Quantum Devices Come in Many Shapes!

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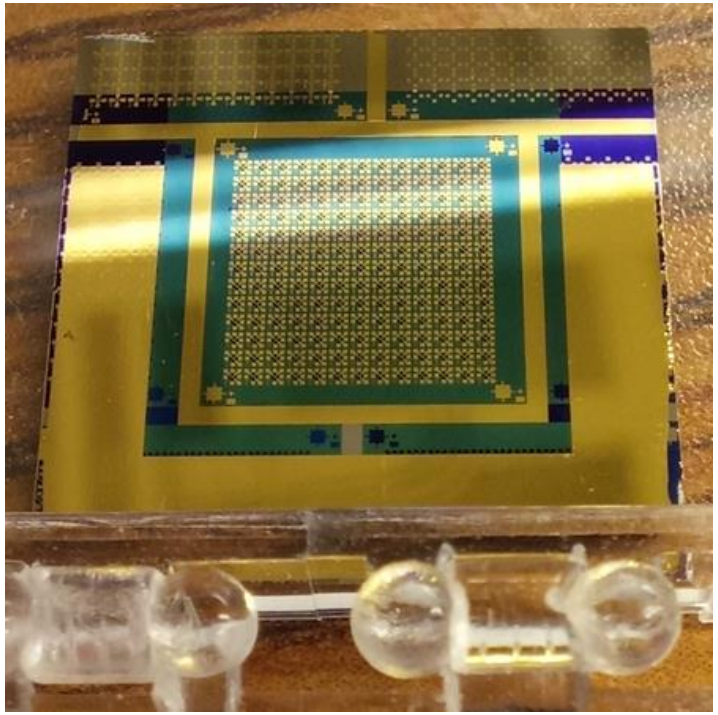


Spin-Orbit Torque Magnetic Tunnel Junction Array Chip
(Onri Jay Benally)

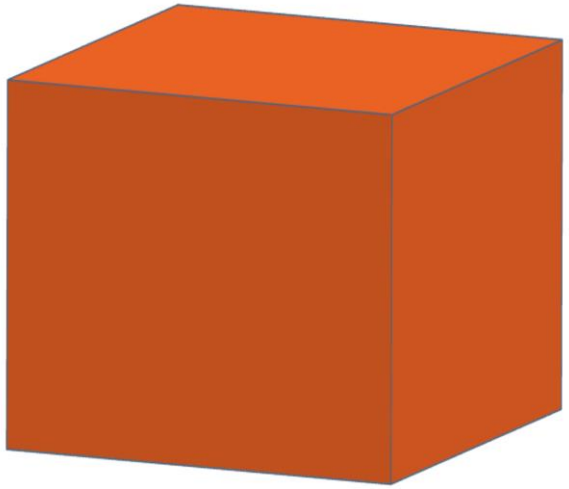
Quantum Systems Range in Size

- In configuring quantum machines, it is useful to know that **control components** have changed over the years for various purposes.
- Control components for qubits can take up a lot of space, however an effort has been made to miniaturize them using complementary Metal Oxide Semiconductor (CMOS) chips.

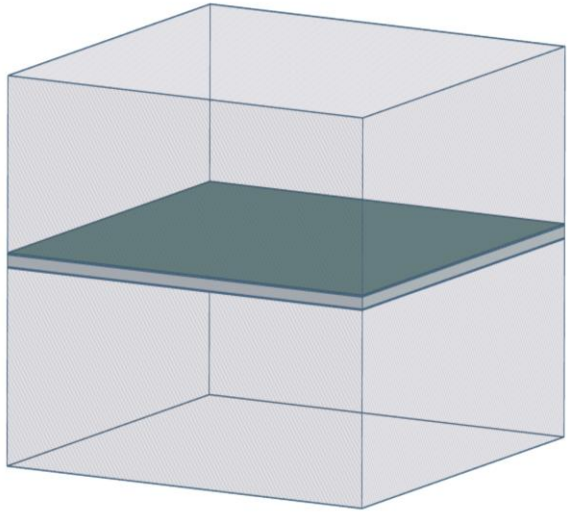
More Desktop-Like **More Server-Farm-Like**

Quantum Devices Also Come in Basic Shapes

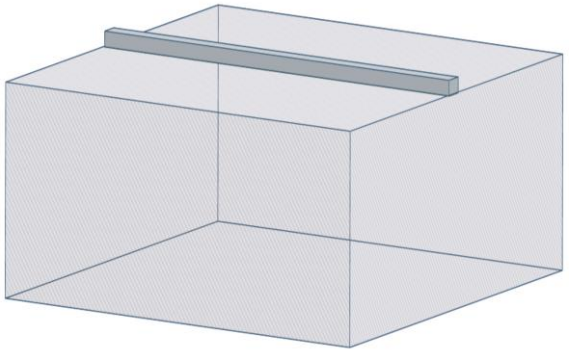
- In manufacturing, building quantum devices are continuously shaped to achieve desired size.
- A bulk material is selected ➔ nano scale structure ➔ quantum properties exploited.



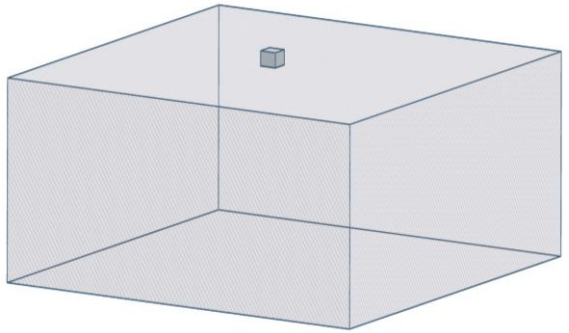
Bulk Structure



Quantum Well



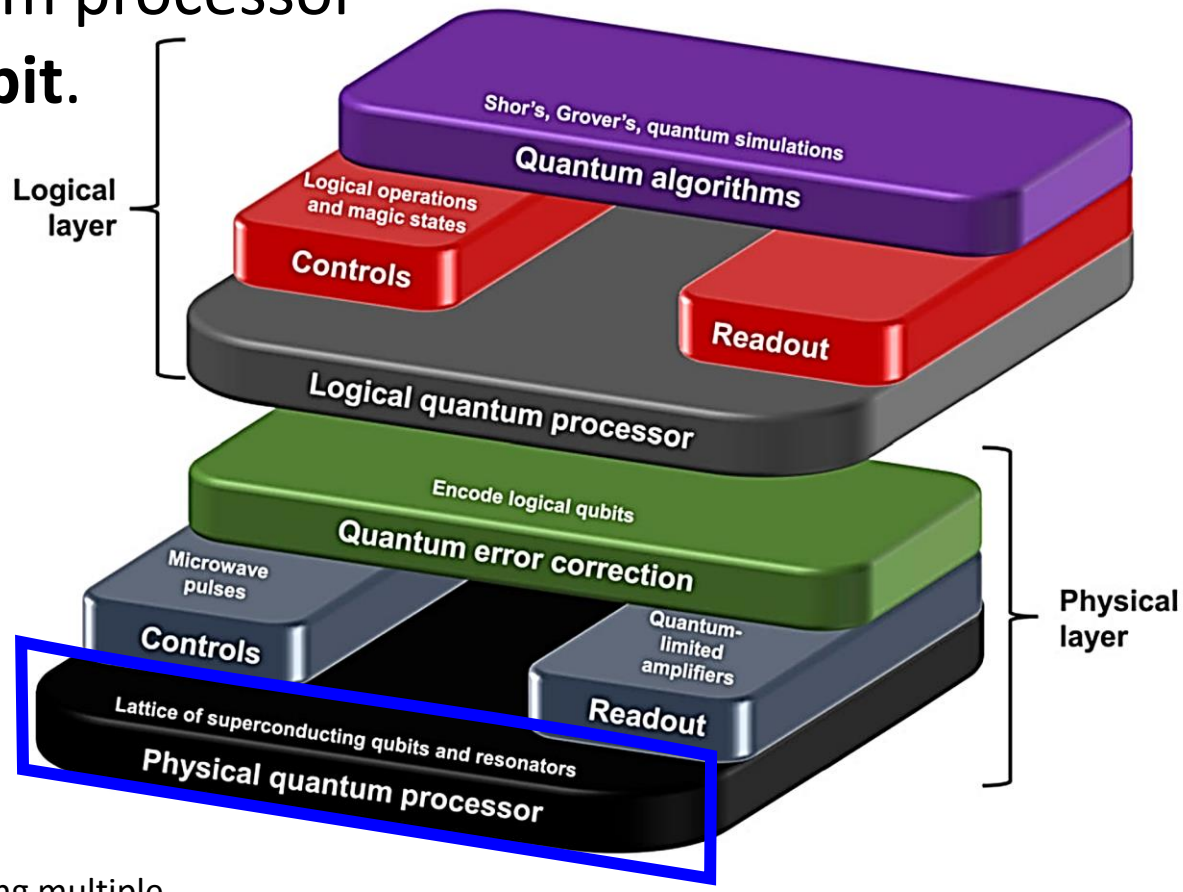
Nanowire/ Quantum Wire



Quantum Dot

Layered Architecture

- The quantum stack consists of 2 parts: software & hardware.
  - Software = logical layer
  - Hardware = physical layer
- At the device level, the physical quantum processor can be replaced with **your choice of qubit**.
- QPU = Quantum Processing Unit
- Quantum hardware uses analog.

