QY4. Qubit Devices

- A Quantum Computer
  - General aspects

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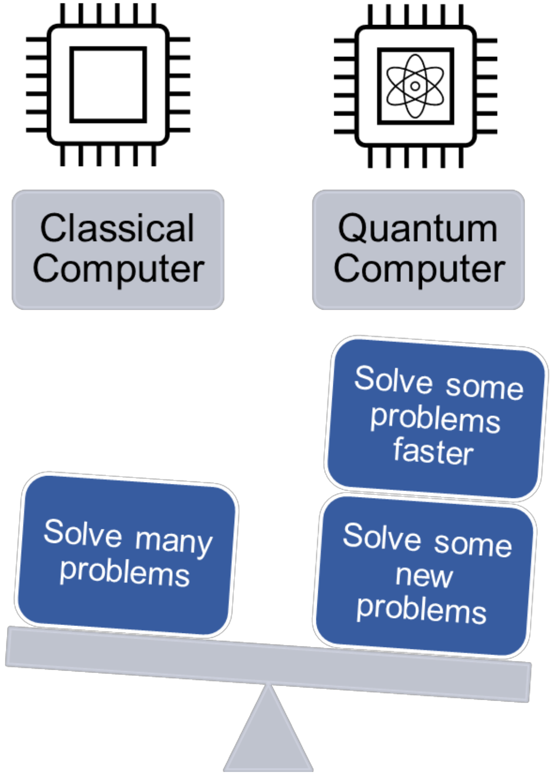
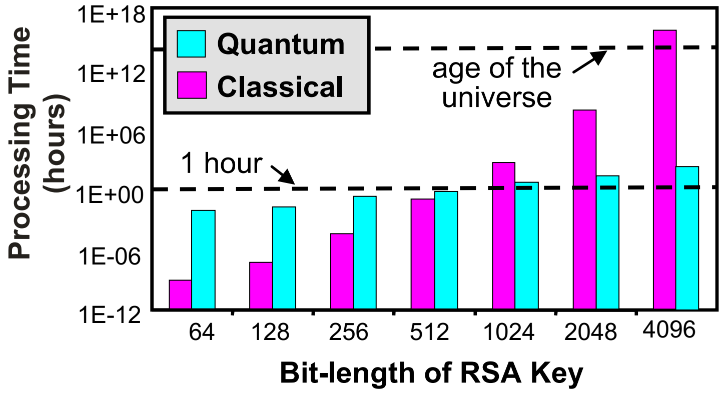
Classical vs Quatnum



Universal, Fault-Tolerant Quantum Computer

Shor's Algorithm for Prime Factorization:
RSA Key Decryption



Gate-Based Applications:

- RSA key decryption
- Database searching
- Linear equation sampling

Quantum speed-up exists over known classical algorithms

Which Industries Have Problems Quantum Computing Could Solve?

Aerospace

- Higher sensitivity sensors and precision timing
- LIDAR
- Neuromorphic processing
- Secure communications
- Advanced fluid dynamics
- Finite element simulations
- Aerodynamics
- Flight mechanics
- Satellite free navigation

Automotive

- Computational fluid dynamics
- Image recognition
- Workflow scheduling
- Real-time race analysis
- Performance optimization
- Machine learning + Quantum
- Multi-car paint shop problem
- Battery materials

Chemical/Pharma

- Quantum chemistry
- Molecular modeling
- Quantum inspired through to fault-tolerant use-case research
- Drug discovery
- Accelerating searches for both targets and drugs
- Peptide engineering

Financial

- Ultra-fast trading platforms
- Fraud detection
- Portfolio optimization
- Data security
- Communication security
- Multiple currency settlement optimization

DiVincenzo’s Criteria

The 5 DiVincenzo’s Criteria for Implementation of a Quantum Computer:

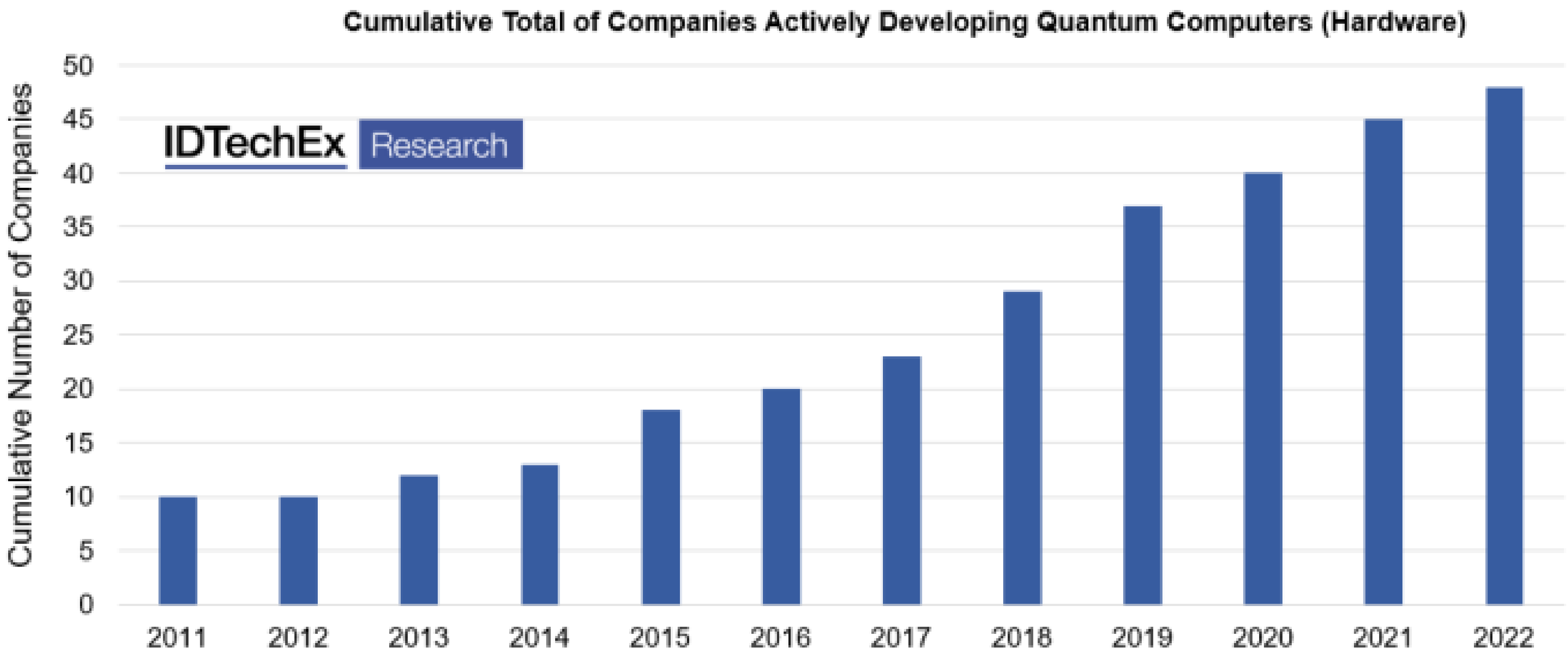
- A scalable physical system with well-characterized qubits.
- The ability to initialize the state of the qubits.
- Long (relative) decoherence times, much longer than the gate-operation time.
- A universal set of quantum gates.
- A qubit-specific measurement capability.

in the standard (circuit approach) to quantum information processing (QIP) plus two criteria requiring the possibility to transmit information:

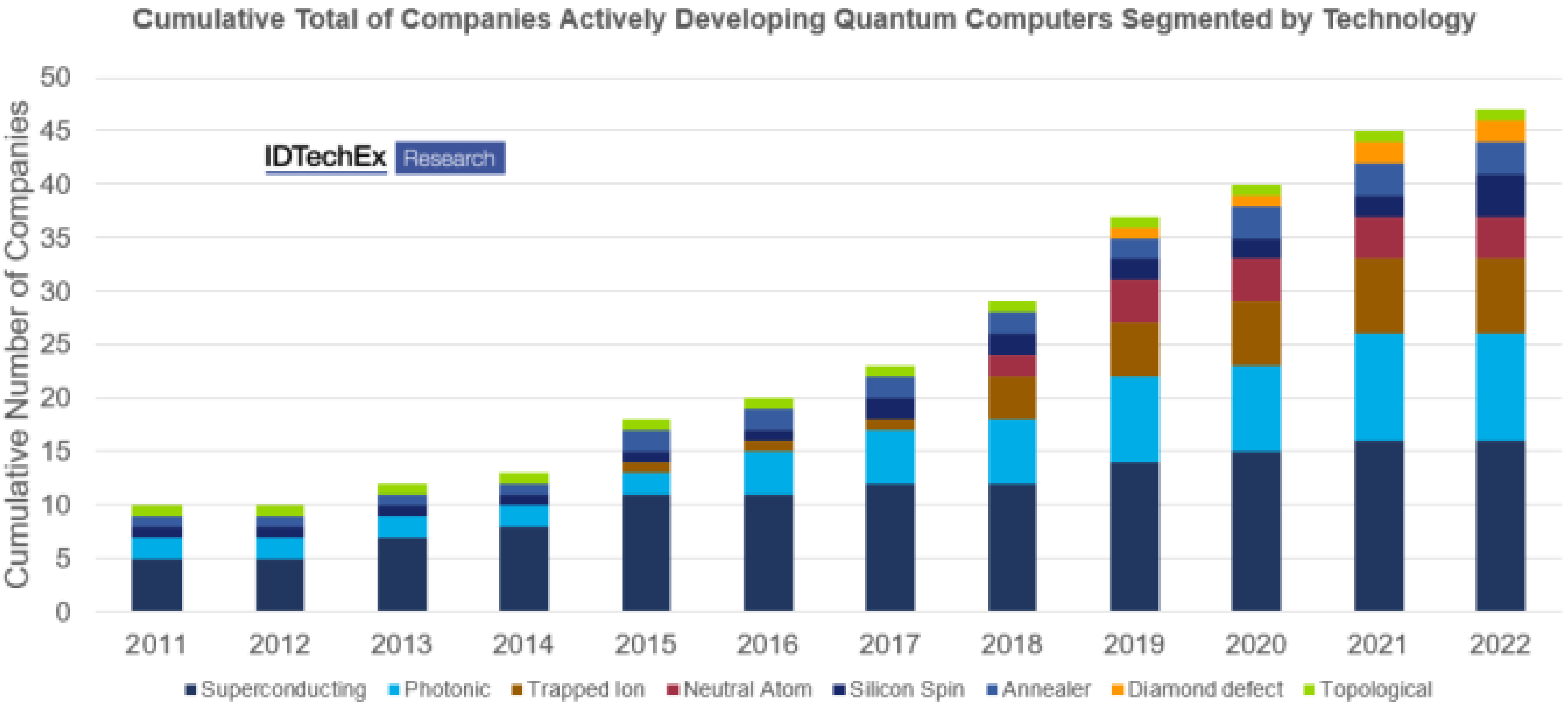
- The ability to interconvert stationary and mobile (or flying) qubits.
- The ability to faithfully transmit flying qubits between specified locations.

DiVincenzo, D., Quantum Computation, Science 270, 255 (1995)

