Top

Left side

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bottom

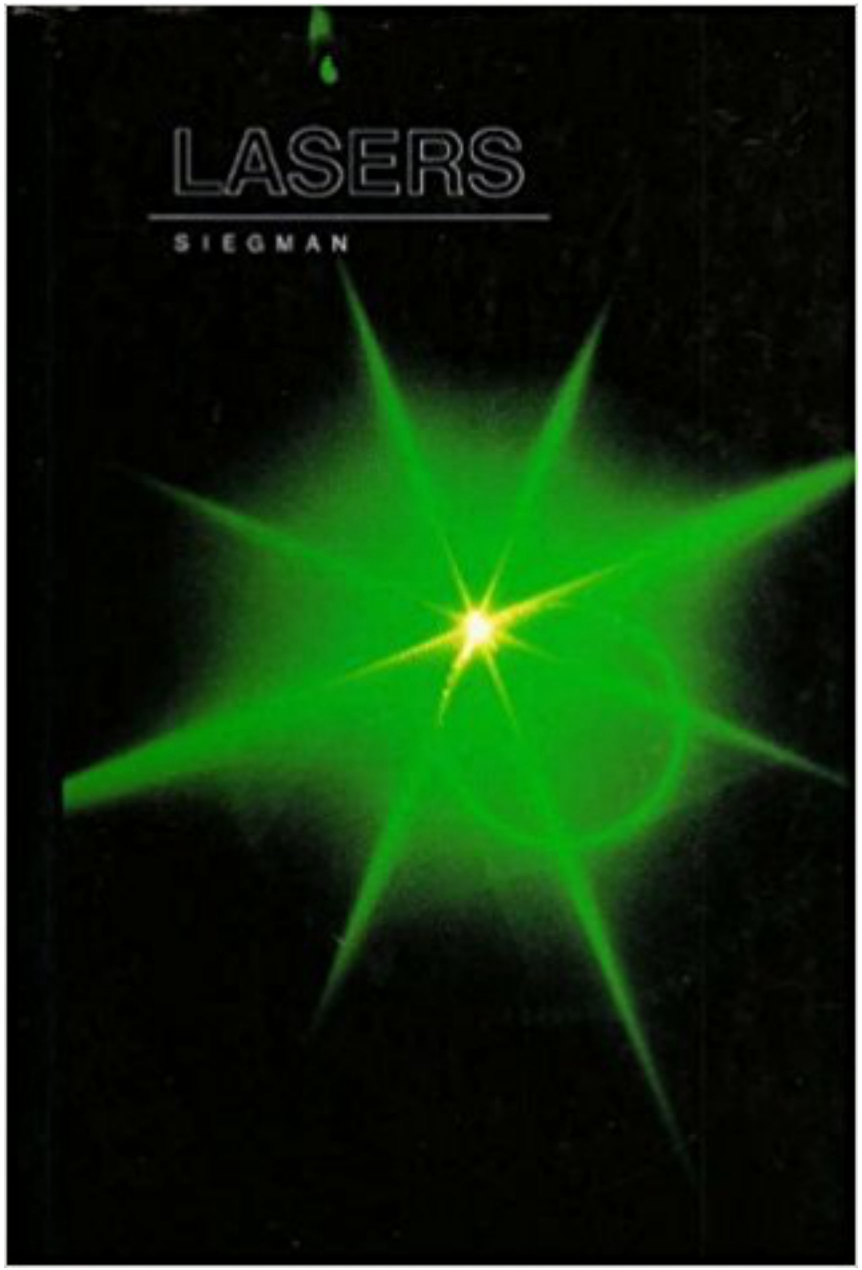
Laser applications to the study of atomic quantum structure.

2017 OSA Siegman International School on Lasers, Lecture 2

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).

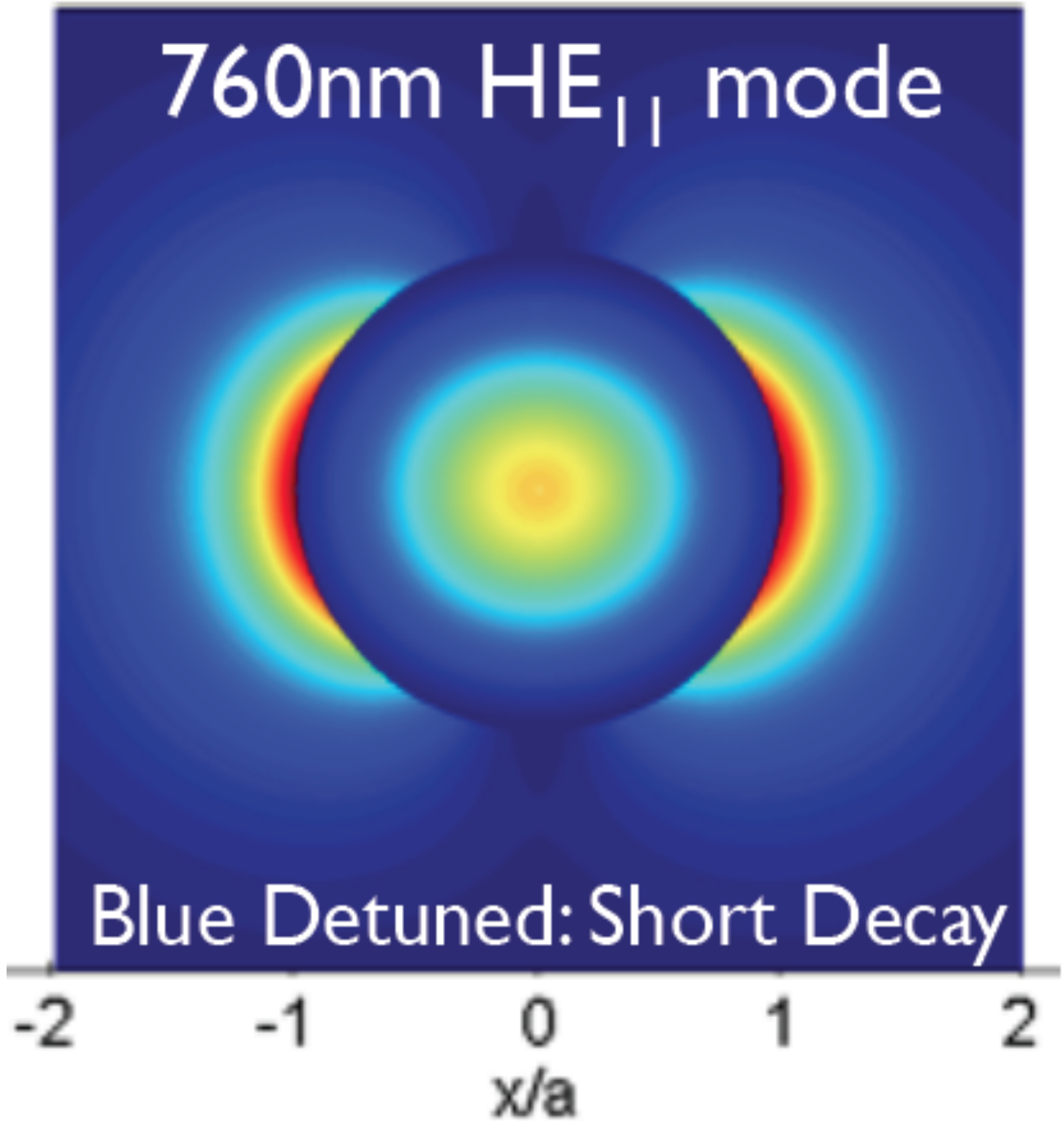
2nd lecture: Atom-light interaction of a two level atom (nanofibers at low intensity).

3rd lecture: Atom-light interaction of a two level atom at high intensity (cavity QED).

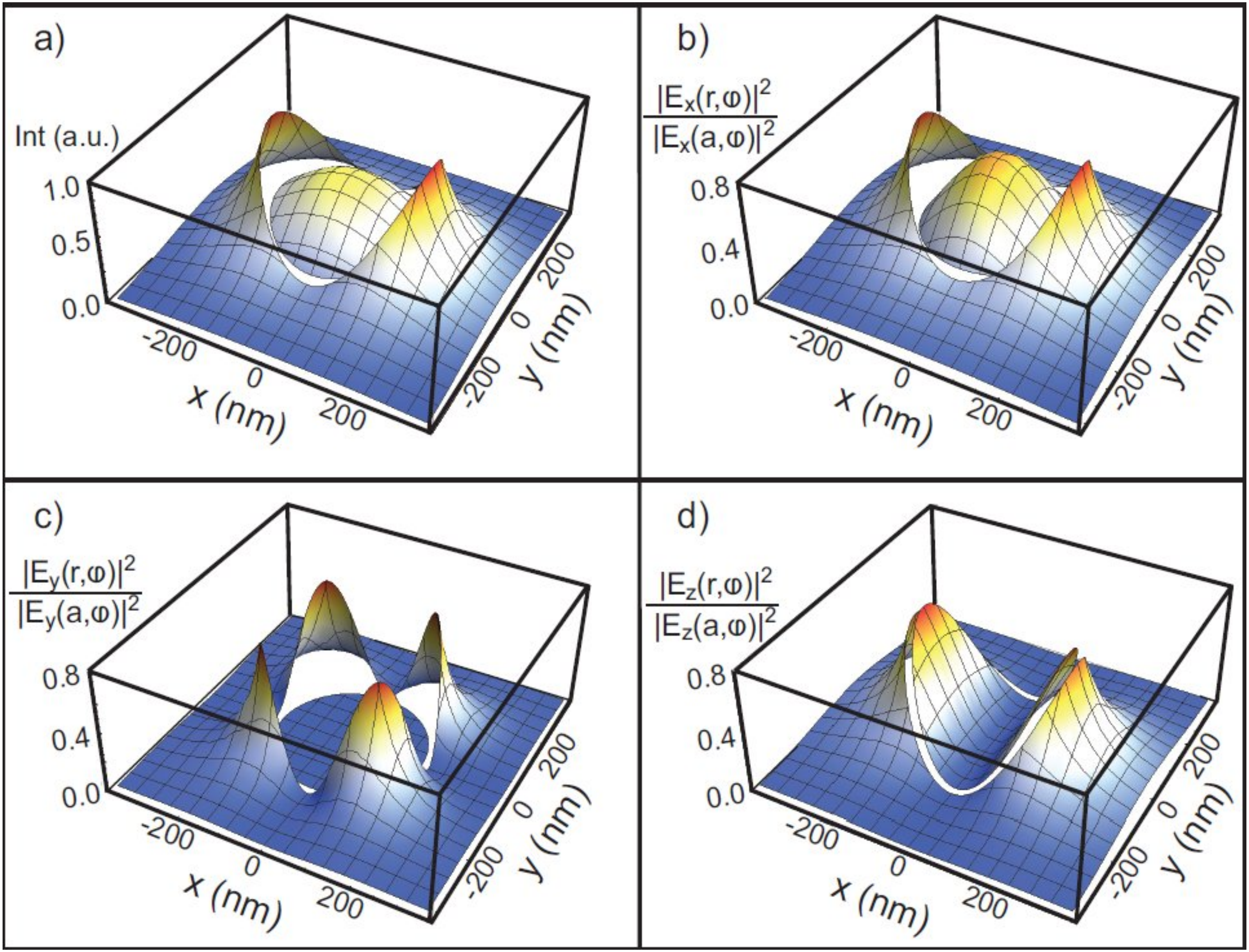
4th lecture: Different types of laser traps for atoms, (nanofibers, cavity QED, and spectroscopy).

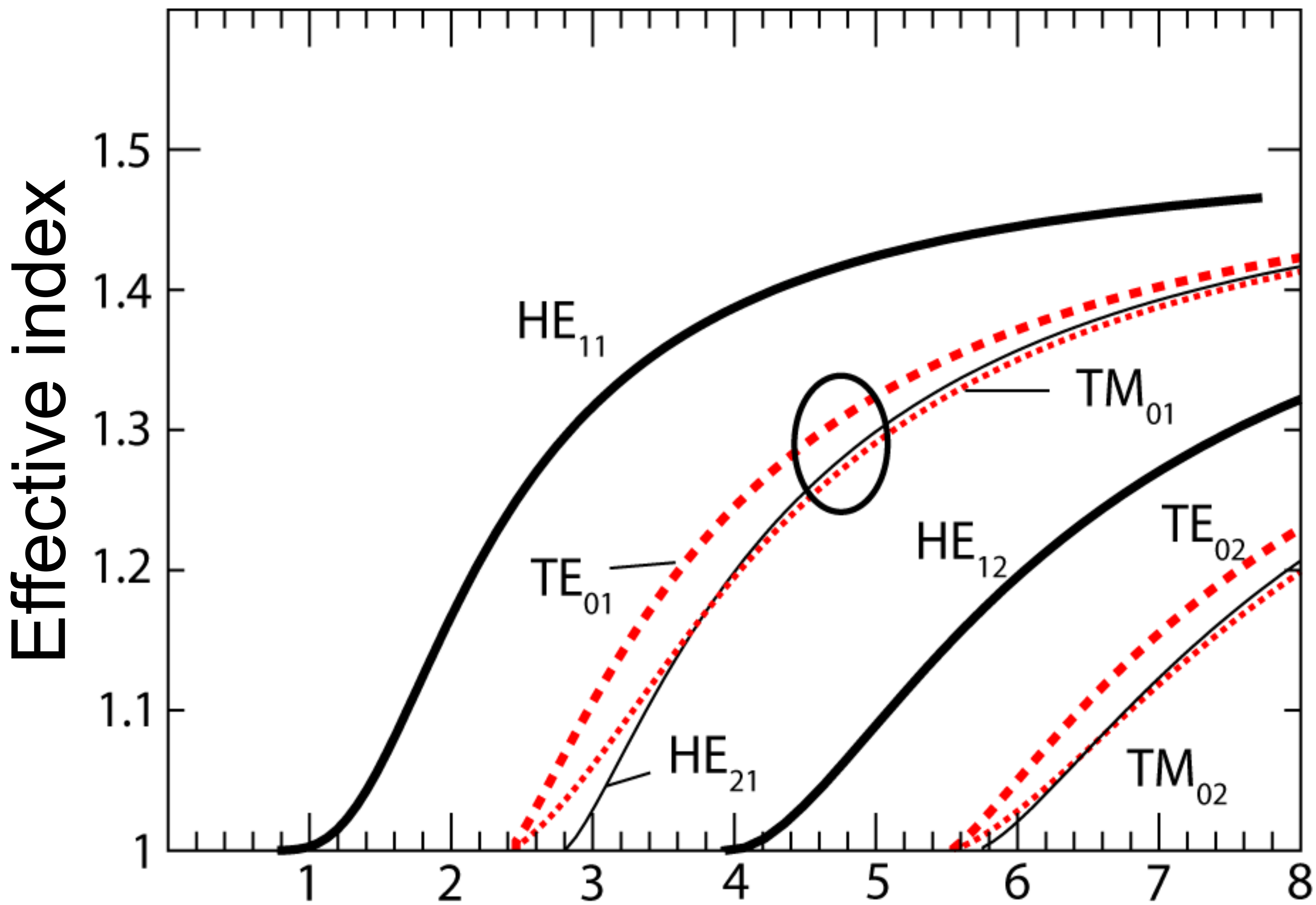
5th lecture: Weak interaction studies with Fr, a proposal.

The HE_{11} mode of the nanofiber with linearly polarized light



Radius ~ 250 nm; Decay length: $\lambda/2\pi$ ~100 nm


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)



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

V is related to the acceptance angle and the radius R of the fiber.

$$\sin\theta = \sqrt{n_{core}^2 - n_{cladding}^2}$$

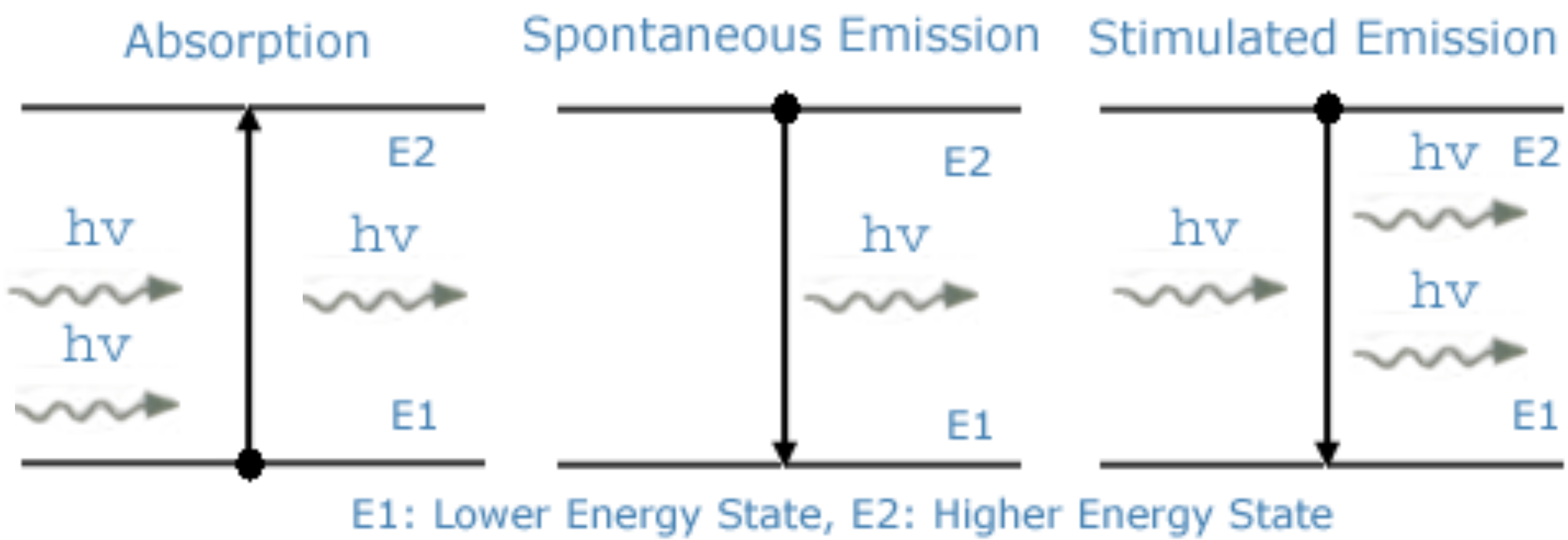
Bibliography 2nd lesson:

Pablo Solano, Jeffrey A. Grover, Yunlu Xu, Pablo Barberis-Blostein, Jeremy N. Munday, Luis A. Orozco, William D. Phillips, Steven L. Rolston. "Alignment-dependent decay rate of an atomic dipole near an optical nanofiber" arXiv:1704.08741

Pablo Solano, Fredrik K. Fatemi, Luis A. Orozco, Steven L. Rolston. "Supe-radiance reveals infinite-range interactions through a nanofiber" arXiv:1704.07486v2

2^{nd} lecture: Atom-light interaction of a two level atom (nanofibers [ONF]).

1. One atom interacting with light in free space.



Absorption and Stimulated Emission are time reversals of each other, you can say this is the classical part. Spontaneous emission is the quantum, that is the jump.

Saturation intensity:

One photon every two lifetimes over the cross section of the atom (resonant)

$$I_0 = \frac{\hbar\omega_0}{2\tau_0\sigma_0} = \frac{\pi}{3}\frac{\gamma_0\hbar\omega_0}{\lambda_0^2}$$

This makes the rate of spontaneous emission equal to the stimulated emission (Rabi Frequency Ω) and the population on the excited state m=1/4.

$$\Omega = \frac{\vec{d}\bullet\vec{E}}{\hbar} = \gamma\sqrt{I/I_0}$$

$$m = \frac{1}{2}\frac{I/I_0}{1 + I/I_0}$$

At low intensity ($I \ll I_0$) only spontaneous emission is relevant.

How to measure the rate of spontaneous emission?

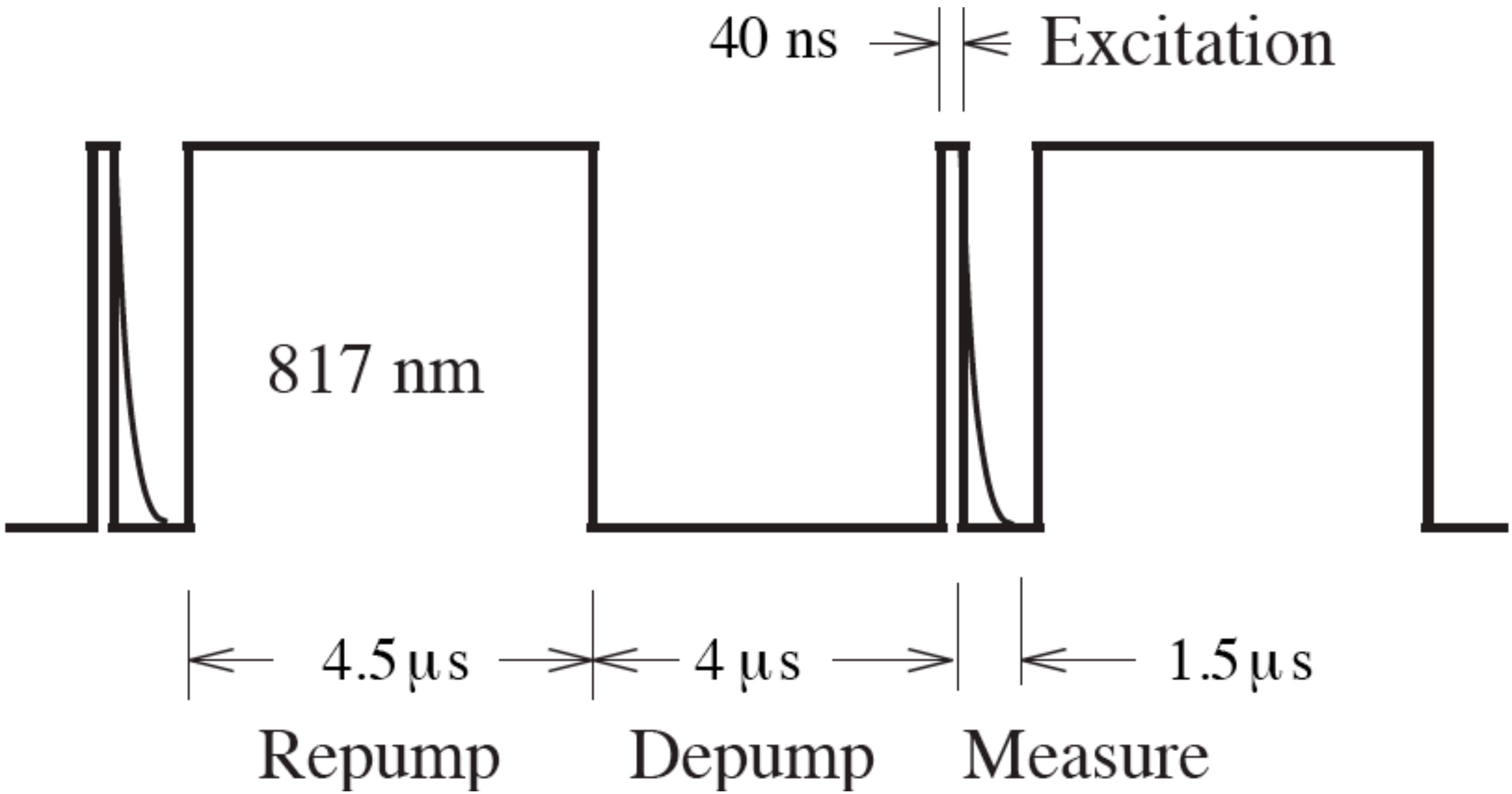
Measure the lifetime when $I \ll I_0$

Method:

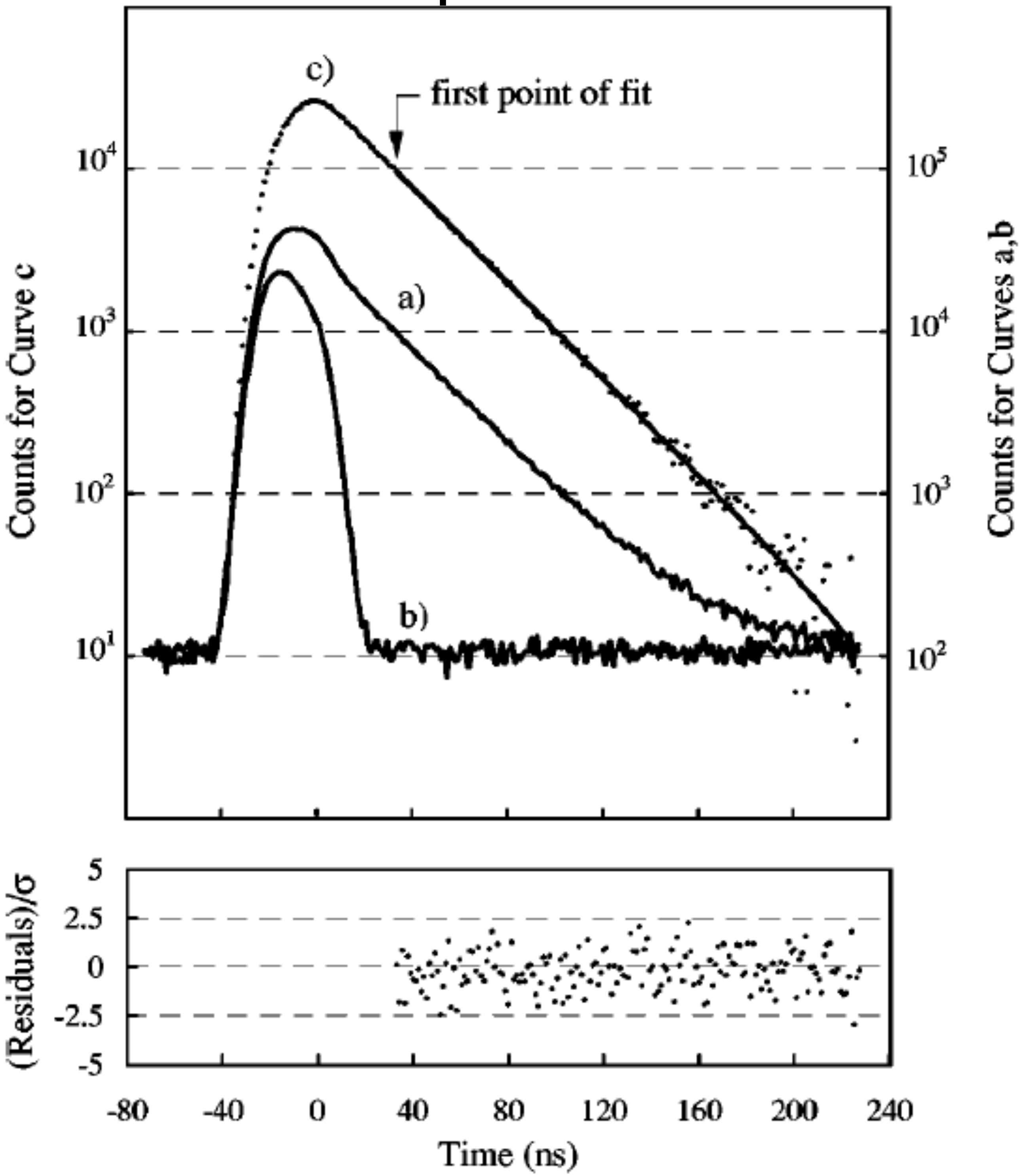
Start a clock when the light turns off and then stop the clock when a photon arrives at the detector. Time Correlated Single Photon Counting (TCSPC)

What is the probability of detecting a photon after we have excited the system, an exponential decay.

Time sequence



Free space atoms



Francium D_1 Line

TABLE I. Error budget for the lifetimes of the D_2 and D_1 lines of Fr in percentage.

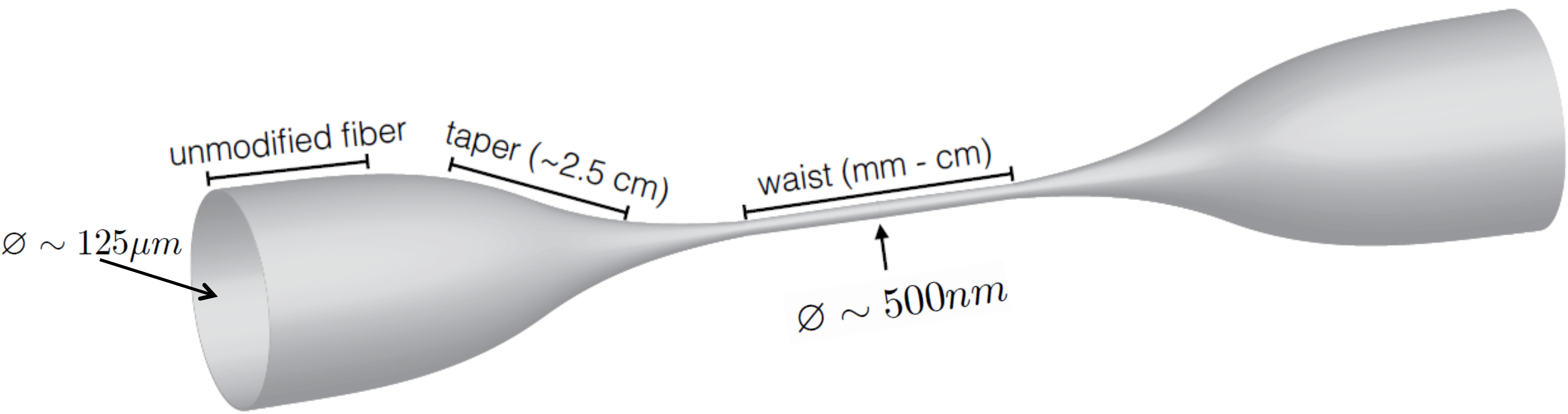
Error	Fr $P_{3/2}$(%)	Fr $P_{1/2}$(%)
Systematic		
TAC-MCA nonlinearity	±0.03	±0.03
Time calibration	±0.04	±0.04
Truncation error	±0.39	±0.19
Zeeman quantum beat	±0.04	±0.00
Other	±0.23	±0.25
Total systematic	±0.46	±0.32
Statistical	±0.24	±0.18
Sum in quadrature	±0.52	±0.37

Final number: 29.45 (11) nm

J. E. Simsarian, et al, "Lifetime measurement of the *7p* levels in francium."Phys Rev. A 57, 2448 (1998)

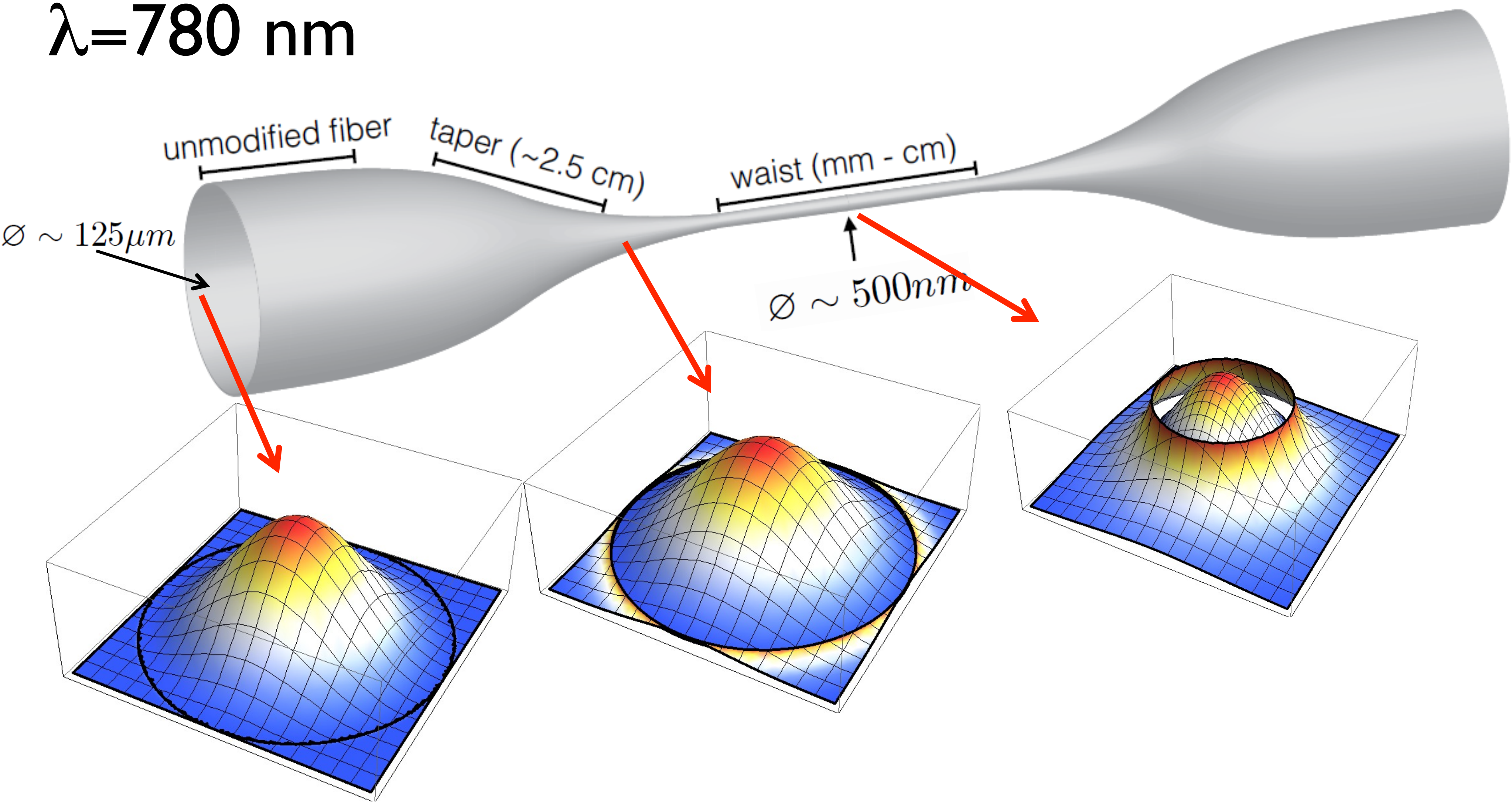
2. One atom interacting with light near a nanofiber, Purcell effect.

