Top

Left side

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bottom

An introduction to light-matter interaction, from cavity QED to waveguide QED 4

USTC, Hefei, China

July 2019

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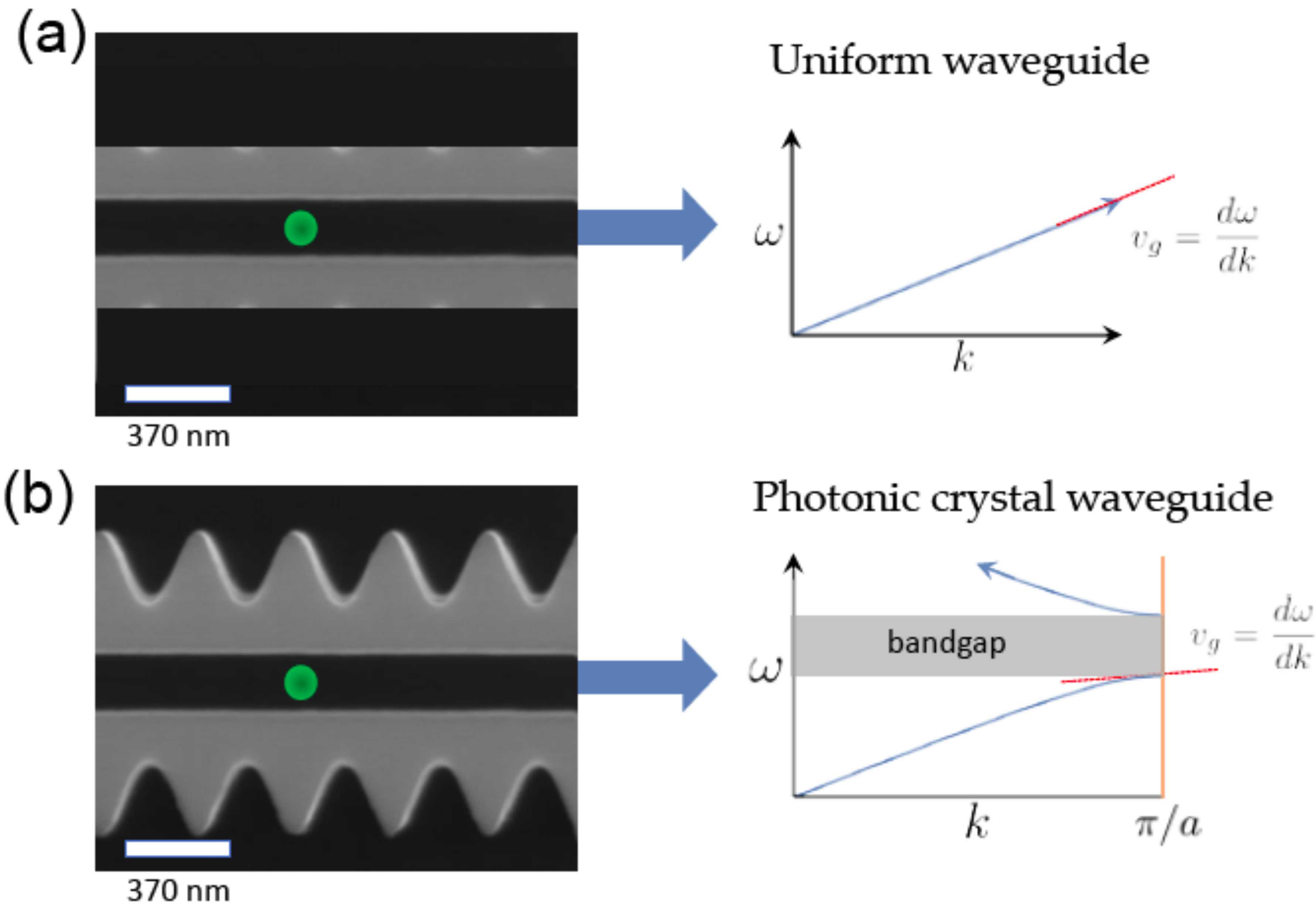
The presentation will be available at:

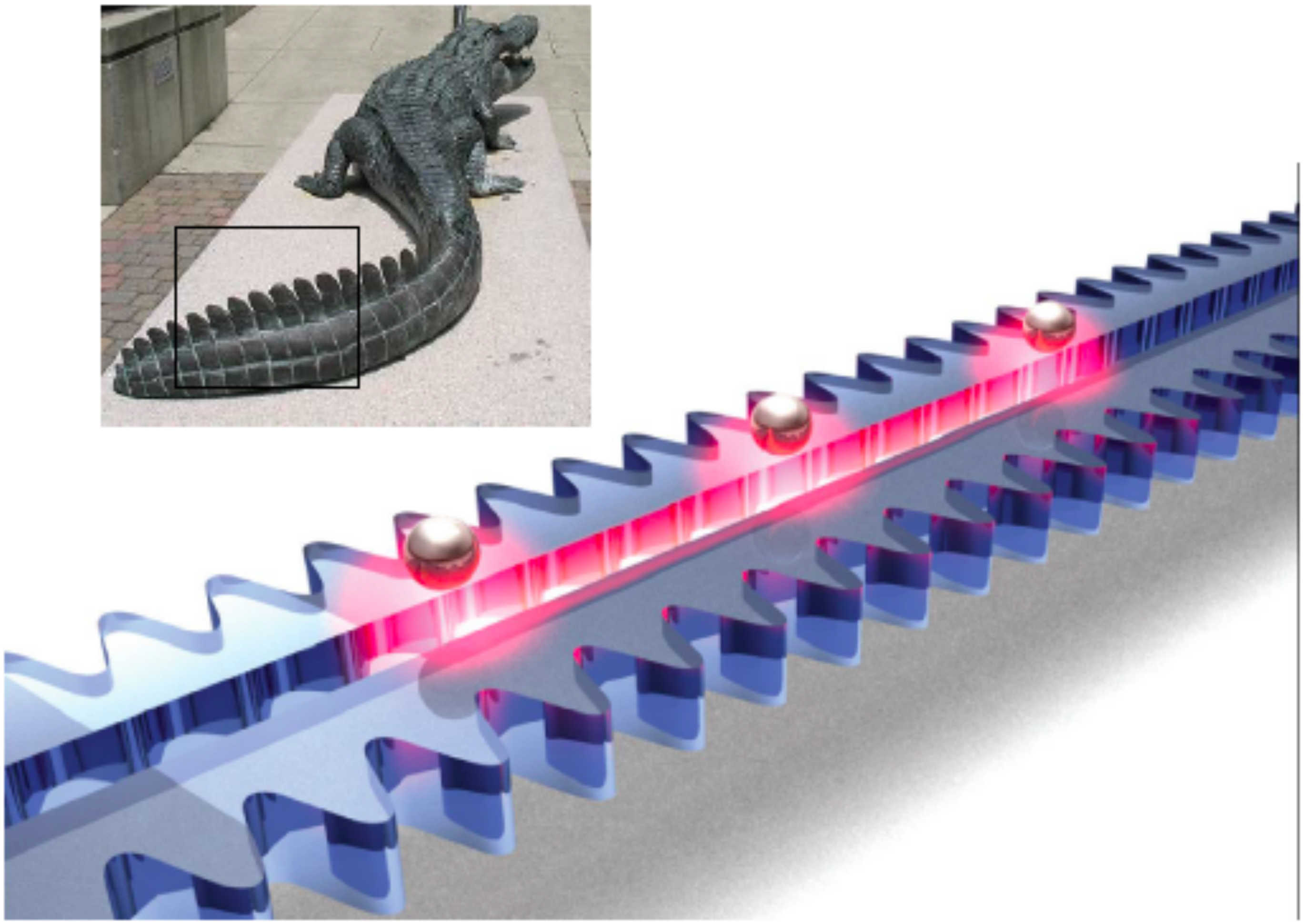
http://www.physics.umd.edu/rgroups/amo/orozco/results/2019/Results19.htm

What happens on a photonic structure?



PhD Thesis Jonathan Hood

The alligator photonic crystal waveguide (Cal Tech)



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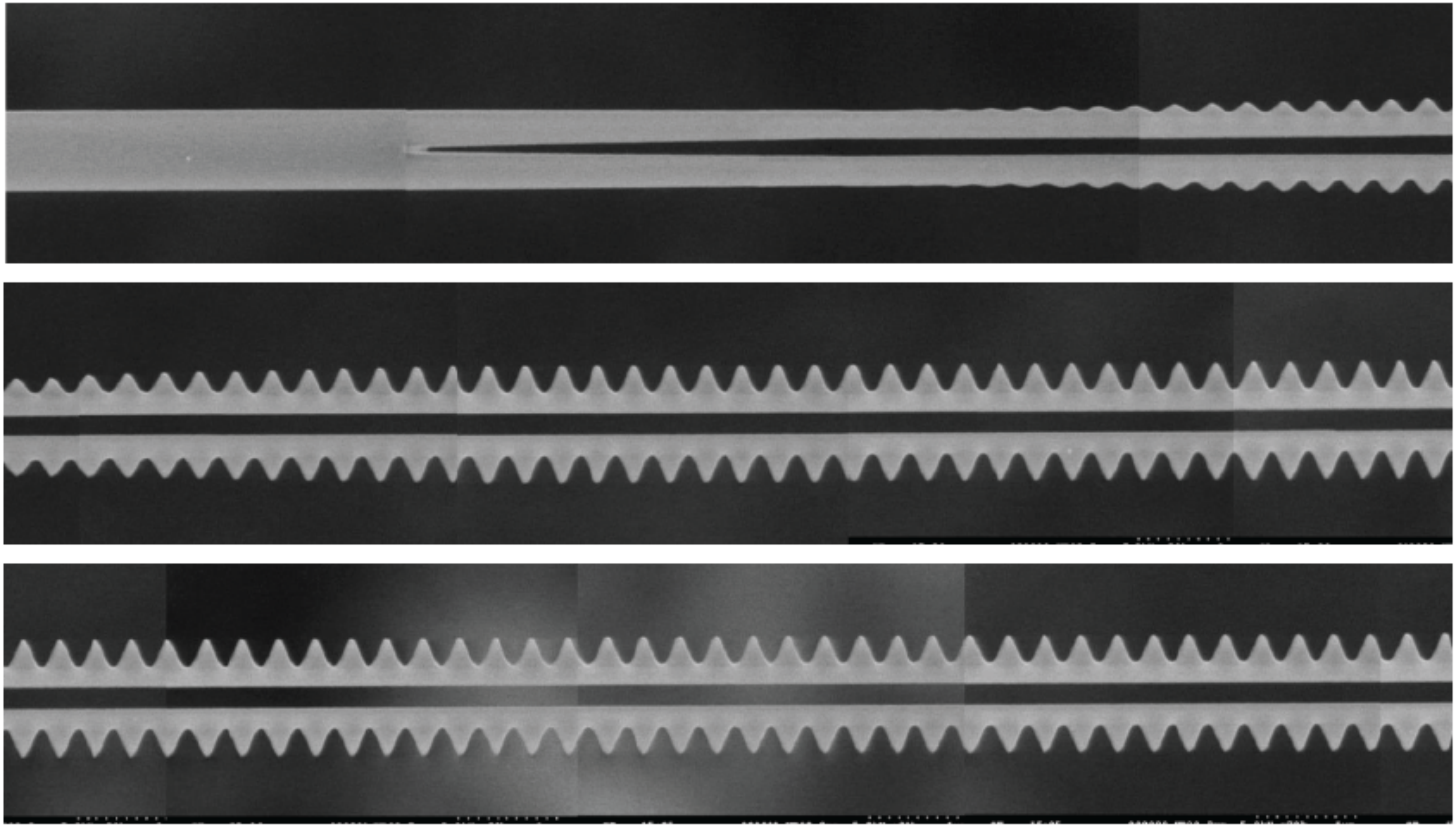
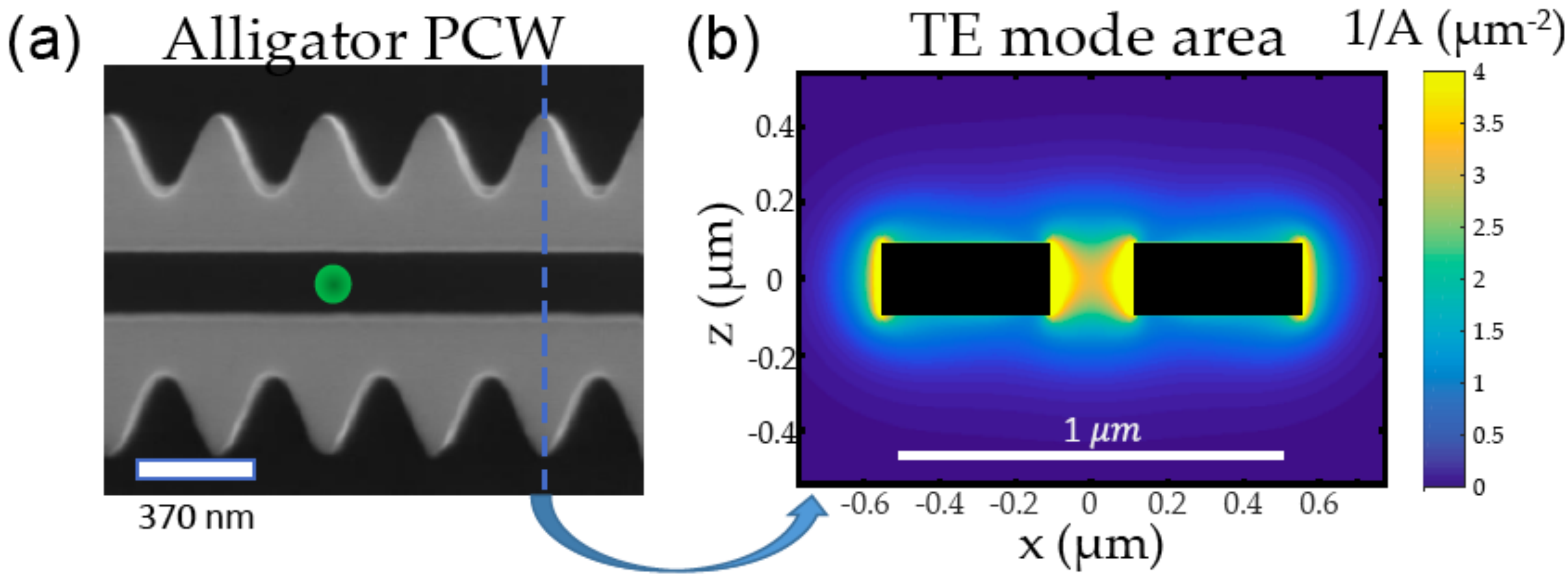


Mode area: $$A_k = \frac{\int_{\text{area}} \mathrm{d}^2\mathbf{r}\, \epsilon(\mathbf{r})|\mathbf{E}_k(\mathbf{r})|^2}{\max\left[\, \epsilon(\mathbf{r})|\mathbf{E}_k(\mathbf{r})|^2 \,\right]}.$$



Scanning electron microscope

Cross section of the intensity

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Because there is a bandgap, the cooperativity grows with it. It can also create a “cavity mode” that does not move attached to the atom

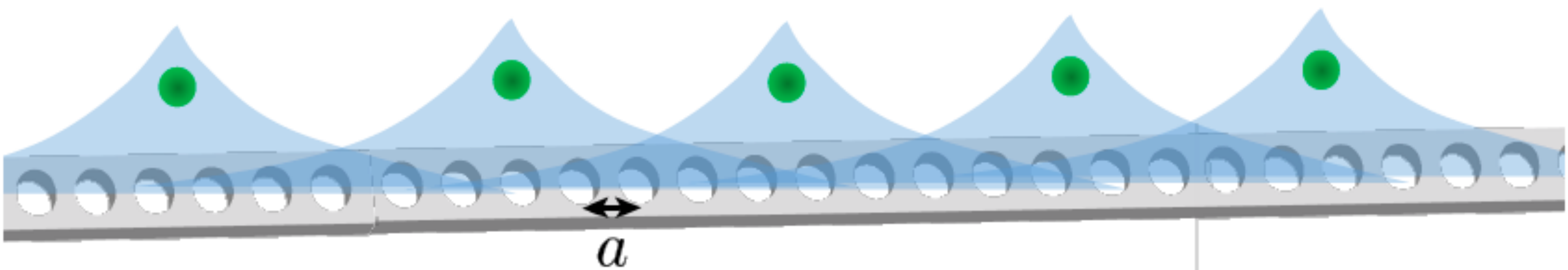

Figure 1.12: Atoms coupled to the bandgap of a photonic crystal waveguide. The atoms and photon cloud form atom-photon bound states.

