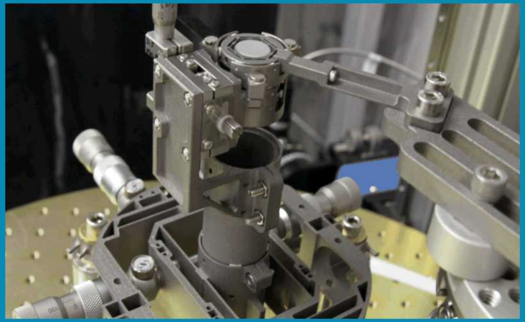
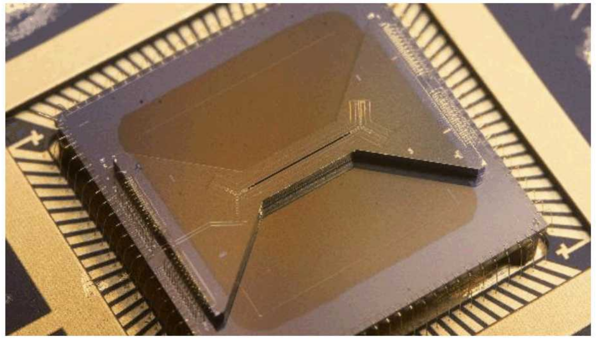
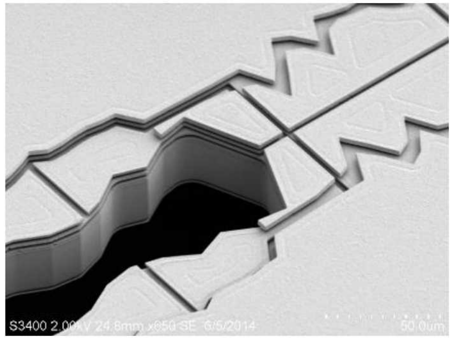
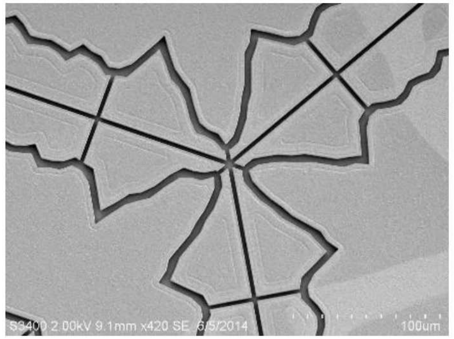
SAND2020-4129PE

Quantum Computing with Microfabricated Surface Ion Traps









Craig W. Hogle ('07)

Sandia National Laboratories

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SAND Number: SAND2020-1534 C

So why quantum computing?

Classical computer

- Single states:
  - A bit can only be one of two states (0 or 1)
  - So two bits can 00 or 01 or 10 or 11 but never a combination

Quantum computer

- Superposition states:
  - $\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$
- Entanglement (non-classical states)

Exponential speedup for ***particular*** algorithms (most notably Shor's factoring algorithm related to RSA encryption)

So why quantum computing?

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Quantum computer

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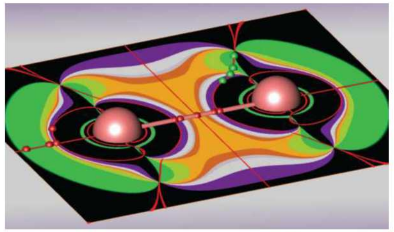
Consider representing the above quantum state with single precision floats (32 bits):

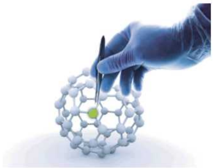
- A 2 qubit system needs $32 \times 2^2 = 128$ bits
- A 10 qubit system needs $32 \times 2^{10} \approx 4\ kB$
- A 50 qubit system needs $32 \times 2^{100} > TB$
- A 100 qubit system need $> 5{,}000{,}000{,}000{,}000{,}000{,}000\ TB$ just represent a given state on a classical computer

Quantum information processing has many applications



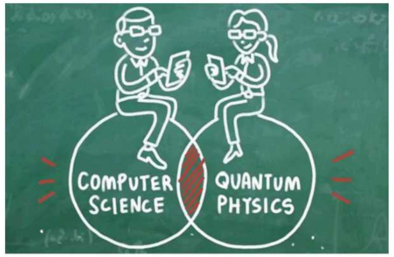
Quantum chemistry

- Calculation of molecular potentials
- Nitrogen and Oxygen fixation, development of catalytic converters



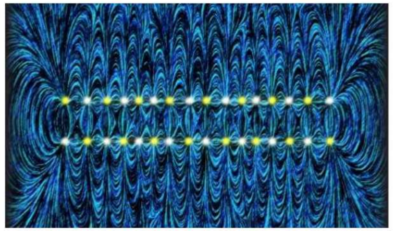
Medicine

- Structure-based drug development



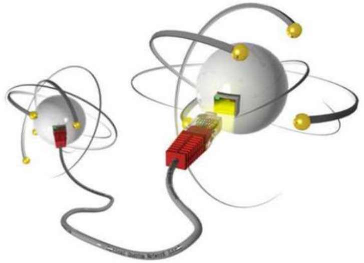
Quantum computing

- Number factorization (Shor's algorithm)
- Search in unstructured data, searching for solutions to hard problems (Grover's search algorithm)



Quantum simulation

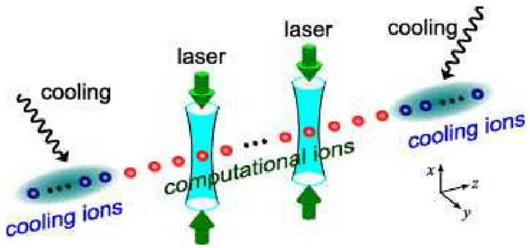
- Simulating many-body systems
- Already for about 20 qubits not possible to simulate classically.



Quantum Communication

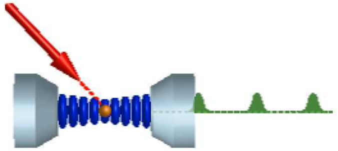
- Securing a quantum channel

What can we use for a qubit?



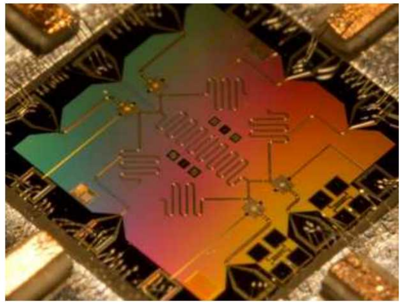
Trapped Ions

- Blatt and Wineland "Entangled States of Trapped Atomic Ions." *Nature* 453, 1008–15 (2008).
- Monroe and Kim. "Scaling the Ion Trap Quantum Processor." *Science* 339, 1169 (2013)



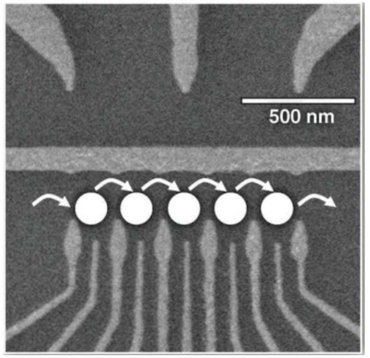
Neutral Atoms

- Rydberg states
- Atoms in cavities



Superconducting Josephson junctions

- Devoret and Schoelkopf. "Superconducting Circuits for Quantum Information: An Outlook." *Science* 339, 1169 (2013).

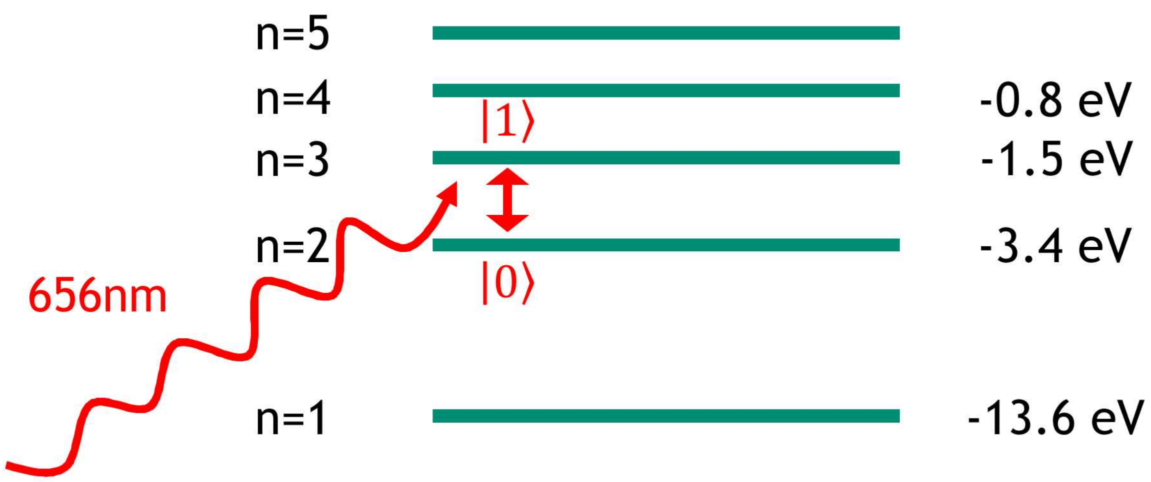


Quantum dots

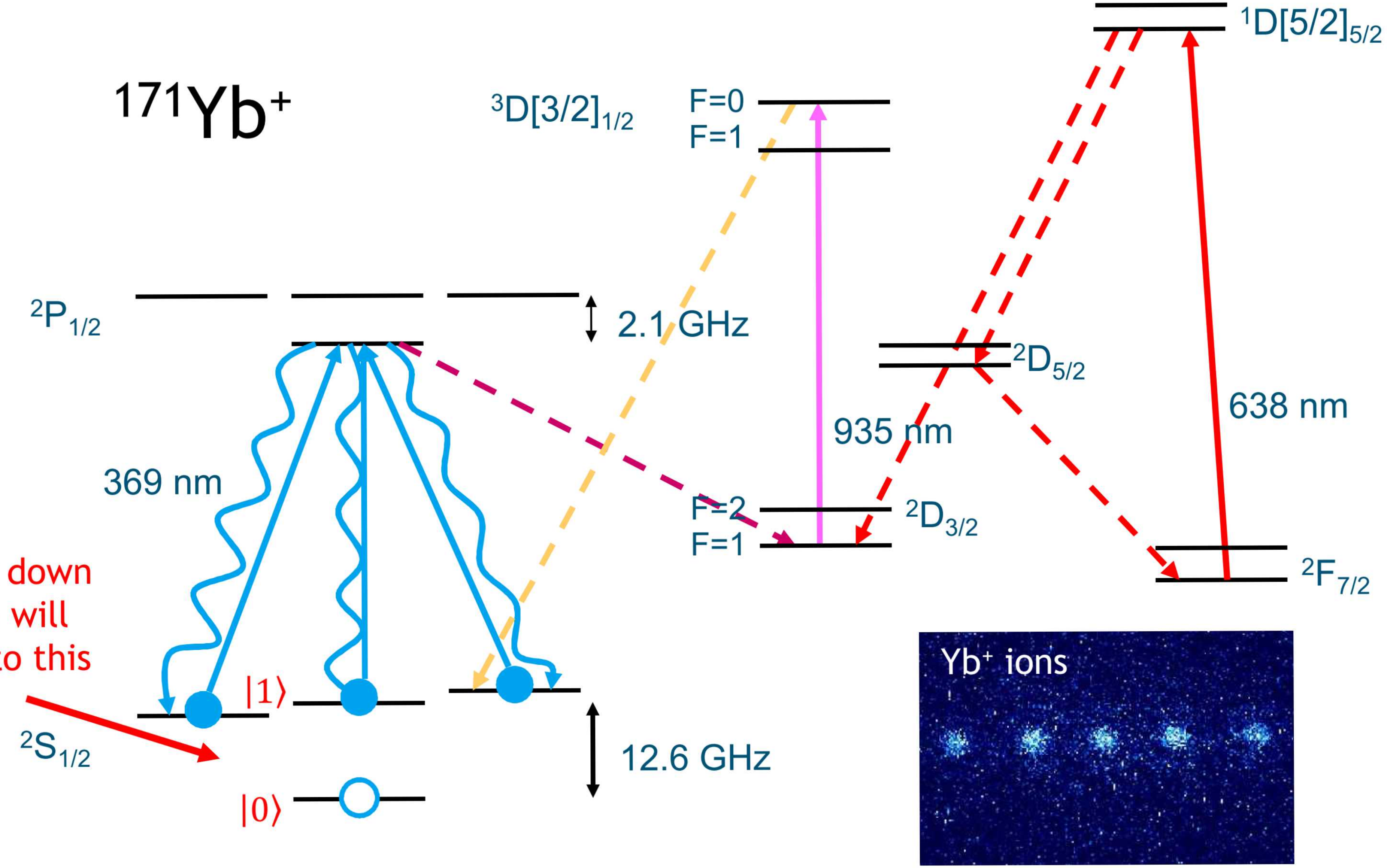
- Awschalom, et al., "Quantum Spintronics: Engineering and Manipulating Atom-Like Spins in Semiconductors." *Science* 339, 1174 (2013).

The logic performed on a qubit is not dependent on its medium, but it needs to be well controlled and isolated.

Consider having the control the electronic state of a simple atom (how about hydrogen). The population between states would act as the logic states of a qubit.



An ion qubit's electronic structure

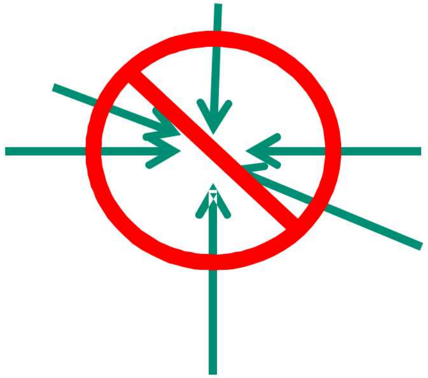


The qubit is down here but we will come back to this later…

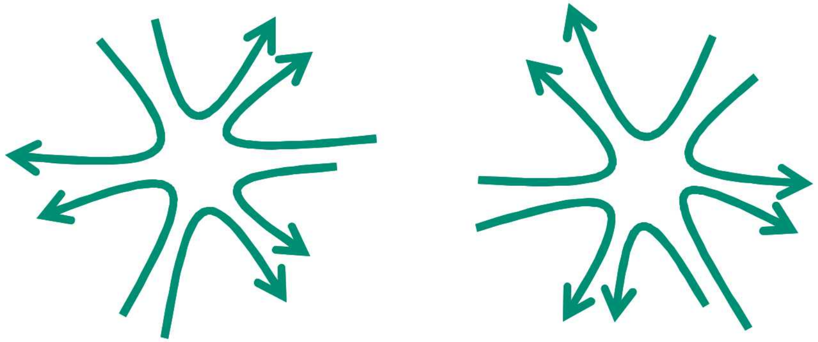
How do we trap an isolated ion from it environment?

