Quantum Information Processing with Single Atoms

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"There's Plenty of Room at the Bottom" (1959 APS annual meeting)

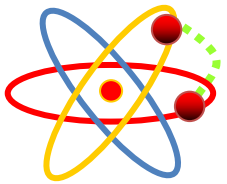
Richard Feynman

"When we get to the very, very small world – say circuits of seven atoms - we have a lot of new things that would happen that represent completely new opportunities for design. **Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics…**"

THE GOLDEN RULES OF QUANTUM MECHANICS

1. Quantum objects are waves and can be in states of superposition……

"quantum bit": $\alpha|\mathbf{0}\rangle + \beta|\mathbf{1}\rangle$



2. …… as long as you don't look!

$\alpha|\mathbf{0}\rangle + \beta|\mathbf{1}\rangle$ → $|\mathbf{0}\rangle$ or $|\mathbf{1}\rangle$

Massive storage and parallelism

- One qubit: $|\psi\rangle = (1/2)^{1/2} (|0\rangle + |1\rangle)$
- Two qubits: $|\psi\rangle = (1/2) (|0\rangle + |1\rangle) \times (|0\rangle + |1\rangle) =$

  $(1/2) (|00\rangle + |01\rangle + |10\rangle + |11\rangle)$

  $(1/2) (\text{“0”} + \text{“1”} + \text{“2”} + \text{“3”})$
- ……
- N qubits: $|\psi\rangle = (1/2)^{N/2} (|0\rangle + |1\rangle) \times (|0\rangle + |1\rangle) \times \ldots =$

  $(1/2)^{N/2} (|00..0\rangle + |0..01\rangle + |0..10\rangle$
  $\ldots + |11..1\rangle)$

  $(1/2)^{N/2} (\text{“0”} + \text{“1”} + \text{“2”} + \ldots + \text{“}2^N\text{-1”})$
- Mere 1000 qubits can store **all numbers** between 0 and $2^{1000}-1 \approx 10^{301}$ >> number of atoms in Universe!

The Entanglement

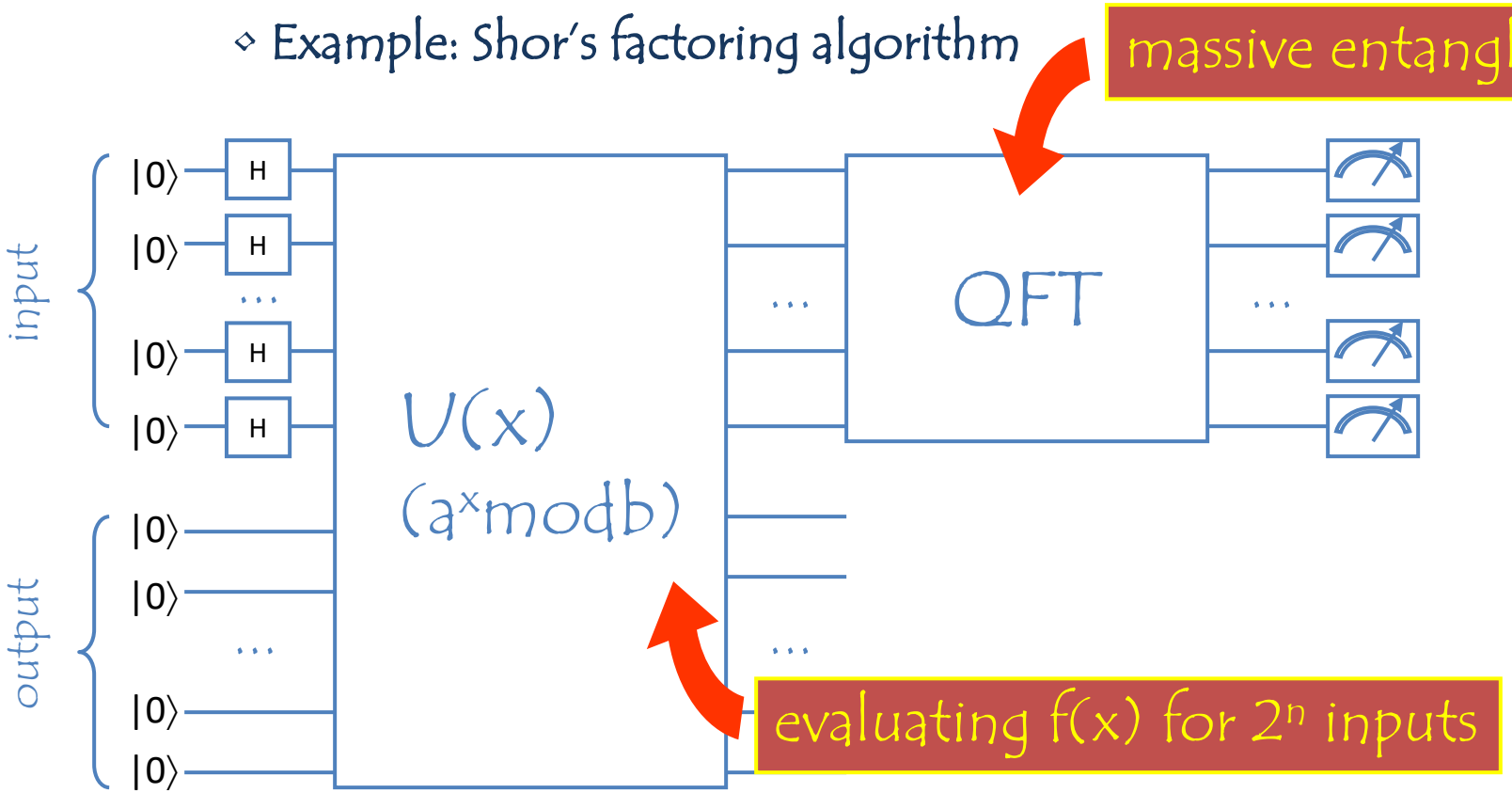
- A particular superposition state of a complex quantum system which cannot be reduced to a product state of the components of the system. Simplest case: two qubits:

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

- One consequence: measurement of one part of the system yields information about other part(s) of the system without directly measuring those.

