Top

Left side

TEST

Right side

bottom

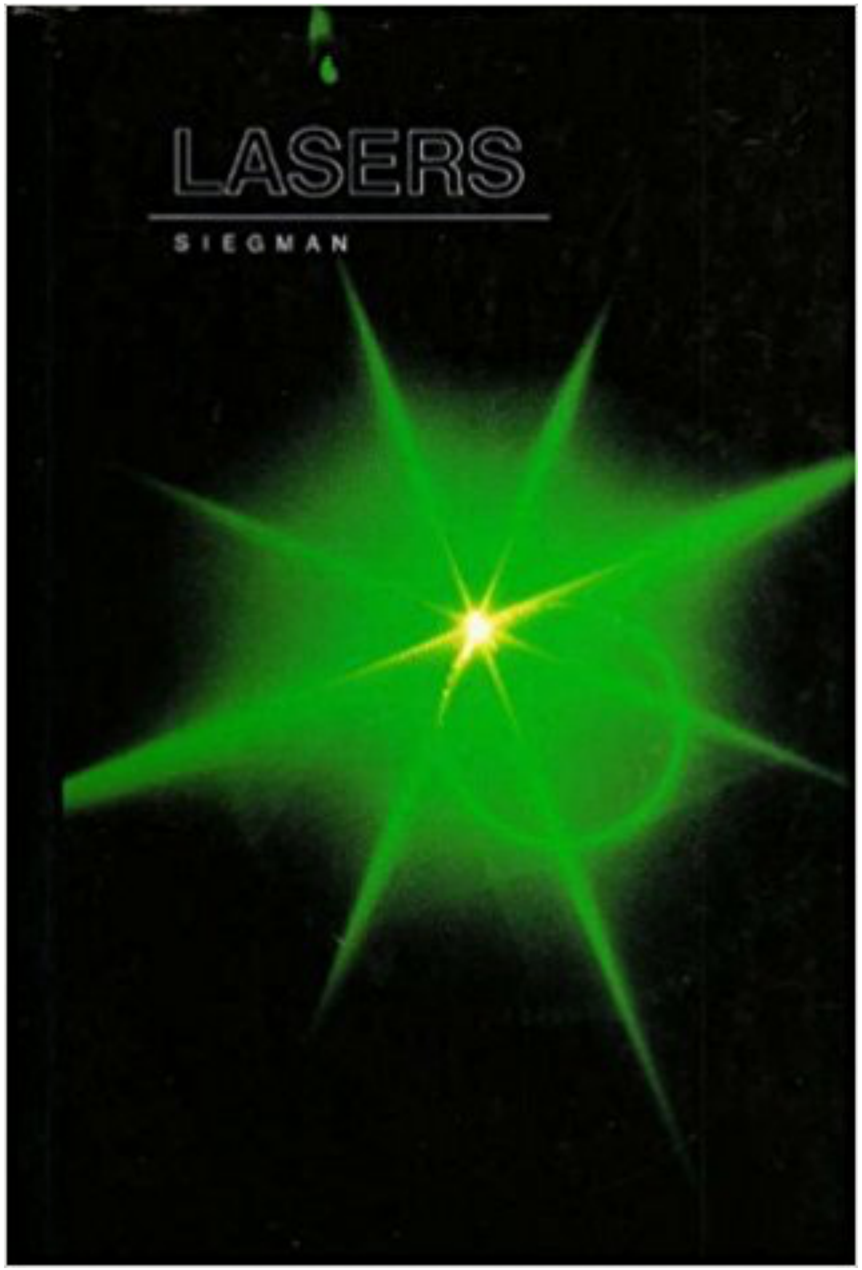
Laser applications to the study of atomic quantum structure.

2017 OSA Siegman International School on Lasers, Lecture 3

CIO, León, México, August 2017

Luis A. Orozco

www.jqi.umd.edu



Anthony E Siegman
(1931-2011)

Plan of the course:

1st lecture: Introduction to the interaction of light with atoms, (nanofibers).

2nd lecture: Atom-light interaction of a two level atom (nanofibers at low intensity).

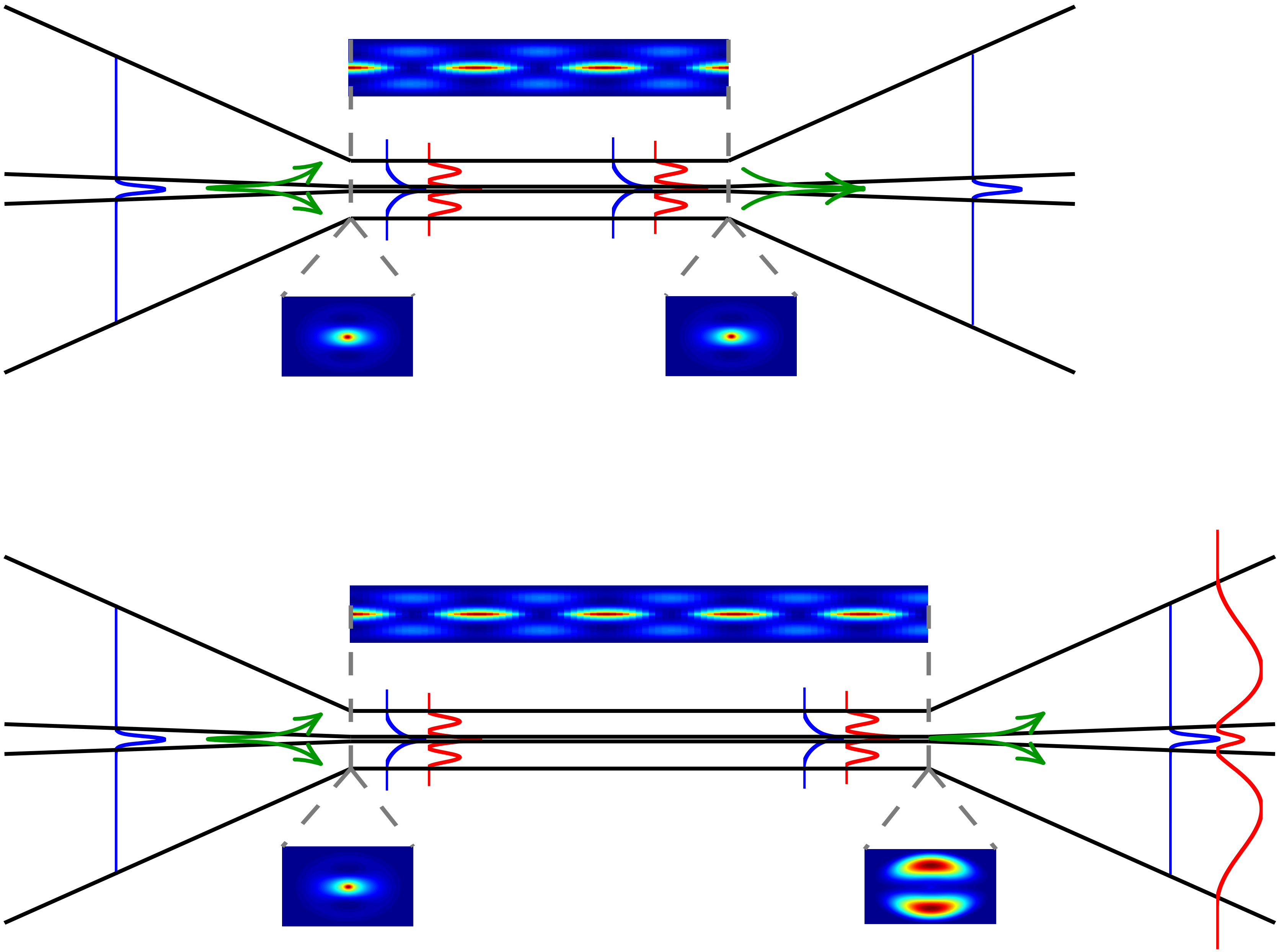
3rd lecture: Atom-light interaction of a two level atom (QO, cavity QED).

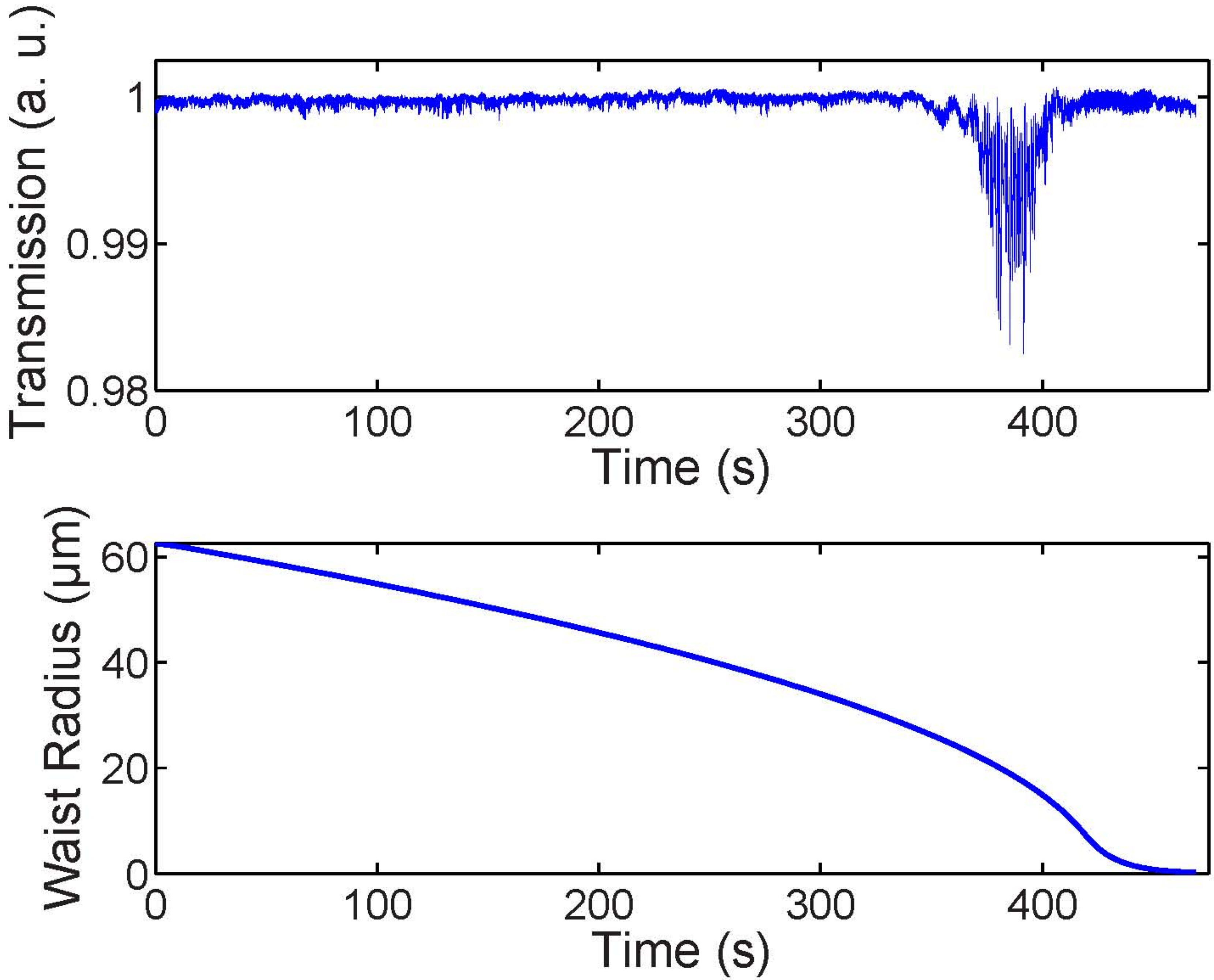
4th lecture: Different types of laser traps for atoms, (nanofibers, cavity QED, and spectroscopy).

5th lecture: Weak interaction studies with Fr, a proposal.

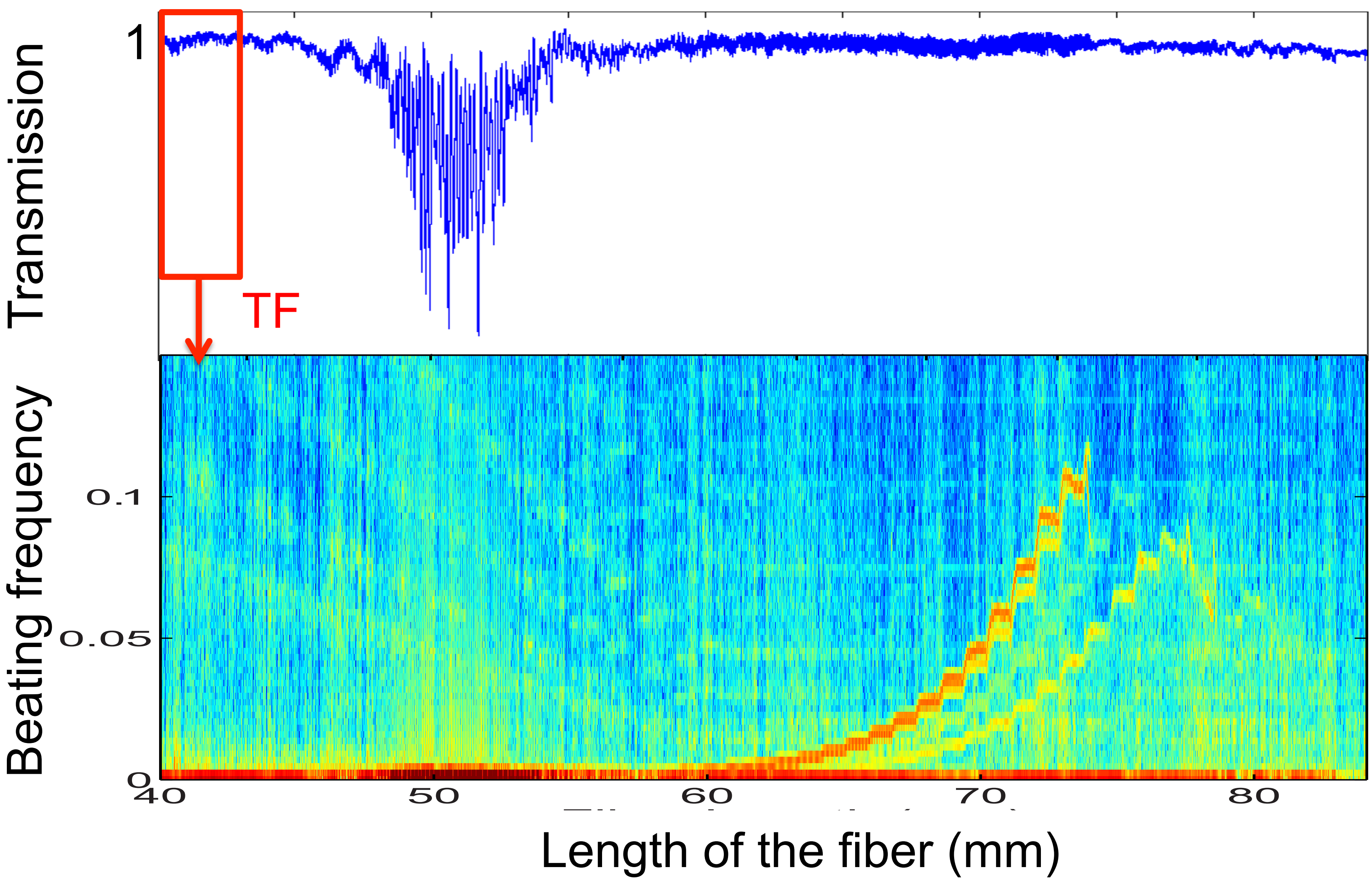
More about beatings in nanofibers.

Mode beating

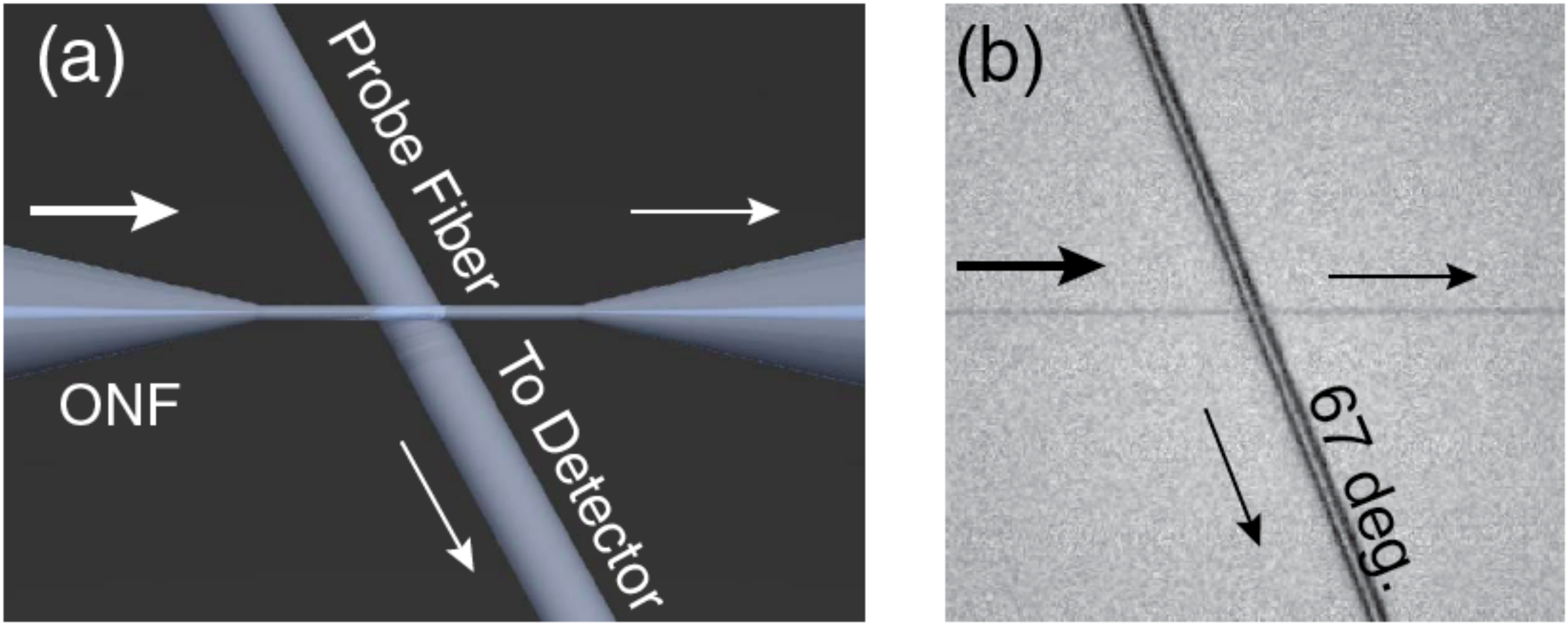



Transmission (a. u.)
1
0.99
0.98
0
100
200
300
400
Time (s)
Waist Radius (μm)
60
40
20
0
0
100
200
300
400
Time (s)