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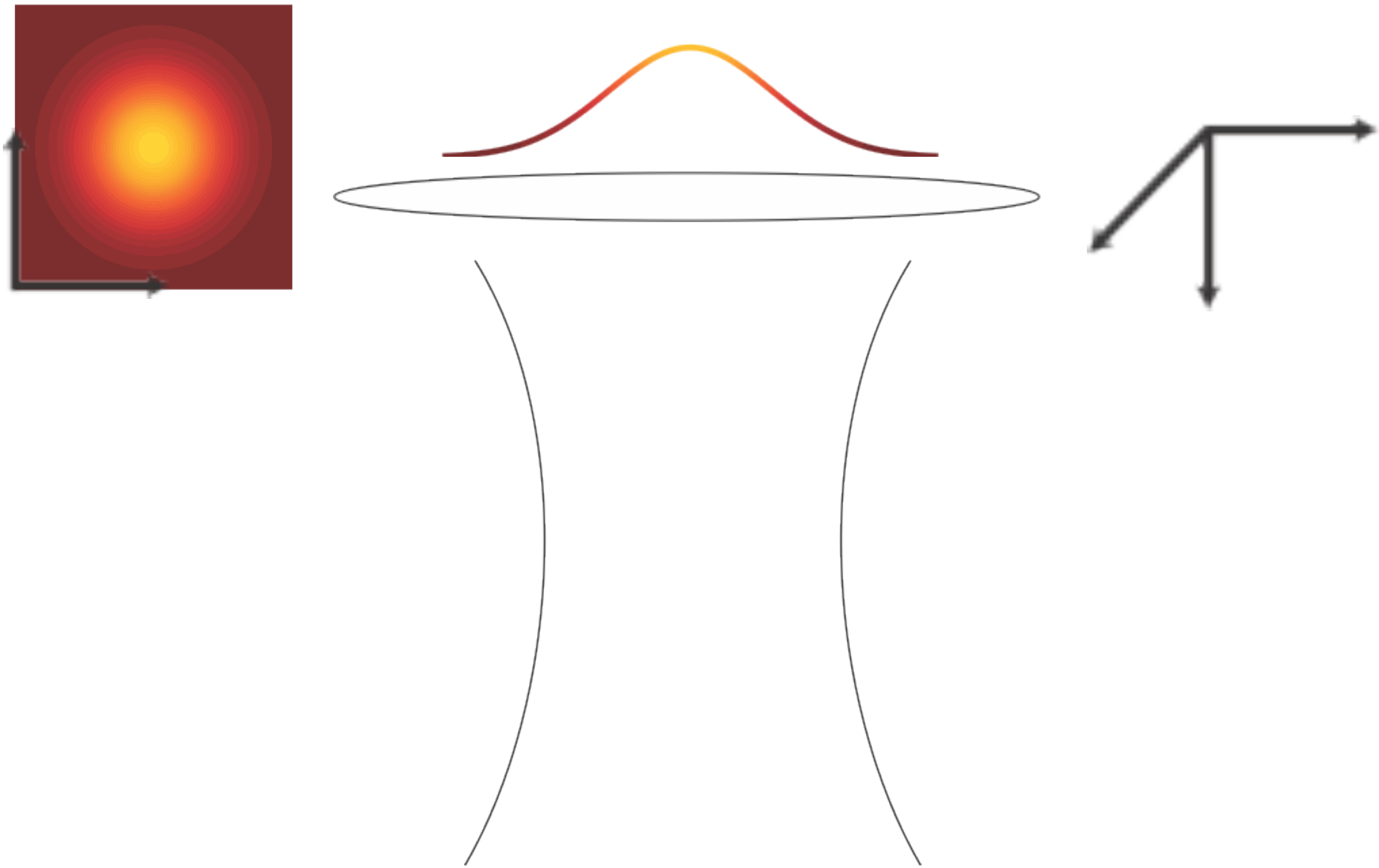
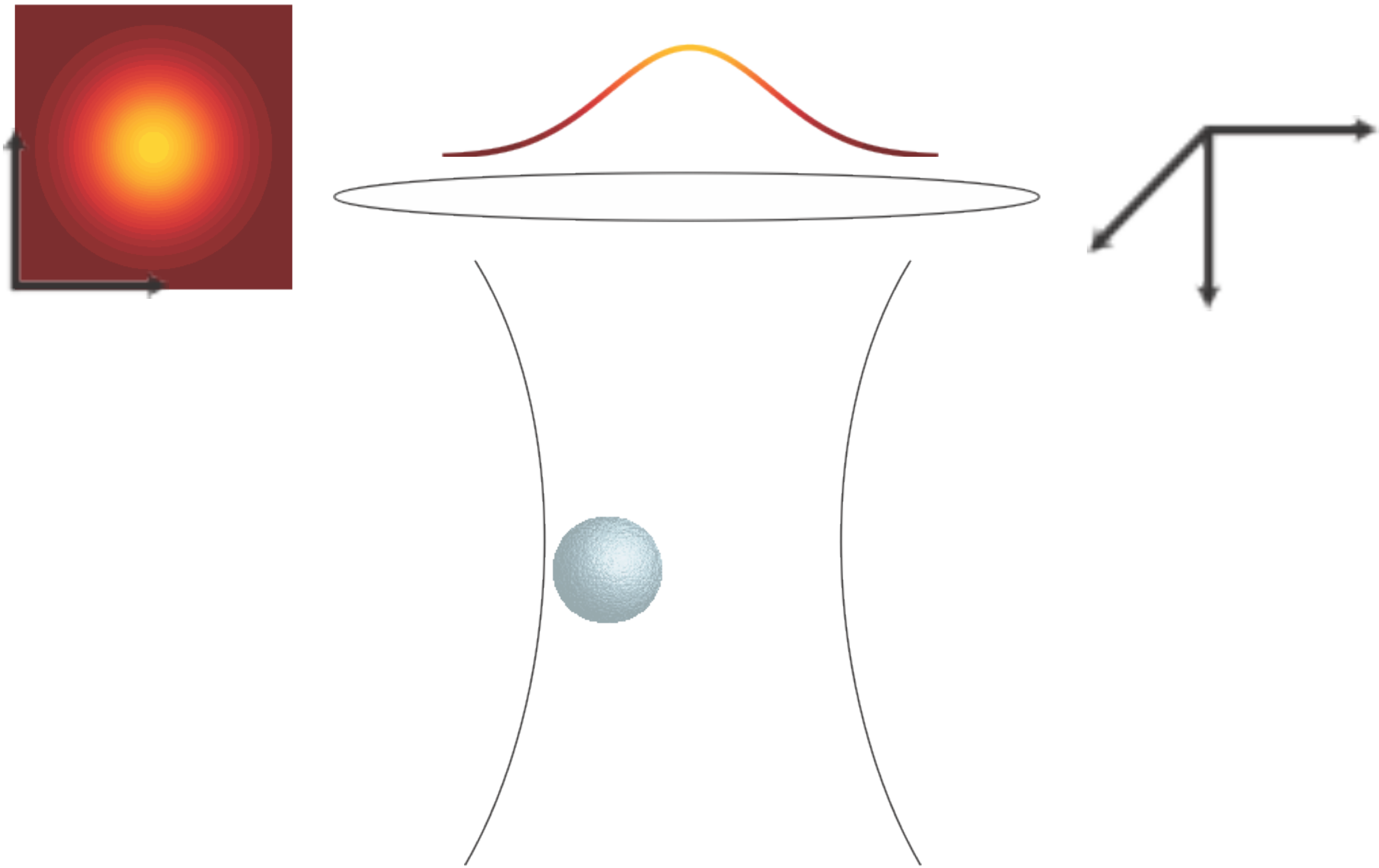
Optical Dipole Trap

