IBM Quantum @Q2B 2023

Dr. Jeannette (Jamie) Garcia

Technical Program Director
Algorithms and Partnerships, IBM Quantum

IBM Quantum Summit 2023

The Era of Quantum Utility

New IBM Quantum Processors: Condor, Heron

IBM Quantum System Two

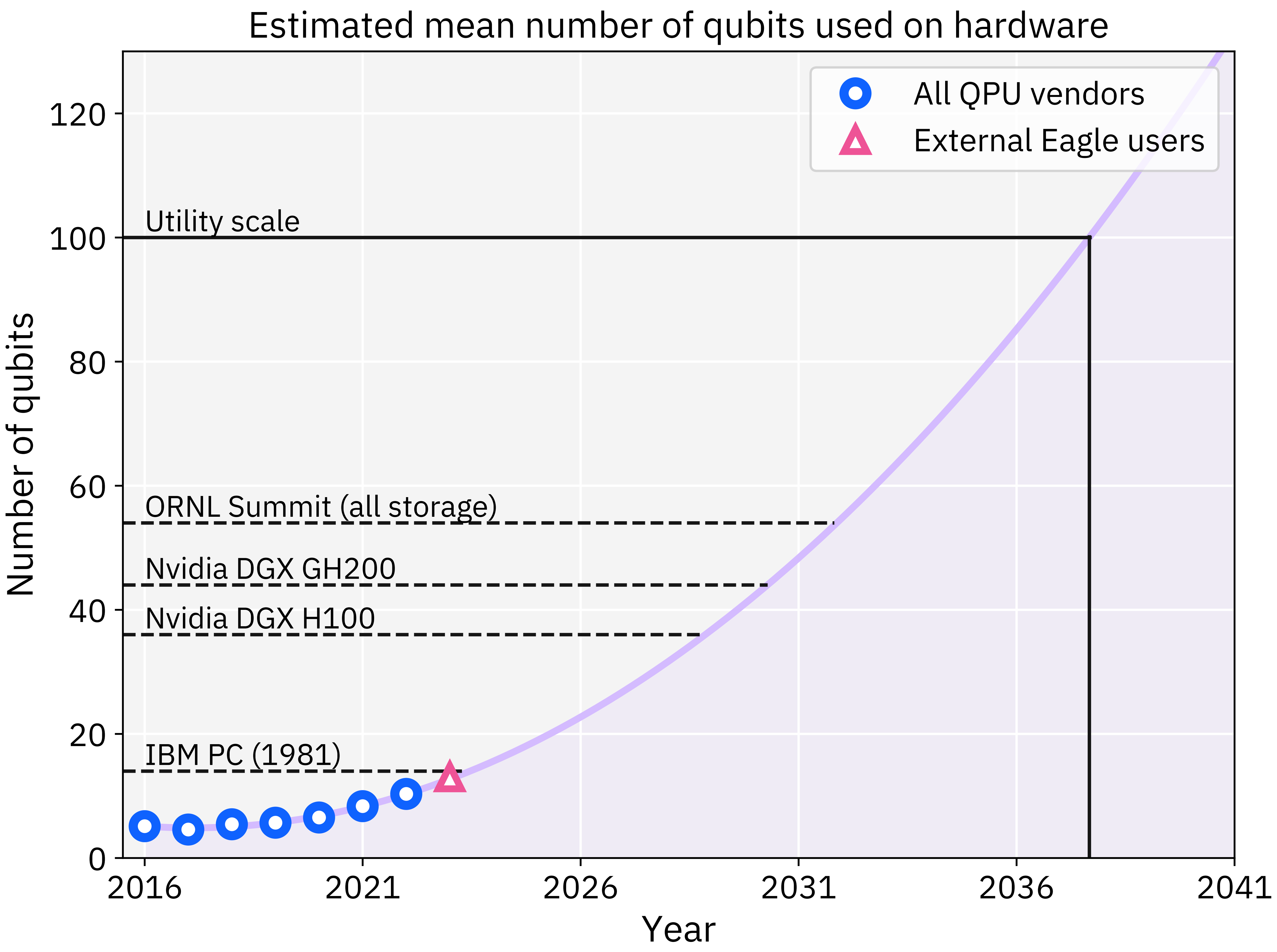
Software: Qiskit 1.0 & Bringing AI to Quantum

IBM Quantum Development Roadmap Expansion

https://www.youtube.com/watch?v=De2IlWji8Ck

The era of quantum utility

Quantum state of play

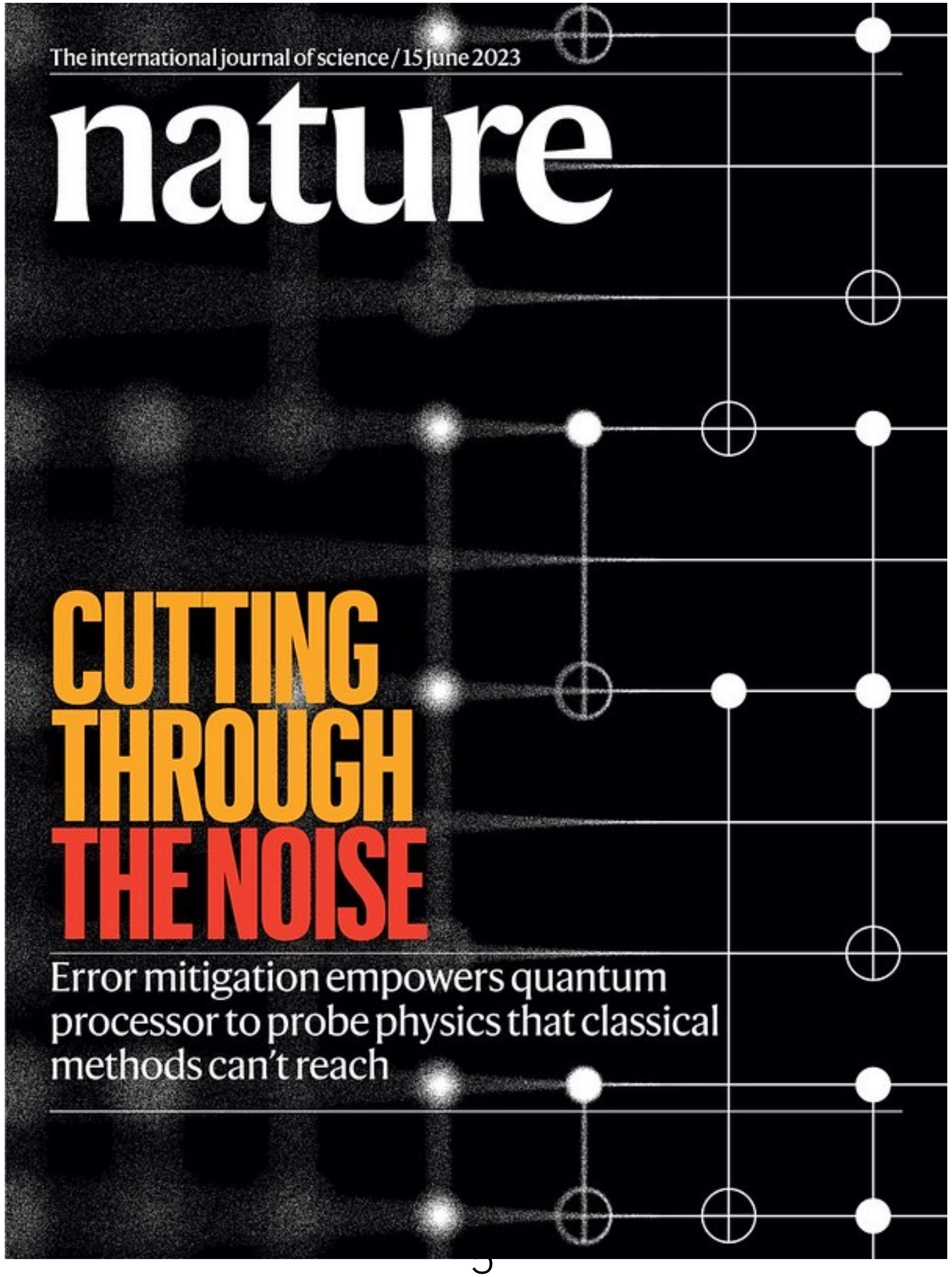


Data for all vendors taken from: arXiv:2307.16130

We need a *disruptive change* to unlock the potential of quantum computation.

A noisy quantum computer produces accurate expectation values on 127 qubits, outside of brute force classical computation.

