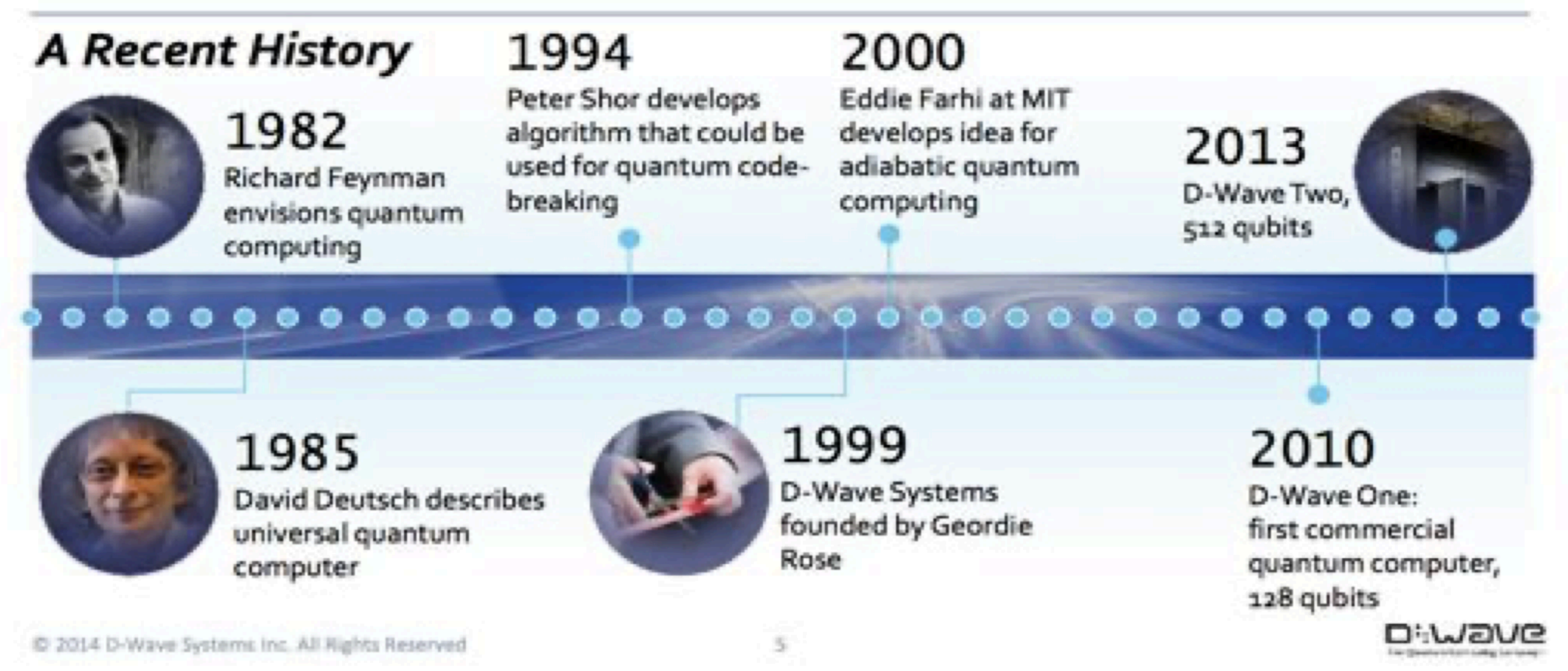
An Introduction to Quantum Computing

Fabio A. González
Universidad Nacional de Colombia

Quantum Computer Programming 2021-2

Past, present and future

Past

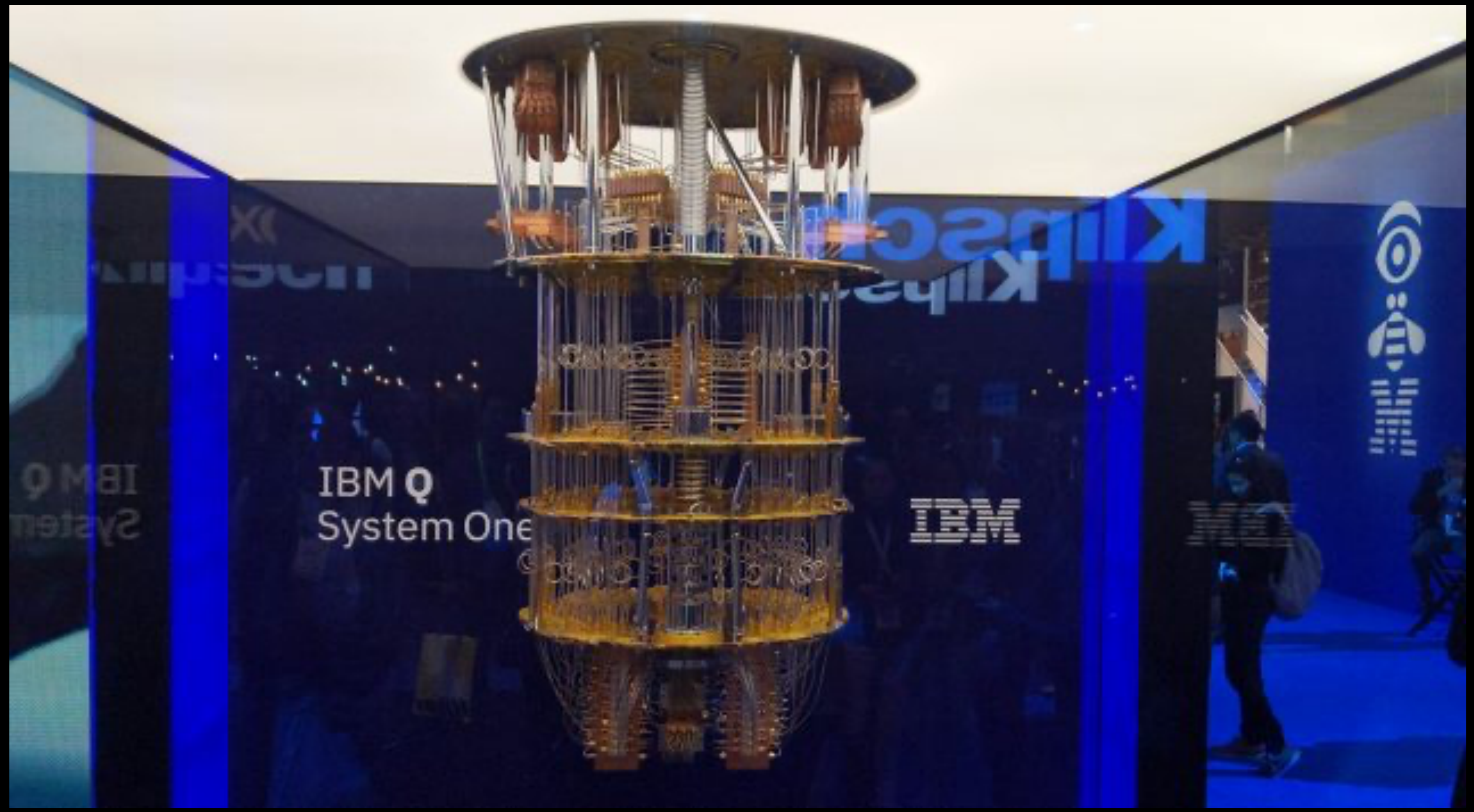


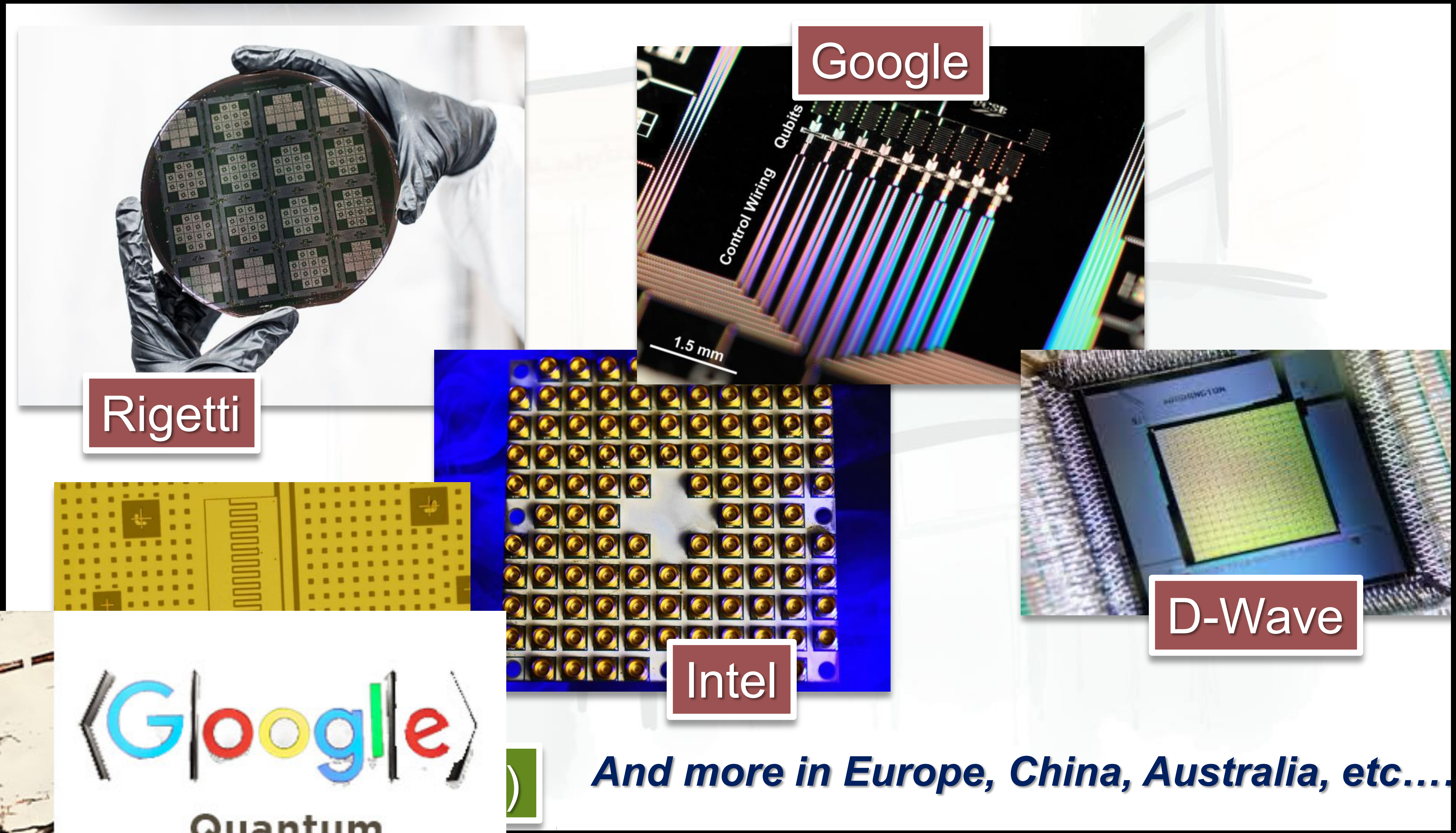
LinkedIn SlideShare: 17 Nov 2014 – "Quantum Computing: Welcome to the Future" by Vern Brownell CEO

https://catonmat.net/ftp/simulating-physics-with-computers-richard-feynman.pdf

Present

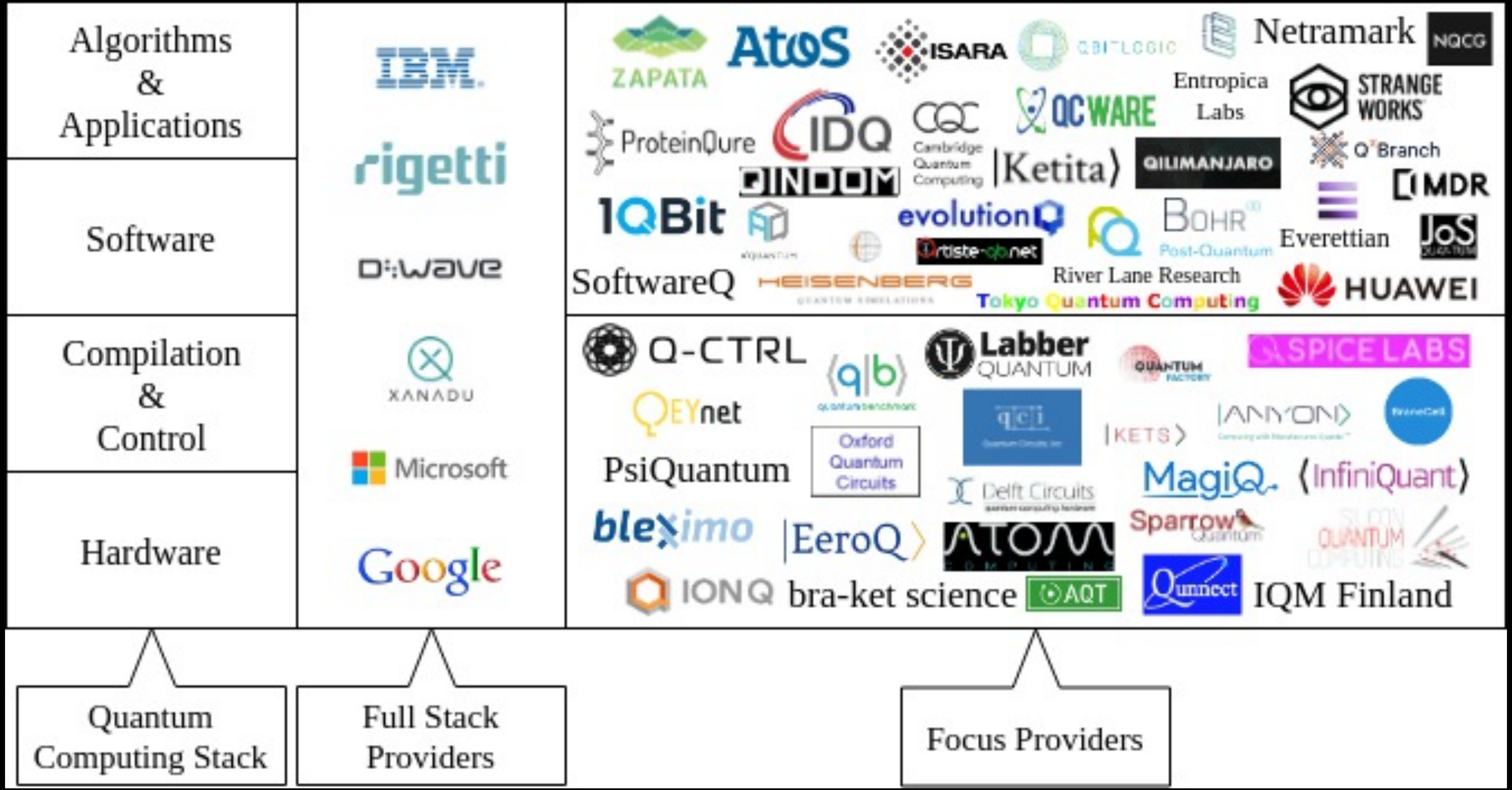
Several companies building quantum hardware





