Optical Nanofibers, a platform for quantum optics

Institute of Physics ,
CAS, Beijing, China
OSA Student Chapter
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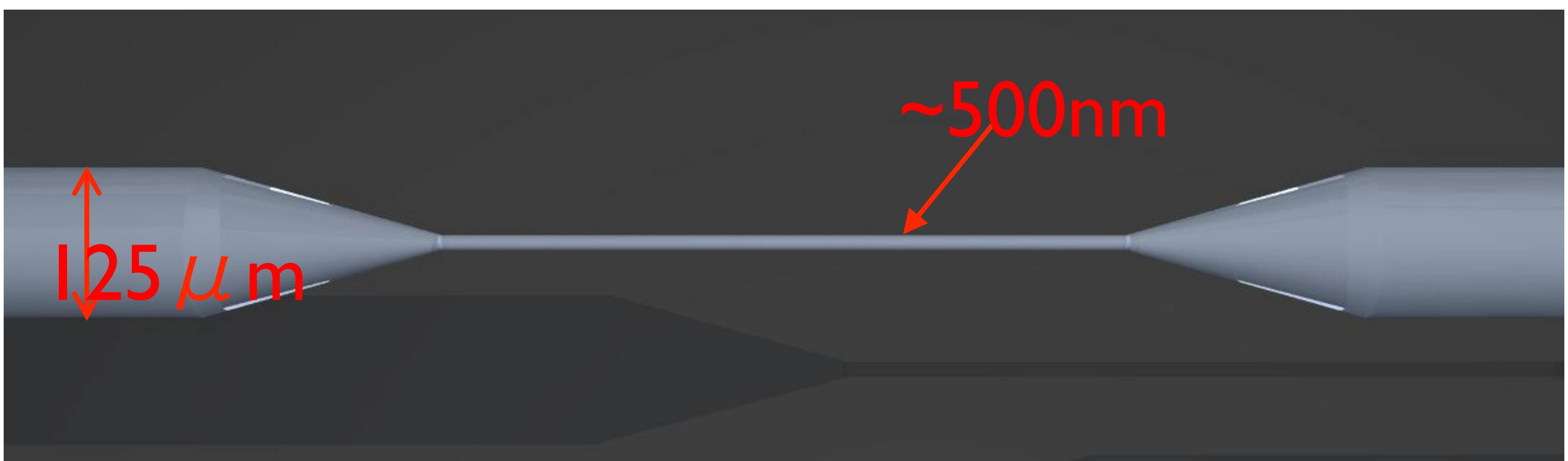
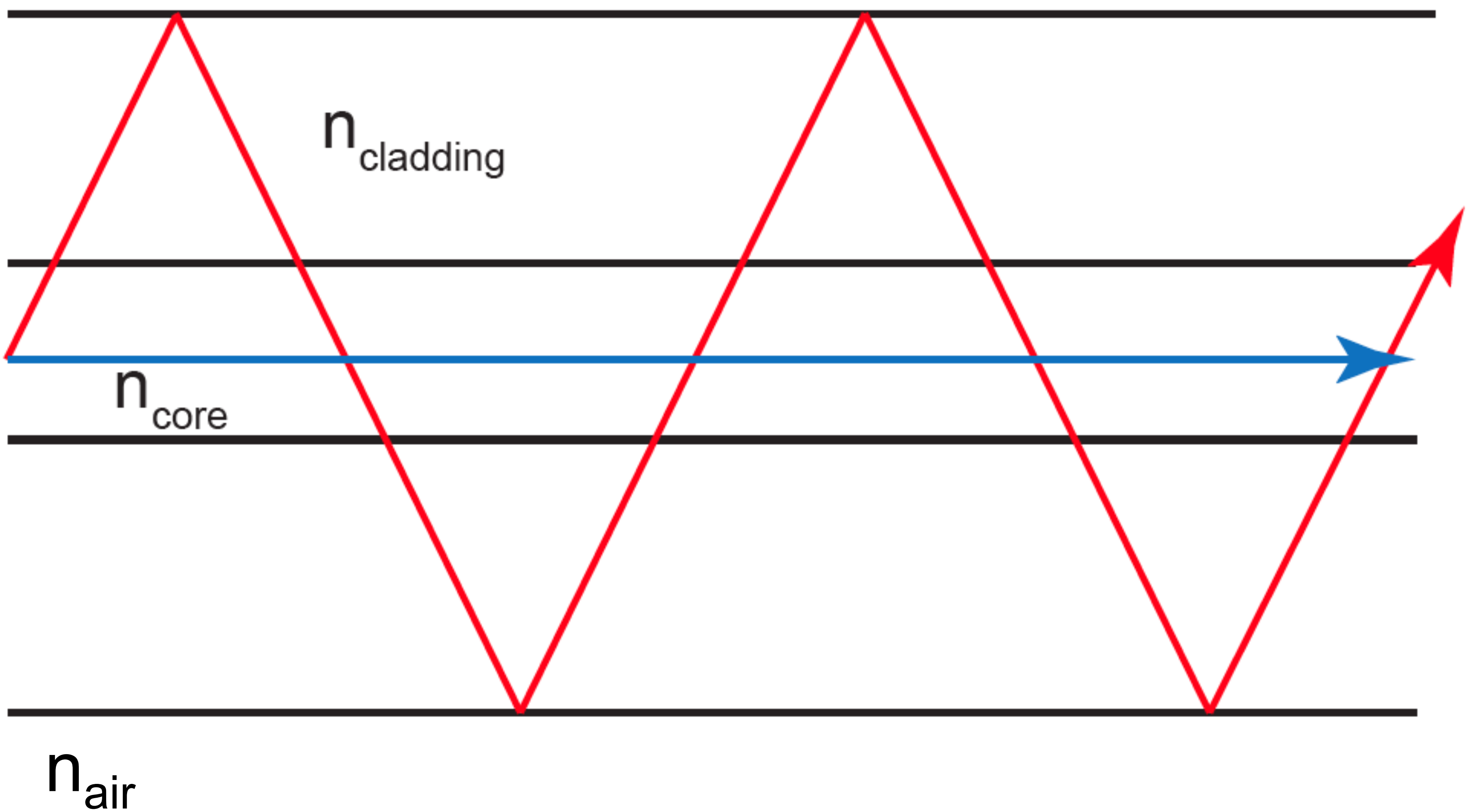
Tapered optical fibers

Waveguide (photonic circuit) for light

Optical interface for atoms
(strong coupling light/atoms)



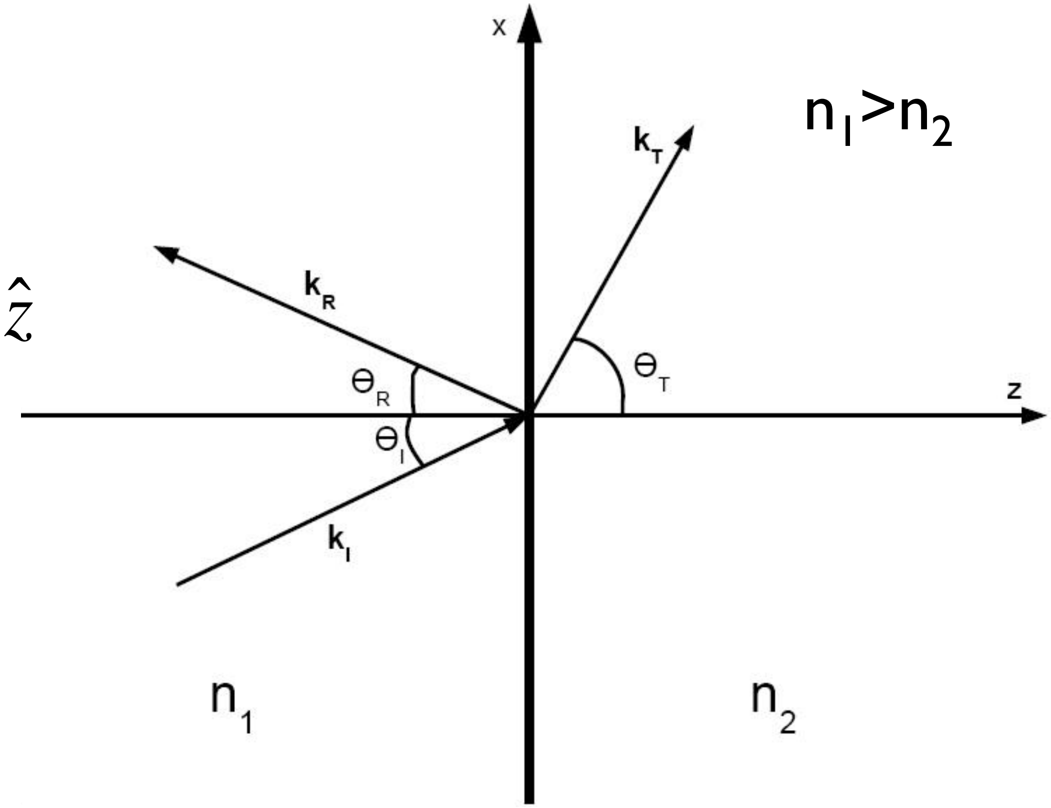
Light rays in a fiber with total internal reflection



$n_{core} > n_{cladding}$

$n_{cladding} > n_{air}$

Evanescent waves:



$$\mathbf{k_T} = k_T \mathrm{sen}(\theta_T)\hat{x} + k_T \cos(\theta_T)\hat{z}$$

$$\mathrm{sen}(\theta_T) = \frac{n_1}{n_2}\mathrm{sen}(\theta_I) > 1$$

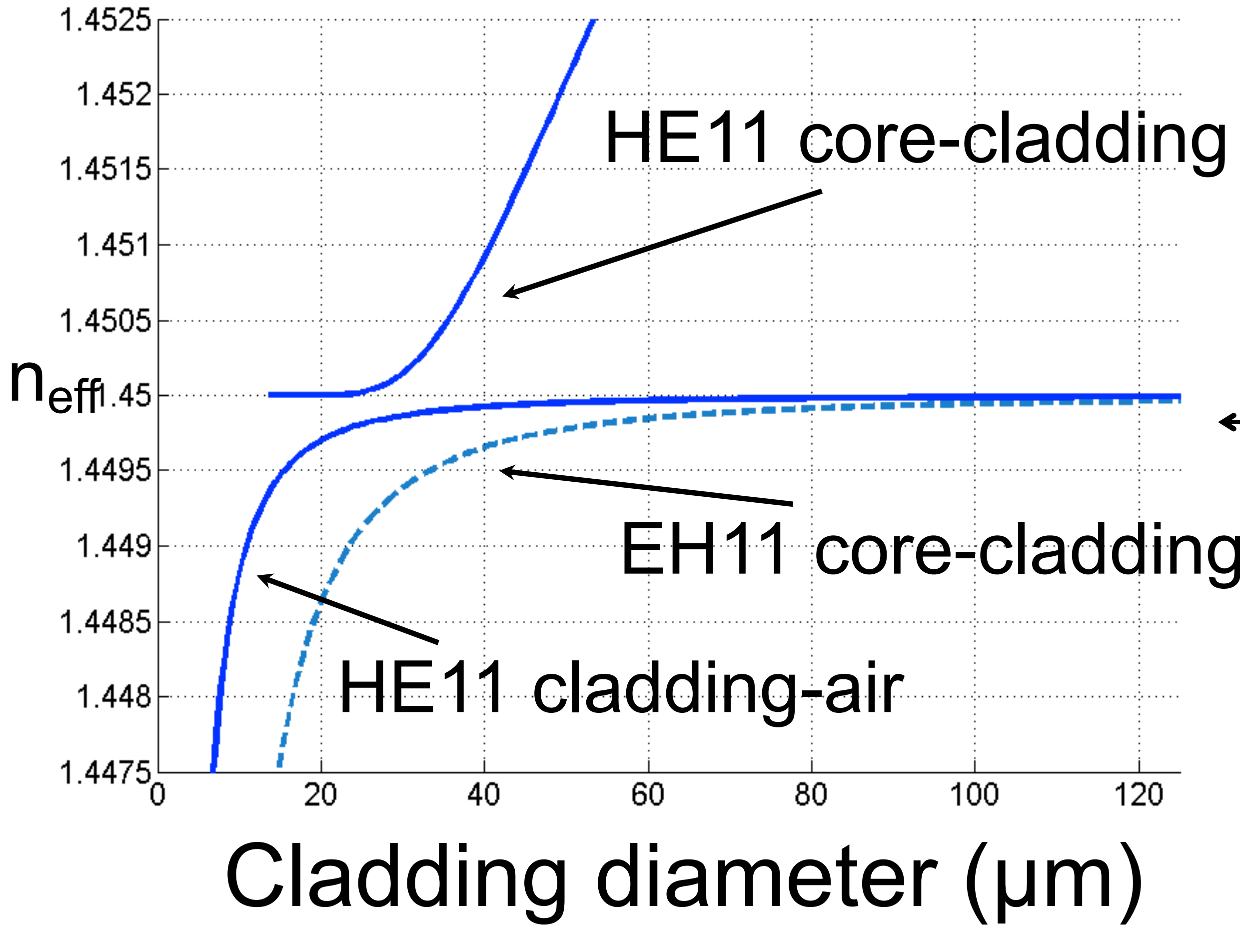
$$\cos(\theta_T) = \sqrt{1 - \mathrm{sen}^2(\theta_T)} = i\sqrt{\mathrm{sen}^2(\theta_T) - 1}$$

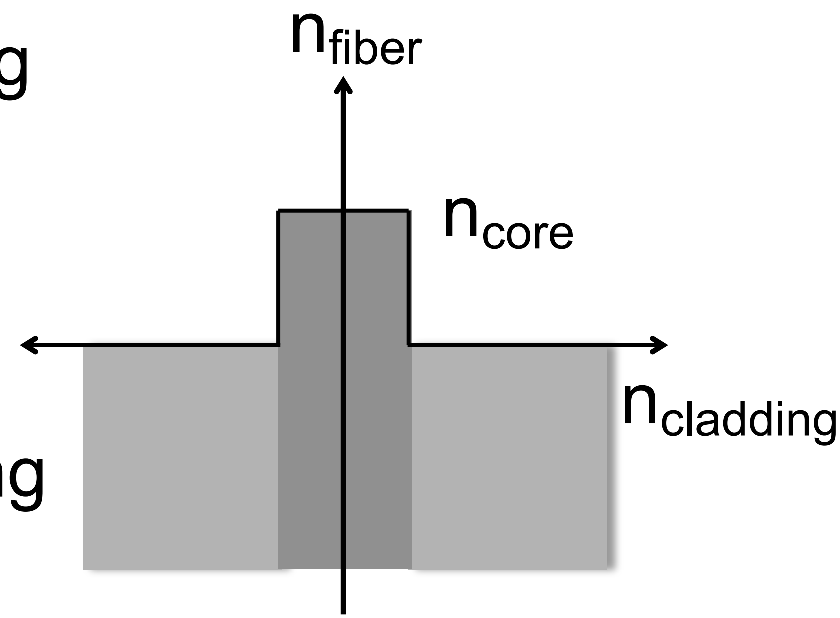
$$\mathbf{E_T} = \mathbf{E_0}\,\mathrm{e}^{i(\mathbf{k_T}\bullet\mathbf{r} - \omega t)}$$

$$\mathbf{E_T} = \mathbf{E_0}\mathrm{e}^{-\kappa z}\mathrm{e}^{i(kx - \omega t)}$$

$$\kappa = \frac{1}{\lambda/2\pi}\sqrt{\left(n_1 \mathrm{sen}(\theta_I)\right)^2 - n_2^2}, \quad k = \frac{n_1}{\lambda/2\pi}\mathrm{sen}(\theta_I)$$

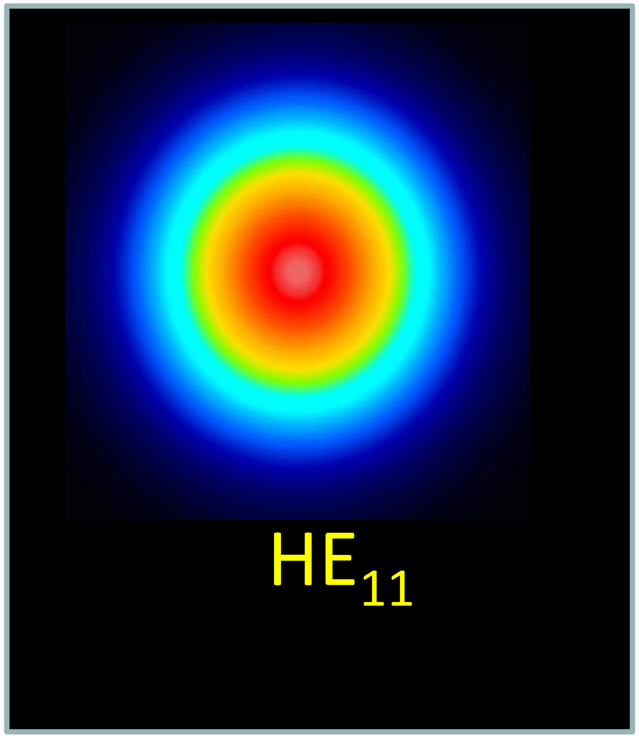
Two-Layer fiber surrounded by air

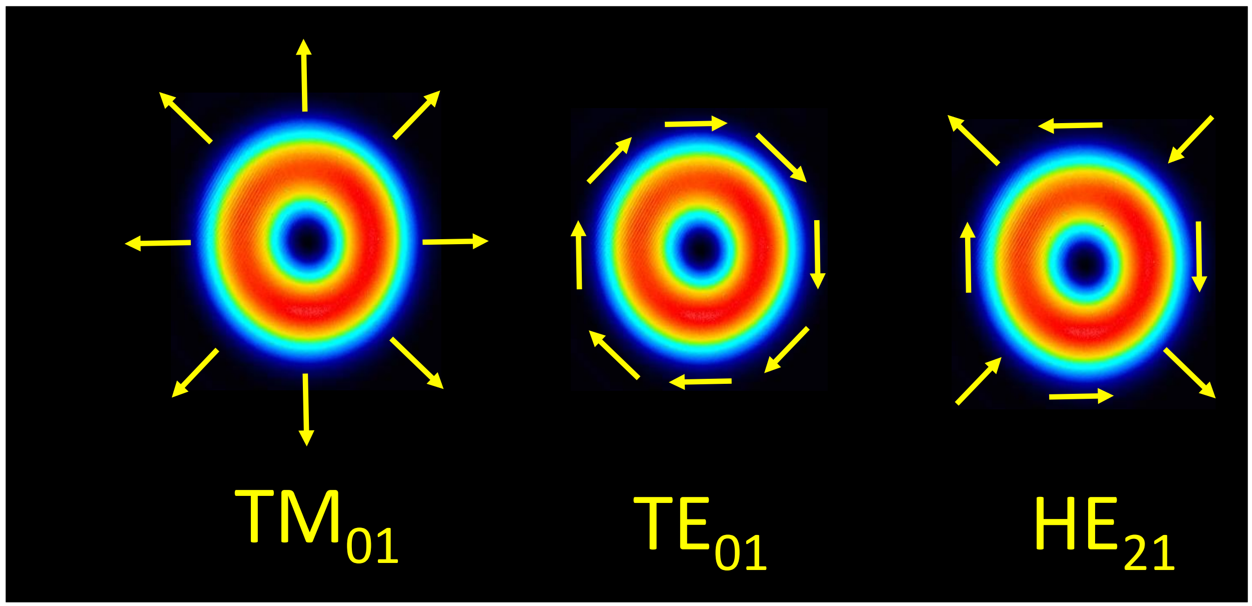




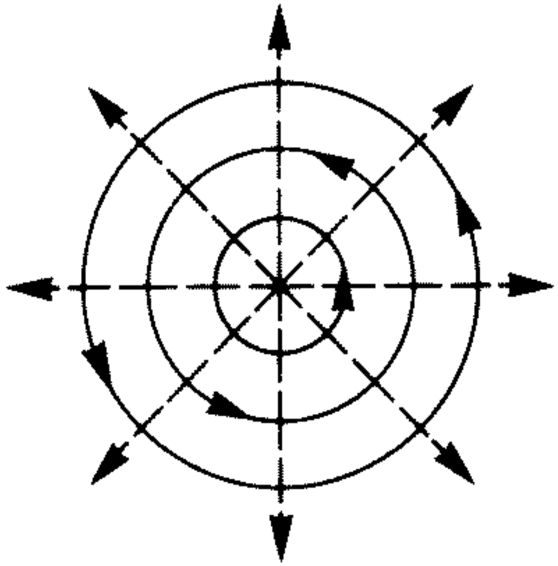
- $\beta = k^* n_{eff}$, propagation constant of a fiber mode