Quantum computing in nutshell

- The power of quantum computing is twofold:
  - parallelism and
  - entanglement
- Example: Shor's factoring algorithm

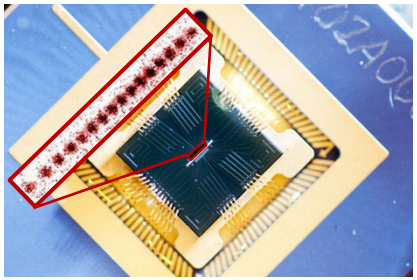


Quantum Simulations

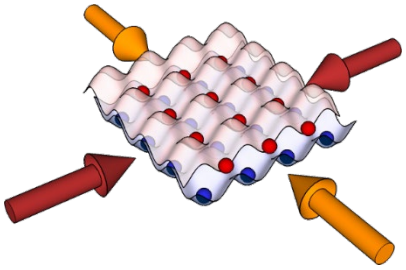
Quantum modelling is hard: *N* quantum systems require solving 2^N coupled equations

$$i\hbar \frac{\partial \Psi}{\partial t} = H\Psi$$

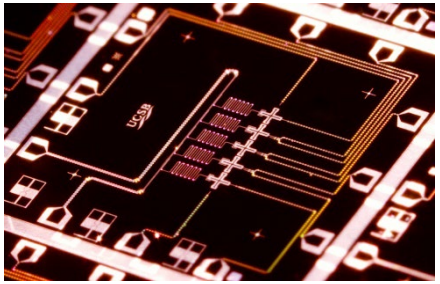
Alternative approach: Implement model of interacting system on a ***quantum simulator***, a standard set of qubits with programmable interactions



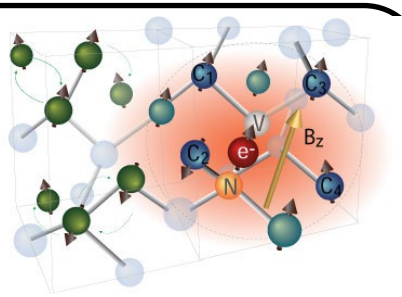
Atomic ions



Trapped atoms

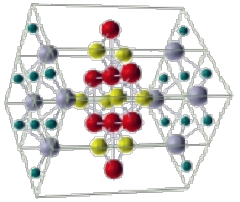


Superconductors

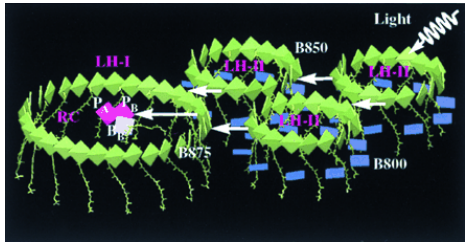


NV-diamond

Quantum Material Design Understand exotic material properties or design new quantum materials from the bottom up



high-T_C super-conductor



Energy and Light Harvesting Use quantum simulator to model photosynthesis and such to develop light harvesting materials.

Quantum Field Theories Program QCD lattice gauge theories, test ideas connecting cosmology to information theory (AdS-CFT etc..)

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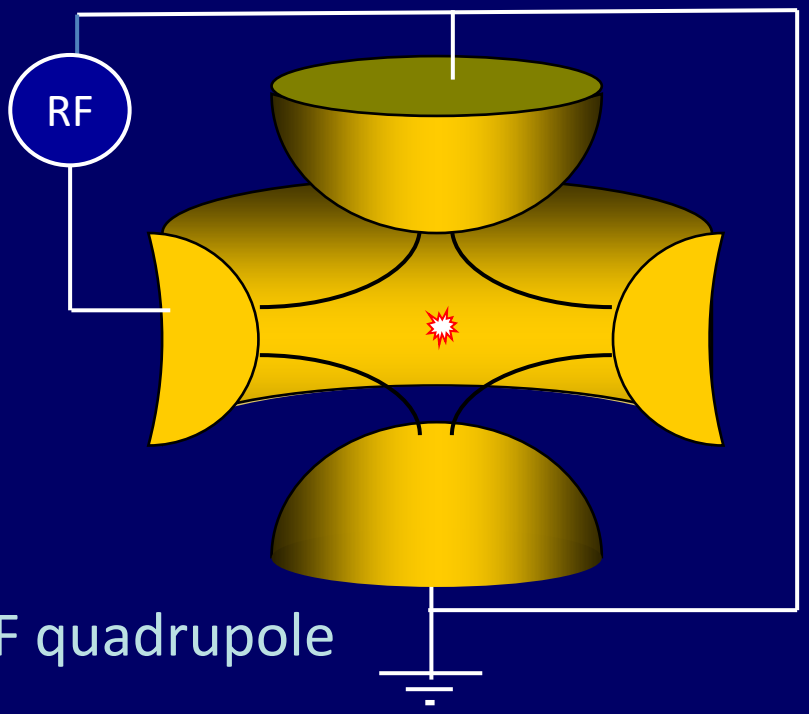
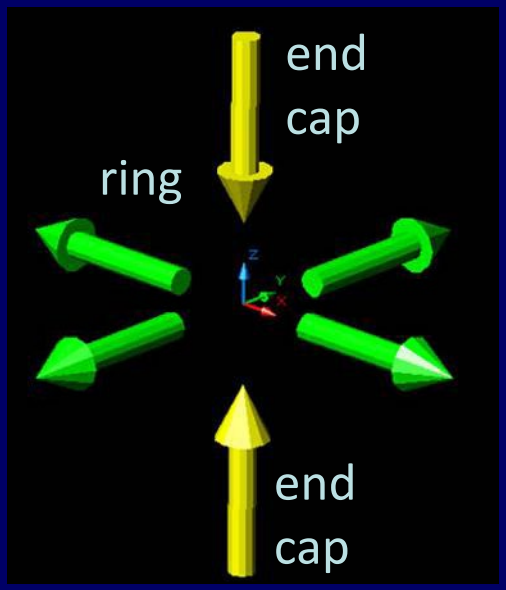
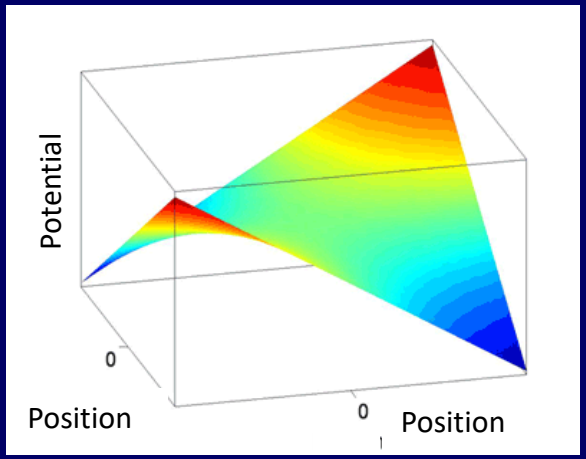
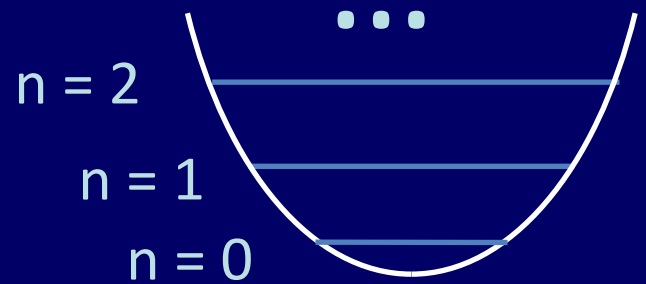
RF (Paul) ion trap



