# Manipulating Single Atoms

MESUMA 2004
Dresden, 14.10.2004, 09:45

Universität Bonn

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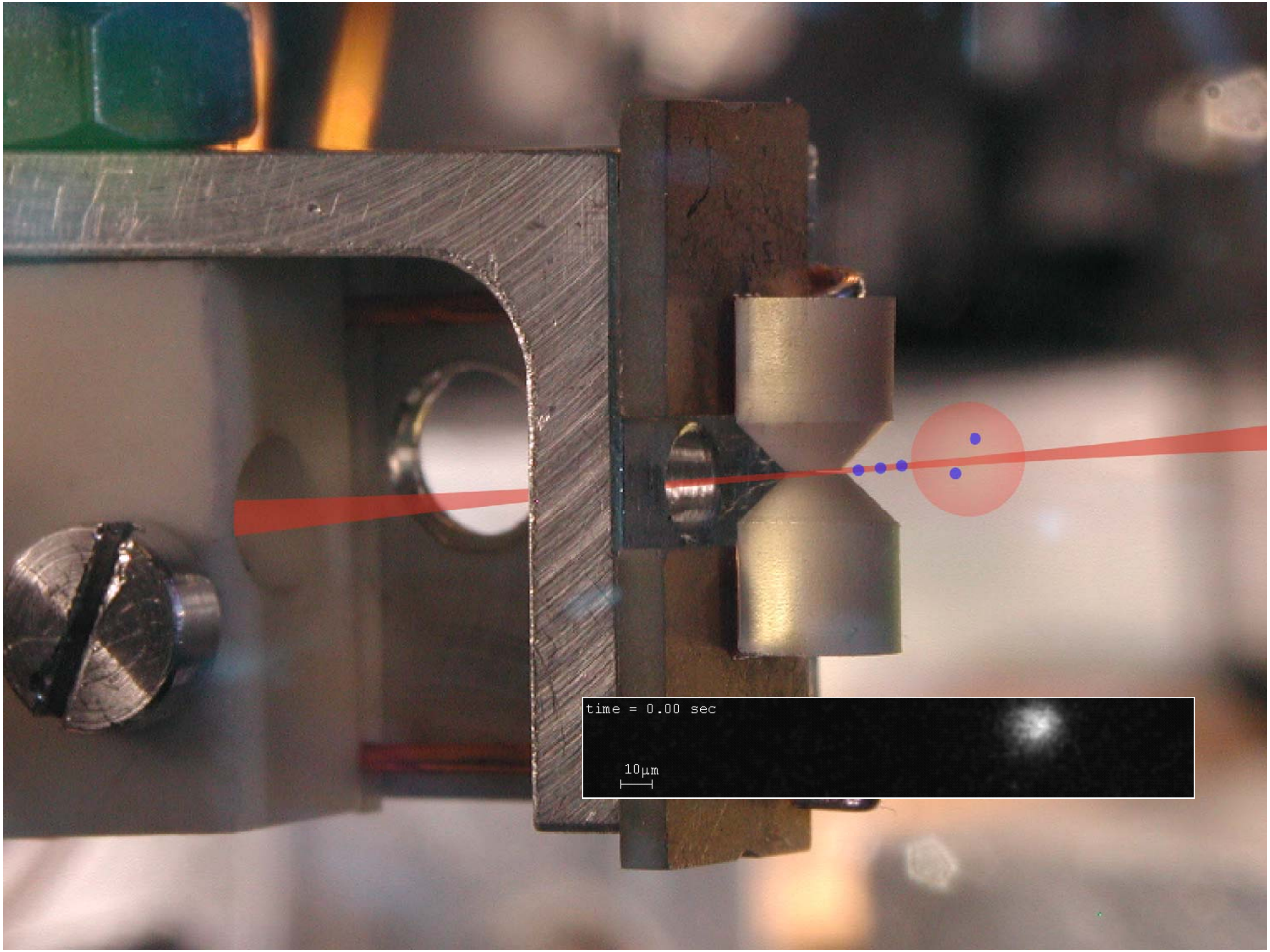
Institut für Angewandte Physik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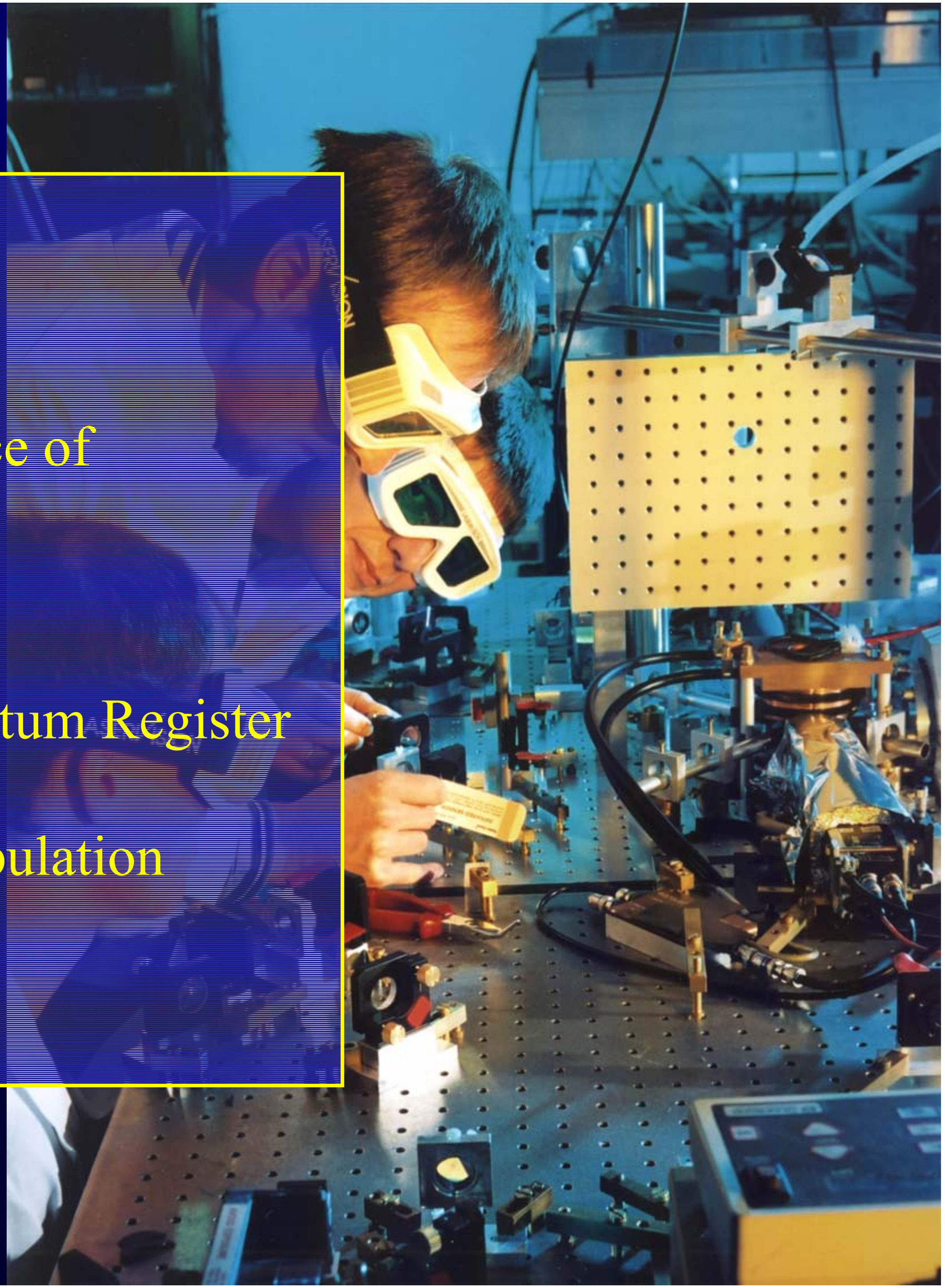
## Overview

1. A Deterministic Source of Single Neutral Atoms

2. Inverting MRI – A Neutral Atom Quantum Register

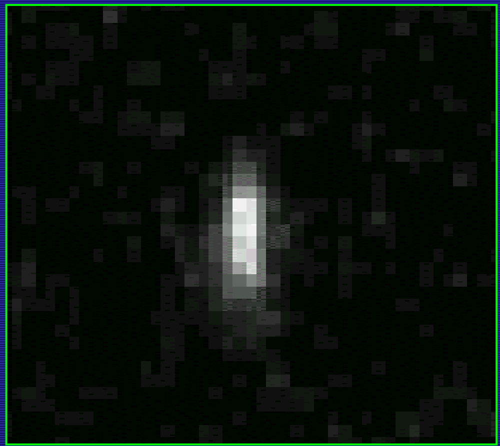
3. Coherent Atom Manipulation

4. The Future

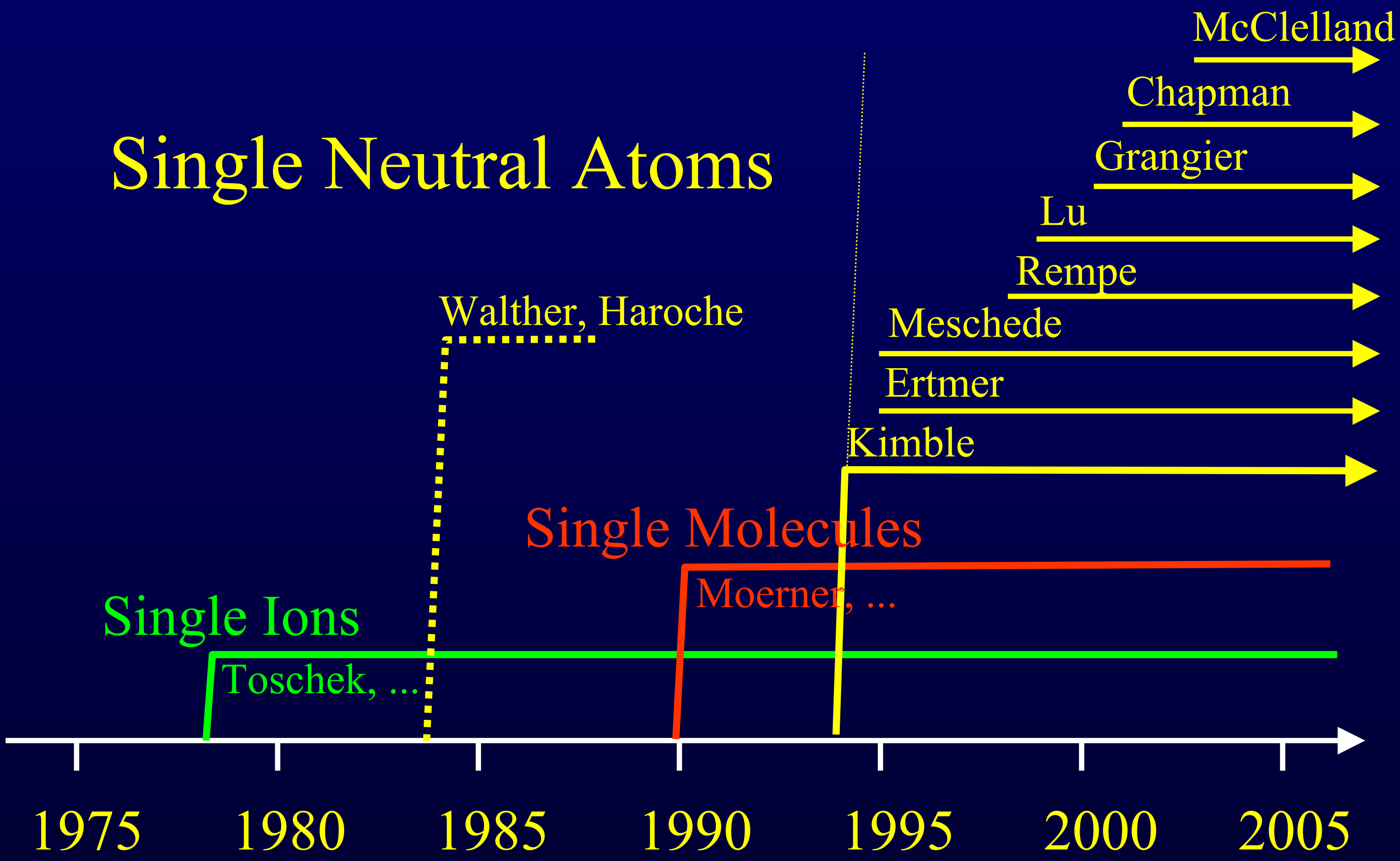


# Overview

1. **A Deterministic Source of Single Neutral Atoms**

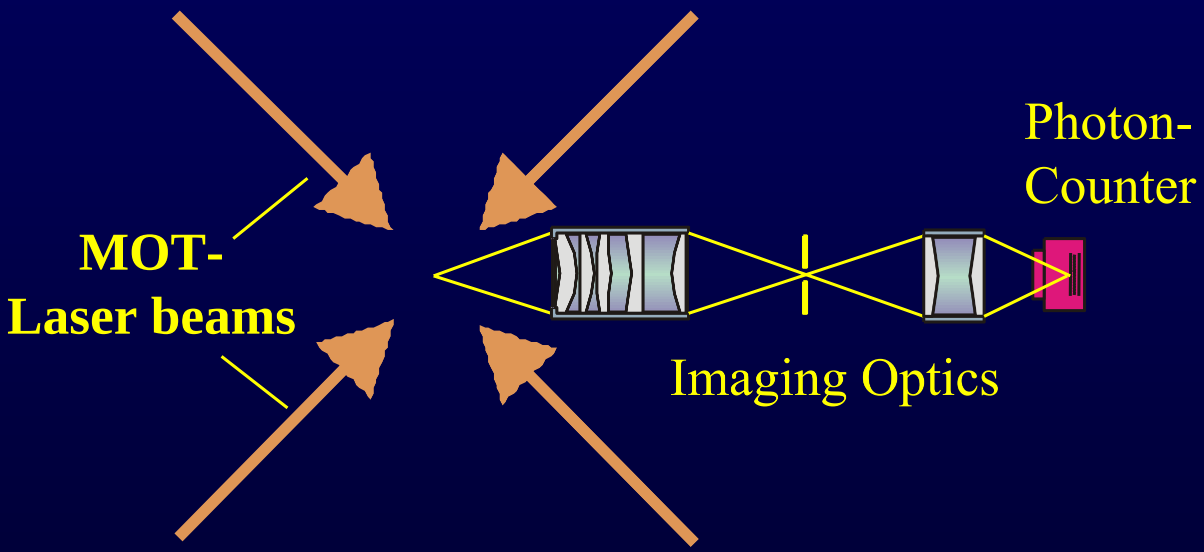


# 1. Deterministic Source of Single Neutral Atoms

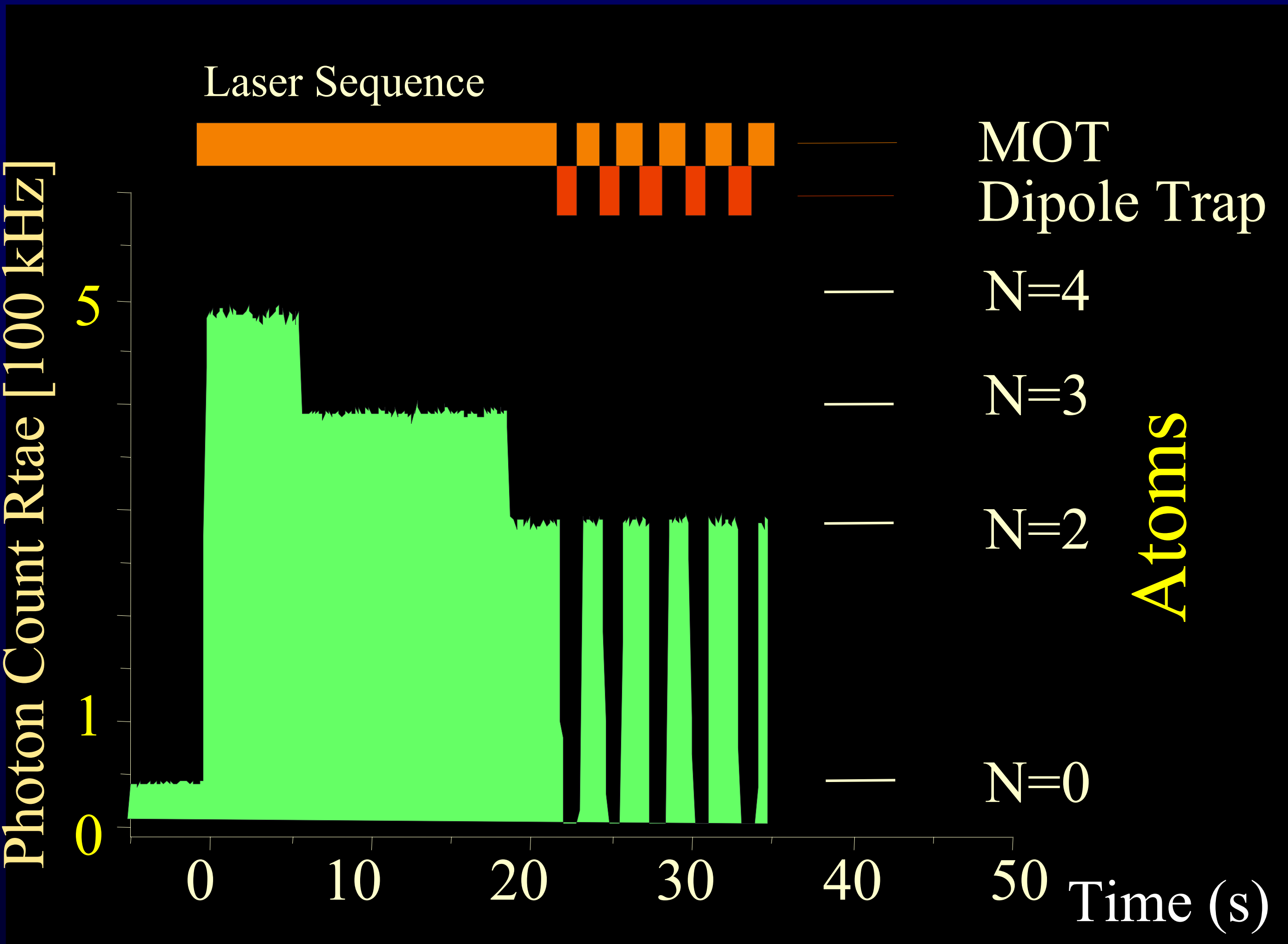


## 1. Deterministic Source of Single Neutral Atoms

Apparatus for manipulating single neutral atoms

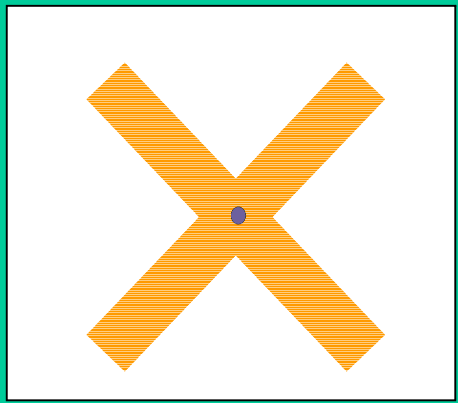


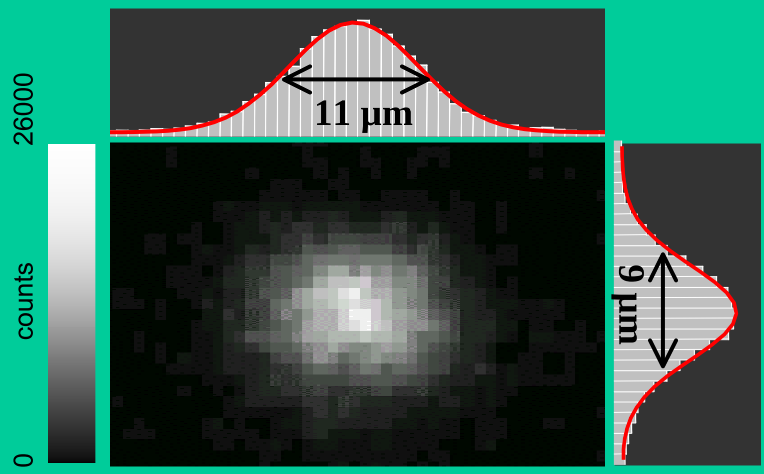
# 1. Deterministic Source of Single Neutral Atoms



