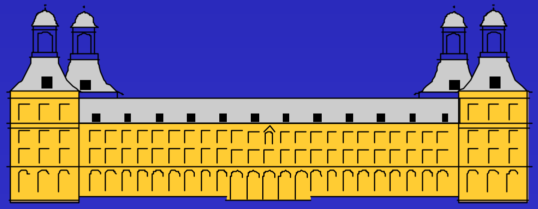
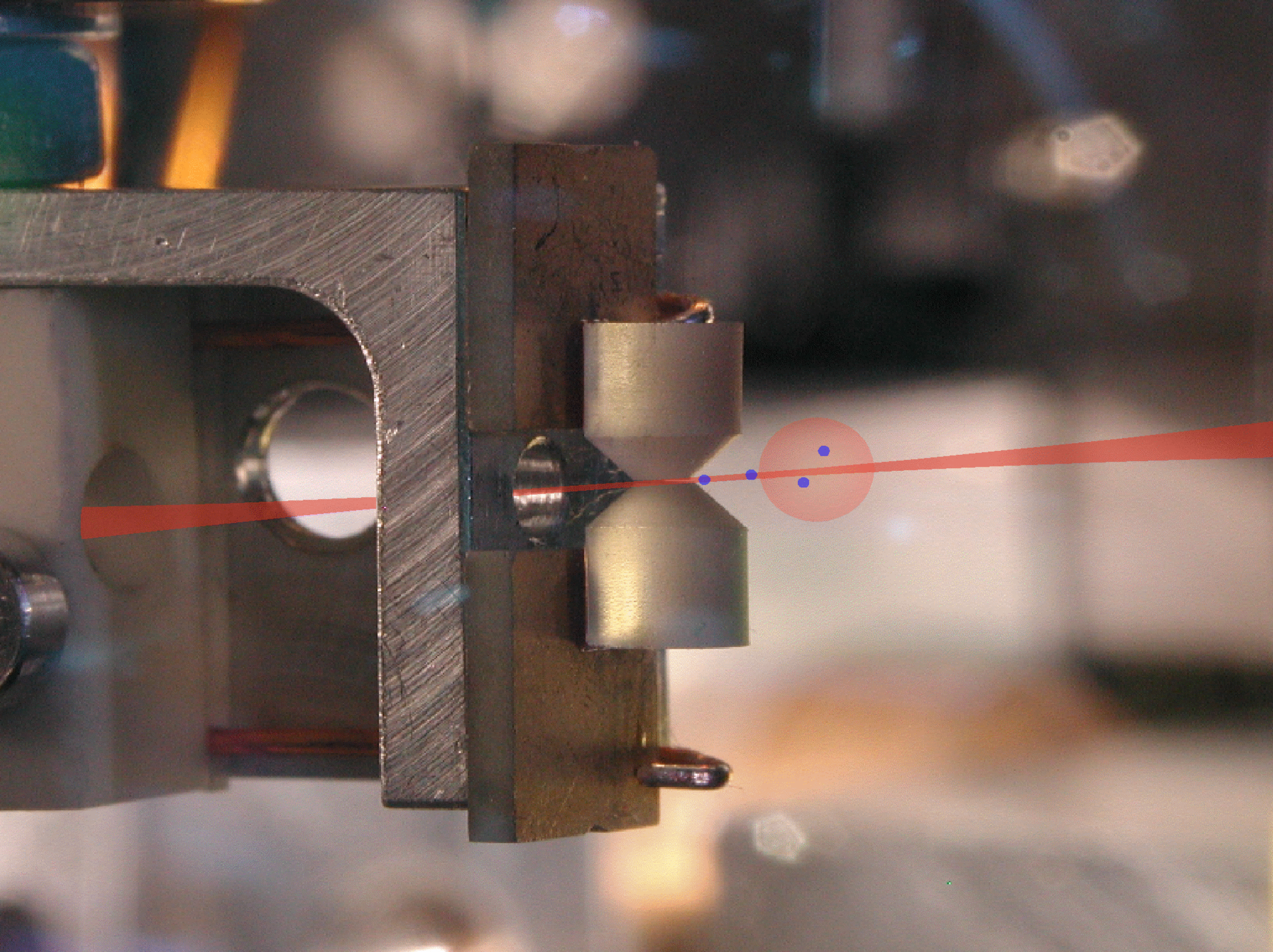
Controlling individual atoms in a dipole trap: Towards quantum information processing with neutral atoms

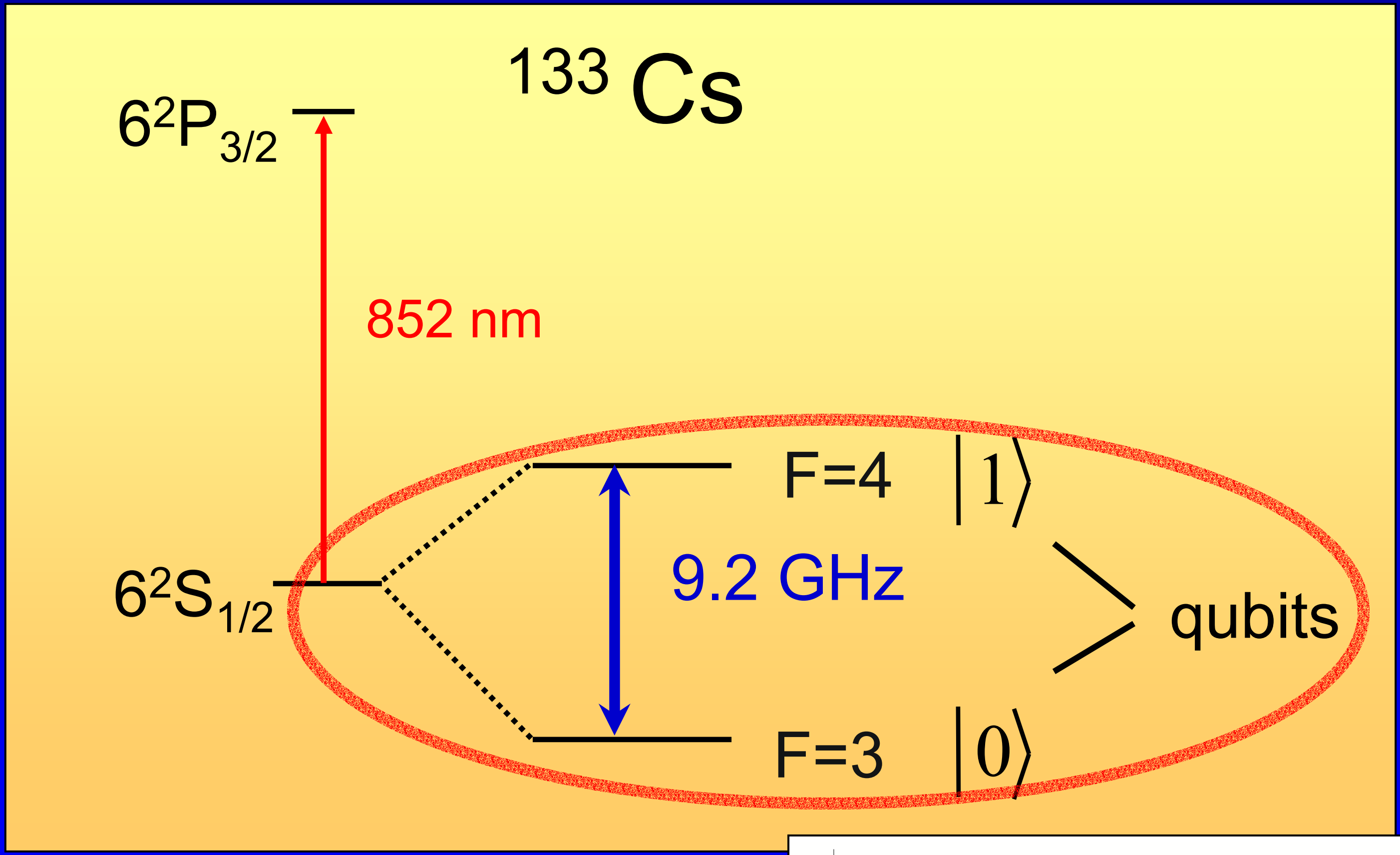
Stefan Kuhr
Institut für Angewandte Physik
Universität Bonn
and
Laboratoire Kastler-Brossel
École Normale Supérieure

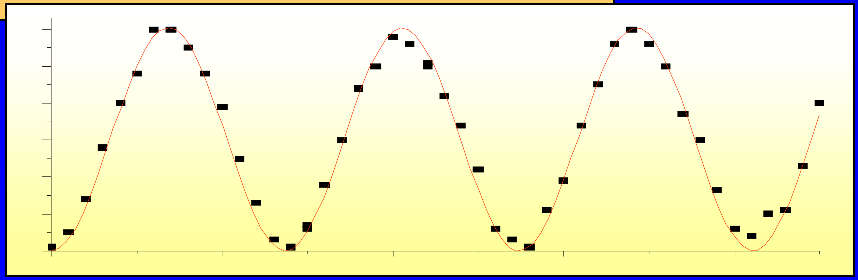


Collège de France, June 2, 2004



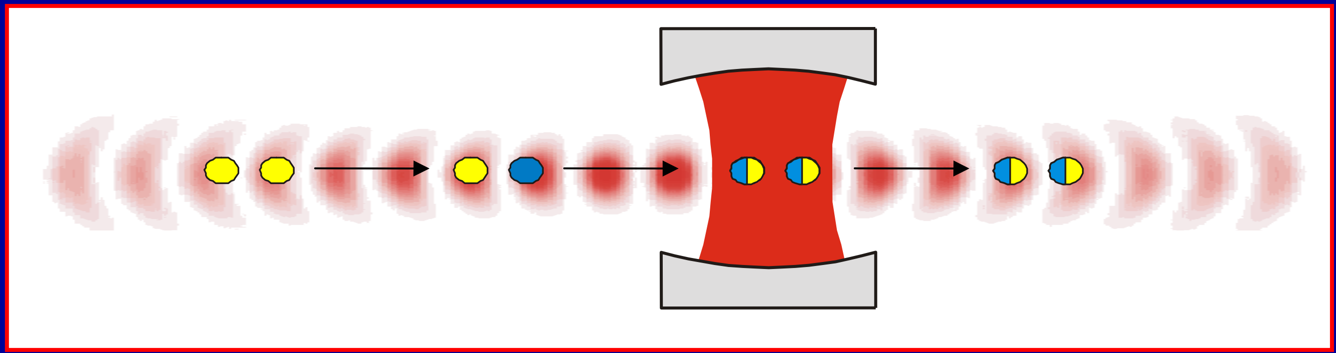
Qubits

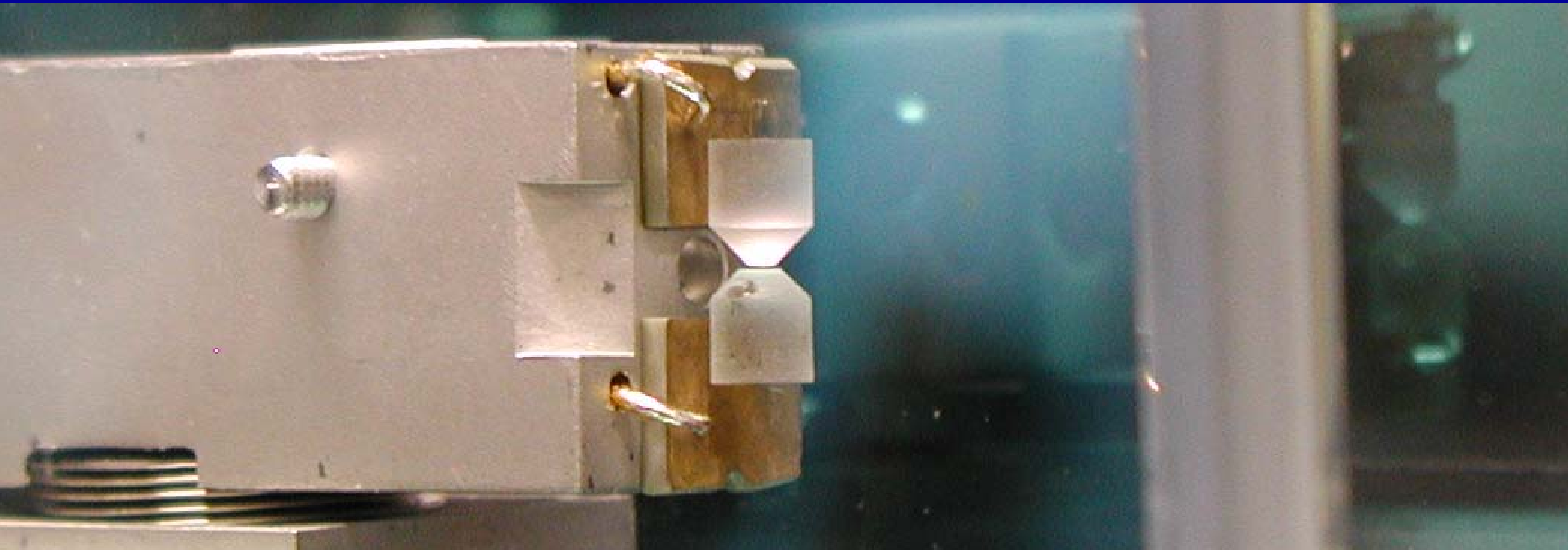




Interaction via photon exchange

Transporting atoms into an optical resonator:





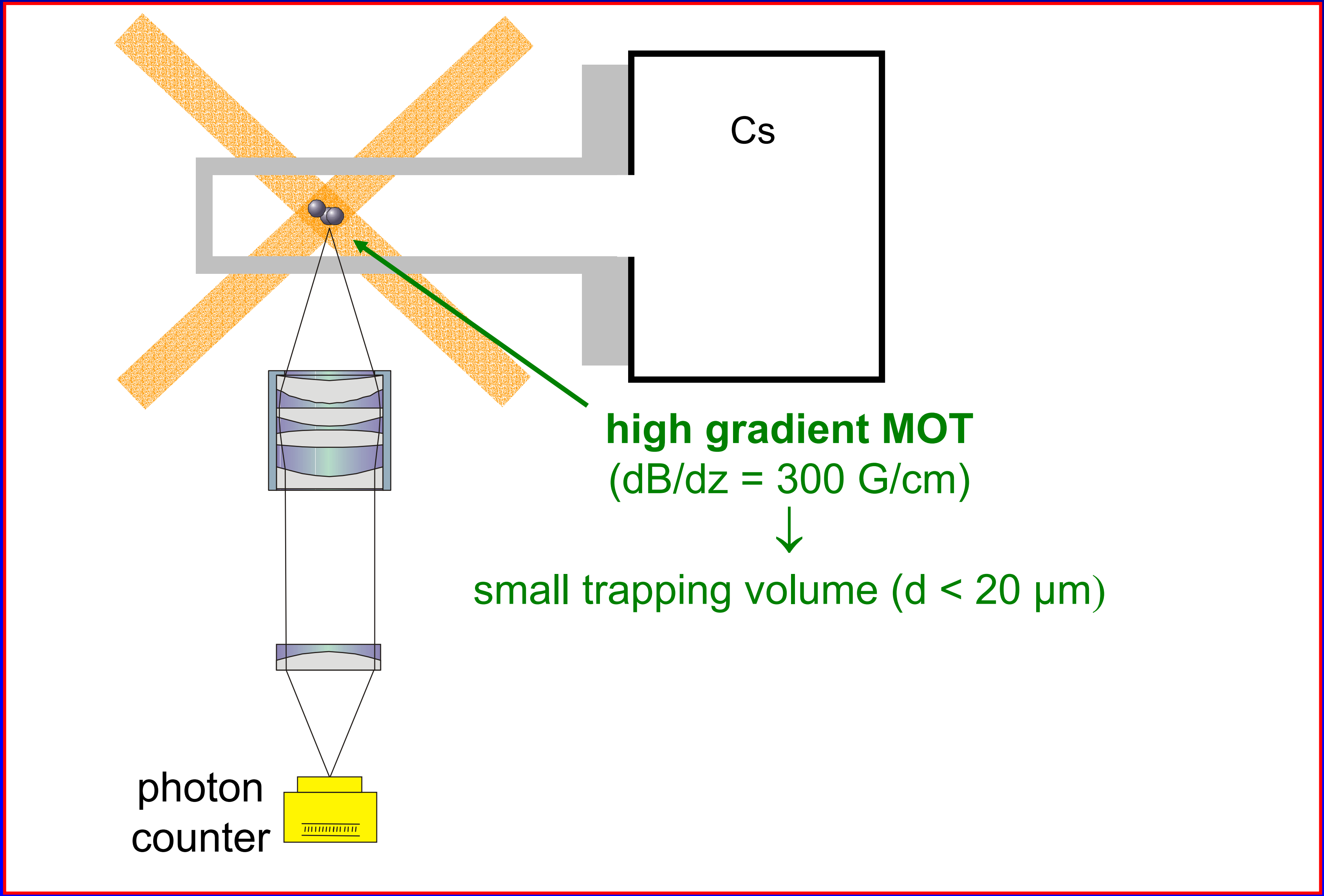
Outline

I.
Trapping and observation of single atoms

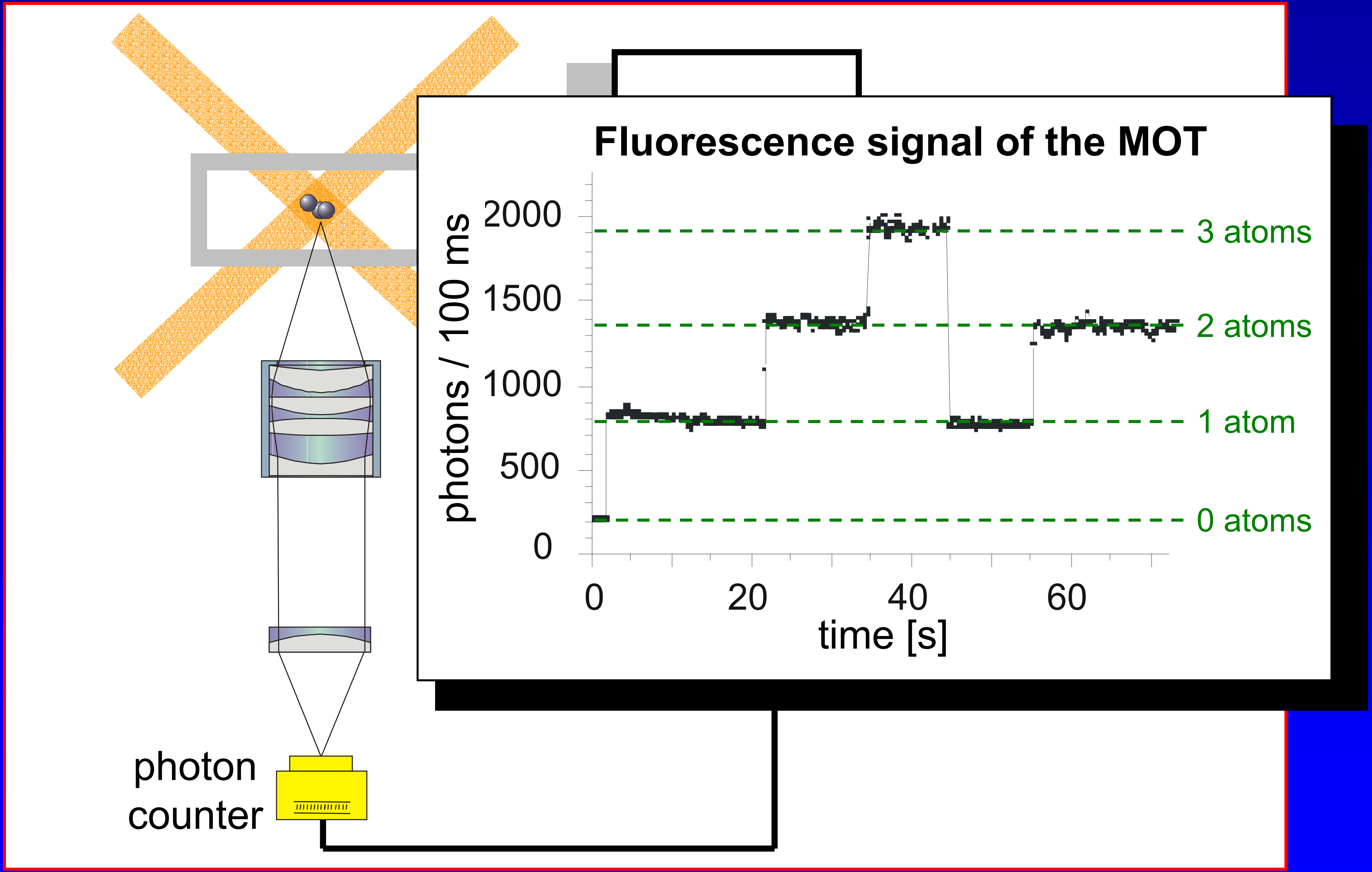
II.
Decoherence of qubit states

III.
A neutral atom quantum register

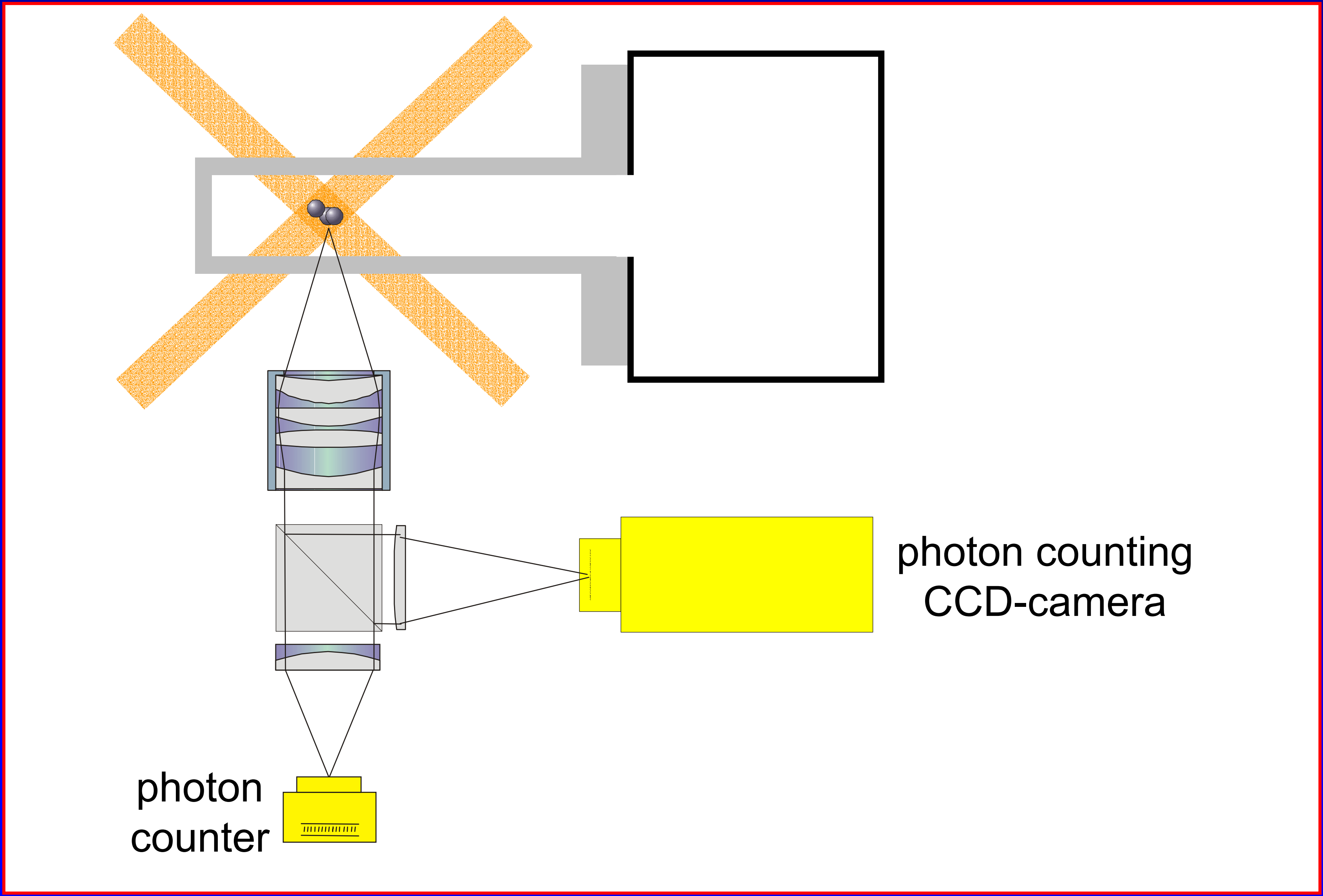
A source of cold atoms



A source of cold atoms

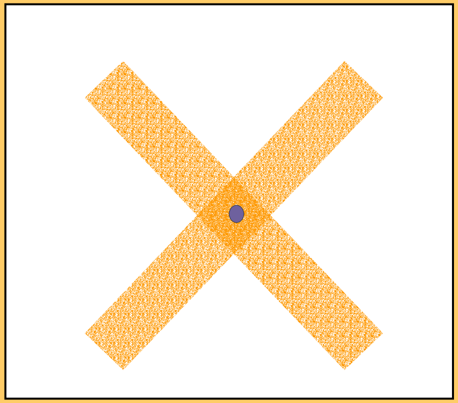


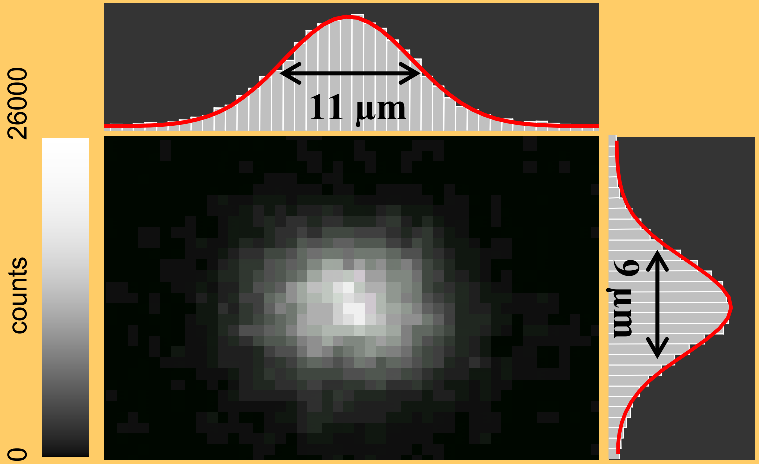
A source of cold atoms



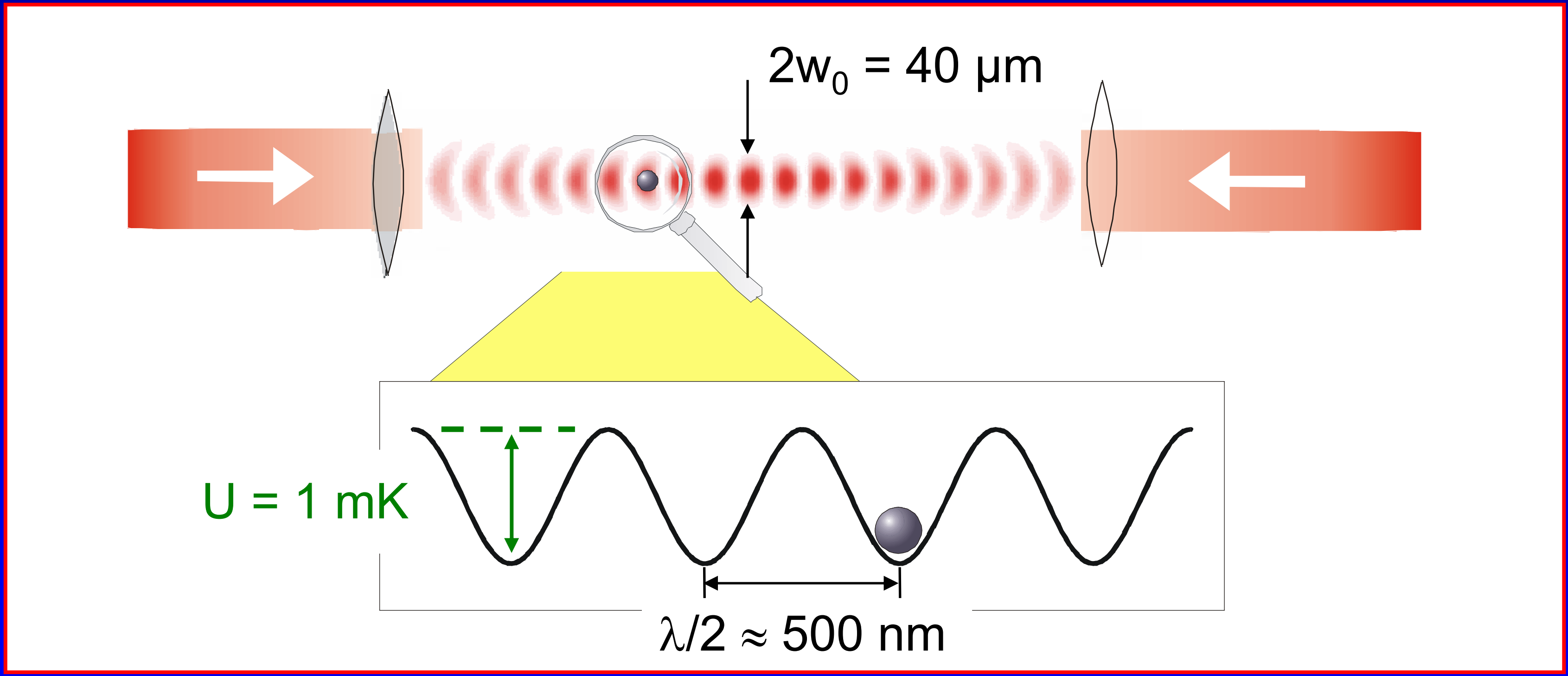
Imaging a single atom...

...in the MOT





Standing wave dipole trap

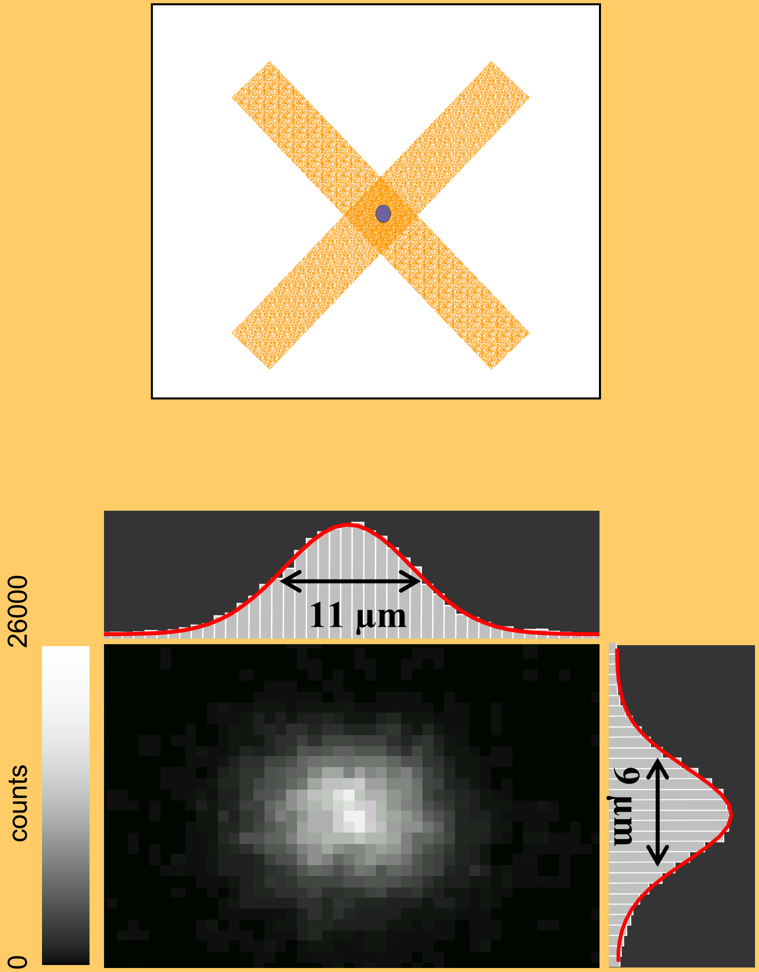


Nd:YAG-Laser (λ = 1064 nm, P = 4 W)

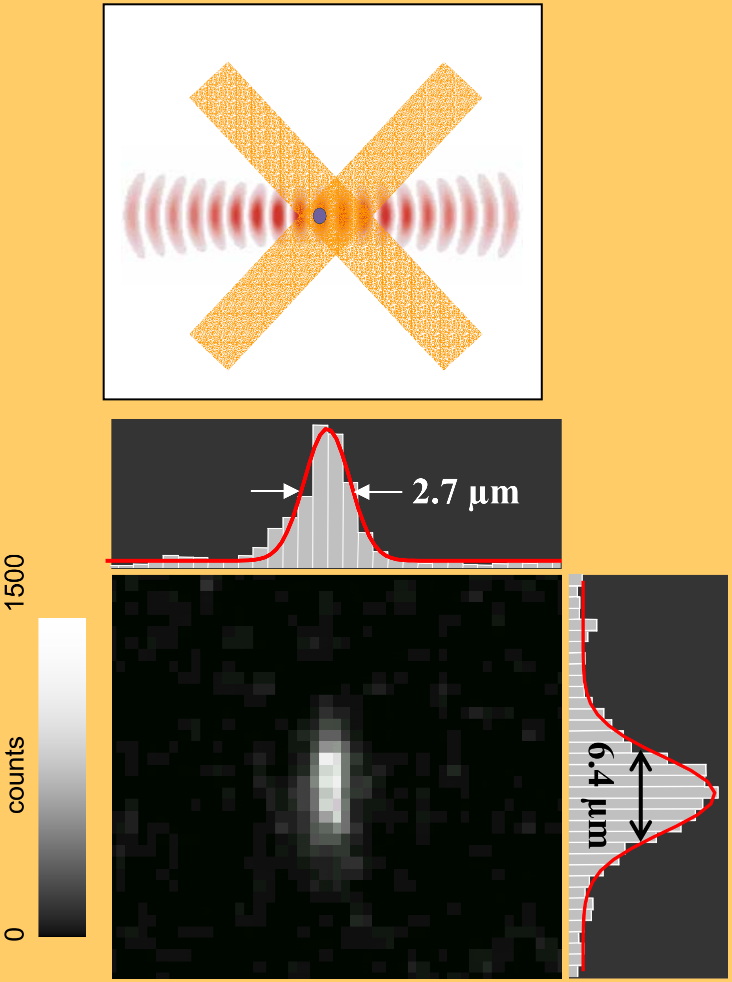
→ population relaxation time T_1 > 4 s

Imaging a single atom...