3-d RF quadrupole

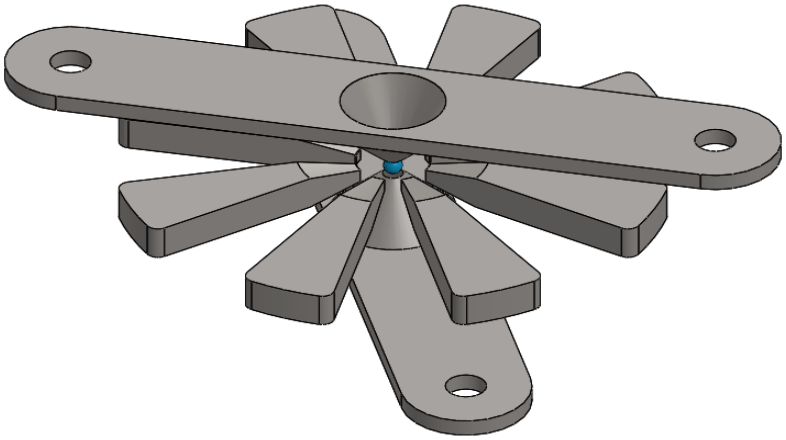


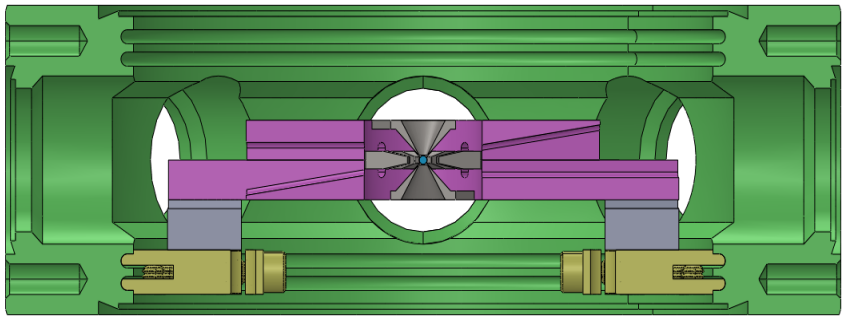


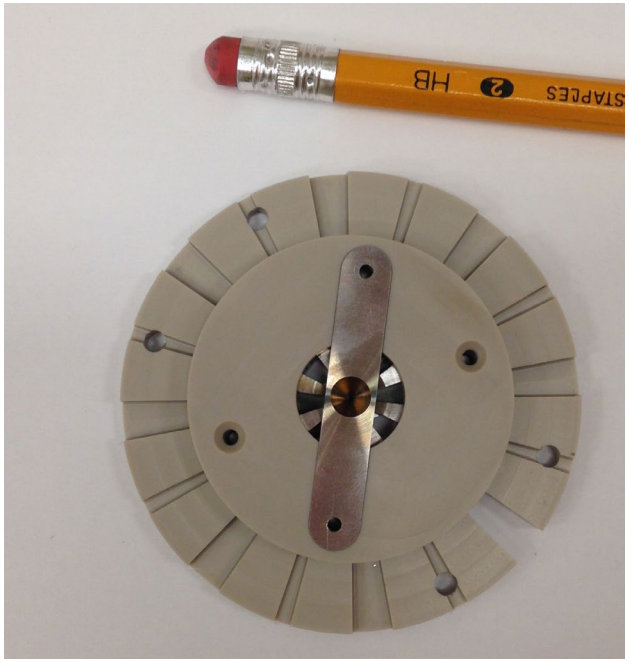


harmonic potential

Oblong trap for large 2-d crystals

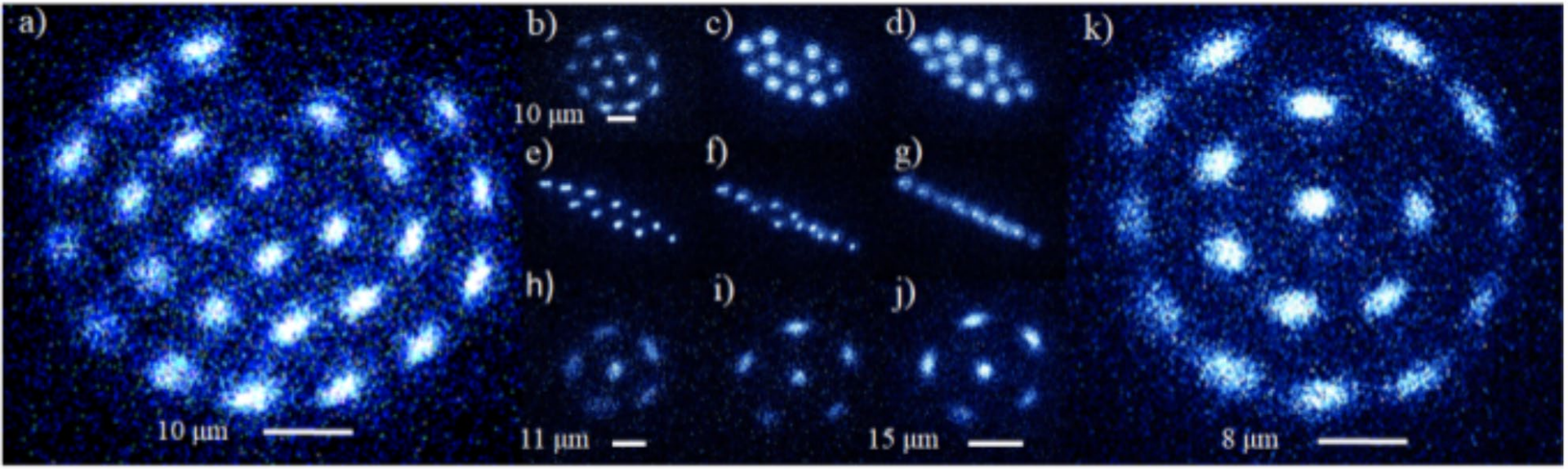






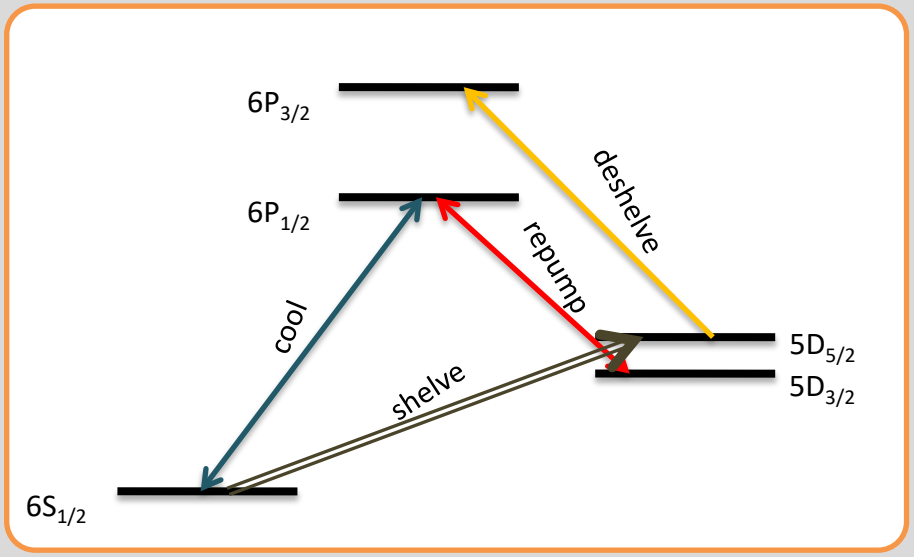
We designed and built a version of Paul trap with segmented ring electrode and hollow cone-shaped endcap electrodes for producing 2-dimensional ion crystals.