Electric fields provide a strong 'handle' for moving a charged ion. We would like a restoring force when displaced from trap center (in any direction)

Cannot use static electric fields to trap a charge because field lines cannot cross, and must start/end on sources/drains



Electric field lines "squirt out" and create anti-traps in some directions



Time for a little math

Trapping requirement: A restoring force when displaced from trap center
(in any direction)

$$\mathbf{F} = -c\mathbf{r}$$

<u>Want a pure electric trapping field:</u>
Force is proportional Electric Field
Electric Field is negative gradient of potential
Thus, integrate Force equation to get desired potential:

$$\phi(x, y, z) = \frac{\phi_0}{2r_0^2}\left(\alpha x^2 + \beta y^2 + \gamma z^2\right)$$

Potential amplitude (ϕ_0)

Size parameter constant (r_0)

Checking to see if Force is a restoring force, take negative gradient,

$$\mathbf{F} = ne\mathbf{E} = ne(-\nabla\phi(x, y, z))$$
$$= -\frac{ne\phi_0}{r_0^2}\left(\alpha x\hat{x} + \beta y\hat{y} + \gamma z\hat{z}\right) \longrightarrow$$

To get restoring force in all directions:

$$\alpha > 0$$
$$\beta > 0$$
$$\gamma > 0$$

Time for a little more math

HOWEVER, we are not free to choose ϕ
Must satisfy Maxwell's Equations

$$\Delta\phi = \nabla \cdot \nabla\phi = 0$$

Gauss's Law in free space

Checking to see if it satisfies Gauss's Law:

$$\nabla \cdot \nabla\phi(x,y,z) = \frac{\phi_0}{r_0^2}(\alpha + \beta + \gamma)$$
$$= 0$$

$$\alpha + \beta + \gamma = 0$$

Does not work with previous condition:

$$\alpha > 0$$
$$\beta > 0$$
$$\gamma > 0$$

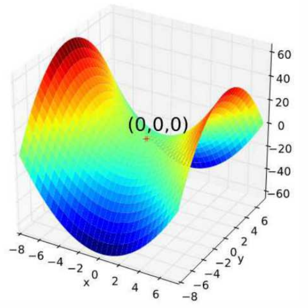
Mathematical way of saying cannot create a trapping potential with electric fields alone

Best we can do is create a saddle potential:

$$\phi(x,y,z) = \frac{\phi_0}{2r_0^2}\left(\alpha x^2 + \beta y^2 + \gamma z^2\right)$$

Common to use the quadrupole solution:

$$\alpha = 1$$
$$\beta = -1$$
$$\gamma = 0$$



Also, sometimes a saddle solution is used:

$$\alpha = 1$$
$$\beta = 1$$
$$\gamma = -2$$

Trapping in a time varying electric field

Want to find a set of stability parameters: How fast does potential "flap"?
How strong is the "flapping"?

Quadrupole: $\alpha = 1$, $\beta = -1$, $\gamma = 0$

$$\phi(x,y,z) = \frac{\phi_0}{2r_0^2}\left(\alpha x^2 + \beta y^2 + \gamma z^2\right) \longrightarrow \Phi(x,y,t) = \frac{\Phi_0(t)}{r_0^2}\left(x^2 - y^2\right)$$

Where: $\Phi_0(t) = U_{\mathrm{DC}} + U_{\mathrm{RF}}\cos(\Omega t)$

$$\Phi(x,y,t) = \frac{U_{\mathrm{RF}}}{r_0^2}\cos(\Omega t)\left(x^2 - y^2\right)$$

Amplitude of DC component

Amplitude of RF (radio frequency) component

Oscillation frequency of RF component

Credit: Wes Campbell, UCLA

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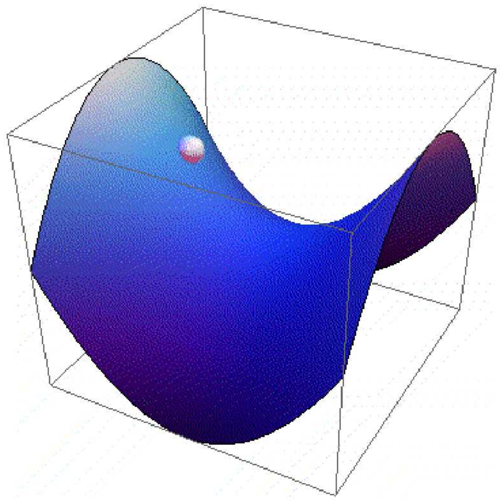
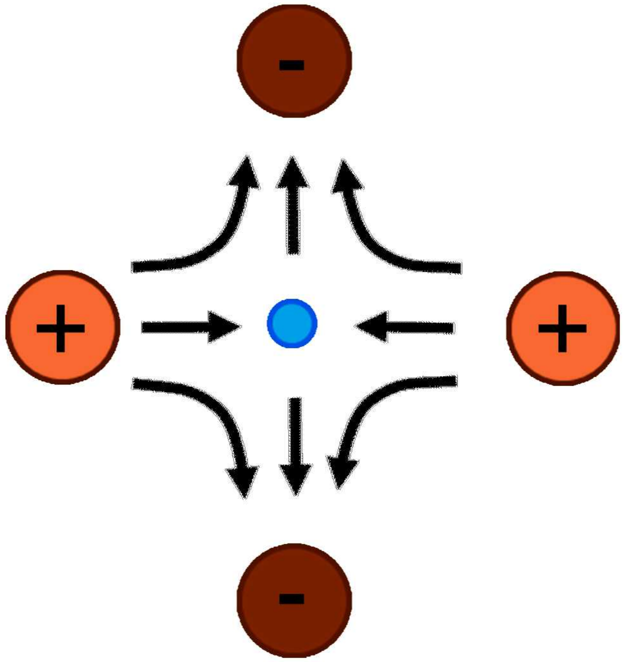


Credit: Wes Campbell, UCLA

Time for a video

Getting a quadrupole potential



$$\phi(x,y,z) = \frac{\phi_0}{2r_0^2}\left(\alpha x^2 + \beta y^2 + \gamma z^2\right)$$

$$\alpha = 1$$
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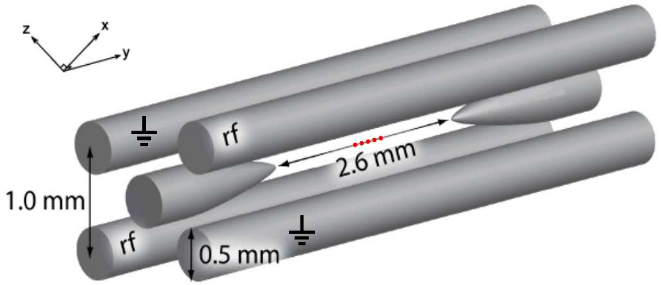
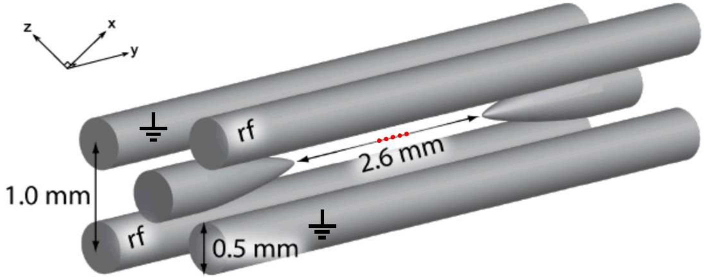


We can think of the quadrupole potential as trapping in one directions and anti-trapping in the other

Two electrodes are held at ground and an RF oscillating voltage is applied to the other two. The remaining axis has a trapping potential due to DC voltages

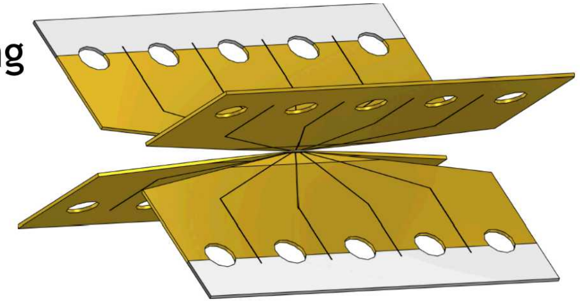
RF Paul Traps

r.f. Paul Trap

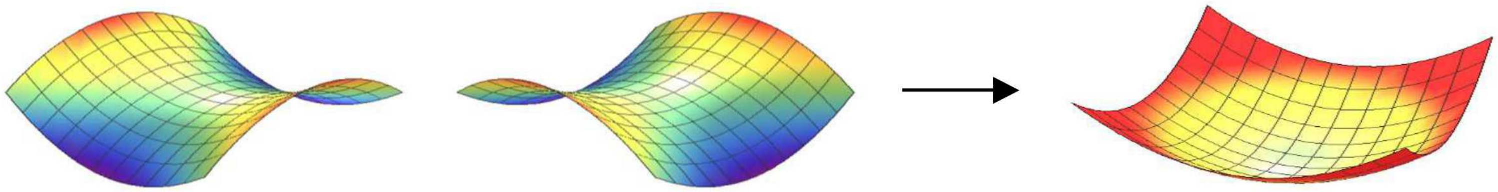


Segmented Paul Trap

- Better control over confining potential
- Difficult to construct
- Doesn't scale well

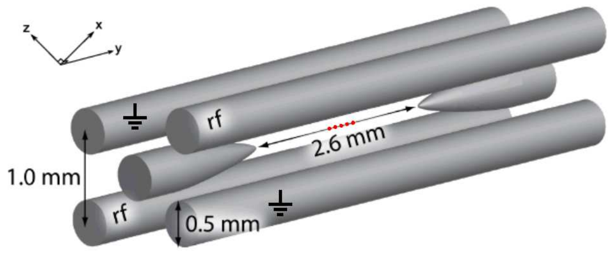


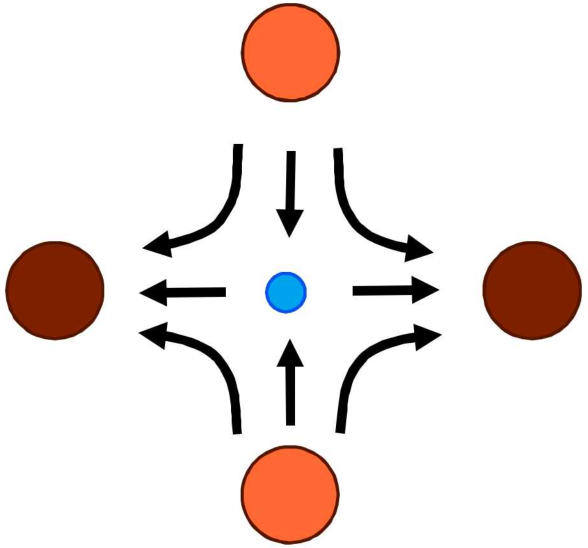
RF pseudopotential



- Time-averaged potential is close to harmonic at the saddle point
- Off the saddle point, ions experience micromotion
- Works well for linear chains of ions
- Doesn't support fine control of ion position or confining potential

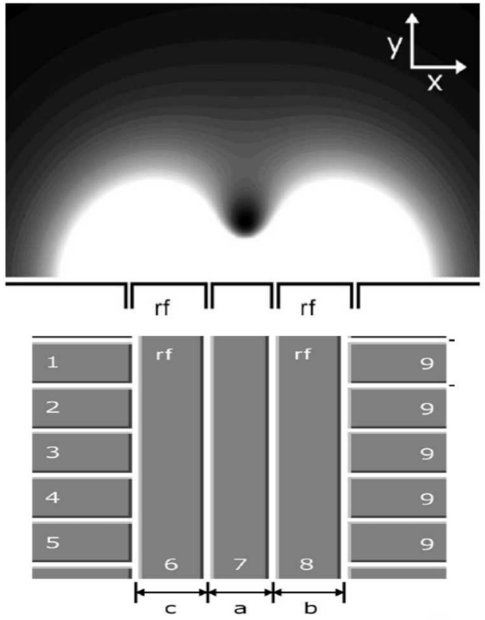
RF Paul Trap on a surface





Microfabricated Surface Trap

- Consistent, well-defined electrode layout
- Microfabrication supports a lot of exotic electrode geometries
- Excellent control over potential
- Very scalable



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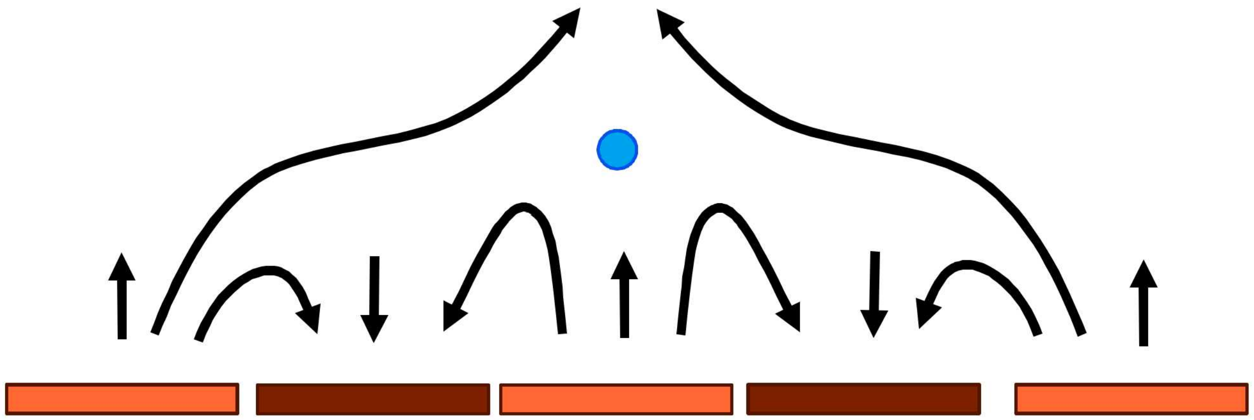
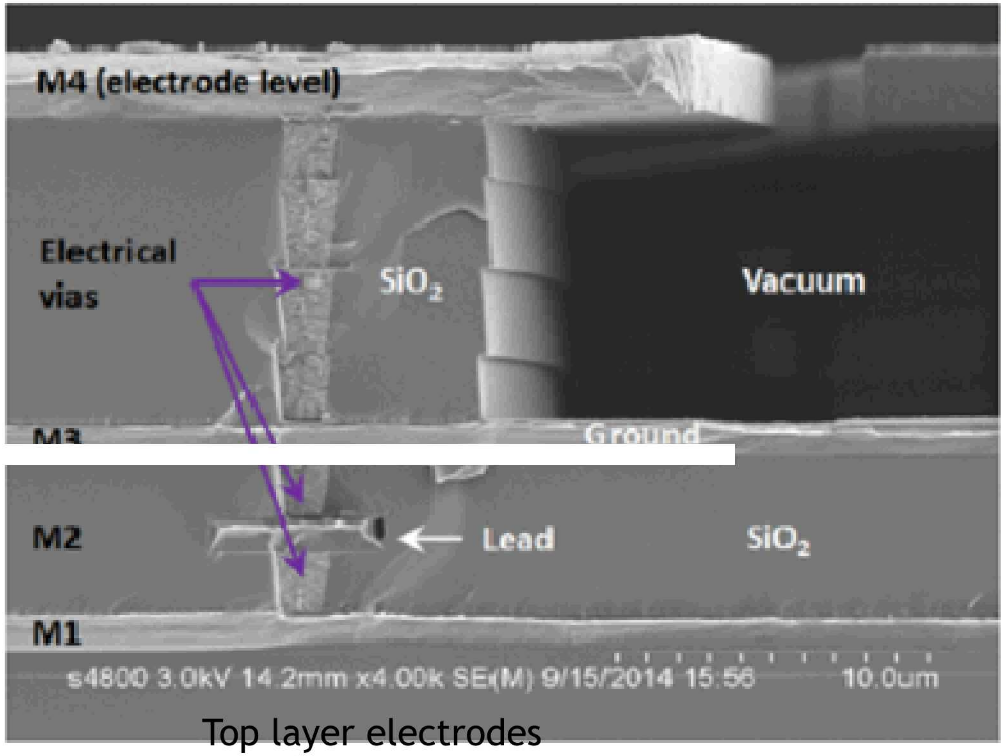
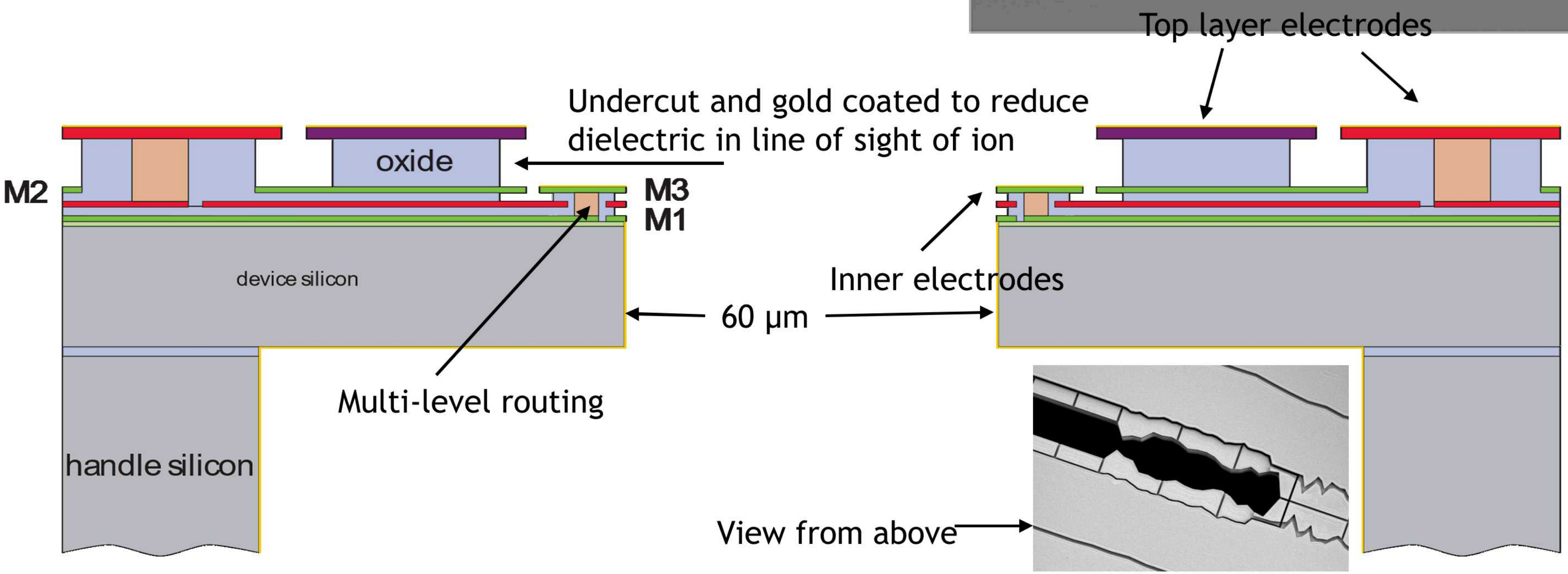


