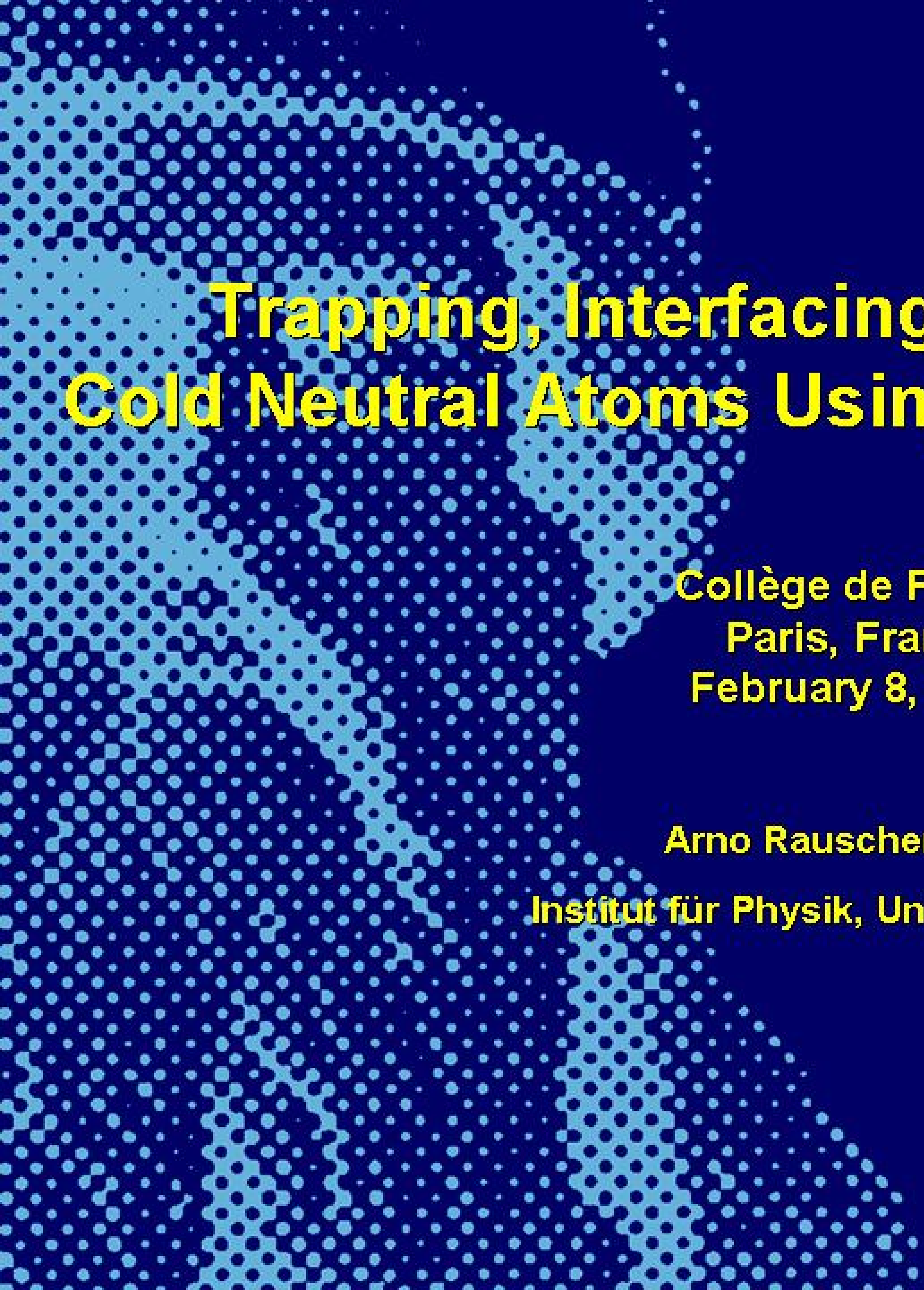

Trapping, Interfacing, and Conveying Cold Neutral Atoms Using Optical Nanofibers

Collège de France
Paris, France
February 8, 2010

Arno Rauschenbeutel

Institut für Physik, Universität Mainz

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GUTENBERG
UNIVERSITÄT
MAINZ

Introduction: Nano Quantum Optics

Goal:

Control of light–matter interaction using integrated nano-devices.

Motivation:

- Applications in research and technology (sensing, filters, switching, non-linear optics, cavity QED, etc.)
- Combine optical technologies and quantum physics for quantum communication & information processing.

Task:

Find suitable nano-devices to interface light & matter.

Introduction: Glass Fibers: “Backbone” of the Modern Communication Society

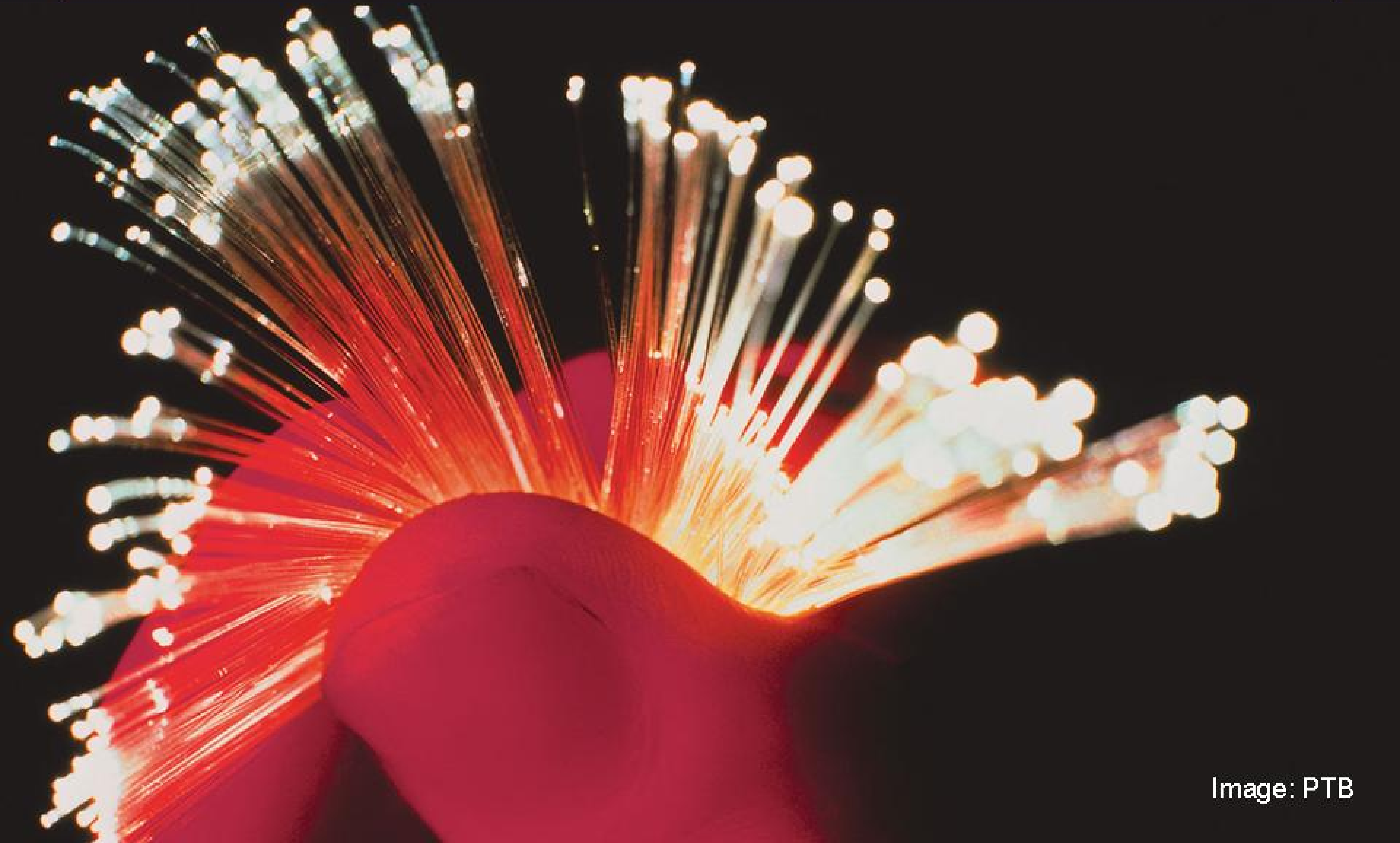
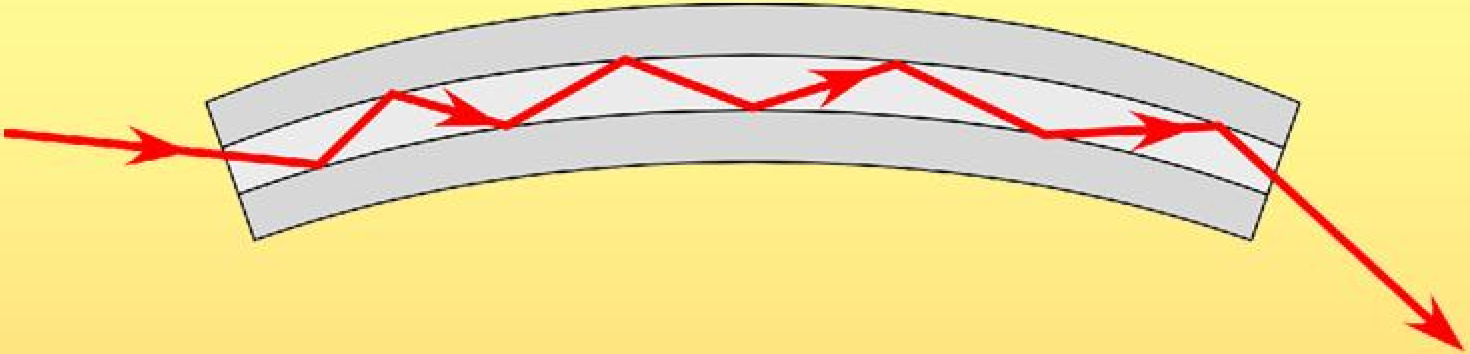


Image: PTB

Introduction: Tapered Fibers

- Problem: Light field in standard optical fibers cannot be accessed from outside.



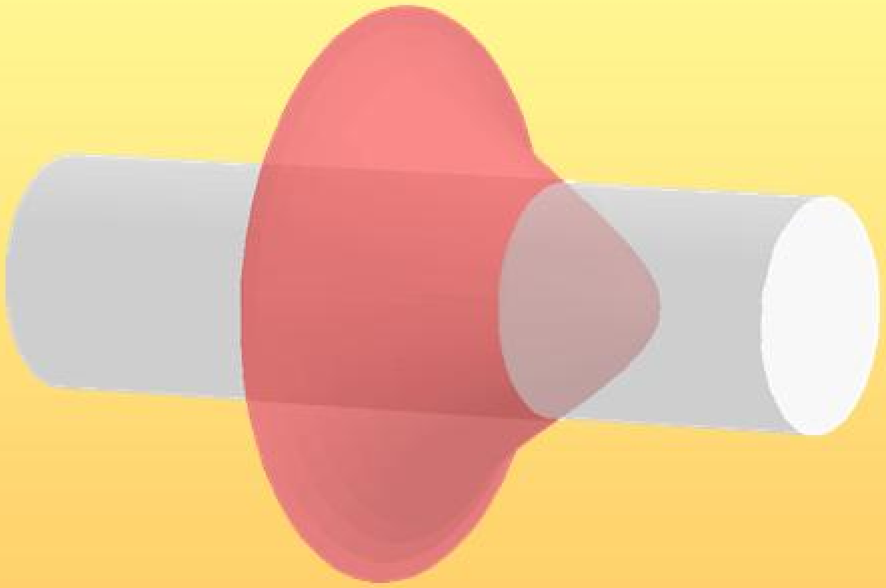
- Trick: Narrow down optical fiber until light field gets to the surface.

Overview

- Optical nanofibers
  - Properties and fabrication
- Probing cold atoms using nanofibers
- Nanofiber-based atom trap
  - Trapping potential
  - Experimental realization
- Summary / Outlook

Optical Nanofibers

- Significant part of the optical power propagates outside of optical nanofiber in form of evanescent wave:



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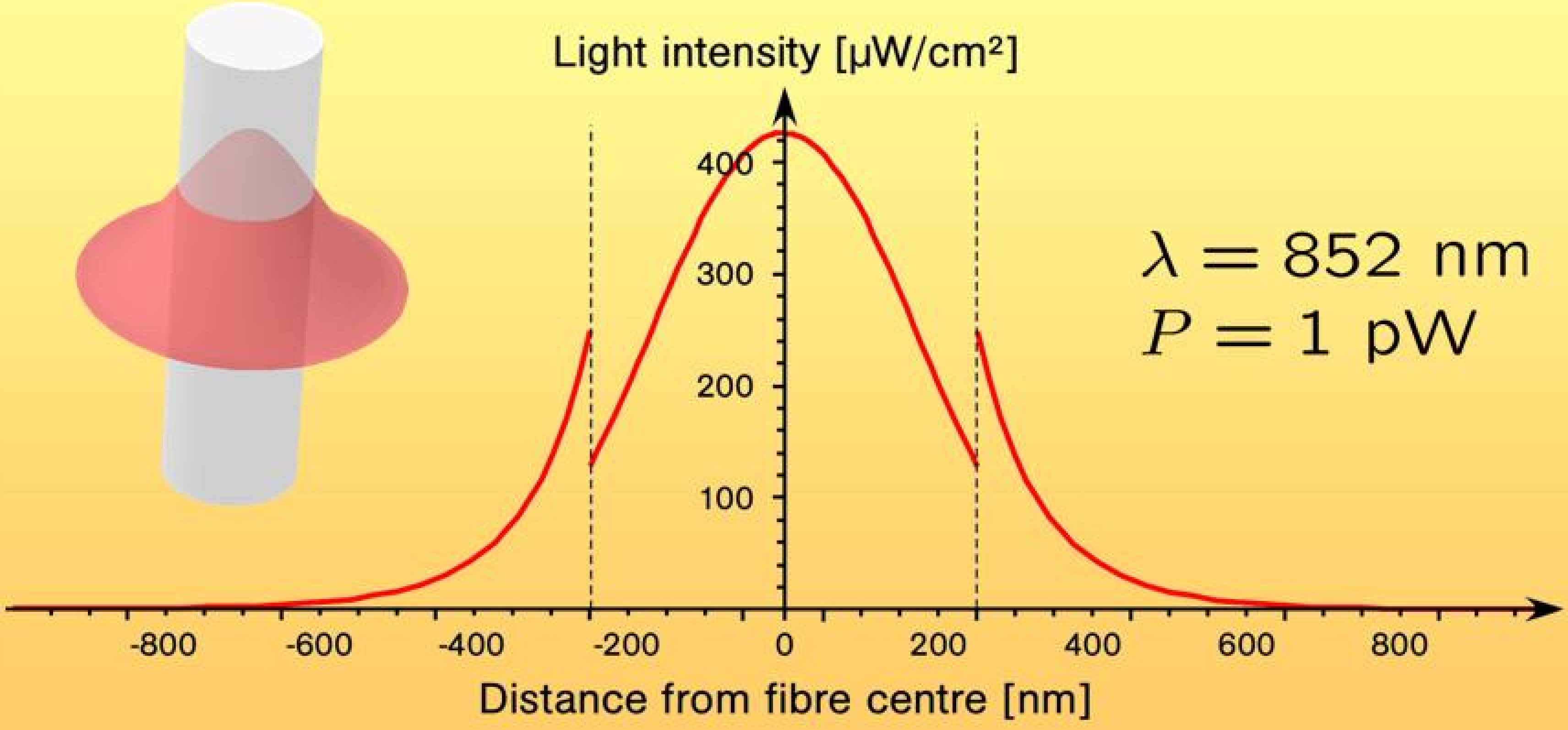
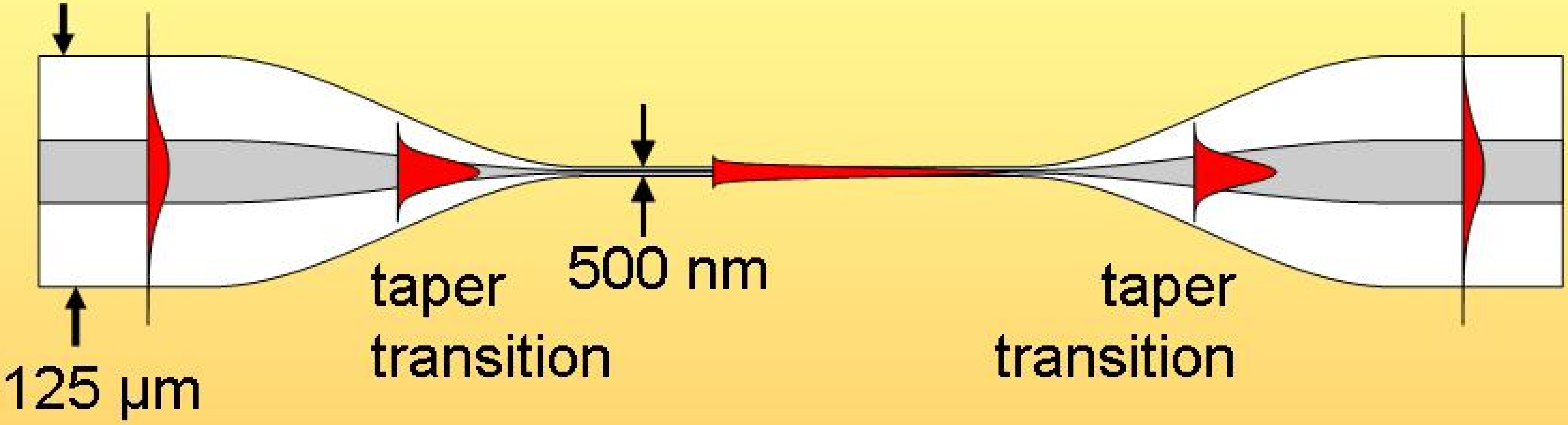


$\lambda = 852$ nm
$P = 1$ pW

Optical Nanofibers

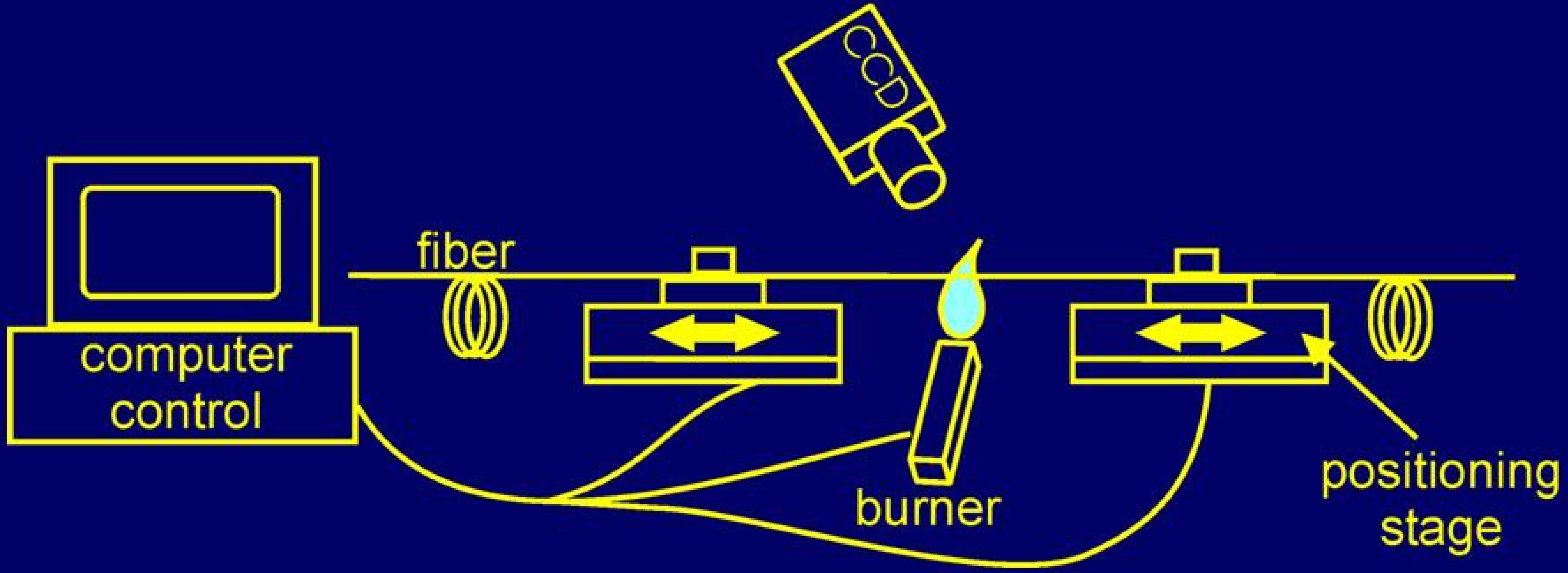
- Tapered fibers allow one to couple light in and out of nanofiber waist:



- Adiabatic mode transformation ⇒ up to 99% transmission!