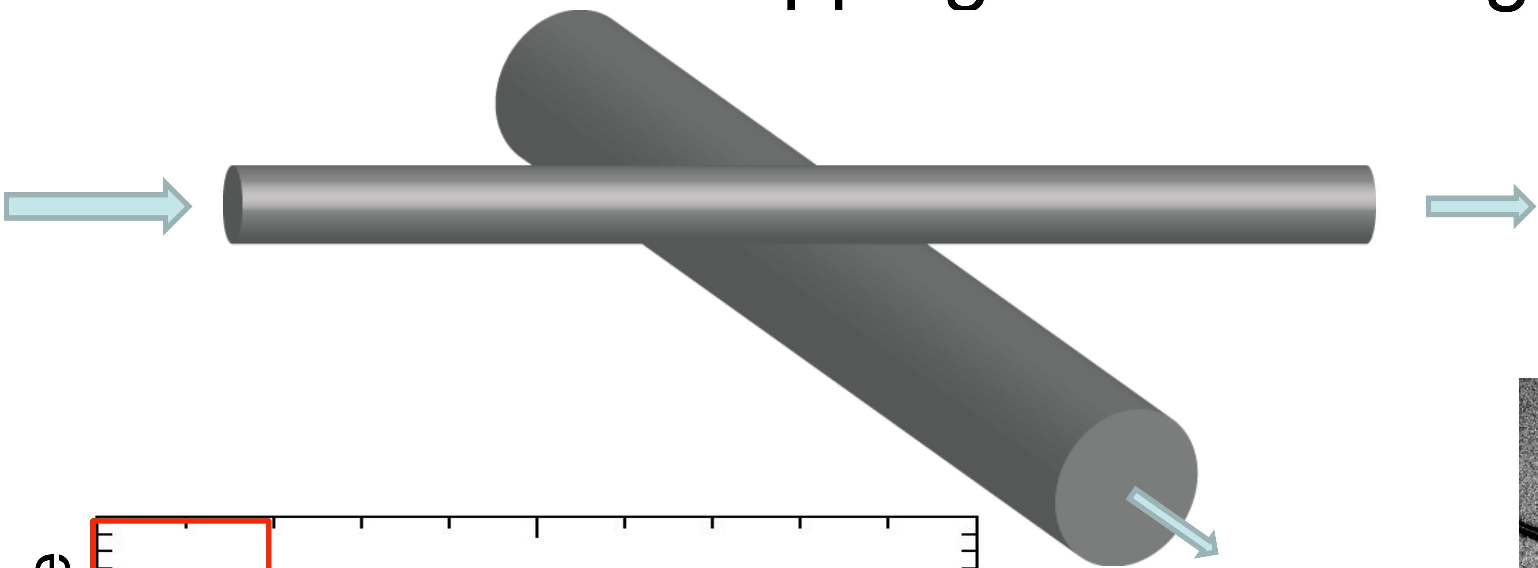
Espectrogram

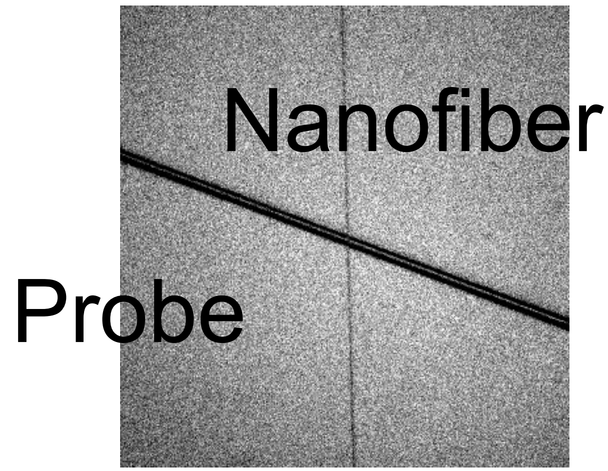


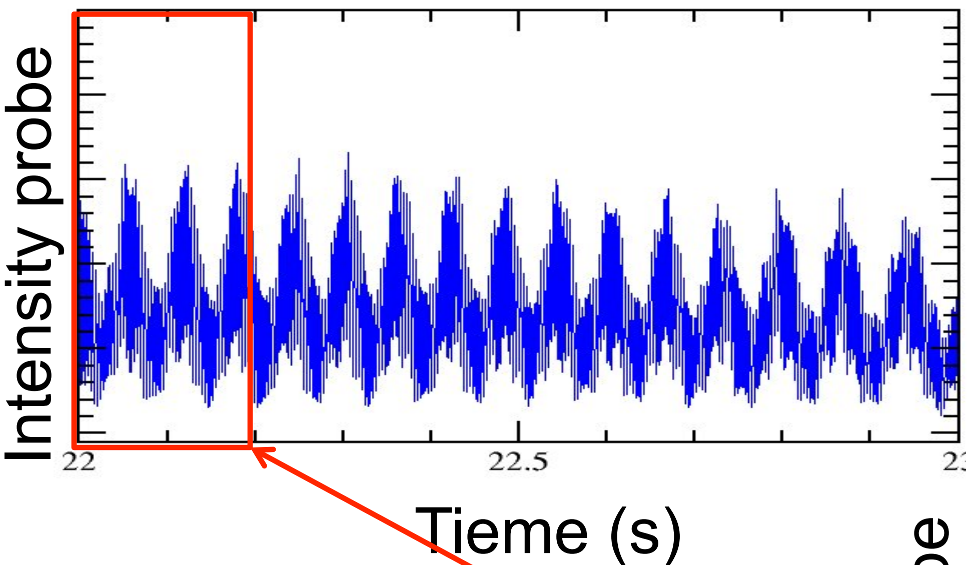
Evanescent coupling

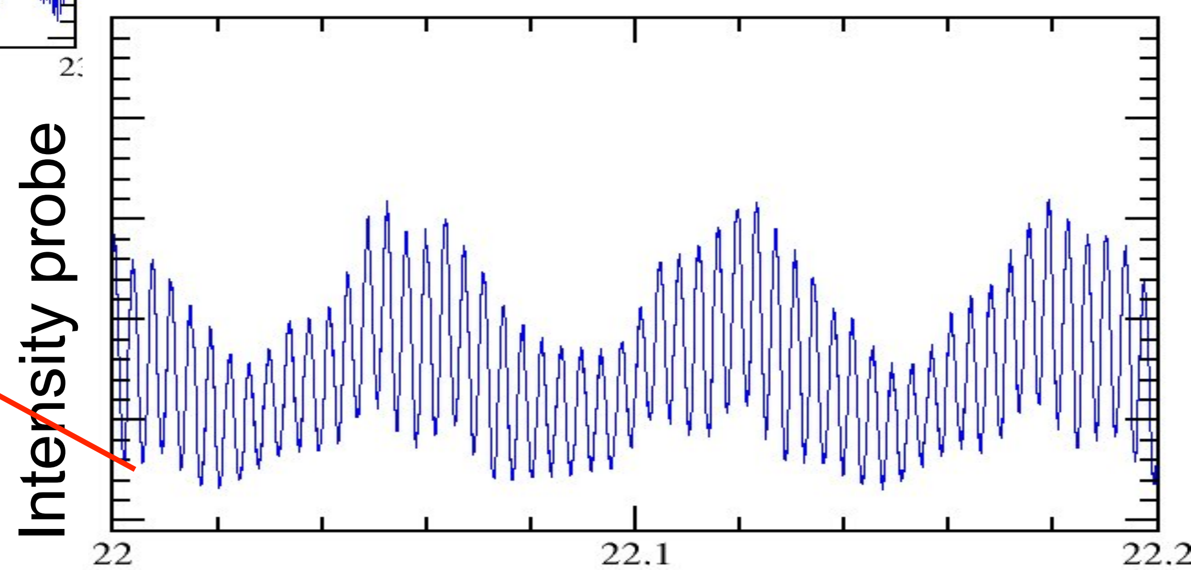


Direct mapping of the beating

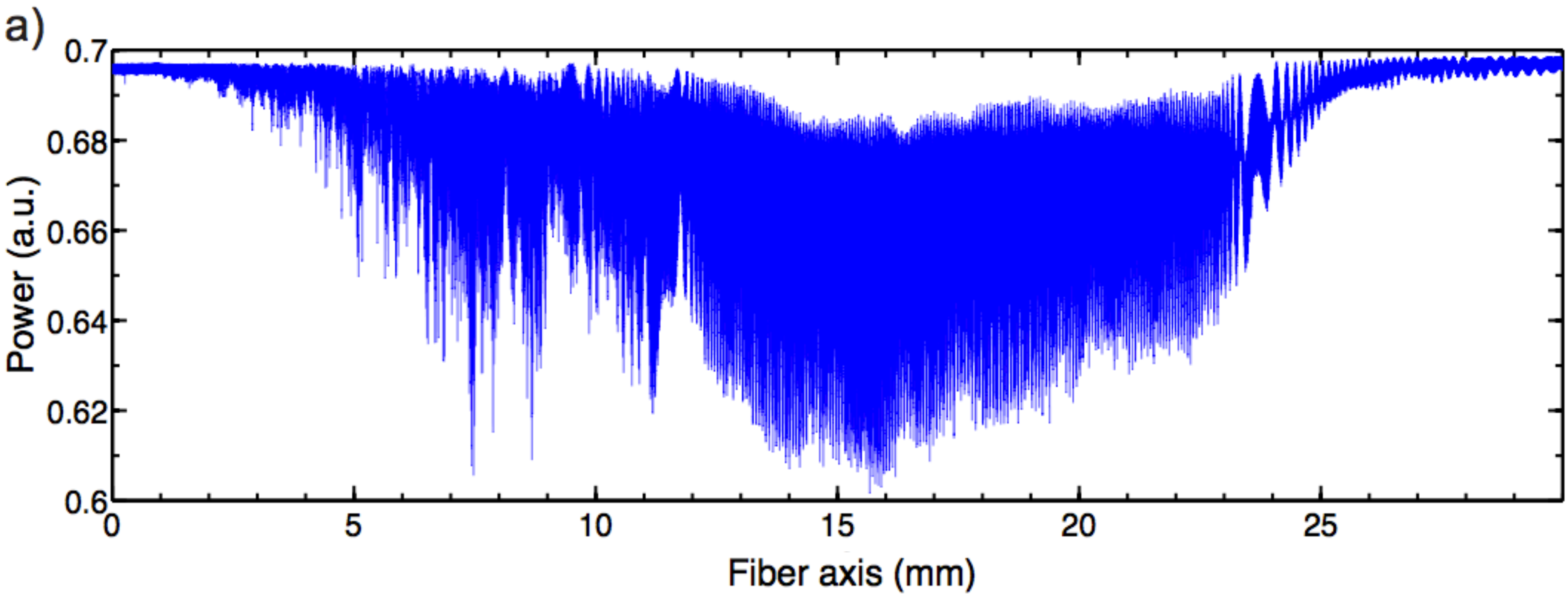




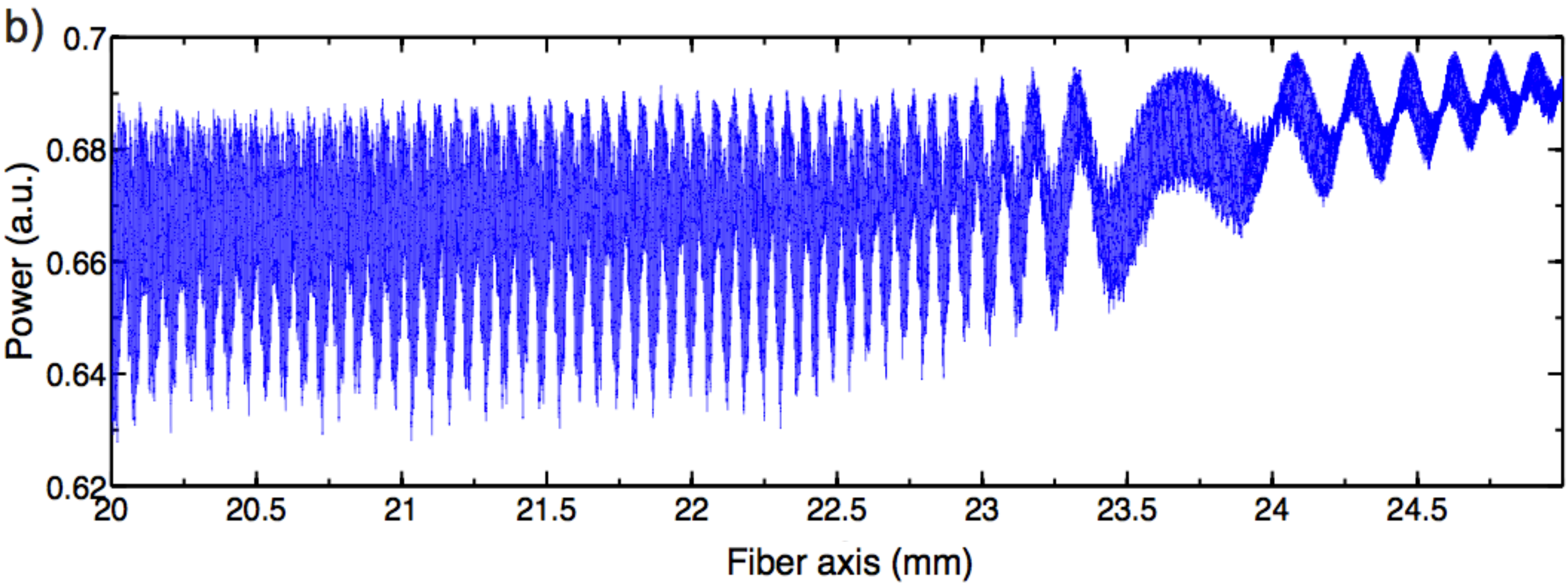




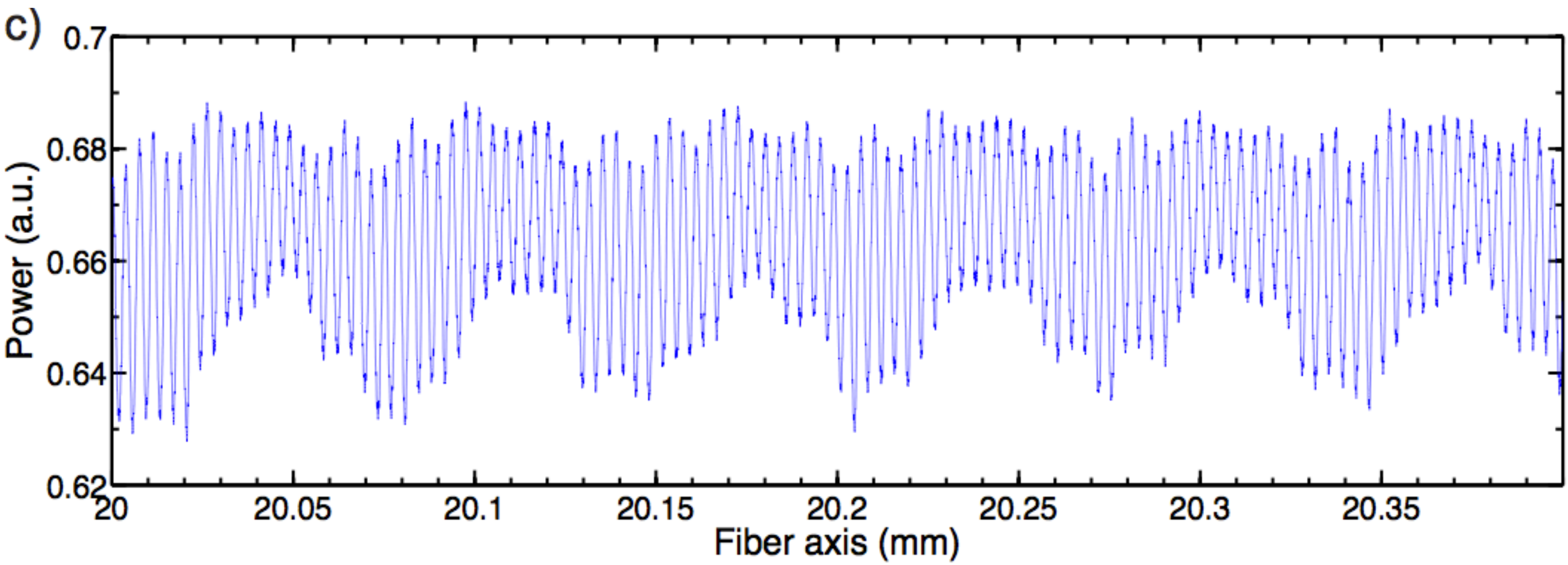
Transmitted light out of the probe

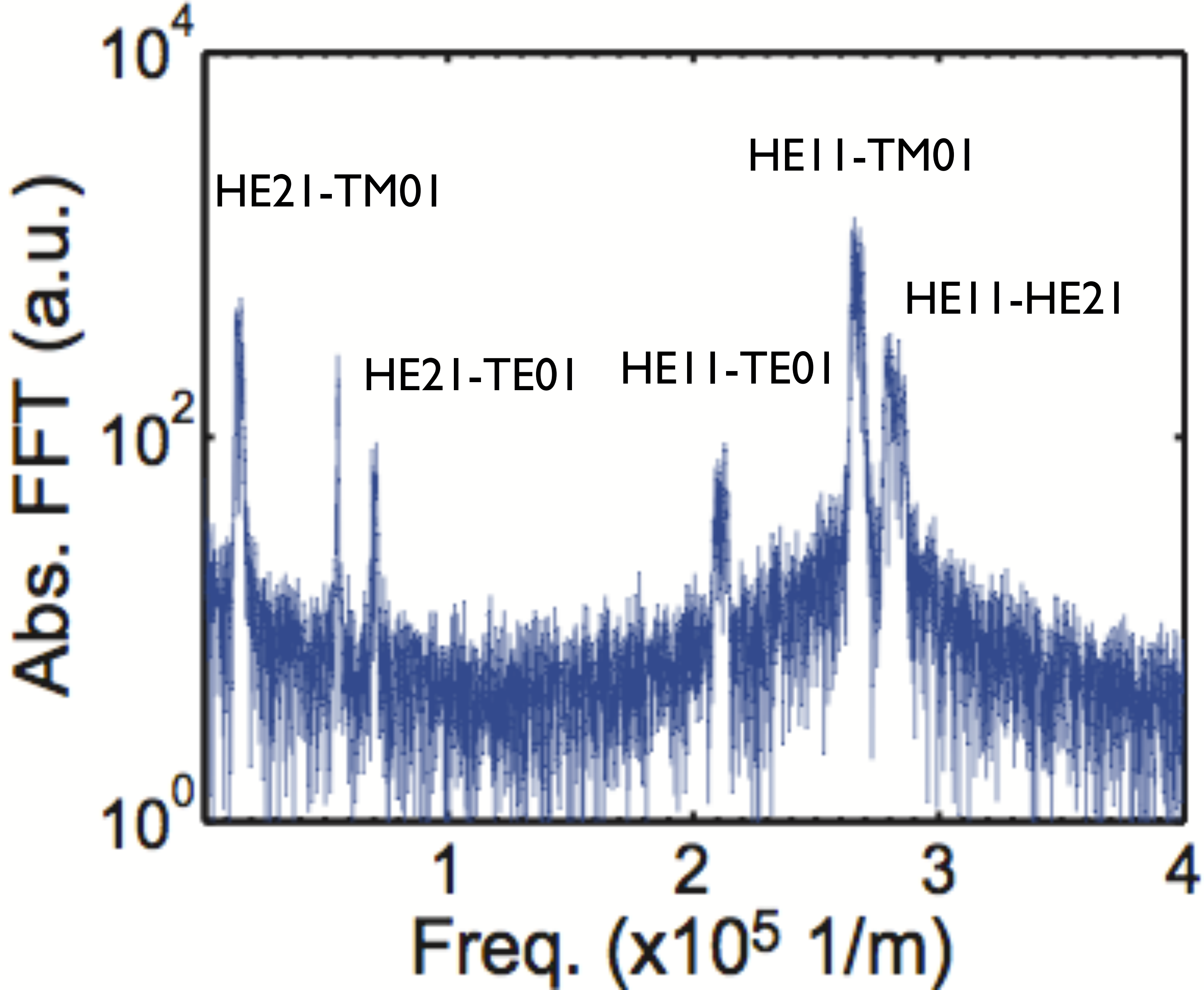


Transmitted light out of the probe

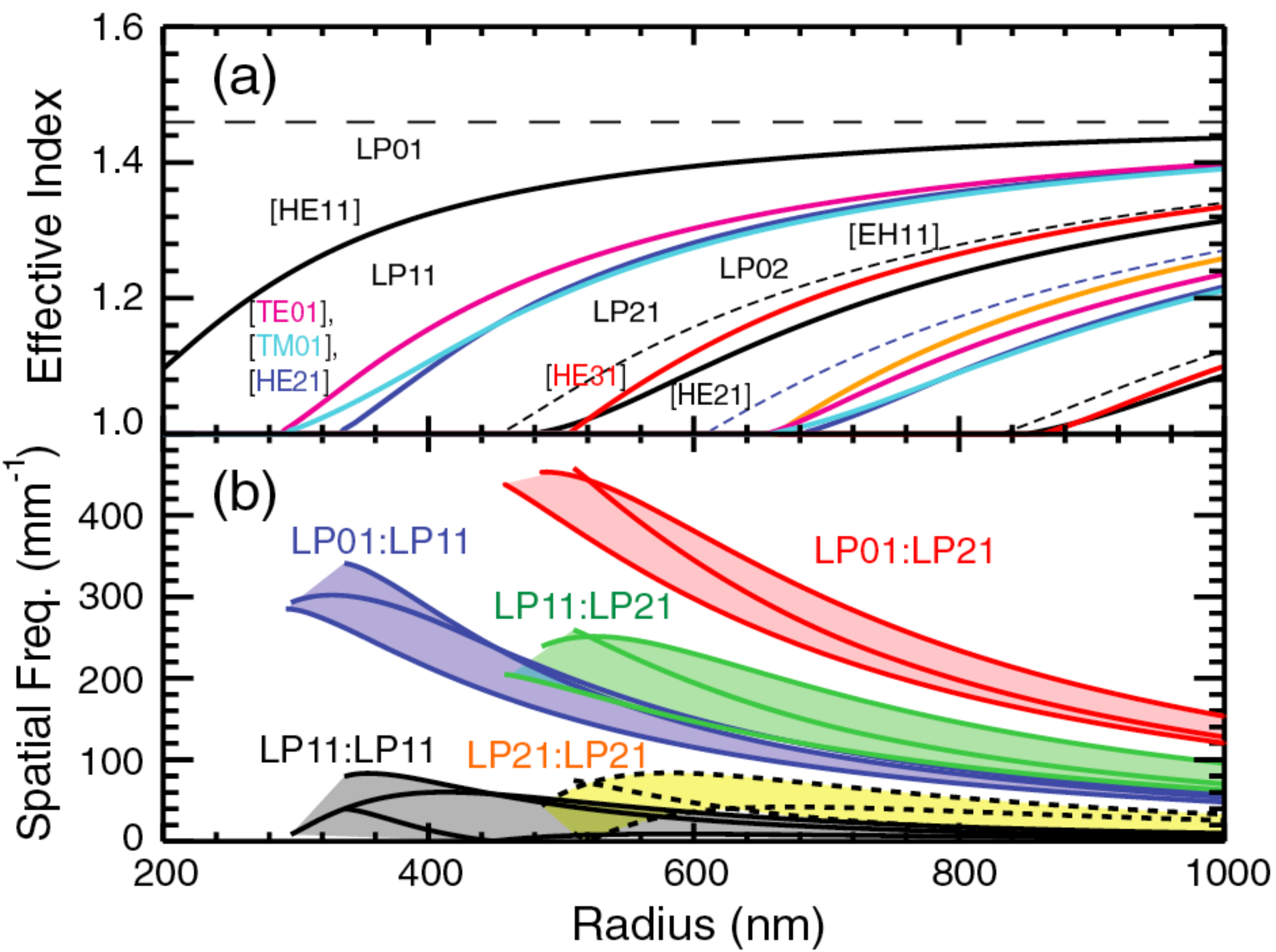


Transmitted light out of the probe



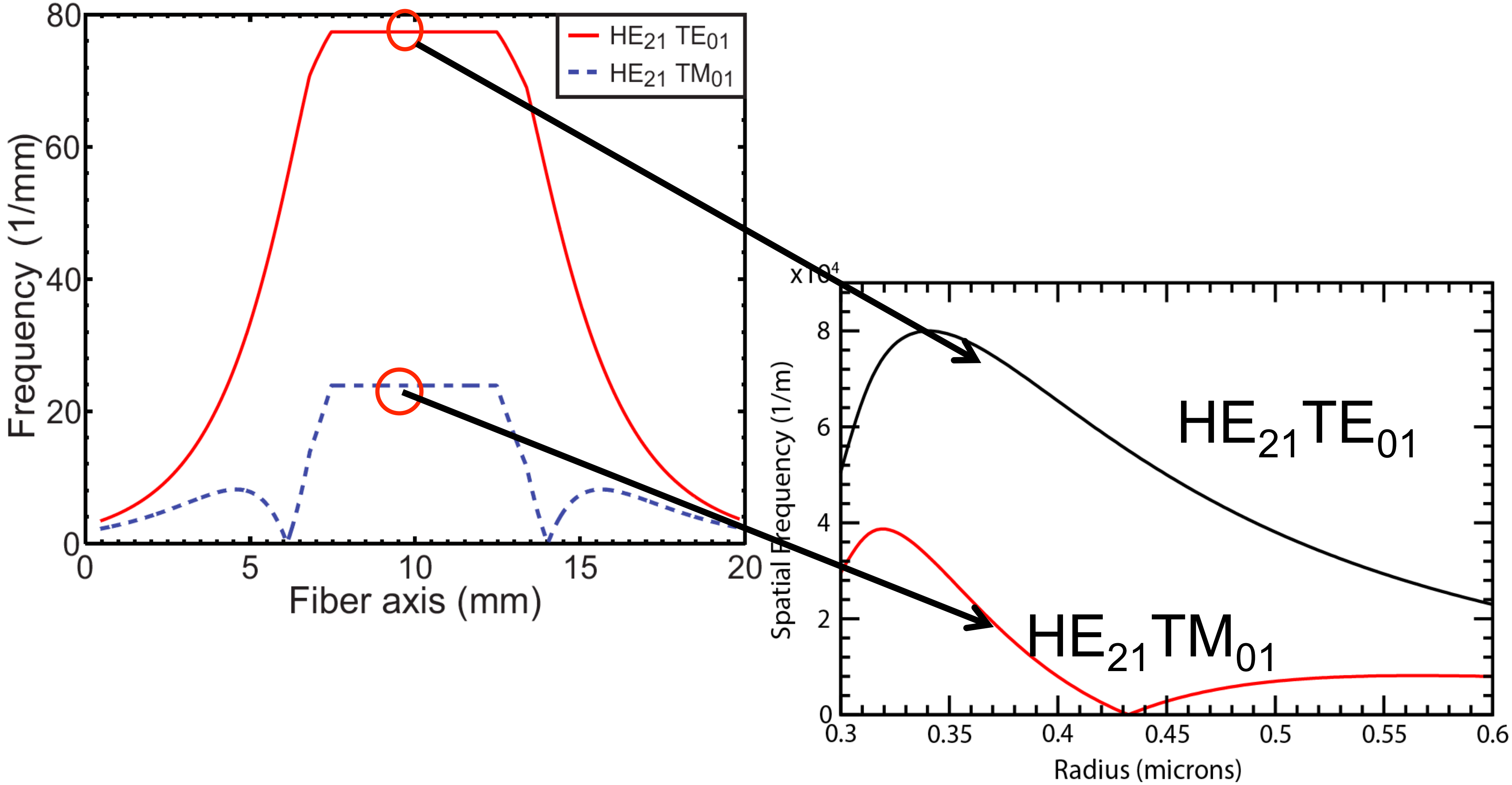


HE21-TM01
HE11-TM01
HE11-HE21
HE21-TE01
HE11-TE01
10^4
10^2
10^0
Abs. FFT (a.u.)
1
2
3
4
Freq. (x10^5 1/m)

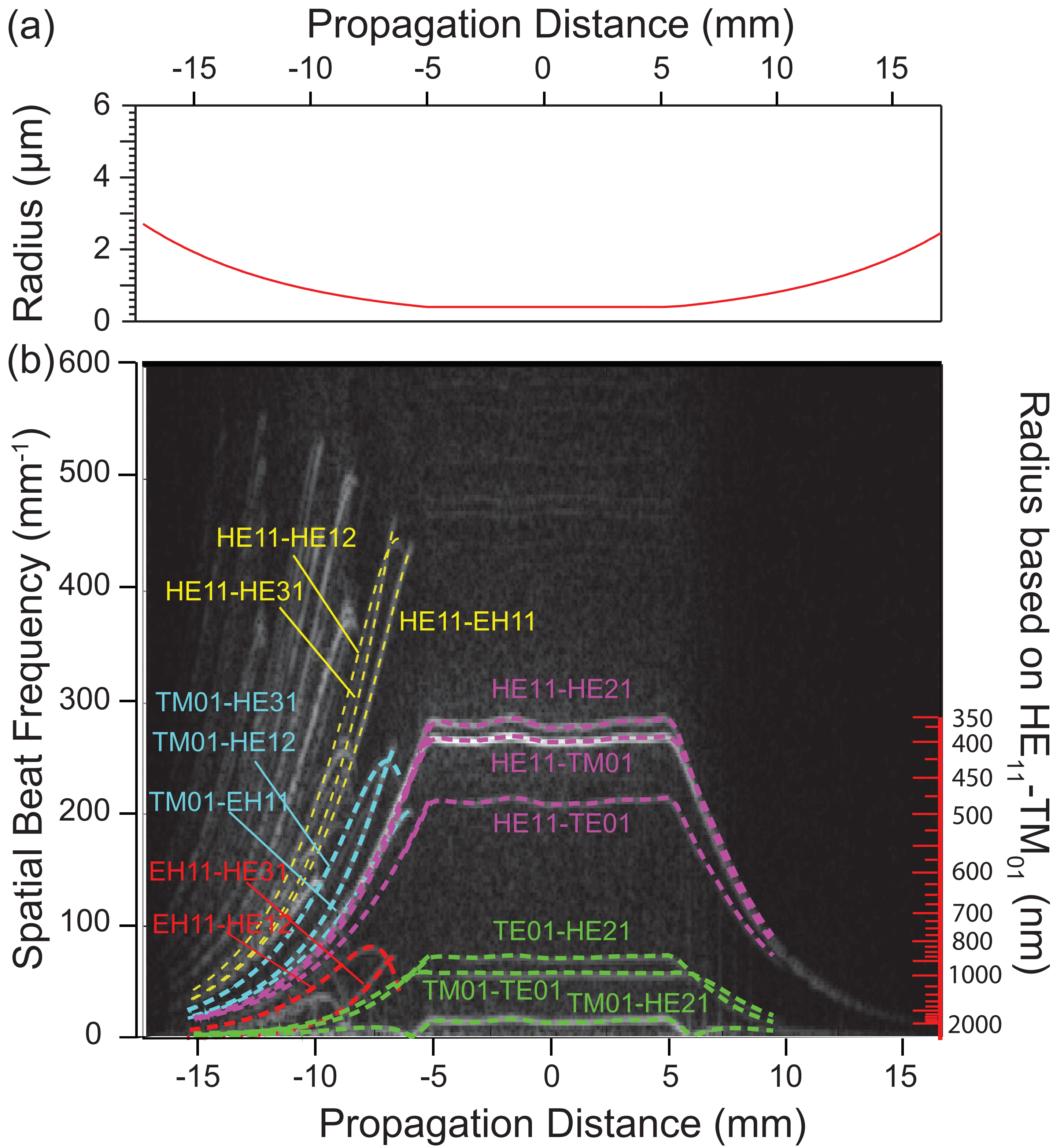


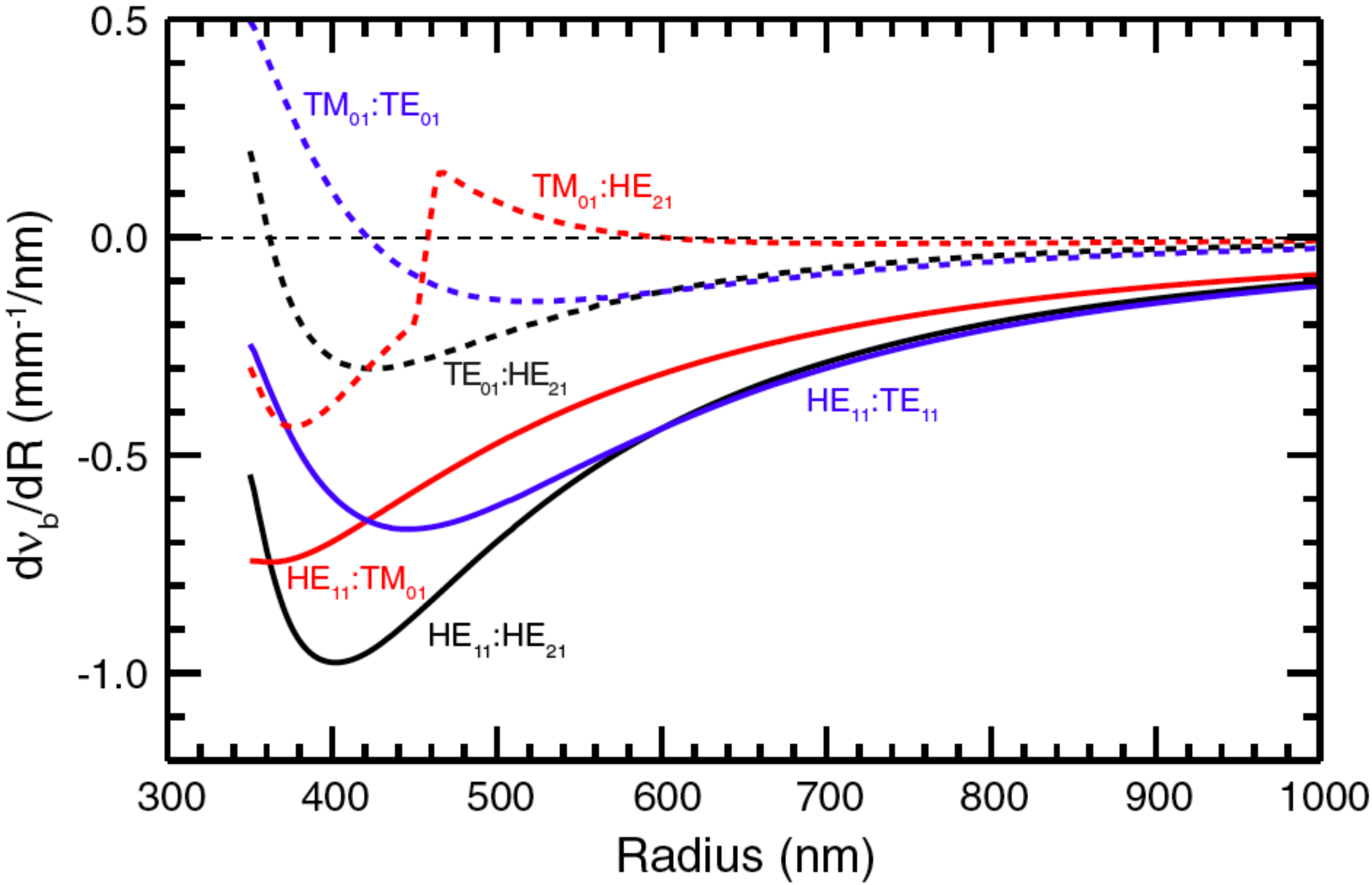
1.6
1.4
1.2
1.0
(a)
Effective Index
LP01
[HE11]
LP11
[TE01],
[TM01],
[HE21]
LP21
[HE31]
[EH11]
LP02
[HE21]
(b)
Spatial Freq. (mm⁻¹)
400
300
200
100
0
LP01:LP11
LP01:LP21
LP11:LP21
LP11:LP11
LP21:LP21
200
400
600
800
1000
Radius (nm)

Spectrogram



The beat frequencies of the spatial modes depend on the radius, (structured illumination microscopy)

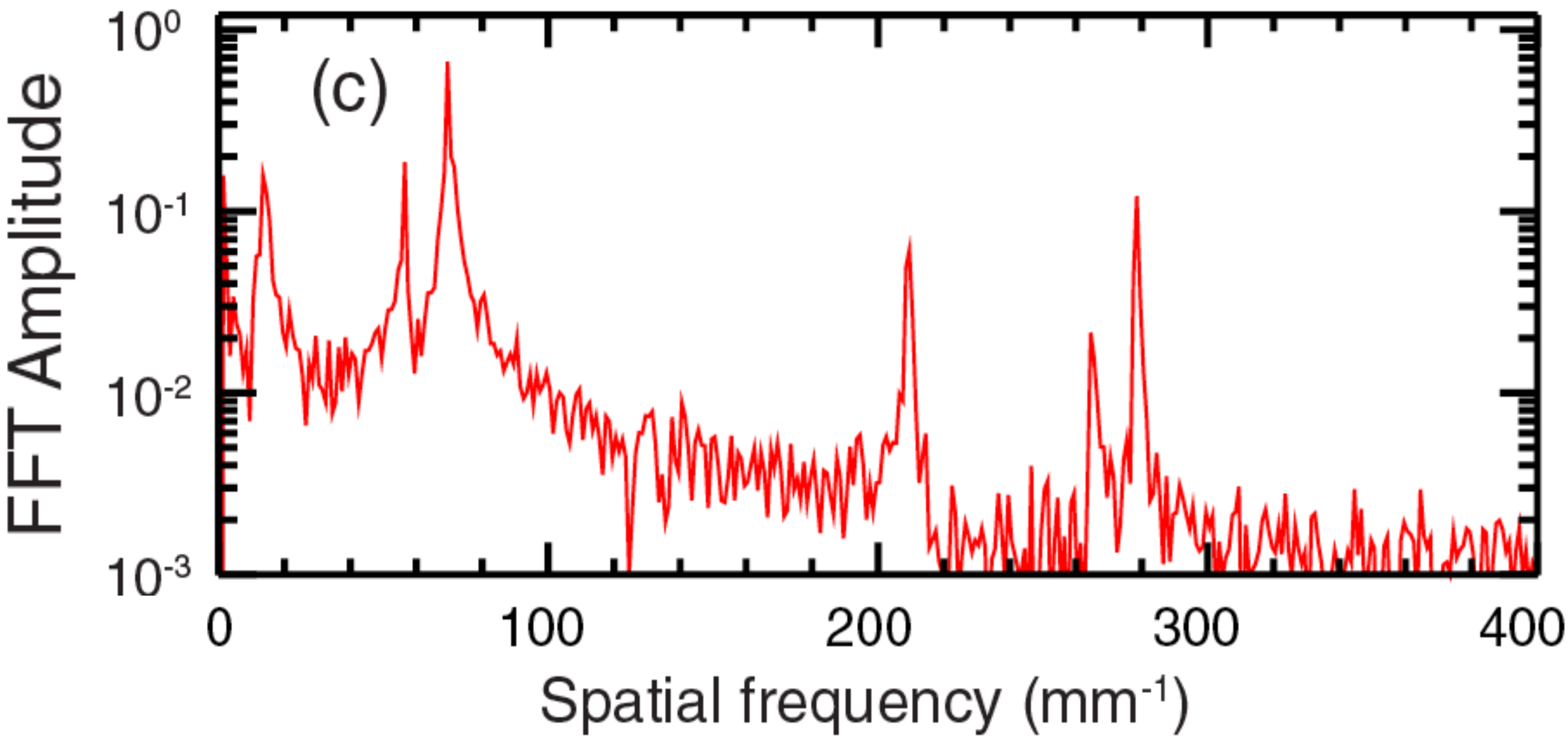

(a)
Propagation Distance (mm)
-15
-10
-5
0
5
10
15
Radius (µm)
6
4
2
0
(b)
600
500
400
300
200
100
0
Spatial Beat Frequency (mm-1)
HE11-HE12
HE11-HE31
HE11-EH11
TM01-HE31
TM01-HE12
TM01-EH11
EH11-HE31
EH11-HE12
HE11-HE21
HE11-TM01
HE11-TE01
TE01-HE21
TM01-TE01
TM01-HE21
Radius based on HE11-TM01 (nm)
350
400
450
500
600
700
800
1000
2000
-15
-10
-5
0
5
10
15
Propagation Distance (mm)



