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QUANTUM TECHNOLOGY CONFERENCE
QT4HEP 20-24 January 2025

quantum computing roadmaps

towards fault-tolerance

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CERN QT4HEP Conference, Geneva, January 22nd, 2025

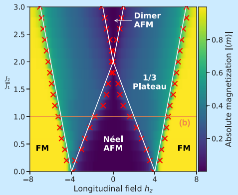
LRE
LABORATOIRE DE RECHERCHE DE L'EPITA

what is this talk about?

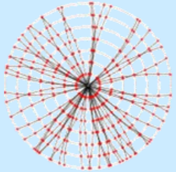
1. defining **practical quantum advantage**.
2. **segmenting** quantum computing use cases and algorithms.
3. providing quantum algorithms **resource estimates**.
4. uncovering hardware **scalability challenges**.
5. updating **qubit modalities** advances and vendor roadmaps.

from science to industry applications

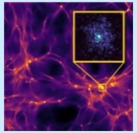
fundamental research



condensed matter physics

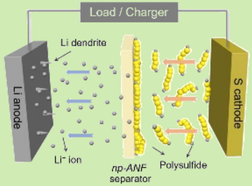


high-energy particle physics

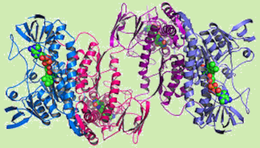


astrophysics

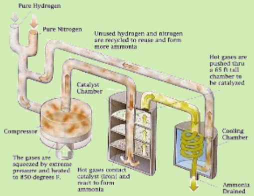
applied research



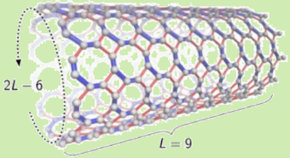
batteries



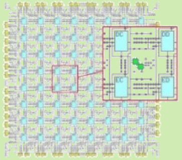
drugs



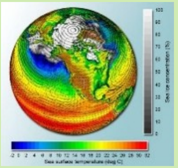
fertilizer production



material design



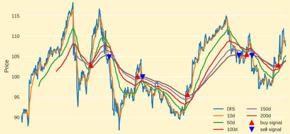
semiconductors



climate modeling

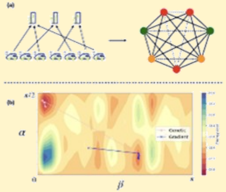
business operations

transportation

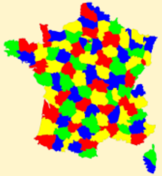


financial services

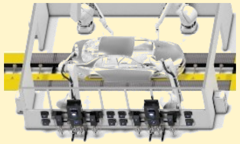
logistics and retail



energy utilities



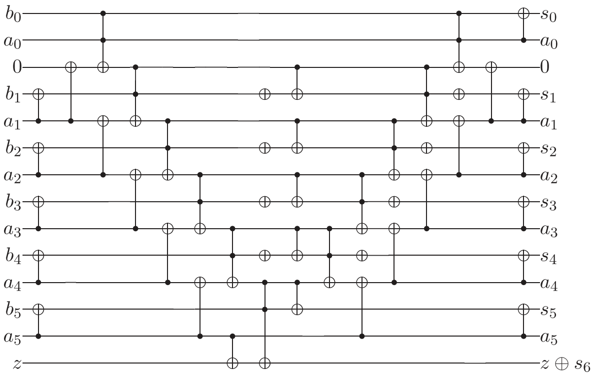
telecoms



manufacturing

main quantum computing paradigms

gates-based quantum computers

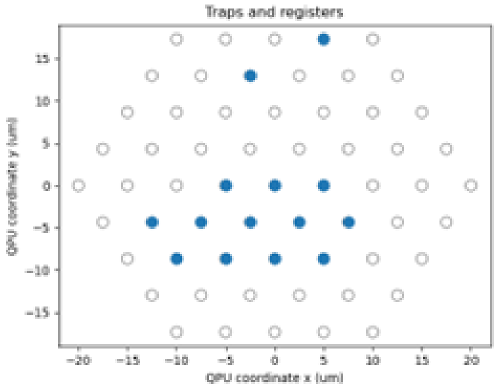


The ripple-carry adder for $n = 6$.

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

IBM QUANDELA

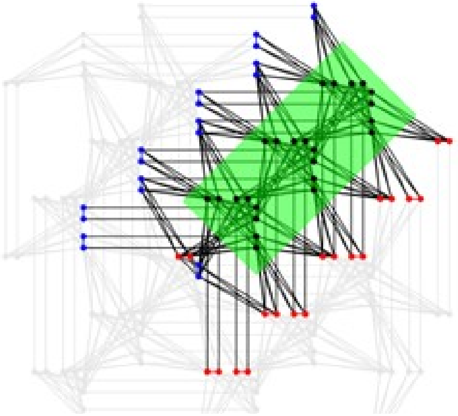
analog quantum **simulators**



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…

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

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

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

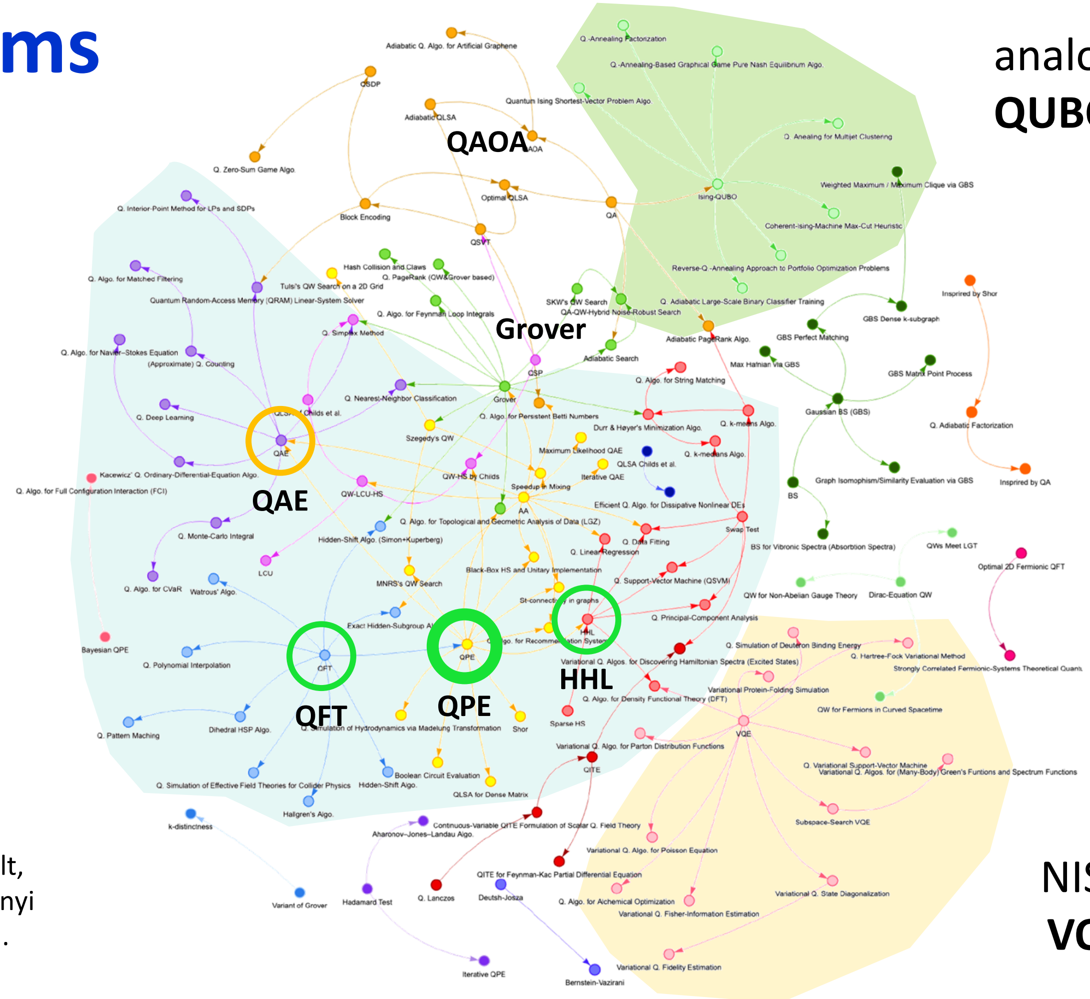
MaxCut problems

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



analog
QUBO

FTQC
QPE & QFT based

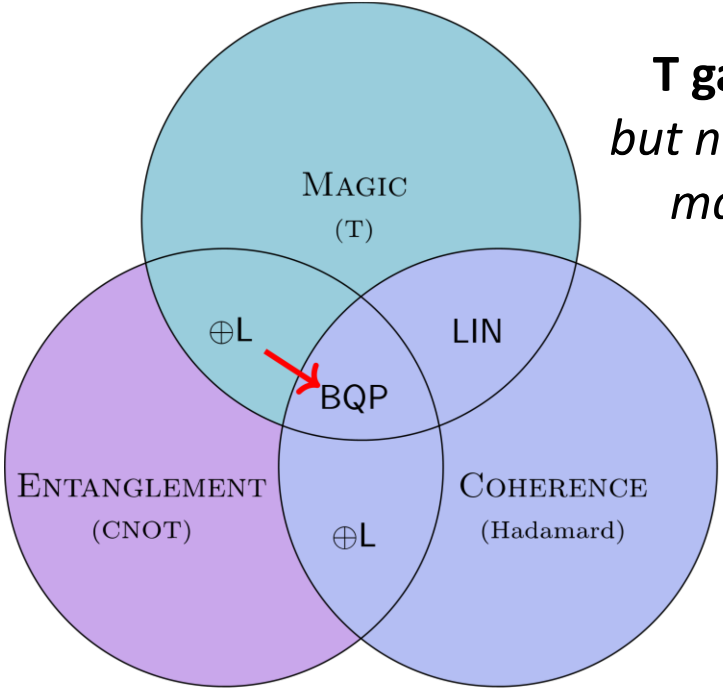
NISQ
VQE

Inria

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?