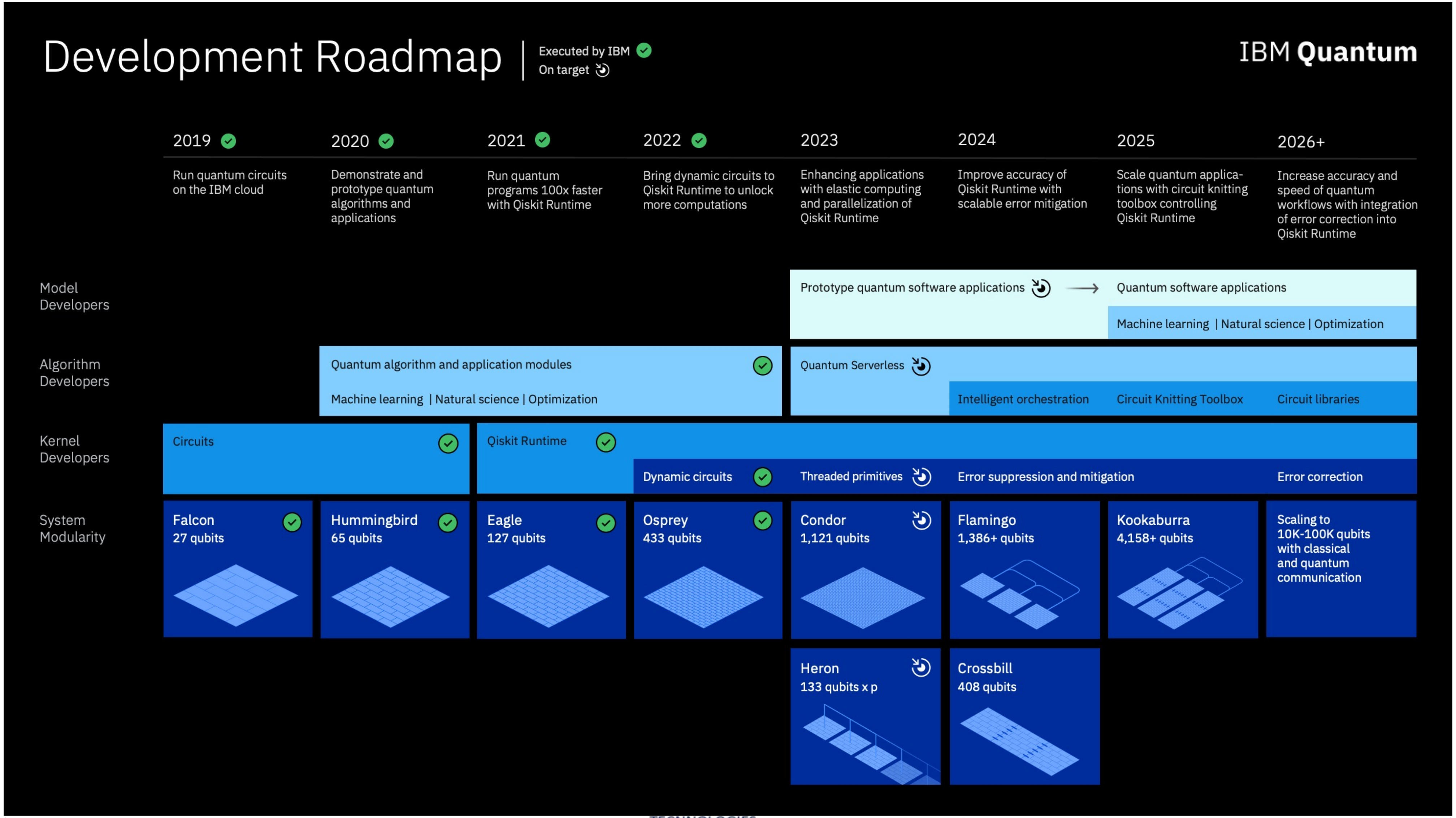
State of the Industry in 2022



State of the Industry in 2022

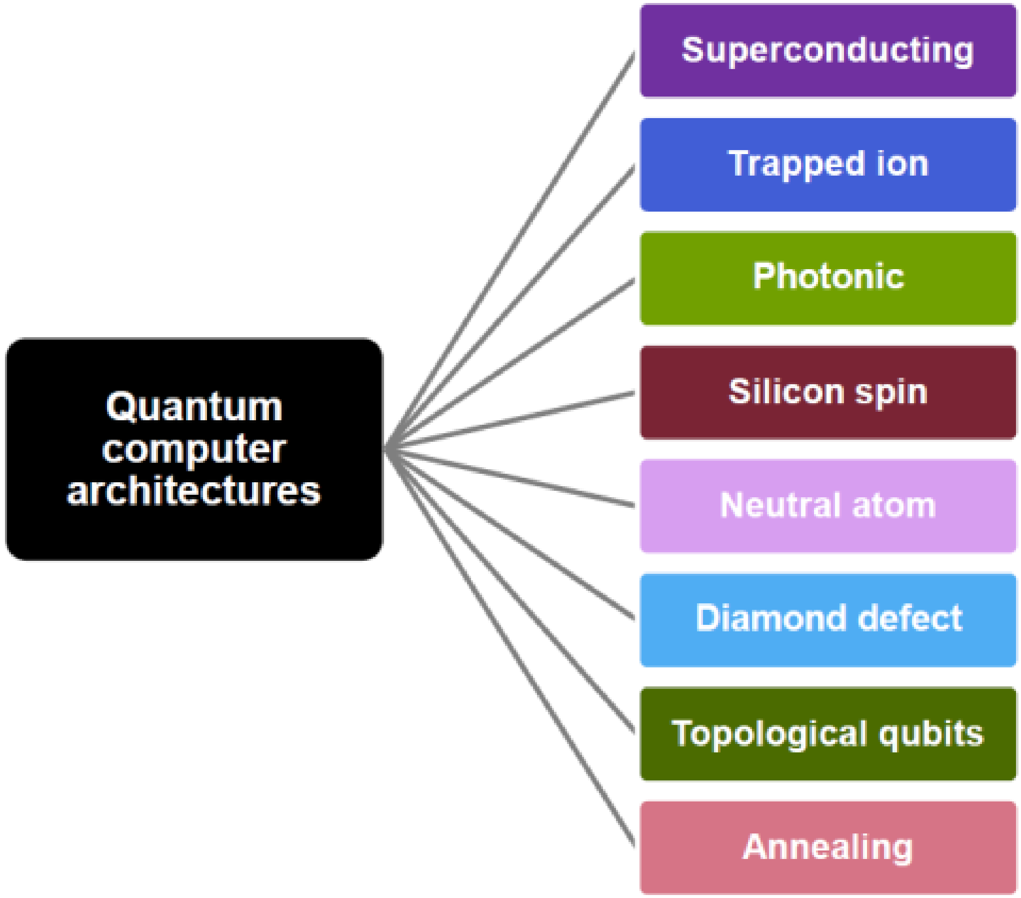


IBM Roadmap

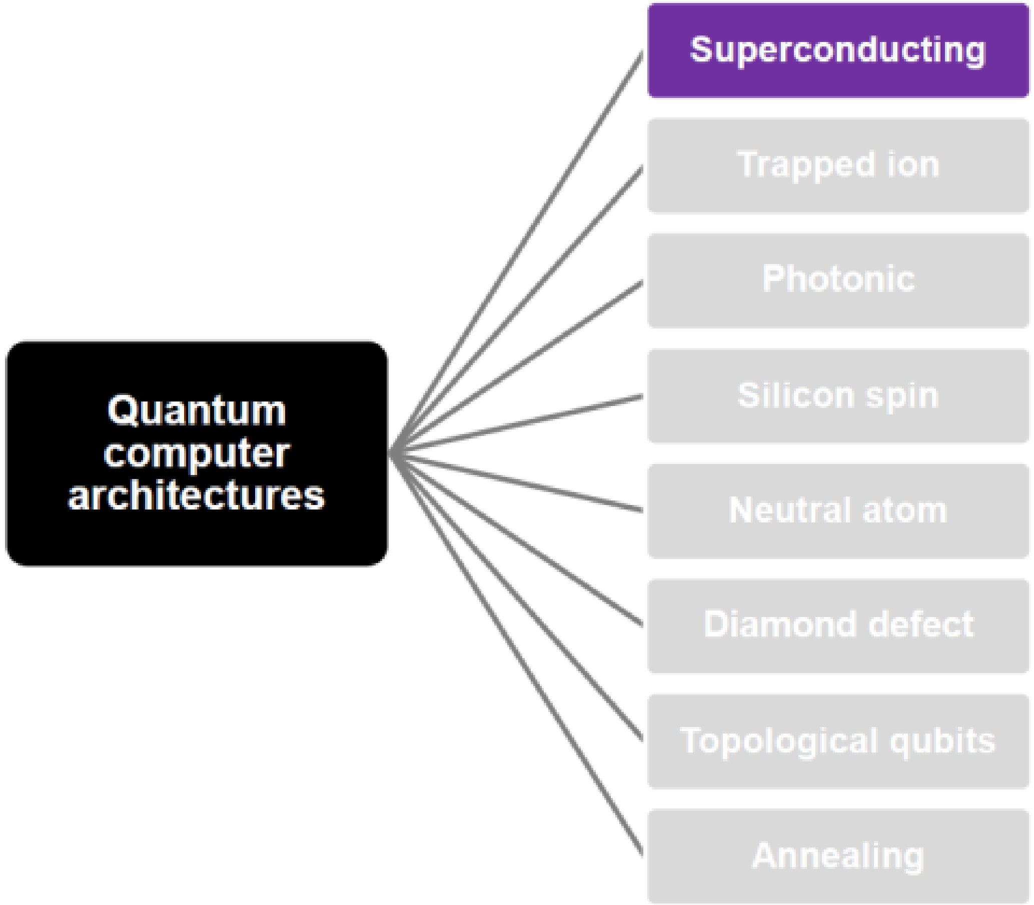

Development Roadmap
Executed by IBM
On target
IBM Quantum
2019
Run quantum circuits on the IBM cloud
2020
Demonstrate and prototype quantum algorithms and applications
2021
Run quantum programs 100x faster with Qiskit Runtime
2022
Bring dynamic circuits to Qiskit Runtime to unlock more computations
2023
Enhancing applications with elastic computing and parallelization of Qiskit Runtime
2024
Improve accuracy of Qiskit Runtime with scalable error mitigation
2025
Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime
2026+
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

