amU QuantA
Aix Marseille Université

the challenges of FTQC

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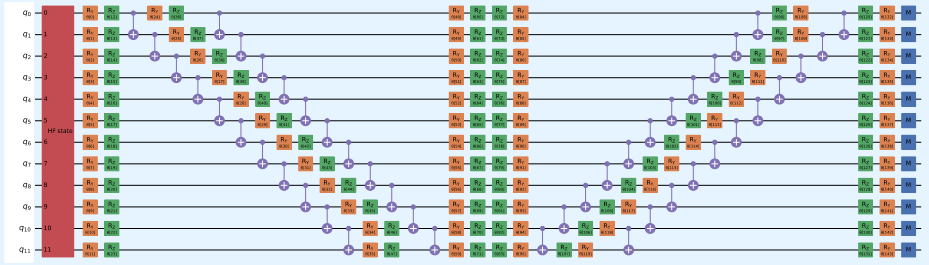
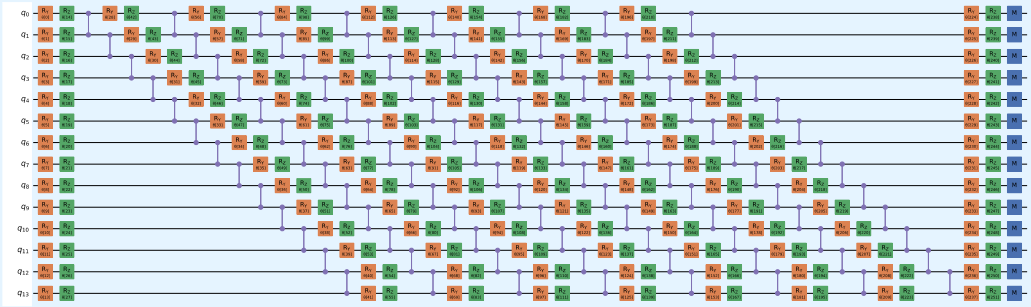
agenda

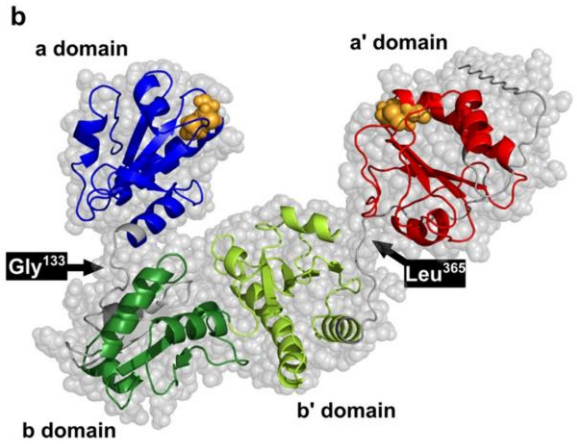
- from use cases to algorithms
- FTQC resource estimates
- FTQC hardware roadmaps and challenges
- quantum computing energetics
- quantum computing ecosystems

from use cases to quantum algorithms



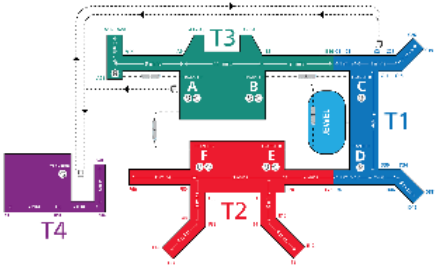


typical difficult problems

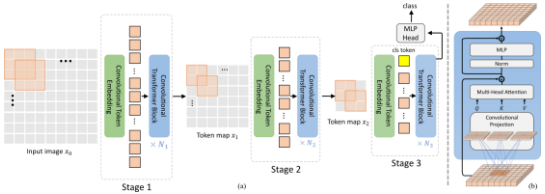


$$i\hbar\frac{\partial\Psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\Psi(x,t)}{\partial x^2} + V(x)\Psi(x,t)$$

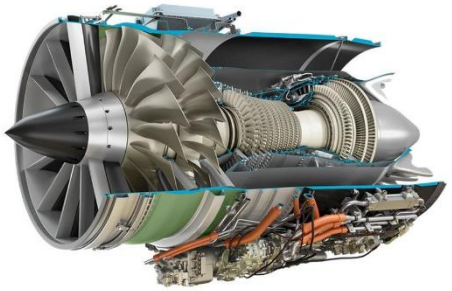
solving Schrodinger's wave equation to simulate quantum matter



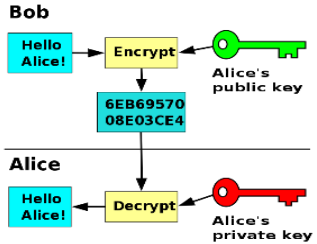
combinatorial optimizations



machine learning and deep learning



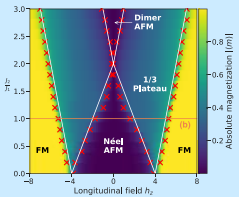
solving partial differential equations



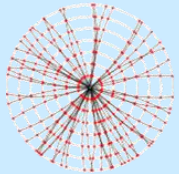
breaking asymmetric cryptography keys

from science to industry applications

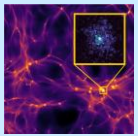
fundamental research



condensed matter physics

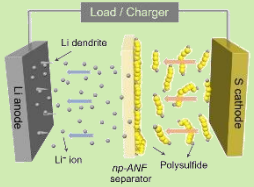


high-energy particle physics

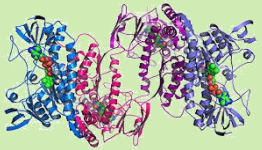


astrophysics

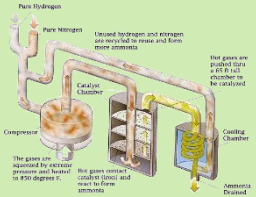
applied research



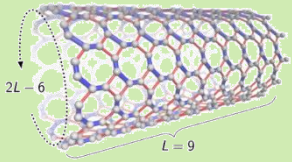
batteries



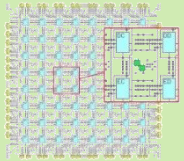
drugs



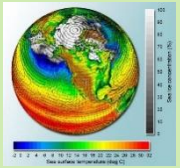
fertilizer production



material design



semiconductors

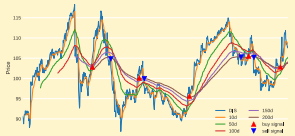


climate modeling

business operations



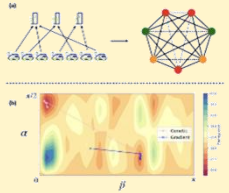
transportation



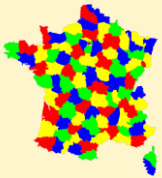
financial services



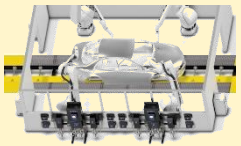
logistics and retail



energy utilities



telecoms



manufacturing

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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…

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

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.

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

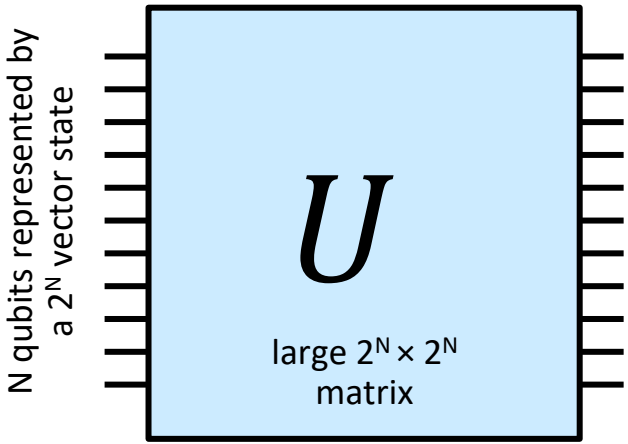
find σ_i^z minimizing a cost function that is the minimum eigenvalue of H

(cc) Olivier Ezratty, 2025

Hamiltonian → unitary → circuit

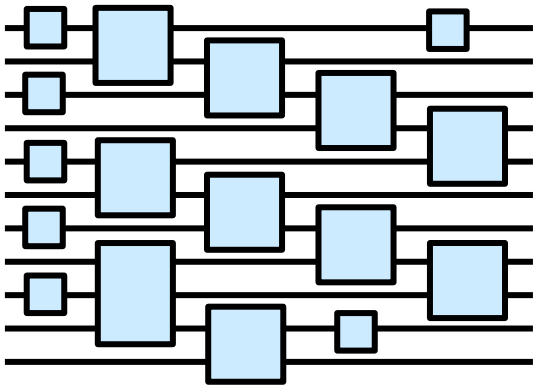
H

problem Hamiltonian describing a system energy



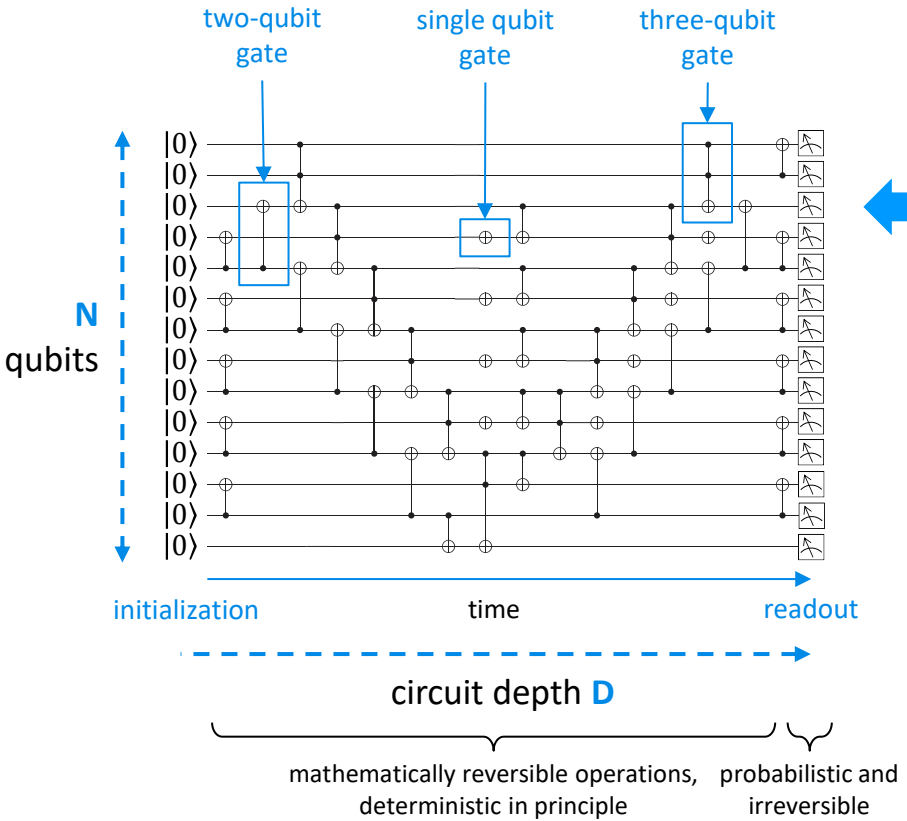
we are looking for U that encode the Hamiltonian variables into qubits and approximates H with:

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



U is decomposed into a series of quantum gates to find eigenvalues or eigenstates of interest of H, i.e. a ground state

what is a quantum algorithm?



quantum algorithm: solves a mathematical problem with generating and executing a quantum circuit.

quantum circuit: series of operations (gates) acting on a quantum memory, on individual qubits or with connecting them.

matrix computing: linear operations on an internal memory of 2^N complex numbers.

mechanism: uses constructive and destructive interferences in the state vector to yield a value of interest as a series of classical bits.

classical computing: used to prepare the circuit, encode the data, and extract some useful result from multiple circuit runs and measurements.

how **Quantum Phase Estimation** works

problem metrics

H = problem Hamiltonian.

M = number of spin-orbitals, conditioning m.

ϵ = desired chemical accuracy ≈ 1.6 10^{-3} Ha

δ = acceptable failure probability.

p_0 = initial state overlap, decreasing exponentially with molecule size.

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

state vector encoding circuit

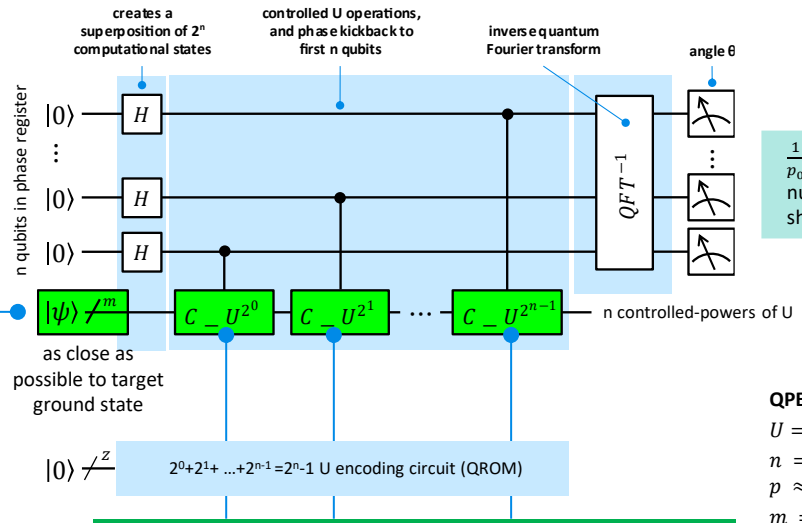
classical computing time scale $O(M^3)$ to $O(2^M)$

classical computing time scale $O(M^3)$ to $O(M^5)$

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

H= system Hamiltonian

U= unitary encoding it



$\frac{1}{p_0}\ln(\frac{1}{\delta})$ QPE number of circuit shots

results post-processing

problem Hamiltonian encoding

find *U* using

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

QPE quantum circuit metrics

U = unitary encoding the Hamiltonian H.

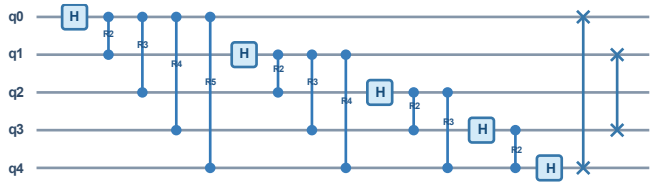
n = phase register qubits, $\lceil \log_2(1/\epsilon) \rceil + p \approx 13$ *to* 15 for $\epsilon \approx 1.6\ 10^{-3}$ Ha

m = system register qubits encoding the initial state $|\psi\rangle$ and on which controlled powers of unitary U are applied.

z = additional ancilla logical qubits required to encode U which depends on its parallelization.

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.

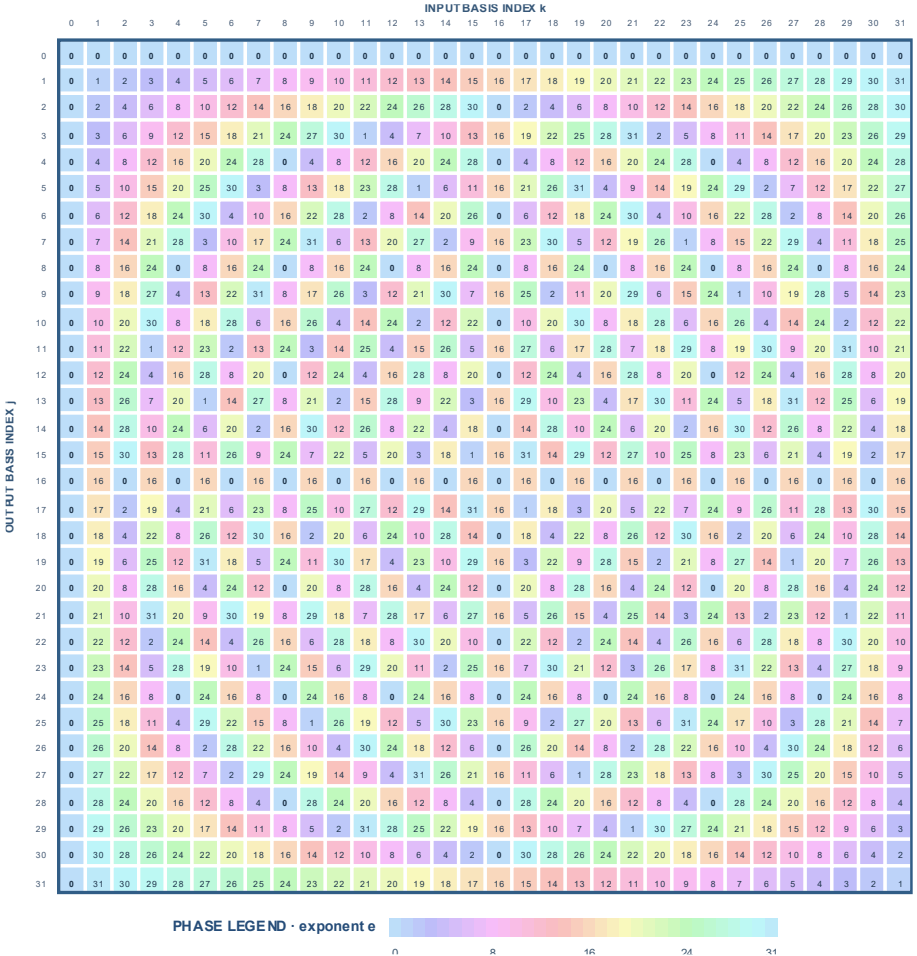
5-qubit QFT unitary



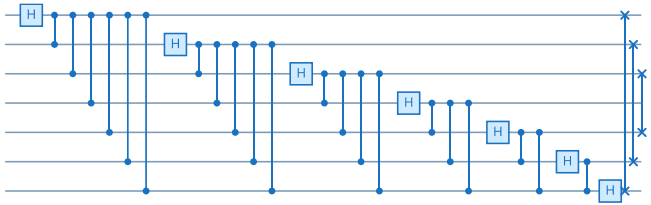
Rk = controlled phase P(2π/2^k). Final SWAPs reverse the qubit order.

provides some insights on why circuits are useful

- they turn a 17-gate circuit into a unitary matrix with 961 non-zero values.
- modulo a symmetry around the diagonal due to the QFT unitary being equal to its transpose unitary.
- imagine the relative sizing with >50 qubits!



