Optical nanofibers.

Shanxi University

Institute for Laser Spectroscopy

Short course

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JOINT QUANTUM INSTITUTE

NIST

Some Bibliography:

P. Solano, J. A. Grover, J. E. Hoffman, S. Ravets, F. K. Fatemi, L. A. Orozco, and S. L. Rolston “Optical Nanofibers: A New Platform for Quantum Optics.” Advances in Atomic Molecular and Optical Physics, Vol. 46, 355-403, Edited by E. Arimondo, C. C. Lin, and S. F. Yelin, Academic Press, Burlington 2017.

Available at: ArXiv:1703.10533

Slides at:
http://www.physics.umd.edu/rgroups/amo/orozco/results/2018/Results18.htm

One atom interacting with light in free space.

Dipole cross section (same result for a classical dipole or from a two level atom):

$$\sigma_0 = \frac{3\lambda_0^2}{2\pi}$$

This is the “shadow” caused by a dipole on a beam of light.

Energy due to the interaction between a dipole and an electric field.

$$H = \vec{d} \cdot \vec{E}$$

The dipole matrix element between two states is fixed by the properties of the states (radial part) and the Clebsh-Gordan coefficients from the angular part of the integral. It is a few times a_0 (Bohr radius) times the electron charge e between the S ground and P first excited state in alkali atoms.

$$\vec{d} = e \left\langle 5S_{1/2} \middle| \vec{r} \middle| 5P_{3/2} \right\rangle$$

Rate of decay (Fermi's golden rule)

$$\gamma_{rad} \approx \frac{2\pi}{\hbar}\rho(k)\left\langle H_{int}\right\rangle^2$$

Phase space density

Interaction

Rate of decay free space (Fermi's golden rule)

$$\gamma_0 = \frac{\omega_0^3 d^2}{\pi \varepsilon_0 \hbar c^3}$$

Where *d* is the dipole moment

Waveguide QED in nanofibers

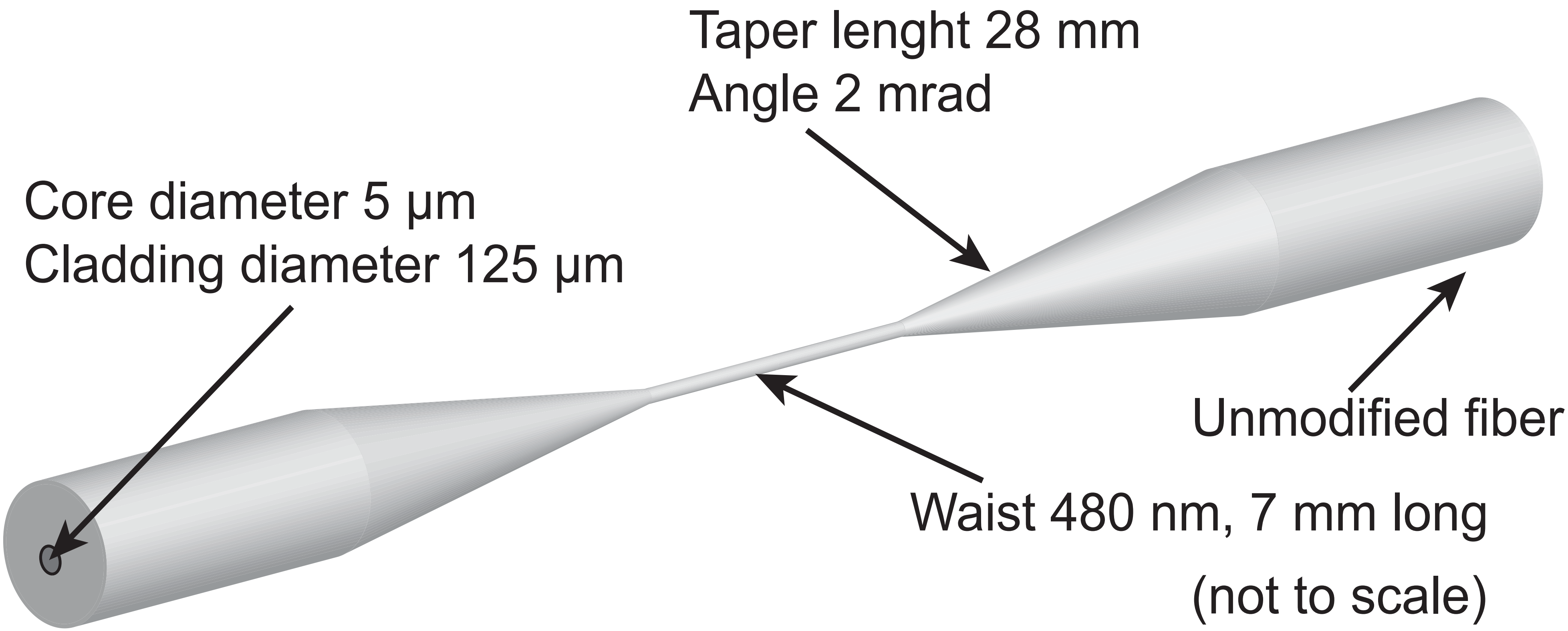
- We will use a waveguide to confine the electromagnetic field; the mode area can be smaller than λ^2

- Focus on how to use it with atoms, we are not going to talk about other qubits (solid state, superconducting, etc.)

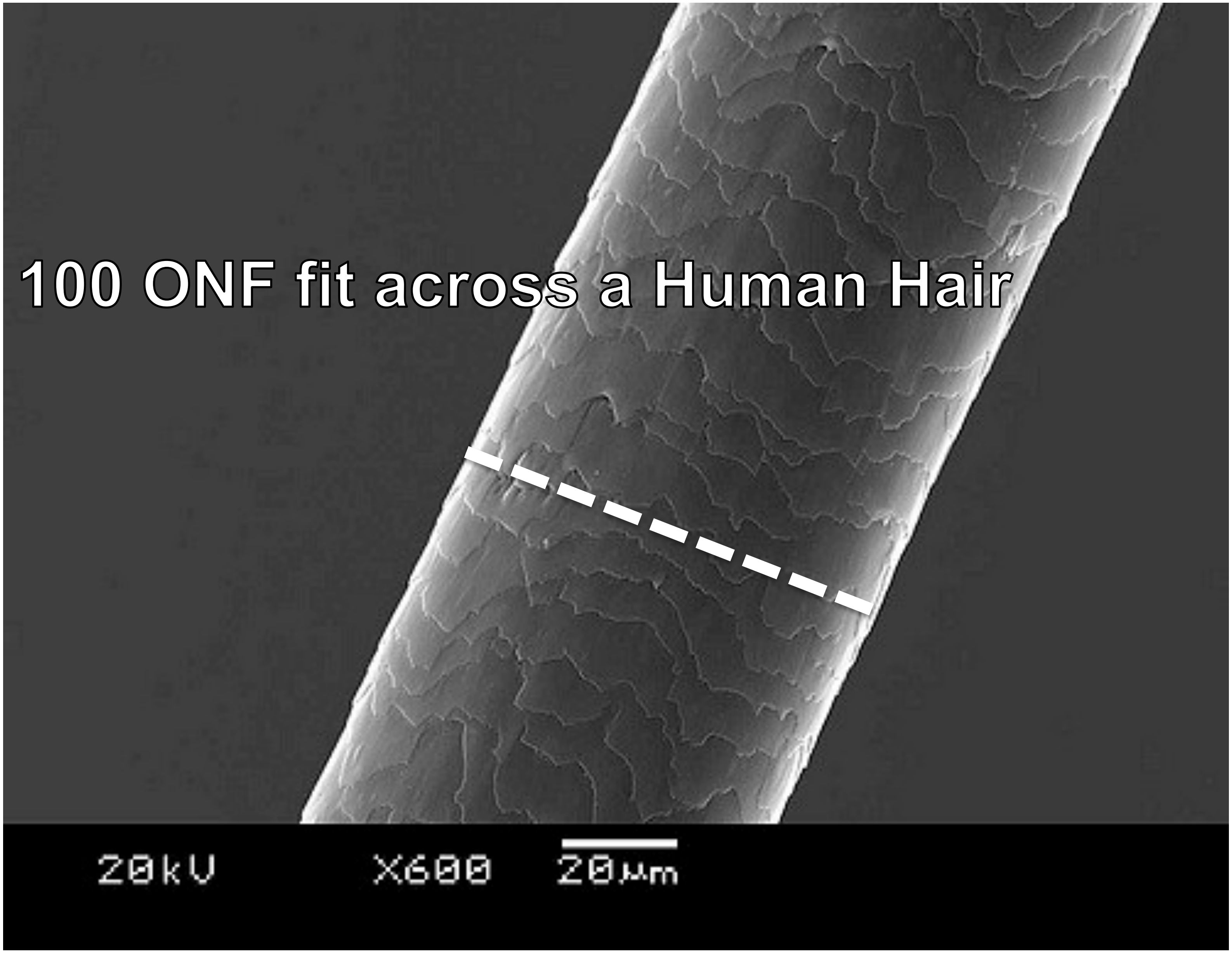
- Photonic Structures, for example optical nanofibers

Introduction to optical nanofibers, as waveguide

Optical Nanofibers

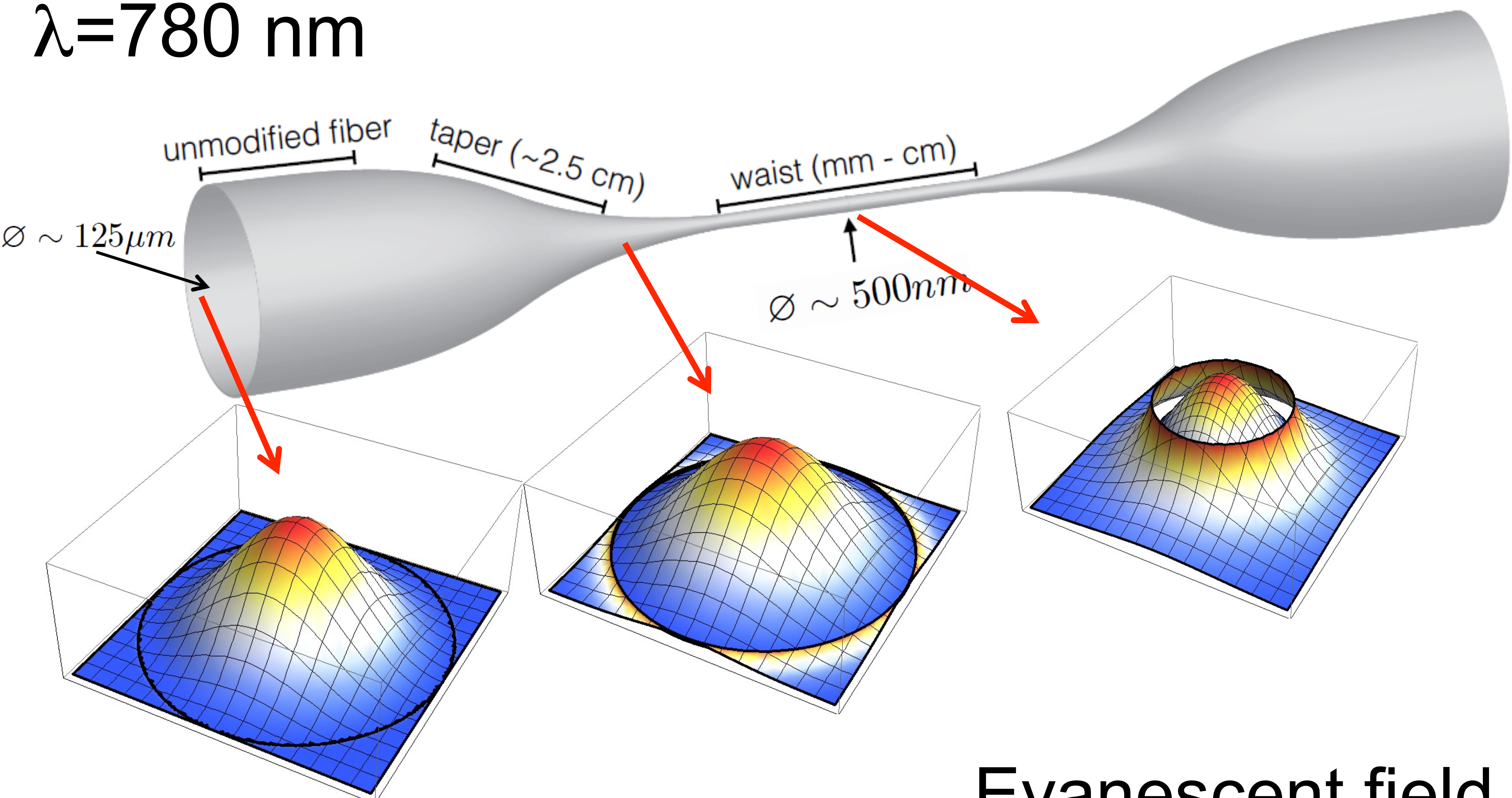


The scale



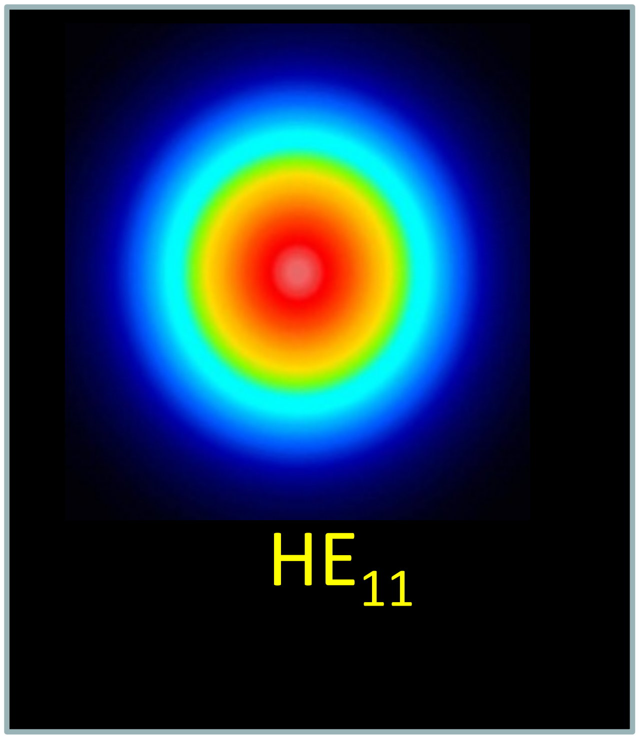
Optical Nanofibers

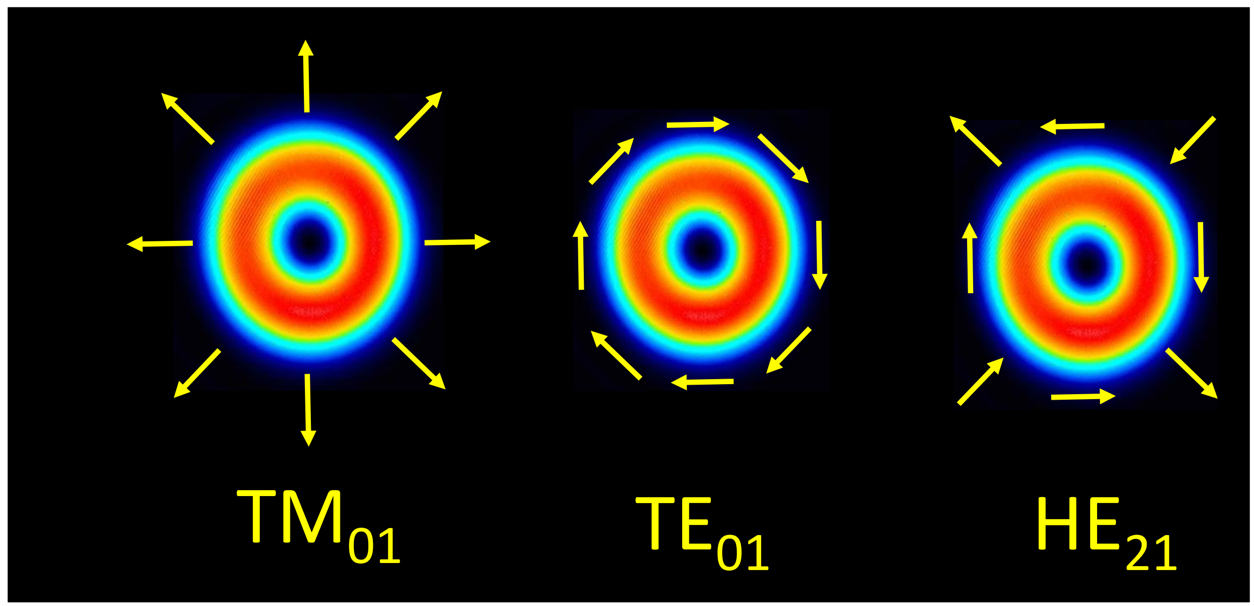
λ=780 nm



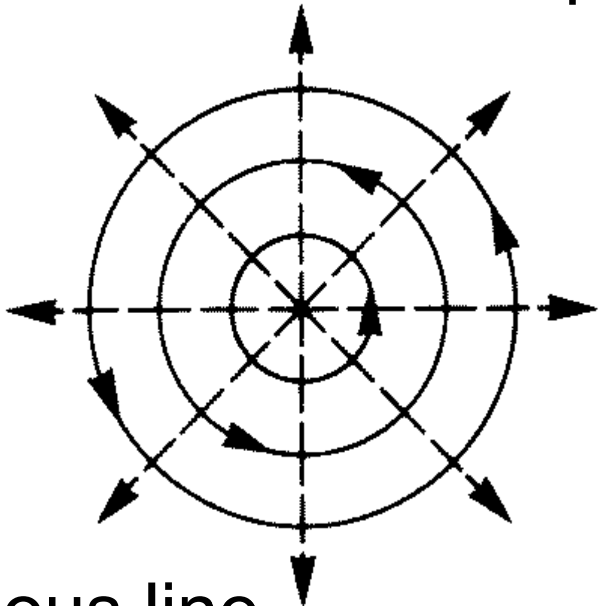
Evanescent field

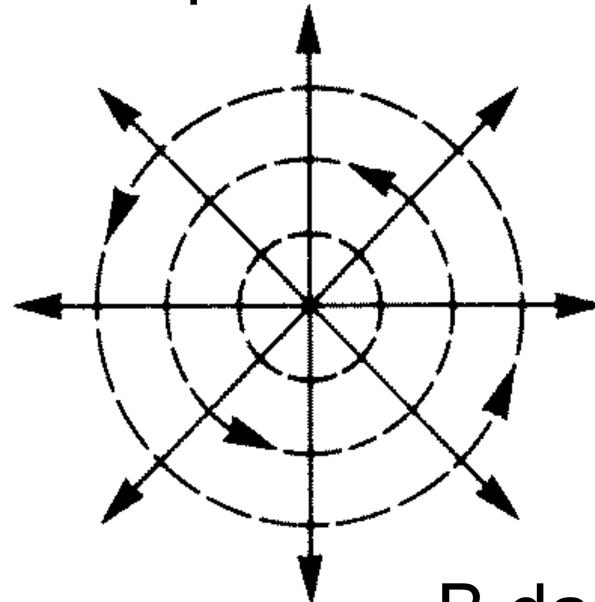
Lowest order fiber modes
Intensities and polarizations





Transversal component of the polarization



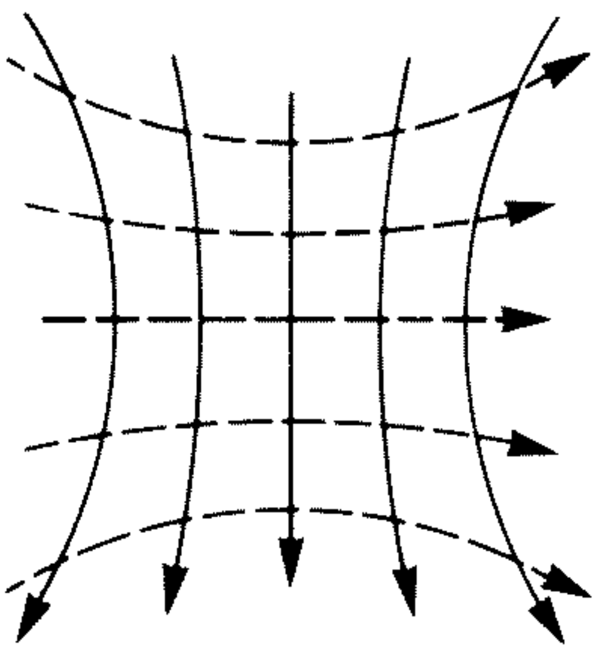


E continuous line

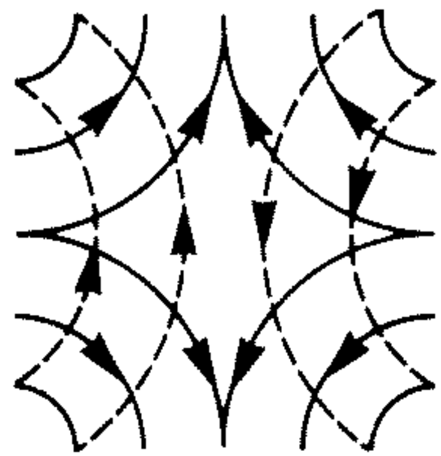
B dashed line

TE_{01}

TM_{01}

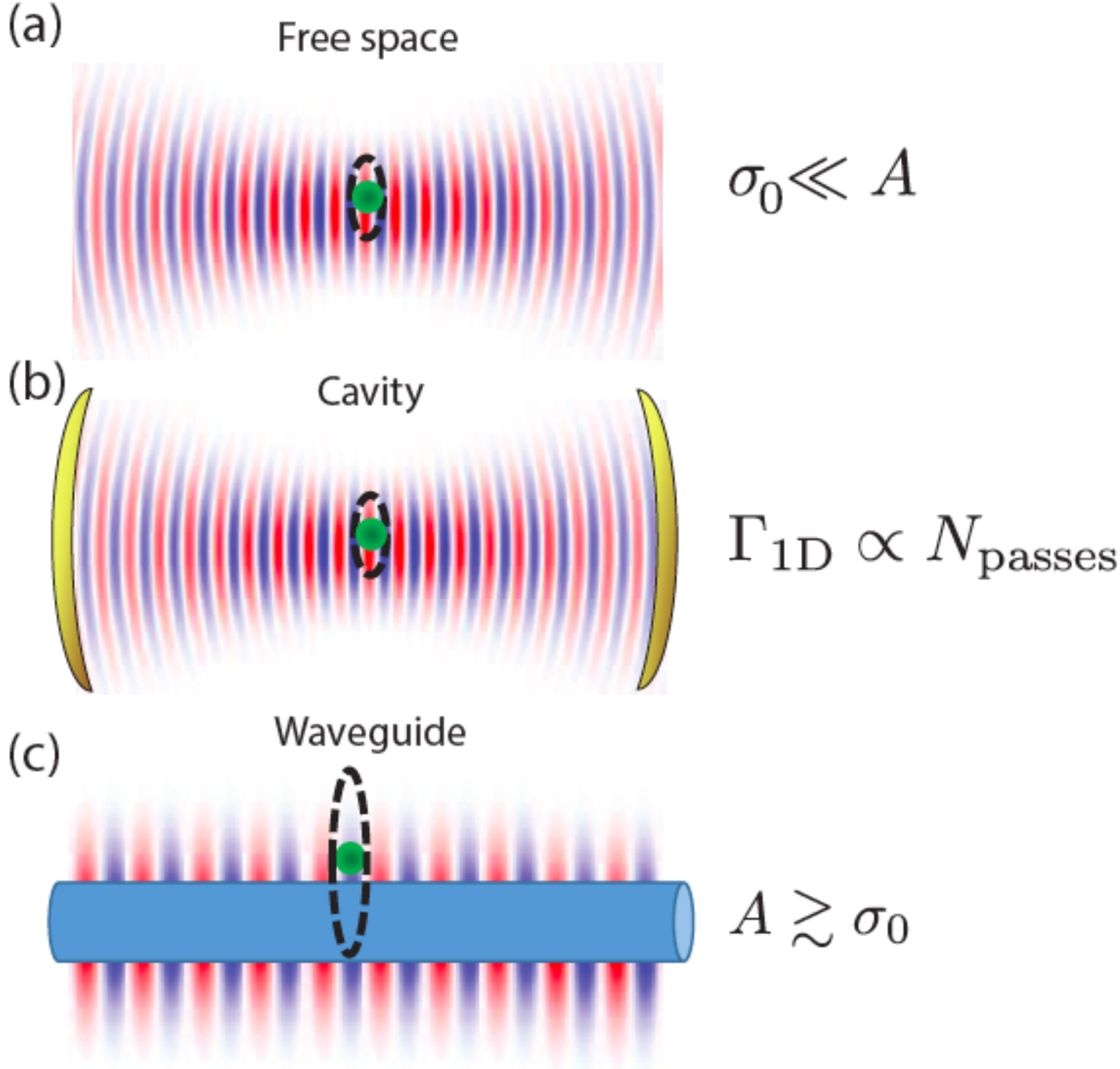


HE_{11}



HE_{21}

Coupling atoms to cavities and waveguides



PhD Thesis Jonathan Hood

Decay into the nanofiber mode

Density of modes in 1D

$$\gamma_{1D} \approx \frac{2\pi}{\hbar}\rho\left(k\right)\langle H_{int}\rangle^2$$

Decay into the nanofiber mode

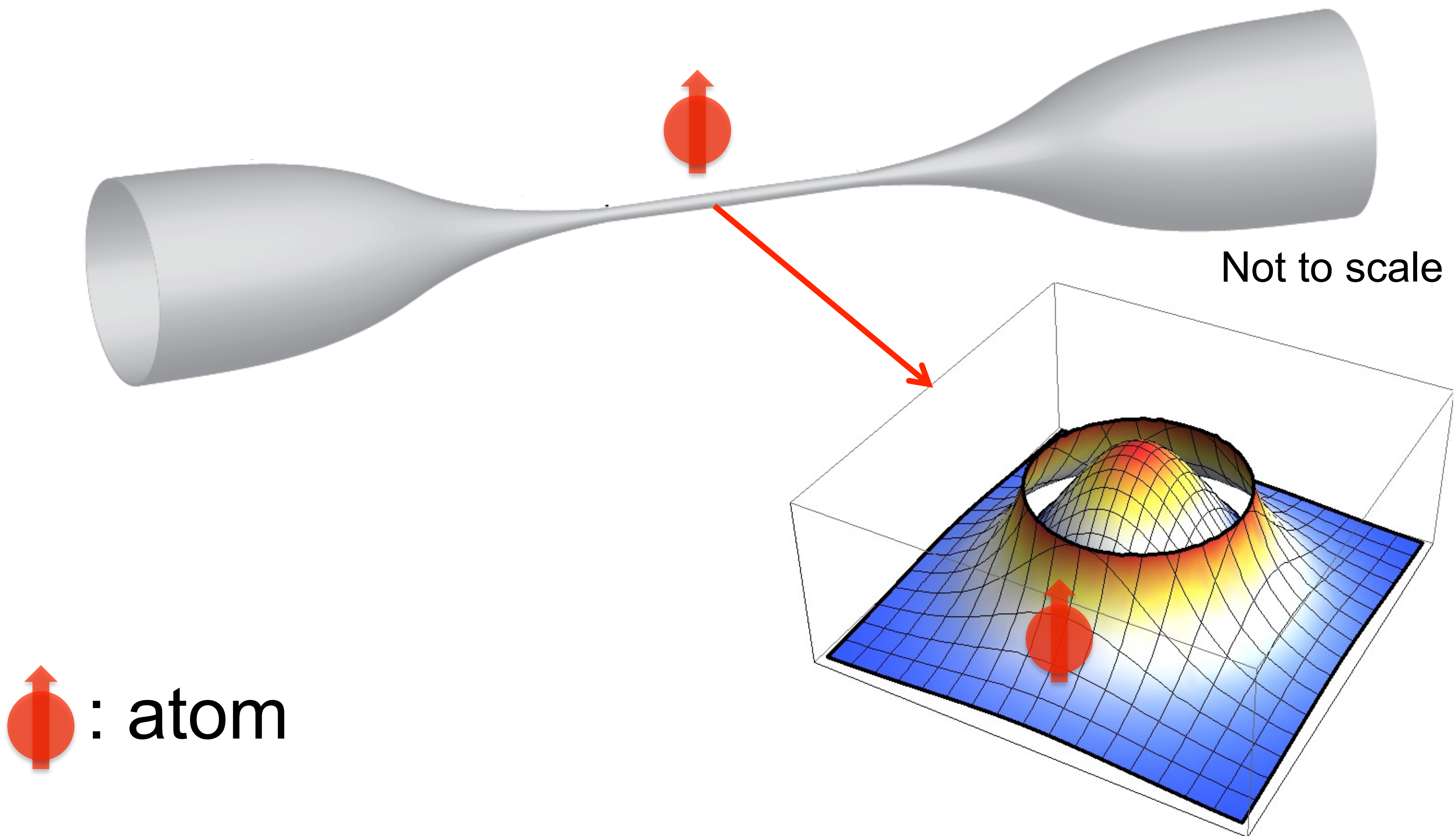
Density of modes

$$\gamma_{1D} \approx \frac{2\pi}{\hbar} \rho\left(k\right) \langle H_{int} \rangle^2$$

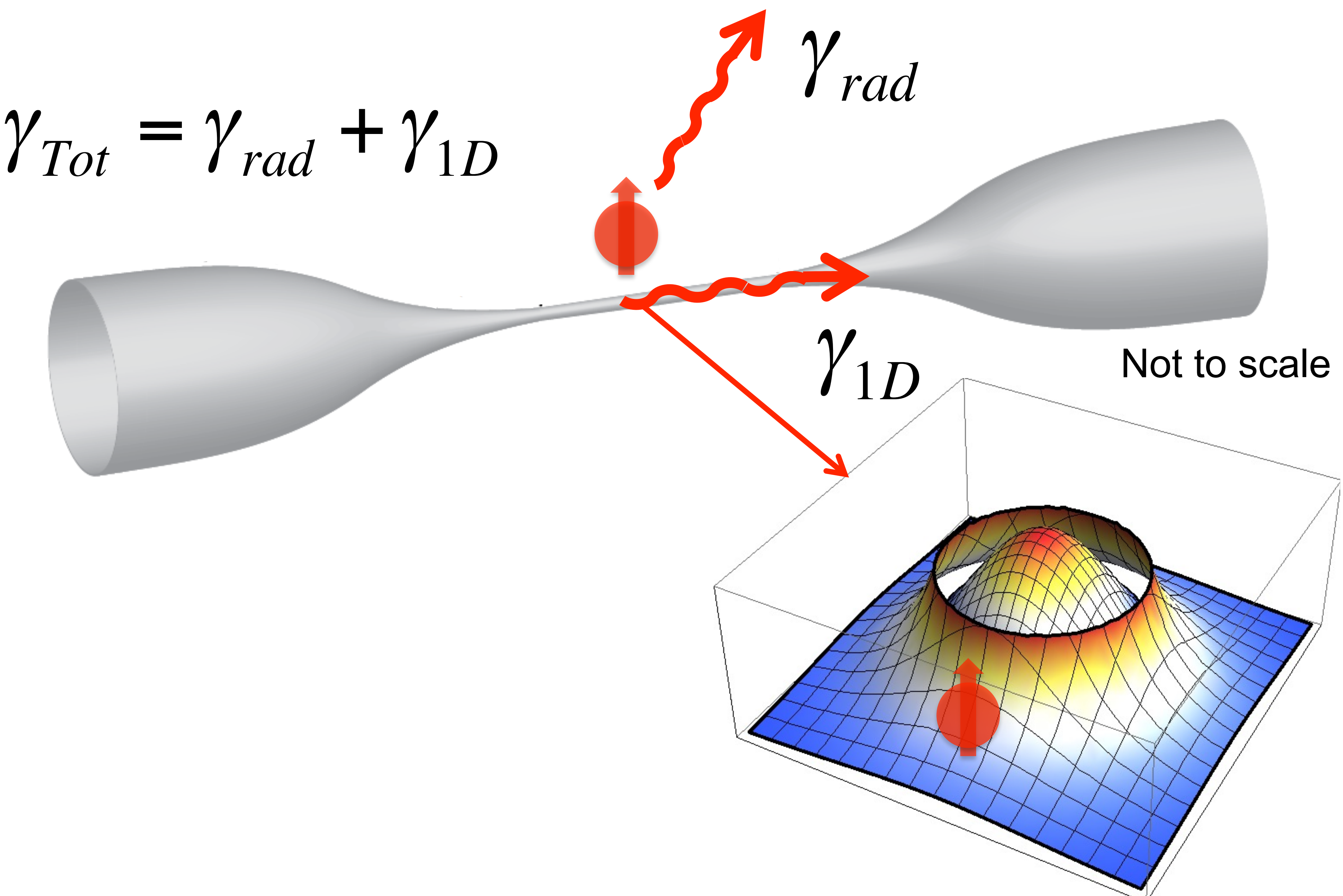
Proportional to the electric field of the guided mode

