Quantum Computing Journey

Technology Advances and Contributions to a Growing Research Community in South Africa

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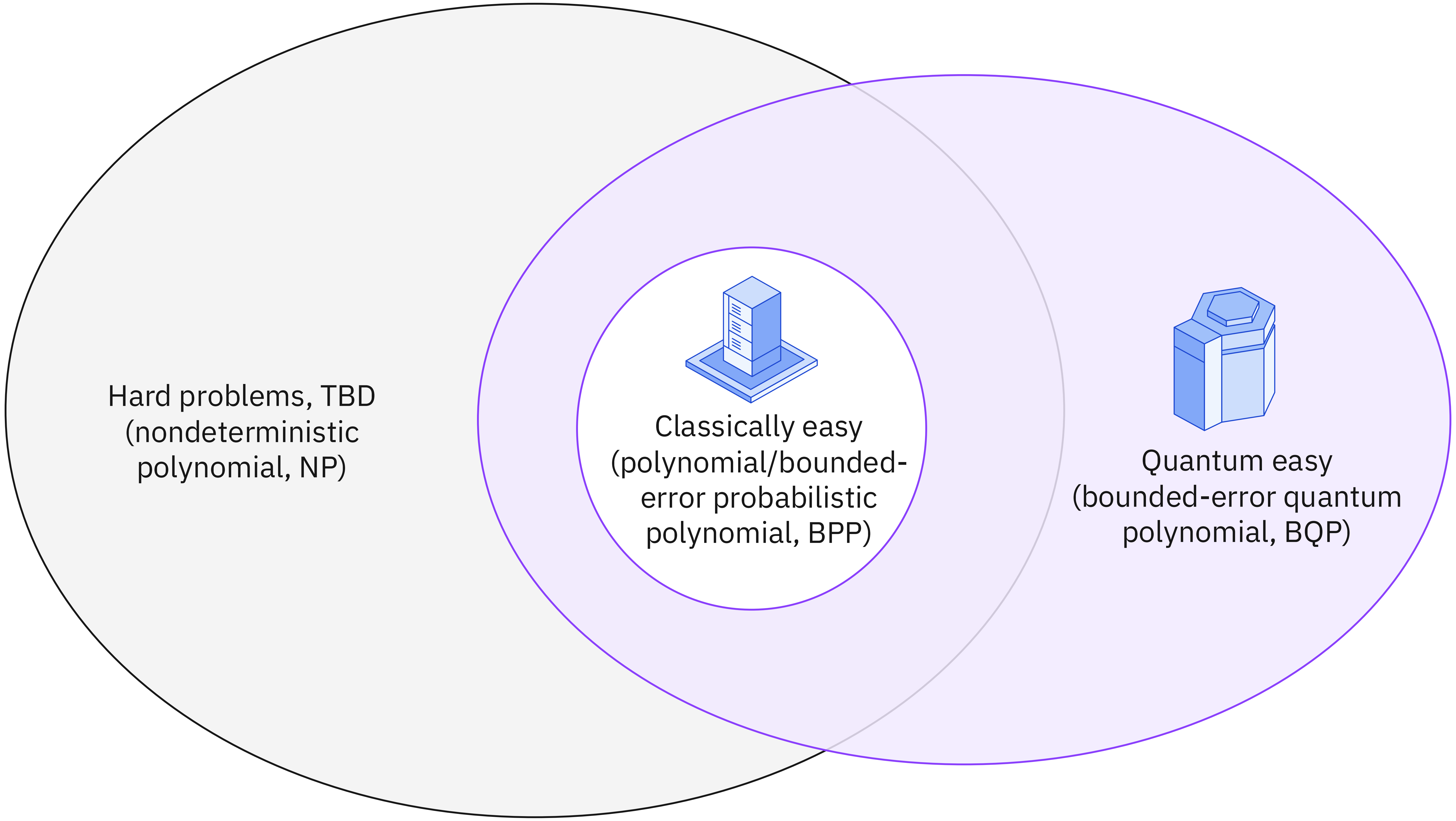
IBM **Quantum**

IBM

→ Bring useful quantum computing to the world

→ Make the world quantum safe

In all the data-driven sciences, there are complex problems beyond the reach of classical computing. These are the problems that quantum computing was designed to solve.



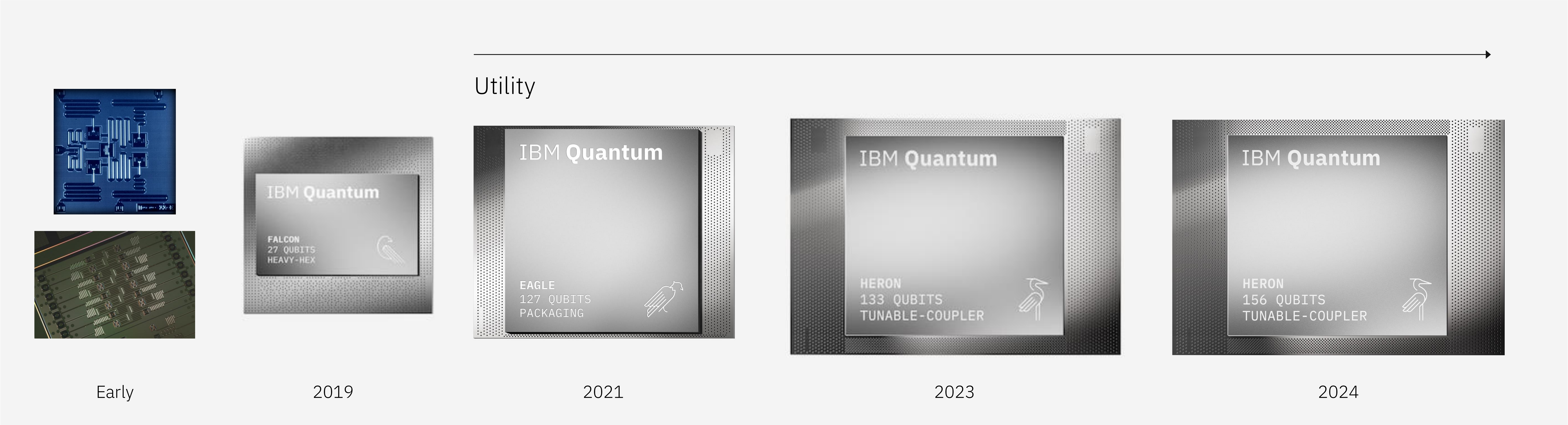
Two key prerequisites for bringing useful quantum computing to the world

Developing a quantum platform that scales beyond classical computation

Activating a network of enterprises and academic institutions to advance algorithm discovery

The era of quantum utility

We have transitioned from quantum devices for studying quantum to quantum computers that enable scientific research with quantum



Since 2016, IBM has publicly deployed:
- √ 60 quantum devices (<100 qubits)
- √ 25 quantum computers (>100 qubits) that can run circuits with >5000 two-qubit gates

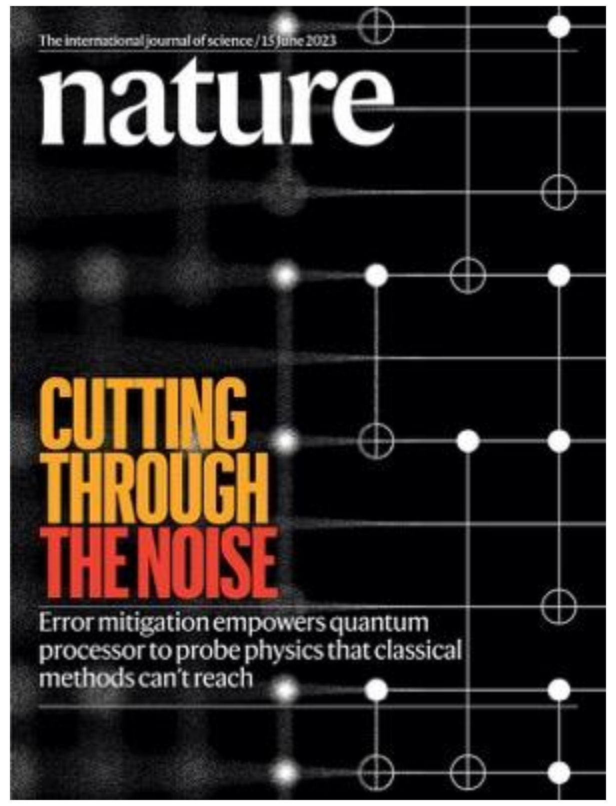
Utility vs. Advantage

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 solve a problem more accurately, cheaper, or more efficiently than classical computing alone

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

Read the white paper → https://ibm.biz/QA-whitepaper
Read the blog → https://ibm.biz/QA-blog

01

Run quantum circuits accurately on quantum hardware

100+ qubit systems and software

Methods that provide execution of quantum circuits on hardware with higher accuracy

02

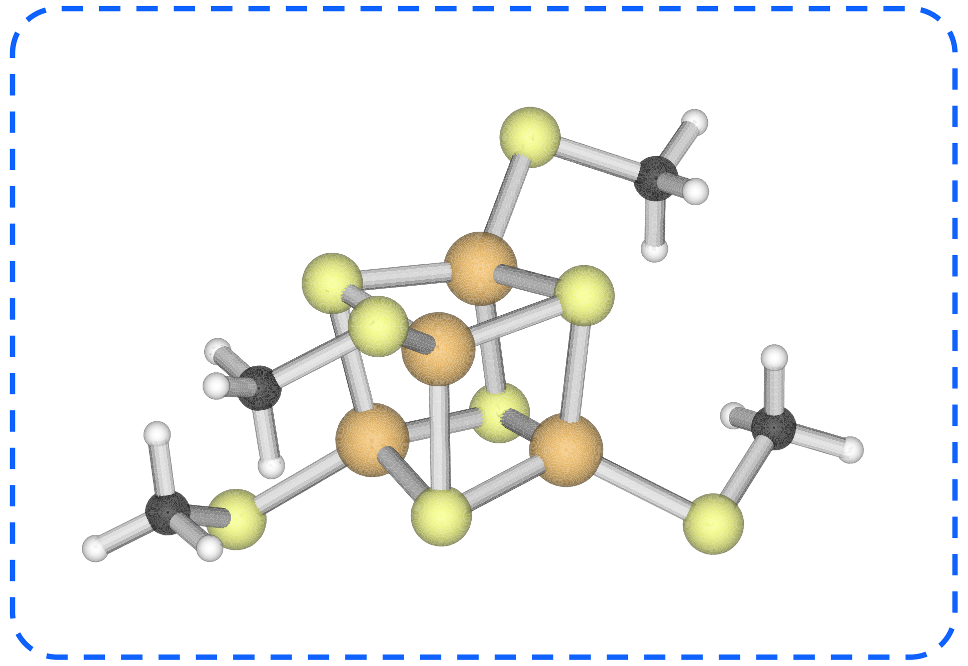
Map interesting problems to quantum circuits

Computational tasks that use those circuits

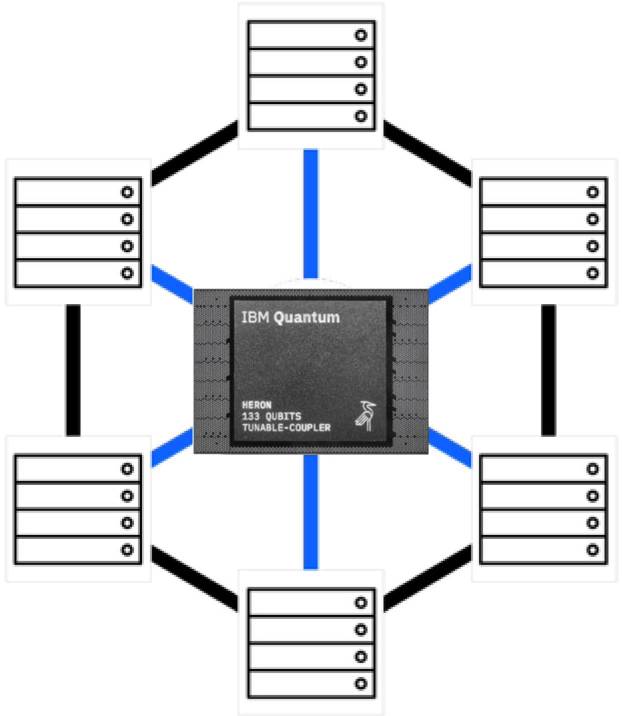
Industry and science applications that use those tasks

What are these problems?

