Quantum Computing Trends

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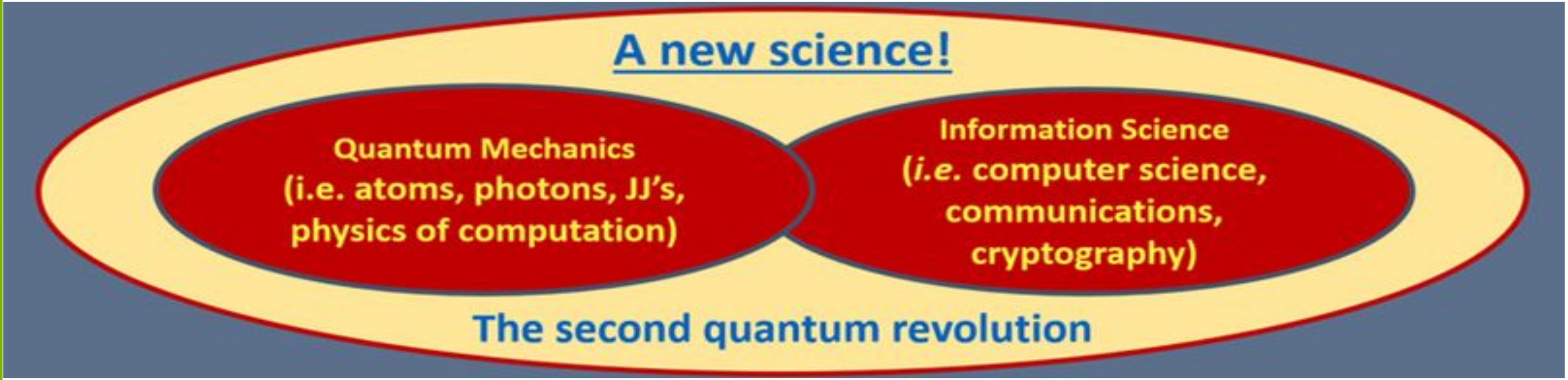
Quantum Information Science (QIS)

- Quantum mechanics explains how world works at microscopic level, which governs behavior of all physical systems, regardless of their size
- Information science revolutionized how information is collected, stored, computed, analyzed, manipulated, protected, and moved
- We see convergence of two 20th century greatest revolutions in the form of Quantum Information Science (QIS)



Quantum Information Science

QIS exploits unique quantum effects such as superposition, interference, and entanglement to obtain, compute, and transmit information in the ways that are superior compared to classical technology (digital, Newtonian)

The key concept is entanglement (“spooky action at a distance”, EPR pair). Works only for only very small object (electrons, photons, atoms etc). It is proven to be essential to achieve “quantum advantage” or for “quantum teleportation”

Classical	
Outcome	Probability
00	1/4
01	1/4
10	1/4
11	1/4

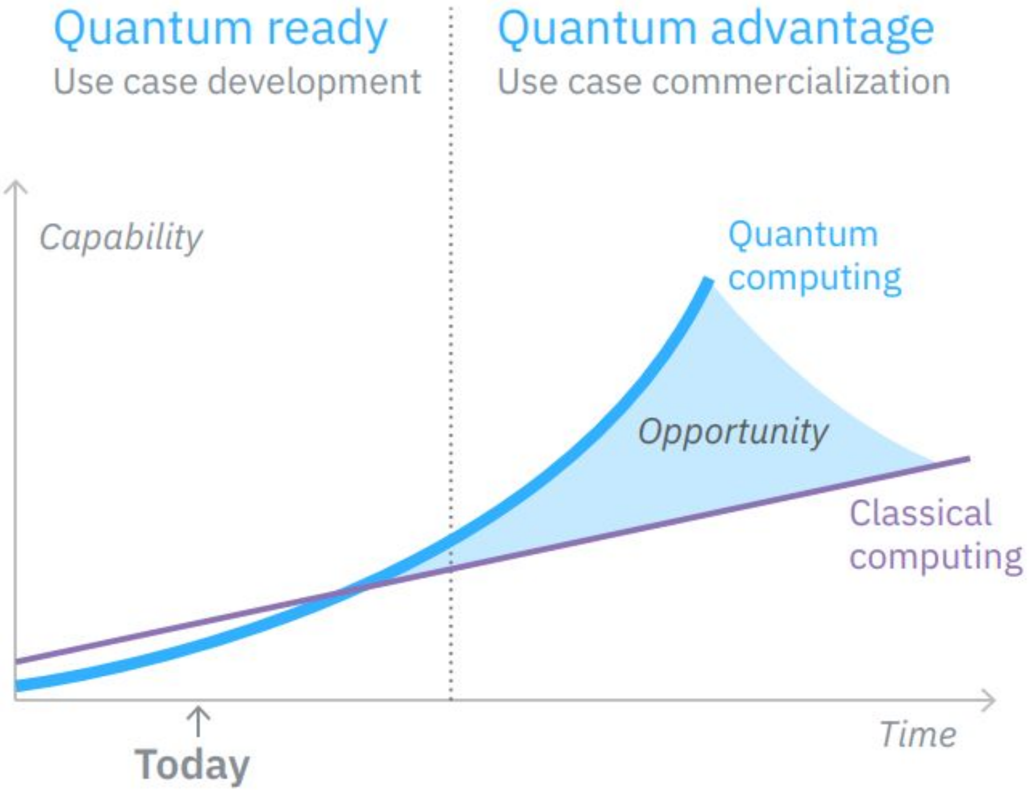
Quantum	
Outcome	Probability
00	1/2
01	0
10	0
11	1/2

Key concepts

- Qubit - basic unit of quantum information, which is the quantum version of the classical binary bit. It can exist in superposition – any state between 0 and 1
- Qubit fidelity – how long qubit stays coherent/operational
- Quantum effects - superposition, interference, and entanglement
- NISQ - Noisy Intermediate-Scale Quantum technology, often refers in the context of modern very noisy quantum computers
- QASM - Quantum Assembly used for programming quantum computers
- Quantum supremacy - demonstration of that a programmable quantum device can solve a problem (any problem) that no classical computer can solve in any feasible amount of time
- Quantum advantage - same as supremacy, but for useful applications

Why quantum computing?

Commercialization of a quantum use case



Why quantum computing?

Quantum computing's potential for significant speedup over classical computers

Type of scaling	Time to solve problem				
Classical algorithm with exponential runtime	10 secs	2 mins	330 years	3300 years	Age of the universe
Quantum algorithm with polynomial runtime	1 min	2 mins	10 mins	11 mins	~24 mins

Quantum Simulator Use Cases: Simulation of Supremacy Circuits

Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article

799k Accesses | **693** Citations | **6025** Altmetric | Metrics

(CNN Business): Google claims it has designed a machine that needs only 200 seconds to solve a problem that would take the world's fastest supercomputer 10,000 years to figure out.

Customers Early Applications

Optimization

Multi-period portfolios

Internet ad placement

Satellite Placement

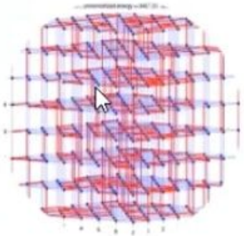
Machine Learning

Image recognition

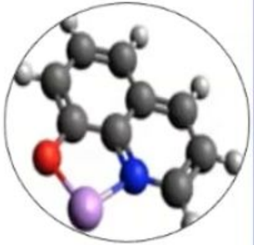
Tree cover classifier

Higgs Boson Detection

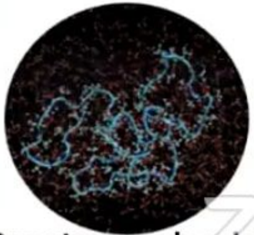
Quantum Materials



Quantum solid state



Quantum Molecules



Quantum molecular dynamics

Quantum Computing for Finance

Stochastic Modeling:
Derivative Pricing: Options. Collateralized Debt Obligations
Risk Modeling: Value at Risk, Economic Capital Requirement, Credit Value Adjustments

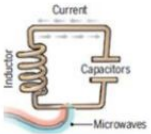
Combinatorial Optimization:
Portfolio Optimization: Combinatorial Formulations, Convex Formulations
Swap Netting, Optimal Arbitrage, Identifying Creditworthiness, Financial Crashes

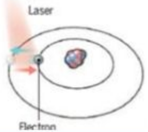
Machine Learning:
Anomaly Detection, Asset Pricing, Implied Volatility

Herman, D., Googin, C., Liu, X., Galda, A., Safro, I., Sun, Y., Pistoia, M. and Alexeev, Y., 2022. A survey of quantum computing for finance. arXiv preprint arXiv:2201.02773.