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



The international journal of science / 15 June 2023

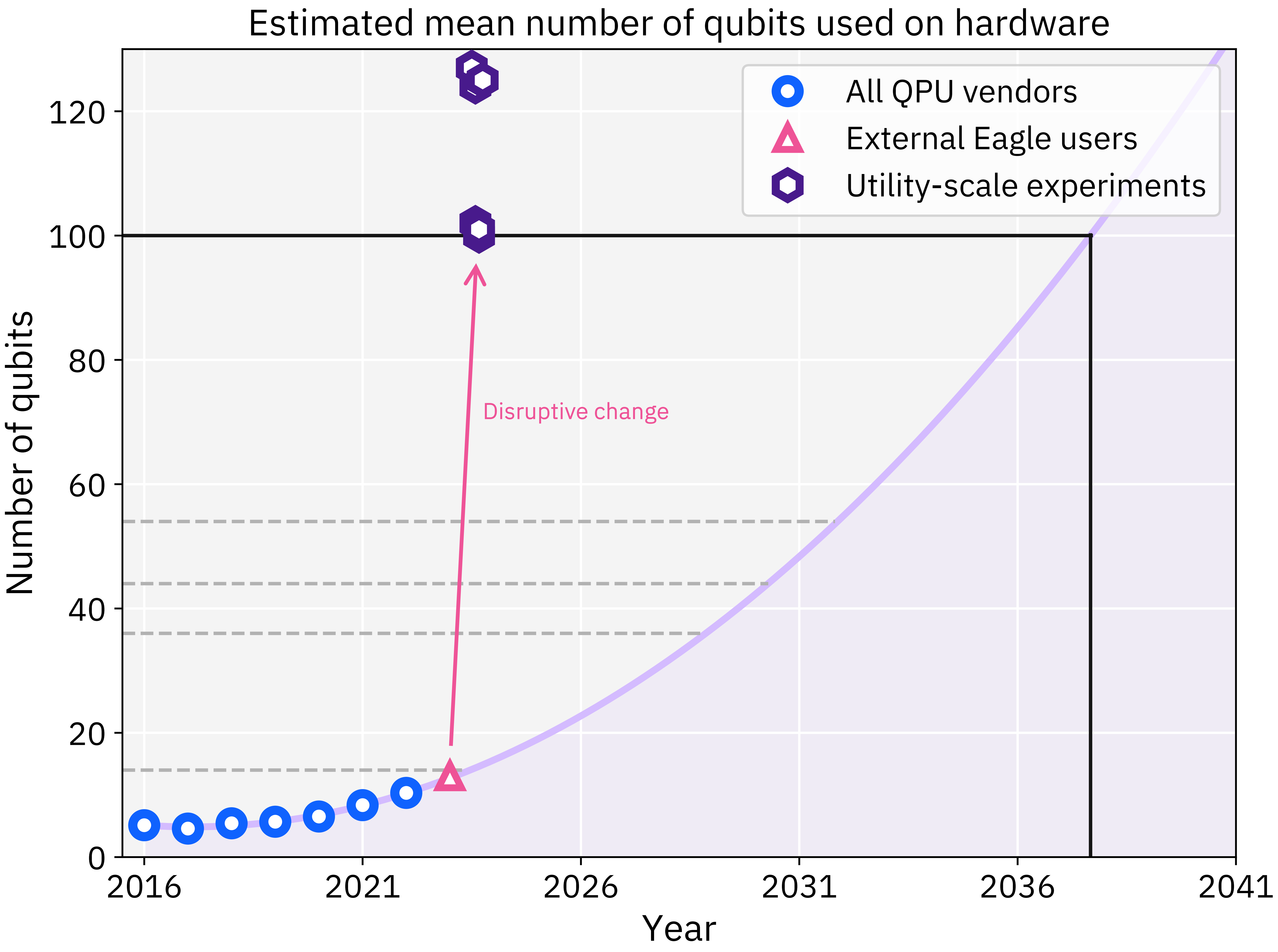
nature

CUTTING THROUGH THE NOISE

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

IBM Quantum systems and Qiskit are bringing a disruptive change.

Data for all vendors taken from: arXiv:2307.16130

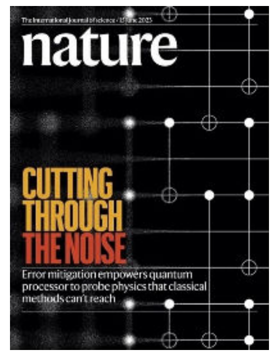


Multiple utility-scale experiments within last 6 months (more to come)

Evidence for the utility of quantum computing before fault tolerance

127 qubits / 2880 CX gates

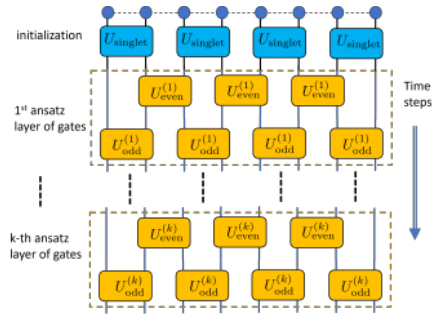
Nature, 618, 500 (2023)



Simulating large-size quantum spin chains on cloud-based superconducting quantum computers

102 qubits / 3186 CX gates

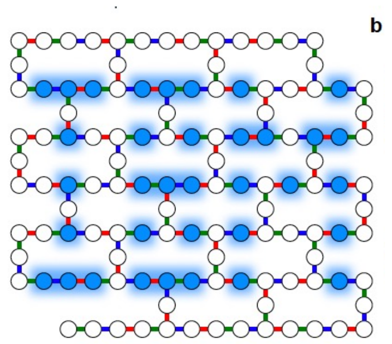
arXiv:2207.09994



Uncovering Local Integrability in Quantum Many-Body Dynamics

124 qubits / 2641 CX gates

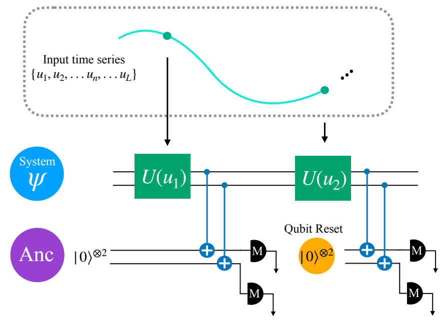
arXiv:2307.07552



Quantum reservoir computing with repeated measurements on superconducting devices

120 qubits / 49470 gates + meas.

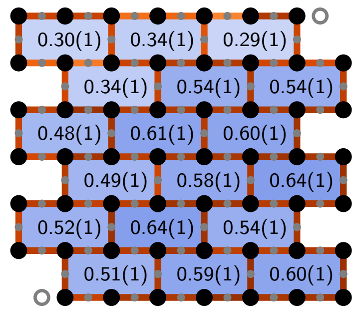
arXiv:2310.06706



Realizing the Nishimori transition across the error threshold for constant-depth quantum circuits

125 qubits / 429 gates + meas.

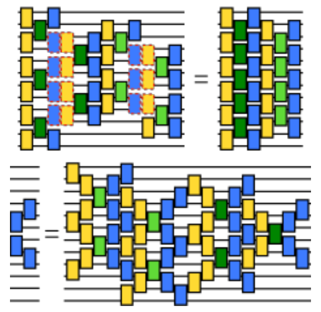
arXiv:2309.02863



Scalable Circuits for Preparing Ground States on Digital Quantum Computers: The Schwinger Model Vacuum on 100 Qubits

100 qubits / 788 CX gates

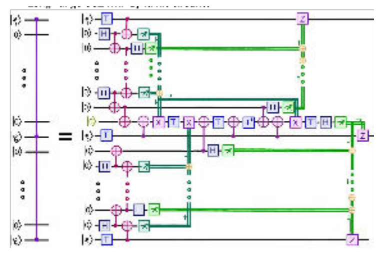
arXiv:2308.04481



Efficient Long-Range Entanglement using Dynamic Circuits

101 qubits / 504 gates + meas.

arXiv:2308.13065



https://www.youtube.com/watch?v=Hd-IGvuARfE

Condor

Pushing the limits of scale & yield

1,121

Superconducting qubits

50%

Increase in qubit density

1 mile +

Of flex cabling

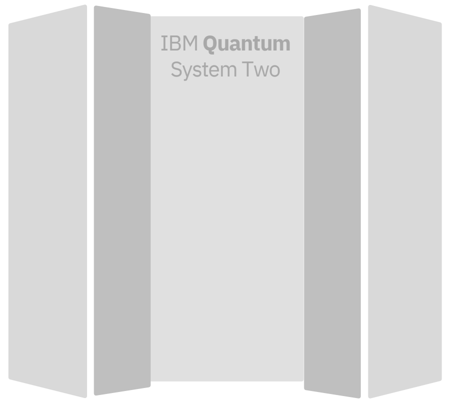
Condor unblocked the road to scaling.

We now need to focus on gate depth and quality.

IBM Quantum Heron: A Four-Year Journey

133-qubit count
tunable coupler architecture

IBM Quantum Platform:
Where users come to do work



Qiskit + Systems = Work

Qiskit
1.0

Now with increased performance, stability, and reliability.

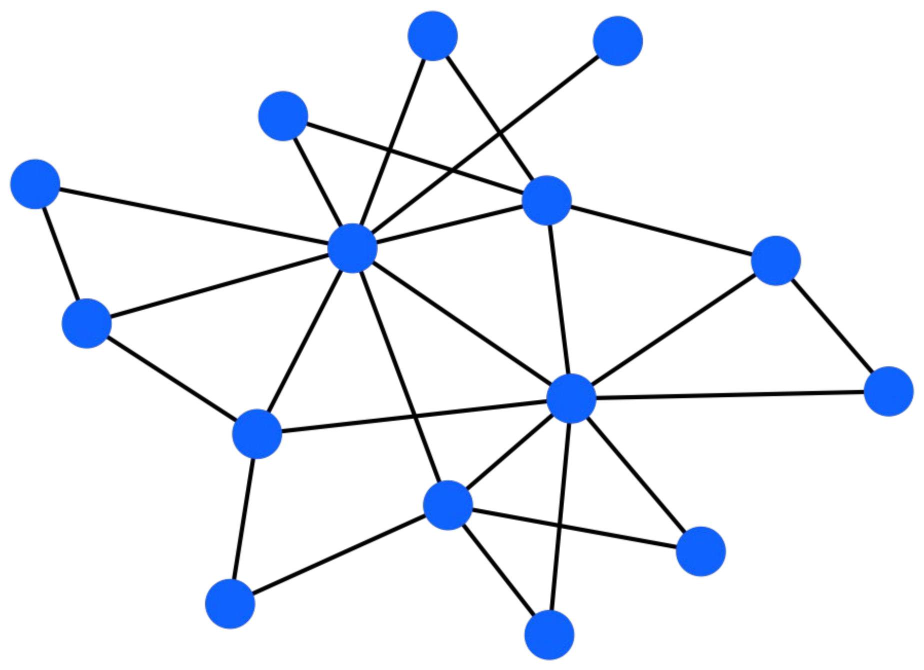
https://www.youtube.com/watch?v=3QGmYr6cyB4

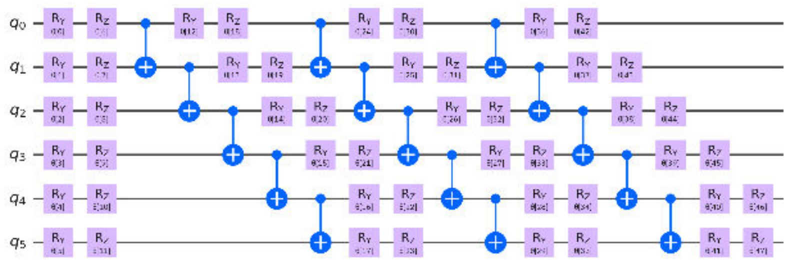
Qiskit Patterns

The anatomy of a quantum algorithm

Step 1

Map quantum circuits and operators.