7-qubit QFT



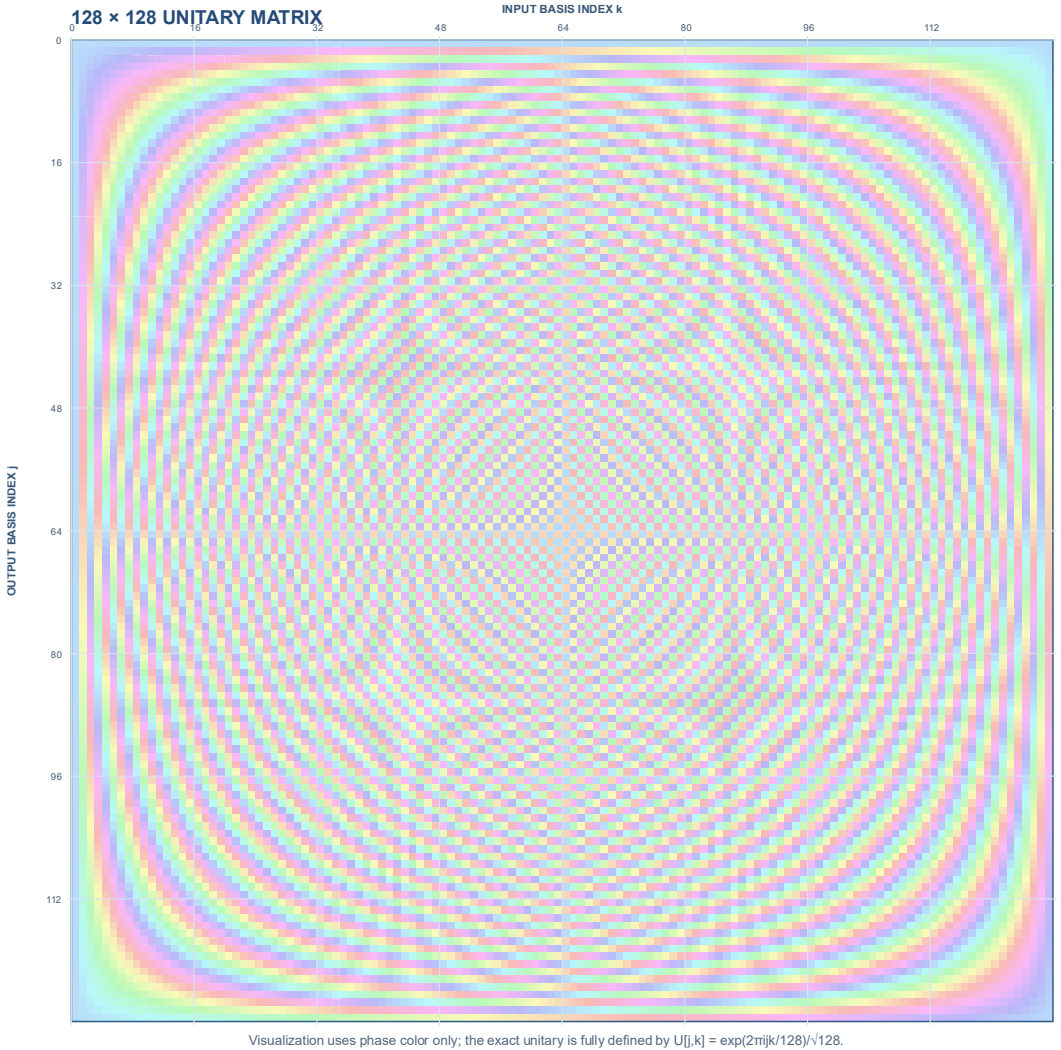
two additional qubits…

- turns a 31-gate circuit into a unitary matrix with 16,129 non-zero values.

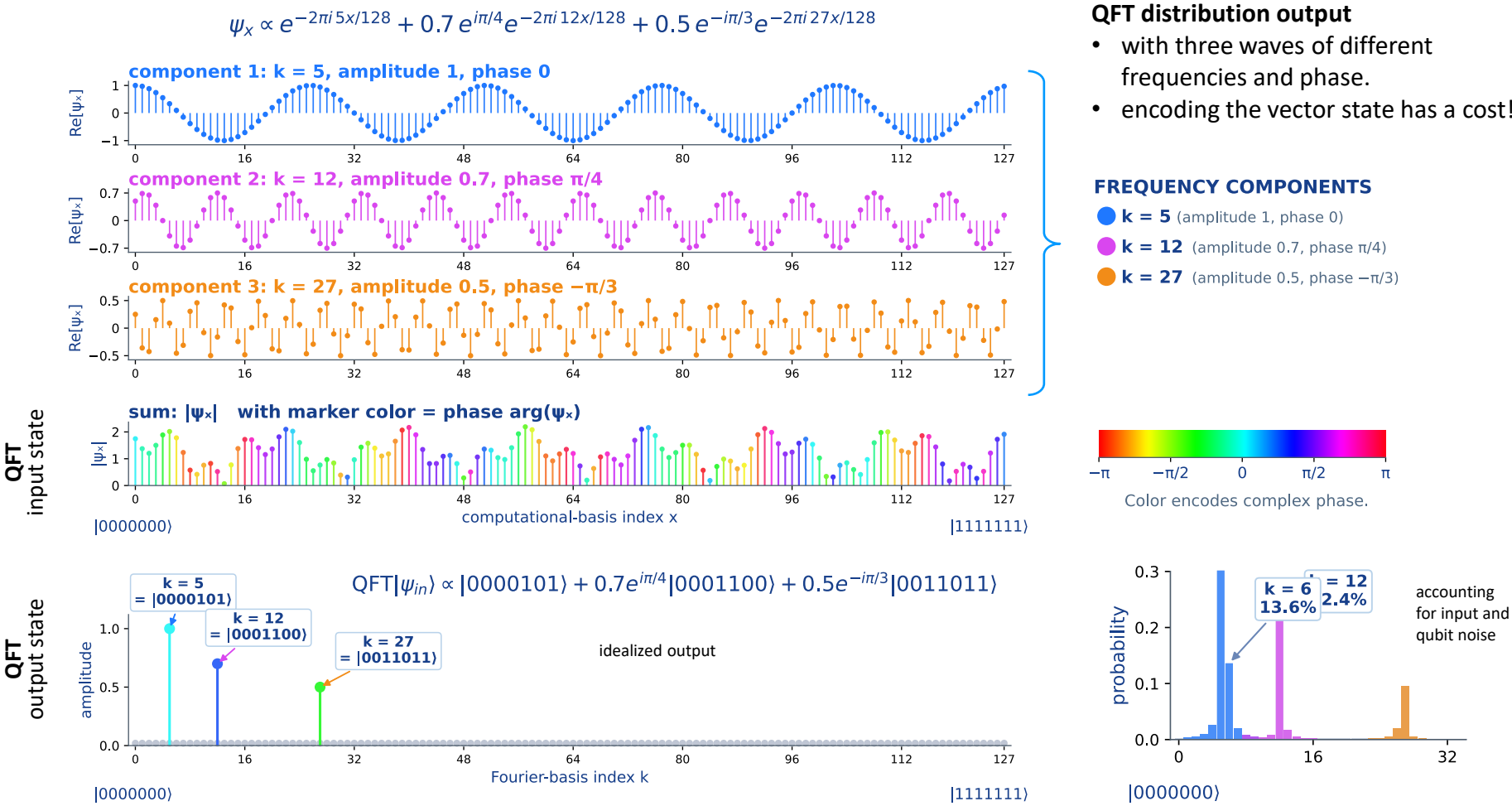
PHASE LEGEND

All 128 roots of unity appear. Sample exponents:

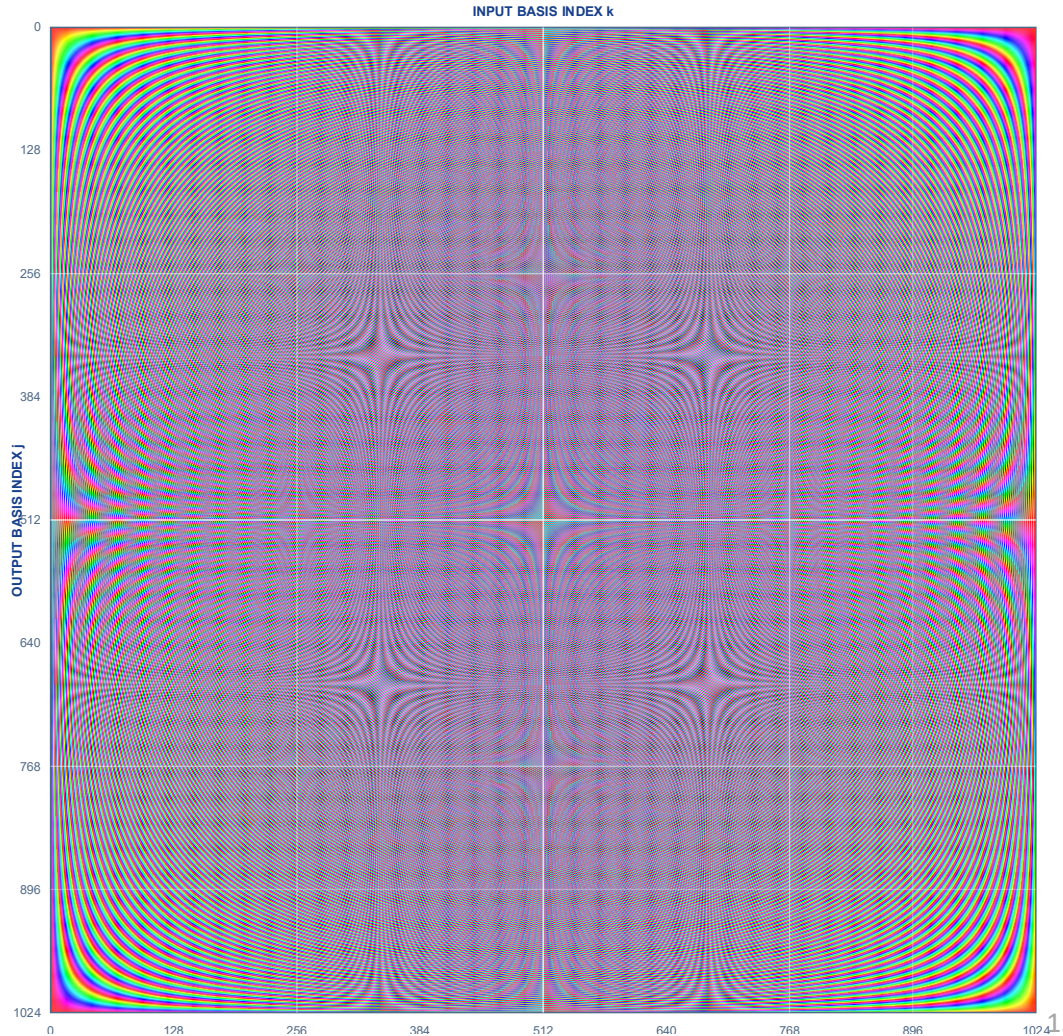
e = 0	e = 8	e = 16	e = 24
e = 32	e = 40	e = 48	e = 56
e = 64	e = 72	e = 80	e = 88
e = 96	e = 104	e = 112	e = 120

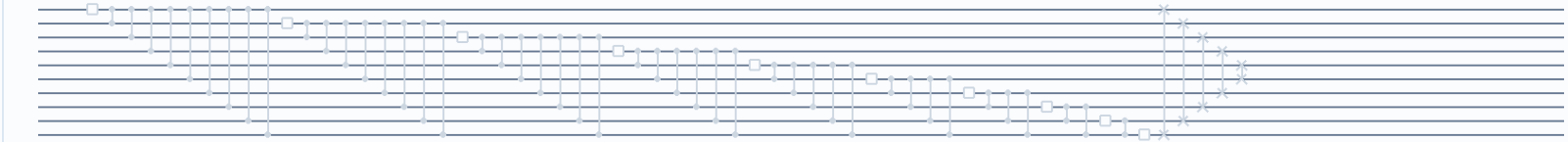


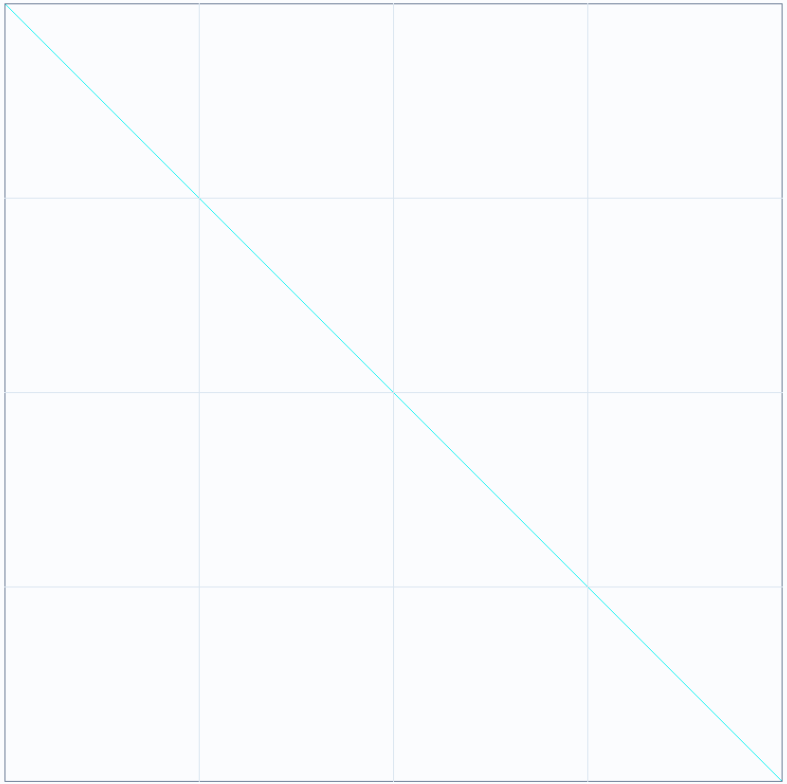
Visualization uses phase color only; the exact unitary is fully defined by U[j,k] = exp(2πijk/128)/√128.

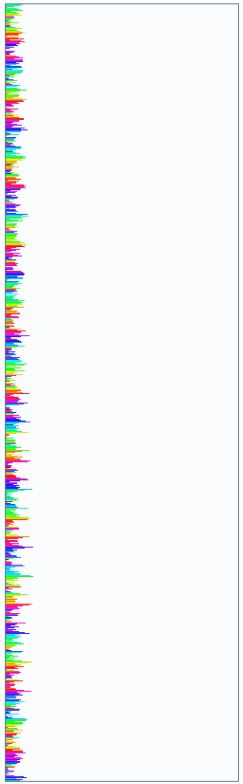

$\psi_x \propto e^{-2\pi i\,5x/128} + 0.7\,e^{i\pi/4}e^{-2\pi i\,12x/128} + 0.5\,e^{-i\pi/3}e^{-2\pi i\,27x/128}$
component 1: k = 5, amplitude 1, phase 0
component 2: k = 12, amplitude 0.7, phase π/4
component 3: k = 27, amplitude 0.5, phase −π/3
Re[ψx]
QFT input state
sum: |ψx| with marker color = phase arg(ψx)
|ψx|
computational-basis index x
|0000000⟩
|1111111⟩
QFT output state
$\mathrm{QFT}|\psi_{in}\rangle \propto |0000101\rangle + 0.7e^{i\pi/4}|0001100\rangle + 0.5e^{-i\pi/3}|0011011\rangle$
k = 5 = |0000101⟩
k = 12 = |0001100⟩
k = 27 = |0011011⟩
idealized output
amplitude
Fourier-basis index k
|0000000⟩
|1111111⟩
QFT distribution output
• with three waves of different frequencies and phase.
• encoding the vector state has a cost!
FREQUENCY COMPONENTS
k = 5 (amplitude 1, phase 0)
k = 12 (amplitude 0.7, phase π/4)
k = 27 (amplitude 0.5, phase −π/3)
−π −π/2 0 π/2 π
Color encodes complex phase.
probability
k = 6 13.6%
= 12 2.4%
accounting for input and qubit noise
|0000000⟩

10-qubit QFT


INPUT BASIS INDEX k
OUTPUT BASIS INDEX j
0
128
256
384
512
640
768
896
1024
Phase index e = jk mod 1024
0
π/2
π
3π/2
2π
Color represents the phase angle
θ = 2πe/1024.







Initial state: seven Fourier waves

The input is a normalized sum of seven complex waves, each with a different grid frequency, amplitude and initial phase.

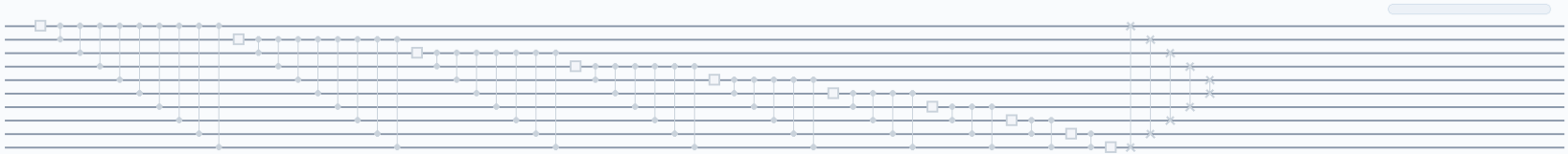
Their frequencies are 11, 37, 91, 173, 254, 389 and 702, out of 1,024 Fourier bins.

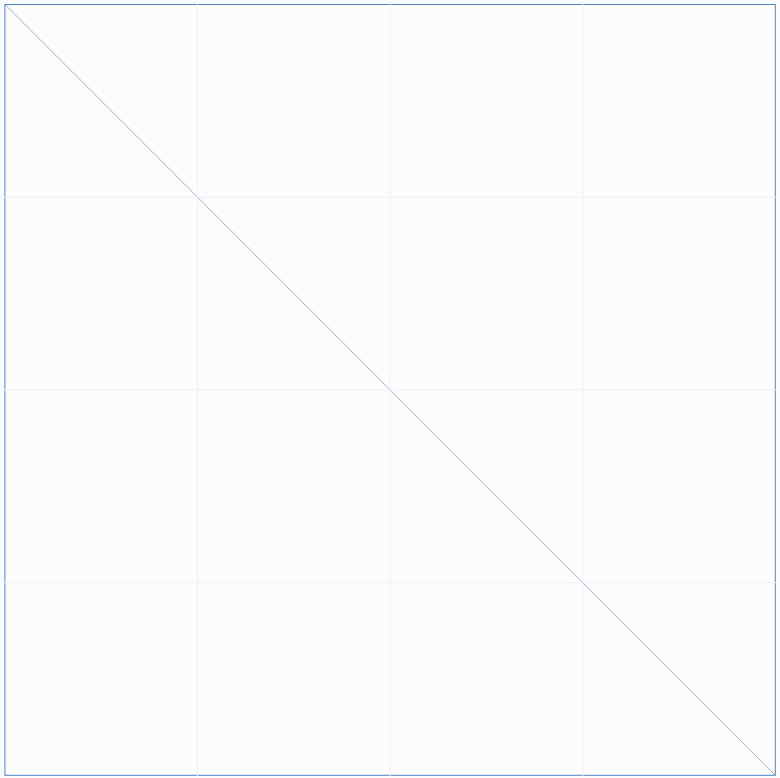
The initial unitary is the identity matrix. The state has 1,024 populated computational-basis amplitudes. Their magnitude reflects interference between the waves and their color represents complex phase.

