Quantum Computing with Entangled Ions and Photons

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Outline

- Quantum computing
- Ion traps and trapped ion qubits
- Ion-photon entangled system
- Scalability and "one-way quantum computing"
- Trapped ion QC at Washington

Quantum computers: when? (or if?)

a) never – they are not possible

a^{*}) never – technical difficulties

b) in the next 10-50 years

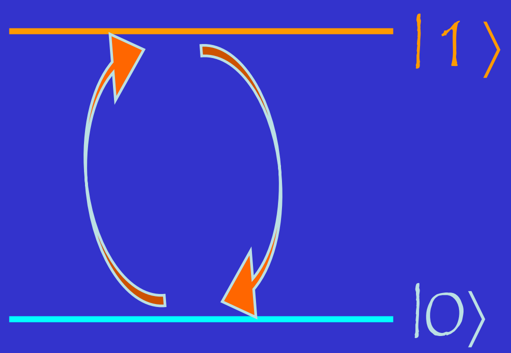
c) in a few months (or "I already have a quantum computer!")

d) "Theoretical computer scientists don't need a quantum computer! They already have it!"

(Ed Fahri @ SQuInT-08)

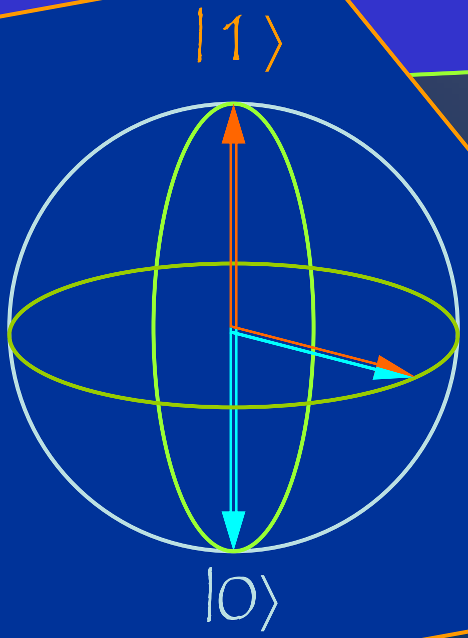
What is a qubit (Qbit, q-bit)?

Quantum two-level system



State of the qubit is
described by its wavefunction

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$



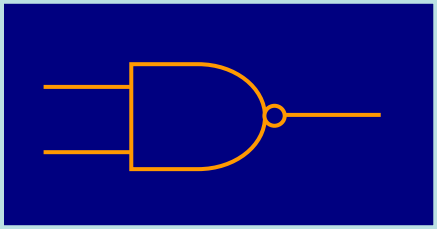
"Bloch sphere"

Classical vs. Quantum

- **In a classical computer, the data is represented in series of *bits*, each taking a value of *either* 0 *or* 1.**

0 1 1 0 0 1 0 0 1 1 1 0 ….

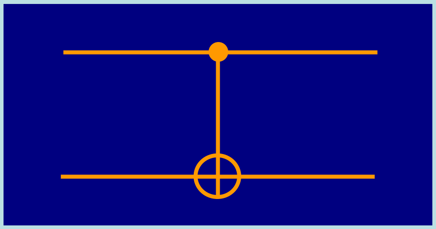
- **Classical computation consists of operations on single bits (NOT) and multiple bits (e.g. NAND).**



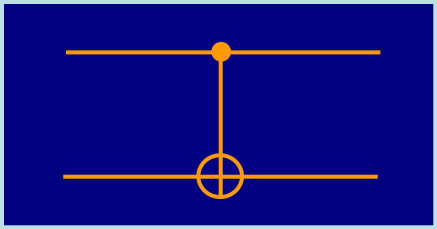
- **In a quantum computer, the data is represented in series of quantum bits, or *qubits*, each taking a value of $|0\rangle$, $|1\rangle$ *or any superposition* of $|0\rangle$ and $|1\rangle$.**

$$\alpha|0\rangle + \beta|1\rangle$$

- **Quantum computation consists of operations on single qubits (called *rotations*) and multiple bits (e.g. CNOT - the Controlled-NOT gate).**



Quantum CNOT gate

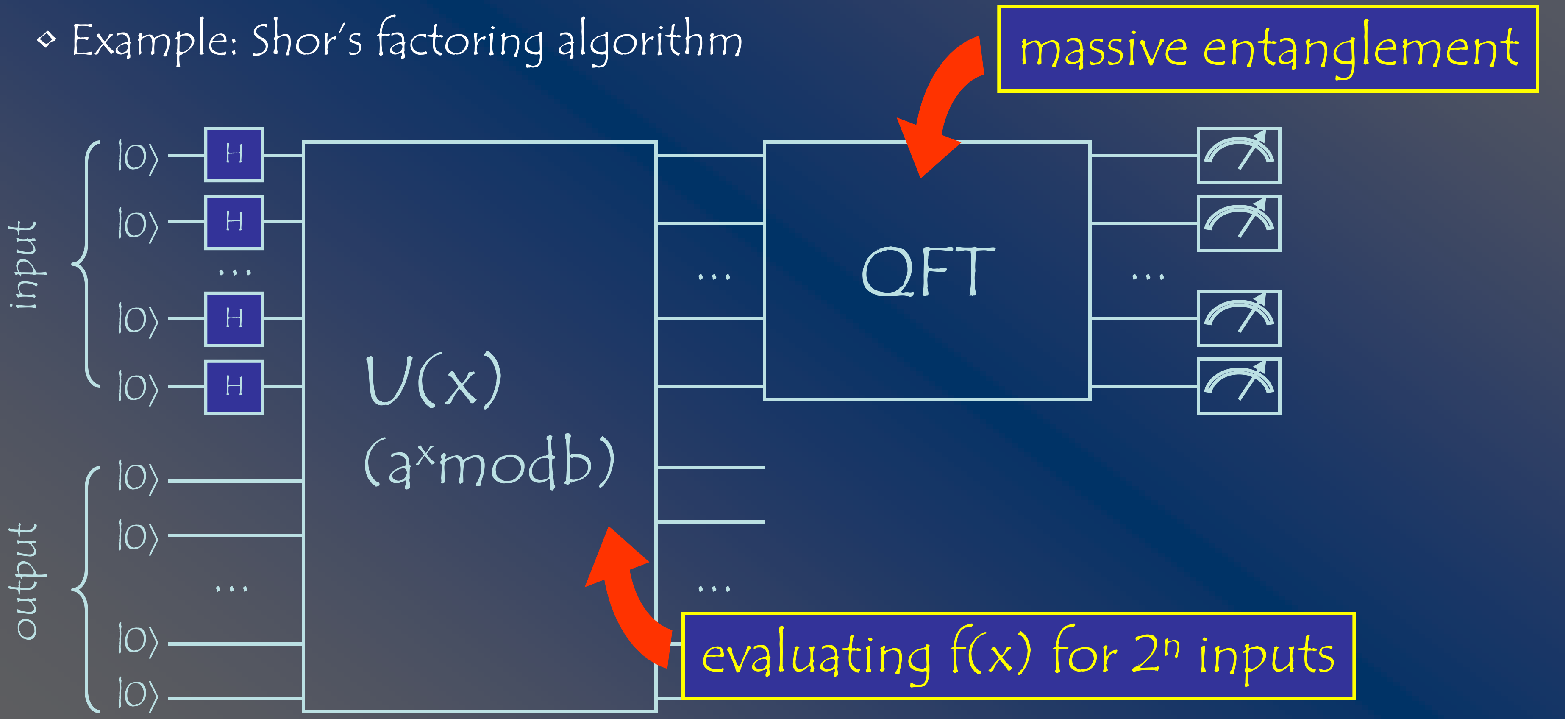


control qubit	target qubit	result
$\|0\rangle$	$\|0\rangle$	$\|0\rangle\ \|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle\ \|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle\ \|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle\ \|0\rangle$
$\alpha\|0\rangle + \beta\|1\rangle$	$\|0\rangle$	$\alpha\|0\rangle\|0\rangle + \beta\|1\rangle\|1\rangle$

Entangled state!

Quantum computing revealed

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



massive entanglement

evaluating f(x) for 2^n inputs

Quantum computing: why?

- Storing exponentially more data than classical: 300 qubits can hold $2^{300} \approx 10^{90}$ numbers *simultaneously* ($\gg$ *number of atoms in the Universe!*)
- (Exponential) speed-up of some important computing tasks:
  - – Factoring large numbers (code breaking)
  - – Unsorted database search
  - – Quantum simulations (modeling *any* quantum system with a universal quantum computer)

Factoring!

- Quantum communication:
  - – Cryptography (ultimately secure key)
  - – "Dense coding" (sending more data per channel)
  - – "Teleportation"