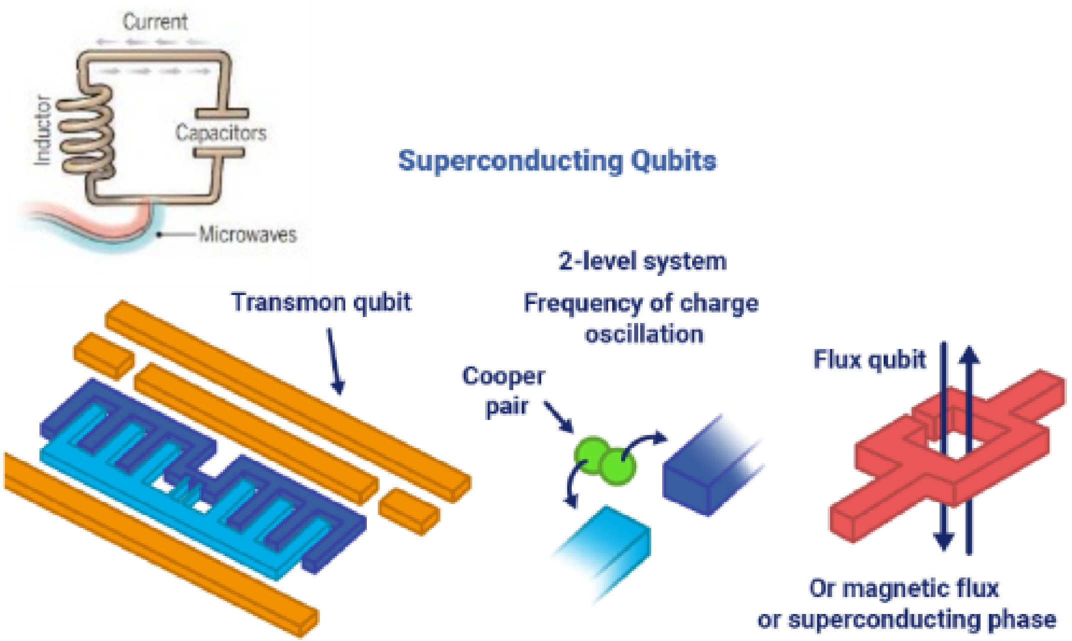
Qubit Technologies

Eight Key Approaches to Creating Quantum Computer Technology



Overview of Superconducting Quantum Computing Technology

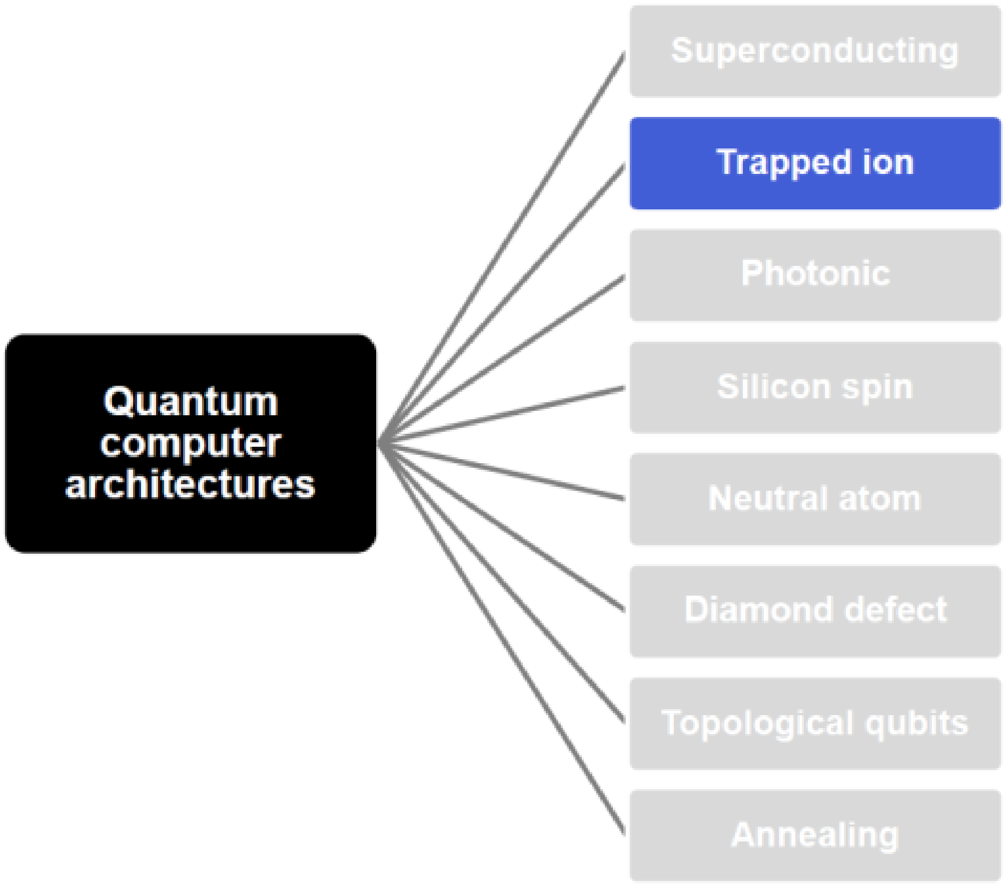


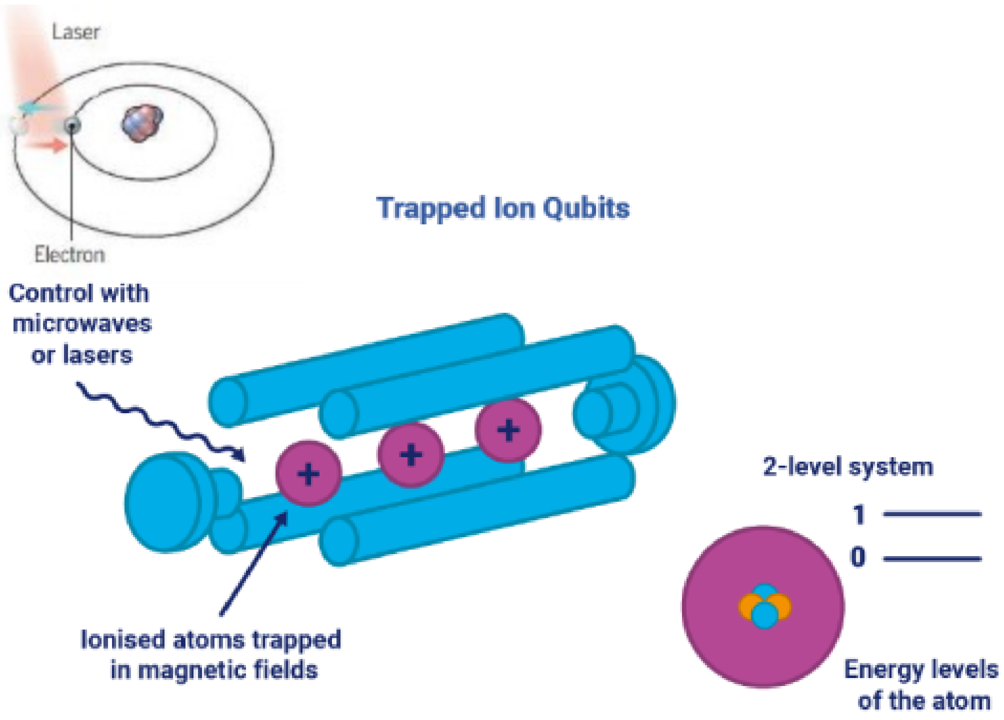


IBM

Google

Overview of Trapped-ion Quantum Computing Technology



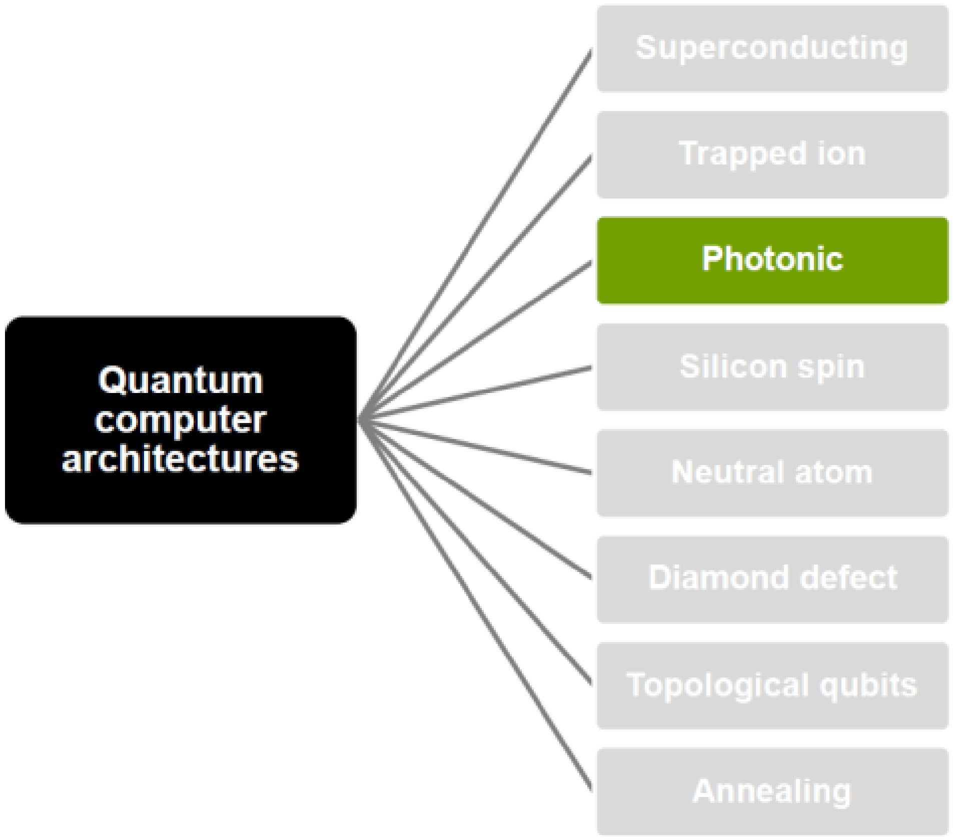


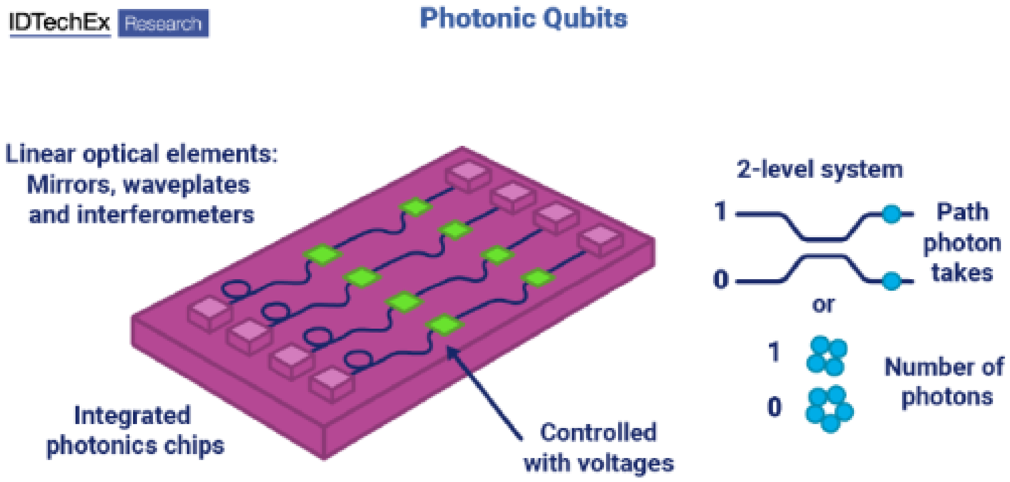