Modeling molecules, atoms, electrons, and quarks with unprecedented accuracy



[4Fe-4S] using an active space of 54 electrons in 36 orbitals from the TZP-DKH basis set



$$H\Psi = E\Psi$$

Classical approximate method (DMRG)	8 hours[2,3]
Quantum method (QCSC)	12 min using 77 qubits + 1.5 hours supercomputer time[1]

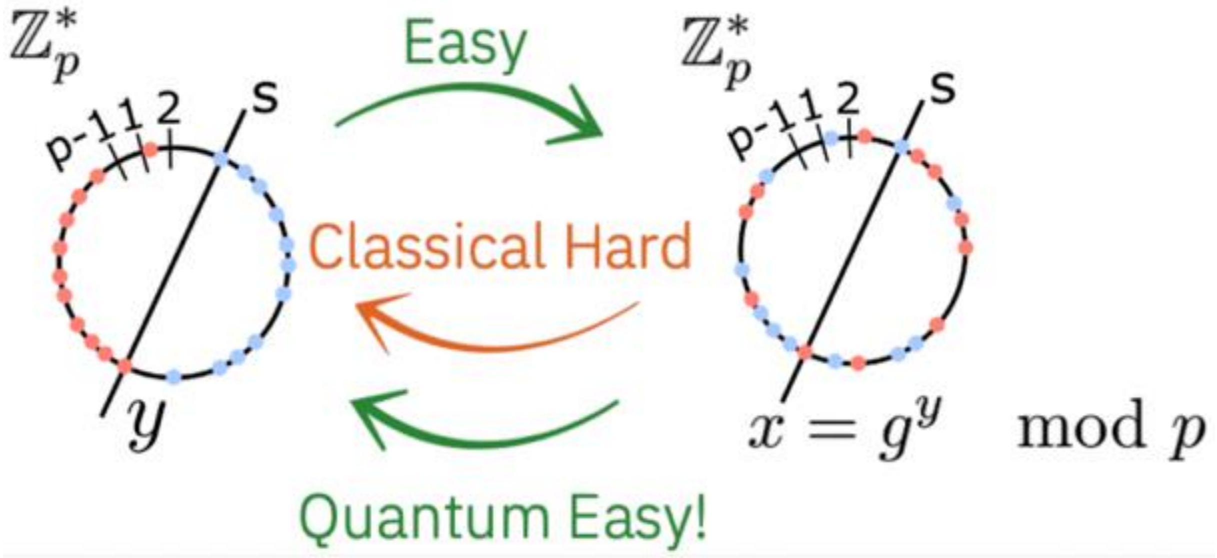
We are already using quantum (Heron, 77 qubits) and HPC (Supercomputer Fugaku) to achieve results comparable with the best classical approximate methods (DMRG) in accuracy and timing

1. Science Advances vol. 11, no. 25 (2025)
2. J. Chem. Theory Comp. 20 (2024): 775–786
3. J. Chem. Phys. 159, 234801 (2023)

What are these problems?

Solving algebra in [exponential] spaces.
Finding hidden patterns in structured problems.

Groups encode symmetries and transformations of data.



$$f(g\mathbf{b}) = f(g) \qquad \forall\, \mathbf{b} \in B$$

$$\frac{1}{\sqrt{|G|}}\sum_{g\in G}|f(g)\rangle|g\rangle = \sqrt{\frac{|B|}{|G|}}\sum_{g_0\in G/B}|f(g_0)\rangle\frac{1}{\sqrt{|B|}}\sum_{\mathbf{b}\in B}|g_0\mathbf{b}\rangle$$

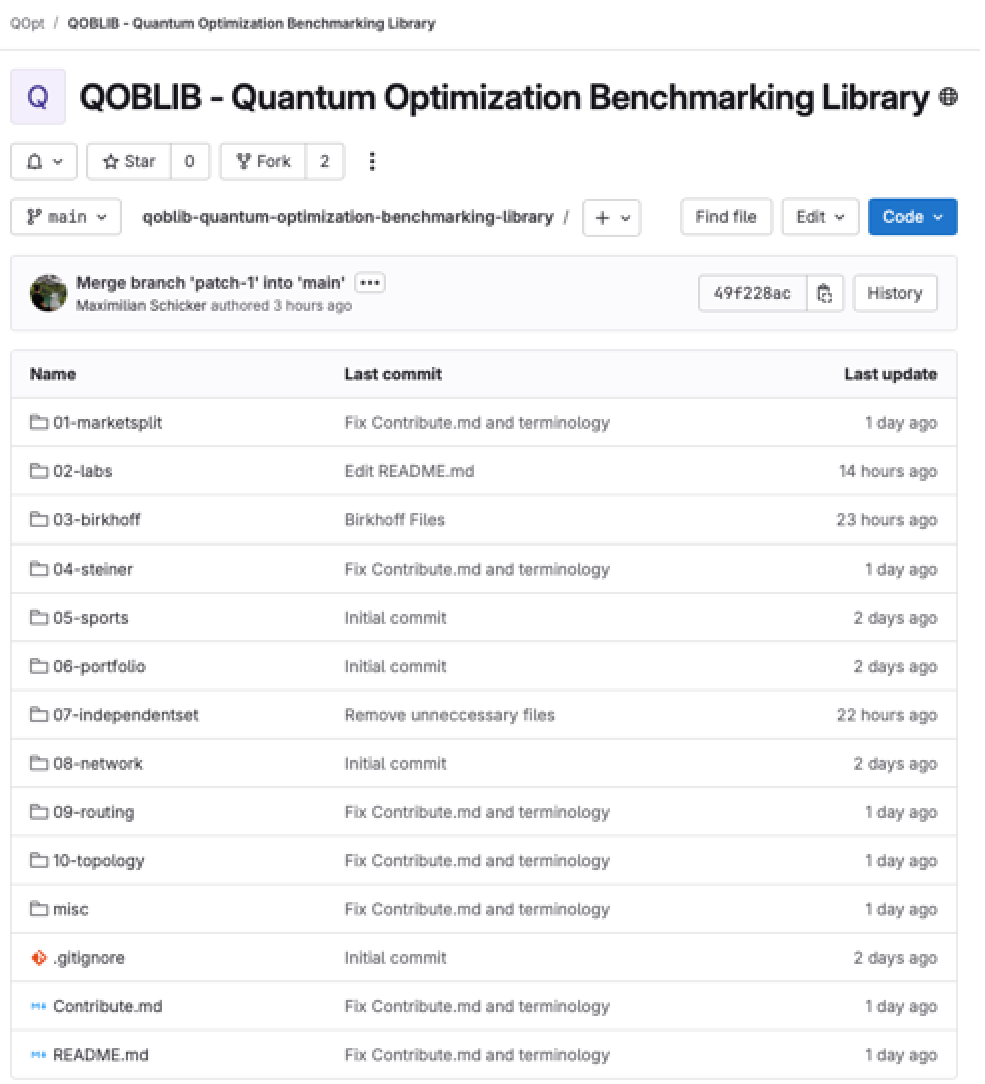
Quantum computers speak the mathematics of group theory and work in the large spaces needed to answer difficult computational problems inaccessible to classical methods.

Optimization

Finding problem solutions within various constraints

Benchmarking library

Optimization Working Group



QOpt / QOBLIB - Quantum Optimization Benchmarking Library

QOBLIB - Quantum Optimization Benchmarking Library

Star 0 Fork 2

main qoblib-quantum-optimization-benchmarking-library / Find file Edit Code

Merge branch 'patch-1' into 'main'
Maximilian Schicker authored 3 hours ago 49f228ac History

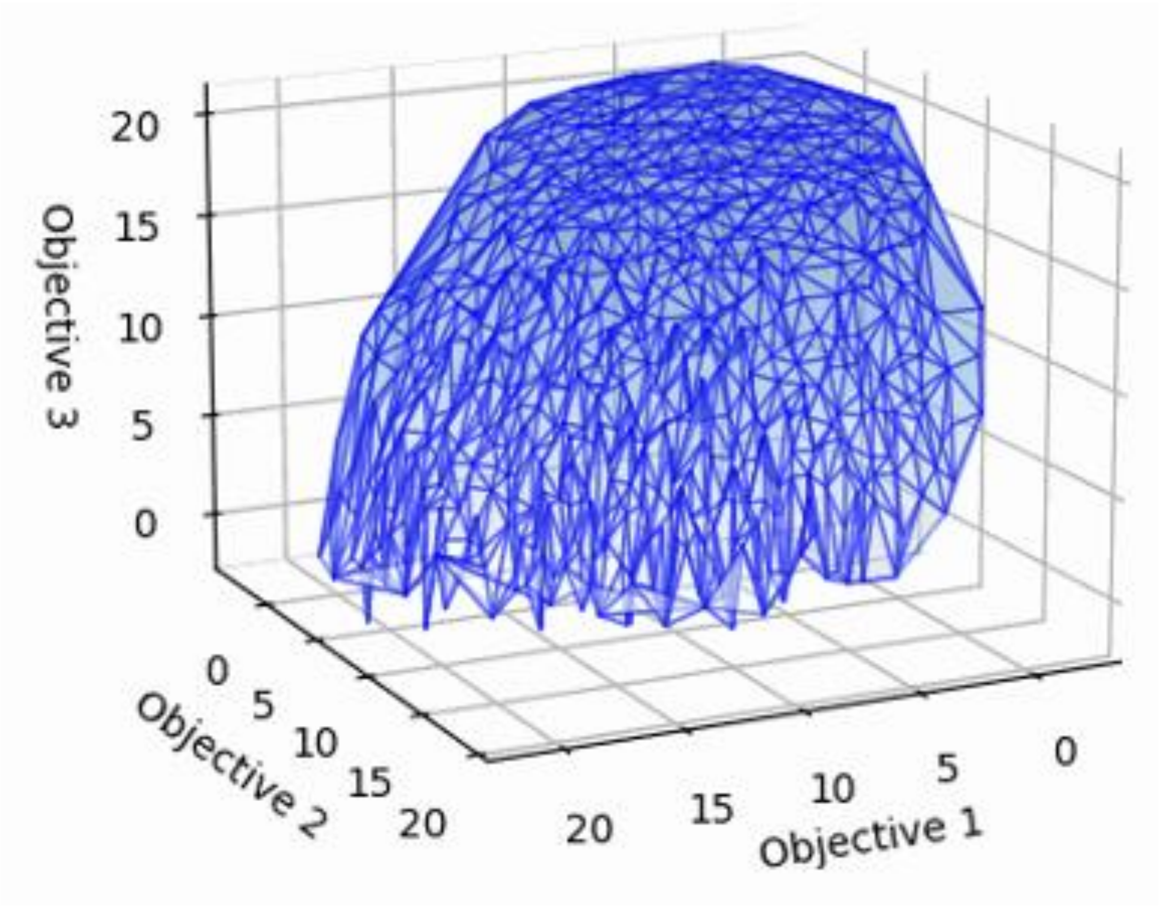
Name	Last commit	Last update
01-marketsplit	Fix Contribute.md and terminology	1 day ago
02-labs	Edit README.md	14 hours ago
03-birkhoff	Birkhoff Files	23 hours ago
04-steiner	Fix Contribute.md and terminology	1 day ago
05-sports	Initial commit	2 days ago
06-portfolio	Initial commit	2 days ago
07-independentset	Remove unneccessary files	22 hours ago
08-network	Initial commit	2 days ago
09-routing	Fix Contribute.md and terminology	1 day ago
10-topology	Fix Contribute.md and terminology	1 day ago
misc	Fix Contribute.md and terminology	1 day ago
.gitignore	Initial commit	2 days ago
Contribute.md	Fix Contribute.md and terminology	1 day ago
README.md	Fix Contribute.md and terminology	1 day ago