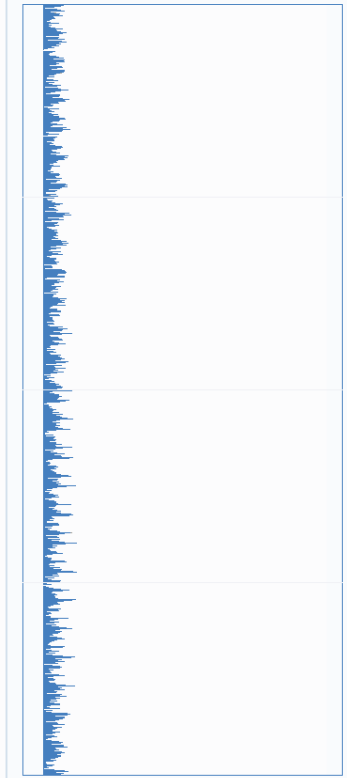
Relative amplitudes: 1, 0.85, 0.72, 0.58, 0.47, 0.36, 0.28

Relative phases: 0, π/6, −π/4, π/3, −2π/5, π/2, −π/7

Blue: completed • Orange: current gate







Initial seven-frequency state

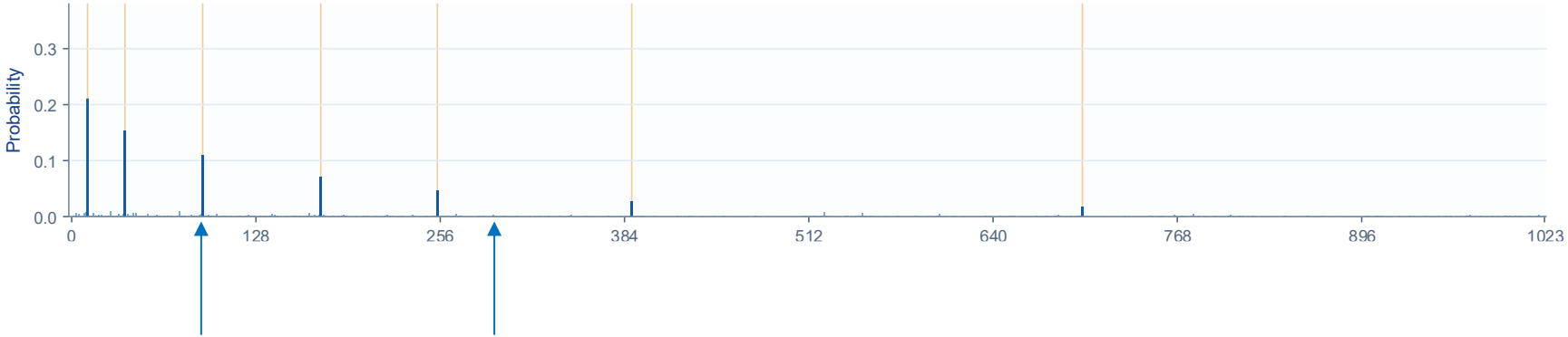
The 1024 complex amplitudes contain seven superposed Fourier modes at k = 11, 37, 91, 173, 254, 389 and 702. Their relative weights are 1.00, 0.85, 0.72, 0.58, 0.47, 0.36 and 0.28, with distinct phases. The ideal cumulative unitary is the identity matrix. The noisy ensemble starts in exactly the same pure input state.

NOISE MODEL

2-qubit native Favg: 99.6%
Pauli fault probability: 0.50%
Native entangling error locations: 0/105
CP: 2 locations; SWAP: 3
Readout: 99.5% per qubit
Single-qubit gates and preparation: ideal
Estimated ideal-state fidelity: 100.0%
Measurement weight in 7 target bins: 0.9%

how to get a QFT output result?

you need to “sample” the circuit multiple times

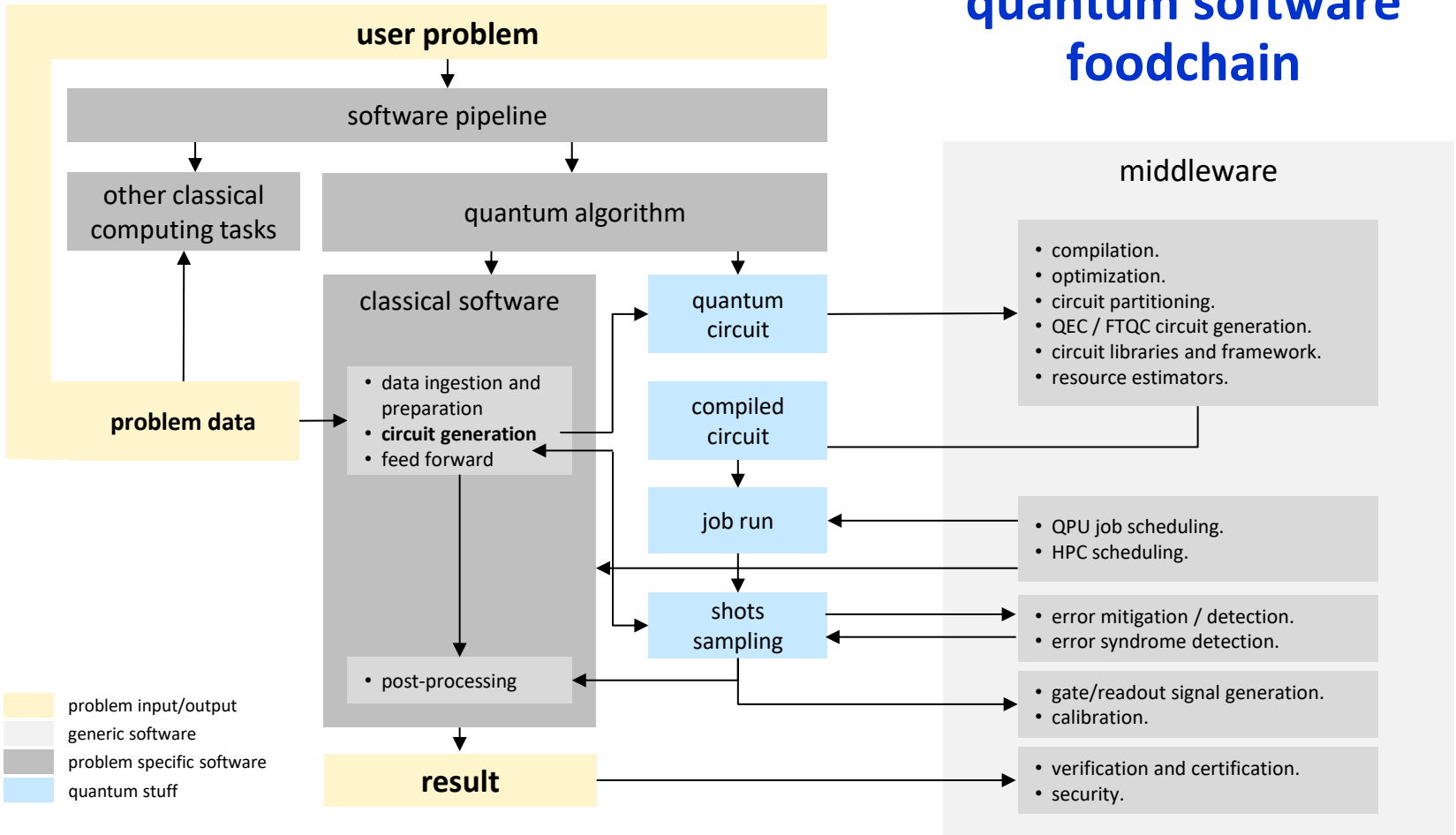


one 10-bit number
with probability 11%

another 10-bit number
with small probability
due to noise

in practice, you want to avoid this

quantum software foodchain



quantum advantage challenges

- **data encoding** reasonable time.
- preferably not relying on a **qRAM**.

- **computing time** advantage compatible with the user need.
- reasonable quantum computing **physical resources**.
- includes the **classical resources** generating the quantum circuit.

- good or better **result quality** vs classical methods (chemical accuracy, heuristics).

not dequantized by some classical method (i.e. tensor network based).

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FTQC resource estimations

The Grand Challenge of Quantum Applications

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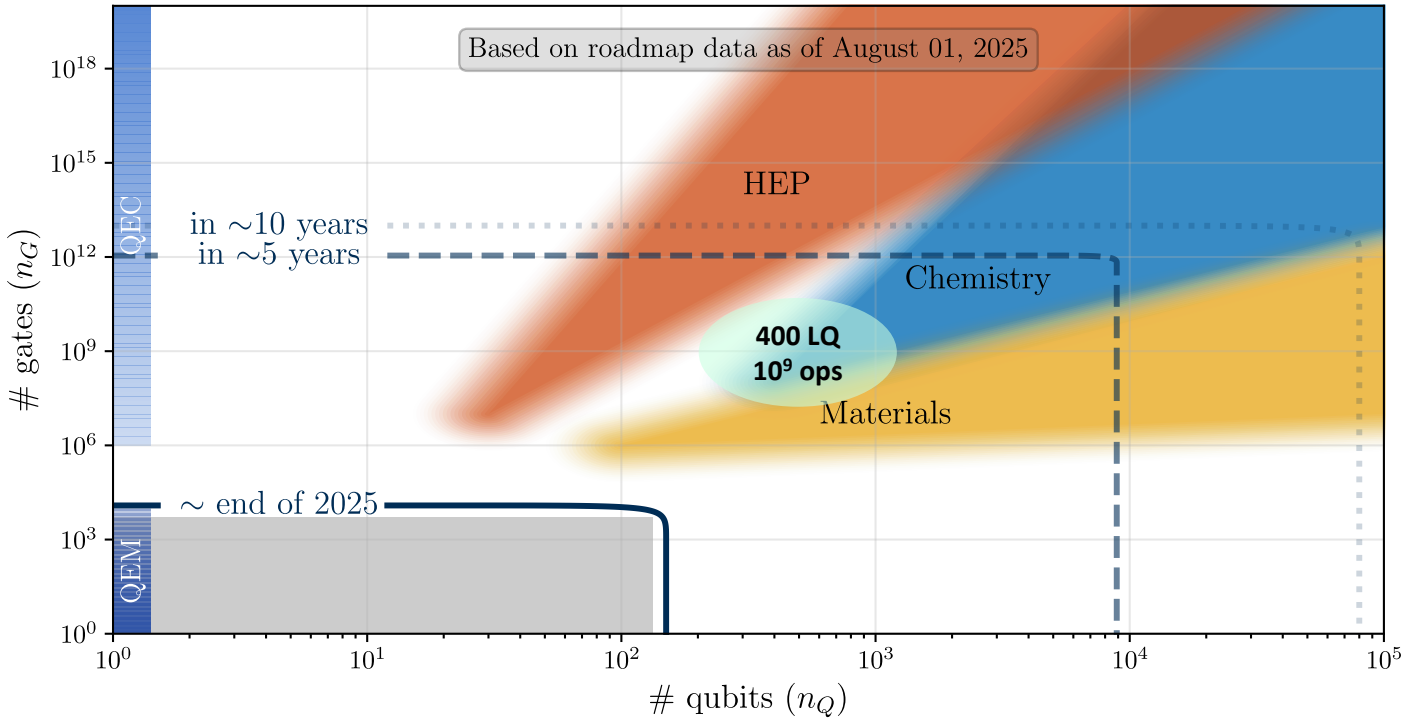
Google Quantum AI, Santa Barbara, CA 93111, United States
(Dated: December 5, 2025)

arxiv.org/abs/2511.09124

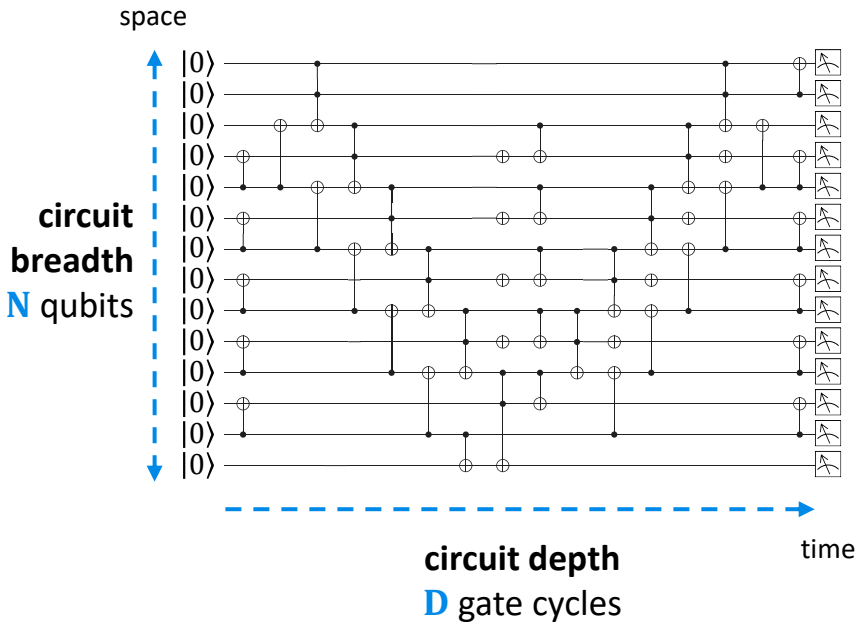
Horizon	Problem	Stage III applications	Problem size	Stage IV(b)		Stage IV(c)	
				Logical q.	Toffolis	Phys. q.	Time
Medium	Trapdoor claw-free functions [104]	Classically verifiable quantum advantage	1024 bits	1600 [141]	$8 \cdot 10^6$	–	–
	DQI for OPI [58]		4095 variables 70 constraints	1900	$6 \cdot 10^6$	$8 \cdot 10^5$ [142]	1 hour
	Topological data analysis of random graphs [62]	Unknown	256 vertices 16-cliques	500 [143]	$7 \cdot 10^9$	–	–
	Factoring [34]	Breaking RSA	2048 bits	1400	$7 \cdot 10^9$	$1 \cdot 10^6$ [44]	1 week
	Binary discrete log [34]	Breaking outdated cryptosystems	233 bits	3000	$4 \cdot 10^6$	$4 \cdot 10^6$ [36]	8 min
Furthest	Elliptic curve cryptography [34]	Breaking elliptic curve cryptography	256 bits	3000	$5 \cdot 10^7$	$9 \cdot 10^6$ [35]	4 hours
	Tensor PCA [30]	Unknown	100 variables	900 [144]	$1 \cdot 10^{15}$	–	–
	XOR-SAT refutation [82]	Unknown					
	QAOA for max 8-SAT [102]	Unknown	179 variables	28000	$5 \cdot 10^{11}$	$7 \cdot 10^7$ [145]	15 hours

physics simulation resource estimates



Quantum Computing Technology Roadmaps and Capability Assessment for Scientific Computing -- An analysis of use cases from the NERSC workload by Daan Camps, et al, arXiv, September 2025 (69 pages).

operations fidelity needs



$$\epsilon_{operations} < \frac{1}{\mathbf{N} \times \mathbf{D}}$$

corresponds to all qubit operations:

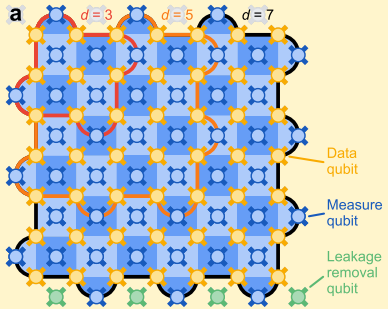
- single qubit gates errors
- two-qubit gates errors
- idle state errors
- readout errors

(cc) Olivier Ezratty

QEC vs FTQC

QEC
error correction
on logical qubits

tens to thousands physical qubits per logical qubits



error rate ≈10^{-4} to 10^{-18}

FTQC
fault tolerant quantum computing

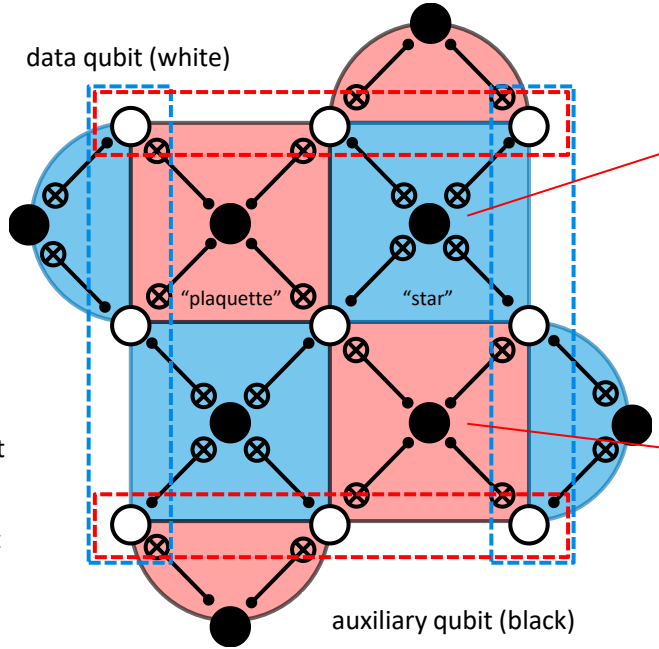
- supports large quantum circuits.
- support logical gates on a universal gate set.
- magic states generation and consumption.
- avoid error propagation and amplification.
- fault-tolerant results readout.

code boundaries
for lattice surgery

red edge: X

blue edge: Z

data qubit (white)

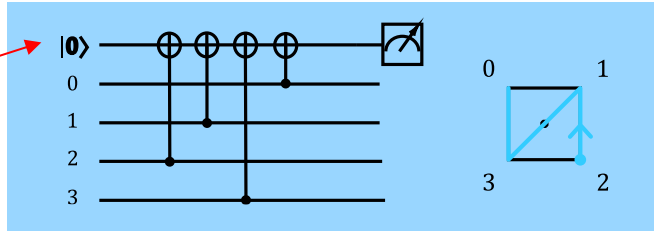


inside squares: weight four stabilizers

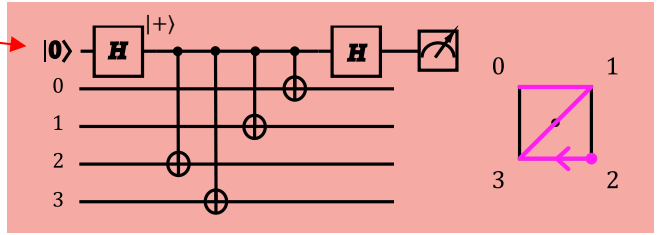
on the edges : weight two stabilizers

auxiliary qubit (black)

blue Z stabilizers detect X errors "star"



red X stabilizers detect Z errors "plaquettes"



distance 3 rotated surface code with 9 data qubits (white) and 8 auxiliary measurement qubits (black). CNOT gates indicate the local interactions between the data and auxiliary qubits. blue auxiliary qubits detect X error, and red auxiliary qubits detect Z errors. there are weight-four (inside the rectangle) and weight two stabilizers (on the edges of the code). the red squares are "plaquettes" and the blue square are "stars" due to the direction of the CNOTs. d^2 data qubits + d^2-1 auxiliary qubits = $2d^2$-1 total physical qubits.

https://arxiv.org/abs/2411.10406 (Qolab blueprint)