maximally entangled states

T gates *but not too many*

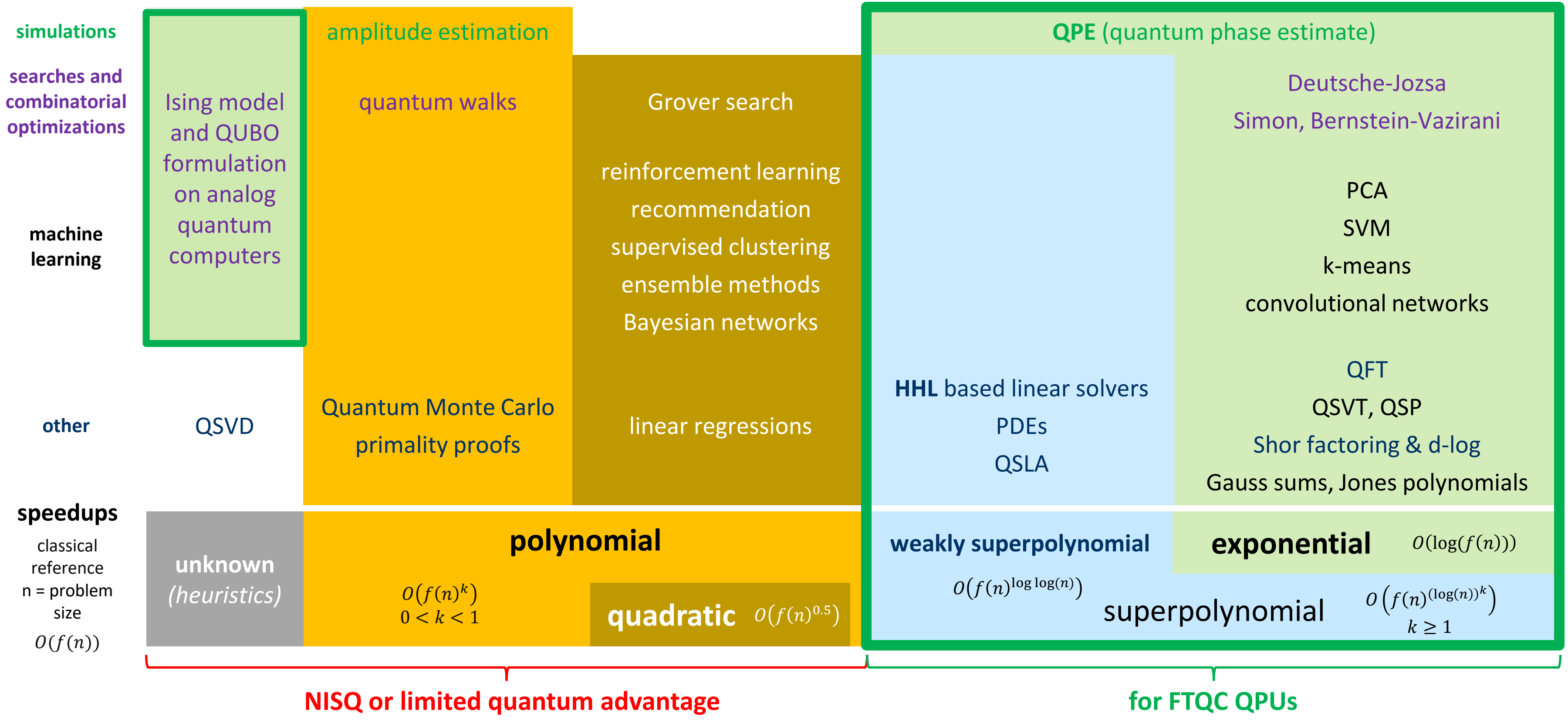
not too deep

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



simulations

searches and combinatorial optimizations

machine learning

other

speedups

classical reference n = problem size $O(f(n))$

Ising model and QUBO formulation on analog quantum computers

QSVD

unknown *(heuristics)*

amplitude estimation

quantum walks

Quantum Monte Carlo

primality proofs

Grover search

reinforcement learning

recommendation

supervised clustering

ensemble methods

Bayesian networks

linear regressions

polynomial

$O(f(n)^k)$

$0 < k < 1$

quadratic $O(f(n)^{0.5})$

QPE (quantum phase estimate)

HHL based linear solvers

PDEs

QSLA

weakly superpolynomial

$O(f(n)^{\log\log(n)})$

Deutsche-Jozsa

Simon, Bernstein-Vazirani

PCA

SVM

k-means

convolutional networks

QFT

QSVT, QSP

Shor factoring & d-log

Gauss sums, Jones polynomials

exponential $O(\log(f(n)))$

superpolynomial $O\left(f(n)^{(\log(n))^k}\right)$

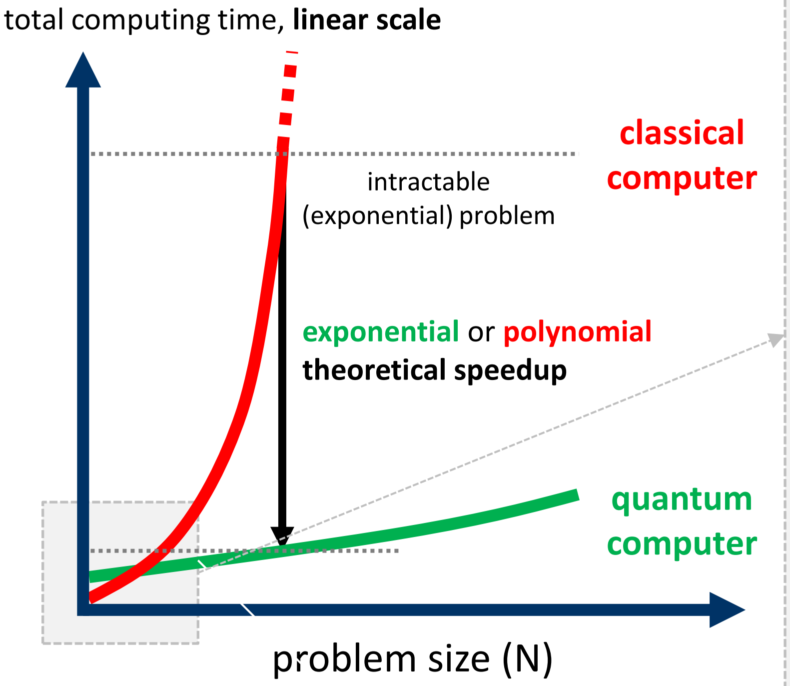
$k \geq 1$

NISQ or limited quantum advantage

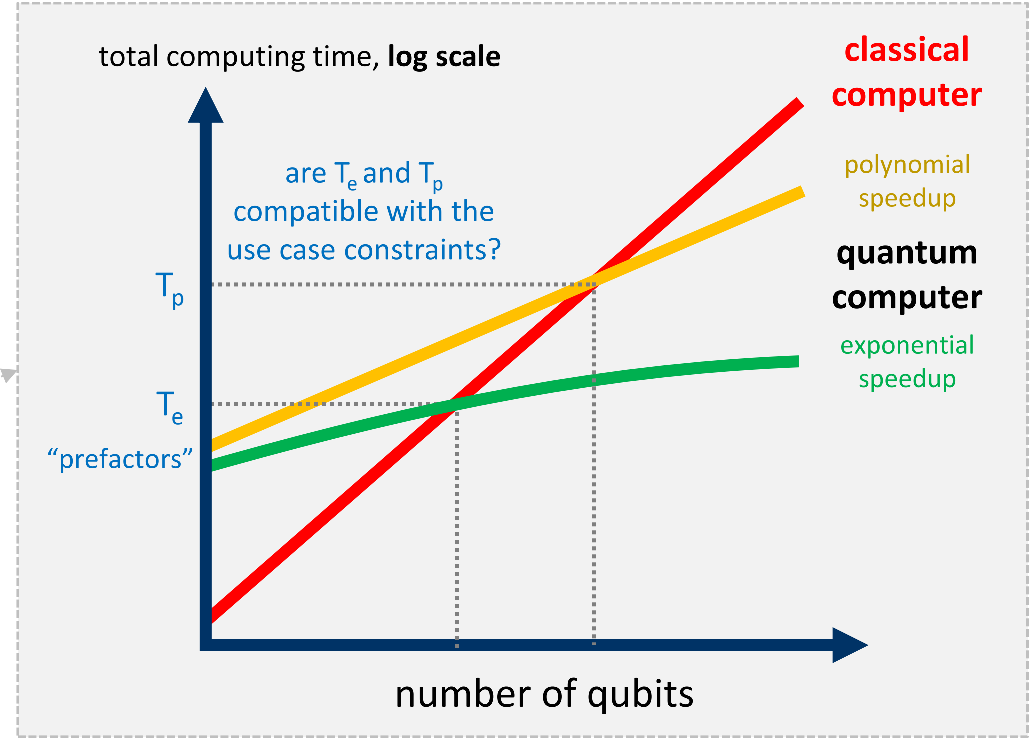
for FTQC QPUs

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

Grover

Simon

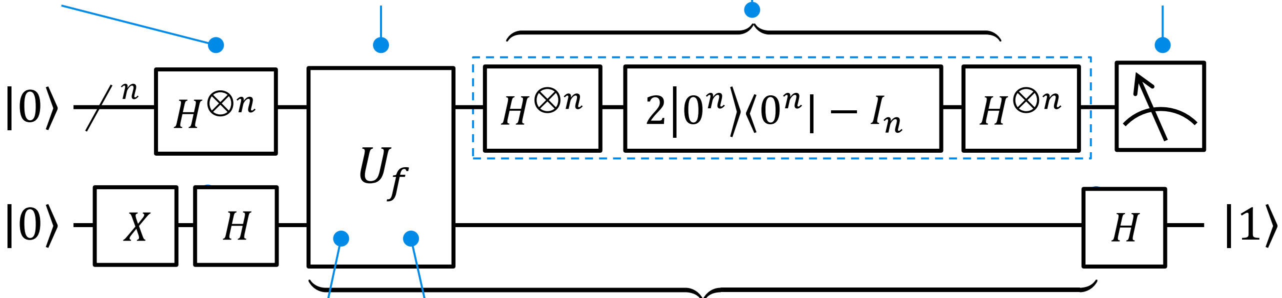
Bernstein-Vazirani

creates a superposition of N=2ⁿ 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

