Advanced Research and Technology Symposium 2018

The Future of Advanced (Secure) Computing

Quantum Computing

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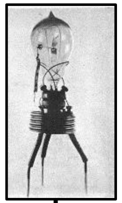
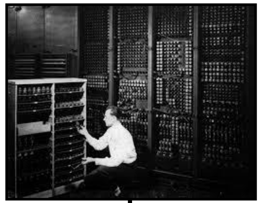
Historical Perspective on Computing

Classical (Electronic) Computing

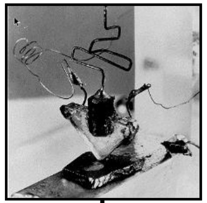
First vacuum tube (1907)



ENIAC (1946)

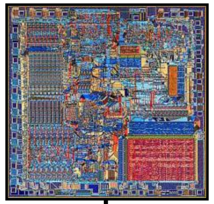


Transistor invented (1947)

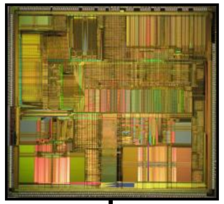


First fully transistor-based computer: TX-0 (1953)

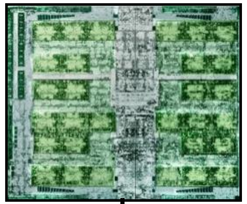
30k transistors: i8088 (1971)



4.5M transistors: Pentium (1998)



15B transistors: GP100 (2016)

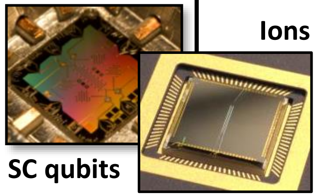


Quantum Computing

Richard Feynman

Quantum computer proposed (1981)

Shor's algorithm developed (1994)

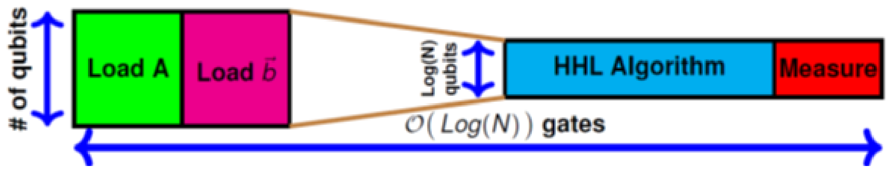


Several to tens of quantum bits manipulated (2010–18)

Progress on both quantum computing algorithms and hardware is supporting the exploration and development of a revolutionary approach to information processing

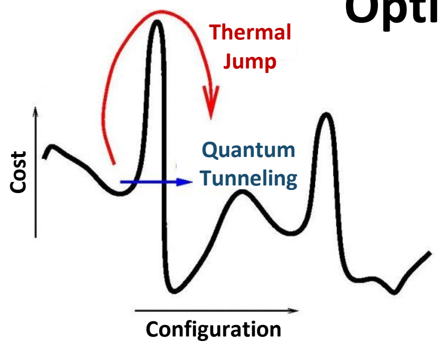
Quantum Computing Applications

Linear Algebra (HHL)



Exponential speed-up is possible with continued progress on efficient data loading for large matrices

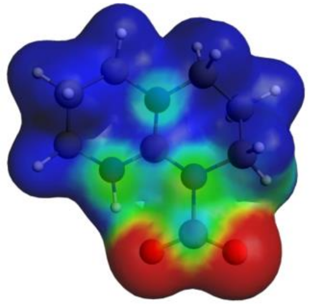
Optimization



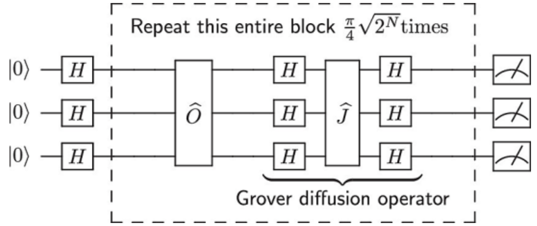
Quantum annealing may improve optimization with a faster time to more diverse and optimal solutions