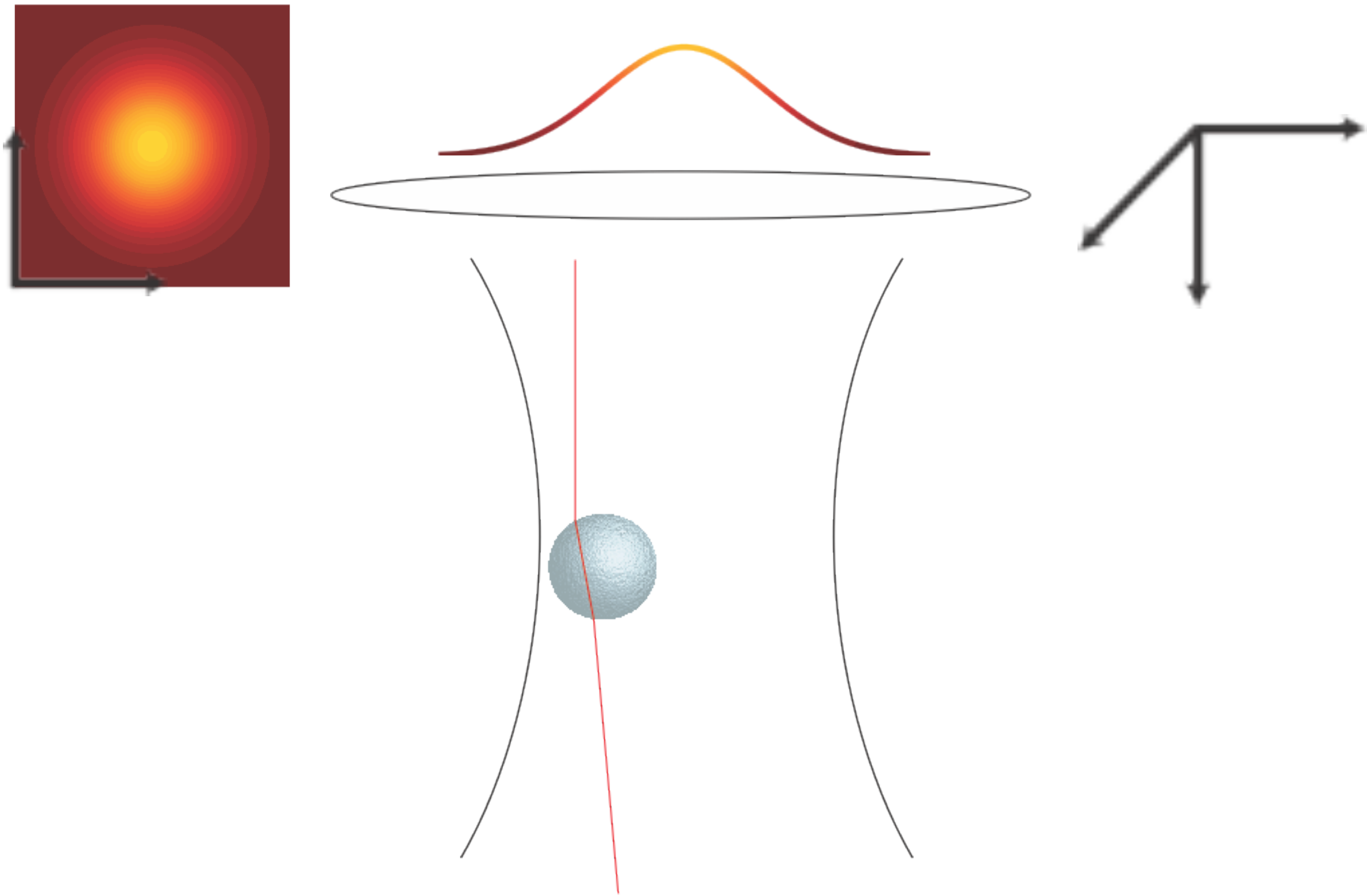
Dipole Trap



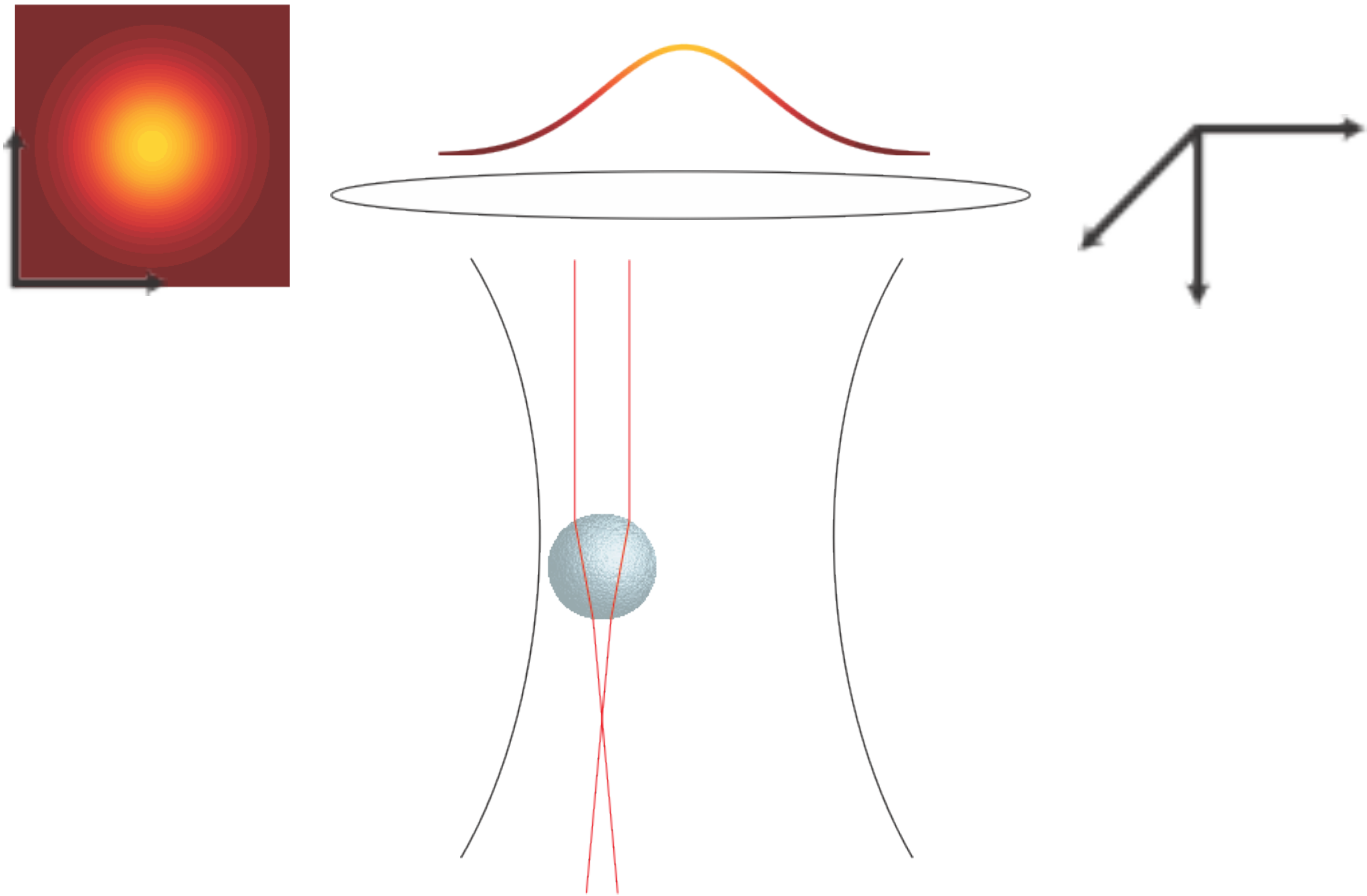
Dipole Trap



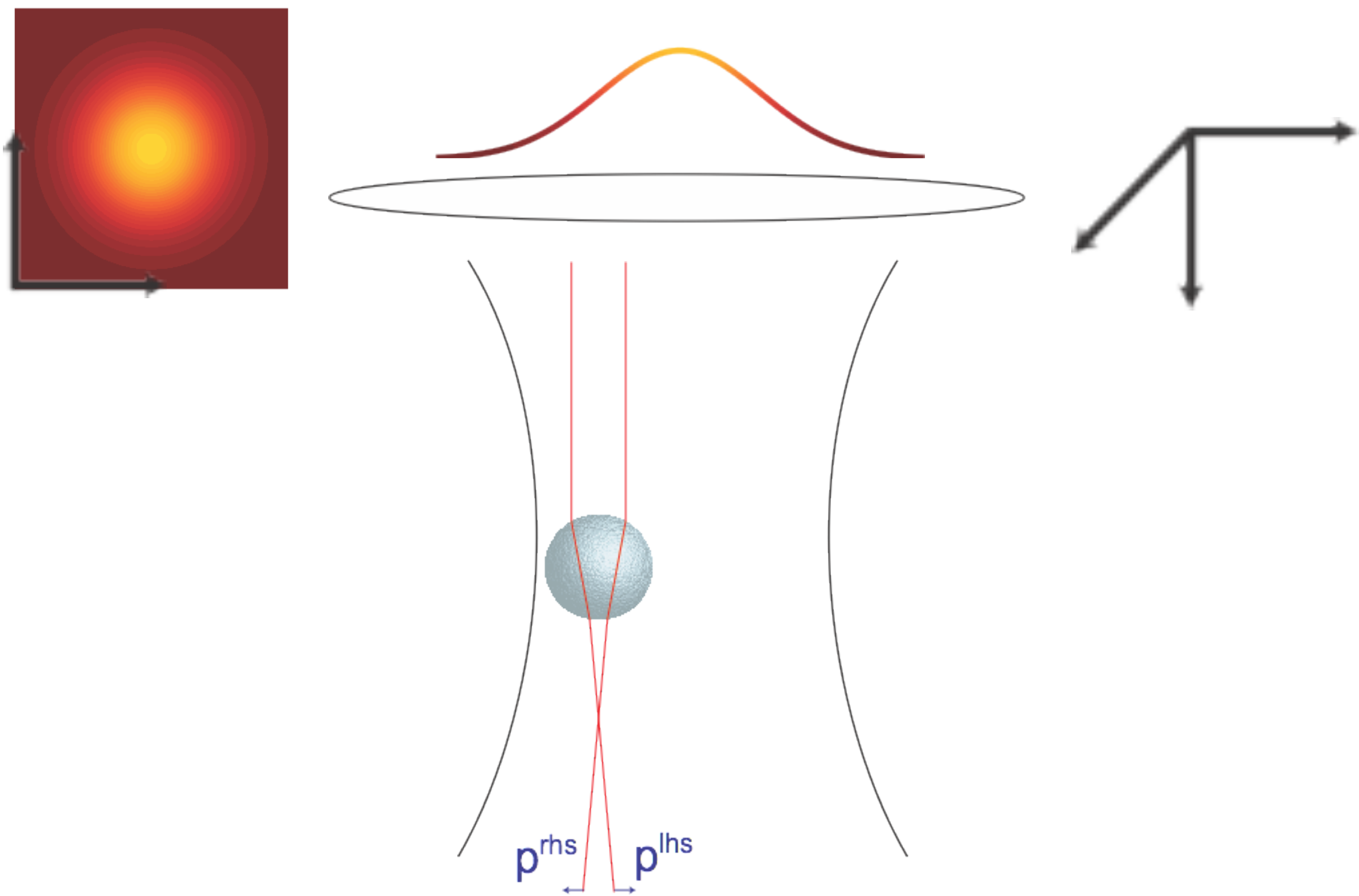
Dipole Trap



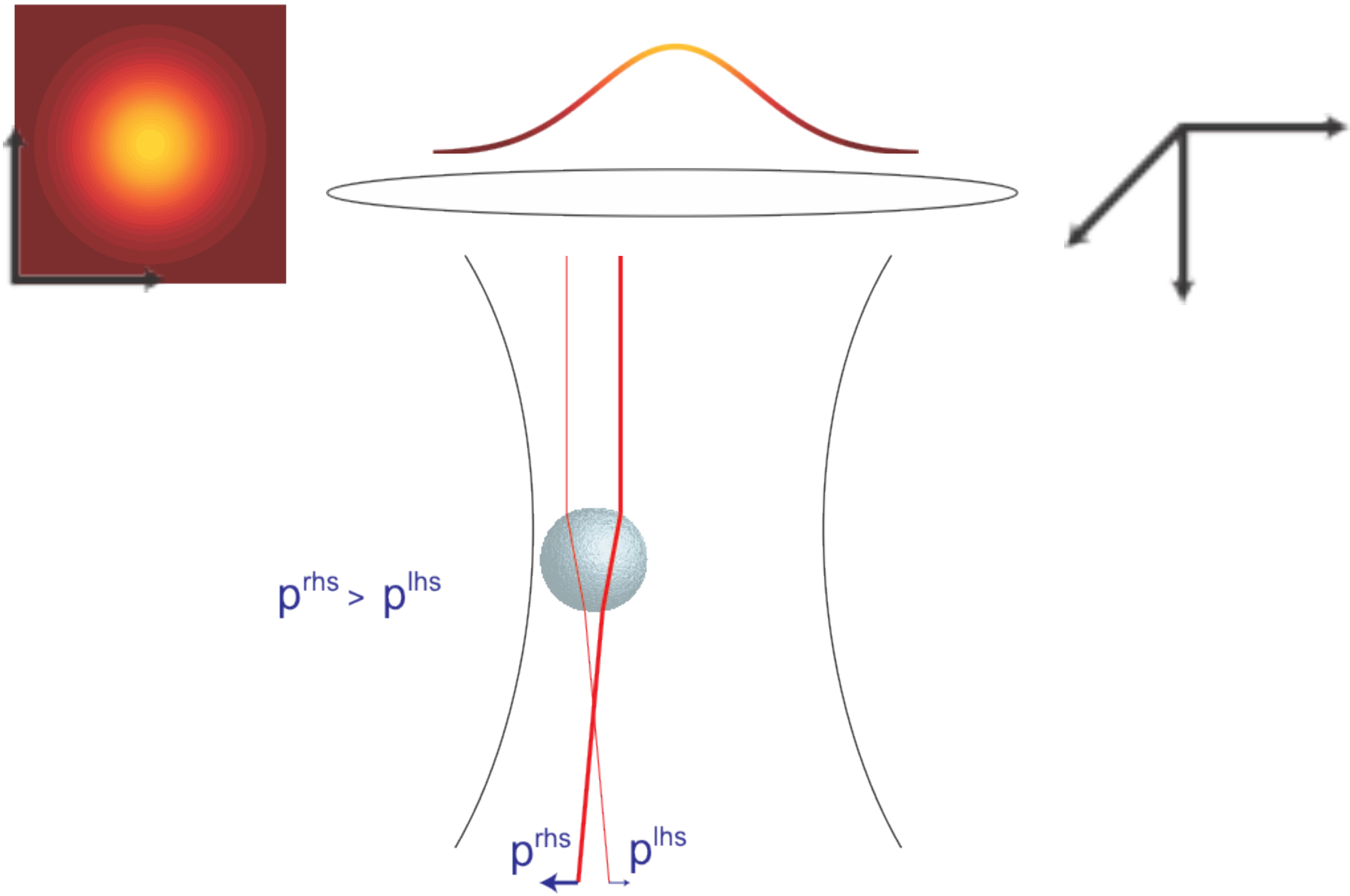
Dipole Trap



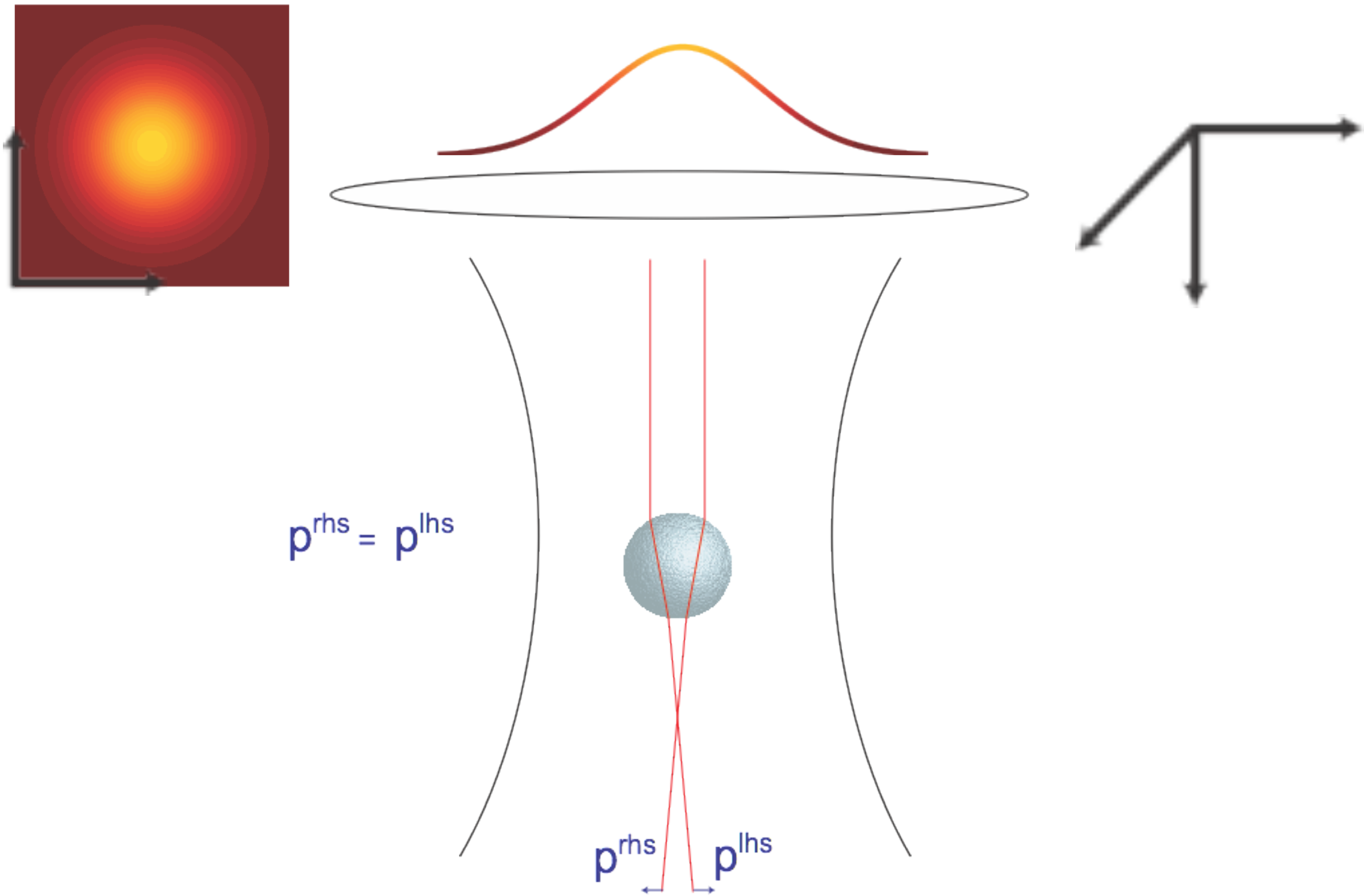
Dipole Trap



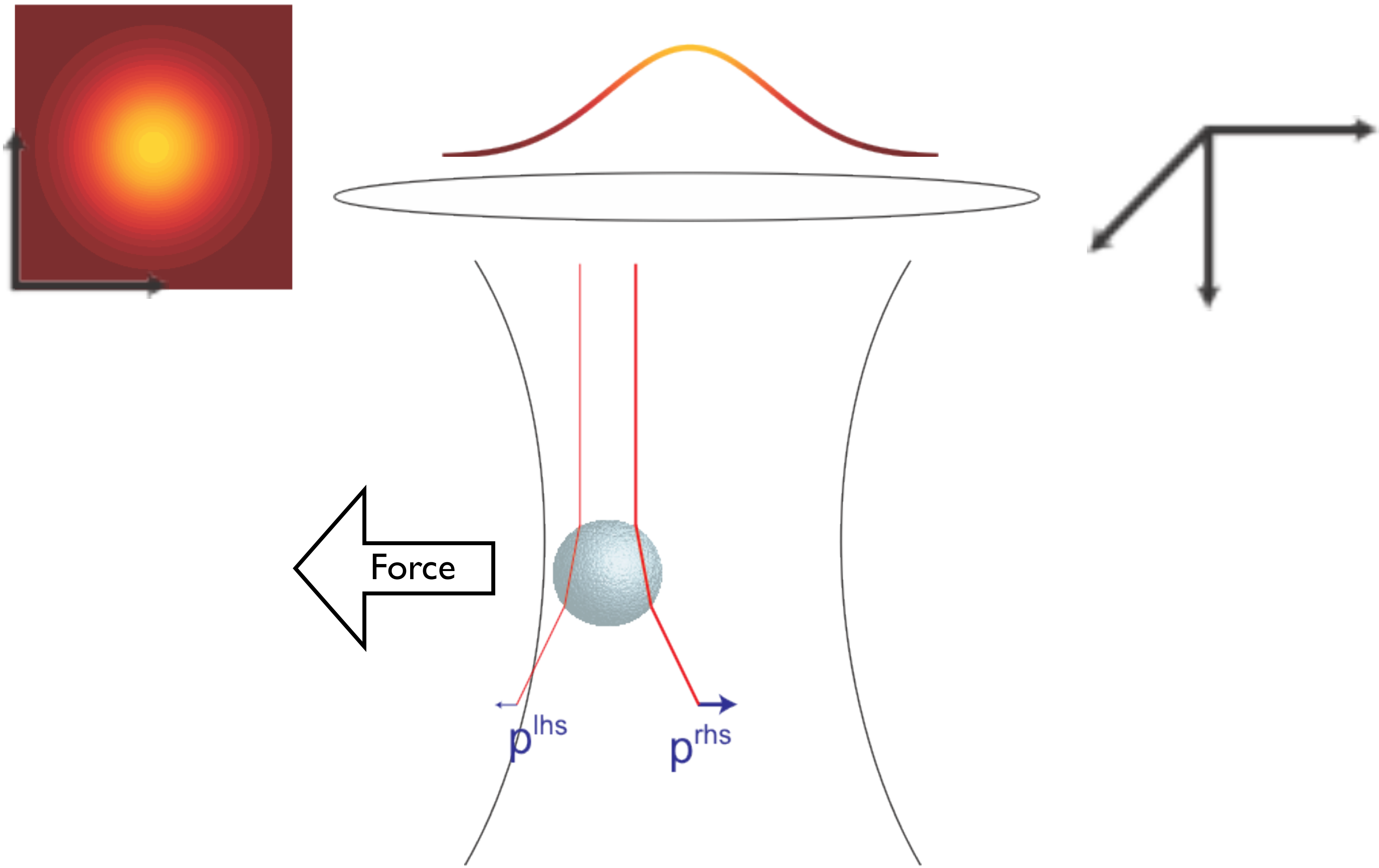
Dipole Trap



Dipole Trap



Air bubble in water



