The era of quantum utility with IBM Quantum

Voica Radescu, PhD | IBM Quantum Innovation Centers | EMEA Lead

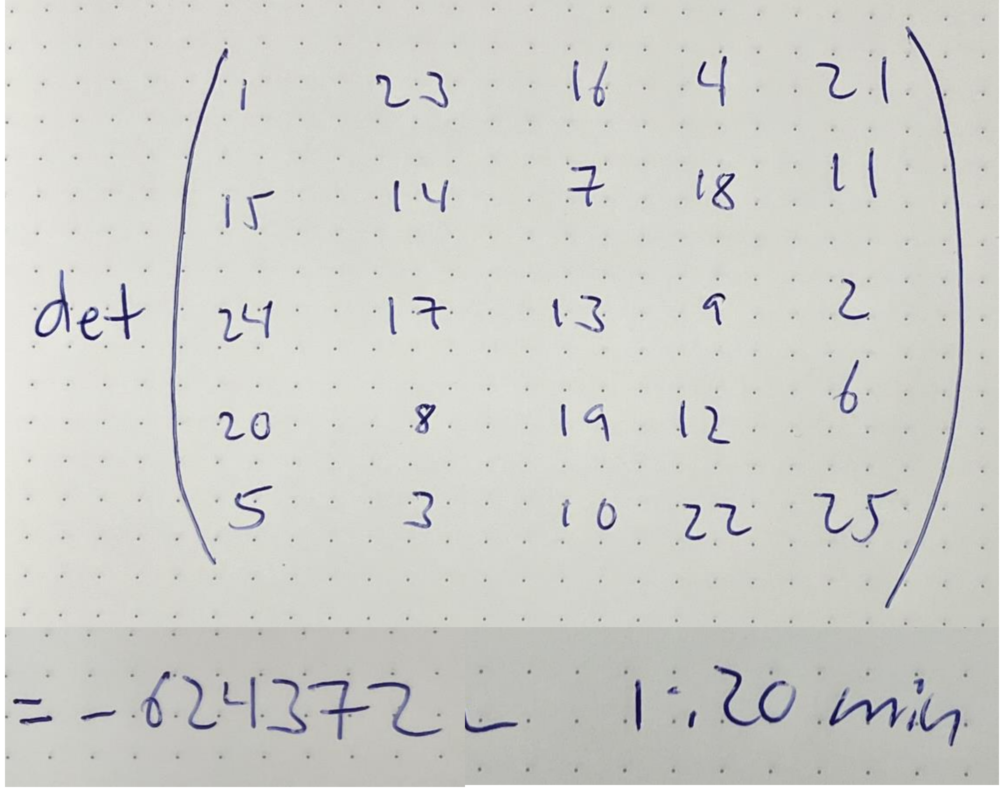
- Why Quantum?
- Path to useful Quantum Computing
- IBM Quantum Development Roadmap
- Utility scale examples
- What's next?

Why do we use computers?

The determinant

A sub-routine for linear-systems solutions, and used extensively in vector calculus

Scientist:



$$\det\begin{pmatrix} 1 & 23 & 16 & 4 & 21 \\ 15 & 14 & 7 & 18 & 11 \\ 24 & 17 & 13 & 9 & 2 \\ 20 & 8 & 19 & 12 & 6 \\ 5 & 3 & 10 & 22 & 25 \end{pmatrix}$$

$= -624372$ 1:20 min

NumPy:

```
la.det(np.array([[1, 23, 16, 4, 21],
                  [15, 14, 7, 18, 11],
                  [24, 17, 13, 9, 2],
                  [20, 8, 19, 12, 6],
                  [5, 3, 10, 22, 25]]))
```

Answer: -623999.9999999994

Solution time: 2.17 us (2 billion times faster)

Why do we use computers?

Accuracy Speed Scalability Versatility

We have learned to trust that classical computers can be accurate at scale.

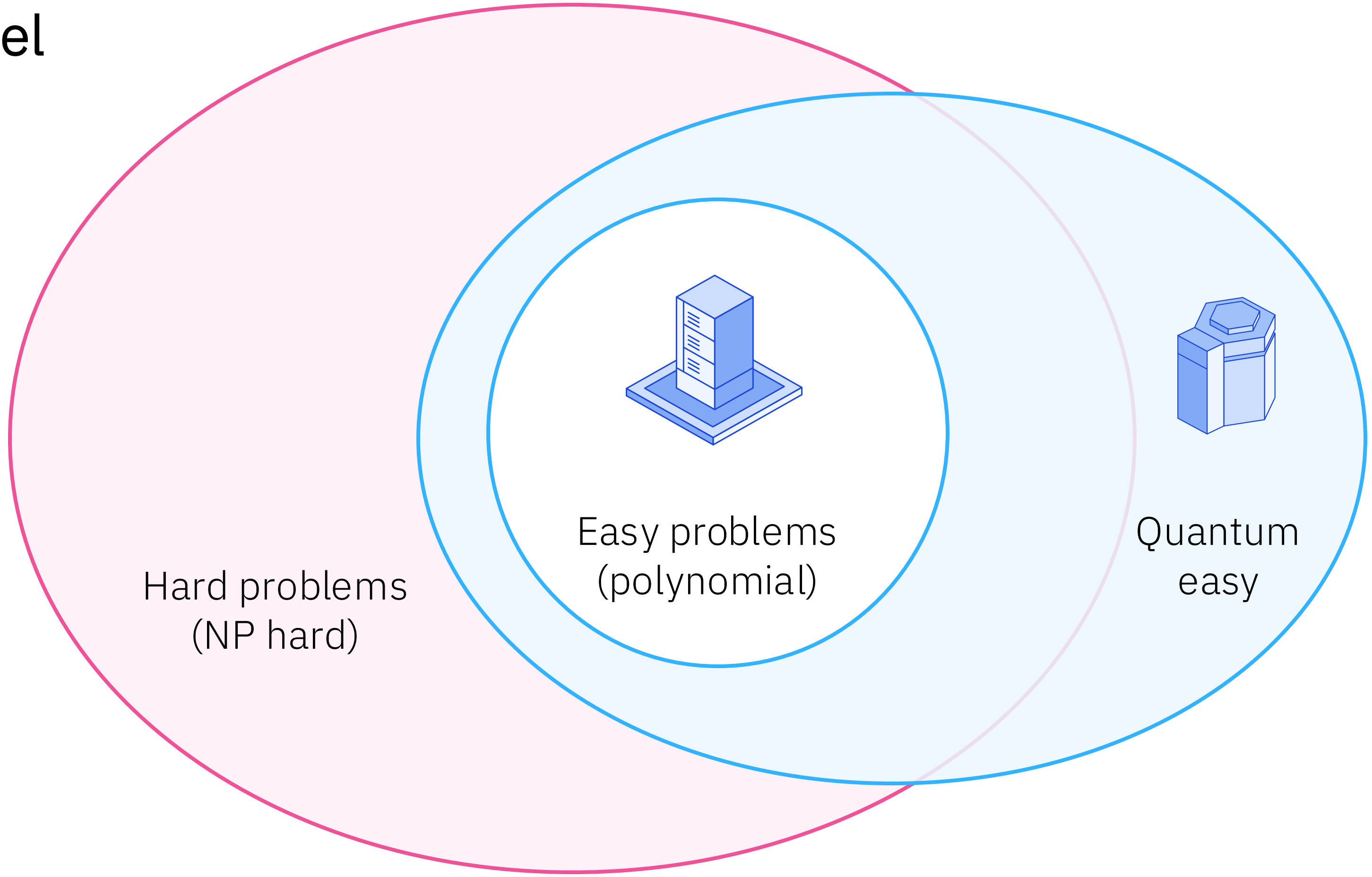
Quantum computers are the only novel hardware that changes the game

Quantum computing is not just a faster or better version of classical systems.
It is an entirely new branch of computing:

- Applies principles of quantum mechanics
- Qubits can be in more states than 0 and 1

Quantum computing follows the laws of nature to represent data in ways that mimic the randomness and unpredictability of the natural world.

Ultimately, GPUs and classical hardware are not built for this.



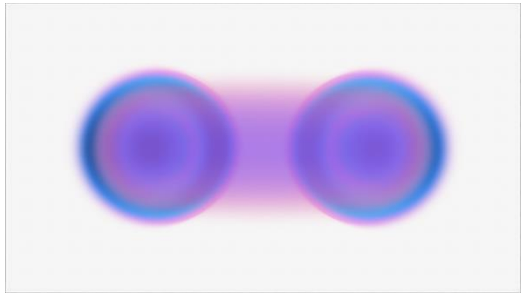
Classical computer
Well suited for many problems.

Quantum computer
Unlock classically intractable problems

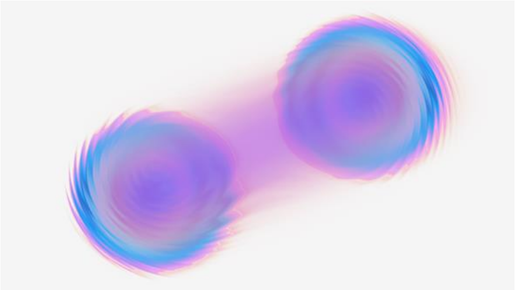
Quantum Computing's basic properties:

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

Our IBM mission

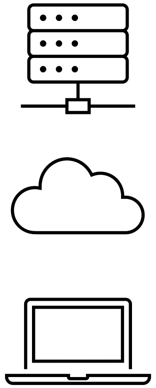
Bring useful quantum computing to the world

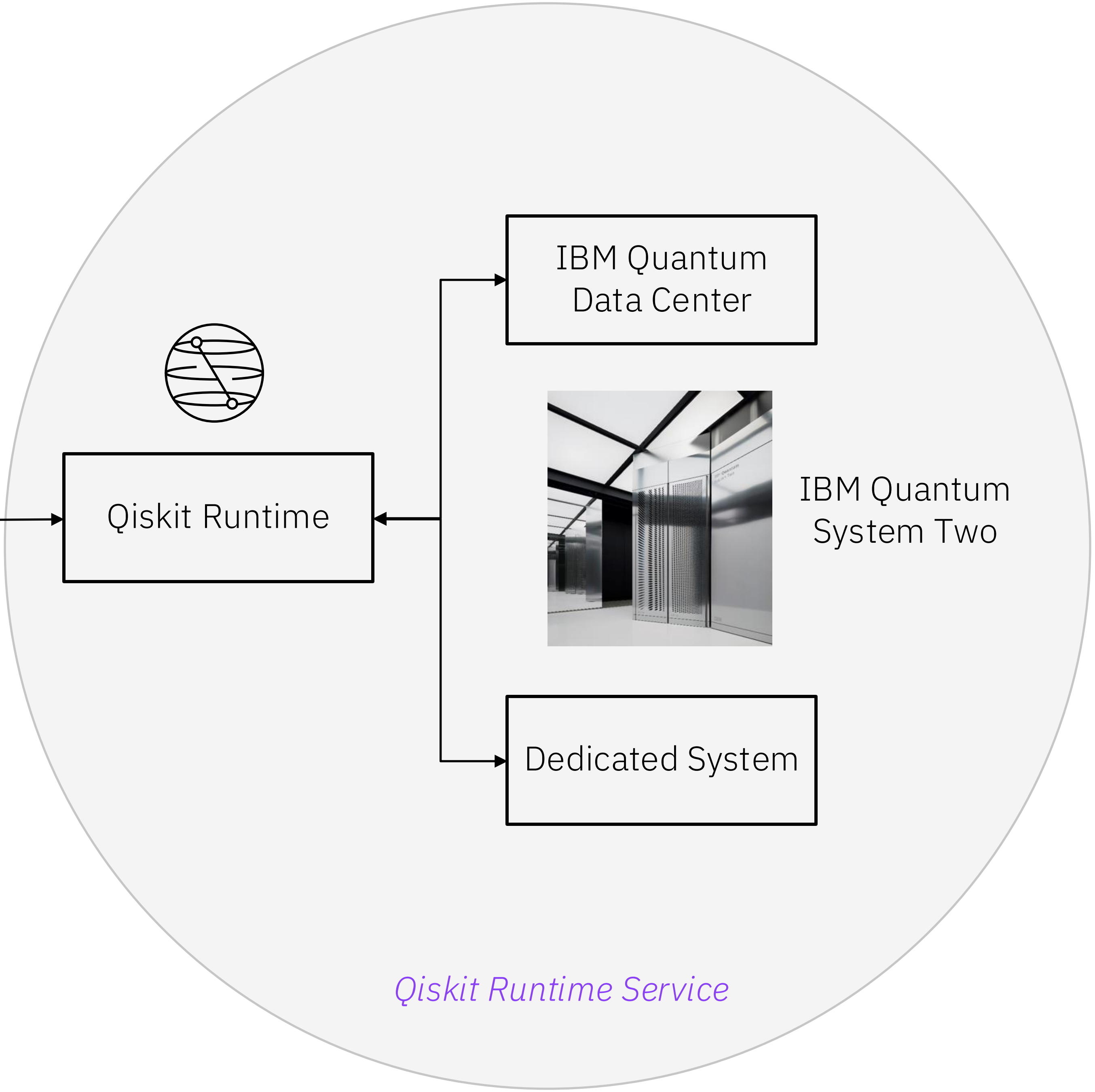
Since 2016, we've made quantum computers available through the cloud

Running quantum workloads requires infrastructure that coordinates quantum resources with near-time and real-time classical resources.

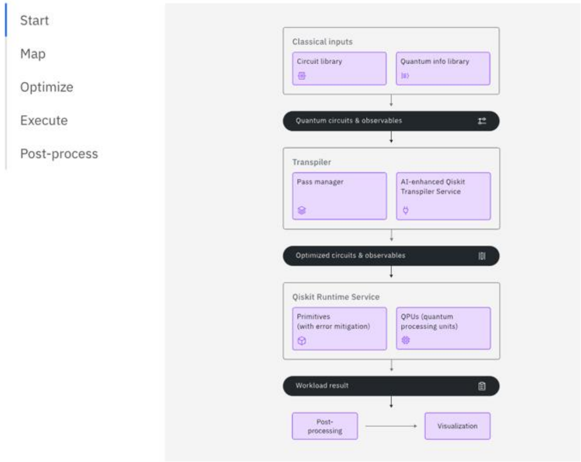
Enterprise Client

API





Qiskit offers a simplified quantum workflow



The IBM Quantum platform unlocks research with quantum

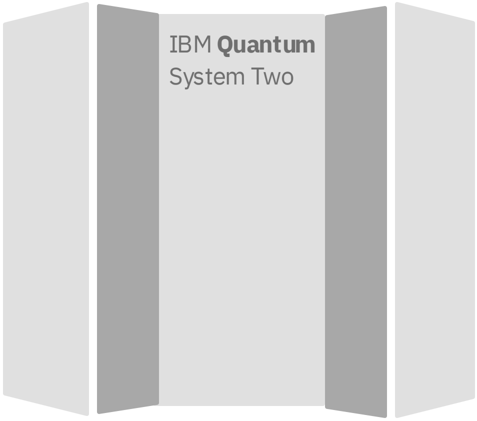
https://quantum.ibm.com/

Quantum Software
(powered by Qiskit add-ons
and Qiskit Functions)

+

Qiskit

+



QPUs

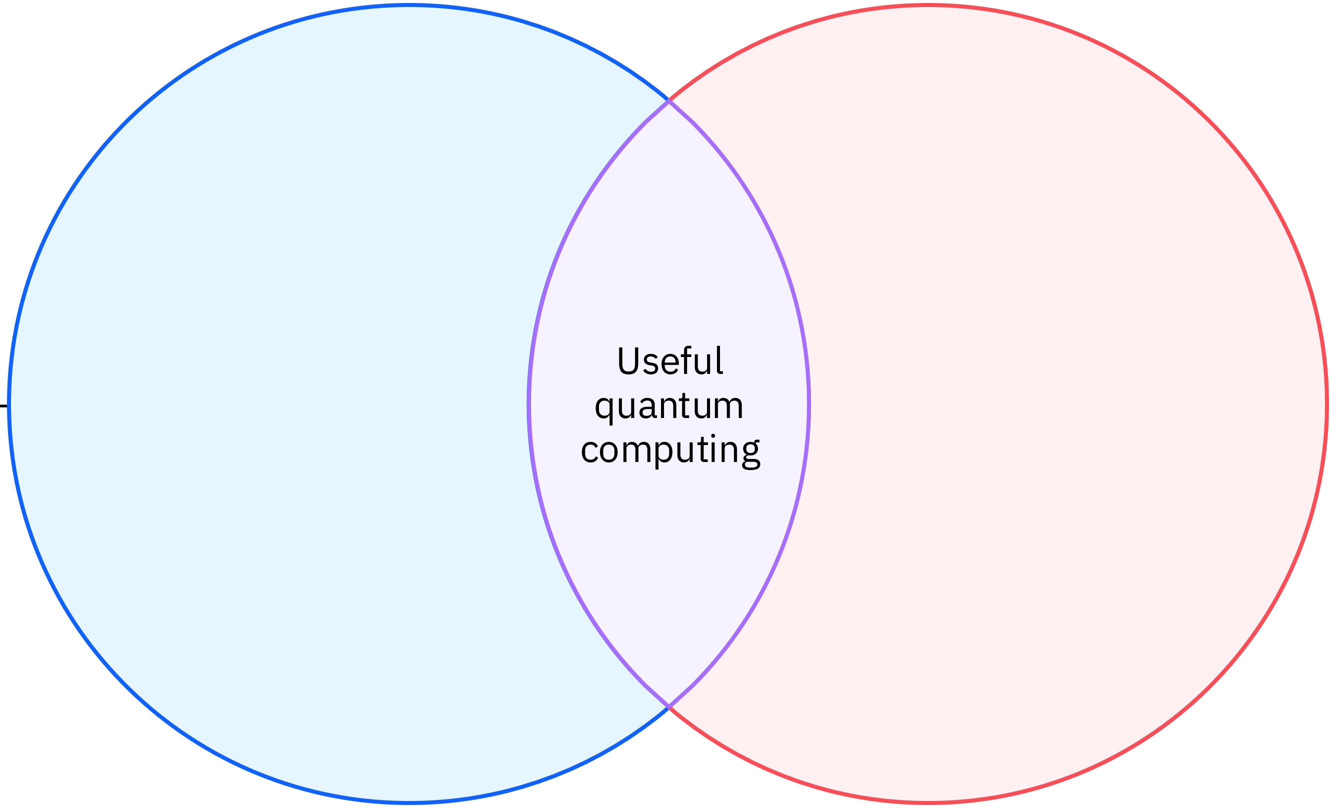
=

Useful Work

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.



Useful
quantum
computing

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.