# 1. Deterministic Source of Single Neutral Atoms

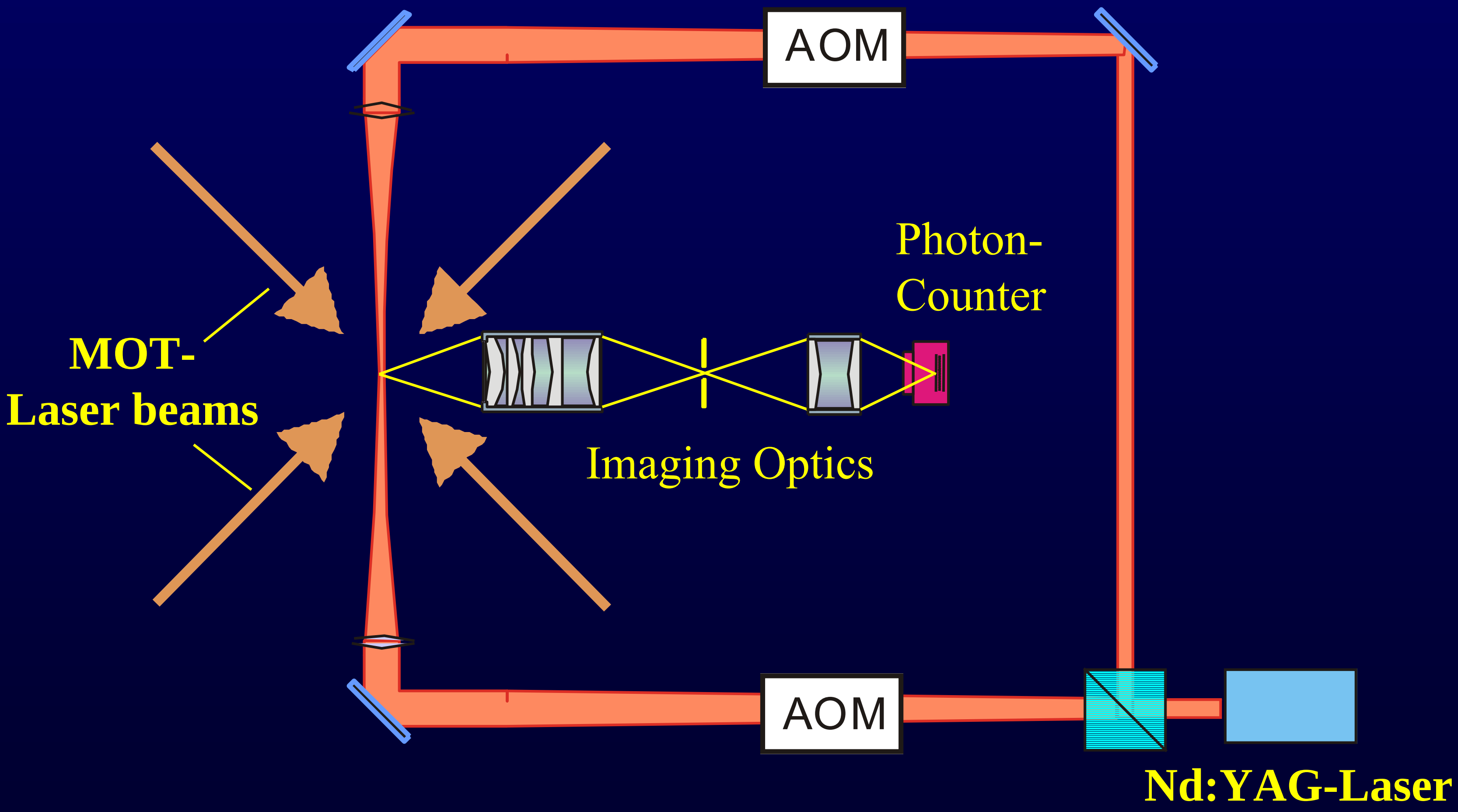
## ...in the MOT





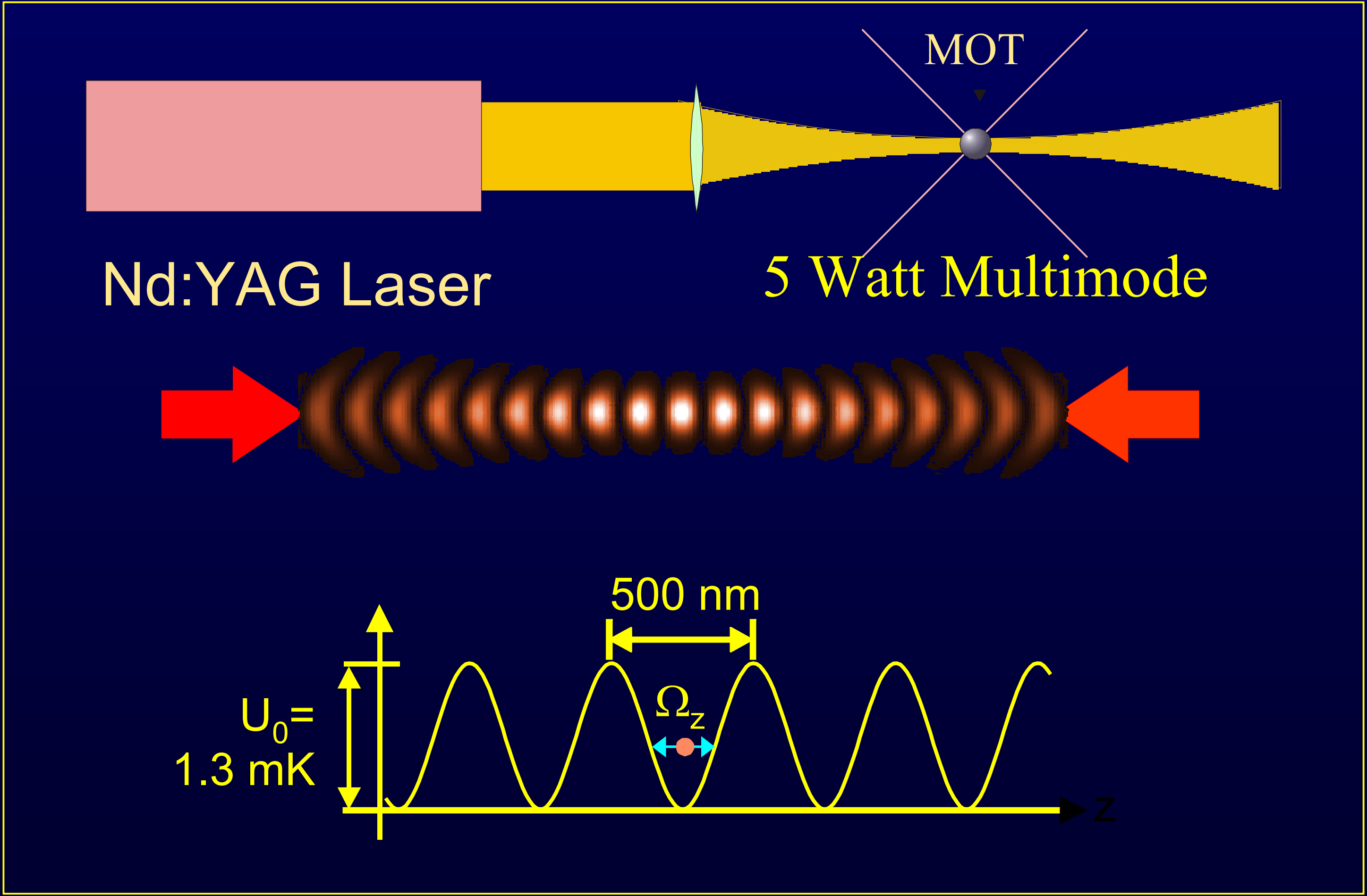
# 1. Deterministic Source of Single Neutral Atoms

## Optical conveyor belt (single atom tweezer)



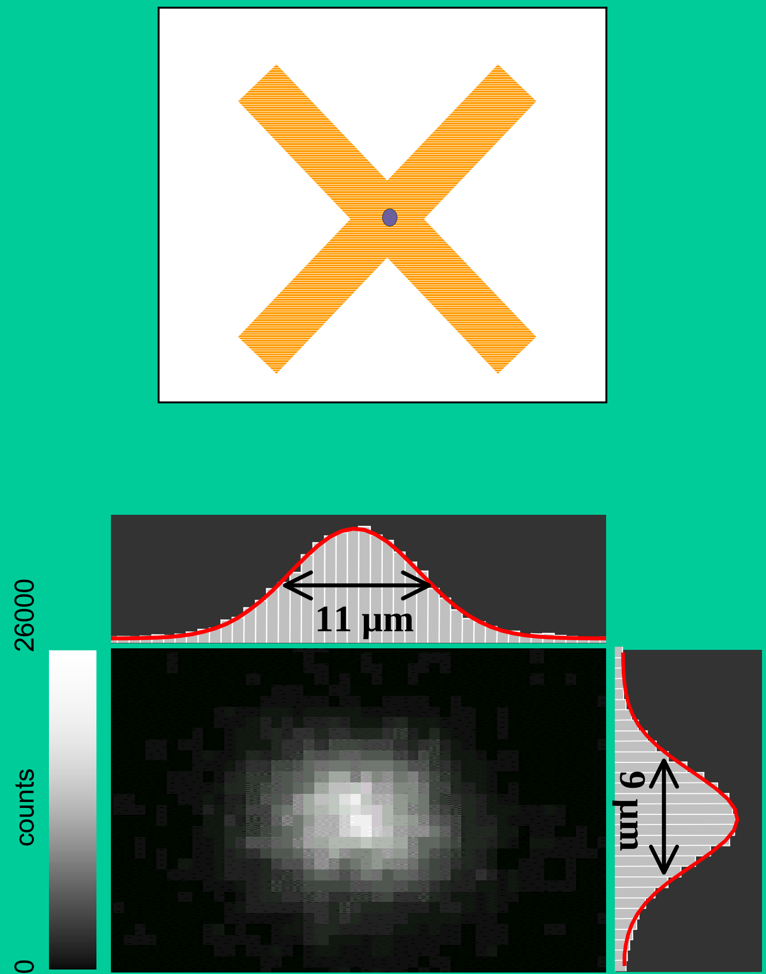
# 1. Deterministic Source of Single Neutral Atoms

## Characteristics of the optical dipole potential

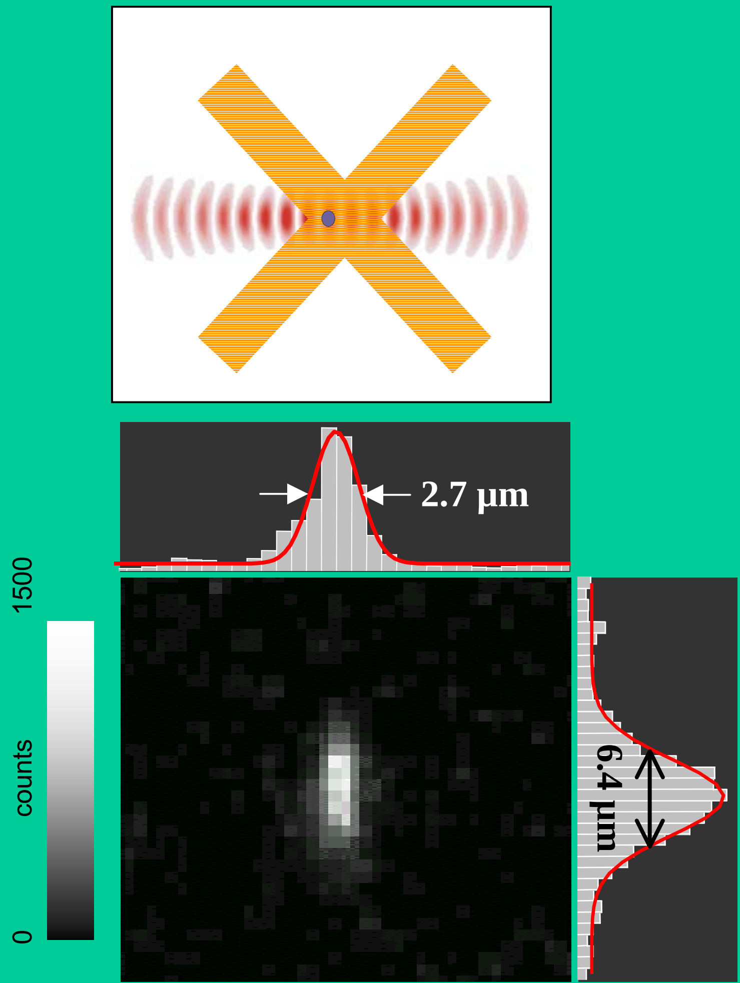


# 1. Deterministic Source of Single Neutral Atoms

## ...in the MOT

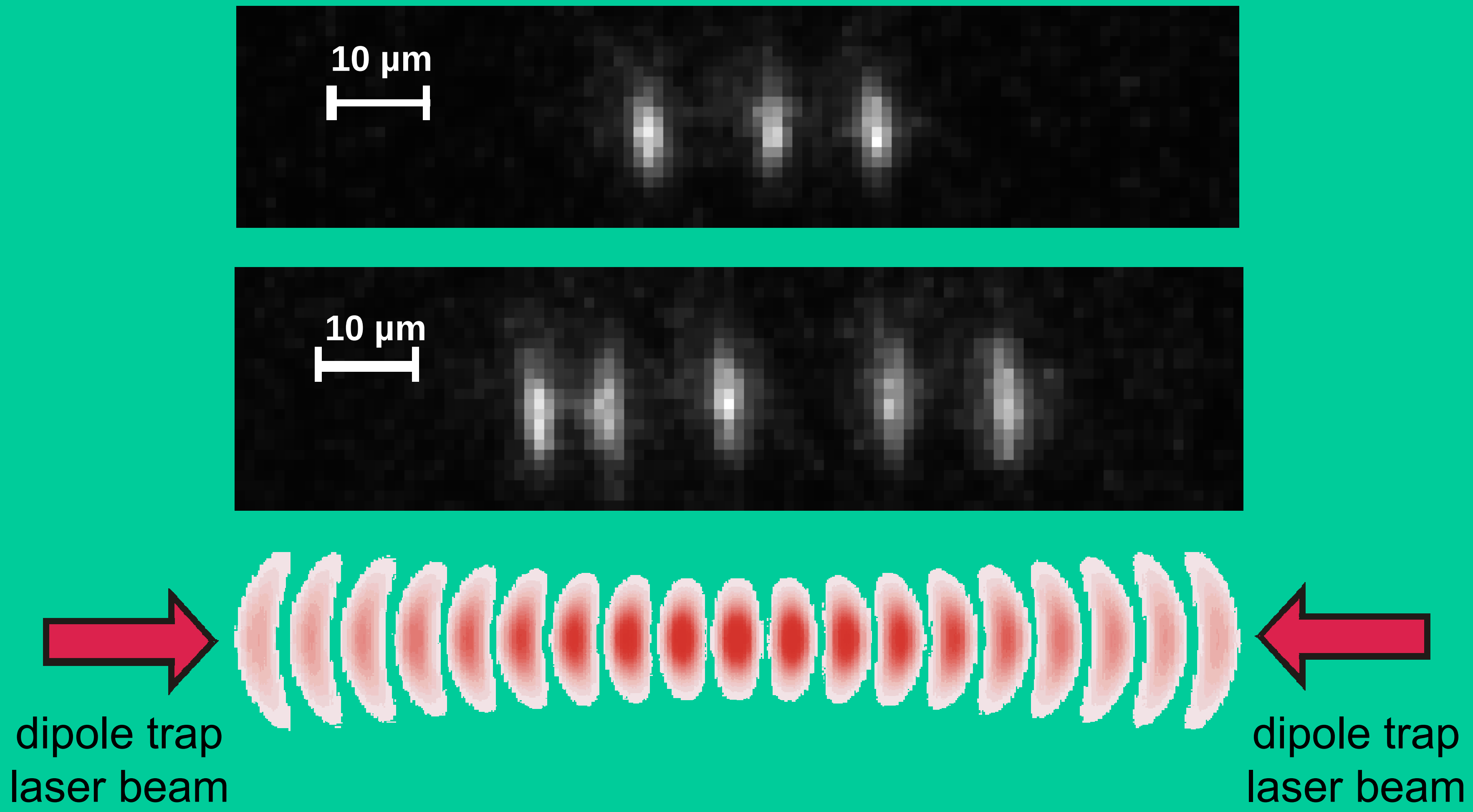



## ...in the dipole trap



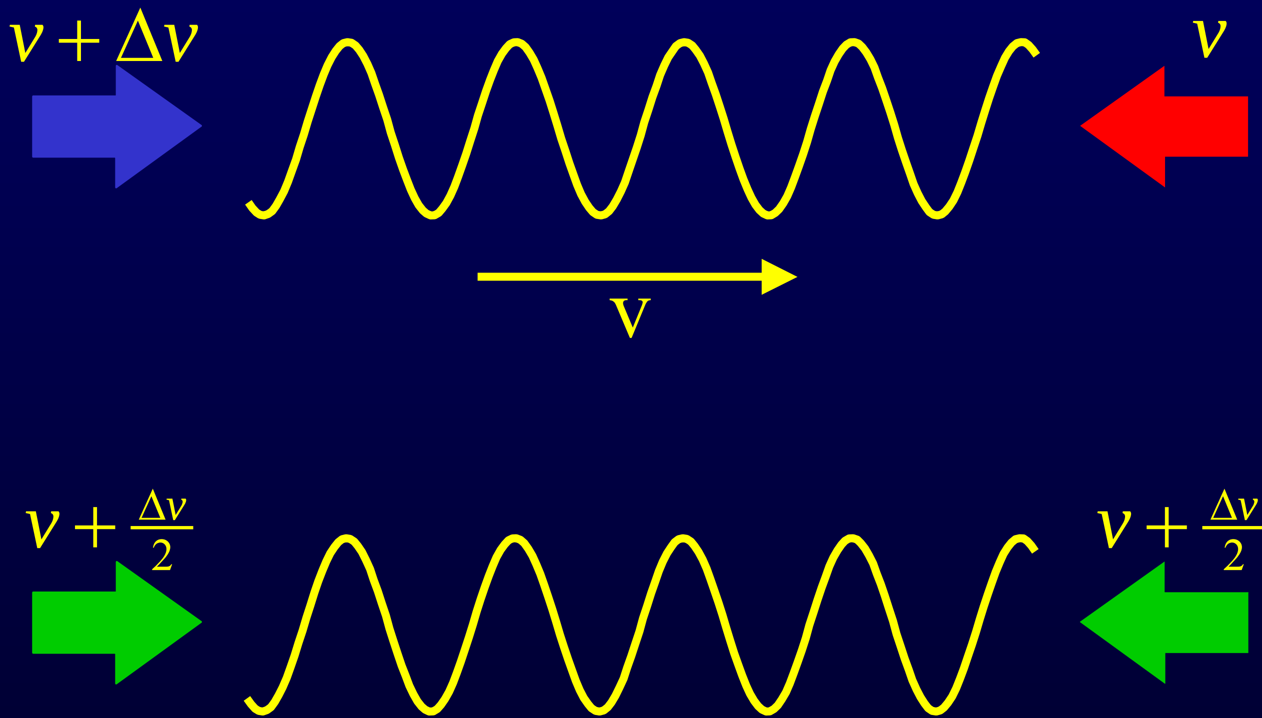
# 1. Deterministic Source of Single Neutral Atoms