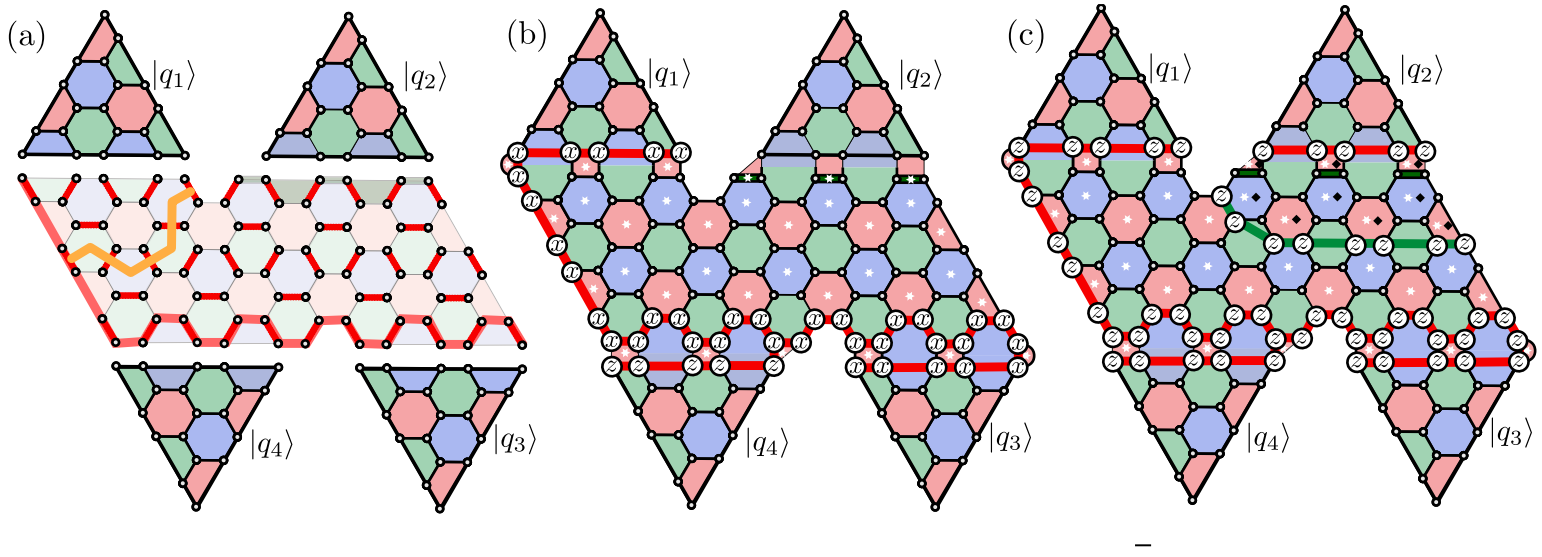
https://arxiv.org/abs/2409.14765v1

color codes and lattice surgery

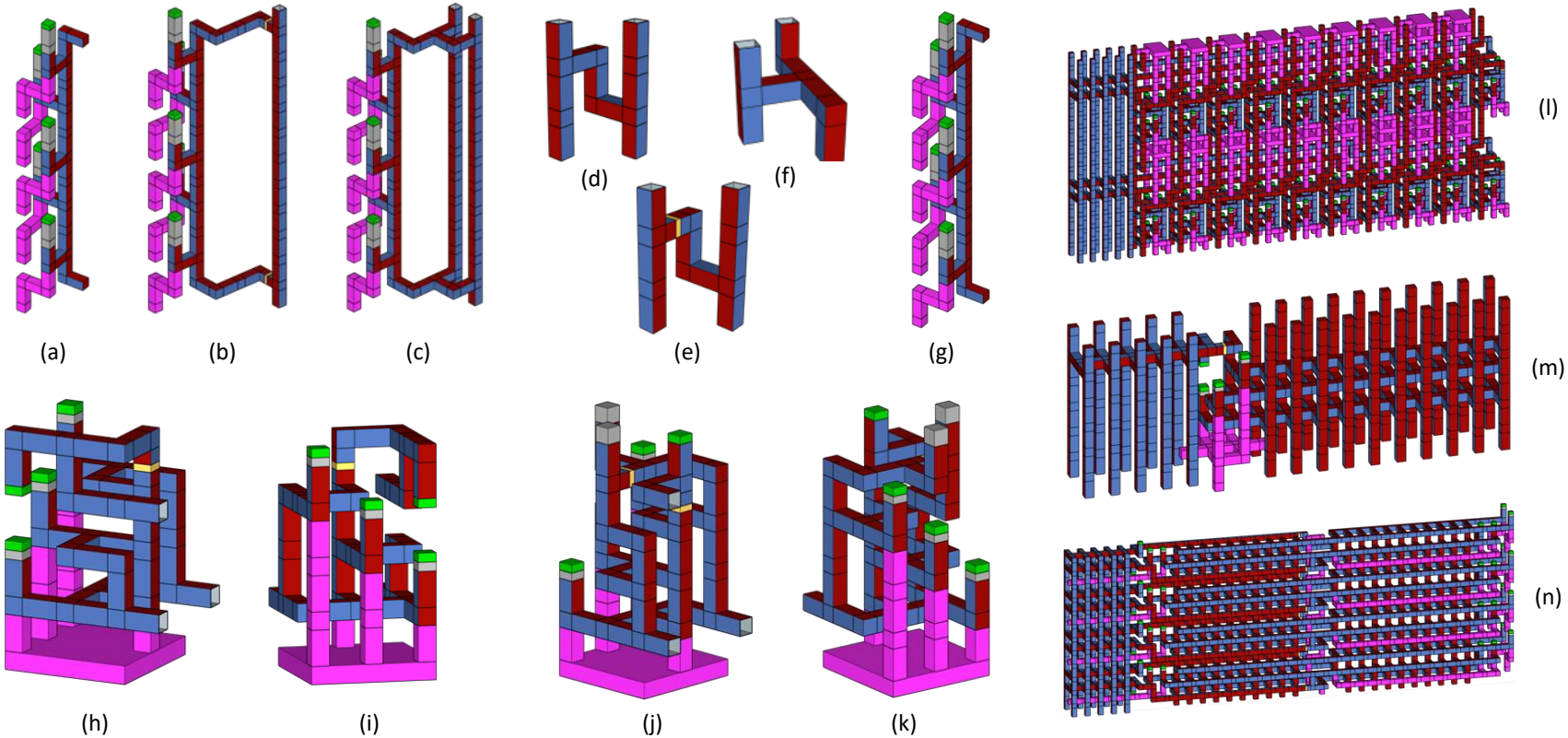
2 distance 3 logical qubits

auxiliary qubits for lattice surgey

2 distance 3 logical qubits

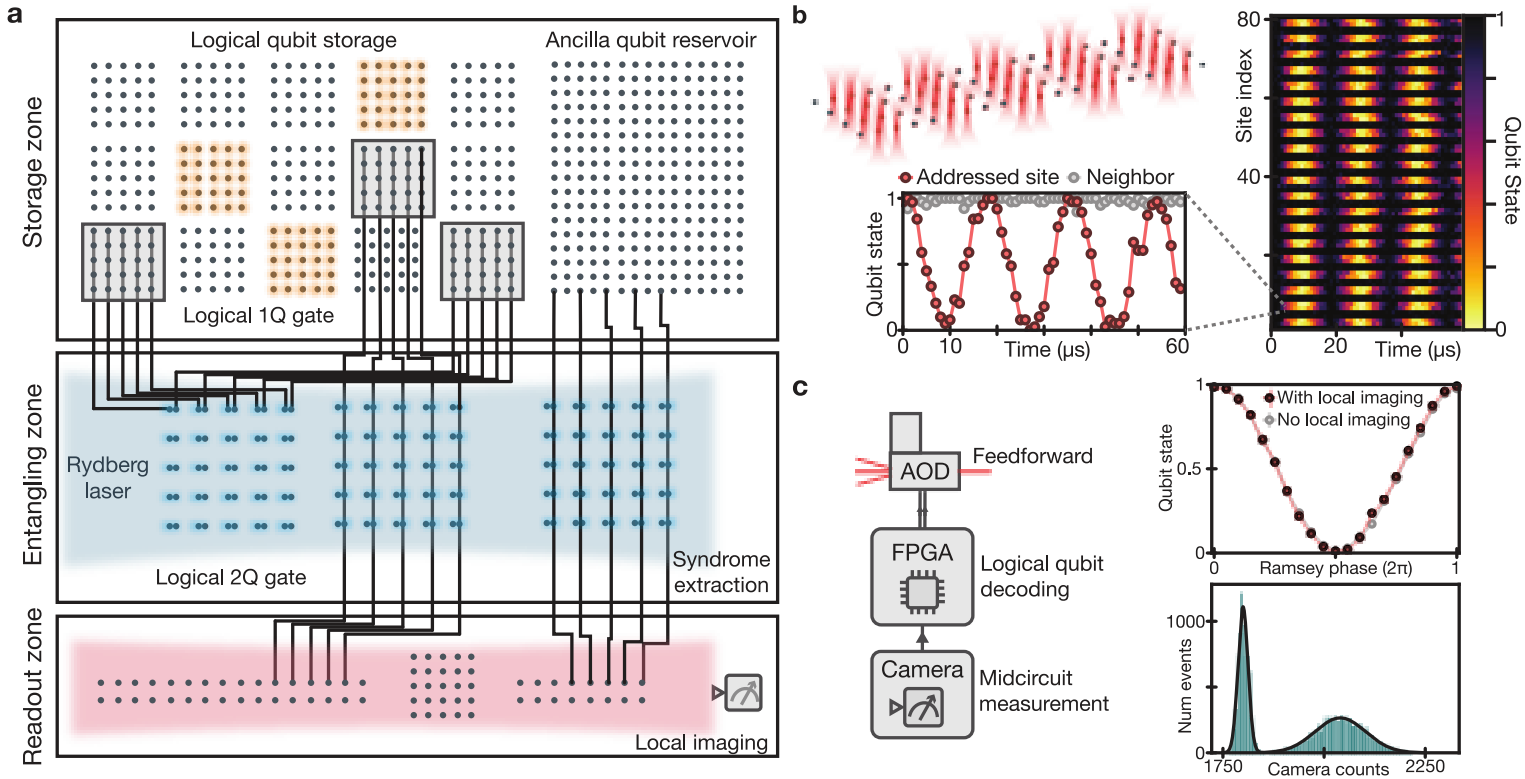


pipes representation (Google)

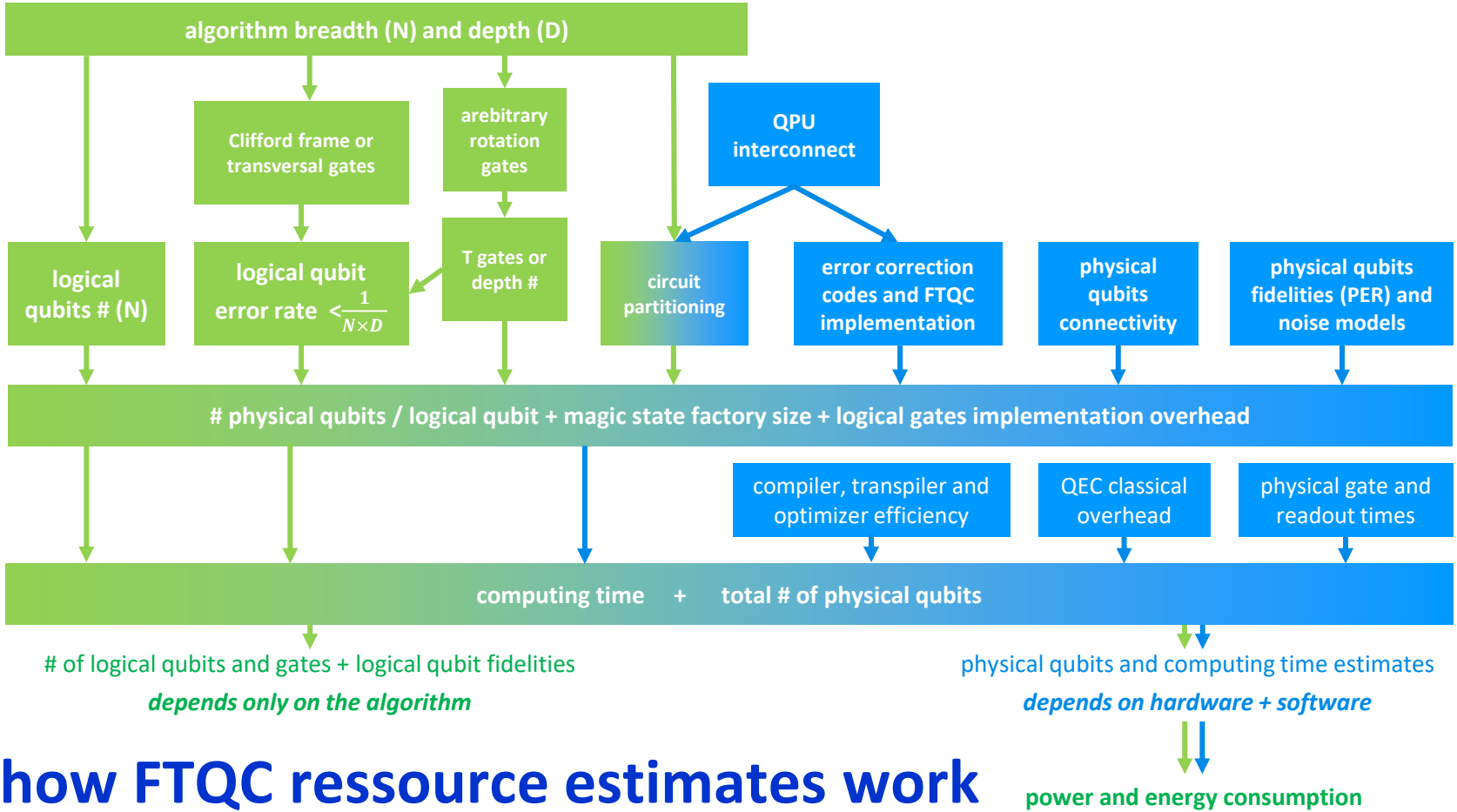


https://arxiv.org/abs/2511.08508

cold-atom shuttling

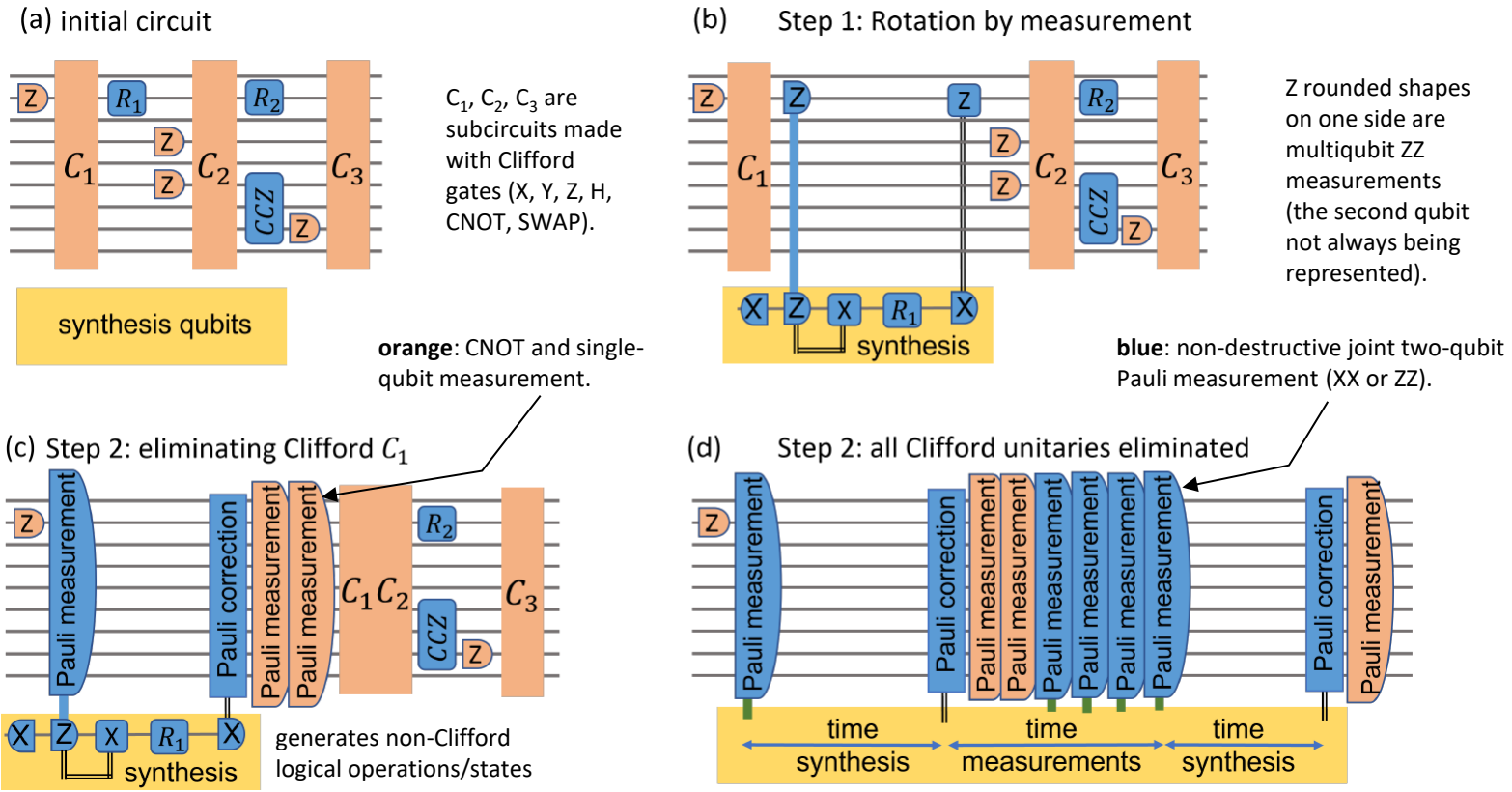


source: Logical quantum processor based on reconfigurable atom arrays by Dolev Bluvstein, Mikhail D. Lukin et al, December 2023 (32 pages)..