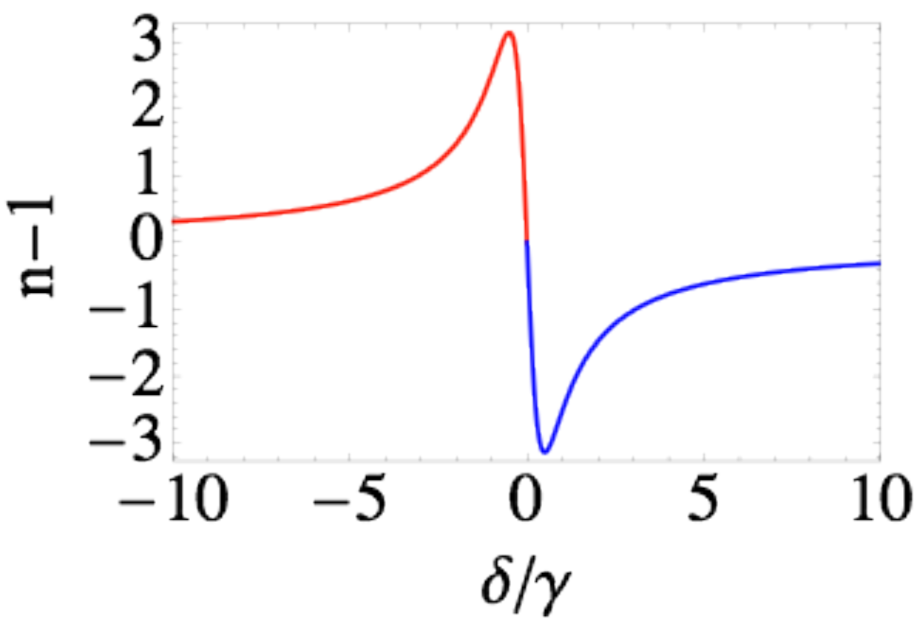
What causes the electromagnetic pressure on the atomic dipole? In a plane wave is the magnetic field wave.

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.

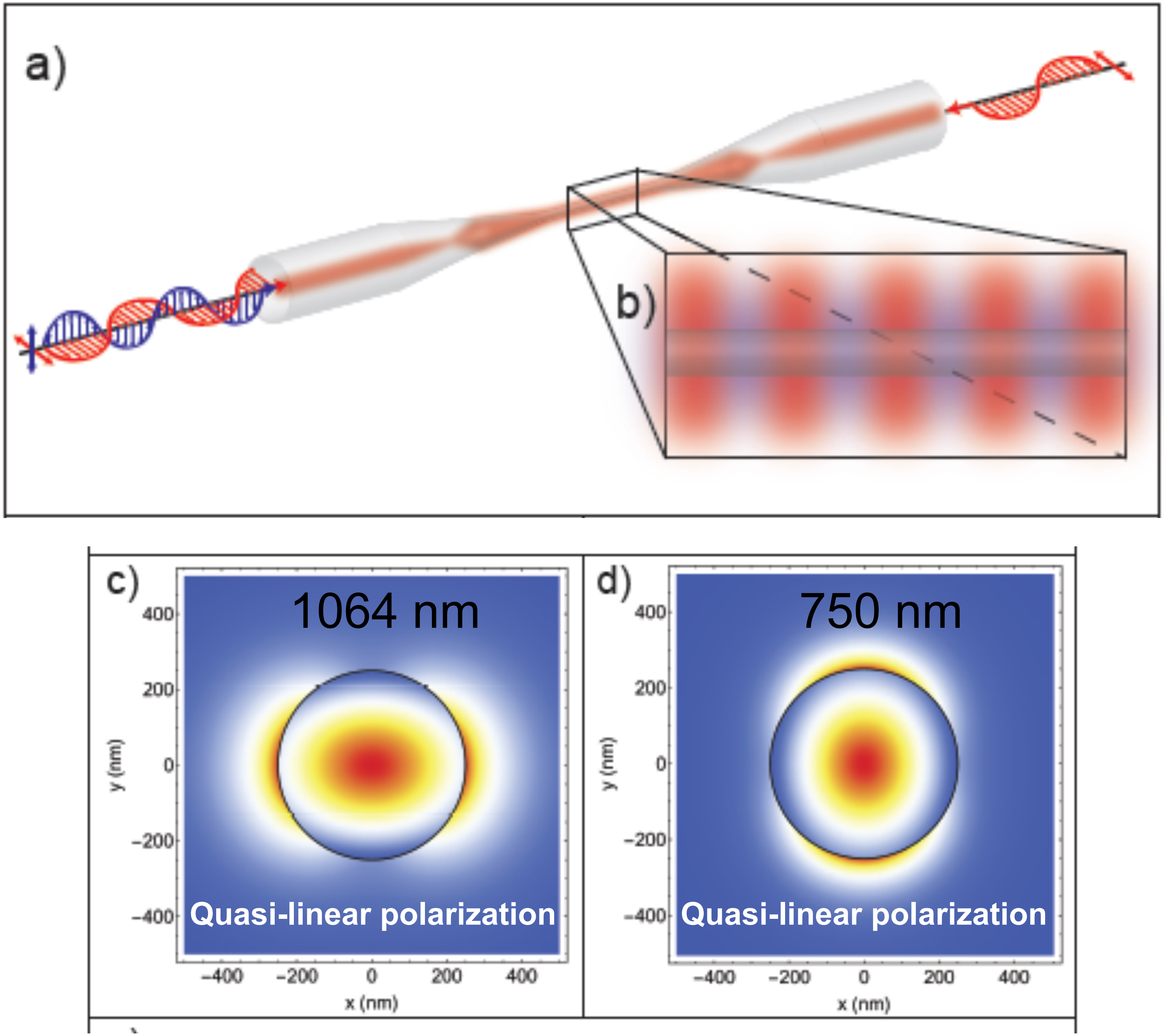
Oscillator model of an atom

- 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) $F \propto \nabla (I/\delta)$