...in the dipole trap



## 1. Deterministic Source of Single Neutral Atoms

### The Single Atom Conveyor Belt

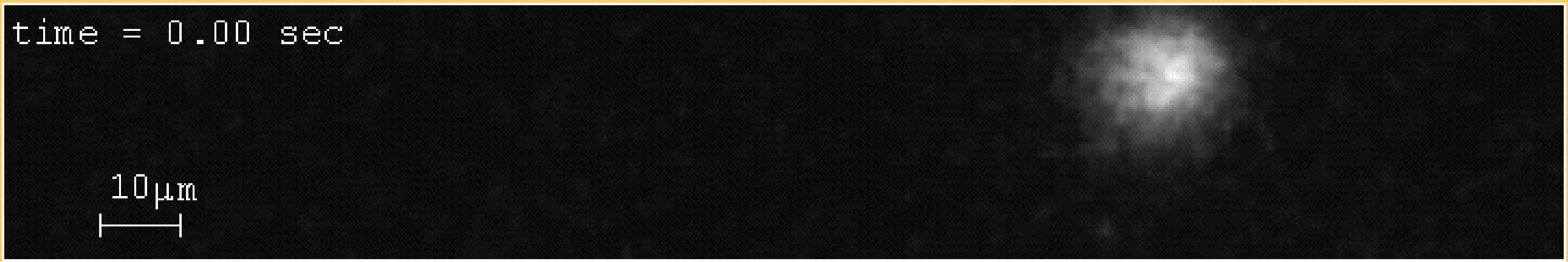



$$v = \frac{\lambda \Delta \nu}{2}$$

# 1. Deterministic Source of Single Neutral Atoms

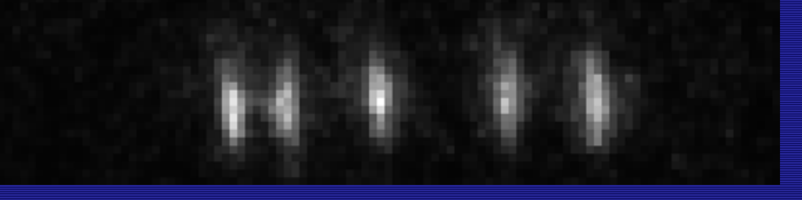
## 1 Atom

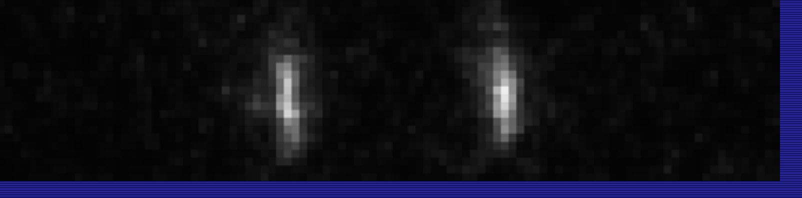

## 3 Atoms



# Overview

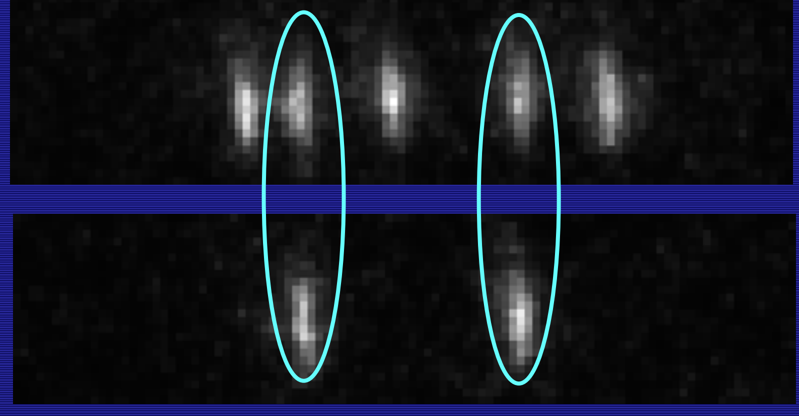
2. **Inverting MRI –**
   **A Neutral Atom Quantum Register**



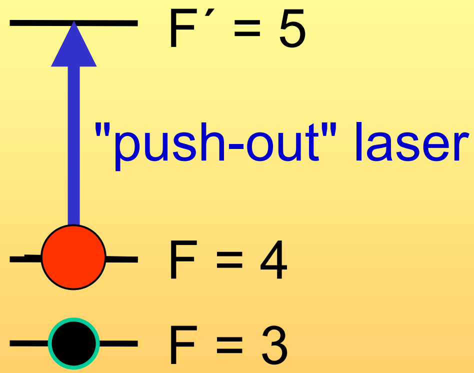


# Overview

2. **Inverting MRI –**
   **A Neutral Atom Quantum Register**

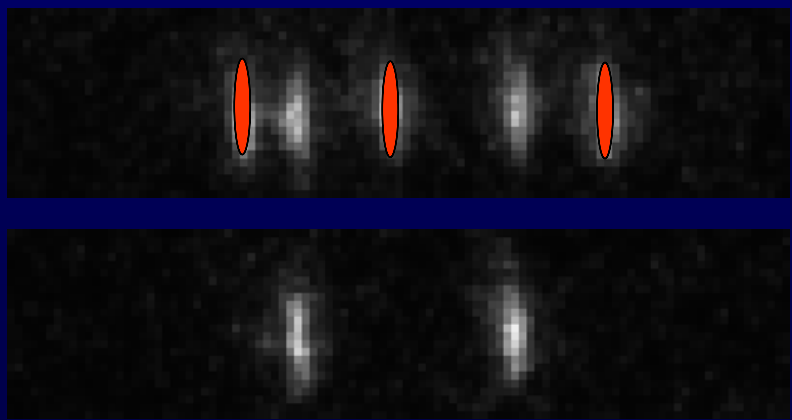


# 2. A Neutral Atom Quantum Register

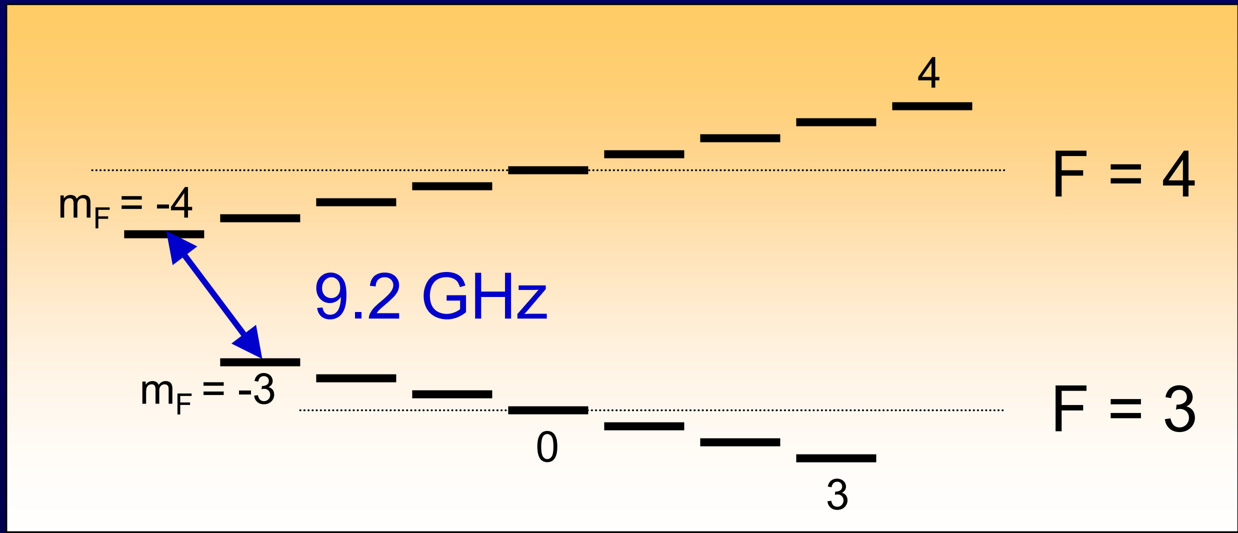


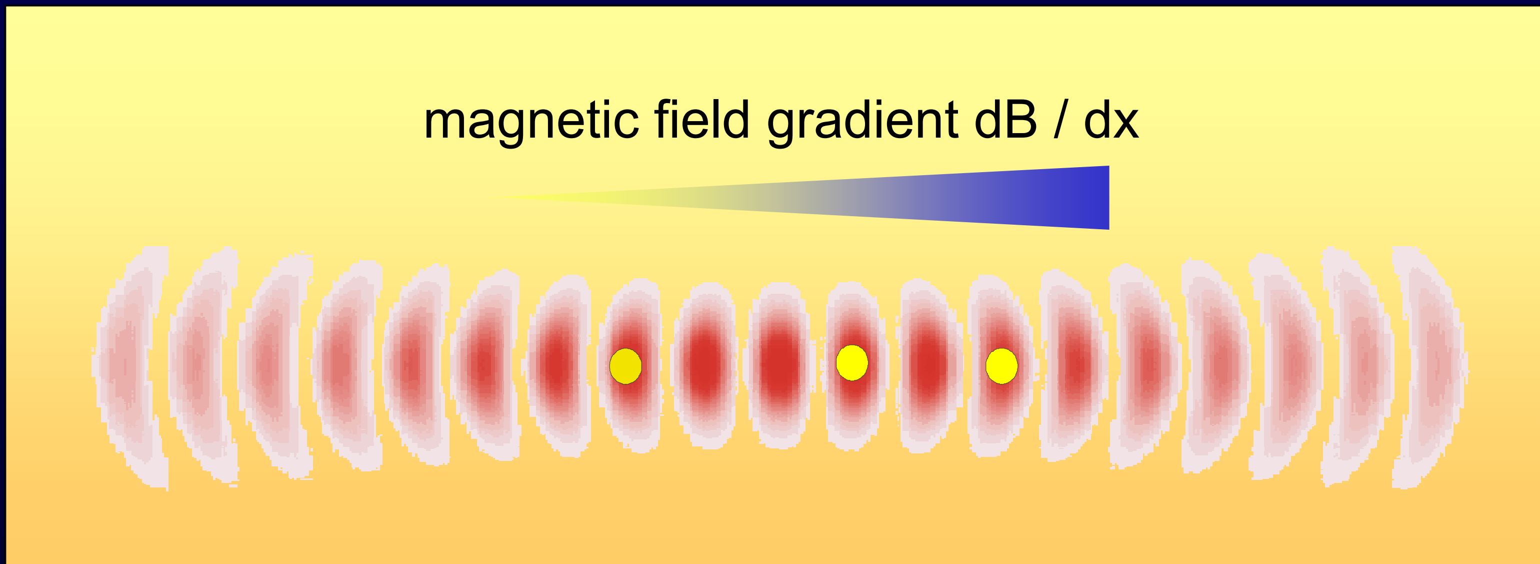

survival probability:

P(F = 3) > 99 %
P(F = 4) < 0.5 %

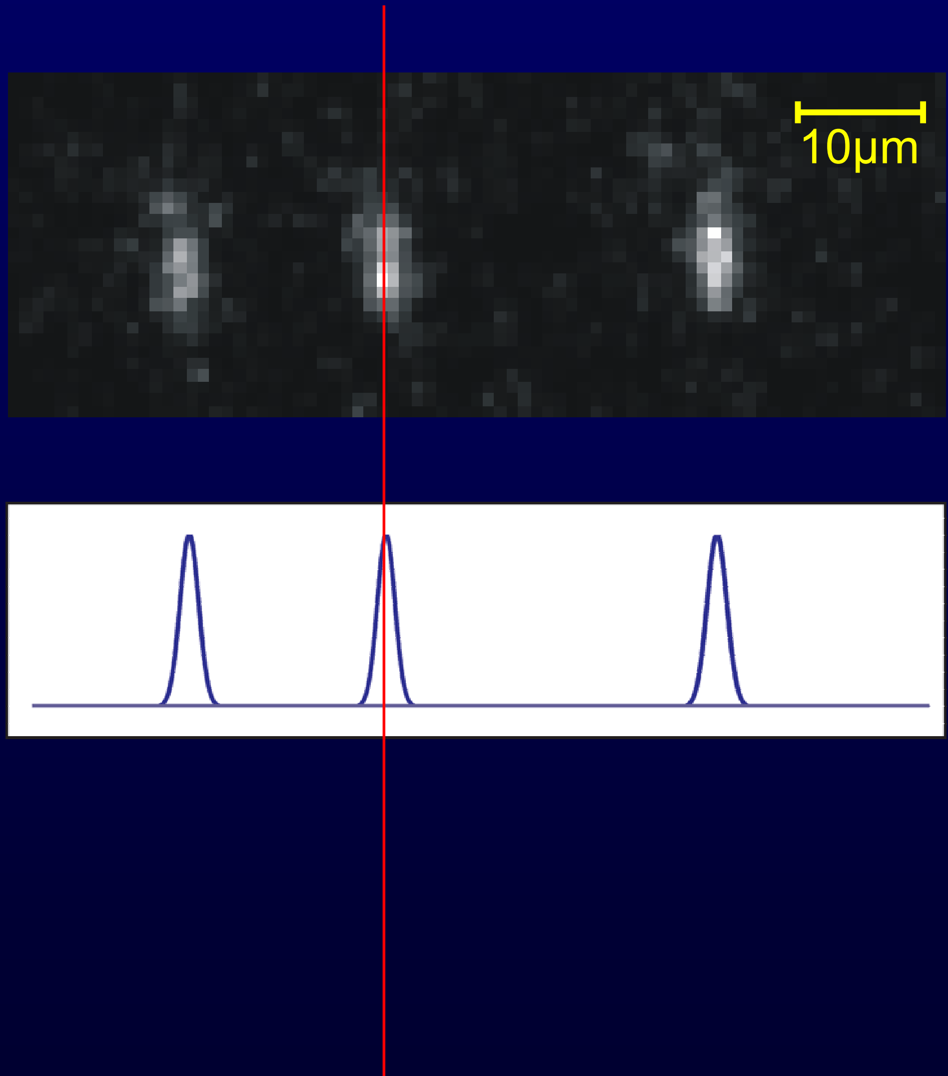


# 2. A Neutral Atom Quantum Register



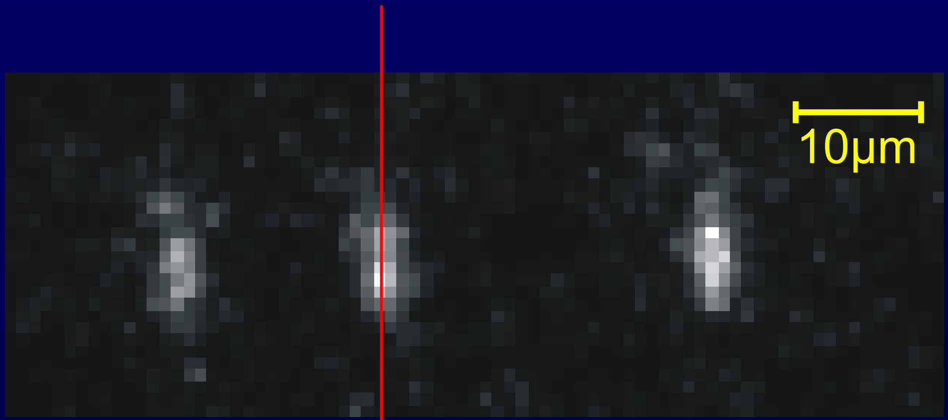



# 2. A Neutral Atom Quantum Register

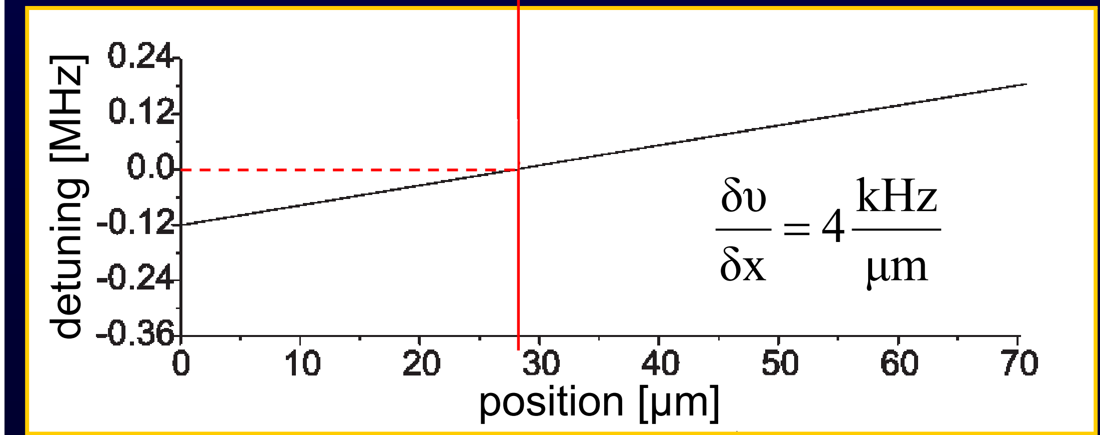



- take camera picture
- determine position of all atoms

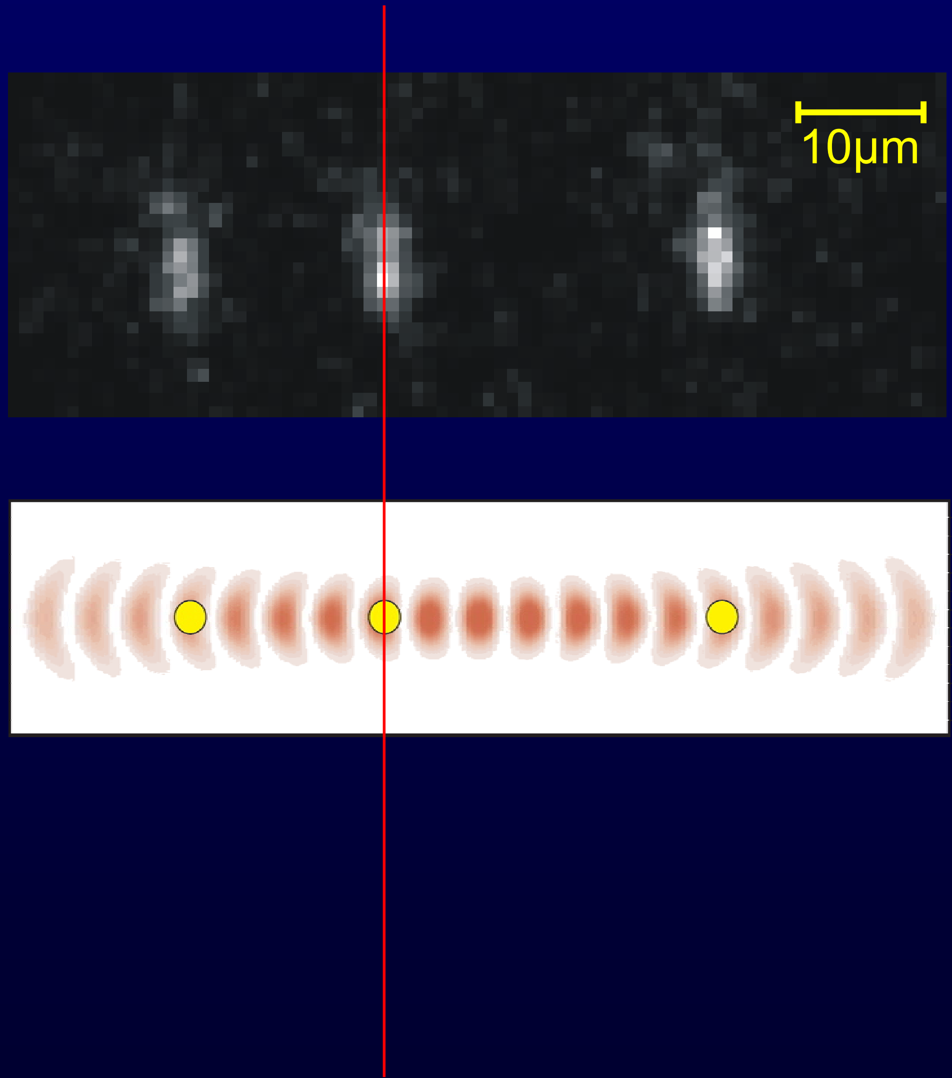
# 2. A Neutral Atom Quantum Register




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



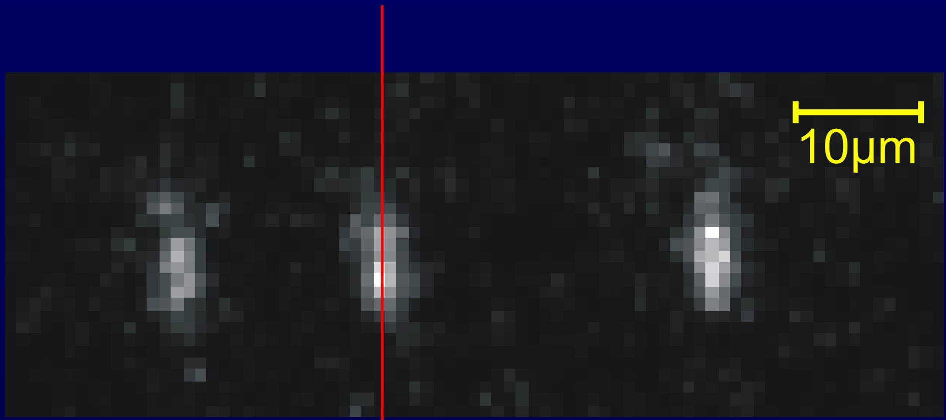
# 2. A Neutral Atom Quantum Register

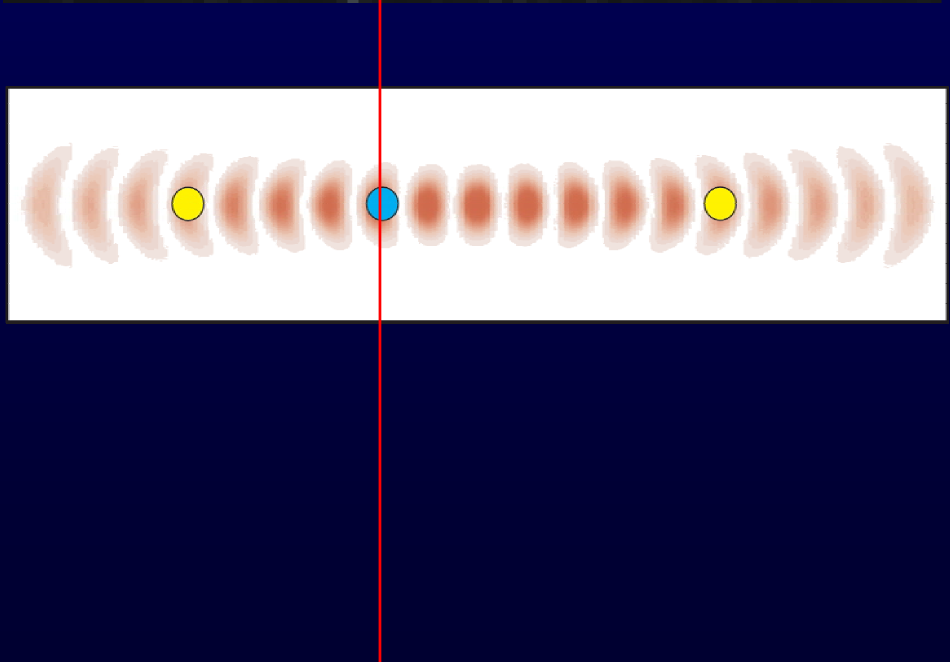



- take camera picture
- determine position of all atoms
- calculate resonance frequency of center atom

