANDELA



bosonic qubits

engineered dissipation at qubit level, lower QEC overhead than transmons, could reach 100 logical qubits without interconnect.

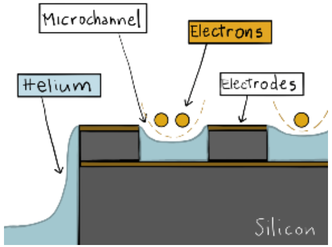
cold atoms and nanofiber connectivity

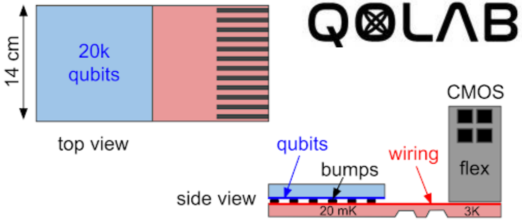
scaling cold atoms through photonic interconnectivity and routing.

deterministic photonic cluster states

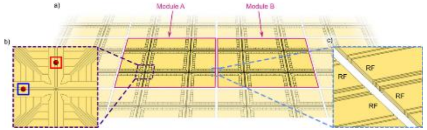
for scaling with FBQC.

EeroQ
QUANTUM HARDWARE





QOLAB



electron spin on superfluid helium

better isolation.

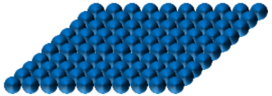
CPW wafer for cryoelectronics control

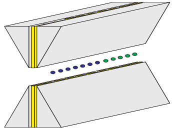
scaling cabling, optimizing connectivity.

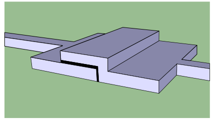
tiled ion traps & microwave drive

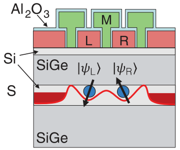
better scaling, excellent ions shuttling fidelities.

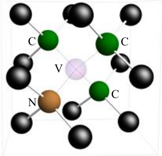
rough qubit modalities comparison

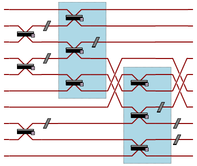






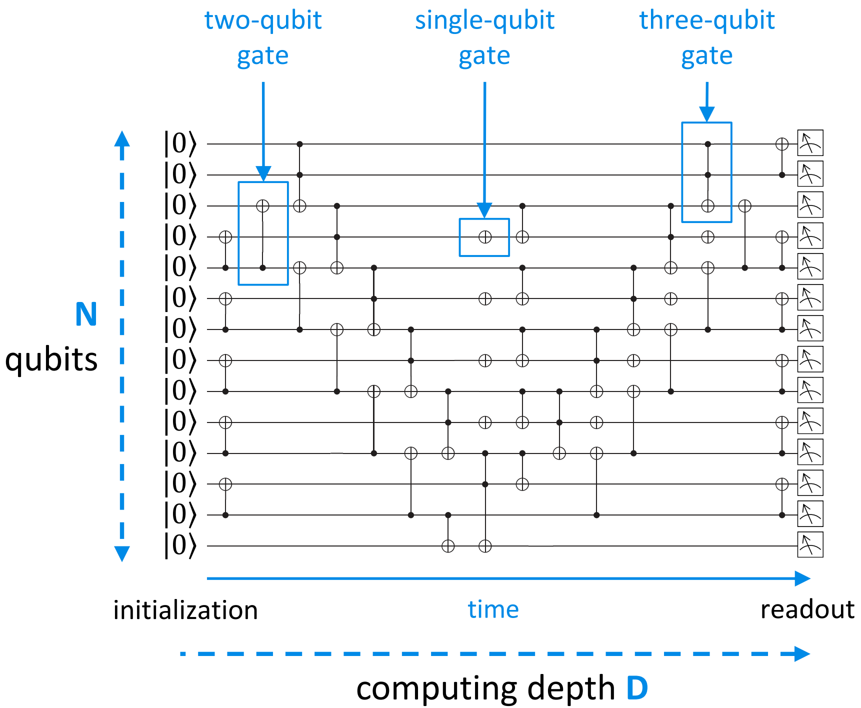






	atoms		**electrons** *controlled spin and microwave cavities*			**photons**
	cold atoms	**trapped ions**	**superconducting**	**silicon**	**NV centers**	**photons**
operations fidelities						
gate times	with no shuttling					
qubit connectivity	with shuttling					
cooling needed	4K	4K	15 mK	≈500 mK	TBD	1.8 to 4K
qubit size						
scalability		with tiled chips				