example with the Grover algorithm

how **variational algorithms** work

VQE

QAOA

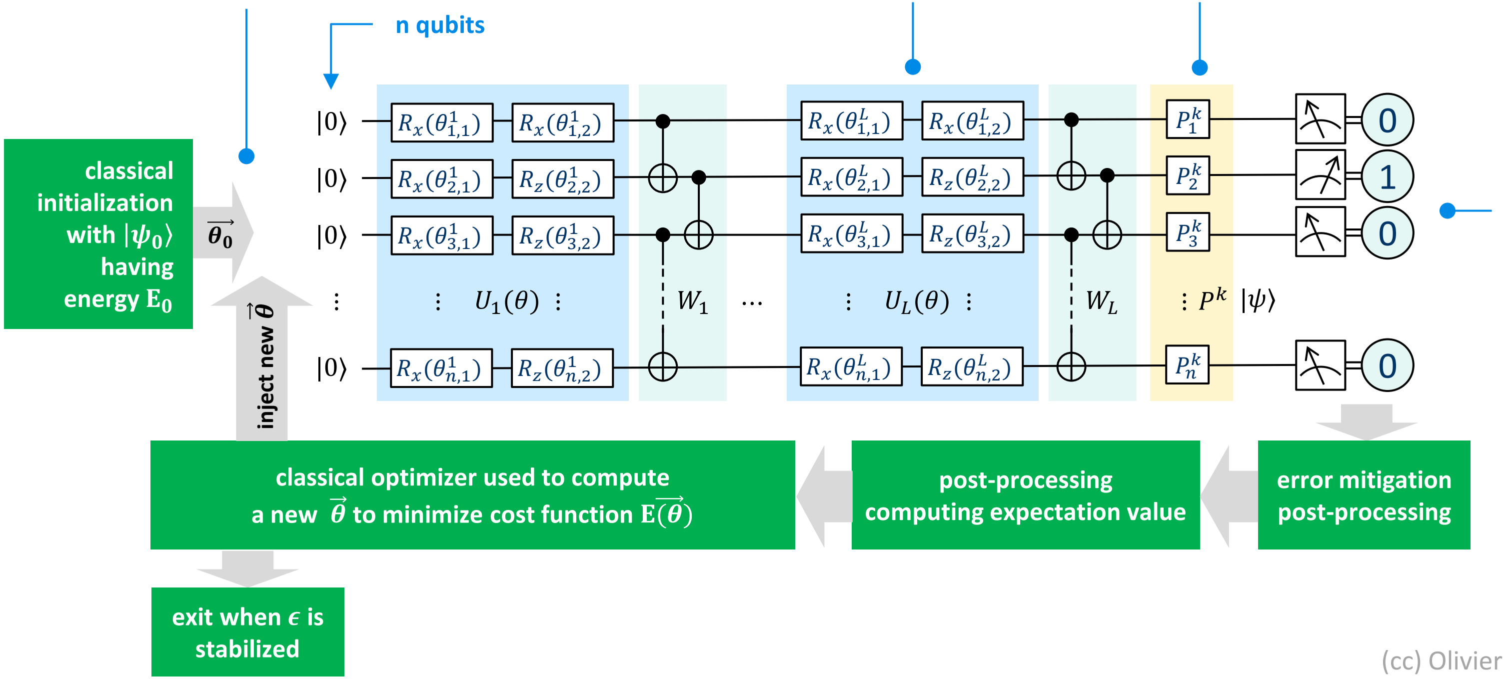
QML

unknown number of ansatz iterations

n qubits

number of L layers depending on the algorithm

number of Pauli strings
$O(n^M)$
M=4 for electronic structure
M=1 for Heisenberg model
M=1 for QAOA



classical initialization with $|\psi_0\rangle$ having energy E_0

classical optimizer used to compute a new $\vec{\theta}$ to minimize cost function $E(\vec{\theta})$

post-processing computing expectation value

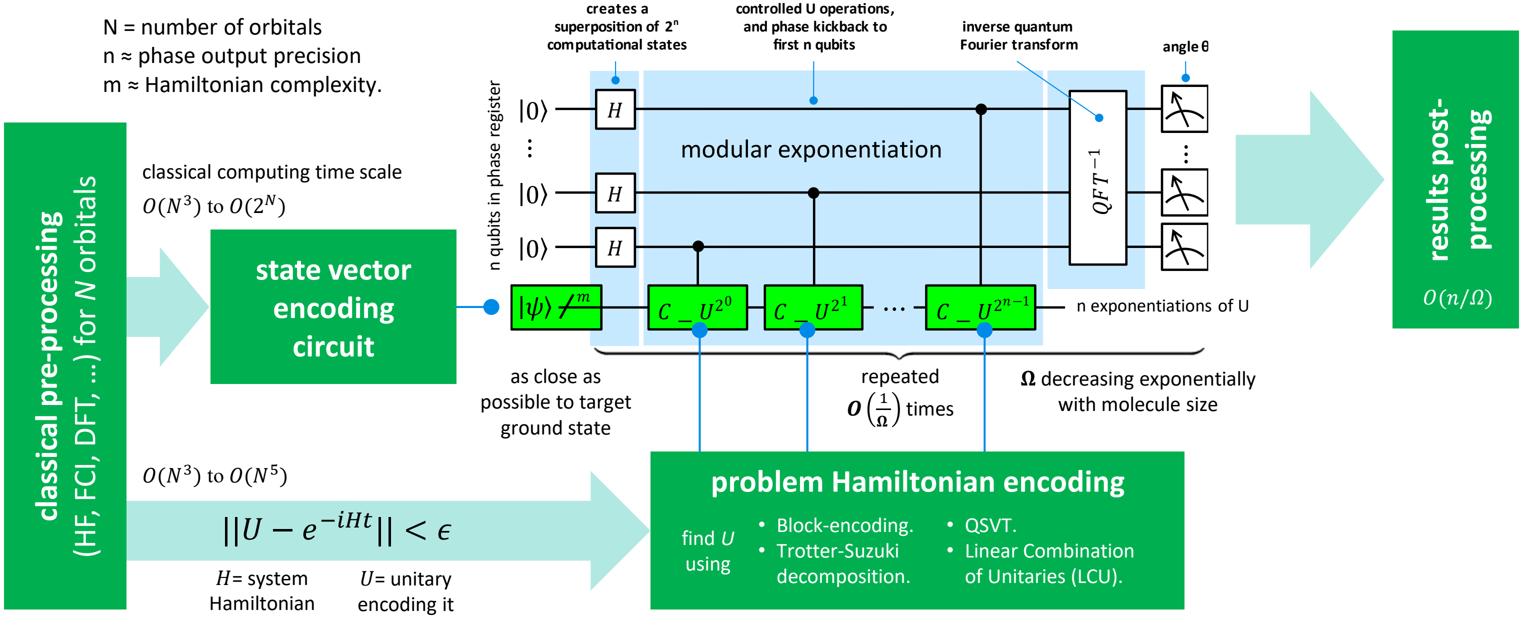
error mitigation post-processing

exit when ϵ is stabilized

number of shots per Pauli strings?
$O(1/\epsilon^2)$
1 million for VQE and chemical ground state computing

how **Quantum Phase Estimation** works

N = number of orbitals
n ≈ phase output precision
m ≈ Hamiltonian complexity.



classical pre-processing
(HF, FCI, DFT, …) for N orbitals

classical computing time scale
$O(N^3)$ to $O(2^N)$

state vector encoding circuit

as close as possible to target ground state

creates a superposition of 2^n computational states

controlled U operations, and phase kickback to first n qubits

inverse quantum Fourier transform

modular exponentiation

n exponentiations of U

repeated $O\left(\frac{1}{\Omega}\right)$ times

Ω decreasing exponentially with molecule size

results post-processing
$O(n/\Omega)$

$O(N^3)$ to $O(N^5)$

$$||U - e^{-iHt}|| < \epsilon$$

H= system Hamiltonian

U= unitary encoding it

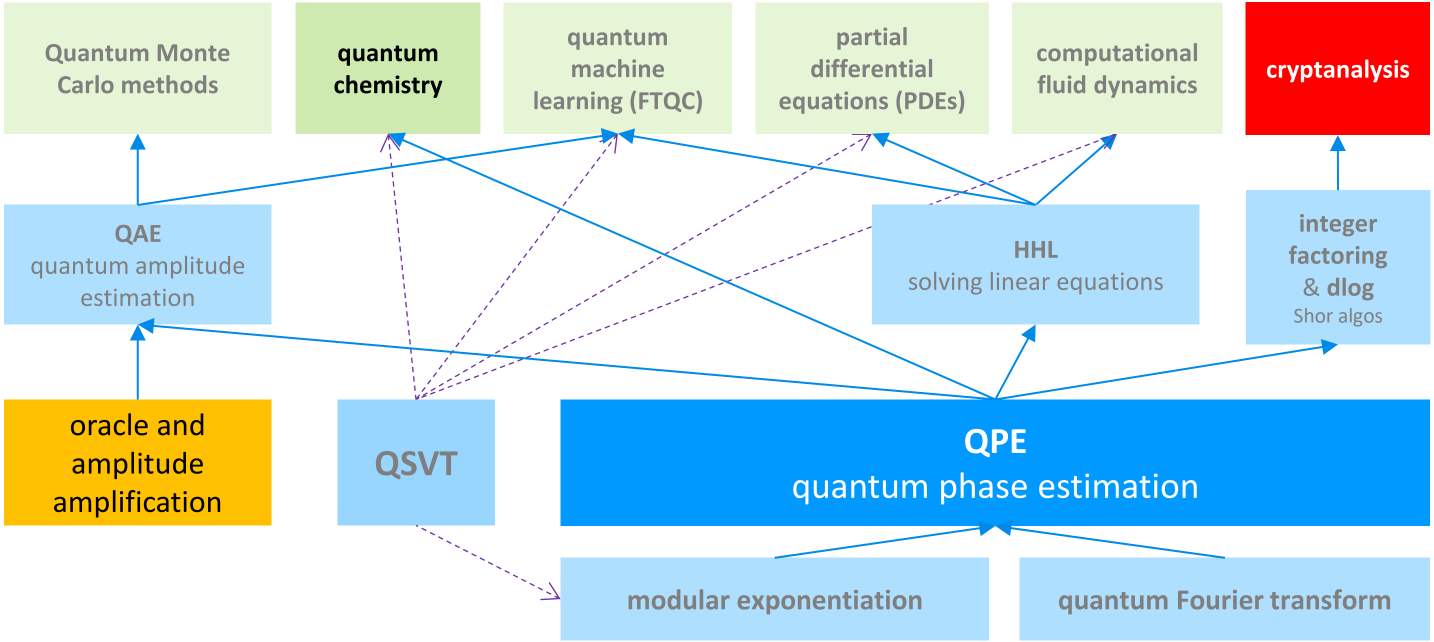
problem Hamiltonian encoding

find U using

- Block-encoding.
- Trotter-Suzuki decomposition.
- QSVT.
- Linear Combination of Unitaries (LCU).