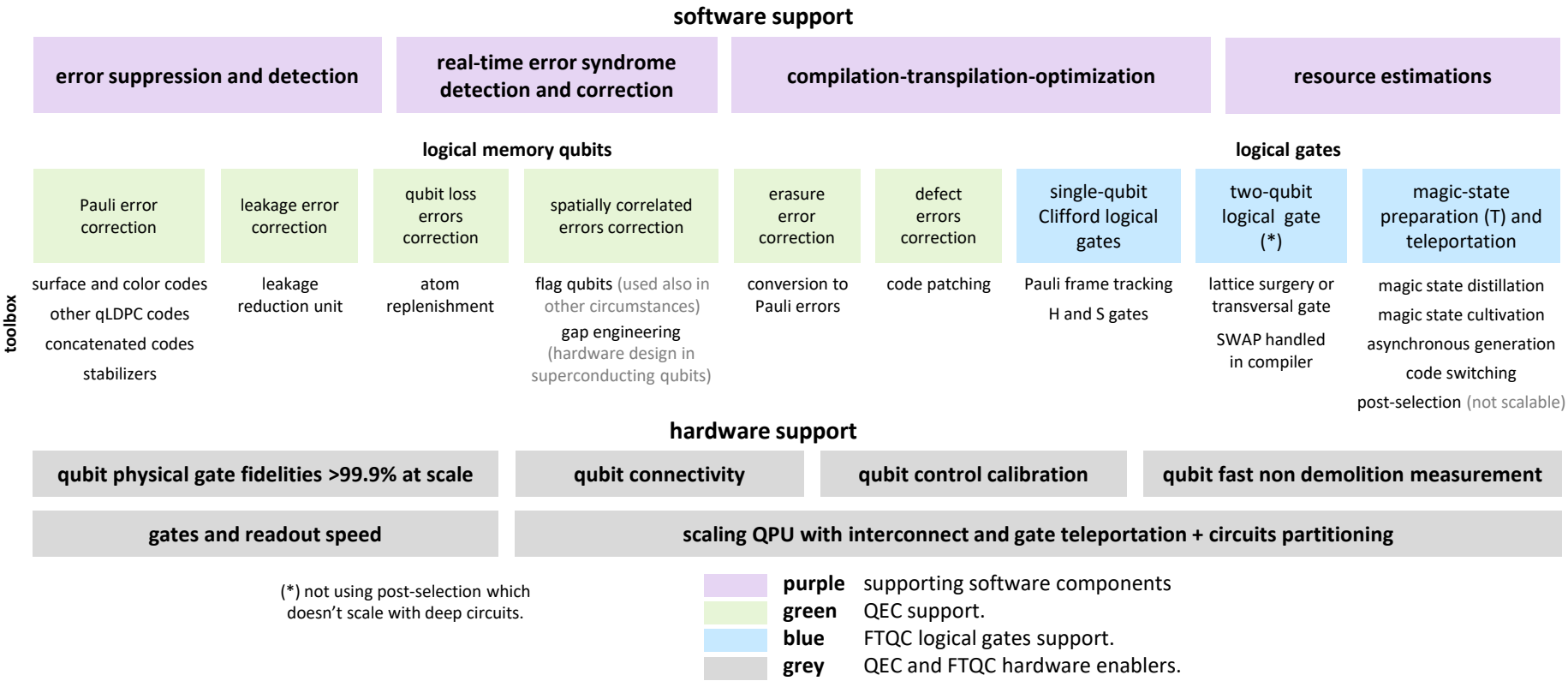
how FTQC ressource estimates work

circuit QEC “shape shifting” example



https://arxiv.org/abs/2211.07629

QEC/FTQC software + hardware components



(*) not using post-selection which doesn't scale with deep circuits.

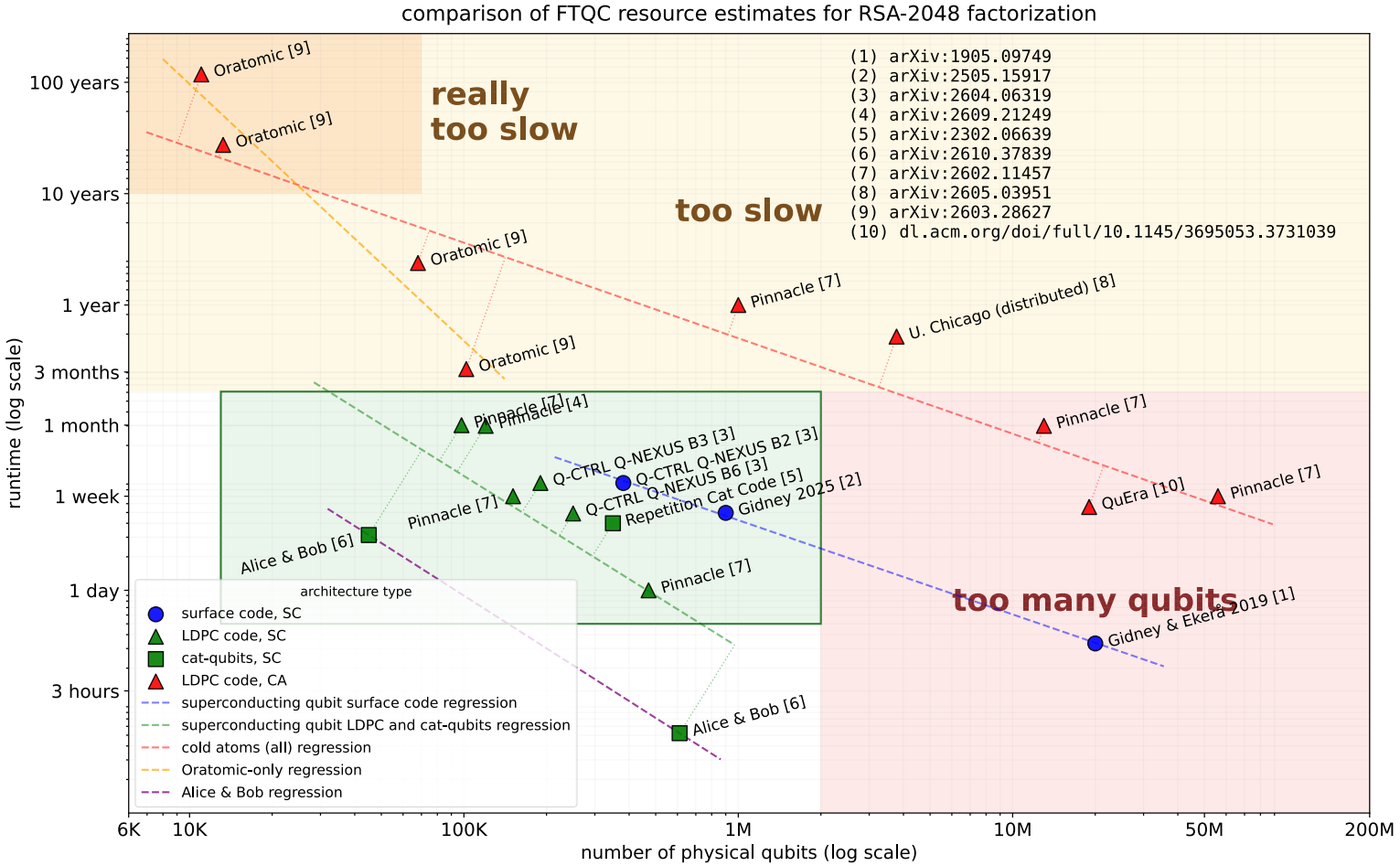
purple supporting software components
green QEC support.
blue FTQC logical gates support.
grey QEC and FTQC hardware enablers.

source: Understanding Quantum Technologies 2026, Olivier Ezratty, September 2026

General information			QEC features						FTQC features											
quantum computing hardware vendor	number of logical qubits	supporting physical qubits	main QEC codes	logical memory experiment	breakeven logical error rate	leakage error correction	erasure error correction	correlated error correction	< breakeven fidelities	single qubit logical gate	singe logical error rate	two qubit logical gate	two qubit error rate	lattice surgery	magic state preparation	gate teleportation	code switching	postselection or detection	logical GHZ fidelity	full universal gate set support
QuEra	96 [1132]	448 [1132]	color codes	[1853]	[1853]	[1132]	[1132]	[1132]	[1853]	[1132, 1853]	[1132]	[1132, 1853]	[1132, 1853]	[1132, 1868]	[1132]	[1132]	[1132]	[1132]	[1132]	[1853]
Infleqtion	12 [1857]	114 [1857]	qLDPC variants	[1857]	[1857]	[1857]	[1857]			[1857]		[1857]	1859		CCZ 1859	CCZ 1859		[1859]		[1859]
Atom Computing	24 [1869]	208 [1869]	Bacon Shor, 4D code, and other codes [1869]	[1869]			[1869, 1870]			[1869]		[1869]						[1869]		
Pasqal	2	4																yes		
Quantinuum	48 [1871]	98 [1397]	sc, Tesseract, Iceberg, concat, C_4-Helix	[1697, 1855, 1872]	[1872, 1873]		[1855]		[1872, 1873]	[1855, 1856]	[1873]	[1855, 1856, 1872]	[1872, 1873]		[1858]	[1858]		[1855, 1872]	[1872, 1873]	[1858]
IonQ	12 (2026)	256 (2026)	qLDPC bb [1874], walking cats [1826]	[1875, 1876]	[1875, 1876]		[1877]		[1876]		[1826]		[1826]		[1826]	[1826]				[1826]
AQT	2	30	cc, holographic codes [1878]	[1879, 1880]	[1881]	[1882]				[1880, 1883]	[1880]	[1847, 1883, 1884]	[1885]	[1881, 1883]	[1847]	[1847]	[1847]			[1847]
Google	1 [1642]	105 [1642]	sc, cc	[1642]	[1642]	[1642]		[1642]	[1642]					[1886]	[1886]		[1886]	no		
IBM	200 (2029)	n×120	gross code (bb)		[1613]	[1613]				[1613, 1887]		[1613, 1887]		[1613]	[1613, 1888–1891]	[1613]	[1892]			[1613, 1891, 1892]
IQM	4-36 (2026)	54 (2025)	bb, tile codes (qLDPC)	[1615]						[1893]		[1893]								
Alice & Bob	100 (2030))	2000 (2030)	LDPC, elevator codes							[1894]		[1894, 1895]		[1896]	[1896]					
PsiQuantum	100 (2030))	1M (2030)	qLDPC, sc, dual rail				[1897, 1898]			[1897, 1898]		[1897, 1898]		[1899]	[1897–1899]					
Xanadu			GKP, qLDPC, bb				[1900–1902]			[1900–1902]		[1900–1902]			[1900–1902]					
Quandela		12	Floquet							[1903]		[1904]								
ORCA Quantum		12	qLDPC, sc			not applic	[1905]			[1905]		[1905]								

post-selection

source: Understanding Quantum Technologies 2026, Olivier Ezratty, September 2026

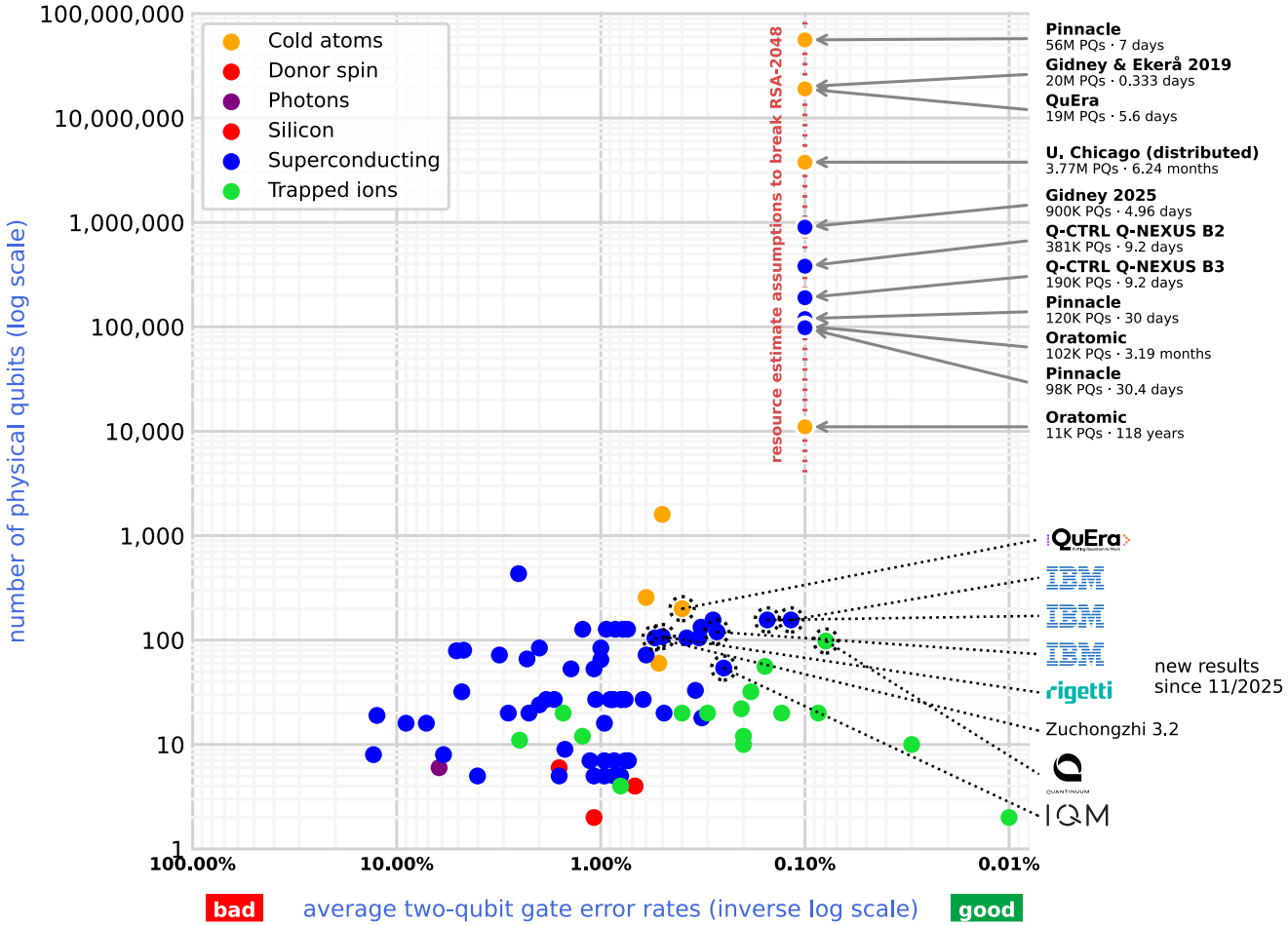

comparison of FTQC resource estimates for RSA-2048 factorization
really too slow
too slow
too many qubits
(1) arXiv:1905.09749
(2) arXiv:2505.15917
(3) arXiv:2604.06319
(4) arXiv:2609.21249
(5) arXiv:2302.06639
(6) arXiv:2610.37839
(7) arXiv:2602.11457
(8) arXiv:2605.03951
(9) arXiv:2603.28627
(10) dl.acm.org/doi/full/10.1145/3695053.3731039
Oratomic [9]
Oratomic [9]
Oratomic [9]
Oratomic [9]
Pinnacle [7]
U. Chicago (distributed) [8]
Pinnacle [7]
Pinnacle [4]
Pinnacle [7]
Q-CTRL Q-NEXUS B3 [3]
Q-CTRL Q-NEXUS B2 [3]
Q-CTRL Q-NEXUS B6 [3]
Repetition Cat Code [5]
Gidney 2025 [2]
Pinnacle [7]
Alice & Bob [6]
Pinnacle [7]
QuEra [10]
Pinnacle [7]
Gidney & Ekerå 2019 [1]
Alice & Bob [6]
architecture type
surface code, SC
LDPC code, SC
cat-qubits, SC
LDPC code, CA
superconducting qubit surface code regression
superconducting qubit LDPC and cat-qubits regression
cold atoms (all) regression
Oratomic-only regression
Alice & Bob regression
runtime (log scale)
100 years
10 years
1 year
3 months
1 month
1 week
1 day
3 hours
number of physical qubits (log scale)
6K
10K
100K
1M
10M
50M
200M

physical error rate assumptions in QEC/FTQC resource estimates:

- 99.9% reset fidelity
- 99.9% single qubit gate fidelity
- **99.9% two qubit gate fidelity**
- 99.9% idle state fidelity
- **99.9% readout fidelity**
- usually, missing correlated noise sources + unknown noise sources at scale.

=>

- quantum energetics.
- material sciences.
- high-quality manufacturing.
- high-quality qubit control.
- QPU interconnect overhead.



QEC / FTQC space and time overheads

	space cost 		**time** cost 
QEC codes	QEC encoding rate	qubit connectivity	number of QEC rounds / cycle
error syndrome decoding	from a laptop to an HPC		classical computing cost
two-qubit logical gates	surgery (2D)	qubit connectivity	atom shuttling (atoms, ions)
magic states generation	T state factory size		can be asynchrone
magic state consumption	gate teleportation (2D)	qubit connectivity	transversal logical gates
physical gate speed			≈ 10 ms to 100 ms (ions or atoms shuttling) / ≈ 10 ns to 300 ns (superconducting qubits)
readout speed	classical readout control chain		variable
mitigating physical noise	QPU interconnect		QPU interconnect latency, LR bound

source: Olivier Ezratty, October 2026

FTQC hardware roadmaps and challenges



quantum & classical computing paradigms

classical computers

analog quantum computers

digital quantum computers

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

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

quantum **annealing computers**

analog **quantum simulators**

gate-based

NISQ (Noisy Intermediate Scale Quantum)
no error correction
with a few noisy qubits

FTQC (Fault-Tolerant Quantum Computers)
error correction and fault tolerance

classical algorithms improvements

quantum algorithms debug and testing

optimization problems and quantum physics simulation

general purpose quantum computing, adds search and integer factoring

Microsoft
MULTIVERSE COMPUTING
ZAPATA AI

EVIDEN
IBM
FUJITSU
Google
Microsoft
aws

D-Wave The Quantum Computing Company™
PASQAL
IQuEra COMPUTING INC.

