Sievert Lecture Series: The Rise of Quantum Machines

Lecture VIII: Current progress and ecosystem in quantum computing

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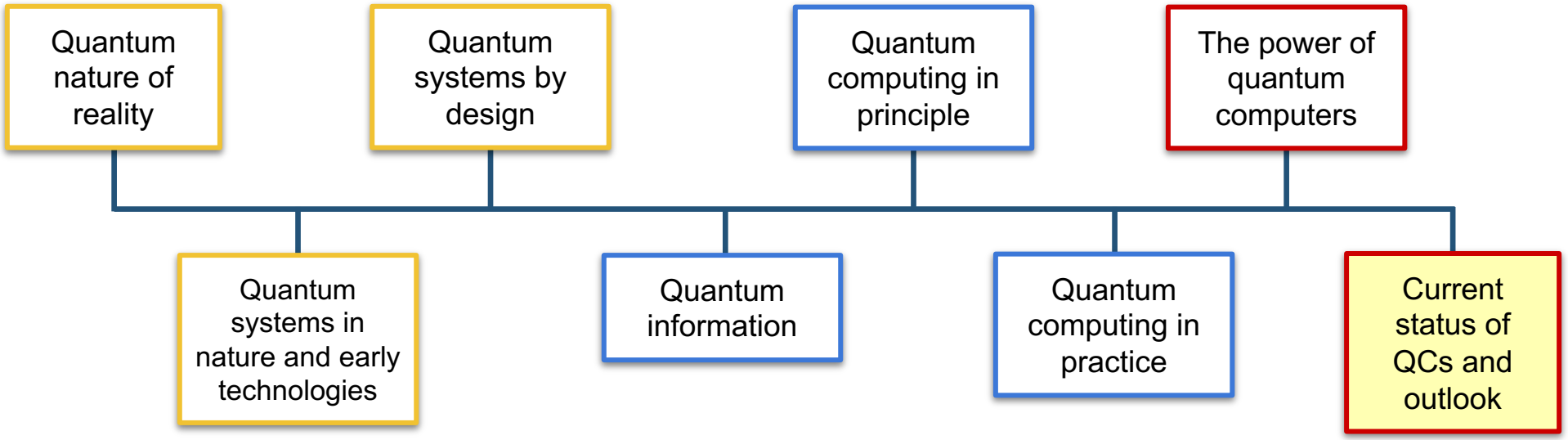
Sievert Lecture Series: The Rise of Quantum Machines

Roadmap



NISQ era and beyond

- **N**oisy **I**ntermediate-**S**cale **Q**uantum technology
  - Noisy: qubits are prone to decoherence, no error correction
  - Intermediate-Scale: processors with 50-100 qubits
- May surpass the capabilities of classical computers for *certain* tasks

" … will not change the world right away - we should regard it as a significant step toward the more powerful quantum technologies of the future."

— John Preskill (2018)

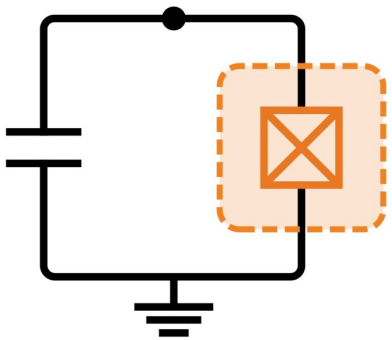
Current progress and ecosystem in quantum computing

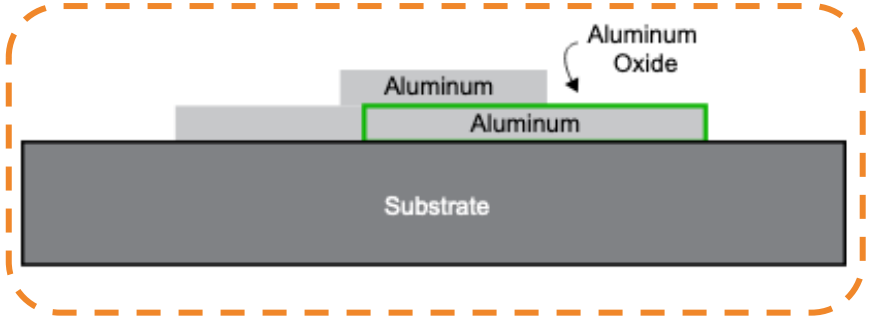
- Superconducting circuits
- IBM Q experience
- Trapped ions & neutral atoms
- Quantum ecosystem

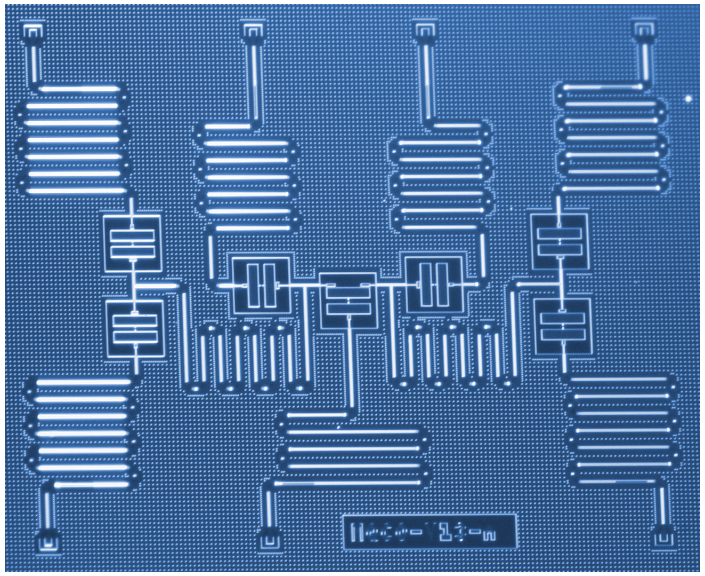
Quantum computer based on superconducting circuits