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.

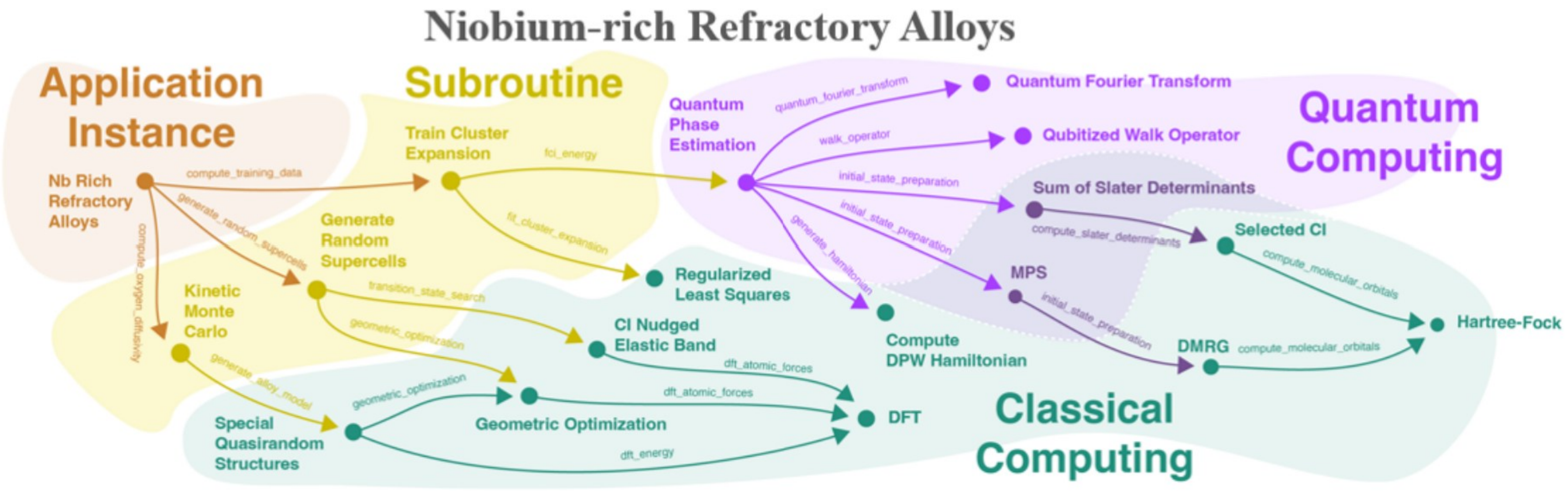
key FTQC quantum algorithms food chain



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).

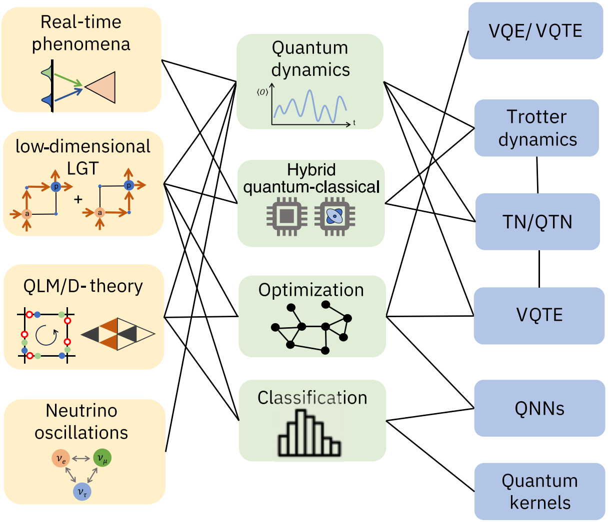
HEP quantum algorithms

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.

theoretical physical models



Real-time phenomena

low-dimensional LGT

QLM/D-theory

Neutrino oscillations

Quantum dynamics

Hybrid quantum-classical

Optimization

Classification

VQE/ VQTE

Trotter dynamics

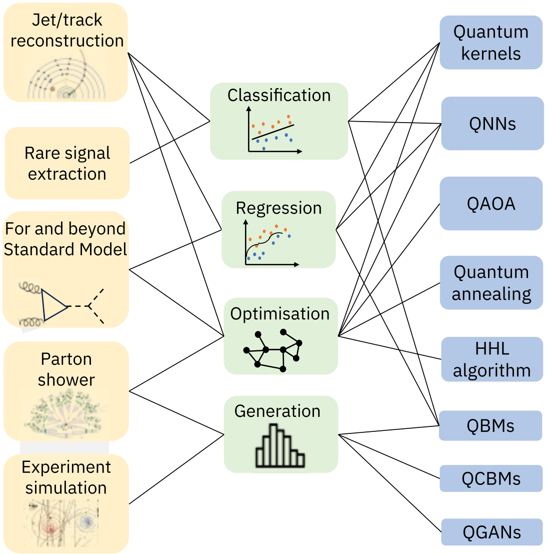
TN/QTN

VQTE

QNNs

Quantum kernels

experimental challenges



Jet/track reconstruction

Rare signal extraction

For and beyond Standard Model

Parton shower

Experiment simulation

Classification

Regression

Optimisation

Generation

Quantum kernels

QNNs

QAOA

Quantum annealing

HHL algorithm

QBMs

QCBMs

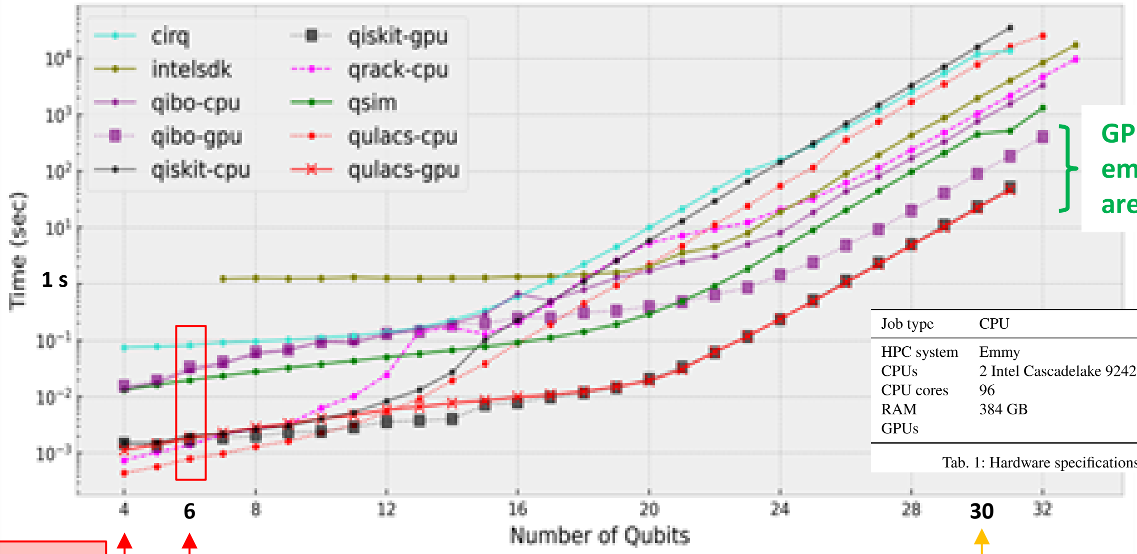
QGANs

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

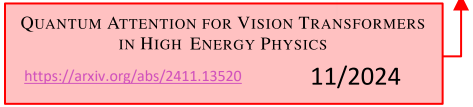


GPU-based emulations are faster

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

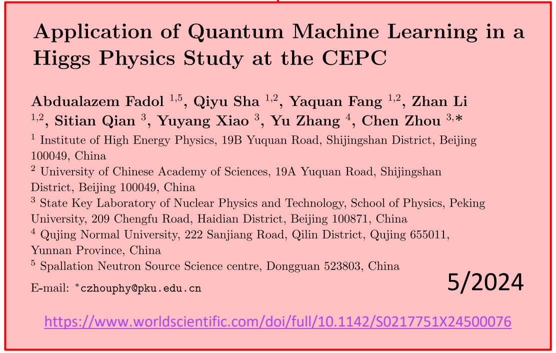
Tab. 1: Hardware specifications for single node jobs

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

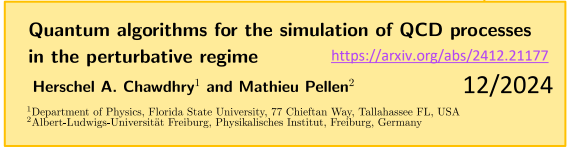
Abdualazem Fadol [1,5], Qiyu Sha [1,2], Yaquan Fang [1,2], Zhan Li [1,2], Sitian Qian [3], Yuyang Xiao [3], Yu Zhang [4], Chen Zhou [3,*]

[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

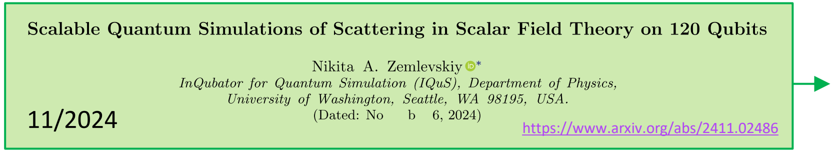
Quantum Simulations of Hadron Dynamics in the Schwinger Model using 112 Qubits