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

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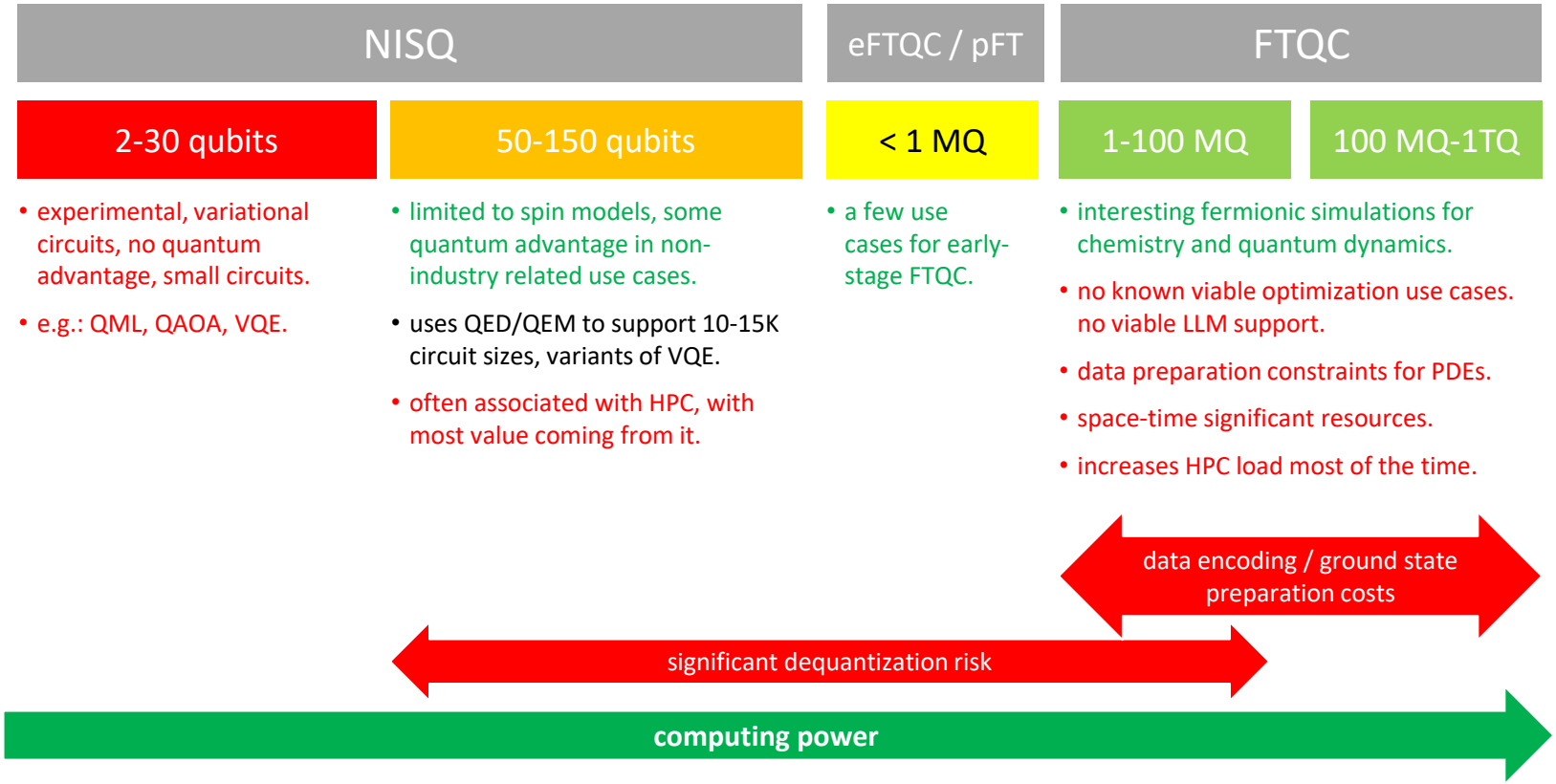
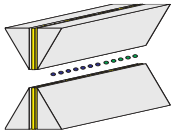
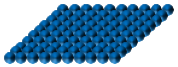
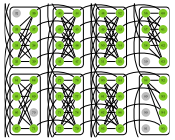
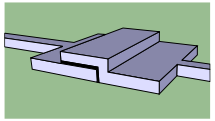
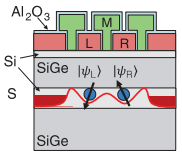
from NISQ to FTQC

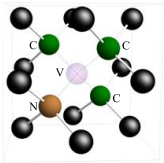
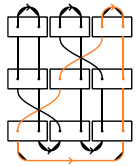
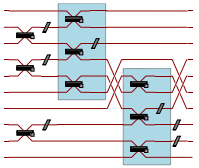


MQ: megaquop, TQ: teraquop, pFT : partial fault tolerance with no QEC on non-Clifford gates, eFTQC: early stage FTQC.

>90 QPUs industry vendors!

atoms | **electrons** *controlled spin and microwave cavities* | **photons**

trapped ions | cold atoms | annealing | superconducting | silicon | vacancies | topological | photons

1
- QUANTINUUM
- AQT
- NEQT
- ZuriQ
- Quantum Art
- FOXCONN
- Qubitcore
- 华翊量子
- 幺正量子 UNITARY QUANTUM

2
- IONQ
- eleQtron
- QUDORA TECHNOLOGIES

3
- CRYSTAL QUANTUM COMPUTING

4
- QuEra Computing Inc.
- Pasqal
- Infleqtion
- Oratomic
- logiqal
- Google
- planqc
- EQCITED
- Q-Factor
- QUANTUM SOURCE
- 本一量生
- BuchowAtom
- 中器无量
- 中科酷原 CAS COLD ATOM
- MatriQ
- Yaqumo

5
- atom computing

6
- Atom Quantum Labs

annealing
- D-Wave The Quantum Computing Company
- QILIMANJARO

7 superconducting
- IBM
- rigetti
- IQM
- Google
- QOLAB
- 本源量子 Origin Quantum
- OQC
- Peak Quantum
- SQ SRSTI QUANTUM
- ANYON
- Anyon TECHNOLOGIES
- SPINQ
- QUINT
- FUJITSU
- QuamCore
- sdt Quantum

8
- ALICE & BOB
- D-Wave The Quantum Computing Company
- amazon
- Nord Quantique
- Qolumbus

9 silicon
- diraq
- quobly
- QUANTUM MOTION
- equal1.labs

10
- Groove Quantum
- ARQUE
- intel

11
- Silicon Quantum Computing
- EeroQ QUANTUM HARDWARE
- C12
- ARCHER

vacancies
12
- quantum brilliance
- TURING
- XEED
- SaxonQ
- Quantum Transistors
- FUJITSU

13
- photonic

topological
- Microsoft
- QUOHERENT
- QUANTUM GRAVITY RESEARCH
- NOKIA

photons
14
- PsiQuantum
- QUANDELA
- QUIX QUANTUM
- ORCA COMPUTING
- DUALITY QUANTUM PHOTONICS
- aegiq
- TUNDRA SYSTEMS GLOBAL Inc.

15
- XANADU
- Qluster
- QUANFLUENCE

16
- QCi
- QBoson

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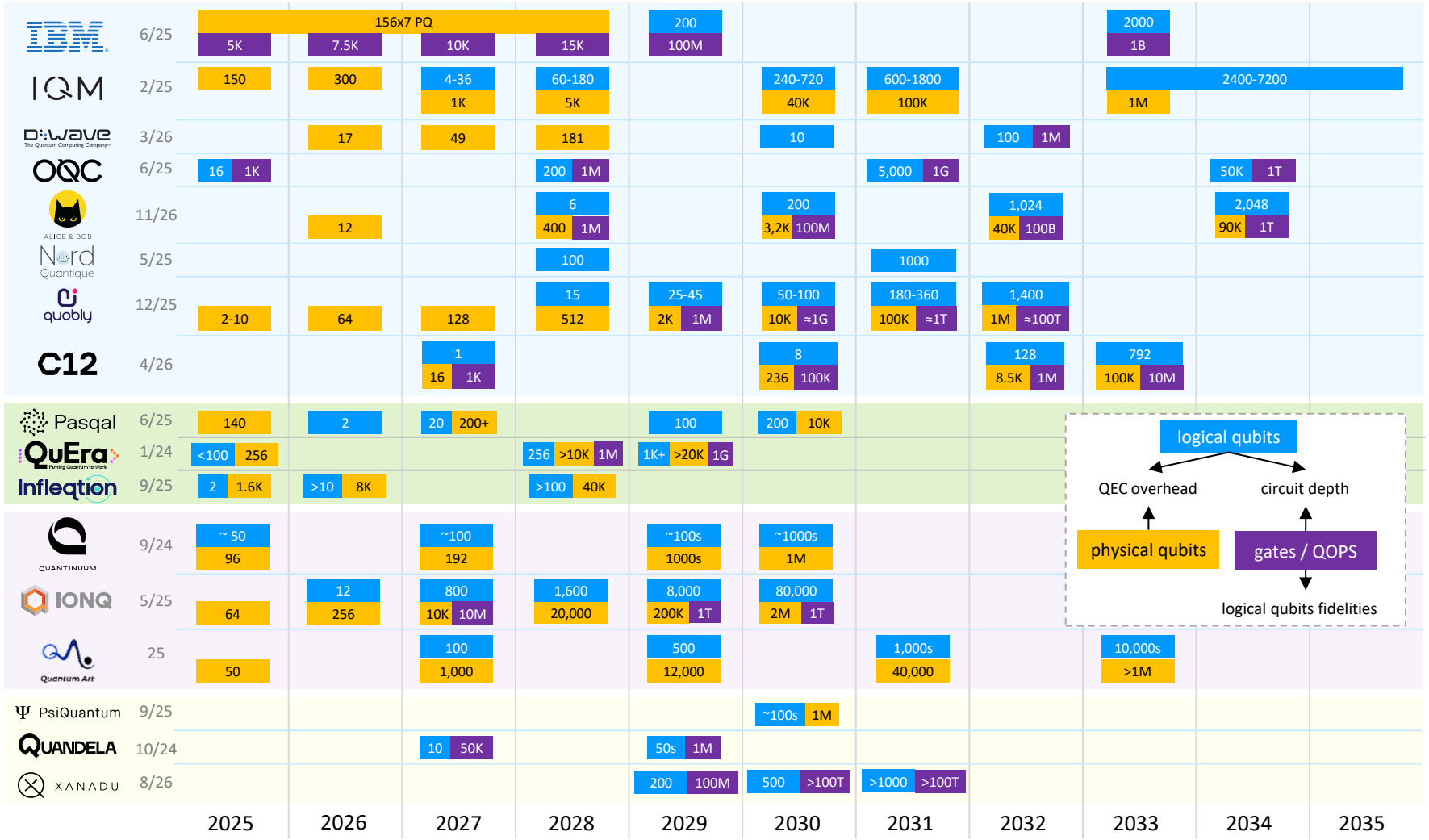
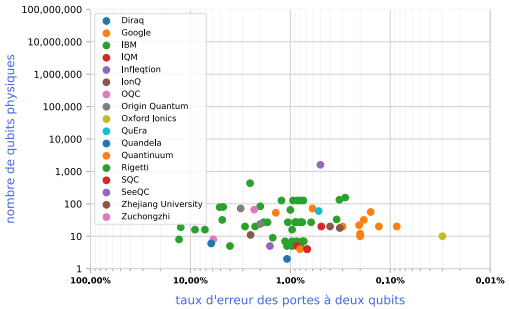
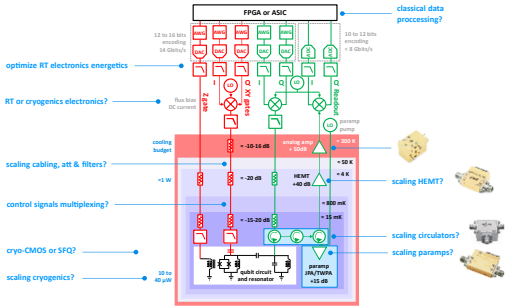


(cc) Olivier Ezratty, November 2026.

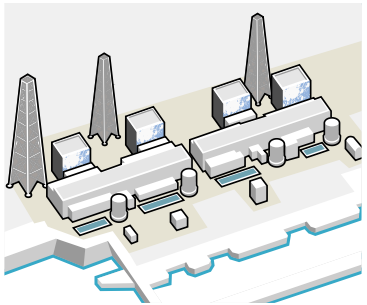
key hardware challenges



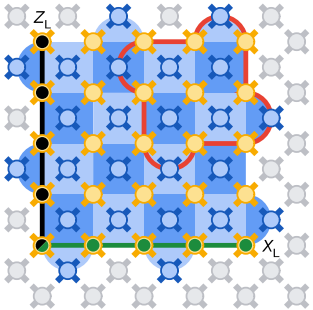
qubit quality



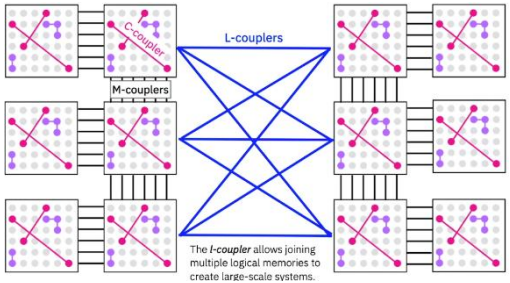
electronics, cabling, cryogeny



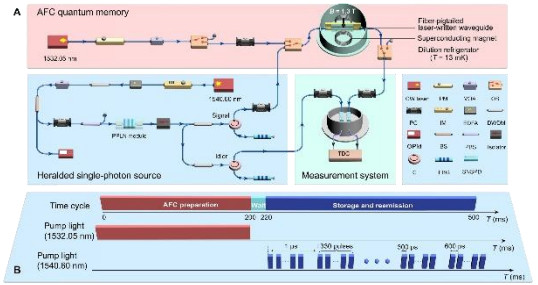
cost and power/energy



error correction



interconnection



quantum memory

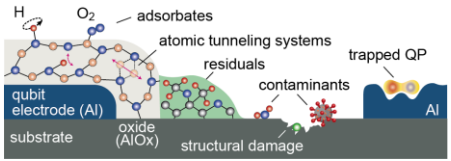
qubit errors sources

generic sources

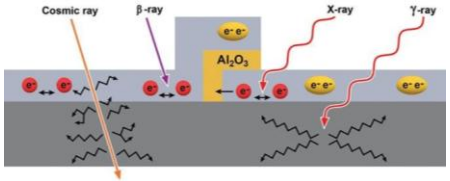
- many body interactions
- back-action
- vacuum quantum fluctuations

environmental noise

- charge and phase noise
- magnetic flux noise
- electromagnetic noise
- TLS errors
- quasiparticles poisoning
- material defects



- cosmic rays



control and signals errors

- signals jitter
- calibration



- crosstalk
- frequency crowding
- gravity

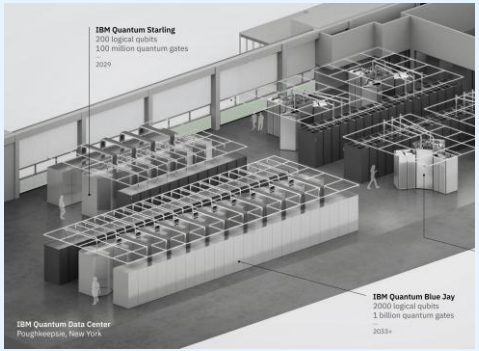
photon and atoms qubit specifics

- laser phase noise
- photon losses
- detectors inefficiency

(cc) Olivier Ezratty, 2023-2024

quantum computing energetics







#QEI

the quantum energy initiative

quantum-energy-initiative.org/





QEI 2025 (Grenoble) and 2026 (Barcelona)

why

- ICT energy consumption is growing fast.
- most quantum technologies will add an incremental energetic cost to existing ICT.
- it is time to work on this as quantum technologies and applications are designed.
- responsible innovation imperative.

what

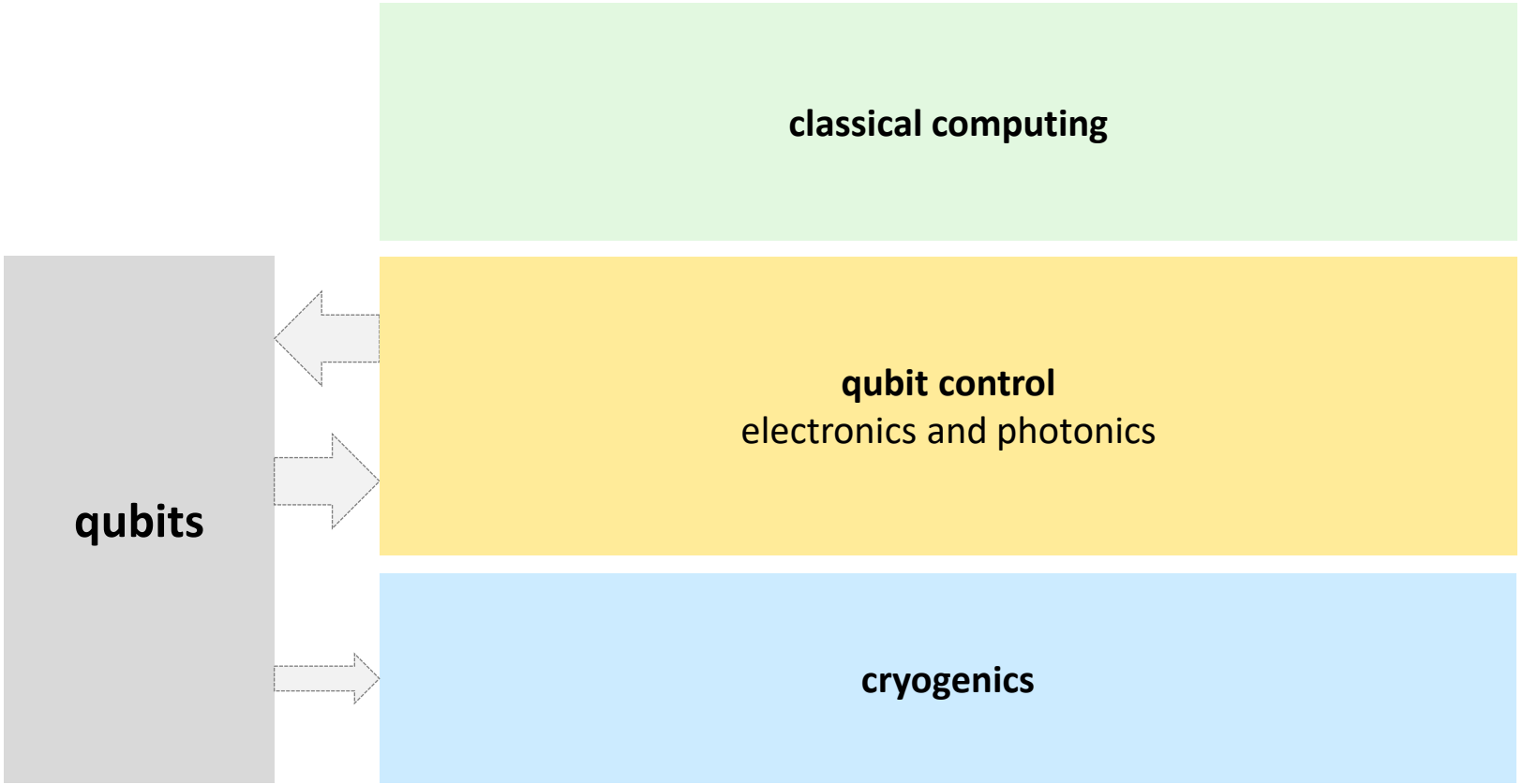
- build a **new** science and engineering field.
- create full-stack methodologies and standards to **evaluate**, **optimize**, and **benchmark** quantum technologies energy consumption.
- favor integrative **full-stack approaches**.

how

- QEI scientific board (10).
- QEI community (545 participants from 67 countries) *.
- QEI workshops (2023 in Singapore, 2025 in Grenoble, 2026 in Barcelona, 2027 in Lisbon).
- QEI IEEE standards Workgroup.
- ≈30 industry partners including IBM, Quandela, etc.

