Developments in quantum computing hardware and software with IBM

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(On behalf of our team consisting of:
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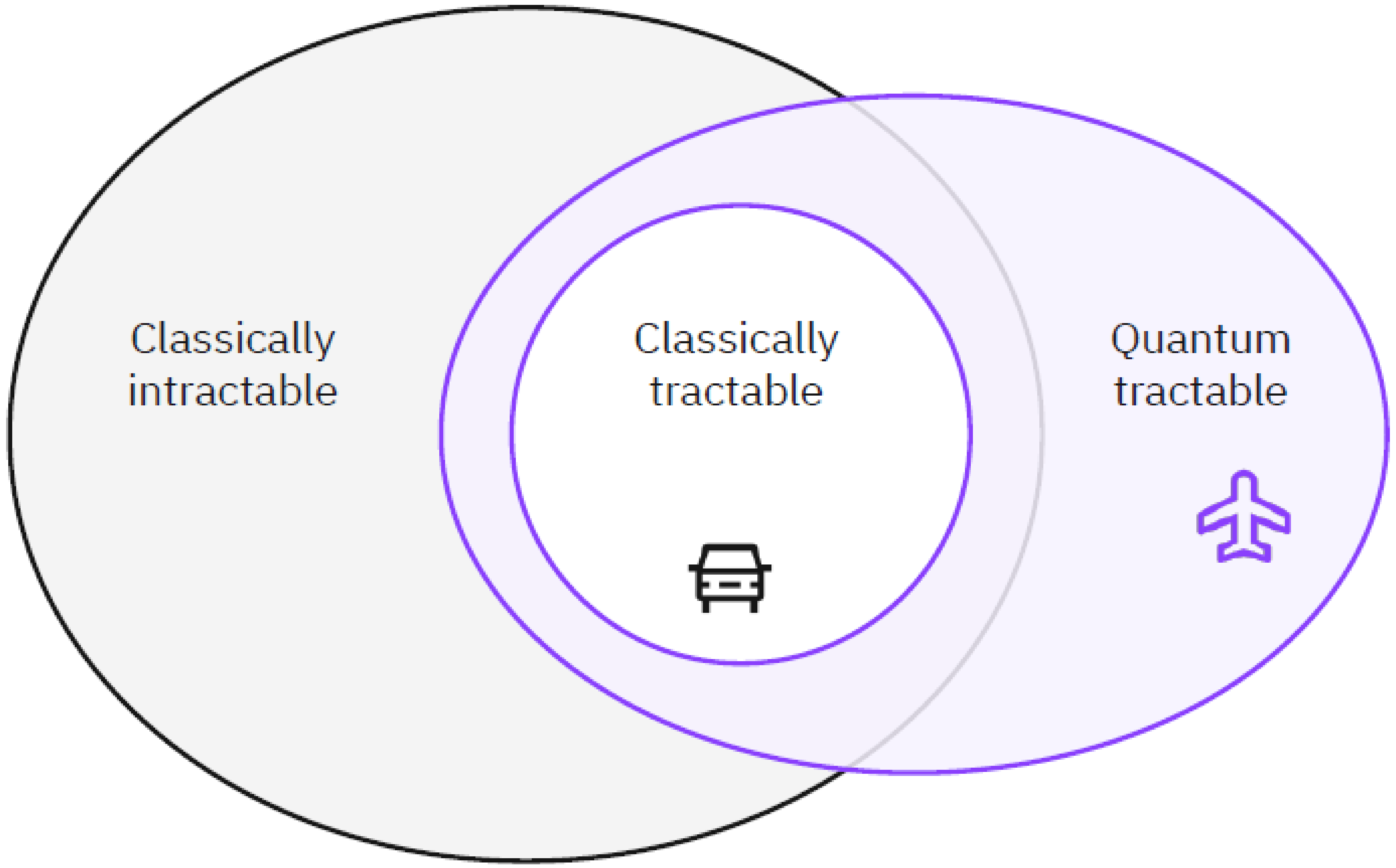
Unlock discovery with quantum computing

Harnesses the capacity to advance conceptual and tools-based discovery

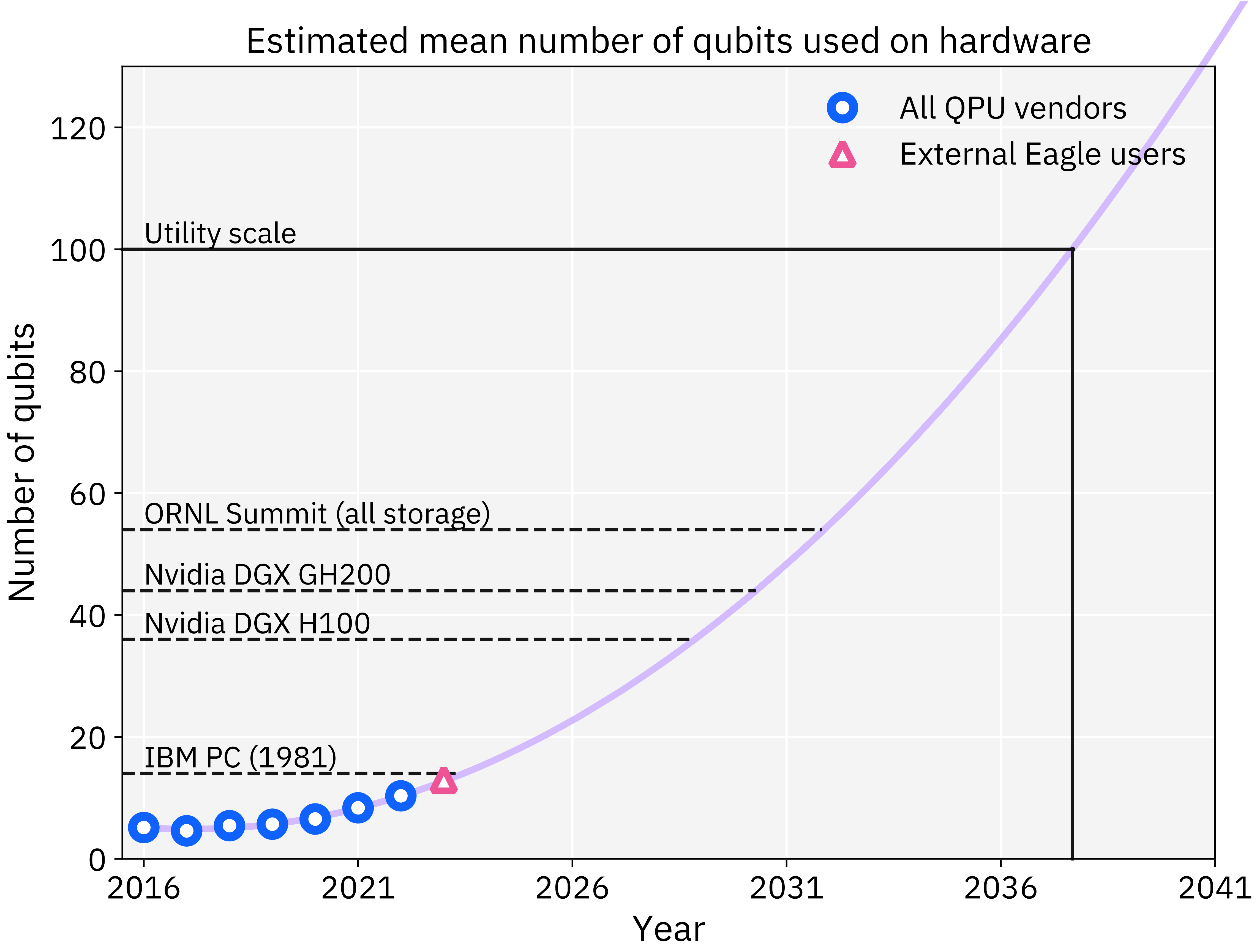
Quantum computers are exponentially more powerful than classical computers



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

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

Quantum state of play

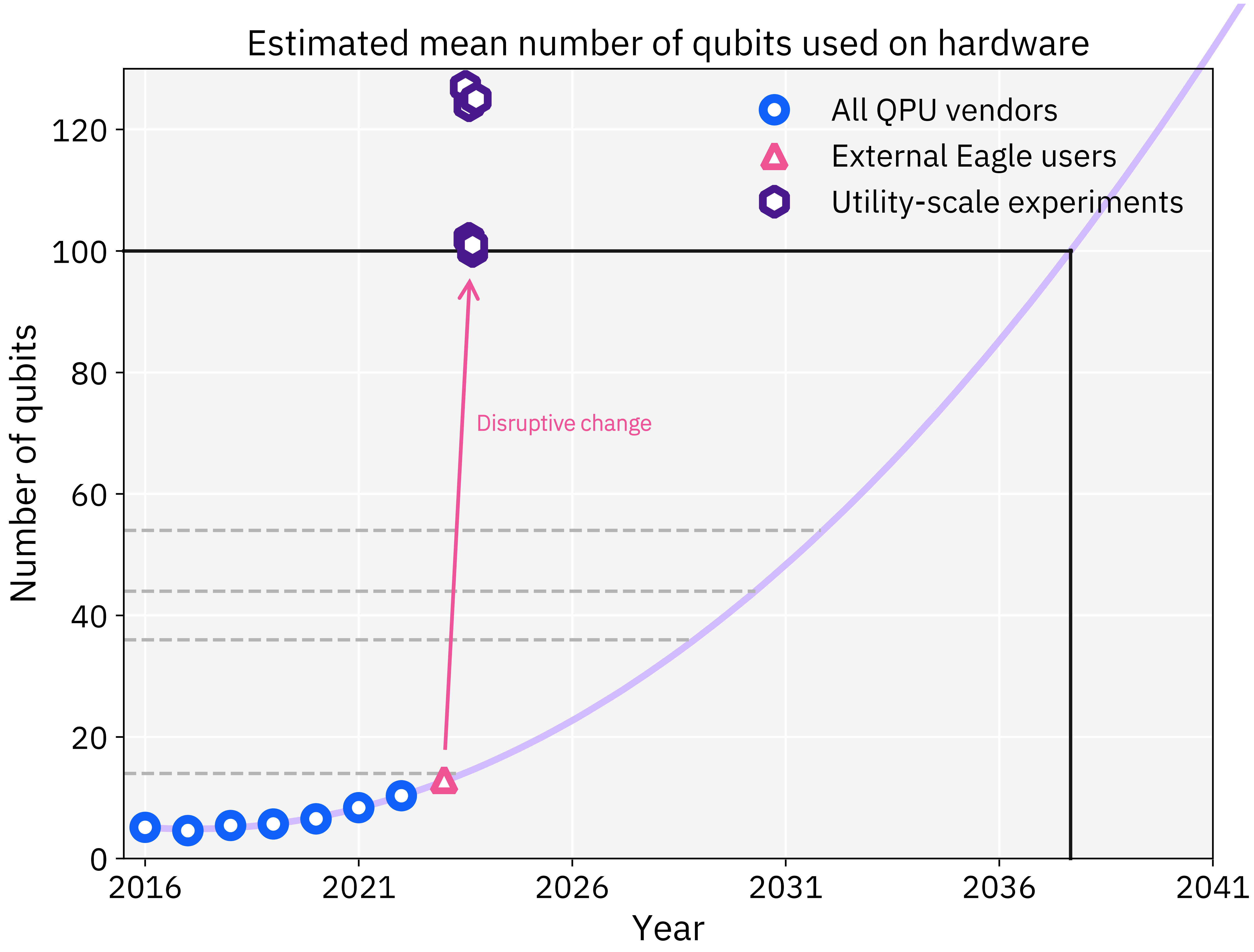


Data for all vendors taken from: arXiv:2307.16130

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

IBM Quantum systems and Qiskit are bringing a disruptive change.