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

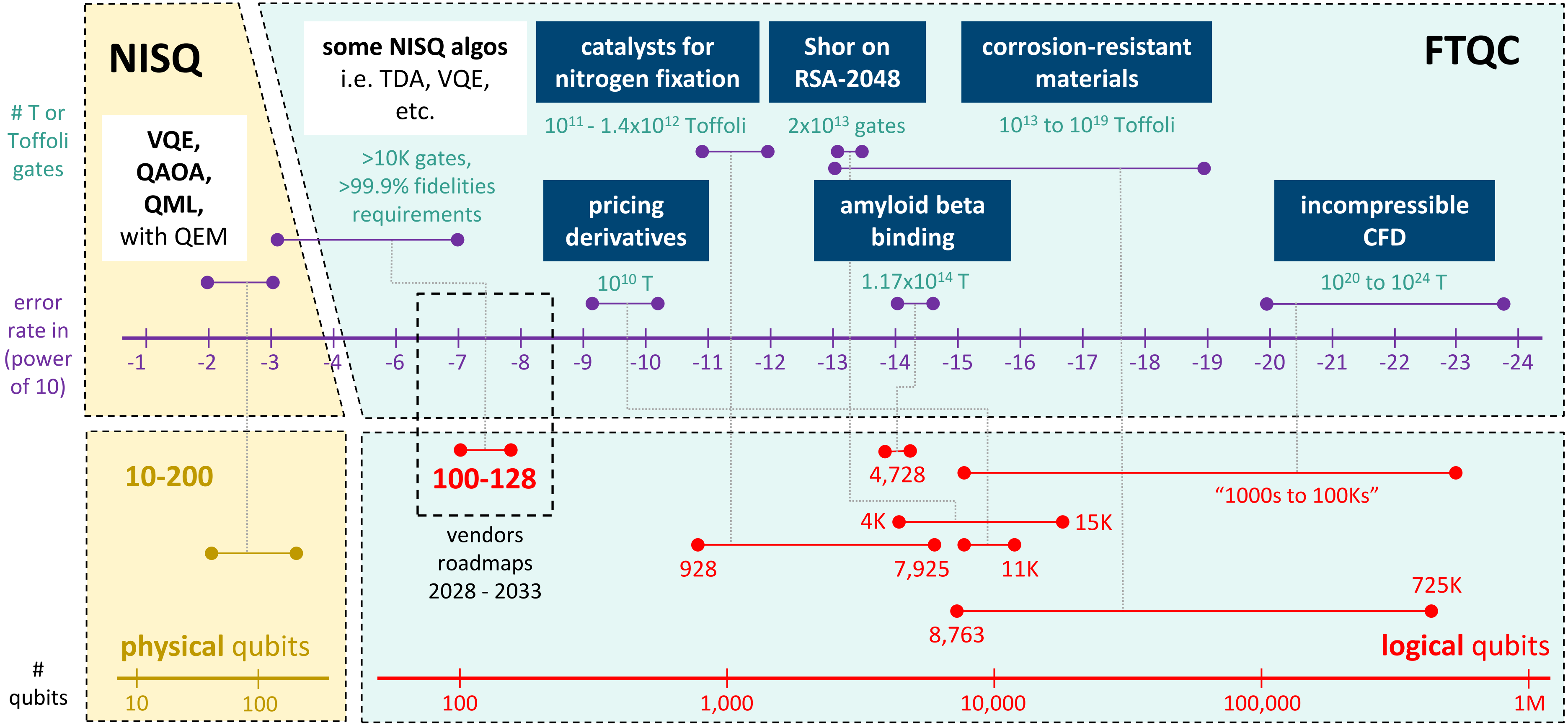
Nikita A. Zemlevskiy *

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



NISQ

FTQC

T or Toffoli gates

VQE, QAOA, QML, with QEM

some NISQ algos i.e. TDA, VQE, etc.

>10K gates, >99.9% fidelities requirements

catalysts for nitrogen fixation

10^{11} - 1.4×10^{12} Toffoli

Shor on RSA-2048

2×10^{13} gates

corrosion-resistant materials

10^{13} to 10^{19} Toffoli

pricing derivatives

10^{10} T

amyloid beta binding

1.17×10^{14} T

incompressible CFD

10^{20} to 10^{24} T

error rate in (power of 10)

10-200

100-128

vendors roadmaps 2028 - 2033

4,728

"1000s to 100Ks"

4K

15K

928

7,925

11K

725K

8,763

physical qubits

logical qubits

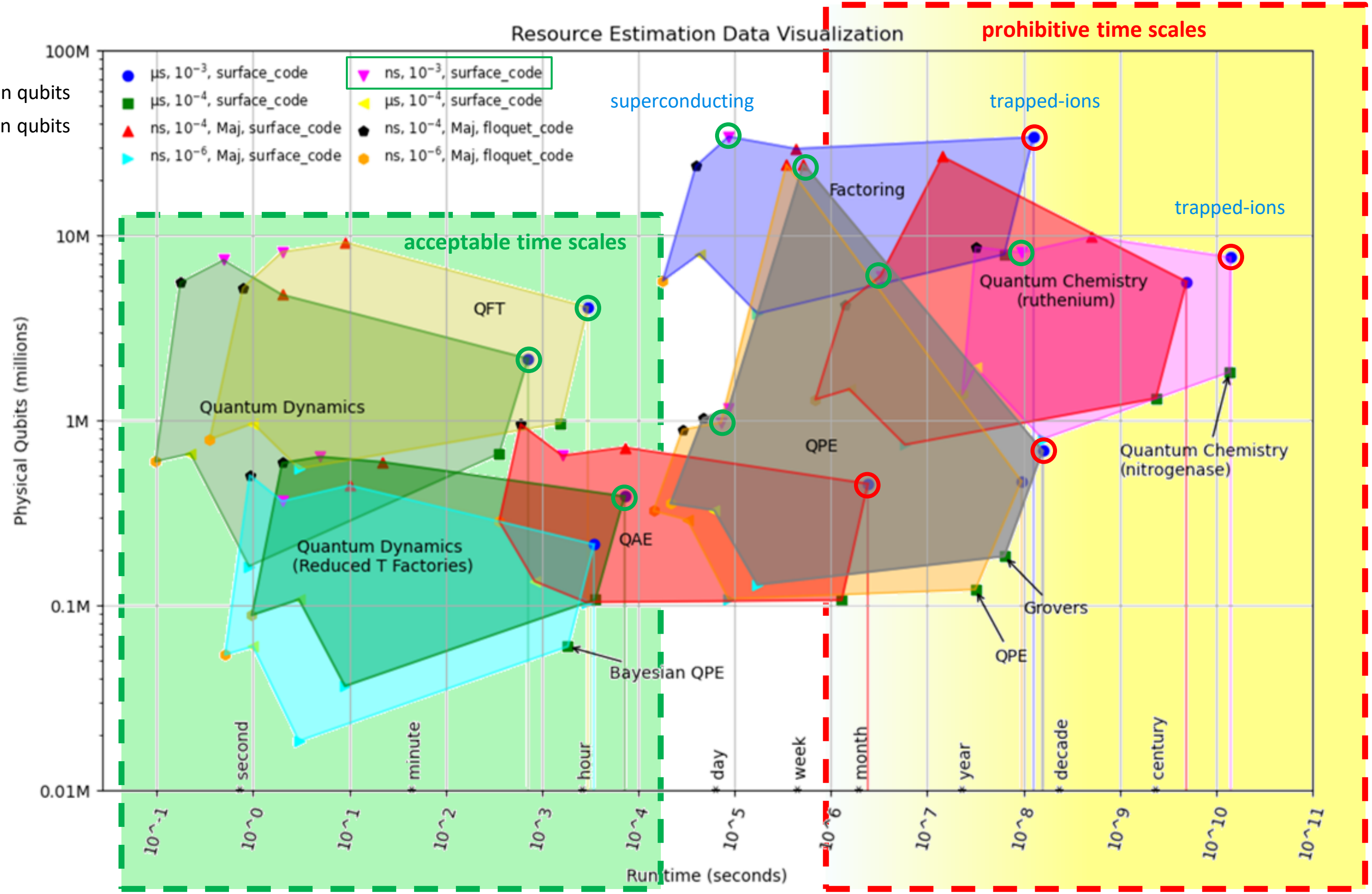
qubits

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

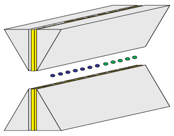
by Doug Finke, Quantum Computing Report, August 2024.

QPUs vendors per qubit type

atoms

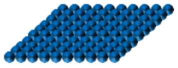
electrons *controlled spin and microwave cavities*

photons



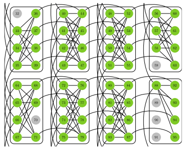
trapped ions

- QUANTINUUM
- IONQ
- AQT
- oxford ionics
- eleQtron
- FOXCONN
- Quantum Art
- CRYSTAL QUANTUM COMPUTING
- NEQXT
- QUDORA TECHNOLOGIES
- HYQ Co



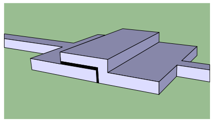
cold atoms

- Pasqal
- QuEra
- Infleqtion
- atom computing
- planqc
- QUANTier
- NanoQT Nanofiber Quantum Technologies
- Atom Quantum Labs



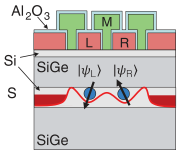
annealing

- D:WAVE The Quantum Computing Company™
- QILIMANJARO QUANTUM·TECH
- NEC



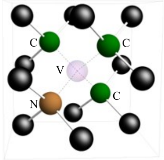
superconducting

- 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



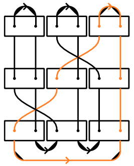
silicon

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



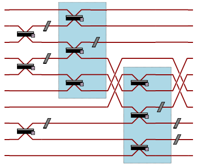
vacancies

- QUANTUM BRILLIANCE
- SaxonQ
- TURING
- photonic
- Quantum Transistors
- SQUTEC
- XEED
- FUJITSU
- NTT



topological

- Microsoft
- QUOHERENT
- QUANTUM GRAVITY RESEARCH
- NOKIA



photons

- PsiQuantum
- QUANDELA
- ORCA COMPUTING
- XANADU
- DUALITY QUANTUM PHOTONICS
- QUIX QUANTUM
- BardeenQ LABS
- QBoson
- QCi
- photonicsQ
- QUANFLUENCE
- TUNDRASYSTEMS GLOBAL Ltd
- aegiq