Modern Quantum Computers

Operate at almost absolute zero temperature -460 F or -273 C, colder than deep space

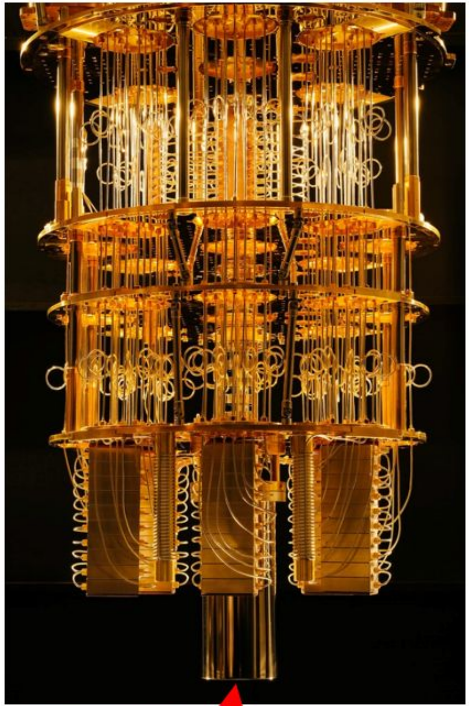


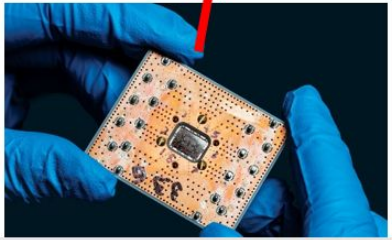


Computers are ranked by number of qubits decoherency time

		Superconducting (IBM, Google, Rigetti)	**Trapped ions (IonQ, U. of Innsbruck)**
Qubit Modality	Materials	Al on the Silicon substrate	Yb+, Ca+, Sr+, Be+, Ba+, Mg+
	Type	Transmon	Optical transitions
	Control	Microwaves	Microwaves + optics
	State	Junction phase	Atomic state of election
Approximate Decoherency Times (ns)		~100-200	Very long
	1qb gate	10	5,000
	2qb gate	40	50,000
Fidelity	1qb gate	99.9%	99.999%
	2qb gate	99.0%	99.5%
Speed (MHz)	1qb gate	100.00	0.20
	2qb gate	25.00	0.02

IBM quantum computers



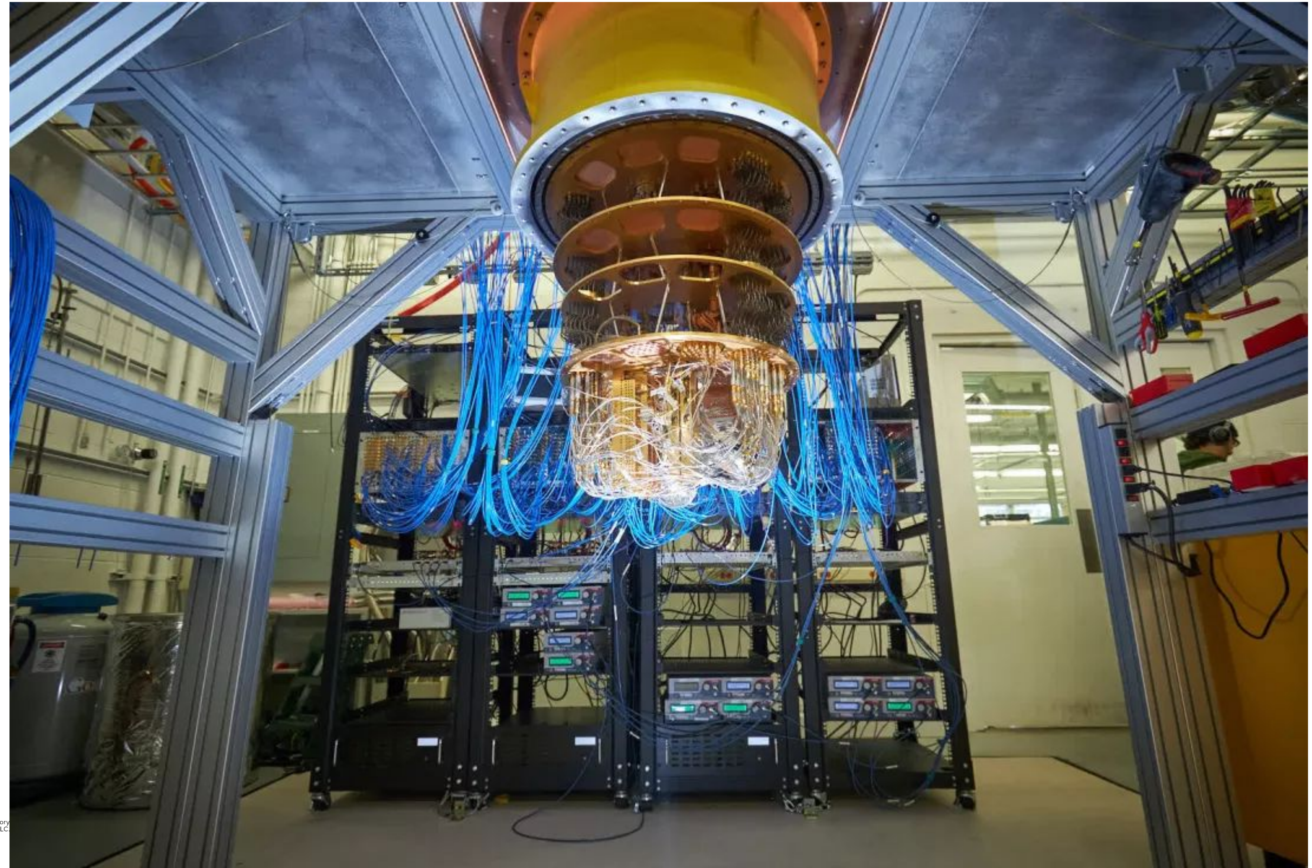


The key piece of the Quantum Computer is the Dilution Refrigerator
Working Temperature 15 mK uses mix of $^{3}He/^{4}He$

