AN INTRODUCTION TO TRAPPED ION QUANTUM COMPUTING

PRESENTED BY:

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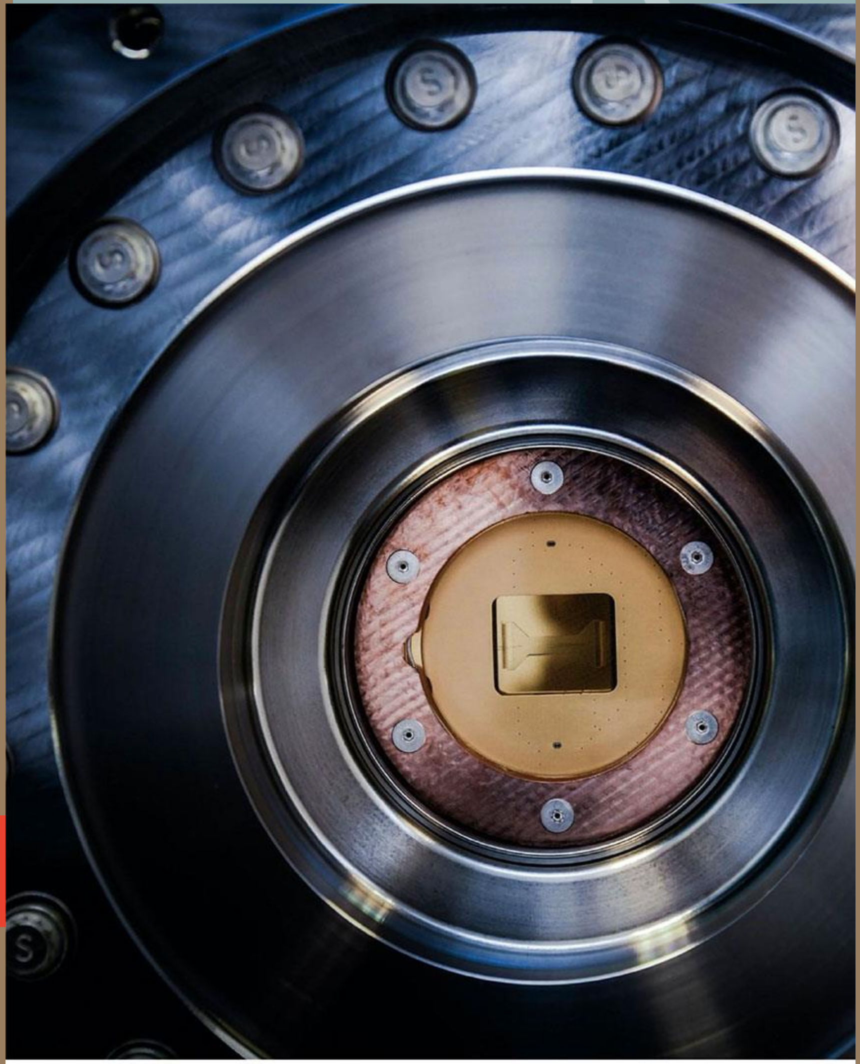
Womanium Quantum 2022

July 21, 2022



QUANTINUUM

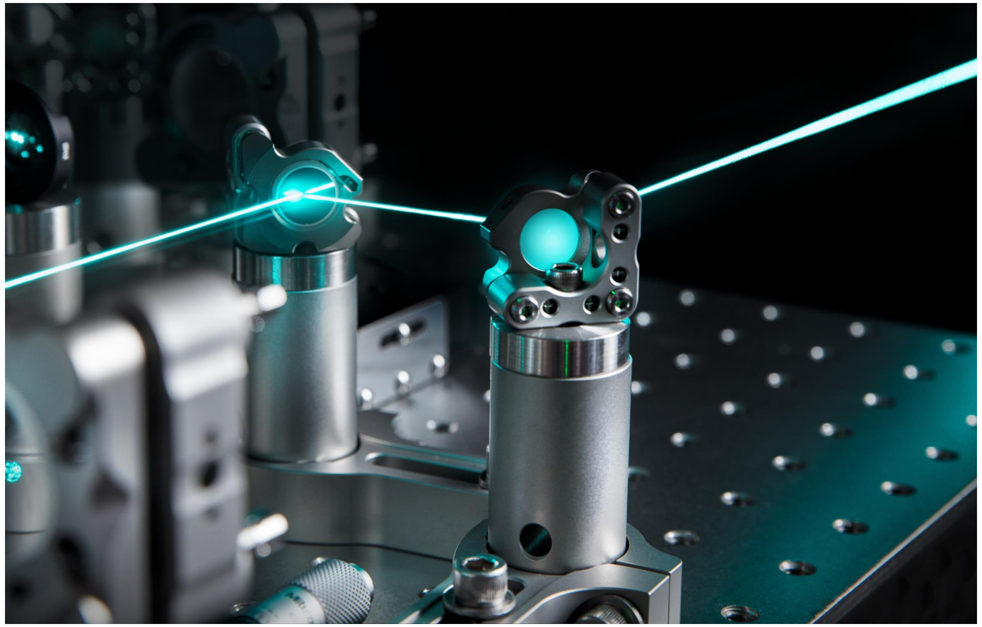
OUTLINE

- **How to build a quantum computer with trapped ions**
  - **DiVincenzo criteria**
- Intermission
- Quantinuum’s quantum computer
  - Architecture
  - Features
  - Recent progress
- Careers in ion trap quantum computing

KEYS TO A QUALITY QUANTUM COMPUTER

DiVincenzo's criteria

	Ion Trap QCs
A scalable physical system with well characterized qubit	✓
Long relevant decoherence times	✓
The ability to initialize the state of the qubits to a simple fiducial state	✓
Qubit measurement capability	✓
A "universal" set of quantum gates	✓
Qubit connectivity	✓



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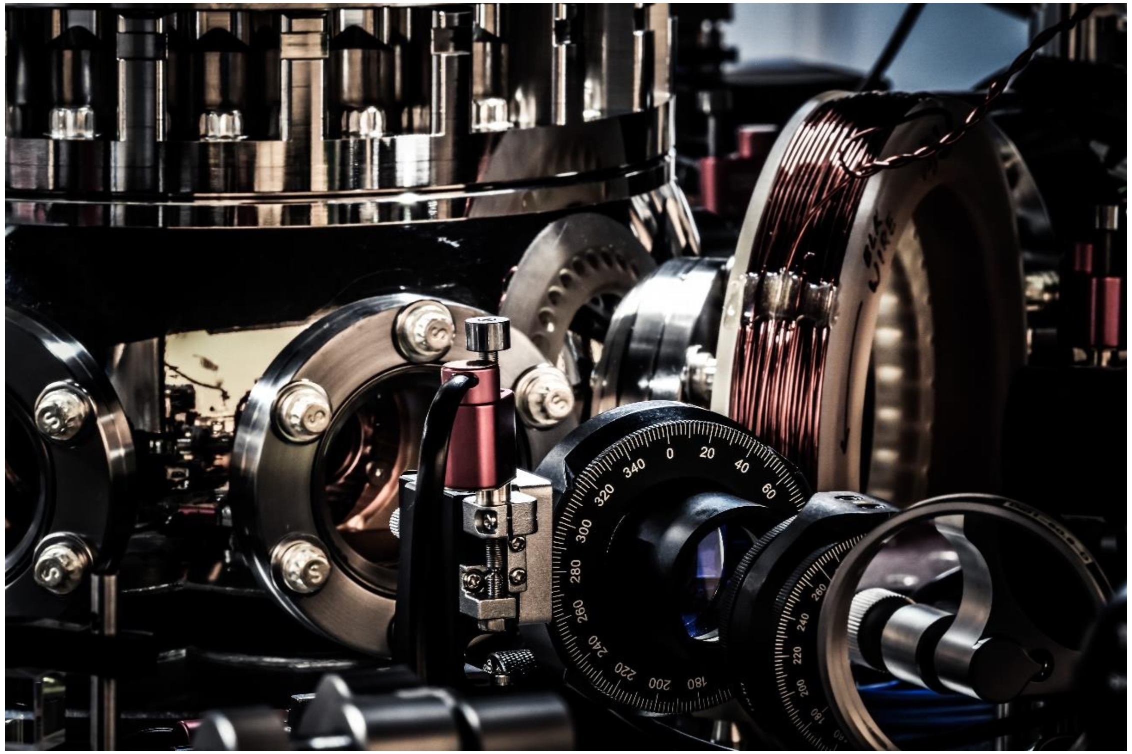
HIGH-QUALITY QUBITS: TRAPPED IONS



- Qubits defined in nature by their atomic structure
- Identical, defect-free qubits
- Reconfigurable qubits that can be rearranged and interacted to improve algorithm opportunities

QUANTINUUM

HOW TO TRAP AN ION

Do you think we can hold ions with only static electric potentials?

A. Yes
B. No

HOW TO TRAP AN ION

Do you think we can hold ions with only static electric potentials?

A. Yes
B. No

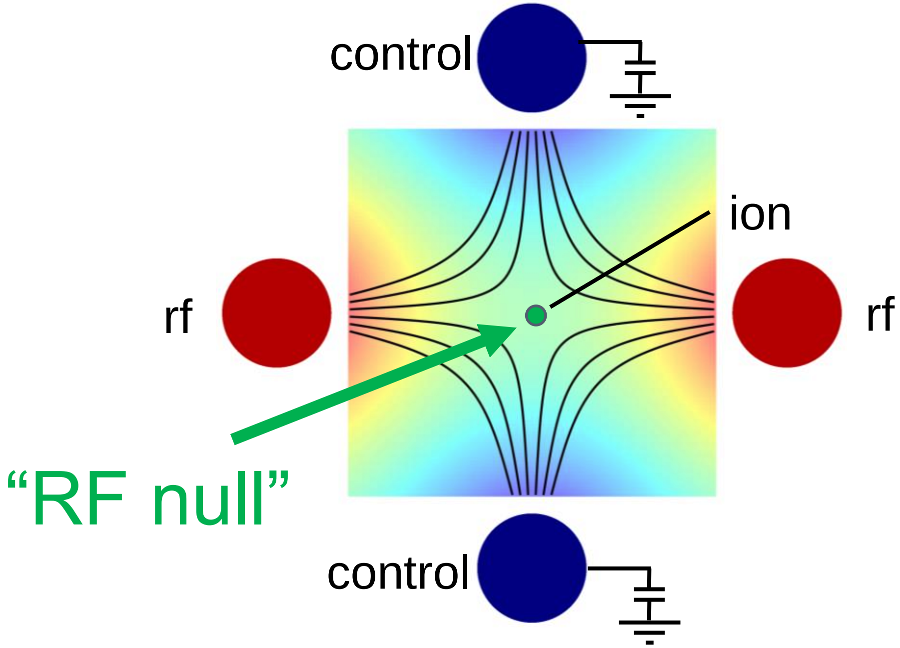
Answer: no.

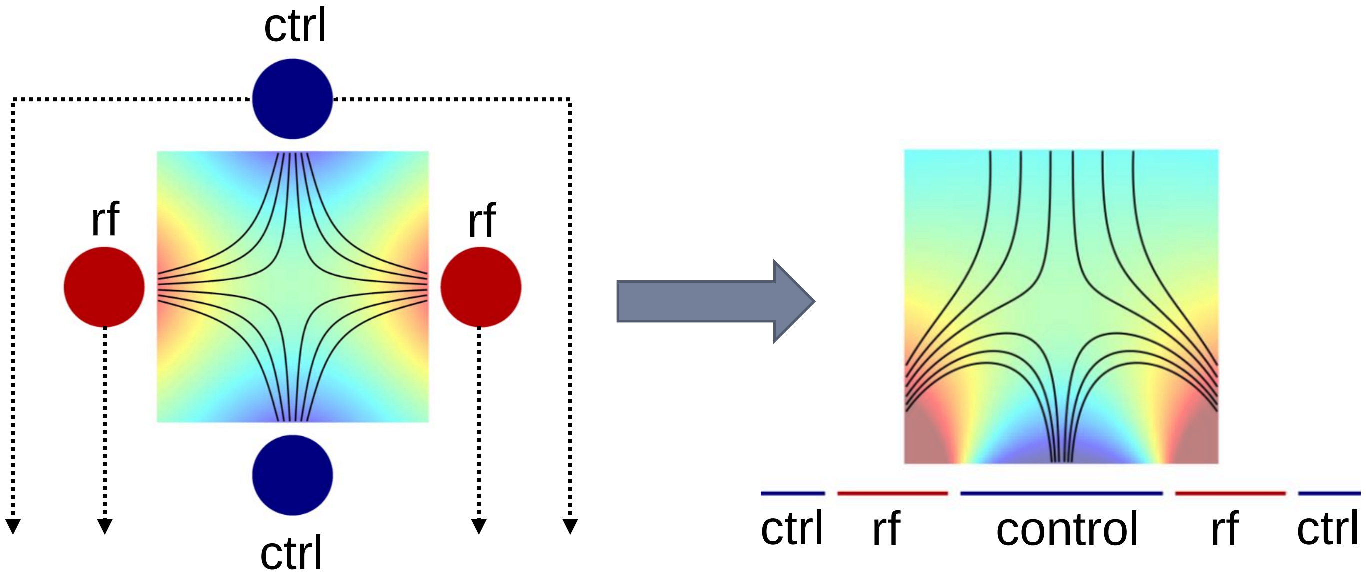
The equations that govern electricity and magnetism do not have a solution that can statically hold a charged particle in 3 dimensions.