Data for all vendors taken from: arXiv:2307.16130

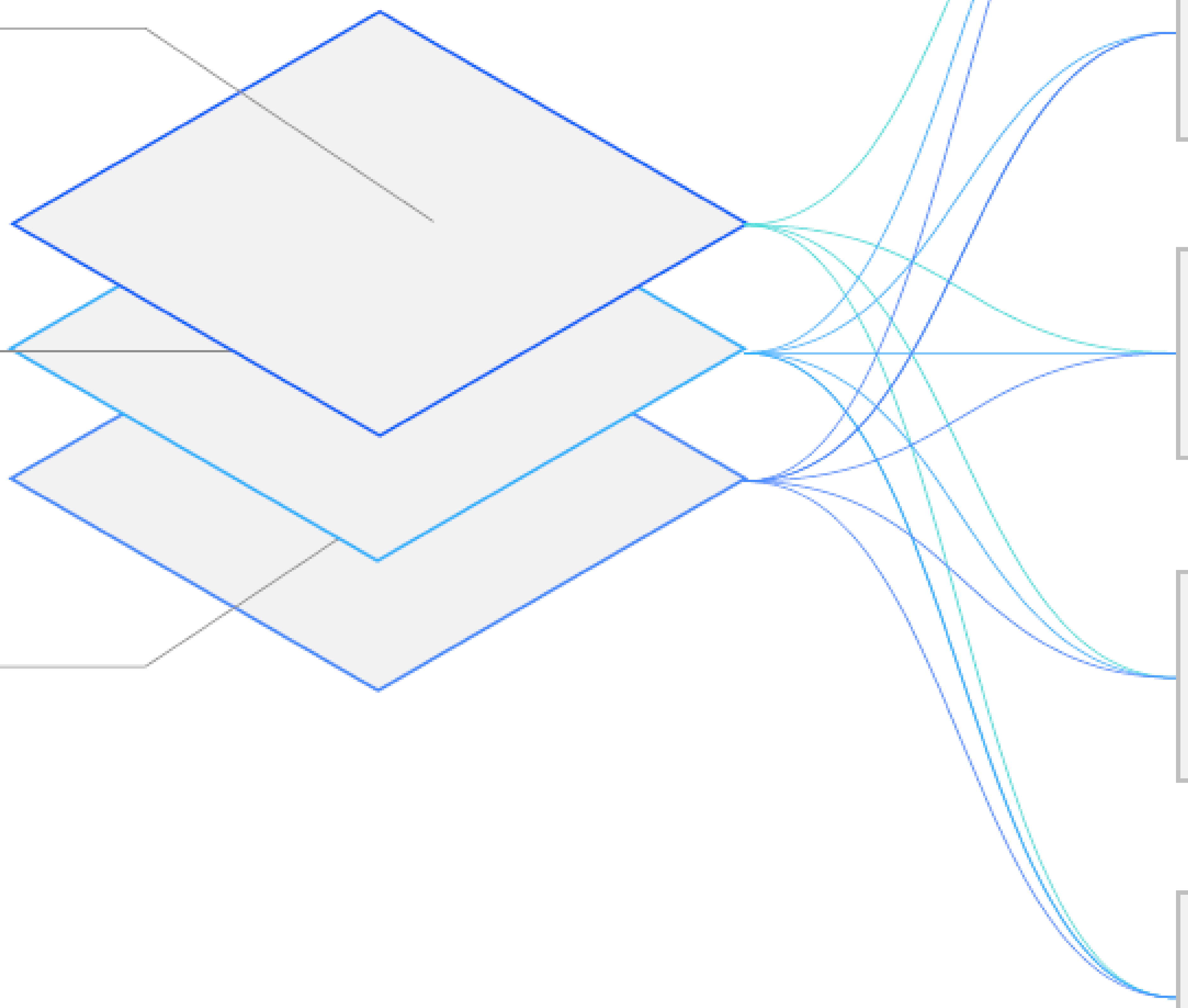


Quantum computing is expected to have an impact across industries

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

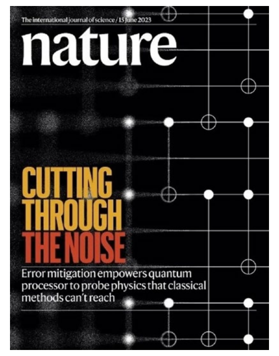
Health Care & Life Sciences
- Disease risk prediction
- Drug discovery and design
- Protein folding predictions
- And more

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

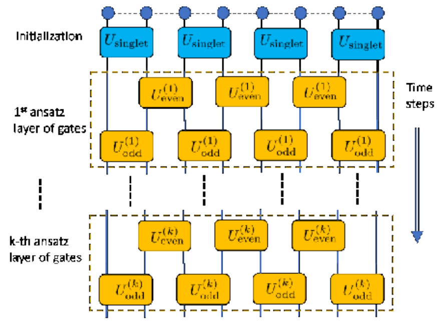
Nature, 618, 500 (2023)



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

102 qubits / 3186 CX gates

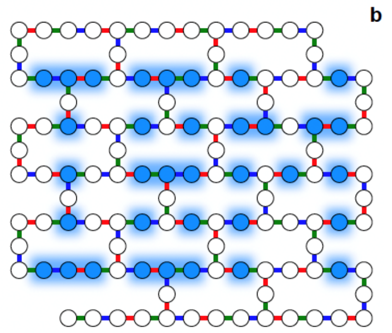
arXiv:2207.09994



Uncovering Local Integrability in Quantum Many-Body Dynamics

124 qubits / 2641 CX gates

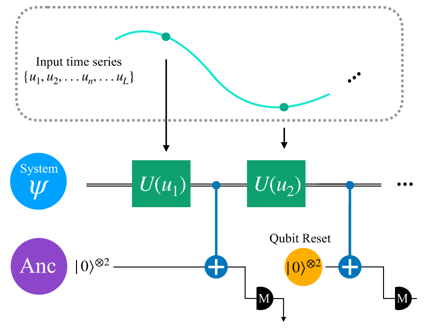
arXiv:2307.07552



Quantum reservoir computing with repeated measurements on superconducting devices

120 qubits / 49470 gates + meas.

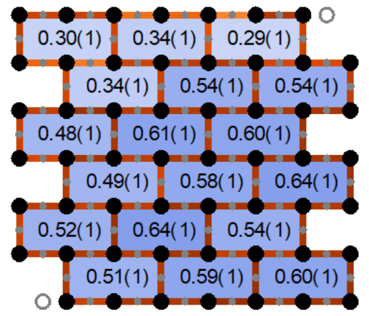
arXiv:2310.06706



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

125 qubits / 429 gates + meas.

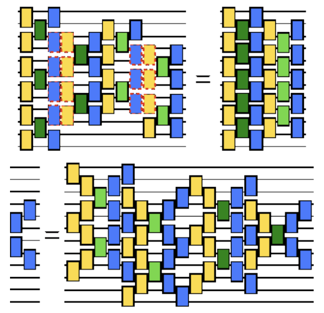
arXiv:2309.02863



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

100 qubits / 788 CX gates

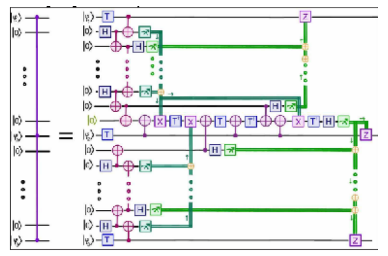
arXiv:2308.04481



Efficient Long-Range Entanglement using Dynamic Circuits

101 qubits / 504 gates + meas.

arXiv:2308.13065



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

Development Roadmap

IBM **Quantum**

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

- Quantum Physicist: IBM Quantum Experience ✓ (2016–2020)
- Early ✓: Canary 5 qubits; Albatross 16 qubits; Penguin 20 qubits; Prototype 53 qubits

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

- Falcon ✓: Benchmarking 27 qubits (2020–2021)

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

- Qiskit Runtime (2021 onward)
- QASM3 ✓

2022 ✓
Bring dynamic circuits to unlock more computations

- Dynamic circuits ✓
- Eagle ✓: Benchmarking 127 qubits (2022–2023)

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

- Middleware (2023 onward)
- Quantum Serverless ✓
- Execution Modes ✓

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

- Platform (2024 onward)
- Code assistant (on target)
- Transpiler Service (on target)
- Heron (5K) (on target): Error Mitigation; 5k gates; 133 qubits; Classical modular; 133x3 = 399 qubits

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

- Functions
- Resource Management
- Flamingo (5K): Error Mitigation; 5k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits

2026
Improving quantum circuit quality to allow 7.5K gates

- Mapping Collection
- Circuit Knitting x P
- Flamingo (7.5K): Error Mitigation; 7.5k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits

2027
Improving quantum circuit quality to allow 10K gates

- Specific Libraries (2027–2029)
- Intelligent Orchestration (2027–2029)
- Flamingo (10K): Error Mitigation; 10k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits

2028
Improving quantum circuit quality to allow 15K gates

- Flamingo (15K): Error Mitigation; 15k gates; 156 qubits; Quantum modular; 156x7 = 1092 qubits

2029
Improving 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 power of quantum computing

- General purpose QC libraries
- Circuit libraries
- Blue Jay (1B): Error correction; 1B gates; 2000 qubits; Error corrected modularity

