AG Quantenoptik und Spektroskopie

Quantum information processing with trapped ions

universität innsbruck

Courtesy of Timo Koerber
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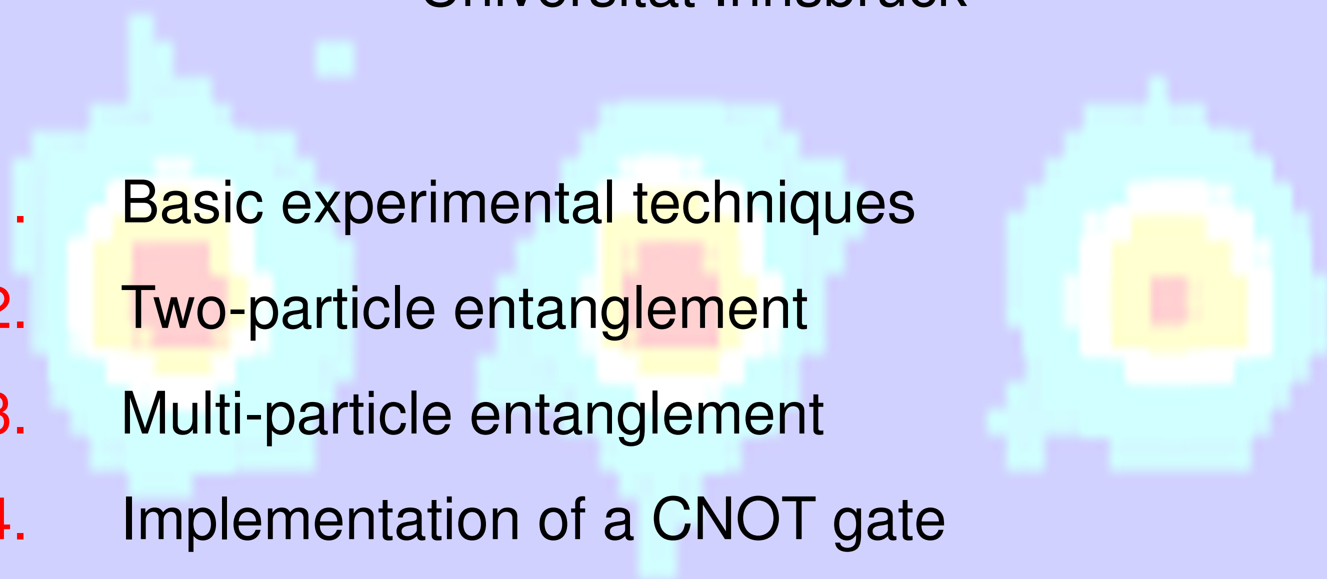


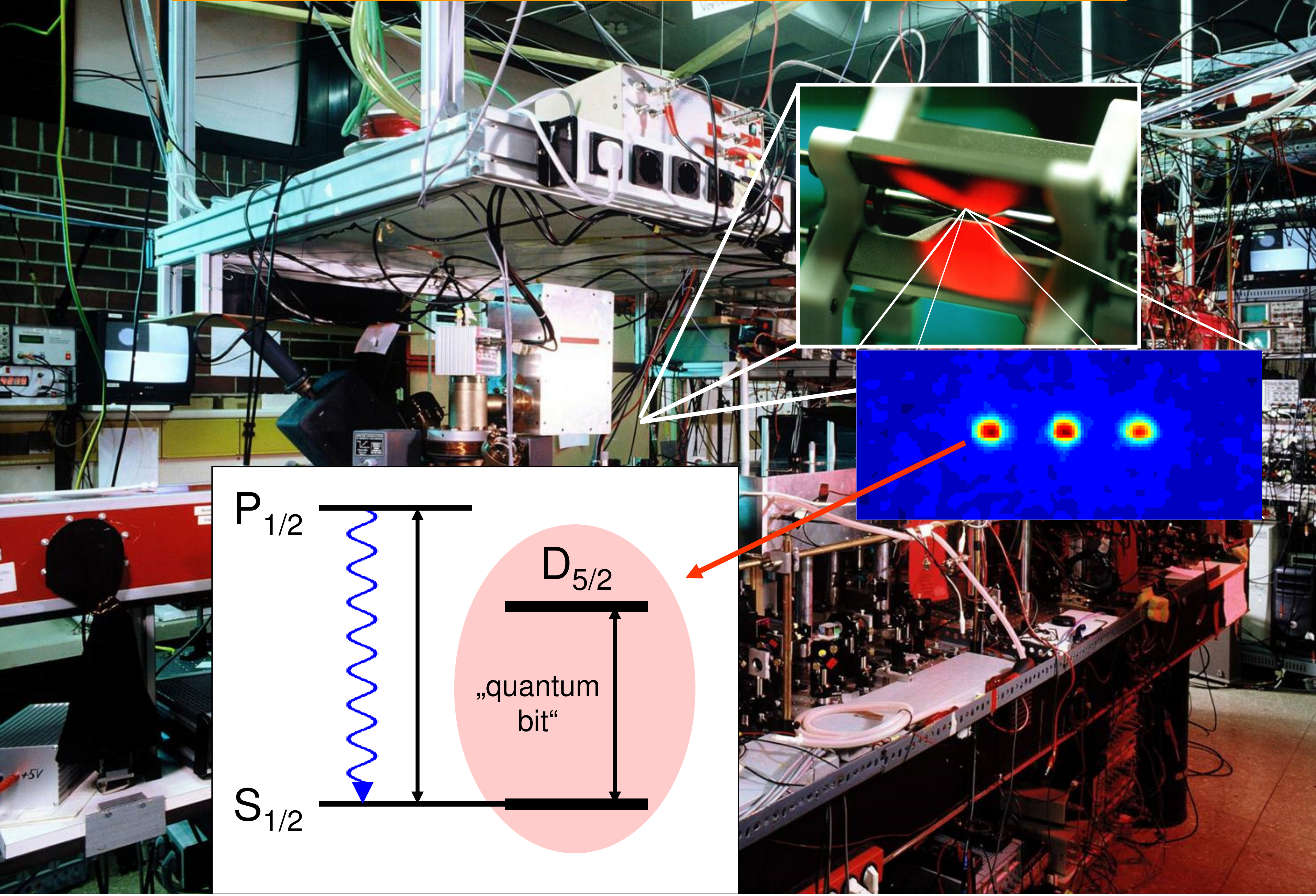
1. Basic experimental techniques
2. Two-particle entanglement
3. Multi-particle entanglement
4. Implementation of a CNOT gate
5. Teleportation
6. Outlook

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

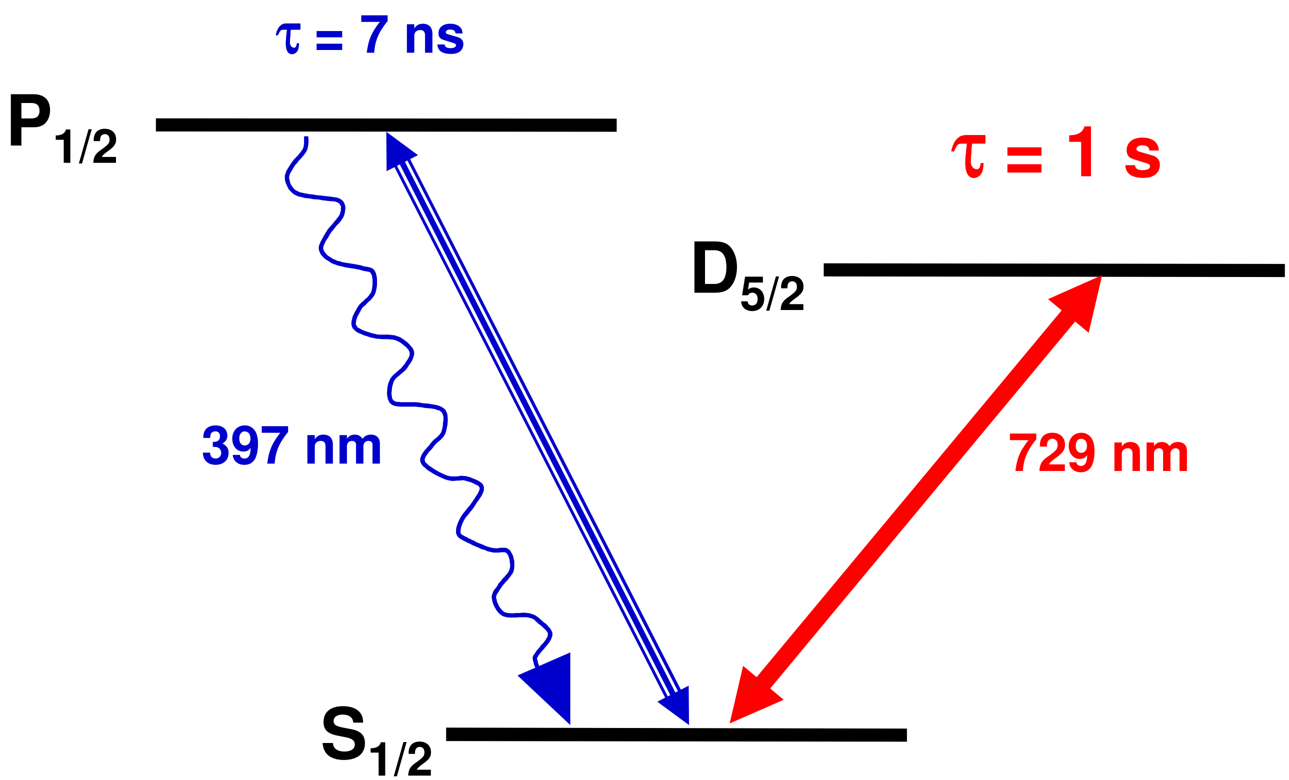


Important energy levels

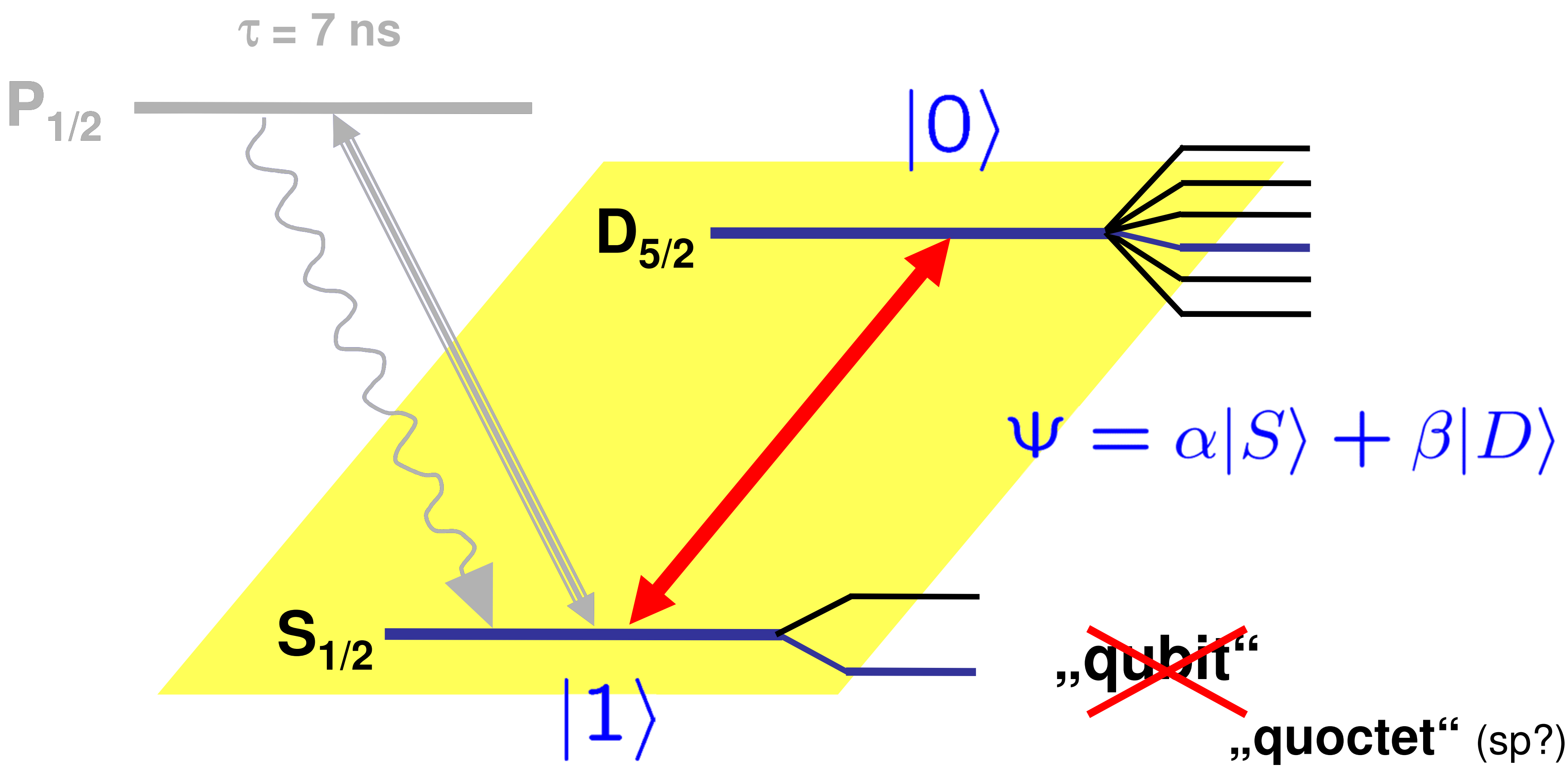
- The important energy levels are shown on the next slides; a fast transition is used to detect ion fluorescence and for Doppler cooling, while the narrow D5/2 quadrupole transition has a lifetime of 1 second and is used for coherent manipulation and represents out quantum bit. Of course a specific set 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

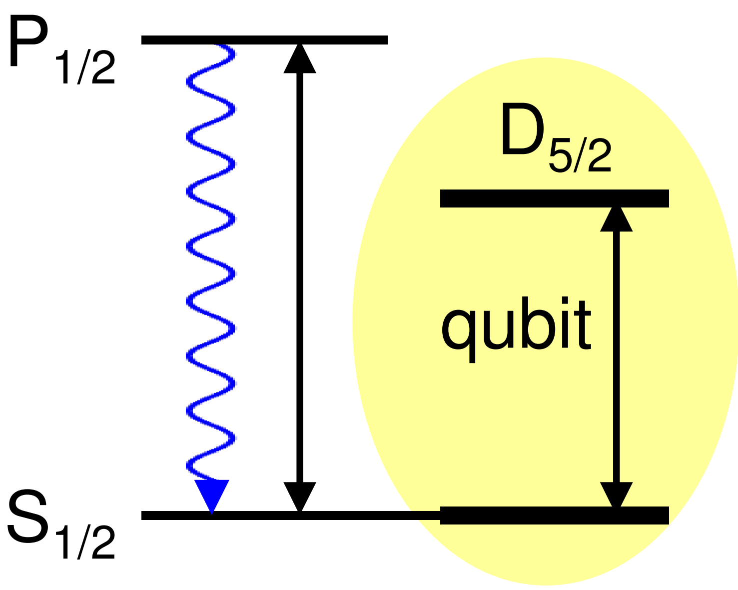
Encoding of quantum information requires long-lived atomic states:

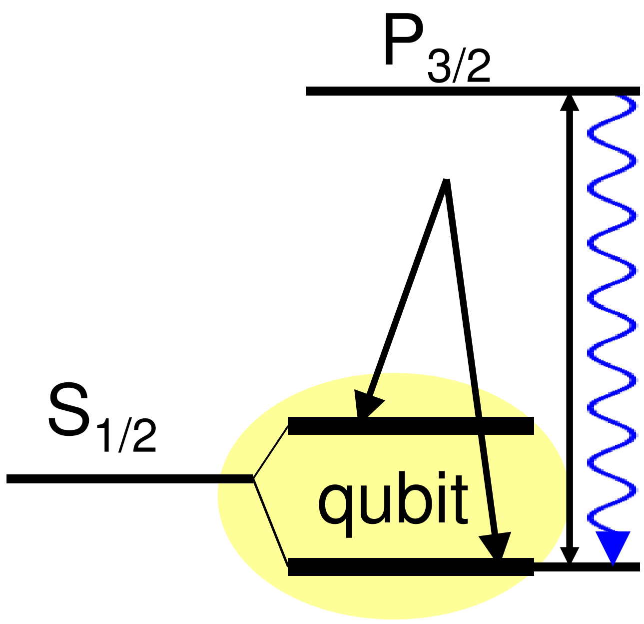
- optical transitions

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

- microwave transitions

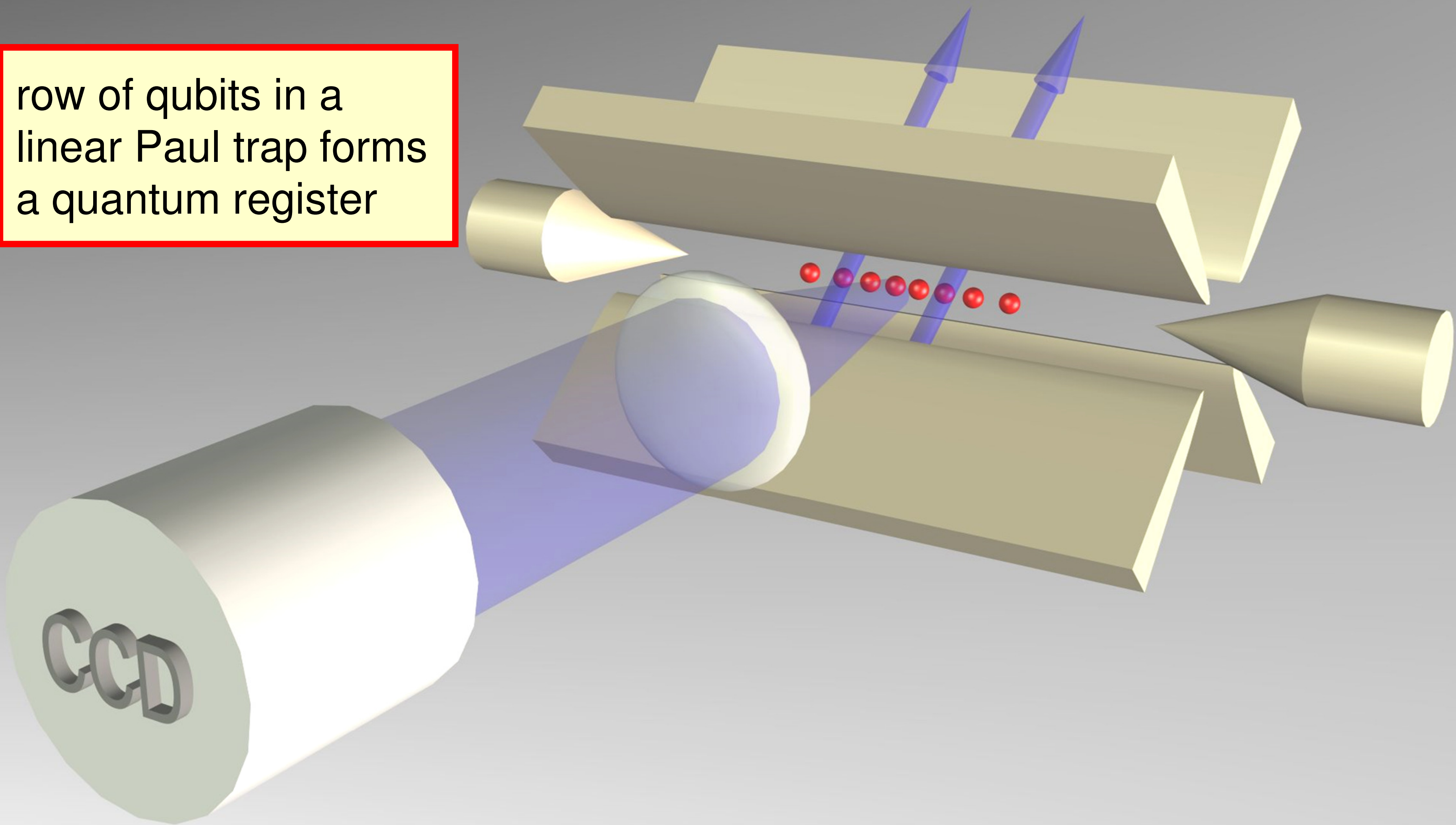
  $^{9}Be^+$, $^{25}Mg^+$, $^{43}Ca^+$, $^{87}Sr^+$, $^{137}Ba^+$, $^{111}Cd^+$, $^{171}Yb^+$





String of Ca+ ions in Paul trap

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



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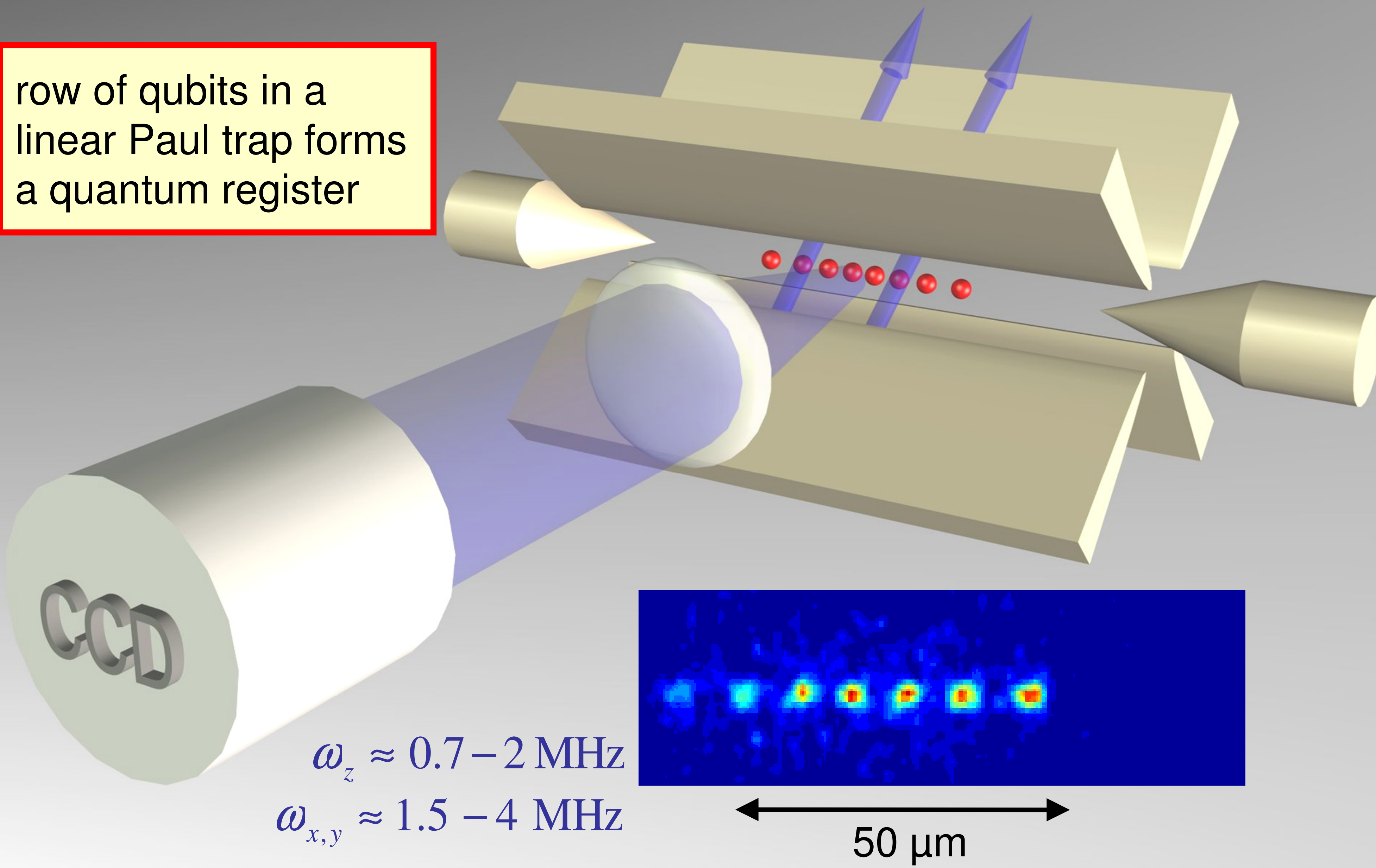
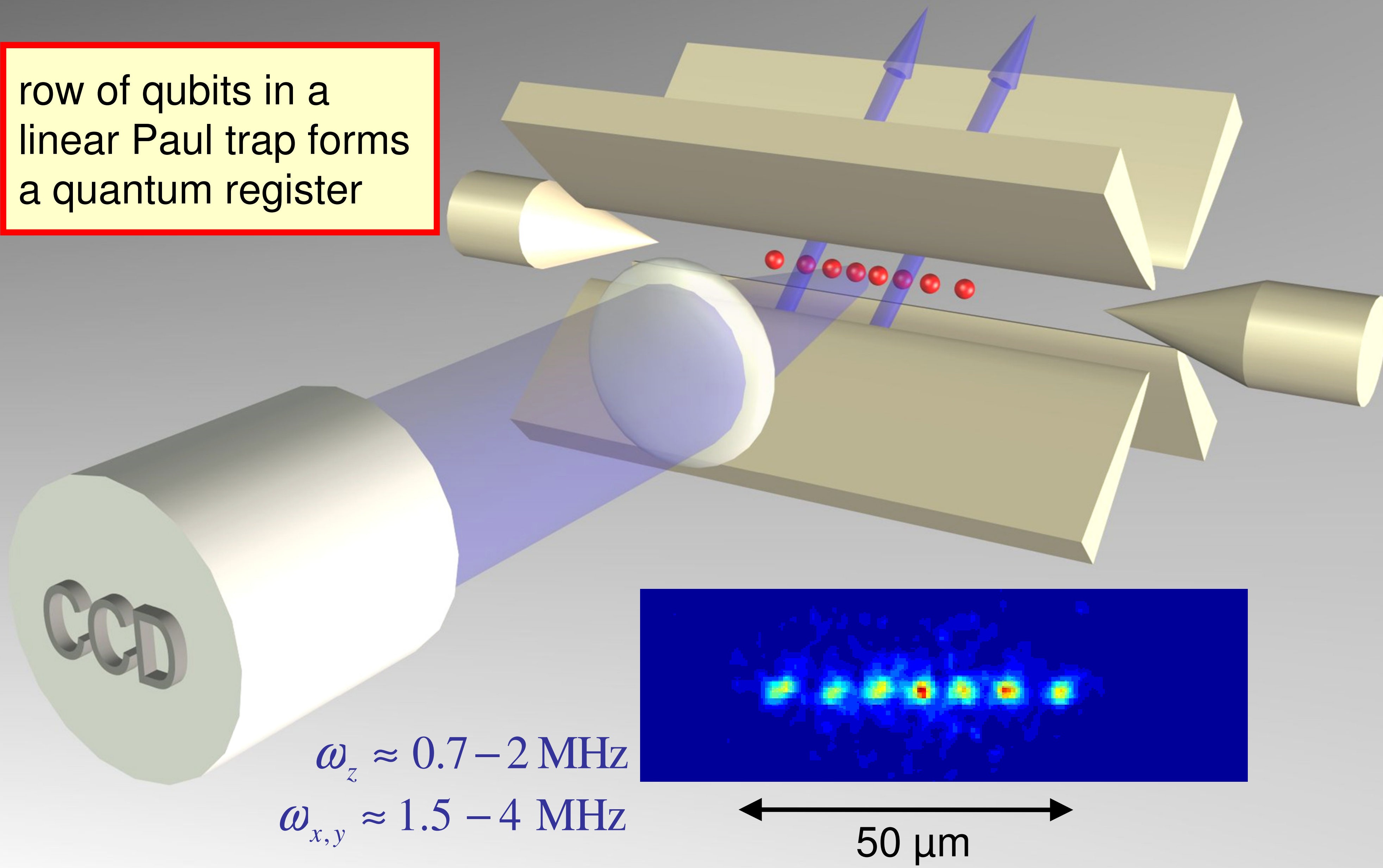