QUANTINUUM

ION CONFINEMENT

- Ions cannot be trapped using only static electric fields
- Combinations of RF and static fields allow us to confine an ion in space
- Not on RF null: micromotion
- Can “flatten” sources to electrodes on a surface trap





QUANTINUUM

TRAPPED IONS AS QUBITS

How do you think quantum information is stored in a trapped ion?

A. Hyperfine energy levels
B. Highly excited Rydberg energy levels
C. Vibrational energy levels
D. In its pockets

TRAPPED IONS AS QUBITS

How do you think quantum information is stored in a trapped ion?

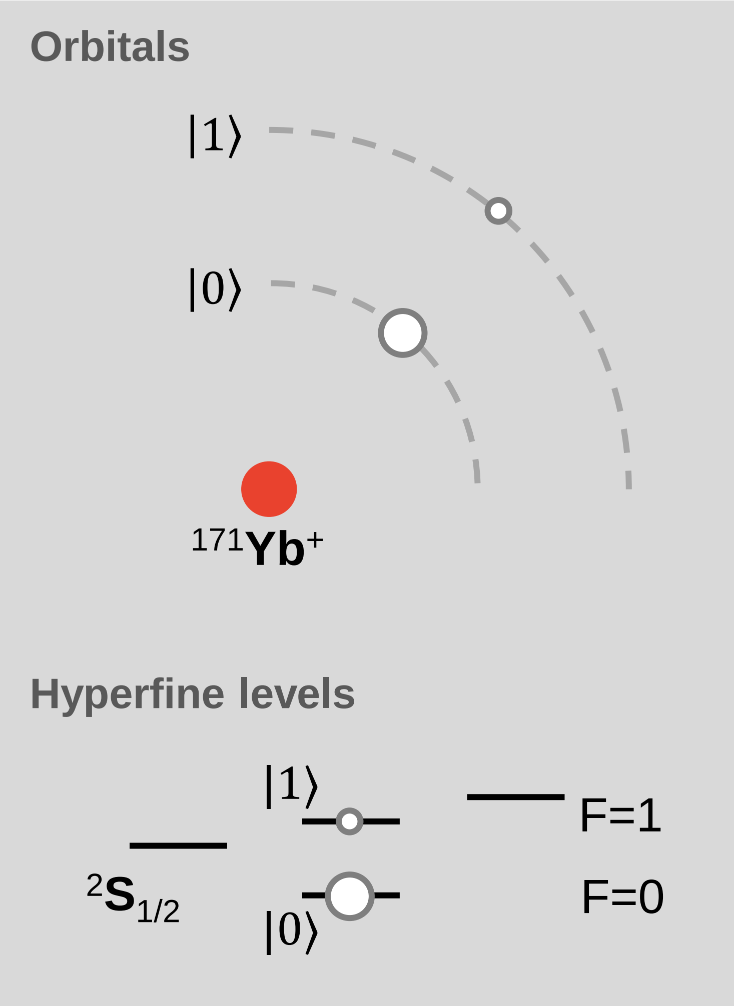
A. Hyperfine energy levels
B. Highly excited Rydberg energy levels
C. Rotational energy levels
D. In its pockets

Answer: A. Hyperfine energy levels.

The hyperfine energy levels of an atom are all the possible electronic energy levels in an atom once you take into account electron spin, electron orbitals, and the nuclear spin.

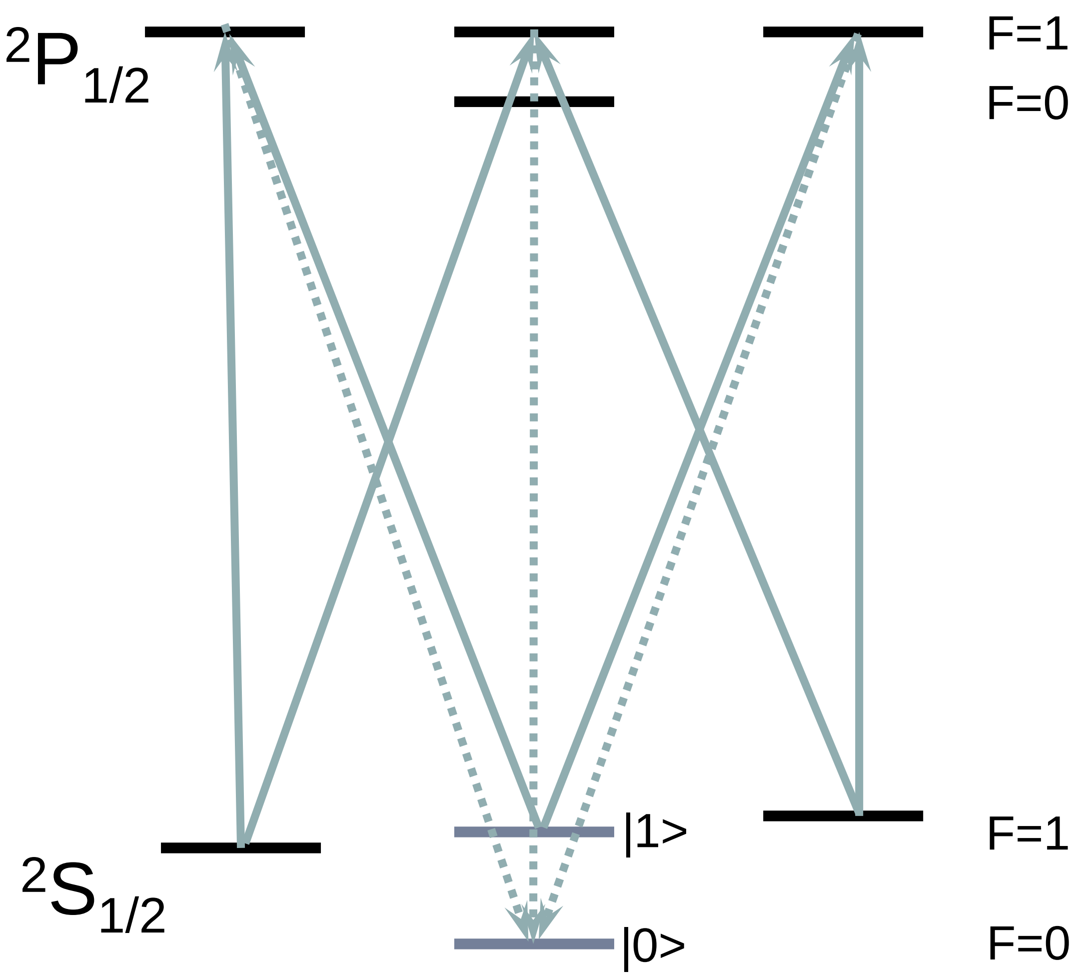
(Honorable mention for Rydberg energy levels, which is how some neutral atom QCs store quantum information.)

PERFECT QUBITS FROM YTTERBIUM ATOMS



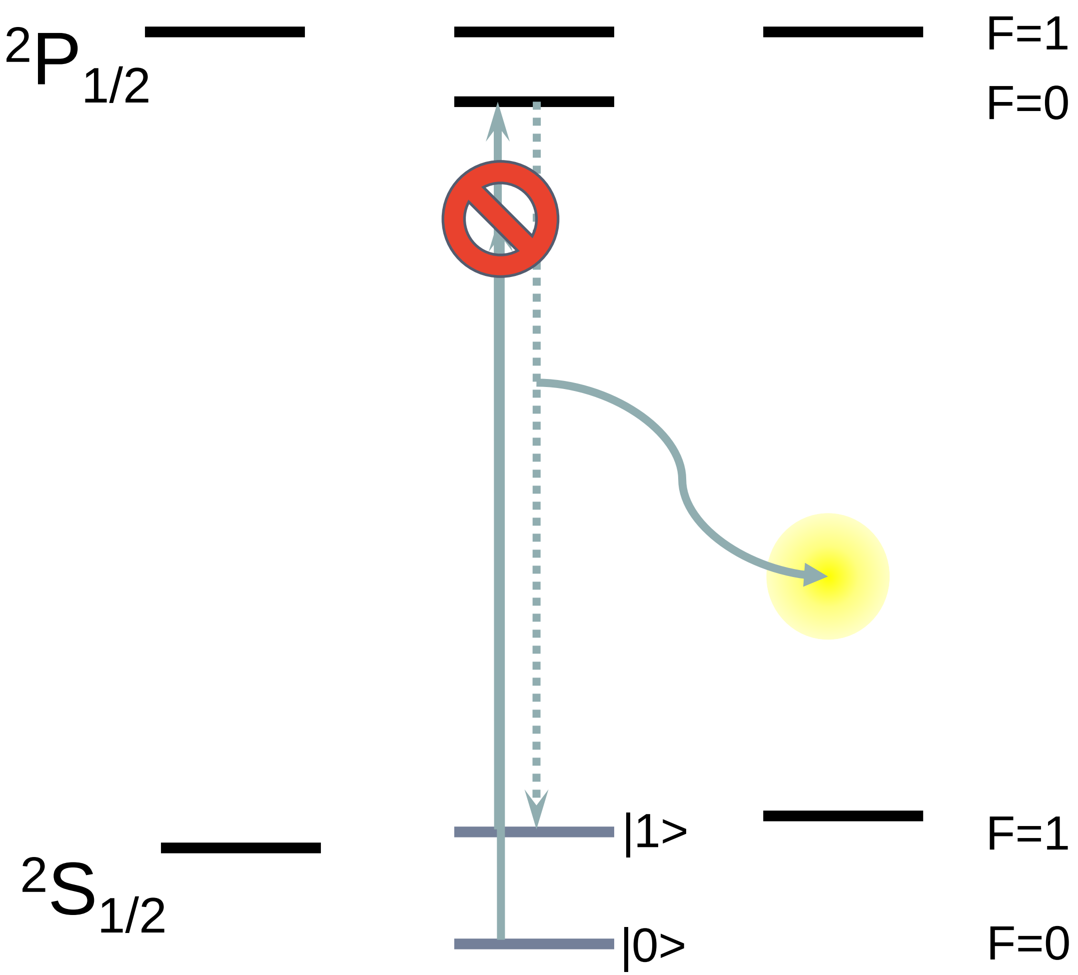
- Each atom is identical, each qubit is identical
- Quantum information is stored in hyperfine energy levels
- Lasers are used to address, entangle, and measure qubits
- Long coherence times: atomic energy levels don't drift over time
  - Errors arise from controllers and external environment
  - Errors are fundamentally understood
- The secret is to precisely capture, control, and manipulate ions for quantum operations

INITIAL STATE PREPARATION



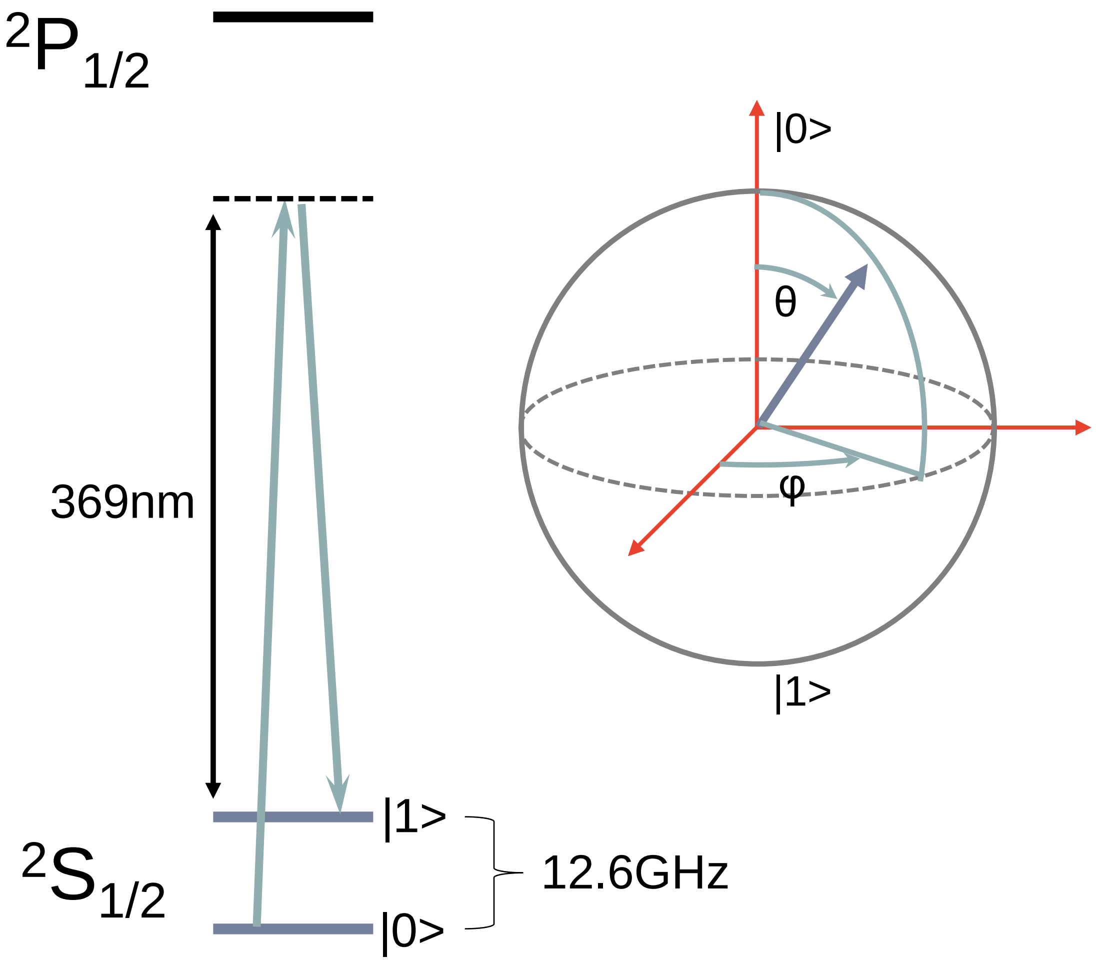
- Laser cooling techniques bring ion to its motional ground state
  - Doppler cooling, sideband cooling, etc.
- Optical pumping laser pulse brings ion to its electronic ground state, |0>
- Laser control of atomic state allows for qubit initialization to |0>