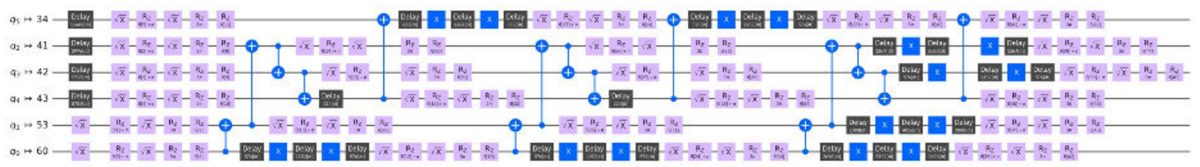




Step 2

Optimize problem for quantum execution.

```
PassManager(UnitarySynthesis(),
            BasisTranslator(),
            EnlargeWithAncilla(),
            AISwap(),
            Collect1qRuns(),
            Optimize1qGates(),
            Collect2qBlocks(),
            ConsolidateBlocks())
```



Step 3

Execute using Qiskit Runtime Primitives.

Sampler

000101...,
110110...

circuit$(\vec{\theta})$

bit-strings

Estimator

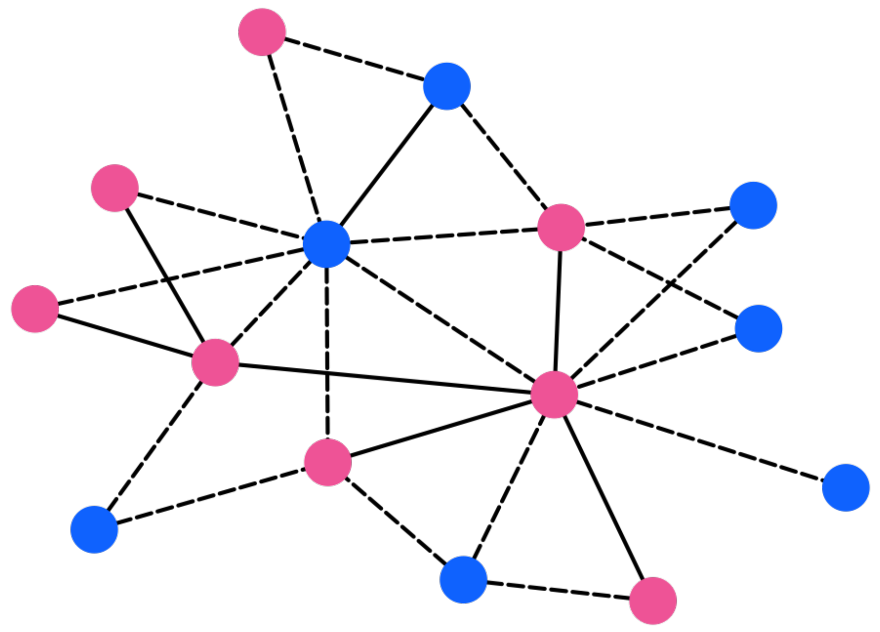
$\langle \tilde{\hat{O}} \rangle$

circuit$(\vec{\theta})$ + observable $\hat{O}$

expectation value

Step 4

Post-process, return result in classical format.



The full promise of quantum computing at scale delivered via error correction

A 100,000-qubit quantum centric super computer lets us move toward practical fault-tolerance.

Low-overhead fault tolerant quantum computing using long-range connectivity

High-threshold and low-overhead fault-tolerant quantum memory

Sergey Bravyi[1], Andrew W. Cross[1], Jay M. Gambetta[1], Dmitri Maslov[1], Patrick Rall[2], and
Theodore J. Yoder[1]

[1]IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, NY 10598 (USA)
[2]IBM Quantum, MIT-IBM Watson AI Lab, Cambridge, MA 02142 (USA)

August 16, 2023

arXiv:2308.07915v1 [quant-ph] 15 Aug 2023

Abstract

Quantum error correction becomes a practical possibility only if the physical error rate is below a threshold value that depends on a particular quantum code, syndrome measurement circuit, and a decoding algorithm. Here we present an end-to-end quantum error correction protocol that implements fault-tolerant memory based on a family of LDPC codes with a high encoding rate that achieves an error threshold of 0.8% for the standard circuit-based noise model. This is on par with the surface code which has remained an uncontested leader in terms of its high error threshold for nearly 20 years. The full syndrome measurement cycle for a length-n code in our family requires n ancillary qubits and a depth-7 circuit composed of nearest-neighbor CNOT gates. The required qubit connectivity is a degree-6 graph that consists of two edge-disjoint planar subgraphs. As a concrete example, we show that 12 logical qubits can be preserved for ten million syndrome cycles using 288 physical qubits in total, assuming the physical error rate of 0.1%. We argue that achieving the same level of error suppression on 12 logical qubits with the surface code would require more than 4000 physical qubits. Our findings bring demonstrations of a low-overhead fault-tolerant quantum memory within the reach of near-term quantum processors.

1 Introduction

Quantum computing attracted attention due to its ability to offer asymptotically faster solutions to a set of computational problems compared to the best known classical algorithms [1]. It is believed that a scalable functioning quantum computer may help solve computational problems in such areas as scientific discovery, materials research, chemistry, and drug design, to name a few [2, 3, 4, 5].

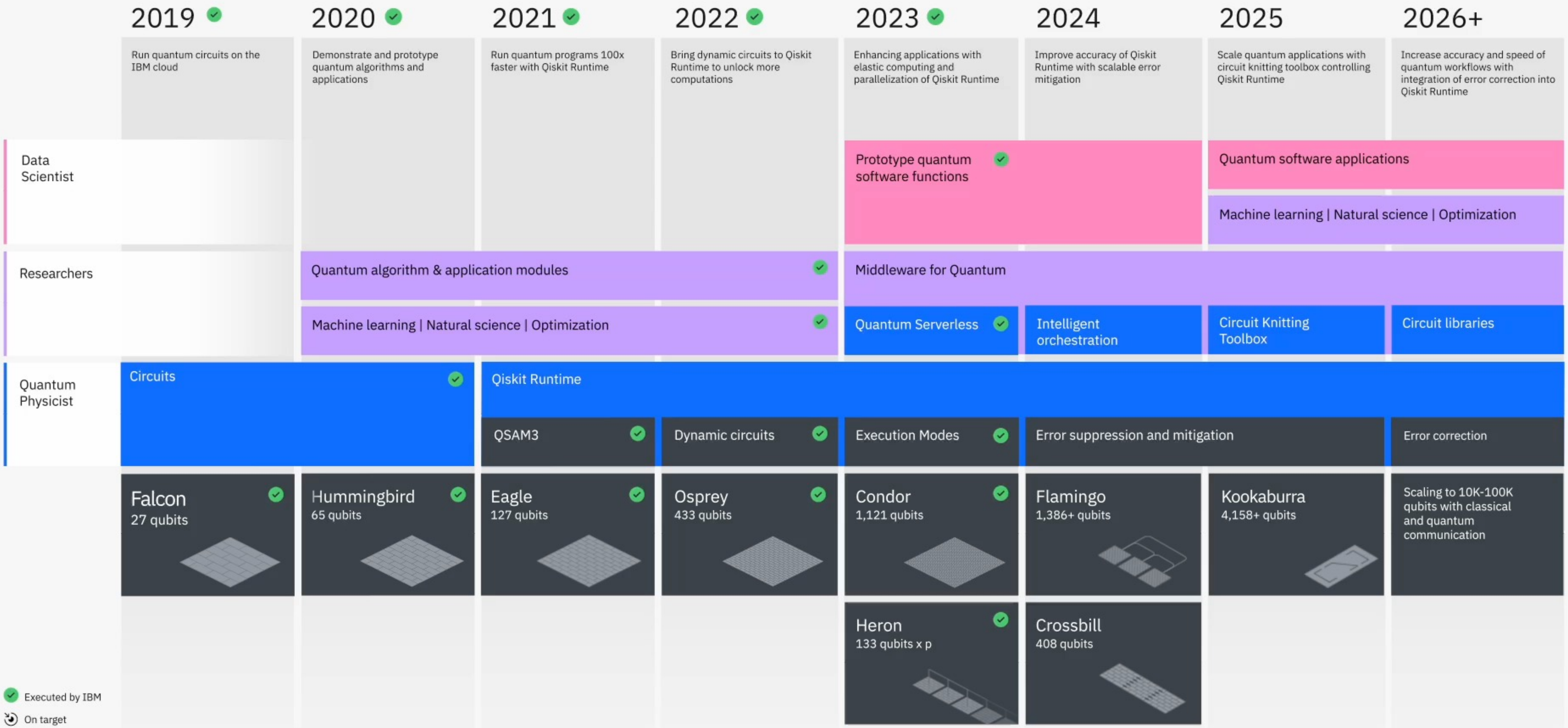
The main obstacle to building a quantum computer is the fragility of quantum information, owing to various sources of noise affecting it. Since isolating a quantum computer from external effects and controlling it to induce a desired computation are in conflict with each other, noise appears to be inevitable. The sources of noise include imperfections in qubits, materials used, controlling apparatus, State Preparation and Measurement (SPAM) errors, and a variety of external factors ranging from local man-made, such as stray electromagnetic fields, to those inherent to the Universe, such as cosmic rays. See Ref. [6] for a summary. While some sources of noise can be eliminated with better control [7], materials [8], and shielding [9, 10, 11], a number of other sources appear to be difficult if at all possible to remove. The latter kind can include spontaneous and stimulated emission in trapped ions [12, 13], and the interaction with the bath (Purcell Effect) [14] in superconducting circuits—covering both leading quantum technologies. Thus, error correction becomes a key requirement for building a functioning scalable quantum computer.

