IBM Quantum

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Quantum Computational Scientist & Architect

SPGI Quantum Ambassador Lead

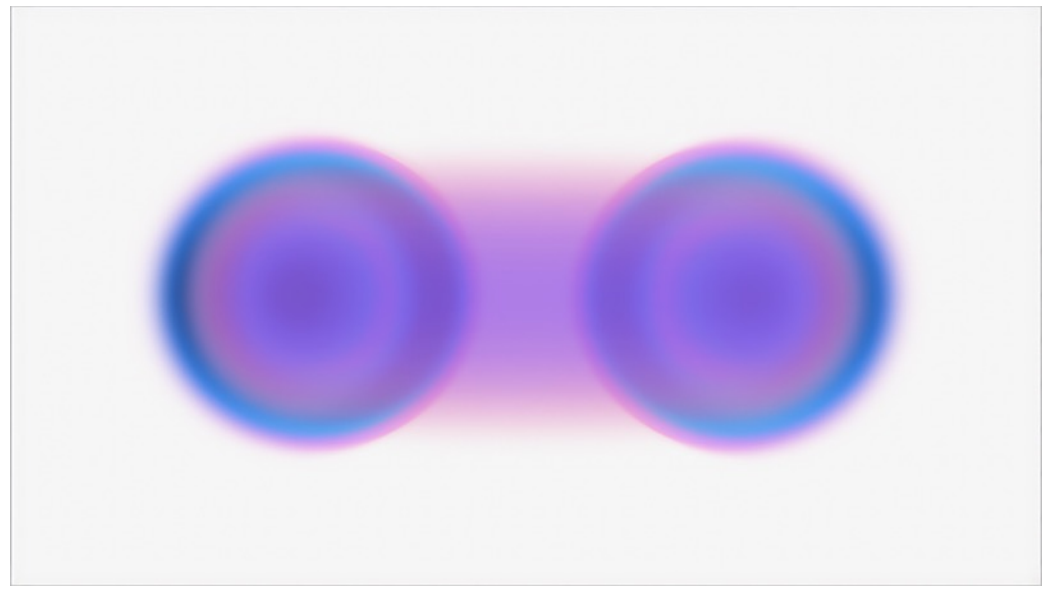
What is quantum computing?

Uniquely quantum

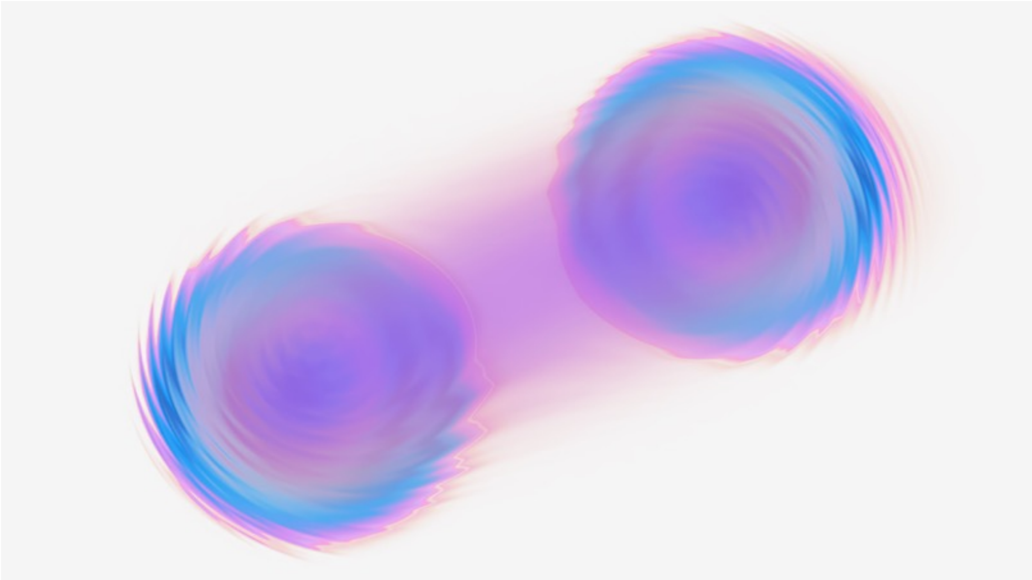
Some problems are classically intractable and will never be solvable with traditional computers

N qubits → 2^N bits
127 qubits → 2^{127} bits = 1.7×10^{38} bits

Superposition
A quantum system existing in multiple states simultaneously until it is measured



Entanglement
Information shared jointly between entangled pairs or groups



Interference
Interaction that affects likelihood of solutions

Moore's law: the number of transistors in a classical integrated circuit doubles about every two years
... but we are approaching the end due to physical limitations

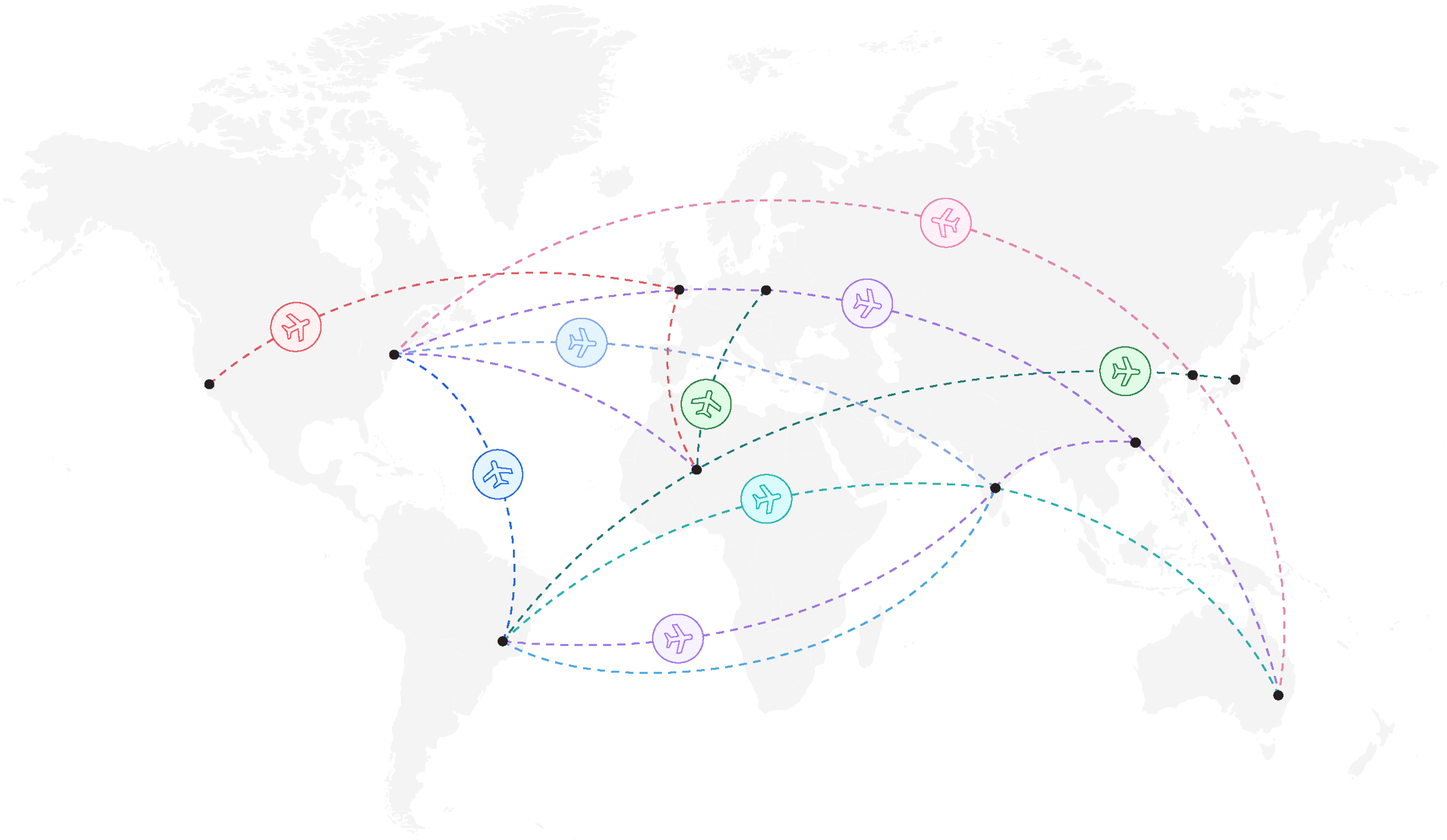
Approaching the physical limit: IBM created the world's first 2 nm node chip in 2021, with transistors as small as 10 silicon atoms

Quantum computing
The new wave of computing

Potential to Unlock previously unsolvable problems with quantum computing, cutting computing time **from years to hours.**

A new paradigm of thinking launches inventors into previously unnavigated discovery territories with **new use cases.**

Accelerate discovery through a **powerful** hybrid quantum-classical approach.

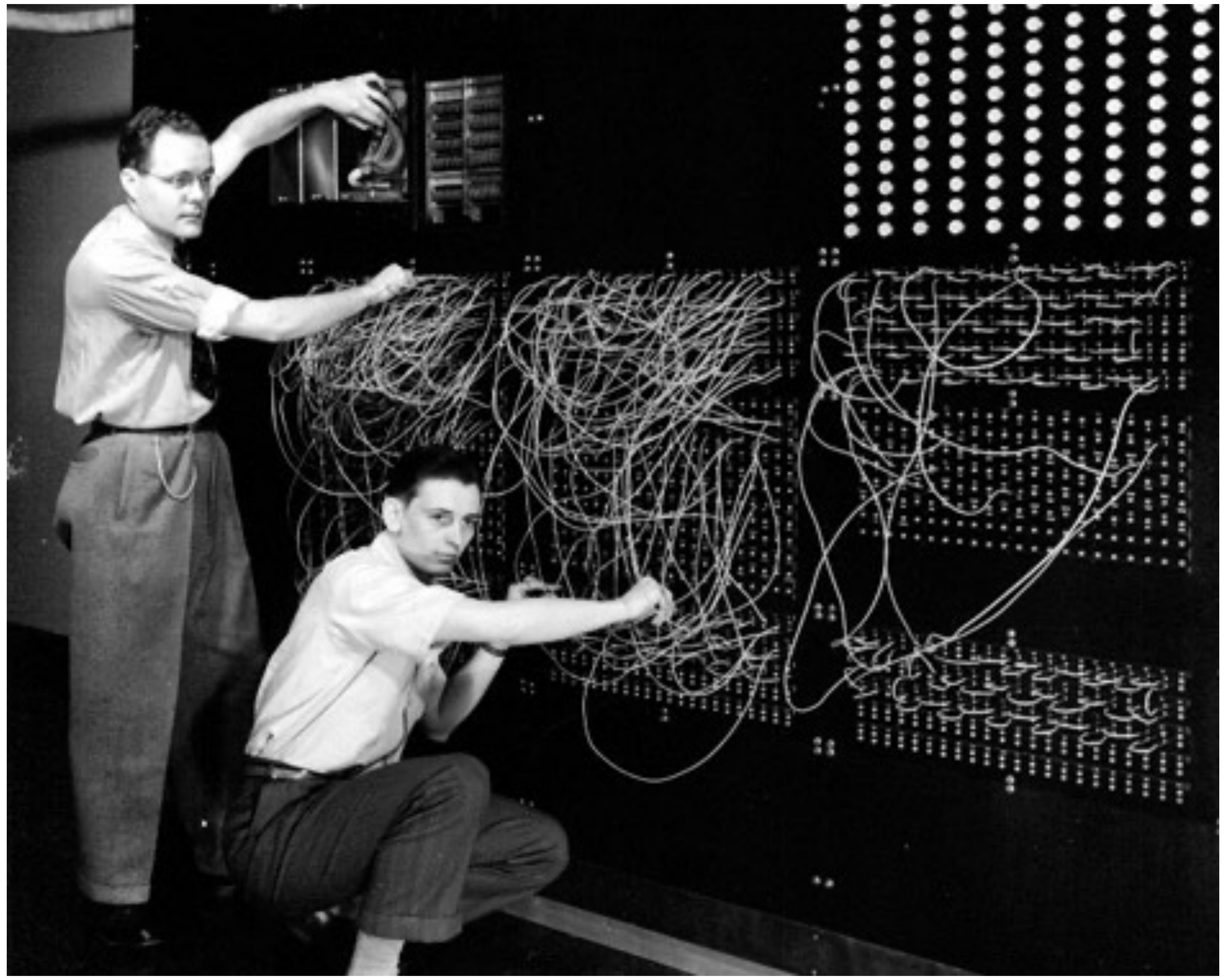


The new wave of computing

Classical computer
Well suited for many problems.

Quantum computer
Unlock classically intractable problems

Classical computers before error correction



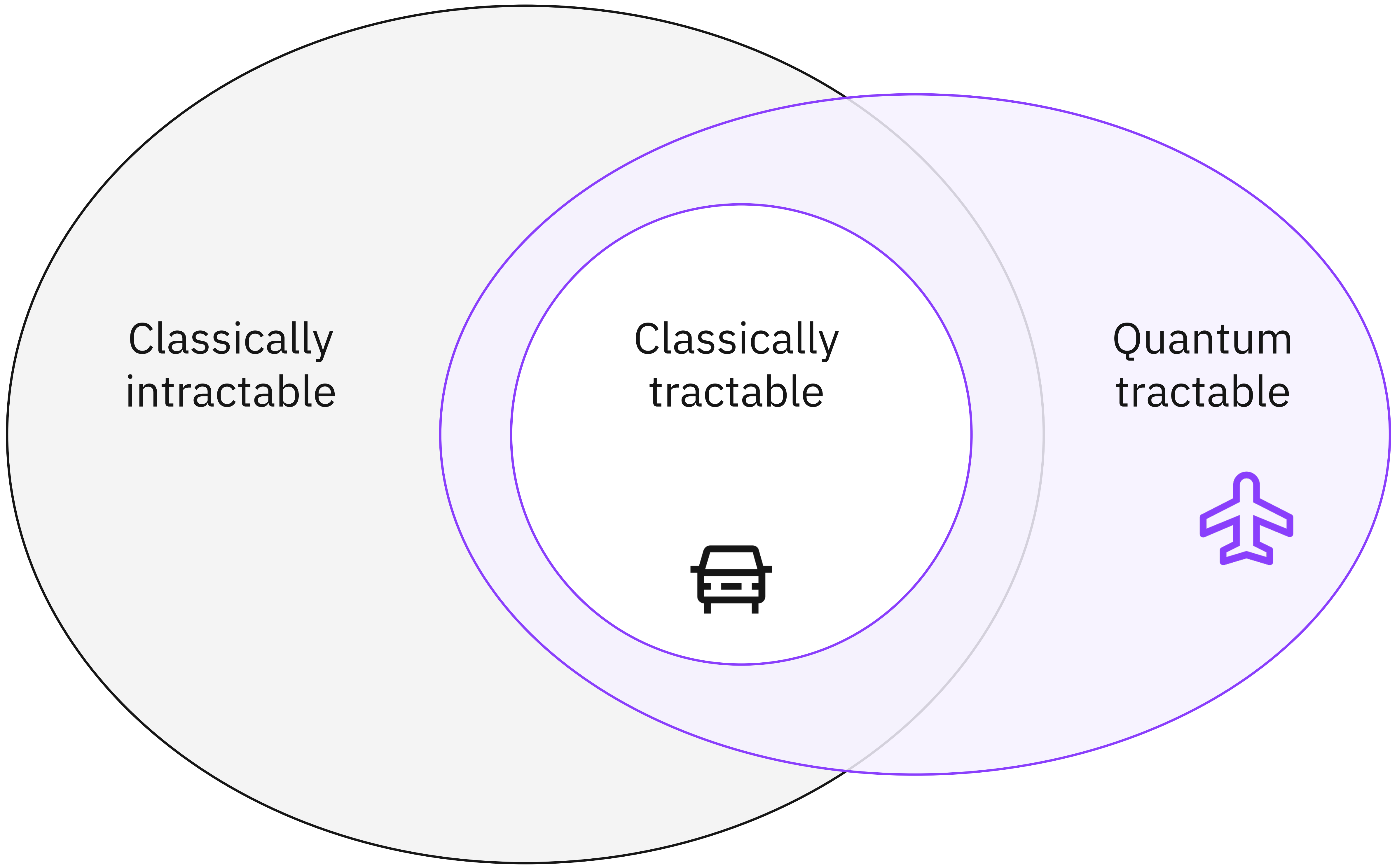
1937	Atanasoff-Berry computer solves systems of linear equations for astronomy research.
1941	British Bombe deciphers German Enigma codes.
1944	IBM Harvard Mark I simulates atomic reactions for Manhattan Project.
1945	ENIAC calculates artillery firing tables for the US Army.
↳ 1950	Hamming "error correction" codes are introduced.

Source: BCG

Unlock discovery with quantum computing

Harnesses the capacity to advance conceptual and tools-based discovery

Quantum computers are exponentially more powerful than classical computers



1. A new way of computing
   New paradigm of problem-solving and thinking
2. Solving new problems
   Unlock classically unsolvable problems, cutting computation time down from hours to minutes
3. Discovery of new use cases
   Expand discovery into new computational spaces

Source: https://matt-rickard.com/dyson-tool-driven-scientific-revolutions

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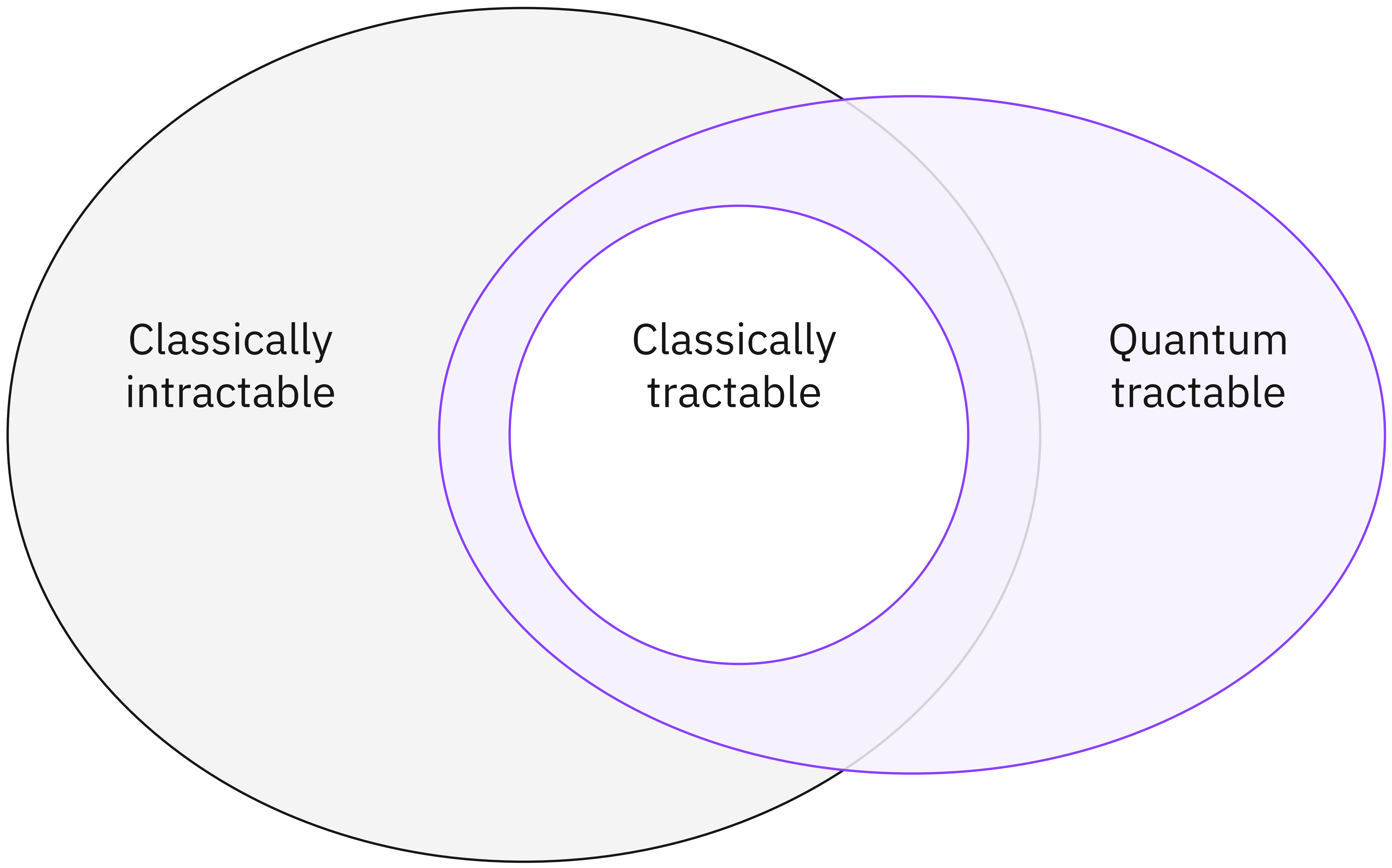

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Source: https://matt-rickard.com/dyson-tool-driven-scientific-revolutions

Quantum computing

The new discovery-accelerating tool

From new concepts to new tools, quantum computing allows us to explain new things in new ways.

