AG Quantenoptik
und Spektroskopie

Quantum information processing with trapped ions

universität
innsbruck

Courtesy of Timo Koerber
Institut für Experimentalphysik
Universität Innsbruck

Terminology

Atom is neutral (all electrons are present)
Ion has one or more electrons removed - therefore it is charged. In quantum information, we use either neutral atoms or singly-charged ions that have one electron removed.

The qubit representations are the same in atoms and ions but trapping and logic gate technologies are completely different. Therefore, we first discuss what make a good qubit for atom/ion and then separately consider and ions for quantum information.

In the discussion below, I will use "atom" for either atom or ion unless we discuss a specific system.

Main info about atoms:

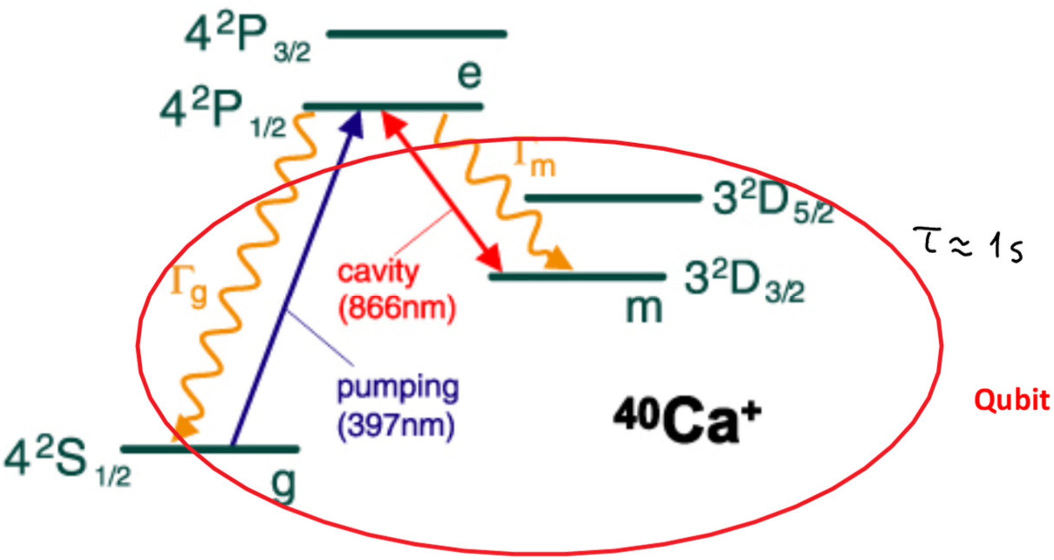
(1) Atom have different "energy levels"

(2) This energy levels are discrete by the rules of quantum mechanics.

(3) The levels are described by "quantum numbers"

(4) The lowest energy level is called the ground state

(5) Higher energy levels are called excited states



Main info about atoms contd.:

(6) The atoms can absorb photons of only specific wavelengths given by the difference of two these discrete energy levels.

(5) There are vastly different separation between different energy levels - some can be in microwave region and some in ultraviolet or even X-ray (for ions)

(6) When the atom emits a photon and jumps to lower energy level it is called spontaneous emission.

There are also vastly different "lifetimes" of the excited states defined by their electronic structure. Some can live for years and some will decay in nanoseconds.

(7) Table-top lasers can be built from VUV (not too deep in VUV) to infrared run (generally under 2000 nm except 10.6 micron case)

Which atoms make good qubits?

(1) Need two level system - generally ground state will be state |0>

(2) Upper level should not decay fast

(3) Other states should not inflict significant errors

(4) Either difference between the |0> and |1> levels is laser-accessible or there are other states accessible from |0> and |1> that are laser accessible.

(5) This atom/ ion can be cooled and trapped.

(6) Simple electronic structure is preferred.

(7) Specific isotopes are preferred over others (for example with zero or $I=1/2$ nuclear spin)

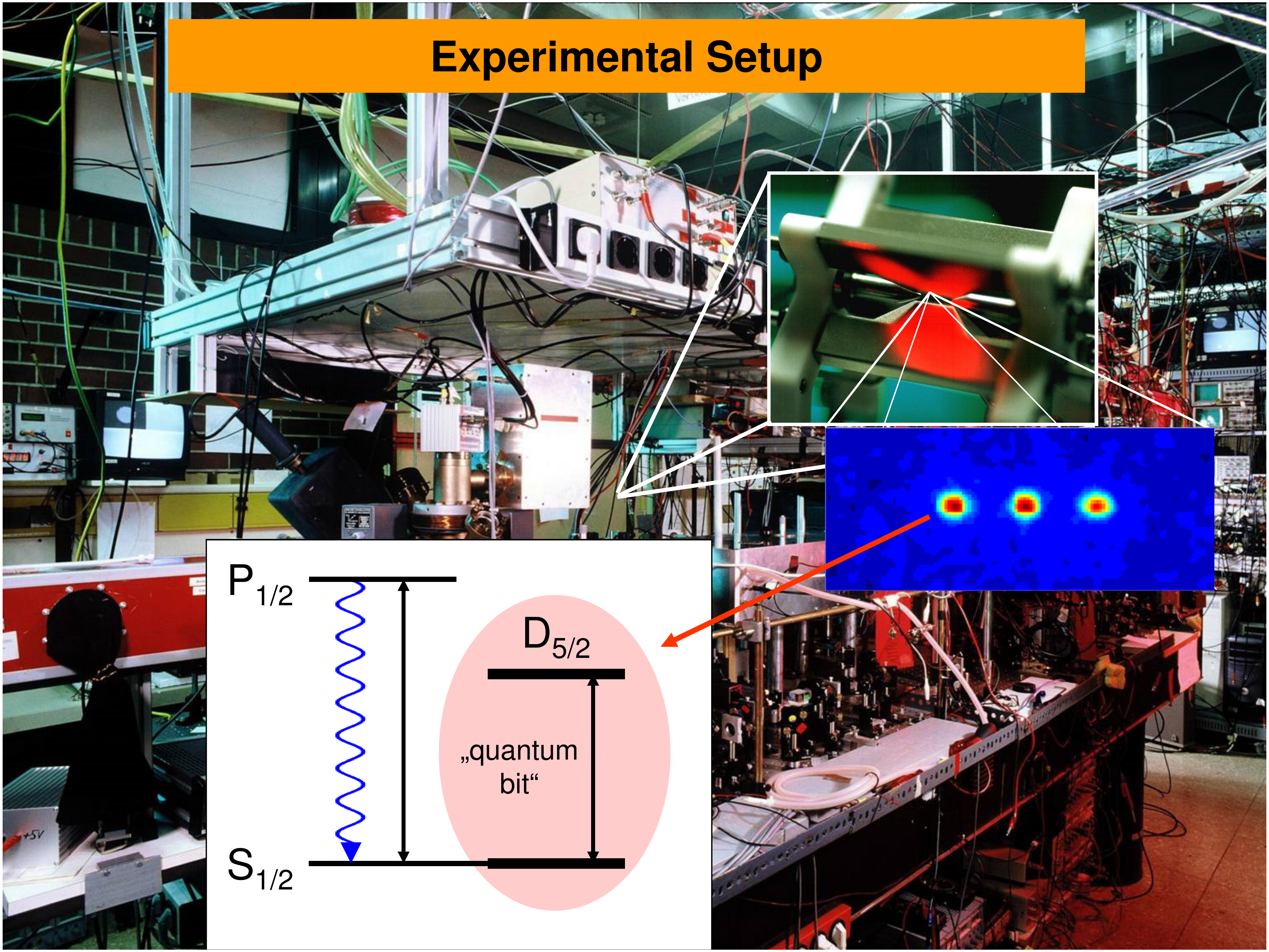
(8) Generally, stable isotopes are used (with some recent exceptions to get $I=1/2$ in a favorable system)

The requirements for quantum information processing

D. P. DiVincenzo, Quant. Inf. Comp. **1** (Special), 1 (2001)

I. Scalable physical system, well characterized qubits
II. Ability to initialize the state of the qubits
III. Long relevant coherence times, much longer than gate operation time
IV. “Universal” set of quantum gates
V. Qubit-specific measurement capability

Experimental Setup

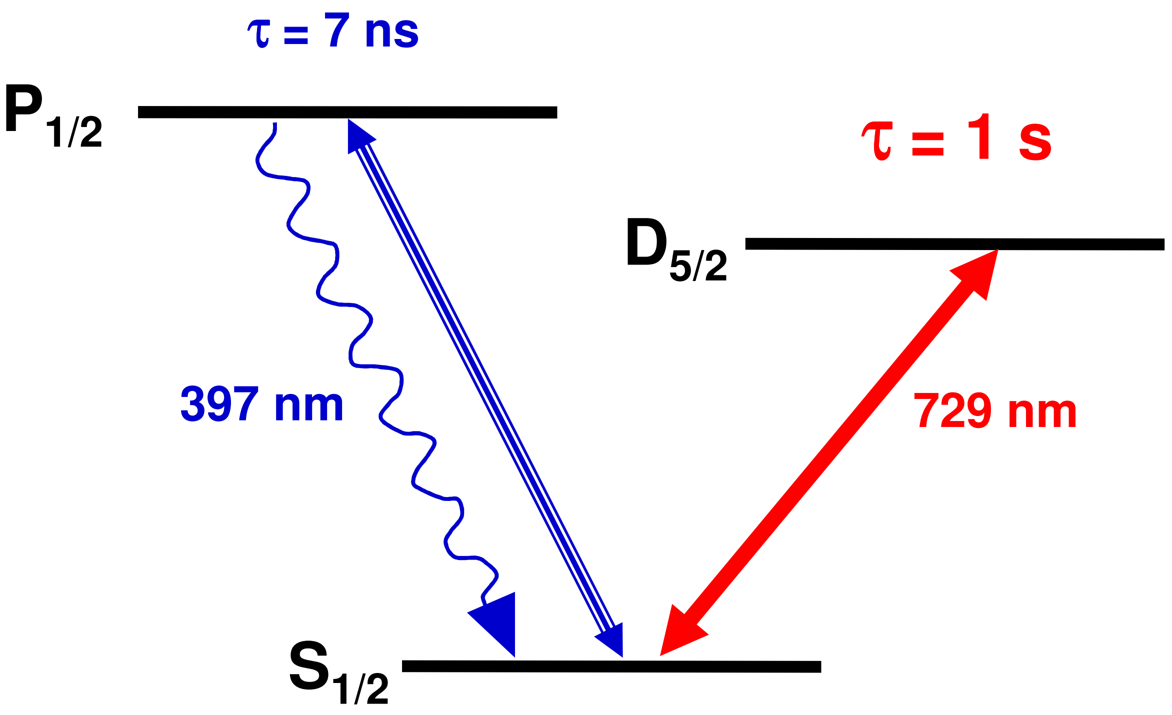


Important energy levels

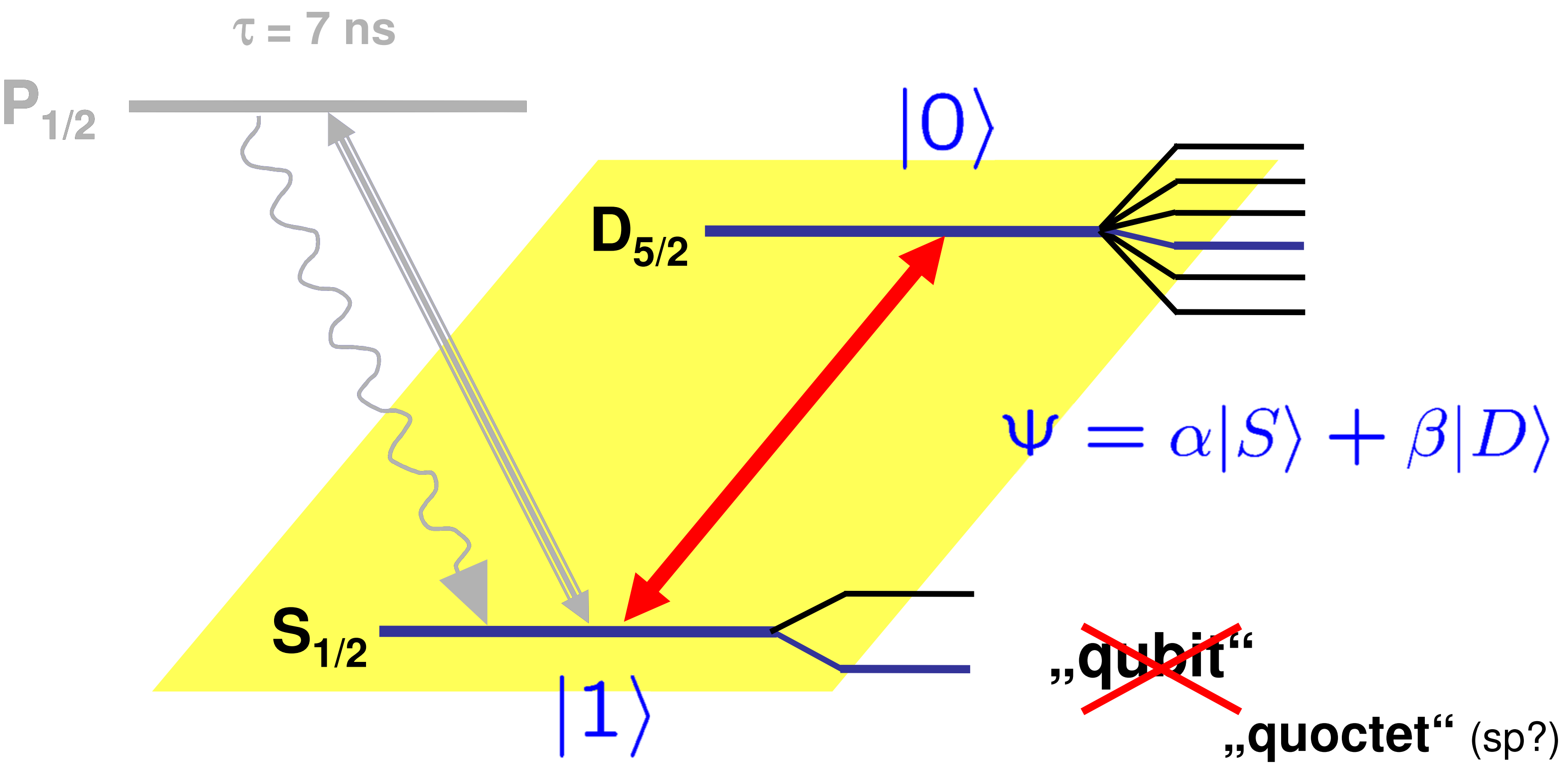
- The important energy levels are shown on the next slides; a fast transition is used to detect ion fluorescence and for Doppler cooling, while the narrow D5/2 quadrupole transition has a lifetime of 1 second and is used for coherent manipulation and represents out quantum bit. Of course a specific set of Zeeman states is used to actually implement our qubit. The presence of other sublevels give us additional possibilities for doing coherent operations.