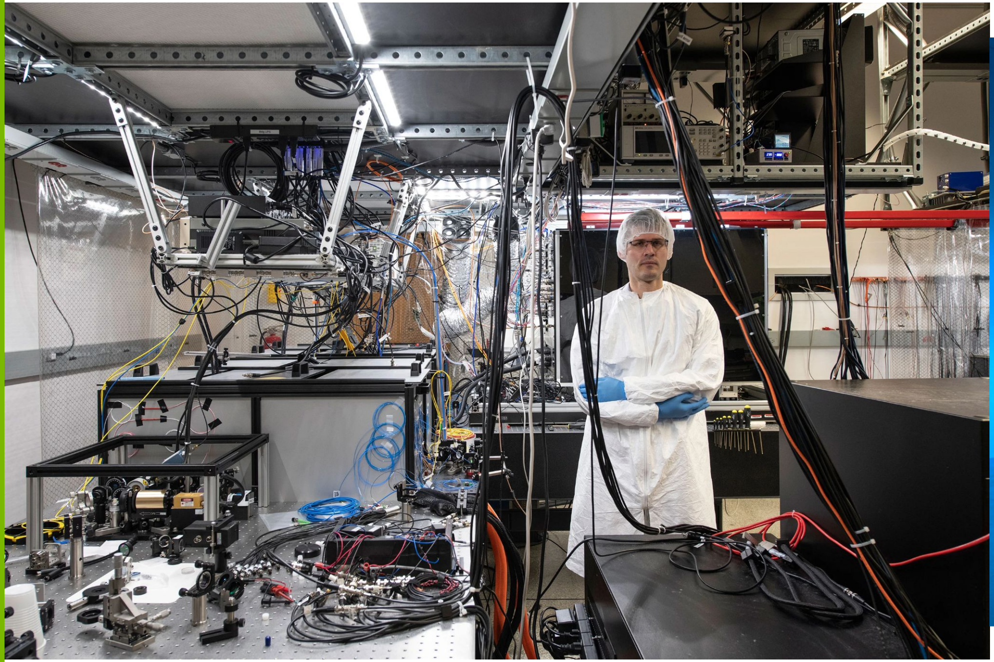
Source: IBM Research

DWave quantum computer

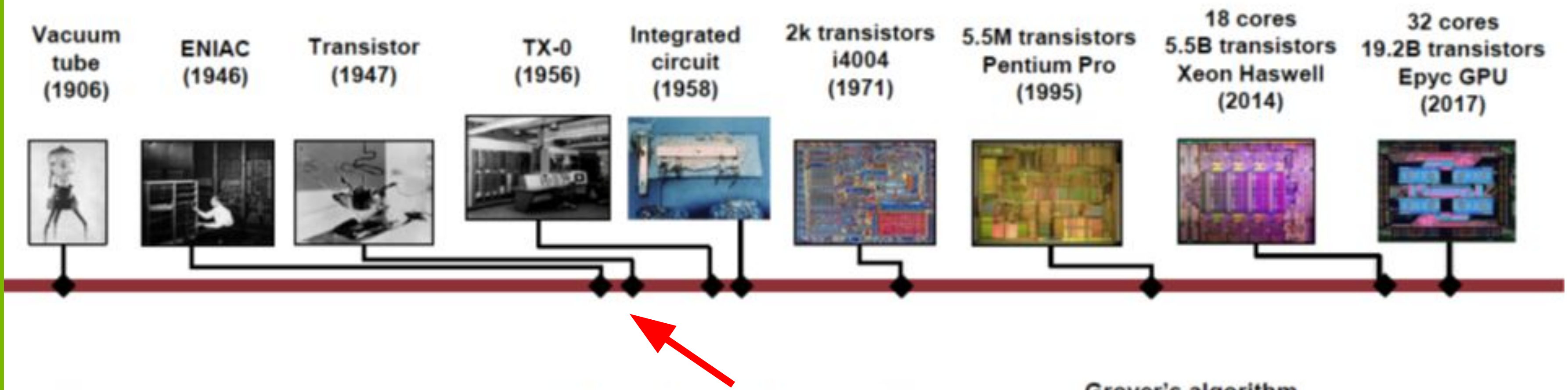
Google's Sycamore quantum computer



Ion trap quantum computer



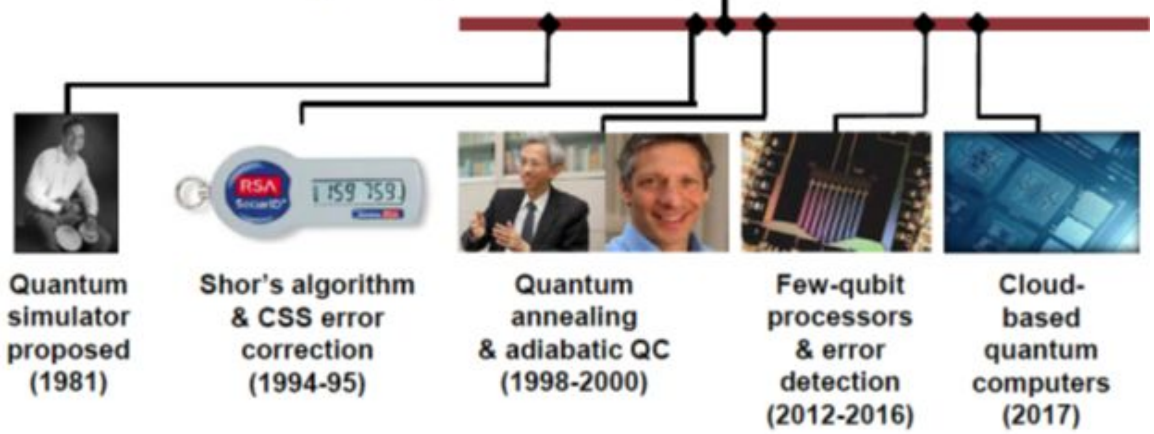
Classical Computing (Electronic)



Quantum computing is transitioning from scientific curiosity to technical reality.

Advancing from discovery to prototype to useful machines takes time.

