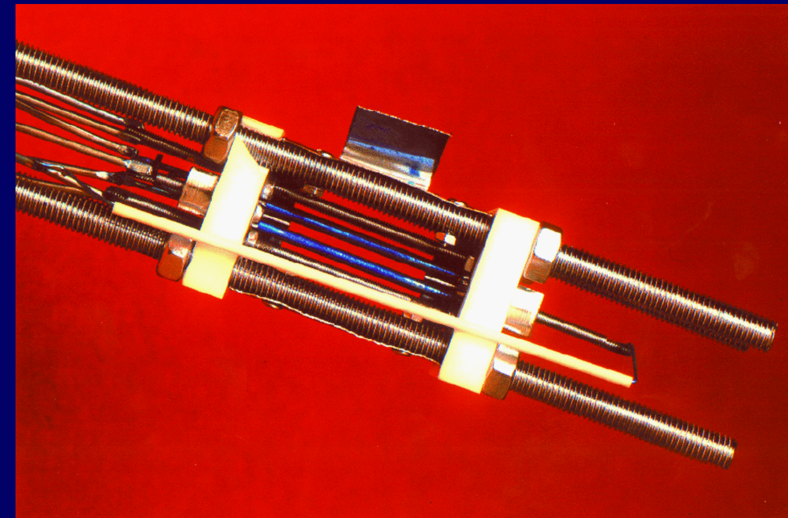
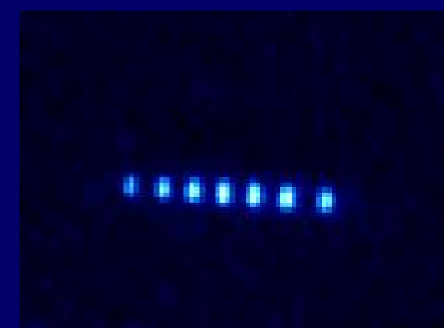
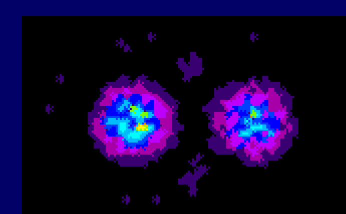
Ion Traps

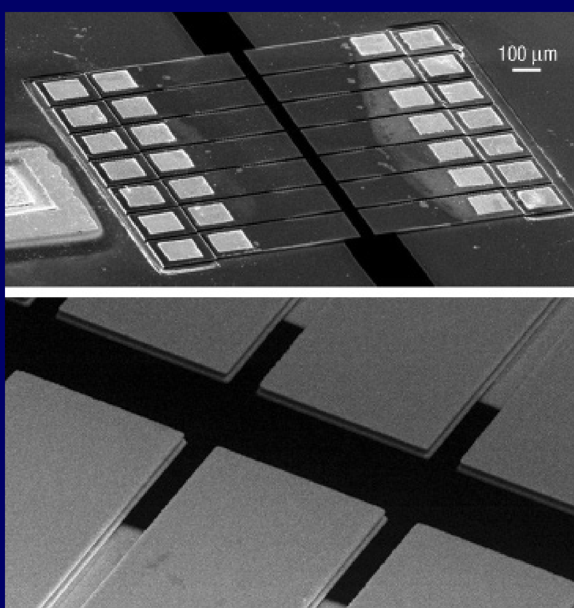
http://nodens.physics.ox.ac.uk/~mcdonnell/wardPres/wardPres.html





http://www.physics.gatech.edu/ultracool/Ions/7ions.jpg





http://www.nature.com/nphys/journal/v2/n1/images/nphys171-f2.jpg

Outline

- A brief history
- "Trapology"
- Two types of qubits
- Entangling gates
- Scalability

Table 4.0-1
The Mid-Level Quantum Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria						
	Quantum Computation					QC Networkability	
	#1	#2	#3	#4	#5	#6	#7
NMR	Red	Yellow	Yellow	Green	Yellow	Red	Red
Trapped Ion	Yellow	Green	Yellow	Green	Green	Yellow	Yellow
Neutral Atom	Yellow	Green	Yellow	Yellow	Yellow	Yellow	Yellow
Cavity QED	Yellow	Green	Yellow	Yellow	Green	Yellow	Yellow
Optical	Yellow	Yellow	Green	Yellow	Yellow	Yellow	Green
Solid State	Yellow	Yellow	Yellow	Yellow	Yellow	Red	Red
Superconducting	Yellow	Green	Yellow	Yellow	Yellow	Red	Red
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.						

Legend: Green = a potentially viable approach has achieved sufficient proof of principle

Yellow = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

Red = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.

#2. The ability to initialize the state of the qubits to a simple fiducial state.

#3. Long (relative) decoherence times, much longer than the gate-operation time.

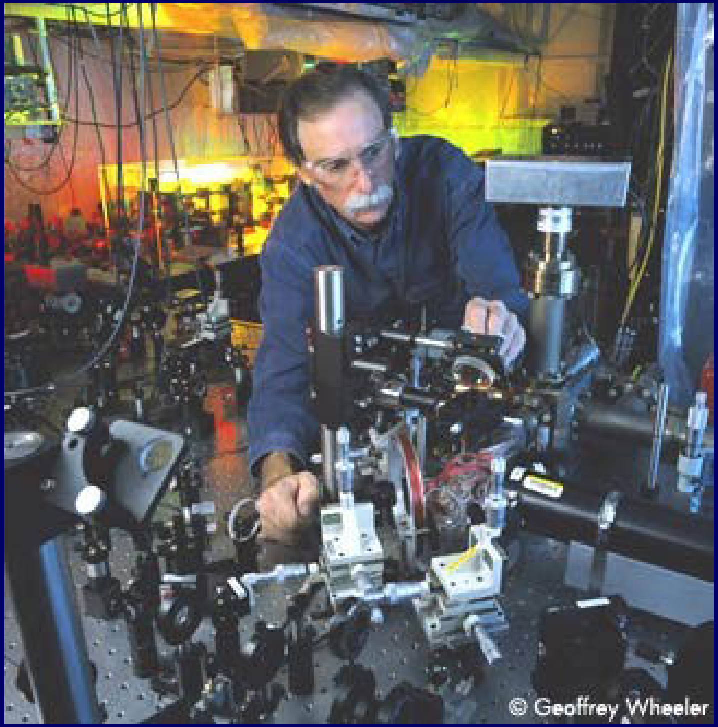
#4. A universal set of quantum gates.

#5. A qubit-specific measurement capability.

#6. The ability to interconvert stationary and flying qubits.

#7. The ability to faithfully transmit flying qubits between specified locations.

http://qist.lanl.gov/qcomp_map.shtml



David Wineland, NIST-Boulder

"Ion trappers are encouraged because we can at least see a straightforward path to making a large processor, but the technical problems are extremely challenging. It might be fair to say that ion traps are currently in the lead; however, a good analogy might be that we're leading in a marathon race, but only one metre from the start line."

Trapped ion qubits – a timeline

D. J. Wineland and H. Dehmelt, "Proposed 10^{14} Δν/ν laser fluorescence spectroscopy on Tl+ mono-ion oscillator," Bull. Am. Phys. Soc. 20, 657 (1975).

Cirac and Zoller: proposal

Wineland and Monroe: experiment

Kielpinski, Monroe, Wineland: QCCD

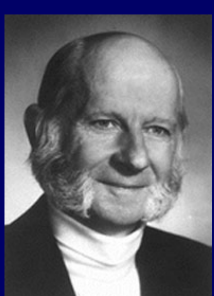
Kielpinski, Monroe, Wineland: QCCD

Wineland, Blatt: better gates

Wineland, Blatt: teleportation

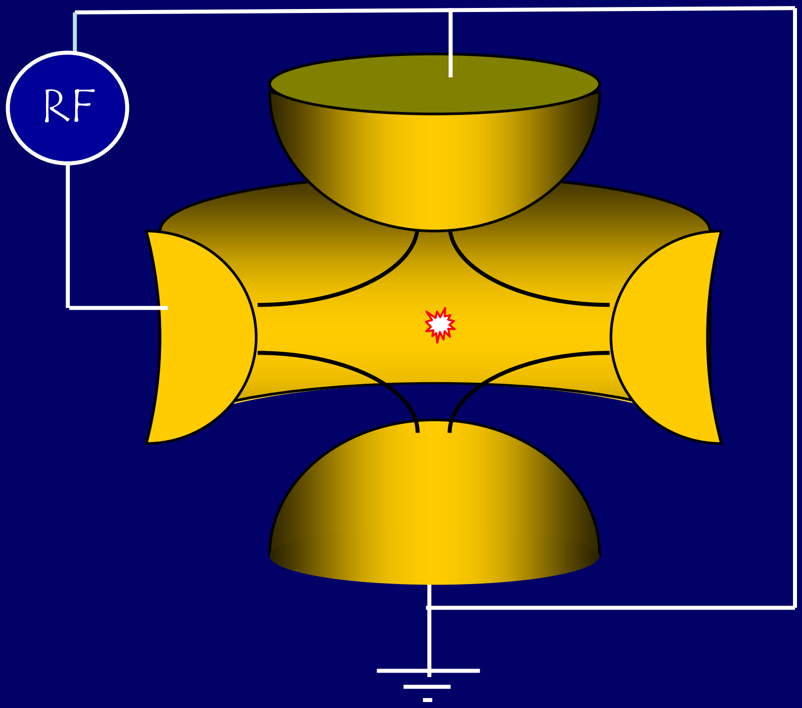
Wineland, Blatt: 6 and 8 qubit entangleme

