how to analyze quantum computing use cases

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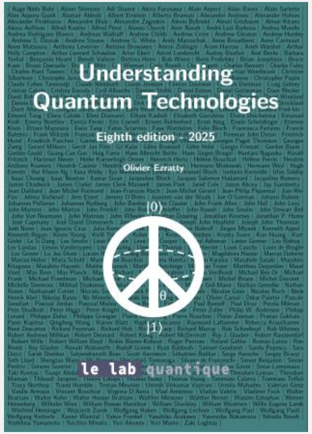
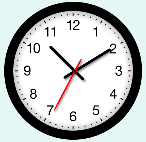
Q2B 2025, Santa Clara, December 11th, 2025



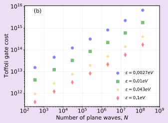
potential quantum computing benefits



- **computing faster than classical systems.**

or

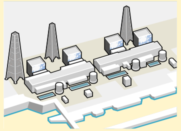
- **solving problems inaccessible to classical computers.**



- **improving results quality**: chemical accuracy, better heuristics, etc.

today's talk

- **reducing required training data**, particularly for machine learning tasks.



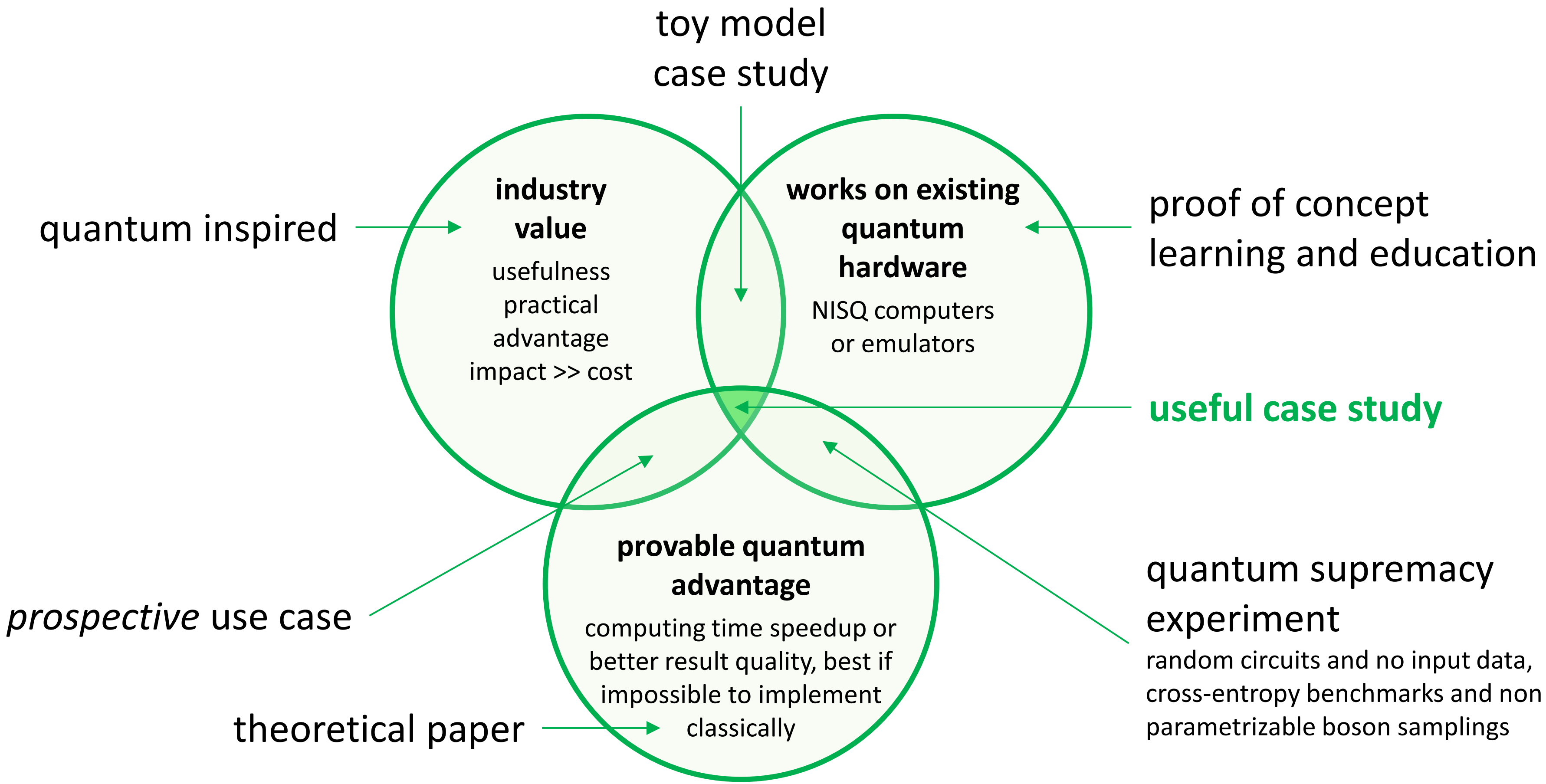
- **energetic advantage** (NISQ).