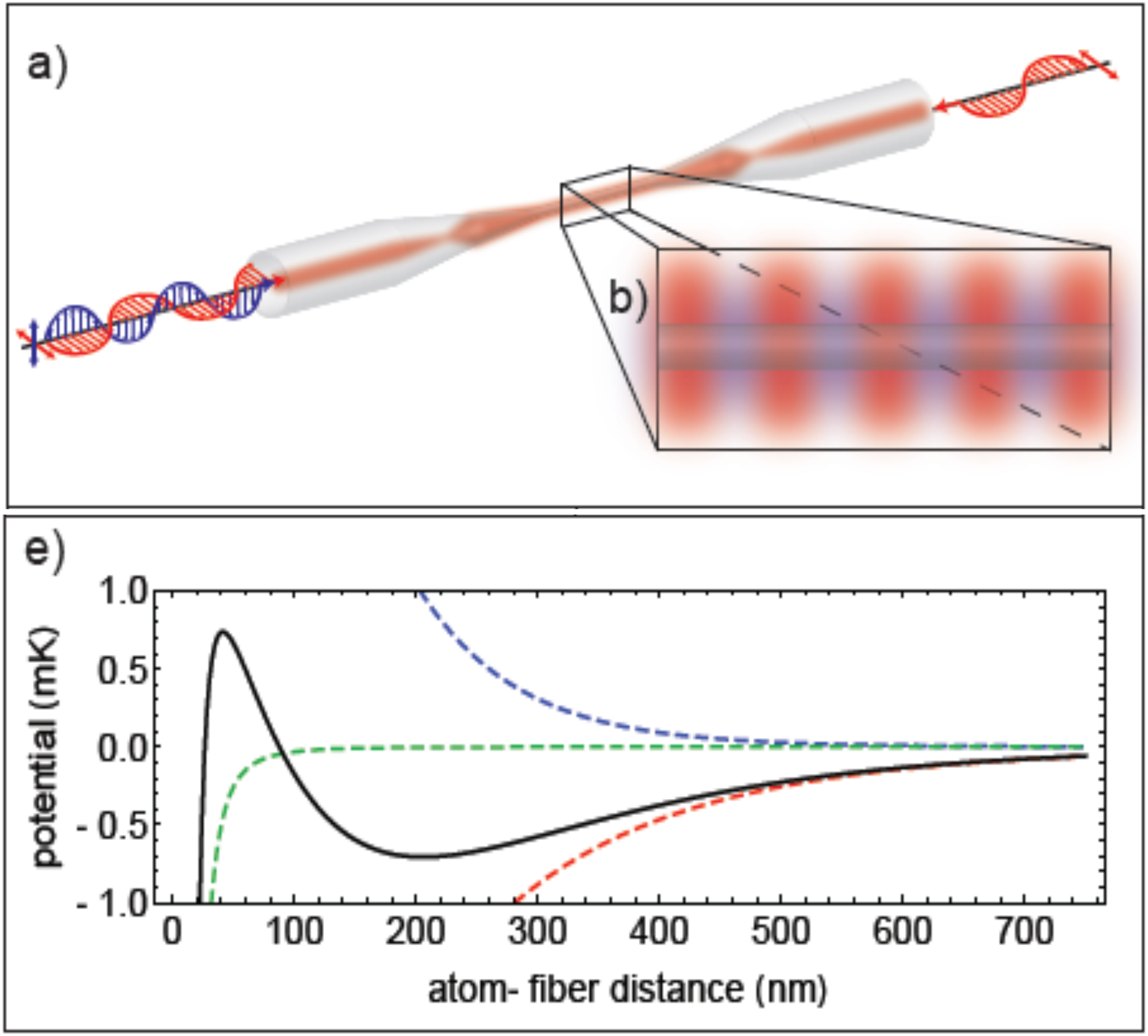


Atom trapping

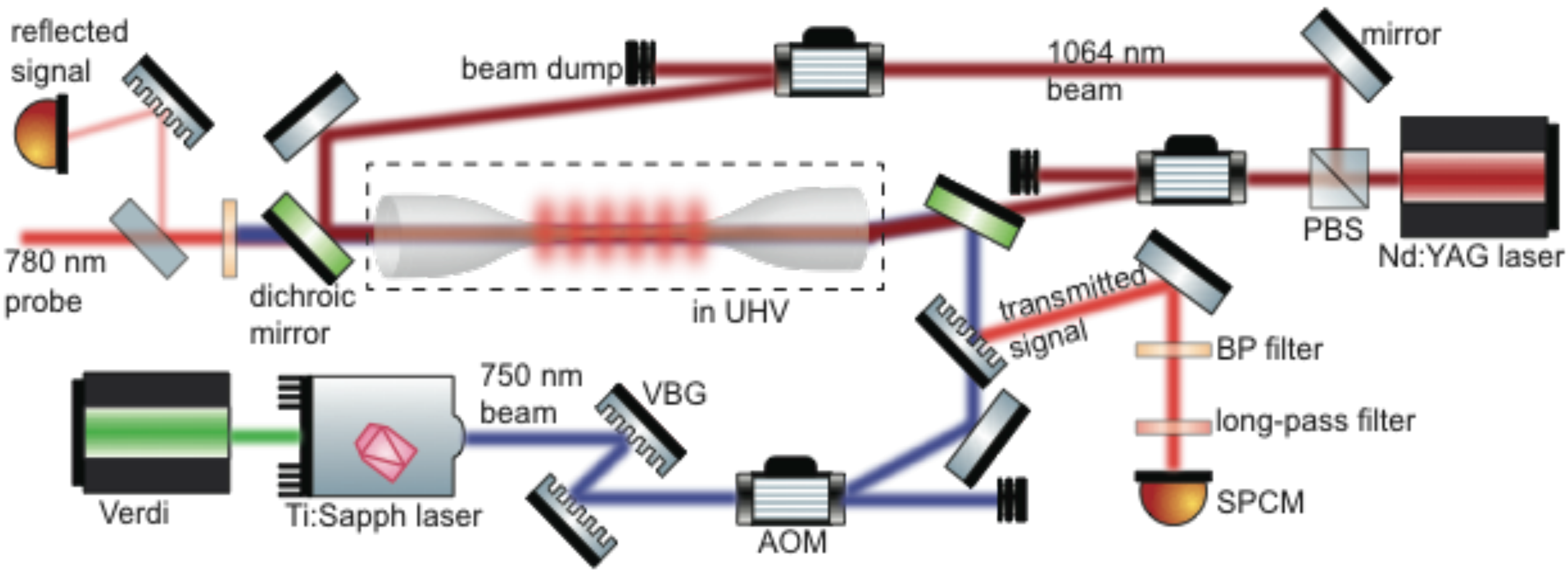
Trapping scheme

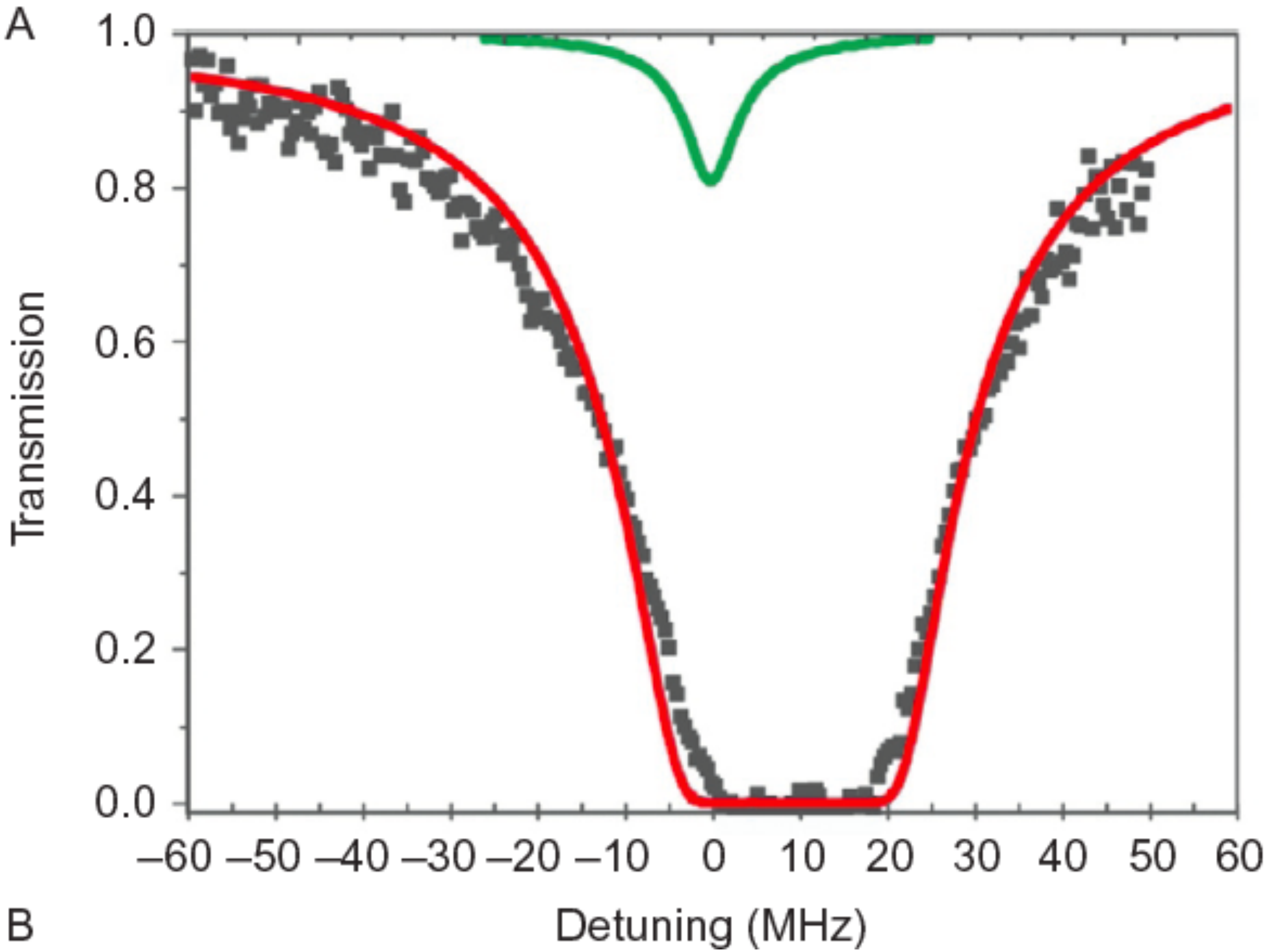


Trapping scheme



Optical Nanofiber Trapping





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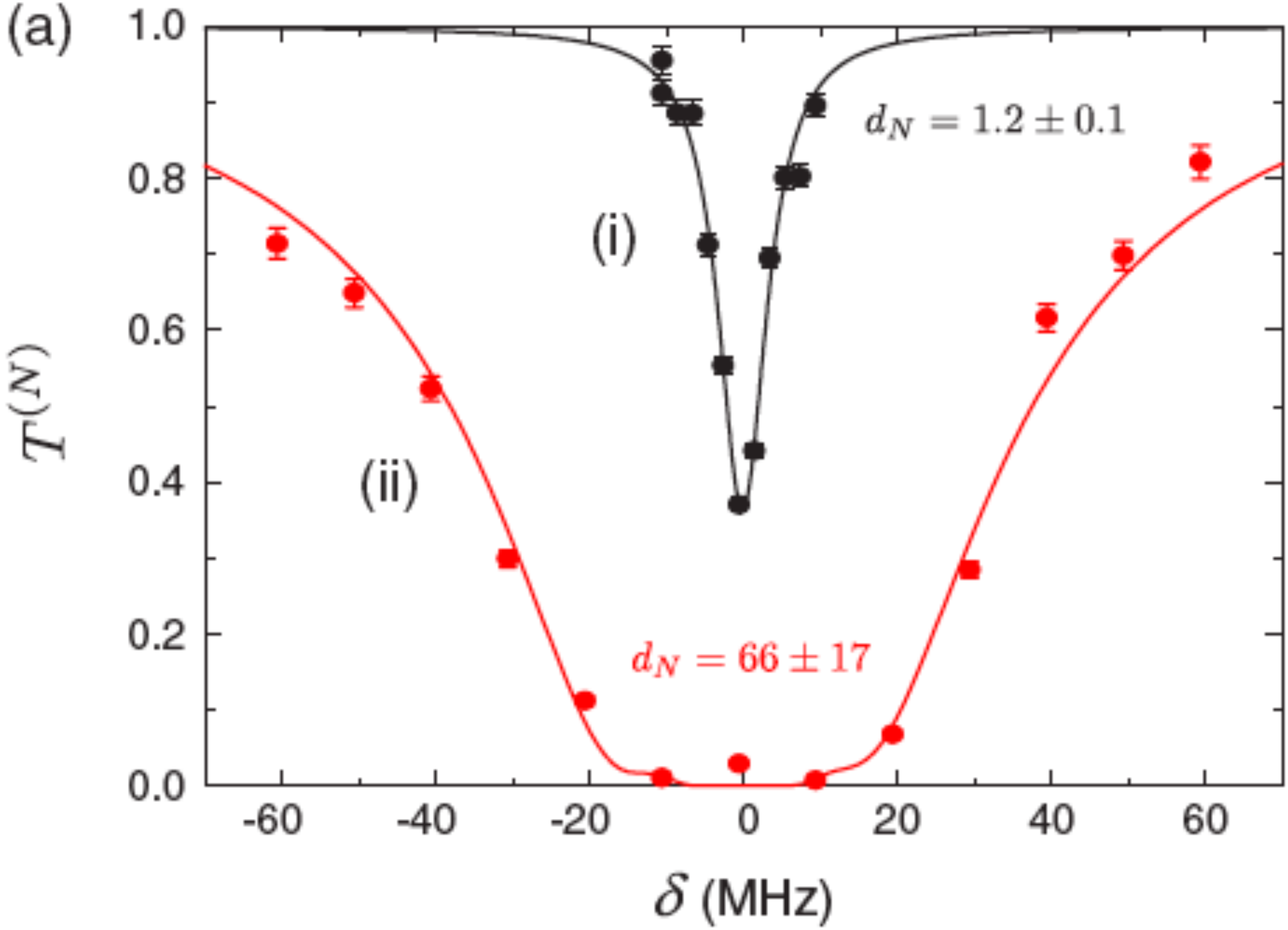

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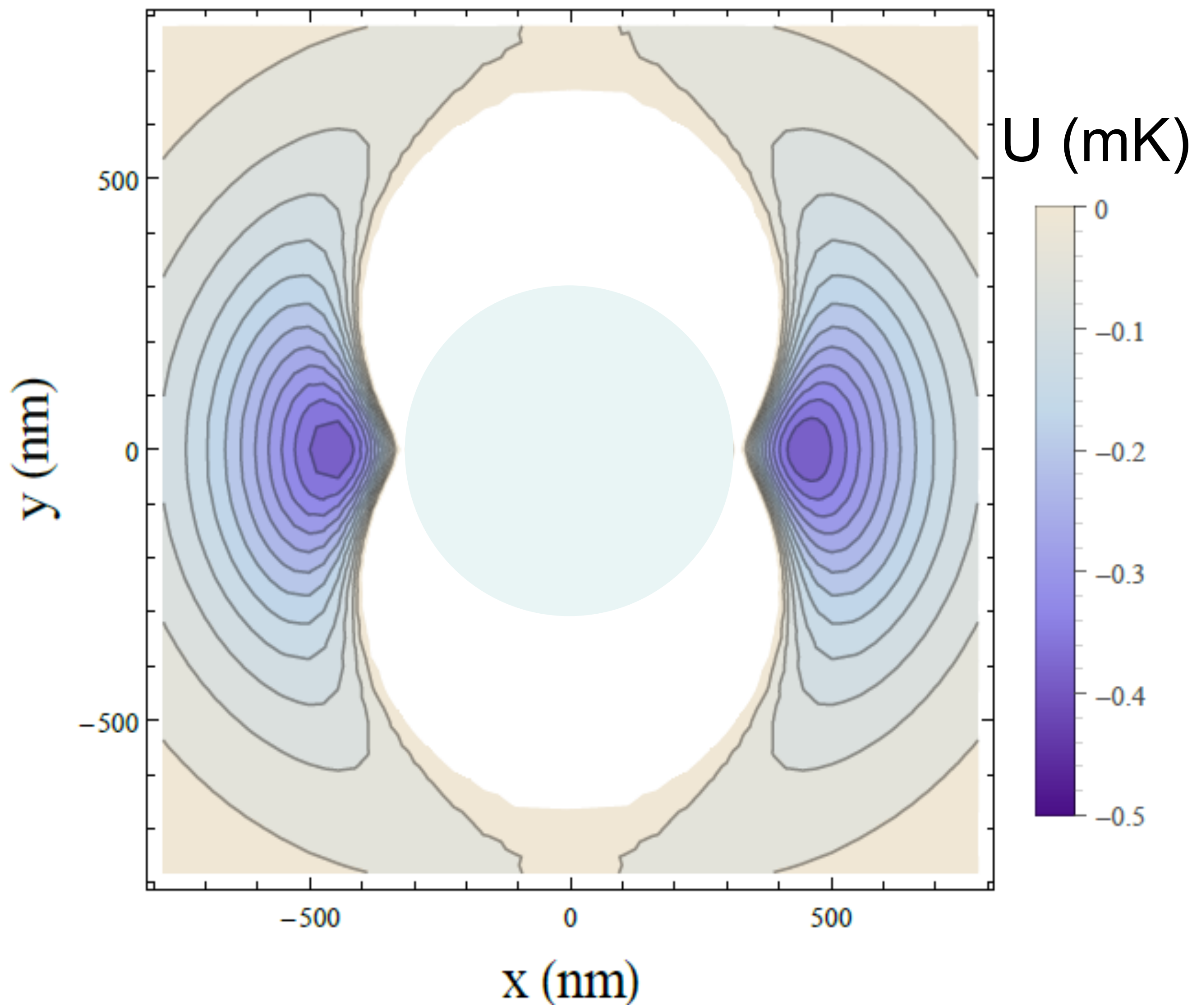
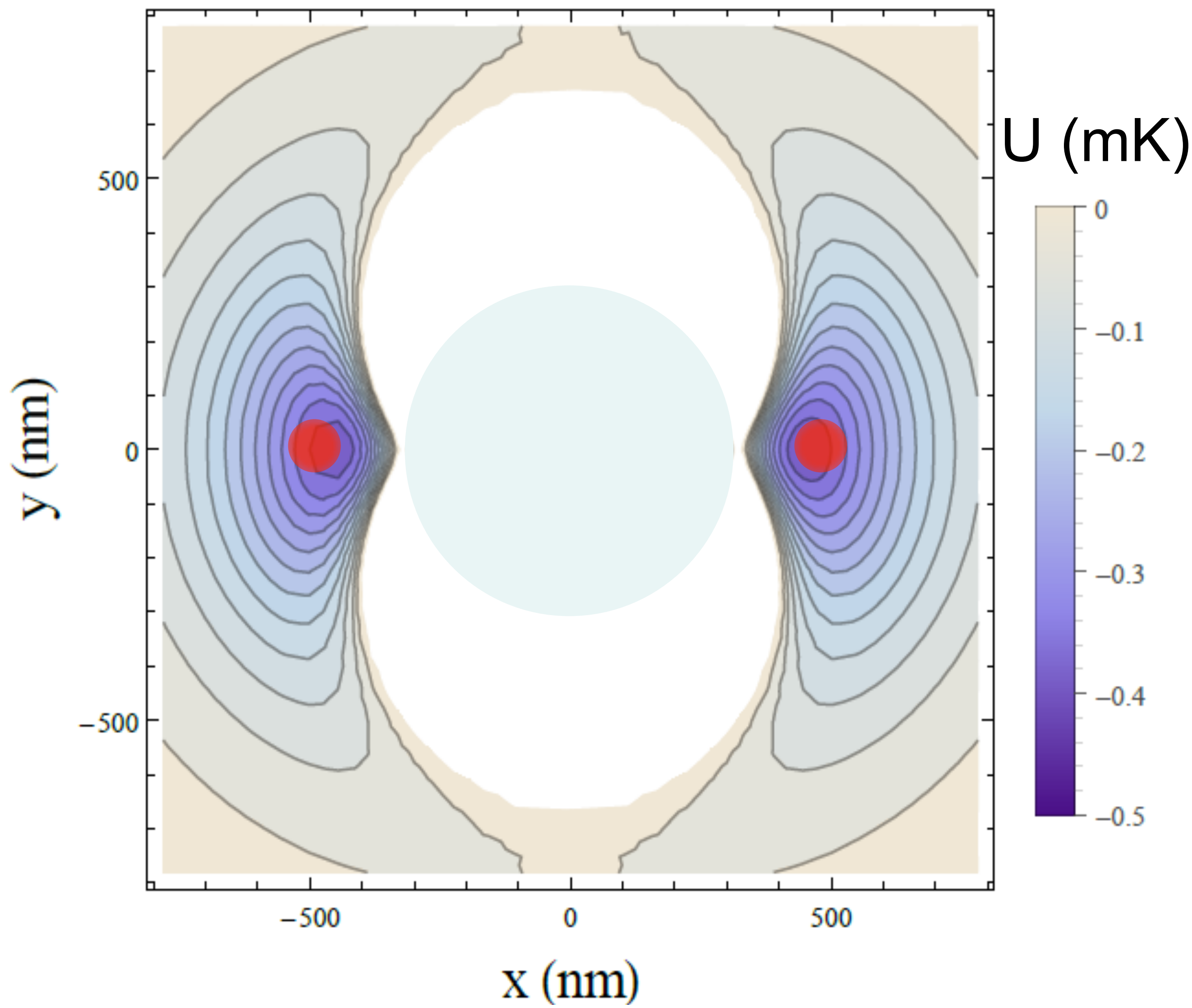
Atoms as a birefringent medium