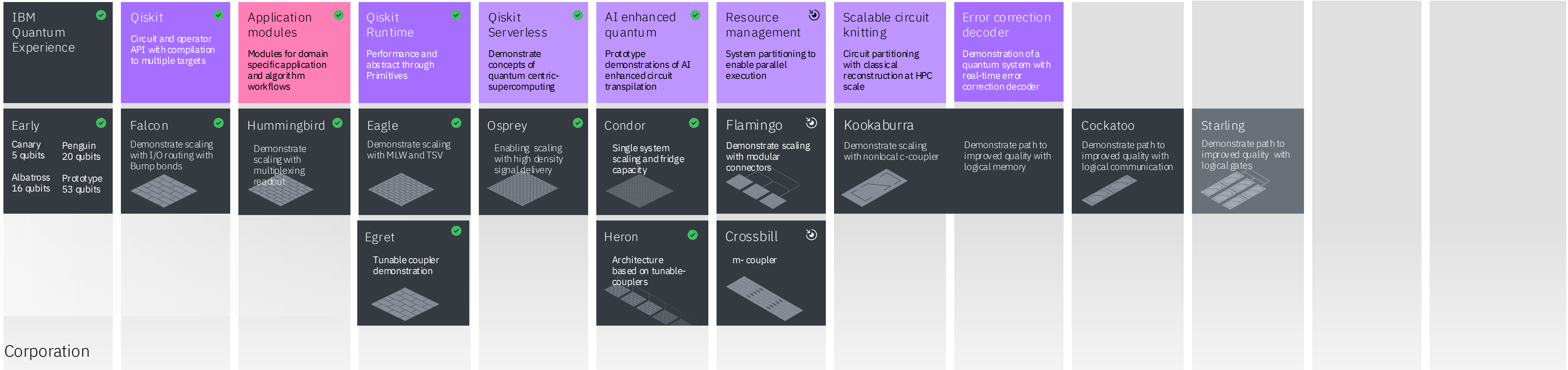
Development Roadmap

https://www.ibm.com/quantum/assets/IBM_Quantum_Development_&_Innovation_Roadmap.pdf

IBM Quantum

	2016–2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023 ✓	2024	2025	2026	2027	2028	2029	2033+
	Run quantum circuits on the IBM Quantum Platform	Release multi-dimensional roadmap publicly with initial aim focused on scaling	Enhancing quantum execution speed by 100x with Qiskit Runtime	Bring dynamic circuits to unlock more computations	Enhancing quantum execution speed by 5x with quantum serverless and Execution modes	Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving 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 Scientist						Platform						
						Qiskit Code Assistant ↻	Qiskit Functions Service	Mapping Collection	Specific Libraries			General purpose QC libraries
Researchers					Middleware							
					Qiskit Serverless ✓	Qiskit Transpiler Service ↻	Resource Management	Circuit Knitting x P	Intelligent Orchestration			Circuit libraries
Quantum Physicist			Qiskit Runtime Service									
	IBM Quantum Experience ✓		QASM3 ✓	Dynamic circuits ✓	Execution Modes ✓	Heron (5K) ↻ Error Mitigation 5k gates 133 qubits Classical modular 133x3 = 399 qubits	Flamingo (5K) Error Mitigation 5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (7.5K) Error Mitigation 7.5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (10K) Error Mitigation 10k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (15K) Error Mitigation 15k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Starling (100M) Error correction 100M gates 200 qubits Error corrected modularity	Blue Jay (1B) Error correction 1B gates 2000 qubits Error corrected modularity
	Early ✓ Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits	Falcon ✓ Benchmarking 27 qubits		Eagle ✓ Benchmarking 127 qubits								

Innovation Roadmap



Software Innovation	IBM Quantum Experience ✓	Qiskit ✓ Circuit and operator API with compilation to multiple targets	Application modules ✓ Modules for domain specific application and algorithm workflows	Qiskit Runtime ✓ Performance and abstract through Primitives	Qiskit Serverless ✓ Demonstrate concepts of quantum centric-supercomputing	AI enhanced quantum ✓ Prototype demonstrations of AI enhanced circuit transpilation	Resource management ↻ System partitioning to enable parallel execution	Scalable circuit knitting Circuit partitioning with classical reconstruction at HPC scale	Error correction decoder Demonstration of a quantum system with real-time error correction decoder				
Hardware Innovation	Early ✓ Canary 5 qubits Penguin 20 qubits Albatross 16 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 modular connectors	Kookaburra Demonstrate scaling with nonlocal c-coupler	Demonstrate path to improved quality with logical memory	Cockatoo Demonstrate path to improved quality with logical communication	Starling Demonstrate path to improved quality with logical gates		
				Egret ✓ Tunable coupler demonstration		Heron ✓ Architecture based on tunable-couplers	Crossbill ↻ m- coupler						

✓ Executed by IBM

↻ On target

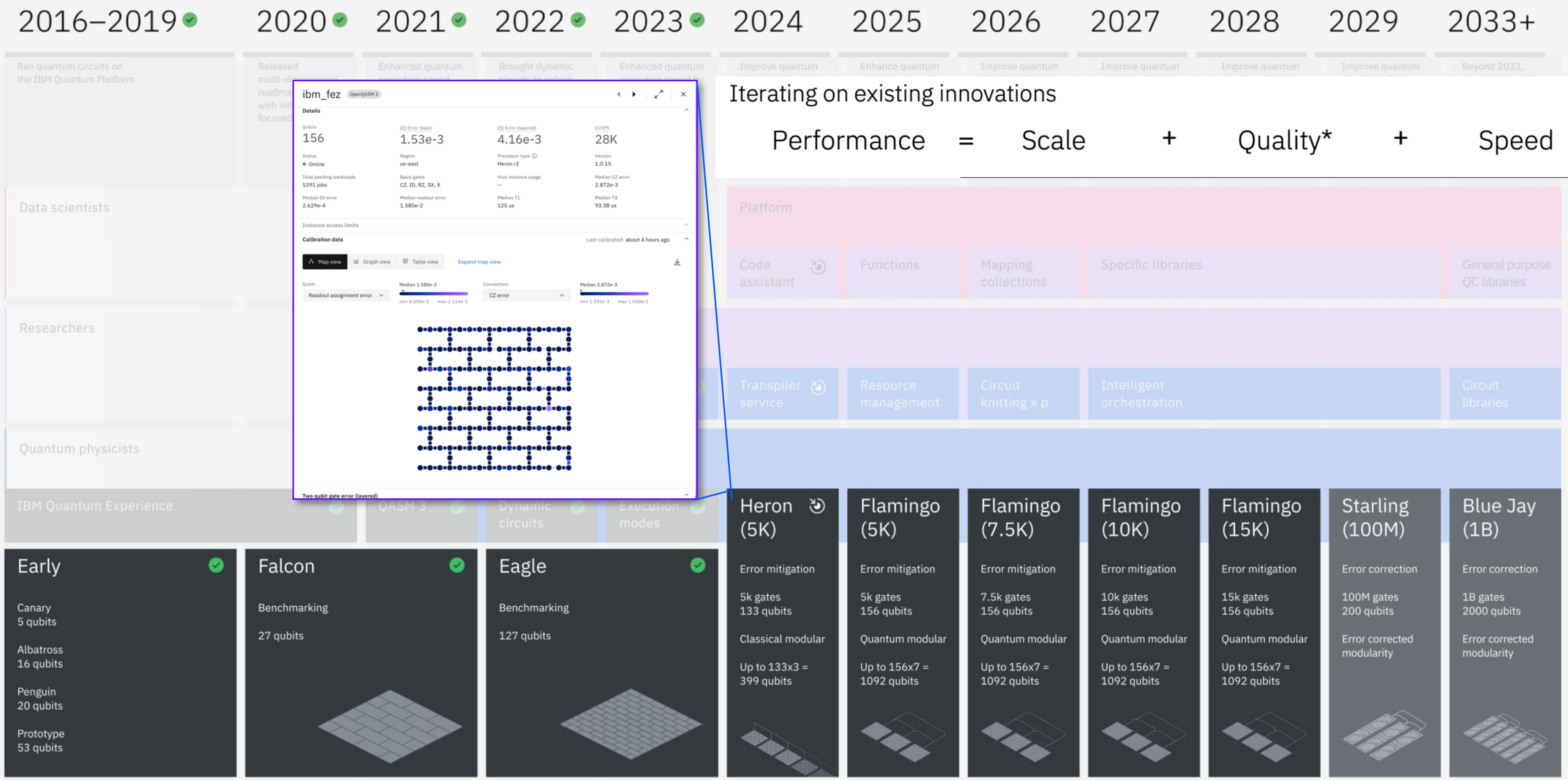
From 2020 to 2023, we focused on solving single-chip scaling with the IBM Quantum Falcon, Hummingbird, Eagle, Osprey, and Condor chips.

In 2023, we debuted the IBM Quantum Heron chip, Heron will serve as the basis for modular scaling of quantum processors.

Through classical and quantum modularity, we plan to achieve an **IBM Quantum Flamingo** system capable of running 15,000 gates with the help of error mitigation by 2028.

2029: We foresee advances in quantum error correction allowing us to debut **IBM Quantum Starling**, a system capable of running circuits with **100 million gates on 200 logical qubits**

In 2033, we will debut **IBM Quantum Blue Jay**, a system capable of running circuits **with a billion gates on 2,000 logical qubits.**



2016–2019 ✓ | 2020 ✓ | 2021 ✓ | 2022 ✓ | 2023 ✓ | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2033+

ibm_fez OpenQASM 3

Details

Qubits	2Q Error (best)	2Q Error (layered)	CLOPS
156	1.53e-3	4.16e-3	28K

Status	Region	Processor type ⓘ:	Version
● Online	us-east	Heron r2	1.0.15
Total pending workloads	**Basis gates**	**Your instance usage**	**Median CZ error**
5391 jobs	CZ, ID, RZ, SX, X	--	2.872e-3
Median SX error	**Median readout error**	**Median T1**	**Median T2**
2.629e-4	1.580e-2	125 us	93.38 us

Instance access limits

Calibration data

Last calibrated: about 4 hours ago

Map view | Graph view | Table view | Expand map view

Qubit: Readout assignment error

Median 1.580e-2 min 4.500e-3 max 2.114e-1

Connection: CZ error

Median 2.872e-3 min 1.531e-3 max 1.040e-1

Two qubit gate error (layered)

Iterating on existing innovations

Performance = Scale + Quality* + Speed

Early ✓	Falcon ✓	Eagle ✓	Heron (5K)	Flamingo (5K)	Flamingo (7.5K)	Flamingo (10K)	Flamingo (15K)	Starling (100M)	Blue Jay (1B)
Canary 5 qubits	Benchmarking	Benchmarking	Error mitigation	Error mitigation	Error mitigation	Error mitigation	Error mitigation	Error correction	Error correction
Albatross 16 qubits	27 qubits	127 qubits	5k gates 133 qubits	5k gates 156 qubits	7.5k gates 156 qubits	10k gates 156 qubits	15k gates 156 qubits	100M gates 200 qubits	1B gates 2000 qubits
Penguin 20 qubits			Classical modular	Quantum modular	Quantum modular	Quantum modular	Quantum modular	Error corrected modularity	Error corrected modularity
Prototype 53 qubits			Up to 133x3 = 399 qubits	Up to 156x7 = 1092 qubits	Up to 156x7 = 1092 qubits	Up to 156x7 = 1092 qubits	Up to 156x7 = 1092 qubits		

https://docs.quantum.ibm.com/guides/processor-types

✓ Executed by IBM

On target

As we roll out error correction, developers need not change how they write quantum programs. They will simply notice that they can run longer workloads.

Middleware and Software, Execution and orchestration

Running quantum workloads requires infrastructure that coordinates quantum resources with near-time and real-time classical resources.

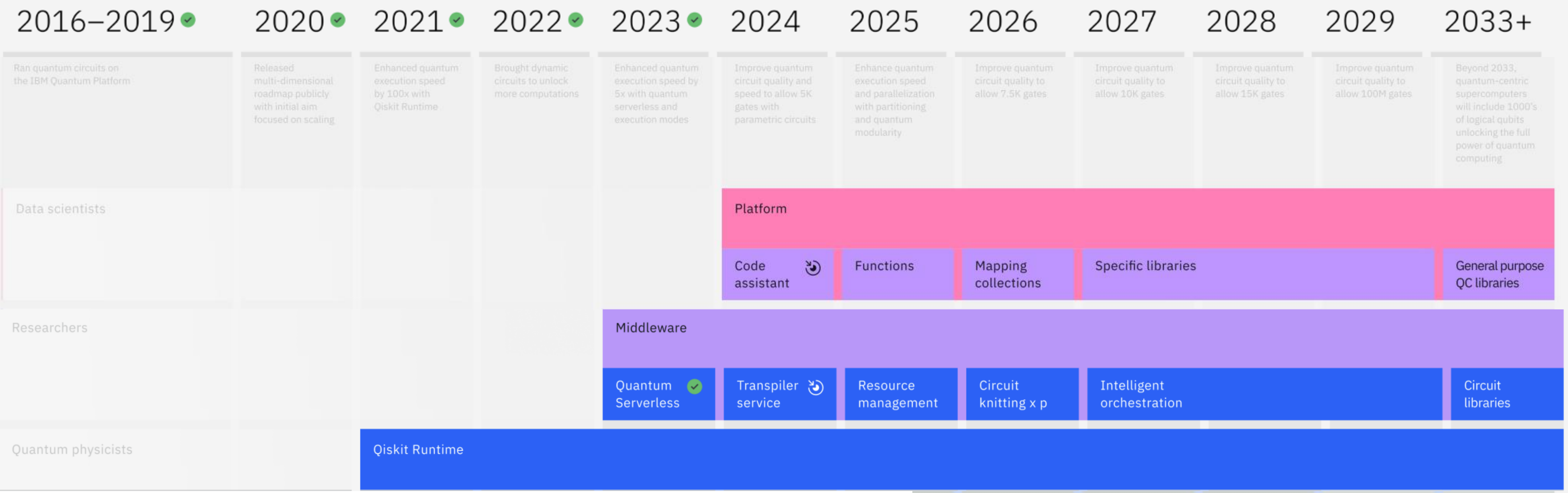
Since 2016, we have worked to create Qiskit and a variety of application libraries.

In 2024 we redefined Qiskit to represent the full-stack software for quantum at IBM, **extending the Qiskit SDK with middleware software and services**

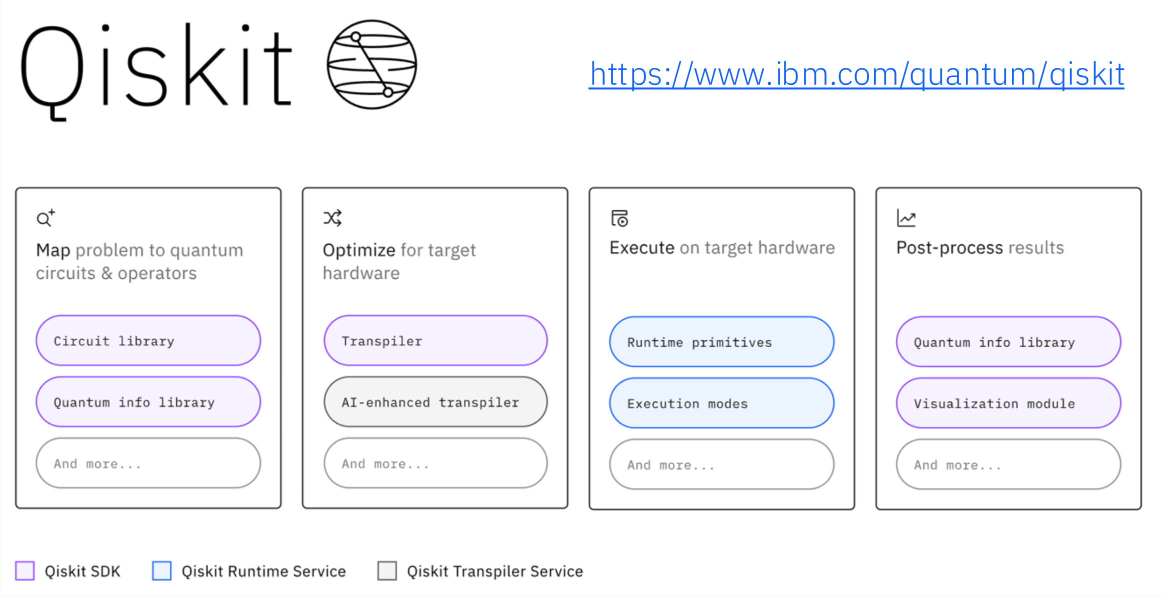
Useful quantum computing requires performant software.

In 2025, we will introduce **quantum functions** so users can create and share reusable blocks of Qiskit code.

2026 will bring mapping collections so users can start **automating** the process of **mapping their specific use cases** to quantum circuits.



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



Qiskit

https://www.ibm.com/quantum/qiskit

Map problem to quantum circuits & operators
- Circuit library
- Quantum info library
- And more...

Optimize for target hardware
- Transpiler
- AI-enhanced transpiler
- And more...

Execute on target hardware
- Runtime primitives
- Execution modes
- And more...

Post-process results
- Quantum info library
- Visualization module
- And more...

☐ Qiskit SDK ☐ Qiskit Runtime Service ☐ Qiskit Transpiler Service

By 2033, we expect to see general-purpose quantum computing libraries that users can incorporate into a wide variety of quantum applications.

IBM Quantum Network

The **largest** quantum ecosystem **in the industry**

The **IBM Quantum Network** is the core of our global user community and ecosystem — driving innovation and shaping the future of quantum computing.

- Universities and research laboratories
- Business partners
- Startups
- Industry leaders

600K

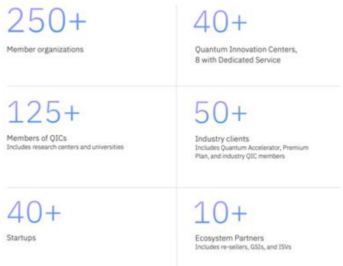
Registered users worldwide

3K+

Research papers using IBM quantum computers

250+

Organizations in the IBM Quantum Network



250+
Member organizations

40+
Quantum Innovation Centers,
8 with Dedicated Service

125+
Members of QICs
Includes research centers and universities

50+
Industry clients
Includes Quantum Accelerator, Premium Plan, and industry QIC members

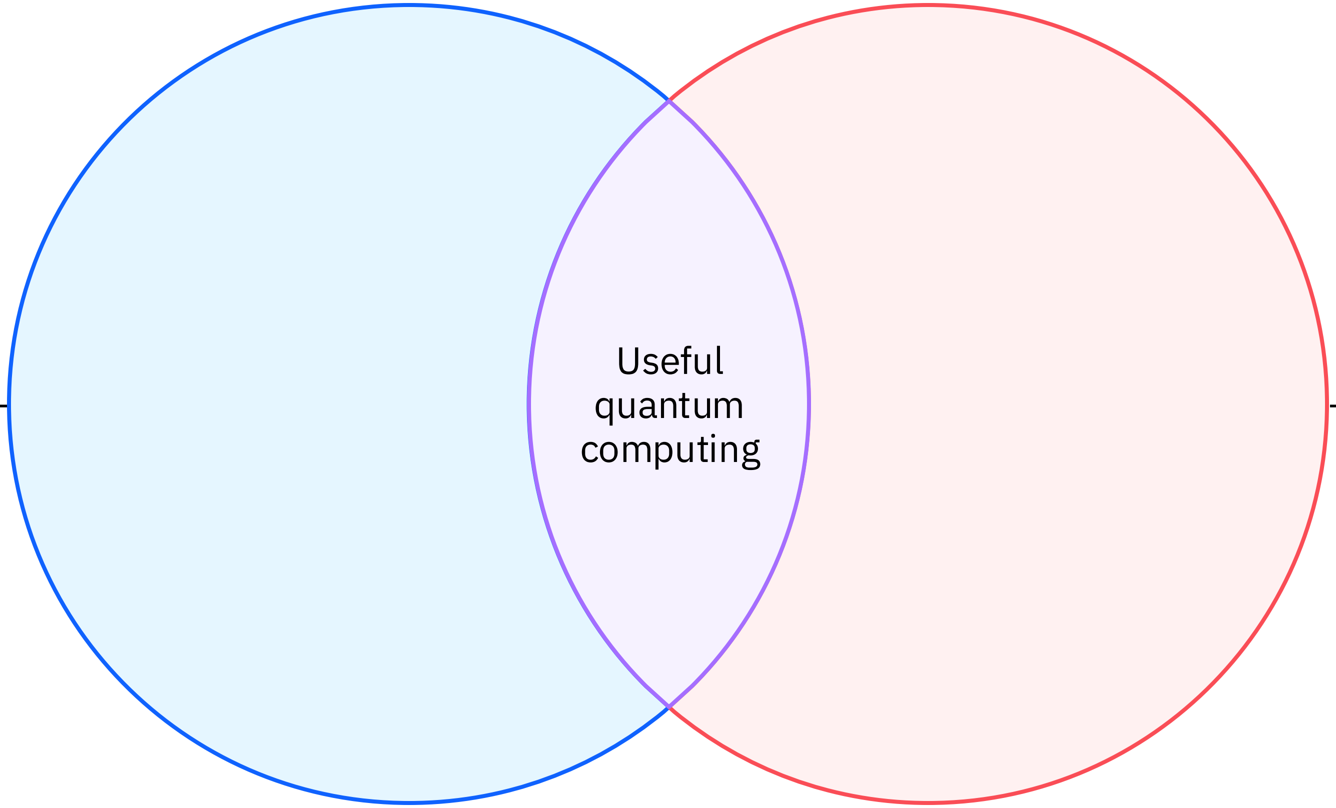
40+
Startups

10+
Ecosystem Partners
Includes re-sellers, GSIs, and ISVs

500+

Qiskit Advocates

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.

Useful quantum computing

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.