The road is clear to extending quantum utility

https://www.youtube.com/watch?v=L5PwmFnHCBI

Development Roadmap

IBM **Quantum**

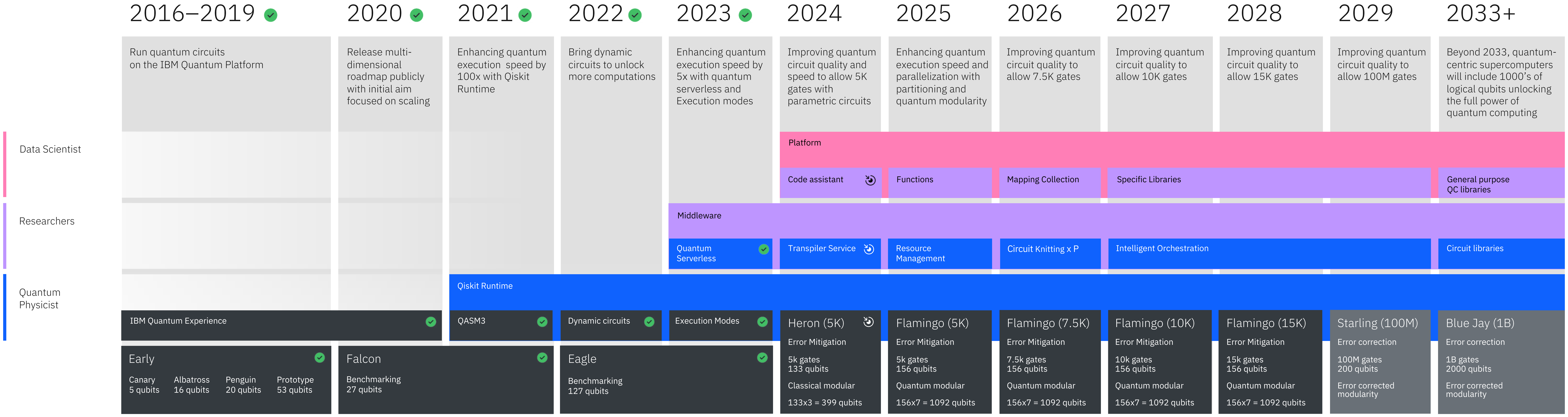


	2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023 ✓	2024	2025	2026+
	Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime
Data Scientist					Prototype quantum software functions ✓		Quantum software applications	
							Machine learning | Natural science | Optimization	
Researchers		Quantum algorithm & application modules ✓			Middleware for Quantum			
		Machine learning | Natural science | Optimization ✓			Quantum Serverless ✓	Intelligent orchestration	Circuit Knitting Toolbox	Circuit libraries
Quantum Physicist	Circuits ✓		Qiskit Runtime					
			QSAM3 ✓	Dynamic circuits ✓	Execution Modes ✓	Error suppression and mitigation		Error correction
	Falcon ✓ 27 qubits	Hummingbird ✓ 65 qubits	Eagle ✓ 127 qubits	Osprey ✓ 433 qubits	Condor ✓ 1,121 qubits	Flamingo 1,386+ qubits	Kookaburra 4,158+ qubits	Scaling to 10K-100K qubits with classical and quantum communication
					Heron ✓ 133 qubits x p	Crossbill 408 qubits		

✓ Executed by IBM

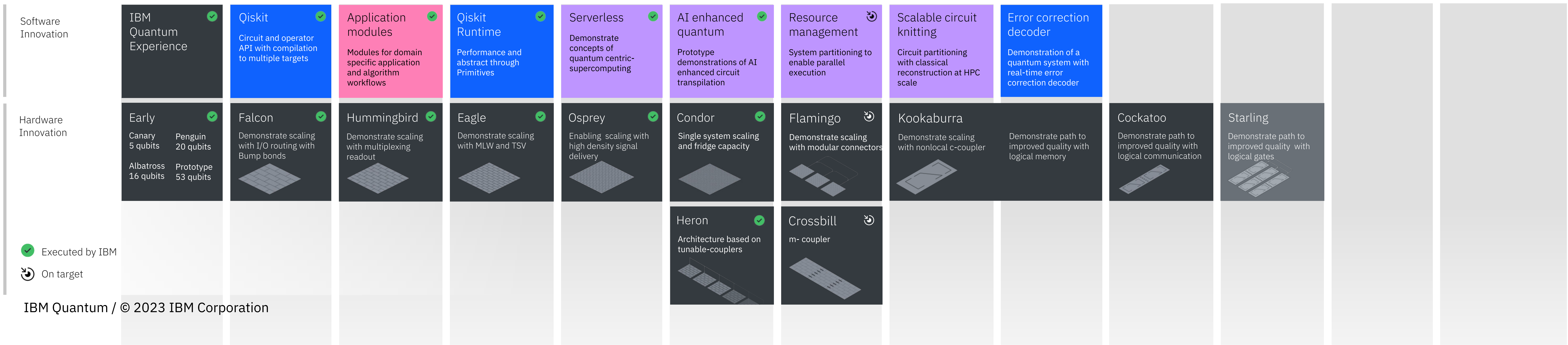
◎ On target

Development Roadmap



	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						
						Code assistant ◎	Functions	Mapping Collection	Specific Libraries			General purpose QC libraries
Researchers					Middleware							
					Quantum Serverless ✓	Transpiler Service ◎	Resource Management	Circuit Knitting x P	Intelligent Orchestration			Circuit libraries
Quantum Physicist			Qiskit Runtime									
	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



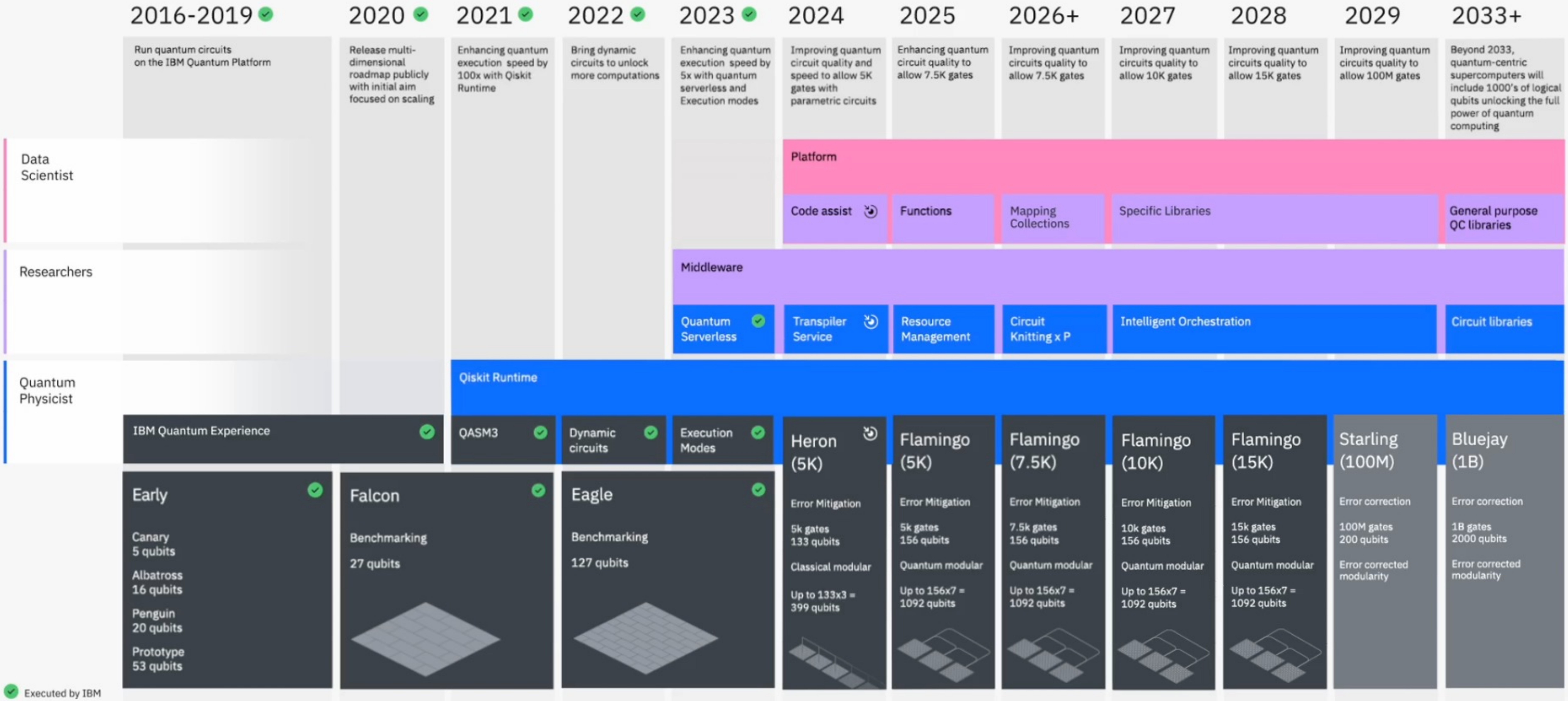
Software Innovation	IBM Quantum Experience ✓	Qiskit ✓ Circuit and operator API with compilation to multiple targets	Application modules ✓ Modules for domain specific application and algorithm workflows	Qiskit Runtime ✓ Performance and abstract through Primitives	Serverless ✓ Demonstrate concepts of quantum 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		
						Heron ✓ Architecture based on tunable-couplers	Crossbill ◎ m- coupler						

✓ Executed by IBM

◎ On target

Development Roadmap

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 circuit quality to allow 7.5K gates	Improving quantum circuits quality to allow 7.5K gates	Improving quantum circuits quality to allow 10K gates	Improving quantum circuits quality to allow 15K gates	Improving quantum circuits 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						
						Code assist ↻	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 Physicist			Qiskit Runtime									
	IBM Quantum Experience ✓		QASM3 ✓	Dynamic circuits ✓	Execution Modes ✓	Heron (5K) ↻ Error Mitigation 5k gates 133 qubits Classical modular Up to 133x3 = 399 qubits	Flamingo (5K) Error Mitigation 5k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits	Flamingo (7.5K) Error Mitigation 7.5k gates 156 qubits Quantum modular Up to 156x7 = 1092 qubits	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	Bluejay (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								

