Quantum Hardware

On the road to Quantum Advantage

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Technology Development

IBM Quantum

Understanding quantum systems

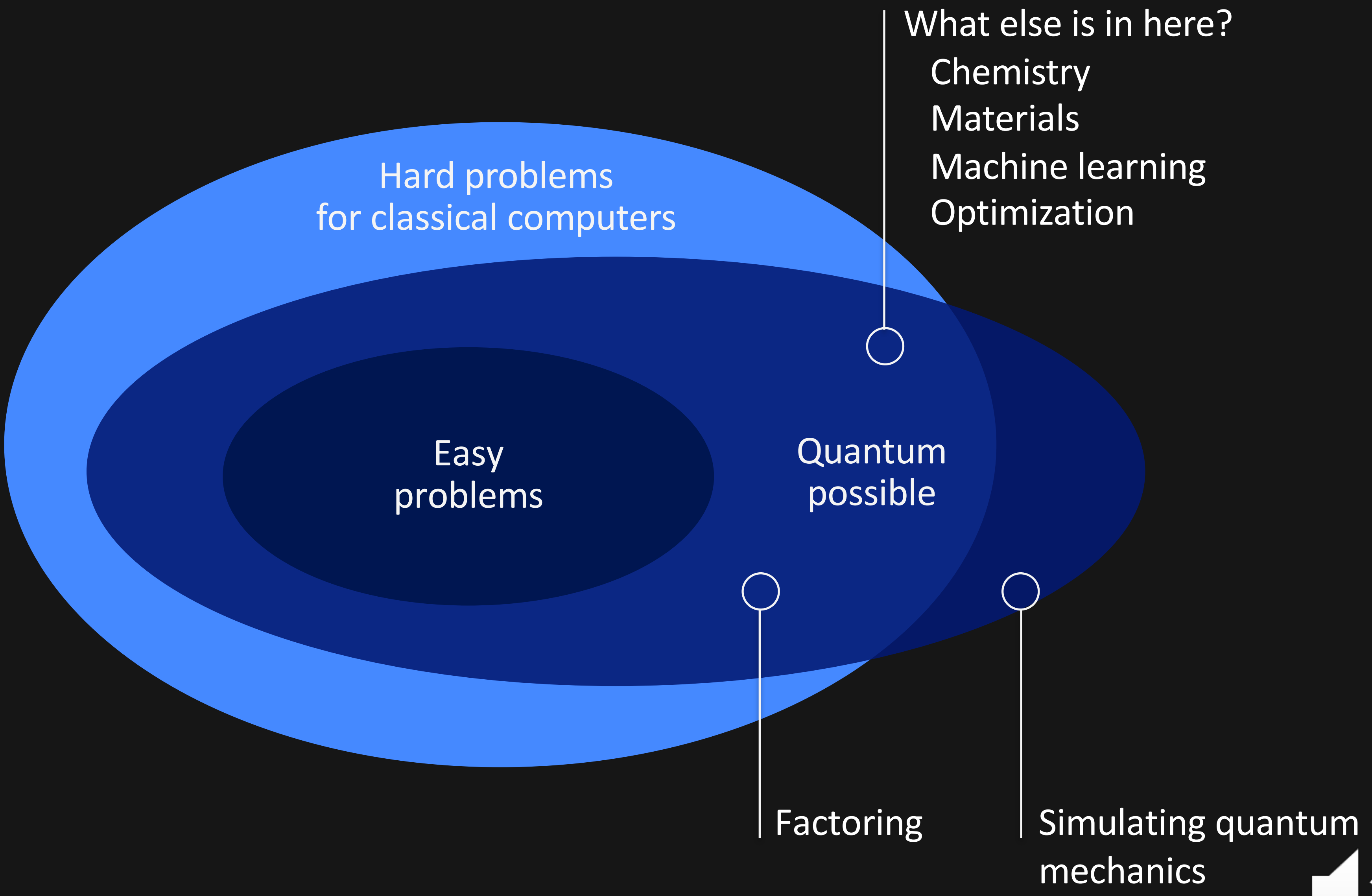
IBM **Quantum**

How can we leverage quantum computing?

How do we benchmark quantum computers?

Where are we today and what are the main objectives of quantum hardware research?

Application space for quantum computers



The road to quantum advantage

Quantum science

Create the fundamental theoretical and physical building blocks of quantum computing.

Quantum ready

Engage the world to prepare for the quantum computing era.

Quantum advantage

Commercial advantage to solving real
world problems with quantum computers.