MEASUREMENT



- Apply laser pulse resonant with $|^2S_{1/2},F=1\rangle \leftrightarrow |^2P_{1/2},F=0\rangle$
  - If qubit in |1>: excitation occurs; decay releases a photon via spontaneous emission
  - If qubit in |0>: off-resonant, so no excitation, no decay, no photon
- During a measurement laser pulse, the |1> state is bright, while the |0> state is dark

SINGLE QUBIT GATES



- Stimulated Raman transitions create single-qubit gates with arbitrary angle rotations R(θ, φ)
  - Duration of pulse sets θ
  - Phase of pulse sets φ
- Can also do direct microwave gates
- Can rotate anywhere on Bloch sphere with 1-3 pulses
- Single qubit rotations in ions can perform any single qubit unitary

TWO QUBIT ENTANGLING GATES

How do you think we “connect” and exchange quantum information for two trapped ion qubits for a two-qubit entangling gate?

A. Shared laser beam
B. Create a molecule
C. Motional modes
D. The internet

TWO QUBIT ENTANGLING GATES

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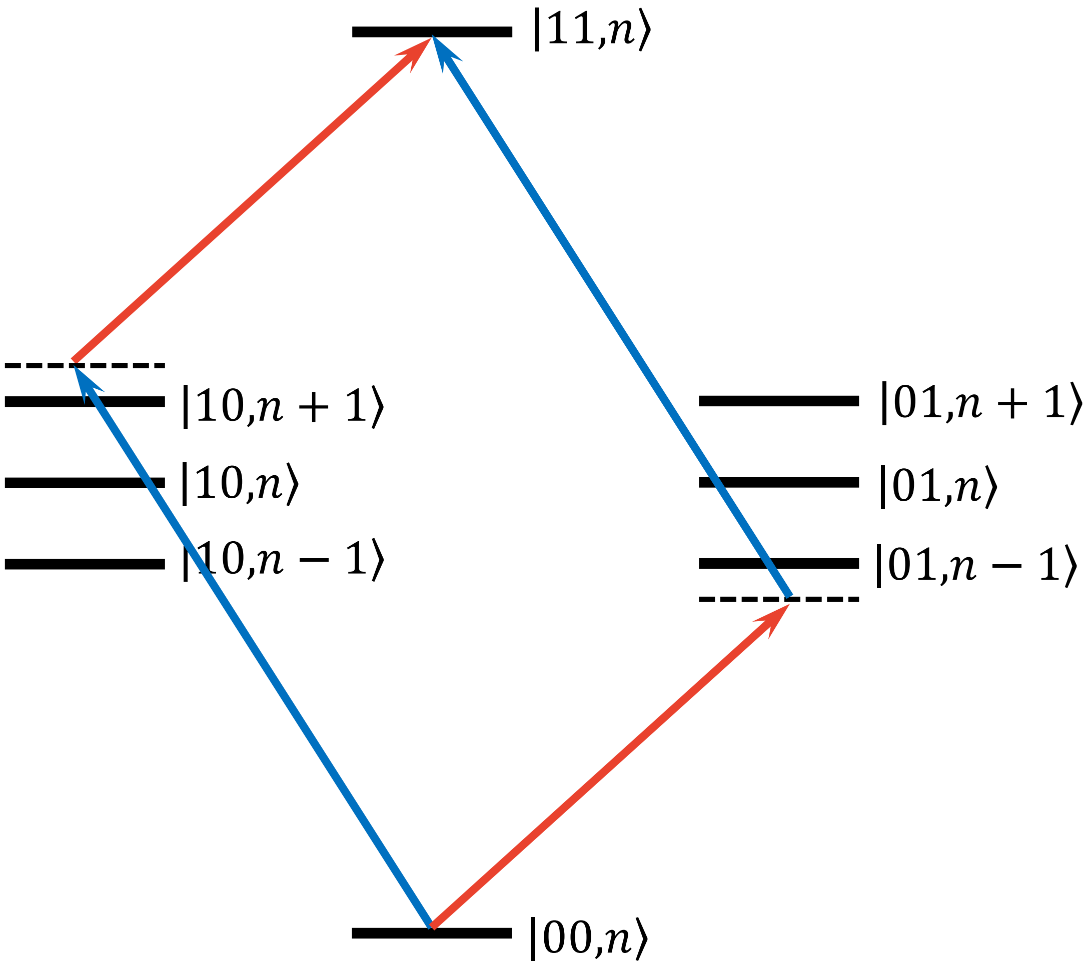
A. Shared laser beam
B. Create a molecule
C. Motional modes
D. The internet

Answer: C. Motional modes

Multiple ions trapped in the same potential well form a linear crystal. The Coulomb force from the charged ions push them apart from each other, while the potential well pushes them back together. This creates a set of shared normal modes of motion for all the ions in the trap, which can be used as a "bus" to transfer quantum information.

QUANTINUUM

TWO QUBIT ENTANGLING GATES



- Mølmer-Sørensen interaction couples 2 ions through their shared modes of motion
- Creates entangling gate:

$$|00\rangle \rightarrow \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

  - With a few additional SQ rotations, this becomes a CNOT gate
- Ion qubits achieve a universal quantum gate set through arbitrary angle 1Q gates plus entangling 2Q gates

K. Molmer and A. Sorensen, Phys. Rev. Lett. **82**, 1835 (1999)

QUANTINUUM

ION TRAP QC ARCHITECTURES

How do you think we could construct the overall architecture of a trapped ion QC to connect many qubits?

A. Long chain of ions in single trapping potential, individually focused beams that can be turned on/off
B. Long chain of ions in single trapping potential, few focused beams that can be moved to different ions
C. Microwave gates with large magnets to create gradient for individual addressing
D. Many small trapping potentials holding few ions, ions moved around by transport

ION TRAP QC ARCHITECTURES

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Trick question!

Answer: all of the above

ION TRAP QC ARCHITECTURES

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- Many small trapping potentials holding few ions, ions moved around by transport

…and many university and government research labs…

OUTLINE

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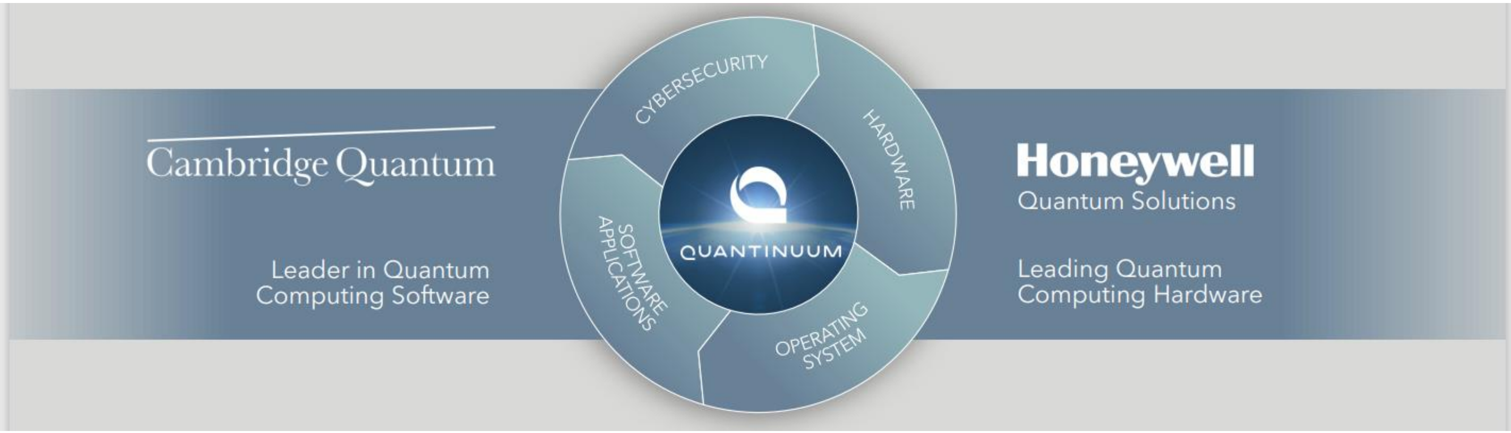
WHAT SHOULD YOU KNOW ABOUT QUANTINUUM?

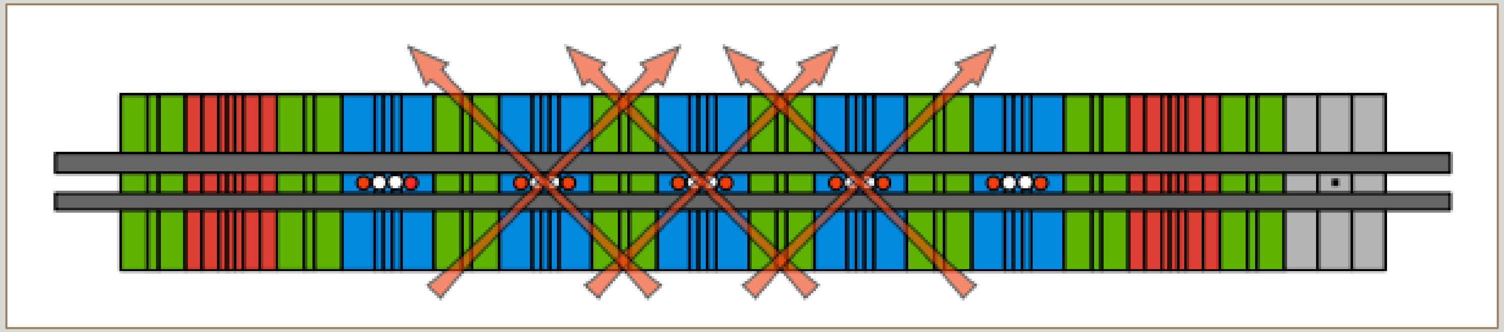


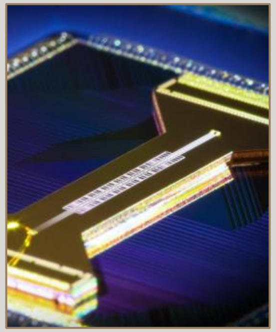
1. Combination of Honeywell Quantum Solutions (HQS) and Cambridge Quantum Computing (CQC); deal closed November 29, 2021
2. Global Company with offices in US, UK, Germany, Japan. 420 Employees; 330 of which are technical. Dual HQs in Broomfield, CO and Cambridge, UK
3. Full stack capabilities: Best-in-class software joins high-performing, differentiated ion trap hardware
4. Has already launched its first two products:
   1. Quantum Origin, a cyber security offering to create provably non-deterministic random numbers for cryptographic key generation using entropy from Quantinuum H-Series quantum computers
   2. InQuanto, a state-of-the-art quantum computational chemistry software platform using quantum computers.