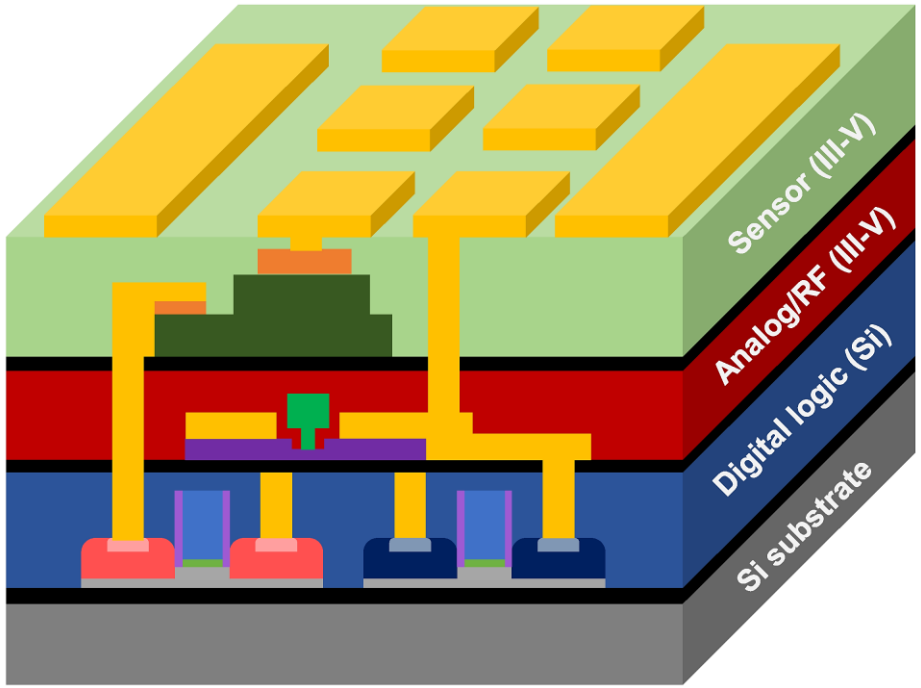


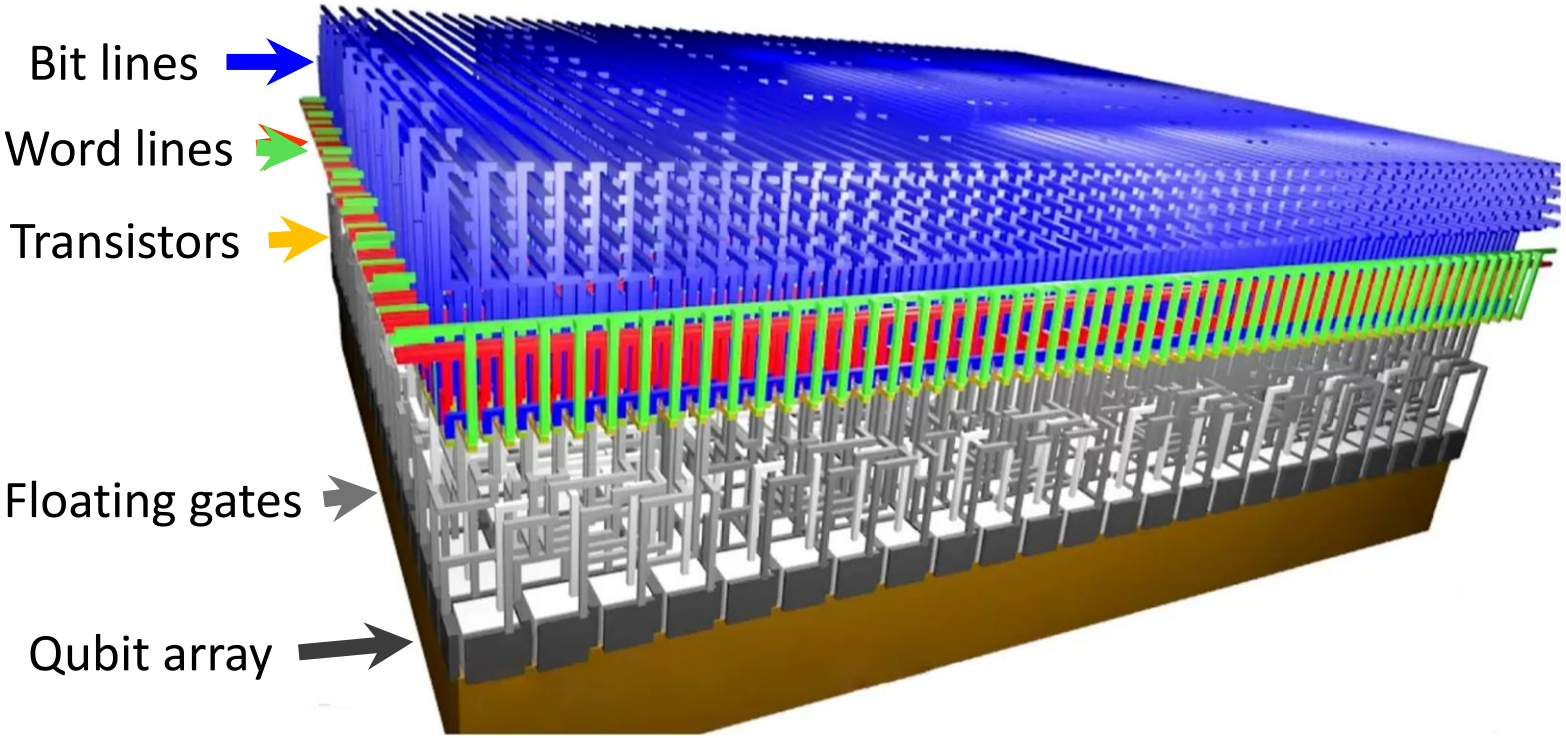
*Magic state [distillation]: a process of combining multiple noisy quantum states into few reliable quantum states.

1. Gambetta et al., *Nature.* (2017)

Digital Integrated Chip vs. Quantum Integrated Chip

- Typically, in an integrated quantum circuit the **larger components** sit at the **top**, while the **smaller components** exist at the **bottom**.
  - Like conventional classical chips.





1. Wikimedia Commons – KAIST
2. Veldhorst et al., *Nat Commun* (2017)

*Word lines = green & red bars on quantum integrated chip

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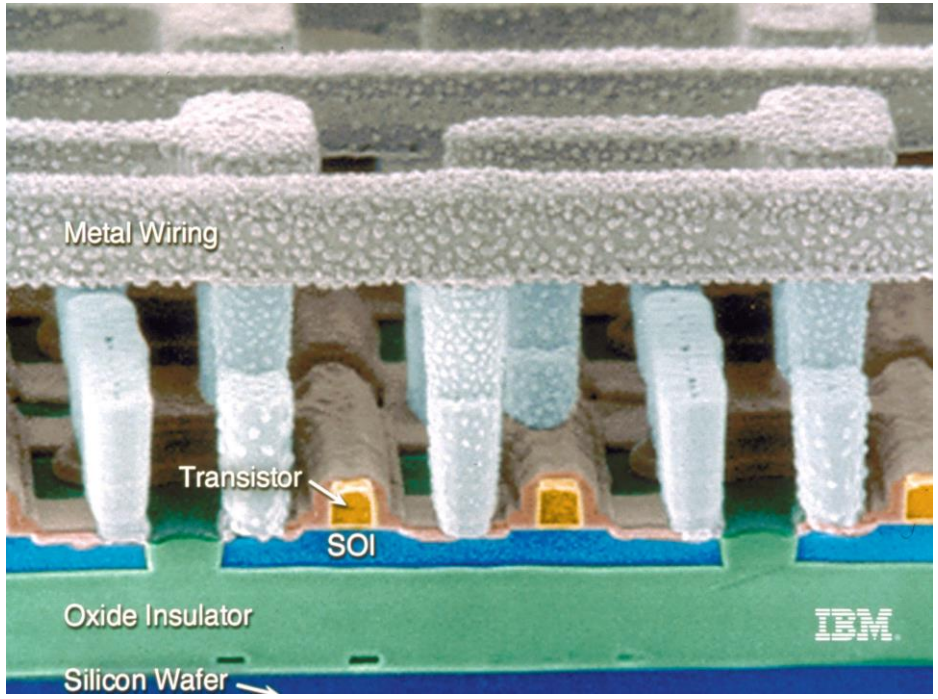
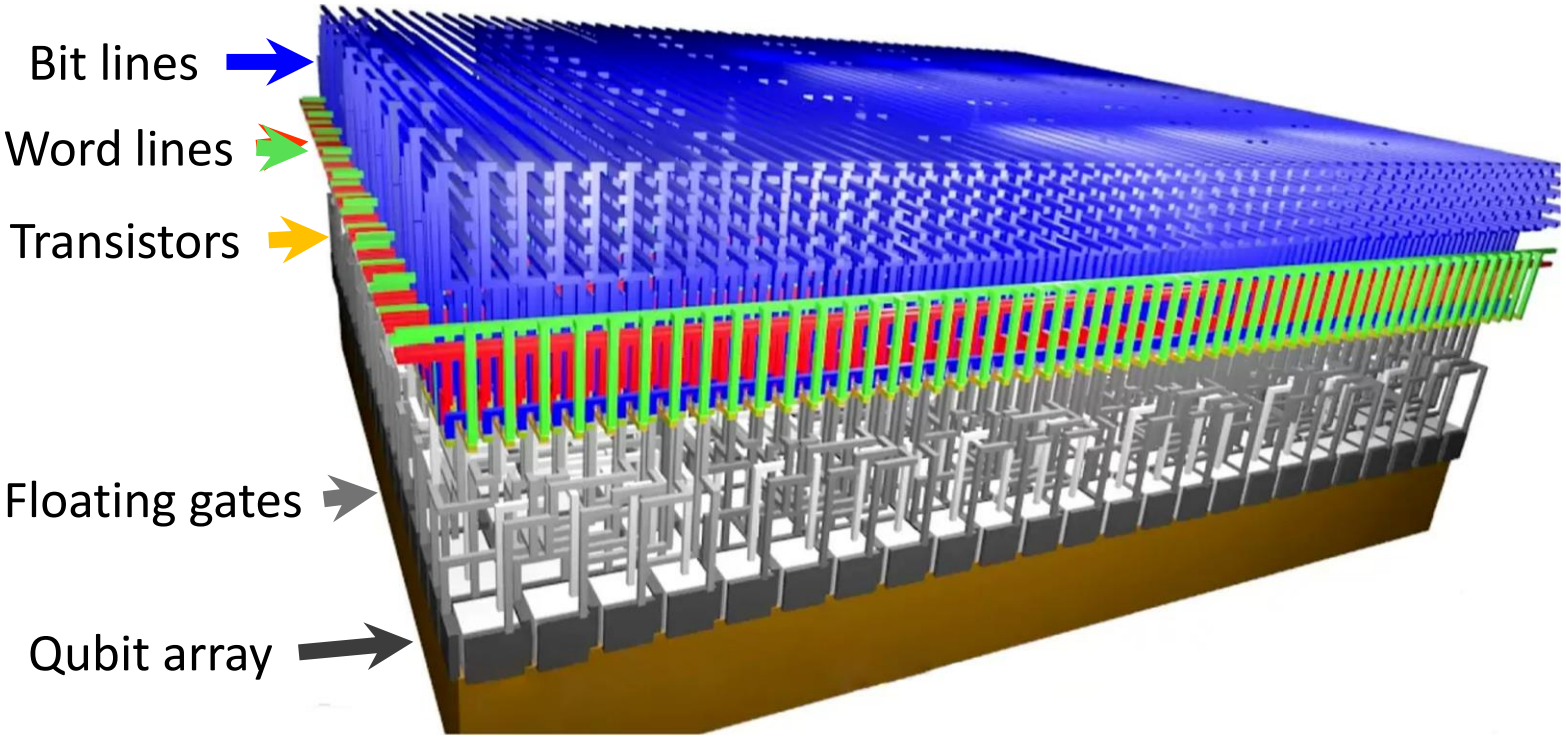
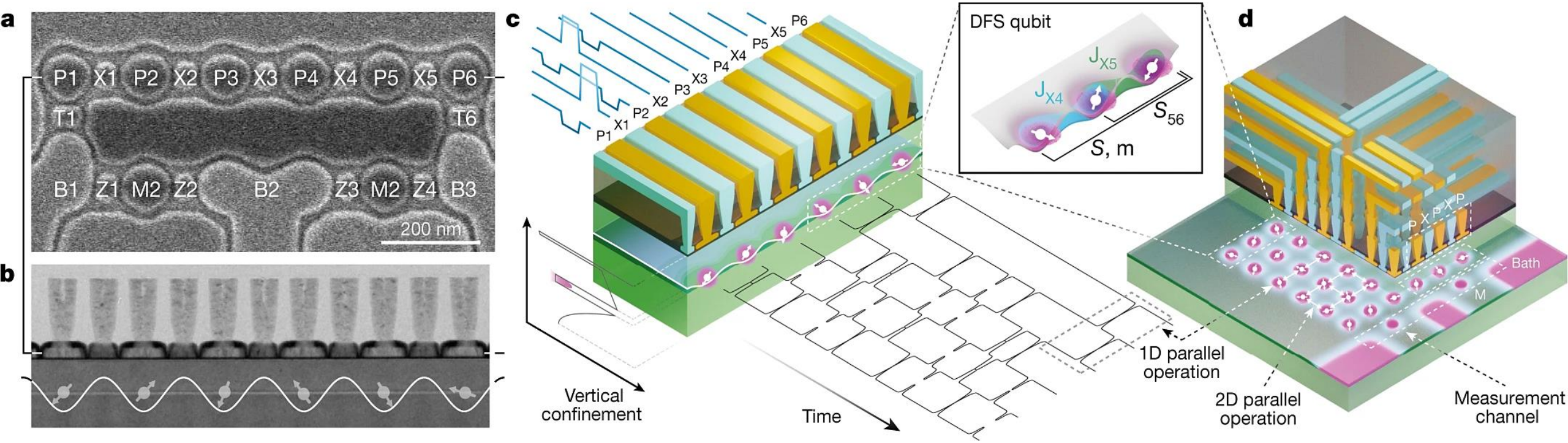




1. IBM Research
2. Veldhorst et al., *Nat Commun* (2017)

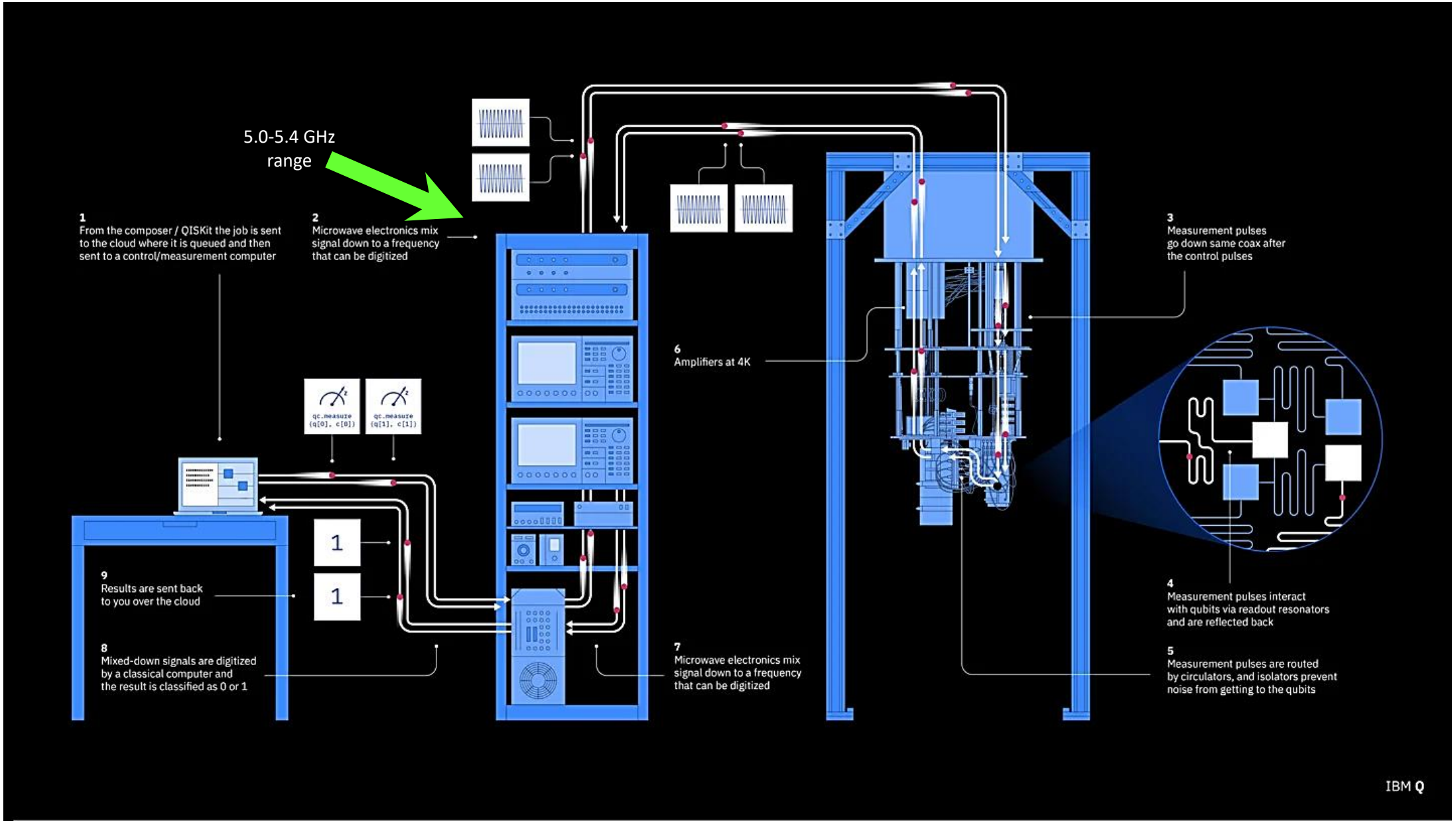
*Word lines = green & red bars on quantum integrated chip