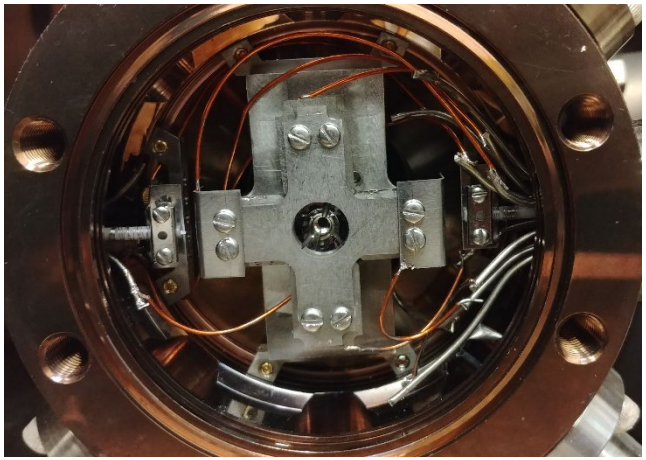
2-d crystals

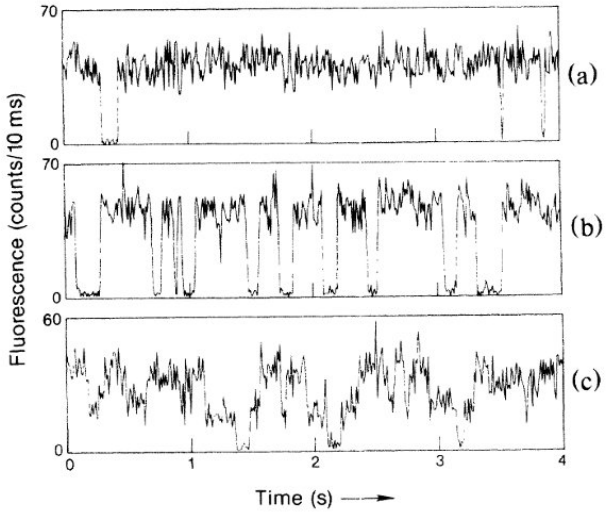


Parabolic mirror trap

- Ion is trapped at the focus of a parabolic mirror.
- About 40% of the photons emitted by the ion are collected into a collimated beam.
- Study ion-photon entanglement, single photon generation and quantum jumps.



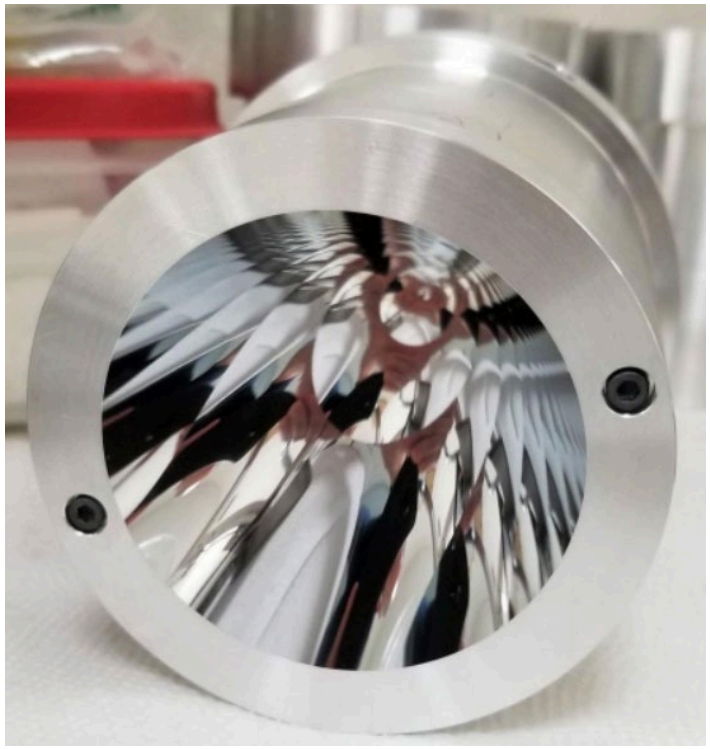


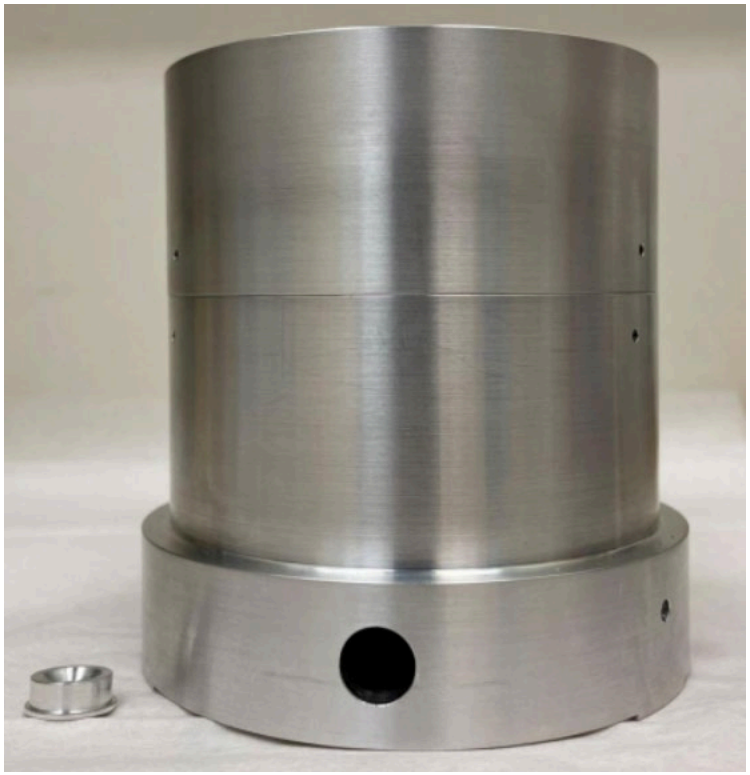


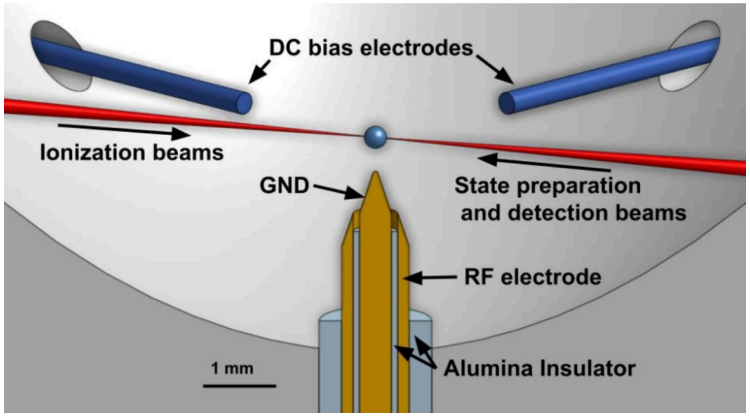
Bergquist, J., Hulet, R., Itano, W., & Wineland, D. (1986). Observation of Quantum Jumps in a Single Atom *Physical Review Letters,*