Present

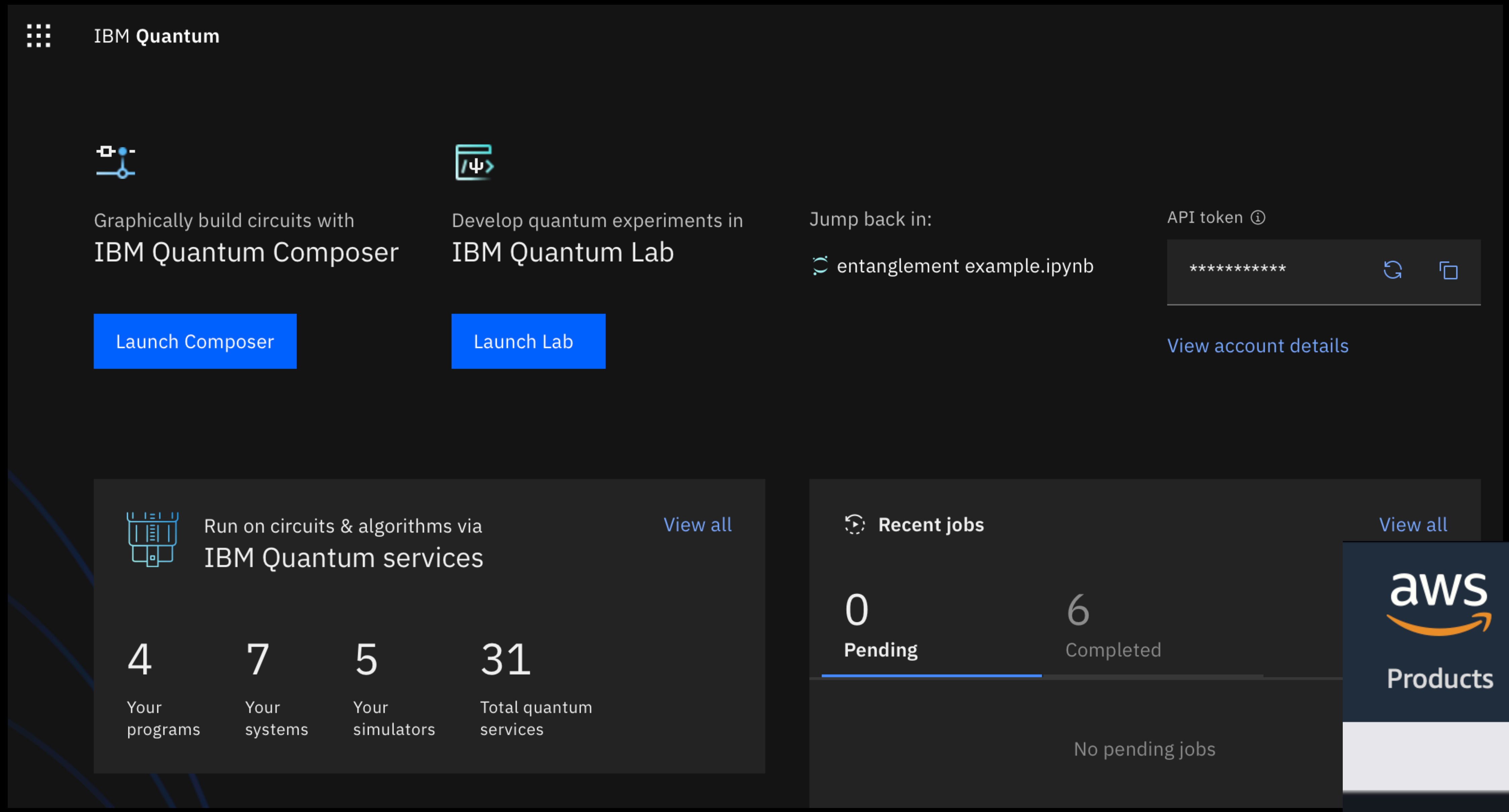
Different quantum computing frameworks

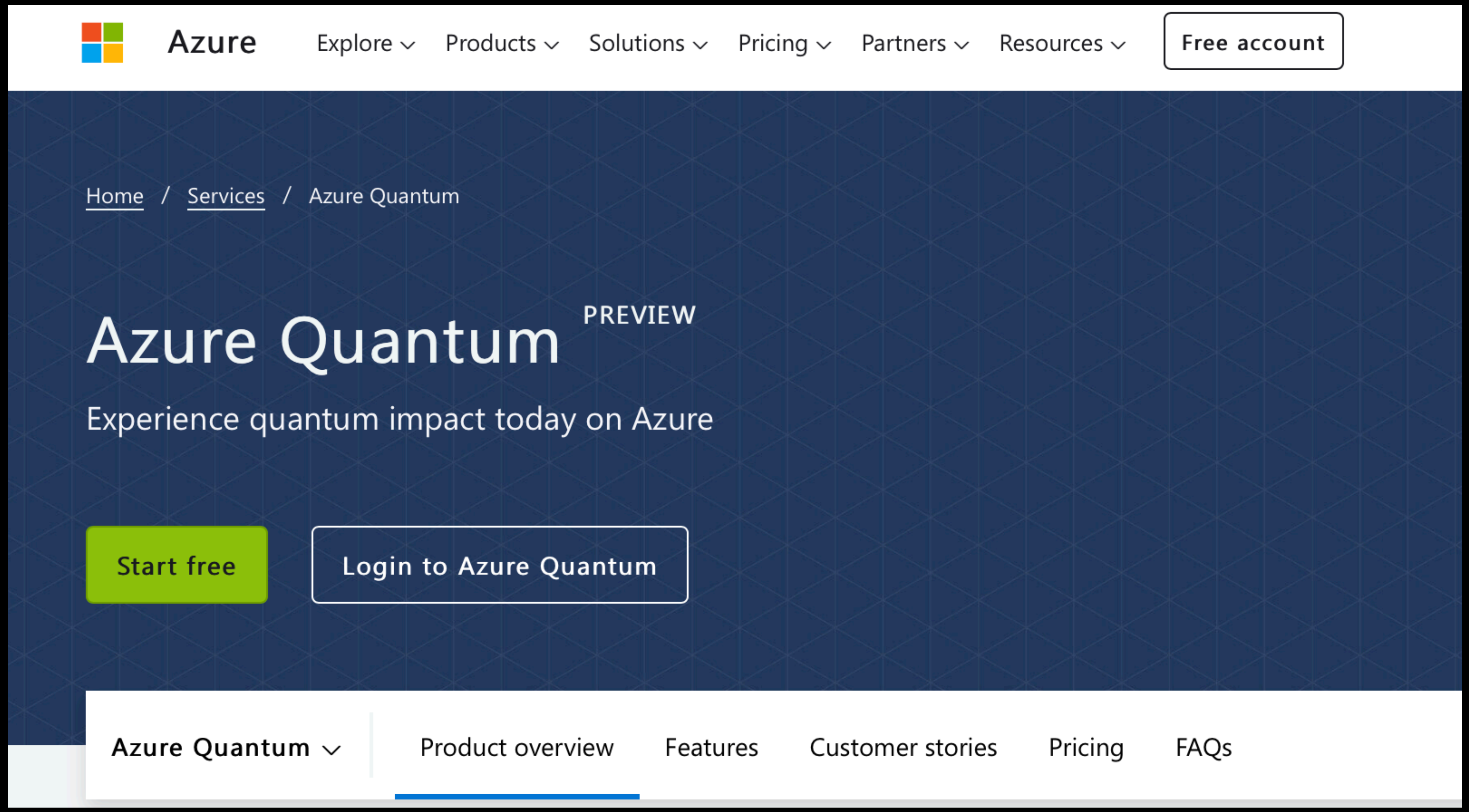


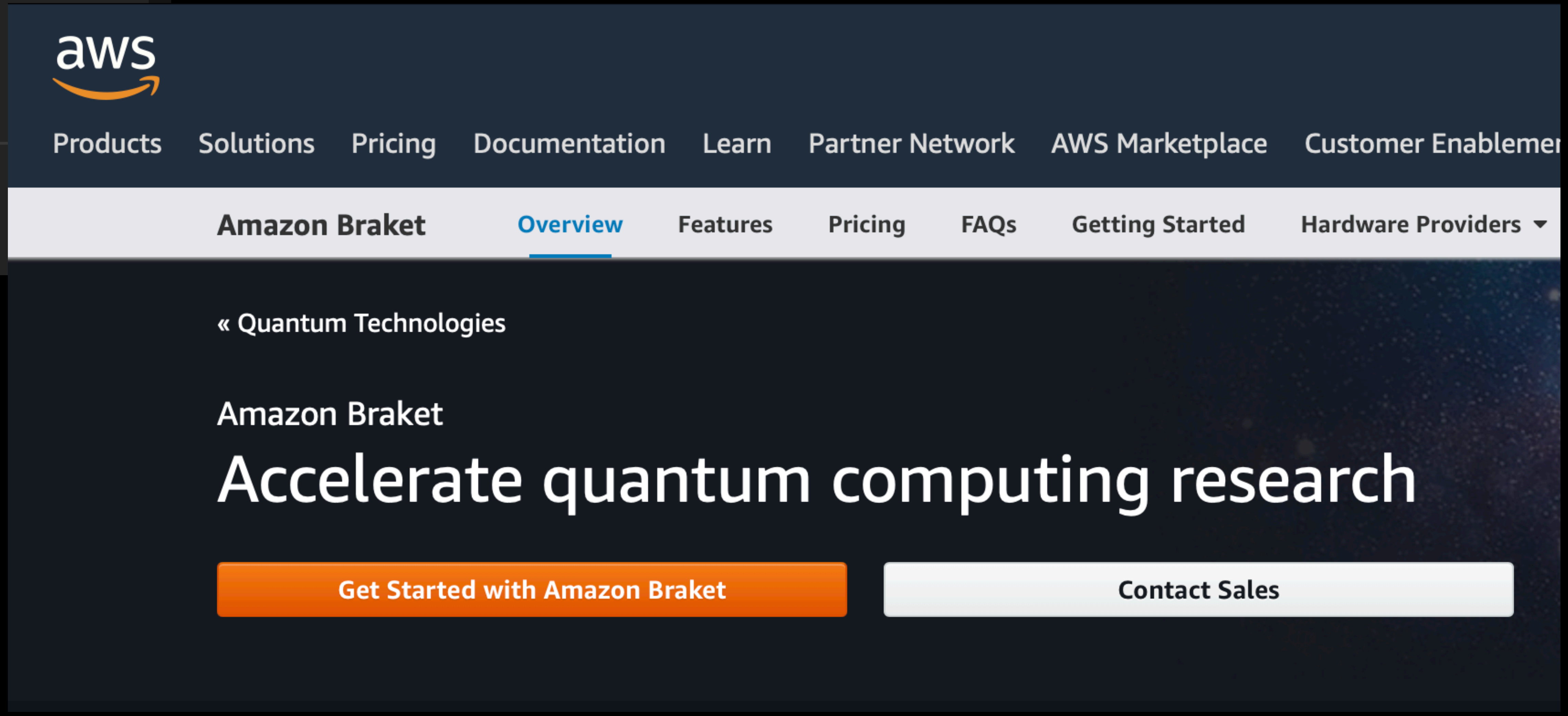
Source: https://quantumcomputingreport.com/review-of-the-cirq-quantum-software-framework/

Present

Quantum cloud services

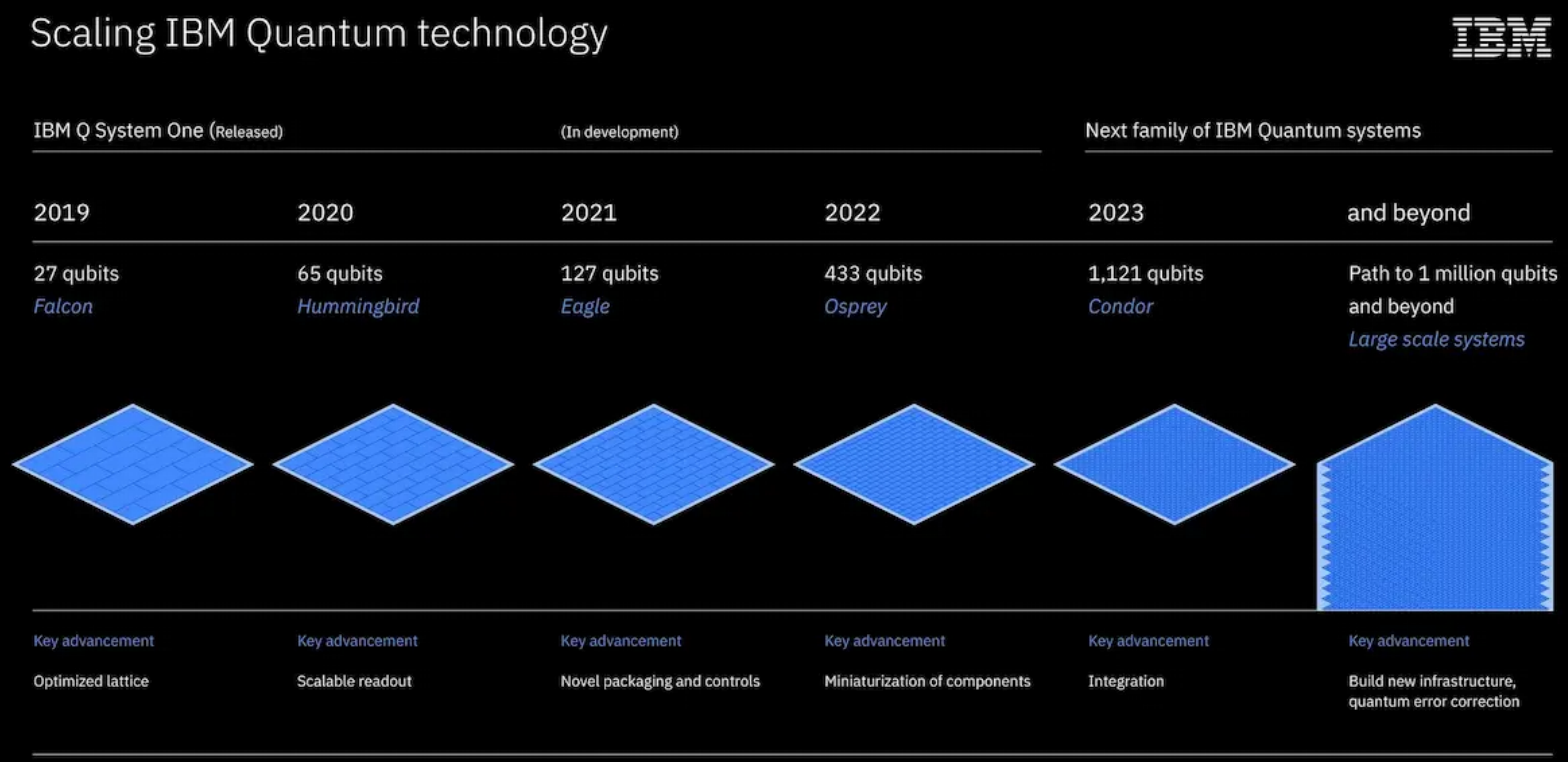




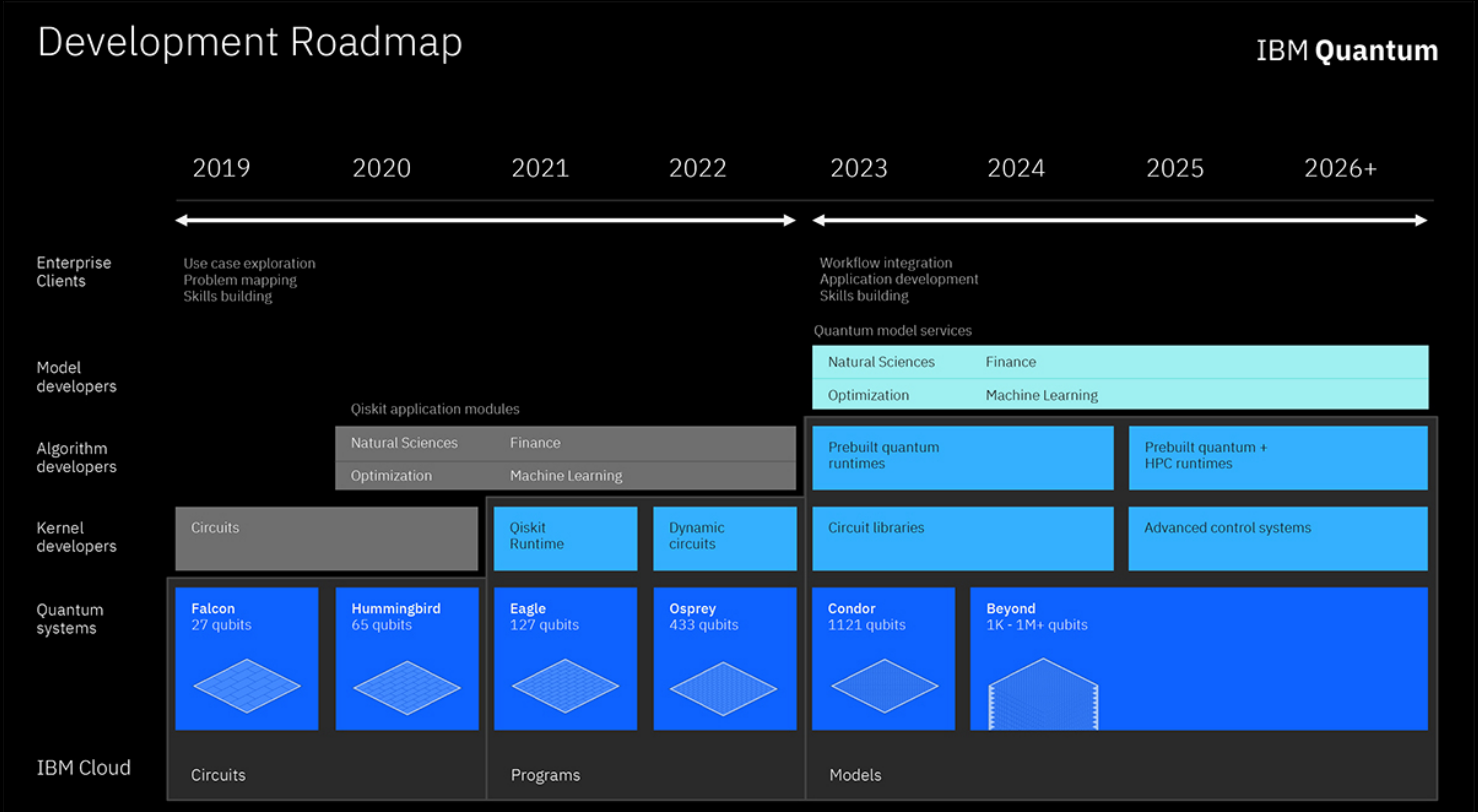


Future

IBM’s quantum roadmap



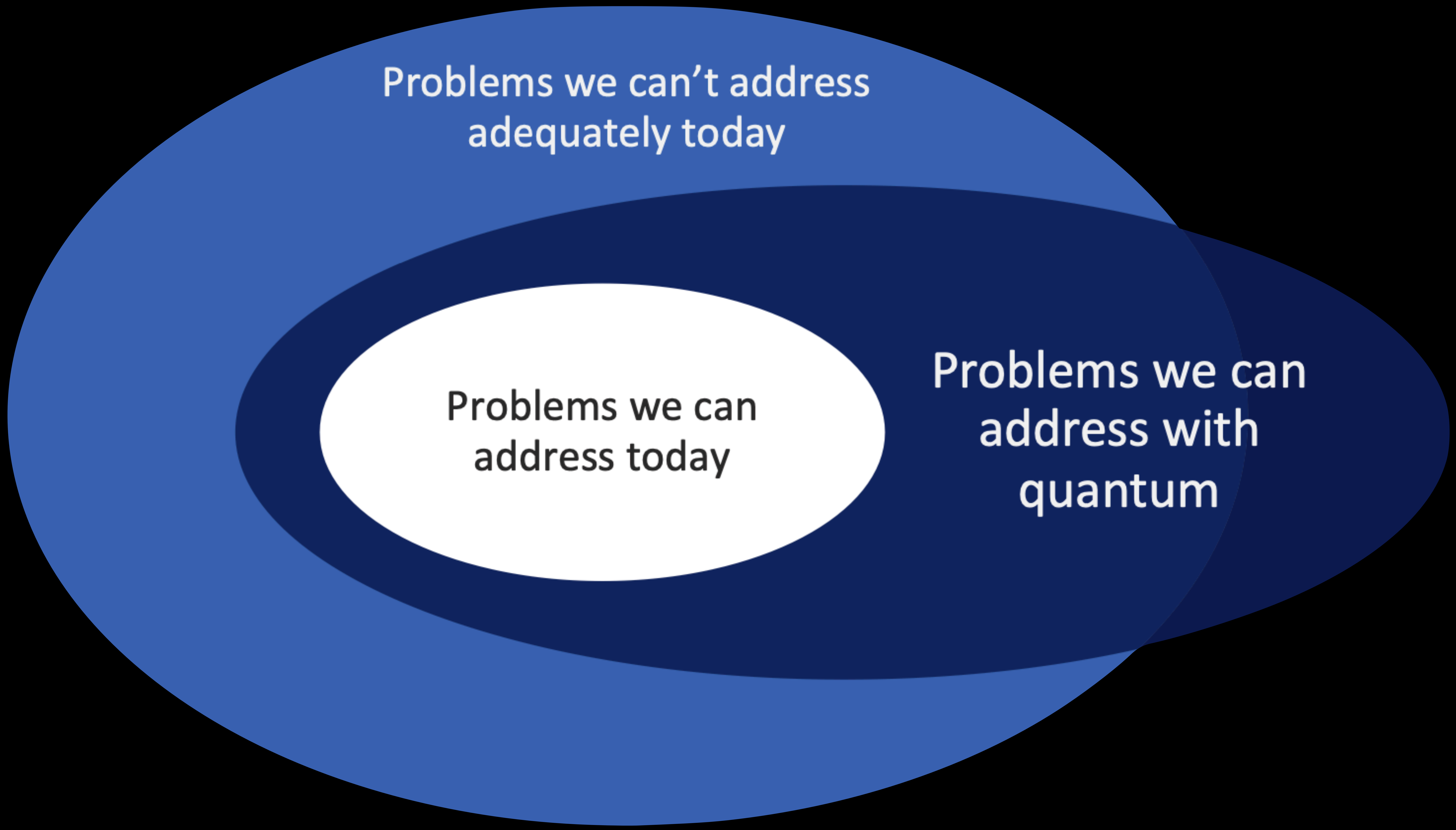
Future



Development Roadmap
IBM Quantum
2019
2020
2021
2022
2023
2024
2025
2026+
Enterprise Clients
Use case exploration
Problem mapping
Skills building
Workflow integration
Application development
Skills building
Model developers
Quantum model services
Natural Sciences
Finance
Optimization
Machine Learning
Algorithm developers
Qiskit application modules
Natural Sciences
Finance
Optimization
Machine Learning
Prebuilt quantum runtimes
Prebuilt quantum + HPC runtimes
Kernel developers
Circuits
Qiskit Runtime
Dynamic circuits
Circuit libraries
Advanced control systems
Quantum systems
Falcon
27 qubits
Hummingbird
65 qubits
Eagle
127 qubits
Osprey
433 qubits
Condor
1121 qubits
Beyond
1K - 1M+ qubits
IBM Cloud
Circuits
Programs
Models

Why quantum computing?

Problems



Source: https://ispd.cc/ispd2022/slides/2021/protected/9_3_Stok.pdf

Are quantum computers “faster”?

Multiplication

$p * q = N$

How long does it take to multiply 2048 bit integers ?

Classical Cost of multiplication [1]:
~ 0.0025s

[1]: A. Emerencia,. "Multiplying huge integers using fourier transforms." (2007).

Quantum Cost of multiplication [2]:
~ 75.0000s

[2]: C. Gidney, Craig, and M. Ekerå. arXiv preprint arXiv:1905.09749 (2019).

Source: https://ispd.cc/ispd2022/slides/2021/protected/9_3_Stok.pdf

Are quantum computers “faster”?

Factorization

$N = p * q$

How long does it take to factor 2048 bit integers ?

Classical Cost of factoring [1]:

~ 4.7 billion CPU years

(largest factored number RSA-768 bit for approx. 1500 CPU years)

[1]: Kleinjung, Thorsten, et al. "Factorization of a 768-bit RSA modulus." Annual Cryptology Conference. Springer, Berlin, Heidelberg, 2010.

Quantum Cost of factoring [2]:

~ 8 hours

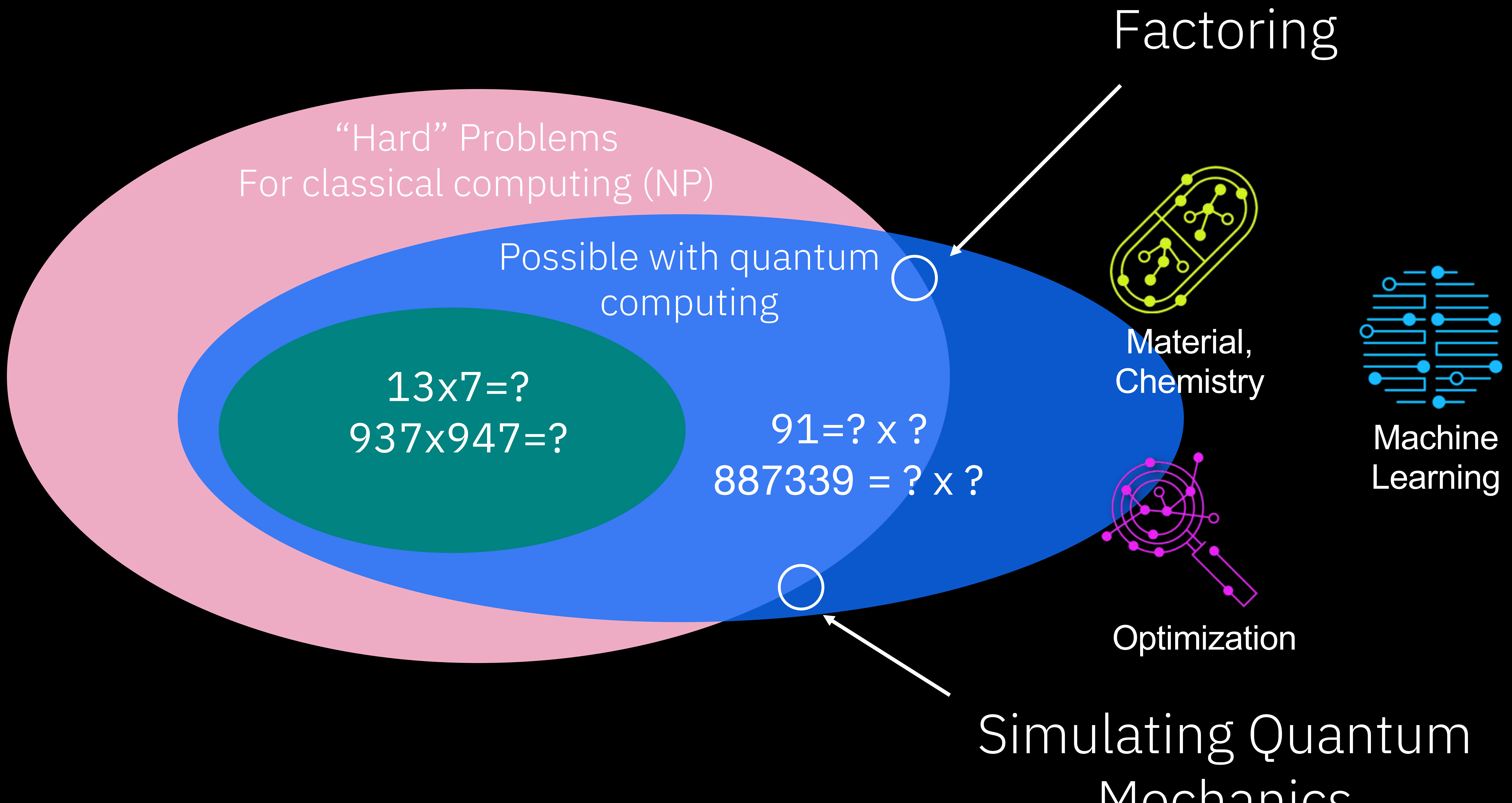
[2]: C. Gidney, Craig, and M. Ekerå. arXiv preprint arXiv:1905.09749 (2019).