✓ Executed by IBM

↻ On target

Innovation Roadmap

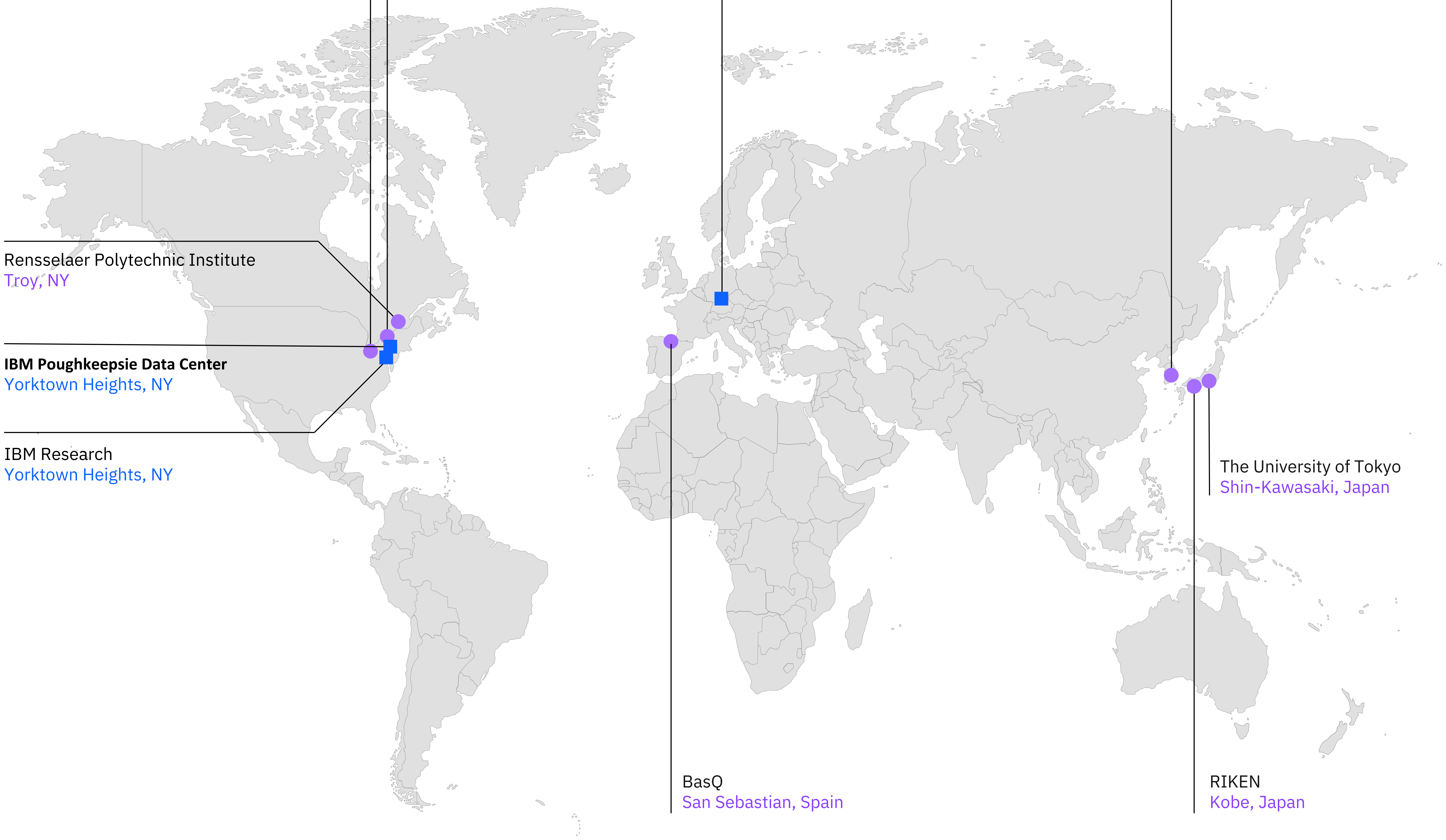
IBM Quantum

	2016–2019 ✓		2020 ✓	2021 ✓	2022 ✓	2023 ✓	2024	2025	2026	2027	2028	2029	2033+
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	**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 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 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		
						Heron ✓ Architecture based on tunable-couplers	**Crossbill** ⟳ m-coupler						

✓ Executed by IBM

⟳ On target

Scaling collaboration through Quantum Computation Centers



Cleveland Clinic
Cleveland, Ohio

PinQ^2
Bromont, Québec

IBM Ehningen Data Center [2024]
Ehningen, Germany

Fraunhofer
Ehningen, Germany

Yonsei University
Seoul, Korea

Rensselaer Polytechnic Institute
Troy, NY

IBM Poughkeepsie Data Center
Yorktown Heights, NY

IBM Research
Yorktown Heights, NY

The University of Tokyo
Shin-Kawasaki, Japan

BasQ
San Sebastian, Spain

RIKEN
Kobe, Japan

Technical Working Groups

Bringing together experts from classical + quantum + industry to identify the most pressing scientific challenges in the area today

Biological Sciences & Drug Discovery

Image processing, Biomarkers – Omics technologies, Radiotherapy planning, Clinical trial optimization and design, Disease mechanism...

THE UNIVERSITY OF CHICAGO
UNIVERSITY OF TORONTO
Cleveland Clinic

High Energy Physics

Anomaly detection
Lattice Gauge Theory
Sensing...

PSNC
DESY.
東京大学 THE UNIVERSITY OF TOKYO
CERN

Materials

Materials properties
Dynamics of chemical systems
Ground and excited states...

OAK RIDGE National Laboratory
THE UNIVERSITY OF CHICAGO
東京大学 THE UNIVERSITY OF TOKYO
RIKEN

Optimization

Risk analysis
Portfolio Optimization
Transaction Settlement...

e.on
Los Alamos NATIONAL LABORATORY
UKRI Science and Technology Facilities Council
Fraunhofer

https://youtu.be/6p-0XYgIi7Q?si=mFDXwO1bml8eStZz

Healthcare & Life Sciences

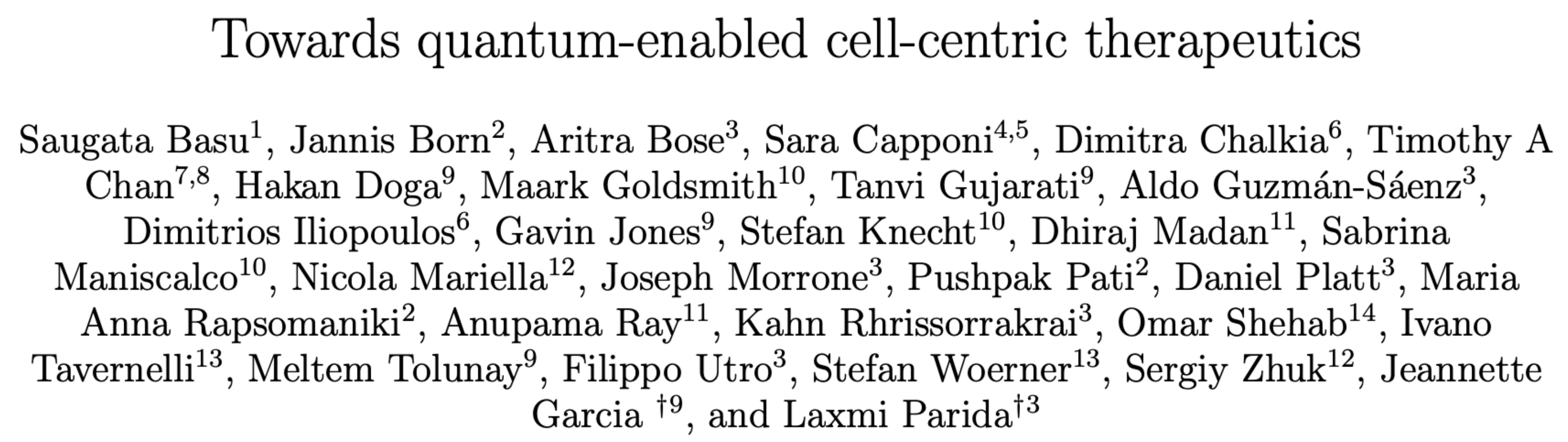
Tackling challenges for HCLS with quantum computing

Goals

Establish that now is the time to focus on HCLS for which quantum computing (through quantum chemistry and QML algorithms) will be of paramount importance

Gain consensus on key scientific questions for quantum computing and HCLS.

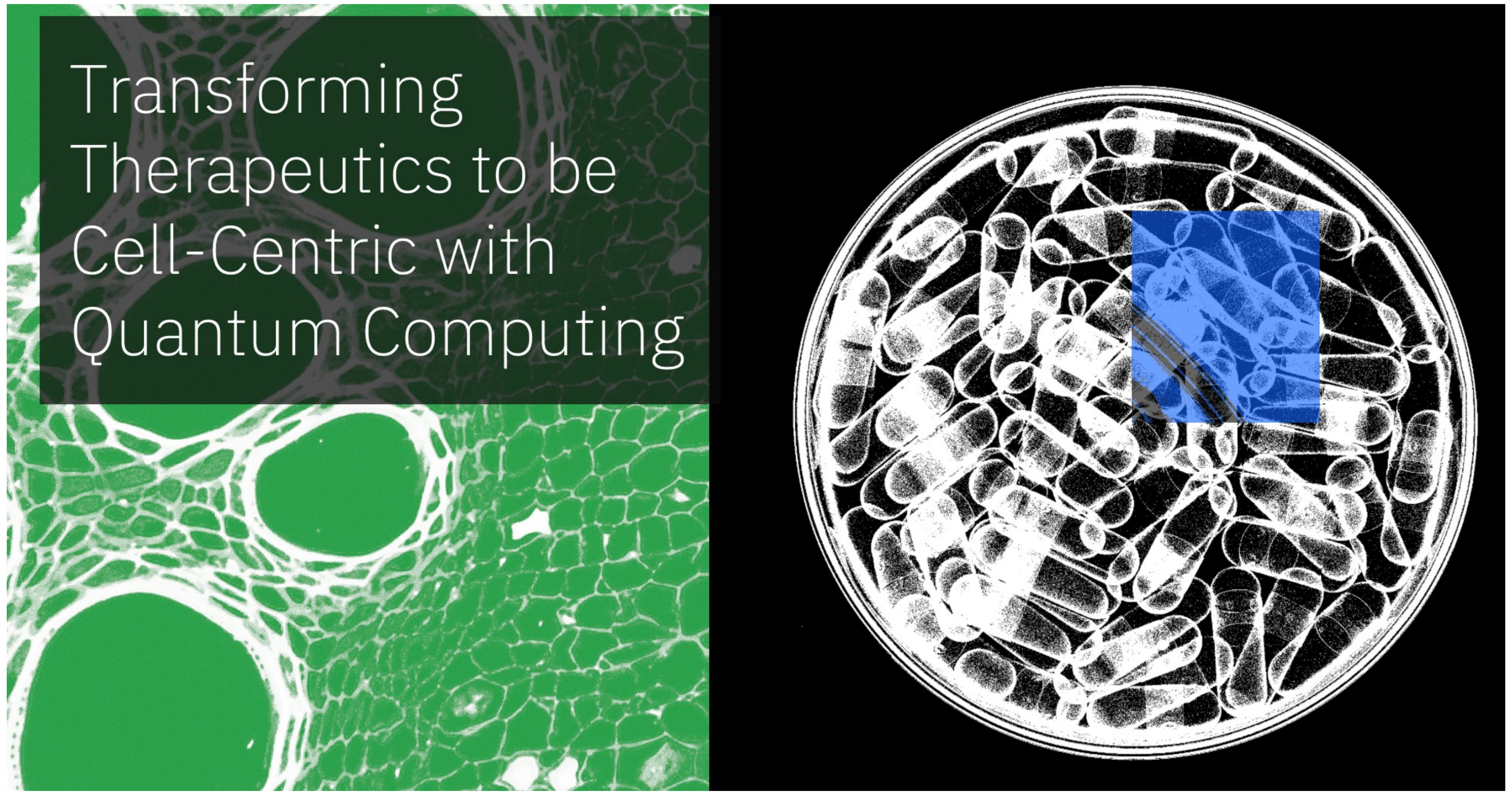
Establish a roadmap/perspective on key challenges over next 3-6 years