$\omega_z \approx 0.7 - 2\,\mathrm{MHz}$

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

String of Ca+ ions in linear Paul trap

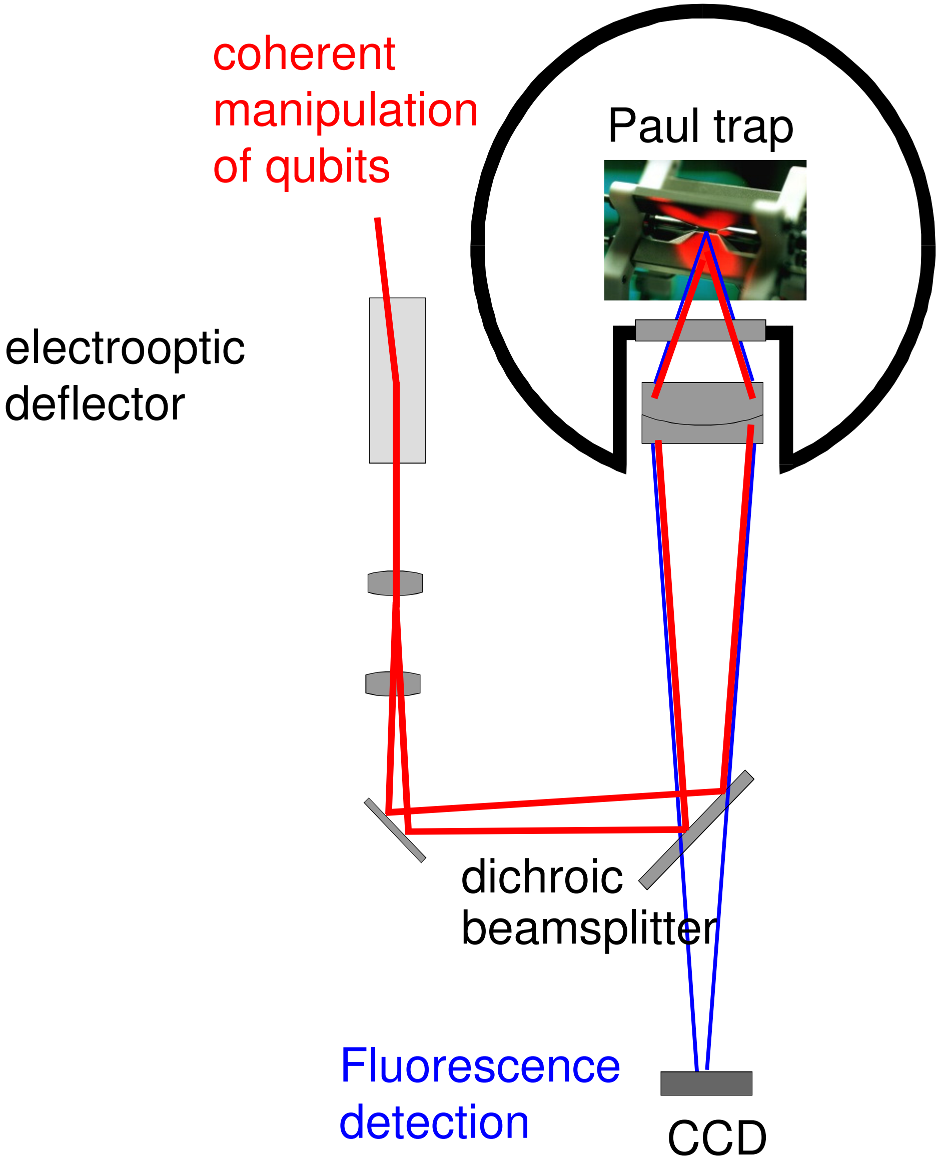
row of qubits in a linear Paul trap forms a quantum register

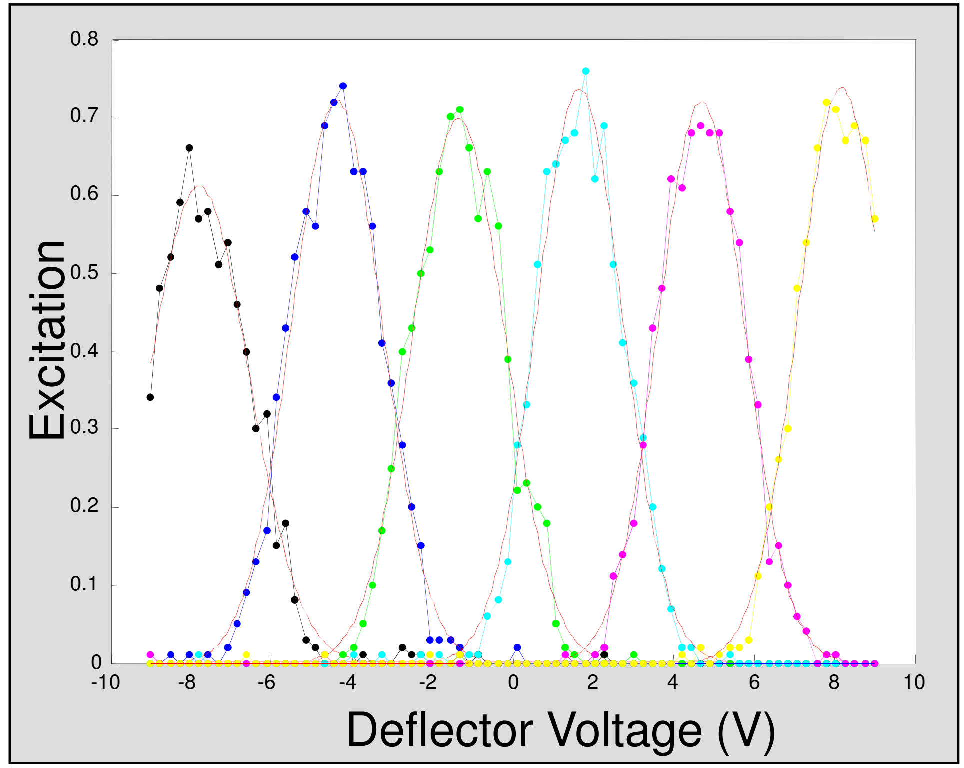


$\omega_z \approx 0.7 - 2\,\mathrm{MHz}$

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

Addressing of individual ions





- 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:

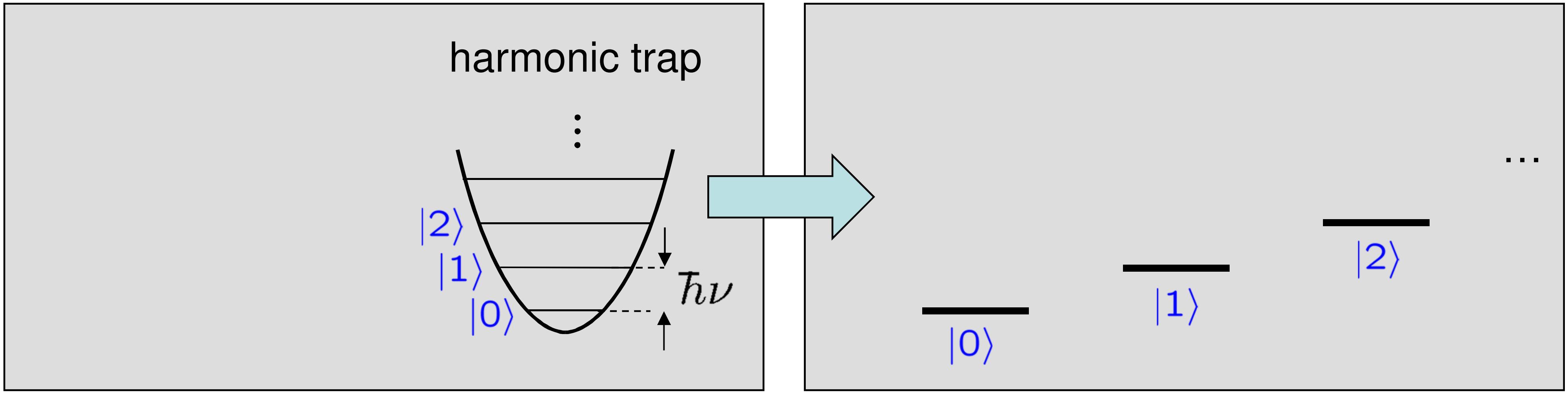
Now let's have a look at the qubit transition in the presence of the motional degrees of freedom. If we focus on just one motional mode , we just get a ladder of harmonic oscillator levels.

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...

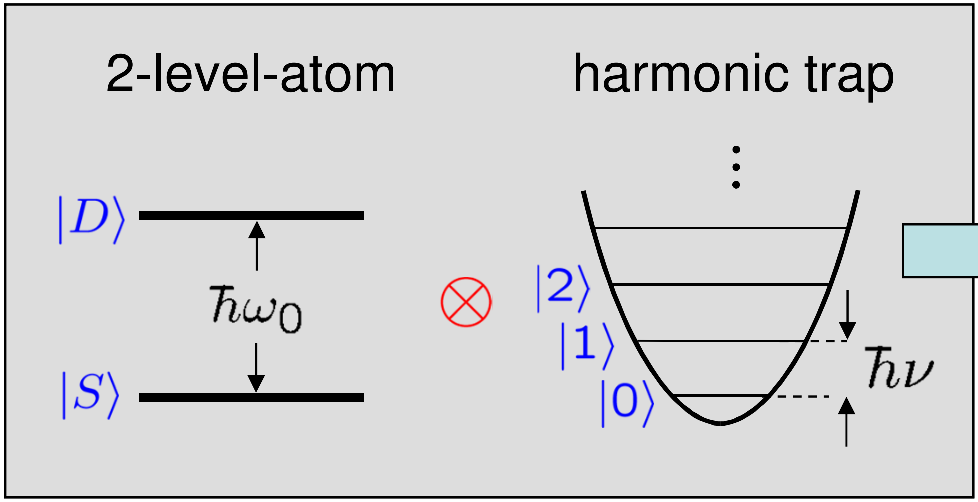
Or use the blue sideband and red sideband transitions, where we can change the motional state.

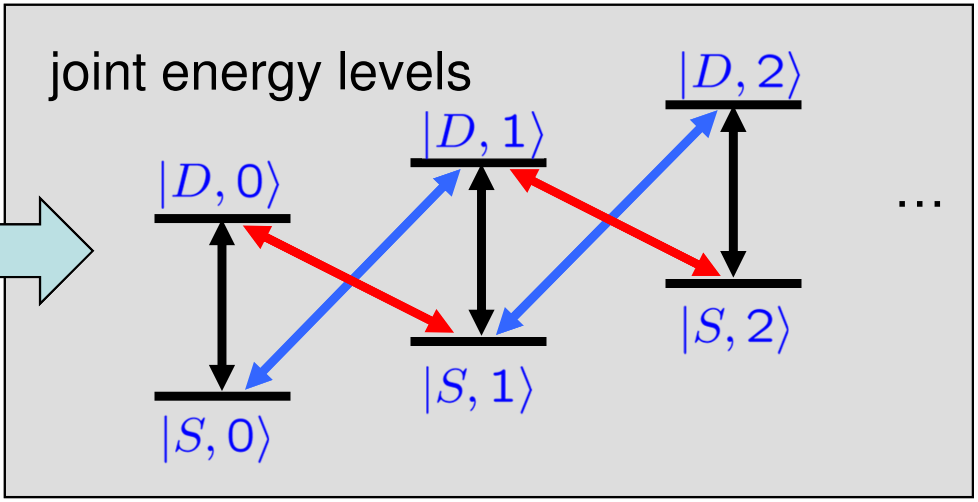
We can walk down the double ladder by exciting the red sideband and returning the ion dissipatively to the grounsstate. With this we can prepare the ions in the motional ground state with high probability, thereby initializing our quantum register.

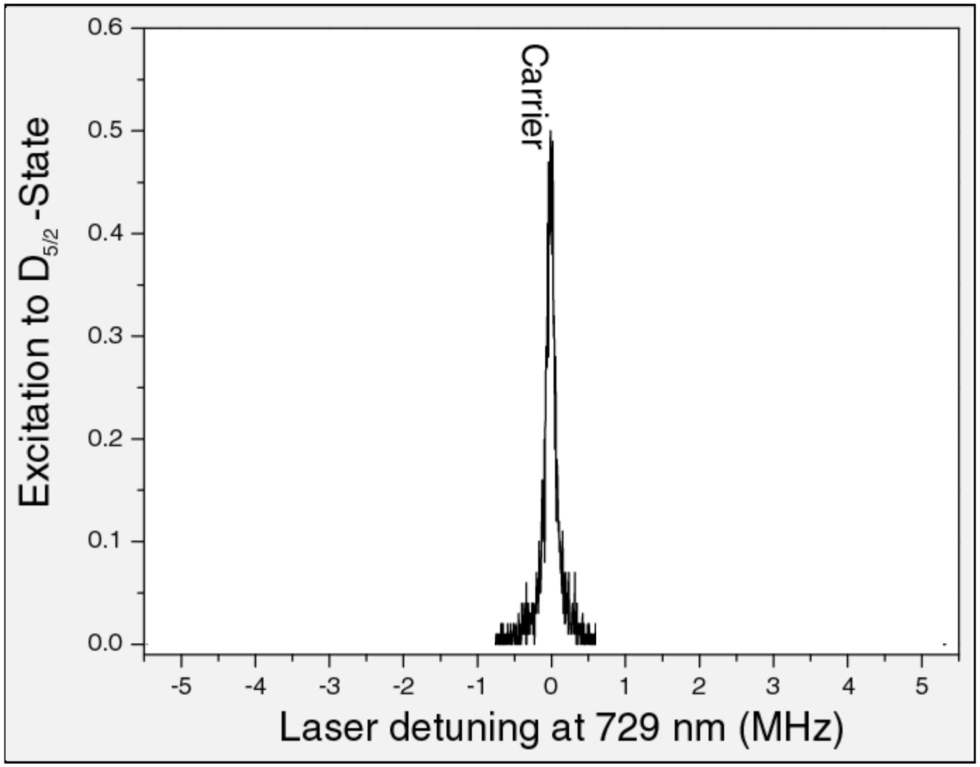
External degree of freedom: ion motion



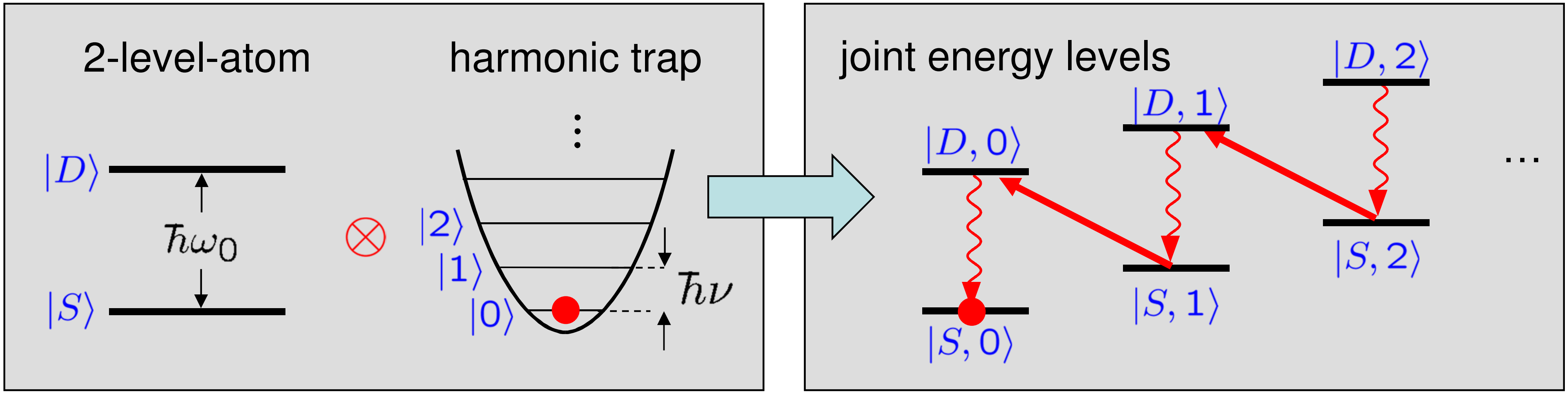
External degree of freedom: ion motion







External degree of freedom: ion motion

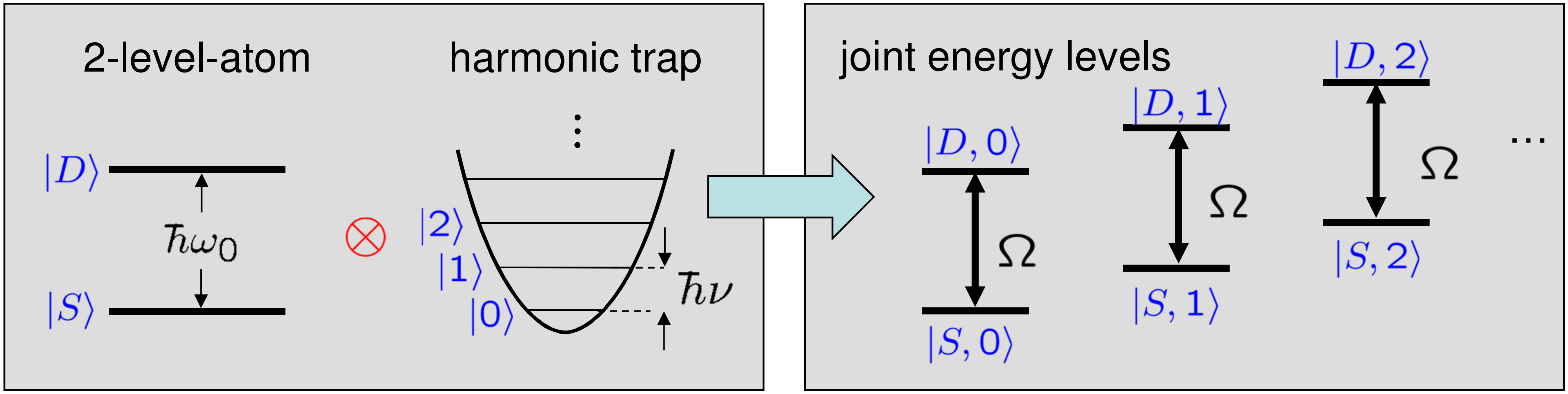


Laser cooling to the motional ground state:

Cooling time: 5-10 ms

> 99% in motional ground state

Coherent manipulation



Interaction with a resonant laser beam :

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

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 $\quad \theta = 2\Omega\tau$

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.