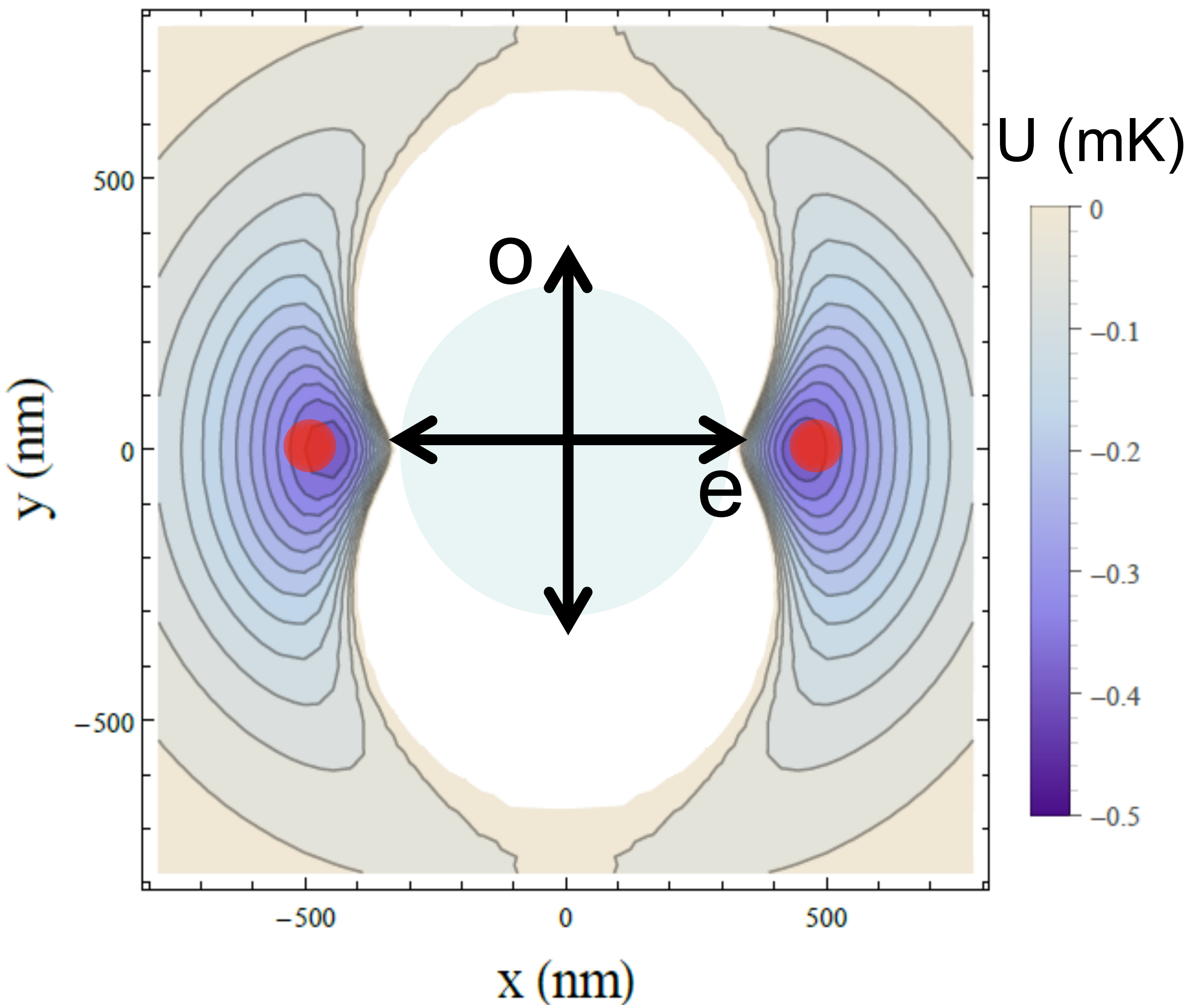
Trapped atoms as a birefringent media



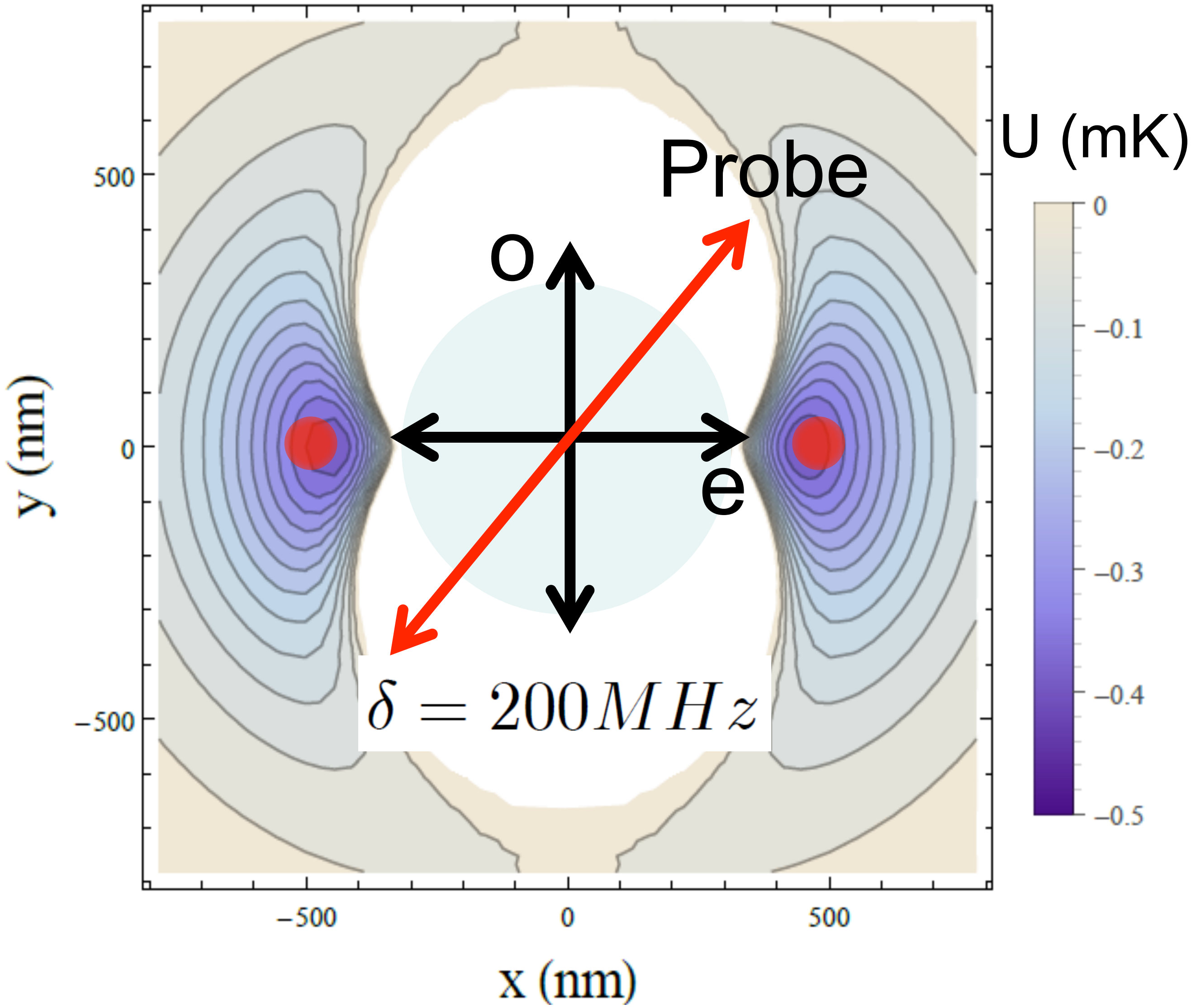
Trapped atoms as a birefringent media



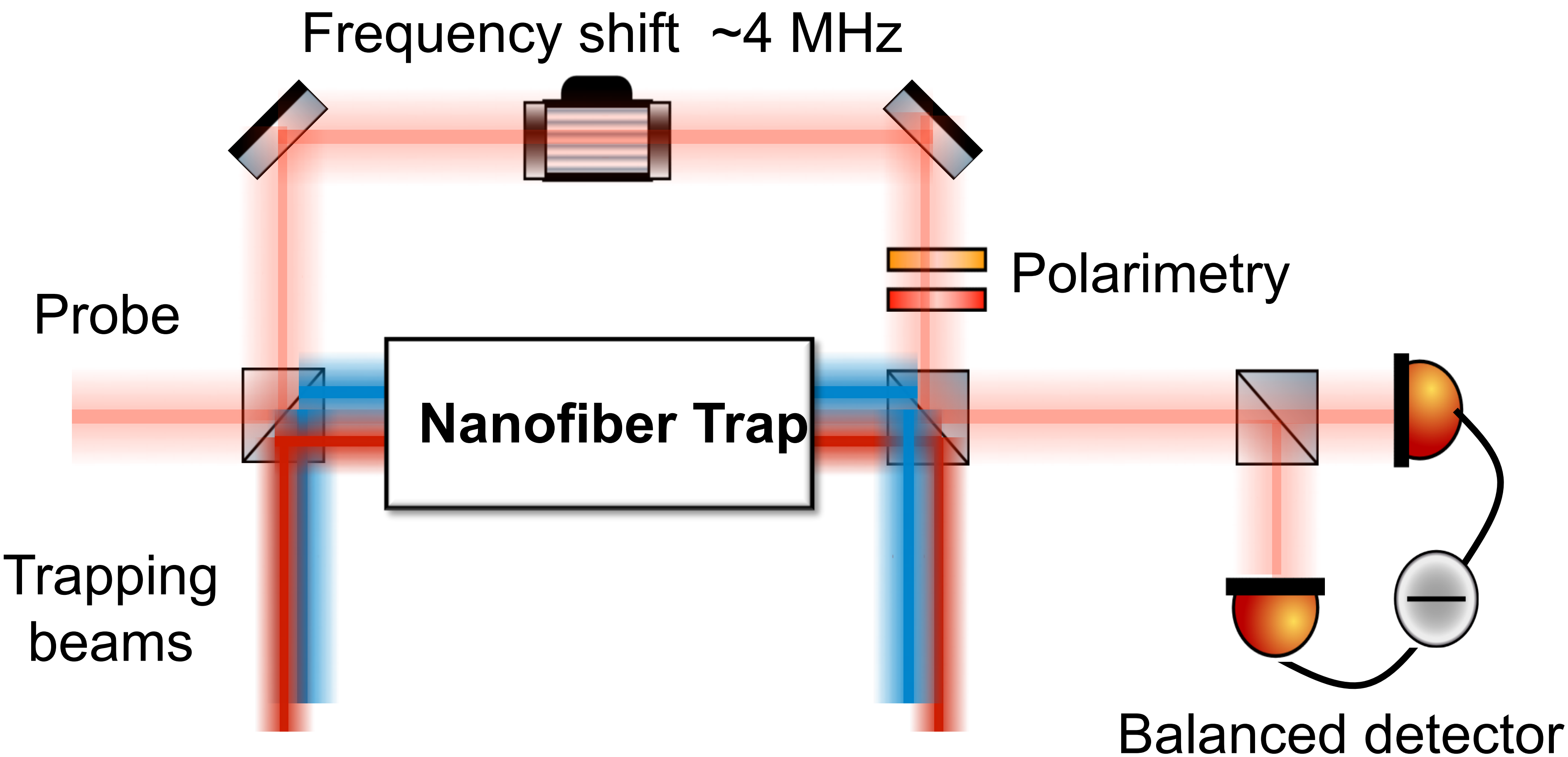
Trapped atoms as a birefringent media



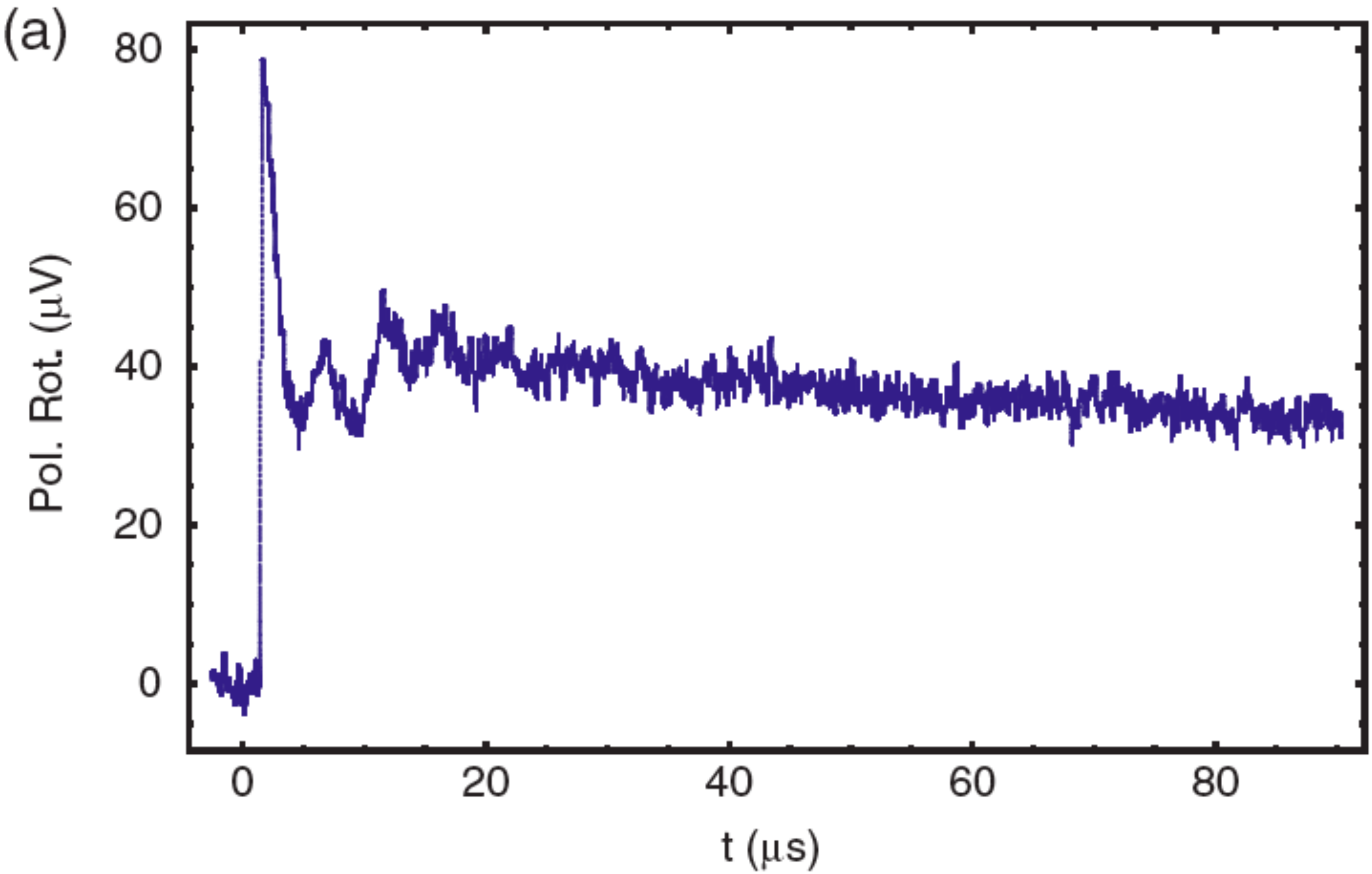
Trapped atoms as a birefringent media



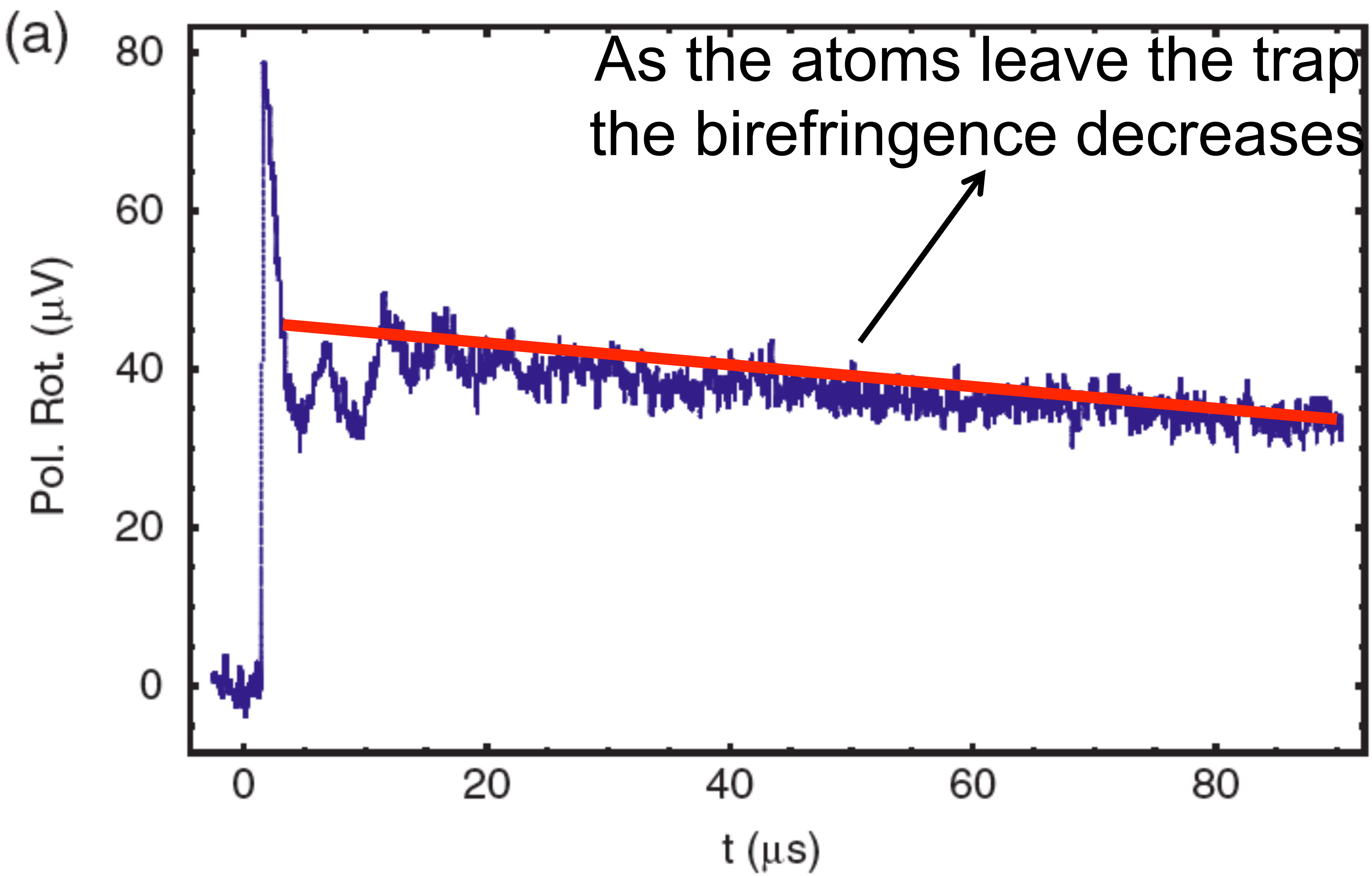
(Heterodyne detection)