Fabrication of Tapered Fibers

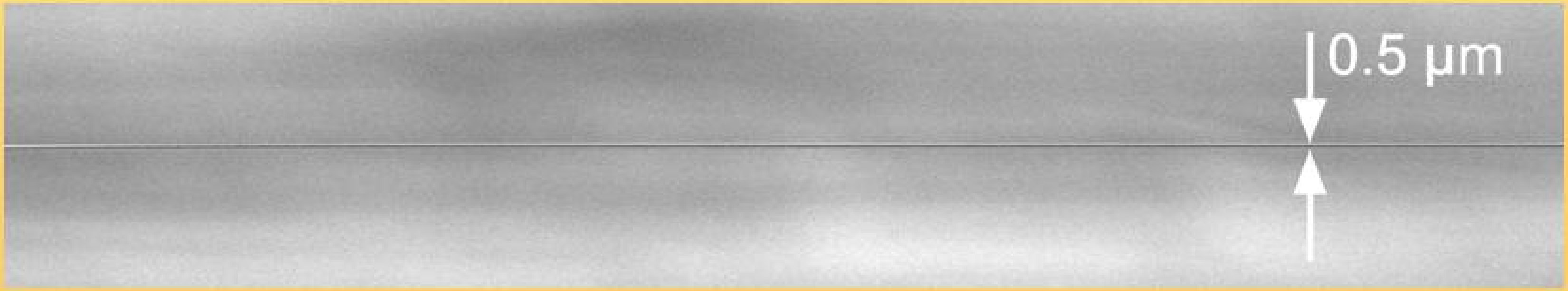
- Tapering standard optical fibers by flame pulling:



Fabrication of Tapered Fibers

- Taper transition:

- Nanofiber waist:



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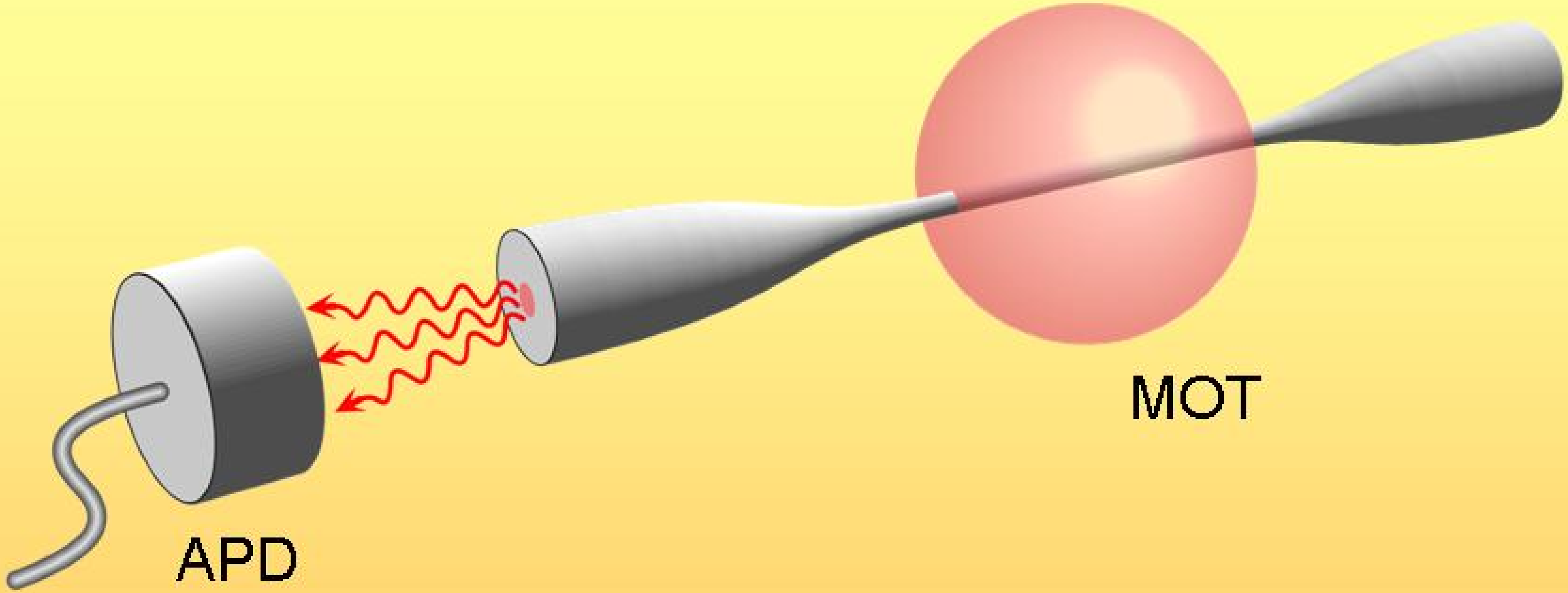
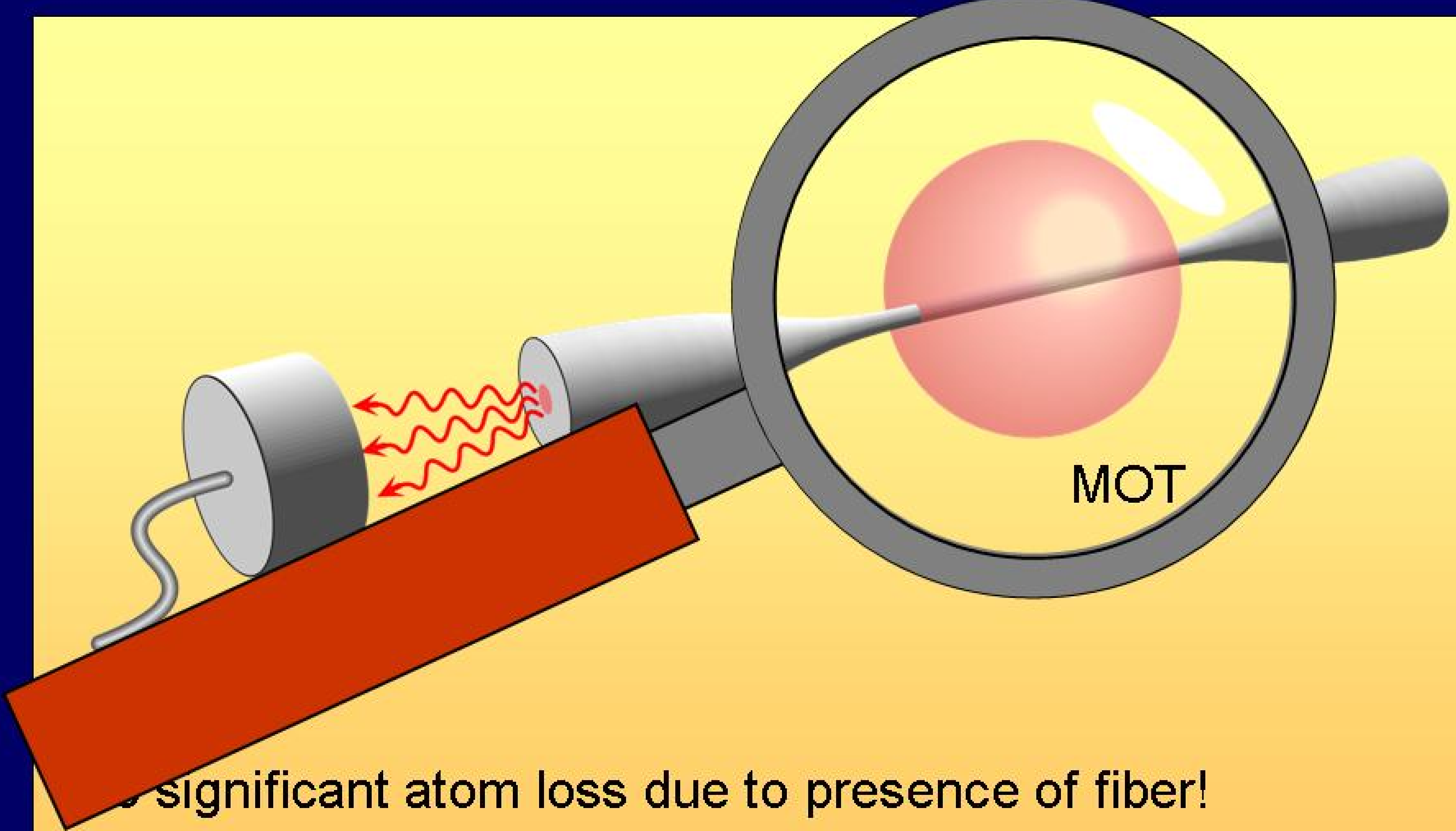
Probing Cold Atoms Using Nanofibers



No significant atom loss due to presence of fiber!

Very small coupling of MOT laser beams into fiber mode!

Probing Cold Atoms Using Nanofibers



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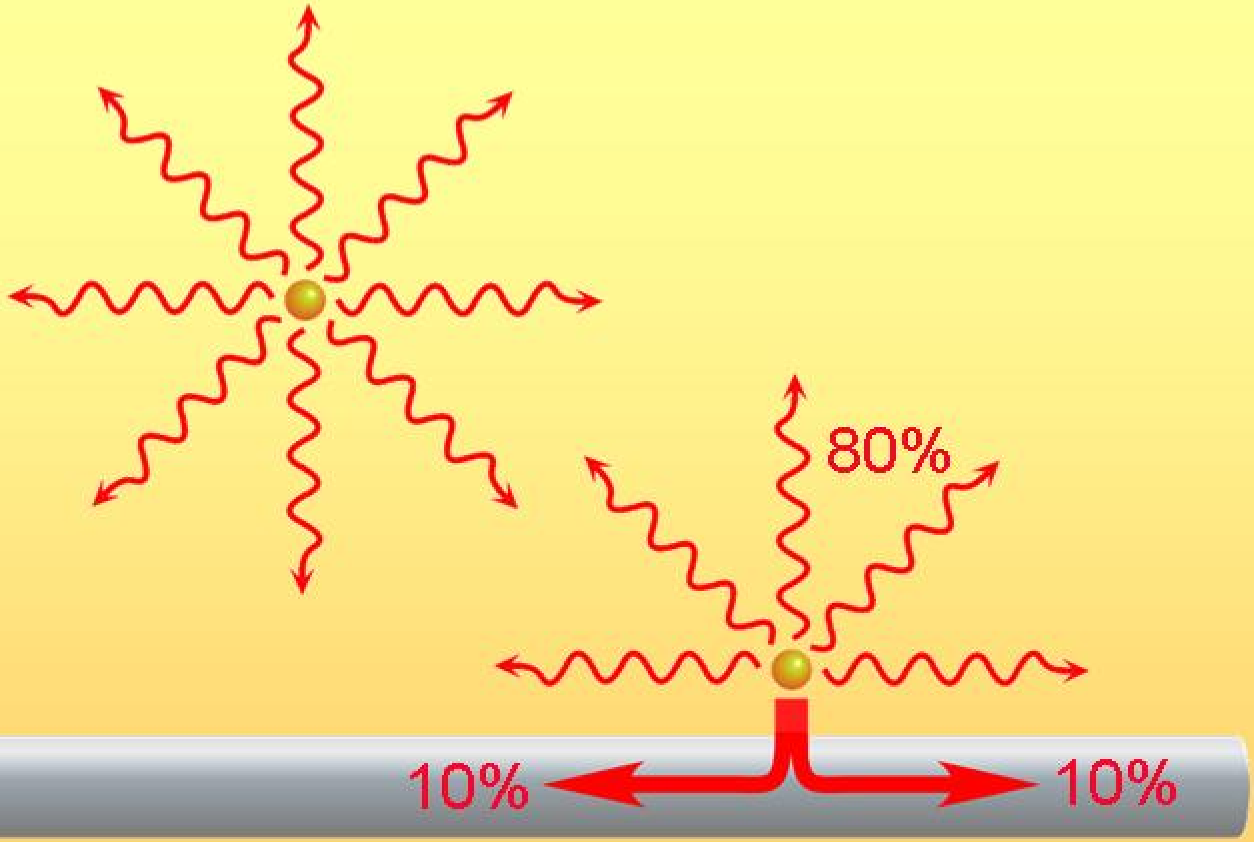
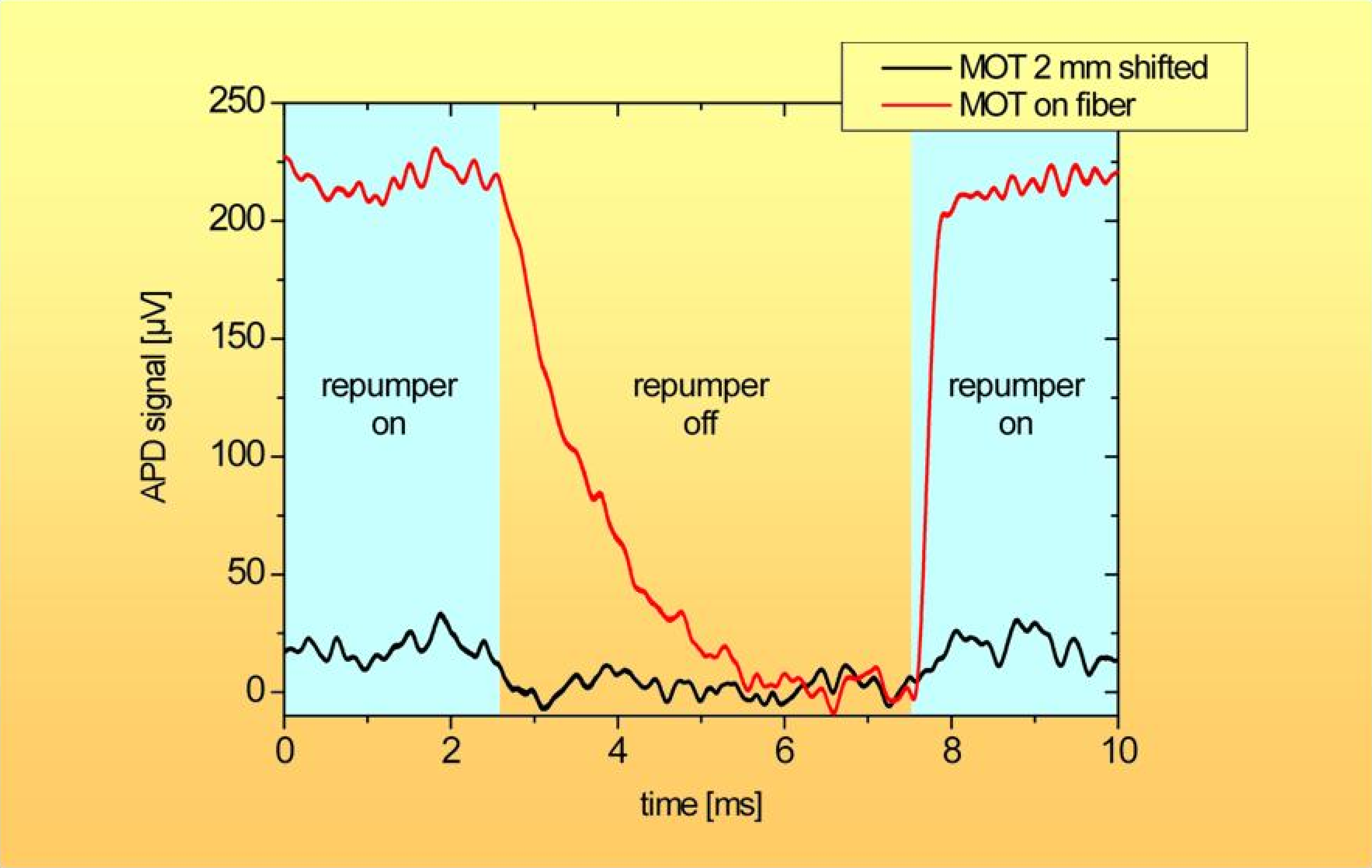
Evanescent Coupling of Fluorescence