IBM Quantum Experience

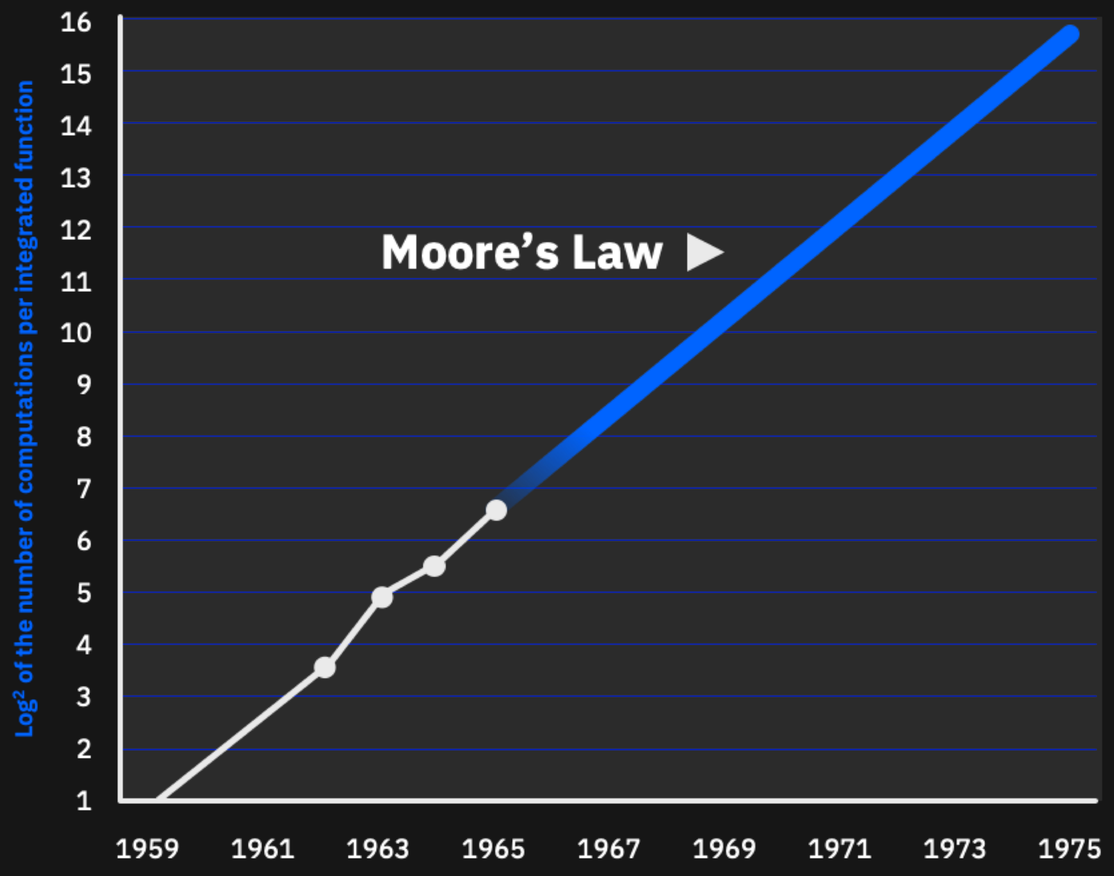
Launch of the IBM Quantum Network

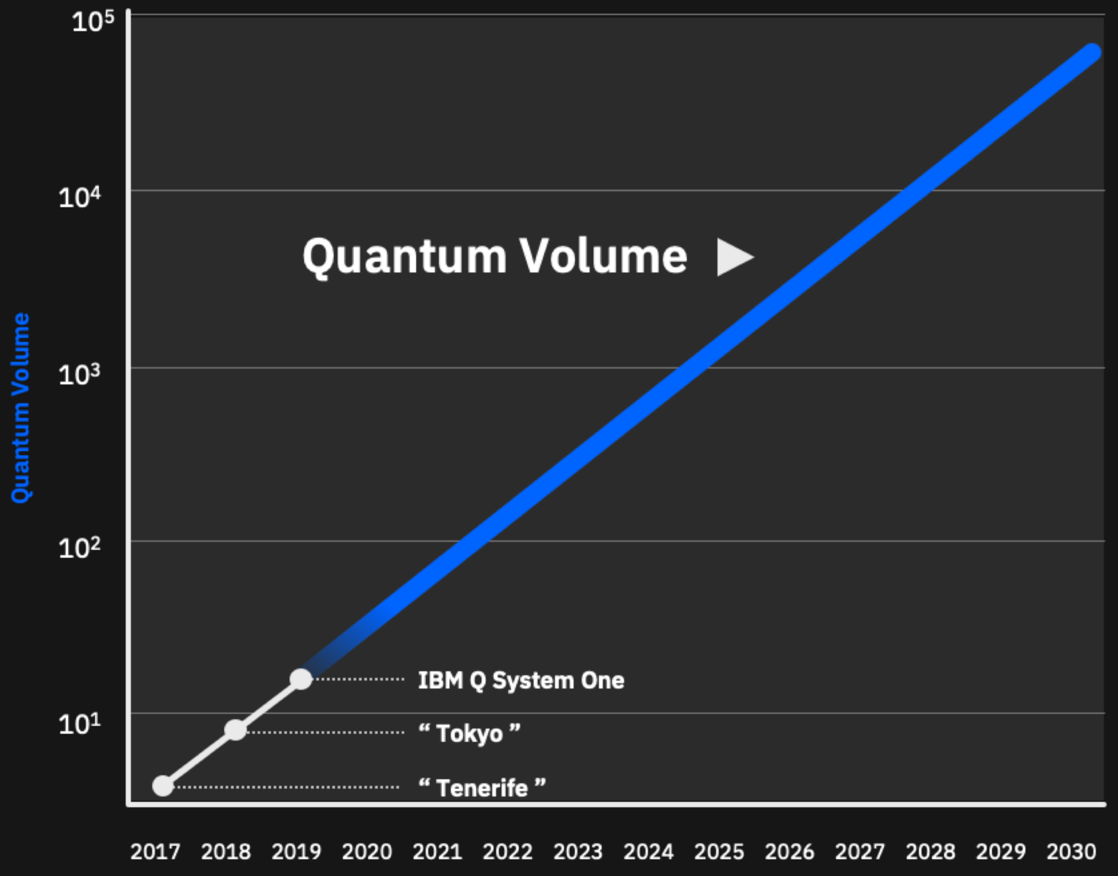
IBM Quantum Computation Center

1960s — 2016 — ~2020s — 2050+

A new era of computing

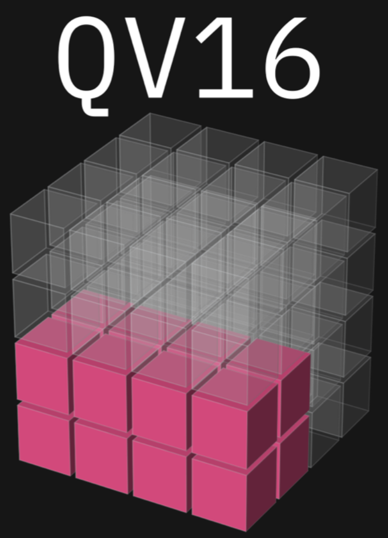
Scaling quantum volume by 2x/year





Quantum volume

Represents the largest model circuit a quantum computer can successfully implement



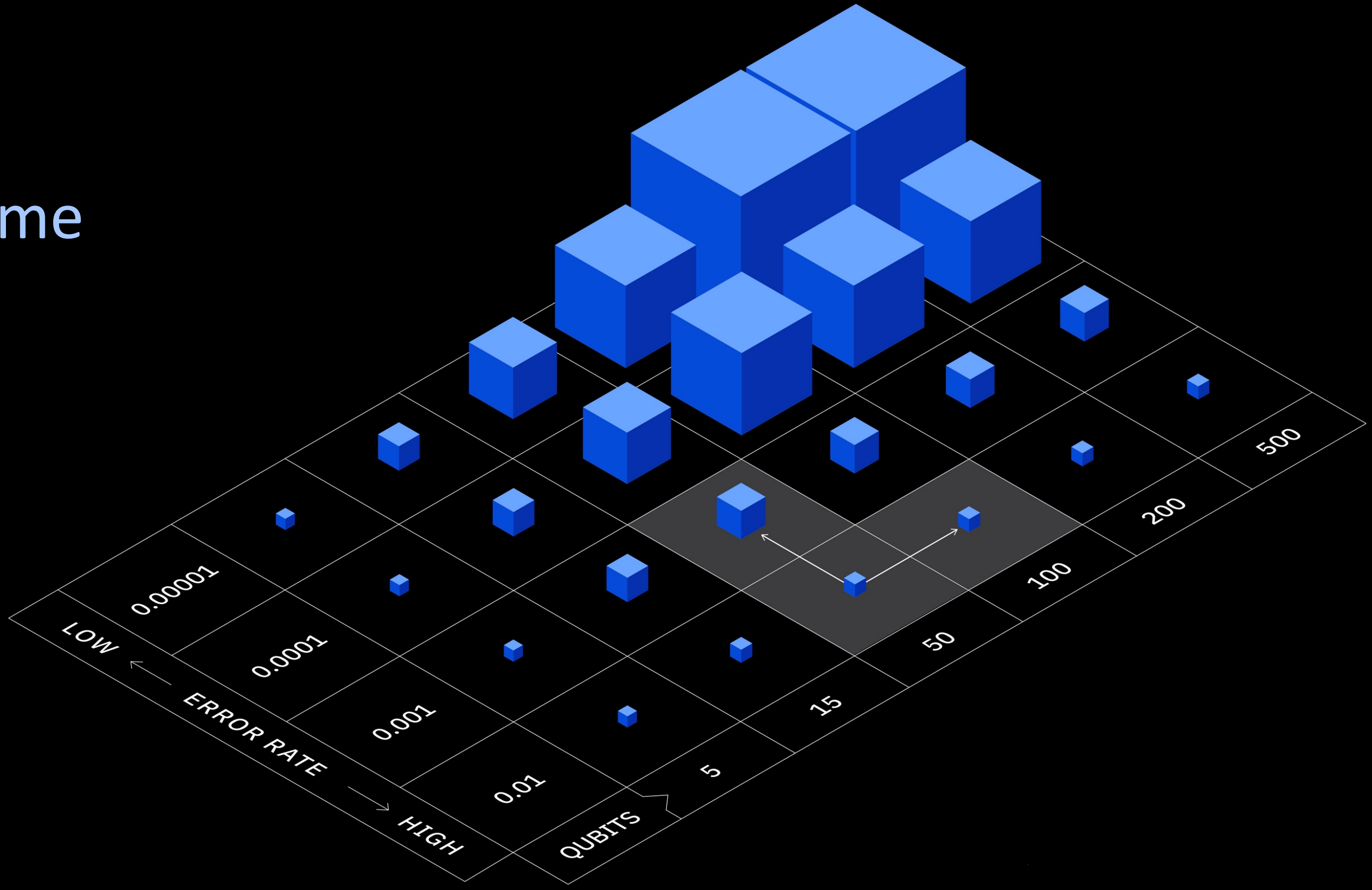
- Larger QV demands low error rates:
  - High-fidelity two-qubit gates.
  - Low single-qubit errors.
  - Long coherence times
  - Low measurement errors.
  - Gate parallelism.
  - Good connectivity.
  - Minimal crosstalk.
  - Smart circuit rewriting software.
  - Stable control electronics.
- QV captures all of these error rates in a single numerical value