Lowest order fiber modes
Intensities

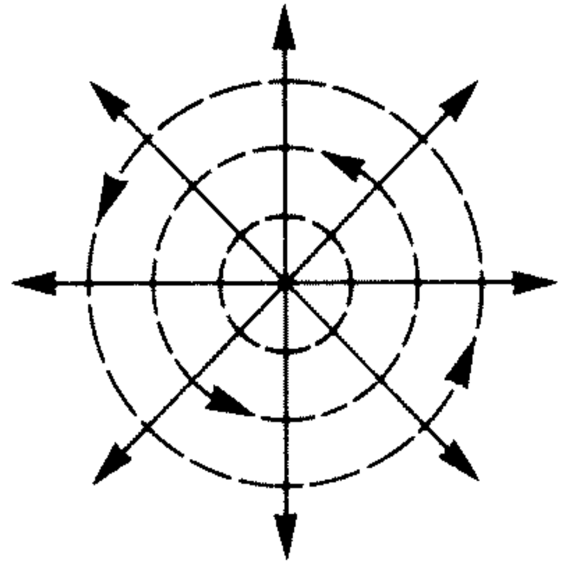




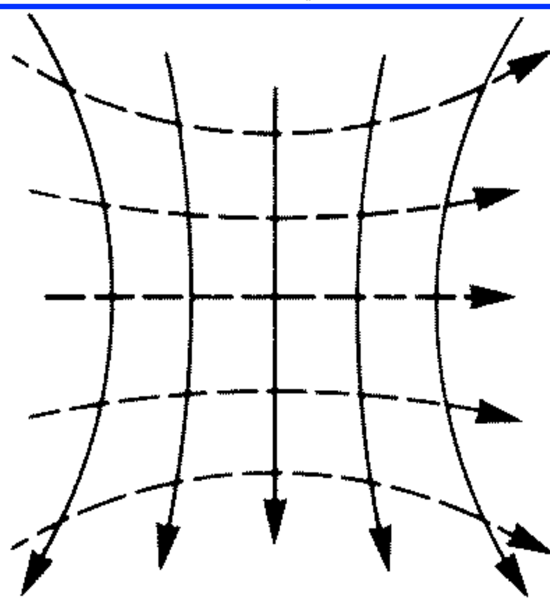
Polarization of the lowest order modes



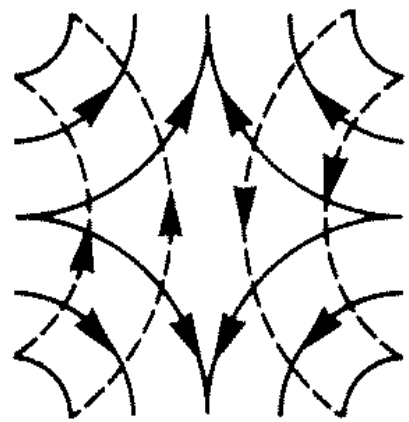
TE_{01}



TM_{01}

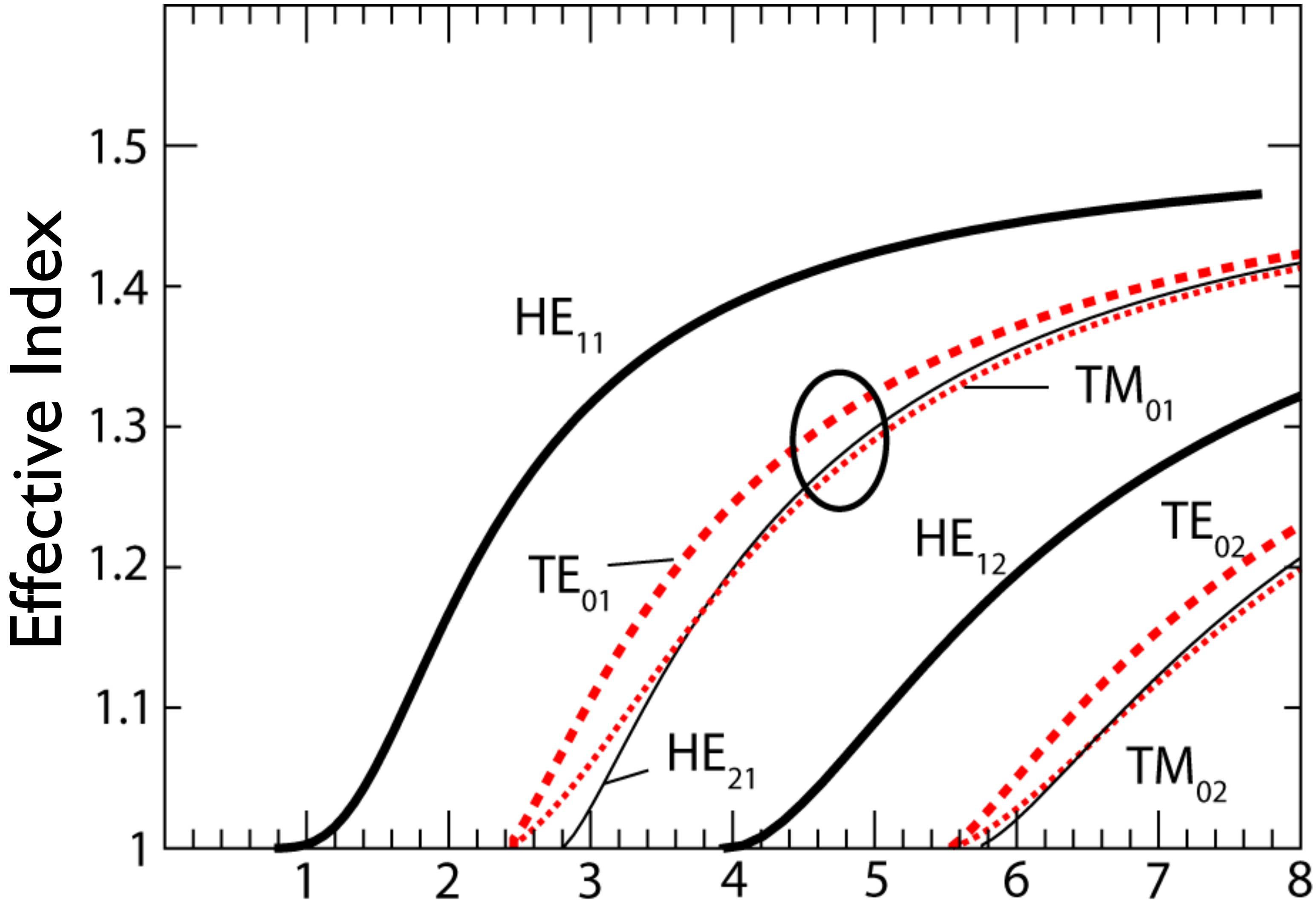


HE_{11}

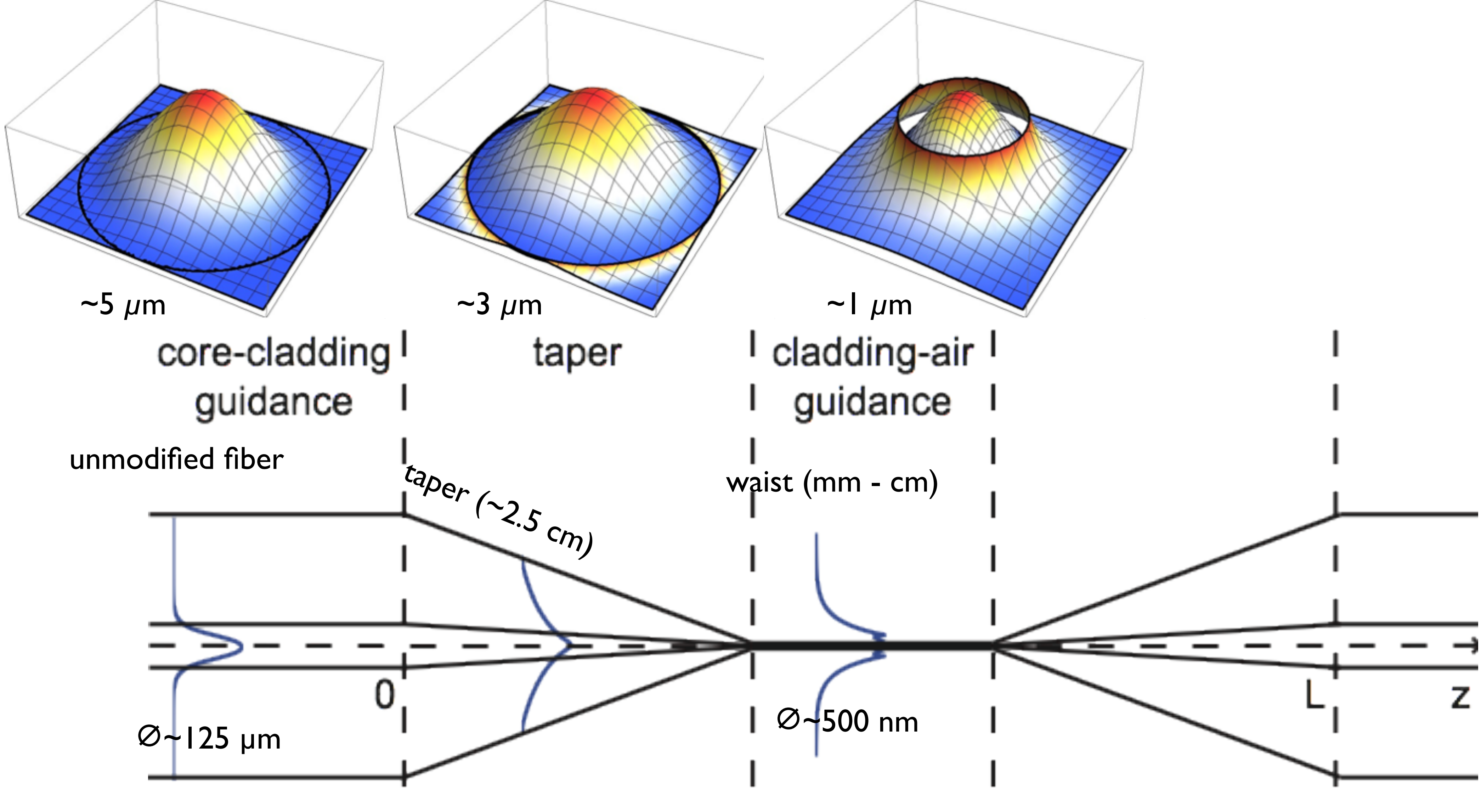


HE_{21}

Higher order fiber modes



$$V = \frac{2\pi R}{\lambda}\sqrt{n_1^2 - n_2^2}$$



Evanescent field in the nanofiber.
The wave decays in a length of $\lambda/2\pi$.
The nanofiber guides the mode and there is no radiation nor diffraction.
Very different from a focused beam.

Very large radial gradients of E

- Div E=0 implies large longitudinal components.

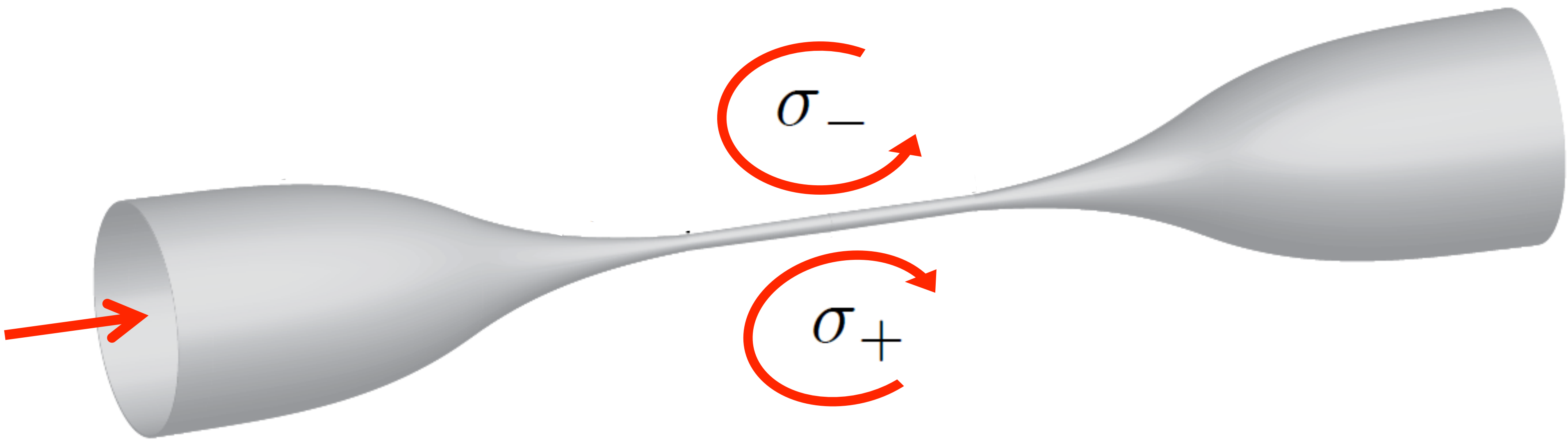
$$\frac{\partial E_r}{\partial r} + \frac{\partial E_z}{\partial z} = 0$$

- The evanescent field can have a longitudinal component of the polarization! No transverse fields!

Polarization at the fiber waist

$$\nabla \cdot \vec{E} = 0$$

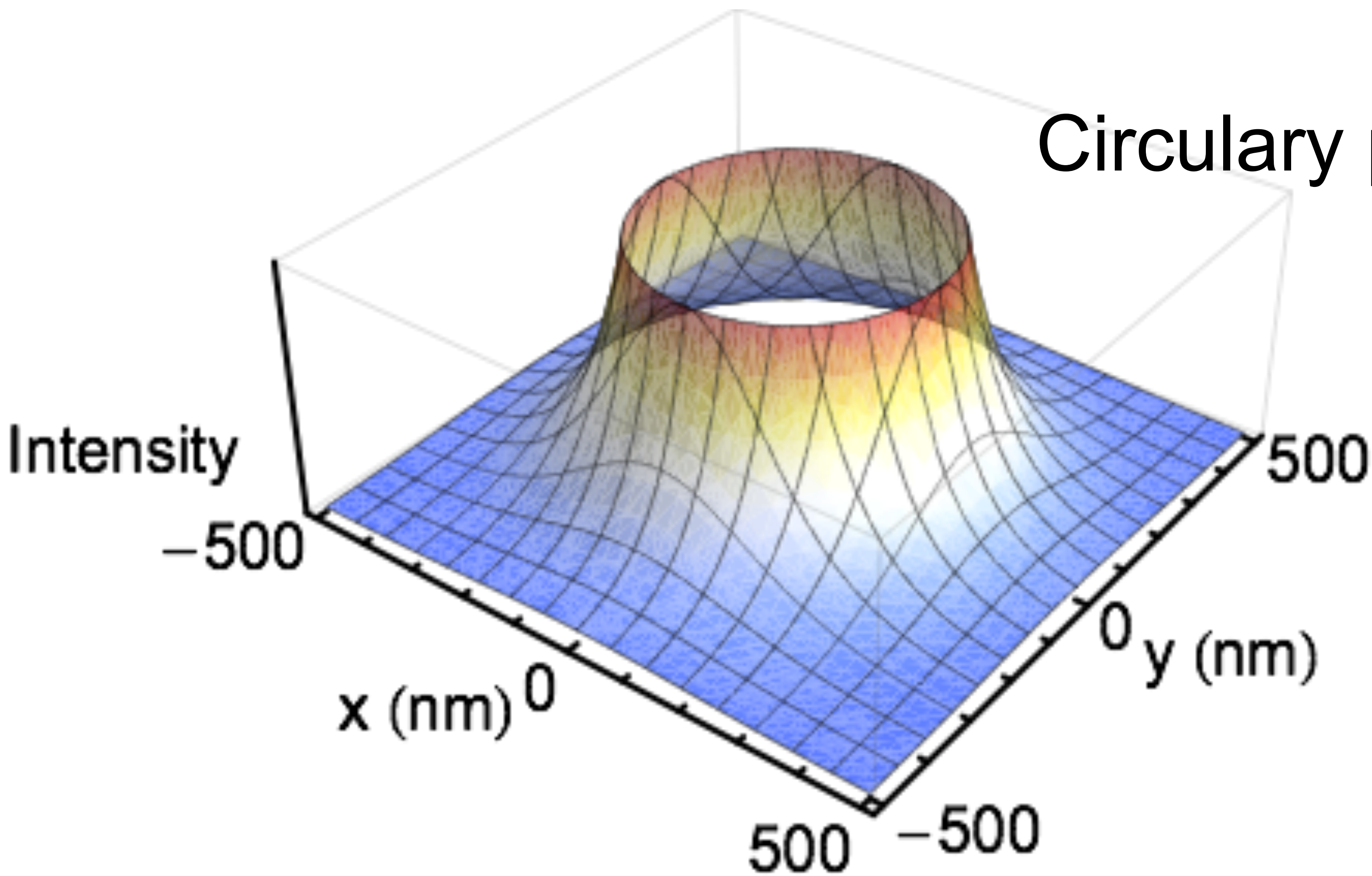
$$\nabla_T \cdot \vec{E} + \frac{2\pi}{\lambda} i E_Z = 0$$



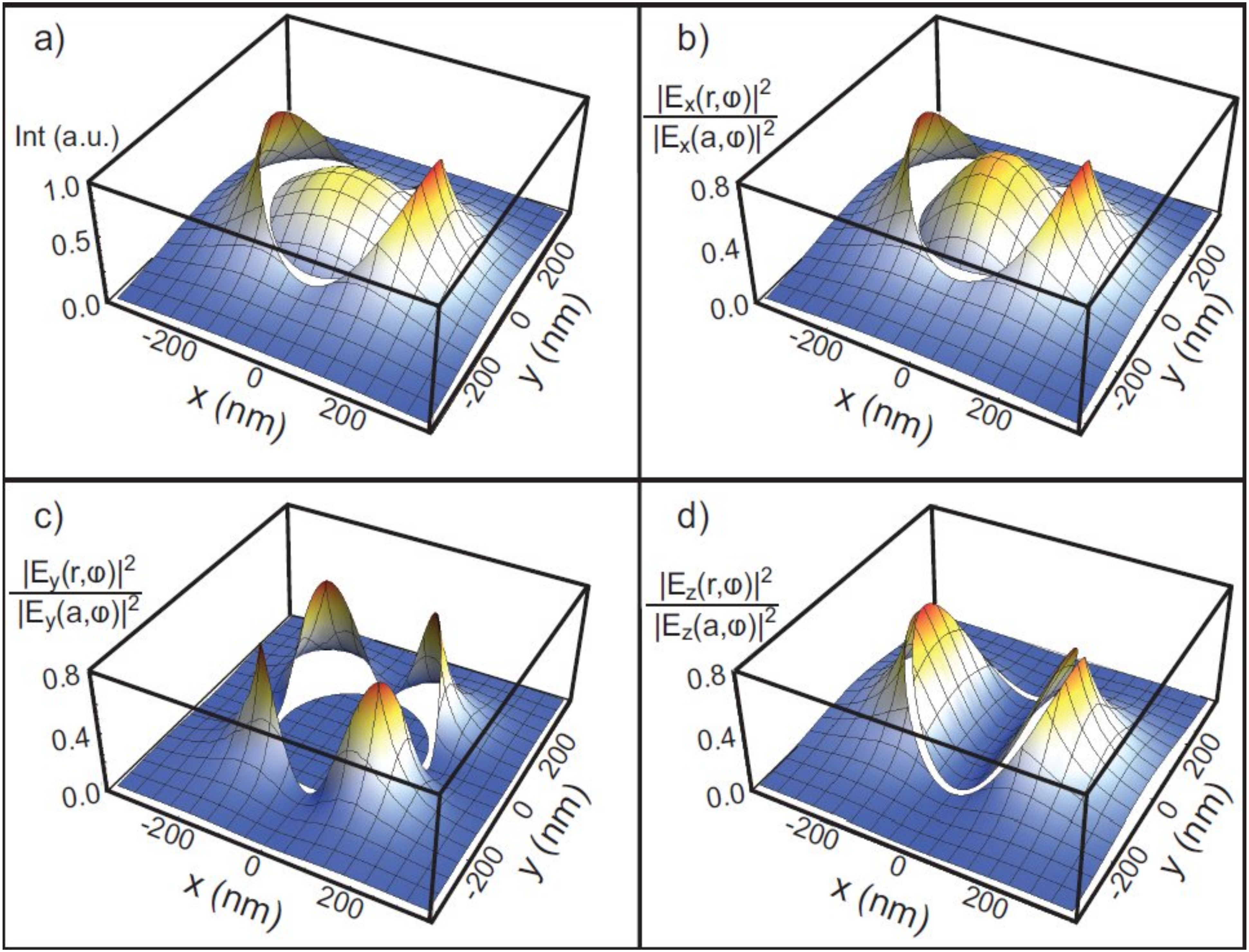
Rotates like a bicycle

Nanofiber mode structure

Circulary polarized



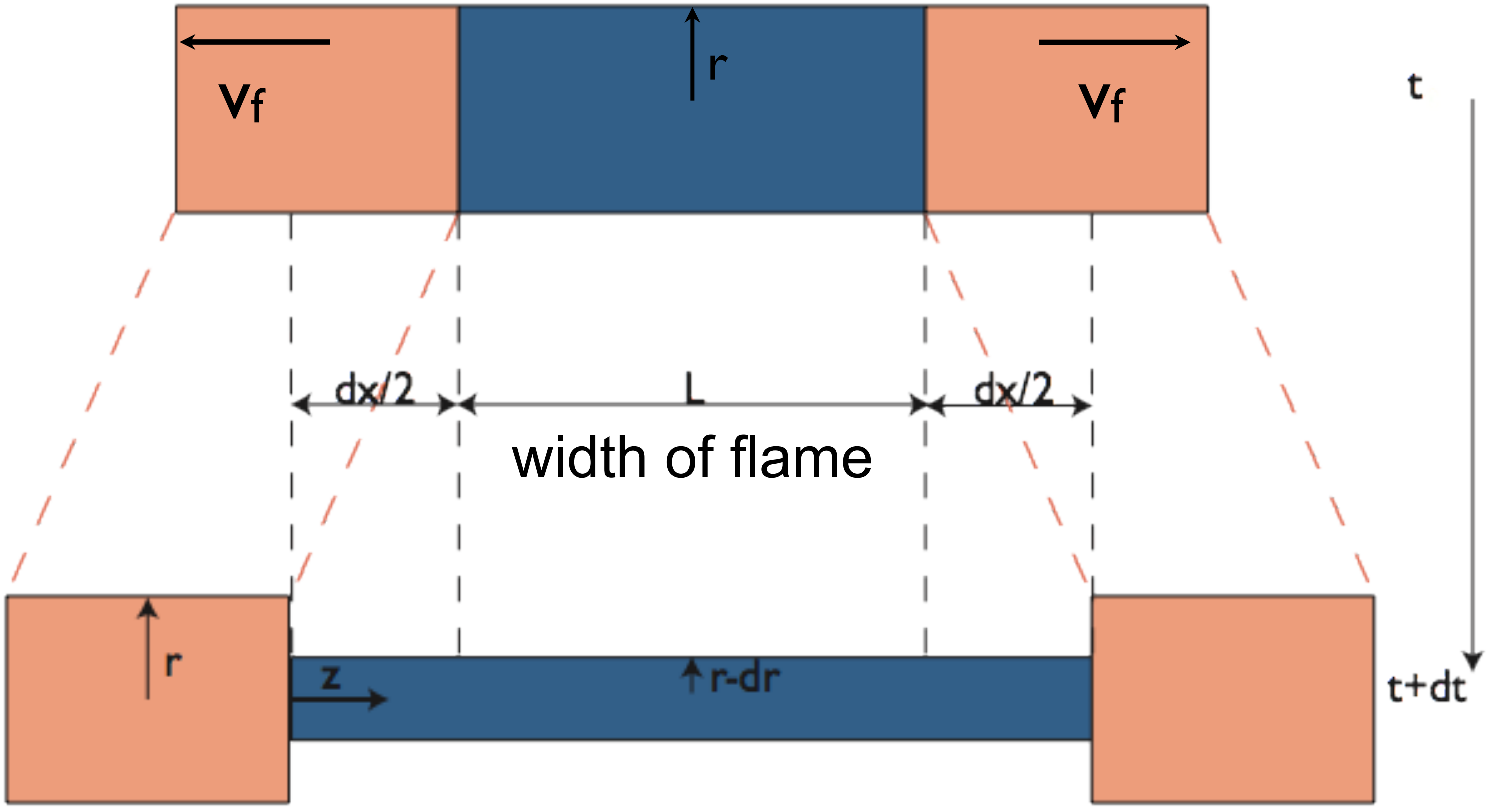
$$|E|^2 = \mathcal{E}^2 \left[K_0^2(qr) + wK_1^2(qr) + fK_2^2(qr)\right]$$



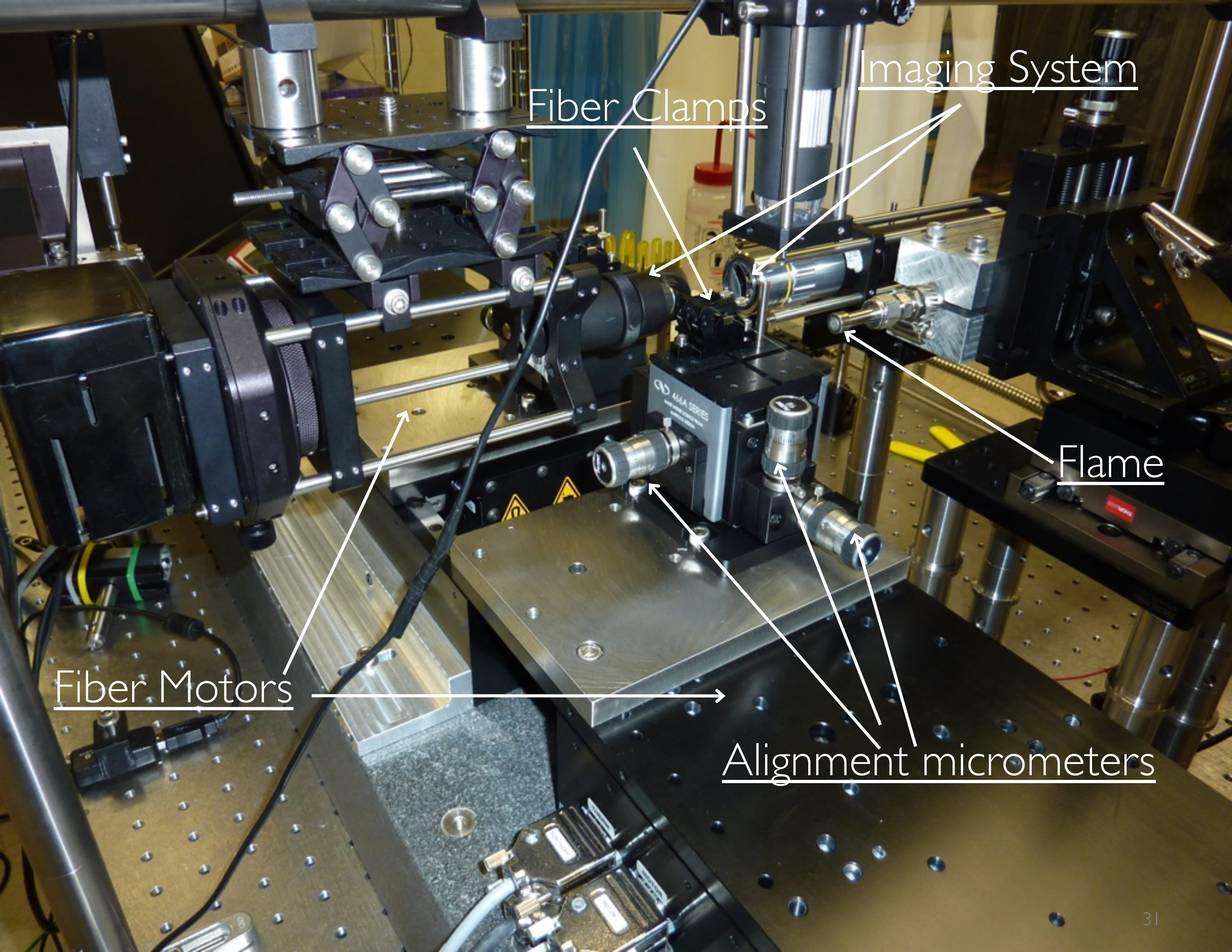
a)
Int (a.u.)
1.0
0.5
0.0
-200
0
200
x (nm)
-200
0
200
y (nm)
b)
$\frac{|E_x(r,\omega)|^2}{|E_x(a,\omega)|^2}$
0.8
0.4
0.0
-200
0
200
x (nm)
-200
0
200
y (nm)
c)
$\frac{|E_y(r,\omega)|^2}{|E_y(a,\omega)|^2}$
0.8
0.4
0.0
-200
0
200
x (nm)
-200
0
200
y (nm)
d)
$\frac{|E_z(r,\omega)|^2}{|E_z(a,\omega)|^2}$
0.8
0.4
0.0
-200
0
200
x (nm)
-200
0
200
y (nm)