$$|E|^2 = \mathcal{E}^2 \left[K_0^2(qr) + wK_1^2(qr) + fK_2^2(qr) \right]$$

Evanescent Coupling

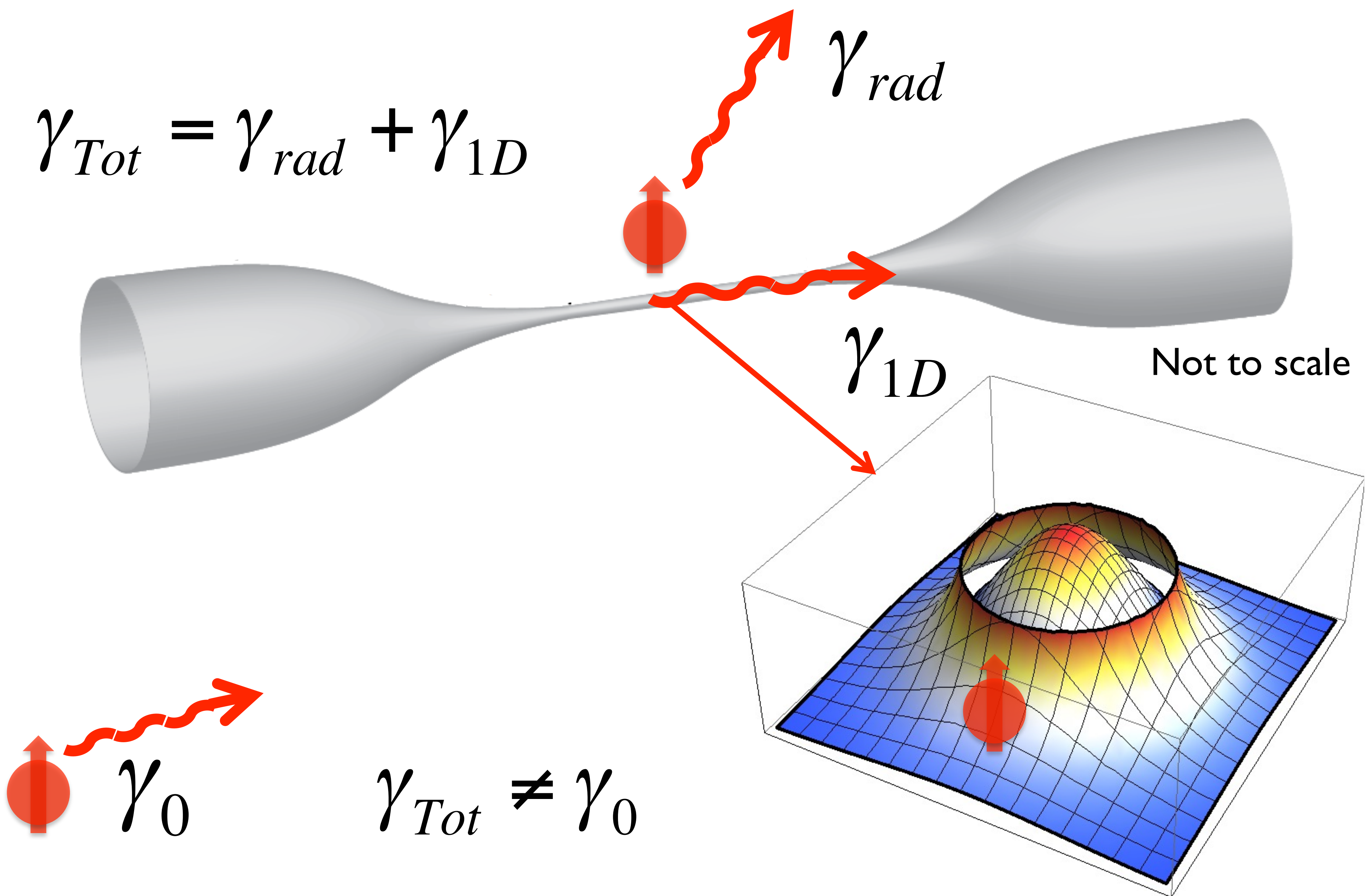


Evanescent Coupling



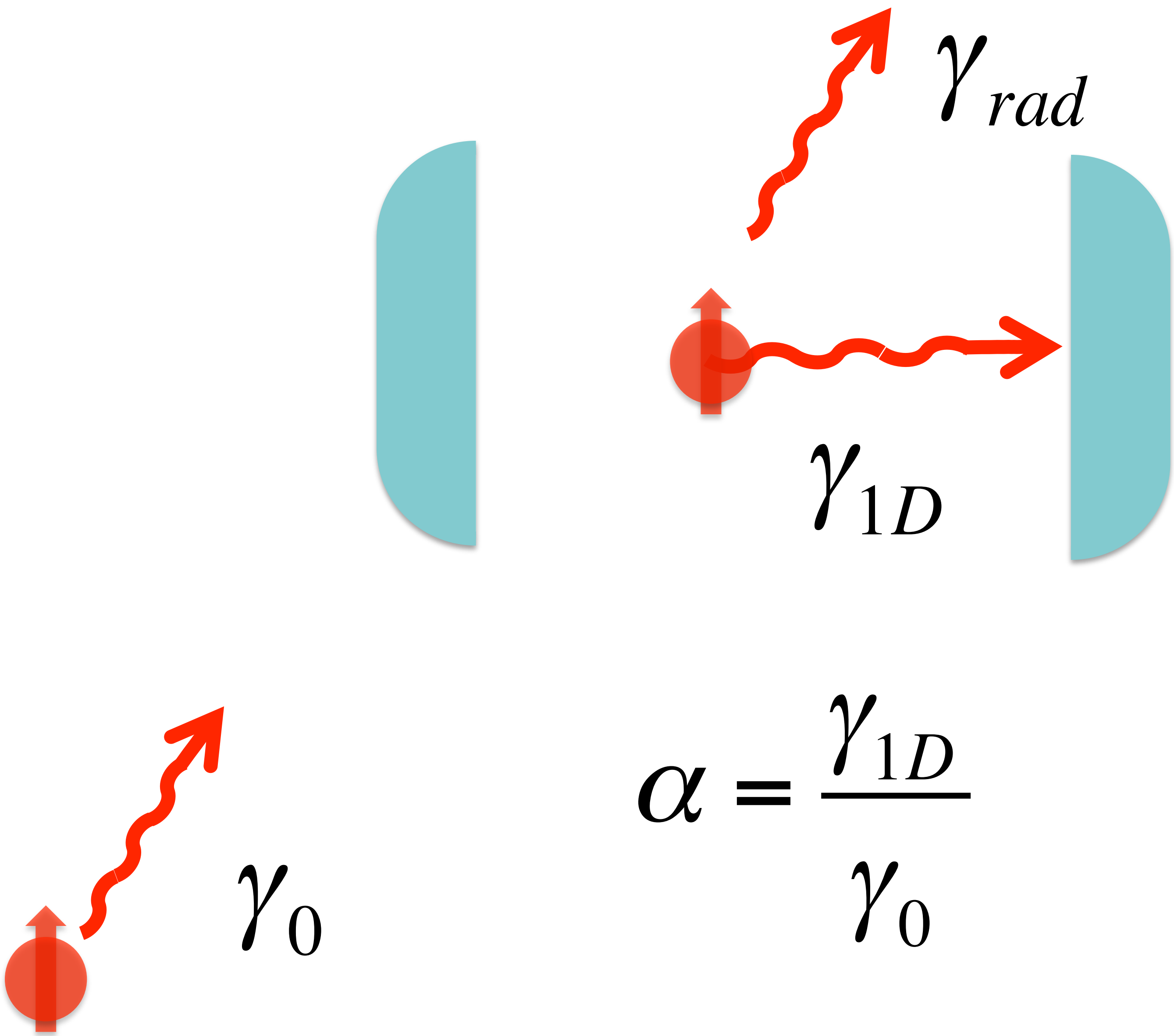
Evanescent Coupling

$$\gamma_{Tot} = \gamma_{rad} + \gamma_{1D}$$



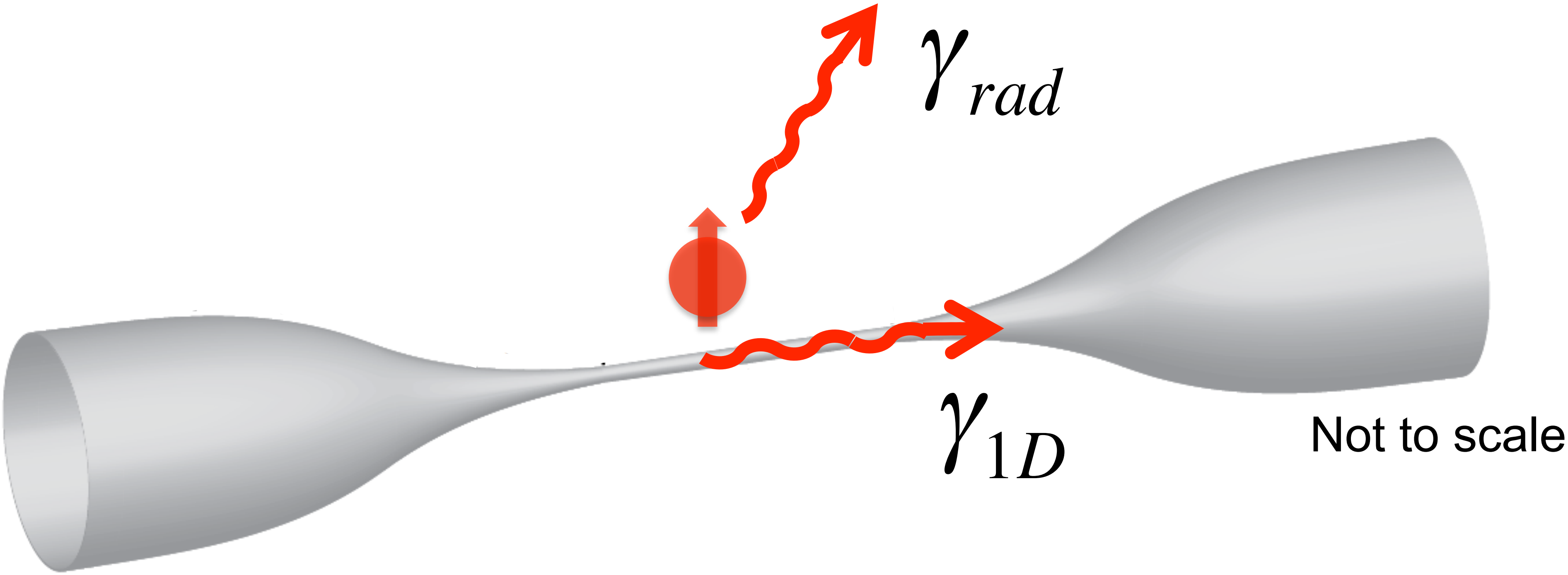
$$\gamma_{Tot} \neq \gamma_0$$

Coupling Enhancement

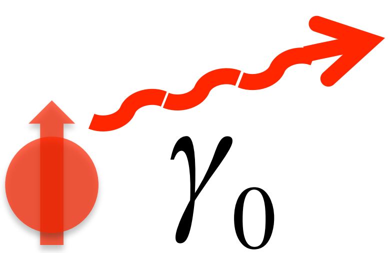


$$\alpha = \frac{\gamma_{1D}}{\gamma_0}$$

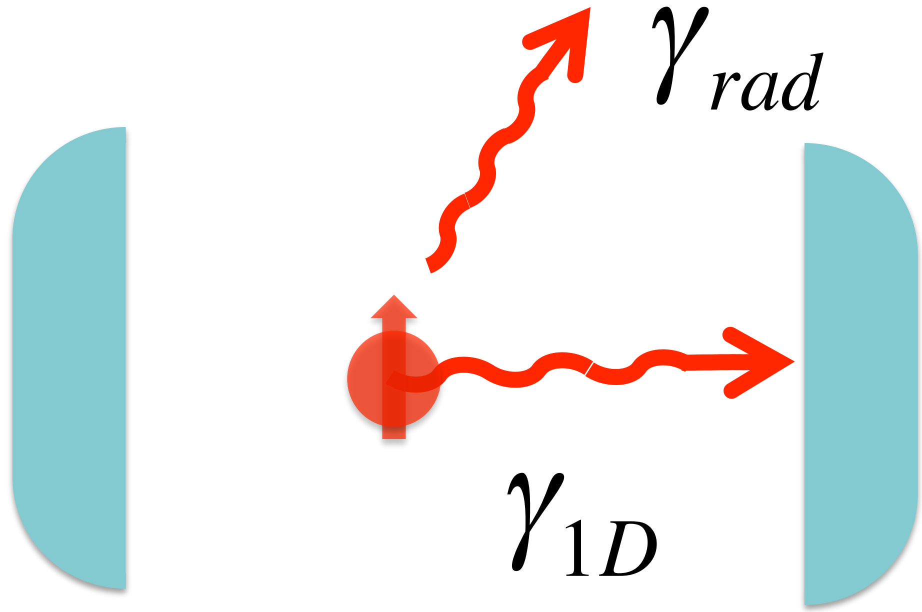
Coupling Enhancement

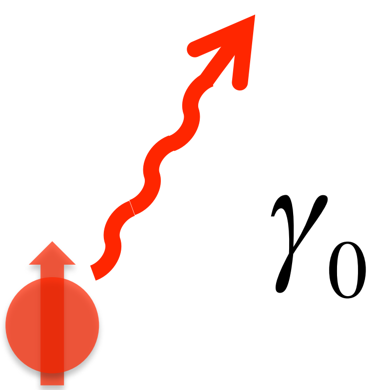


$$\alpha = \frac{\gamma_{1D}}{\gamma_0}$$



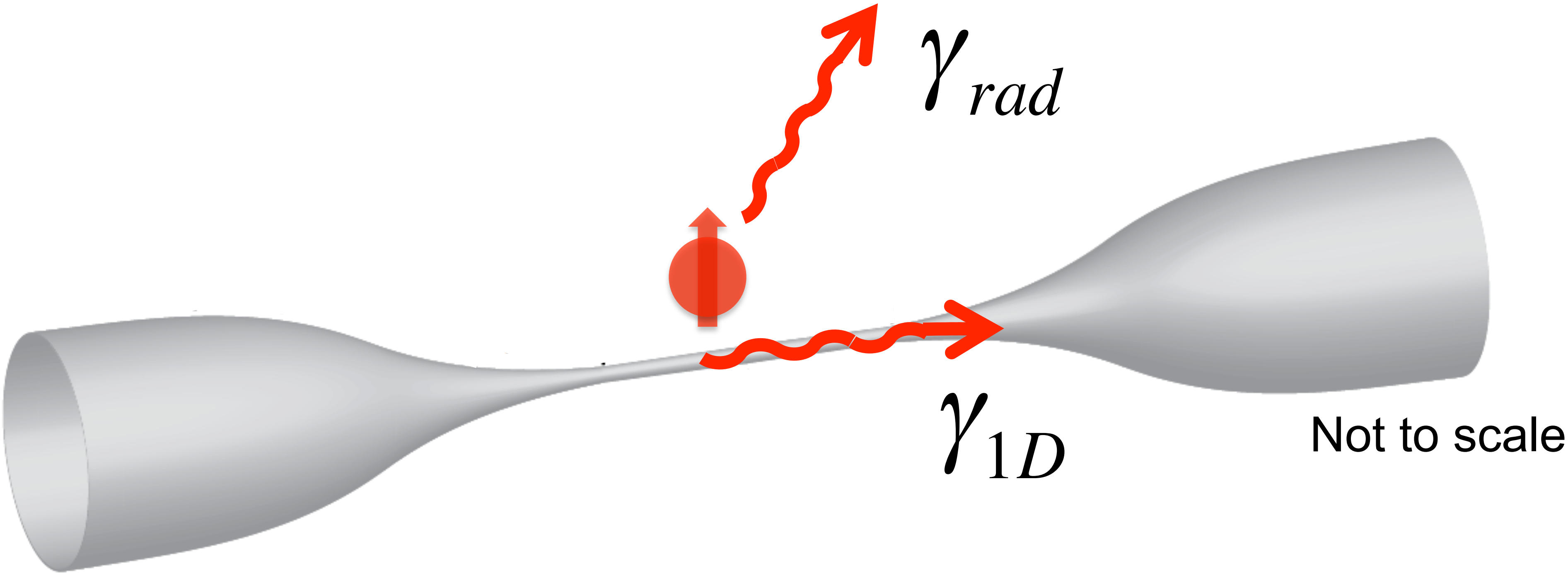
Coupling Efficiency





$$\beta = \frac{\gamma_{1D}}{\gamma_{Tot}} \quad ; \quad \gamma_{Tot} = \gamma_{1D} + \gamma_{rad}$$

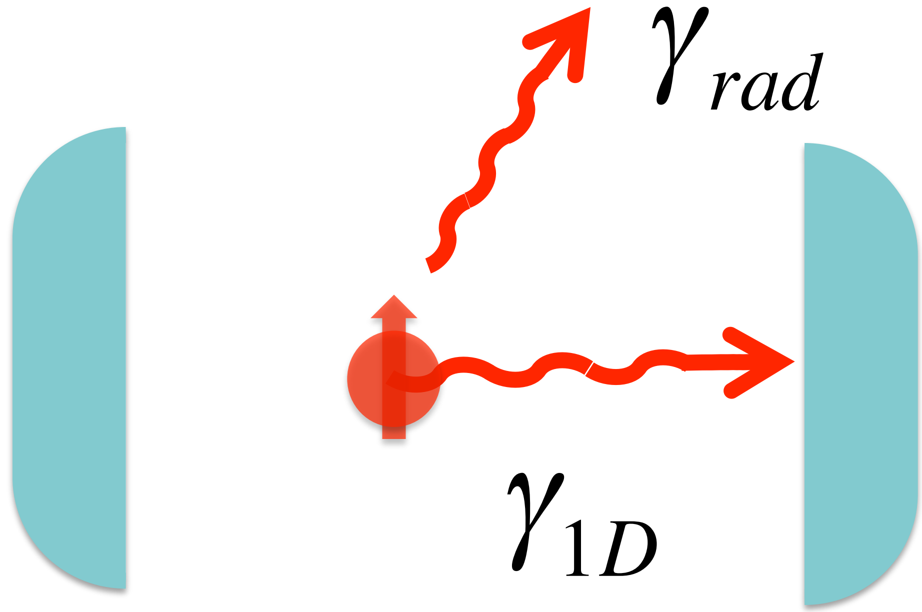
Coupling Efficiency

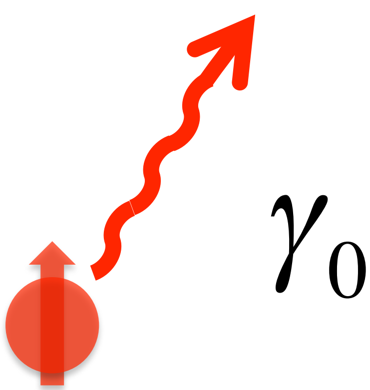


$$\beta = \frac{\gamma_{1D}}{\gamma_{Tot}}$$

$$\gamma_{Tot} = \gamma_{rad} + \gamma_{1D}$$

Purcell Factor

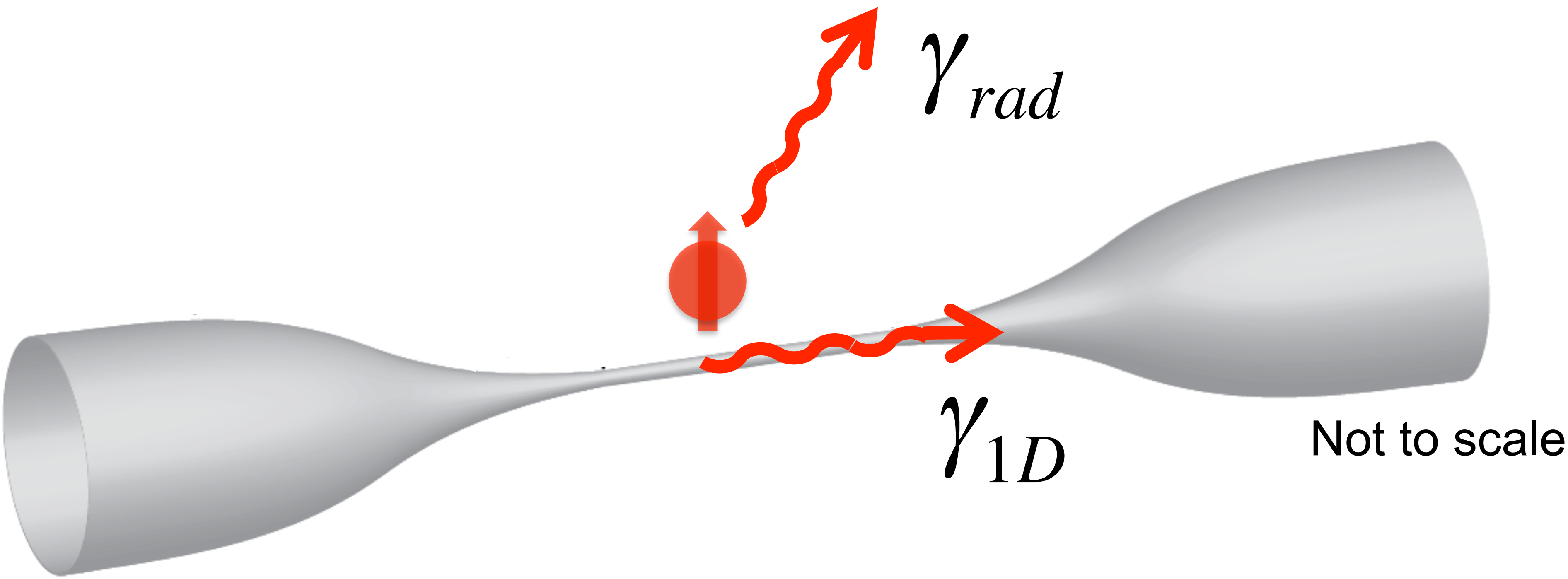




$$F_P = \frac{\gamma_{tot}}{\gamma_0} = \frac{\alpha}{\beta}$$

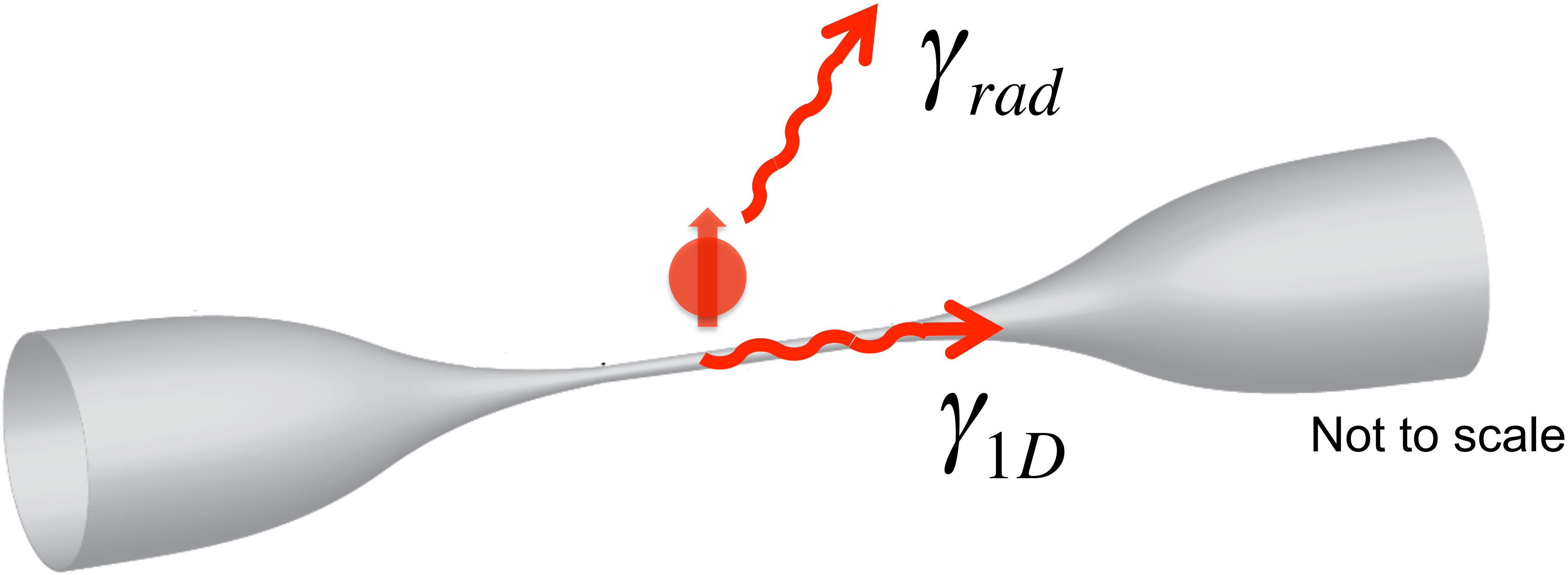
$$\gamma_{Tot} = \gamma_{1D} + \gamma_{rad}$$

Purcell Factor



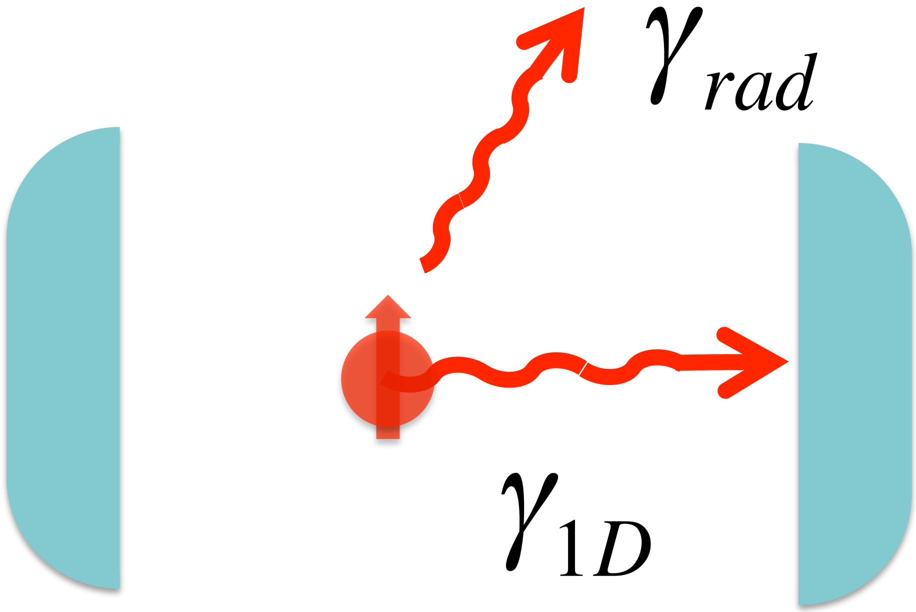
$$F_P = \frac{\gamma_{tot}}{\gamma_0} = \frac{\alpha}{\beta}$$

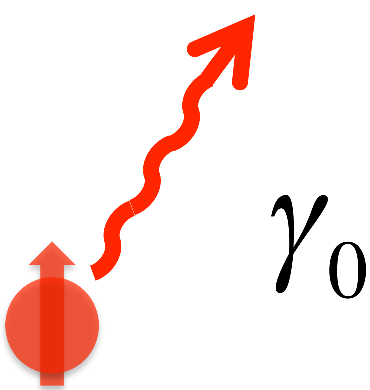
Cooperativity



$$C_1 = \frac{\beta}{(1-\beta)} = \frac{\gamma_{1D}}{\gamma_{rad}}$$

Cooperativity





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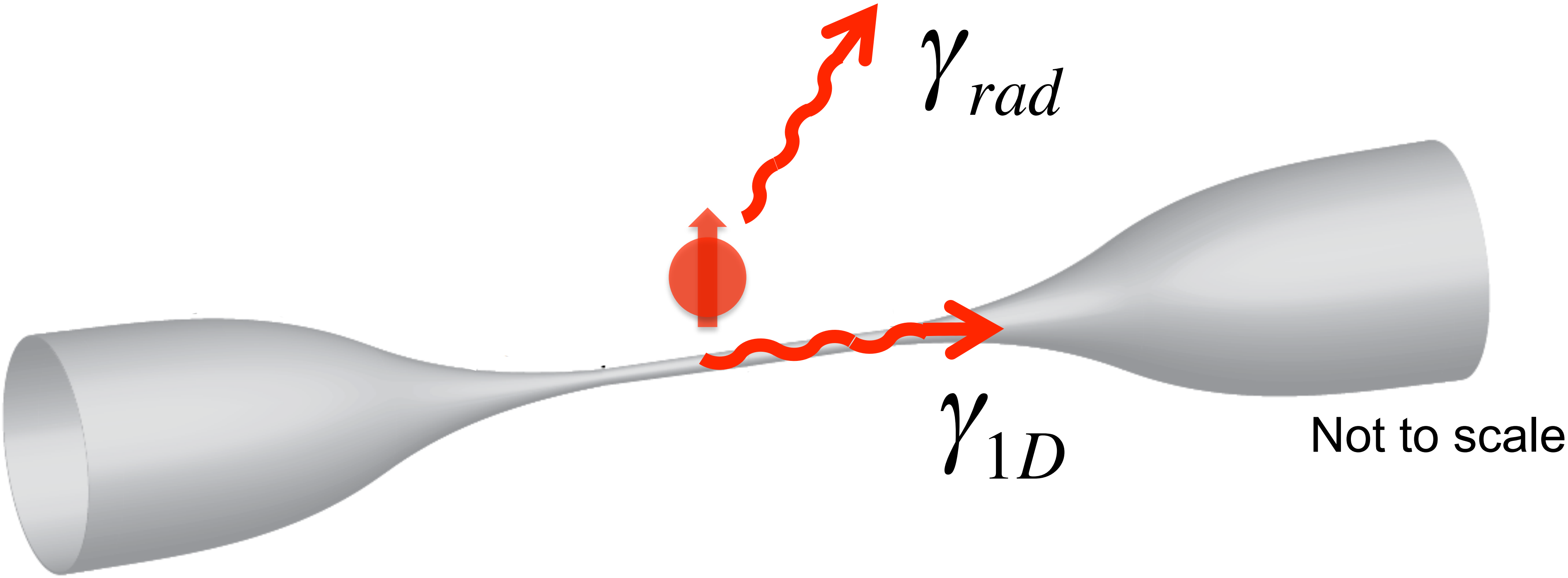

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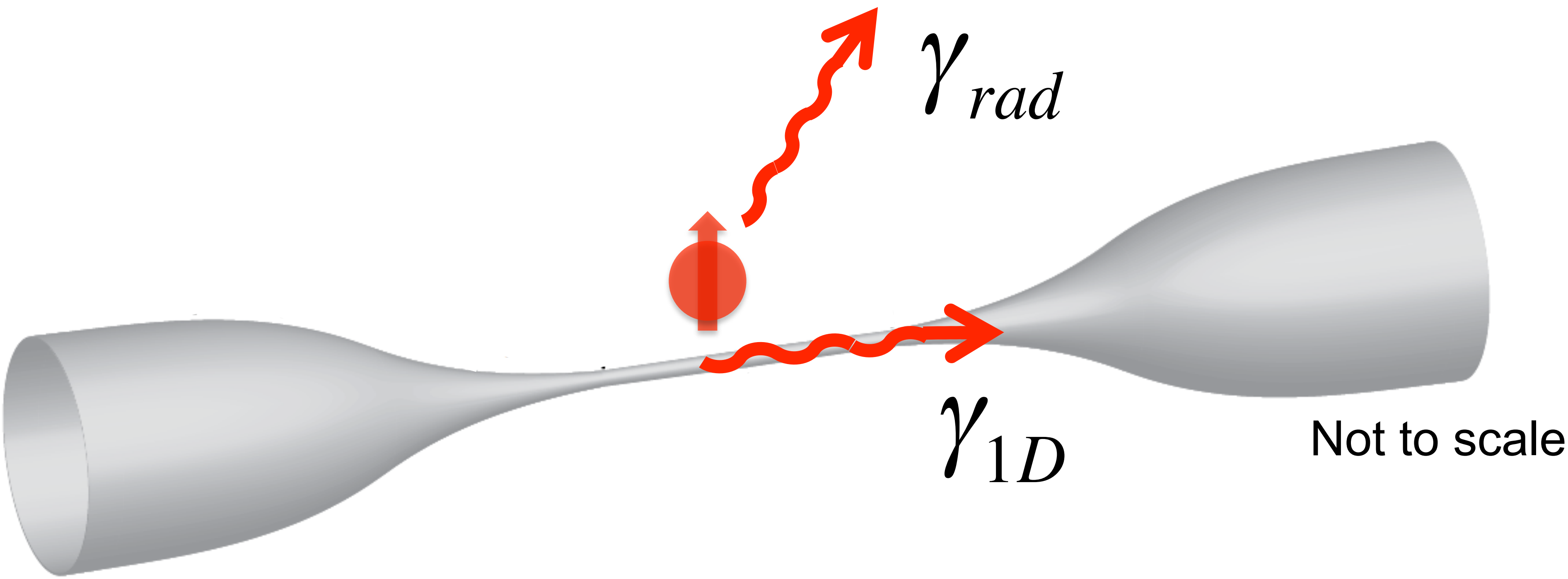
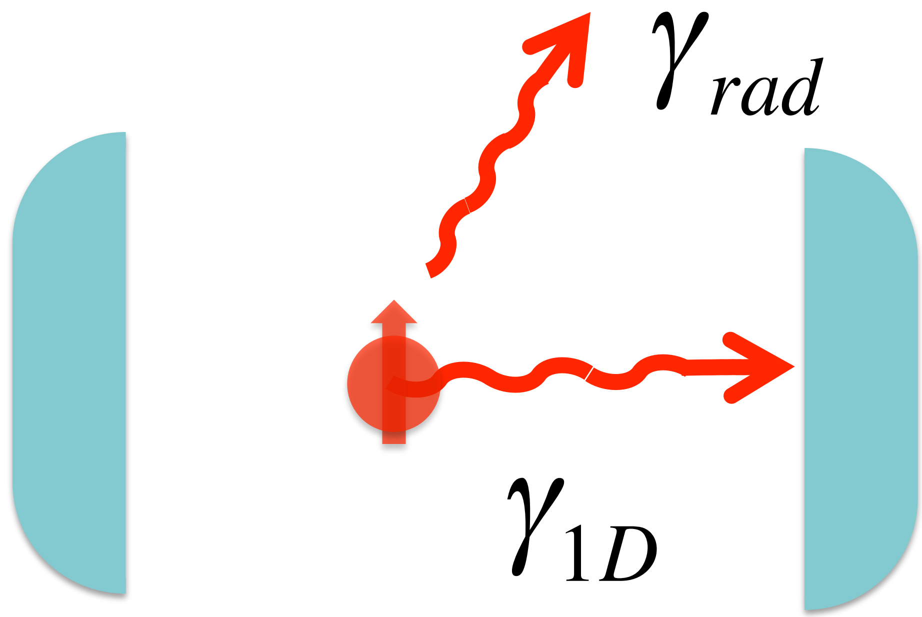
Cooperativity

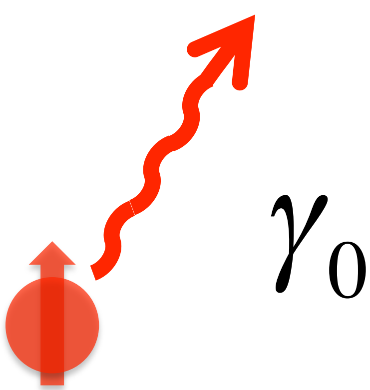


$$C_1 = \frac{\beta}{(1-\beta)} = \frac{\gamma_{1D}}{\gamma_{rad}}$$

C_1 is the ratio of what goes into the selected mode to what goes into all the rest

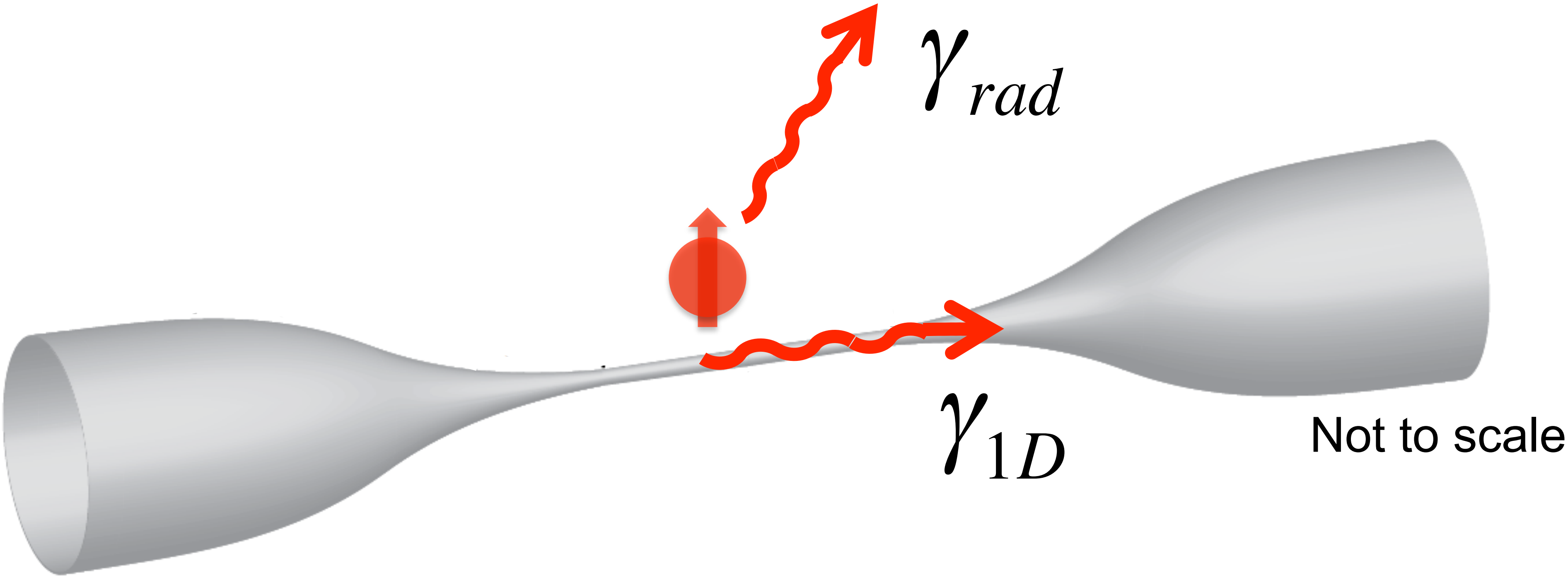
Cooperativity





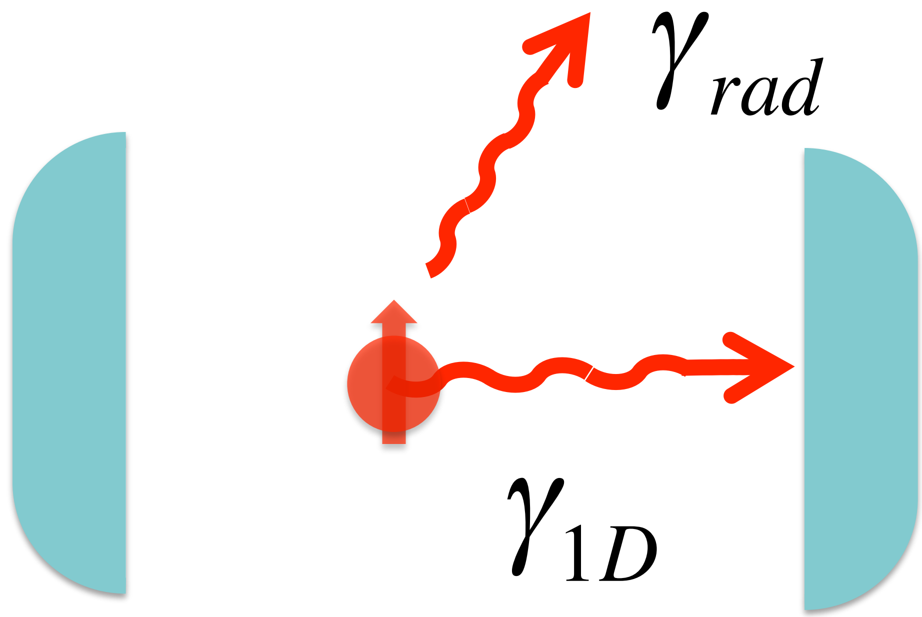
$$C_1 = \frac{\sigma_0}{Area_{\text{mode}}}\frac{1}{T}$$

Cooperativity



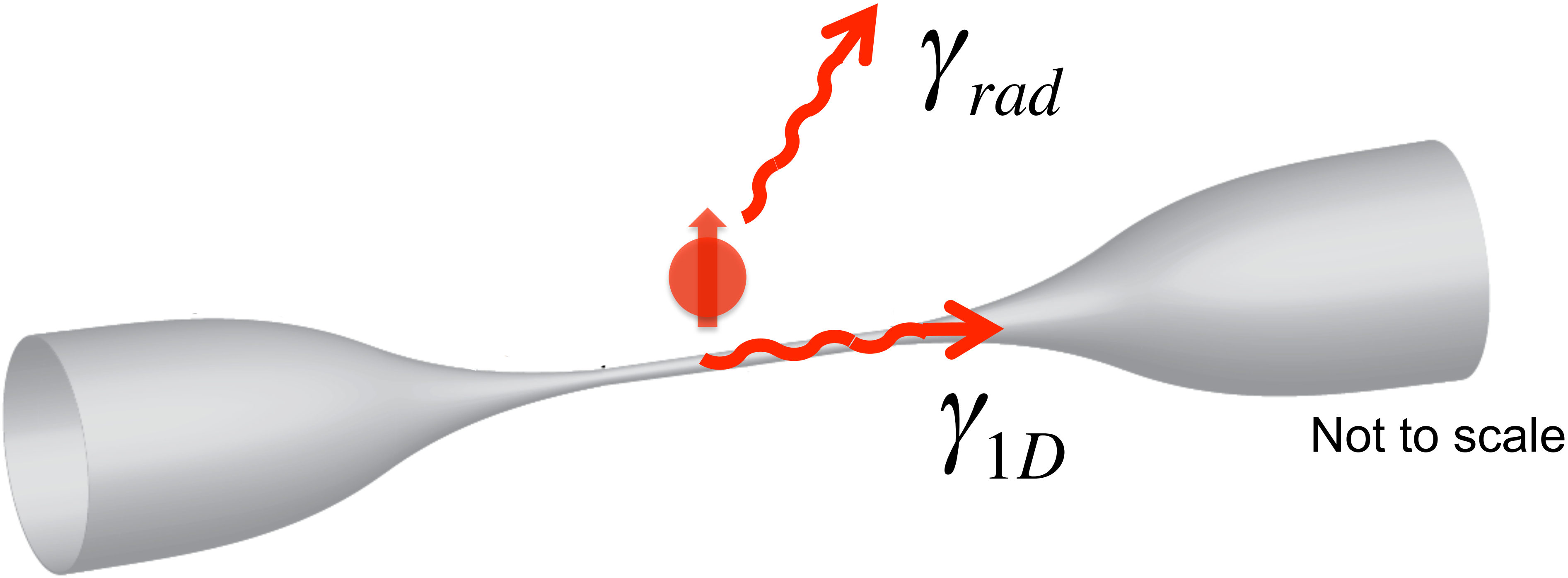
$$C_1 = \frac{\sigma_0}{Area_{\text{mode}}}(Enhancement)$$