Molecular and Material Simulations

Accurate simulation of molecular and material properties that are poorly approximated by classical methods



Search and Database (Grover)



Offers a polynomial speed-up that is useful within other quantum algorithms or with efficient data loading

Quantum computing algorithms and applications continue to expand

Computation vs. Optimization (Quantum Computing vs. Annealing)

Classical vs. **Quantum**

Computation

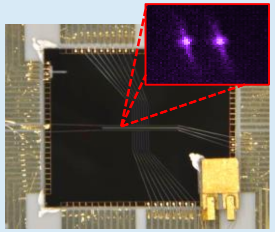
Solve a problem deterministically to find: *its unique solution*

Proven exponential speed-up over classical for few problems

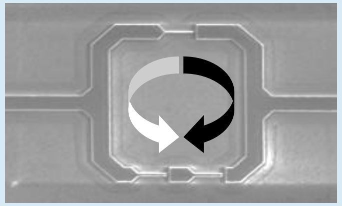
e.g., Shor's integer factoring algorithm

Quantum fault-tolerance protocols can suppress decoherence

Quantum Computing



Trapped ion qubits
(MIT LL and Prof. Chuang/Ram)



Superconducting qubits
(MIT LL and Prof. Oliver/Orlando)

vs.

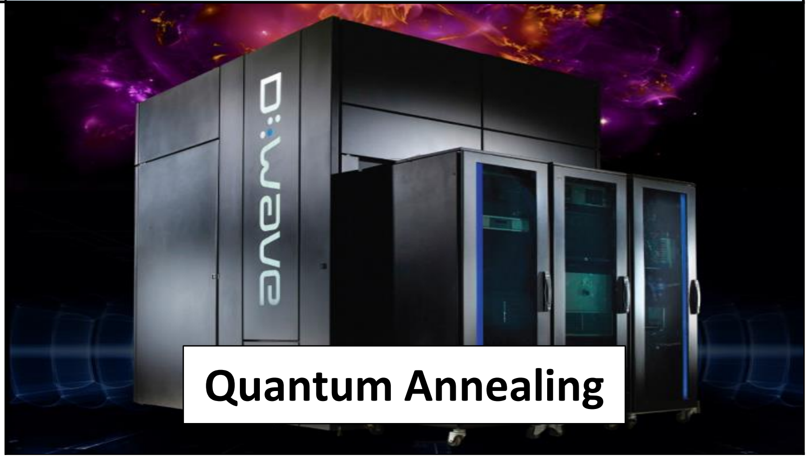
Optimization

From among many solutions, find: *those with highest possible quality*

Computational power virtually unknown

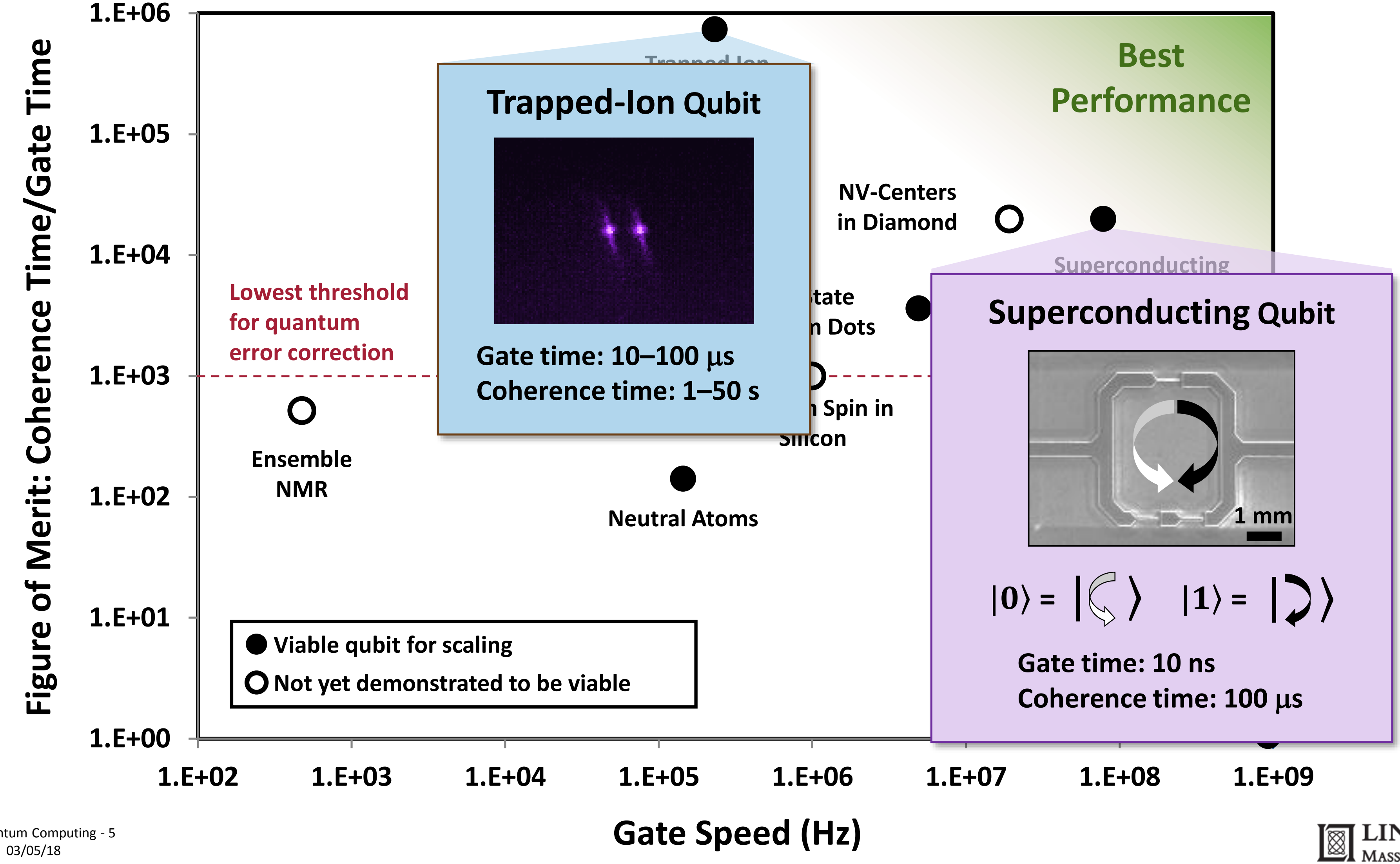
Requirements on qubits appear to be substantially less