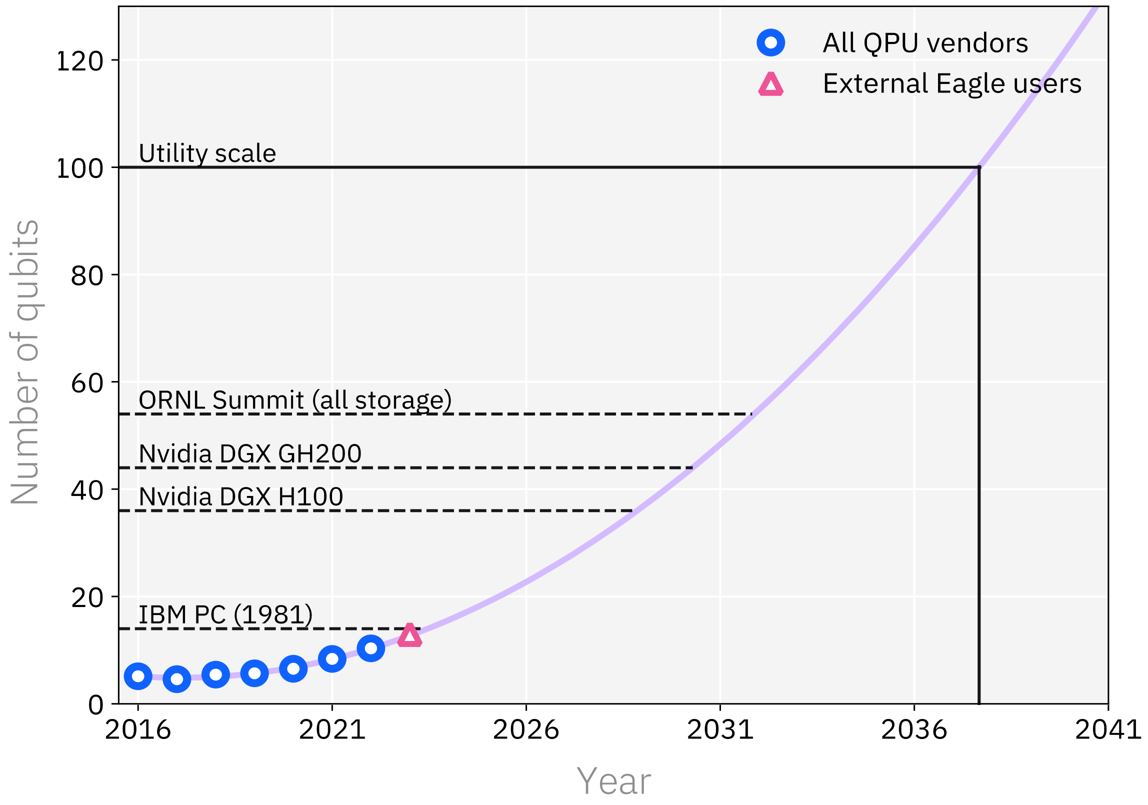
Quantum state of play

Since we put the first quantum computer on the cloud in 2016, quantum computing has largely been in an exploratory phase.

Experiments validate the tenets of quantum computation, but do not push the field beyond the reach of classical compute.

To move beyond simple experiments to demonstrate the utility of quantum computing in multiple domains,

Estimated mean number of qubits used on hardware



Data for all vendors taken from: arXiv:2307.16130

We need a disruptive change!

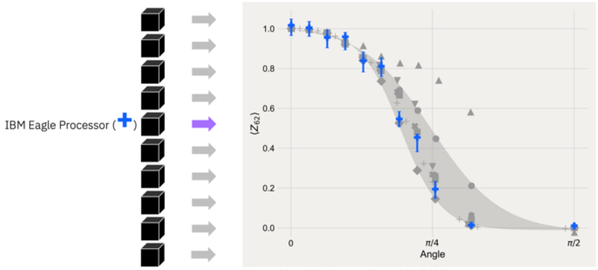
We are already seeing a disruptive change in how researchers are doing quantum

With quantum systems composed of 100+ qubits, researchers are beginning to explore algorithms and applications at scales beyond brute-force classical computation using IBM Quantum systems.

Evidence for the utility of quantum computing before fault tolerance

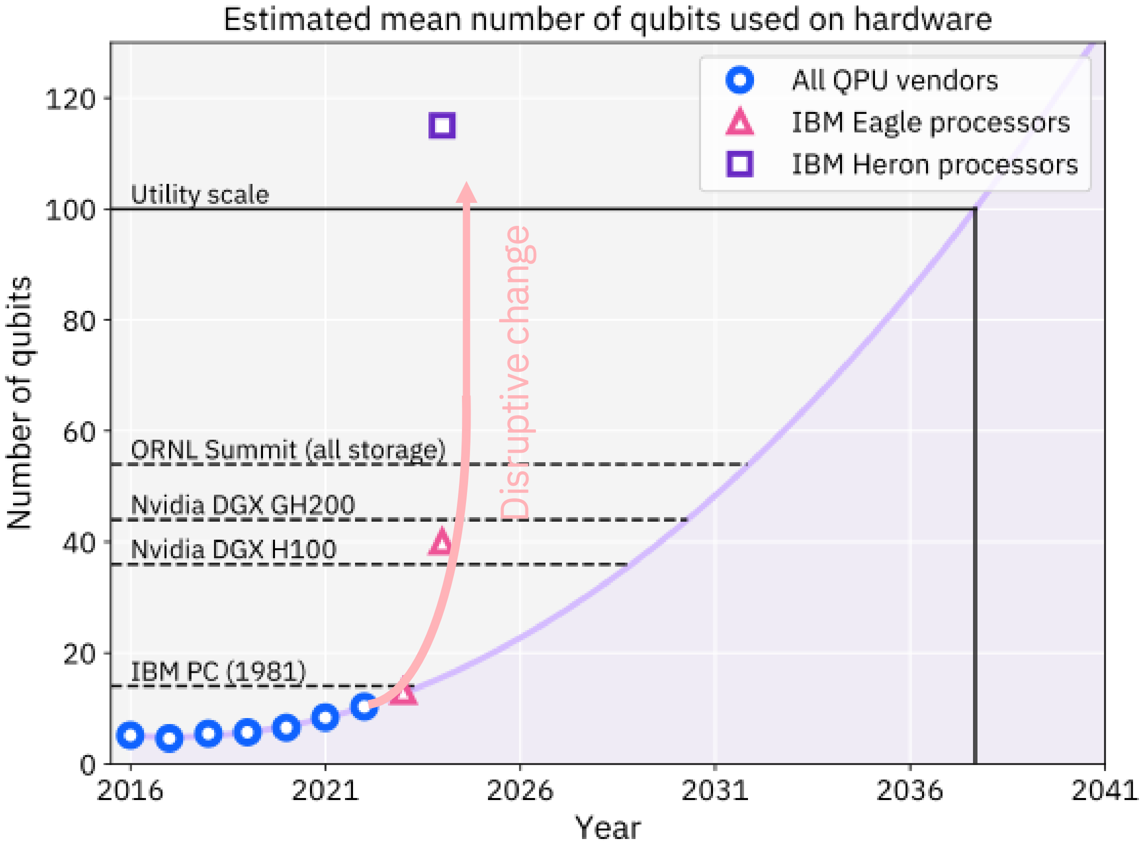
127 qubits / 2880 CX gates

Nature, **618**, 500 (2023)



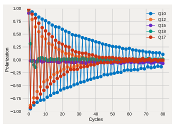
Adapted from PRX Quantum 5, 010308 (2024)

- Comparison of various approaches to simulating the kicked transverse-field Ising model on the 127-qubit Eagle processor with new classical heuristic methods
- Results vary by ~20%, and no one knows which method is the most correct!



Flip the script: using quantum computers to verify the accuracy of classical simulations

Examples of utility-scale problems * (>70qubits, >150 CX /200 ECR gates)

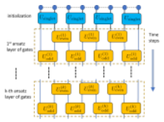


Characterizing quantum processors using discrete time crystals
arXiv:2301.07625
80 qubits / 7900 CX gates

materials

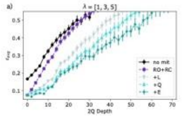
Evidence for the utility of quantum computing before fault tolerance
Nature, 618, 500 (2023)
127 qubits / 2880 CX gates

spin models



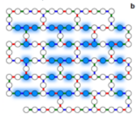
Simulating large-size quantum spin chains on cloud-based superconducting quantum computers
Phys. Rev. Research 5, 013183 (2023)
102 qubits / 3186 CX gates

spin models



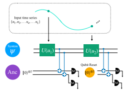
Best practices for quantum error mitigation with digital zero-noise extrapolation
arXiv:2307.05203
104 qubits / 3605 ECR gates

tools



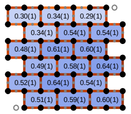
Uncovering Local Integrability in Quantum Many-Body Dynamics
arXiv:2307.07552
124 qubits / 2641 CX gates

materials



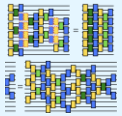
Quantum reservoir computing with repeated Measurements on superconducting devices
arXiv:2310.06706
120 qubits / 49470 gates + meas.

materials



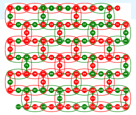
Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits
arXiv:2309.02863
125 qubits / 429 gates + meas.

spin models



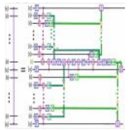
Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits
PRX Quantum 5, 020315 (2024)
100 qubits / 788 CX gates

High energy physics



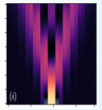
Scaling Whole-Chip QAOA for Higher-Order Ising Spin Glass Models on Heavy-Hex Graphs
arXiv:2312.00997
127 qubits / 420 CX gates

optimization



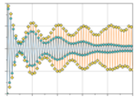
Efficient Long-Range Entanglement using Dynamic Circuits
arXiv:2308.13065
101 qubits / 504 gates + meas

tools



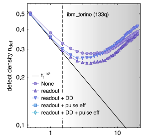
Quantum Simulations of Hadron Dynamics in the Schwinger Model using 112 Qubits
arXiv:2401.08044
112 qubits / 13,858 gates

High energy physics



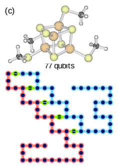
Unveiling clean two-dimensional discrete time quasicrystals on a digital quantum computer
arXiv:2403.16718
133 qubits / 15,000 CZ gates

materials



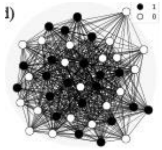
Benchmarking digital quantum simulations and optimization above hundreds of qubits using quantum critical dynamics
arXiv:2404.08053
133 qubits / 1440 CX gates

spin models



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

chemistry



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

optimization

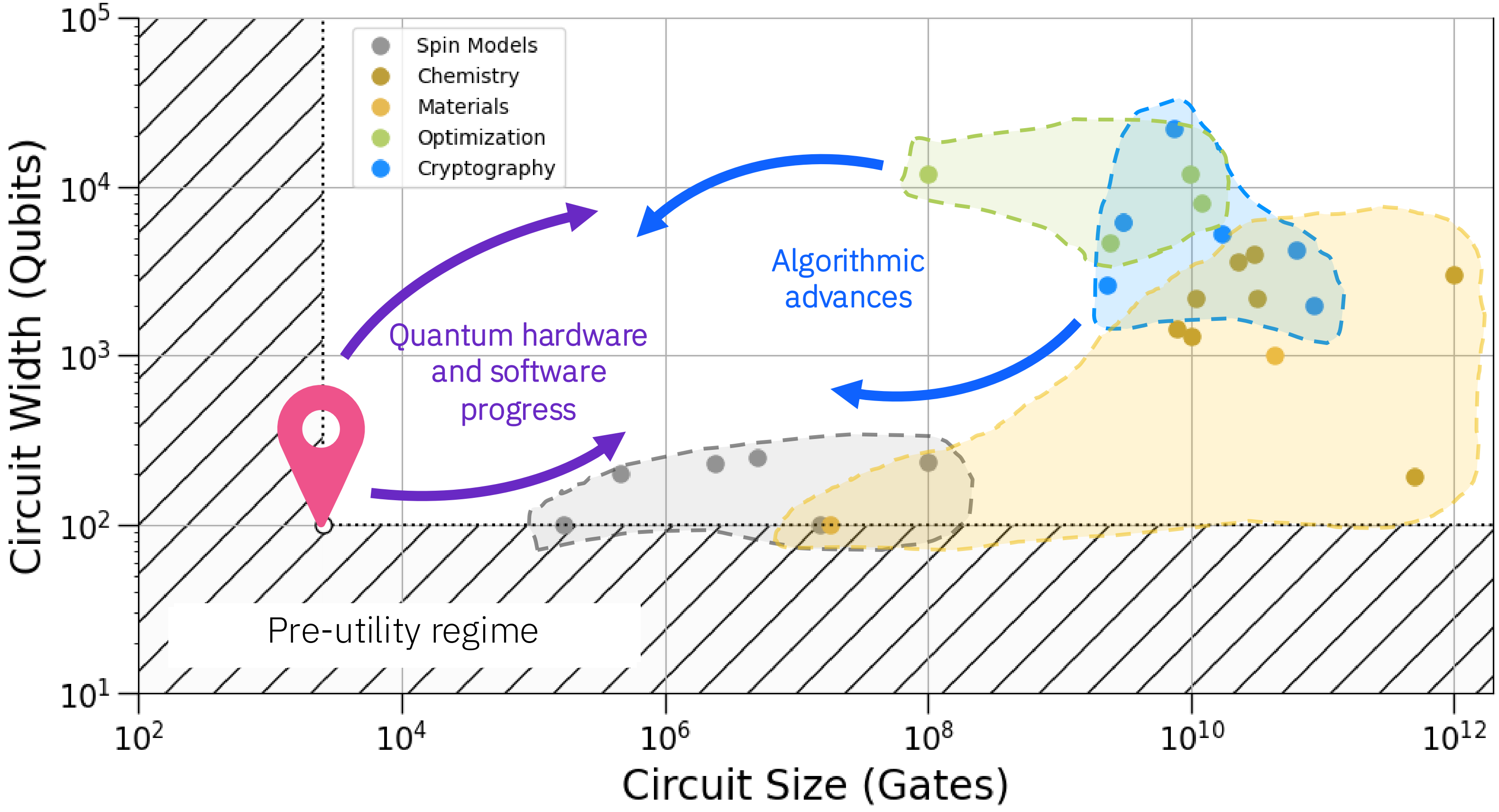
A landscape of single circuits:

Map problem to quantum circuits & operators

Optimize for target hardware

Execute on target hardware

Post-process results



> *“This variant of my algorithm was undiscovered for 30 years and came out of the blue. There’s still probably lots of other quantum algorithms to be found.”*
>
> Peter Shor

Quantum Working Groups

IBM Quantum working groups bring together the best scientists in our field to accelerate our path to achieving Quantum Advantage with near term devices, across domain areas:

High-Energy Physics

Quantum Computing for High-Energy Physics: State of the Art and Challenges. Summary of the QC4HEP Working Group

PRX Quantum 5, 037001

Partners
CERN QTI, DESY CQTA, Oak Ridge National Lab, U. of Washington, U. of Tokyo, and more

Optimization

Quantum Optimization: Potential, Challenges, and the Path Forward

arXiv:2312.02279

Partners
STFC Hartree Centre, E.ON., Fraunhofer, Los Alamos National Lab, University of Amsterdam/QAL, and more

Materials & HPC

Quantum-centric Supercomputing for Materials Science: A Perspective on Challenges and Future Directions

arXiv:2312.09733

Partners
Oak Ridge National Lab, University of Chicago, Argonne National Lab, RIKEN, BasQ, and more

Healthcare & Life Sciences

Towards quantum-enabled cell-centric therapeutics

arXiv:2307.05734

Partners
Cleveland Clinic, U. of Chicago, QuantumBasel, Virginia Tech, Algorithmiq, and more

Sustainability

Collaborative projects in the fields of Materials and Energy leveraging quantum computers.

-

Partners
PINQ^2, Hydro-Quebec, University of Sherbrooke, E.ON., DTU, and more

The QC4HEP community paper

https://journals.aps.org/prxquantum/abstract/10.1103/PRXQuantum.5.037001

A study initiated by workshop on high-energy physics (HEP) held in November 2022 at CERN in Geneva to define a Roadmap to outline the current state of quantum computing in HEP that can be pursued with near-term quantum computers

PRX QUANTUM **5**, 037001 (2024)

Roadmap

Quantum Computing for High-Energy Physics: State of the Art and Challenges

Alberto Di Meglio,[1,*] Karl Jansen,[2,3,†] Ivano Tavernelli,[4,‡] Constantia Alexandrou,[3,5]
Srinivasan Arunachalam,[6] Christian W. Bauer,[7] Kerstin Borras,[8,9] Stefano Carrazza,[1,10]
Arianna Crippa,[2,11] Vincent Croft,[12] Roland de Putter,[6] Andrea Delgado,[13] Vedran Dunjko,[12]
Daniel J. Egger,[4] Elias Fernández-Combarro,[14] Elina Fuchs,[1,15,16] Lena Funcke,[17]
Daniel González-Cuadra,[18,19] Michele Grossi,[1] Jad C. Halimeh,[20,21] Zoë Holmes,[22]
Stefan Kühn,[2] Denis Lacroix,[23] Randy Lewis,[24] Donatella Lucchesi,[1,25]
Miriam Lucio Martinez,[26,27] Federico Meloni,[8] Antonio Mezzacapo,[6] Simone Montangero,[1,25]
Lento Nagano,[28] Vincent R. Pascuzzi,[6] Voica Radescu,[29] Enrique Rico Ortega,[30,31,32,33]
Alessandro Roggero,[34,35] Julian Schuhmacher,[4] Joao Seixas,[36,37,38] Pietro Silvi,[1,25]
Panagiotis Spentzouris,[39] Francesco Tacchino,[4] Kristan Temme,[6] Koji Terashi,[28] Jordi Tura,[12,40]
Cenk Tüysüz,[2,11] Sofia Vallecorsa,[1] Uwe-Jens Wiese,[41] Shinjae Yoo,[42] and Jinglei Zhang[43,44]

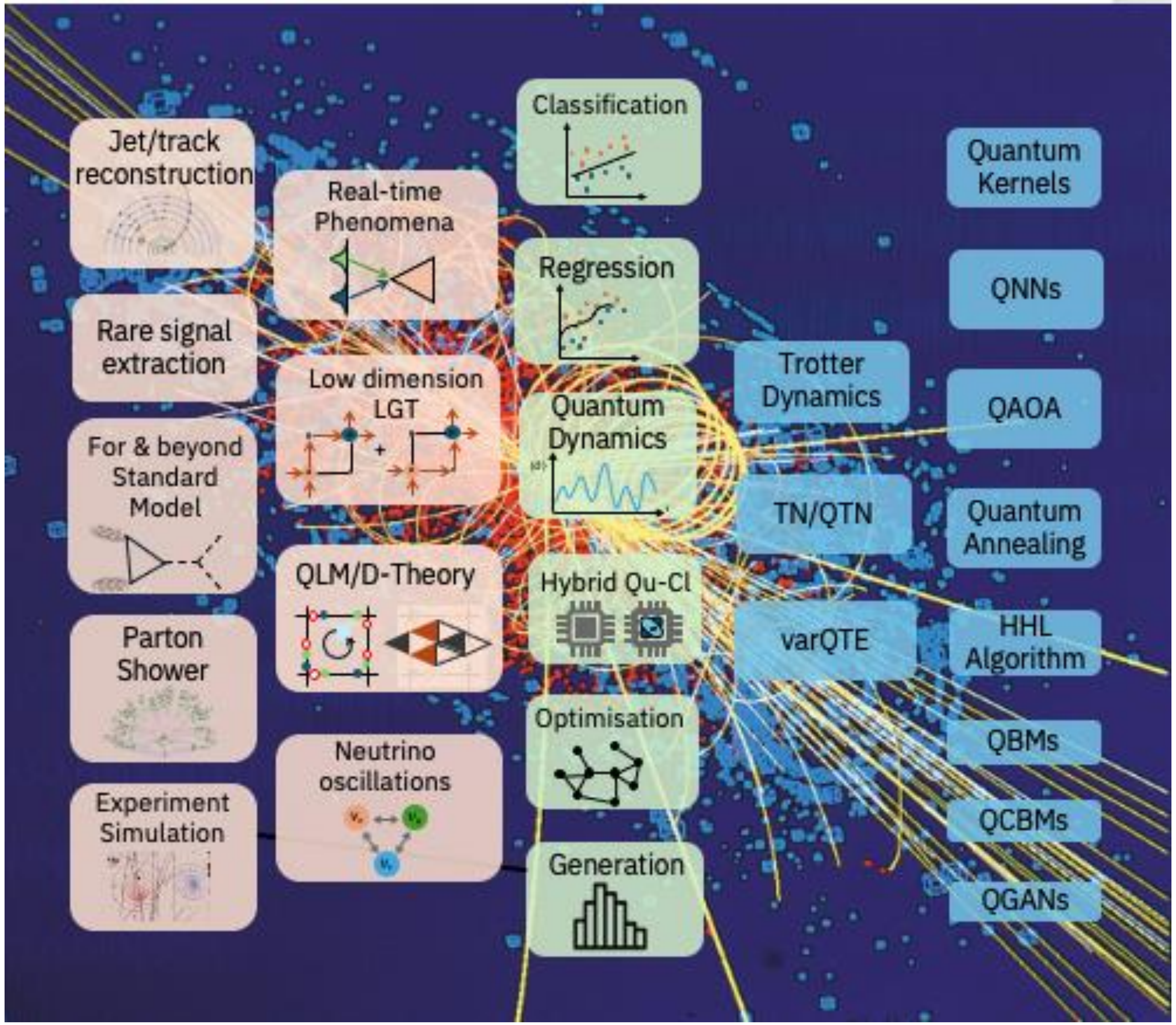
[1] *European Organization for Nuclear Research (CERN), 1211 Geneva, Switzerland*
[2] *CQTA, Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany*
[3] *Computation-based Science and Technology Research Center, The Cyprus Institute, 20 Konstantinou Kavafi Street, CY-2121 Nicosia, Cyprus*
[4] *IBM Research Europe — Zurich, 8803 Rüschlikon, Switzerland*
[5] *Department of Physics, University of Cyprus, PO Box 20537, CY-1678 Nicosia, Cyprus*
[6] *IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, NY 10598, USA*
[7] *Physics Division Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Mailstop 50A5104, Berkeley, California, USA*
[8] *Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, 22607 Hamburg, Germany*
[9] *RWTH Aachen University, Templergraben 55, 52062 Aachen, Germany*
[10] *TIF Lab, Dipartimento di Fisica, Università degli Studi di Milano and INFN Sezione di Milano, Milan, Italy*
[11] *Institut für Physik, Humboldt-Universität zu Berlin, Newtonstraße 15, 12489 Berlin, Germany*
[12] *⟨aQa^L⟩ Applied Quantum Algorithms – Leiden, Leiden, Netherlands*
[13] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[14] *Department of Computer Science, Facultad de Ciencias, University of Oviedo, 33007 Asturias, Spain*
[15] *Institute of Theoretical Physics, Leibniz University Hannover, 30167 Hanover, Germany*
[16] *Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany*
[17] *Transdisciplinary Research Area "Building Blocks of Matter and Fundamental Interactions" (TRA Matter) and Helmholtz Institute for Radiation and Nuclear Physics (HISKP), University of Bonn, Nußallee 14–16, 53115 Bonn, Germany*
[18] *Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria*
[19] *Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, 6020 Innsbruck, Austria*
[20] *Department of Physics and Arnold Sommerfeld Center for Theoretical Physics, Ludwig-Maximilians-Universität München, Munich, Germany*
[21] *Munich Center for Quantum Science and Technology, Munich, Germany*
[22] *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland*
[23] *CNRS/IN2P3, IJCLab, Paris-Saclay University, 91405 Orsay, France*
[24] *Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada*
[25] *INFN—Sezione di Padova, Via Marzolo 8, 35131 Padua, Italy*
[26] *Nikhef—National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands*

---

[*] Contact author: alberto.di.meglio@cern.ch
[†] Contact author: karl.jansen@desy.de
[‡] Contact author: ita@zurich.ibm.com

Proposed applications | Approach | Algorithm

Experiment | Theory



QCD is the theory of the strong force that binds the nuclei of atoms together, and it presents enormous challenges when it comes to observing, modelling, and predicting the behaviour of fundamental particles.