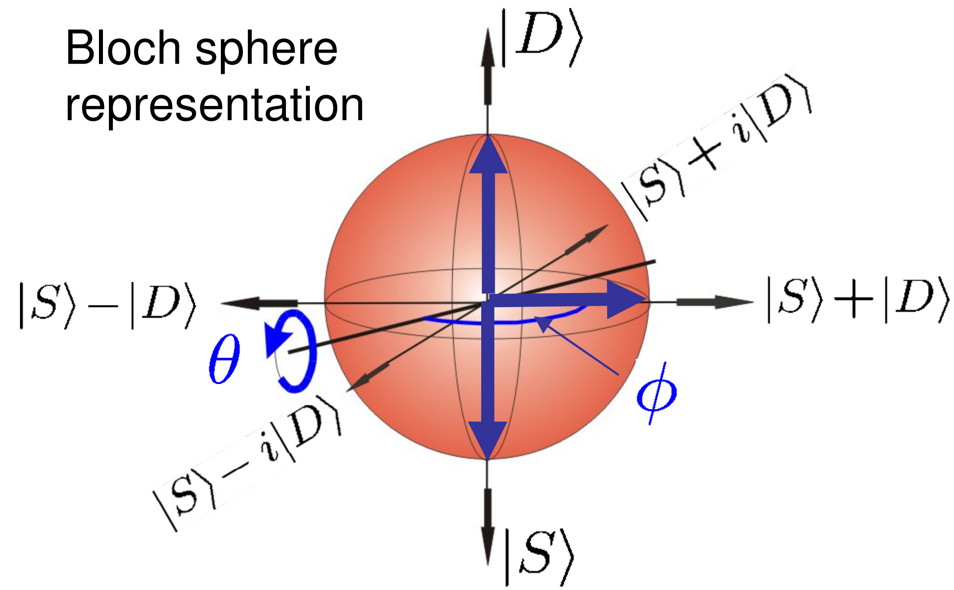
The effect of such a pulse is a rotation of the state vector on the Bloch sphere, where the poles represent the two states and the equator represents superposition states with different relative phases. The roation axis is determined by the laser frequency and phase. The important message is here that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

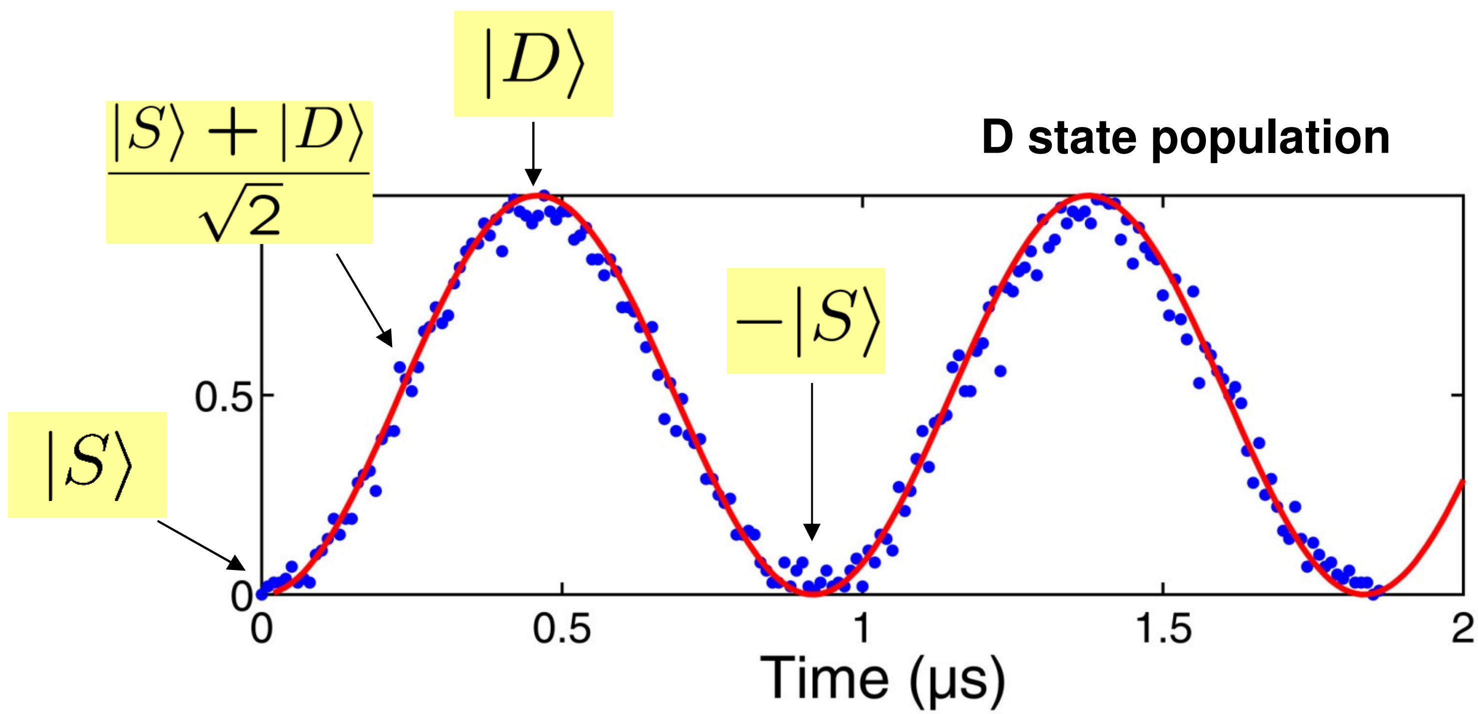
„Carrier" pulses:

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



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

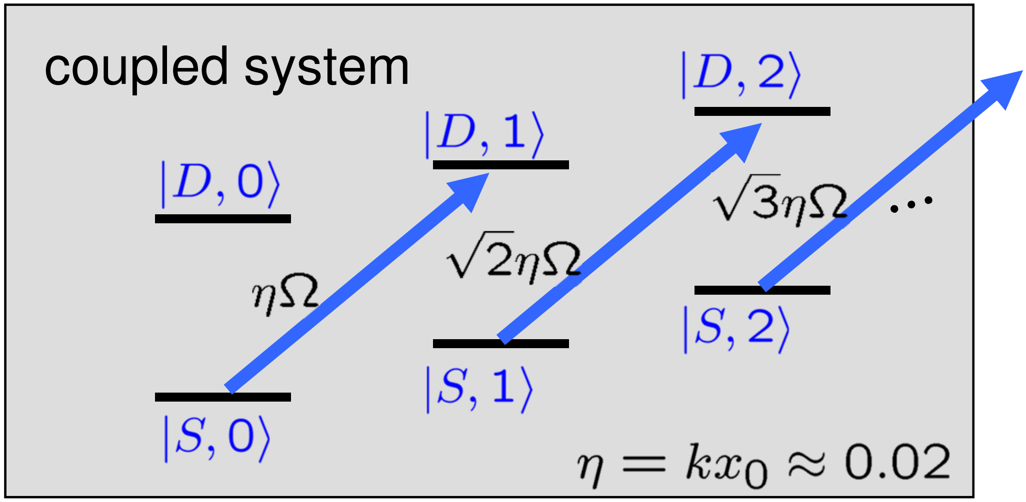
$\tau 2\pi$



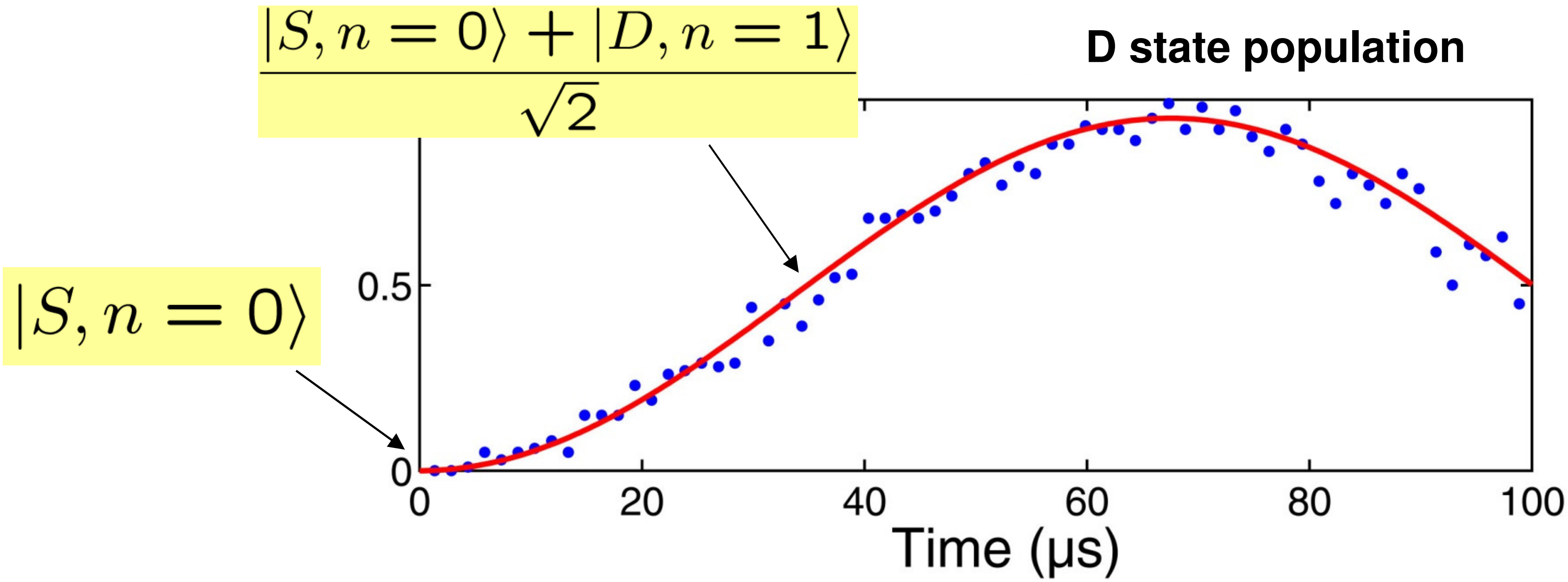
Coherent excitation on the sideband

„Blue sideband" pulses:

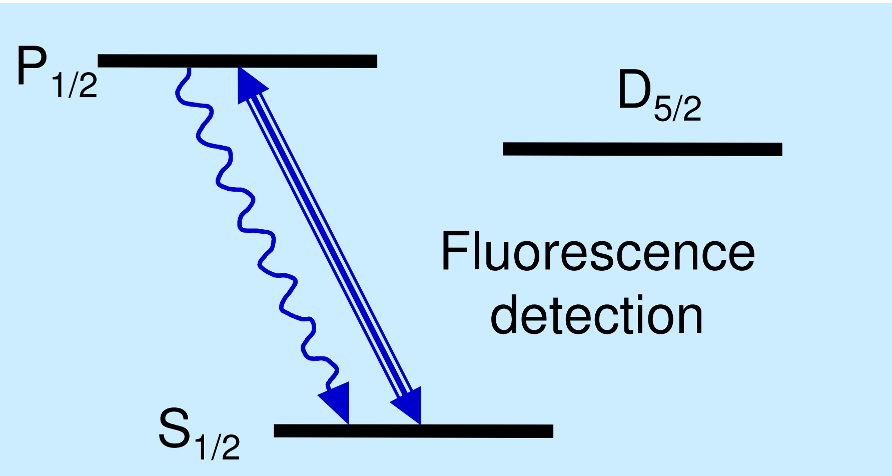
$$|S\rangle|n\rangle \longleftrightarrow |D\rangle|n+1\rangle$$