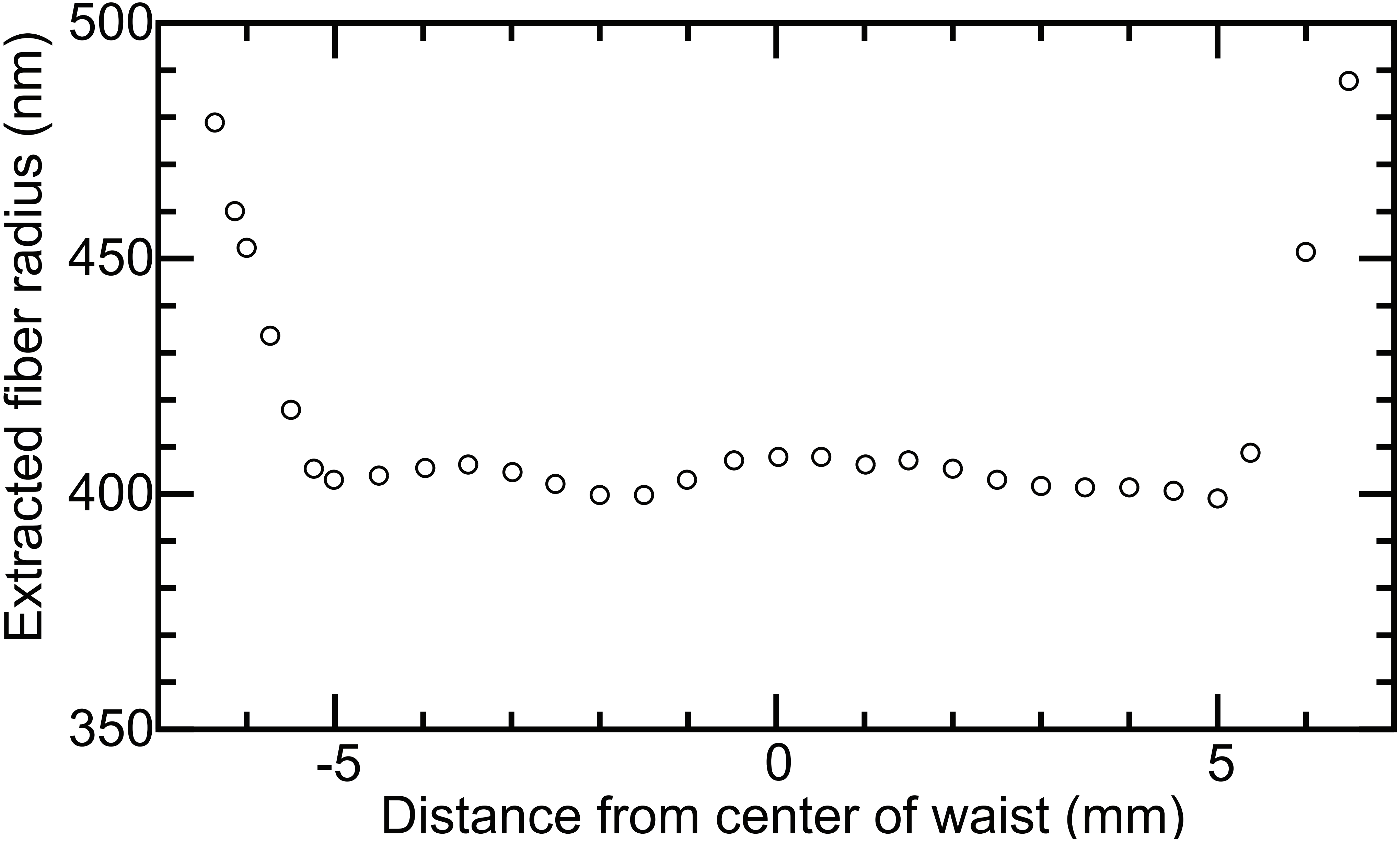
0.5
0.0
-0.5
-1.0
300
400
500
600
700
800
900
1000
Radius (nm)
$d\nu_b/dR$ (mm^{-1}/nm)
$TM_{01}:TE_{01}$
$TM_{01}:HE_{21}$
$TE_{01}:HE_{21}$
$HE_{11}:TE_{11}$
$HE_{11}:TM_{01}$
$HE_{11}:HE_{21}$

ŏ

FFT within the length of 300 μm



Extraction of the radious from the beating frequency with resolution better than 1 angstrom.



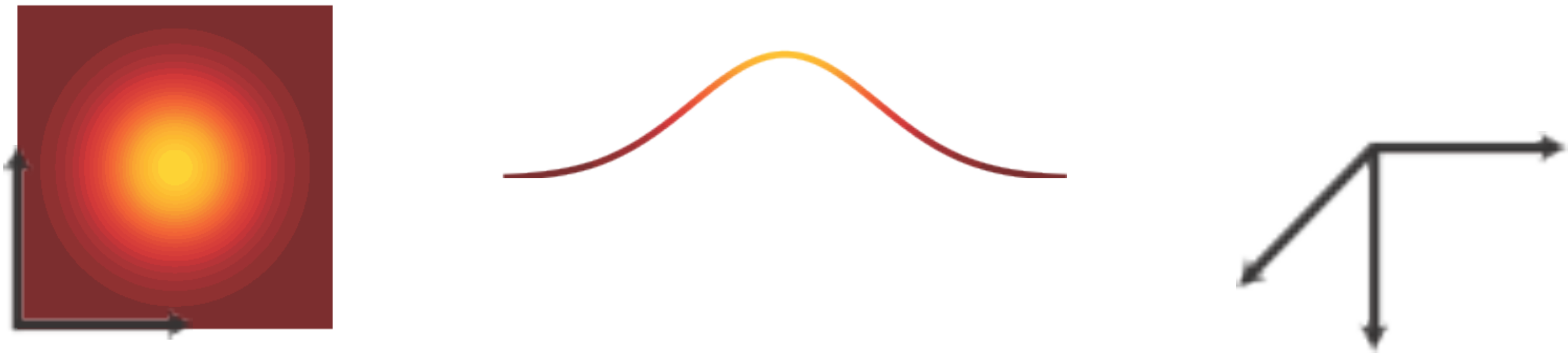
Bibliography 4rd lesson:

1. “Proceedings of the International School of Physics Enrico Fermi Course CXVIII,” Edited by E. Arimondo, W. D. Phillips, and F. Strumiea, North Holland (Amsterdam 1991), Contributions by W. D. Phillips, Claude C. Tannoudji, S. Chu.
2. W. D. Phillips, “Nobel Lecturre: Laser coolingg and trapping of neutral atoms,” Rev. Mod. Physc. 70, 721 (1998).
3. H. J. Metcalf, and P. van der Stratten, *Laser Cooling and Trapping,* Springer, NewYork, 1999
4. L. A. Orozco, "Laser Cooling and Trapping of Neutral Atoms" Latin-American School of Physics XXXI ELAF. Editors Shahen Hacyan, Rocío Jauregui and Ramón López Peña. AIP Conference Proceedings 464, p. 67 (New York 1999). Available at: [doi: http://dx.doi.org/10.1063/1.58237](http://dx.doi.org/10.1063/1.58237)

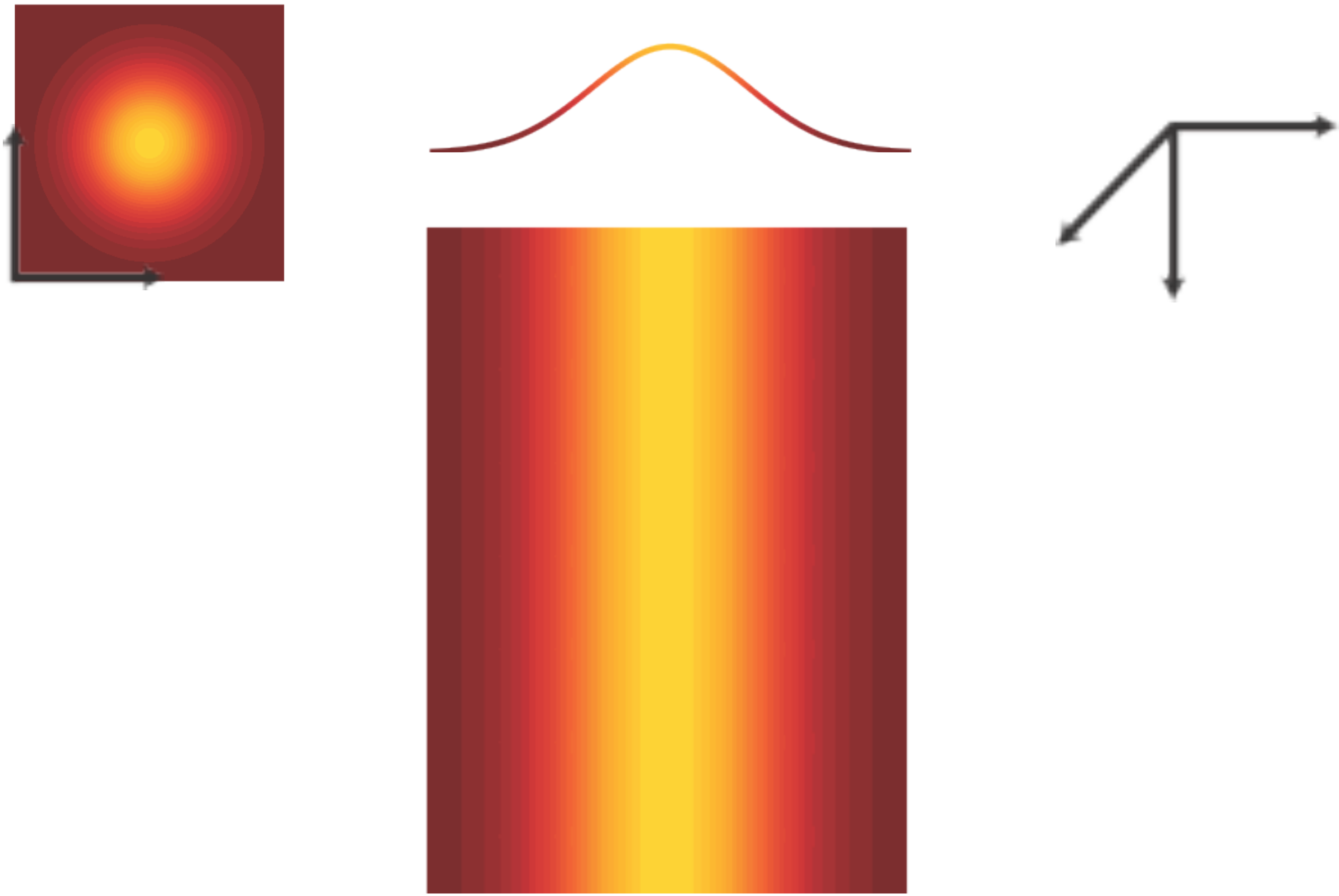
4^{th} lecture: Different types of laser traps for atoms.

1. Forces on an electric dipole

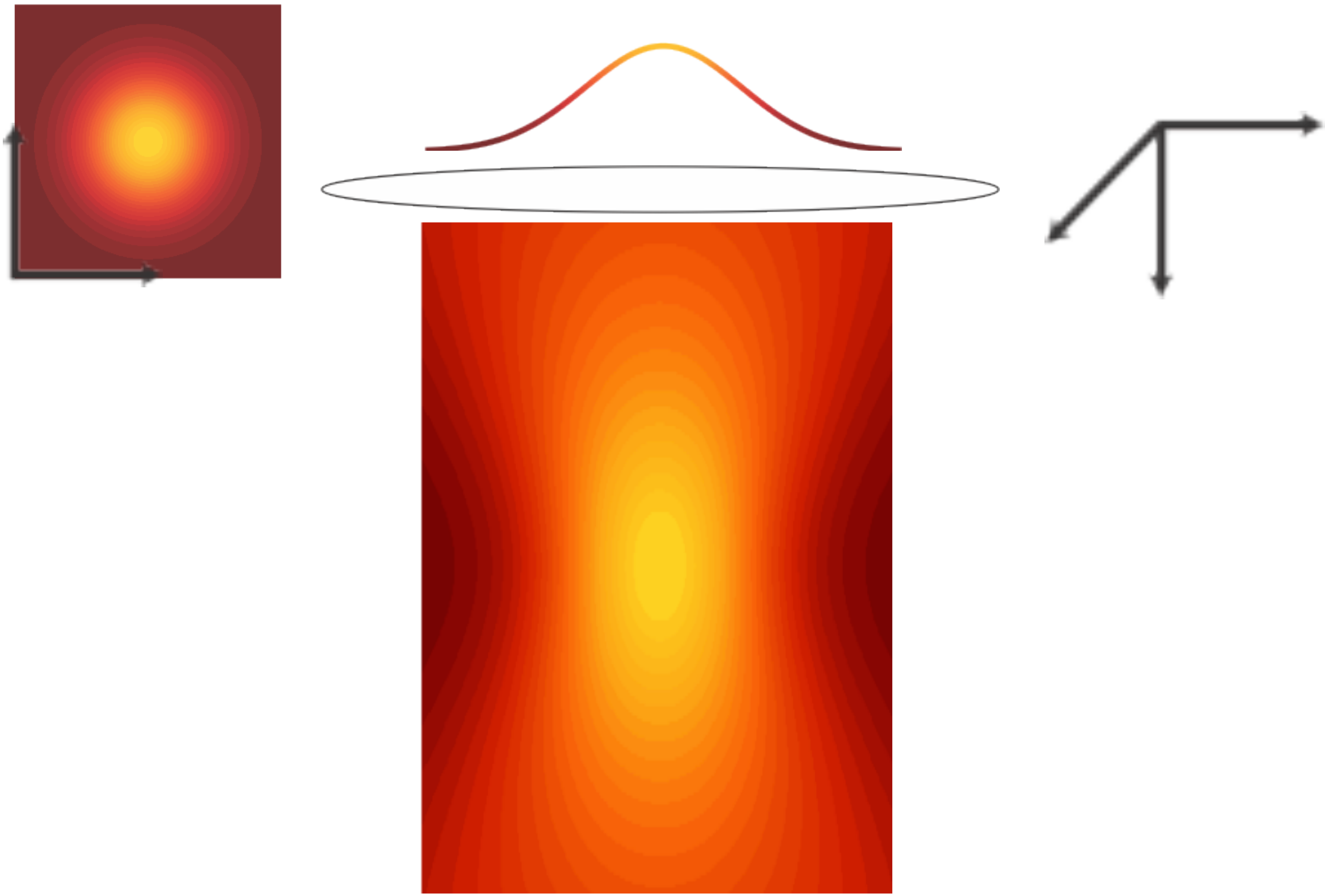
Trap (Gaussian beam)



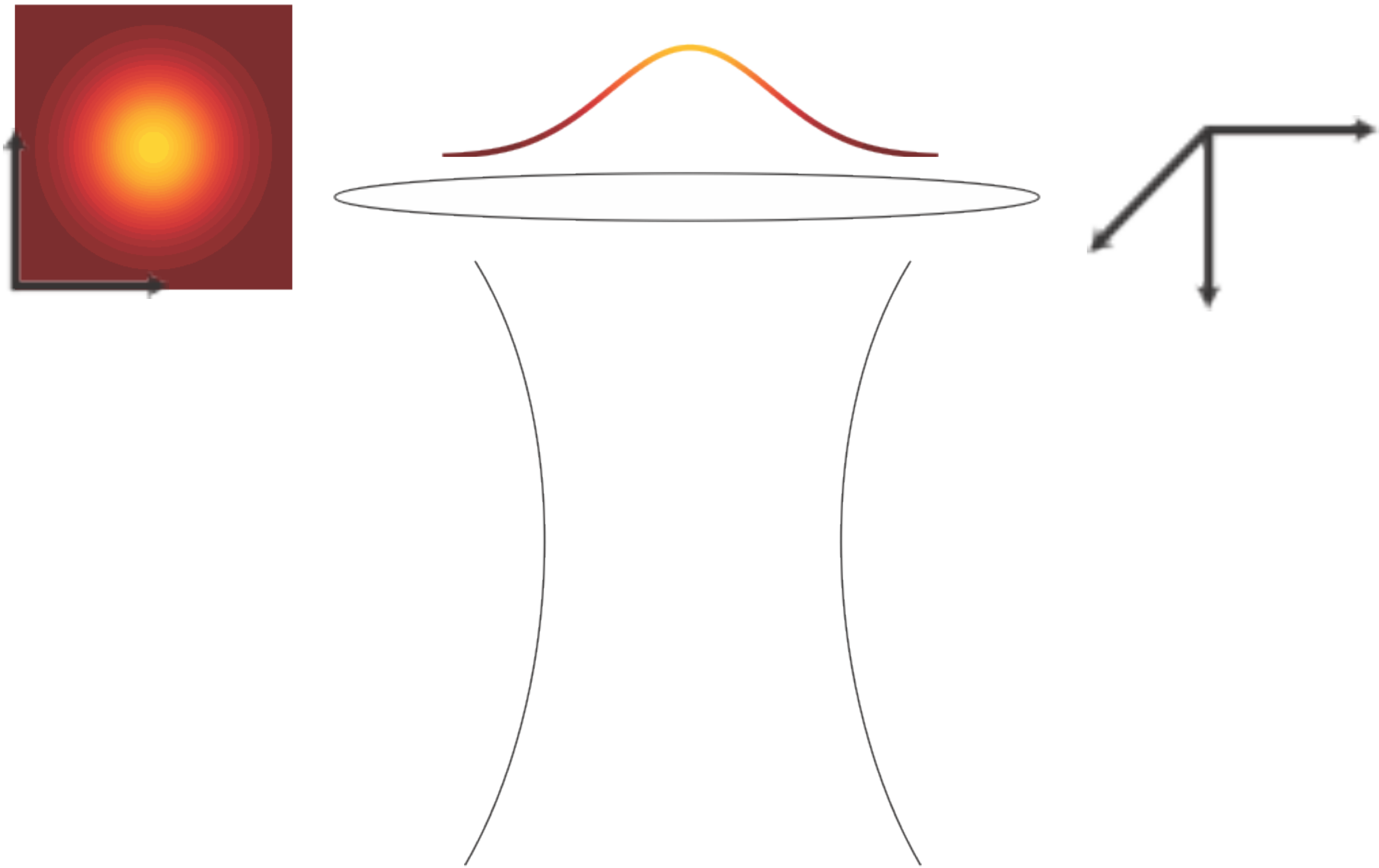
Trap (Gaussian beam)



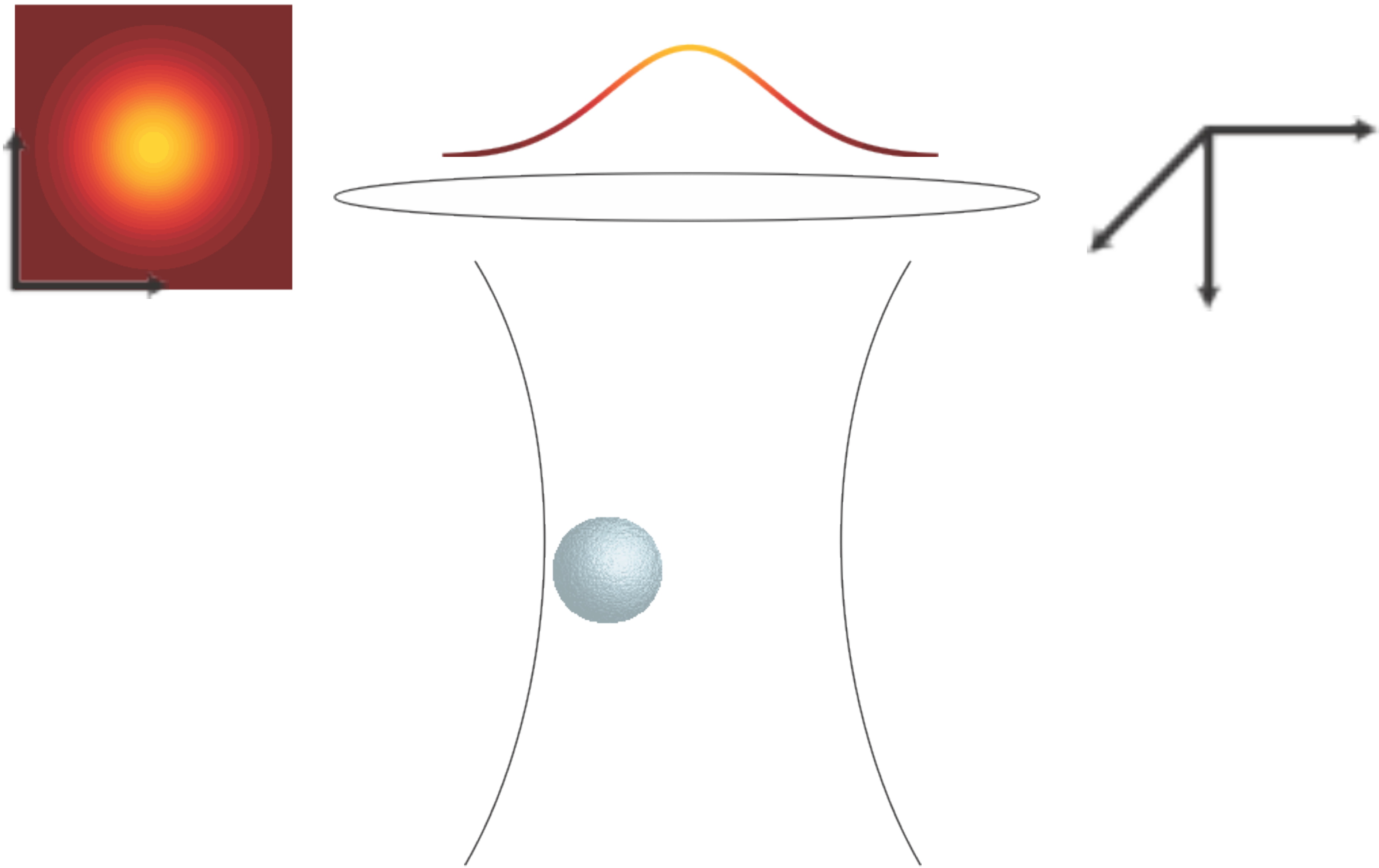
Trap (Focused Gaussian beam)



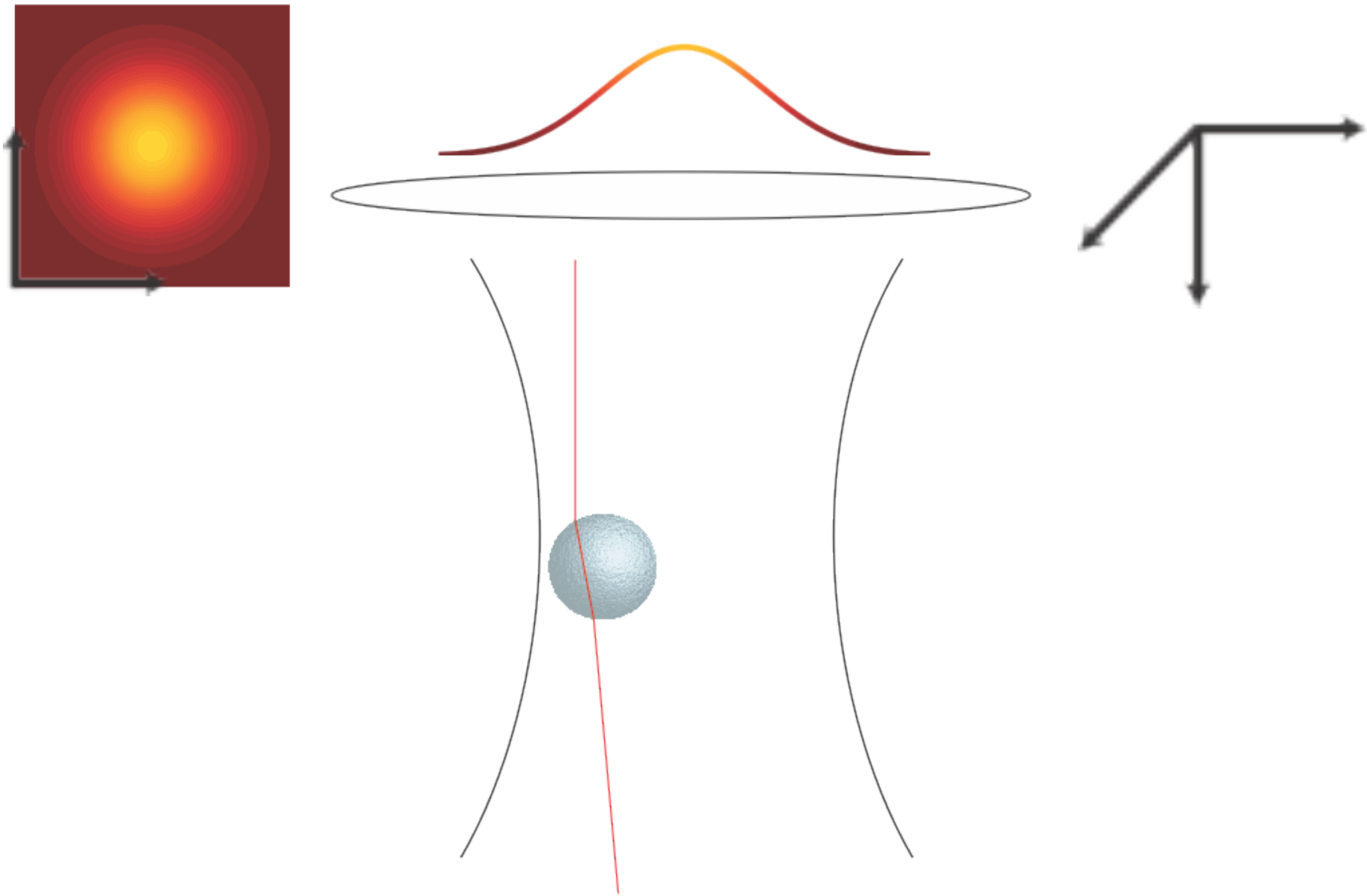
Trap (Focused Gaussian beam)