Source: https://ispd.cc/ispd2022/slides/2021/protected/9_3_Stok.pdf

Applications

- **Chemestry, molecular simulation:** drug discovery, new fertilizers, more efficient batteries
- **Optimization**: better financial models, transport optimization
- **Machine learning**: quantum machine learning

Problems



Source: https://indico.cern.ch/event/719844/contributions/3019718/attachments/1749768/2835637/CERN_Tavernelli4_1.pdf

How quantum computers work?

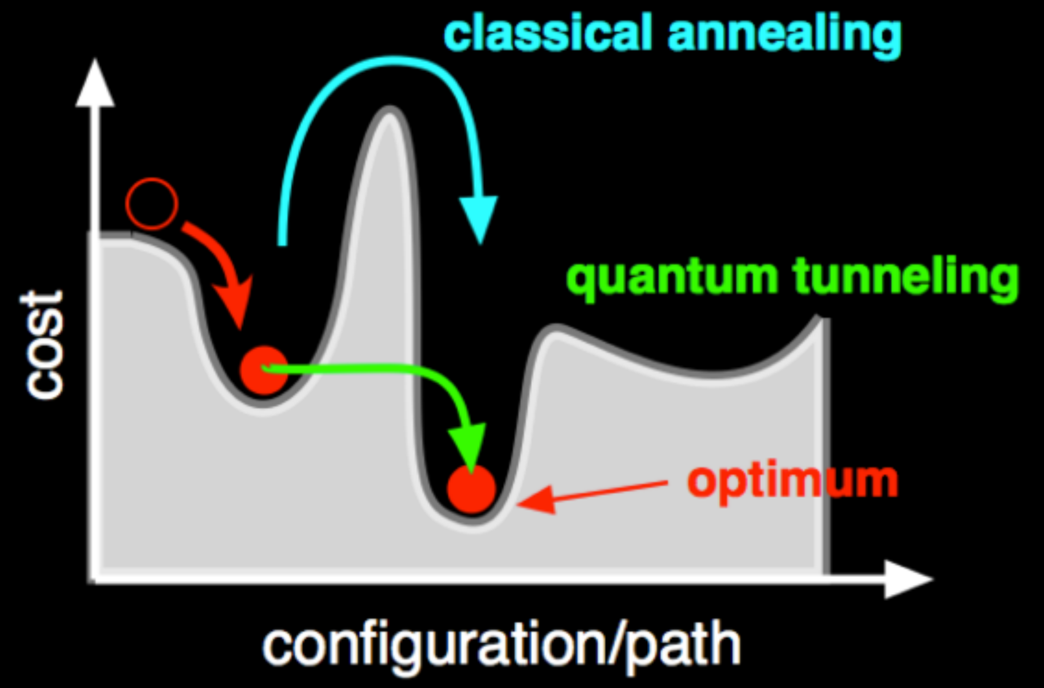
Quantum computers types

Noisy Intermediate-Scale Quantum

Quantum Annealing

Optimization Problems

- Machine learning
- Fault analysis
- Resource optimization
- etc…

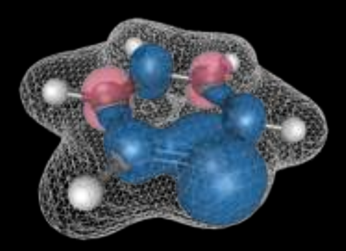


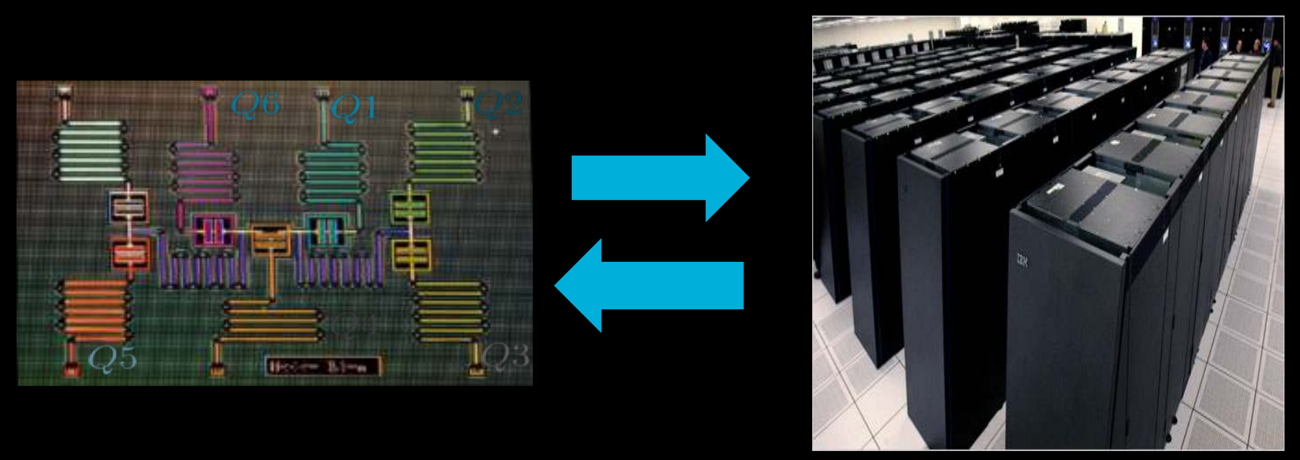
Many 'noisy' qubits can be built;
large problem class in optimization;
amount of quantum speedup unclear

Approximate NISQ-Comp.

Simulation of Quantum Systems, Optimization

- Material discovery
- Quantum chemistry
- Optimization
  (logistics, time scheduling,…)
- Machine Learning



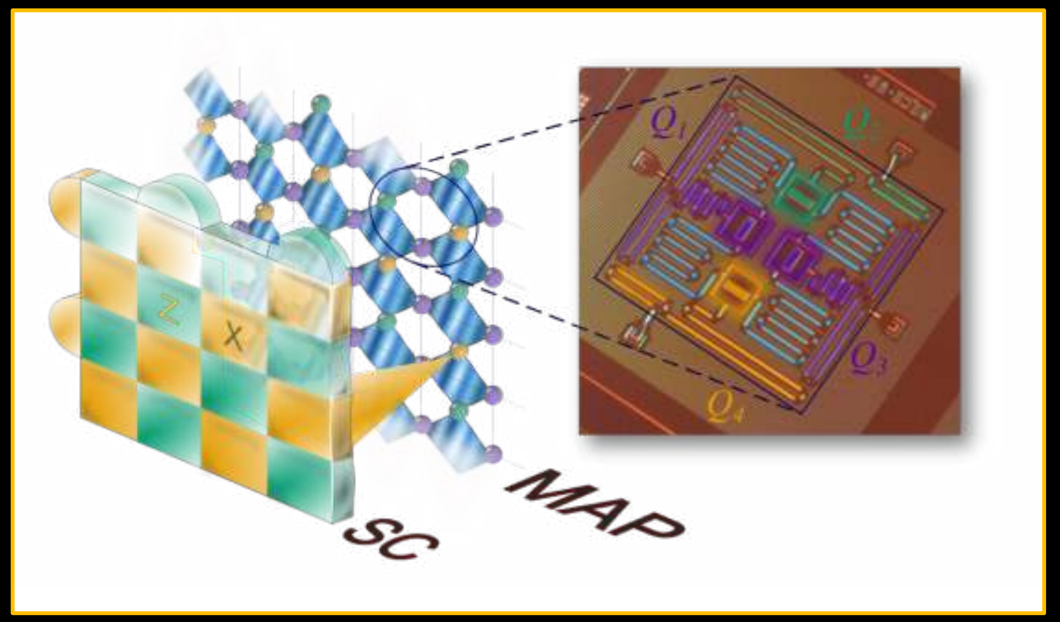


Hybrid quantum-classical approach;
already 50-100 "good" physical qubits
could provide quantum speedup.

Fault-tolerant Universal Q-Comp.

Execution of Arbitrary Quantum Algorithms

- Algebraic algorithms
  (machine learning, cryptography,…)
- Combinatorial optimization
- Digital simulation of quantum systems



Surface Code: Error correction in a Quantum Computer

Proven quantum speedup;
error correction requires significant qubit overhead.

Source: https://indico.cern.ch/event/719844/contributions/3019718/attachments/1749768/2835637/CERN_Tavernelli4_I.pdf

Quantum annealing

Adiabatic quantum computer

H_B = Initial Hamiltonian, which ground state is easy to find

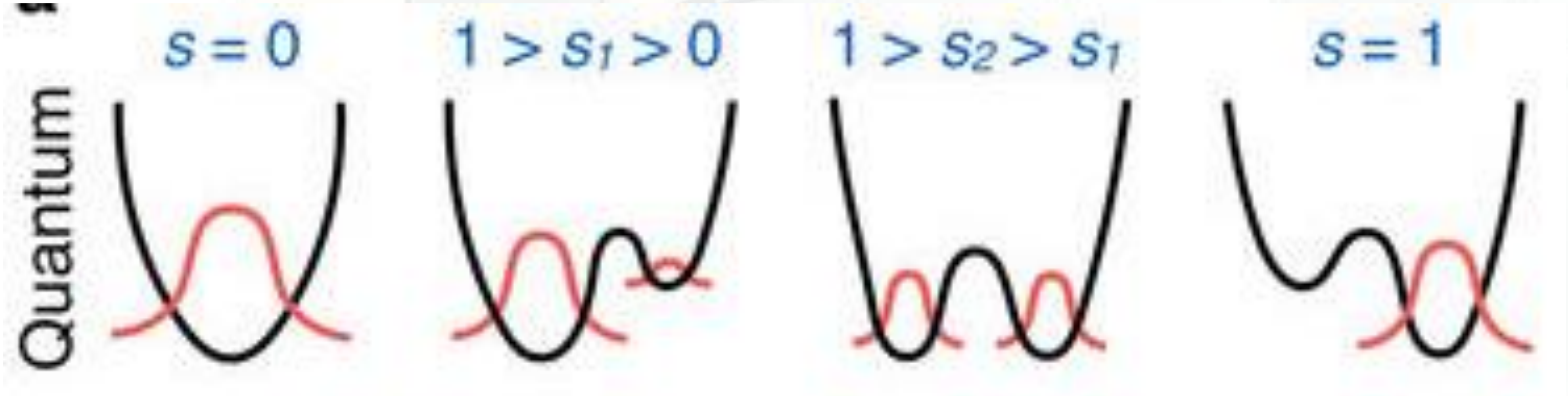
H_P = Problem Hamiltonian, whose ground state encodes the solution to the problem

H(s) = Combined Hamiltonial to evolve slowly:

A(s) decrease smoothly and monotonically

B(s) increase smothly and monotonically

$$H(s) = A(s)H_B + B(s)H_P$$



Source: https://indico.cern.ch/event/865287/attachments/1971786/3280301/Lecture_1_v1.pdf

Universal quantum computer

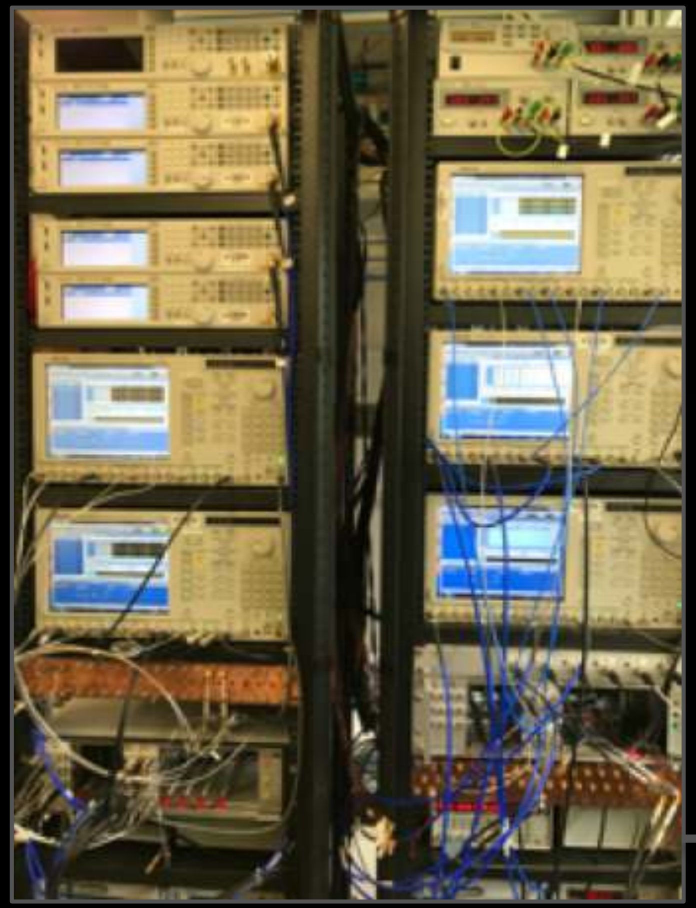
DiVincenzo’s Criteria

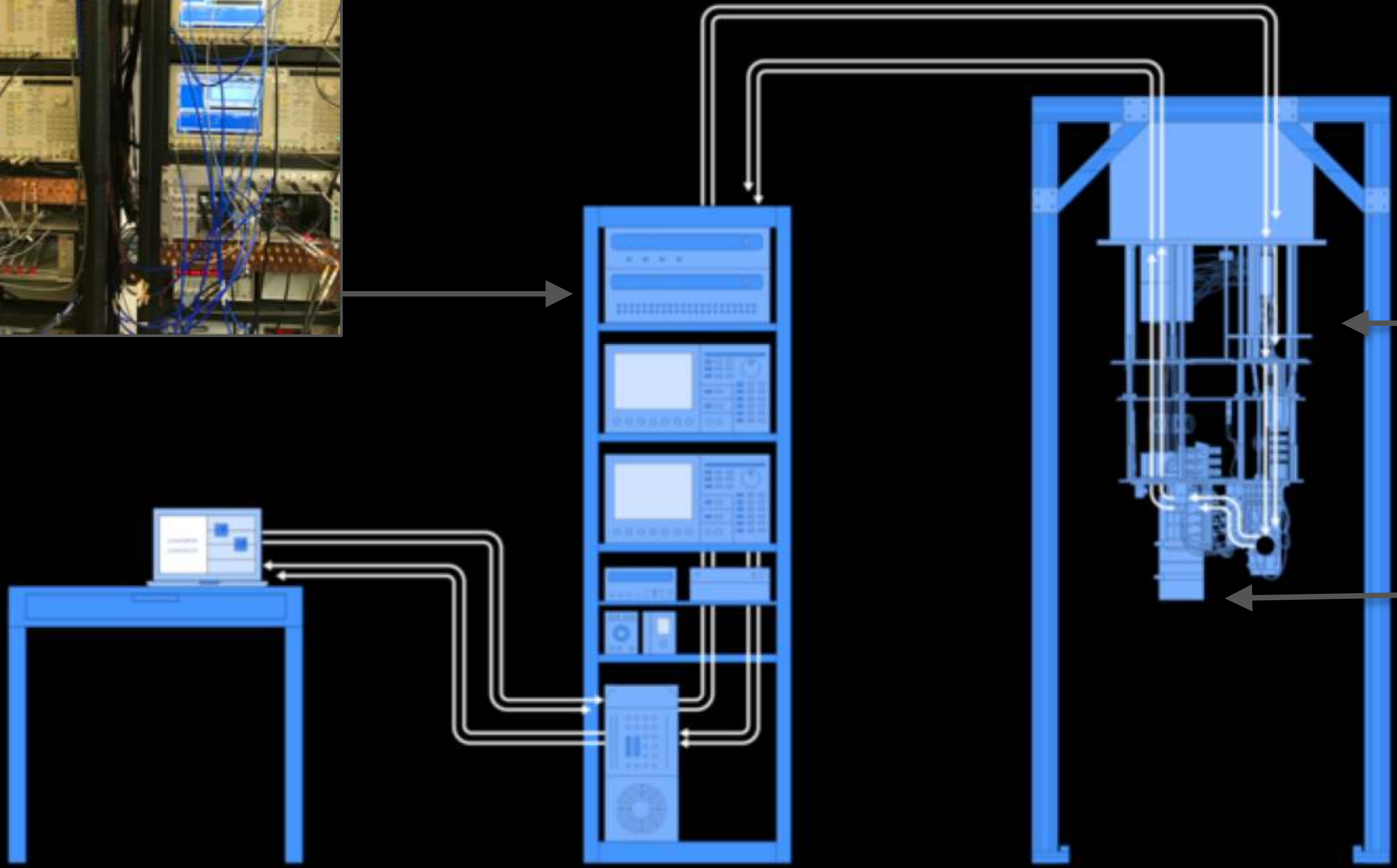
- A scalable physical system with well characterized qubits.
- The ability to initialize the state of the qubits to a simple fiducial state, such as |000....000>
- Long relevant decoherence times, much longer than the gate operation time.
- A “universal” set of quantum gates.
- A qubit-specific measurement capability.

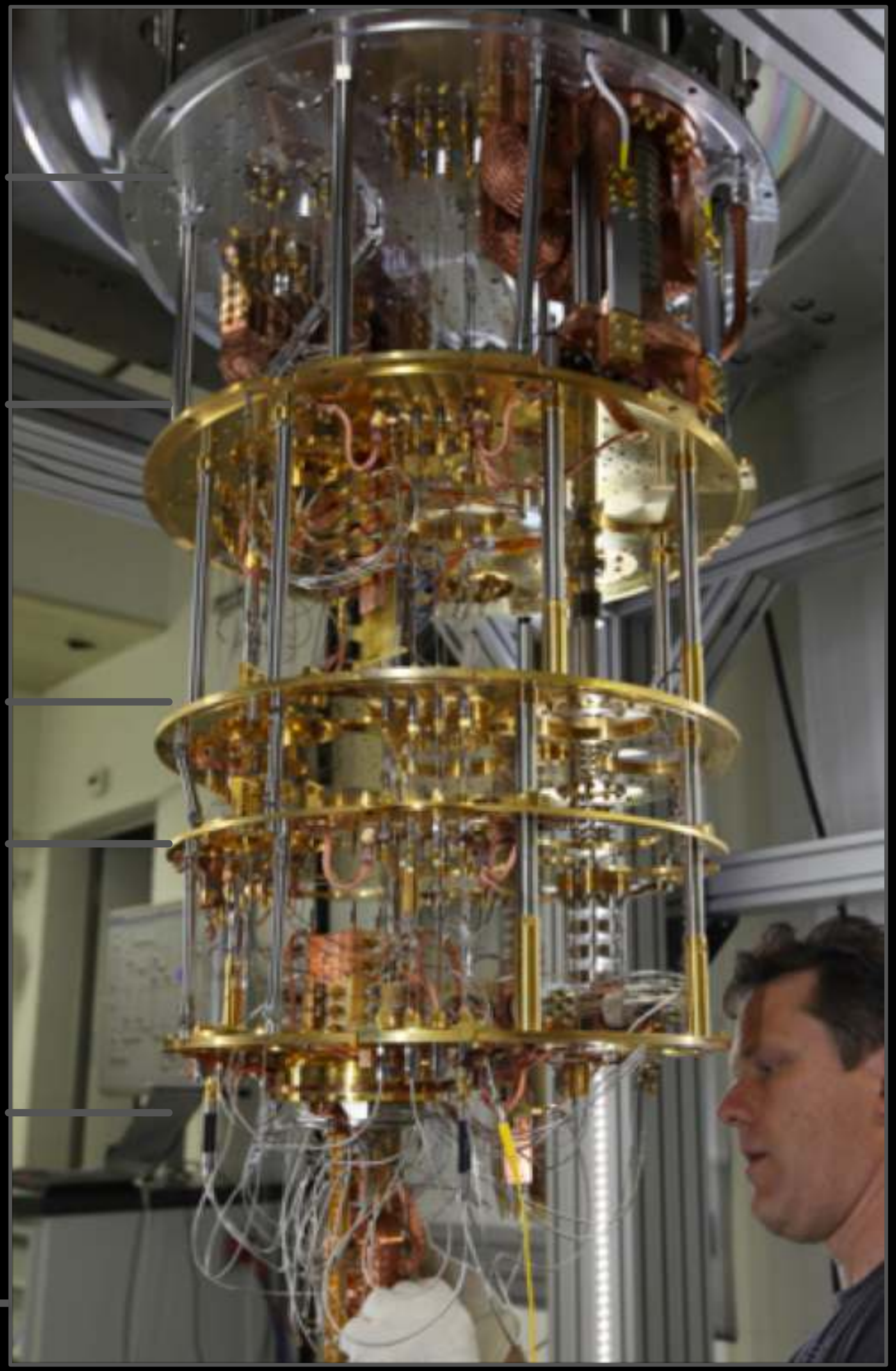
DiVincenzo, D. P. (2000). The physical implementation of quantum computation. Fortschritte der Physik: Progress of Physics, 48(9-11), 771-783.