Fabrication and optical properties of nanofibers

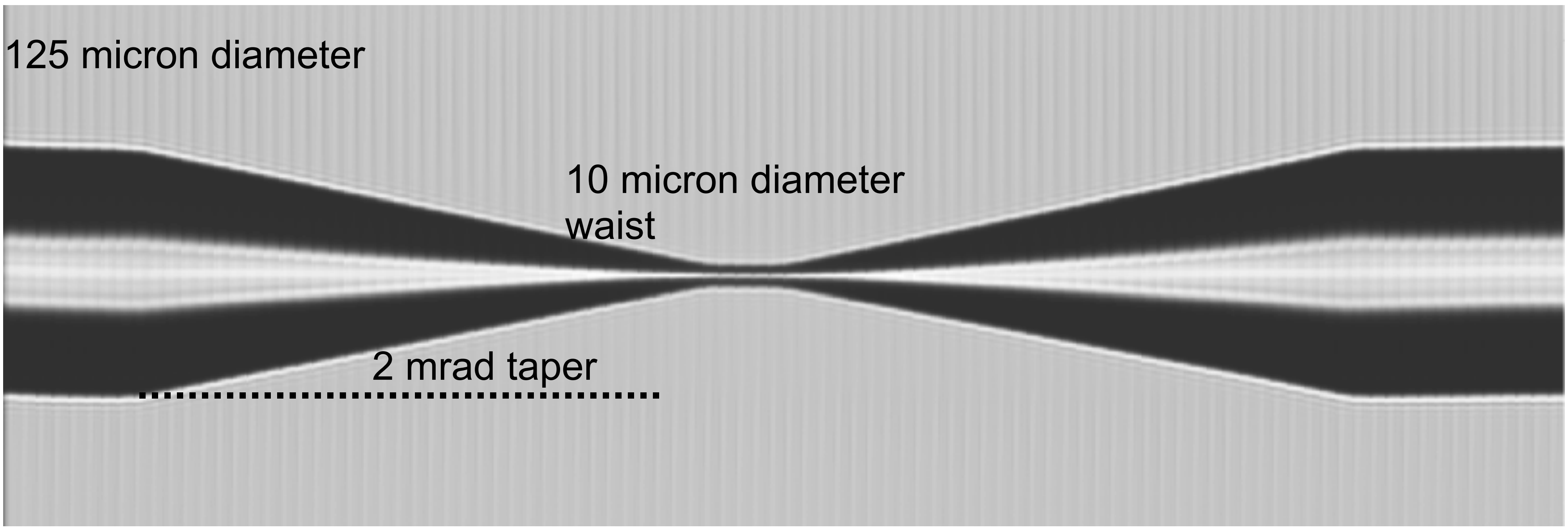
Conservation of Volume



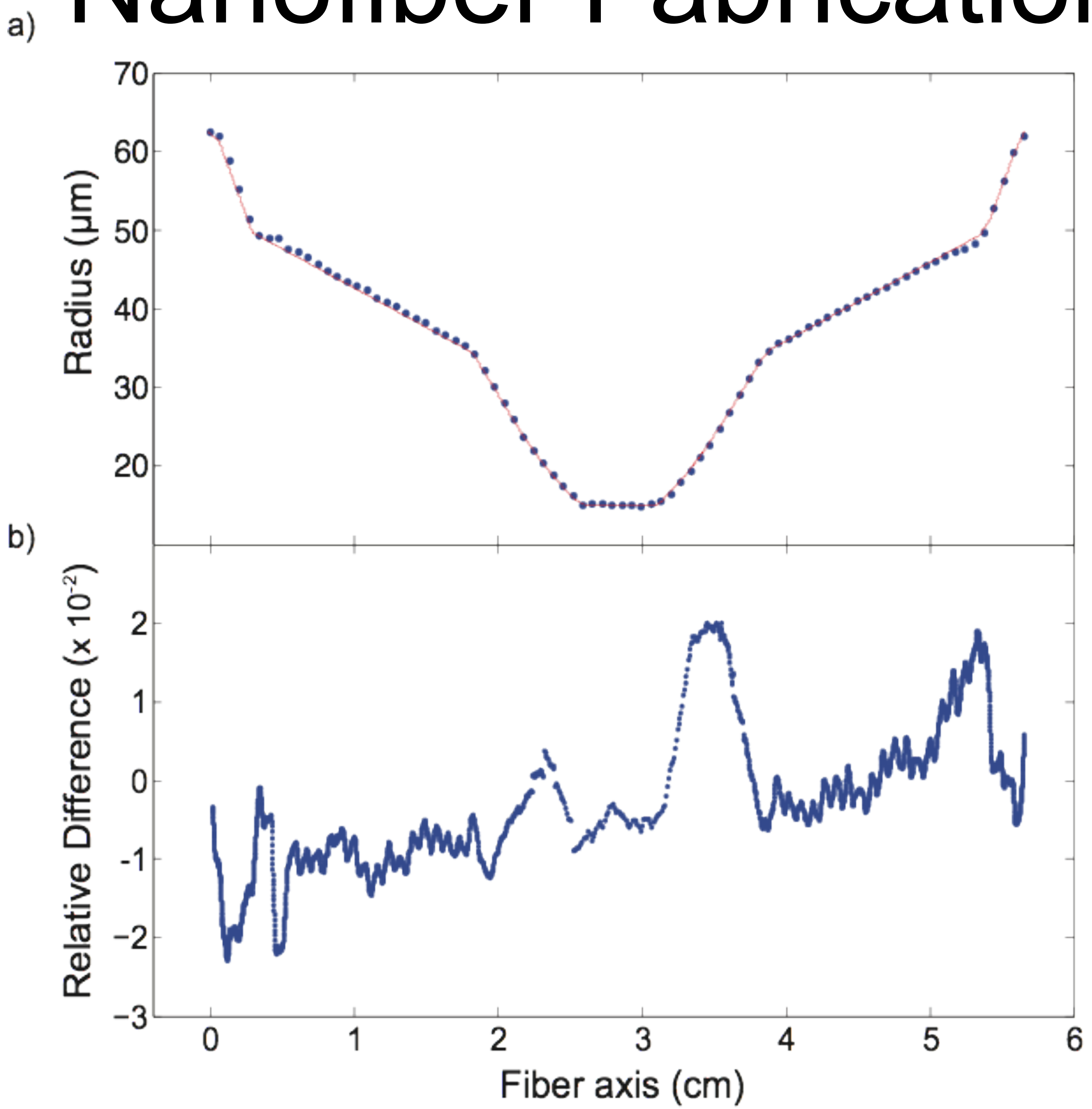
$$\frac{dr}{dx} = -\frac{r}{2L} \quad \Rightarrow \quad r(t) = r_0 \exp\left(-\frac{v_f t}{2L_0}\right)$$


Imaging System
Fiber Clamps
Flame
Fiber Motors
Alignment micrometers

Nanofiber Fabrication: Heat and Pull

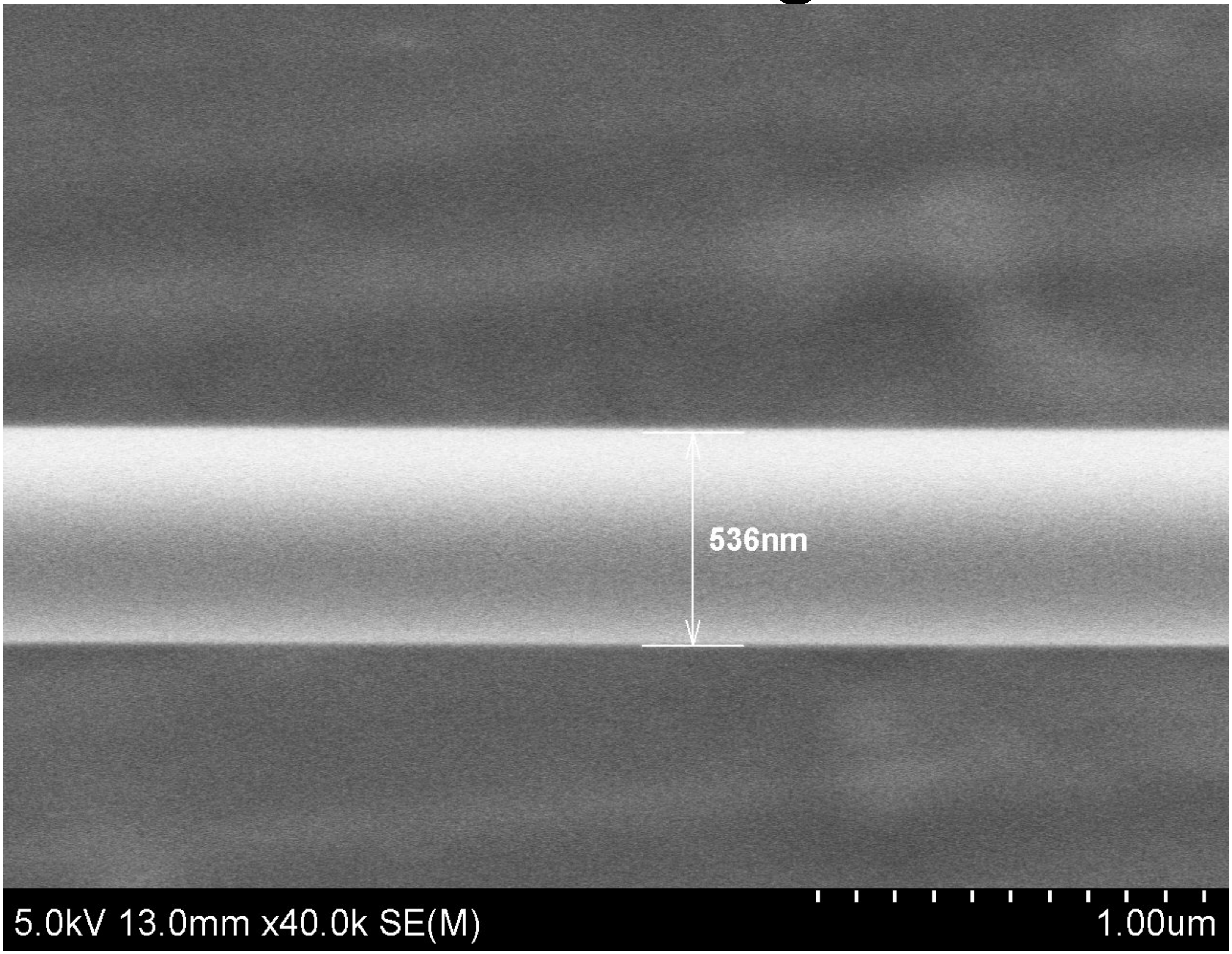


Nanofiber Fabrication

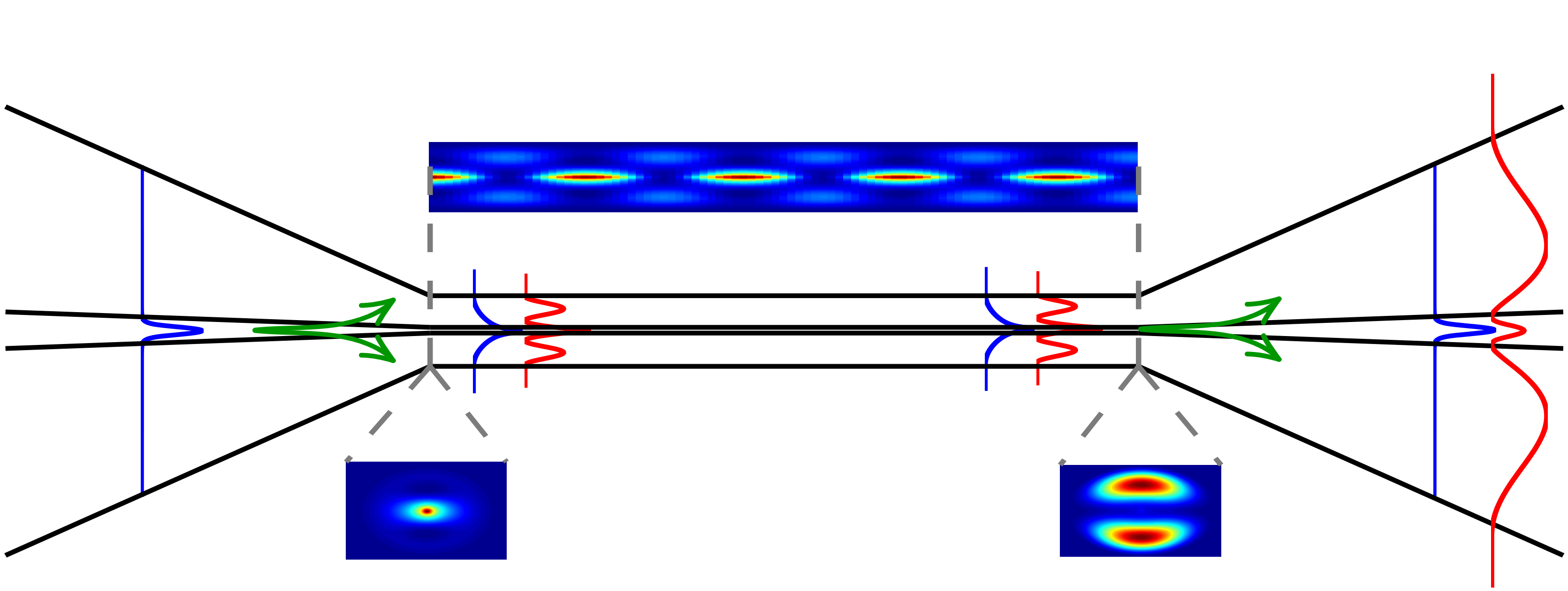


Optical microscope

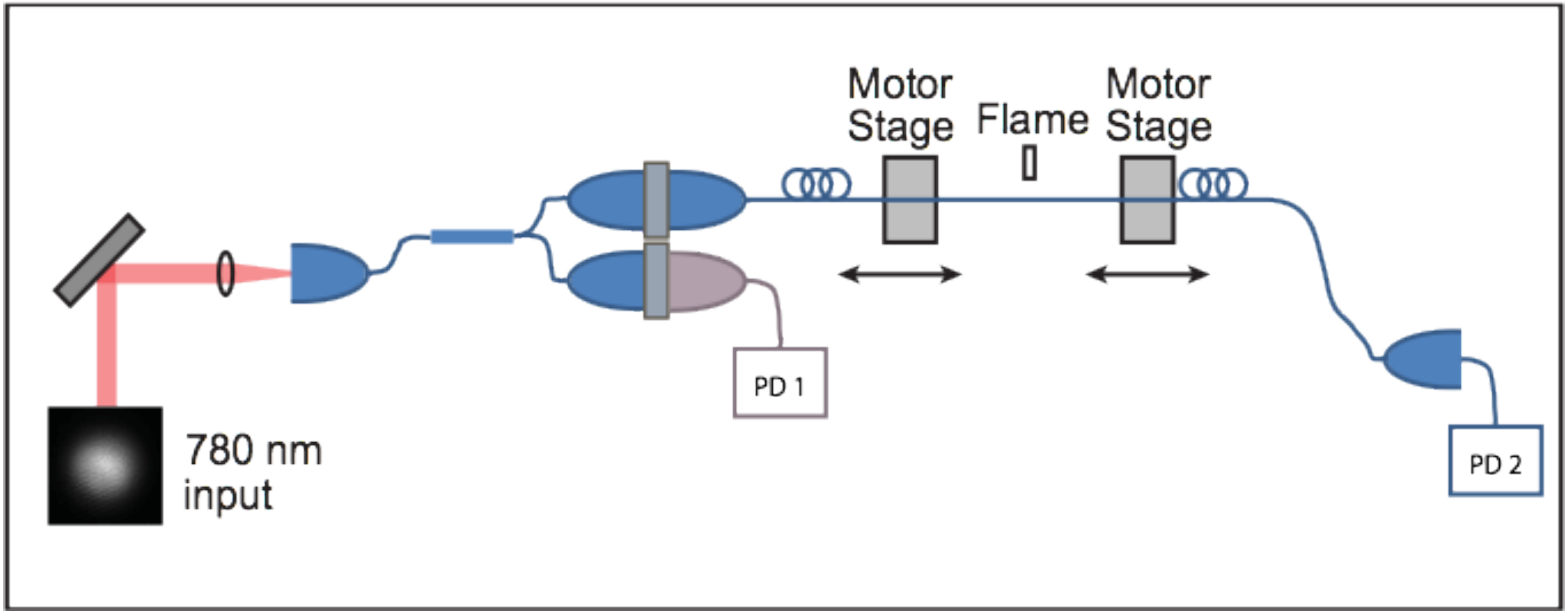
SEM image



Modes beating

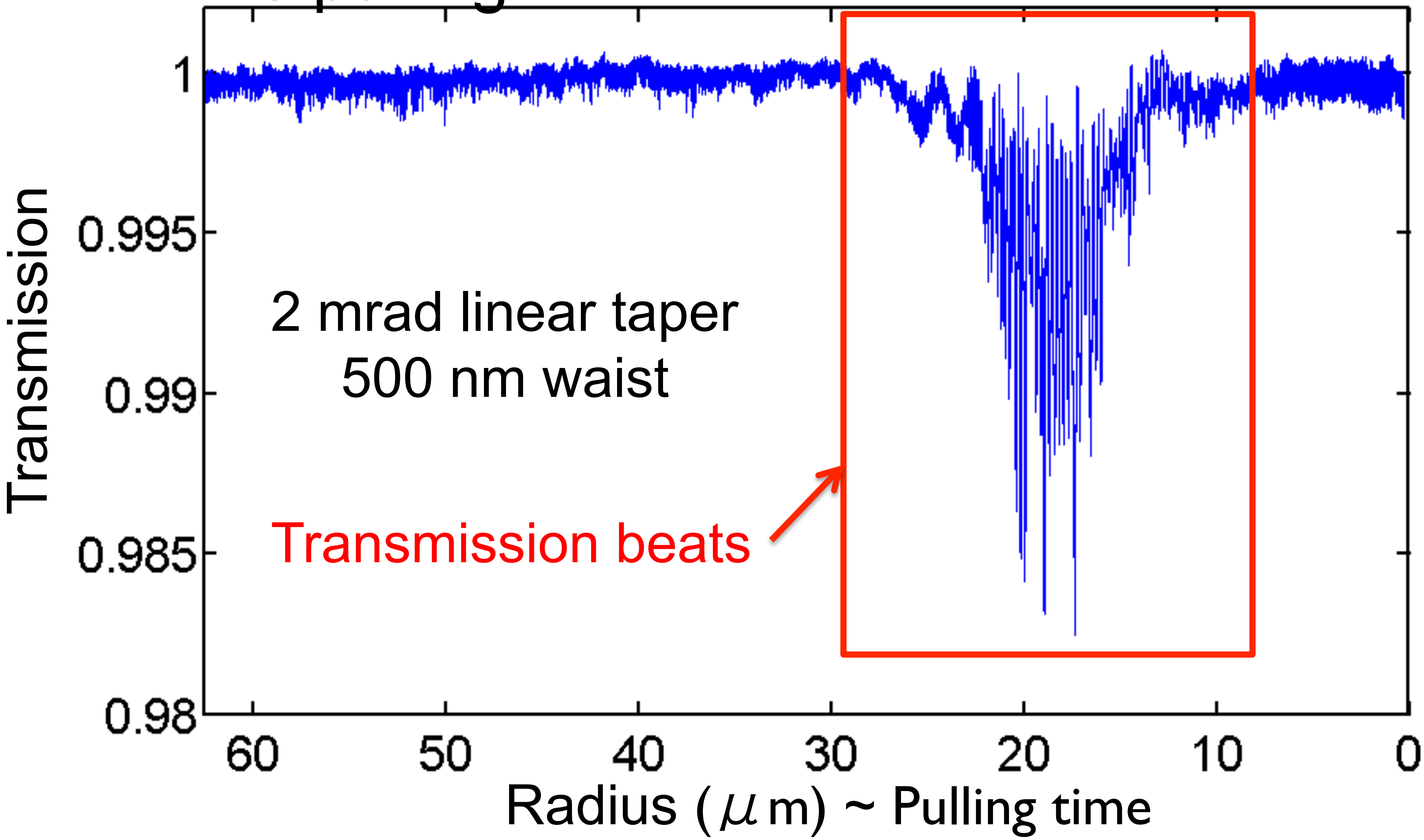


Setup



Transmission (t) = (PD2(t) / PD1(t))/Normalization

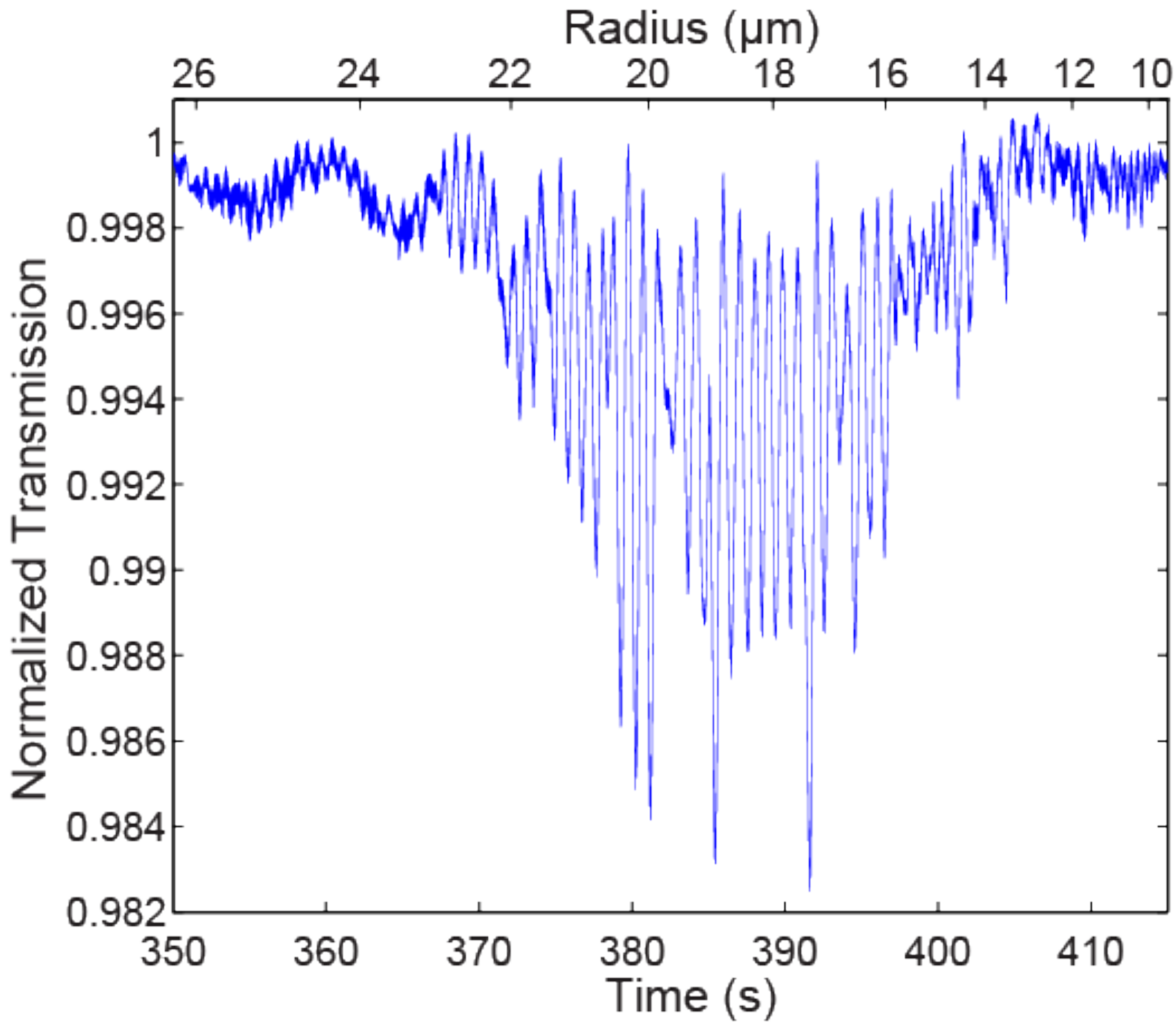
Normalized transmission through the fiber while pulling