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



Experimental procedure

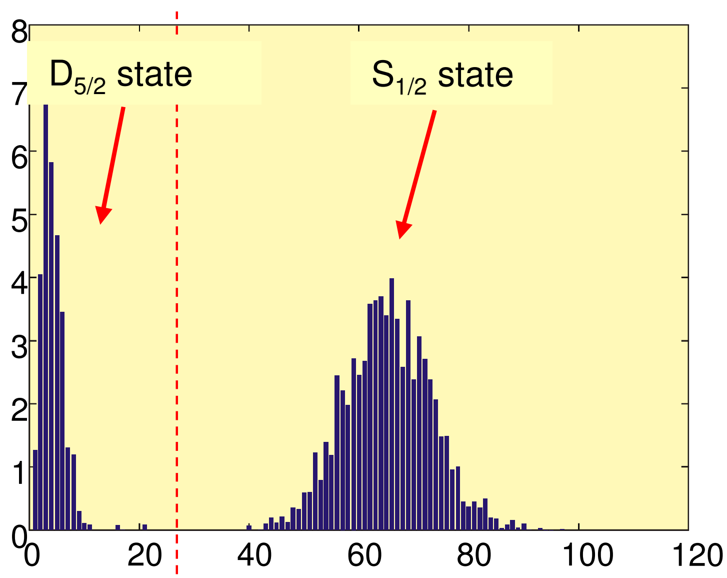


1. Initialization in a pure quantum state: laser cooling,optical pumping

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

3. Quantum state measurement by fluorescence detection

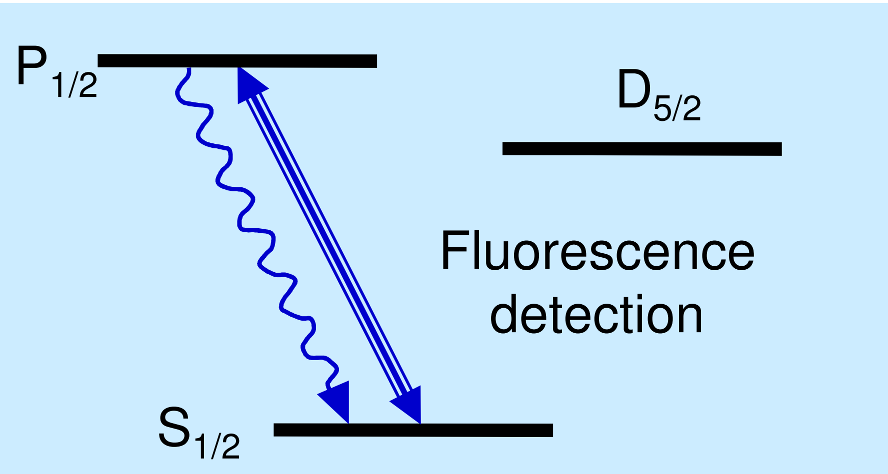
One ion : Fluorescence histogram



50 experiments / s

Repeat experiments 100-200 times

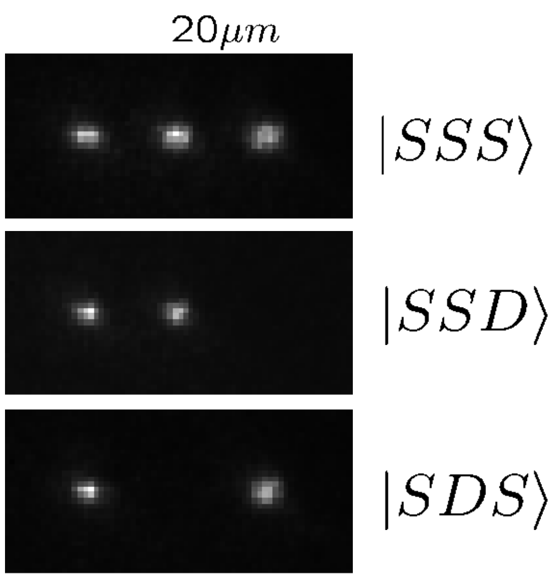
Experimental procedure



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

1. Basic experimental techniques
2. **Two-particle entanglement**
3. Multi-particle entanglement
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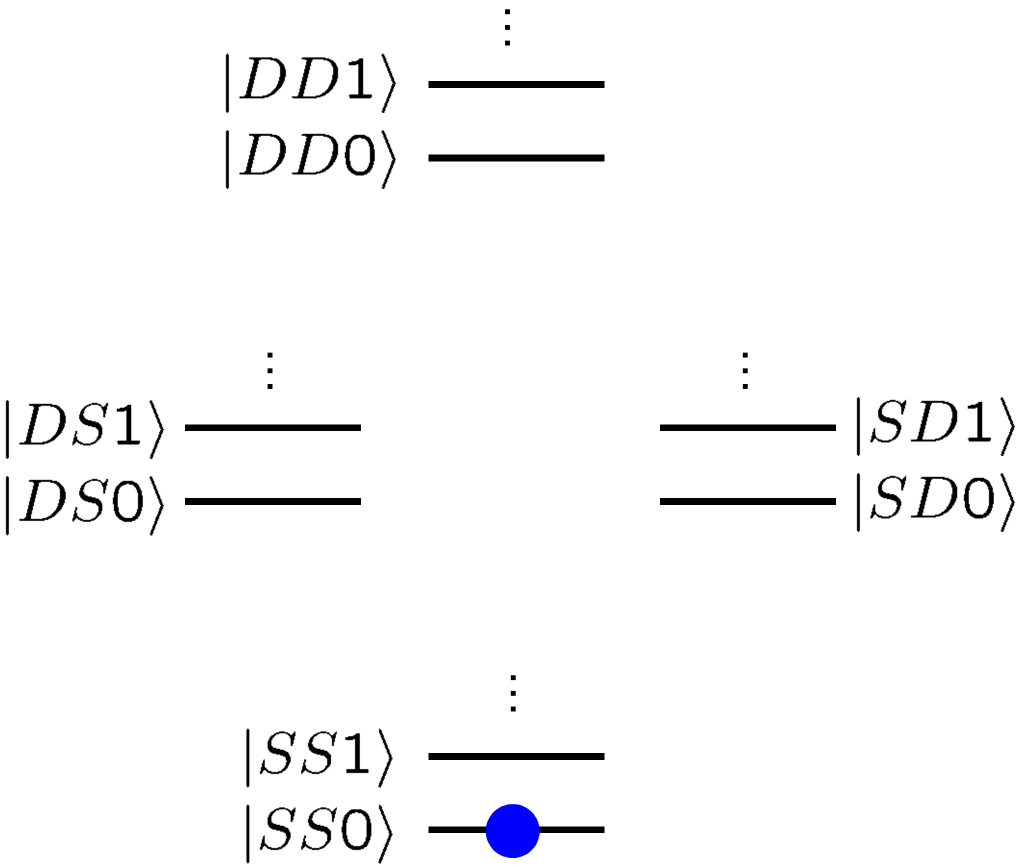
$$\frac{1}{\sqrt{2}}(|S\rangle|D\rangle + |D\rangle|S\rangle)$$

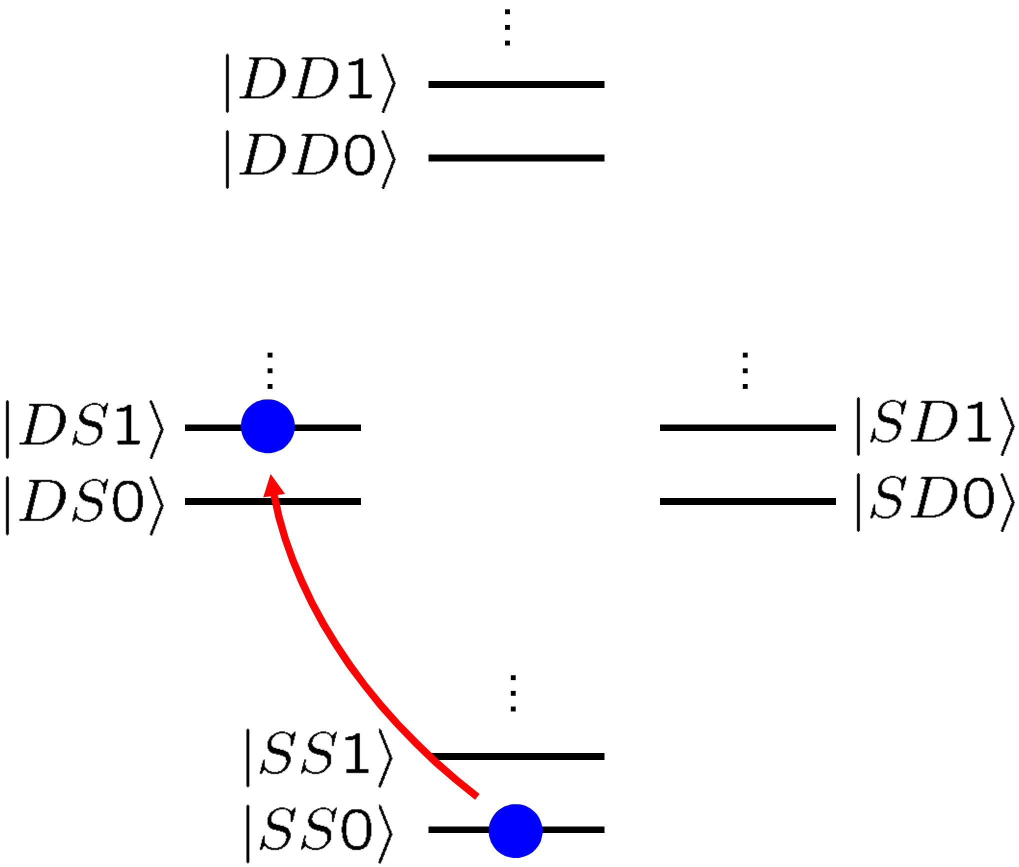
Creation of Bell state



Pulse sequence:

$|SS0\rangle$

Creation of Bell states

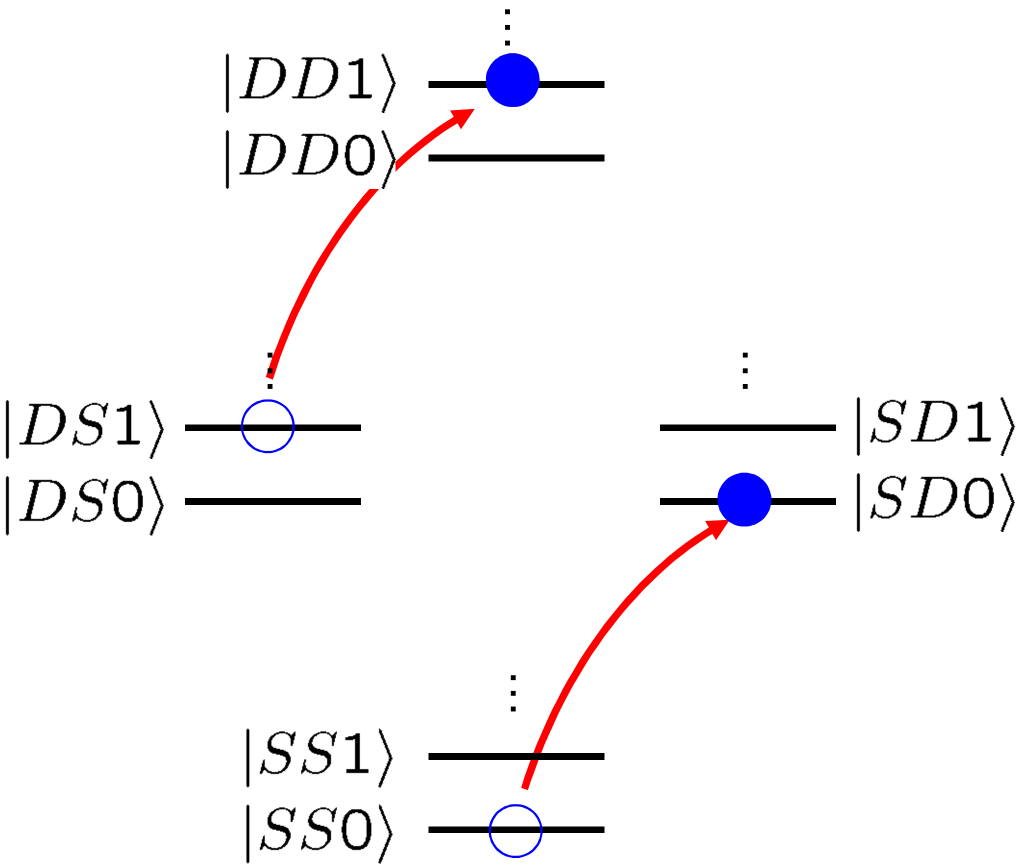


Pulse sequence:

Ion 1: $\pi/2$, blue sideband

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

Creation of Bell states



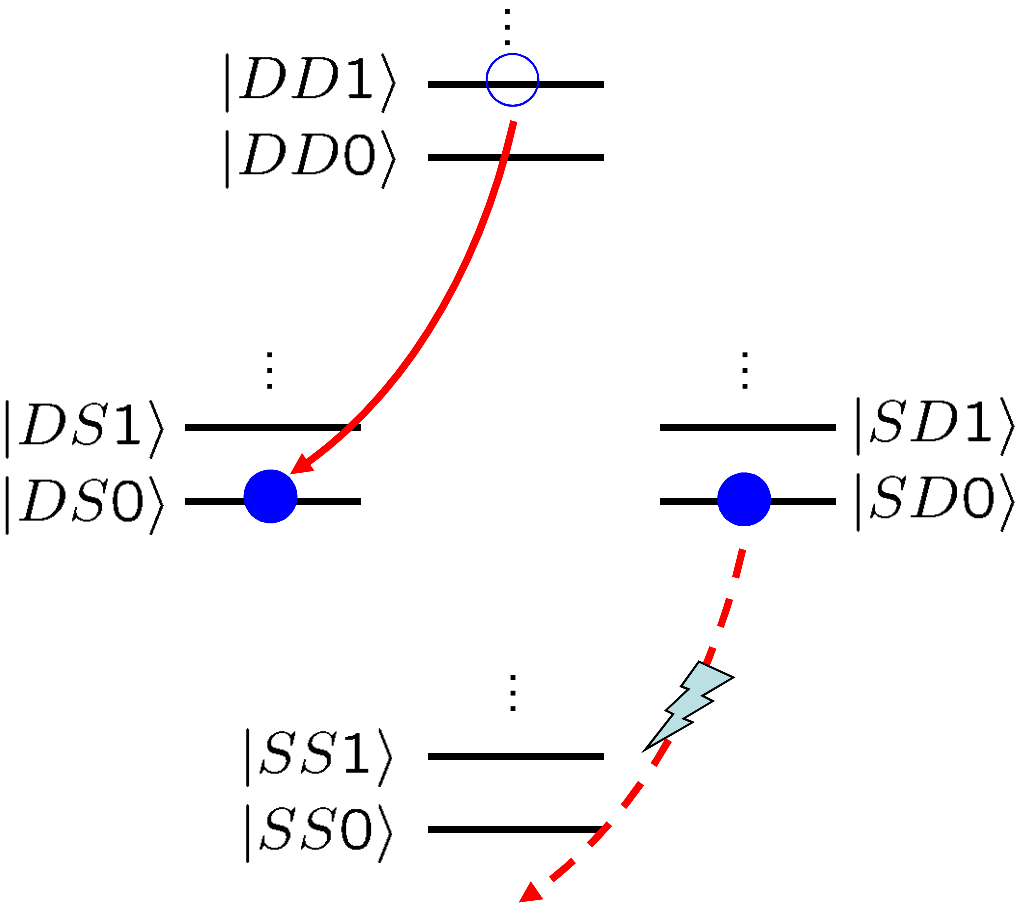
Pulse sequence:

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:

$|SS\rangle$

$|SD\rangle$

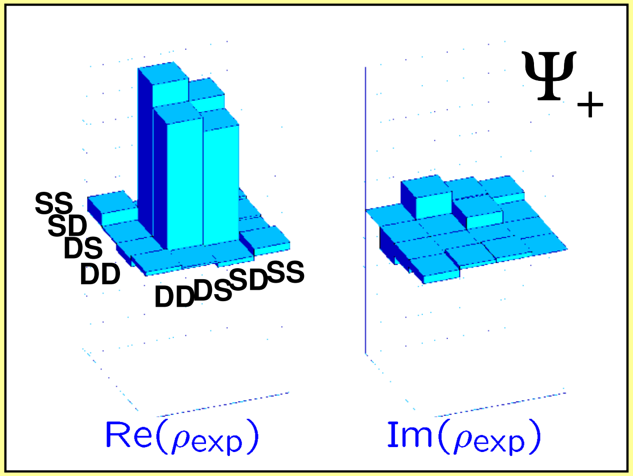
$|DS\rangle$

$|DD\rangle$

Coherent superposition or incoherent mixture ?