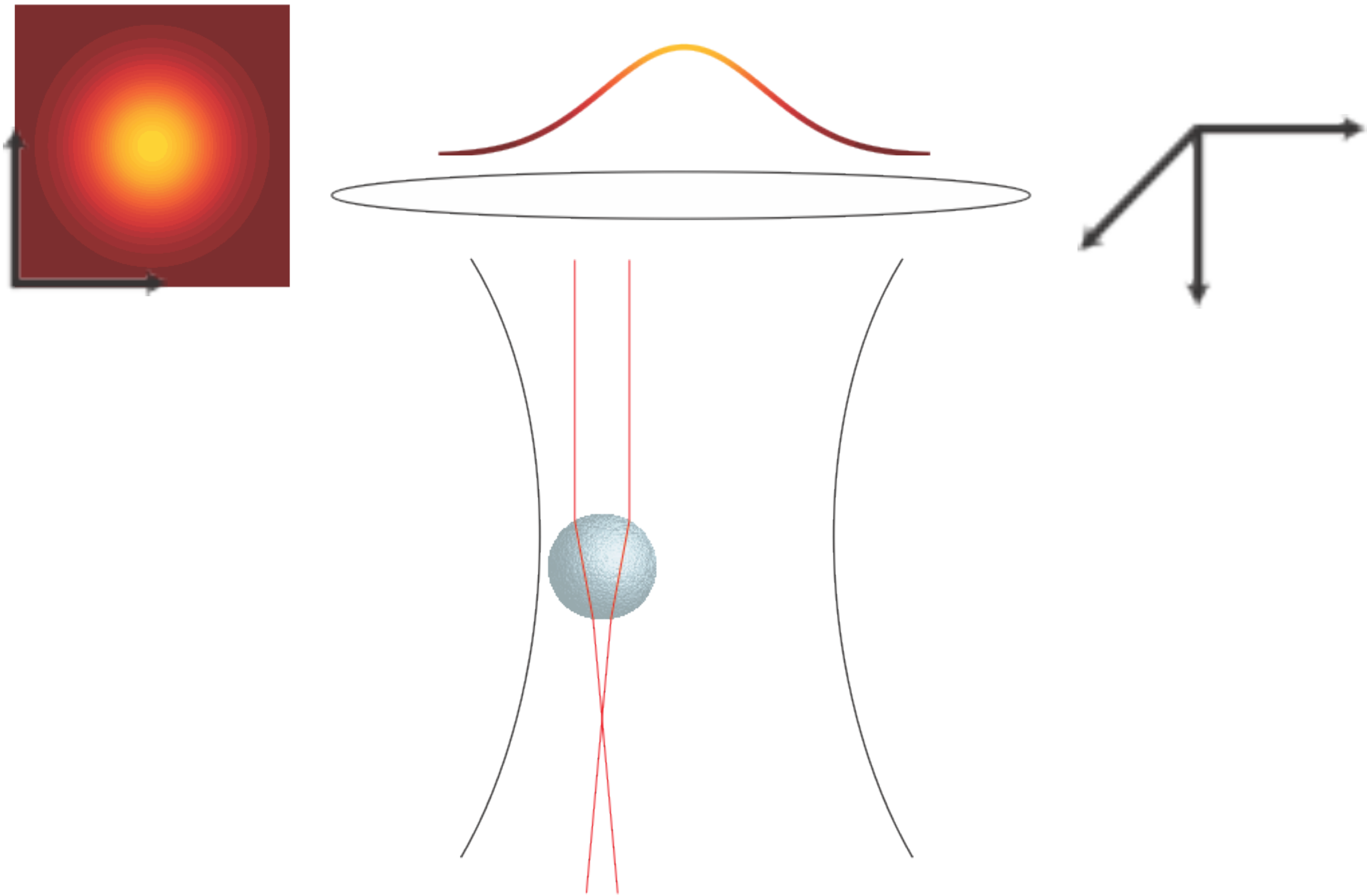
Trap (Focused Gaussian beam)



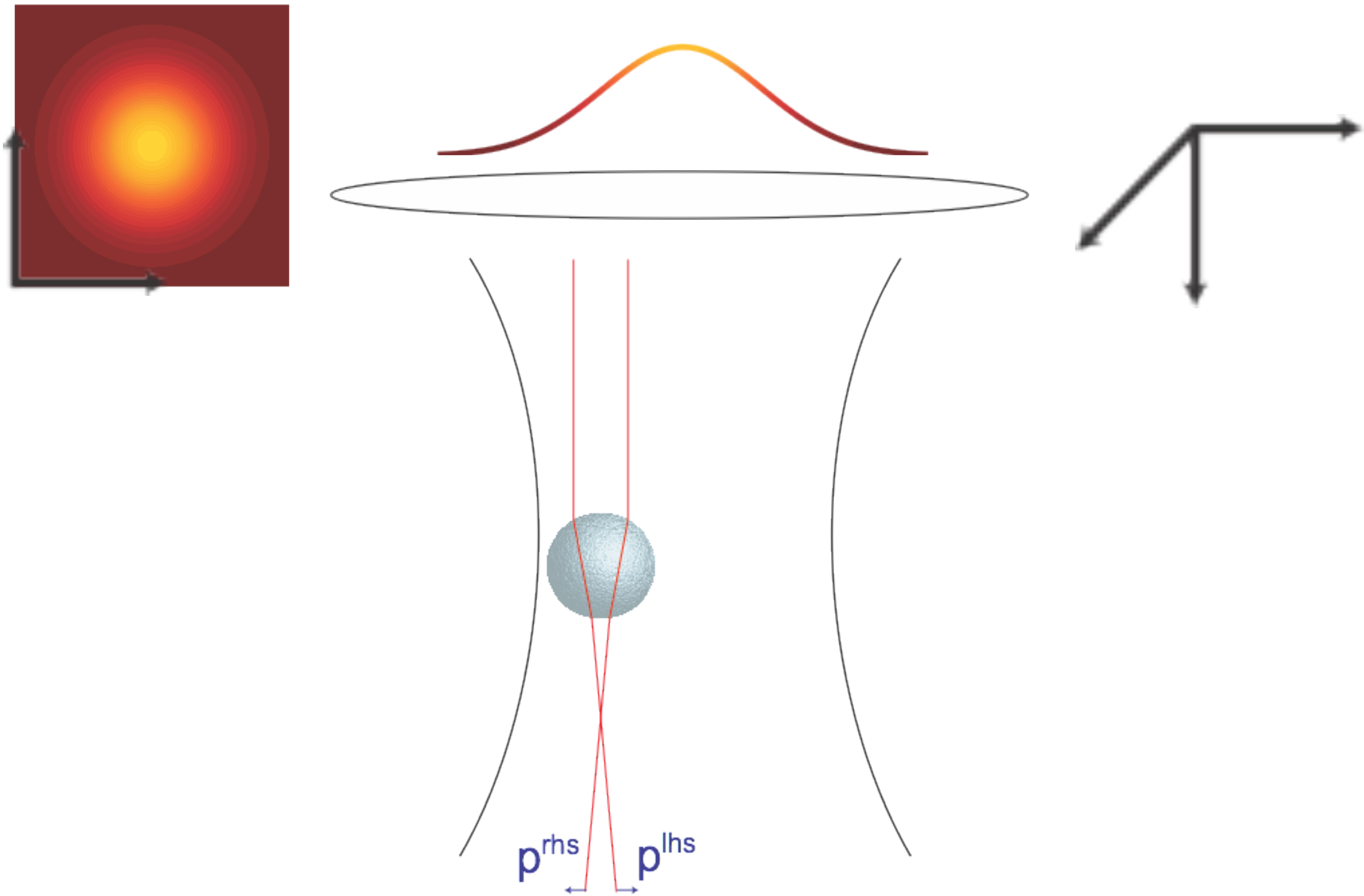
Trap (Focused Gaussian beam)



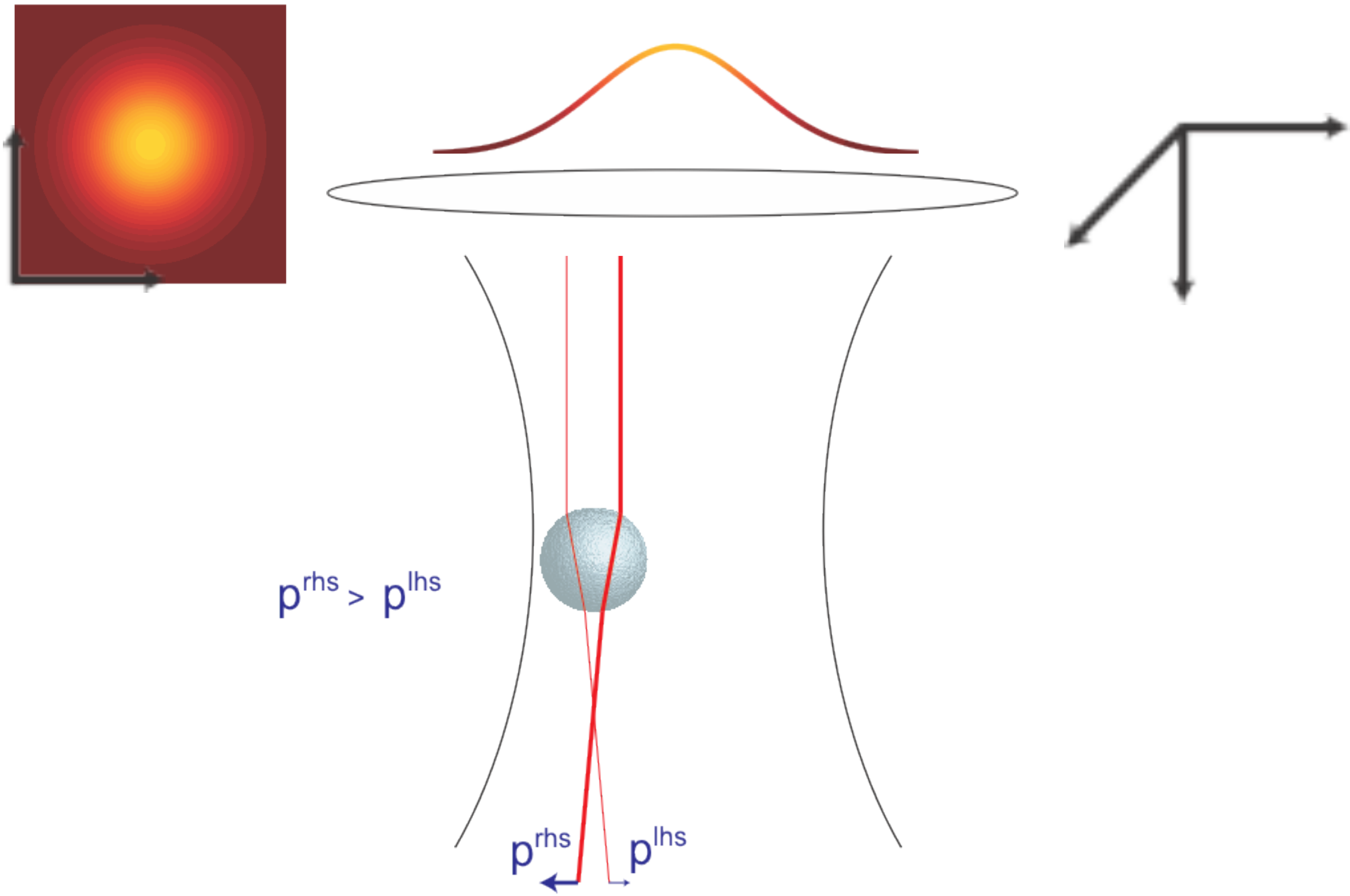
Trap (Focused Gaussian beam)



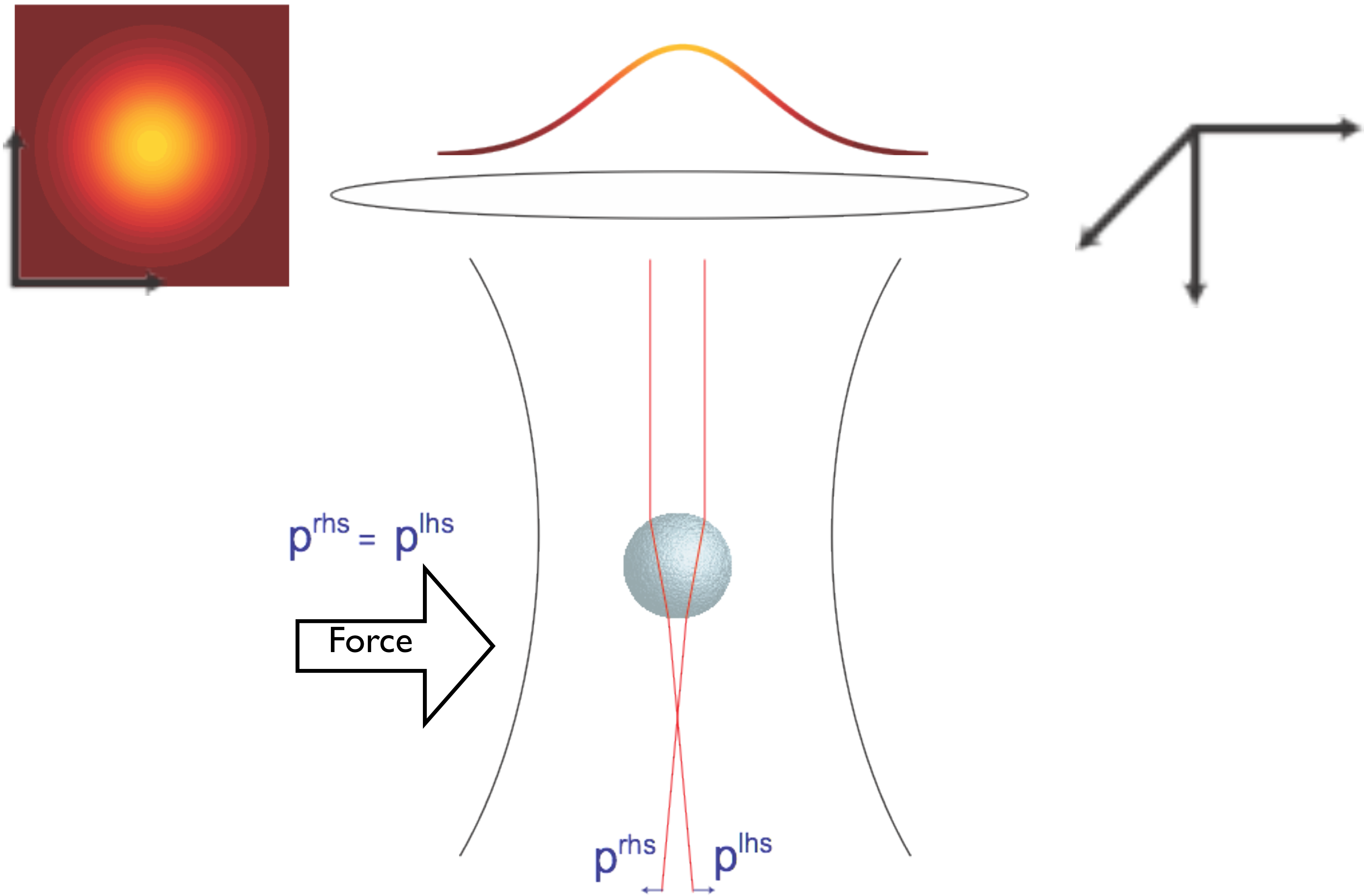
Trap (Focused Gaussian beam)



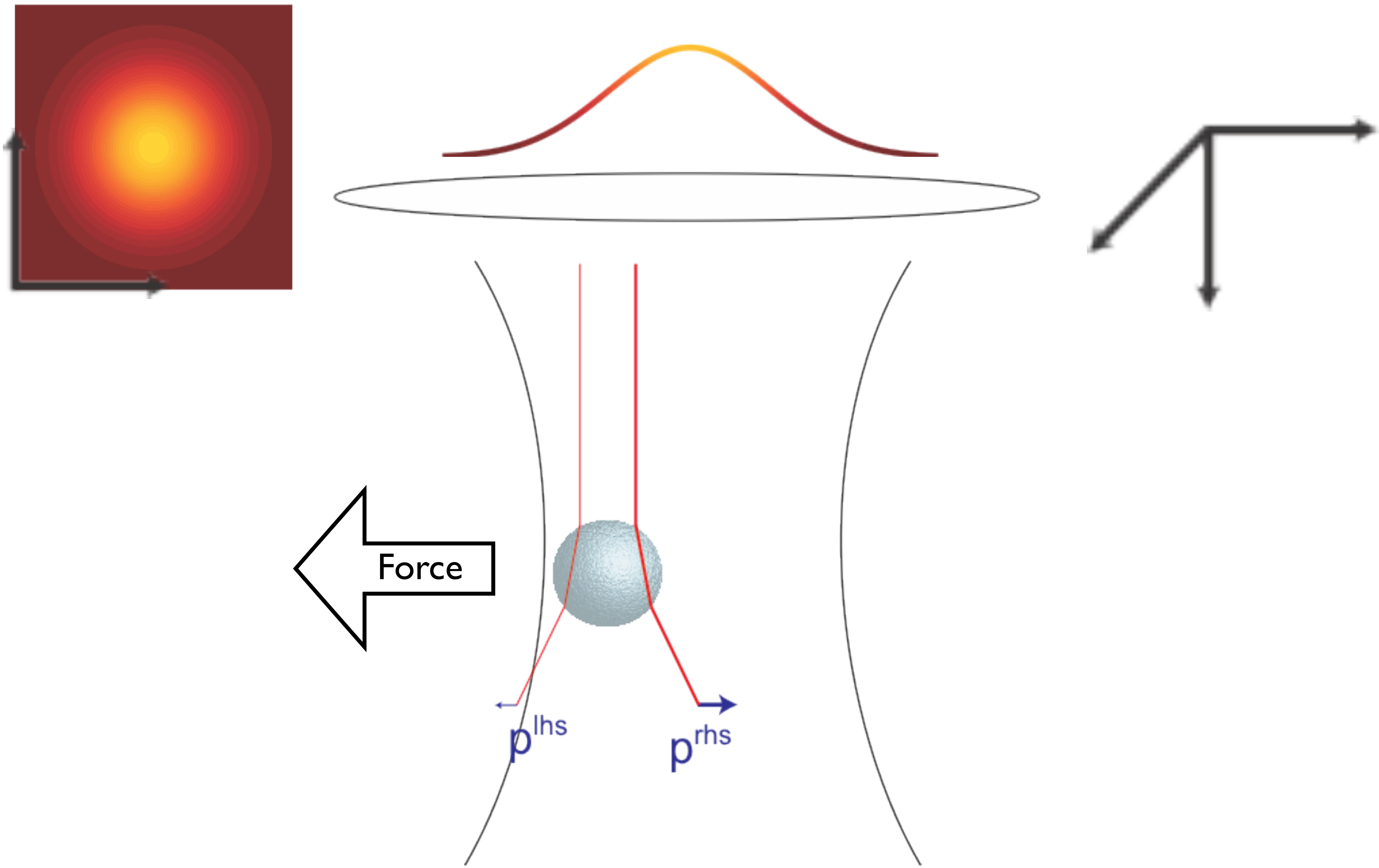
Trap (Focused Gaussian beam)



Trap (Focused Gaussian beam)



Bubble of air in water



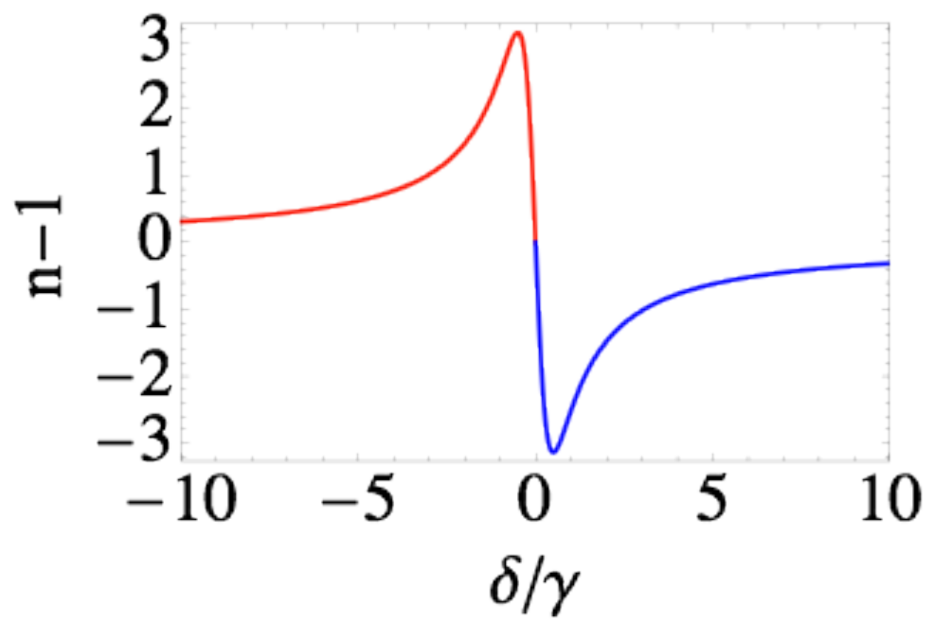
What causes the electromagnetic pressure on the atomic dipole? In a plane wave is the magnetic field wave.

Careful with resonances on the surface if the diameter ~λ. Light can escape in a different direction and the pressure decreases.

QM: transfer of the momentum of light to the atom.

Model: atoms as oscillating dipoles

- The glass sphere in air responds as if it were an oscillator excited below resonance: Red detuned ($\delta=\omega-\omega_0 < 0$) the atom is attracted towards the regions of higher intensity (I).
- The air bubble in water responds as an oscillator excited above resonance: Blue deturned ($\delta=\omega-\omega_0 > 0$) the atom is repelled from the higher intensity
- Potential (U) $U \propto I/\delta$
- Force (F) $F \propto \nabla (I/\delta)$

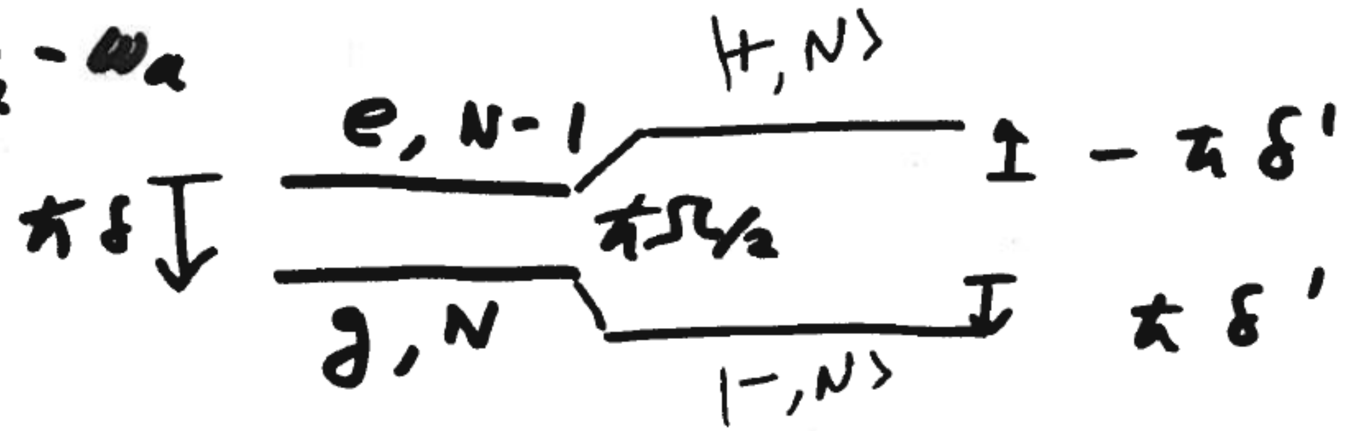


AC Stark shifts
(Light shifts of atomic ground states).

Dressed atom interpretation.

Uncoupled states (atom + photon)

$\delta = \omega_L - \omega_a$

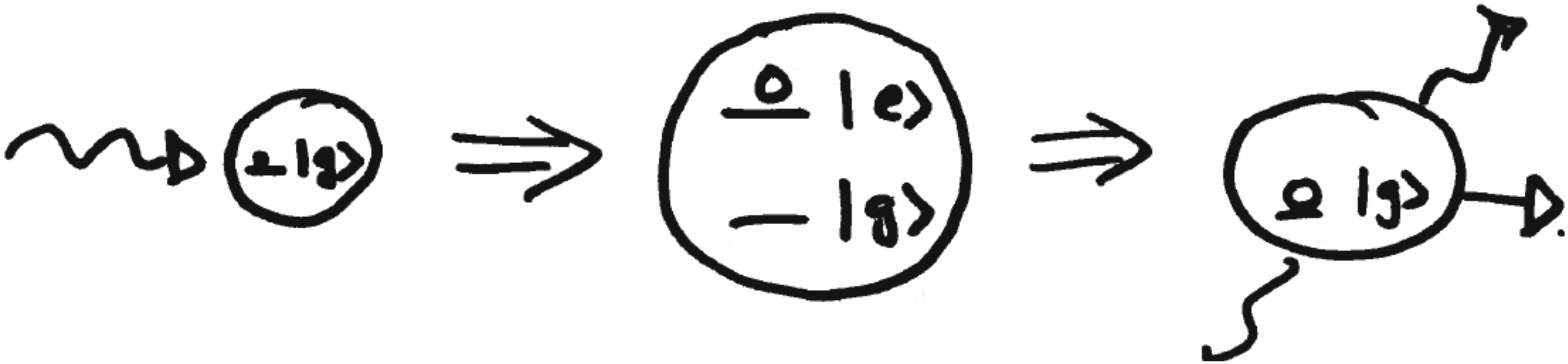


$$\langle e, N-1 | V_{AC} | g, N \rangle = \frac{\hbar \Omega}{2}$$

$$\delta' = \frac{\Omega_1^2}{4\delta}$$ Light shift for $\Omega_1 \ll |\delta|$

Laser Cooling

Radiation Forces (Spontaneous emission):



Spontaneous emission is in a symmetric pattern, so the emission does not contribute on average to the momentum

$$\vec{F}_{TOT} = \vec{F}_{abs} + \vec{F}_{emis.}$$

$$= \langle F_{abs} \rangle + \delta \vec{F}_{abs} + \langle \vec{F}_{em} \rangle + \delta \vec{F}_{em}$$

$$= R \hbar \vec{k} + \delta F_{abs} + 0 + \delta \vec{F}_{em}.$$

Average Force:

$$\langle \vec{F} \rangle = \hbar \vec{k} \cdot \frac{\Gamma}{2} \cdot \frac{I/I_0}{1 + I/I_0 + \left(\frac{2\delta}{\Gamma}\right)^2}$$

With Doppler shift and no recoil

$v_R \ll \Gamma/k$

$$= \hbar \vec{k} \frac{\Gamma}{2} \frac{(I/I_0)/(1 + I/I_0)}{1 + \left(\frac{2}{\Gamma} \frac{(\delta - \vec{k} \cdot \vec{v})}{\sqrt{1 + I/I_0}}\right)^2}$$

A force that depends on velocity is dissipative!