QUANTINUUM

CQC Honeywell

IONQ

Overview of Photonic Quantum Computing Technology

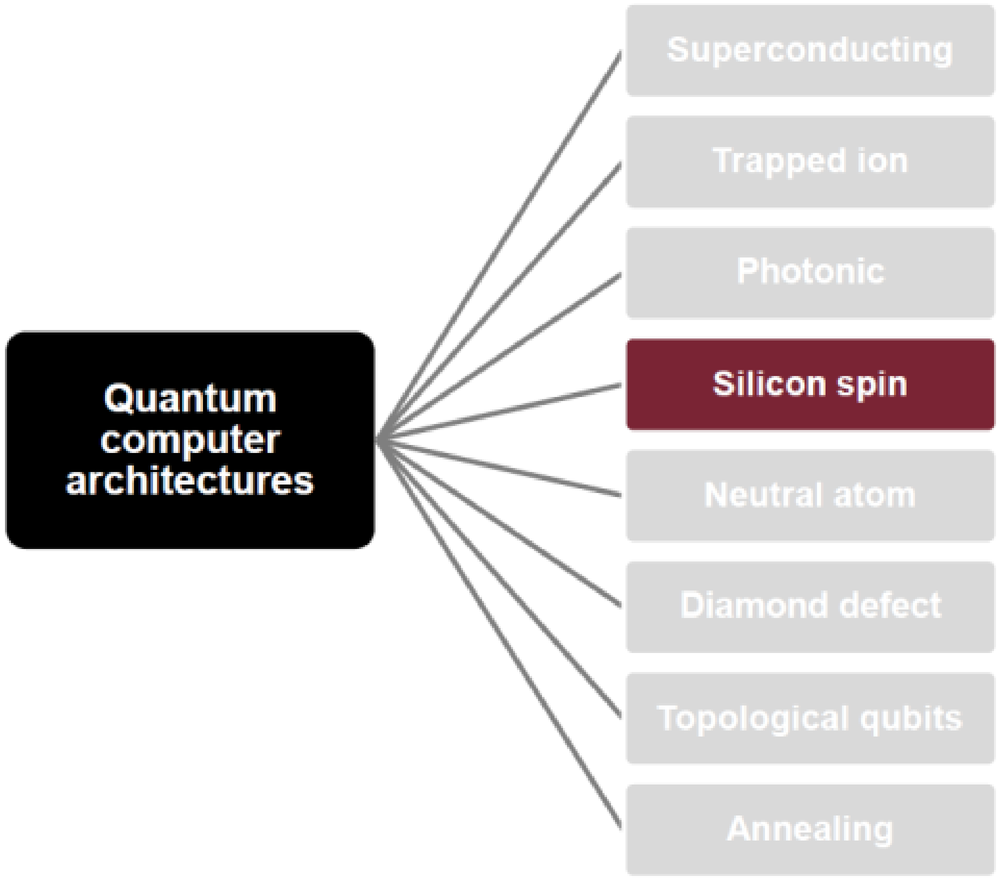


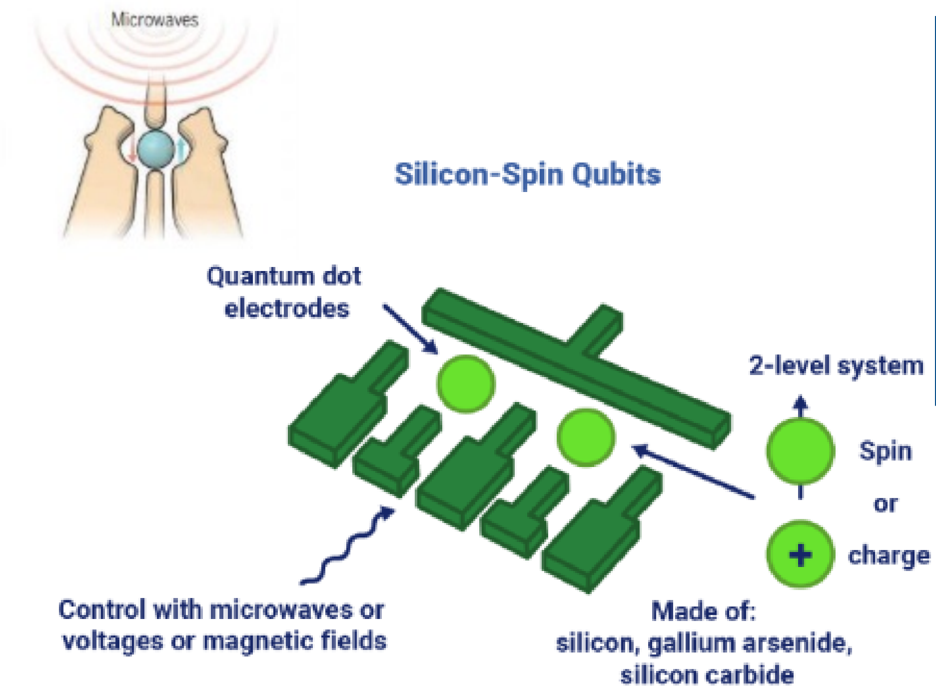


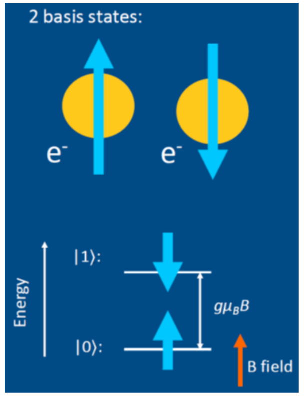
PsiQuantum

XANADU

Overview of Silicon-Spin Quantum Computing Technology

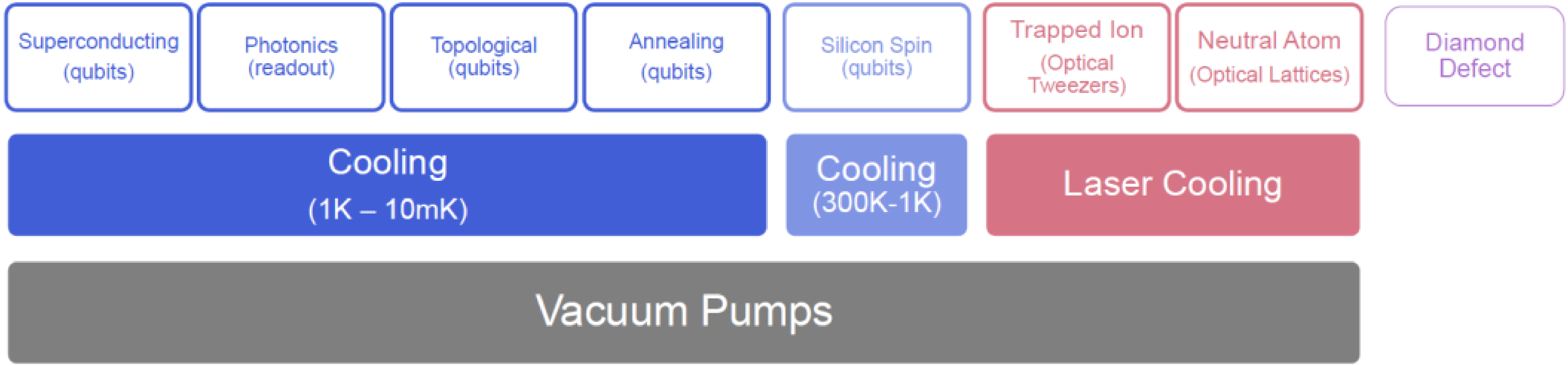






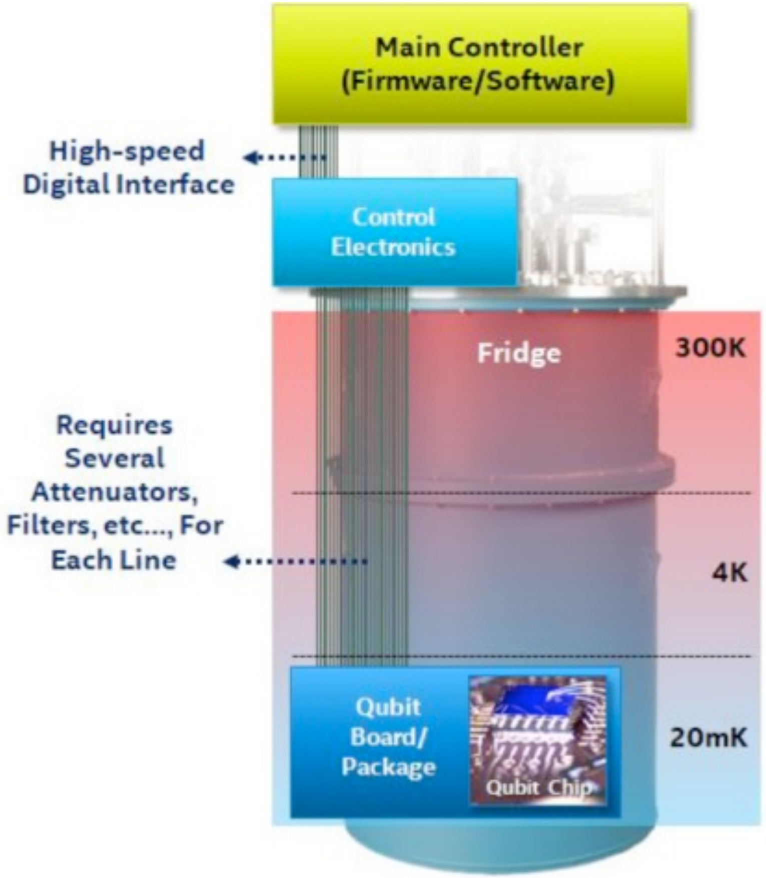