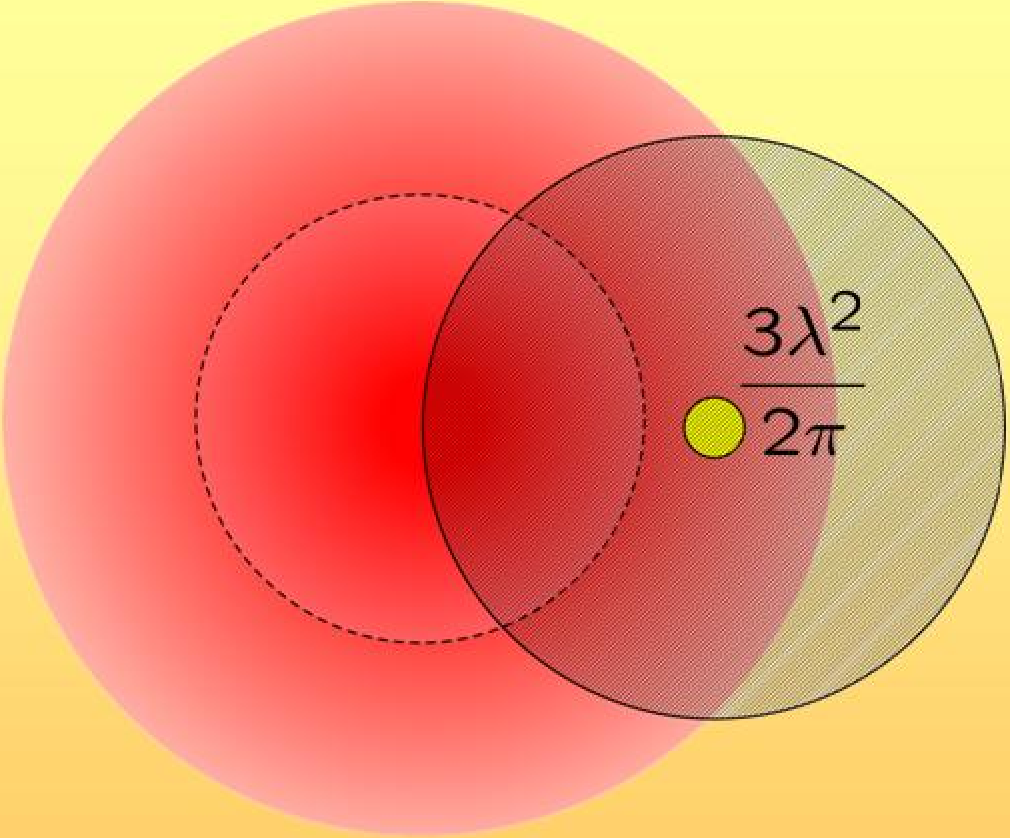
Effective number of coupled atoms ≈ 1

⇒ detect “single atom” fluorescence out of 10^8 ?!

Evanescent Coupling of Fluorescence

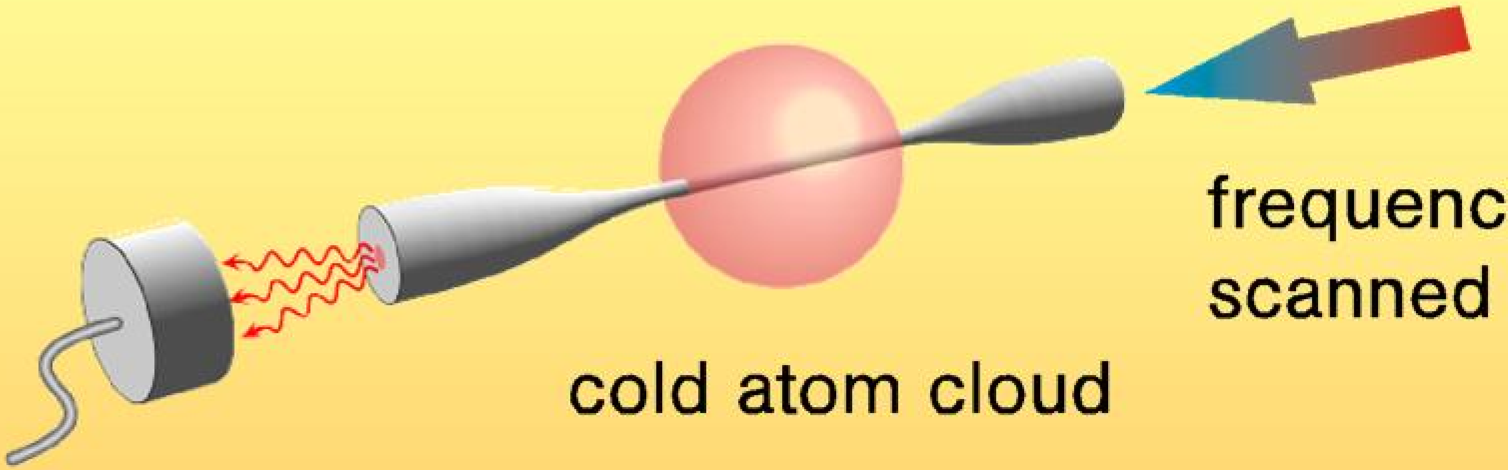


Single Atom Absorption


$$\frac{3\lambda^2}{2\pi}$$

Single atom should have significant effect on transmission!