What is the relative phase of the superposition ?

→ **Measurement of the density matrix:**



Reconstruction of a density matrix

Representation of ρ as a sum of orthogonal observables A_i :

$$\rho = \sum_i \lambda_i A_i \;\; \text{with} \;\; Tr(A_i A_j) = \delta_{ij}$$

ρ is completely detemined by the expectation values $<A_i>$:

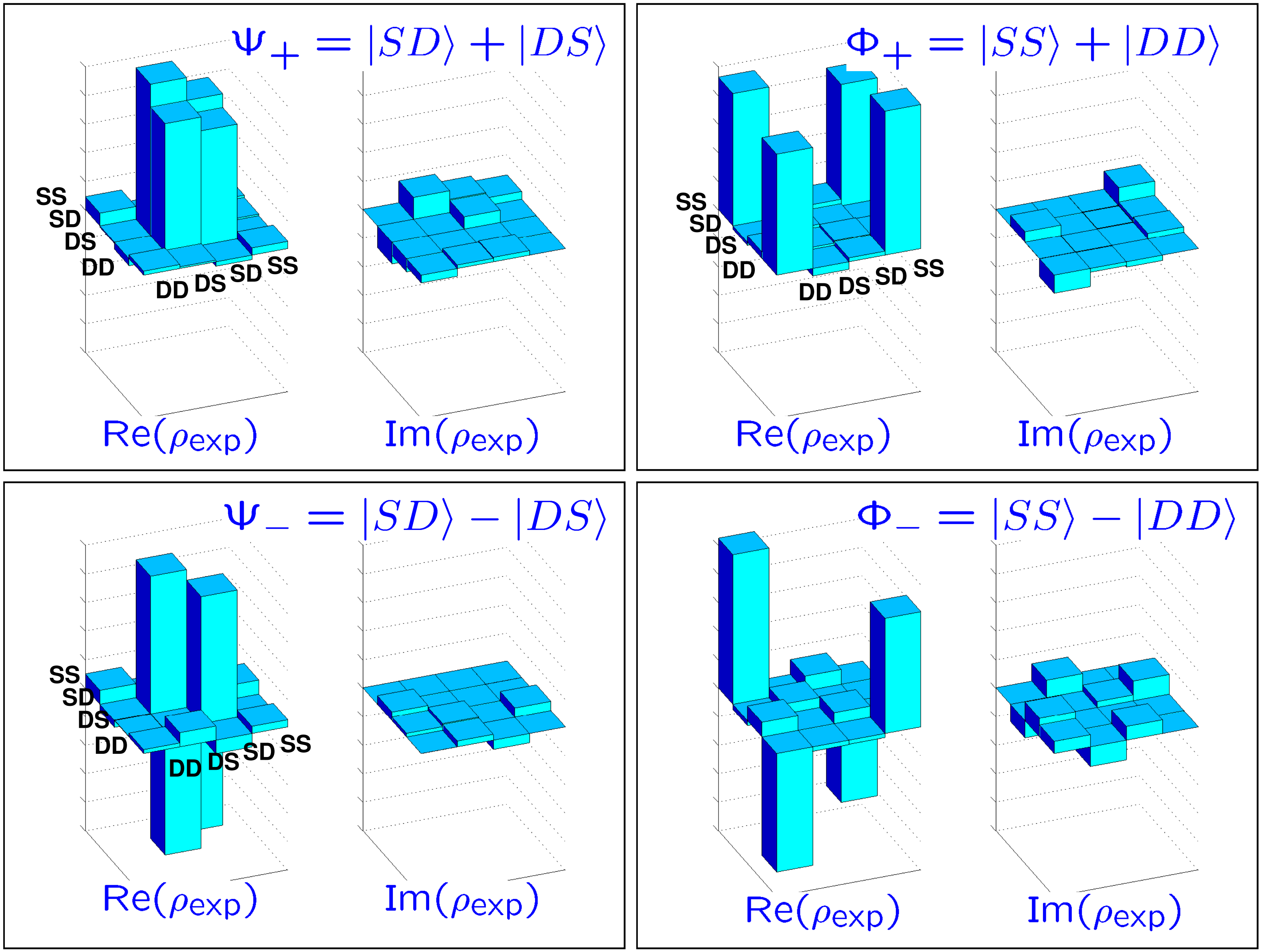
$$\langle A_j \rangle = Tr(\rho A_j) = \sum_i \lambda_i Tr(A_i A_j) = \lambda_j$$

Finally: maximum likelihood estimation (Hradil '97, Banaszek '99)

For a two-ion system : $A_i \in \{\sigma_i^{(1)} \otimes \sigma_j^{(2)}, \sigma_i \in \{I, \sigma_x, \sigma_y, \sigma_z\}\}$

⟶ Joint measurements of all spin components $\sigma_i^{(1)} \otimes \sigma_j^{(2)}$

Preparation and tomography of Bell states



Fidelity:

F = 0.91

Entanglement of formation:

$E(\rho_{exp}) = 0.79$

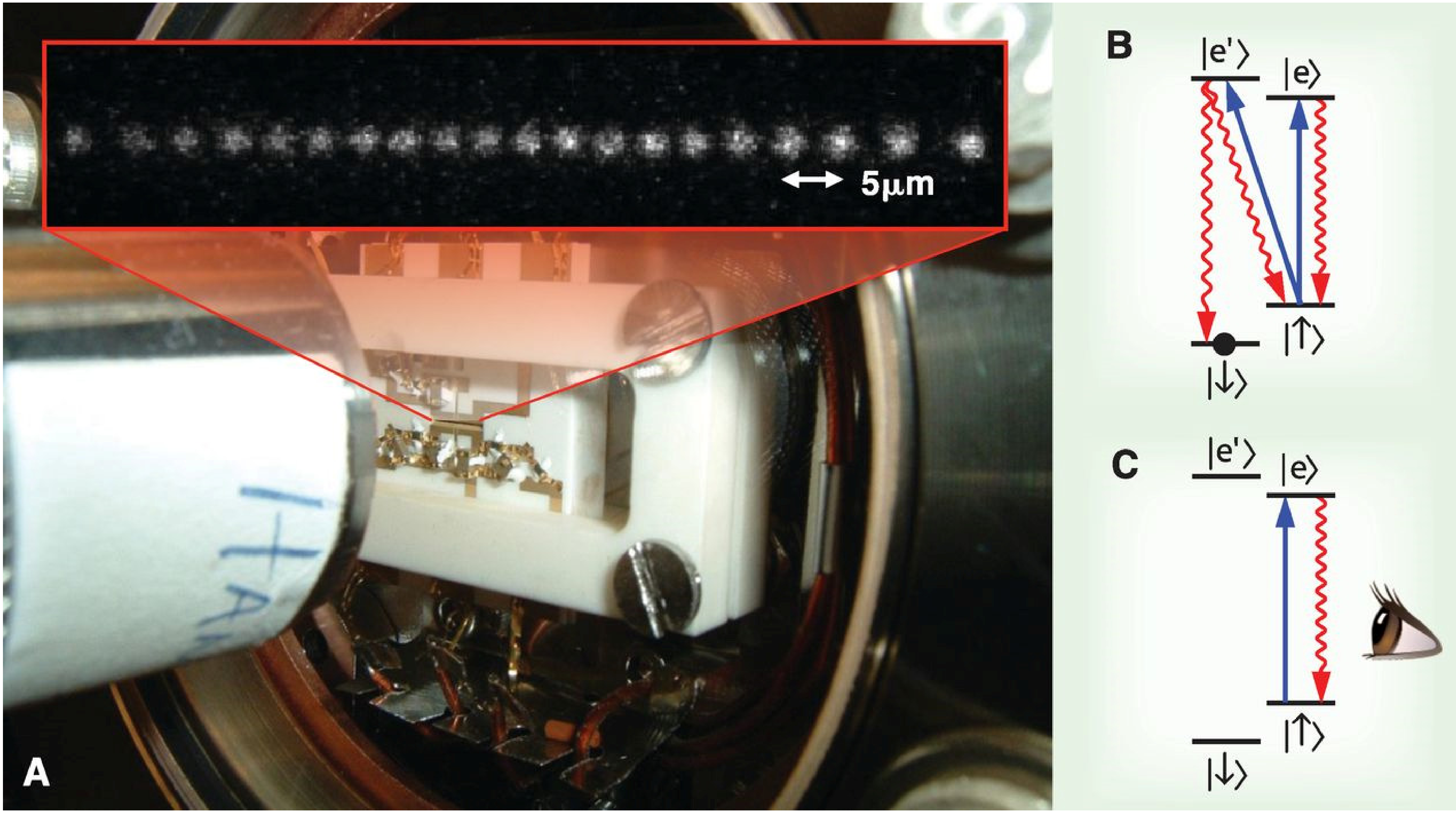
Violation of Bell inequality:

$S(\rho_{exp}) = 2.52(6)$
> 2

C. Roos et al., Phys. Rev. Lett. **92**, 220402 (2004)

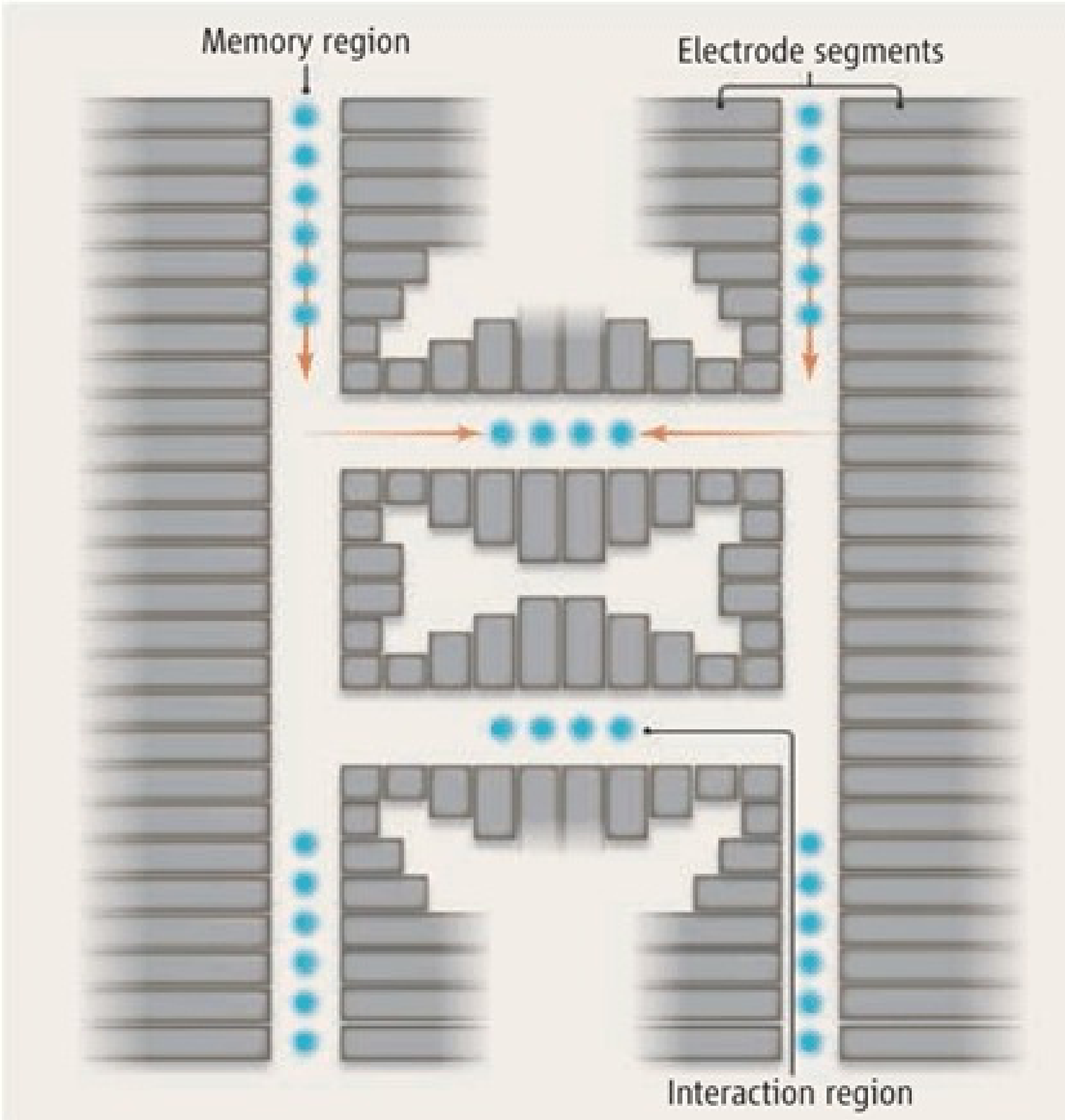
How to build a large-scale quantum computer with trapped ions