Rows: Data Scientist · Researchers · Quantum Physicist

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 (on target): 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
- Heron ✓: Architecture based on tunable-couplers
- Flamingo (on target): Demonstrate scaling with modular connectors
- Crossbill (on target): m- coupler
- 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

✓ Executed by IBM

On target

Innovation Roadmap

IBM **Quantum**

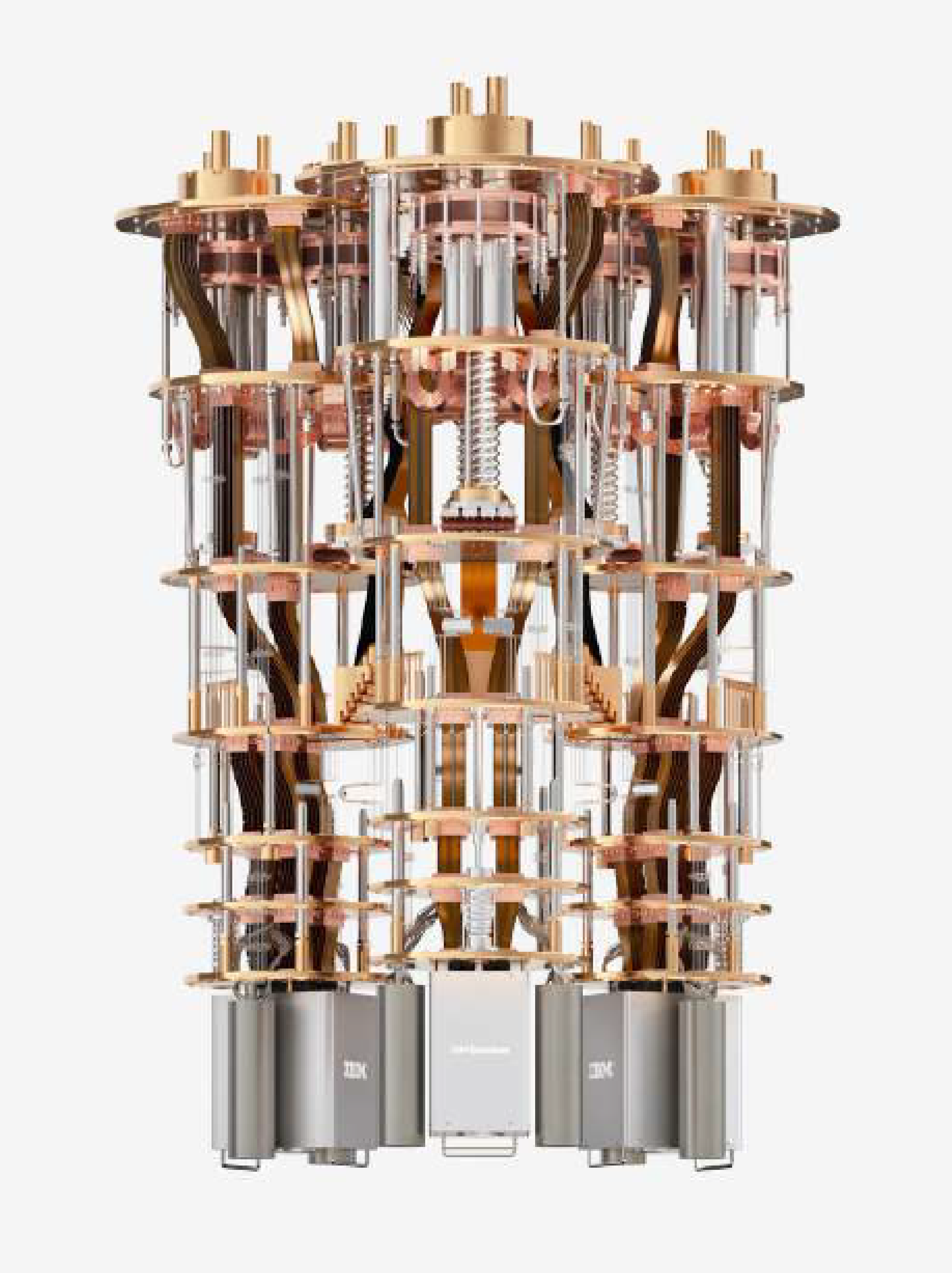
	2016–2019 ✓		2020 ✓	2021 ✓	2022 ✓	2023 ✓	2024	2025	2026	2027	2028	2029	2033+
Software Innovation	**IBM Quantum Experience** ✓	**Qiskit** ✓ Circuit and operator API with compilation to multiple targets	**Application modules** ✓ Modules for domain specific application and algorithm workflows	**Qiskit Runtime** ✓ Performance and abstract through Primitives	**Serverless** ✓ Demonstrate concepts of quantum centric-supercomputing	**AI enhanced quantum** ✓ Prototype demonstrations of AI enhanced circuit transpilation	**Resource management** (On target) 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** (On target) 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** (On target) m-coupler						

✓ Executed by IBM

On target

2029

Large-scale fault-tolerant systems



What do we mean by a large-scale fault-tolerant quantum computer?

Large-scale

Hundreds of qubits capable of running hundreds of millions of gates

Fault-tolerant

>100 million operations with broad resistance to failures

What's the difference between error correction and fault tolerance?

Quantum error correction refers to a family of techniques using quantum error-correcting codes where we encode quantum information into physical qubits so that the information can be detected or corrected by post-selection or with feedback using dynamic circuits. Some techniques are important tests but may not reach the desired scale on their own.

Fault tolerance is about computing capabilities. It applies quantum error-correcting codes so that computations scale efficiently, without incurring an exponential overhead.

Modern laptop

30 qubits

IBM Summit
Supercomputer

48 qubits

All classical computers
on earth connected

60 qubits

2029 IBM Quantum Starling

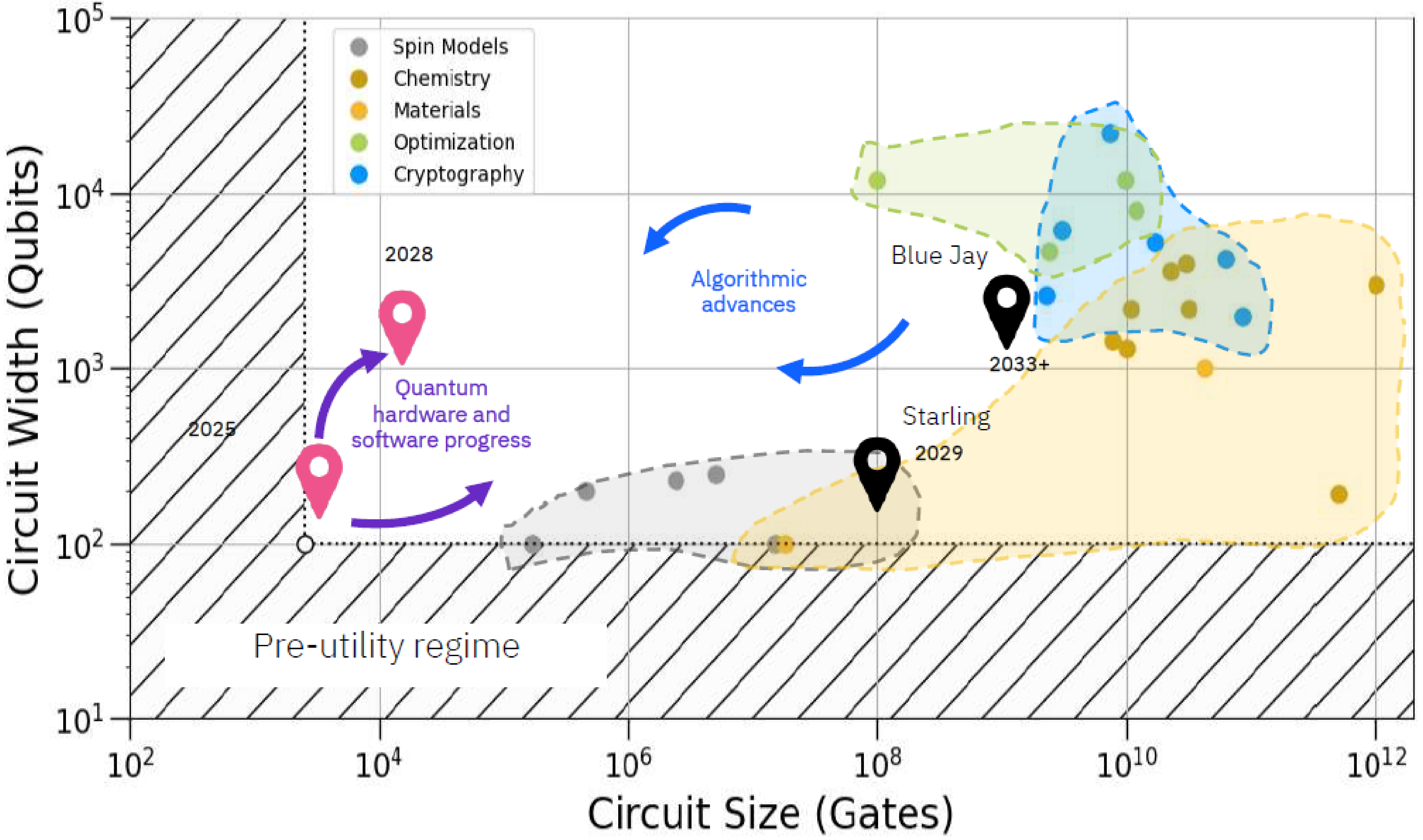
200 qubits

* Logical qubits

What can you do with a large-scale, fault-tolerant quantum computer?

Adoption of quantum computing systems enables new applications or use cases to be discovered, potentially with current or near-future systems.

Investments in algorithm research should enable known applications to be realized sooner.