Cross et al., Phys. Rev. A 100, 032328 (2019)

Quantum volume measures progress toward improved system-wide gate error rates

Increasing the number of qubits will only increases quantum volume if the effective error rate is sufficiently low

From a hardware perspective, qubit coherence is a key parameter to reduce error rate



Qubits and errors

A qubit is a quantum two-level system

Finite qubit coherence times

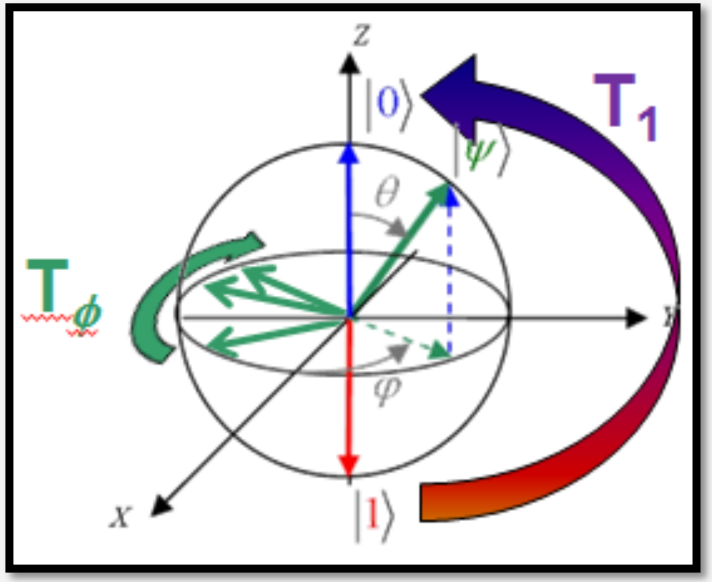
- T1: relaxation (dissipation)
- Tϕ: dephasing (randomization)
  - Results from measurement (intentional or not)
- T2: parallel combination of above

Imperfect control pulses

Spurious inter-qubit couplings

Imperfect qubit state measurements

➢ **Errors unavoidable —**
Will they destroy our computation?



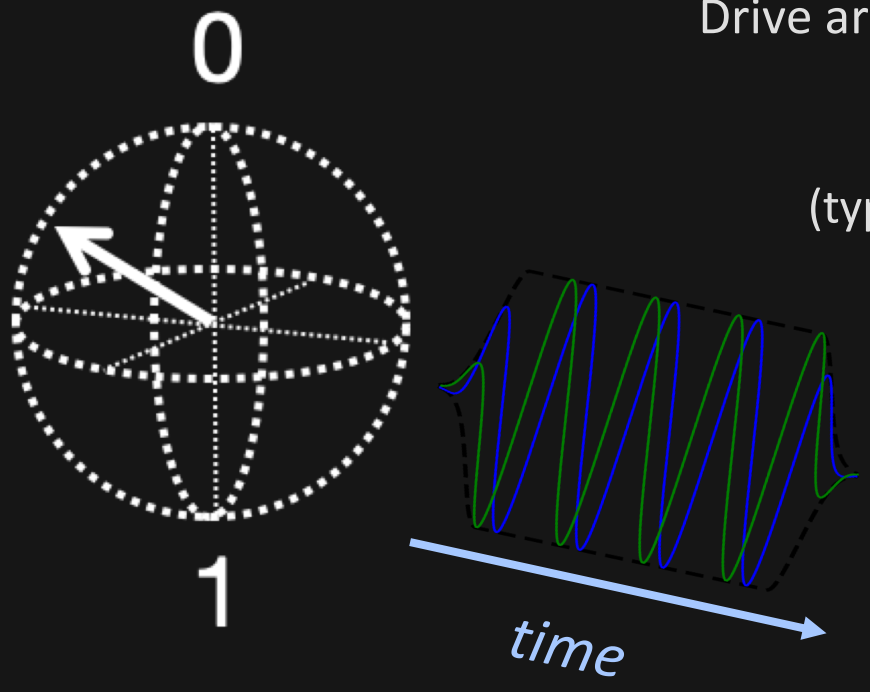
$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