Identifying candidate problem classes that are challenging classically

arXiv:2504.03832

Multi-objective optimization

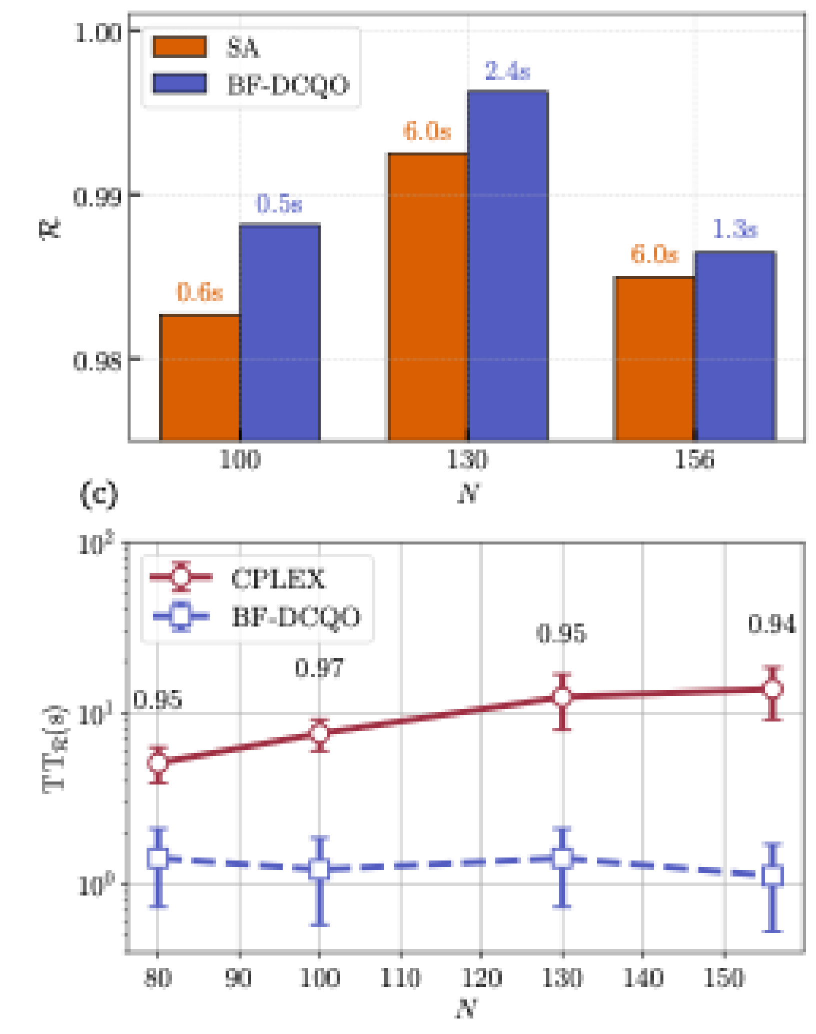
Los Alamos National Laboratory



Sampling a diverse set of good solutions quickly to approximate the Pareto front

arXiv:2503.22797

Higher-order unconstrained binary optimization (HUBO)



Kipu Quantum's BF-DCQO algorithm outperforms simulated annealing and CPLEX

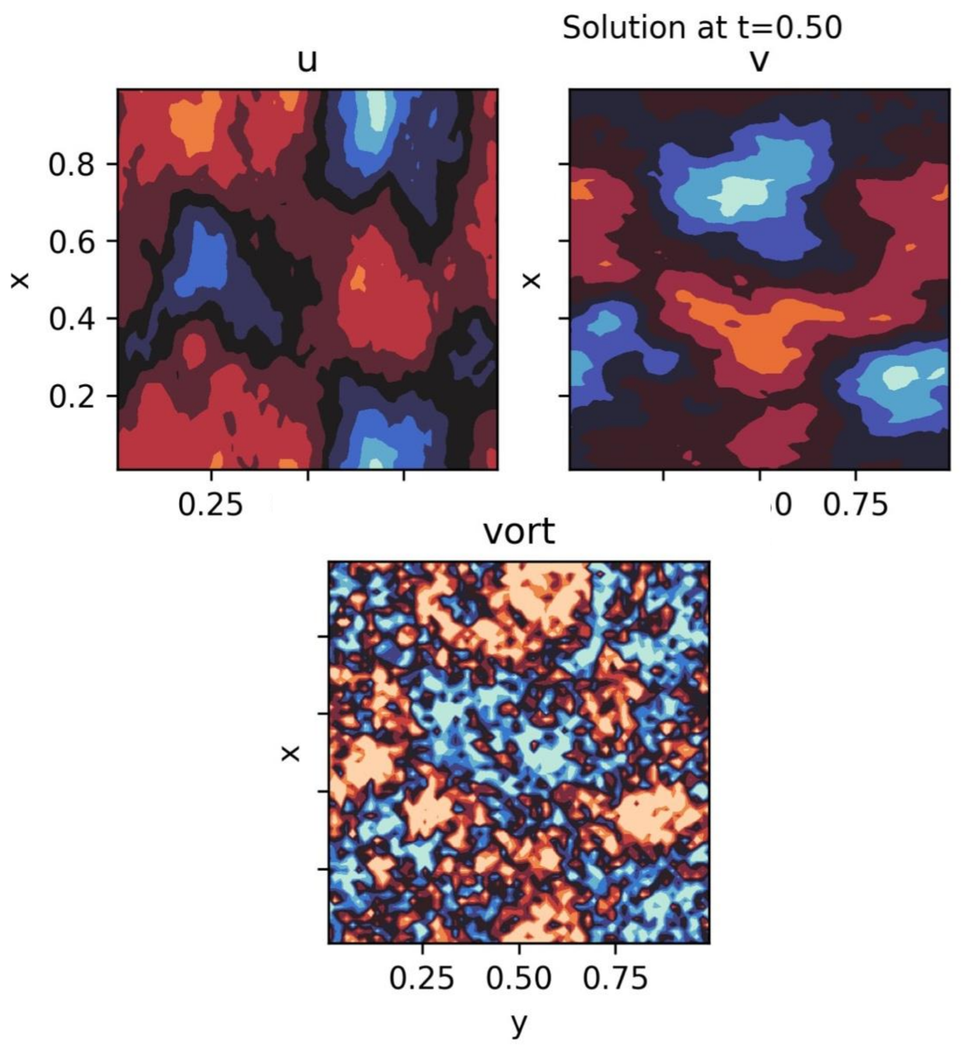
arXiv:2505.08663

Differential equations

New ways to solve differential equations difficult for classical

Kolmogorov embedding

Navier-Stokes



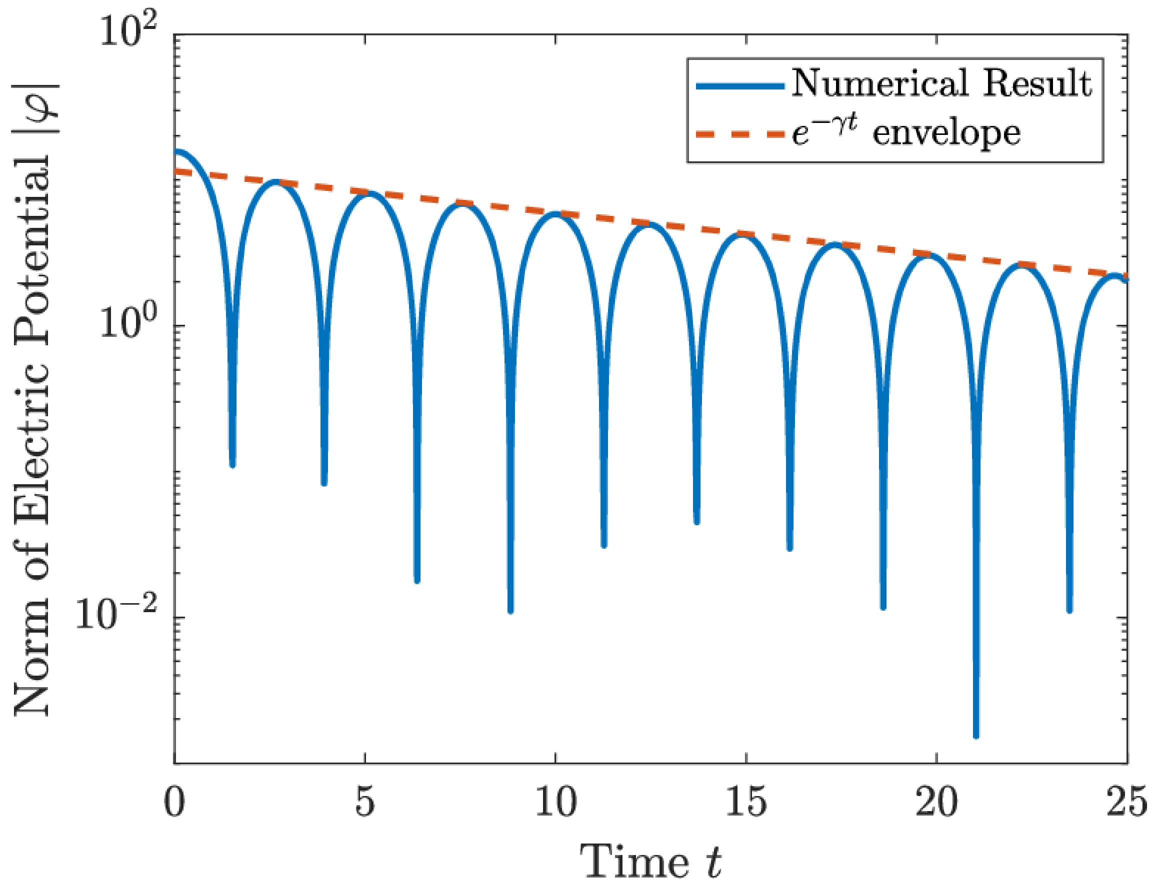
First end-to-end quantum algorithm for simulating noisy dynamics of nonlinear systems