Roadmap to **value today: utility-scale** experiments

> "Scientific revolutions are more often driven by new tools than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained."
> – Freeman J. Dyson

Economically **impactful before** quantum error correction, resulting in **near-term practical value**

Value drivers

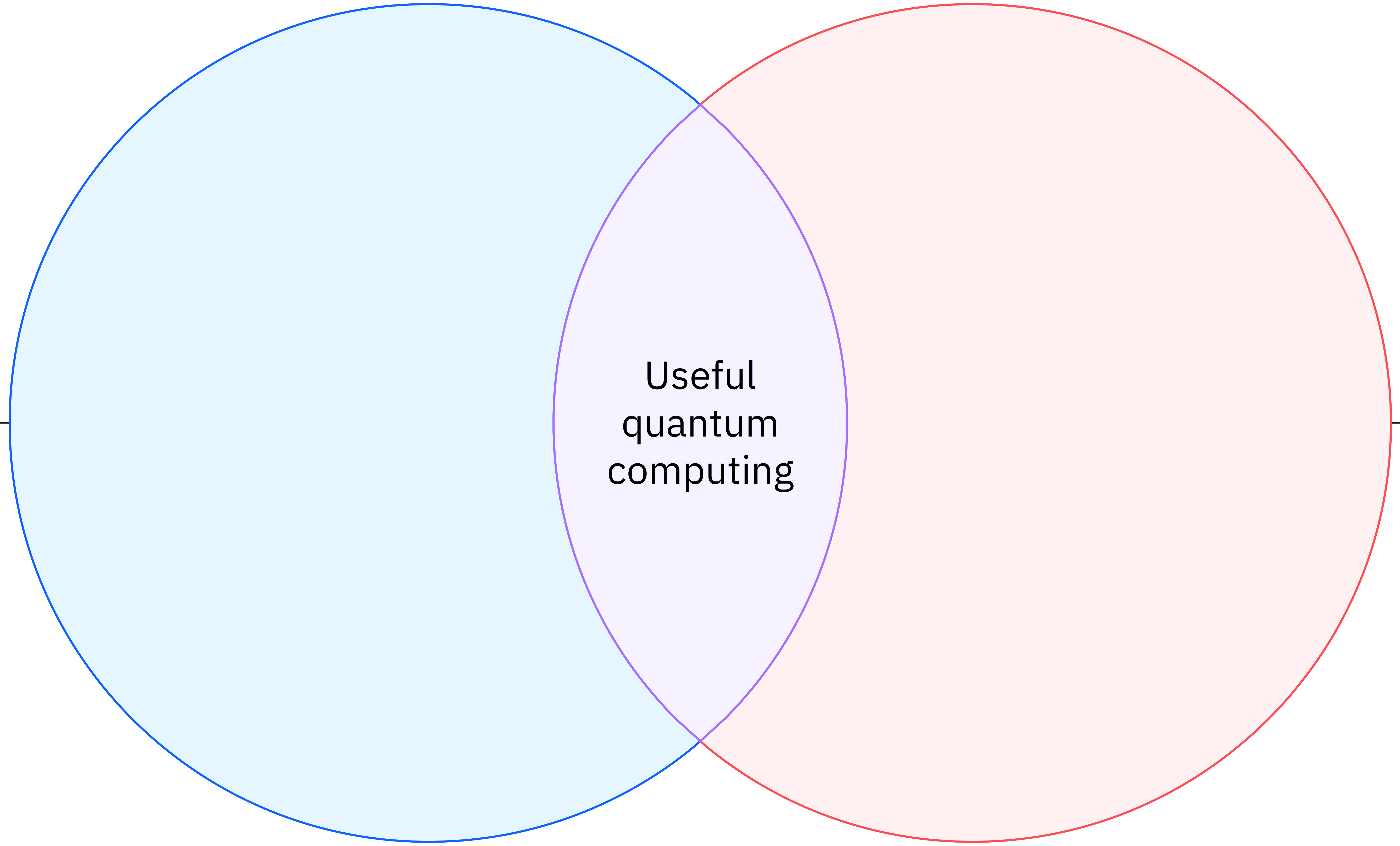
1. Variational algorithms Shallow-depth circuits on near-future HW
2. Error mitigation Noise handling
3. Circuit knitting Problem decomposition
4. Commercial exploration of quantum Use cases

Source: https://arxiv.org/abs/2401.16317

The path to useful quantum computing

Run quantum circuits faster on quantum hardware

Chart a path to develop quantum technology (hardware + software) that runs noise-free estimators of quantum circuits faster than can be done using classical hardware alone.



Map interesting problems to quantum circuits

We need applications that can be solved only with quantum circuits that are known to be difficult to simulate. This must be done in partnership with our clients and users.

Why now?

Early adopters are projected to gain substantial competitive advantage

↓

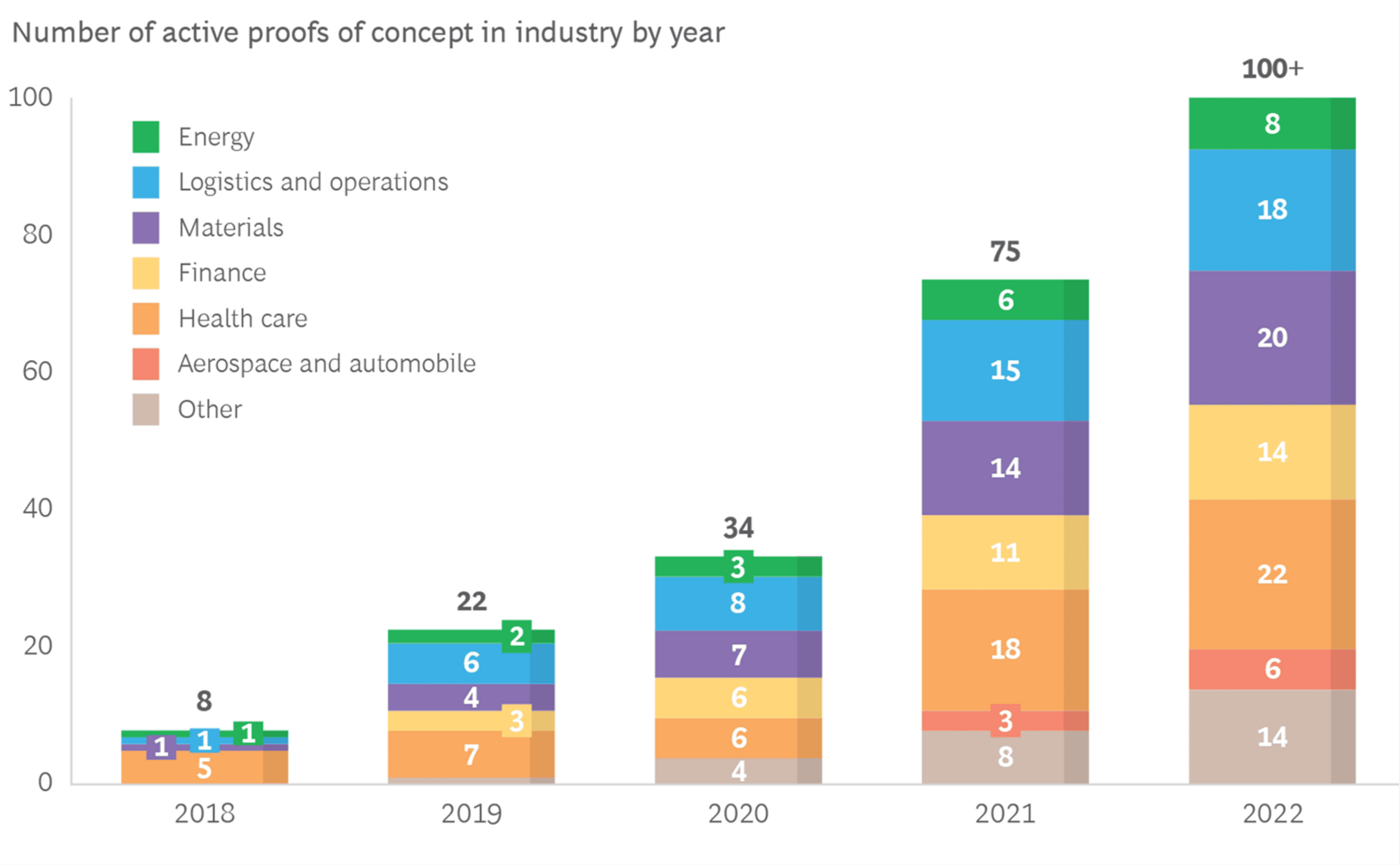
Estimated 90% value capture by early adopters

Source: Boston Consulting Group ("Quantum Computing Is Becoming Business Ready," 2023)

Investment in quantum computing is accelerating at an unprecedented pace

Accelerating adoption and usage

48%	Customer spend CAGR[1]
$42B	Global investment[2]
80%	Increase in expected investment by users[3]
3x	Enterprise use case activity 2020–2022[4]

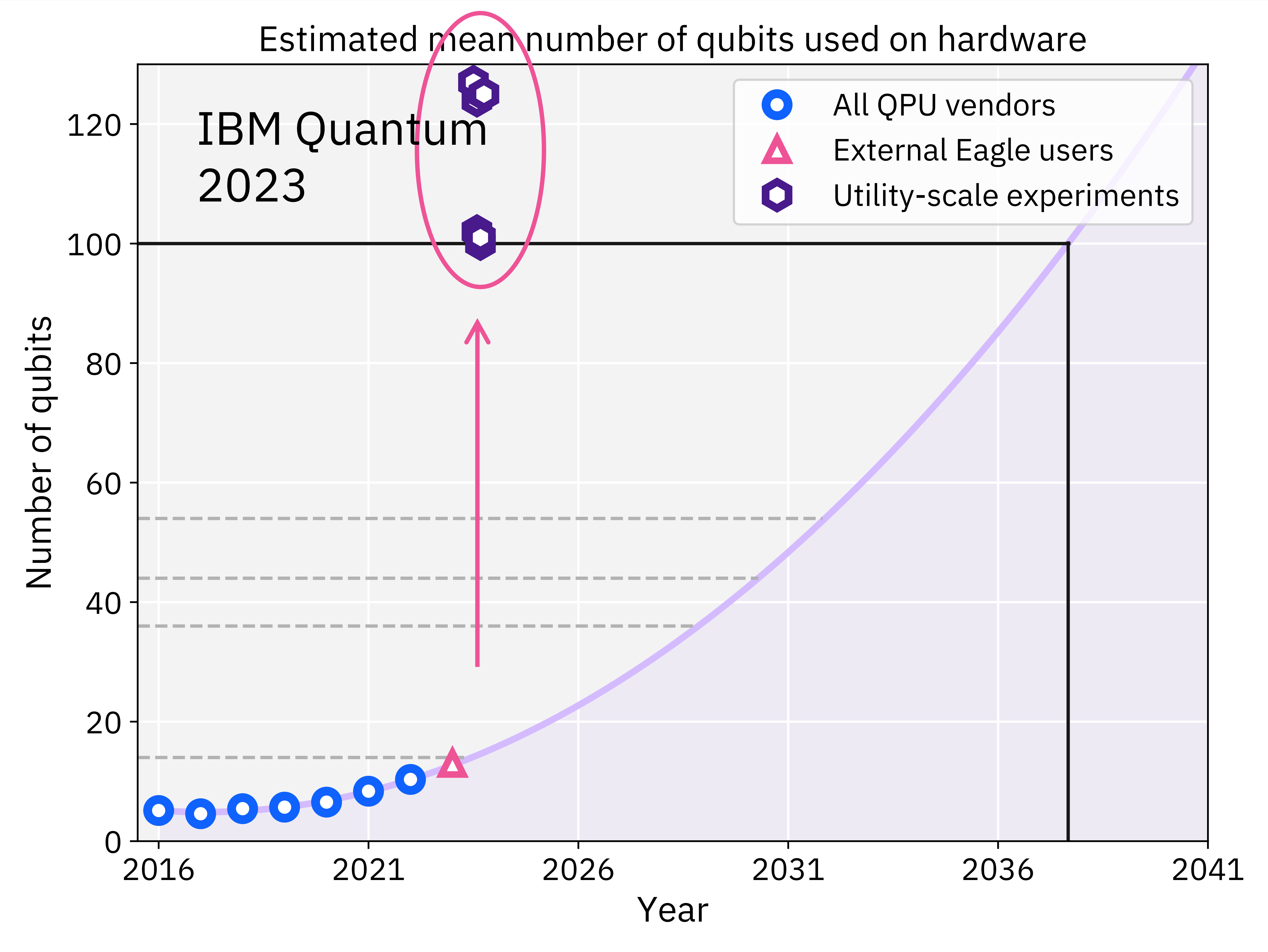


Source 1: IDC, IDC's Worldwide Quantum Computing Forecast: 2023–2027: Surfing the Next Wave of Quantum Innovation," IDC #US49198322, 2023.
Source 2: McKinsey & Co., "Steady progress in approaching the quantum advantage," 2024.
Source 3: BCG, "Why users should start building [quantum] capabilities now," 2022 Q2B Conference.
Source 4: BCG, "Quantum Computing Is Becoming Business Ready," 2023.

The era of quantum utility

IBM Quantum Systems + Qiskit = disruptive change

Accelerating adoption and usage



The purple line represents the industry pace needed to reach quantum utility.

Source: Data for all vendors taken from: arXiv:2307.16130

IBM Quantum

Driving the era of utility

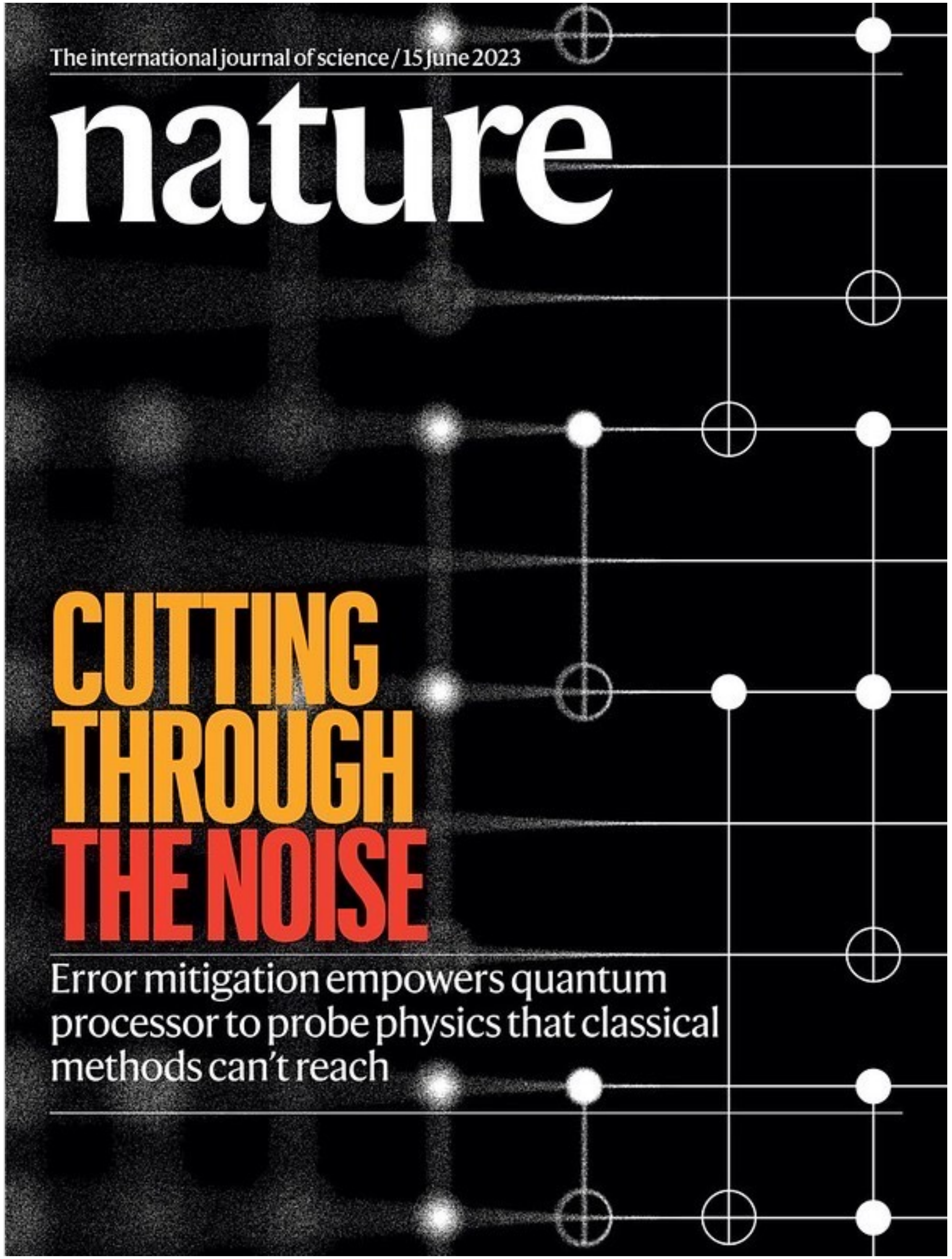
IBM Quantum and UC Berkeley demonstrated that quantum is competitive with leading classical methods.

Demonstrated IBM Quantum computers can produce accurate expectation values beyond the reach of brute-force classical computation.

IBM Quantum is the only company with the trinity of **scale, quality and speed** needed for demonstrations of useful quantum computation.

The IBM Quantum mission is to bring useful quantum computing to the world. **IBM Quantum endeavors to run more complex circuits than classical at a lower simulation cost.** And we want everyone to start using a system capable of utility-scale work.

All access plans feature utility-scale systems.



If you're not using 100+ qubits, you're not doing quantum.