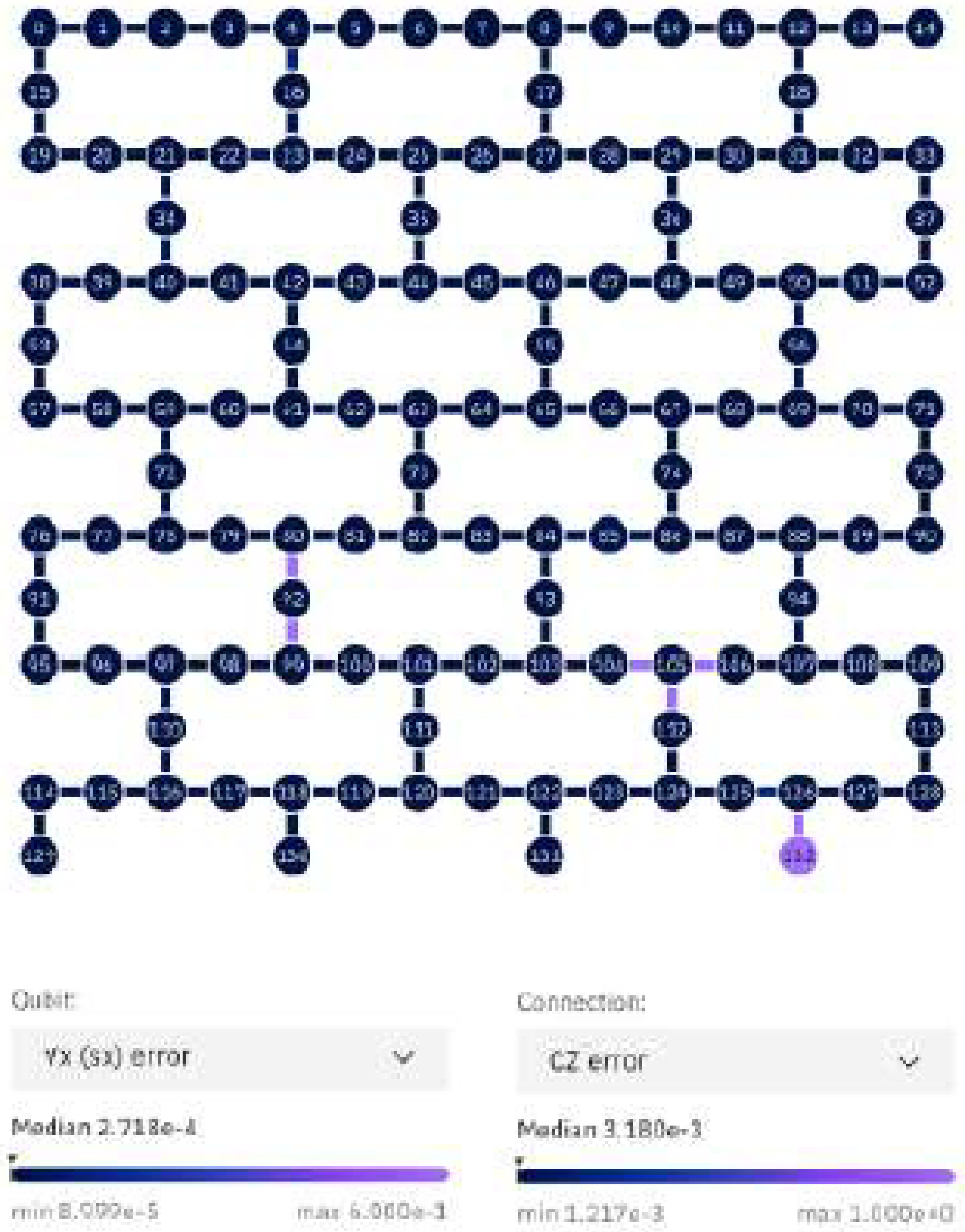
Heron

R1: 133-qubit systems
R2: 156-qubit systems

Tunable coupler architecture

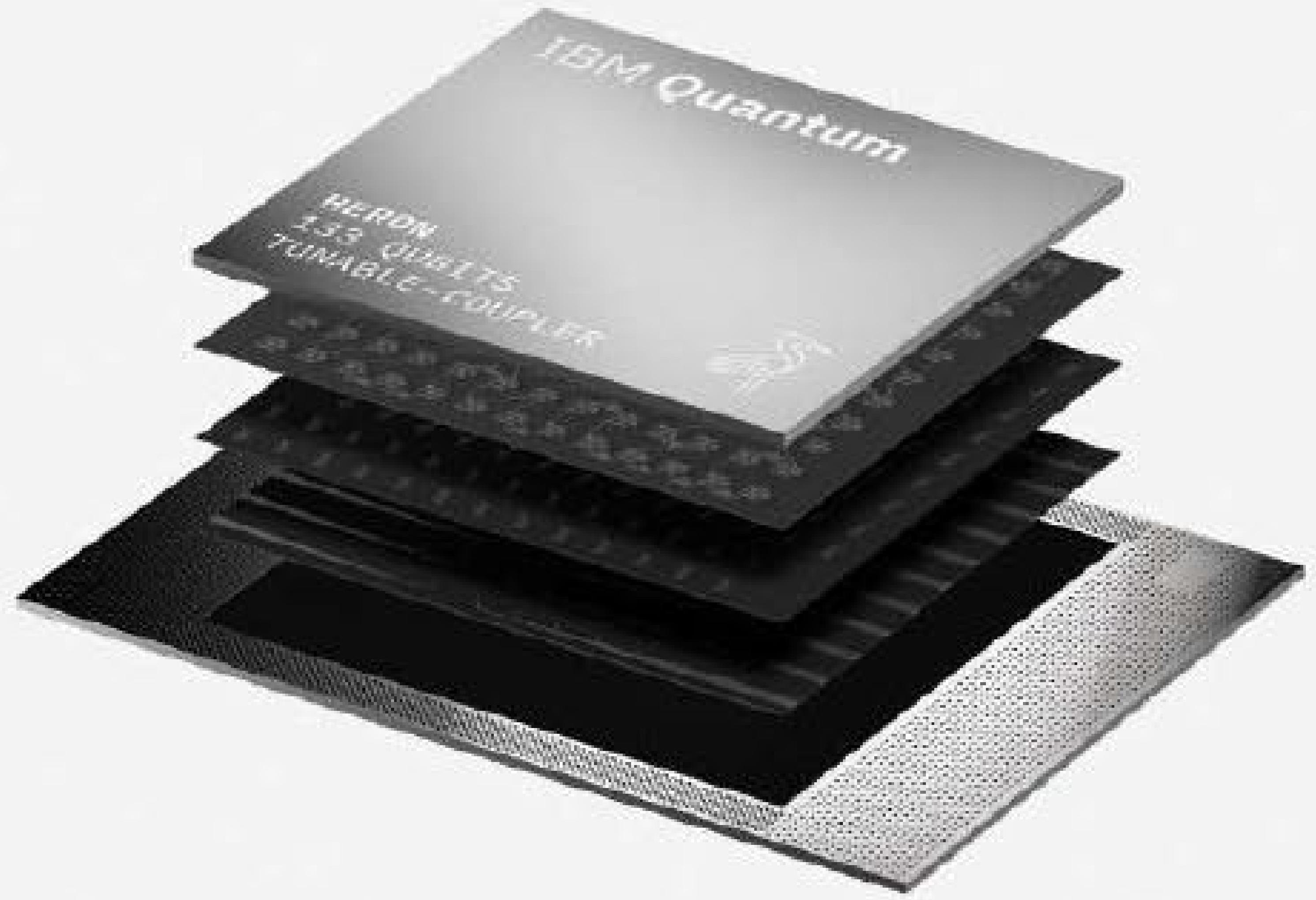
R2: Includes ability to tune away two-level system defects during calibration

IBM Monte Carlo



	IBM Sherbrooke Eagle	IBM Monte Carlo (Heron)
Gate error (best system)	0.6%–0.7%	0.3% – Best ~ 0.1%
Crosstalk	High (qubit-qubit collisions)	Almost zero!
Gate time	500–600ns	90–100ns