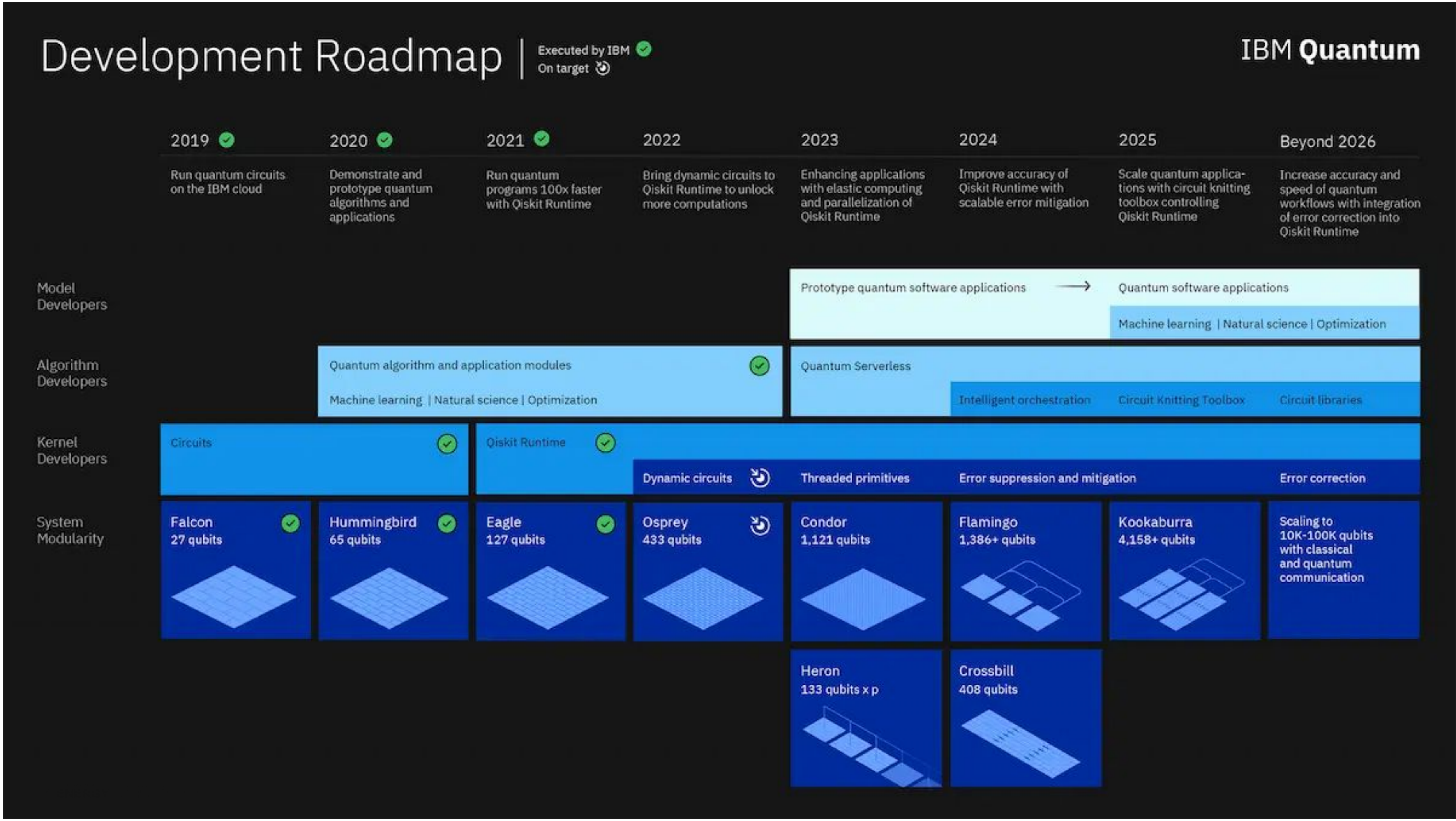
Quantum Computing



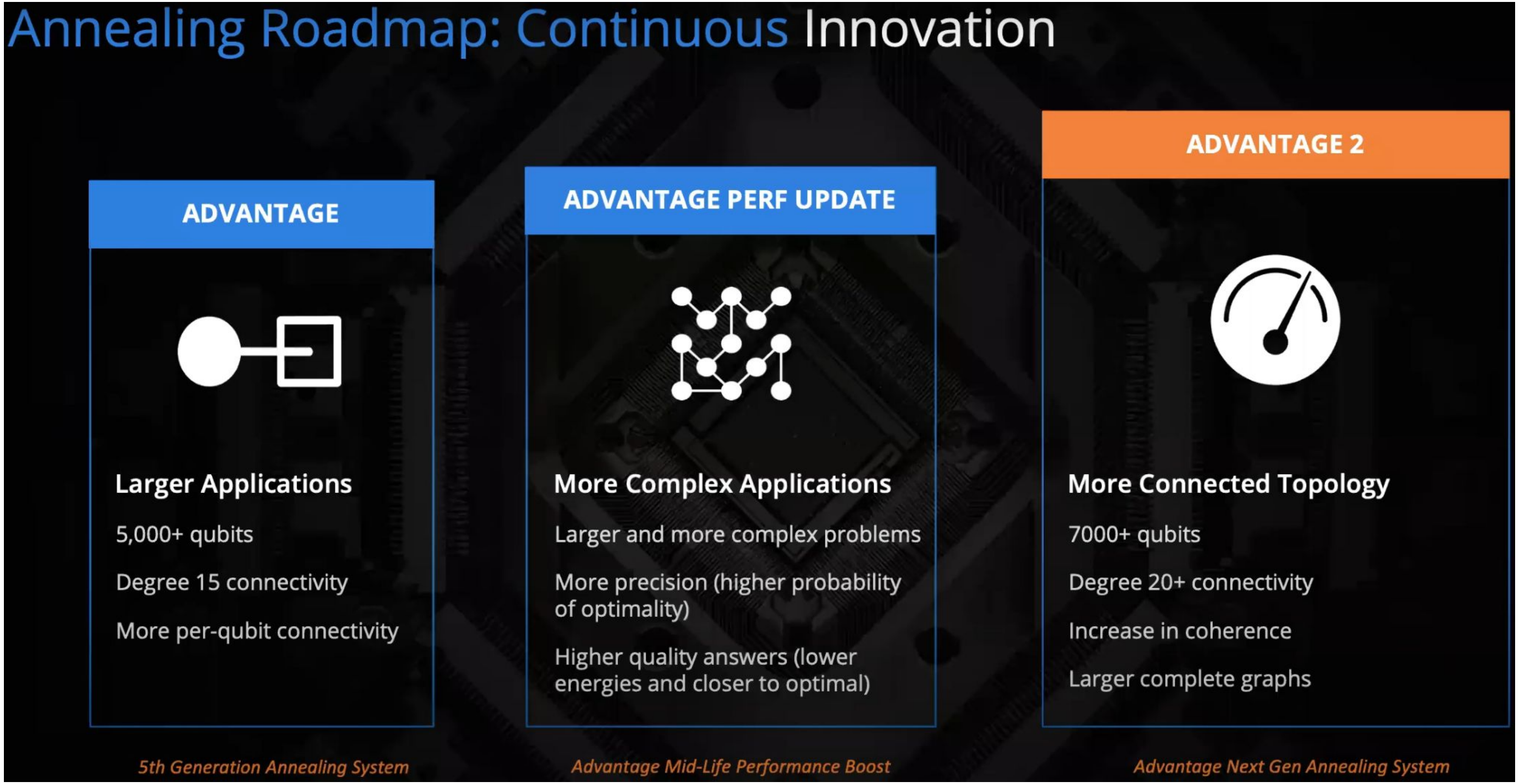
Available and announced quantum computers

Company*	Operational	Cloud Access	Framework	Announced
IBM	72 qubits	Open to Q hub members	Qiskit	120+ qubit in 2021
Rigetti	31 (8) qubits	Access by request	AWS and Forest	50+ qubit near future
Google	72 qubits	No access	Cirq	120+ qubit in 2021
Alibaba	11 qubits	-	Alyun	-
IonQ	32 qubits	Paid Access	AWS and Azure	-
Honeywell	10 qubits (512 volume)	Paid Access	Azure	-
D-Wave	5000Q (annealer)	Open (1 minute per month)	AWS and Leap	10,000Q near future

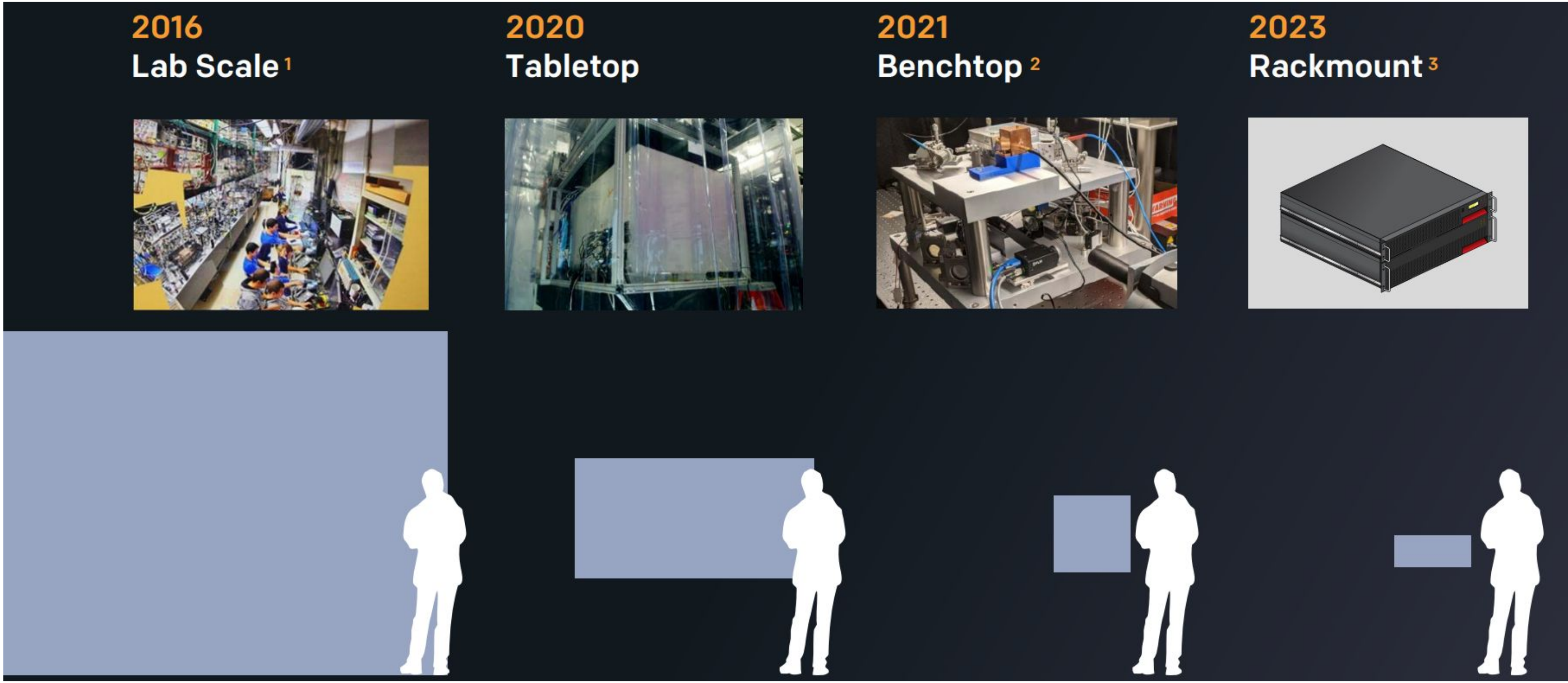
**Intel not included – announced 49 qubit chip in January 2018*


Development Roadmap
Executed by IBM
On target
IBM Quantum
2019
2020
2021
2022
2023
2024
2025
Beyond 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
Model Developers
Prototype quantum software applications
Quantum software applications
Machine learning | Natural science | Optimization
Algorithm Developers
Quantum algorithm and application modules
Machine learning | Natural science | Optimization
Quantum Serverless
Intelligent orchestration
Circuit Knitting Toolbox
Circuit libraries
Kernel Developers
Circuits
Qiskit Runtime
Dynamic circuits
Threaded primitives
Error suppression and mitigation
Error correction
System Modularity
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