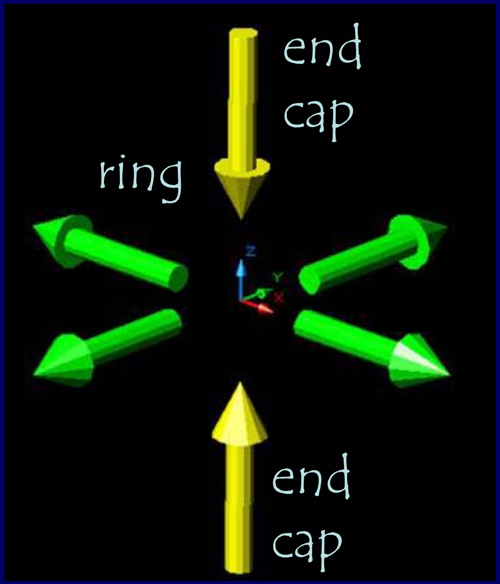
1975 | 95 | 97 | 97 | 98 | 99 | 2000 | 02 | 02 | 03 | 04 | 05 | 06

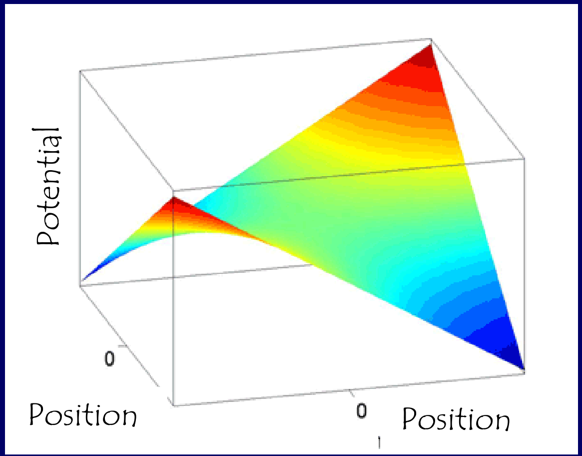


Trapology

RF (Paul) ion trap

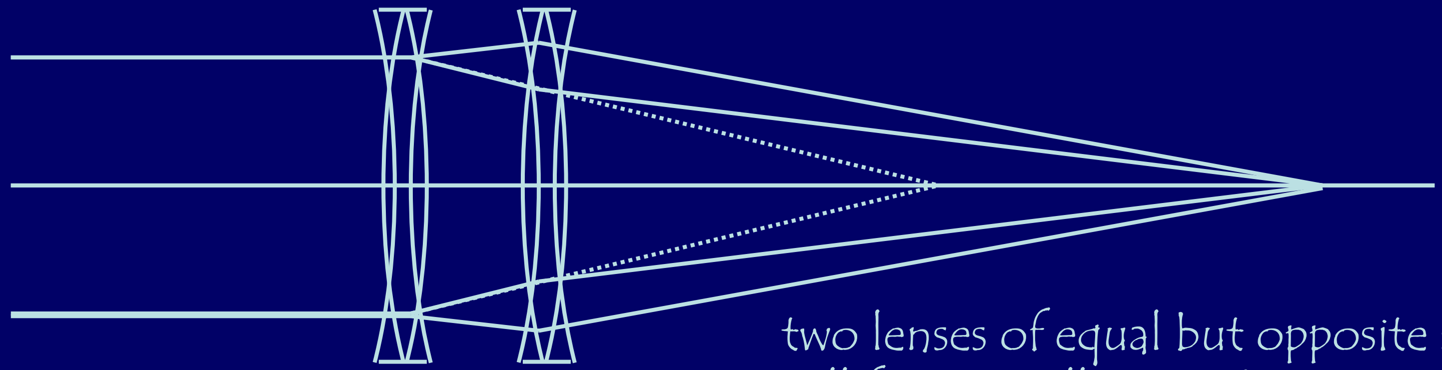




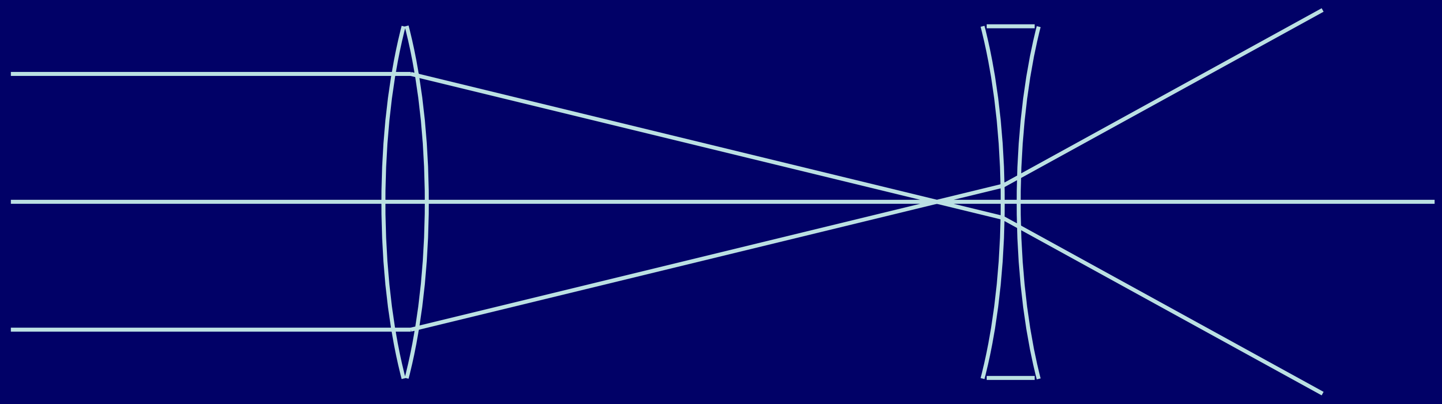


- Hyperbolic surfaces
- Good for trapping single ions
- Poor optical access

Ray optics analogy



two lenses of equal but opposite strength
will focus a collimated beam...

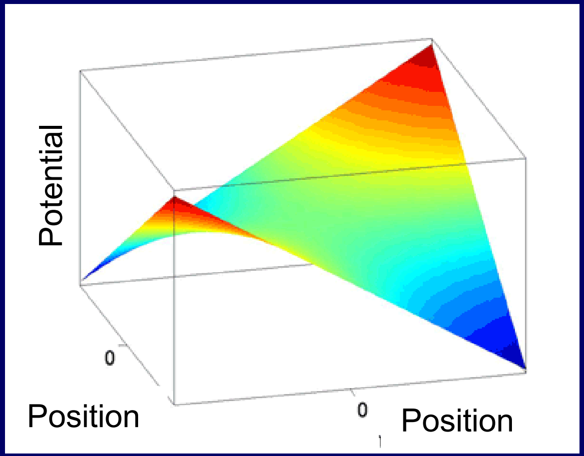


(... unless placed too far apart)


Ready
01:23

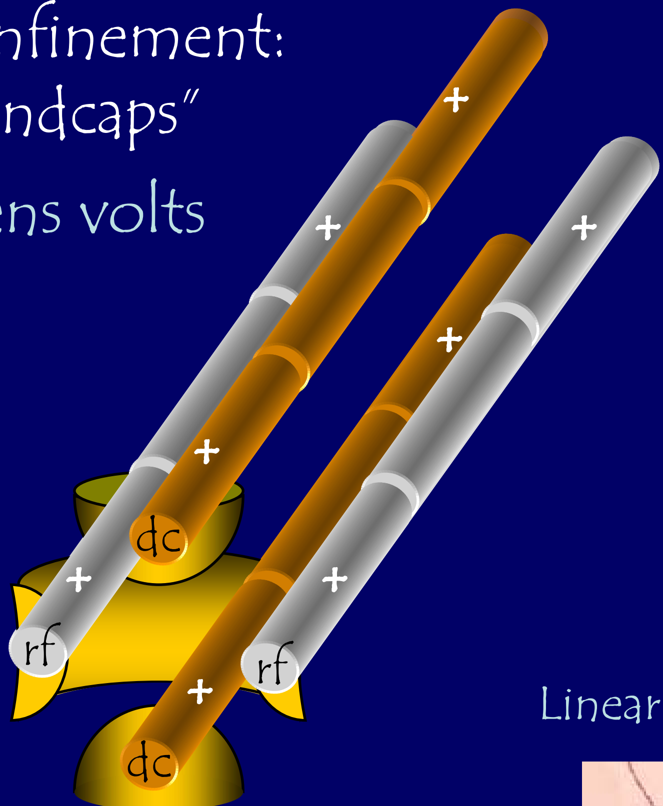
Linear RF Ion Trap

transverse confinement:
2D rf ponderomotive potential



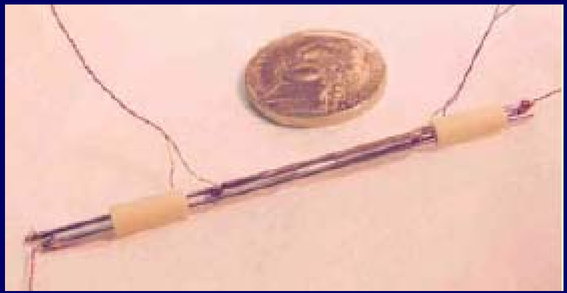
axial confinement:
static "endcaps"