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

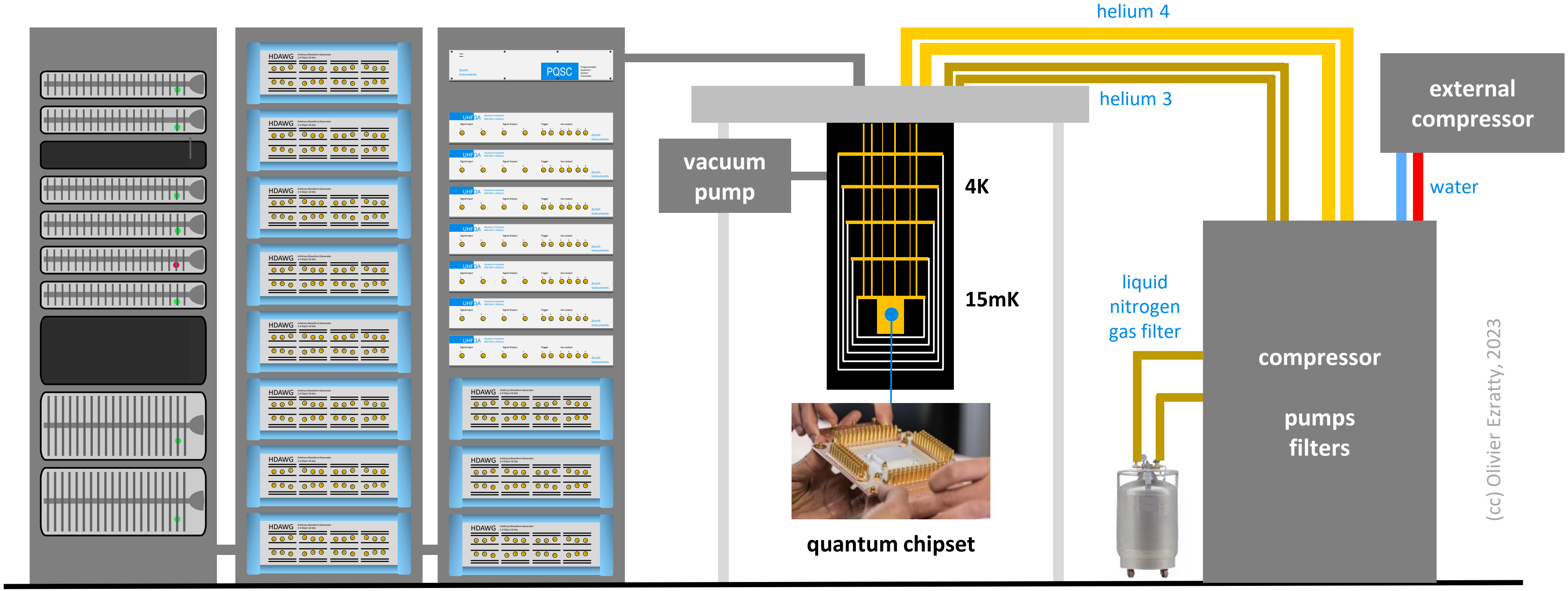
inside a typical quantum computer

computing
servers, network,
software, data

qubits control electronics
microwave generators, readout
systems and various electronics

« chandelier » in cryostat
where quantum stuff happens!

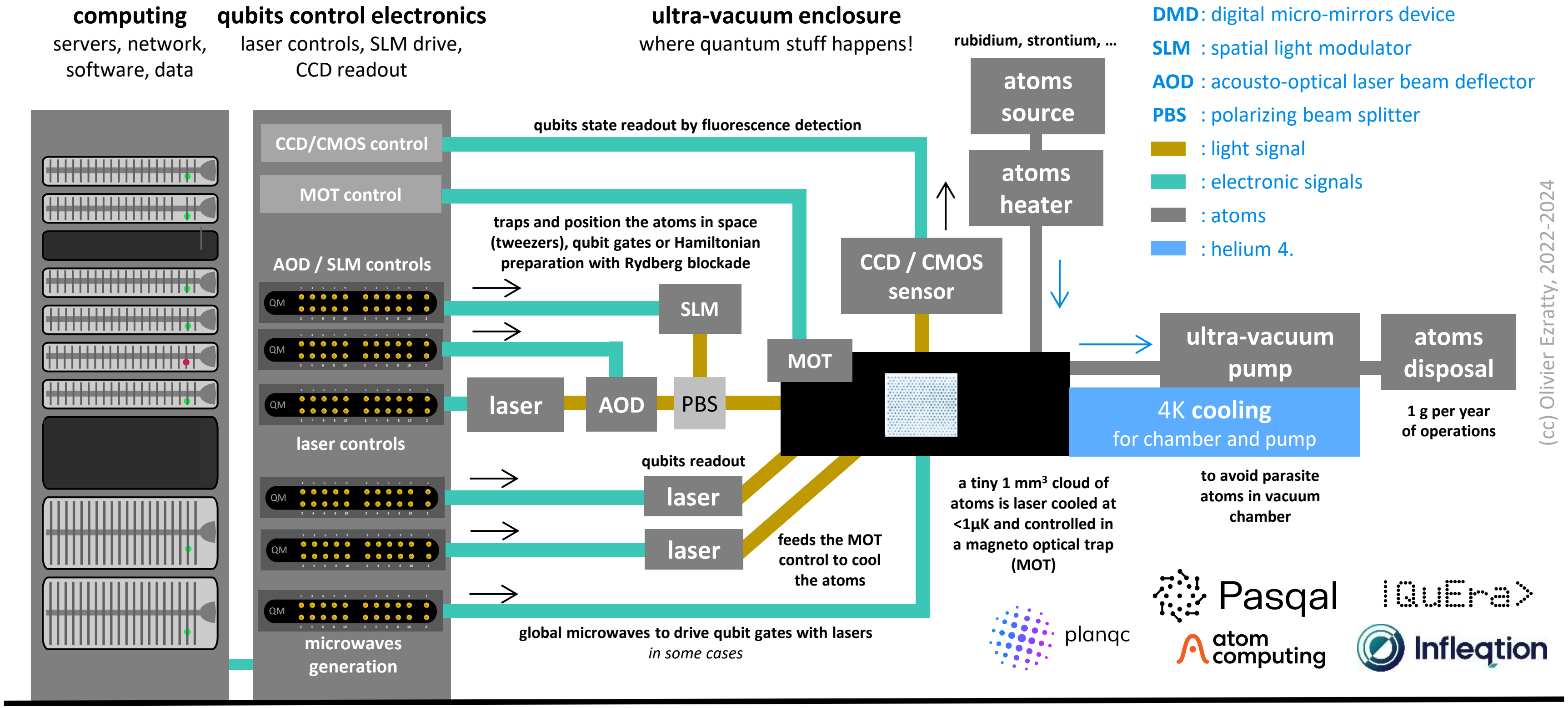
cryogenic installation
helium 3 & 4
gas pumps and compressor



(cc) Olivier Ezratty, 2023

for superconducting or electron spin qubits

with a neutral atoms quantum computer



computing
servers, network,
software, data

qubits control electronics
laser controls, SLM drive,
CCD readout

ultra-vacuum enclosure
where quantum stuff happens!

rubidium, strontium, …

DMD: digital micro-mirrors device
SLM : spatial light modulator
AOD : acousto-optical laser beam deflector
PBS : polarizing beam splitter
🟨 : light signal
🟩 : electronic signals
▨ : atoms
🟦 : helium 4.

qubits state readout by fluorescence detection

traps and position the atoms in space (tweezers), qubit gates or Hamiltonian preparation with Rydberg blockade

qubits readout

feeds the MOT control to cool the atoms

global microwaves to drive qubit gates with lasers
in some cases

a tiny 1 mm³ cloud of atoms is laser cooled at <1µK and controlled in a magneto optical trap (MOT)

to avoid parasite atoms in vacuum chamber

1 g per year of operations

Pasqal
|QuEra>
planqc
atom computing
Infleqtion

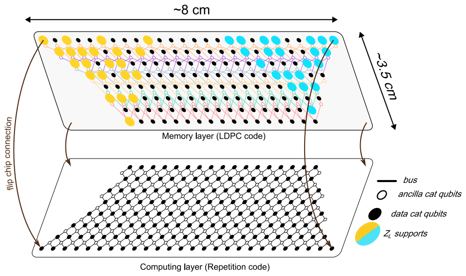
(cc) Olivier Ezratty, 2022-2024

original QPU ideas

ALICE & BOB

Nord Quantique

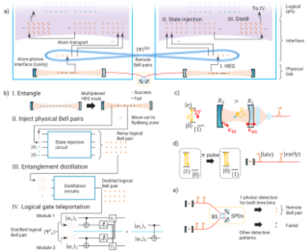
amazon



bosonic qubits

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

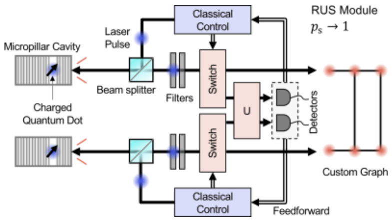
NanoQT
Nanofiber Quantum Technologies



cold atoms and nanofiber connectivity

scaling cold atoms through photonic interconnectivity and routing.

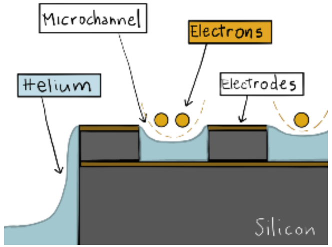
QUANDELA



deterministic photonic cluster states

for scaling with FBQC.

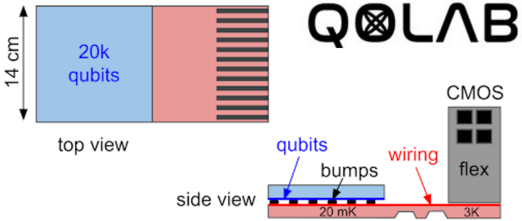
EeroQ
QUANTUM HARDWARE



electron spin on superfluid helium

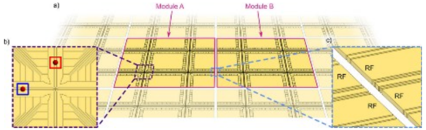
better isolation.