BIGGER parabolic mirror trap

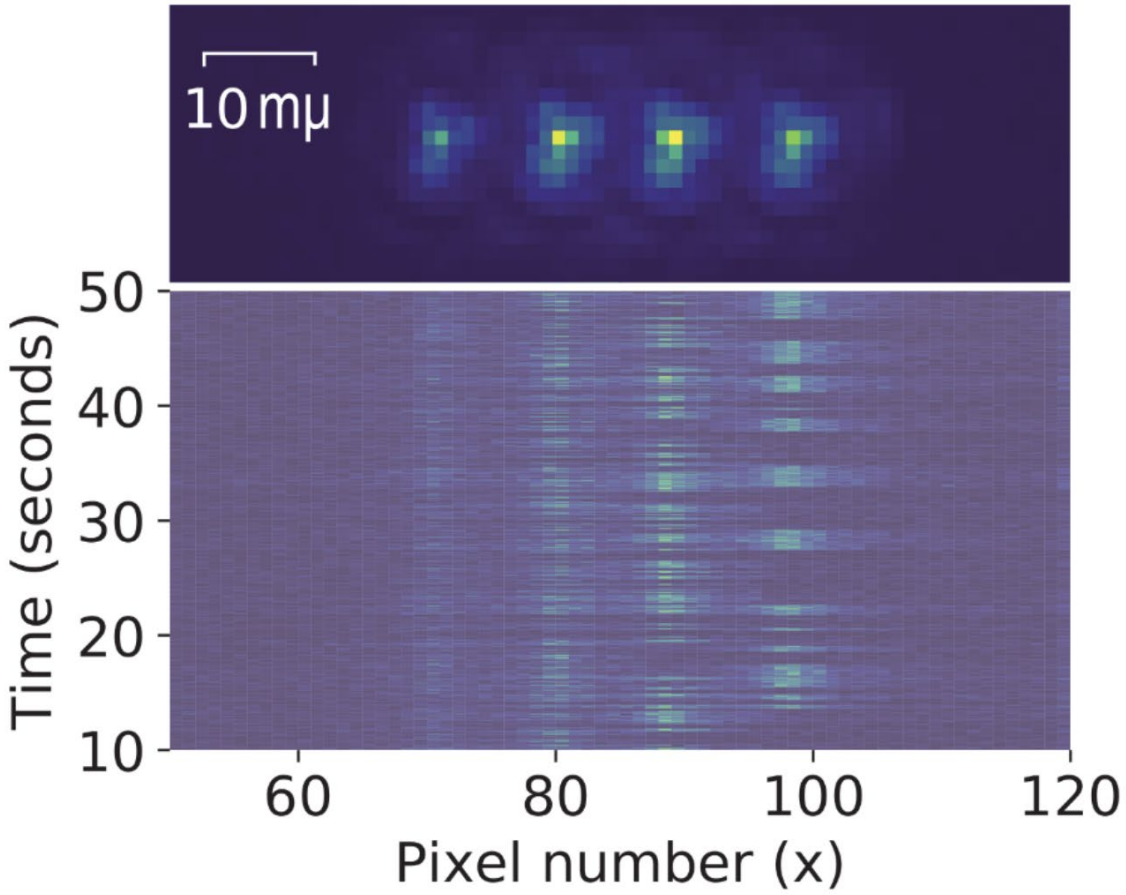
- New, larger parabolic mirror with >95% solid angle coverage
- Need >80% photon detection efficiency to “catch and reverse” quantum jumps
- Geometry is known. Now, knowing exact reflectivity is key





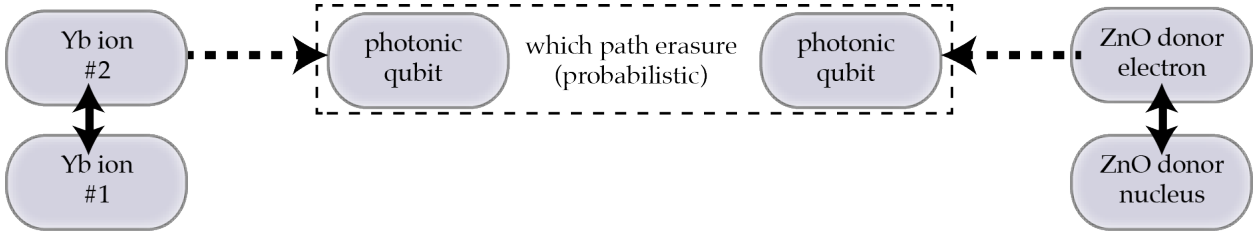


Quantum jumps in a linear trap

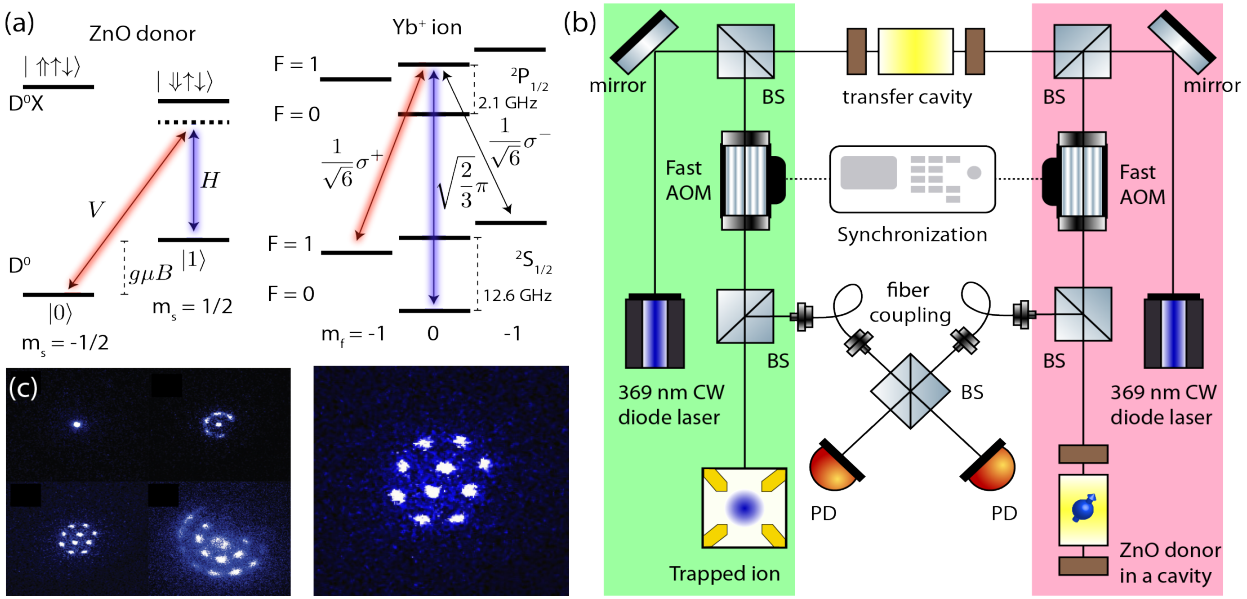


- 4 Ba+ ions undergoing quantum jumps
- High-resolution CMOS camera with 1.5 ns temporal resolutions records time of arrival of every photon
- We are able to track and study quantum jumps in several ions at the same time

QUANTUM ENTANGLEMENT BETWEEN A SOLID-STATE SPIN AND A TRAPPED ION VIA A PHOTONIC LINK



Yb ions and quantum defects in zinc oxide (ZnO) have very similar (but not quite) transition frequencies, so their emitted photons can be made identical. “Which-path erasure” is performed by interfering the two photons on a beam splitter. Long-term quantum information storage is accomplished by local quantum gates.