Example of Encoded Spin Qubits with 6 Quantum Dots



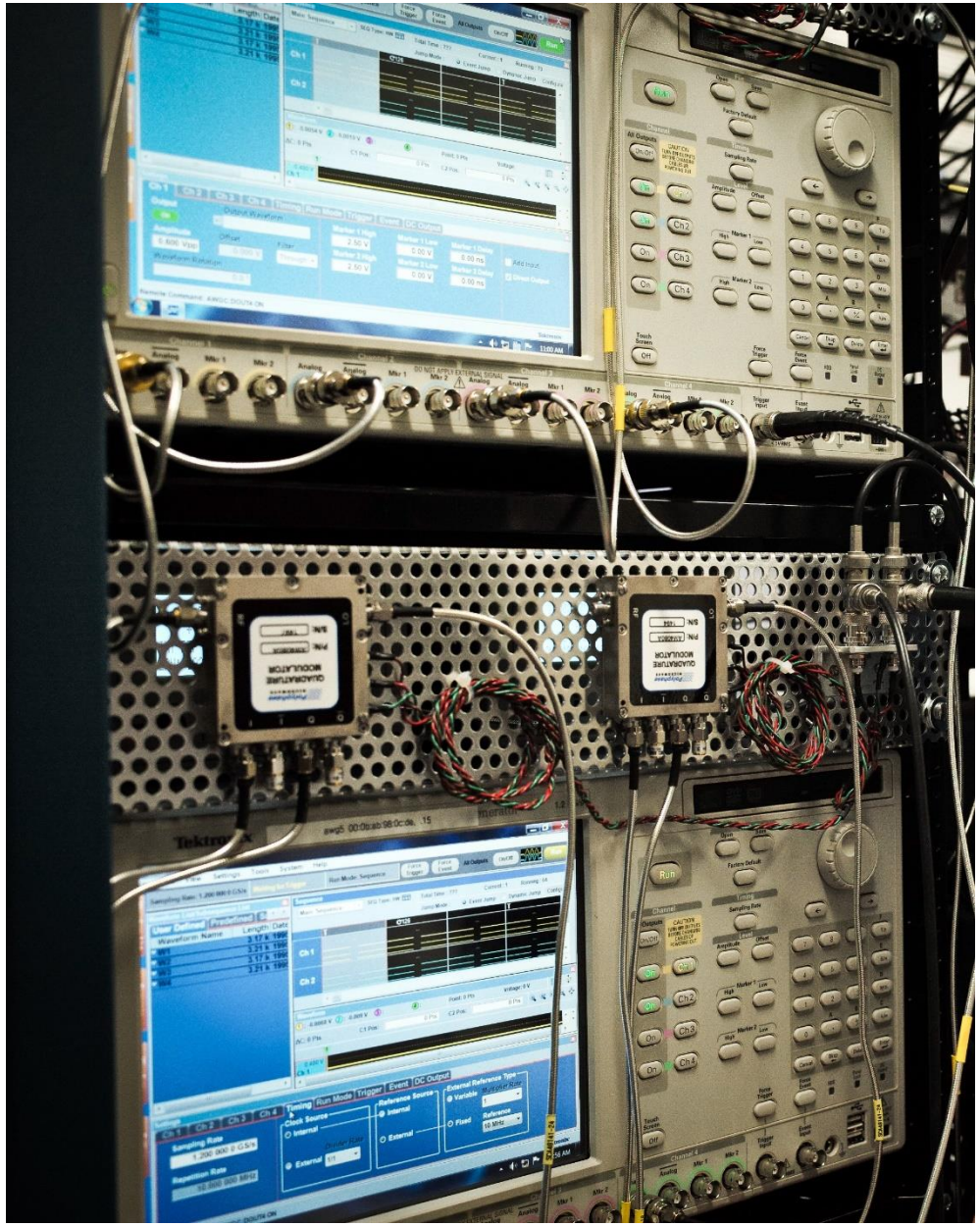
1. Weinstein et al., *Nature* (2023)

Example System Overview



1. IBM Quantum, *System One.* (2020)

Example System Overview



Example System Overview

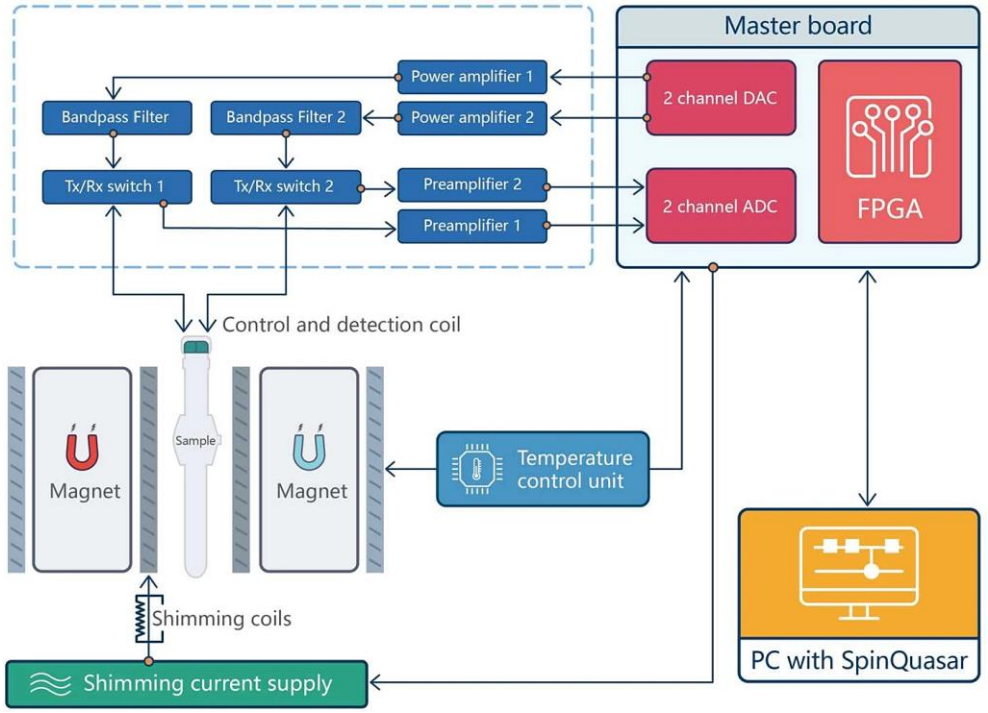
1. IBM Quantum

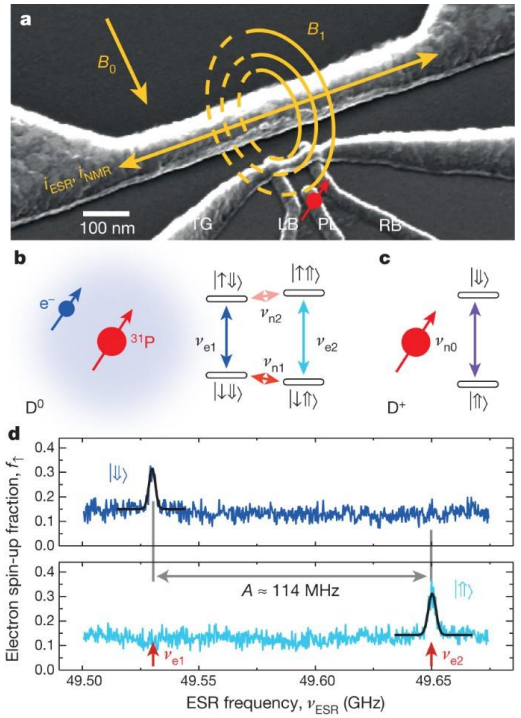
Example System Overview

1. IBM Quantum

Nuclear Magnetic Resonance Qubits

- In nuclear magnetic resonance qubit systems, a oscillating 1T magnetic field resonates with electron spins into which enters a state preparation electrode, into a nearby radio frequency gate for superposition control.
- The final stage involves taking the readout from the quantum gate with into a spin conversion contact for measurement output.



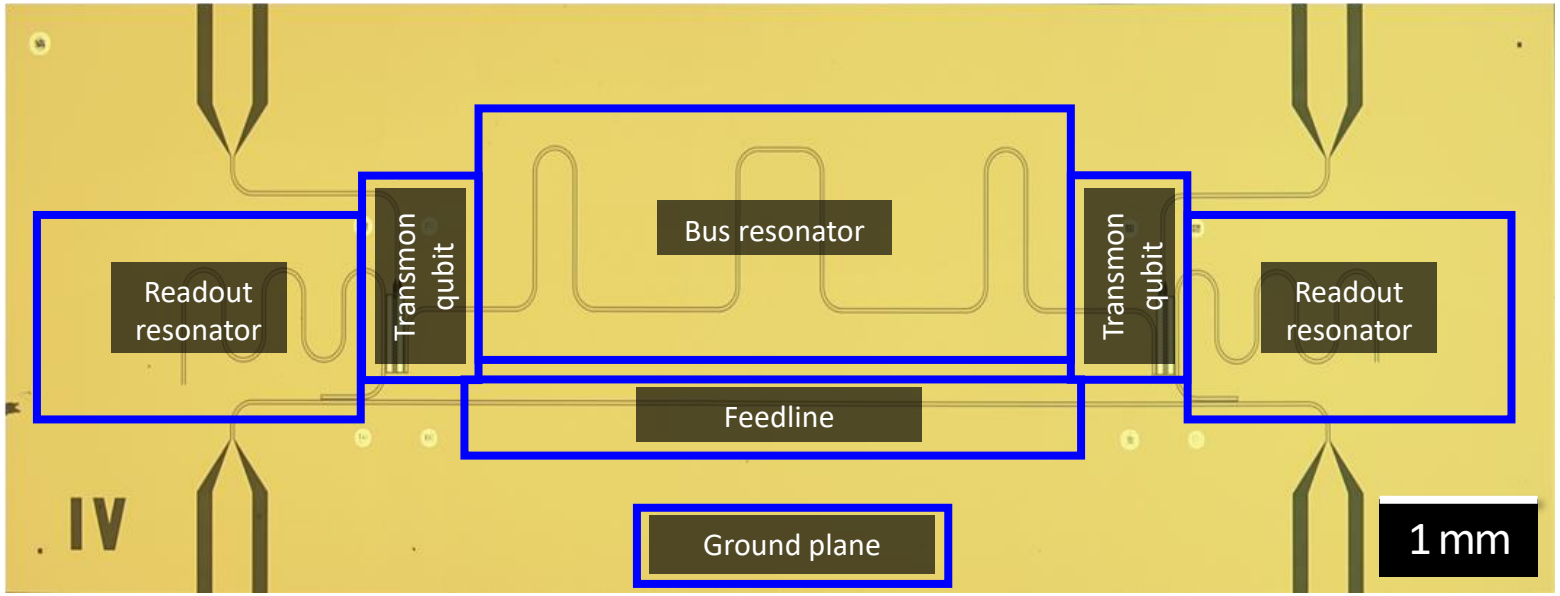


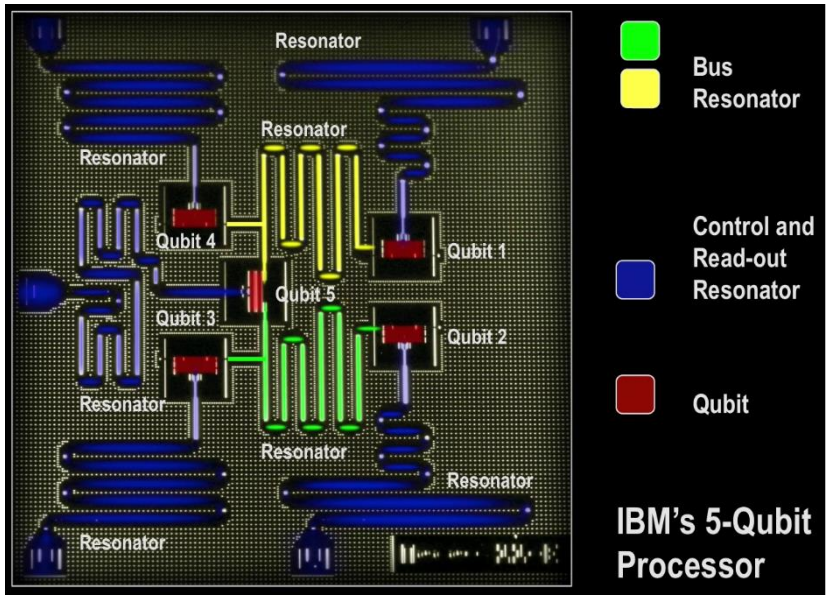
Up to 3-qubit desktop quantum PC (novelty).
Price ≈ $5,000