Basic elements:

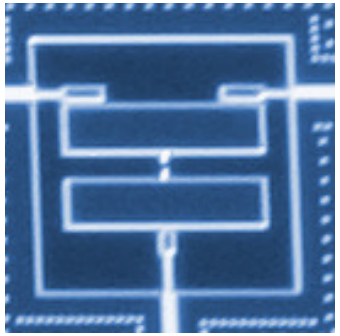
- Capacitors and inductors
- Josephson junctions



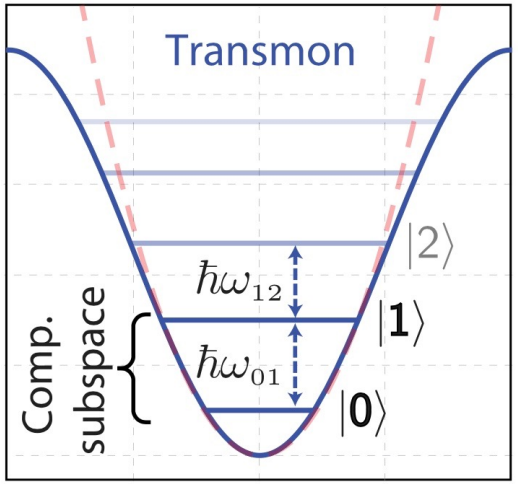




IBM 7-qubit processor



First two levels encode a quantum bit



Advantage:

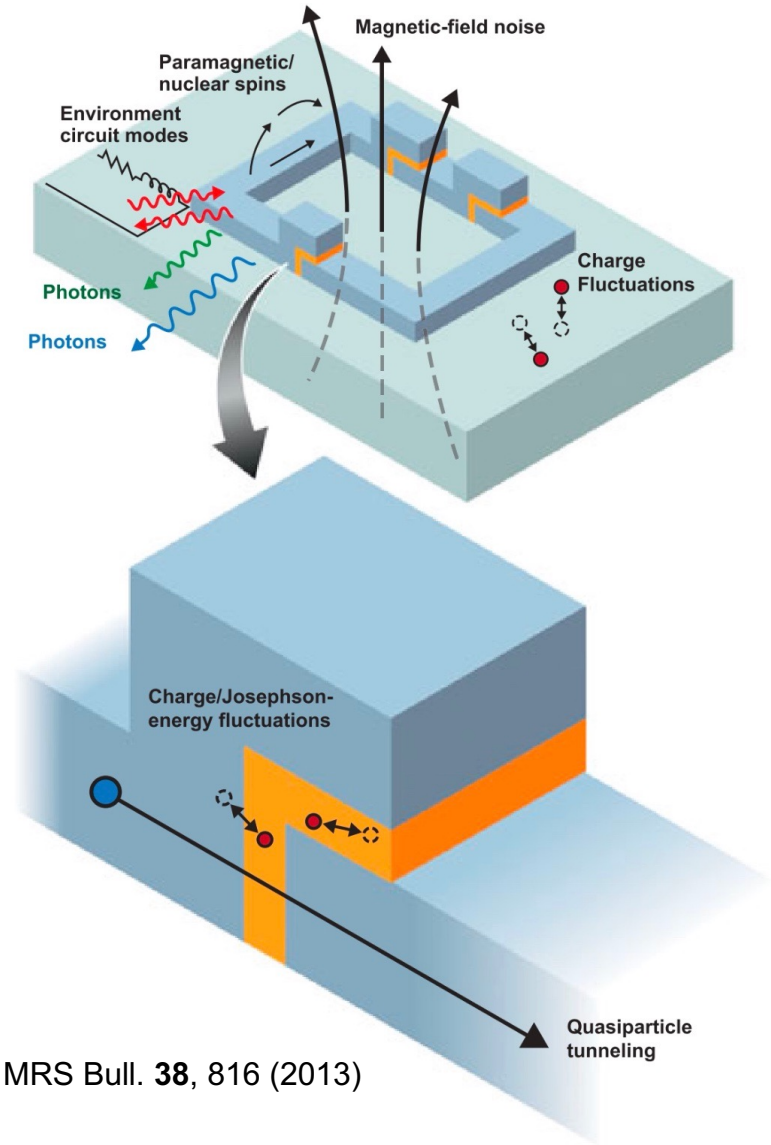
- Fast gate operation (10s ns)

Challenge:

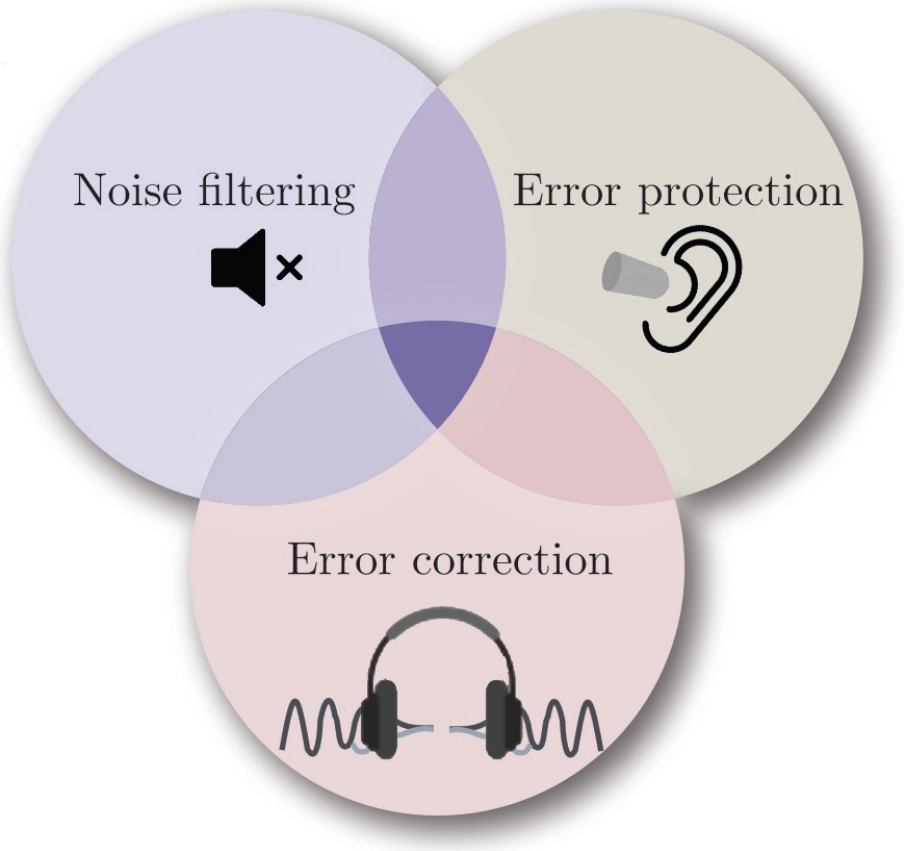
- Short qubit lifetime (100s us)

J. Koch, *et al.*, Phys. Rev. A **76**, 042319 (2007)
M. Kjaergaard, *et al.*, Annu. Rev. Condens. Matter Phys. **11**, 369 (2020)

Origin of decoherence and strategy of mitigation

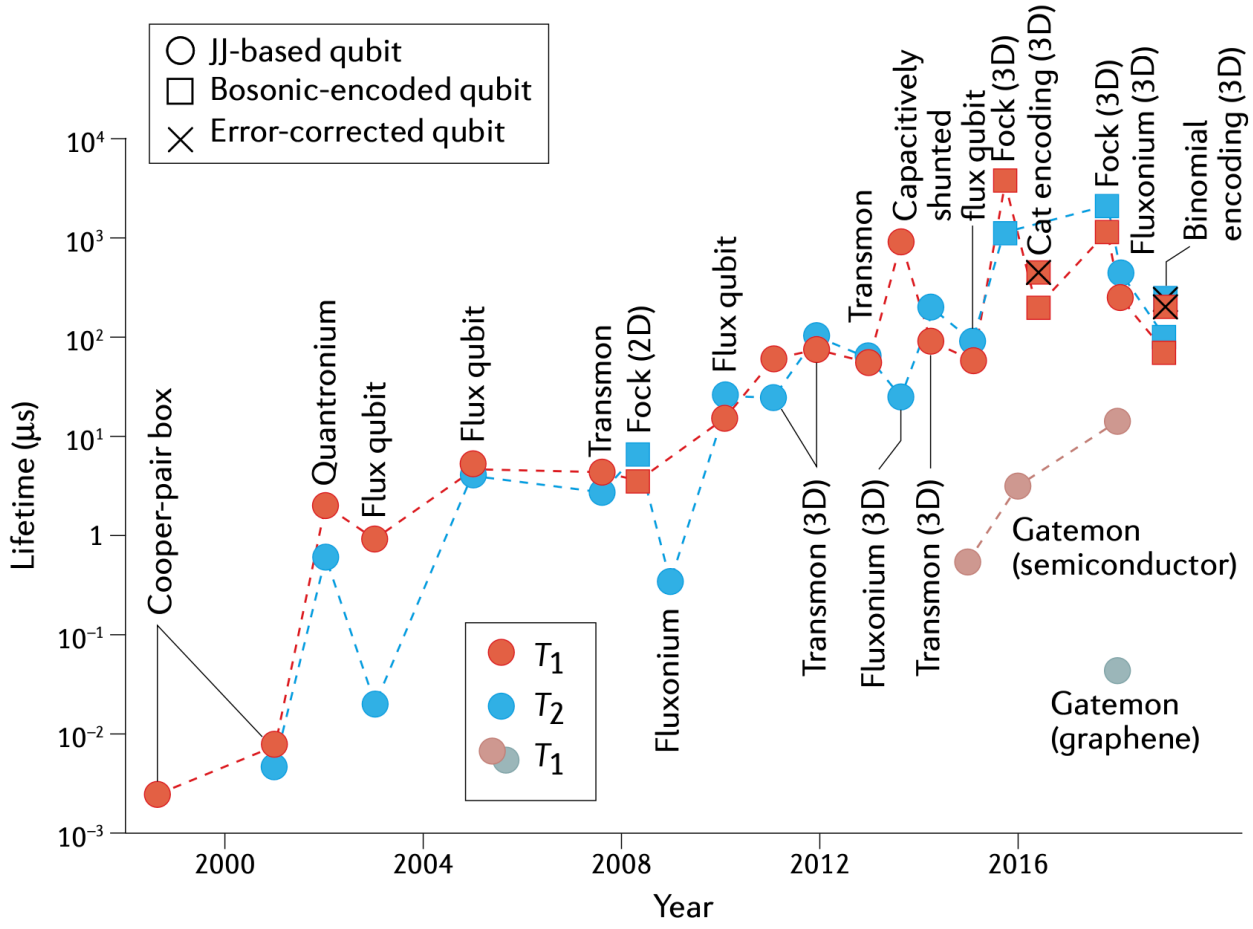


W.D. Oliver, *et al.*, MRS Bull. **38**, 816 (2013)