Absorption Spectroscopy



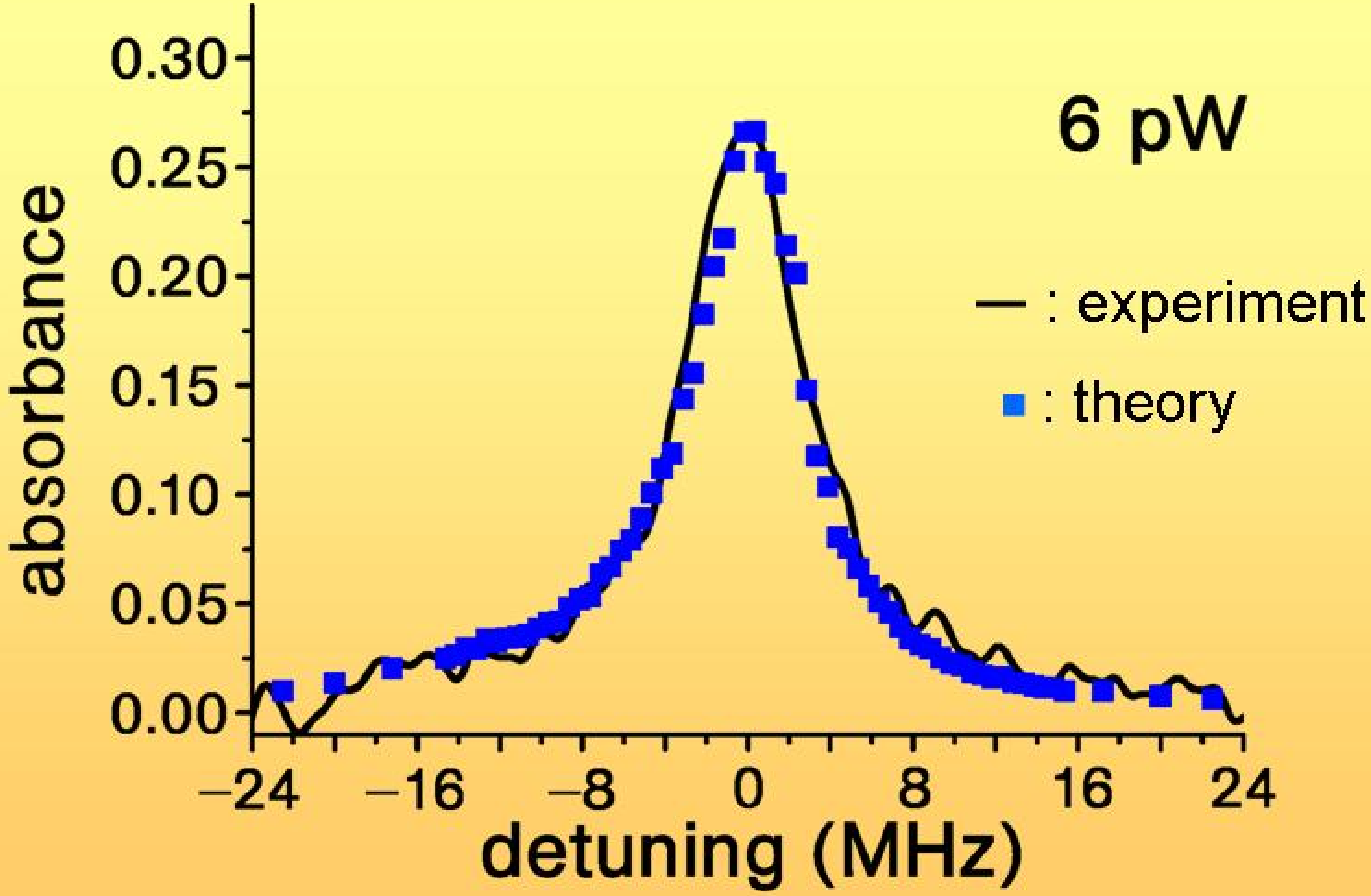
frequency
scanned laser

cold atom cloud

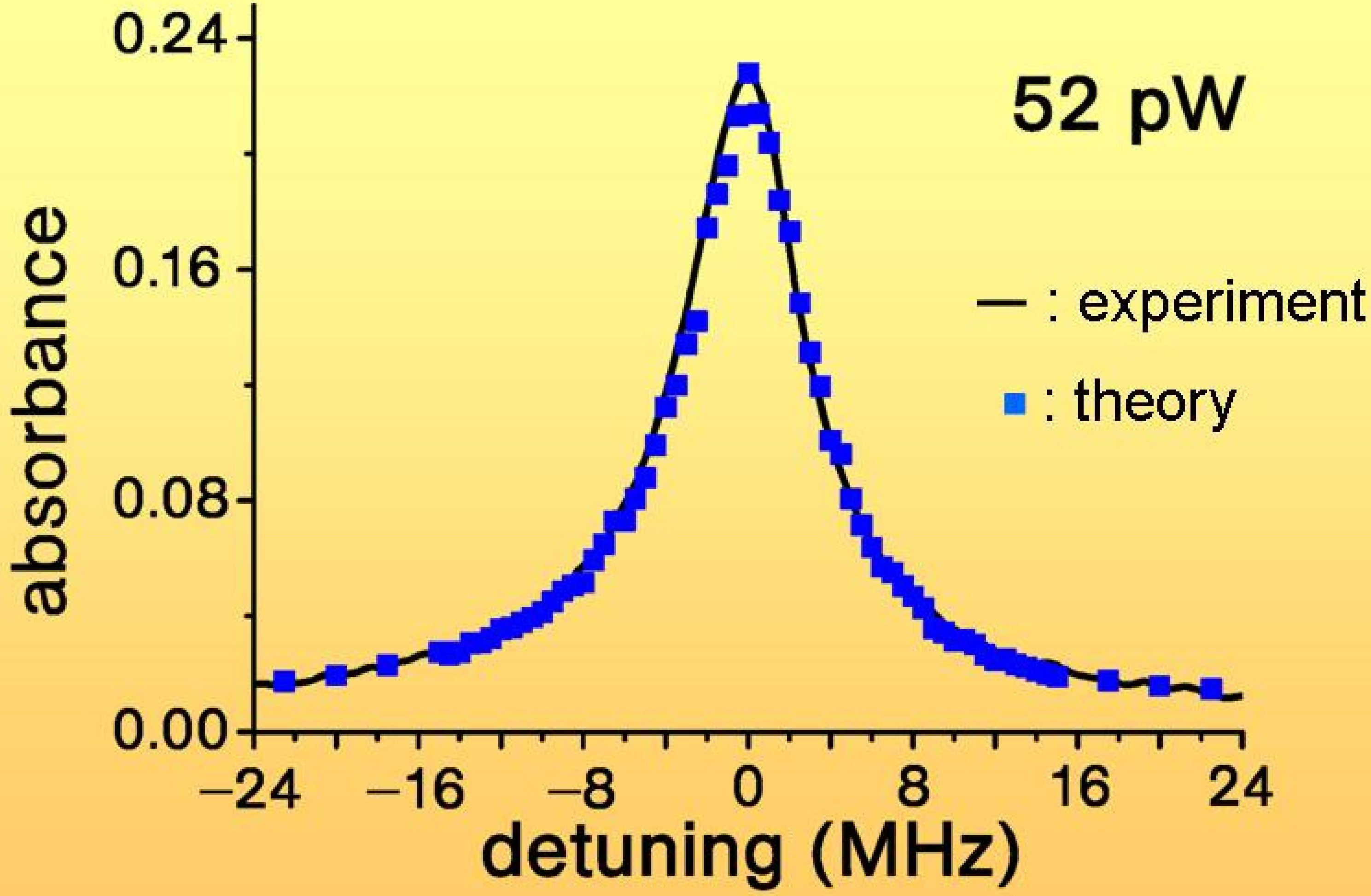
photodetector

G. Sagué *et al.*, Phys. Rev. Lett. **99**, 163602 (2007)

Absorption Spectra



Absorption Spectra



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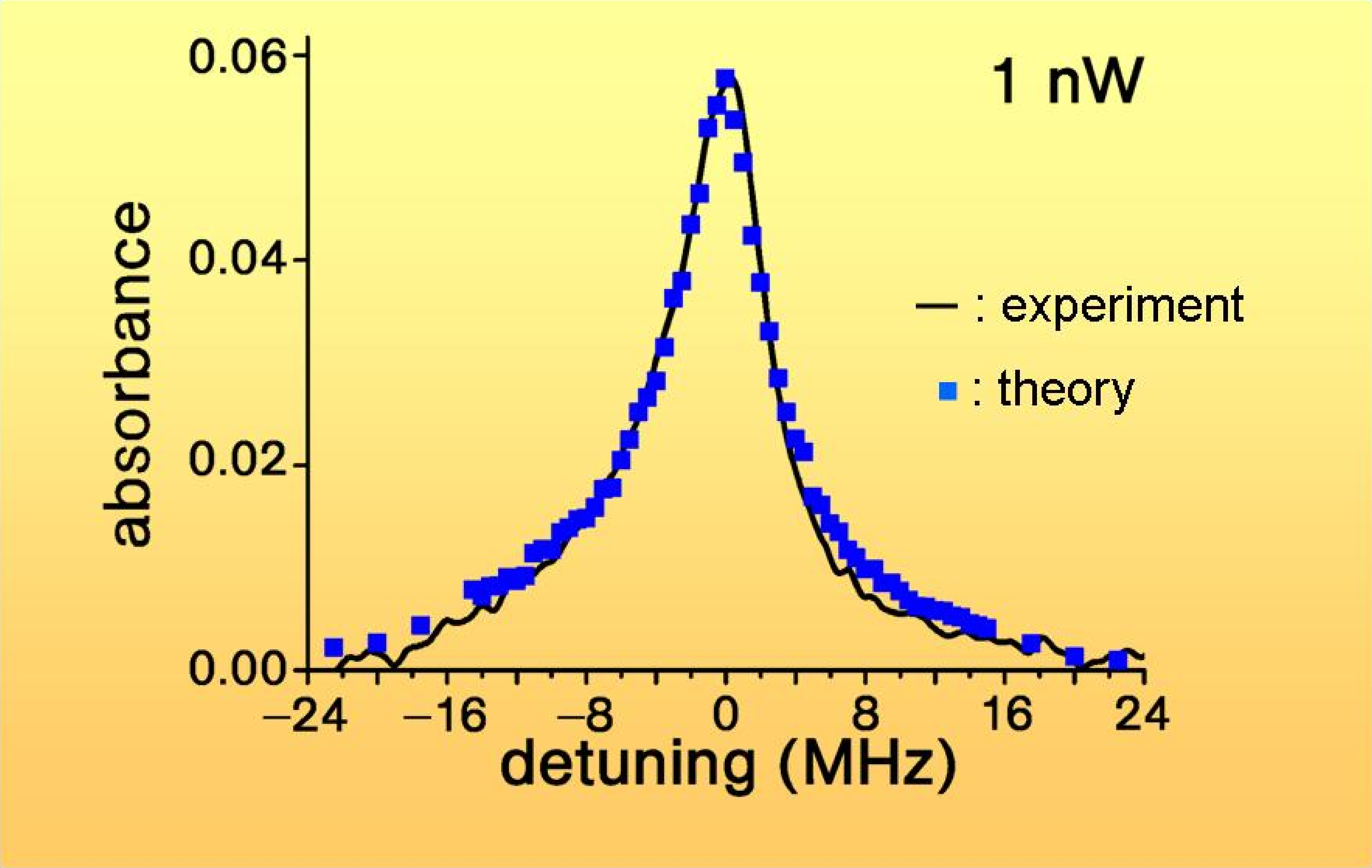
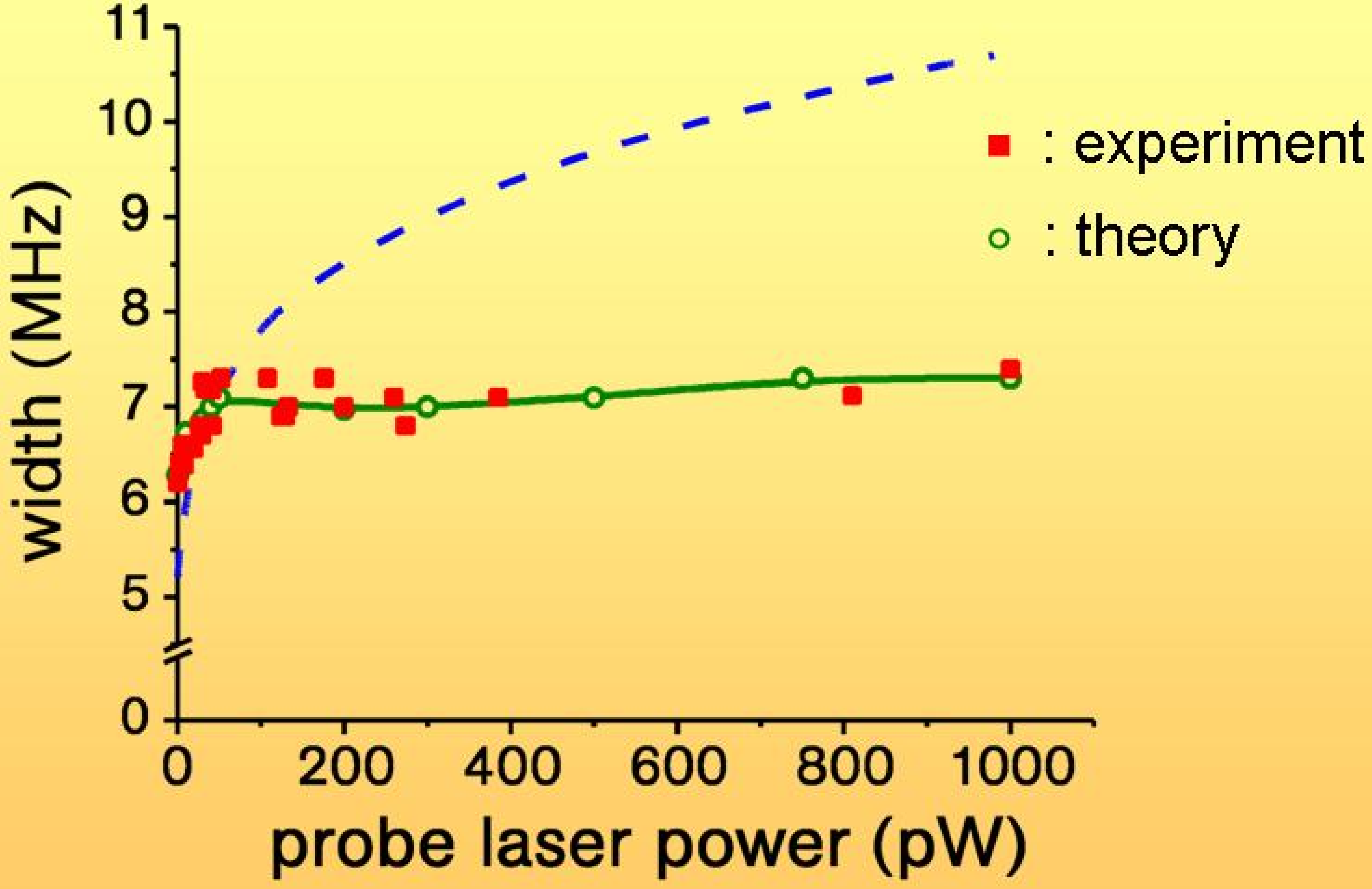
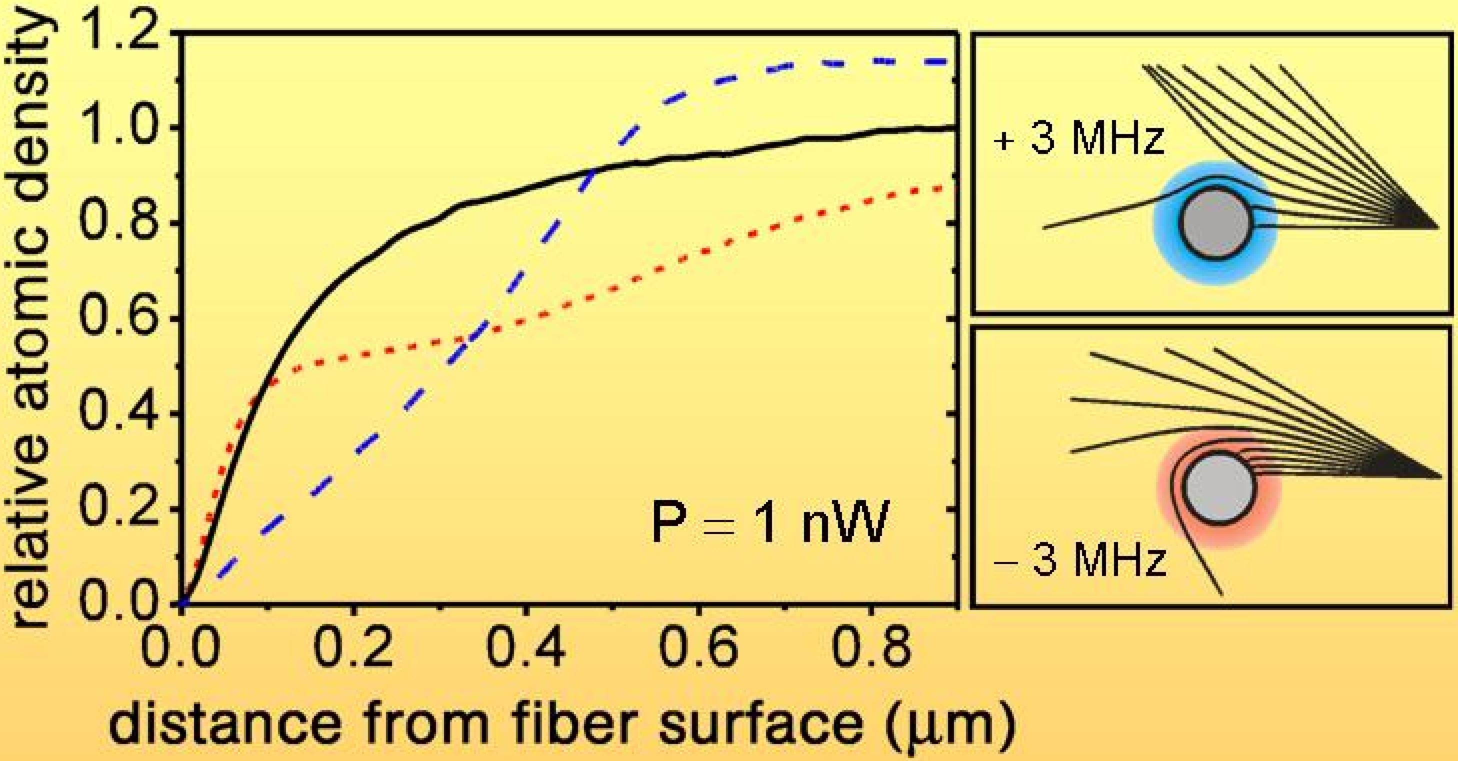


Modelling of Line Widths

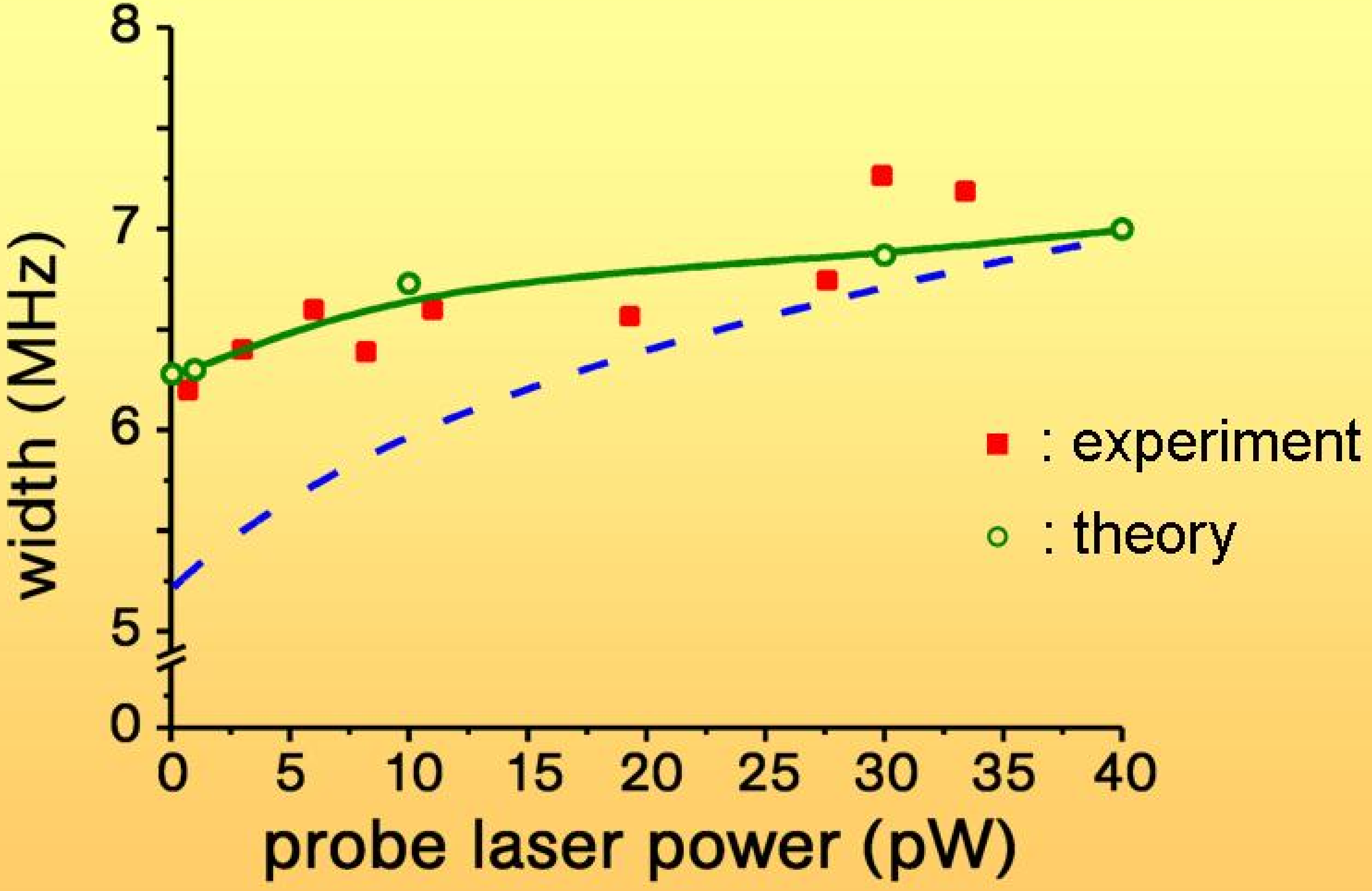


Light Induced Dipole Forces



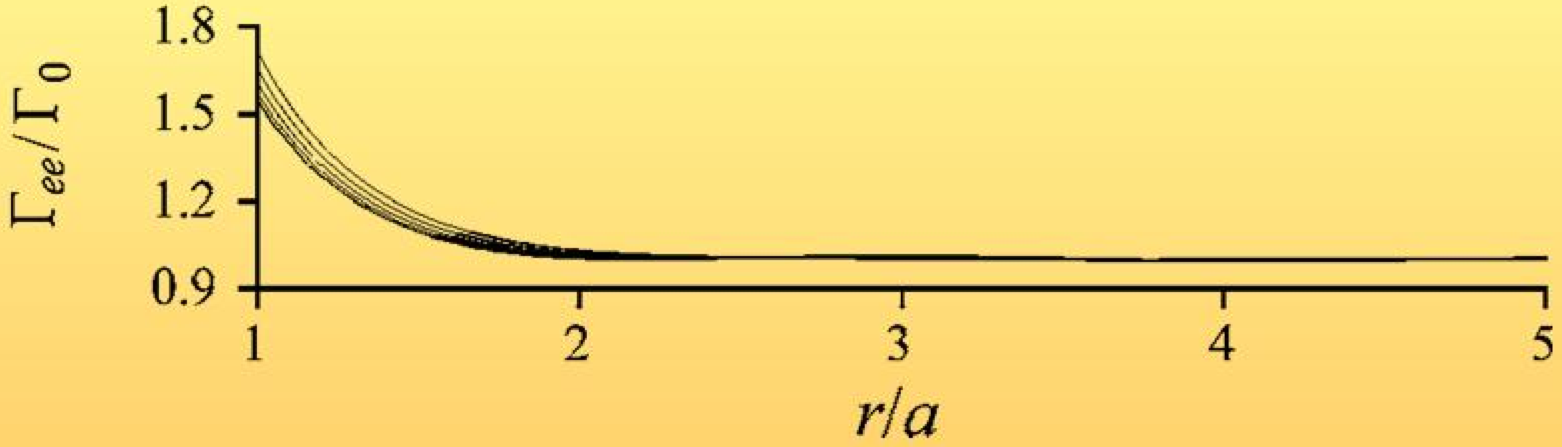
Density close to the fiber is strongly influenced by van der Waals force and light induced dipole forces.

Modelling of Line Widths



Enhanced Spontaneous Emission

- Significant enhancement of the spontaneous emission due to modified density of states in vicinity of the fiber.
- 20 % of the total emission goes into fiber guided mode!



Fam Le Kien, S. Dutta Gupta, V. I. Balykin, and K. Hakuta,
Phys. Rev. A **72**, 032509 (2005)

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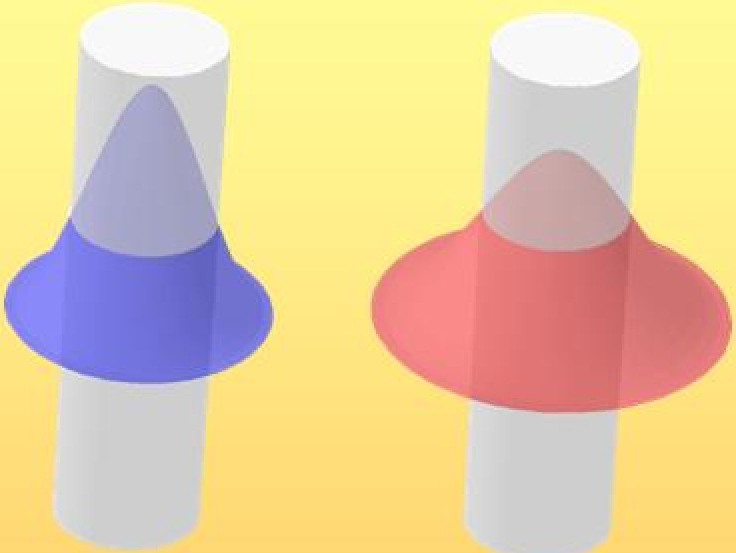
Radial Trapping Potential

Evanescent field around fiber exerts dipole force on atoms.



Blue light is more tightly bound to nanofiber than red light.

Fam Le Kien, V. I. Balykin, and K. Hakuta, PRA **70**, 063403 (2004)

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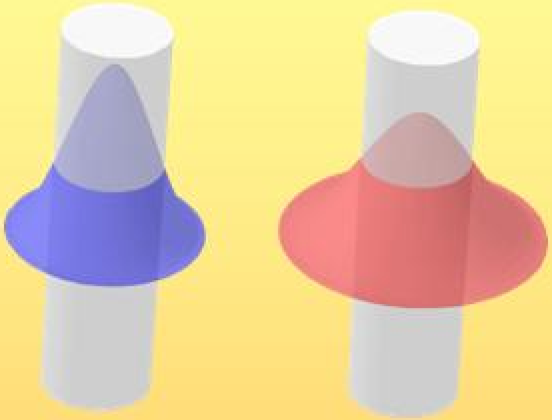