Conservation of momentum and energy:

$$\vec{v}' - \vec{v} = \frac{\hbar \vec{k}}{M} = v_R \qquad \text{recoil velocity}$$

$$\hbar(\omega_L - \omega_A) = \underbrace{\hbar \vec{k} \cdot \vec{v}}_{\text{Doppler shift}} + \underbrace{\frac{\hbar k^2}{2M}}_{\text{recoil shift}}$$

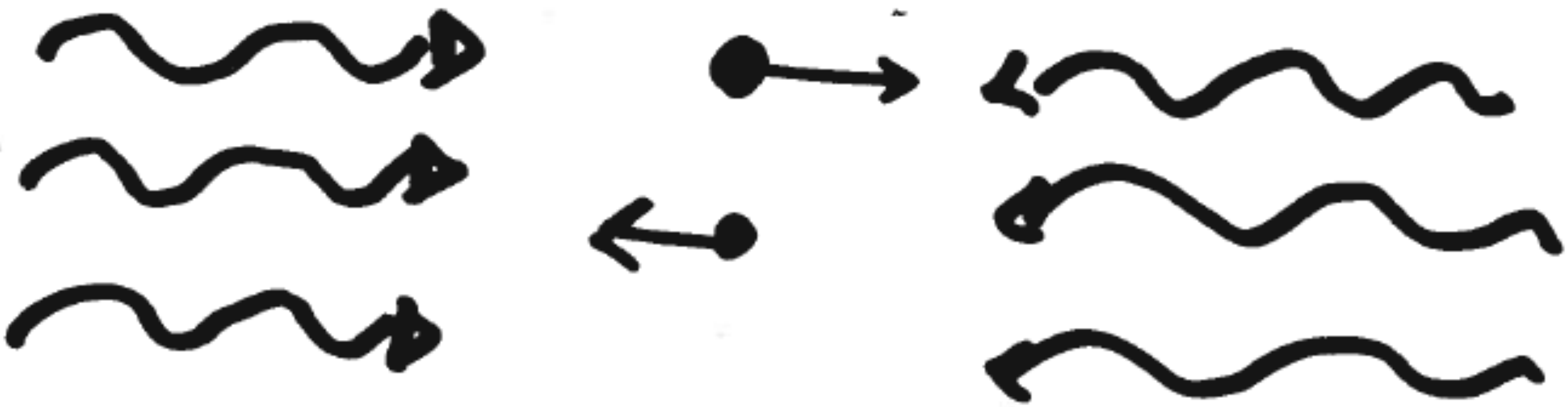
recoil energy $\frac{1}{2} k v_R$

Maximum force

$$F/M = \frac{\hbar \vec{k}}{M} \cdot \frac{\Gamma}{2}$$

$$= \frac{\Gamma}{2} v_{REC}$$

Optical Molasses



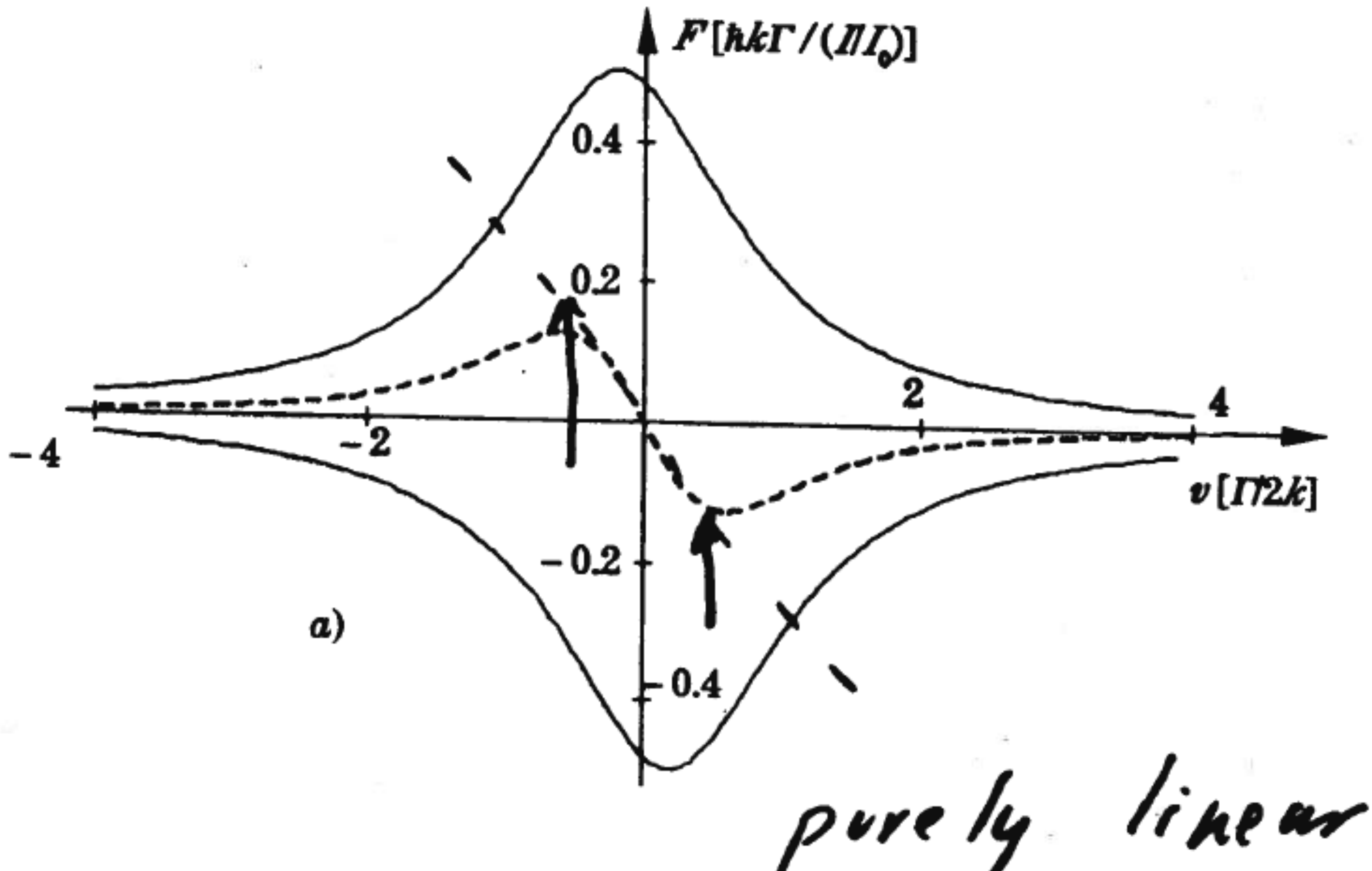
$$F \Rightarrow F(v) \Rightarrow F(v, k)$$

$$F = -\hbar k \frac{\Gamma}{2} \frac{I/I_0}{1 + \left(\frac{2(\delta - kv)}{\Gamma}\right)^2} + \hbar k \frac{\Gamma}{2} \frac{I/I_0}{1 + \left(\frac{2(\delta + kv)}{\Gamma}\right)^2}$$

We find a force that is linear on the velocity, for small Doppler shifts

$$F = \left\{ \overbrace{2\hbar k^2 \frac{(2I/I_0)\, 2\delta/\Gamma}{[1 + (2\delta/\Gamma)^2]^2}}^{\alpha} \right\} v = \alpha v$$

This is great for cooling



Capture velocity $v_c \approx \Gamma/2k$

The Doppler Cooling limit:
(One dimension two level atoms)

Remember the force can have fluctuations! We based everything on the average!

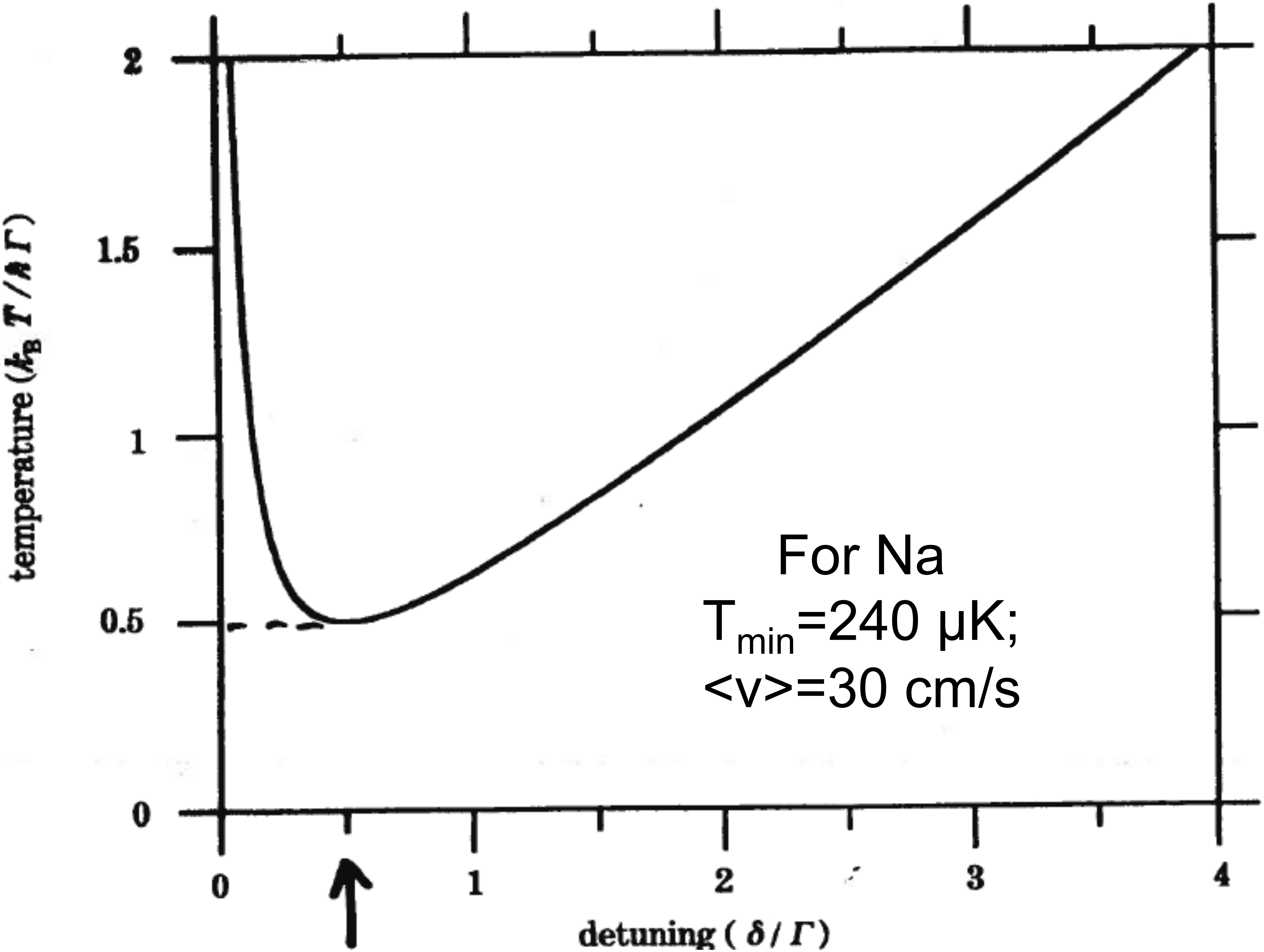
Rate of heating=Rate of cooling

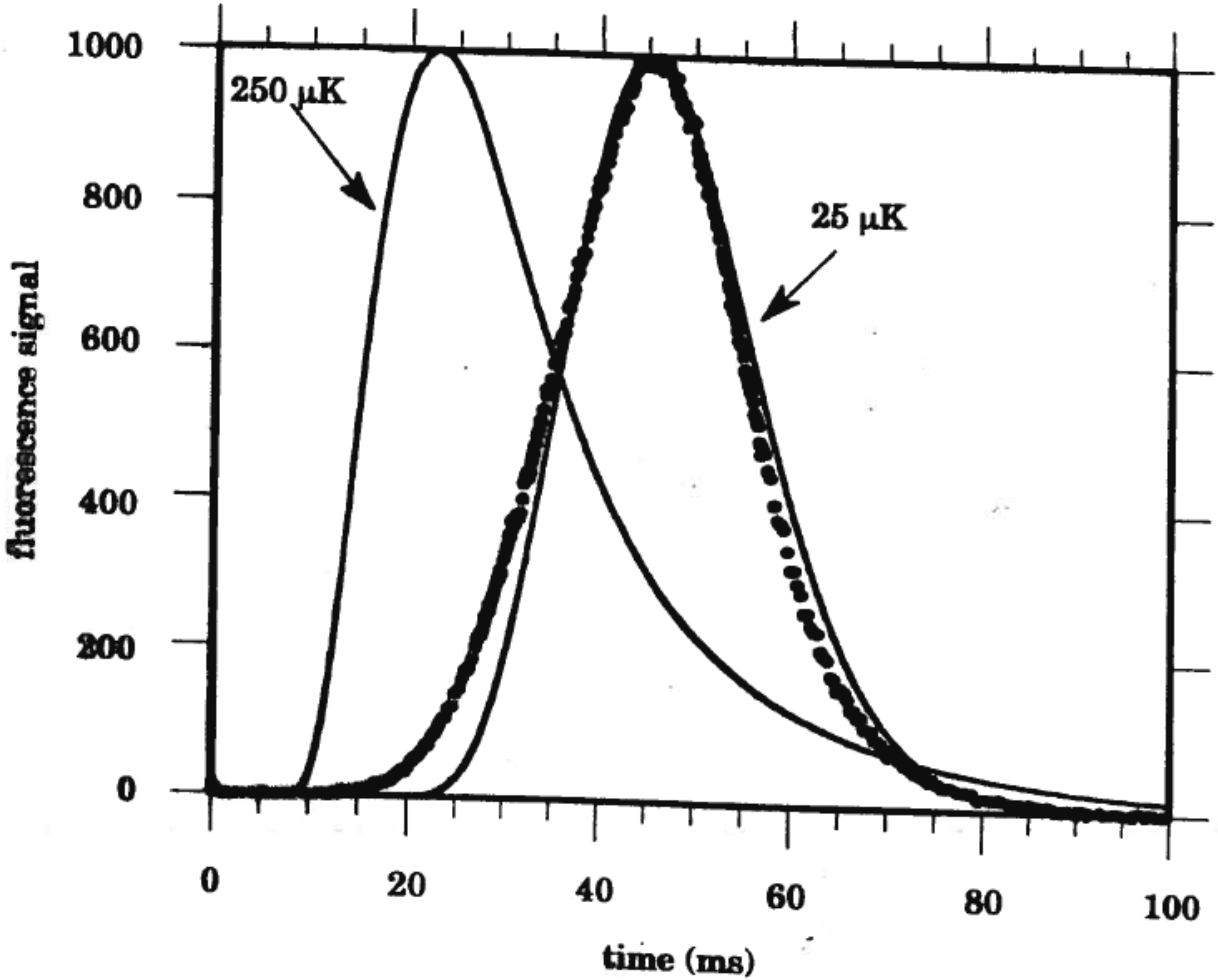
$$\vec{F} \bullet \vec{v} = \hbar\omega_{rec}\ \Gamma_{sc}$$

$$\alpha v^2 = \hbar\omega_{rec}\ \Gamma_{sc}$$

$$\frac{M}{2}\left\langle v^2 \right\rangle = k_B T$$

$$k_B T = \frac{\hbar\Gamma_{sc}}{2}$$ Temperature LIMIT


For Na
T_{min}=240 µK;
<v>=30 cm/s
temperature ($k_B T/\hbar\Gamma$)
2
1.5
1
0.5
0
0
1
2
3
4
detuning (δ/Γ)



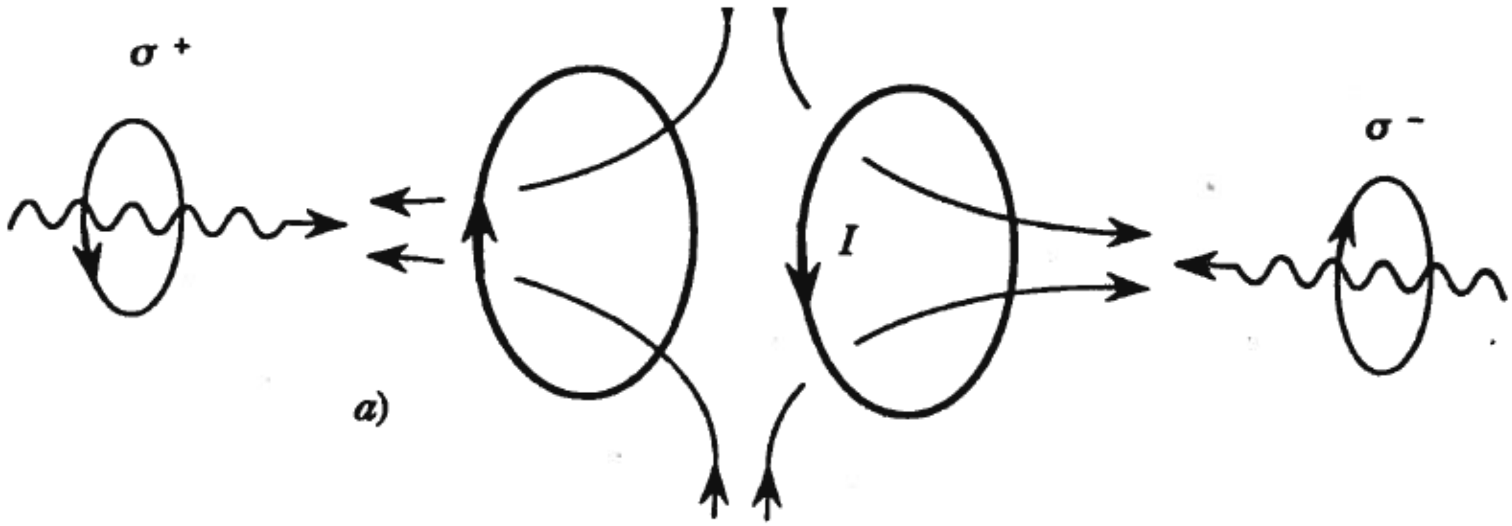
250 μK
25 μK
1000
800
600
400
200
0
fluorescence signal
0
20
40
60
80
100
time (ms)

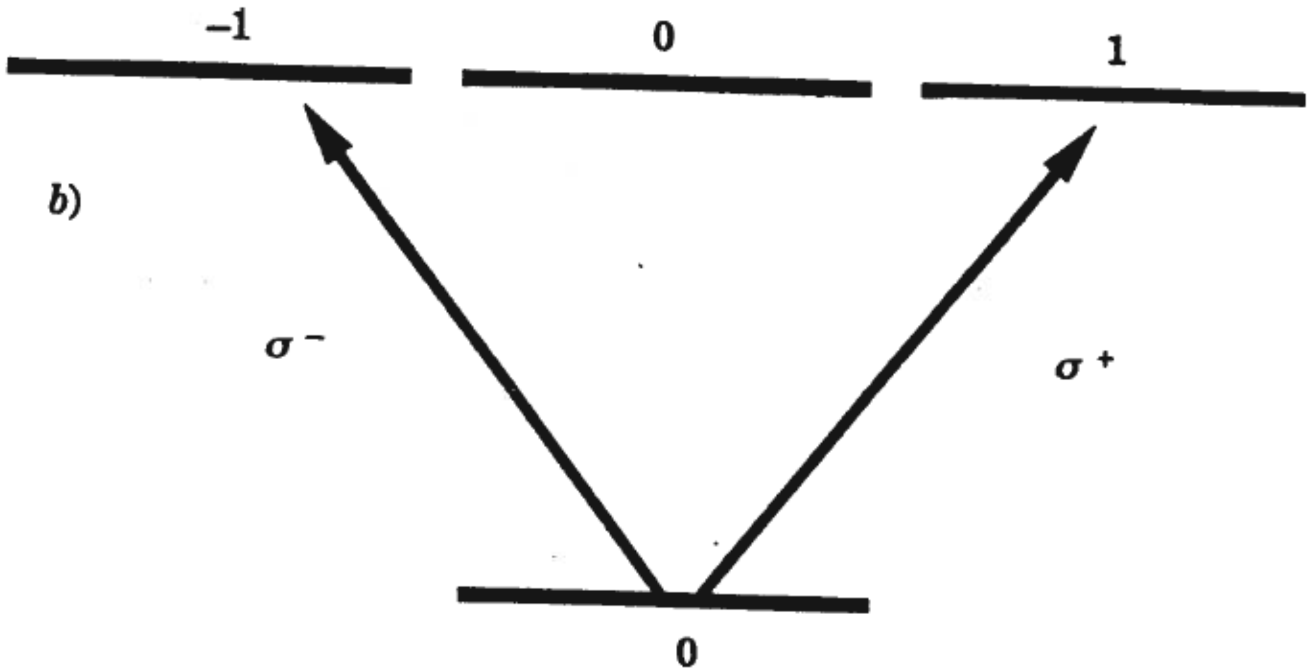
Limit of the temperature, by a characteristic time:

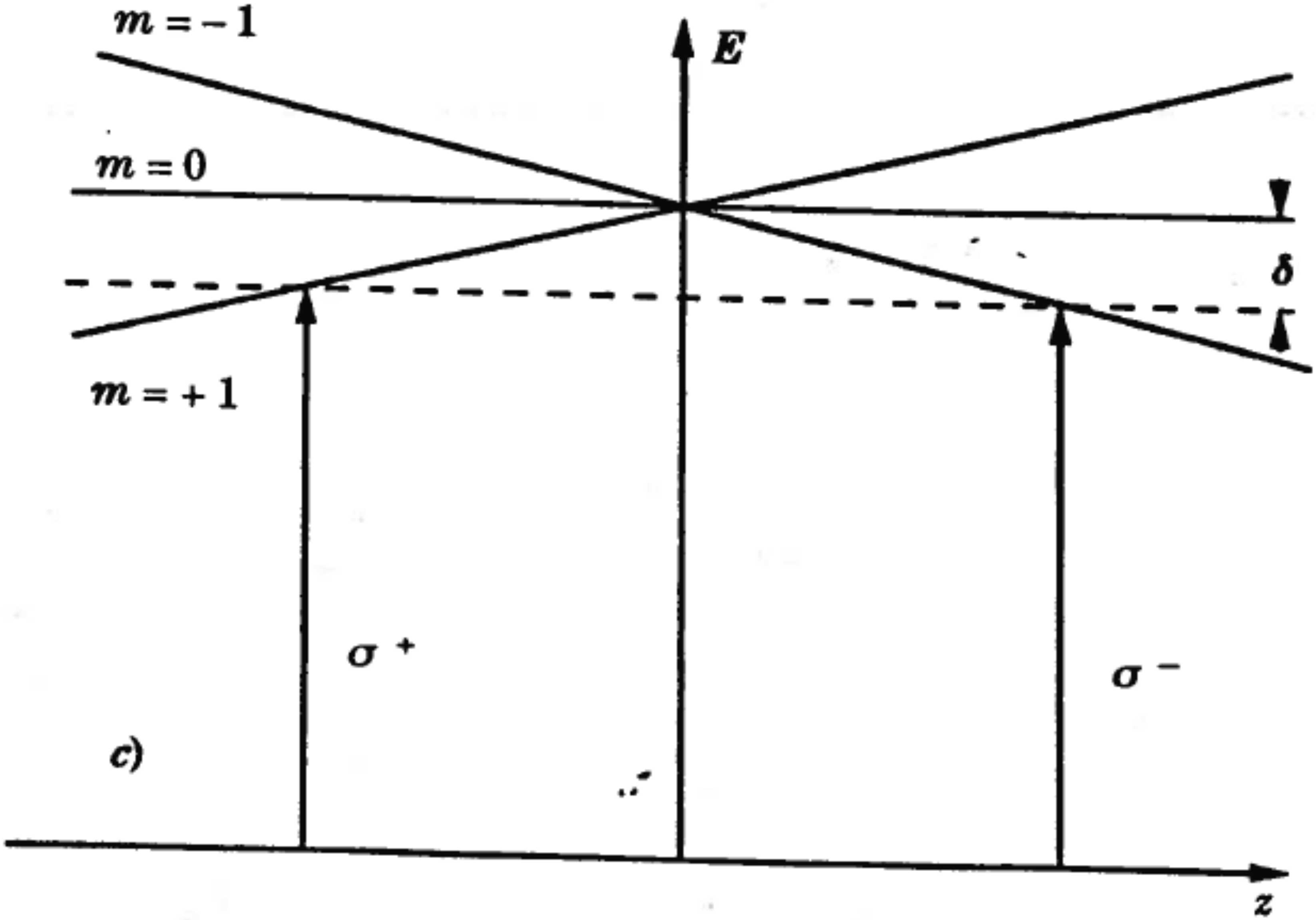
$$k_B T \approx \frac{\hbar}{t_{characteristic}}$$

For a two level atom it the characteristic time is the inverse of the lifetime, but if you have more structure it could be the optical pumping time

Magneto Optical Trap (MOT)







$m = -1$
E
$m = 0$
δ
$m = +1$
σ^+
σ^-
c)
z

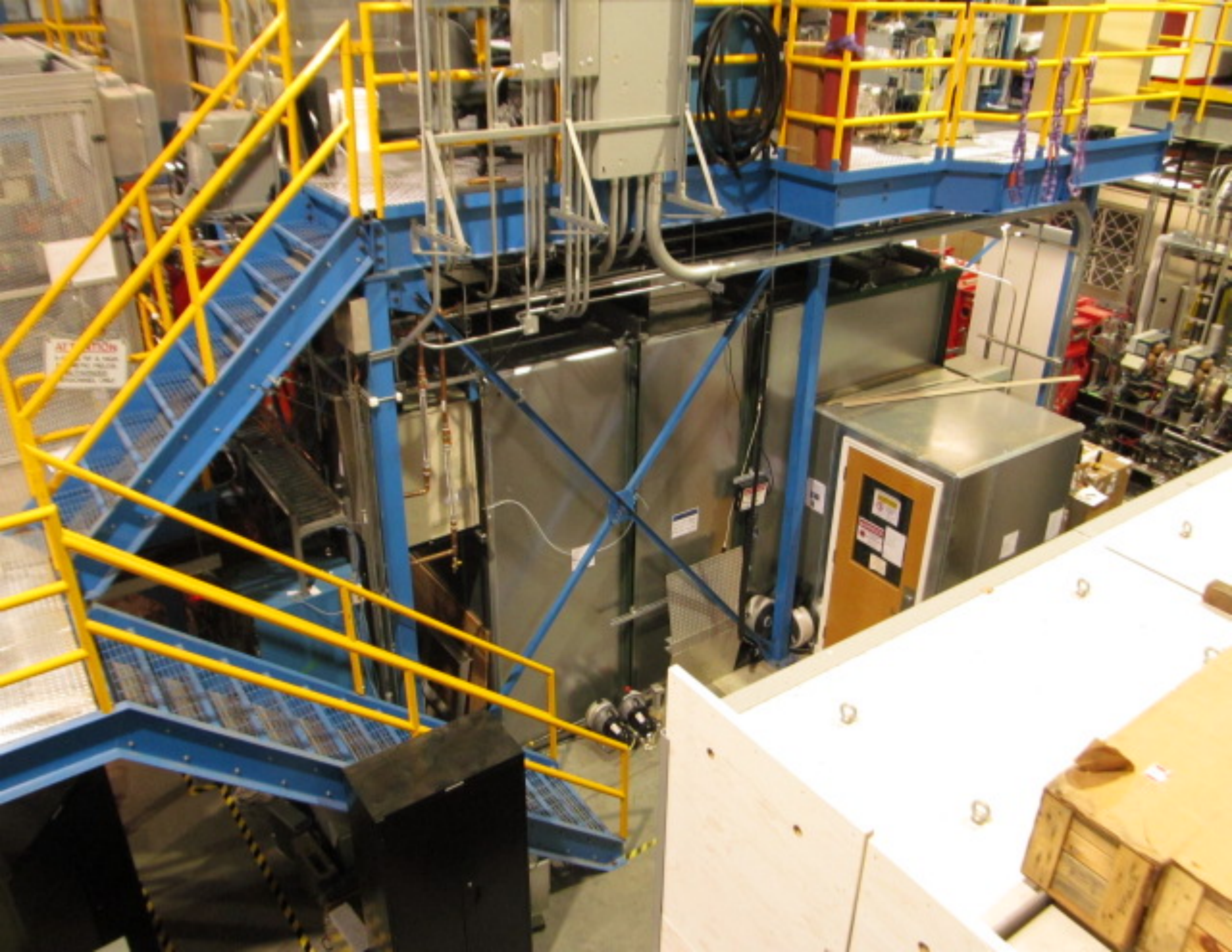
Linear Zeeman Shift

$$F = F_{\sigma^+} + F_{\sigma^-}$$

$$= \frac{\hbar k \Gamma}{2}\left[\frac{I/I_0}{1+4\left(\frac{\delta - kv - \beta z}{\Gamma}\right)^2} - \frac{I/I_0}{1+4\left(\frac{\delta + kv + \beta z}{\Gamma}\right)^2}\right]$$

$$F = F(v, z) = \frac{2\hbar k\,(2I/I_0)\,(2\delta/\Gamma)\,[kv + \beta z]}{[1 + (2\delta/\Gamma)^2]^2}$$

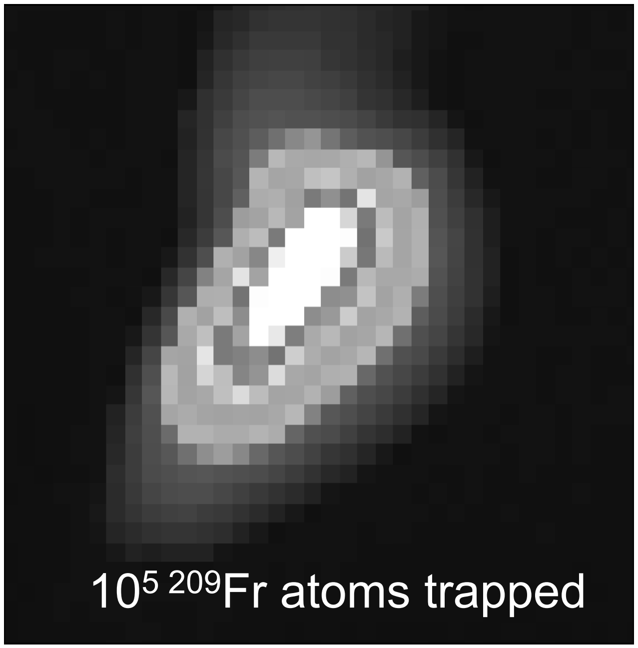
$$\ddot{z} + \gamma\,\dot{z} + \omega_{Trap}^2\, z = 0$$

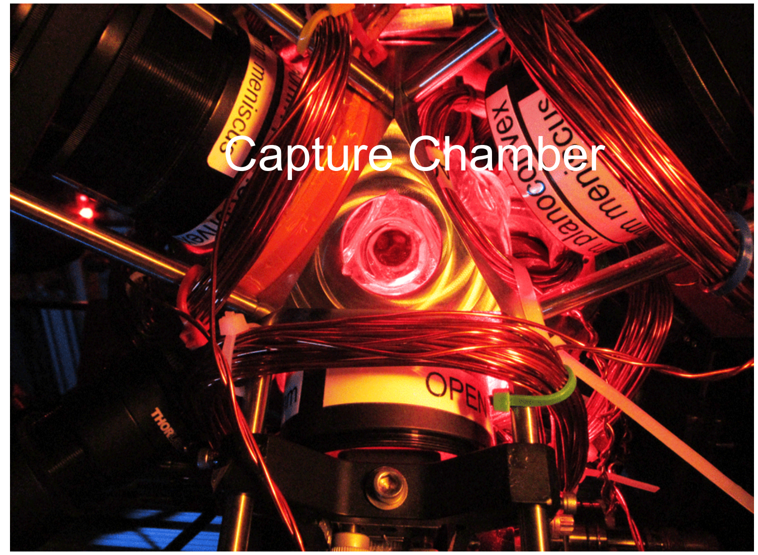


Francium Trapping Facility (FTF) at ISAC Hall 1

Sep 2012: Commissioning run (1)