Ca+: Important energy levels

$S_{1/2} – D_{5/2}$: quadrupole transition



Ca+: Important energy levels



Qubits with trapped ions

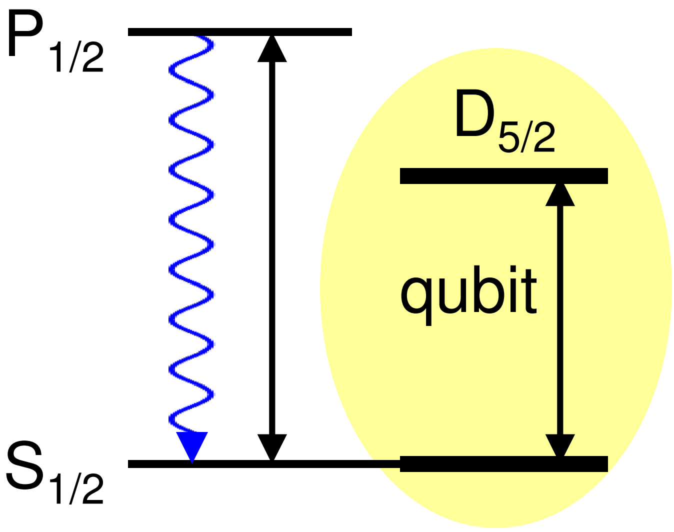
Encoding of quantum information requires long-lived atomic states:

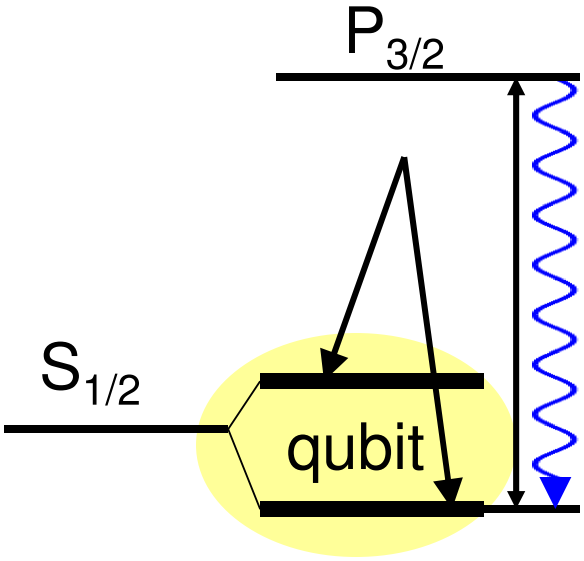
- optical transitions

  Ca^+, Sr^+, Ba^+, Ra^+, Yb^+, Hg^+ etc.

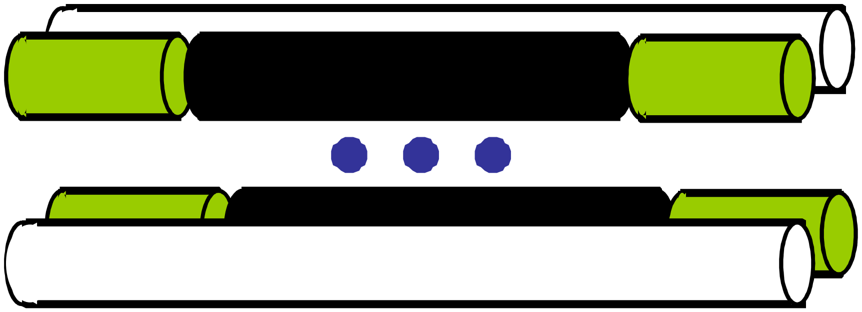
- microwave transitions

  $^{9}Be^+$, $^{25}Mg^+$, $^{43}Ca^+$, $^{87}Sr^+$, $^{137}Ba^+$, $^{111}Cd^+$, $^{171}Yb^+$





Linear RF Paul trap

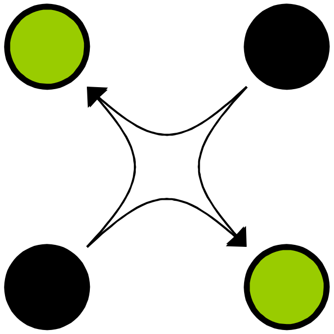


● Positive ion

▭ RF electrode

🟩 High dc potential
control electrode

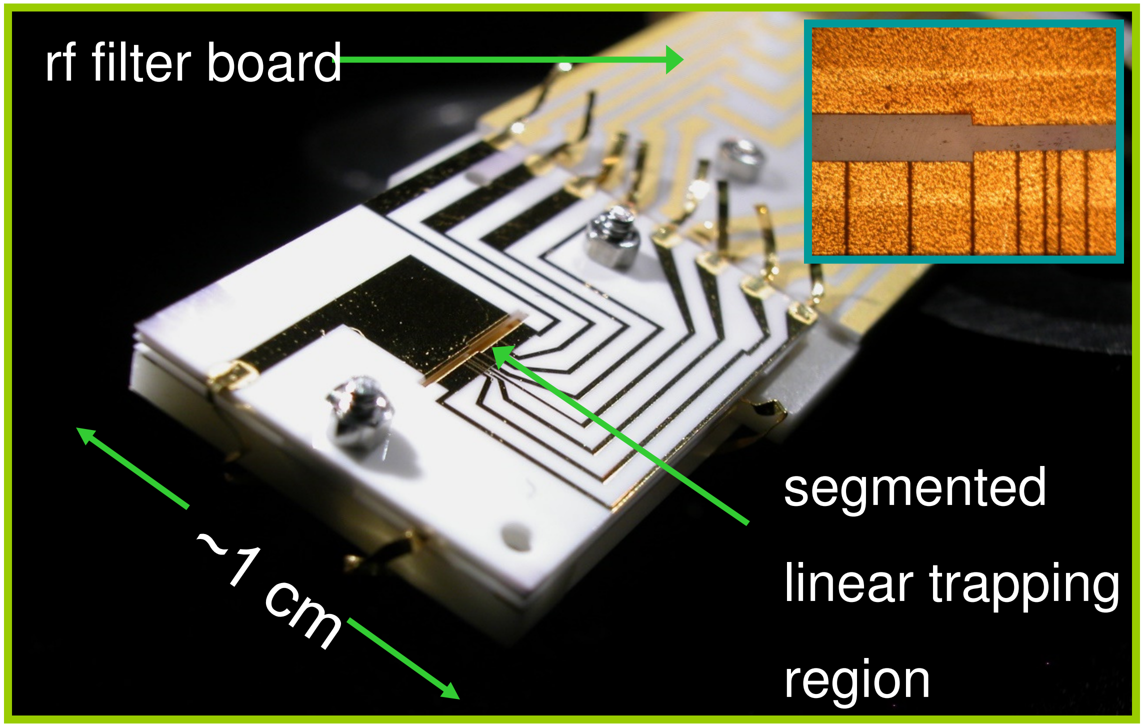
■ Low dc voltage
control electrode



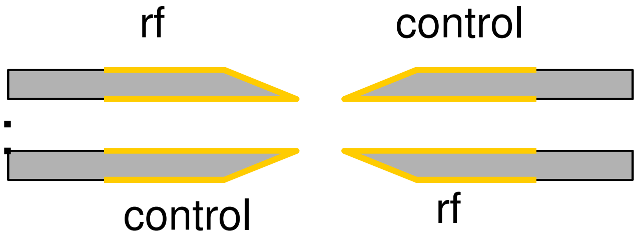
- Drive freq ~ 100-150 MHz
- RF amp ~ 200-400 V
- Secular freq
  - Radial ~ 15 MHz
  - Axial ~ 4 MHz

Slides from :R. Ozeri

Multi-zone ion trap

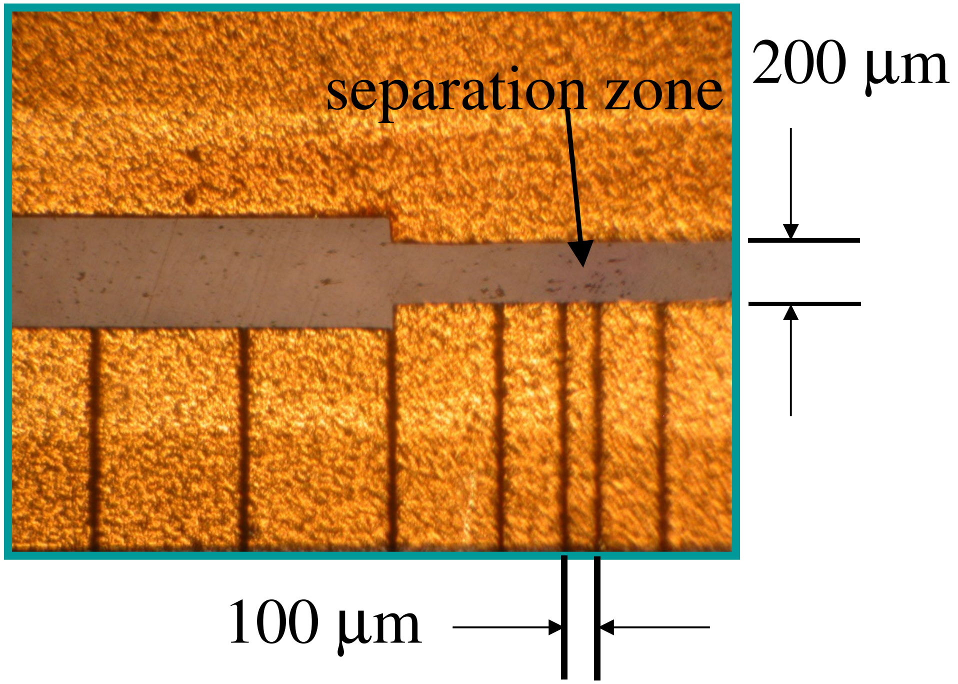


view along axis:



- Gold on alumina construction
- RF quadrupole realized in two layers
- Six trapping zones
- Both loading and experimental zones
- One narrow separation zone
- Closest electrode ~140 μm from ion

Ion transport

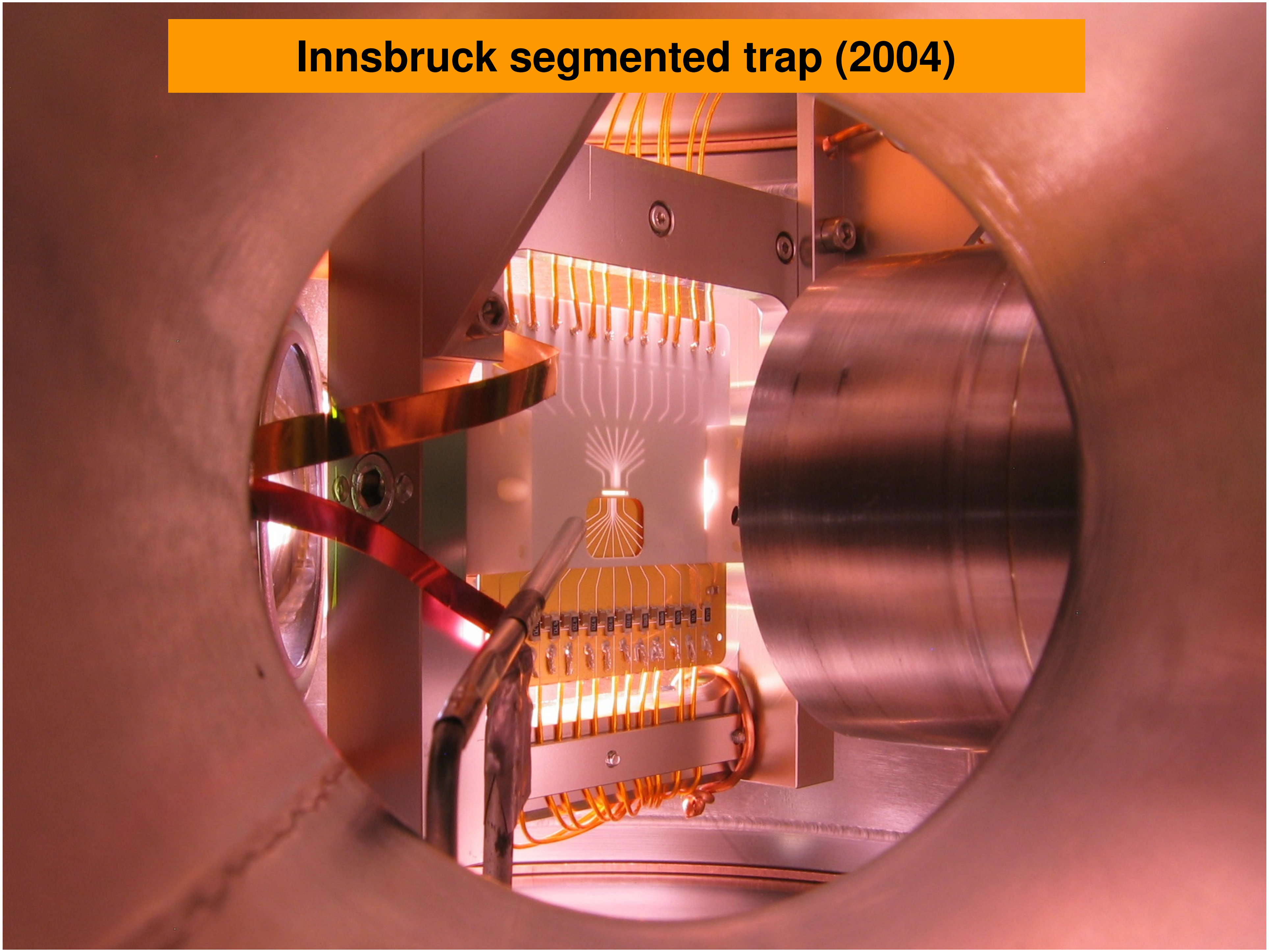


6-zone alumina/gold trap

(Murray Barrett, Tobias Schaetz *et al.*)