Cooperativity



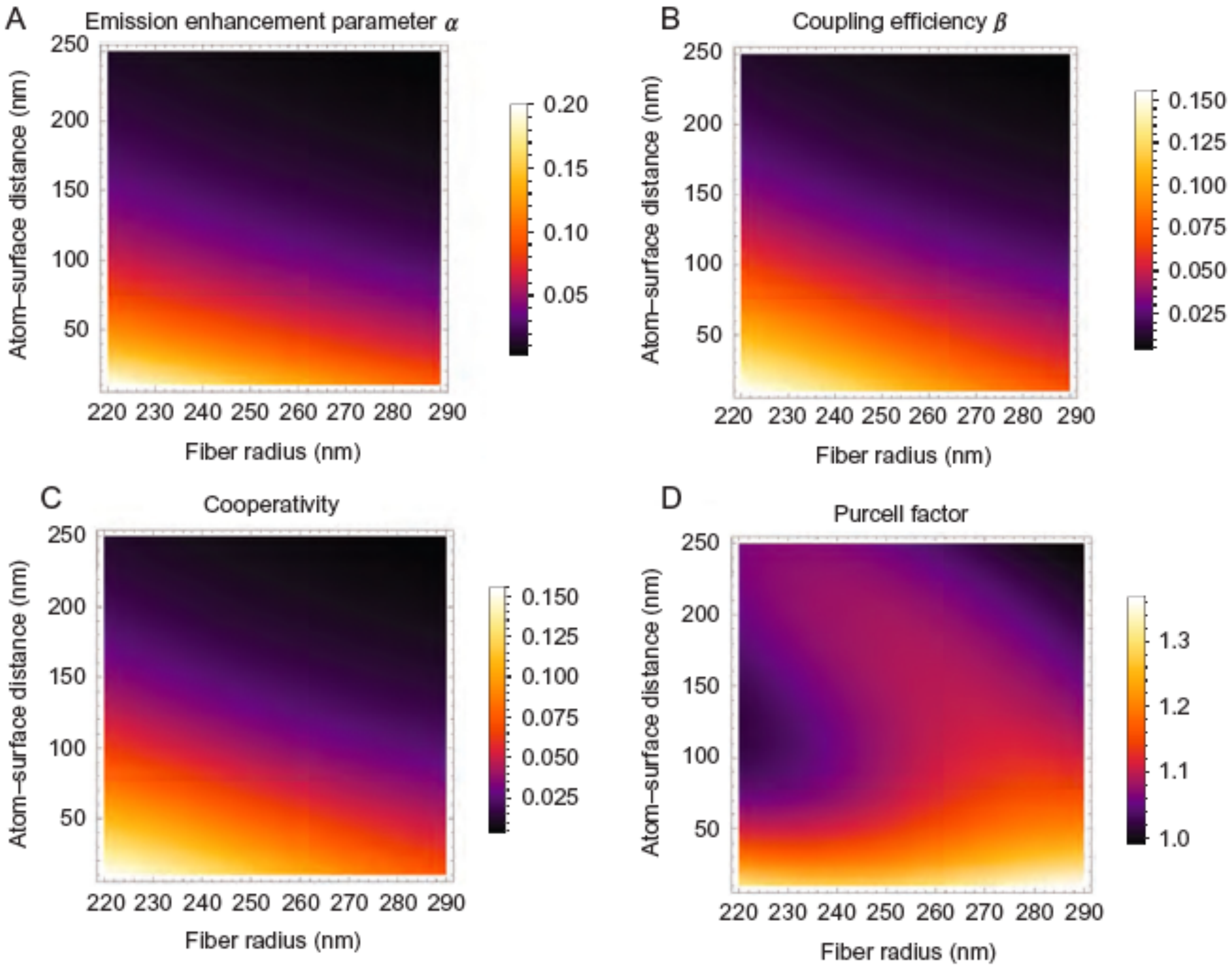
$$C_1 = \frac{g^2}{\kappa\gamma_{rad}} = \left(\frac{\sigma_0}{A_{\mathrm{mode}}}\right)\left(\frac{c}{v_g}\right) = \frac{\gamma_{1D}}{\gamma_{rad}}$$

Cooperativity

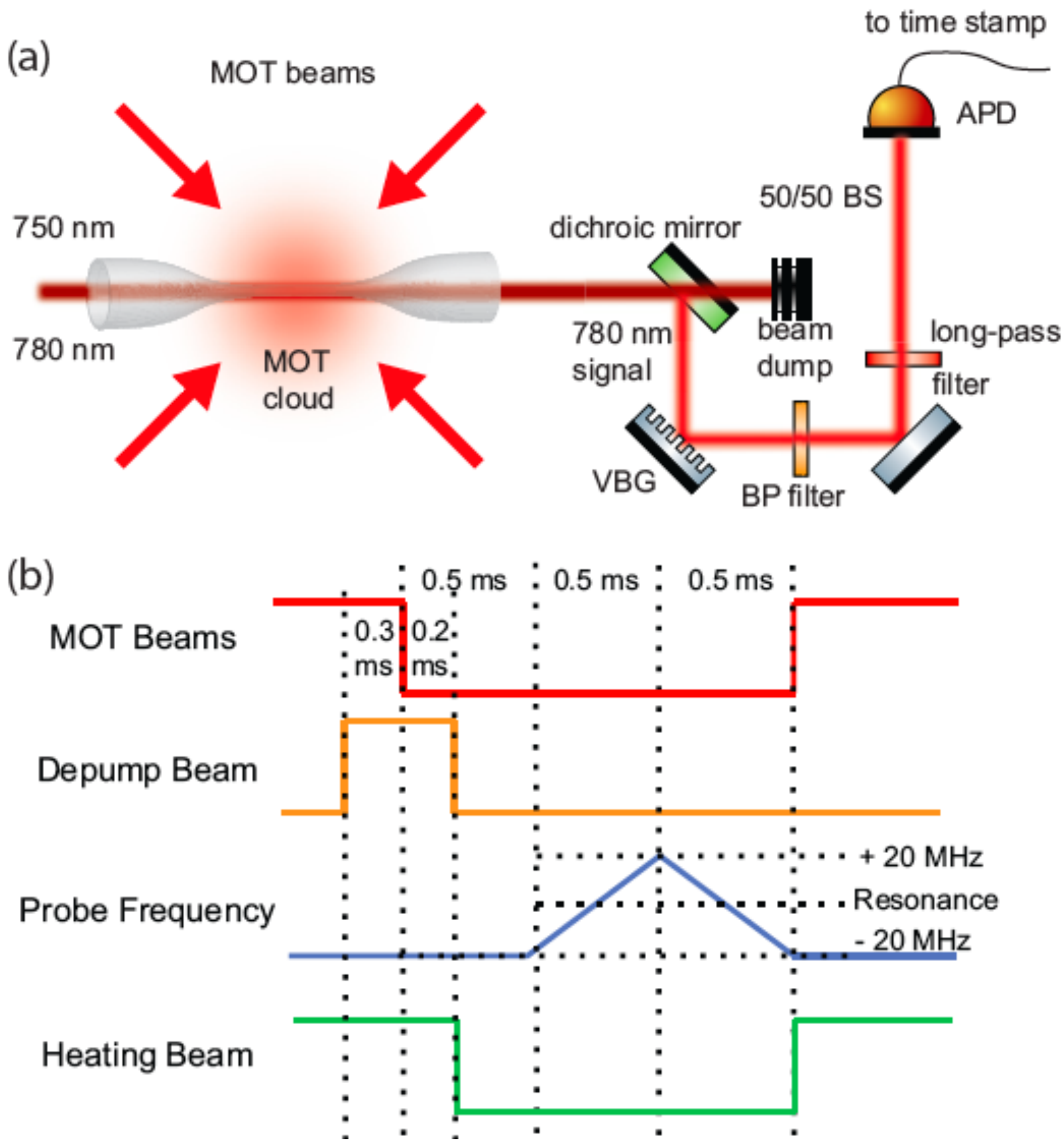


$$C_1 = \frac{\sigma_0}{Area_{\mathrm{mode}}} n_{eff} = \frac{\gamma_{1D}}{\gamma_{rad}}$$

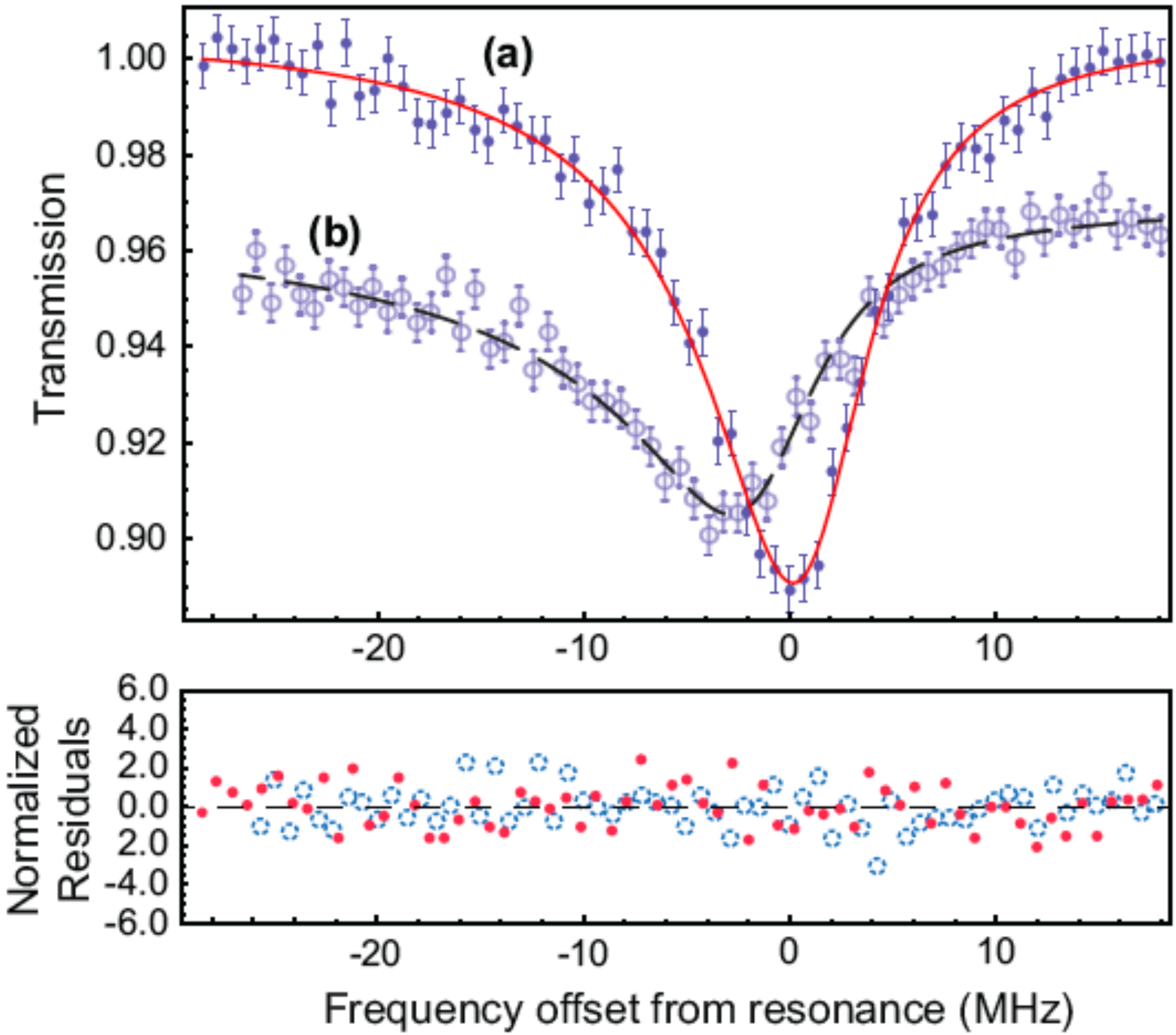
Atom-mode coupling parameters for nanofibers



Atoms near the nanofiber, spectrum

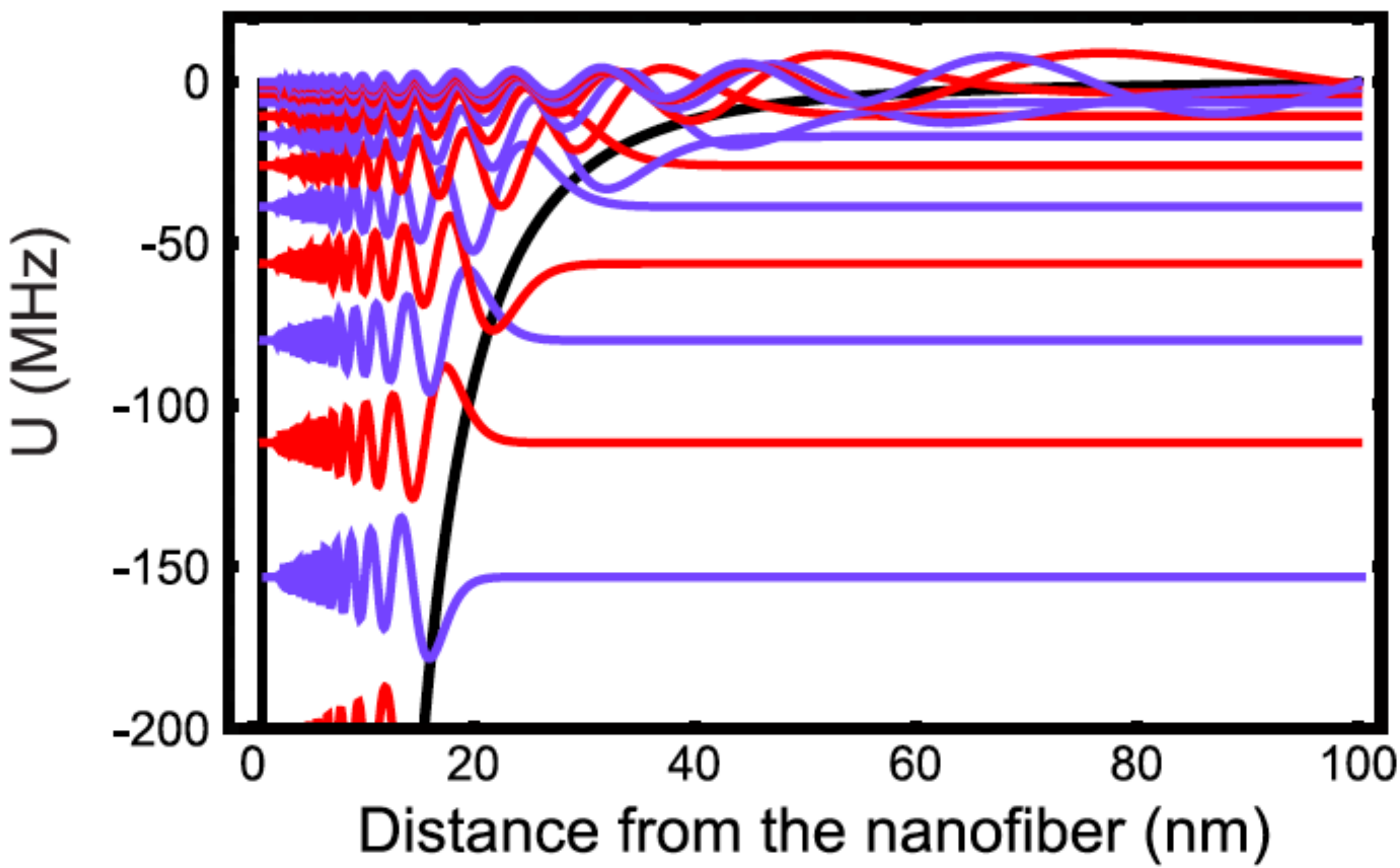


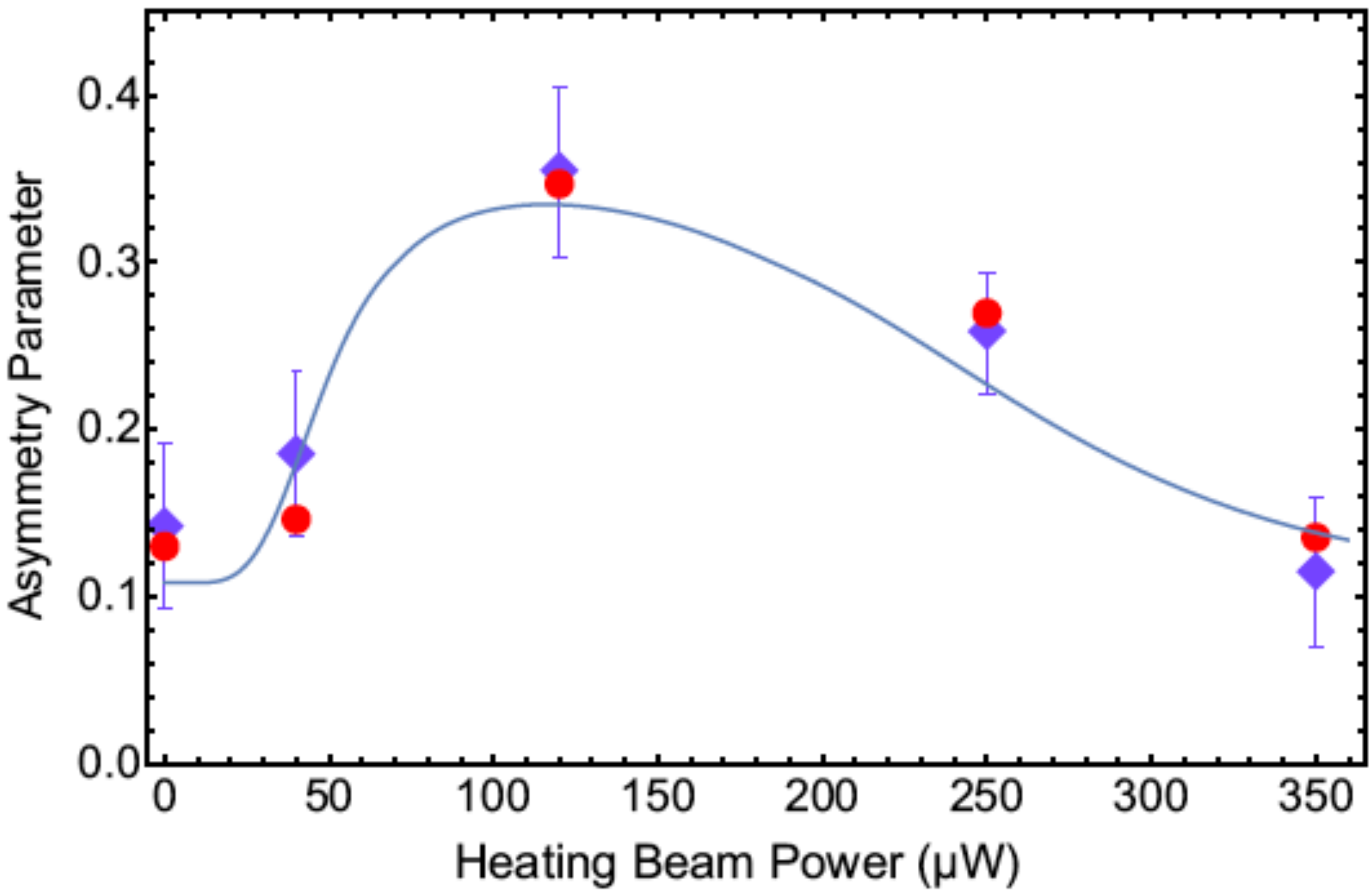
(a)
MOT beams
to time stamp
APD
50/50 BS
750 nm
dichroic mirror
780 nm
780 nm
signal
beam
dump
long-pass
filter
MOT
cloud
VBG
BP filter
(b)
0.5 ms
0.5 ms
0.5 ms
MOT Beams
0.3
ms
0.2
ms
Depump Beam
+ 20 MHz
Resonance
Probe Frequency
- 20 MHz
Heating Beam



(a)
(b)
Transmission
1.00
0.98
0.96
0.94
0.92
0.90
-20
-10
0
10
Normalized Residuals
6.0
4.0
2.0
0.0
2.0
-4.0
-6.0
-20
-10
0
10
Frequency offset from resonance (MHz)

Radial wave functions of the atomic bound states in the van der Waals potential




0.0
0.1
0.2
0.3
0.4
Asymmetry Parameter
0
50
100
150
200
250
300
350
Heating Beam Power (μW)

Temperature of atoms around the nanofiber

Intensity-Intensity correlation

$$g^{(2)}(\tau) = \frac{\langle I(t)\, I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

For uncorrelated emitters:

$$g^{(2)}(\tau) = 1 + \left|g_A^{(1)}(\tau)\right|^2 + \frac{1}{\bar{N}} g_A^{(2)}(\tau)$$

Intensity-Intensity correlation

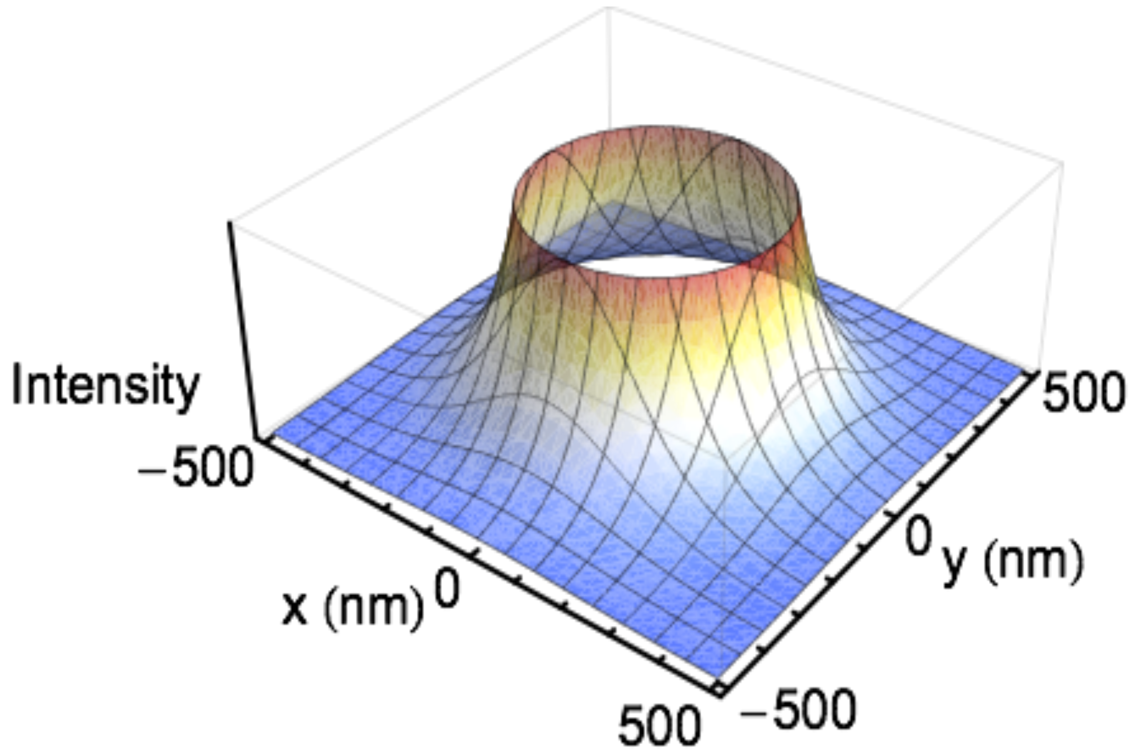
$$g^{(2)}(\tau) = \frac{\langle I(t)\, I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

For uncorrelated emitters:

$$g^{(2)}(\tau) = 1 + \left|g_A^{(1)}(\tau)\right|^2 + \frac{1}{\bar{N}} g_A^{(2)}(\tau)$$

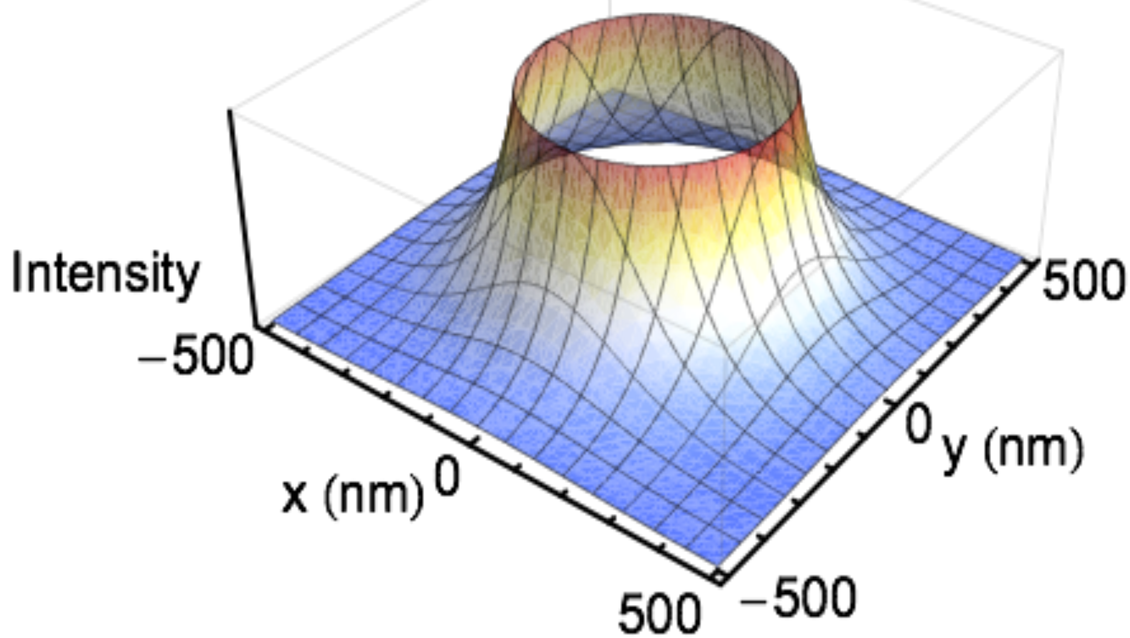
"Antibunching term"

Finite transit time



$$g^{(2)}(\tau) = 1 + f(\tau)|g_A^{(1)}(\tau)|^2 + \frac{1}{\bar{N}} f(\tau) g_A^{(2)}(\tau)$$

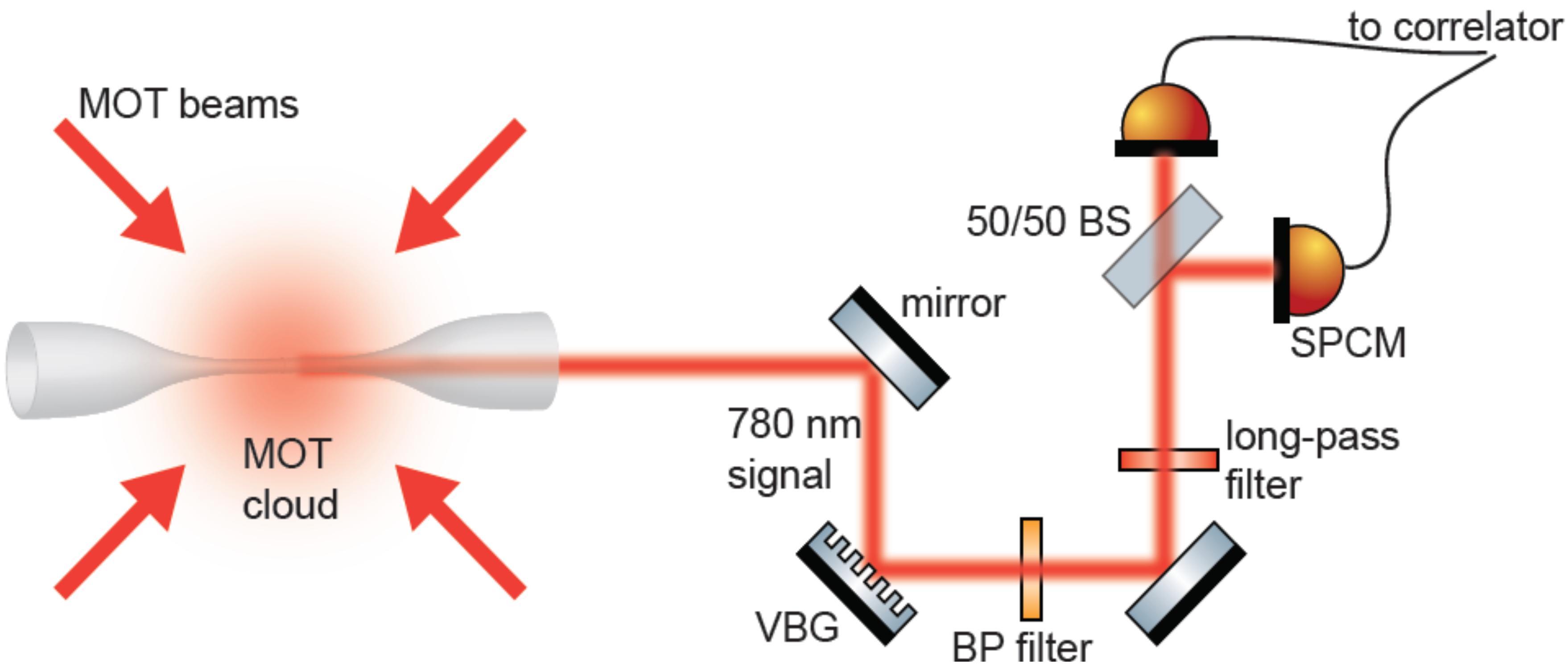
Finite transit time



$$g^{(2)}(\tau) = 1 + f(\tau)|g_A^{(1)}(\tau)|^2 + \frac{1}{N} f(\tau) g_A^{(2)}(\tau)$$

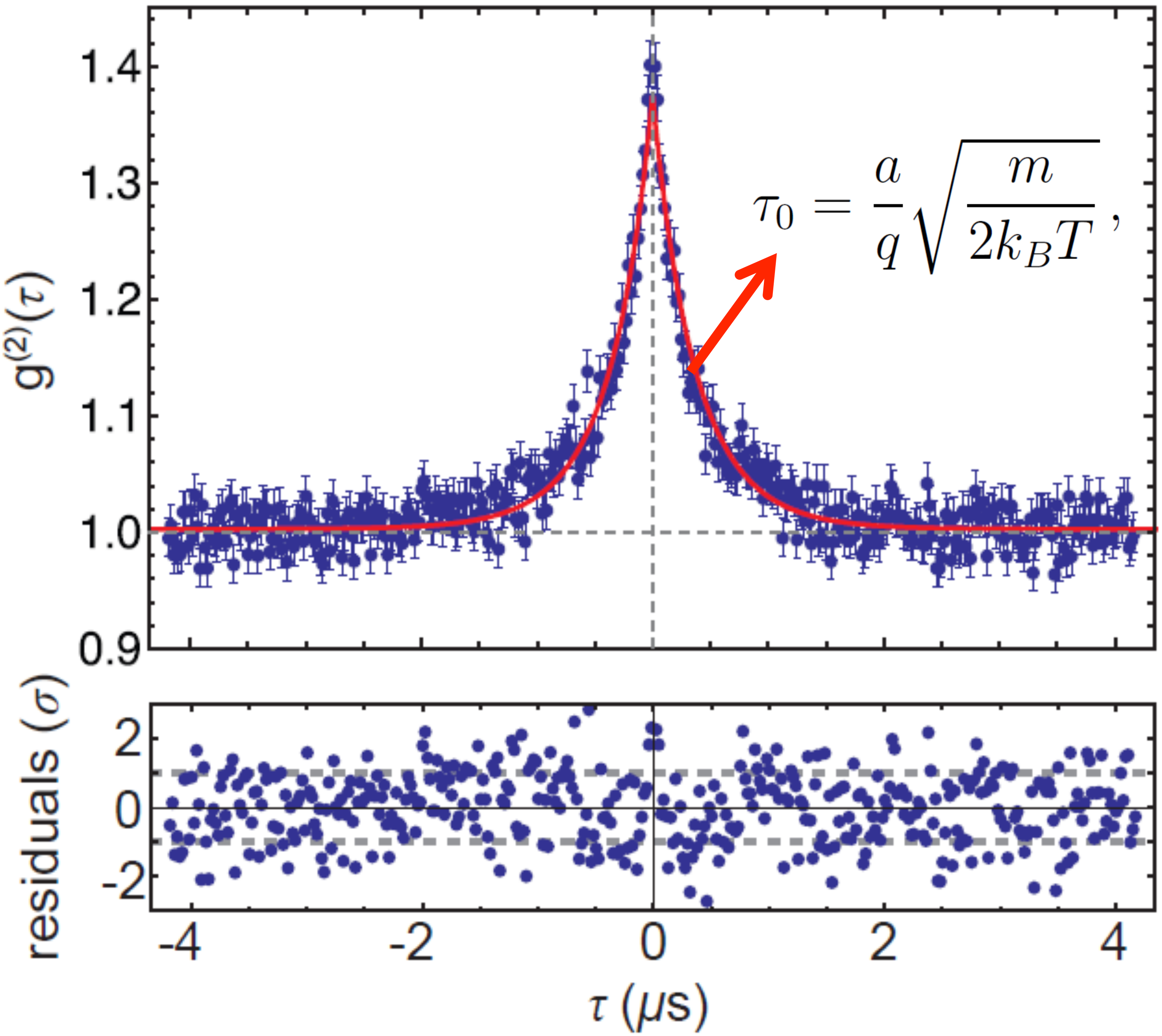
Temporal envelope proportional to the mode shape and the **atomic velocity**.