1. Hou et al., *EPJ Quantum Technology* (2021)
2. SpinQ, *Gemini 2 [2-Qubit System]* (2022)
3. Pla et al., *Nature* (2013)

Superconducting Transmon Qubits

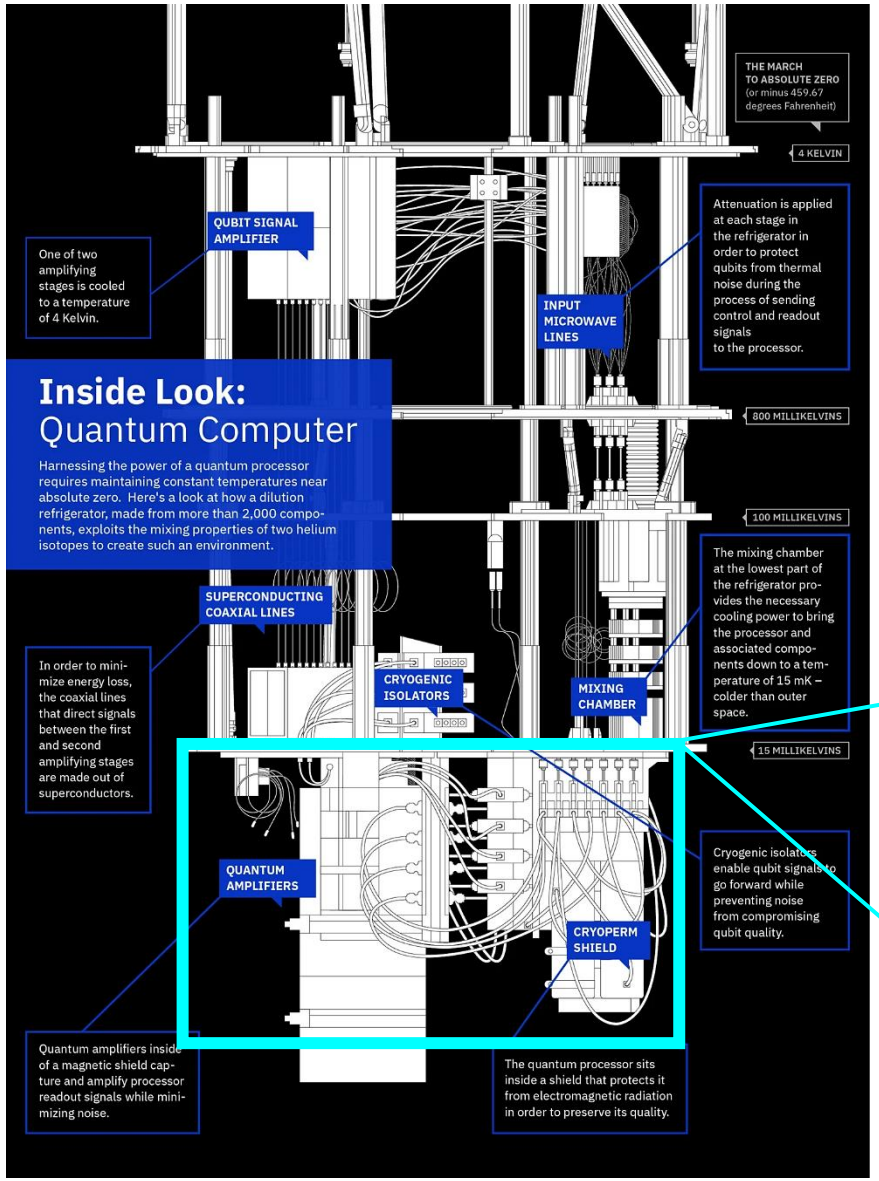
- In transmon qubit systems, a coplanar waveguide pumps microwaves (≈5 GHz) into an inducting Josephson junction, which couples via a bus resonator for superposition control (multiple Hadamards).
- The final stage involves taking the readout from the quantum gate into a feedline for measurement output.

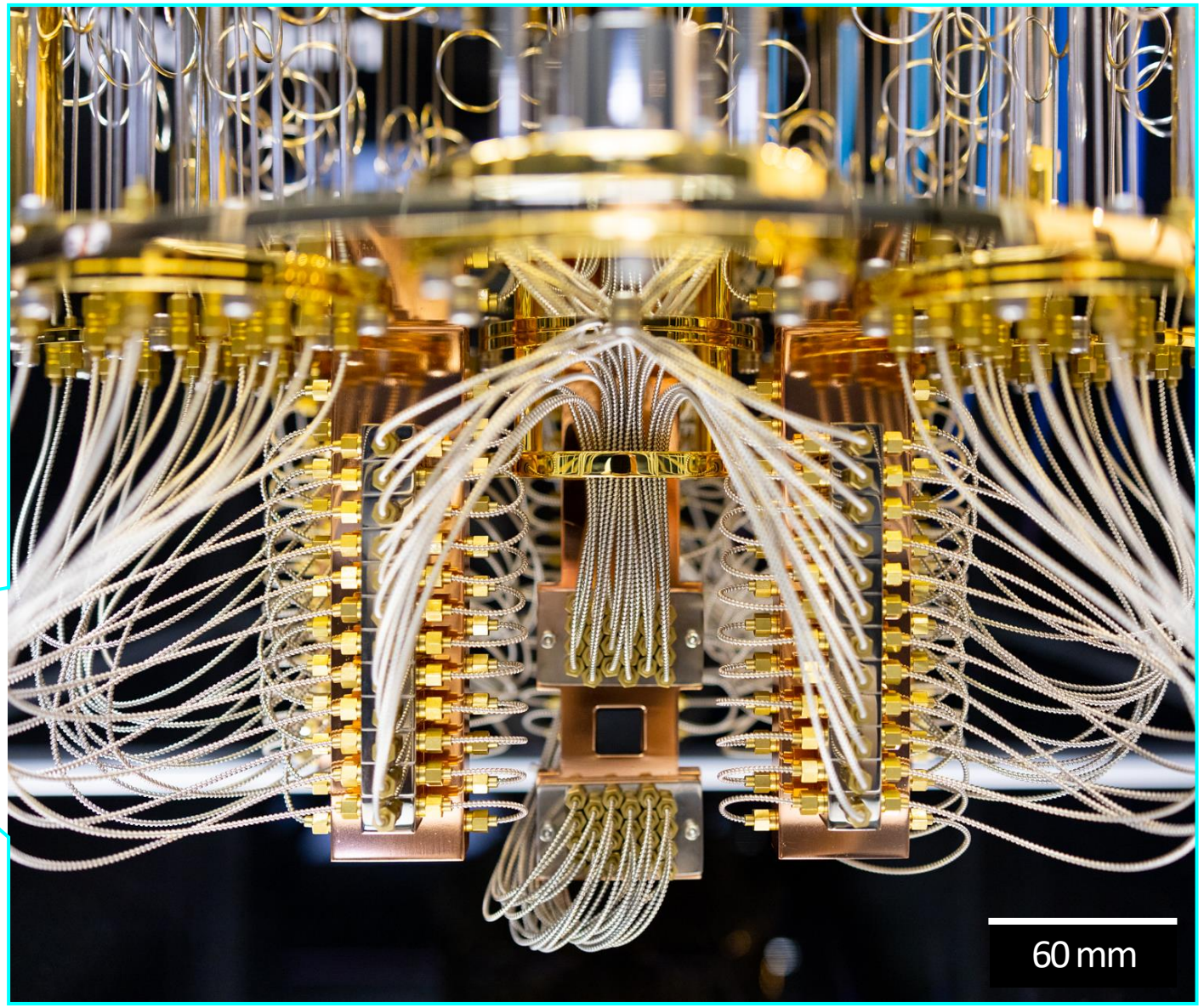




1. Delft University of Technology, *Hardware of a Quantum Computer* (2019)
2. IBM Research, *5-Qubit Processor* (2020)

Superconducting Qubit Placement (Bonus)