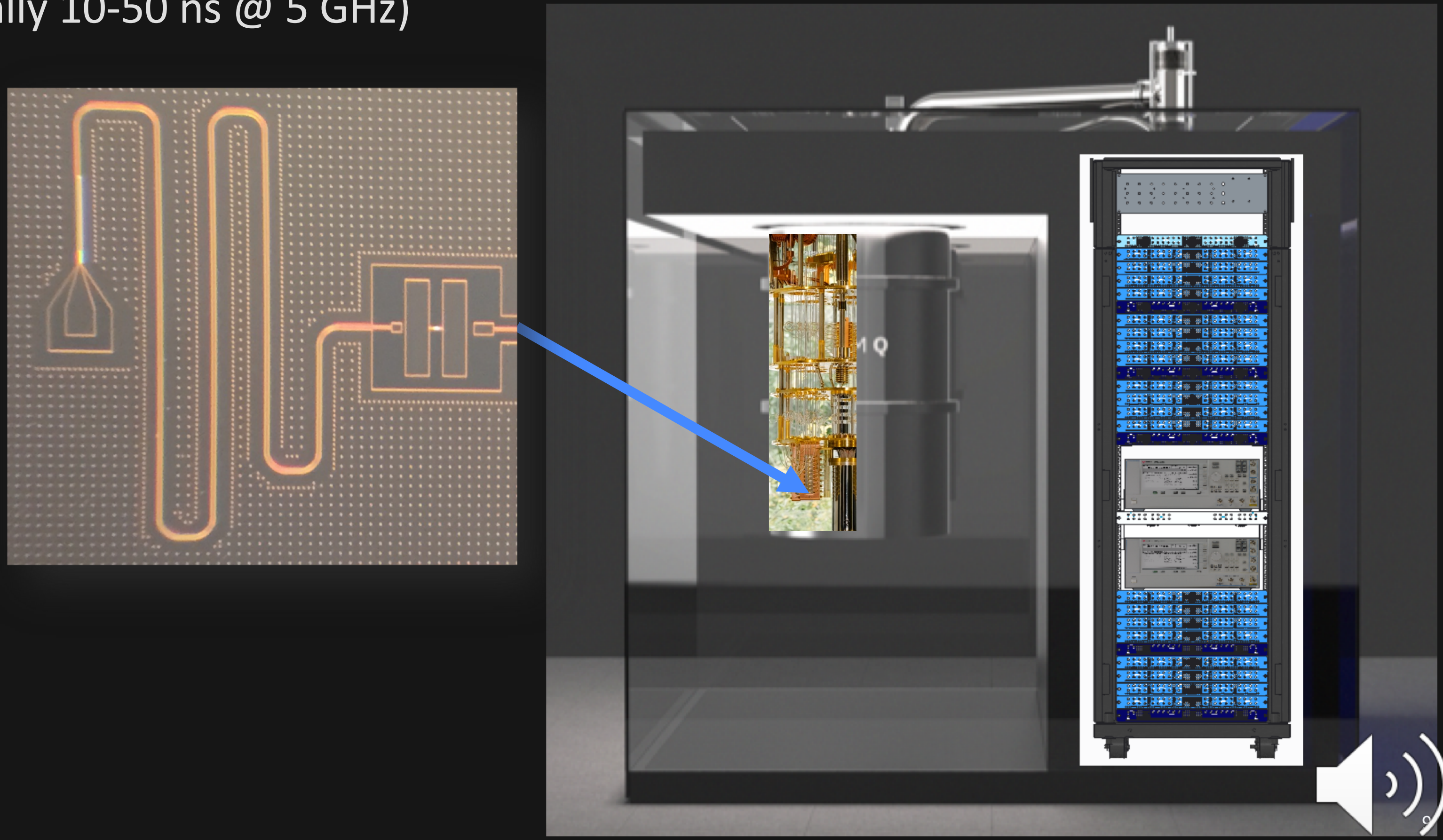
Yes but there is error correction

Controlling the qubit State

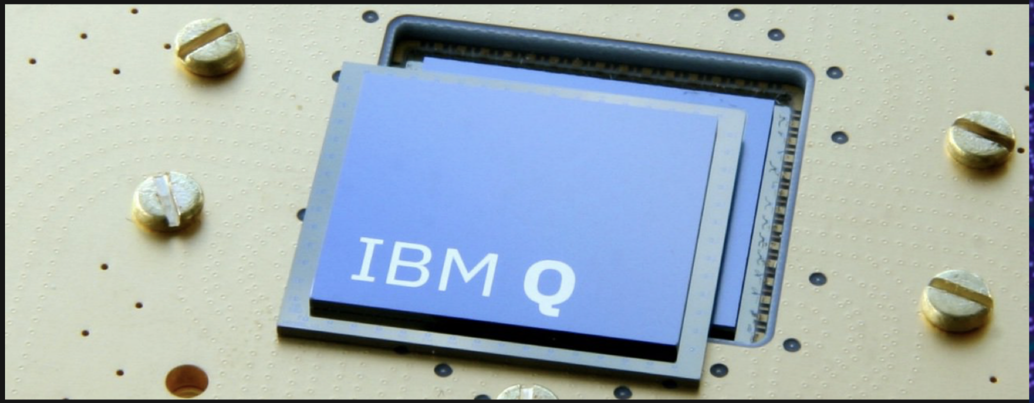
Drive around the Bloch sphere using microwave pulses

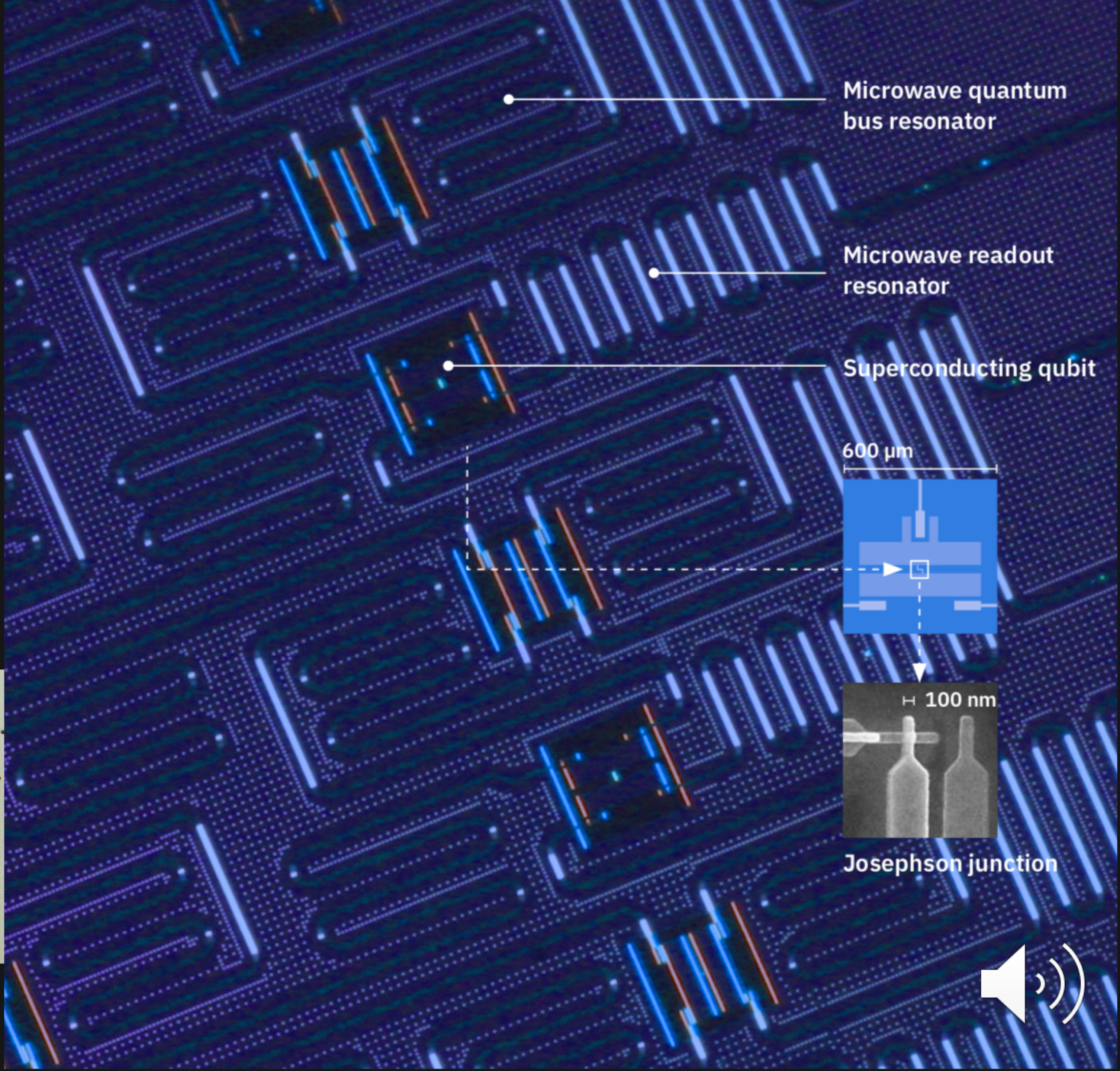
(typically 10-50 ns @ 5 GHz)