The setup



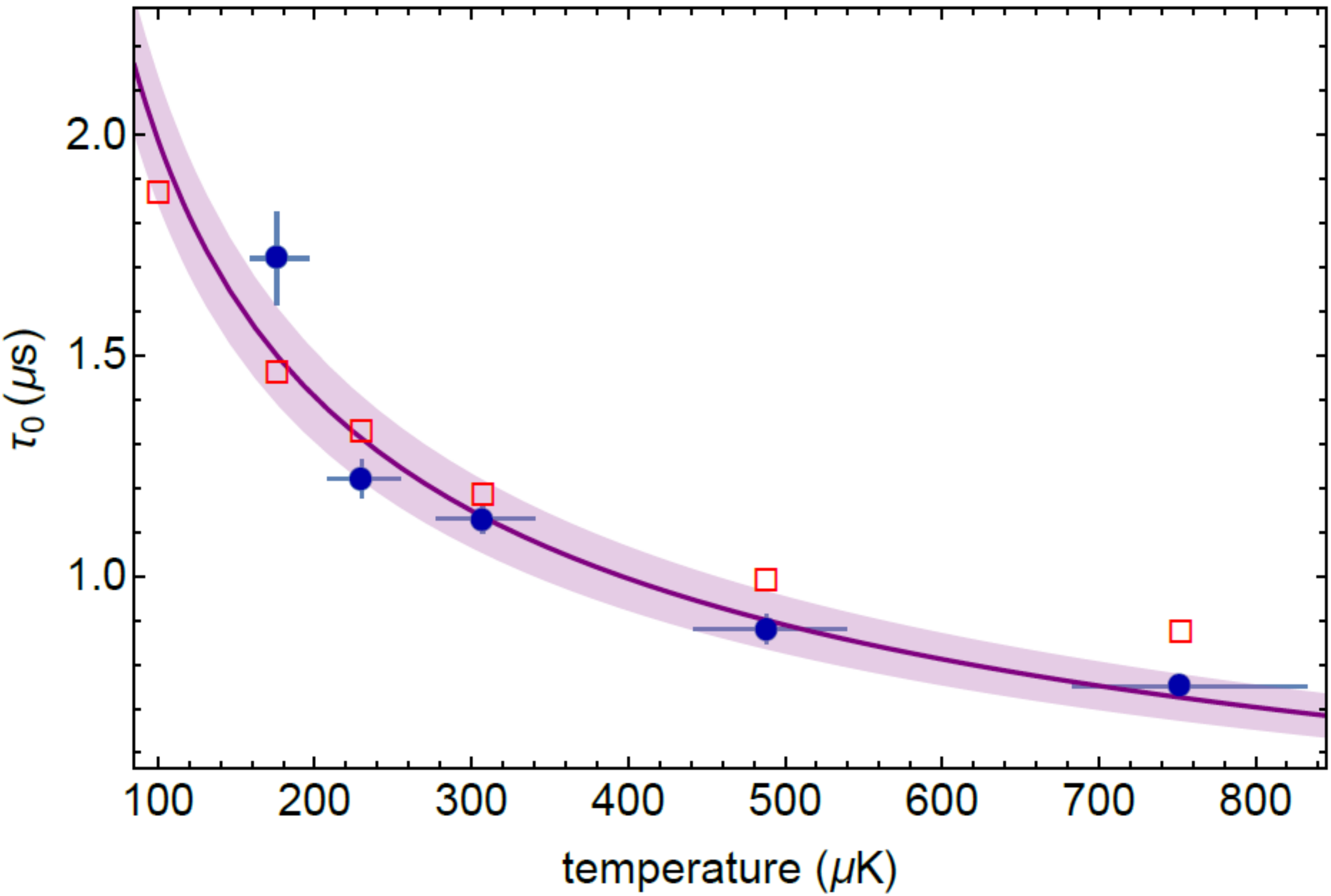
MOT beams
MOT cloud
780 nm signal
mirror
VBG
BP filter
50/50 BS
long-pass filter
SPCM
to correlator

The data



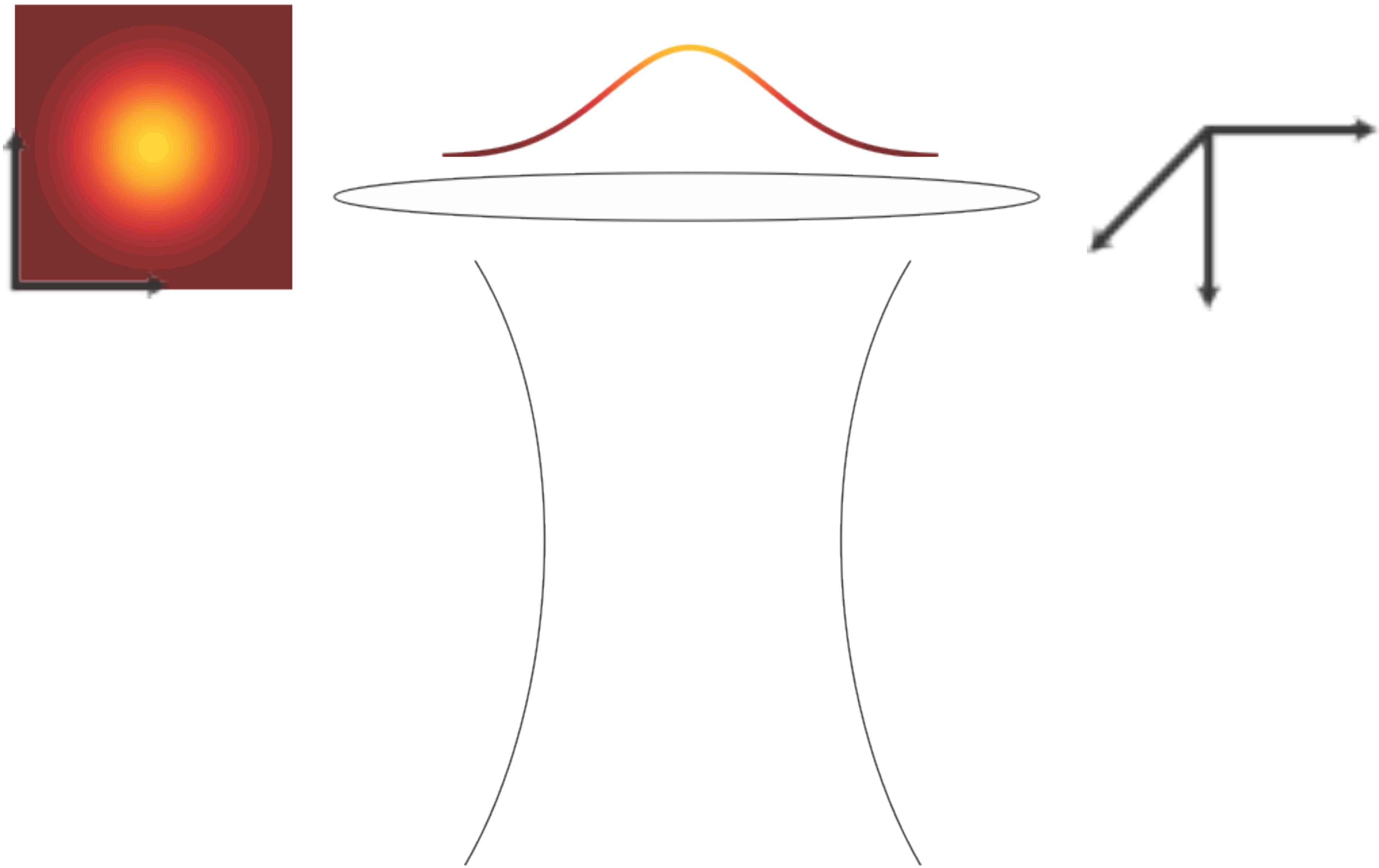
$\tau_0 = \frac{a}{q}\sqrt{\frac{m}{2k_BT}}$,
$g^{(2)}(\tau)$
1.4
1.3
1.2
1.1
1.0
0.9
residuals (σ)
2
0
-2
-4
-2
0
2
4
τ (μs)

Data and Simulations

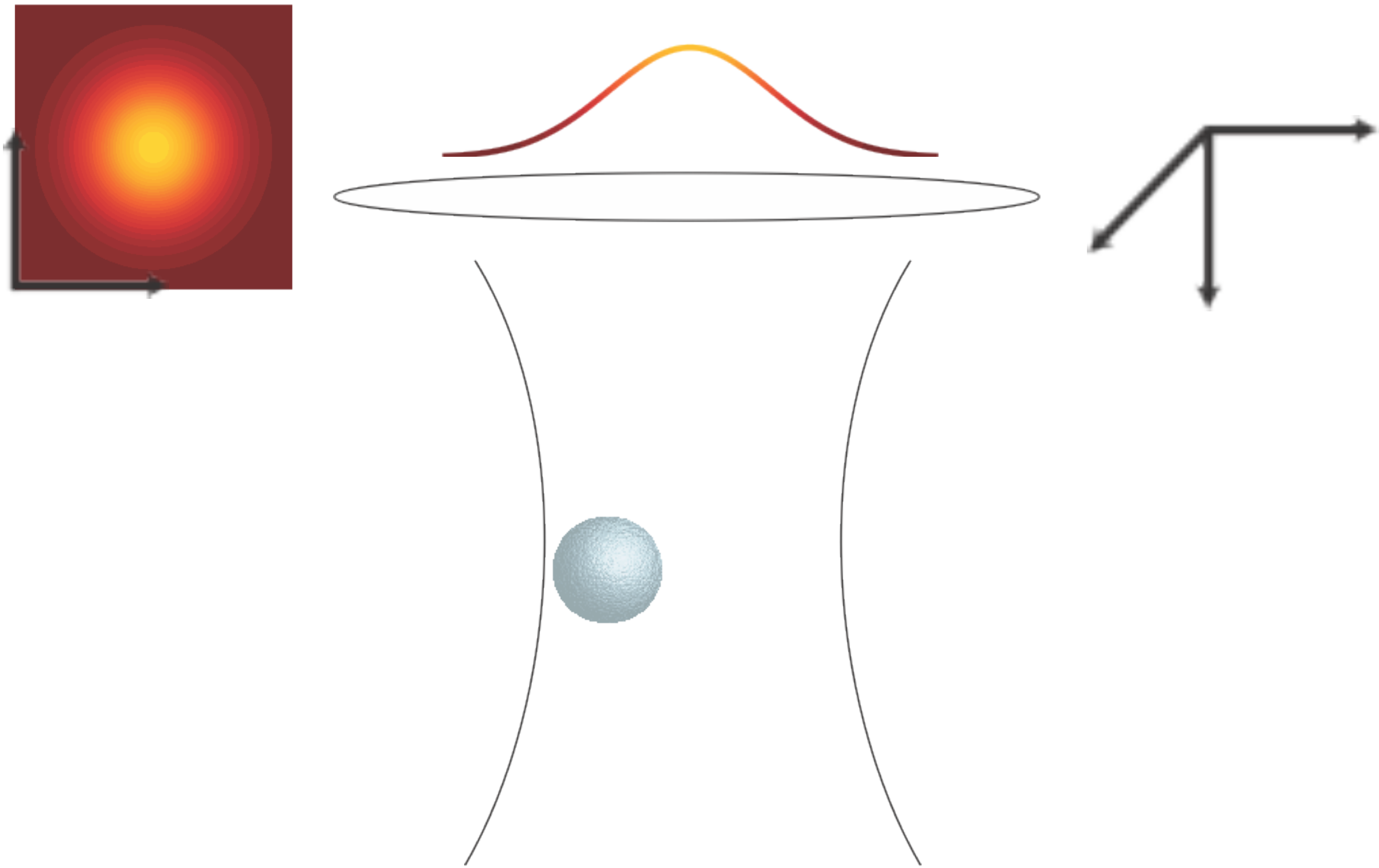


Optical Dipole Trap

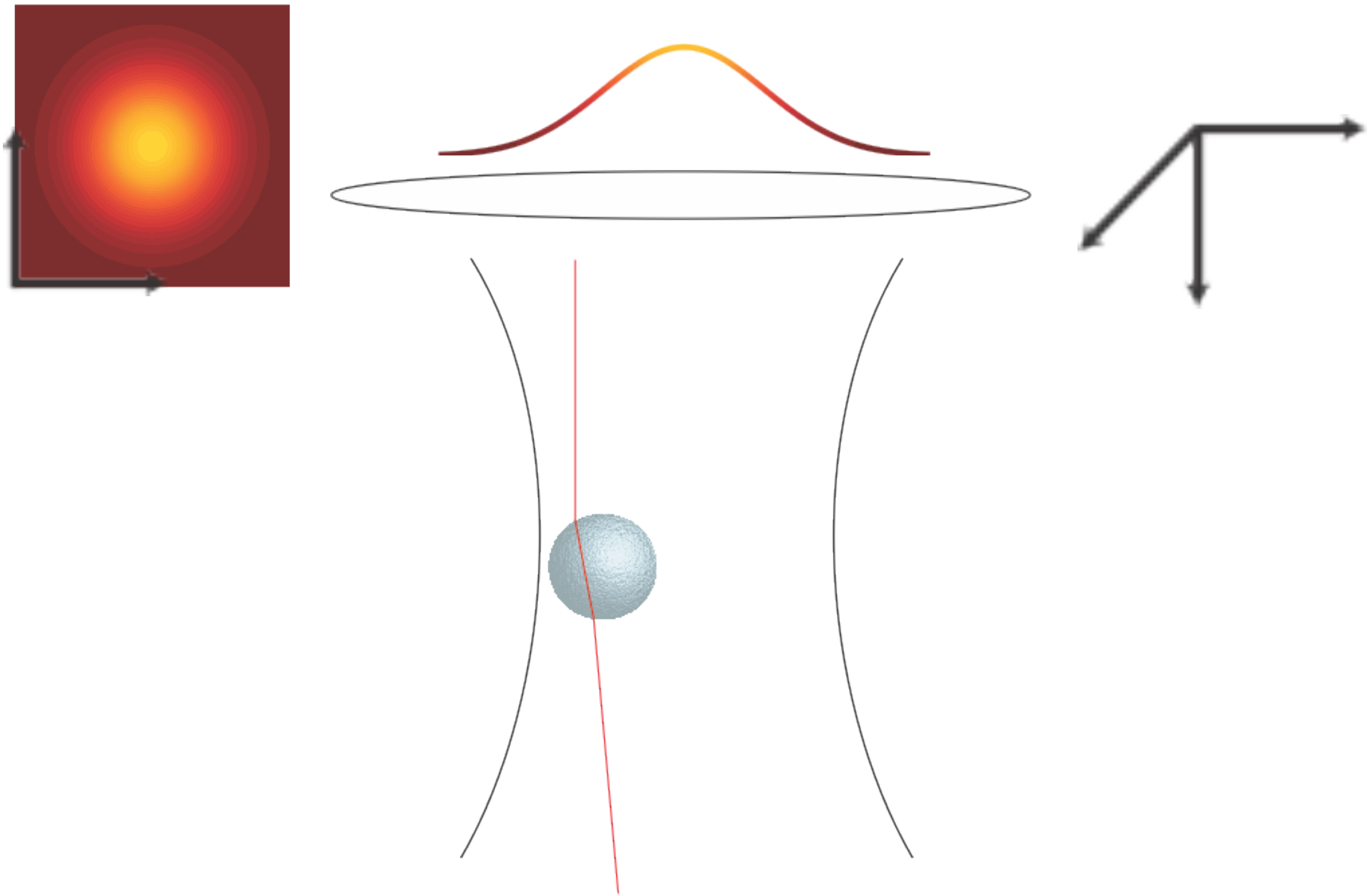
Dipole Trap



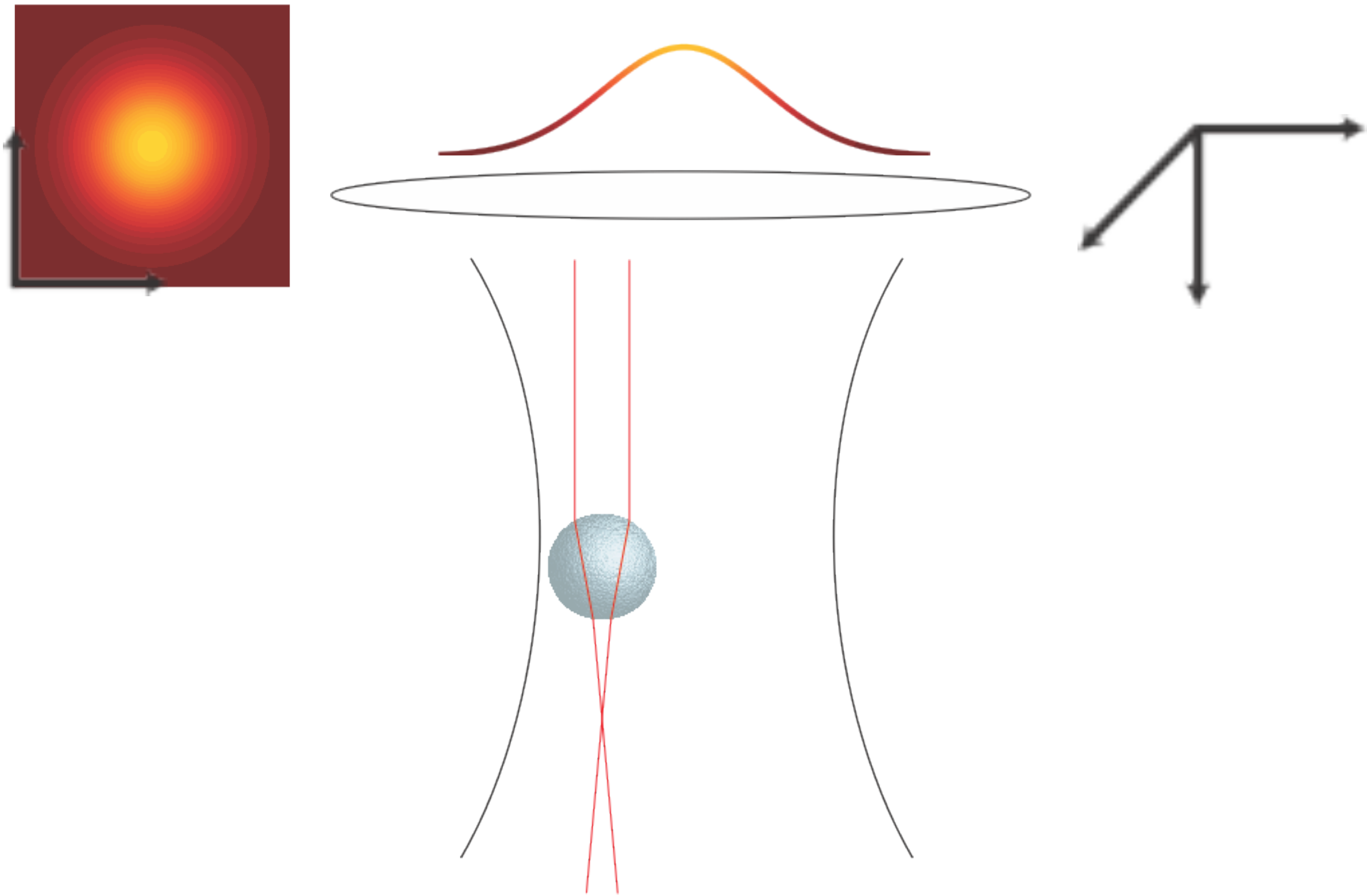
Dipole Trap



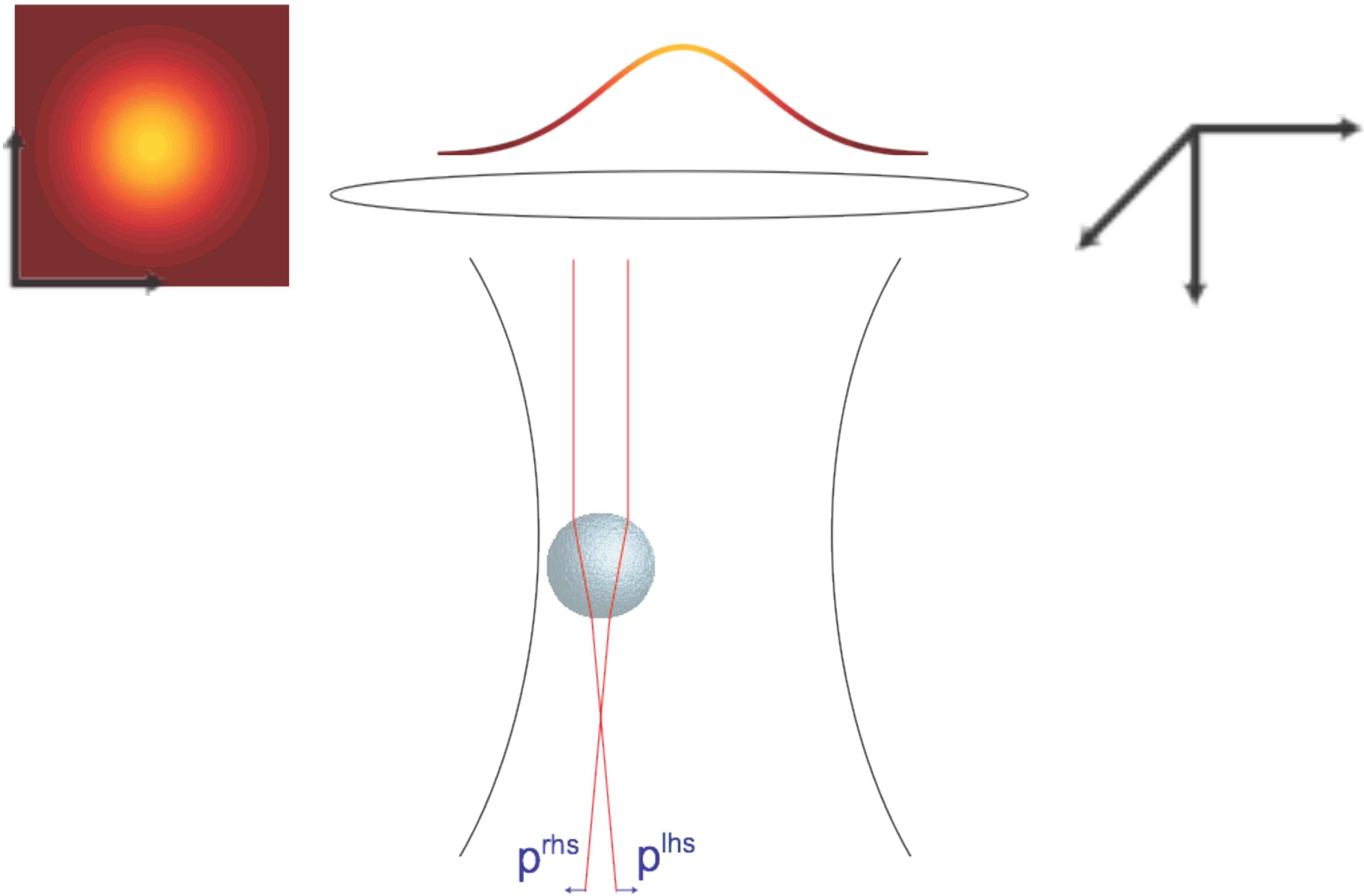
Dipole Trap



Dipole Trap



Dipole Trap



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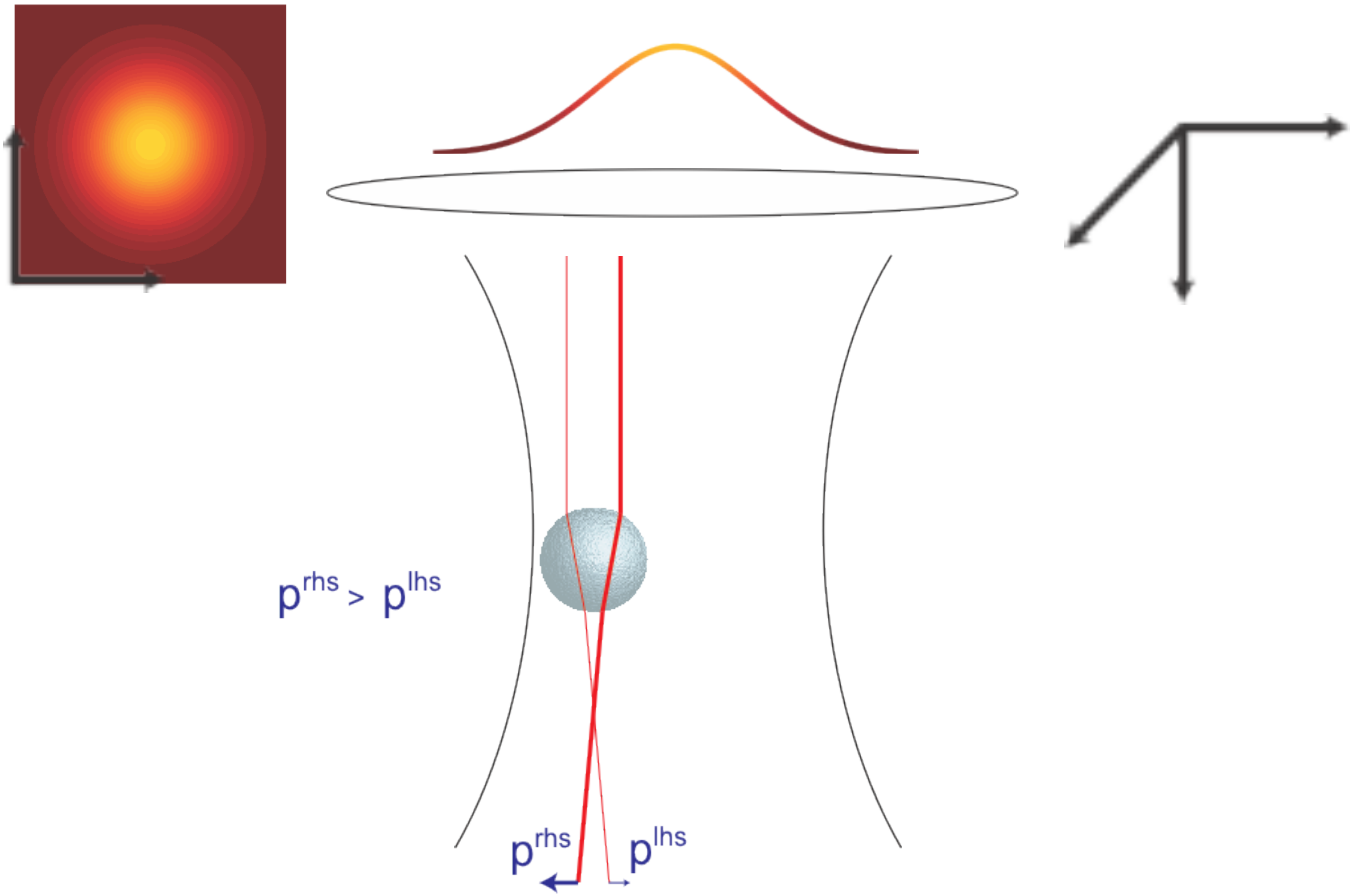
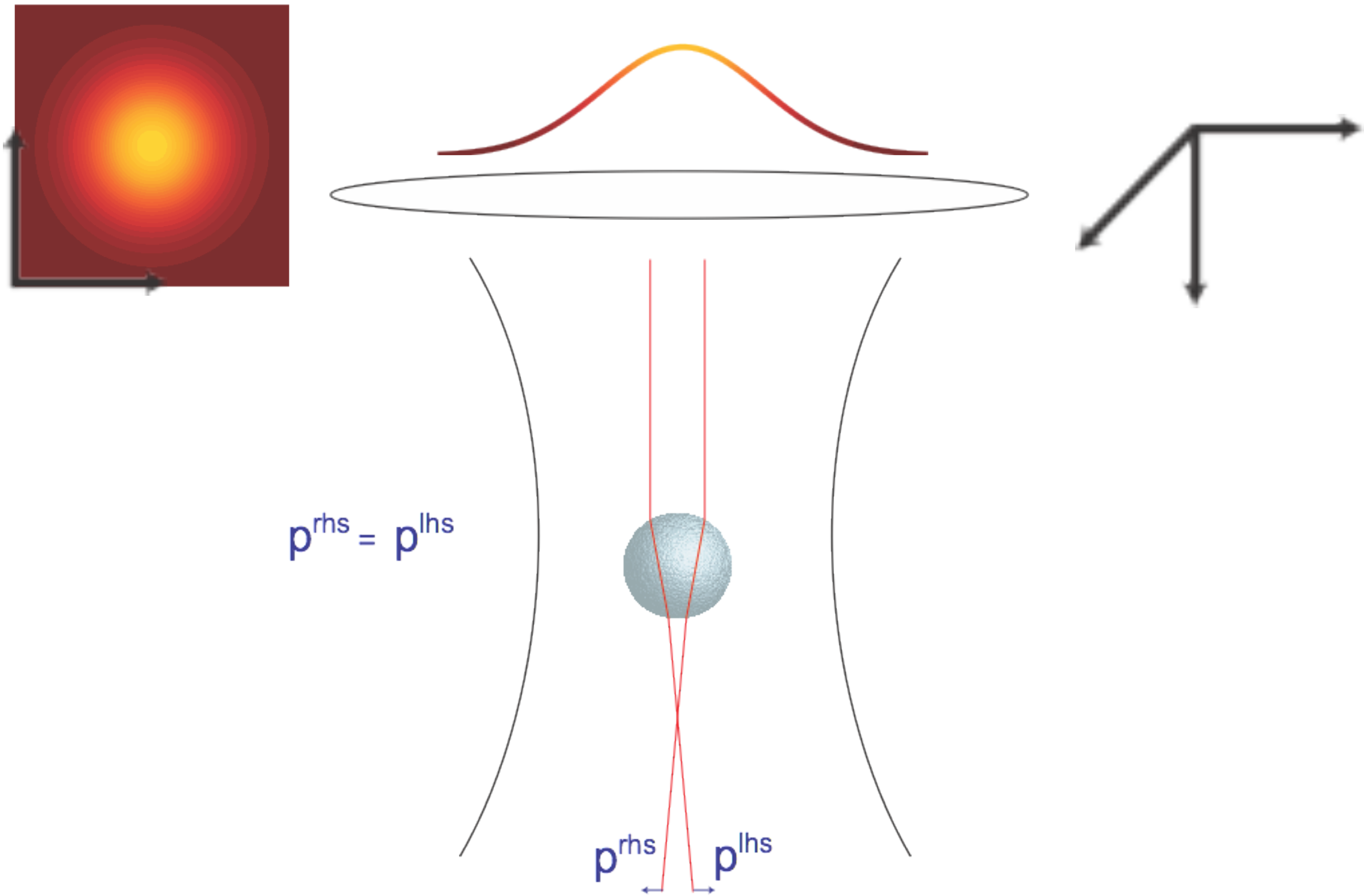
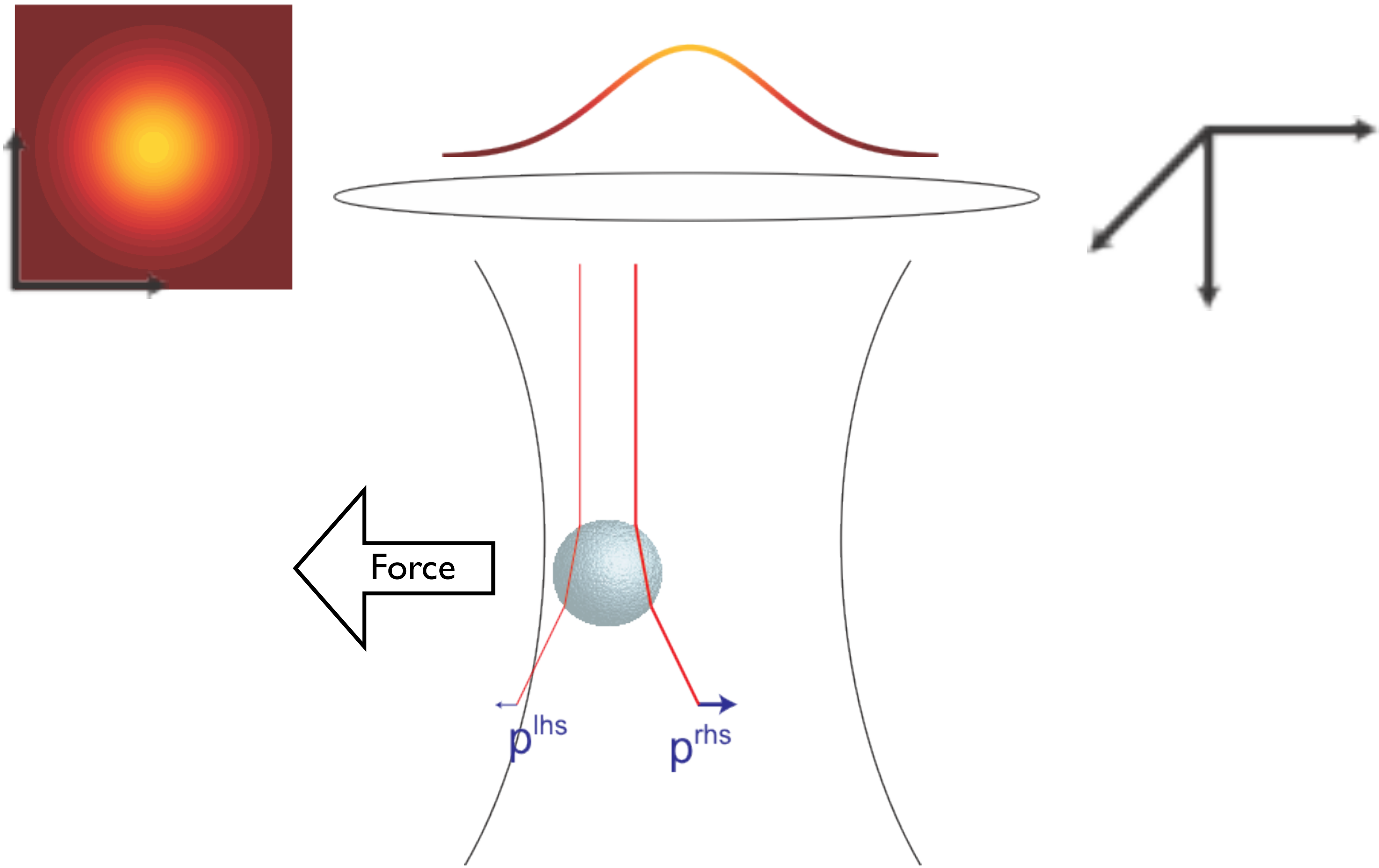