System	System status	Processor type	Qubits	EPLG	CLOPS
ibm_**torino**	Online - Queue paused *maintenance*	Heron r1	133	0.8%	3.8K
ibm_**sherbrooke**	Online - Queue paused *internal*	Eagle r3	127	1.7%	5K
ibm_**brisbane**	Online	Eagle r3	127	1.9%	5K
ibm_**kyiv**	Offline *maintenance*	Eagle r3	127	2.1%	5K
ibm_**rensselaer**	Online	Eagle r3	127	2.1%	5K
ibm_**quebec**	Online	Eagle r3	127	2.3%	5K
ibm_**kawasaki**	Online	Eagle r3	127	2.4%	5K
ibm_**osaka**	Online	Eagle r3	127	2.8%	5K
ibm_**cleveland**	Online	Eagle r3	127	2.9%	5K
ibm_**nazca**	Online - Queue paused *in maintenance*	Eagle r3	127	3.2%	5K
ibm_**kyoto**	Online	Eagle r3	127	3.6%	5K
ibm_**cusco**	Online	Eagle r3	127	5.9%	5K

Inventing what's next in quantum

Providing our partners technology for the quantum future

Hardware
Utility-scale fleet
100+ qubit utility-scale fleet
Middleware
Suite of tools for workload optimization

Software
Qiskit® Runtime: enables **easy build** and **deployment** of cloud-based quantum workflows
Qiskit: open-source SDK

Expertise
Ecosystem
IBM Quantum Network
Trust and reputation
Development and innovation roadmap

Join us in creating the future of quantum computing

IBM Quantum capabilities

Utility-scale quantum fleet enabling utility-scale work

100+ qubits
The world's largest fleet of quantum computing systems, all with more than 100 qubits

Advanced processors offering error per layered gate (EPLG) as low as 0.8% and CLOPS (a measure of how quickly our processors run quantum volume circuits in a series) as high as 5K

Enhanced connectivity
New coupling technologies to forge more connections between qubits

Powerful processors
Tunable couplers between fixed-frequency qubits dramatically reduce noise

See all available system metrics:
quantum.ibm.com/services/resources?tab=systems

Learn more about performance metrics:
www.ibm.com/quantum/blog/quantum-metric-layer-fidelity

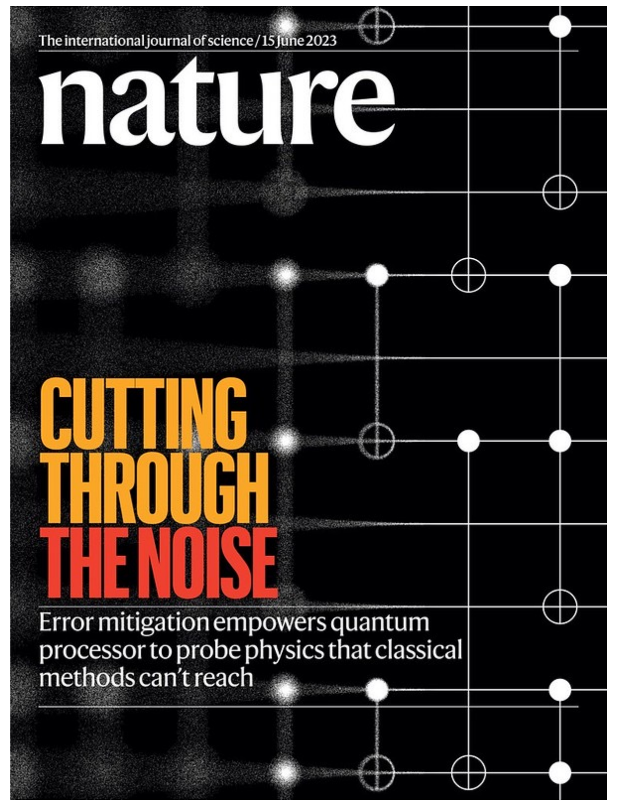
Utility vs. Advantage

Theory Utility Advantage

Quantum Utility (2023)

Demonstration that a quantum computer can run quantum circuits beyond the ability of a classical computer simulating a quantum computer

Confirmation via research, papers, & theory



IBM's 2023 research paper ("Evidence for the utility of quantum computing before fault tolerance") provided evidence and methods to move the industry into the Utility era

https://www.nature.com/articles/s41586-023-06096-3

Quantum Advantage (TBD)

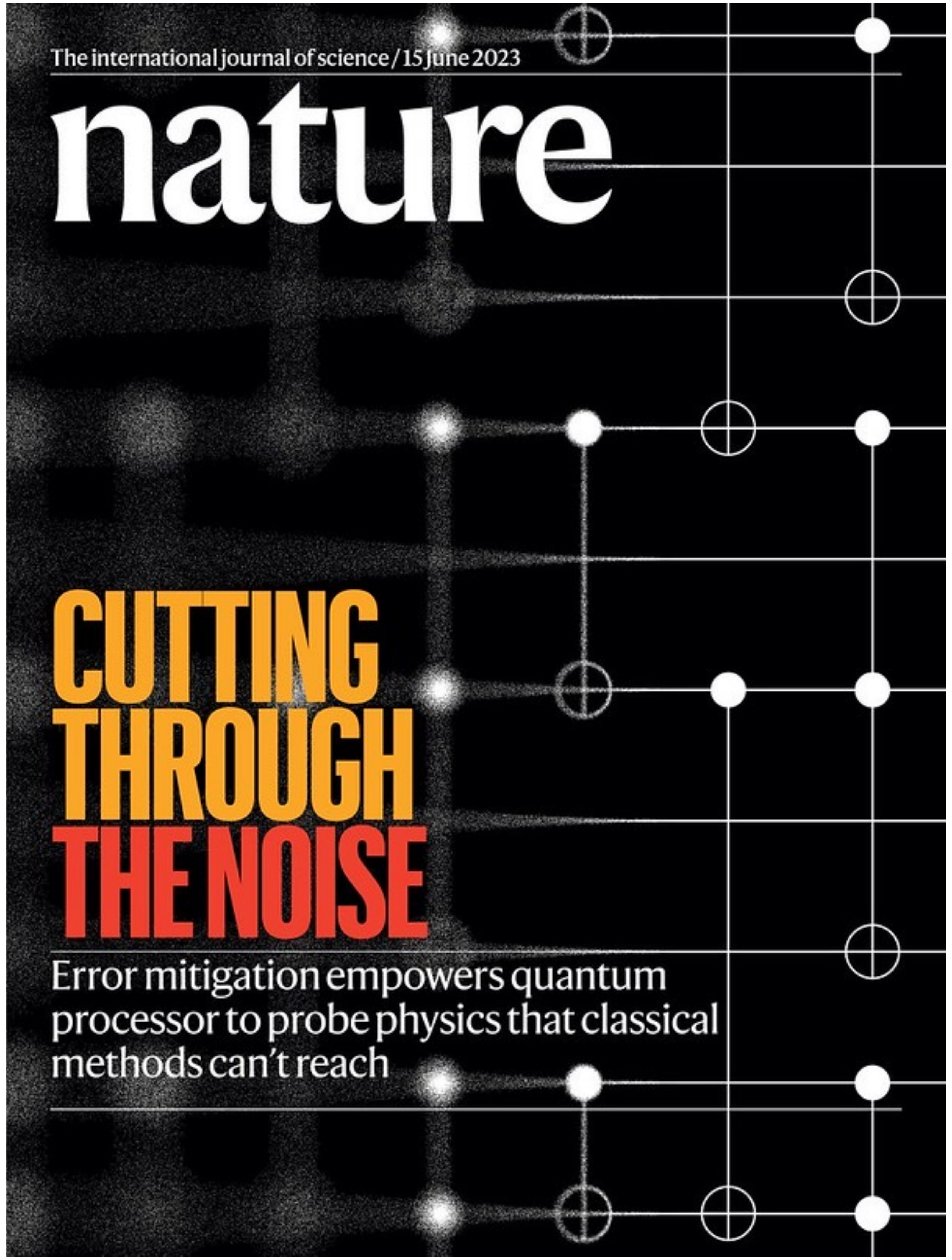
Demonstration that a quantum computer can run quantum circuits beyond the ability of all known classical methods

Confirmation via real-world usage

Advantage will come at different times in different domains and depends on the continued advancement of quantum algorithm implementations across industries

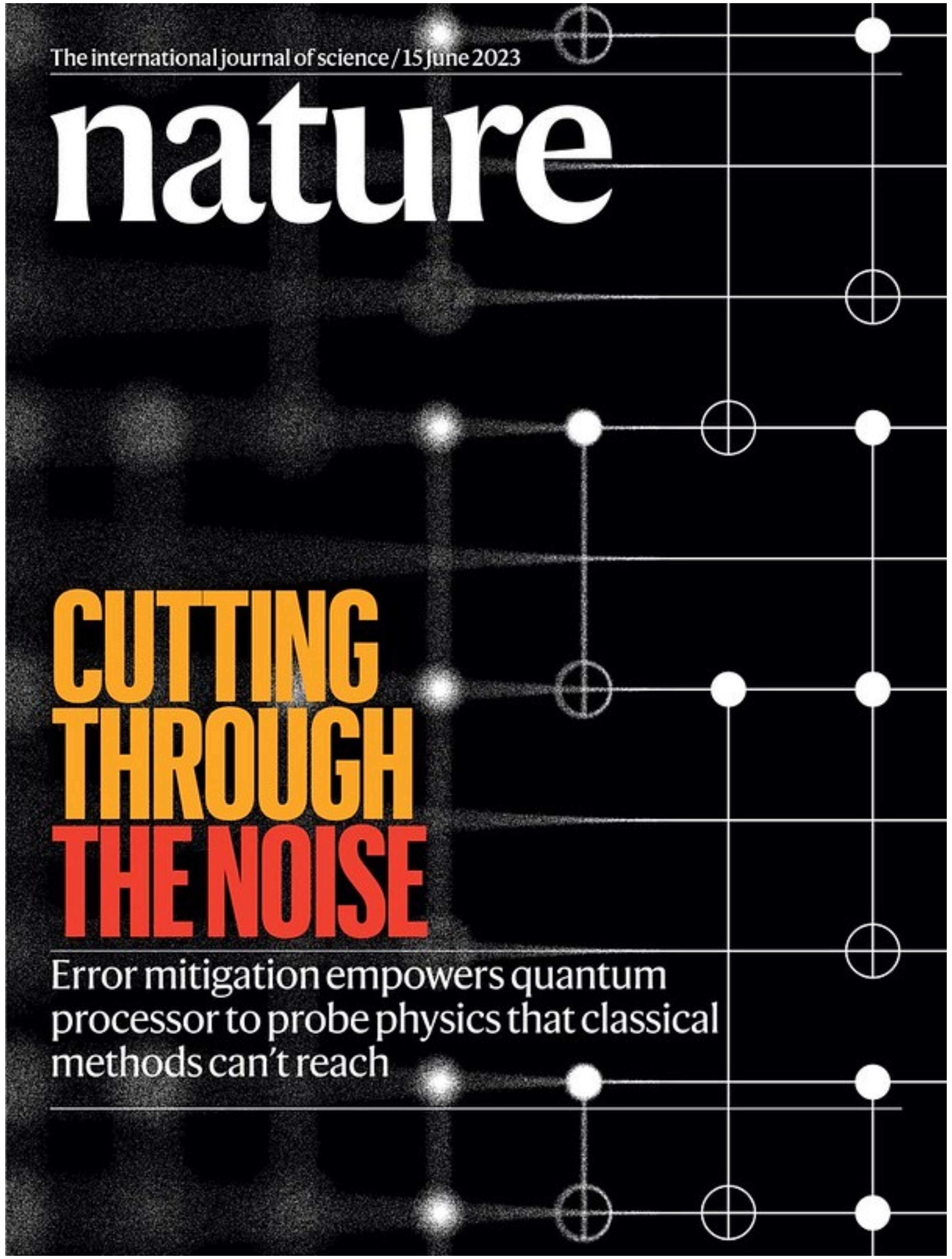
→ 2023

Evidence of utility before fault tolerance



Leading Innovation

Propelling us into the quantum computing frontier



2023 – Demonstrating quantum utility over brute force classical computing regarding optimization

2024 – Charting a path towards quantum error correction, demonstrating high-threshold, low-overhead fault-tolerant quantum memory

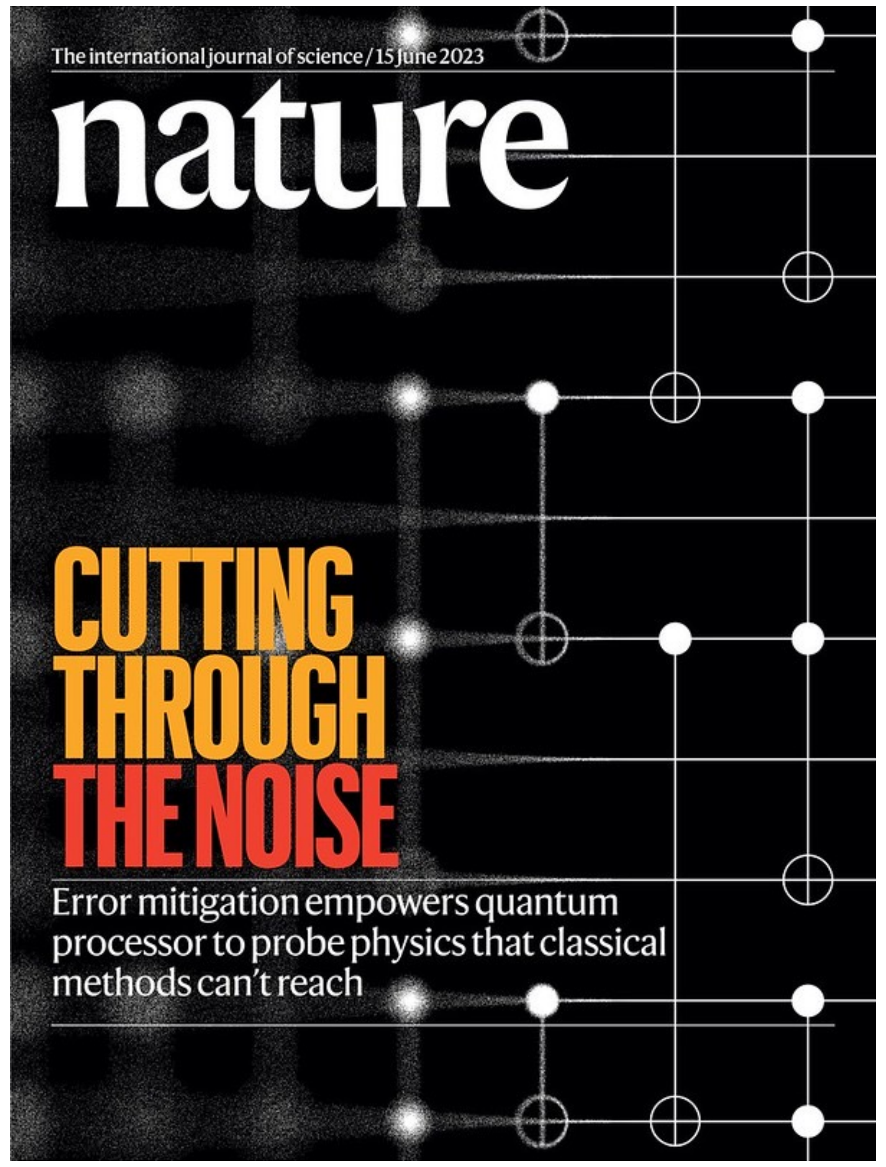
Source: 1. https://www.nature.com/articles/s41586-024-07107-7
Source: 2. https://www.nature.com/articles/s41586-023-06096-3

Only IBM offer quantum at Utility scale (>100 qubits)

Major advances in past 12 months

01 - The ‘Utility paper’

Proves there is plenty of business value to extract from the era of quantum utility



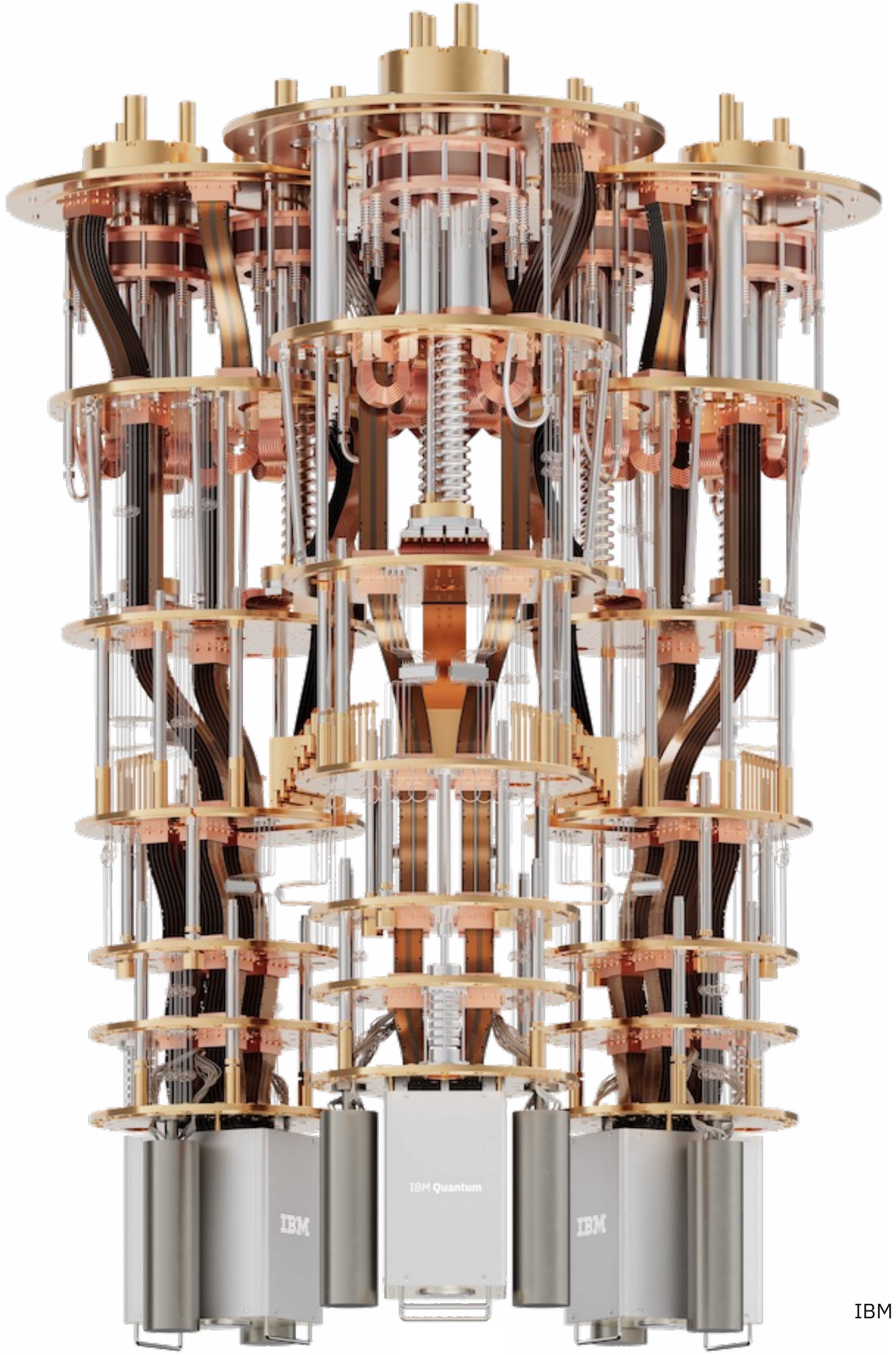
02 - A new error correcting code

We brought error correction closer by 10 years by reducing the number of qubits required by 90%.

Exploring business value in the era of quantum utility

Only IBM offers organizations an opportunity to do meaningful exploration of business value in this new era of quantum utility.

Together with IBM and the 250+ members of the IBM Quantum Network, we can help you build expertise, algorithms, and IP to take full advantage of quantum computing as it happens.



Our formula for bringing useful quantum computing to the world includes:

Maintaining the industry's largest fleet of **utility-scale quantum systems** on the cloud for our clients and the quantum community to experiment with.

Building and updating a **development and innovation roadmap** that will help us scale quantum computing, from the hardware to the software necessary for quantum advantage.

Nurturing a **community of clients and partners** that includes 290+ Fortune 500 companies, academic institutions, national labs and startups—all working to solve real scientific and business problems with quantum computing.

Developing Qiskit, an open source toolkit and world-class **user experience** that makes quantum computing easy to learn and use by bringing resources together in one place.

Making the world **quantum safe** with technologies that will secure enterprises in the quantum future.