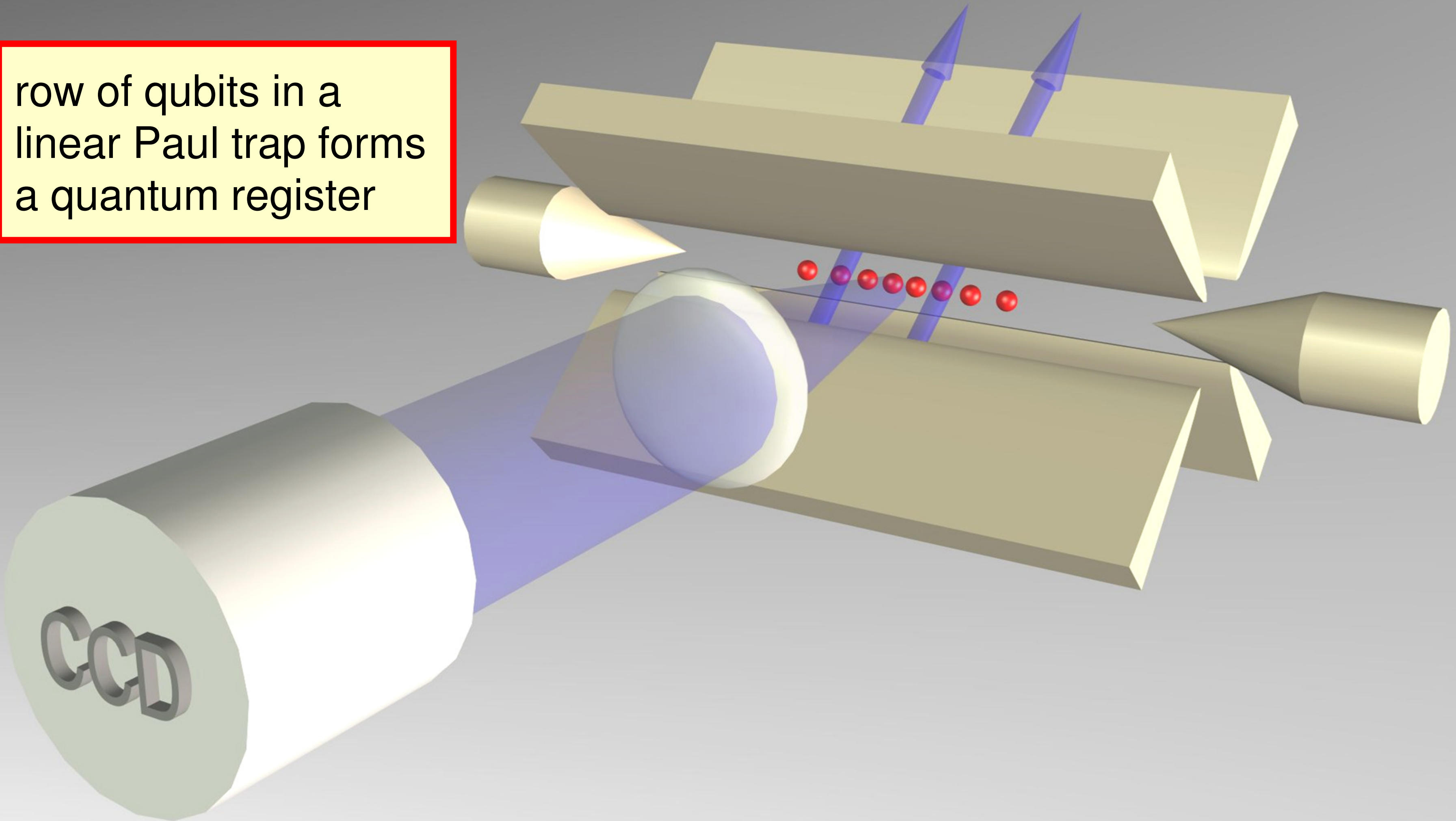
- Ions can be moved between traps.
  - Electrode potentials varied with time
- Ions can be separated efficiently in sep. zone
  - Small electrode's potential raised
- Motion (relatively) fast
  - Shuttling: several 10 μs
  - Separating: few 100 μs

Innsbruck segmented trap (2004)