Inside an IBM superconducting quantum chip

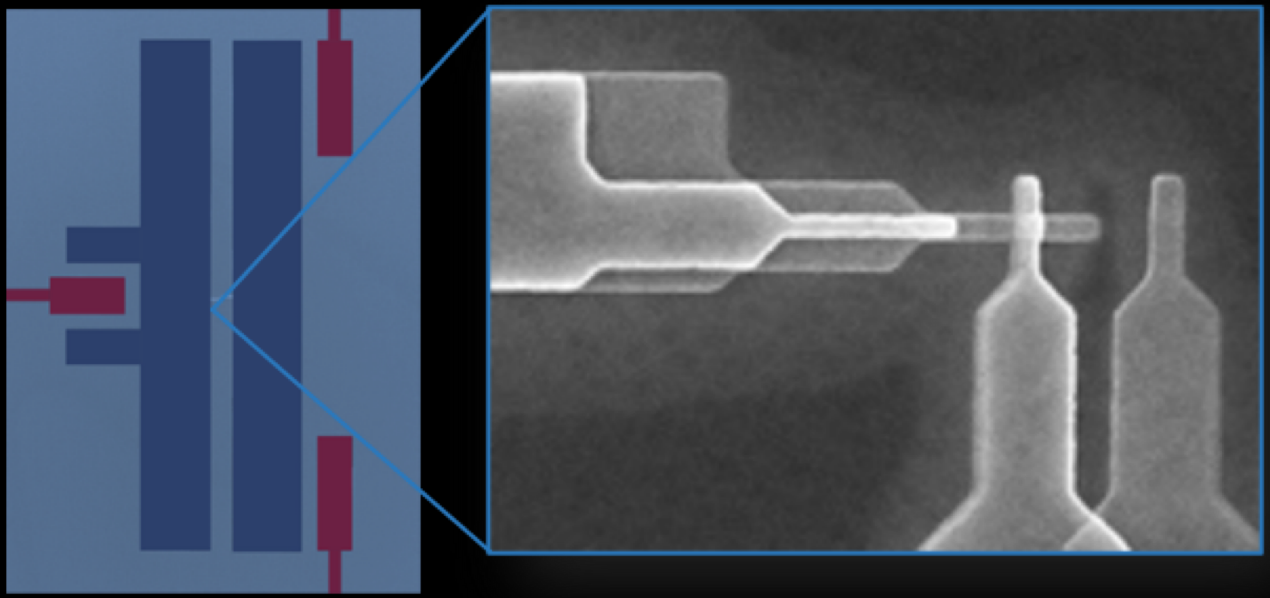




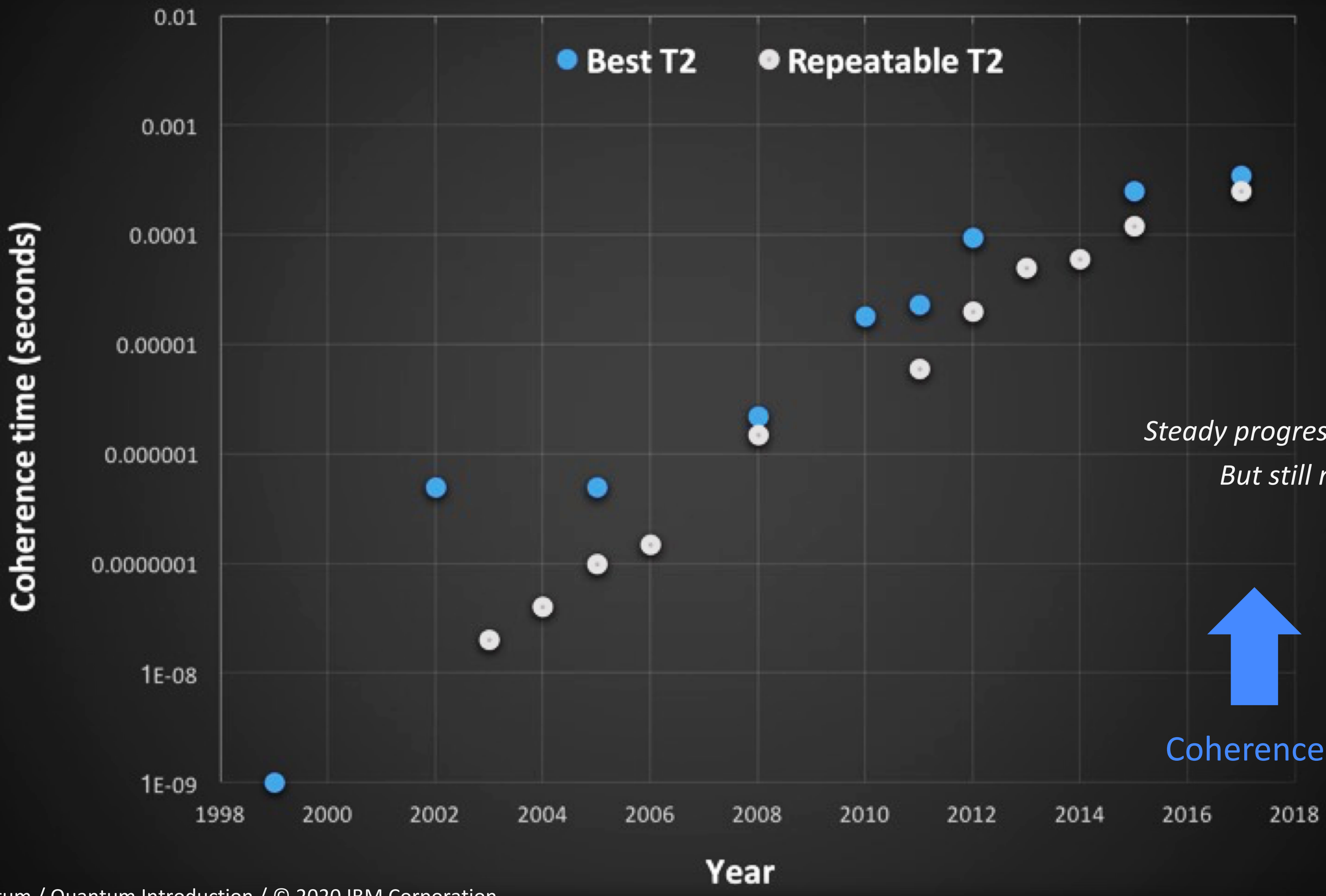
Quantum hardware research areas

Superconducting Qubit:

- Coherence: design, materials, interfaces
- Frequency Control: design, process, process control
- Scaling to higher numbers of qubits: low loss interconnect & packaging solutions

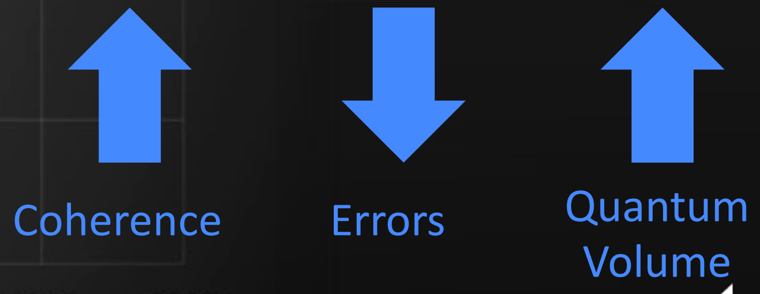


Coherence: How long can a qubit hold its quantum state?