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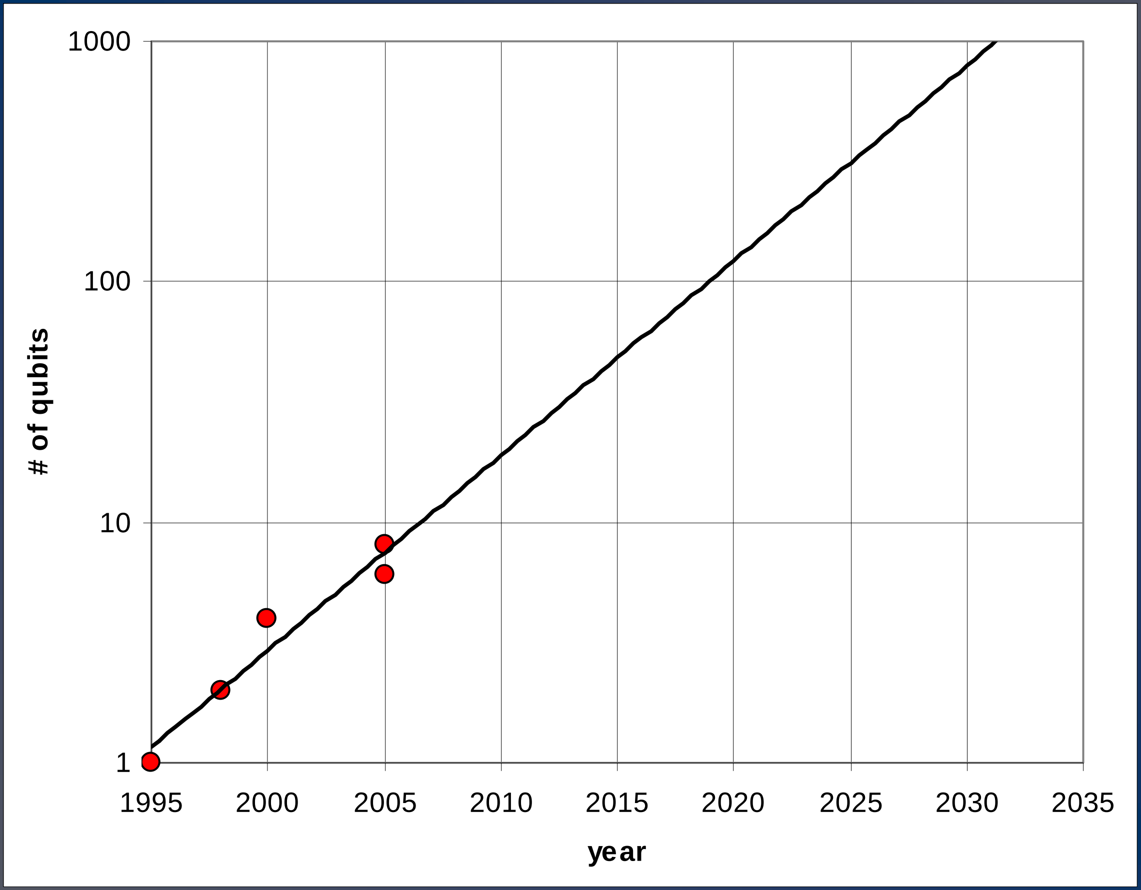
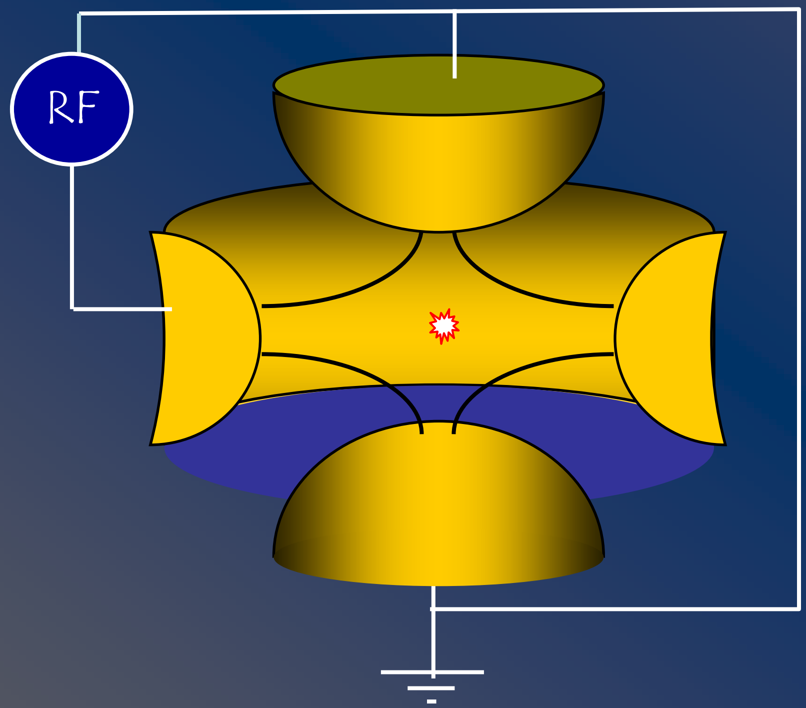
"Moore's law" for trapped ion qubits

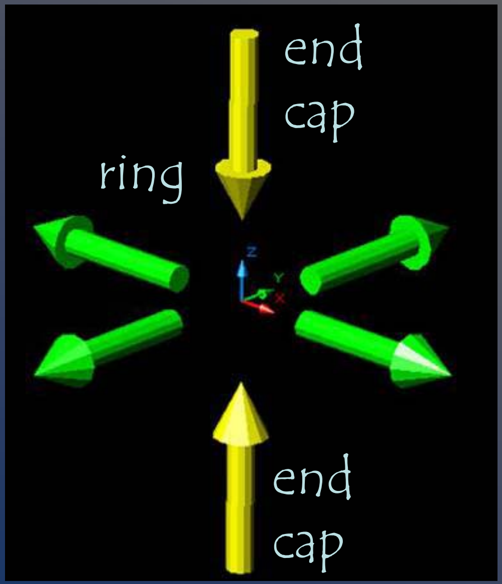


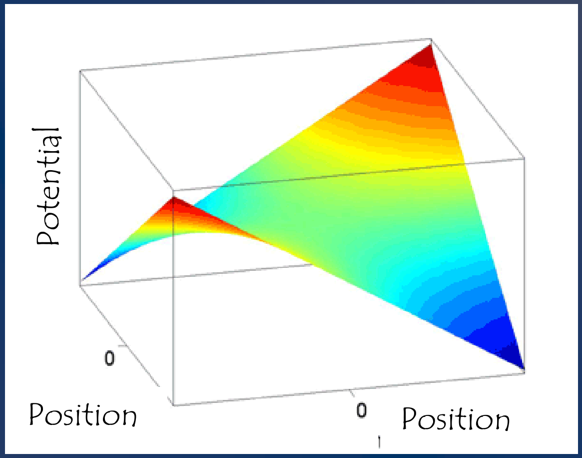
(courtesy of M. Chapman, Georgia Tech)