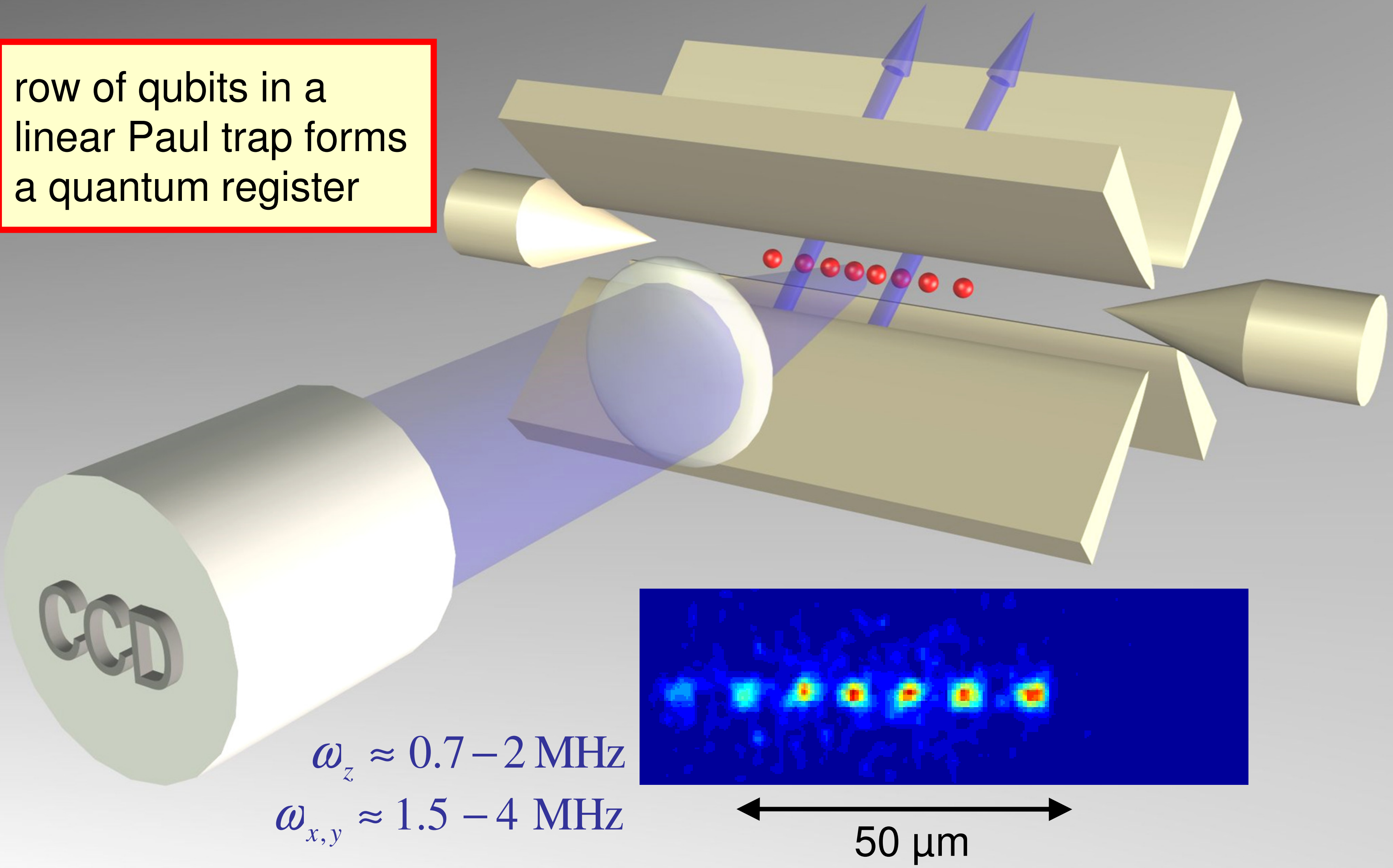
String of Ca+ ions in Paul trap

row of qubits in a linear Paul trap forms a quantum register



String of Ca+ ions in linear Paul trap

row of qubits in a
linear Paul trap forms
a quantum register

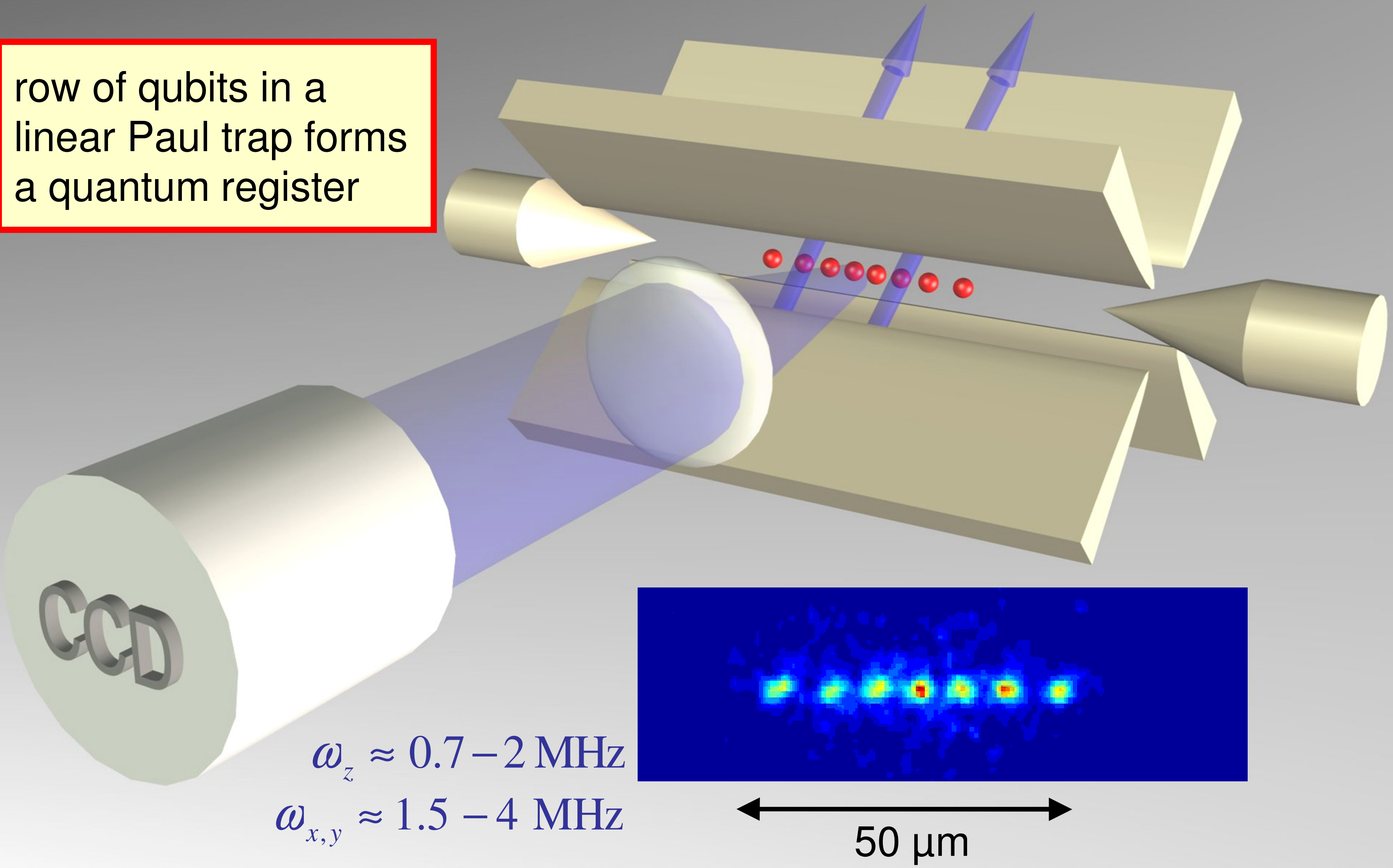


$$\omega_z \approx 0.7 - 2\ \mathrm{MHz}$$

$$\omega_{x,y} \approx 1.5 - 4\ \mathrm{MHz}$$

String of Ca+ ions in linear Paul trap

row of qubits in a linear Paul trap forms a quantum register

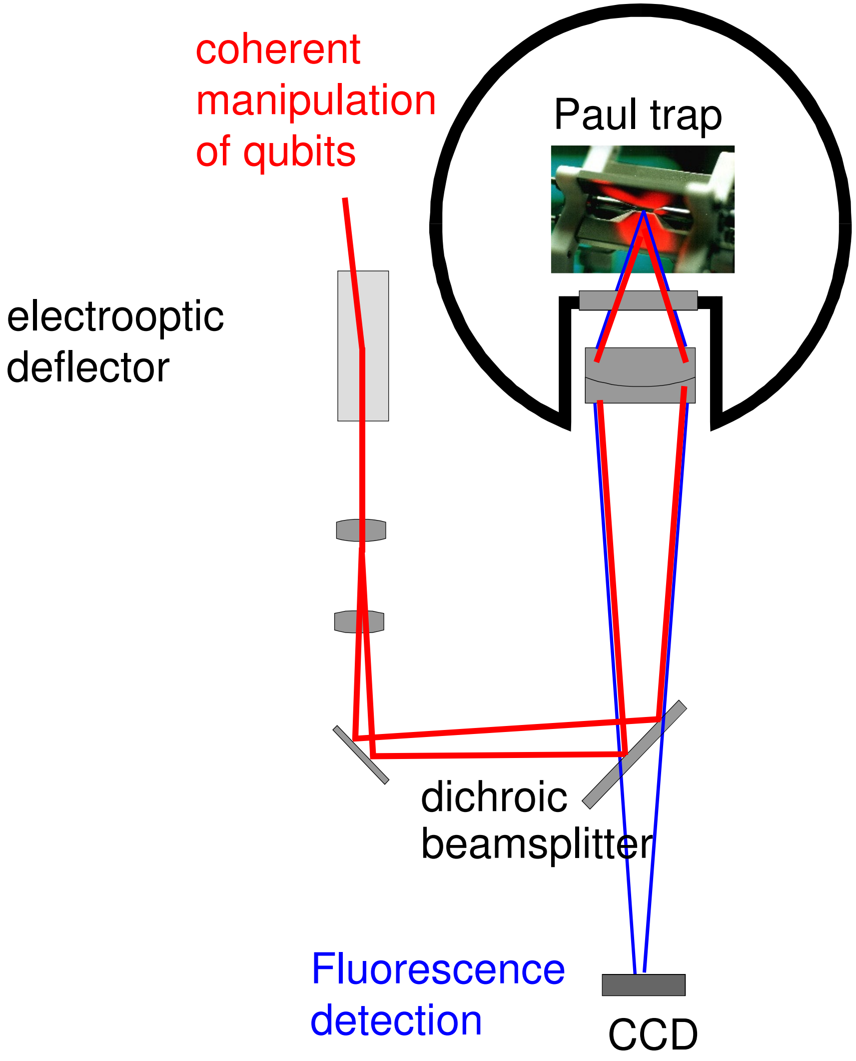


$\omega_z \approx 0.7 - 2\,\mathrm{MHz}$

$\omega_{x,y} \approx 1.5 - 4\ \mathrm{MHz}$

50 µm

Addressing of individual ions



coherent manipulation of qubits

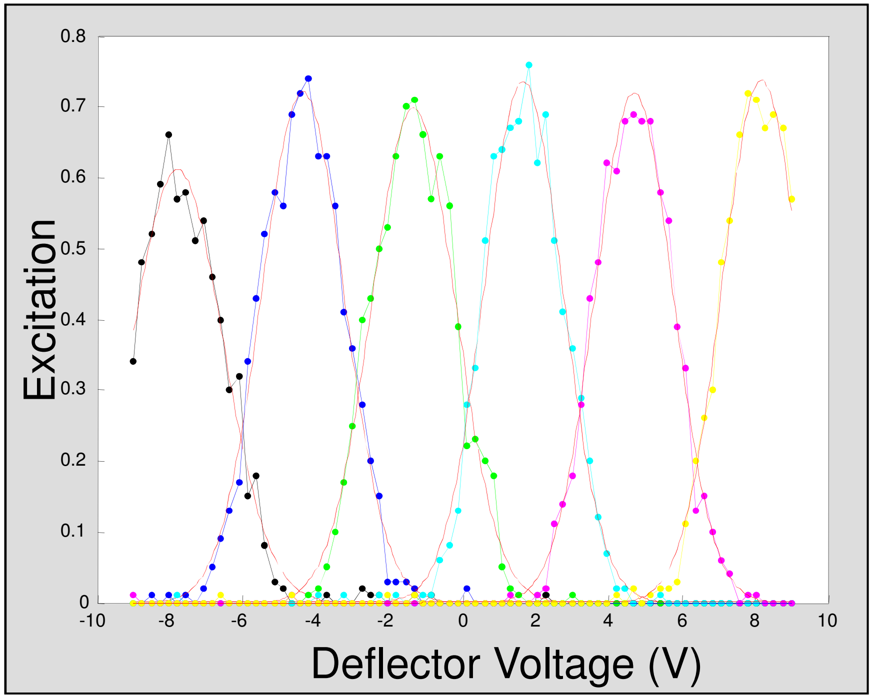
Paul trap

electrooptic deflector

dichroic beamsplitter

Fluorescence detection

CCD



- inter ion distance: ~ 4 µm
- addressing waist: ~ 2.5 µm

< 0.1% intensity on neighbouring ions

Ion addressing

The ions can be addressed individually on the qubit transition with an EO deflector which can quickly move the focus of the 729 light from one ion to another, using the same optical path as the fluorescence detection via the CCD camera.

How well the addressing works is shown on the previous slide: The graph shows the excitation of the indiviual ions as the deflector is scanned across the crystal.

External degree of freedom: ion motion

Notes for next slides:

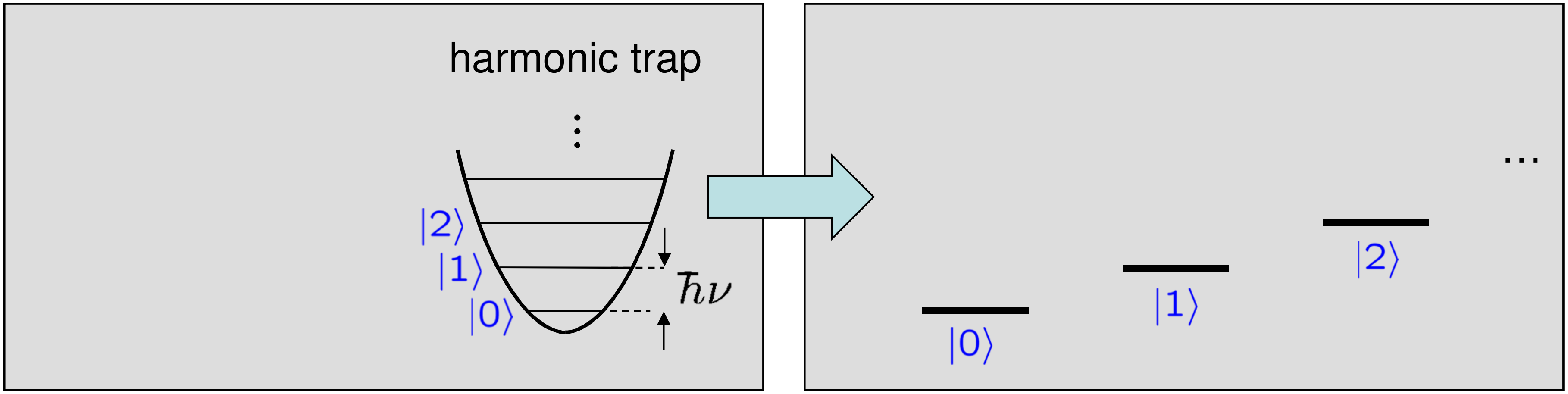
Now let's have a look at the qubit transition in the presence of the motional degrees of freedom. If we focus on just one motional mode , we just get a ladder of harmonic oscillator levels.

The joint (motion + electronic energy level) system shows a double ladder structure. With the narrow laser we can selectively excite the carrier transition, where the motional state remains unchanged...

Or use the blue sideband and red sideband transitions, where we can change the motional state.

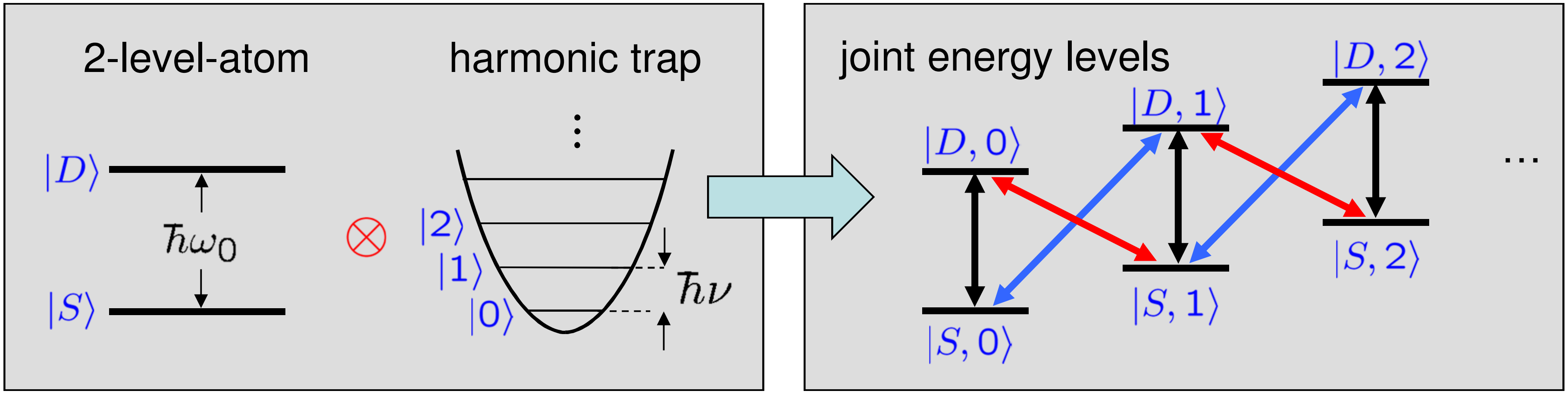
We can walk down the double ladder by exciting the red sideband and returning the ion dissipatively to the grounsstate. With this we can prepare the ions in the motional ground state with high probability, thereby initializing our quantum register.