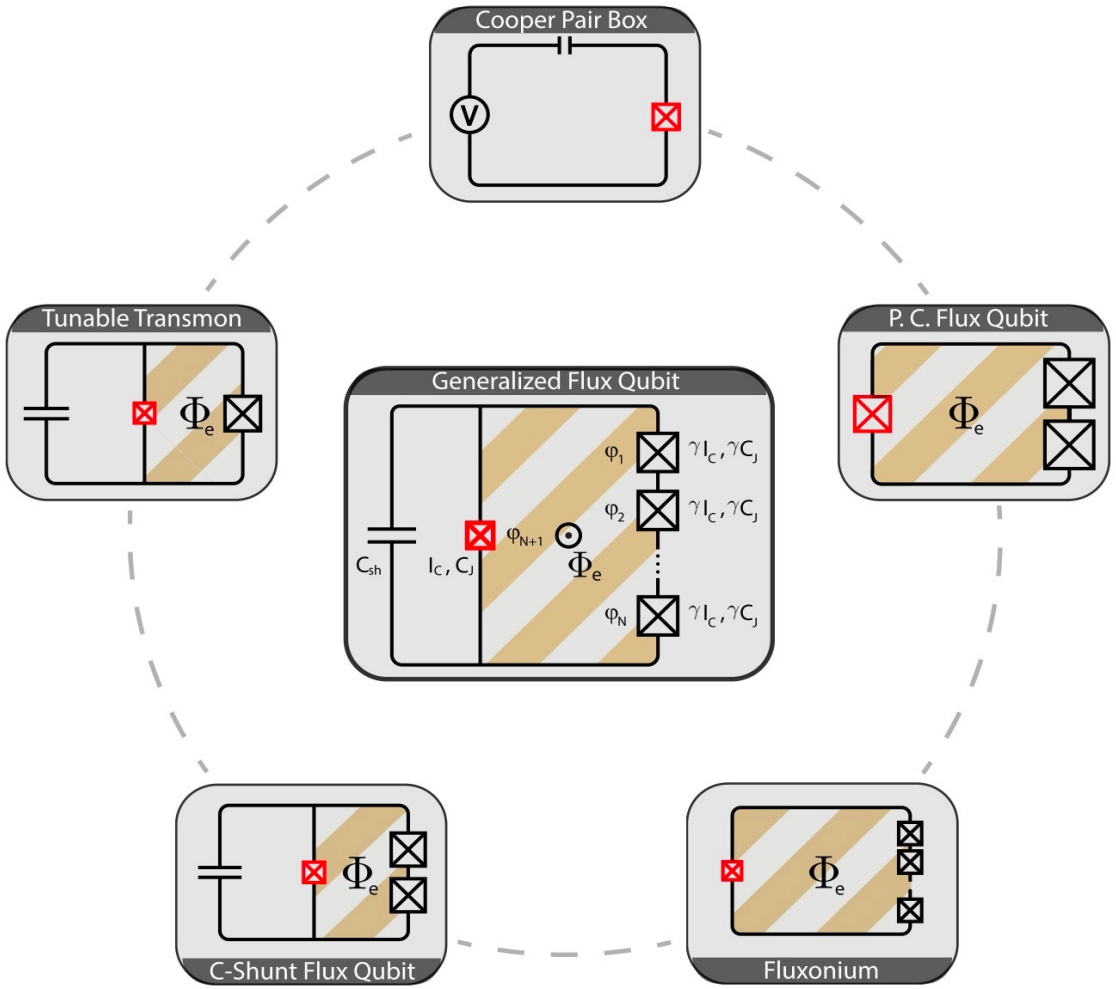


A. Gyenis, *et al.*, PRX Quantum **2**, 030101 (2021)

Progress on superconducting qubit lifetime



I. Siddiqi, Nat. Rev. Mat. **6**, 875 (2021)



F. Yan, *et al.*, arXiv:2006.04130 (2020)

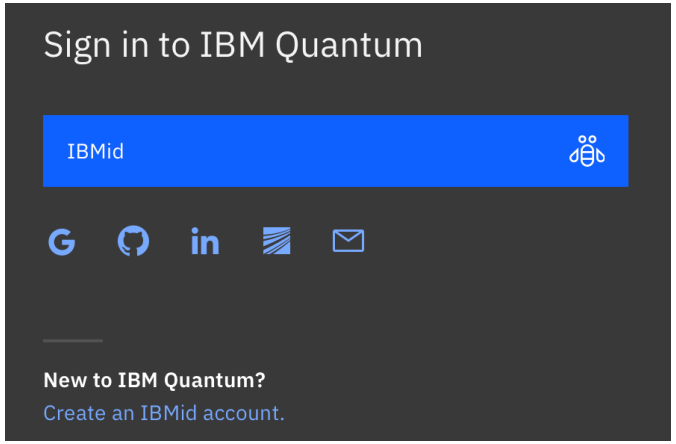
Progress on superconducting qubit scaleup