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

# 2. A Neutral Atom Quantum Register

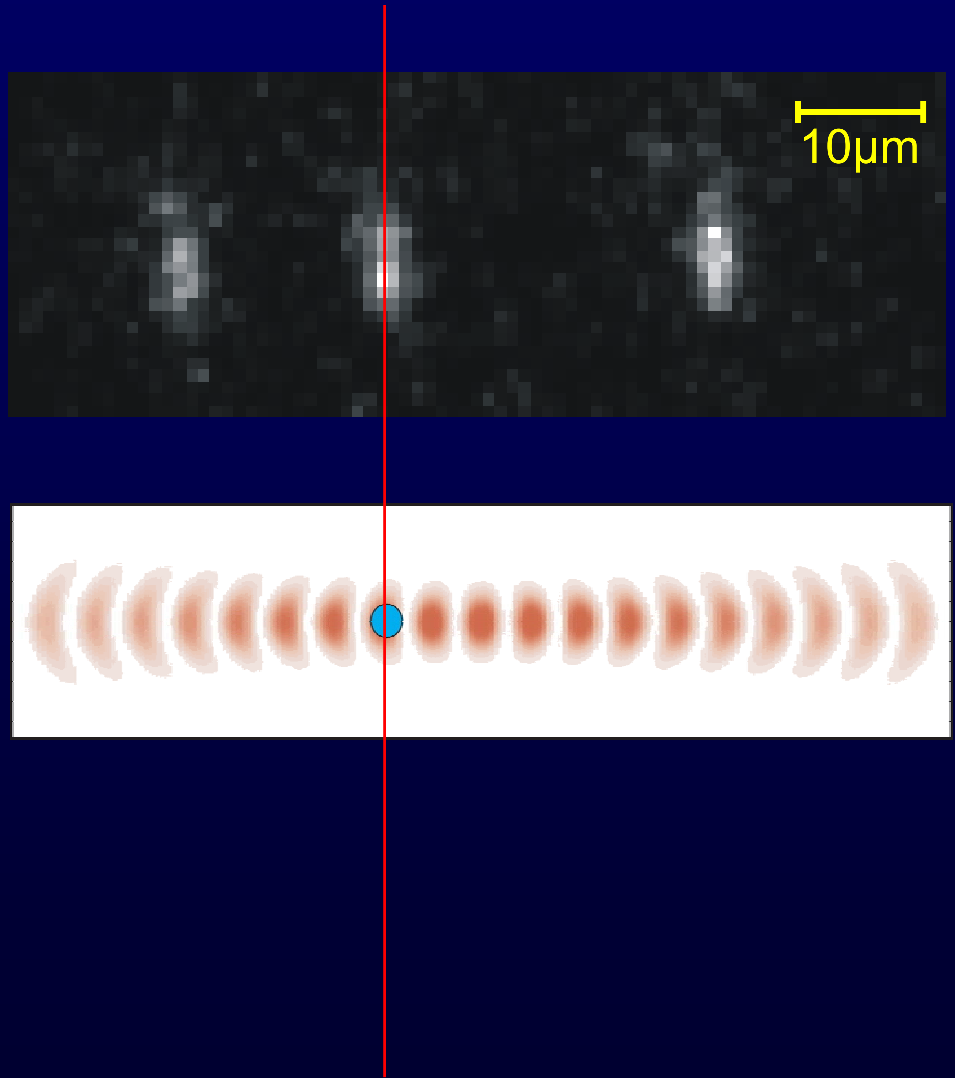


- take camera picture
- determine position of all atoms
- calculate resonance frequency of center atom

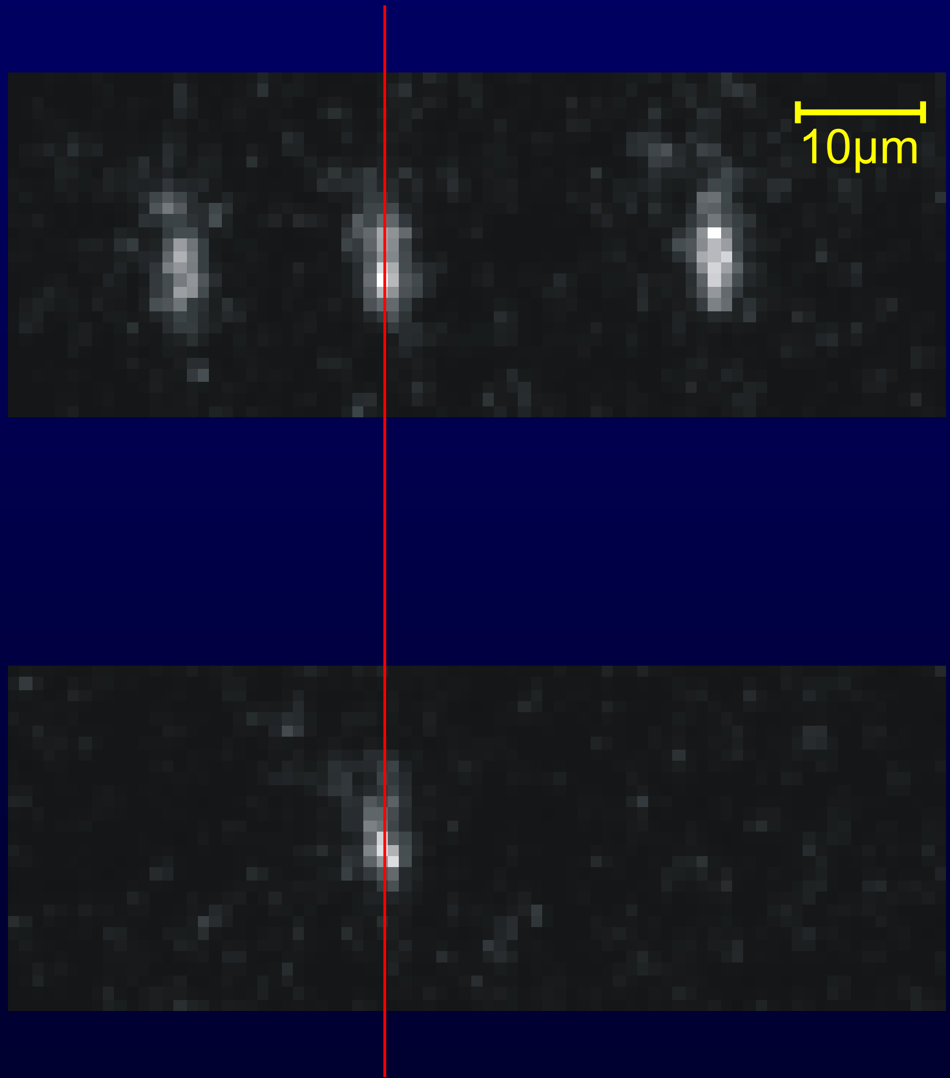
- prepare atoms in $| F = 4, m_F = -4 >$
- apply microwave pulse

# 2. A Neutral Atom Quantum Register




- 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

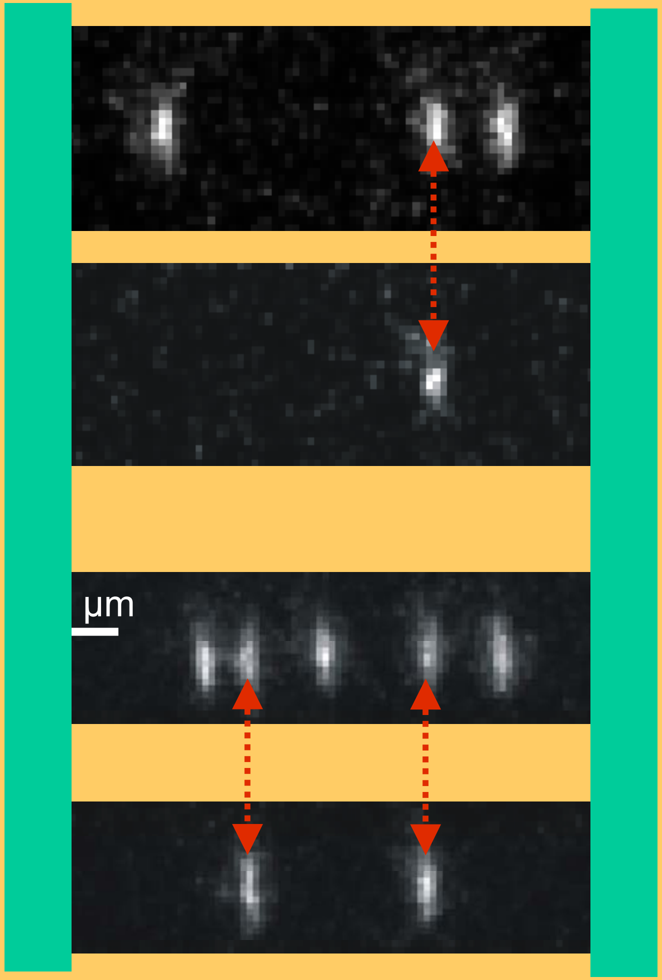
# 2. A Neutral Atom Quantum Register




- 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 → F=3
- apply push-out laser
- take camera picture

# 2. A Neutral Atom Quantum Register

some typical pictures



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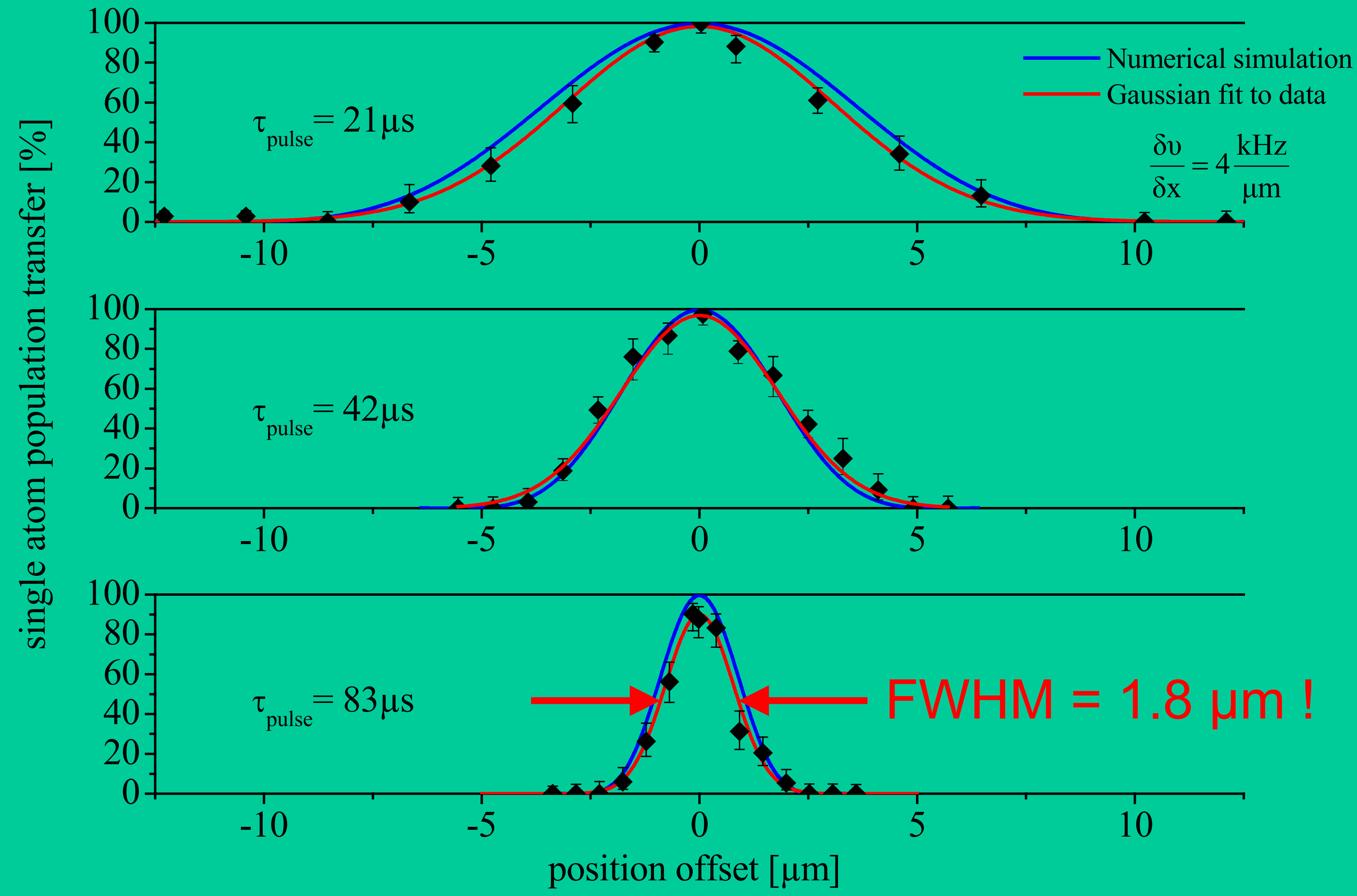

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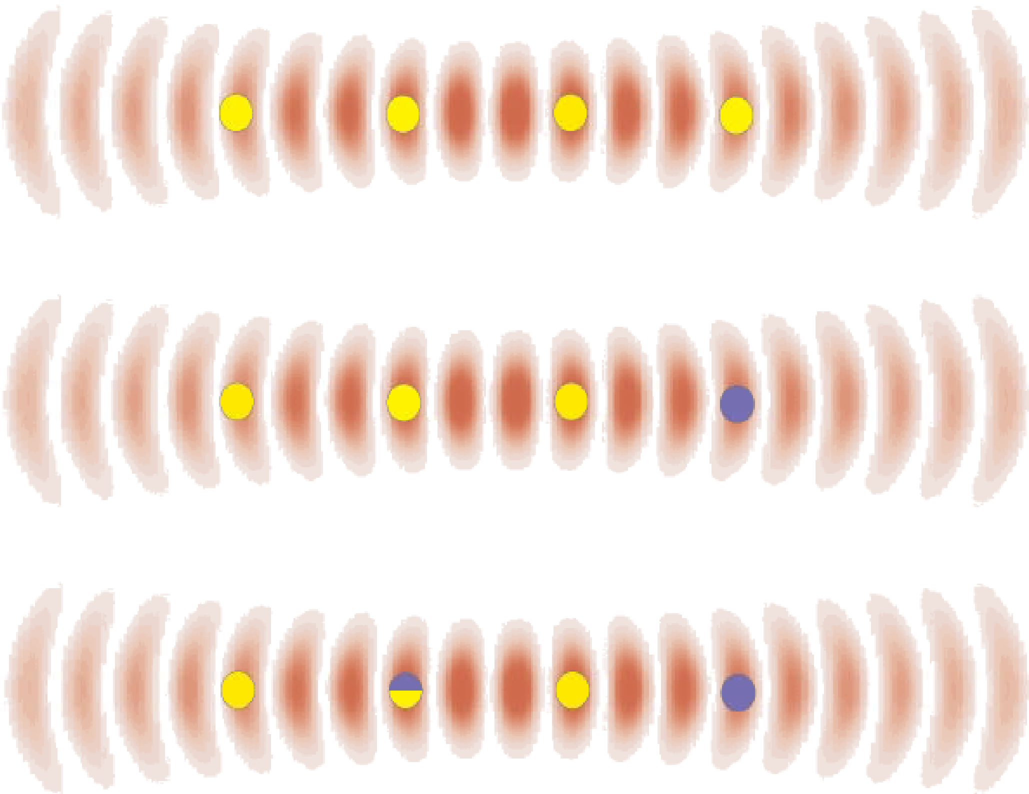


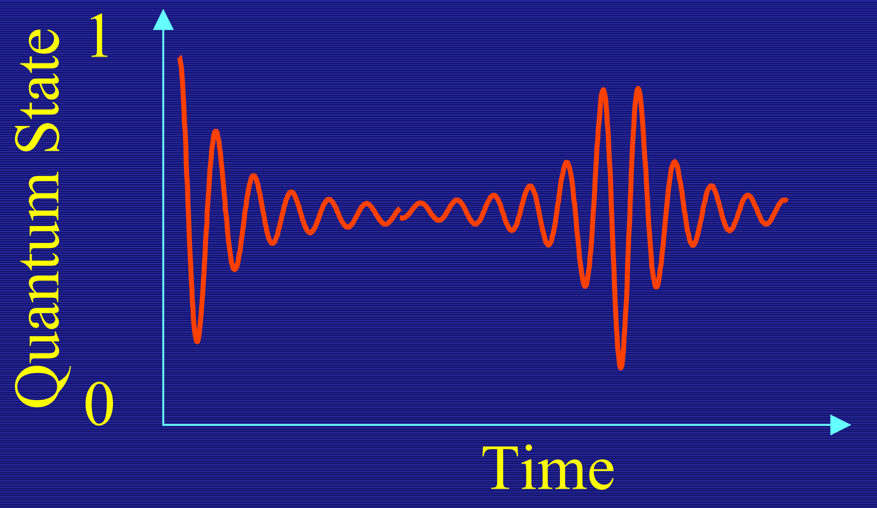
$$|0\rangle|0\rangle|0\rangle|0\rangle$$