QCCD ARCHITECTURE

QUANTUM CHARGE-COUPLED DEVICE PROPOSED BY NIST ION STORAGE GROUP (1998)

ION TRAP ARCHITECTURE

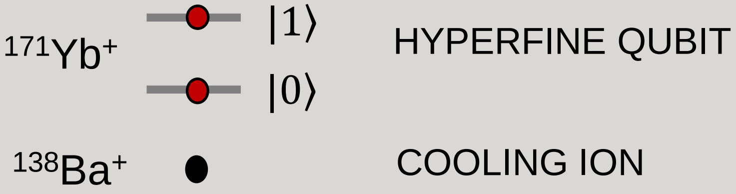




ARCHITECTURE FEATURES

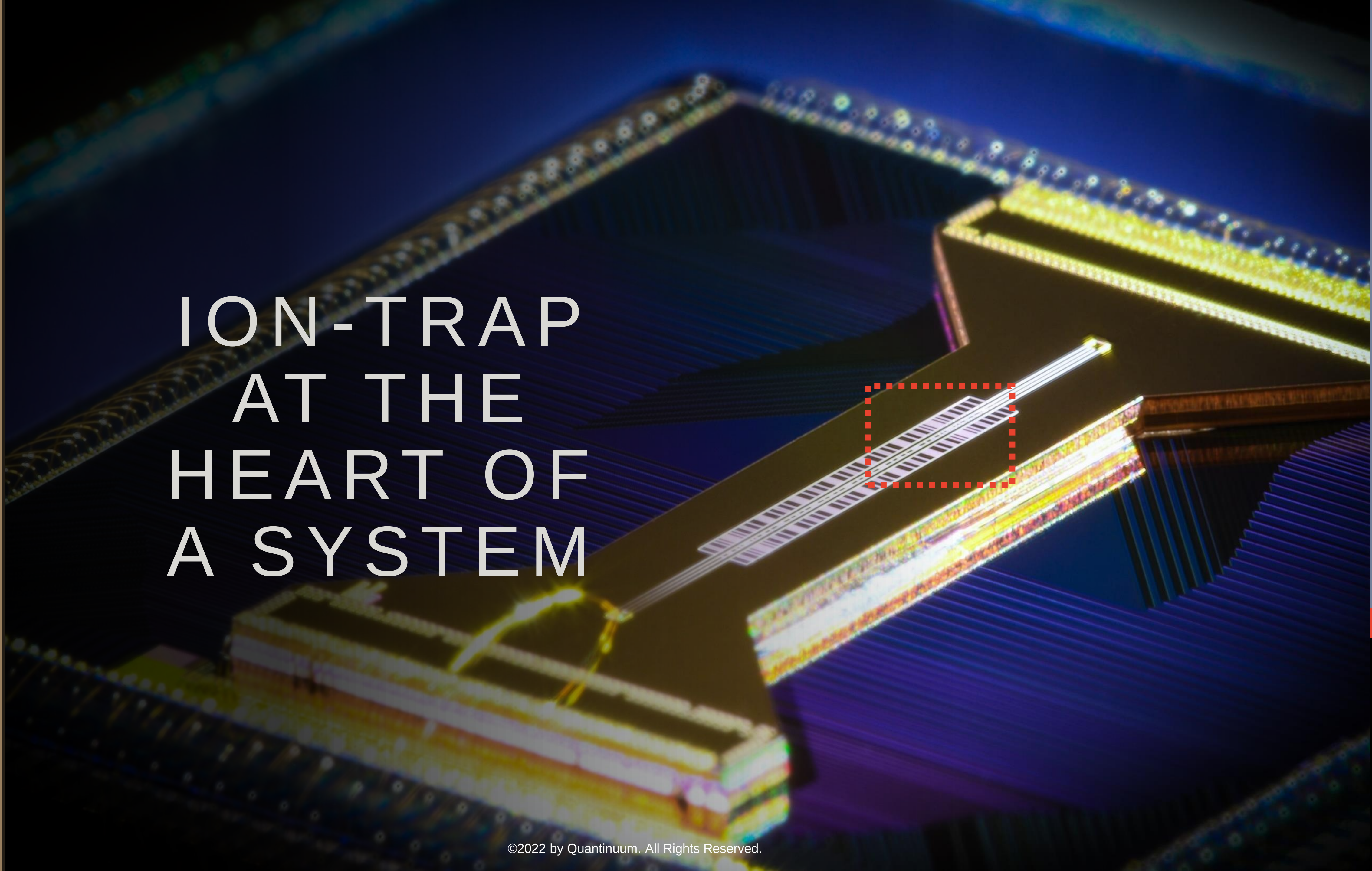
- Identical, high-quality qubits
- Dedicated interaction zones
- Short ion chains
- High fidelity quantum gates
- Ions transport from zone to zone

Quantum bits (qubits) are stored in the electronic states of Yb^+ ions



Wineland, D.J., Monroe, C., Itano, W.M., Leibried, D., King, B.E., Meekhof, D.M., Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions, J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998)

Pino, J.M., Dreiling, J.M., Figgatt, C. *et al.* Demonstration of the trapped-ion quantum CCD computer architecture. *Nature* **592,** 209–213 (2021).



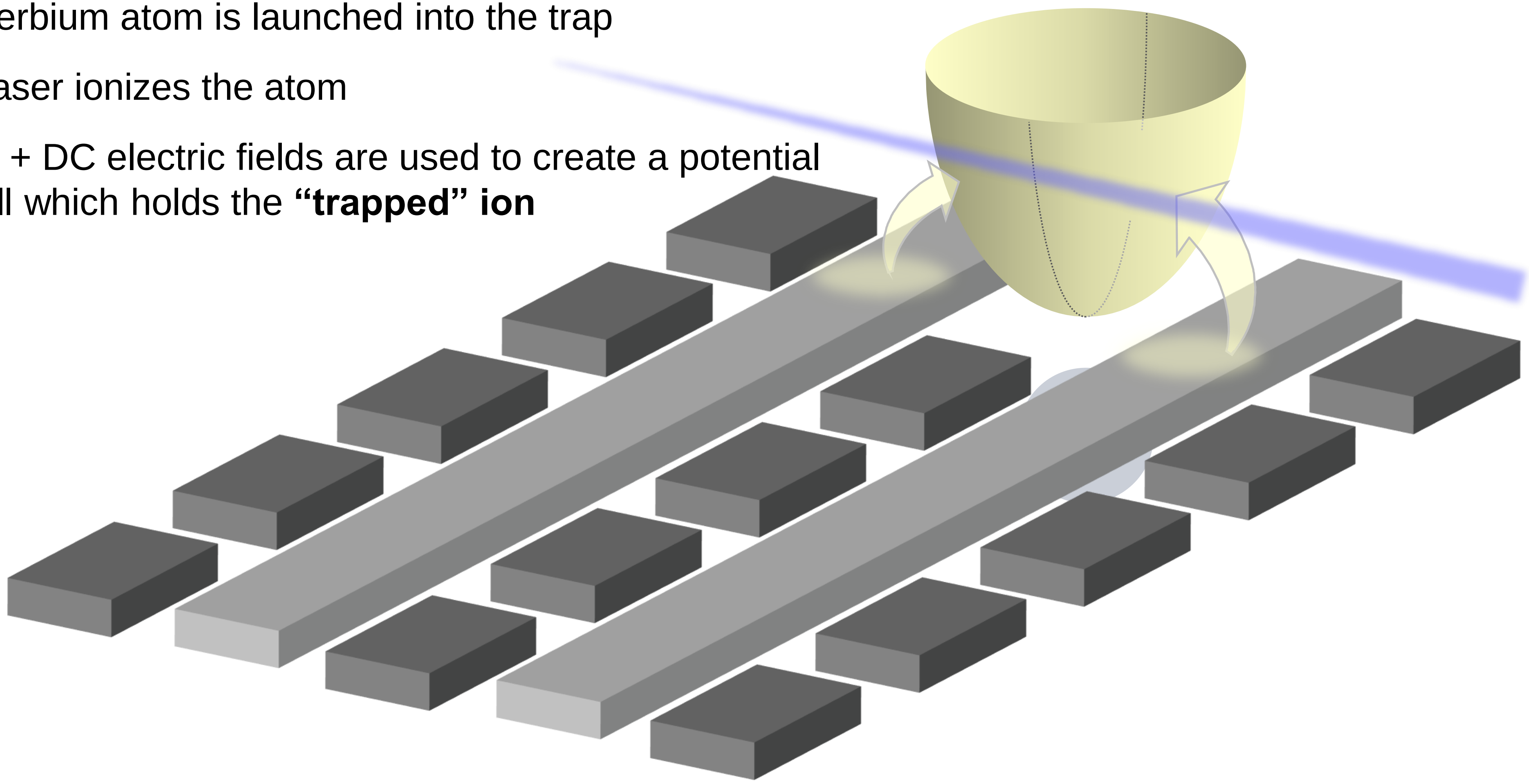
ION-TRAP AT THE HEART OF A SYSTEM

LOADING IONS

Ytterbium atom is launched into the trap

A laser ionizes the atom

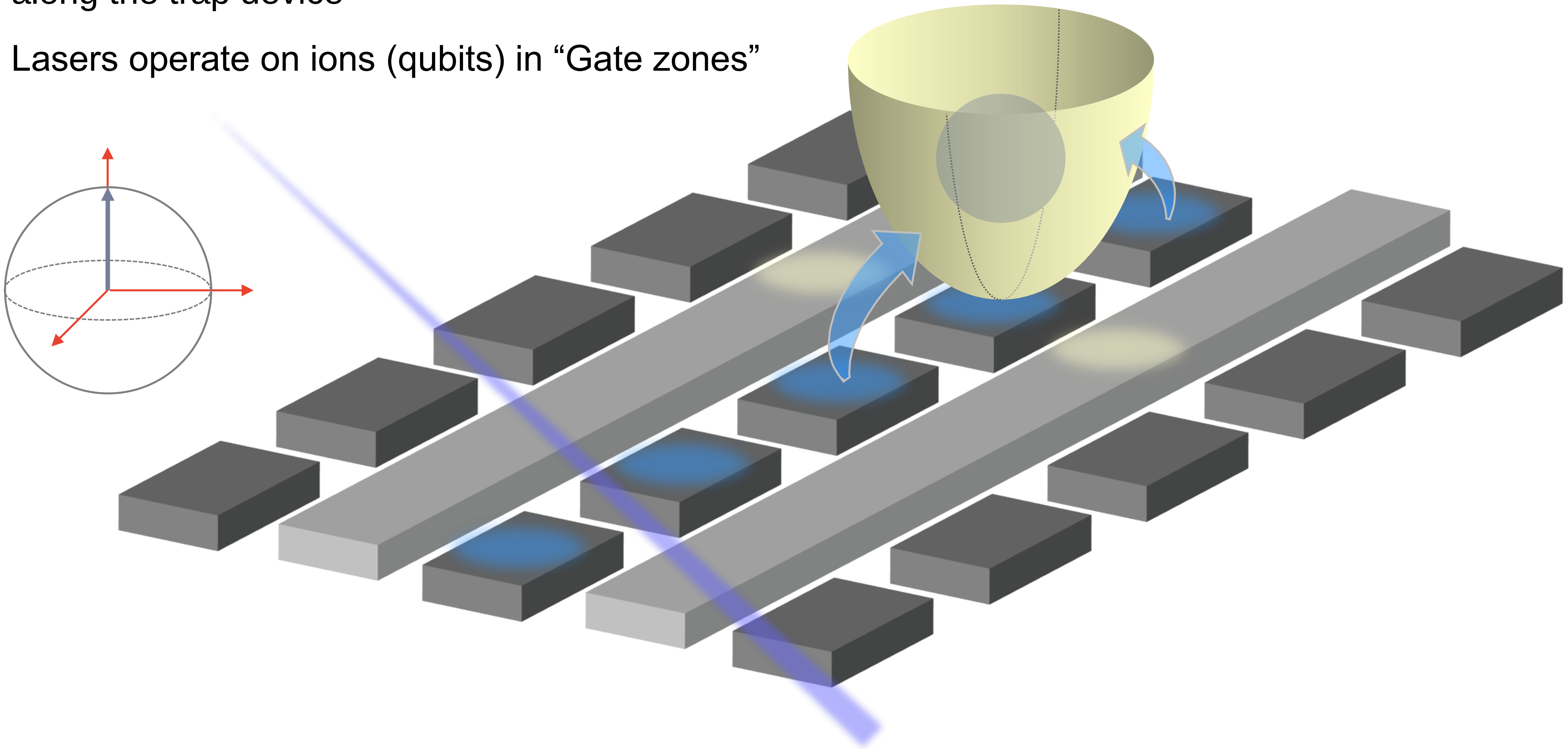
RF + DC electric fields are used to create a potential well which holds the **"trapped" ion**