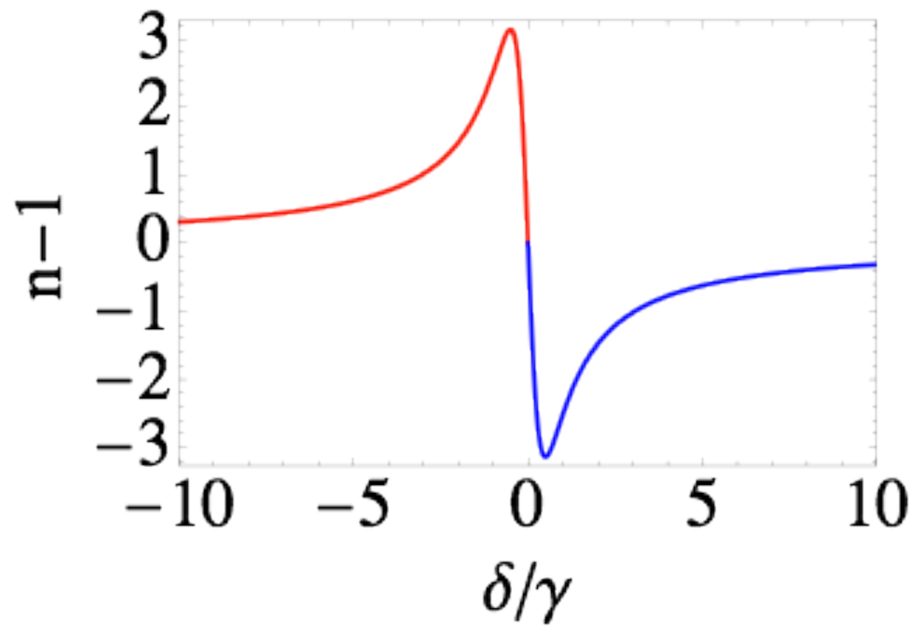
Dipole Trap



Air bubble in water

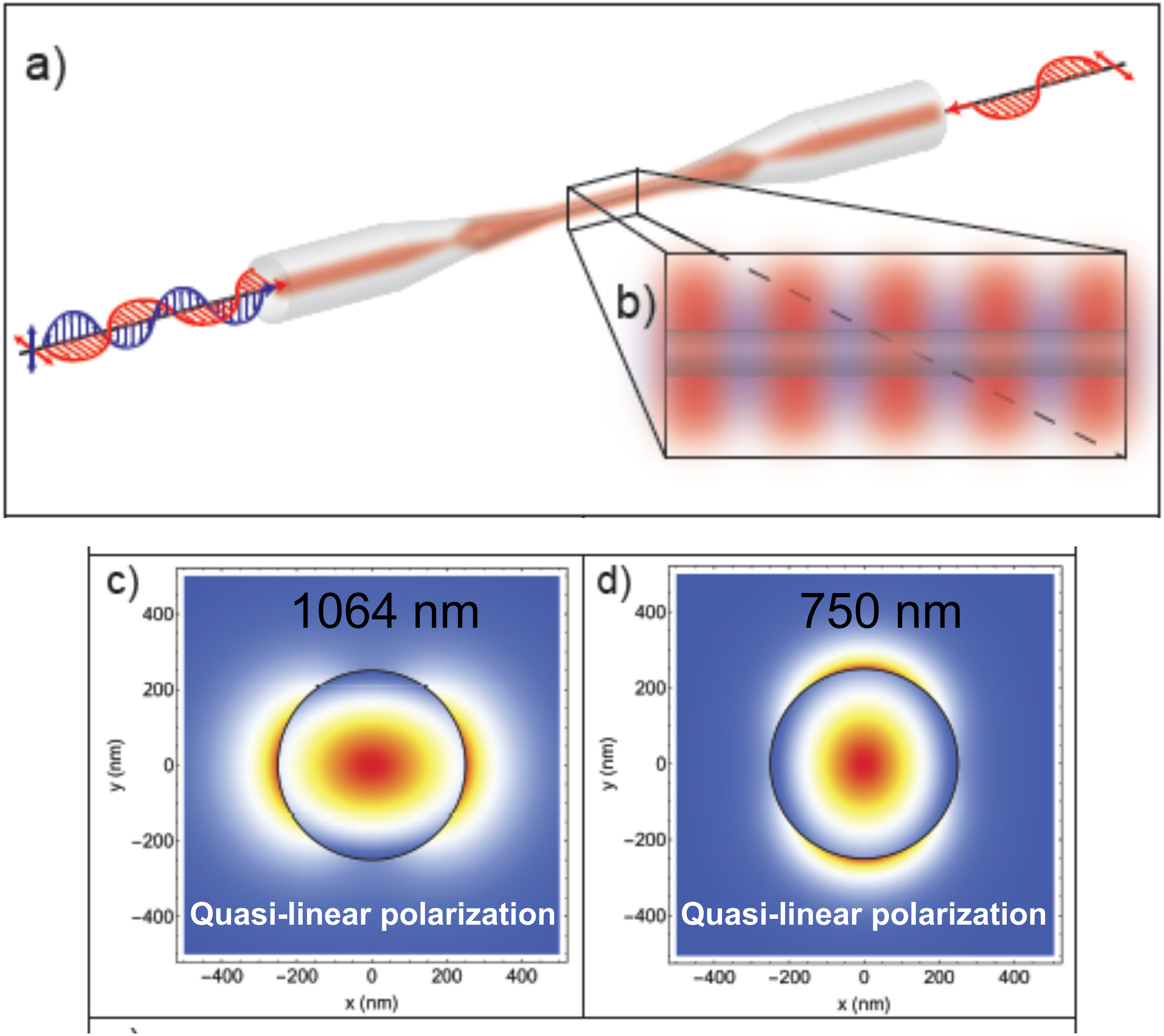


Oscillator model of an atom

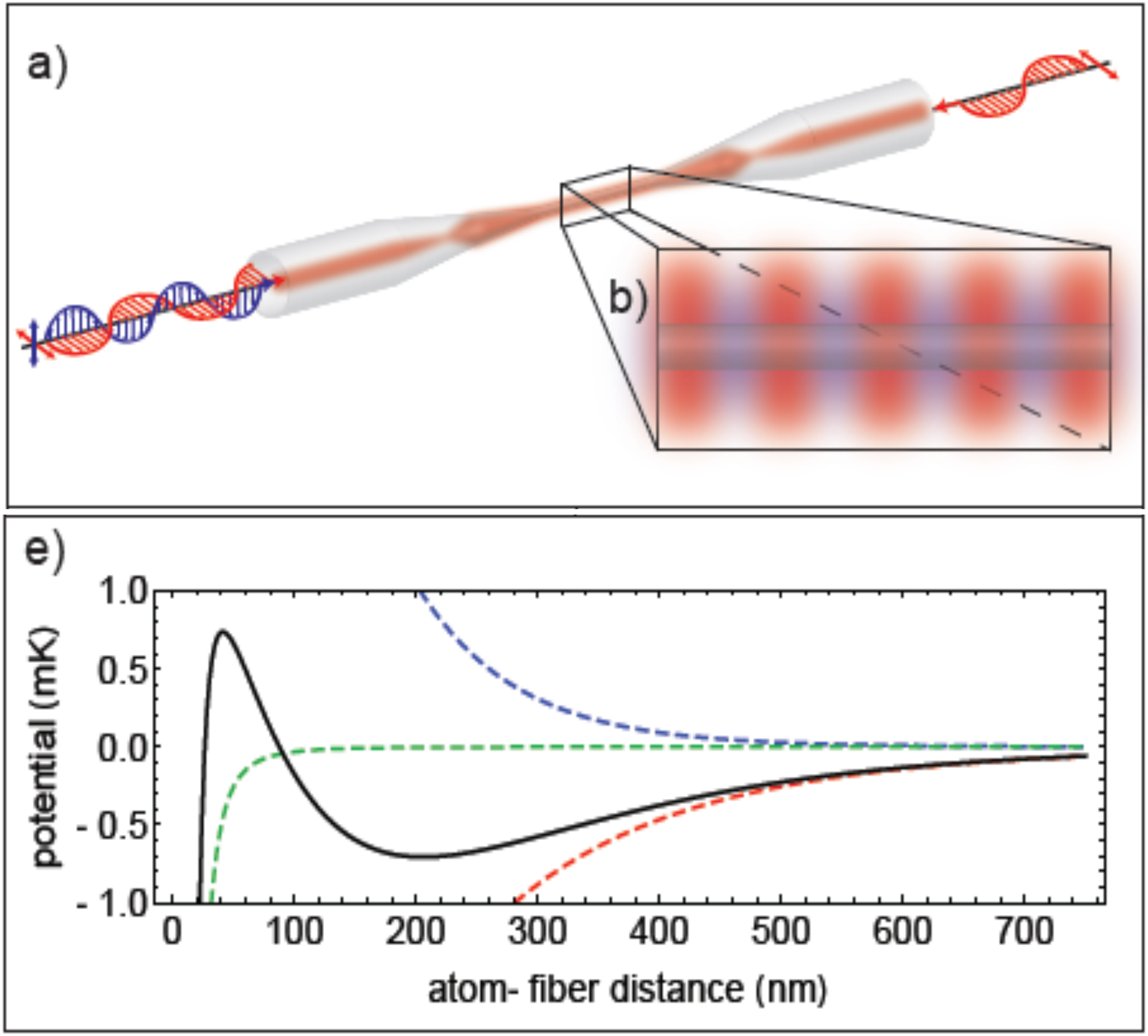


Atom trapping

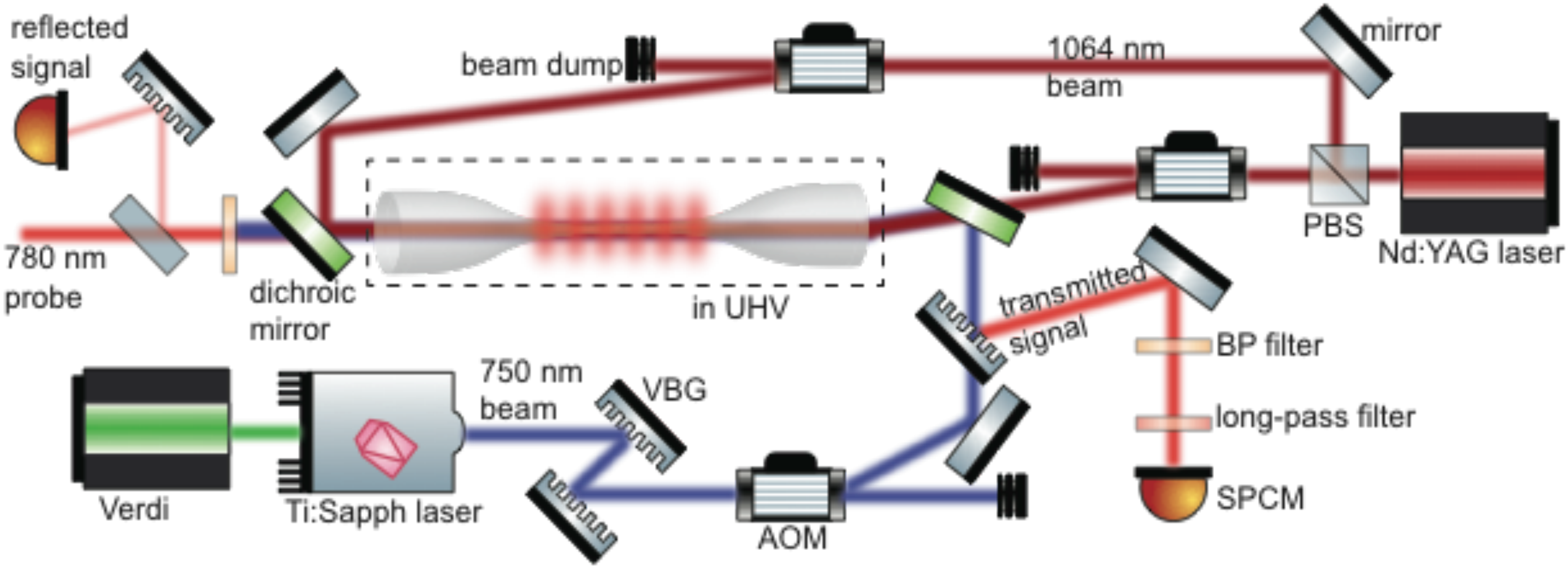
Trapping scheme



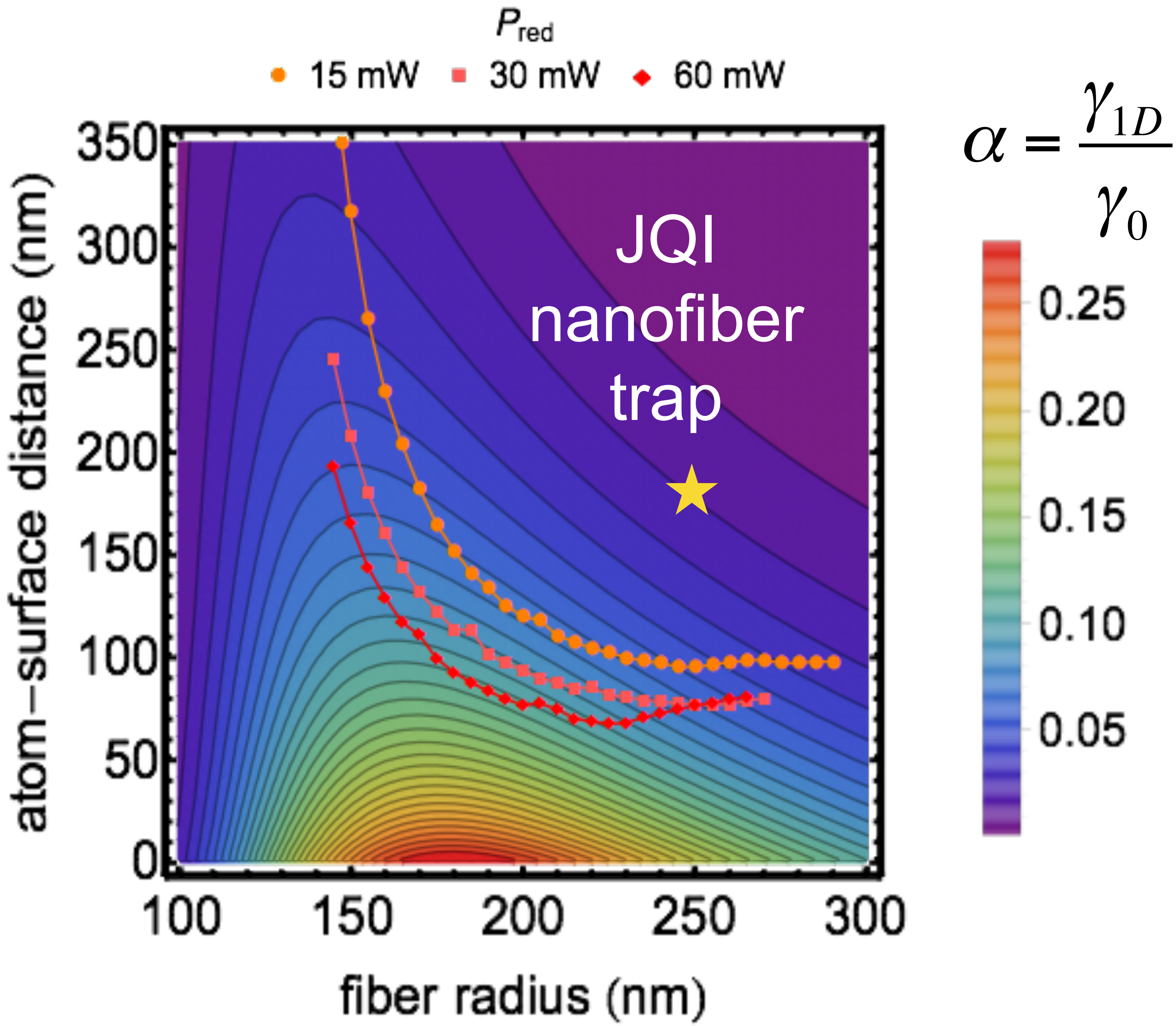
Trapping scheme



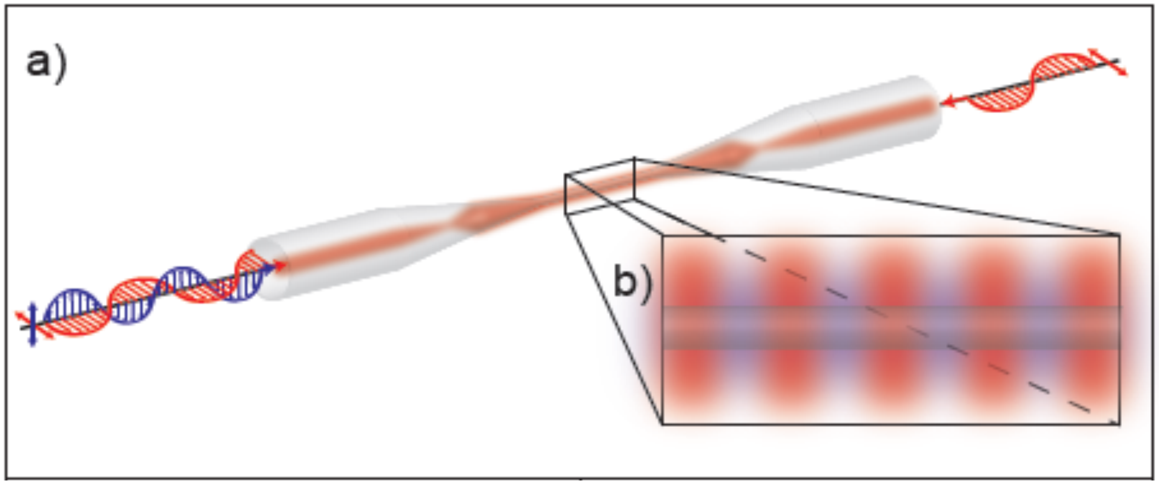
Optical Nanofiber Trapping

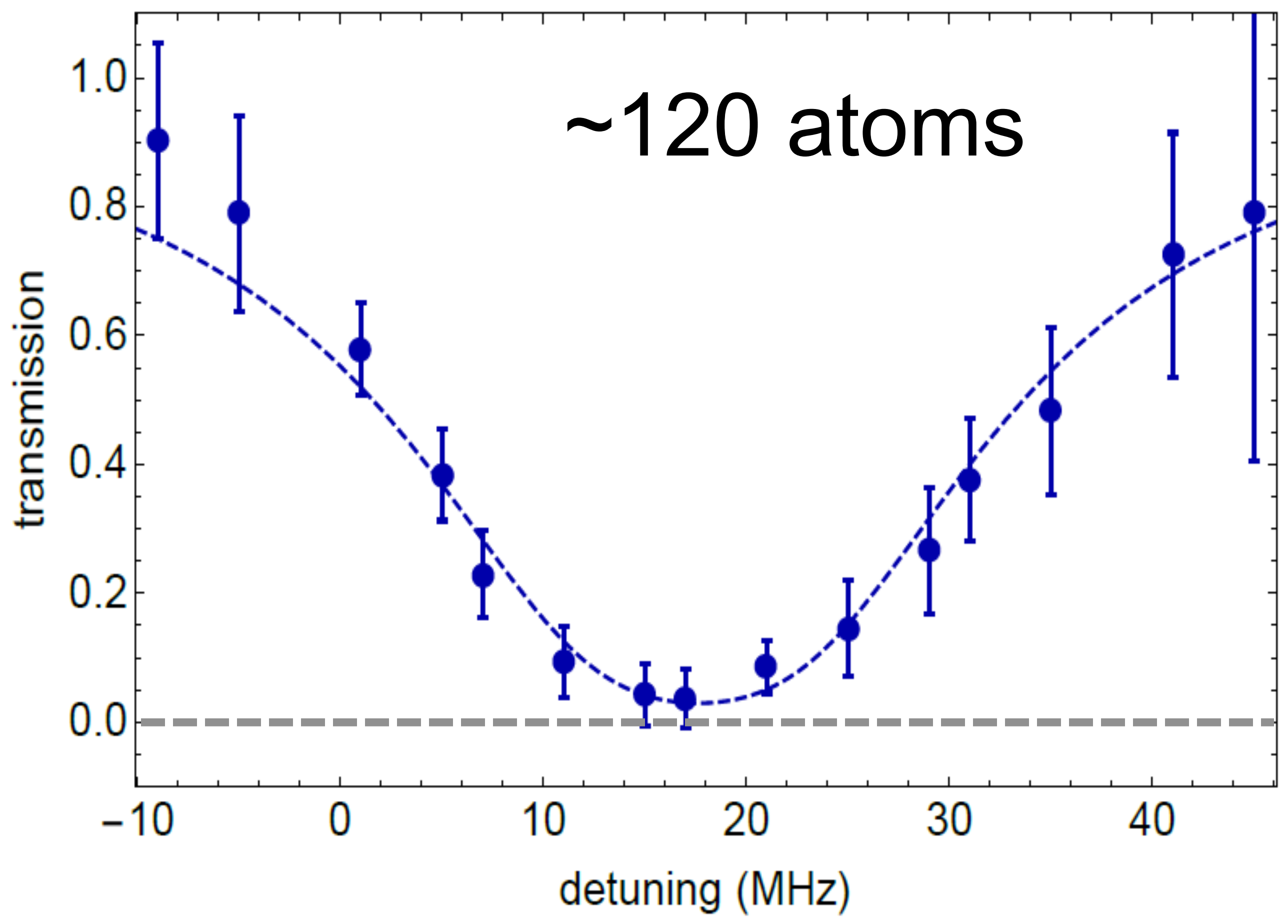


Coupling Enhancement

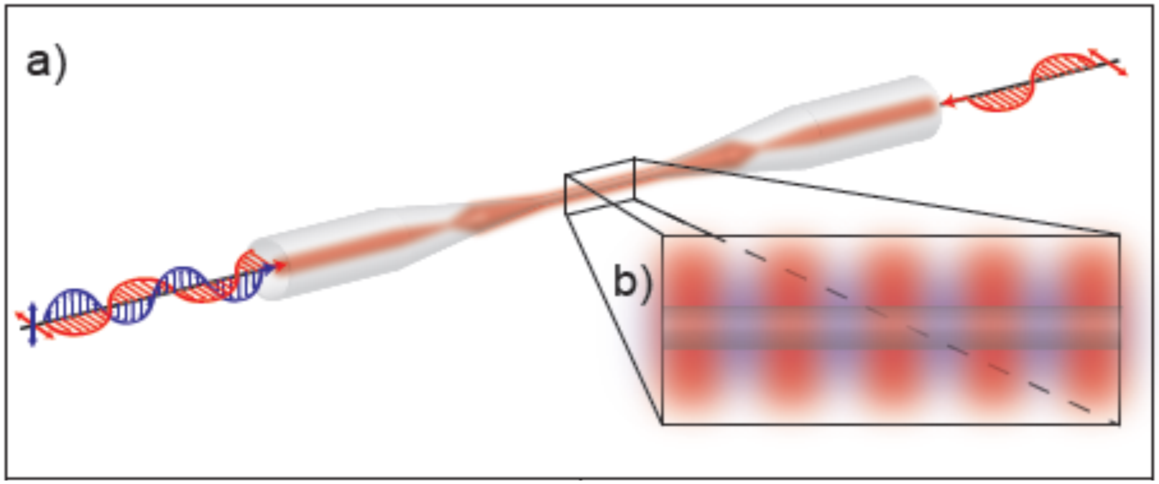


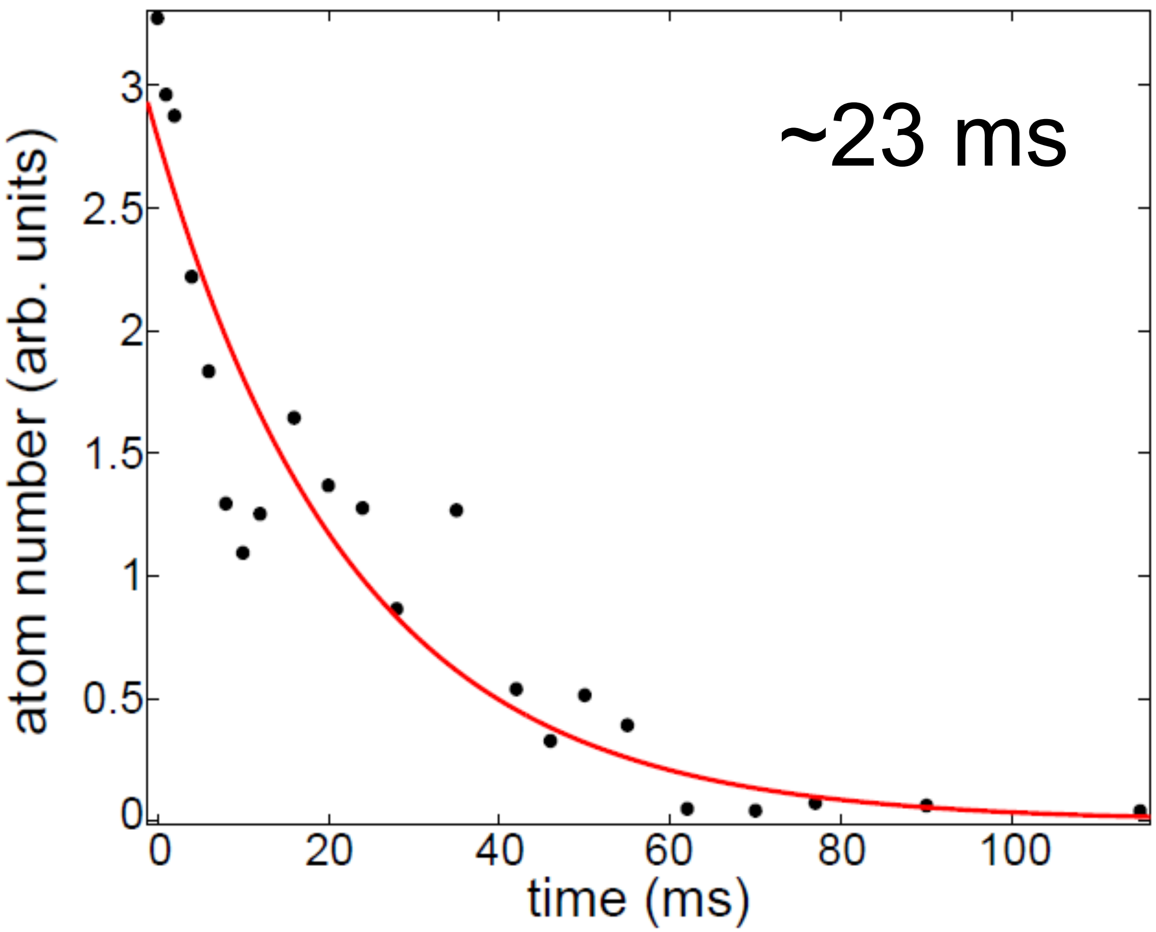
Trapping scheme



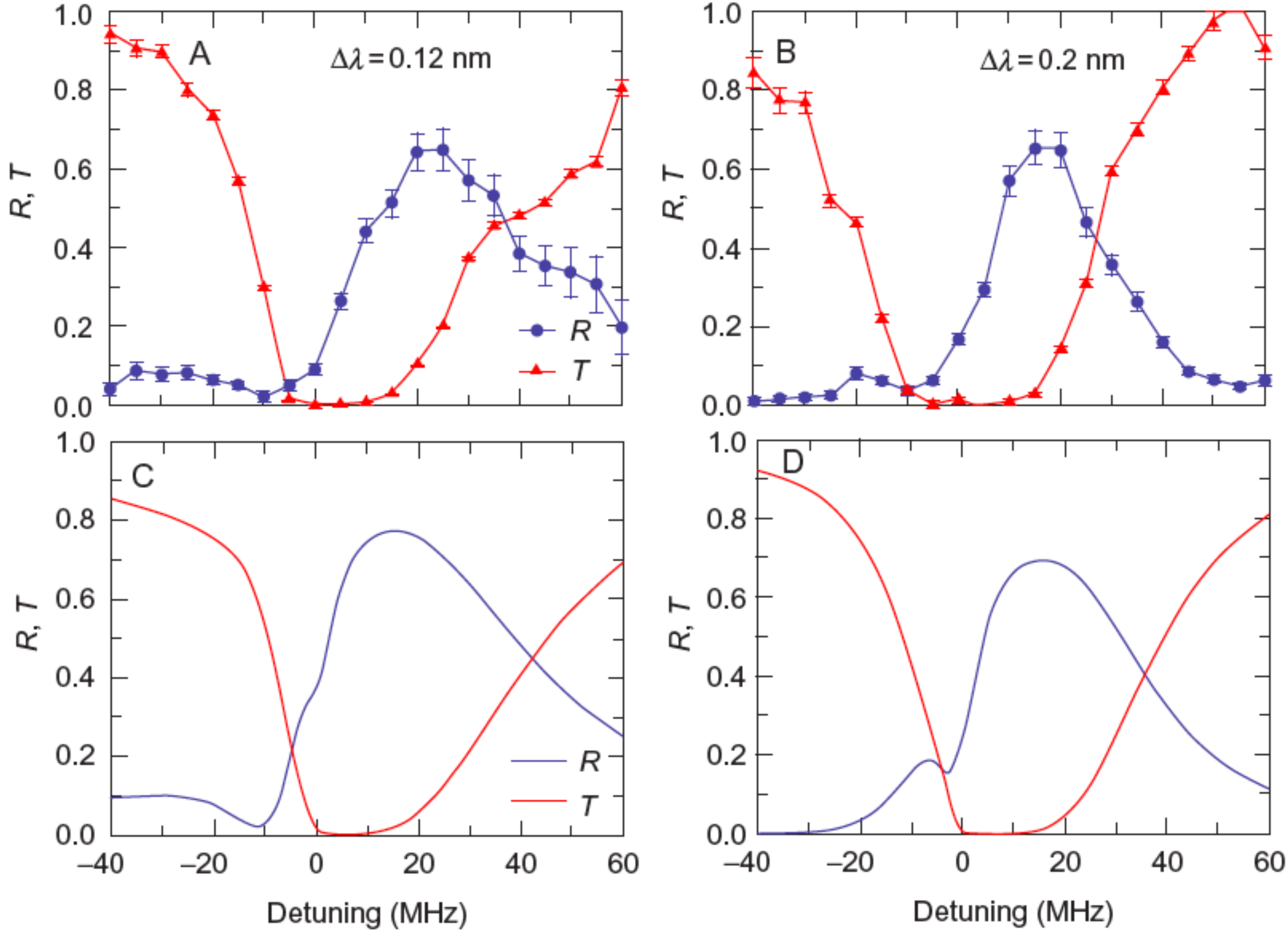


Trapping scheme

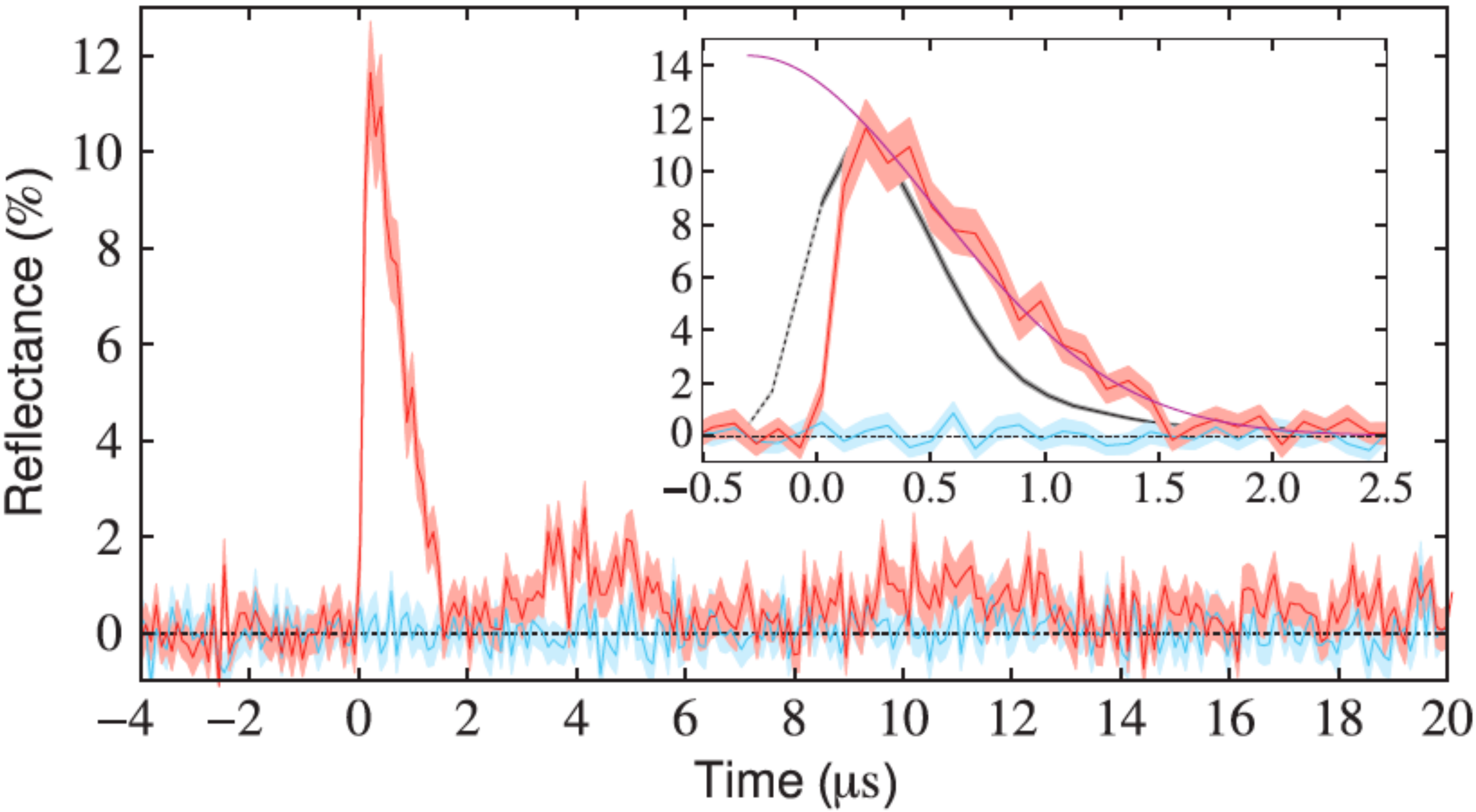




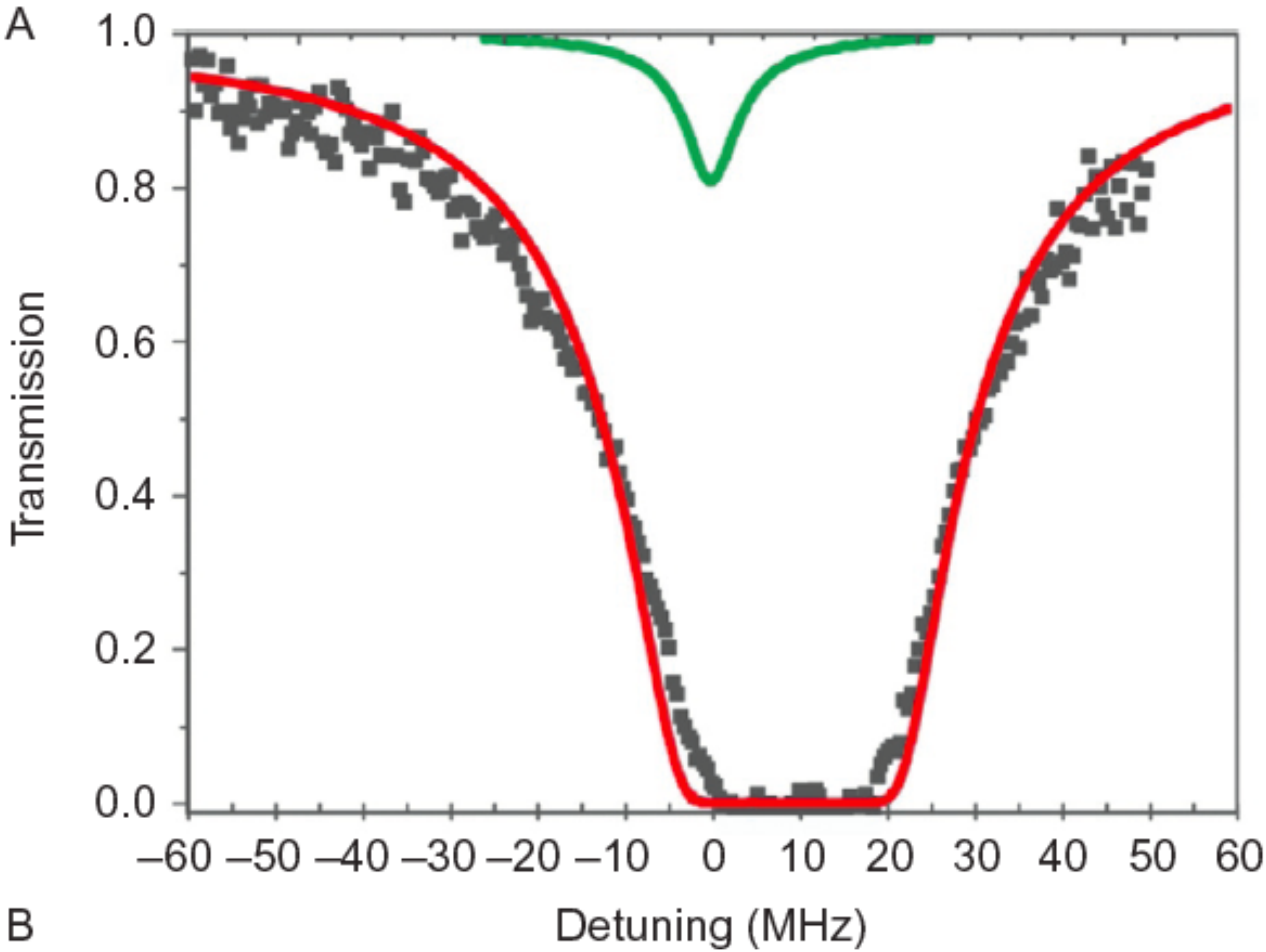
Reflection and Transmission from atoms trapped in the nanofiber. Periodic array



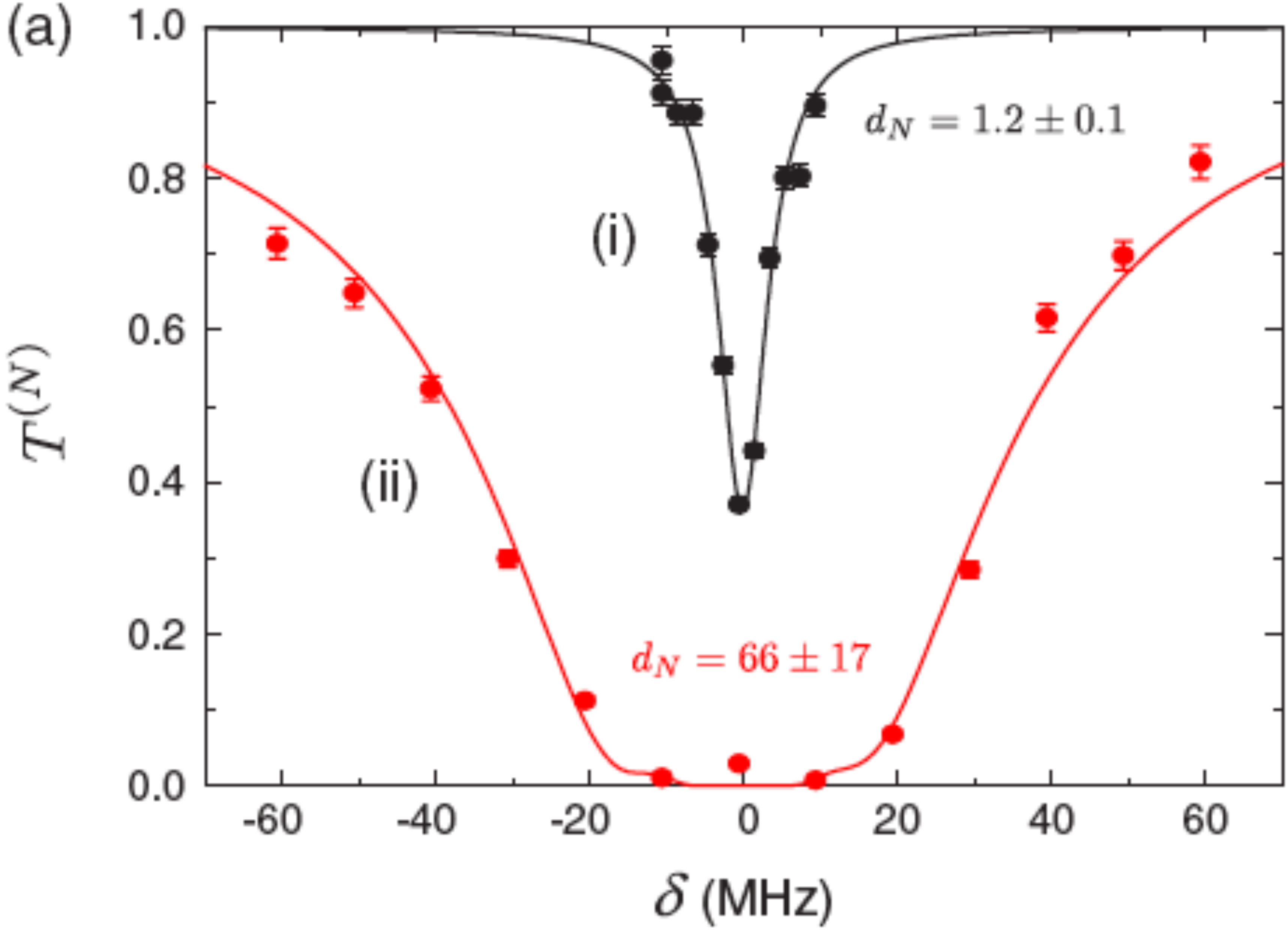
N. V. Corzo, B. Gouraud, A. Chandra, A. Goban, A. S. Sheremet, D. Kupriyanov, J. Laurat. "Large Bragg reflection from one-dimensional chains of trapped atoms near a nanoscale waveguide." Phys. Rev. Lett. 117, 133603 (2016).



H. L. Sørensen, J. B. Beguin, K. W. Kluge, I Iakoupov, A. S. Sørensen, J. H. Müller, E. S. Polzik, J. Appel, 2016. “Coherent backscattering of light on one-dimensional atomic strings.” Phys. Rev. Lett. **117**, 133604 (2016).



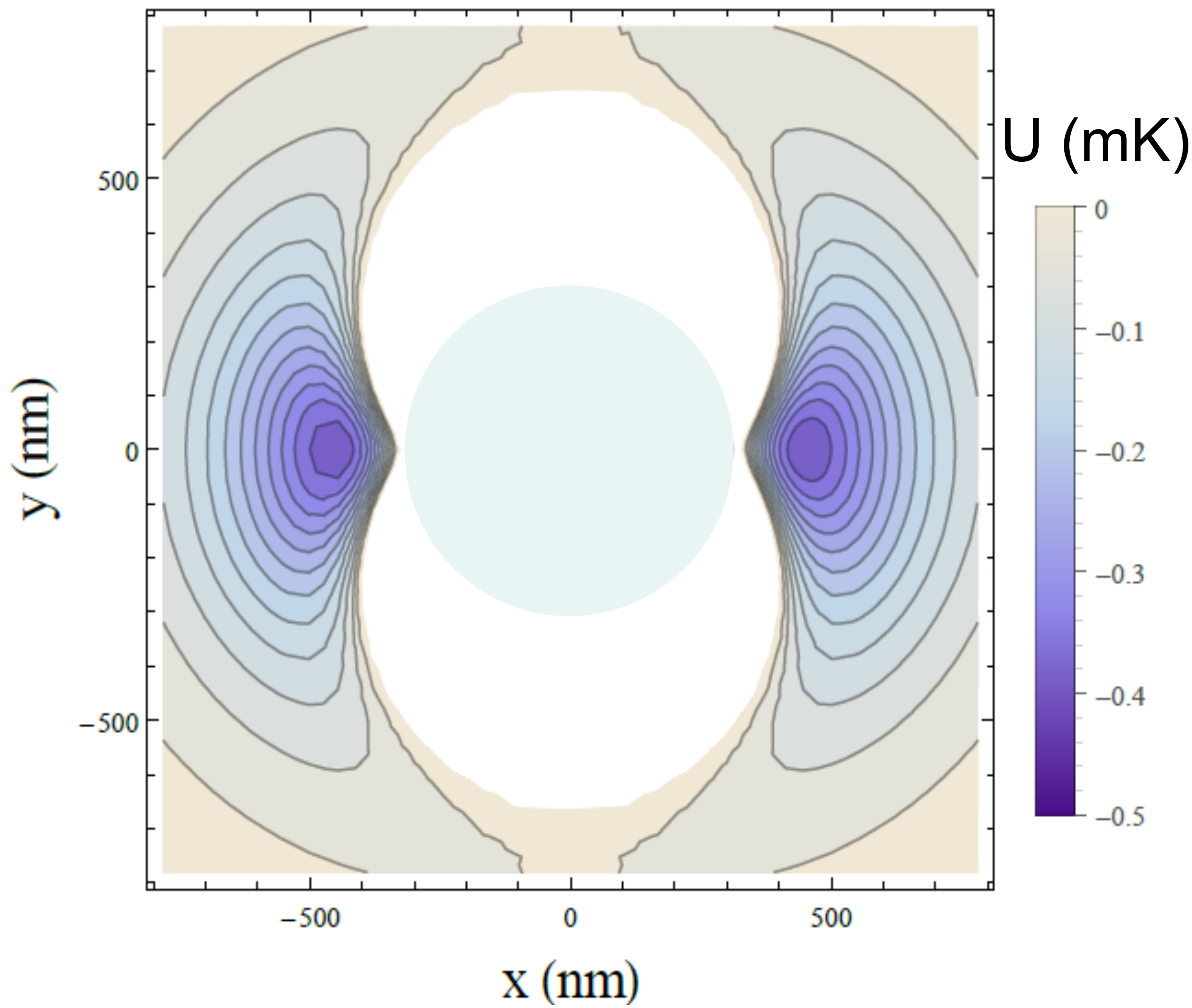
E. Vetsch, D. Reitz, G. Sagué, R. Schmidt, S. T. Dawkins, A. Rauschenbeutel, A. "Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber." Phys. Rev. Lett. 104, 203603 (2010).