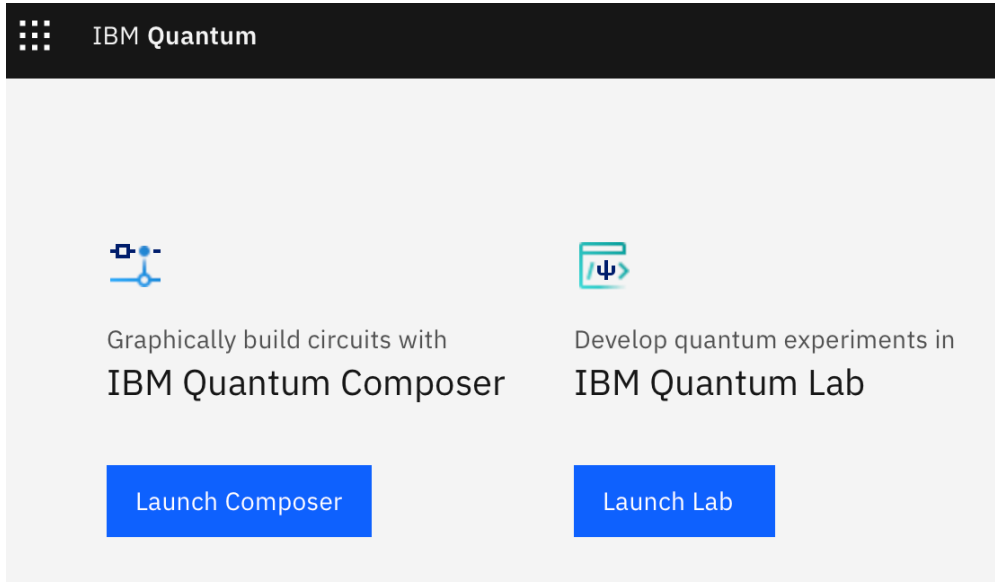
Organization	Designation	Year	# Qubits	T1 (us)	T2 (us)	Fid 1Q (%)	Fid 2Q (%)
IBM Q	Tokyo	2018	**20**	84	50	99.81	
	Montreal	2020	**27**	109	97	99.96	98.58
	Osprey	2022	**433**				
Google Quantum AI	Bristlecone	2018	**72**			99.9	99.4
	Sycamore	2019	**53**			99.85	99.35
rigetti	Aspen-4	2019	**13**	30	20	99.88	94.28
	Aspen-M	2022	**80**	29	22	98.94	91.13
	Lyra	2023	**336**				

Find more in https://databaseline.tech/quantum.html

Cloud-based quantum computing platform

- Run algorithm remotely on real quantum processors https://quantum-computing.ibm.com





- Online tutorials and interactive textbooks
  - Quantum composer: https://quantum-computing.ibm.com/composer/docs/iqx/
  - Quantum lab: https://quantum-computing.ibm.com/lab/docs/iql/
  - Qiskit textbook: https://qiskit.org/textbook/preface.html

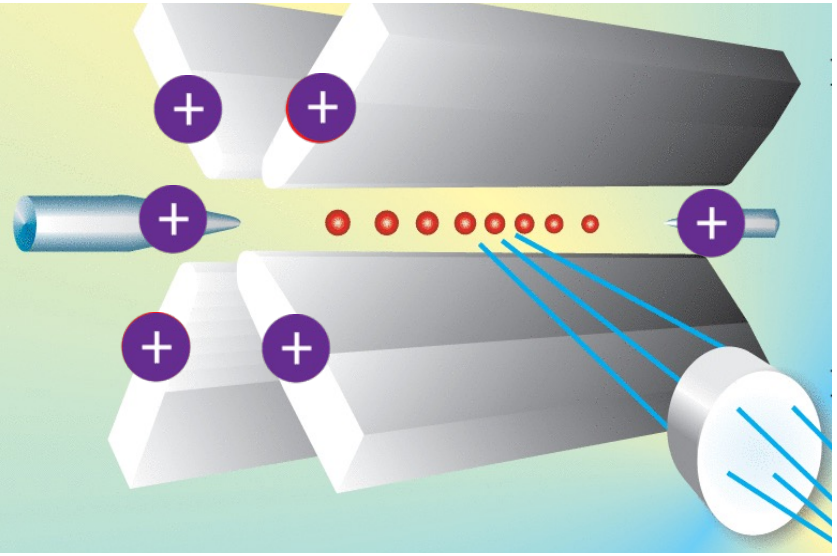
Quantum computer based on trapped ions

- Ions of interest for quantum computing
  e.g., Ca^+, Sr^+, Yb^+

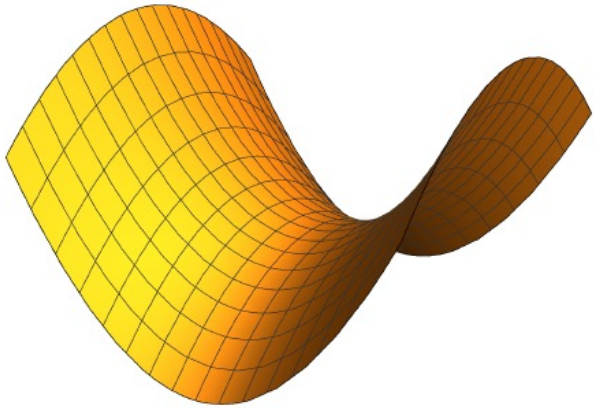
- Quantum information can be encoded in
  e.g., hyperfine states