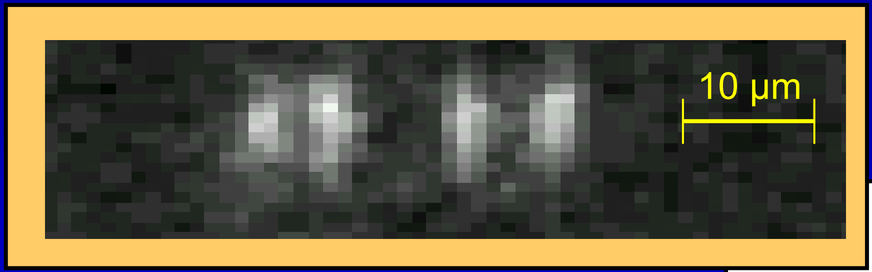
...in the MOT

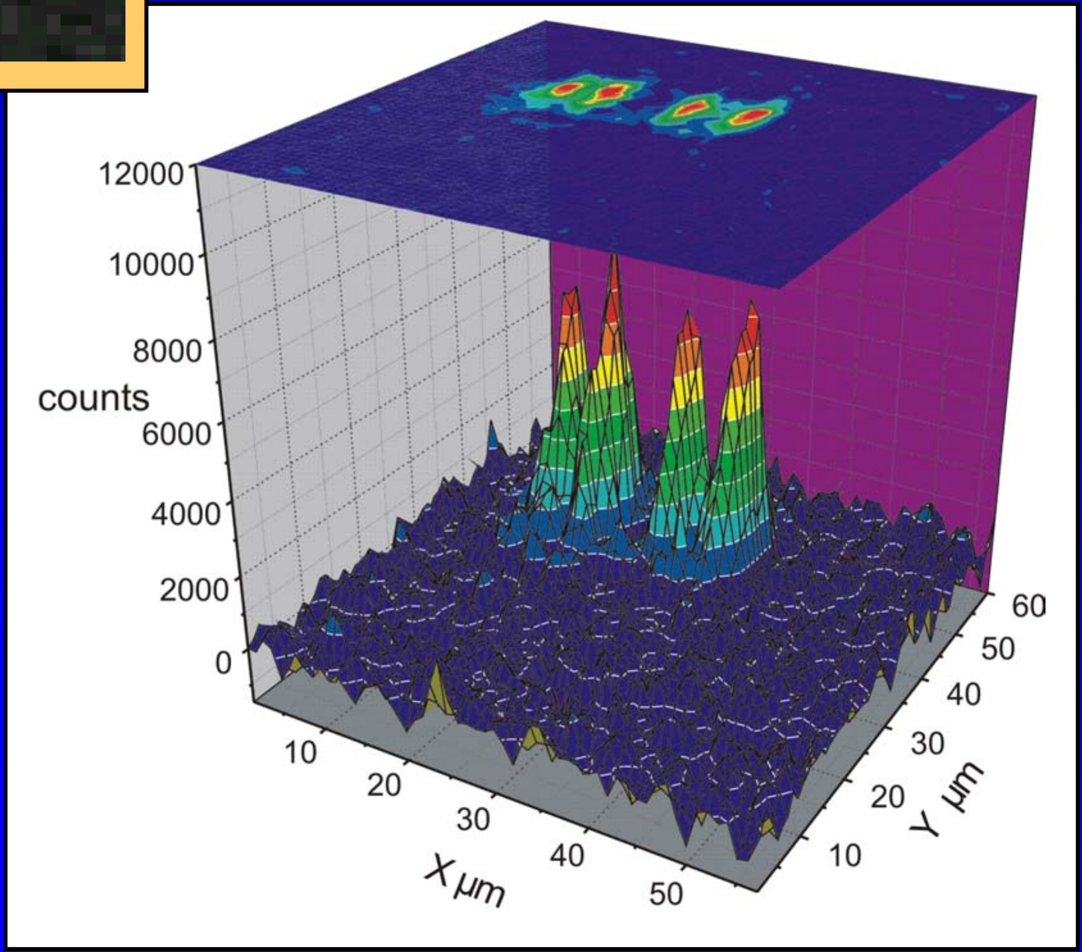


...in the dipole trap



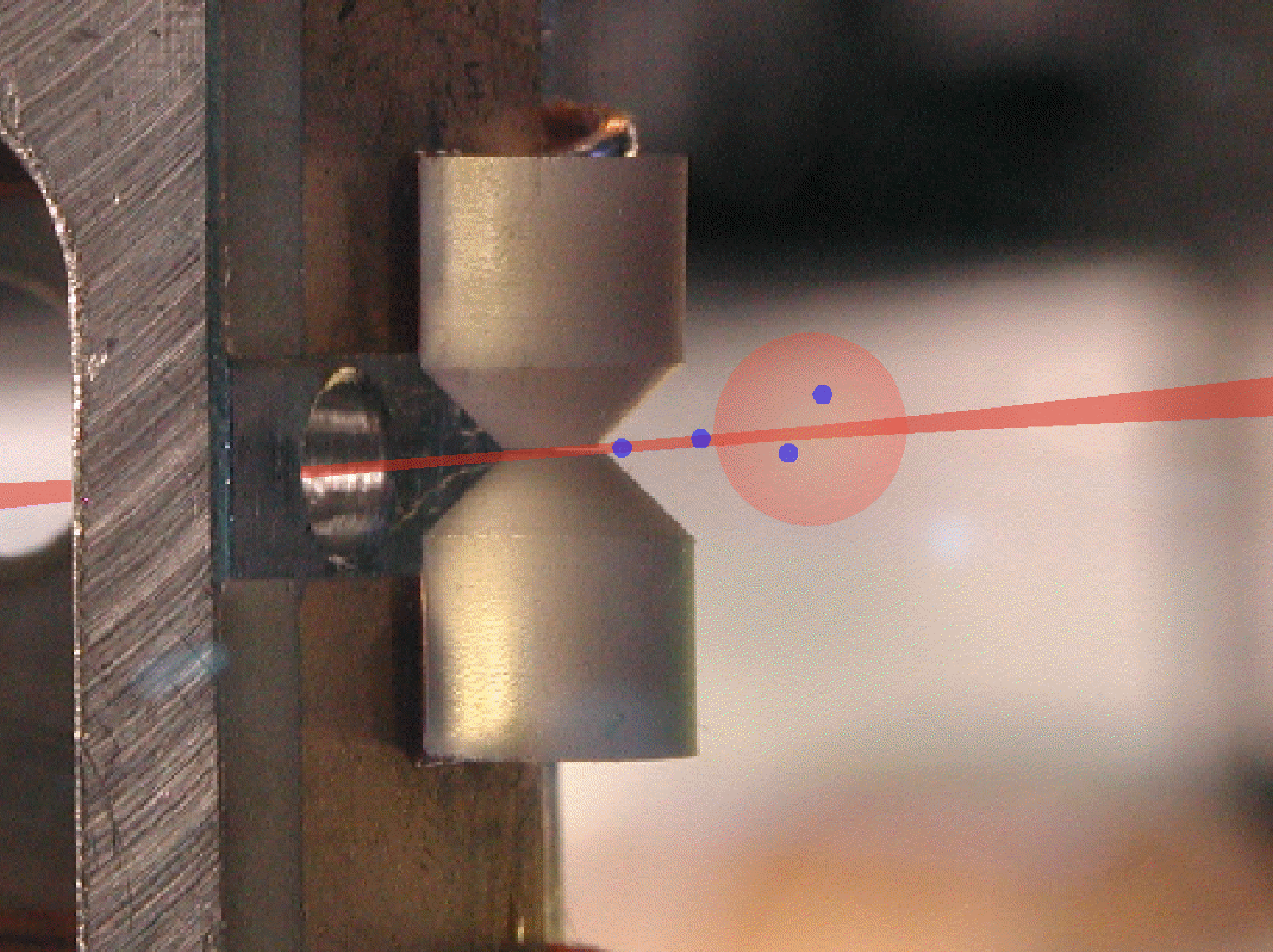
Four atoms in the dipole trap



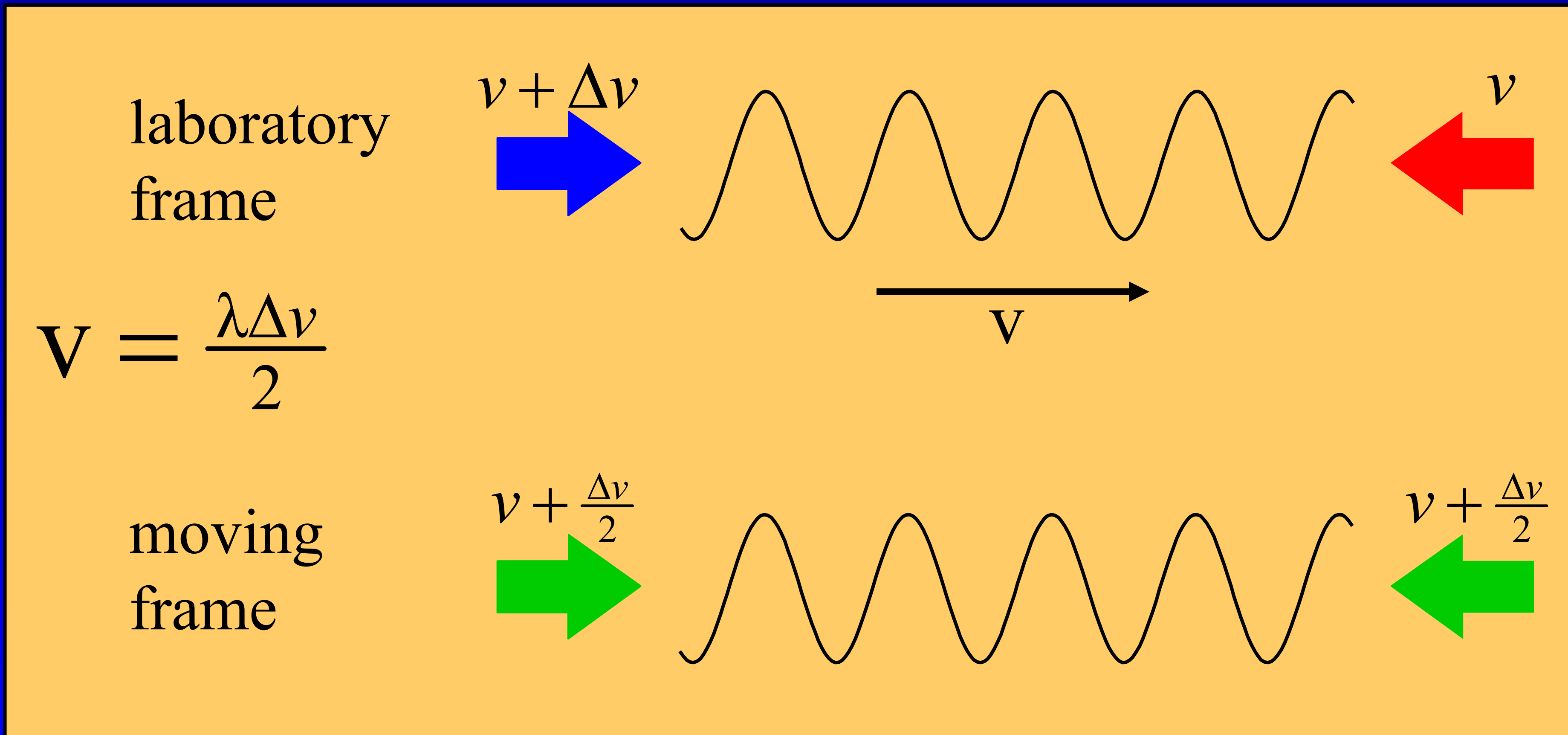


<u>CCD camera:</u>
measures position

<u>photon counter:</u>
measures
number of atoms

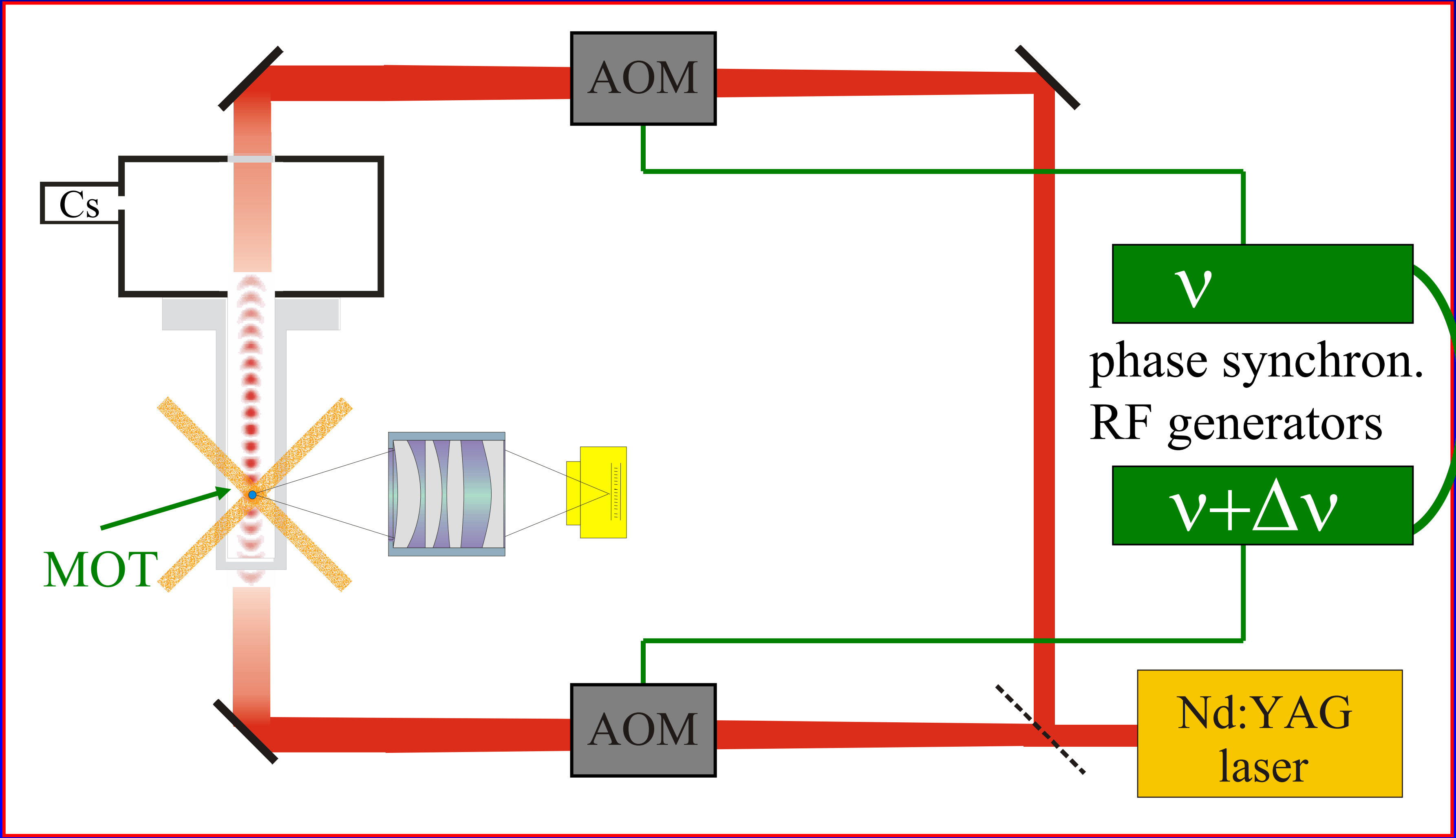


An optical conveyor-belt

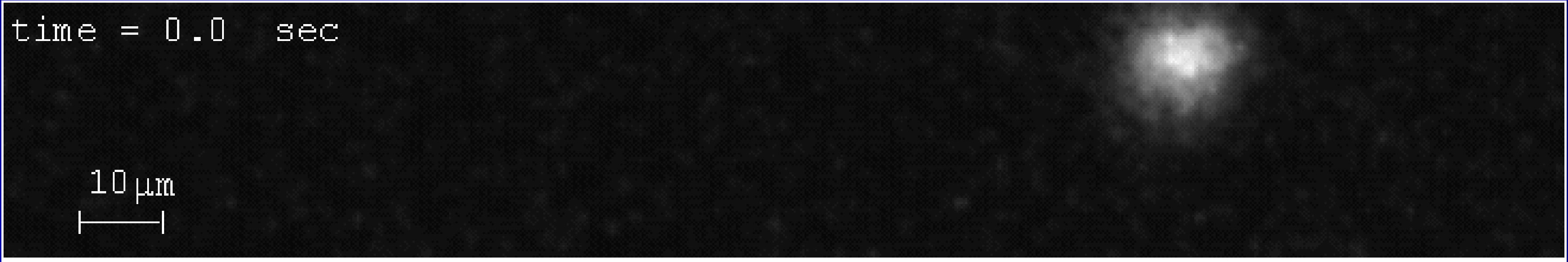


S. Kuhr *et al.*, Science **293**, 278 (2001)
D. Schrader *et al.*, Appl. Phys. B. **73**, 819 (2001)

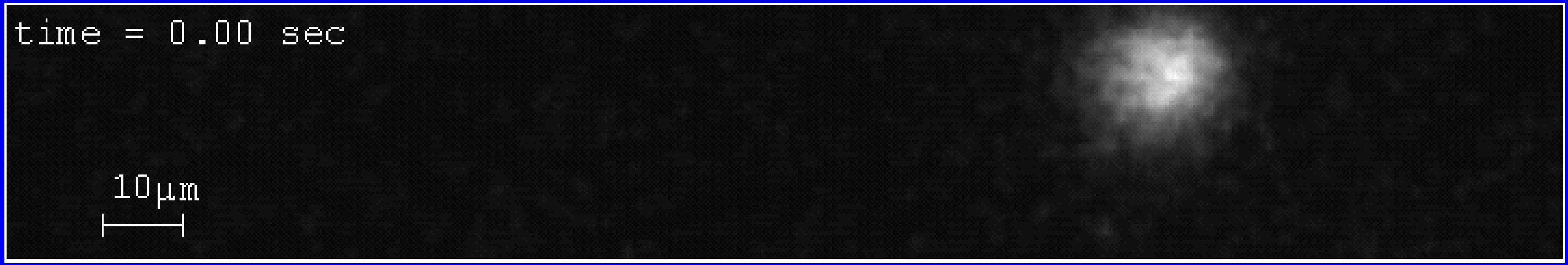
An optical conveyor-belt



Transportation of a single atom

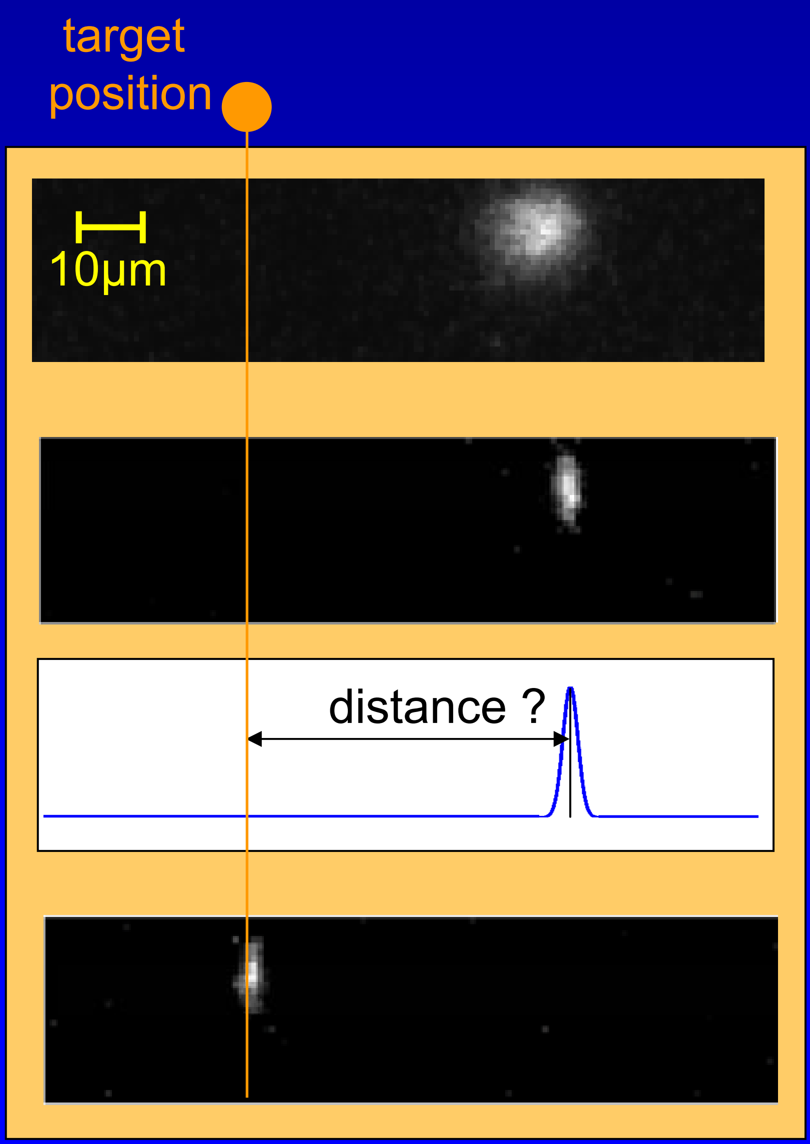


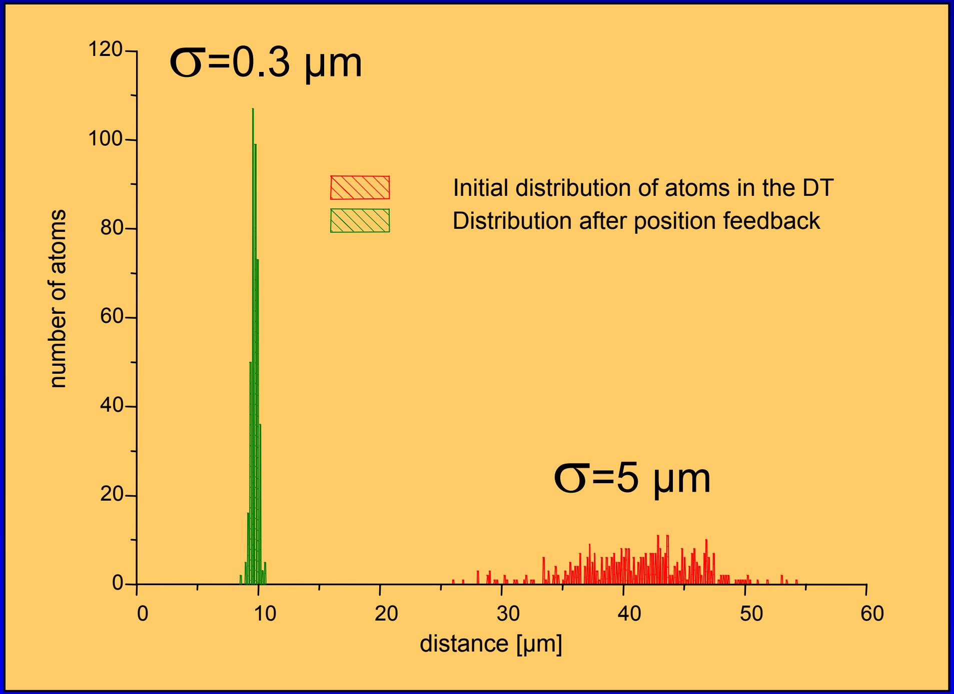
Three moving atoms



Y. Miroshnychenko *et al.*, Optics Express **11**, 3498 (2003)

Absolute position control





"position feedback"