The Schwinger model is **quantum electrodynamics in (1 + 1) space-time dimensions**. This model shares many properties with QCD, including confinement (in the massive case) and chiral symmetry breaking.

spin models

https://www.ibm.com/quantum/blog/hadron-dynamics-simulations

Schwinger model used to demonstrate the first essential step in building future simulations of high-energy collisions of matter: preparing a simulation of the quantum vacuum state in which particle collisions would occur:

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

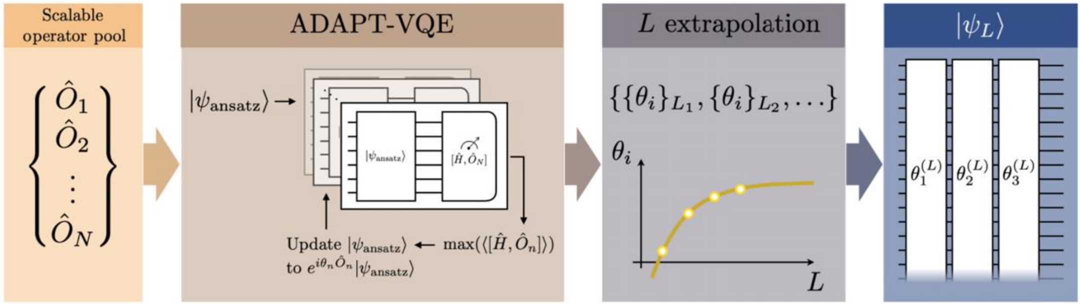


FIG. 1. Pictorial description of the SC-ADAPT-VQE algorithm. Once a pool of scalable operators $\{\hat{O}_i\}$ has been identified, ADAPT-VQE is performed with use of *classical* computers to determine a quantum circuit (parameterized by $\{\theta_i\}$) that prepares the vacuum up to a desired tolerance. ADAPT-VQE is repeated for multiple lattice sizes, $\{L_1, L_2, \ldots\}$, and the circuit parameters are extrapolated to the desired L, which can be arbitrarily large. The extrapolated circuits are executed on a quantum computer to prepare the vacuum on a system of size L.

A follow-up to that paper shows techniques preparing a beam of particles time evolving in the quantum vacuum:

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

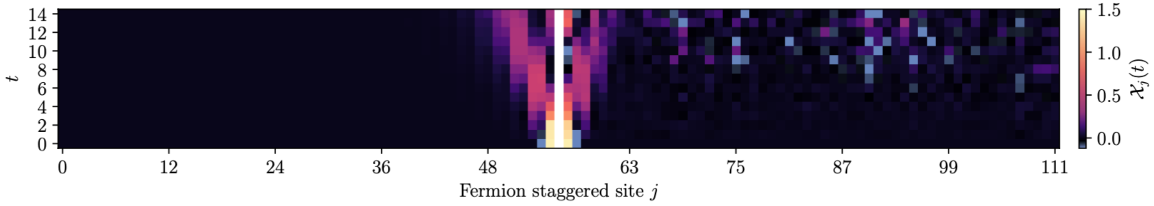
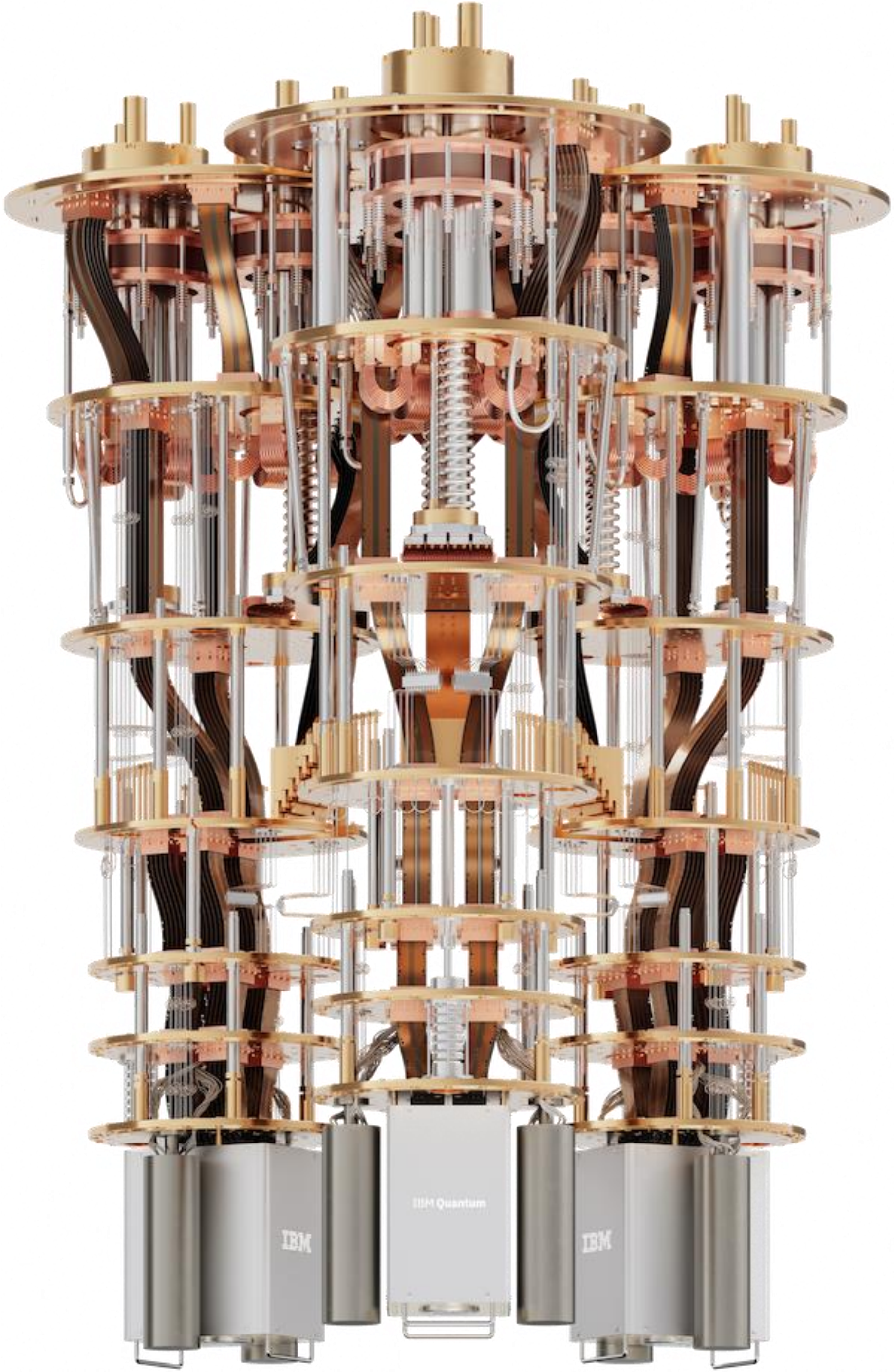


FIG. 10. The time evolution of the vacuum subtracted chiral condensate $\mathcal{X}_j(t)$, defined in Eq. (18), for a $L = 56$ (112 qubits) spatial-site lattice. The initial state is prepared using the 2-step SC-ADAPT-VQE vacuum and wavepacket preparation circuits. Time evolution is implemented using a second-order Trotterization of the Hamiltonian with the $\bar{\lambda} = 1$ truncated electric interaction. The left side shows the results of error-free classical simulations from the `cuQuantum` MPS simulator, while the right side shows the CP-averaged results obtained using IBM's superconducting-qubit digital quantum computer `ibm_torino` (both sides show the MPS result for $t = 0$). Due to CP symmetry, the right and left halves would be mirror images of each other in the absence of device errors. A more detailed view for each time slice is given in Fig. 11, and discussions of the error-mitigation techniques are presented in the main text and App. G.



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 250+ 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.

Quantum-centric *supercomputing*

01 Modularity for quantum

02 Communication for quantum

03 Middleware for quantum

IBM **Quantum**

Development Roadmap

2024	2025	2026	2027	2028	2029	2033+
Improving quantum circuit quality and speed to allow 5K gates with parametric circuits	Enhancing quantum execution speed and parallelization with partitioning and quantum modularity	Improving quantum circuit quality to allow 7.5K gates	Improving quantum circuit quality to allow 10K gates	Improving quantum circuit quality to allow 15K gates	Improving 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
Platform						
Code assistant	Functions	Mapping Collection	Specific Libraries			General purpose QC libraries
Transpiler Service	Resource Management	Circuit Knitting x P	Intelligent Orchestration			Circuit libraries
Heron (5K) Error Mitigation 5k gates 133 qubits Classical modular 133x3 = 399 qubits	Flamingo (5K) Error Mitigation 5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (7.5K) Error Mitigation 7.5k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (10K) Error Mitigation 10k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Flamingo (15K) Error Mitigation 15k gates 156 qubits Quantum modular 156x7 = 1092 qubits	Starling (100M) Error correction 100M gates 200 qubits Error corrected modularity	Blue Jay (1B) Error correction 1B gates 2000 qubits Error corrected modularity

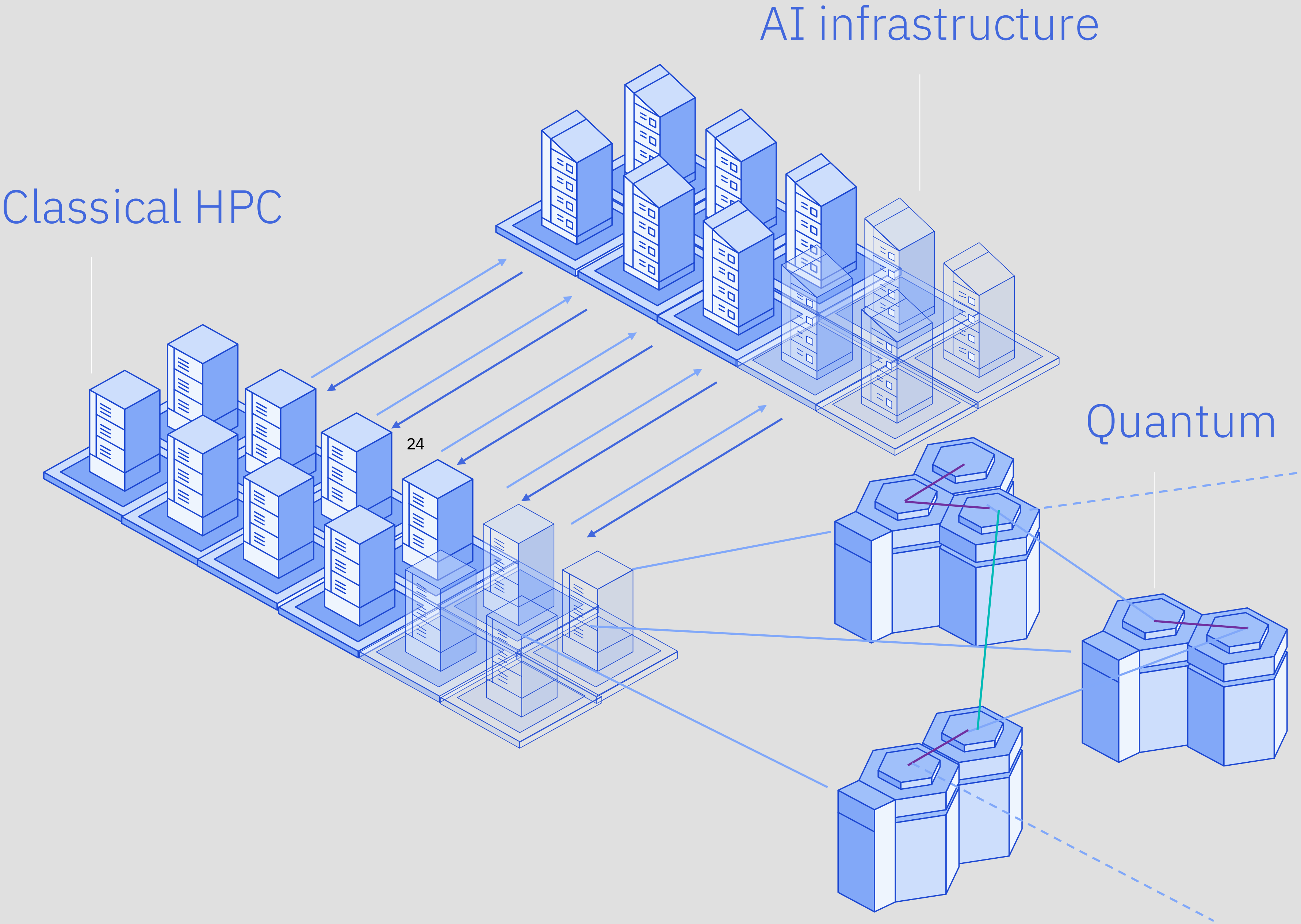
Innovation Roadmap

Resource management System partitioning to enable parallel execution	Scalable circuit knitting Circuit partitioning with classical reconstruction at HPC scale	Error correction decoder Demonstration of a quantum system with real-time error correction decoder				
Flamingo Demonstrate scaling with modular connectors	Kookaburra Demonstrate scaling with nonlocal c-coupler	Demonstrate path to improved quality with logical memory	Cockatoo Demonstrate path to improved quality with logical communication	Starling Demonstrate path to improved quality with logical gates		
Crossbill m- coupler						

Quantum is a component in the future of advanced computing

In the future, quantum will integrate with other components, including AI, to enhance the overall capability of our computational tools.

Each tool is best suited for certain types of tasks, and all will work together to solve the hardest problems that face society today.



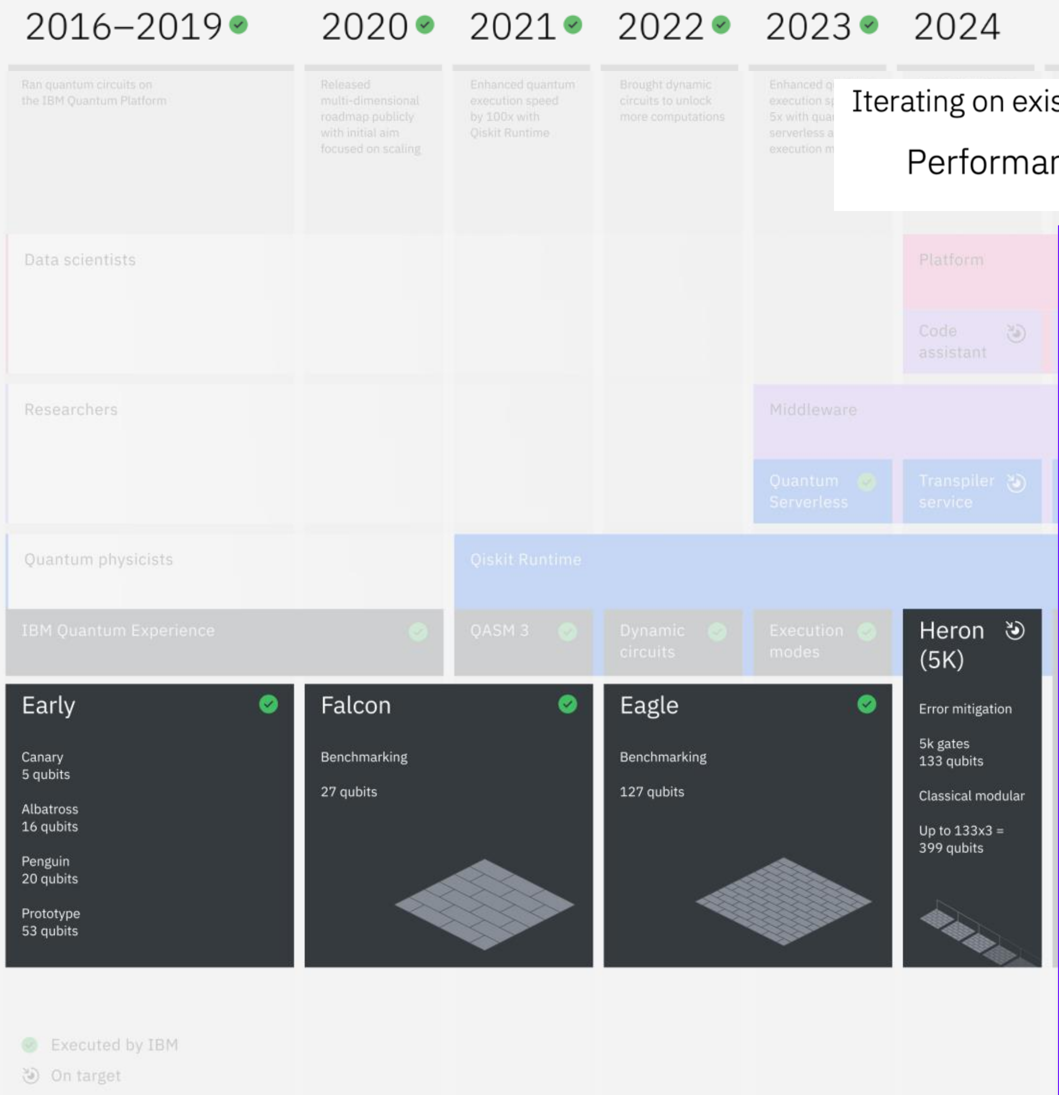
IBM **Quantum**

What we have accomplished:
Hardware

From 2020 to 2023, we **focused on solving single-chip scaling** with the IBM Quantum Falcon, Hummingbird, Eagle, Osprey, and Condor chips.