TRANSPORT AND GATE

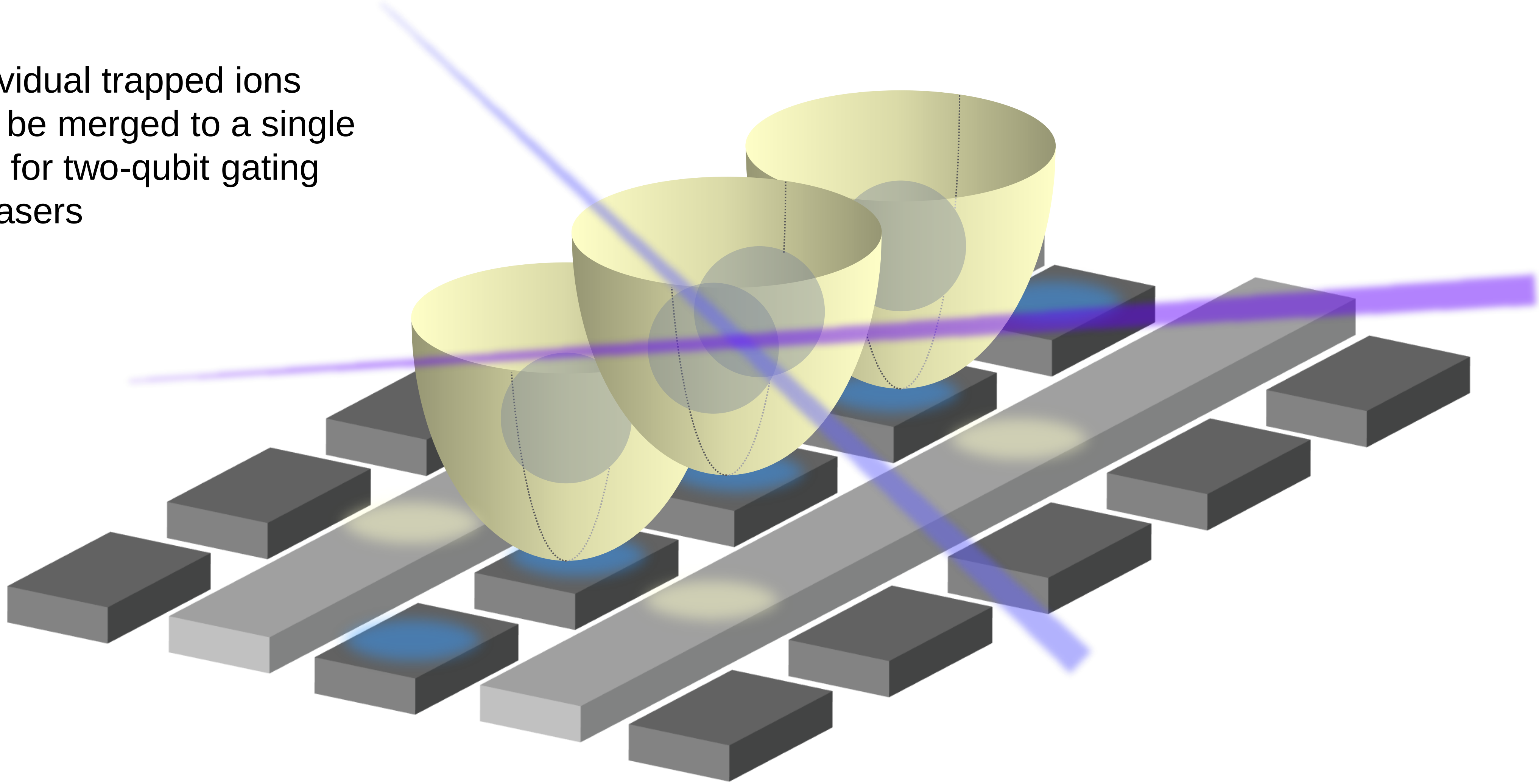
DC electrodes transport the ion to different zones along the trap device

Lasers operate on ions (qubits) in “Gate zones”



MERGE AND ENTANGLEMENT

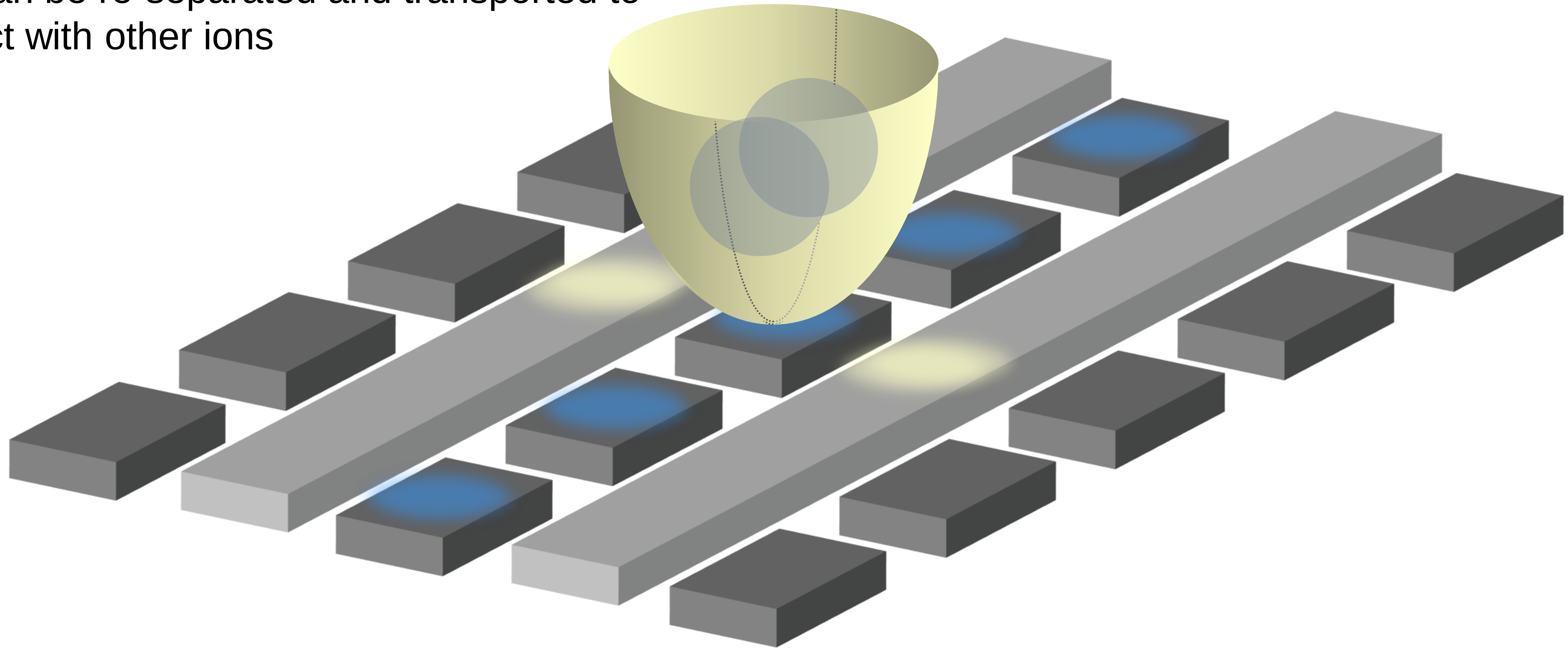
Individual trapped ions can be merged to a single well for two-qubit gating by lasers



MERGE AND ENTANGLEMENT

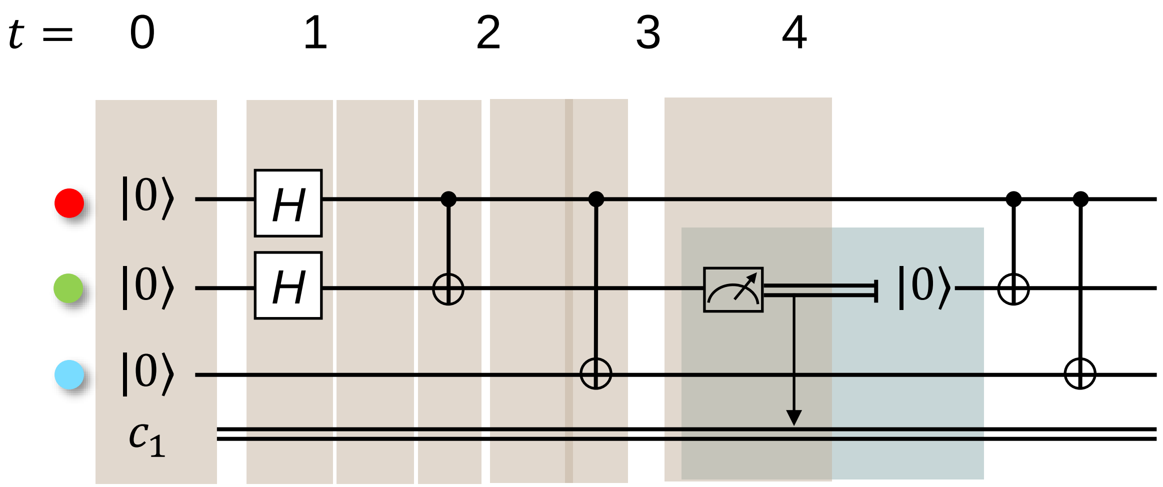
Individual trapped ions can be merged to a single well for two-qubit gating by lasers

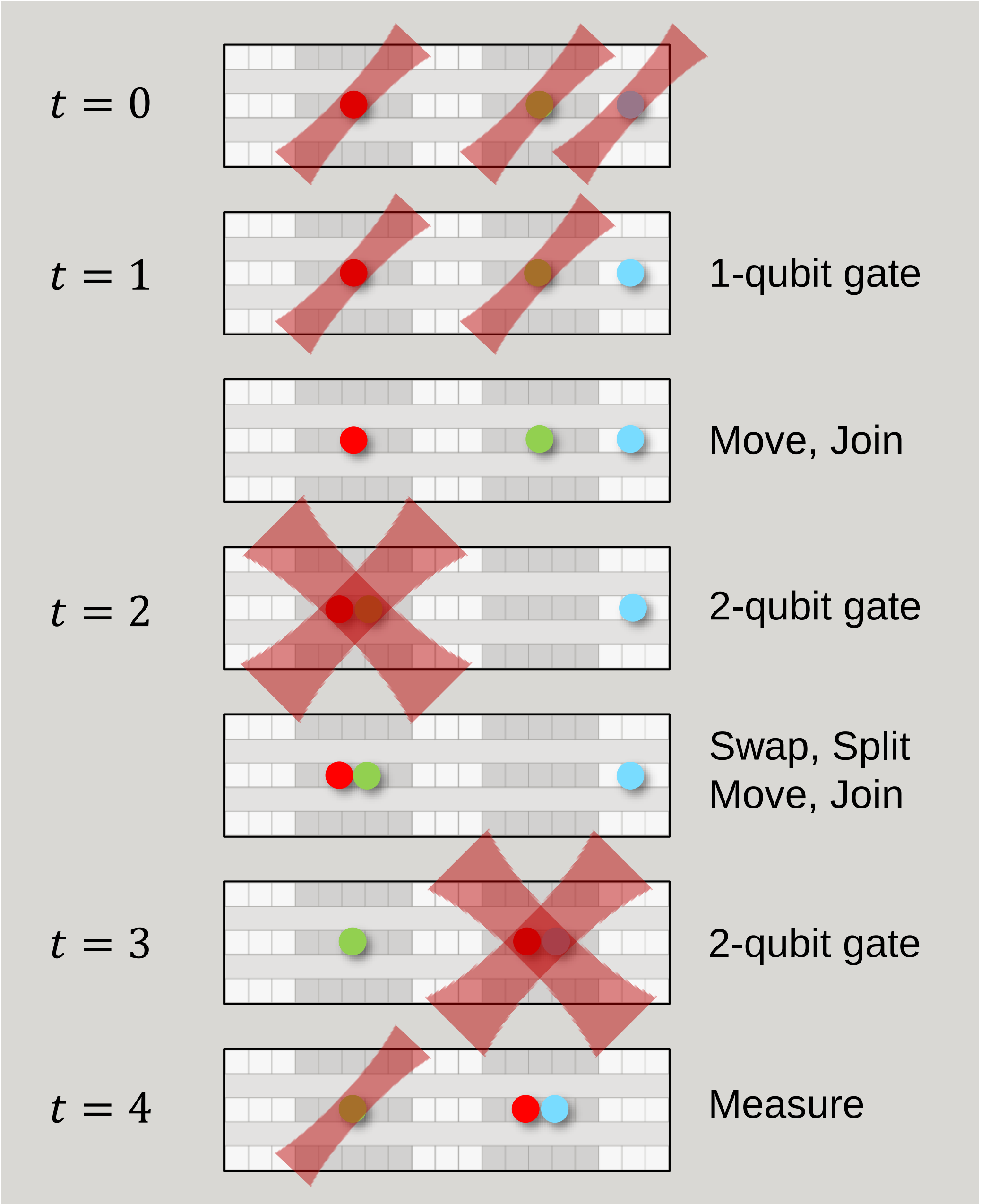
Ions can be re-separated and transported to interact with other ions