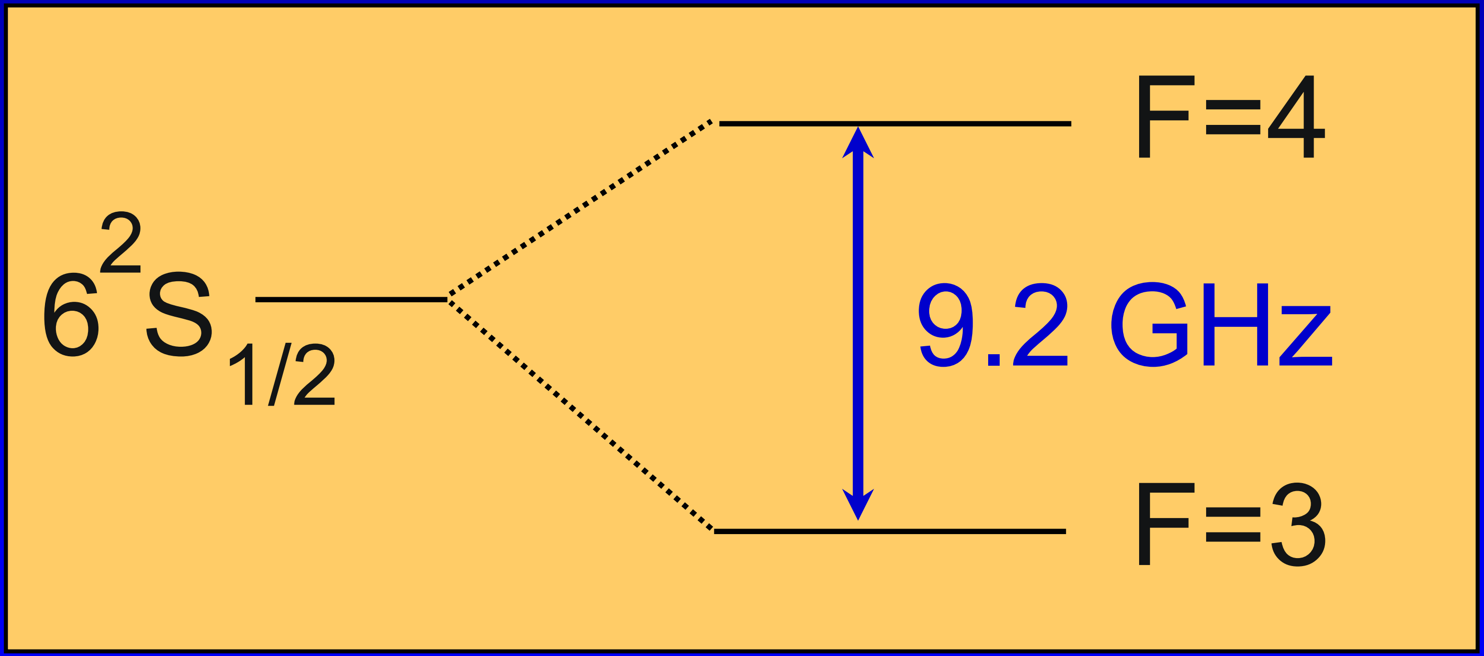
- take camera picture
- calculate distance to target position
- take second camera picture

Summary Part I

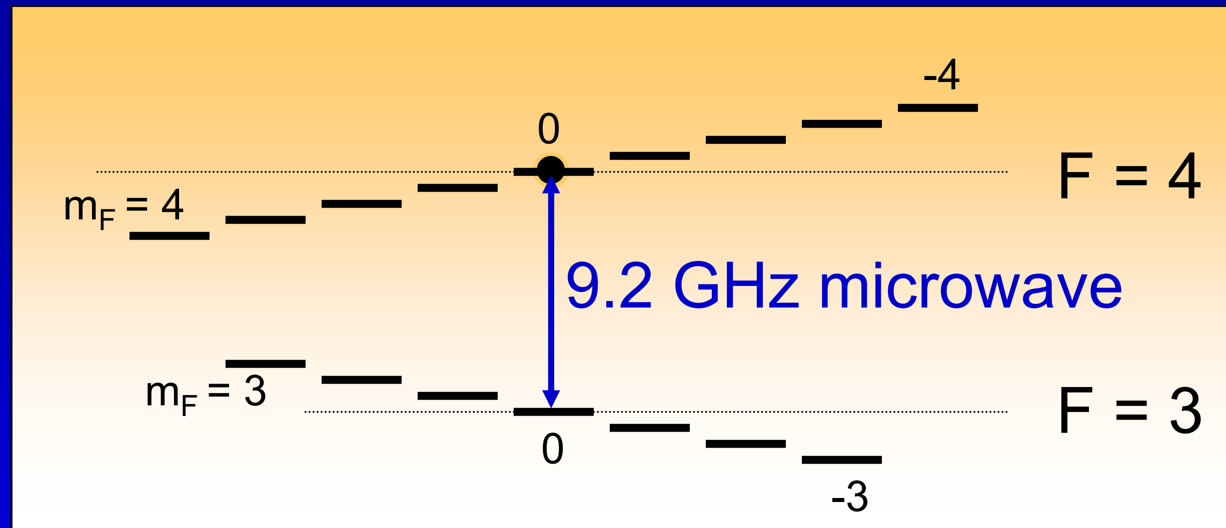
<u>Deterministic source of cold atoms:</u>

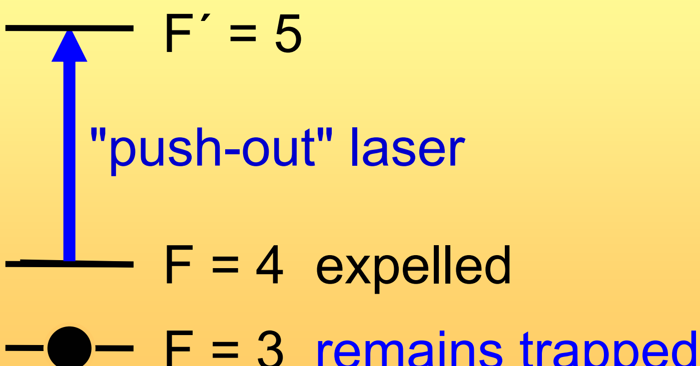
- number of atoms exactly known
- position control
- diffraction limited imaging