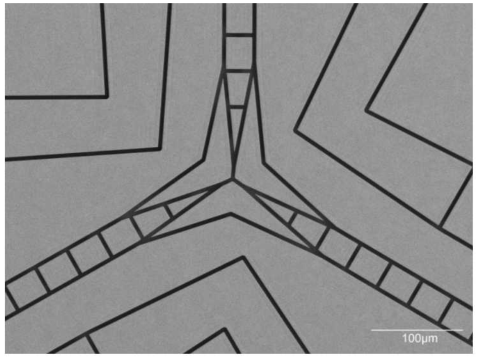
Trap microfabrication

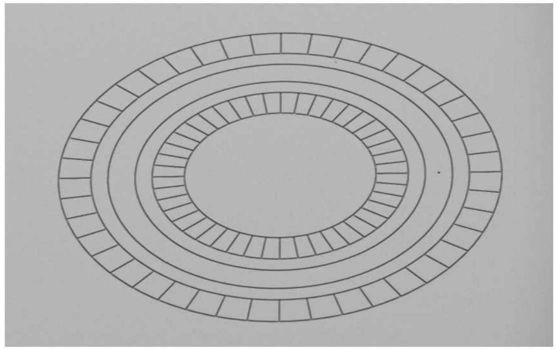
- Standardization of devices with lithography
- Multiple until production
- Isolated electrodes with multi-level routing
- Small, reliable features for ion control

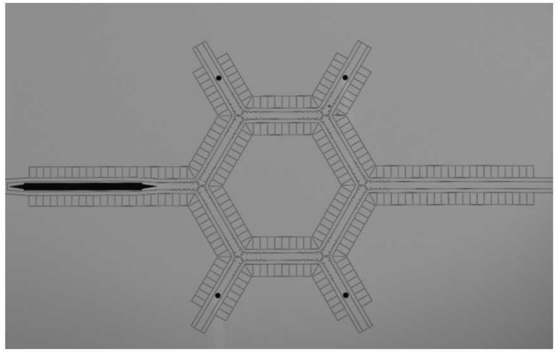


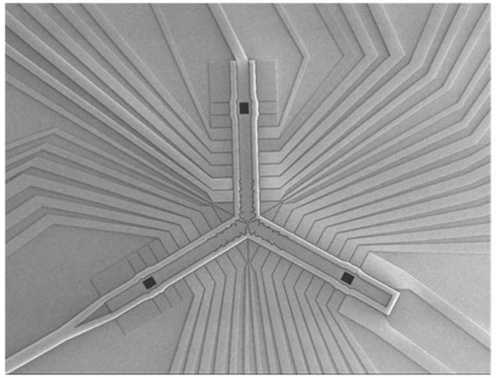


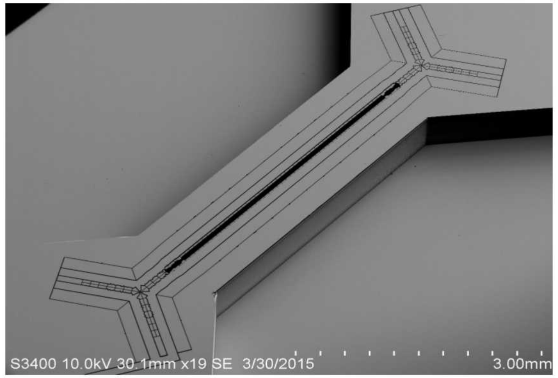
Microfabrication allows for variety of trap geometries