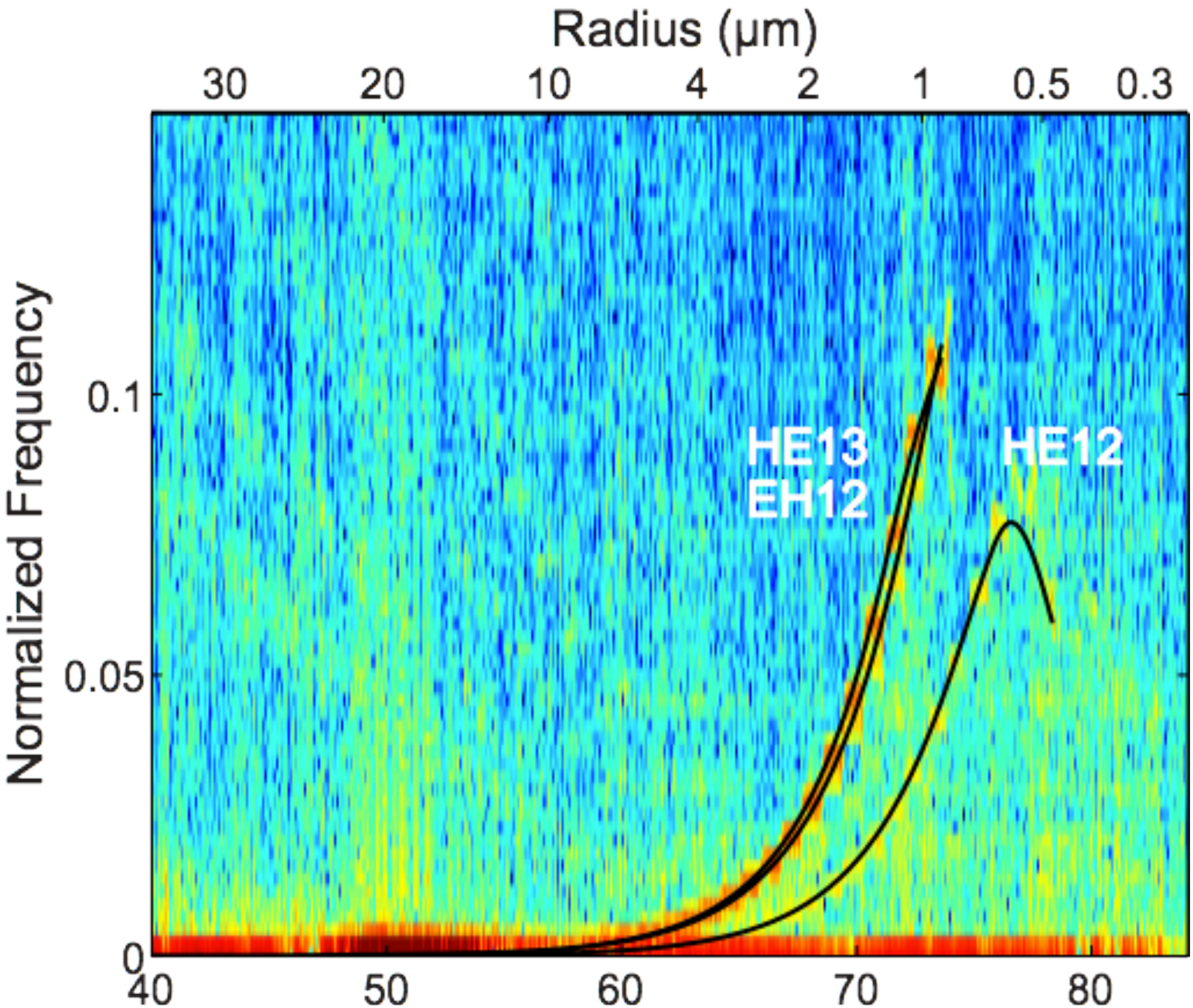


Transmission = 99.95 ± 0.02 %

Loss = 2.6×10^{-5} dB/mm

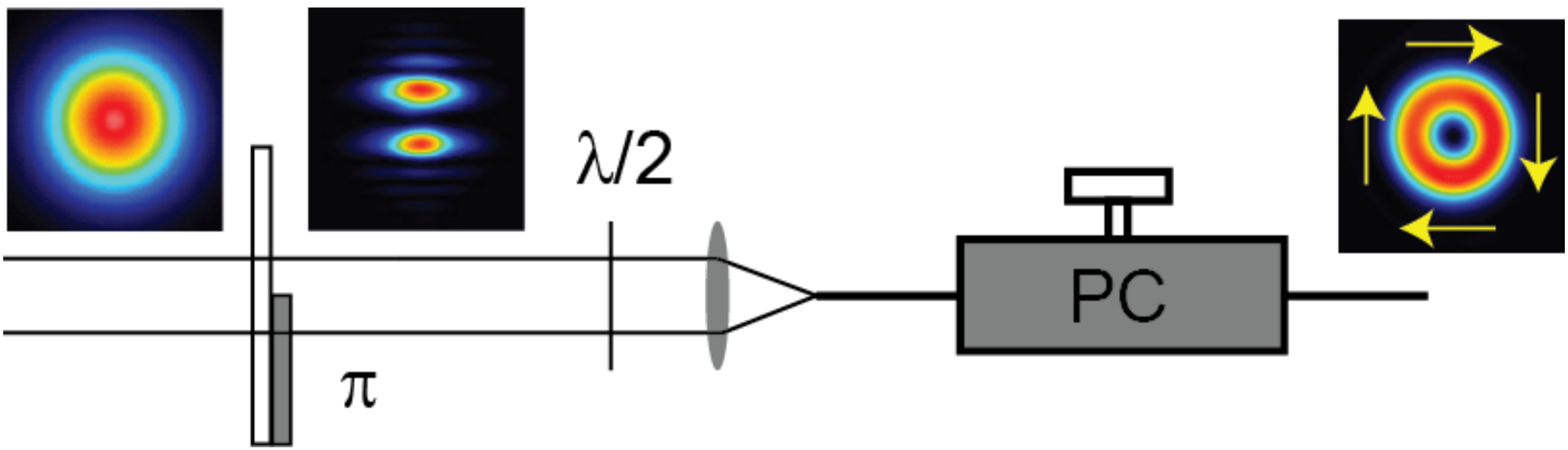
Oscillations during pull



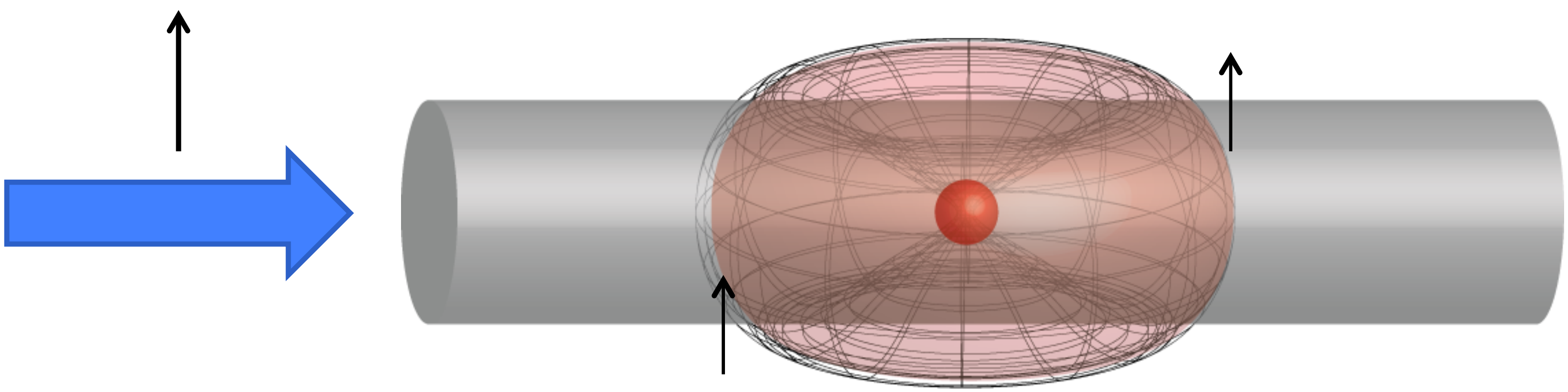

Radius (μm)
30
20
10
4
2
1
0.5
0.3
Normalized Frequency
0.1
0.05
0
40
50
60
70
80
HE13
EH12
HE12

Optical properties of nanofibers

Production of higher order modes

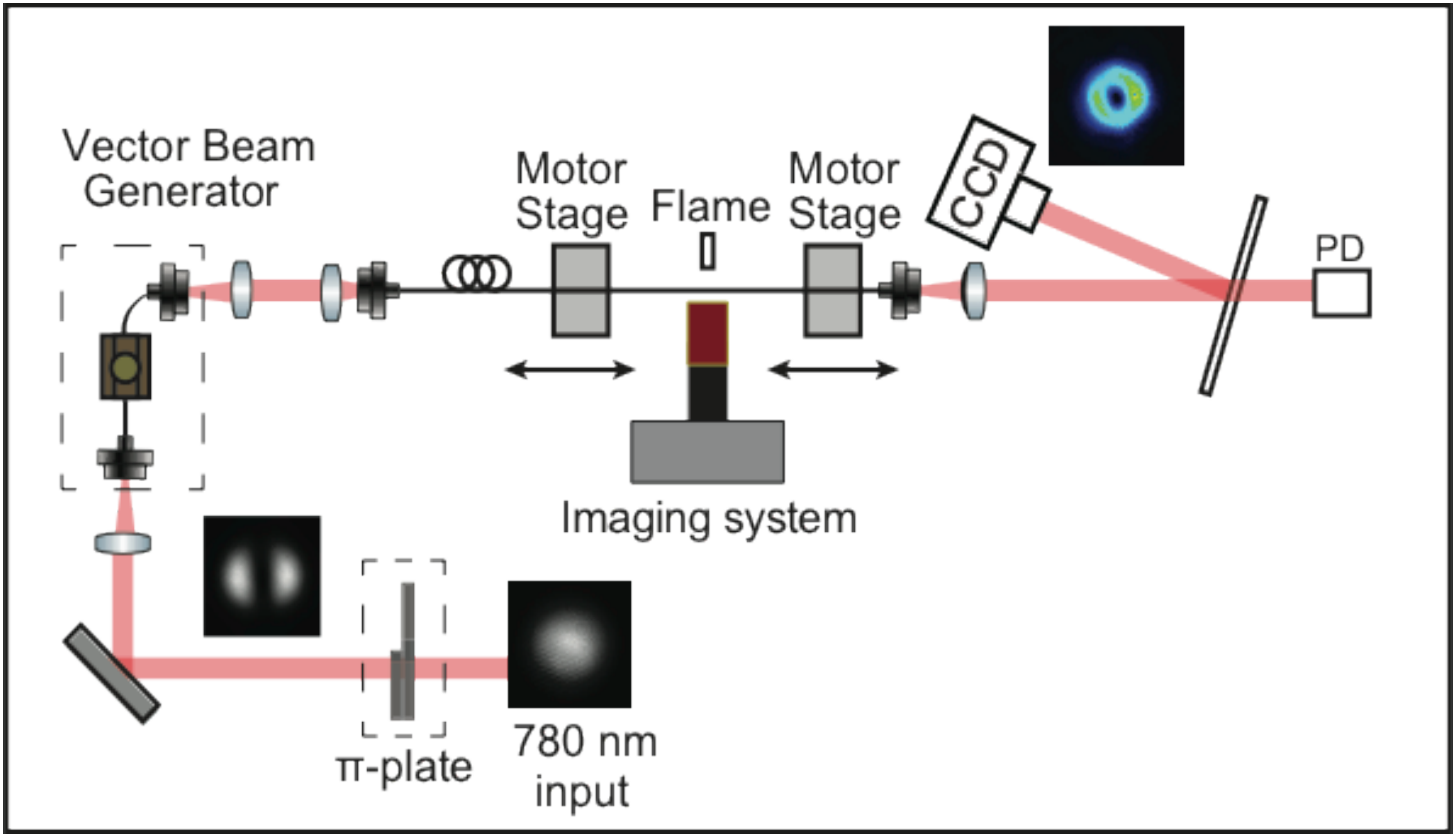


Rayleigh Scattering



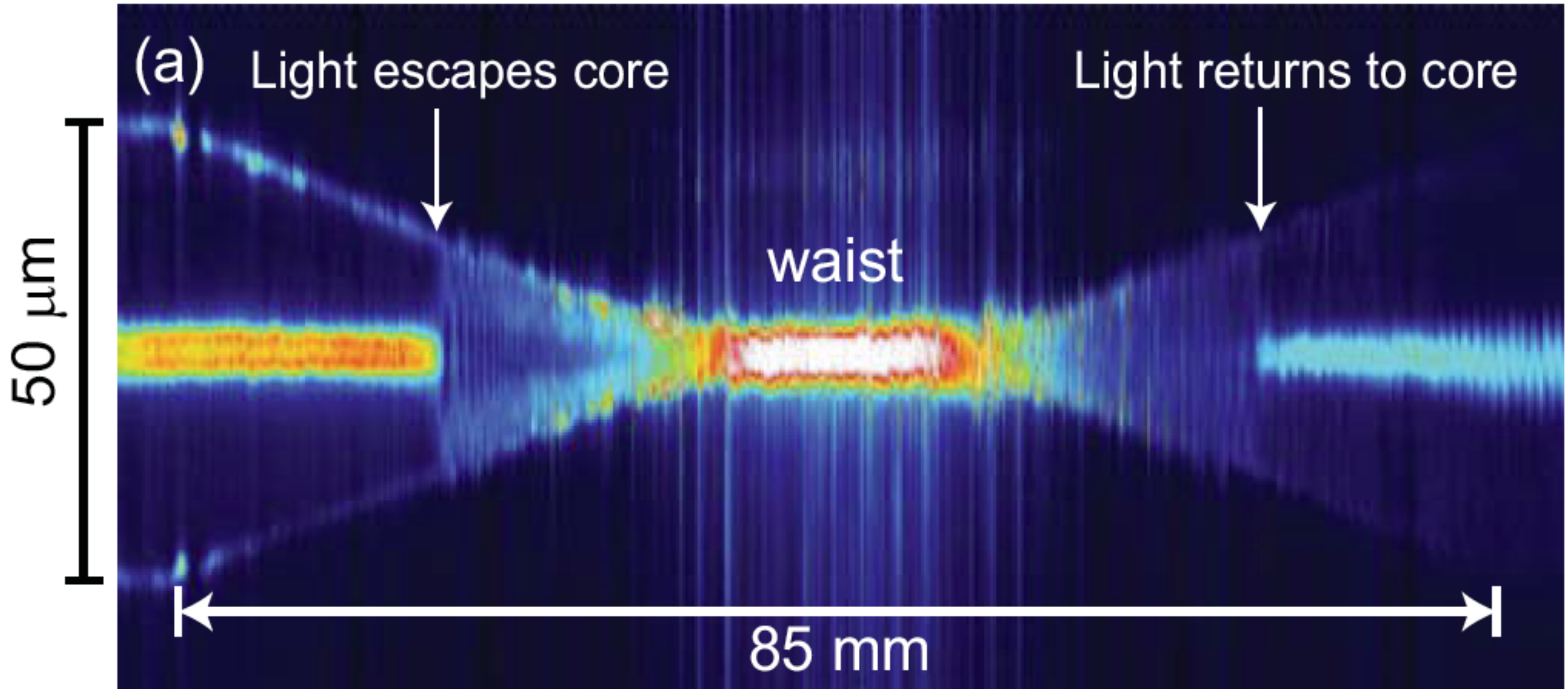
Can be due to many factors:

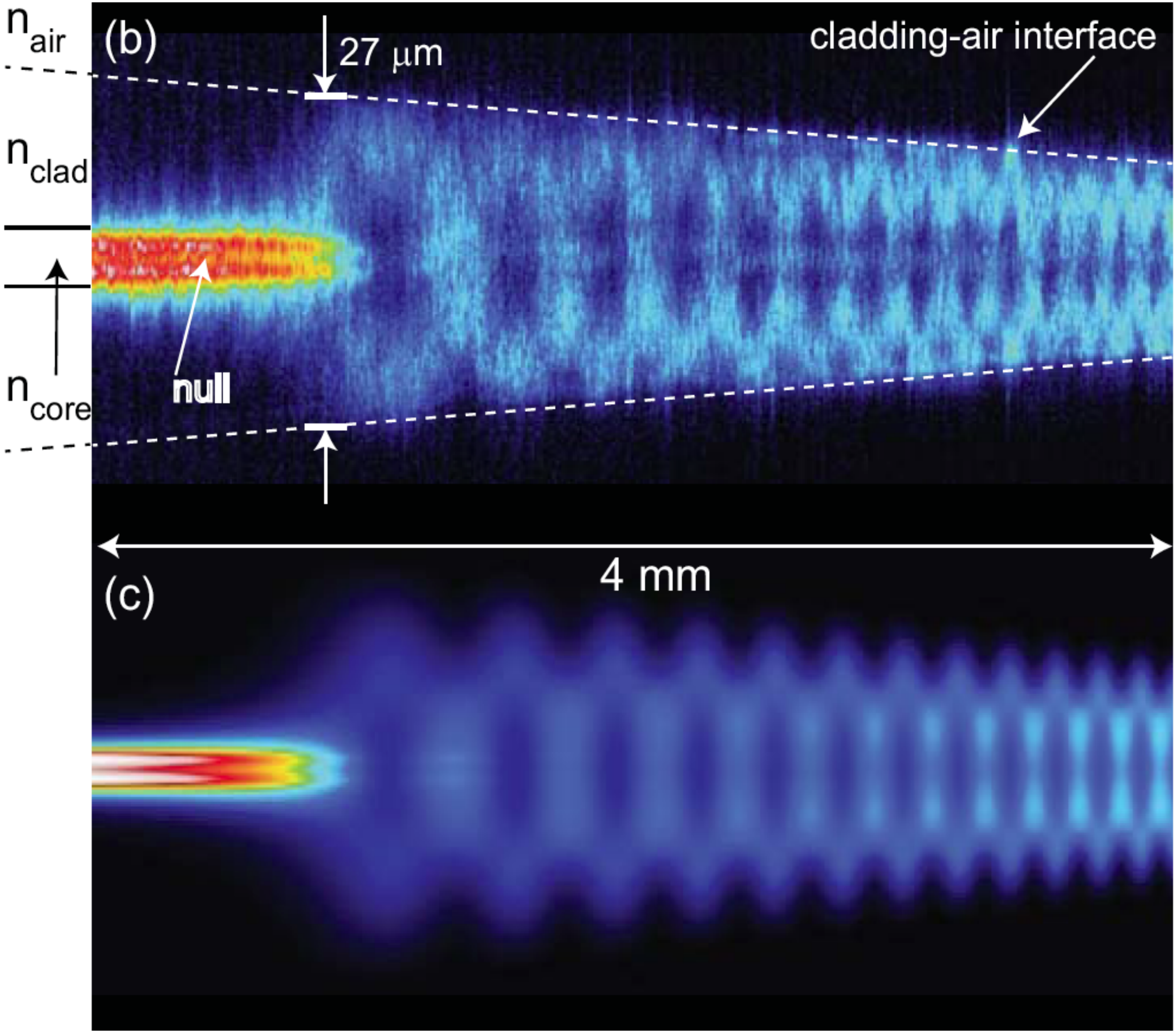
•Index / density fluctuations
•Impurity ions / atoms
•Roughness at core-cladding interface
•Bubbles at core-cladding interface



Vector Beam Generator
Motor Stage
Flame
Motor Stage
CCD
PD
Imaging system
π-plate
780 nm input

Rayleigh Scattering

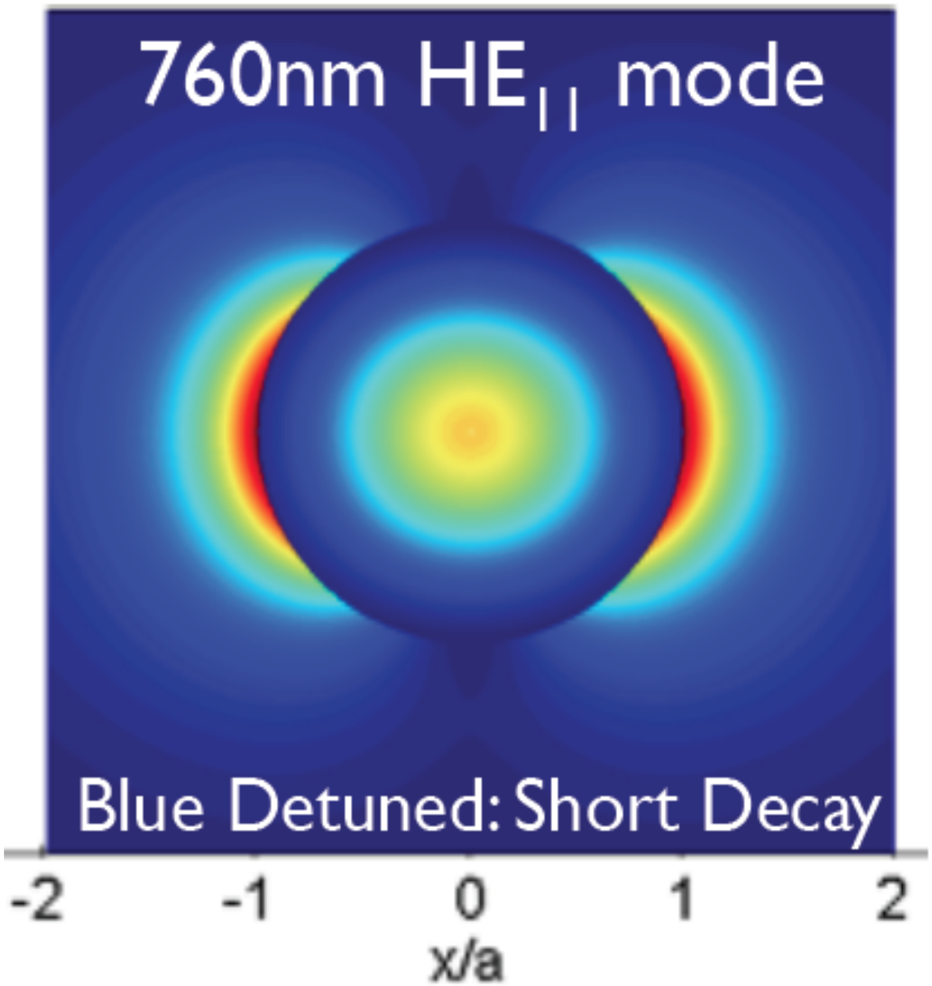



n_{air}
(b)
27 μm
cladding-air interface
n_{clad}
n_{core}
null
4 mm
(c)

- Low Loss fibers for fundamental and higher order modes.

- There is a lot of interesting nanomechanics (torsional and string modes of the nanofiber) that I have not mentioned!