RF (Paul) ion trap

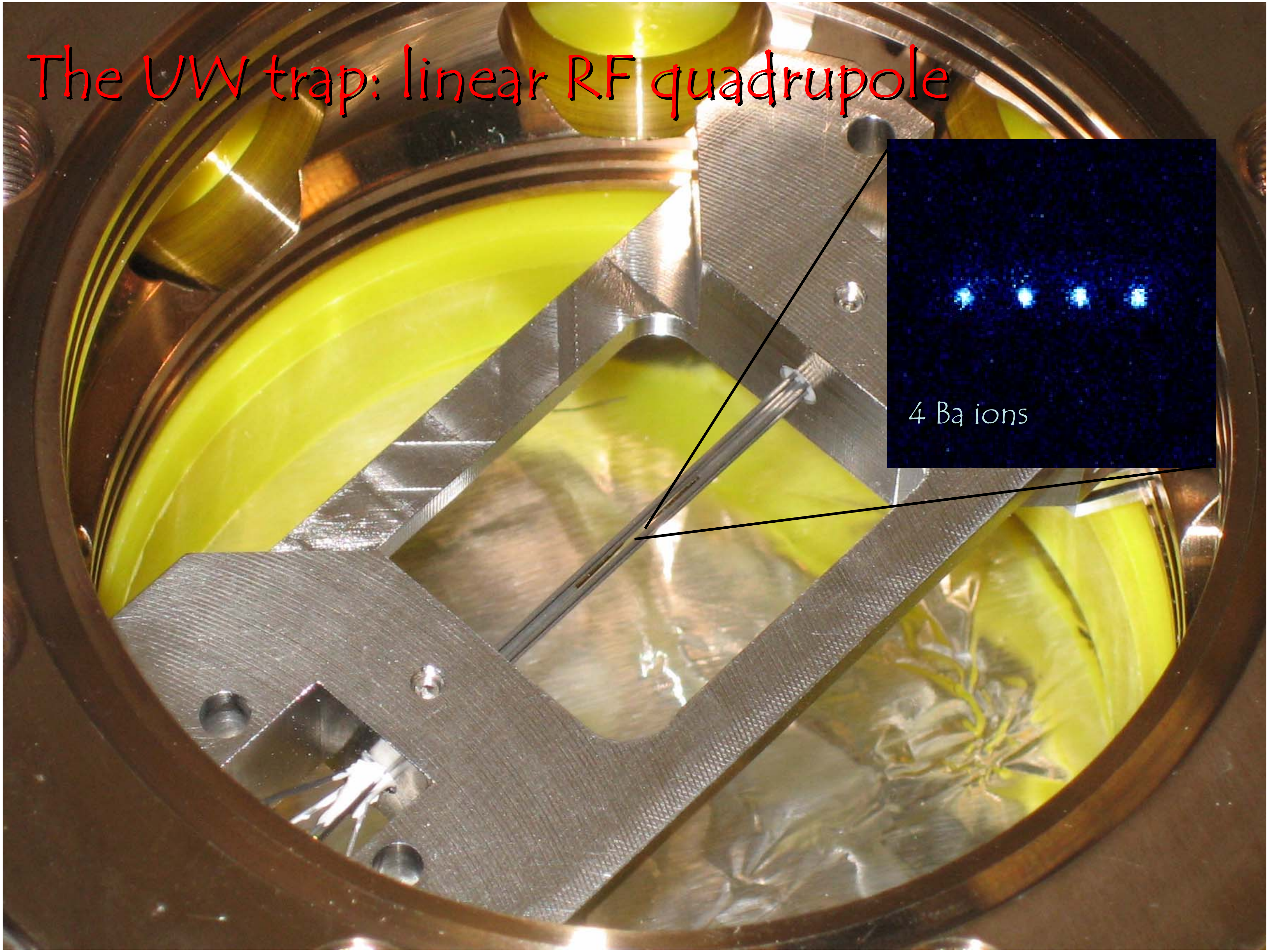


3-d RF quadrupole

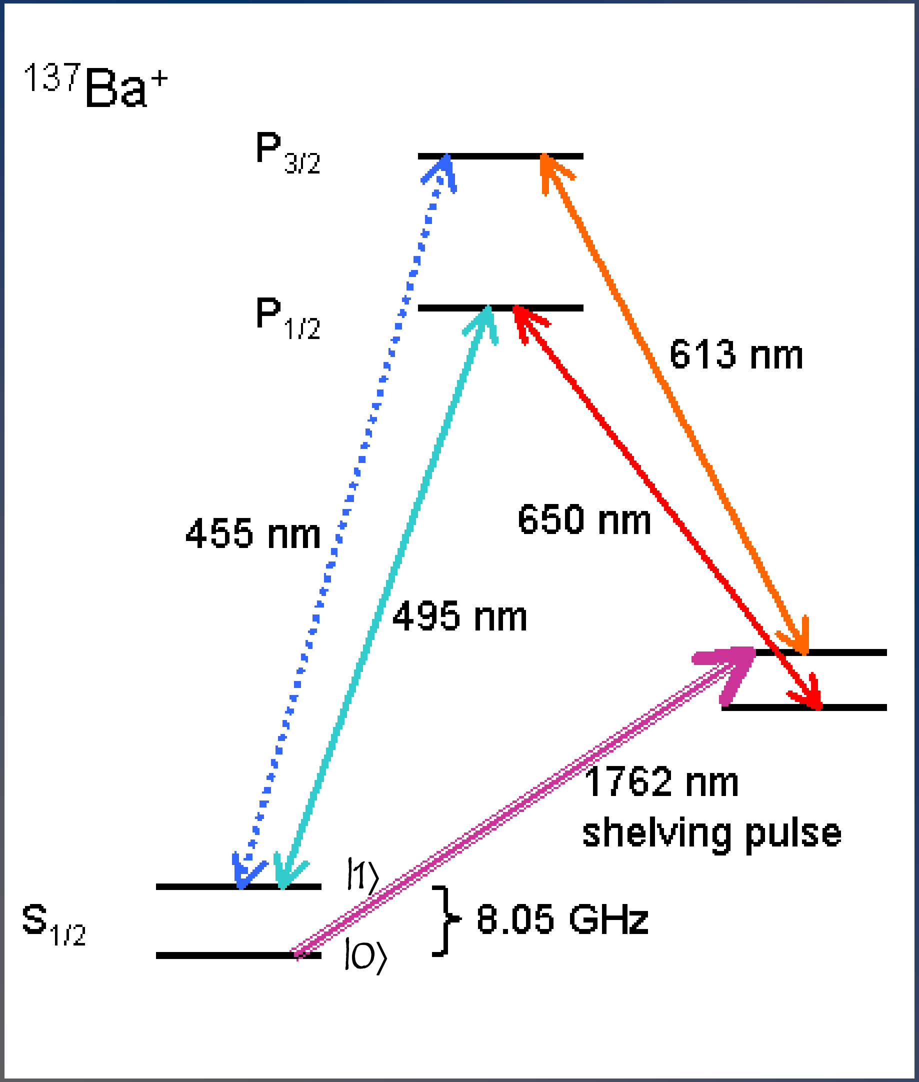




The UW trap: linear RF quadrupole



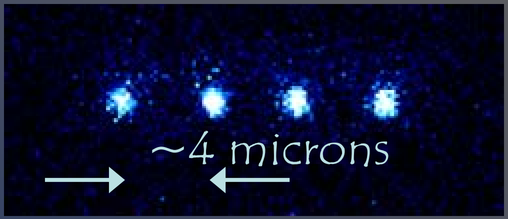
$^{137}Ba^{+}$ qubit



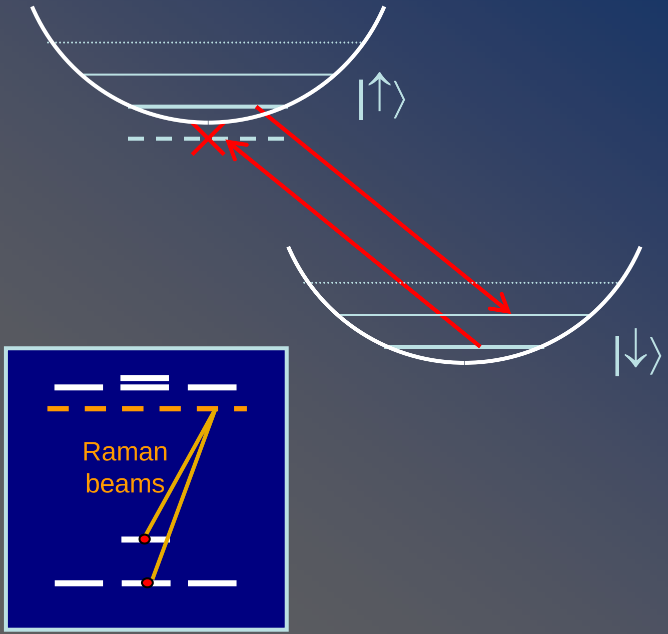
- Qubit: the hyperfine levels of the ground state
- Initialization by optical pumping
- Detection by state-selective shelving and resonance fluorescence
- Single-qubit operations with microwaves or optical Raman transitions
- Multi-qubit quantum logic gates via Coulomb interaction or via photon coupling

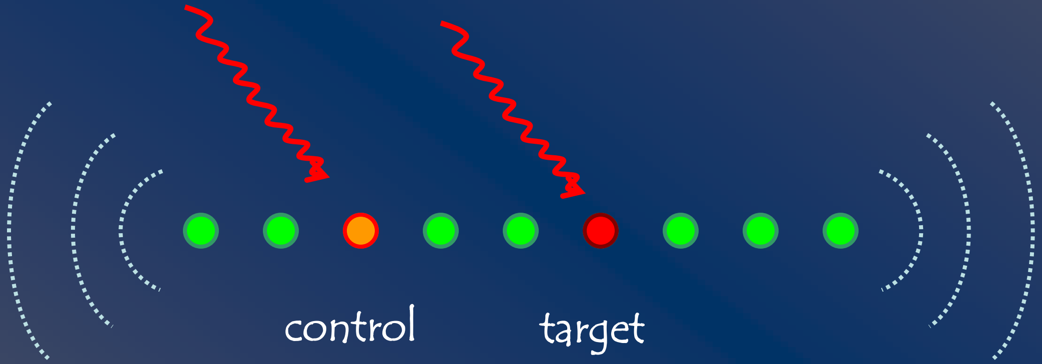
Cirac-Zoller CNOT gate – the classic trapped ion gate

Ions are too far apart, so their spins do not talk to each other directly.



To create an effective spin-spin coupling, "control" spin state is mapped on to the motional "bus" state, the target spin is flipped according to its motion state, then motion is remapped onto the control qubit.





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

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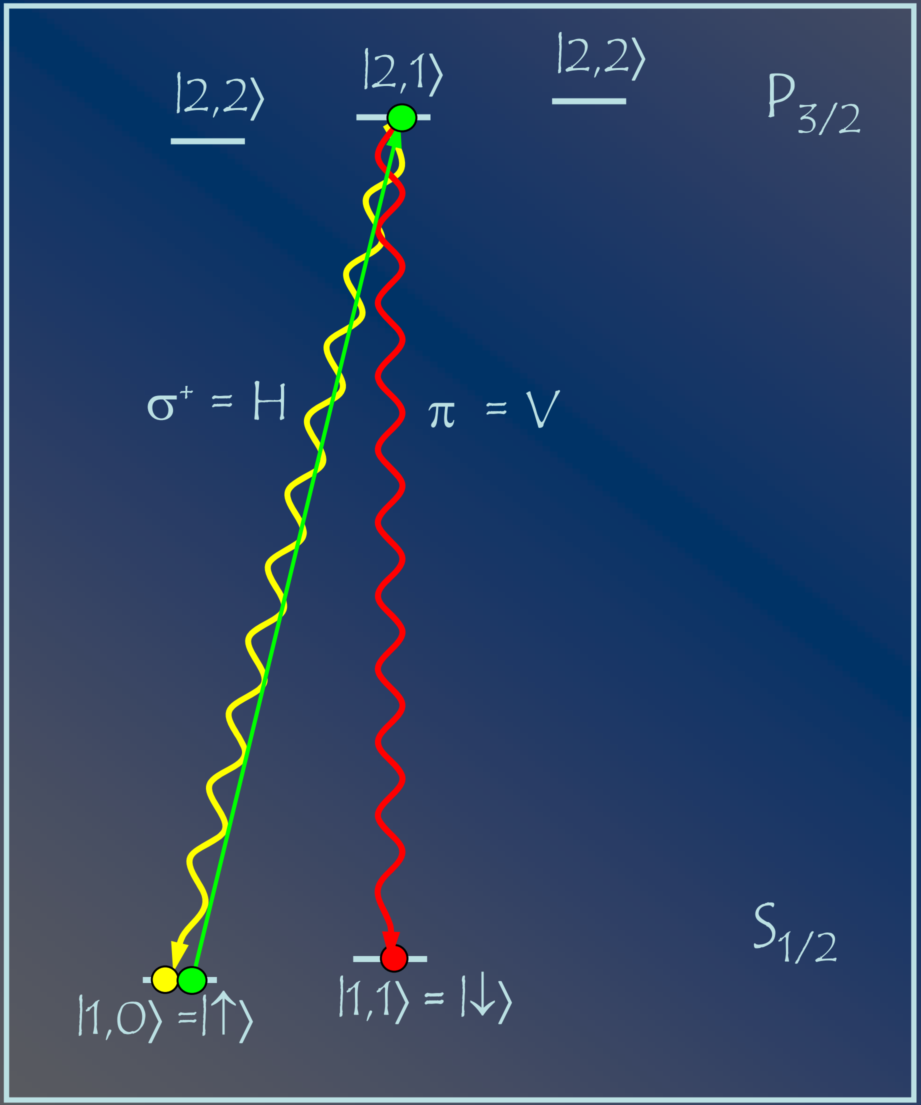
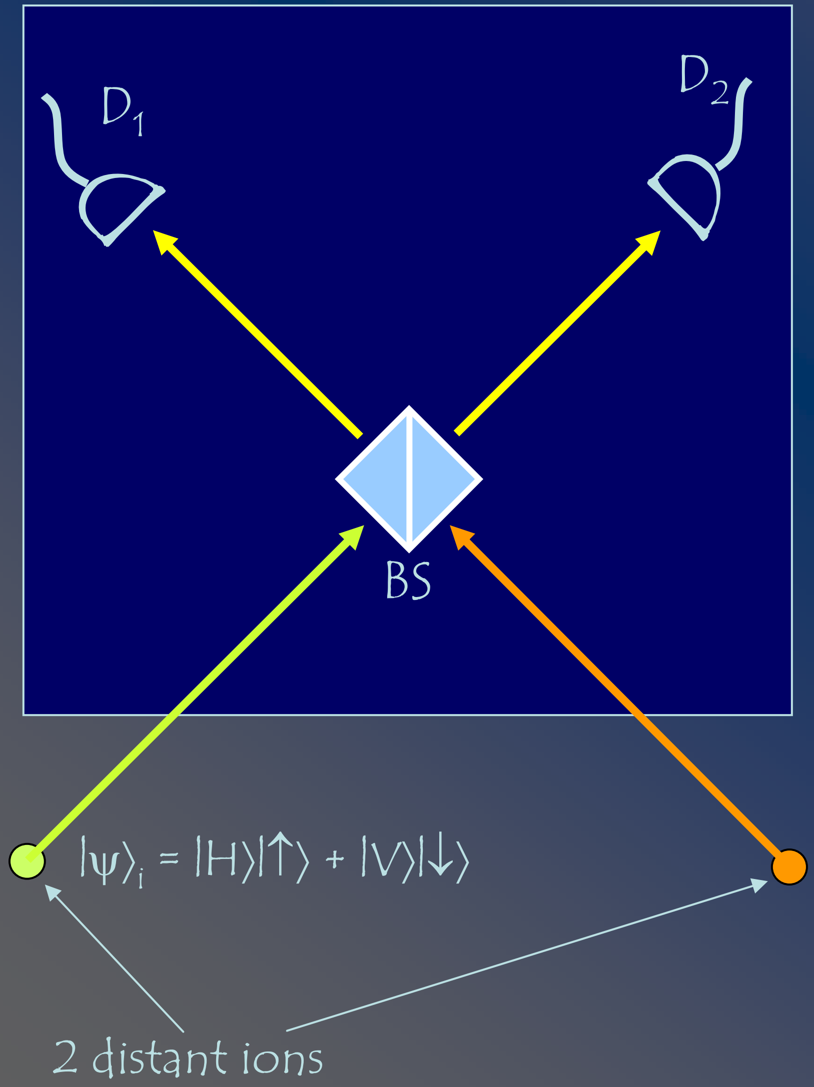
Ion-photon entanglement via spontaneous emission



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

Remote Ion Entanglement

using entangled ion-photon pairs



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

Coincidence only if photons 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!