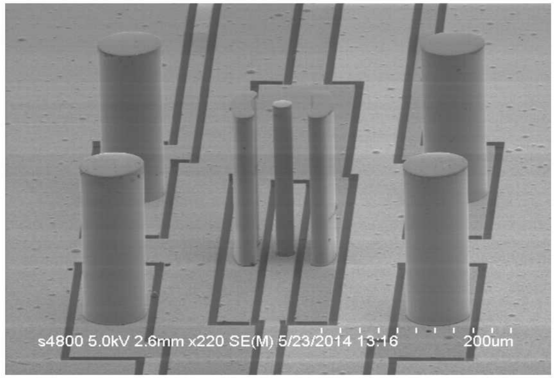












Sandia traps in operation

Duke University

University of Maryland

universität innsbruck

Albert-Ludwigs-Universität Freiburg

UNI FREIBURG

Albert-Ludwigs-Universität Freiburg

ETH zürich

IONQ

NIST National Institute of Standards and Technology U.S. Department of Commerce

Georgia Tech

MIT Massachusetts Institute of Technology

JG|U Johannes Gutenberg Universität Mainz

MIT Lincoln Laboratory

University of Oxford

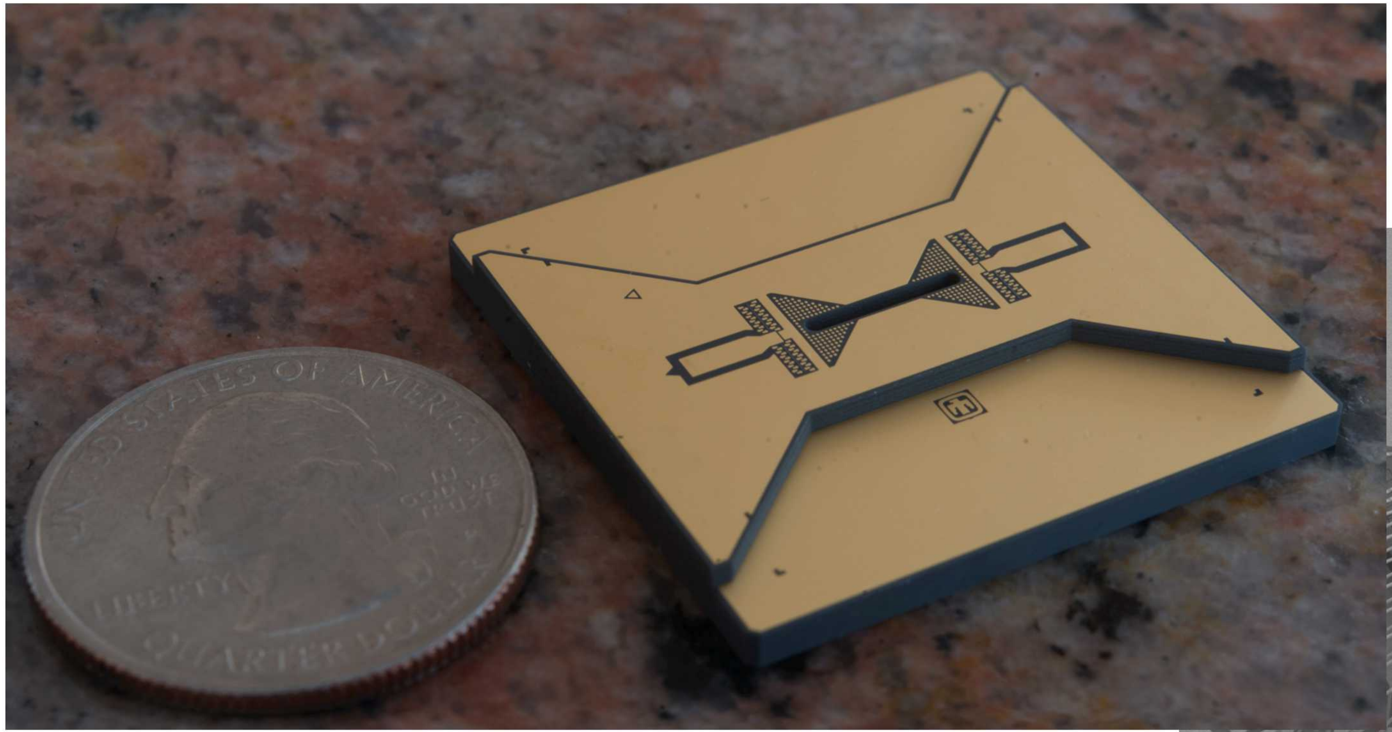
ARL

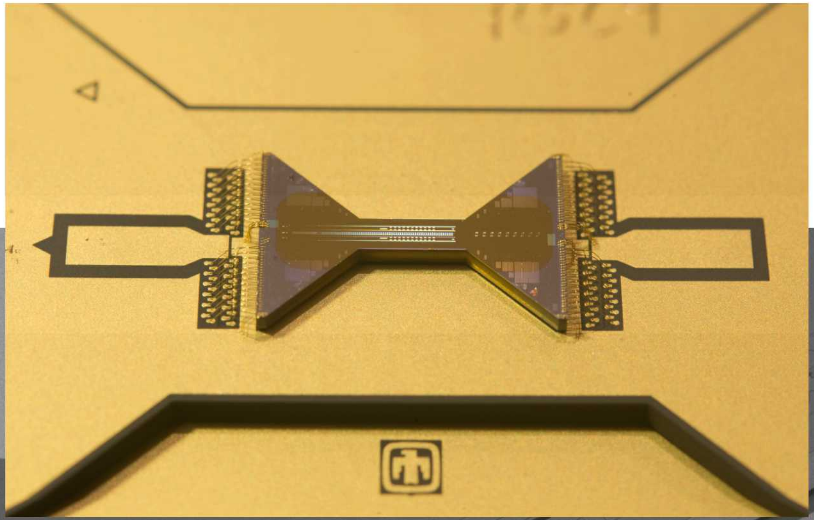
Sandia National Laboratories

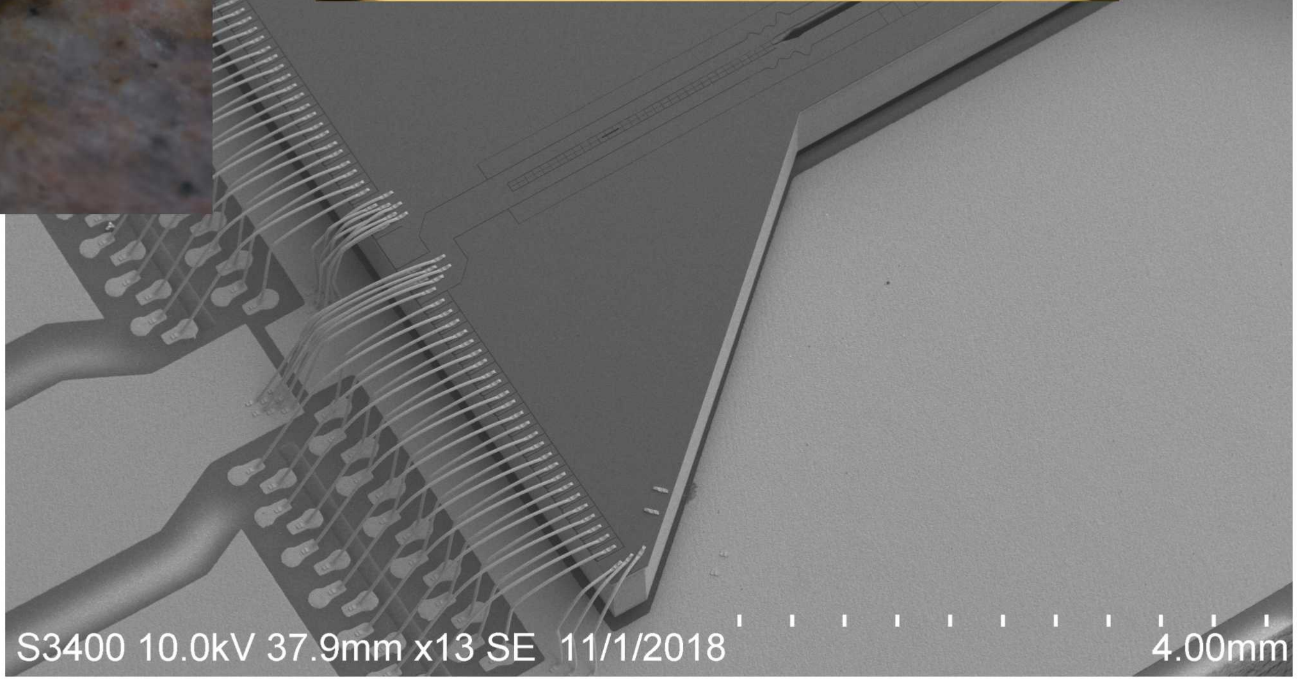
W University of Washington

AFRL

After fabrication a trap is then packaged

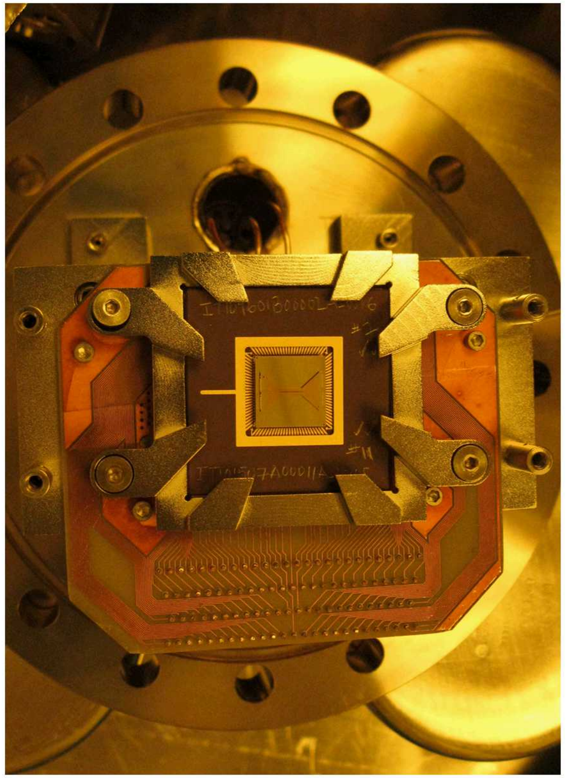


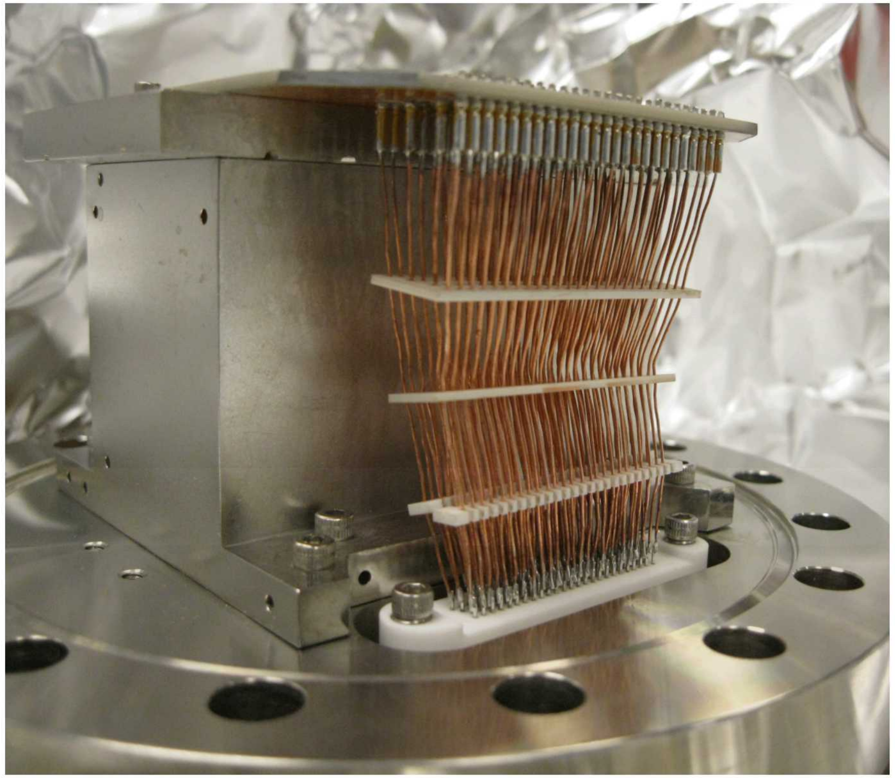


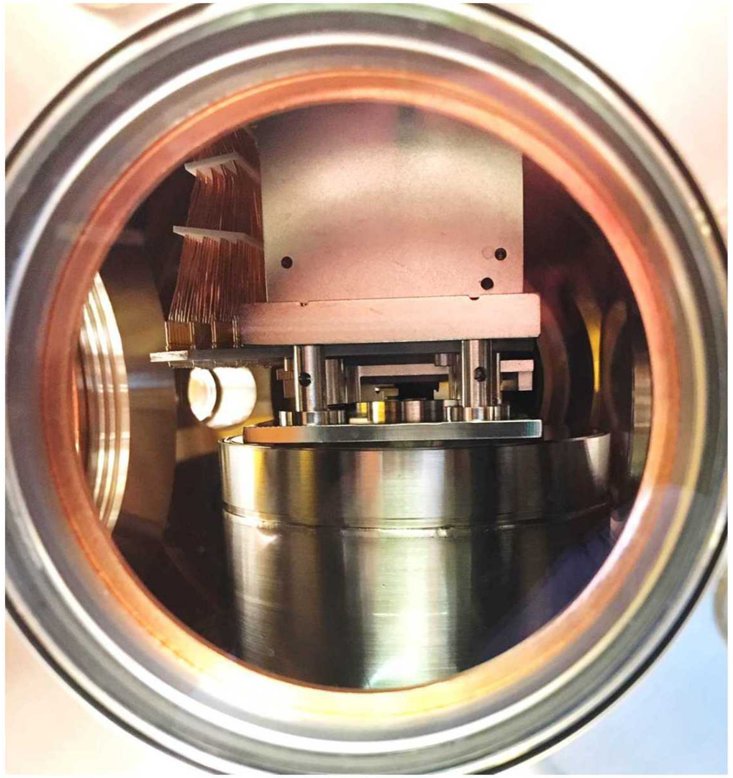


Typical trap can have >100 electrodes to
Secure and reproduceable installation
Electrical and optical access
Maintain robustness of the fabrication process

Vacuum chamber installation





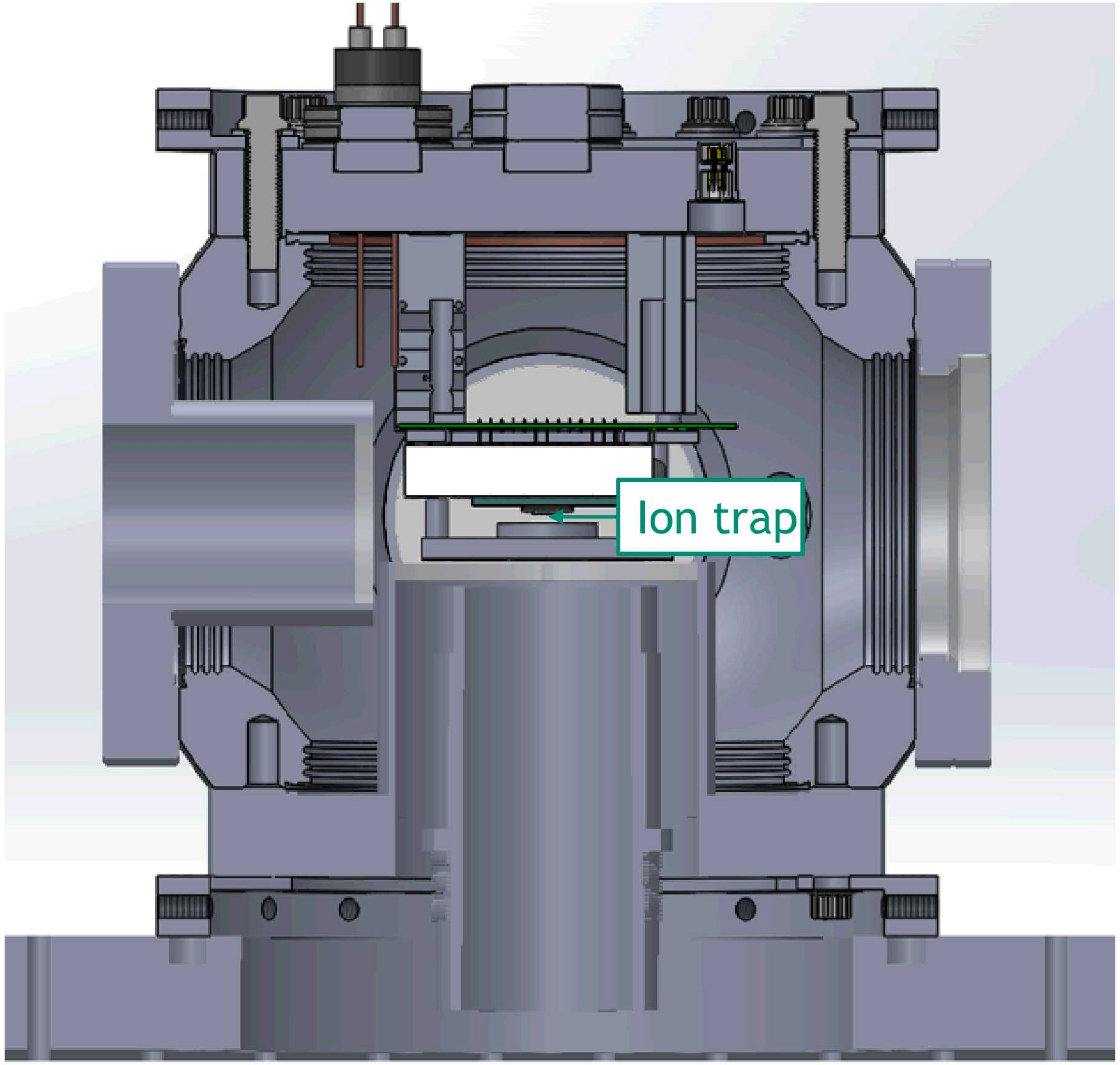


Trapping must be done in an ultra-high vacuum environment (1 x 10^{-11} torr)

Stray molecules will change the ions electronic state or knock it out of the trap

Electrical and optical access remain important for control and detection of the ion

Full vacuum assembly



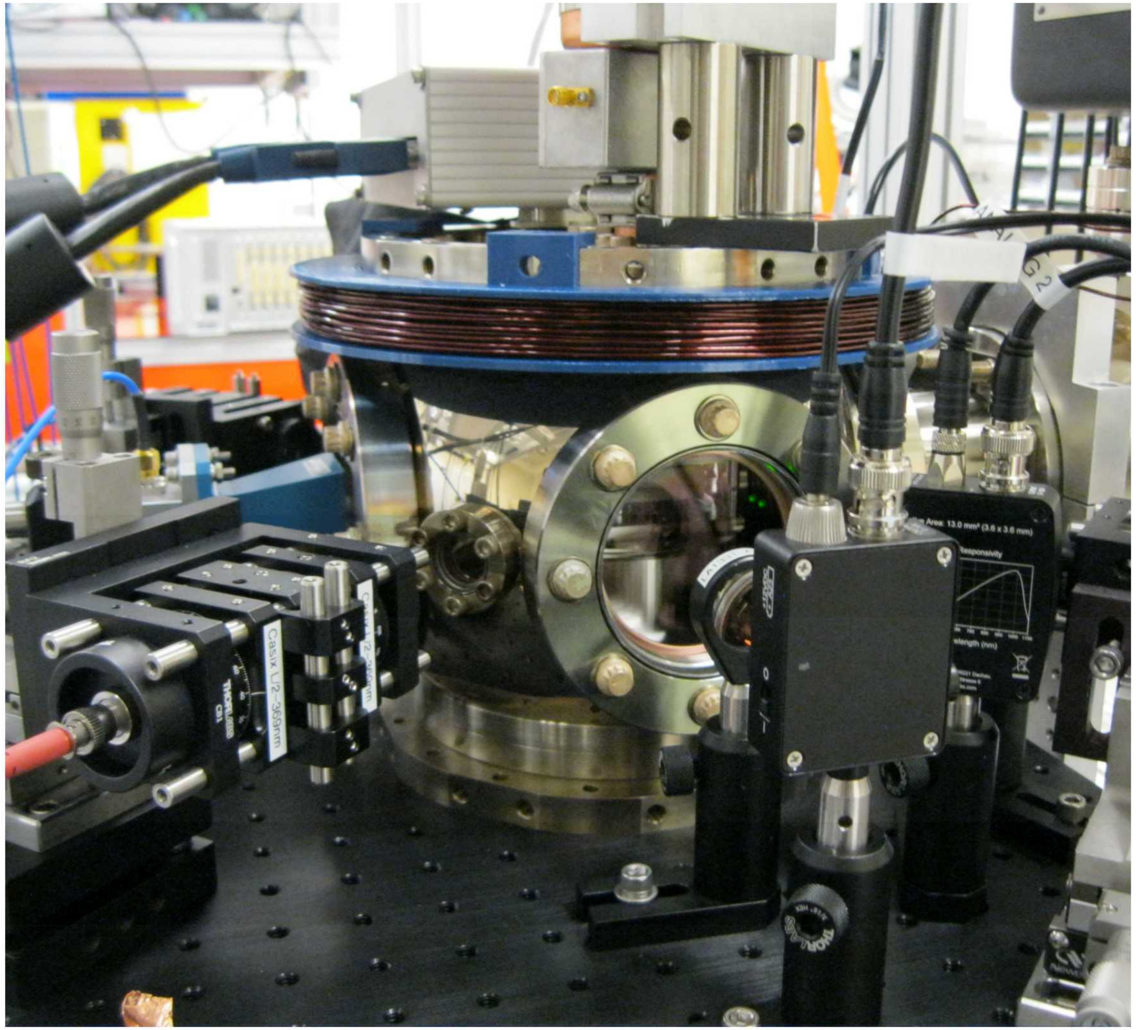
- Current designs focus on maintaining our optical access
- Design work is important so that distances are correct during the installation (window to metal spacing <10mm
- Not shown are multiple pumps and a gauge for maintain ultra high vacuum

Installing a ion trapping experiment

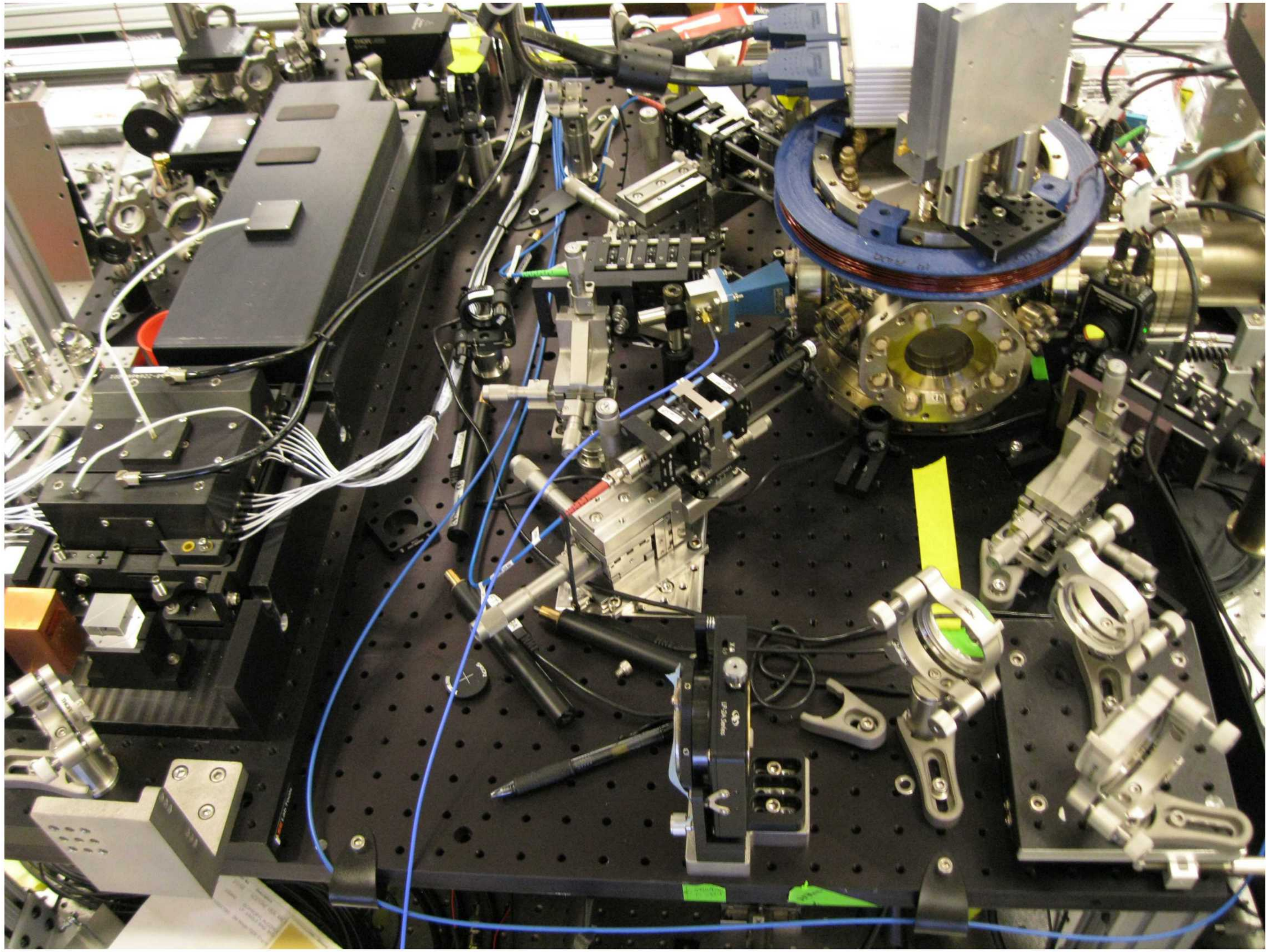
An experimental setup requires:

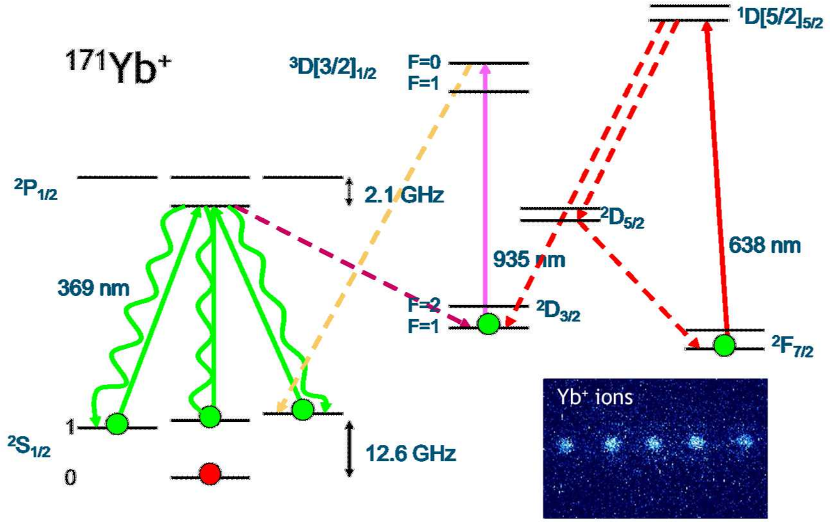
- Alignment of 4-7 different lasers
- >100 DC voltage controls
- High voltage RF
- Magnetic field control
- Feedback for power stability
- Microwave delivery
- Fluorescence detection

Controls allow for not only trapping but for setting the ion position and electronic state

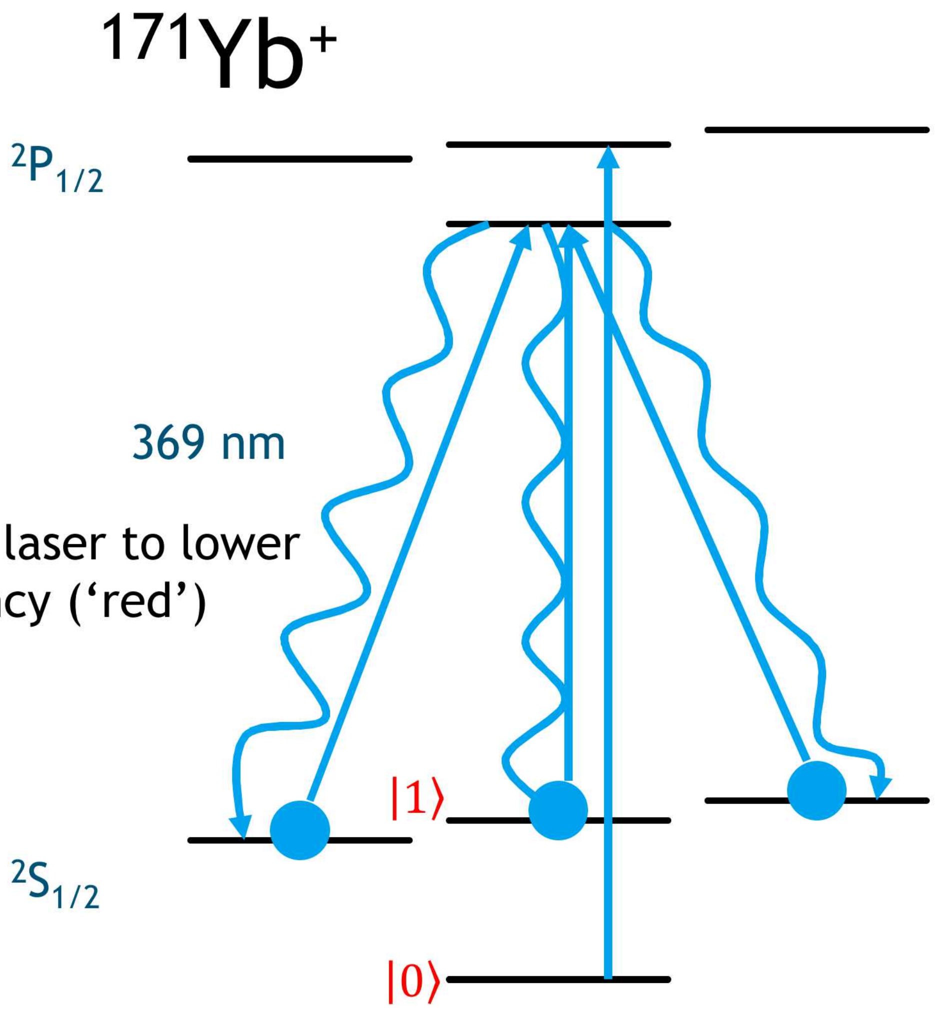


Overall system

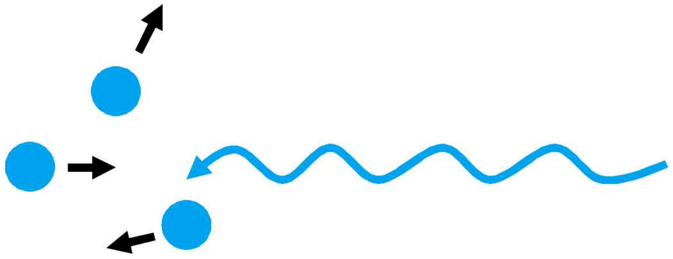




Doppler cooling

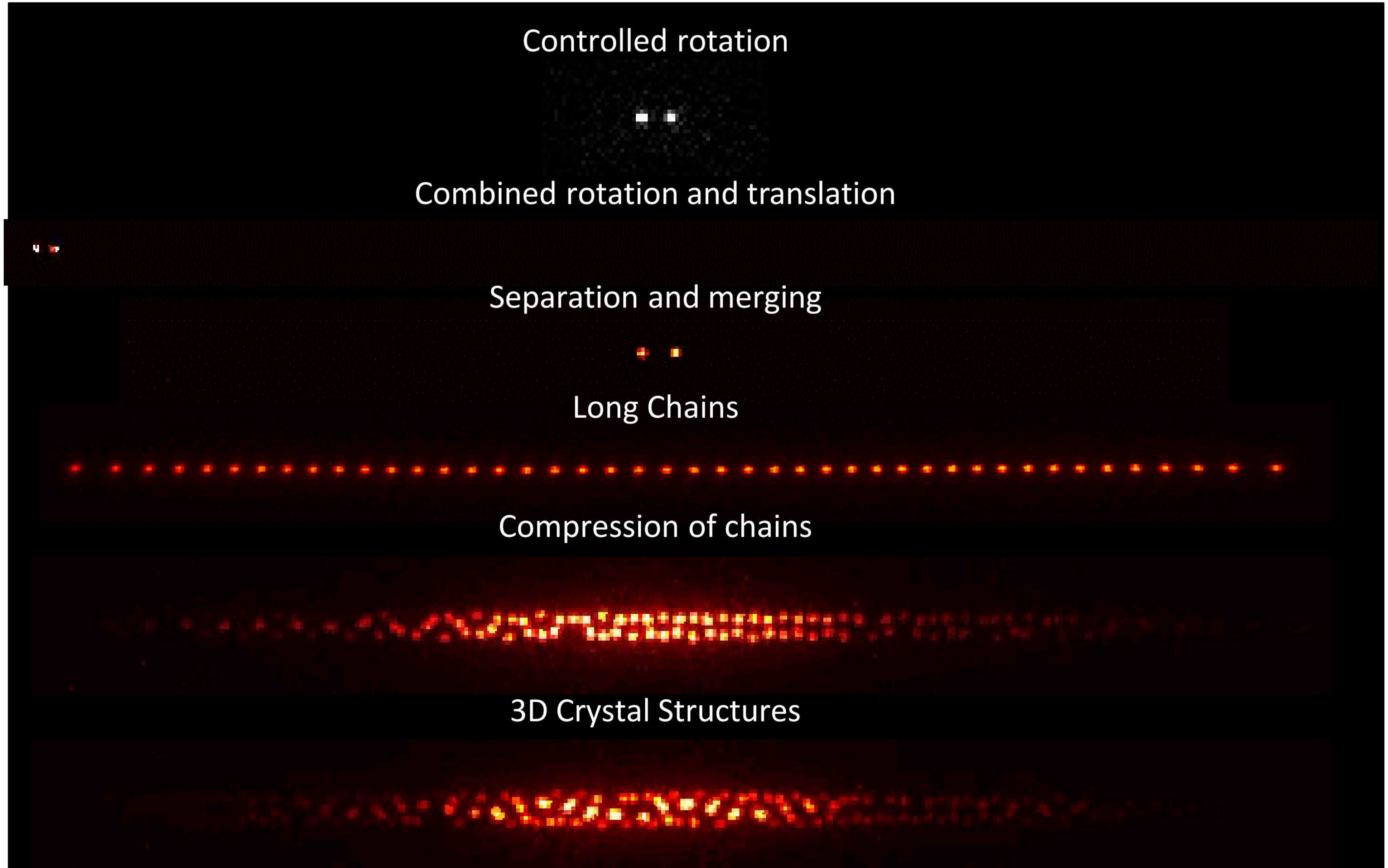


Detune laser to lower frequency ('red')

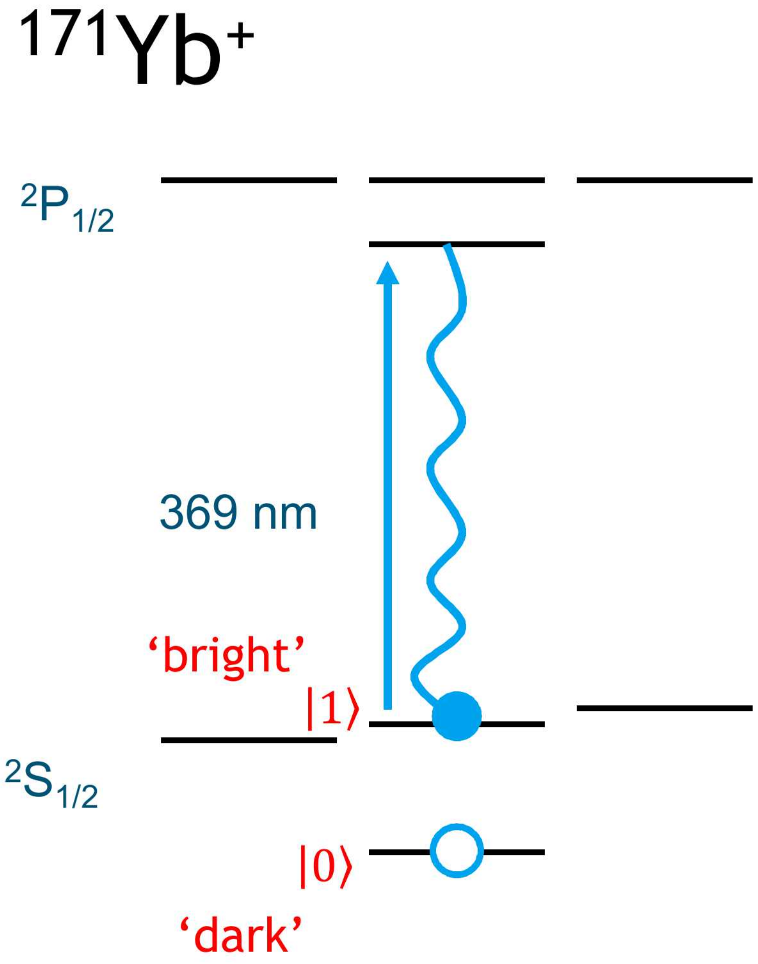


An ion moving in the direction of the of the oncoming light will 'see' the Doppler shifted light on resonance and absorb a photon.
A photon is emitted in a random direction. This is repeated many time. Other lasers are necessary to not lose an ion to a different electronic state.