PHYSICAL IMPLEMENTATION

Quantum Circuit





REAL-WORLD VIEW

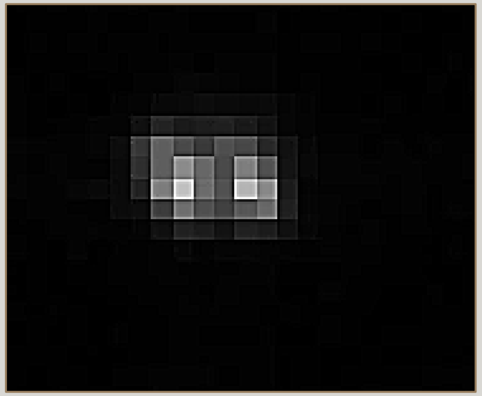
SPLIT AND COMBINE

Ion is transported into the same zone

Ions are combined into a single potential well and then re-separated

SWAP

Ions are carefully manipulated to reorder positions



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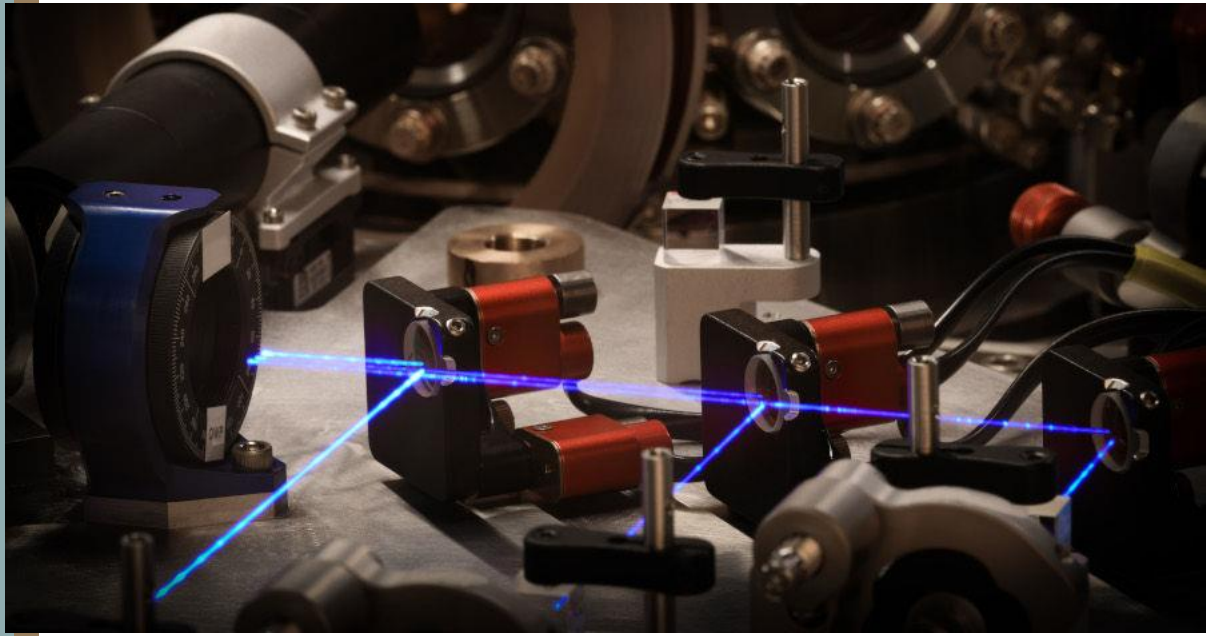
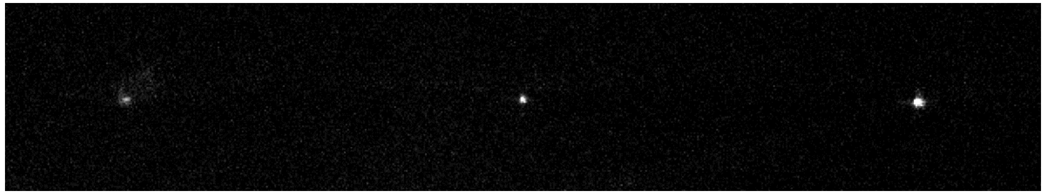
PARALLEL QUANTUM COMPUTING WITH IONS



- The process of implementing parallel, independent zones provides faster quantum algorithm execution times as well as greater options for qubit connectivity.



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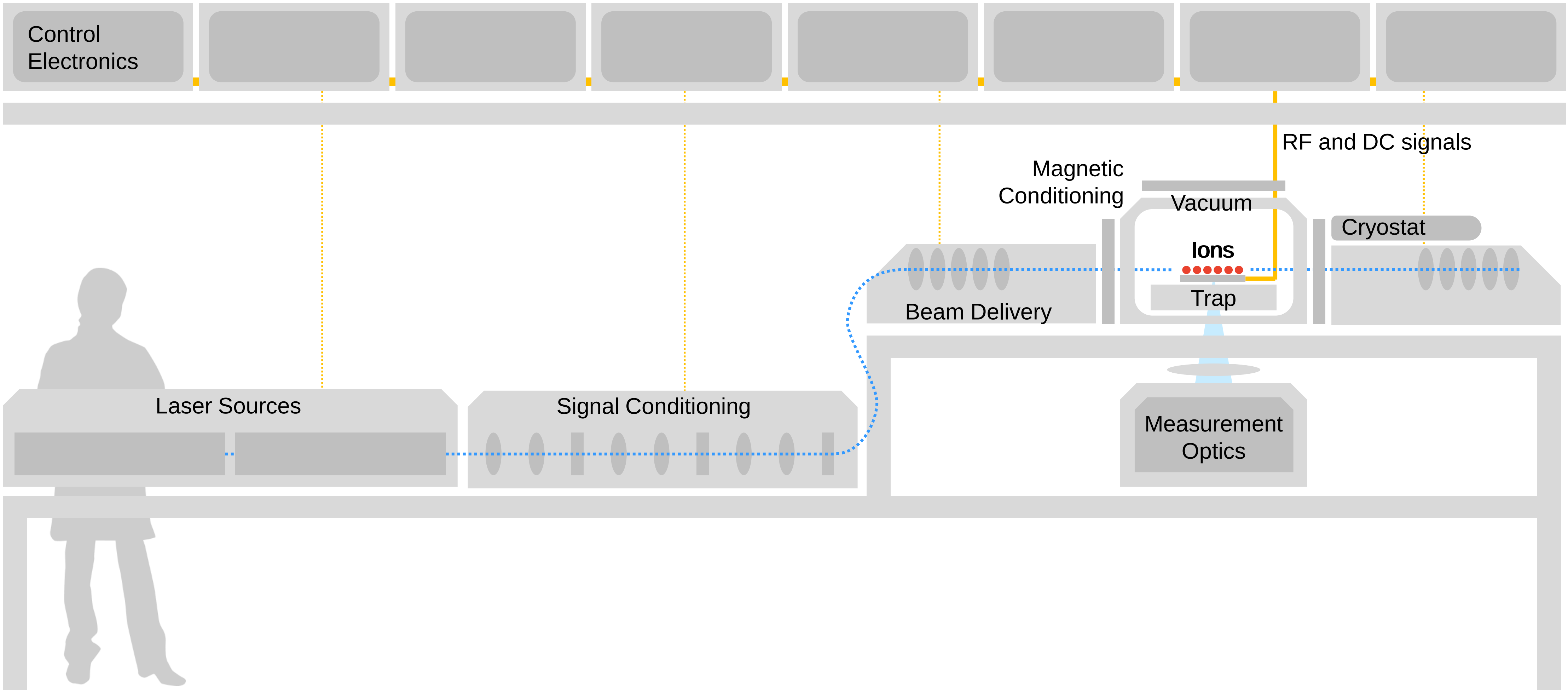
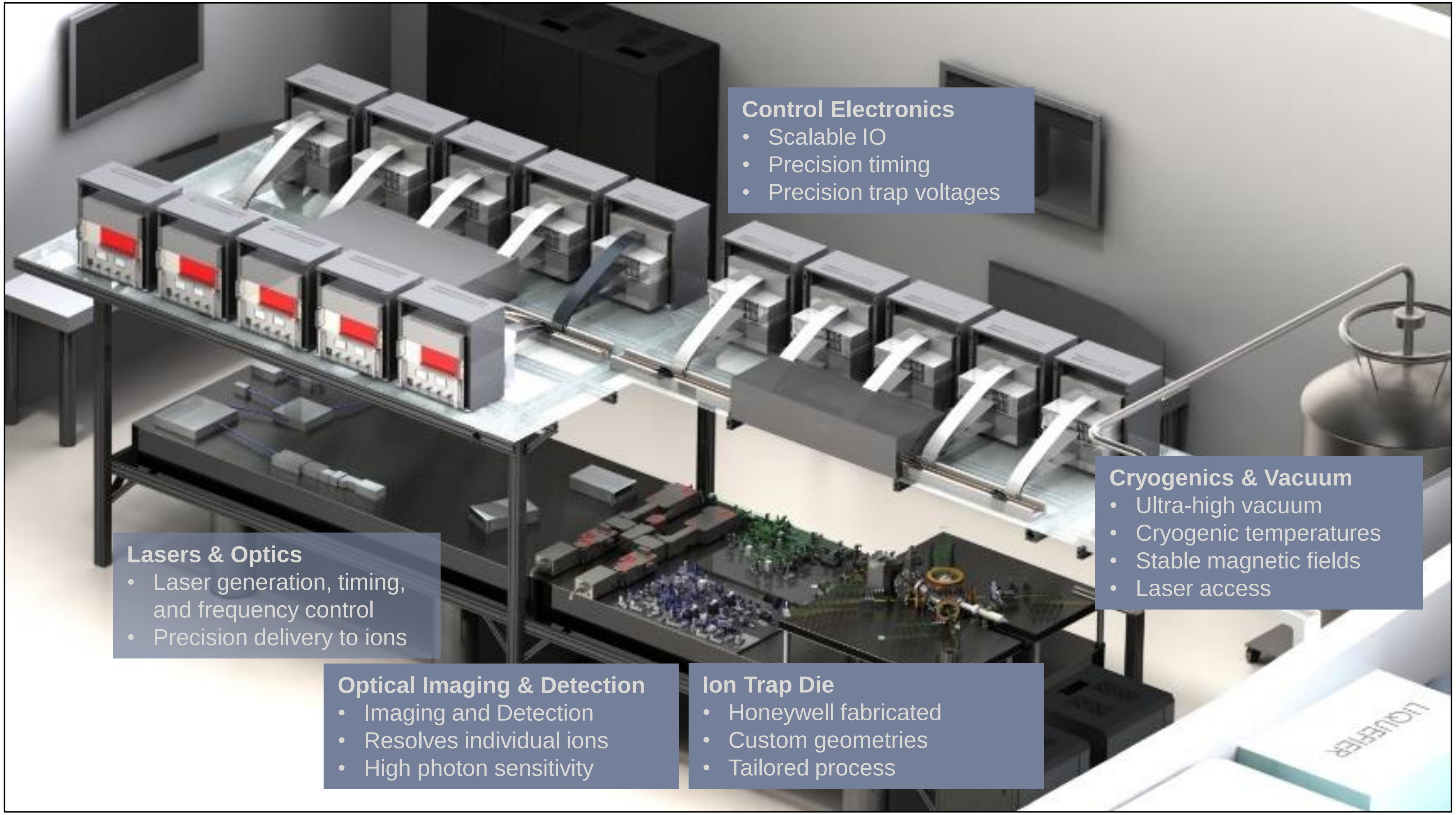
TRAPPED-ION QUANTUM COMPUTER