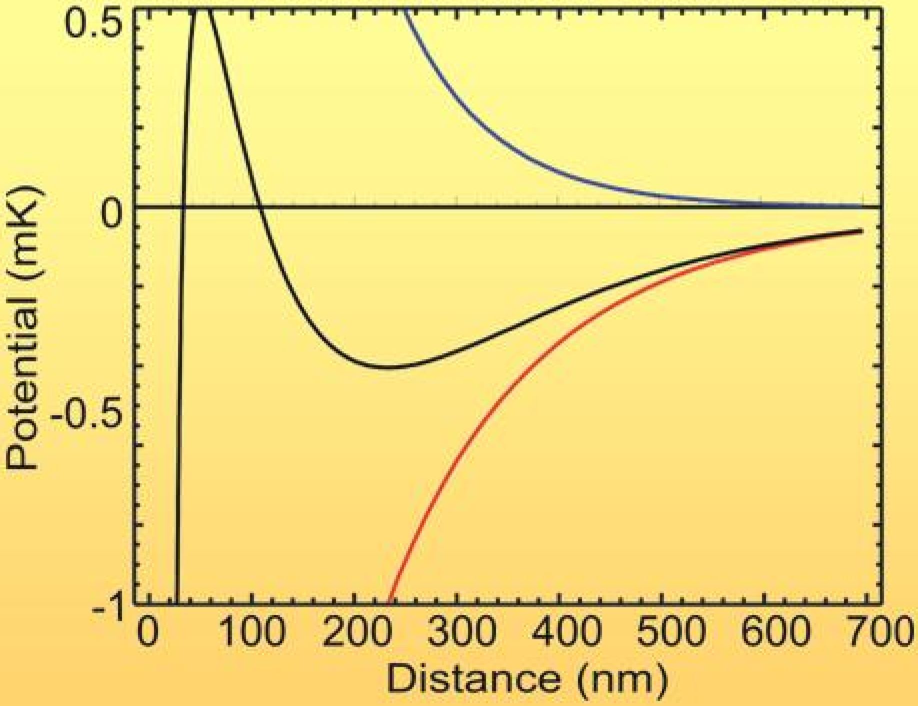

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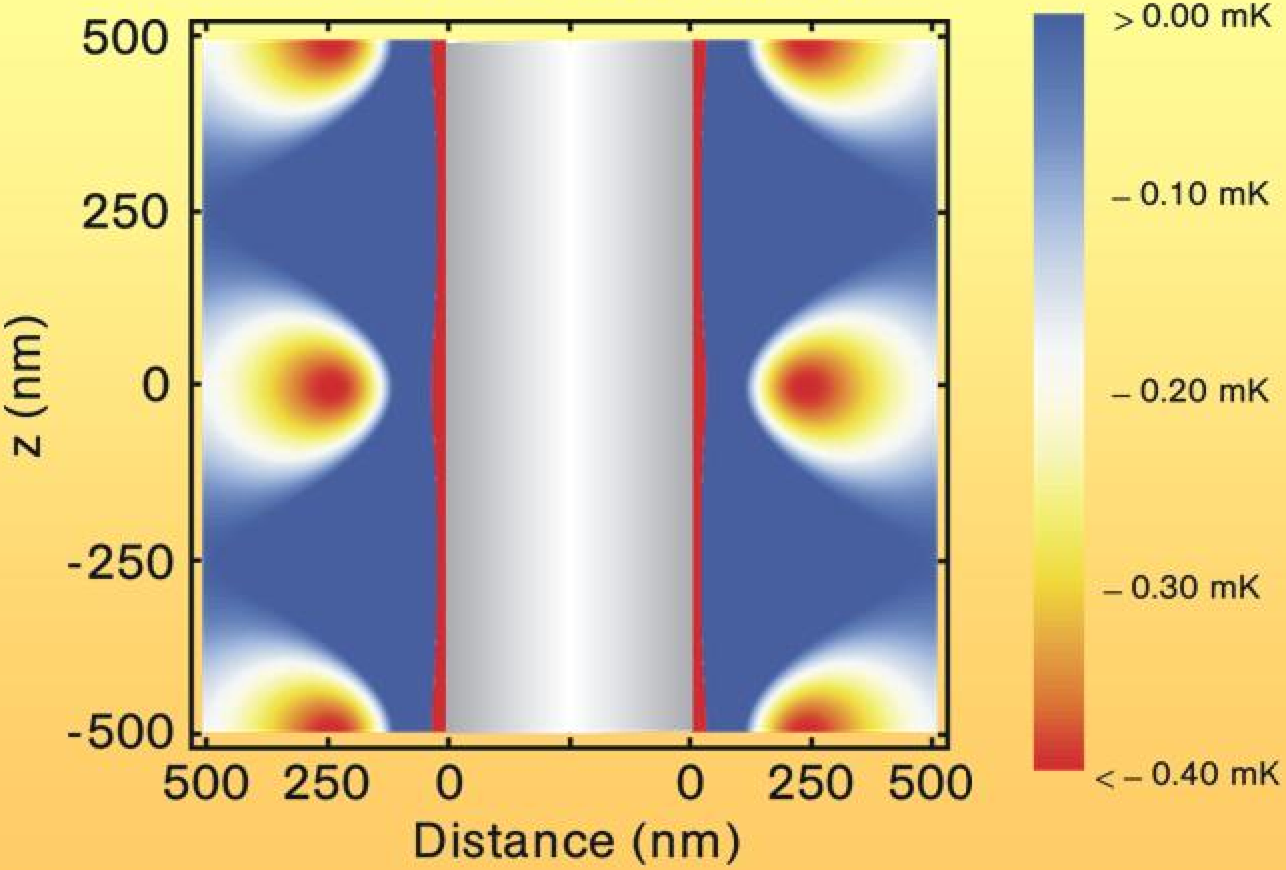
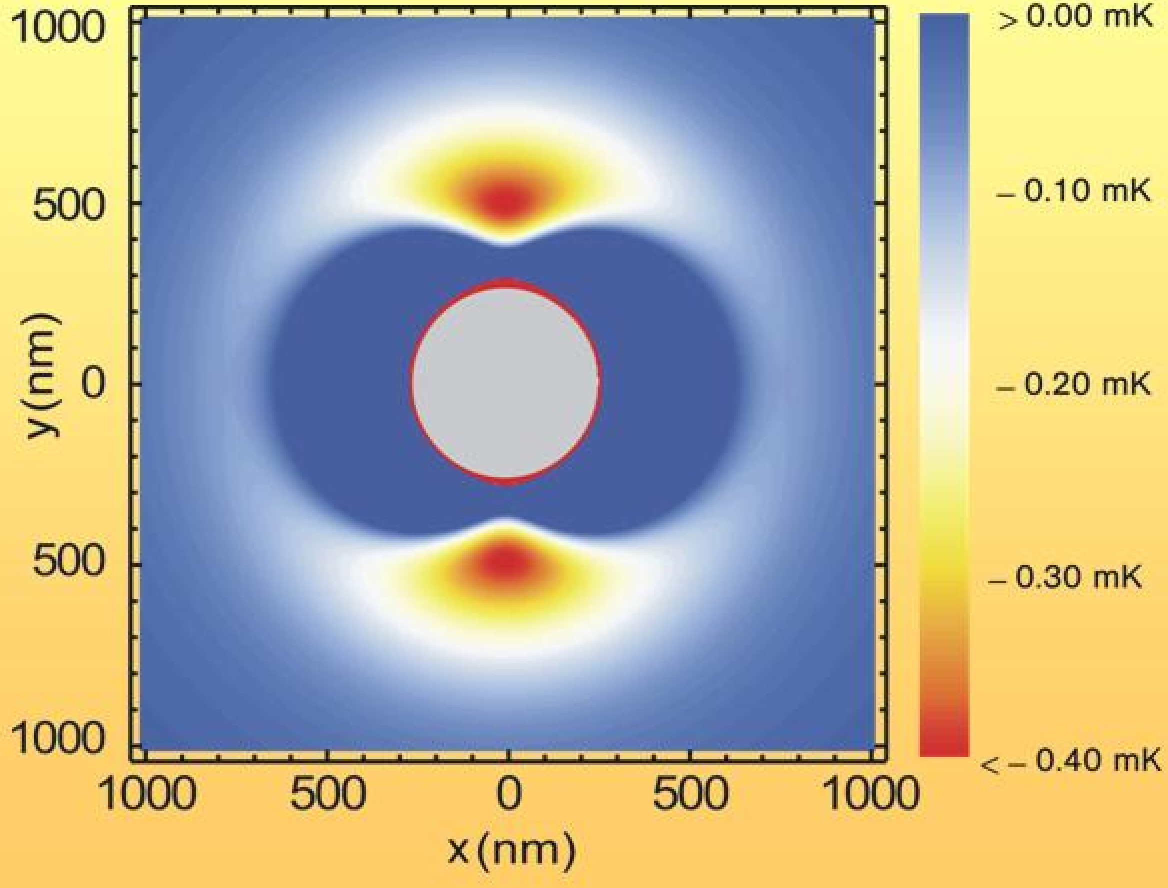
Axial Trapping Potential

Two counterpropagating red beams create standing wave $\Rightarrow$ axial confinement:



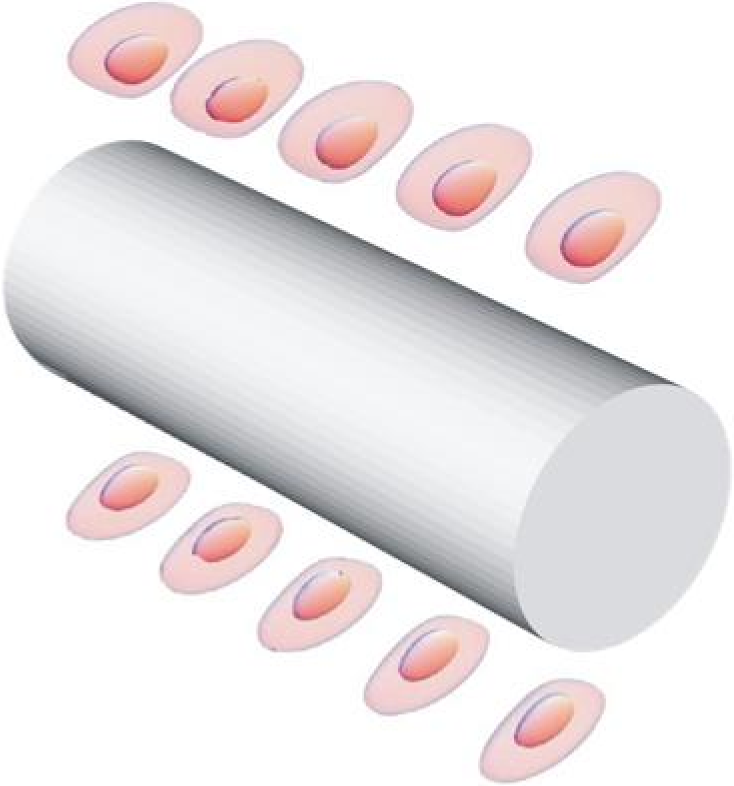
Azimuthal Trapping Potential

Linear polarization breaks cylindrical symmetry
⇒ azimuthal confinement:



1d Optical Lattice

Resulting potential:
Array of trapping sites on both sides of the fiber!



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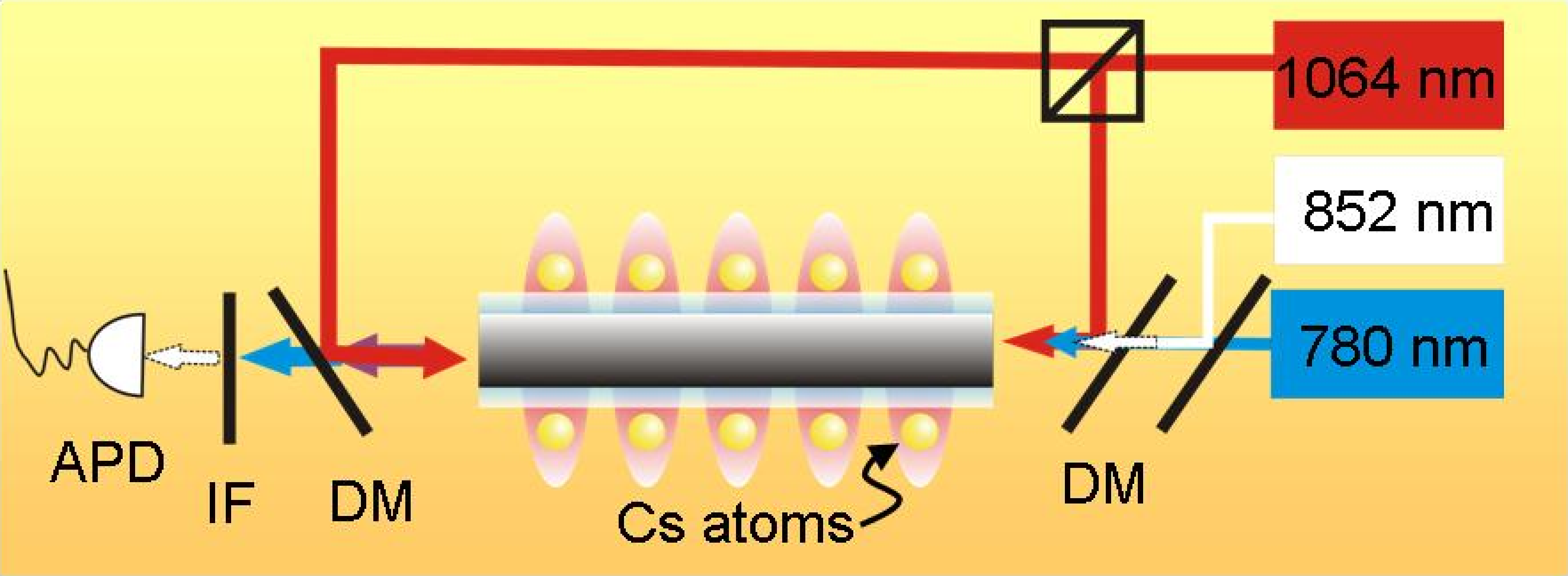
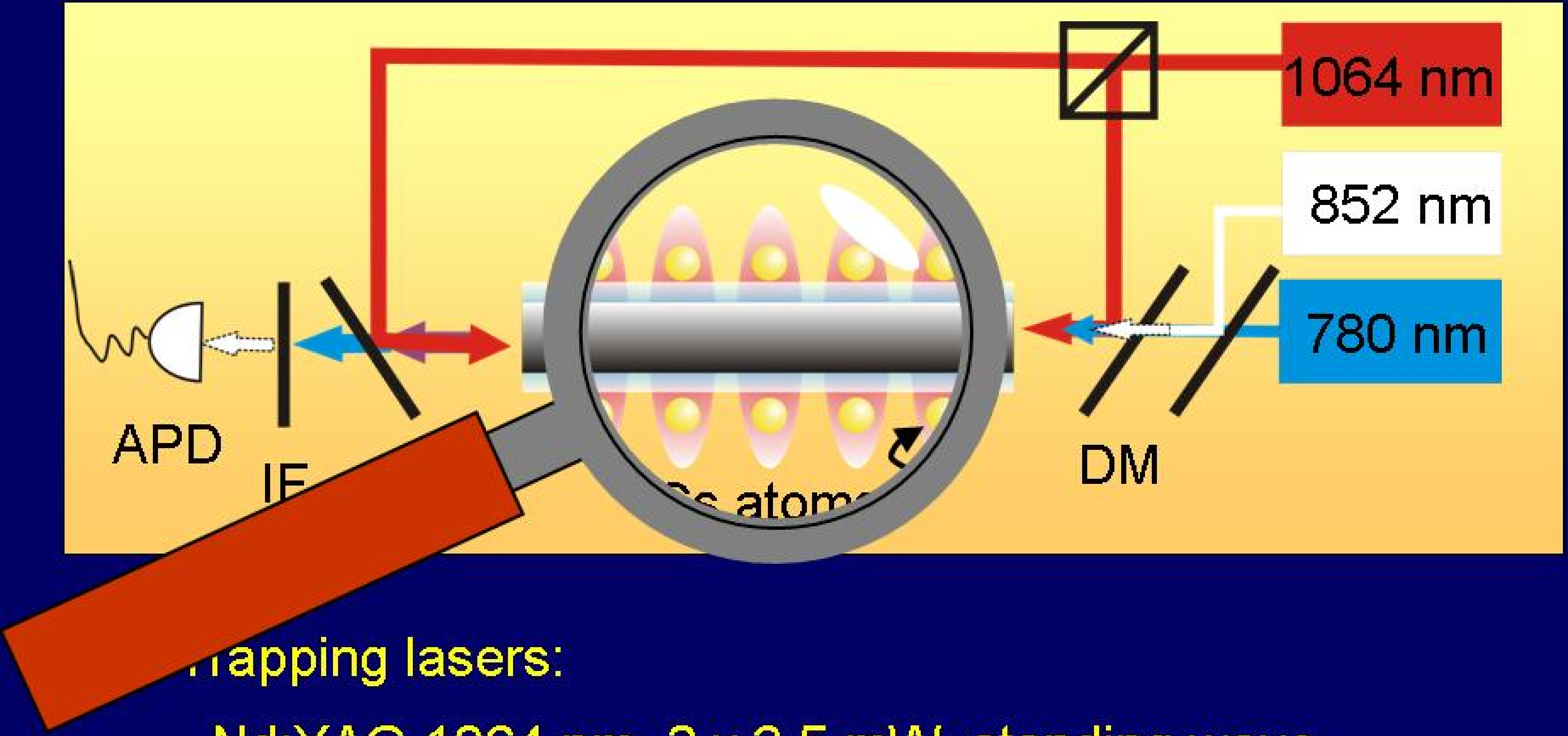
Experimental Setup



- Trapping lasers:
  - Nd:YAG 1064 nm, 2 x 3.5 mW, standing wave
  - Diode laser 780 nm, 25 mW, running wave
- Fiber diameter: 500 nm $\Rightarrow$ trap depth ~ 0.4 mK

Experimental Setup



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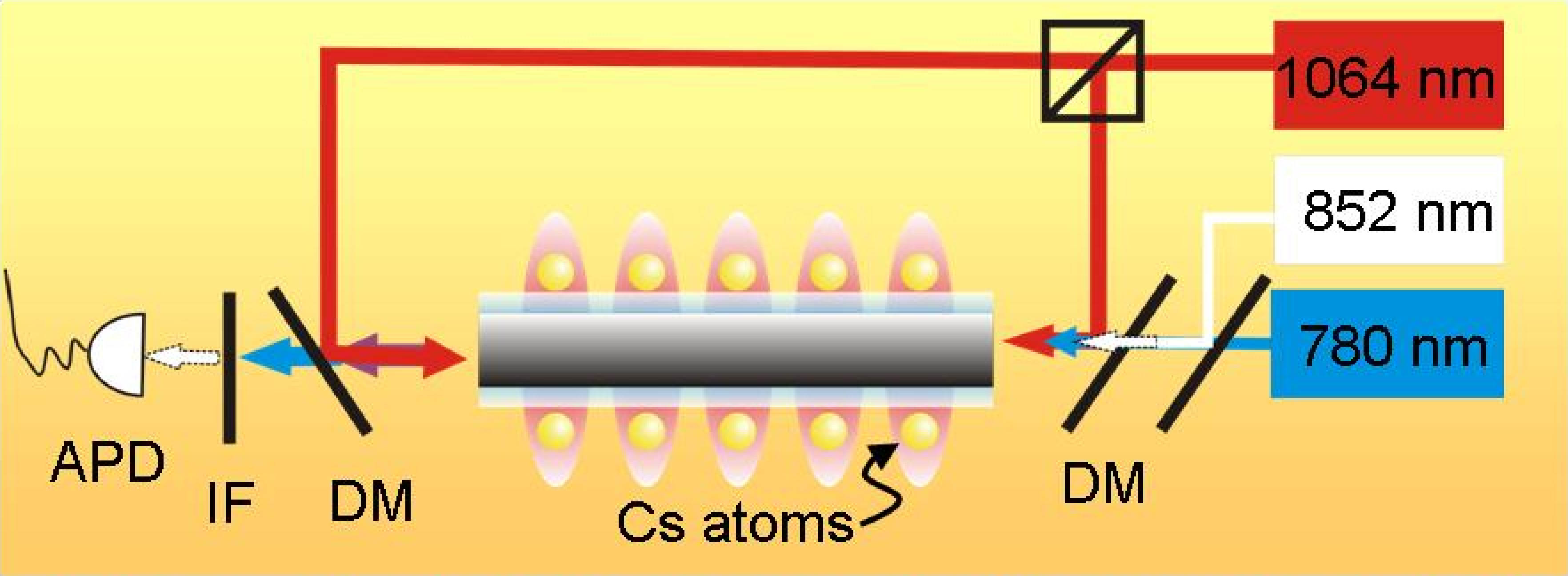
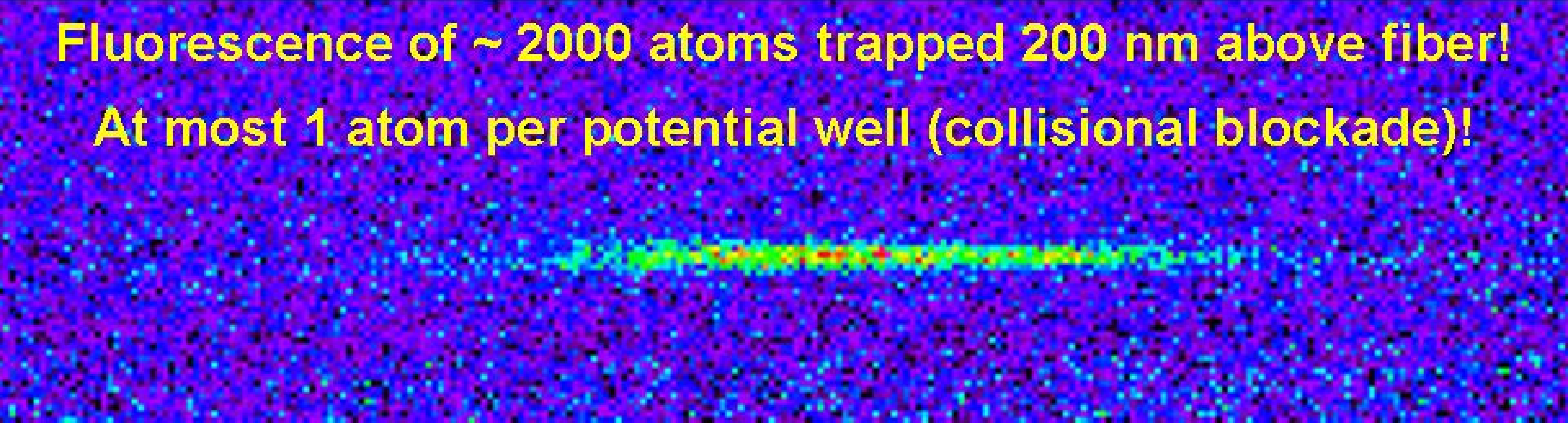


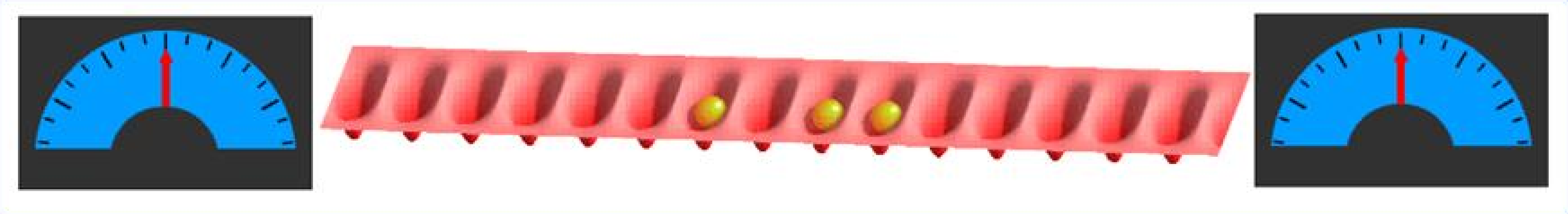


Fluorescence of ~ 2000 atoms trapped 200 nm above fiber!