II. Manipulation of the Qubit states



State selective detection



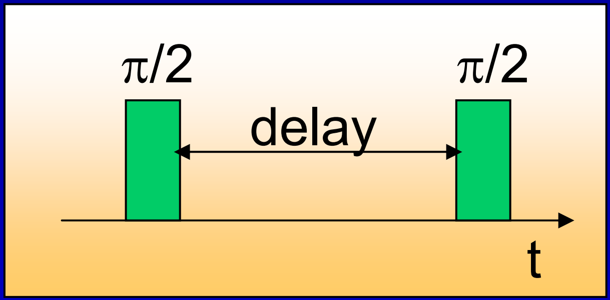


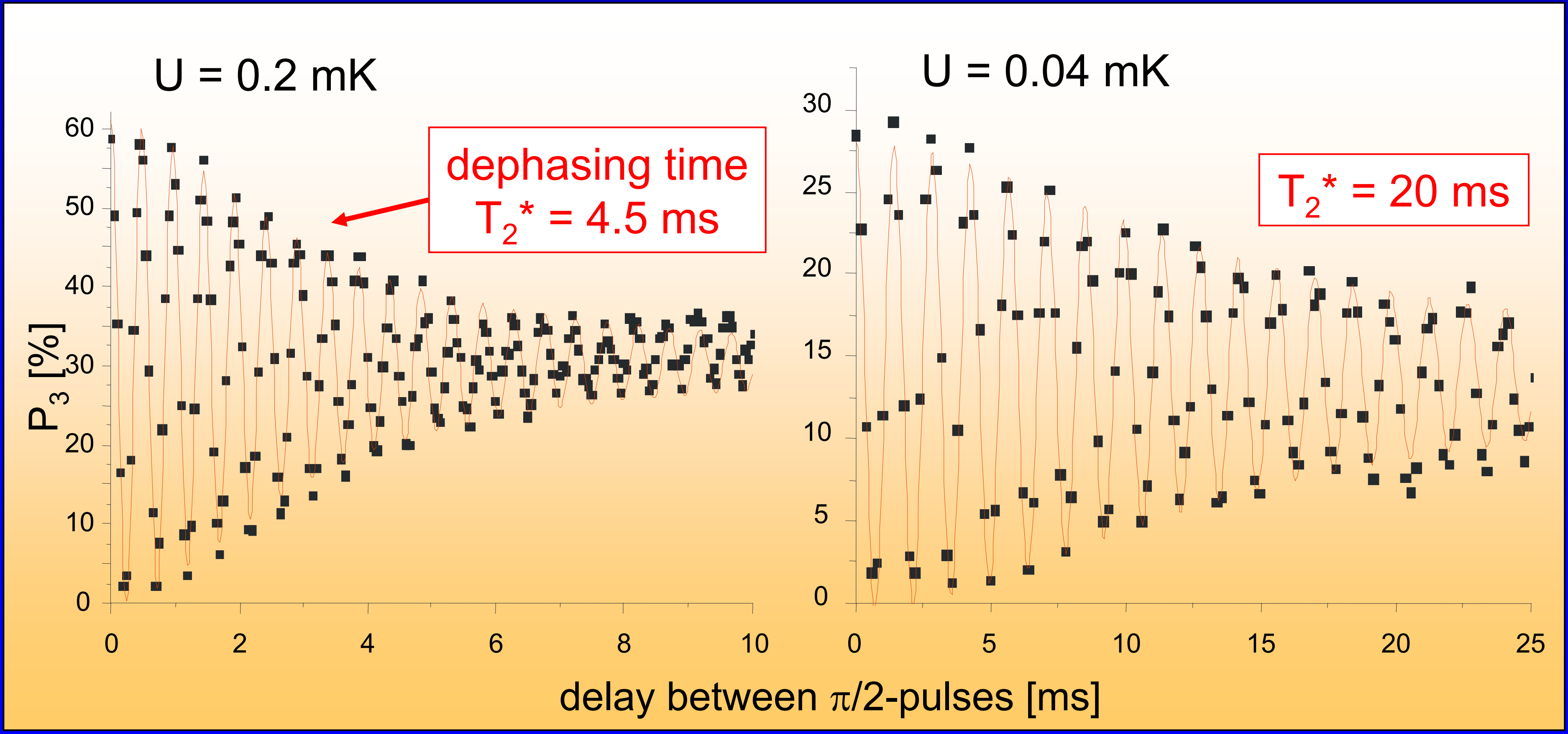
<u>survival probability:</u>

$P(F = 3) > 95\%$

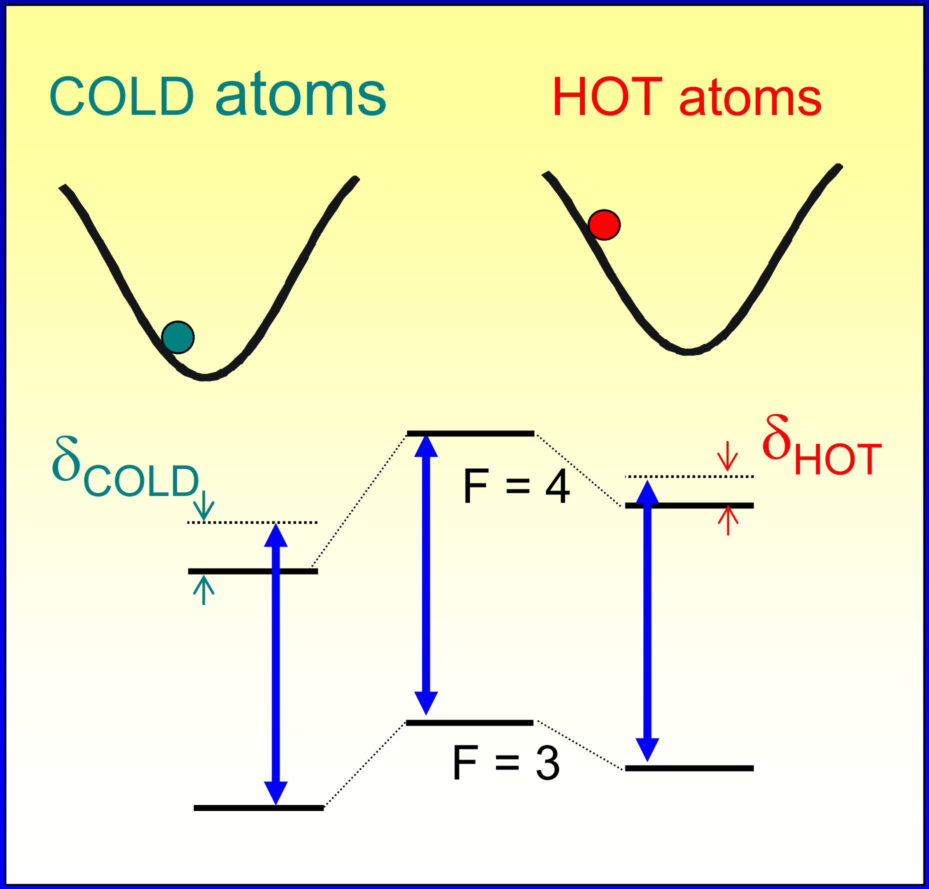
$P(F = 4) < 1\ \%$

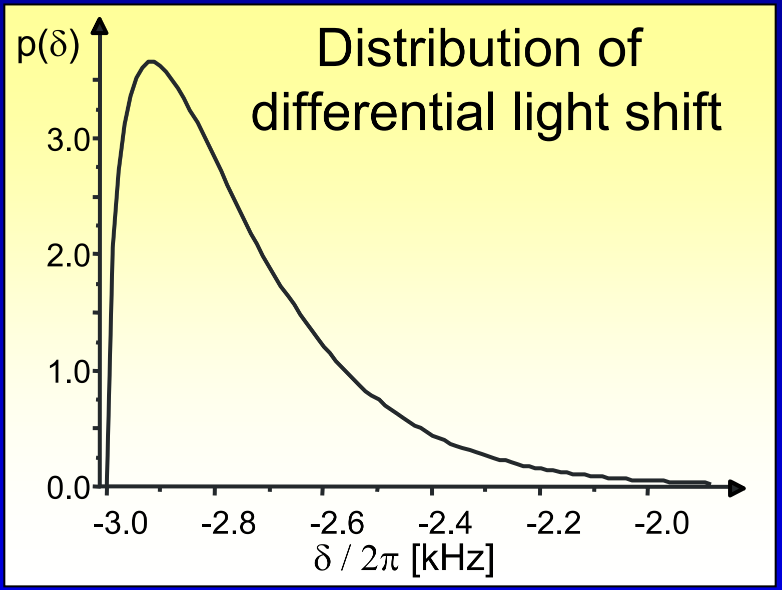
Ramsey spectroscopy

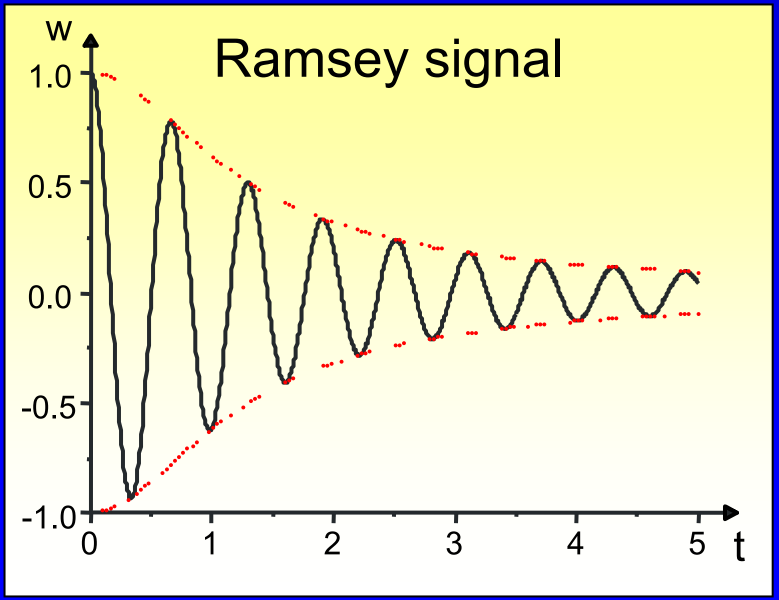




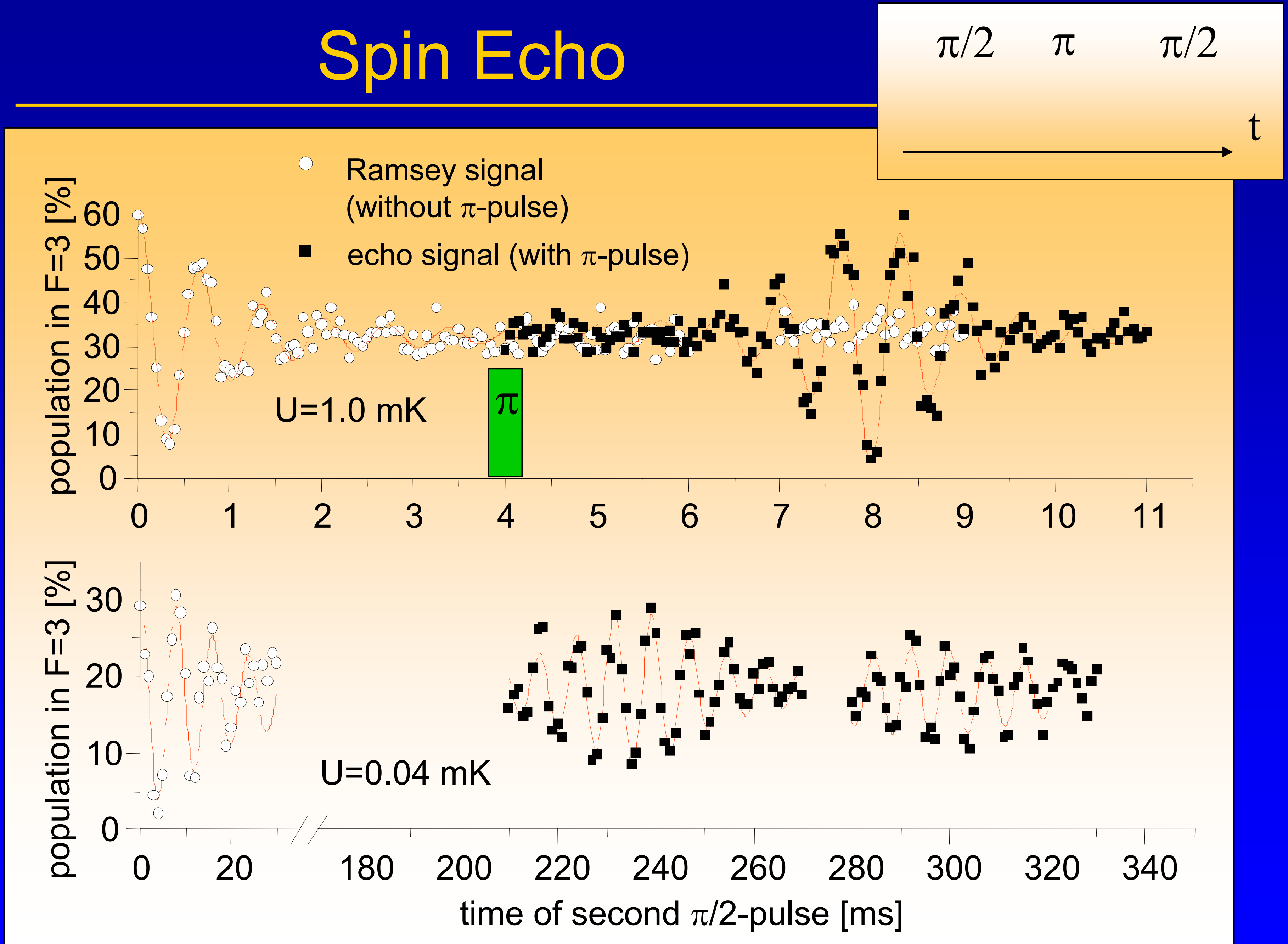
Dephasing due to thermal distribution







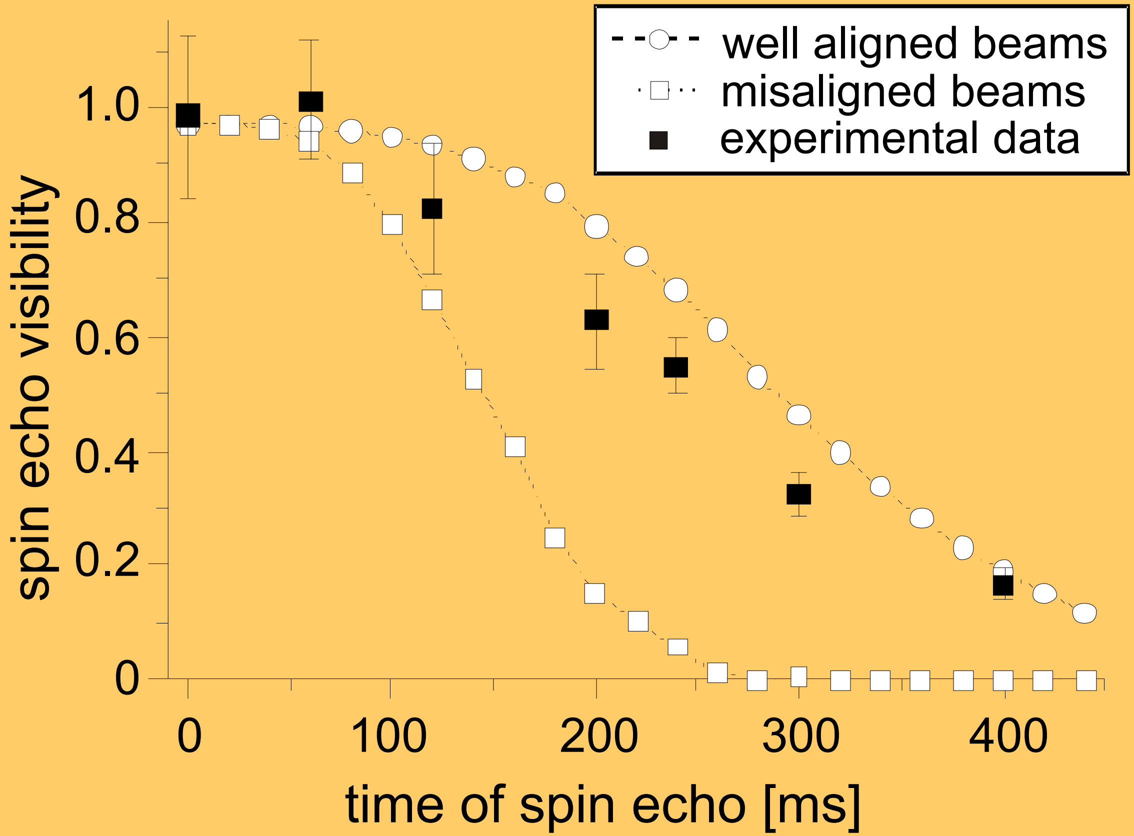
Spin Echo



π/2
π
π/2
t
Ramsey signal
(without π-pulse)
echo signal (with π-pulse)
U=1.0 mK
π
population in F=3 [%]
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
U=0.04 mK
population in F=3 [%]
30
20
10
0
0
20
180
200
220
240
260
280
300
320
340
time of second π/2-pulse [ms]

Analysis of decoherence

Spin echo visibility (U = 0.04 mK)



Dominant decoherence effect:

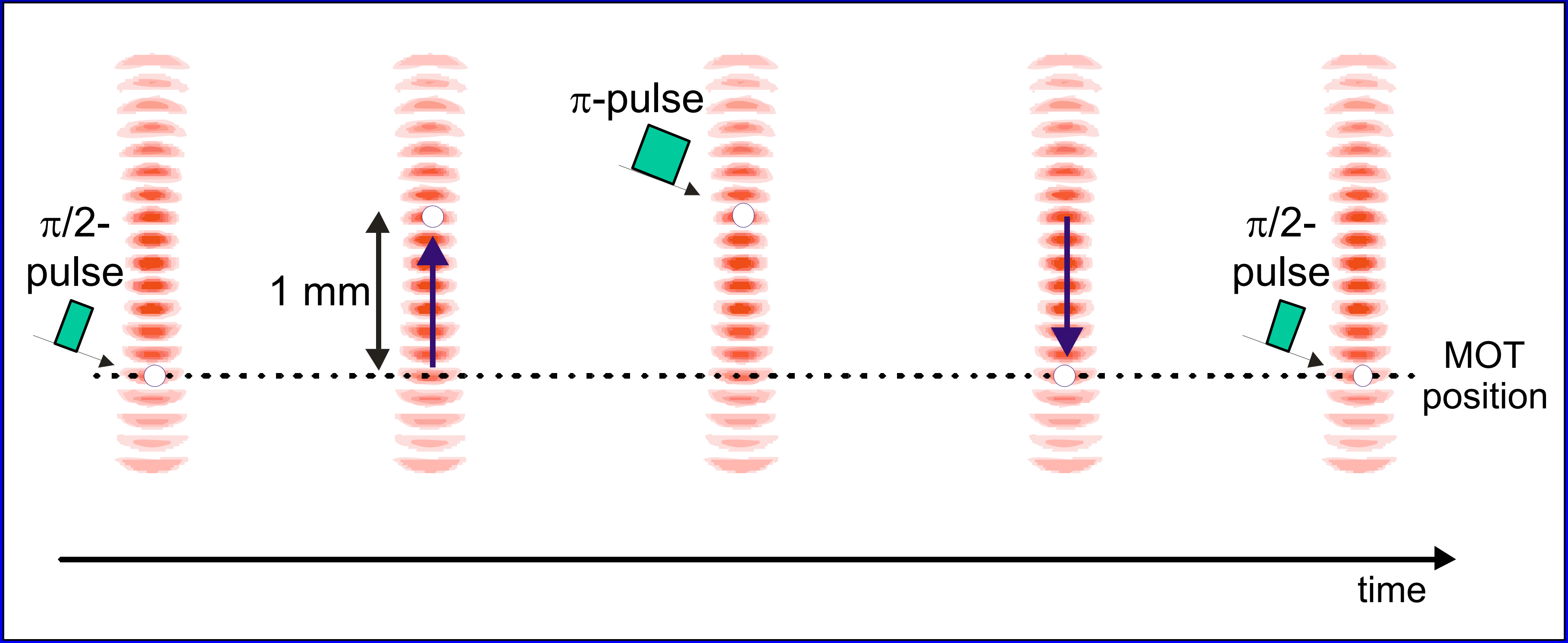
Pointing instability of trapping laser

↓

time-varying light shift (i.e. detuning)

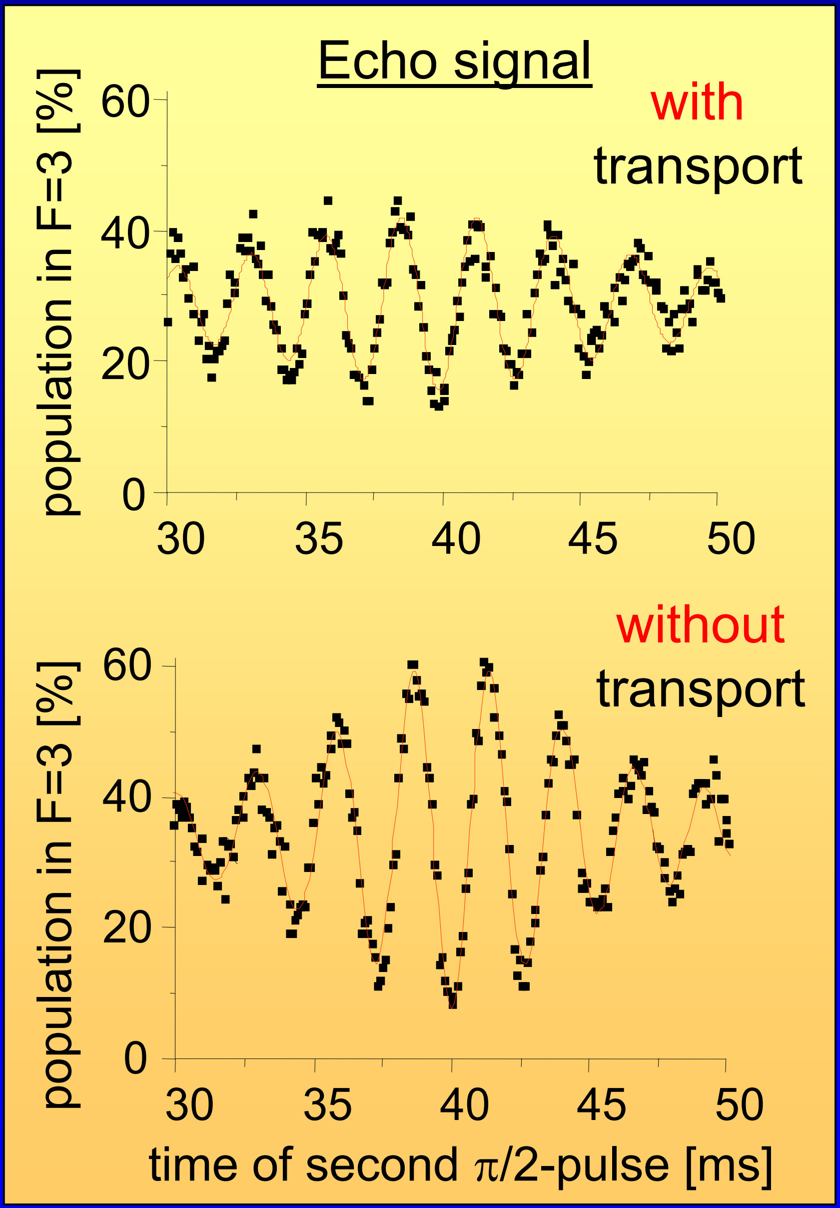
S. Kuhr *et al.*, Phys. Rev. Lett. **91**, 213002 (2003)

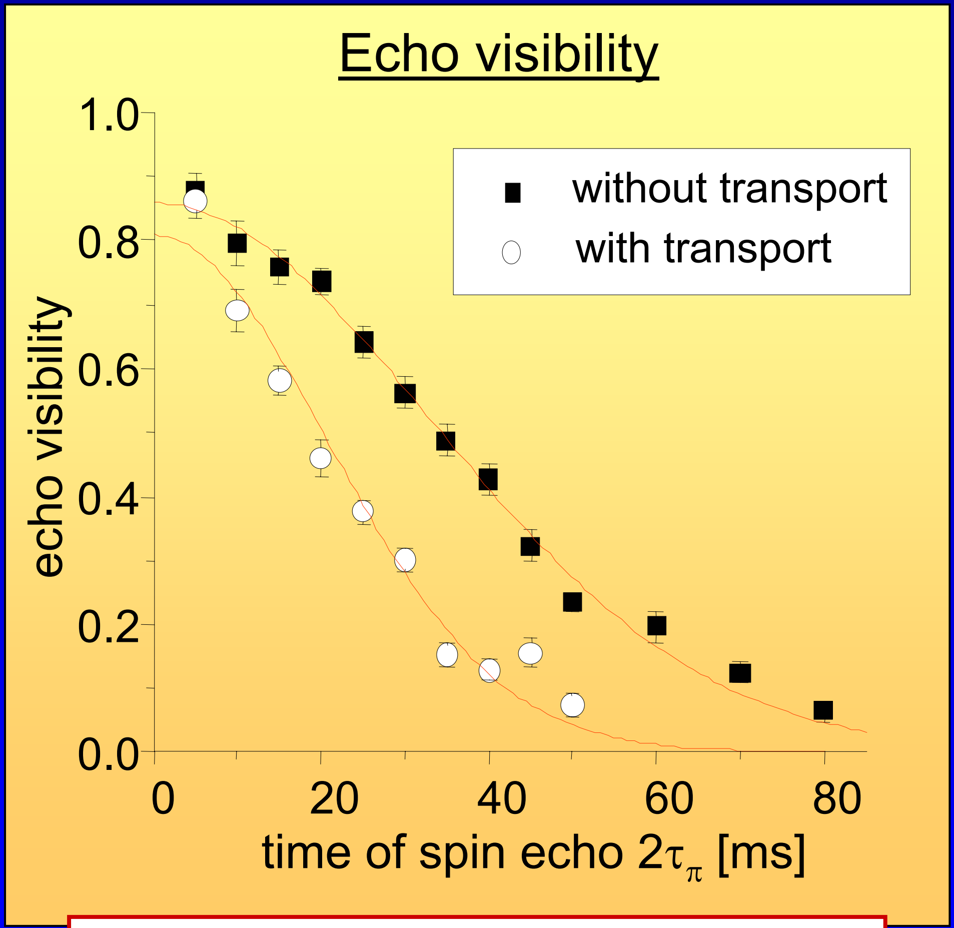
Quantum state transportation



S. Kuhr *et al.*, Phys. Rev. Lett. **91**, 213002 (2003)

Transport maintains coherence



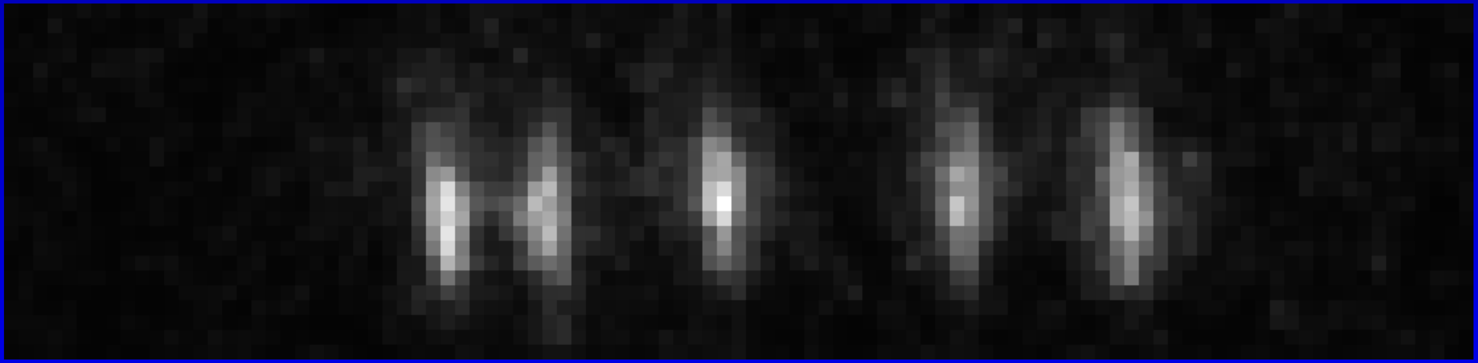


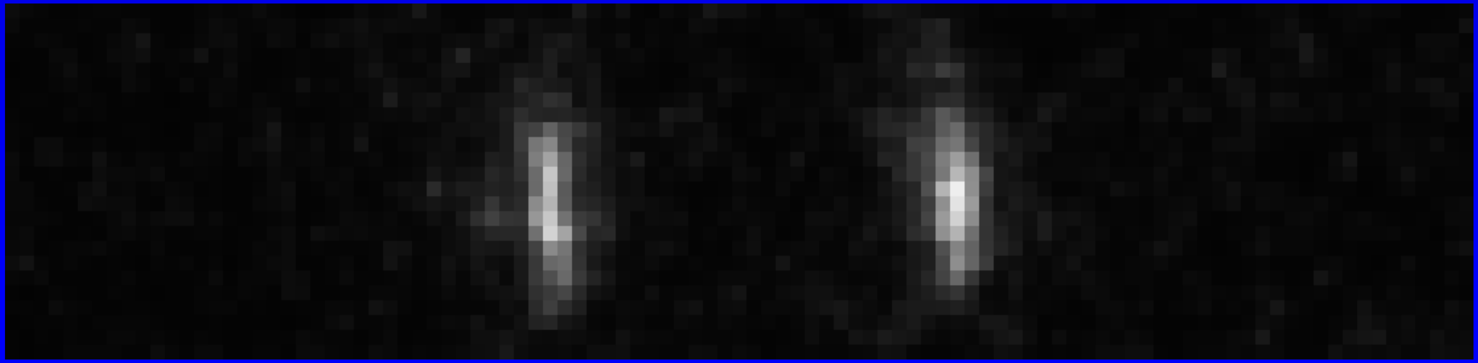
loss of coherence due
to heating by abrupt acceleration

Summary Part II

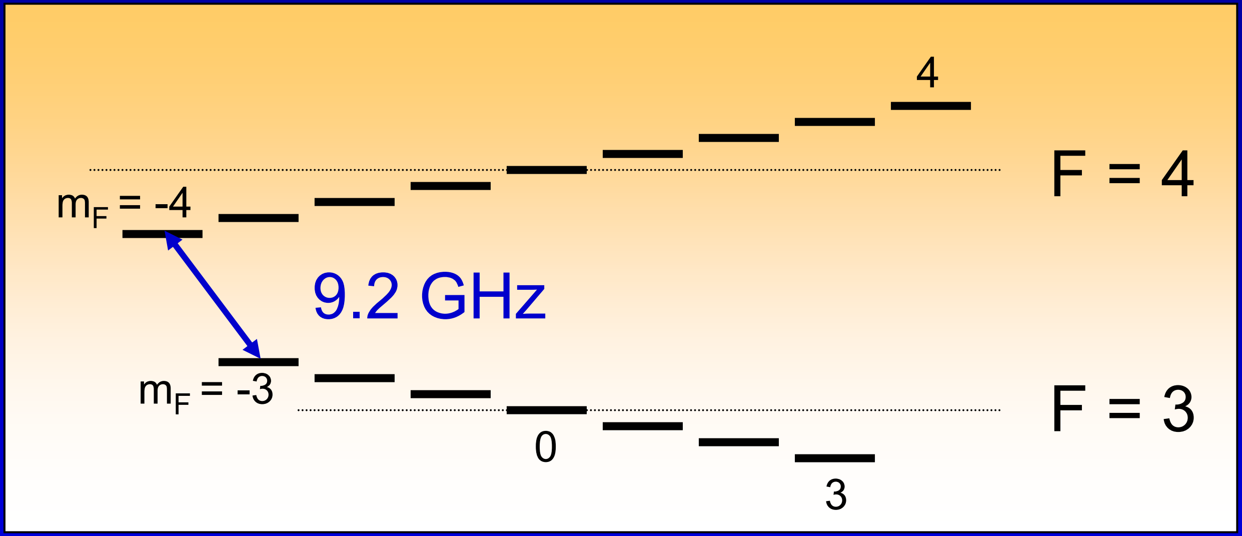
- measured coherence times of qubits
  $T_2^* > 20$ ms, $T_2' > 200$ ms
- decoherence mechanisms understood
- coherence is maintained during transportation