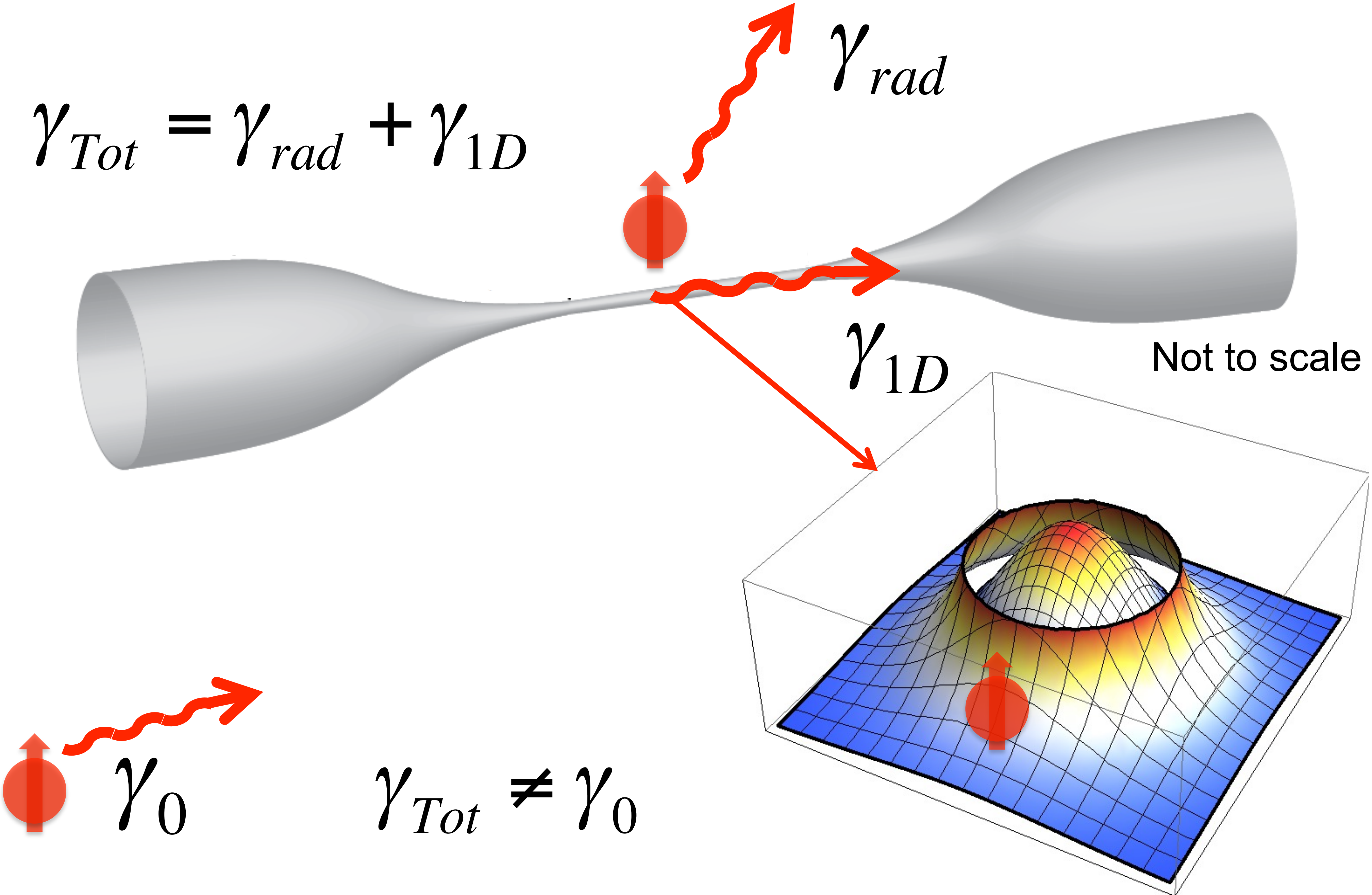
Fundamental mode of an optical nanofiber linearly polarized.



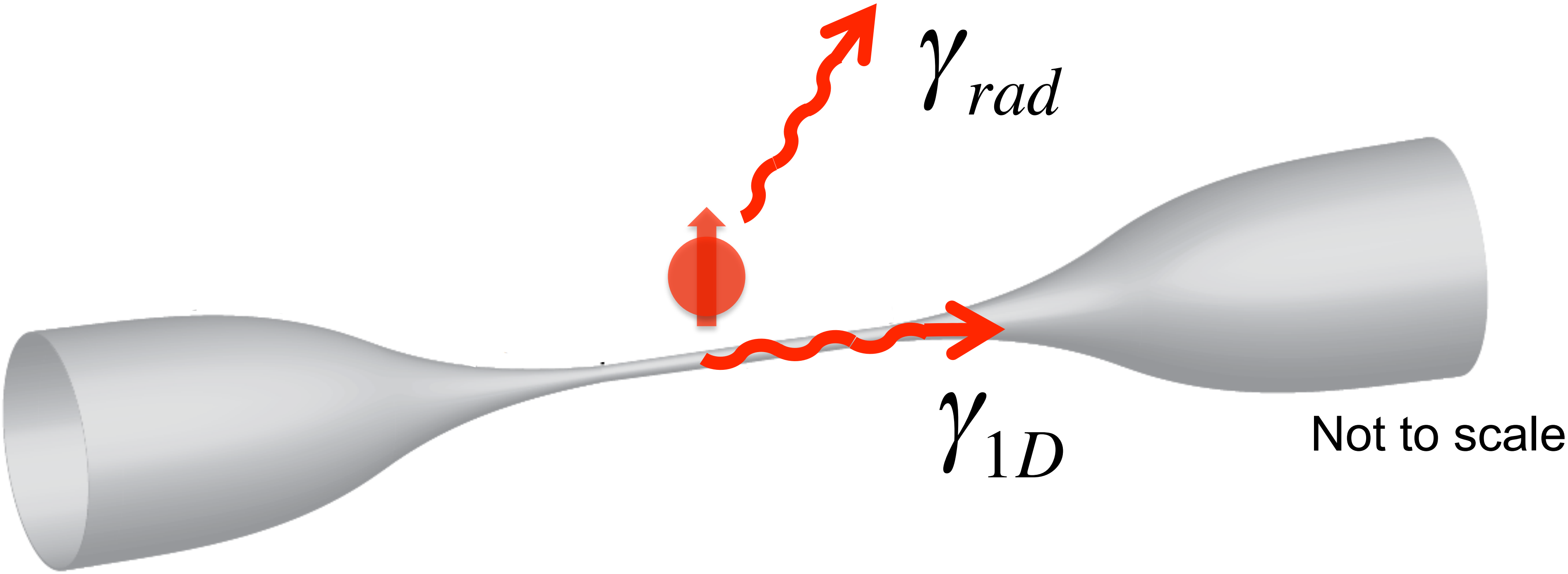
- Decreasing mode area increases atom-light interaction
- radius ~ 250 nm
- Decay length: ~100 nm
- Intensity of 1 mW in the evanescent field 5×10^8mW/cm^2 about 10^8 the saturation intensity of the D_2 line of Rb.

Atoms interacting with light (decay) near an ONF.

Evanescent Coupling



Cooperativity

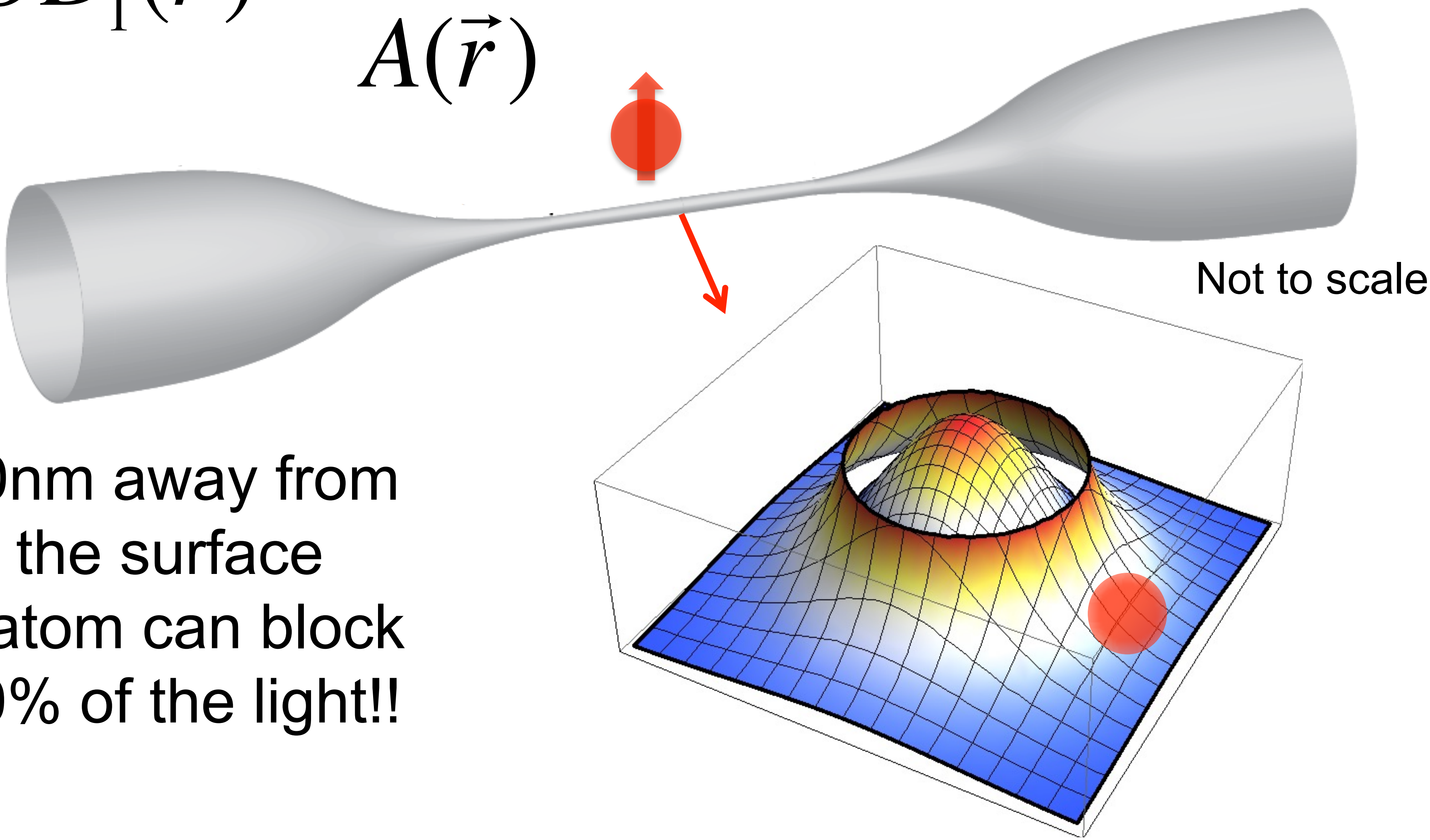


$$C_1 = \frac{\beta}{(1-\beta)} = \frac{\gamma_{1D}}{\gamma_{rad}}$$

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

ONF Optical Density

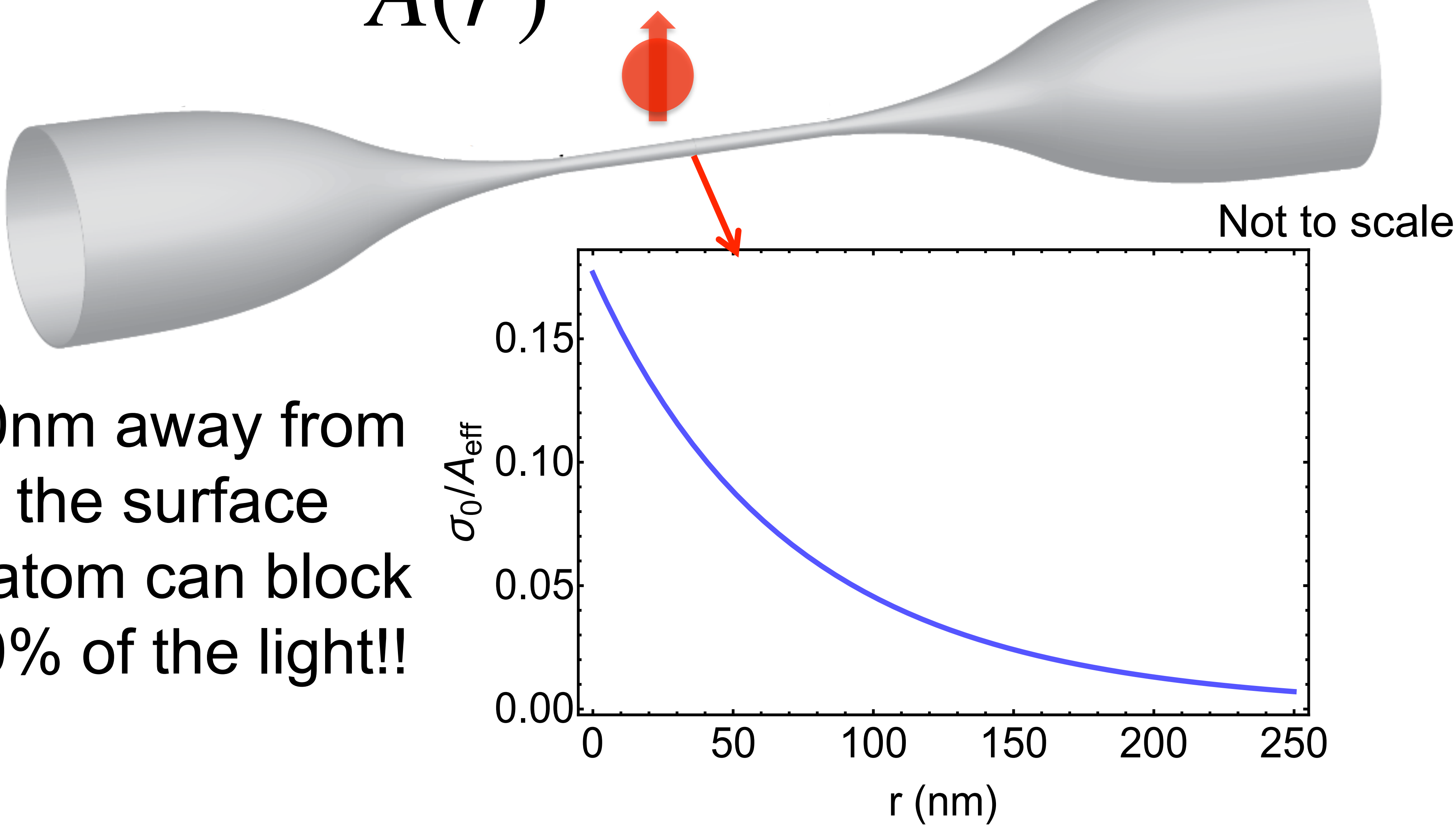
$$OD_1(\vec{r}) = \frac{\sigma_0}{A(\vec{r})}$$



50nm away from the surface
1 atom can block 10% of the light!!

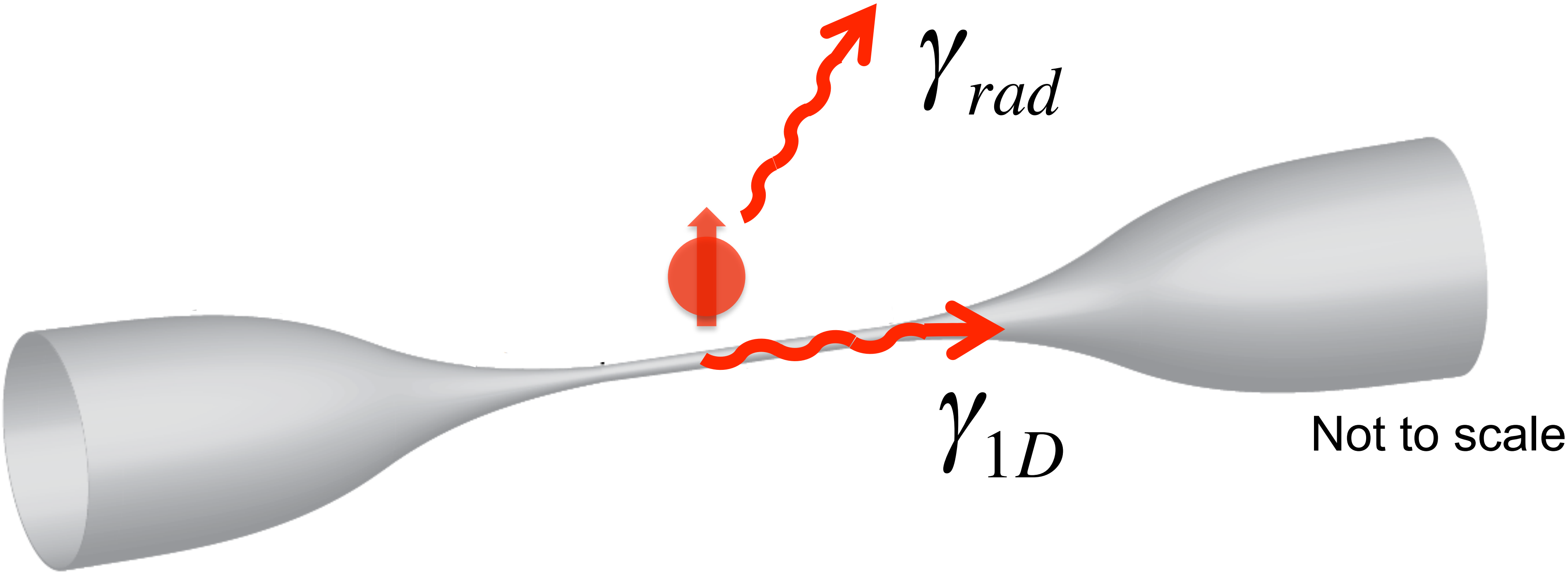
ONF Optical Density

$$OD_1(\vec{r}) = \frac{\sigma_0}{A(\vec{r})}$$



50nm away from the surface
1 atom can block 10% of the light!!

Cooperativity and Optical Density



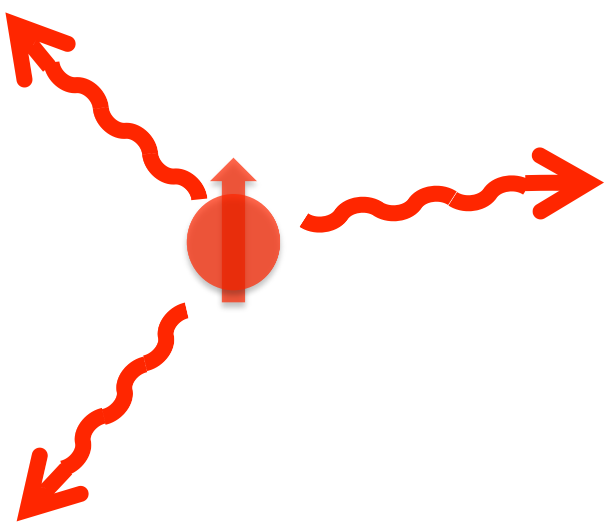
$$C_1 = OD_1 \frac{1}{n_{eff}} \frac{\gamma_0}{\gamma_{rad}}$$

Enhancement

Many atoms interacting with light (decay) near an ONF. Super- and sub-radiance.

Super- and Sub-radiance

(a classical explanation)



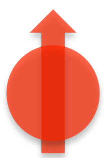
$$P = \frac{\varepsilon}{\Delta t} = IA \Rightarrow \Delta t = \frac{\varepsilon}{IA}$$

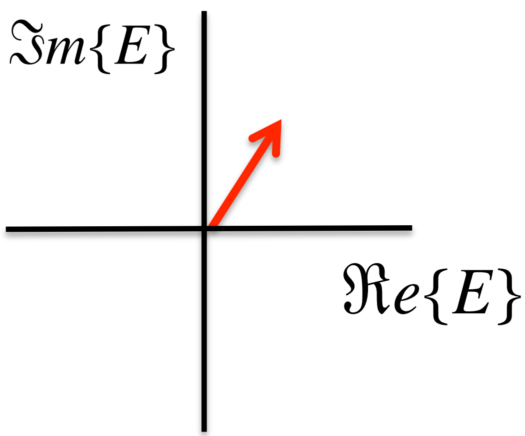
For N dipoles $\varepsilon \Rightarrow N\varepsilon$

Super- and Sub-radiance

(a classical explanation)

Normal radiance





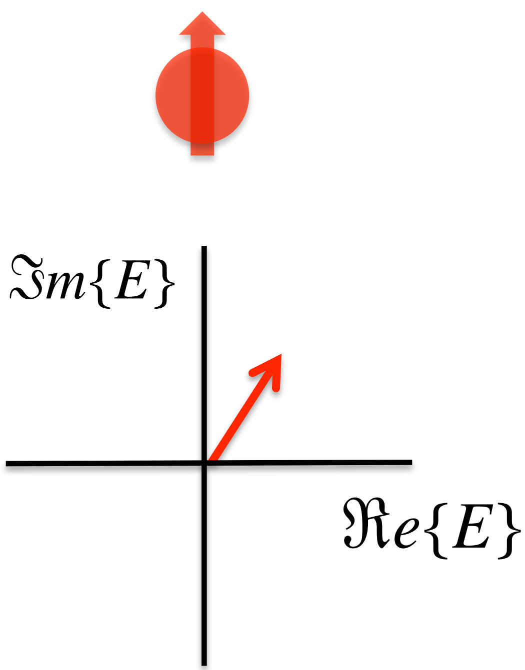
$$I = |E_0|^2 = I_0$$

$$\Delta t = \tau_0$$

Super- and Sub-radiance

(a classical explanation)

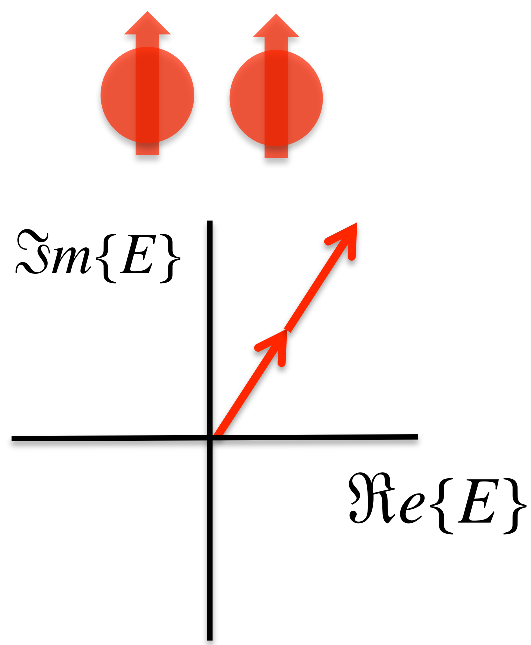
Normal radiance



$$I = |E_0|^2 = I_0$$

$$\Delta t = \tau_0$$

Super-radiance



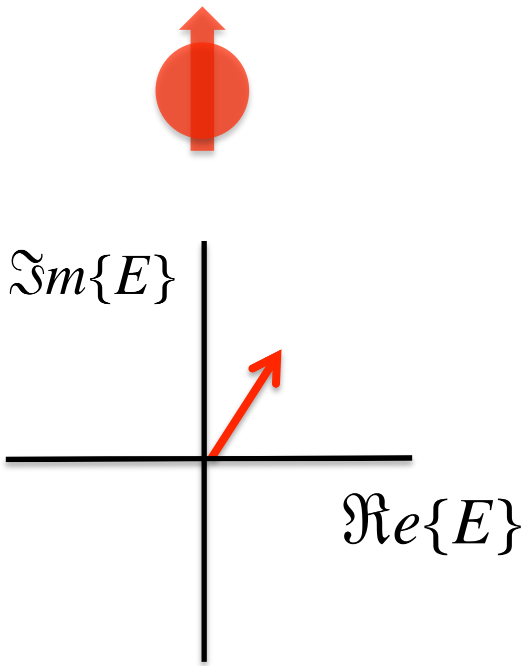
$$I = 4I_0$$

$$\Delta t = \frac{1}{2}\tau_0$$

Super- and Sub-radiance

(a classical explanation)