or

- **energetic acceptability** (FTQC).

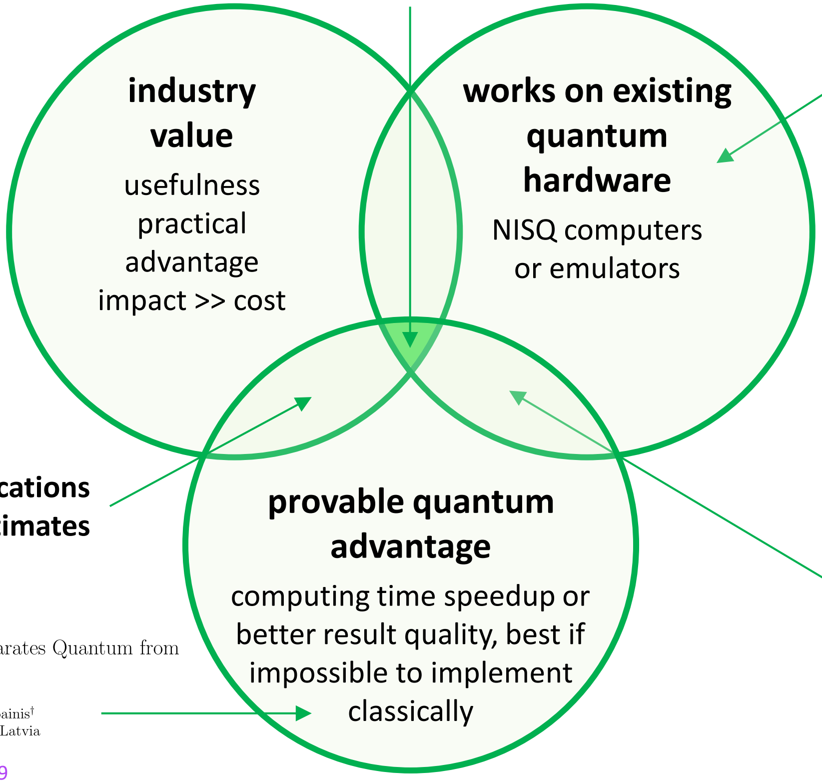
Tuesday's past talk

- **usefulness**: which depends on the stakeholder (fundamental research, governments, industry).



inspired by https://www.linkedin.com/posts/activity-7390023359759298561-Nl6O/

some D-Wave and
Kipu Quantum
use cases



FTQC applications resource estimates

Forrelation: A Problem that Optimally Separates Quantum from Classical Computing

Scott Aaronson* — MIT
Andris Ambainis† — University of Latvia

arxiv.org/abs/1411.5729

Google

arXiv > quant-ph > arXiv:2510.19550

Quantum Physics

[Submitted on 22 Oct 2025]

Quantum computation of molecular geometry via many-body nuclear spin echoes

9 and 15 qubits

arxiv.org/abs/2510.19550

Article

Observation of constructive interference at the edge of quantum ergodicity

https://doi.org/10.1038/s41586-025-09526-6
Received: 3 November 2024
Accepted: 13 August 2025
Published online: 22 October 2025
Open access
Check for updates