Roadmap

World-leading quantum hardware and software

Development Roadmap

IBM **Quantum**

2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
Ran quantum circuits on the IBM Quantum Platform	Released multi-dimensional roadmap publicly with initial aim focused on scaling	Enhanced quantum execution speed by 100x with Qiskit Runtime	Brought dynamic circuits to unlock more computations	Enhanced quantum execution speed by 5x with Quantum Serverless and execution modes	Improve quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhance quantum execution speed and parallelization with partitioning and quantum modularity	Improve quantum circuit quality to allow 7.5K gates	Improve quantum circuit quality to allow 10K gates	Improve quantum circuit quality to allow 15K gates	Improve quantum circuit quality to allow 100M gates	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing

Data scientists

Platform (2024–2033+)

- Code assistant (2024)
- Functions (2025)
- Mapping collections (2026)
- Specific libraries (2027–2029)
- General purpose QC libraries (2033+)

Researchers

Middleware (2023–2033+)

- Quantum Serverless (2023)
- Transpiler service (2024)
- Resource management (2025)
- Circuit knitting x p (2026)
- Intelligent orchestration (2027–2029)
- Circuit libraries (2033+)

Quantum physicists

Qiskit Runtime (2021–2033+)

- IBM Quantum Experience (2016–2020)
- QASM 3 (2021)
- Dynamic circuits (2022)
- Execution modes (2023)

Early (2016–2019)	Canary 5 qubits; Albatross 16 qubits; Penguin 20 qubits; Prototype 53 qubits
Falcon (2020–2021)	Benchmarking; 27 qubits
Eagle (2022–2023)	Benchmarking; 127 qubits
Heron (5K) (2024)	Error mitigation; 5k gates; 133 qubits; Classical modular; 133x3 = 399 qubits
Flamingo (5K) (2025)	Error mitigation; 5k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits
Flamingo (7.5K) (2026)	Error mitigation; 7.5k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits
Flamingo (10K) (2027)	Error mitigation; 10k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits
Flamingo (15K) (2028)	Error mitigation; 15k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits
Starling (100M) (2029)	Error correction; 100M gates; 200 qubits; Error corrected modularity
Blue Jay (1B) (2033+)	Error correction; 1B gates; 2000 qubits; Error corrected modularity

Innovation Roadmap

Software innovation

- **IBM Quantum Experience** (2016–2019)
- **Qiskit** (2016–2019) — Circuit and operator API with compilation to multiple targets
- **Application modules** (2020) — Modules for domain specific application and algorithm workflows
- **Qiskit Runtime** (2021) — Performance and abstraction through primitives
- **Quantum Serverless** (2022) — Demonstrate concepts of quantum-centric supercomputing
- **AI-enhanced quantum** (2023) — Prototype demonstrations of AI-enhanced circuit transpilation
- **Resource management** (2024) — System partitioning to enable parallel execution
- **Scalable circuit knitting** (2025) — Circuit partitioning with classical reconstruction at HPC scale
- **Error correction decoder** (2026) — Demonstration of a quantum system with real-time error correction decoder

Hardware innovation

- **Early** (2016–2019) — Canary 5 qubits; Penguin 20 qubits; Albatross 16 qubits; Prototype 53 qubits
- **Falcon** (2016–2019) — Demonstrate scaling with I/O routing with bump bonds
- **Hummingbird** (2020) — Demonstrate scaling with multiplexing readout
- **Eagle** (2021) — Demonstrate scaling with MLW and TSV
- **Osprey** (2022) — Enabling scaling with high density signal delivery
- **Condor** (2023) — Single system scaling and fridge capacity
- **Heron** (2023) — Architecture based on tunable-couplers
- **Flamingo** (2024) — Demonstrate scaling with modular connectors
- **Crossbill** (2024) — Demonstrate m-couplers
- **Kookaburra** (2025–2026) — Demonstrate scaling with nonlocal c-coupler; Demonstrate path to improved quality with logical memory
- **Cockatoo** (2027) — Demonstrate path to improved quality with logical communication
- **Starling** (2028) — Demonstrate path to improved quality with logical gates

Beware of imitations

AI imitations

AI hardware companies are keen to expand into every market they can, prompting the joke:

“The answer is more GPUs—now what’s the question?”

Simulating quantum on AI or classical is inefficient, costly, and very constrained (to <46 qubits).

These are nowhere near utility-scale systems

Classical imitations

Companies that sell classical cloud computing are keen to jump on the quantum bandwagon...

despite no viable quantum hardware.

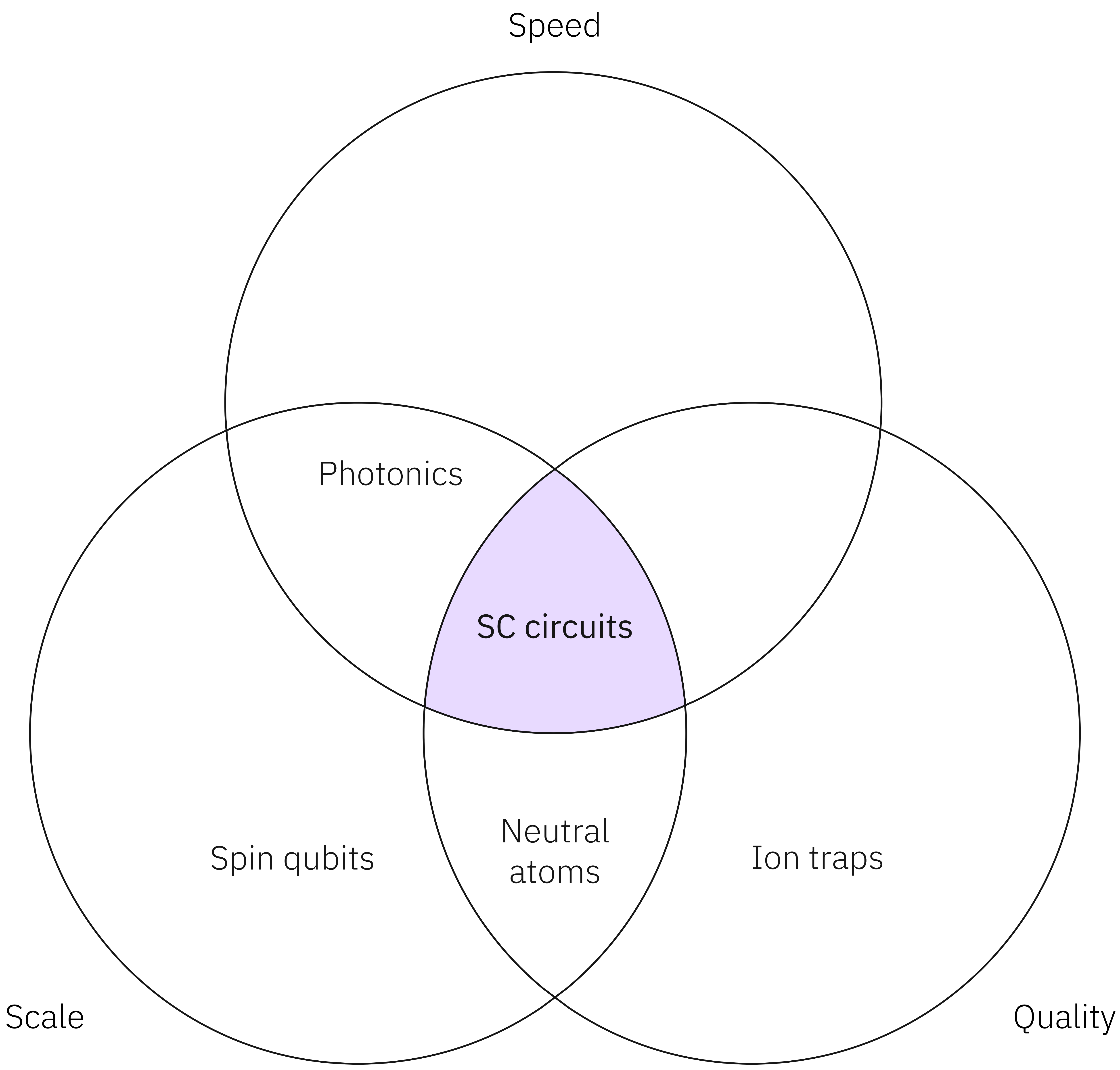
“Quantum-inspired” is repackaging classical cloud compute.

Beware of hype

You need speed, scale, and quality—all three.

Some “full-stack” quantum computing companies are selling access to quantum hardware that may be too slow or inaccurate to do anything remotely useful.

IBM Quantum is the only full-stack quantum computing company that has demonstrated utility-scale hardware (>100 qubits), and we have made it available via the cloud.



Industry & Use Cases

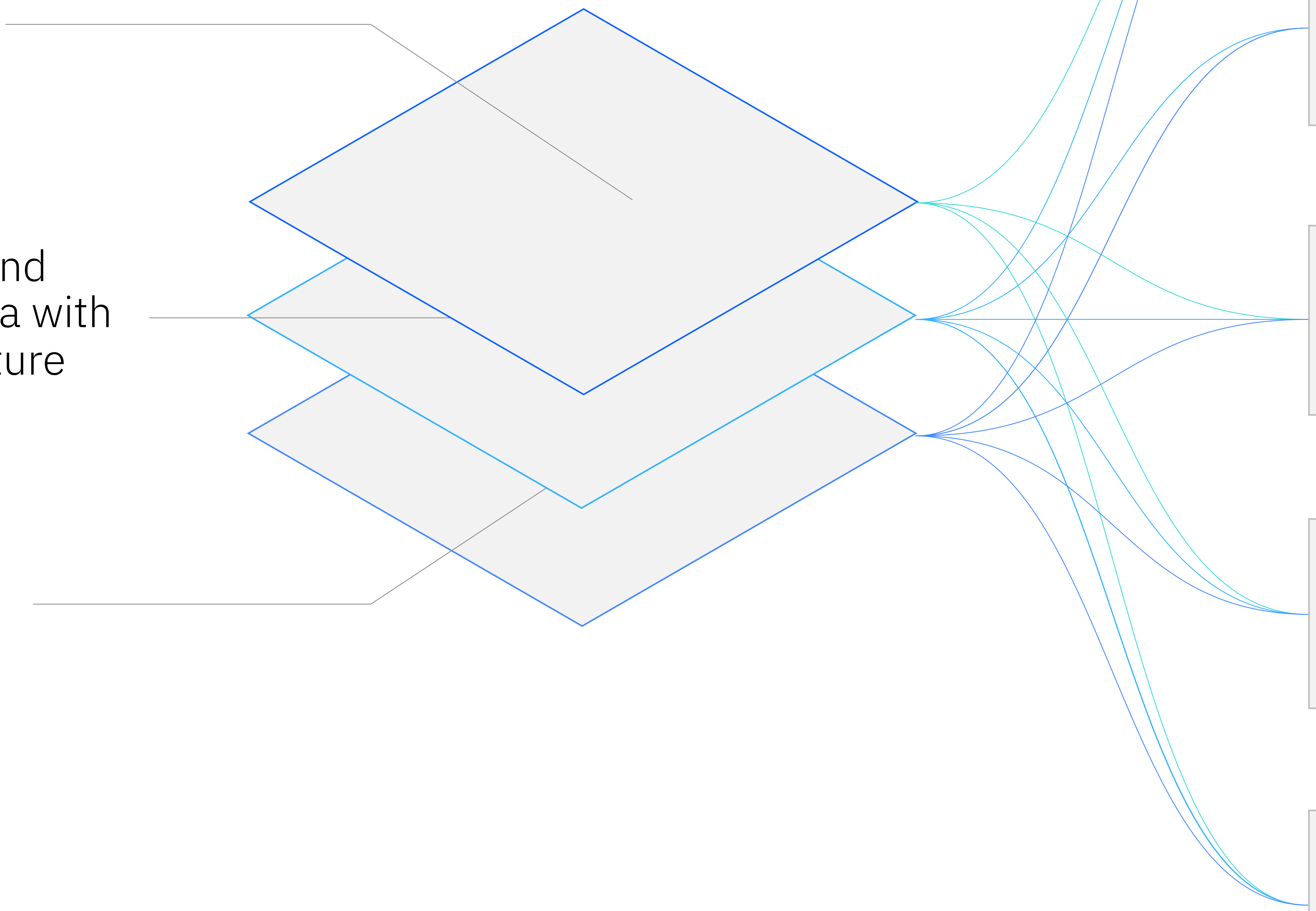
Industry examples

Quantum computing is expected to have impact across industries

Simulating nature

Mathematics and processing data with complex structure

Search and optimization



Aerospace & Automotive

- Customer Experience
- Materials Design
- Structural Design Optimization
- And more

Financial Services

- Fraud Detection
- Derivatives/options pricing
- Portfolio optimization
- Risk analysis
- And more

High Tech

- Seismic Imaging
- Catalysts
- Supply chain planning
- Manufacturing scheduling
- And more

Energy, Environment, Utilities

- Portfolio optimization
- Grid optimization
- Risk Analysis and Options Pricing
- Battery Design
- And more

Health Care & Life Sciences

- Disease risk prediction
- Drug discovery and design
- Protein folding predictions
- And more

These computationally complex problems exist across almost every industry.

Banking

- Fraud monitoring
- Portfolio optimization
- Risk simulation
- Customer analytics
- Time series forecasting

Automotive

- Battery material design
- Material design
- Mobility as a Service
- Quality control
- Self-driving and ADAS
- Production optimization

Chemicals

- Sustainable products
- Low-carbon manufacturing
- Resilient supply chains
- Process optimization
- Asset health

Life sciences

- Efficient drug research and development
- Clinical trials
- Tractable protein folding
- Call-centric therapeutics
- mRNA

Healthcare

- Accelerated diagnoses
- Personalized interventions
- Adherence to drugs
- Biomarkers
- Image processing

Logistics

- Global logistics optimization
- Disruption management
- Routing optimization
- Predictive maintenance
- Forecasting

Public services

- Security/safety
- Multimodal transport
- City resource planning
- Disaster management
- Fraud detection in tax and social

Insurance

- Catastrophe modeling
- Precise customer profiling
- Efficient risk management
- Optimized pricing of premiums

Electronics

- Faster product design
- Circuit defect identification
- Process optimization
- Production optimization
- Quality control

Airlines

- Forecasting and revenue
- Irregular operations
- Network planning
- Safety and maintenance
- Hyper-personalization

Energy and utilities

- Energy trading
- Optimization of energy grid
- Renewables system design
- Energy forecasting
- Hyper-personalization
- Asset health

Aerospace

- Material discovery
- Aircraft design
- Asset health
- Corrosion and material interaction
- Fuel efficiency

Oil and gas

- Emissions reduction
- Reservoir simulation
- Virtual flow meters
- Subsurface modeling
- Failure prediction

Telecom

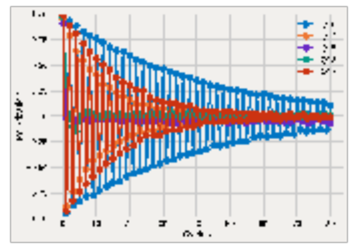
- Network optimization
- Network anomaly detection
- Contextual customer segmentation
- Cybersecurity network

Quantum Computing is changing research & discovery

With IBM Quantum, our partners have demonstrated value of quantum computing adoption within their R&D.

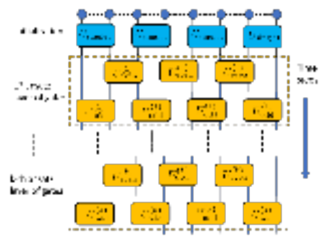
ExxonMobil	Moderna	Wells Fargo	HSBC
Challenge: Modeling maritime inventory routing to identify optimal shipping routes	**Challenge**: Accelerating mRNA therapeutics research on vaccines with optimal safety and performance characteristics.	**Challenge**: Financial sequence modeling inspired by the mid-price movement prediction use case.	**Challenge:** Improving fraud pattern recognition in financial transactions to counter financial crime - a growing global challenge
Today: ExxonMobil + IBM are pursuing different strategies for vehicle and inventory routing. Laying the foundation for constructing practical solutions for their operations.	**Today:** Moderna and IBM Quantum are working on benchmarking quantum computing approaches against existing classical solutions for mRNA optimization, identifying potential areas for quantum benefits within the mRNA Optimization workflows, and understanding quantum utility and time to value.	**Today:** Wells Fargo + IBM Quantum have published several research papers exploring new kinds of algorithms and new ways of thinking about this problem in the financial services industry.	**Today:** Leverage classical machine learning models to differentiate between genuine and fraudulent transactions, while fighting with emerging complex data patterns and false positive rates
Opportunity: More efficient shipping routes could help us transport fuel more efficiently around the globe.	**Opportunity:** Different quantum computing algorithms, including quantum optimization and quantum machine learning methods maybe relevant. Hybrid quantum-classical approaches may improve the quality and the diversity of mRNA optimization solutions.	**Opportunity:** Research focus on training quantum systems to mimic the probability distributions and stochastic processes seen in the real world, then use that system for predictive modeling. The goal is to use quantum model to enrich the ensemble of algorithms Wells Fargo uses to estimate stock price.	**Opportunity:** Pushing the limits of classical capabilities with hybrid quantum AI models to improve the distinguishability of anomalous low-statistical signals of fraud. While initial efforts using real data have shown promising, the next step is to move toward utility scale and practical value.
The Quantum Decade – Fourth edition	newsroom.ibm.com/2023-04-20-Moderna-and-IBM-to-Explore-Quantum-Computing-and-Generative-AI-for-mRNA-Science	The Quantum Decade – Fourth edition	arXiv:2312.00260

If you build it, they will come… (1/2)

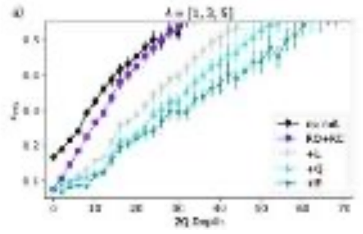


Characterizing quantum processors using discrete time crystals
arXiv:2301.07625
80 qubits / 7900 CX gates
simulation

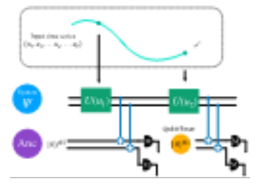
Evidence for the utility of quantum computing before fault tolerance
Nature, 618, 500 (2023)
127 qubits / 2880 CX gates
simulation



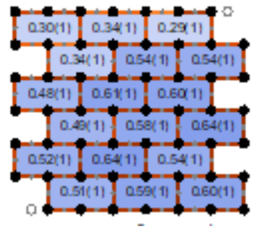
Simulating large-size quantum spin chains on cloud-based superconducting quantum computers
Phys. Rev. Research 5, 013183 (2023)
102 qubits / 3186 CX gates
simulation



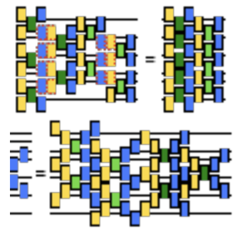
Best practices for quantum error mitigation with digital zero-noise extrapolation
arXiv:2307.05203
104 qubits / 3605 ECR gates
tools



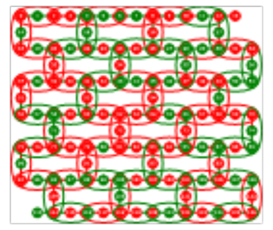
Quantum reservoir computing with repeated Measurements on superconducting devices
arXiv:2310.06706
120 qubits / 49470 ECR gates + meas.
QML



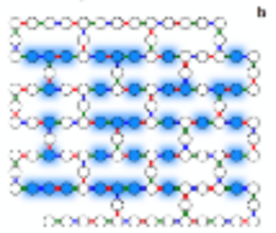
Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits
arXiv:2309.02863
125 qubits / 429 gates + meas.
simulation



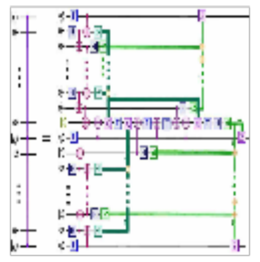
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
PRX Quantum 5, 020315 (2024)
100 qubits / 788 CX gates
simulation



Scaling Whole-Chip QAOA for Higher-Order Ising Spin Glass Models on Heavy-Hex Graphs
arXiv:2312.00997
127 qubits / 420 CX gates
optimization



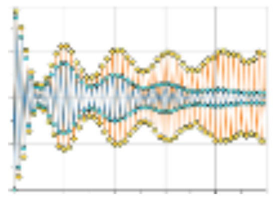
Uncovering Local Integrability in Quantum Many-Body Dynamics
arXiv:2307.07552
124 qubits / 2641 CX gates
simulation