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

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

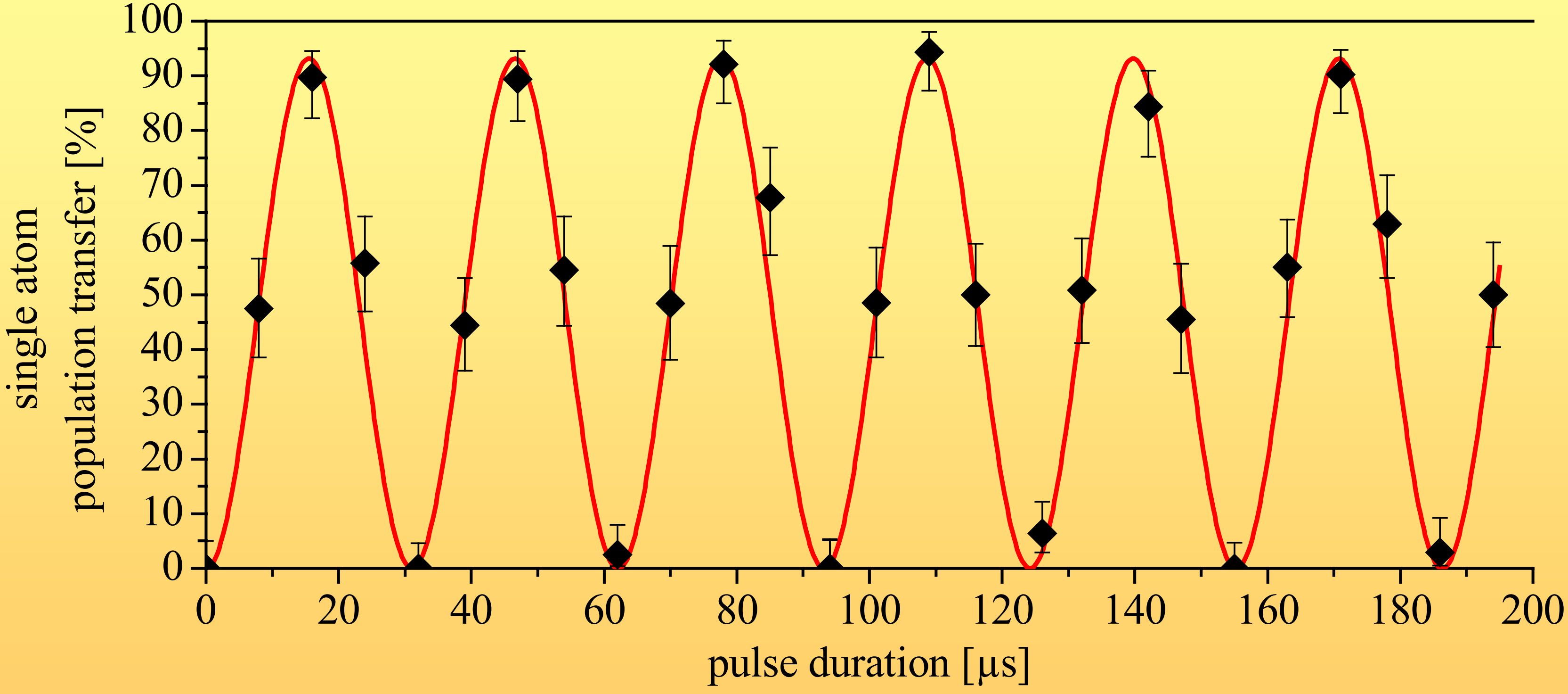
## Overview

3. Coherent Atom Manipulation

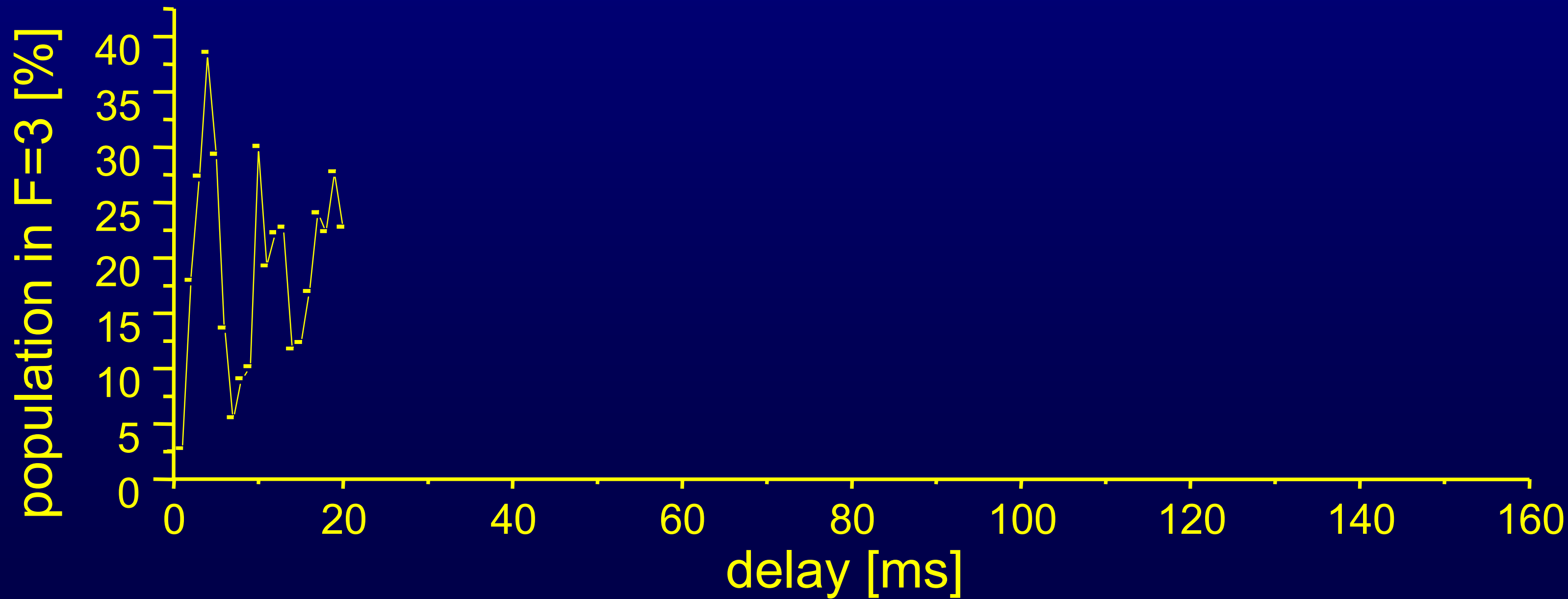


# 3. Coherent Atom Manipulation

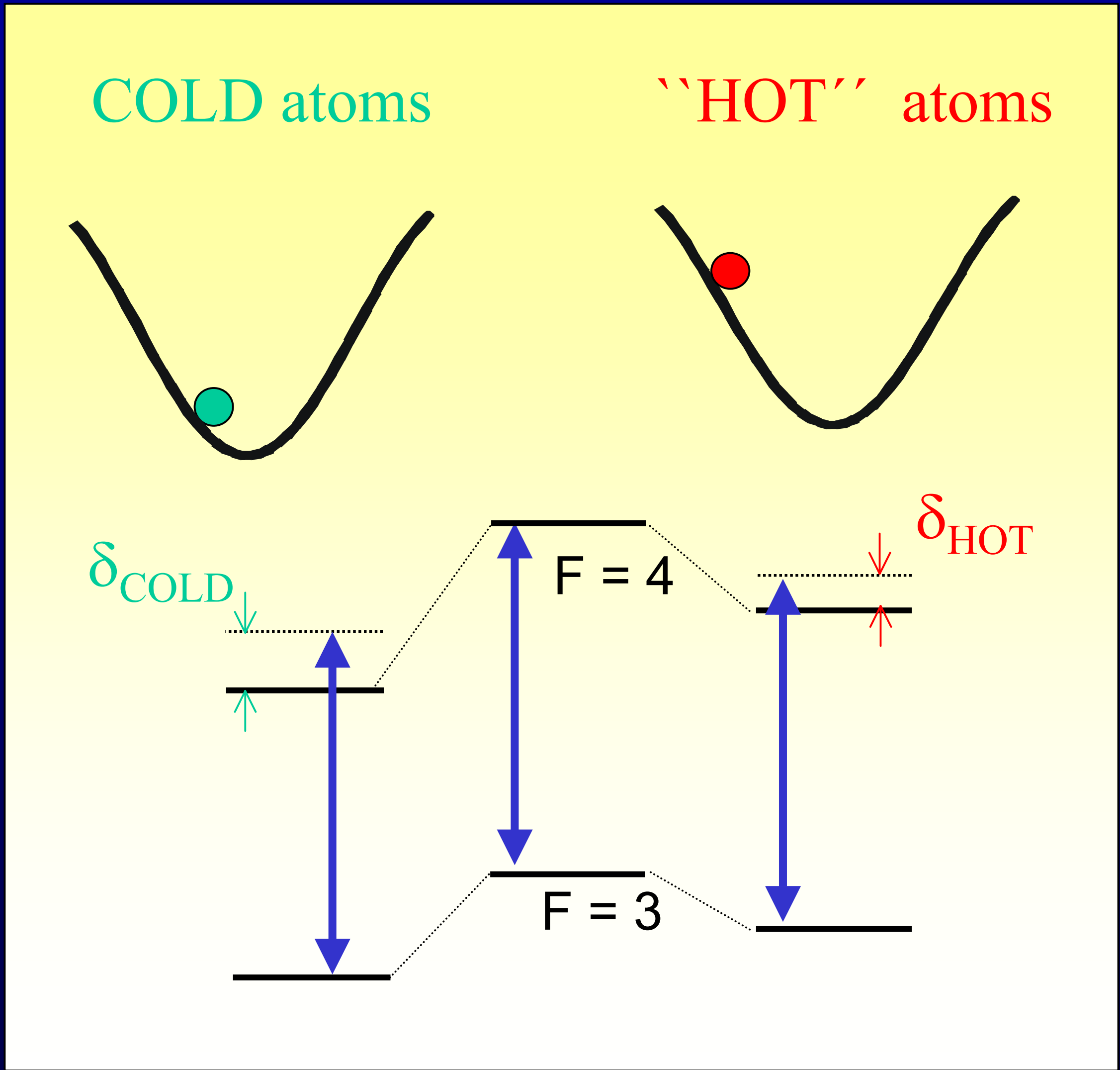
## Driven Rabi-Oscillation

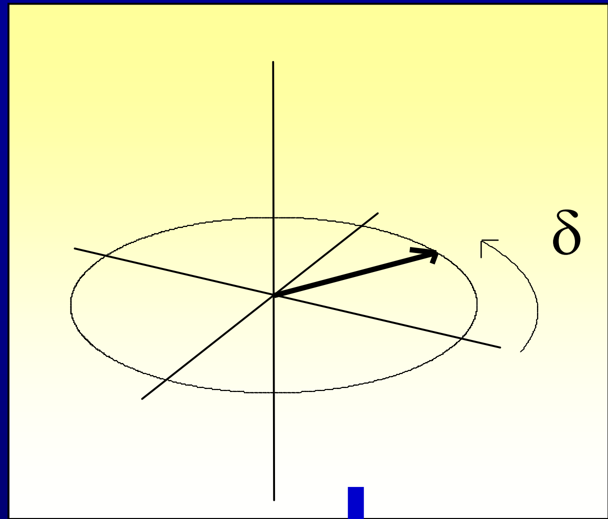


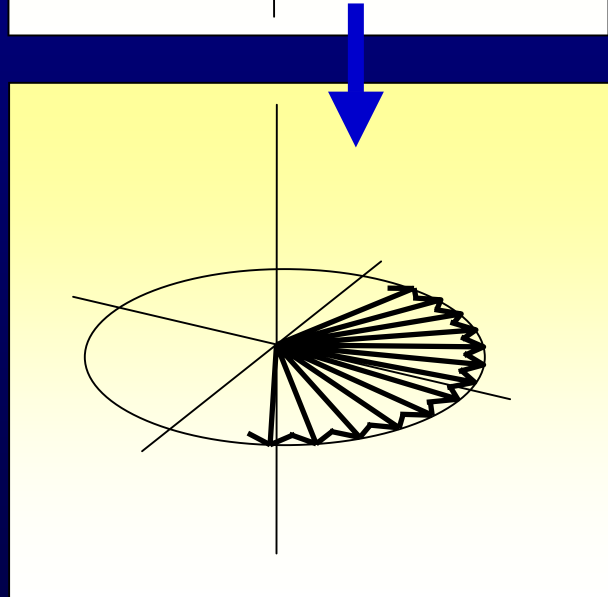
# 3. Coherent Atom Manipulation

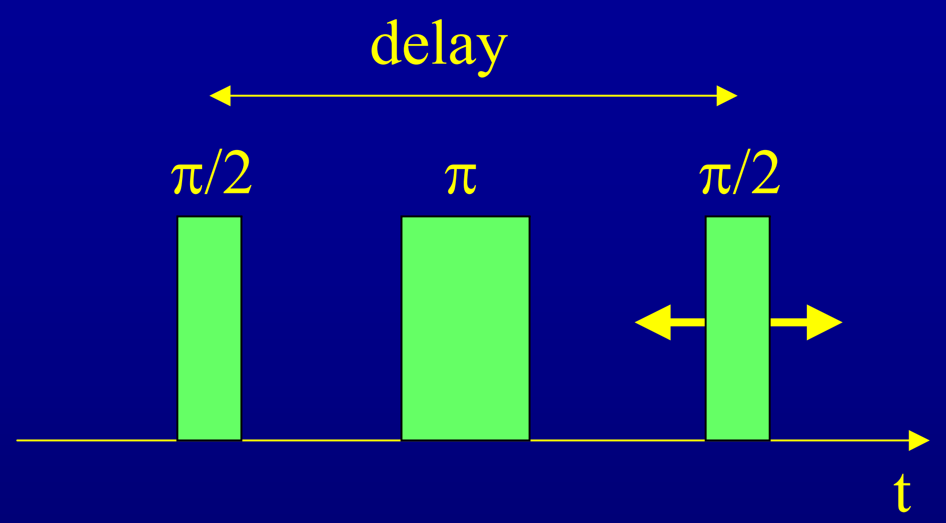
# 3. Coherent Atom Manipulation

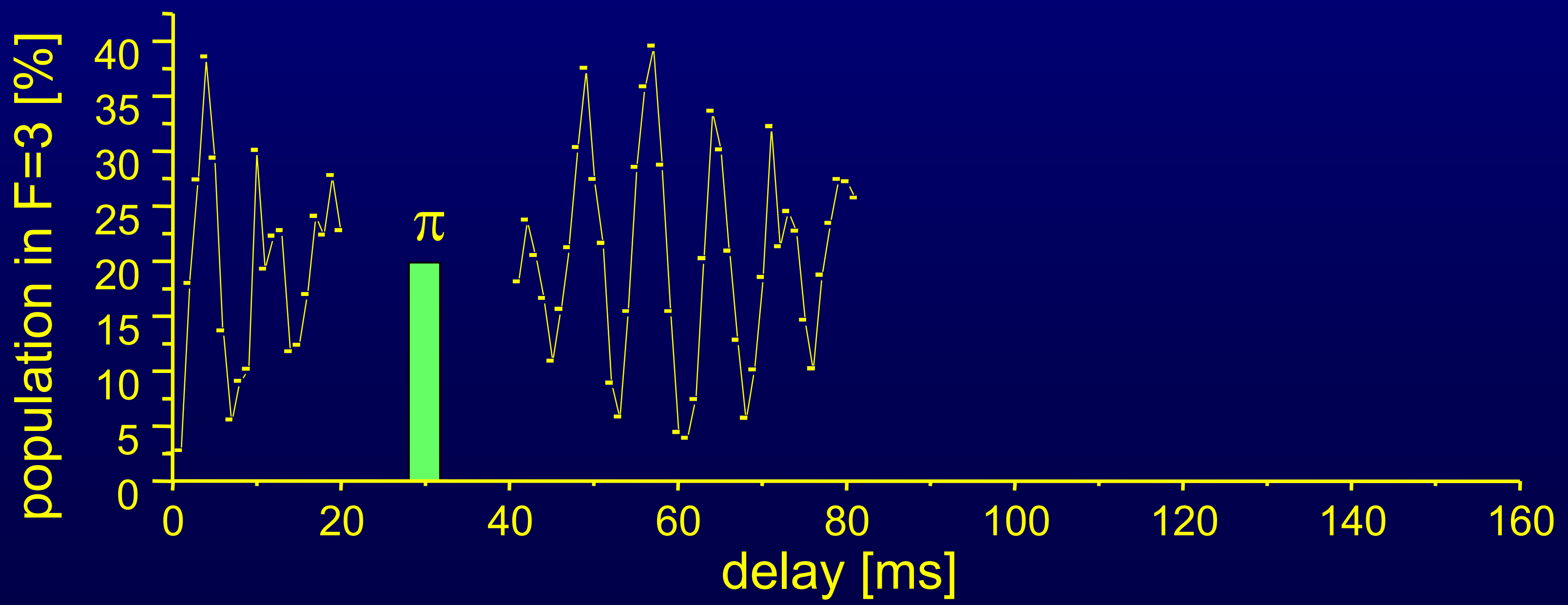


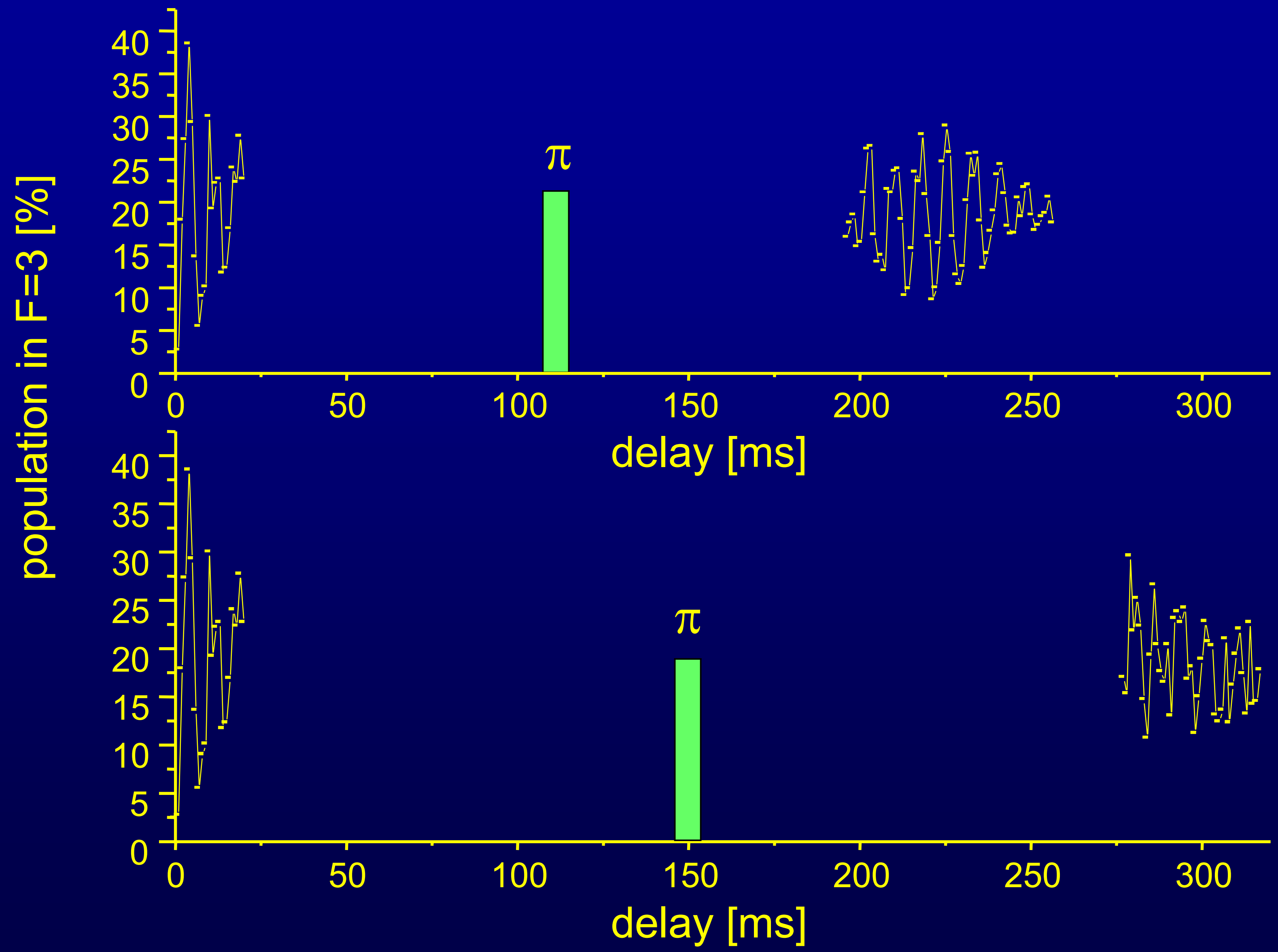



# 3. Single Qubit Operations

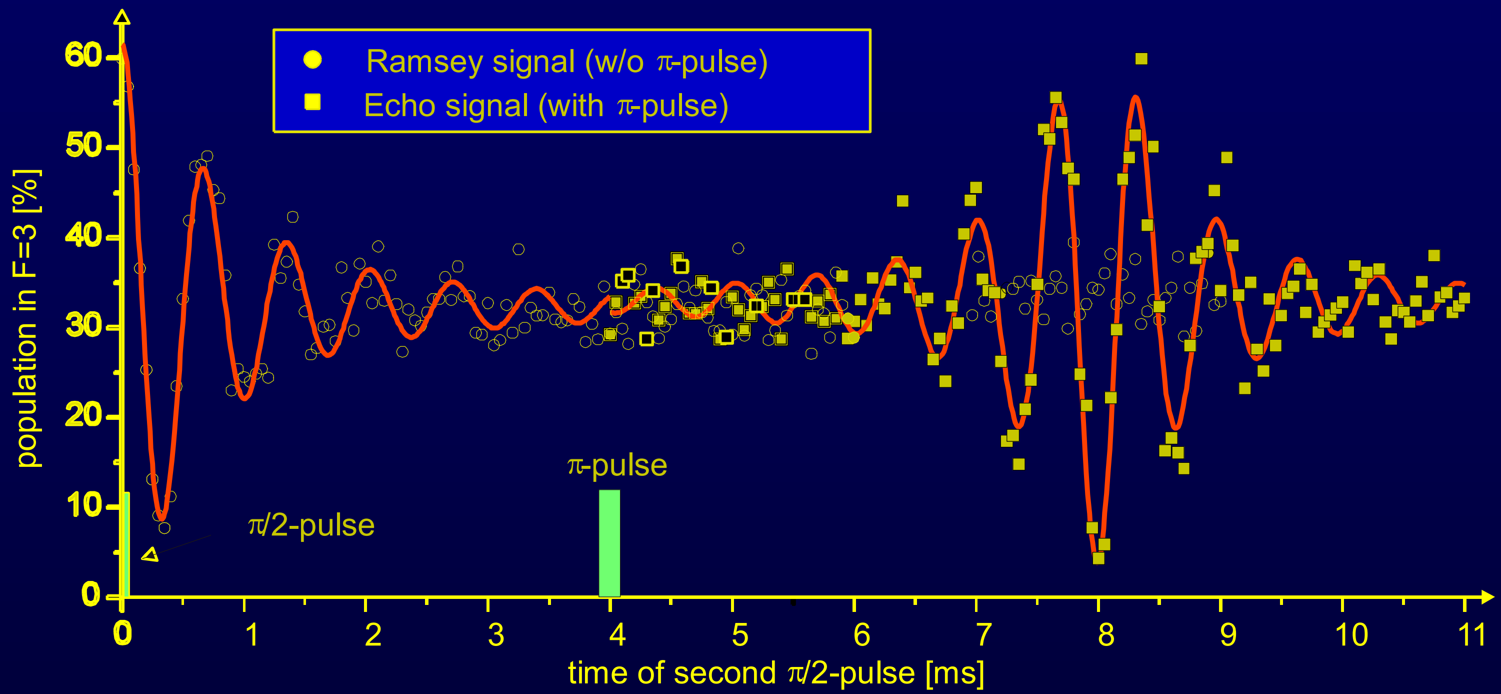


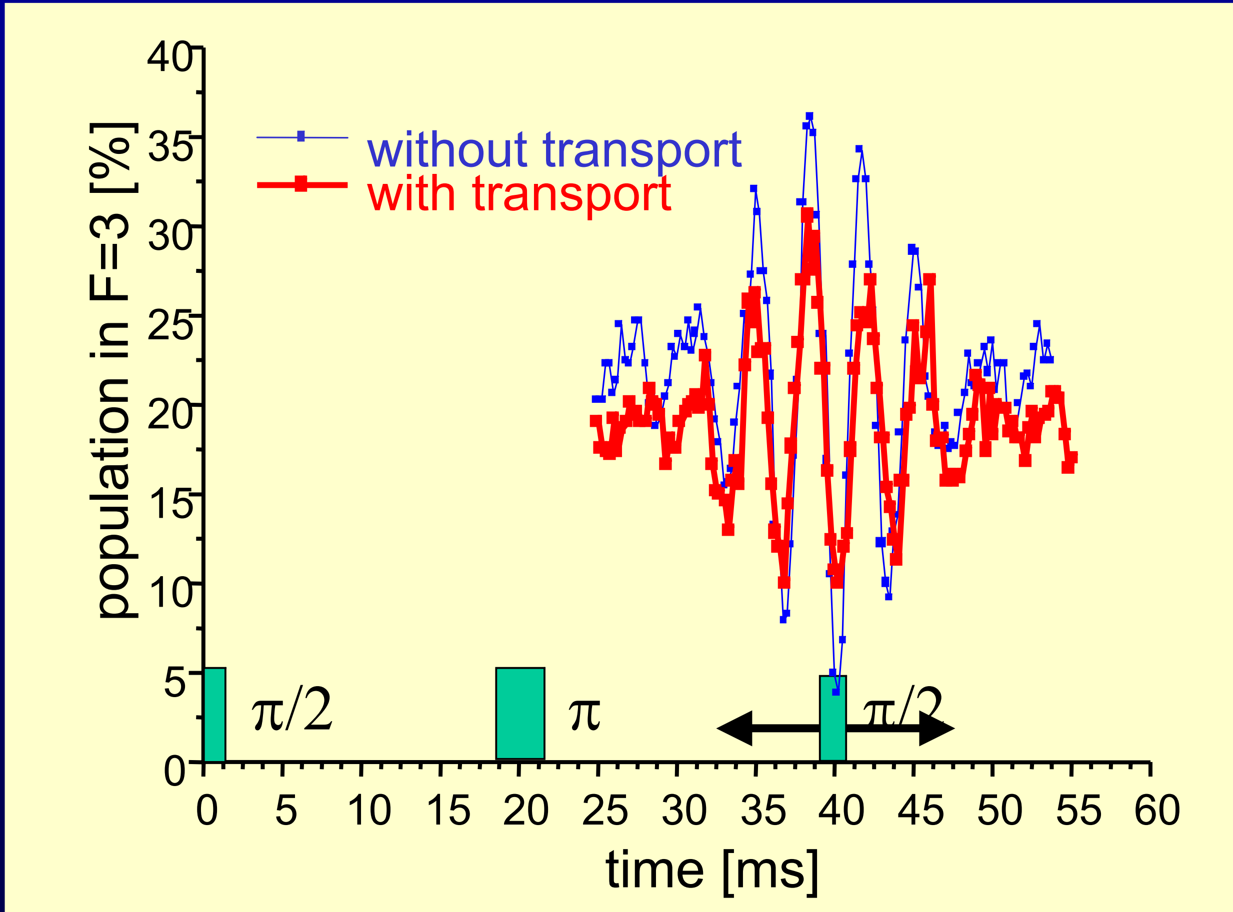
# 3. Coherent Atom Manipulation



# 3. Coherent Atom Manipulation



# 3. Coherent Atom Manipulation



# 3. Coherent Atom Manipulation

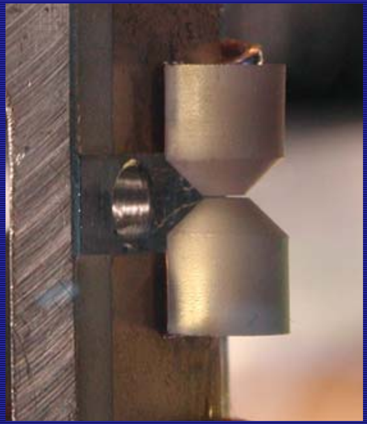
## Controlling neutral atoms:

Table 1: *Measured hyperfine relaxation times of atoms in our dipole trap*