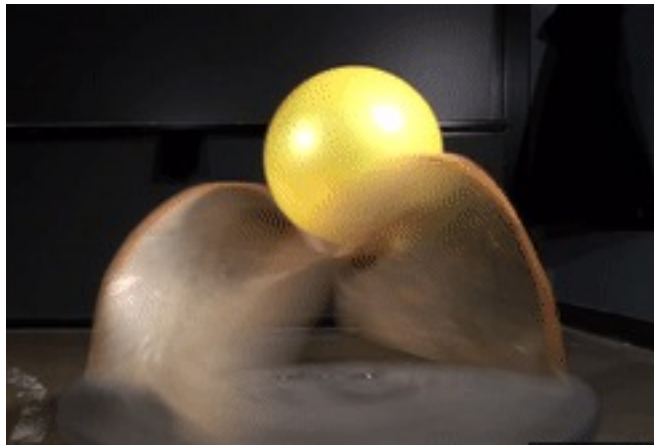
- Trapping of charged ions
  e.g., Paul trap

  Wolfgang Paul
  Nobel prize in physics 1989



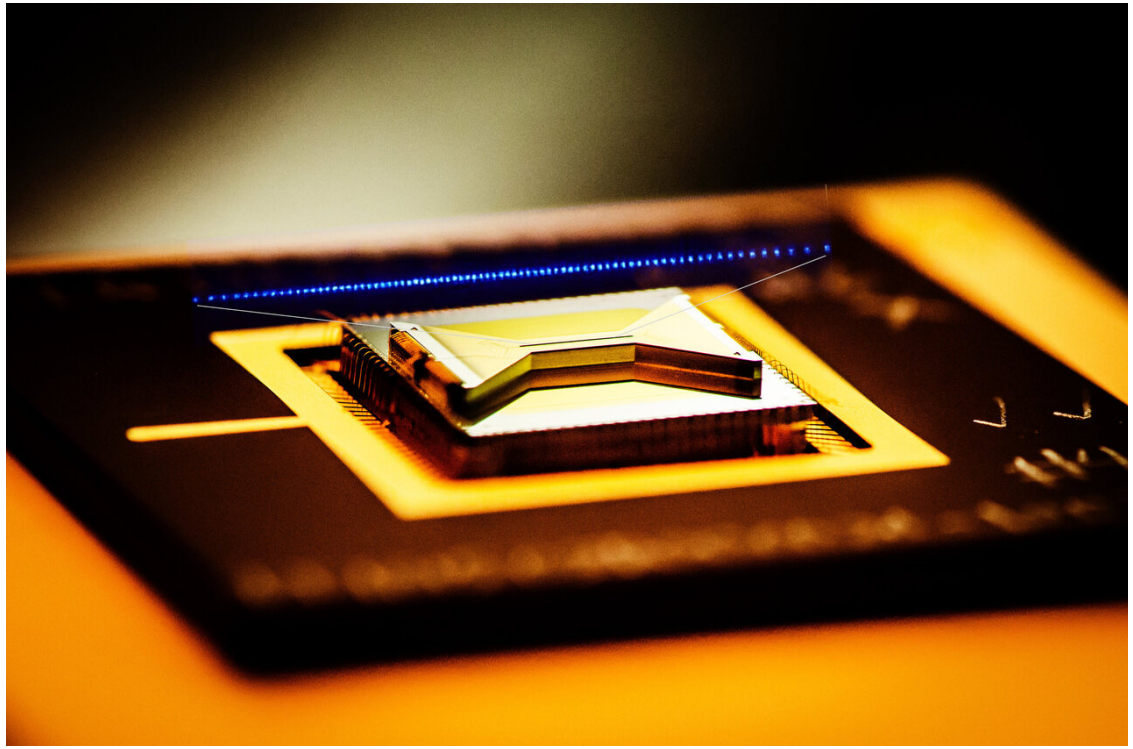
J. I. Cirac and P. Zoller, Phys. Today **57**, 38 (2004)





Pros and cons of trapped ion quantum computer

- Advantages
  - Long coherence time (10s seconds)
  - Best gate and readout fidelity (> 99.9%)
  - Perfect reproducibility
- Challenges
  - Absolute gate time is slow (10s us)
  - Difficult to scaleup



K. Hudek & E. Edwards/Univ. of Maryland/IonQ, Inc./JQI

Progress on trapped ion quantum computing

Organization	Designation	Year	# Qubits	T1 (s)	T2 (s)	Fid 1Q (%)	Fid 2Q (%)
IONQ	Harmony	2019	11	10-100	1	99.72	96.54
	Aria	2020	32	10-100	1	99.98	99.3
	Forte	2022	32	10-100	1	99.98	99.6
QUANTINUUM	H1-1	2022	20			99.996	99.8
	H1-2	2022	12			99.996	99.7