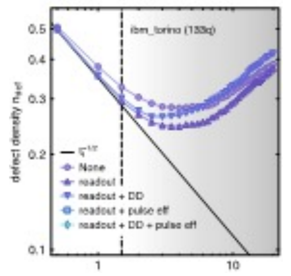
Efficient Long-Range Entanglement using Dynamic Circuits
arXiv:2308.13065
101 qubits / 504 ECR gates + meas
tools

If you build it, they will come… (1/2)

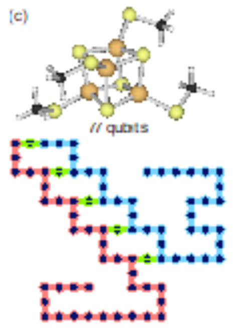
Quantum Simulations of Hadron Dynamics in the Schwinger Model using 112 Qubits
arXiv:2401.08044
112 qubits / 13,858 CZ gates
simulation



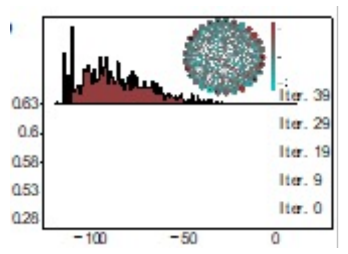
Unveiling clean two-dimensional discrete time quasicrystals on a digital quantum computer
arXiv:2403.16718
133 qubits / 15,000 CZ gates
simulation



Benchmarking digital quantum simulations and optimization above hundreds of qubits using quantum critical dynamics
arXiv:2404.08053
133 qubits / 1440 CX gates
simulation

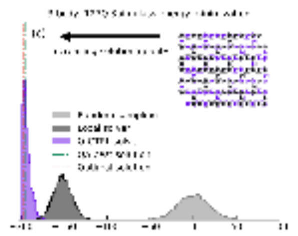


Chemistry Beyond Exact Solutions on a Quantum-Centric Supercomputer
arXiv:2405.05068
77 qubits / 3590 CZ gates
simulation

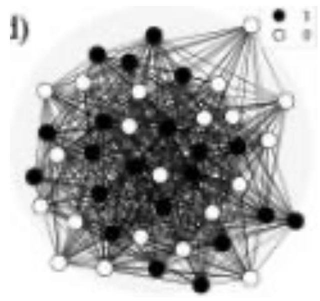


Bias-field digitized counterdiabatic quantum optimization
arXiv:2405.13898
100 qubits / 198 ECR gates
optimization

mRNA secondary structure prediction using utility-scale quantum computers
arXiv:2405.20328
80 qubits / 158 CX gates
simulation



Quantum optimization using a 127-qubit gate-model IBM quantum computer can outperform quantum annealers for nontrivial binary optimization problems
arXiv:2406.01743
optimization
ts / 2500 CX gates



Towards a universal QAOA protocol: Evidence of quantum advantage in solving combinatorial optimization problems
arXiv:2405.09169
109 qubits / 21,200 ECR gates
optimization

Technical Working Groups

What they are

Experts from (classical + quantum) x (academia + industry) come together to discuss the most pressing scientific challenges in the area today.

Outcomes

Identify and work on concrete examples of open problems (with commercial or scientific value) that can be tackled with a quantum computer within 2-5 years.

High Energy Physics	Healthcare & Life Sciences	Optimization	Materials Science	Sustainability (NEW GROUP)
Partners CERN, DESY, Oak Ridge National Lab, U. of Washington, U. of Tokyo, and more	Partners Cleveland Clinic, U. of Chicago, QuantumBasel, Virginia Tech, Algorithmiq, and more	Partners STFC Hartree Centre, E.ON., Fraunhofer, Los Alamos National Lab, University of Amsterdam, and more	Partners Oak Ridge National Lab, University of Chicago, Argonne National Lab, RIKEN, BasQ, and more	Partners PINQ^2, Hydro-Quebec, University of Sherbrooke, E.ON., DTU, and more
White Paper Quantum Computing for High-Energy Physics: State of the Art and Challenges. Summary of the QC4HEP Working Group arXiv:2307.03236	White Paper Towards quantum-enabled cell-centric therapeutics arXiv:2307.05734	White Paper Quantum Optimization: Potential, Challenges, and the Path Forward arXiv:2312.02279	White Paper Quantum-centric Supercomputing for Materials Science: A Perspective on Challenges and Future Directions arXiv:2312.09733	This new working group aims to create collaborative projects in the fields of Energy and Material leveraging quantum computers towards a sustainable future.

Industry & Use Cases

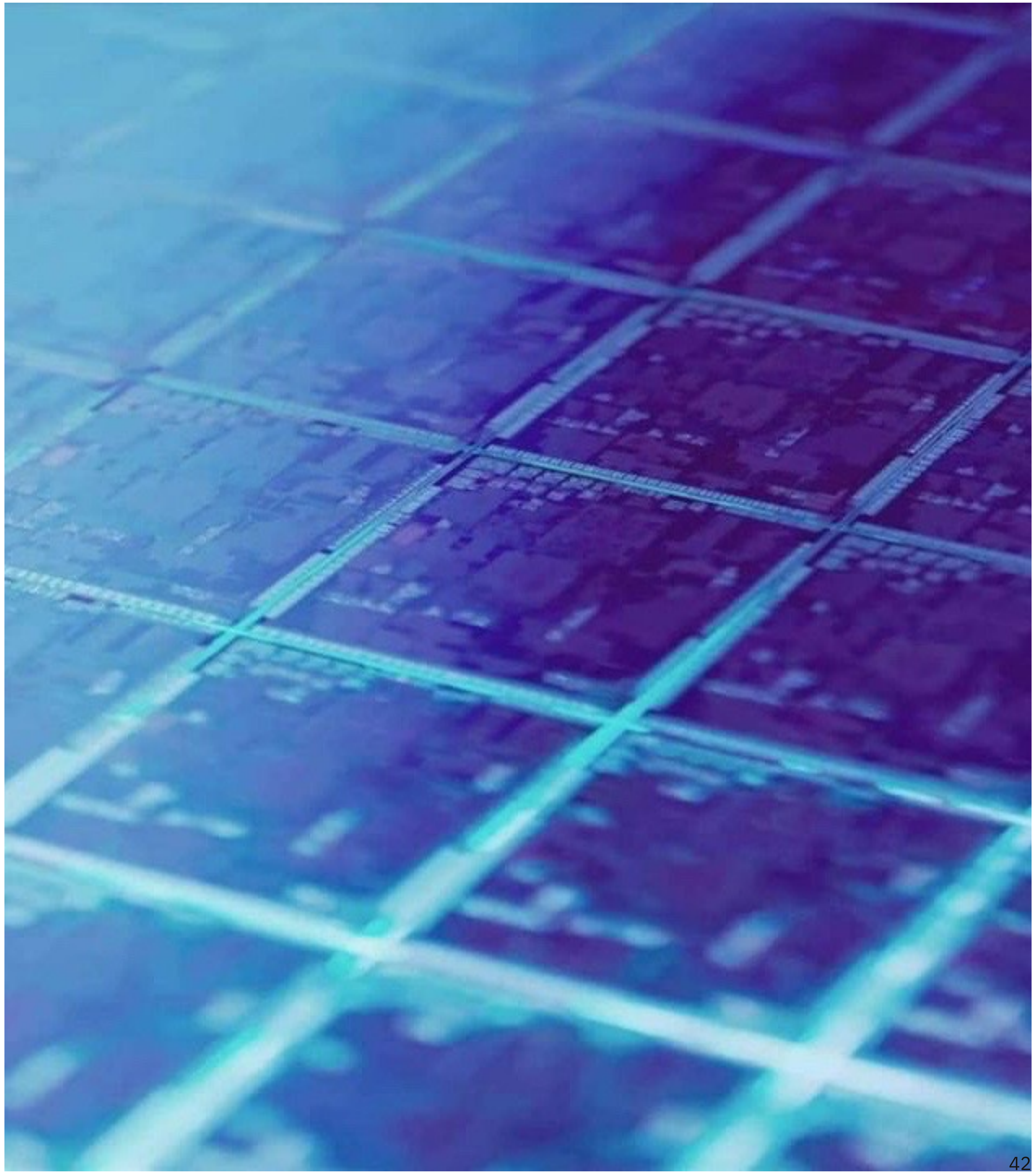
Chemistry & Material Science

Exploring business value with chemistry and material science

JSR

- JSR and IBM are experimenting with chemical simulations to help improve the development and manufacture of photoresists.
- We've already demonstrated that we can simulate small molecules that mimic parts of the photoresist.
- We hope that simulations like these will help us realize even faster chips.

Case Study: https://www.ibm.com/case-studies/jsr



Industry & Use Cases

Optimization

Exploring business value with quantum optimizations

Quantum routing optimization

Business Story

Need:

- Routing optimization is a critical problem for many industries such as logistics, supply chain, automotive, telecommunications, and manufacturing.

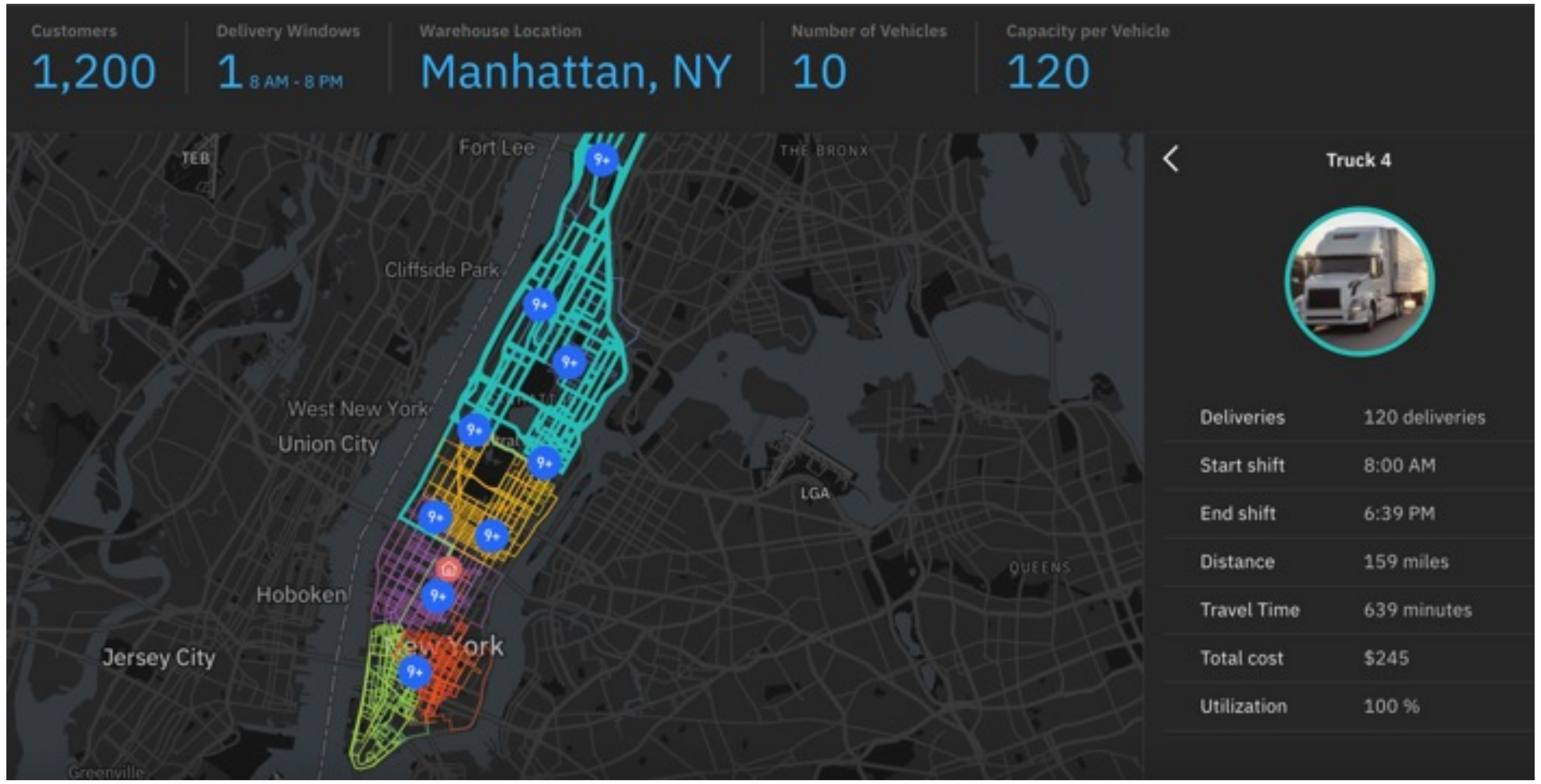
Value:

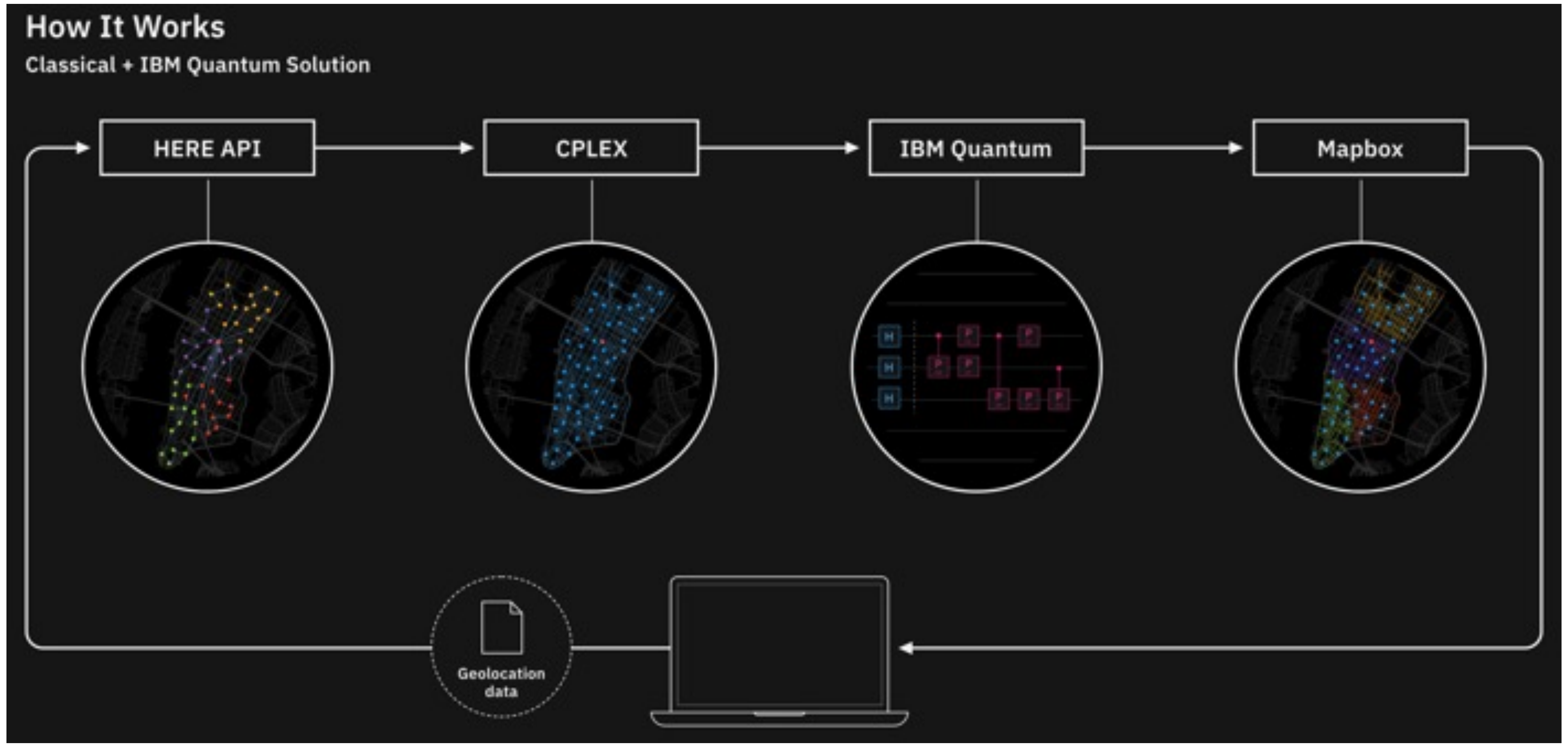
- Reduces the total cost of delivery:
  - vehicle cost per day,
  - driving cost per hour,
  - and distance cost per mile/km)
- Constrains: 1,200 delivery locations, vehicle capacity, single depot and delivery time windows

Learning asset:

- Last mile delivery modeled by the CVRPTW (Capacitated Vehicle Routing Problem with Time Windows)

Link: https://vrp-demo-ny.4ww07dugj2l.us-south.codeengine.appdomain.cloud/





What is a near-term improvement worth in financial fraud?

Financial fraud is **on the rise globally** and carries **staggering costs** for financial institutions, regulators and consumers

Consider what even a 1% improvement in these sectors yields

Up to $3.1T	Illicit funds laundered every year
$485 B	Total fraud losses
$442 B	Bank loss from payment, check and credit card
$43.6 B	Consumer scams
$6.6B	Enforcement actions by regulators

Sources: NASDAQ 2024 Global Financial Crime Report, Fenergo Report: AML enforcement actions surge in 2023

Quantum applications

Financial services industry

Fraud detection

Detect fraud with greater accuracy, fewer false positives

Current state
ML techniques restricted by high false positive rates

Business value exploration
Heuristic exploration of classical + quantum ML novel fraud prediction reducing false positives

Portfolio optimization

Optimize portfolios for better risk-adjusted returns

Current state
Optimization uses approximations that ignore real-world constraints

Business value exploration
More accurate optimization factoring in additional real-world constraints

Time series forecasting

Better predict financial time series and sequences

Current state
ML methods have limited accuracy or require large models/training as complexity of data increases

Business value exploration
QML methods model complex relationships more effectively, improving prediction accuracy and reducing model training overhead

Customer analytics

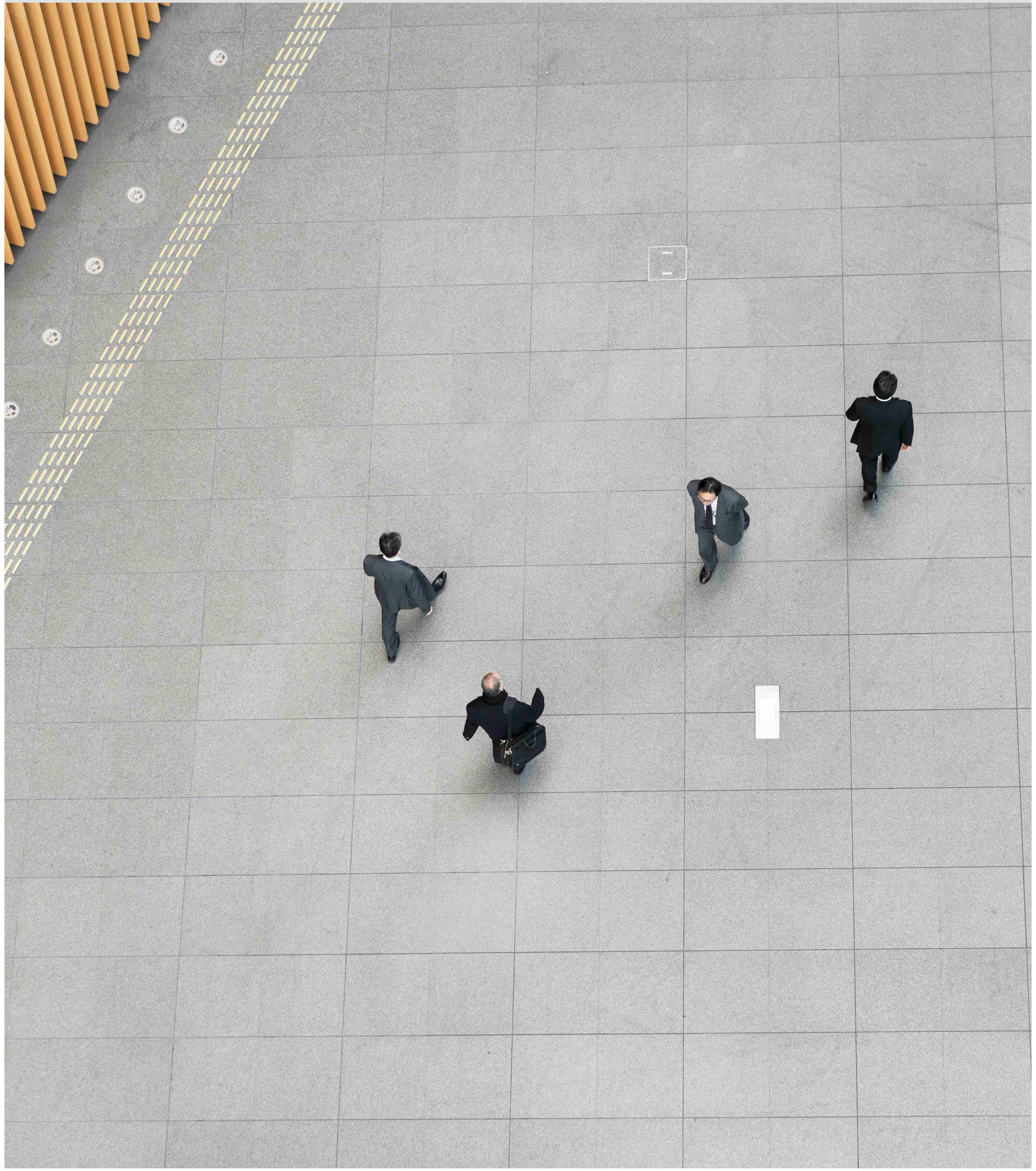
Spot hidden patterns in customer data to increase membership

Current state
Use ML to identify and engage clients

Business value exploration
Classical + quantum ML identifies complex customer behavior relationships to better target and engage clients

Voice of our first adopters

Wells Fargo



Predicting time series and sequences

- Price formation
- Price volatility modeling
- Markets microstructure simulation
- Limit order book mid-price models
- Potential extension to credit risk processes

"Not engaging is not an option. ...We saw a line of sight for solving mathematical problems which would be a big **amplification of productivity**."