| $T_{\text{relax}}$ | $U_{\max}/k$ (ms) | $m_F$ | Value | Limiting mechanism |
|---|---|---|---|---|
| $T_1$ | 1 | 0, −4 | 8.6 s | spontaneous Raman scattering |
| $T_2^*$ | 0.1 | 0 | 3 ms | thermal motion, scalar light shift |
| | 0.04 | 0 | 19 ms | thermal motion, scalar light shift |
| | 0.1 | −4 | 270 $\mu$s | thermal motion, vector light shift |
| $T_2'$ | 0.1 | 0 | 34 ms | beam pointing instability |
| | 0.04 | 0 | 150 ms | beam pointing instability |
| | 0.1 | −4 | 2 ms | without gradient: thermal motion, vector light shift |
| | 0.1 | −4 | 600 $\mu$s | with gradient: thermal motion, inhomogeneous magnetic field |

# Overview

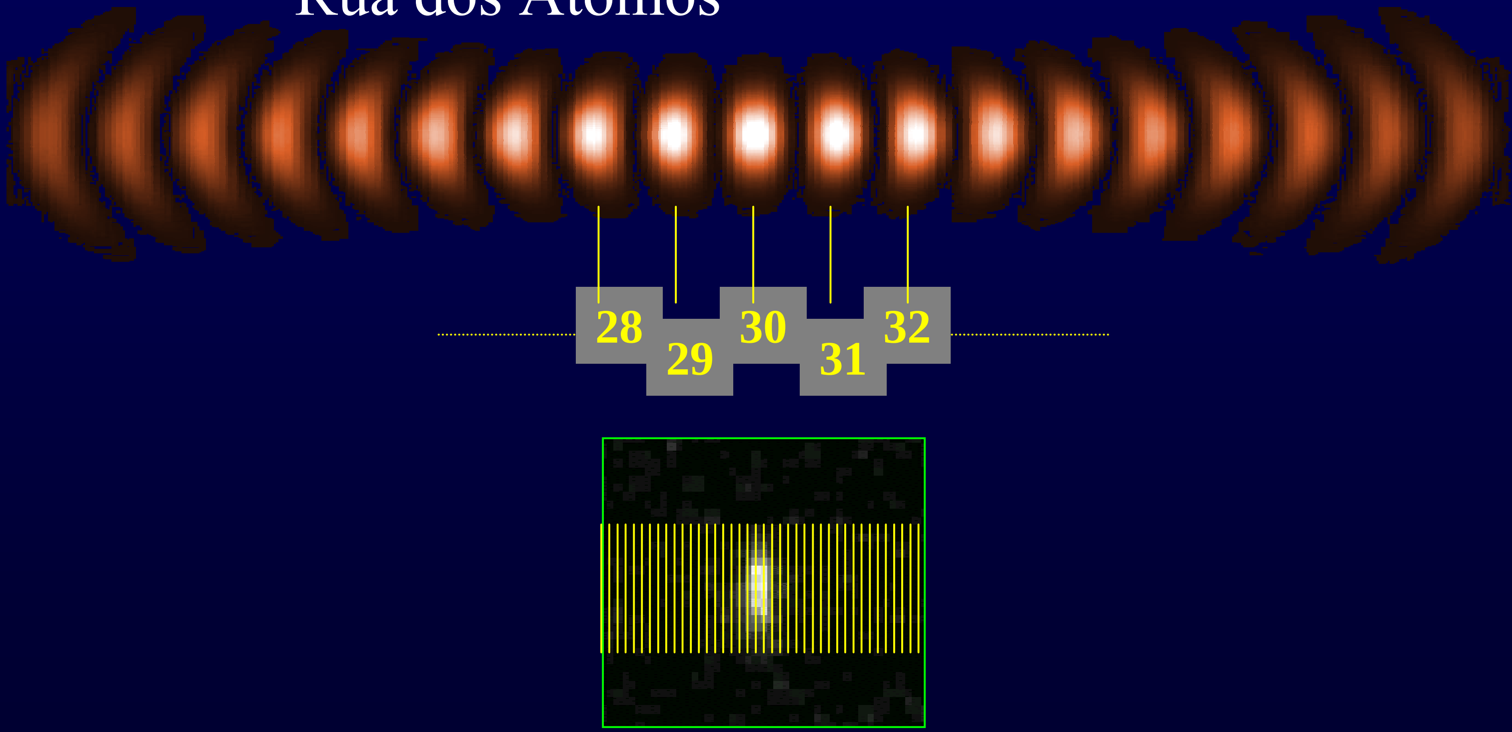
4. The Future –
   towards Entanglement



# We need better position control:

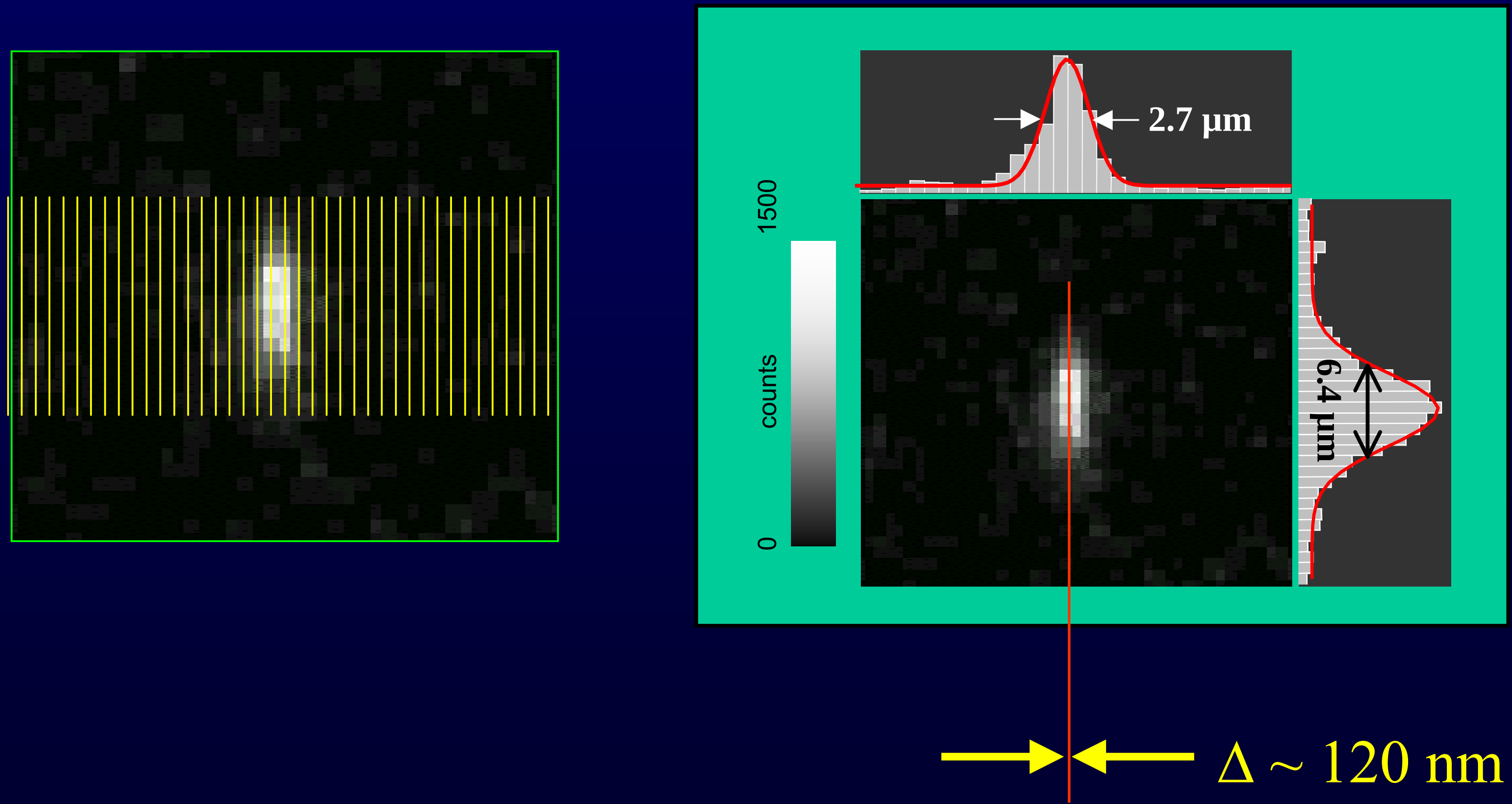
## Measuring the „house number“ of the atom

Rua dos Atomos



# We need perfect position control:

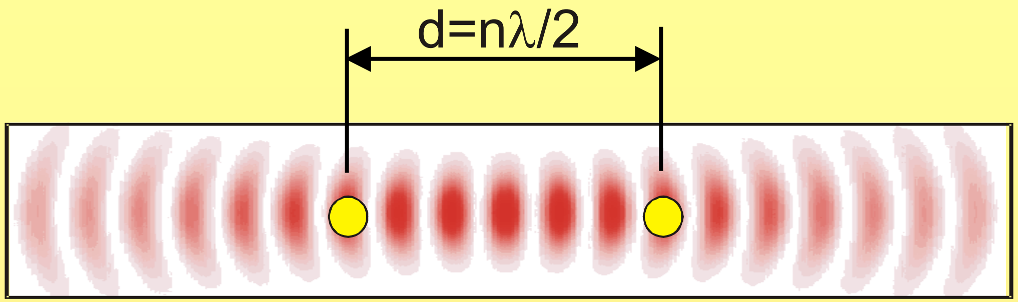
## Measuring the „house number“ of the atom

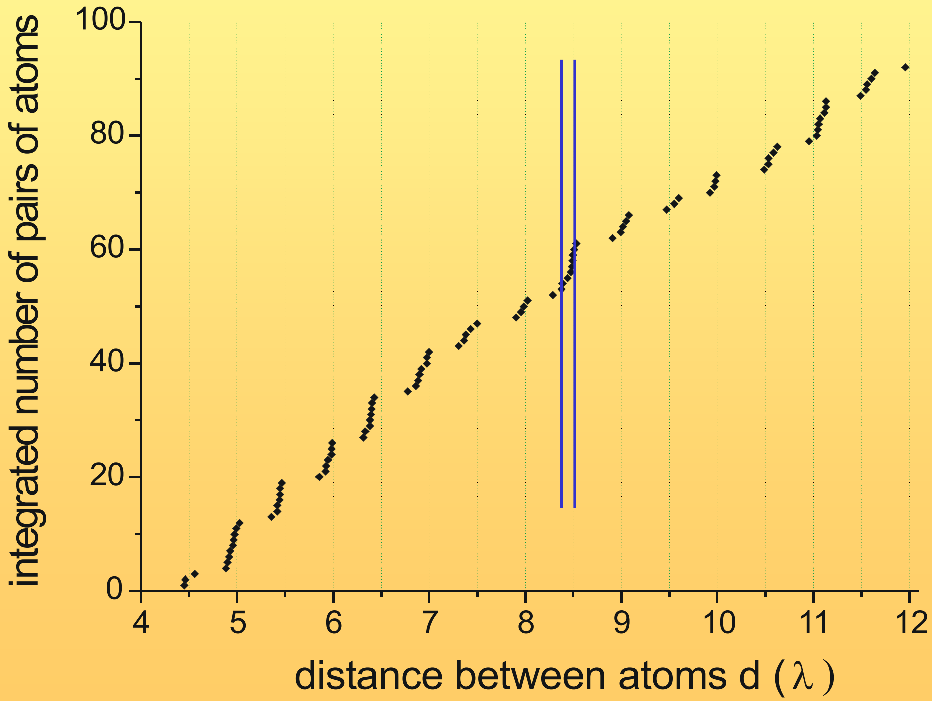



$\Delta \sim 120$ nm

(Limit: 1s int.-time, drifts)