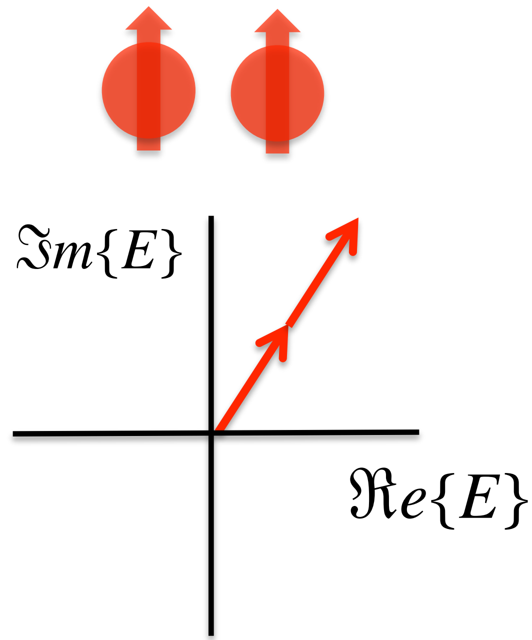
Normal radiance



$$I = |E_0|^2 = I_0$$

$$\Delta t = \tau_0$$

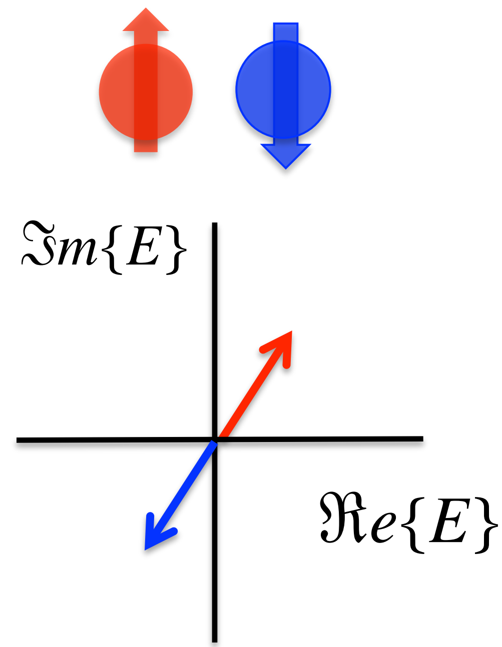
Super-radiance



$$I = 4I_0$$

$$\Delta t = \frac{1}{2}\tau_0$$

Sub-radiance

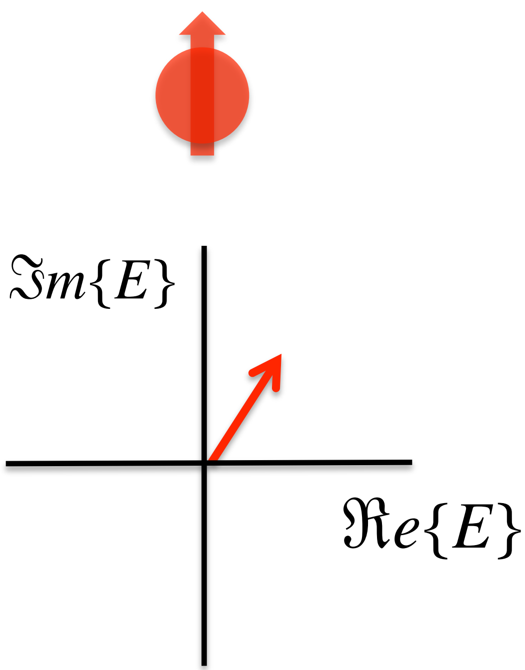


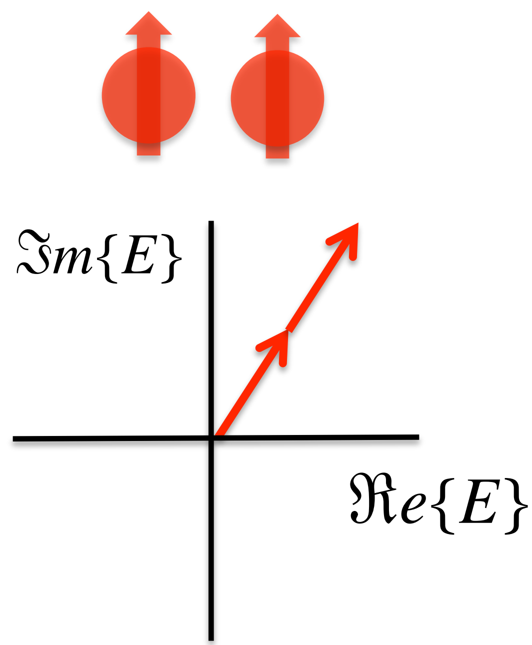
$$I = 0$$

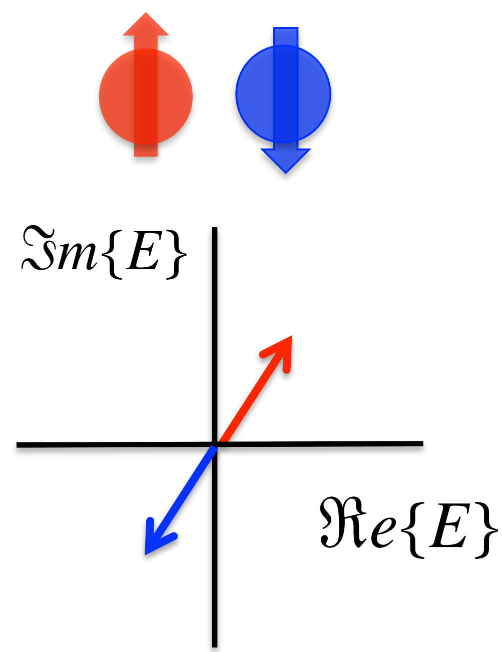
$$\Delta t = \infty$$

Super- and Sub-radiance
(a classical explanation)

Normal radiance	Super-radiance	Sub-radiance







$$|ge\rangle + |eg\rangle \qquad |ge\rangle - |eg\rangle$$

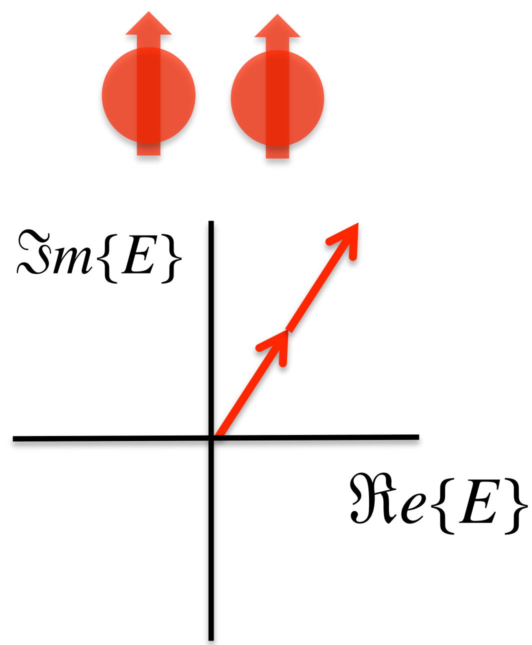
$$\Delta t = \tau_0 \qquad \Delta t = \frac{1}{2}\tau_0 \qquad \Delta t = \infty$$

Super- and Sub-radiance

(a classical explanation)

Super- and sub-radiance are **interference** effects!

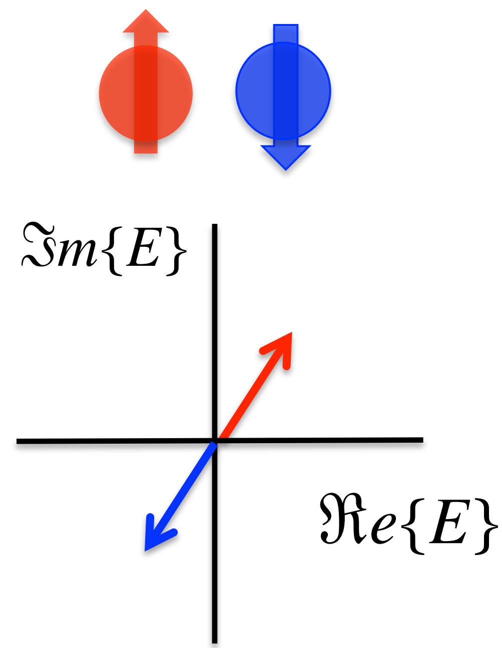
Super-radiance



$$|ge\rangle + |eg\rangle$$

$$\Delta t = \frac{1}{2}\tau_0$$

Sub-radiance

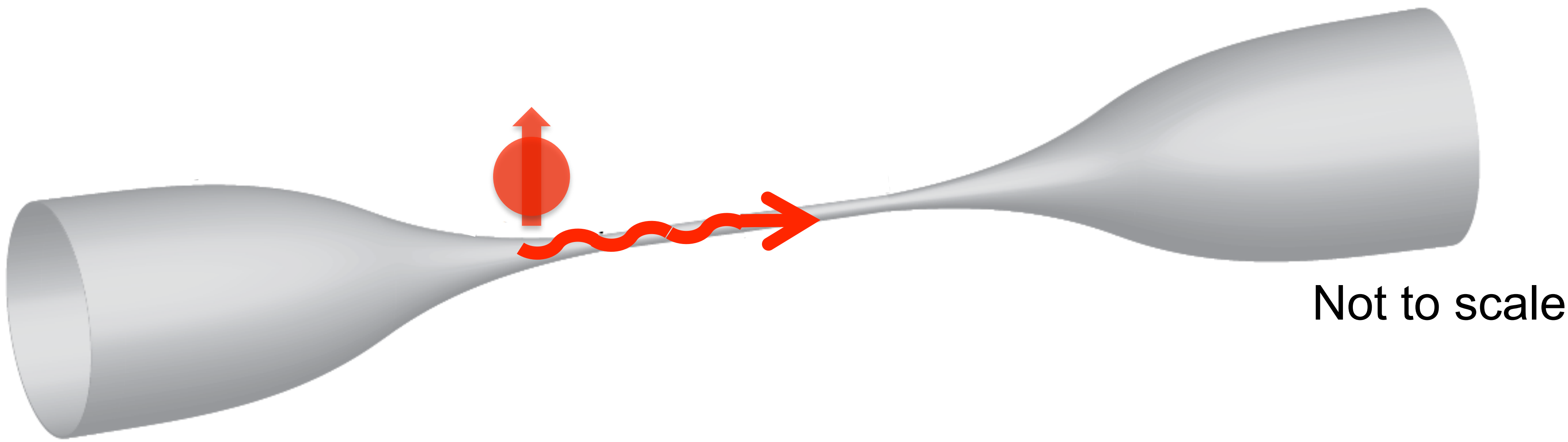


$$|ge\rangle - |eg\rangle$$

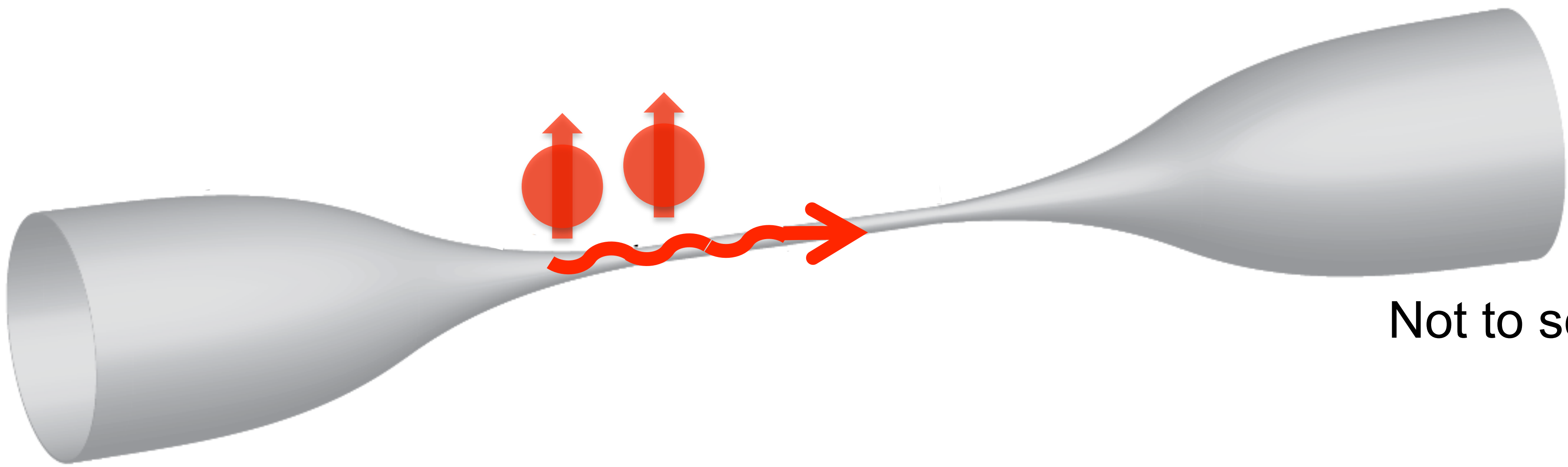
$$\Delta t = \infty$$

Observation of infinite-range interactions

Infinite Range Interactions

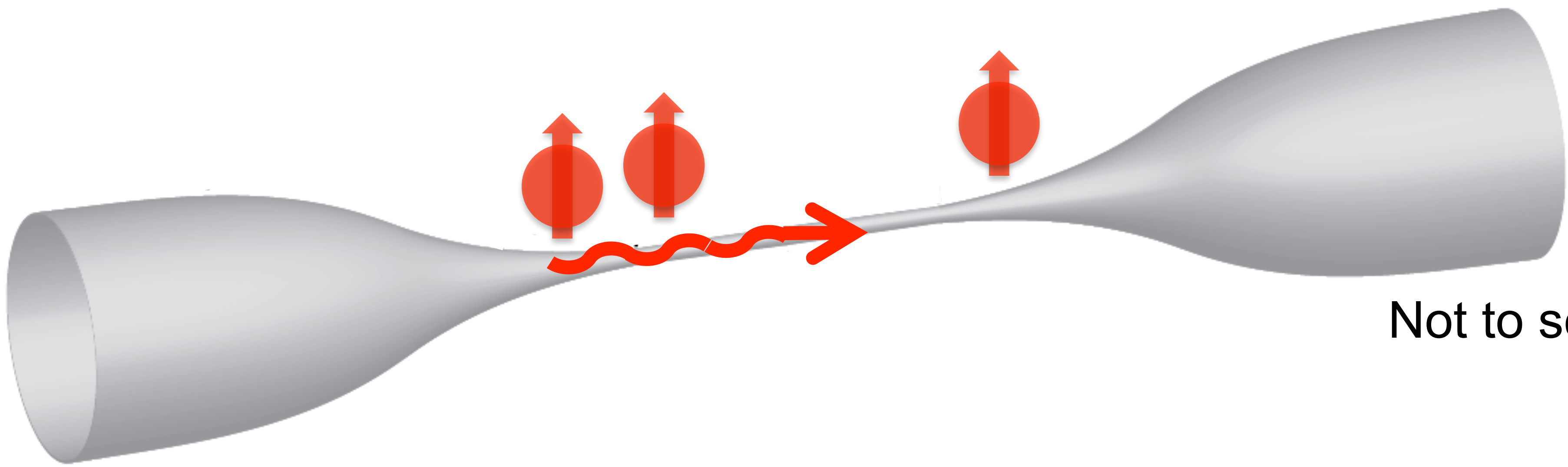


Infinite Range Interactions



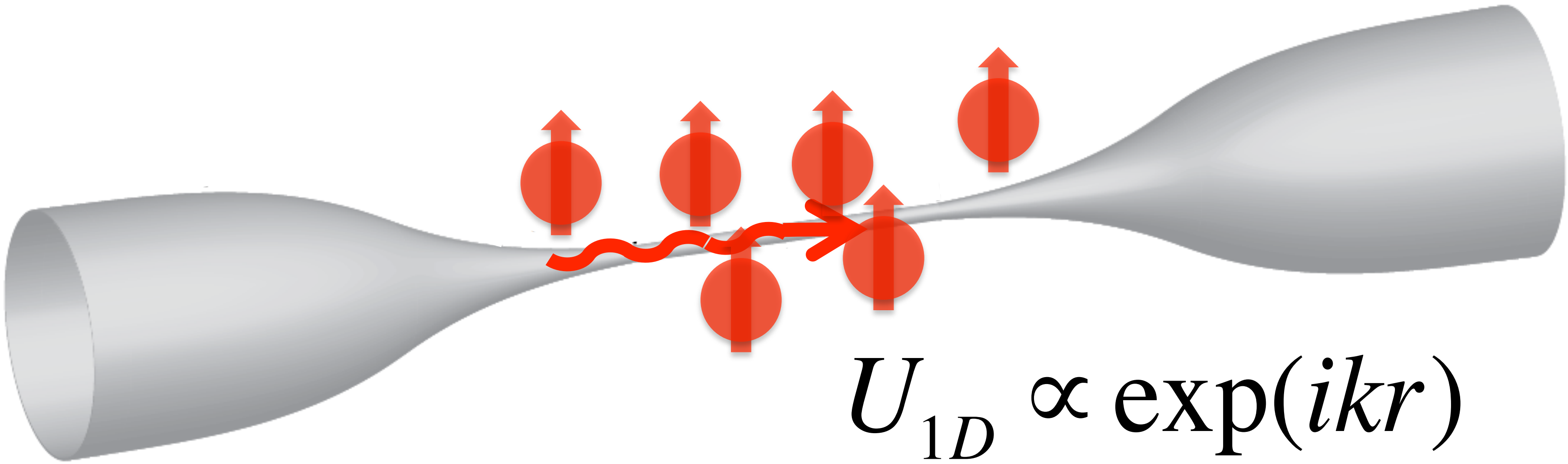
Not to scale

Infinite Range Interactions



Not to scale

Infinite Range Interactions



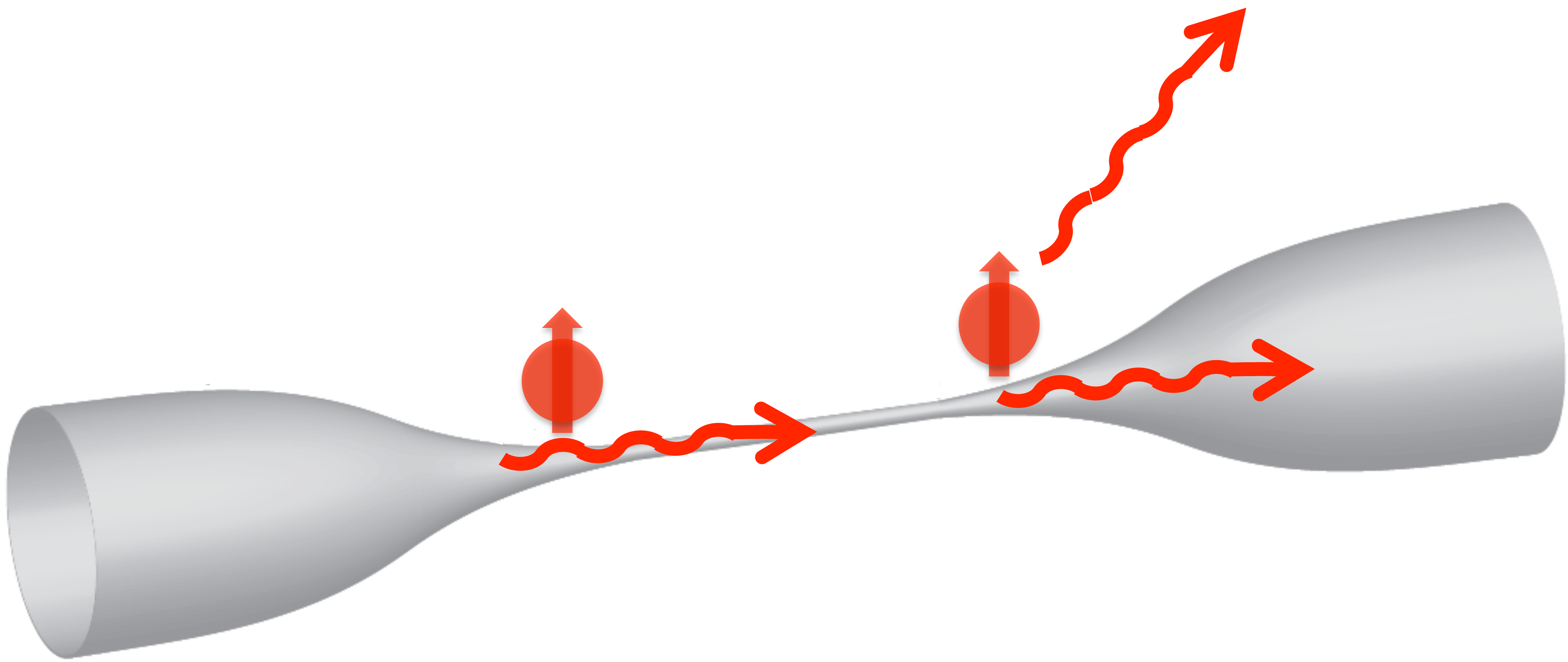
$$U_{1D} \propto \exp(ikr)$$

$$\Omega_{12} \propto \sin kz$$

$$\gamma_{12} \propto \cos kz$$

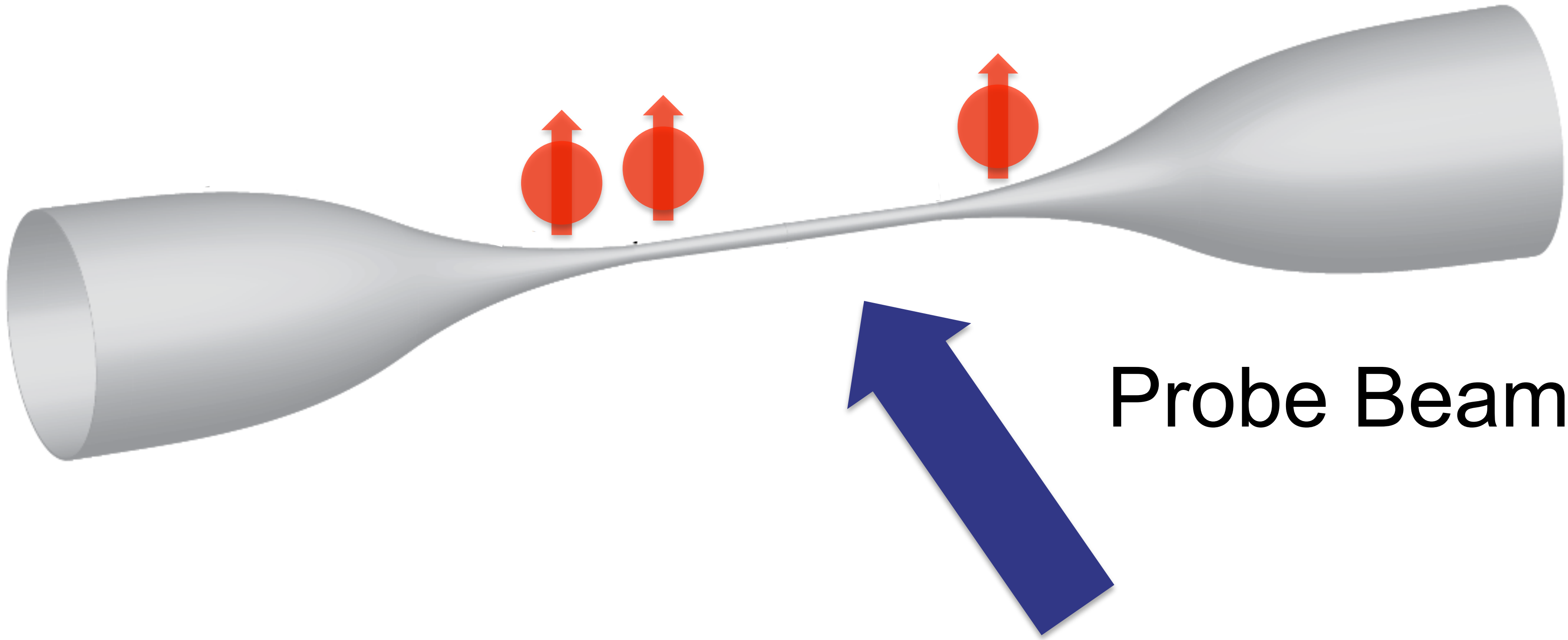
The limit is now how many atoms can we put withing the coherence length associated with the spontaneous emission.