Chintan Mehta
CIO of Digital Technology and Innovation

Crédit Mutuel

As the first enterprise in France to join the IBM Quantum Network, Crédit Mutuel is partnering with IBM to explore quantum computing use cases in:

→ Customer and employee experience
→ Fraud management
→ Risk management

"Back in 2016, we were among the first financial institutions to apply artificial intelligence and its industrialization. Our ambition for quantum computing is similar: **to explore, then industrialize**, in order to further transform the banking and insurance businesses, all with the underlying goal of also keeping our customers' information secure."

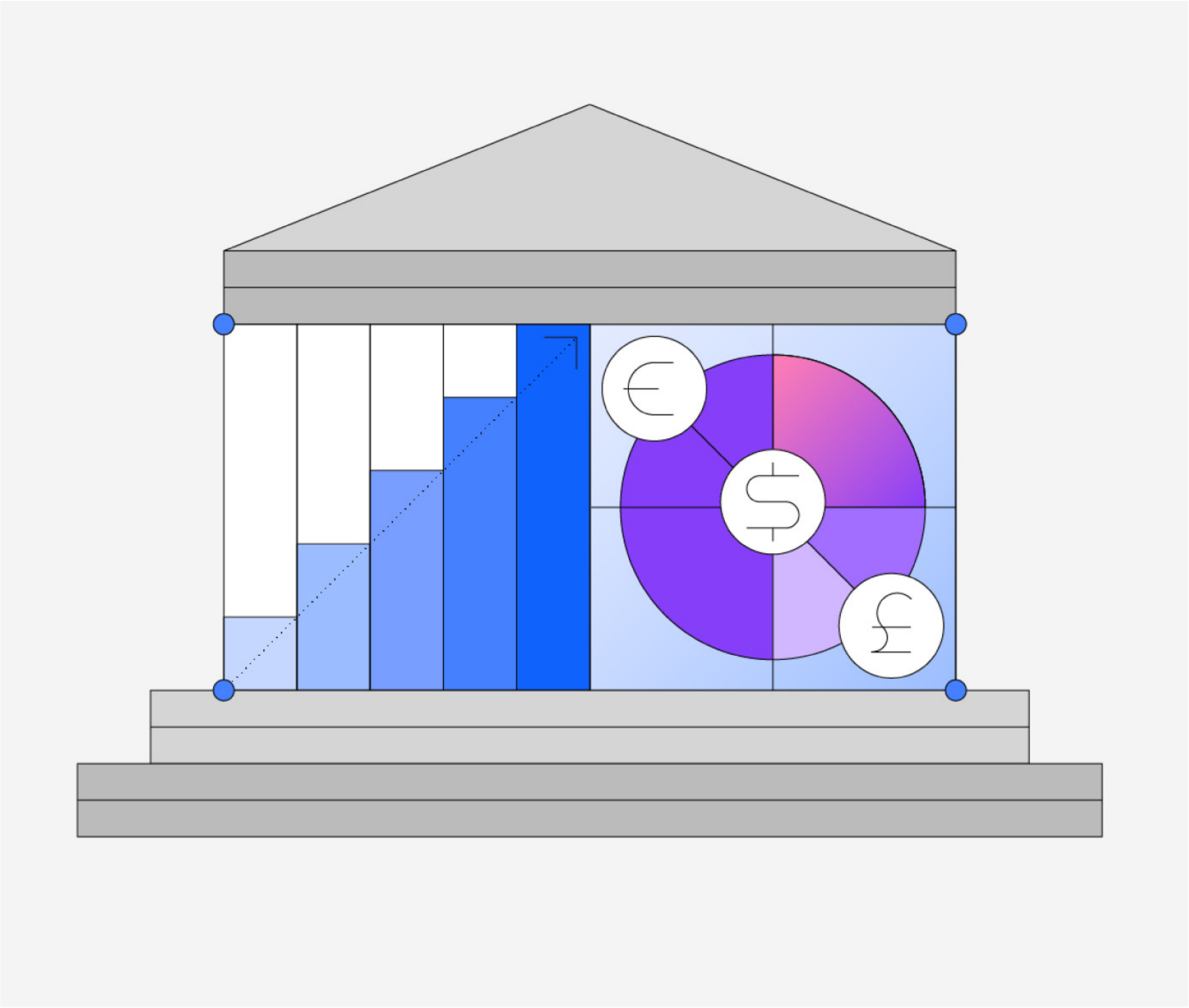
Nicolas Théry, President of Crédit Mutuel Alliance Fédérale, and Frantz Rublé, President of Euro-Information

Source: "Crédit Mutuel Alliance Fédérale and Euro-Information Collaborating with IBM to Shape the Bank's Quantum Future," IBM Newsroom, June 14, 2023.

Voice of our first adopters

HSBC

→ Pricing and portfolio optimization
→ Sustainability
→ Fraud management
→ Risk management



"This technology has the potential to transform how we run areas of the bank by addressing challenges which classical computers may never be able to solve, alone. Our work with IBM, a leading provider of quantum computing, is essential to harnessing this potentially game-changing technology for financial services."

Colin Bell, CEO of HSBC Bank and HSBC Europe

Quantum computing applications for financial services

Financial institutions in the IBM Quantum Network

And new FSS members in 2H 2024:

- → American Express
- → Banco Bradesco
- → Banco Itaú

Crédit Mutuel

Exploring quantum computing for banking and insurance use cases and starting workforce development

Erste Group

Using quantum computers to improve the accuracy and speed of complex calculations in risk management, fraud detection, and simulation

HSBC

Using quantum computing for pricing and portfolio optimization, to advance net zero goals, and to mitigate risks, including identifying and addressing fraudulent activity

Mizuho Bank

Major bank from Japan, a member of the Quantum Innovation Initiative Consortium (QIIC) by University of Tokyo

Truist Financial

A top-10 US commercial bank exploring industry-relevant applications of quantum computing

Wells Fargo

Using quantum computers to explore how advances in quantum computing can help make banking faster, easier, smarter, and safer

Derivatives pricing and risk

Financial services organizations typically model equity prices and price insurance premiums by using algorithms to generate random scenarios such as Monte Carlo paths.

Classical solution

Use many Monte Carlo simulations to compute the average of a stochastic process or use the Feynman-Kac partial differential equation to determine the average.

Quantum solution

Use a variational quantum algorithm for the Feynman-Kac formula to encode the financial derivative price (solution of the differential equation) in the amplitude of a quantum state.

Benefits of quantum

Initial explorations on an illustrative example found an exponential speedup over classical partial differential equation solvers and a 2% error rate with limited quantum resources.

https://arxiv.org/pdf/2108.10846

Customer experience/next best action

Business imperative

Providing memorable experiences by offering personalized recommendations and relevant next best actions, is essential for attracting and retaining customers.

Current state

Serving individualized content and making successful recommendations and offers is an evolving process that could be helped by new approaches.

Future state

Quantum computing may help by enabling more precise customer profiling, earlier identification of consumer needs, and timely next best action recommendations. QML algorithms used for classifications and forecasts may enable computational speedups from exploring exponentially large quantum state spaces.

Quantum computing applications for healthcare and life sciences

Quantum computing applications for healthcare

Optimizing healthcare operations and improving end-to-end patient experience

Treatment adherence

Prediction of medication persistence by systematically exploring regimes where quantum machine learning may perform better than classical machine learning.

Precision medicine

Quantum convolutional neural networks may optimize CAR T-cell therapy by better learning from limited experimental data compared to classical methods.

Early diagnostics

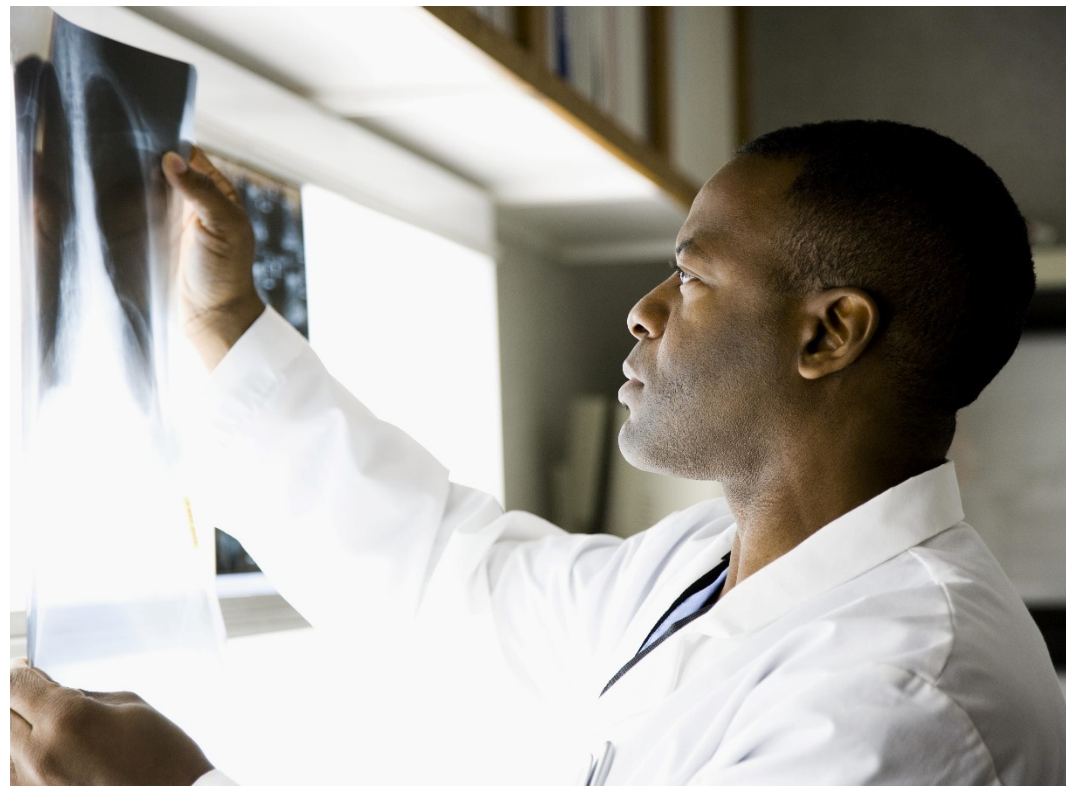
Heart diseases may be detected with quantum unsupervised machine learning and perform better than classical counterparts and supervised approaches.

Clinical trials

By applying multiple quantum machine learning algorithms and comparing with state-of-the-art classical machine learning, the best approach for predicting clinical trial site enrollment may be determined.

Fraud detection

Quantum classifiers may detect different patterns in data than classical methods. A hybrid quantum-classical machine learning model may perform best when detecting insurance fraud patterns.



Personalized medicine

Cancer immunotherapy

Business imperative

Improve patient outcomes with personalized medicine.

Current state

CAR-T therapy is a form of cancer immunotherapy that uses immune cells that are genetically modified to enable them to identify and destroy cancer cells more effectively. A cell's phenotype can be reprogrammed by engineering and combining different cell modular components, generating a vast, complex combinatorial design space that is difficult for classical computers to explore experimentally. Classical approaches also struggle due to the limited amount of data.

Business value exploration

Quantum neural networks may serve as higher accuracy computational models learning from limited experimental data.

Fraud detection

Healthcare insurance plans

Business imperative

Optimize insurance premiums and pricing with better risk and fraud models.

Current state

Machine learning attempts to keep fraud losses at a minimum. Better fraud detection models are created by including more data from more sources. The challenge is that healthcare fraud detection must strike a balance between detecting fraudulent activities and allowing legitimate customers by analyzing large and diverse data sources.

Business value exploration

Quantum machine learning may identify different patterns in data that are difficult for classical machine learning algorithms to recognize, potentially improving the detection of fraud patterns.

Clinical trial site selection

Business imperative

Currently, most clinical trials within the US fail to meet planned recruitment on time, and about one-third of clinical sites involved in a clinical trial fail to recruit a single subject.

Current state

Machine learning may be used to predict the success or failure to enroll patients at clinical trial sites. To achieve accuracy, machine learning models require a lot of high-quality data. However, clinical trial site data contains a high degree of missing values and correlated features, limiting accuracy for classical ML models.

Business value exploration

Quantum machine learning has shown promise for challenging datasets (small, noisy ones).

Virtual screening in drug discovery

Business imperative

Machine learning (ML) is used in virtual screening for discovering drug candidates in a faster and more cost-effective manner.

Current state

A conventional ligand-based virtual screening strategy consists of using ML algorithms to train a classifier that can identify potential drug candidates from a digitalized library of compounds. To achieve accuracy, ML models require a lot of high-quality data. However, when dealing with rare or new diseases such as COVID-19, the limited amount of training data can be challenging.

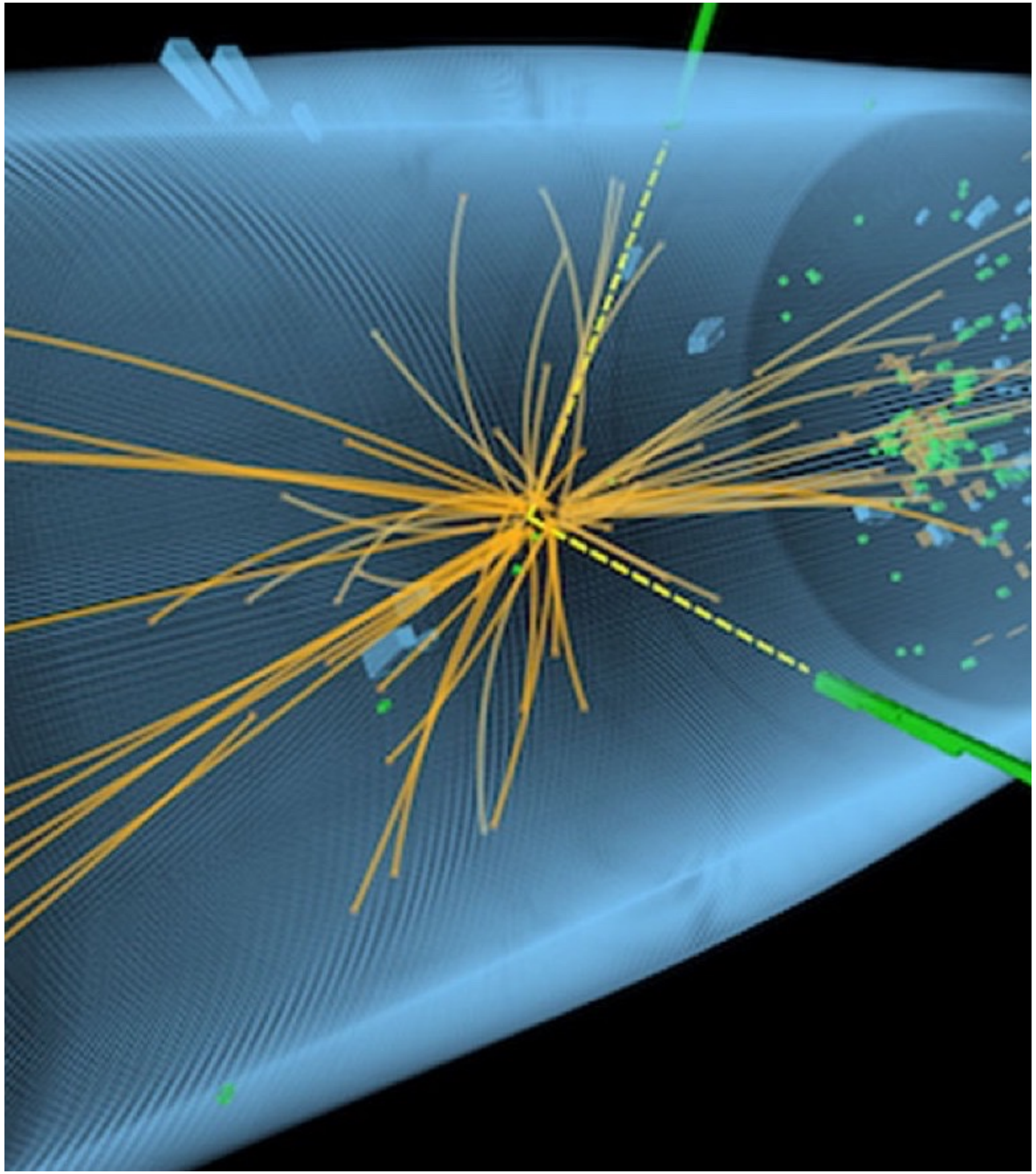
Business value exploration

In POC studies with limited data, quantum machine learning (QML) has shown increased accuracy compared to classical ML and deep learning algorithms.

CERN

- CERN and IBM are exploring how quantum machine learning algorithms can help find notable events in their vast datasets.

- We're using some of the smallest parts of the universe—the parts we do understand—to learn more about the smallest parts of the universe that we don't understand.