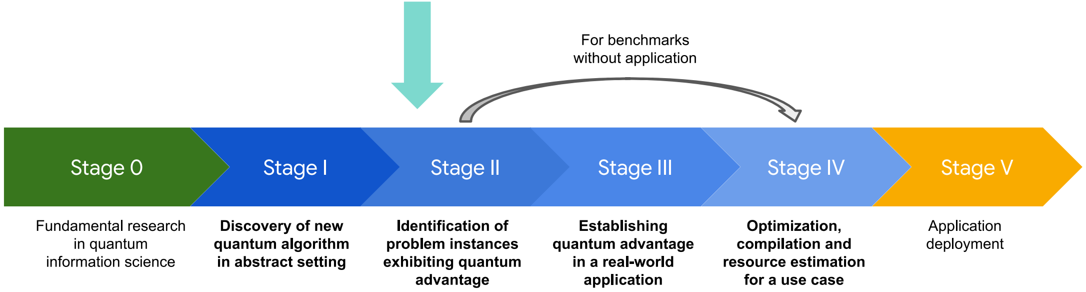
Google Quantum AI and Collaborators*

The dynamics of quantum many-body systems is characterized by quantum observables that are reconstructed from correlation functions at separate points in space and time[1–3]. In dynamics with fast entanglement generation, however, quantum observables generally become insensitive to the details of the underlying dynamics at long times due to the effects of scrambling. To circumvent this limitation and enable access to relevant dynamics in experimental systems, repeated time-reversal protocols have been successfully implemented[4]. Here we experimentally measure the second-order out-of-time-order correlators ($OTOC^{(2)}$)[5–18] on a superconducting quantum processor and find that they remain sensitive to the underlying dynamics at long timescales. Furthermore, $OTOC^{(2)}$ manifests quantum correlations in a highly entangled quantum many-body system that are inaccessible without time-reversal techniques. This is demonstrated through an experimental protocol that randomizes the phases of Pauli strings in the Heisenberg picture by inserting Pauli operators during quantum evolution. The measured values of $OTOC^{(2)}$ are substantially changed by the protocol, thereby revealing constructive interference between Pauli strings that form large loops in the configuration space. The observed interference mechanism also endows $OTOC^{(2)}$ with high degrees of classical simulation complexity. These results, combined with the capability of $OTOC^{(2)}$ in unravelling useful details of quantum dynamics, as shown through an example of Hamiltonian learning, indicate a viable path to practical quantum advantage.

65 qubits, random circuit

www.nature.com/articles/s41586-025-09526-6

QuEra September 2025 https://www.quera.com/3stages	Google November 2025 arxiv.org/abs/2511.09124	Preskill et al August 2025 arxiv.org/abs/2508.05720	IBM and Pasqal June 2025 arxiv.org/abs/2506.20658
advantage: speed, quality, cheaper	finding hard instances and ensembles	predictability	quantum separation
production grade ↔	**real-world applications** ↔	**genericity**	QC performance
QEC and FTQC toolbox ↔	FTQC focused	robustness	QEM / QED / QEC
stable qubits	verifiability ↔	verifiability ↔	validation
accurate operations	5-step journey	**usefulness**	



benefit
mean
operations

assessing QC use case and case studies

criteria	possible values					
problem sizing	small scale case study	indication of real-life use case sizing	case study with real-life size business needs			
resource estimates	no	qubit # and fidelities related to a real-life business need	classical resources	computing time estimates		
quantum advantages	tested with <30 qubits	speedup	result quality	data needs	energetic footprint	TCO ROI
benchmarking	no comparison	honest comparison with best-in-class classical algorithms and hardware, incl. quantum inspired and/or legacy systems				
newness	nothing new	something new in the case study vs state of the art which turns other flags in green				
computing paradigm	quantum inspired	present analog	future analog	present NISQ	future NISQ	FTQC
documentation	press release, vendor or analyst web site	review paper	arXiv preprint	peer reviewed journal paper		

quantum machine learning

nature > npj digital medicine > articles > article

Article | Open access | Published: 02 May 2025

A systematic review of quantum machine learning for digital health

Riddhi S. Gupta, Carolyn E. Wood, Teyl Engstrom, Jason D. Pole & Sally Shrapnel

QML evaluation criteria:

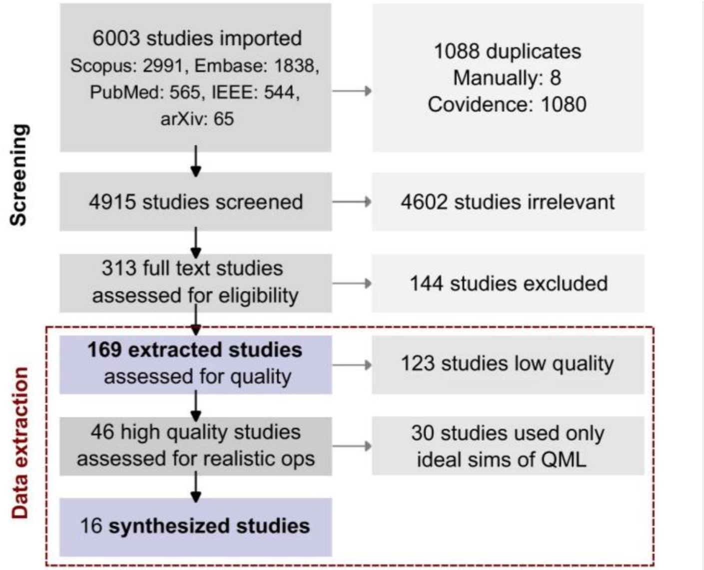
- explains quantum algorithm selection by referencing learning problem class or dataset structure.
- identifies/discusses **impact of data encoding** on quantum algorithm performance.
- identifies/discusses **impact of classical input data processing** on quantum algorithm performance.
- (EMPIRICAL ONLY) **dimensionality of data input** for quantum algorithm.

https://www.nature.com/articles/s41746-025-01597-z

QML advantage conditions:

- training data is quantum (quantum circuit/state, quantum sensor).
- or futuristic qRAM.

https://arxiv.org/abs/2511.15969



Exclusion reasons		
Wrong intervention	Quantum inspired / not quantum algorithm	61
	Quantum sensing	3
Wrong setting	Data not EHR-adjacent	42
	Study not digital health related	18
Wrong study characteristics	Non-reputable publisher / not found	14
	Wrong publication type (e.g. review, opinion)	4
	Outside search period	2

recent quantum advantages

who and when	architecture	algorithm	input data	Comment
D-Wave, March 2025	D-Wave Advantage-2 annealer, 4,400 qubits	quench dynamics of 1, 2 and 3D infinite-dimensional spin glasses	problem Hamiltonian	not yet beaten by quantum inspired techniques
China, August 2025	Jiuzhang 4.0	Gaussian boson sampling.	None	random interferometer
Google, September 2025	Sycamore 68-qubits	generative quantum model	bitstream generation, learning to generate compressed simulation circuits, learning to generate quantum states	very theoretical constructs, practical use cases not demonstrated
Google Echoes, October 2025	Willow 103-qubits used with 65 qubits	Measuring Out-of-Time-Order Correlators (OTOC).	random circuit	some observables, but no practical utility
BlueQubit random peaked circuits, October 2025	Quantinuum H2 56-qubit QPU.	random peaked circuits.	None	circuits are easier to classically verify.
PhaseCraft, October 2025.	Quantinuum H2 56-qubit QPU.	time-dynamics of a 2D Fermi-Hubbard fermionic many-body systems	problem Hamiltonian	computing some ground state.

Google

Article

Visualizing dynamics of charges and strings in (2+1)D lattice gauge theories

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Check for updates

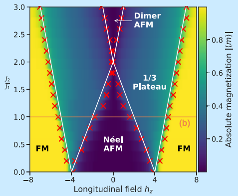
Lattice gauge theories (LGTs)[1–4] can be used to understand a wide range of phenomena, from elementary particle scattering in high-energy physics to effective descriptions of many-body interactions in materials[5–7]. Studying dynamical properties of emergent phases can be challenging, as it requires solving many-body problems that are generally beyond perturbative limits[8–10]. Here we investigate the dynamics of local excitations in a $\mathbb{Z}_2$ LGT using a two-dimensional lattice of superconducting qubits. We first construct a simple variational circuit that prepares low-energy states that have a large overlap with the ground state; then we create charge excitations with local gates and simulate their quantum dynamics by means of a discretized time evolution. As the electric field coupling constant is increased, our measurements show signatures of transitioning from deconfined to confined dynamics. For confined excitations, the electric field induces a tension in the string connecting them. Our method allows us to experimentally image string dynamics in a (2+1)D LGT, from which we uncover two distinct regimes inside the confining phase: for weak confinement, the string fluctuates strongly in the transverse direction, whereas for strong confinement, transverse fluctuations are effectively frozen[11,12]. We also demonstrate a resonance condition at which dynamical string breaking is facilitated. Our LGT implementation on a quantum processor presents a new set of techniques for investigating emergent excitations and string dynamics.