# 4. Towards Entanglement



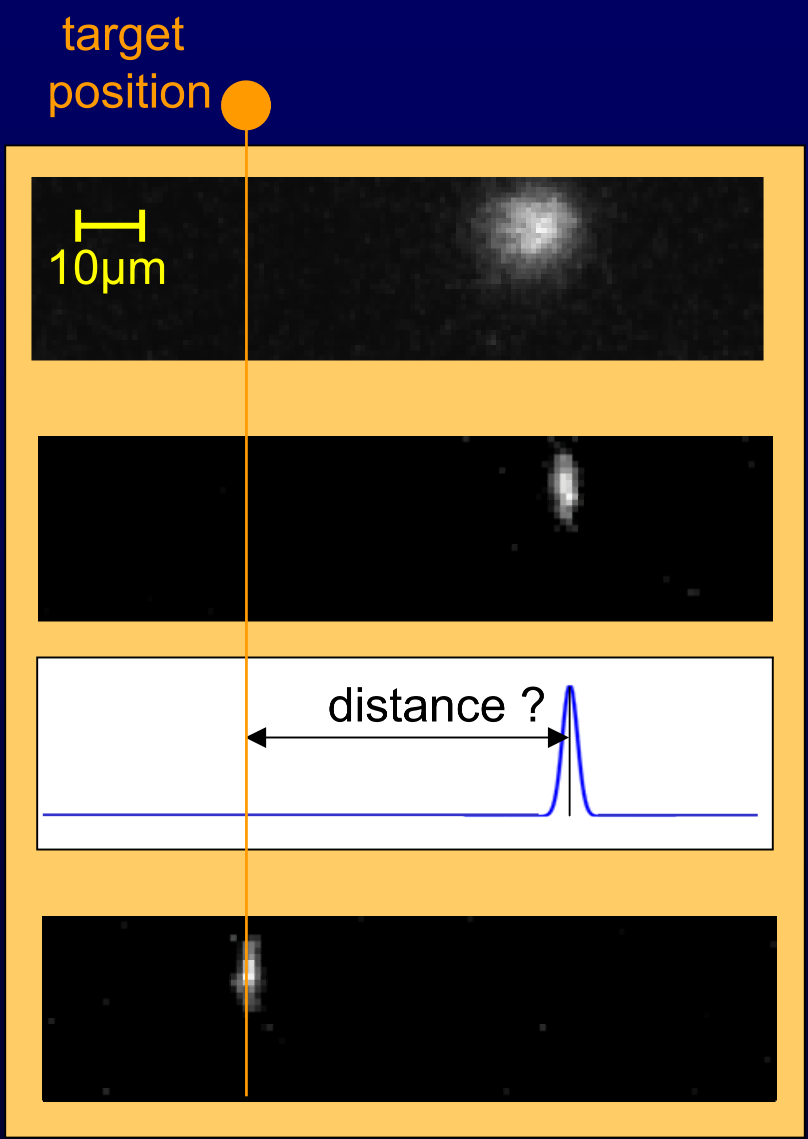

$\Delta \sim 55$ nm

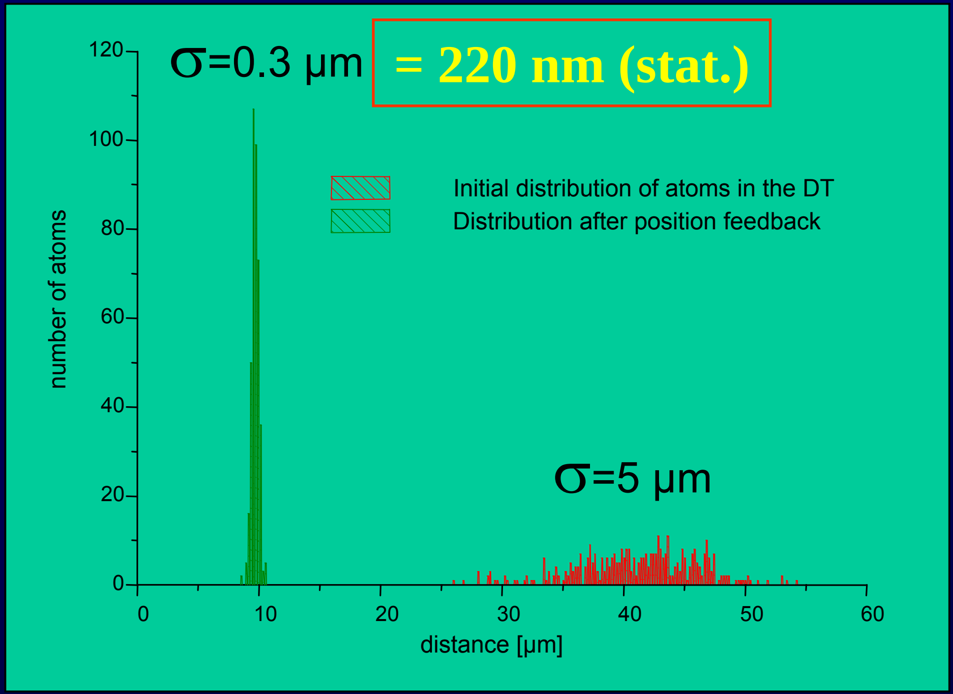
**Extension of wave-packet:**

$\Delta \sim 35\text{-}50$ nm

**→ Fundamental limit!**

# 4. Towards Entanglement



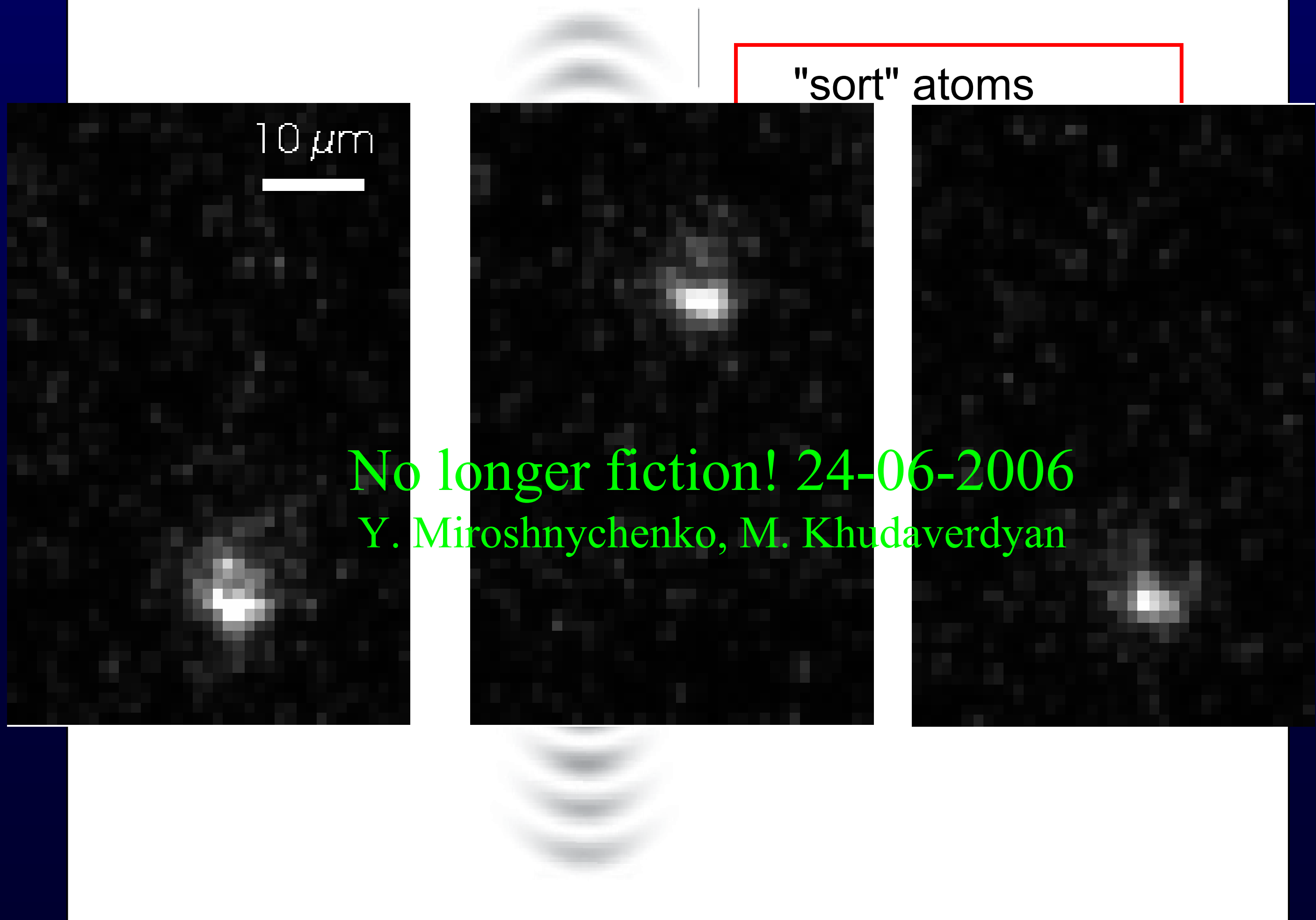




"position control"

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

# 4. Towards Entanglement

**Two perpendicular conveyor-belts**

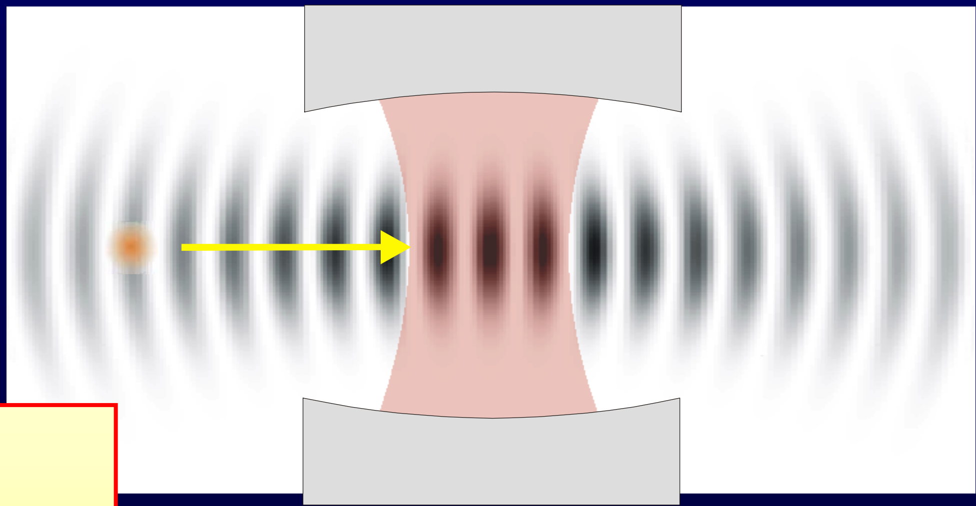



No longer fiction! 24-06-2006

Y. Miroshnychenko, M. Khudaverdyan

# 4. Towards Entanglement

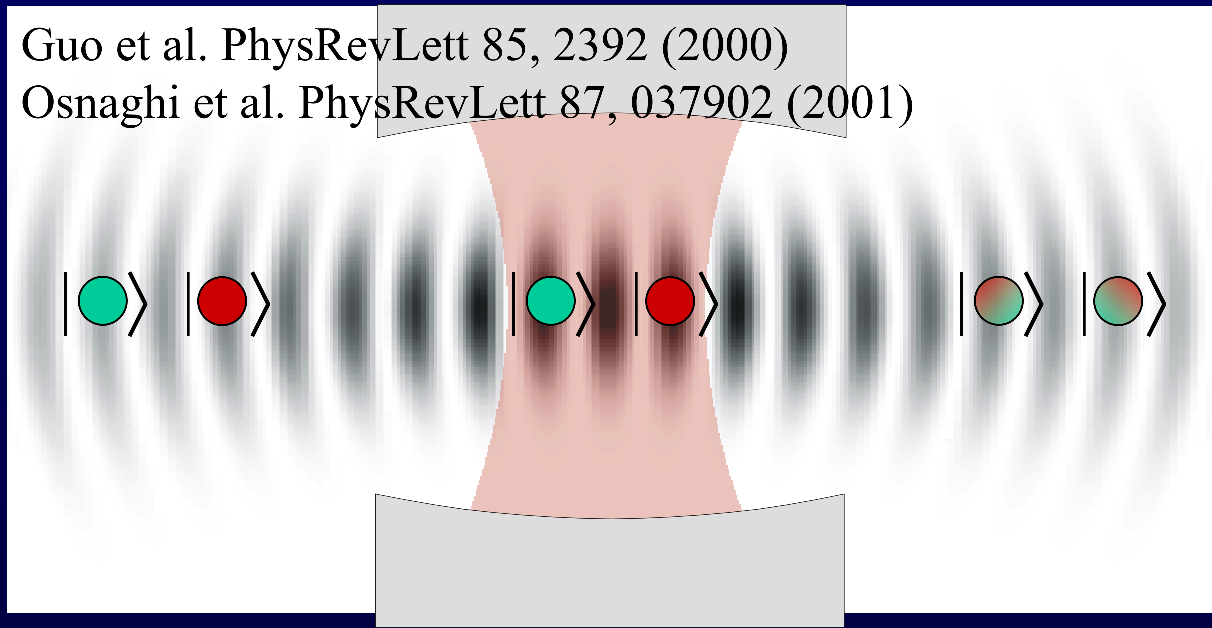
**"Conveyor Belt"**

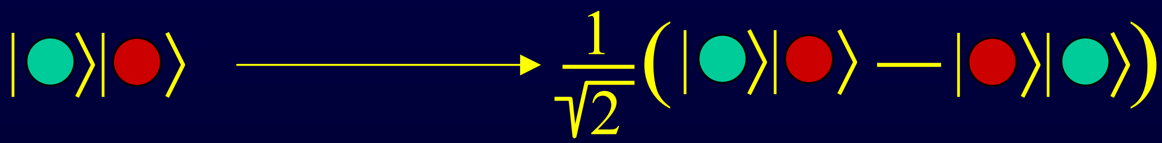


Delivery of atoms
**ON DEMAND** !!

1, 2, 3, ... Atoms
0, 1, 2, ... Photons

# 4. Towards Entanglement



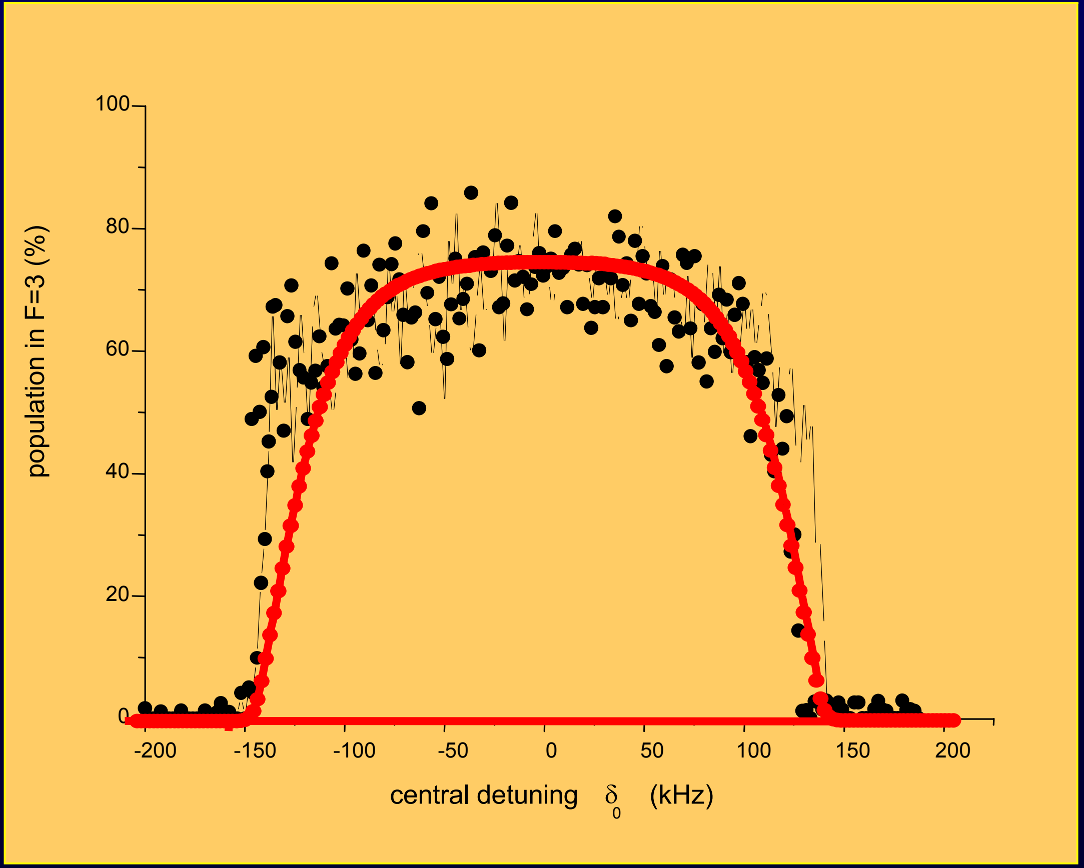
**Creation of entangled and fully controlled atoms**

## Adressing individual atoms by adiabatic passage

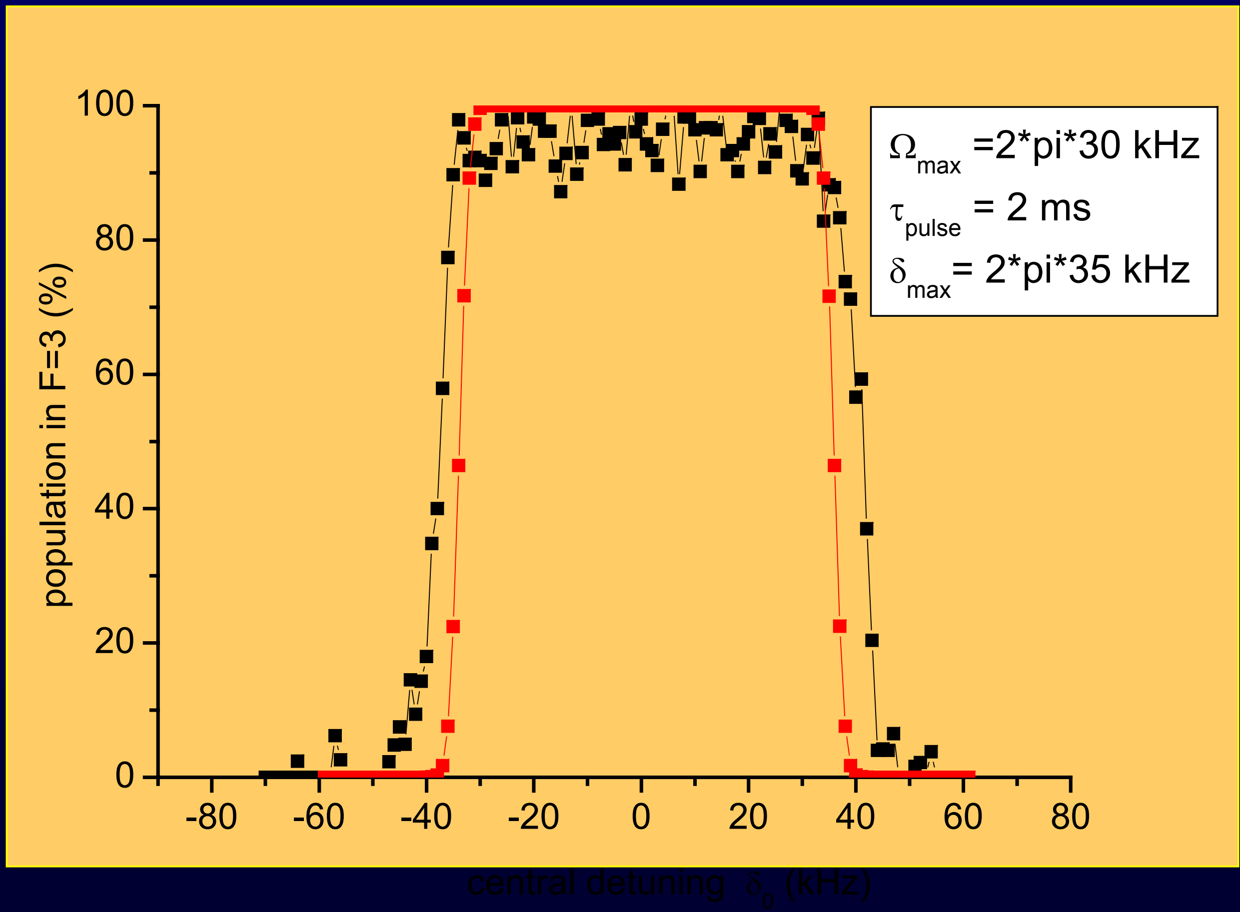
1. **Choose center frequency of frequency sweep**
2. **Magnetic field gradient for spatial discrimination**

# 3. Coherent Atom Manipulation

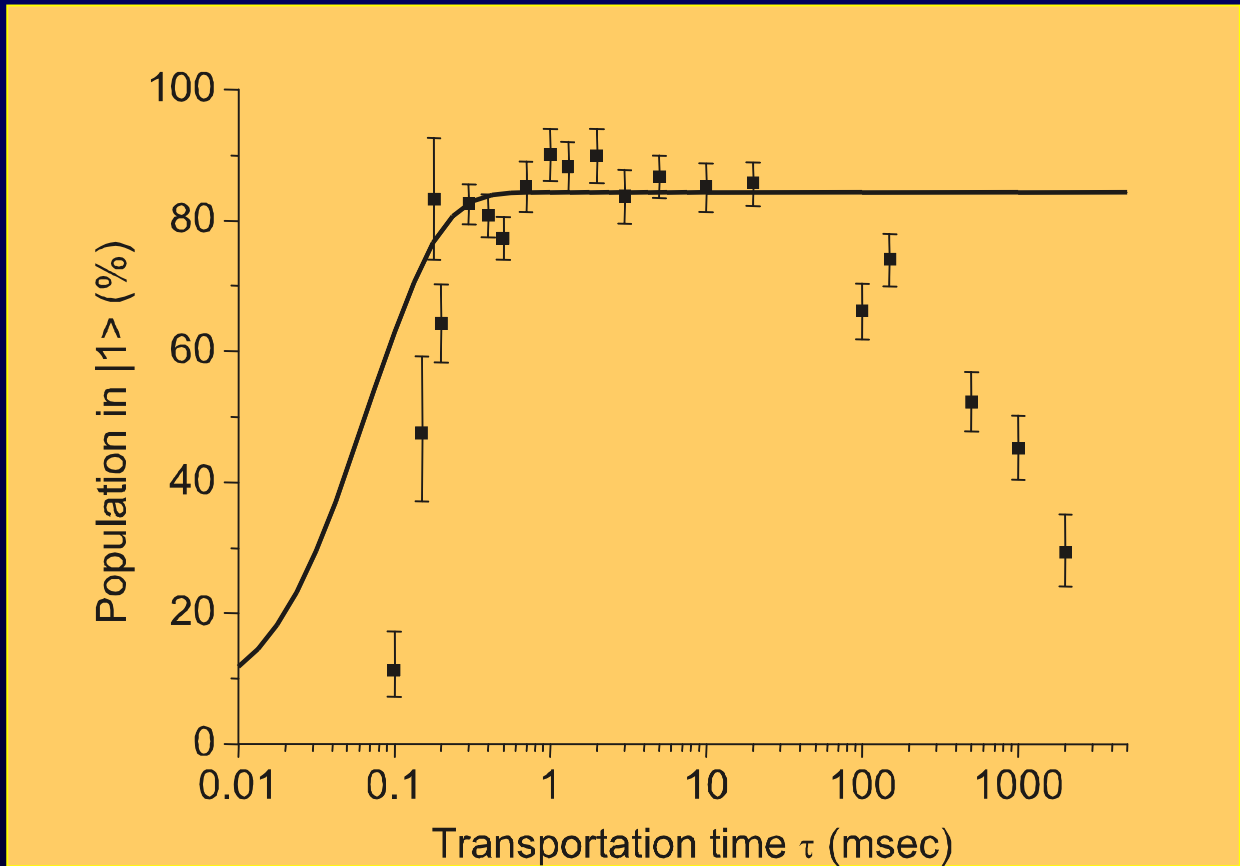
Adiabatic passage by **microwave sweep** 9.2 GHZ
(F=4, $m_F$=4 → F=5, $m_F$=5) →2003