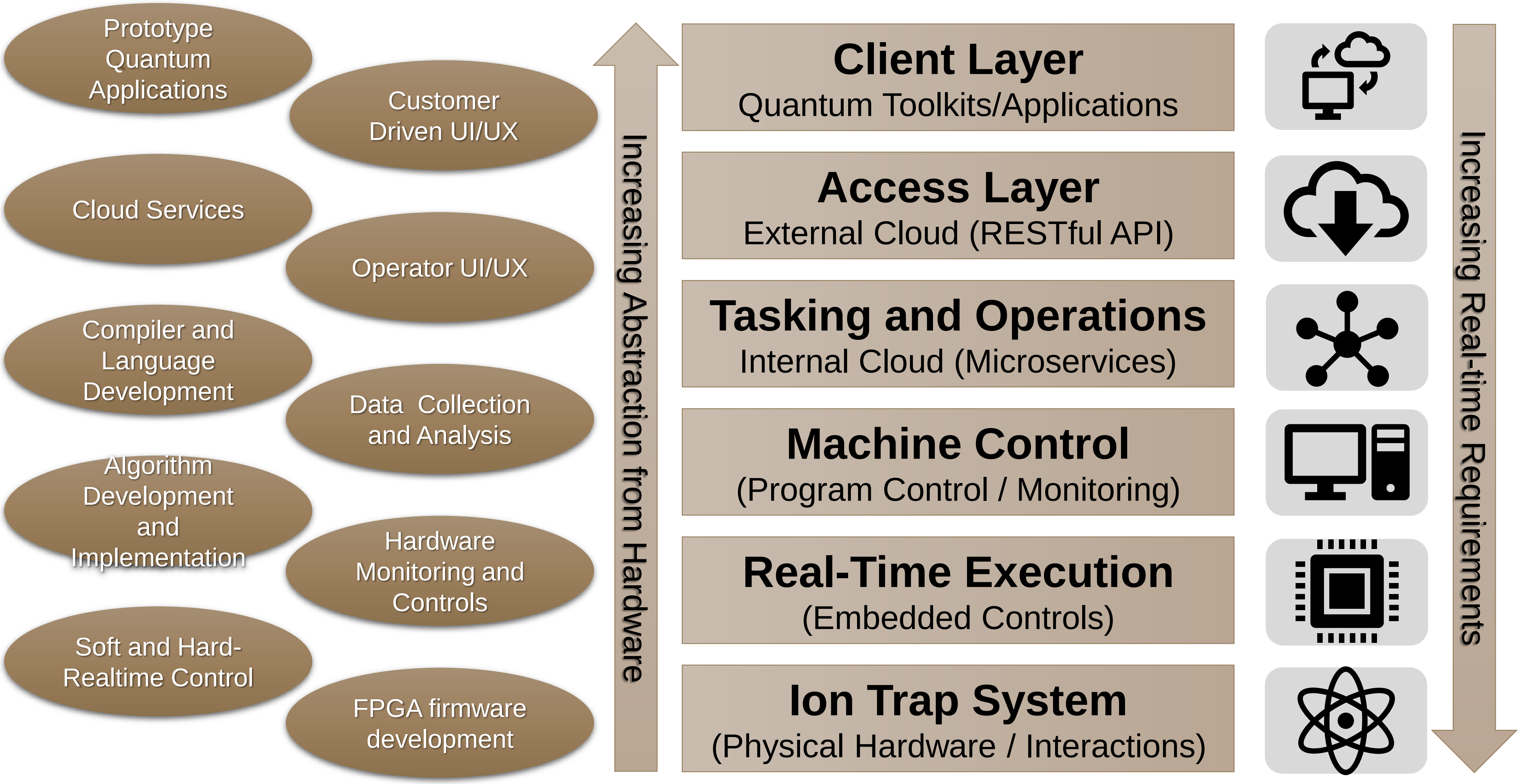


QUANTINUUM

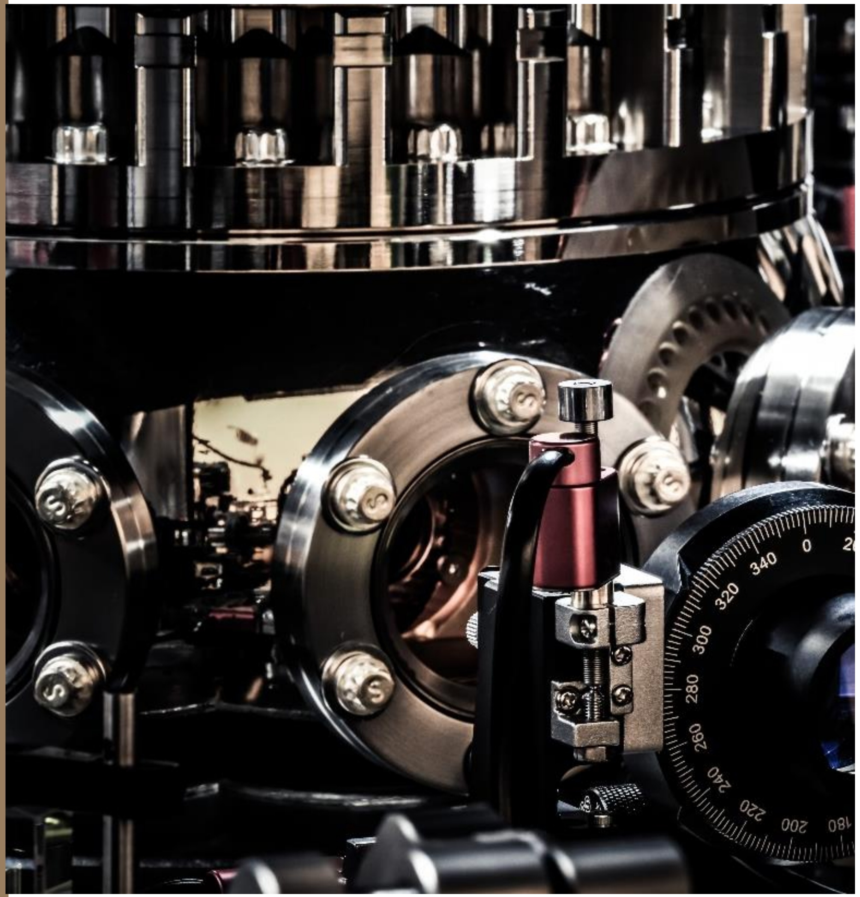
OUR TRAPPED-ION QUANTUM COMPUTER



LAYERED SOFTWARE



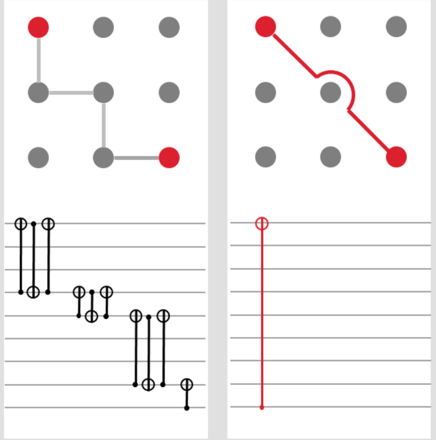
H-SERIES POWERED BY HONEYWELL
QUANTUM COMPUTERS ON THE CLOUD



	MODEL **H1** (2 systems)
Measured Quantum Volume	4096
Physical Qubits	20
Coherence Time (s)	≥ 3
Typical Limiting Fidelity	≥ 99.7%

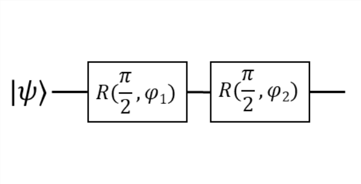
All-to-All Connectivity

Nearest Neighbor All-to-All

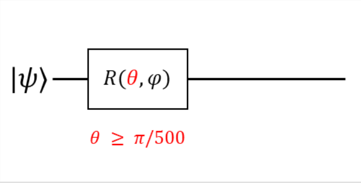


High-Resolution Rotations

Fixed amplitude systems

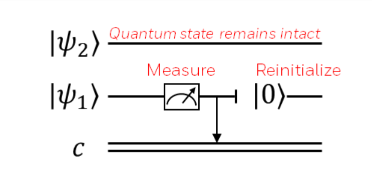


Trapped-ion system

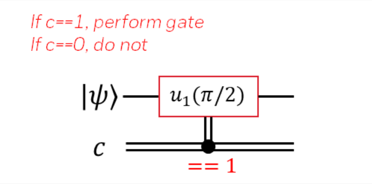


Qubit Branching and Reuse

Measurement and reuse



Conditional logic



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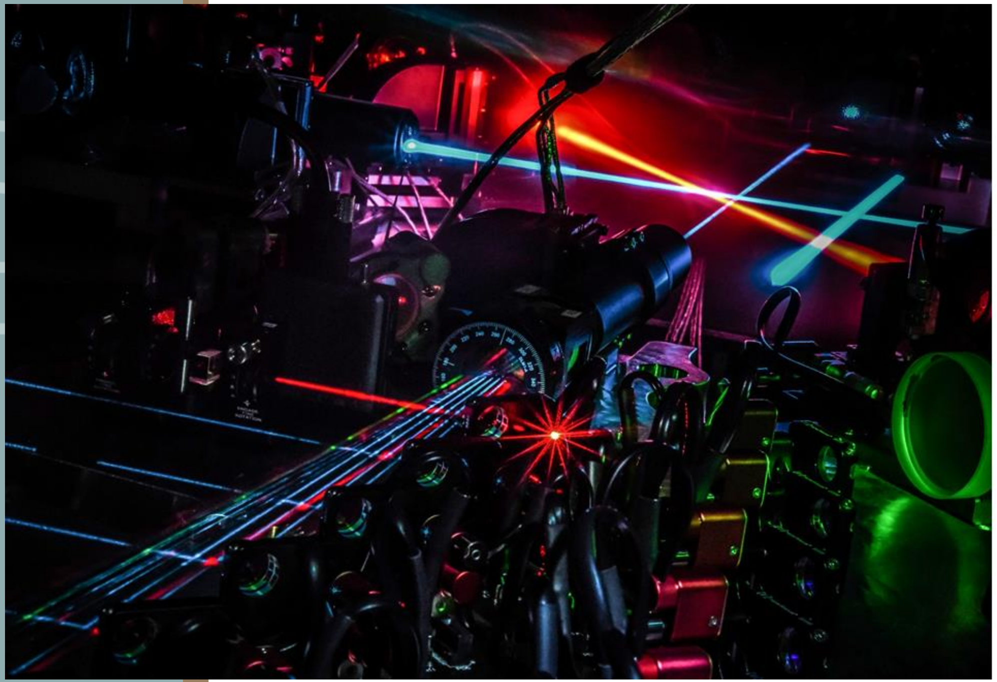


Quantinuum Trapped-Ion Quantum Processors

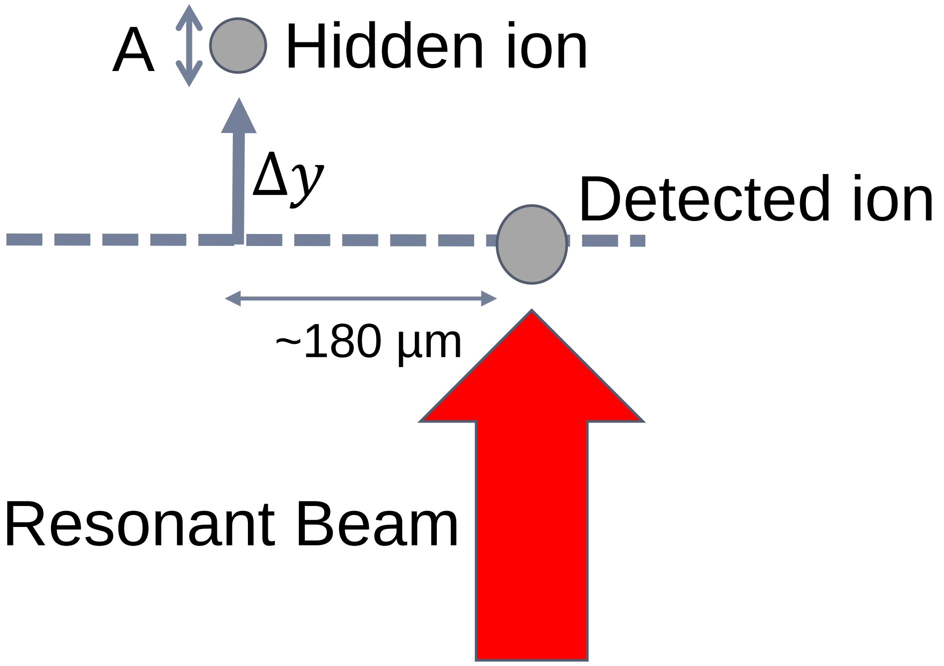
- World's highest demonstrated quantum volume: **QV = 4096**[1] QCCD architecture provides flexibility and performance
- Only commercial quantum processor to demonstrate real-time quantum error correction[2]
- Lowest commercial error rates[3]:
  - Two-qubit gate fidelity: ≥ 99.7%
  - Single-qubit gate fidelity: ≥ 99.99%
  - State prep & measurement fidelity: ≥ 99.6%
- Advanced algorithmic features:
  - All-to-all qubit connectivity
  - Low qubit cross-talk
    - Mid-circuit measurement
    - Qubit re-use
    - Conditional logic

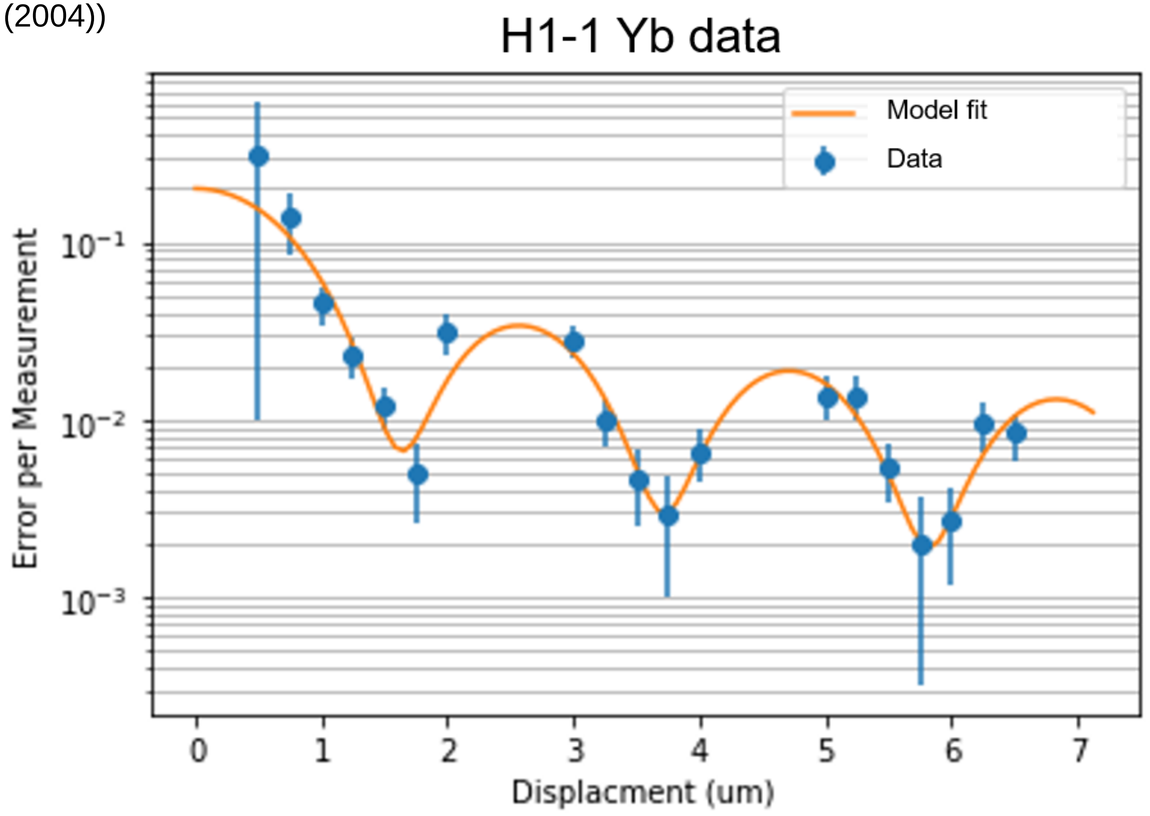
1. Based on measured quantum volume as supported by an independent analysis completed by Los Alamos National Laboratory in March 2022: https://arxiv.org/pdf/2203.03816.pdf
2. https://journals.aps.org/prx/abstract/10.1103/PhysRevX.11.041058
3. https://www.quantinuum.com/pressrelease/demonstrating-benefits-of-quantum-upgradable-design-strategy-system-model-h1-2-first-to-prove-2-048-quantum-volume