At most 1 atom per potential well (collisional blockade)!

A Conveyor Belt for Atoms

Mutually detuning the two laser beams sets the standing wave in motion → controlled transport of atoms!



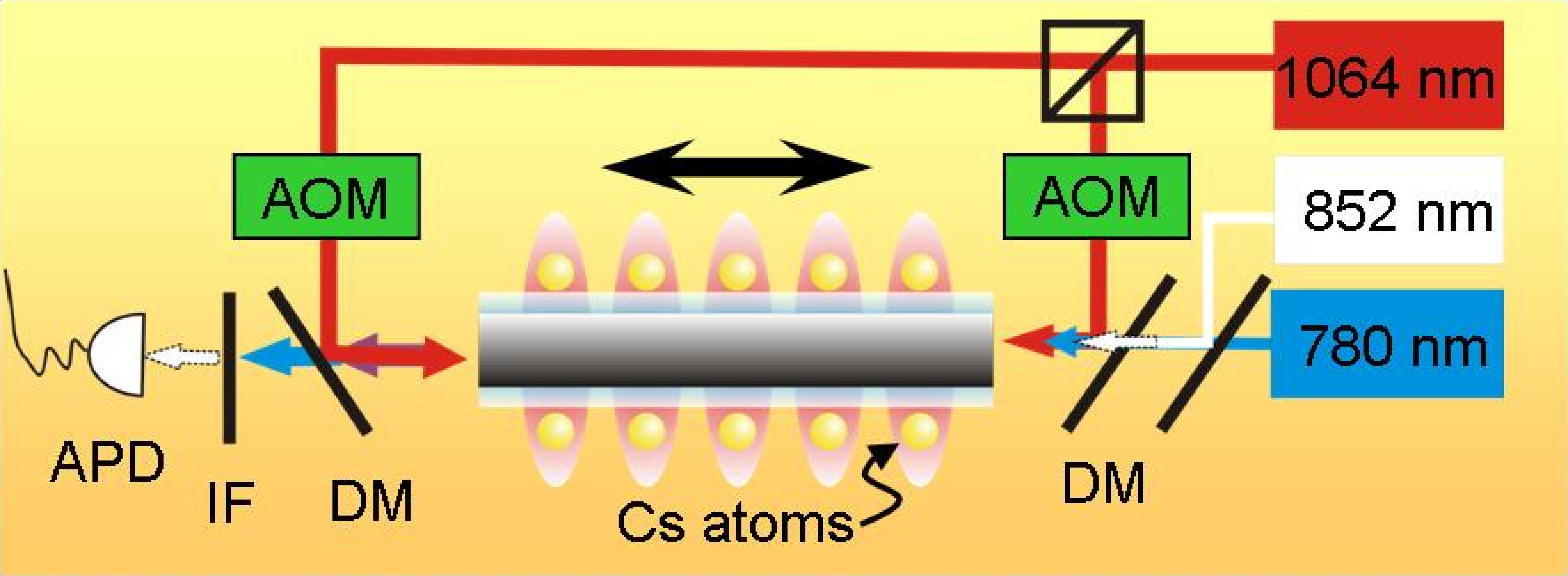
frequency laser beam 1

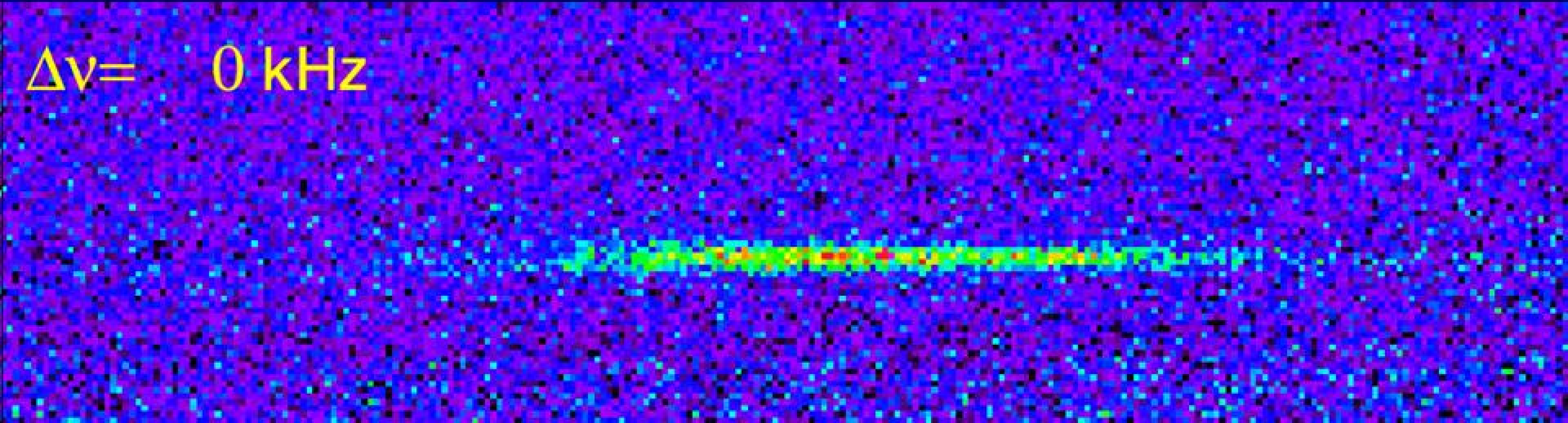
frequency laser beam 2

atomic velocity: $v = \Delta\nu \cdot \frac{\lambda}{2}$

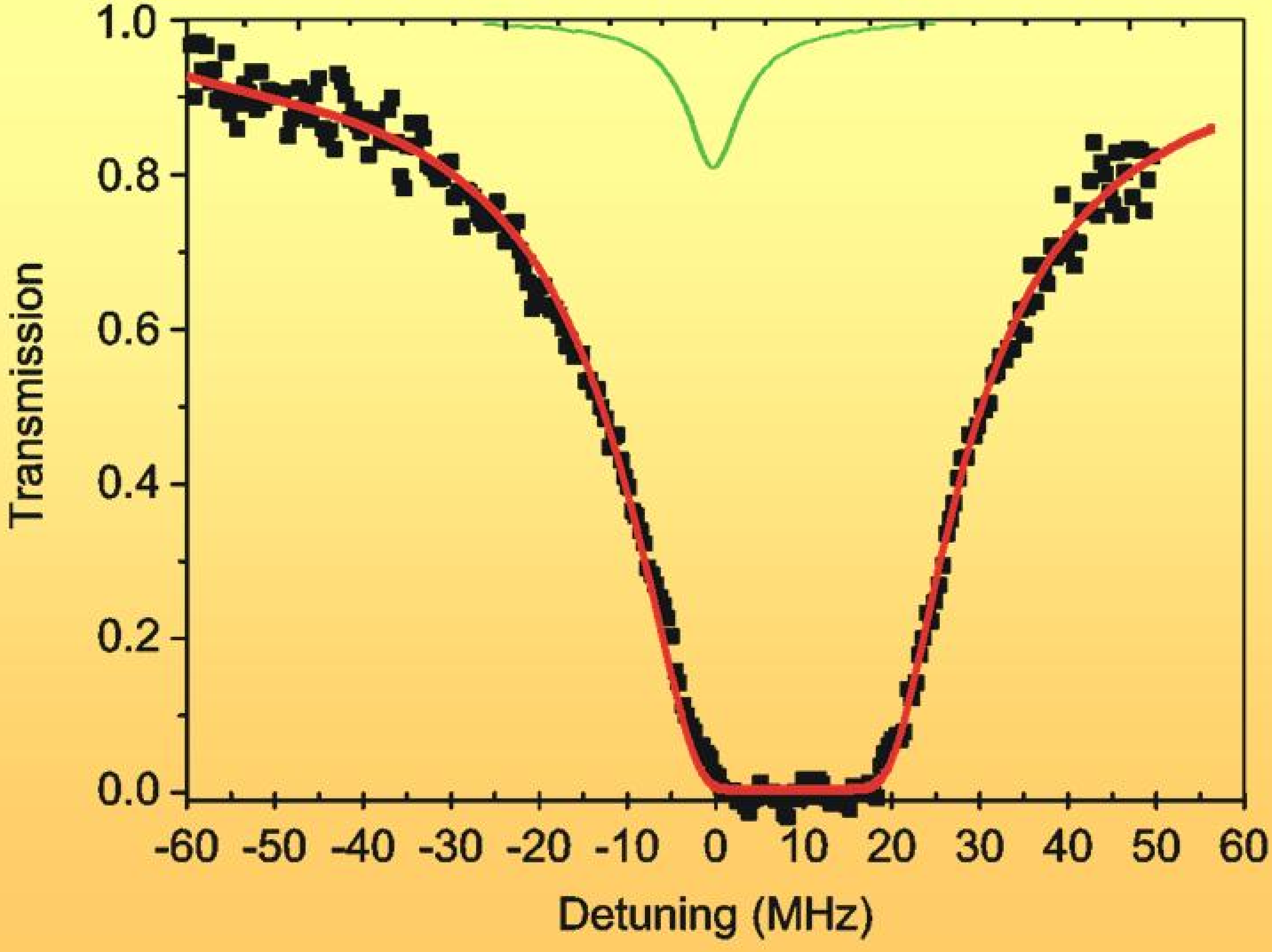
$\Delta\nu$: mutual detuning, λ: laser wavelength

A Conveyor Belt for Atoms





Spectroscopy of Trapped Atoms



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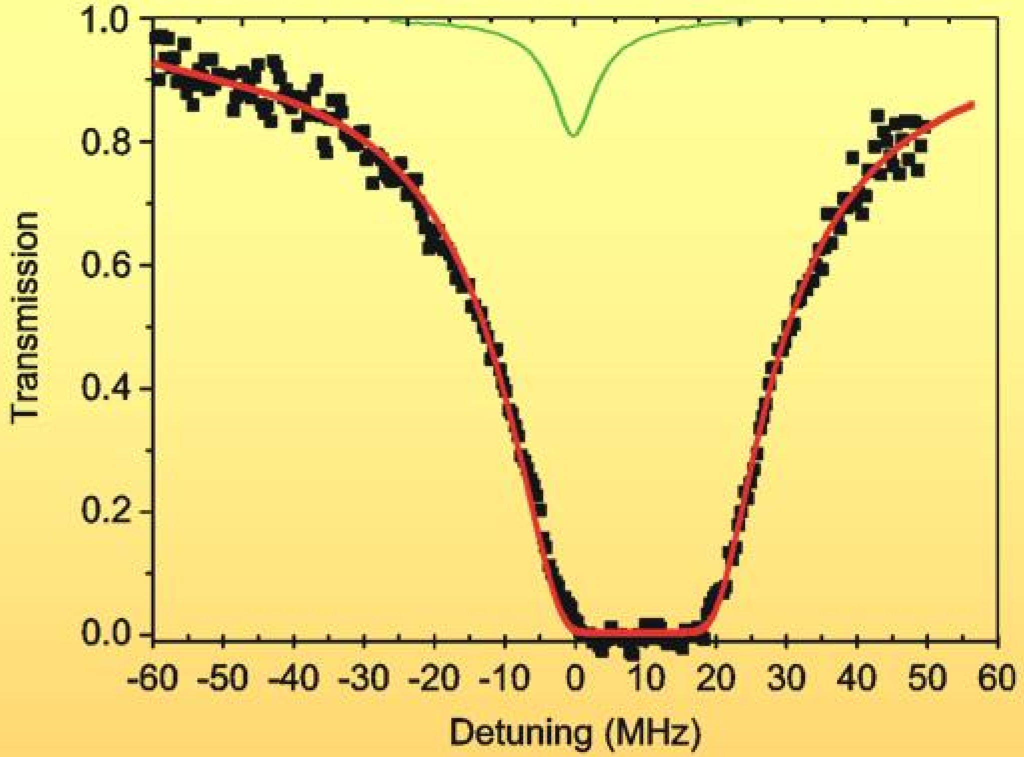
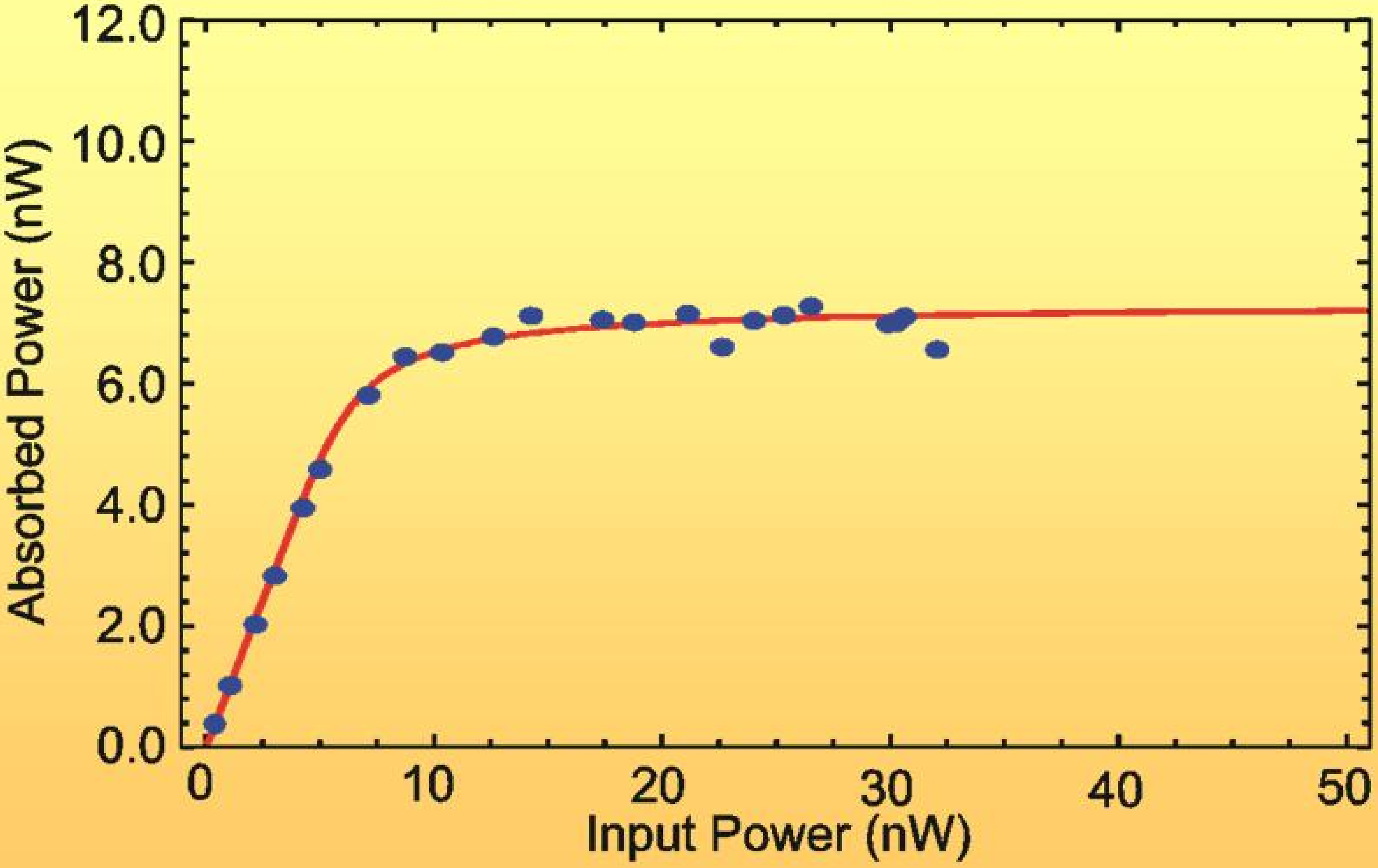