~ few tens volts

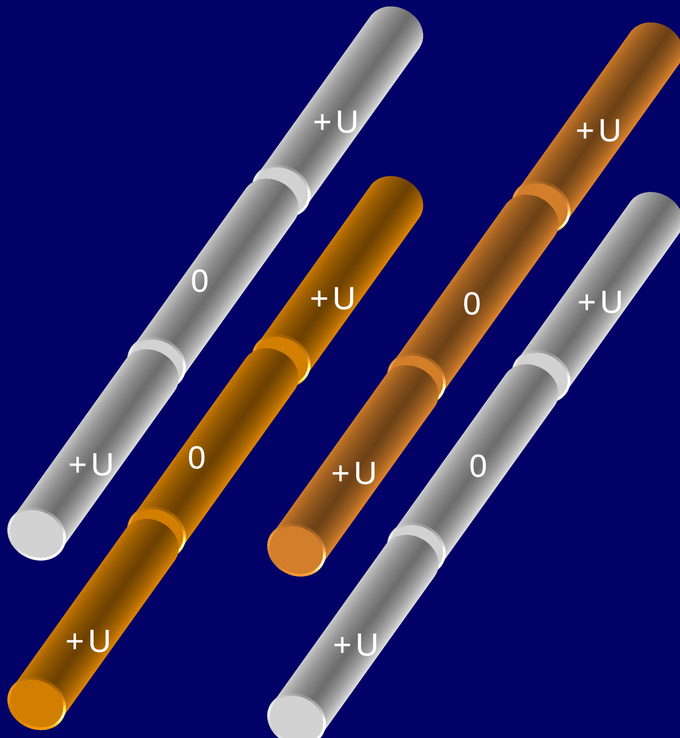


~ few tens MHz
~ few hundred volts

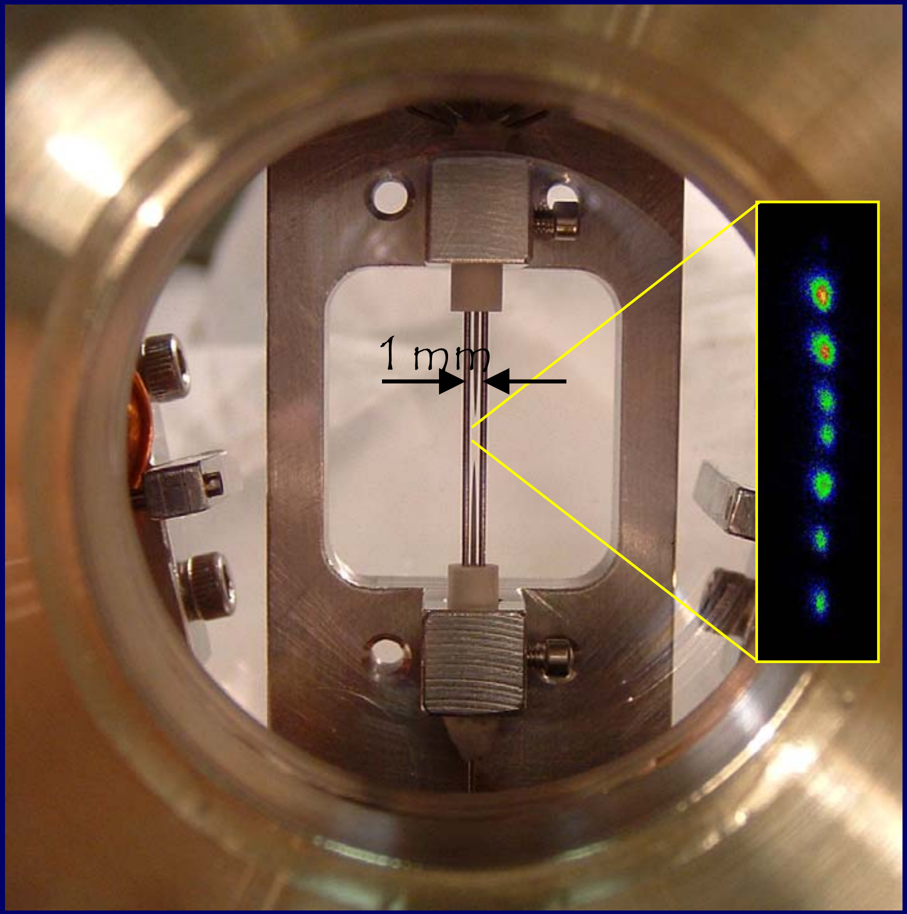
Linear trap (D. Berkeland, LANL)



Linear RF Ion Trap continued...

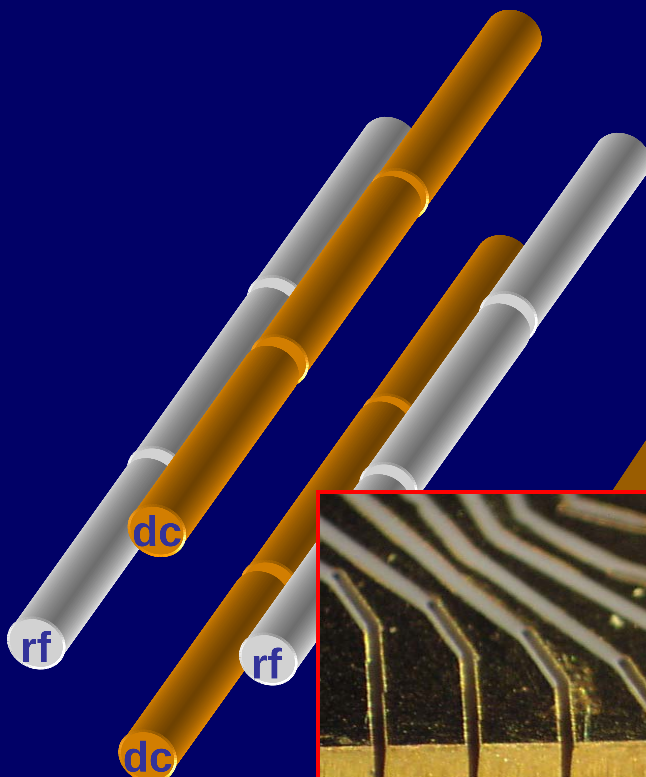


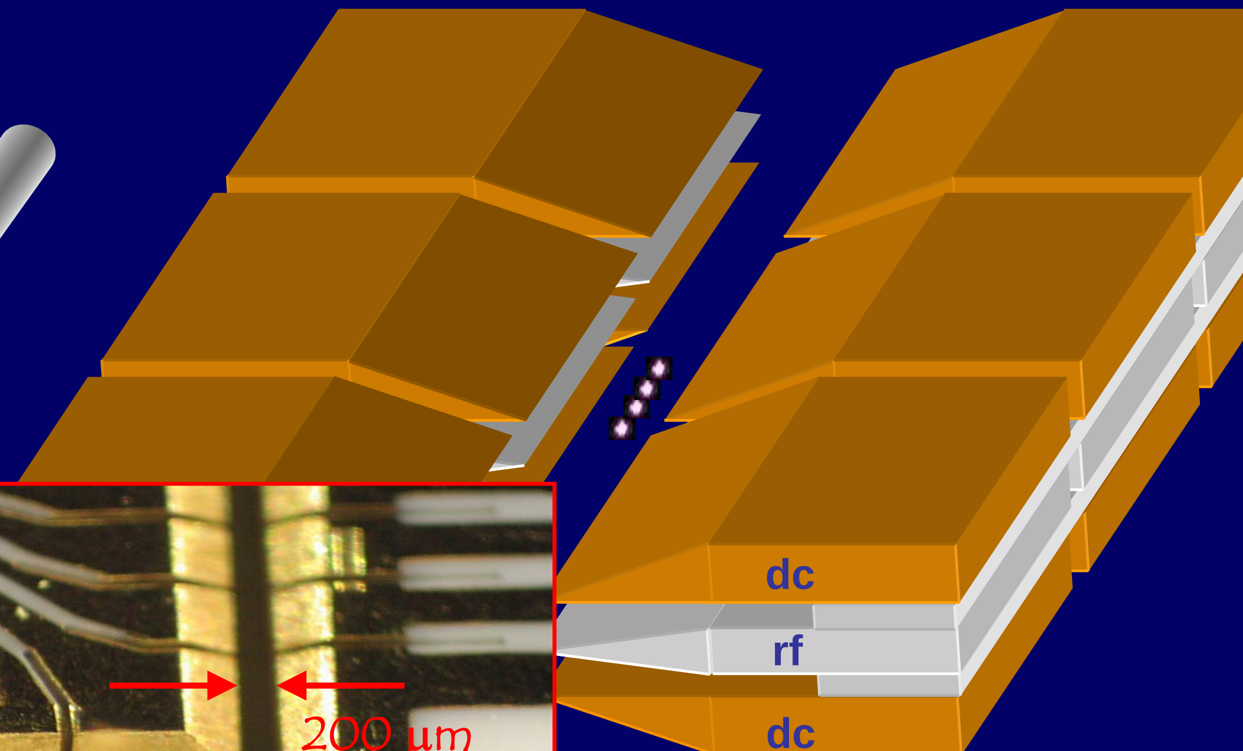
"Endcap" linear trap –
U. Mich, UW, Oxdord...

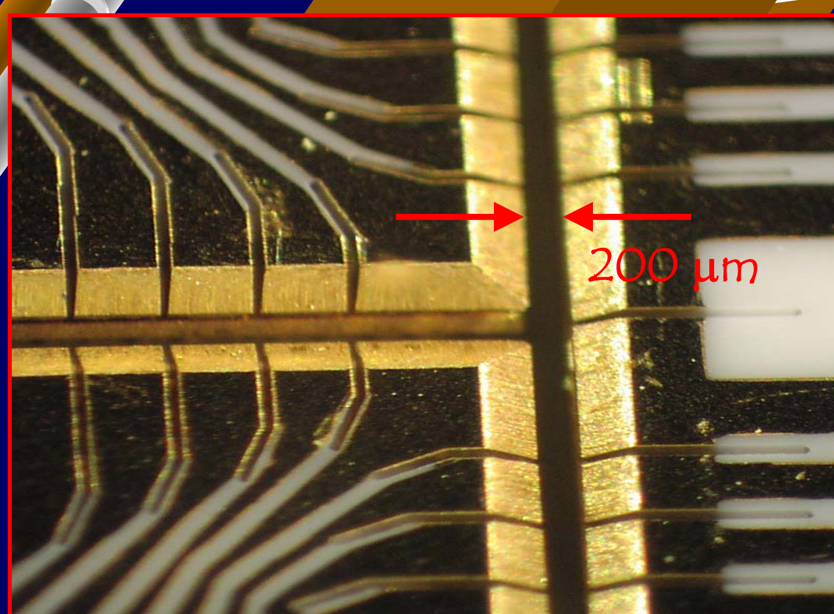


3-layer geometry:

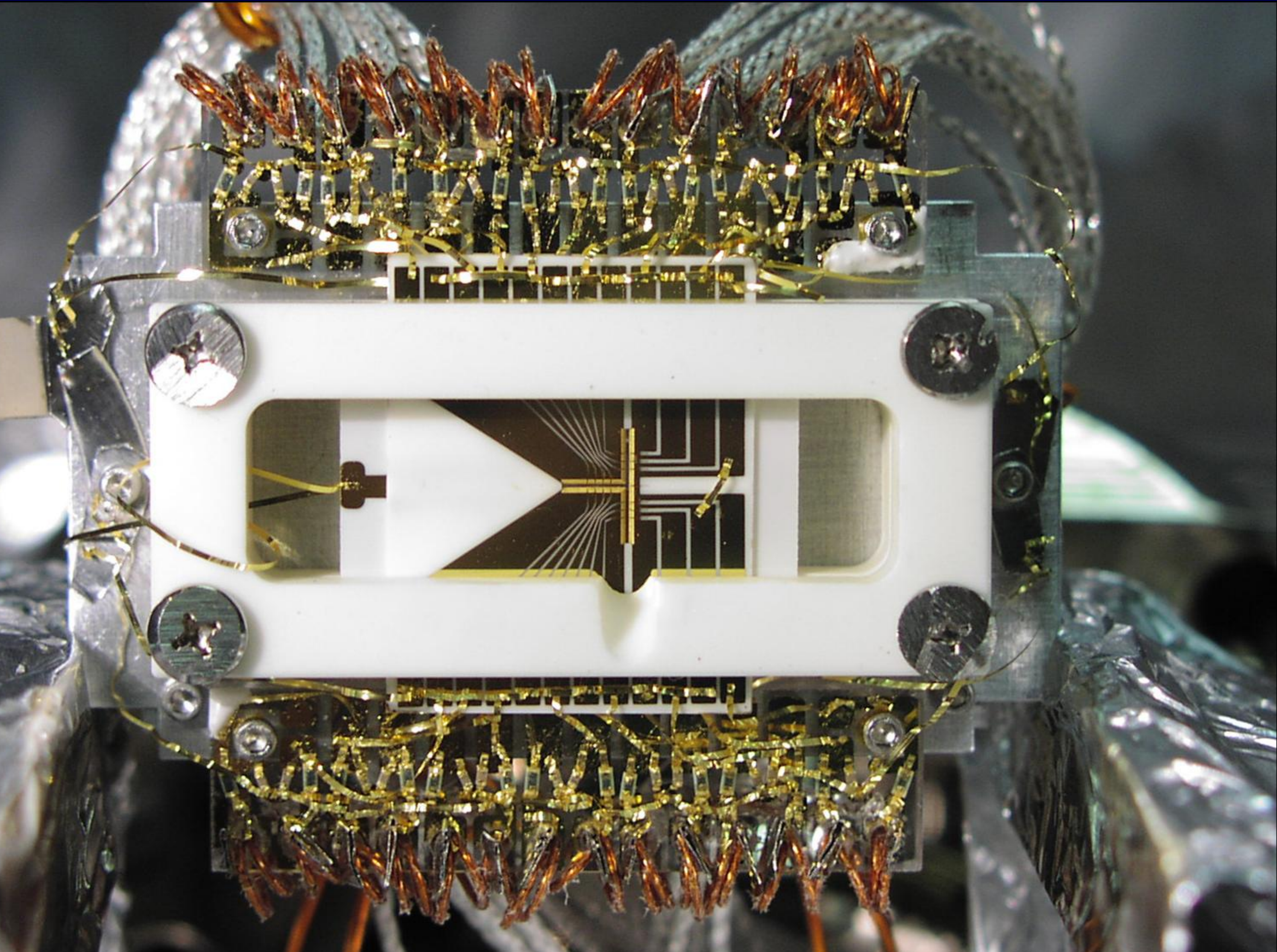
- allows 3D offset compensation
- scalable to larger structures



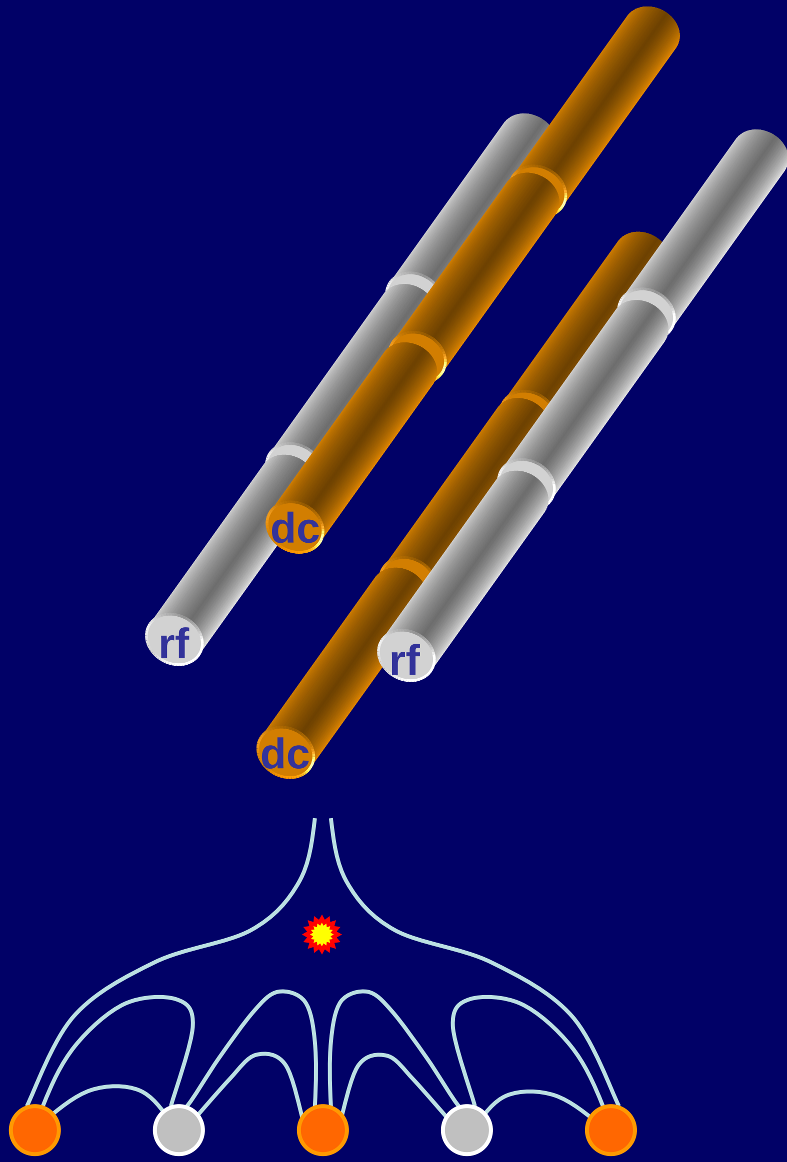


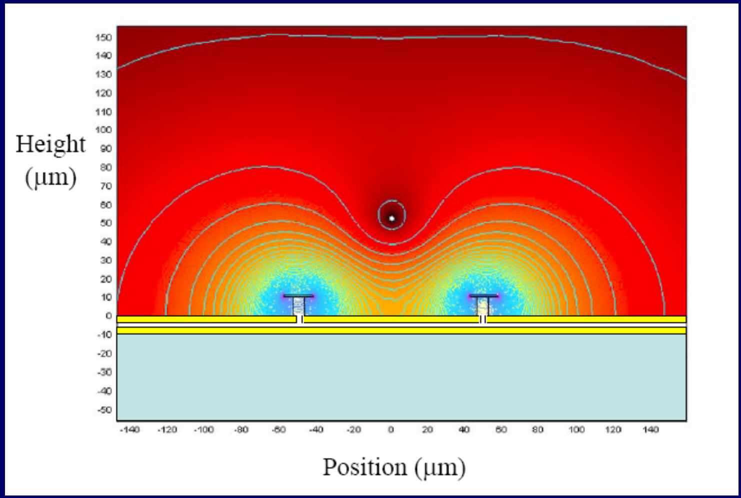


3-layer Tee-trap
(U. Michigan)



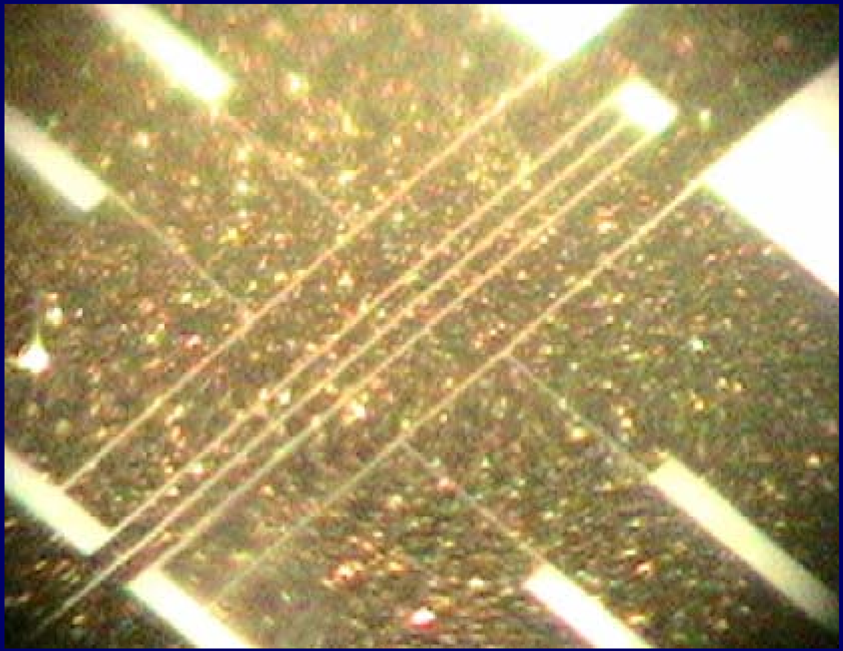
Planar, or surface, traps





Planar trap field simulation
(R. Slusher, Lucent Labs)