Inside an IBM Q quantum computing system

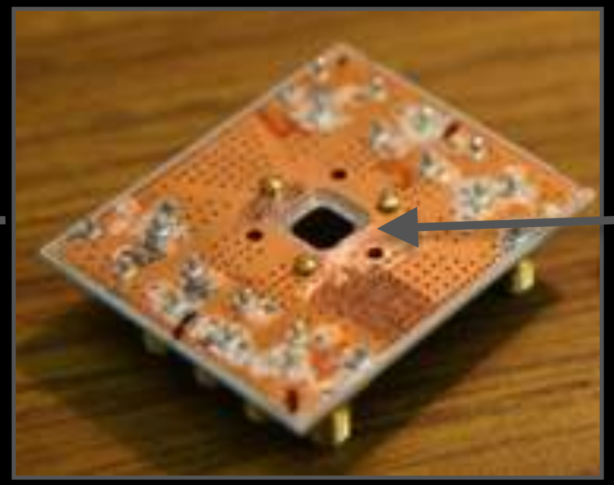
Microwave electronics



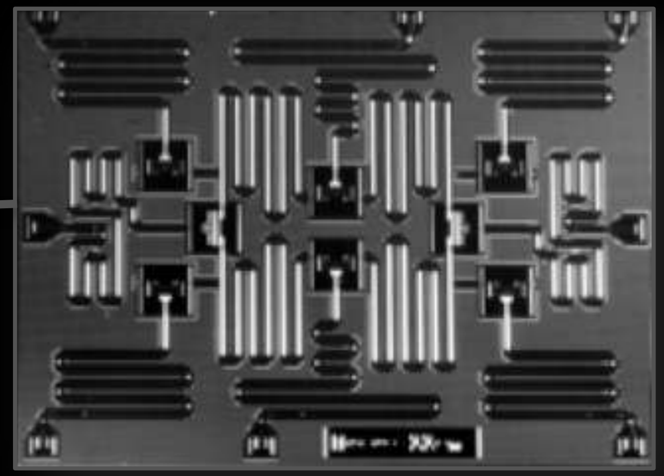




Refrigerator to cool qubits to 10 - 15 mK with a mixture of ^3He and ^4He



PCB with the qubit chip at 15 mK protected from the environment by multiple shields



Chip with superconducting qubits and resonators

Source: https://indico.cern.ch/event/719844/contributions/3019718/attachments/1749768/2835637/CERN_Tavernelli4_l.pdf

The Quantum Era of Accelerated Discovery

Dario Gil, Ph.D.

Director of IBM Research

IBM Quantum

https://youtu.be/zOGNoDO7mcU?t=650 https://youtu.be/zOGNoDO7mcU?t=1887

The power of quantum computing is more than the number of qubits

Quantum Volume depends upon

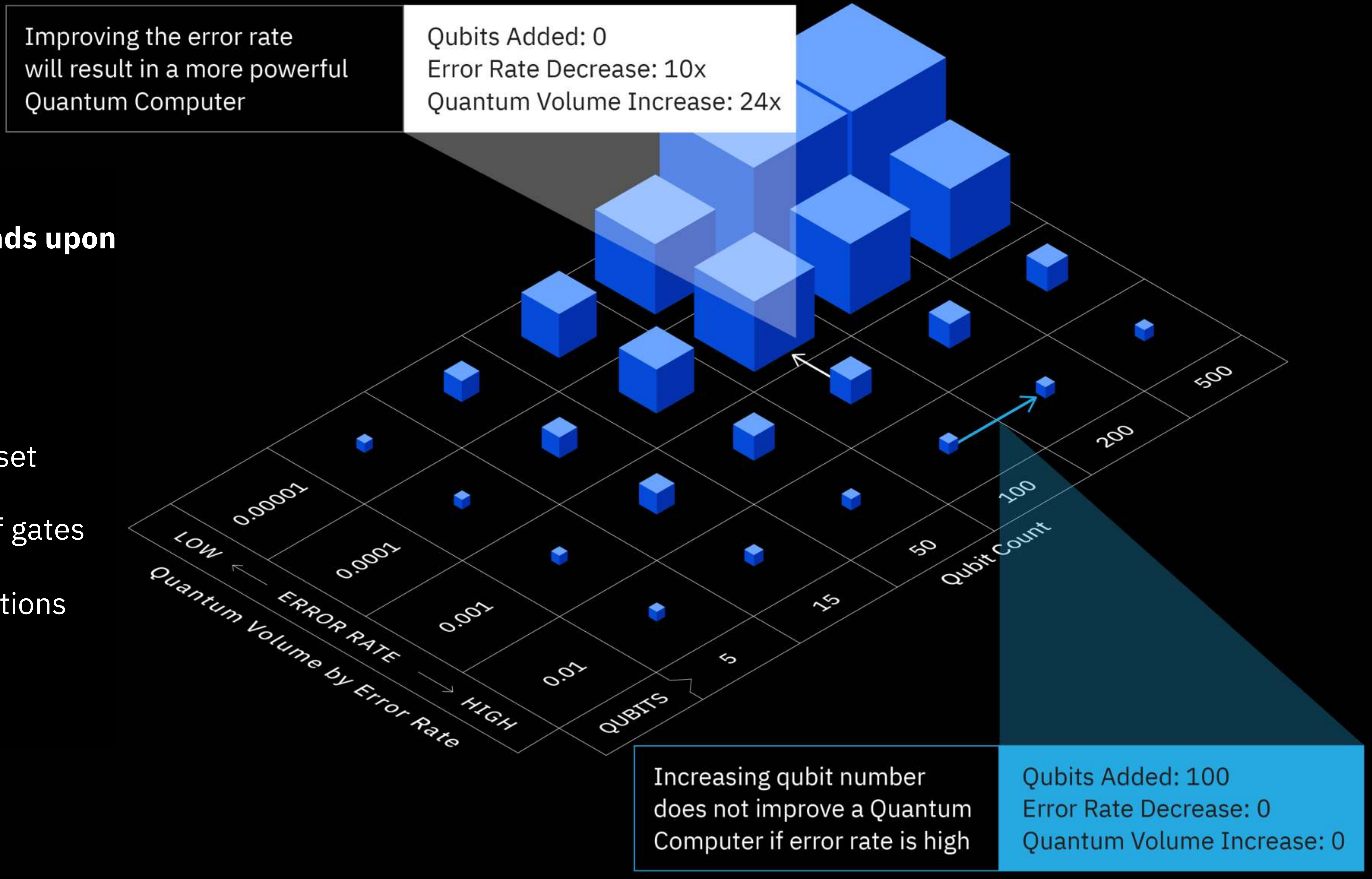
Number of physical QBs

Connectivity among QBs

Available hardware gate set

Error and decoherence of gates

Number of parallel operations



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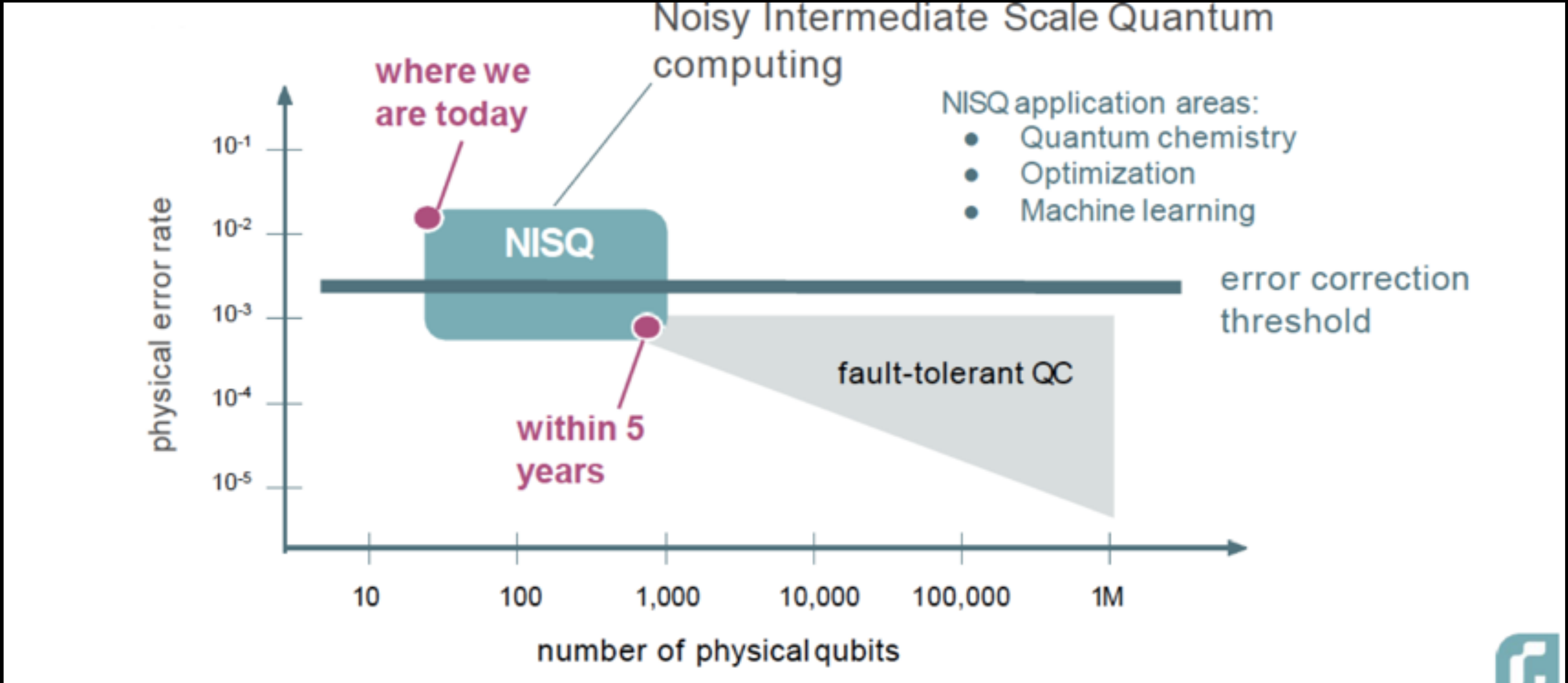
Fault-tolerant universal quantum computer



"Quantum computing in the NISQ era and beyond" Preskill, 2018 https://arxiv.org/abs/1801.00862

Quantum supremacy

Article

Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5

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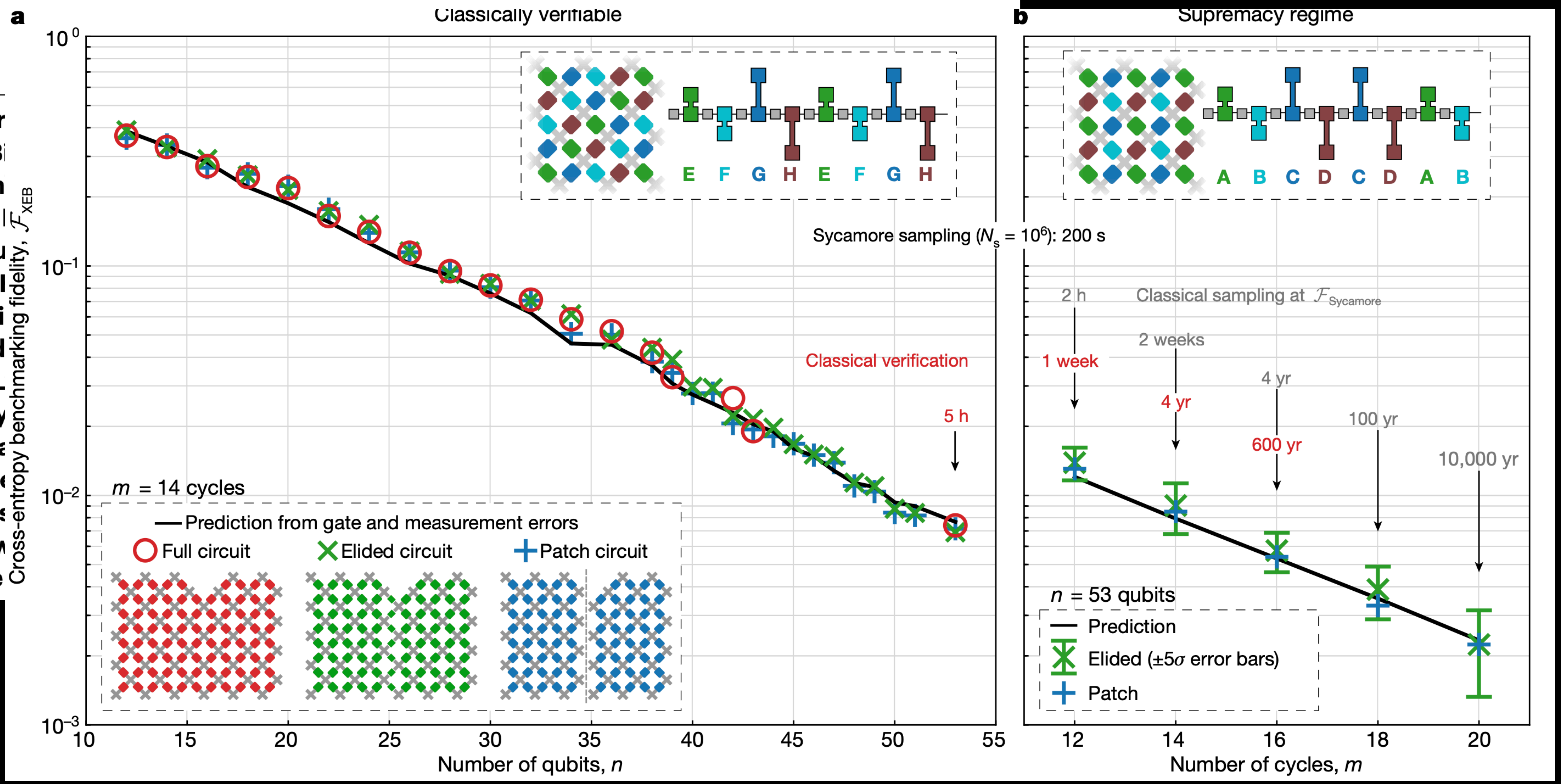
Frank Ar
Rupak Bi
Yu Chen
Edward I
Keith Gu
Markus I
Zhang Ji
Alexand
Dmitry L
Anthony
Ofer Naa
Andre P
Nicholas
Matthew
Z. Jamie



https://youtu.be/-ZNEzzDcllU

Quantum information

Quantum information

Basic concepts

- Qubit
- Superposition
- Measurement
- Quantum operations
- Entanglement

The Quantum Era of Accelerated Discovery

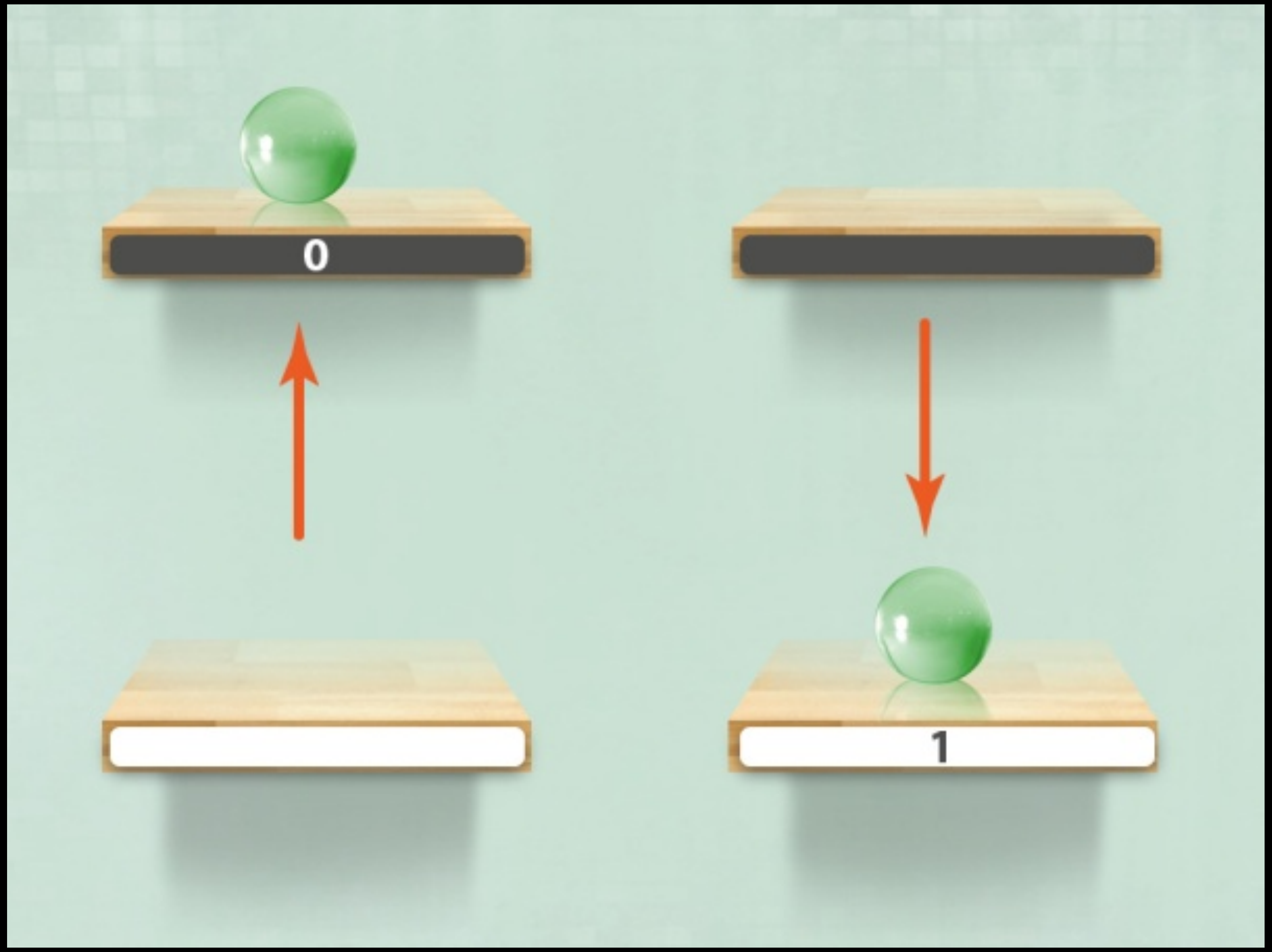
Dario Gil, Ph.D.