arXiv:2507.06198

Plasma science

MIT

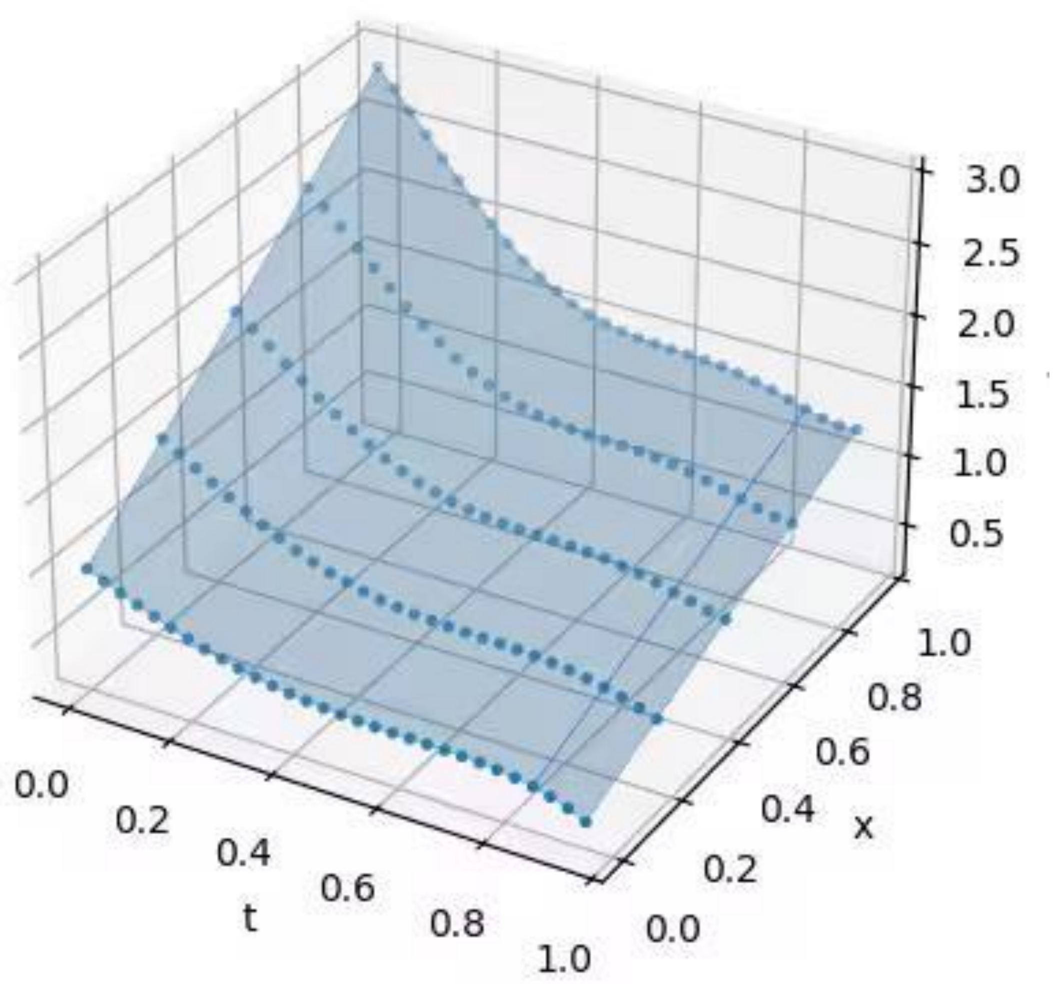
Landau damping



Quantum algorithms for fusion and plasma dynamics

arXiv:2303.03450

QUICK-PDE



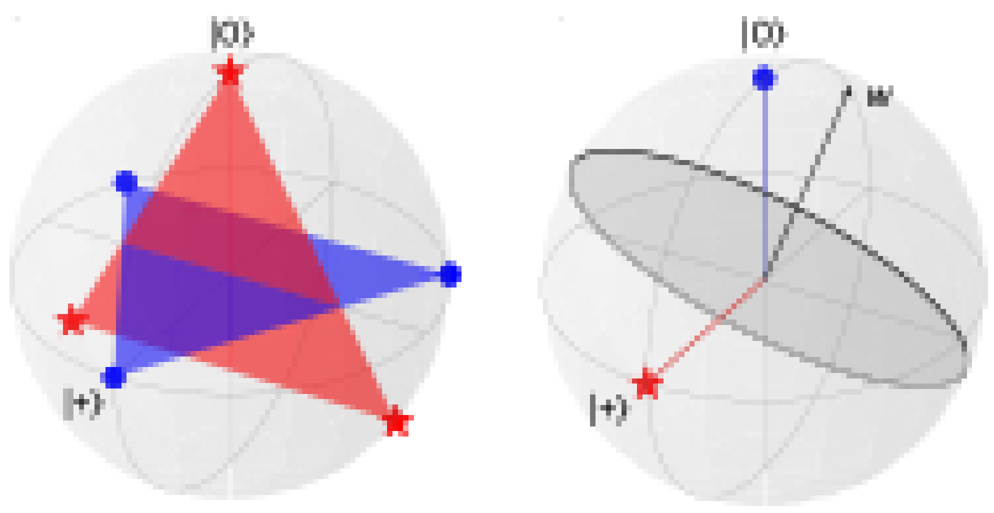
A Qiskit Function from our startup network using variational methods

arXiv:2410.01130
https://ibm.biz/quick-pde

Quantum machine learning

Applying quantum techniques to improve machine learning performance

Covariant quantum kernels

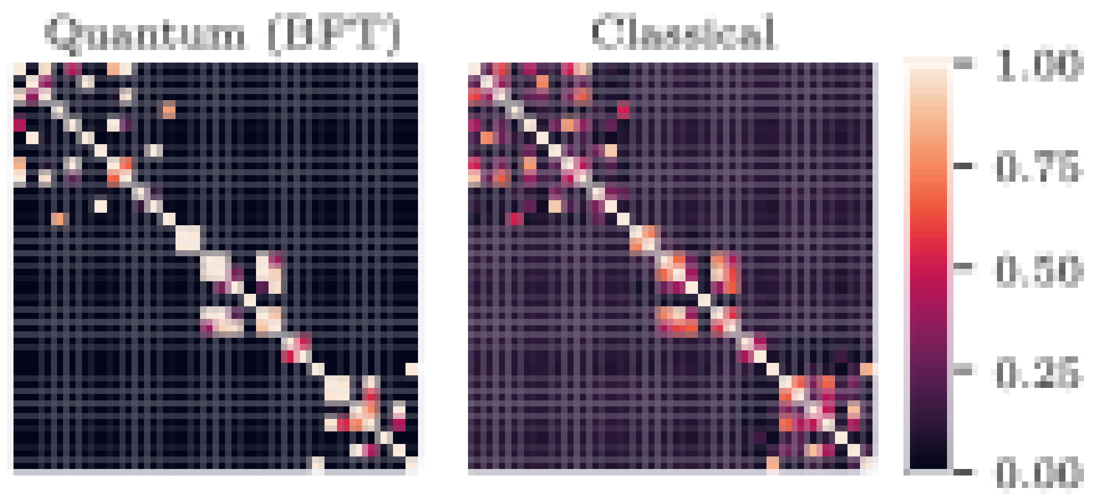


Data with group structure

Rigorous quantum speed up for discrete log problem

Nature Physics 20, 479-483 (2024)

Quantum kernels in practice



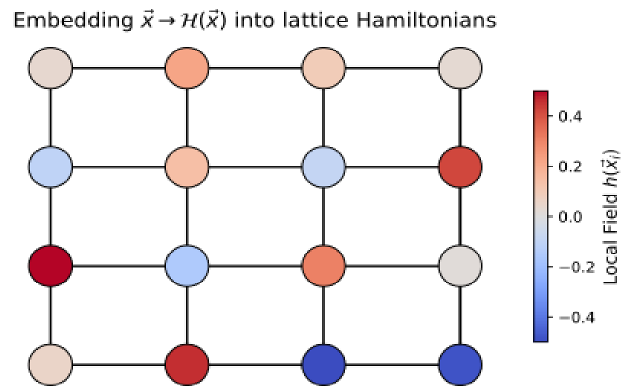
Error-mitigated quantum kernels

Multiclass classification demonstrated on real & synthetic data with up to 156 qubits

arXiv:2412.07915

Beyond kernels: Hamiltonian-based embeddings

Features: $\vec{x}$, labels: y



→ Approximate ground state of $H(\vec{x})$ using SKQD: $\psi(\vec{x})$

↓

y: property of $\psi(\vec{x})$

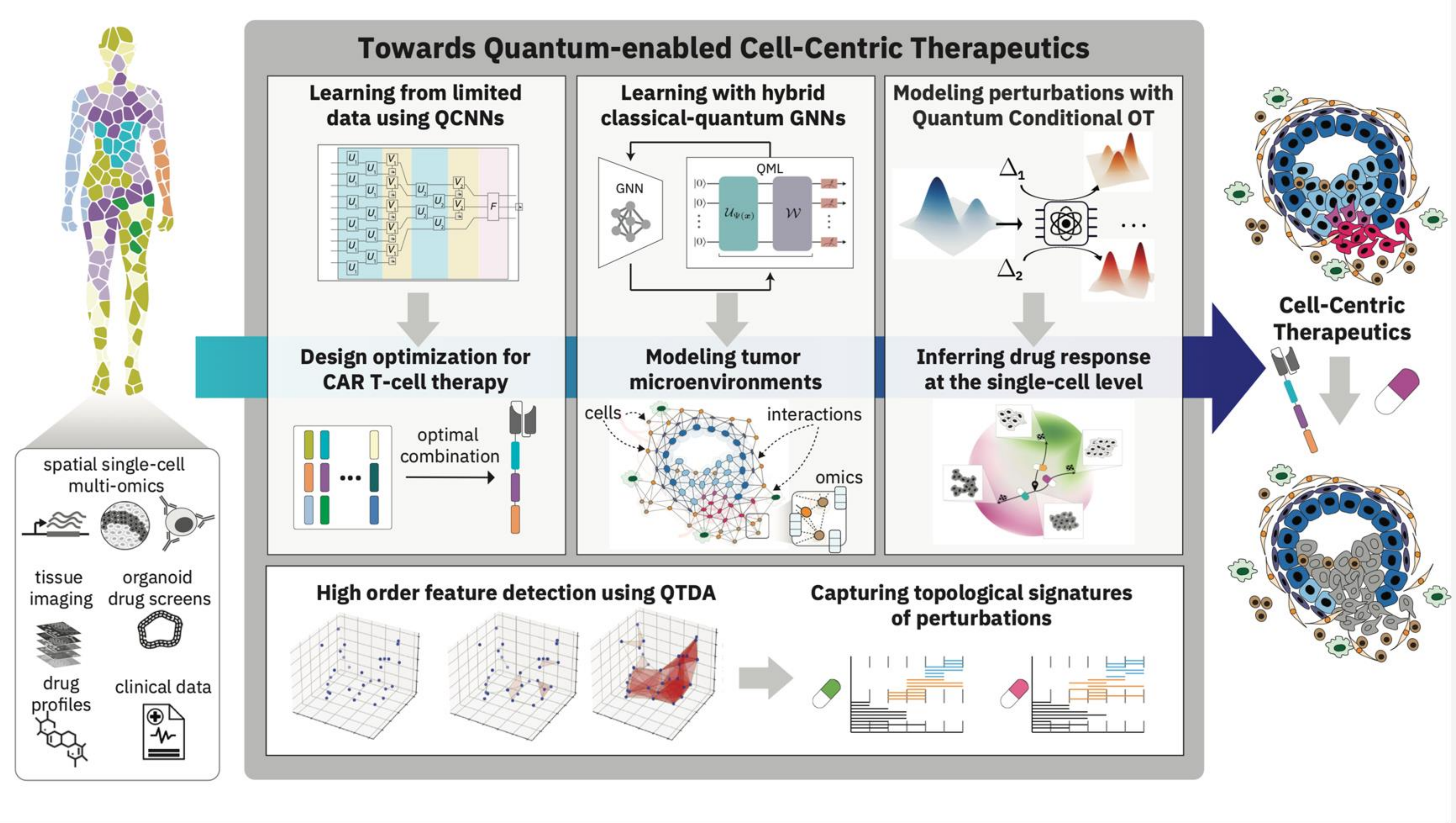
Encoding data in Hamiltonian and ground states

Ongoing work

Quantum Computing Applications **Research**

The Africa Quantum focus on demonstrating the utility of Quantum Computing through applications in healthcare.