Quantum computing applications for the electronics industry

Electronics leaders join the IBM Quantum Network

Sony

Demonstrating quantum computing for image processing, mobile communications, and finance

arXiv:2108.10854
arXiv:2103.13211

LG Electronics

Applying quantum computing's potential to deliver advanced computation to electronics

arXiv:2111.03167

Tokyo Electron

Advancing state-of-the-art semiconductors with quantum computing

Dell Technologies

Exploring hybrid classical-quantum HPC and with Dell EMC HPCs and IBM Qiskit Runtime

[Exploring Hybrid Classical-Quantum Compute | Dell Technologies United States]

JSR

Modeling photoresists for semiconductor manufacturing and new light sources for flat panel displays

arXiv:2208.02414

Bosch

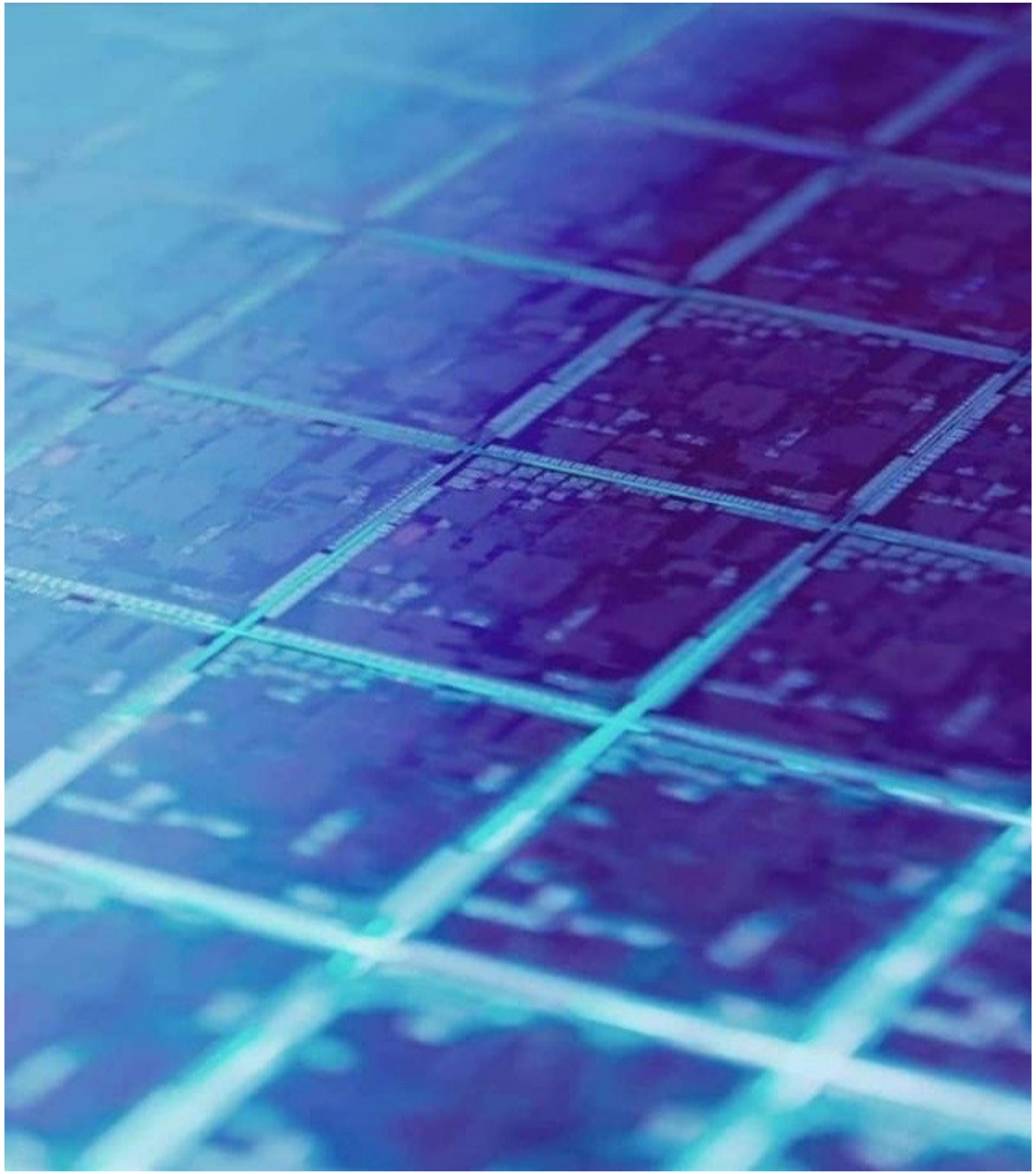
Demonstrating the materials science of fuel cells, electric engines, and advanced sensors on quantum computers

JSR

- JSR and IBM are experimenting with chemical simulations to help improve the development and manufacture of photoresists.

- We’ve already demonstrated that we can simulate small molecules that mimic parts of the photoresist.

- We hope that simulations like these will help us realize even faster chips.



Brighter, more energy-efficient displays

JSR and Mitsubishi Chemical

- JSR, Mitsubishi, and IBM modeled the electronic structure of OLED molecules that have the potential for **100% internal quantum efficiency**

- Conventional OLED emitters are inherently limited to 25% internal quantum efficiencies

Source: Computational Materials 7.1 (2021): 70.

Battery design and development

Business imperative

Accelerating the discovery of higher performance and lower cost batteries is essential for the manufacturing of more efficient and more profitable electric vehicles (EV).

Current state

Battery development relies on labor- and time-intensive empirical techniques. The order of magnitude time to develop new materials is ~10 years.

Business value exploration

Quantum chemistry simulations may help shorten the battery cycles by conducting the material and design exploration computationally. The potential benefits include higher-capacity, lighter-weight, lower-cost batteries and faster time to market.

Battery remaining useful lifetime

Business imperative

Predicting the remaining useful lifetime of a battery is challenging. Underestimation needlessly wastes battery value, while overestimation can cause unexpected battery failure and safety issues.

Current state

Machine learning (ML) models require a lot of training and data, which can be time-consuming and expensive to obtain, particularly for products whose useful lifetimes are on the order of years.

Business value exploration

Quantum machine learning (QML) models on some datasets have demonstrated greater accuracy and faster learning with less data than classical methods, thus able to achieve better results while reducing development time and cost.

Quantum computing applications for the automotive industry

Quantum computing applications for automotive

Enhancing product design through materials simulation and optimizing manufacturing

Battery design

Using quantum computers to model material systems critical to battery performance may enhance battery design and development processes.

Design optimization

Quantum computers are being applied to topology optimization problems to explore the potential to enhance product design.

Quality control

Smart quality analytics based on ML/QML may help identify defects early in the production process and with higher accuracy, reducing the cost of scrap and rework.

Production optimization

While fault detection and classification suffers from high false positive rates, quantum machine learning methods may be explored to potentially increase manufacturing uptime.

Predictive maintenance

We are exploring the potential to build predictive/reliability models for complex systems by leveraging quantum machine learning and quantum simulation algorithms.

Mercedes-Benz

Materials discovery and manufacturing optimization

Mercedes-Benz and IBM have published a series of papers demonstrating progress toward using quantum computers to model material systems, including lithium-sulfur, that are relevant to advancing the performance of batteries.

The teams are also exploring applications in manufacturing defect analysis and product recommendation.

- Journal of Chemical Physics 154.13 (2021): 134115.
- Nature 567.7749 (2019): 491-495.
- arXiv:2004.00957

"Developing and perfecting these hypothetical batteries could unlock a billion-dollar opportunity."

Benjamin Boeser
[Former] Director of Innovation Management
Silicon Valley at Mercedes-Benz R&D America

Quality control

Business imperative

Quality control is a foundational part of the modern automotive manufacturing process, ensuring the safety and comfort of the drivers for years on the road.

Current state

Quality control requires laborious and time-consuming efforts. The current classical AI algorithms could produce a high number of false positive and false negative defect identifications in practical time frames. Manual inspections carry high risks of human error.

Business value exploration

Quantum machine learning and neural network algorithms may help in quality inspections by identifying defects and anomalies faster and with higher accuracy.

Higher manufacturing uptime

Business imperative

The uptime of the production line is one of the most important metrics in manufacturing. When the production line is interrupted, costs continue to accrue, while product is not produced.

Current state

Fault detection and classification (FDC) suffers from high false positive rates. Data is often difficult, time-consuming, and expensive to obtain. This is particularly true for highly imbalanced datasets, such as FDC, where the ratio of non-faults to faults can exceed 10,000:1.

Business value exploration

Quantum machine learning models have demonstrated higher accuracy on smaller datasets.

Predictive maintenance

Business imperative

Maintenance and health management of complex systems is key to cost reduction and asset availability improvement.

Current state

Most of the predictive/reliability solutions focus on sub-systems due to the inherent complexity of the mathematical models employed in the system of systems analysis and simulation.

Business value exploration

We are exploring the potential to build predictive/reliability models for complex systems by leveraging quantum machine learning and quantum simulation algorithms.

Factory scheduling optimization

Business imperative

Maximizing equipment utilization in production processes is important to optimizing manufacturing throughput and increasing revenue.

Current state

Production scheduling currently requires the solution of classically intractable computational problems (for example, combinatorial problems like car sequencing, job-shop scheduling). Dispatch rules are generally used to find feasible solutions that may be far from optimal.

Business value exploration

Quantum scheduling optimization has the potential to identify more optimal solutions and lead to more efficient production schedules.

Quantum computing applications for aerospace and defense

Delta Air Lines

Gate scheduling optimization

Optimizing large combinations of cargo and passenger traffic among the planes, gates, personnel, and the air traffic flows originating and terminating at an airport helps airlines to control costs and reduce inefficiencies.

Delta and IBM partnered to explore the application of quantum computing to airline gate-scheduling quadratic assignment problems (QAP).

The team applied the variational quantum eigensolver (VQE) with a new space-efficient quadratic unconstrained binary optimization (QUBO) algorithm that maps a *k*-coloring problem to a lower number of qubits.

https://arxiv.org/abs/2111.09472

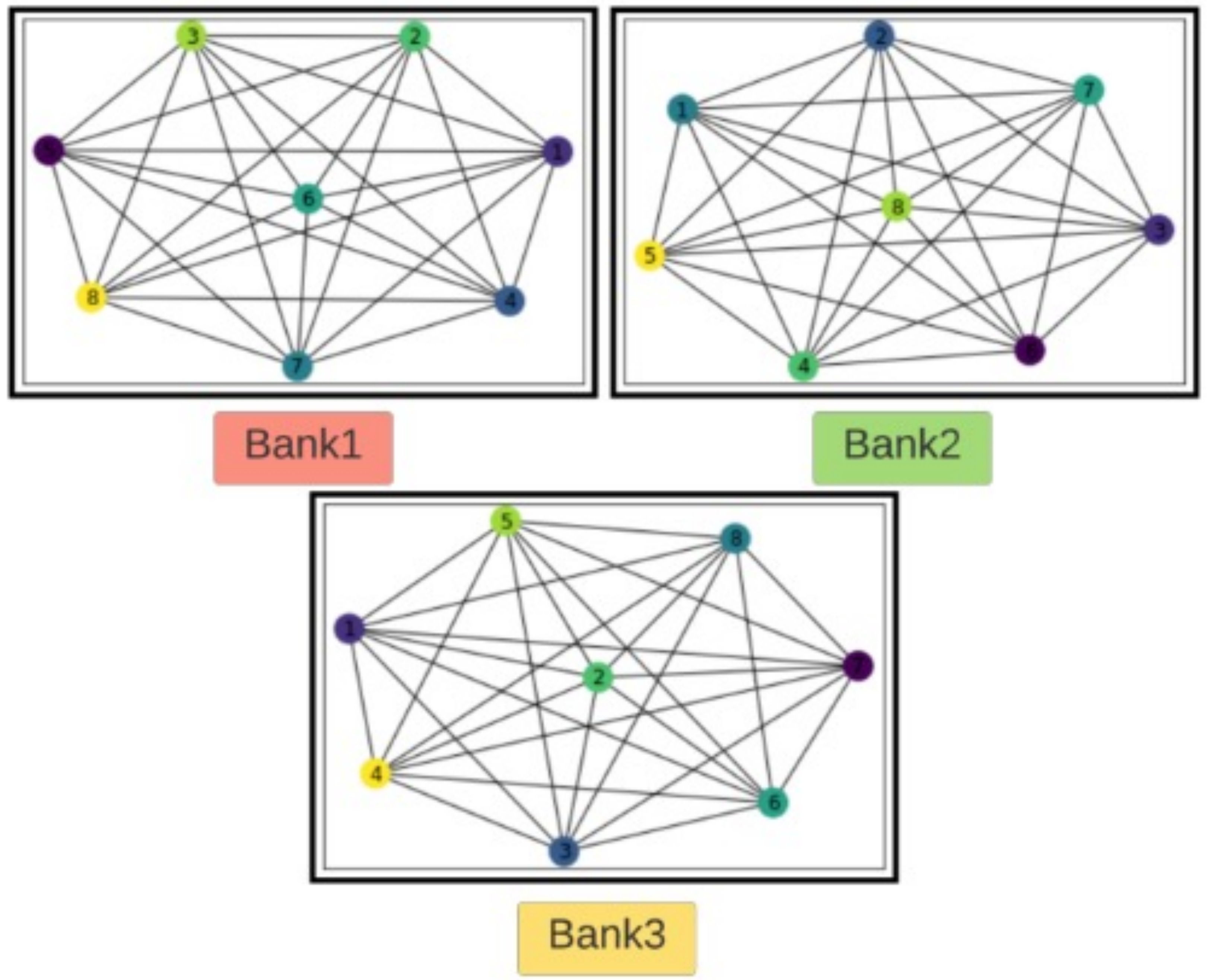


Figure 4 Quantum simulation results for 24 flights and eight gates. The graph successfully colored by the applying the efficient embedding technique.

Table 1 Comparison between the standard QUBO and the efficient embedding approaches

	Standard Embedding	Efficient Embedding
# Qubits	$n \times k$: 25	$n \times log(k)$: 15
Circuit Depth	29	19
Run-time (sec)	5569.84	395.48

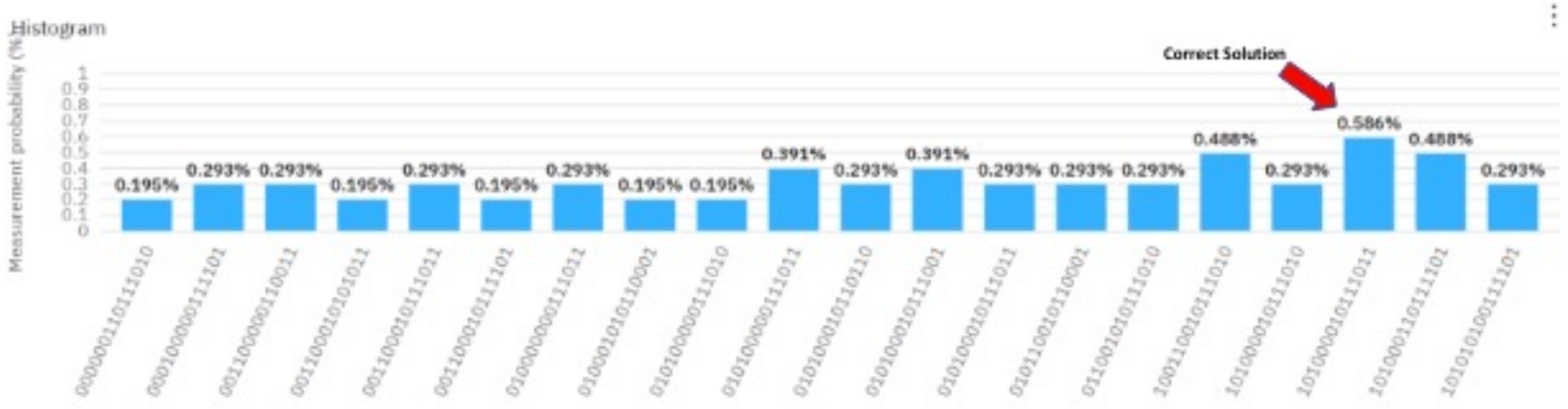


Figure 6 Hardware results with the measurement probabilities for a bank with eight flights and eight gates.

Boeing

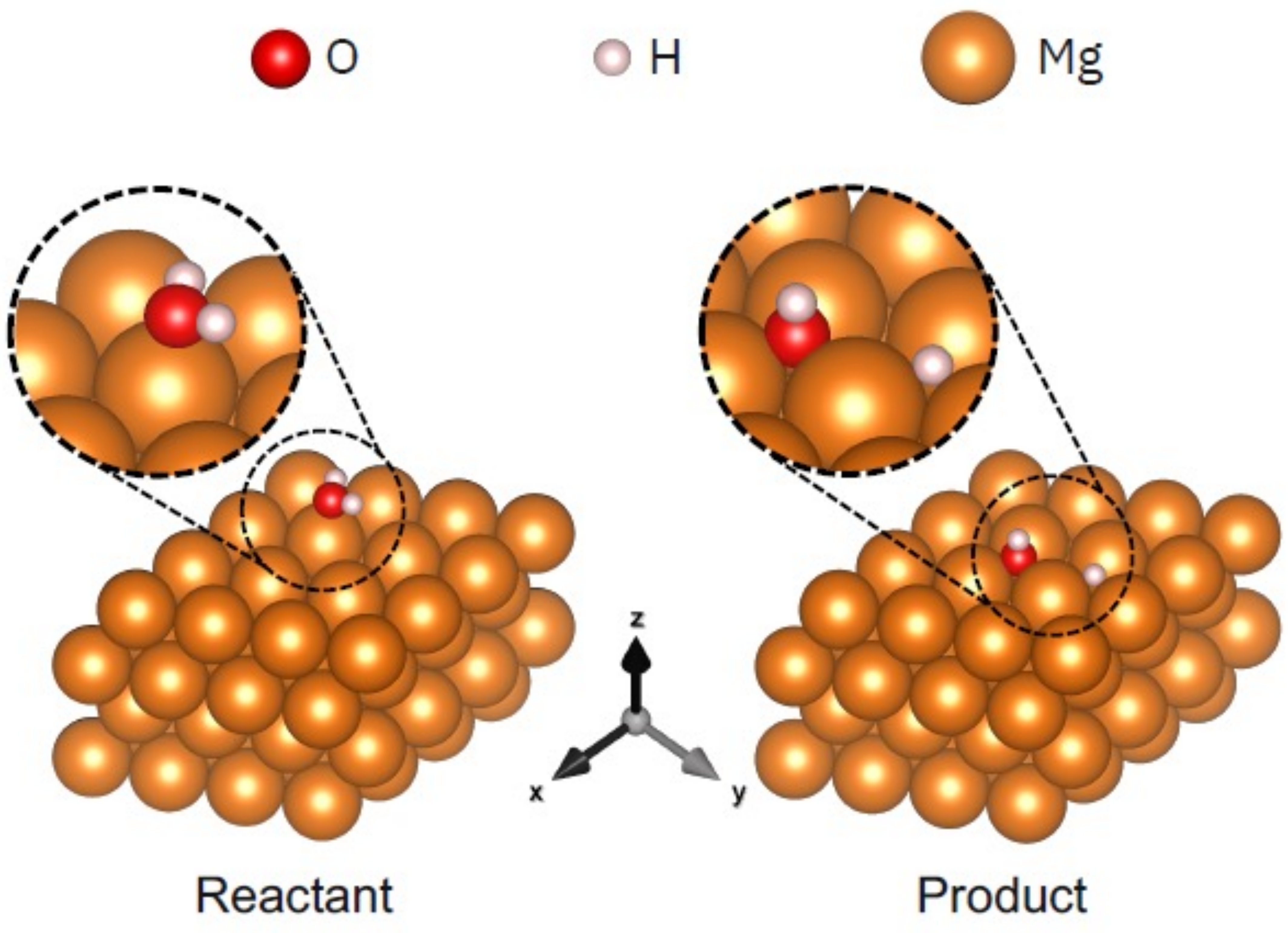
New materials qualification

IBM and Boeing model corrosion reactions for magnesium, the lightest structural metal

Magnesium has the potential to improve the weight of critical aerospace structures. However, magnesium reacts with water and corrodes readily.

IBM simulated the reaction of water with magnesium to better understand its reaction mechanisms to explore the possibility of lighter, higher-performance aerospace structures.

$$Mg + H_2O \rightarrow Mg(OH)_{ads}(H)_{ads}$$



arXiv:2203.07536

Exoplanet discovery

Business imperative

With new and advanced telescopes, data in astronomy is growing at a fast pace. Conventional methods to discover exoplanets that involve human judgment are not efficient and are prone to variability depending on the investigating expert.

Current state

Commonly used data analysis techniques for exoplanet detection with the transition method produce many false positives in the case of noisy data. These false positives must be reviewed manually.

Business value exploration

Quantum machine learning methods may help improve the classification accuracy of exoplanet candidates and reduce the rate of false positives.