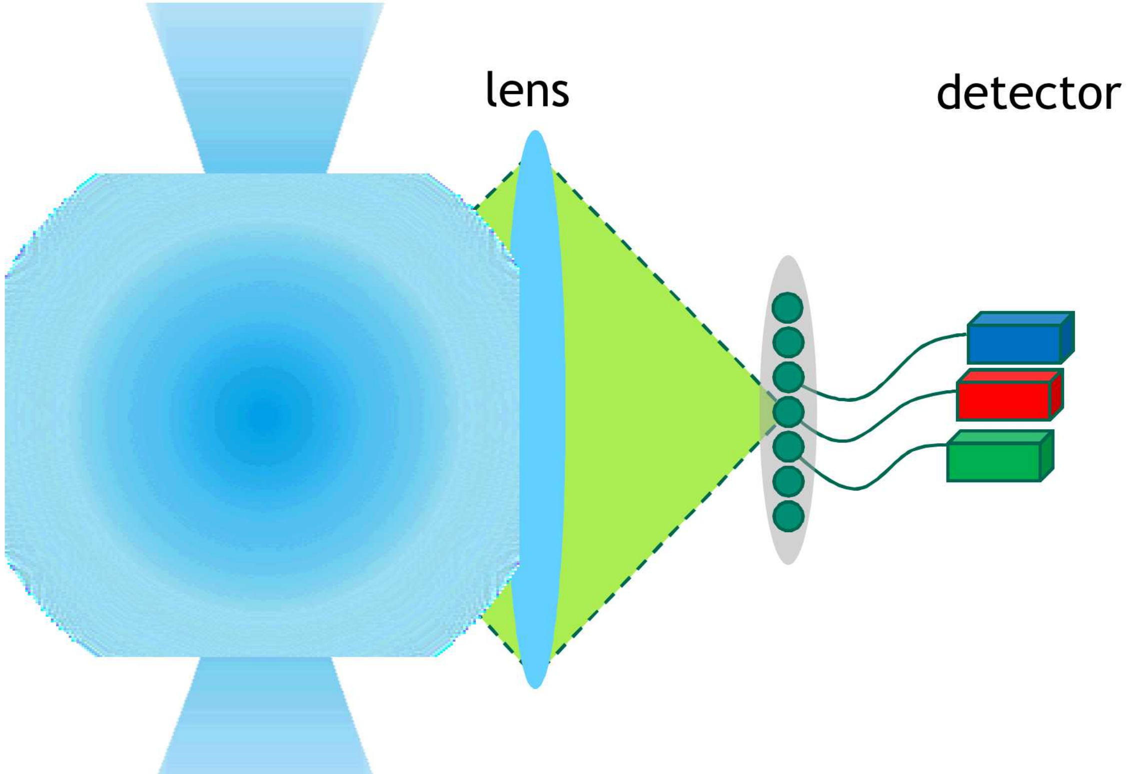
Can trap multiple ions and much more



State Detection



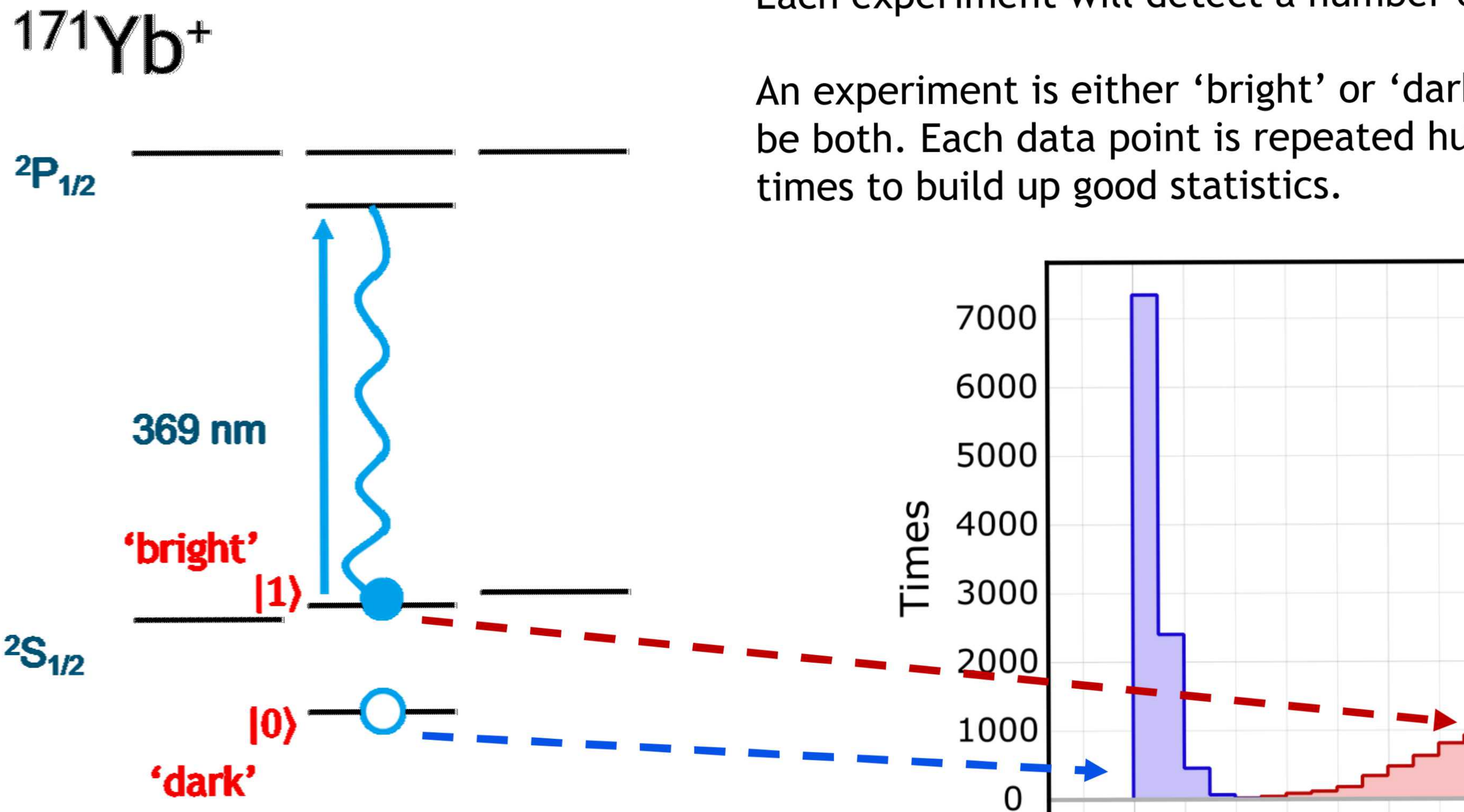
Same laser that Doppler cools is set to resonance such that one electronic state is bright and one is dark. Detector will report the number of photons collected

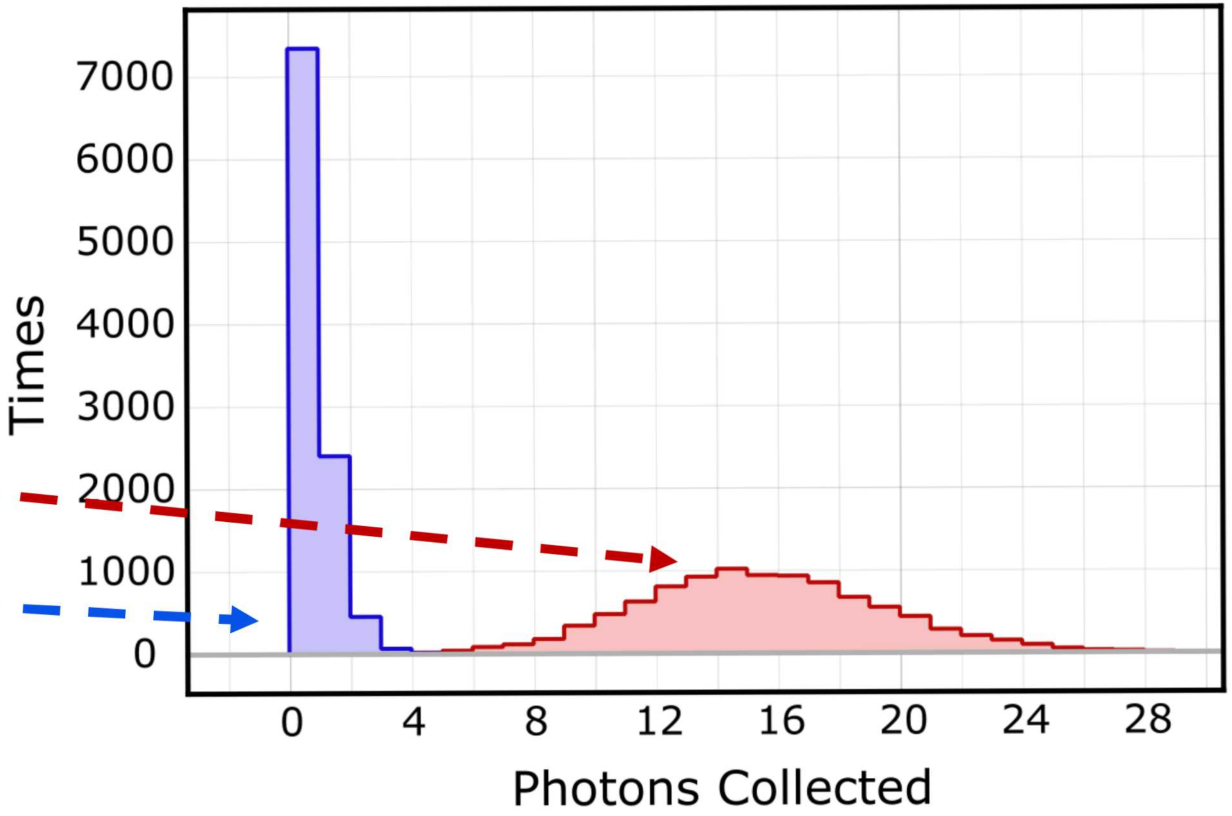


State Detection

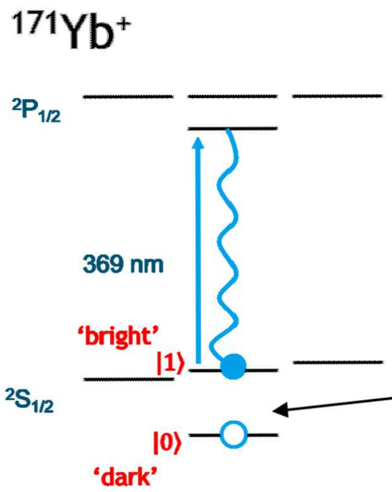
Each experiment will detect a number of photons.

An experiment is either 'bright' or 'dark'. It cannot be both. Each data point is repeated hundreds of times to build up good statistics.



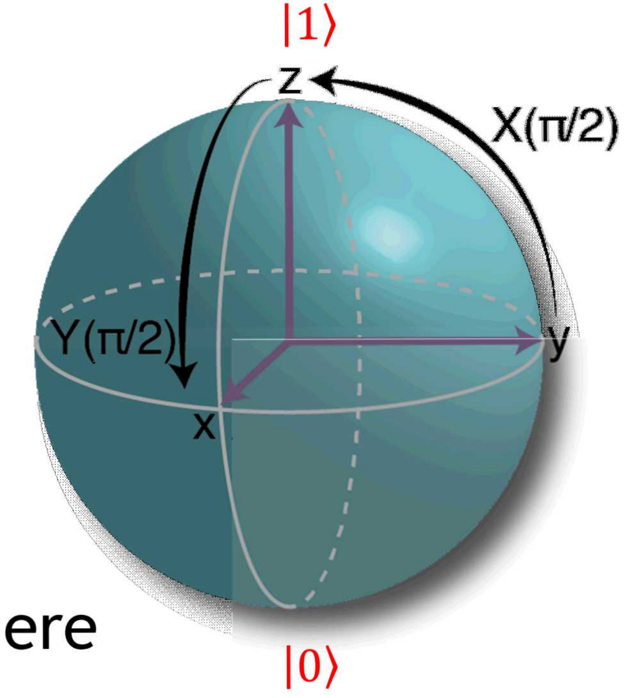


State operations on a single ion (Rabi Oscillations)

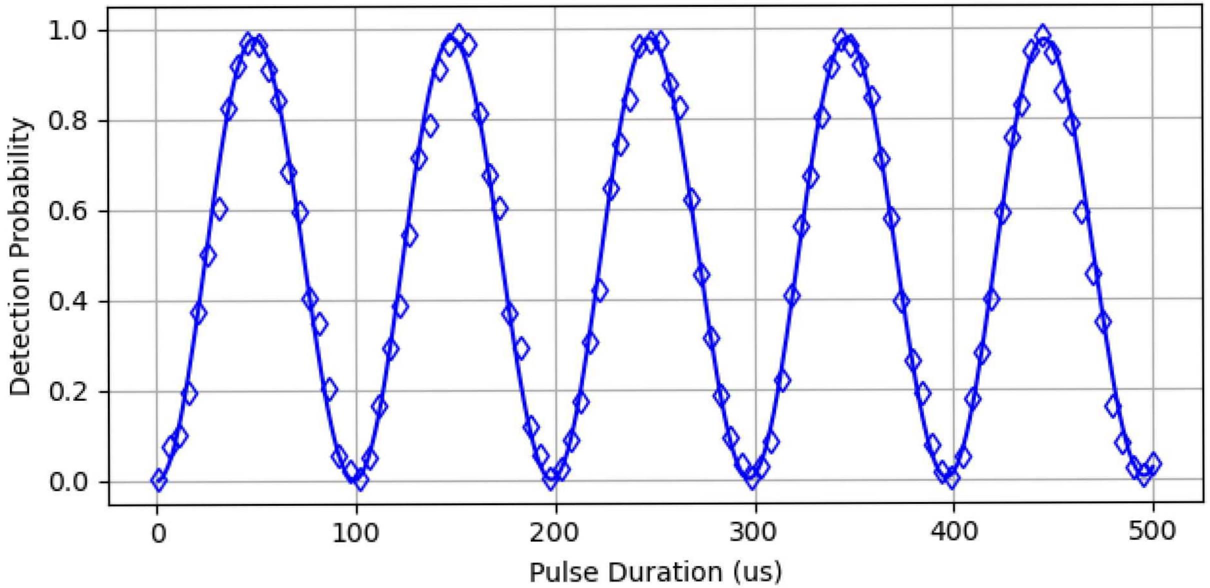


Qubit transition

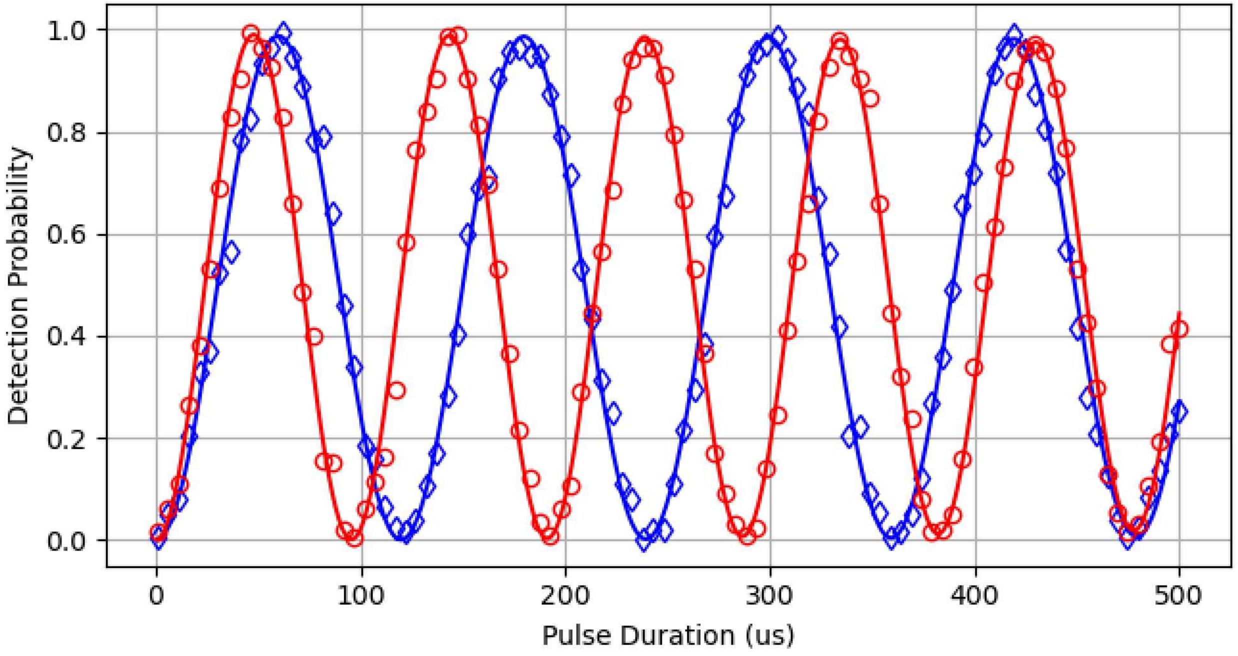
Apply a pulse transferring the population from bright to dark.