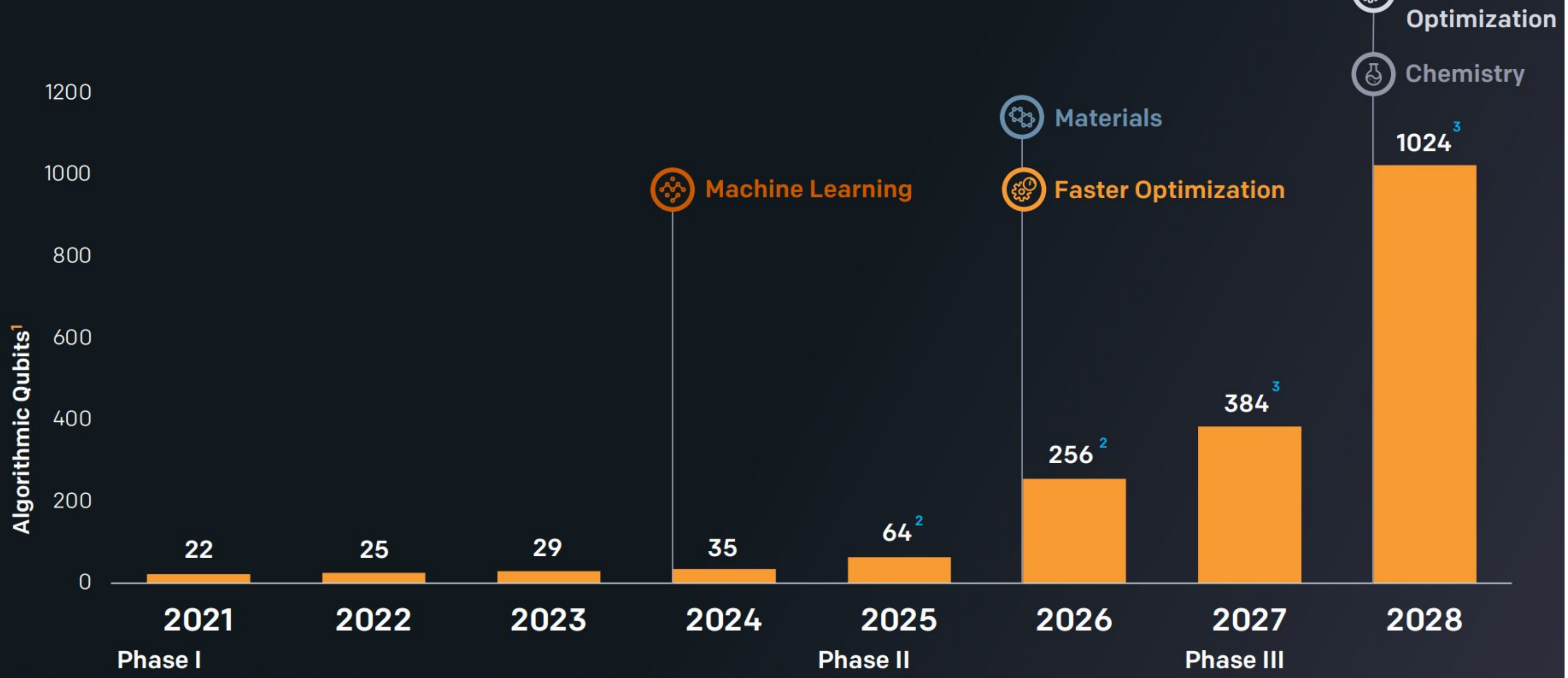
DWave


Annealing Roadmap: Continuous Innovation
ADVANTAGE
Larger Applications
5,000+ qubits
Degree 15 connectivity
More per-qubit connectivity
5th Generation Annealing System
ADVANTAGE PERF UPDATE
More Complex Applications
Larger and more complex problems
More precision (higher probability of optimality)
Higher quality answers (lower energies and closer to optimal)
Advantage Mid-Life Performance Boost
ADVANTAGE 2
More Connected Topology
7000+ qubits
Degree 20+ connectivity
Increase in coherence
Larger complete graphs
Advantage Next Gen Annealing System

IonQ Quantum Computers



Roadmap For Growth & Market Leadership



Note Prepared on the basis of certain technical, market, competitive and other assumptions to be subsequently described in further detail, and which may not be satisfied. As a result, these projections are subject to a high degree of uncertainty and may not be achieved within the time-frames described or at all.

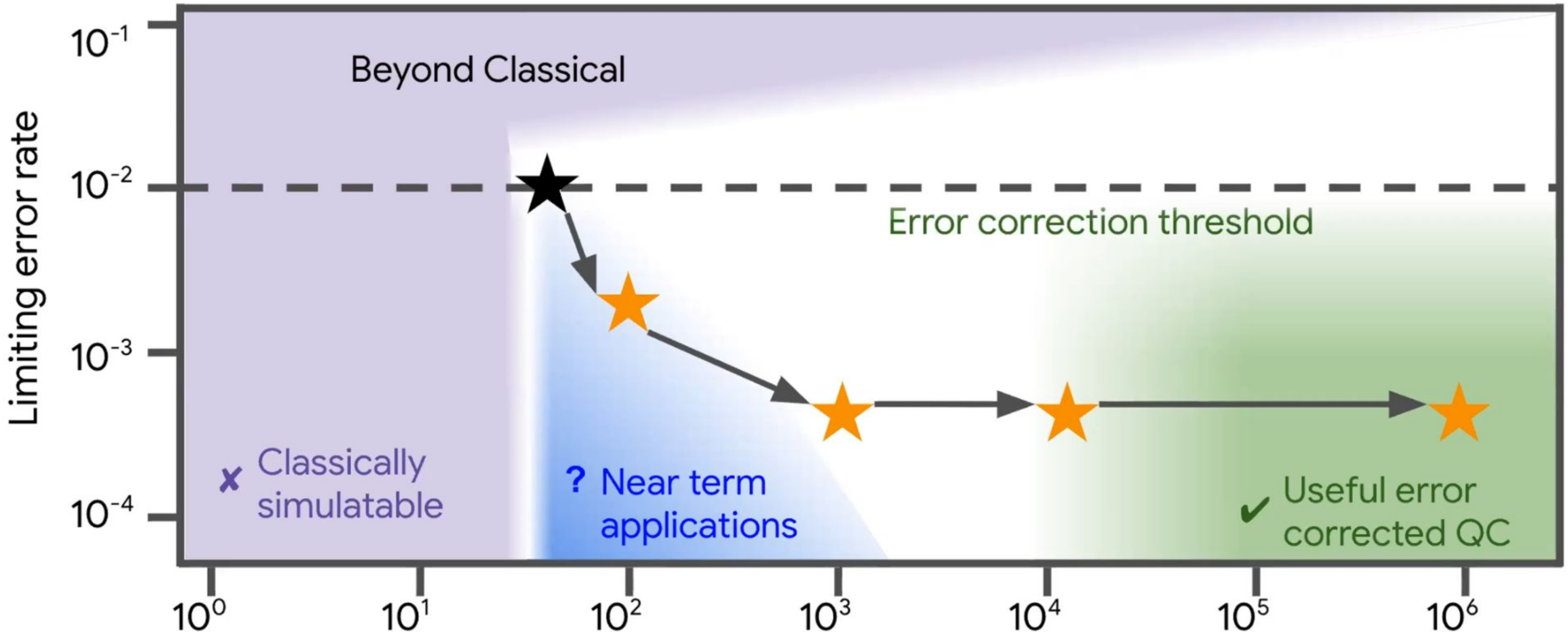
Note Market inflection points are estimated based on alignment of IonQ technical roadmap with publicly documented quantum research problems in each market

1 Algorithmic qubit number defined as the effective number of qubits for typical algorithms, limited by the 2Q fidelity

2 Employs 16:1 error-correction encoding

3 Employs 32:1 error-correction encoding

Google's path to an error corrected machine

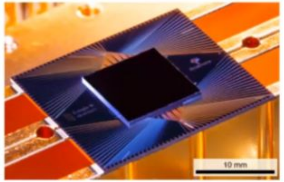


- Can quantum outperform classical on any computation task?
- Can we demonstrate a path toward achieving low *enough* error rates for practical tasks?
- Can we achieve such a low error rate?
- Can we build a large *enough* system with low error rate?

Beyond-classical milestone: Random sampling

Anthony Megrant

2019					2029	Year
54	10^2	10^3	10^4	10^5	10^6	Physical qubits
Beyond classical	Logical qubit prototype	1 Logical qubit	Tileable module (Logical gate)	Engineering scale up	Error-corrected quantum computer	

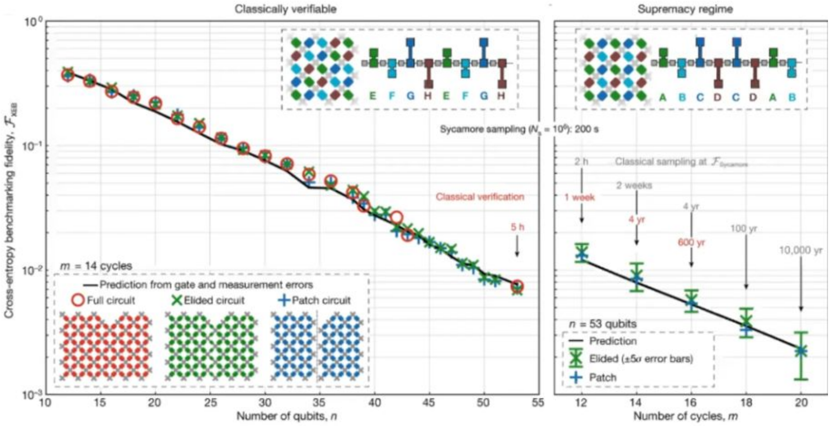


Processor:
Gen-I Sycamore

Pauli and measurement errors

Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%

Component performance:
High-fidelity gate: iSwap-like (“Syc”)
High-fidelity readout: Single, terminal