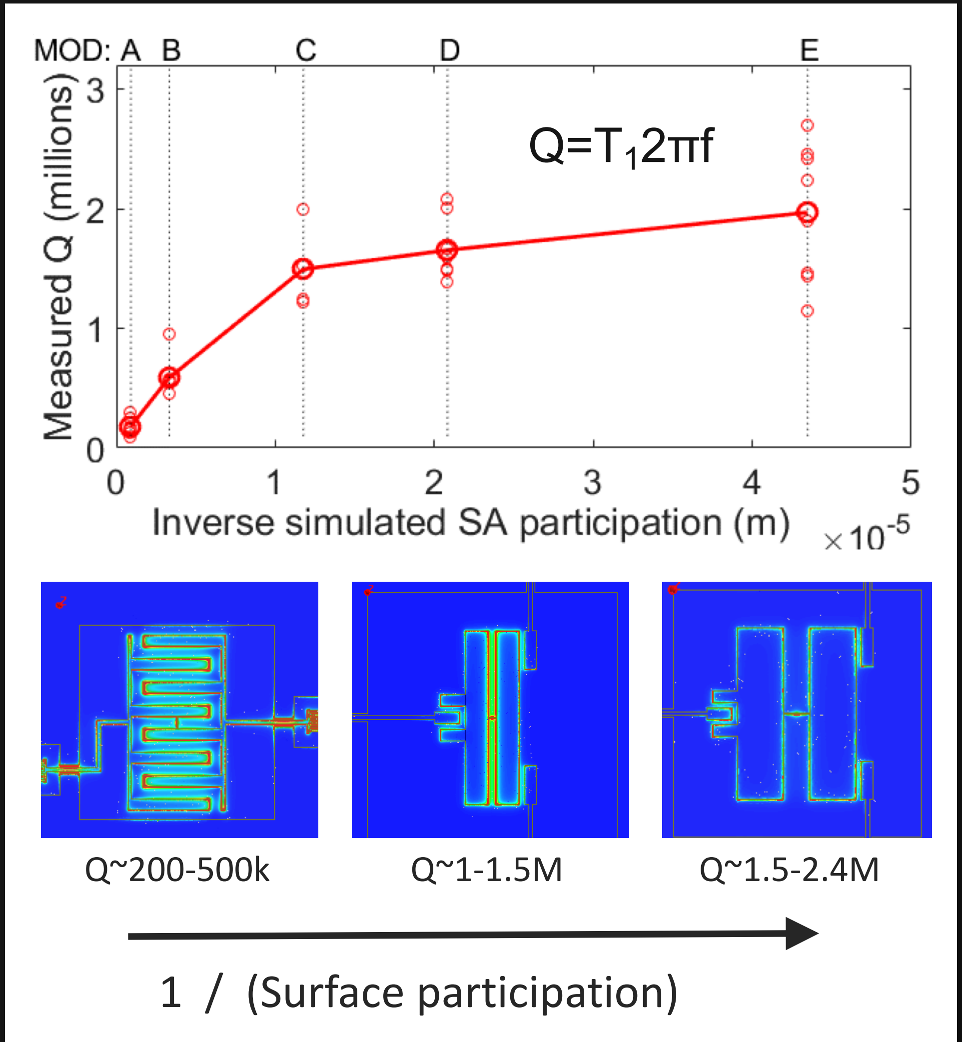
Steady progress in coherence over the years

But still need ~ 1 more order of magnitude



IBM **Quantum**

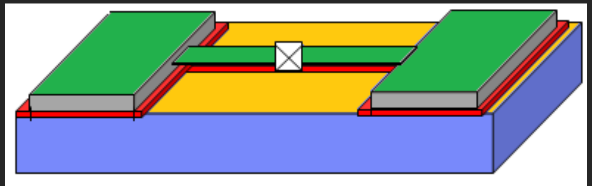
Improving coherence



Gambetta et al., IEEE Trans. App. Supercond. 27 (2017)

Surfaces:

- Metal-Substrate (MS)
- Metal-Air (MA)
- Substrate-Air (SA)

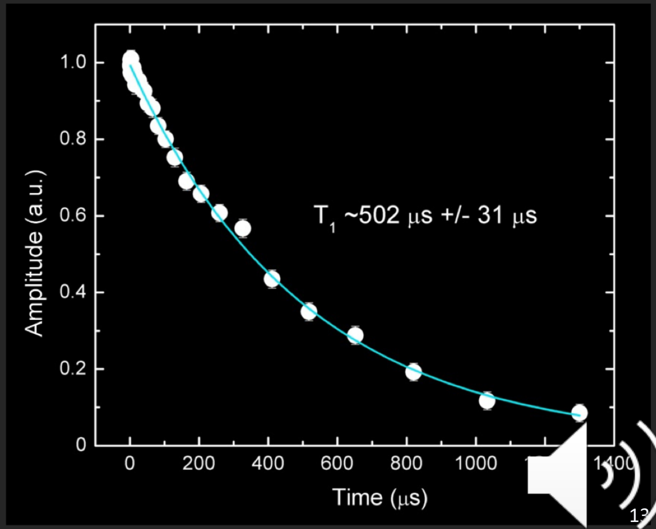


Coherence is material- and fabrication-dependent

Perform processes that influence different interfaces, and explore other designs that change sensitivities

Now through various iterations

- Single-qubit quality factors ~ 12-15 M
- Multi-qubit quality factors ~ 2-3 M



Frequency control

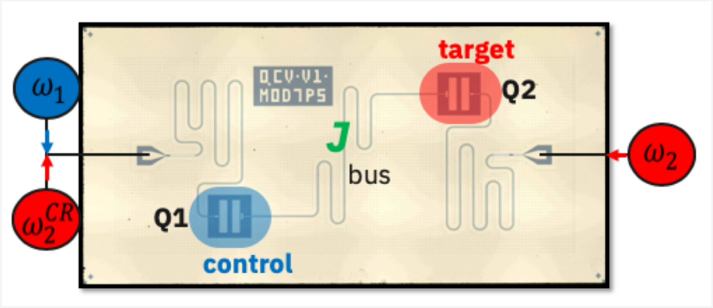
Superconducting qubits have fixed, narrow windows of allowed frequencies

Heavy Hexagonal lattice requires three different frequency assignments

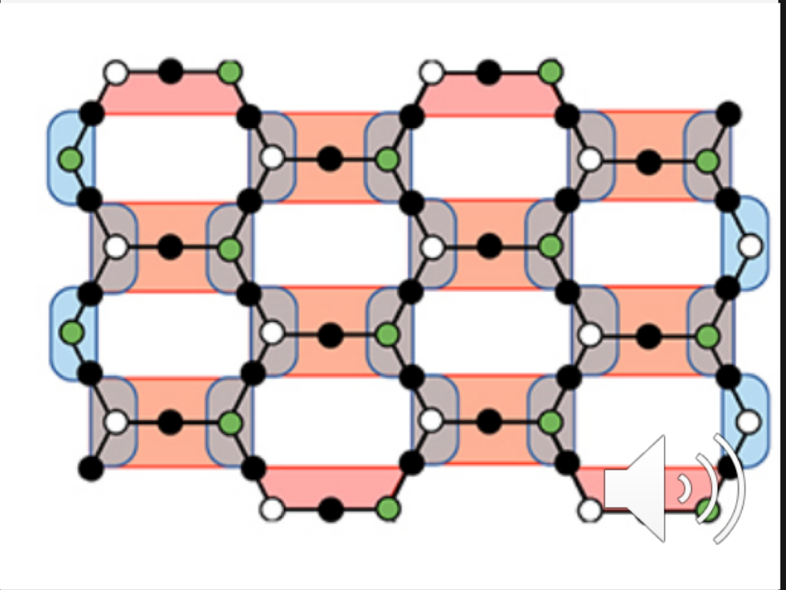
Random fluctuations during chip fabrication can lead to frequency collisions, impacting yield and limiting scaling

Process controls and selective anneal of junctions show promise in minimizing collisions