- Fr laser trapping demonstrated
- isotopes 209, 207, 221



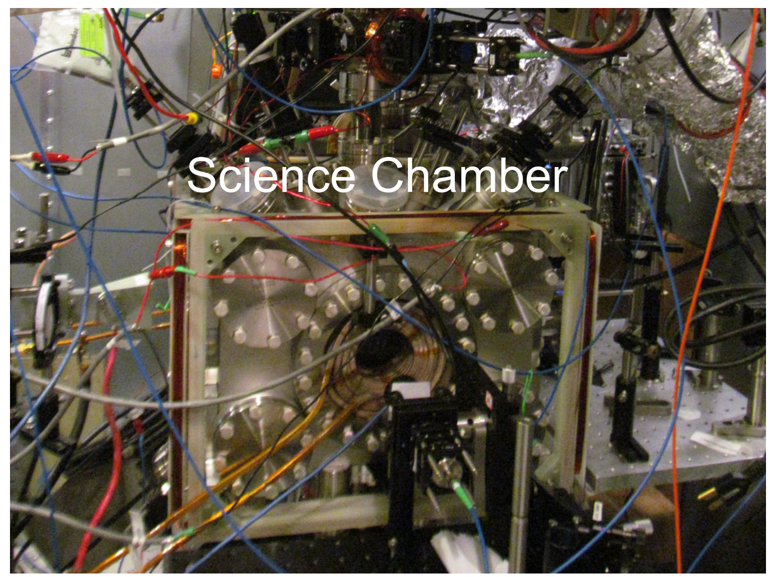


Nov 2012: Commissioning run (2),

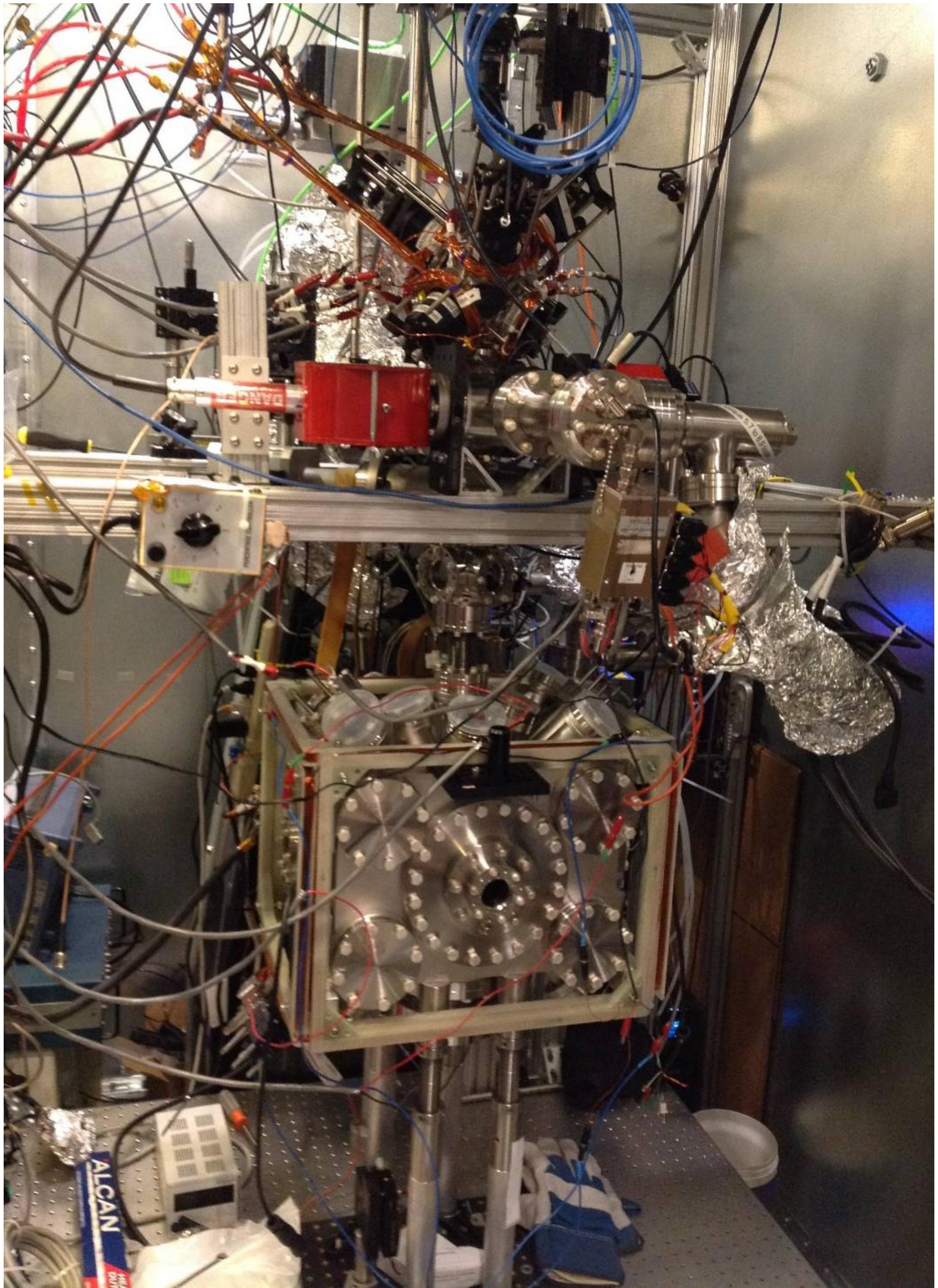
- Hyperfine anomalies and isotope shifts in isotopes 209, 207, 213, 206m.

Sep 2013: Commissioning run (3),

Hyperfine anomalies and isotope shifts in isotopes 221, 206m, 206g.

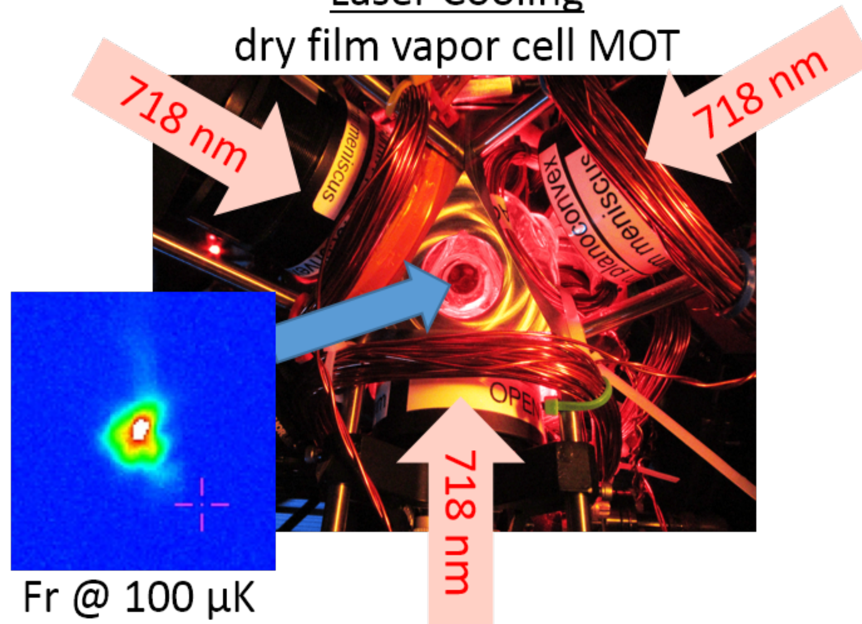


Francium Trapping Facility @ TRIUMF



Laser Cooling

dry film vapor cell MOT

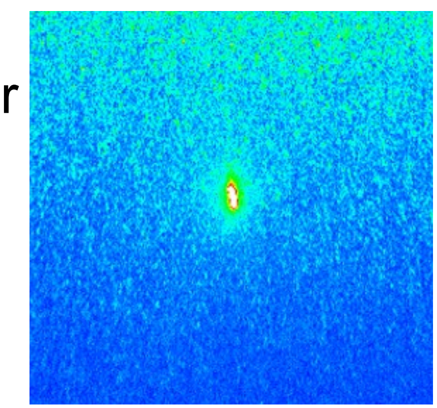


Fr @ 100 μK

0.7 m transfer

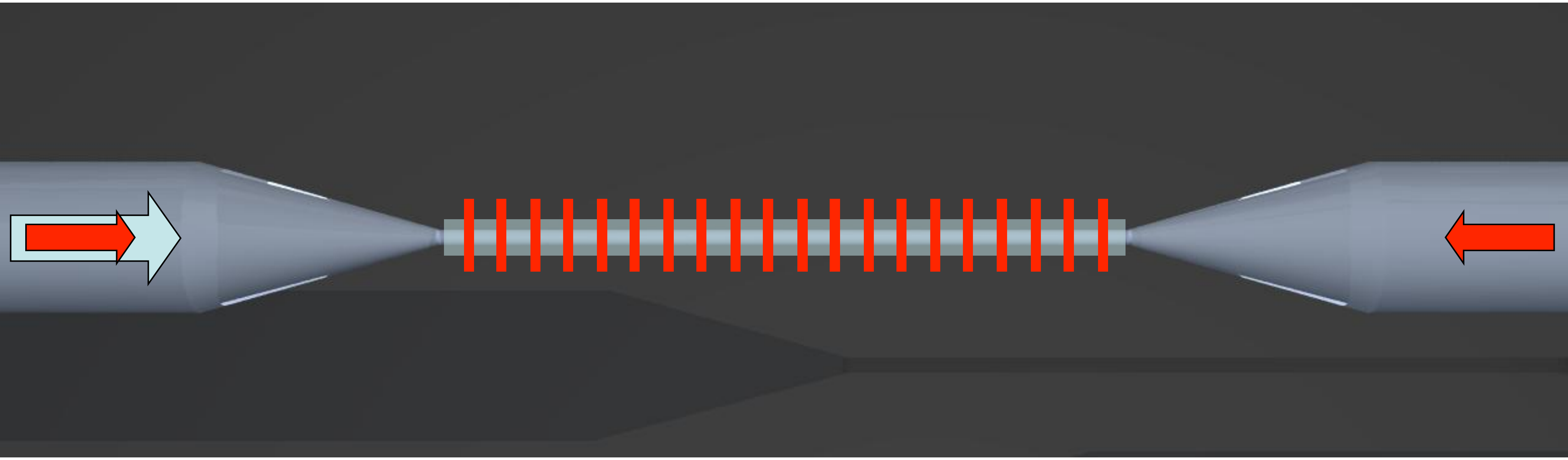
science chamber MOT

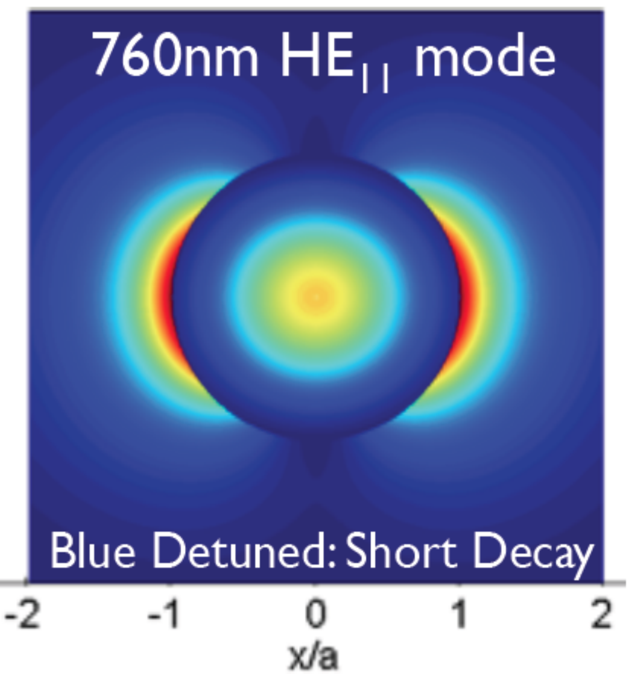
40% transfer efficiency



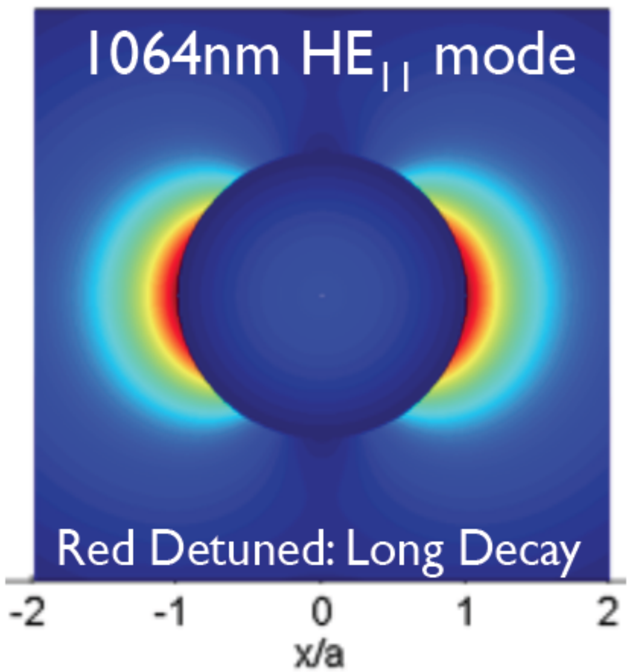
3. Trapped atoms around a nanofiber.

Potential of trapping (Dipole)