Initial work by D-Wave Systems has led to efforts by Google and IARPA



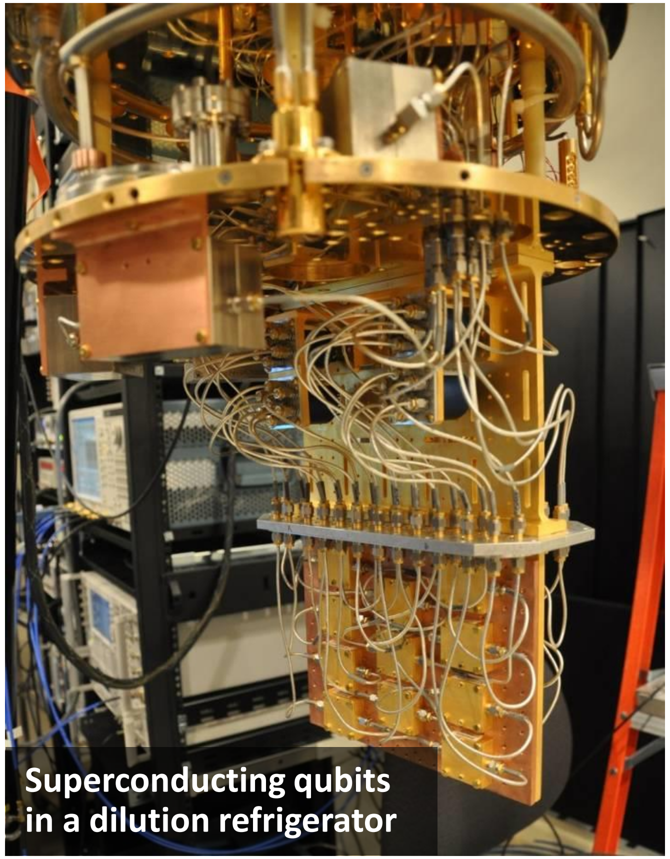
Quantum Annealing

Qubit Modalities



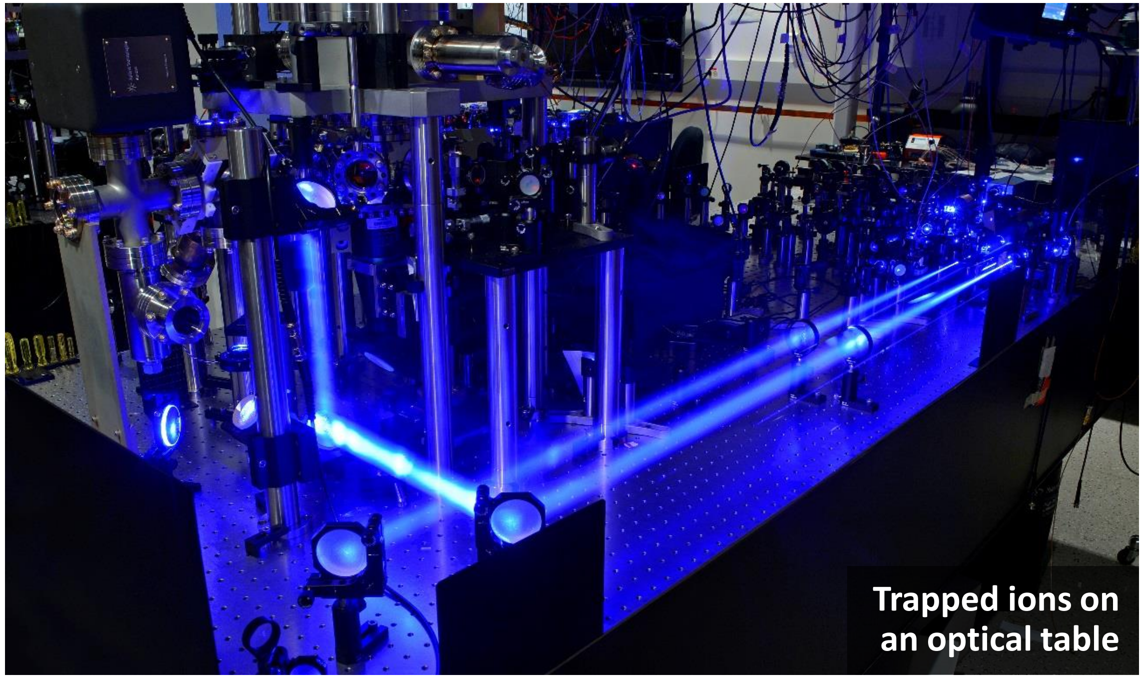
Quantum Computing Experiments

Superconducting Qubits



Superconducting qubits in a dilution refrigerator

Trapped Ion Qubits



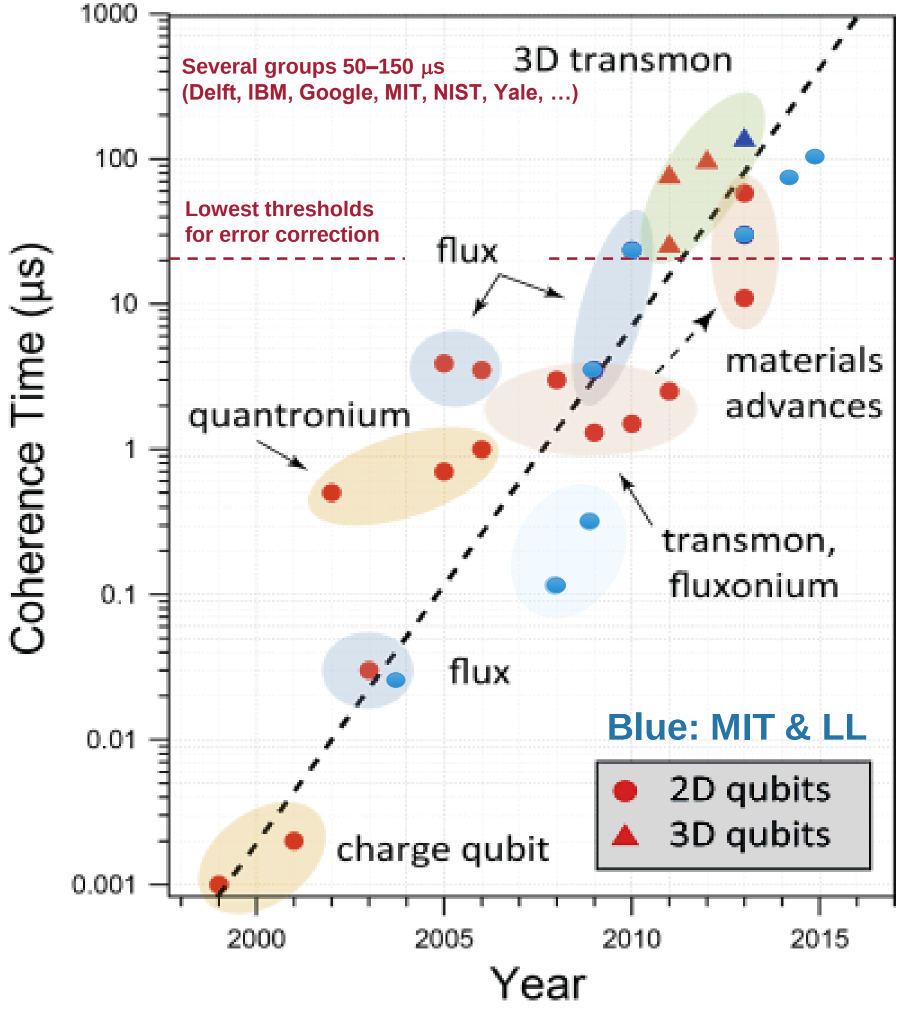
Trapped ions on an optical table

Qubits must be sufficiently isolated from the classical environment, noise…