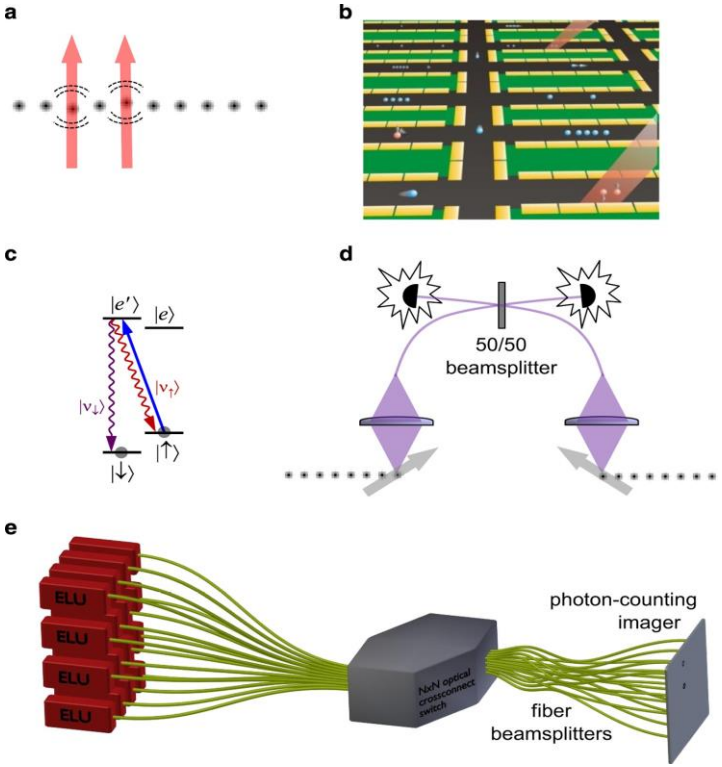


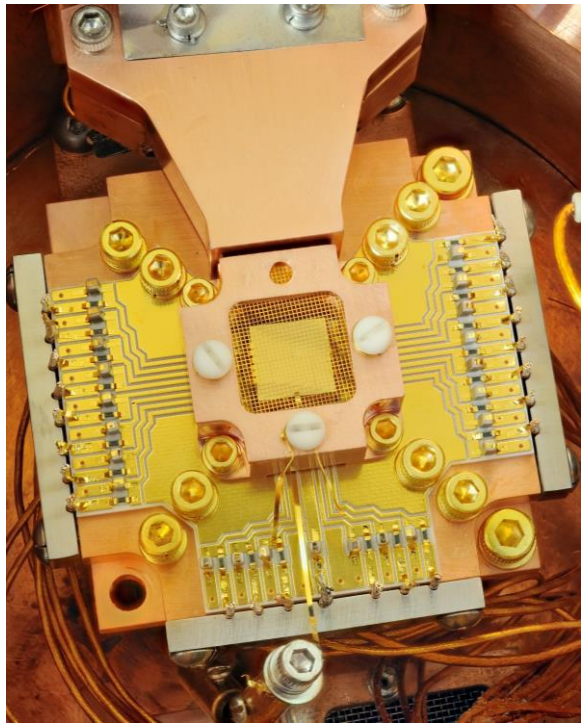


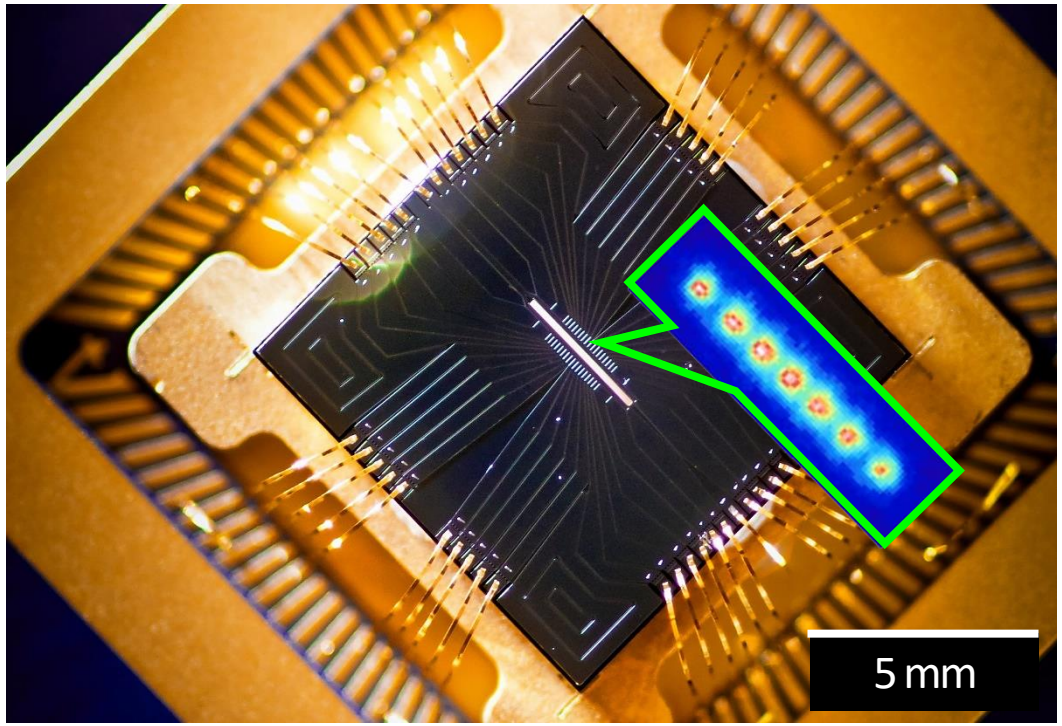
1. IBM Research, *Inside Look: Quantum Computer* (2020)
2. IBM Research, *IBM Quantum System One at Shin-Kawasaki* (2023)

Trapped Ion Qubits

- In trapped ion qubit systems, a diode laser pumps light into a polarization controller (PC), which enters a state preparation electromagnetic linear electrode trap & polarizing beam splitter (PBS), for superposition control.
- The final stage involves taking the readout from the quantum gate with a photon counting imager into a bundle of fiber beamsplitters for measurement output.



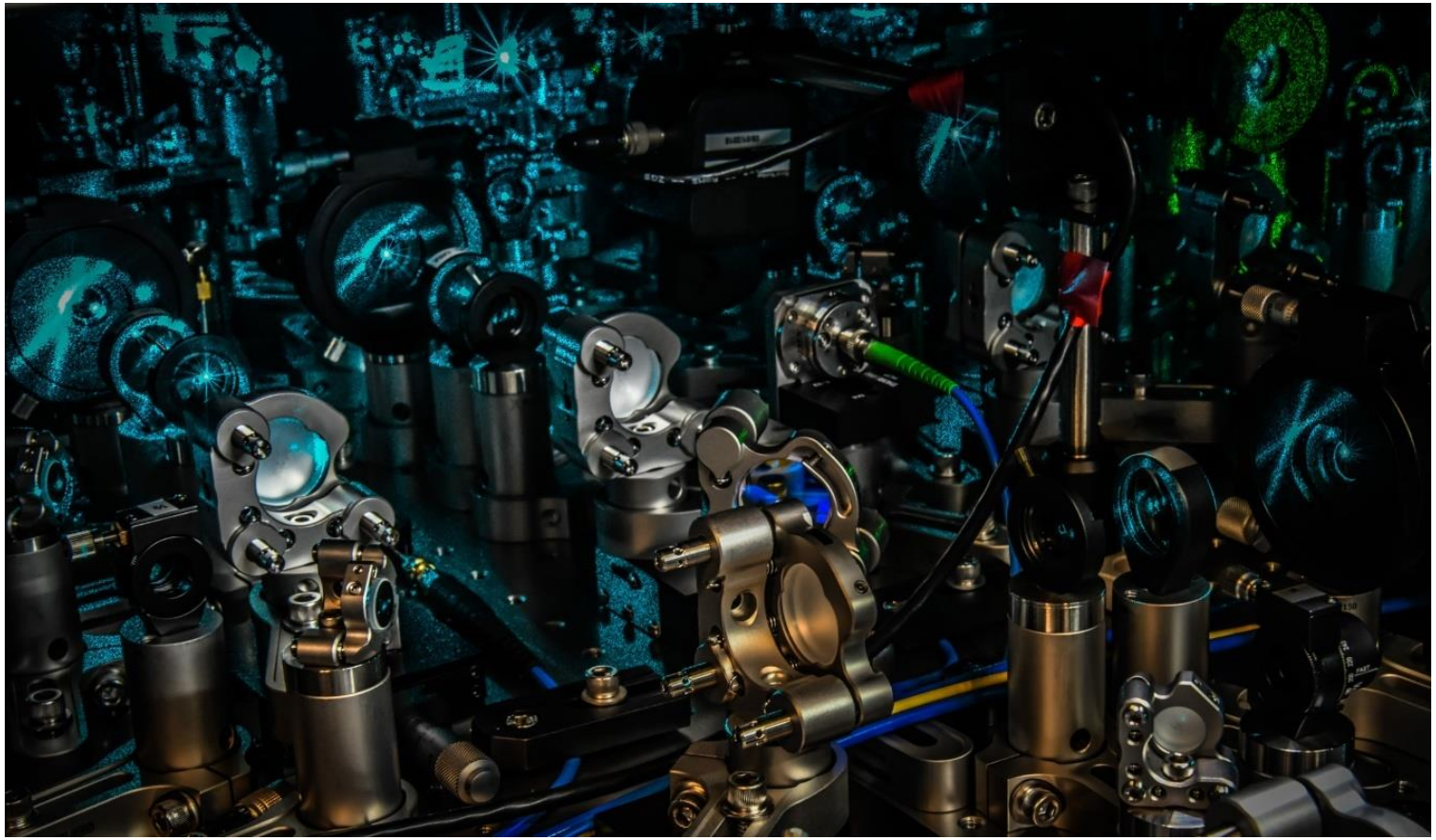


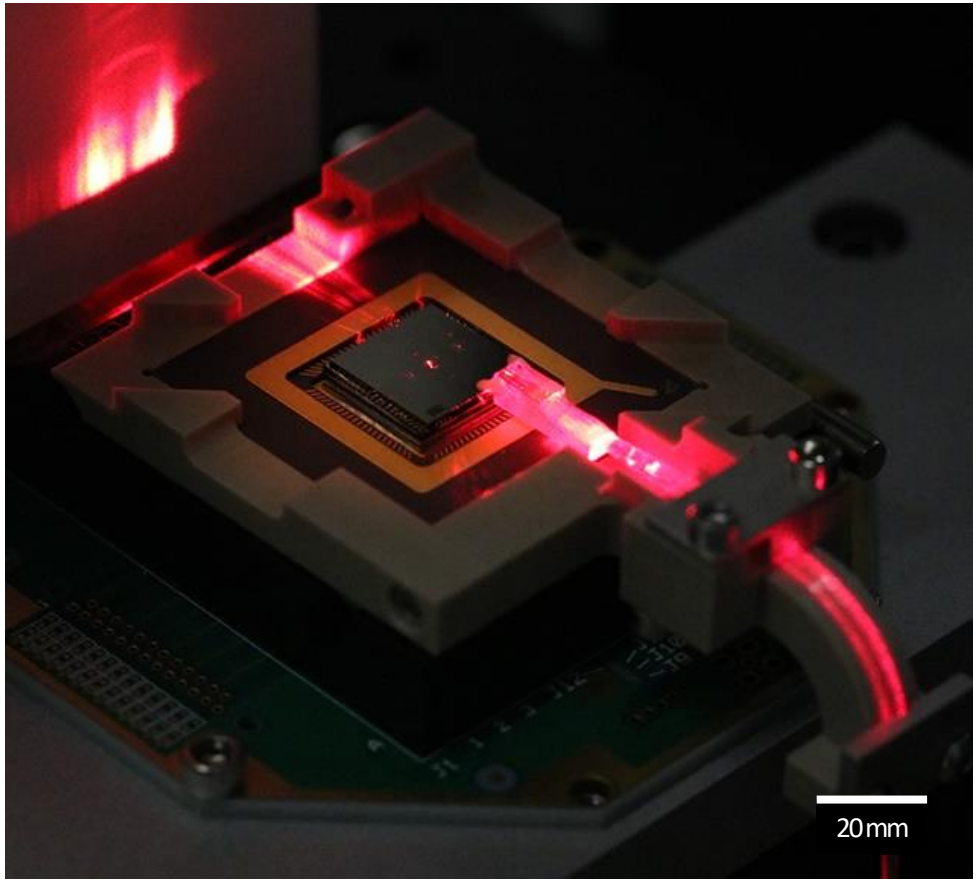


*Yb^+ ions are commonly used in this system, it contains 1 more electron than a neutral Yb atom

1. Brown et al., *Nature* (2016)
2. Wikimedia Commons – NIST
3. Rainer, *Institute for Quantum Optics and Quantum Information* (2018)

Trapped Ion Qubits (Bonus)

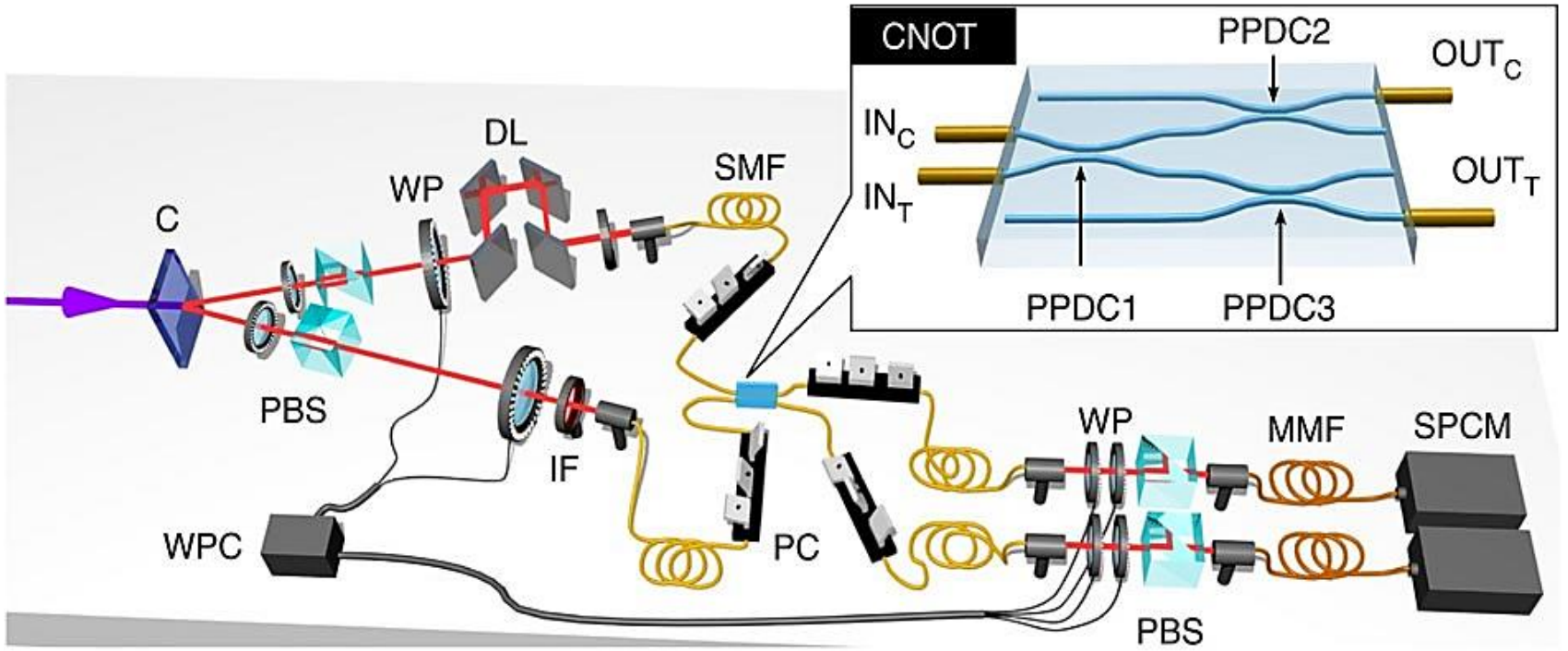


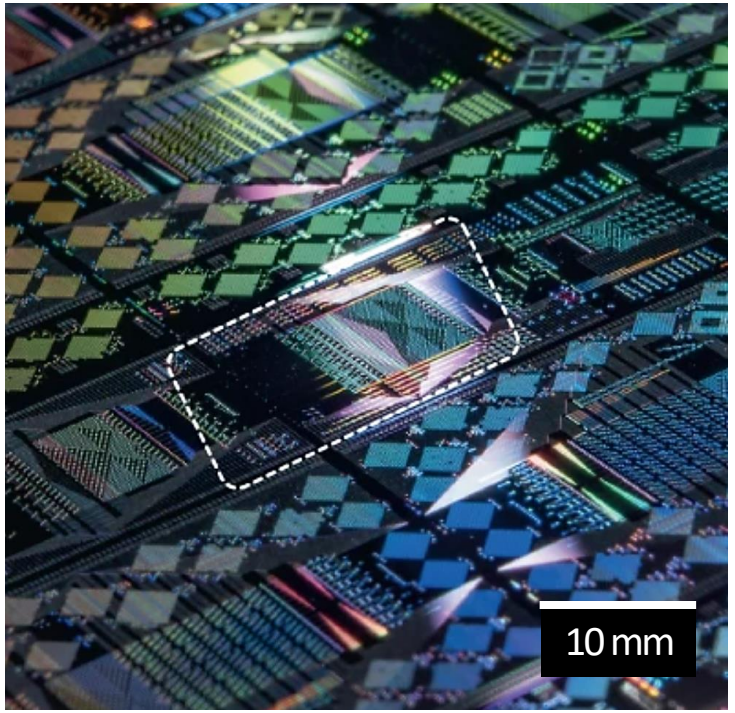


1. Honeywell, *Trapped Ion Quantum Computer* (2021)
2. MIT Lincoln Laboratory, Quantum Information and Integrated Nanosystems Group (2018)