QUANTINUUM

MID-CIRCUIT MEASUREMENT WITH MICROMOTION HIDING

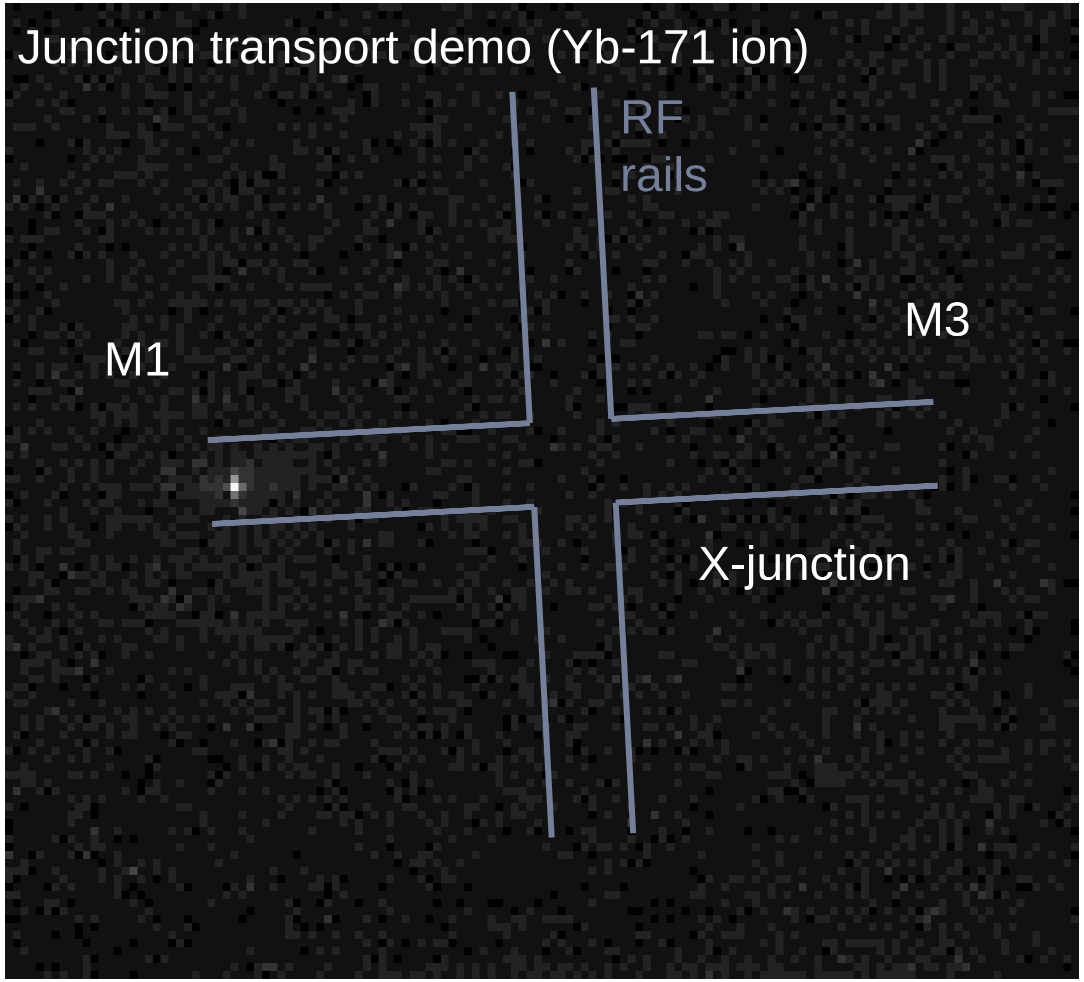
1. Transport ions to separate locations (e.g. NIST - Barrett et al., Nature 429, 737 (2004), Wan et al., Science 364, 6443 (2019), Duke – Crain et. al., Commun Phys 2, 97 (2019))
2. Map qubit information to a second ion species (e.g. NIST - P. O. Schmidt et. al., Science 309, 749 (2005), ETH – Negnevitsky et al., Nature 563, 527 (2018))
3. Hide qubit states in other metastable levels (e.g. Innsbruck – Riebe et al., Nature 429, 734 (2004))
4. Micromotion hiding (e.g. Quantinuum - Gaebler et al, Phys. Rev. A 104, 062440 (2021))





QUANTINUUM

JUNCTION TRANSPORT PROGRESS



Credit: Brian Estey, Cody Burton, Gabe Price, Curtis Volin, Ian Hoffman

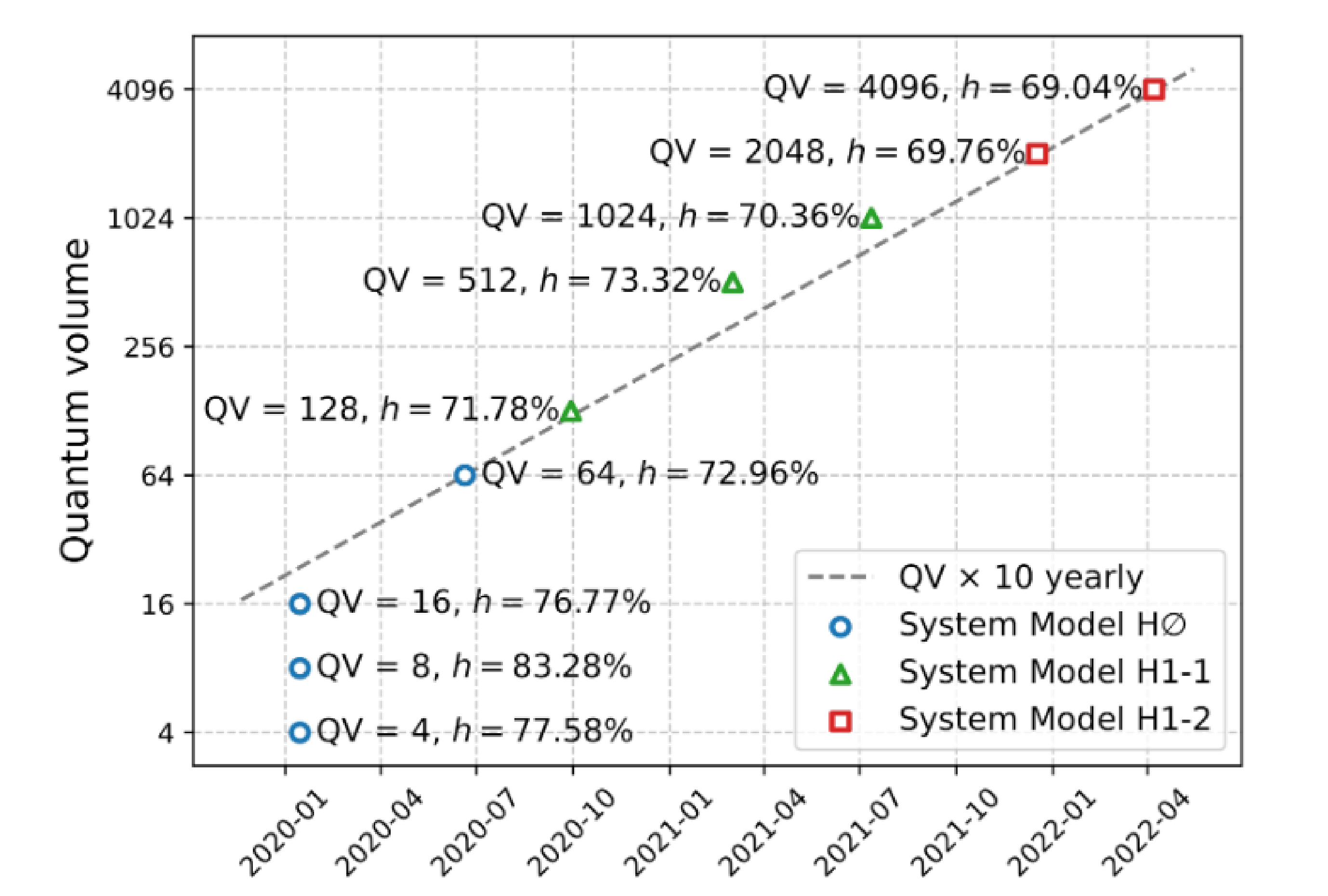
Credit: Curtis Volin, Bob Horning, Bob Higashi, Rob McCroskey

5 m/s junction transport with ~0.02 quanta of heating per round trip

Burton et. al., “Transport of multispecies ion crystals through a junction in an RF Paul trap.” arXiv:2206.11888 (2022)

Demonstrated Performance of Quantinuum H1 Processors

10X Increase in Performance Year-over-Year



Note: All data available at www.Quantinuum.com

QUANTINUUM

H-SERIES HARDWARE ROADMAP

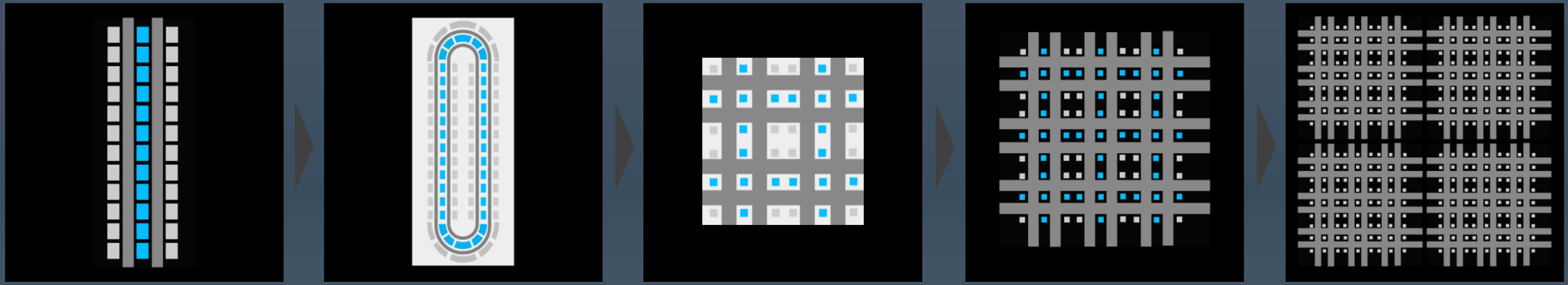
Noisy Intermediate-Scale Quantum (NISQ) Era

2030

2020

Fault-Tolerant Quantum Computing

Model H1 | Model H2 | Model H3 | Model H4 | Model H5



Linear | *Racetrack* | *Grid* | *Integrated Optics* | *Large Scale*

Upcoming proof-points for Roadmap

- Step-function increase in H1 qubit number without loss of fidelity
- Second Generation Model H2 in new product development phase – commercial launch in late 2022
- System Model H3 in design review process; critical enablers demonstrated
- Early progress on integrated optics for use in H4 and beyond

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- **Careers in ion trap quantum computing**

CAREERS IN THE ION TRAP QC INDUSTRY

People

- Atomic Physicists
- Optical Scientists/Engineers
- Electrical Engineers
- Mechanical Engineers
- Test/Lab Engineers
- Software Engineers
- Theoretical Physicists
- Systems Engineers

Skills of interest

- Integrated photonics
- Electronic and other components in cryogenic and UHV (ultra-high vacuum) environments
- Optomechanics
- FPGA, RF, and DAC expertise
- Trap design and fab/microfabrication
- Quantum algorithms

Skills for everyone

- Quantum literacy
- Works well with others
- Teamwork- and solution-oriented
- Troubleshooting and problem solving

QUANTINUUM ACCELERATING QUANTUM COMPUTING

Many open positions!

https://www.Quantinuum.com/careers

PROVIDING H1 ACCESS
FOR QC RESEARCH:

- **Quantum Computing User Program** from Oak Ridge National Laboratory

  https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/

- **Azure Quantum Credits Program** from Microsoft

  https://aka.ms/aq/credits