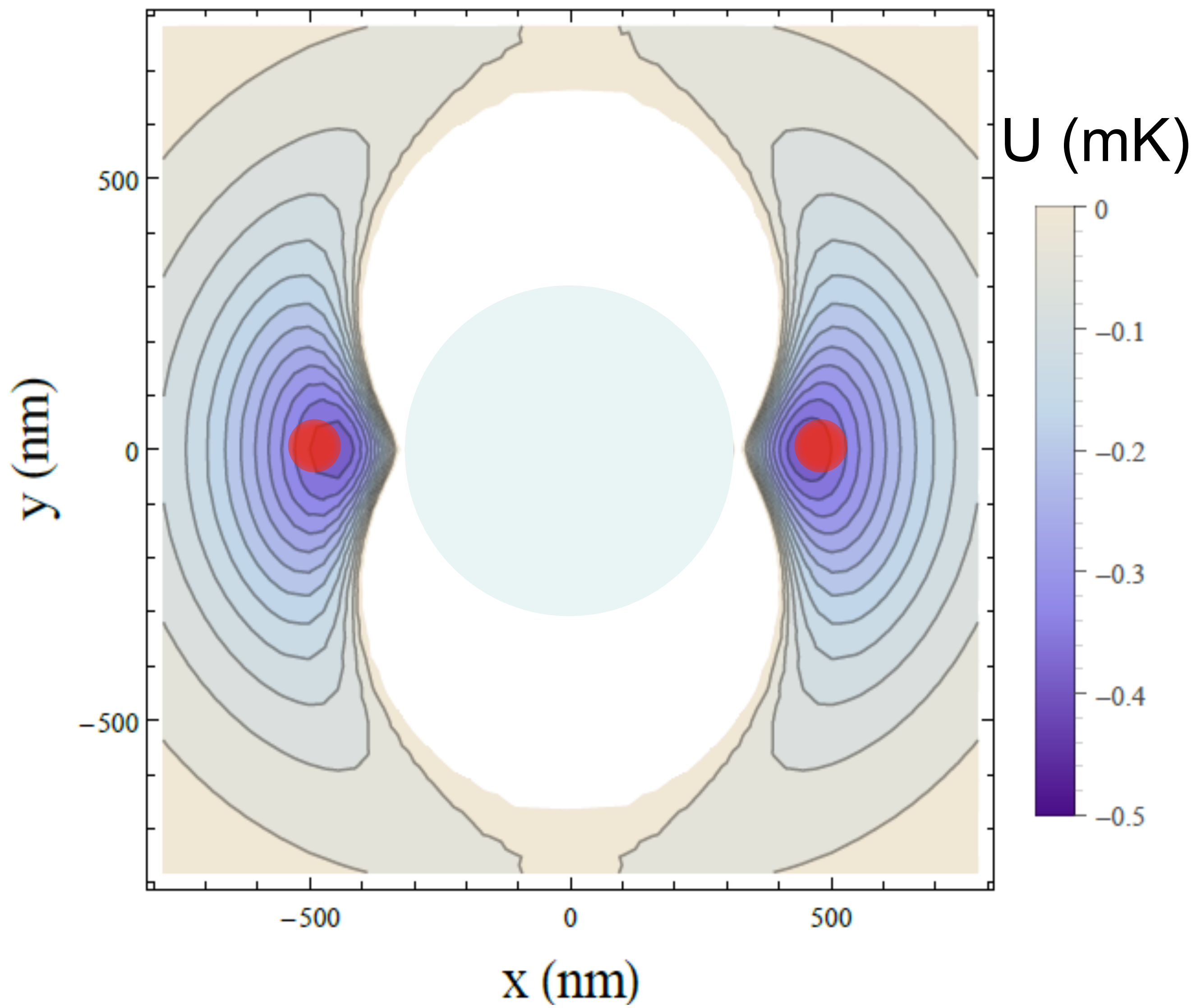
A. Goban, K. S. Choi, D. J. Alton, D. Ding, C. Lacroûte, M. Pototschnig, T. Thiele, N. P. Stern, and H. J. Kimble “Demonstration of a State-Insensitive, Compensated Nanofiber Trap,” Phys. Rev. Lett. 109, 033603 (2012).

Atoms as a birefringent medium

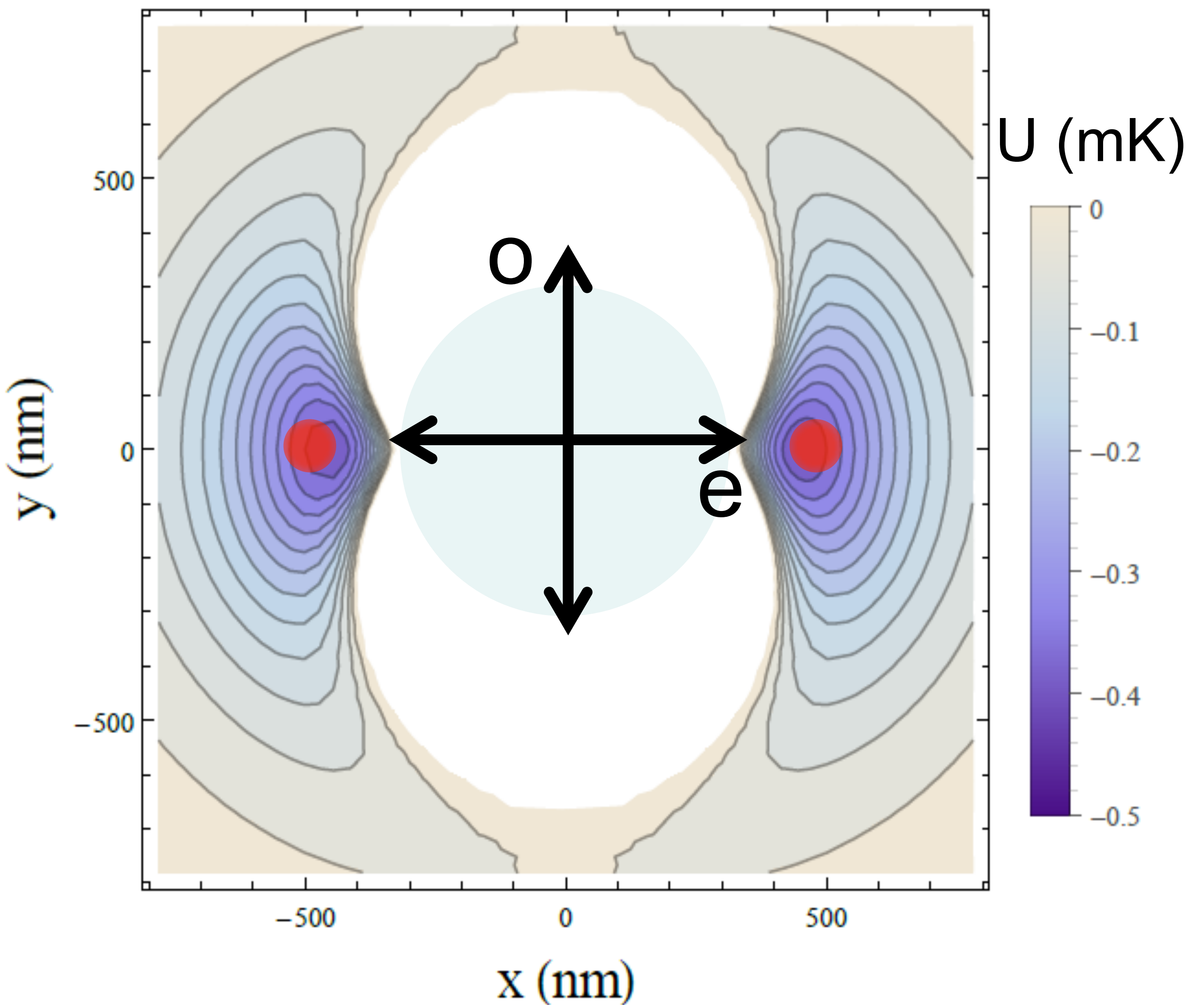
Trapped atoms as a birefringent media



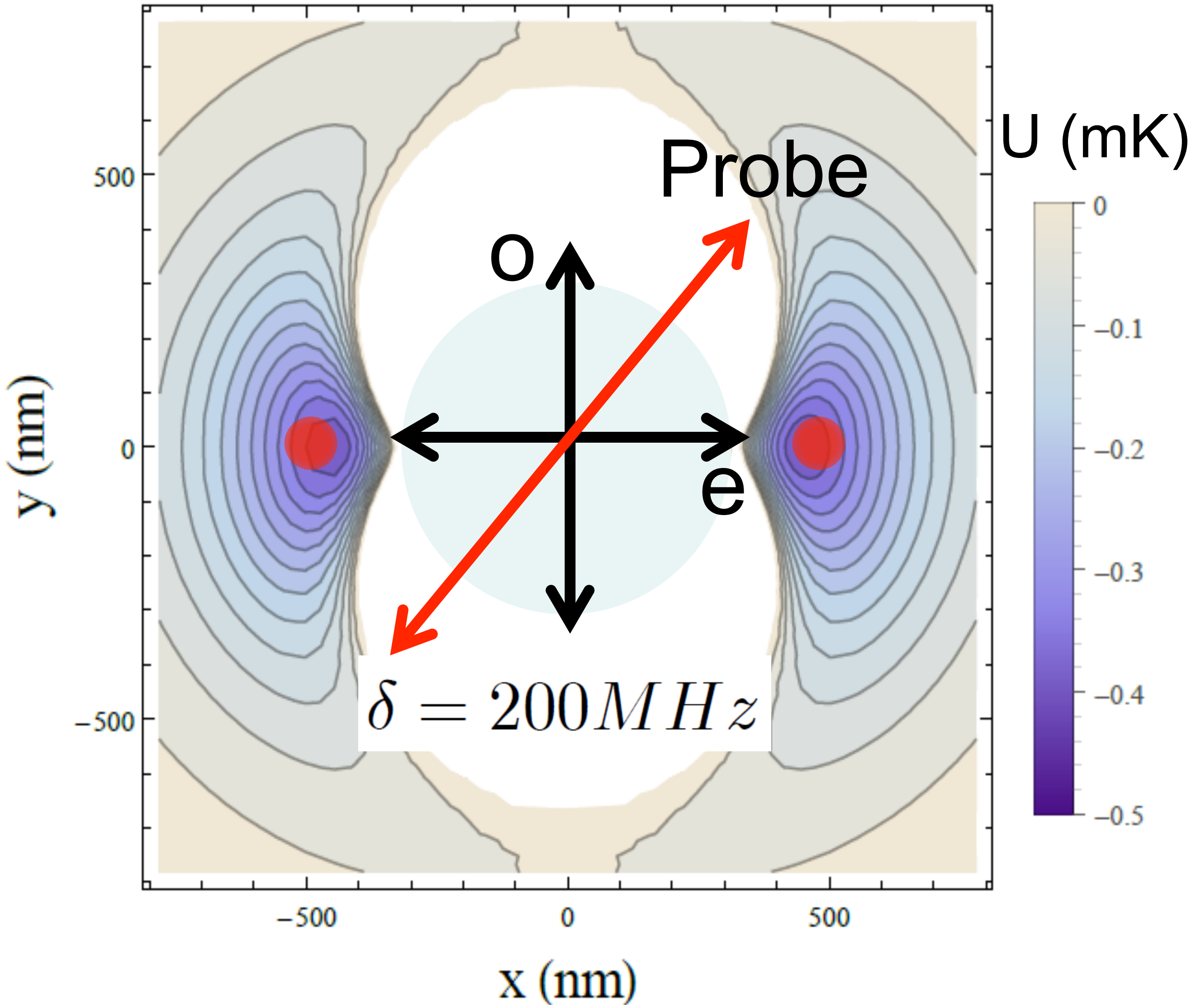
Trapped atoms as a birefringent media



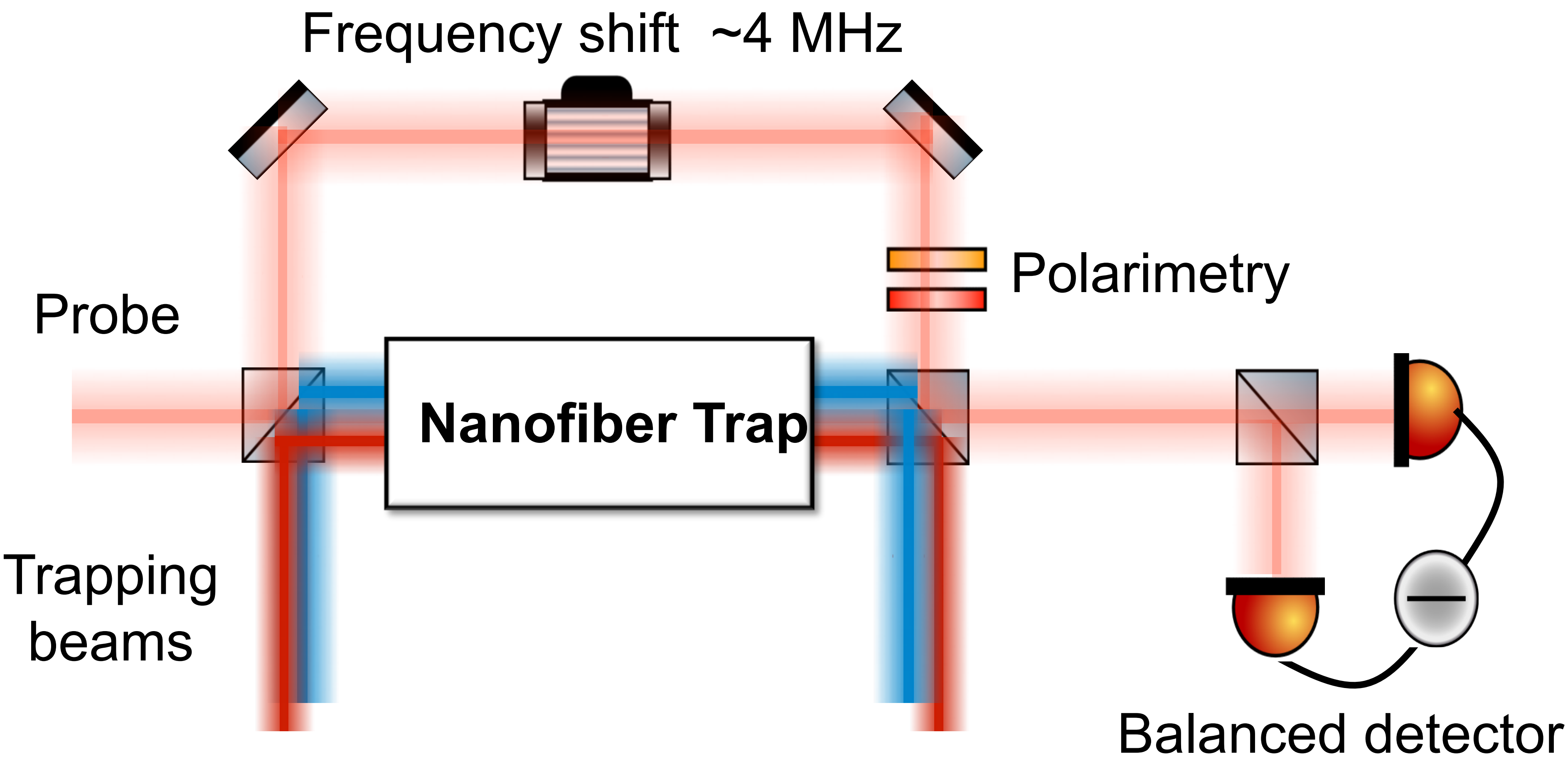
Trapped atoms as a birefringent media



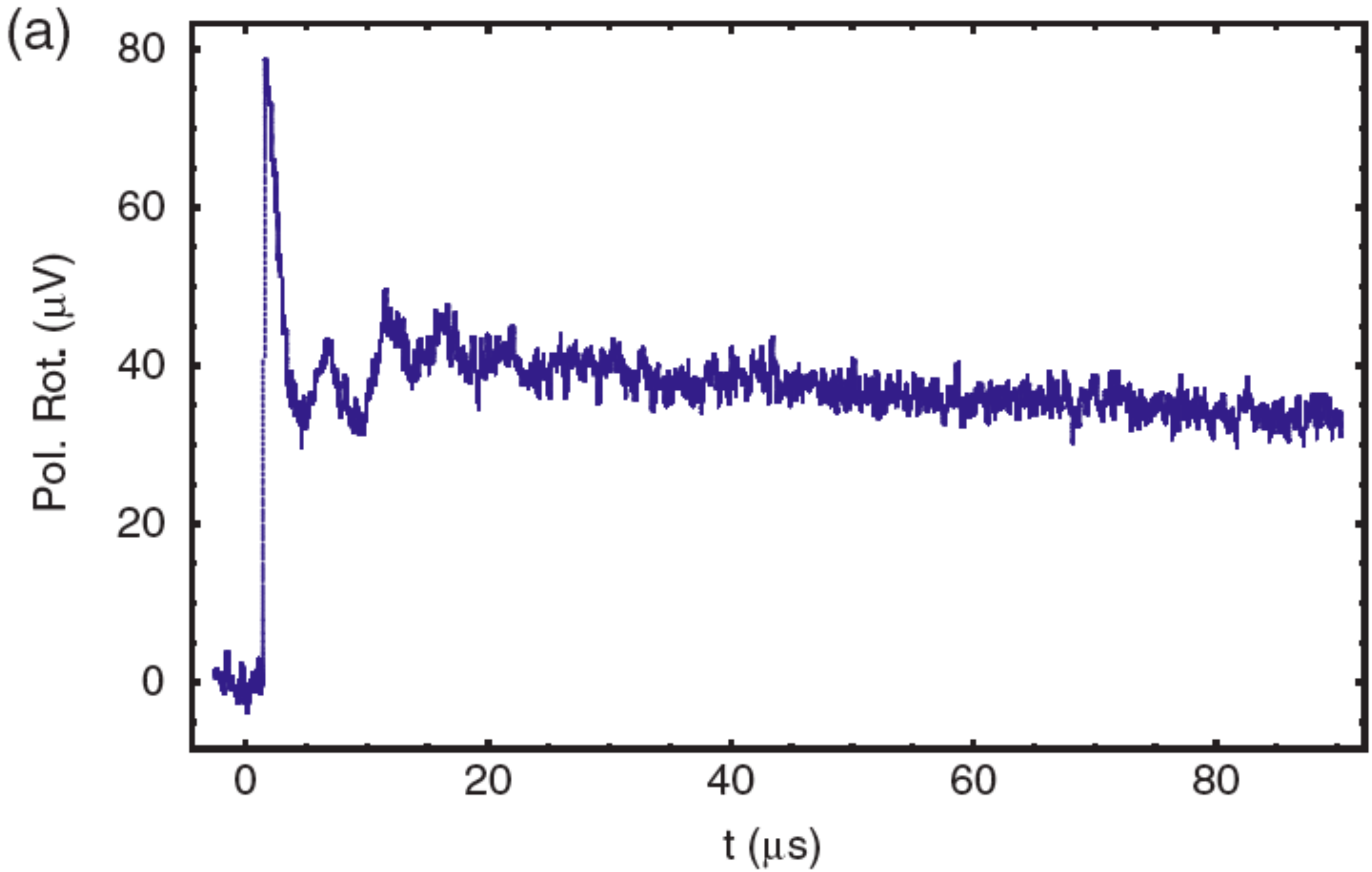
Trapped atoms as a birefringent media



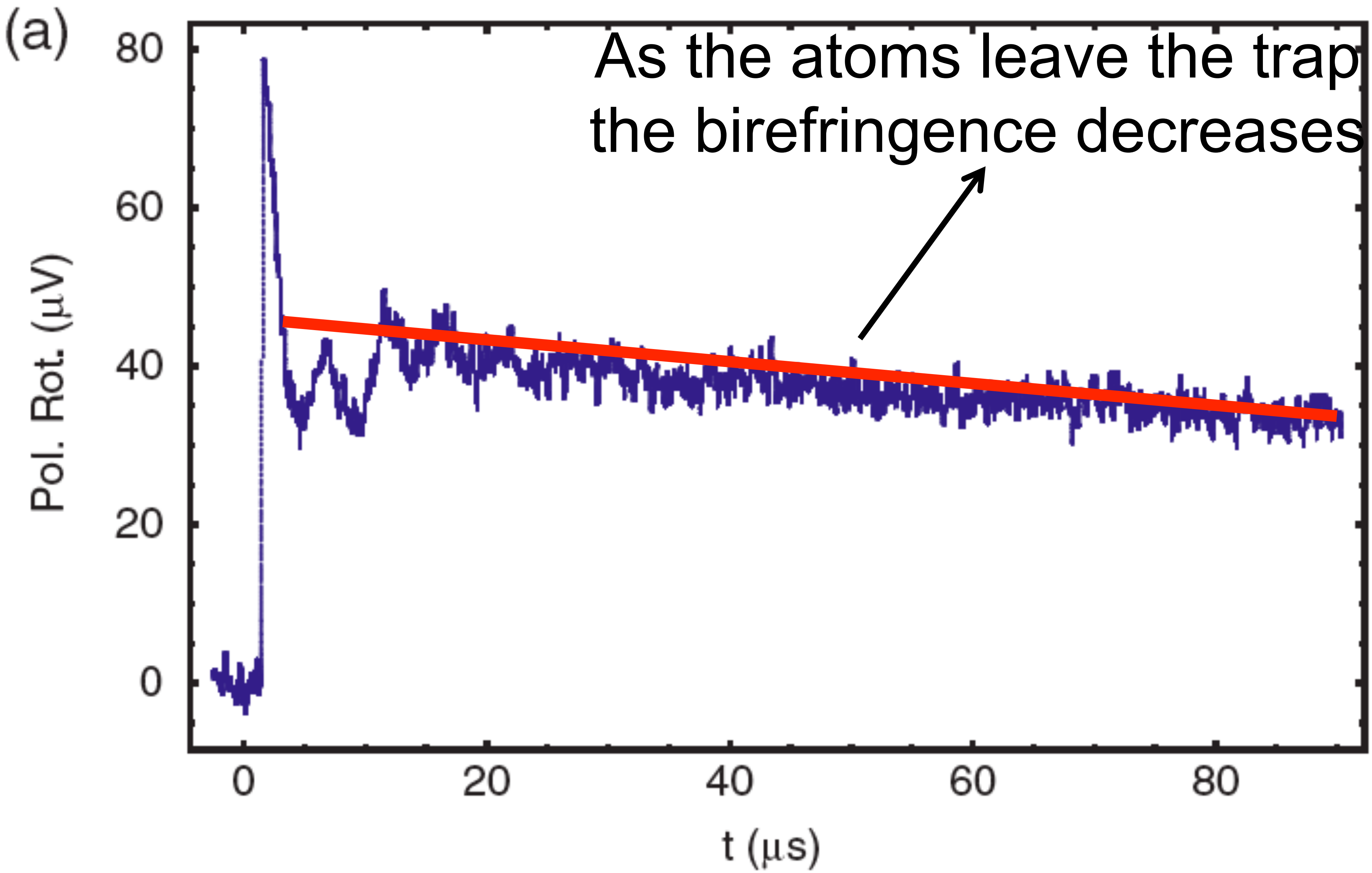
(Heterodyne detection)