IBM Heron R3

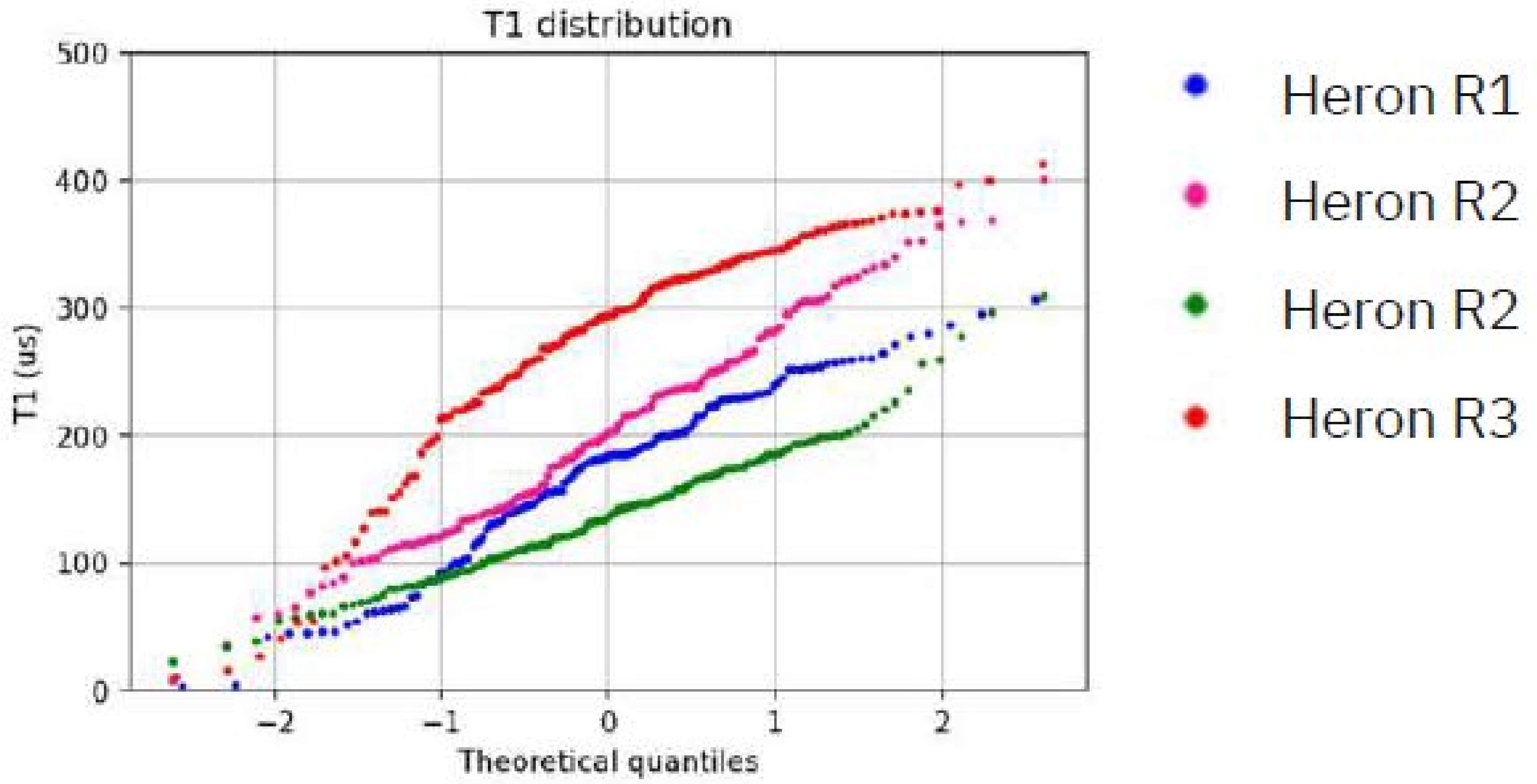


ibm_pittsburgh

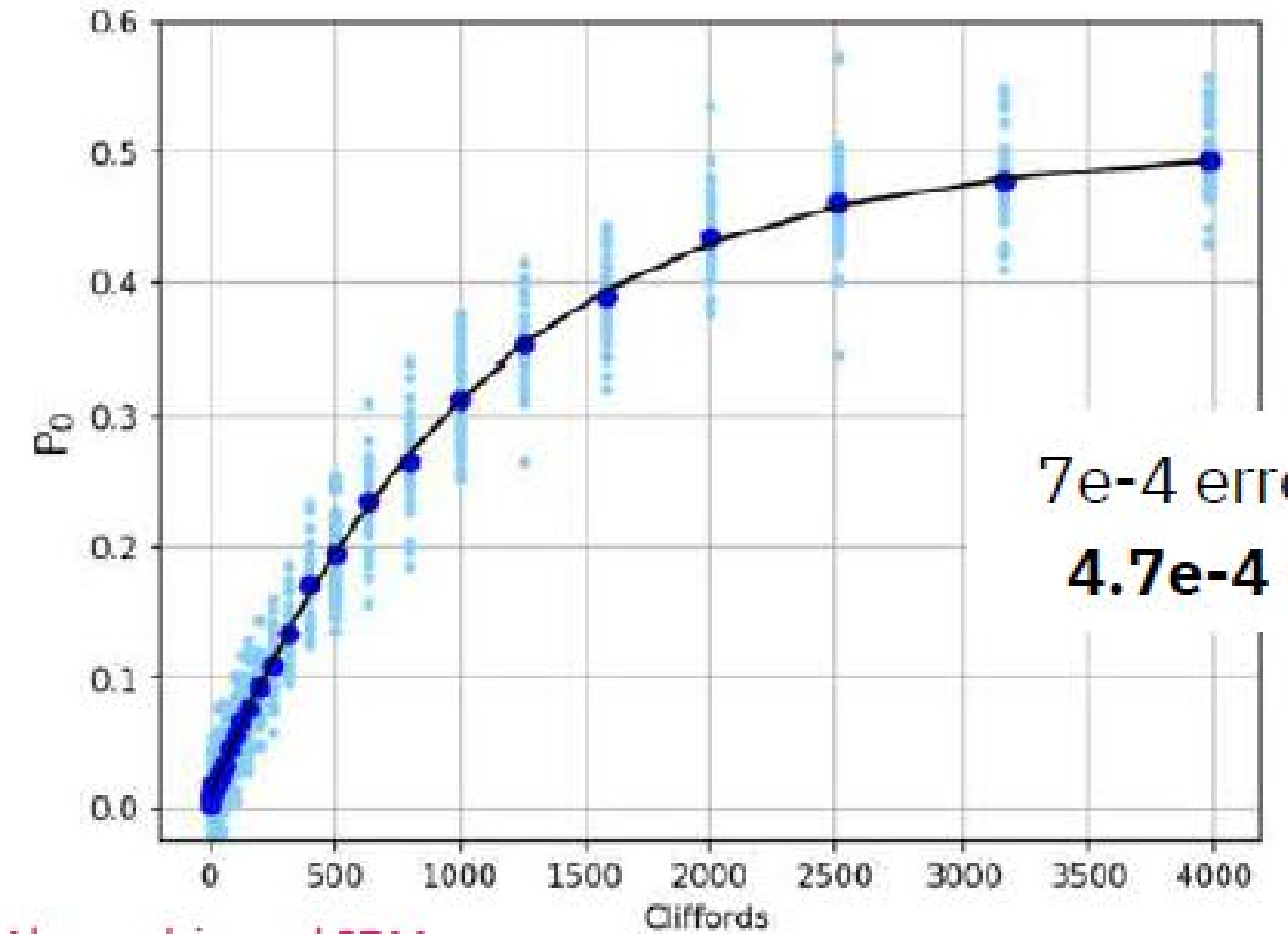
Details

Qubits	2Q error (best)	2Q error (layered)	CLOPS
156	5.19e-4	3.20e-3	N/A
Status: Online	Region: us-east	Heron r3	Version: 1.0.0
Total pending workloads: 0 jobs	Your instance usage: 0 jobs	Basis gates: CZ, ID, RZ, SX, X	Median CZ error: 1.727e-3
Median SX error: 1.515e-4	Median readout error: 3.550e-3	Median T1: 295.81 us	Median T2: 372.59 us

Median T1 now up to 300 microseconds



Some best gates now below 5e-4



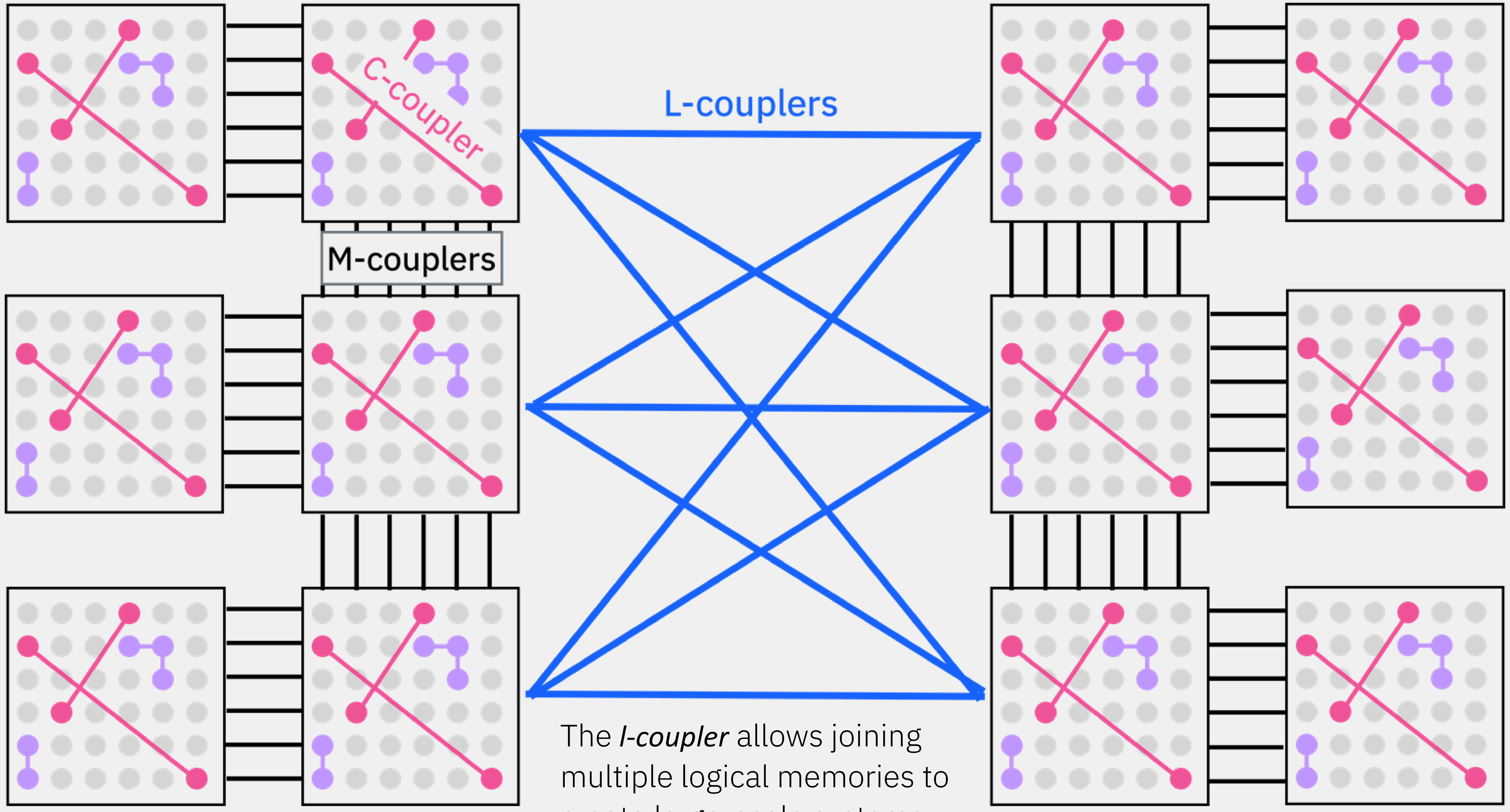
7e-4 error per Clifford

4.7e-4 error per CZ

New error correction codes and system modularity

Requires new coupler (*c-coupler*) to produce long-range degree-6 couplings.

Can be comprised of small building blocks coupled by *l*- and *m*-couplers to scale to logical communication and gates.