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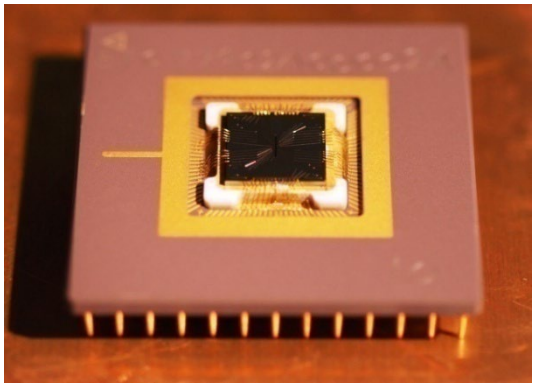
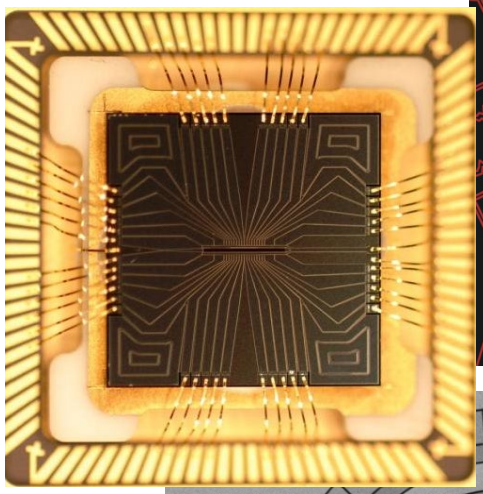
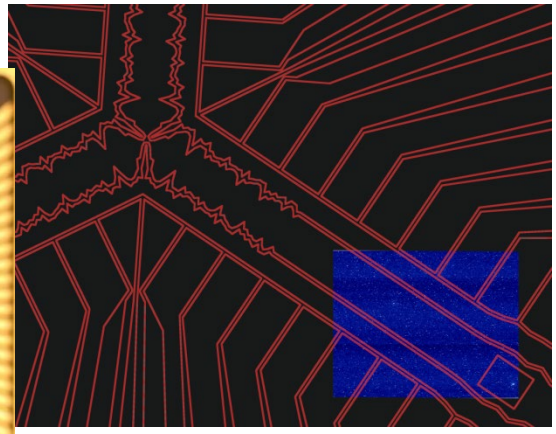
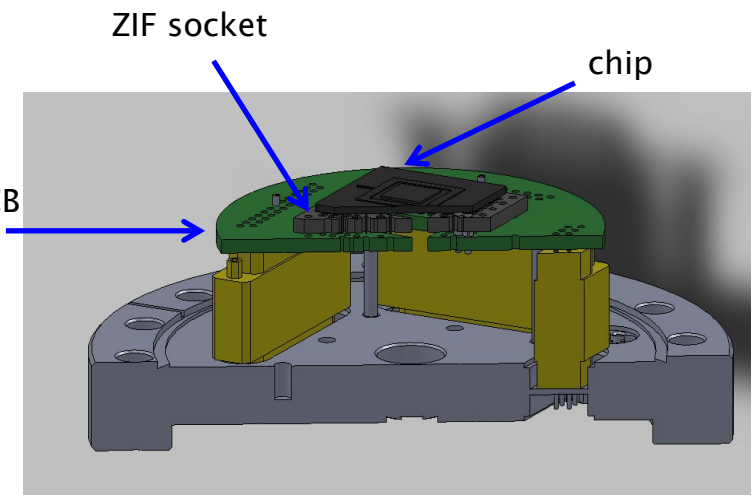
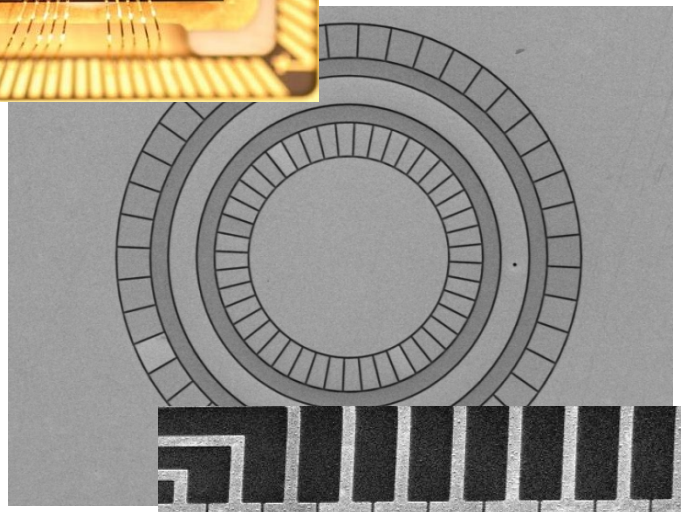
Microfabricated ion traps