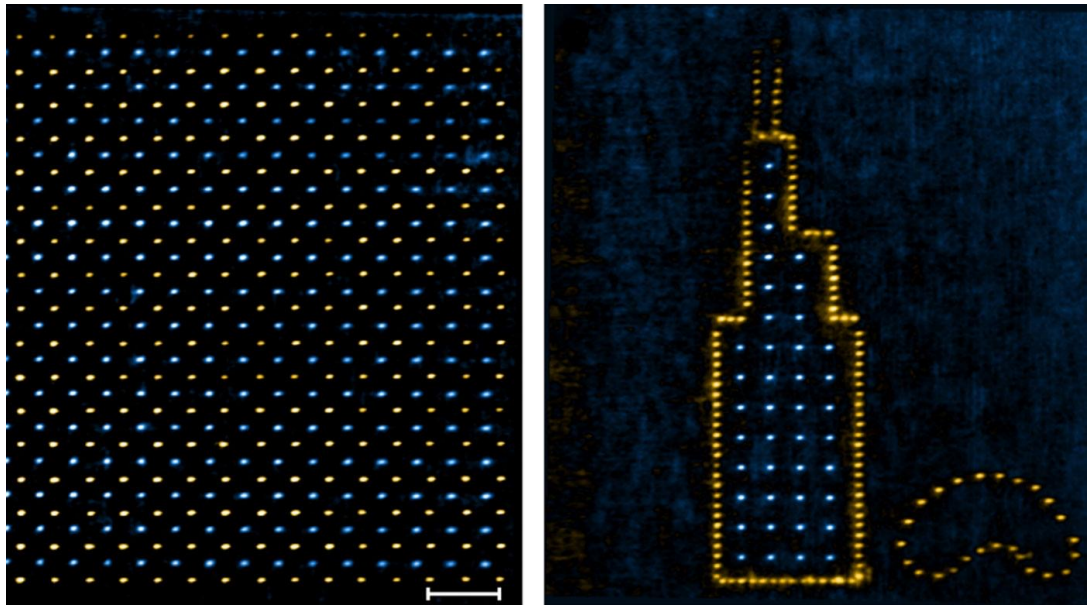
Find more in https://databaseline.tech/quantum.html

Quantum computer based on neutral atoms

- Atoms of interest for quantum computing
  e.g., Rb, Cs
- Quantum information can be encoded in
  e.g., hyperfine states
- Trapping of neutral atoms
  e.g., optical tweezer

  Arthur Ashkin
  Nobel prize in physics 2018

- Advantages
  Long lifetime (10s s), large scale
- Challenges
  Slow gates (ms)



K. Singh *et al.*, Phys. Rev. X **12**, 011040 (2022)

Organization	Designation	Year	# Qubits
ColdQuanta	Hilbert	2024	1000
PASQAL		2022	324
QuEra	Aquila	2022	256

National Quantum Initiative (2018)

- Accelerate research and development in quantum science and technology
- Facilitate collaboration between government agencies, industry, and academic researchers
- 13 quantum information science centers

Q-NEXT
NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING

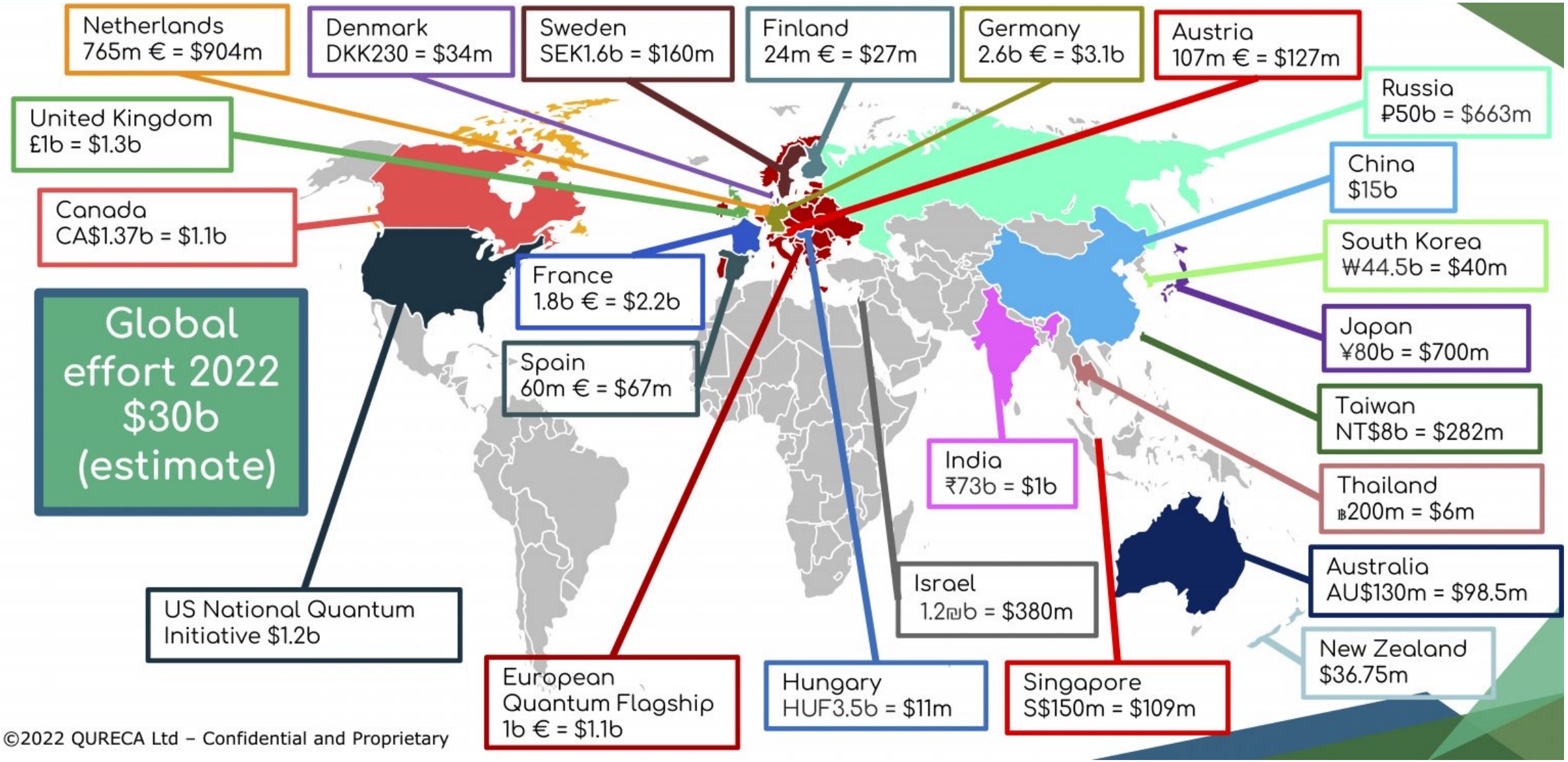
C²QA
Co-design Center for Quantum Advantage

SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

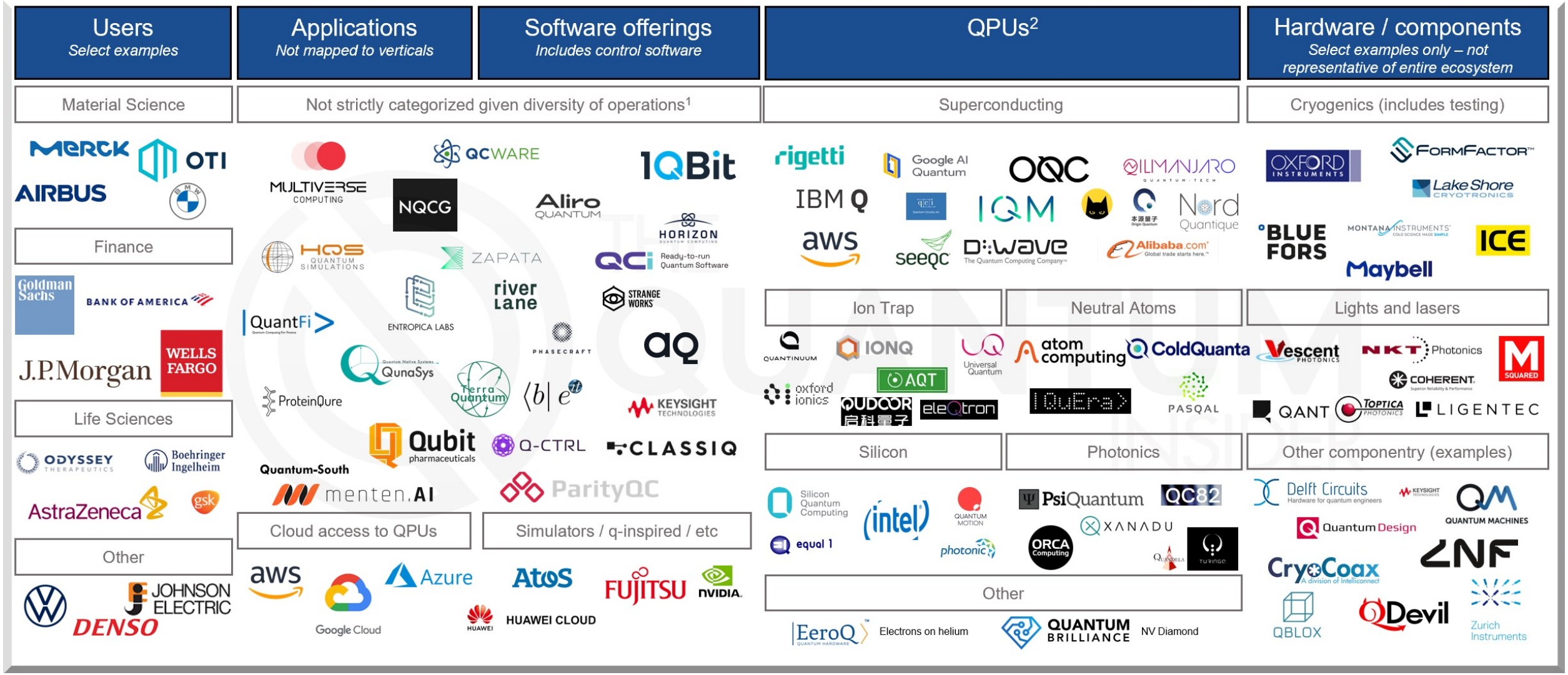
QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem

QUANTUM SCIENCE CENTER

Quantum effort worldwide



Market overview of quantum computing



Quantum Computing Market map – The Quantum Insider

Workforce development in quantum information science

- Diverse background

  Physicists, electrical engineers, computer scientists, material scientists, chemists, mathematicians…

- Many opportunities
  - Summer schools
  - Internships
  - Online education

Lecture VIII: Current progress and ecosystem in quantum computing

- Overview of current status of quantum computer
- Quantum ecosystem and workforce development