Long distance modification of the atomic radiation

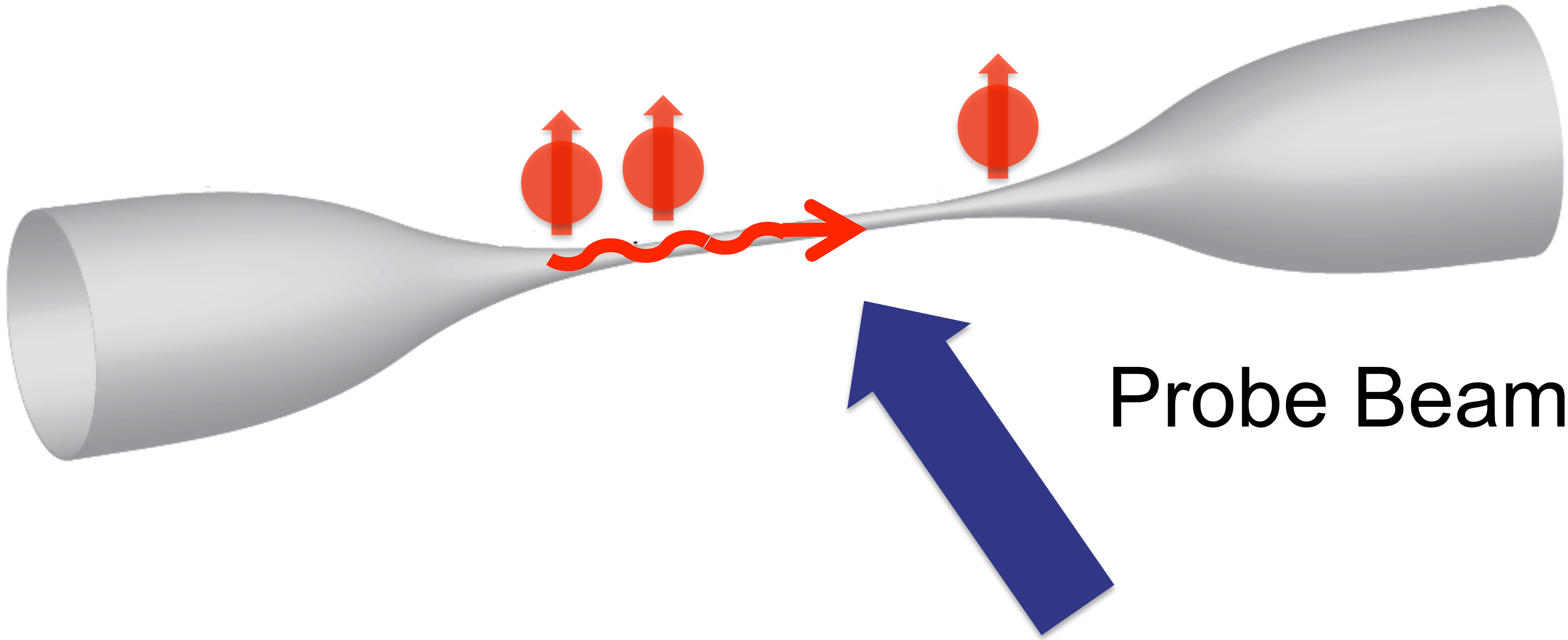


Experimental idea

The idea behind the experiment

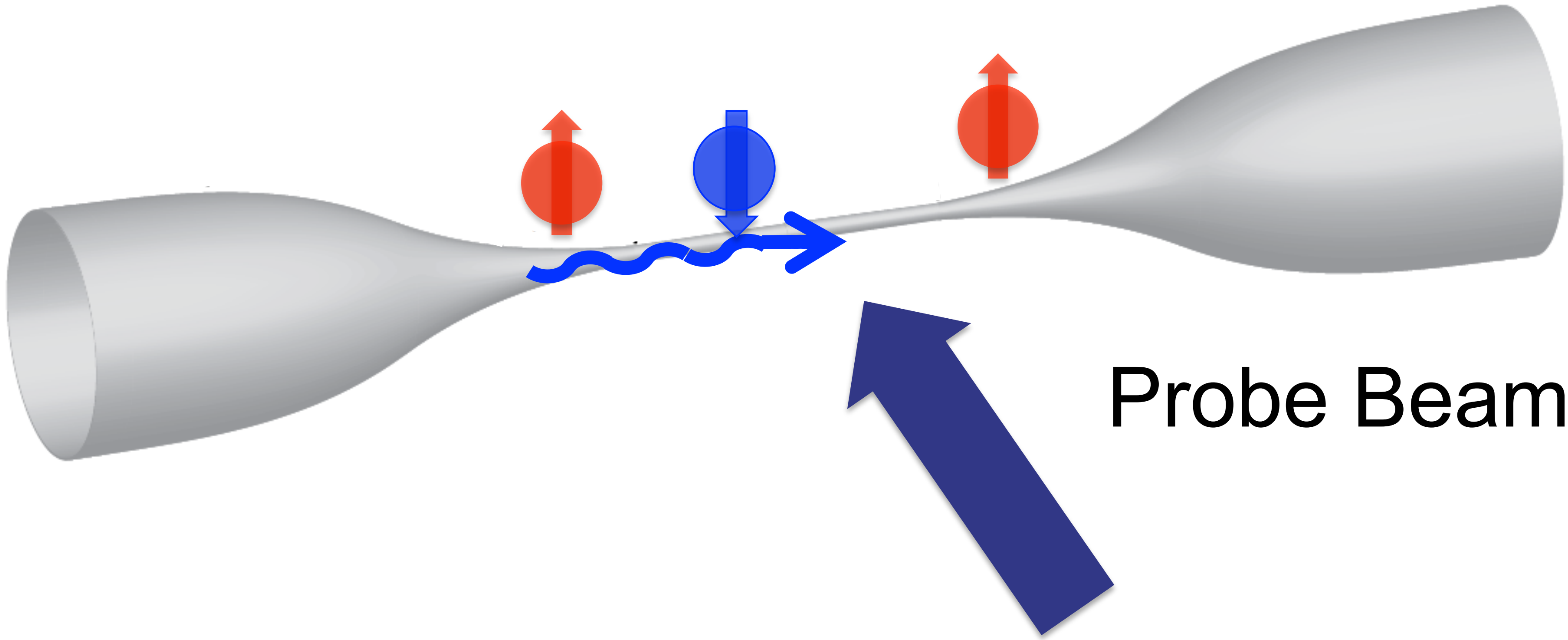


The idea behind the experiment



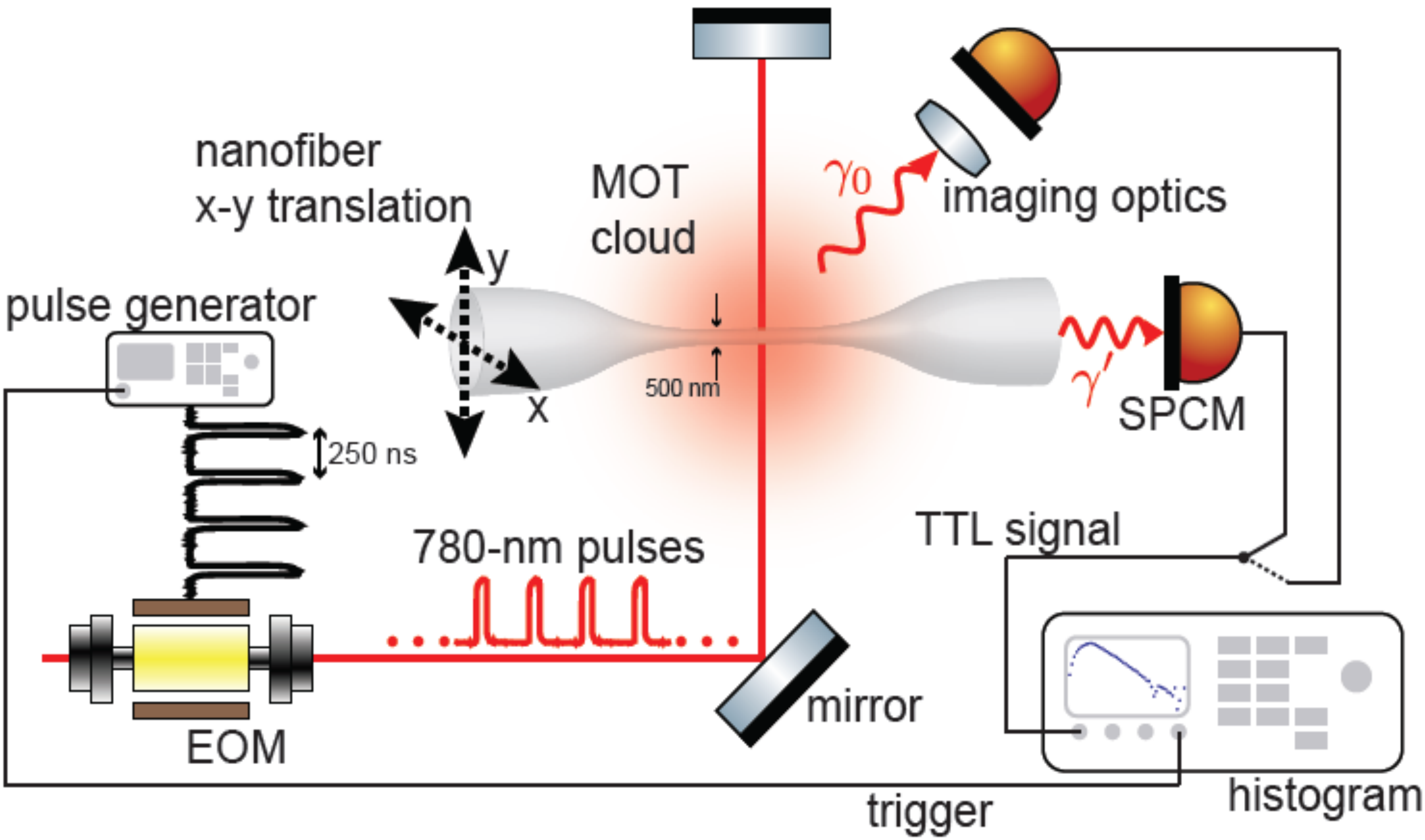
We look for modifications of the radiative lifetime of an ensemble of atoms around the ONF.

The idea behind the experiment

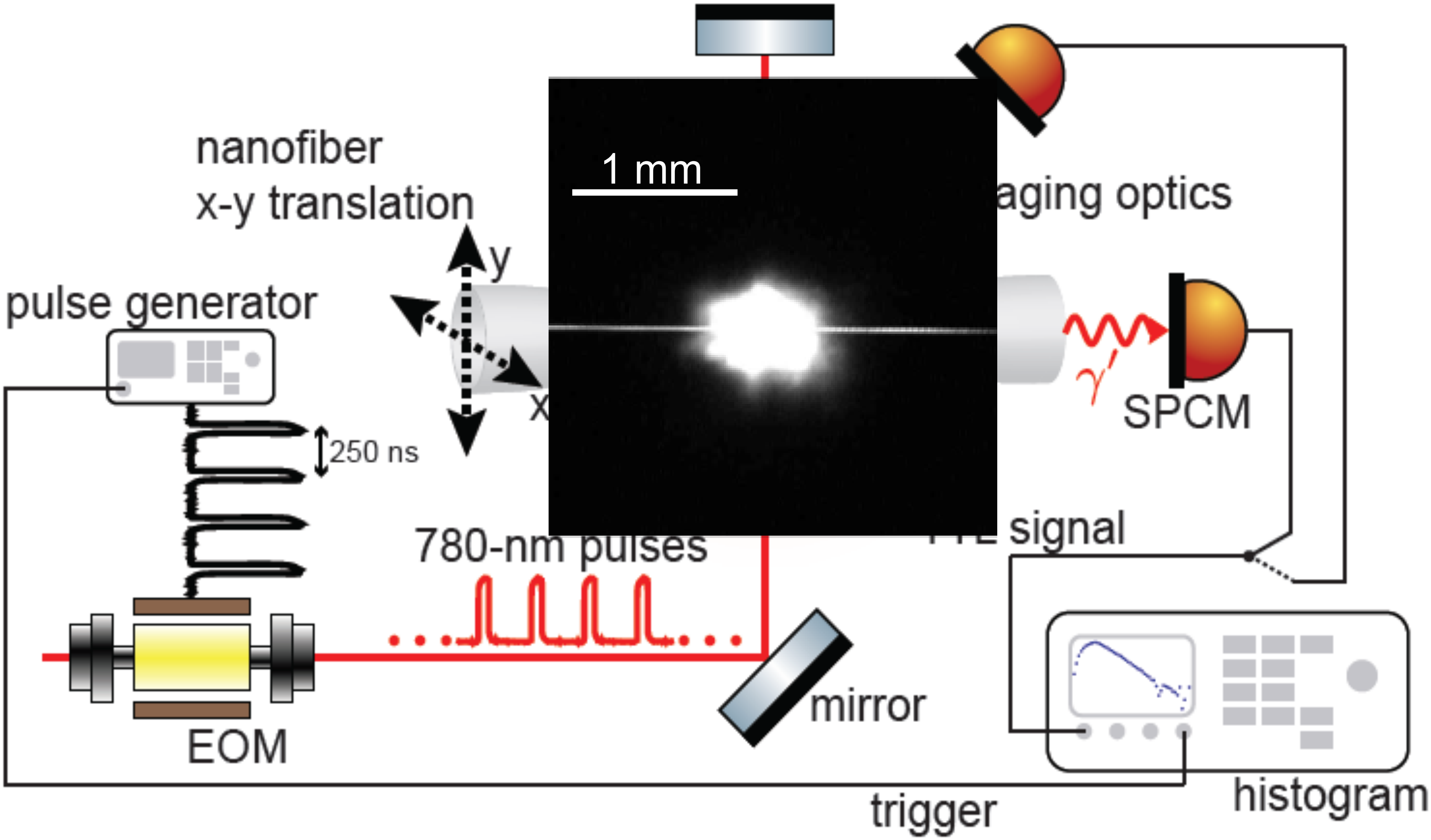


The sub- and super-radiant behavior depend on the phase relation of the atomic dipoles along the common mode