Photonic Qubits

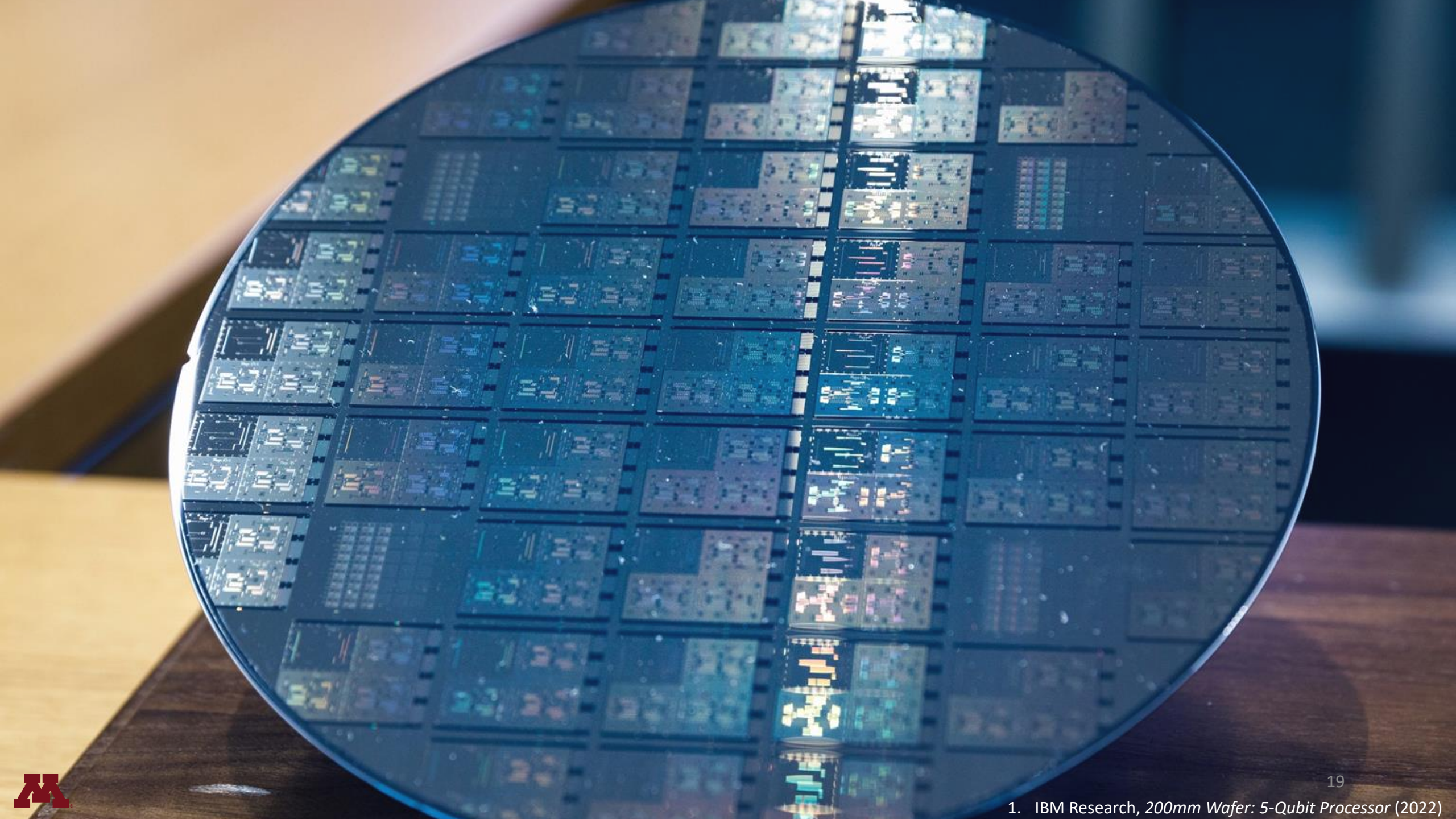
- In photonic qubit systems, a diode laser pumps light into a polarization controller (PC), which enters a state preparation waveguide (WP) & polarizing beam splitter (PBS), into a delay line (DL) for superposition control.
- The final stage involves taking the readout from the quantum gate with directional couplers (PPDC) into a single photon counter (SPCM) for measurement output.





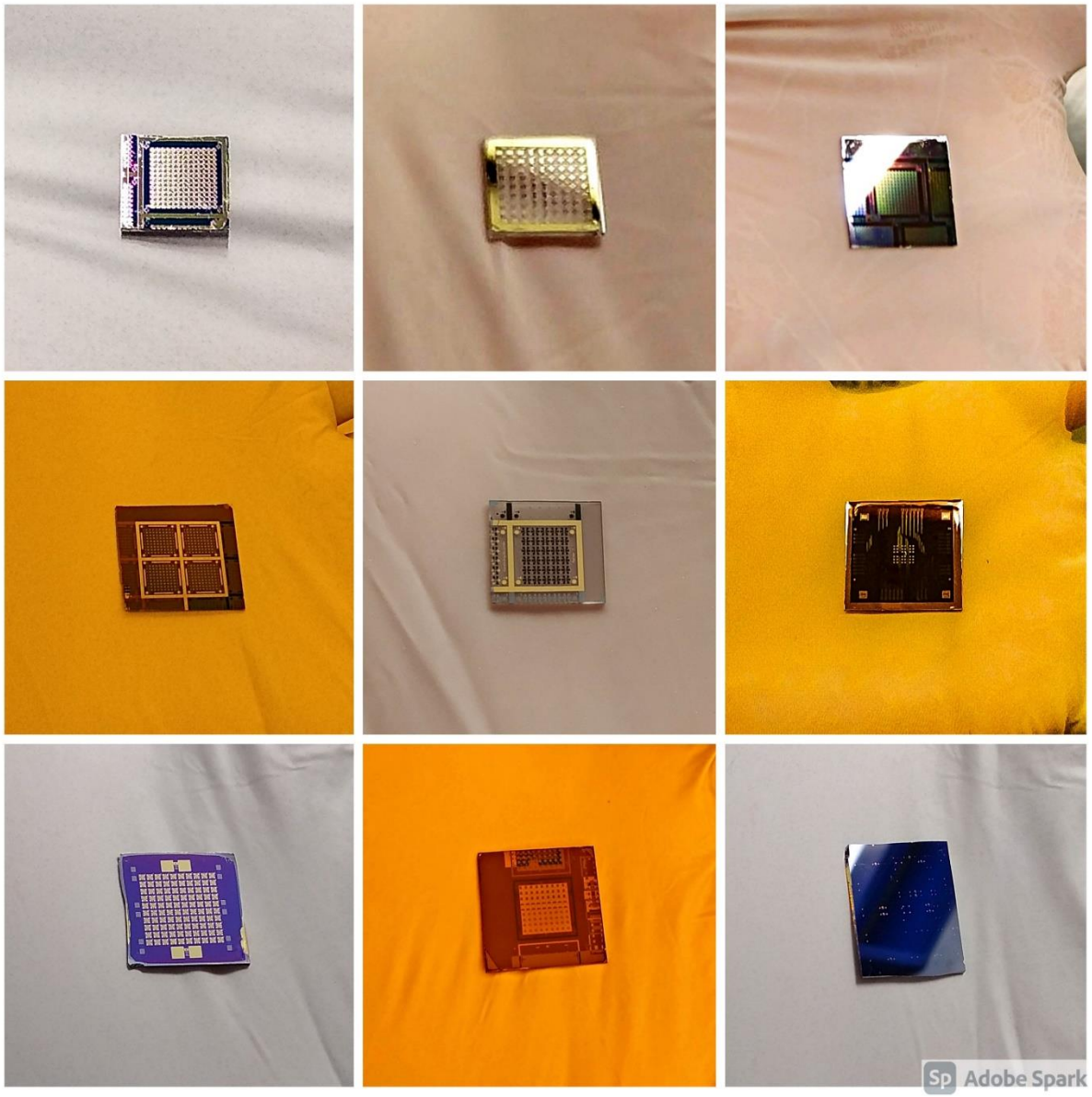
*PPDC: partially polarizing directional coupler
**MMF: multimode fiber

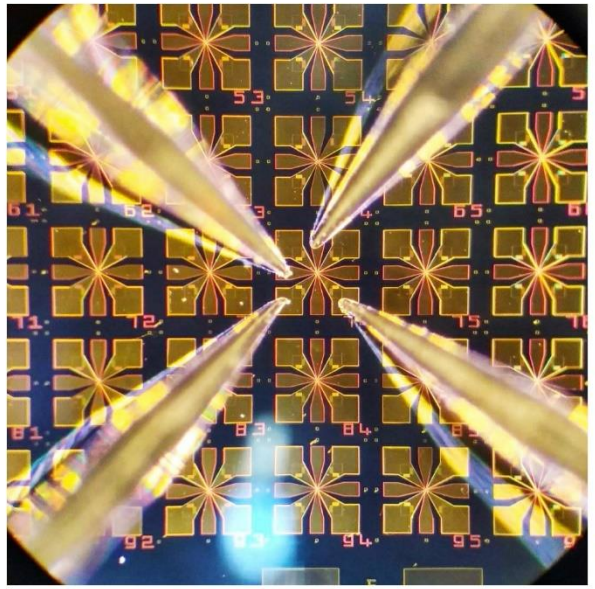
1. Crespi et al., *Nature Communications* (2011)
2. Bao et al., *Nature Photonics* (2023)

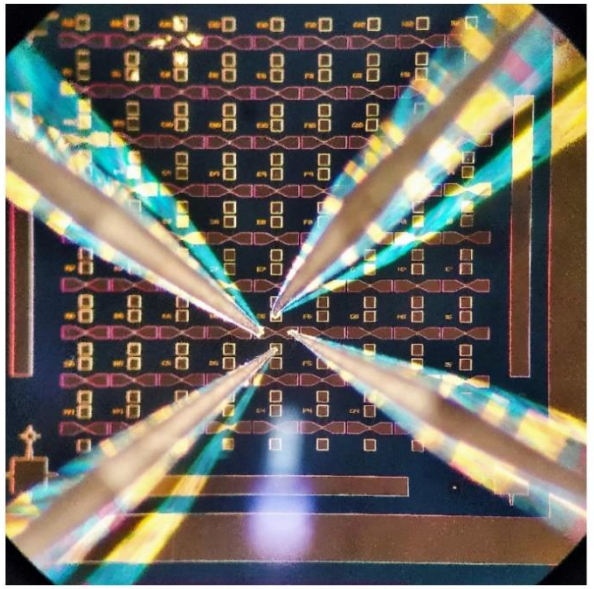


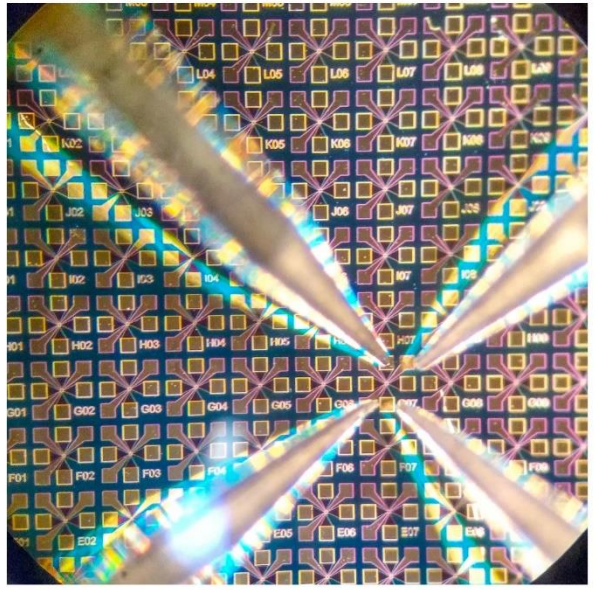
1. IBM Research, *200mm Wafer: 5-Qubit Processor* (2022)