Cross Resonance Gate



IBM Quantum's 65-qubit topology



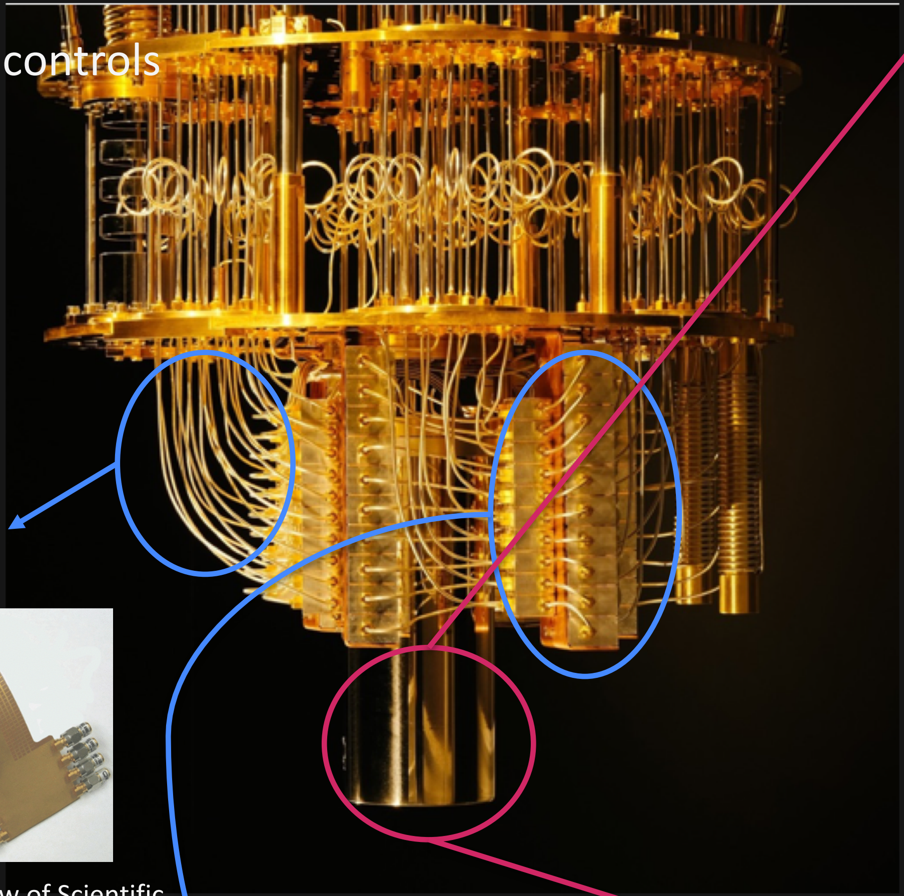
Scaling to higher numbers of qubits

Room temp electronics

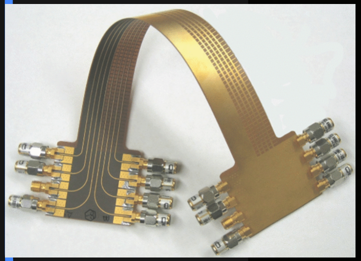
(stable, low-noise, cost)

Inside the Cryostat

Cryo-CMOS controls



Cryo flex lines

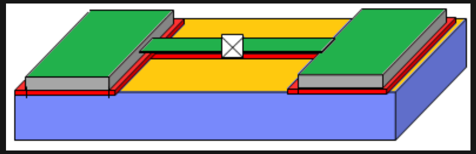


Harris et al., Review of Scientific Instruments 83, 086105 (2012)

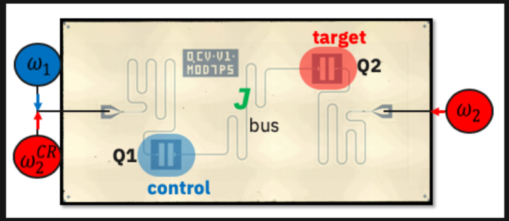
Amplifiers, Attenuators, Isolators, Packaging