Optical Nanofibers



Optical Nanofibers

λ=780 nm

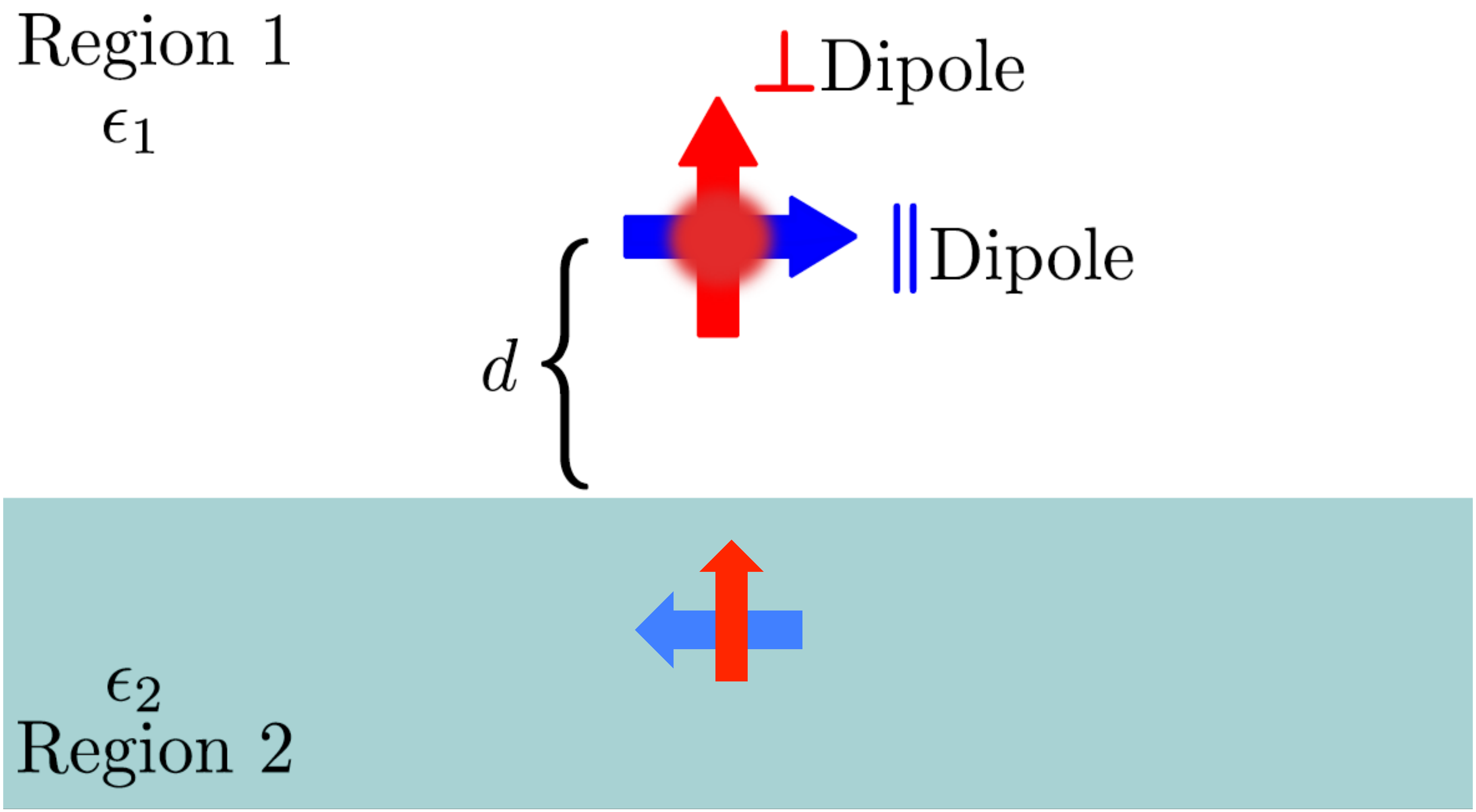


Modified decay rate

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

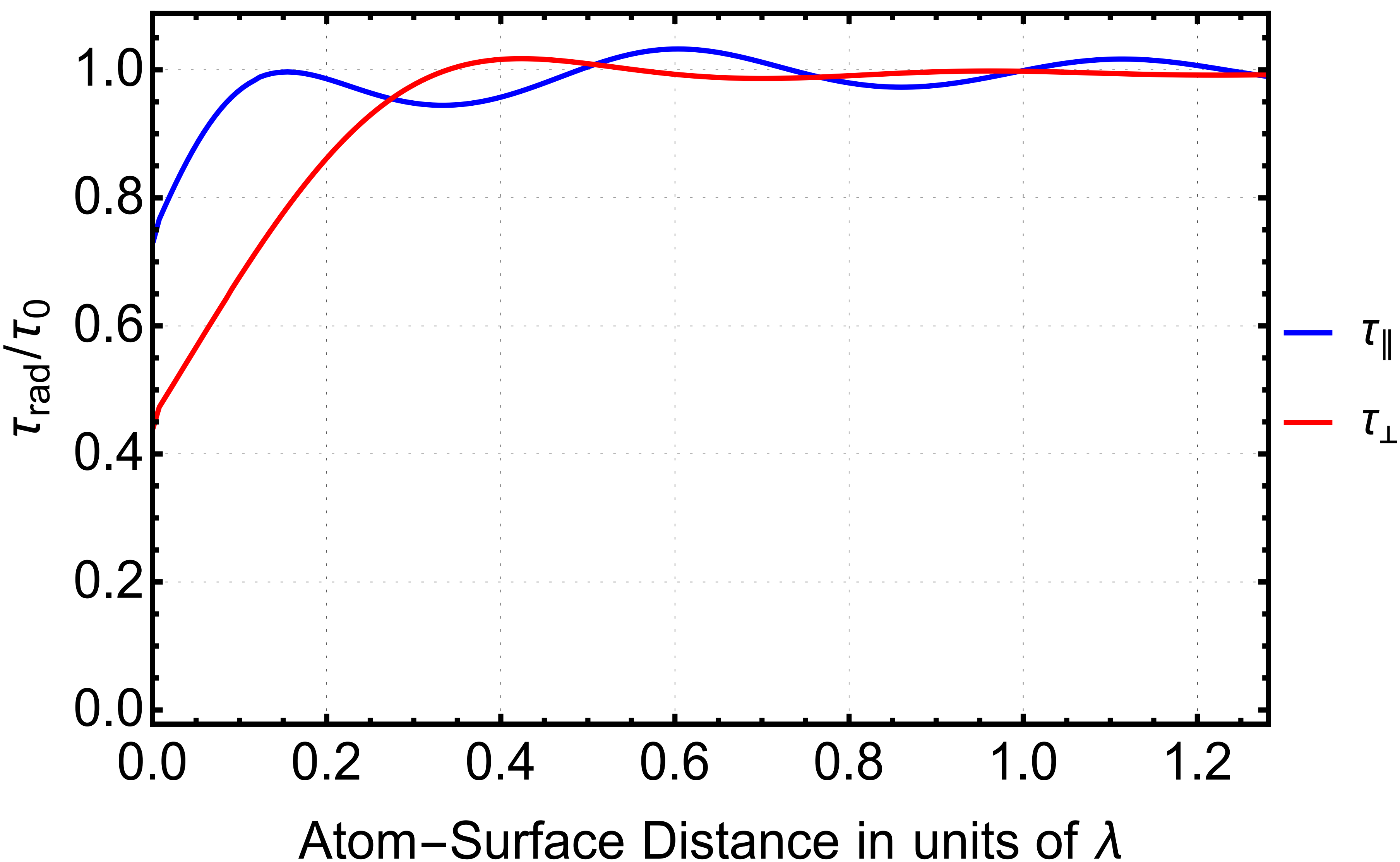
Proportional to the electric field of the radiated mode.

Effect of a dielectric surface

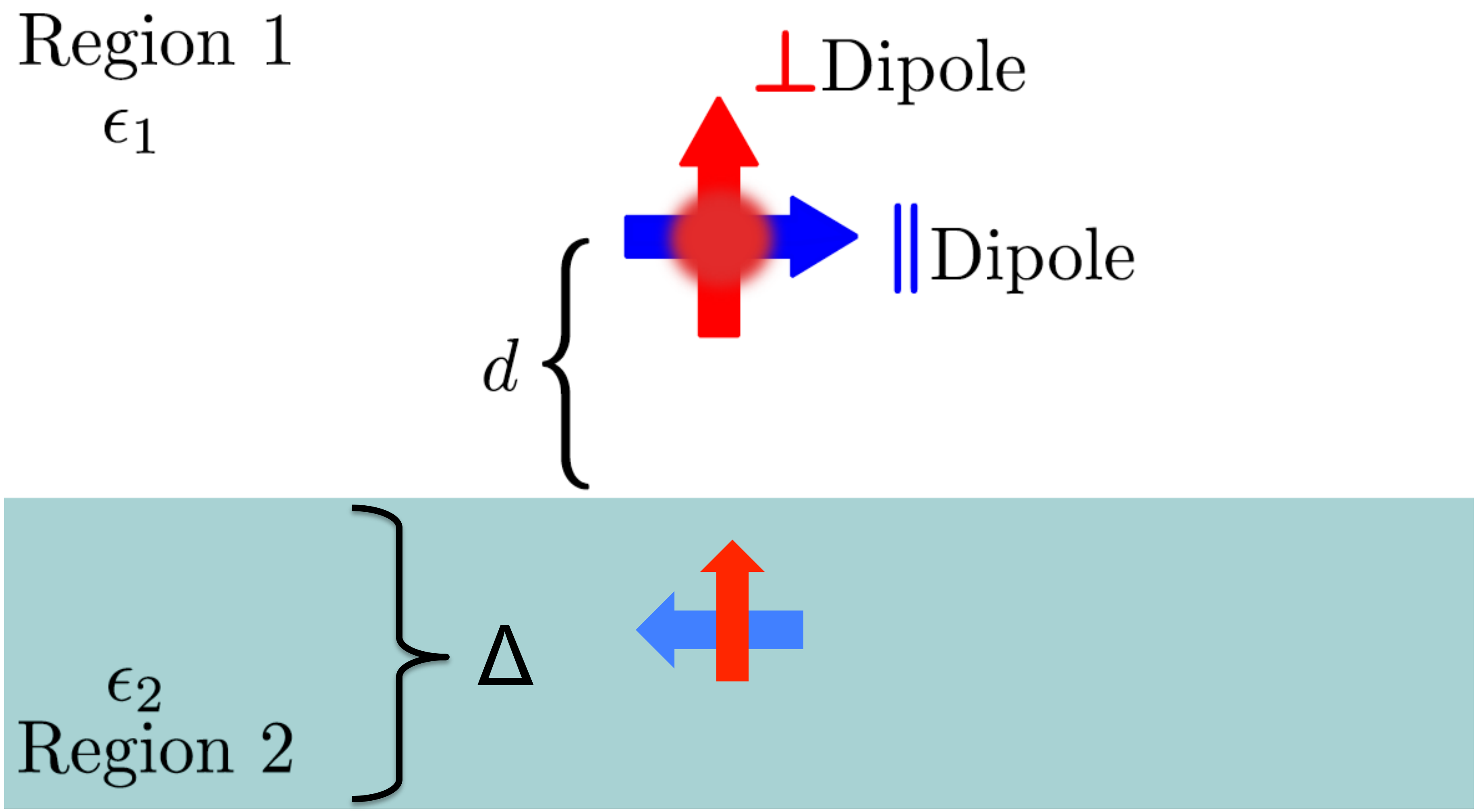


Induced Dipoles (images)

Effect of a dielectric surface

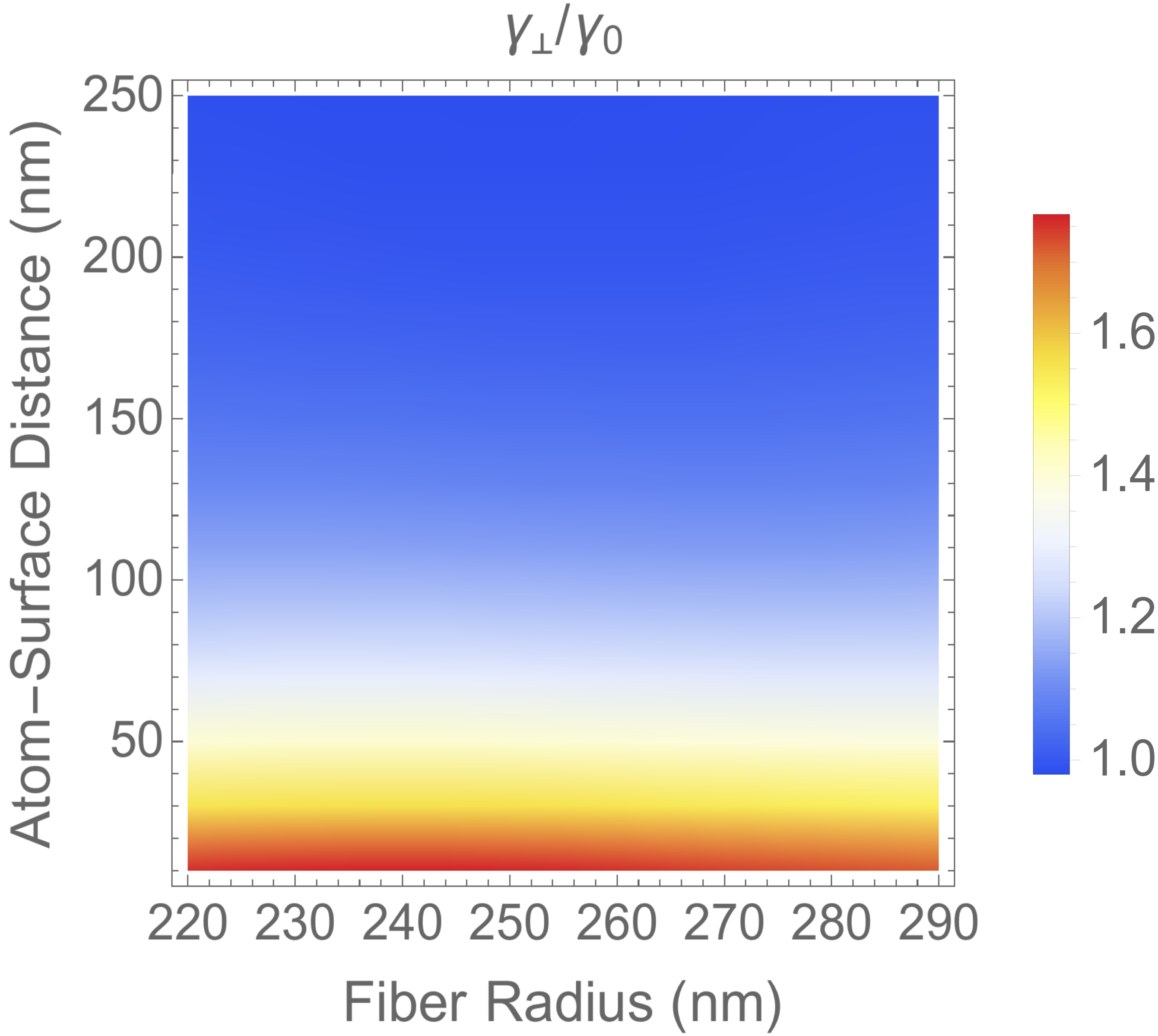


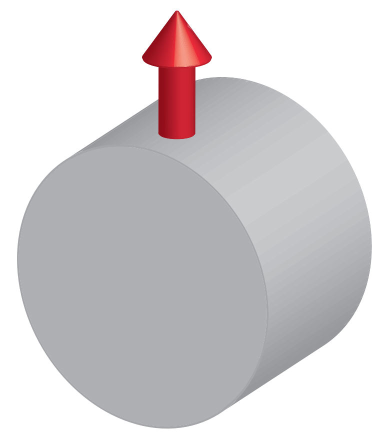
Effect of a dielectric surface



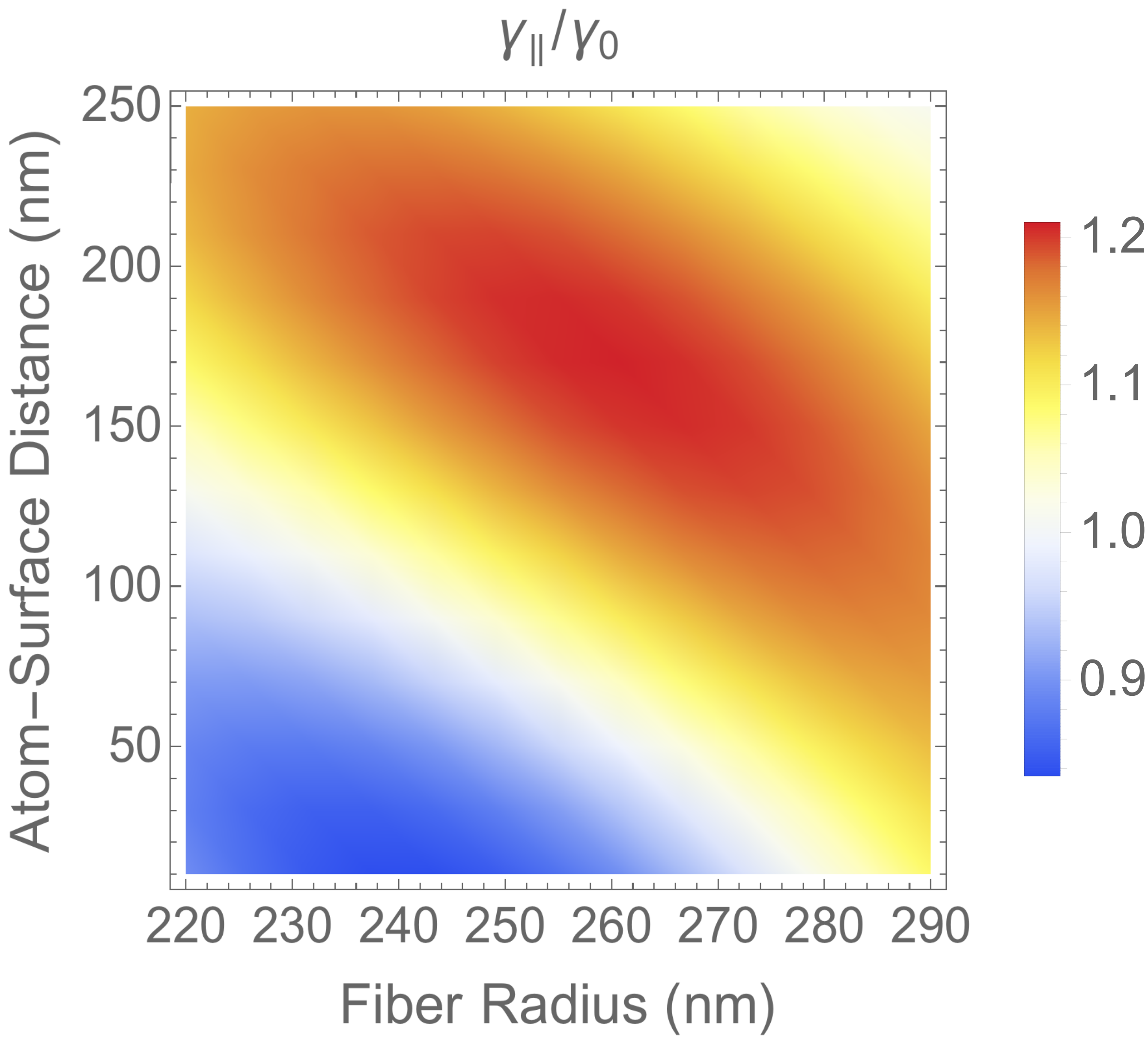
Reflection on the second surface.