raw algorithm fidelities requirements



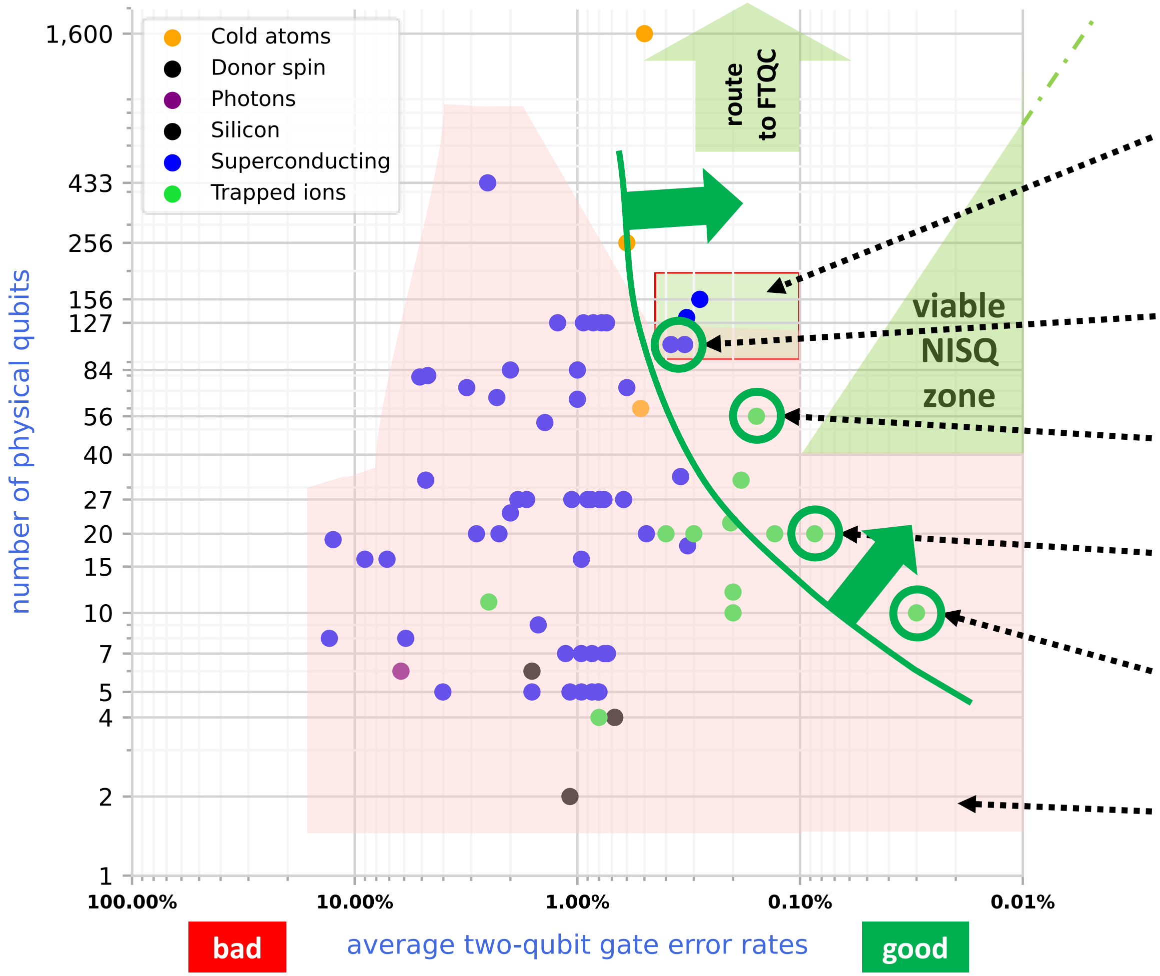
desired error rate $< \frac{1}{N \times D}$