Classical control signals are used to initialize, manipulate, and measure qubits

Superconducting Qubits

- Manufactured/designed “atoms”
- Planar fabrication
- RF and microwave control
- 100 MHz gate operations
- “Moore’s Law” for coherence times



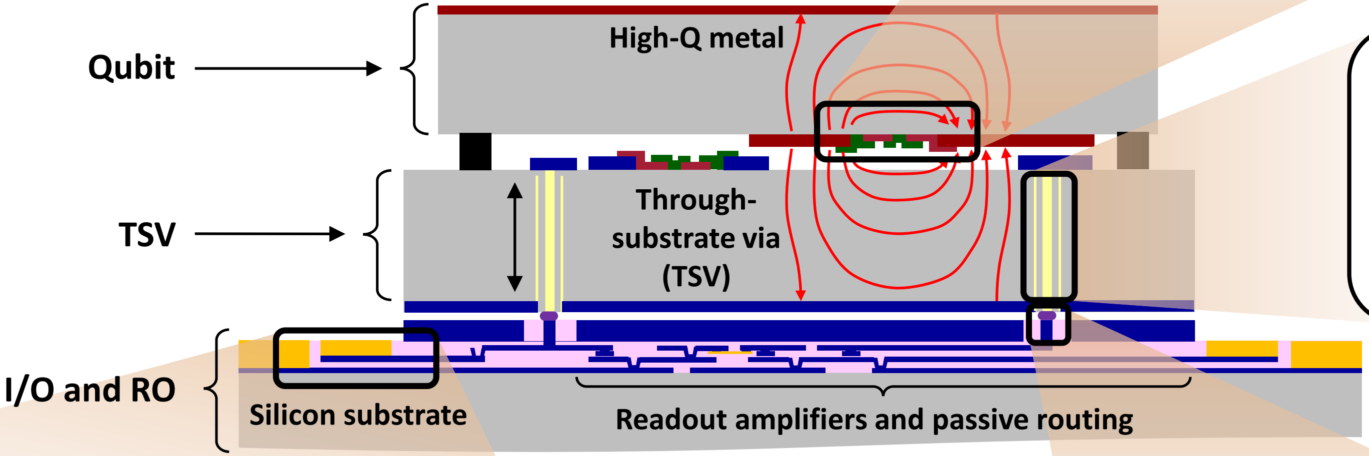
MIT and Lincoln Laboratory are at the forefront of superconducting qubit materials, fabrication, design, and extensible 3D integration