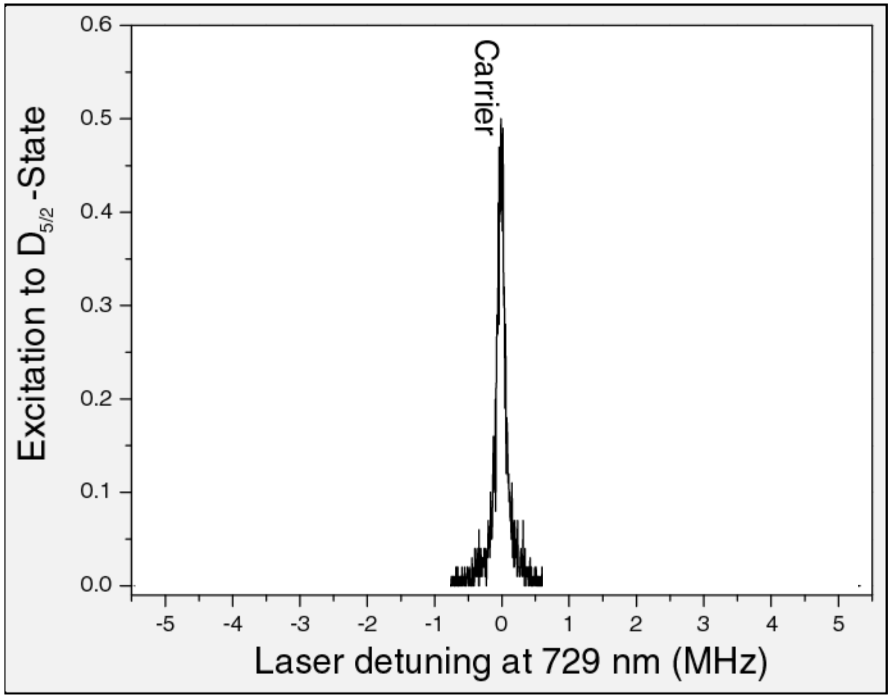
External degree of freedom: ion motion



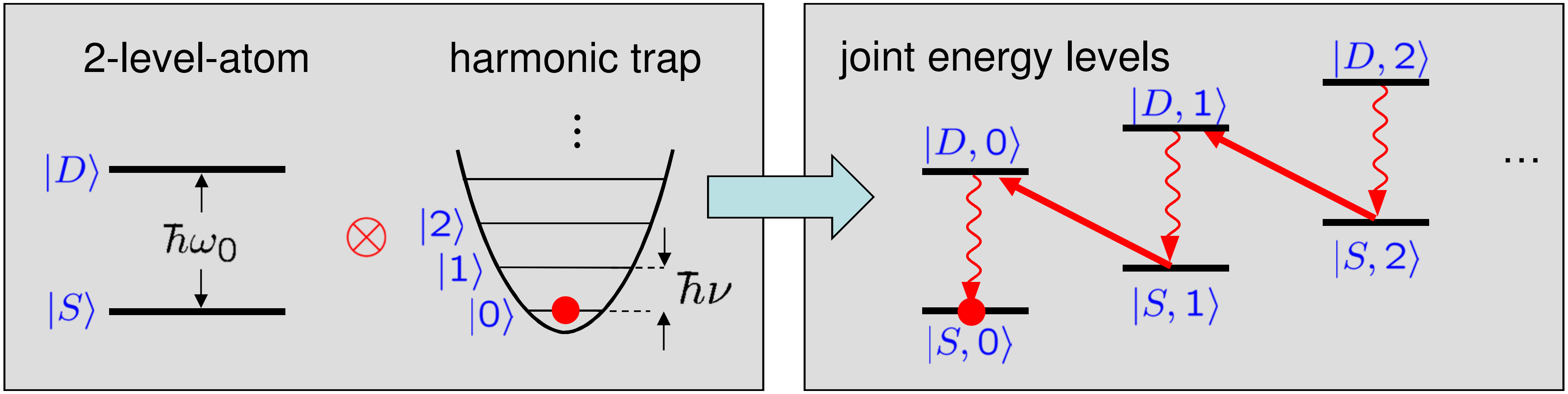
harmonic trap

External degree of freedom: ion motion





External degree of freedom: ion motion

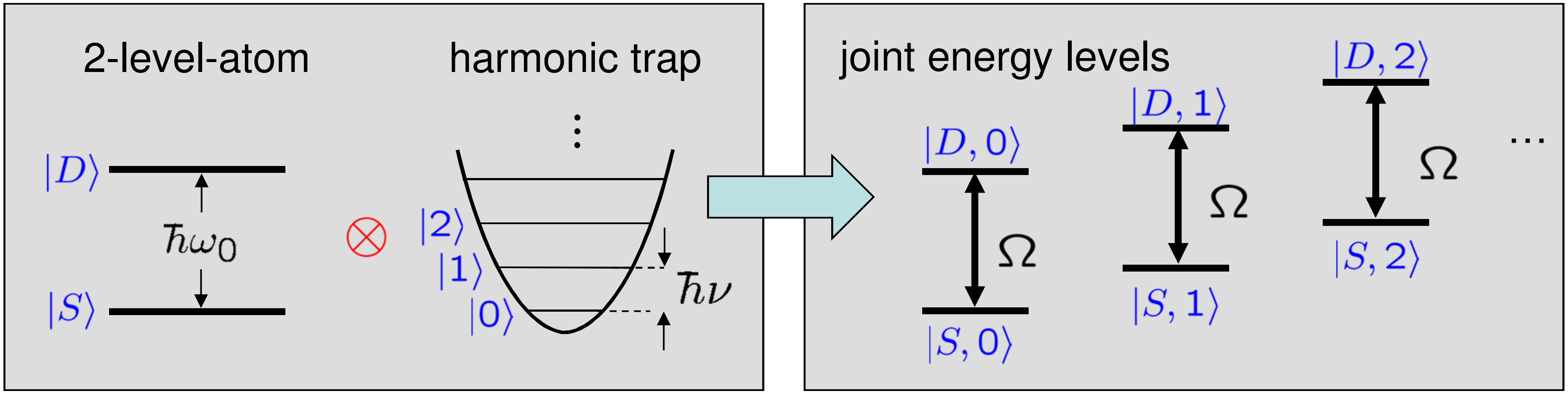


Laser cooling to the motional ground state:

Cooling time: 5-10 ms

> 99% in motional ground state

Coherent manipulation



Interaction with a resonant laser beam :

$$H_I = \hbar\Omega\ (|D\rangle\langle S|e^{i\phi} + |S\rangle\langle D|e^{-i\phi})$$

Ω : Rabi frequency

ϕ : phase of laser field

Laser beam switched on for duration τ :

$$U = e^{-i\frac{H}{\hbar}\tau}$$

θ : rotation angle $\qquad \theta = 2\Omega\tau$

If we resonantly shine in light pulse at the carrier transition, the system evolves for a time tau with this Hamiltonian, where the coupling strength Omega depends on the sqroot of the intensity, and phi is the phase of the laser field with respect to the atomic polarization.

Coherent manipulation

Let's now begin to look at the coherent state manipulation. If we resonantly shine the light pulse at the carrier transition, the system evolves for a time τ with this Hamiltonian, where the coupling strength Ω depends on the square root of the intensity, and ϕ is the phase of the laser field with respect to the atomic polarization.

The effect of such a pulse is a rotation of the state vector on the Bloch sphere, where the poles represent the two states and the equator represents superposition states with different relative phases. The roation axis is determined by the laser frequency and phase. The important message is here that we can position the state vector anywhere on the Bloch sphere, which is a way of saying that we can create arbitrary superposition states.

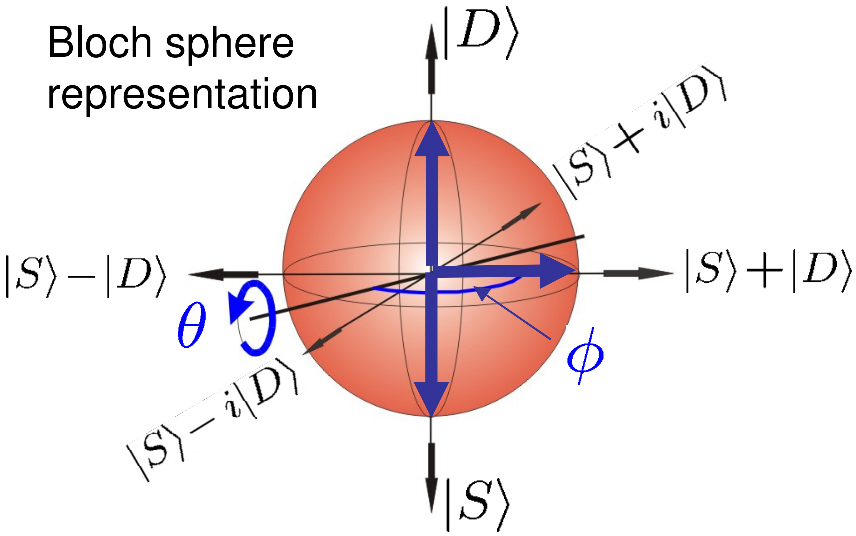
The same game works for sideband pulses. With a $\pi/2$ pulse, for example, we entangle the internal and the motional state! Since the motional state is shared by all ions, we can use the motional state as a kind of bus to mediate entanglement between different qubits in the ion chain.

Coherent excitation: Rabi oscillations

„Carrier“ pulses:

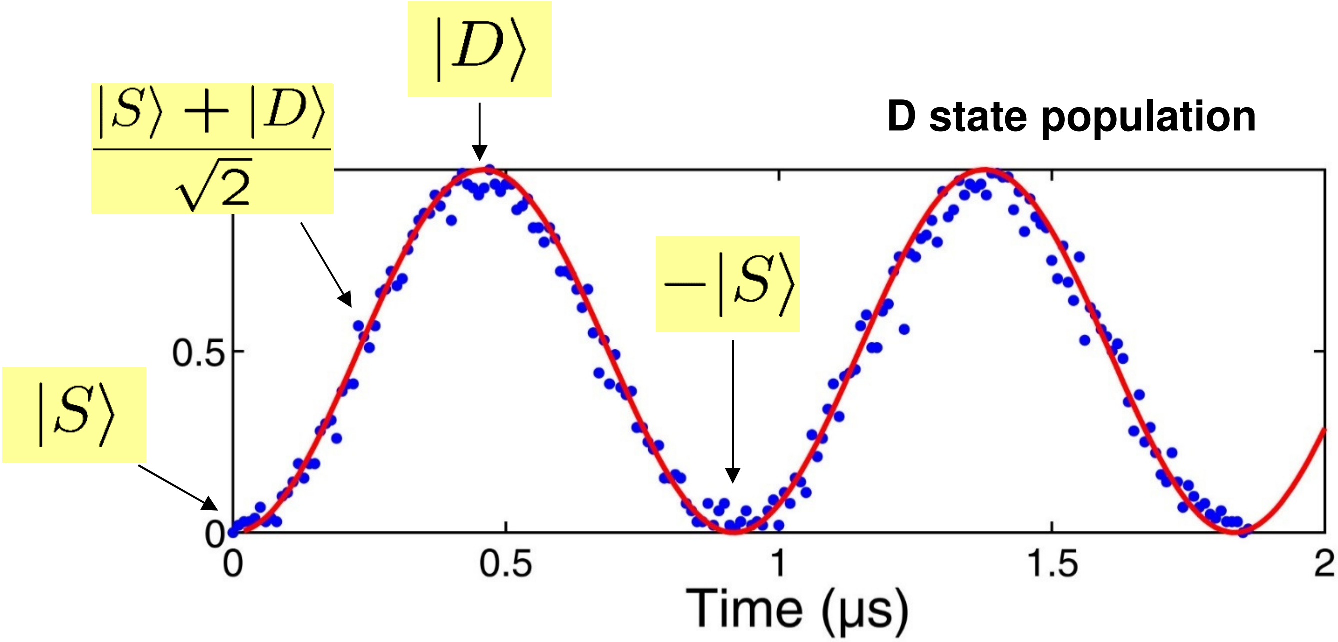
$$|S\rangle \longleftrightarrow |D\rangle$$

Bloch sphere representation



$$\theta/2 = \Omega\tau$$

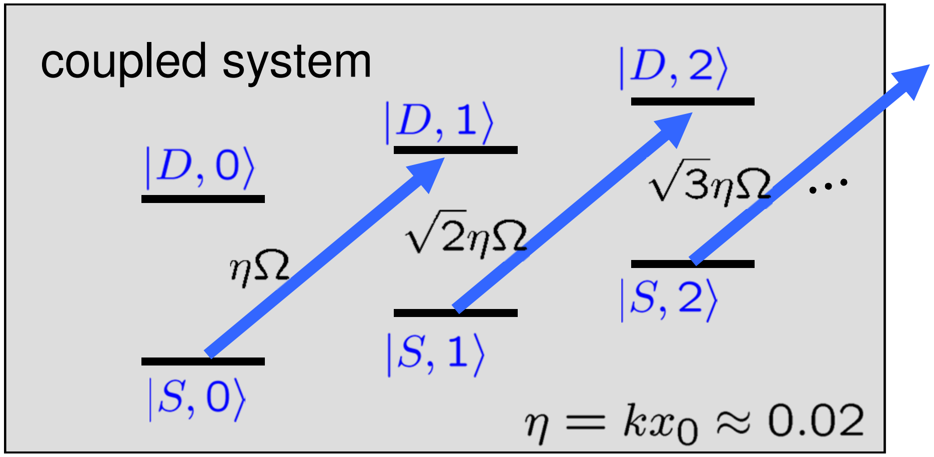
$\tau 2\pi 2$



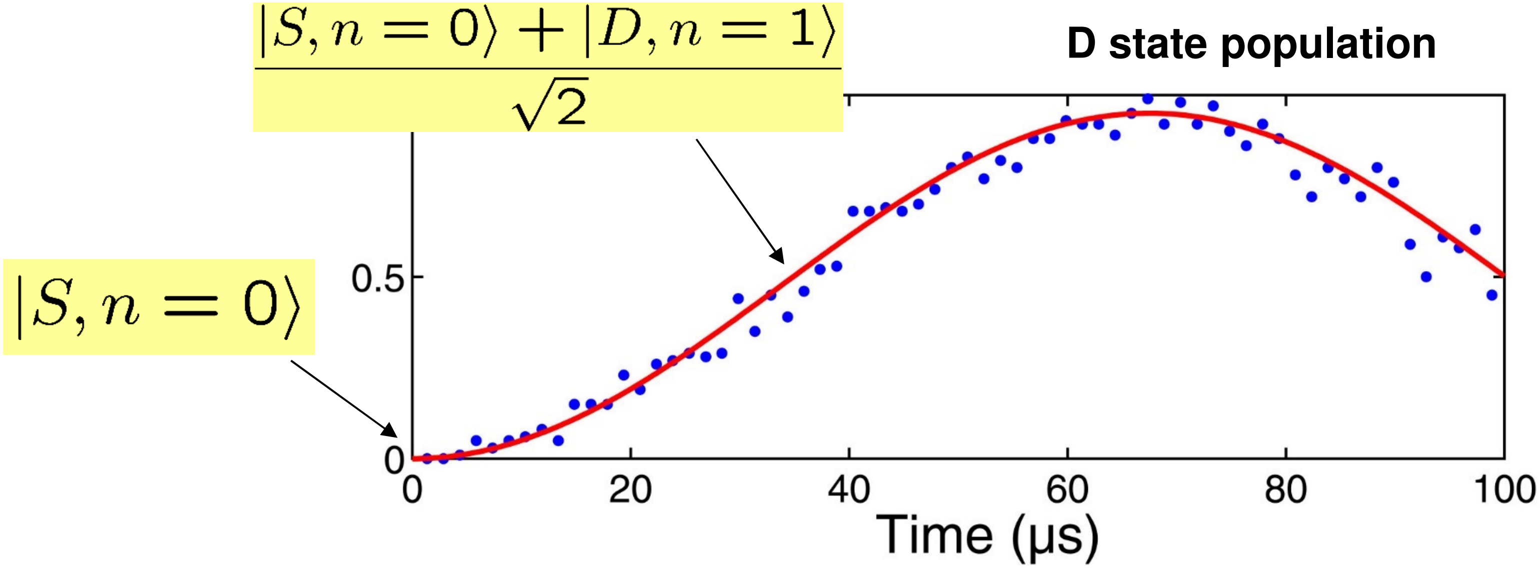
Coherent excitation on the sideband

„Blue sideband“ pulses:

$$|S\rangle|n\rangle \longleftrightarrow |D\rangle|n+1\rangle$$



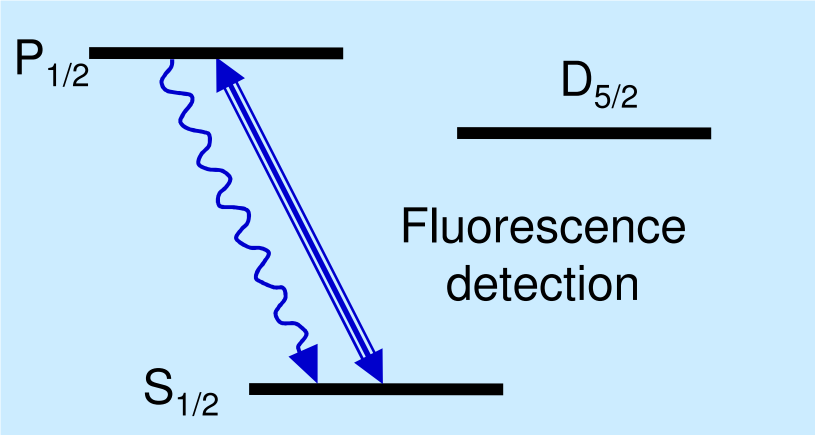
$\theta = \pi/2$: Entanglement between internal and motional state !