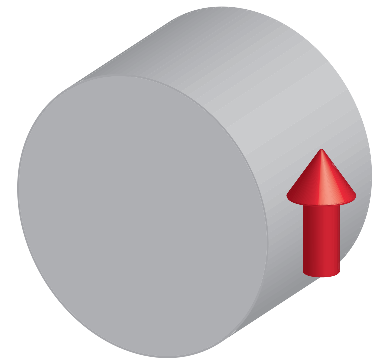
Purcell effect around an ONF



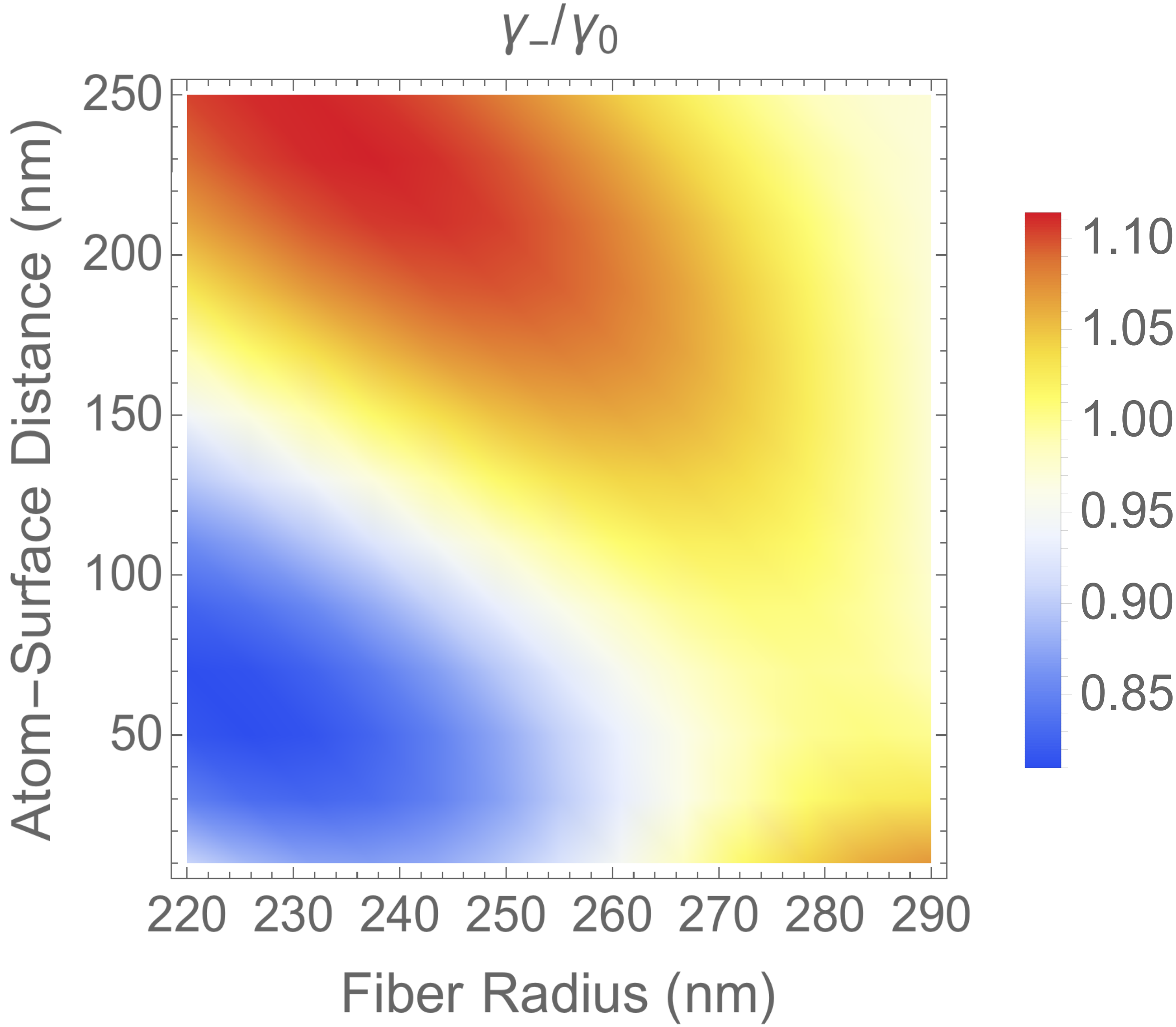


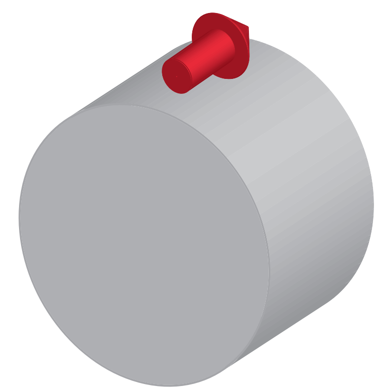
Purcell effect around an ONF



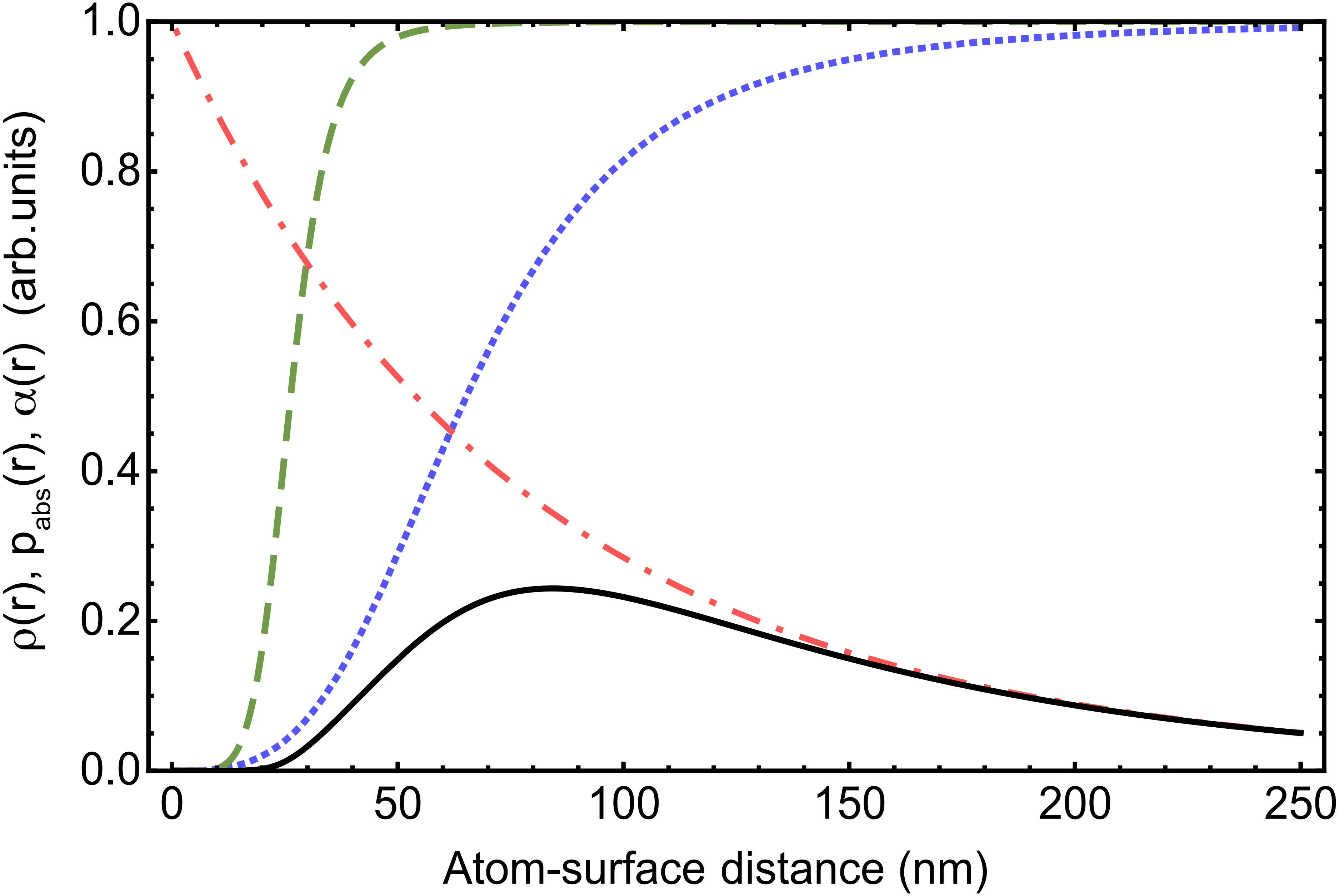


Purcell effect around an ONF

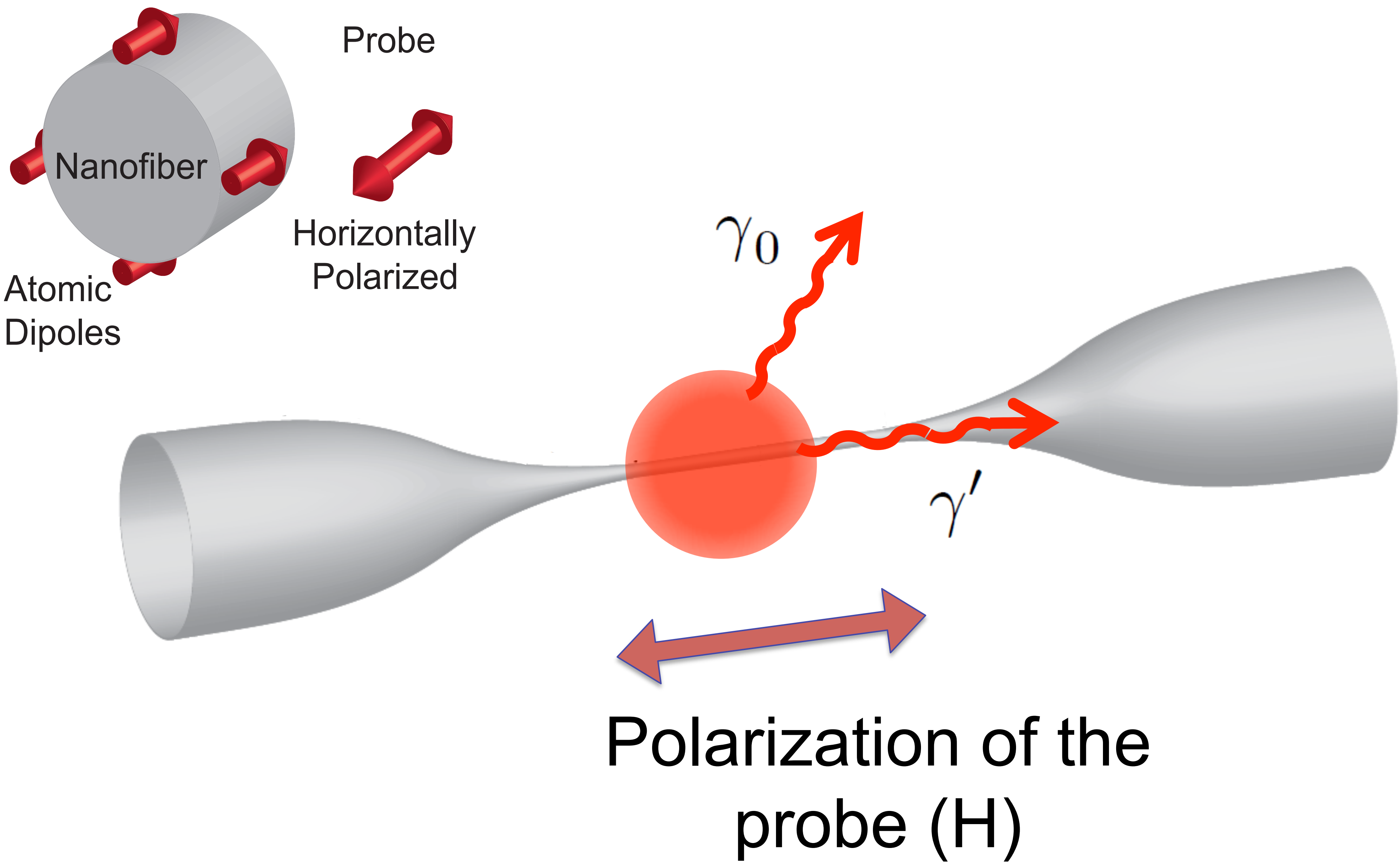




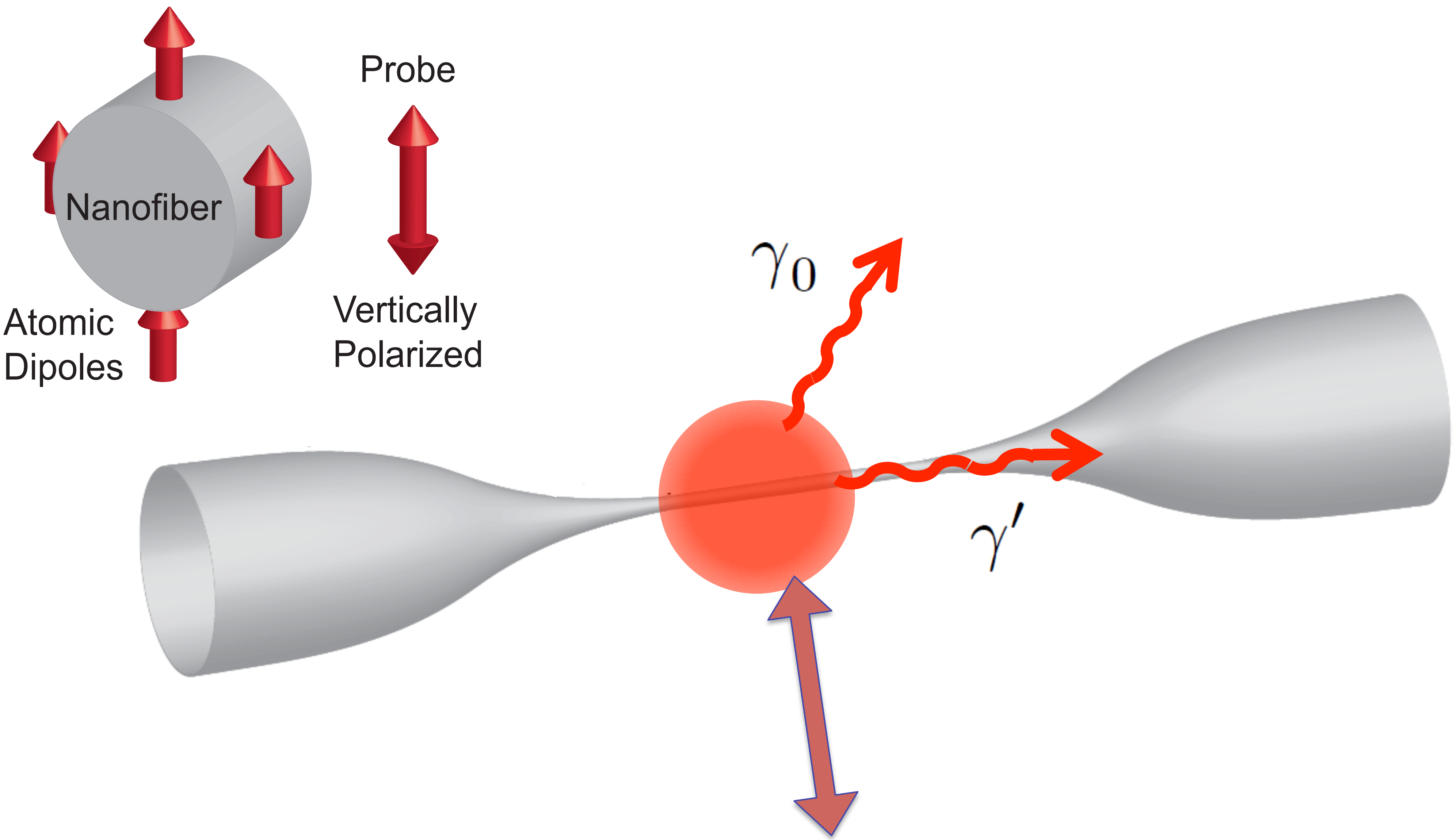
Use free atoms around the nanofiber, distribution peaks around 70 nmm from density, mode and Van der Walls interaction



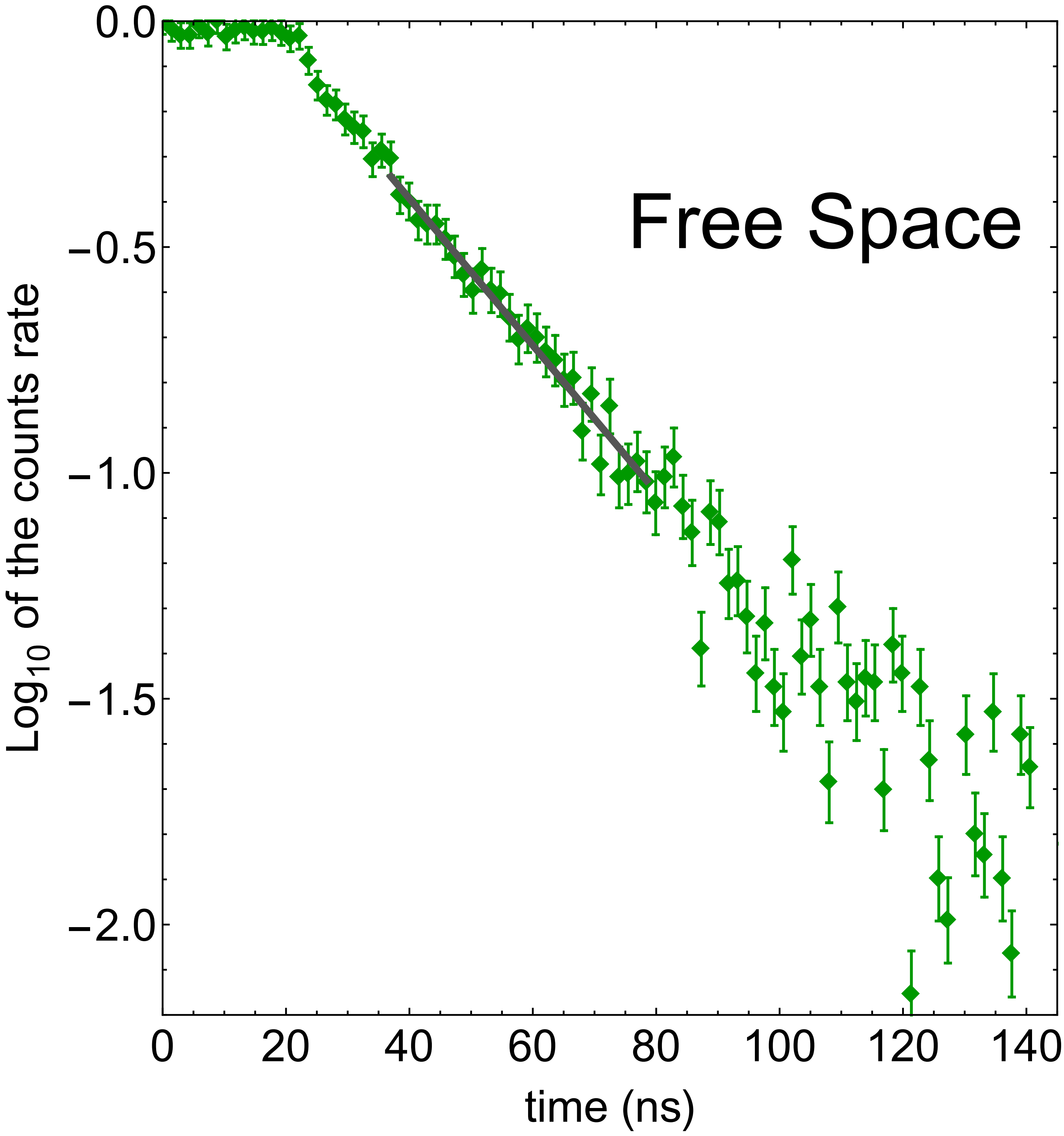
Dipole orientation

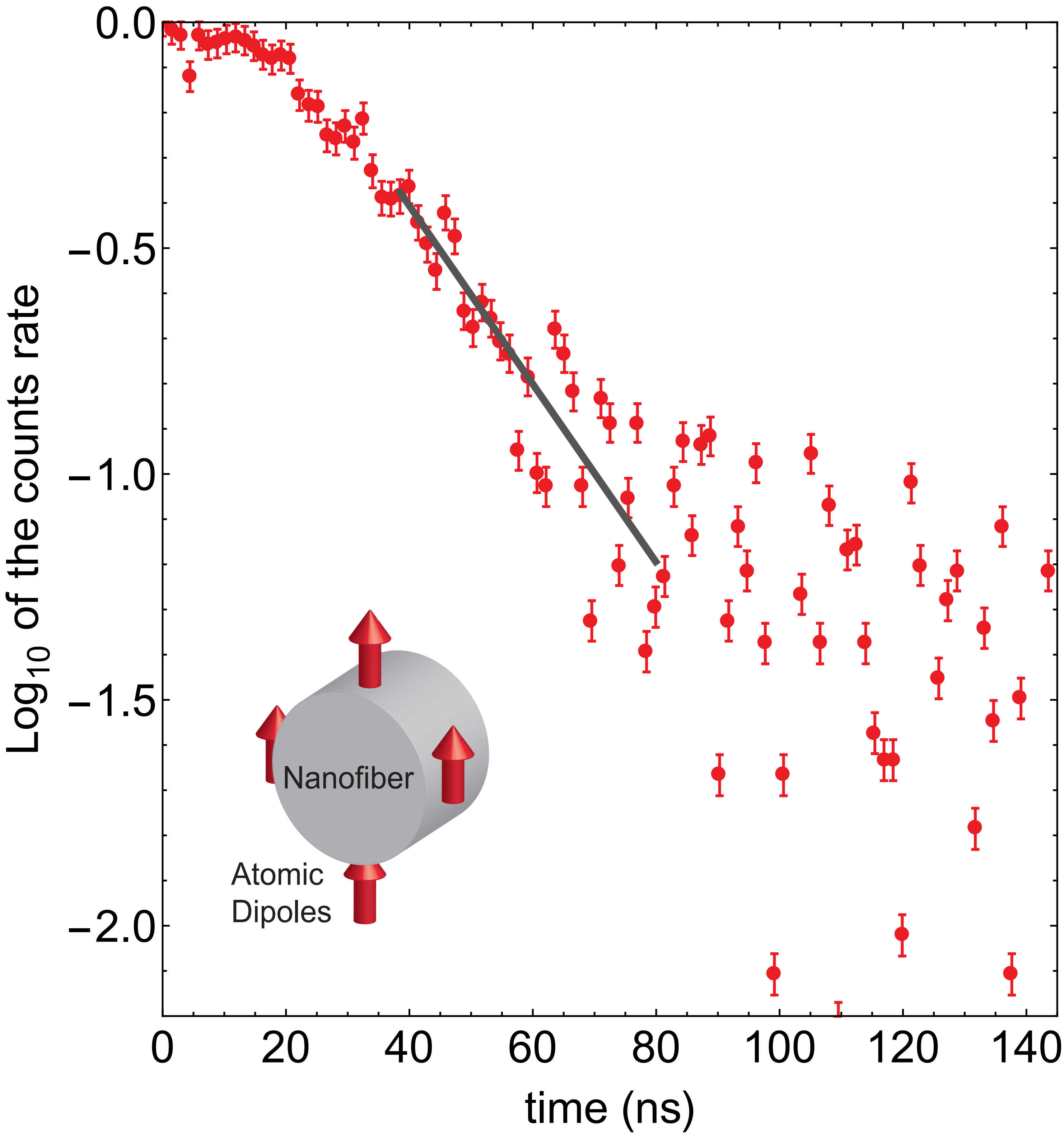


Dipole orientation

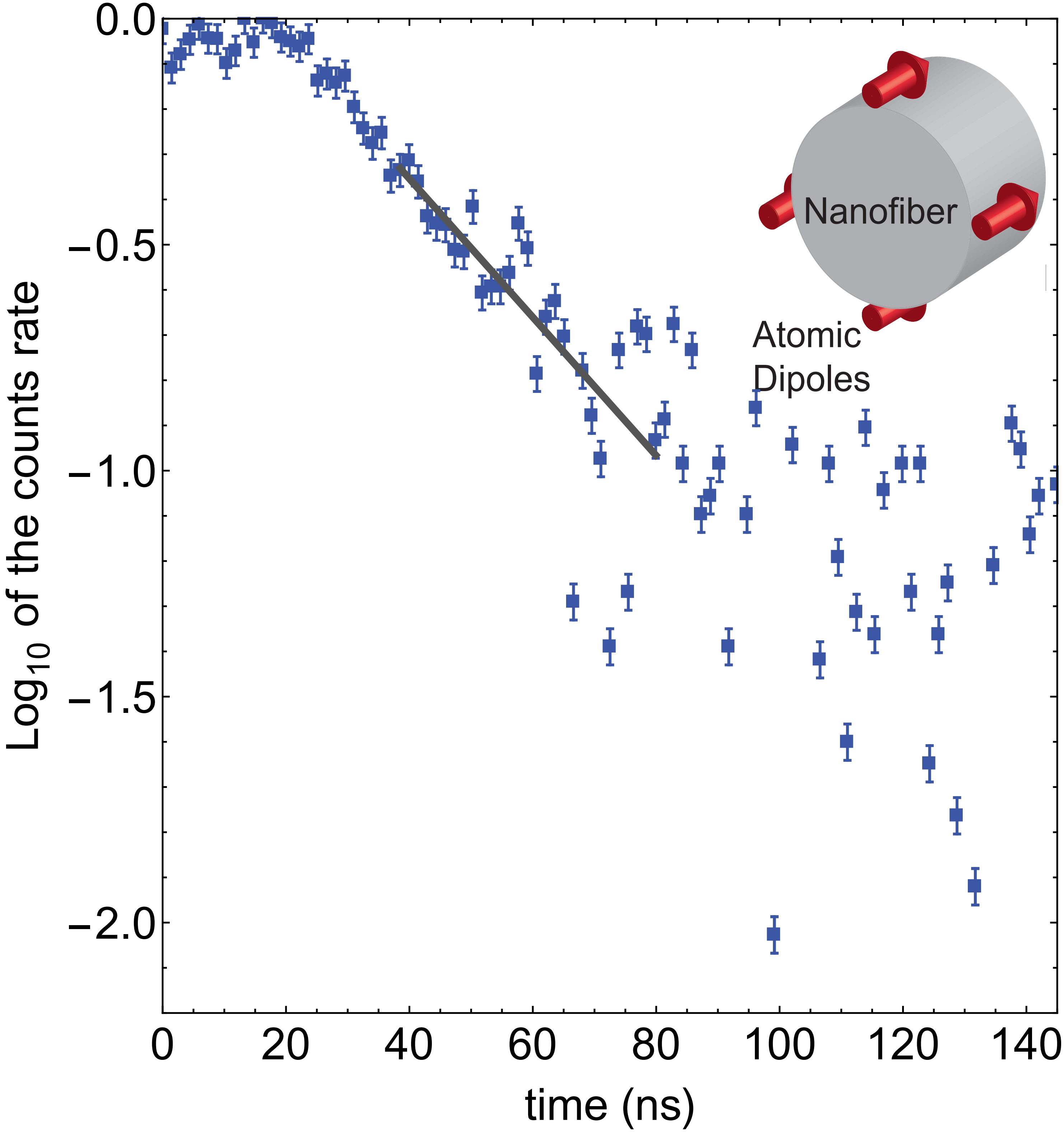


Polarization of the probe (V)

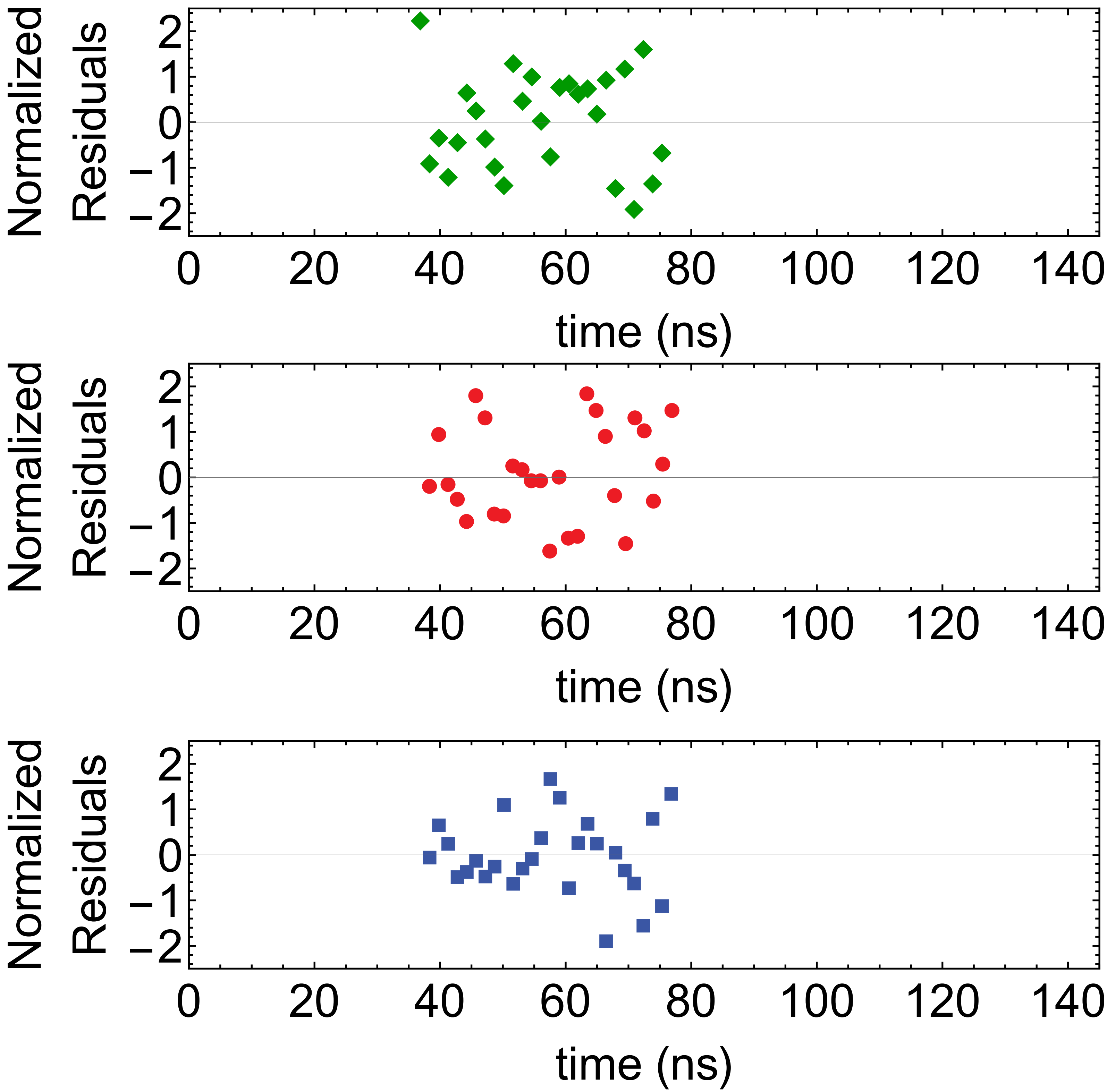

Free Space
Log10 of the counts rate
time (ns)
0.0
−0.5
−1.0
−1.5
−2.0
0
20
40
60
80
100
120
140

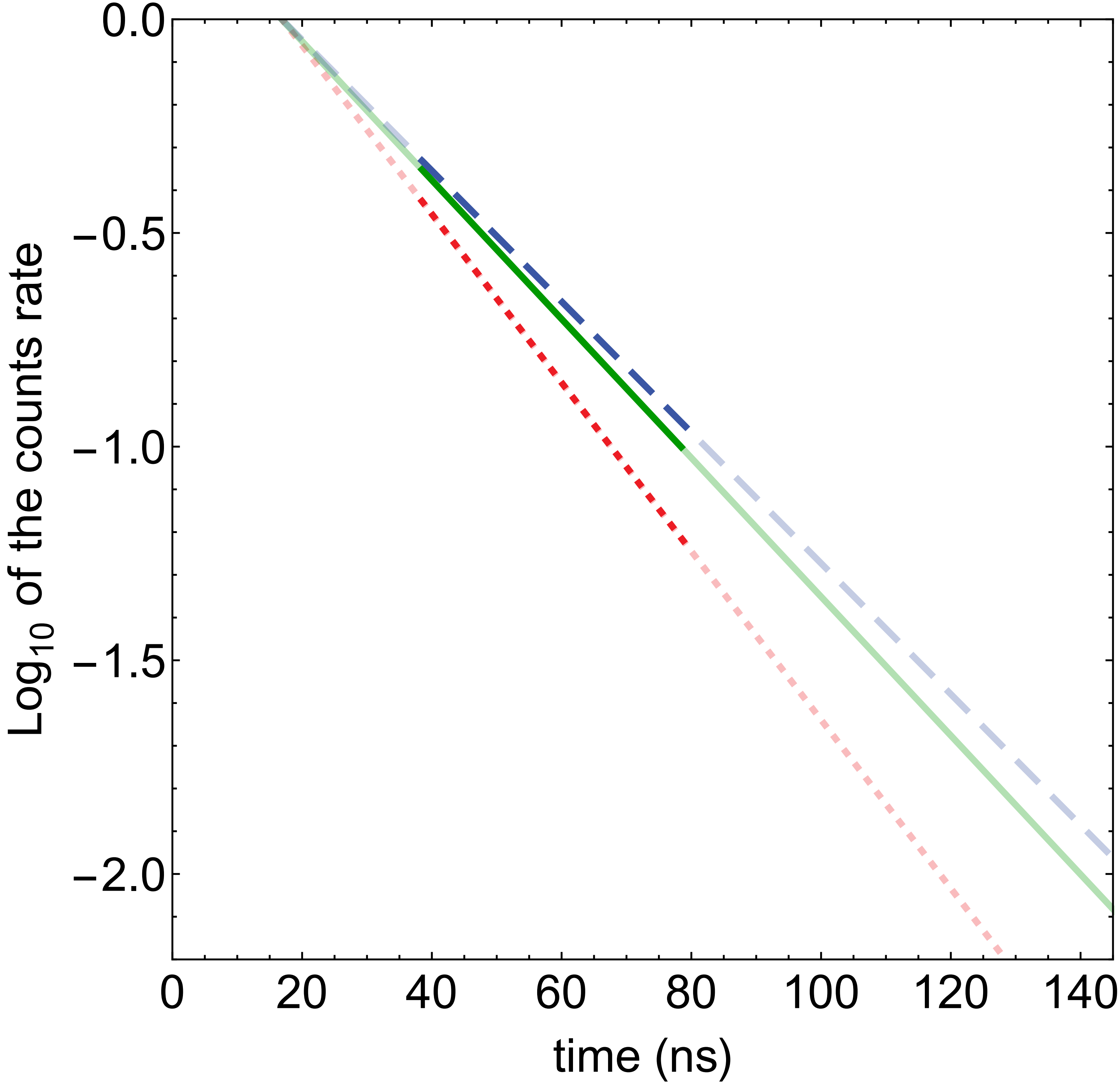


0.0
−0.5
−1.0
−1.5
−2.0
Log10 of the counts rate
0
20
40
60
80
100
120
140
time (ns)
Nanofiber
Atomic
Dipoles



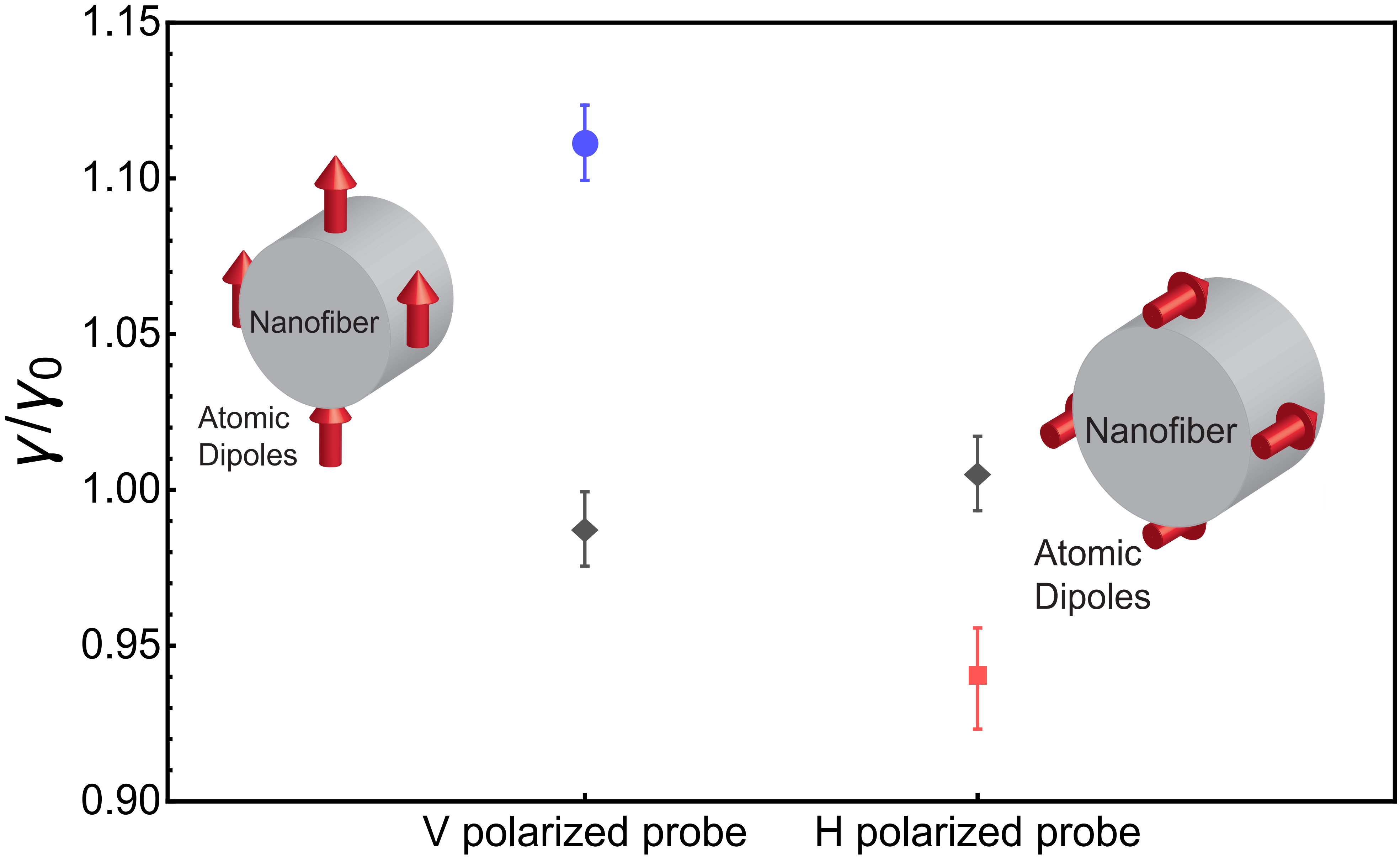
Nanofiber
Atomic
Dipoles
Log_{10} of the counts rate
time (ns)
0.0
−0.5
−1.0
−1.5
−2.0
0
20
40
60
80
100
120
140


Normalized Residuals
time (ns)
Normalized Residuals
time (ns)
Normalized Residuals
time (ns)

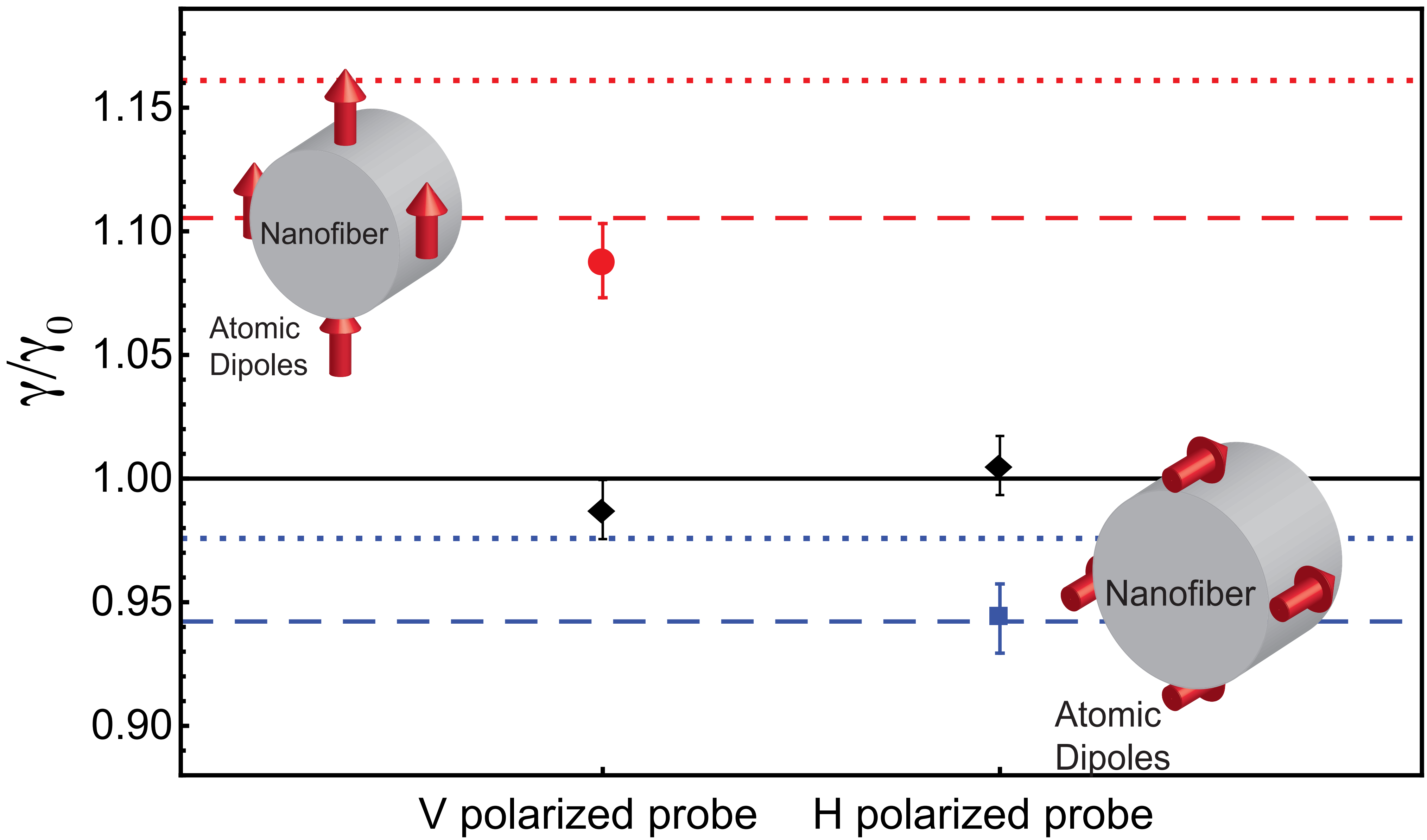


0.0
−0.5
−1.0
−1.5
−2.0
Log$_{10}$ of the counts rate
0
20
40
60
80
100
120
140
time (ns)

Measured decay rates (one atom)



Measured decay rates (one atom)



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

Super- and Sub-radiance

(a classical explanation)

“When two organ pipes of the same pitch stand side by side, complications ensue which not infrequently give trouble in practice. In extreme cases the pipes may almost reduce one another to silence. Even when the mutual influence is more moderate, it may still go so far as to cause the pipes to speak in absolute unison,

in spite of inevitable small differences.