intel leti ceatech QUANTUM MOTION diraq

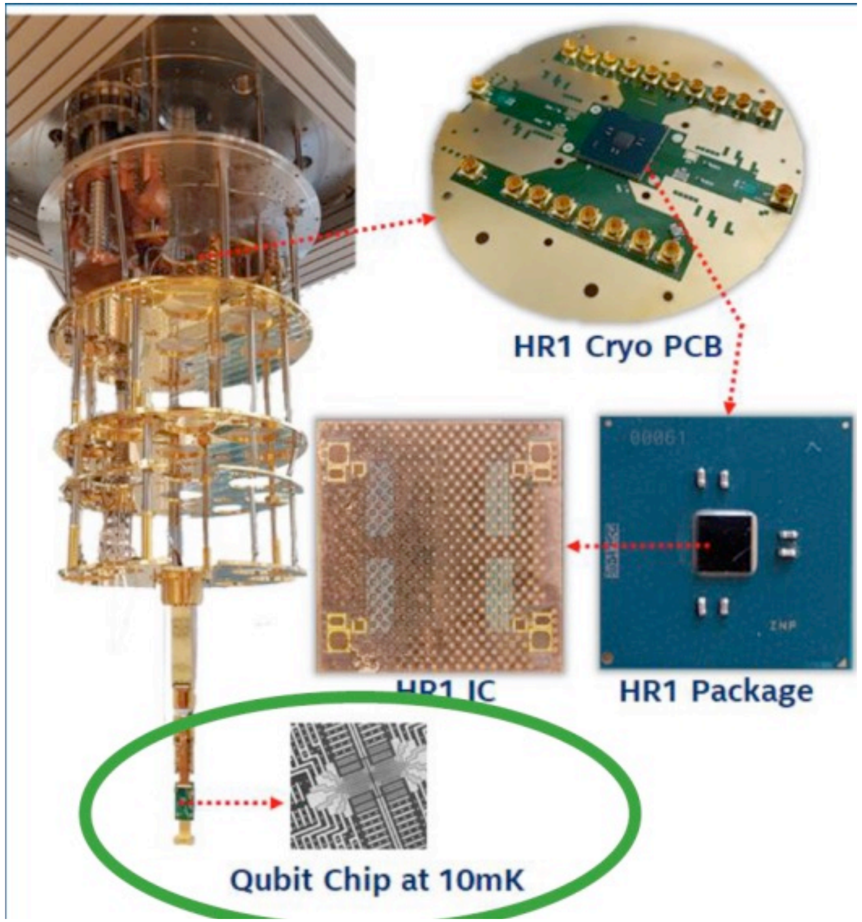
Hardware Agnostic Platforms for Quantum Computing Represent a New Market for Established Technologies



A quantum computer

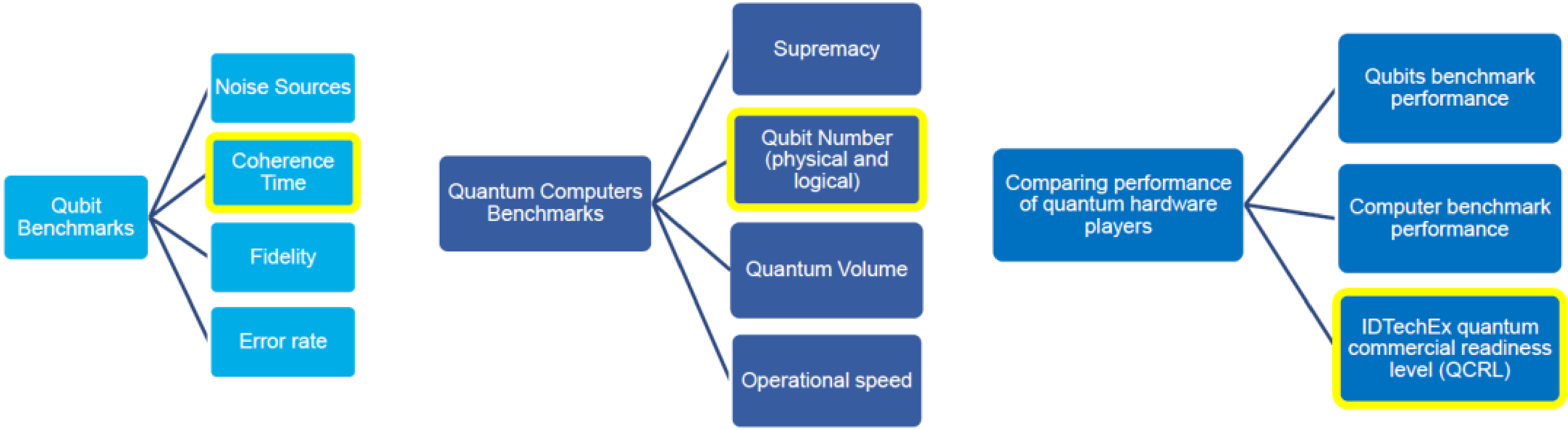
Inside a quantum computer



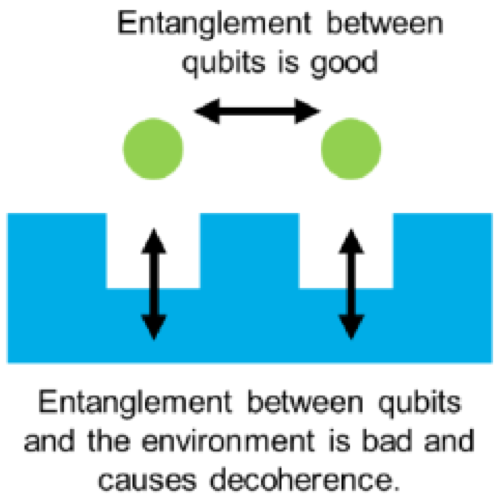


Eight Key Approaches to Creating Quantum Computer Technology – Which Ones Have the Most Potential?