Towards quantum-enabled cell-centric therapeutics

Saugata Basu[1], Jannis Born[2], Aritra Bose[3], Sara Capponi[4,5], Dimitra Chalkia[6], Timothy A Chan[7,8], Hakan Doga[9], Maark Goldsmith[10], Tanvi Gujarati[9], Aldo Guzmán-Sáenz[3], Dimitrios Iliopoulos[6], Gavin Jones[9], Stefan Knecht[10], Dhiraj Madan[11], Sabrina Maniscalco[10], Nicola Mariella[12], Joseph Morrone[3], Pushpak Pati[2], Daniel Platt[3], Maria Anna Rapsomaniki[2], Anupama Ray[11], Kahn Rhrissorrakrai[3], Omar Shehab[14], Ivano Tavernelli[13], Meltem Tolunay[9], Filippo Utro[3], Stefan Woerner[13], Sergiy Zhuk[12], Jeannette Garcia [†9], and Laxmi Parida[†3]

https://arxiv.org/abs/2307.05734



High Energy Physics

Approaches to studying high energy physics problems with quantum

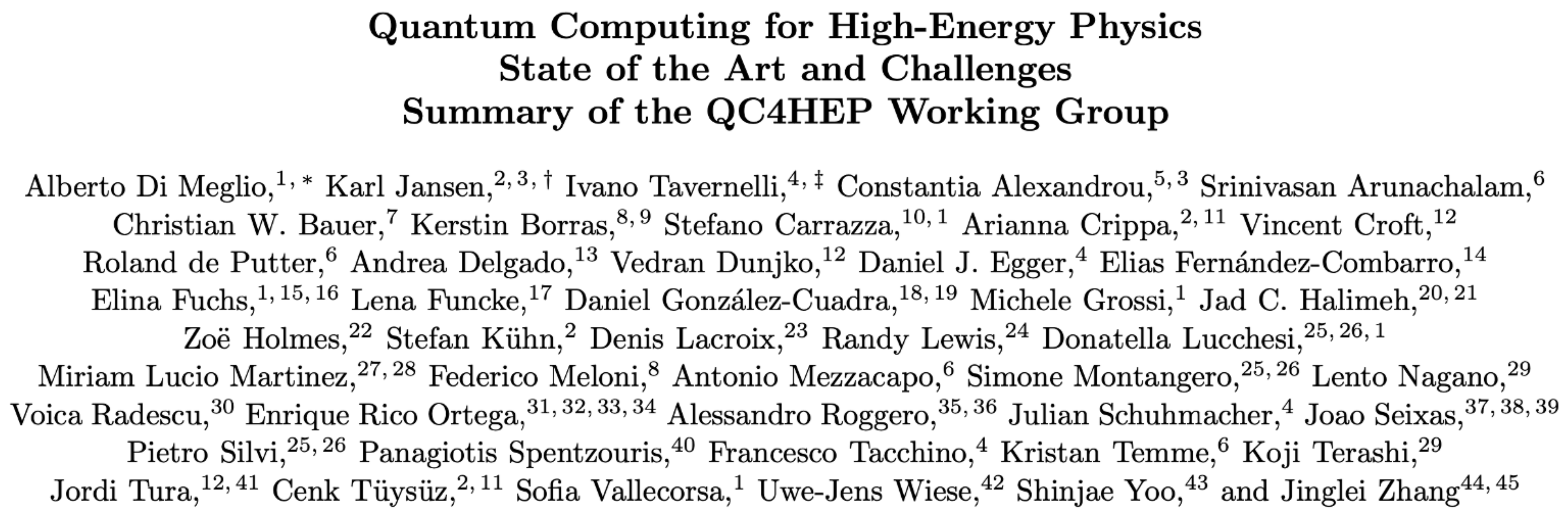
Goals

Deep dive look at the state of High Energy Physics challenges (from both experiment and theory)

Understand how quantum computing can boost the solution of open challenges in HEP

Demonstrate quantum advantage with near-term devises on relevant HEP problems

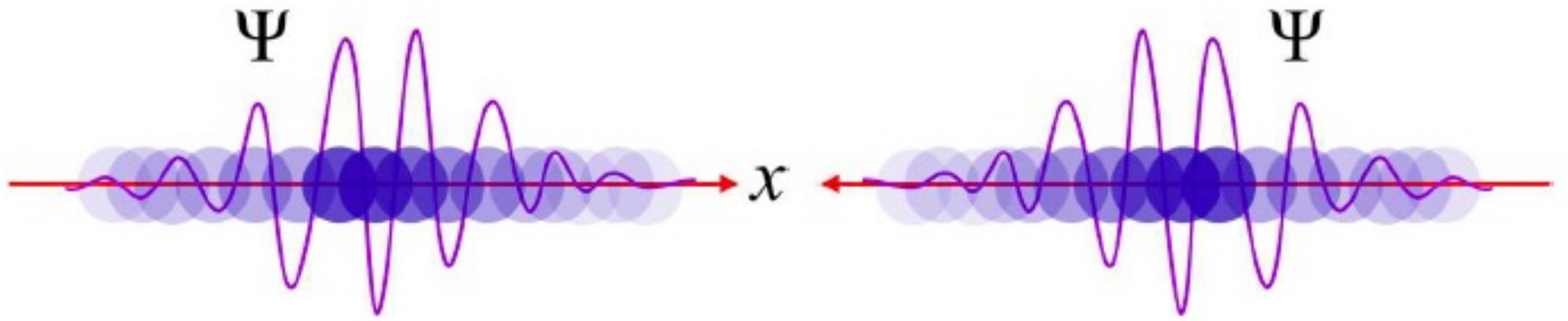
Catalyze new developments within HEP



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

Alberto Di Meglio,[1,*] Karl Jansen,[2,3,†] Ivano Tavernelli,[4,‡] Constantia Alexandrou,[5,3] Srinivasan Arunachalam,[6]
Christian W. Bauer,[7] Kerstin Borras,[8,9] Stefano Carrazza,[10,1] 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,[25,26,1]
Miriam Lucio Martinez,[27,28] Federico Meloni,[8] Antonio Mezzacapo,[6] Simone Montangero,[25,26] Lento Nagano,[29]
Voica Radescu,[30] Enrique Rico Ortega,[31,32,33,34] Alessandro Roggero,[35,36] Julian Schuhmacher,[4] Joao Seixas,[37,38,39]
Pietro Silvi,[25,26] Panagiotis Spentzouris,[40] Francesco Tacchino,[4] Kristan Temme,[6] Koji Terashi,[29]
Jordi Tura,[12,41] Cenk Tüysüz,[2,11] Sofia Vallecorsa,[1] Uwe-Jens Wiese,[42] Shinjae Yoo,[43] and Jinglei Zhang[44,45]

https://arxiv.org/abs/2307.03236



Optimization

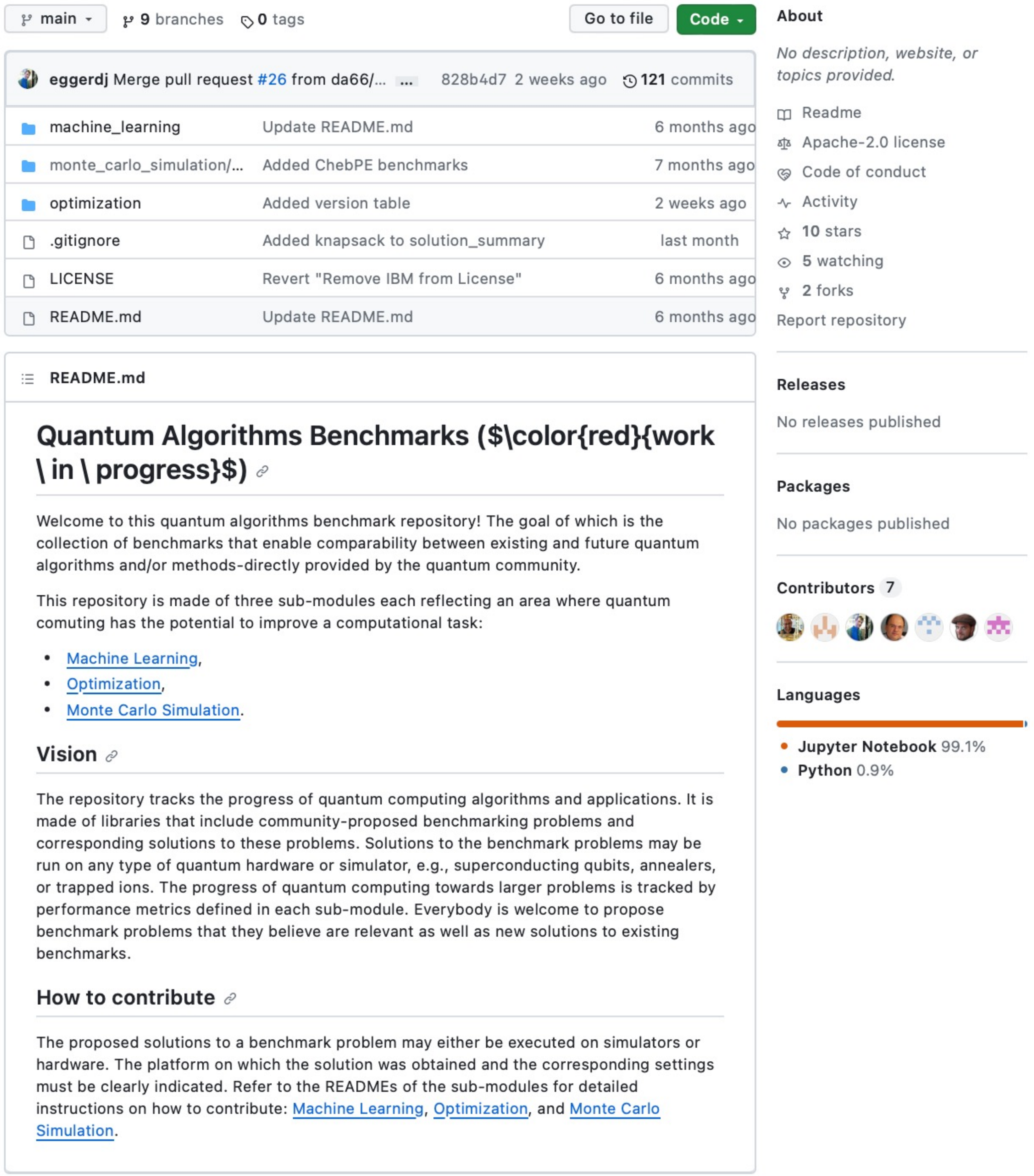
Identifying the next steps for optimization