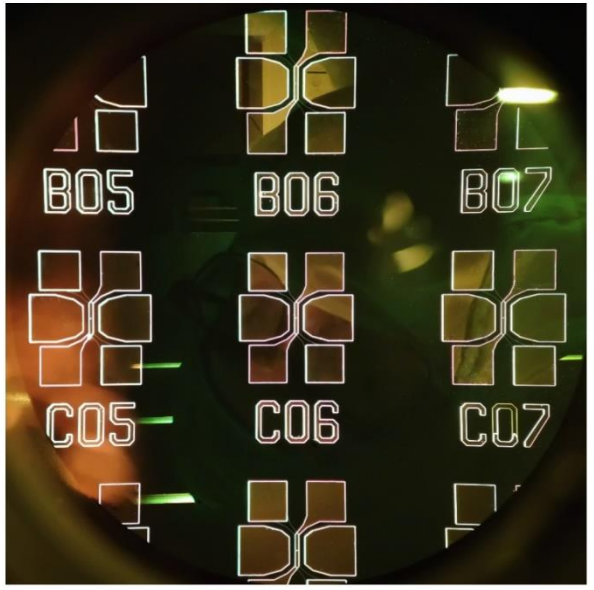
Nanomagnetic Devices that Employ Quantum Tunneling