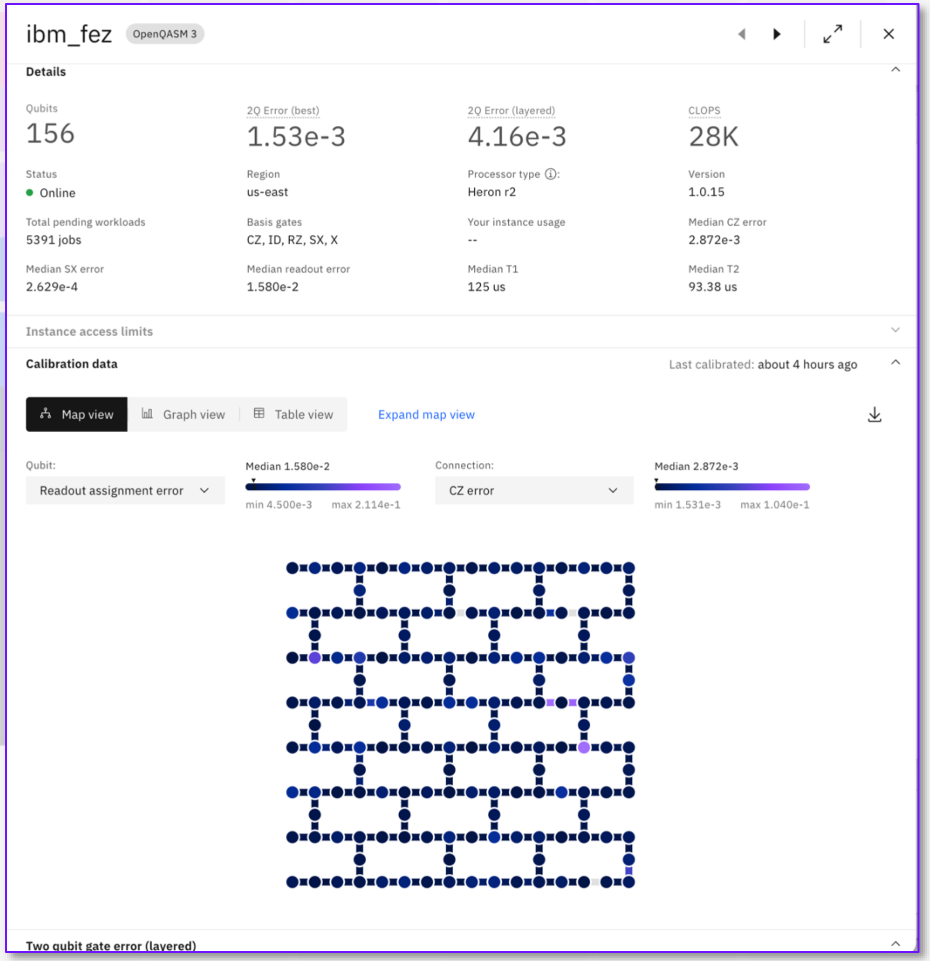
In 2023, **we debuted the IBM Quantum Heron chip**, which uses tunable couplers to achieve our lowest error rates yet. **Heron will serve as the basis for modular scaling of quantum processors.**

In 2024, **Heron is capable of running 5,000 gates.**



Iterating on existing innovations

Performance = Scale + Quality* + Speed



ibm_fez

Details

Qubits	2Q Error (best)	2Q Error (layered)	CLOPS
156	1.53e-3	4.16e-3	28K

Status: Online
Region: us-east
Processor type: Heron r2
Version: 1.0.15
Total pending workloads: 5391 jobs
Basis gates: CZ, ID, RZ, SX, X
Your instance usage: --
Median CZ error: 2.872e-3
Median SX error: 2.629e-4
Median readout error: 1.580e-2
Median T1: 125 us
Median T2: 93.38 us

Instance access limits

Calibration data

Last calibrated: about 4 hours ago

Qubit: Readout assignment error
Median 1.580e-2
min 4.500e-3 max 2.114e-1
Connection: CZ error
Median 2.872e-3
min 1.531e-3 max 1.040e-1

Two qubit gate error (layered)

https://docs.quantum.ibm.com/guides/processor-types

https://quantum.ibm.com/

Looking forward:
Hardware

Now, we use **error mitigation and interconnects to run larger circuits** so users can look for quantum advantages in their domains. Through classical and quantum modularity, we plan to achieve an IBM Quantum Flamingo system capable of running 15,000 gates with the help of error mitigation by 2028.

2029: We foresee advances in quantum error correction allowing us to debut **IBM Quantum Starling**, a system capable of running circuits with **100 million gates on 200 logical qubits**

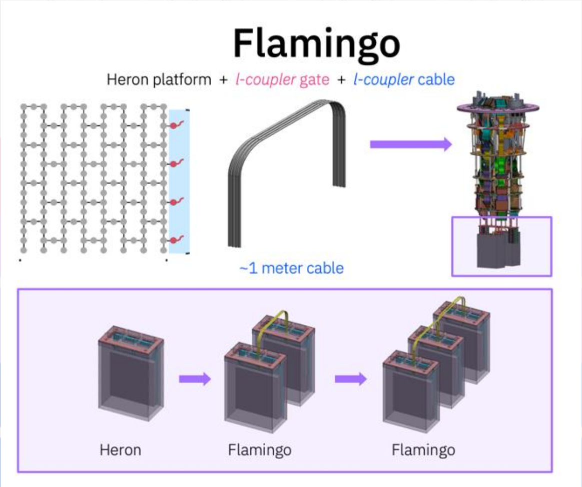
In 2033, we will debut **IBM Quantum Blue Jay**, a system capable of running circuits **with a billion gates on 2,000 logical qubits.**

Year	Milestone	Processor
2016–2019 ✓	Ran quantum circuits on the IBM Quantum Platform	**Early** ✓ Canary 5 qubits Albatross 16 qubits Penguin 20 qubits Prototype 53 qubits
2020 ✓	Released multi-dimensional roadmap publicly with initial aim focused on scaling	**Falcon** ✓ Benchmarking 27 qubits
2021 ✓	Enhanced quantum execution speed by 100x with Qiskit Runtime	
2022 ✓	Brought dynamic circuits to unlock more computations	**Eagle** ✓ Benchmarking 127 qubits
2023 ✓	Enhanced quantum execution speed by 5x with quantum serverless and execution modes	
2024	Improve quantum circuit quality and speed to allow 5K gates with parametric circuits	**Heron (5K)** ◎ Error mitigation 5k gates 133 qubits Classical modular Up to 133x3 = 399 qubits
2025	Enhance quantum	**Flamingo (5K)** Error mitigation 5k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits
2026	Improve quantum	**Flamingo (7.5K)** Error mitigation 7.5k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits
2027	Improve quantum	**Flamingo (10K)** Error mitigation 10k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits
2028	Improve quantum	**Flamingo (15K)** Error mitigation 15k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits
2029	Improve quantum circuit quality to allow 100M gates	**Starling (100M)** Error correction 100M gates 200 qubits Error corrected modularity
2033+	Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full	**Blue Jay (1B)** Error correction 1B gates 2000 qubits Error corrected modularity

Data scientists: Platform; Code assistant ◎

Researchers: Middleware; Quantum Serverless ✓; Transpiler service ◎

Quantum physicists: IBM Quantum Experience ✓; Qiskit Runtime; QASM 3 ✓; Dynamic circuits ✓; Execution modes ✓


Flamingo

Heron platform + *l-coupler* gate + *l-coupler* cable


The international journal of science / 28 March 2024

nature

outline Cancer vaccines

QUBIT QUOTA

Code cuts overhead for quantum error correction by 90%

Wooden ideal Do trees cooperate as much as some experiments suggest?

Liquid assets Local communities are key to ensuring safe access to water for all

Continental drift Dating the arrival and spread of the first hominins in Europe

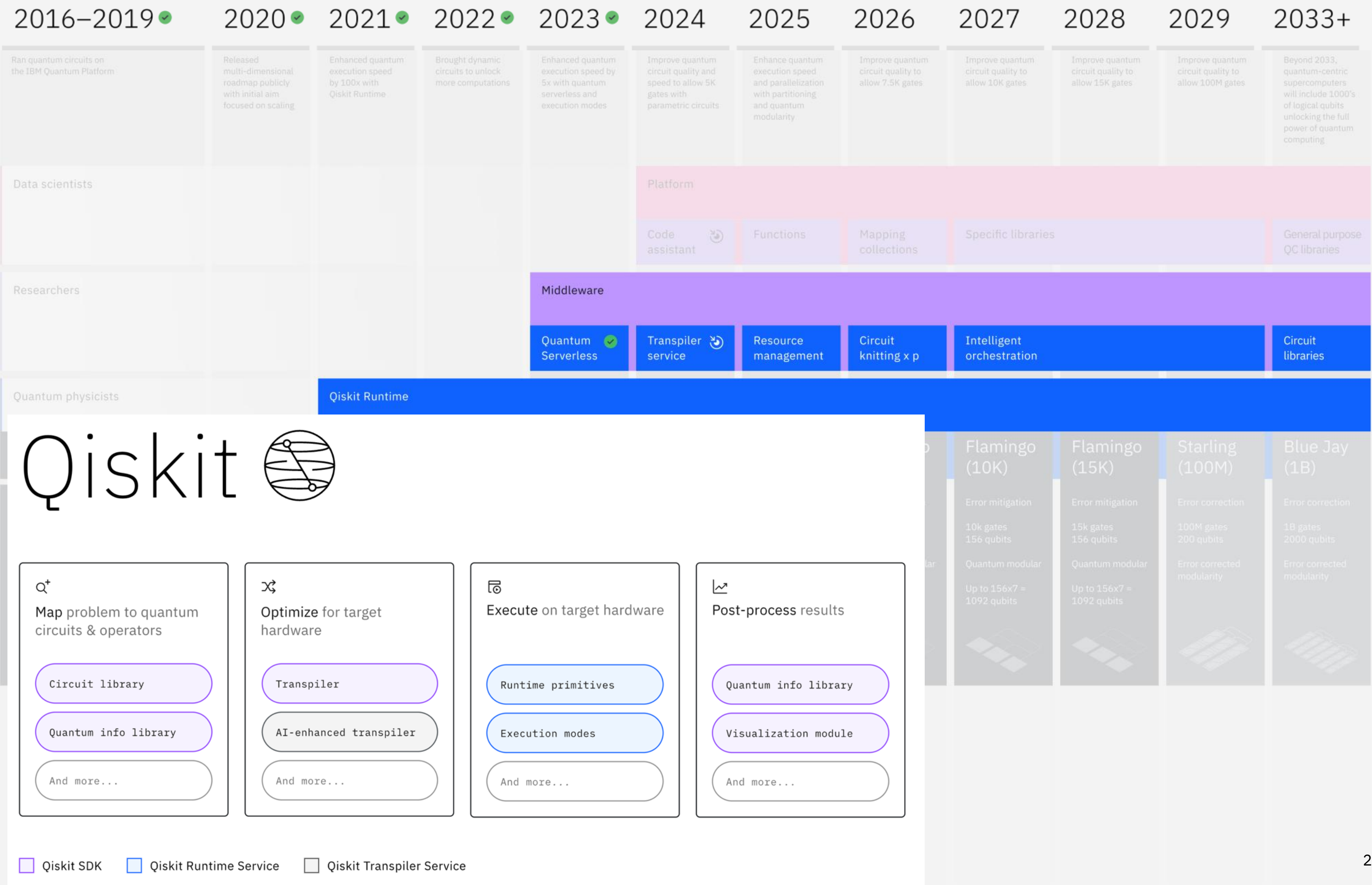
✓ Executed by IBM
◎ On target

As we roll out error correction, developers need not change how they write quantum programs. They will simply notice that they can run longer workloads.

Looking forward:
Execution and orchestration

Running quantum workloads requires infrastructure that coordinates quantum resources with near-time and real-time classical resources.

Since 2016, we have worked to create Qiskit and a variety of application libraries which has now evolved into Qiskit SDK (Open Source), Qiskit Runtime Services and Qiskit Transpiler



2016–2019 ✓ Ran quantum circuits on the IBM Quantum Platform

2020 ✓ Released multi-dimensional roadmap publicly with initial aim focused on scaling

2021 ✓ Enhanced quantum execution speed by 100x with Qiskit Runtime

2022 ✓ Brought dynamic circuits to unlock more computations

2023 ✓ Enhanced quantum execution speed by 5x with quantum serverless and execution modes

2024 Improve quantum circuit quality and speed to allow 5K gates with parametric circuits

2025 Enhance quantum execution speed and parallelization with partitioning and quantum modularity

2026 Improve quantum circuit quality to allow 7.5K gates

2027 Improve quantum circuit quality to allow 10K gates

2028 Improve quantum circuit quality to allow 15K gates

2029 Improve quantum circuit quality to allow 100M gates

2033+ Beyond 2033, quantum-centric supercomputers will include 1000's of logical qubits unlocking the full power of quantum computing

Data scientists

Platform

Code assistant

Functions

Mapping collections

Specific libraries

General purpose QC libraries

Researchers

Middleware

Quantum Serverless ✓

Transpiler service

Resource management

Circuit knitting x p

Intelligent orchestration

Circuit libraries

Quantum physicists

Qiskit Runtime

Flamingo (10K)
Error mitigation
10k gates
156 qubits
Quantum modular
Up to 156x7 = 1092 qubits

Flamingo (15K)
Error mitigation
15k gates
156 qubits
Quantum modular
Up to 156x7 = 1092 qubits

Starling (100M)
Error correction
100M gates
200 qubits
Error corrected modularity

Blue Jay (1B)
Error correction
1B gates
2000 qubits
Error corrected modularity

Qiskit

Map problem to quantum circuits & operators
- `Circuit library`
- `Quantum info library`
- `And more...`

Optimize for target hardware
- `Transpiler`
- `AI-enhanced transpiler`
- `And more...`

Execute on target hardware
- `Runtime primitives`
- `Execution modes`
- `And more...`

Post-process results
- `Quantum info library`
- `Visualization module`
- `And more...`

☐ Qiskit SDK ☐ Qiskit Runtime Service ☐ Qiskit Transpiler Service

]

Looking forward:
Execution and orchestration

In 2021, we released Qiskit Runtime, a service allowing users to orchestrate their programs across IBM Quantum processors and the cloud.

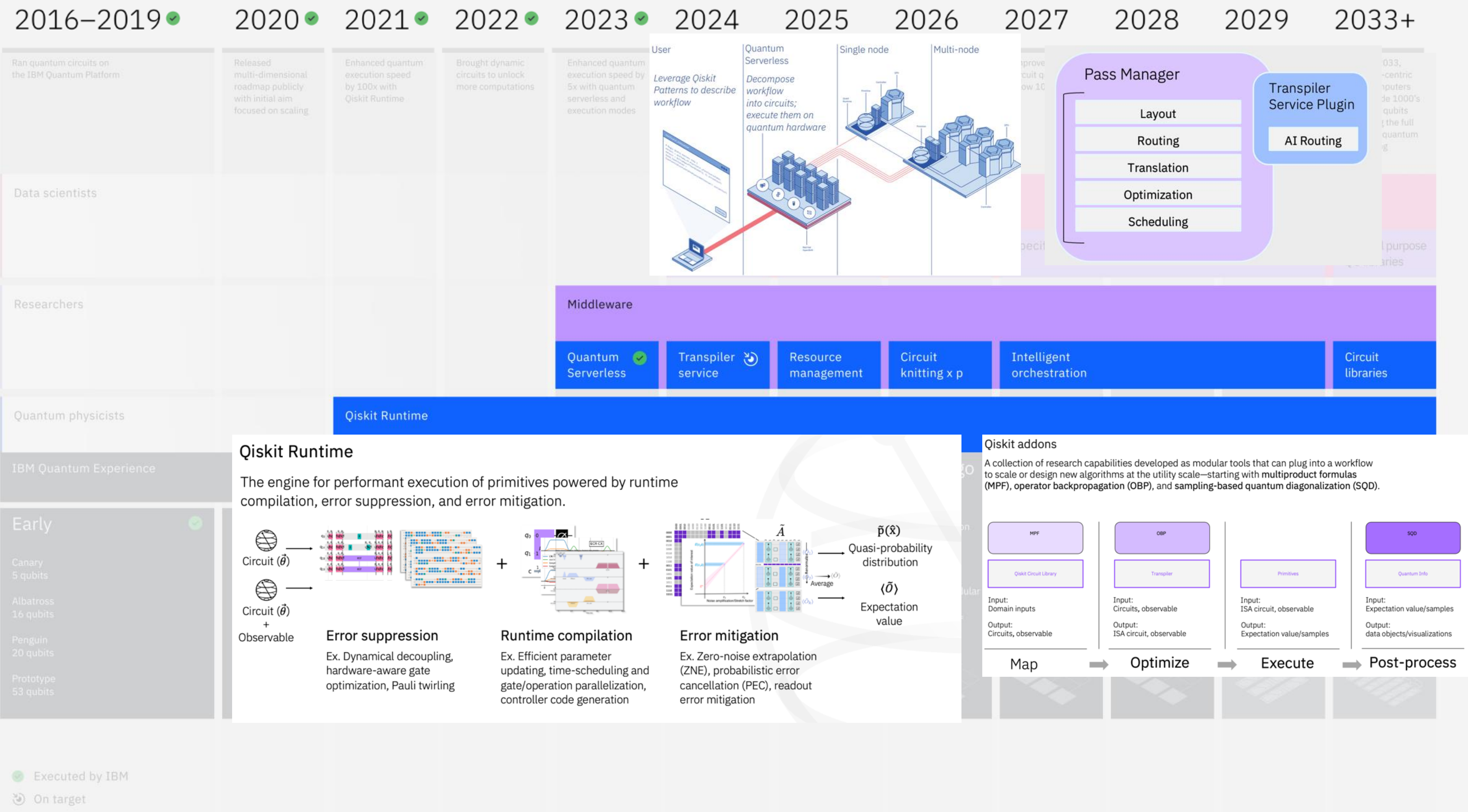
In 2023, we introduced middleware for quantum tools to automate and optimize heterogeneous compute tasks. That included quantum serverless

In 2024, our AI-powered transpiler service will optimize circuits with fewer gates.

In 2025, we will introduce resource management tools to facilitate system partitioning and enable parallel execution.

2026 will bring us circuit knitting across parallel quantum processors

From 2027 we will focus on intelligent orchestration: optimizing workflows to combine classical and quantum efficiently, thus improving performance.



Qiskit Runtime

The engine for performant execution of primitives powered by runtime compilation, error suppression, and error mitigation.

Error suppression
Ex. Dynamical decoupling, hardware-aware gate optimization, Pauli twirling

Runtime compilation
Ex. Efficient parameter updating, time-scheduling and gate/operation parallelization, controller code generation

Error mitigation
Ex. Zero-noise extrapolation (ZNE), probabilistic error cancellation (PEC), readout error mitigation

Qiskit addons

A collection of research capabilities developed as modular tools that can plug into a workflow to scale or design new algorithms at the utility scale—starting with **multiproduct formulas (MPF)**, **operator backpropagation (OBP)**, and **sampling-based quantum diagonalization (SQD)**.

Map	Optimize	Execute	Post-process
Input: Domain inputs	Input: Circuits, observable	Input: ISA circuit, observable	Input: Expectation value/samples
Output: Circuits, observable	Output: ISA circuit, observable	Output: Expectation value/samples	Output: data objects/visualizations

What we have accomplished: Software

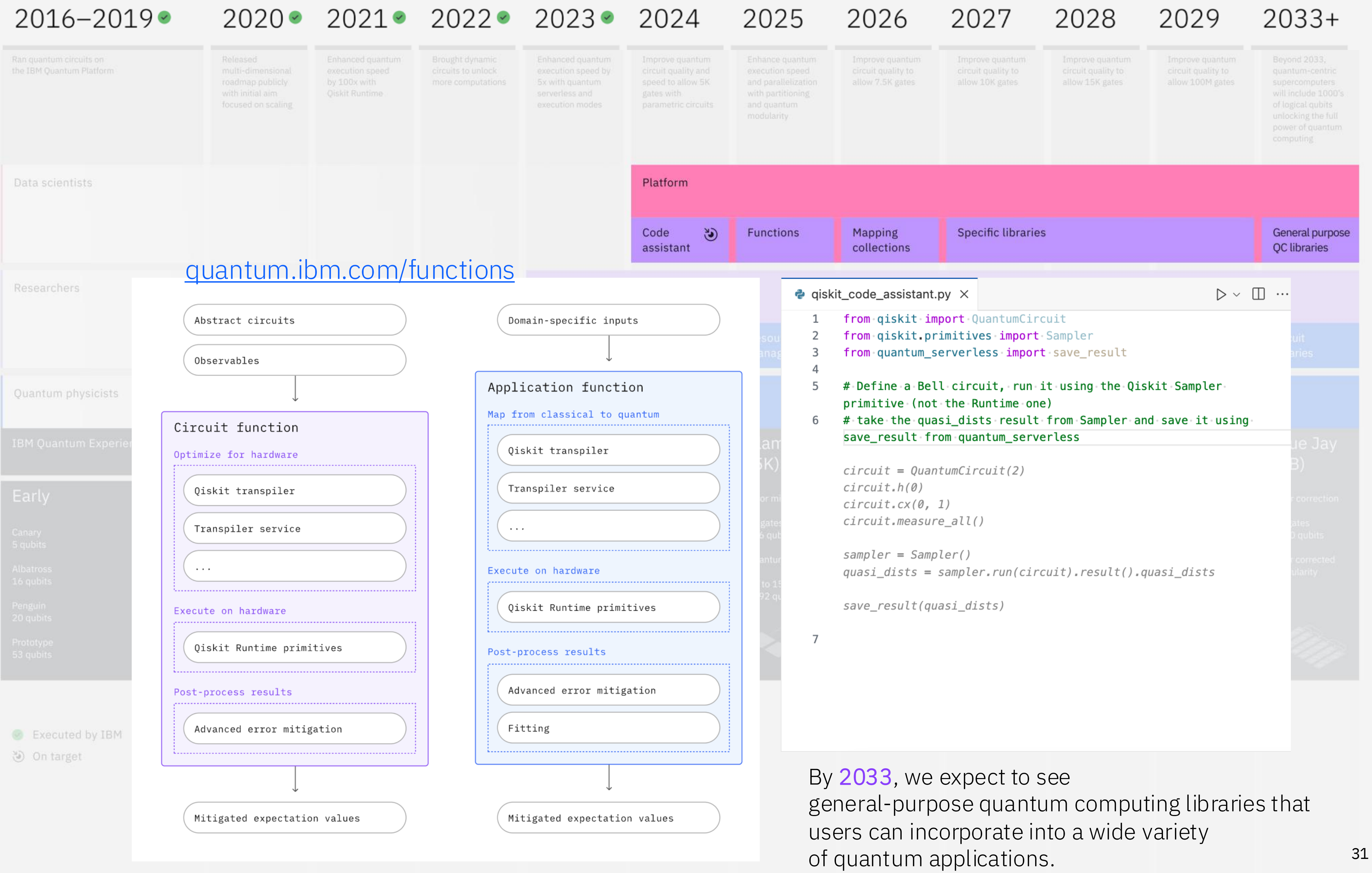
Useful quantum computing requires performant software.