- Developing end-to-end hybrid classical & quantum machine learning pipelines to identify abnormal tissue based on breast tissue biopsy images & gene expression data.
- Hybrid quantum-classical graph neural networks for tumor classification in digital pathology (Kohlakala, et al 2024 -IEEE Quantum Week, QCE, Canada)
    - End-to-end training performed significantly better than the serially-trained models (Serial F1-score: 57%; End-to-end F1-score: 72%)
    - Quantum compression via amplitude encoding can significantly improve qubit requirements without information loss



Basu et al. *arXiv* 2023

The advantage era will be defined by two parallel paths

Empirical tests of quantum usefulness

HSBC
arXiv:2509.17715

Cleveland Clinic
Communications Physics **8**, 396 (2025)

moderna
arXiv:2405.20328

Vanguard
arXiv:2508.13557

Scientifically rigorous proofs of advantage

The advantage era will be defined by two parallel paths

Empirical tests of quantum usefulness

HSBC
arXiv:2509.17715

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Communications Physics **8**, 396 (2025)

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arXiv:2508.13557

Scientifically rigorous proofs of advantage

Oak Ridge National Laboratory
arXiv:2501.09702

RIKEN
Science Advances 11, 25

Los Alamos National Laboratory
Nature Computational Science (2025)

BasQ Basque Quantum
arxiv:2507.08088

Flatiron Institute

BlueQubit

Validation

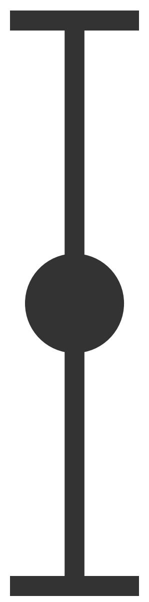
We must establish trust in the outcome of the computation

Methods that provide provable confidence bounds

Observable Estimation:

Perturbed

Mirror circuits



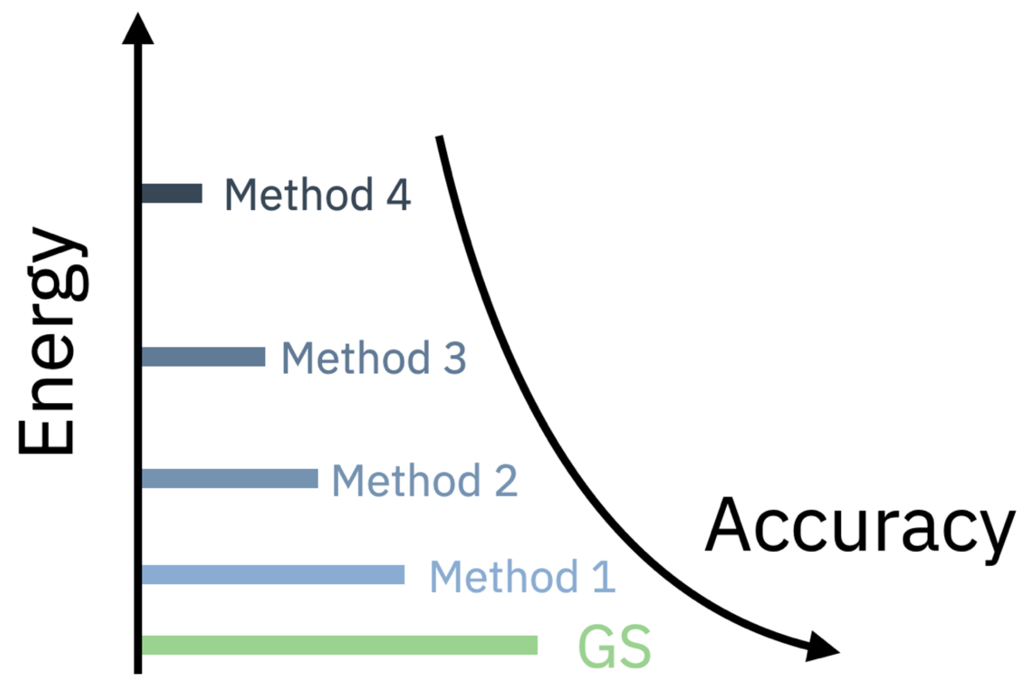
Algorithmic approaches with guaranteed solution bounds

Variational problems:

Sample based

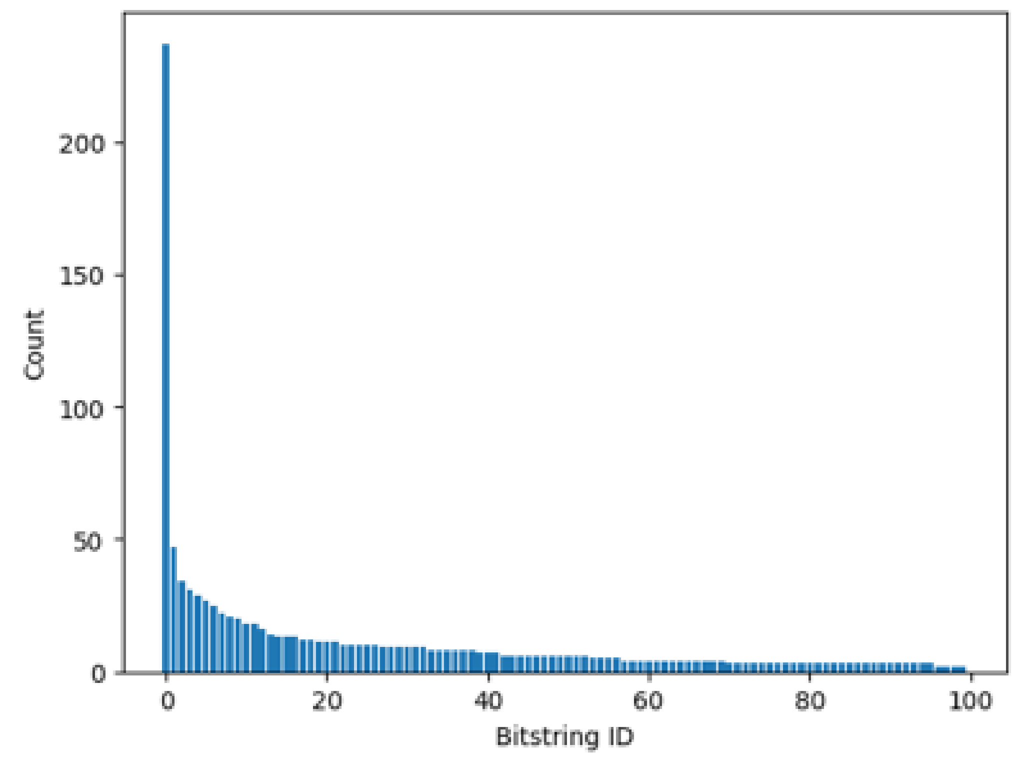
Krylov Quantum

Diagonalization



Problems with efficient classical verification

Peaked circuits



Quantum Advantage Tracker

Advantage trackers | Participate

Advantage trackers

Track verifiable quantum advantage candidates across three pathways, with current status of classical and quantum computations, supporting evidence and contributing organizations.

Observable estimations | Variational problems | Classically verifiable problems

Observable estimations

Submissions in this tracker report expectation values for observables alongside rigorous error bars. Validation requires mathematically provable confidence intervals over the reported value.

View circuit options | Open submission ticket

View circuit options | Open submission ticket

Date ↑	Name	Method	Circuit	Exp. values...	Runtime	Compute resou...	Institution	Activity
2025-11-12	Submission name	Global Rescaling	Operator Loschmidth Echo_49_2400	0.7 [upper bound, lower bound]	Q: 2h C: –	Q: ibm_pittsburgh C: –	IBM Research, Algorithmiq, Flatiron	4
2025-11-12	Submission name	Belief propagation tensor network	Operator Loschmidth Echo_49_2400	0.98 [±1.1, -0.3]	Q: – C: 6h	Q: – C: 8x NVIDIA H100	IBM Research, Algorithmiq, Flatiron	5
2025-11-11	Submission name	Global Rescaling + partial PEC	Operator Loschmidth Echo_49_2400	0.68 [±1.1, -0.3]	Q: 10h C: –	Q: ibm_pittsburgh C: –	IBM Research, Algorithmiq, Flatiron	1
2025-11-10	Submission name	Global Rescaling + partial PEC	Operator Loschmidth Echo_49_2400	0.66 [±1.1, -0.3]	Q: 9h 6m C: –	Q: ibm_boston C: –	IBM Research, Algorithmiq, Flatiron	0
2025-11-09	Submission name	Pauli propagation	Operator Loschmidth Echo_49_2400	0.8 [±1.1, -0.3]	Q: – C: 24h	Q: – C: 32 core Intel...	Caltech	0

Participate

Have a quantum advantage candidate? Contribute it using the provided problem instances or your own circuit specifications, and help expand the list of verified candidates.

Learn more

Community run tool to track progress towards quantum advantage

https://quantum-advantage-tracker.github.io

2025
Development & Innovation Roadmap

IBM **Quantum**

Development Roadmap

IBM **Quantum**

2016–2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023 ✓	2024 ✓	2025 ✓	2026	2027	2028	2029	2033+
Ran quantum circuits on IBM Quantum Platform	Released multi-dimensional roadmap publicly with initial focus 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	Demonstrated accurate execution of a quantum circuit at a scale beyond exact classical simulation (5K gates on 156 qubits)	Deliver quantum + HPC tools that will leverage Nighthawk, a new higher-connectivity quantum processor able to execute more complex circuits	Enable the first examples of quantum advantage using a quantum computer with HPC	Improve quantum circuit quality to allow 10K gates	Improve quantum circuit quality to allow 15K gates	Deliver a fault-tolerant quantum computer with the ability to run 100M gates on 200 qubits	Beyond 2033, quantum computers will run circuits comprising a billion gates on up to 2000 qubits, unlocking the full power of quantum computing

Code assistant ✓

Applying algorithms to applications

- Functions ✓
- Use case benchmarking toolkit (on target)
- Computation libraries

Discovering new algorithms for advantage

- Advanced classical transpilation tools ✓
- Advanced classical mitigation tools ✓
- Utility mapping tools (on target)
- Circuit libraries

Orchestrating workloads for quantum + HPC

Resource Management

- Qiskit Serverless ✓
- Plugins for HPC ✓
- C API ✓
- Profiling tools (on target)
- Workflow accelerators
- Execution modes ✓

Accurately and efficiently executing on quantum computers

Qiskit Runtime

- IBM Quantum Experience ✓
- OpenQASM 3 ✓
- Dynamic Circuits ✓
- Error mitigation ✓
- 200K CLOPS ✓
- Utility-scale dynamic circuits ✓
- Fault-tolerant ISA