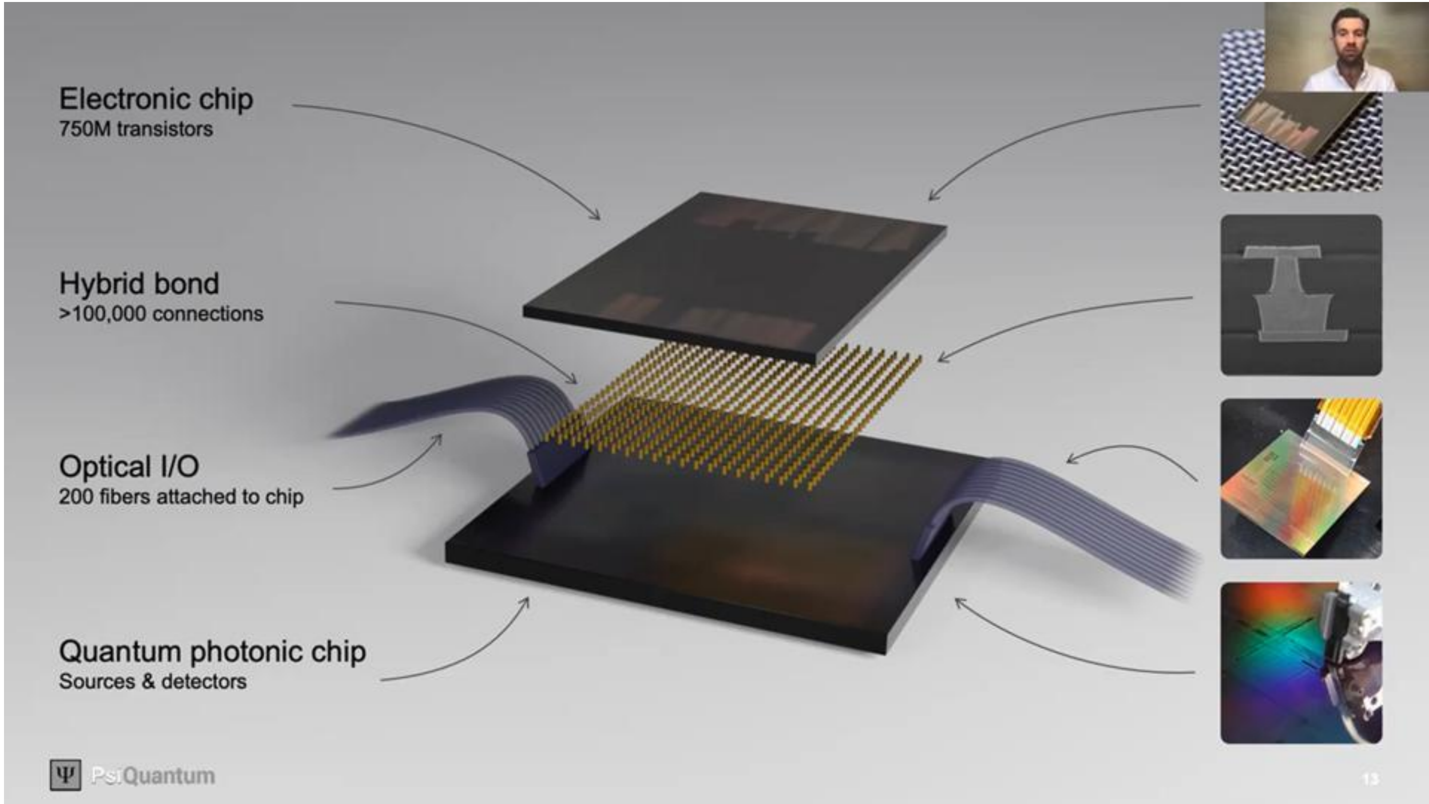
Computation task:
Beyond-classical sampling with random circuits

Quantum AI

PsiQuantum

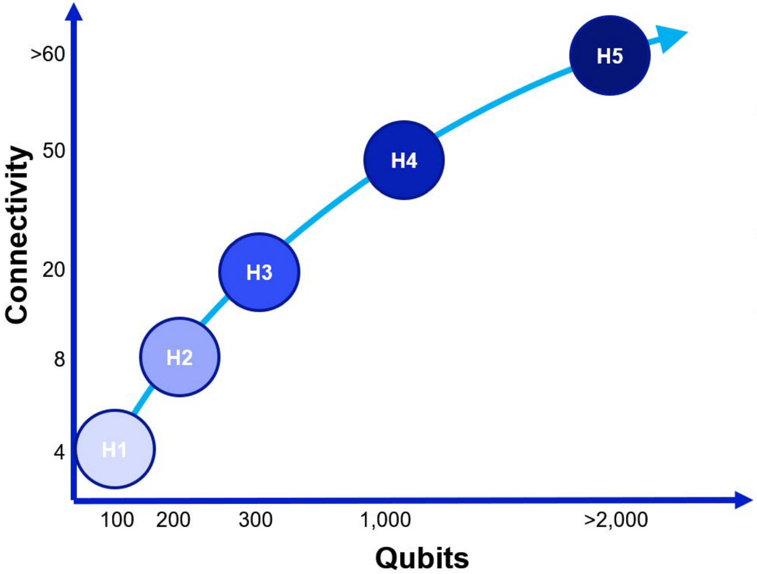
Goal build: 1 million qubit device in 5 years

Activities: manufacturing 300-millimeter wafers containing a 25 layer stack, single-photon detectors, and high-performance optical switches



ColdQuanta

Hilbert Commercial Roadmap



- Scaling to unexplored parts of the NISQ-era quantum parameter space
- Hardware + algorithms + use cases
- Active work with near-term customer use cases

ColdQuanta

Chinese quantum computers

1. Zuchongzi - 56 superconducting qubit quantum computer. It was used for sampling from a random distribution. They found Zuchongzi completed such a sampling task in 1.2 hours, one they estimated would take Summit at least 8.2 years to finish.

   https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.127.180501

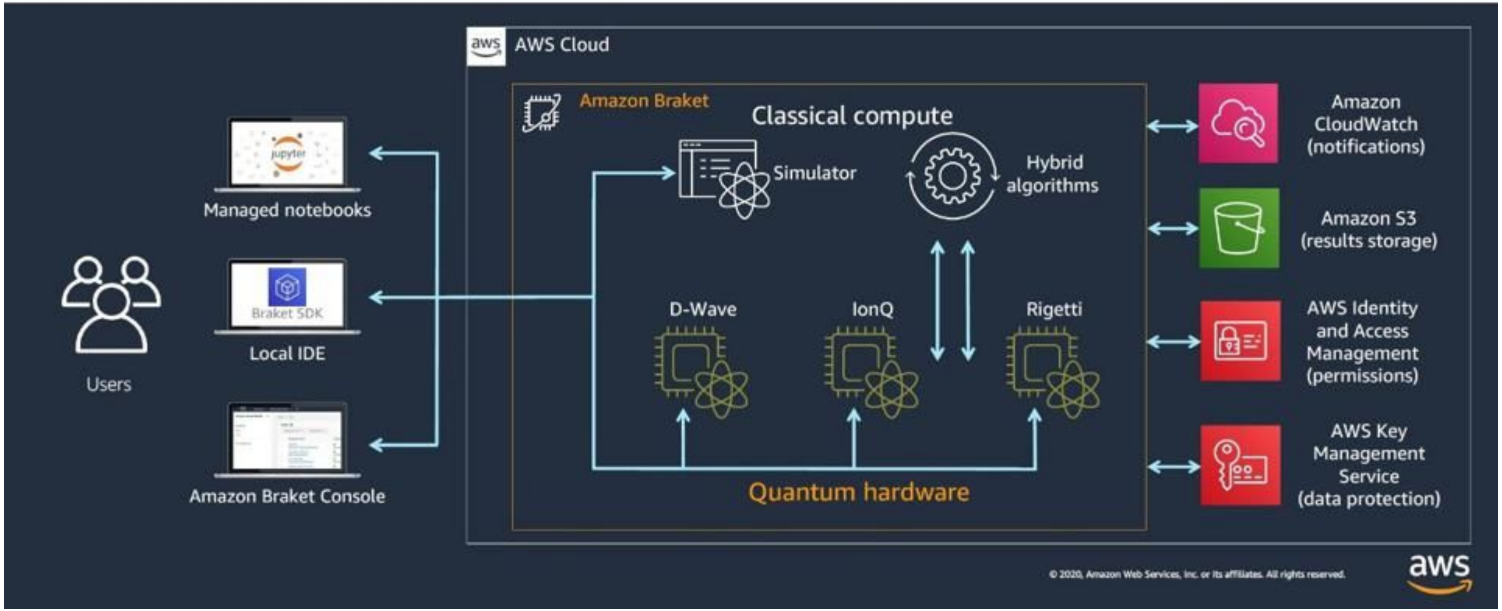
2. Jiuzhang 2.0 - a photonic quantum computer. It is used for Gaussian boson sampling, a task where the machine analyzes random patches of data. Using 113 detected photons, they estimated Jiuzhang 2.0 could solve the problem roughly 10^24 faster than classical supercomputers.
   https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.127.180502