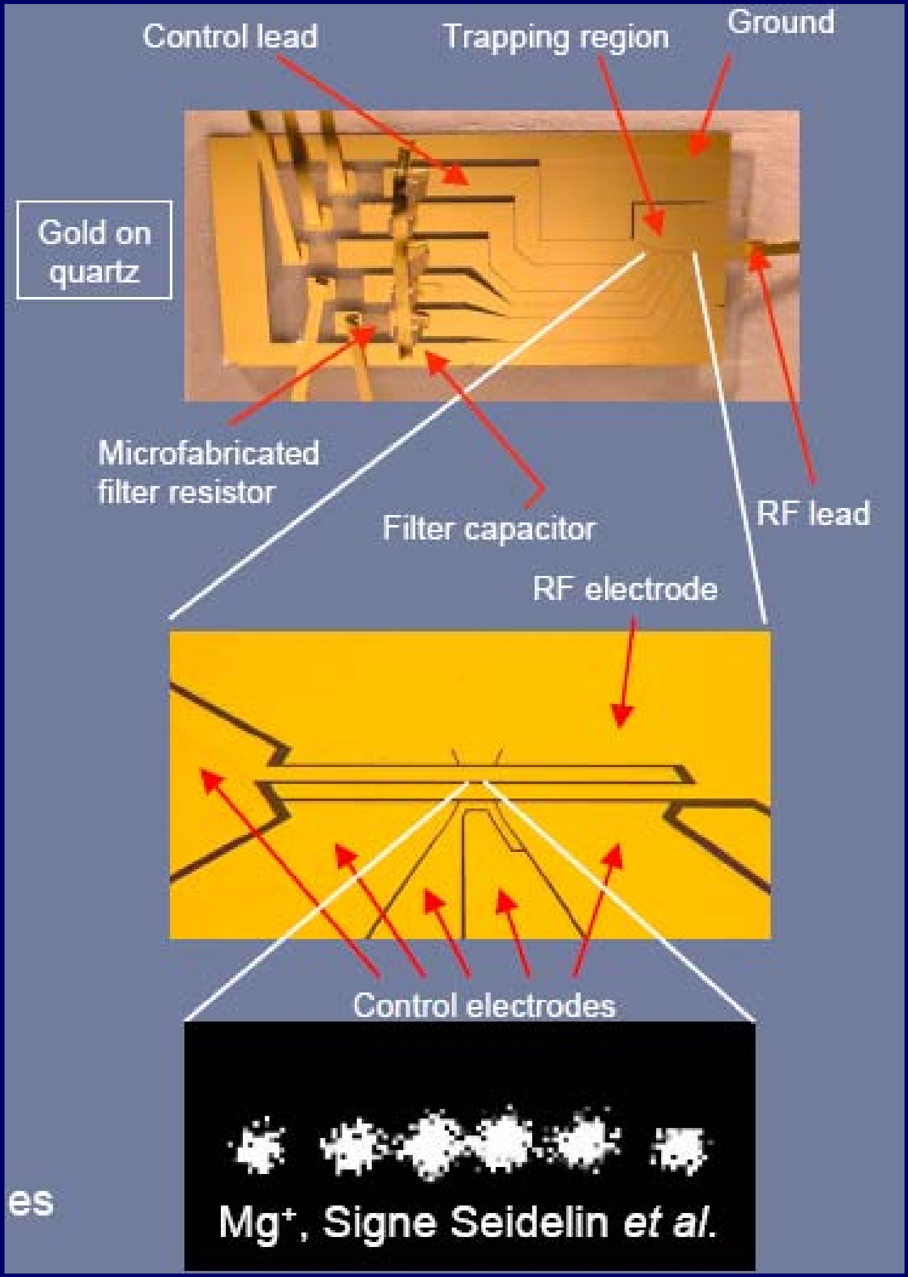
Gold-on-alumina planar trap (U. Mich)



NIST planar traps and trap arrays

The planar traps are in fact even "more scalable" than the 3-layer traps.

The electrodes are patterned on the surface; control electronics may be integrated in the same chip.



Qubits

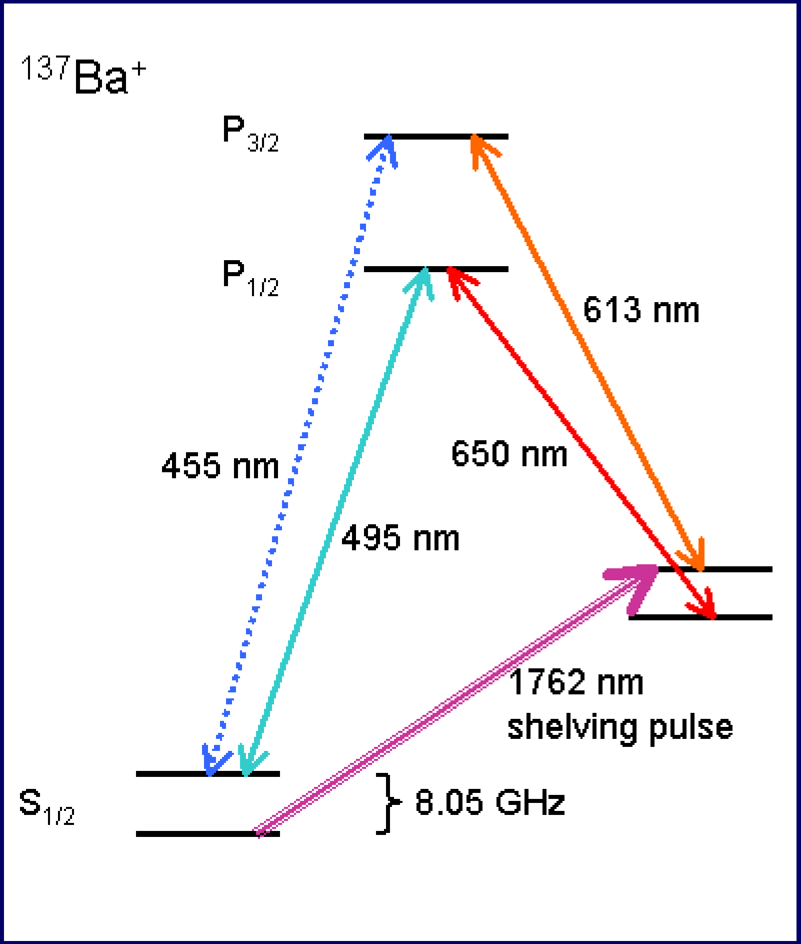
"Hyperfine" and "optical" qubits: an unbiased view

Hyperfine qubits:

- Spontaneous emission negligible
- Require stable RF sources (easy!)
- Fun to work with

Optical qubits:

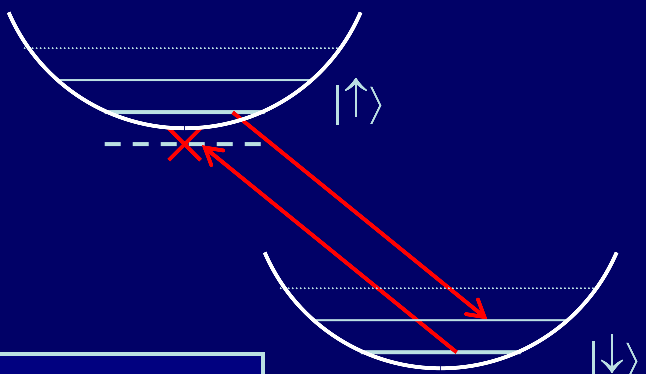
- Upper state decays on the timescale of seconds
- Require stable laser sources (hard!)
- Pain to work with

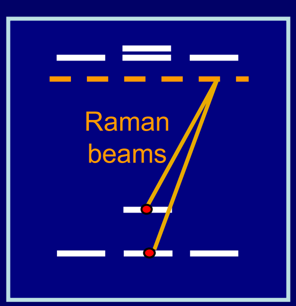


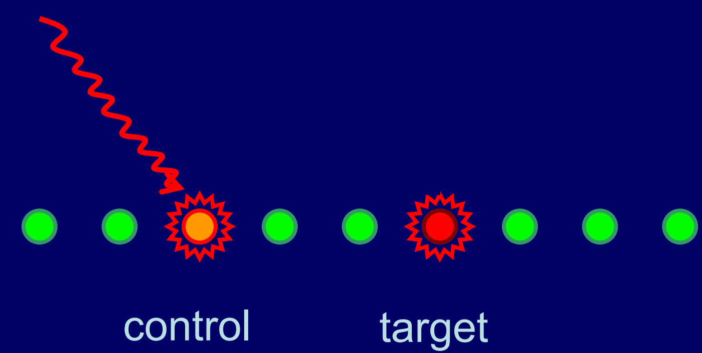
Entanglement

Cirac-Zoller CNOT gate

1. Ion string is prepared in the ground state of motion (n=0)
2. Control ion's spin state is mapped onto quantized motional state of the ion string
3. Target ion's spin is flipped conditional on the motional state of the ion string
4. Motion of the ion string is extinguished by applying pulse #2 with negative phase to the control ion