Goals

Engage with quantum & classical optimization communities

Identify and work on key questions to scale quantum optimization towards quantum advantage

Establish a set of benchmarks to track progress towards quantum advantage (in optimization and/or finance)



eggerdj Merge pull request #26 from da66/... … 828b4d7 2 weeks ago 121 commits

machine_learning	Update README.md	6 months ago
monte_carlo_simulation/...	Added ChebPE benchmarks	7 months ago
optimization	Added version table	2 weeks ago
.gitignore	Added knapsack to solution_summary	last month
LICENSE	Revert "Remove IBM from License"	6 months ago
README.md	Update README.md	6 months ago

README.md

Quantum Algorithms Benchmarks ($\color{red}{work \ in \ progress}$)

Welcome to this quantum algorithms benchmark repository! The goal of which is the collection of benchmarks that enable comparability between existing and future quantum algorithms and/or methods-directly provided by the quantum community.

This repository is made of three sub-modules each reflecting an area where quantum comiting has the potential to improve a computational task:

- Machine Learning,
- Optimization,
- Monte Carlo Simulation.

Vision

The repository tracks the progress of quantum computing algorithms and applications. It is made of libraries that include community-proposed benchmarking problems and corresponding solutions to these problems. Solutions to the benchmark problems may be run on any type of quantum hardware or simulator, e.g., superconducting qubits, annealers, or trapped ions. The progress of quantum computing towards larger problems is tracked by performance metrics defined in each sub-module. Everybody is welcome to propose benchmark problems that they believe are relevant as well as new solutions to existing benchmarks.

How to contribute

The proposed solutions to a benchmark problem may either be executed on simulators or hardware. The platform on which the solution was obtained and the corresponding settings must be clearly indicated. Refer to the READMEs of the sub-modules for detailed instructions on how to contribute: Machine Learning, Optimization, and Monte Carlo Simulation.

About

No description, website, or topics provided.

Readme
Apache-2.0 license
Code of conduct
Activity
10 stars
5 watching
2 forks
Report repository

Releases

No releases published

Packages

No packages published

Contributors 7

Languages

Jupyter Notebook 99.1%
Python 0.9%

https://github.com/qiskit-community/quantum-algorithms-benchmarks

Optimization

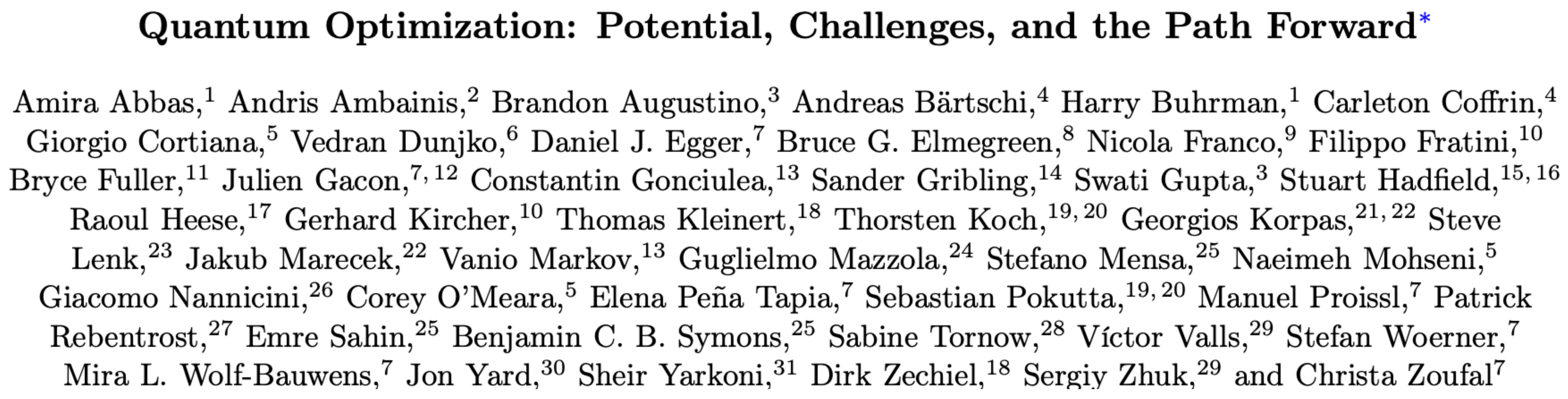
Identifying the next steps for optimization

Goals

Engage with quantum & classical optimization communities

Identify and work on key questions to scale quantum optimization towards quantum advantage

Establish a set of benchmarks to track progress towards quantum advantage (in optimization and/or finance)



Quantum Optimization: Potential, Challenges, and the Path Forward*

Amira Abbas,[1] Andris Ambainis,[2] Brandon Augustino,[3] Andreas Bärtschi,[4] Harry Buhrman,[1] Carleton Coffrin,[4] Giorgio Cortiana,[5] Vedran Dunjko,[6] Daniel J. Egger,[7] Bruce G. Elmegreen,[8] Nicola Franco,[9] Filippo Fratini,[10] Bryce Fuller,[11] Julien Gacon,[7, 12] Constantin Gonciulea,[13] Sander Gribling,[14] Swati Gupta,[3] Stuart Hadfield,[15, 16] Raoul Heese,[17] Gerhard Kircher,[10] Thomas Kleinert,[18] Thorsten Koch,[19, 20] Georgios Korpas,[21, 22] Steve Lenk,[23] Jakub Marecek,[22] Vanio Markov,[13] Guglielmo Mazzola,[24] Stefano Mensa,[25] Naeimeh Mohseni,[5] Giacomo Nannicini,[26] Corey O'Meara,[5] Elena Peña Tapia,[7] Sebastian Pokutta,[19, 20] Manuel Proissl,[7] Patrick Rebentrost,[27] Emre Sahin,[25] Benjamin C. B. Symons,[25] Sabine Tornow,[28] Víctor Valls,[29] Stefan Woerner,[7] Mira L. Wolf-Bauwens,[7] Jon Yard,[30] Sheir Yarkoni,[31] Dirk Zechiel,[18] Sergiy Zhuk,[29] and Christa Zoufal[7]

https://arxiv.org/abs/2312.02279

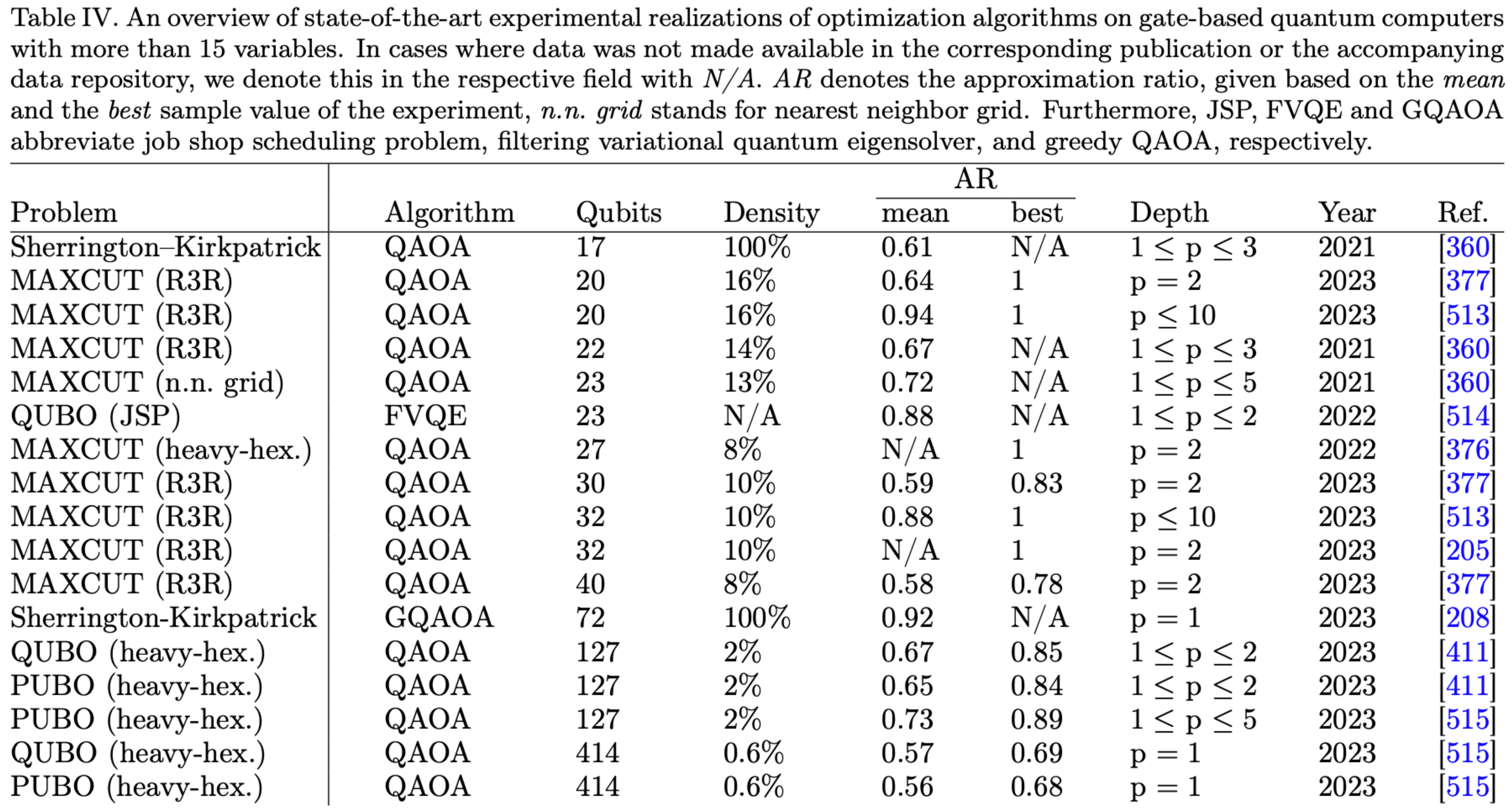


Table IV. An overview of state-of-the-art experimental realizations of optimization algorithms on gate-based quantum computers with more than 15 variables. In cases where data was not made available in the corresponding publication or the accompanying data repository, we denote this in the respective field with *N/A*. *AR* denotes the approximation ratio, given based on the *mean* and the *best* sample value of the experiment, *n.n. grid* stands for nearest neighbor grid. Furthermore, JSP, FVQE and GQAOA abbreviate job shop scheduling problem, filtering variational quantum eigensolver, and greedy QAOA, respectively.