Director of IBM Research

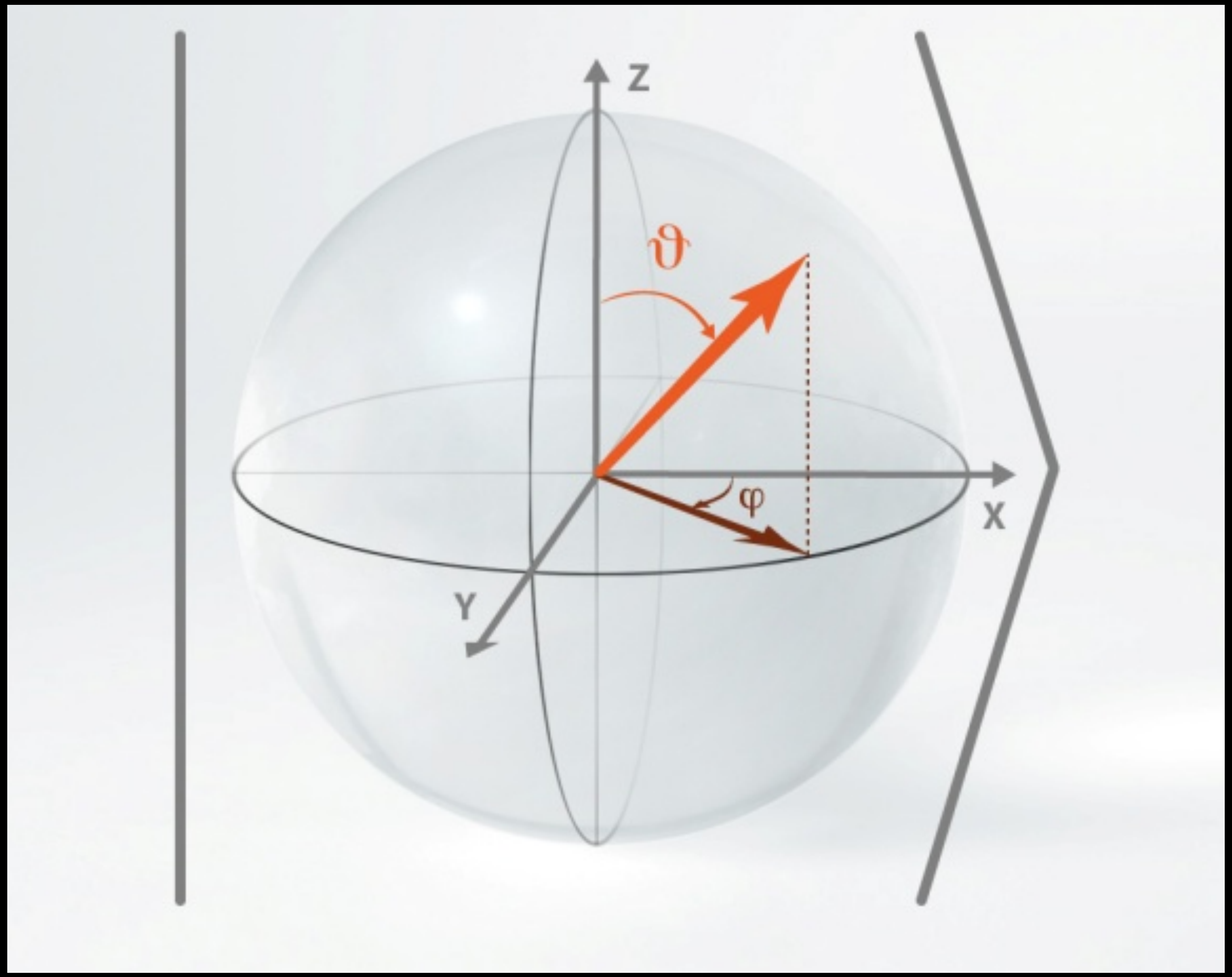
https://youtu.be/zOGNoDO7mcU?t=156

Bit vs Qubit

Classical bit

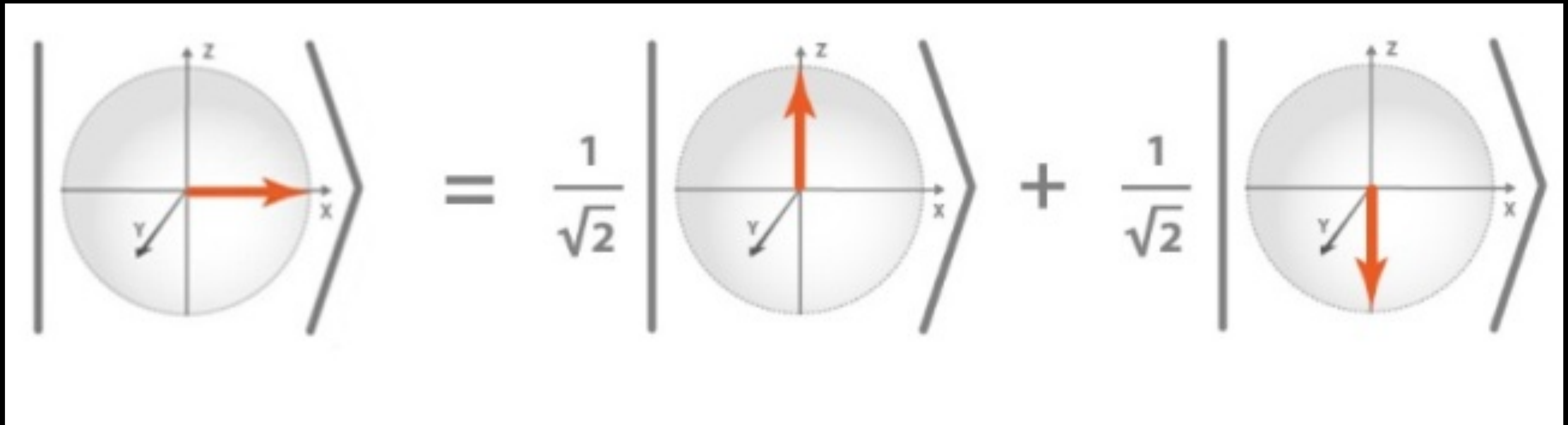


Qubit



Dür, W., & Heusler, S. (2013). What we can learn about quantum physics from a single qubit. arXiv preprint arXiv:1312.1463.

Superposition

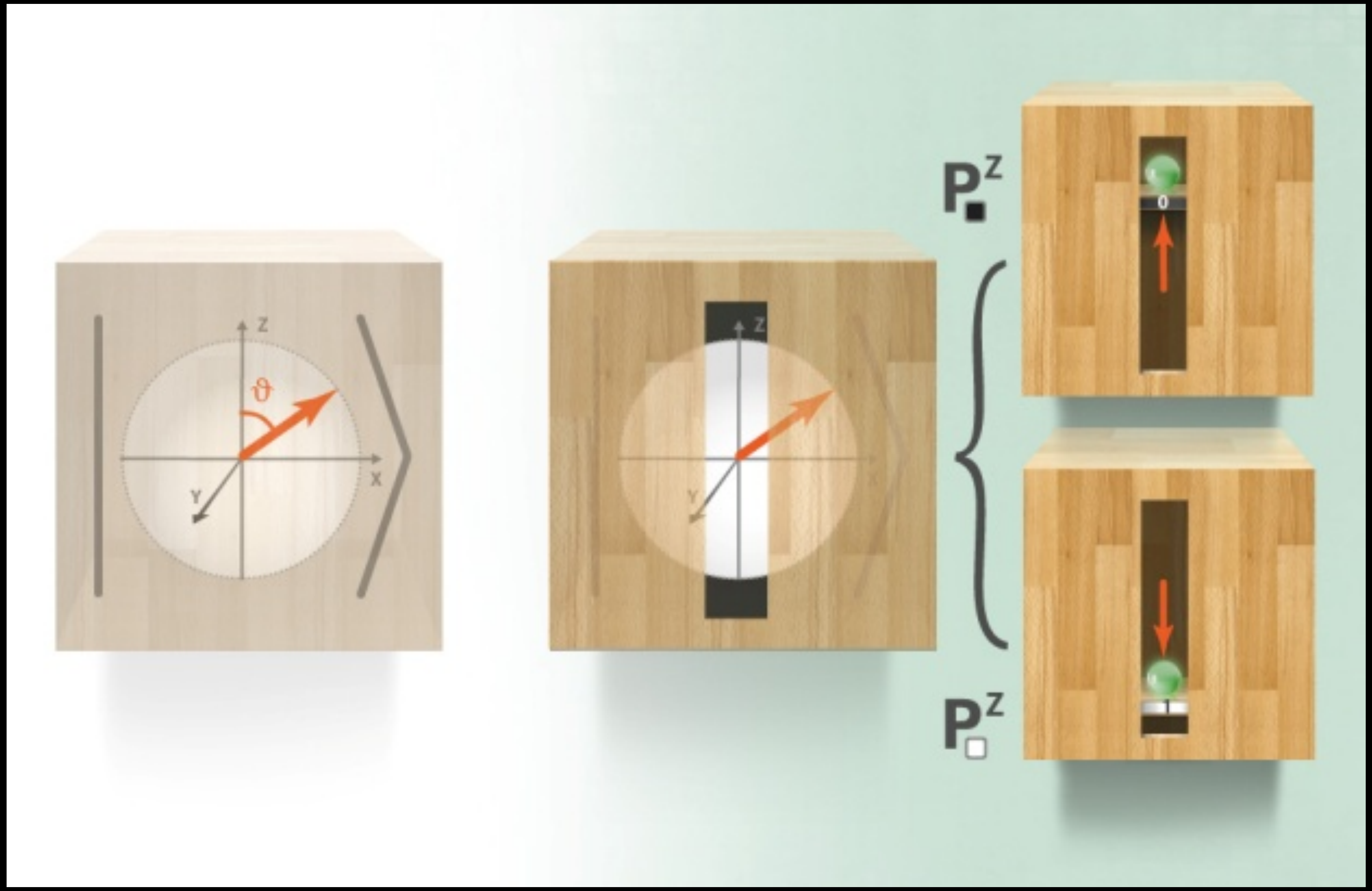


$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}.$$

Dür, W., & Heusler, S. (2013). What we can learn about quantum physics from a single qubit. arXiv preprint arXiv:1312.1463.

Measurement

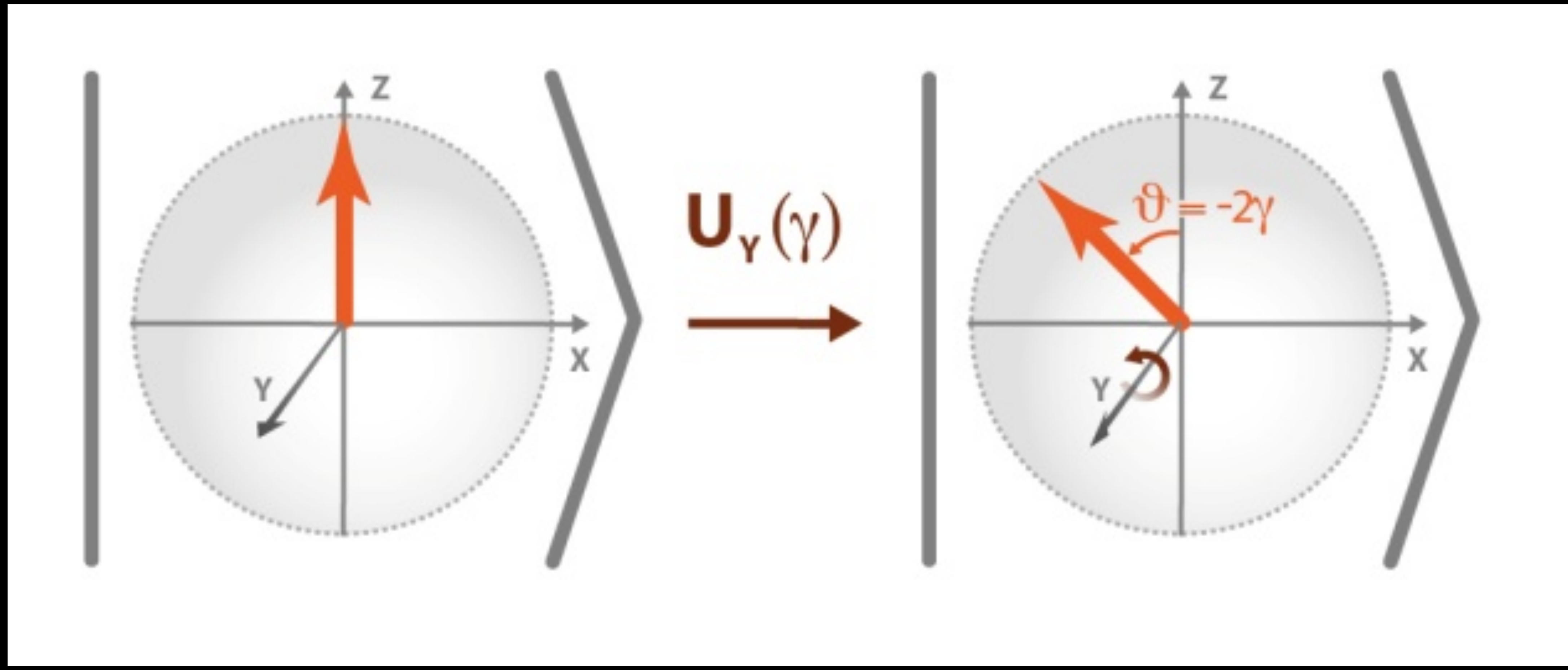


$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

$$p_0 = \langle\psi|0\rangle\langle 0|\psi\rangle = |\langle 0|\psi\rangle|^2 = |\alpha|^2,$$
$$p_1 = \langle\psi|1\rangle\langle 1|\psi\rangle = |\langle 1|\psi\rangle|^2 = |\beta|^2.$$

Dür, W., & Heusler, S. (2013). What we can learn about quantum physics from a single qubit. arXiv preprint arXiv:1312.1463.

Unitary operation



$$U^\dagger U = UU^\dagger = \mathbb{1}$$

Pauli matrices

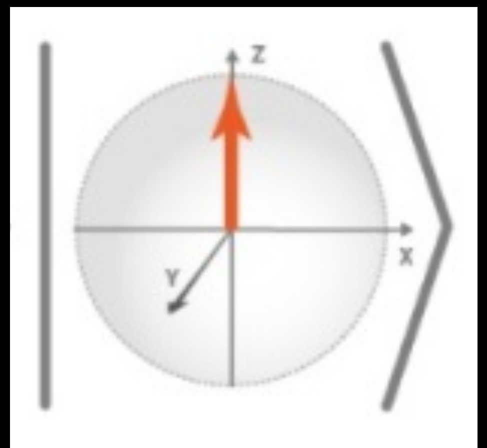
$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

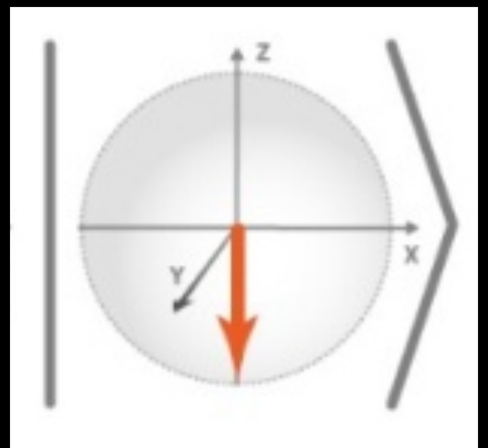
Dür, W., & Heusler, S. (2013). What we can learn about quantum physics from a single qubit. arXiv preprint arXiv:1312.1463.

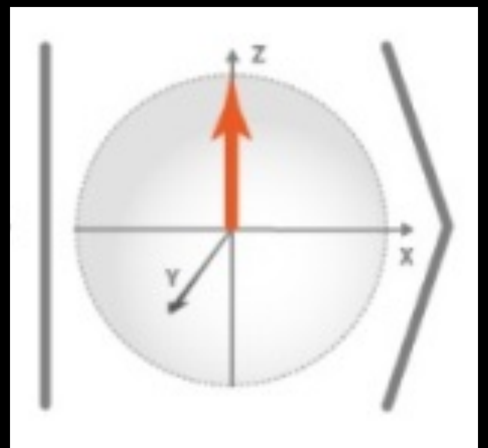
Entanglement

Multiple qubits

superposition of 2^n basis states





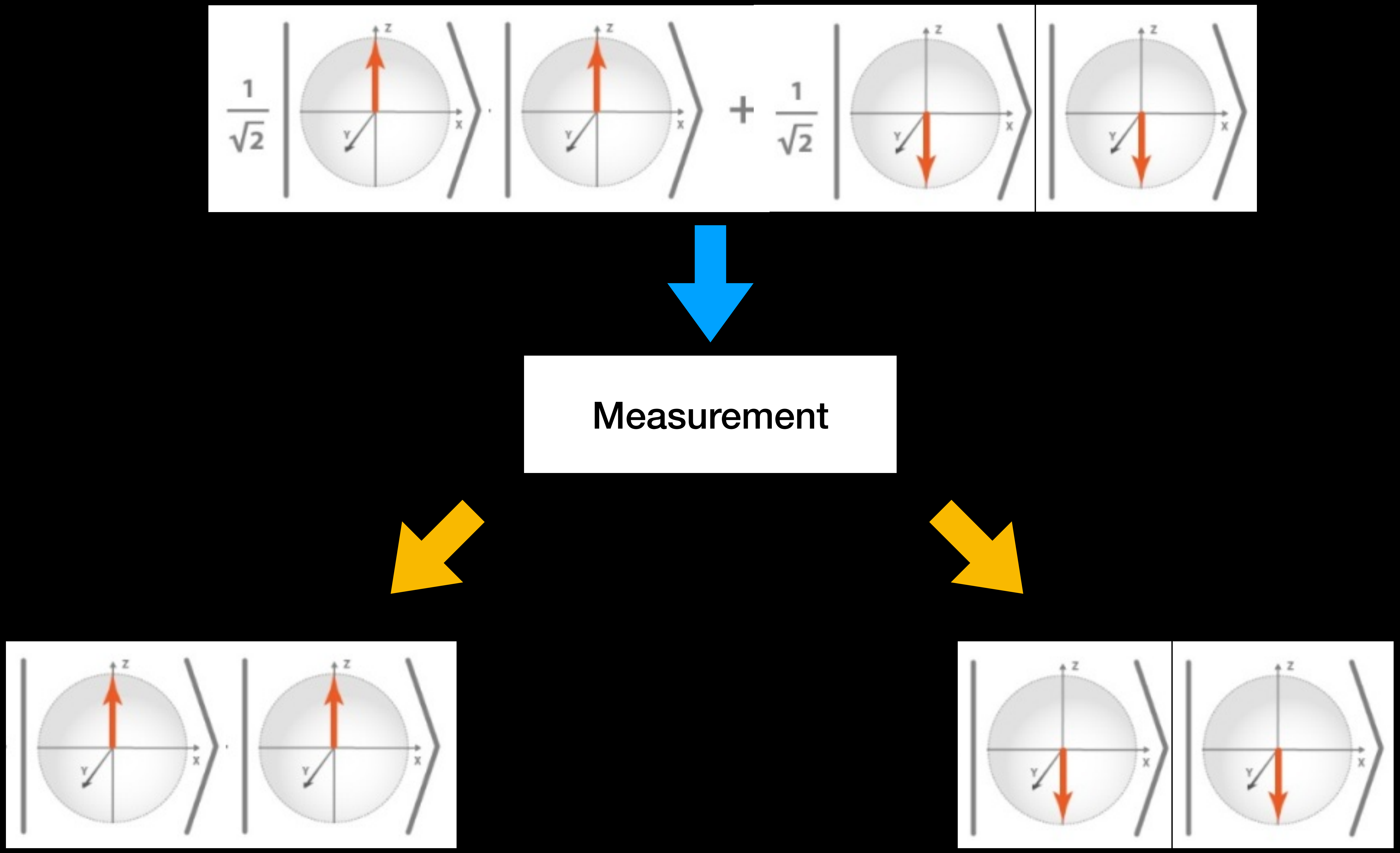


$$|cba\rangle = \begin{bmatrix} c_0 b_0 a_0 \\ c_0 b_0 a_1 \\ c_0 b_1 a_0 \\ c_0 b_1 a_1 \\ c_1 b_0 a_0 \\ c_1 b_0 a_1 \\ c_1 b_1 a_0 \\ c_1 b_1 a_1 \end{bmatrix}$$

Dür, W., & Heusler, S. (2013). What we can learn about quantum physics from a single qubit. arXiv preprint arXiv:1312.1463.

Entanglement

Measurement



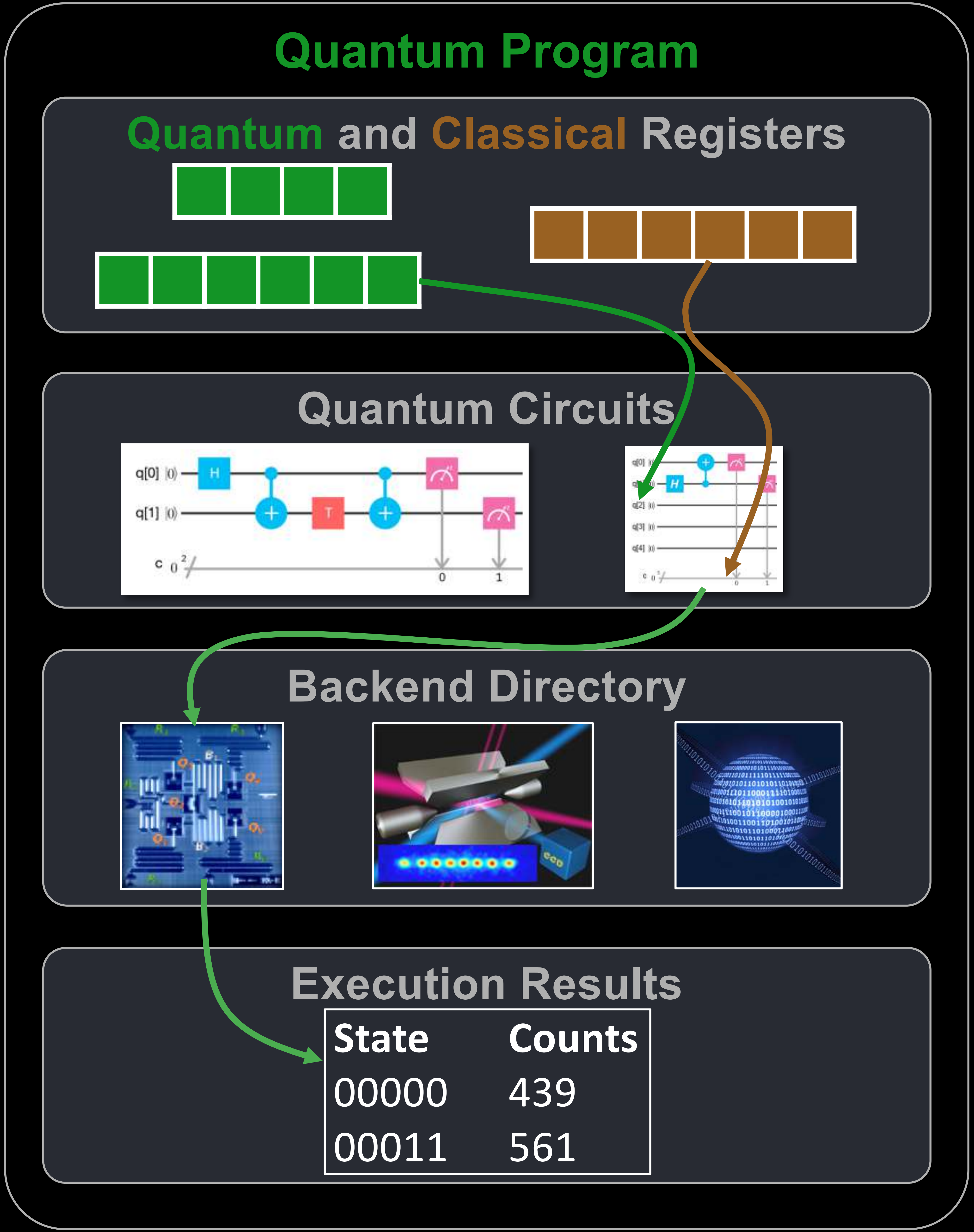
How to program a quantum computer?