How Is the Industry Benchmarked?



Ranking Competing Technologies by Coherence Time



**grey coloring indicates minimal data available*

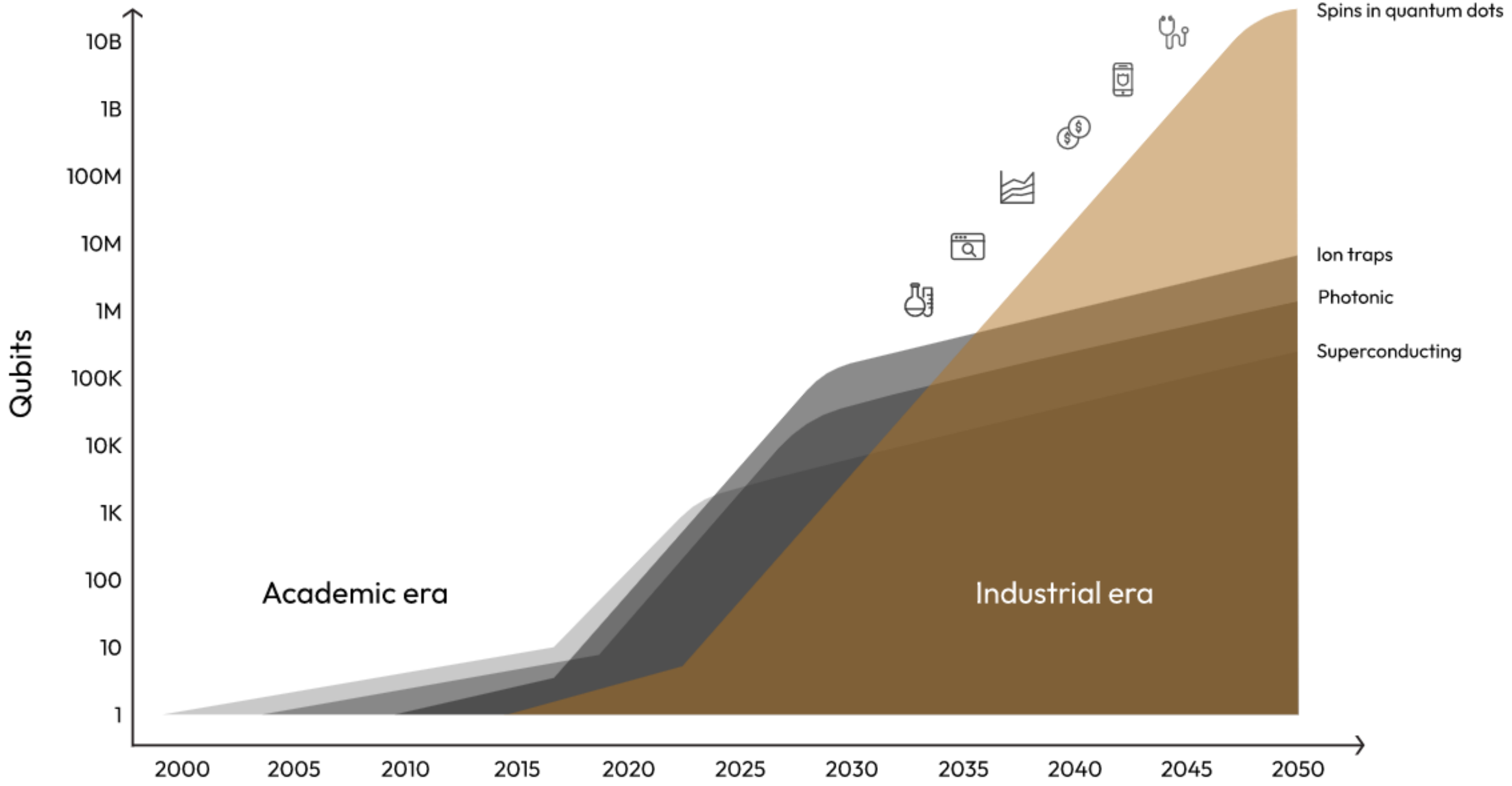
Longer decoherence time is better

Nano-seconds → Micro-seconds → Milli-seconds → Seconds → Minutes → Hours → Days

SUPERCONDUCTING

TRAPPED ION

Qubit Number Continues to Be a Key Benchmark

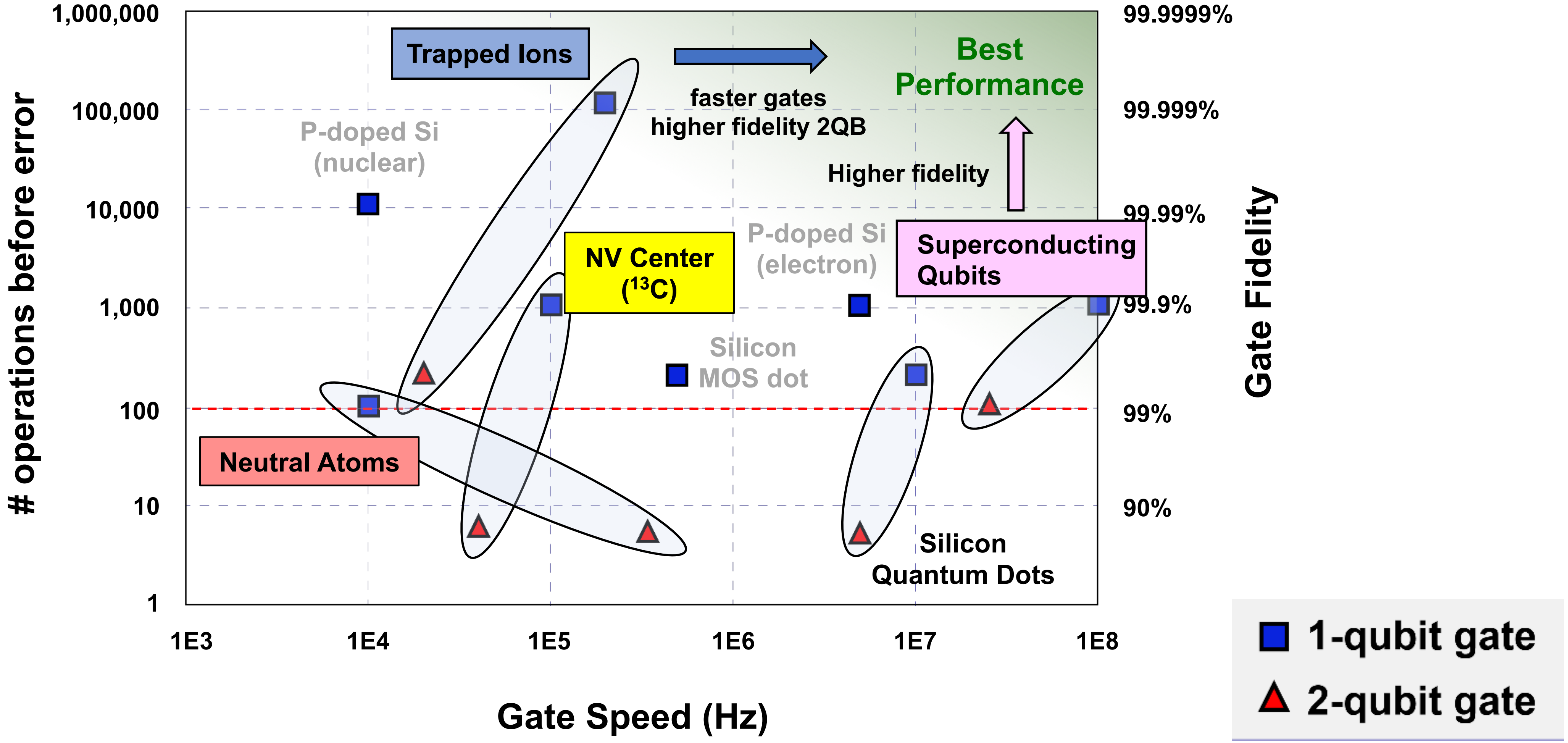


Developments of Standards and Benchmarks Remains a Challenge for the Industry

Benchmark	Description
Qubit Number	Quantum 'bits' used to store quantum information. More qubits = more computational power.
Coherence Time	Qubits are sensitive to error from environmental noise. Coherence time is a measure of how long qubit maintains quantum information.
Error rate	Used to describe the fraction or percentage of operations which in some way fail.
Quantum Volume	Measure of qubit number and circuit depth (linked to the number of operations/gate layers in a quantum circuit calculable). Developed by IBM.
Algorithmic Volume	Measure of gate number, circuit width and error rate. Developed by ionq.
Circuit layer operations per second	Number of quantum circuits a quantum processing unit (QPU) can execute per unit of time. Developed by IBM.