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 operations accumulated errors quickly kills algorithms accuracy

possible solutions:

- **use shallow circuits on a few qubits** (NISQ).
- **quantum error mitigation** (NISQ).
- **quantum error correction** (FTQC).



quantum error mitigation NISQ utility window

algorithmiq IBM

99.67% « Willow »
August 2024
+ China Zuchongzhi 3.0

Google

99.87%
June 2024

99.9%
April 2024

QUANTINUUM

99.97%
July 2024

oxford ionics

easy to emulate classically below 99.9% fidelities (tensor networks) or below 40 qubits (state vector).

logical qubits and FTQC

physical qubit

error rates ≈0.1%

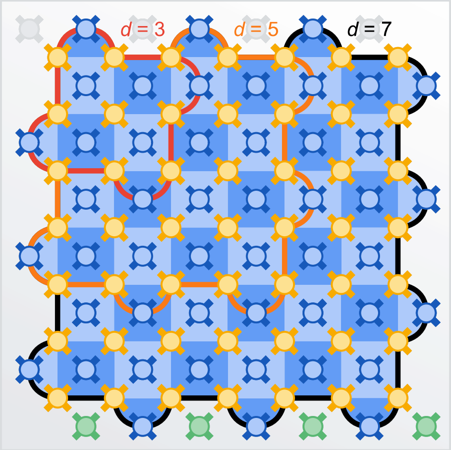
+

error correction code

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

logical qubits

error rate ≈10^{-4} to ≈10^{-18}

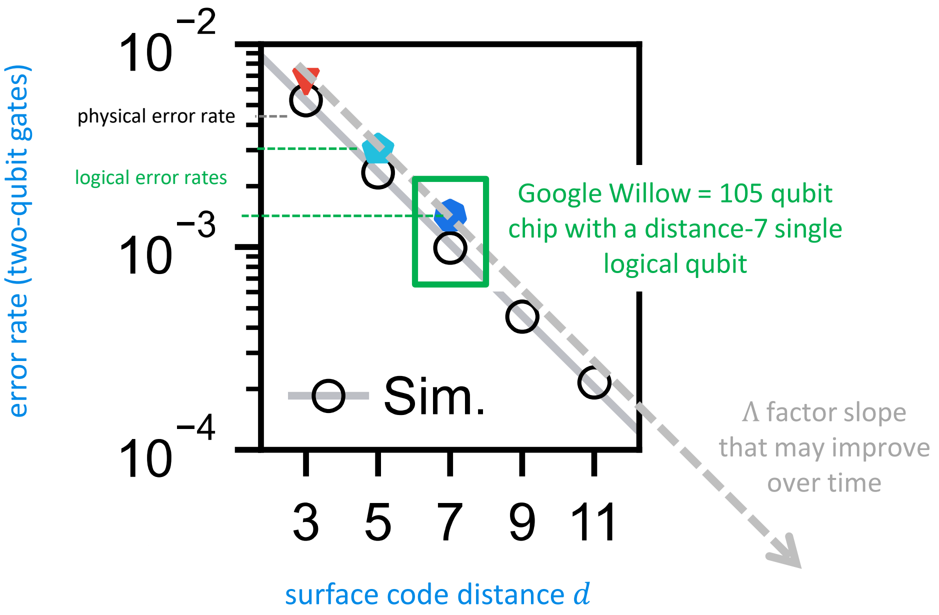


tens to thousands physical qubits per logical qubits

fault tolerance

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

beyond the first breakeven logical qubits



number n_q of physical qubits per logical qubit

$$n_q = 2d^2 - 1$$

10^{-6} logical error rates would require 1,457 physical qubits per logical qubits and a distance-27 surface code with existing qubit fidelities.