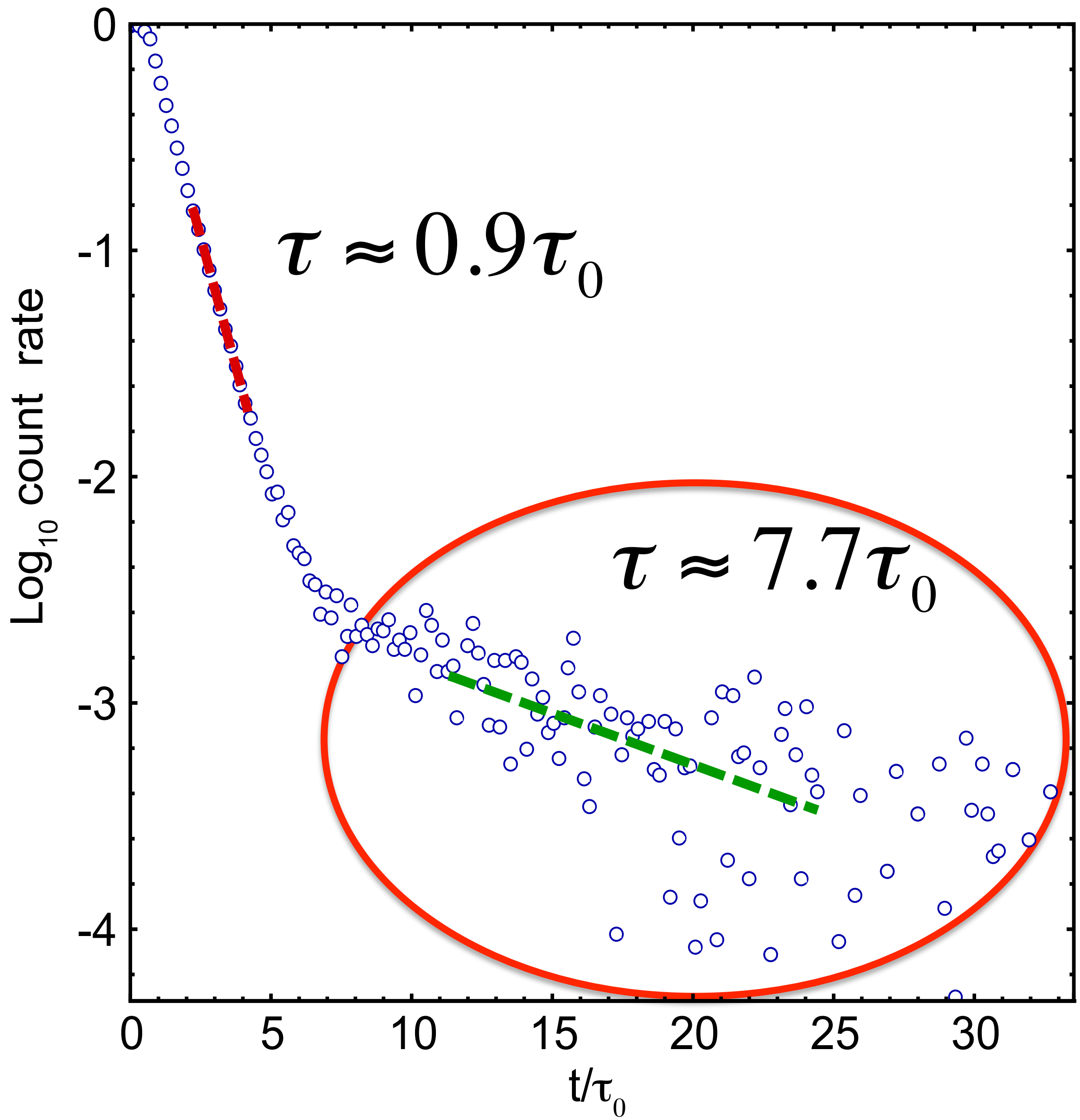
Measuring the Radiative Lifetime



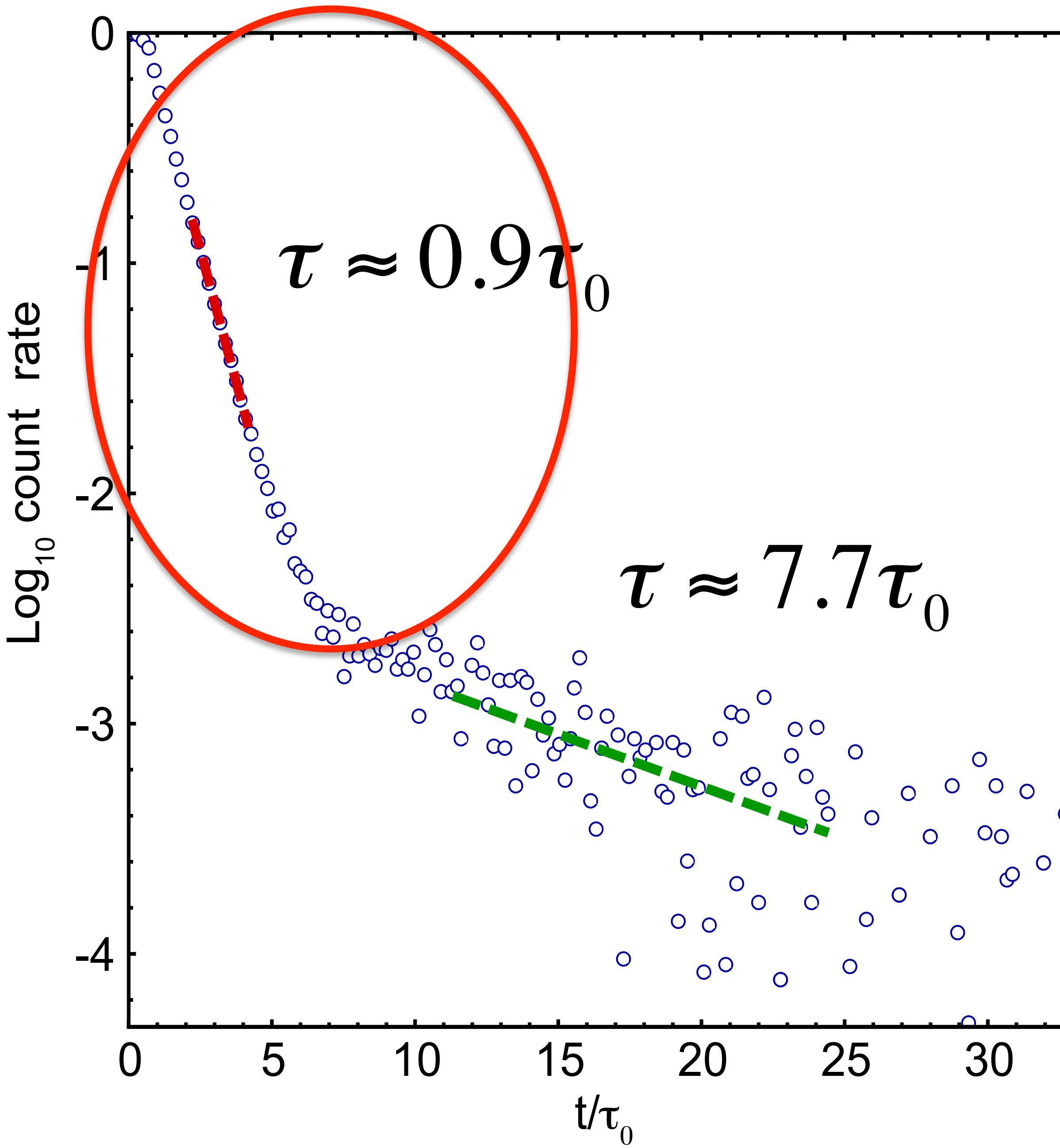
Measuring the Radiative Lifetime

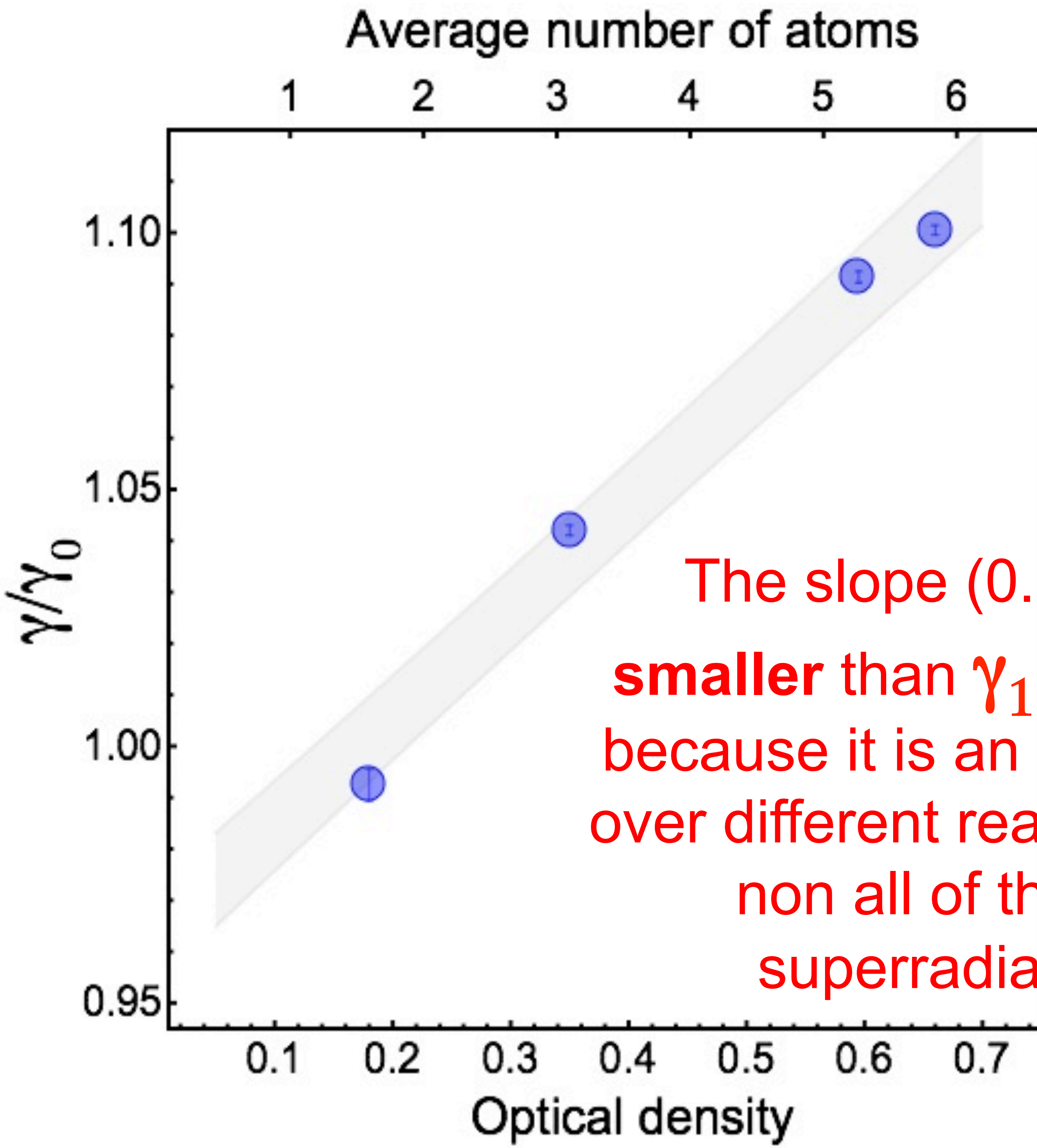


Two distinct lifetimes



Two distinct lifetimes

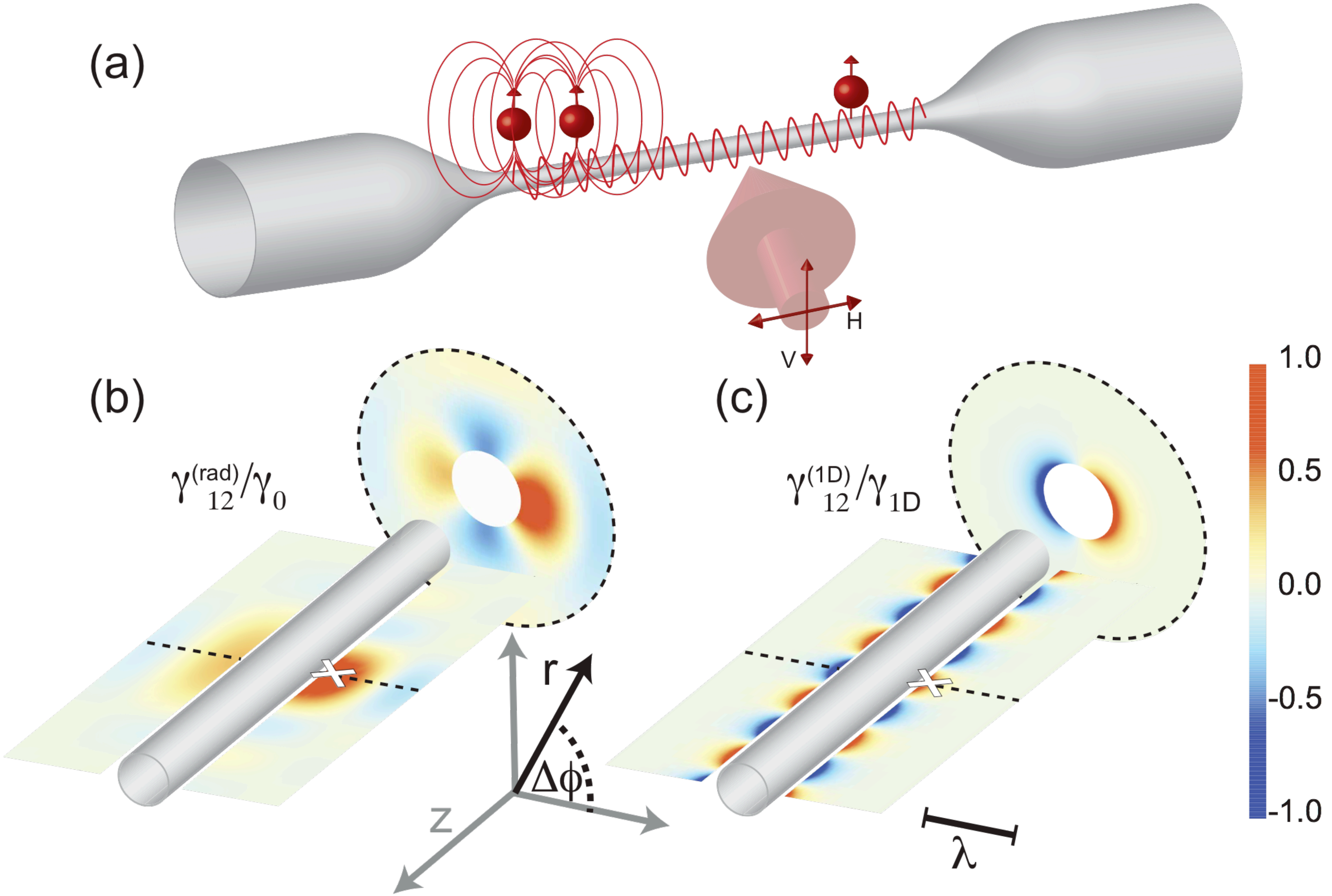




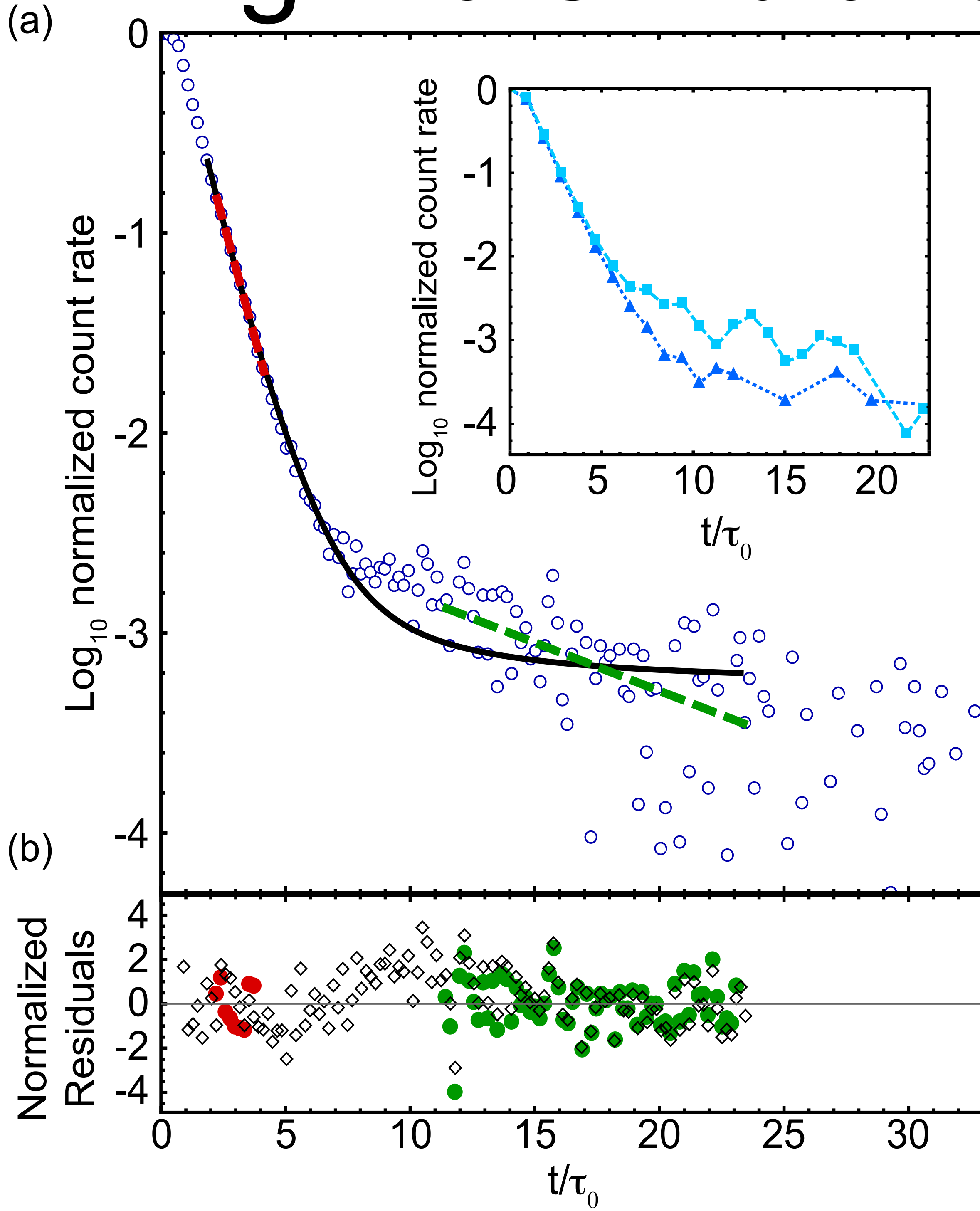
The slope (0.02) is **smaller** than γ_{1D} (0.10) because it is an **average** over different realizations, non all of them superradiant.

Understanding the Signal

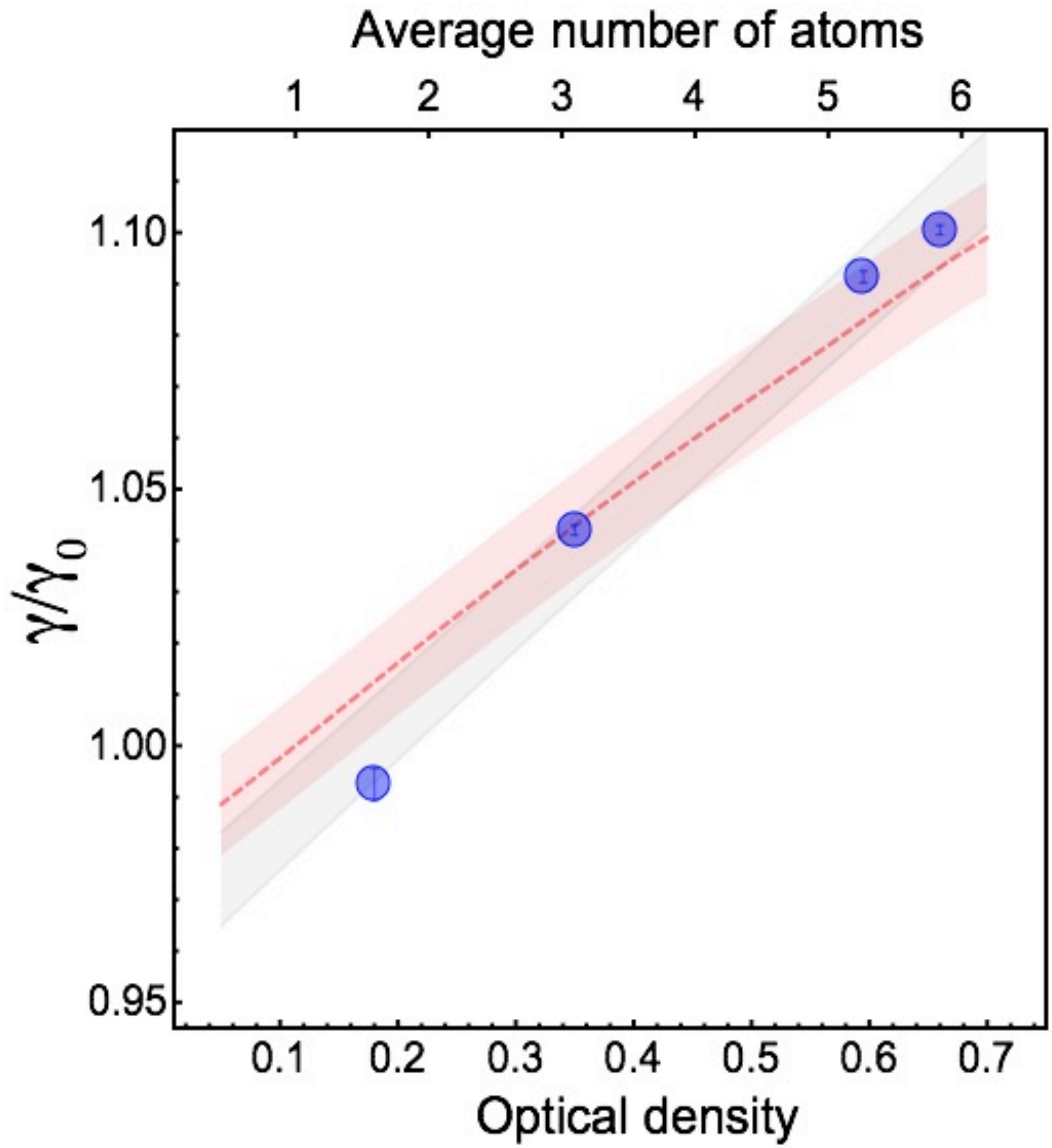
Understanding the Signal



Fitting the Simulation

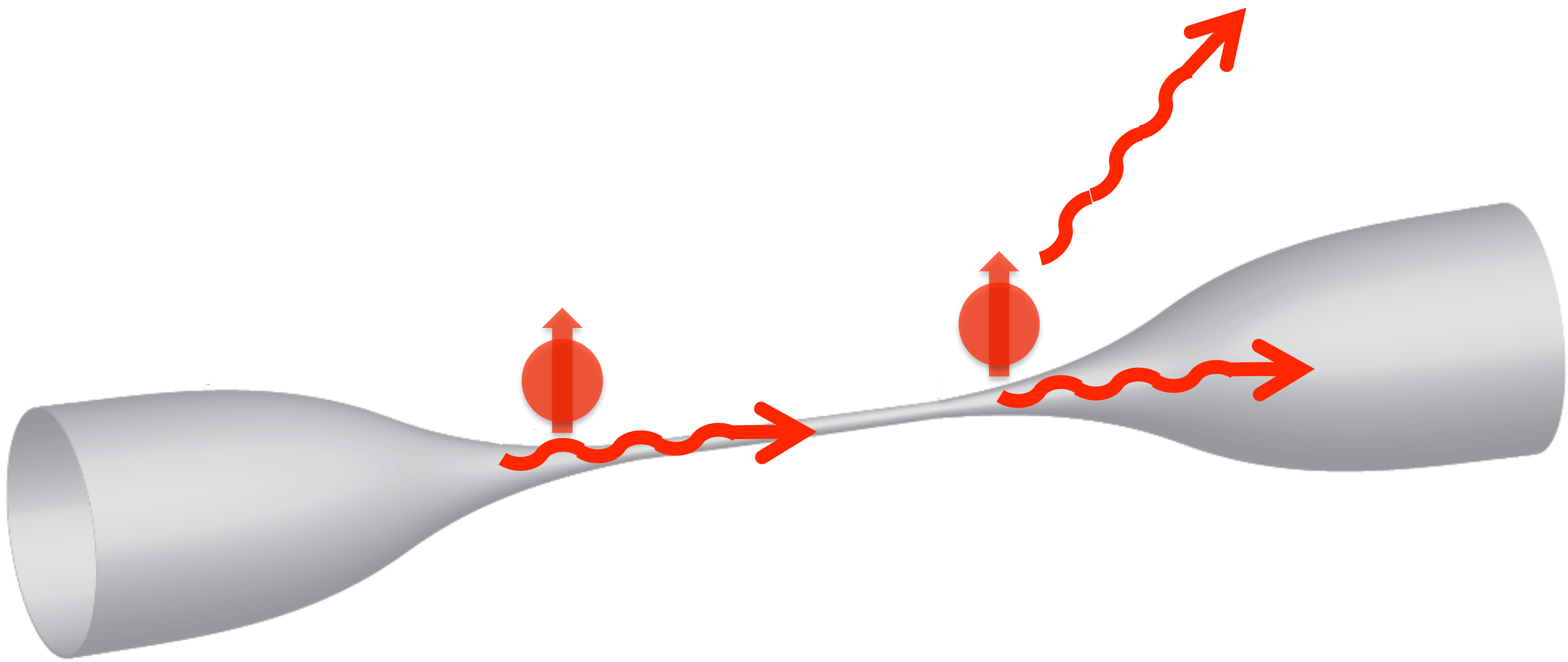


Fitting the Simulation

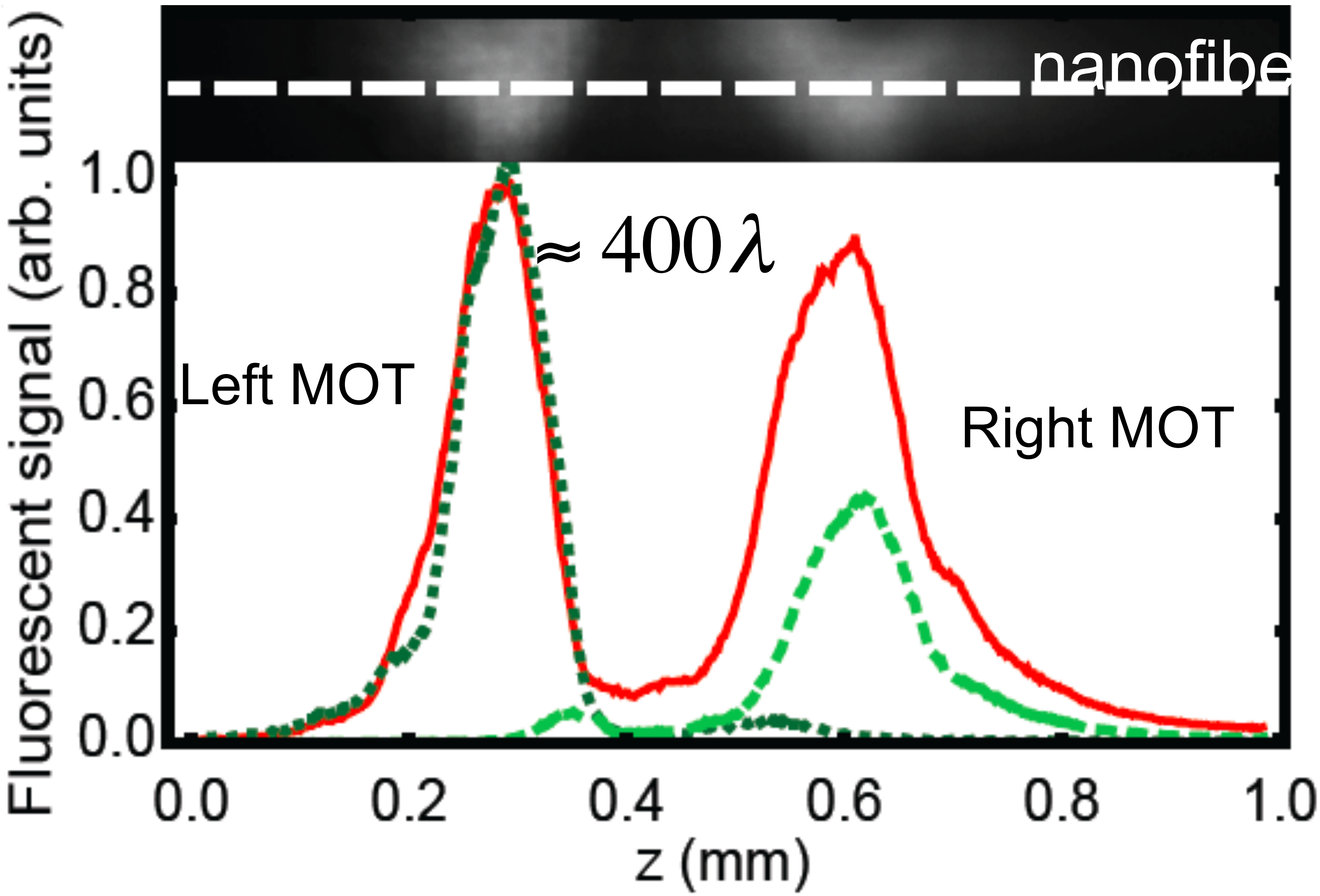


Can we see a collective atomic effect of atoms around the nanofiber?

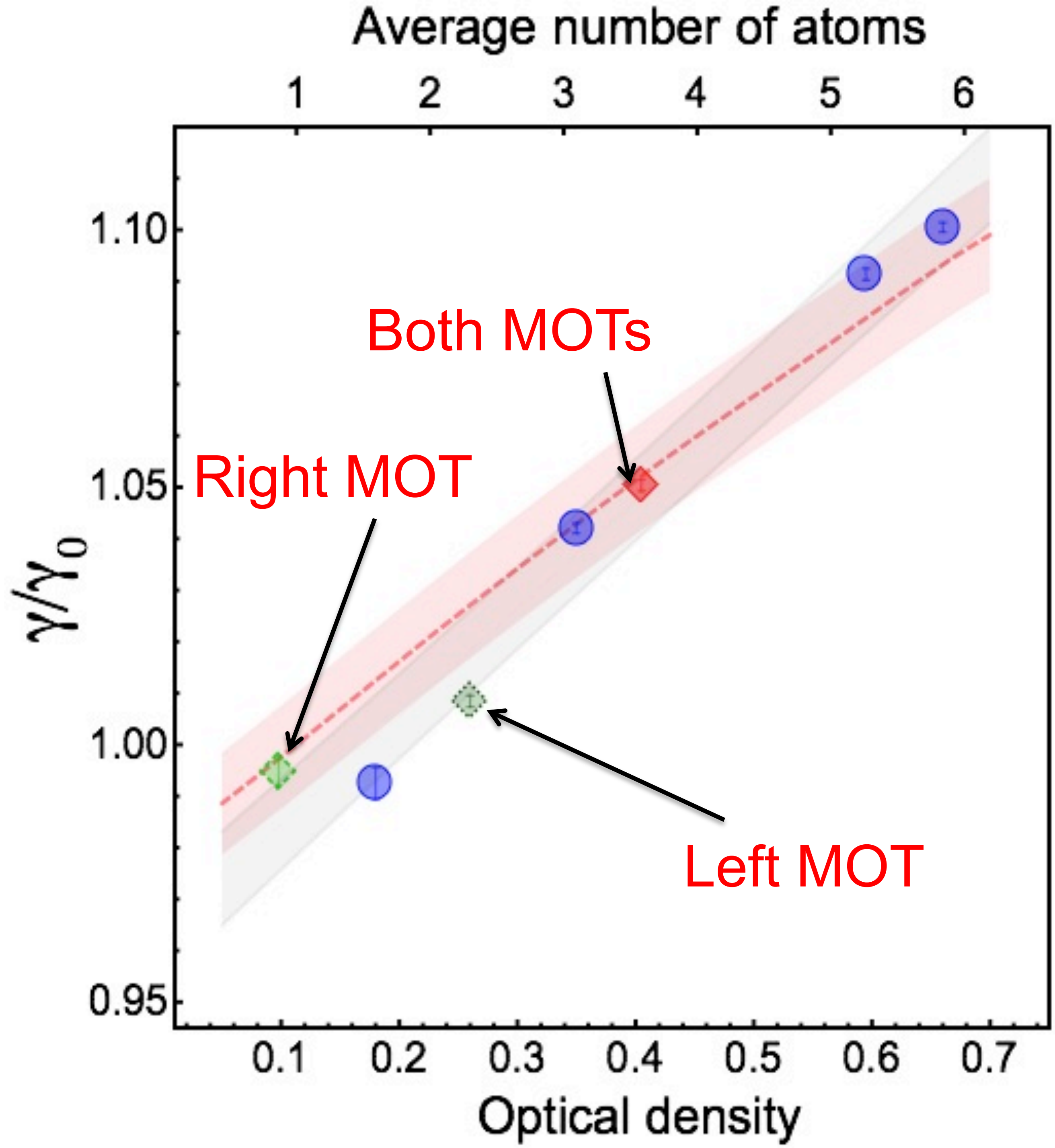
Long distance modification of the atomic radiation



Splitting the MOT in two



Evidence of infinite-range interactions



Final remarks

- Low Loss fibers for fundamental and higher order modes.
- Coupling atoms to evanescent mode.
- Birefringence of system tells of trapped atoms dynamics.
- Collective effects in the lifetime sub-radiance and super-radiance.

Thank you!