QOLAB



CPW wafer for cryoelectronics control

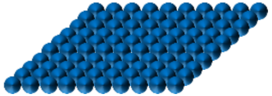
scaling cabling, optimizing connectivity.

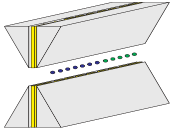


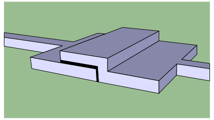
tiled ion traps & microwave drive

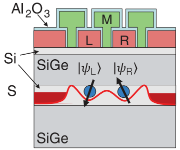
better scaling, excellent ions shuttling fidelities.

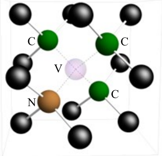
rough qubit modalities comparison

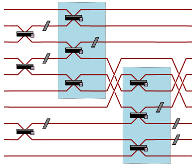






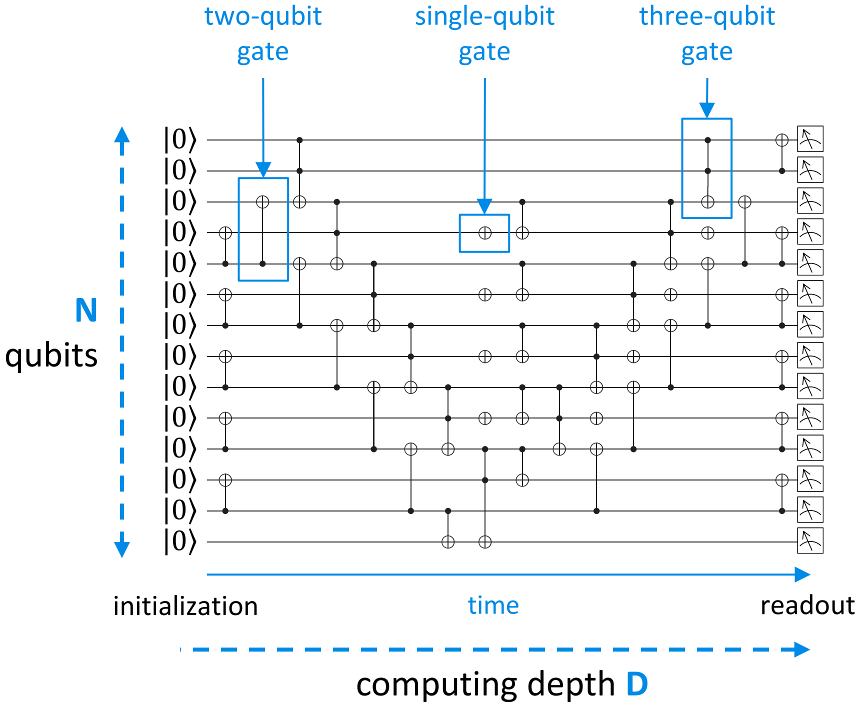






	atoms		**electrons** *controlled spin and microwave cavities*			**photons**
	cold atoms	**trapped ions**	**superconducting**	**silicon**	**NV centers**	**photons**
operations fidelities	🟨	🟩	🟨	🟧	🟧	🟨
gate times	🟨 with no shuttling	🟧	🟩	🟩	🟨	🟩
qubit connectivity	🟧 with shuttling	🟩	🟨	🟨	🟨	🟨
cooling needed	🟨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

raw algorithm fidelities requirements



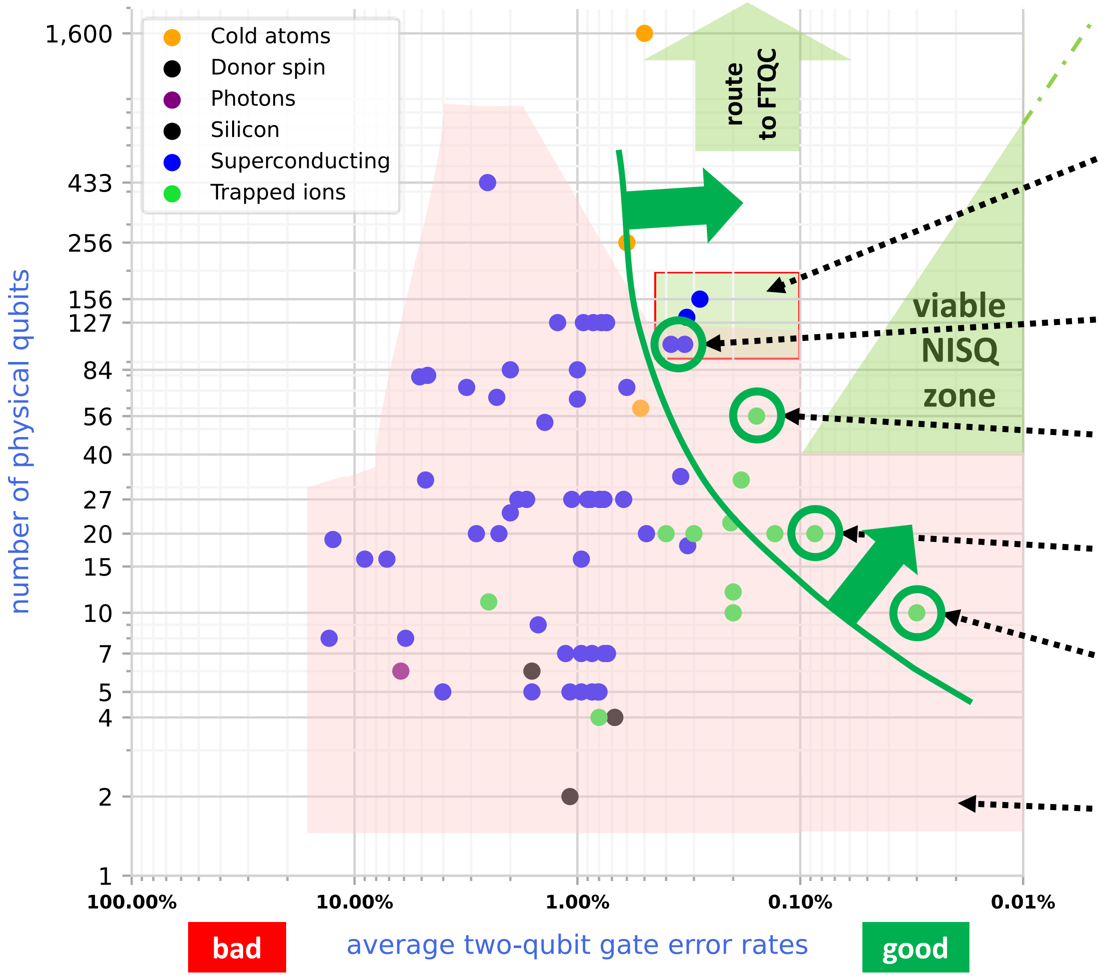
desired error rate $< \frac{1}{N \times D}$

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

99.67% « Willow »
August 2024
+ China Zuchongzhi 3.0

99.87%
June 2024

99.9%
April 2024

99.97%
July 2024

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

(cc) Olivier Ezratty, January 2025.

logical qubits and FTQC

physical qubit

error rates ≈0.1%

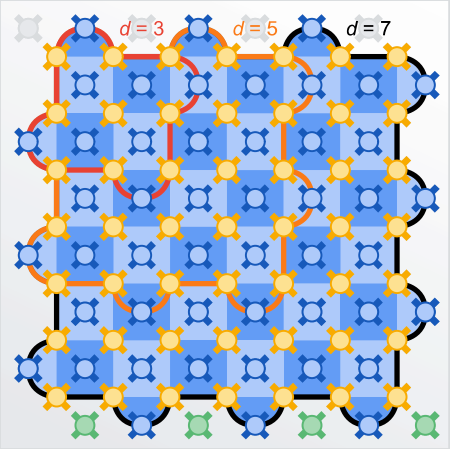
+

error correction code

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

logical qubits

error rate $\approx 10^{-4}$ to $\approx 10^{-18}$

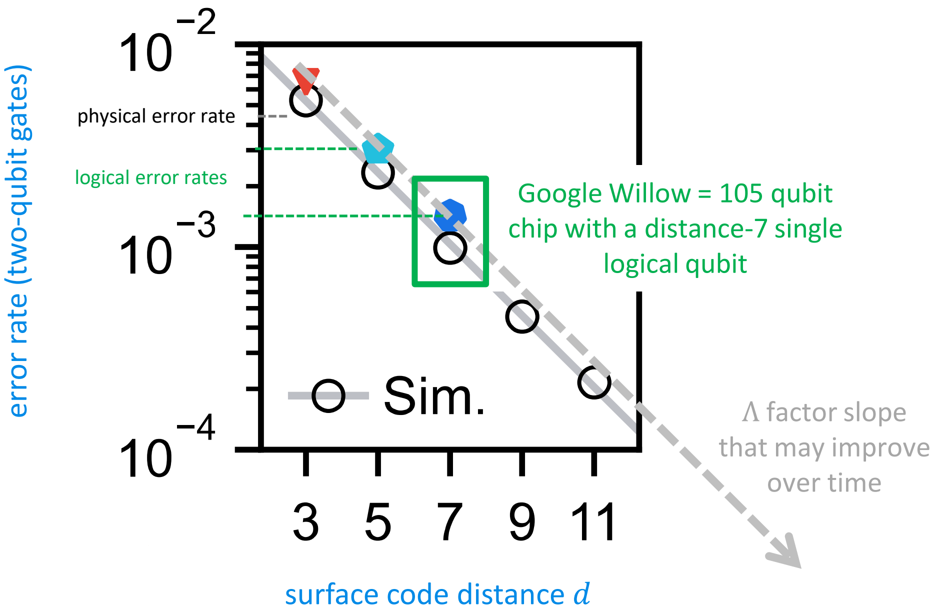


tens to thousands physical qubits per logical qubits

fault tolerance

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

beyond the first breakeven logical qubits



Google Willow = 105 qubit chip with a distance-7 single logical qubit

Λ factor slope that may improve over time

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.