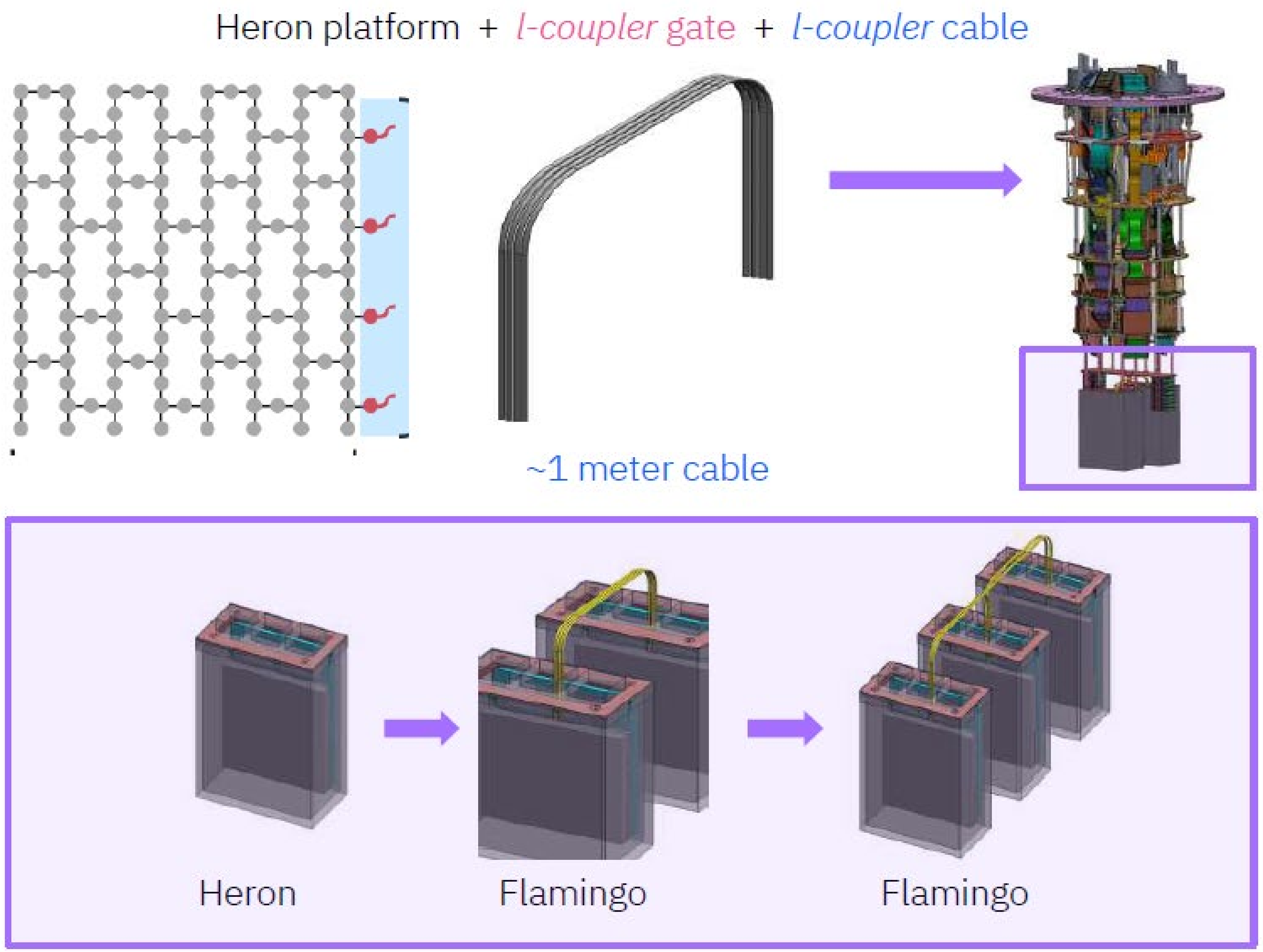


The *c-coupler* enables long-range on-chip connections for high-rate LDPC codes.

The *l-coupler* allows joining multiple logical memories to create large-scale systems.