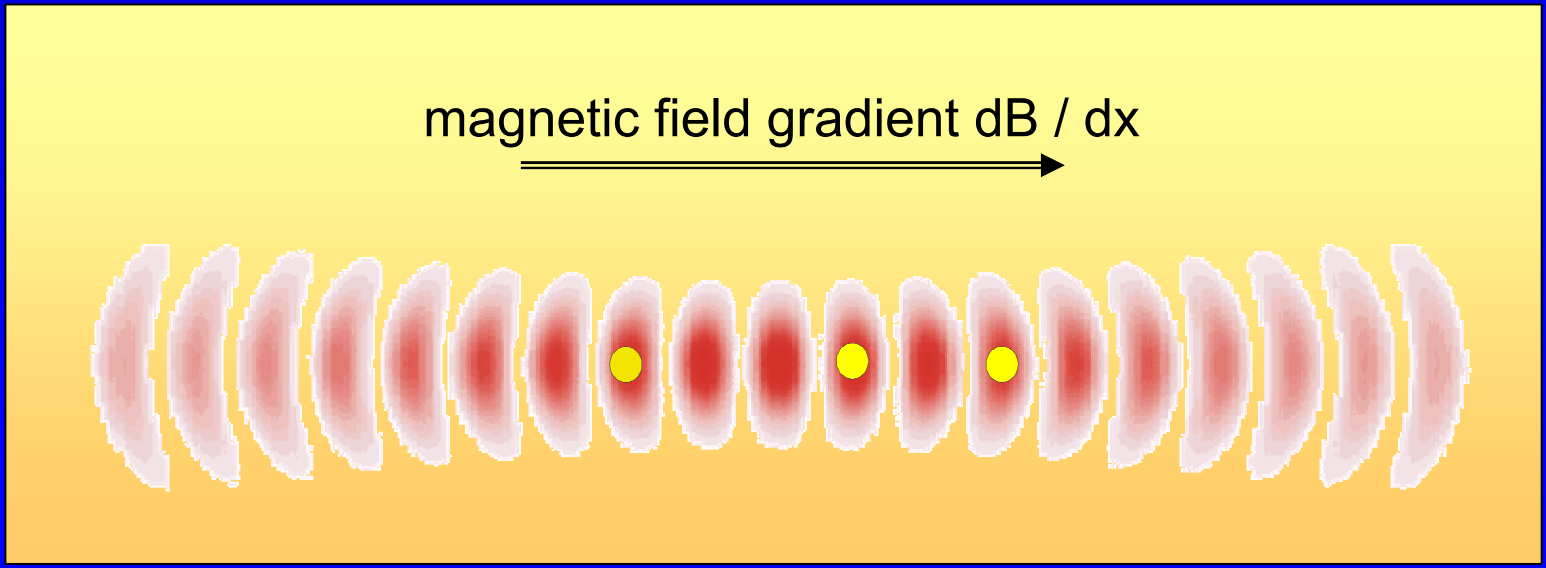
III.
A neutral atom quantum register



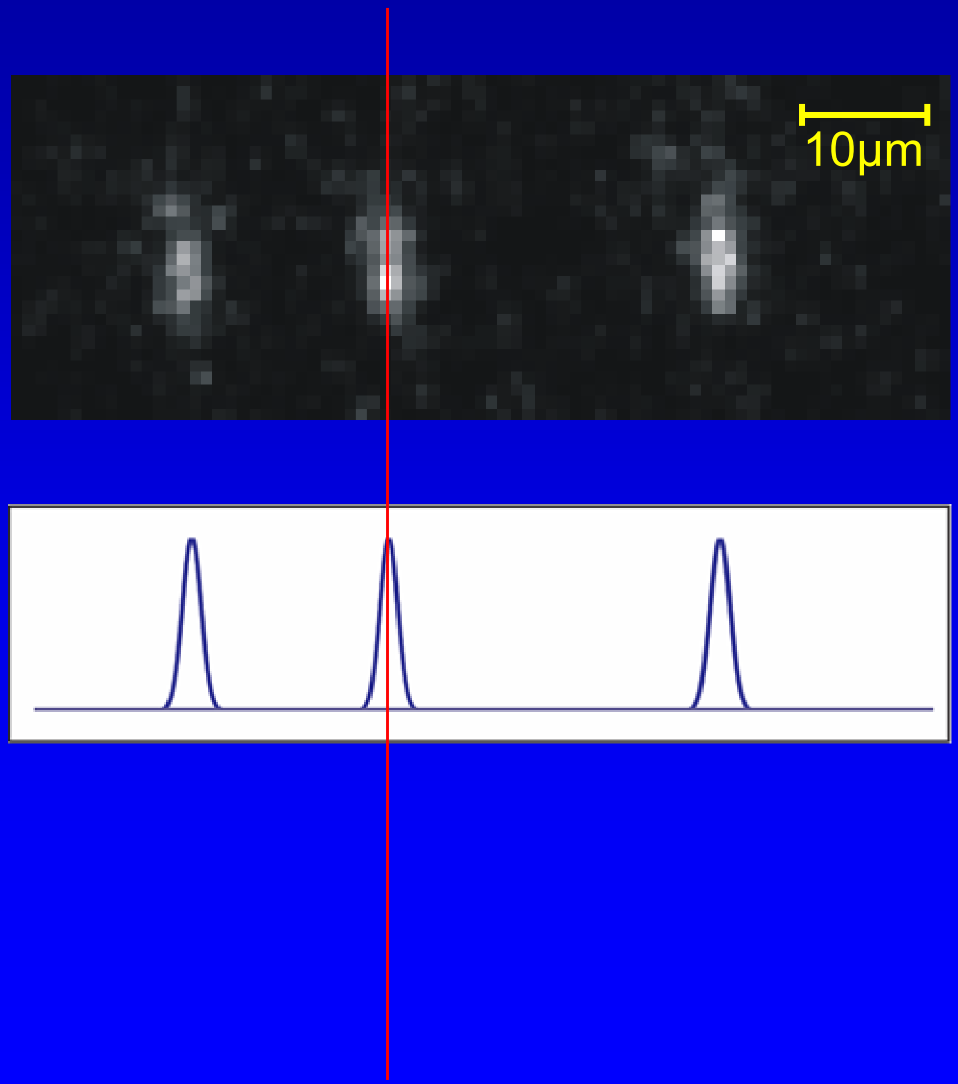


Selective addressing of atoms



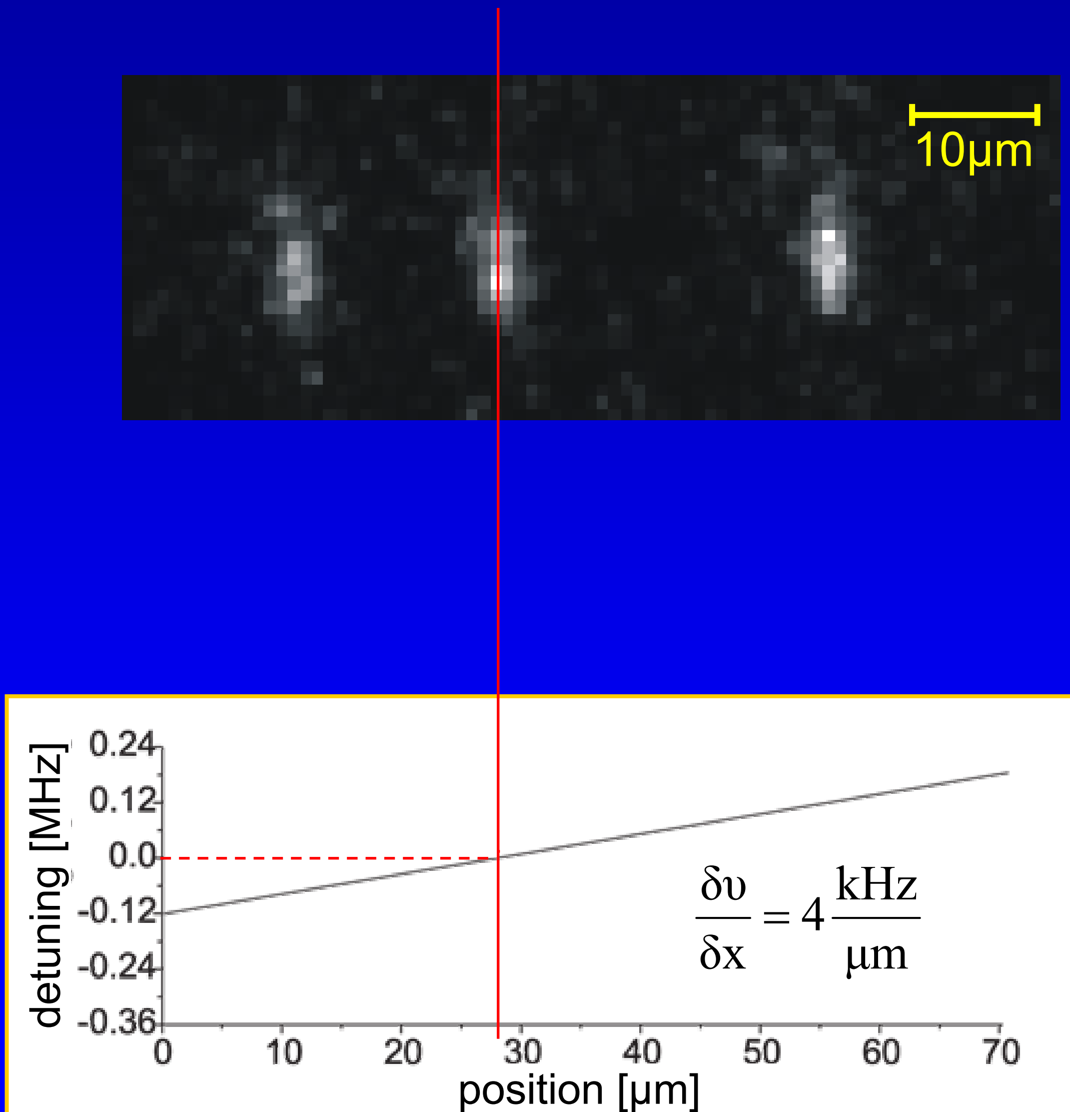


Addressing of a single atom



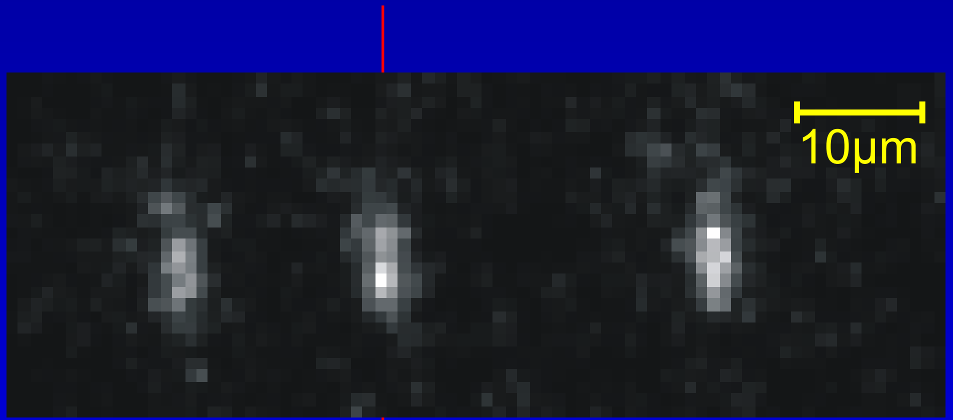
- take camera picture
- determine position of all atoms

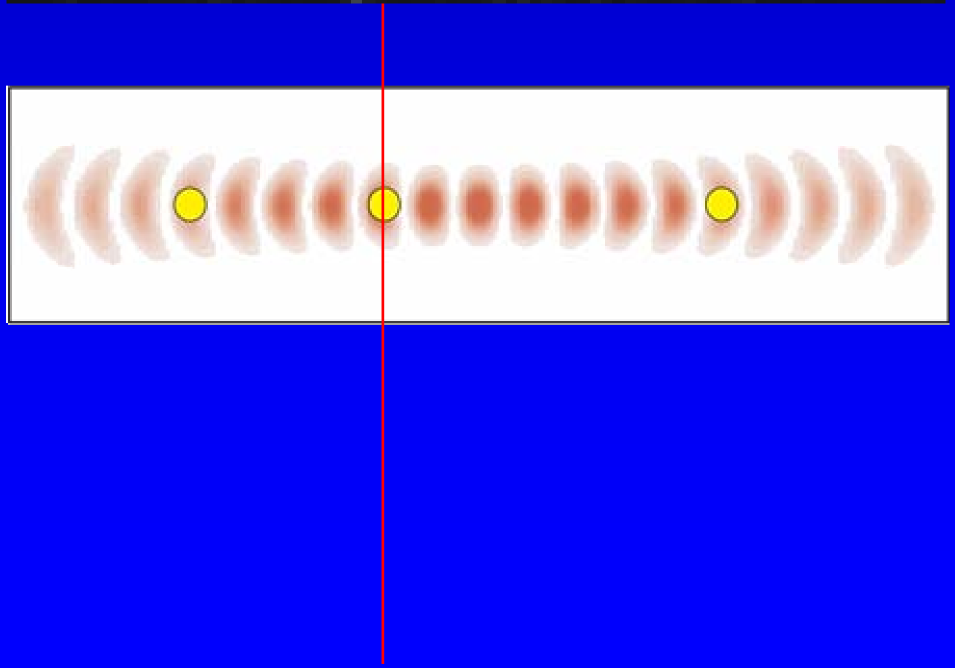
Addressing of a single atom



- take camera picture
- determine position of all atoms
- calculate resonance frequency of center atom

Addressing of a single atom

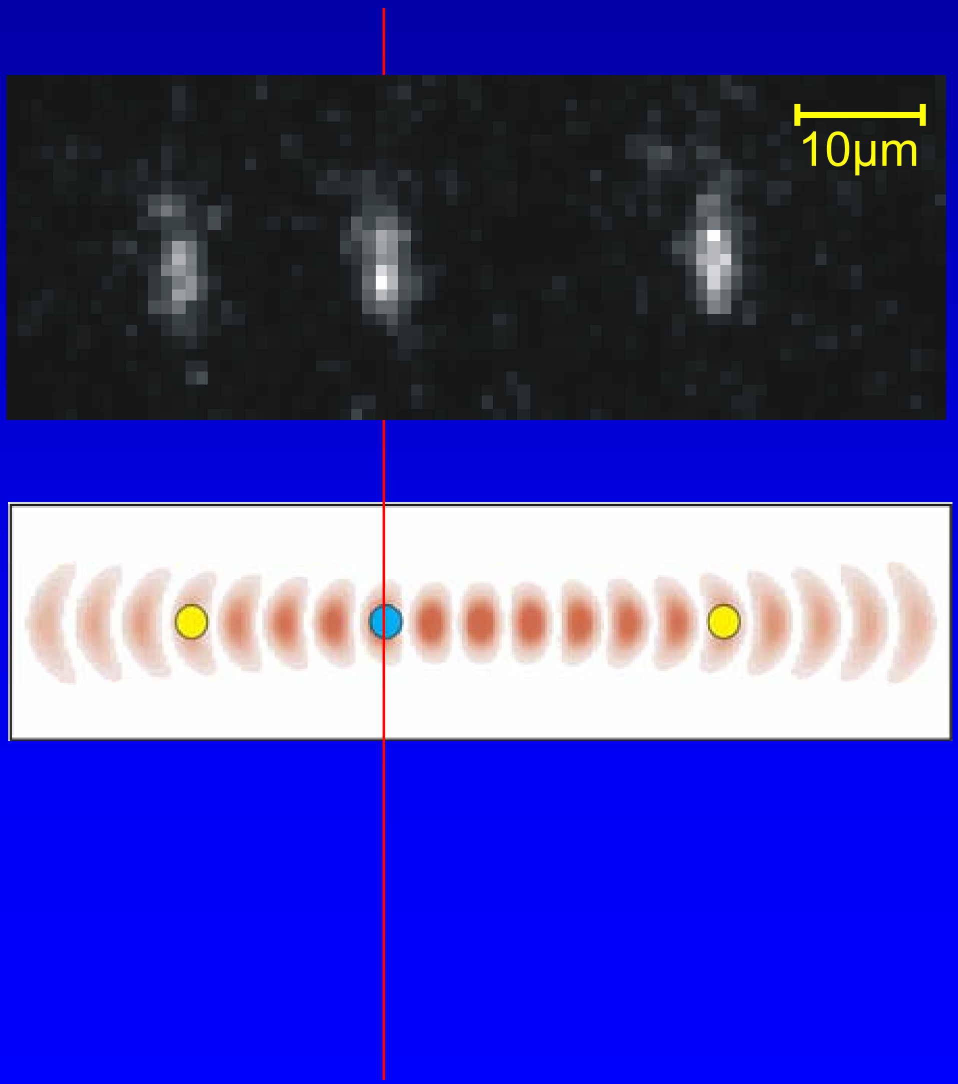




- take camera picture
- determine position of all atoms
- calculate resonance frequency of center atom

- prepare atoms in $| F = 4, m_F = -4 >$

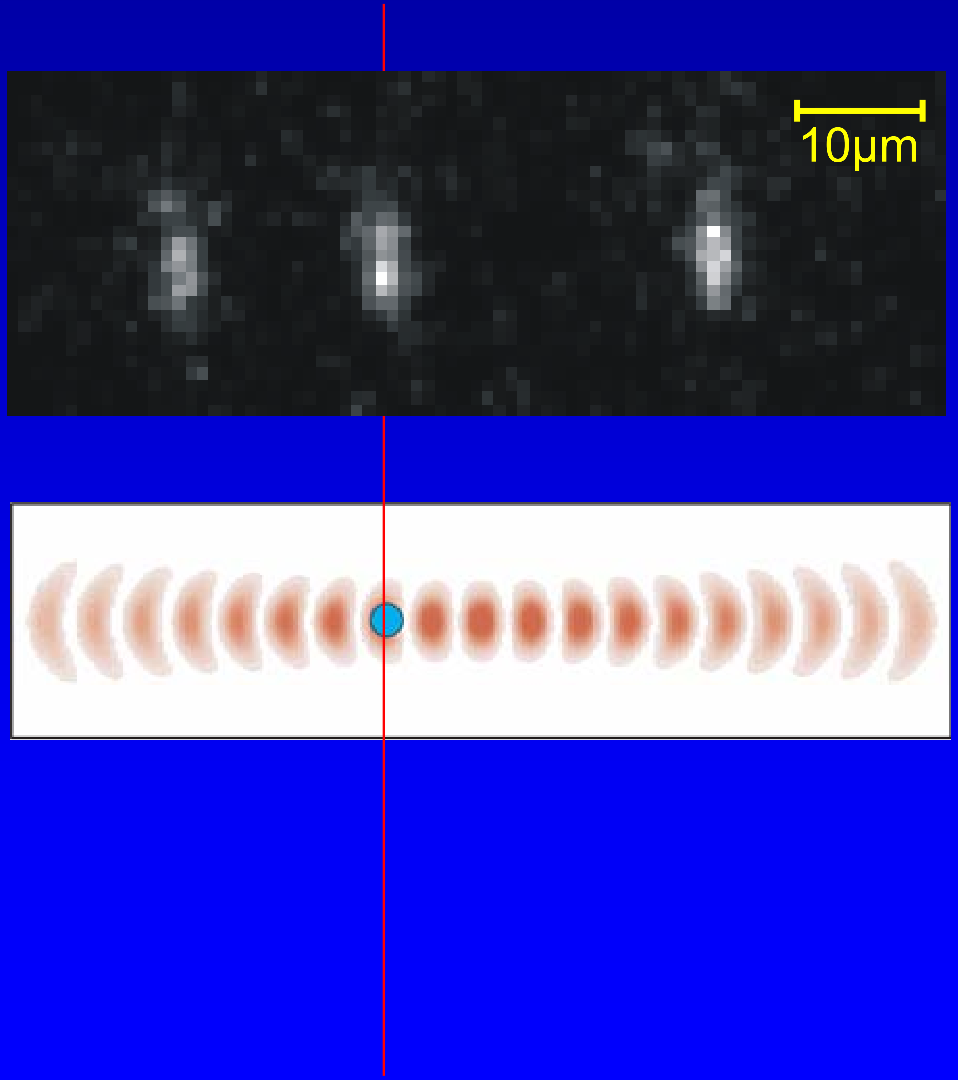
Addressing of a single atom



- take camera picture
- determine position of all atoms
- calculate resonance frequency of center atom