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

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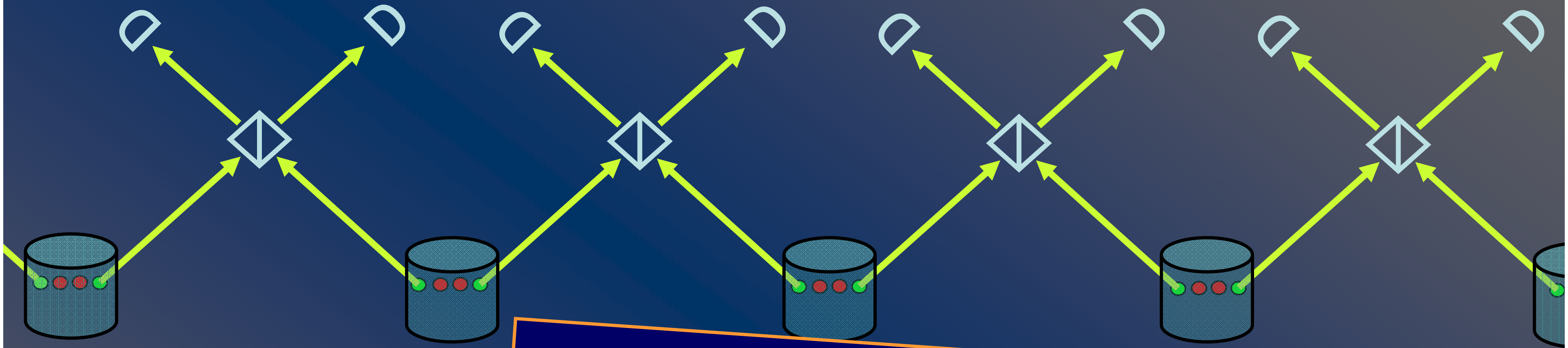
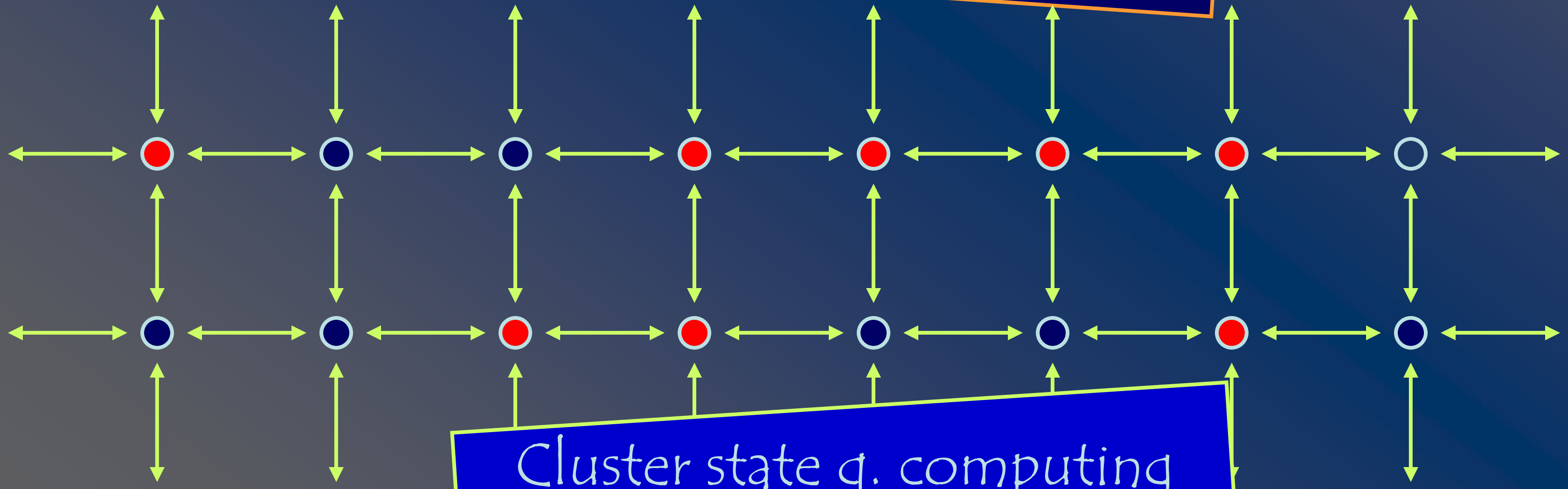
Quantum networking and quantum computing using ion-photon entanglement



Quantum repeater network



Cluster state q. computing

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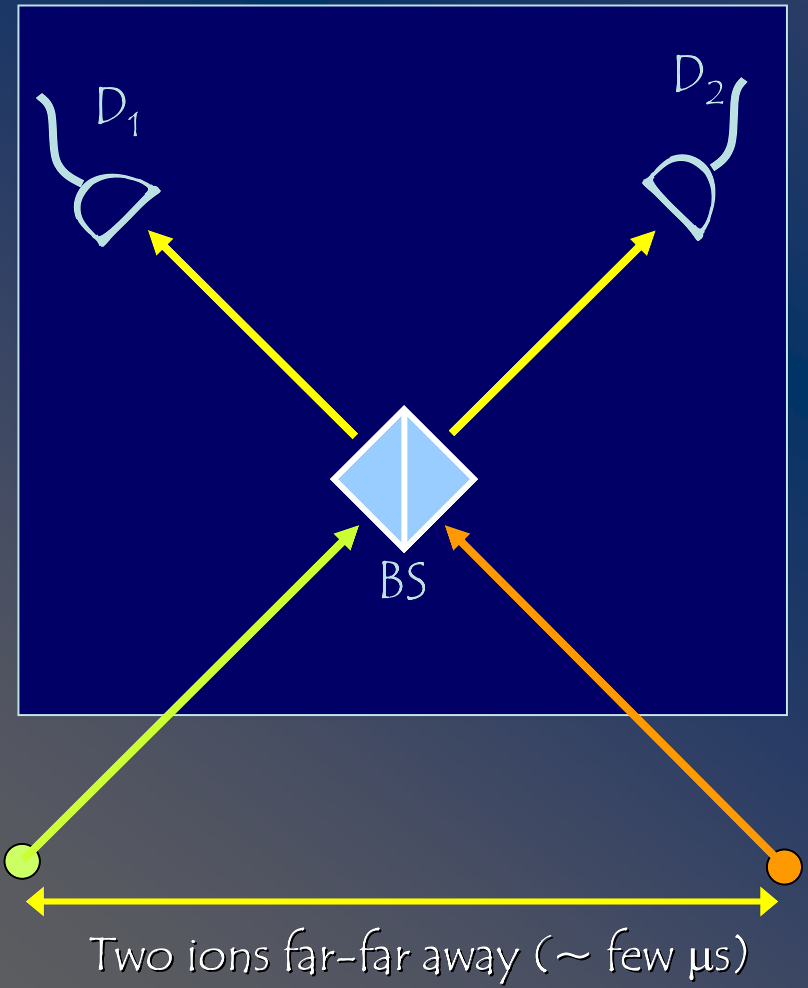
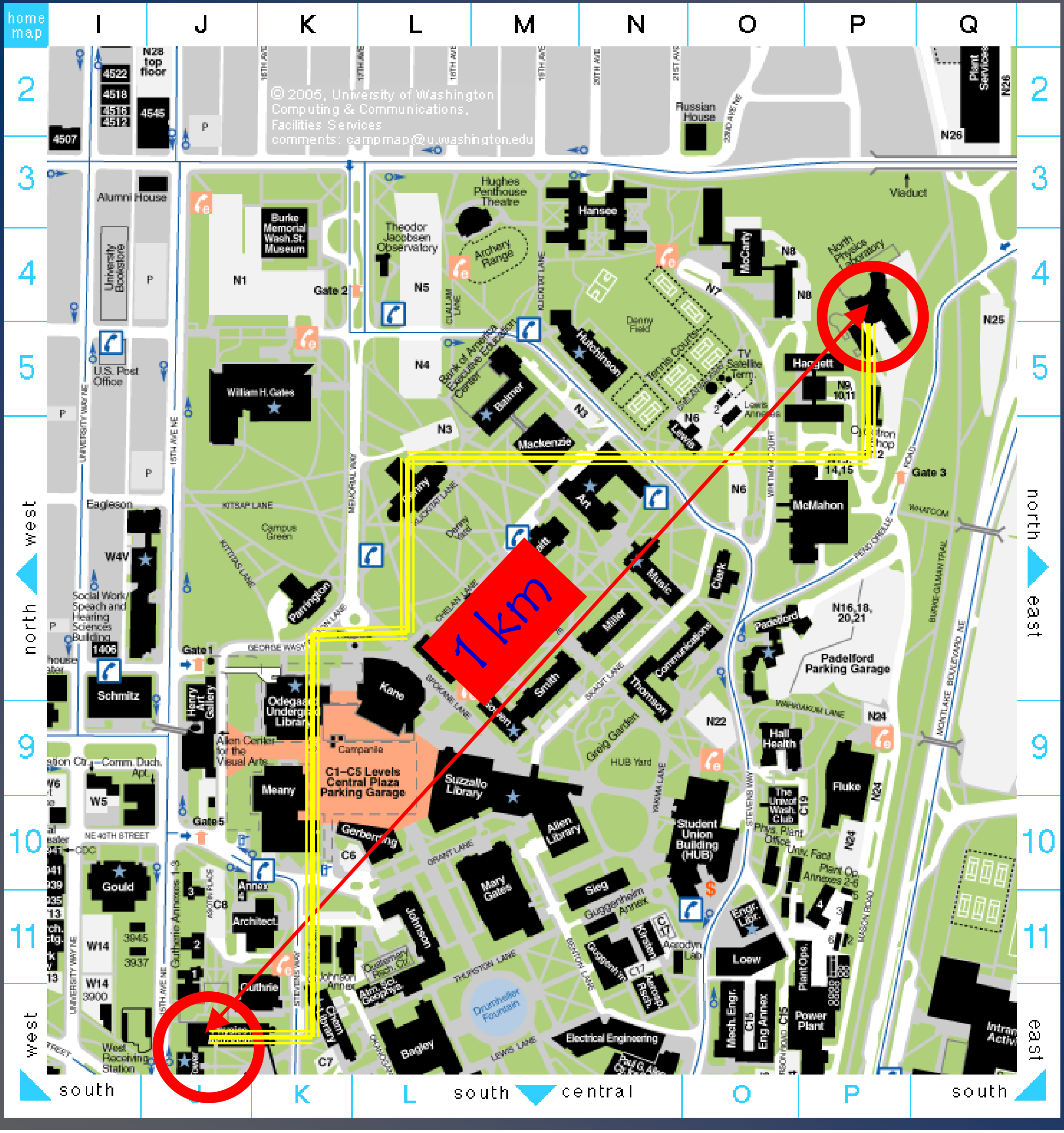
Loophole-free Bell inequality test



- While the ion-photon entanglement is probabilistic, the remote entanglement of ions is "heralded".
- This entangled state of the ions can be used to measure the Bell inequality violation with both major loopholes (the locality and the detection) closed, thus providing the first ever loophole-free verification of nonlocal nature of quantum mechanics.