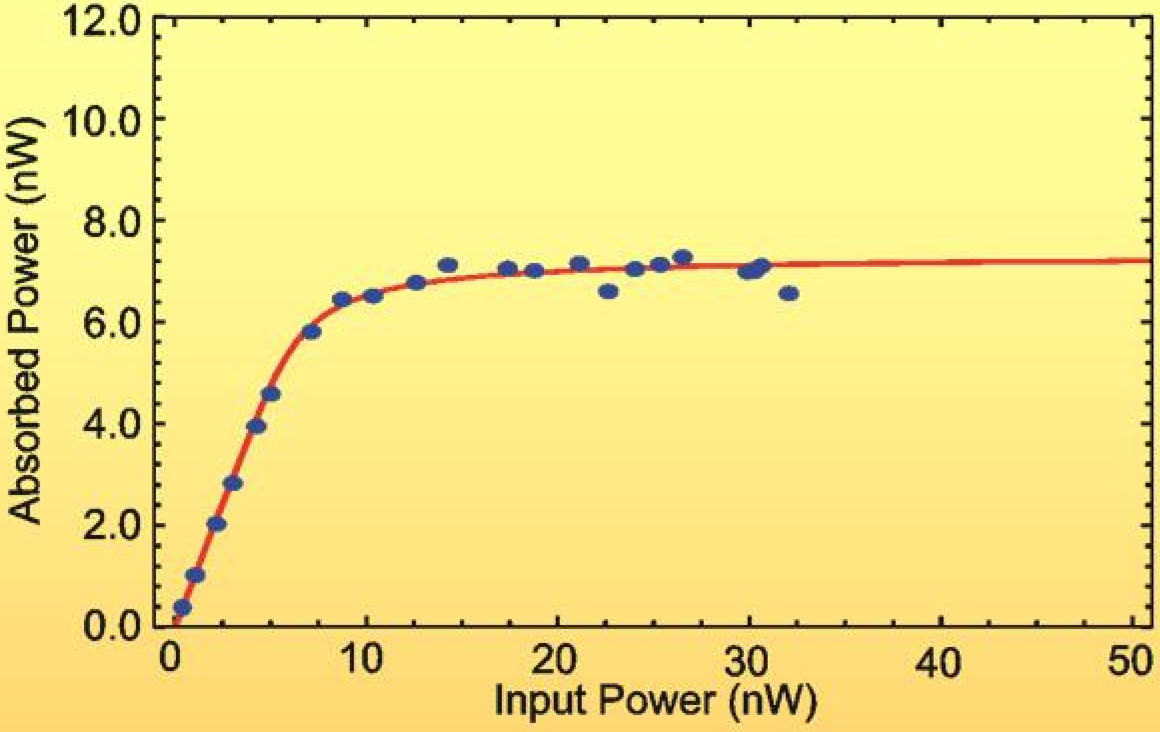
- Inhomogeneous line width ↔ light shifts of m_F-states.
- Realizes optically dense (OD 20) ensemble of fiber coupled atoms!

E. Vetsch *et al.*, submitted (2009)

Atom Number Measurement



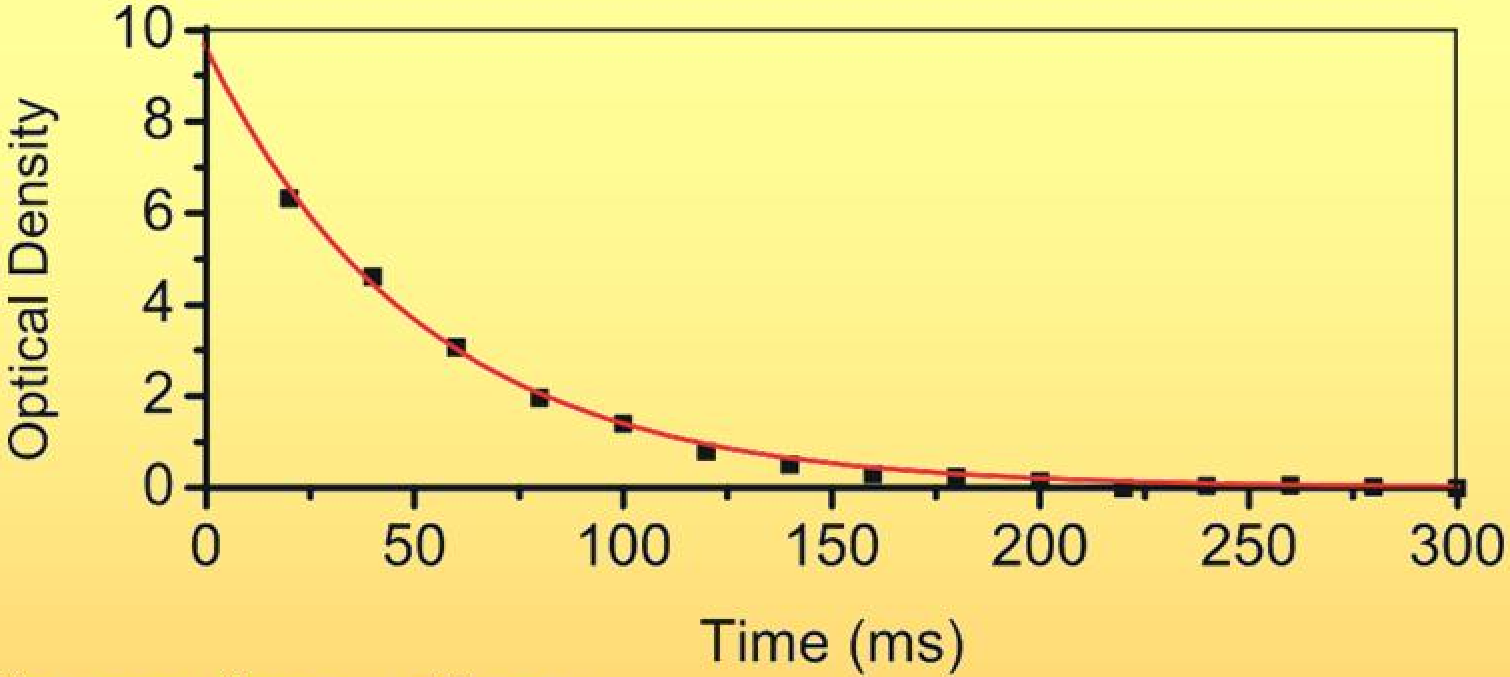
Atom Number Measurement



- Absorbed power saturates at ~ 8 nW
- Maximum scattered power per atom ~ 4 pW
- Number of trapped atoms ~ 2000

E. Vetsch *et al.*, submitted (2009)

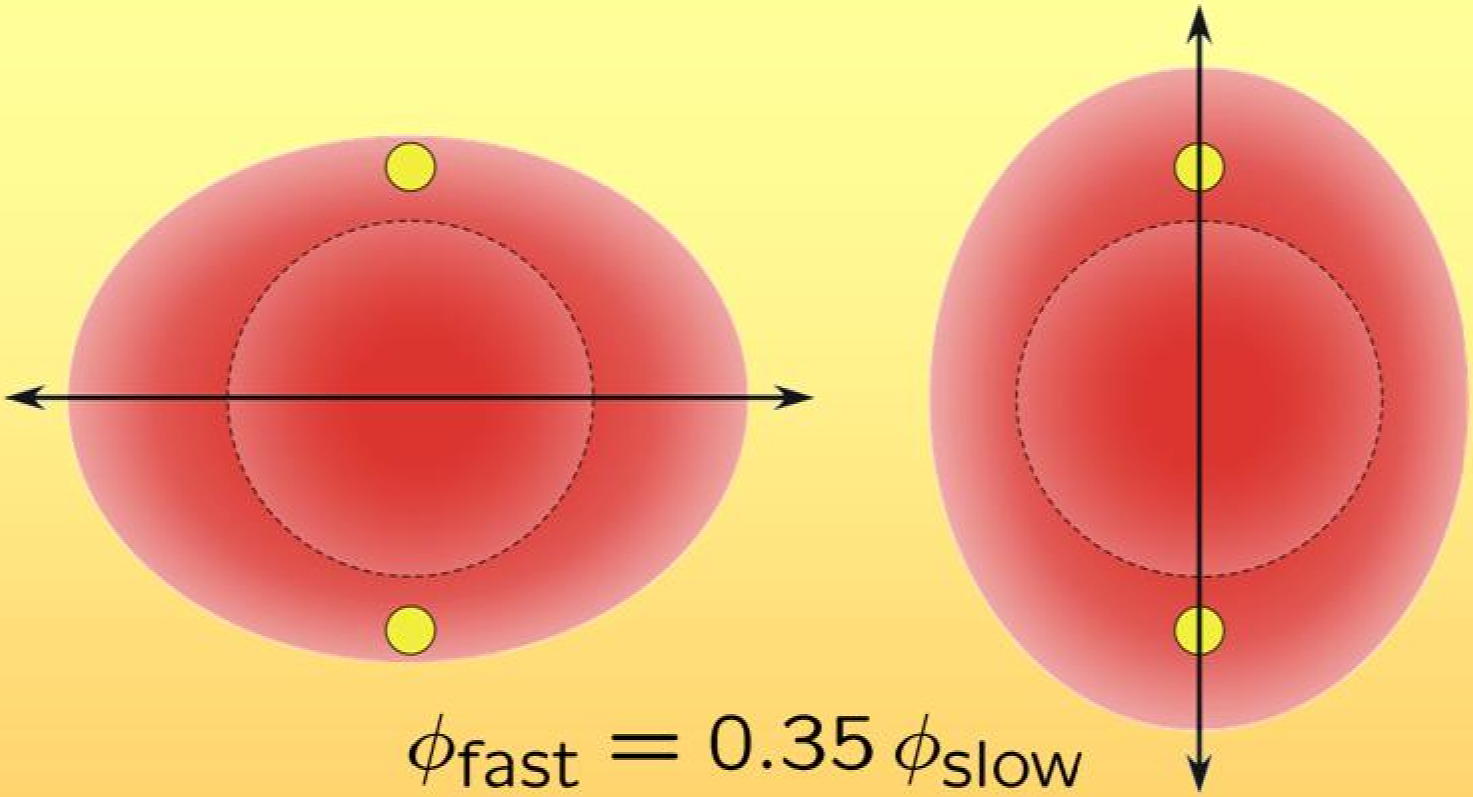
Lifetime Measurement



- Storage time ~ 50 ms
- Loss mechanism still under investigation.
- Most probably: Heating due to intensity fluctuations of the red-detuned trapping laser.

E. Vetsch *et al.*, submitted (2009)

Dispersive Measurements (Preliminary)



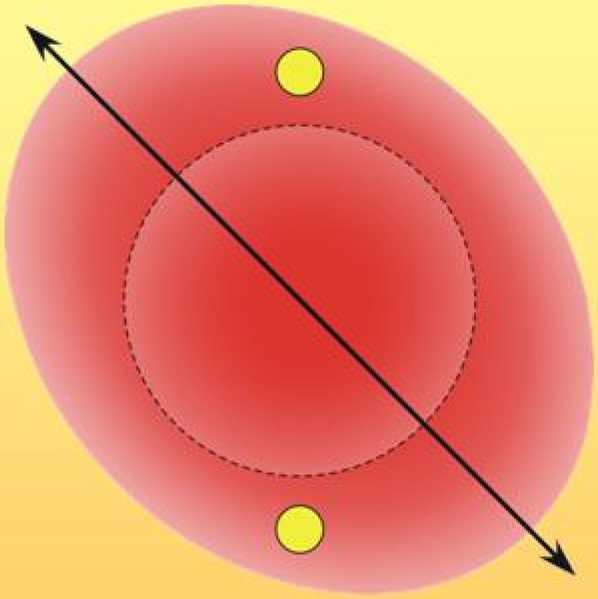
$$\phi_{\text{fast}} = 0.35\,\phi_{\text{slow}}$$

Strength of atom-light couping depends on polarization

$\Rightarrow$ dispersive interaction leads to birefringence

Dispersive Measurements (Preliminary)

Probe light polarized at 45° with respect to atomic axis:

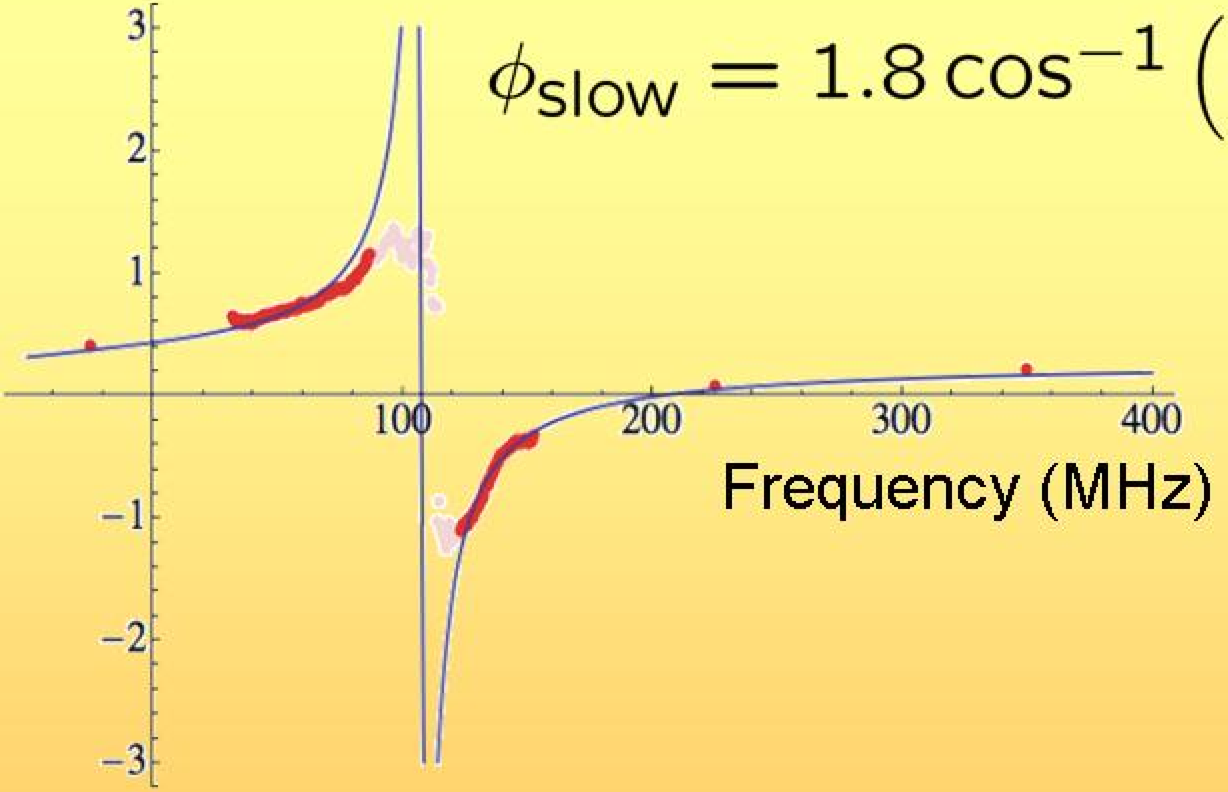


Resulting Stokes vector:

$$\begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} I \\ I\cos(\Delta\phi) \\ 0 \\ I\sin(\Delta\phi) \end{pmatrix}$$

where $\phi_{\mathrm{slow}} = 1.8\Delta\phi$

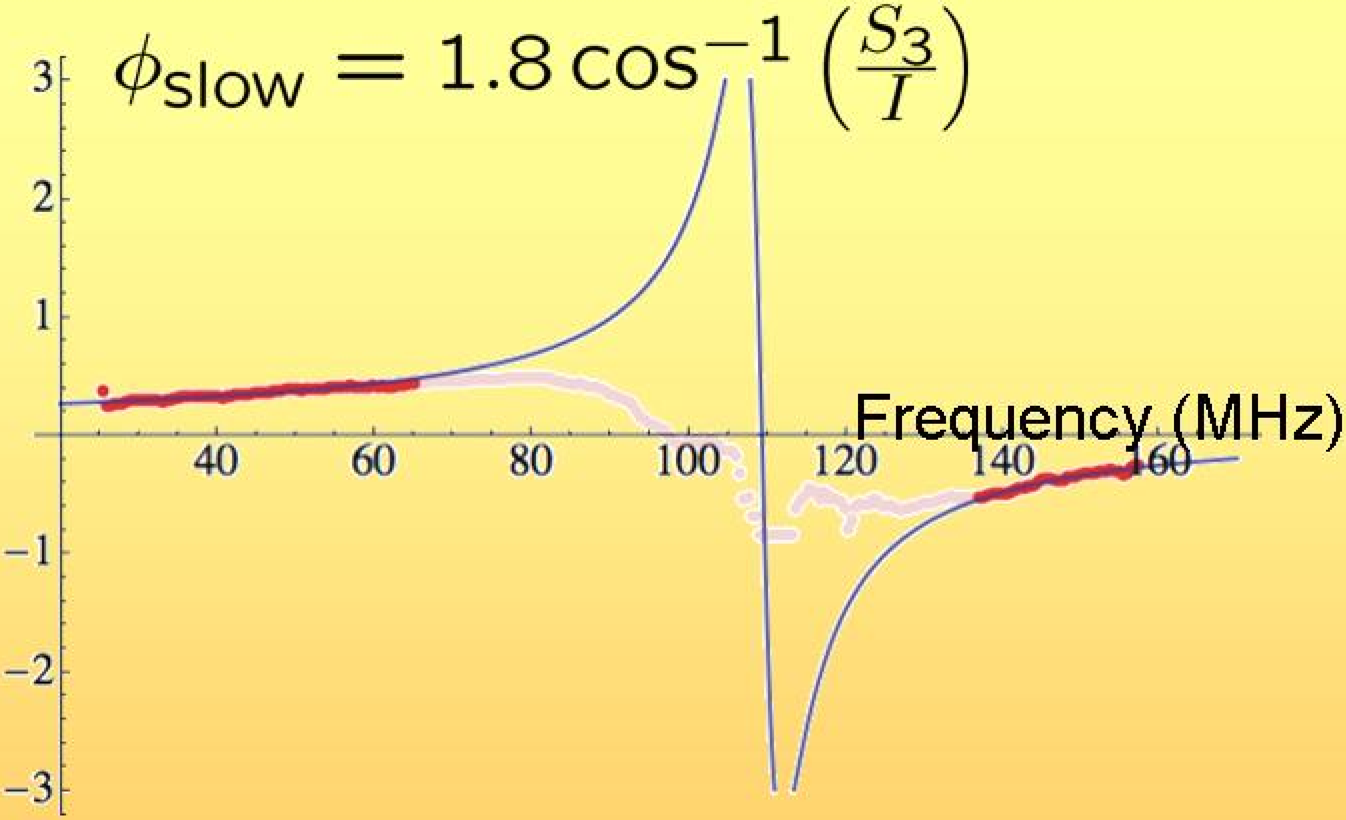
S_1 Measurement (Preliminary)



$$\phi_{\mathsf{slow}} = 1.8\cos^{-1}\left(\frac{S_1}{I}\right)$$

- Probed transition: F=4 ↔ F'=5.
- Fit assumes 5.2 MHz linewidth.
- Optical density ~ 31