- prepare atoms in $|\, F = 4, m_F = -4 >$
- apply microwave pulse

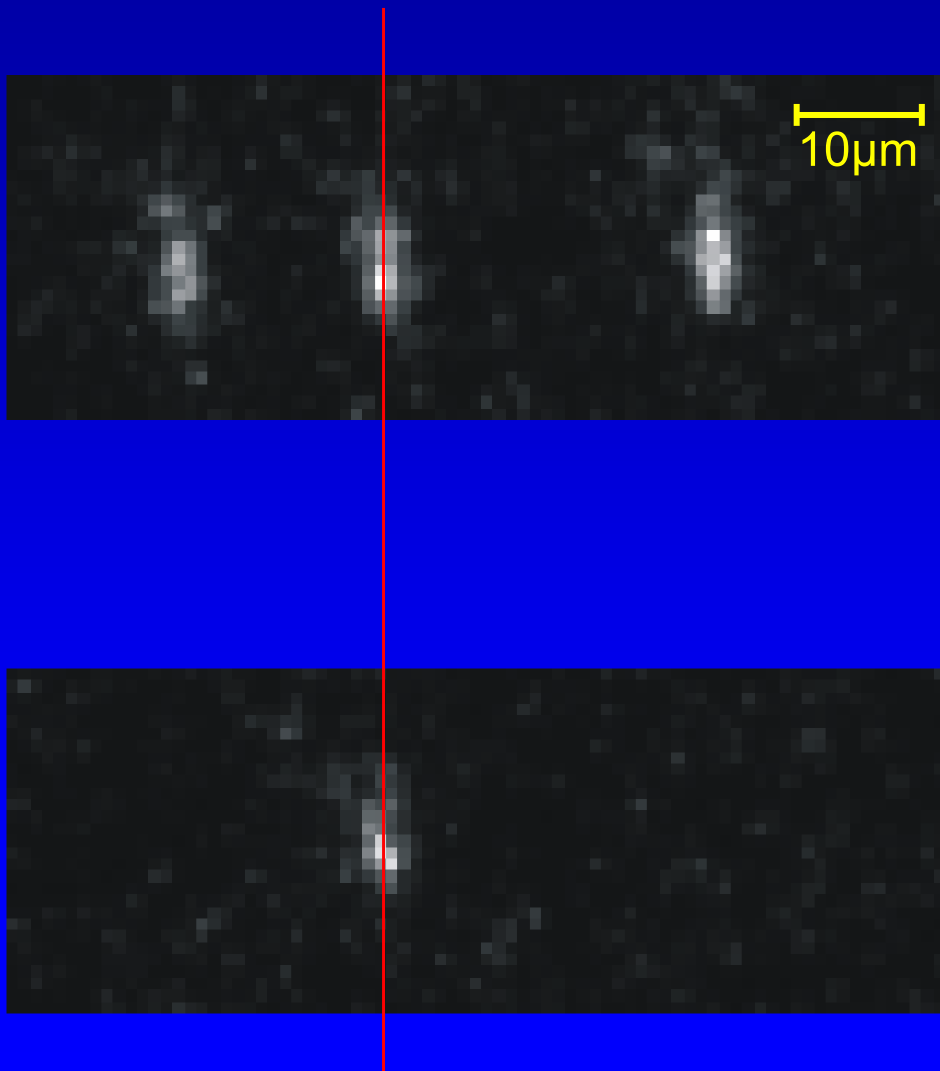
Addressing of a single atom



- take camera picture
- determine position of all atoms
- calculate resonance frequency of center atom

- prepare atoms in $| F = 4, m_F = -4 >$
- apply microwave pulse
- apply push-out laser

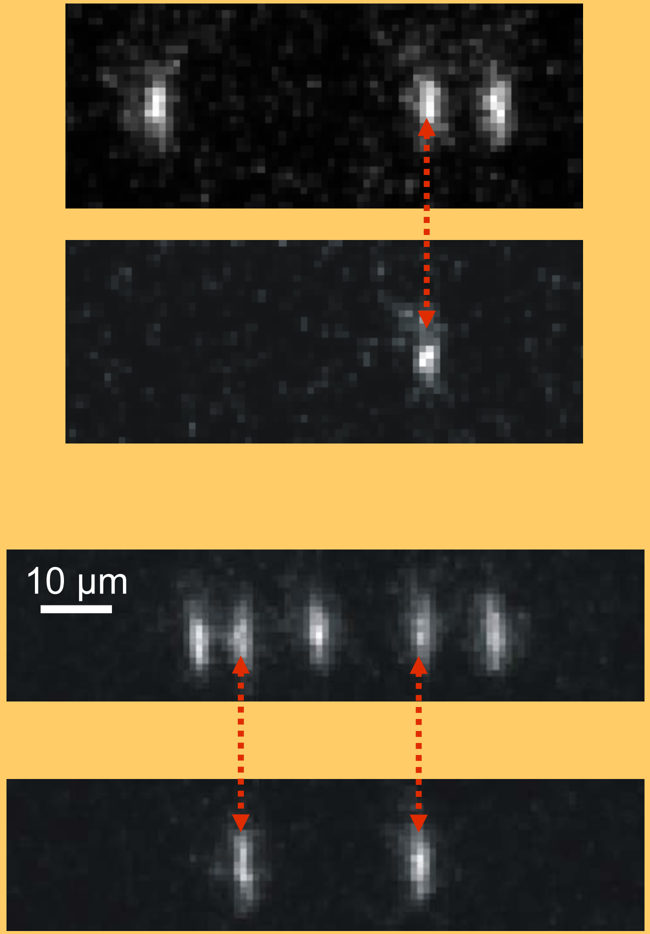
Addressing of a single atom



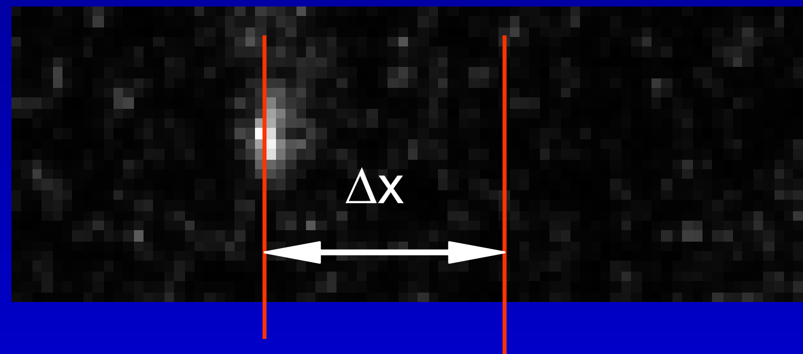
- take camera picture
- determine position of all atoms
- calculate resonance frequency of center atom
- prepare atoms in $| F = 4, m_F = -4 >$
- apply microwave pulse
- apply push-out laser
- take camera picture