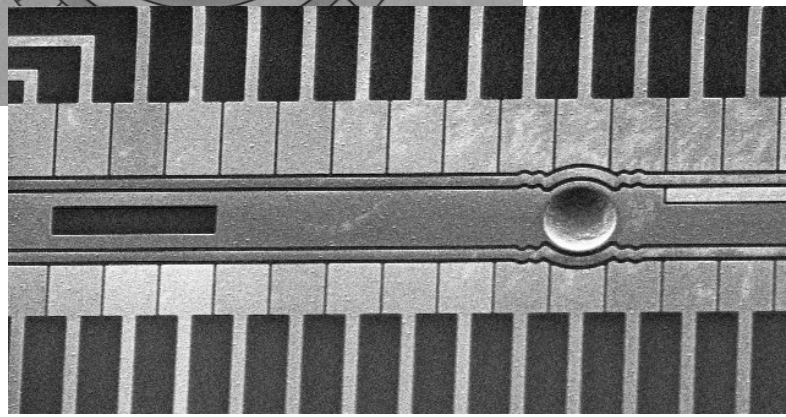






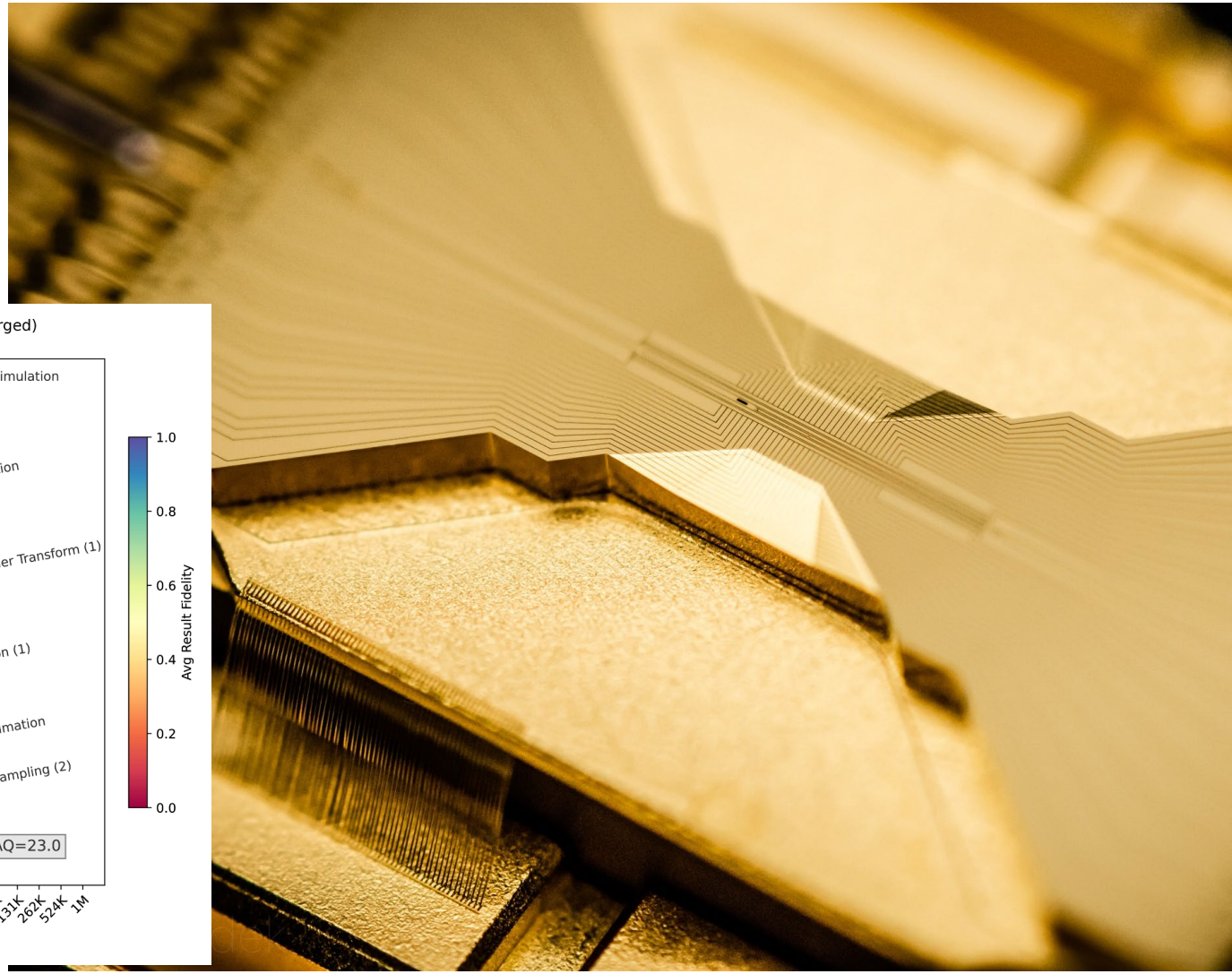


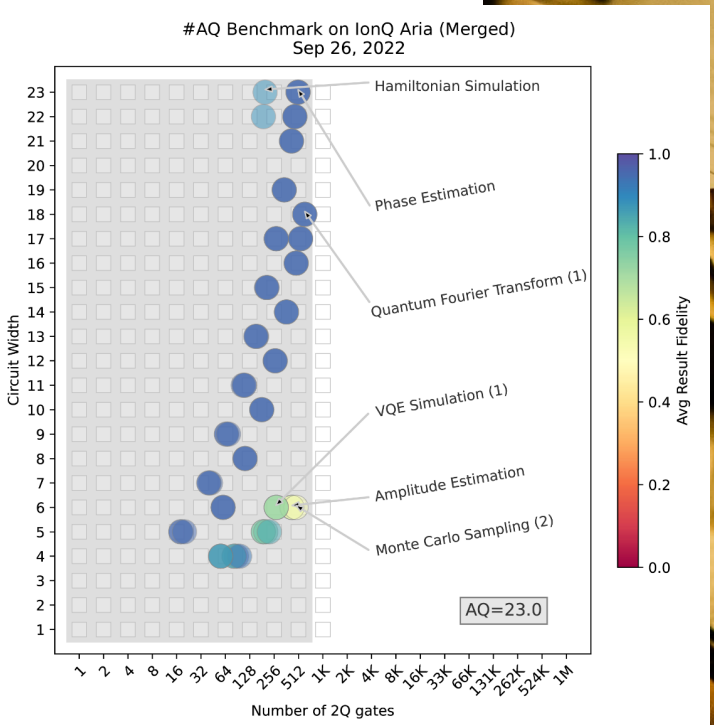




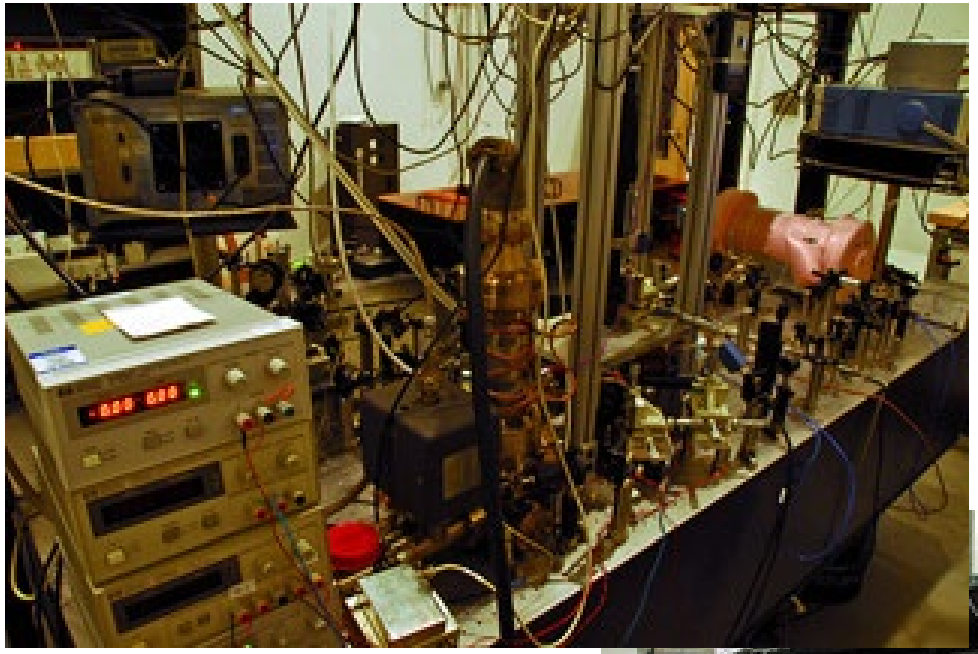
- Traps mounted in a UHV-compatible PCB system with in-vacuum RF filtering
- ZIF-socket to prevent solder joint cracking
- Laser-cooled lifetimes of order 1 hour or more