Lord Rayleigh (1877) in "The Theory of Sound".

Super- and Sub-radiance

(a classical explanation)

We need the response of one oscillator due to a nearby oscillator (interference):

$$\ddot{x}_1 + \gamma_0 \dot{x}_1 + \omega_0^2 x_1 = \frac{3}{2}\omega_0 \gamma_0 \hat{d}_1 \cdot \vec{\mathcal{E}}_2(\vec{r})\, x_1,$$

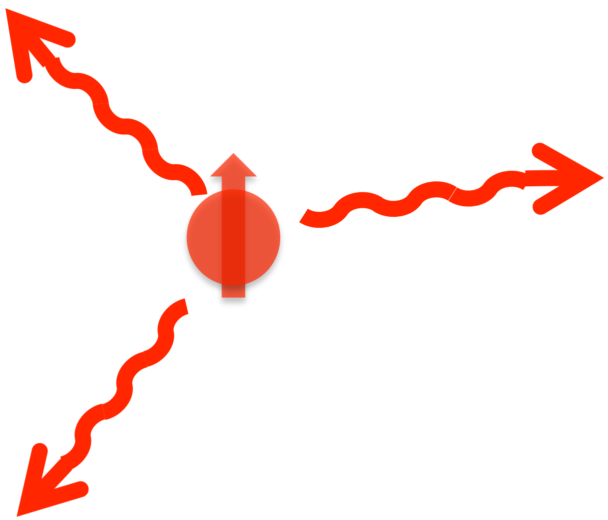
assuming $\mathrm{x}_1 = x_{10} \exp i(\omega - i\gamma/2)t$

$$\gamma = \gamma_0 + \frac{3}{2}\gamma_0 \mathrm{Im}\left\{\hat{d}_1 \cdot \vec{\mathcal{E}}_2(\vec{r})\right\}, \quad \text{with} \left|\hat{d}_1 \cdot \vec{\mathcal{E}}_2(0)\right| = \frac{2}{3}$$

$$\omega = \omega_0 - \frac{3}{4}\gamma_0 \,\mathrm{Re}\left\{\hat{d}_1 \cdot \vec{\mathcal{E}}_2(\vec{r})\right\}$$

Super- and Sub-radiance

(a classical explanation)



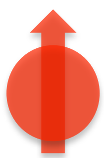
$$P = \frac{\varepsilon}{\Delta t} = IA \Rightarrow \Delta t = \frac{\varepsilon}{IA}$$

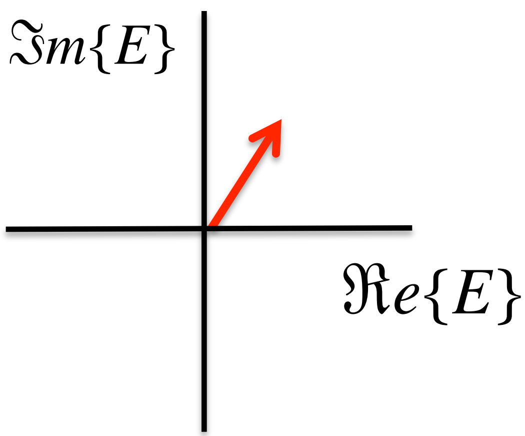
For N dipoles $\varepsilon \Rightarrow N\varepsilon$

Super- and Sub-radiance

(a classical explanation)

Normal radiance



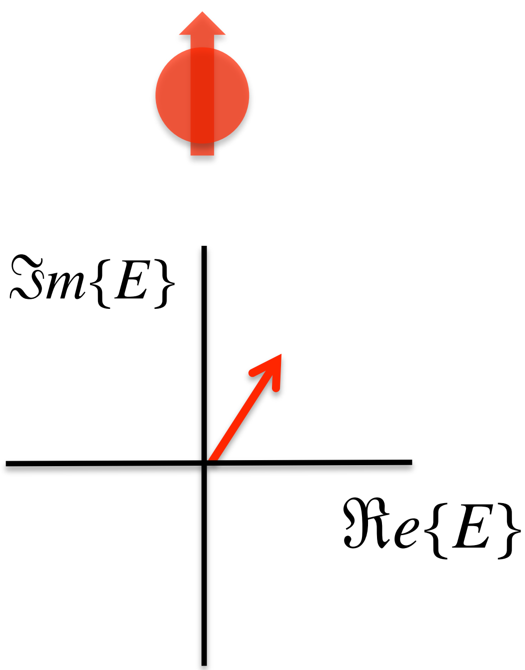


$$I = |E_0|^2 = I_0$$

$$\Delta t = \tau_0$$

Super- and Sub-radiance
(a classical explanation)

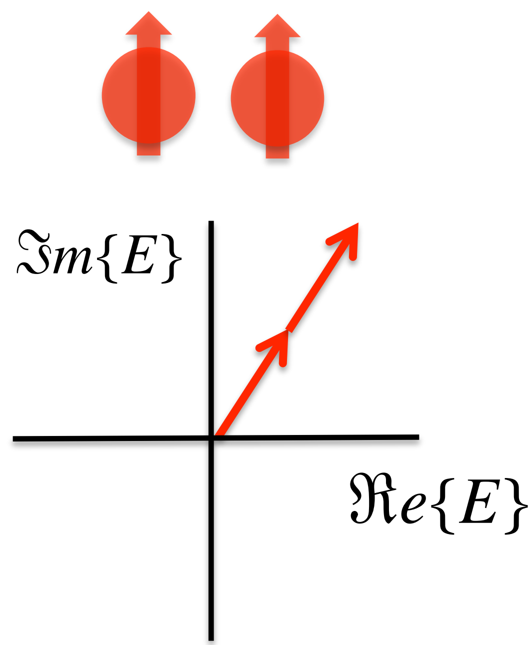
Normal radiance



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

$$\Delta t = \tau_0$$

Super-radiance



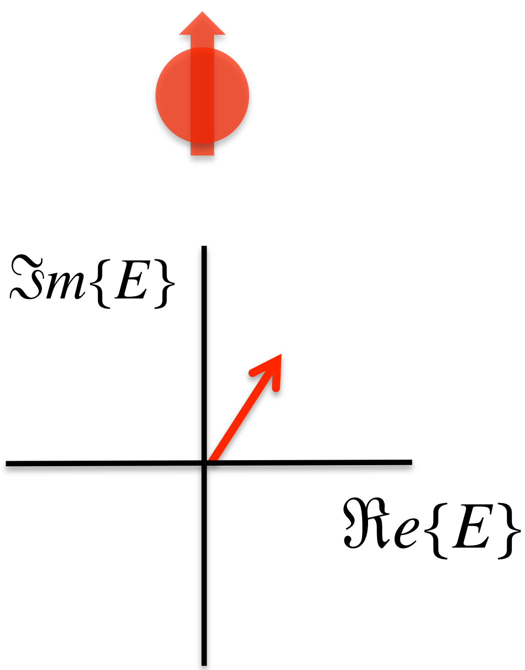
$$I = 4I_0$$

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

Super- and Sub-radiance

(a classical explanation)

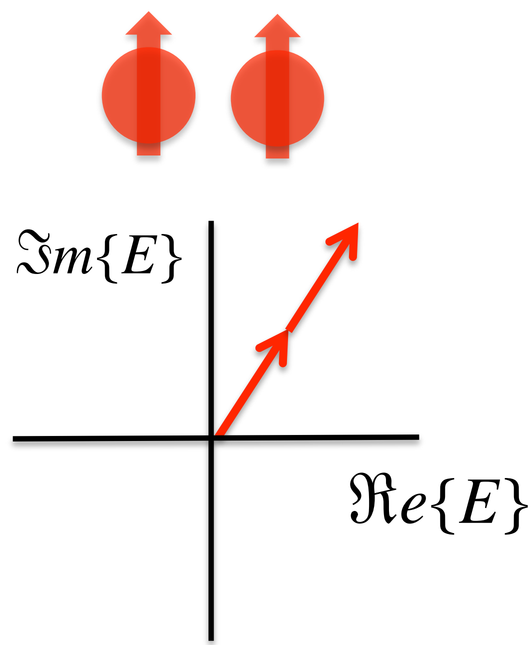
Normal radiance



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

$$\Delta t = \tau_0$$

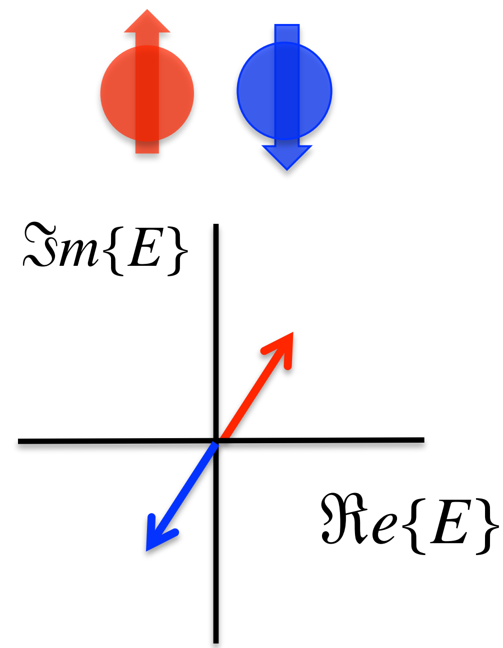
Super-radiance



$$I = 4I_0$$

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

Sub-radiance

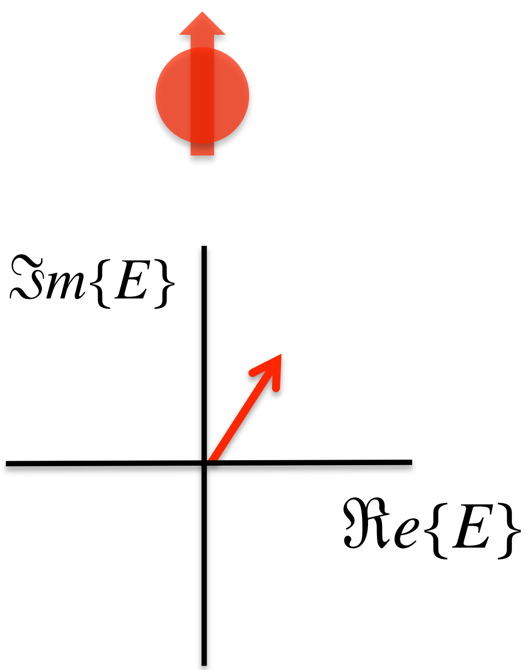


$$I = 0$$

$$\Delta t = \infty$$

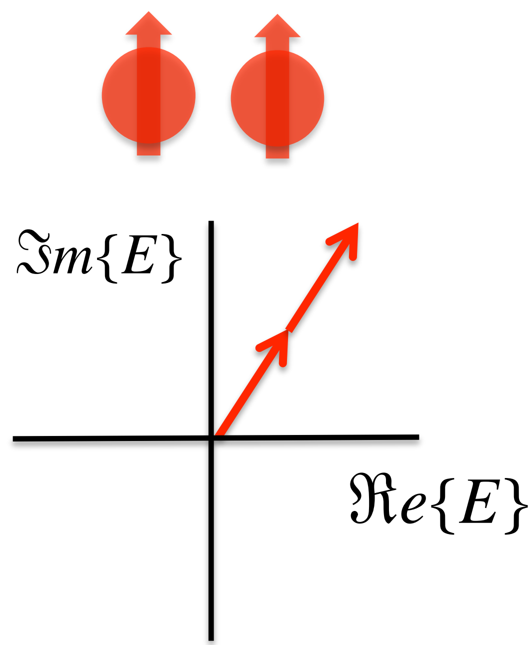
Super- and Sub-radiance
(a classical explanation)

Normal radiance



$$\Delta t = \tau_0$$

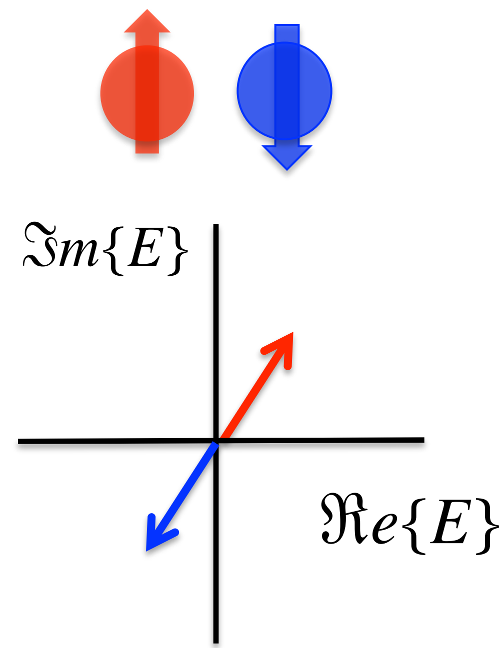
Super-radiance



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

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

Sub-radiance



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

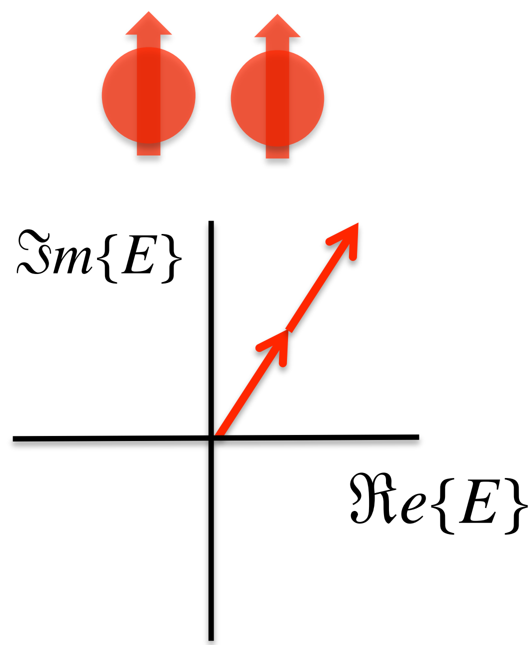
$$\Delta t = \infty$$

Super- and Sub-radiance

(a classical explanation)

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

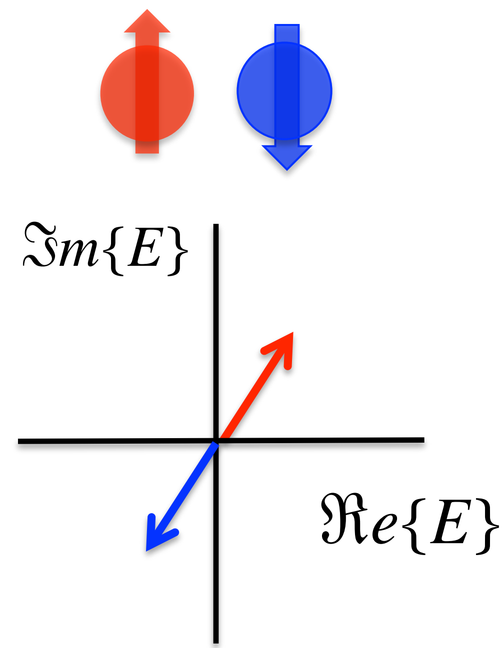
Super-radiance



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

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

Sub-radiance

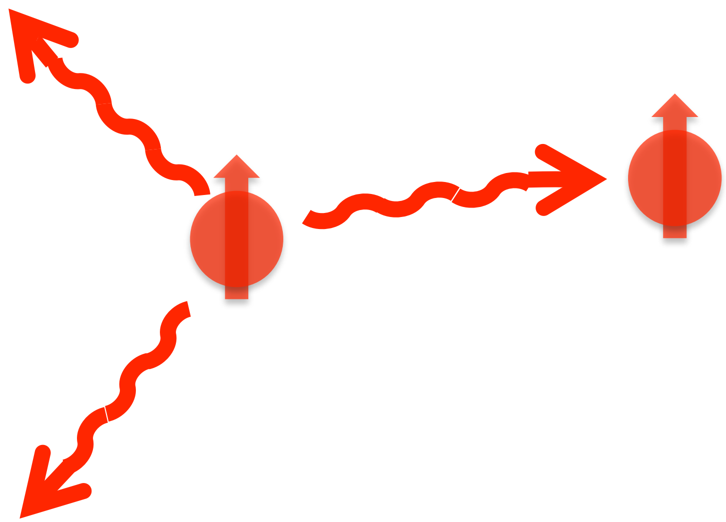


$$|ge\rangle - |eg\rangle$$

$$\Delta t = \infty$$

Interacting dipoles

Interacting dipoles

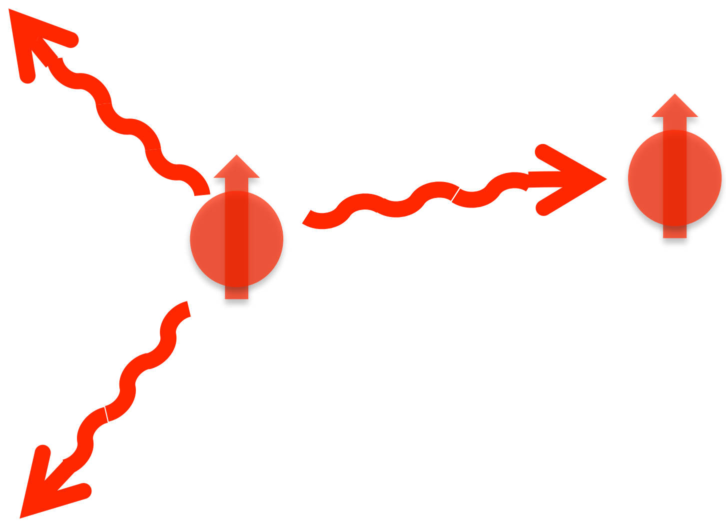


$$U_{free} \propto \frac{\exp(ikr)}{kr}$$

$$\Omega_{12} \propto \frac{\cos kr}{kr}$$

$$\gamma_{12} \propto \frac{\sin kr}{kr}$$

Interacting dipoles



$$U_{free} \propto \frac{\exp(ikr)}{kr}$$

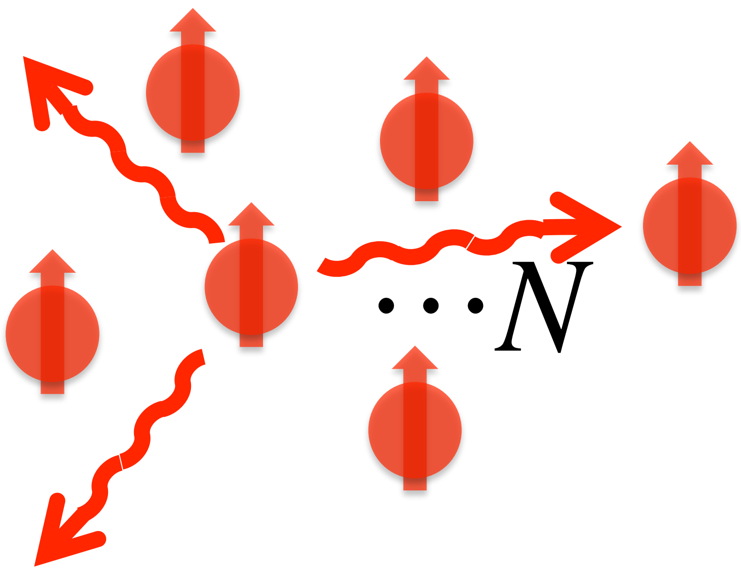
$$\Omega_{12} \propto \frac{\cos kr}{kr}$$

If the atoms are too close this diverges.

$$\gamma_{12} \propto \frac{\sin kr}{kr}$$

If the atoms are too far this goes to zero.

Interacting dipoles



$$U_{free} \propto \frac{\exp(ikr)}{kr}$$

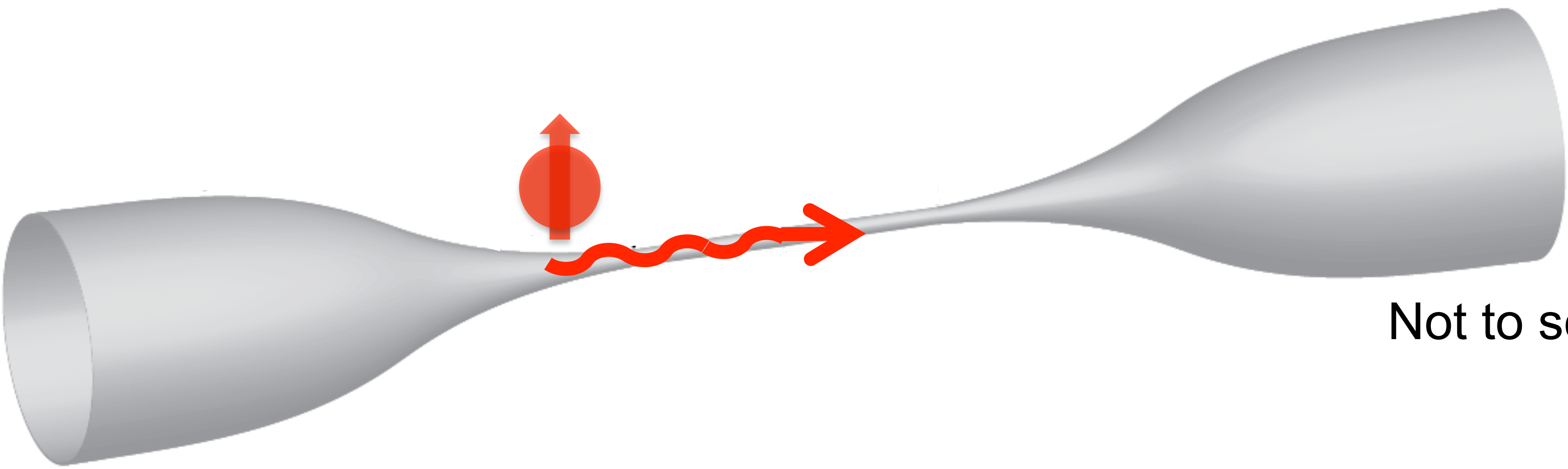
$$\Omega_{12} \propto \frac{\cos kr}{kr}$$

The atoms have to be near, but not too near which limits N.

$$\gamma_{12} \propto \frac{\sin kr}{kr}$$

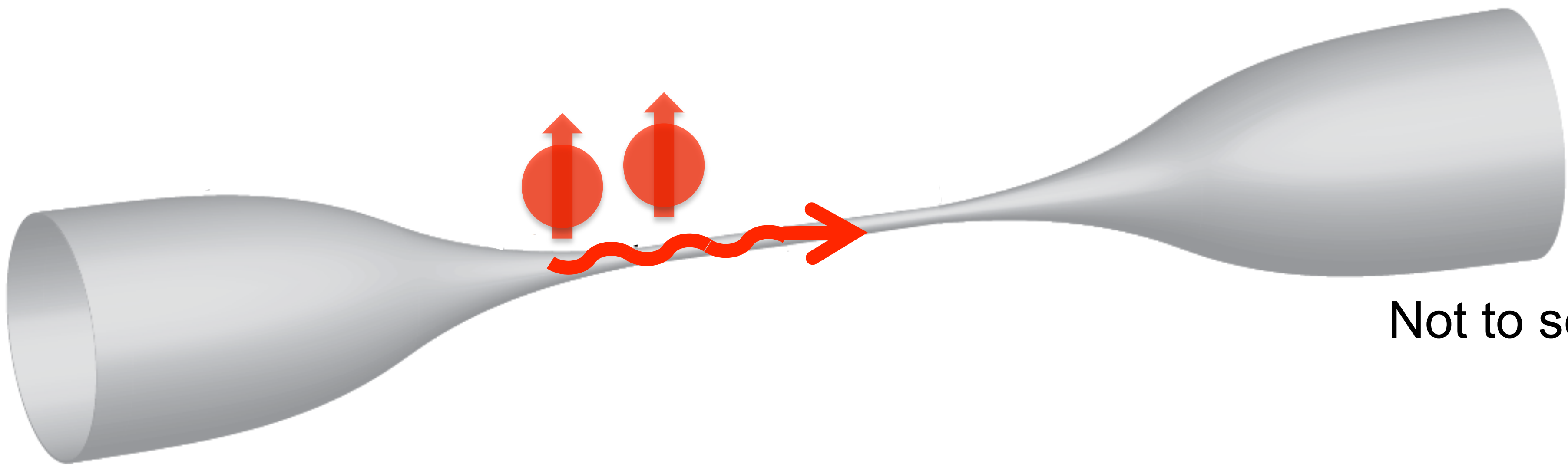
Observation of infinite-range interactions