				AR				
Problem	Algorithm	Qubits	Density	mean	best	Depth	Year	Ref.
Sherrington–Kirkpatrick	QAOA	17	100%	0.61	N/A	$1 \leq p \leq 3$	2021	[360]
MAXCUT (R3R)	QAOA	20	16%	0.64	1	$p = 2$	2023	[377]
MAXCUT (R3R)	QAOA	20	16%	0.94	1	$p \leq 10$	2023	[513]
MAXCUT (R3R)	QAOA	22	14%	0.67	N/A	$1 \leq p \leq 3$	2021	[360]
MAXCUT (n.n. grid)	QAOA	23	13%	0.72	N/A	$1 \leq p \leq 5$	2021	[360]
QUBO (JSP)	FVQE	23	N/A	0.88	N/A	$1 \leq p \leq 2$	2022	[514]
MAXCUT (heavy-hex.)	QAOA	27	8%	N/A	1	$p = 2$	2022	[376]
MAXCUT (R3R)	QAOA	30	10%	0.59	0.83	$p = 2$	2023	[377]
MAXCUT (R3R)	QAOA	32	10%	0.88	1	$p \leq 10$	2023	[513]
MAXCUT (R3R)	QAOA	32	10%	N/A	1	$p = 2$	2023	[205]
MAXCUT (R3R)	QAOA	40	8%	0.58	0.78	$p = 2$	2023	[377]
Sherrington-Kirkpatrick	GQAOA	72	100%	0.92	N/A	$p = 1$	2023	[208]
QUBO (heavy-hex.)	QAOA	127	2%	0.67	0.85	$1 \leq p \leq 2$	2023	[411]
PUBO (heavy-hex.)	QAOA	127	2%	0.65	0.84	$1 \leq p \leq 2$	2023	[411]
PUBO (heavy-hex.)	QAOA	127	2%	0.73	0.89	$1 \leq p \leq 5$	2023	[515]
QUBO (heavy-hex.)	QAOA	414	0.6%	0.57	0.69	$p = 1$	2023	[515]
PUBO (heavy-hex.)	QAOA	414	0.6%	0.56	0.68	$p = 1$	2023	[515]

Materials

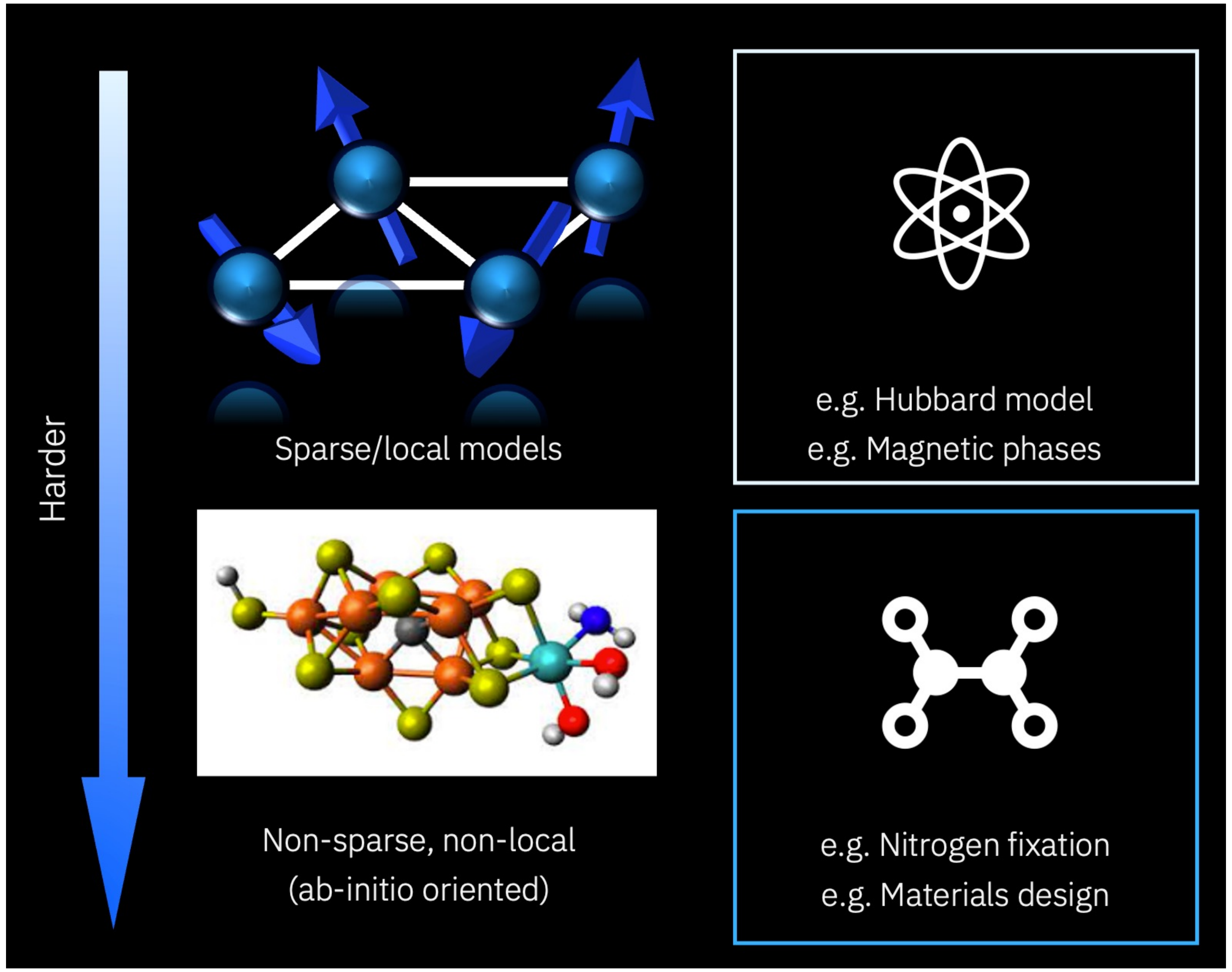
Workflows for materials simulations

Goals

Identify key algorithms that make optimal use of quantum computing and HPC

Identify use cases in materials science for quantum/HPC algorithms

How best to model materials with quantum computers?



Harder

Sparse/local models

e.g. Hubbard model
e.g. Magnetic phases

Non-sparse, non-local
(ab-initio oriented)

e.g. Nitrogen fixation
e.g. Materials design

Paper coming soon!!!

Bringing together experts from classical + quantum + industry to identify the most pressing scientific challenges in the area today

Coming in 2024: Sustainability

Biological Sciences & Drug Discovery

Image processing, Biomarkers – Omics technologies, Radiotherapy planning, Clinical trial optimization and design, Disease mechanism...

THE UNIVERSITY OF CHICAGO
UNIVERSITY OF TORONTO
Cleveland Clinic

High Energy Physics

Anomaly detection
Lattice Gauge Theory
Sensing...

PSNC
DESY.
東京大学 THE UNIVERSITY OF TOKYO
CERN

Materials

Materials properties
Dynamics of chemical systems
Ground and excited states...

OAK RIDGE National Laboratory
THE UNIVERSITY OF CHICAGO
東京大学 THE UNIVERSITY OF TOKYO
RIKEN

Optimization

Risk analysis
Portfolio Optimization
Transaction Settlement...

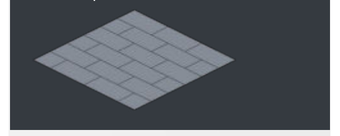
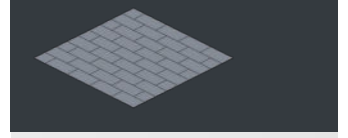
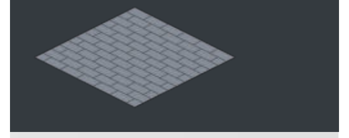
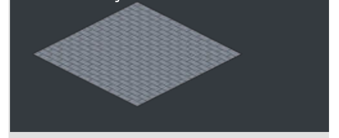
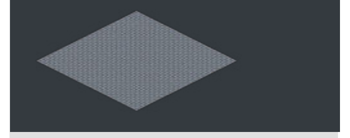
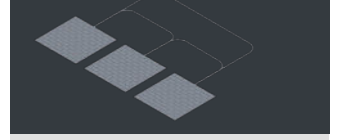
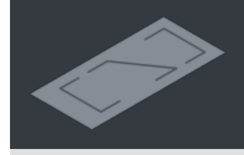
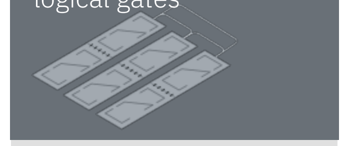
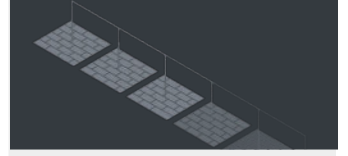
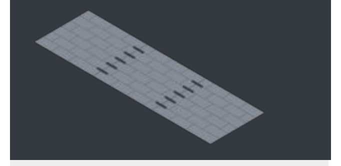
e·on
Los Alamos NATIONAL LABORATORY
UKRI Science and Technology Facilities Council
Fraunhofer

Working group interest form:
https://airtable.com/appL9KALjjbTDaueh/shrmeubXExazSH9vv

Development Roadmap

	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						
						Code assistant ⟳	Functions	Mapping Collection	Specific Libraries			General purpose QC libraries
Researchers					Middleware							
					Quantum Serverless ✓	Transpiler Service ⟳	Resource Management	Circuit Knitting x P	Intelligent Orchestration			Circuit libraries
Quantum Physicist			Qiskit Runtime									
	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	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 		
						Heron ✓ Architecture based on tunable-couplers 	Crossbill ⟳ m- coupler 						

✓ Executed by IBM

⟳ On target