+

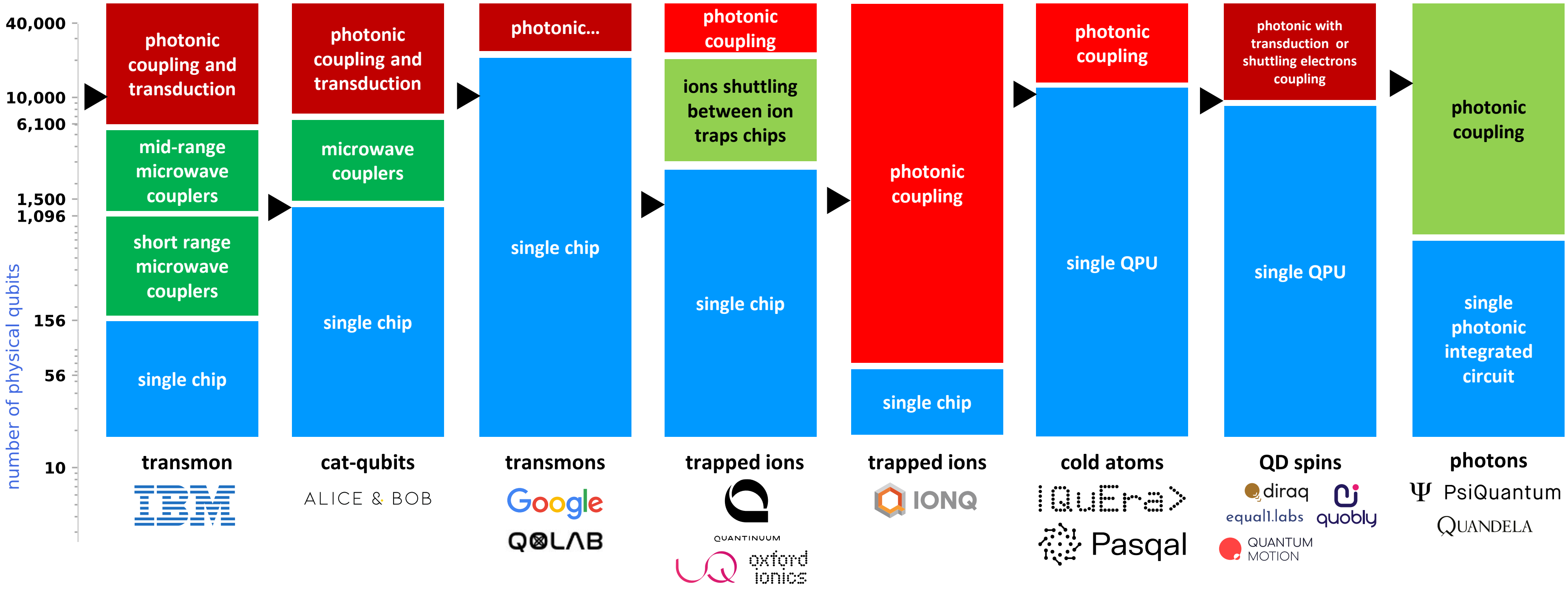
plan for 10K qubits chips

⬇

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



🟦 single monolithic chip or QPU	🟩 interconnect using same qubit modality	🟩 short range or mid-range microwave couplers	🟥 direct photonic coupling	🟥 photonic coupling requiring a qubit transduction

▶ approximate physical qubits # required to reach 100 logical qubits at 10^{-8} error rate, the lower being the better.

growing complexity with rough estimates thresholds requiring these techniques

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

QPUs roadmaps consolidation

🟦 logical qubits
🟨 physical qubits
🟪 gates / QOPS

100 logical qubits

2,000 logical qubits

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
IBM	156x7 PQ 5K gates	7.5K gates	10K gates	15K gates	200 LQ 100M gates				2000 LQ 1B gates		
IQM	150 PQ	300 PQ	4-36 LQ 1K PQ	60-180 LQ 5K PQ		240-720 LQ 40K PQ	600-1800 LQ 100K PQ		2400-7200 LQ 1M PQ		
ALICE & BOB		4 LQ 48 PQ		5 LQ 250 PQ		100 LQ 2K PQ					
quobly				50-200 LQ 10K PQ	300-1K LQ 100K PQ	2K-4K LQ 1M PQ	5K-10K LQ 5M PQ	10K+ LQ 10M PQ			
Pasqal	1K PQ ~ 10M gates	10K PQ ~ 40M gates	~ 200M gates	128+ LQ 200M+ gates							
QuEra	30 LQ 3K PQ	100 LQ >10K PQ									
Infleqtion	2 LQ 1.6K PQ	>10 LQ 8K PQ		>100 LQ 40K PQ							
QUANTINUUM	~ 50 LQ 96 PQ		~100 LQ 192 PQ		~100s LQ 1000s PQ						
PsiQuantum						~100s LQ 1M PQ					
QUANDELA			10 LQ 50K QOPS		50s LQ 1M QOPS						

Beyond NISQ: The Megaquop Machine

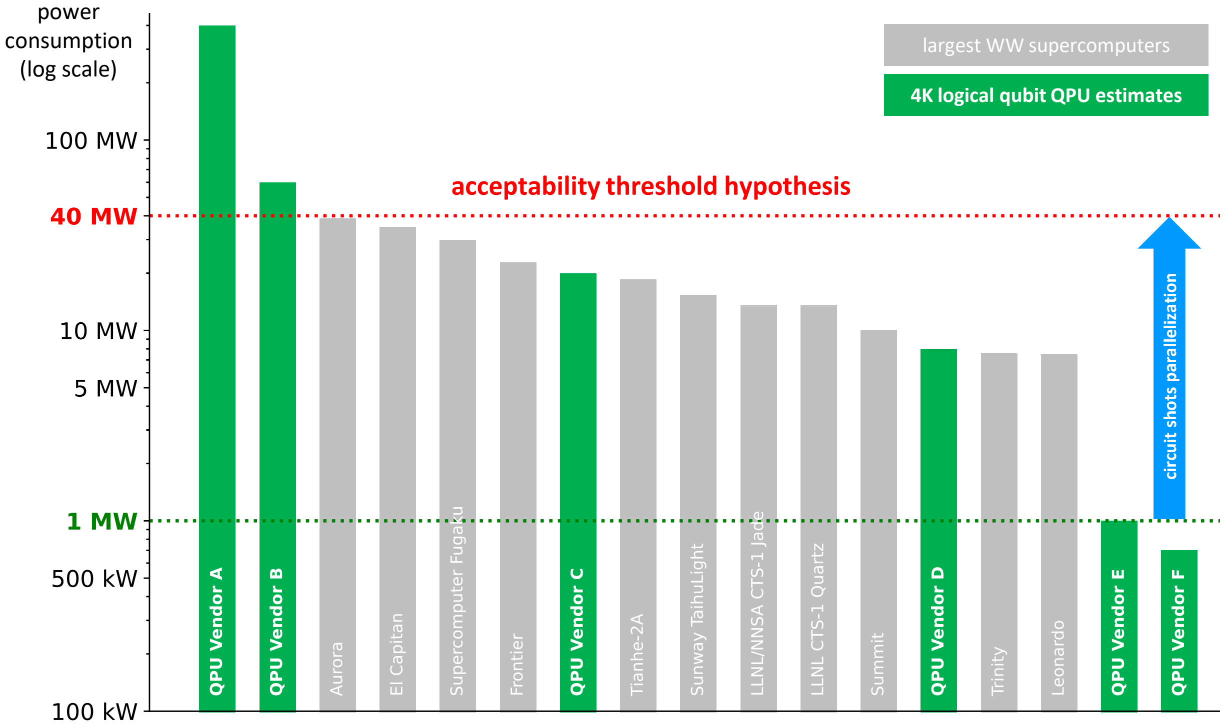
Image generated by ChatGPT

John Preskill
Q2B 2024 Silicon Valley
11 December 2023

@preskill

(cc) Olivier Ezratty, December 2024.

QPU vs HPC power scale guesstimates

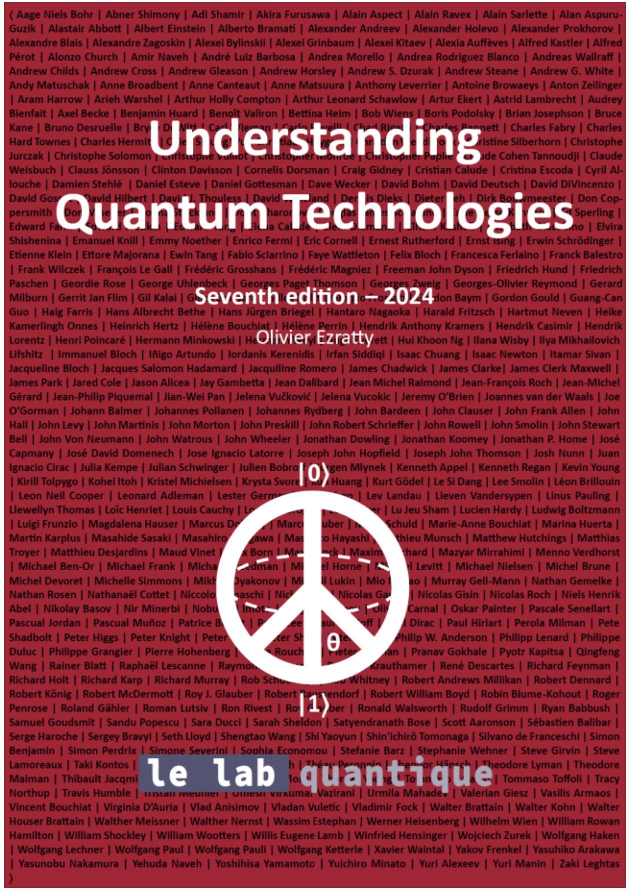


estimate base power for various QPUs and actual for existing largest HPCs WW.
HPC source: https://www.top500.org/lists/top500/2024/06/.

#QEI
the quantum energy initiative

IEEE

get these slides



Understanding Quantum Technologies

Seventh edition – 2024

Olivier Ezratty

le lab quantique

(free) 1,554 pages ebook, 7th edition including 24 pages on energetics