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

Loophole-free Bell inequality violation: two ions far-far away



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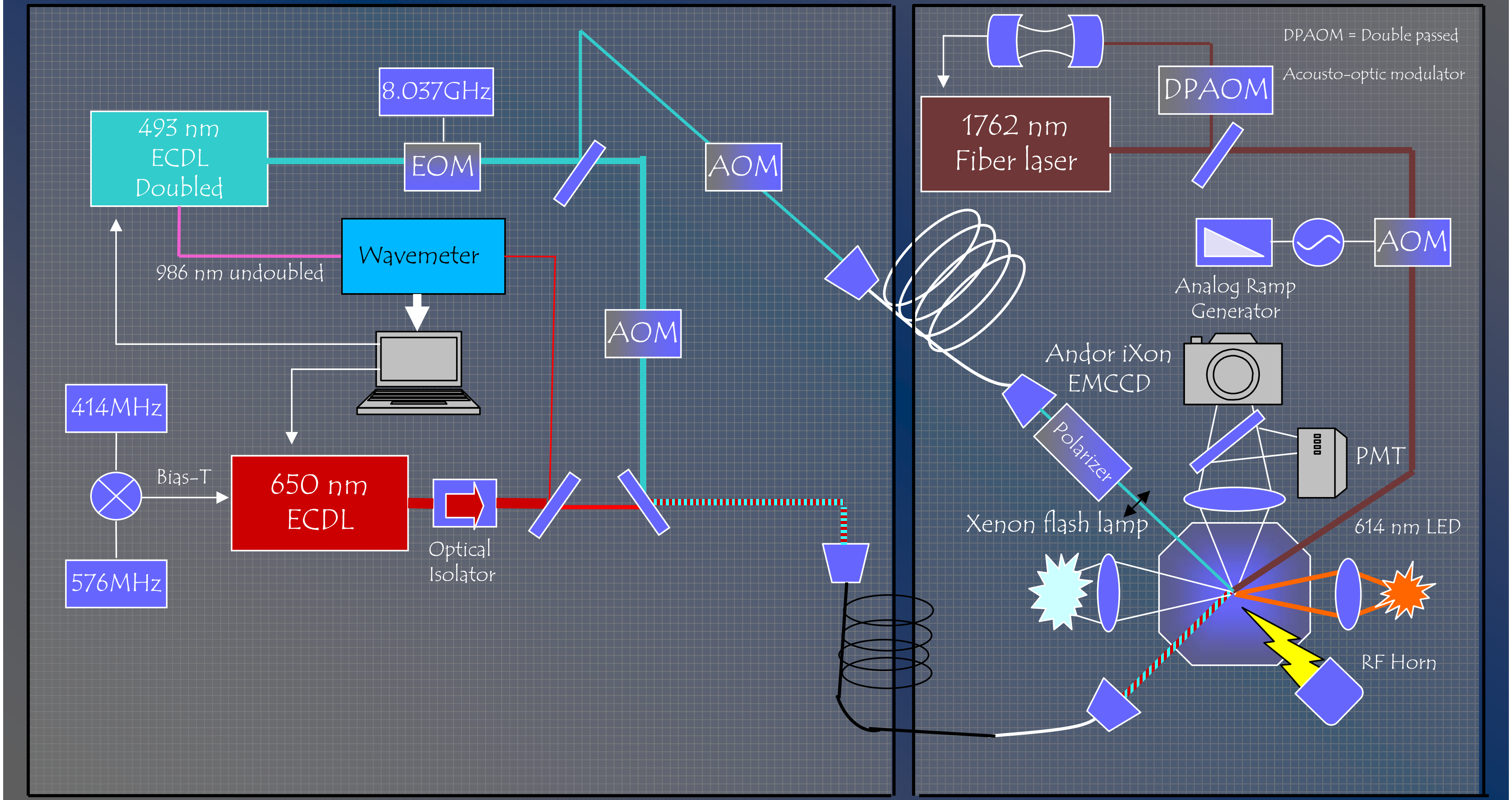
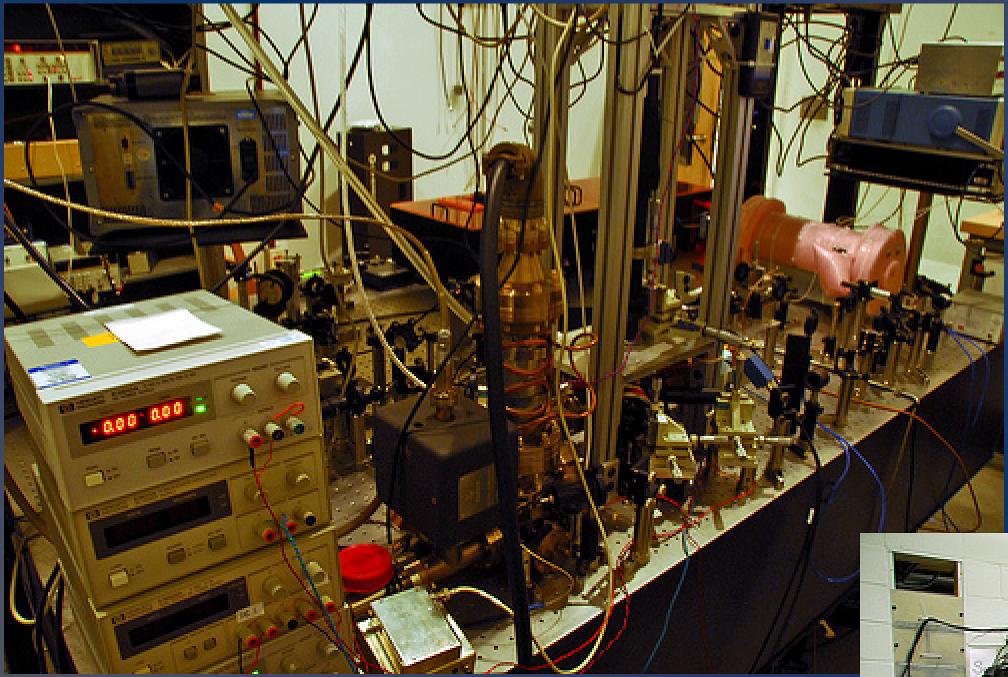
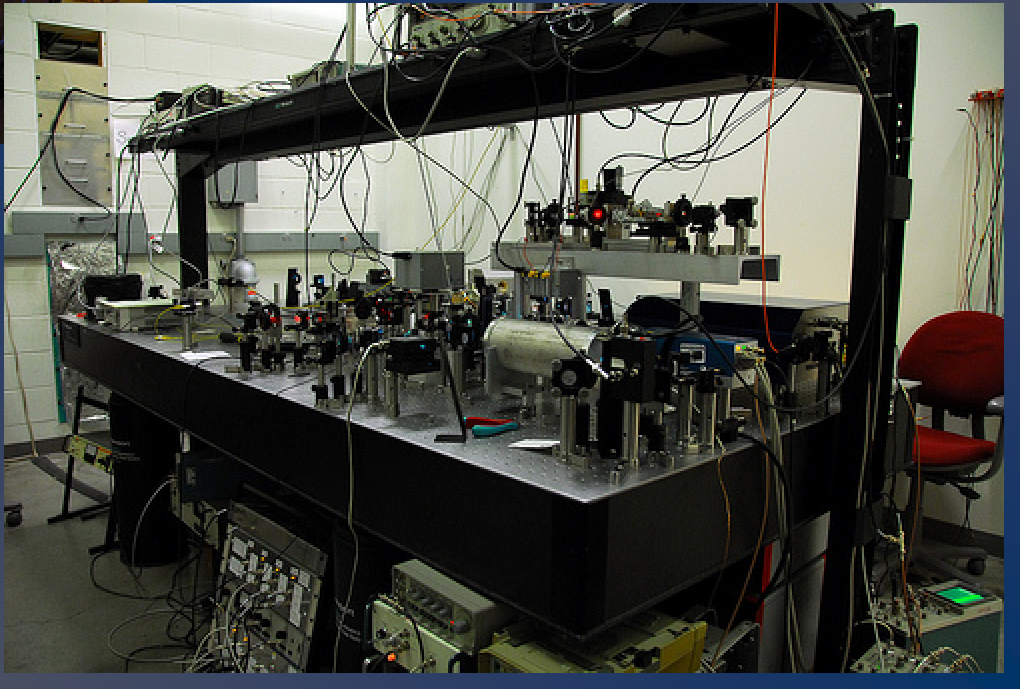
Experimental Apparatus