Microsoft


Azure Quantum
The full-stack, cloud ecosystem to enable quantum impact today.
Application Areas
Optimization
Machine Learning
Quantum Simulation
Software Tools & Services
Q# QDK
Development Tools
Microsoft 1QBit
Quantum Solutions
Simulators
Resource Estimators
Classical Hardware
Microsoft Azure
Be future ready
Build on your terms
Operate hybrid seamlessly
Trust your cloud
Quantum Hardware
Microsoft
Topological (Future)
IONQ
Honeywell
Ion Traps
qci
Superconducting

Amazon

Amazon Braket



QCUP

Oak Ridge Leadership Computing Facility (OLCF) Quantum Computing User Program (QCUP)

https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/

Quantum Project Application:

https://www.olcf.ornl.gov/for-users/documents-forms/quantum-project-proposal/

Quantum Account Application:

https://www.olcf.ornl.gov/for-users/documents-forms/quantum-account-application/

Available quantum systems: IBM, Rigetti, Honeywell

Current Public and Private Funding Situation

China: $15 billion

European Union: $7.2 billion

U.K. $1.2 billion

Russia: $790 million

India and Japan $1 billion each

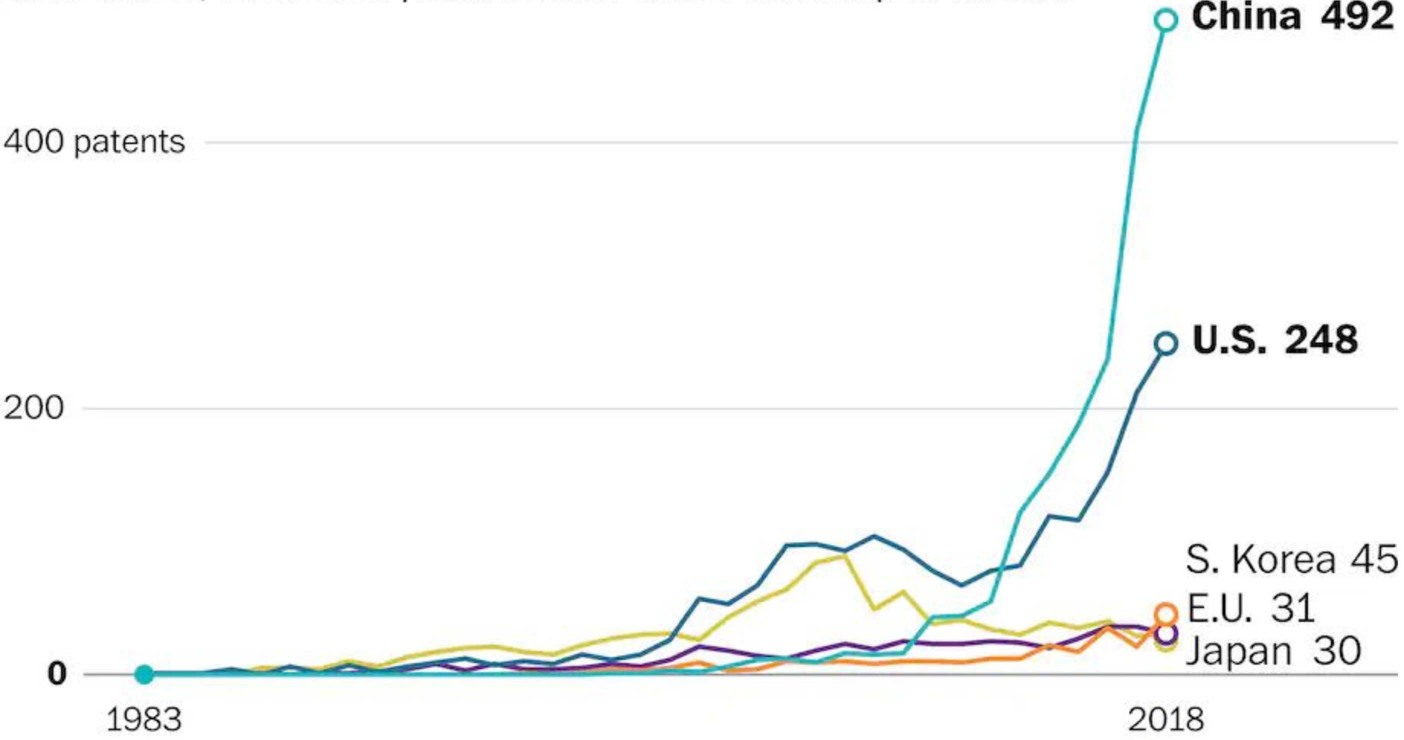
U.S. $1.3 billion

Private funding $1.7 billion in 2021

National Laboratory for
Quantum Information Science in Hefei

Patent filings for quantum technology by country

The United States used to produce more patents for quantum technology than China, but in the past decade China has leaped ahead.

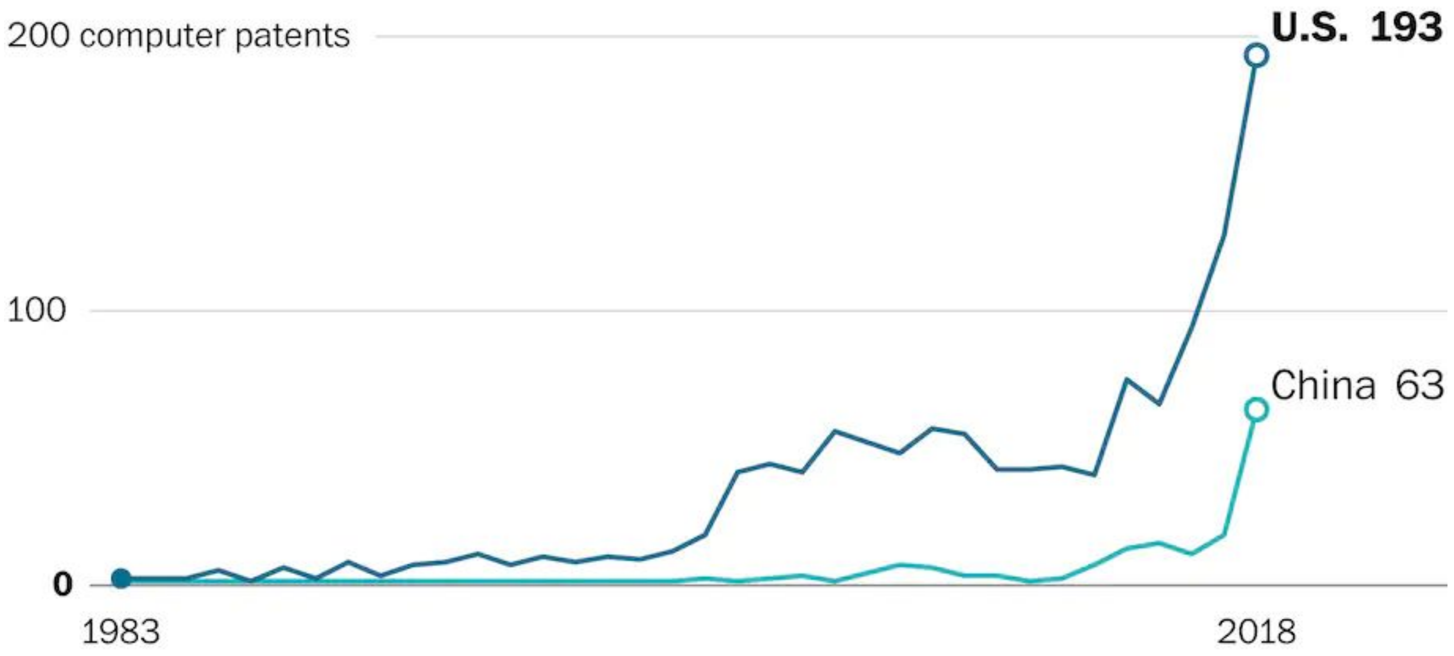


Source: Patinformatics LLC

THE WASHINGTON POST

Patent filings for quantum computers by country

China has overtaken the United States in quantum technology patents overall, but the United States still has a large lead in patents for quantum computers.



Source: Patinformatics LLC

THE WASHINGTON POST

Major Players in U.S.