QISKit: Basic workflow

At the highest level, quantum programming in QISKit is broken up into three parts:

1. **Building** quantum circuits
2. **Compiling** quantum circuits to run on a specific backend
3. **Executing** quantum circuits on a backend and analyzing results

Important: Step 2 (compiling) can be done automatically so that a basic user only needs to deal with steps 1 and 3.



Panagiotis Barkoutsos - bpa@zurich.ibm.com

Source: https://indico.cern.ch/event/719844/contributions/3019718/attachments/1749768/2835637/CERN_Tavernelli4_l.pdf

QISKit: Basic workflow

At the highest level, quantum programming in QISKit is broken up into three parts:

```
[python3] $ pip install qiskit
```

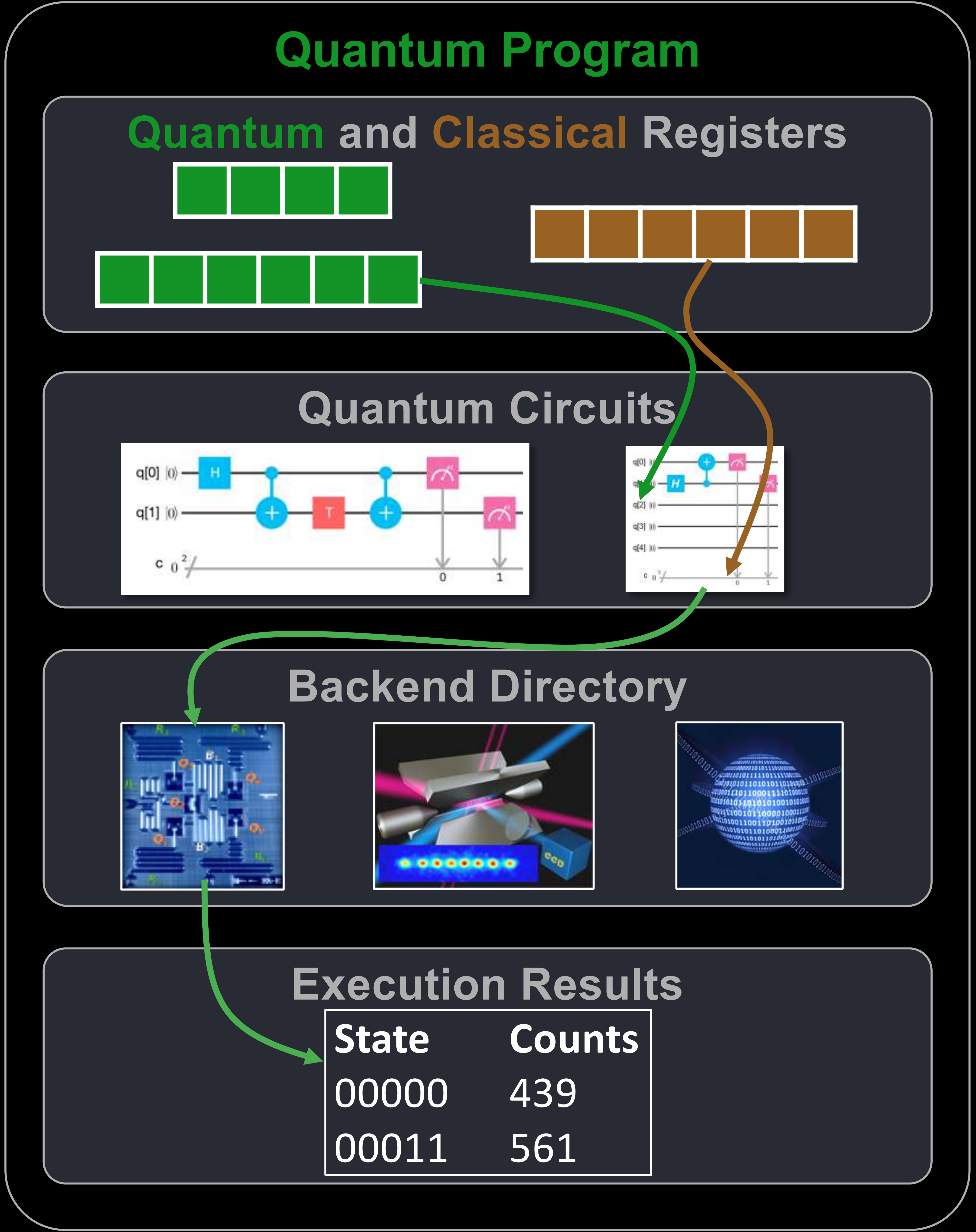
```python
from qiskit import QuantumRegister, ClassicalRegister
from qiskit import QuantumCircuit, Aer, execute

q = QuantumRegister(2)
c = ClassicalRegister(2)
qc = QuantumCircuit(q, c)

qc.h(q[0])
qc.cx(q[0], q[1])
qc.measure(q, c)

backend = Aer.get_backend('qasm_simulator')
job_sim = execute(qc, backend)
sim_result = job_sim.result()

print(sim_result.get_counts(qc))
```



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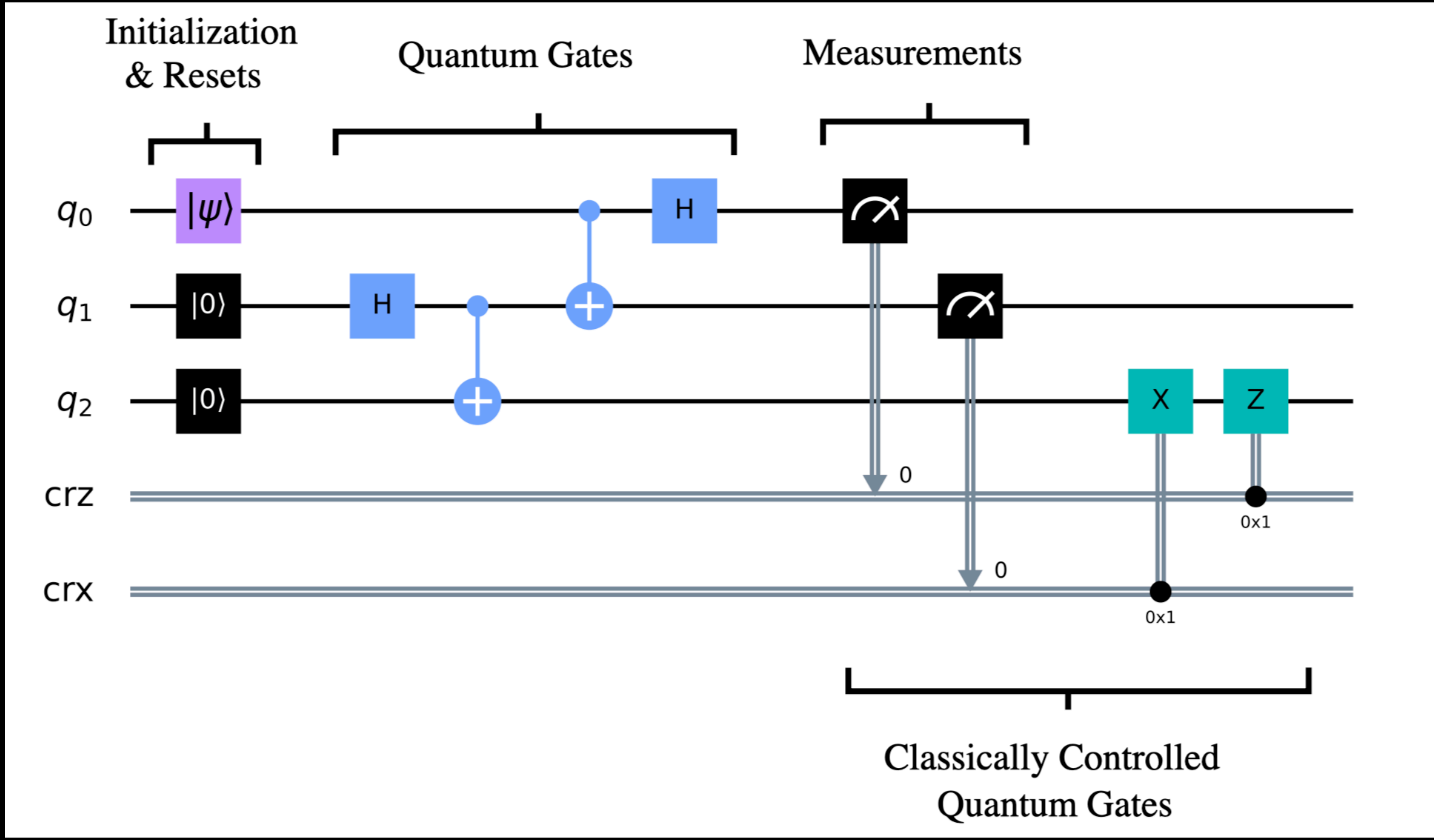
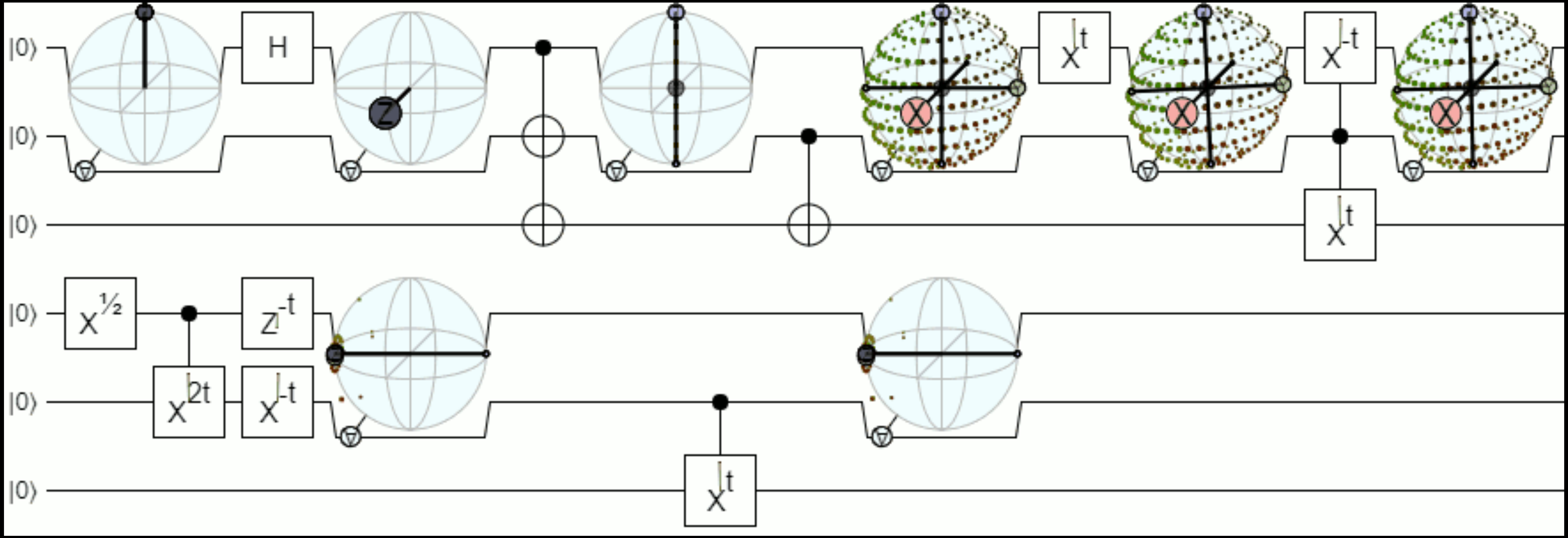
Quantum circuit



Source: https://qiskit.org/textbook/ch-algorithms/defining-quantum-circuits.html

Quantum circuit



Source: https://algassert.com/post/1716

The Quantum Era of Accelerated Discovery

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IBM Quantum

https://youtu.be/zOGNoDO7mcU?t=905

Quantum machine learning

The Quantum Era of Accelerated Discovery

Dario Gil, Ph.D.

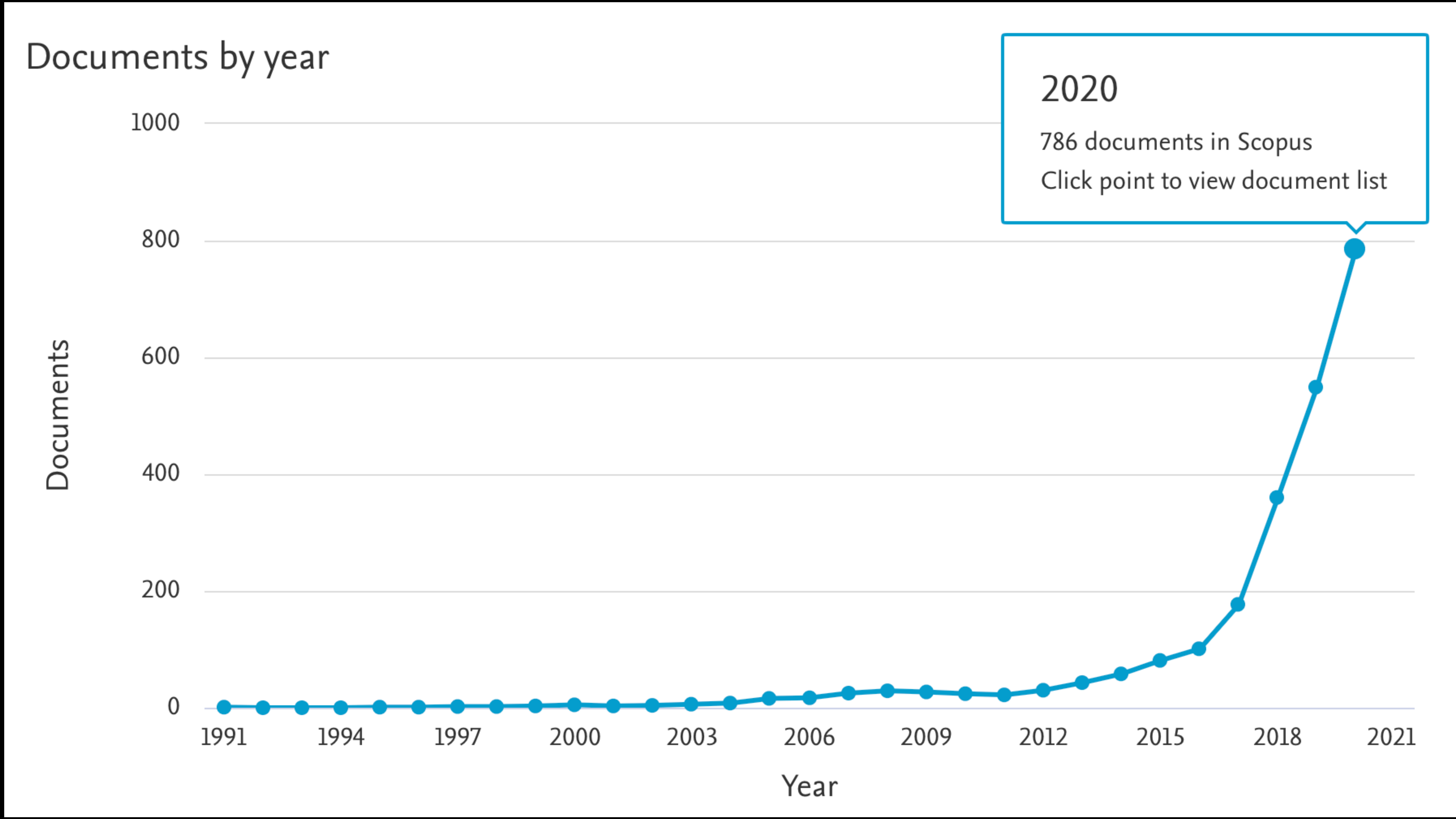
Director of IBM Research

IBM Quantum

https://youtu.be/zOGNoDO7mcU?t=1550

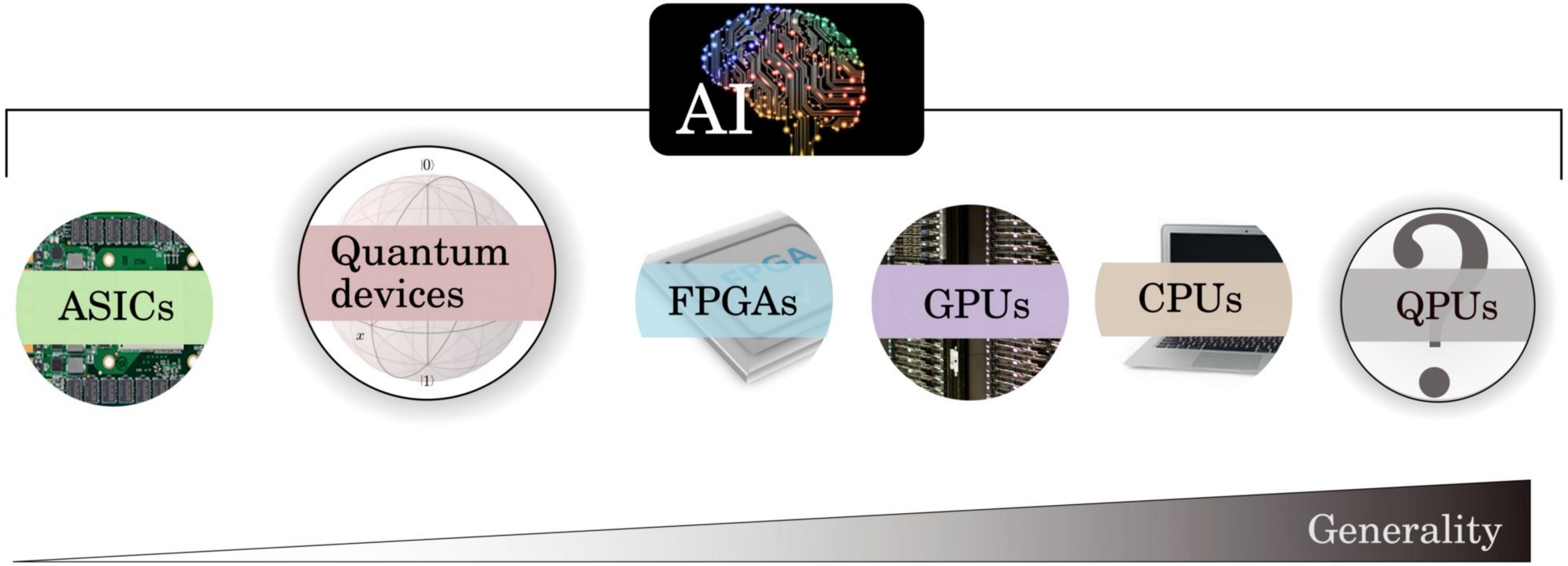
Quantum machine learning

Number of papers per year



Quantum Machine Learning

- AI/ML already uses special-purpose processors: GPUs, TPUs, ASICs
- Quantum computers (QPUs) could be used as special-purpose AI accelerators
- May enable training of previously intractable models