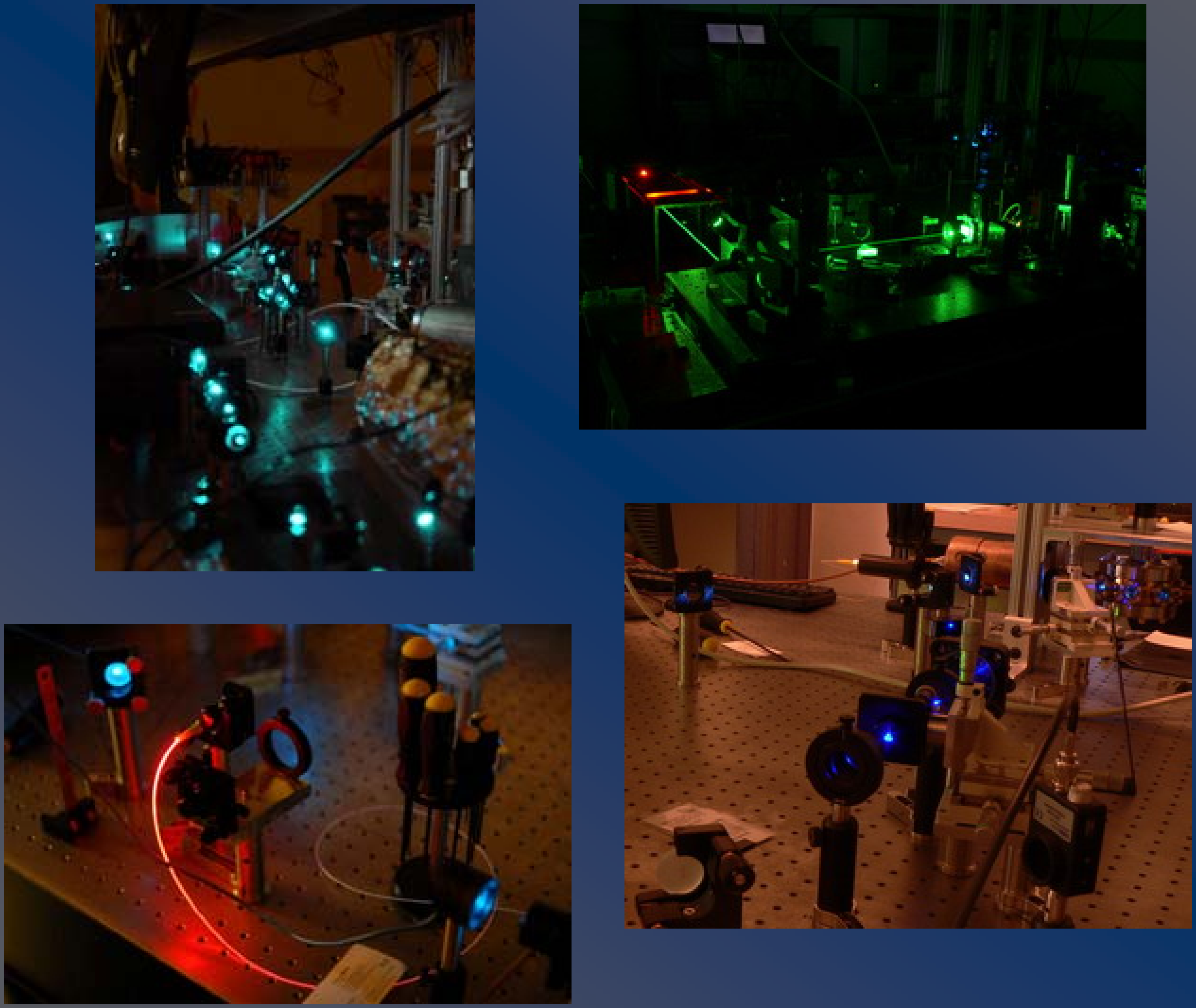


UW ion trap QC lab

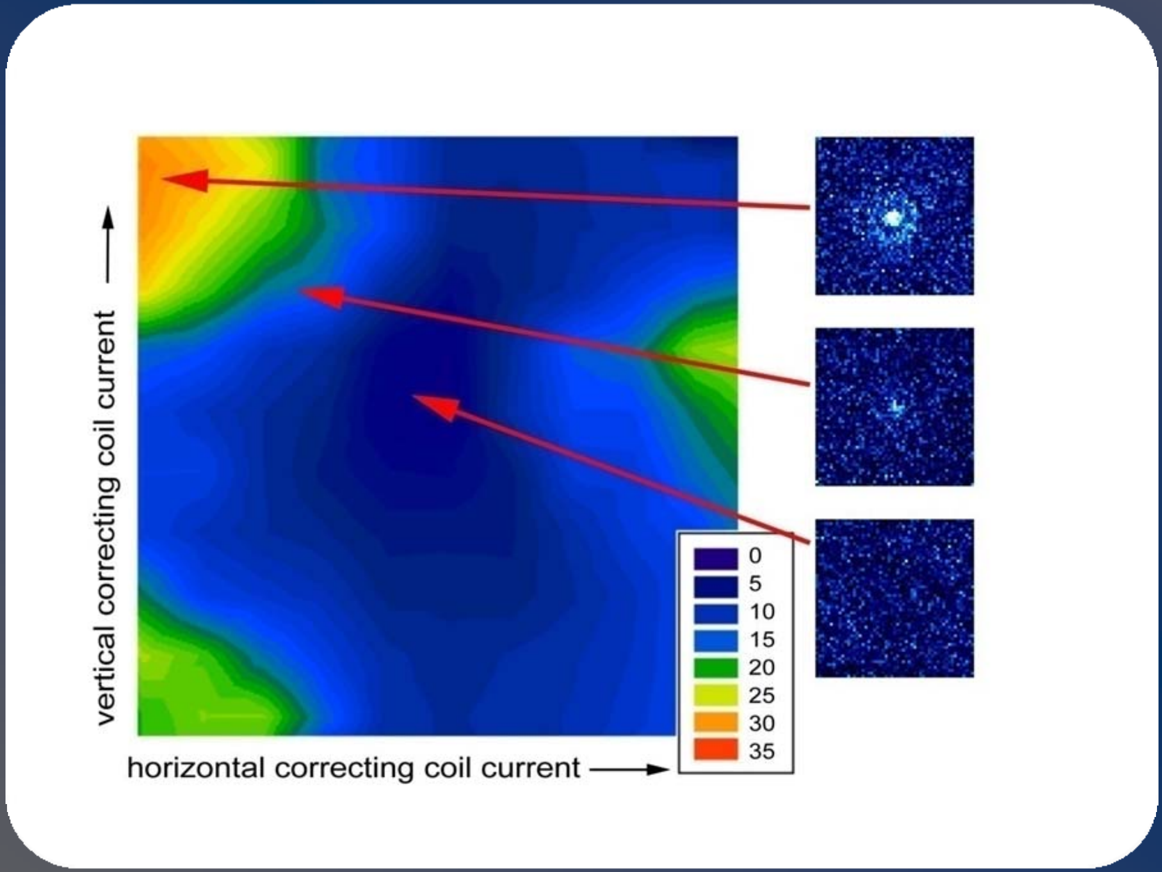




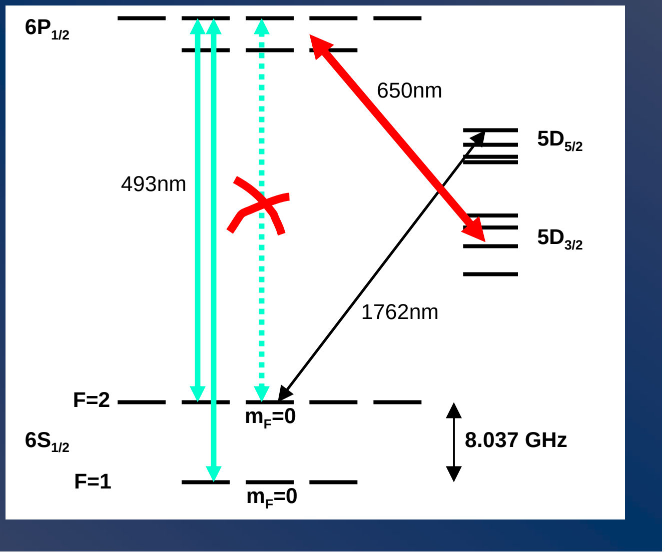
Pictures from the lab



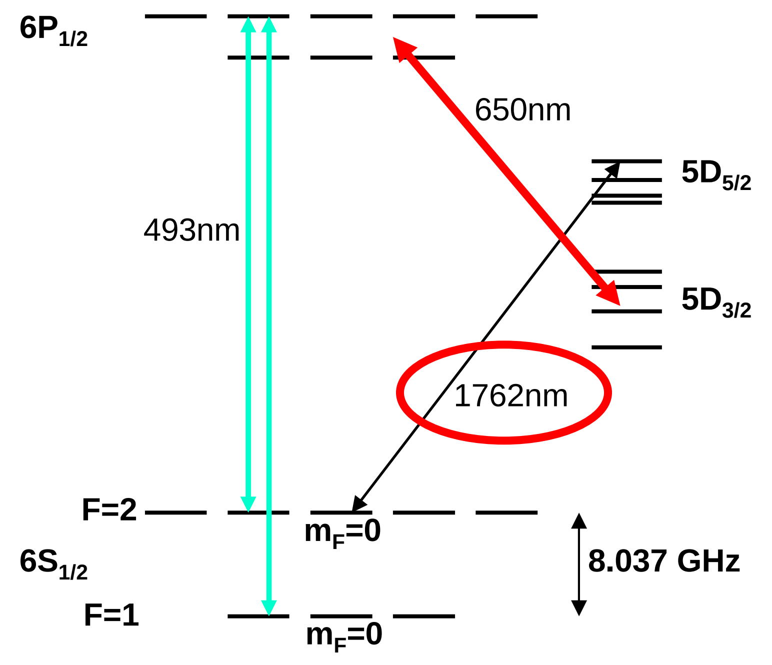
Optical pumping: qubit initialization



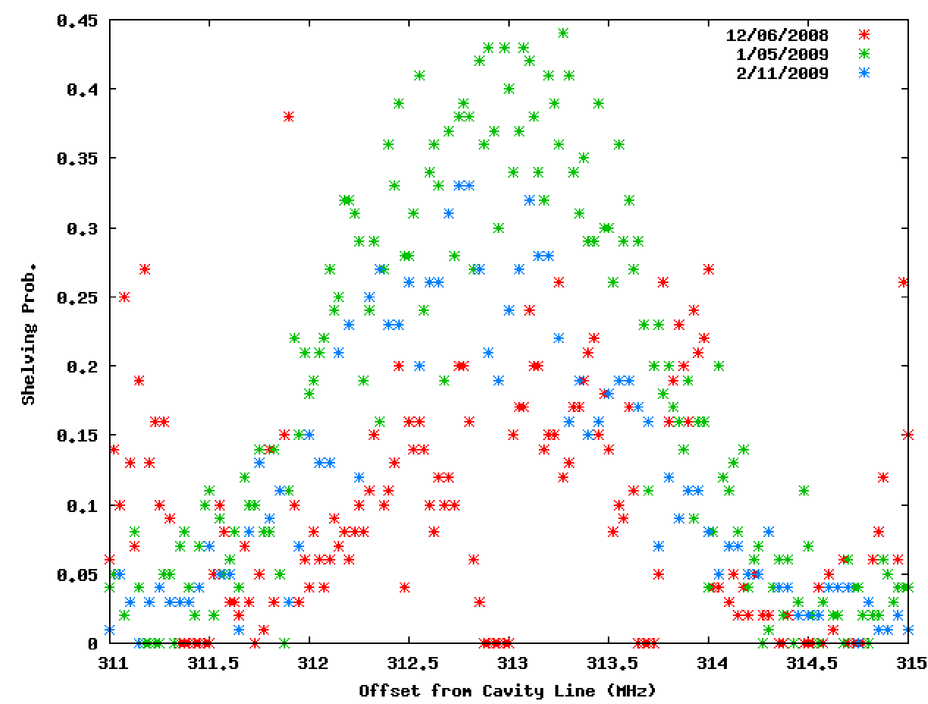
pi-polarized light pumps the population into the F=2, m_f=0 state. When pumped, ion stops fluorescing. We adjust the pump light polarization by tuning the magnetic field direction instead.



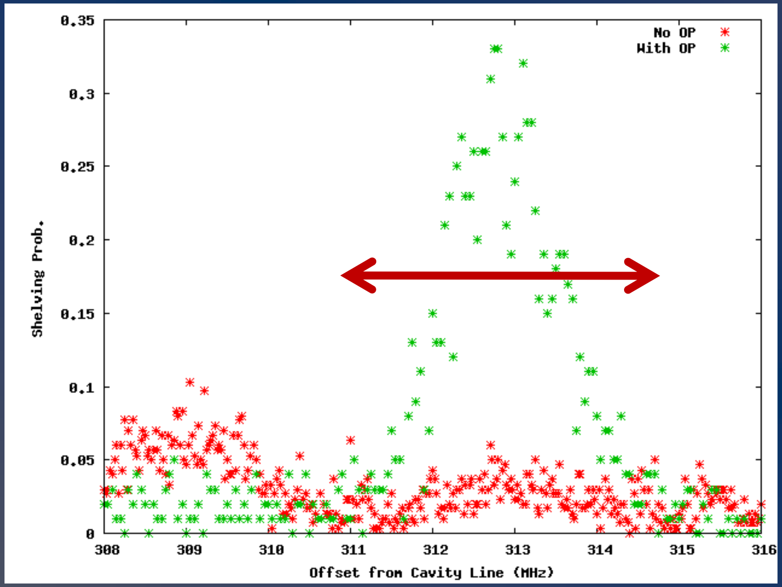
Shelving via adiabatic passage: qubit readout



To detect qubit state we selectively "shelve" the electron to the $5D_{5/2}$ state which remains dark when the cooling laser light is applied.