Oliver & Welander, MRS Bulletin (2013)

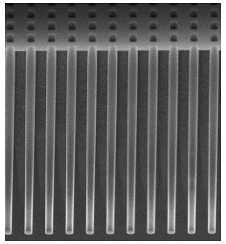
Technologies for 3D Integration of Superconducting Qubits

Three-Layer stack architecture with separate qubit and I/O layers separated by a TSV chip

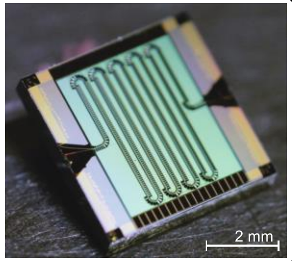
Increase qubit coherence (unchanged by introducing additional layer)



Through-substrate vias



Traveling wave parametric amplifiers (TWPAs)

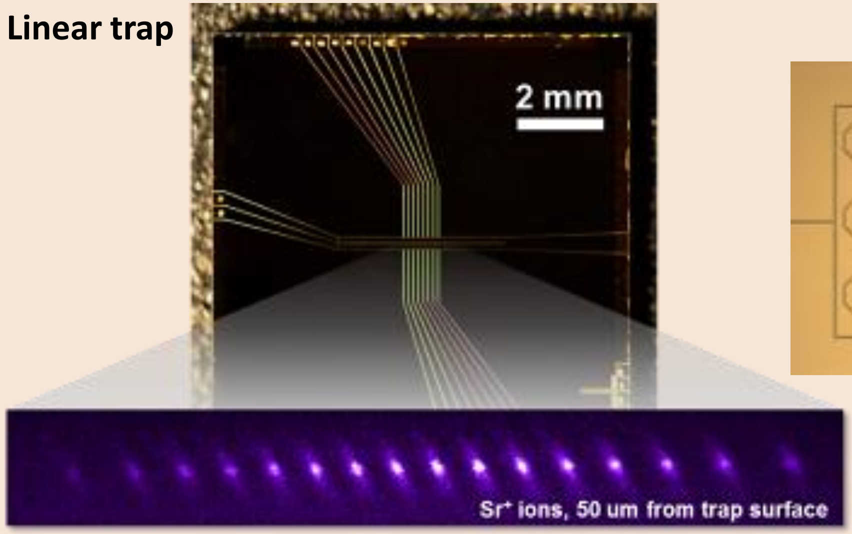


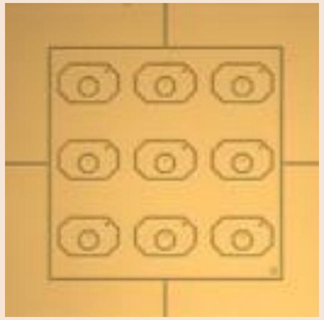
Superconducting bumps

Trapped Ion Qubits

- Electronic states of ionized atoms
- RF trapping, optical control
- Coupling via Coulomb interaction
- 100 kHz gate times
- High-fidelity preparation, control, and readout (99.9%–99.999%)