Infinite Range Interactions



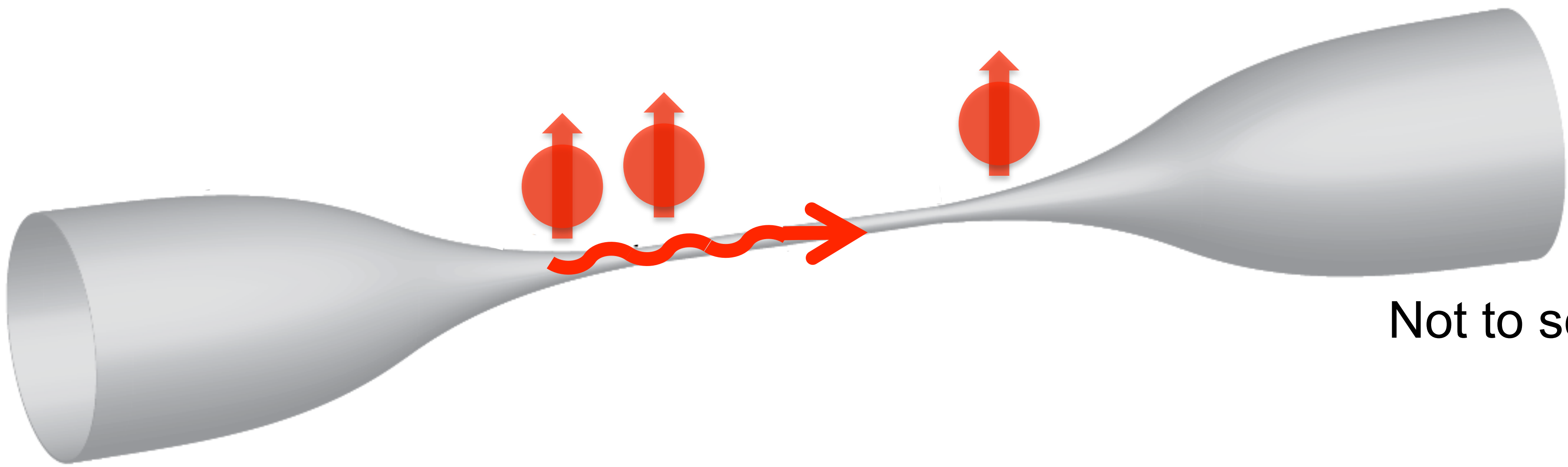
Not to scale

Infinite Range Interactions



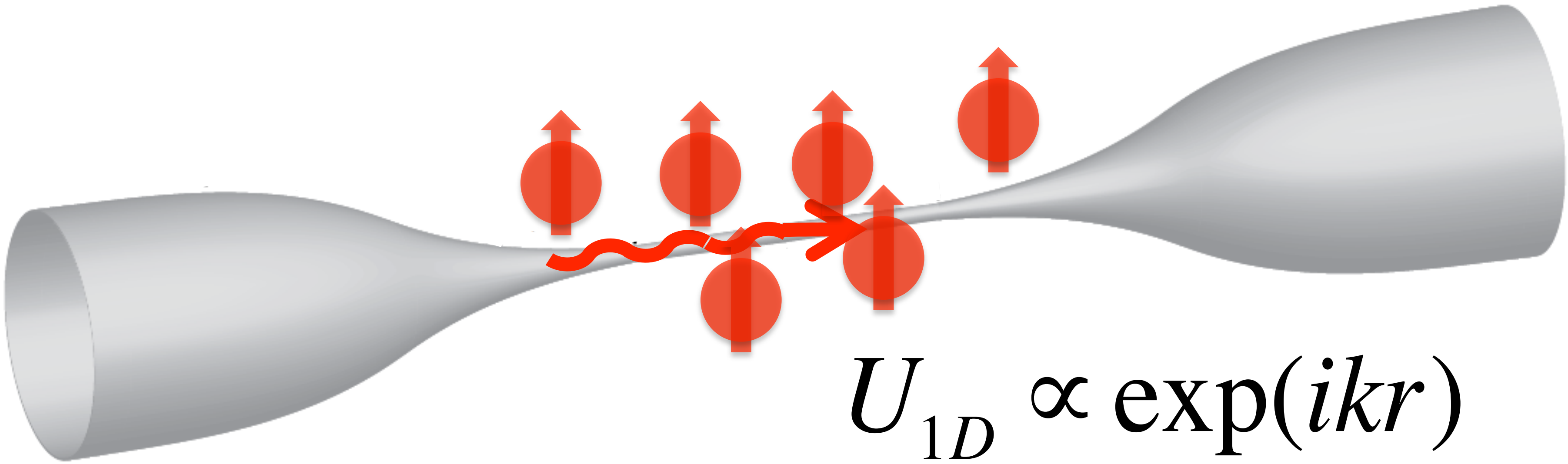
Not to scale

Infinite Range Interactions



Not to scale

Infinite Range Interactions



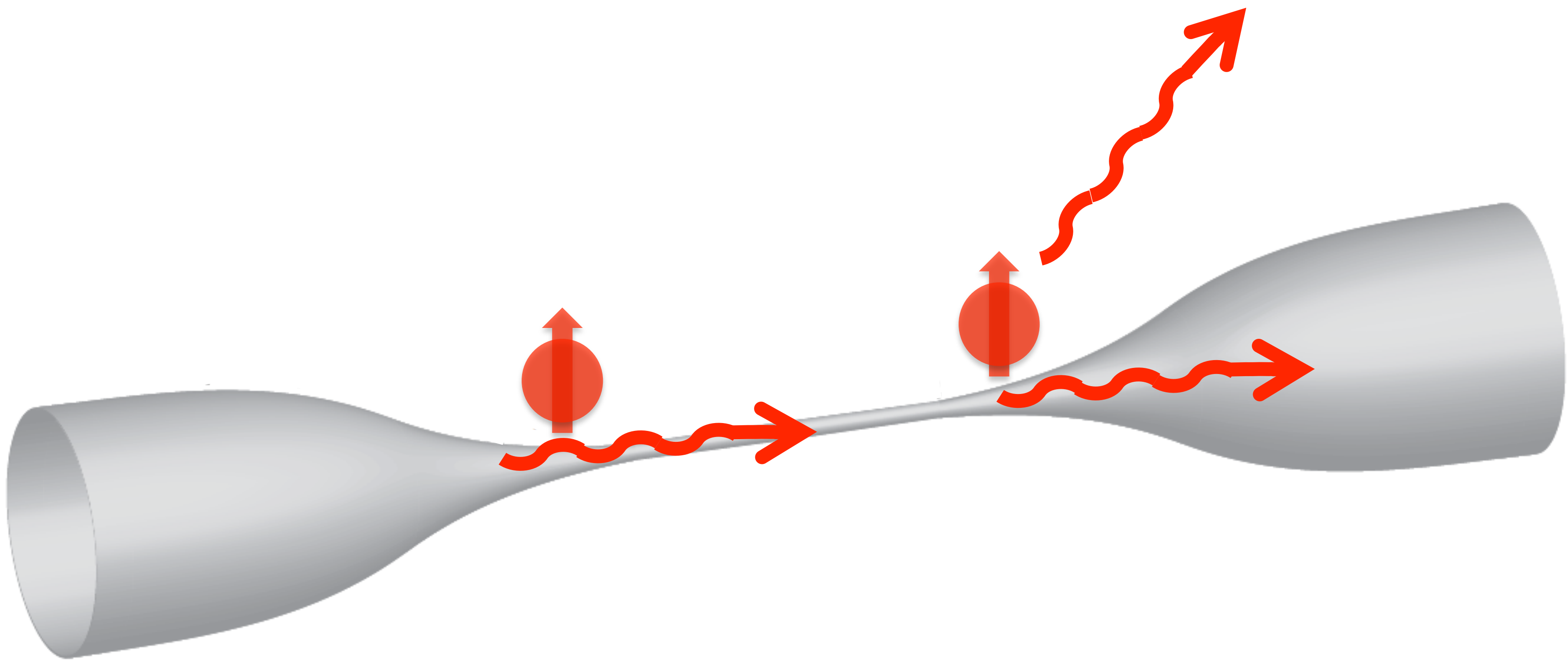
$$U_{1D} \propto \exp(ikr)$$

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

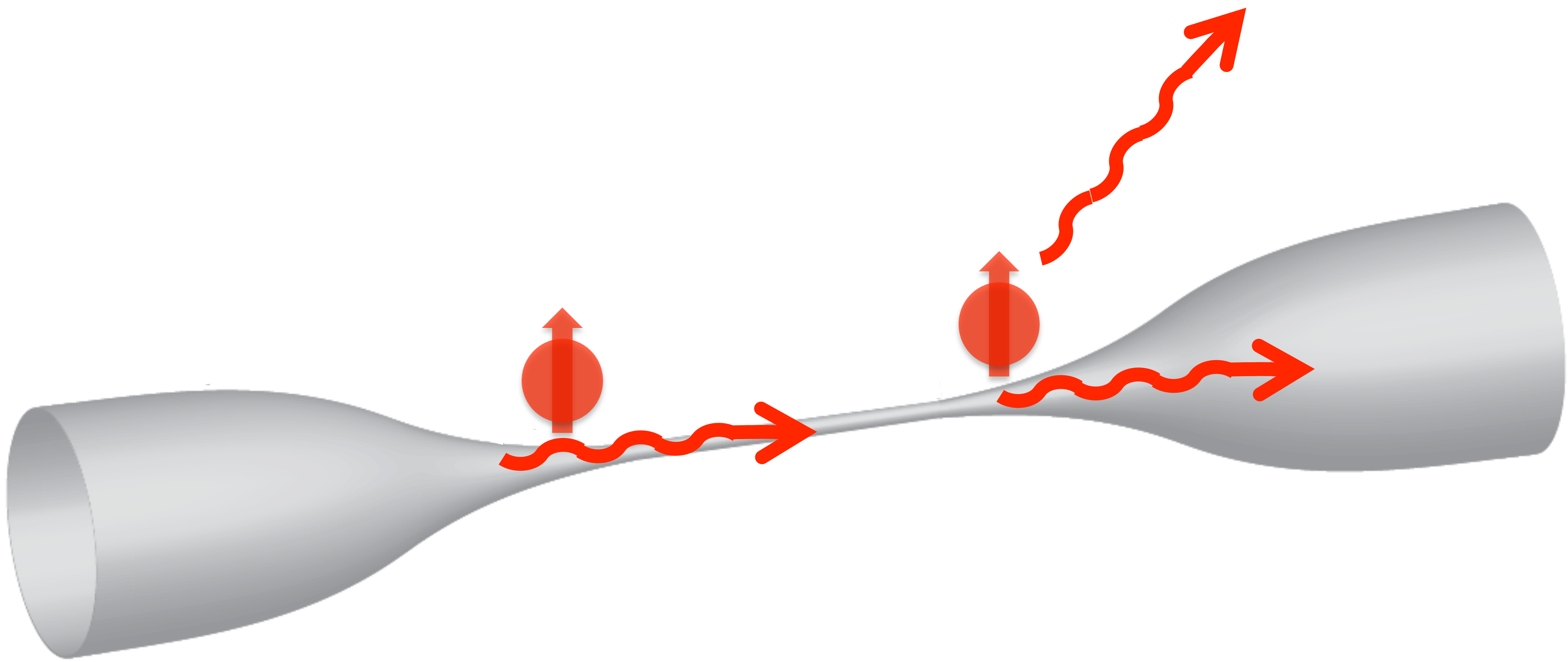
$$\gamma_{12} \propto \cos kz$$

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



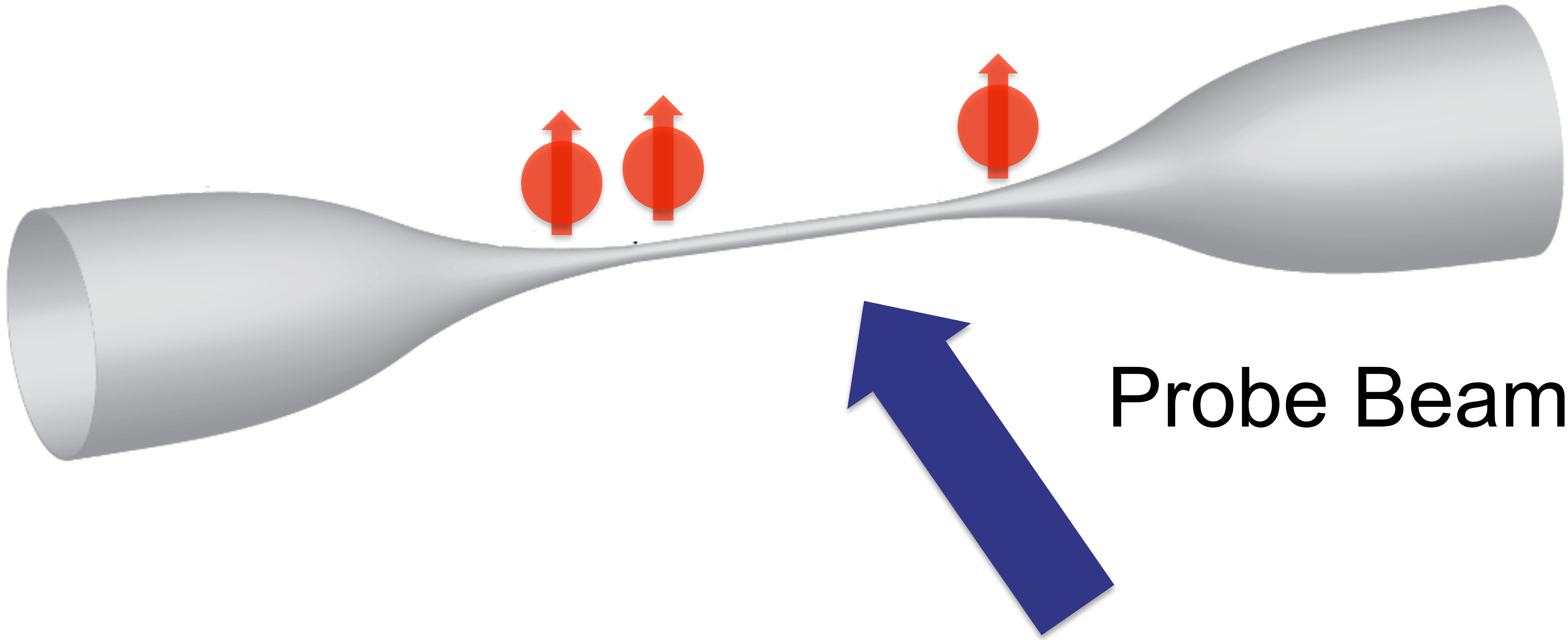
Long distance modification of the atomic radiation



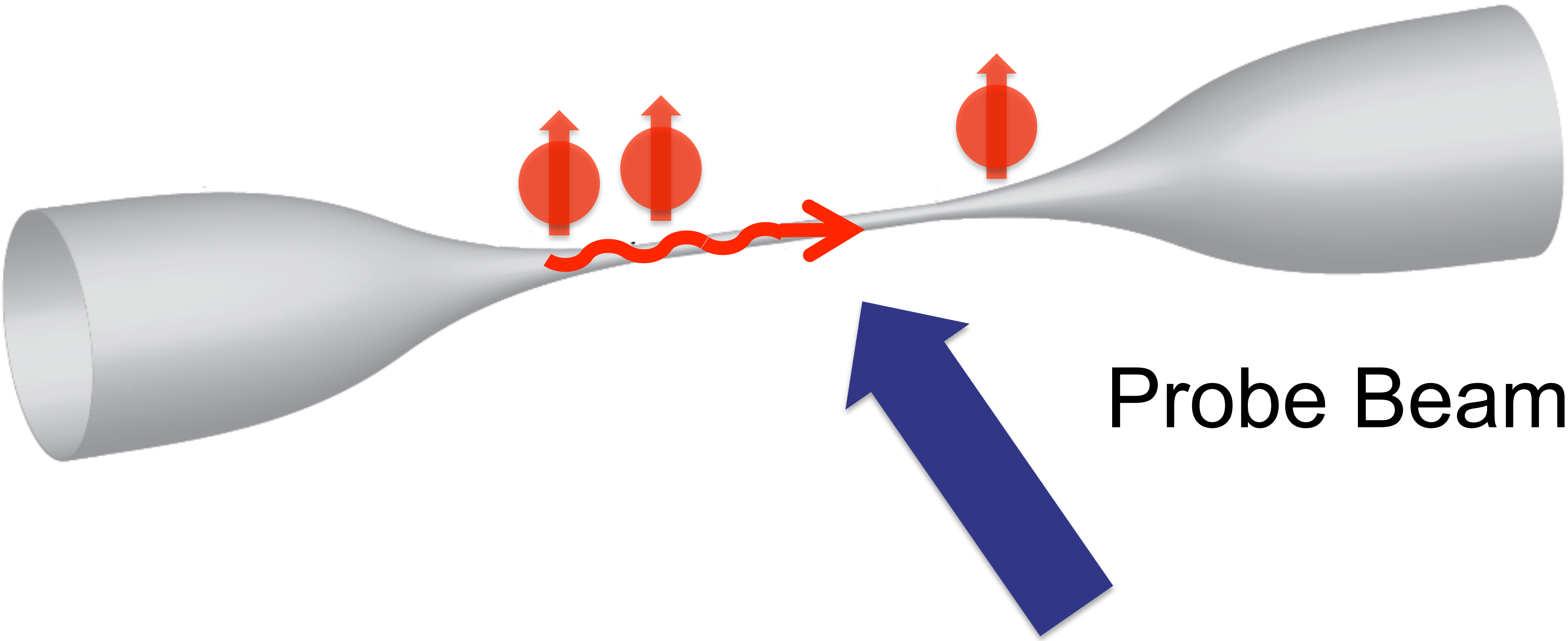
We have atomic densities low enough to observe mostly infinite-range interactions

Experimental idea

The idea behind the experiment

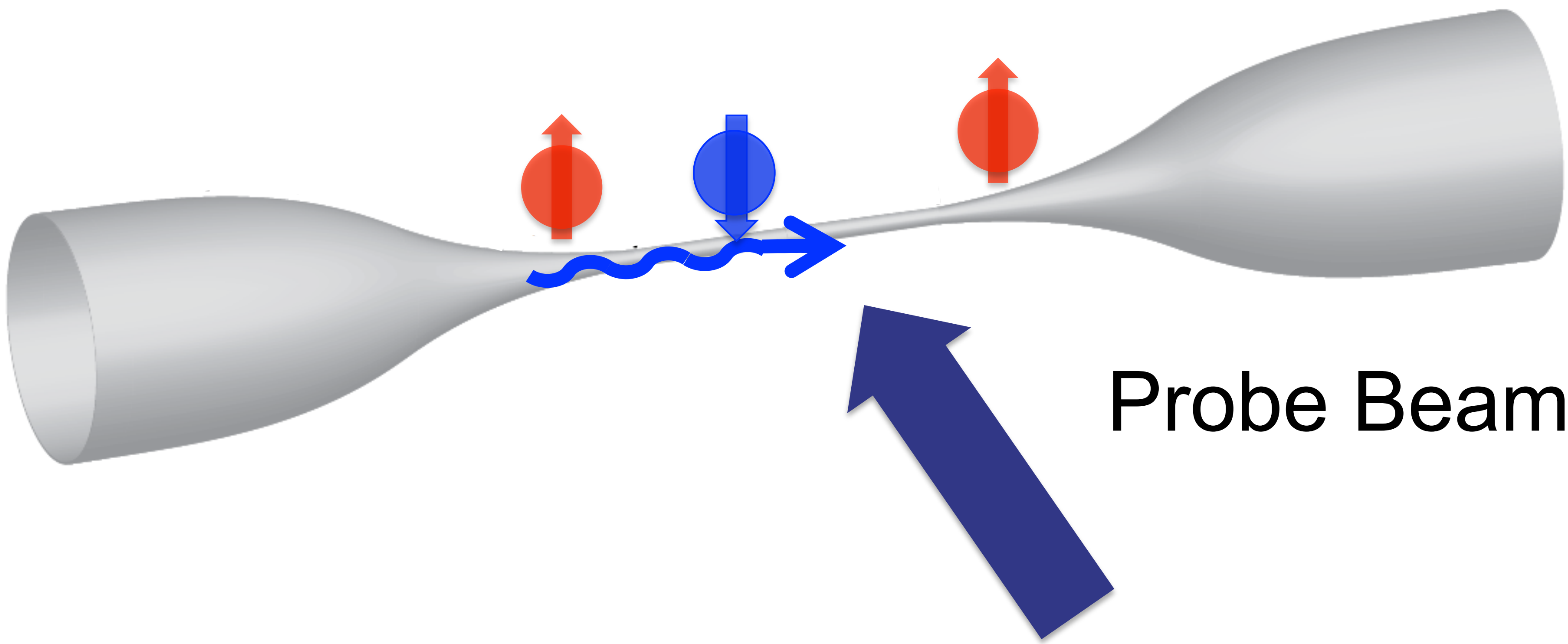


The idea behind the experiment



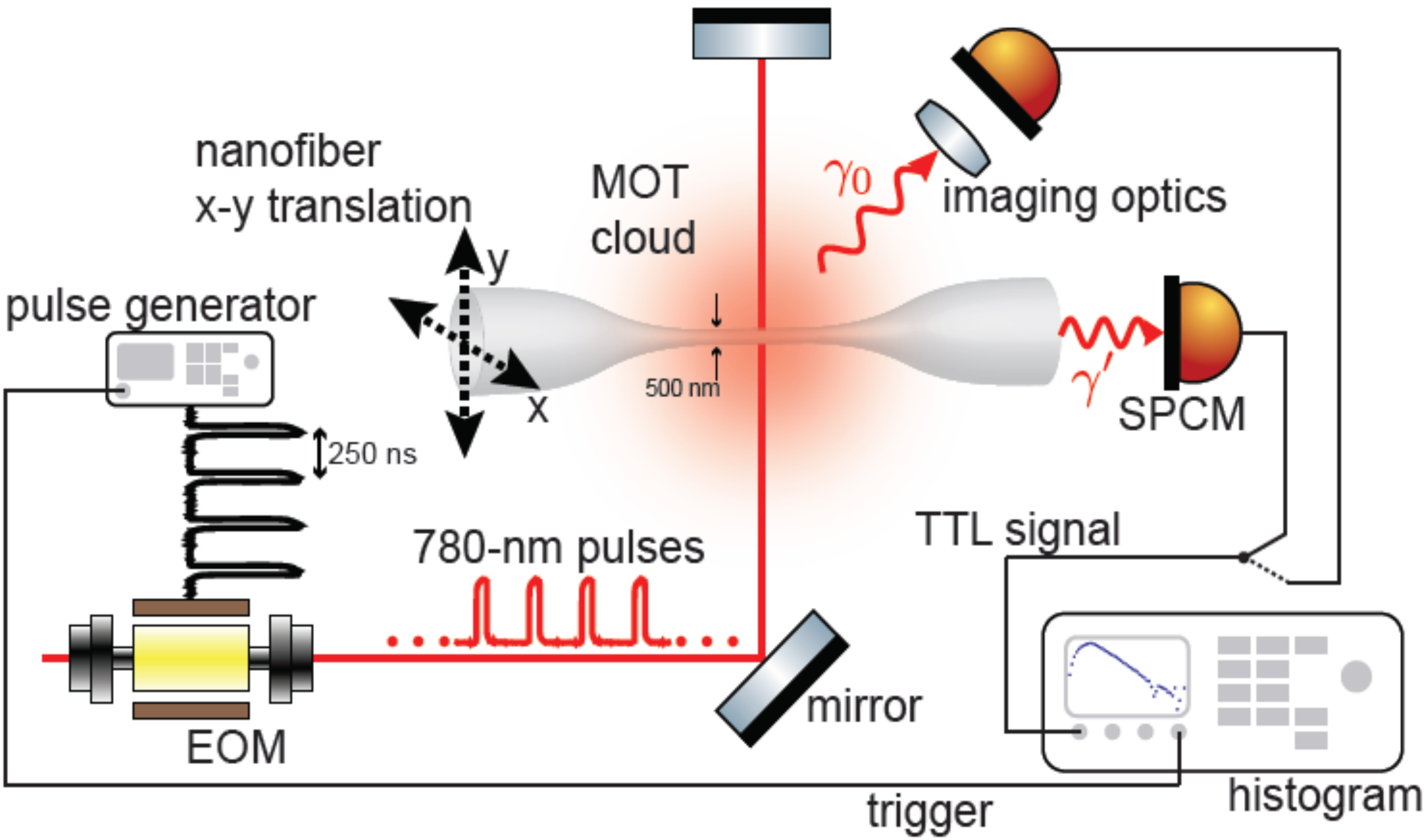
We look for modifications of the radiative lifetime of an ensemble of atoms around the ONF.

The idea behind the experiment

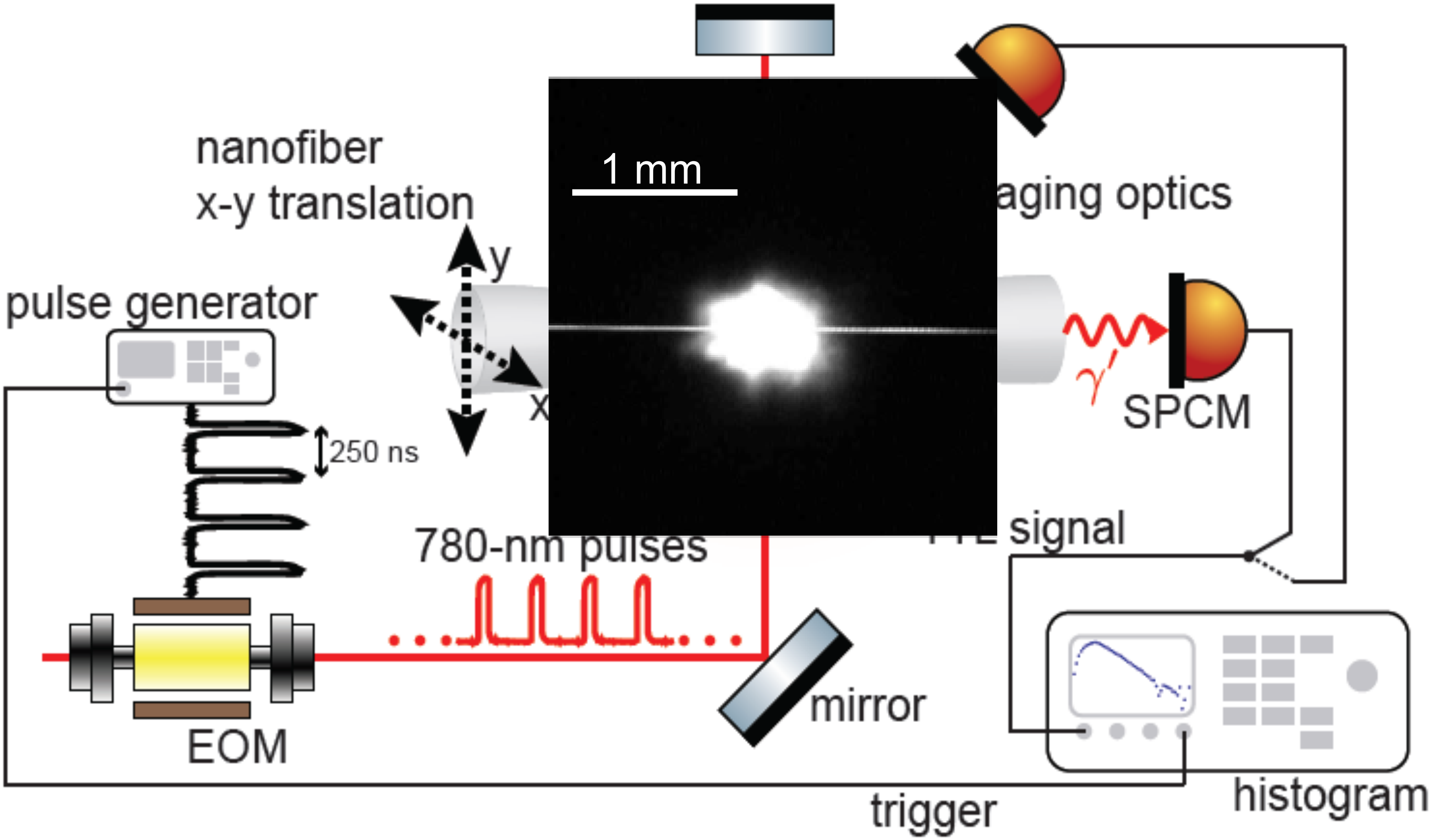


The sub- and super-radiant behavior depend on the phase relation of the atomic dipoles along the common mode

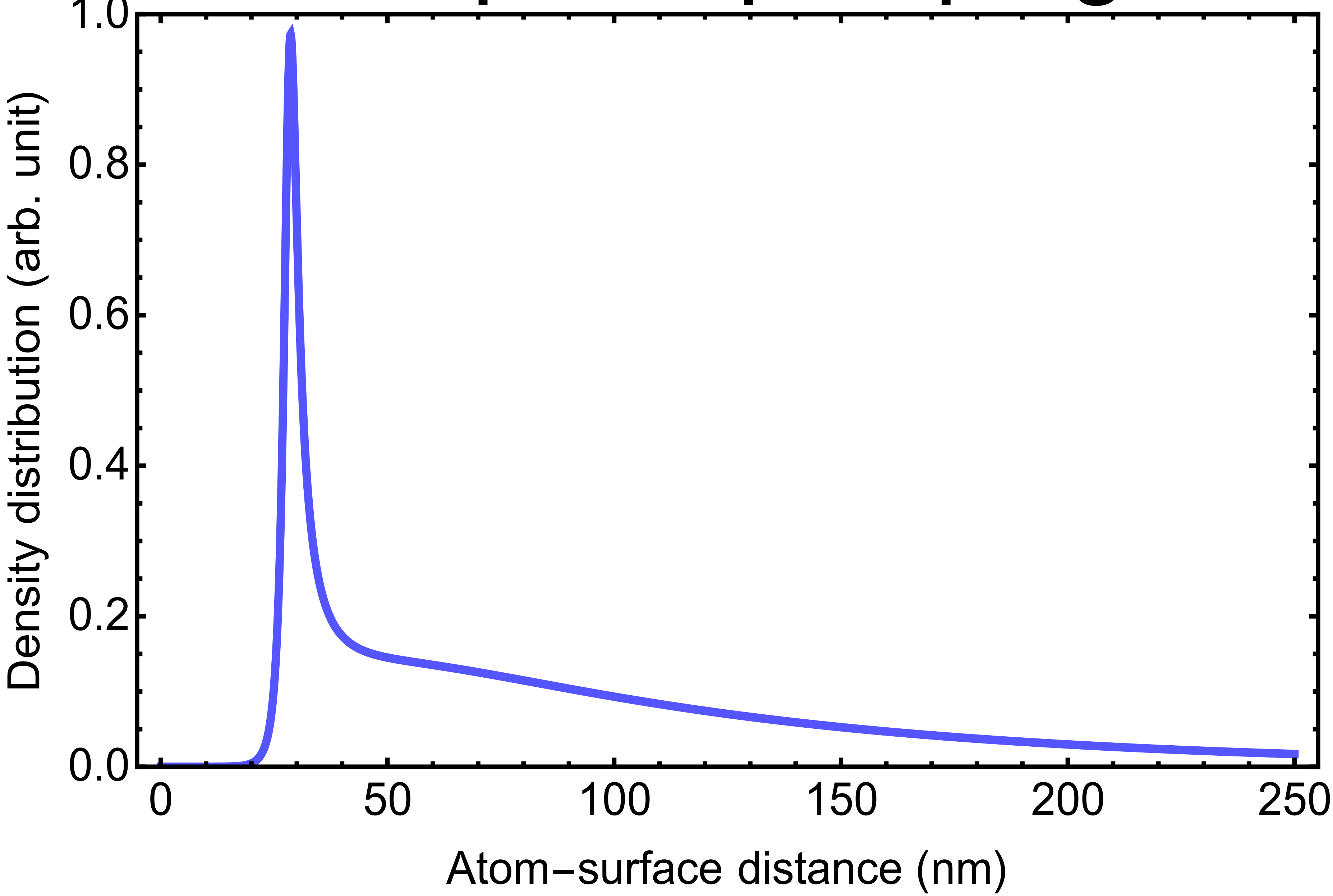
Measuring the Radiative Lifetime



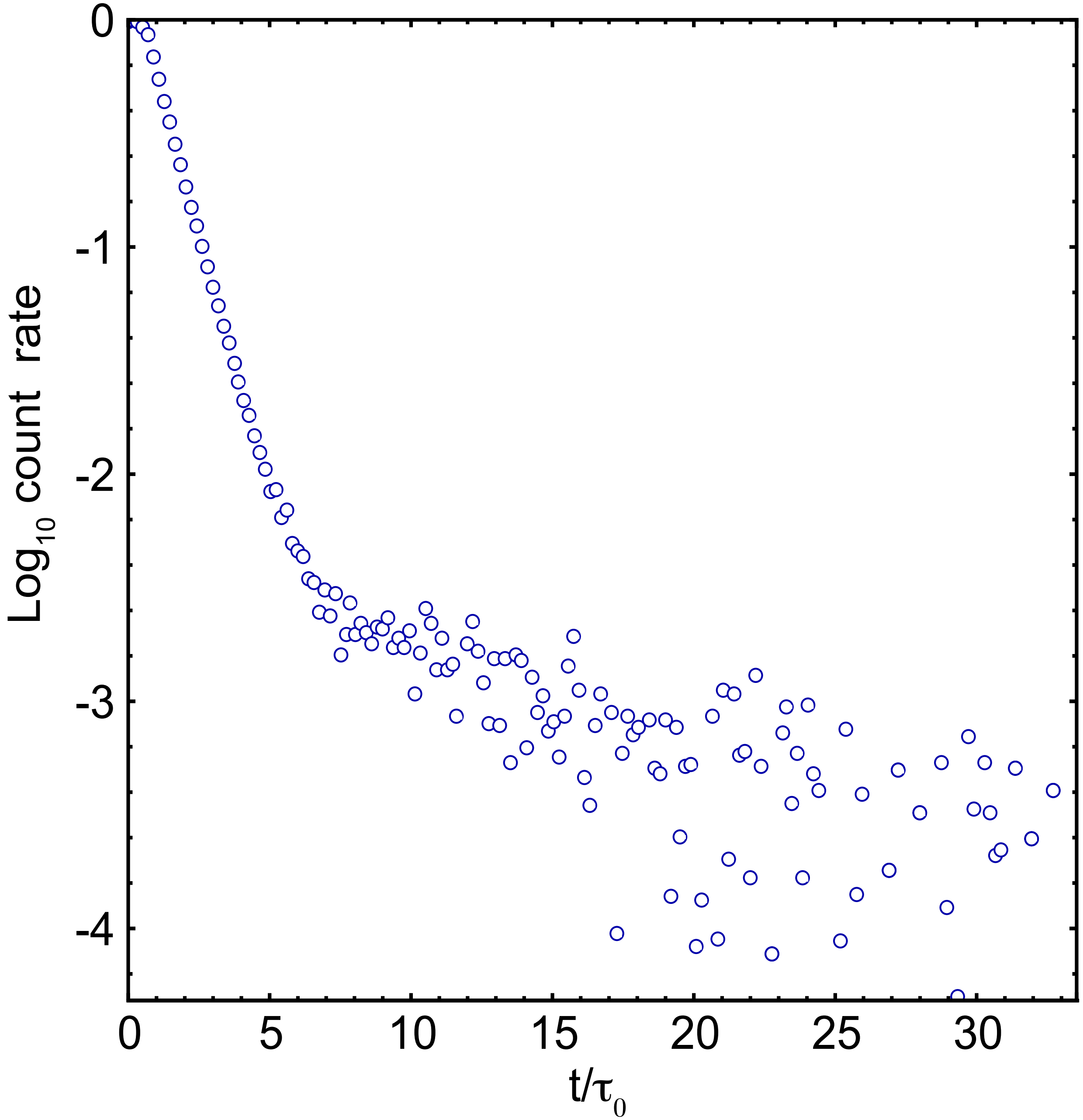
Measuring the Radiative Lifetime



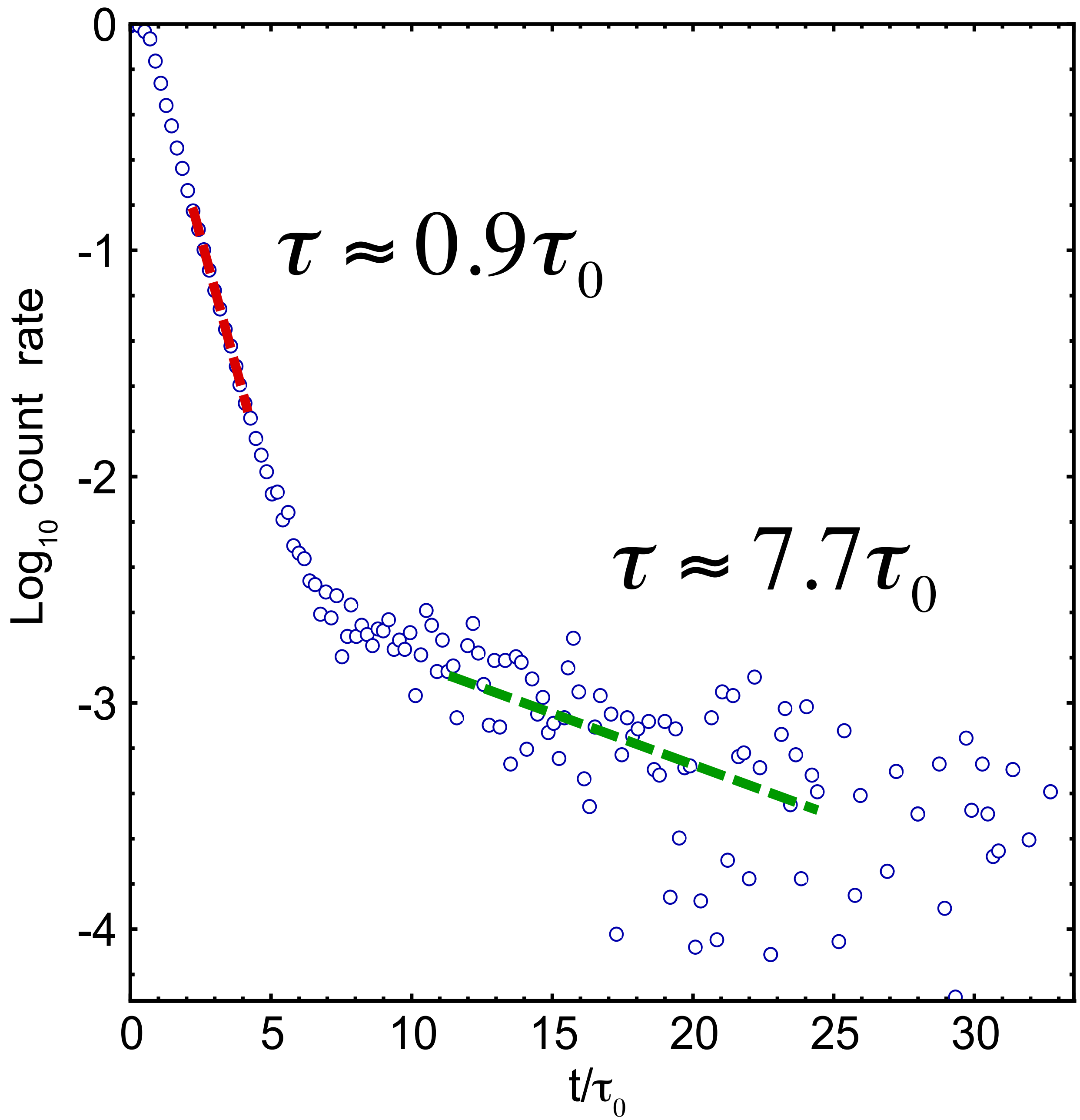
Atomic distribution with optical pumping