In 2024 we redefined Qiskit to represent the full-stack software for quantum at IBM, **extending the Qiskit SDK with middleware software and services** to write, optimize, and execute programs on IBM Quantum systems.

In 2025, we will introduce **quantum functions** so users can create and share reusable blocks of Qiskit code.

2026 will bring mapping collections so users can start **automating** the process of **mapping their specific use cases** to quantum circuits.

From 2027 onward, we will work alongside clients to build use-case-specific libraries as quantum advantages emerge for a variety of use cases.



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

Code assistant

Functions

Mapping collections

Specific libraries

General purpose QC libraries

Researchers

Quantum physicists

IBM Quantum Experien

Early

Canary
5 qubits

Albatross
16 qubits

Penguin
20 qubits

Prototype
53 qubits

✓ Executed by IBM

On target

quantum.ibm.com/functions

Abstract circuits

Observables

Circuit function

Optimize for hardware

Qiskit transpiler

Transpiler service

...

Execute on hardware

Qiskit Runtime primitives

Post-process results

Advanced error mitigation

Mitigated expectation values

Domain-specific inputs

Application function

Map from classical to quantum

Qiskit transpiler

Transpiler service

...

Execute on hardware

Qiskit Runtime primitives

Post-process results

Advanced error mitigation

Fitting

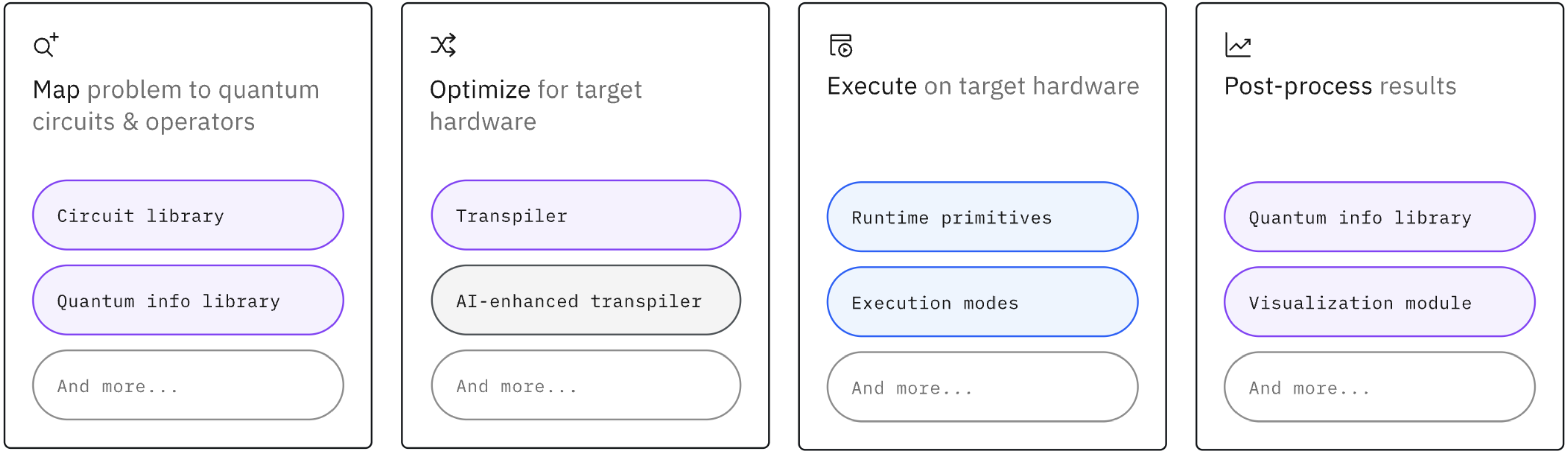
Mitigated expectation values

qiskit_code_assistant.py

```python
from qiskit import QuantumCircuit
from qiskit.primitives import Sampler
from quantum_serverless import save_result

# Define a Bell circuit, run it using the Qiskit Sampler primitive (not the Runtime one)
# take the quasi_dists result from Sampler and save it using save_result from quantum_serverless

circuit = QuantumCircuit(2)
circuit.h(0)
circuit.cx(0, 1)
circuit.measure_all()

sampler = Sampler()
quasi_dists = sampler.run(circuit).result().quasi_dists

save_result(quasi_dists)

```

By 2033, we expect to see general-purpose quantum computing libraries that users can incorporate into a wide variety of quantum applications.

Qiskit



Map problem to quantum circuits & operators

- Circuit library
- Quantum info library
- And more...

Optimize for target hardware

- Transpiler
- AI-enhanced transpiler
- And more...

Execute on target hardware

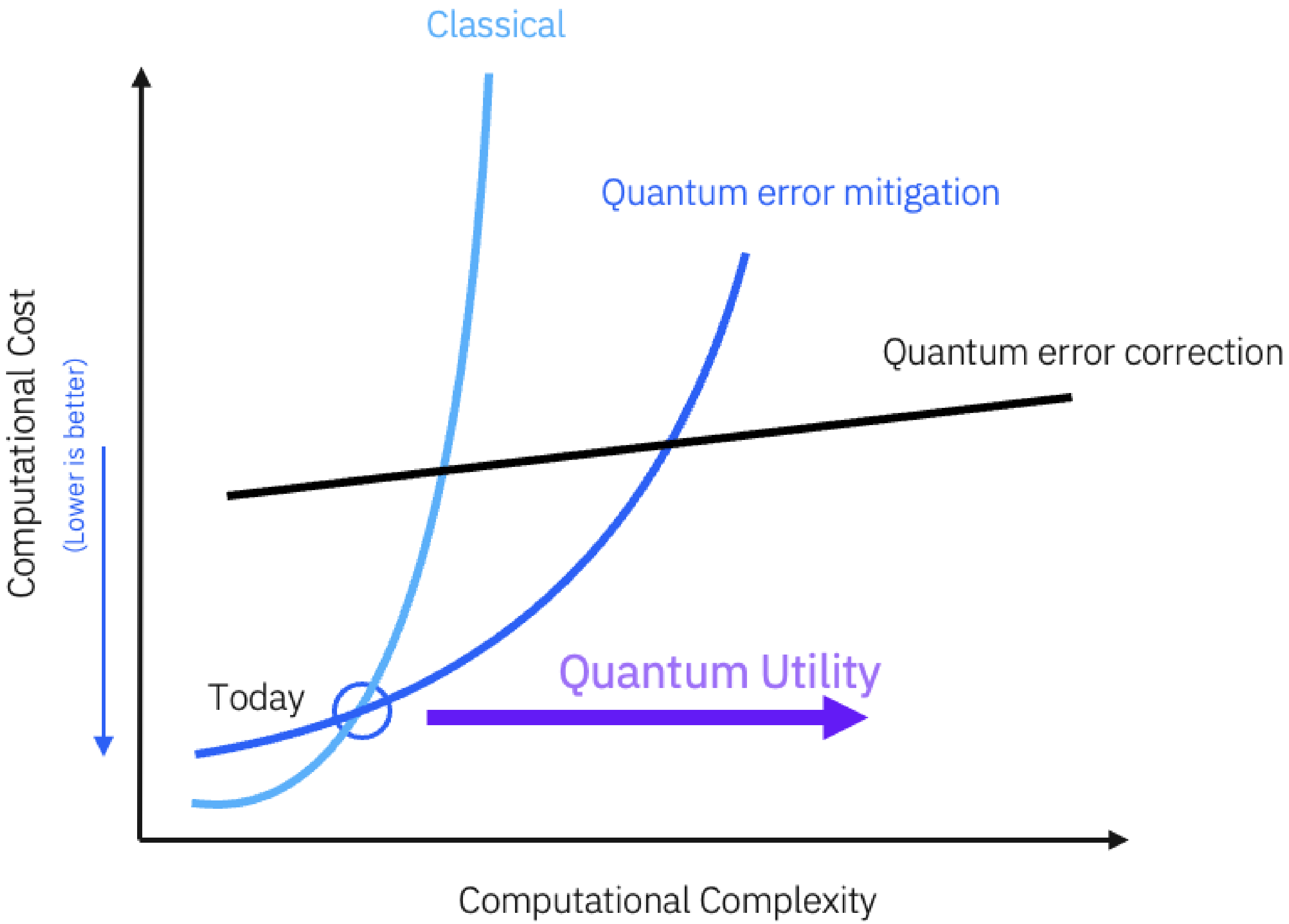
- Runtime primitives
- Execution modes
- And more...

Post-process results

- Quantum info library
- Visualization module
- And more...

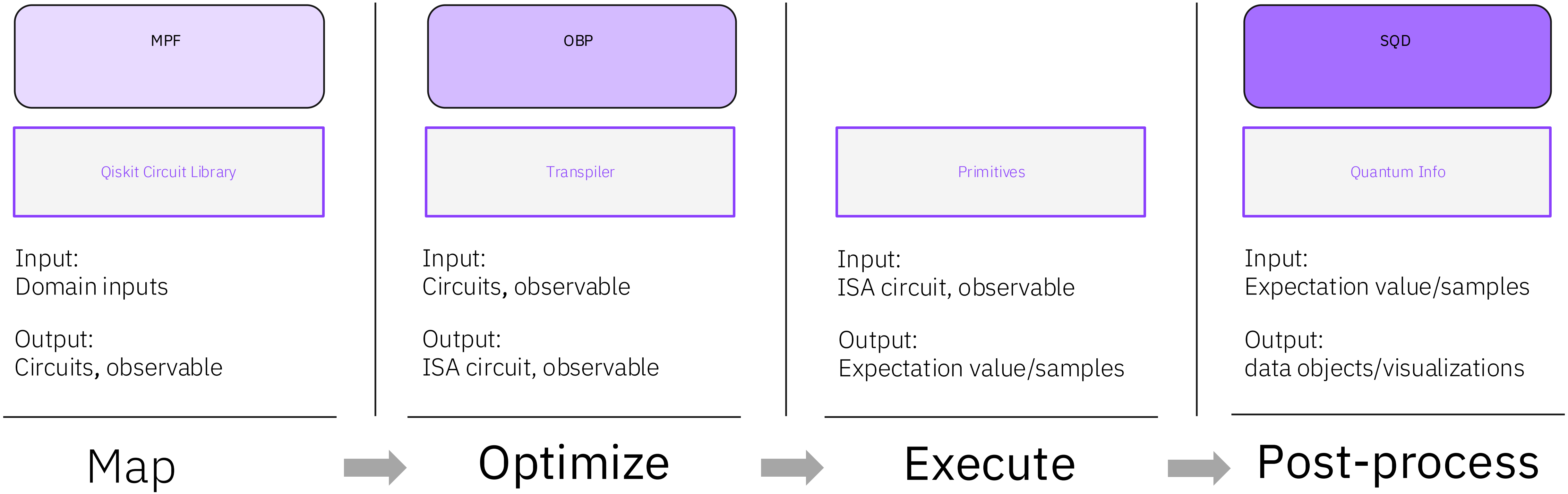
🟪 Qiskit SDK 🟦 Qiskit Runtime Service ⬜ Qiskit Transpiler Service

Quantum state of play



Qiskit addons

A collection of research capabilities developed as modular tools that can plug into a workflow to scale or design new algorithms at the utility scale—starting with **multiproduct formulas (MPF)**, **operator backpropagation (OBP)**, and **sampling-based quantum diagonalization (SQD)**.



MPF

Qiskit Circuit Library

Input:
Domain inputs

Output:
Circuits, observable

Map

OBP

Transpiler

Input:
Circuits, observable

Output:
ISA circuit, observable

Optimize

Primitives

Input:
ISA circuit, observable

Output:
Expectation value/samples

Execute

SQD

Quantum Info

Input:
Expectation value/samples

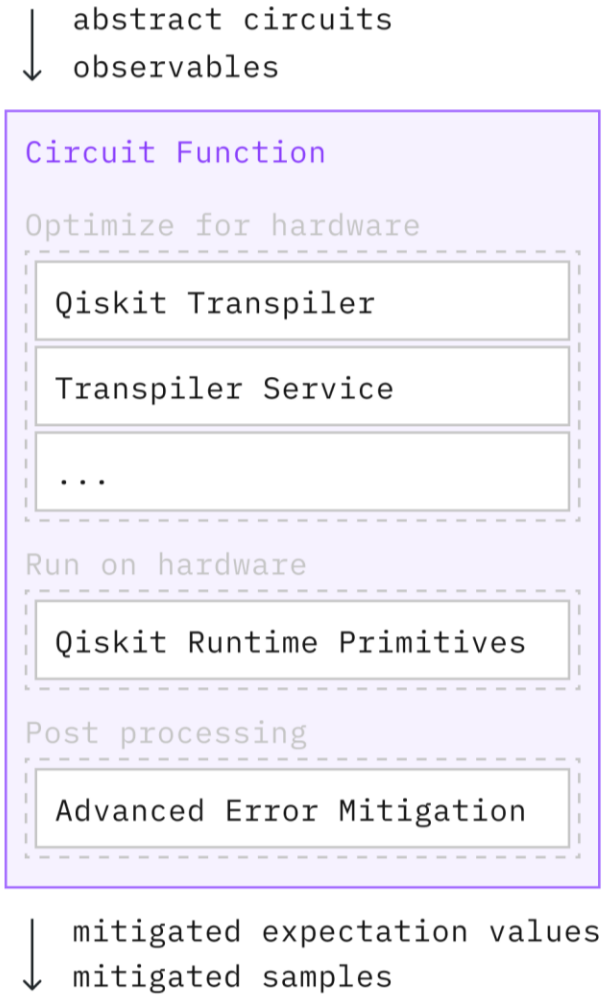
Output:
data objects/visualizations

Post-process

Qiskit Functions are abstracted services, designed to accelerate development

In late September, we're previewing a catalog of managed, utility-scale services to unlock new users:

- **Circuit Functions**: Enabling quantum computational scientists to discover new algorithms and applications, without needing to manage transpilation, error suppression, or error mitigation
- **Application Functions**: Enabling data scientists and enterprise developers to integrate quantum into industry workflows, while leveraging familiar domain abstractions



↓ abstract circuits
observables

Circuit Function

Optimize for hardware

- Qiskit Transpiler
- Transpiler Service
- ...

Run on hardware

- Qiskit Runtime Primitives

Post processing

- Advanced Error Mitigation

↓ mitigated expectation values
mitigated samples

↓ domain-specific inputs

Application Function

Map from classical to quantum

- Mapper

Optimize for hardware

- Qiskit Transpiler
- Transpiler Service
- ...

Run on hardware

- Qiskit Runtime Primitives

Post processing

- Advanced Error Mitigation
- Fitting

↓ domain-specific outputs

Qiskit Code Assistant Preview

Transforming the Quantum developer experience

Intelligent Code Completion

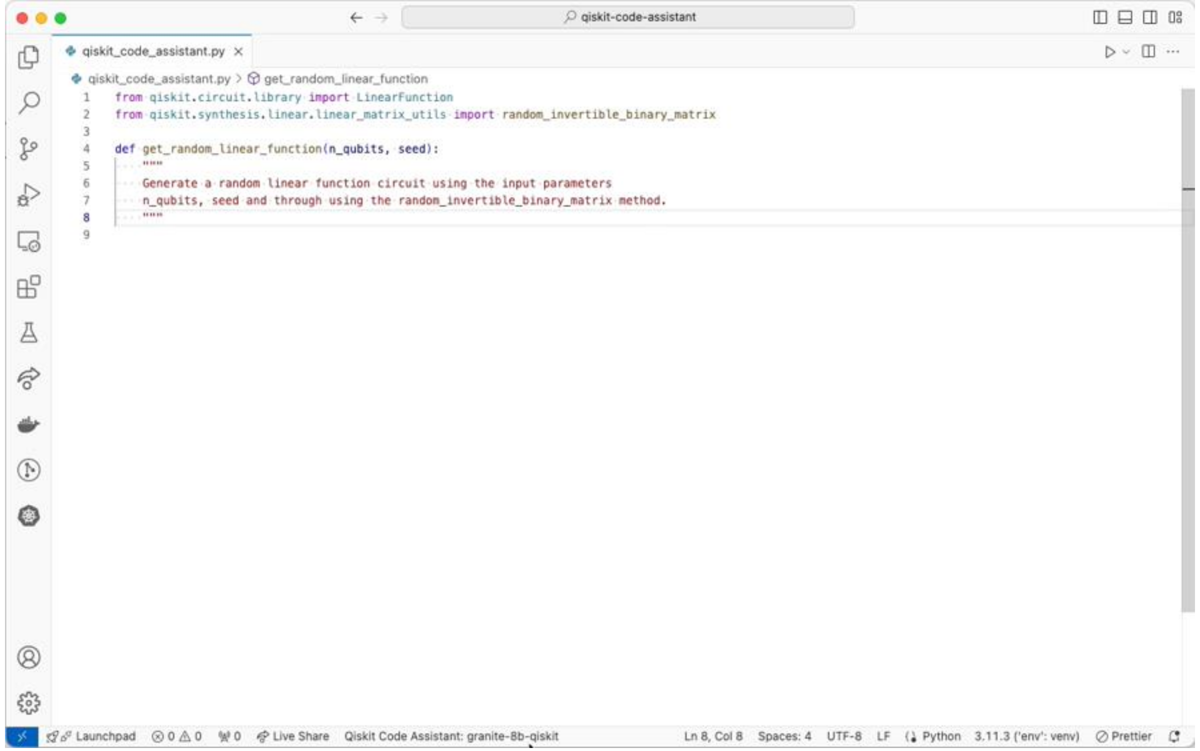
- Context-aware suggestions for Qiskit SDK
- Auto-completion for complex quantum gates and algorithms

Quantum Specific Features

- Helps identify and resolve common quantum programming pitfalls
- Assists in implementing quantum algorithms (e.g., *VQE)*

Integration and Workflow

- Seamless integration with popular IDEs and Jupyter Lab
- Version-aware: adapts to your Qiskit SDK version

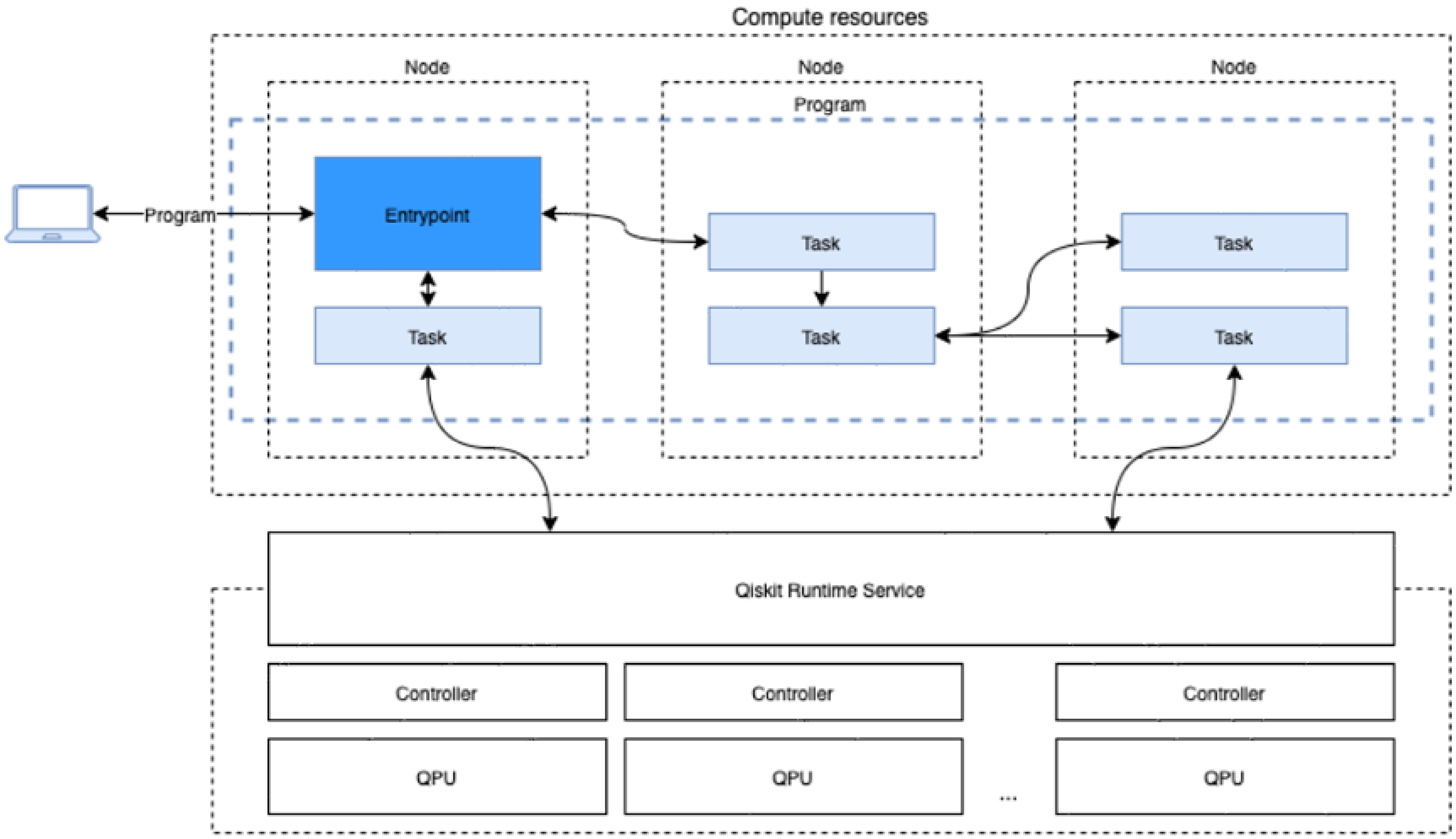


```
from qiskit.circuit.library import LinearFunction
from qiskit.synthesis.linear.linear_matrix_utils import random_invertible_binary_matrix

def get_random_linear_function(n_qubits, seed):
    """
    Generate a random linear function circuit using the input parameters
    n_qubits, seed and through using the random_invertible_binary_matrix method.
    """

```

https://docs.quantum.ibm.com/guides/qiskit-code-assistant

Qiskit Serverless

With Qiskit Serverless users can build, deploy, and run workloads remotely using the compute resources of the IBM Quantum platform.