https://www.nature.com/articles/s41586-025-08999-9

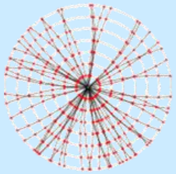
from science to industry applications

most NISQ existing identified advantages

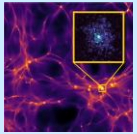
fundamental research



condensed matter physics

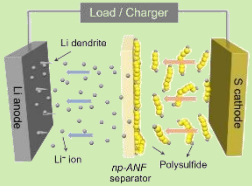


high-energy particle physics

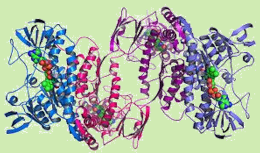


astrophysics

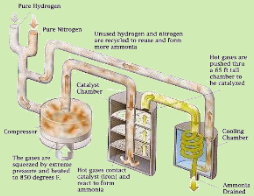
applied research



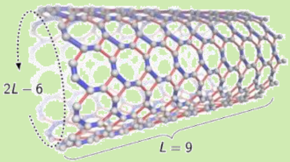
batteries



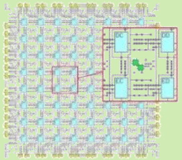
drugs



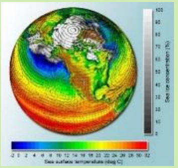
fertilizer production



material design

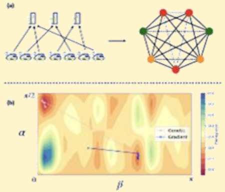


semiconductors

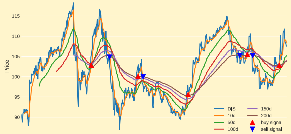


climate modeling