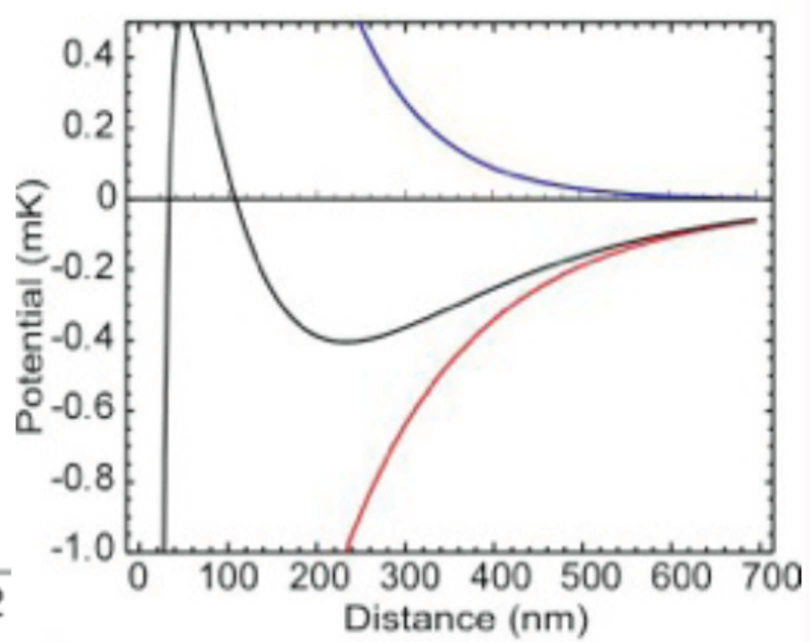




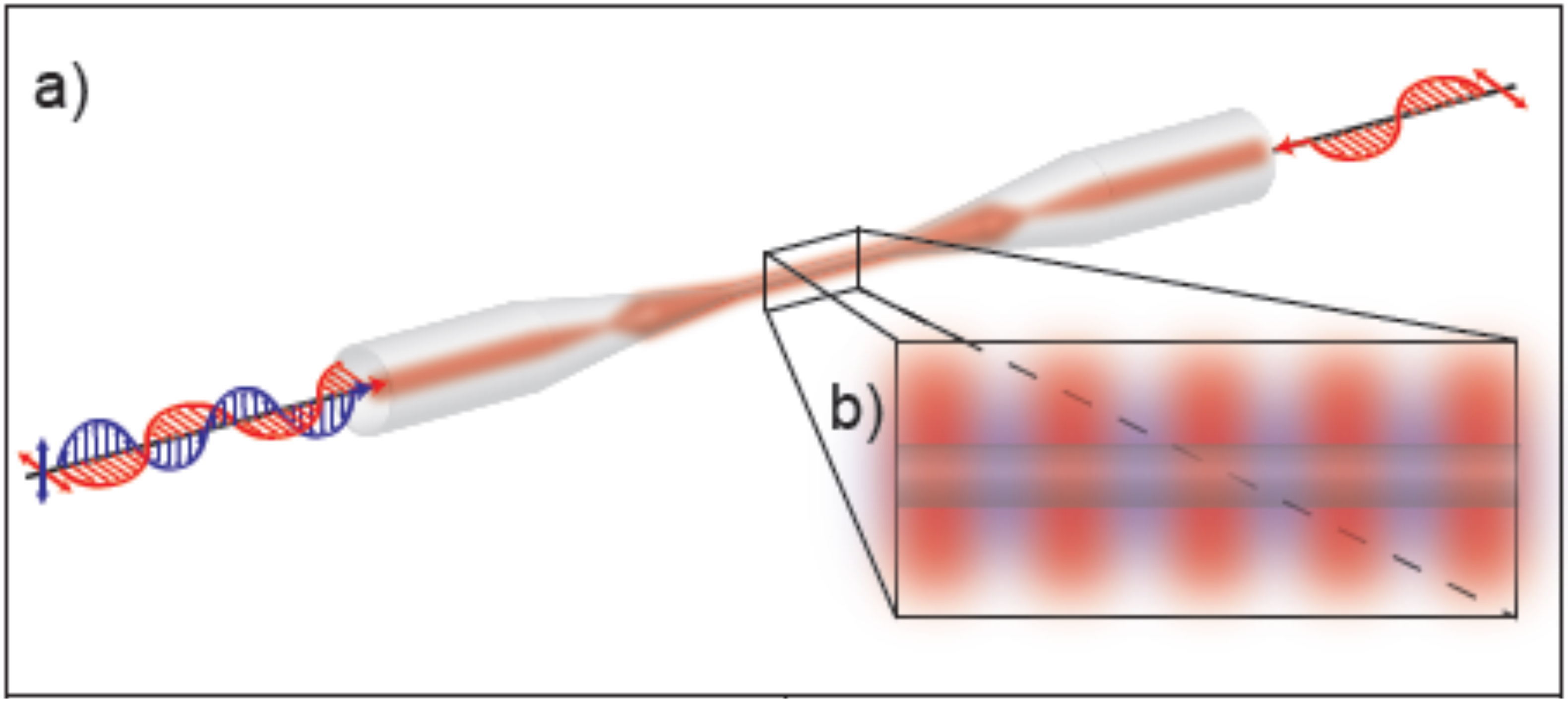
Atoms repelled

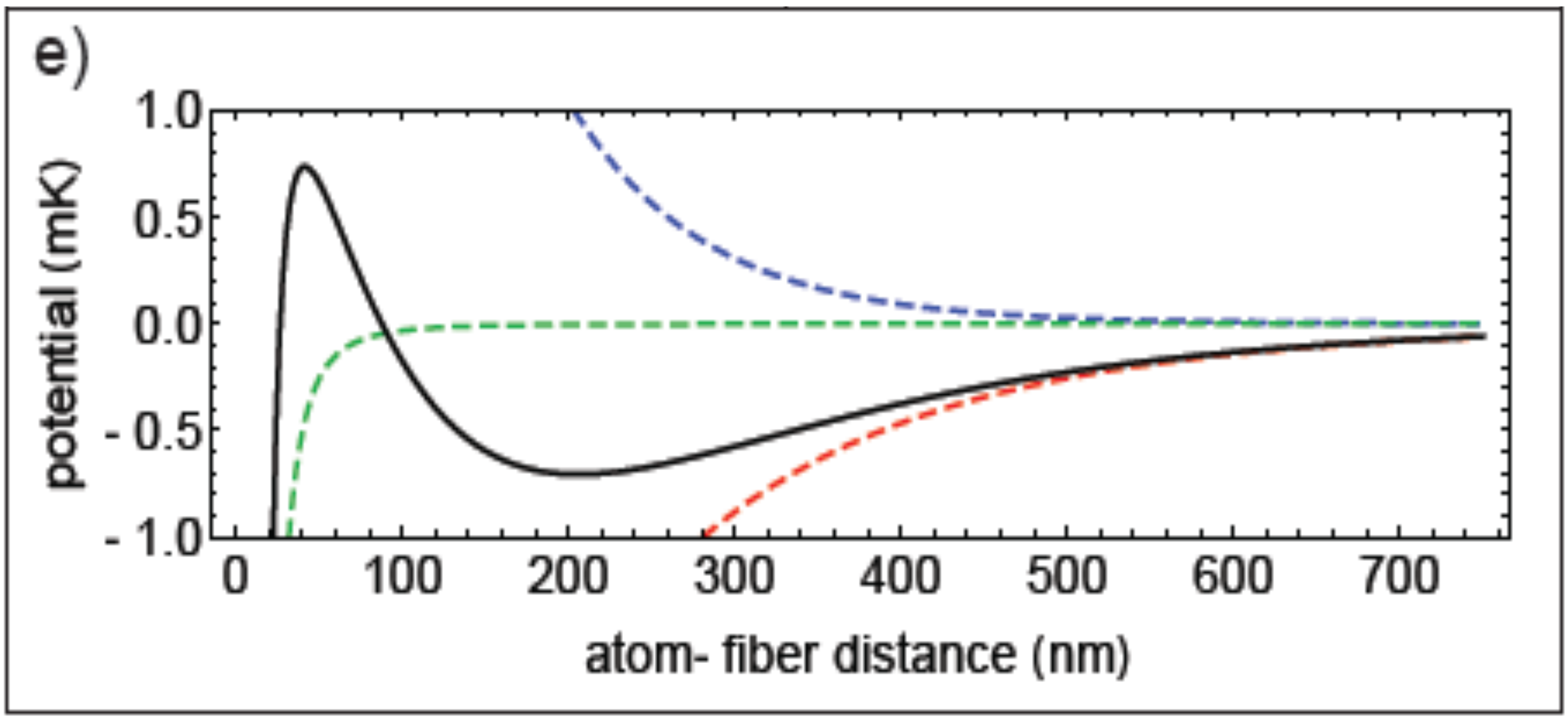


Atoms attracted

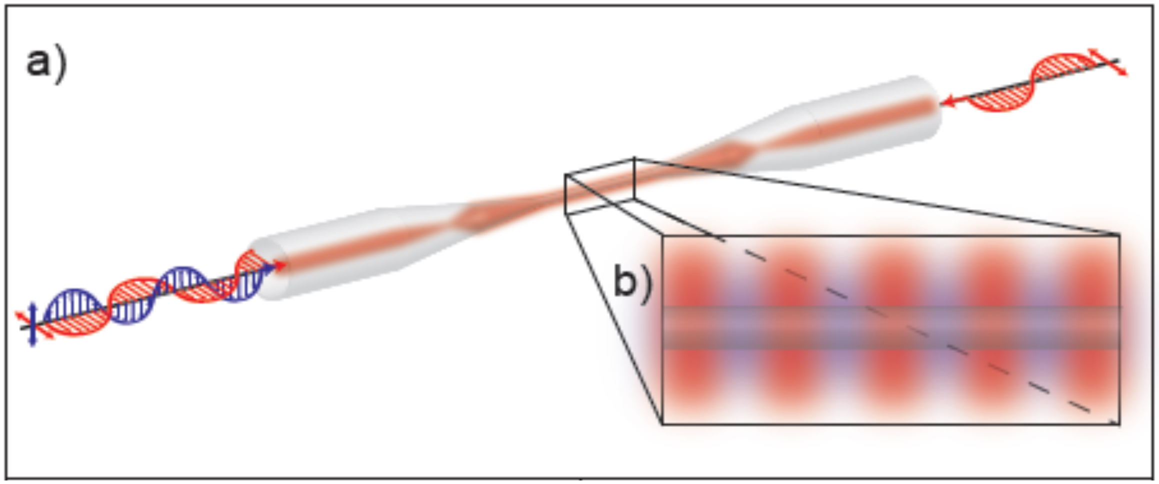


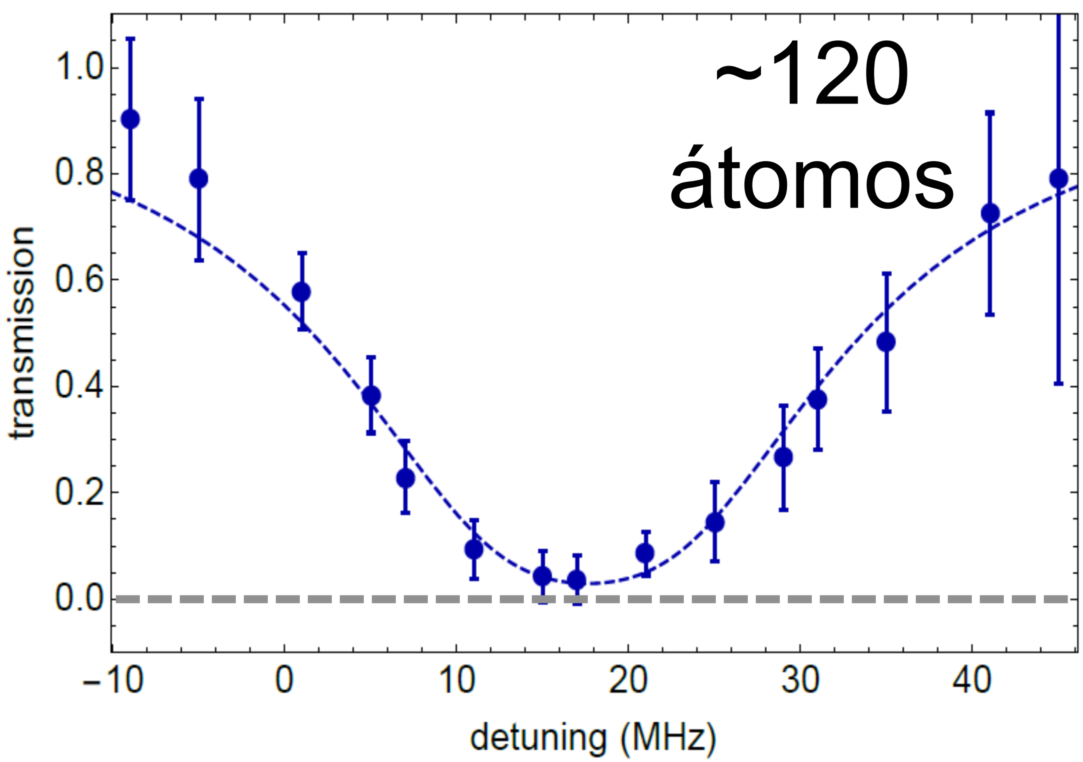
Trapping Scheme

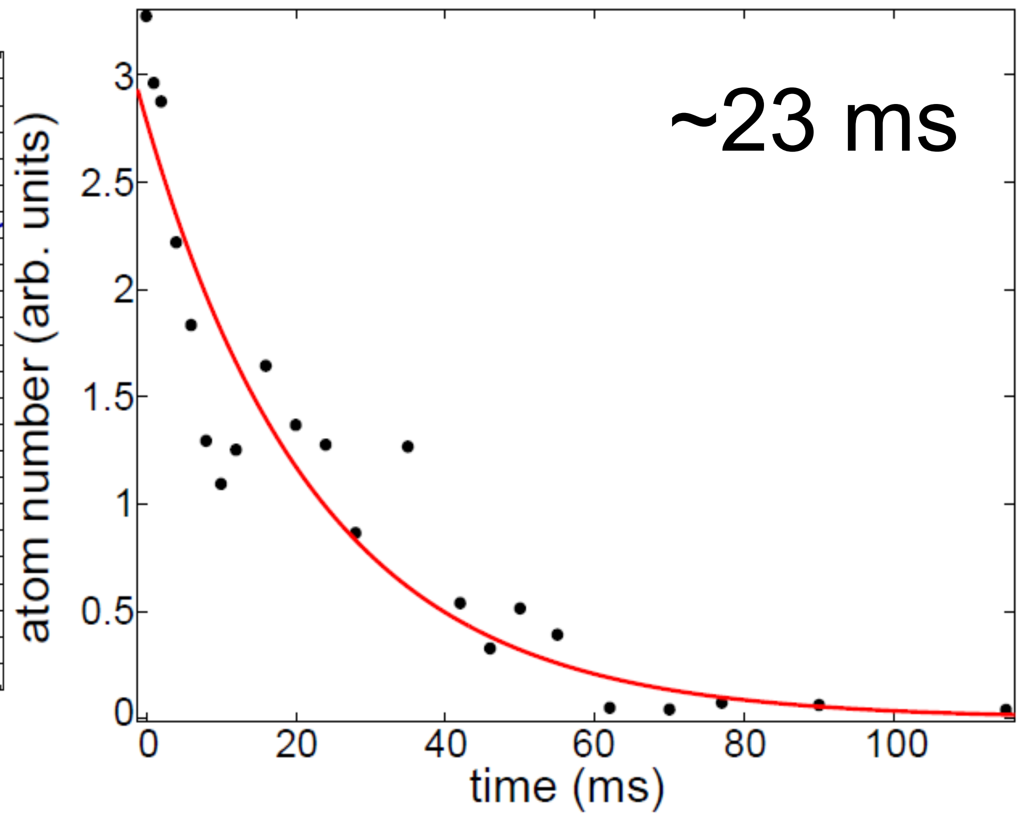




Trapping Scheme

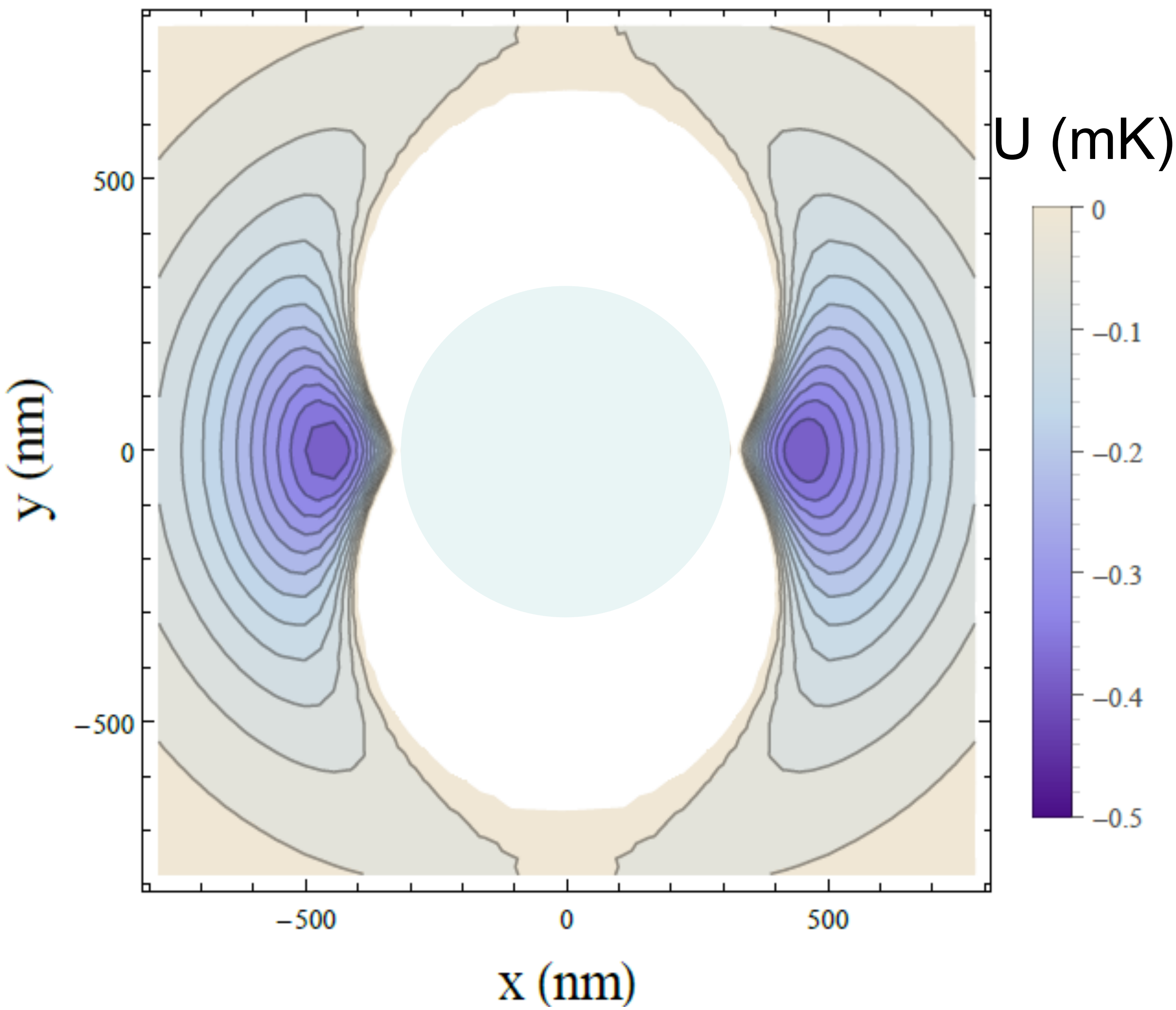




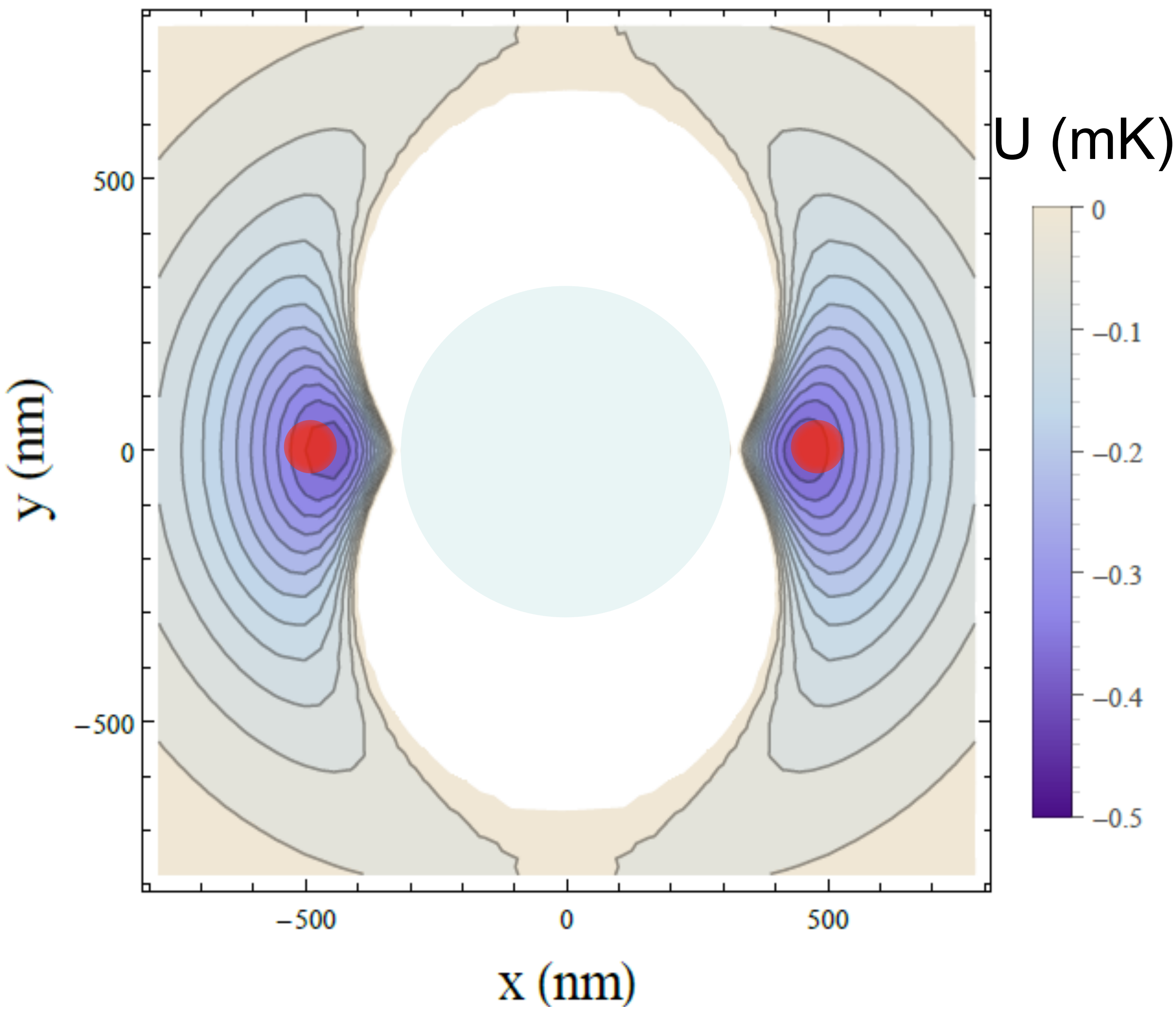


4. Dinamics of atoms trapped around the nanofiber.

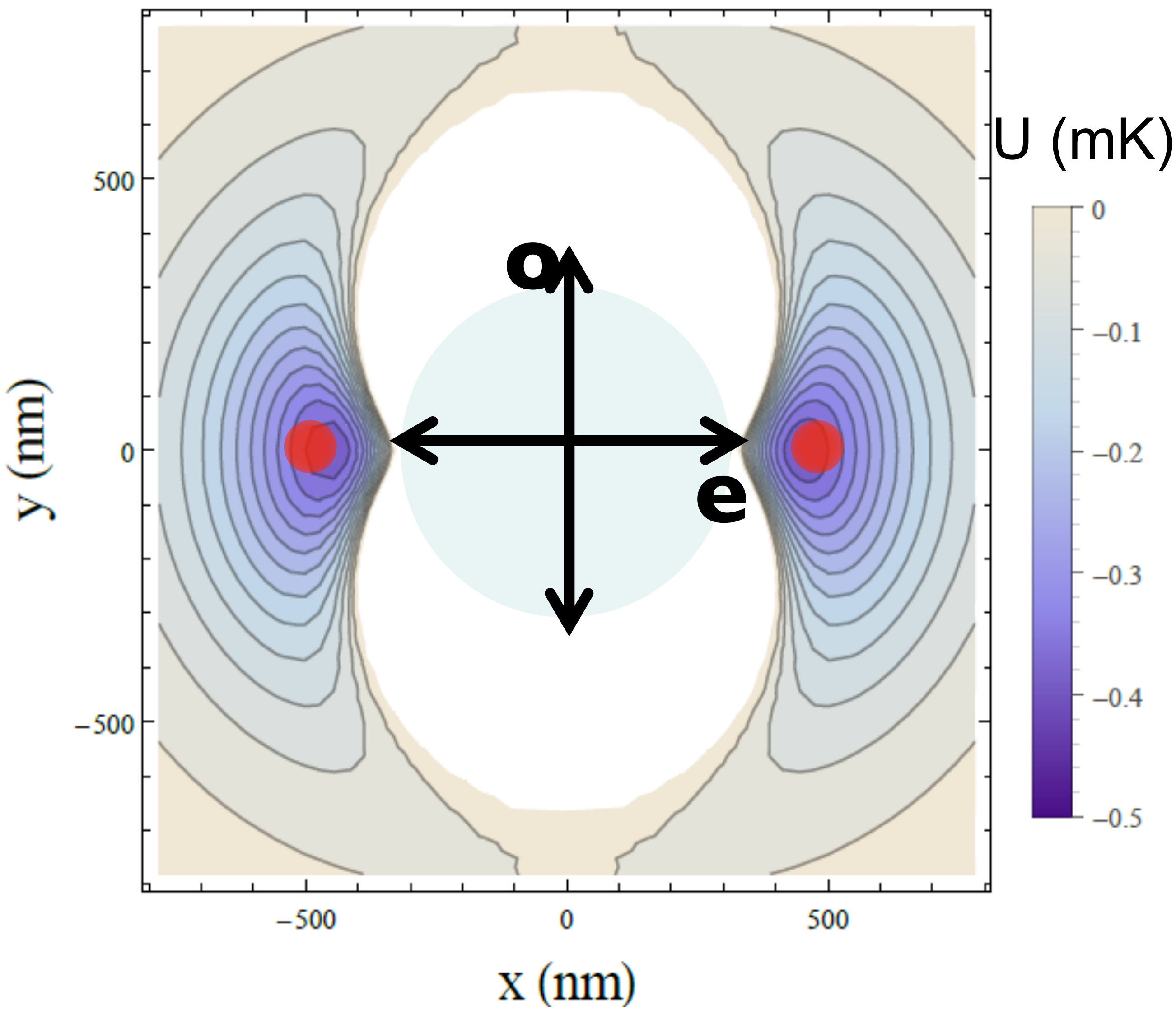
Atoms as a birefringent medium



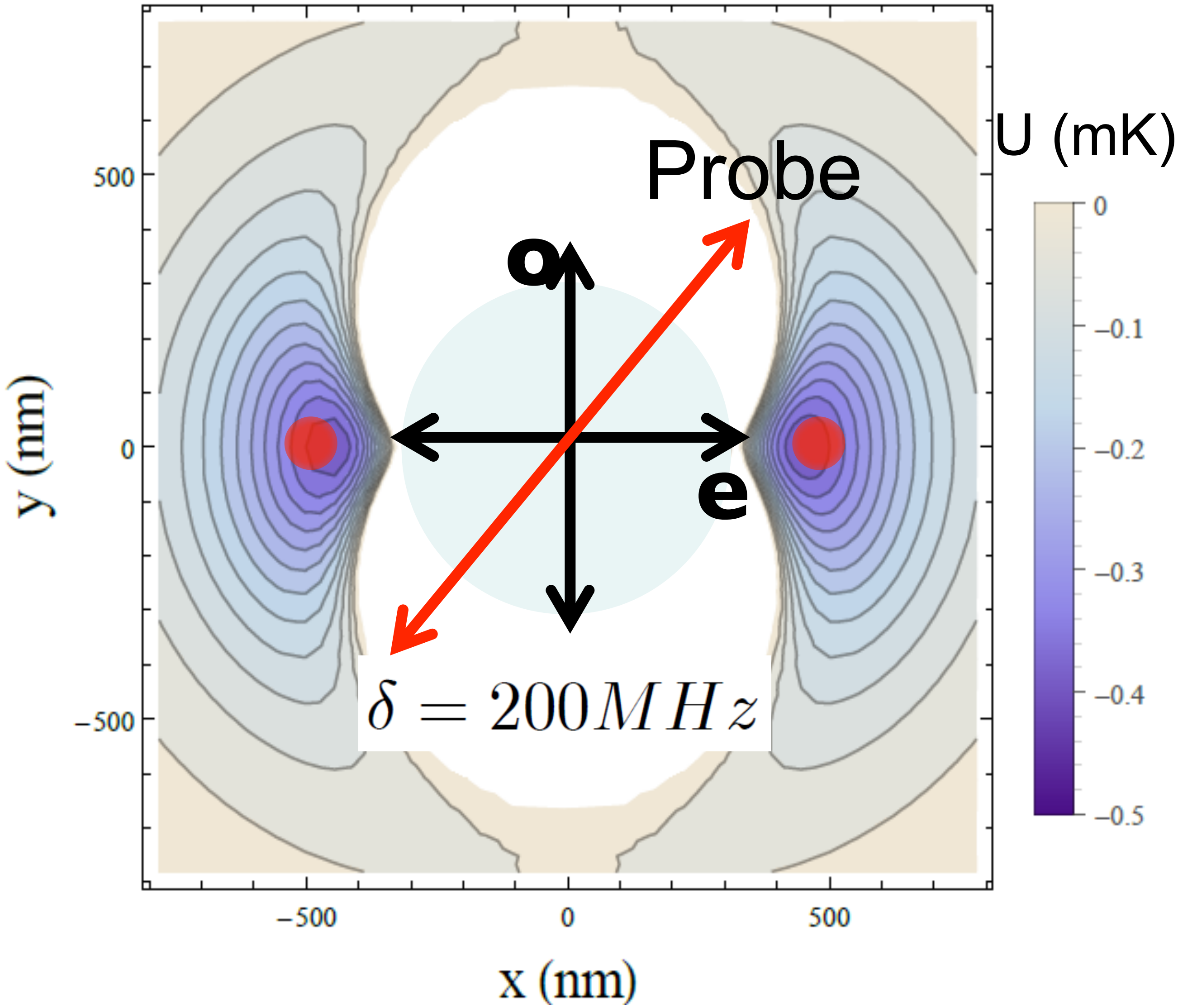
Atoms as a birefringent medium



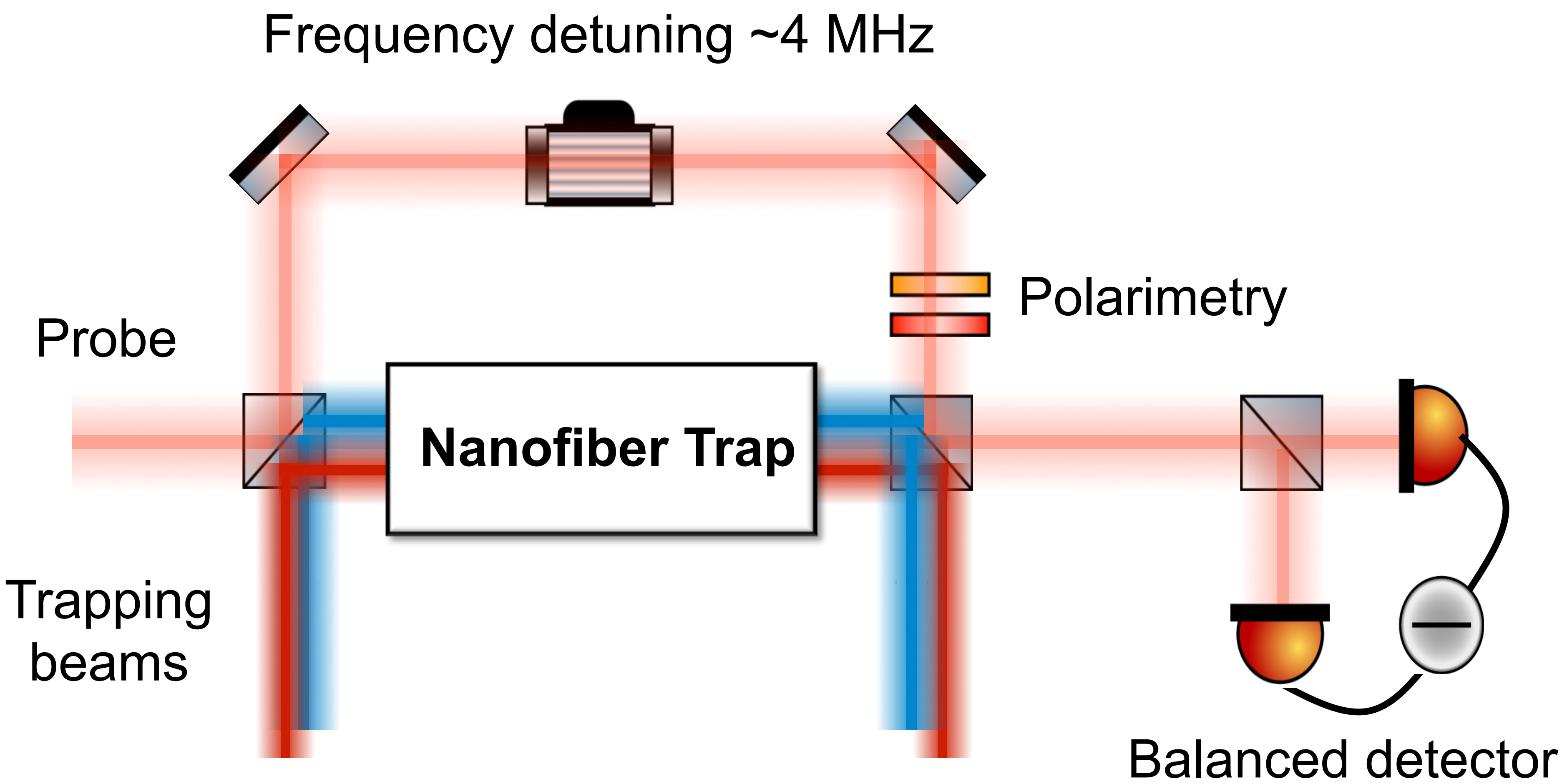
Atoms as a birefringent medium



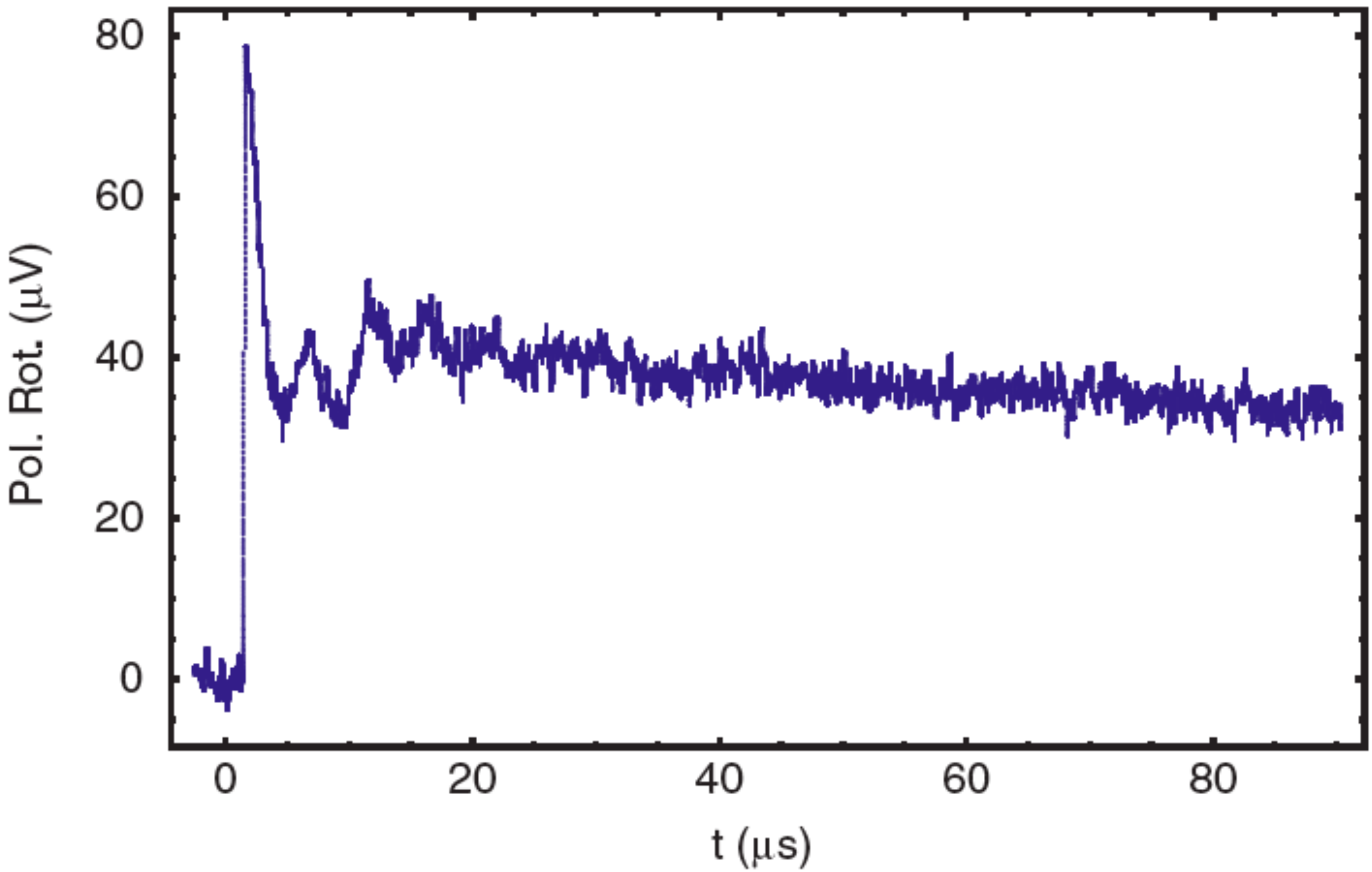
Atoms as a birefringent medium



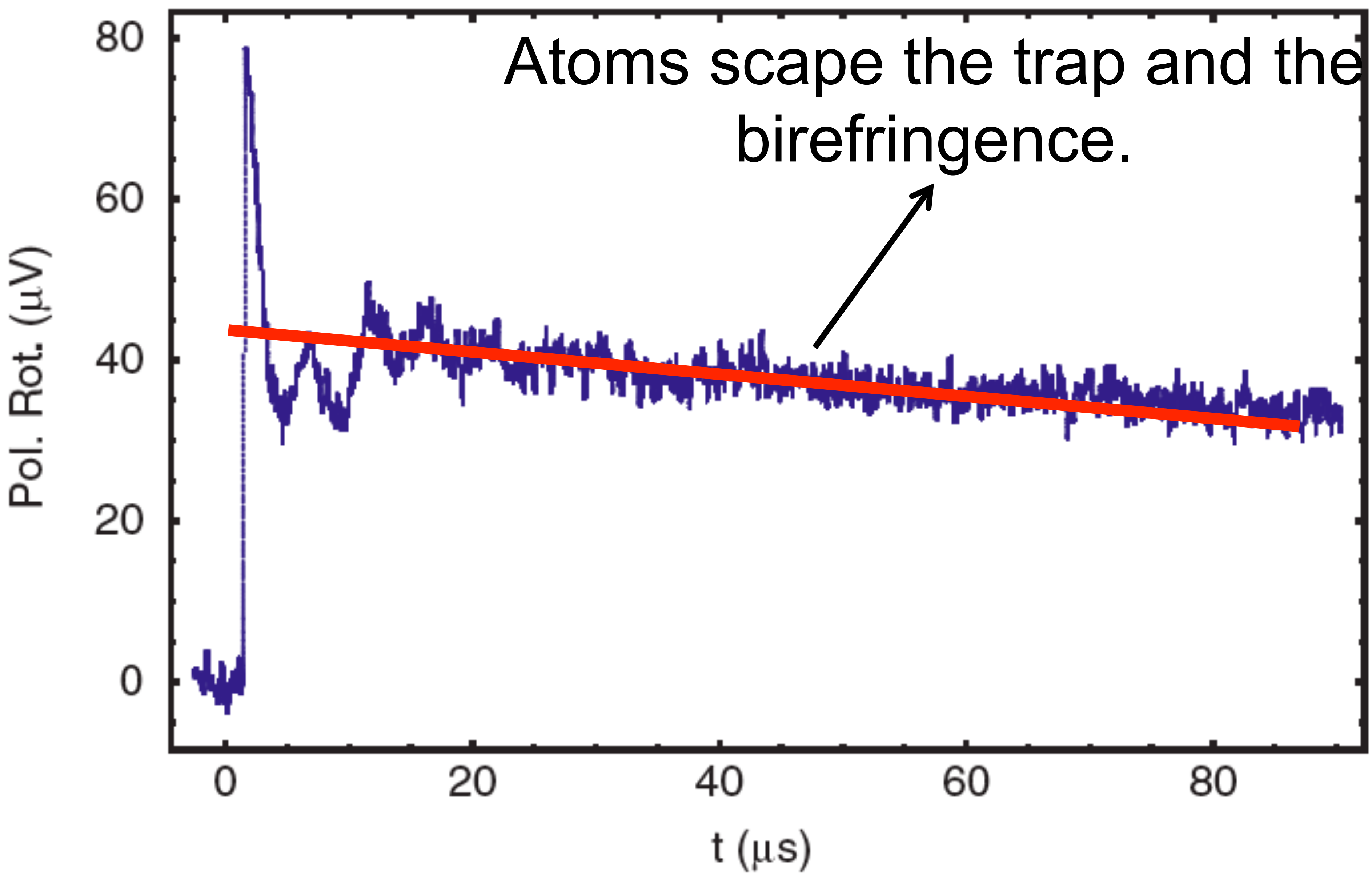
Detection
Heterodyne polarimetry