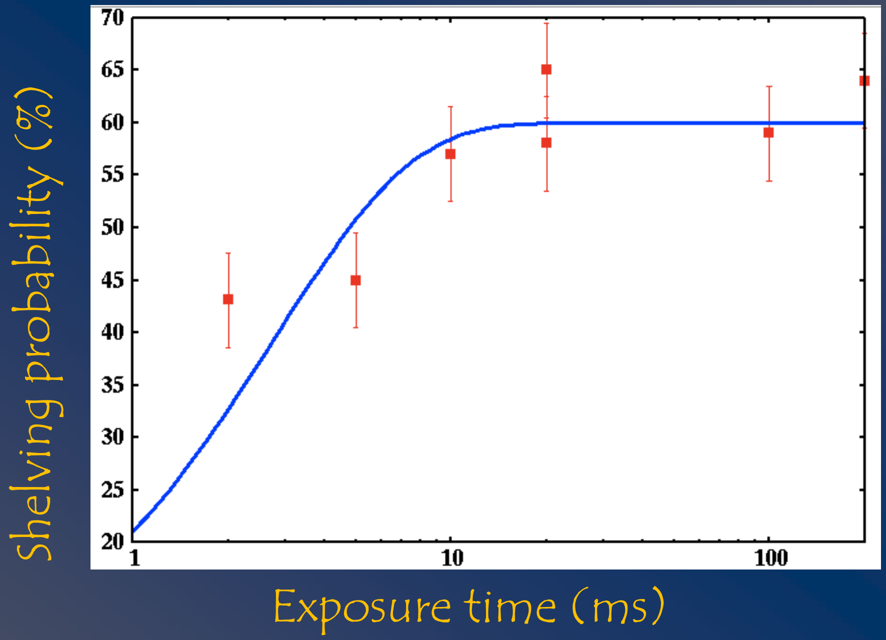
Shelving via adiabatic passage: qubit readout



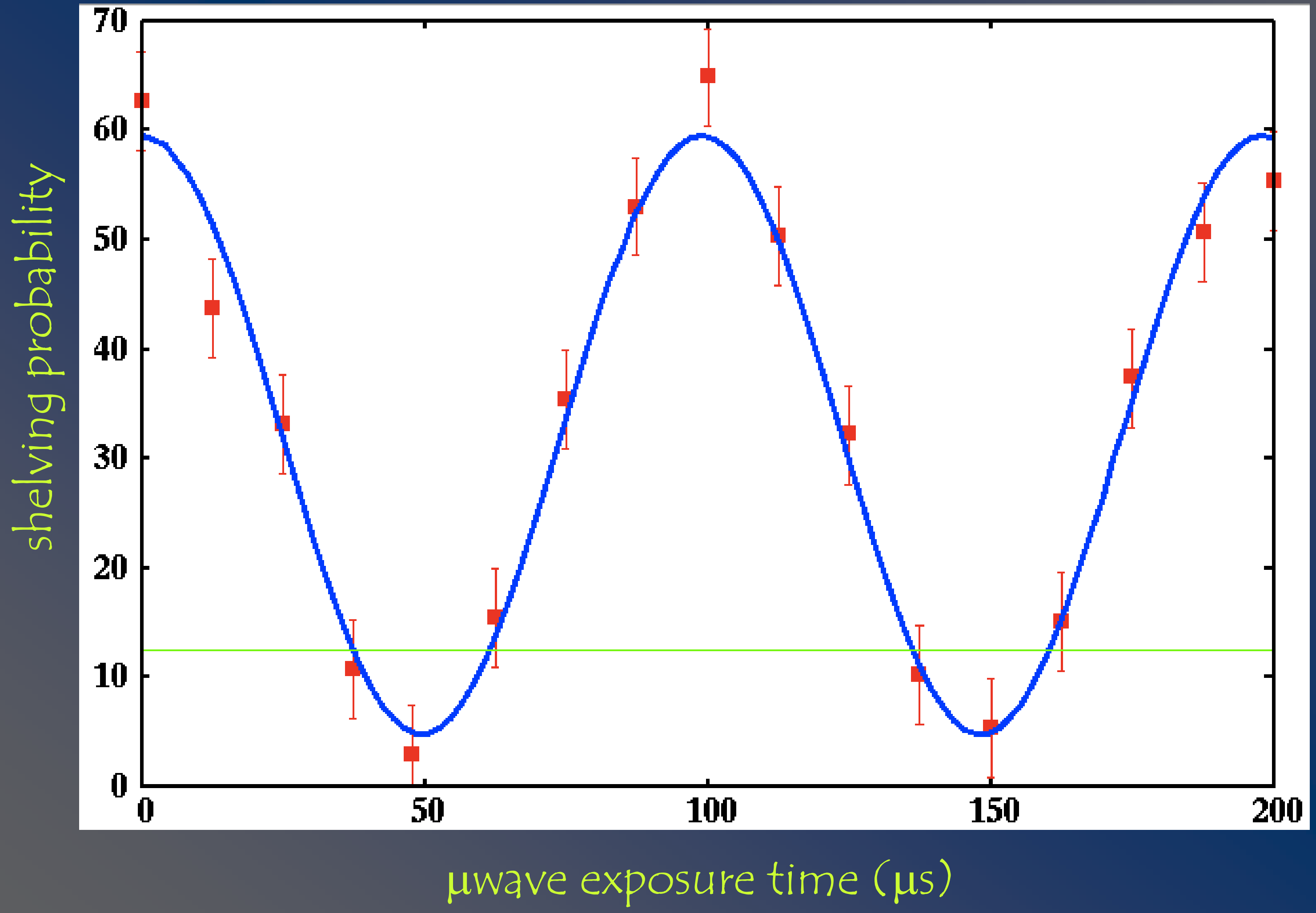
The "adiabatic passage" method allows high-fidelity population transfer, and is robust against laser intensity noise and frequency drift.

However, laser line width has to be small compared to the (power broadened) width of the atomic transition.