Addressing of a single atom

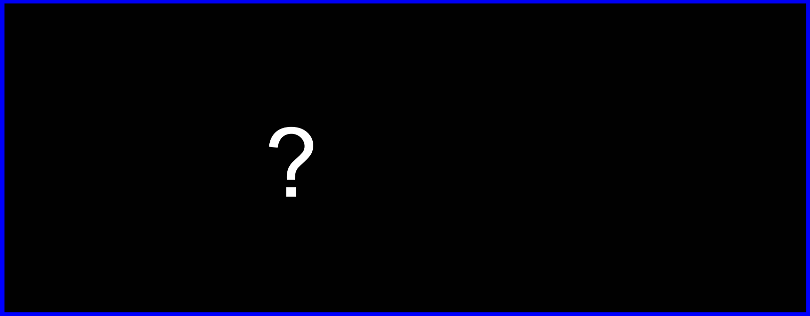
some typical pictures



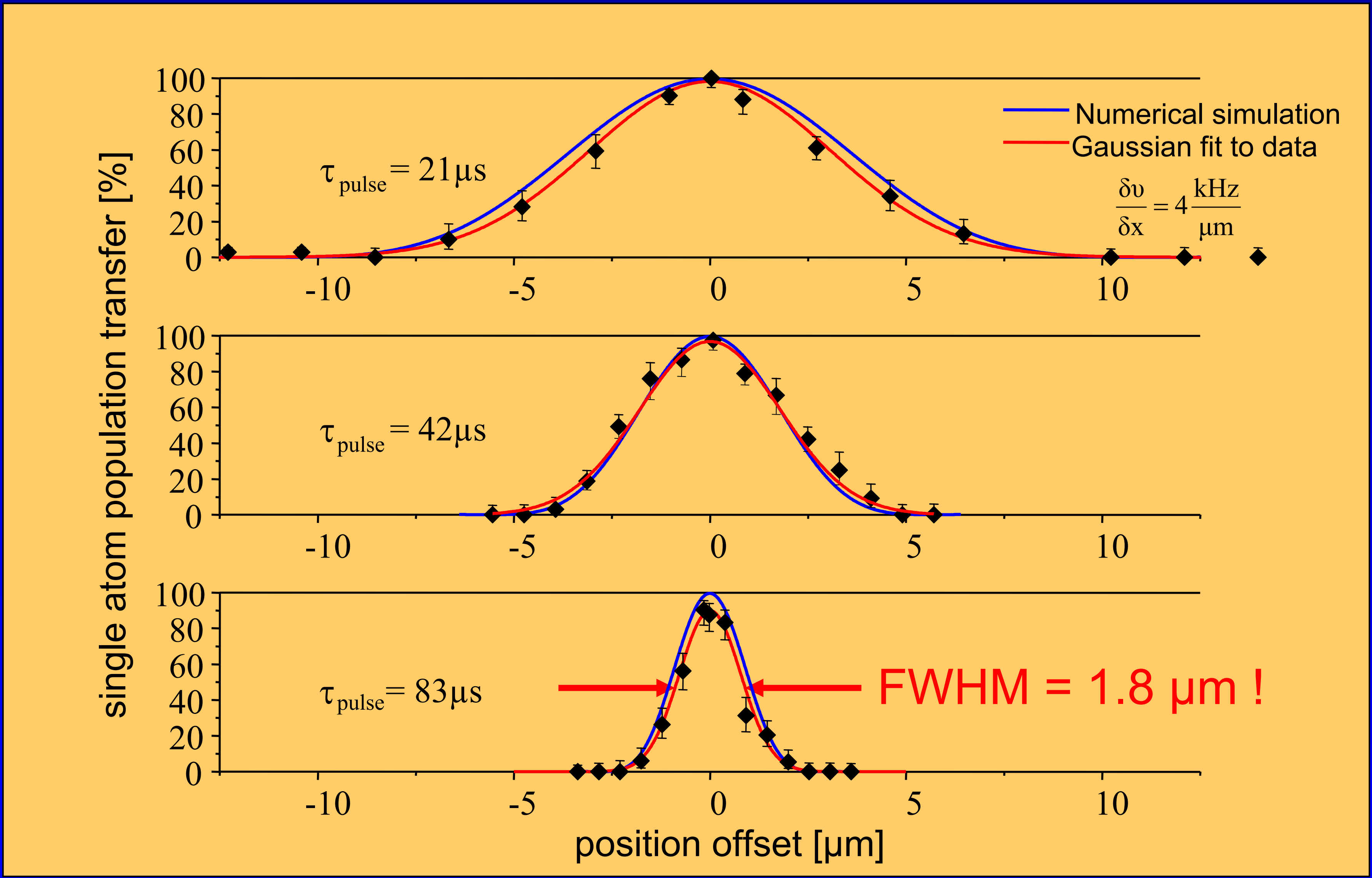
Addressing resolution



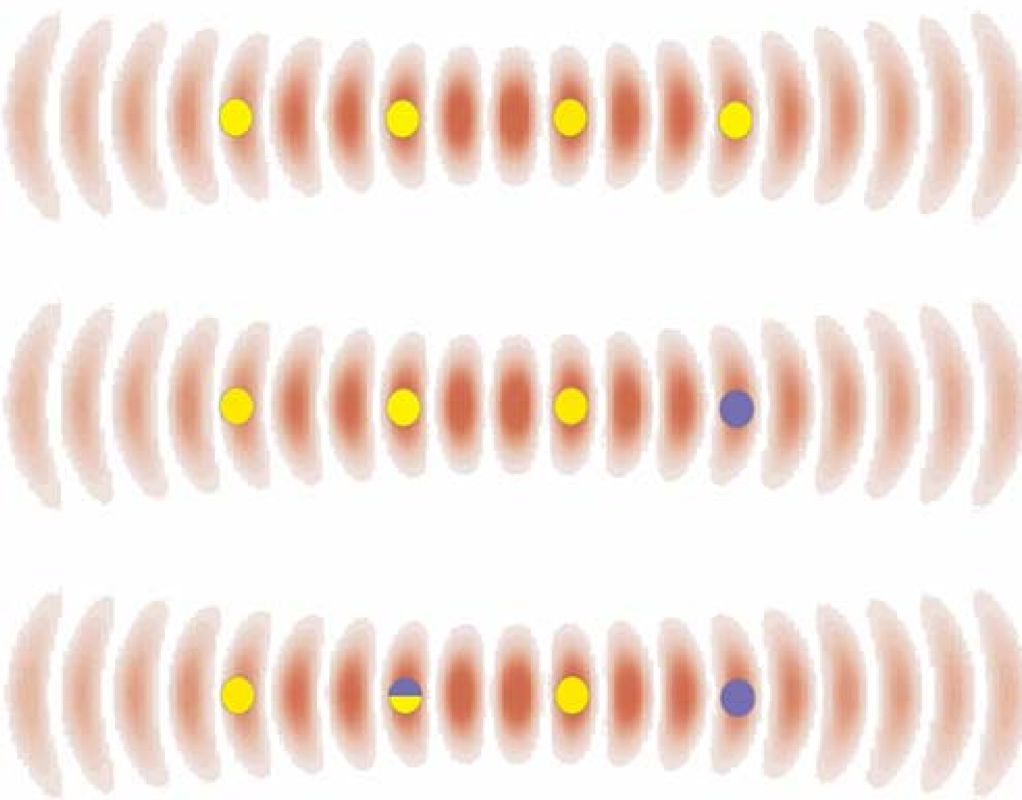
Apply microwave
π-pulse



Addressing resolution



Preparation of state superpositions

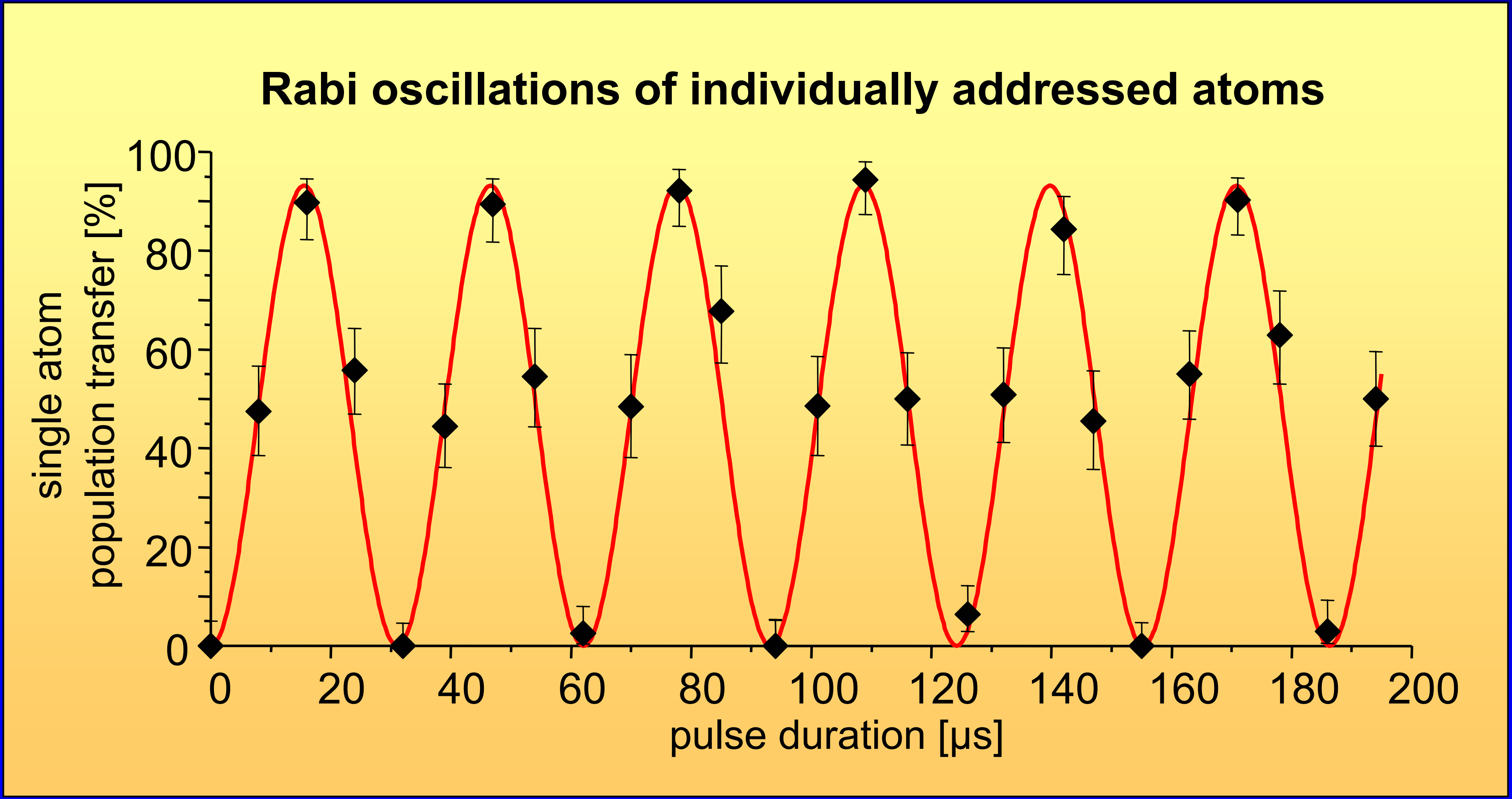


$$|0\rangle|0\rangle|0\rangle|0\rangle$$

$$|0\rangle|0\rangle|0\rangle|1\rangle$$

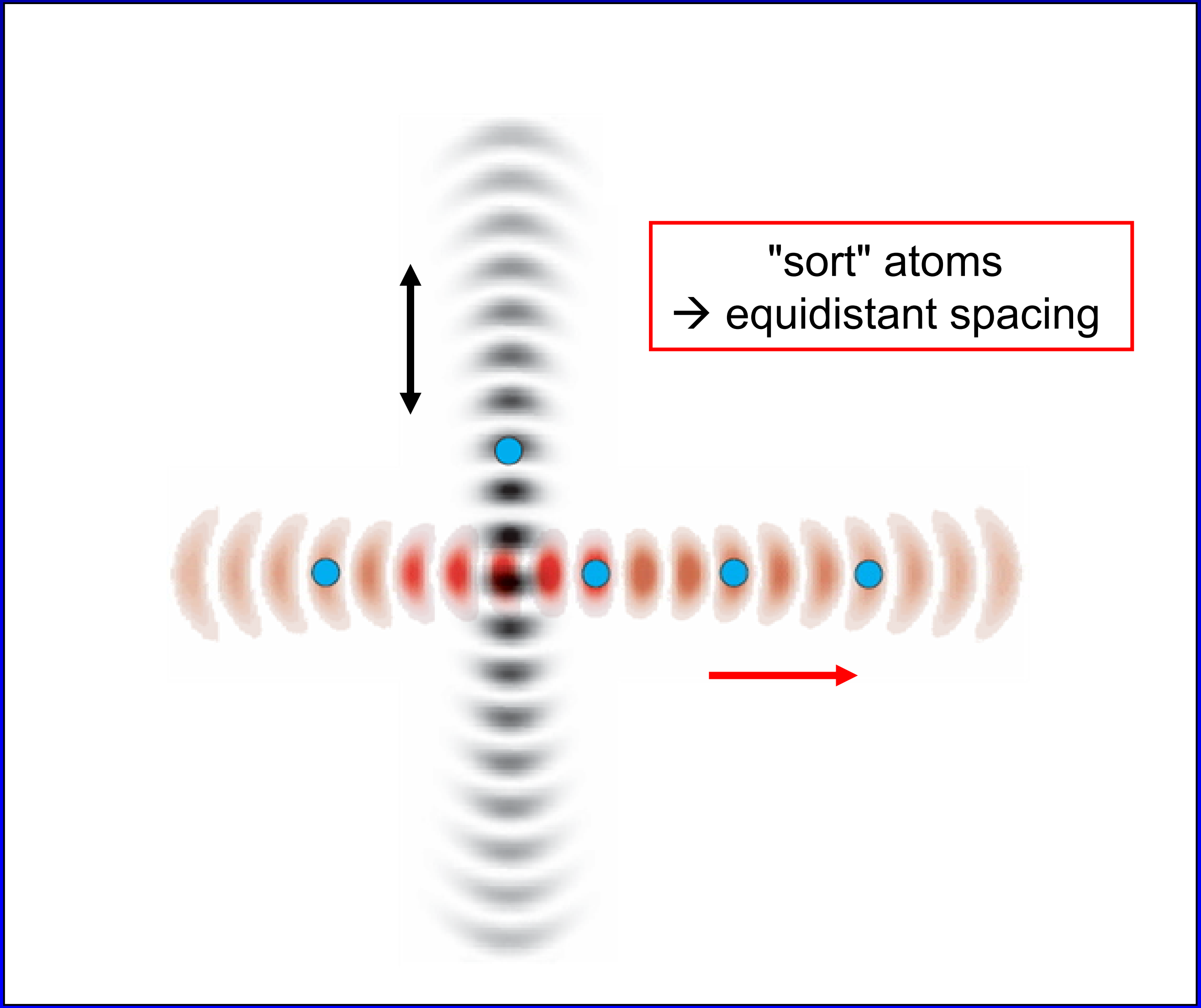
$$|0\rangle\left(|0\rangle+|1\rangle\right)|0\rangle|1\rangle$$

Preparation of state superpositions

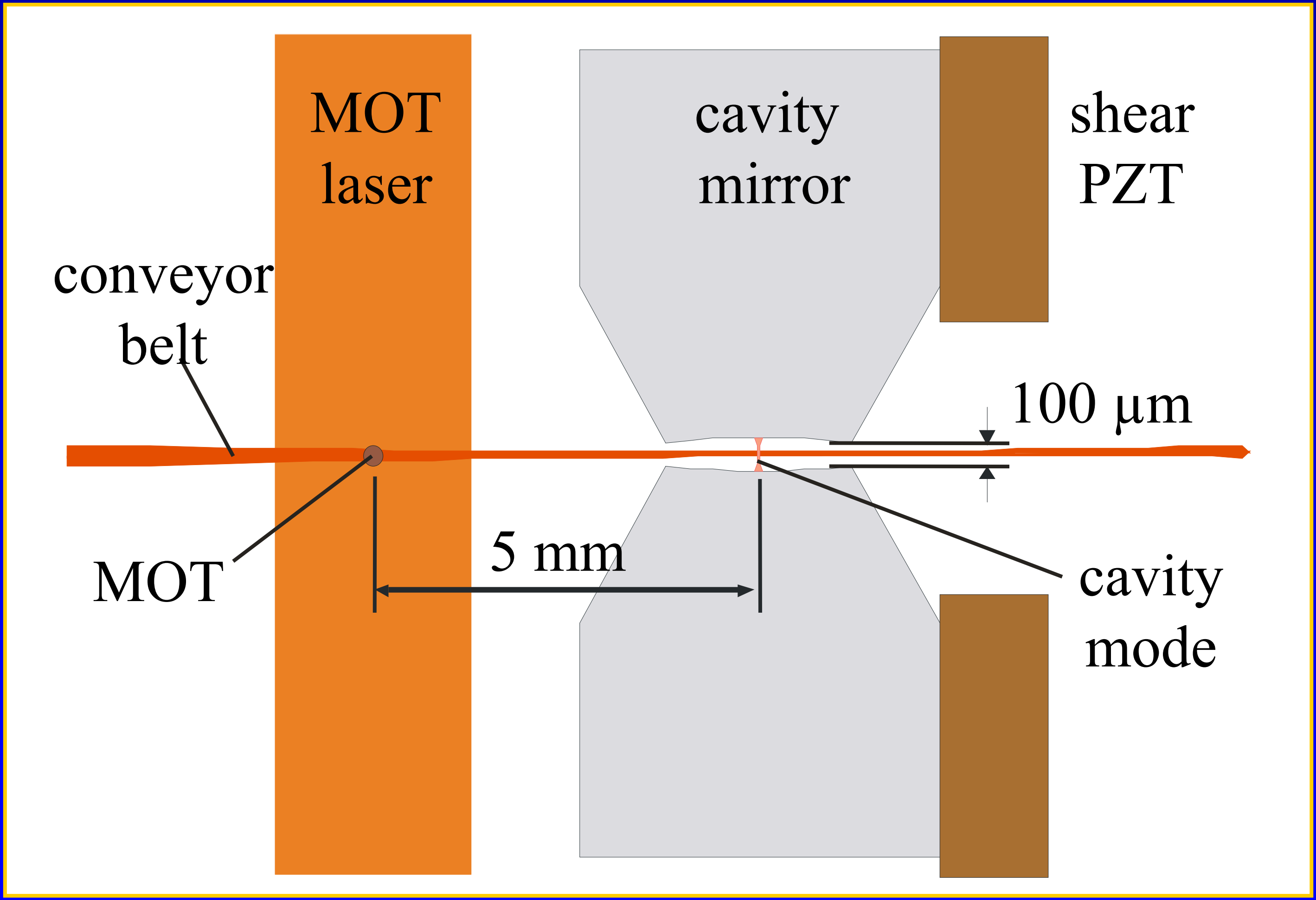


Coherence time T_2 > 600 μs

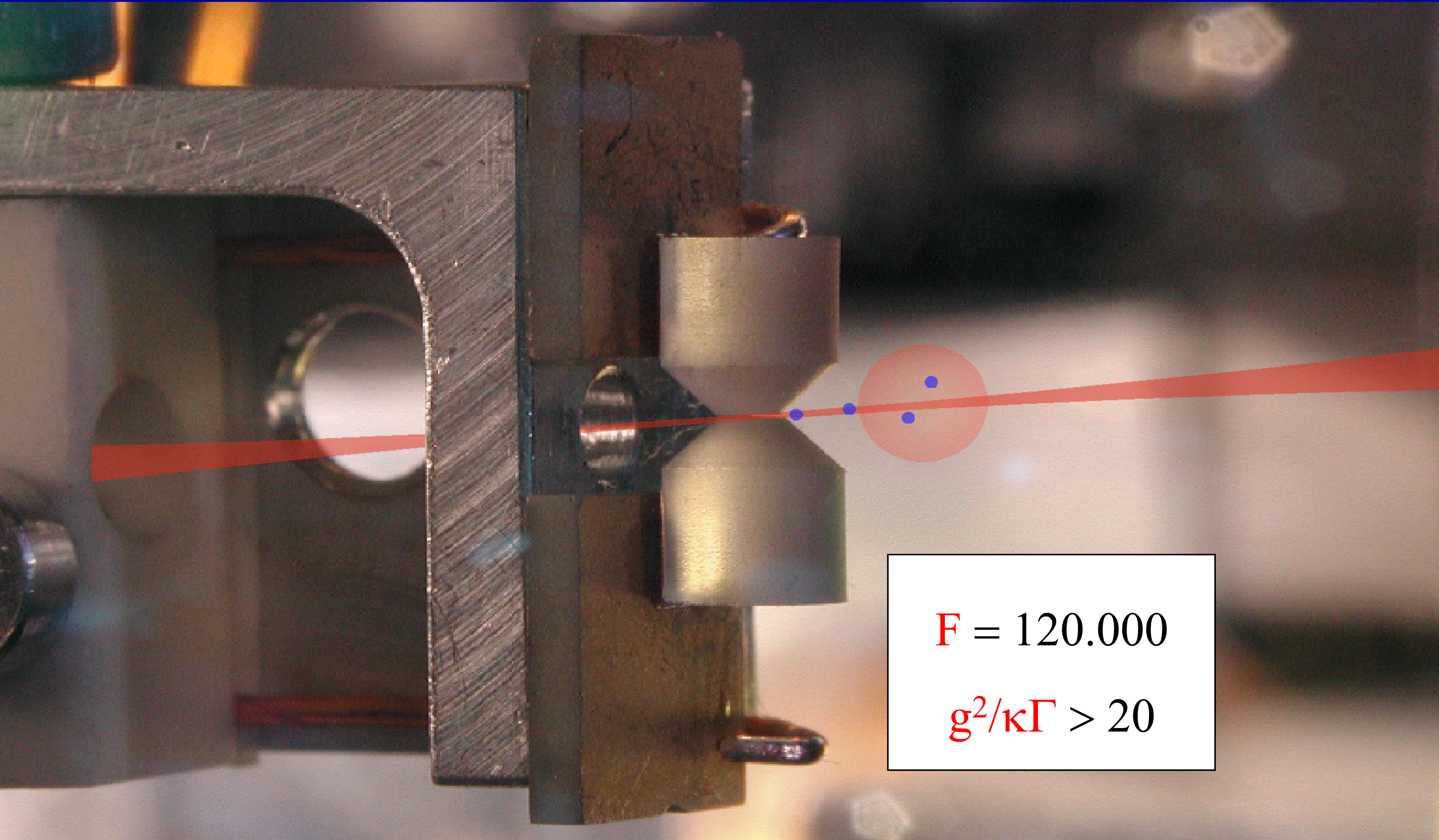
Outlook:
Two conveyor belts



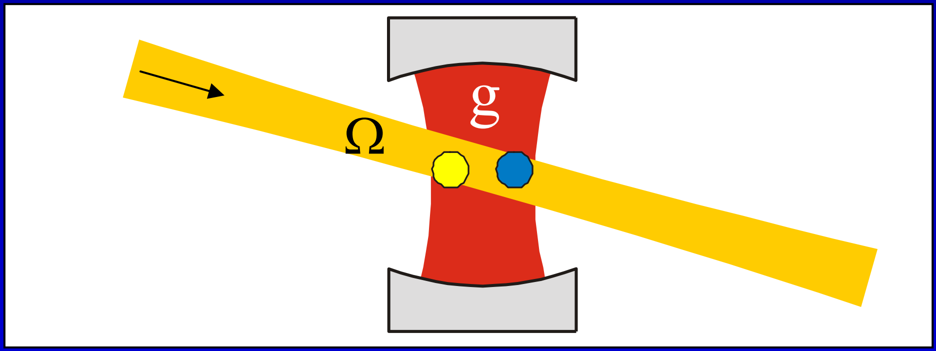
Outlook:
Transport of atoms into a resonator

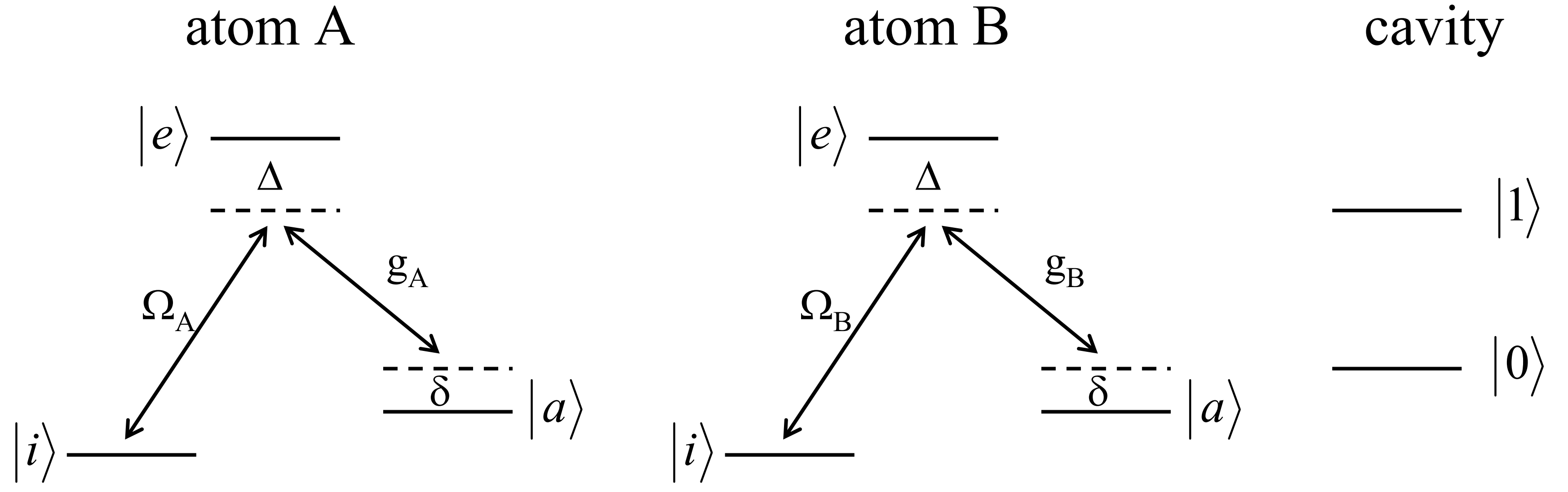


Outlook: Transport of atoms into a resonator



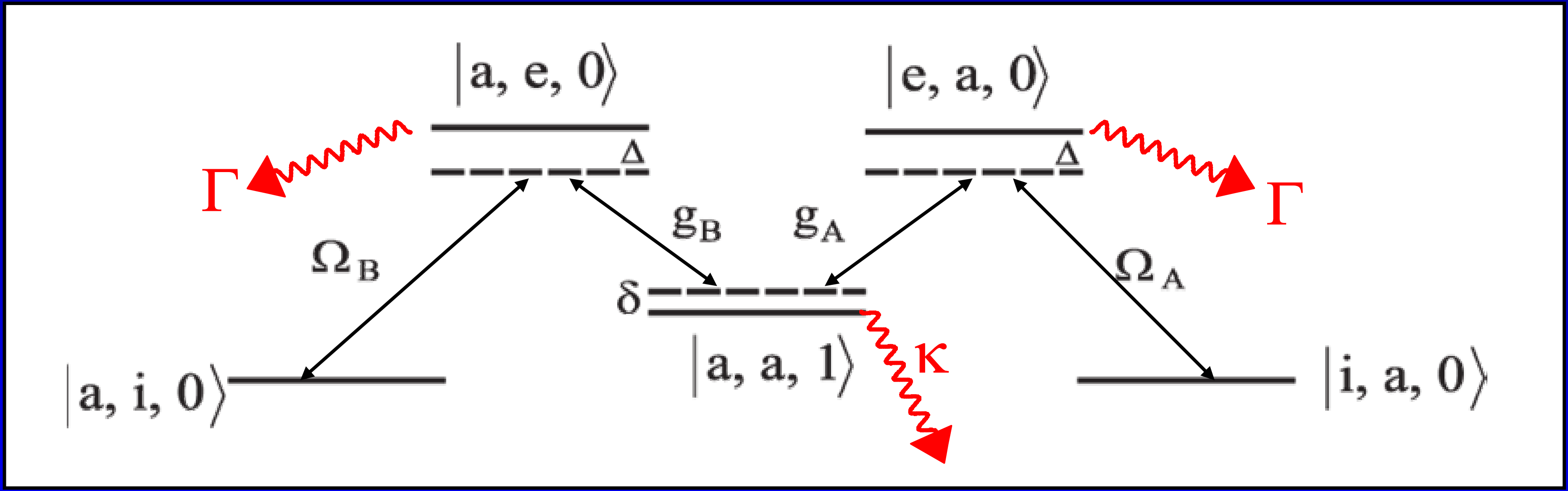
Entanglement scheme via four-photon resonance



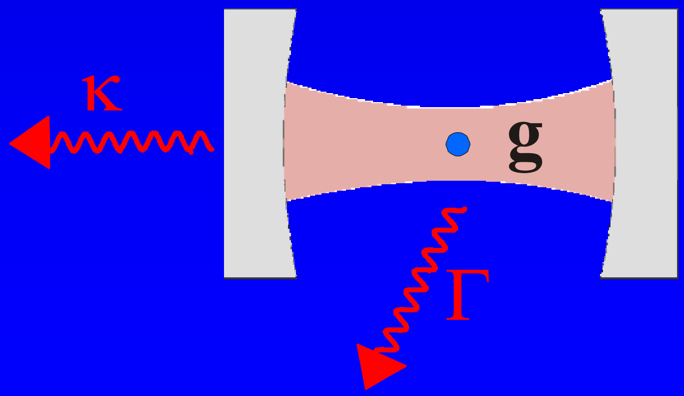


L. You *et al.*, Phys. Rev. A **67**, 032308 (2003)

Entanglement scheme via four-photon resonance



$$\pi/2\text{–pulse:}\quad \psi_{ent} = \frac{|a,i,0\rangle + |i,a,0\rangle}{\sqrt{2}}$$



Summary

A controlled quantum system of individual neutral atoms:

- control of all degrees of freedom of a single atom (position + internal states)
- measured coherence times
- addressing of a single atom

next steps:

- insert cavity into current setup
- achieve deterministic atom-field coupling

The team

Wolfgang Alt

Dominik Schrader

Stefan Kuhr

Yevhen Miroshnychenko

Igor Dotsenko

Wenjamin Rosenfeld

Mika Khudaverdyan

Victor Gomer

Arno Rauschenbeutel

Dieter Meschede