Hardware →

Early ✓	Falcon ✓	Eagle ✓	Heron (5K) ✓	Nighthawk (5K) ✓	Nighthawk (7.5K) (on target)	Nighthawk (10K)	Nighthawk (15K)	Starling (100M)	Blue Jay (1B)
Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	Benchmarking 27 qubits	Benchmarking 127 qubits	Error mitigation 5K gates 133 qubits	Error mitigation 5K gates 120 qubits	Error mitigation 7.5K gates 120 qubits Up to 120x3 = 360 qubits	Error mitigation 10K gates 120 qubits Up to 120x9 = 1080 qubits	Error mitigation 15K gates 120 qubits Up to 120x9 = 1080 qubits	Fault-tolerant 100M gates 200 qubits	Fault-tolerant 1B gates 2000 qubits

✓ Completed

On target

Development Roadmap: Hardware

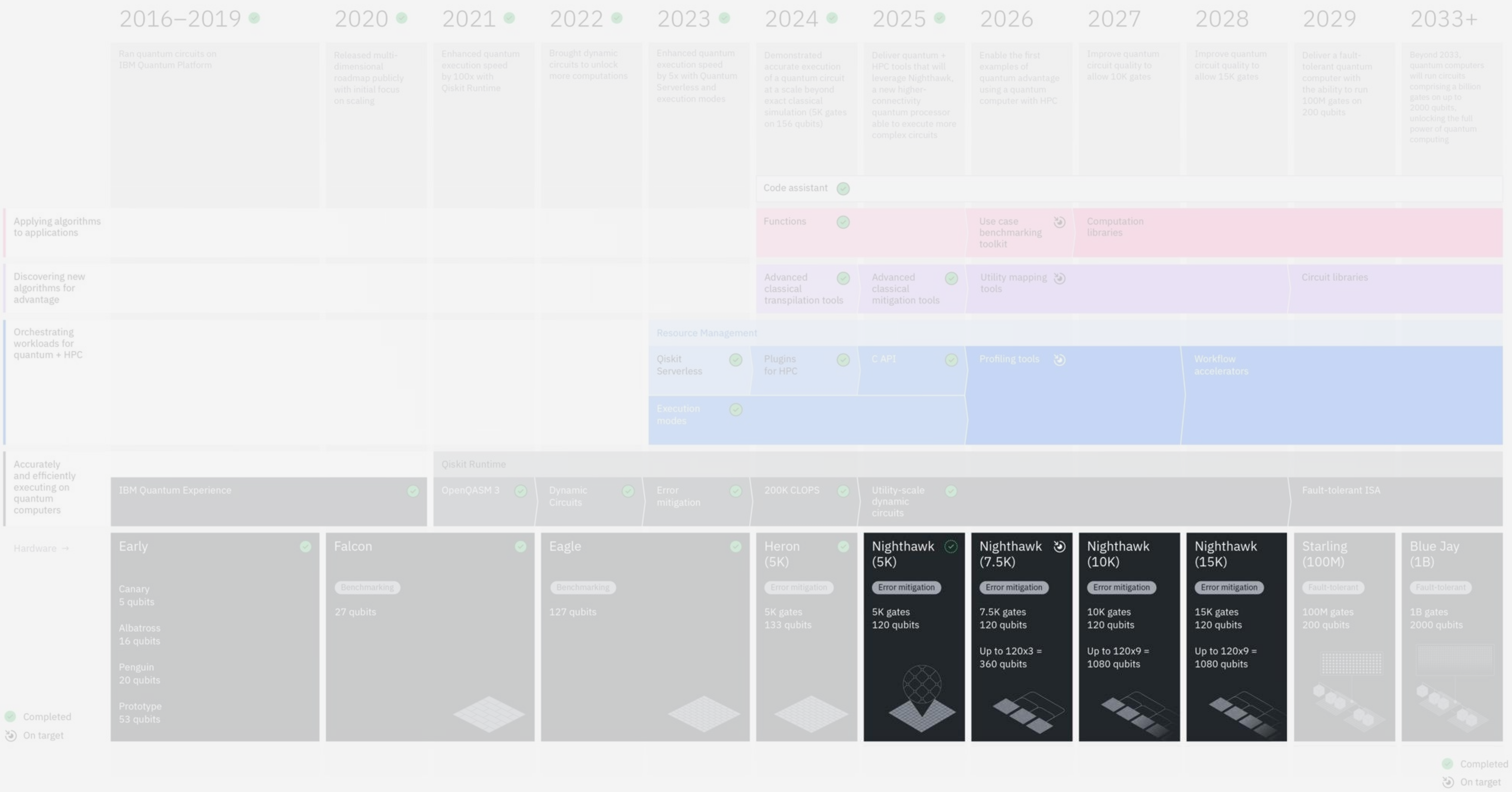
IBM Quantum Nighthawk is our platform for exploring and scaling quantum advantage ahead of large-scale fault-tolerant quantum computing.

Earlier quantum processors use a “heavy-hex” lattice, with each qubit connected to up to three neighbors. Nighthawk moves us to a square lattice, connecting each qubit to up to four neighbors.

This square lattice supports more efficient circuits, with fewer gates required for information routing. As a result, users can run more complex algorithms at the same gate scale.

Paired with techniques that reduce errors, Nighthawk is expected to run circuits with 5,000 gates by the end of 2025, 7,500 gates in 2026, 10,000 gates in 2027, and 15,000 gates in 2028.

As we improve and scale Nighthawk, we expect our team and partners to make major progress toward quantum advantages.



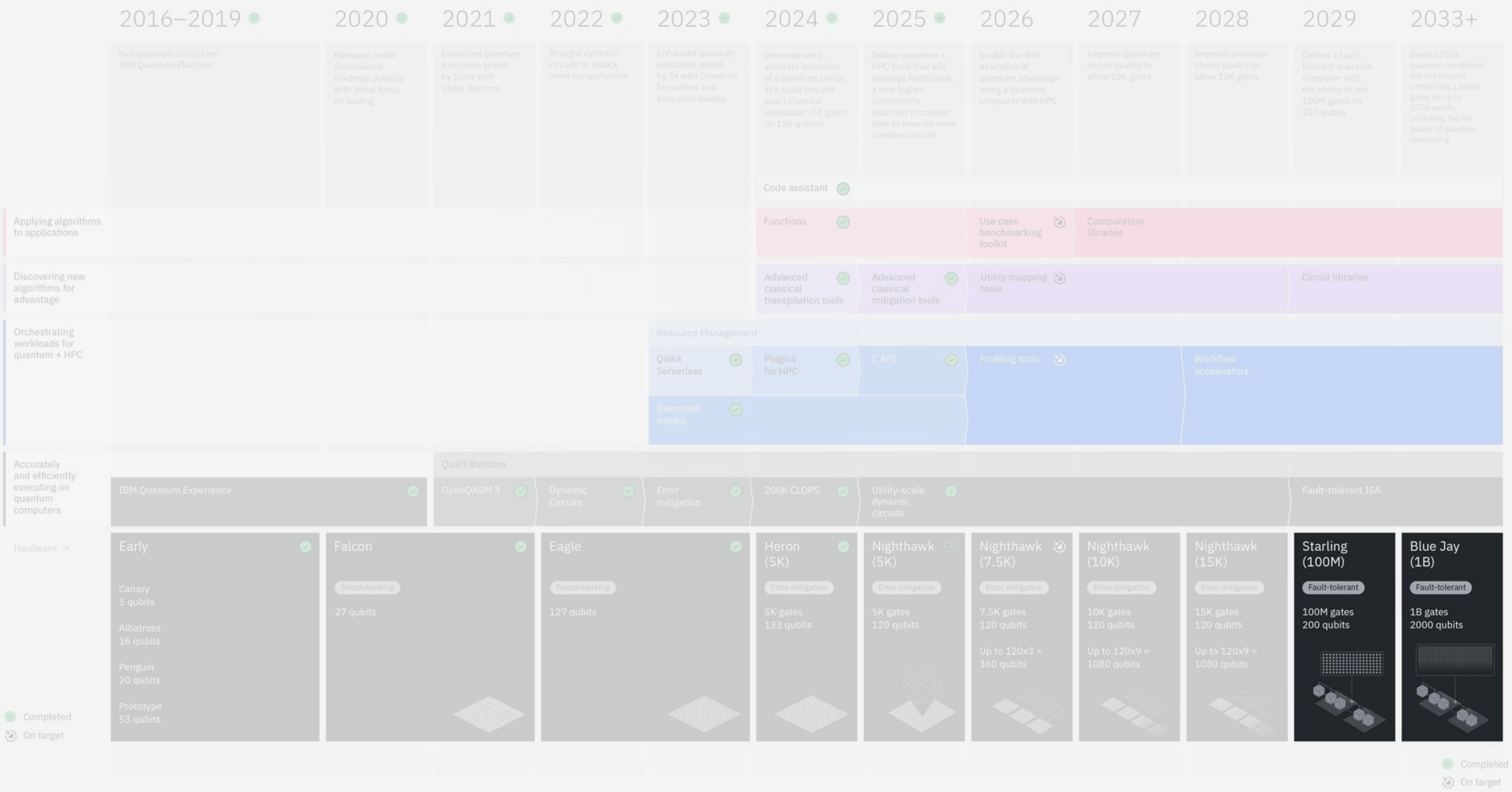
Development Roadmap: Hardware

IBM **Quantum**

At the same time, we are driving toward **IBM Quantum Starling**—a system capable of running circuits with 100 million gates on 200 qubits—and aim to debut it by 2029.

In 2033, we will debut **IBM Quantum Blue Jay**, a system capable of running circuits with a billion gates on 2,000 qubits. These large-scale fault-tolerant quantum computers will unlock a new era of algorithmic complexity and application discovery.

Developers will not need to change how they write quantum programs in this era. They will simply notice that they can run longer workloads.