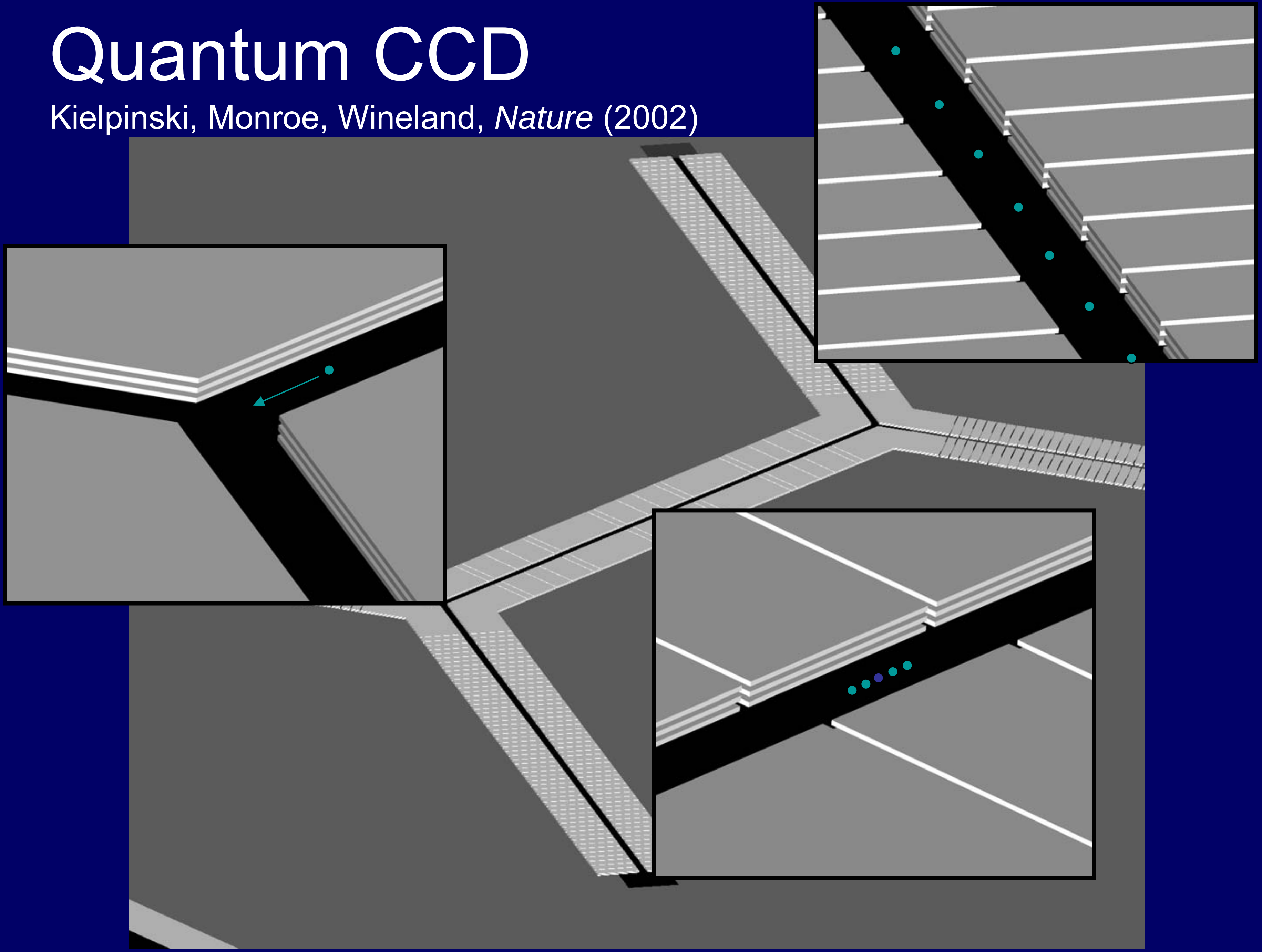


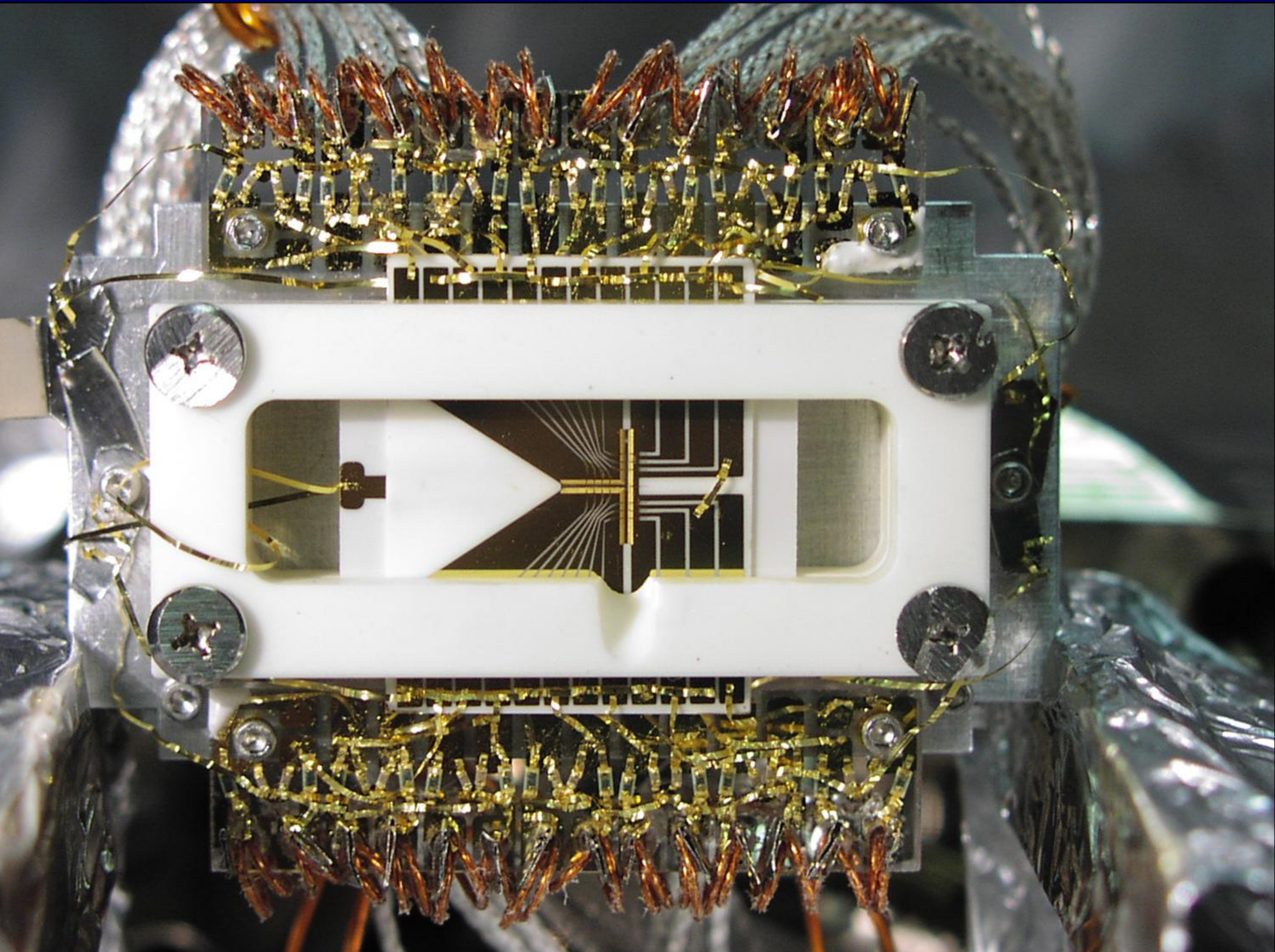
Cirac and Zoller, *Phys. Rev. Lett.* **74**, 4091 (1995)

Scaling up

Quantum CCD

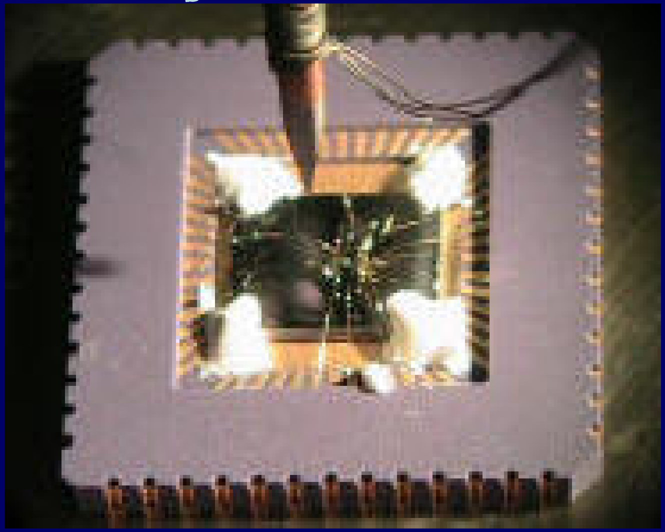
Kielpinski, Monroe, Wineland, *Nature* (2002)