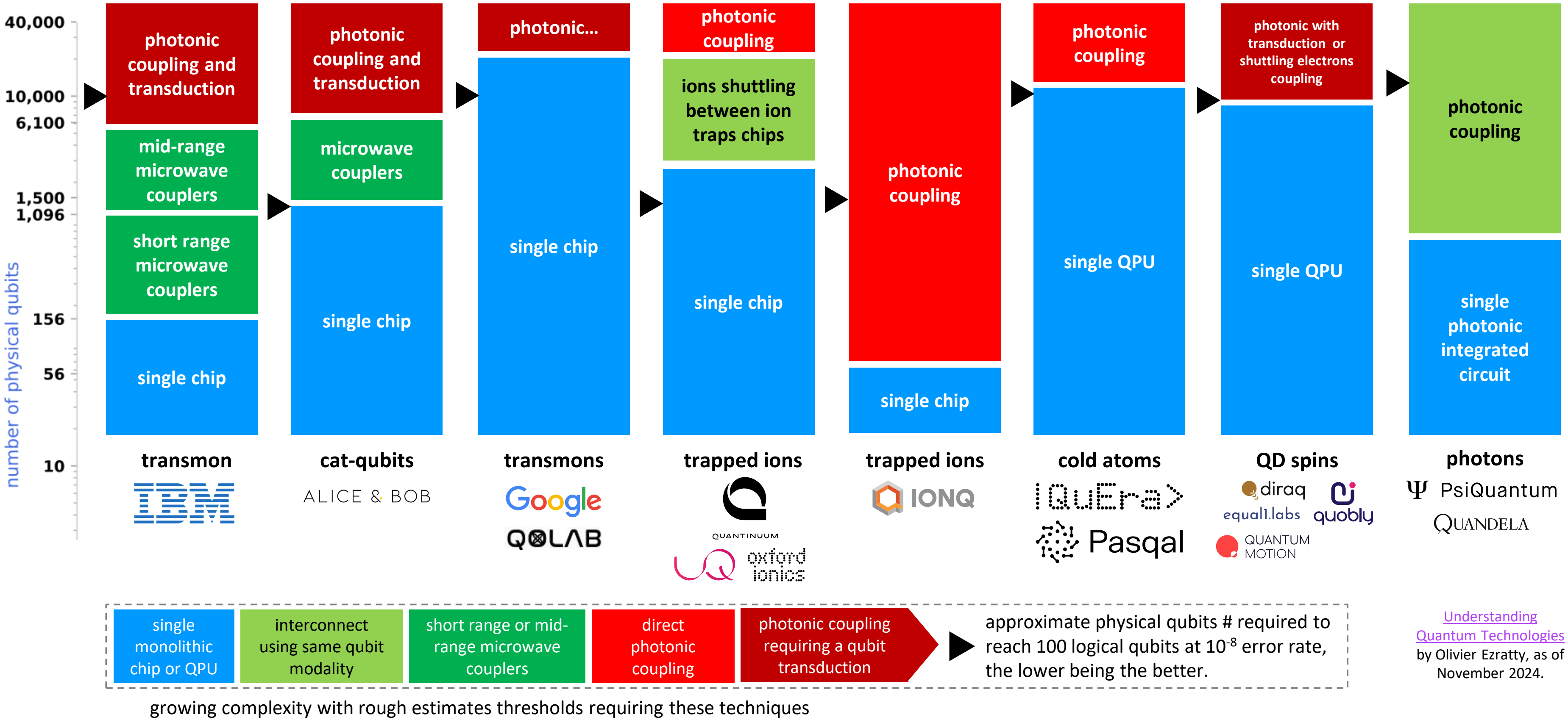
+

plan for 10K qubits chips

QPU interconnect

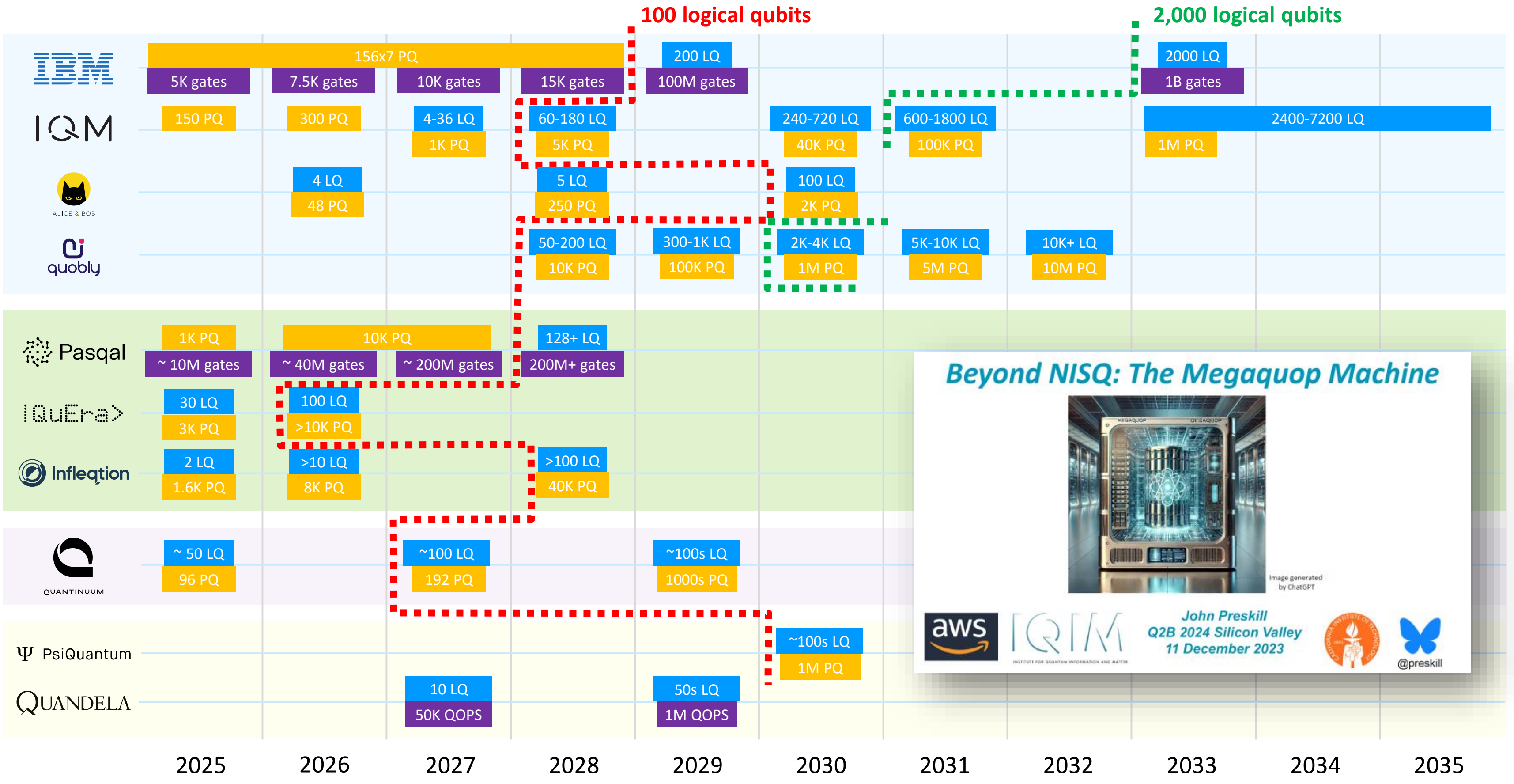
Quantum error correction below the surface code threshold by Rajeev Acharya, Frank Arute, Michel Devoret, Edward Farhi, Craig Gidney, William D. Oliver, Pedram Roushan et al, Google, arXiv, August 2024.