IBM **Quantum**

Development Roadmap: Software, orchestration, and execution

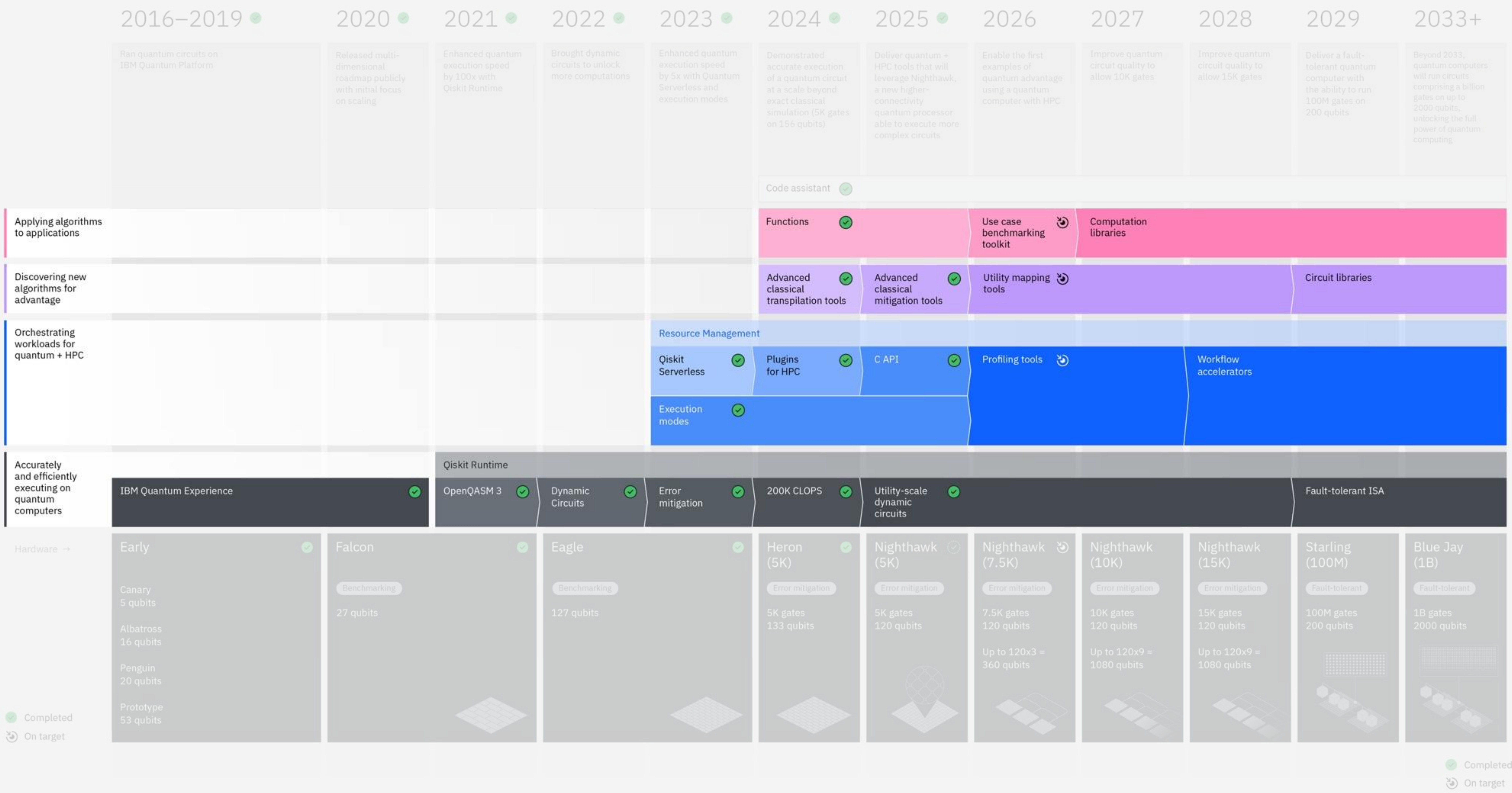
Useful quantum computing requires high-performance software. Our roadmap outlines four broad software objectives:

Apply algorithms to applications. These advances will let users adapt existing algorithms to domain-specific use cases.

Discover new algorithms for advantage. To move quickly to advantage, we must continue to improve and discover new algorithms. These advances provide a roadmap for tools that will enable new algorithm discovery.

Orchestrate workloads for quantum & high-performance computing (HPC). No algorithms are purely quantum, and we can more efficiently scale algorithms when we leverage quantum and classical resources together. So we are developing tools to better integrate and use quantum and classical resources.

Execute accurately and efficiently. We will continue to deliver high-performance software that runs circuits accurately on our evolving quantum hardware.



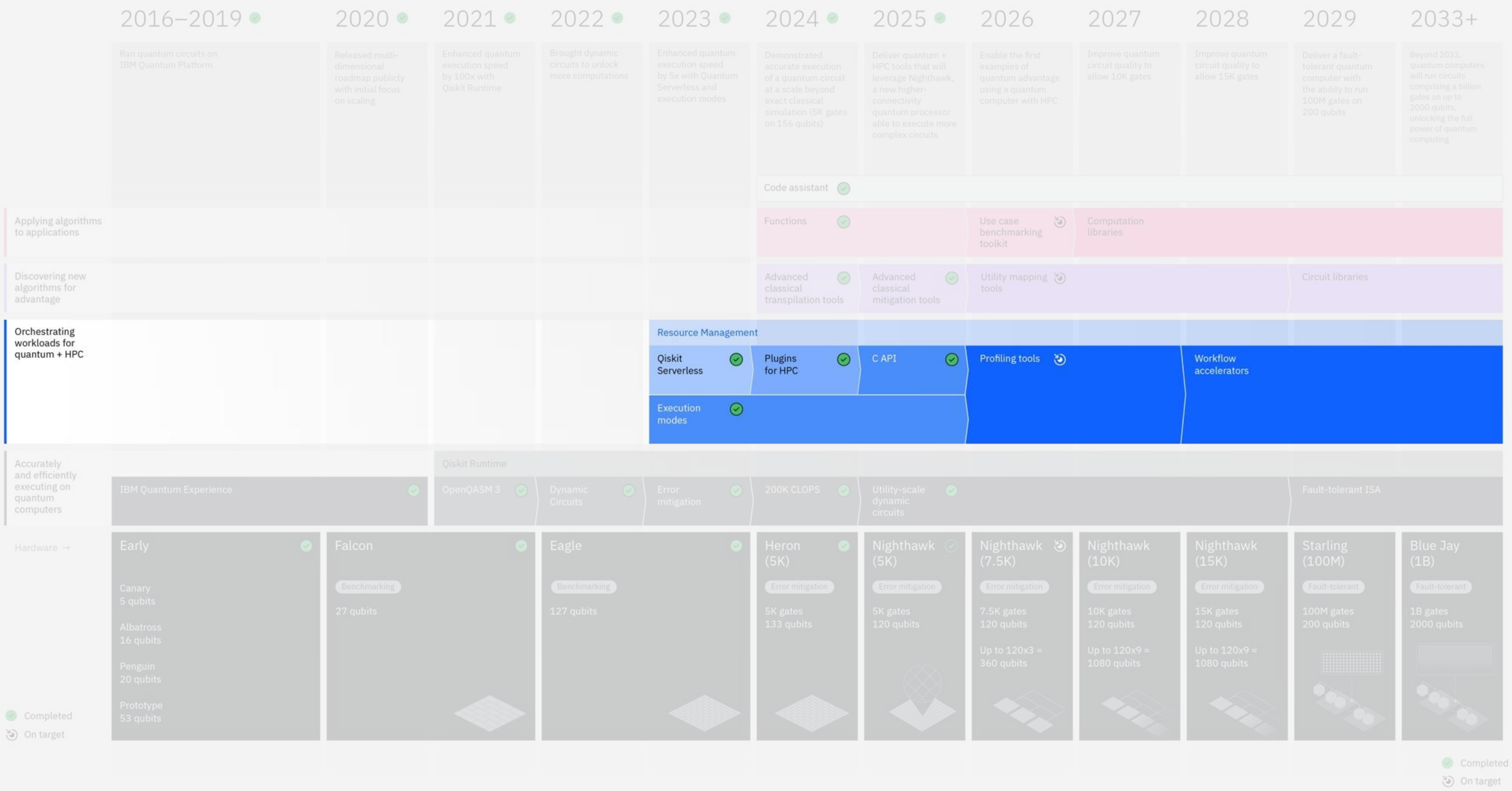
Development Roadmap: Orchestrating workloads for quantum & HPC

Running quantum workloads requires infrastructure that coordinates quantum resources with scalable classical resources.

In 2025, we released the C-API, enabling users to write Qiskit code in C, which is widely used for HPC. Soon, users will be able to write quantum and classical code in the same language and deploy it in an integrated system.

Moving into 2026 and beyond, we will introduce new profiling tools to help users monitor, verify, and debug workloads across quantum and classical resources.

In 2027 we will introduce workflow accelerators that deliver optimized quantum-classical execution pipelines for efficiently running similar tasks.



2025 Innovation Roadmap→

Innovation Roadmap

IBM Quantum

	2016–2019		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
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Software innovation	**IBM Quantum Experience**	**Qiskit** Open-source SDK for building and compiling circuits for quantum hardware	**Application modules** Modules for domain specific application and algorithm workflows	**Qiskit Runtime** Performance and abstraction through primitives	**Quantum Serverless** Demonstrate concepts of managing quantum and cloud classical compute for an end to end workflow	**AI-enhanced quantum** Prototype demonstrations of AI-enhanced circuit transpilation	**HPC-Quantum integration** Realize an integration of classical HPC and a quantum computer at utility scale	**Advantage candidates** Define problem types for advantage in 2026	**Error correction decoder** Demonstrate a real-time error correction decoder	**Workflow accelerator** Demonstrate a workflow accelerator that streamlines execution for a known advantage workflow	**Fault-tolerant ISA** Demonstrate a complete instruction set architecture including magic state distillation for FTQC		
Hardware innovation	**Early** Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	**Falcon** Demonstrate scaling with I/O routing with bump bonds	**Hummingbird** Demonstrate scaling with multiplexing readout	**Eagle** Demonstrate scaling with MLW and TSV	**Osprey** Enabling scaling with high density signal delivery	**Condor** Single-system scaling and fridge capacity	**Flamingo** Demonstrate scaling with l-couplers	**Loon** Demonstrate c-couplers and next-generation packaging for FTQC	**Kookaburra** Demonstrate a complete module consisting of a logical processing unit and quantum memory	**Cockatoo** Demonstrate entanglement of modules using a universal adapter	**Starling** Demonstrate multiple modules and magic state distillation		
				Egret Tunable coupler demonstration		**Heron** Architecture based on tunable couplers	**Crossbill** Demonstrate m-couplers						

Completed

On target

Bringing the quantum revolution to the market

The next four years

2025

Demonstrate the quantum-centric data center with Qiskit + HPC

2026

Demonstrate quantum advantage

2027

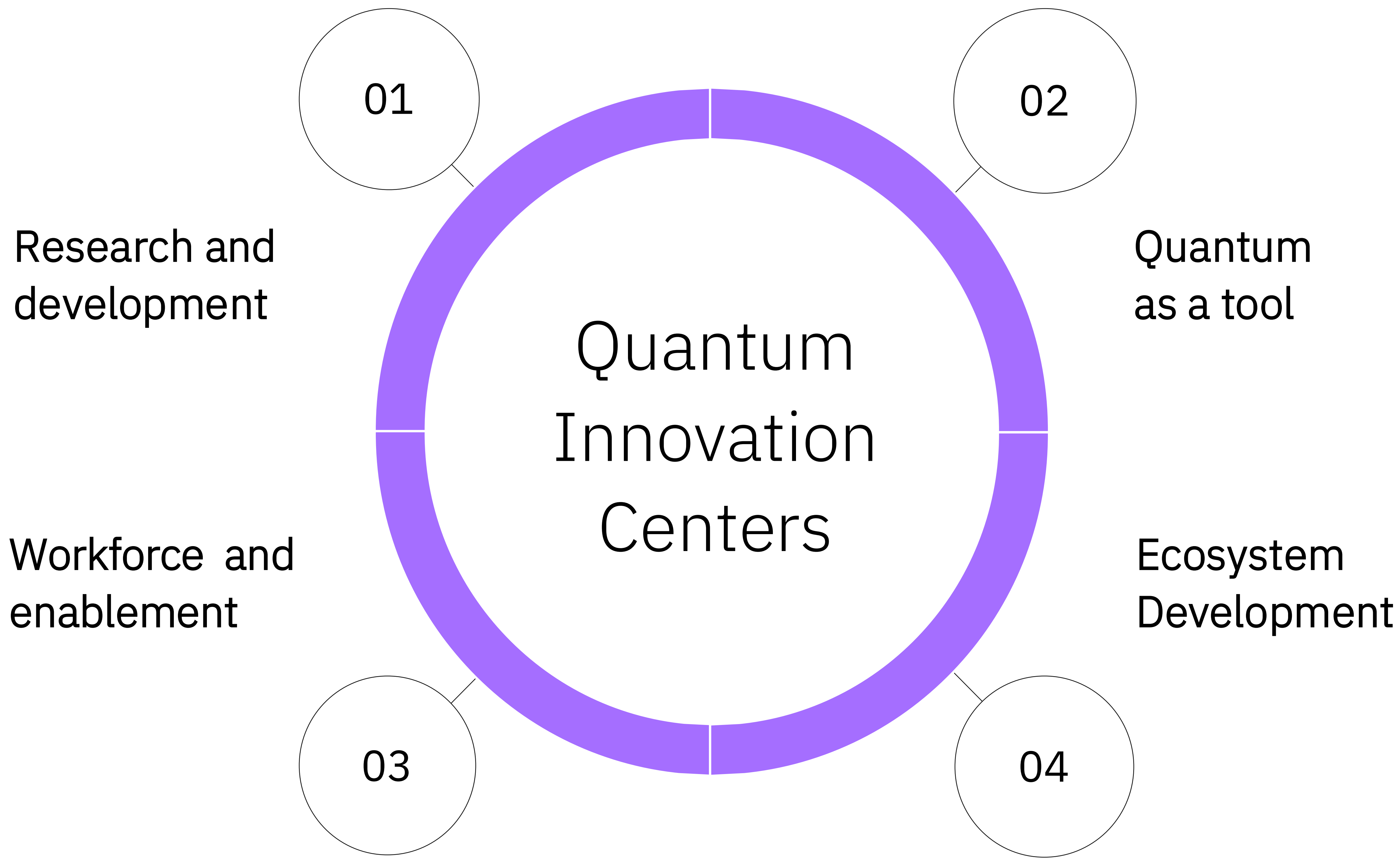
Demonstrate a viable path to an error-corrected quantum computer