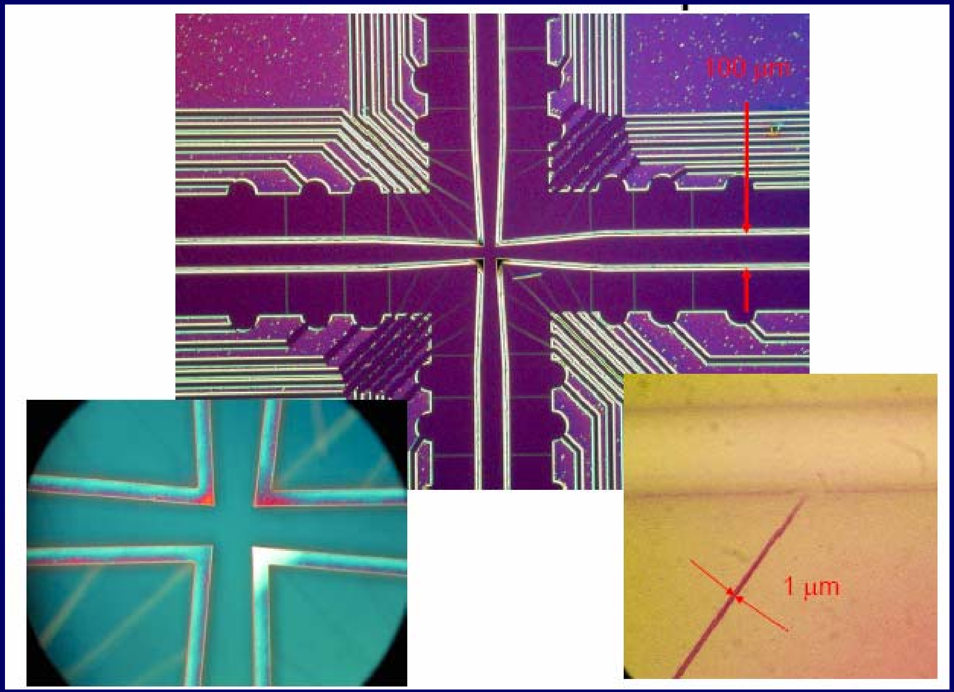


Integration

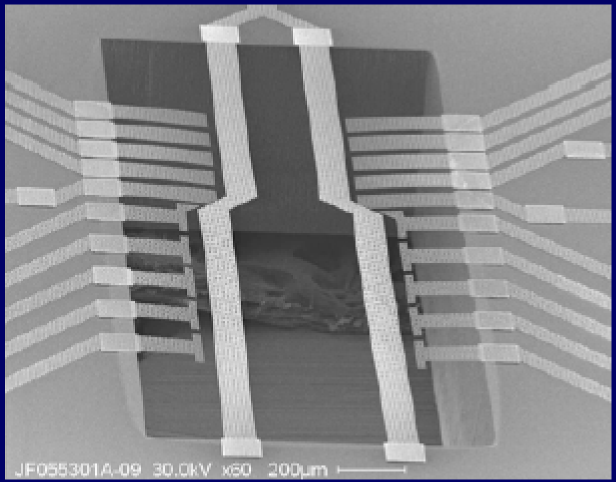
U.Michigan



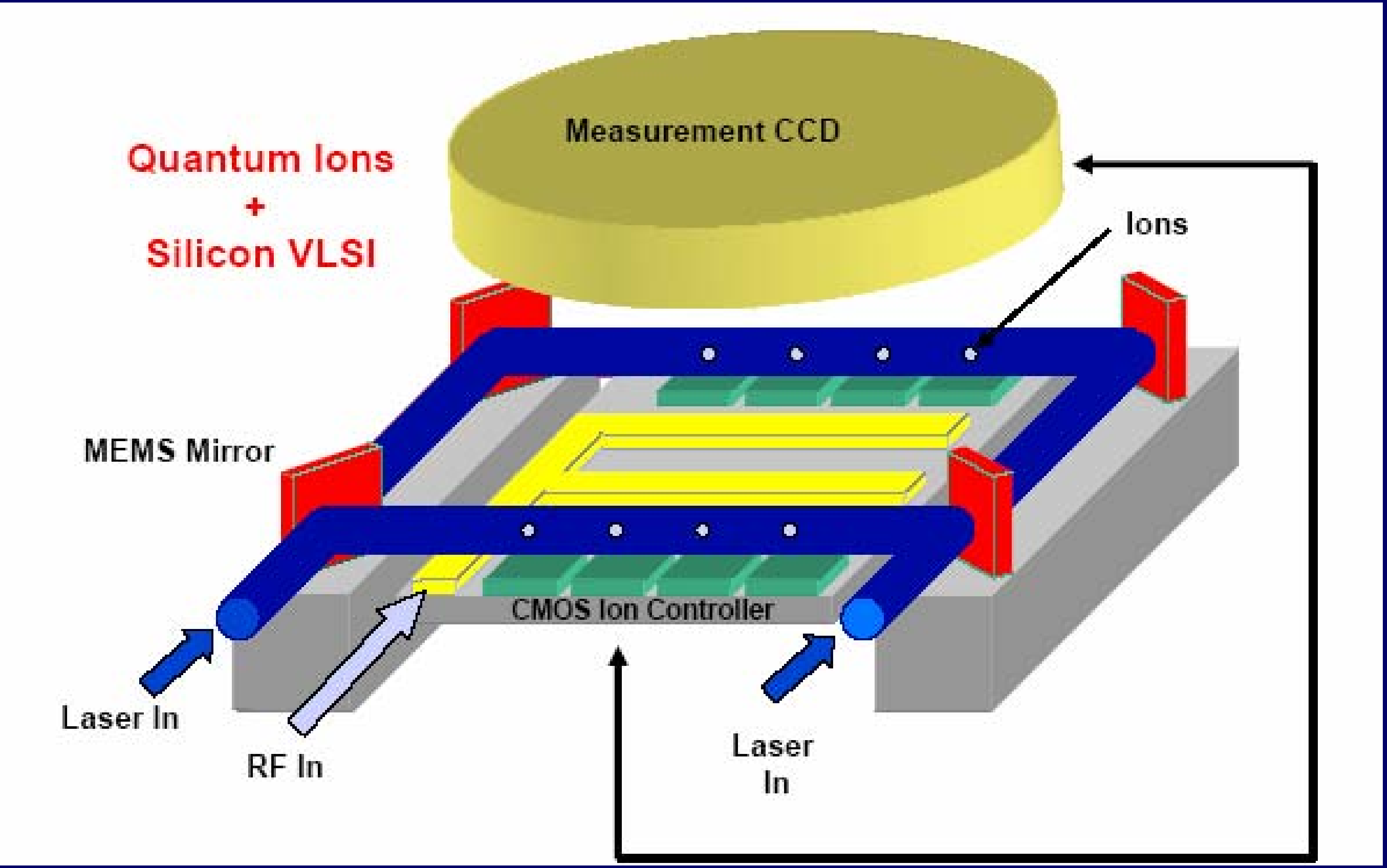
R. Slusher/Lucent Labs



M. Blian, C. Tigges/Sandia Labs



A vision



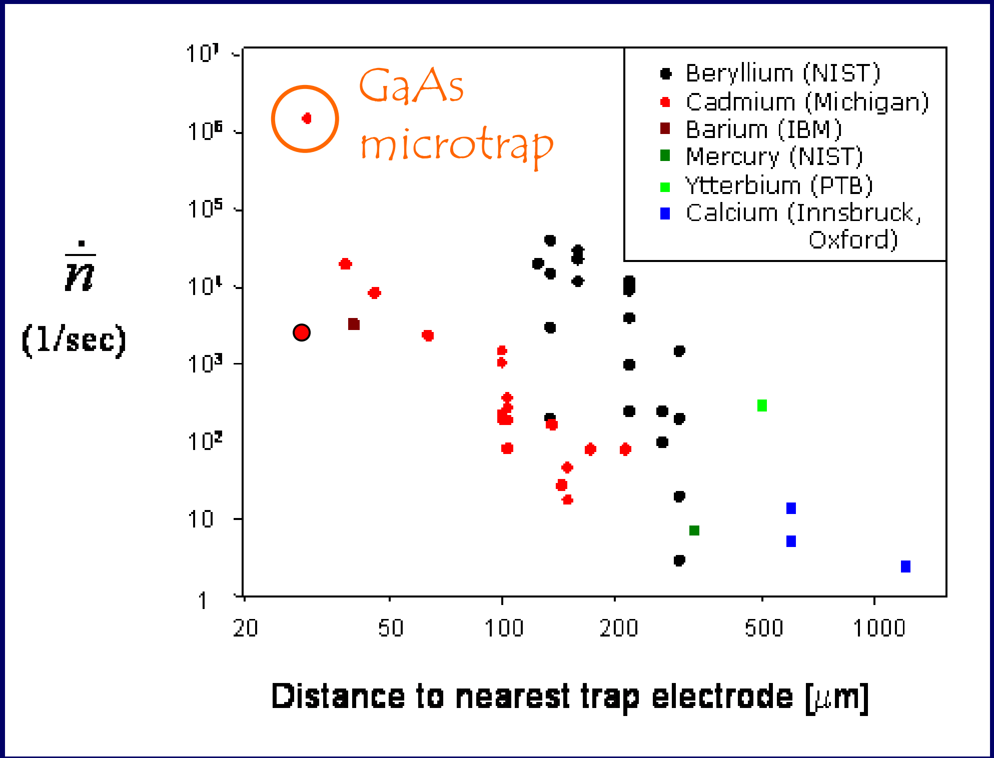
R. Slusher/Lucent Labs

Motion heating is a problem…

- Small traps = faster (quantum logic) gates

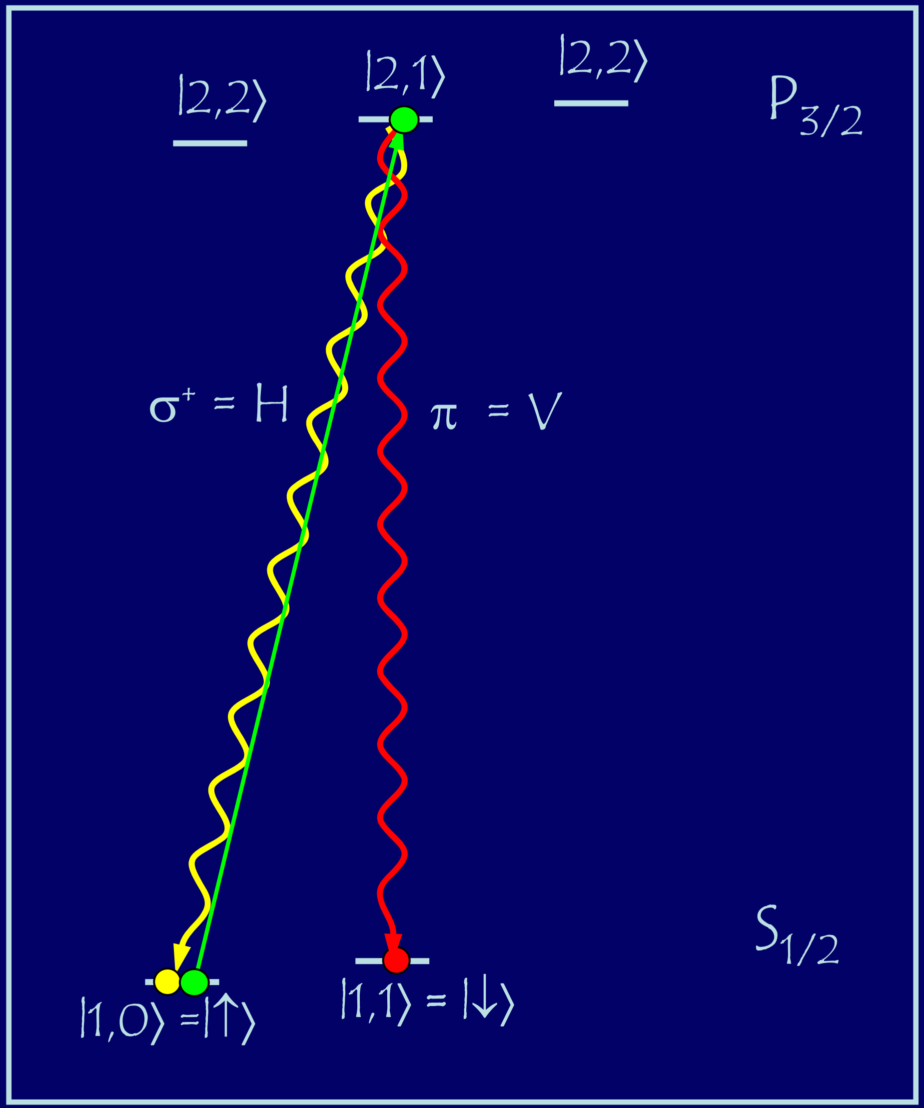
… but…

- Small traps = faster heating of ion's motion
- (Quantized) motion is the quantum data bus, thus heating = decoherence!