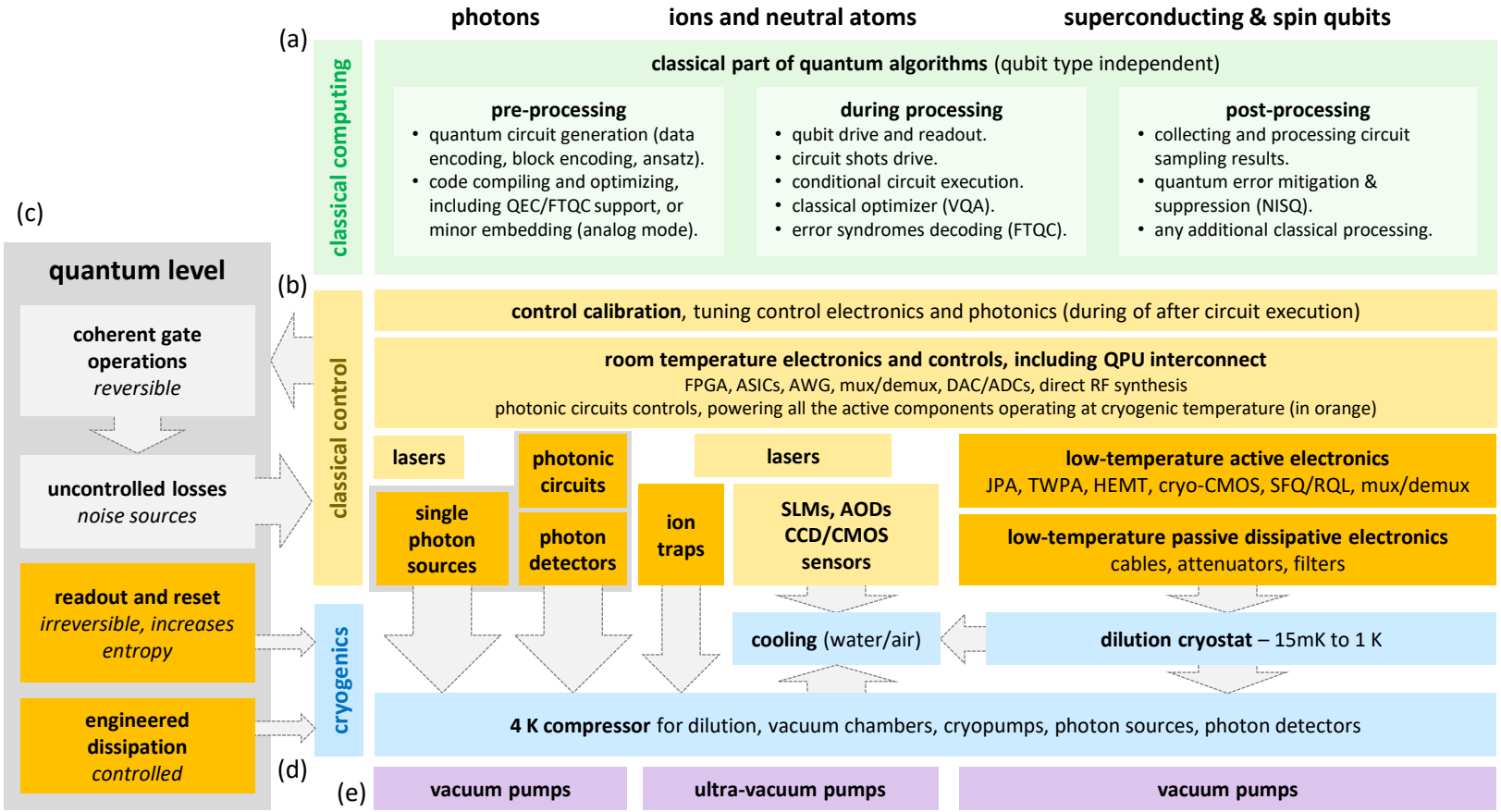
* : as of September 28th, 2026

energy consumption sources



source: Olivier Ezratty, October 2026

quantum ↔ macroscopic costs



source: Understanding Quantum Technologies 2026, Olivier Ezratty, September 2026

quantum energetics scientific fields

quantum technologies energetics

full-stack approaches to model, optimize, and benchmark the energy resources required to implement useful quantum technologies, under specified performance constraints.

macroscopic scale	classical computing software engineering quantum information science all classical enabling technologies classical thermodynamics
quantum scale	quantum electrodynamics, semiconductor spin physics, quantum optics. open quantum system theory, quantum control theory, noise modelling. materials science and semiconductor manufacturing. fundamental quantum energetics. quantum thermodynamics.

counter intuitive insights



cryogenics

- all qubit types rely on cryogenics.
- it's usually a variable cost vs physical qubit #.
- cryogenics may not be the dominant energetic cost for some qubit modalities.

science vs engineering

- still room for progress at the fundamental level.
- enabling technologies key role.
- many interdependencies and potential counterintuitive optimizations.



electronics and photonics

- control electronics and photonics may become the dominant energetic cost in solid state platforms.

classical computing

- classical energetic costs must be considered before, during and after a quantum circuit run.
- compilation is a variable cost vs the problem data.



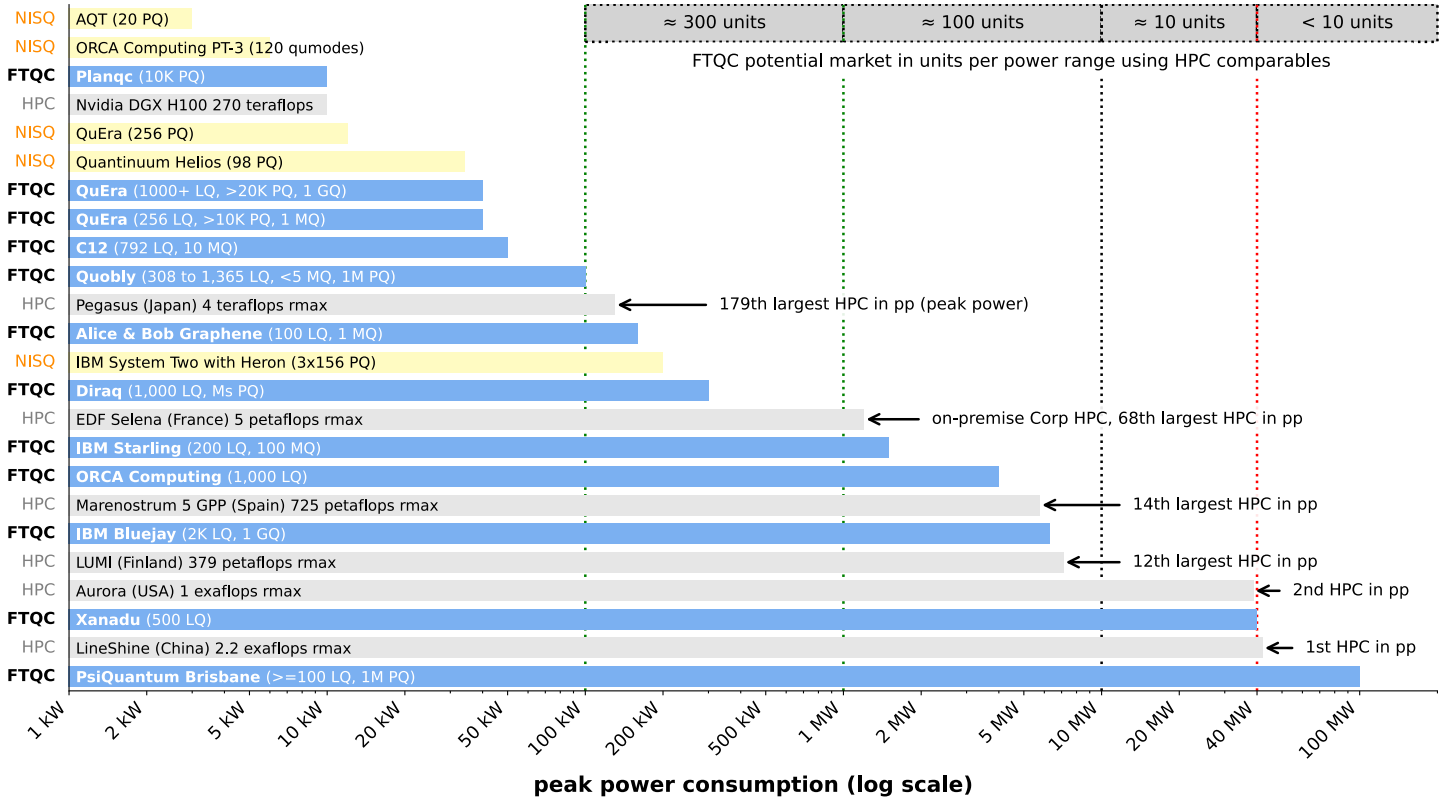
error correction

- error syndrome detection may dominate energetic costs for some qubit modalities.

economics

- energy could represent >30% of an FTQC TCO.
- energy = power (infra) × time (user constraints).
- power is a proxy for all environmental footprint.

NISQ-FTQC-HPC power comparables



estimate base power for various FTQCs and actual for existing largest HPCs WW and NISQ QCs. HPC source: TOP 500 and Nvidia. FTQC sources: vendor data or data reconciliation.
PQ: physical qubits
LQ: logical qubits.
MQ: megaquop (logical operations).
TQ: teraquop.

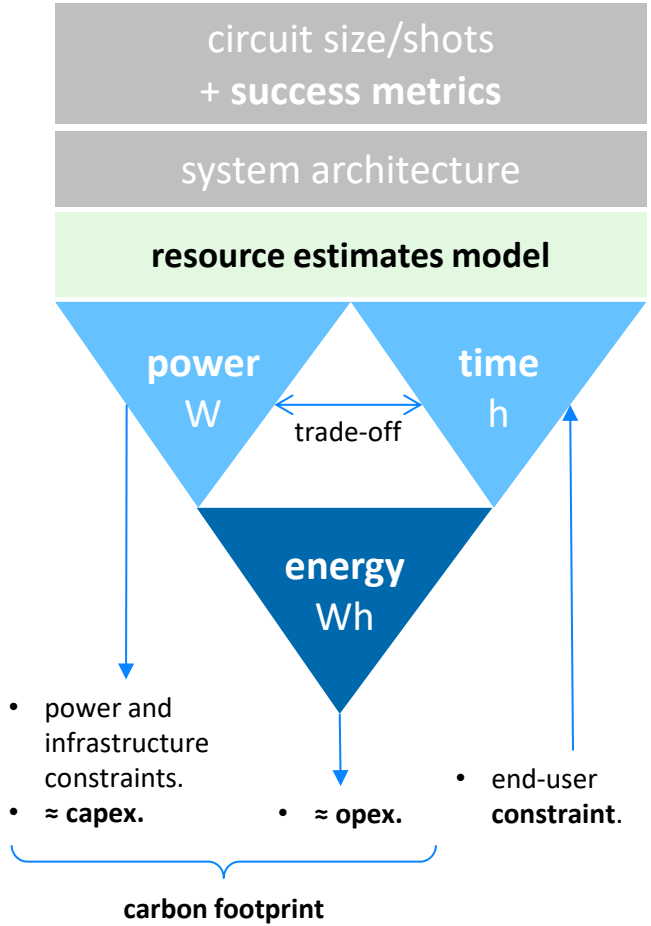
these are based on multiple unverifiable and usually optimistic assumptions (physical error rates, error models, …).

power comparable warnings

1. **vendor numbers give some indication of the potential power/energy needs for future FTQC systems.**
2. **the distribution and comparison with HPC systems gives an indirect indication of a potential market size.**
3. **numbers are based on multiple optimistic assumptions:**
   - circuit sizes and optimistic physical error rates: 99.9% for all operations.
   - incomplete error models: leakage, losses, correlated errors at scale, variability.
   - not accounting for the overhead of quantum interconnect.
   - quantum algorithm success metrics (accuracy, …).
   - enabling technologies efficiencies: cryogenics, electronics, photon losses, QEC.
4. **they do not account for the speed difference between systems.**
   - these differences play a key role when comparing the energy consumption and computing times for specific quantum computing workloads.

why look at both energy and power?

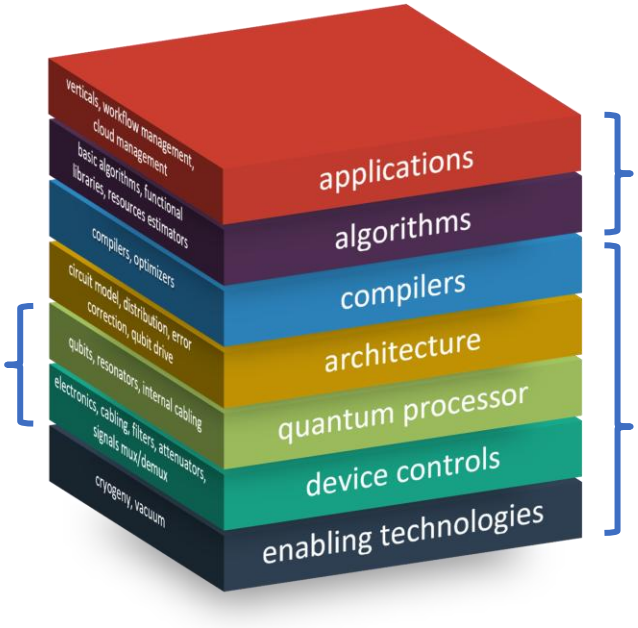
1. **broad range of expected power consumption**
   - 1 to 1000 range under usual optimistic assumptions.
   - maximum = 2,5 the largest exaflops HPCs and 10% of an average nuclear reactor (1 GW).
2. **power consumption**: indication of feasibility.
3. **energy consumption**: potential platform Darwinism through energy-efficiency, « survival of the fittest »?
4. **global environmental footprint**: will depend on # of practical use cases.



QECQ project

quantum computing energy efficiency optimization
2024-2028 project funded by Bpifrance i-demo

- theoretical models.
- fundamental bounds.
- optimization model (PRX Quantum 2023).



- define practical industry relevant use cases (materials, PDEs).
- HPC energy consumption comparable references.

- FTQC systems full-stack architecture.
- resource estimations.
- energy footprint optimization.

- sharing best practices with the QEI community.
- extending models to other qubit modalities.

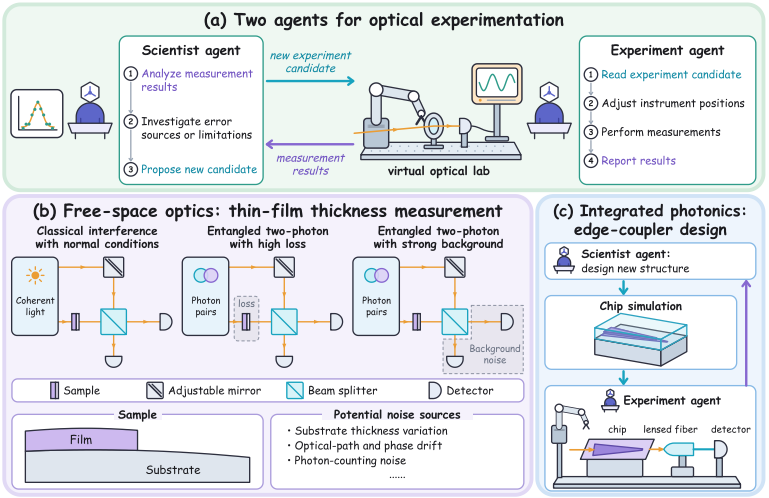
quantum computing ecosystems



the LLM-based research revolution

QuOptLab: Advancing Quantum Optics Experiments with an AI Agent

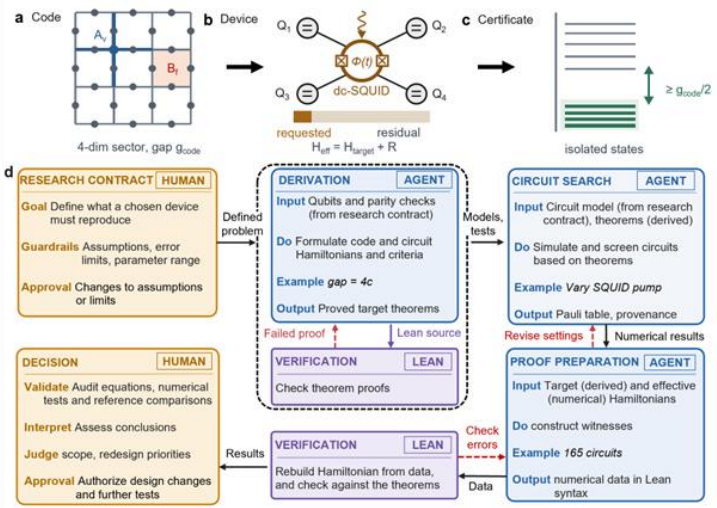
Yuqing Li,* Zeguan Wu,† Yu Gan,‡ Min Chen,§ and Junyu Liu¶
University of Pittsburgh



https://arxiv.org/abs/2611.32000

Agentic Pipelines for Mapping Topological Codes to Quantum Hardware

Arpit Arora,[1] Adam Holmes,[1] Krysta M. Svore,[1] and Taylor L. Patti[1]
[1]*NVIDIA, Santa Clara, California 95051, USA*
(Dated: September 1, 2026)



https://arxiv.org/abs/2611.03329

AI Scientist Discovered Robust Quantum Control

Jiahao Yan,[1,*] Xuanying Lai,[1,*] Xiaoshui Lin,[1,*] Yizhou Wang[1], Changyu Yao[1], Guanghui He[1], Thomas Lewer[1], Chong Zu[1,2,†] Chuanwei Zhang,[1,2,†]

[1]Department of Physics, Washington University, St. Louis, MO 63130, USA
[2]Center for Quantum Leaps, Washington University, St. Louis, MO 63130, USA
[*]These authors contribute equally to this work
[†]To whom correspondence should be addressed; E-mail: zu@wustl.edu, chuanwei.zhang@wustl.edu
(Dated: November 18, 2026)

https://arxiv.org/abs/2611.21765

Agentic Pipelines for Mapping Topological Codes to Quantum Hardware

Arpit Arora,[1] Adam Holmes,[1] Krysta M. Svore,[1] and Taylor L. Patti[1]

[1]*NVIDIA, Santa Clara, California 95051, USA*
(Dated: September 1, 2026)

https://arxiv.org/abs/2611.02833

Agentic AI for Discovering Fault-Tolerant Quantum Circuits

Aritra Lahiri[1,*] and Florian Marquardt[1,2,†]

[1]*Max Planck Institute for the Science of Light, 91058 Erlangen, Germany*
[2]*Department of Physics, Friedrich-Alexander University Erlangen-Nürnberg, 91058 Erlangen, Germany*
(Dated: November 16, 2026)

https://arxiv.org/abs/2611.18504

Discovering state-of-the-art quantum circuits with large language models

Andi Gu,[1,2,3,*] Alek H. Kemeny,[4] Susanne F. Yelin,[1,2] and Mikhail D. Lukin[1,2,5]

[1]*Harvard Quantum Initiative for Science and Engineering, Cambridge, MA 02138, USA*
[2]*Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[3]*Anthropic STEM Fellows Program*
[4]*Anthropic*
[5]*QuEra Computing, 1380 Soldiers Field Road, Boston, MA 02135, USA*

https://arxiv.org/abs/2610.22367

Discovering formally verified quantum programs with AI

Sergey Shirobokov[1,*,†], Ben Jaderberg[1,*,†], Katerina Hristova[‡,*], George Tsoukalas[1,*], Johannes Bausch[1,*], Eric Wieser[1], Francisco J.H. Heras[1], Nicholas C. Rubin[2], Guang Hao Low[2], Sébastien Racanière[1], Nenad Tomašev[1], Lei M. Zhang[1], James D. Watson[2], Tanuj Khattar[2], Aws Albarghouthi[‡], Stavan Jain[‡], Harun Khan[1], Leopoldo Sarra[1], Andrew W. Senior[1], Michael Broughton[2], Hussain Masoom[1], Sergio Boixo[2], Ryan Babbush[2], Swarat Chaudhuri[1], and Pushmeet Kohli[1]

[1]Google DeepMind [2]Google Quantum AI

https://arxiv.org/abs/2611.09822

Reducing RSA-2048 Factoring Resources Below One Billion Toffolis via LLM-Driven Verifiable Quantum Compilation

Xiaodi Li,[1,4,*] Yuqing Wang,[1,2,4,*] Xue Chen,[3,4] Yang-Yang Tang,[3,4] Linghui Chen,[1,4,†] and Tao Zhang[1,3,4,‡]

[1]*Intelligent Quantum Inception Co., Ltd., Haidian, Beijing 100085, China*
[2]*Department of Physics and State Key Laboratory of Low Dimensional Quantum Physics, Tsinghua University, Beijing 100084, China*
[3]*Chen-Ning Yang Institute for Advanced Study, Tsinghua University, Beijing 100084, China*
[4]*Beijing Key Laboratory of Cold Atom Quantum Computation, Tsinghua University, Beijing 100084, China*
(Dated: November 22, 2026)

https://arxiv.org/abs/2611.31158

LLM-assisted discoveries: challenges and cryptographic risks in 2026

Stronger classical competition, limits to quantum advantage and threats to cryptography

Raises barriers to quantum advantage | Cryptographic risk | Mixed QC / crypto impact

Date (2026)	LLM / research system	Scientific discovery	Potential impact and caveat
Feb–Mar	GPT-5.2 / internal OpenAI	Single-minus gluon and graviton amplitudes	Analytical simplification of scattering calculations; indirect classical competition.
Jul 28	Claude Mythos Preview	HAWK post-quantum signatures	Improved attack on a PQC candidate; does not generalize to all lattice schemes.
Jul 28	Claude Mythos Preview	Reduced-round AES	200–800× attack improvement on 7 of 10 rounds; full AES not broken.
Sep 24	OpenAI internal model	2D entanglement area law	Supports compact representations of gapped ground states; not efficient contraction.
Sep 24	OpenAI internal model	Polynomial PEPS approximation	Strengthens classical tensor-network baseline for gapped ground states.
Sep 24	OpenAI internal model	Continuum Coulomb QMA-hardness	Ground-state energy can be hard even for quantum computers; state preparation matters.
Sep 25	Claude (version unverified)	Nine-loop scattering amplitude	Extends classical analytical calculations in supersymmetric Yang–Mills theory.
Oct 16	Claude Mythos 5	Reversible elliptic-curve arithmetic	Improved quantum circuits could lower the cost of attacks on ECC.
Oct 26	OpenAI internal model	Exponential Time Hypothesis (ETH)	Claimed subexponential 3-SAT algorithm; could weaken classical complexity baselines.
Nov 06	Anthropic internal model / PSI	Aaronson–Ambainis conjecture	Limits generic quantum query advantages on typical inputs; not a circuit simulation theorem.
Oct–Nov 24	OpenAI internal model / AI-assisted work	Matrix multiplication exponent 2.25	Claimed matching bounds; could improve classical linear algebra and simulation.