2028

Demonstrate the first error-corrected quantum computer

Innovation Centers

Strategic partners developing regional and national leadership in Quantum Computing by leveraging IBM Quantum capabilities & know-how



01 Research and development

Advancing Utility
Driving use of Quantum for Computational Science

02 Quantum as a tool

Access to quantum systems and software technology
Build on top of the IBM tools

03 Workforce development

Open community
University quantum education
Enterprise skill development

04 Ecosystem development

Regional network in QC
Attraction of investment
Industry application incubation

Quantum Innovation Centers
| South Africa

Wits University: 2019 – 2025
CSIR CHPC: 2025 - 2026

Cloud access

Overview

Wits University was the first African academic partner in the IBM Quantum Network and has acted as a gateway for academic collaboration across South Africa, providing outreach and enablement activities to 17 universities who are part of the African Research Universities Alliance (ARUA)

CSIR CHPC enables broader access & resources for SAQUTI community and

Mission

1. Drive Quantum Readiness and Build a Thriving Quantum Community in Africa
2. Inspire African-based students to pursue MSc or PhD studies in Quantum Computing
3. Enhance the reputation South African researchers as leaders of Quantum Computing in Africa

Some Achievements of SA QICs since 2019

Research and Development

- Joint Development
- Research Enablement
- Grant and Papers

Quantum as a Tool

- Access to IBM quantum systems to academia and industry
- Wits demo Matlab integration at Quantum Summit

Workforce and Enablement

- advance quantum education and quantum readiness in Africa. This is exemplified by combined advocacy and education efforts
- Establish the Quantum MeetUp group

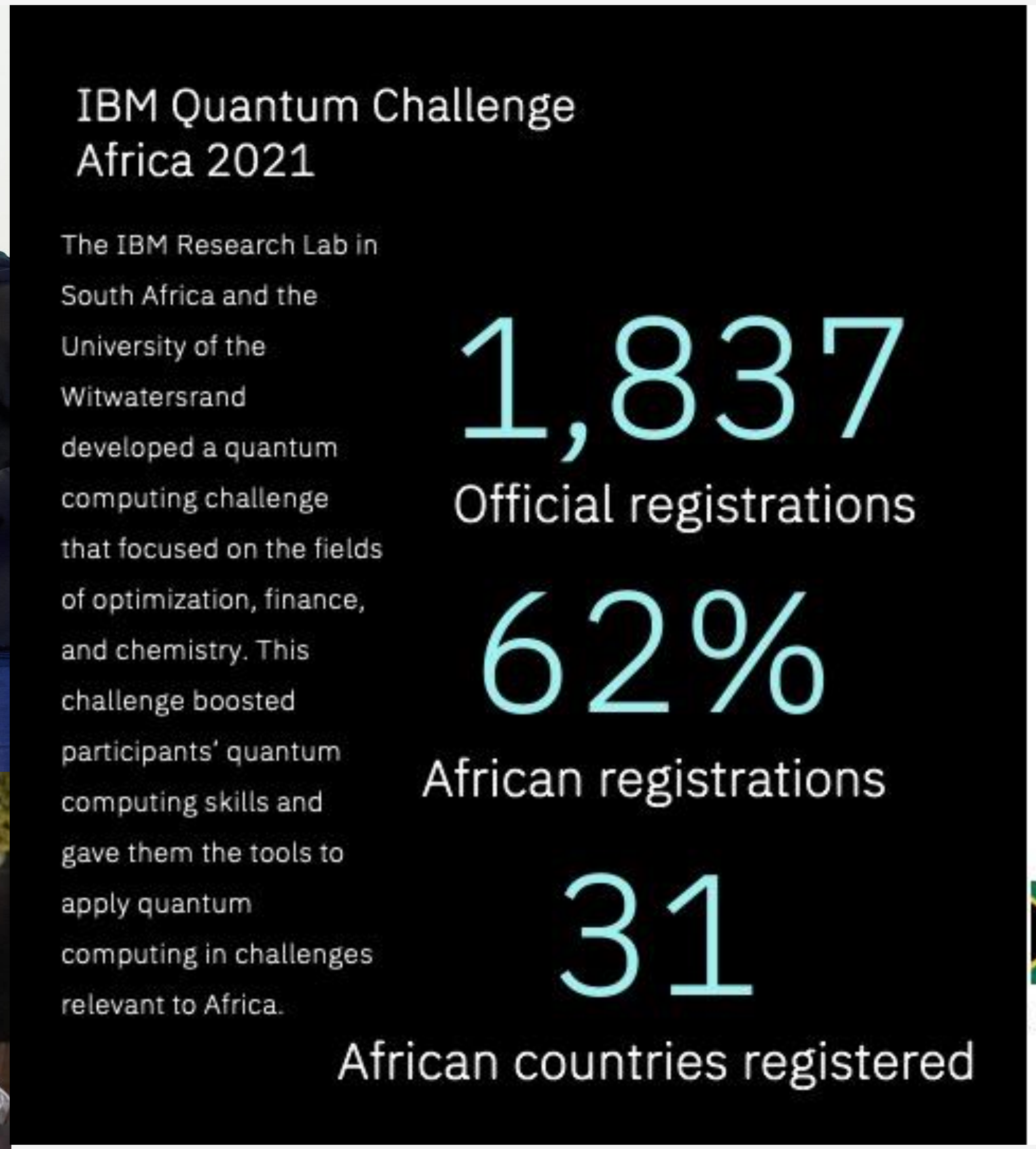
Ecosystem Development

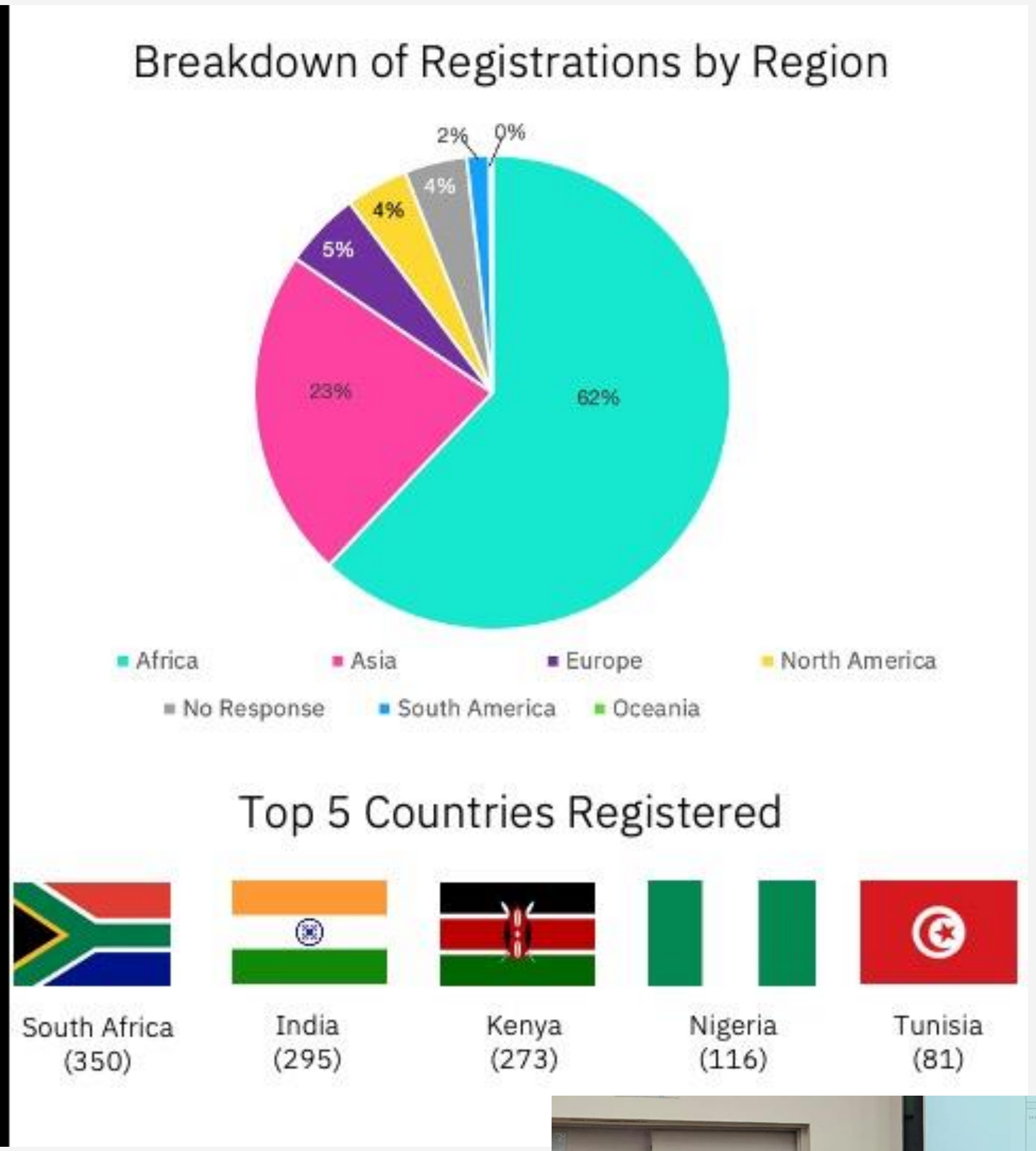
- SA QuTI was formally launched by the South African Department of Science and Innovation

Primary Focus Secondary Focus

Facilitating Quantum Computing Training – Coding with IBM Qiskit

2019: Bringing out the best of the IBM Research Quantum teams to South Africa for the IBM Quantum Qiskit Challenge in Pilannesberg. Students from institutions part of the ARUA network





2021: Bringing out the best of the IBM Research Quantum globally to develop the IBM Quantum Challenge Africa, championed by the South Africa lab from the development of materials to support & delivery

Meetup

Bi-weekly Quantum Computing Meetups - Seminars

2024: IBM-WitsQ Workshop for Researchers & students, ending with global IBM Quantum challenge participation by workshop participants

Activities in 2025 of the Quantum Computing Applications **Community**

Jan

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