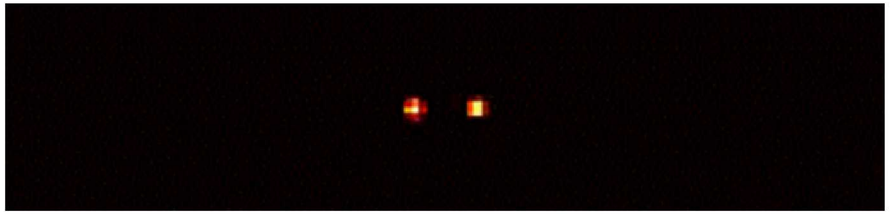


Bloch sphere



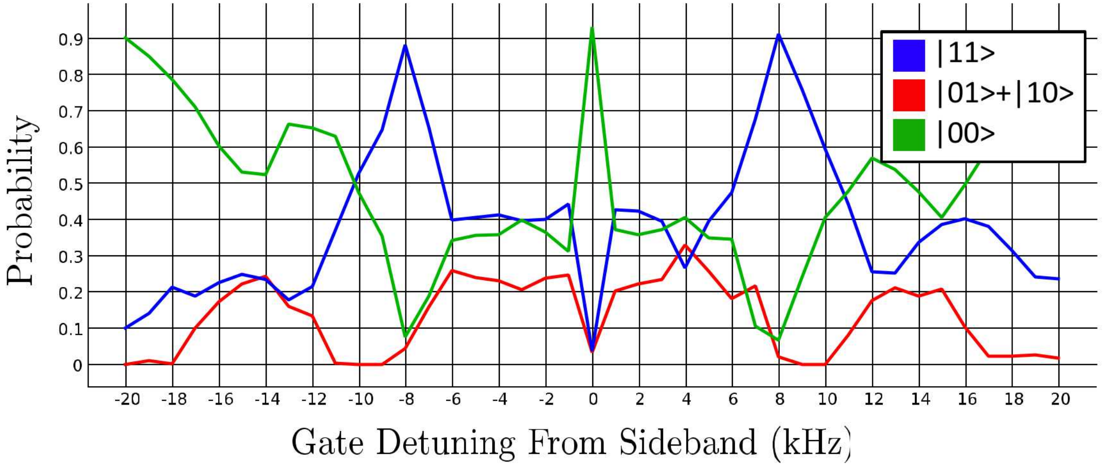
Able to control single qubit rotations on multiple ions

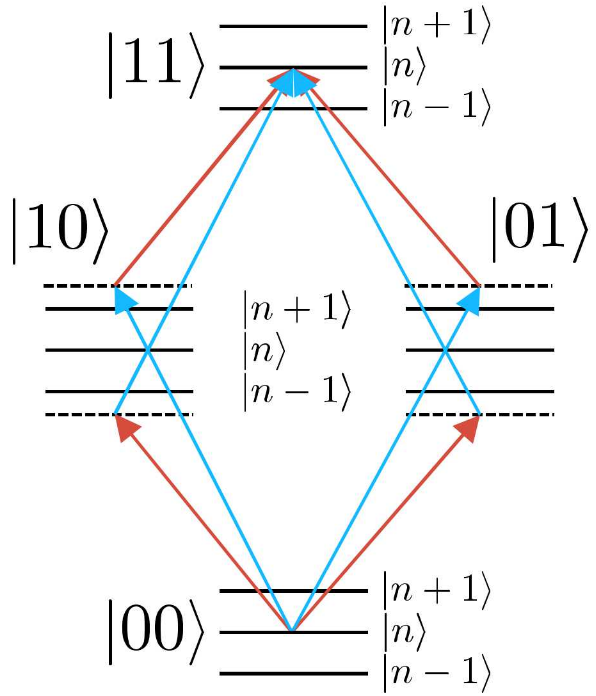




The same control over a single ion can be extended to multiple ions.
Depending on the time of the pulse applied are able to prepare particular states but this is not enough to fully control a multi-qubit space

Two-qubit gate a bit more complicated



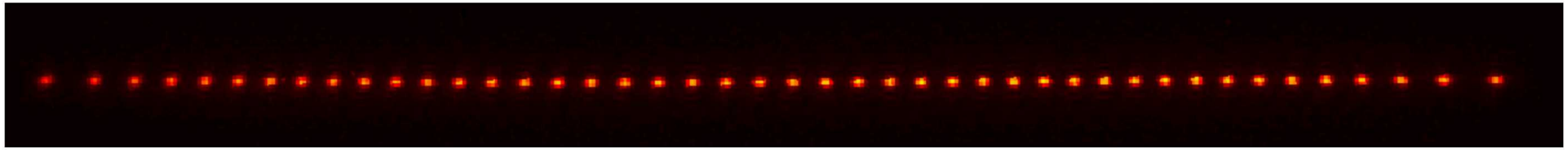


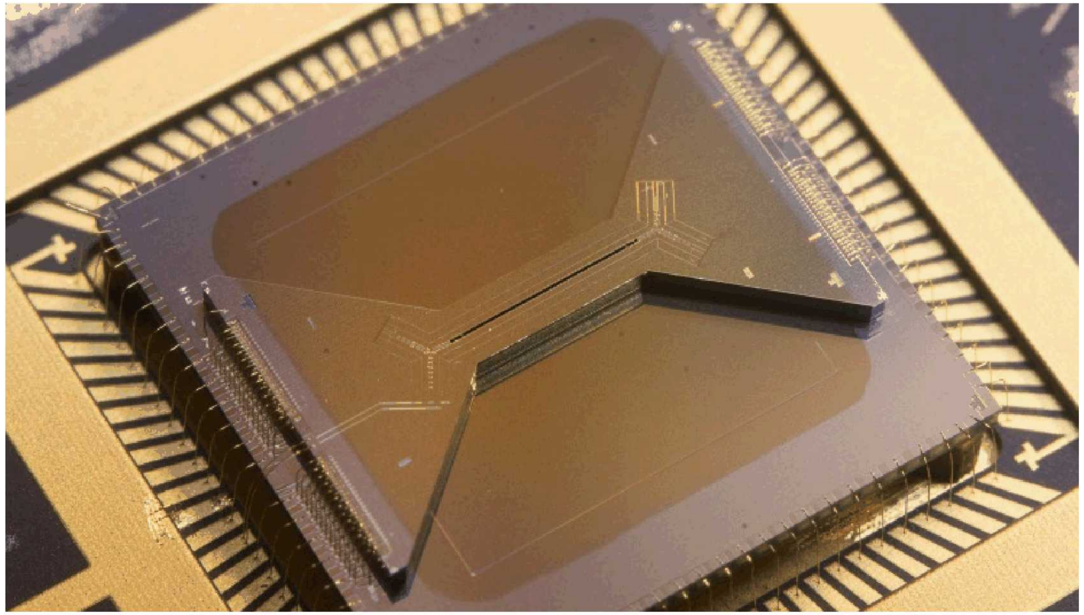
Two qubit gates that couple two ions together use the motional modes of the ions and can leave them in an entangled state.

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

This can done even for pairs of ions that are not neighbors.

Scaling up to many operations requires high fidelities



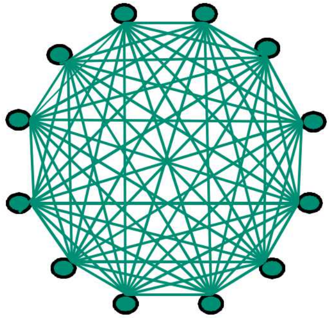


1Q gate fidelity	**99.993% (Sandia, ytterbium, microwave gates)**
2Q gate fidelity	99.5% (Sandia, ytterbium, 355nm Raman lasers)

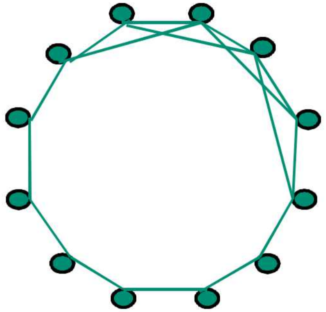
Compared to the fidelity of a classical computer, still have a ways to go.

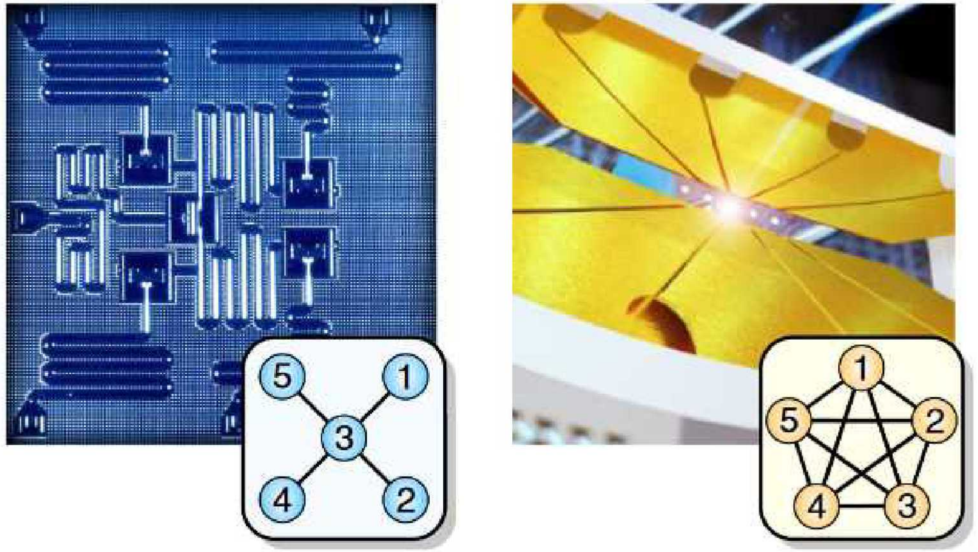
Number of qubits not everything

Trapped Ions:
fully connected



Solid State:
 2D nearest neighbor
coupling



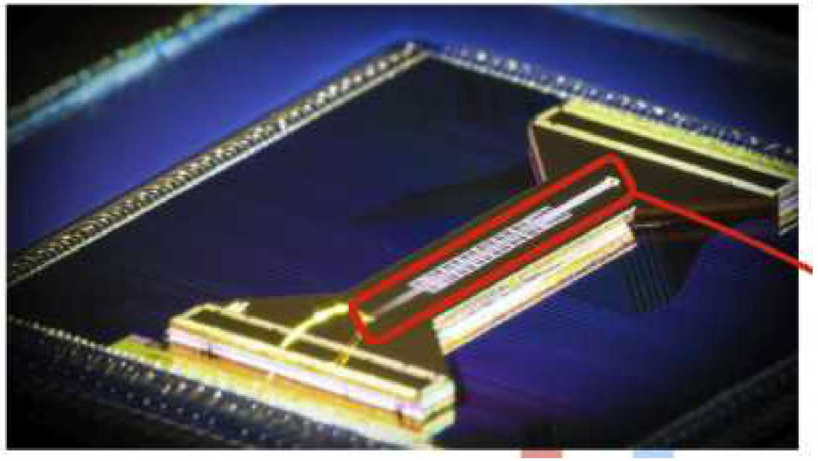


Linke et al., PNAS March 28, 2017 114 (13)

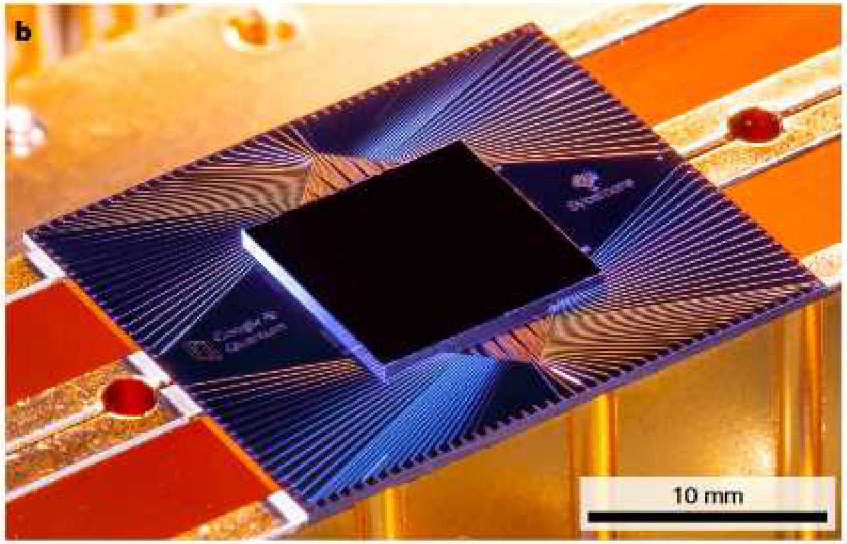
Currently this is a main advantage of trapped ions over superconducting qubits. Superconducting qubits are layout limited but are currently scaled to have more qubits.

Somewhat current state of affairs

Honeywell and Google have both claimed major achievements in regards to quantum volume and quantum supremacy. IBM has been offering cloud access to its quantum devices for years. IonQ has performed state of the art quantum simulations. And there are many others. Quantum information devices are here and available. Current systems are pushing their limitations (number of qubits, connectivity, fidelities…). It is truly an exciting time for this field.

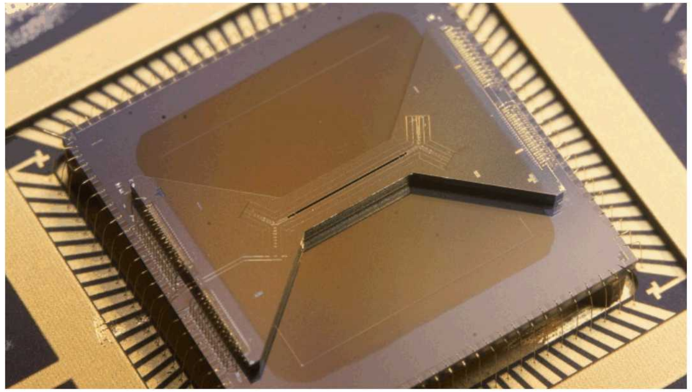


Pino, J.M. et al., arXiv:2003.01293



Arute, F. et al., *Nature* **574,** 505–510 (2019)

Sandia's role as a Federally Funded Research and Development Center



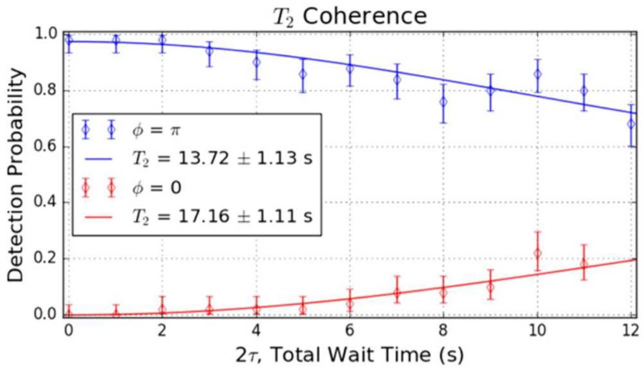
arXiv:2003.01293

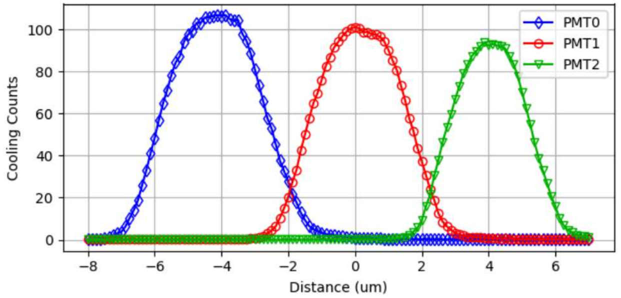
Sandia's traps have an established history with ion trapping groups across the world

Its role allow for collaboration with both academic and industrial partnerships

Performs cutting edge research (not just with ion trapping) and allows for internal collaboration

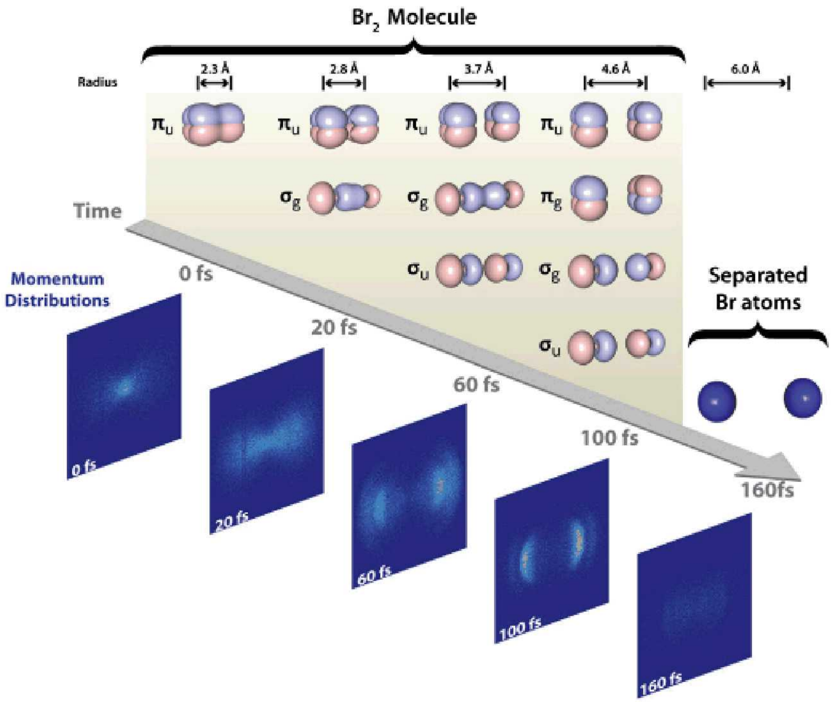
Recruits top scientists and engineers





How I got here

- Ion trapping taught me it is ok to run lasers CW
  - Day to day is similar to an academic lab
- Thesis work was in time domain spectroscopy with ultrafast high harmonic generation
  - Using the some of the shortest pulses available, studying the time evolution of atomic and molecular dynamics
  - Closely related to my Comps (not planned)
- Research Experience for Undergraduates in plasma physics