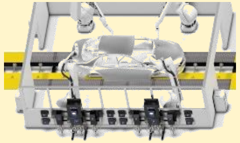
business operations



energy utilities

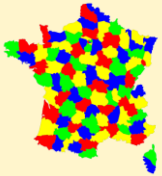


financial services



manufacturing

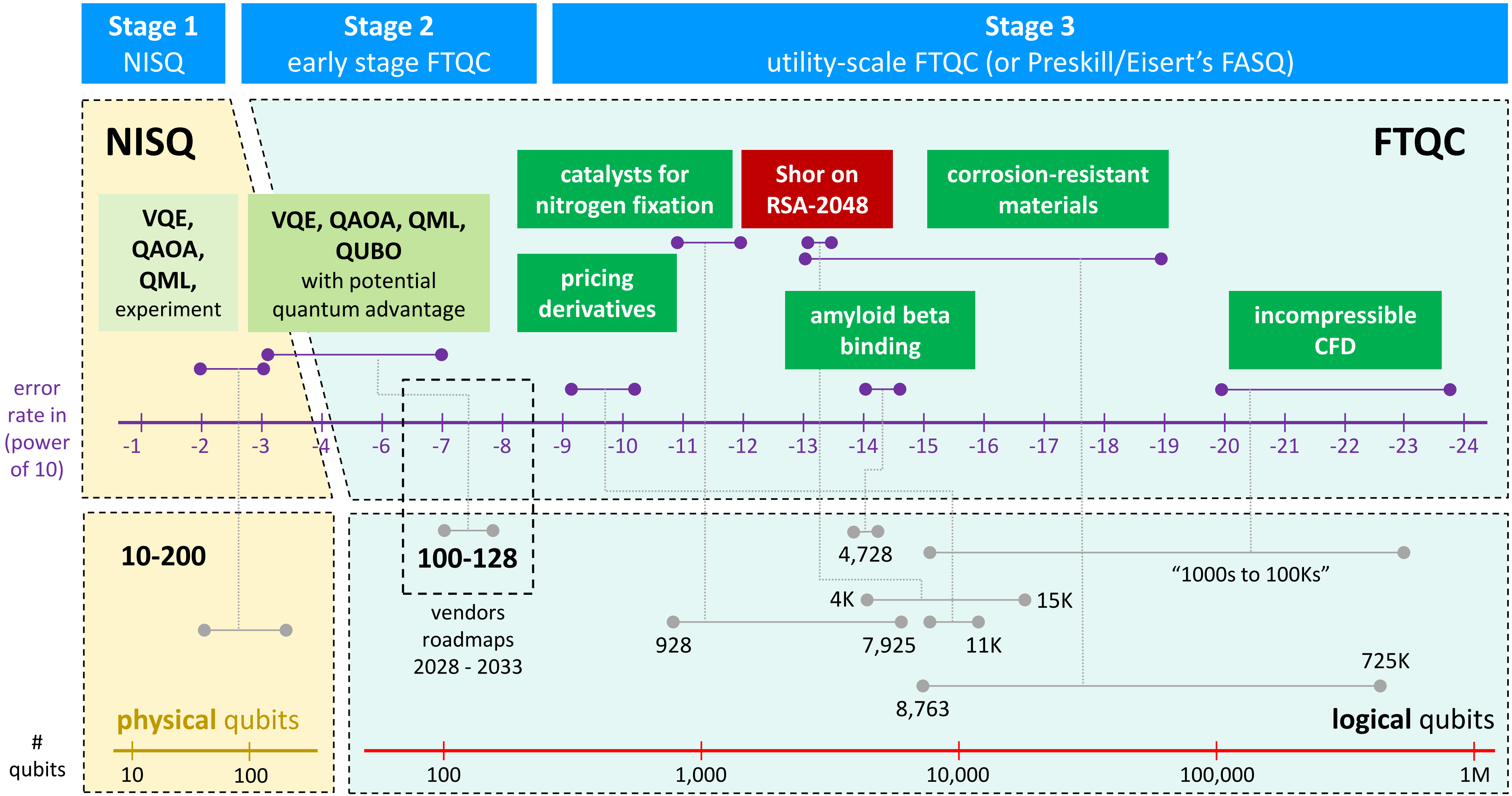
transportation



telecoms

logistics and retail

expected trend



Stage 1
NISQ
Stage 2
early stage FTQC
Stage 3
utility-scale FTQC (or Preskill/Eisert's FASQ)
NISQ
FTQC
VQE, QAOA, QML, experiment
VQE, QAOA, QML, QUBO with potential quantum advantage
catalysts for nitrogen fixation
Shor on RSA-2048
corrosion-resistant materials
pricing derivatives
amyloid beta binding
incompressible CFD
error rate in (power of 10)
-1 -2 -3 -4 -6 -7 -8 -9 -10 -11 -12 -13 -14 -15 -16 -17 -18 -19 -20 -21 -22 -23 -24
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
10
100
100
1,000
10,000
100,000
1M