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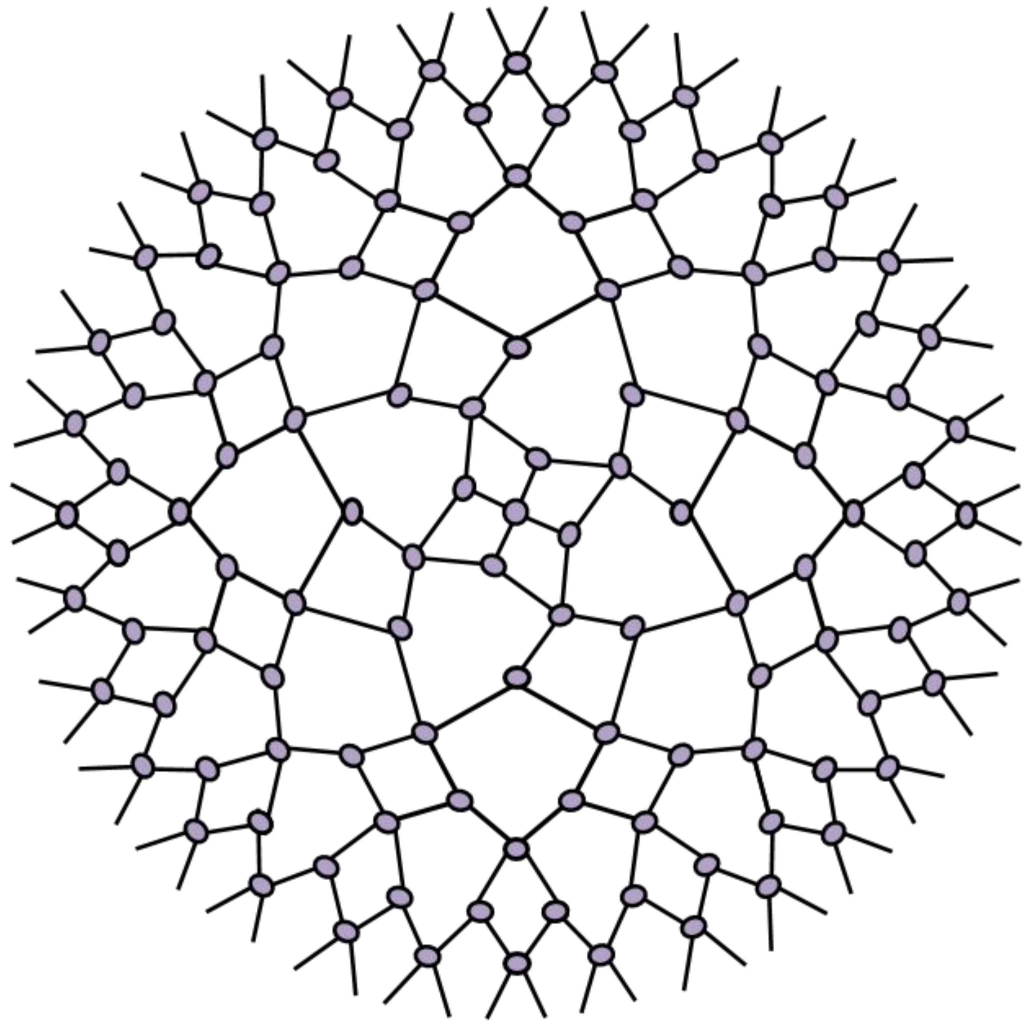
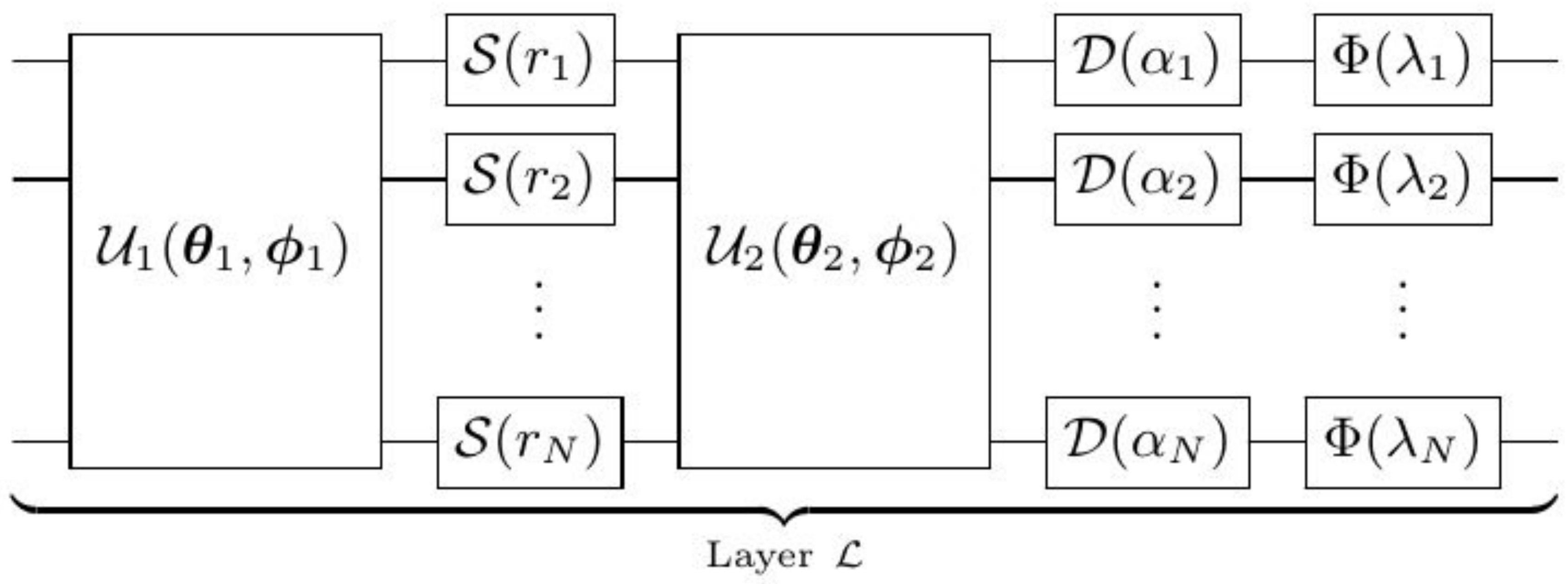
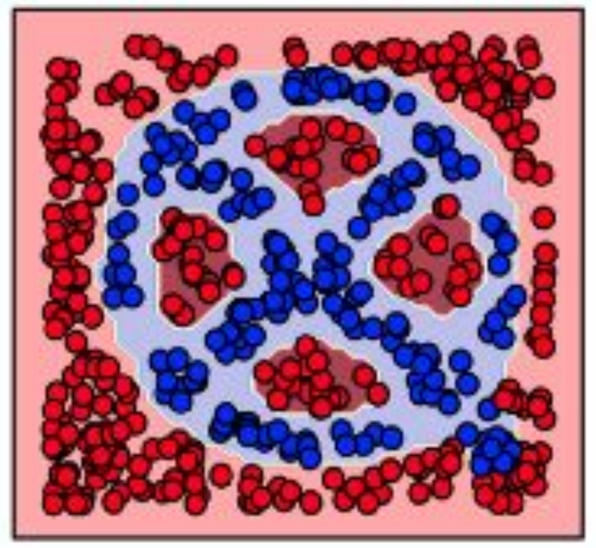
New AI models



- Quantum computing can also lead to new machine learning models
- Examples currently being studied are:
  - Kernel methods
  - Boltzmann machines
  - Tensor Networks
  - Variational circuits
  - Quantum Neural Networks





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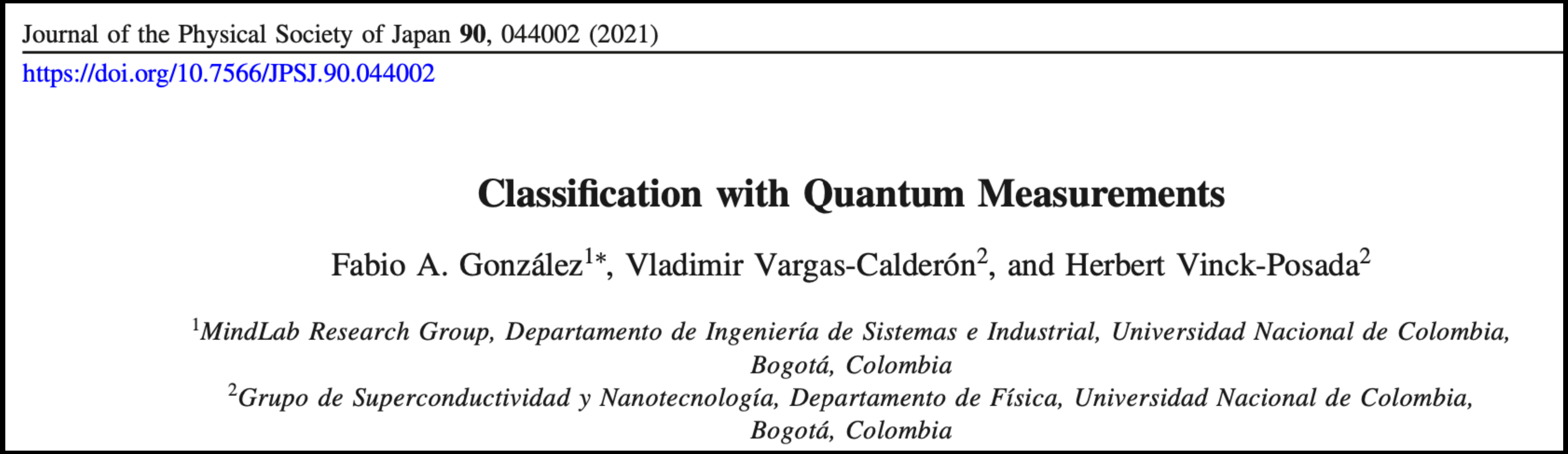
QML at MindLab

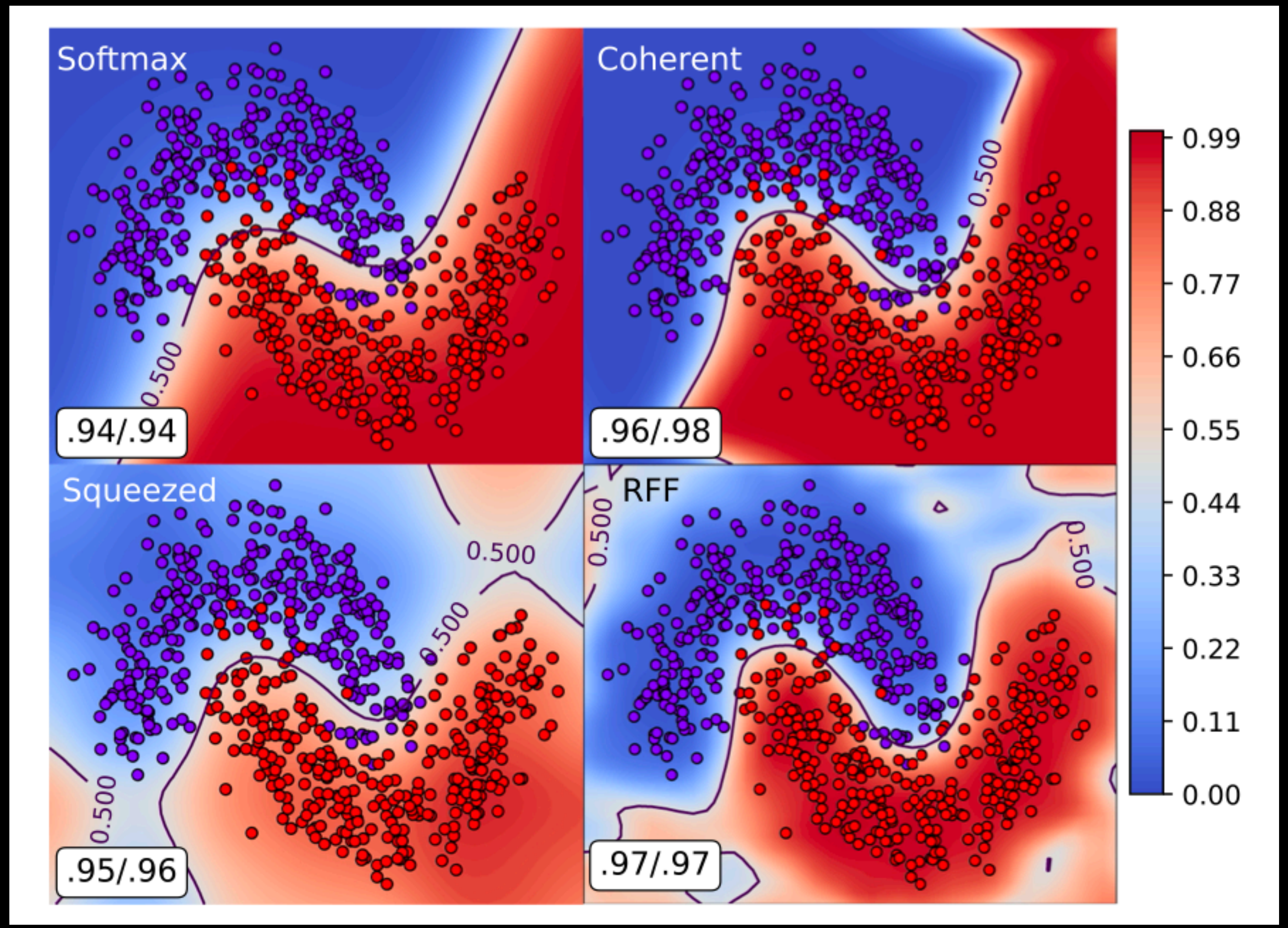


Journal of the Physical Society of Japan **90**, 044002 (2021)
https://doi.org/10.7566/JPSJ.90.044002

Classification with Quantum Measurements

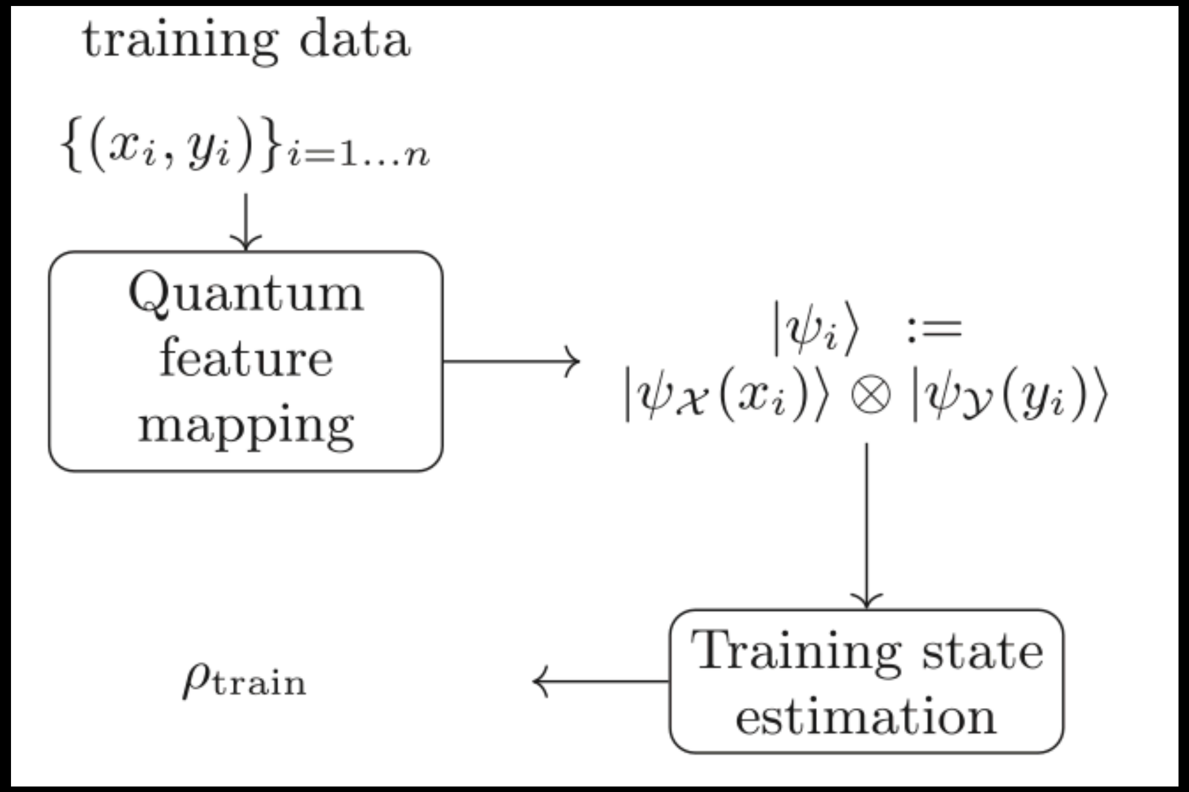
Fabio A. González[1]*, Vladimir Vargas-Calderón[2], and Herbert Vinck-Posada[2]

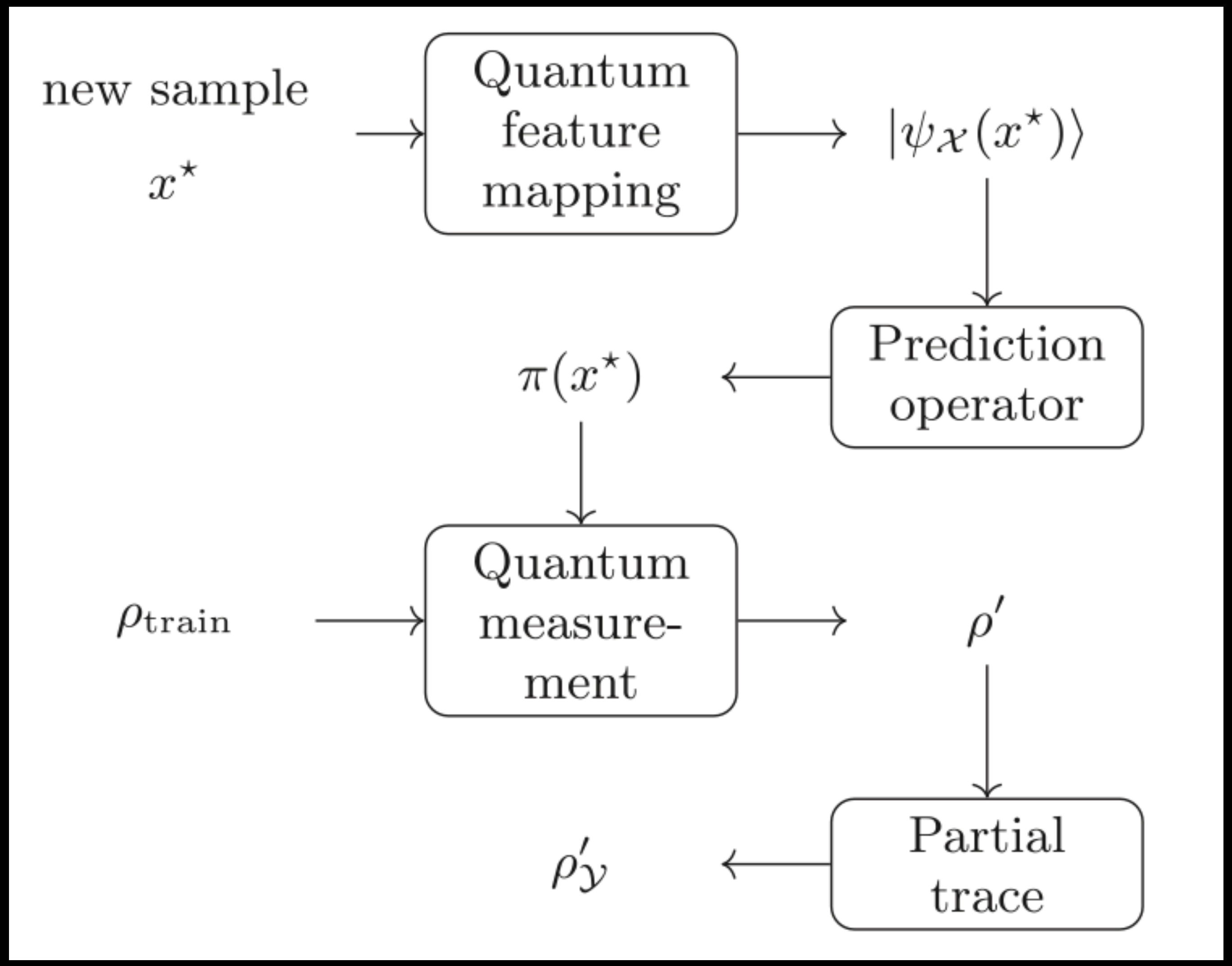
[1]*MindLab Research Group, Departamento de Ingeniería de Sistemas e Industrial, Universidad Nacional de Colombia, Bogotá, Colombia*
[2]*Grupo de Superconductividad y Nanotecnología, Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*