S_3 Measurement (Preliminary)

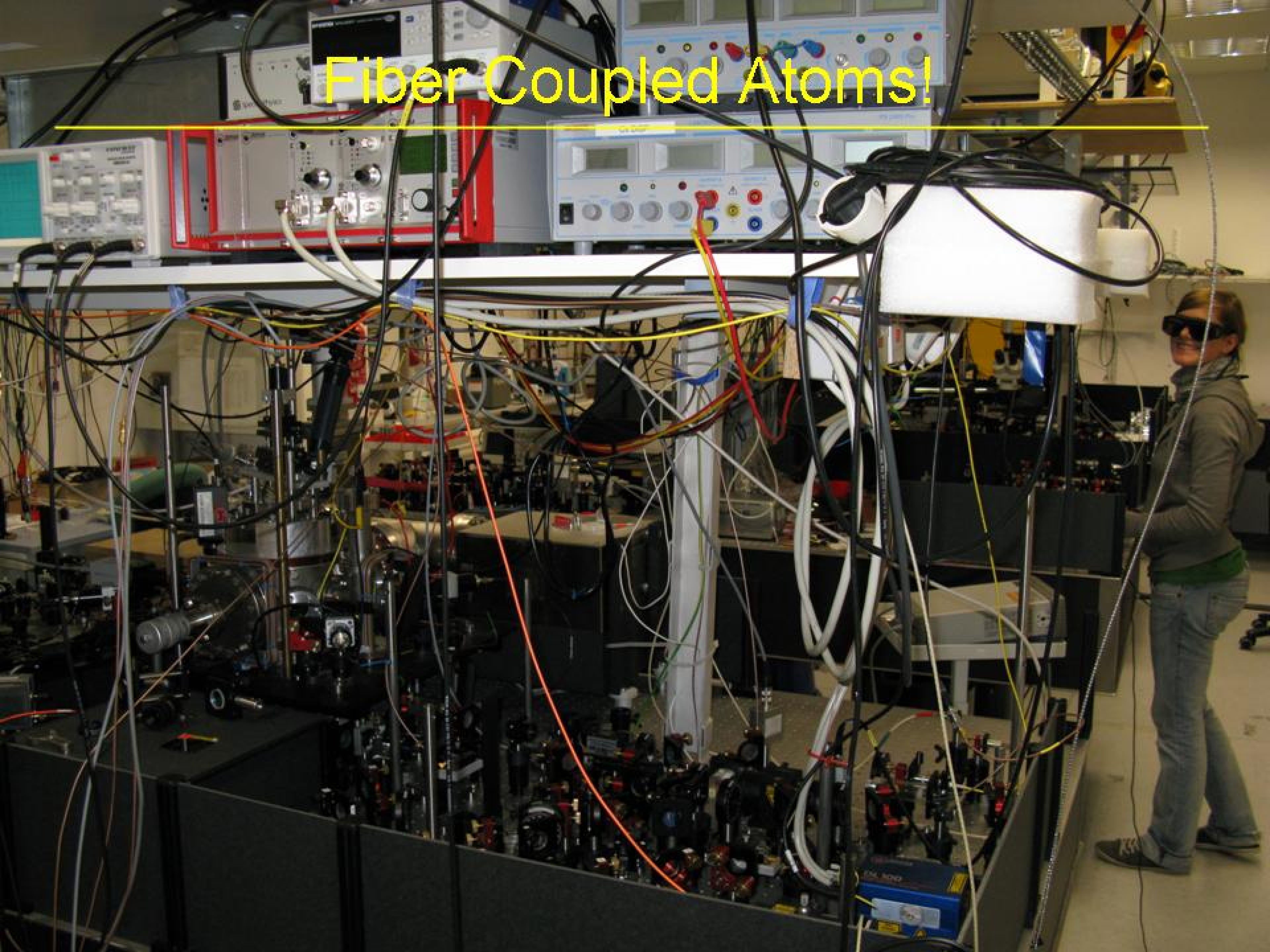


$$\phi_{\text{slow}} = 1.8 \cos^{-1}\left(\frac{S_3}{I}\right)$$

- Probed transition: F=4 ↔ F'=5.
- Fit assumes 5.2 MHz linewidth.
- Optical density ~ 22

Fiber Coupled Atoms?

Fiber Coupled Atoms!



Summary

- Optical nanofibers :
  - High quality tapered optical fibers of predetermined shape (supplied to half a dozen research groups).
- Probing cold atoms using nanofibers:
  - Detection of few-atom fluorescence from MOT via evanescent coupling to nanofiber.
  - Remarkable mode-matching between nanofiber and atoms.
  - Experimental evidence of light-induced dipole forces, surface interactions, and cavity QED effects.

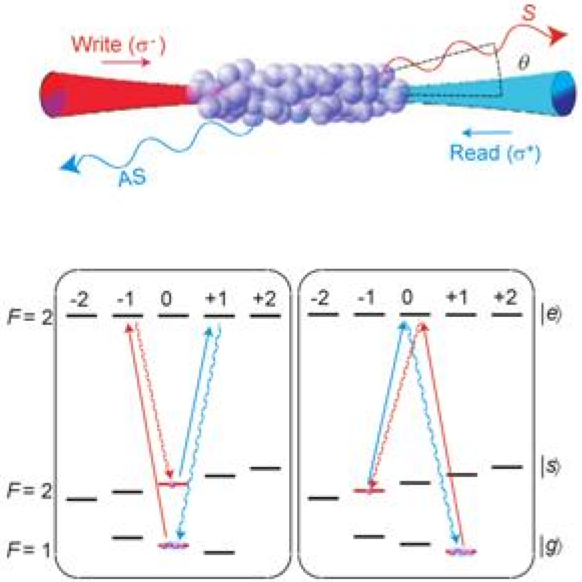
Summary

- Nanofiber-based atom trap:
  - Trapping and transport of cold atoms in the evanescent field around nanofibers.
  - Realization of optically dense ensembles of fiber-coupled atoms.
  - Atoms are trapped in 1d array of trapping minima with at most one atom per potential well (collisional blockade).
  - First dispersive (non-destructive) measurements demonstrated.

Outlook

- Quantum information:
  - Scalable quantum memories and quantum repeaters with fiber-coupled atomic ensembles.
- Bosonic many-body physics in 1d:
  - Collective excitonic states (sub- & superradiance, suppression of spontaneous emission).
  - Dark state polariton physics with variable interactions.

Quantum Memory with Atomic Ensemble



Source:

“A millisecond quantum memory for scalable quantum networks”

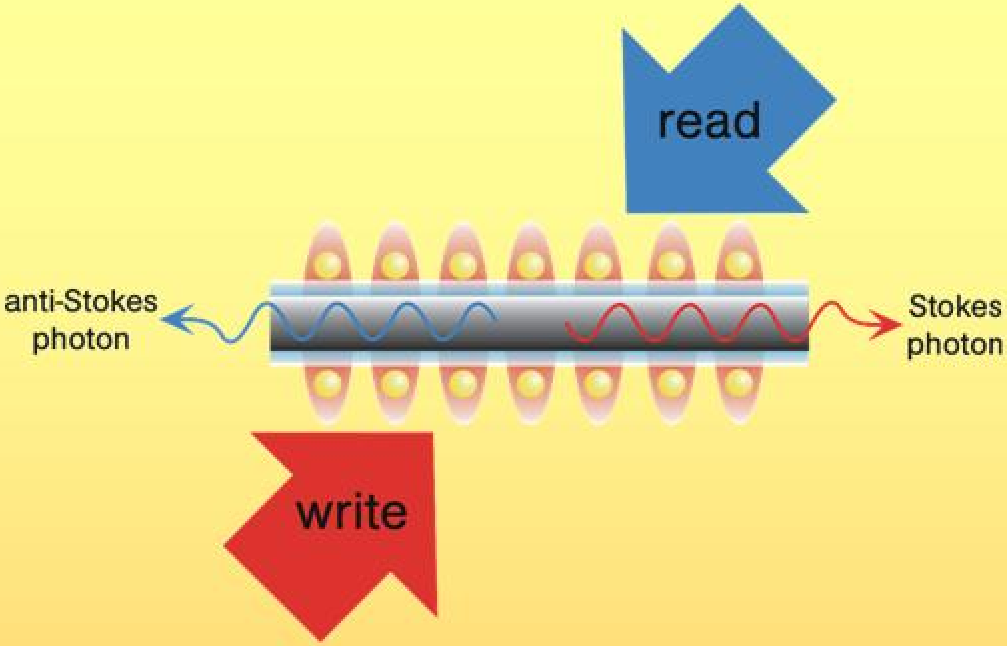
Jörg Schmiedmayer & Jian-Wei Pan et al.,

Nature Physics **5**, 95 (2009).

Experimental challenges:

- Dephasing of spin wave due to thermal atomic motion and atomic collisions limits storage time.
- Mode matching and fiber coupling with free beam optics limits photon collection efficiency.

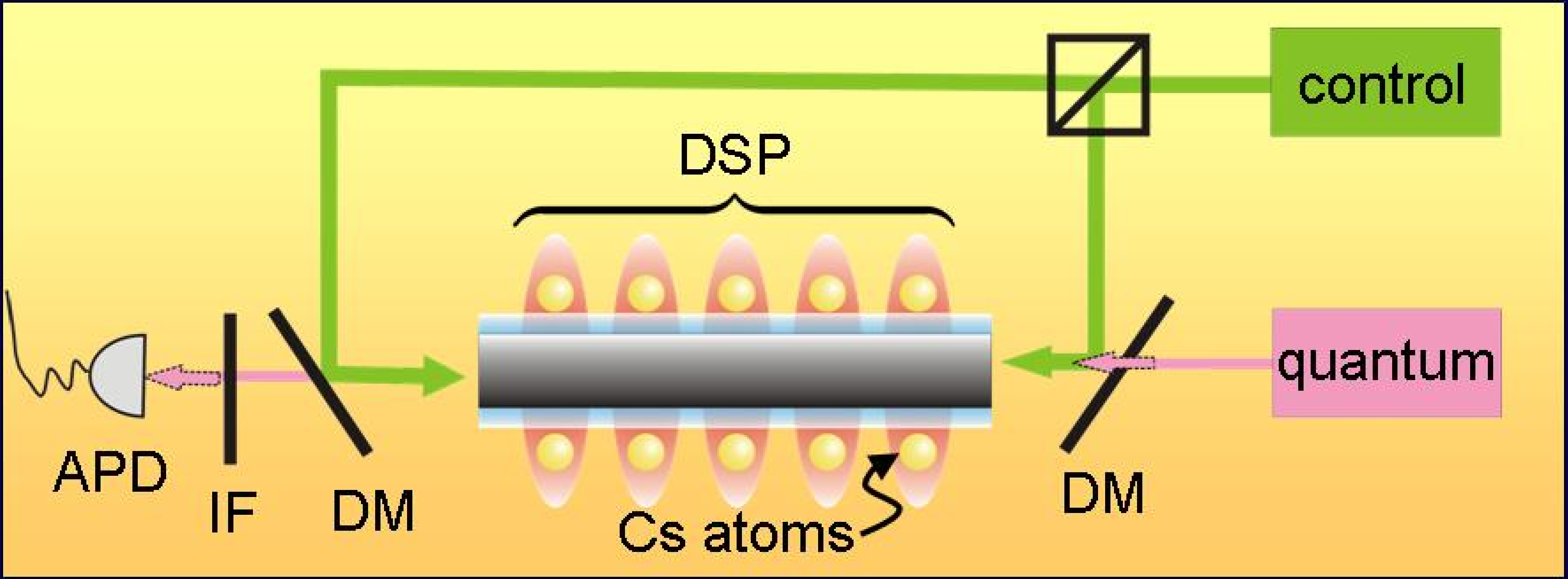
Fiber-Coupled Quantum Memory



Major experimental advantages:

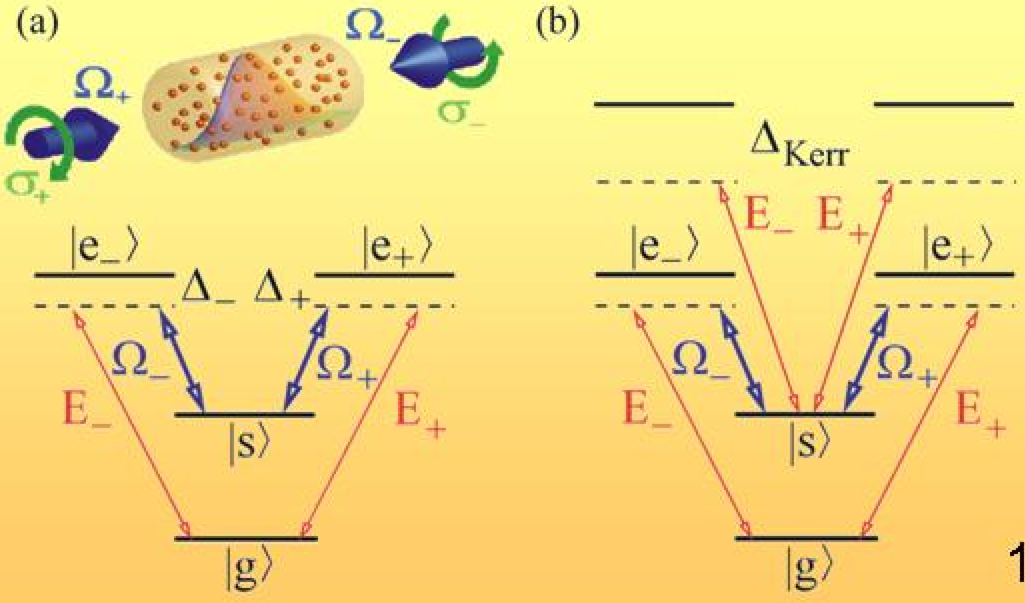
- No thermal motion and collisions (atoms are trapped in optical lattice with filling factor of 1/2).
- Quantum fields are intrinsically mode matched and coupled into single mode optical fiber.

Dark State Polariton Physics



- Coherently prepared atomic ensemble + quantum field $\Rightarrow$ light-matter quasi particles: dark state polaritons (DSPs).

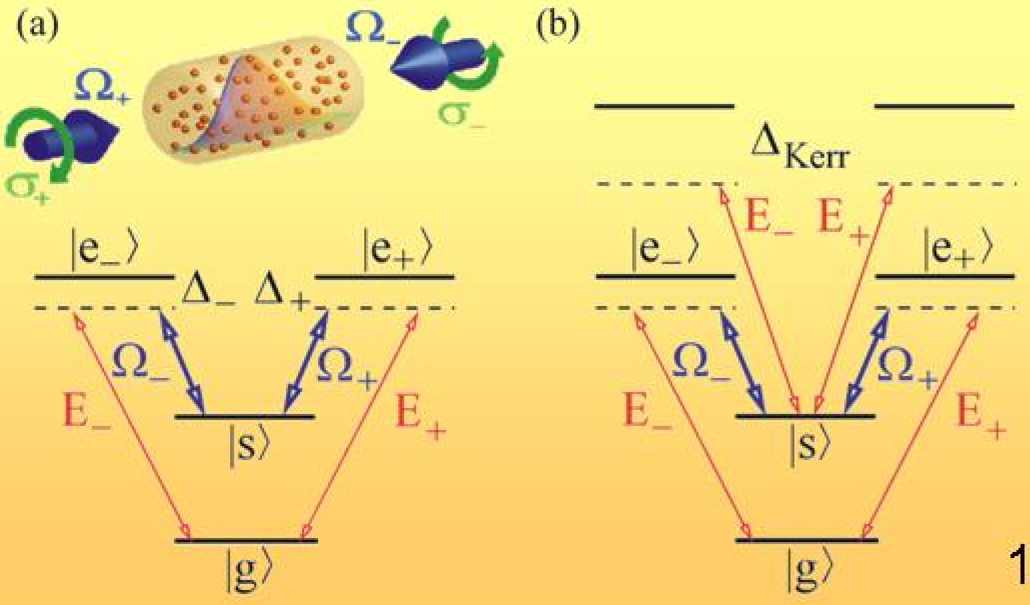
Dark State Polariton Physics



PRL **101**, 163601 (2008)

- Coherently prepared atomic ensemble + quantum field $\Rightarrow$ light-matter quasi particles: dark state polaritons (DSPs).
- DSP dynamics $\leftrightarrow$ non-linear Schrödinger equation.
- Sign and absolute value of the DSP effective mass and of the interaction strength fixed by classical control field.

Dark State Polariton Physics



PRL **101**, 163601 (2008)

- Theoretically predicted: Bose-Einstein condensation, Tonks–Girardeau regime (“crystallization of photons”), vortex lattices, anyonic statistics, bosonic analogue of fractional quantum Hall effect, ...
- Dark state polariton physics $\leftrightarrow$ bosonic many-body physics with variable interactions.

People

Students: Christian Hauswald, Christian Junge, Nils Konken, Rudolf Mitsch, Melanie Müller, Sebastian Nickel, David Papencordt, Jan Petersen, Michael Pöllinger, Daniel Reitz, Danny O'Shea, Ariane Stiebeiner, Eugen Vetsch, Christian Wagner, Christian Wuttke

Post-Doc: Sam Dawkins   Lecturer: Ruth García Fernández

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DFG
: Research Unit 557

: Research Training Network “FASTNet”

Thank you…

… for your attention.