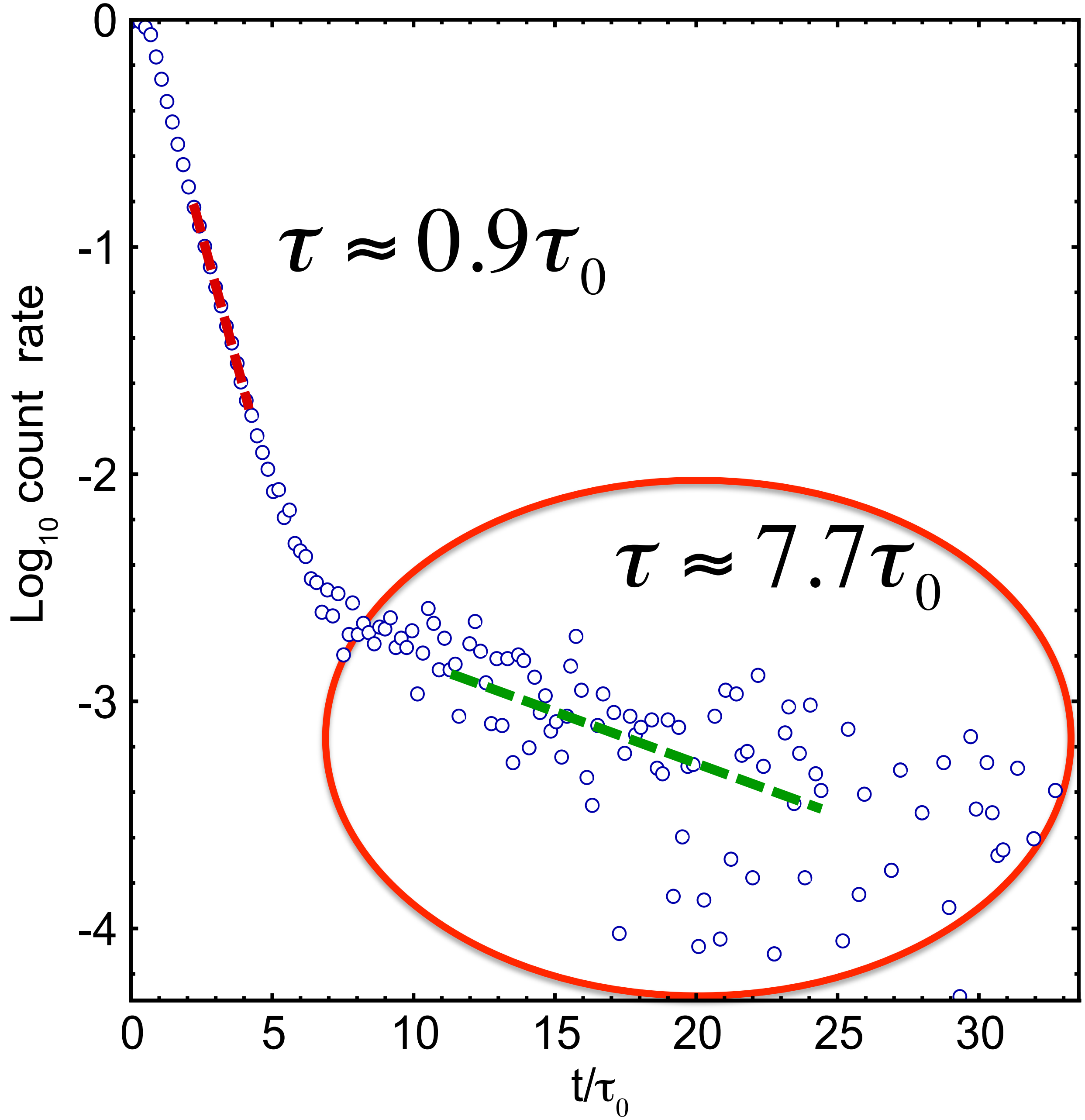
Two distinct lifetimes



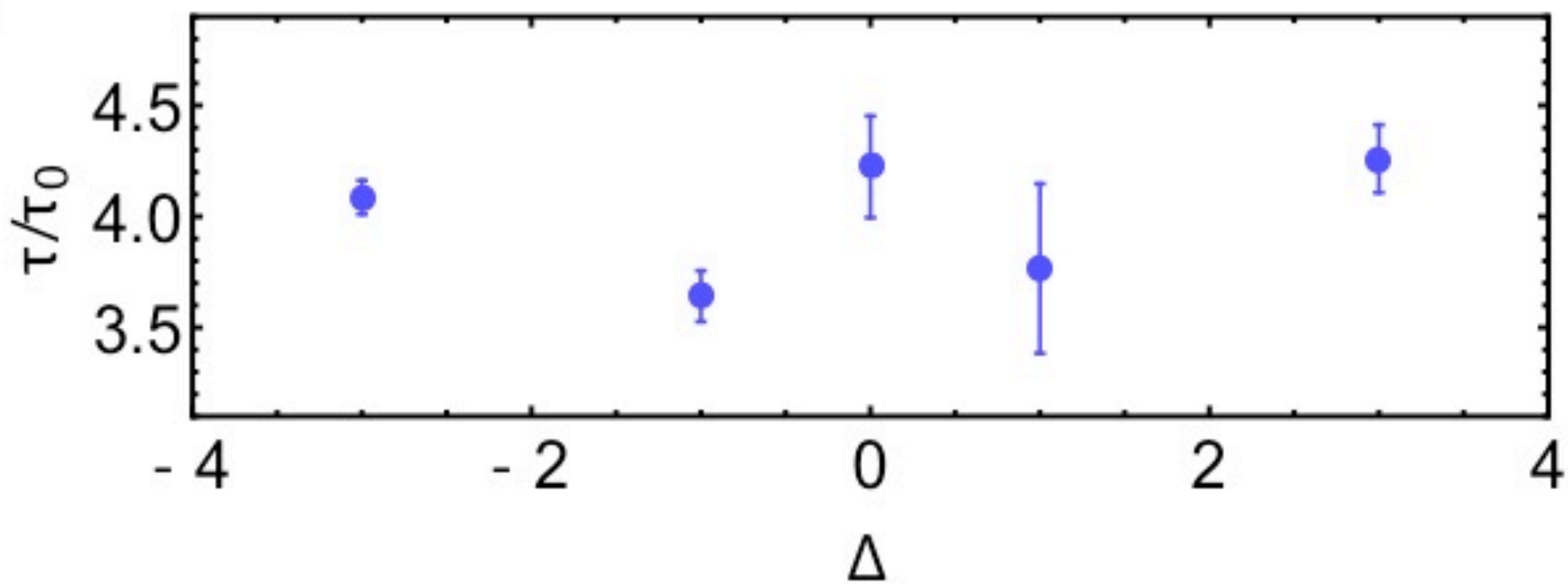
Two distinct lifetimes



Two distinct lifetimes

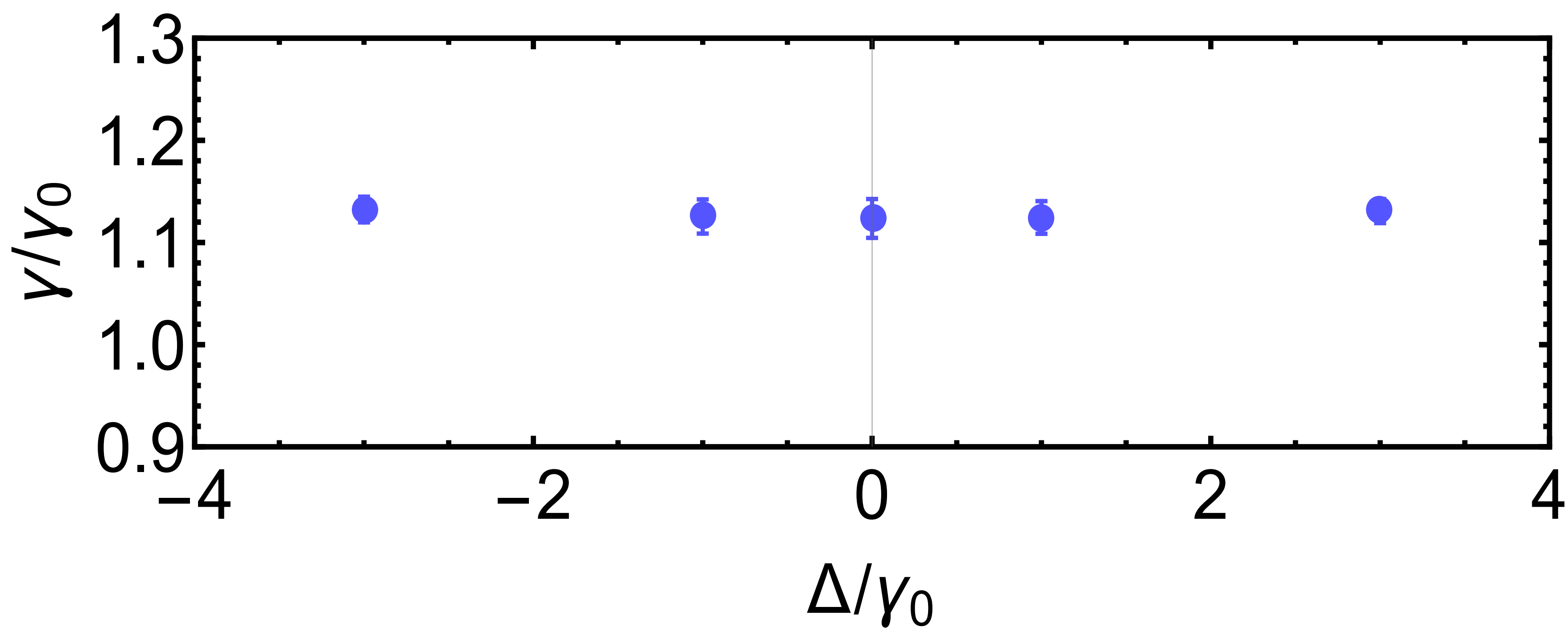


Decay time vs detunning



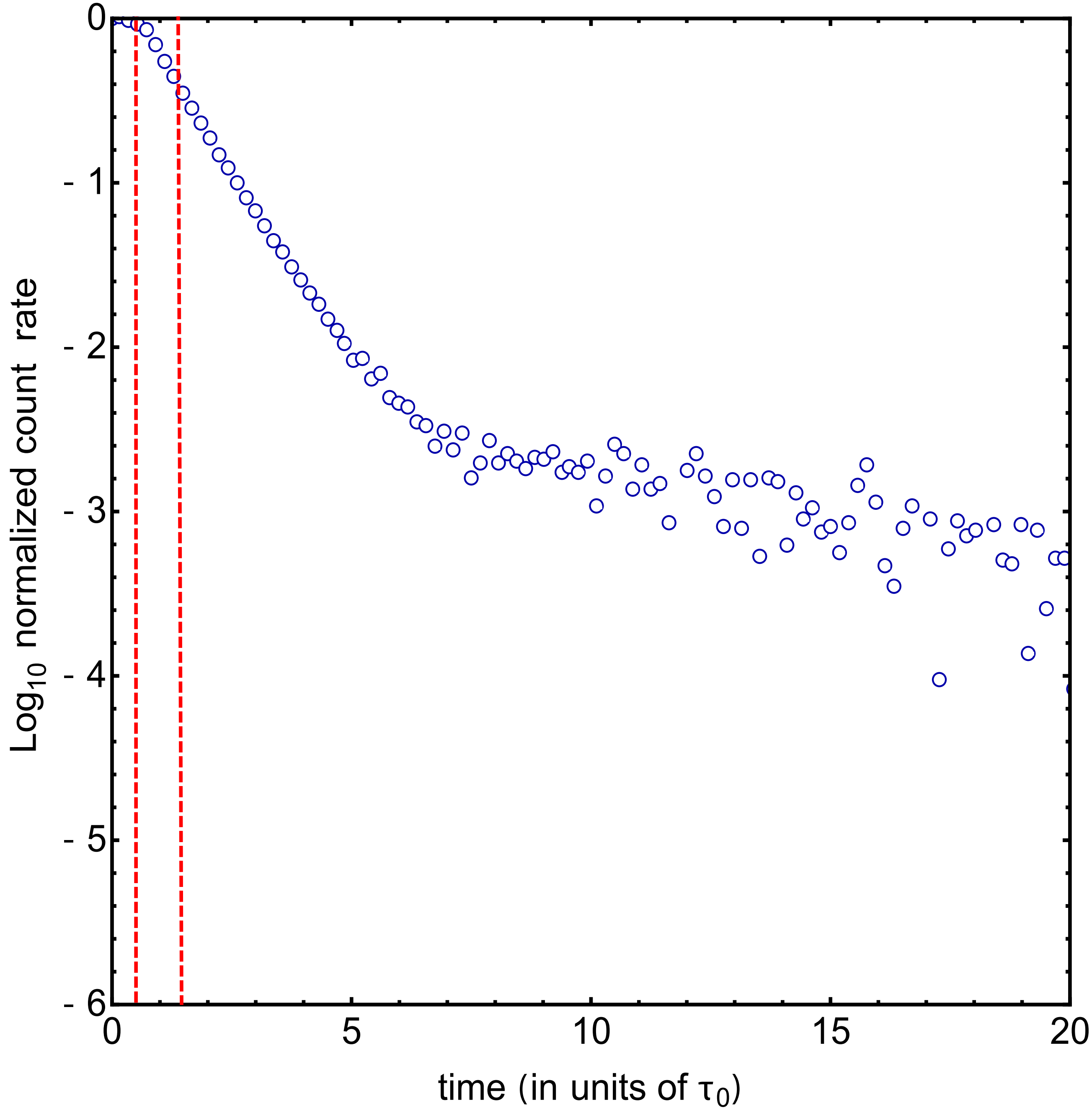
No radiation trapping for long lifetime

Decay time vs detunning

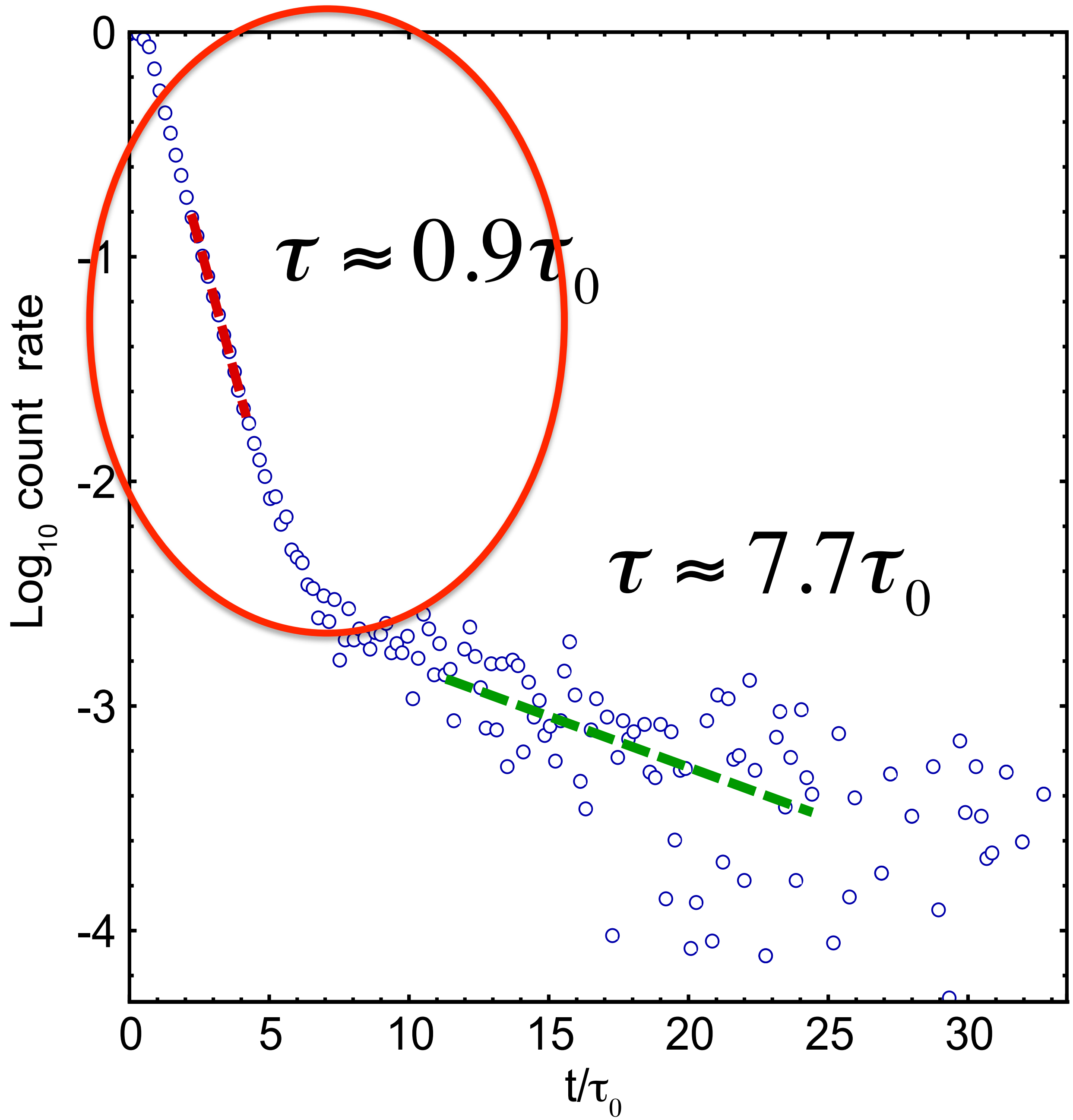


No radiation trapping for short lifetime

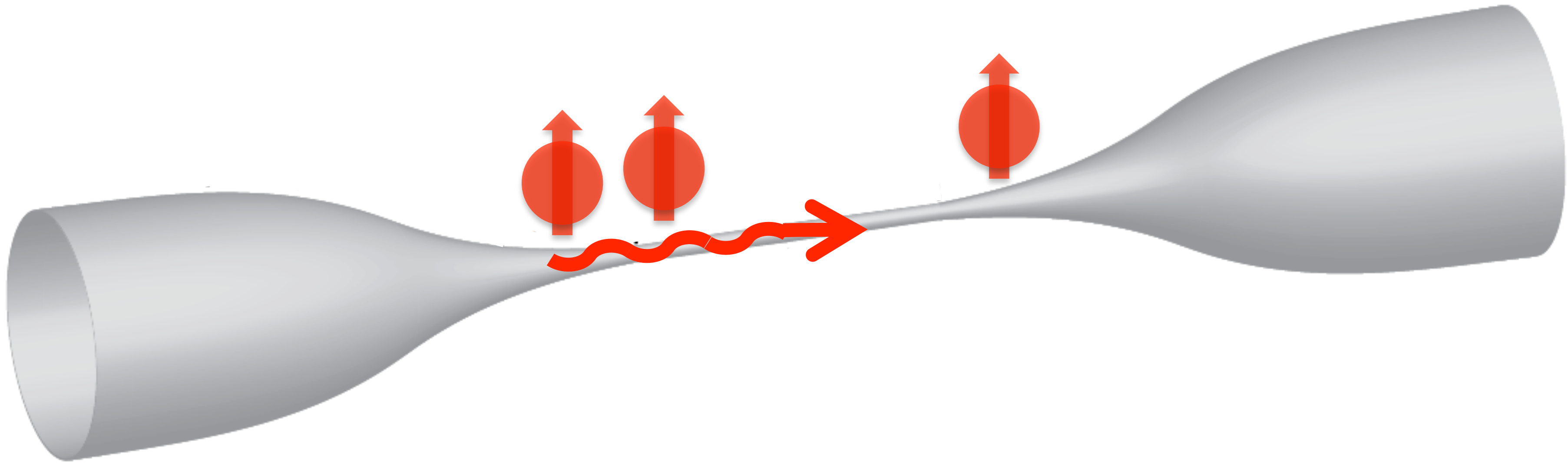
Pulse and signal



Two distinct lifetimes

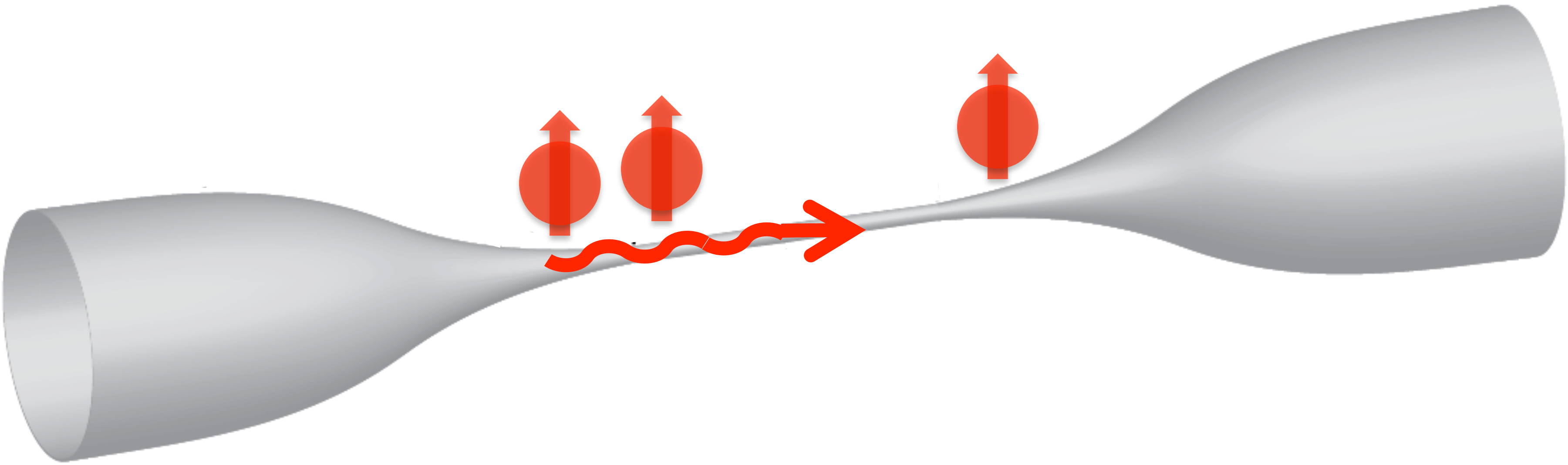


N dependence



$$\gamma_{\sup} = \gamma_{rad} + N\gamma_{1D}$$

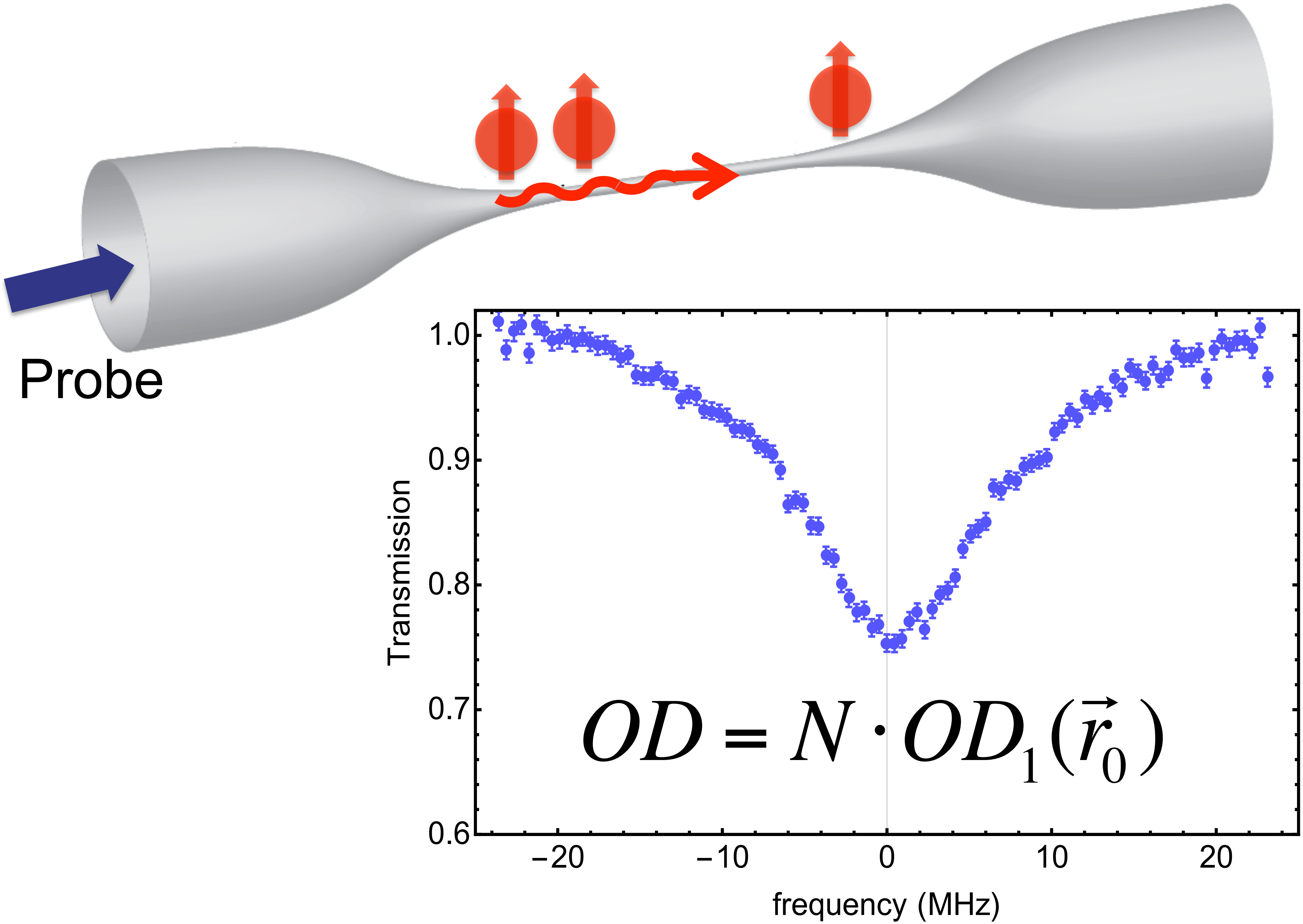
N dependence

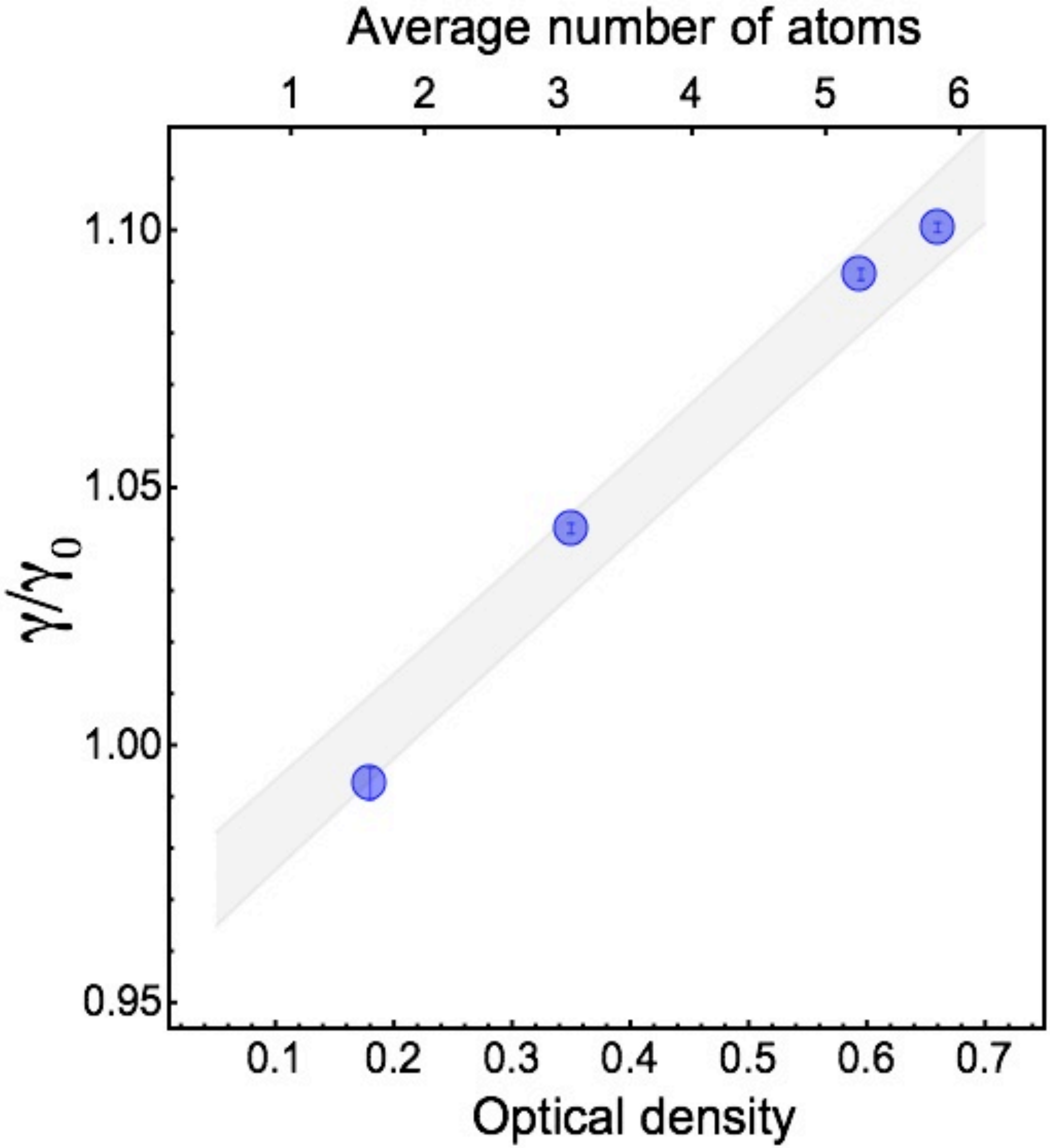


$$\gamma_{\sup} = \gamma_{rad} + N\gamma_{1D}$$

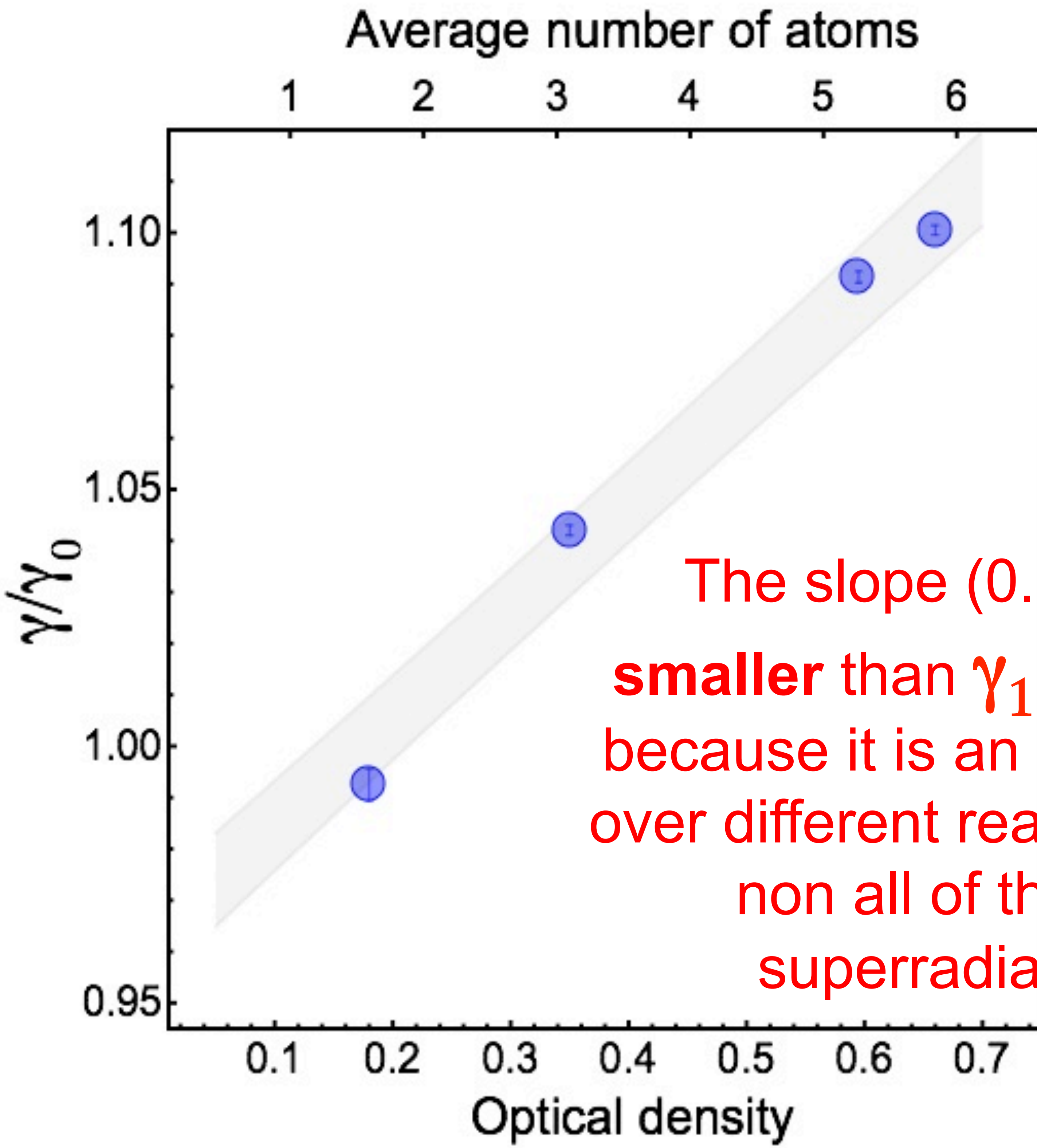
Superradiance depends on the **atom number!**

Measurment of N