Qiskit Serverless is available as a hosted service for IBM Premium clients or as an open-source tool that you can deploy on your own infrastructure.
docs.quantum.ibm.com/guides/serverless
github.com/Qiskit/qiskit-serverless

Organization of the QC4HEP WG

Theory

Two main research Areas

Experiments

Theory - main groups

1. *Real-time evolution,*
2. *Quantum Link Models*
3. *Neutrino physics*
4. *....*

Groups

Experiments - main groups:

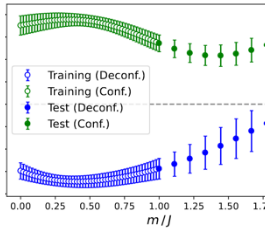
1. *Jet Reconstruction*
2. *Beyond SM (BSM) and*
3. *Anomaly Detection*
4. *.....*

Teams

Researchers working together on a speficic topic defined in the groups

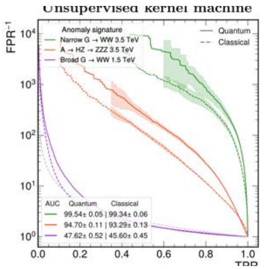
Teams **include students**

Highlights 2023-2024



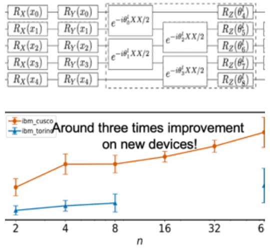
Quantum data learning for quantum simulations in high-energy physics
Phys. Rev. Research 5, 043250

Explores quantum machine learning (QML) applications for quantum data, extending the Quantum Data Learning (QDL) framework to high-energy physics. In particular, by applying quantum convolutional neural networks to quantum data sets generated from quantum simulations of LGT and QFT models. Multiparticle State Analysis with QCNN effectively extracted fermion flavors and coupling constants from simulated parton showers, outperforming conventional methods in certain scenarios.



Quantum anomaly detection in the latent space of proton collision events at the LHC
Commun Phys 7, 334 (2024)

Study presents a realistic study of QML models for anomaly detection in proton collisions at the LHC. A proposed combination of an autoencoder that compresses raw HEP jet features to a tractable size, with quantum anomaly detection models proved to be a viable strategy for data-driven searches for new physics at the LHC.



Symmetry Breaking in Geometric Quantum Machine Learning in the Presence of Noise
PRX Quantum **5**, 030314

Geometric QML incorporates inductive biases to ansatz design. This can lead to: Less parameters / shorter circuits (no BPs). This work enhances understanding of how hardware noise interacts with GQML models and proposes strategies to improve resilience. The findings pave the way for future research aimed at developing robust and scalable GQML applications on quantum hardware.

Preliminary Resource Estimation for Lattice QED and for neutrino oscilations

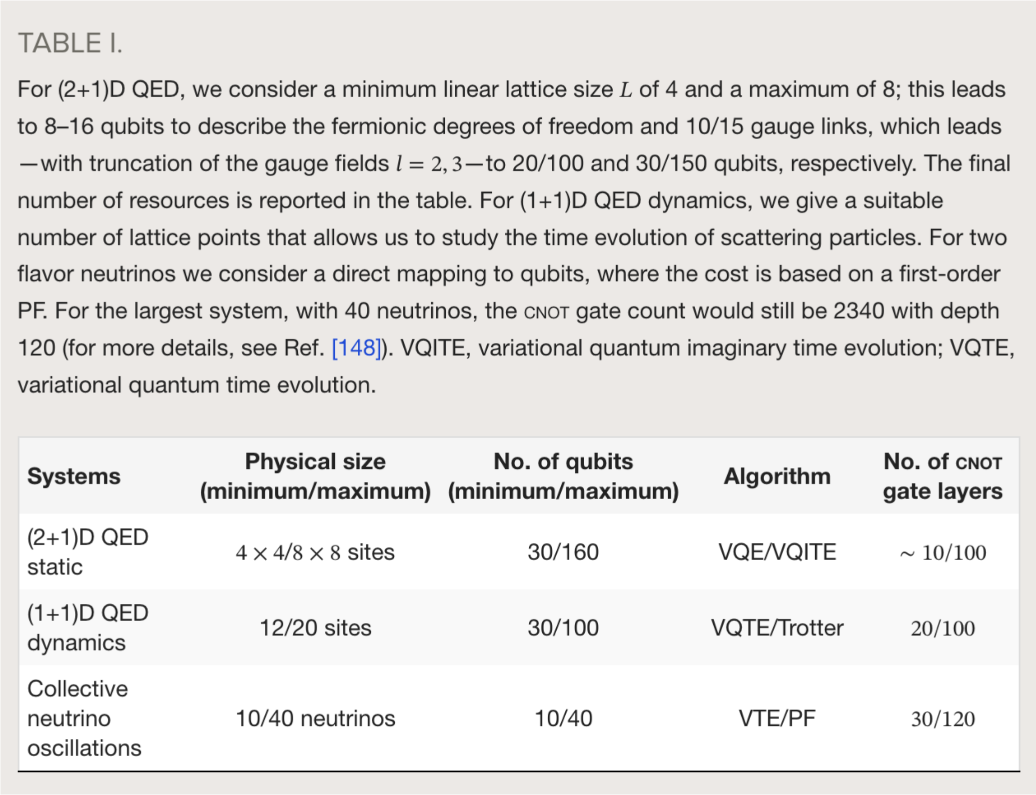


TABLE I.

For (2+1)D QED, we consider a minimum linear lattice size L of 4 and a maximum of 8; this leads to 8–16 qubits to describe the fermionic degrees of freedom and 10/15 gauge links, which leads —with truncation of the gauge fields $l = 2, 3$—to 20/100 and 30/150 qubits, respectively. The final number of resources is reported in the table. For (1+1)D QED dynamics, we give a suitable number of lattice points that allows us to study the time evolution of scattering particles. For two flavor neutrinos we consider a direct mapping to qubits, where the cost is based on a first-order PF. For the largest system, with 40 neutrinos, the CNOT gate count would still be 2340 with depth 120 (for more details, see Ref. [148]). VQITE, variational quantum imaginary time evolution; VQTE, variational quantum time evolution.

Systems	Physical size (minimum/maximum)	No. of qubits (minimum/maximum)	Algorithm	No. of CNOT gate layers
(2+1)D QED static	$4 \times 4/8 \times 8$ sites	30/160	VQE/VQITE	$\sim 10/100$
(1+1)D QED dynamics	12/20 sites	30/100	VQTE/Trotter	20/100
Collective neutrino oscillations	10/40 neutrinos	10/40	VTE/PF	30/120

Tested QML applications

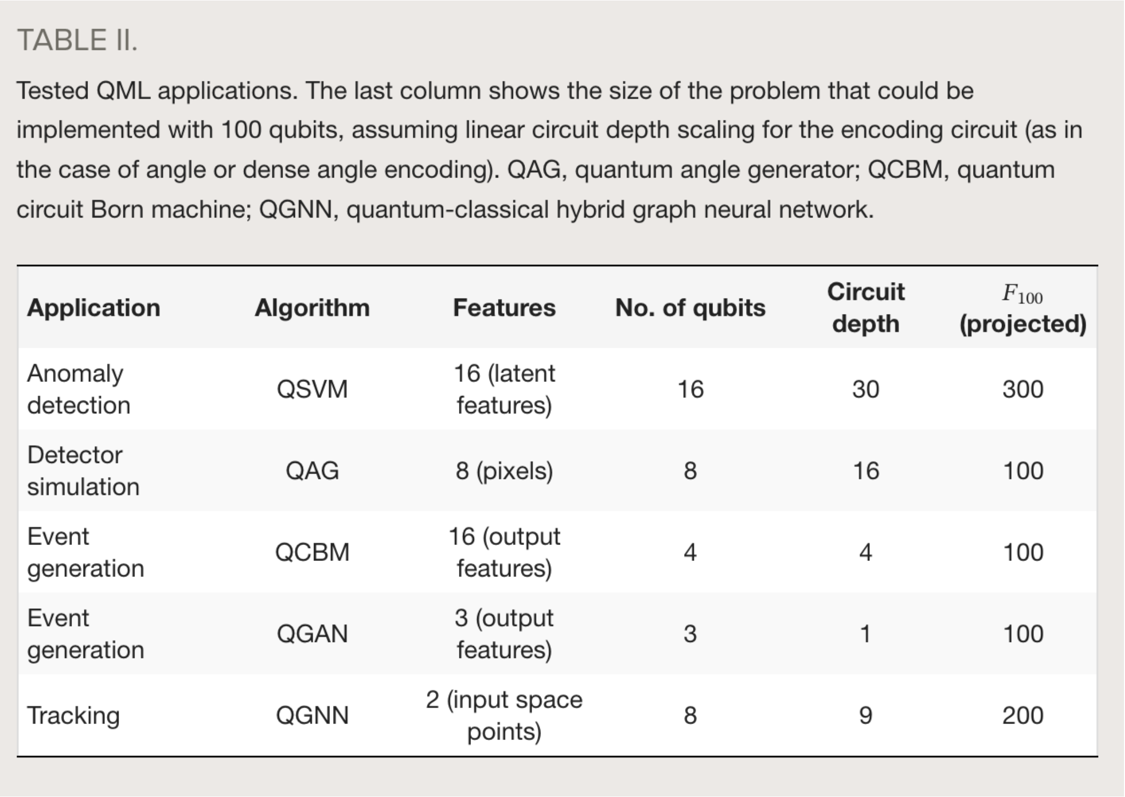


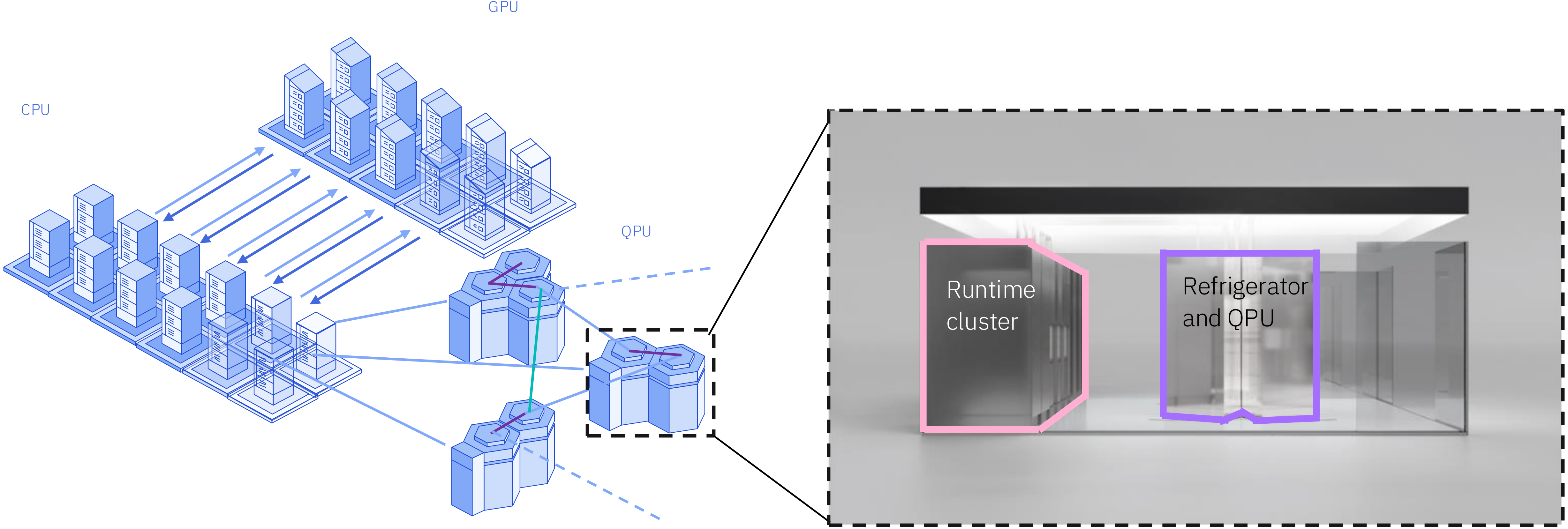
TABLE II.

Tested QML applications. The last column shows the size of the problem that could be implemented with 100 qubits, assuming linear circuit depth scaling for the encoding circuit (as in the case of angle or dense angle encoding). QAG, quantum angle generator; QCBM, quantum circuit Born machine; QGNN, quantum-classical hybrid graph neural network.

Application	Algorithm	Features	No. of qubits	Circuit depth	F_{100} (projected)
Anomaly detection	QSVM	16 (latent features)	16	30	300
Detector simulation	QAG	8 (pixels)	8	16	100
Event generation	QCBM	16 (output features)	4	4	100
Event generation	QGAN	3 (output features)	3	1	100
Tracking	QGNN	2 (input space points)	8	9	200

Quantum-centric supercomputing

Delivering impactful quantum computing requires the interplay of quantum and classical resources at scales; quantum-centric supercomputing is the path toward industrial scale applications

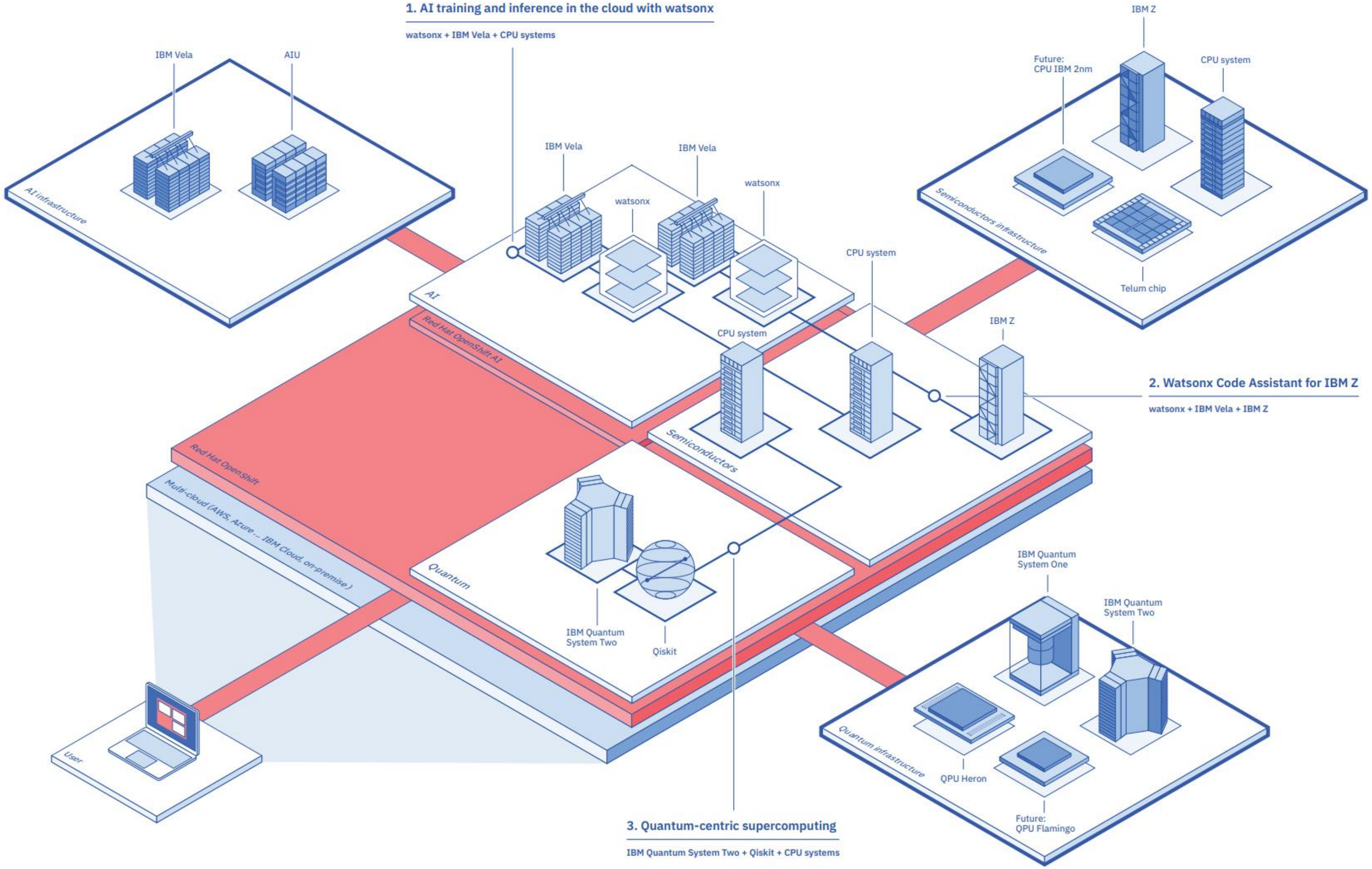


IBM offers **all** the needed components

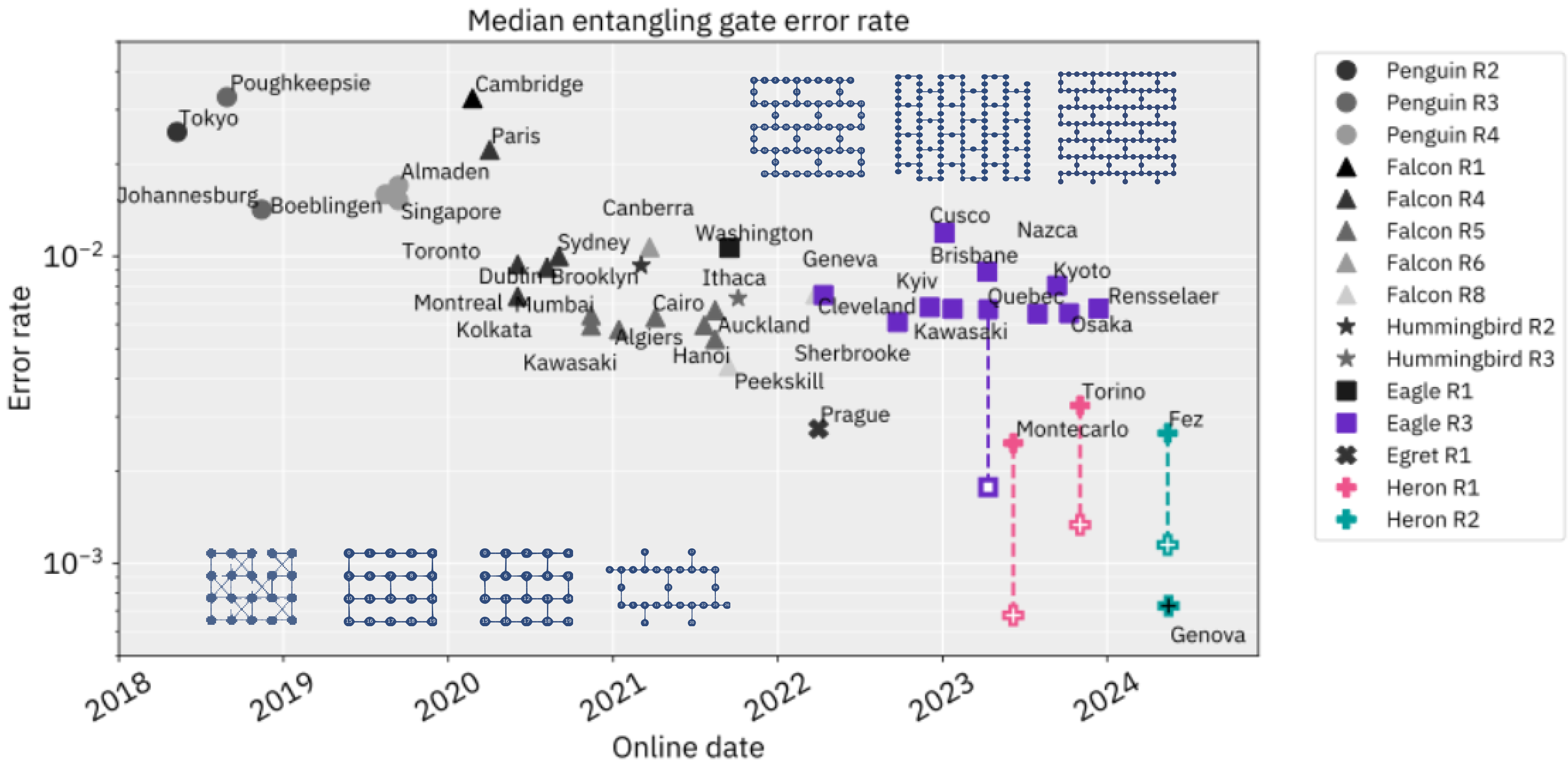
1. Hybrid cloud
   (i.e., classical compute)
2. watsonx
   (artificial intelligence)
3. Quantum
4. IT consulting

Integrations are still evolving between quantum and classical compute.