Ω=120 KHz, Δf=20 MHz

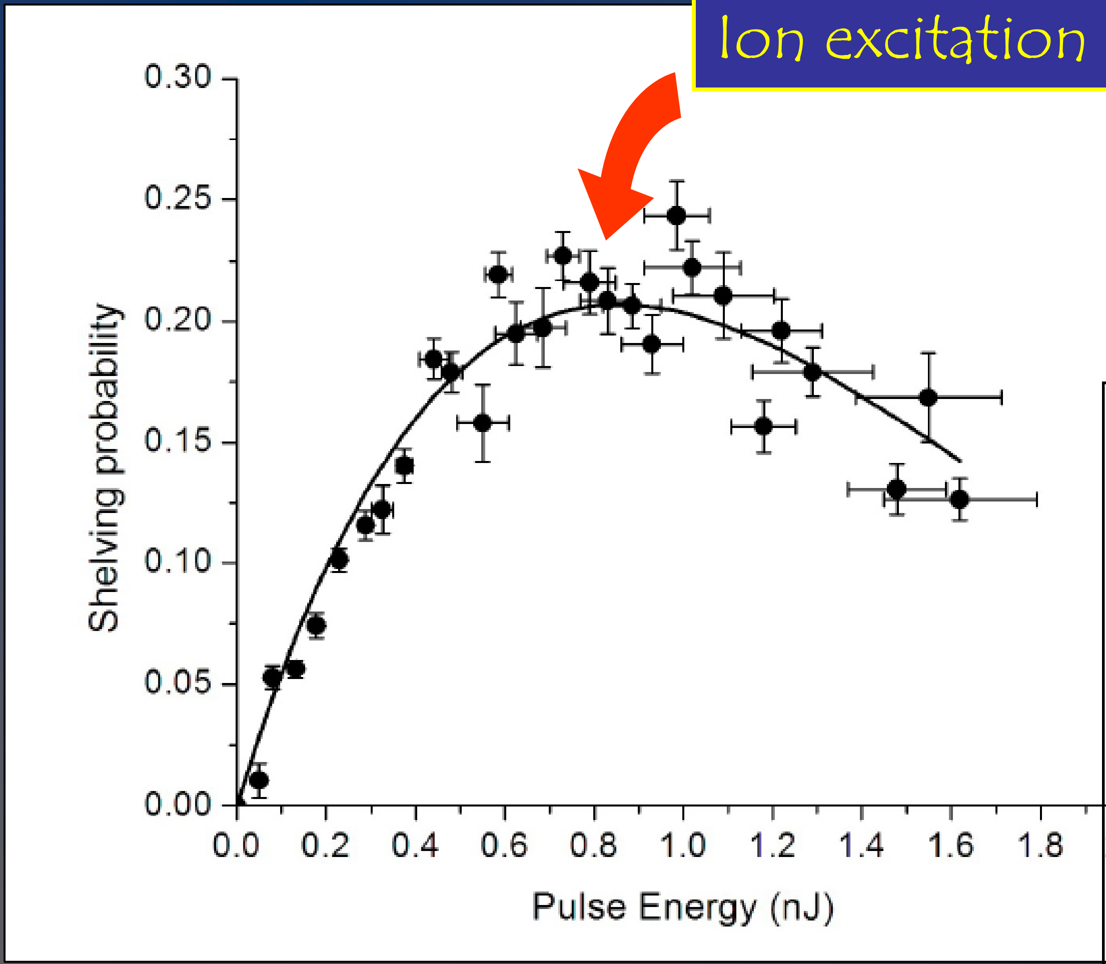


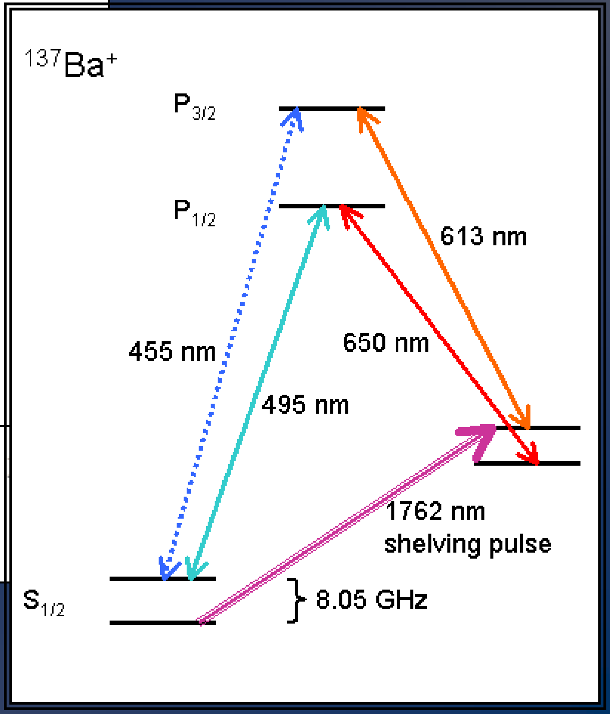
Single qubit Rabi flopping



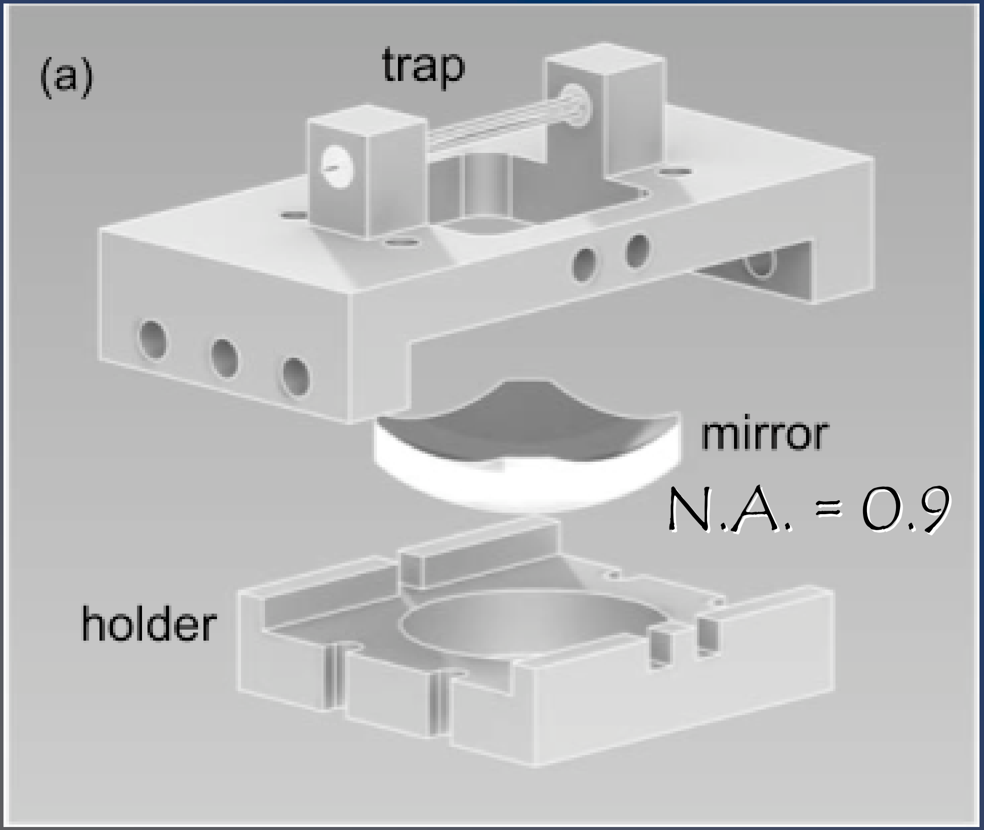
Femtosecond optical Rabi flopping

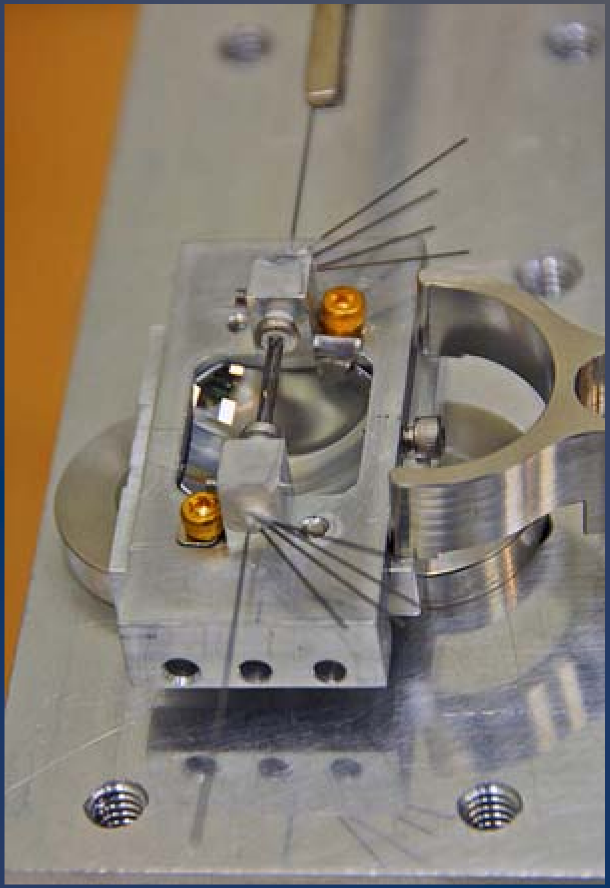
Ion excitation with unit probability



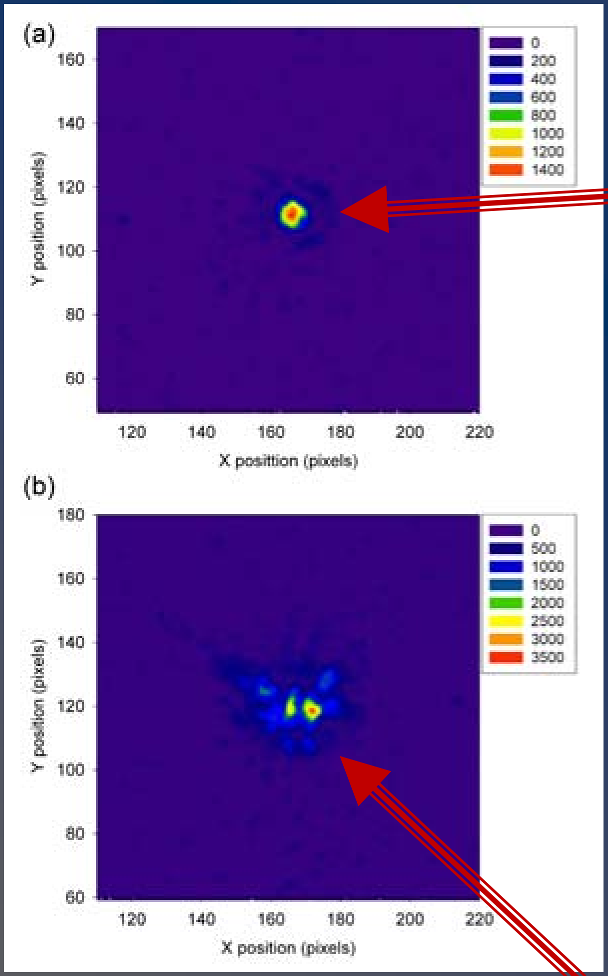


"Integrated optics": ion trap with a spherical mirror





Ion imaging with the spherical mirror

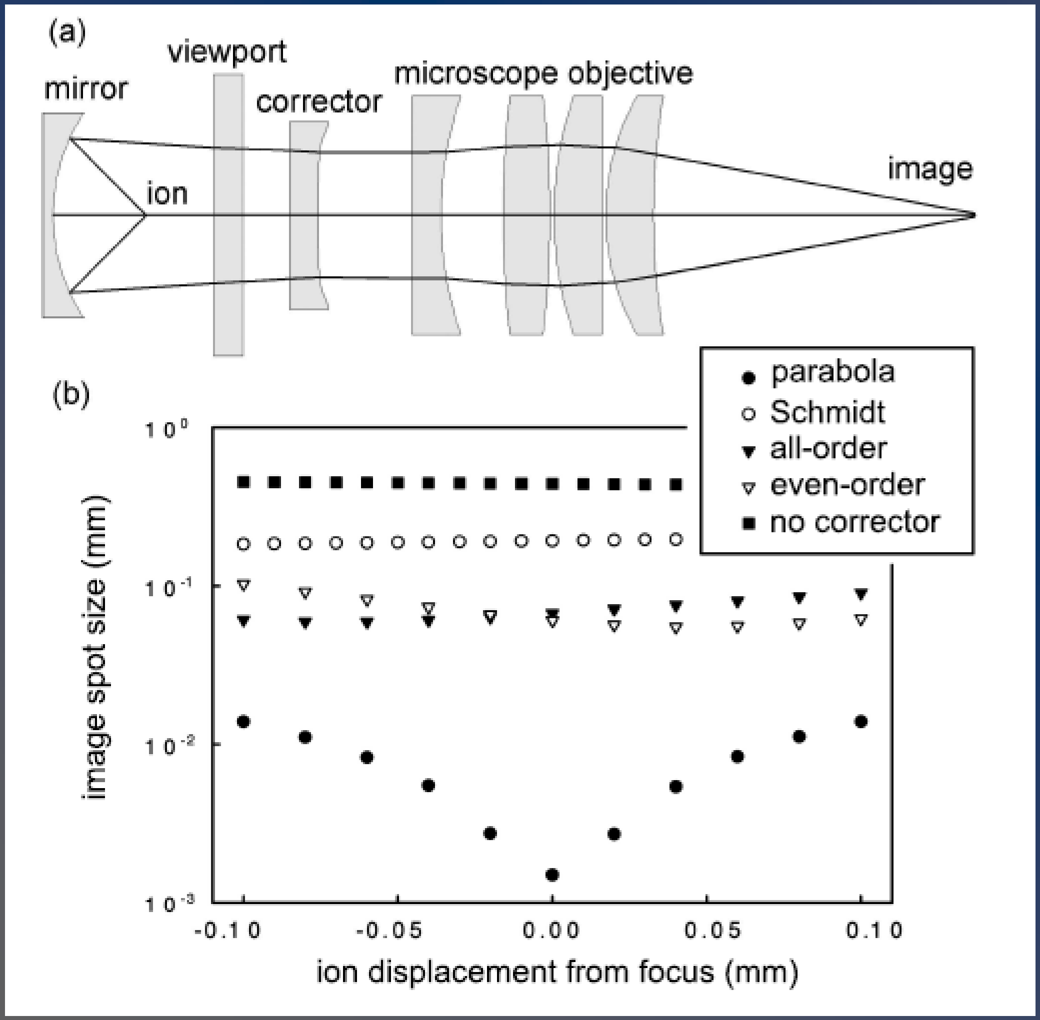


Ion image with a 0.25 N.A. diffraction-limited multielement lens.

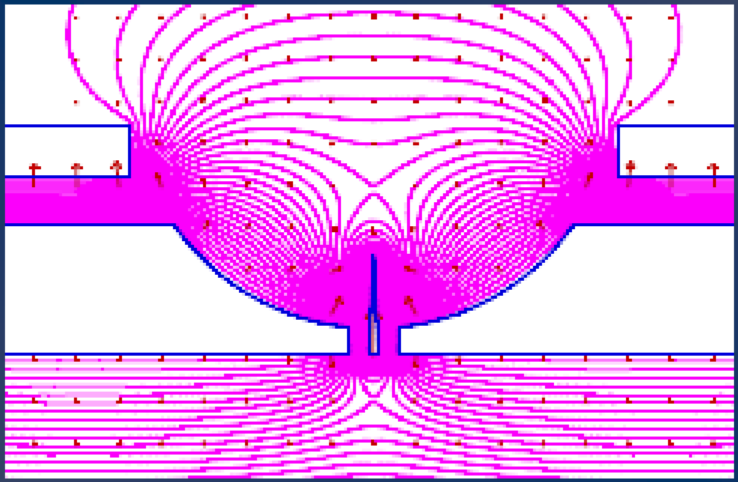
Same ion imaged with a 0.9 N.A. spherical mirror. Total count rate is 7 times higher.

Two ions!

Improving image quality… and the trap!



We can replace the linear trap with a combination of a ring and a needle to trap ions at the focus of the metallic spherical mirror



Final remarks…

Quantum

"Computers in the future may weigh no more than 1.5 tons."

- Popular Mechanics (1949)

Quantum

"I think there is a world market for maybe five computers."

- Thomas Watson, chairman of IBM (1943)

UW ion trappers