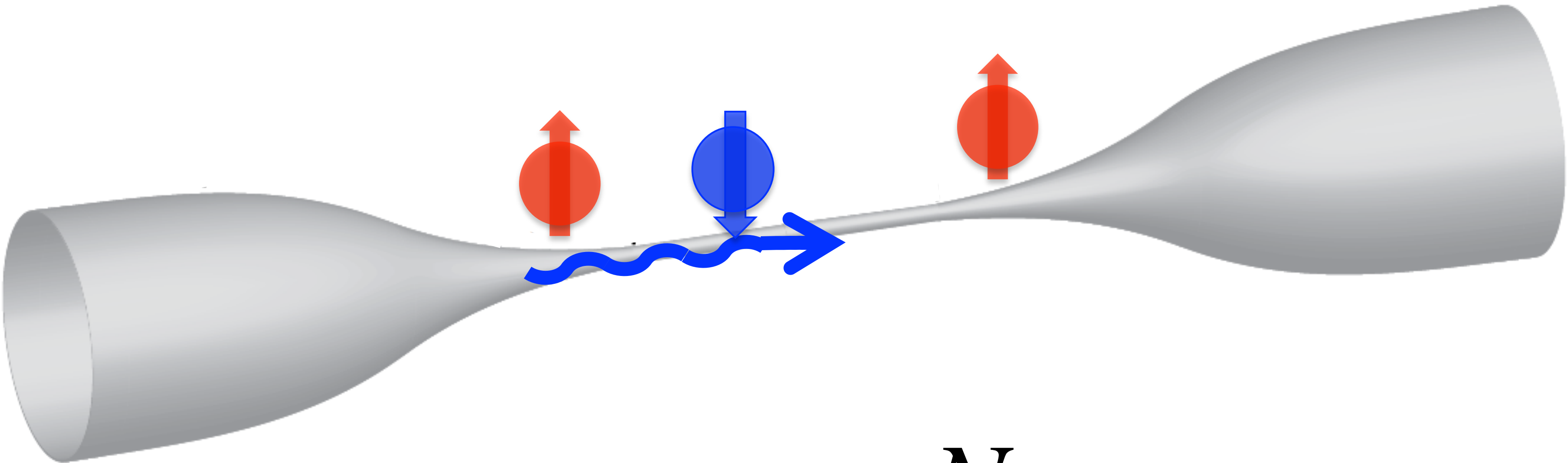


Average number of atoms
1
2
3
4
5
6
1.10
1.05
1.00
0.95
γ/γ_0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Optical density



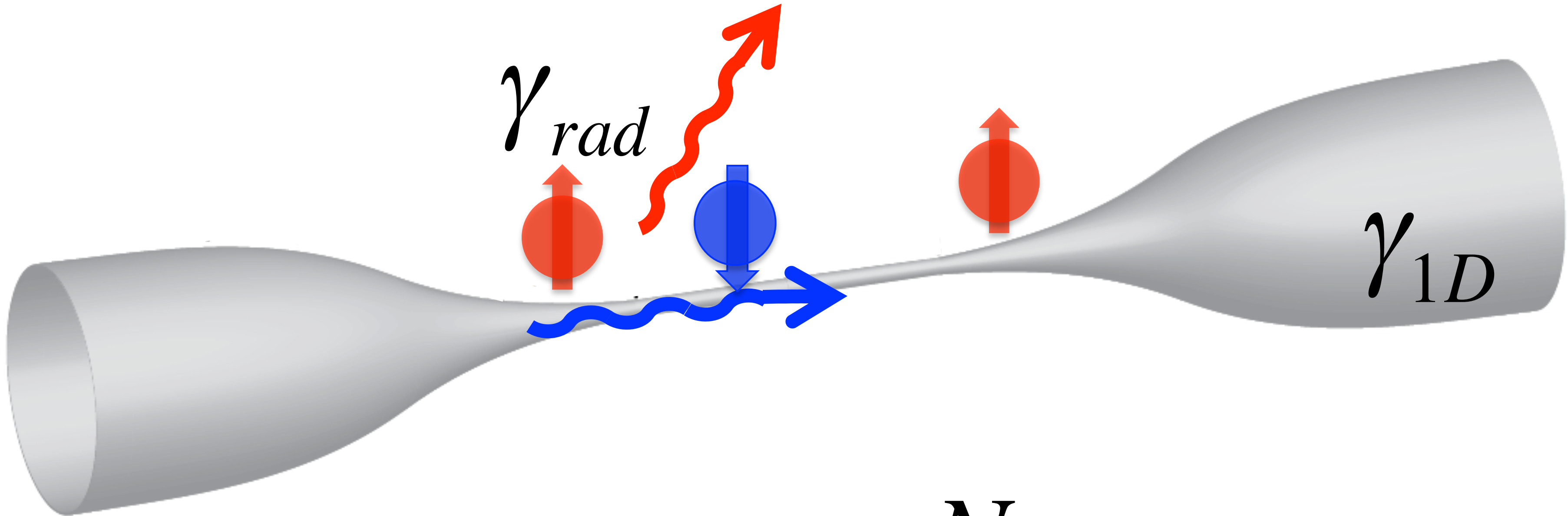
The slope (0.02) is **smaller** than γ_{1D} (0.10) because it is an **average** over different realizations, non all of them superradiant.

Sub-radiance???



$$\gamma_{\sup} = \gamma_{rad} + N\gamma_{1D}$$

Subradiance???

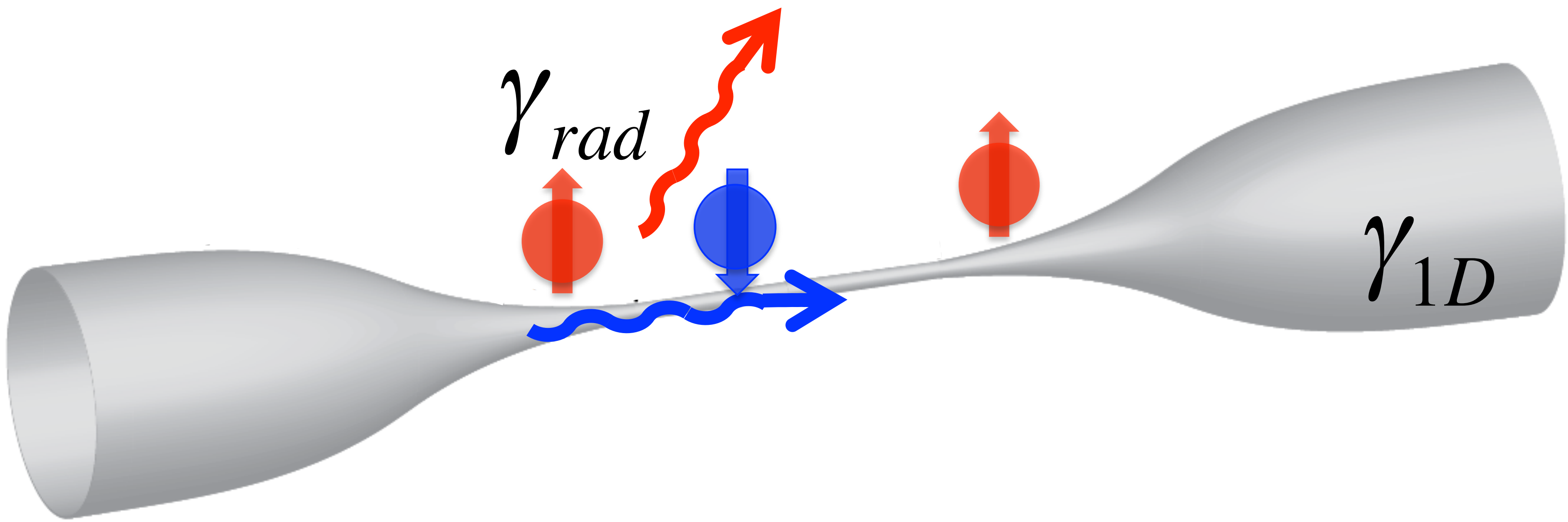


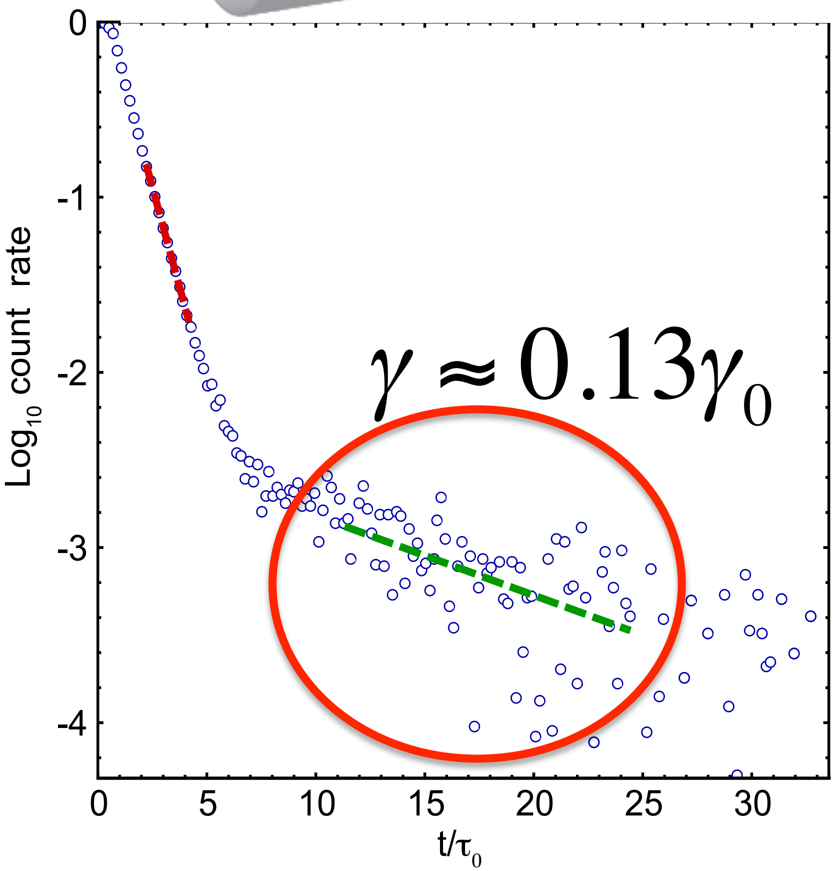
$$\gamma_{\sup} = \gamma_{rad} + N\gamma_{1D}$$

$$\gamma_{sub} = \gamma_{rad} - \gamma_{1D}$$

Infinite-range subradiance is **limited**!

Sub-radiance???



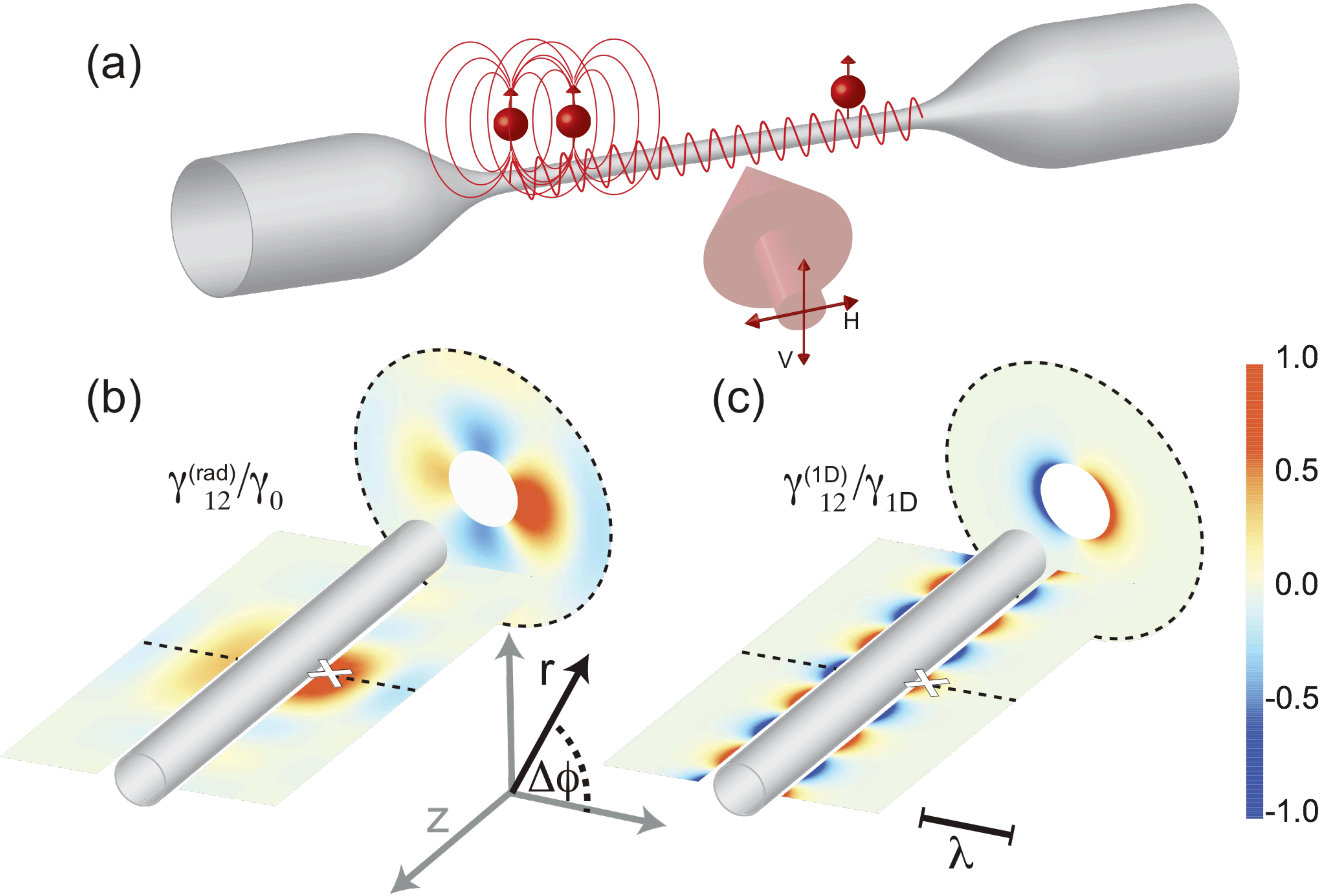


$$\gamma_{sub} = \gamma_{rad} - \gamma_{1D} \approx 0.9\gamma_0$$

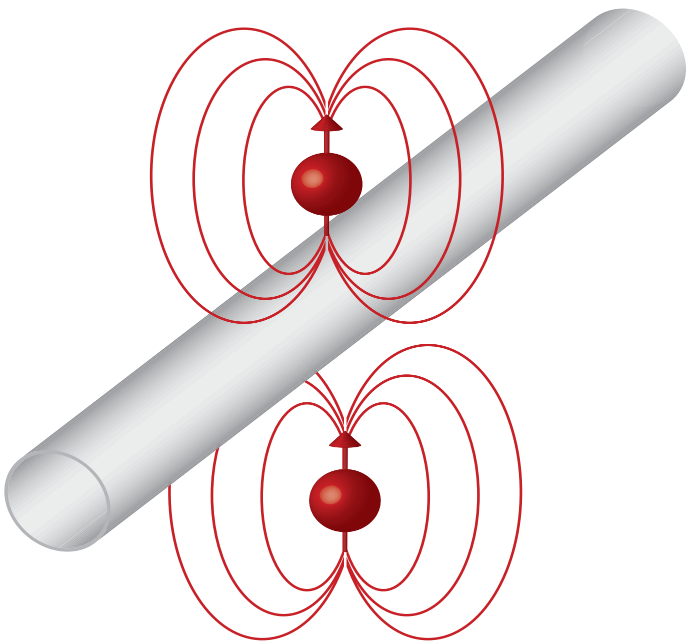
The subradiant decay rate we measure is **too slow**!