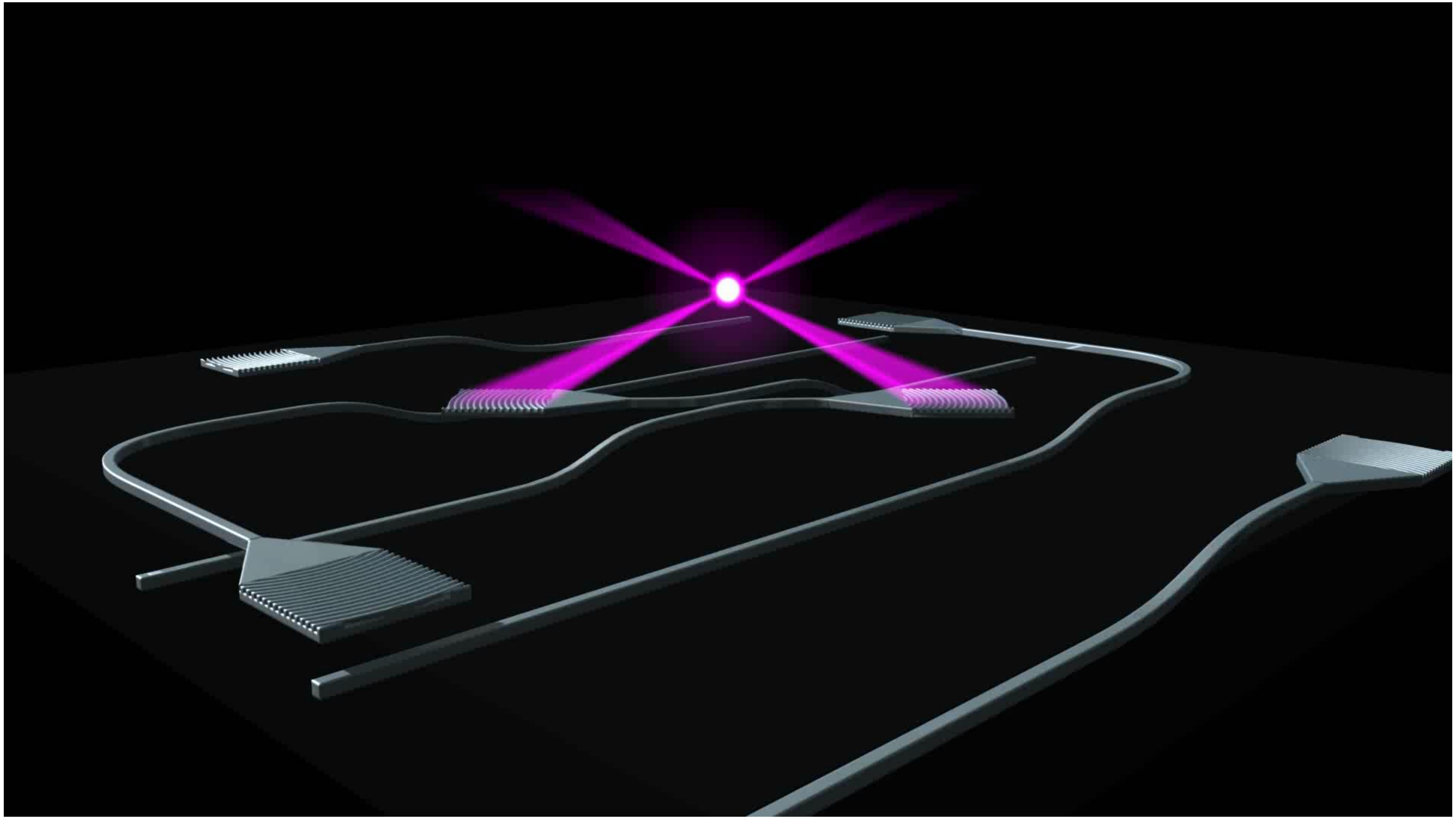
Lincoln Surface-Electrode Chip Traps





MIT and Lincoln Laboratory are leaders in developing integrated technologies for quantum control of trapped ions

Trapped-Ion Quantum Processor



Collaboration Opportunities

- Challenging scientific and fundamental engineering questions remain to be addressed:
  - Spans many academic domains: material science, solid-state and atomic physics, electrical engineering, mathematics, and computer science
  - Collaborations and internships are important to addressing these key research challenges
- Progress is also enabled by specialized research infrastructure:
  - Test equipment and electronics
  - Software tools for experimental control, modeling, and simulation