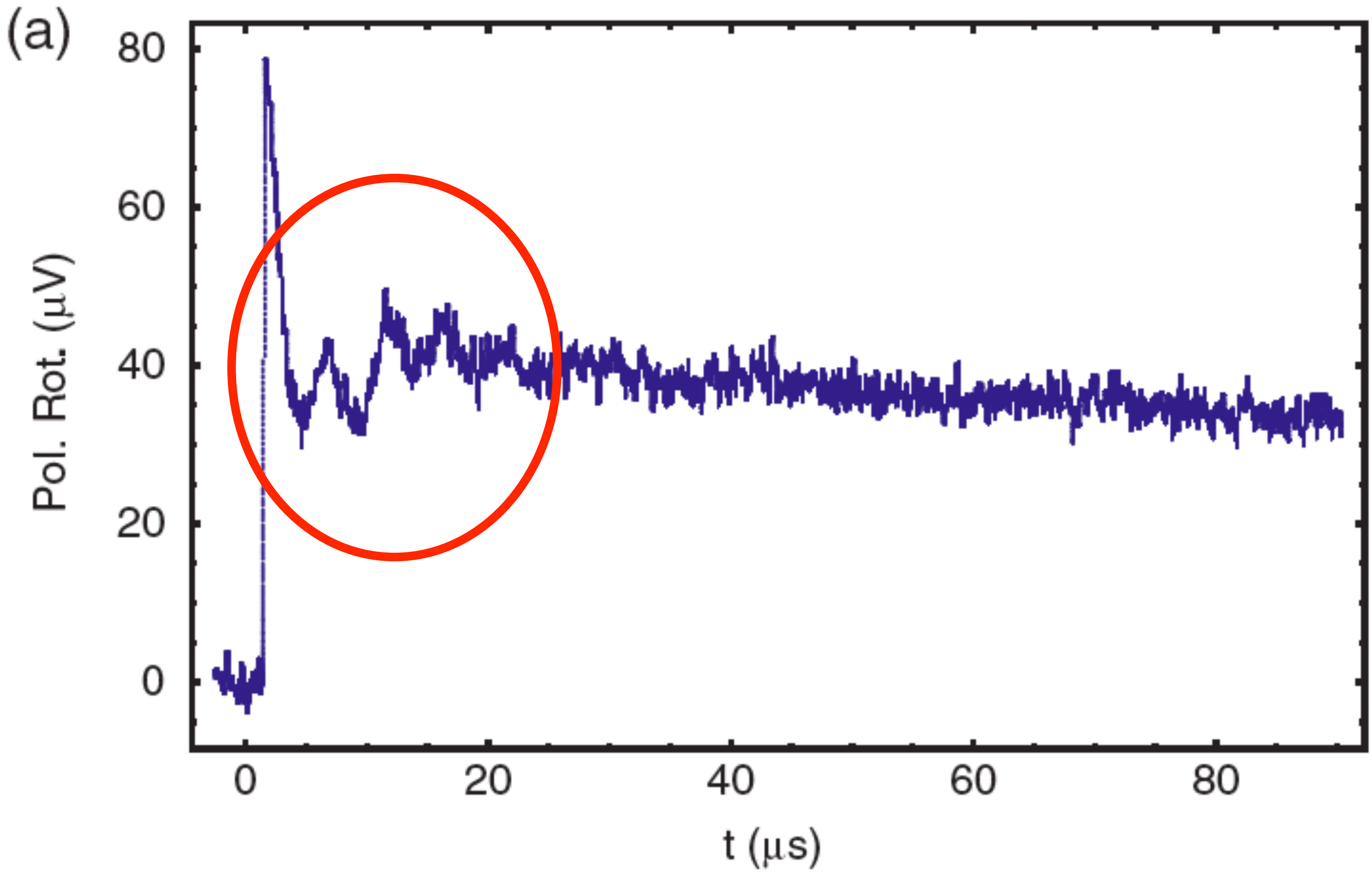
Time dependent signal



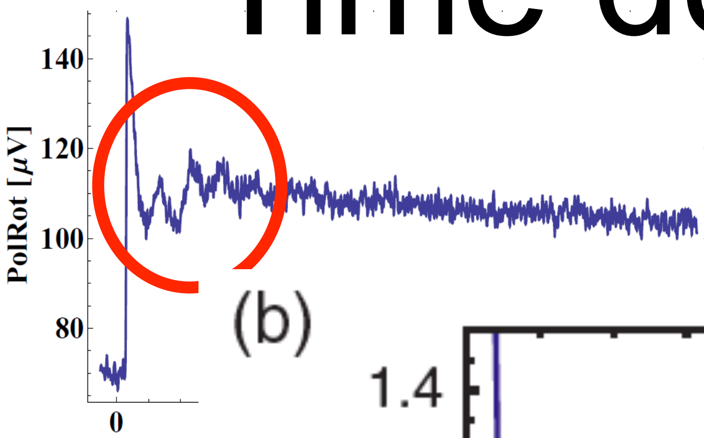
Time dependent signal

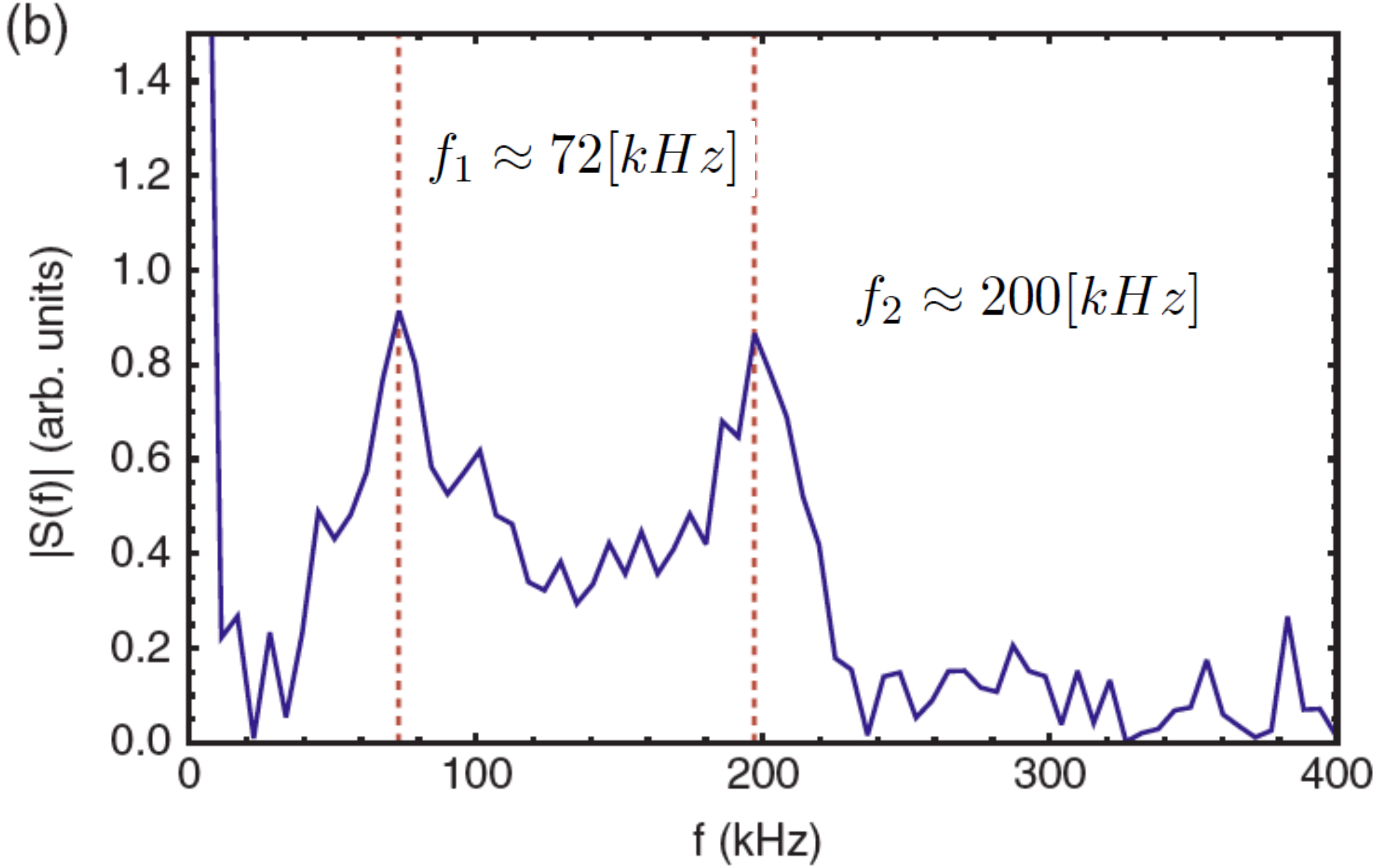


Time dependent signal

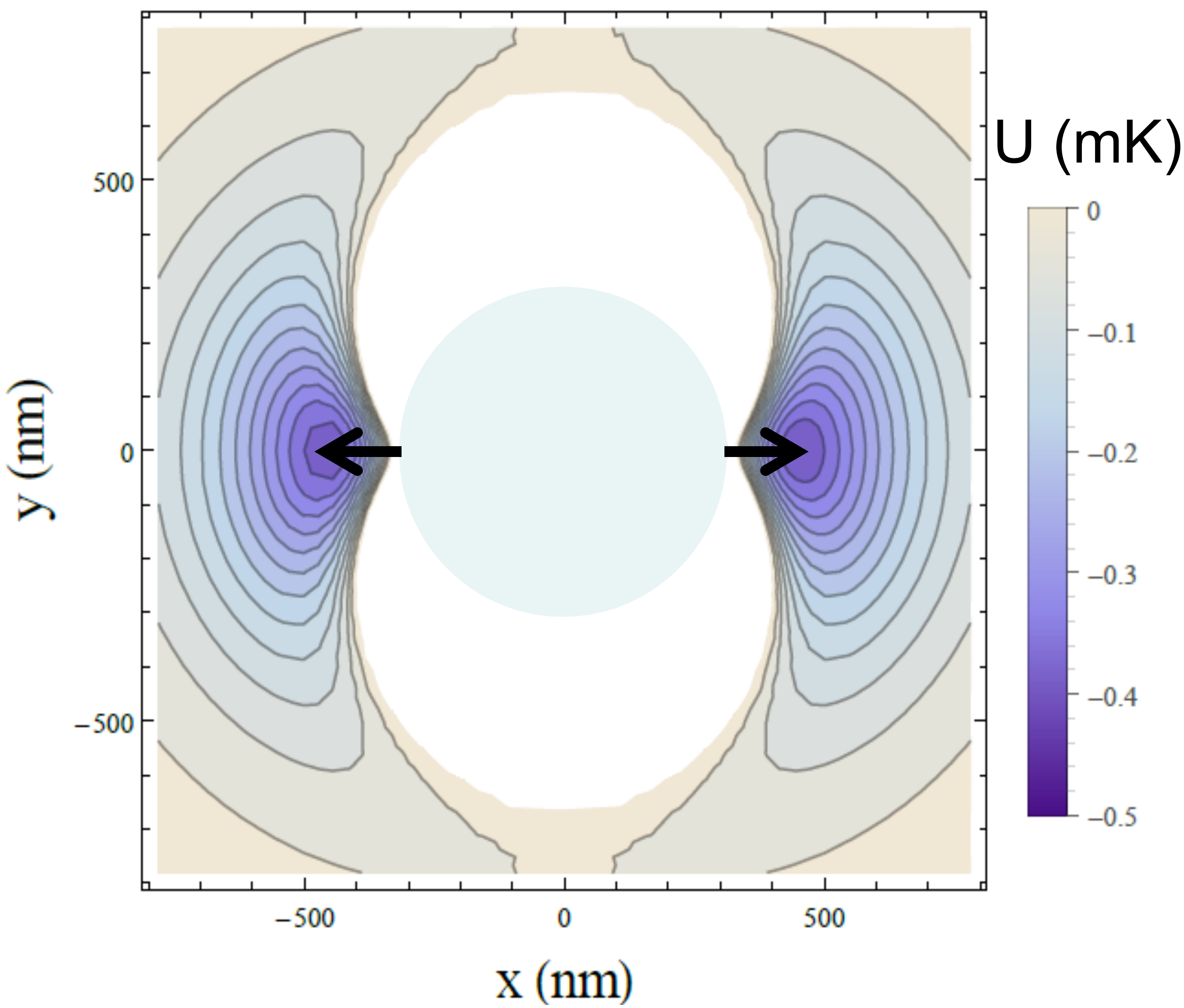


Time dependent signal

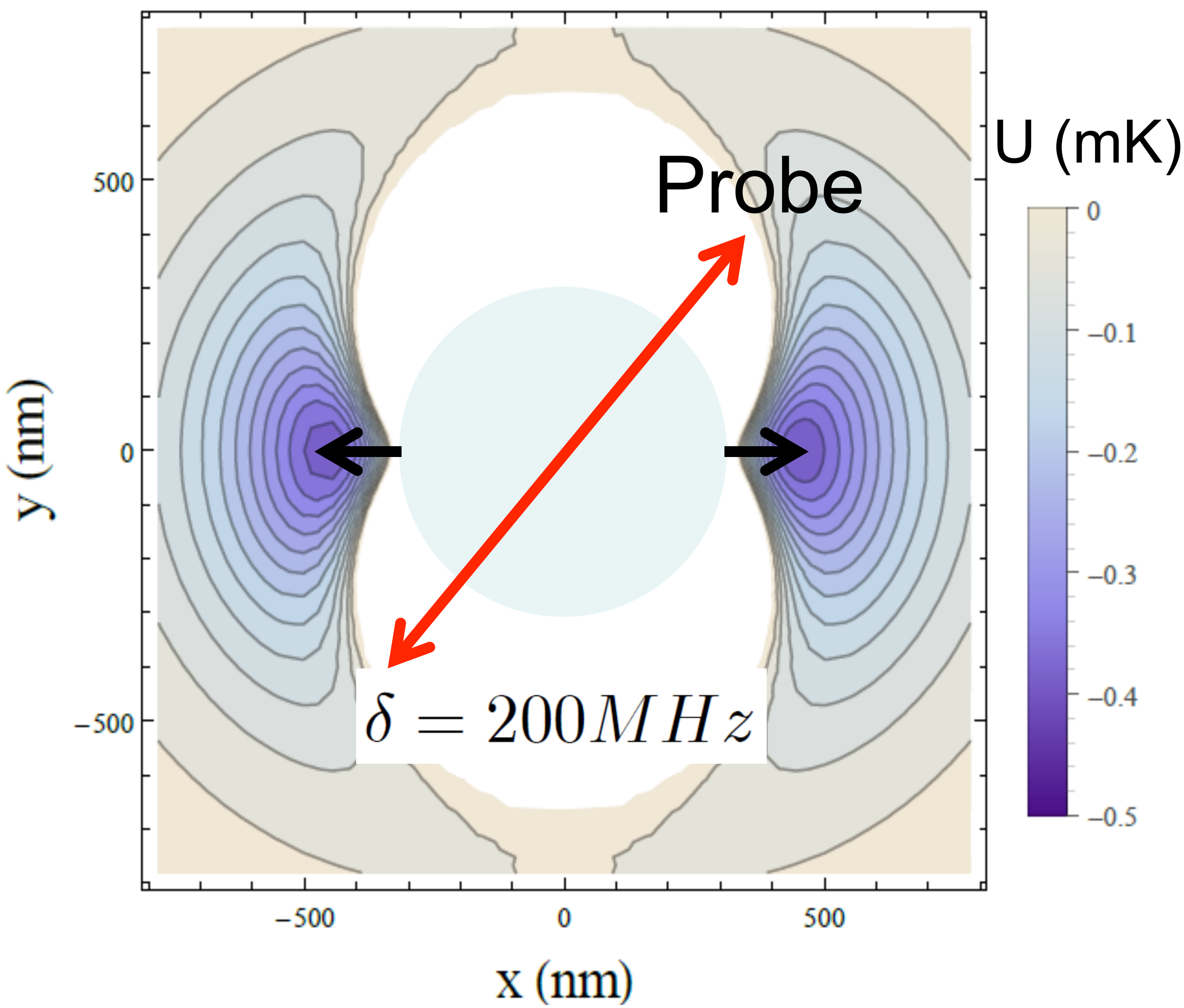




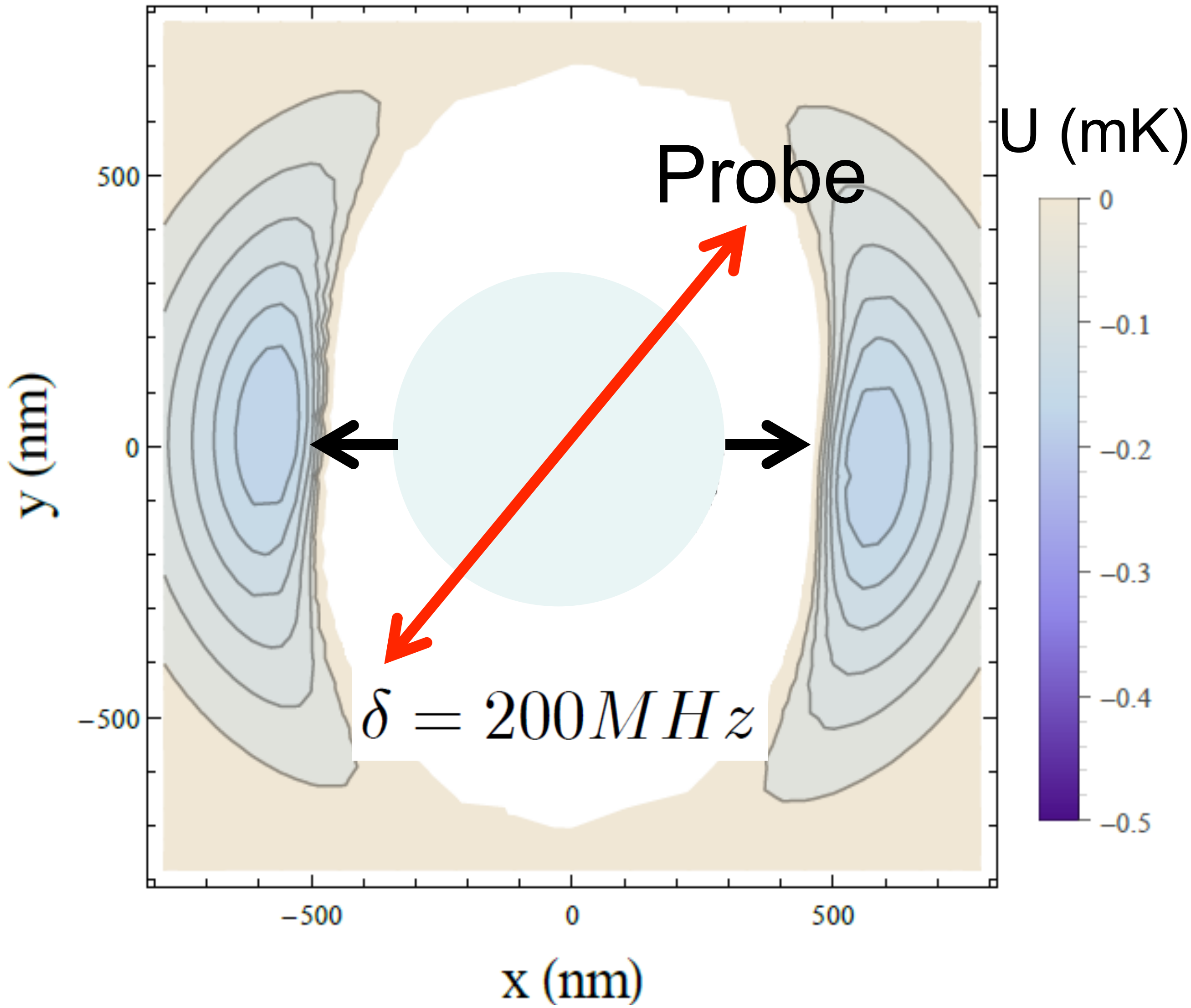
Atoms moving in the trap



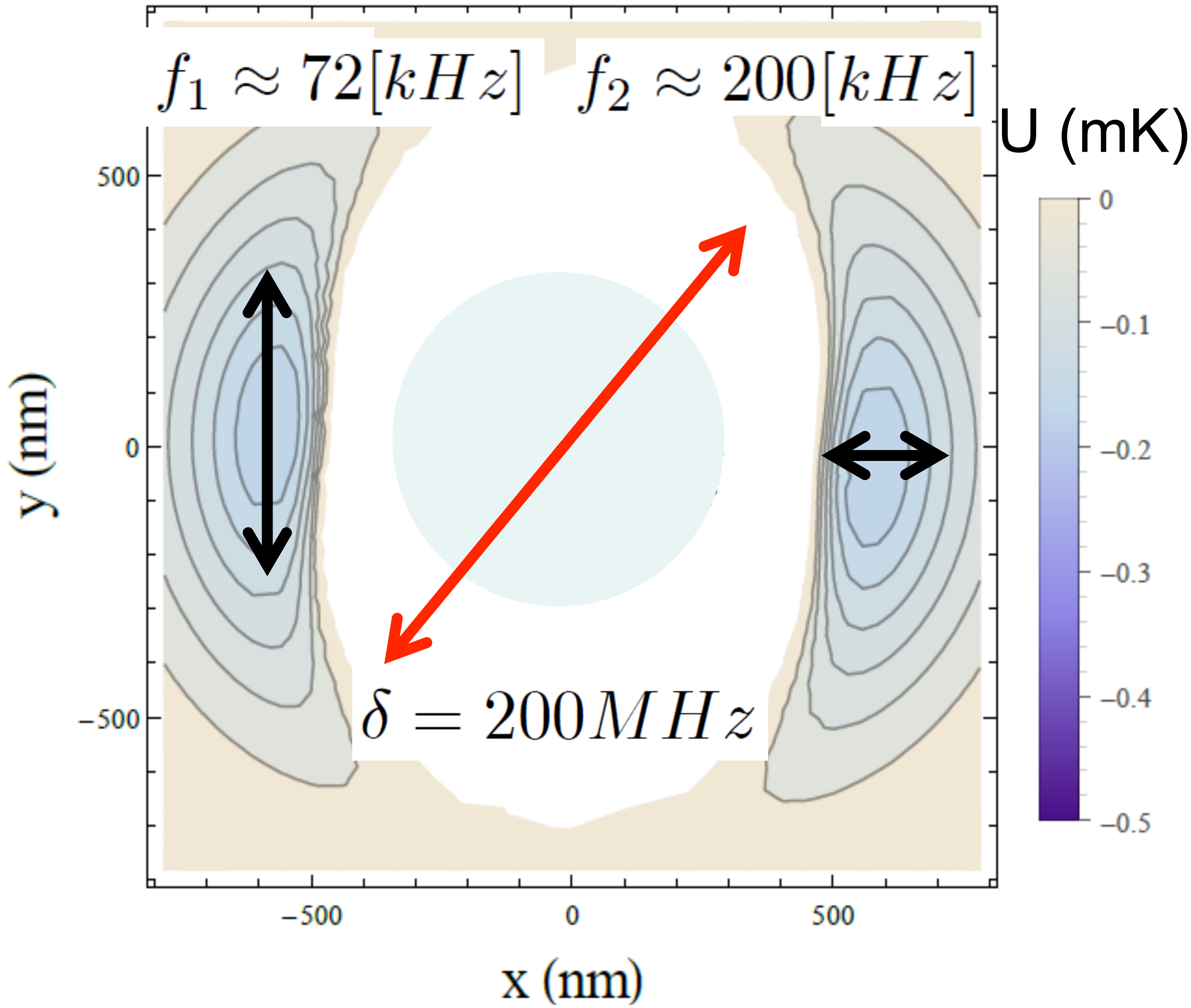
Atoms moving in the trap



Atoms moving in the trap

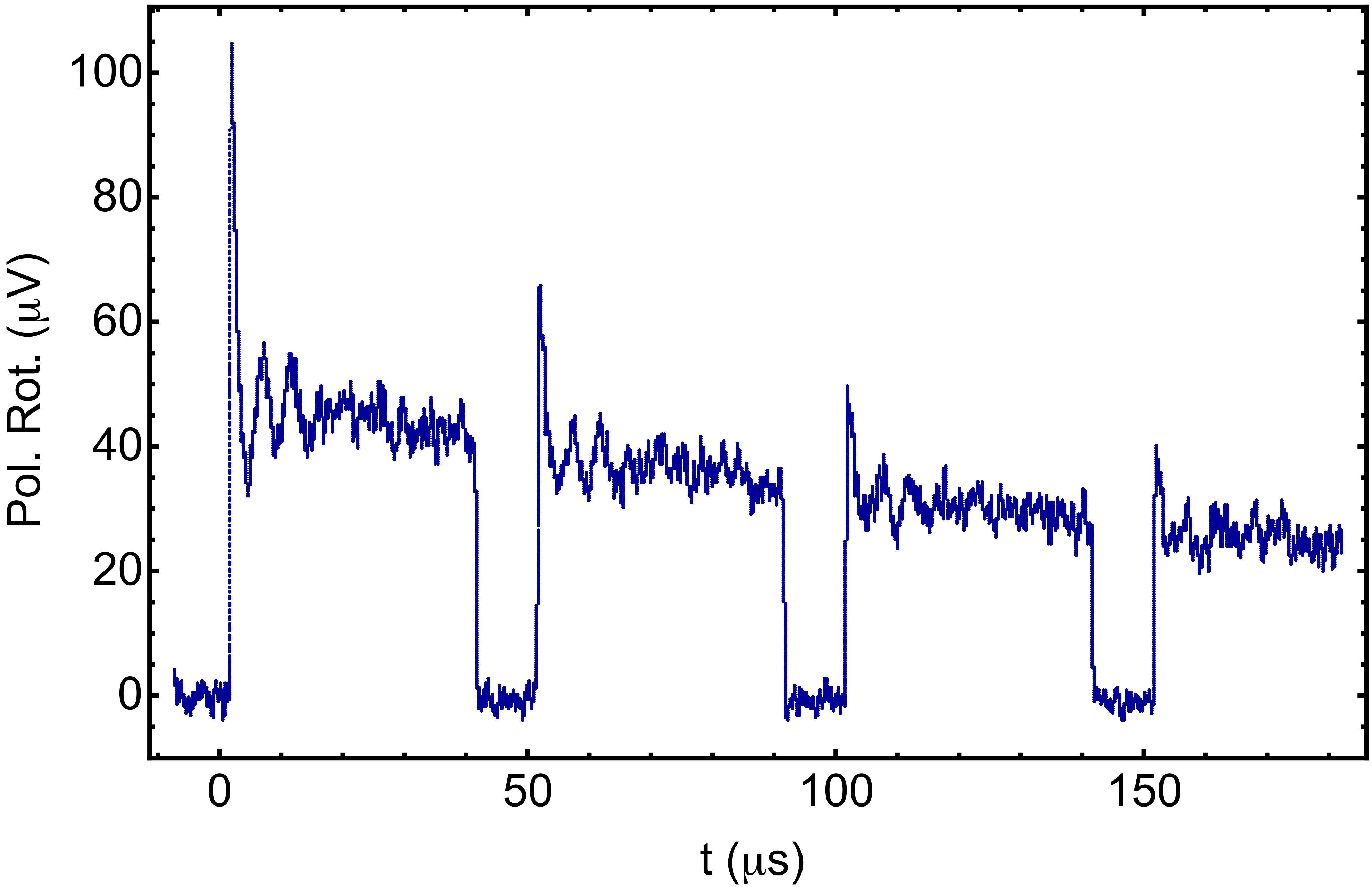


Atoms moving in the trap



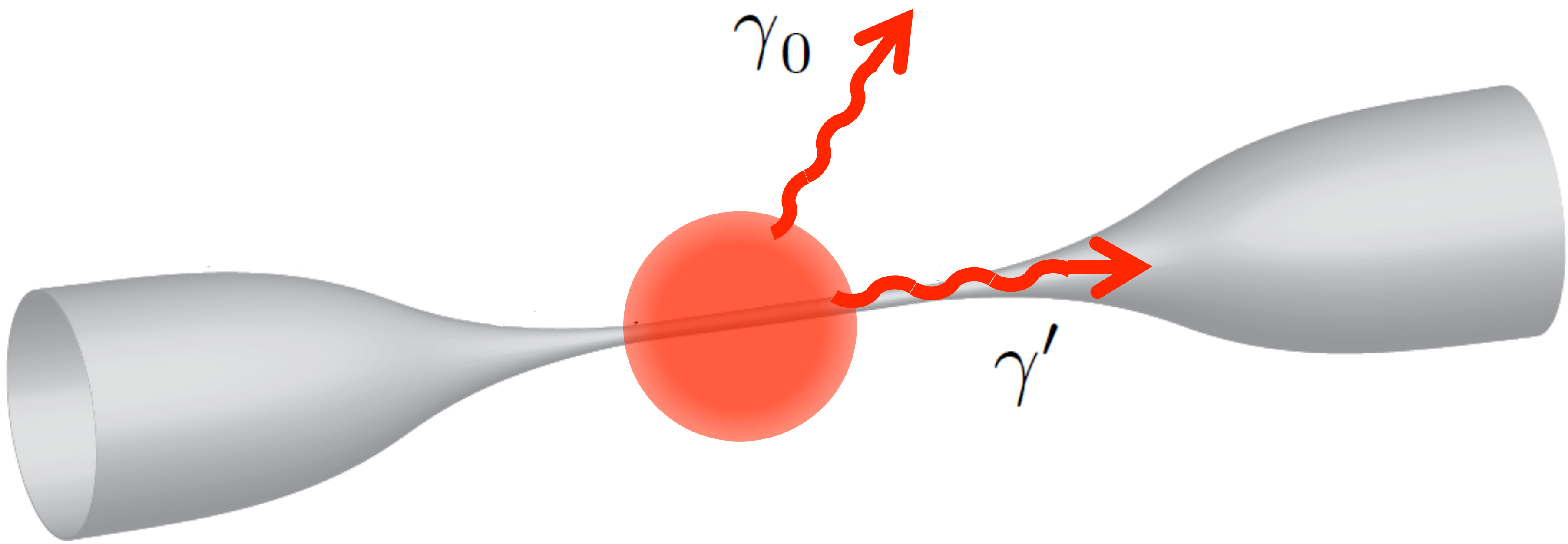
The frequencies agree with the simulation within a 10%

Atoms moving in the trap



How does the presence of a nanofiber modify the spontaneous emission rate of an atom placed close to it?

The experiment



We measured the decay rate of the D2 line of Rb using Time Correlated Single Photon Counting (TCSPC).

Decay rate into the nanofiber

$$\gamma_{1D} \approx \frac{2\pi}{\hbar}\rho\left(k\right)\left\langle H_{int}\right\rangle^2$$

Decay rate into the nanofiber

Modes density in 1D!

$$\gamma_{1D} \approx \frac{2\pi}{\hbar} \rho\left(k\right) \left\langle H_{int} \right\rangle^2$$

Decay rate into the nanofiber

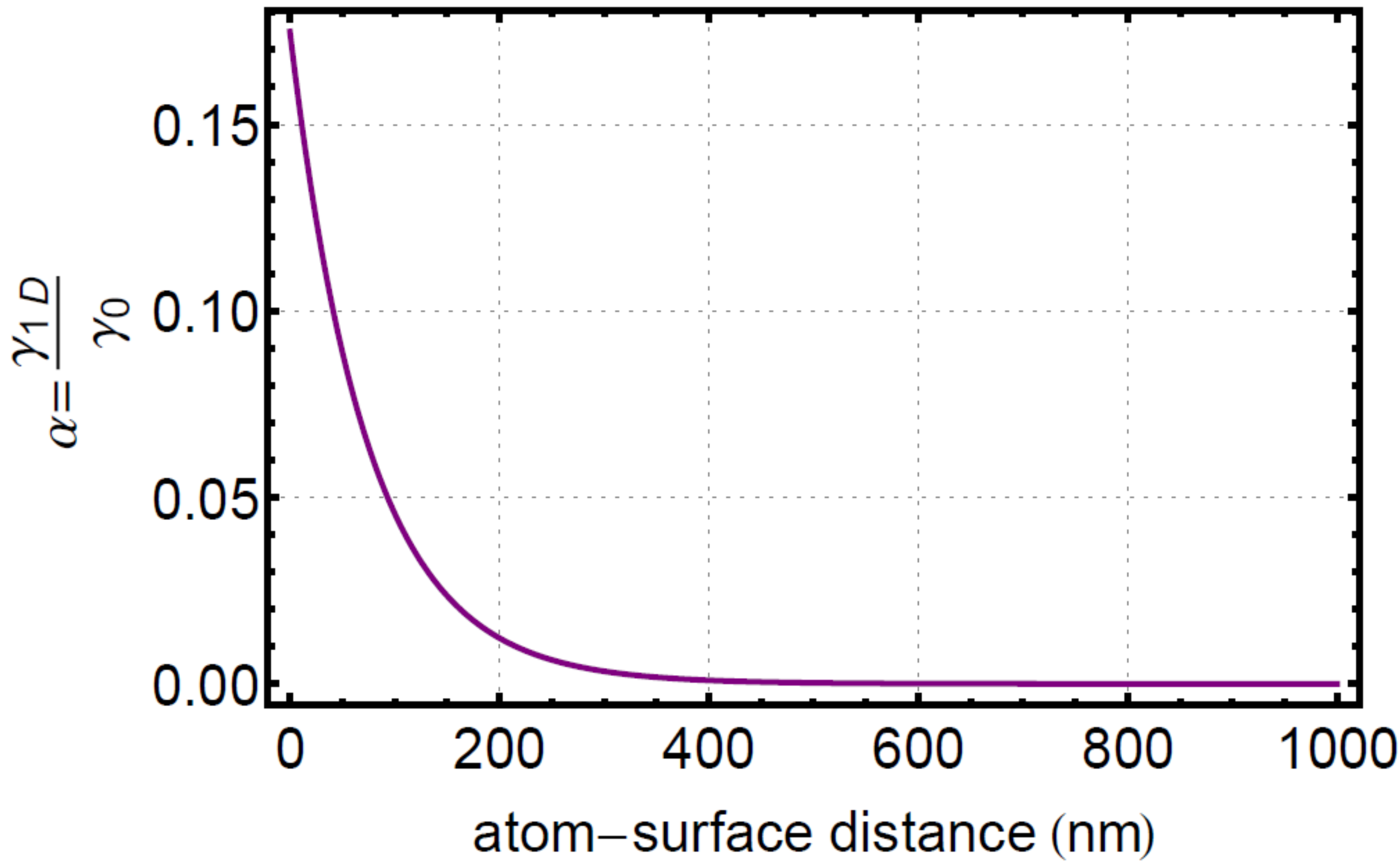
Modes density in 1D!

$$\gamma_{1D} \approx \frac{2\pi}{\hbar} \rho\left(k\right) \left\langle H_{int} \right\rangle^2$$

Proportional to the electric field of the guided mode.

$$|E|^2 = \mathcal{E}^2 \left[K_0^2(qr) + wK_1^2(qr) + fK_2^2(qr)\right]$$

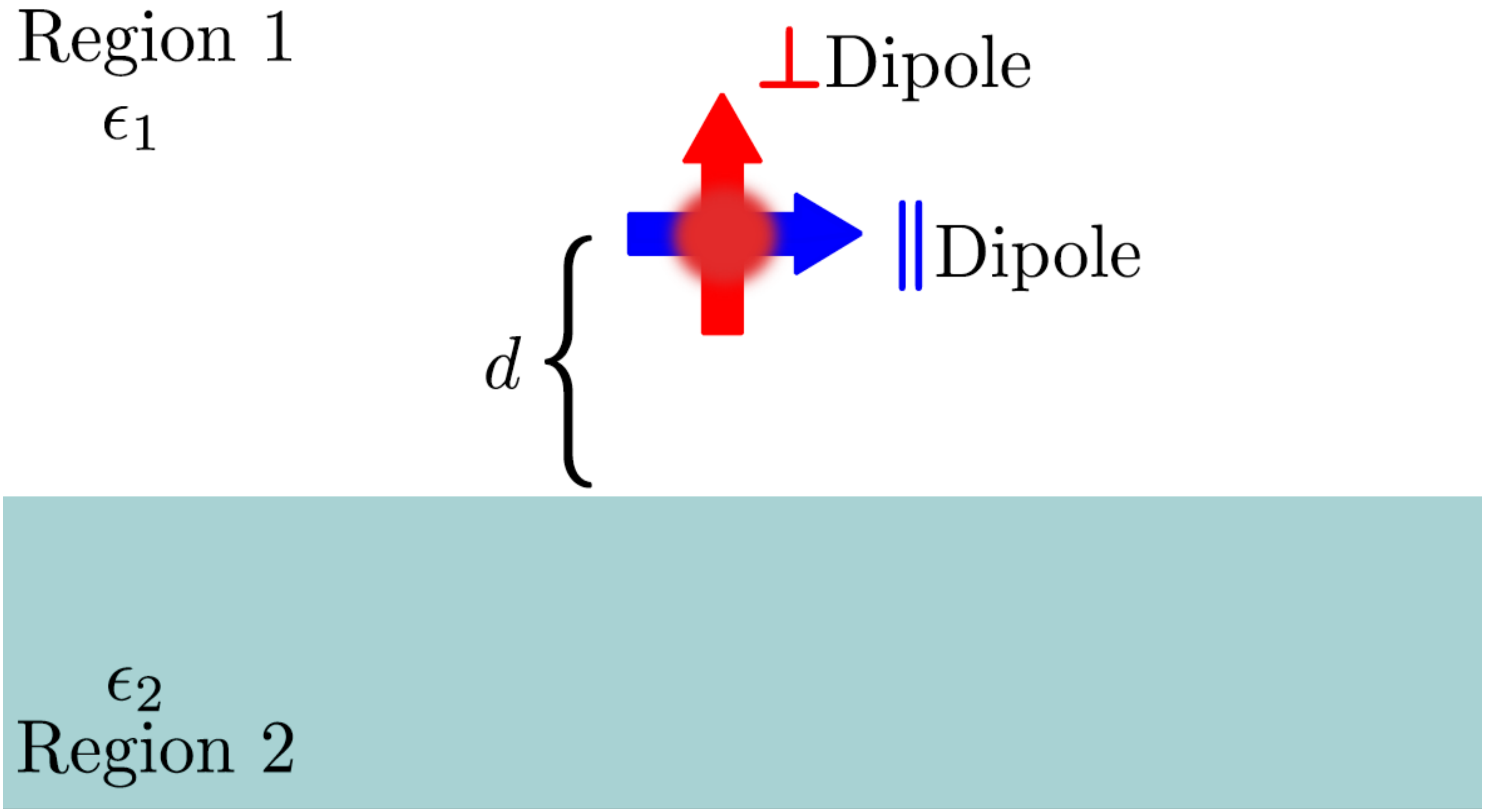
Emission enhancement parameter (coupling into the nanofiber)



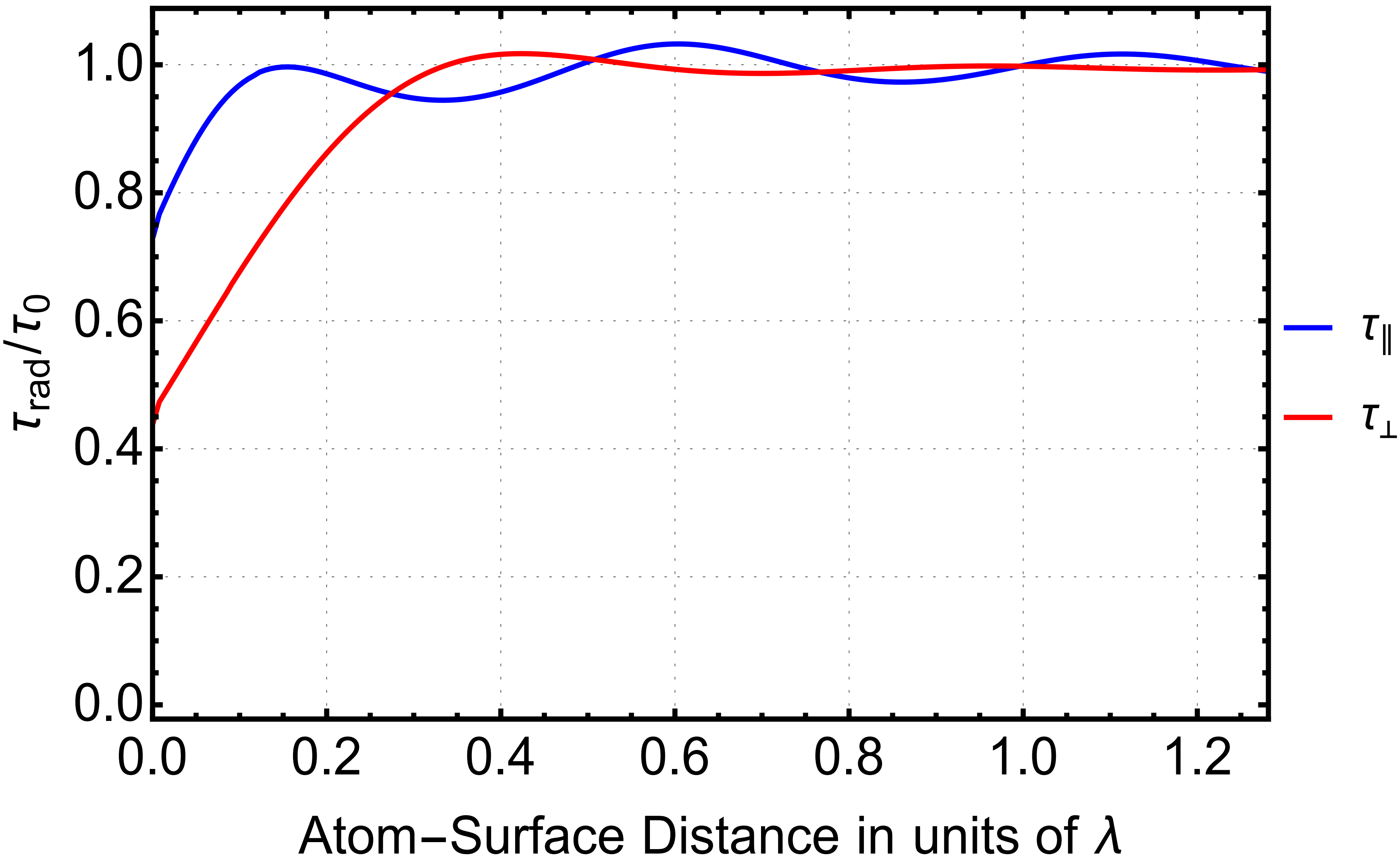
Modified decay rate

$$\frac{\gamma'(r)}{\gamma_0} = \frac{\gamma_{rad}(r) + \gamma_{1D}(r)}{\gamma_0}$$

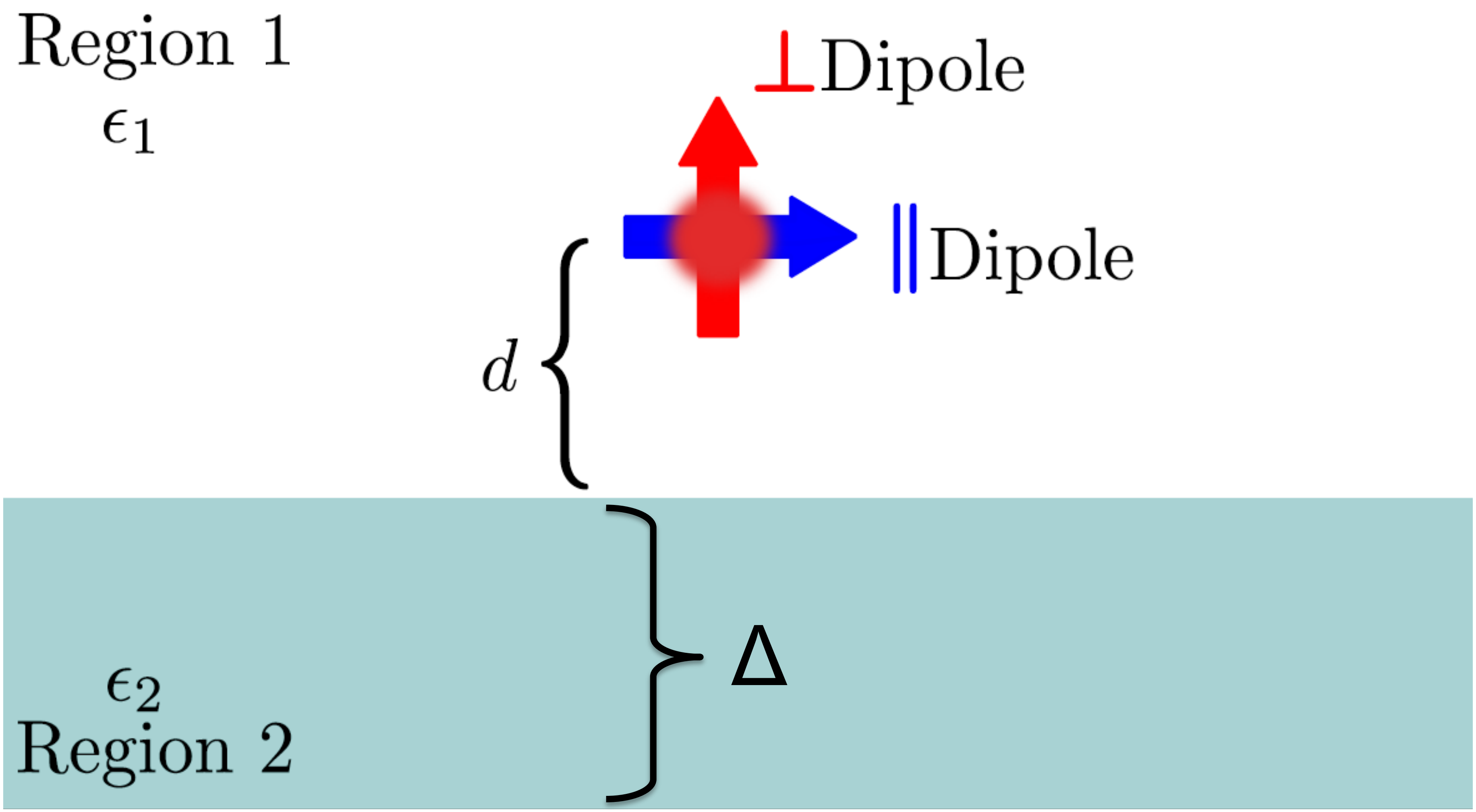
The effect of a dielectric surface (Infinite)



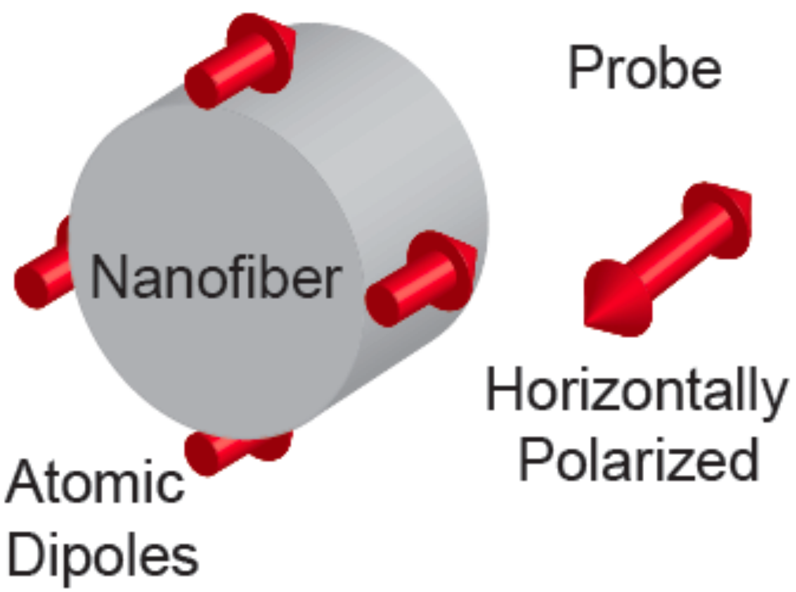
The effect of a dielectric surface

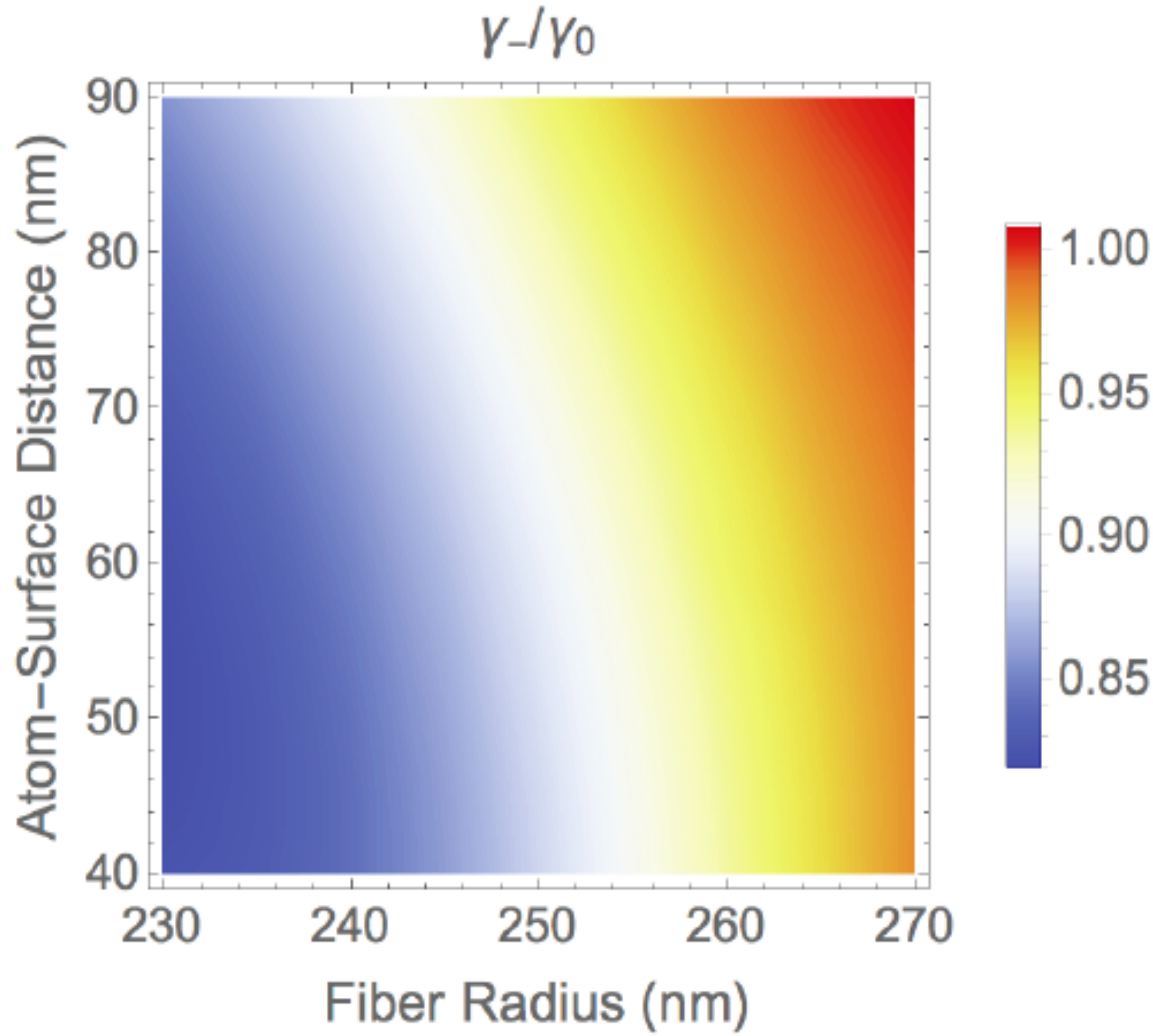


The effect of a dielectric surface (Finite)