Dates: first public disclosures. Discovery titles link to sources. Recent claims may require further independent validation.

LLM-assisted discoveries: opportunities and neutral results in 2026

Advances supporting quantum computing, QEC and FTQC, or with indirect impact

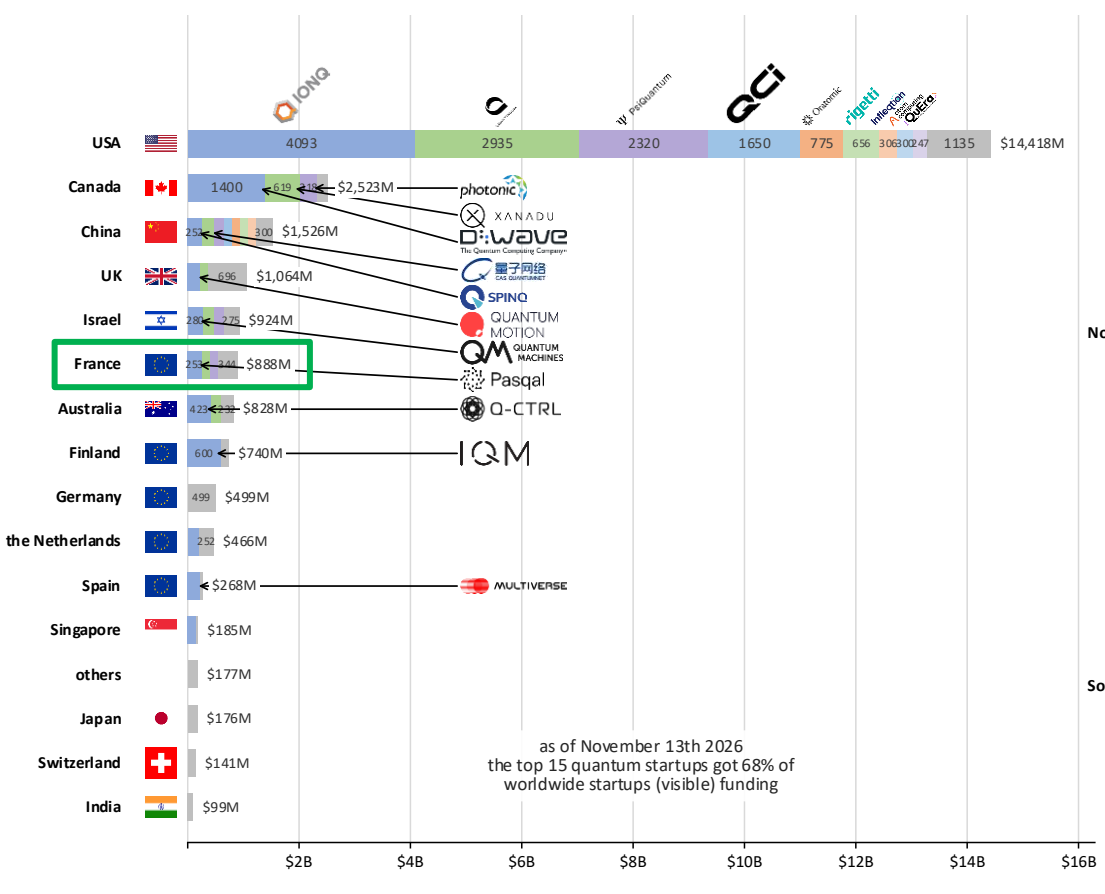
Supports quantum computing Indirect or neutral

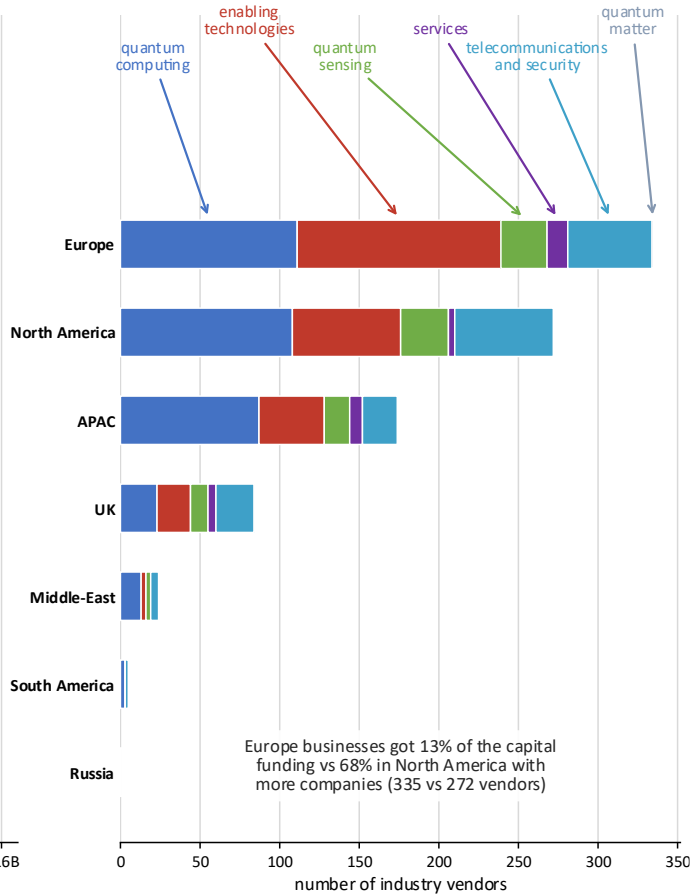
Date (2026)	LLM / research system	Scientific discovery	Potential impact and caveat
Jun 01	Claude Opus 4.6, GPT-5.3-Codex, Gemini 3.1 Pro	Bivariate bicycle QEC codes	LLM-guided search found hundreds of candidate codes; hardware validation remains.
Jun 23	GPT-5.4-mini / nano	Lifted-product qLDPC codes	New high-rate codes; potential reduction in physical-qubit overhead.
Jun 29	Claude Fable 5	QAOA ring conjecture	Exact depth-dependent approximation ratio; no industrial advantage established.
Aug 01	OpenAI internal Astra	Closest vector problem (CVP)	Stronger worst-case hardness bounds; no direct attack on standardized PQC.
Aug 01	OpenAI internal Astra	Binary and spherical code bounds	Tighter theoretical limits; not a constructive QEC code improvement.
Aug 01	OpenAI internal Astra	Parallel repetition of entangled games	Stronger soundness bounds for quantum verification and nonlocal games.
Oct 16	Claude Mythos 5	DQI reversible decoder	Reported ~12× gate reduction in a decoding primitive; not end-to-end speedup.
Oct 16	Claude Mythos 5	Quantum chemistry circuit primitives	Exploits molecular structure to reduce reversible computation costs.
Oct 26	OpenAI internal model	4D Yang–Mills existence	Mathematical existence result; mass gap unresolved.
Nov 20	Claude (version unverified)	Riemann hypothesis / GRH	Reported proof; no efficient factoring algorithm follows.
Nov 23–24	Anthropic / OpenAI internal models	VP versus VNP separation	Claimed permanent lower bounds support exact sampling complexity arguments.

Dates: first public disclosures. Discovery titles link to sources. Recent claims may require further independent validation.



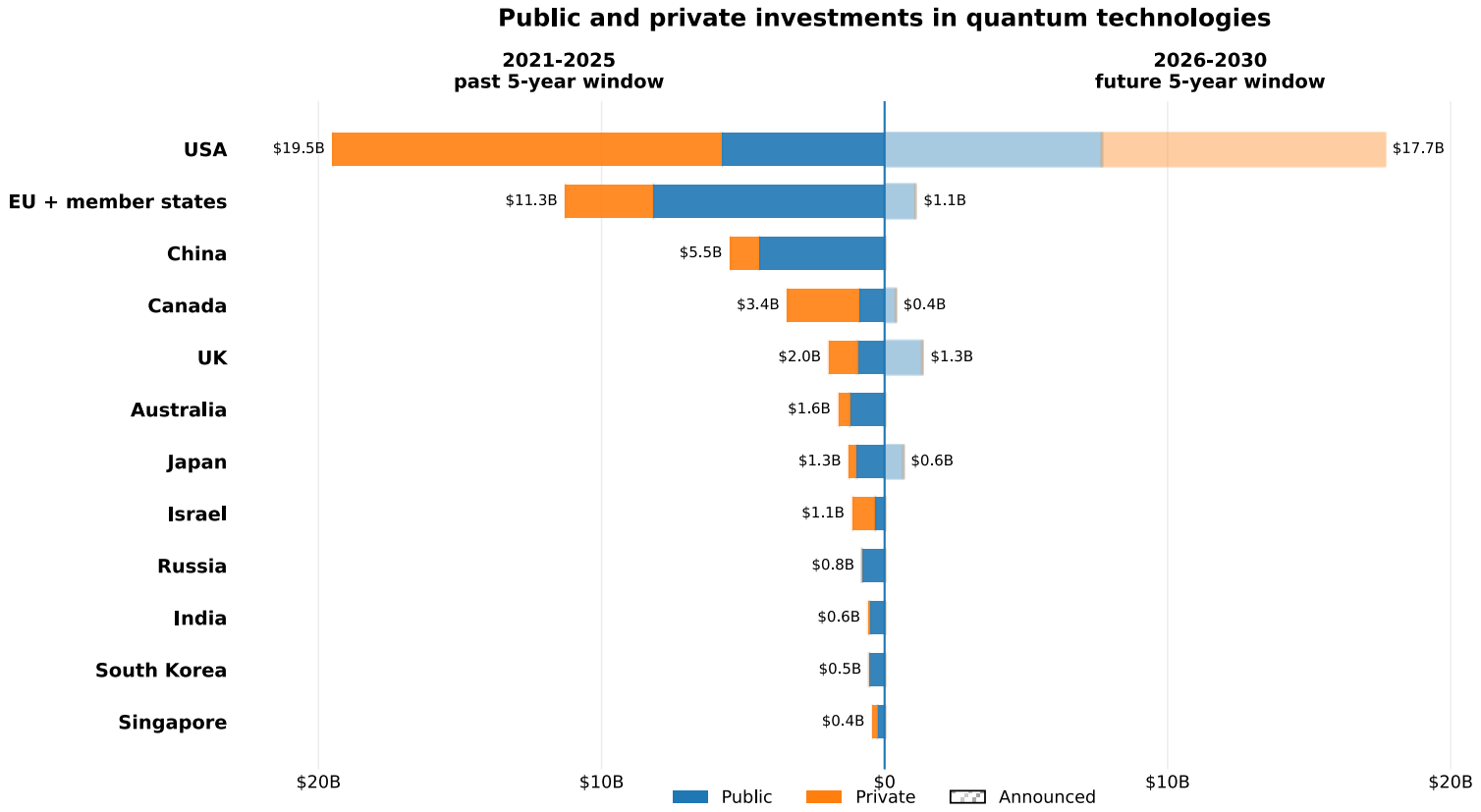
https://x.com/plusnineonzero/status/2125653450855969127





(cc) Olivier Ezratty, 2026

the « true » global investments



(cc) Olivier Ezratty, 2026

industry vendors ecosystem



computing

QUANDELA

ALICE & BOB

quobly

Pasqal

C12

Qluster

CRYSTAL QUANTUM COMPUTING

Qolumbus

software

Qubit PHARMACEUTICALS

Bull

mol|ket

ColibriTD

QPerfect

VeriQloud

QbitSoft Quantum as a Service

QUANTUM SIGNALS

cybersecurity

CryptoNext security

CRYPTO EXPERTS

ravel

WISeKey

CYFERALL

QuRISK ADVISORY

sensing

THALES

exail

kwan-tek

chipiron

MAG 4He alth

SAFRAN

photonics

cailabs

Lytid

exail

SPARK LASERS

LUMIBIRD

AUREA TECHNOLOGY

teem PHOTONICS

SCINTIL PHOTONICS

GLOphotonics

QUANDELA

cryogeny

Air Liquide

INNOVATIVE SOLUTIONS ABSOLUT SYSTEM

electronics

SILENT WAVES

Vigthor

Welinq

Radiall

MECA MAGNETIC magnetic shielding

ATEM

SILENTSYS ultralow noise systems

manufacturing

PLASSYS

RIBER

SERMA TECHNOLOGIES

materials

orano

PIONIQ

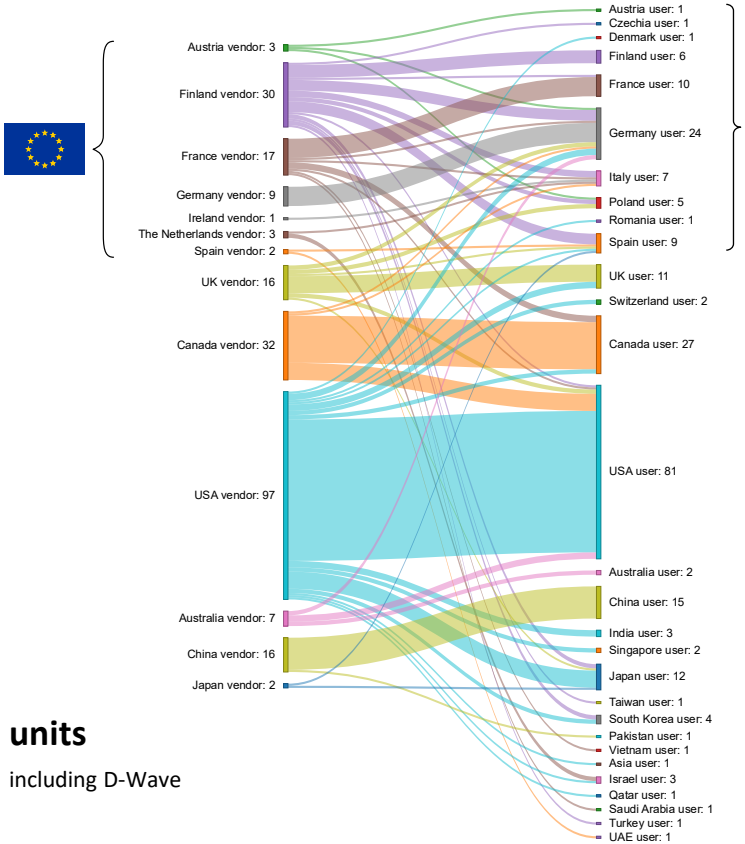
DIAMFAB

HIQUTE DIAMOND

(cc) Olivier Ezratty, 2026

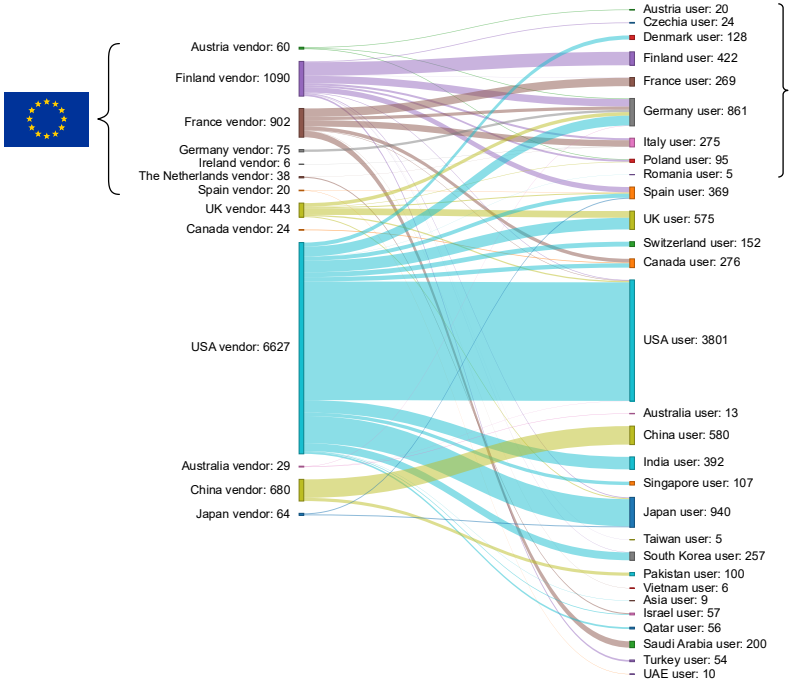
who sells to whom?

China numbers are probably underestimated.



units

including D-Wave



qubits

excluding D-Wave

(cc) Olivier Ezratty, November 2026

discussion



slides