Li et al., PNAS 107, (47) 20219 (2012)

The greatest skill one can learn is the skill to learn

Prof. Kris Wedding, contemporary physics lab:

1. Is it plugged in?
2. Is it turned on?

Thank you

RF Engineering
Christopher Nordquist
Stefan Lepkowski

Mech. Engineering
Jessica Pehr

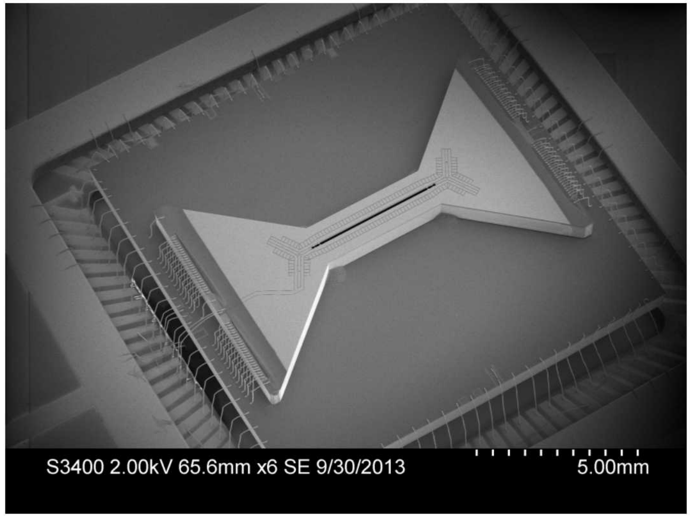
Trap design and fabrication
Matthew Blain
Jason Dominguez
Ed Heller
Corrie Herrmann
Becky Loviza
John Rembetski
SiFab team

Trap packaging
Ray Haltli
Anathea Ortega
Tipp Jennings
Andrew Hollowell

Theory
Jaimie Stephens
Kevin Young
Robin Blume-Kohout

Trap design and testing
Peter Maunz
Susan Clark
Craig Hogle
Daniel Lobser
Melissa Revelle
Dan Stick
Christopher Yale

Questions?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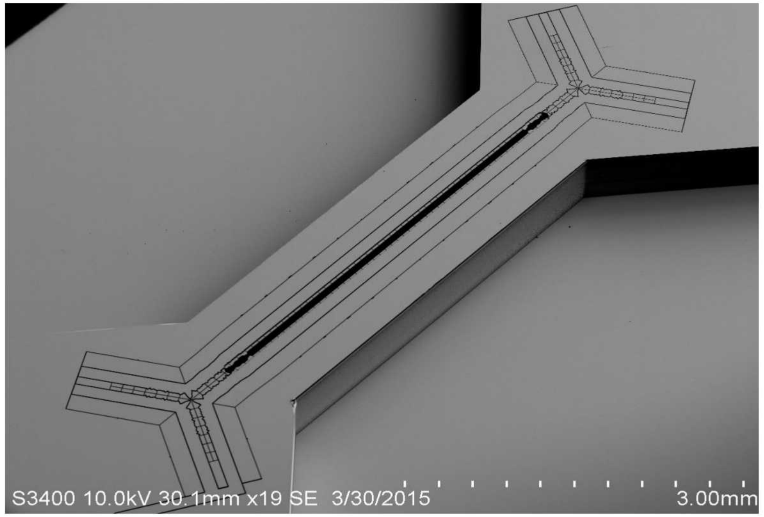
5.00mm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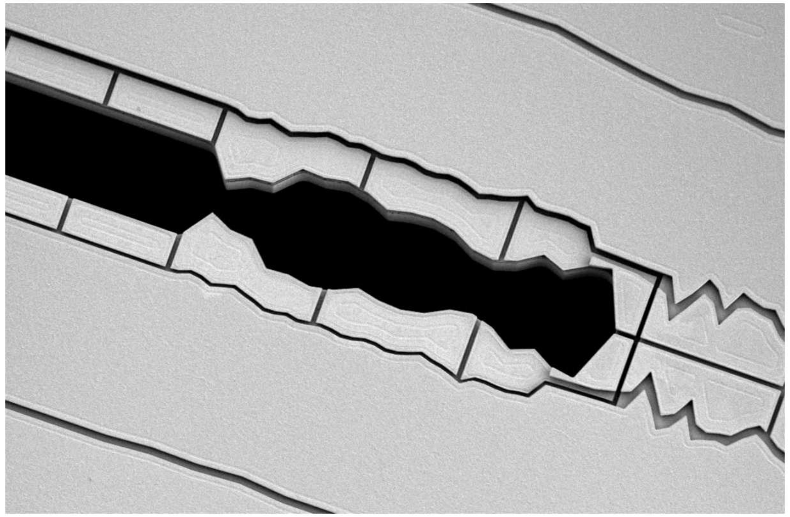
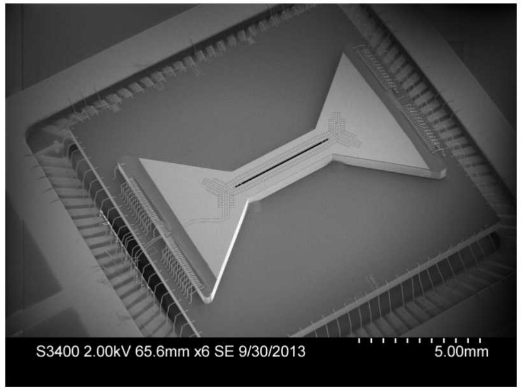
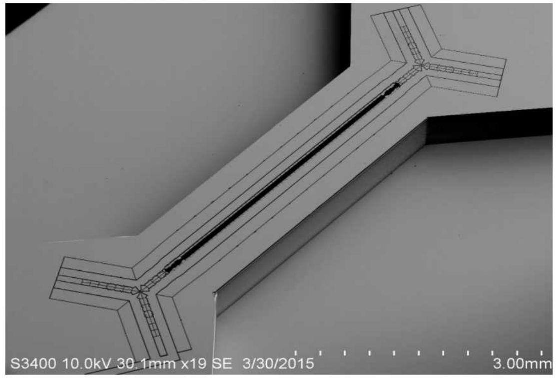
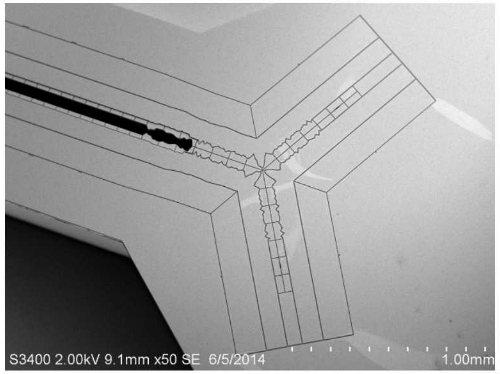
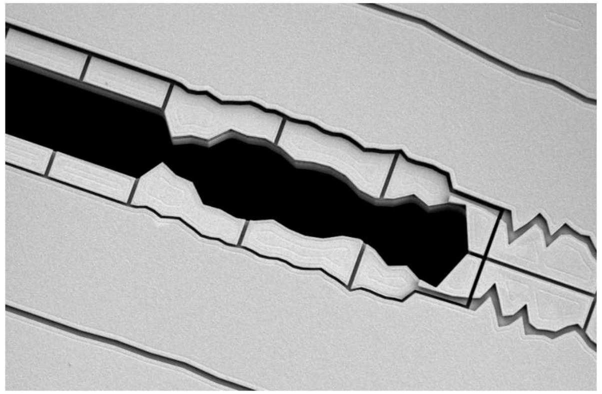


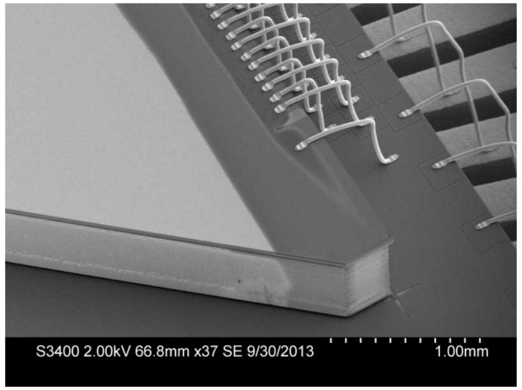
High Optical Access (HOA)

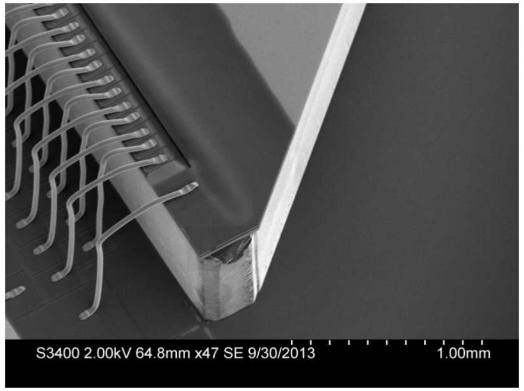












Trapping in a time varying electric field

$$\phi(x,y,t) = \frac{U_{\mathrm{RF}}}{r_0}\cos(\Omega t)\left(x^2 - y^2\right)$$

Use Newtons $\mathbf{F} = m\mathbf{a}$

And Maxwell's equation $\mathbf{F} \propto \mathbf{E} = -\nabla\phi(x,y,t)$

Leads to a pair of differential equations in x-y plane:

$$m\frac{d^2}{dt^2}x = -\frac{2eU_{\mathrm{RF}}}{r_0}\cos(\Omega t)x$$

$$m\frac{d^2}{dt^2}y = -\frac{2eU_{\mathrm{RF}}}{r_0}\cos(\Omega t)y$$

Which we rewrite with the introduction of unitless coefficients: ξ and q

$$\frac{d^2}{d\xi^2}x + 2qcos(2\xi)x = 0 \qquad \xi = \frac{\Omega t}{2}$$

$$\frac{d^2}{d\xi^2}y + 2qcos(2\xi)y = 0 \qquad q = \frac{4eU_{\mathrm{RF}}}{mr_0^2\Omega^2}$$

Largest stability region given by

$$|q| < 0.908\ldots$$

Ion motion is bounded (regardless of initial conditions)

Mathieu Equations

Even more Mathieu equations

$$x(t) = A(1 + \frac{q}{2}\cos(\Omega t))\cos(\frac{1}{2}\beta\Omega t)$$

$$\xi = \frac{\Omega t}{2}$$

$$q = \frac{4eU_{\mathrm{RF}}}{mr_0^2\Omega^2}$$

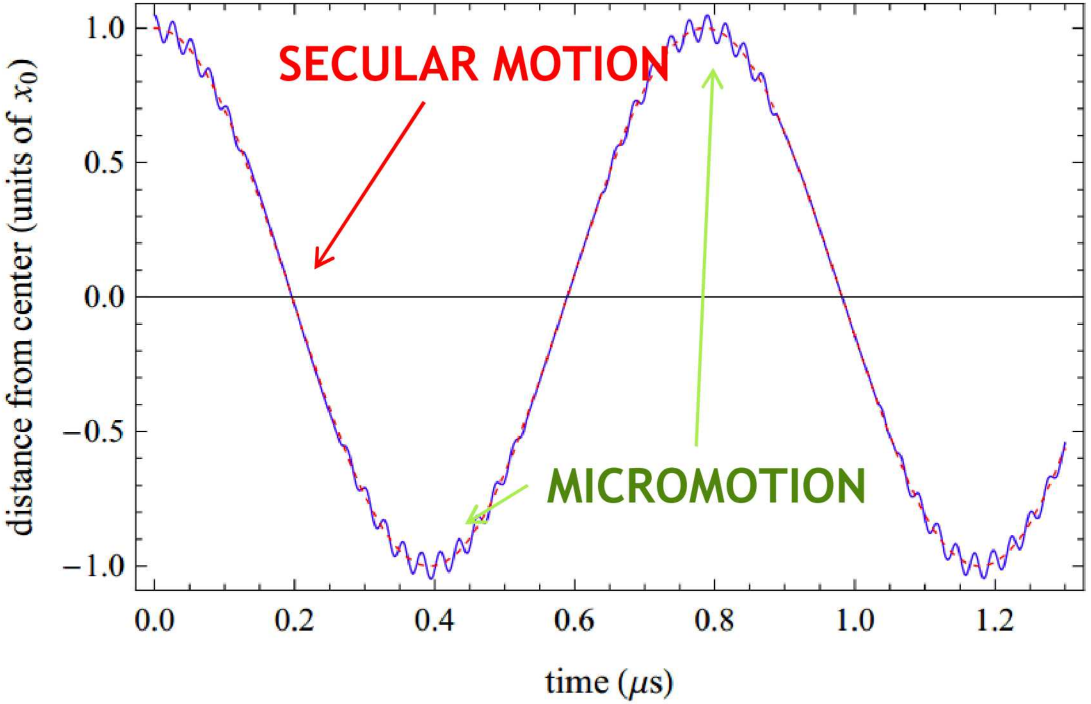
$$\beta = \frac{q}{\sqrt{2}}$$

Harmonic oscillation at frequency:

SECULAR MOTION $\omega_0 = \frac{1}{2}\beta\Omega$

With a superimposed "ripple" at frequency Ω **MICROMOTION**

with amplitude proportional to displacement.



Olmschenk, S. M. "Quantum Teleportation Between Distant Matter Qubits." Ph.D. Thesis, University of Michigan, Chapter 3, p. 14-23 (2009).

Can treat the ion as being in a harmonic oscillator

We already know everything using the Mathieu equations,
But another way of thinking about things:

Can derive the average force on the ion over one "secular" oscillation in an oscillating electric field

$$\mathbf{F} \approx -e\nabla\psi_P$$

$$\psi_P = \frac{e\left(\hat{E}_0(x,y,z)\right)^2}{4m\Omega^2}$$

For an oscillating field, derived by expanding about a point

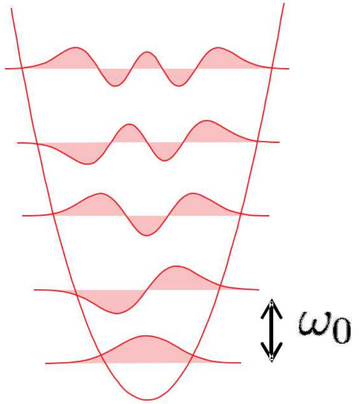
Then plug in our symmetric quadrupole field:

$$\mathbf{F} = -\omega_x^2 x\mathbf{x} - \omega_y^2 y\mathbf{y}$$

$$\omega_0 = \frac{eU_{\mathrm{RF}}}{\sqrt{2}m\Omega r_0^2}$$

A harmonic oscillator!

Not oscillating at Ω



Make use of this when using ions as qubits!

Olmschenk, S. M. "Quantum Teleportation Between Distant Matter Qubits." Ph.D. Thesis, University of Michigan, Chapter 3, p. 14-23 (2009).