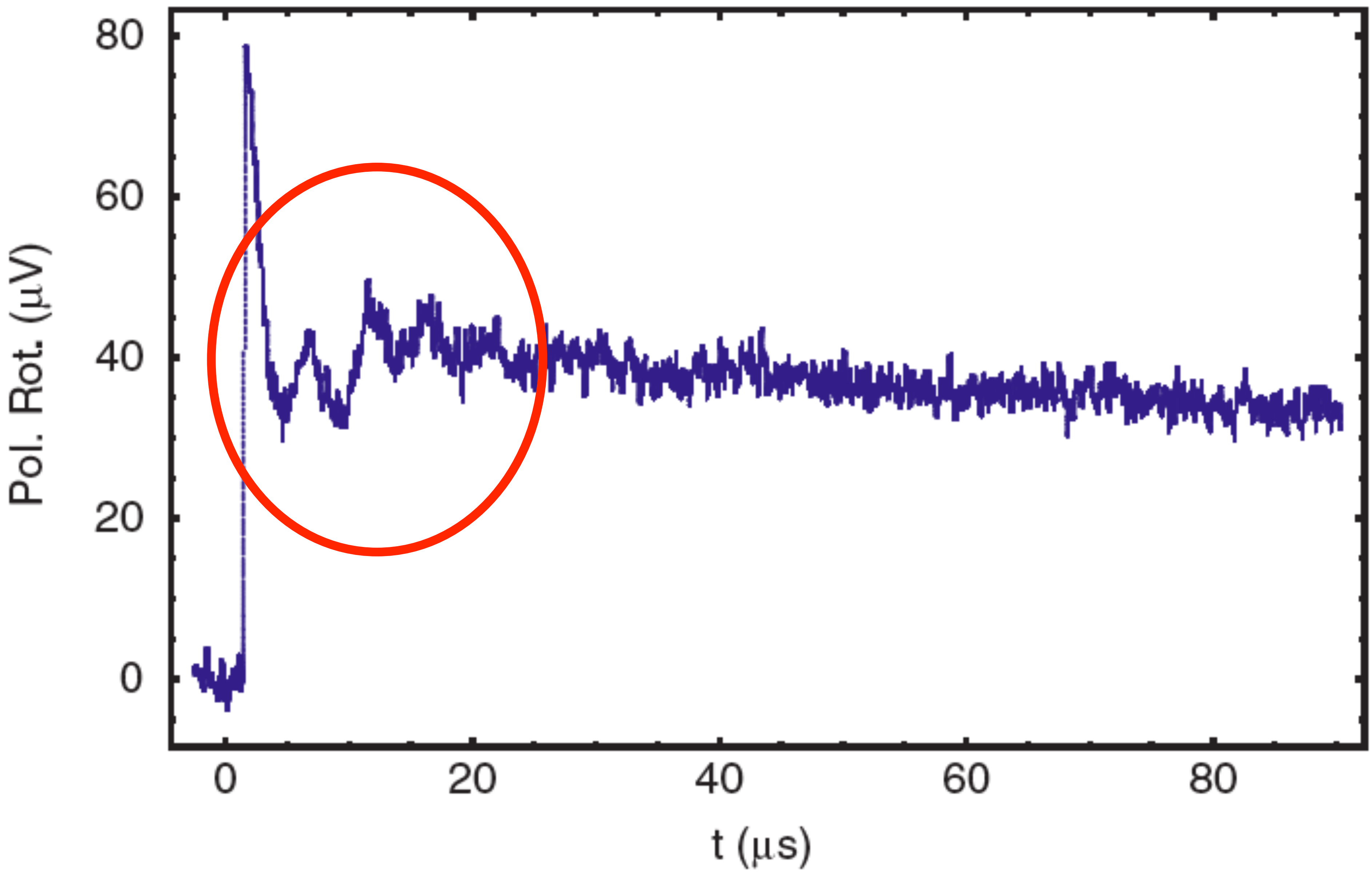
Temporal dependence of the birefingence



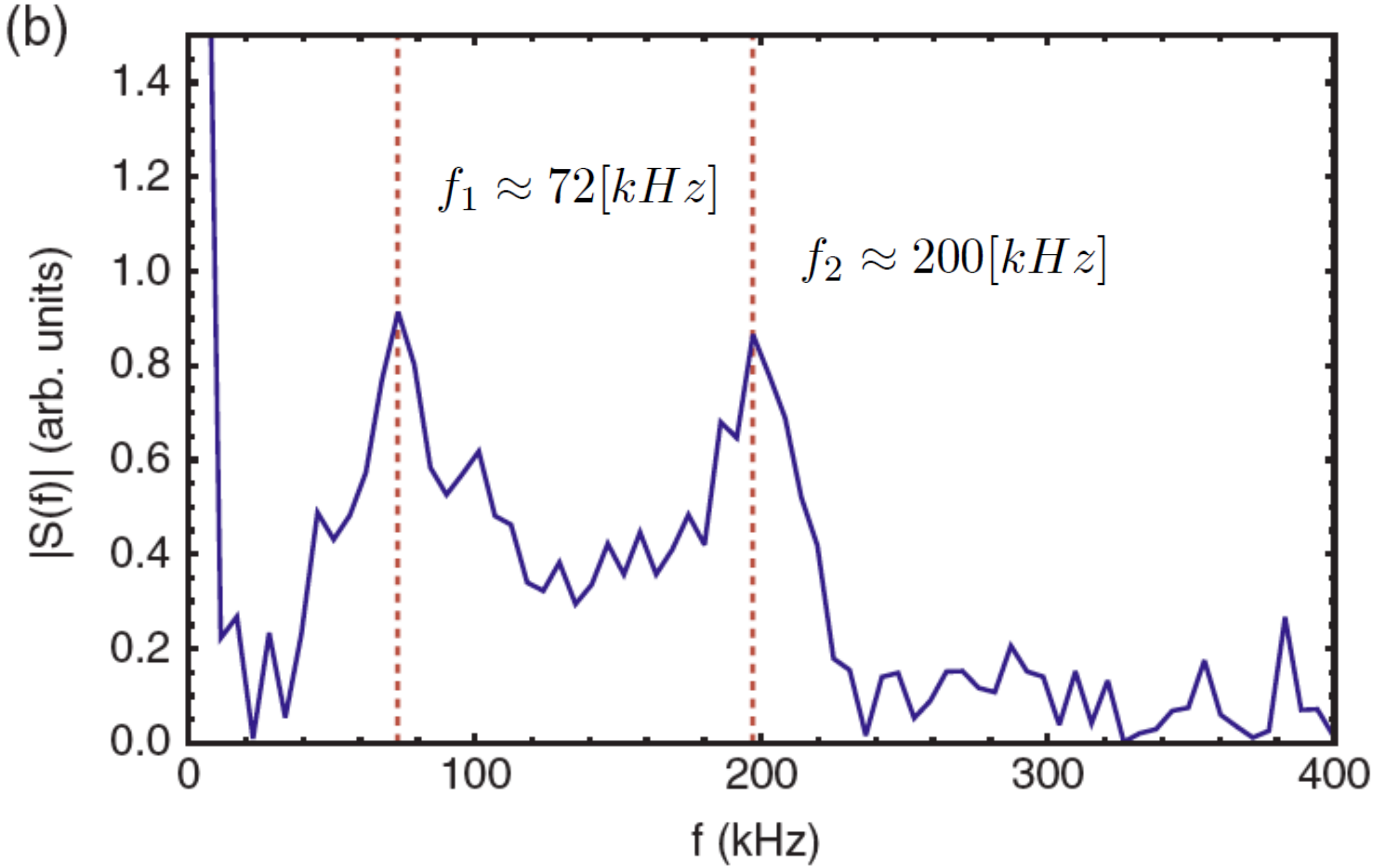
Temporal dependence of the birefingence



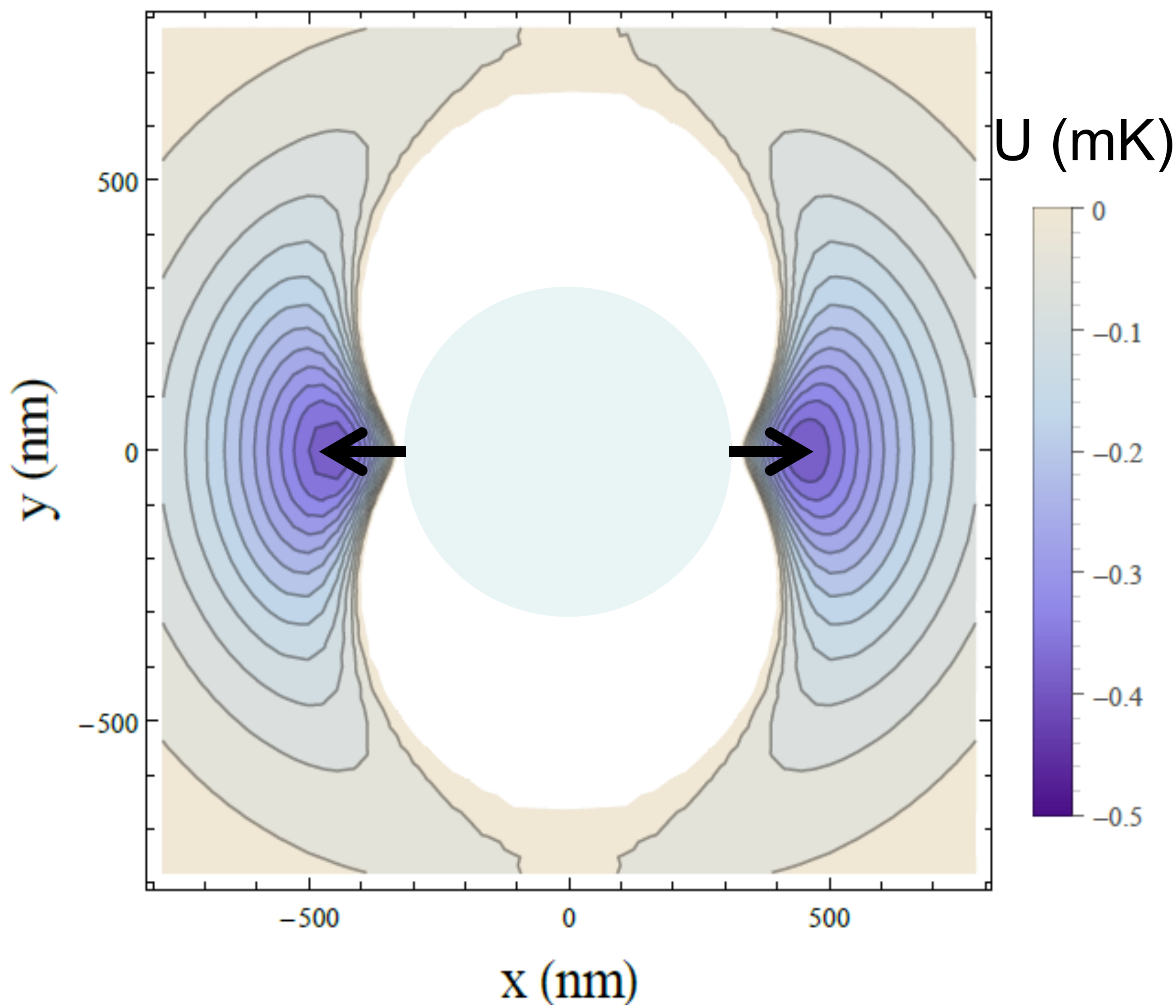
Temporal dependence of the birefingence



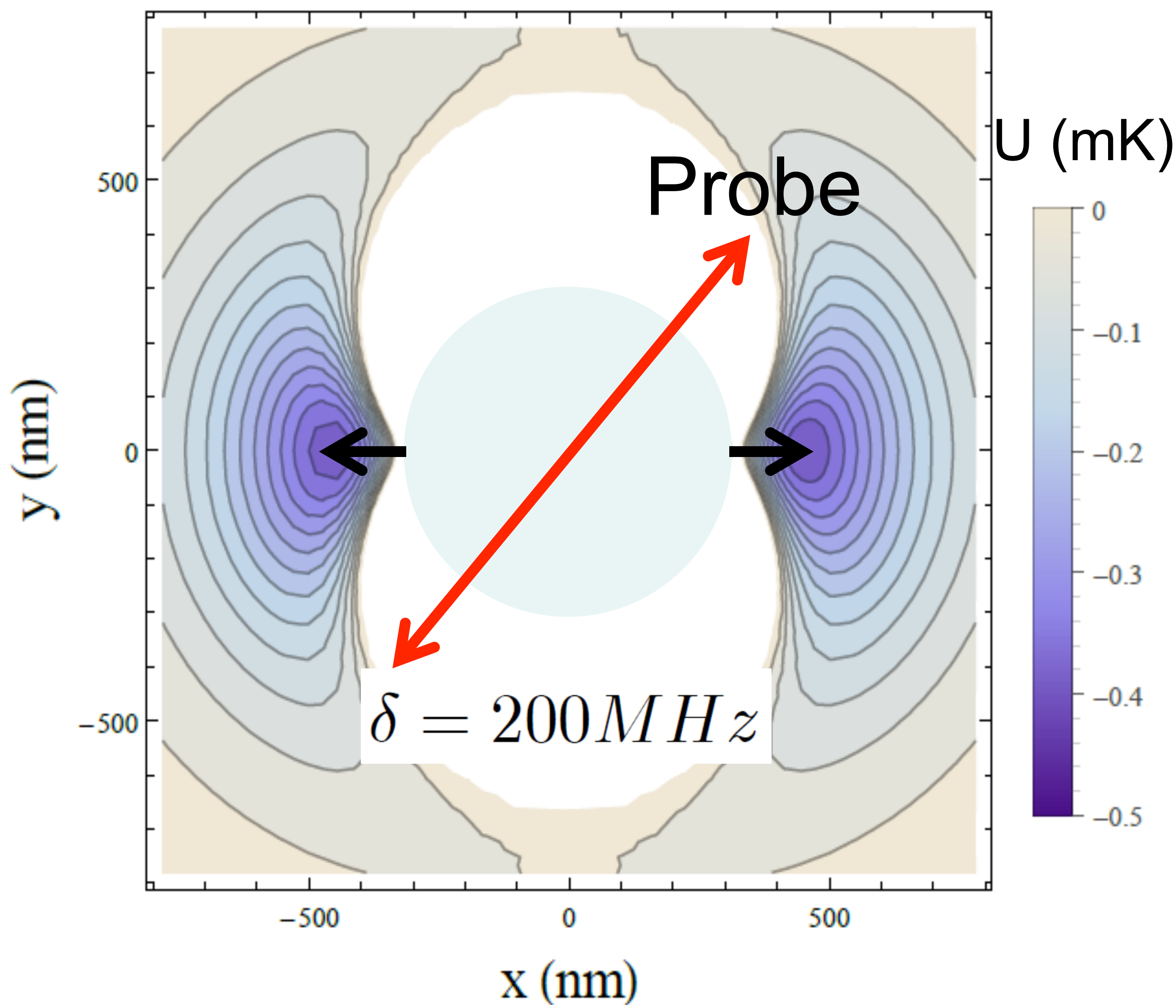
Temporal dependence of the birefingence



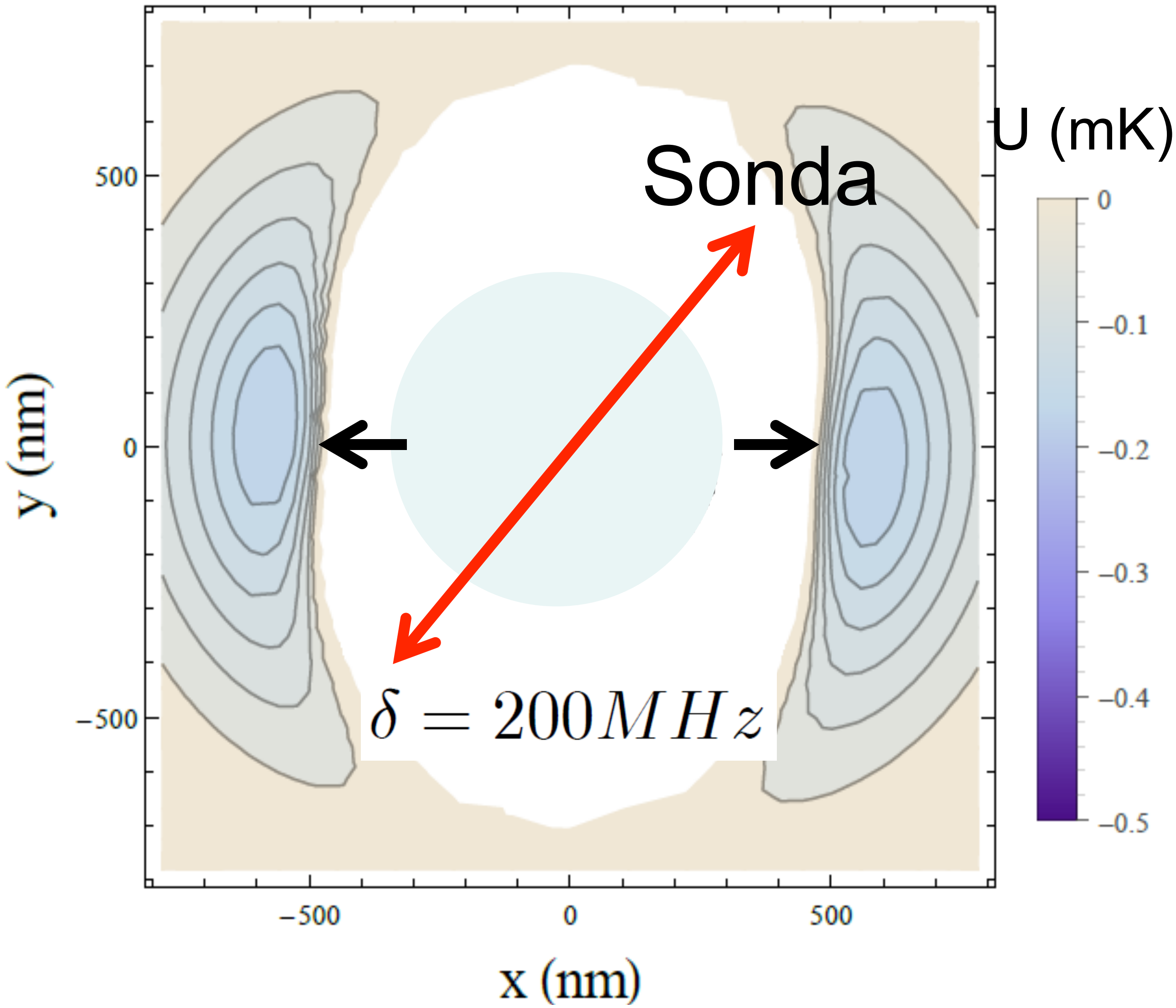
Atoms moving in the trap



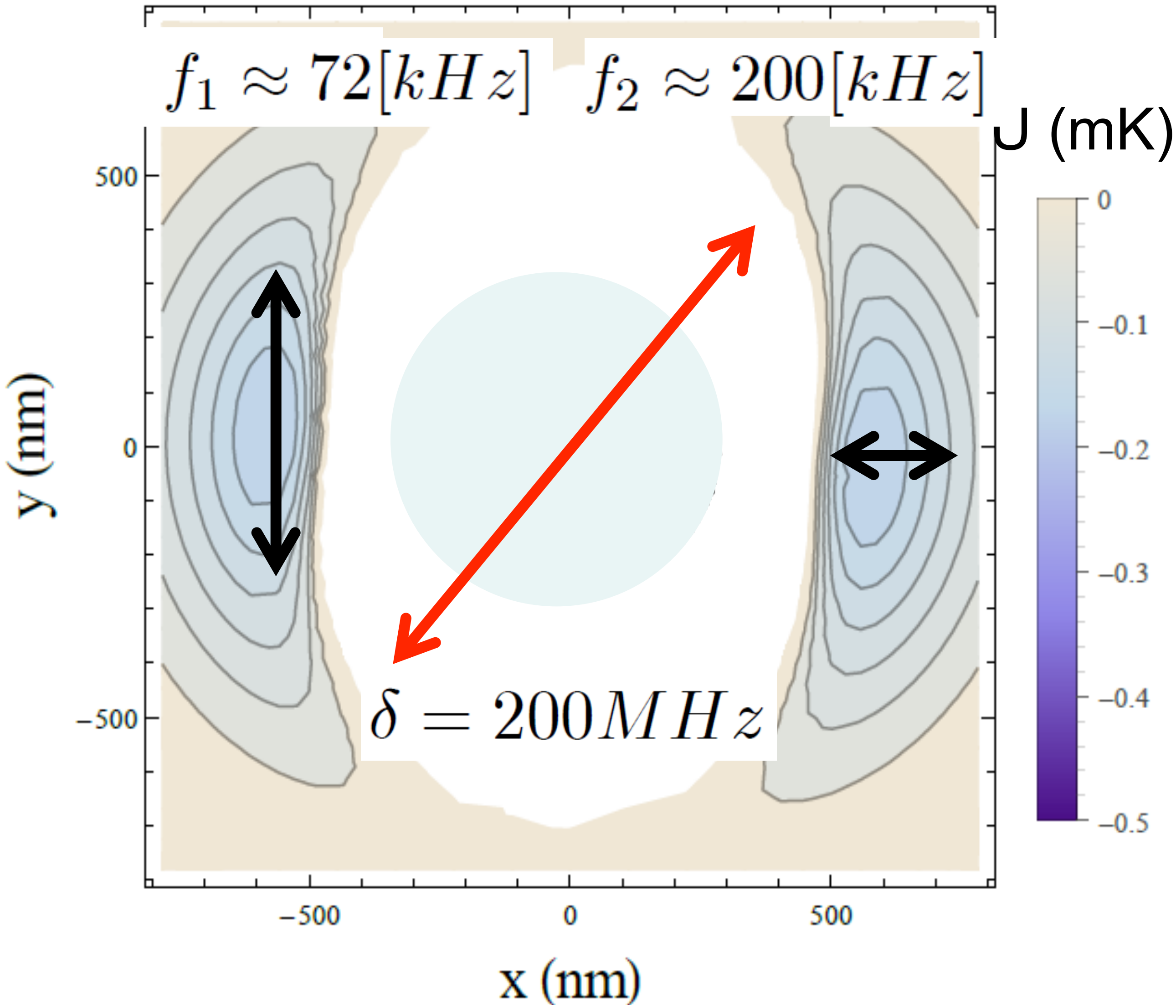
Atoms as a birefringent medium



Atoms as a birefringent medium

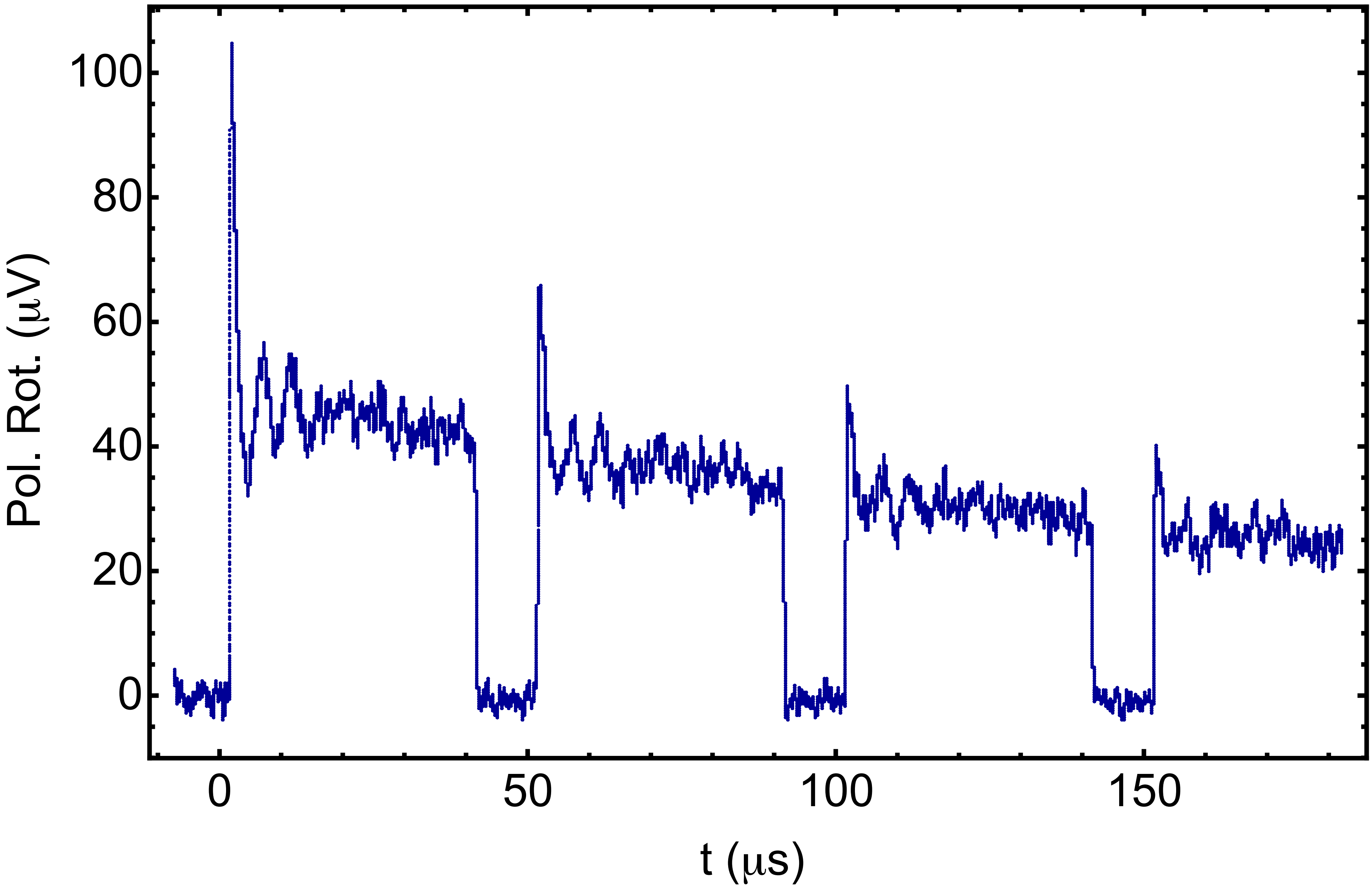


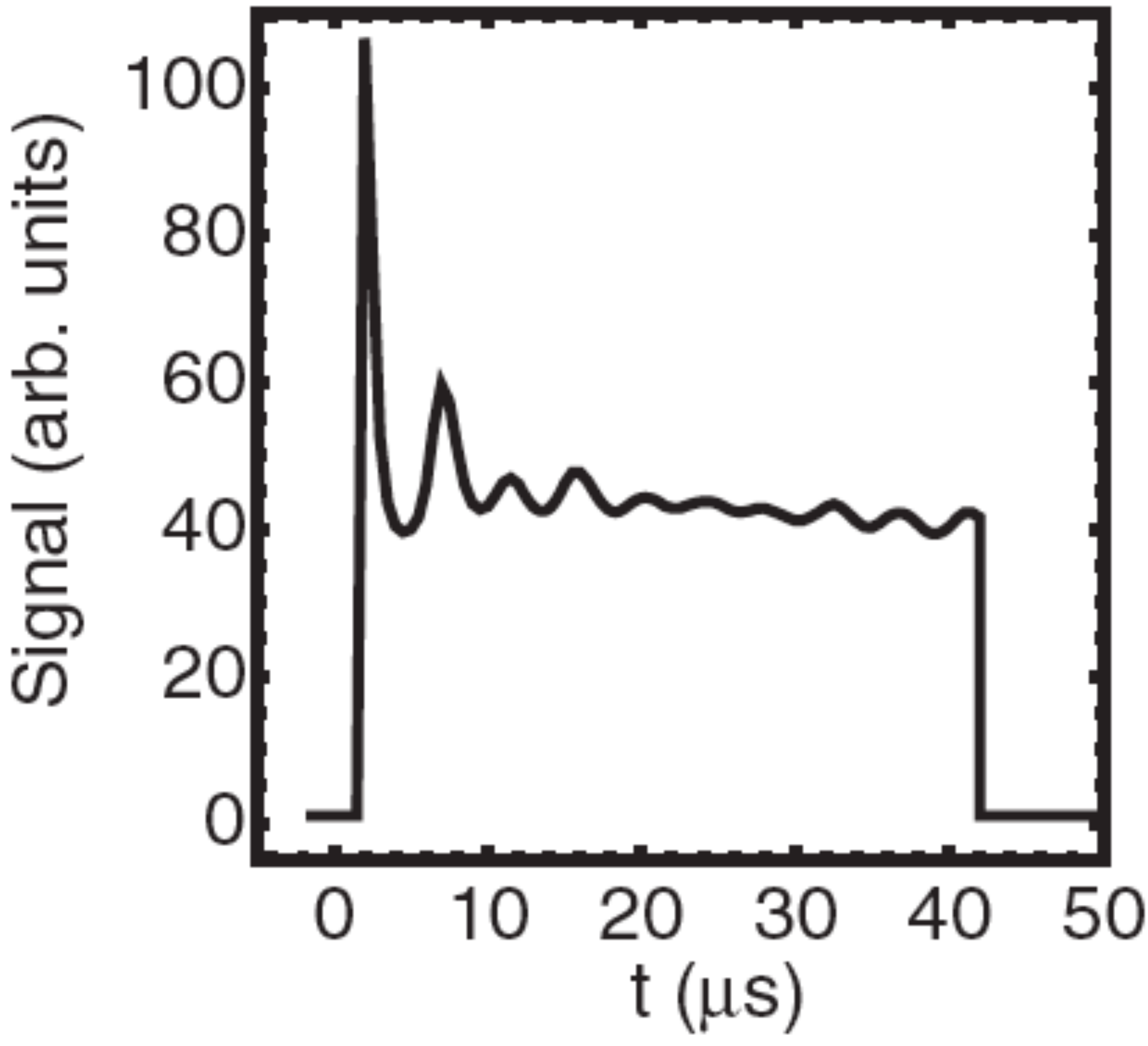
Atoms as a birefringent medium



Experiment and silulation give same frequencies.

Atoms as a birefringent medium





Signal (arb. units)
100
80
60
40
20
0
0
10
20
30
40
50
t (μs)

Summary:

1. Radiation Forces.
2. Traps.
3. Example of trapping atoms around a nanofiber.

Gracias