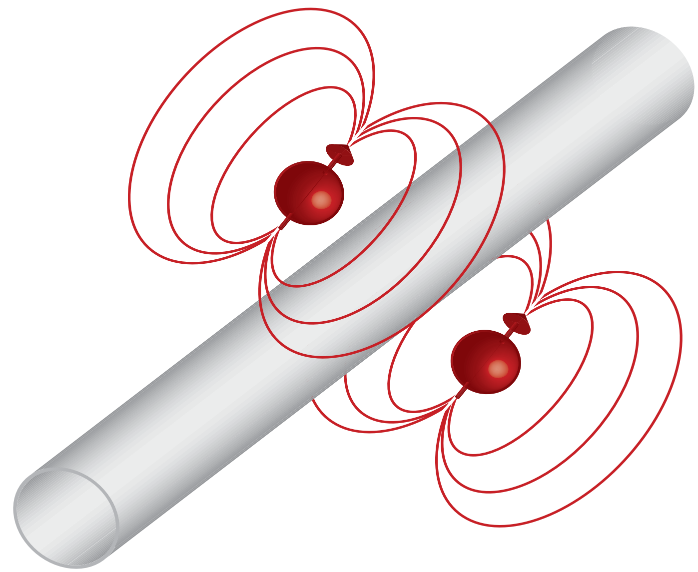
Understanding the Signal

Understanding the Signal

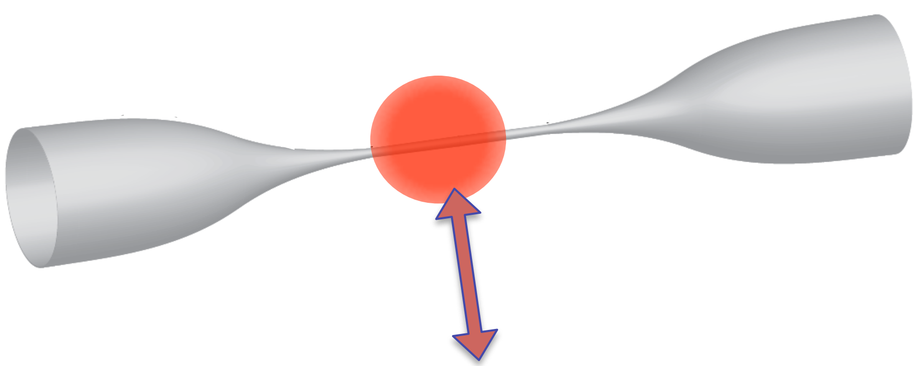


Polarization dependent signal

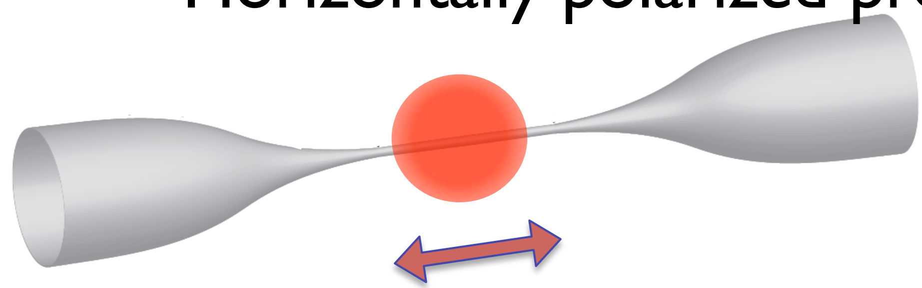




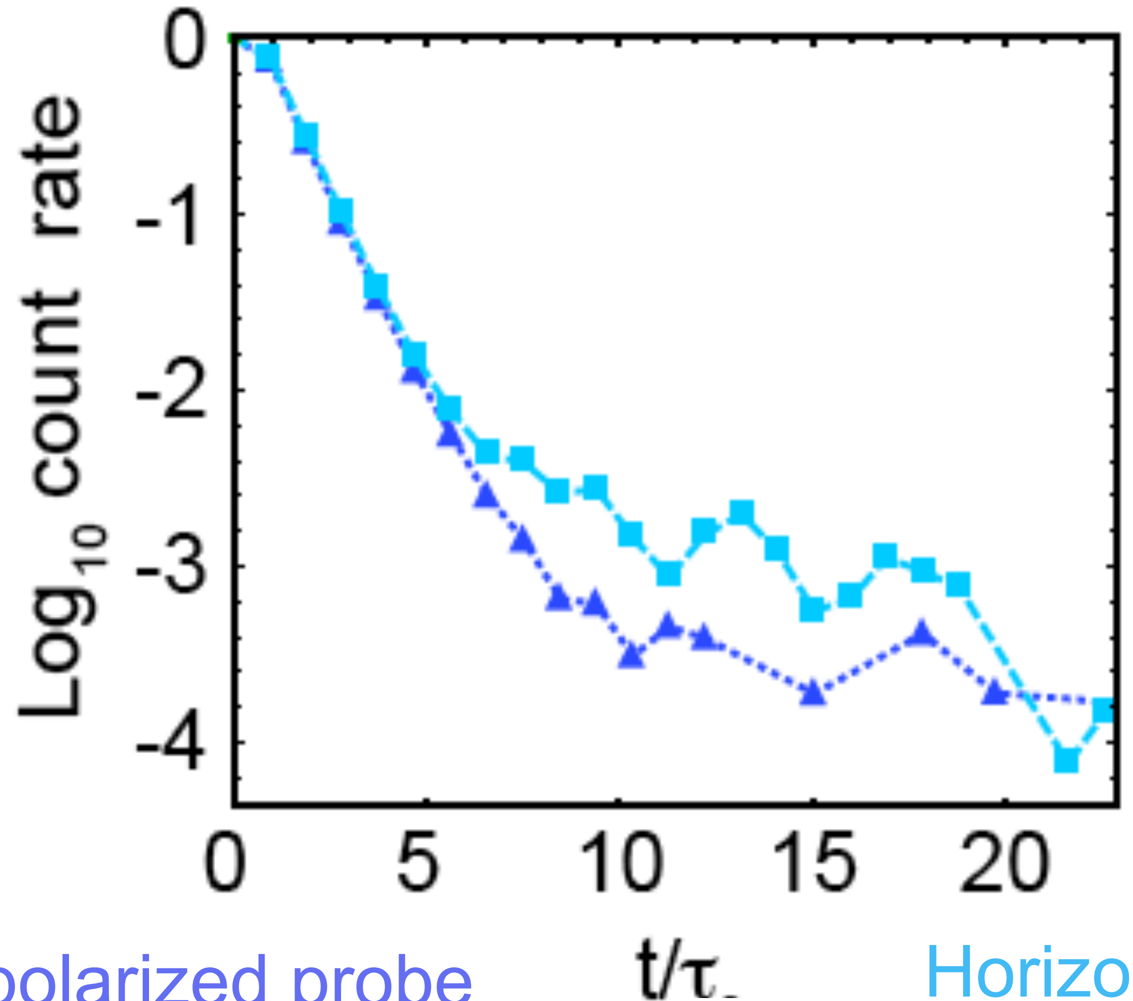
Vertically polarized probe



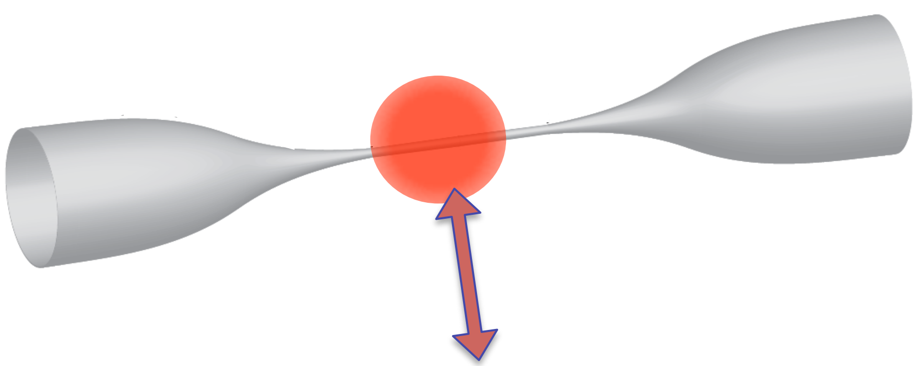
Horizontally polarized probe



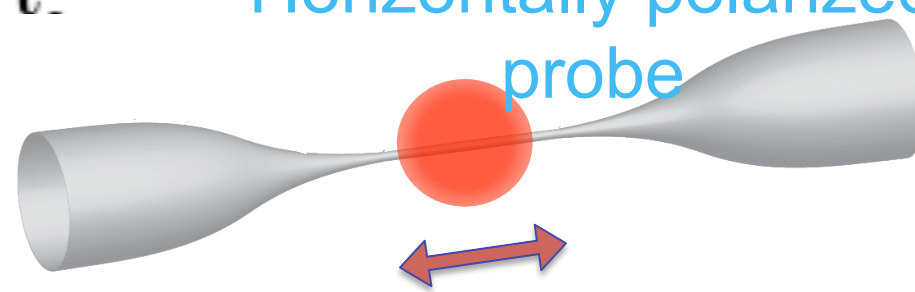
Polarization dependent signal



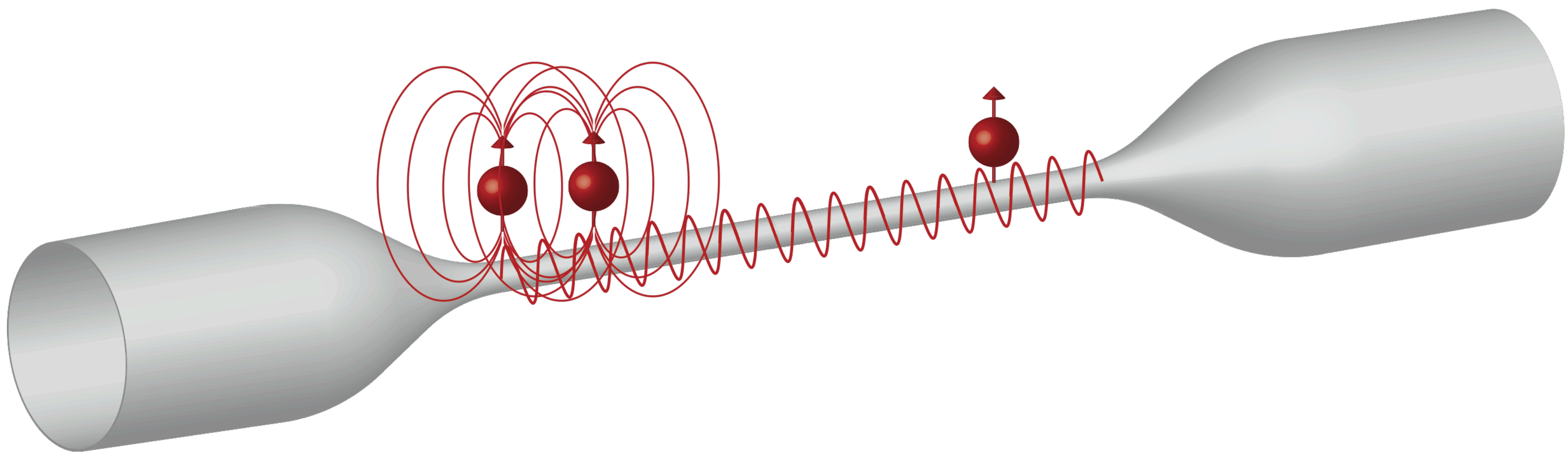
Vertically polarized probe



Horizontally polarized probe



Subradiant Signal



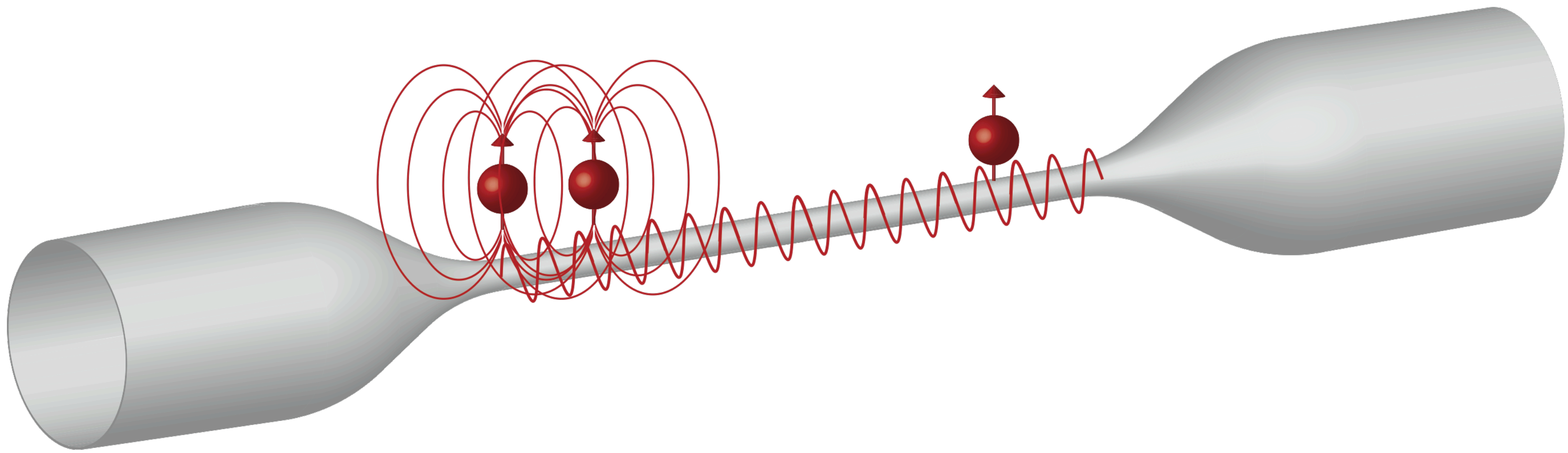
- Interaction distance smaller than λ: all modes get cancelled.
- Interaction distance greater than λ: only one mode gets cancelled

$$\gamma_{sub} = \gamma_{rad} - \gamma_{1D} \approx 0.9\gamma_0$$

We measure

$$\gamma_{sub} = 0.13\gamma_0$$

Super-radiant Signal



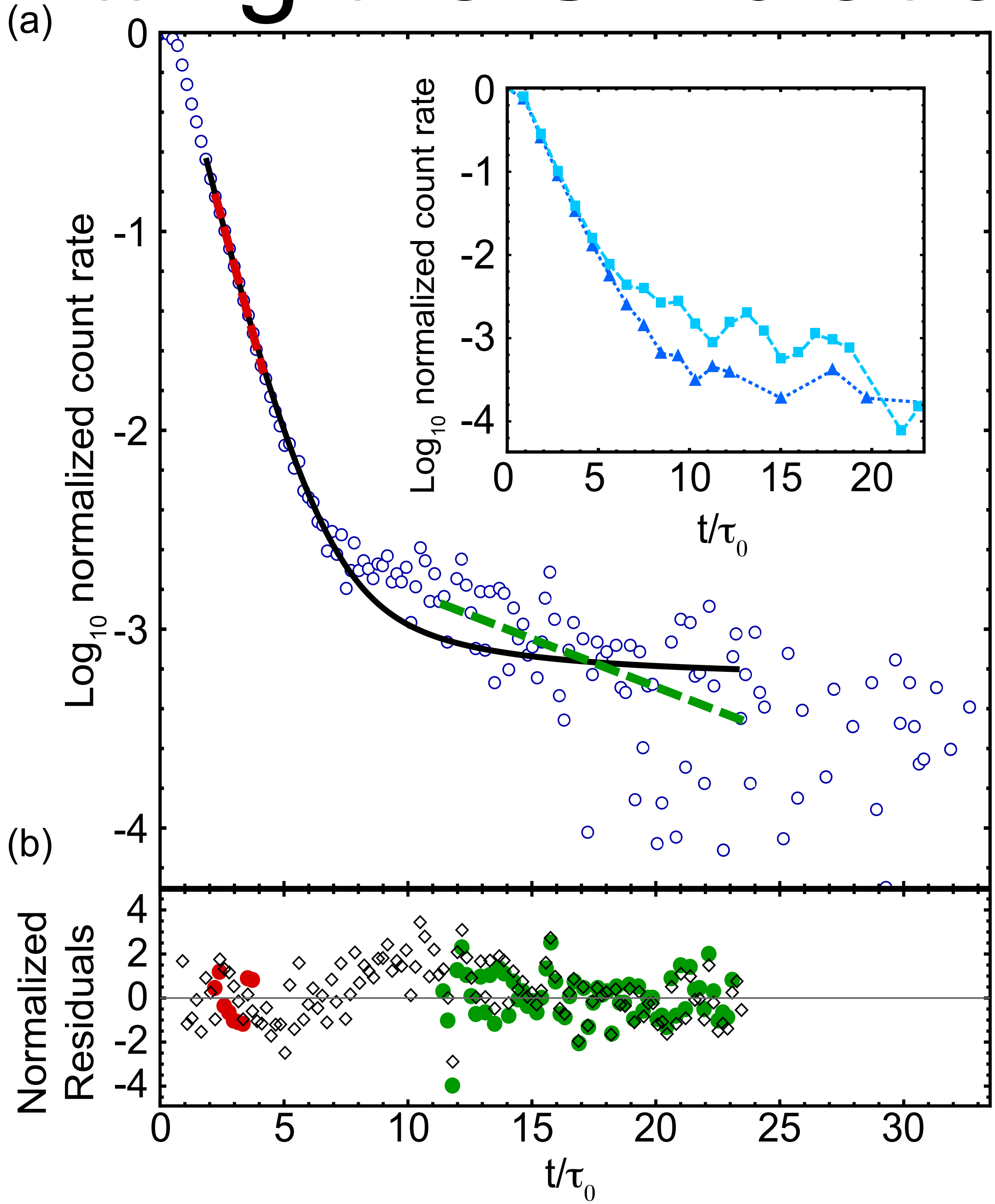
- Interaction distance smaller than λ: all modes get enhanced.
- Interaction distance greater than λ: only one mode gets enhanced

$$\gamma_{\sup} = \gamma_{rad} + N\gamma_{1D}$$

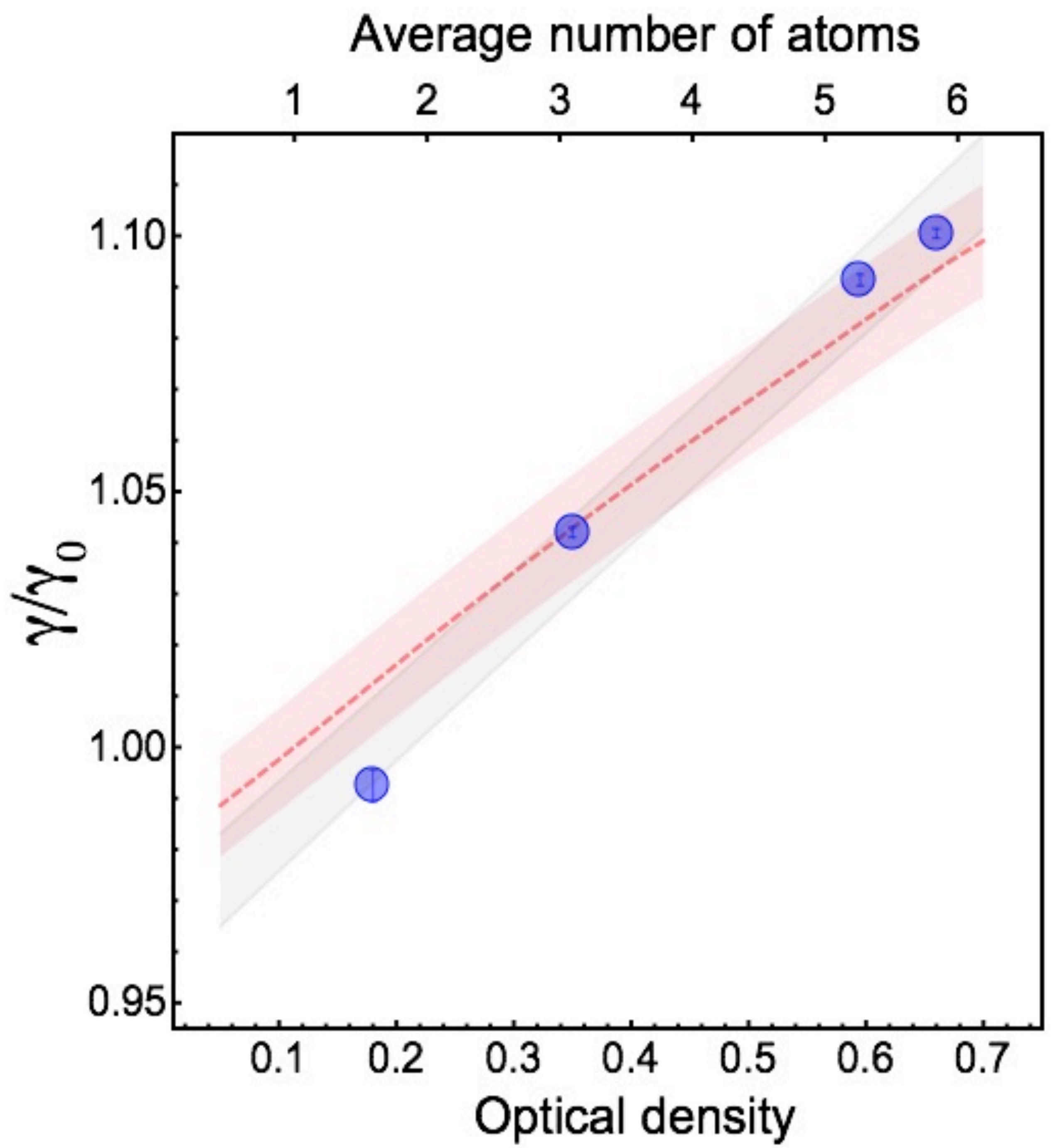
We measure

$$\gamma_{\sup} = 1.1\gamma_0$$

Fitting the Simulation

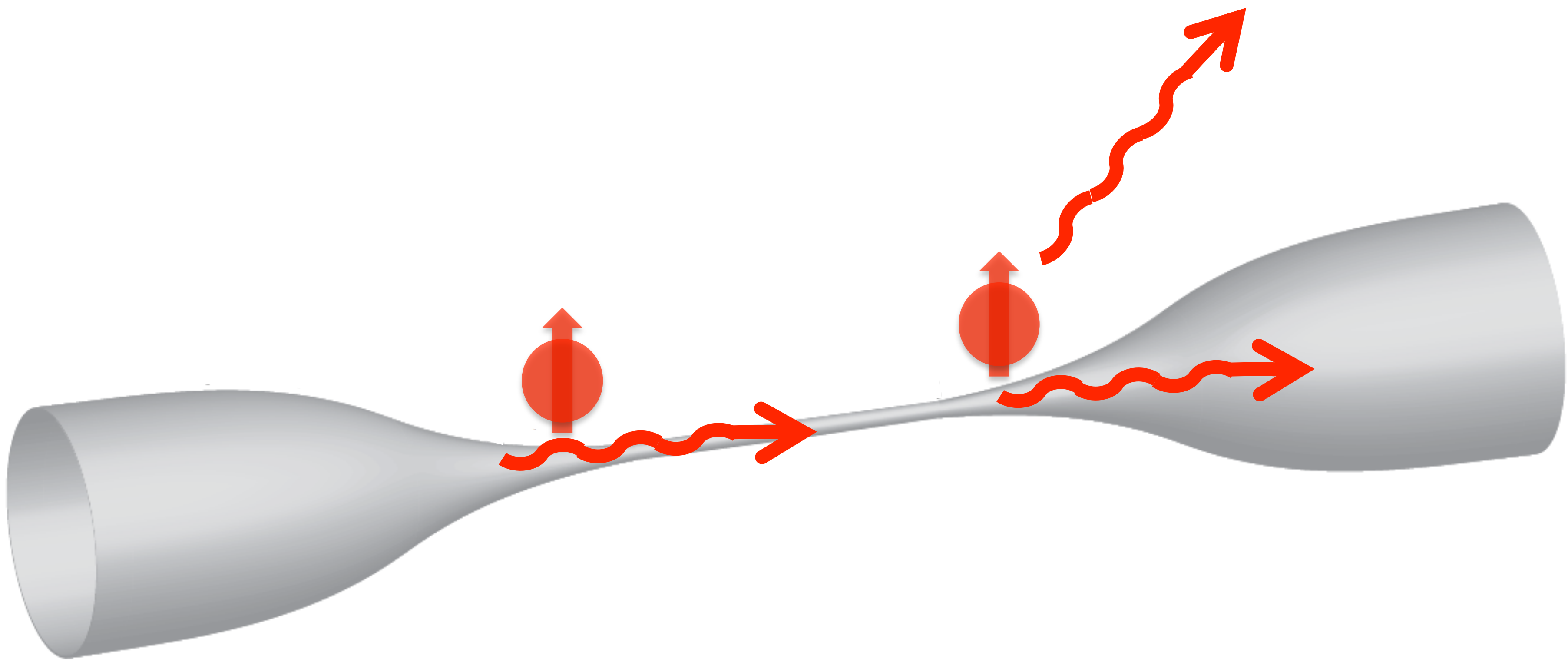


Fitting the Simulation

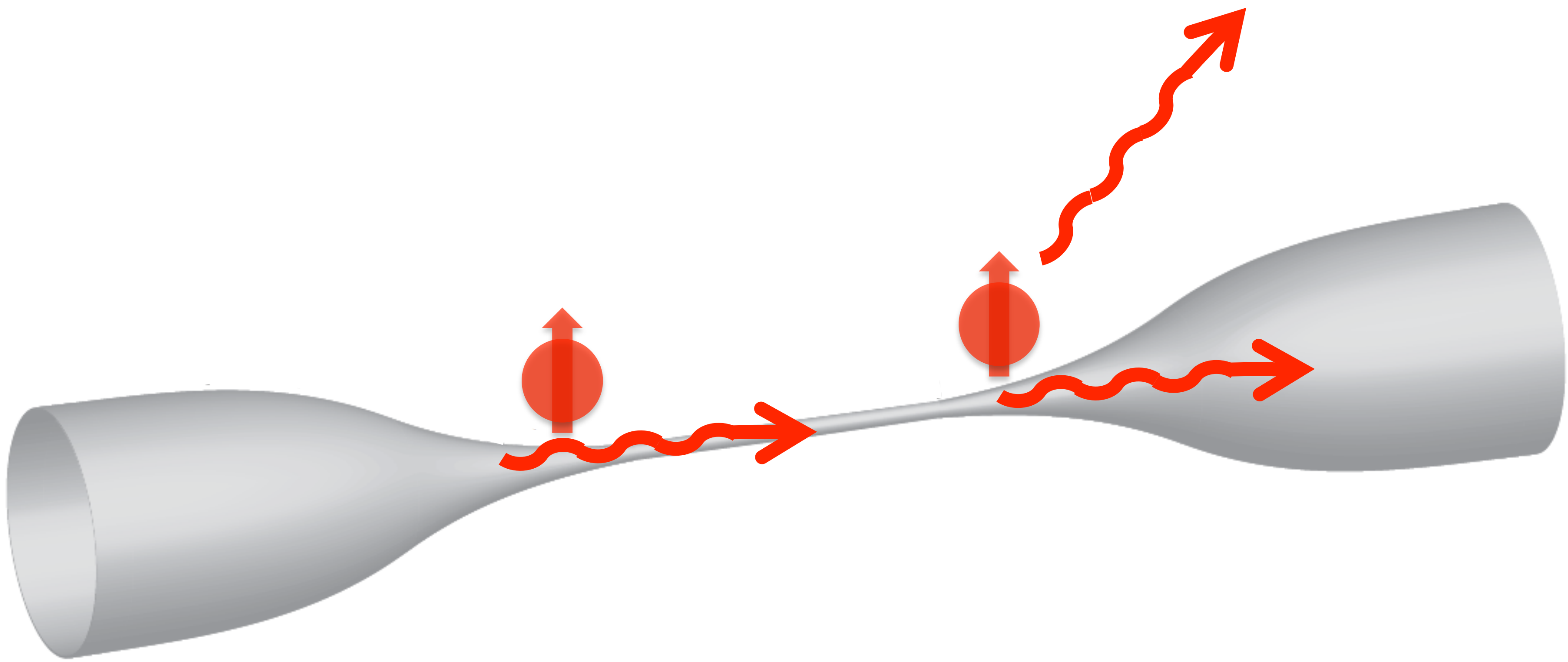


Can we see a collective atomic effect of atoms around the nanofiber?

Long distance modification of the atomic radiation

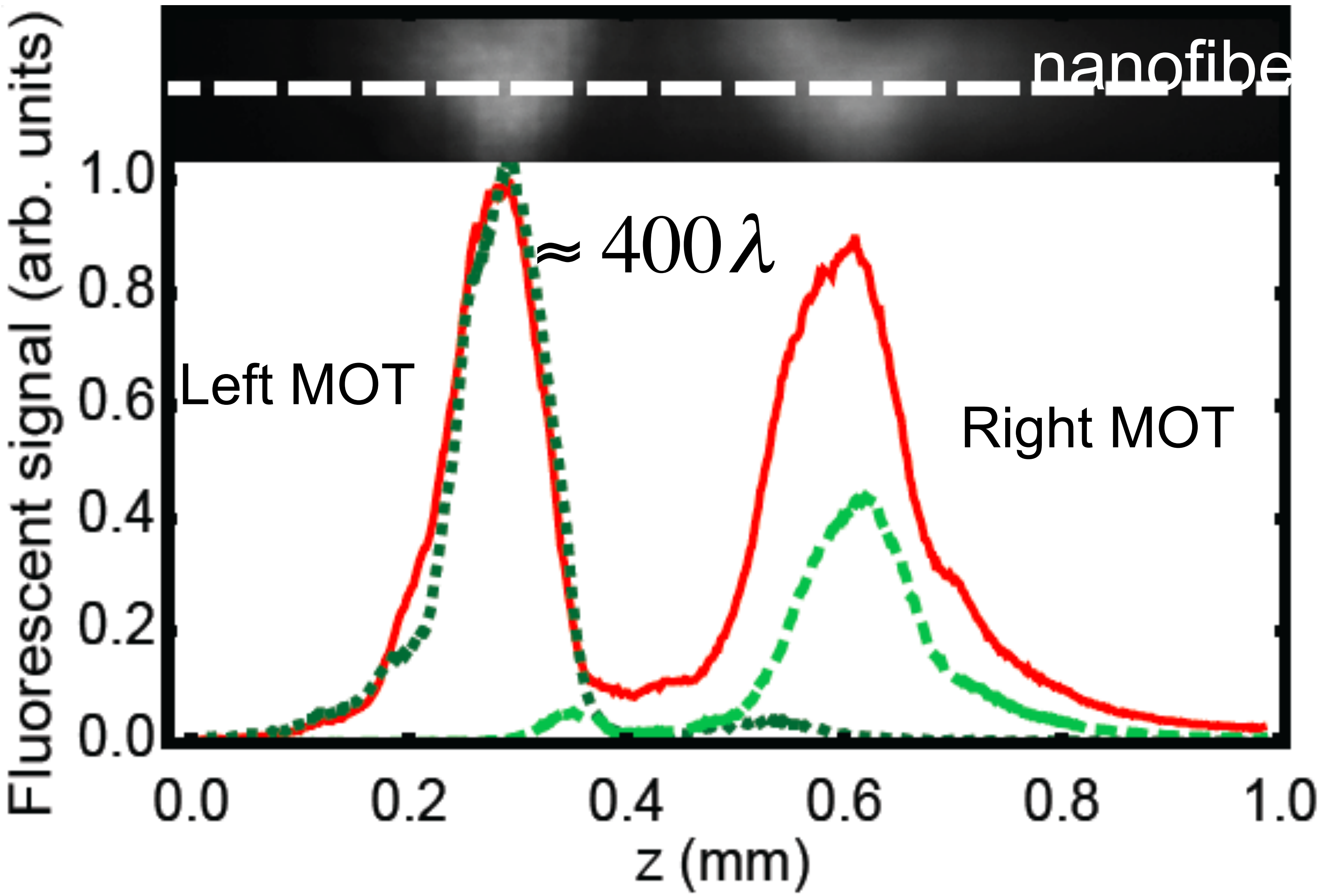


Long distance modification of the atomic radiation

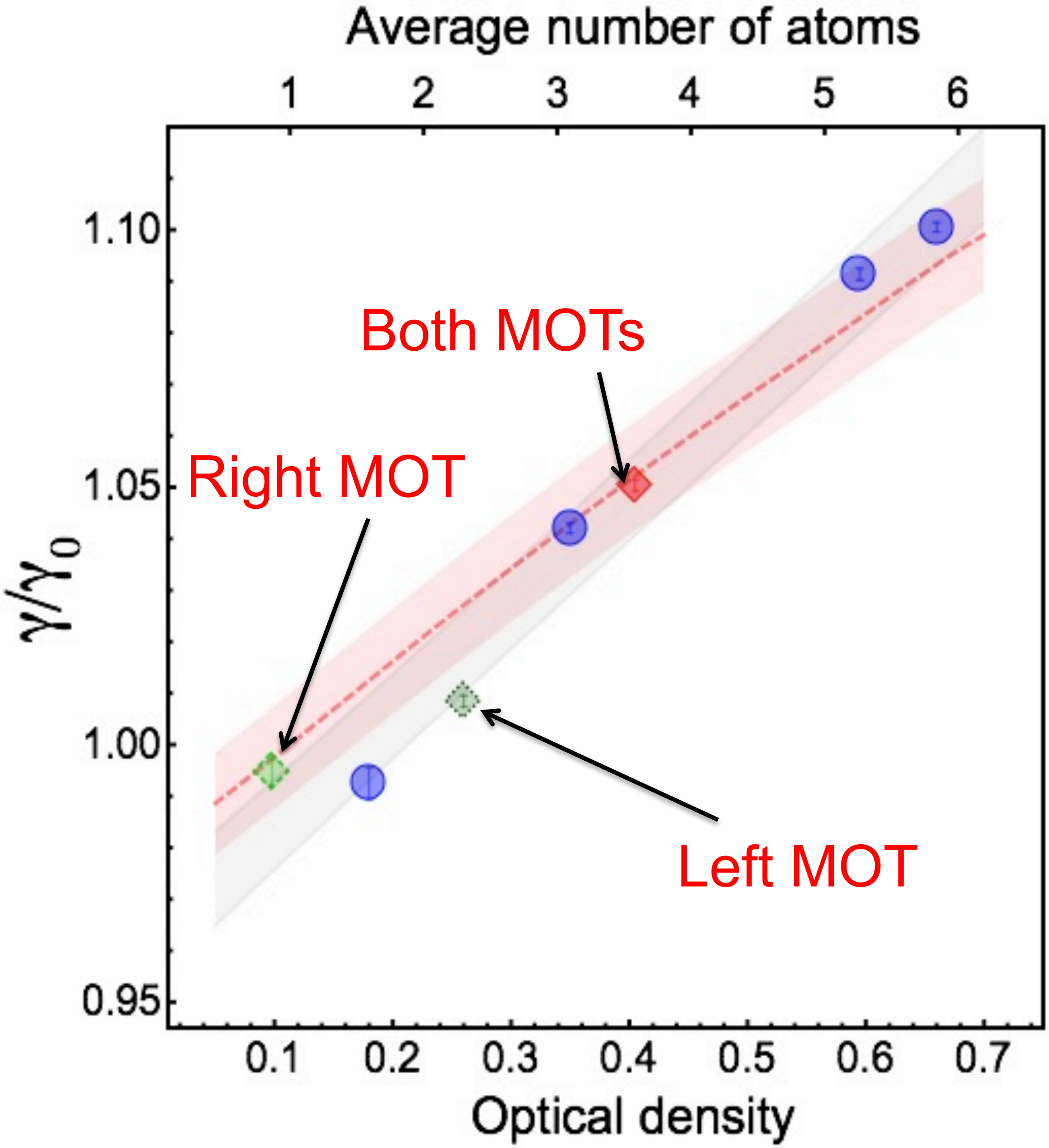


We have atomic densities low enough to observe mostly infinite-range interactions

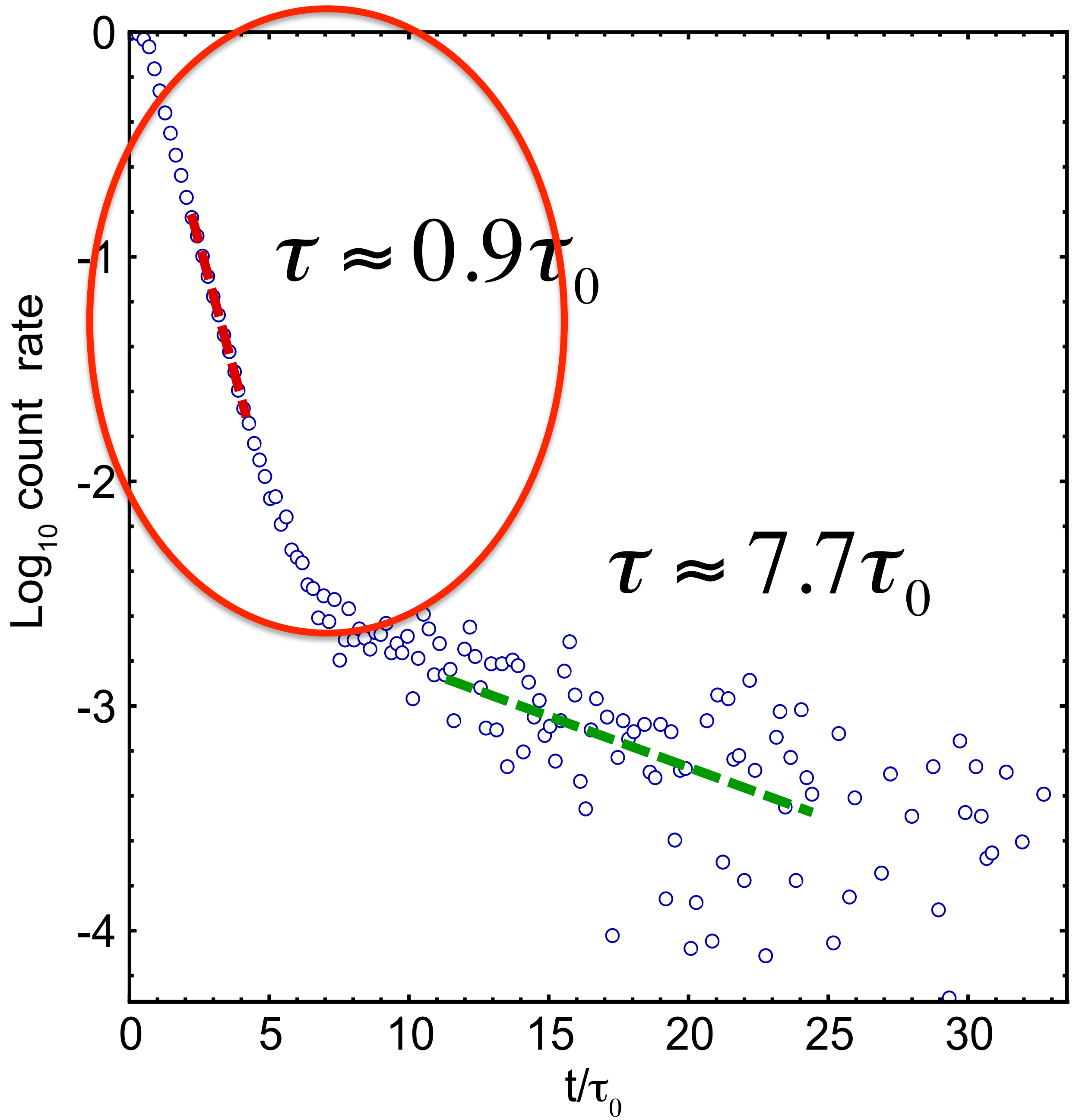
Splitting the MOT in two



Evidence of infinite-range interactions



Two distinct lifetimes



Summary:

1. Spontaneous emission vs stimulated emission.
2. Spontaneous emission of one atom near a nanofiber.
3. Collective effects through super- and sub-radiance through a nanofiber.

Gracias