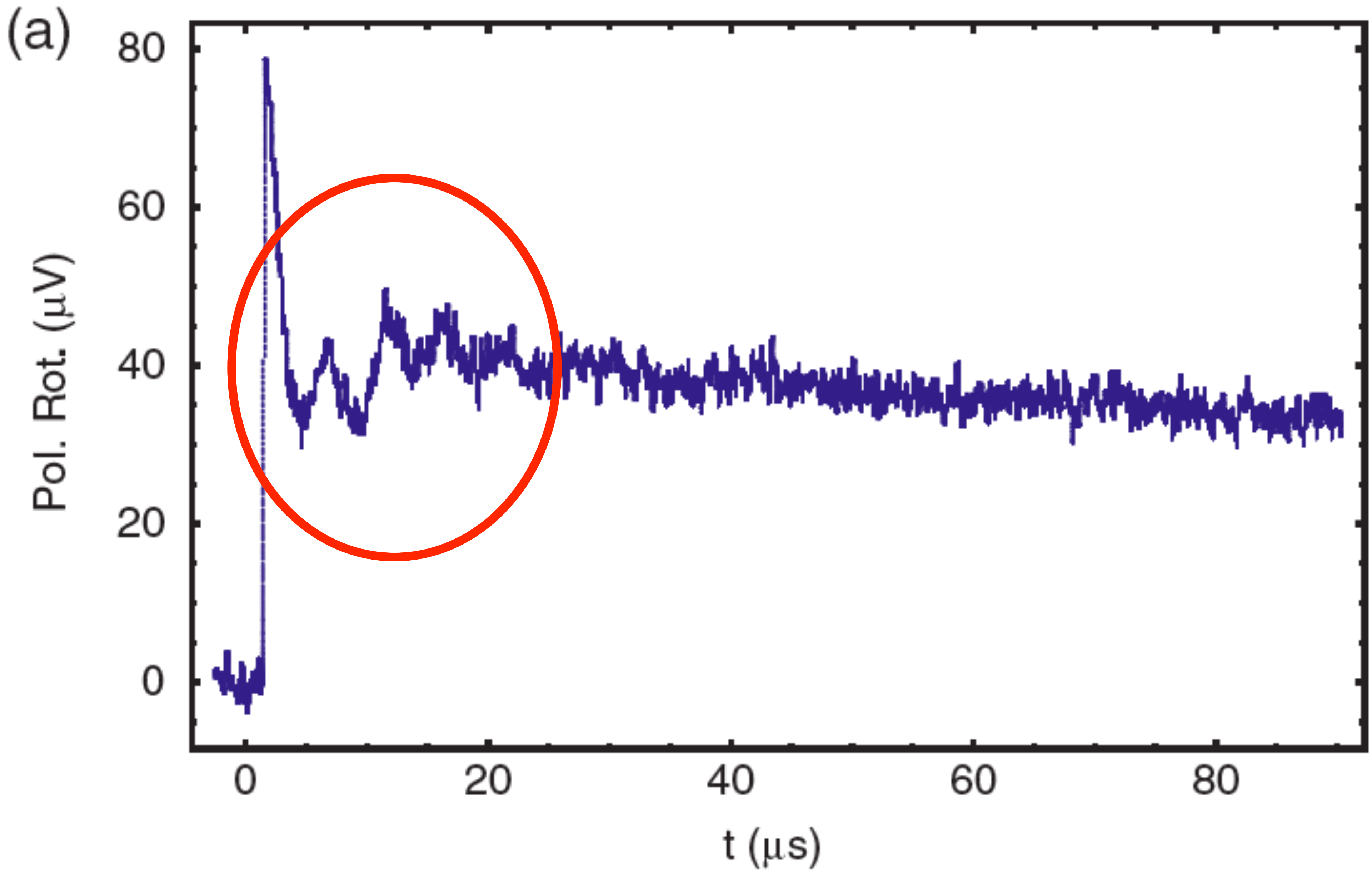
Time dependent signal



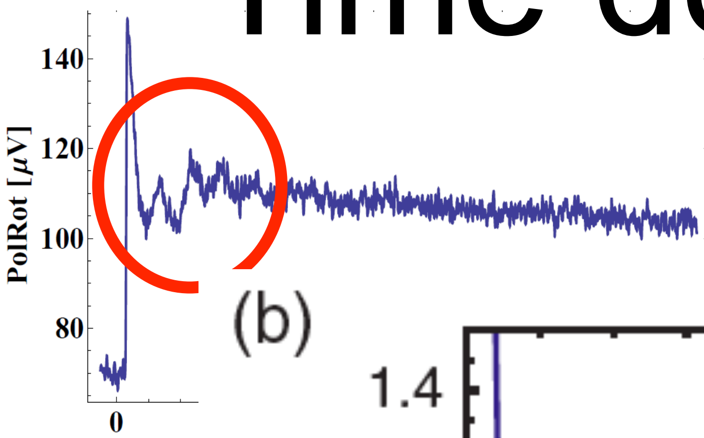
Time dependent signal

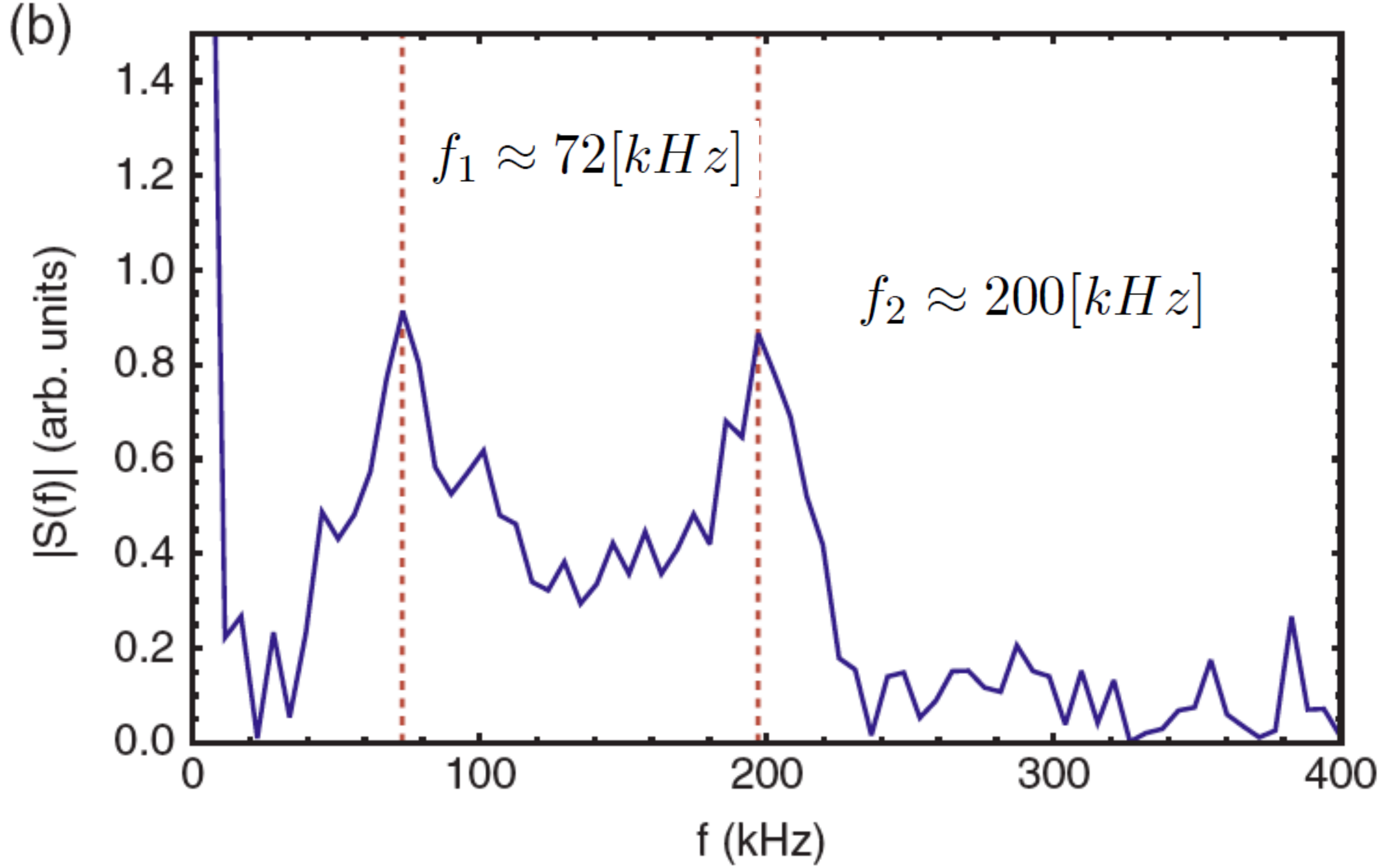


Time dependent signal

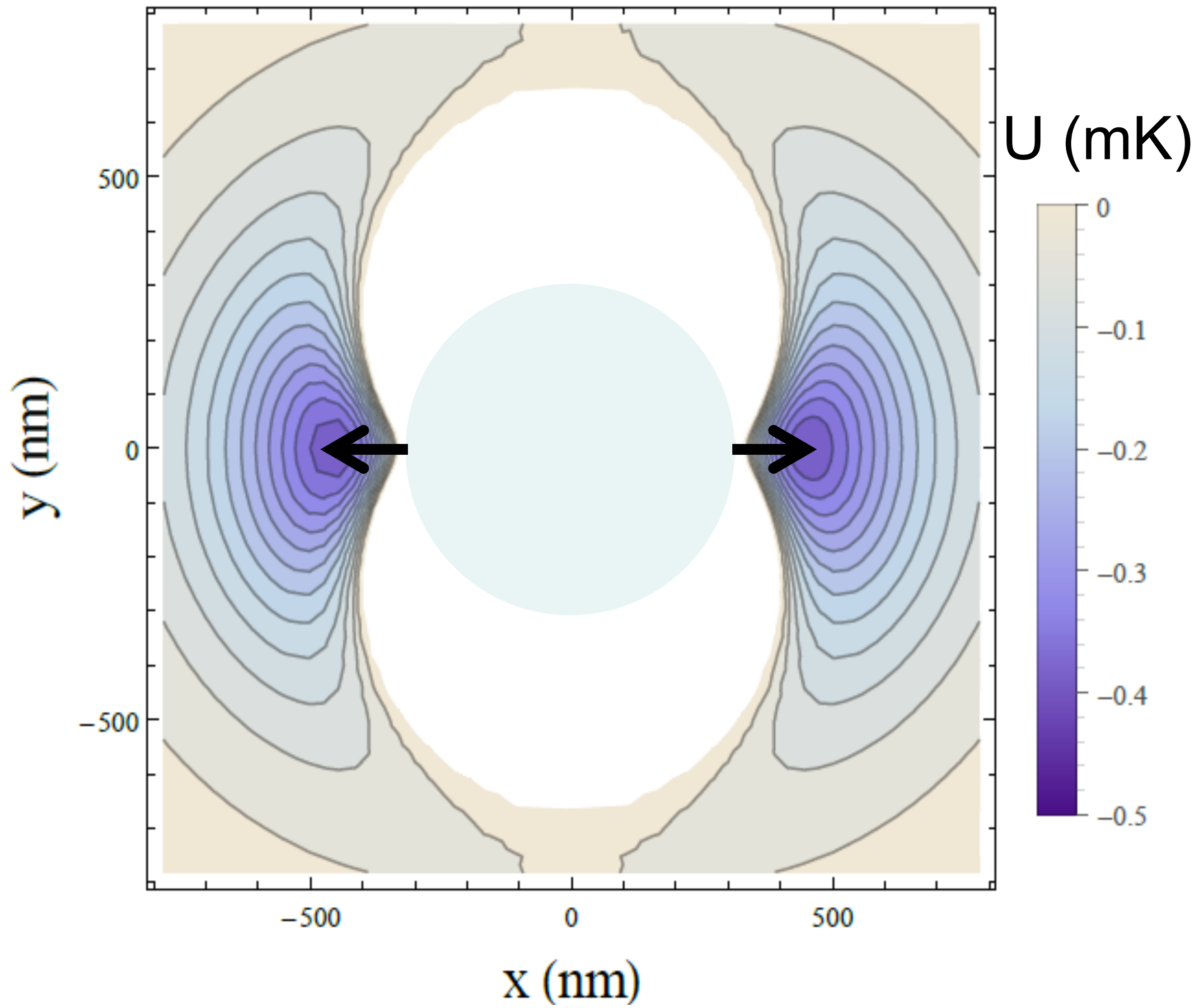