Satellite image classification

Business imperative

Earth observation imagery plays numerous crucial roles, such as monitoring agriculture, water management, and climate change.

Current state

Hundreds of terabytes of images are collected daily. Correctly classifying these images is a first step in deriving useful information.

Business value exploration

Quantum computing may enable more accurate satellite image classification, which in turn can allow faster and more accurate management of crucial resources.

Rare events detection

Business imperative

The success of searches for new physics or for unknown objects in space depends on the detection of extremely rare signals that are hard to characterize upfront.

Current state

Classical machine learning methods for anomaly detection are widely used in system monitoring, healthcare, and cybersecurity. Their accuracy depends on size, quality, and signal to background ratio of the training dataset.

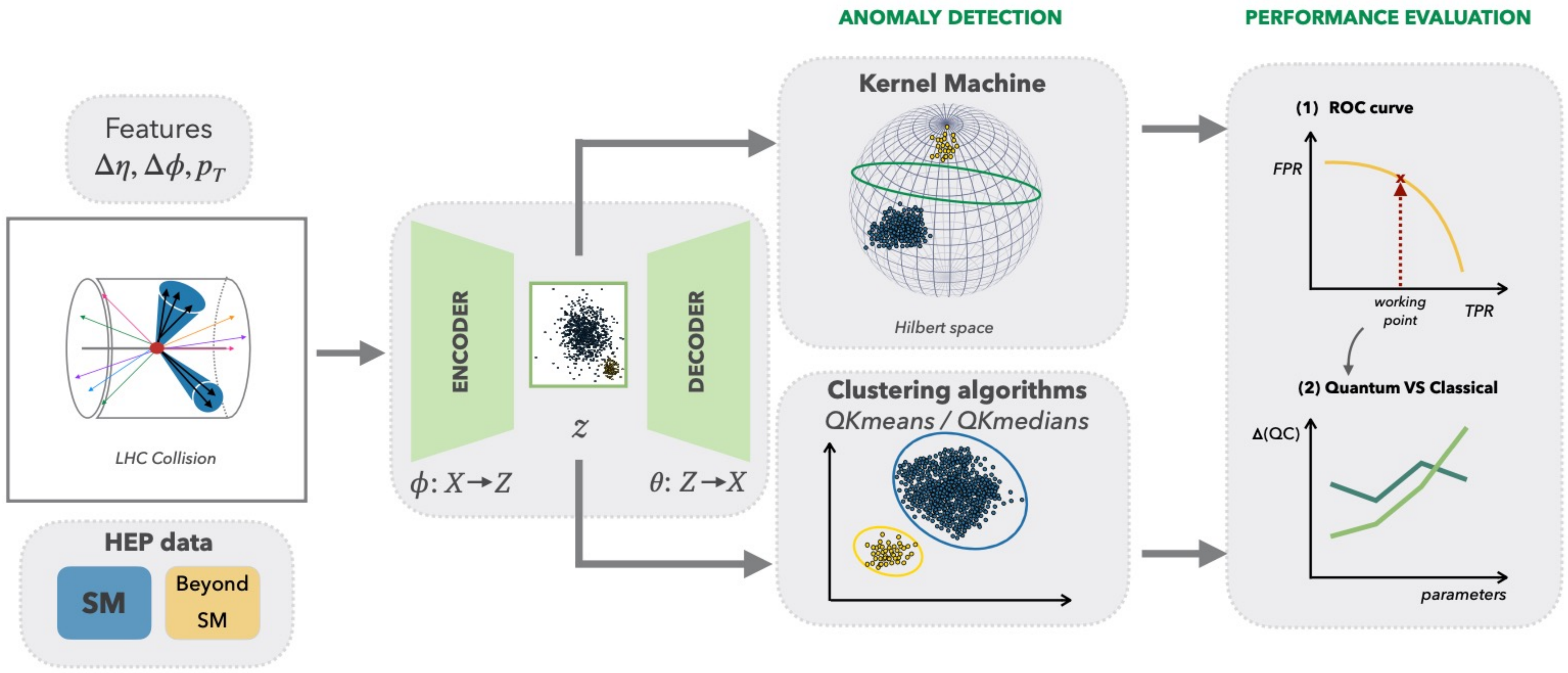
Business value exploration

Quantum machine learning models may complement classical models and improve the detection accuracy of rare events.

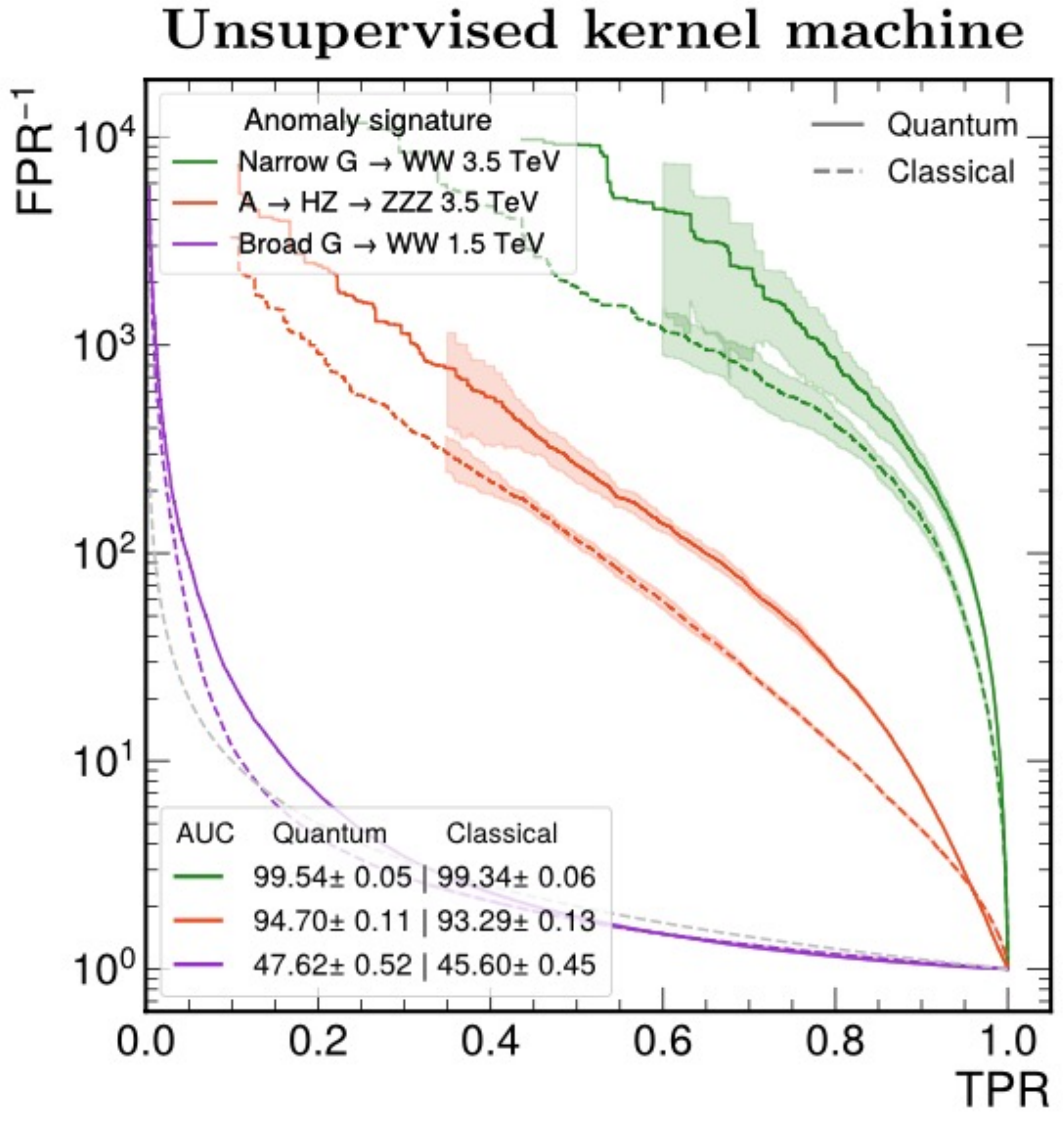
Model-independent rare event detection

- Quantum machine learning has been used to analyze data from the Large Hadron Collider focusing on jets, sprays of hundreds of particles generated from collisions.
- A classical autoencoder was used to compresses raw jet features to a tractable size; then a set of unsupervised classical and quantum algorithms were trained on the latent-space features.
- Quantum kernel methods demonstrated higher accuracy for this problem and a higher background rejection than classical methods.
- Note: Accuracy advantages are dataset specific.

https://arxiv.org/abs/2301.10780



Classical-quantum workflow: data from the LHC is passed through an autoencoder for dimensionality reduction; then classical and quantum anomaly detection models are trained.



The quantum kernel model performs better than classical models on all SM anomaly signatures

Background rejection

Working point	Latent dim.	Quantum	Classical
$\varepsilon_b^{-1}(\varepsilon_s = 0.8)$	16	38.64 ± 2.30	7.54 ± 0.30
	8	27.70 ± 1.06	11.68 ± 0.33
$\varepsilon_b^{-1}(\varepsilon_s = 0.6)$	16	121.35 ± 14.25	41.07 ± 2.59
	8	138.65 ± 13.10	58.92 ± 5.44

Quantum models show much higher background rejection capabilities than classical methods.

Quantum computing applications for logistics

Quantum computing applications for logistics

Optimizing routing and scheduling and enhancing insights for business strategy

Last mile delivery and multimodal transport

Quantum computers may be capable of supporting global routing optimization and more frequent re-optimization. This may improve decision making and increase revenue.

Vehicle routing and scheduling

Quantum computers could potentially provide better solutions to vehicle routing and scheduling problems with large and complex datasets than classical solvers like CPLEX.

Predictive demand forecasting

Quantum computers may improve demand forecasting by using more efficient machine learning techniques through better customer classification or patterns detection.

Global supply chain optimization

Quantum computing may enable complex, global, and rapid optimization of the global supply chain, leading to more profitable procurement, production, storage, distribution, and transportation operations.

Disruption identification and mitigation

Quantum computers may help reoptimize or simulate the impacts of disruptive events to improve decision making and reduce recovery time.

ExxonMobil

Routing optimization

In 2021, more than 500 liquified natural gas (LNG) ships were used to transport critical fuel supplies across the oceans. Together, they make thousands of journeys per year to destination ports where the LNG is deployed to power critical infrastructure.

Finding optimal routes for a fleet of such ships can be a mind-bendingly complex optimization problem.

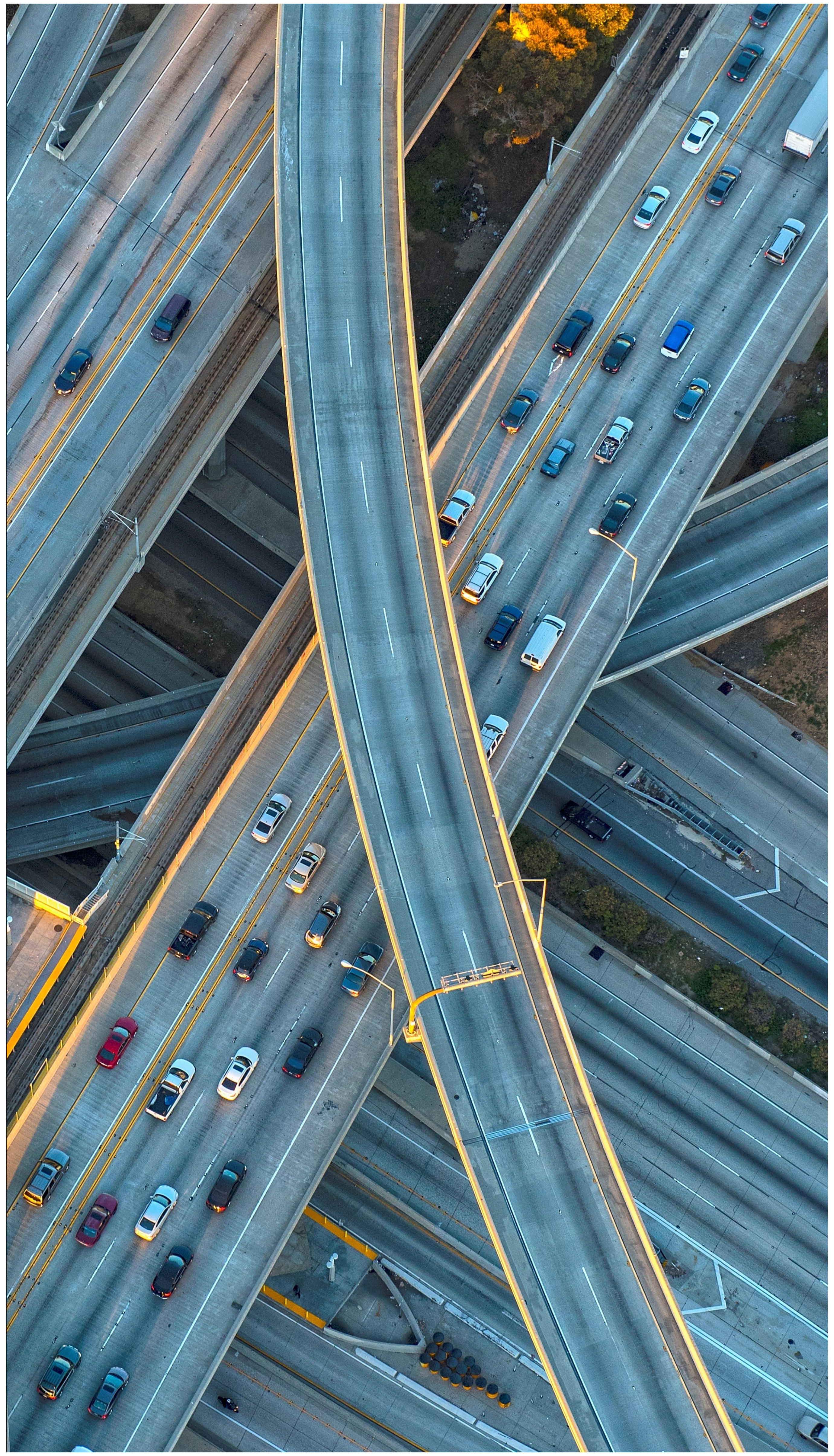
https://www.ibm.com/case-studies/exxonmobil/
https://arxiv.org/abs/2003.02303v2
IEEE Trans Quantum Engineering, vol. 2, p. 1

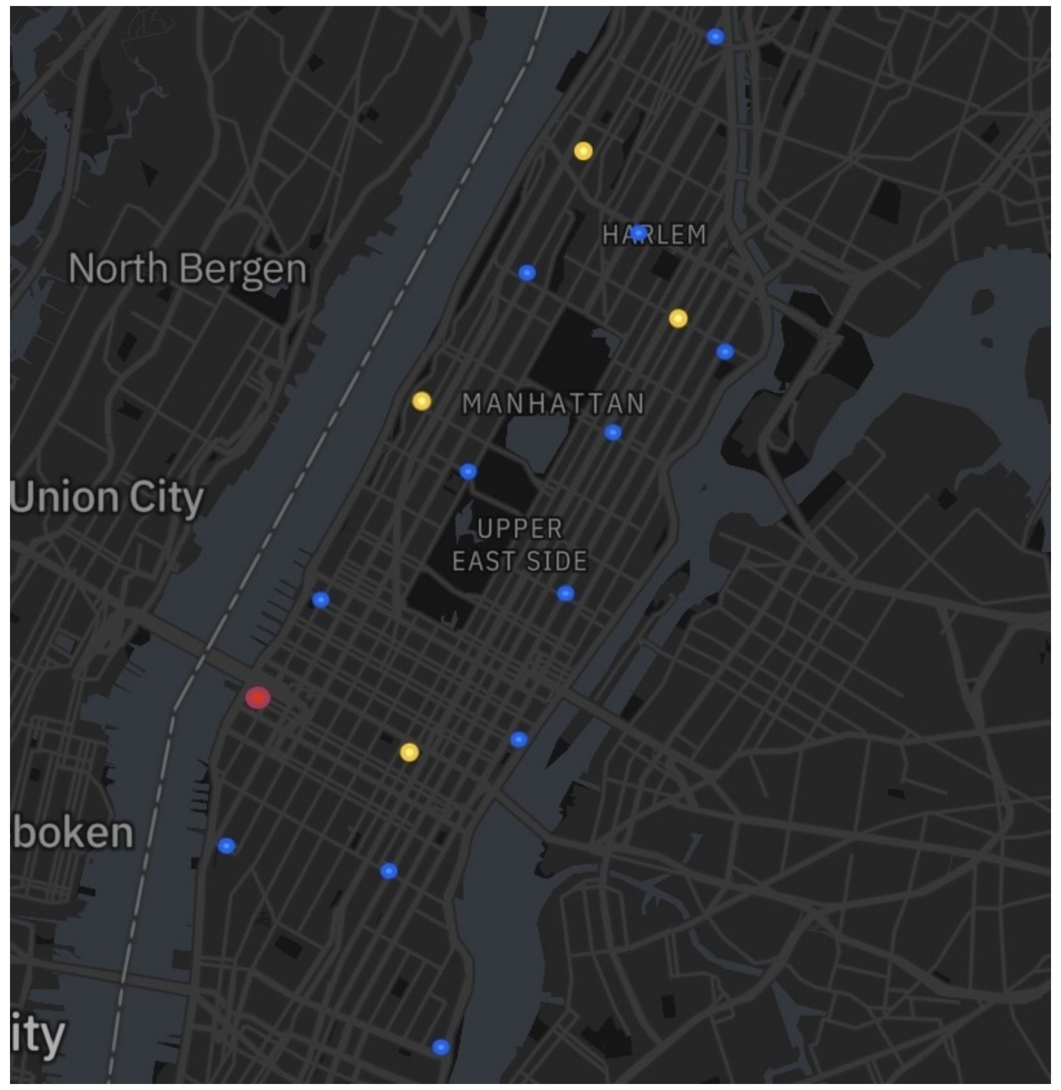
Quantum computers take a new approach to addressing this sort of complexity, with the potential to find solutions that classical supercomputers alone cannot handle. Industry leaders like ExxonMobil are getting involved now to explore how blending classical and quantum computing techniques might solve big, complex, pressing global challenges.

Hyundai

Vehicle routing and scheduling optimization

EV Navigation (eVRP)
Network traffic optimization
Supply chain optimization
Shared mobility





Three key trends in the oil and gas industry

1

Carbon reduction and transition to new energy sources in response to market and regulatory changes have companies scrambling to find carbon neutral paths to energy production.

2

Companies are transitioning to data-driven development that leverages existing digital assets to make critical decisions quickly and more accurately.

3

Margins are tightening on downstream products, forcing the industry to react to market, regulatory, and supply chain fluctuations optimally and profitably.

Quantum computing applications for the oil and gas industry

→

Emissions reduction

Accelerate innovation of sustainable products and carbon sequestration.

Reservoir development

Drill and produce on the best well locations.

Profitable refining

Integrate the management of complex and volatile supply chains.

Additional applications to consider

Optimization of power grids, supply chains and pipelines

Investment optimization

Risk management through better scenario modeling

Complex seismic imaging solutions

Security in data, information technology, operational technology, and IoT

Chemical design for cleaner energy

E.ON

E.ON is partnering with IBM to drive the transformation of the energy industry with quantum computing.

Their goal is to explore the potential of quantum computing to optimize the world's rapidly decentralized energy infrastructure.

Some areas under consideration are whether quantum computing could be used to help control grid-connected renewable energy systems and to optimize electric car charging processes.

Woodside Energy

Since 2019, Woodside Energy has been working with IBM to explore the potential for quantum computing and AI to help realize its vision of an intelligent plant.

“We are deploying advanced technologies to capture, analyse and use all available data as we progress our Burrup Hub growth plans, reducing costs and risk whilst improving reliability and production performance. **The relationship with IBM has been a crucial part of our work in artificial intelligence and will now assist us to build capability in quantum computing.”**

Peter Coleman
CEO, Woodside Energy

IBM **Quantum**