Extending Heron platform through modular coupling

Flamingo



Flamingo
L-coupler innovation

2 × 156 qubits
4x l-coupler connections,
0.7 to 1 meter long

Pluggable (and re-pluggable)
l-coupler connections

Enables modular system design to
avoid I/O bottleneck

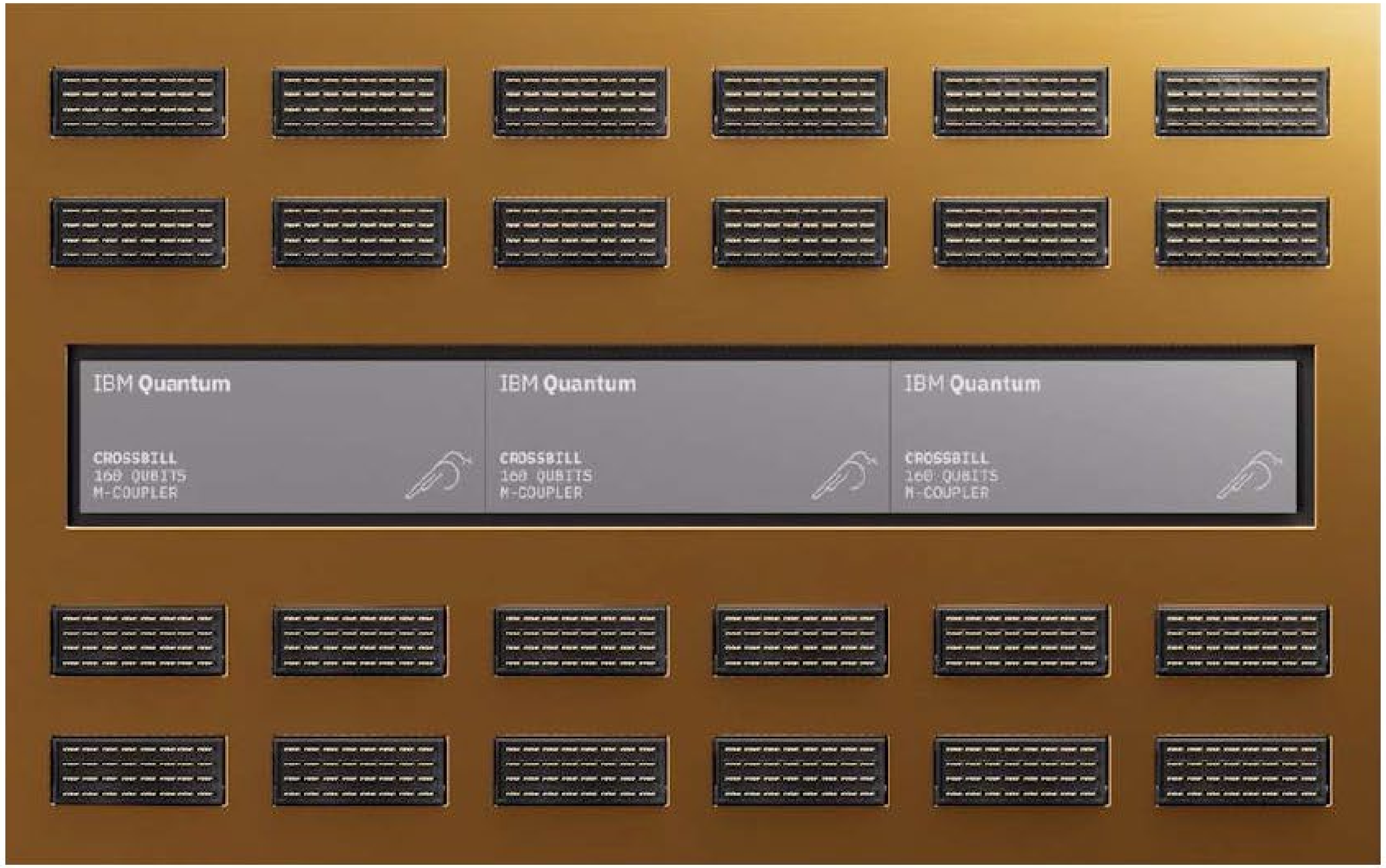
Crossbill
M-coupler innovation

3 × 160 (480) qubits
548 total couplers

√ m-coupler gates on test device

√ high-density scaled connectors

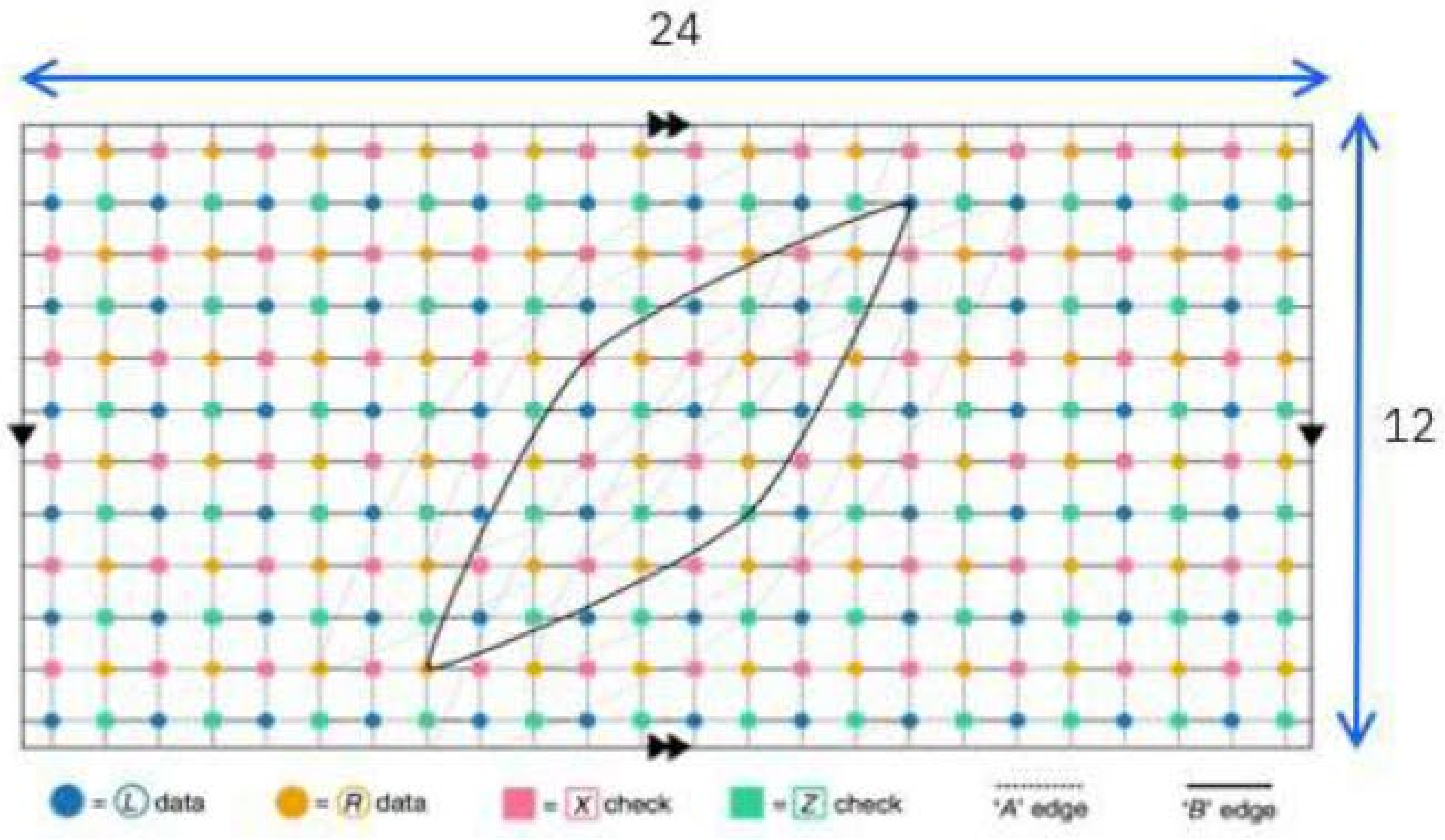
√ large scale silicon packaging



All prototype innovations demonstrated, final assembly and packaging in progress

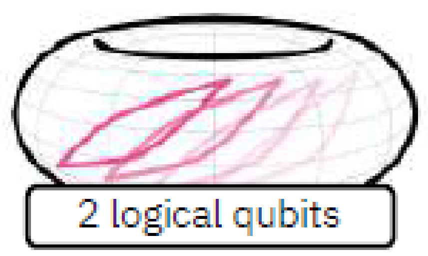
Scaling beyond the surface code

The gross code is 10x more efficient than the surface code



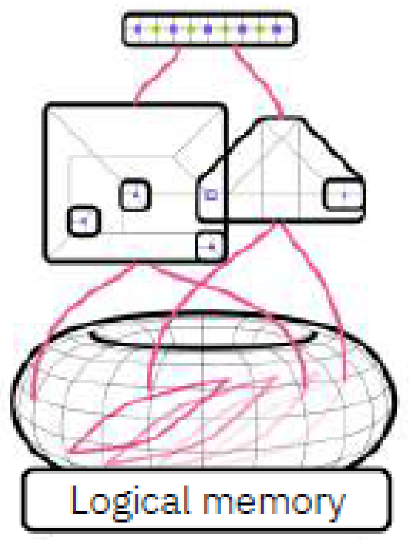
IBM fault-tolerant quantum computing roadmap

Loon (2025)



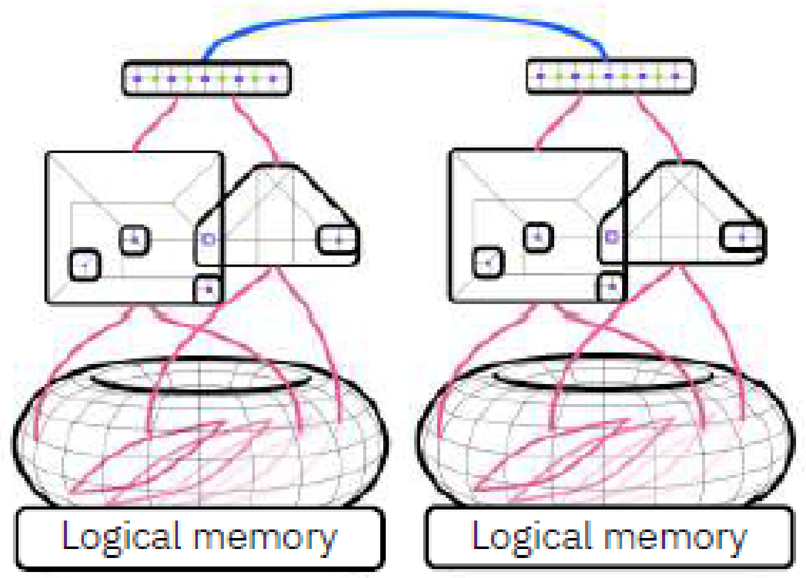
- 6-way connectivity
- c-coupler demo
- Automated design

Kookaburra (2026)



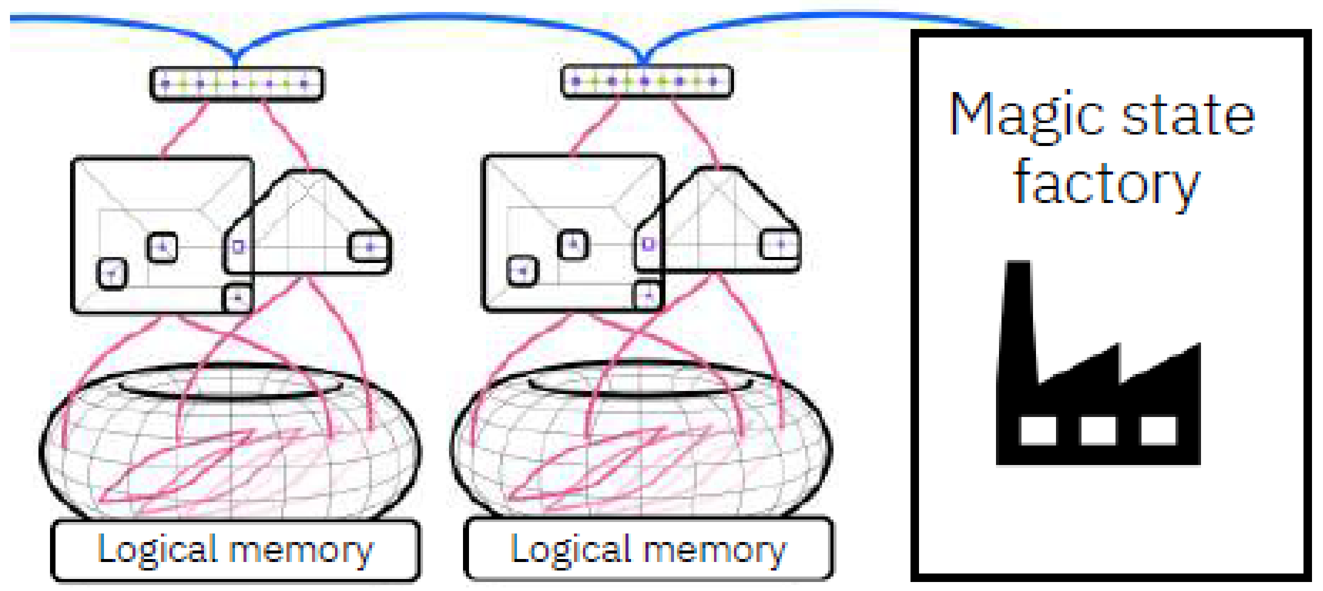
- "Long" c-couplers
- Real-time decoding
- LPU (+~100 qubits) for logical operations

Cockatoo (2027)



- Two blocks of gross code + LPU
- Module-to-module logical communication over l-couplers

Starling (2028)

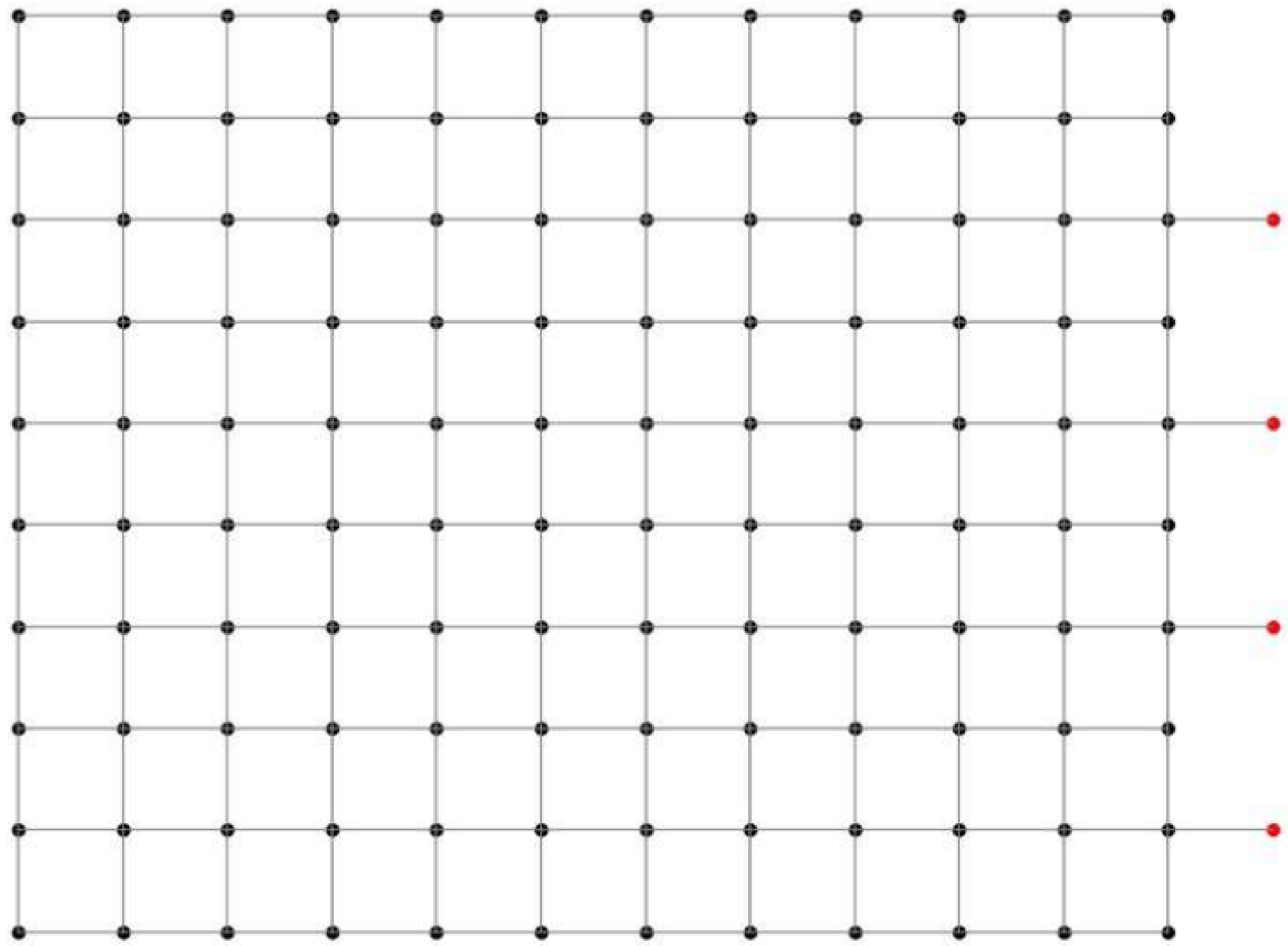


- Multiple blocks of gross code + LPUs
- Universal computation with magic state distillation