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



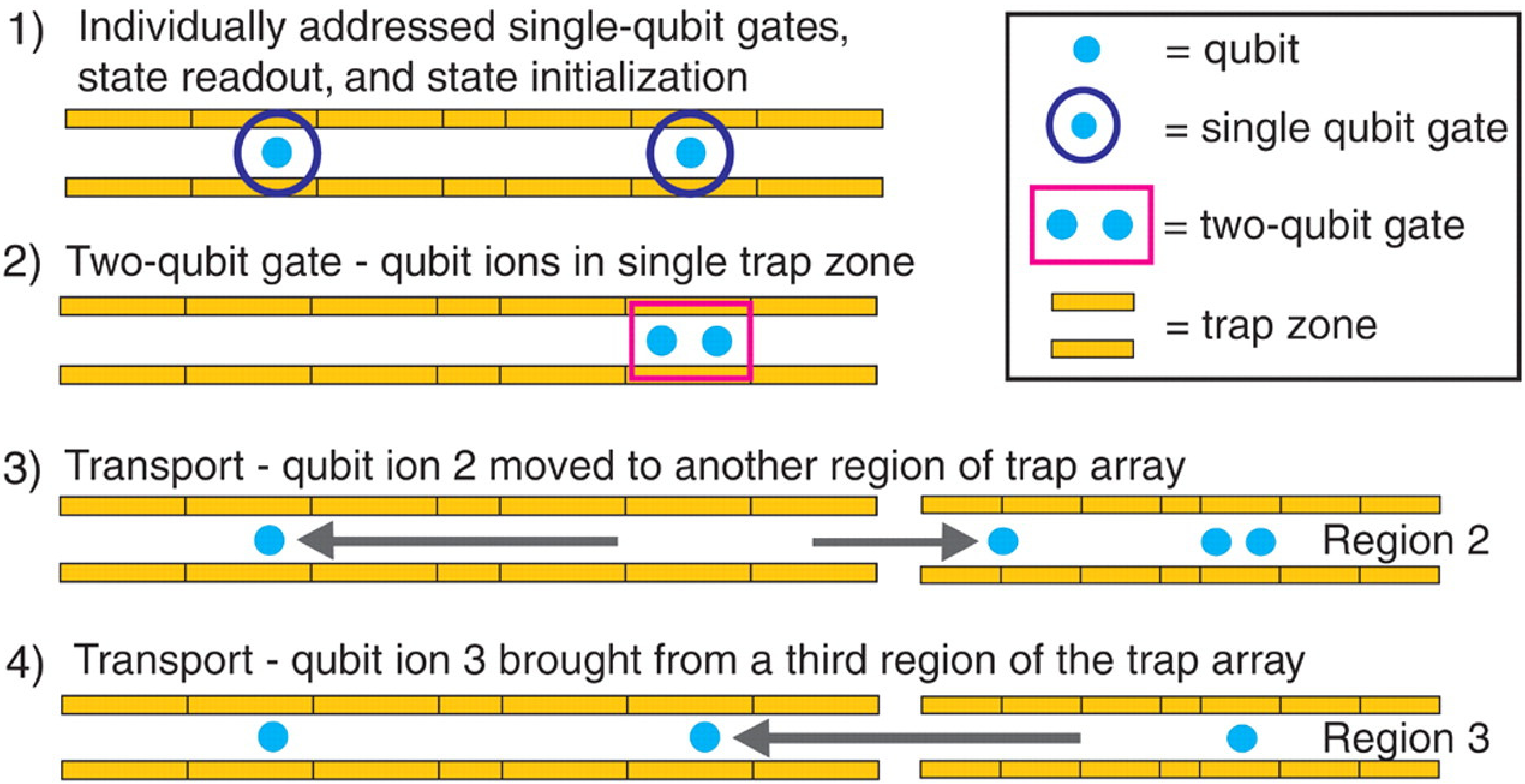
C. Monroe, and J. Kim Science 2013;339:1164-1169

Harnessing ion-trap qubits



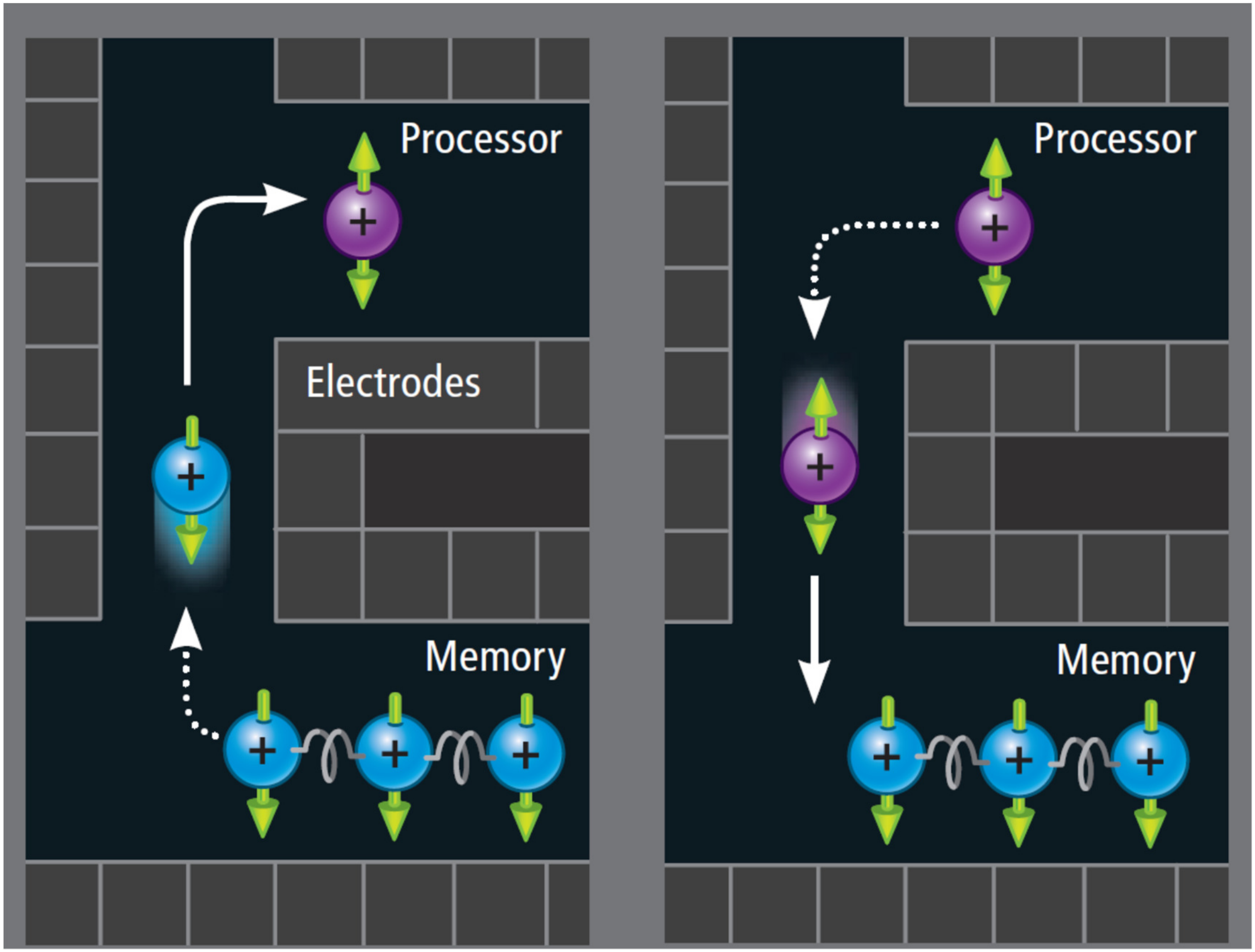
David P. DiVincenzo Science 2011;334:50-51

Schematic of the sequence of operations implemented in a single processing region for building up a computation in the architecture



Jonathan P. Home et al. Science 2009;325:1227-1230

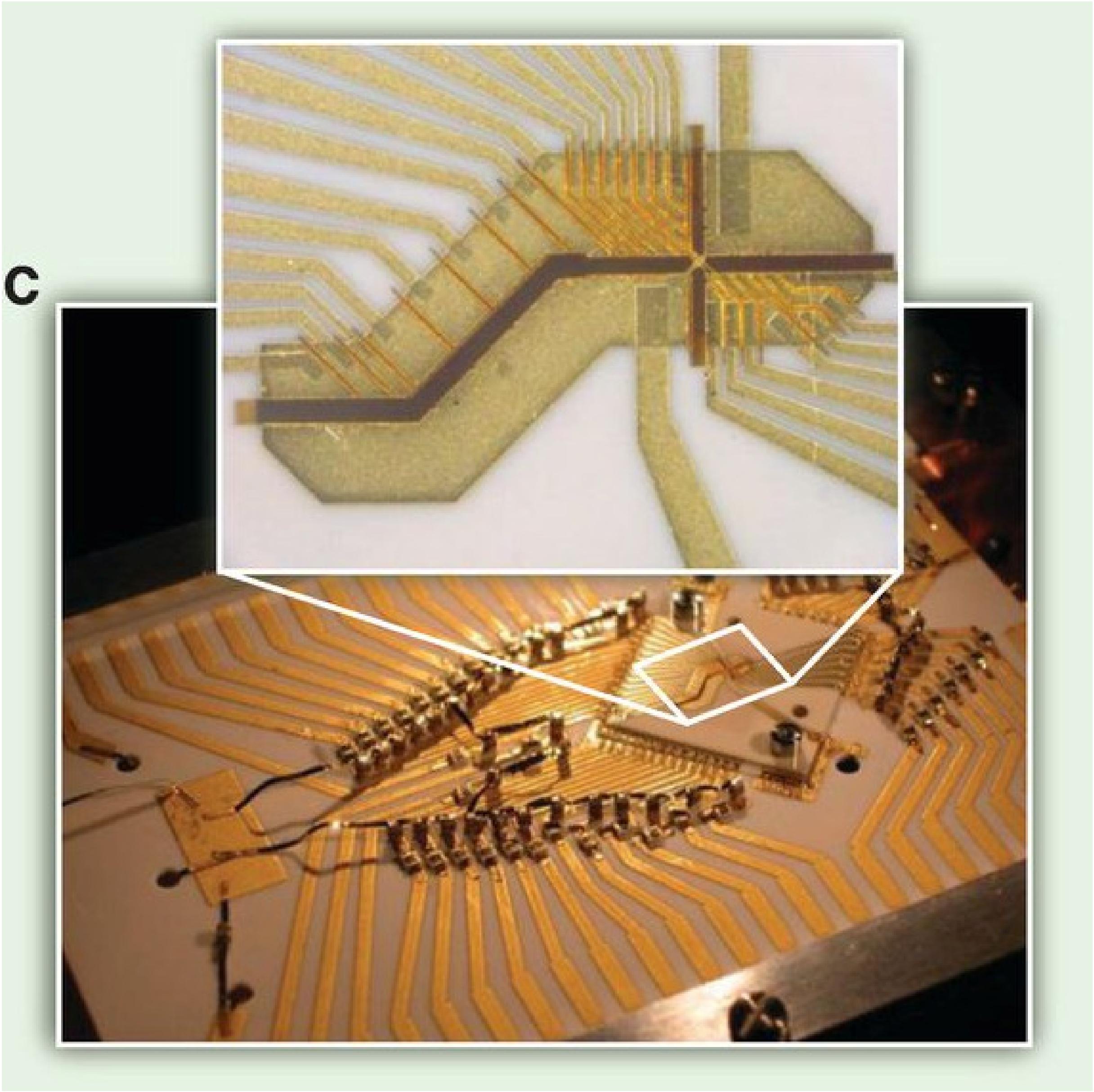
Separating memory and processor zones



Scientific American (August 2008), **299**, 64-71

Ion trap structure for the shuttling of ions through a junction

C



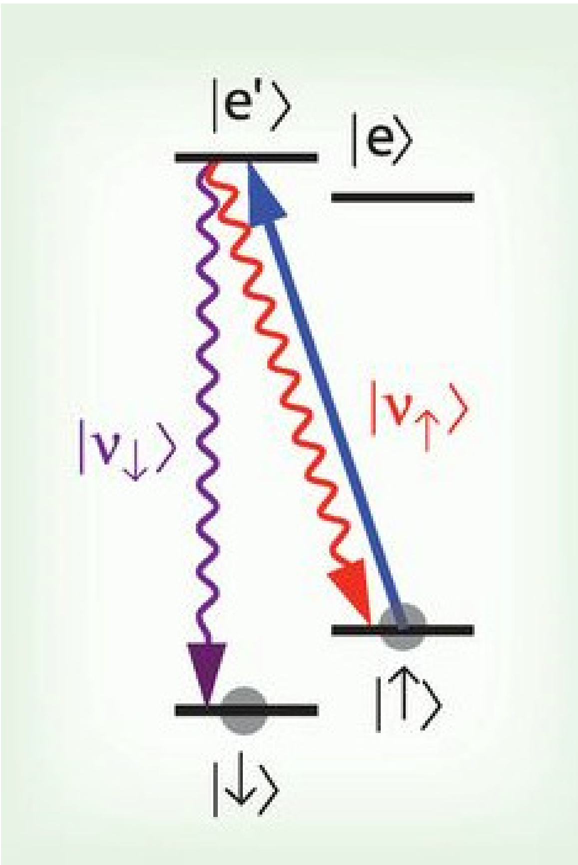
C. Monroe, and J. Kim Science 2013;339:1164-1169

Concept of a quantum CCD trap

Image credit: National Institute of Standards and Technology

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

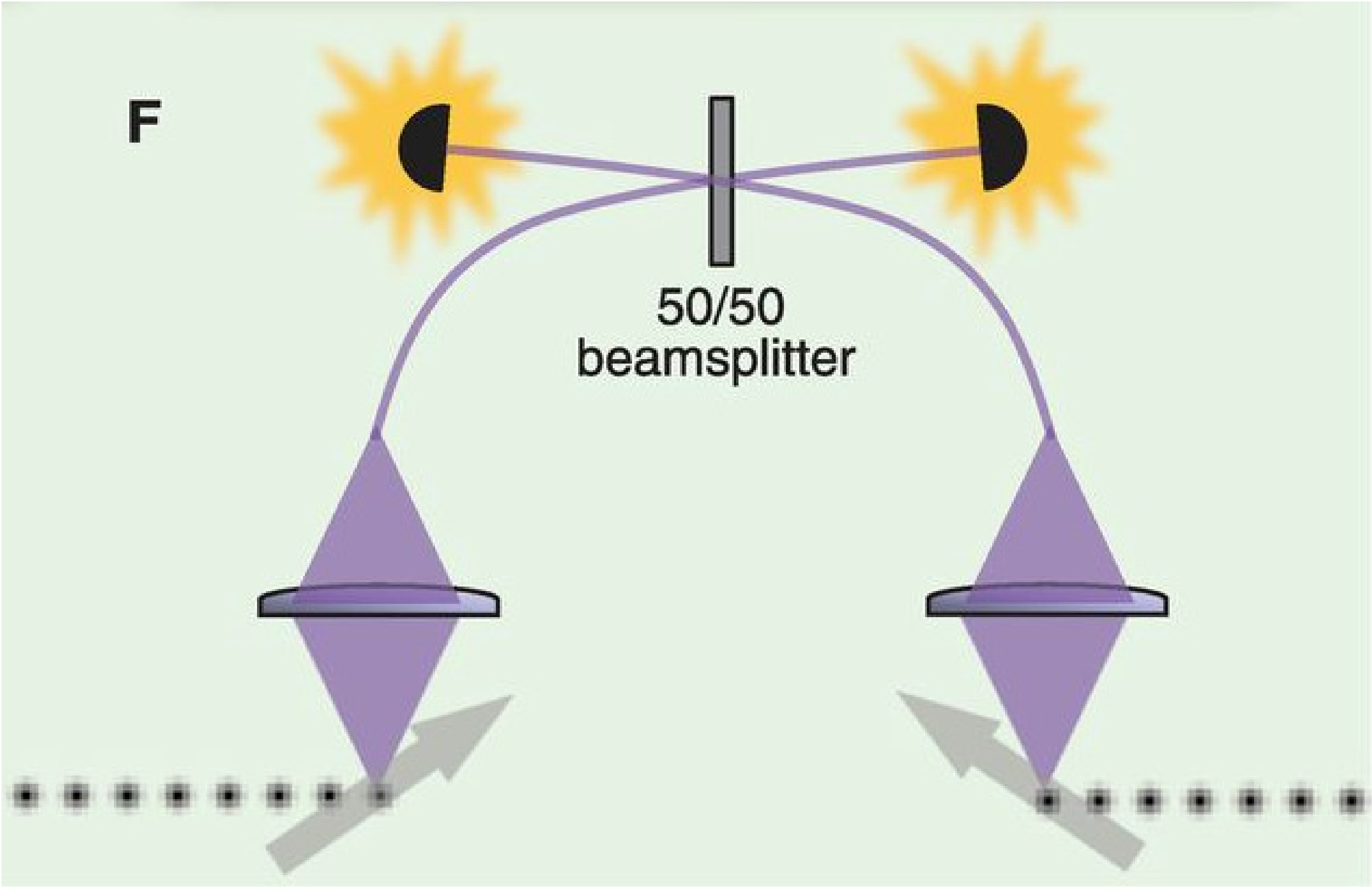
Version 2: Photonics coupling of trapped ions qubits