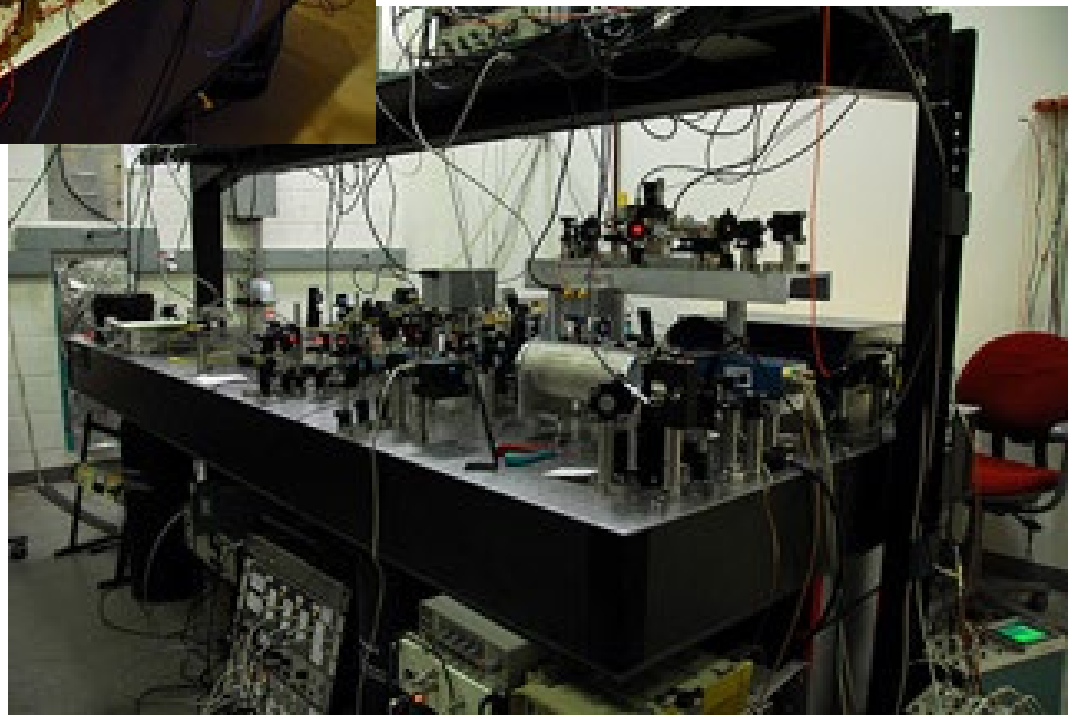
IonQ

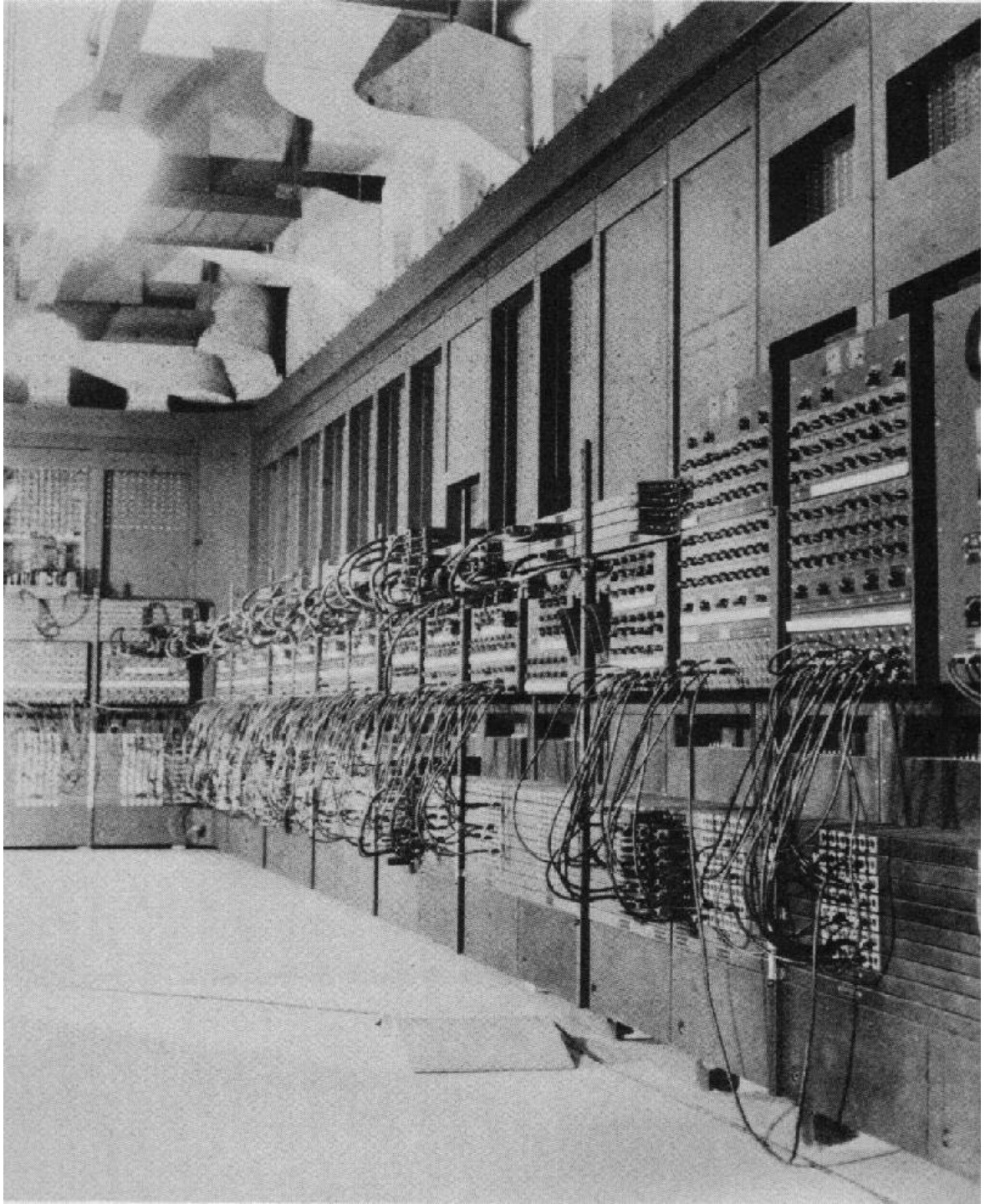



#AQ Benchmark on IonQ Aria (Merged)
Sep 26, 2022
Hamiltonian Simulation
Phase Estimation
Quantum Fourier Transform (1)
VQE Simulation (1)
Amplitude Estimation
Monte Carlo Sampling (2)
AQ=23.0
Circuit Width
Number of 2Q gates
Avg Result Fidelity
1 2 4 8 16 32 64 128 256 512 1K 2K 4K 8K 16K 33K 66K 131K 262K 524K 1M
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
0.0 0.2 0.4 0.6 0.8 1.0

In the lab…







ENIAC
(1946)

UW ion trappers