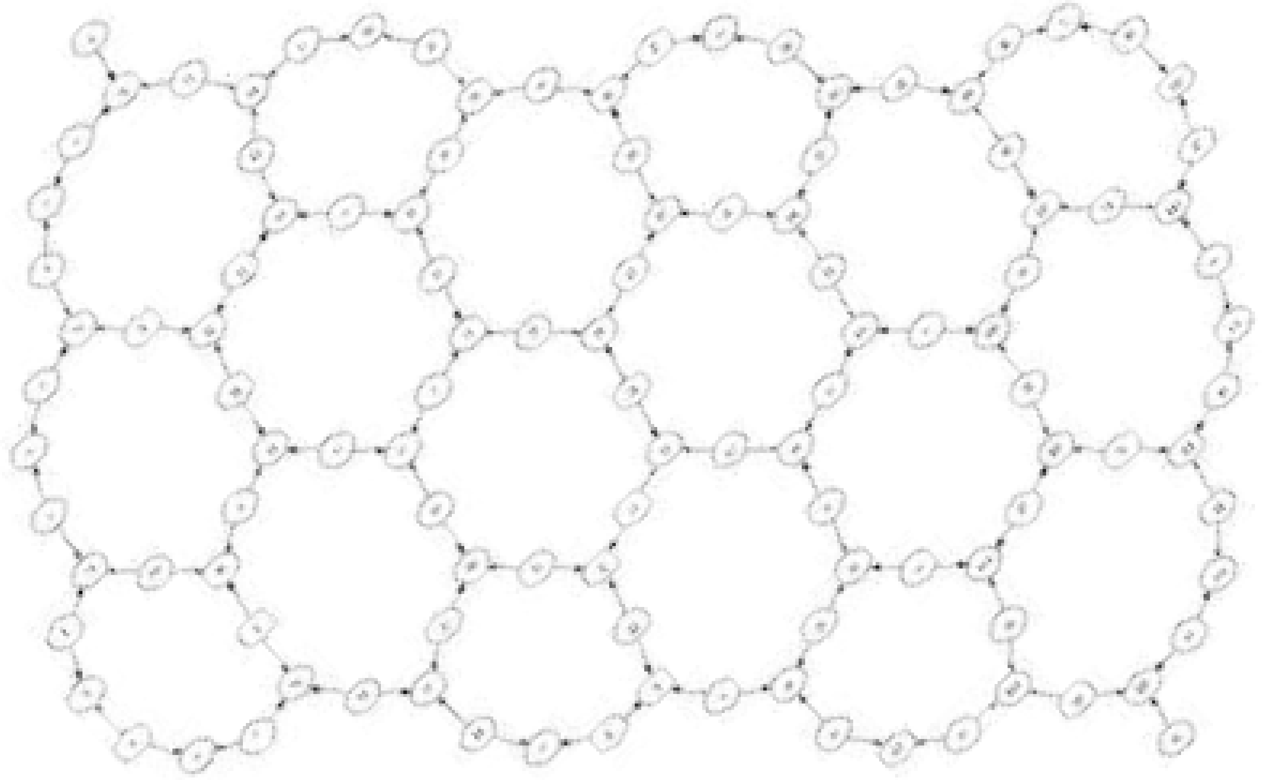
IBM Quantum Nighthawk
120 qubits

Tunable coupler architecture in a square lattice

4-degree connectivity to enable higher circuit complexity

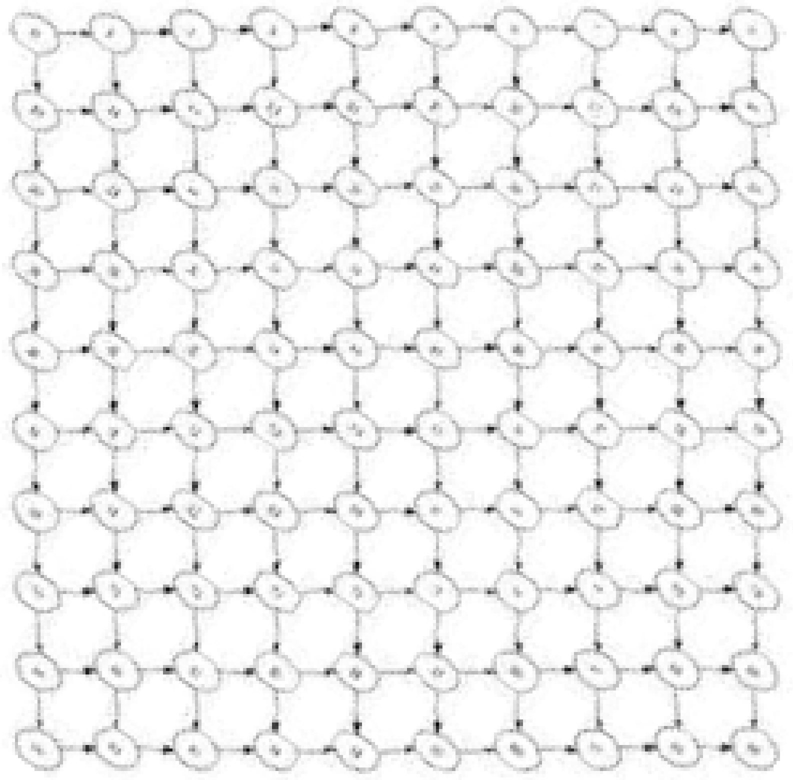


Heavy-hex vs. square connectivity



Avg. #nodes (bulk)

2.5 → 4



$$\frac{SQ_{Nodes}}{HH_{Nodes}} = 1.6$$

Chemistry

Depth | #CNOT	C-butadiene	Ethene	Benzene	C2	4Fe-4S
Square	18 | 68	27 | 102	55 | 380	78 | 804	480 | 5700
Heavy-hex	52 | 140	65 | 175	105 | 542	170 | 1360	930 | 9500

$$\frac{HH_{CNOT}}{SQ_{CNOT}} \approx 1.7$$

$$\frac{HH_{Depth}}{SQ_{Depth}} \approx 1.9$$

Other benchmarks

Reduction ratio	QV_{SWAP}	QV_{CZ}	QFT_{SWAP}	GHZ_{Depth}	2D $QSim_{Depth}$
SQ vs HH	2	1.35	1.45	1.5	3.5

IBM has the most performant quantum computers

	IBM	Others
Speed	250k $CLOPS_h$ 0.1–0.3 ms/shot	No average shot speed or $CLOPS_h$ reported
Scale	156 qubits	105 qubits Google (Willow)
Performance	~99.8% 2Q gate fidelity	~99.7% 2Q gate fidelity Google (Willow)
Reliability	99.2% job success rate (Excluding dedicated systems and ibm_aachen) 96.2% avg. availability	Not reported

Source: Data reported from press releases and published research. Current as of 6/5/25.

Superconducting vs Ions

Speed

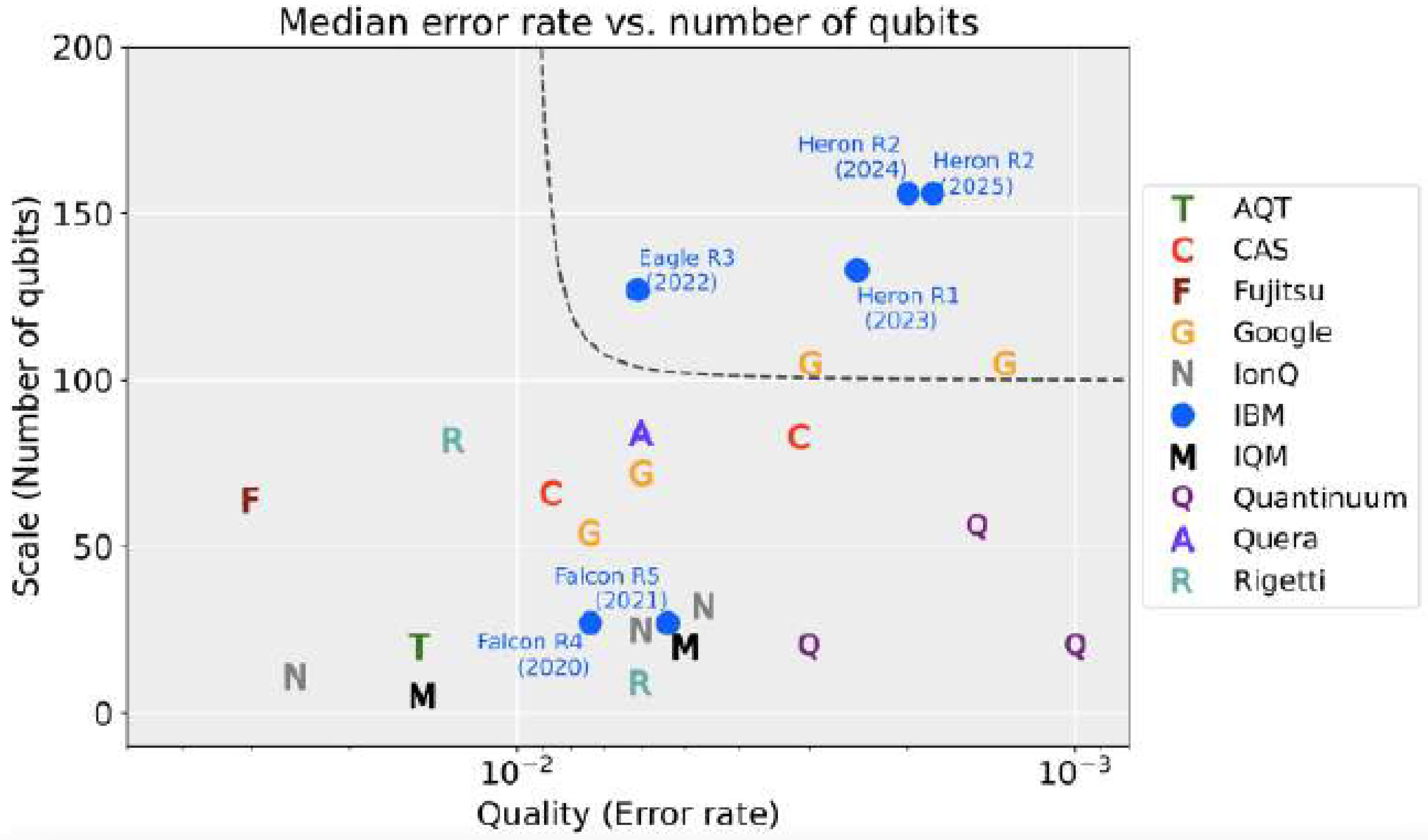
400x-2000x faster

@ 500 shots & 56 Qubits

Cost

1200x-70000x cheaper

@ 500 shots & 56 Qubits



Resources for learning about quantum computing:

About IBM Quantum:
https://www.ibm.com/quantum

About Qiskit:
www.ibm.com/quantum/qiskit

Courses about quantum computing:
https://quantum.cloud.ibm.com/learning/en

IBM

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IBM