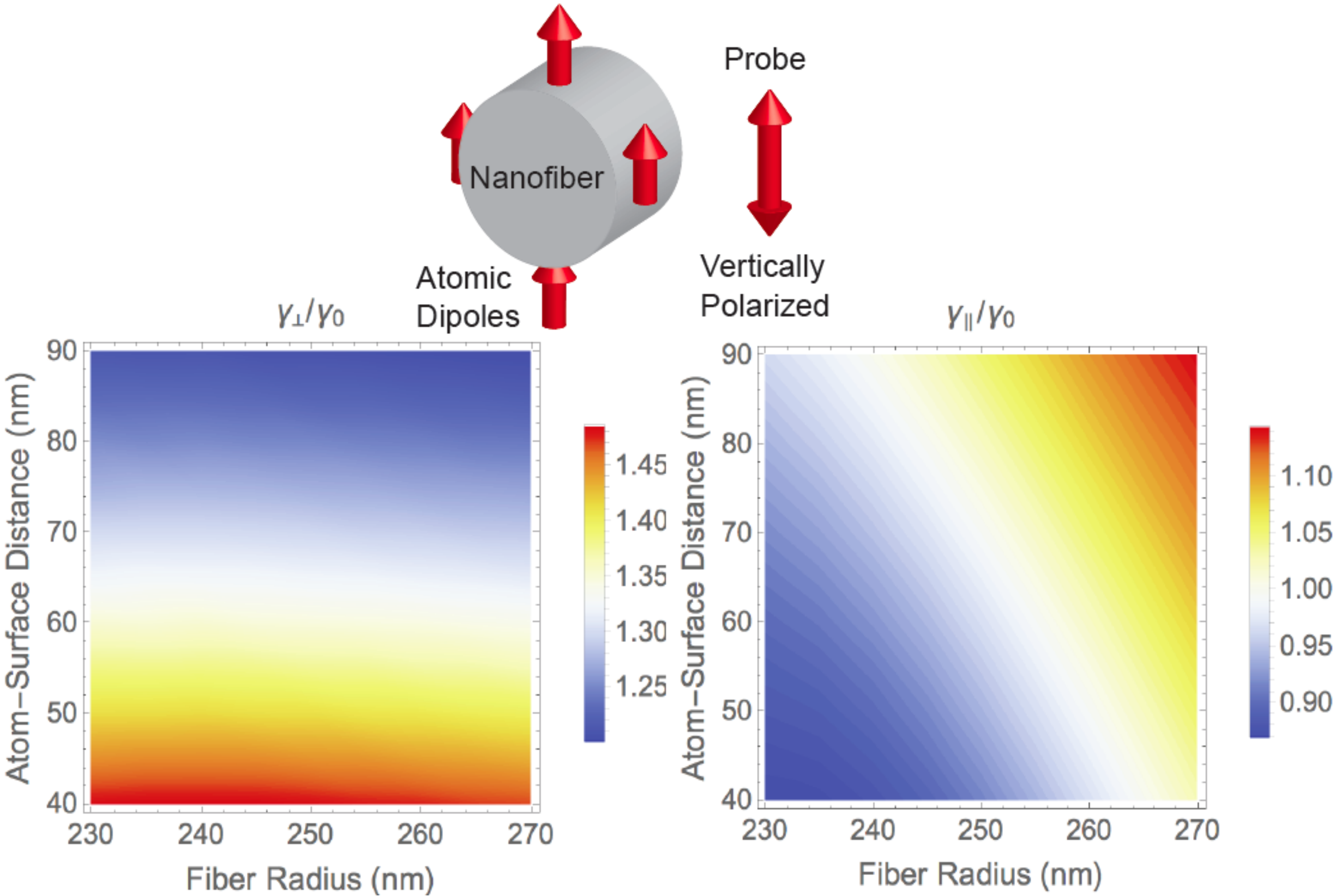


Numerical calculations

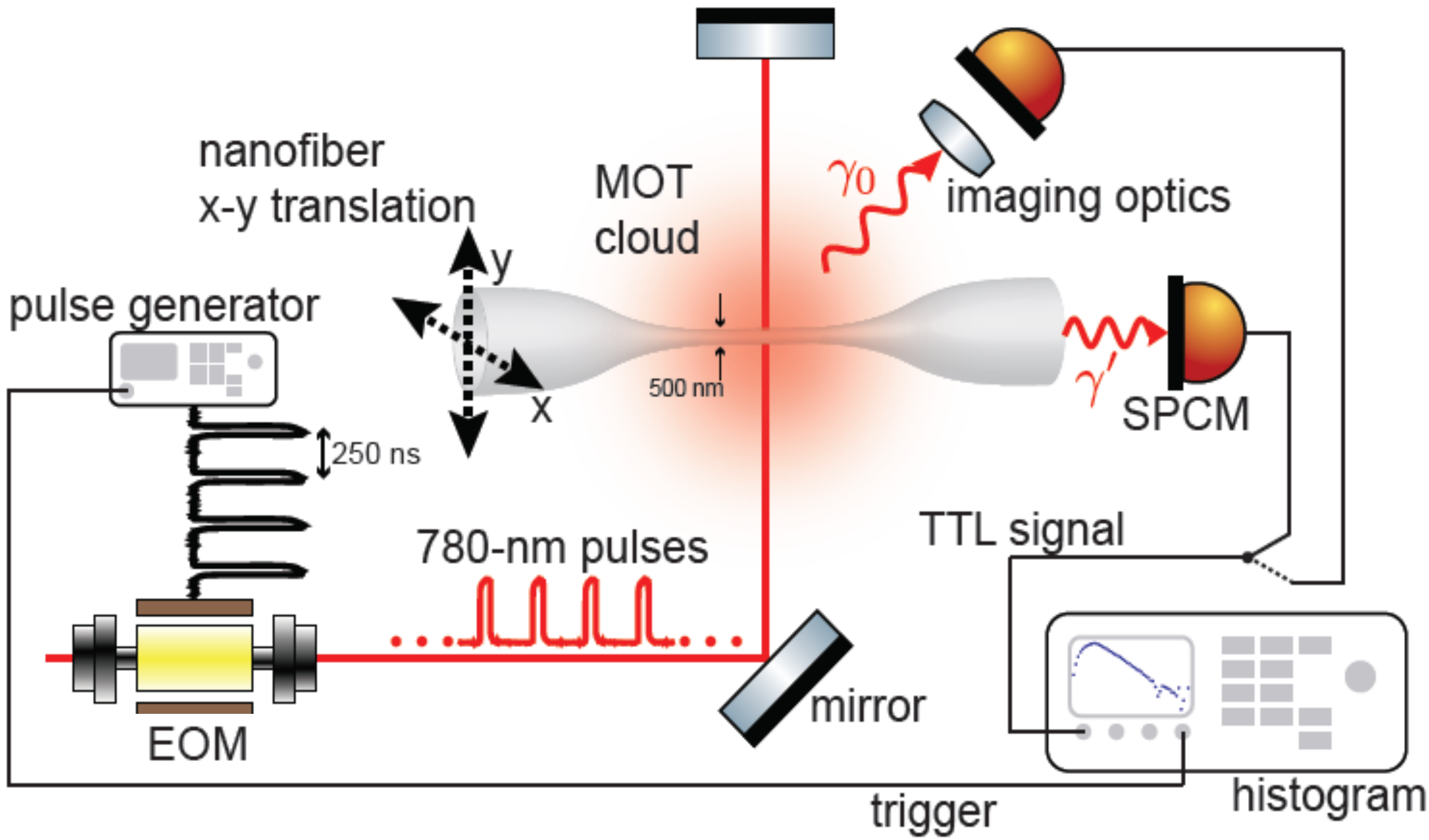




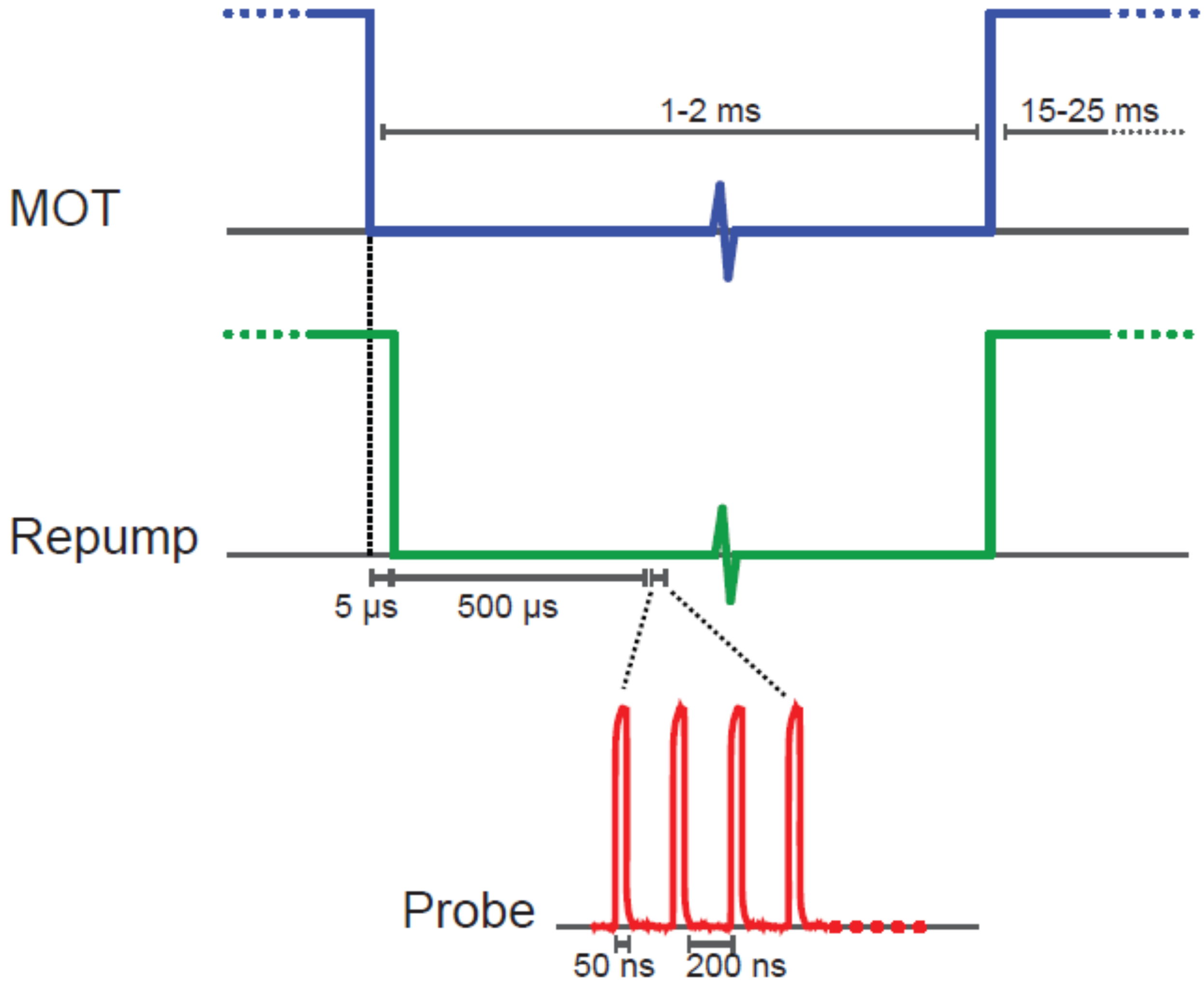
Numerical calculations



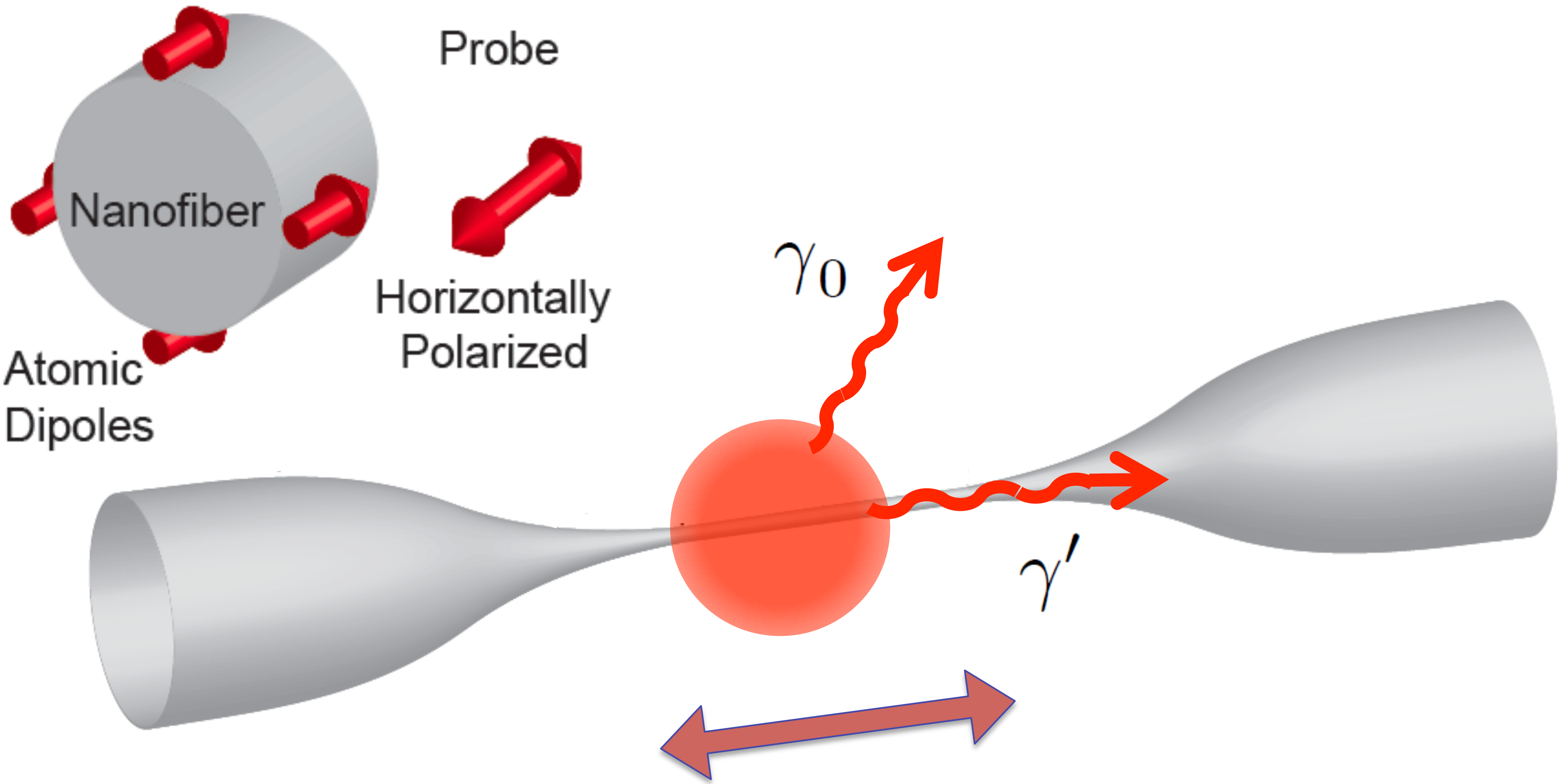
Time Correlated Single Photon Counting



The timing

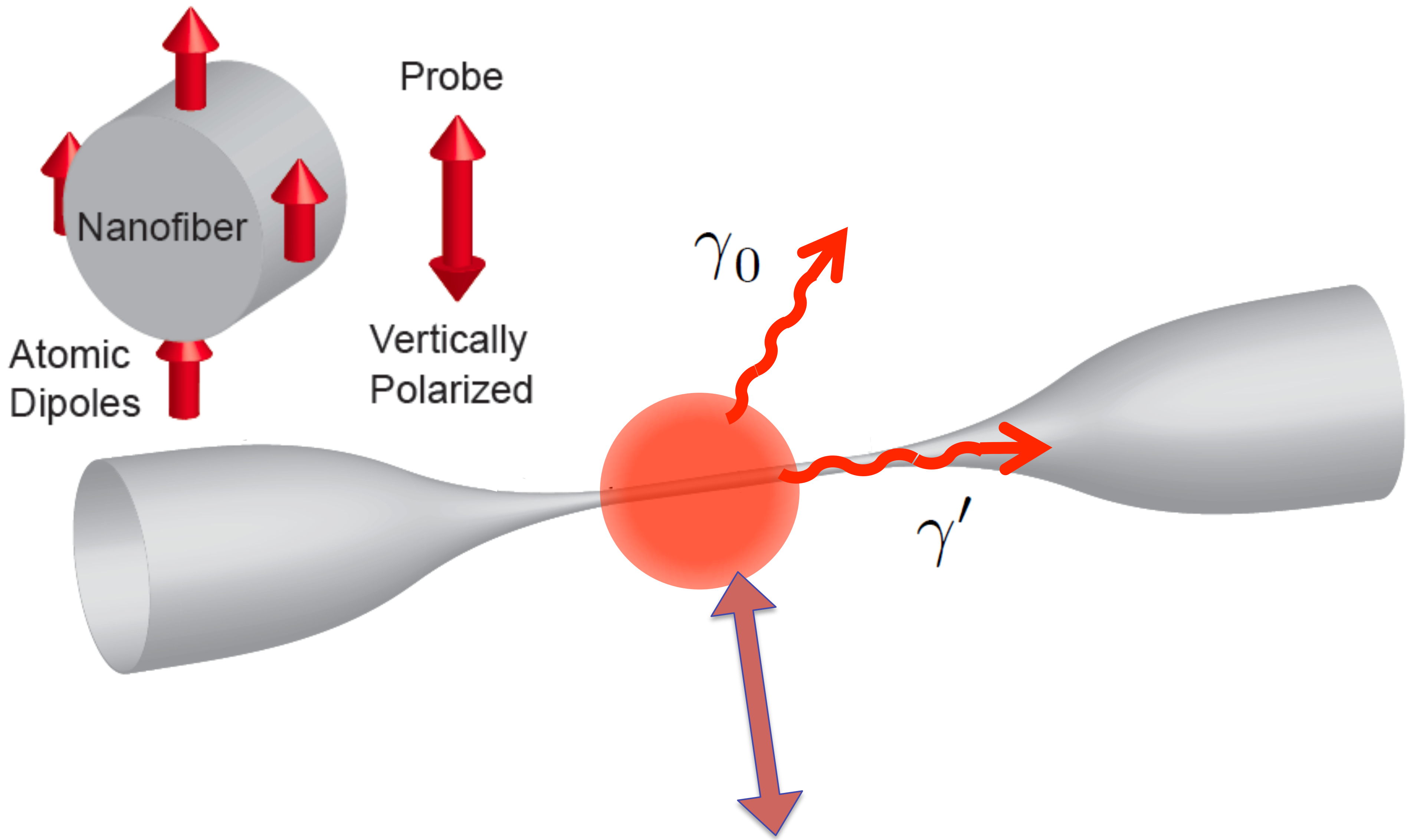


Orienting the dipoles



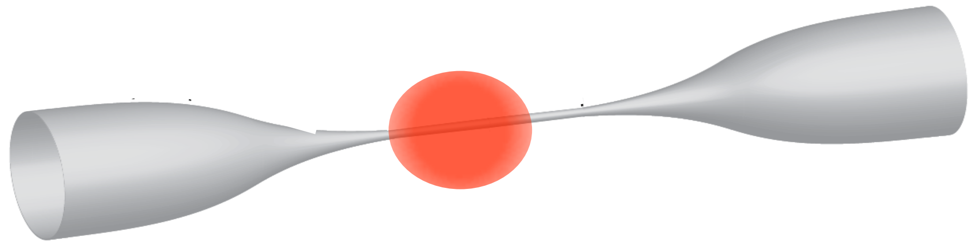
Polarization of the probe beam (H)

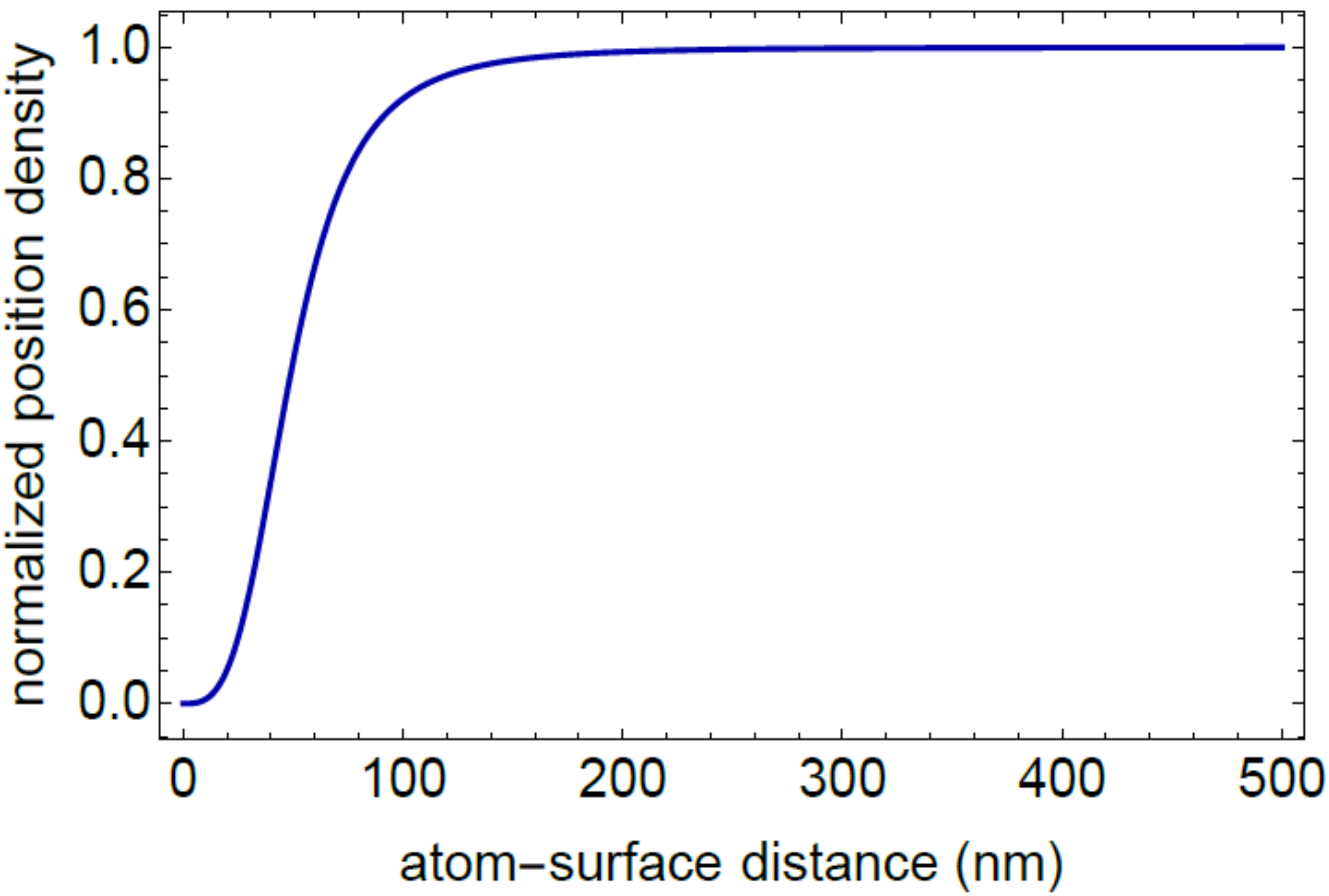
Orienting the dipoles



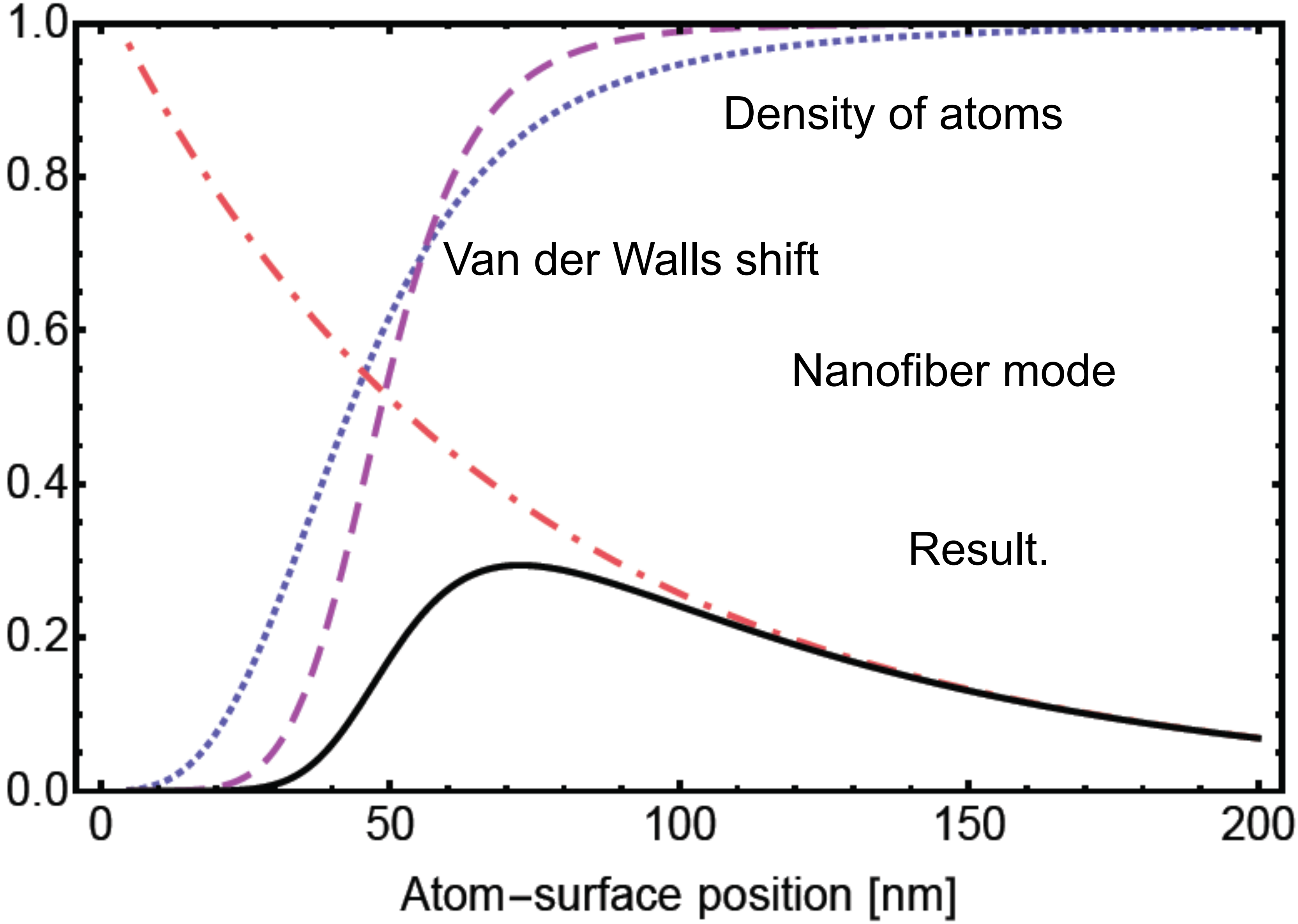
Polarization of the probe beam (V)

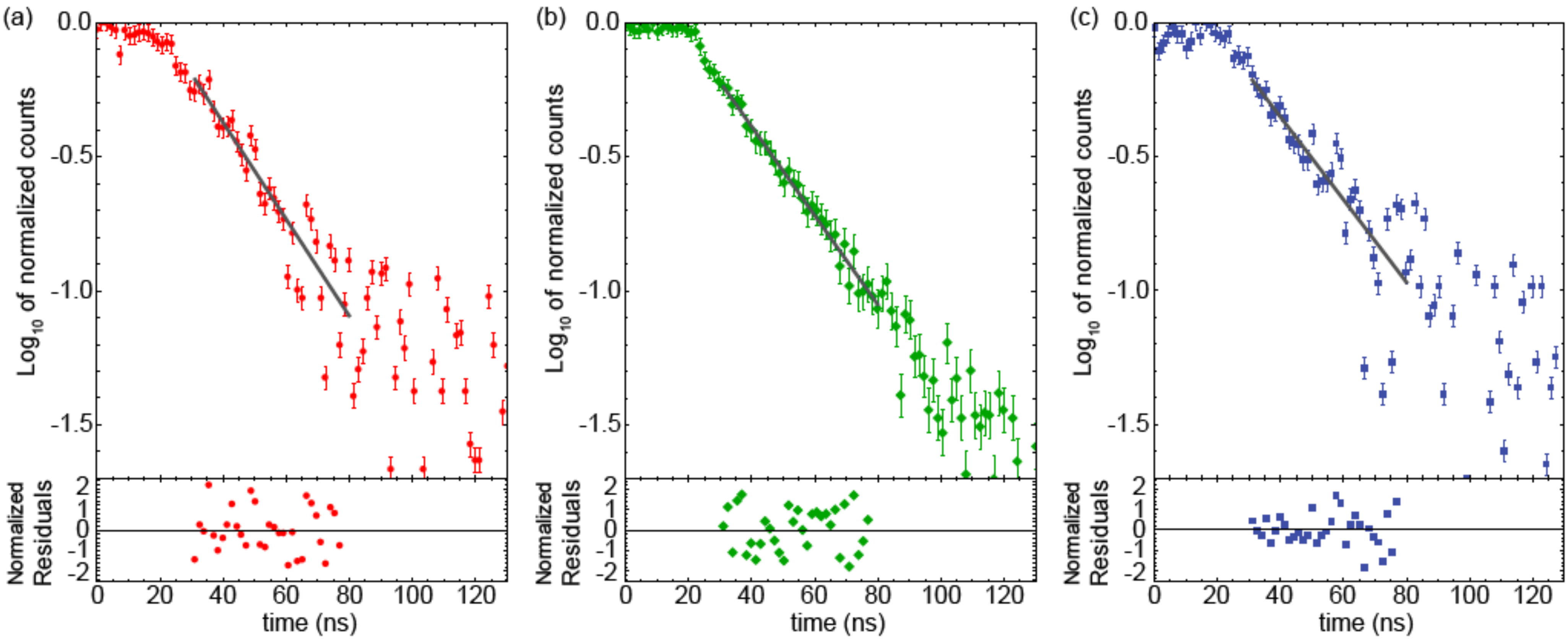
Atomic density around the nanofiber



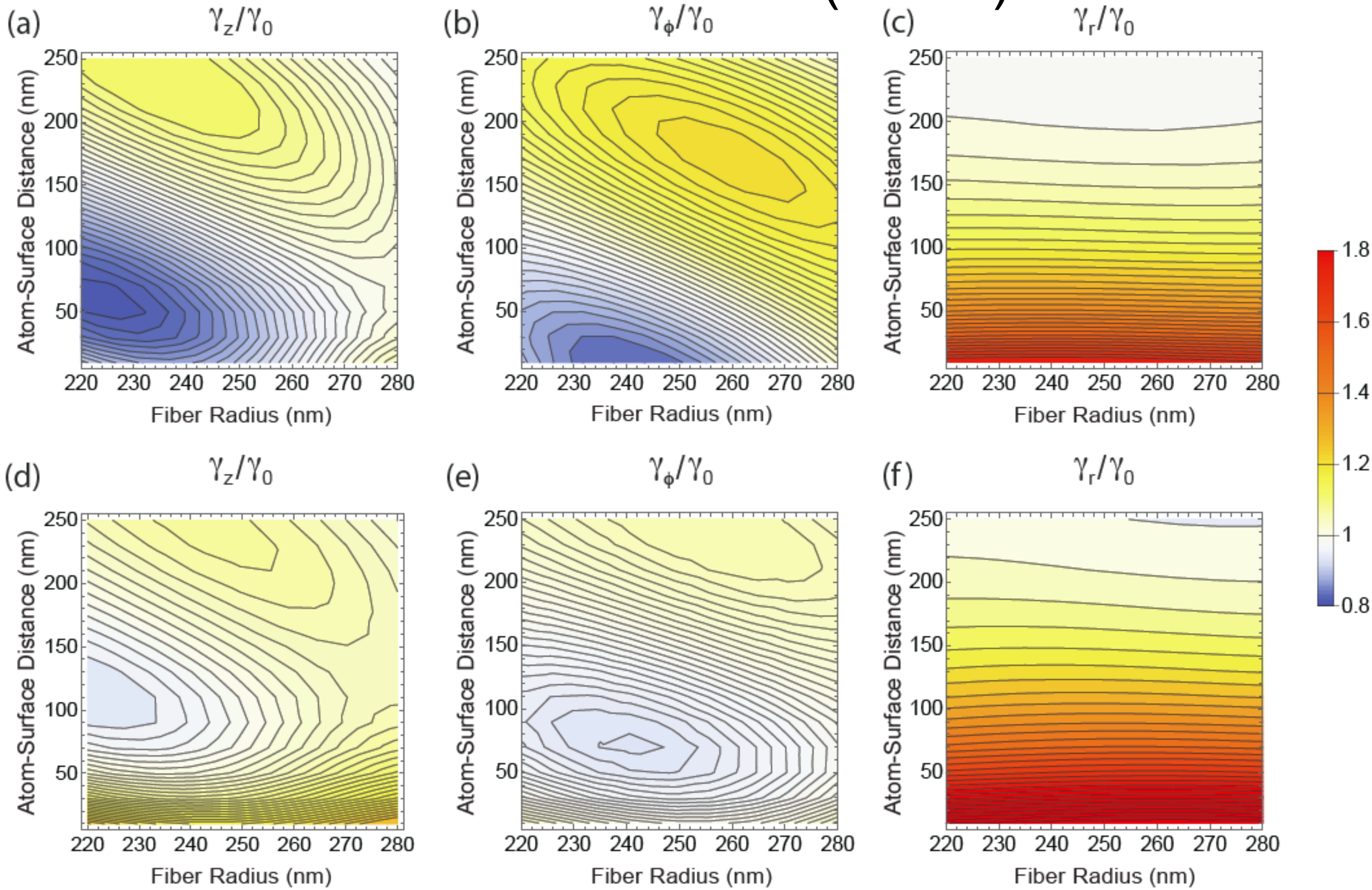


Atomic distribution that participates in the signal

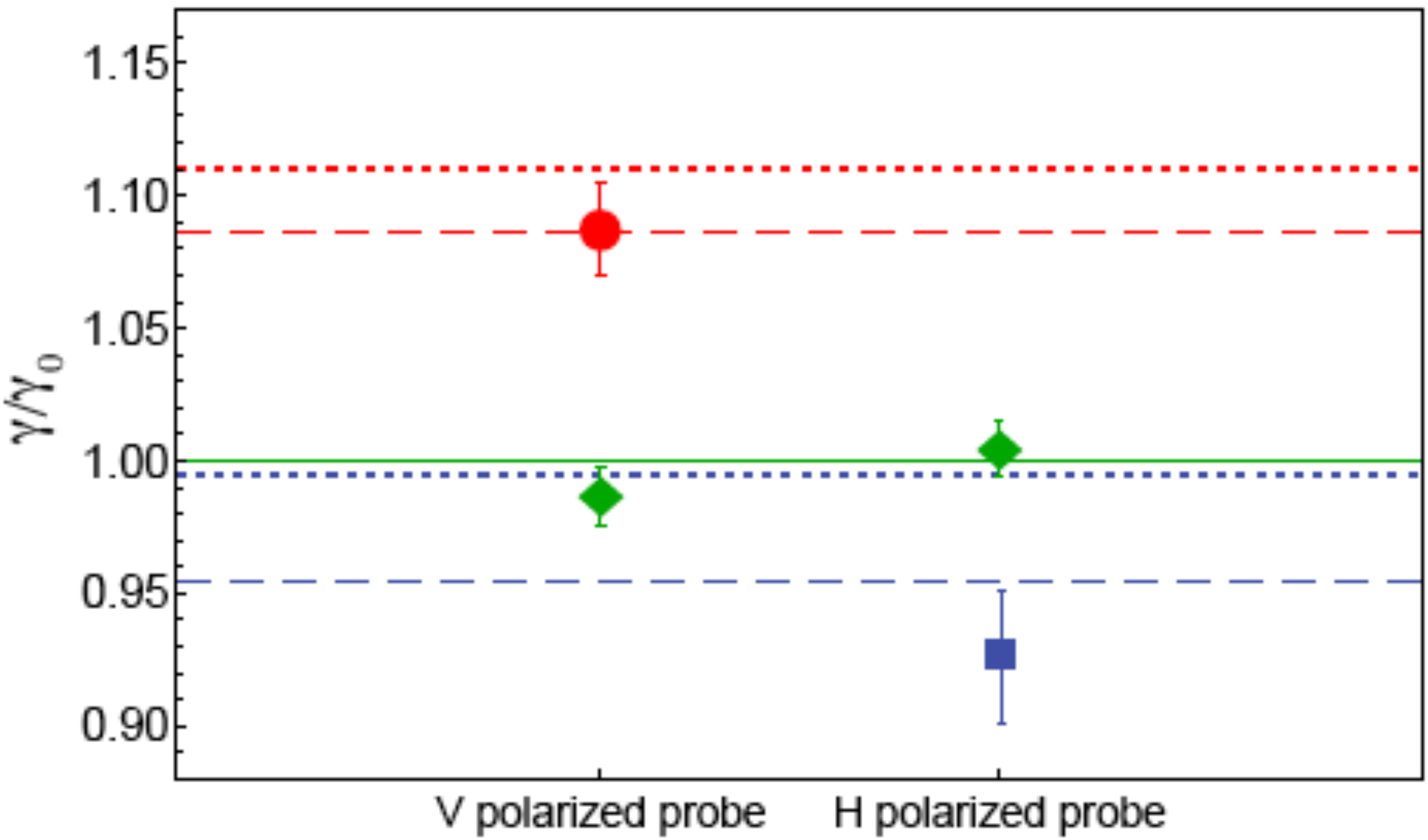



(a)
(b)
(c)
Log$_{10}$ of normalized counts
0.0
-0.5
-1.0
-1.5
Normalized Residuals
2
1
0
-1
-2
0
20
40
60
80
100
120
time (ns)

Finite-difference time-domain (FDTP) calculations



Mode calculations



1.15
1.10
1.05
1.00
0.95
0.90
γ/γ_0
V polarized probe
H polarized probe

Thanks