L. Deslauriers et al.
PRA 70, 043408 (2004)

Probabilistic entanglement of ions and photons



1. The atom is initialized in a particular ground state
2. The atom is excited with a short laser pulse to a particular excited state
3. The atom decays through multiple decay channels (we like when there's only two)
4. The emitted photon is collected and measured

The final state of the atom is entangled with the polarization state of the photon.

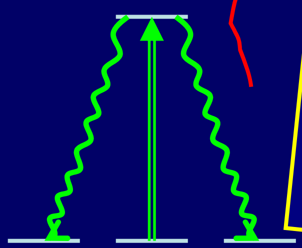
This creates an entangled state

$$|\psi\rangle = |H\rangle|\uparrow\rangle + |V\rangle|\downarrow\rangle$$

Price we pay: this entanglement is probabilistic

Entanglement success probability:

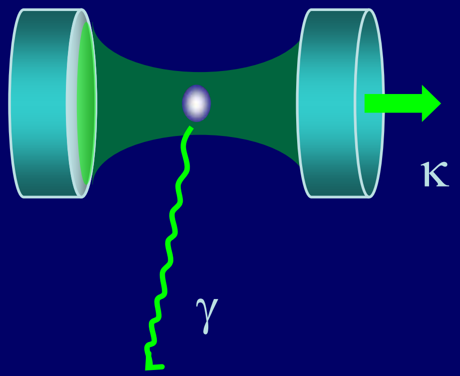
$P = P_{excitation}\, d\Omega\, \eta_{detection}$ ($\sim 10^{-3}$ now)



Unit excitation with a fast (ps) laser pulse

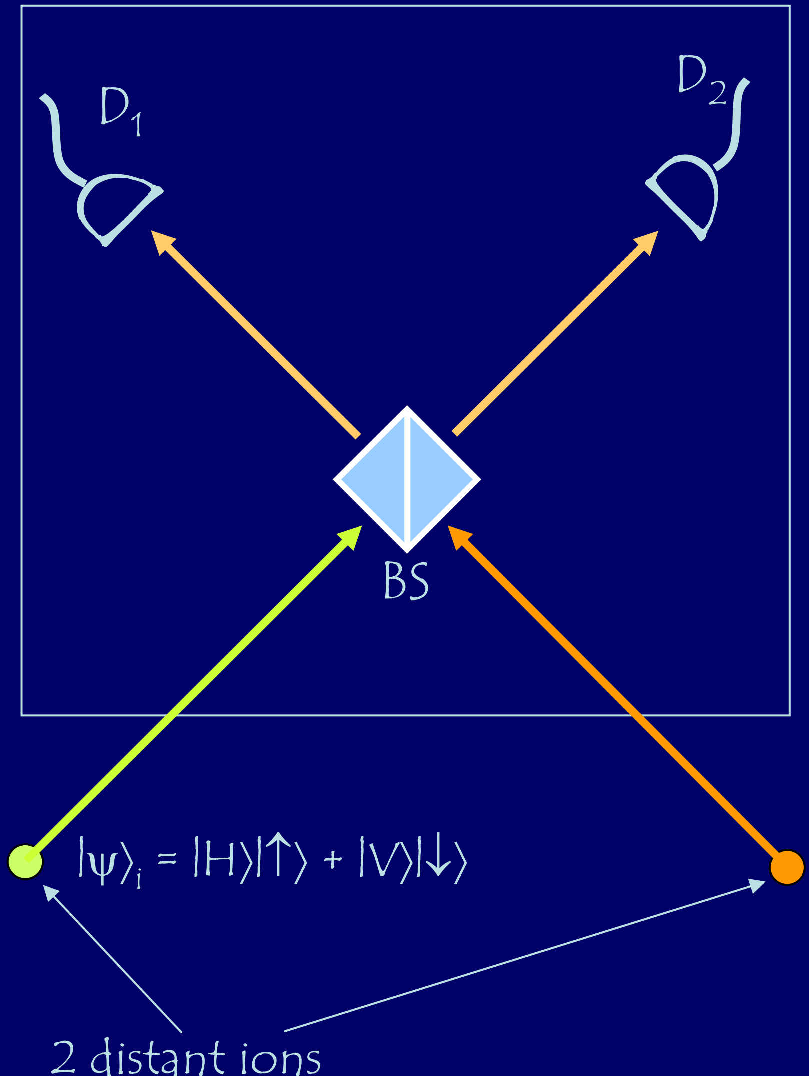
Better detectors!

Cavity QED setup
("bad cavity")
$g^2/\kappa \sim \gamma$ and $\kappa >> g$



Remote Ion Entanglement

using entangled ion-photon pairs



Coincidence only if photons are in state:

$$|\Psi^-\rangle = |H\rangle_1 |V\rangle_2 - |V\rangle_1 |H\rangle_2$$

This projects the ions into …

$$|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2 = |\Psi^-\rangle_{ions}$$

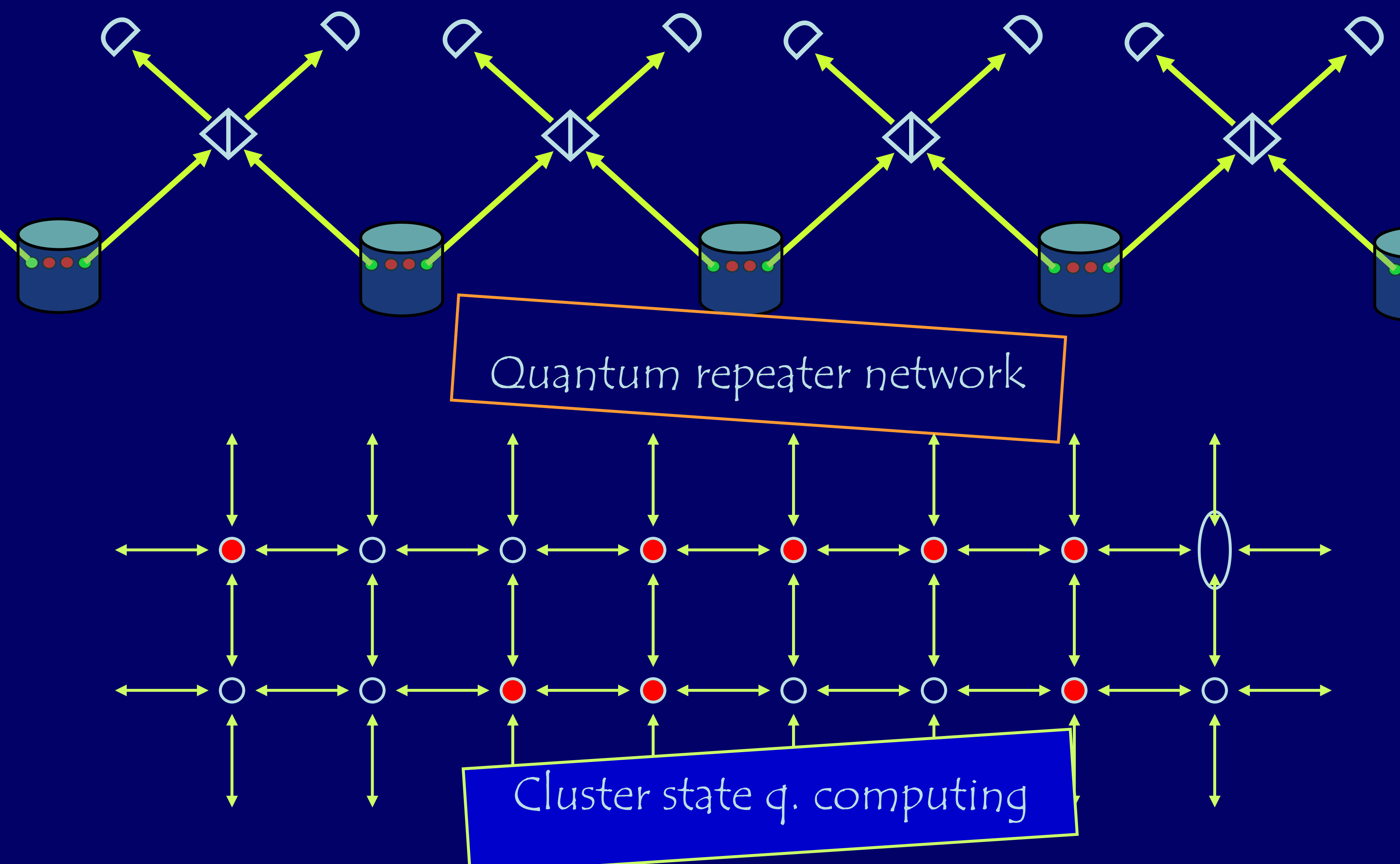
The ions are now entangled!

Things to do with this four-qubit system:

- teleportation between matter and light
- loophole-free Bell inequality tests
- decoherence studies
- quantum repeaters, computers

Simon and Irvine, *PRL*, 91, 110405 (2003)

Quantum networking and quantum computing using ion-photon entanglement



Conclusions…

- Ion trap technology currently a leader, but you've heard the marathon analogy quote

- Clear path to scaling up, but technology needs to mature

- Integration of electronic controls and optics is likely the next step

- An alternative scaling through ion-photon entanglement