IBM is already partnering with other institutions to help define the future of quantum-centric supercomputing (QCSC).



The road to improved 2Q gate errors



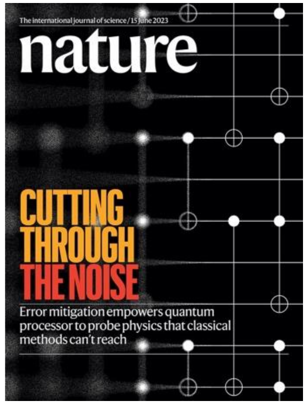
Utility vs. Advantage

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



The international journal of science / 15 June 2023

nature

CUTTING THROUGH THE NOISE

Error mitigation empowers quantum processor to probe physics that classical methods can't reach

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

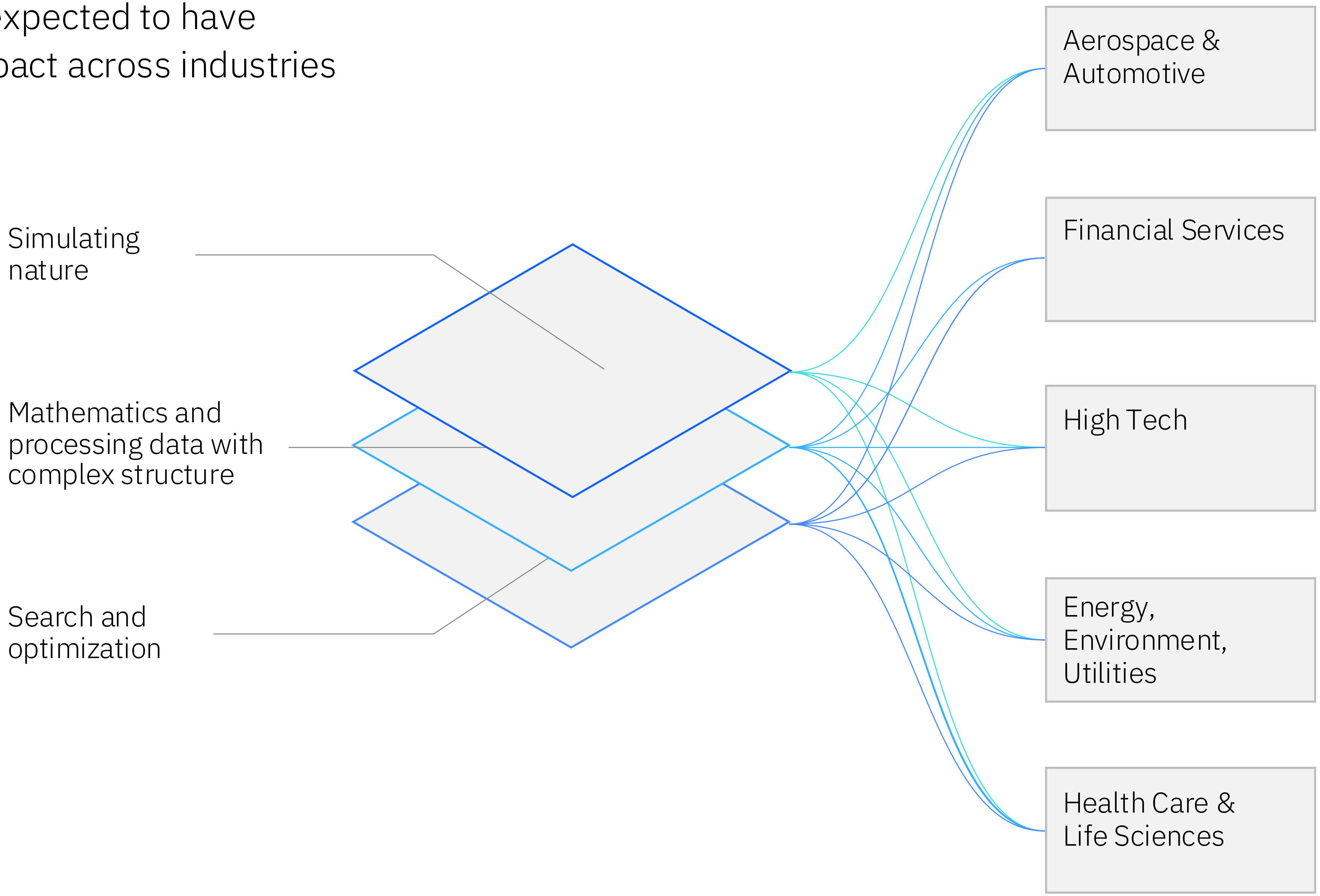
Quantum Advantage (TBD)

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

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

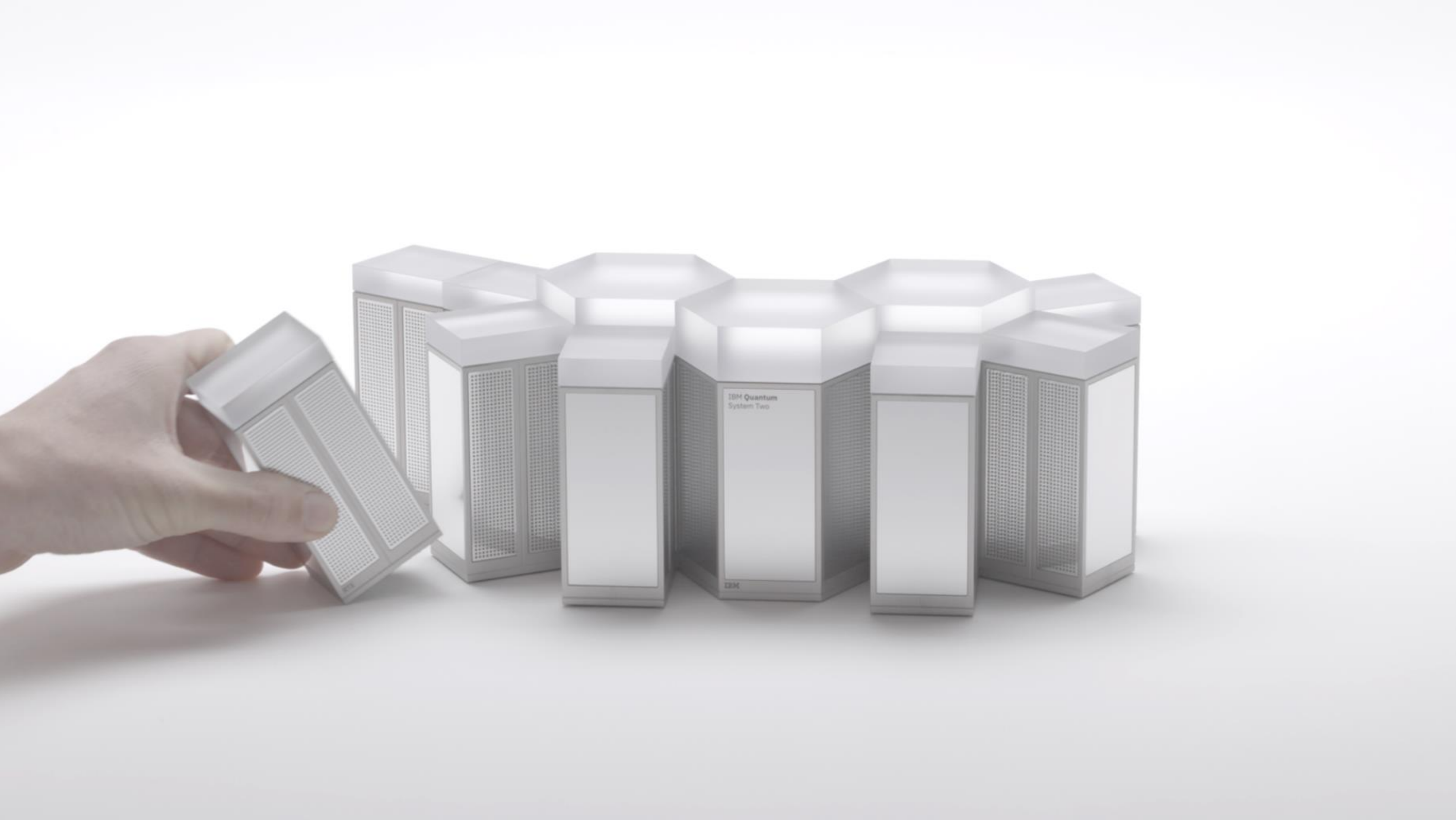
Energy, Environment, Utilities

- 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

Upskilling your teams in quantum computing



IBM Quantum Learning Mission:

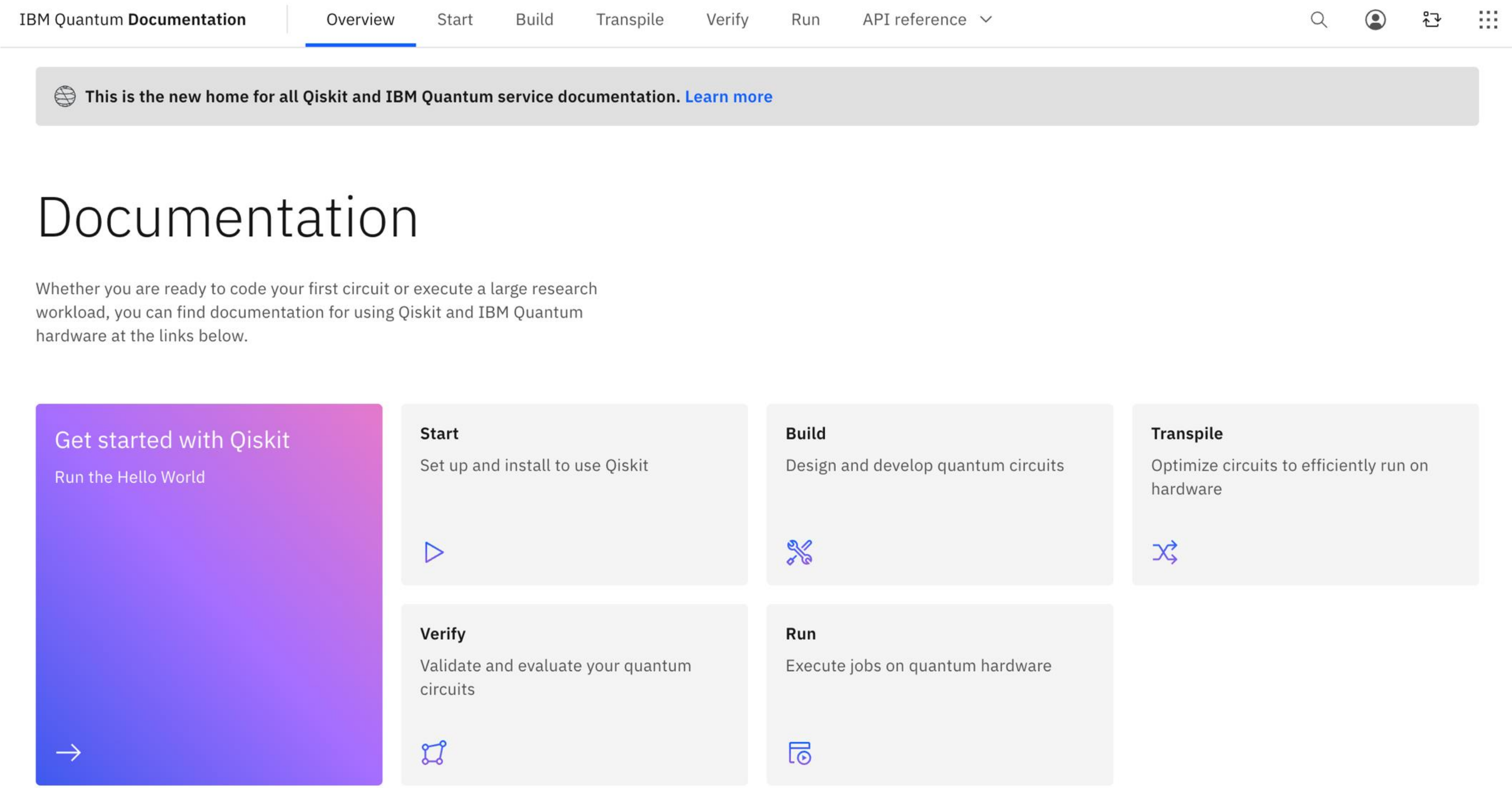
Empower people around the world to use and advance quantum

Documentation

Getting started with Qiskit is easy.

The Documentation can help walk you through the following steps:

Start: Setup and Install
Build: Quantum Circuits
Transpile: Optimize Circuits
Verify: Evaluate your circuits
Run: Execute on hardware



This is the new home for all Qiskit and IBM Quantum service documentation. Learn more

Documentation

Whether you are ready to code your first circuit or execute a large research workload, you can find documentation for using Qiskit and IBM Quantum hardware at the links below.

Get started with Qiskit
Run the Hello World

Start
Set up and install to use Qiskit

Build
Design and develop quantum circuits

Transpile
Optimize circuits to efficiently run on hardware

Verify
Validate and evaluate your quantum circuits

Run
Execute jobs on quantum hardware

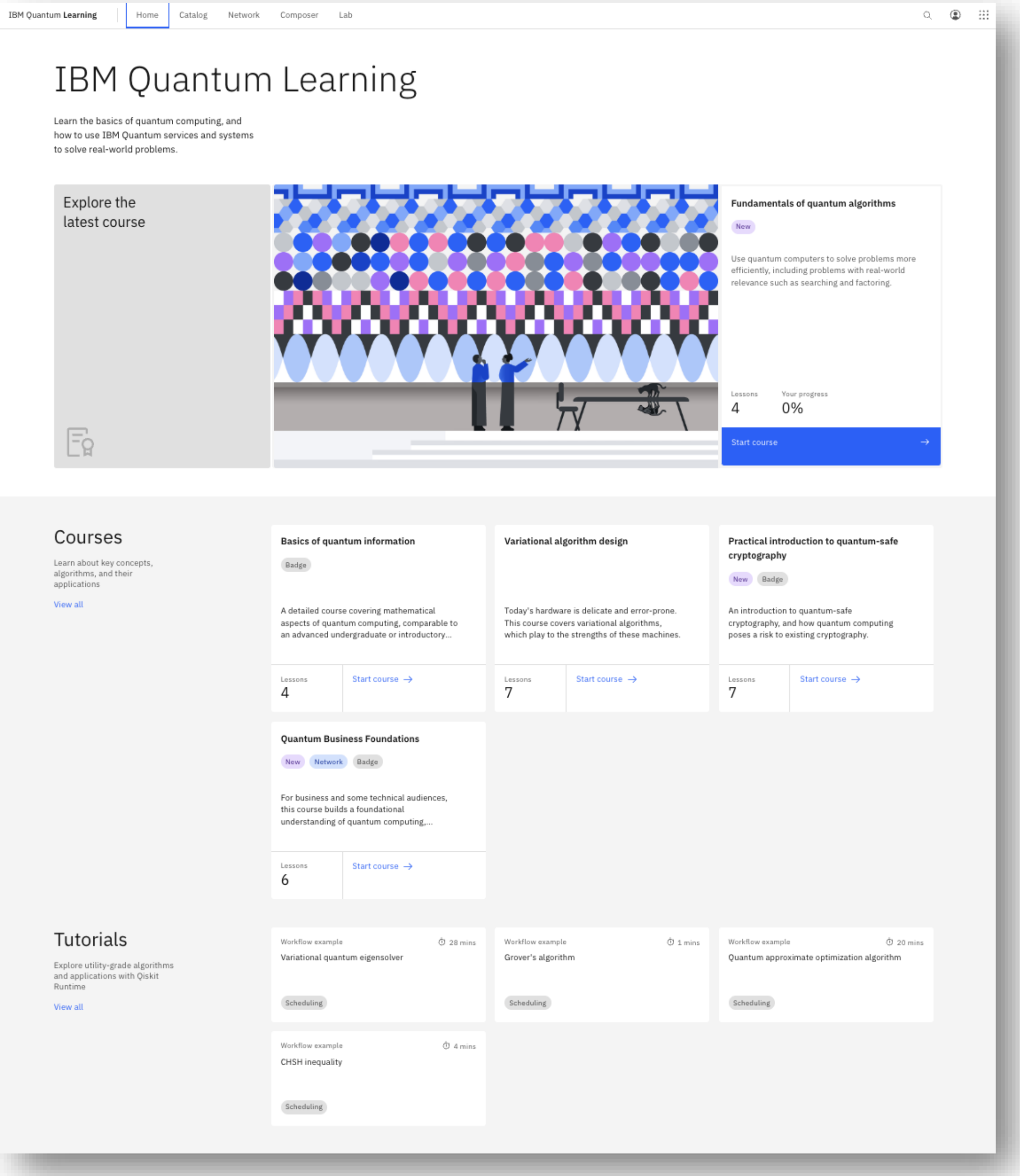
IBM Quantum Learning

Learn the basics of quantum computing and how to solve real-world problems with IBM Quantum services and systems

- Access courses, tutorials, and other learning resources created by leading quantum experts like John Watrous
- Log in to track course progress
- Earn badges for selected courses

Get started today

↓



IBM Quantum Learning

Learn the basics of quantum computing, and how to use IBM Quantum services and systems to solve real-world problems.

Explore the latest course

Fundamentals of quantum algorithms

New

Use quantum computers to solve problems more efficiently, including problems with real-world relevance such as searching and factoring.

Lessons 4 Your progress 0%

Courses

Learn about key concepts, algorithms, and their applications

View all

Basics of quantum information

Badge

A detailed course covering mathematical aspects of quantum computing, comparable to an advanced undergraduate or introductory...

Lessons 4

Variational algorithm design

Today's hardware is delicate and error-prone. This course covers variational algorithms, which play to the strengths of these machines.

Lessons 7

Practical introduction to quantum-safe cryptography

New Badge

An introduction to quantum-safe cryptography, and how quantum computing poses a risk to existing cryptography.

Lessons 7

Quantum Business Foundations

New Network Badge

For business and some technical audiences, this course builds a foundational understanding of quantum computing,...

Lessons 6

Tutorials

Explore utility-grade algorithms and applications with Qiskit Runtime

View all

Workflow example 28 mins
Variational quantum eigensolver
Scheduling

Workflow example 1 mins
Grover's algorithm
Scheduling

Workflow example 20 mins
Quantum approximate optimization algorithm
Scheduling

Workflow example 4 mins
CHSH inequality
Scheduling

Composer

Prototype visually with the Quantum Composer

Interactively build circuits with the the Composer drag and drop interface. You can also visualize amplitude and probabilities within the tool.