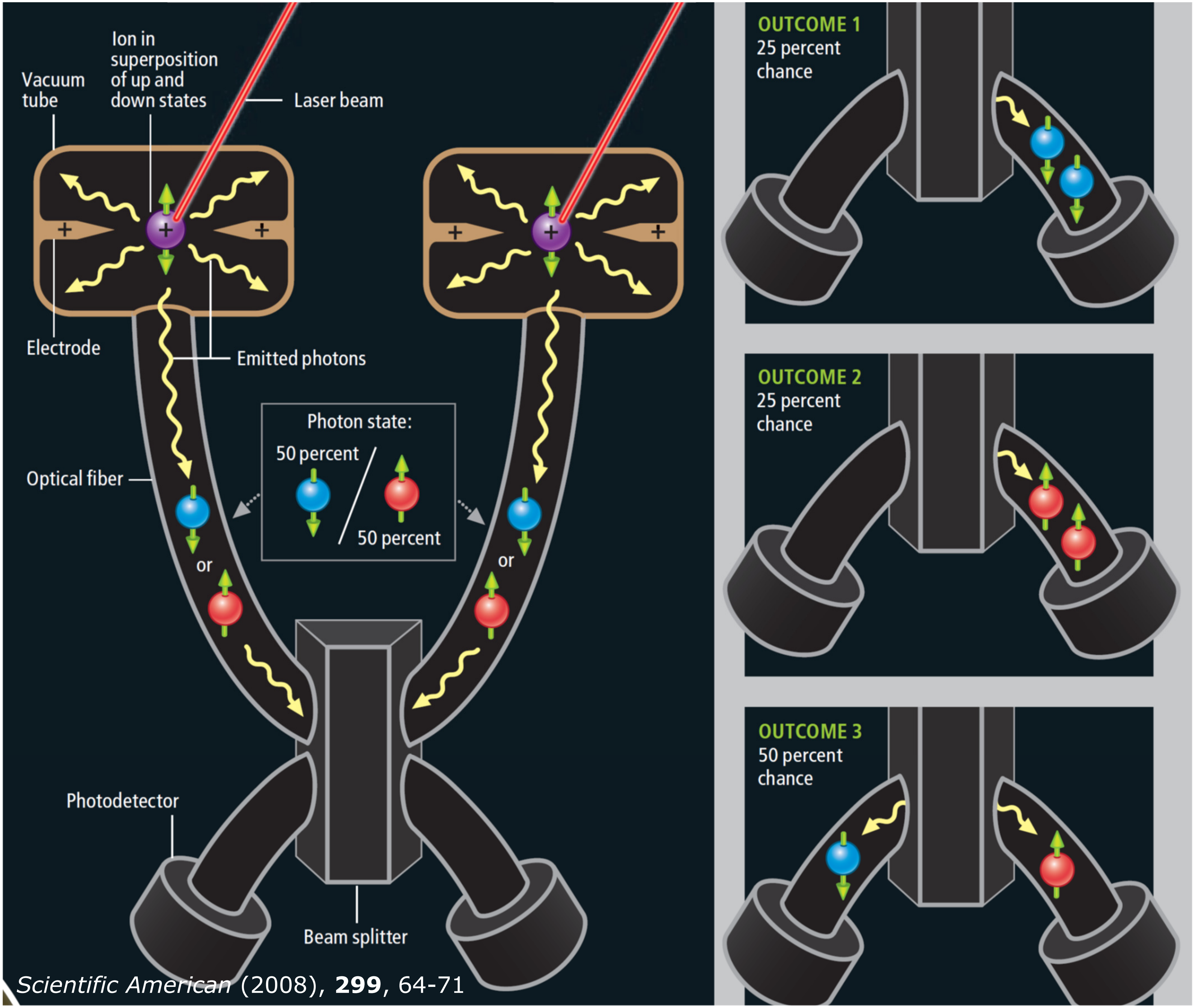
Energy levels of trapped ion excited with a fast laser pulse (blue upward arrow) that produces single photon whose color, represented by the state or , is entangled with the resultant qubit state.

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.



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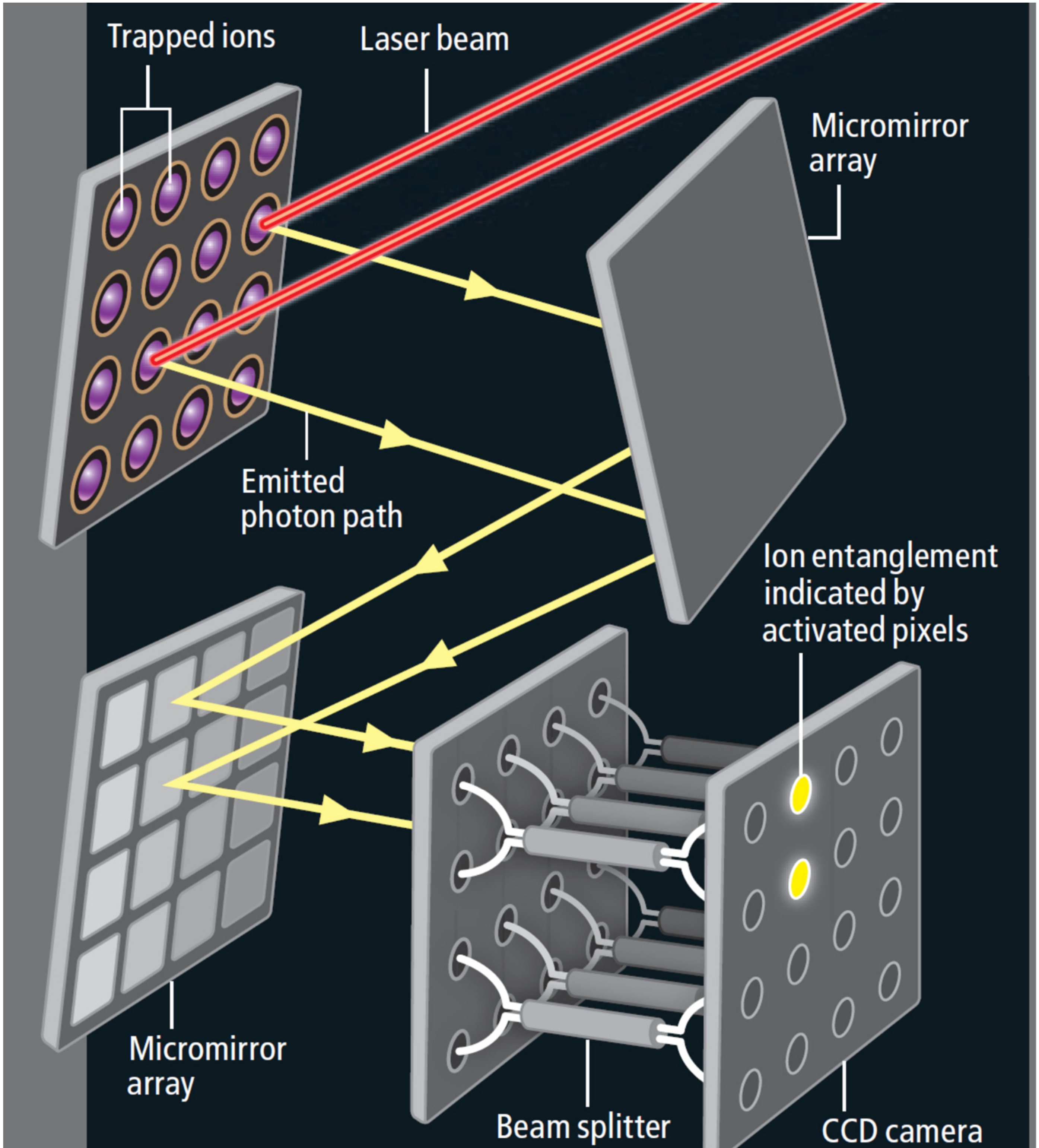
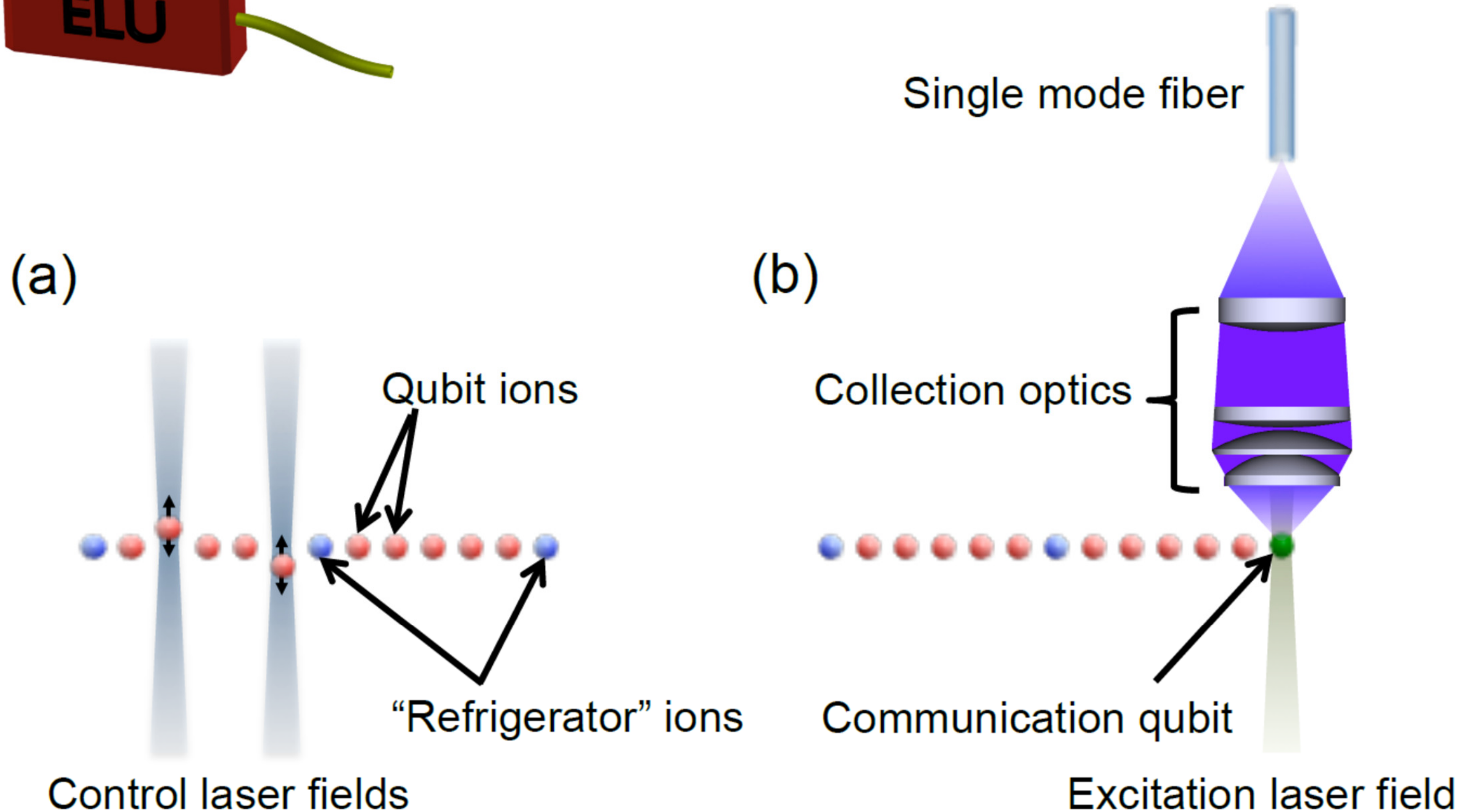


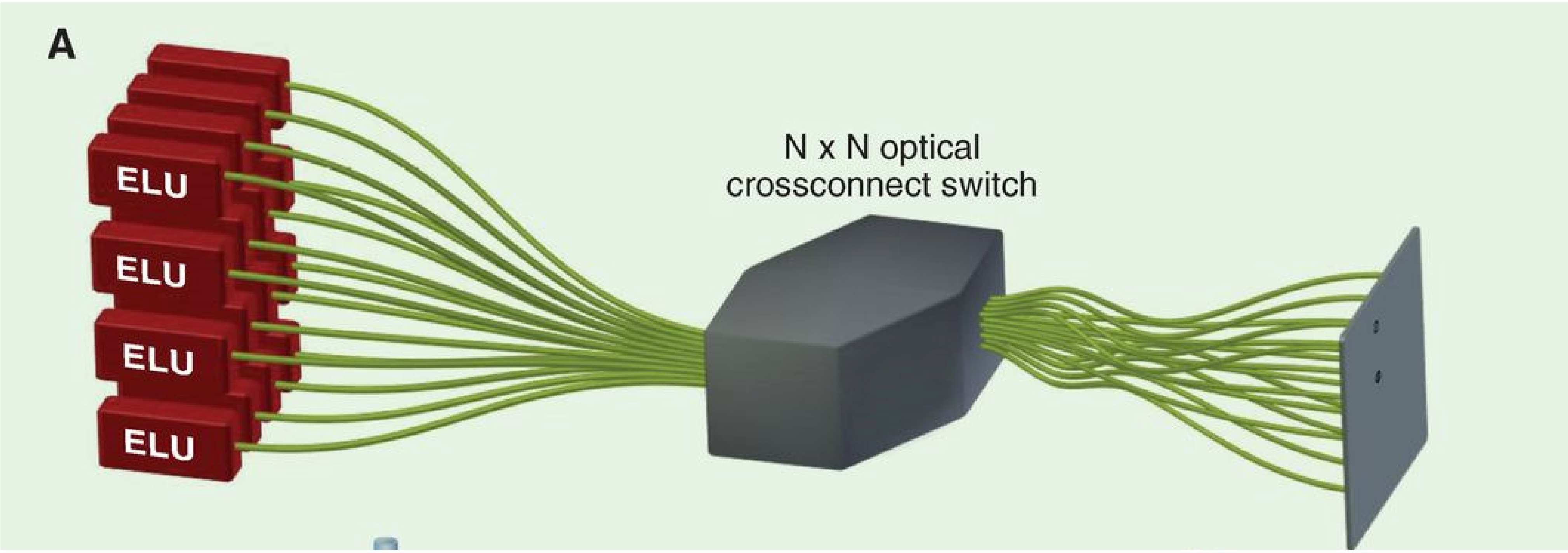
Scientific American (2008), **299**, 64-71

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