Technological giants: IBM, Google, Microsoft, Amazon, Intel, Tesla, Alibaba, JPMorgan Chase

NSF Quantum Leap Challenge Institutes (total 5)

DOE National Quantum Centers:

ANL: Q-NEXT · Next Generation Quantum Science and Engineering

BNL: C2QA · Co-design Center for Quantum Advantage

FNAL: SQMS · Superconducting Quantum Materials and Systems Center

LBNL: QSA · Quantum Systems Accelerator

ORNL: QSC · The Quantum Science Center

Q-NEXT: Quantum Information Science Research Center at Argonne

- **Major Cross-Cutting Challenge:** Manipulating and interconnecting entangled states of matter.
- **Mission:** Deliver quantum interconnects and establish a national resource to provide pristine materials for new quantum devices.
- Nearly 100 researchers from 3 national laboratories, 10 universities, and 10 industry partners
- \$115M from DOE and an additional \$93M from industry partners

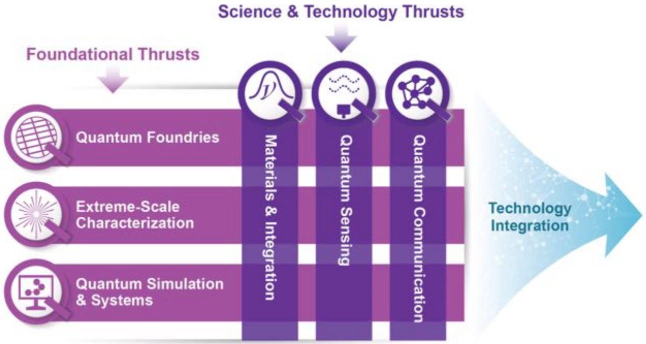
Thrusts and Argonne Leadership:

Executive Team:

Thrust Leaders:

P. Kearns | D. Awschalom | S. Guha

J. Heremans | M. Holt | M. Suchara



Partner institutions:

Q-NEXT Mission

- ✓ Deliver quantum interconnects
- ✓ Establish national foundries
- ✓ Demonstrate communication links, networks of sensors, and simulation testbeds

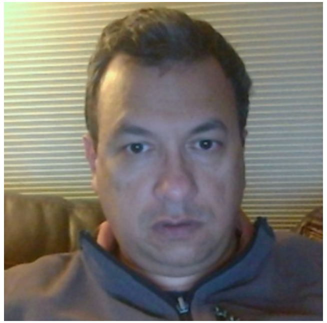
Acknowledgements

Q-NEXT: Quantum Simulation Team

Sahil Gulania, ANL

Bo Peng, PNNL

Niri Govind, PNNL



Funding:

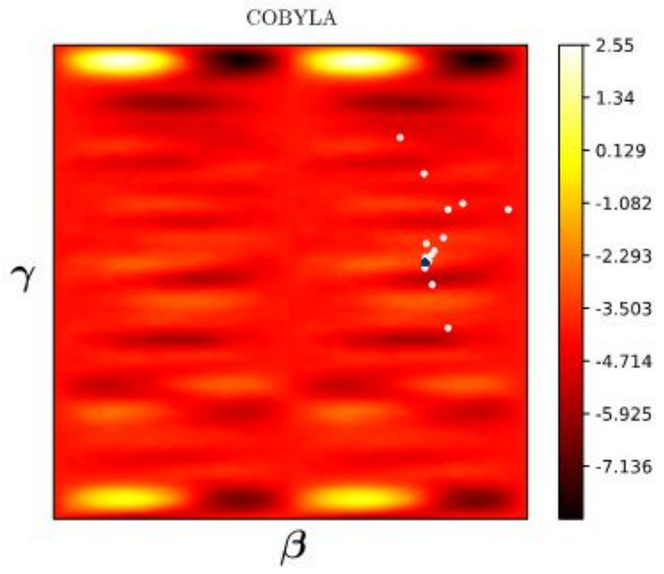
DOE Q-NEXT: *This work was supported by the DOE Office of Science (National Quantum Information Science Research Centers)*

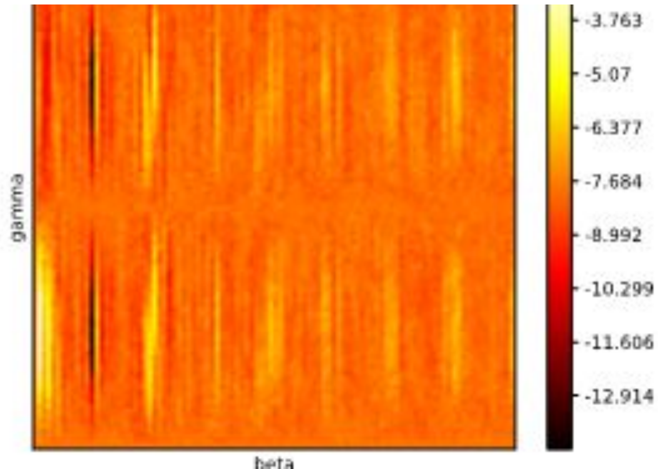
DOE ASCR: This research used resources of the Argonne Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC02-06CH11357.

DOD DARPA: *This research was partially supported by the the Defense Advanced Research Projects Agency (DARPA) project*

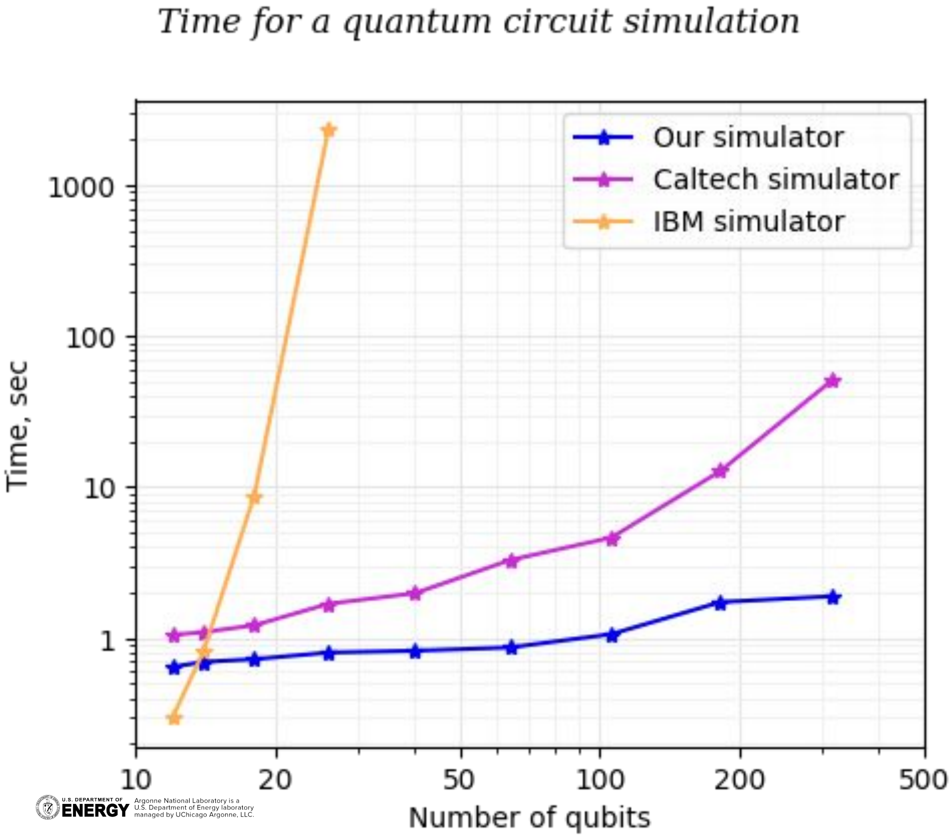
Quantum Simulator Use Cases

- Verification of quantum advantage and supremacy claims
- Verification of large quantum devices
- Co-design quantum computers
- Energy efficiency studies of quantum computers
- Design of new quantum algorithms
- Finding parameters for variational quantum algorithms





Quantum simulators developed at Argonne National Laboratory: QTensor and QuaC



Simulated 1,000,000 qubit QAOA circuit with depth p=6 in 1 hour and 20 minutes on 512 nodes of supercomputer Theta

Limitations of quantum simulators

Qubits	Memory	Time per operation
10	16 KB	Microseconds on a smartwatch
20	16 MB	Milliseconds on a smartphone
30	16 GB	Seconds on a laptop
40	16 TB	Seconds on a PC cluster
50	16 PB	Minutes on modern supercomputers
60	16 EB	Hours on post-exascale supercomputers?
70	16 ZB	Days on supercomputers in distant future?