Processor, device development

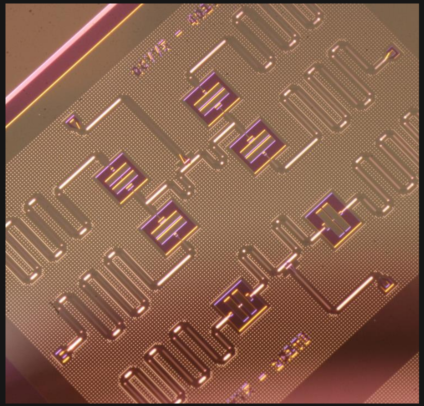
Coherence, junctions, materials



Better two-qubit gates

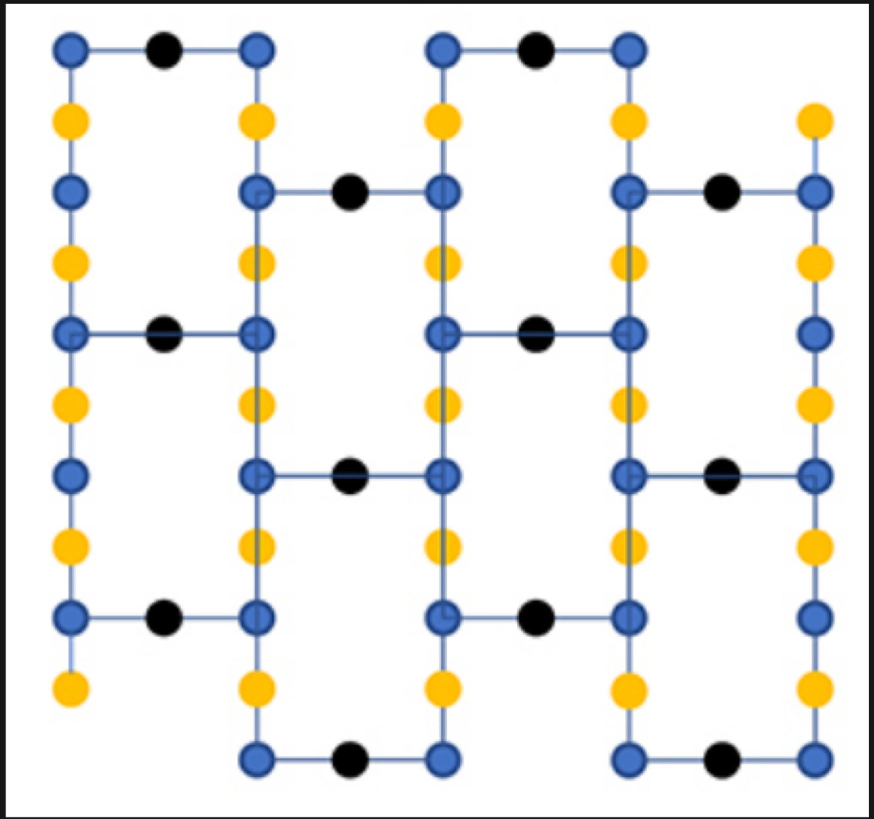


Novel qubit couplers



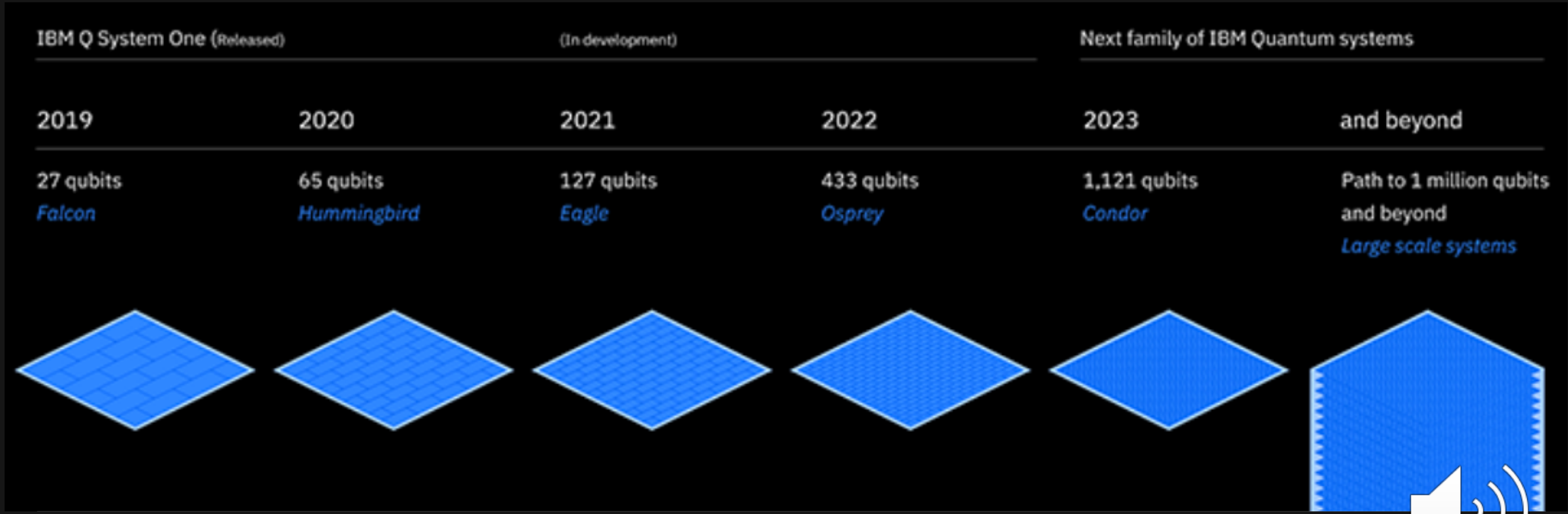
Simulation for quantum computing

- Key requirements for simulation are highly accurate (0.1% to 1%) **frequency estimation** of high-Q resonators and qubits, and extremely low levels of **crosstalk** (< -60 dB)
  - Traditional commercial tools don't typically operate at the level of precision required
  - High levels of required accuracy drive model sizes to be intractable, leading to **composite simulation strategies**, combining lumped element and FEM models.



Design automation for quantum computing

- Design automation and design rule checks are now becoming important as we transition from Research-level chips to **large-scale devices** with hundreds or thousands of qubits.
  - New structures and requirements are resulting in rules which are **unique to quantum**
  - Design automation must take into account aspects such as **crosstalk, qubit coherence, readout and qubit-qubit coupling.**



IBM Quantum hardware strategy

Near-term
quantum computing with errors

Long-term
Universal Fault-tolerant quantum computing

What do we need to get there?

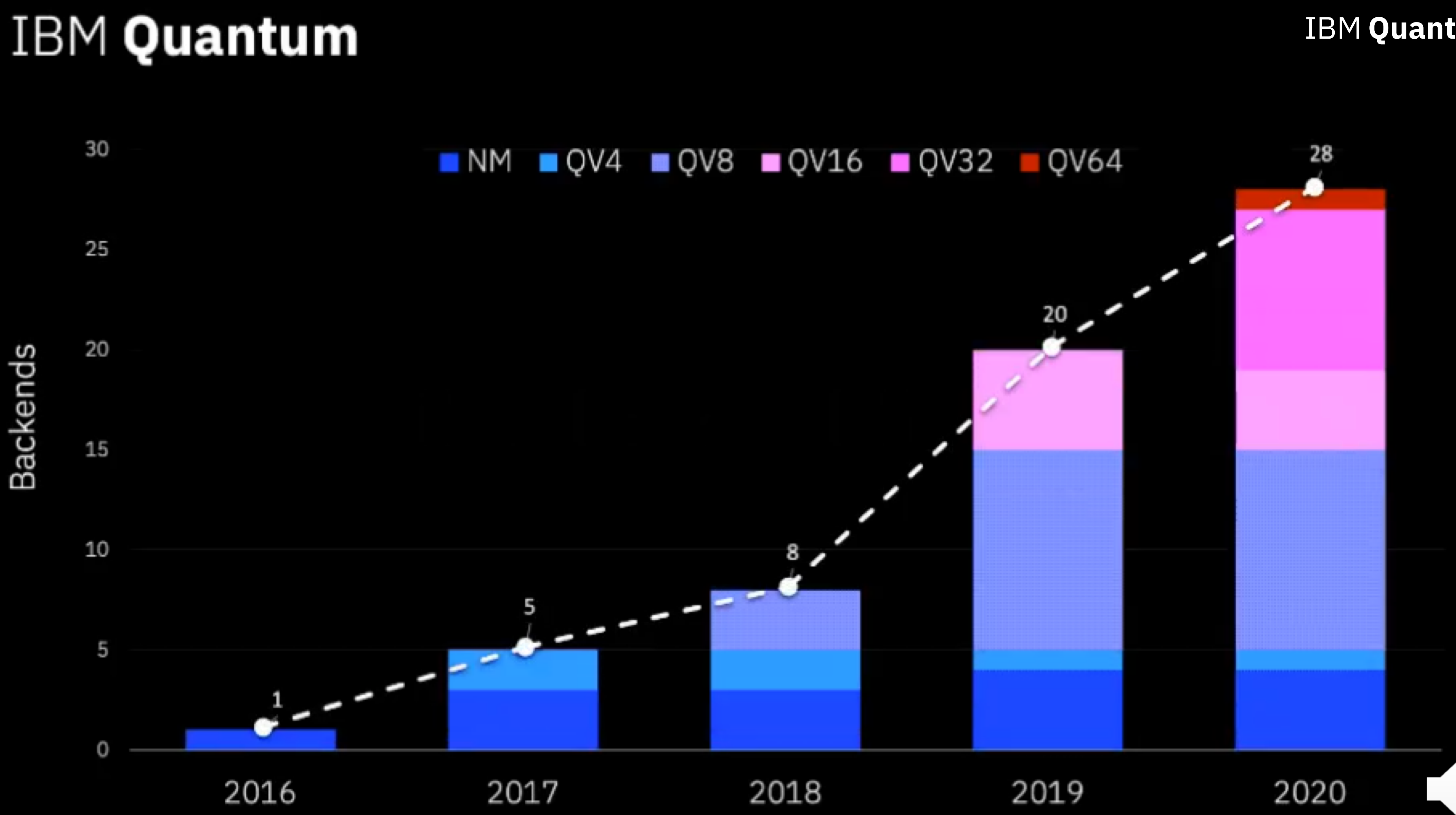
Better gate fidelity
Longer coherence times
More qubits
Higher yield

More reliable systems
Better measurement
Faster measurement
Tight classical integration

Everything for near-term +
Better Error Correcting Codes

These parameters are all coupled; changes in one indirectly impacts the rest.

Reaching our goals requires fundamental research and discovery.


IBM Quantum
NM
QV4
QV8
QV16
QV32
QV64
Backends
30
25
20
15
10
5
0
1
5
8
20
28
2016
2017
2018
2019
2020

IBM Quantum

Quantum Chips

130k

Quantum Simulators

72k

Users

0.0

Top countries

New countries

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Thank You

Check out

- quantum-computing.ibm.com to get started programming
- ibm.com/quantum to partner with IBM
- qiskit.org for more information and join the community