$$\frac{|S,n=0\rangle + |D,n=1\rangle}{\sqrt{2}}$$

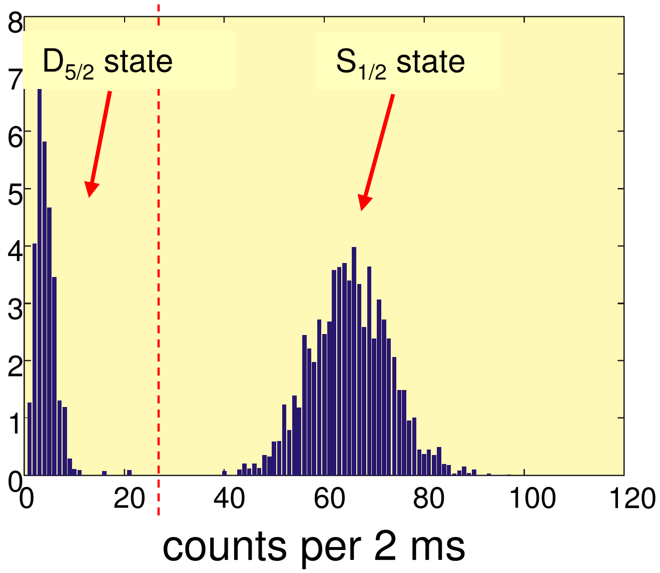
$$|S,n=0\rangle$$

Experimental procedure



1. Initialization in a pure quantum state: laser cooling,optical pumping
2. Quantum state manipulation on $S_{1/2} – D_{5/2}$ qubit transition
3. Quantum state measurement by fluorescence detection

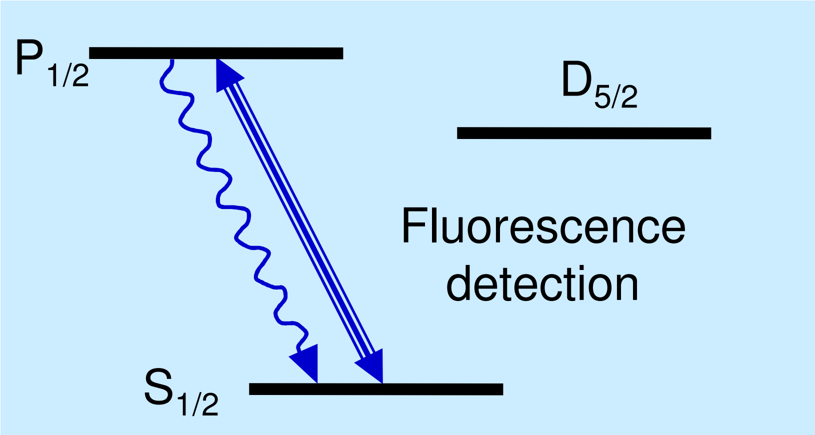
One ion : Fluorescence histogram



50 experiments / s

Repeat experiments 100-200 times

Experimental procedure



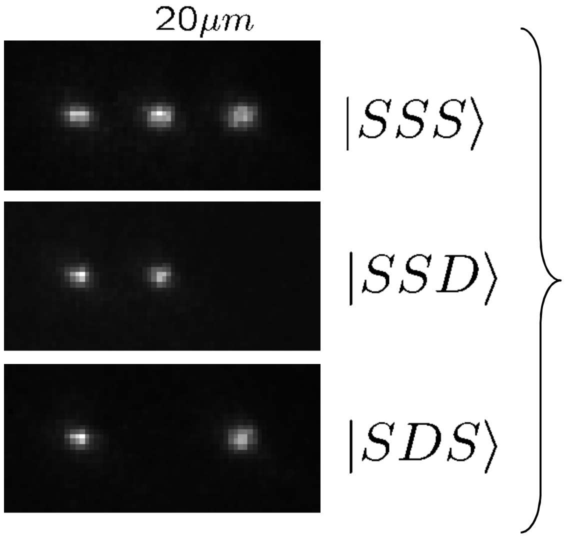
1. Initialization in a pure quantum state: Laser sideband cooling

2. Quantum state manipulation on $S_{1/2}$ – $D_{5/2}$ transition

3. Quantum state measurement by fluorescence detection

Multiple ions:

Spatially resolved detection with CCD camera:

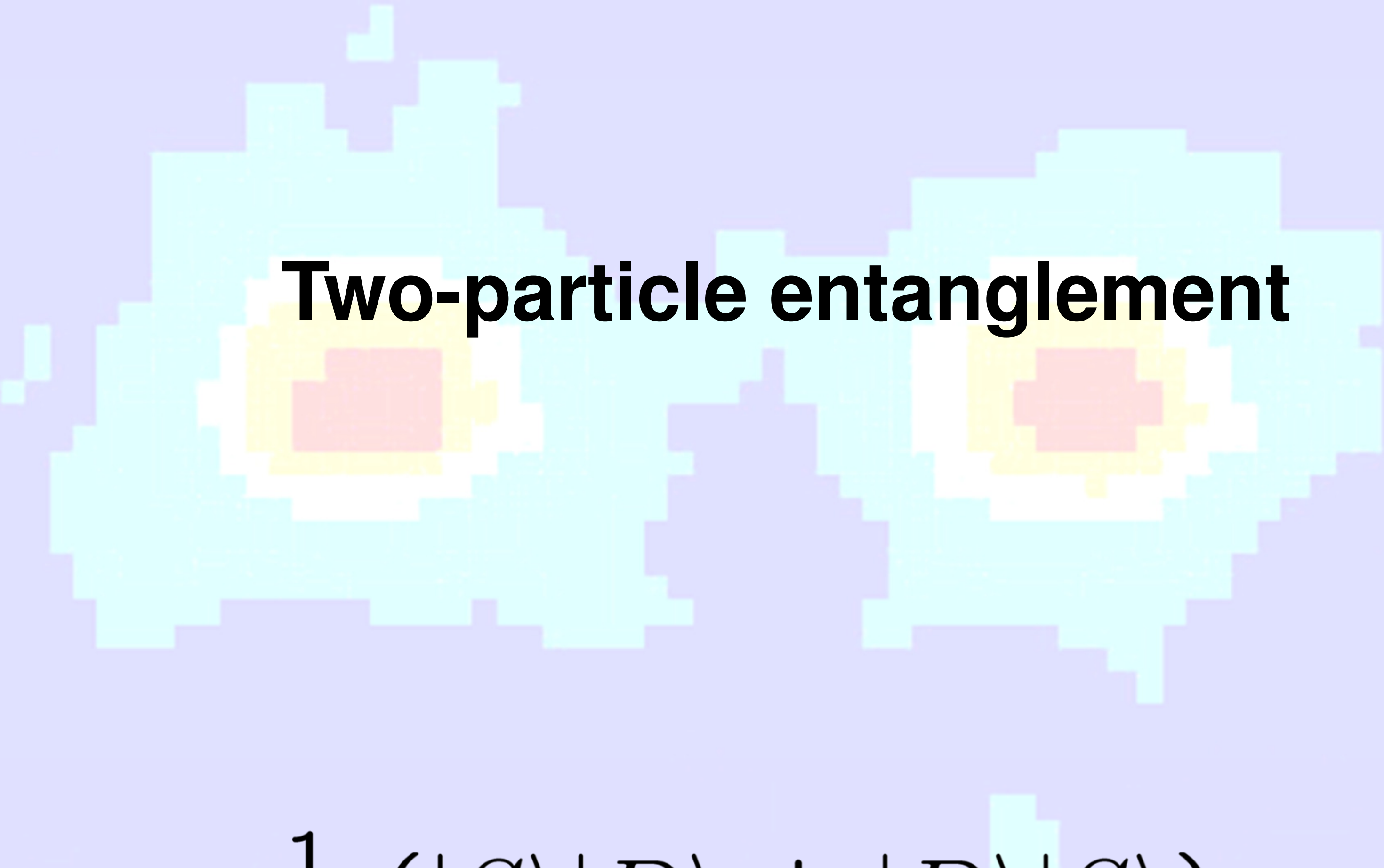


...

50 experiments / s

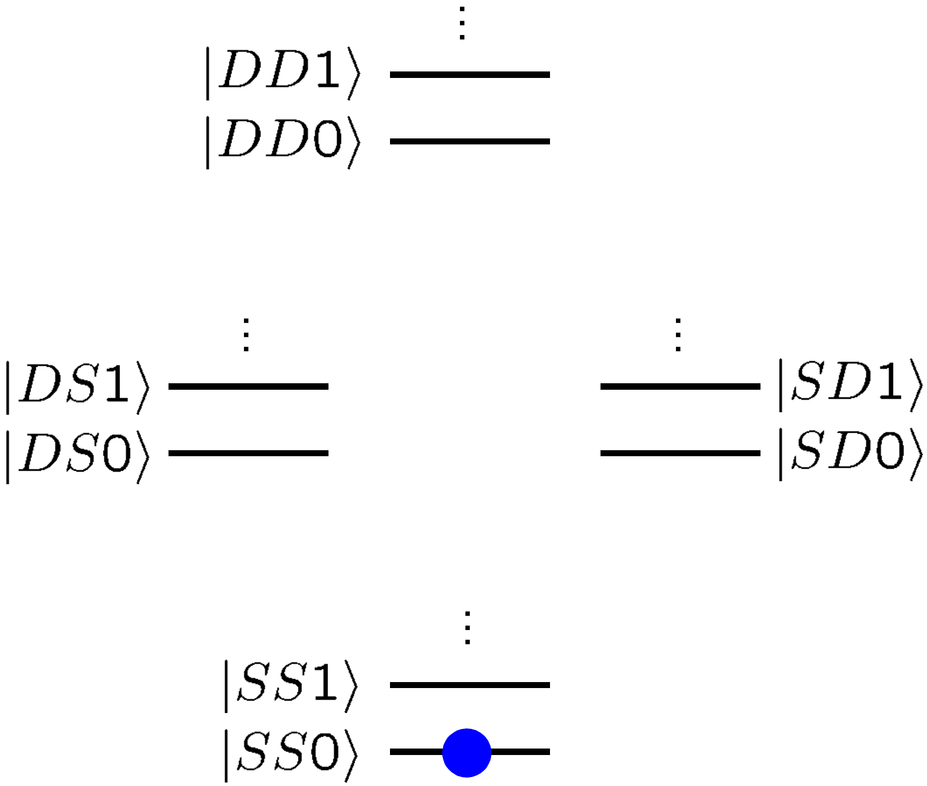
Repeat experiments 100-200 times

Two-particle entanglement



$$\frac{1}{\sqrt{2}}(|S\rangle|D\rangle + |D\rangle|S\rangle)$$

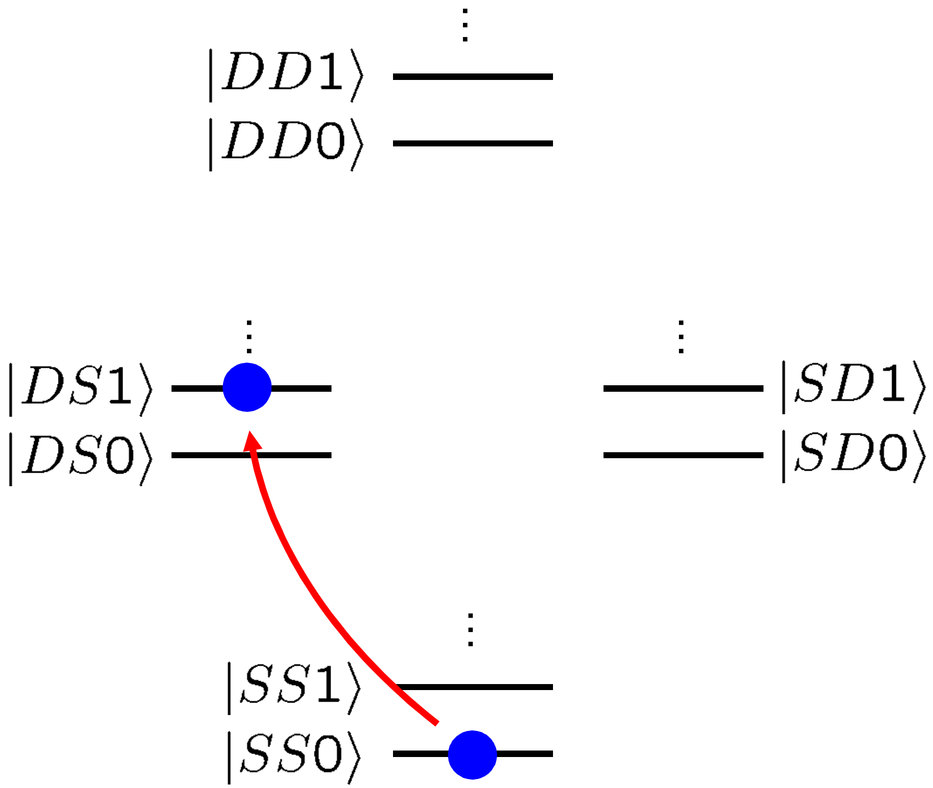
Creation of Bell state



Pulse sequence:

$$|SS0\rangle$$

Creation of Bell states

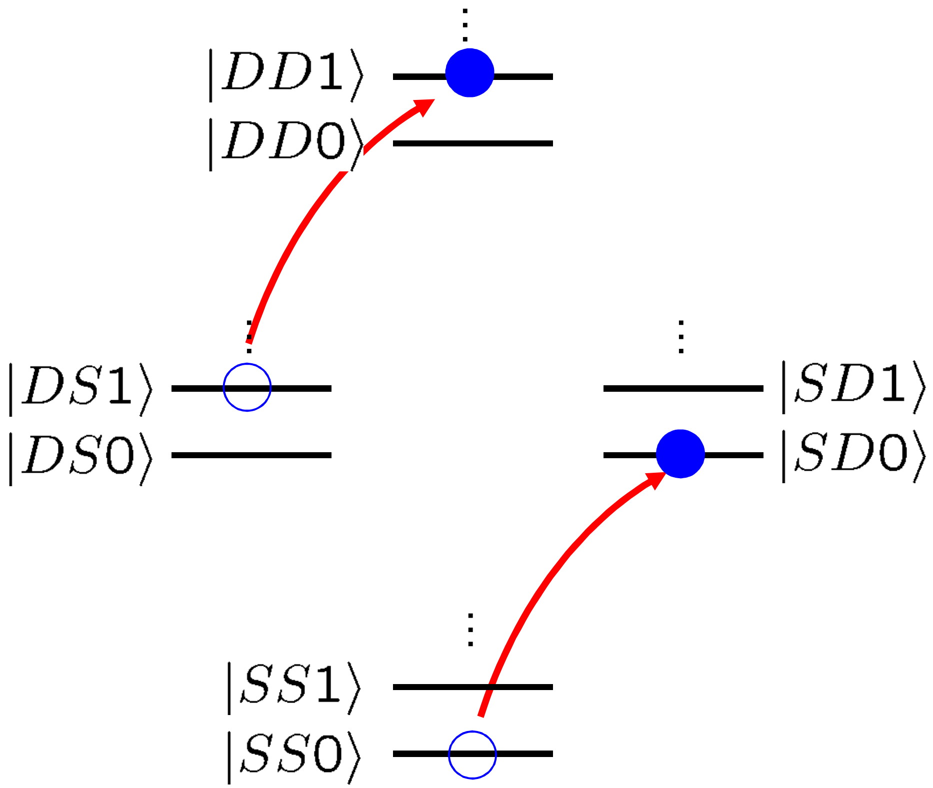


Pulse sequence:

Ion 1: π/2 , blue sideband

$$|SS0\rangle + |DS1\rangle$$

Creation of Bell states



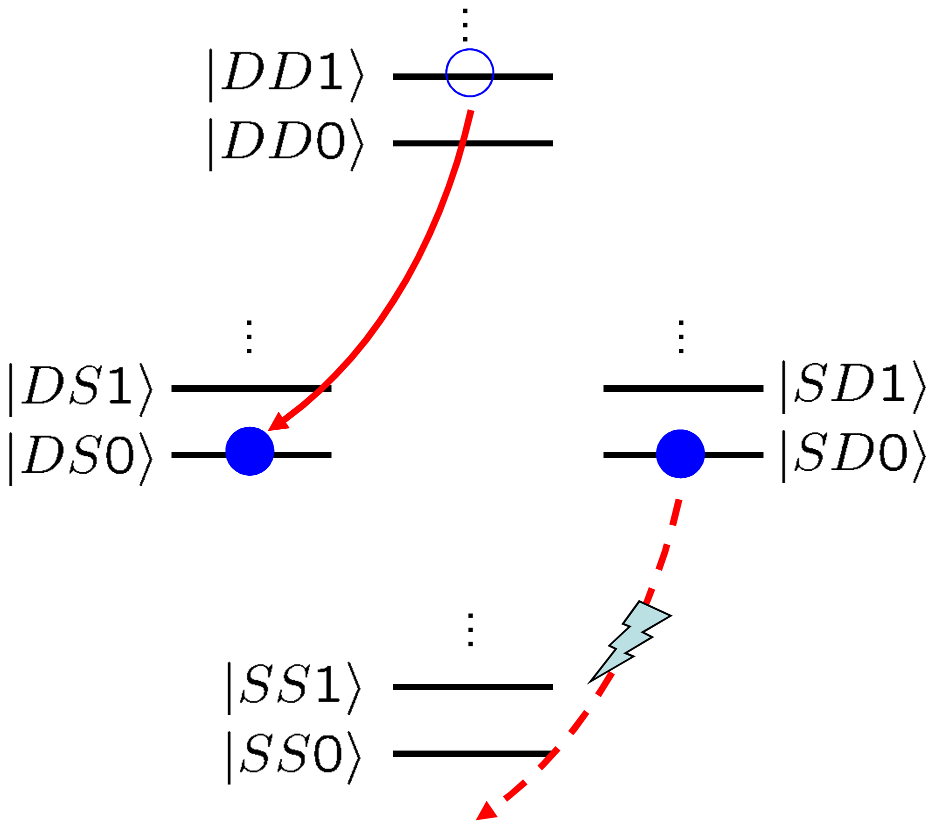
Pulse sequence:

Ion 1: π/2 , blue sideband

Ion 2: π , carrier

$$|SD0\rangle + |DD1\rangle$$

Creation of Bell states



Pulse sequence:

Ion 1: π/2 , blue sideband

Ion 2: π , carrier

Ion 2: π , blue sideband

$$(|SD\rangle + |DS\rangle)|0\rangle$$

Analysis of Bell states

$$|SD\rangle + |DS\rangle$$

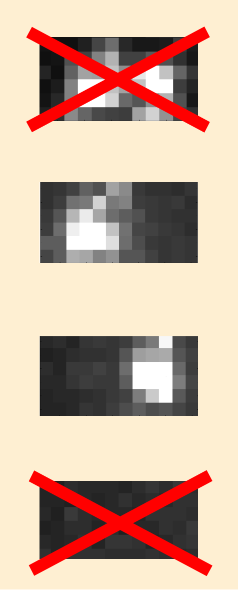
Fluorescence detection with CCD camera:

$|SS\rangle$

$|SD\rangle$

$|DS\rangle$

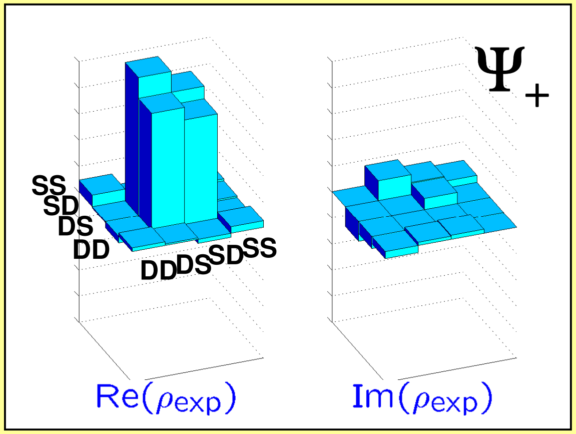
$|DD\rangle$



Coherent superposition or incoherent mixture ?

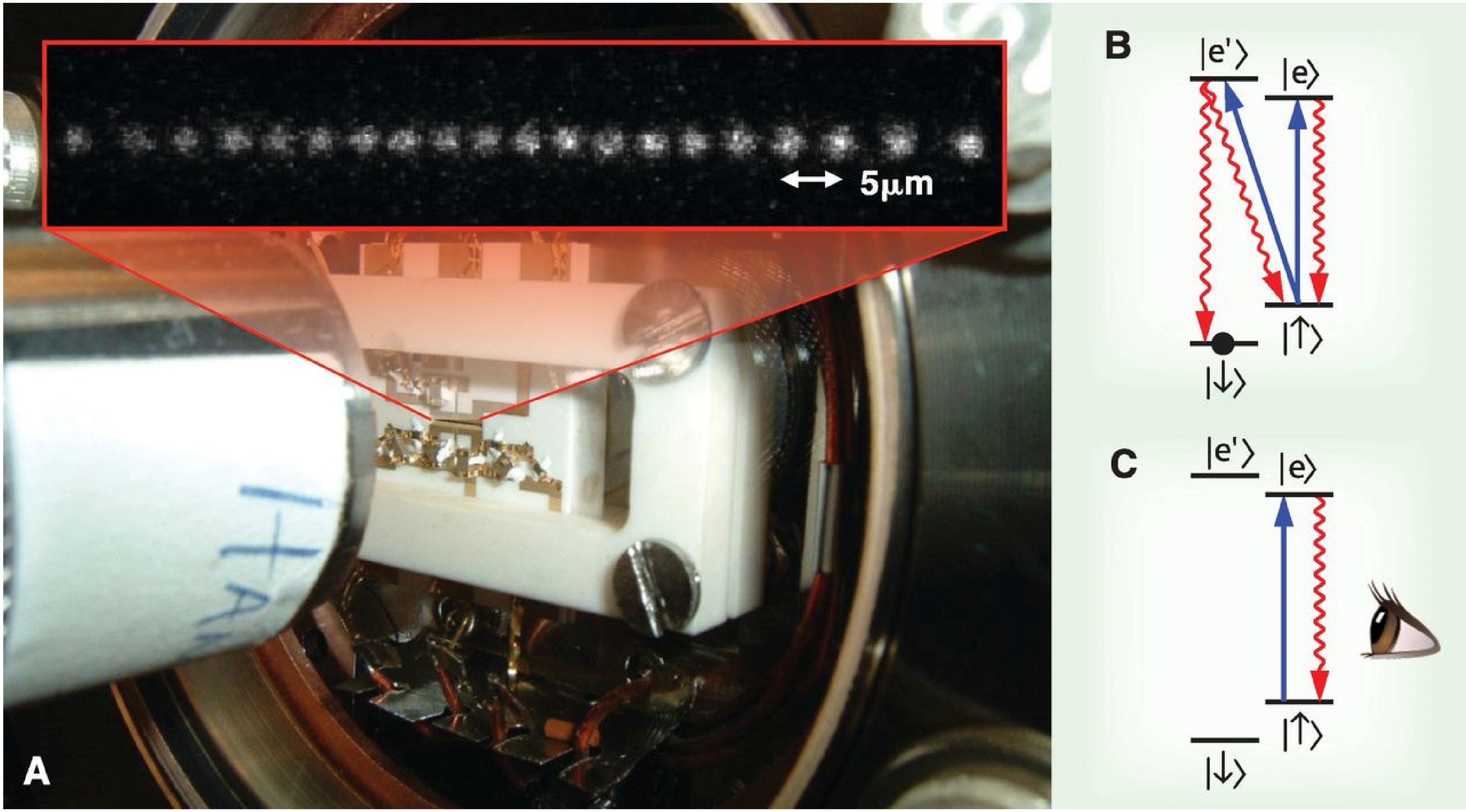
What is the relative phase of the superposition ?

→ **Measurement of the density matrix:**



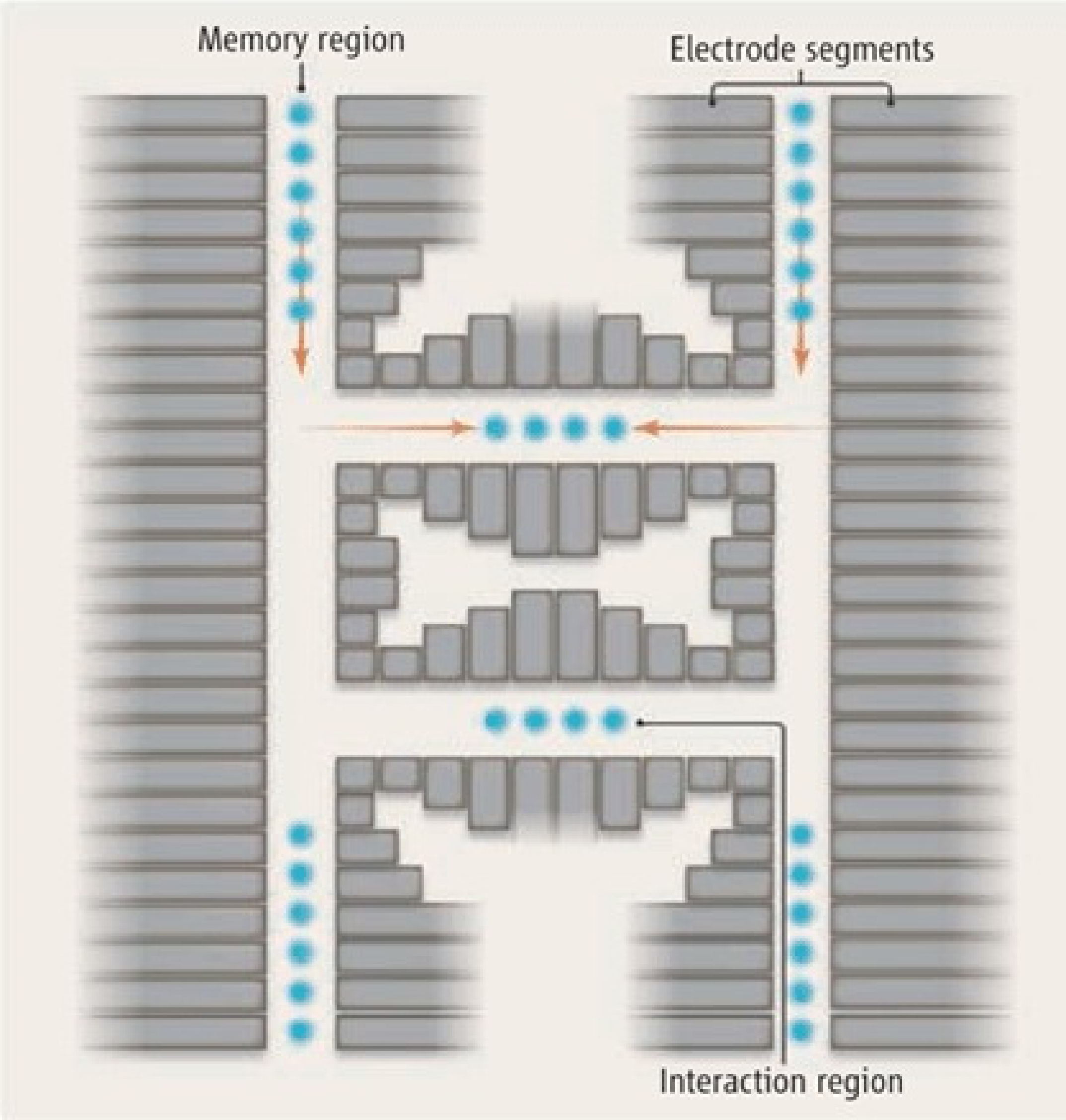
How to build a large-scale quantum computer with trapped ions