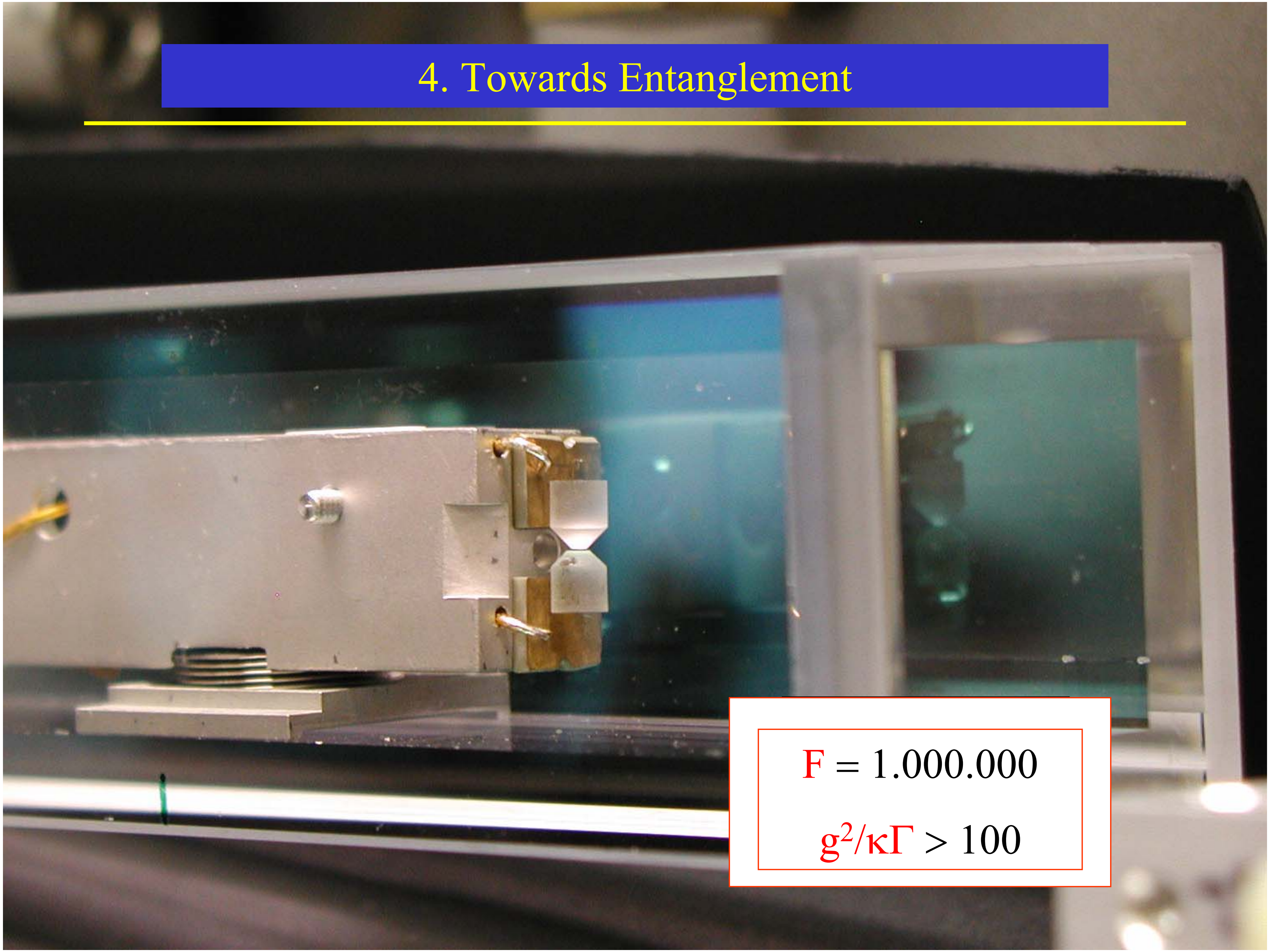
# microwave sweep, homogeneous B-field
# atom at rest → 2004



**microwave constant, inhomogeneous B-field**
**atom pulled through resonance, initially in**



# 4. Towards Entanglement

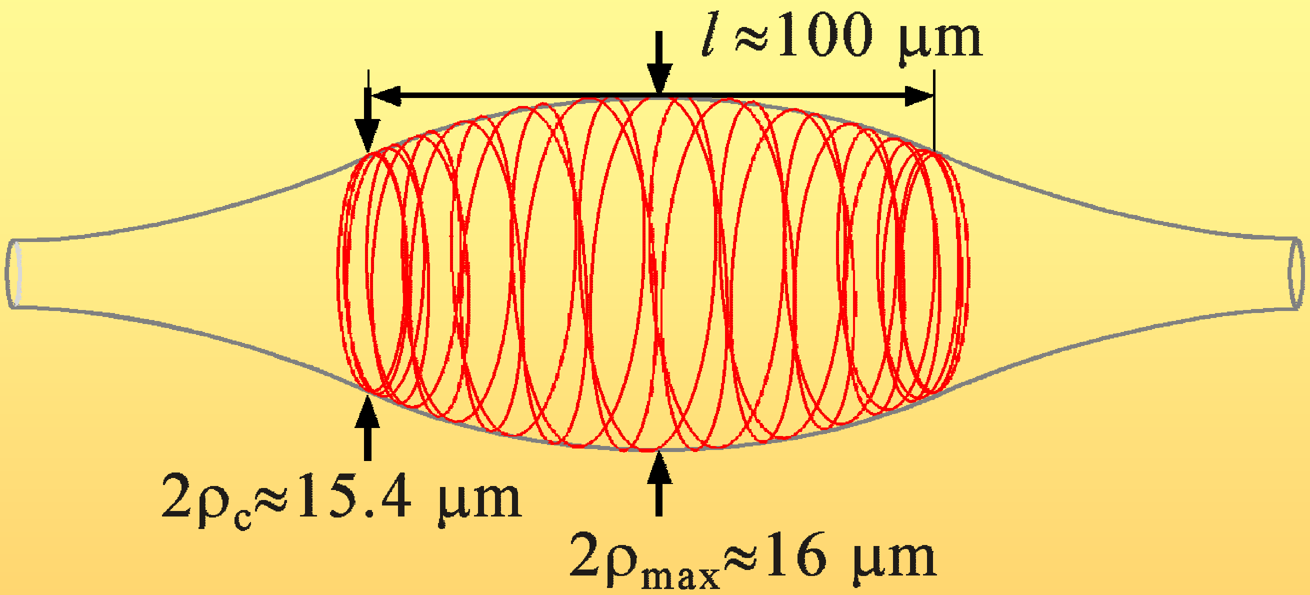


$F = 1.000.000$

$g^2/\kappa\Gamma > 100$

# 4. Towards Entanglement – with novel μ-cavities

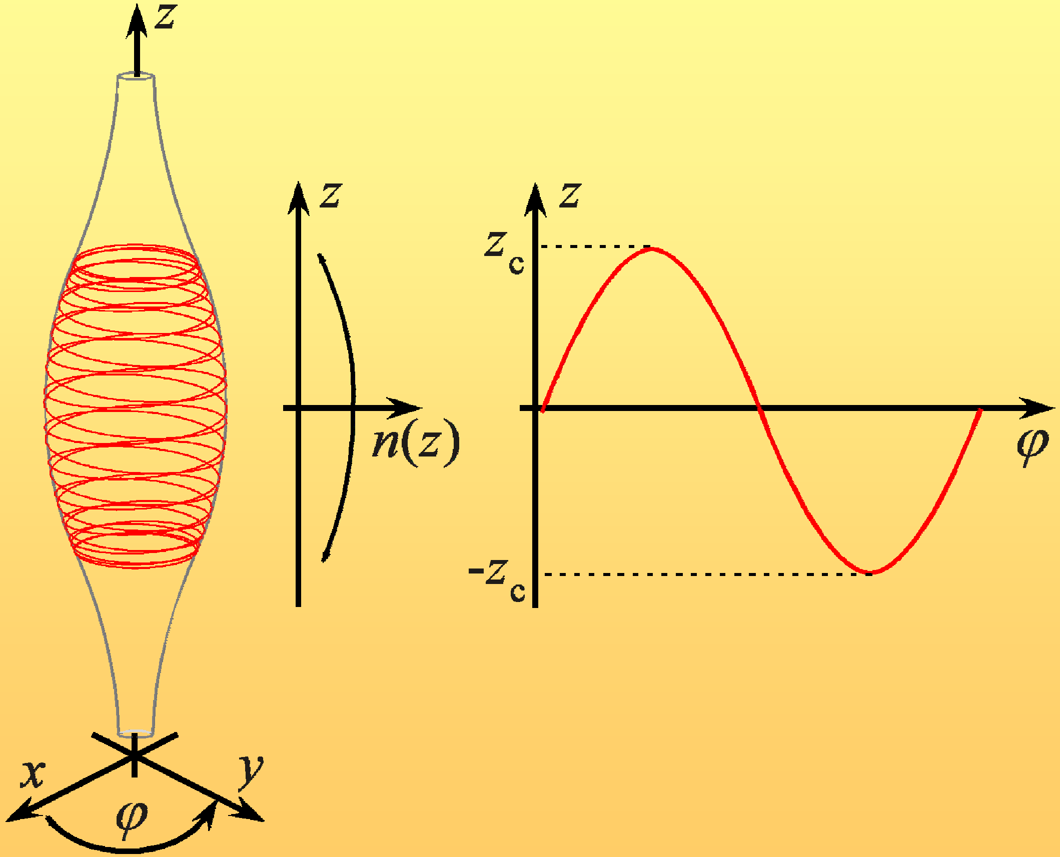
Alternative approach: "roller coaster" modes in a bulge on an optical fiber:




✓ high Q-factor, passively stable, small mode volume
✓ strain tunable, advantageous mode geometry

# 4. Towards Entanglement – with novel μ-cavities

- Describe thickness variation by refractive index gradient.
- Solve Eikonal equation in paraxial approximation.



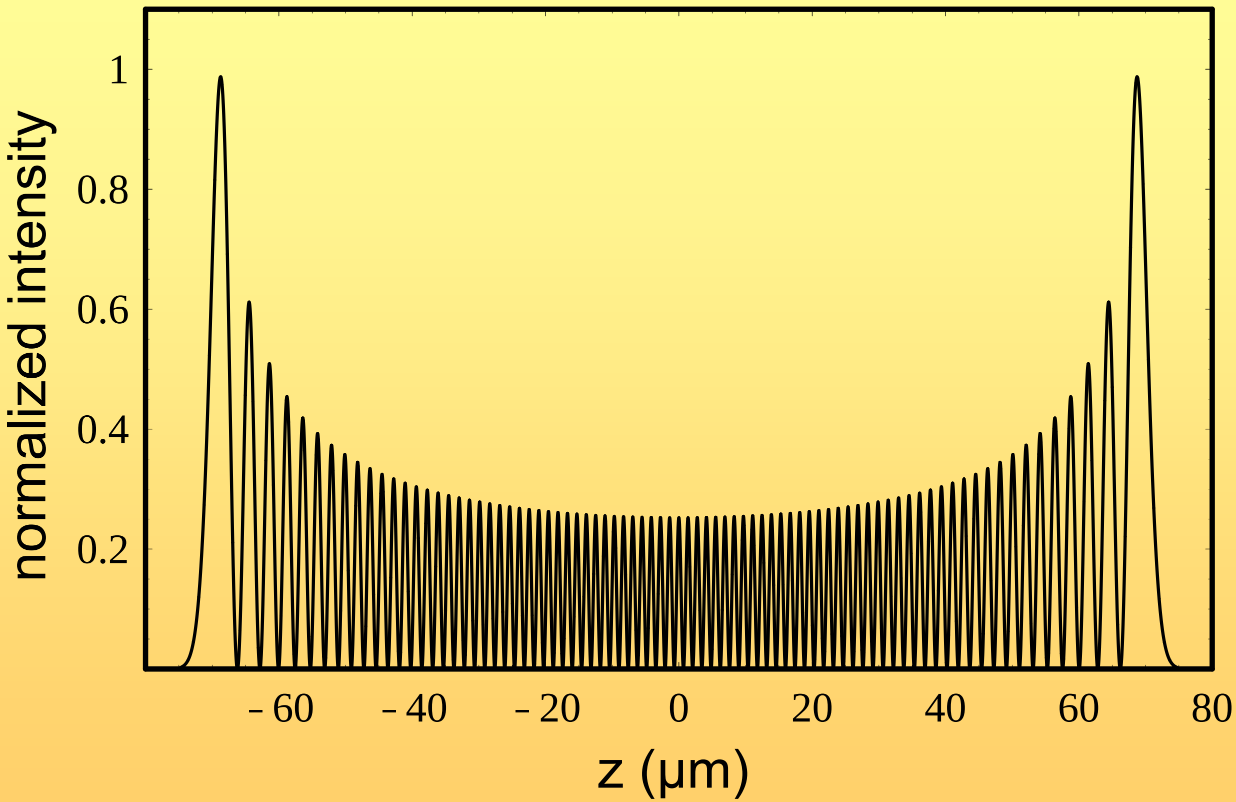

resonance condition:

$$L_{opt}(z_c) = N_{res}\lambda$$

FSR ≈ 100 GHz
for $2\ z_c$= 140 μm
and $\rho_{max}$= 8 μm

# 4. Towards Entanglement – with novel μ-cavities

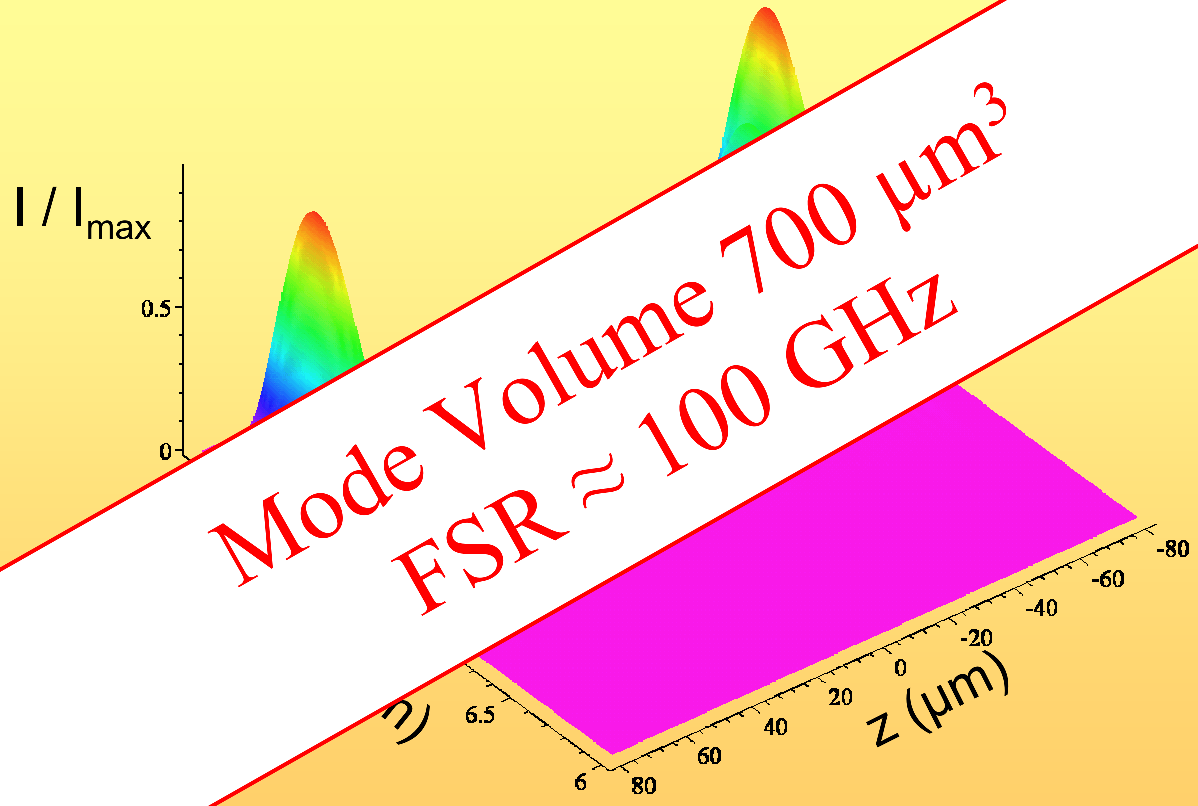
Intensity along *z* (TM mode, m = 84, p = 1, q = 80):




$\rho_{max}$ = 8 μm, $\rho_c = 0.96\ \rho_{max}$ , $\lambda$ = 852 nm, l = 140 μm,

# 4. Towards Entanglement – with novel μ-cavities

Intensity distribution (TM mode, m = 84, p = 1



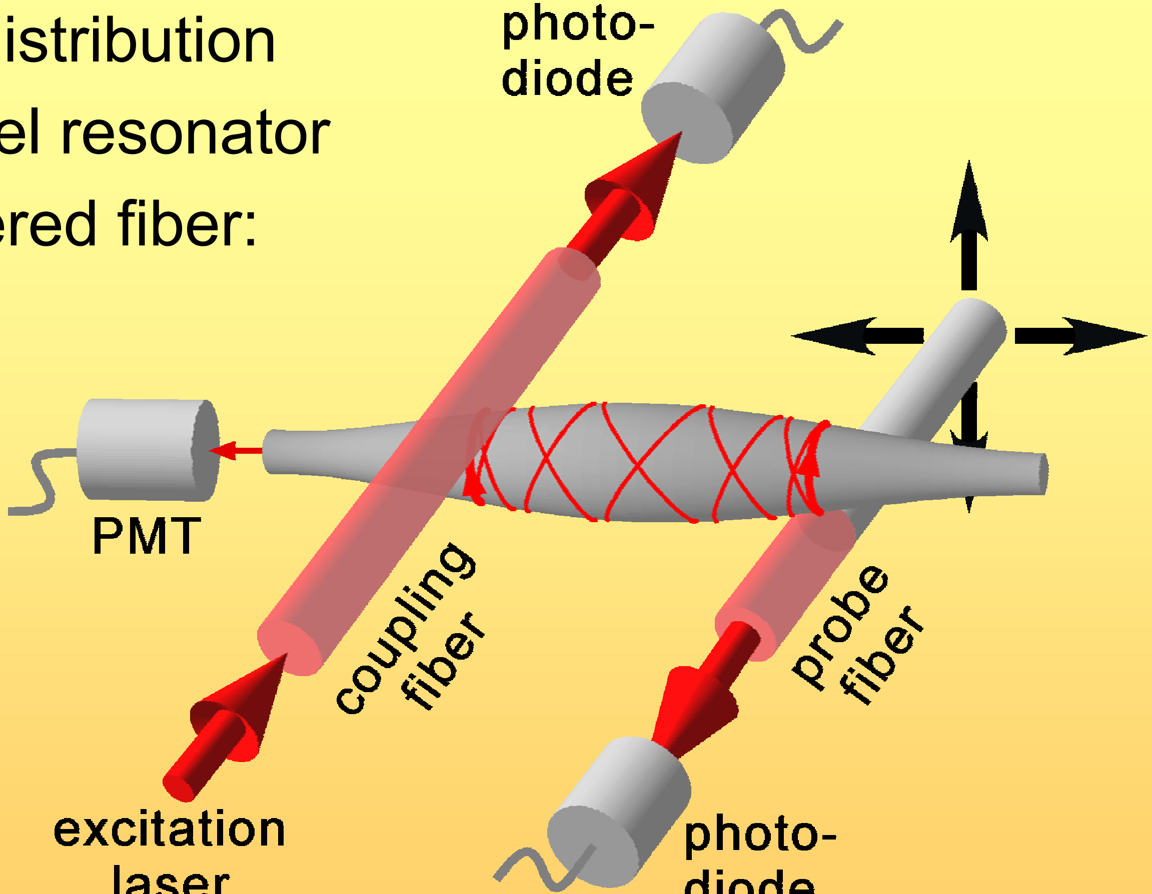

**Mode Volume 700 $\mu m^3$**

**FSR ≈ 100 GHz**

– 8 μm, $\rho_c = 0.96\ \rho_{max}$ , $\lambda$ = 852 nm, l = 140 μm,

# 4. Towards Entanglement – with novel μ-cavities

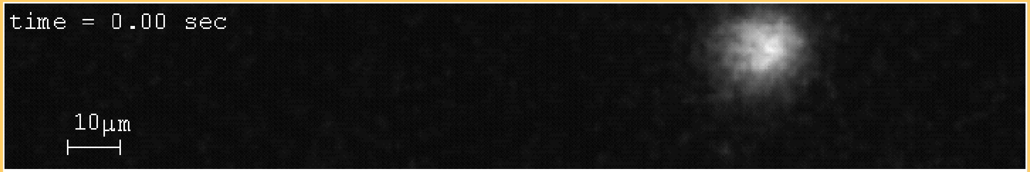
Probe intensity distribution of WGMs in barrel resonator with second tapered fiber:




coupling and probe fiber position have to be controlled on sub-μm scale

# The End

## Thank you for your attention!

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