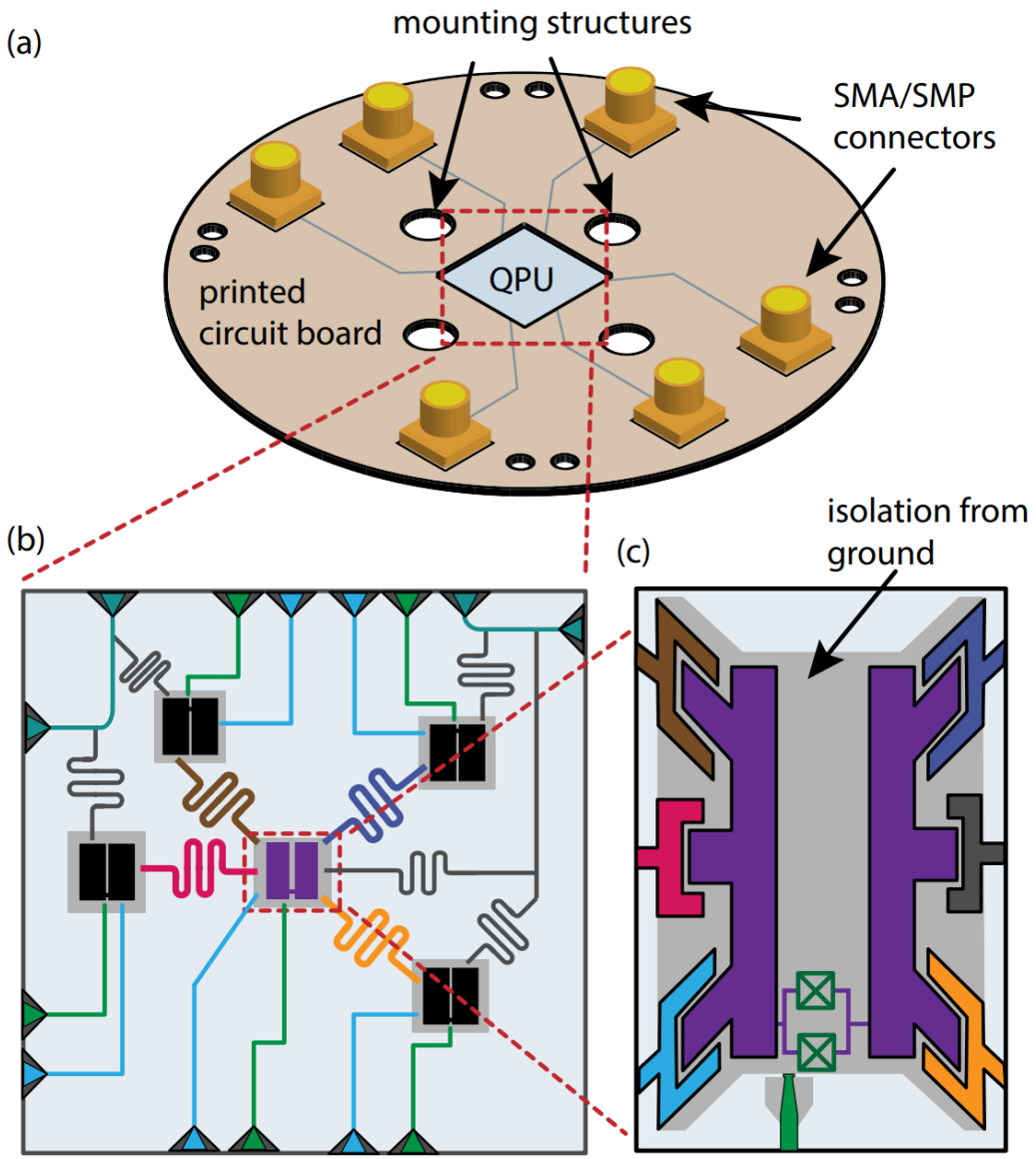


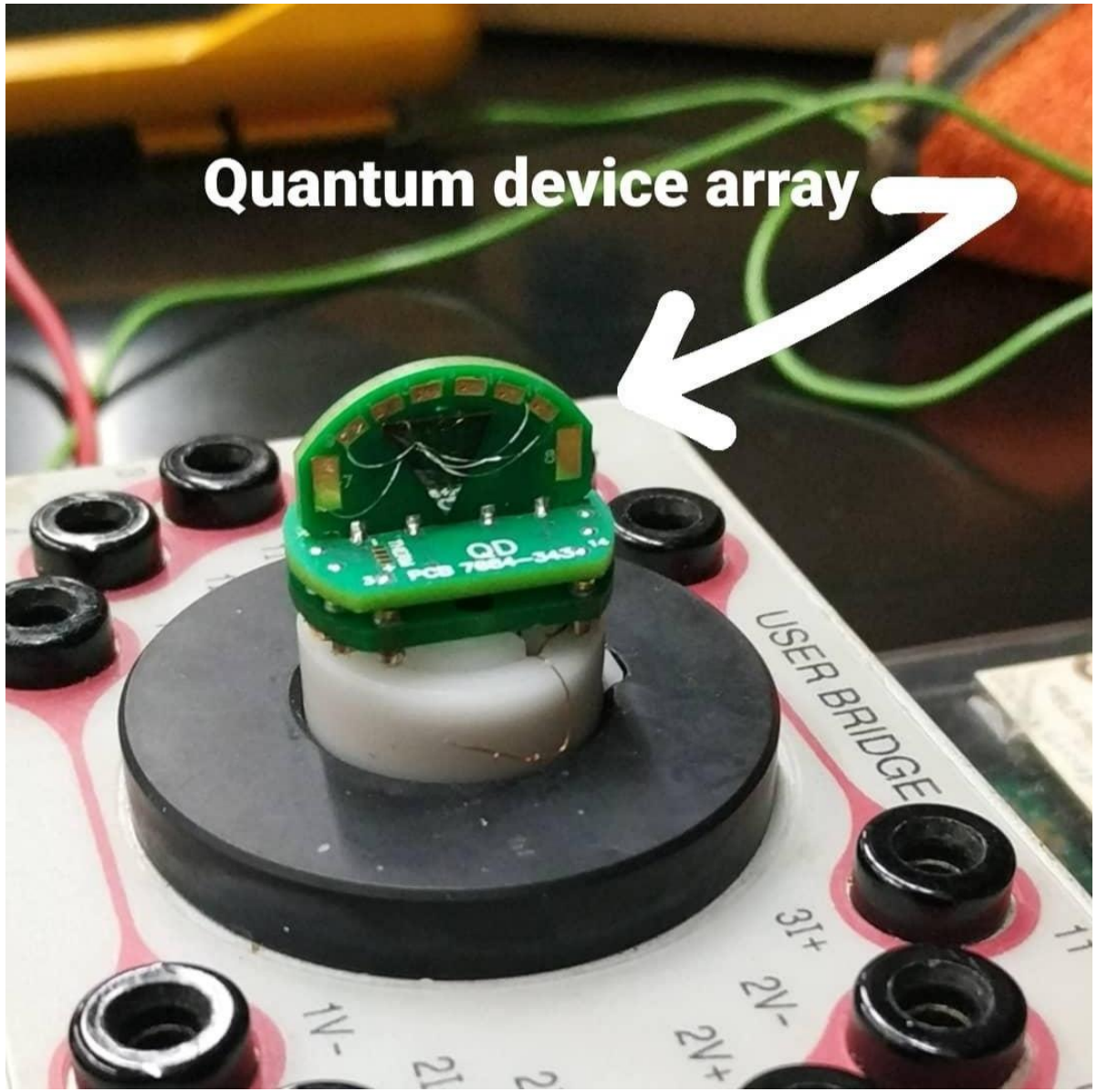






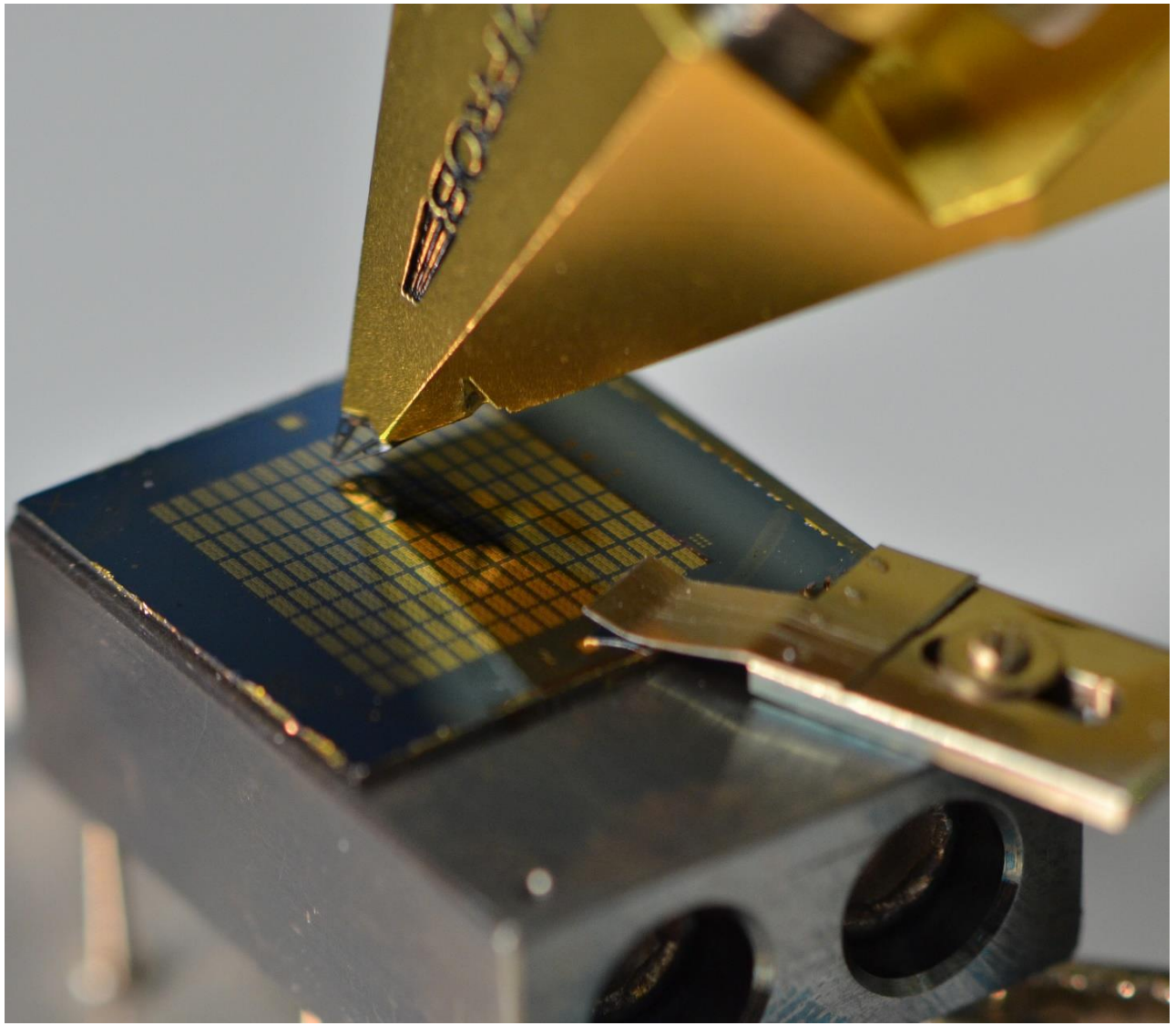
Comparison of Chip Modularity

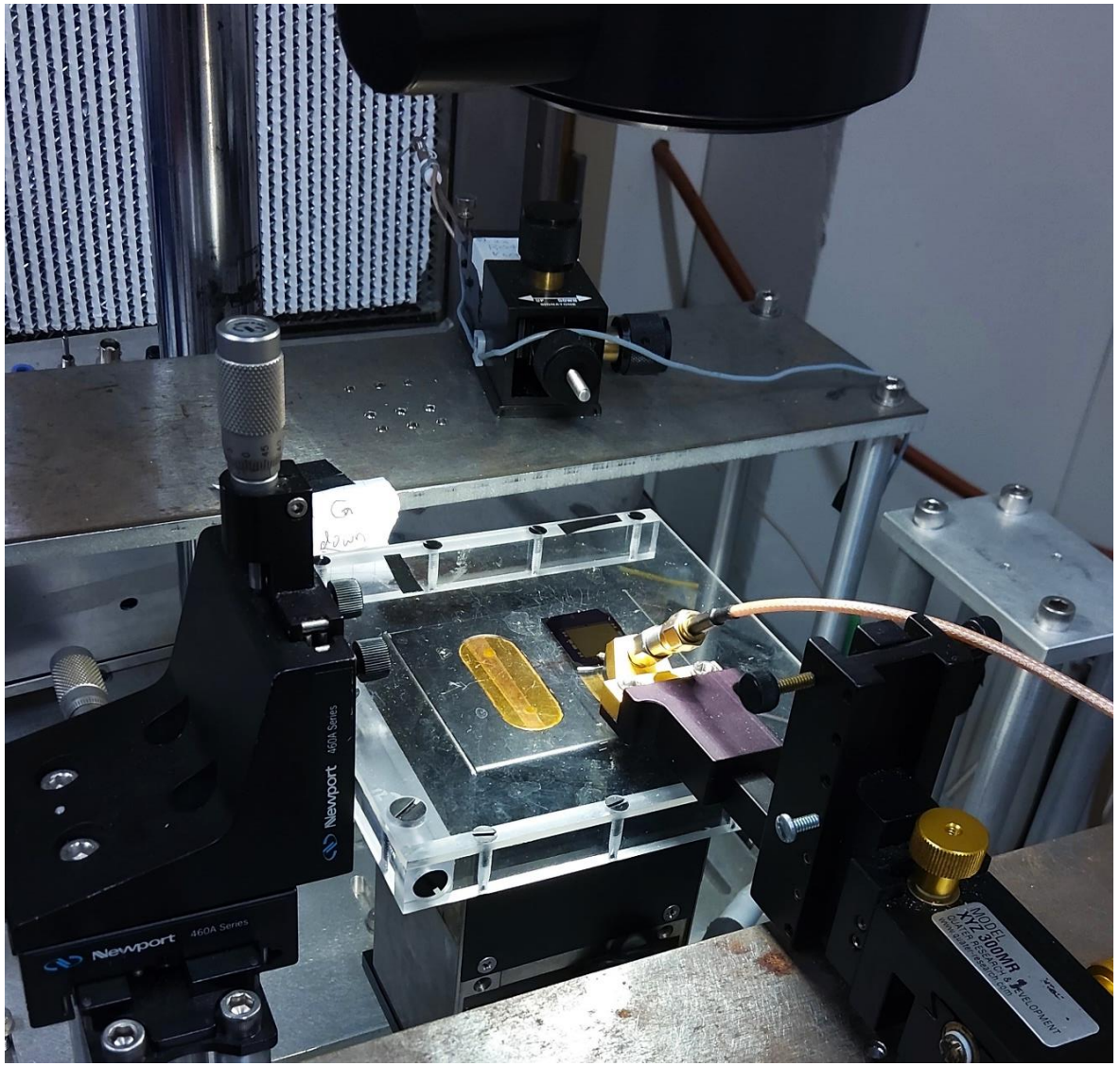




1. Gao et al., *arXiv* (2021)

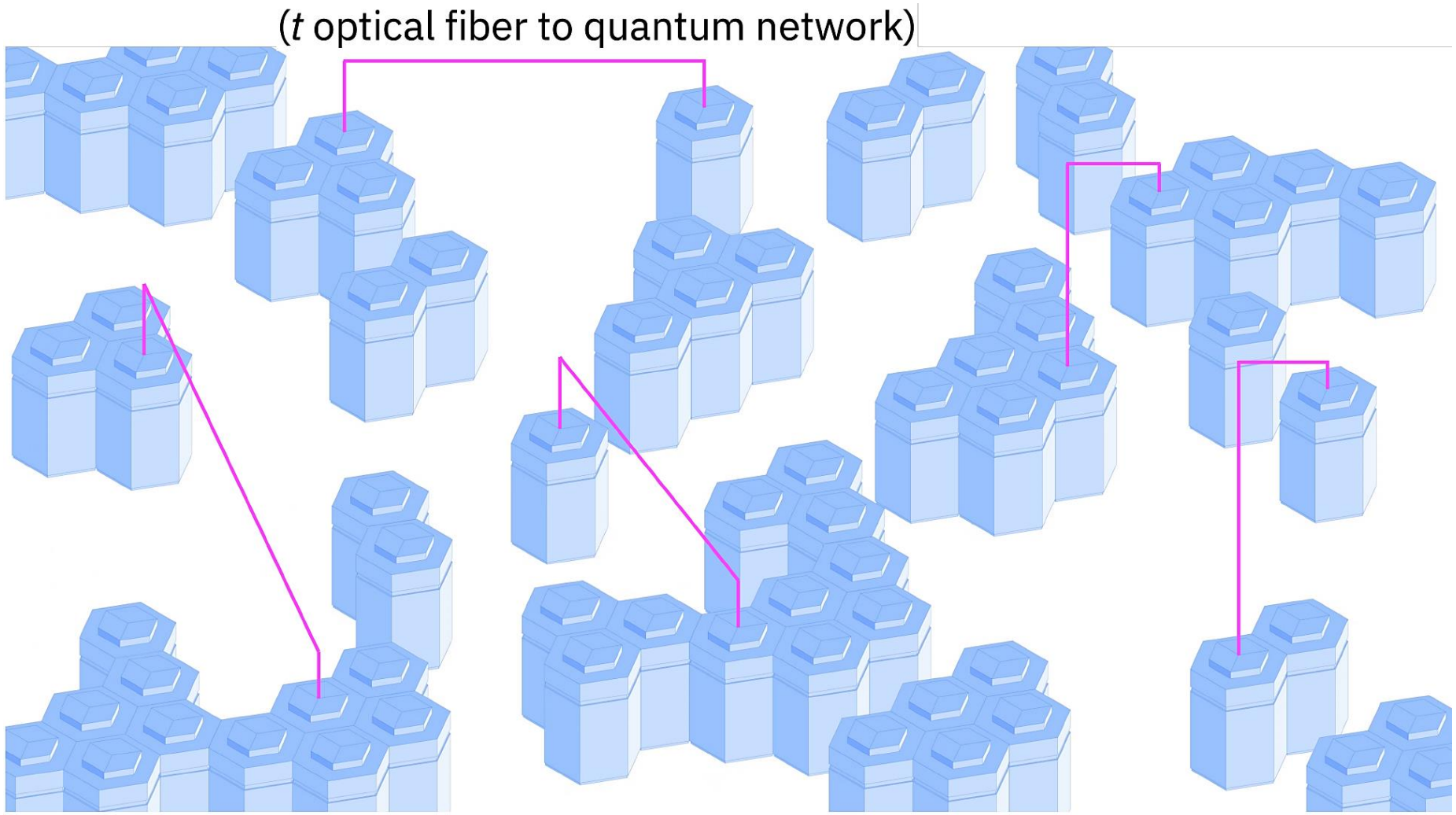
Testing Stage Setup





1. IBM Research, *Testing Probe* (2022)

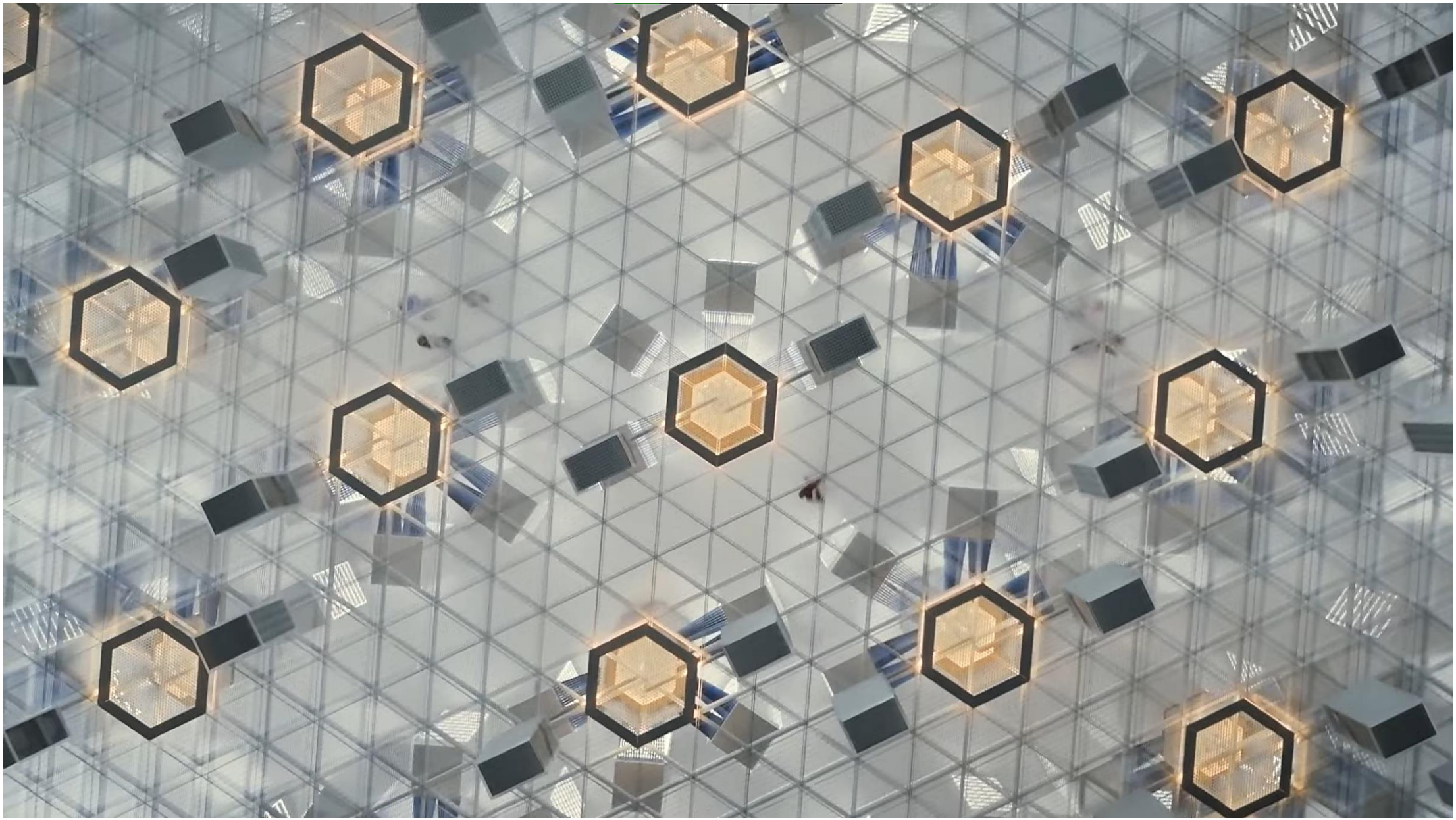
IBM Quantum System 2



(e)t type modularity involves microwave-to-optical transduction to link QPUs in different dilution refrigerators.

1. Bravyi et al., *arXiv* (2022)
2. IBM Research, *System 2* (2022)

IBM Quantum System 2



1. IBM Research, *System 2* (2022)

Summary

- Physical devices used as qubits are come in various shapes to act as quantum anharmonic oscillators.
- There are multiple platforms of physical qubits that exist.
  - The top-3 qubit systems are superconducting, trapped ion, & photonic.
- To scale qubit platforms, a hybrid model can be adopted to integrate more than one form of quantum technology (other degrees of freedom).
- CMOS can also be integrated and fabricated to work with quantum devices.
- Next week, we will cover **nanofabrication** methods & tooling for quantum devices.