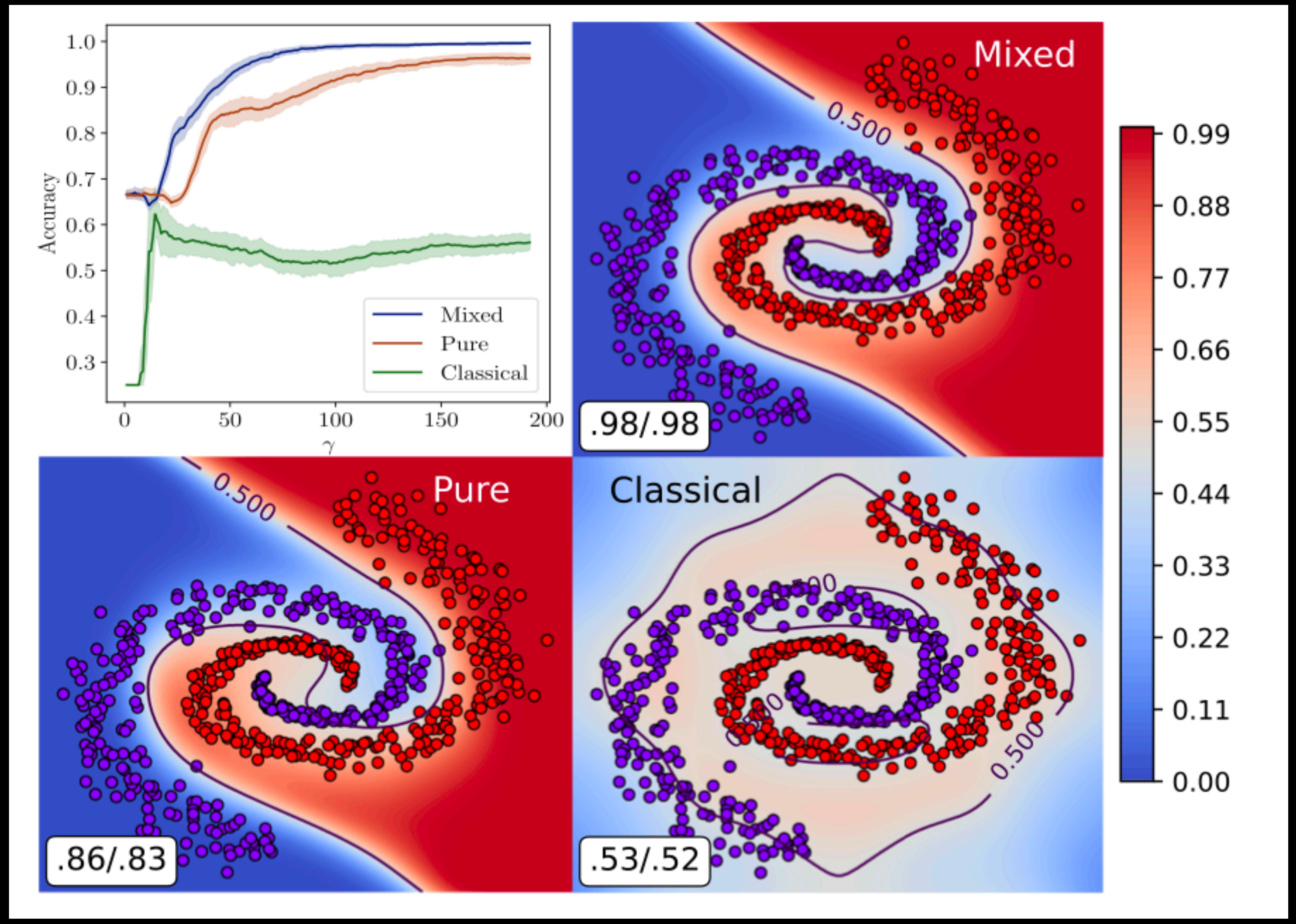


Training

Prediction



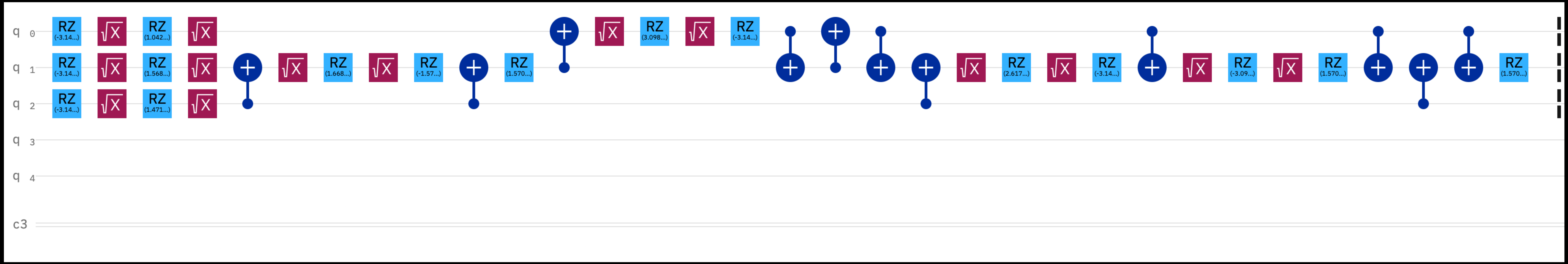




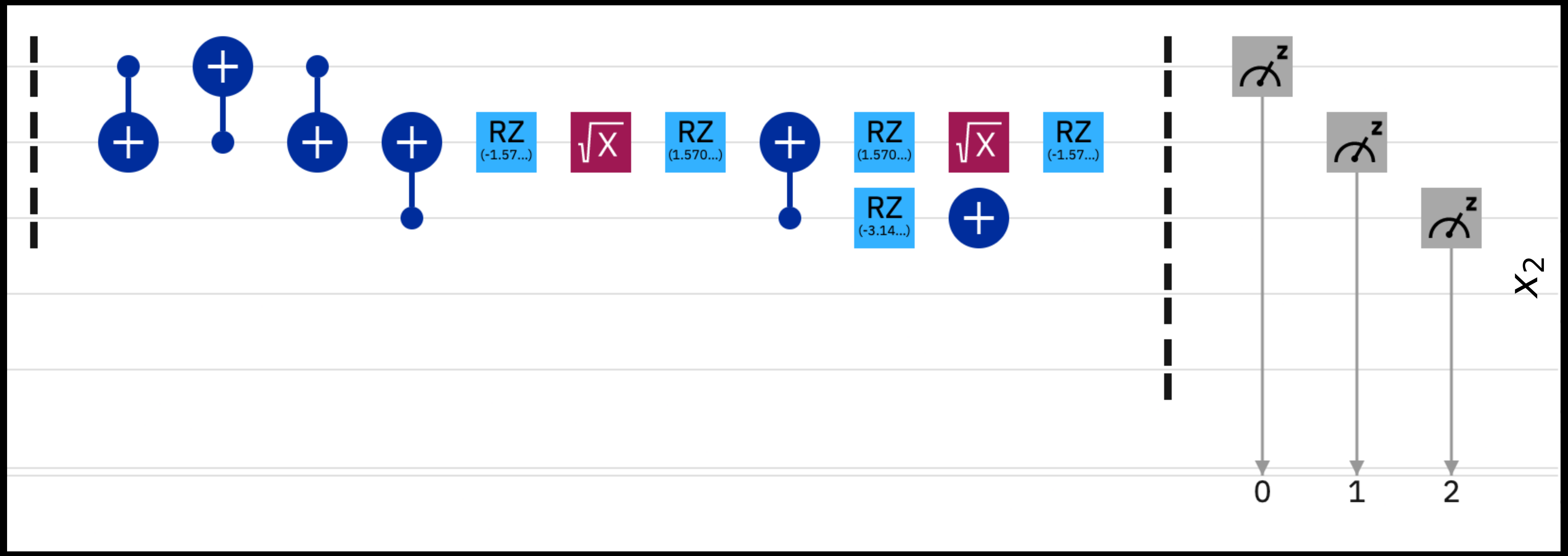
QML at MindLab

Implementation in Qiskit

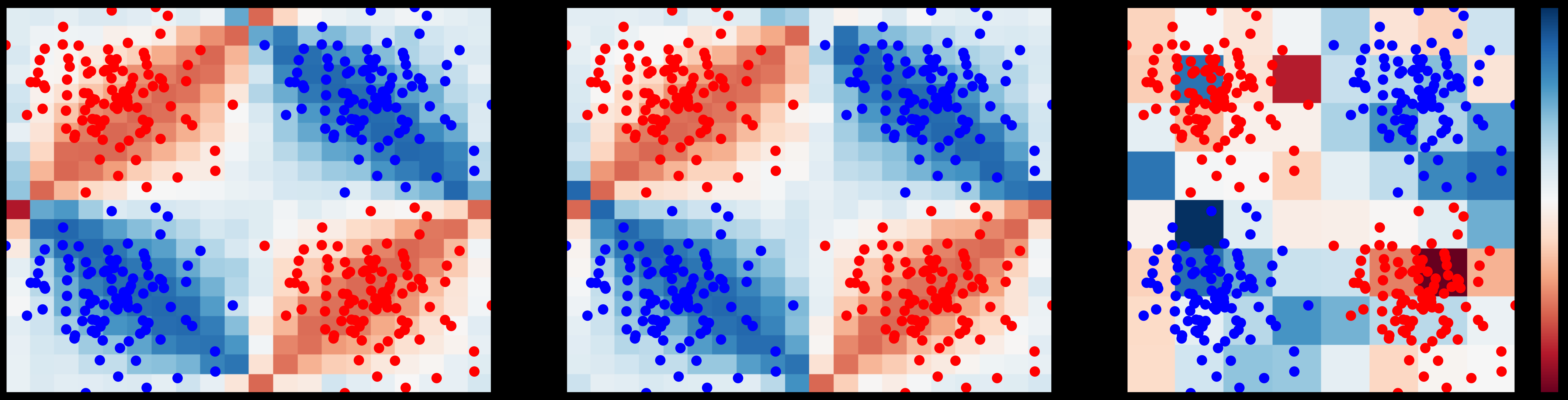
Training state preparation



Prediction

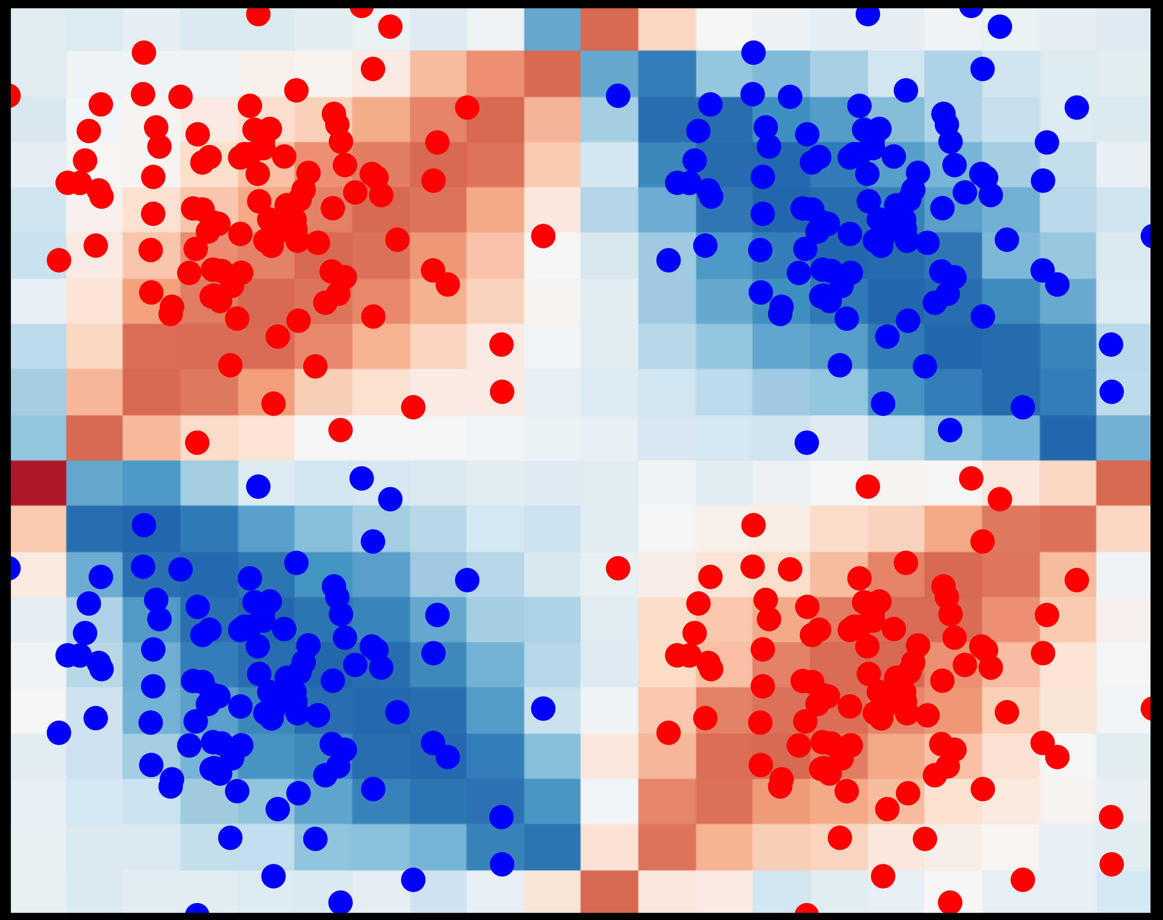


Execution results

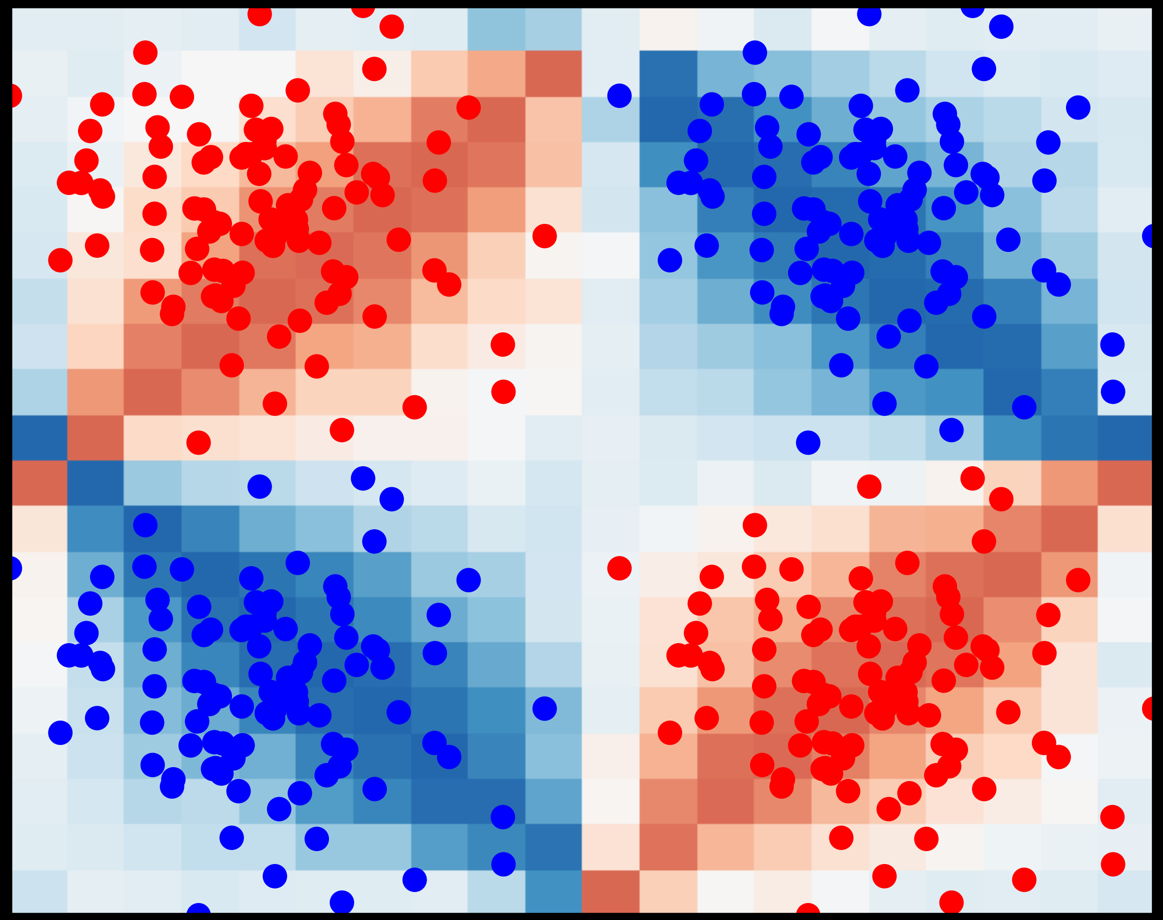


QML at MindLab

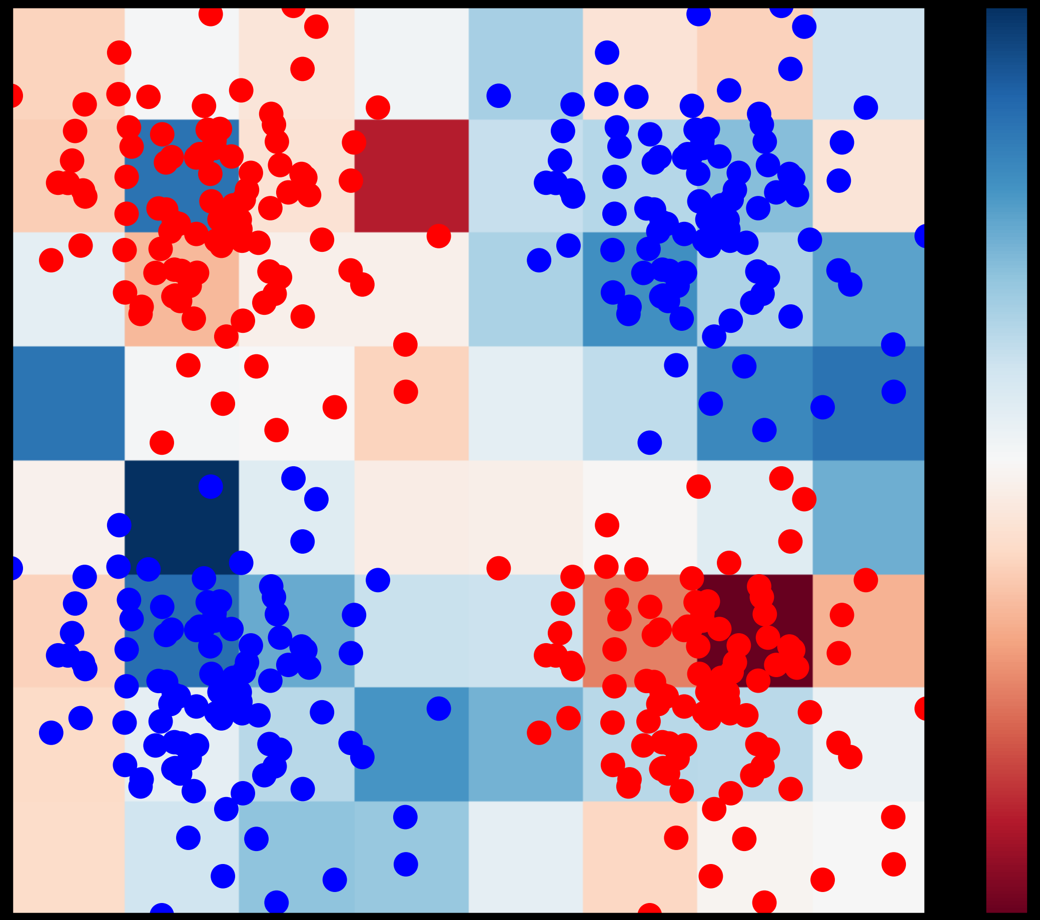
Implementation in Qiskit



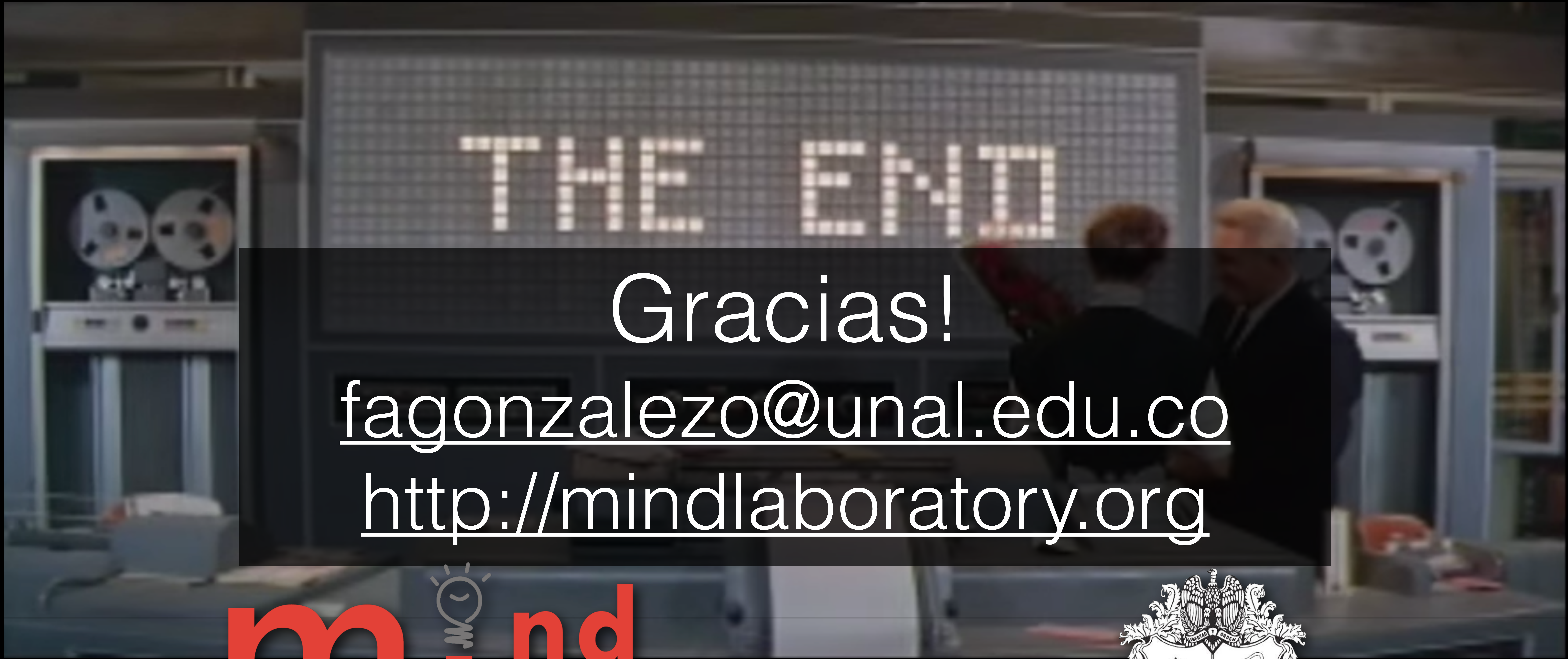
Exact circuit simulator



Noisy circuit simulator



IBM Bogotá Quantum device



Gracias!

fagonzalezo@unal.edu.co

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