Linear crystal of 20 confined atomic ^{171}Yb+ ions laser cooled to be nearly at rest



C. Monroe, and J. Kim Science 2013;339:1164-1169

Harnessing ion-trap qubits



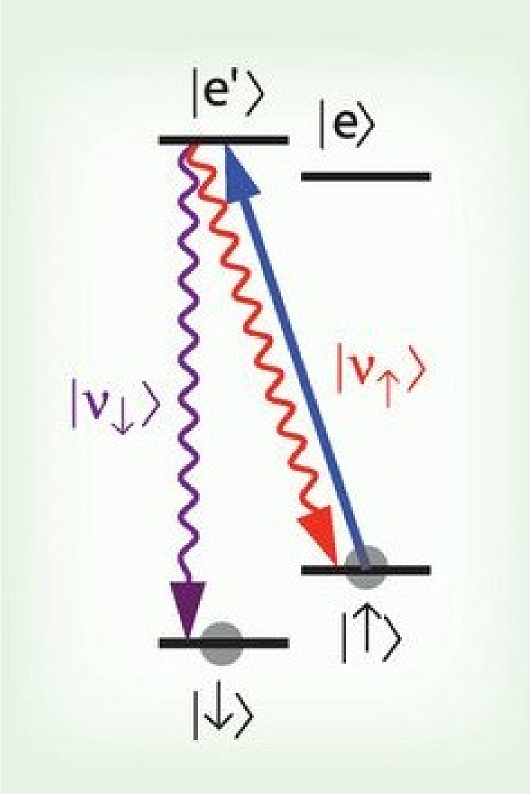
David P. DiVincenzo Science 2011;334:50-51

Concept of a quantum CCD trap

Image credit: National Institute of Standards and Technology

C. Monroe, and J. Kim Science 2013;339:1164-1169

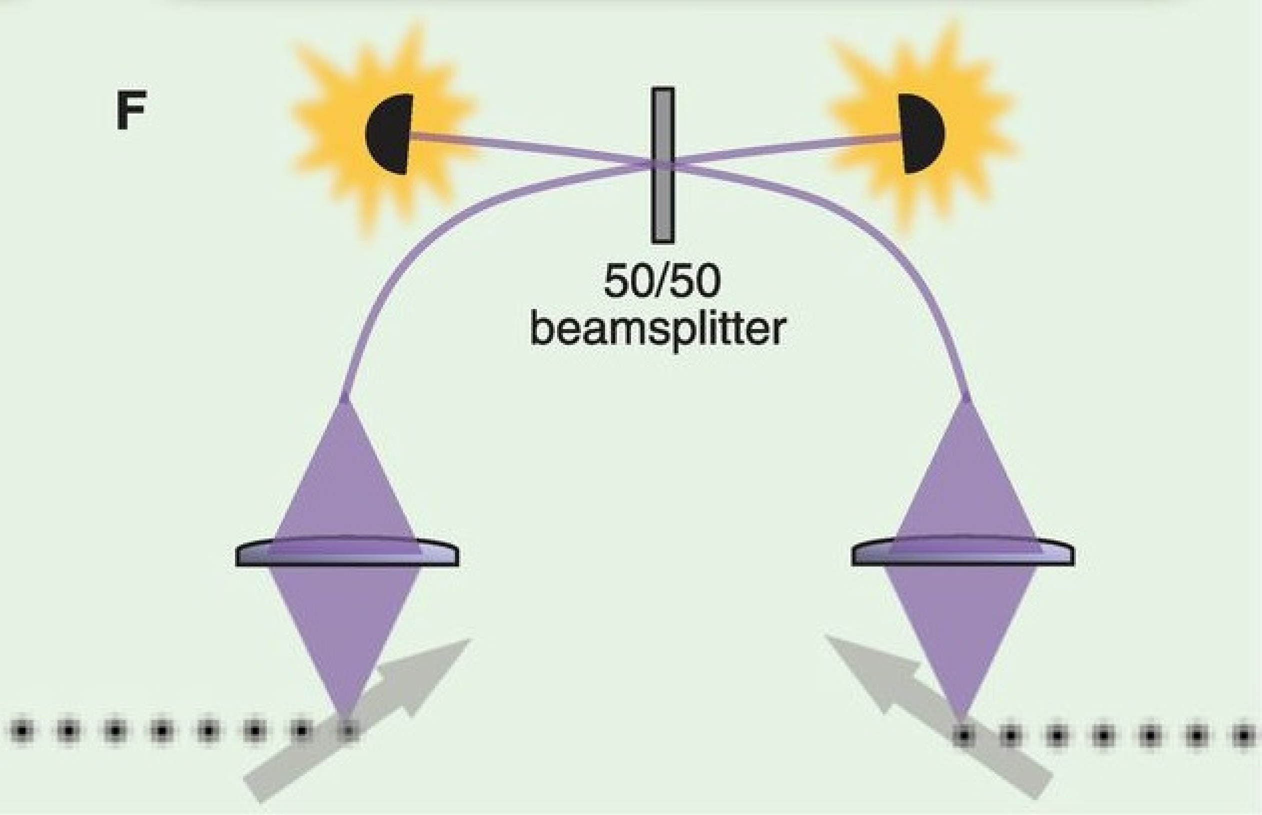
Version 2: Photonics coupling of trapped ions qubits



Energy levels of trapped ion excited with a fast laser pulse (blue upward arrow) that produces single photon whose color, represented by the state or , is entangled with the resultant qubit state.

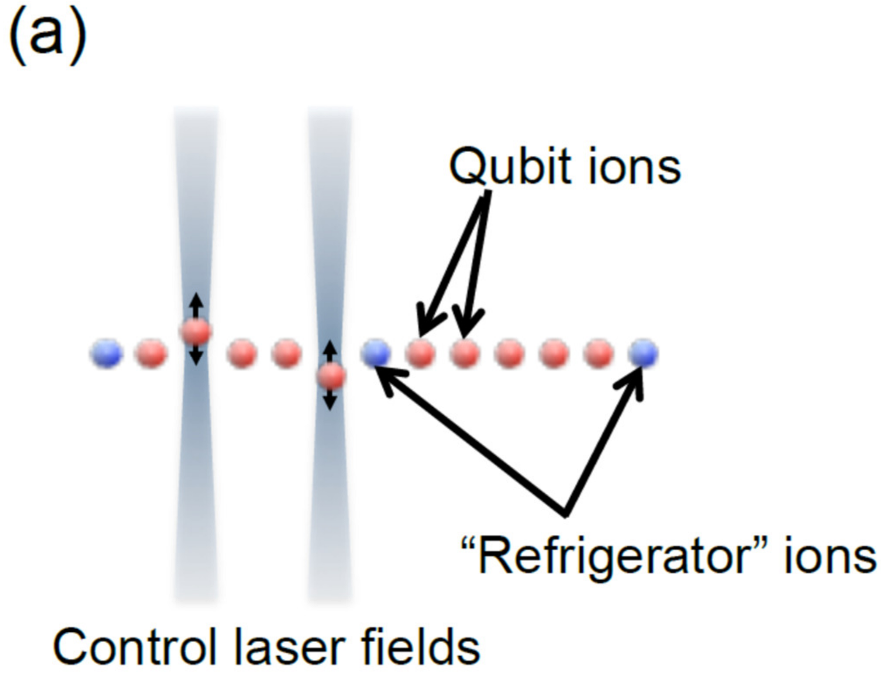
C. Monroe, and J. Kim Science 2013;339:1164-1169

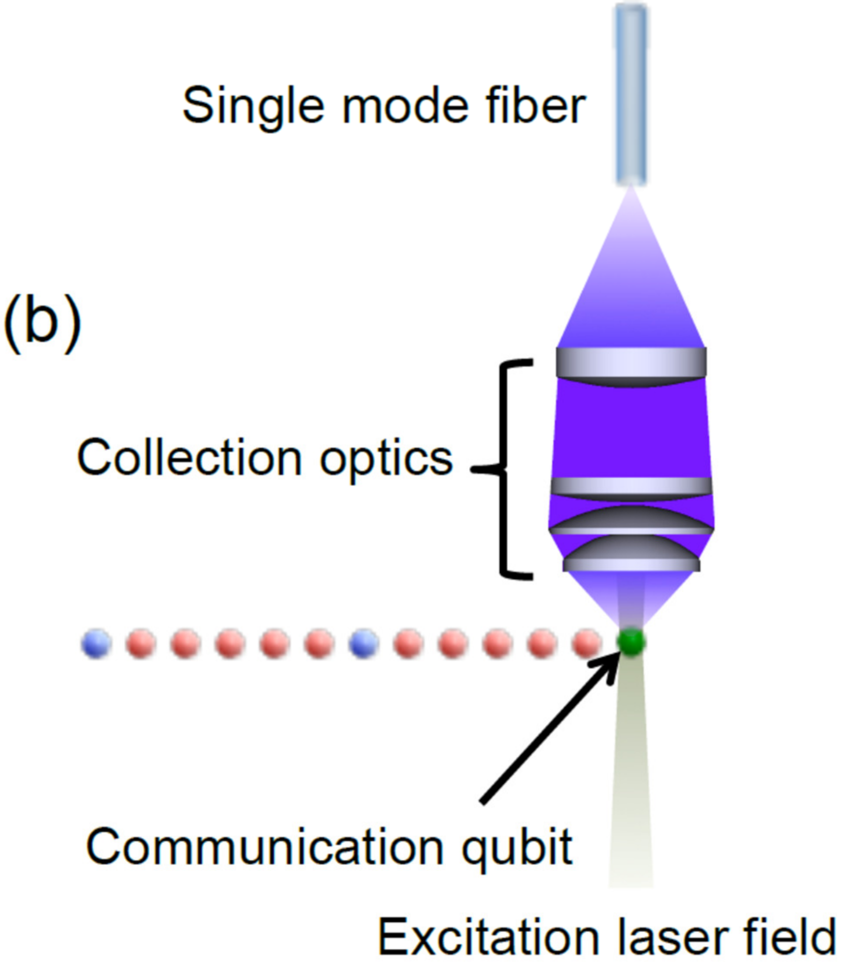
Version 2: Photonics coupling of trapped ions qubits



Two "communication qubit" ions, immersed in separate crystals of other ions, each produce single photons when driven by laser pulses (blue). With some probability, the photons arrive at the 50/50 beamsplitter and then interfere. If the photons are indistinguishable (in polarization and color), then they always leave the beamsplitter along the same path. The simultaneous detection of photons at the two output detectors means that the photons were different colors, this coincidence detection heralds the entanglement of the trapped ion qubits.

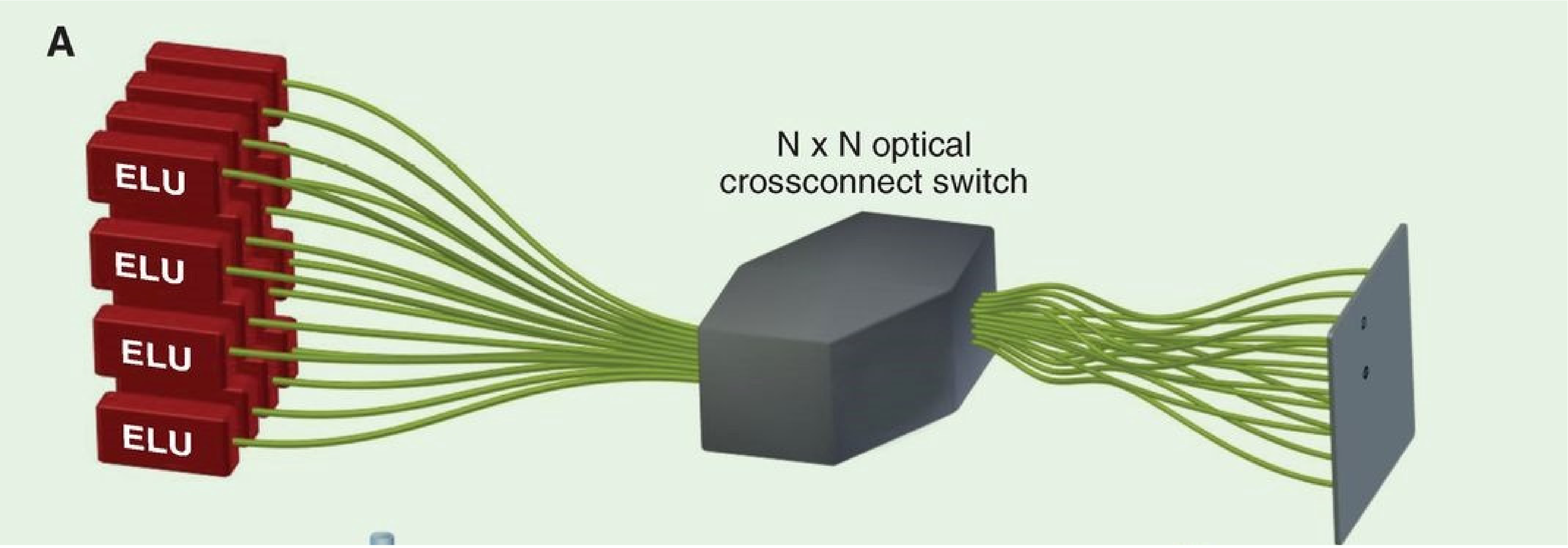
Elementary logic unit (ELU)





Phys. Rev. A 89, 022317 (2013)

Modular distributed quantum computer



Several elementary logic units (ELU)s are connected through a photonic network by using an optical crossconnect switch, inline fiber beamsplitters, and a photon-counting imager.

C. Monroe, and J. Kim Science 2013;339:1164-1169