IDTechEx Research

Benchmarking Graph



Quantum Commercial Readiness Level

	QCRL Score	Performance	Product Description	
NISQ (Noisy Intermediate Scale Quantum)	1	Tool for use-case development or research.	Education tool.	
	2	Computations possible – even if lower performance or already achievable with existing classical hardware.	Early Use-case development tool.	
	3	Solves sub-set of academic or niche problems inaccessible to classical computers (either by speed or fundamental ability)	Advanced use-case development tool.	
	4	Solves sub-set of commercial problems inaccessible to classical computers (either by speed or fundamental ability)	Computer for application specific deployment	
Beyond NISQ	5	Solves general purpose problems for end-users that leads to value creation (revenue, competitive edge, profit optimization, enhanced user experience etc.)	Computer for versatile deployment	
	6	Achieves 5 – and cloud access costs are optimized	It becomes affordable for most players with clear quantum use cases to access it and generate value without buying personal hardware.	
	7	Achieves 5 and personal hardware costs/infrastructure requirements are reduced.	Quantum computing hardware in affordable on-premises and competition with classical alternatives increases.	
	8	General purpose quantum computing is miniaturized, and costs compare with existing expensive consumer electronics.	Quantum computing hardware in high-end consumer PCs.	
	9	General purpose quantum computing is miniaturized for affordable consumer electronics.	Quantum computing hardware in high-end consumer phones.	
IDTechEx Research	10	Quantum computing hardware use becomes standard.	Quantum computing hardware is utilized in most consumer electronics.	

Addressable Market Grows with QCRL

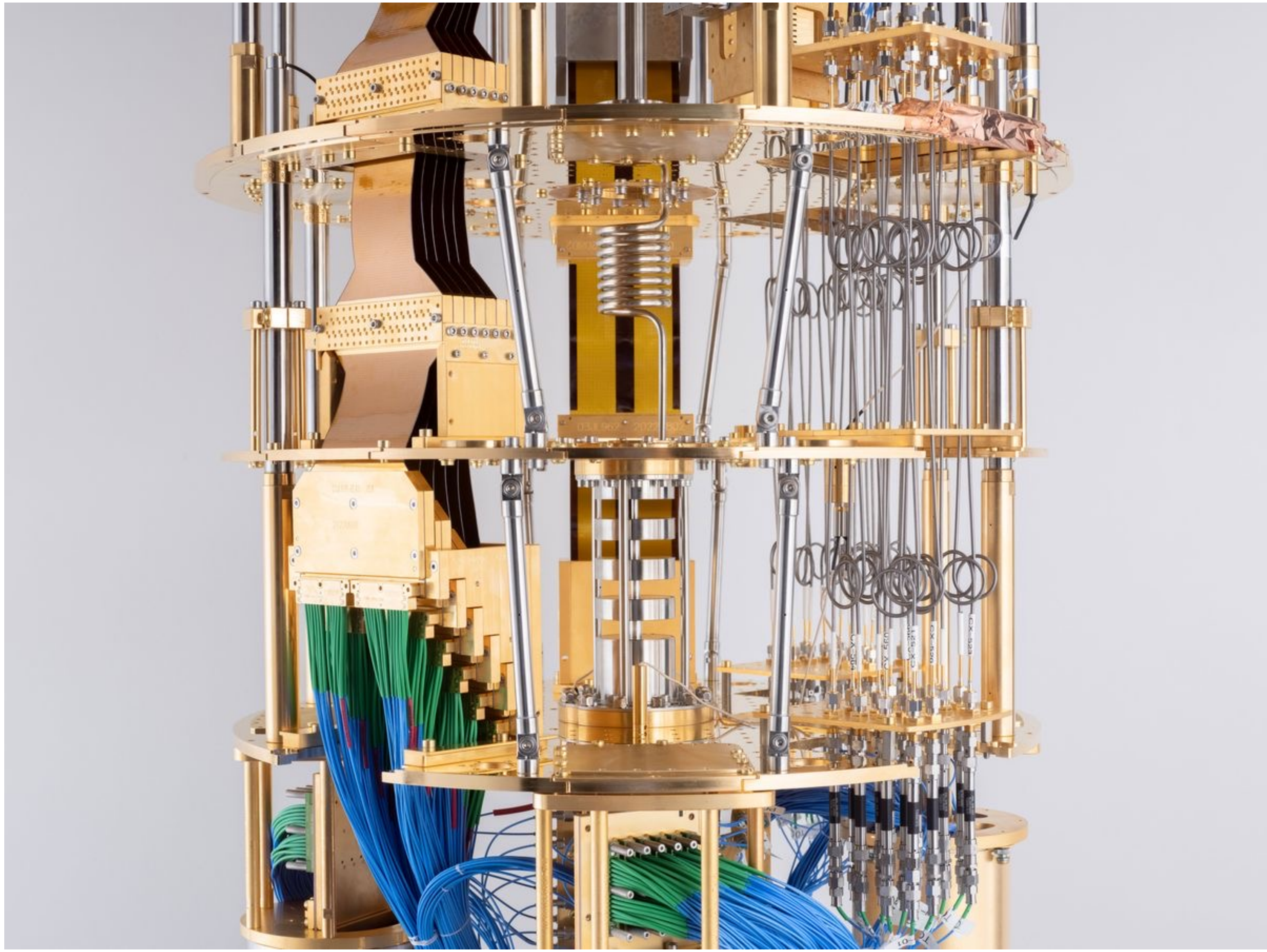
	QCRL Score	Performance	Example	Product	End user value? (most will =3 , 50% will =2, most wont =1)								
					Universities/ Research Institutes	Pharma	Chemical	Aerospace	Finance	Automotive	Factories	Individuals	Mass market
NISQ (Noisy Intermediate Scale Quantum)	1	Tool for use-case development or research.	<10 qubit systems	Education tool.	50%	10%	10%	10%	0%	0%	0%	0%	0%
	2	Computations possible – even if lower performance or already achievable with existing classical hardware.	Hamiltonian/phase estimation (sub routines of unstructured search).	Early Use-case development tool.	90%	50%	50%	50%	10%	10%	0%	0%	0%
	3	Solves sub-set of academic or niche problems inaccessible to classical computers (either by speed or fundamental ability)	Can complete a random circuit simulation in hours where tensor networks would take tens of thousands of years.	Advanced use-case development tool.	90%	90%	90%	50%	50%	10%	0%	0%	0%
	4	Solves sub-set of commercial problems inaccessible to classical computers (either by speed or fundamental ability)	True random number generation for security. Variational quantum eigen solver for quantum chemistry.	Computer for application specific deployment	90%	90%	90%	90%	90%	50%	10%	0%	0%
Beyond NISQ	5	Solves general purpose problems for end-users that leads to value creation (revenue, competitive edge, profit optimization, enhanced user experience etc.)	Programmable, general purpose use cases: Simulations/Optimization/ Big data searches	Computer for versatile deployment	90%	90%	90%	90%	90%	90%	10%	0%	0%

Next Lessons

- Semiconducting Qubits
- Ion traps

- Photonic Qubits
- Neutral atoms
- NV Diamond
- Cold atoms

The end



The interior view of the cryostat that cools the IBM Quantum Eagle, a 127-qubit quantum processor.
IBM