algorithm resources estimates trend

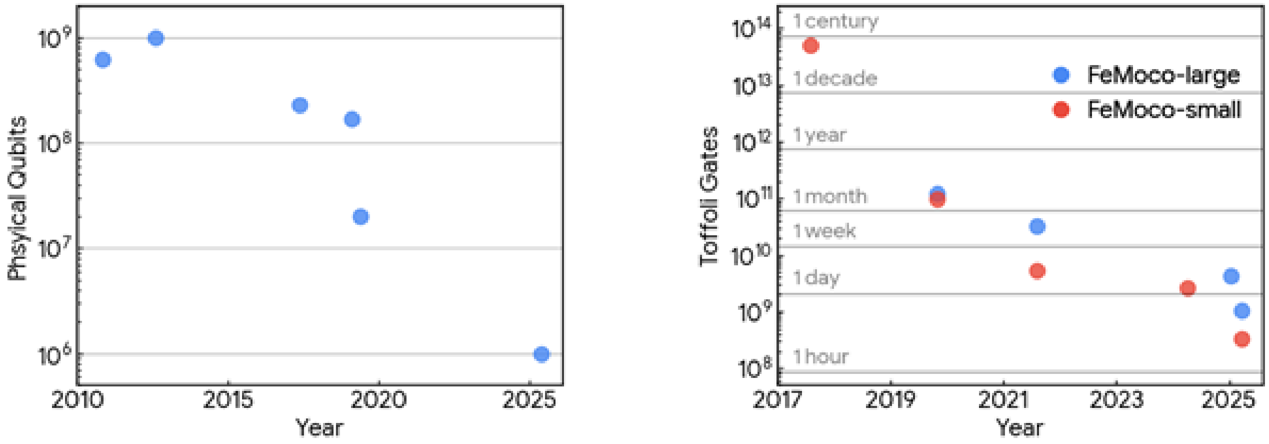


FIG. 2. These figures illustrate that Stage IV research has reduced the resources required to solve important problems by many orders of magnitude over the last decade as function of publication year in both space such as for breaking 2048 bit RSA encryption (left), and time as approximated by the Toffoli count estimating the ground state energy of FeMoco to chemical accuracy for "small" 54-orbital [137] and "large" 76-orbital active spaces [126] (right). The left plot includes Refs. [44, 138–141] and the right plot includes Refs. [41, 43, 137, 142, 143].

The Grand Challenge of Quantum Applications by Ryan Babbush, Robbie King, Sergio Boixo, William Huggins, Tanuj Khattar, Guang Hao Low, Jarrod R. McClean, Thomas O'Brien, and Nicholas C. Rubin, arXiv, November 2025.

		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
superconductors & spins	IBM	156x7 PQ (2025–2028) / 5K	7.5K	10K	15K	200 / 100M				2000 / 1B		
	IQM	150	300	4-36 / 1K	60-180 / 5K		240-720 / 40K	600-1800 / 100K		2400-7200 (2033–2035) / 1M		
	OQC	16 / 1K			200 / 1M			5,000 / 1G			50K / 1T	
	Alice & Bob		4 / 48		5 / 250		100 / 2K / 1M					
	Nord Quantique				100			1000				
	quobly	2-10	64	256	15 / 1K / 100K	25-45 / 4K / 1M	50-100 / 20K / ≈1G	180-360 / 120K / ≈1T	1,400 / 1M / ≈100T			
cold atoms	Pasqal	140	2	20 / 200+		100	200 / 10K					
	QuEra	30 / 3K	100 / >10K									
	Infleqtion	2 / 1.6K	>10 / 8K		>100 / 40K							
tapped ions	Quantinuum	~ 50 / 96		~100 / 192		~100s / 1000s						
	IONQ	64	12 / 256	800 / 10K / 10M	1,600 / 20,000	8,000 / 200K / 1T	80,000 / 2M / 1T					
	Quantum Art	50		100 / 1,000		500 / 12,000		1,000s / 40,000		10,000s / >1M		
photons	PsiQuantum						~100s / 1M					
	Quandela			10 / 50K		50s / 1M						

box color codes

- logical qubits → QEC overhead, circuit depth
- physical qubits → QEC overhead
- gates / QOPS → circuit depth, logical qubits fidelities

key questions

are there quantum computing "case studies" deployed in the industry?

hard to find but D-Wave says it has some (Port of Los Angeles, some retailer in Canada, …).

why building a non-deployed case study?

learning quantum coding, estimating resources to obtain some quantum advantage, create a team, build skills.

what is the interest of a case study running only on a quantum emulator?

emulate logical qubits (<40), debug code easily, adapt code to a specific hardware in the making, learning path.

what is the interest of a FTQC case study that won't run until long?

resource estimates, dialog with hardware vendors, reduce circuit size.

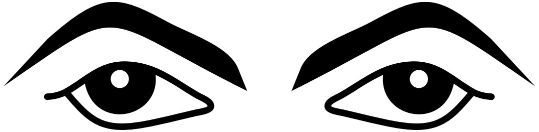
what are the useful information to find in documented "case studies" or "use cases"?

quantitative benefit, resource estimates, cost estimates, clear quantum advantage characterization, honest comparison with best-in-class classical solution, use real-life size problems and data sets.

what to expect in the near future?

advanced NISQ quantum advantages, early-stage FTQC for mid-sized problems, quantum chemistry and material simulations.

some recommendations



1. **quantum advantage figures of merit.**
2. **problem dimensionality and data encoding.**
3. **resource estimates.**
4. **classical computing comparisons.**
5. **solution economics.**

discussion

get the slides now !