multiple QPUs interconnect options

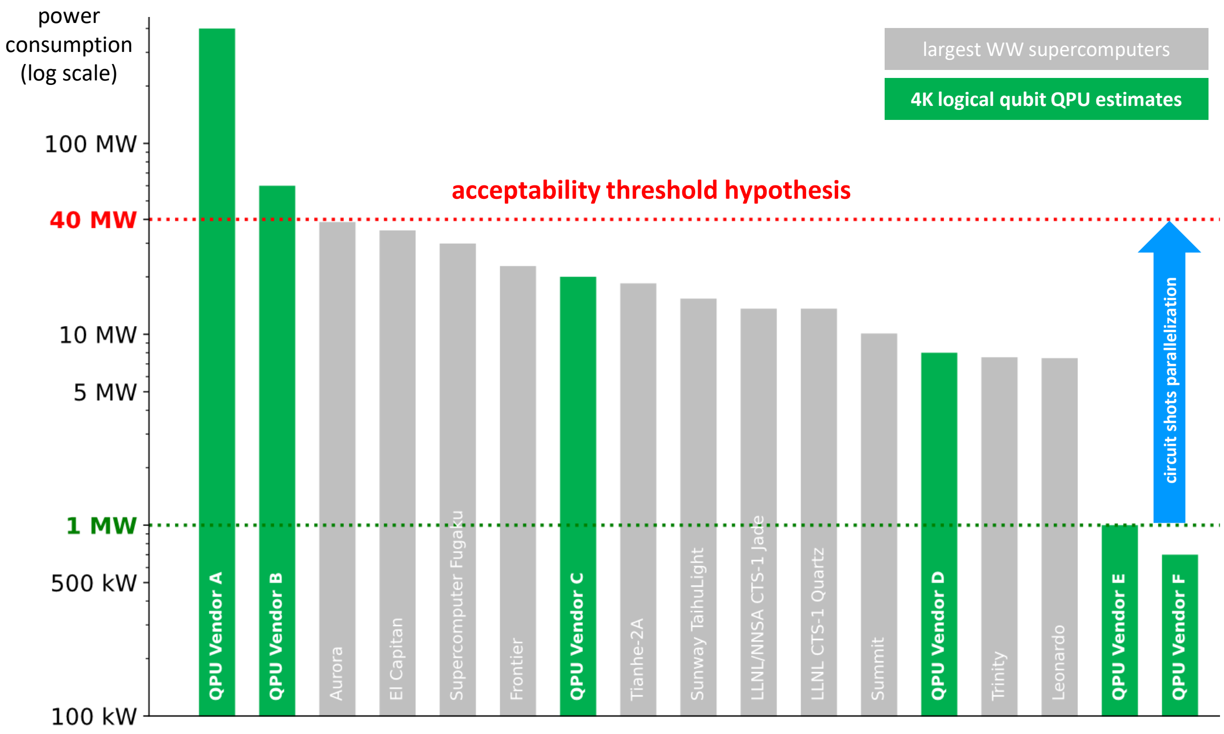


Understanding Quantum Technologies by Olivier Ezratty, as of November 2024.

QPUs roadmaps consolidation



QPU vs HPC power scale guesstimates



estimate base power for various QPUs and actual for existing largest HPCs WW.
HPC source: https://www.top500.org/lists/top500/2024/06/.

#QEI
the quantum energy initiative

IEEE

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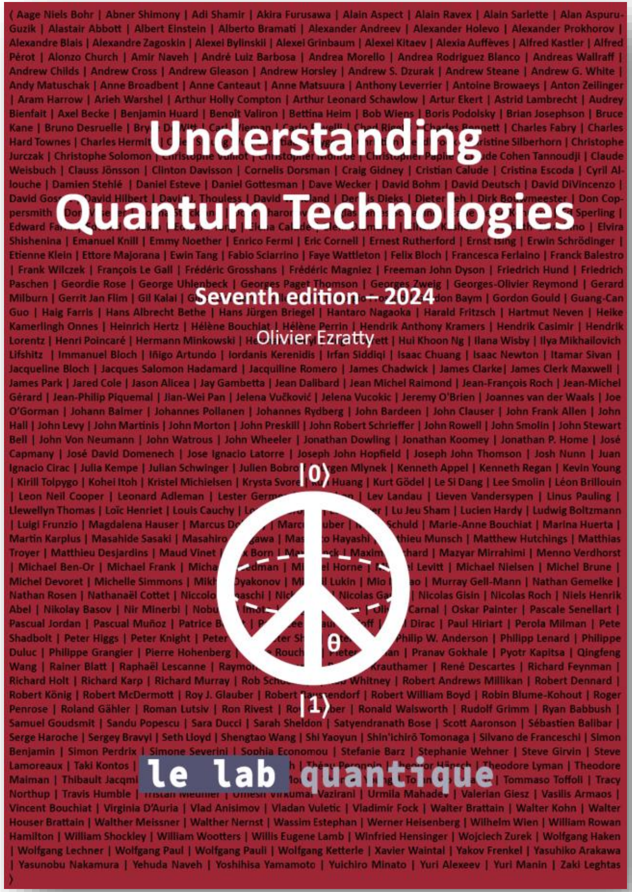

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