Time dependent signal

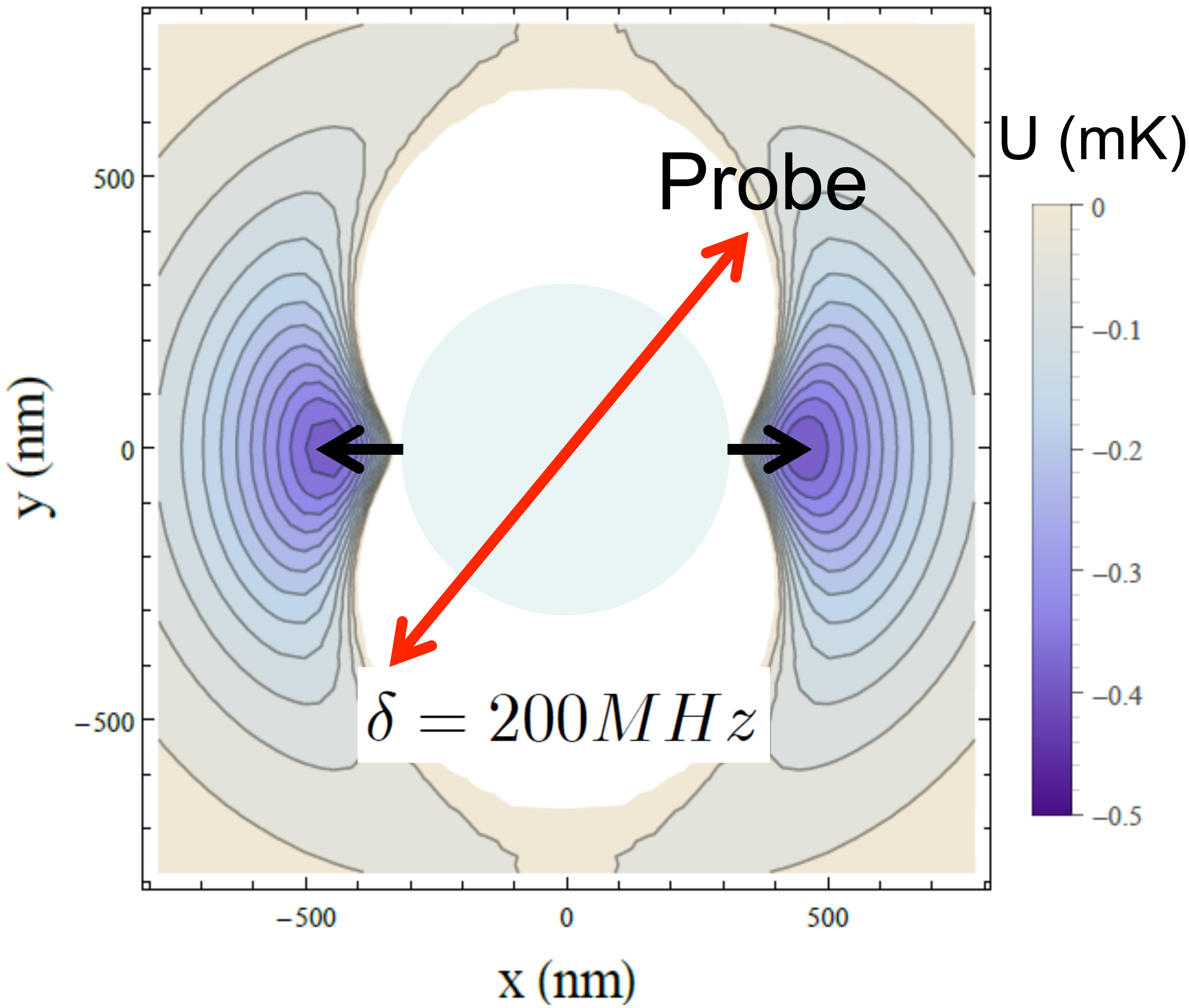




Atoms moving in the trap



Atoms moving in the trap



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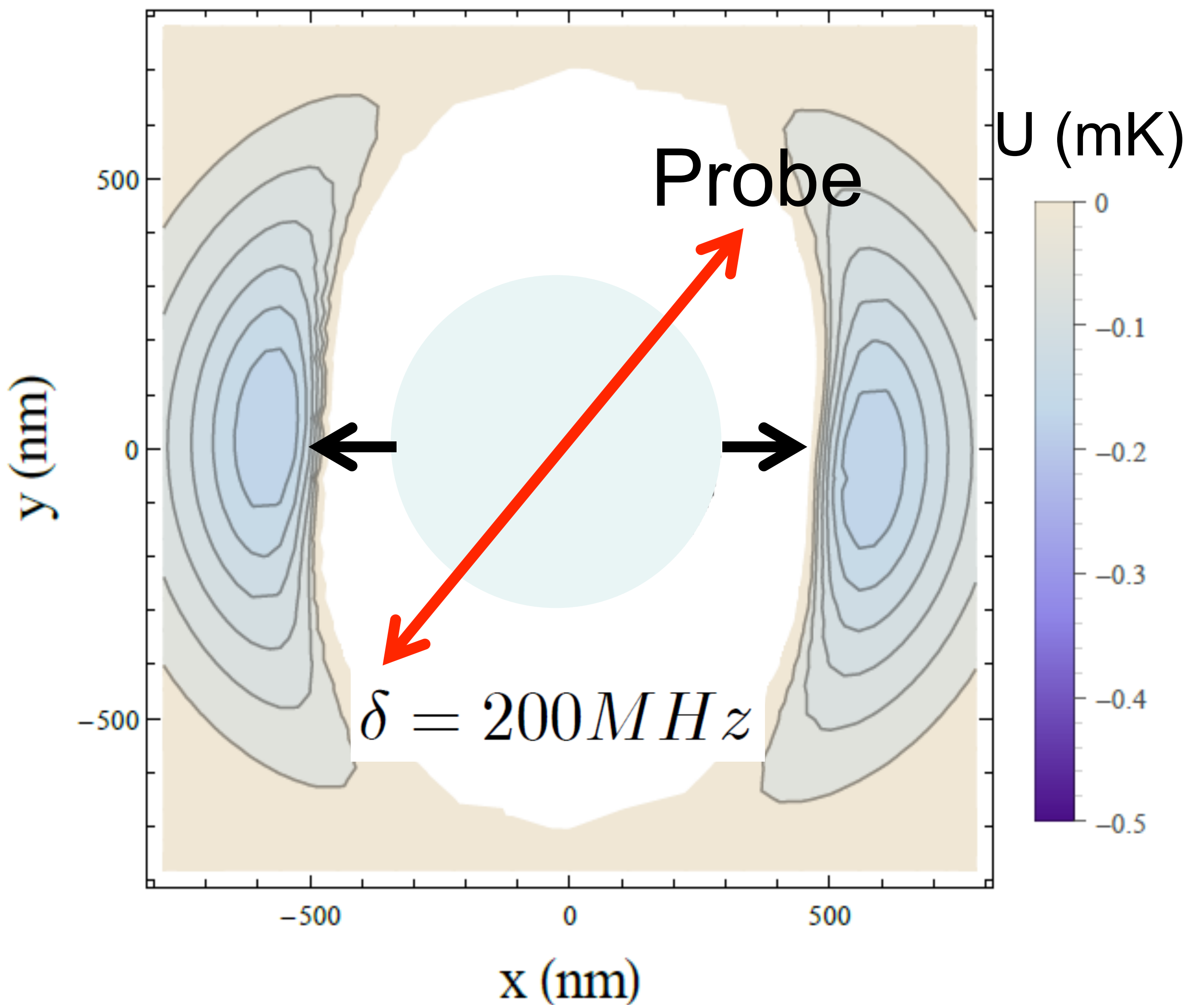
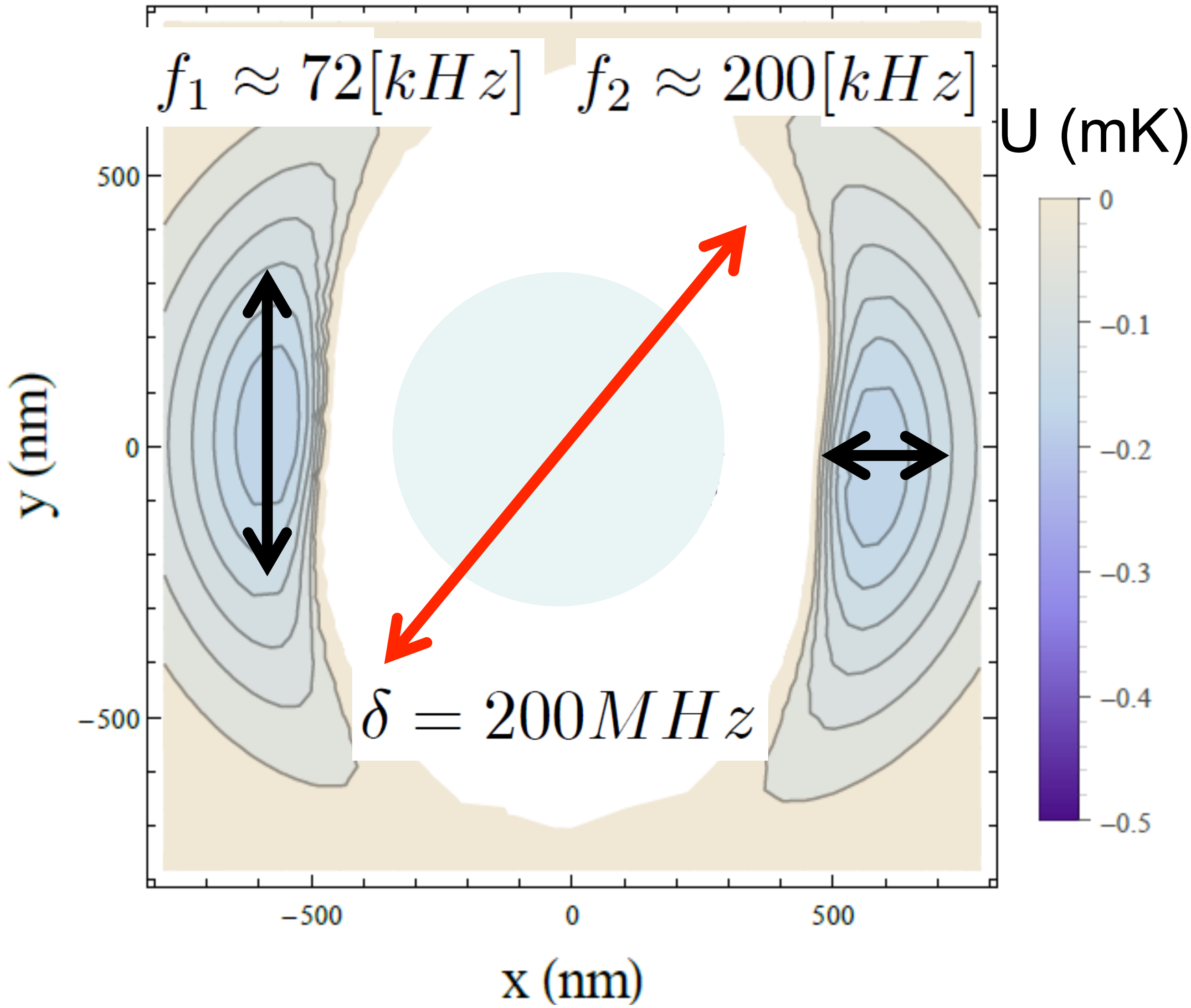
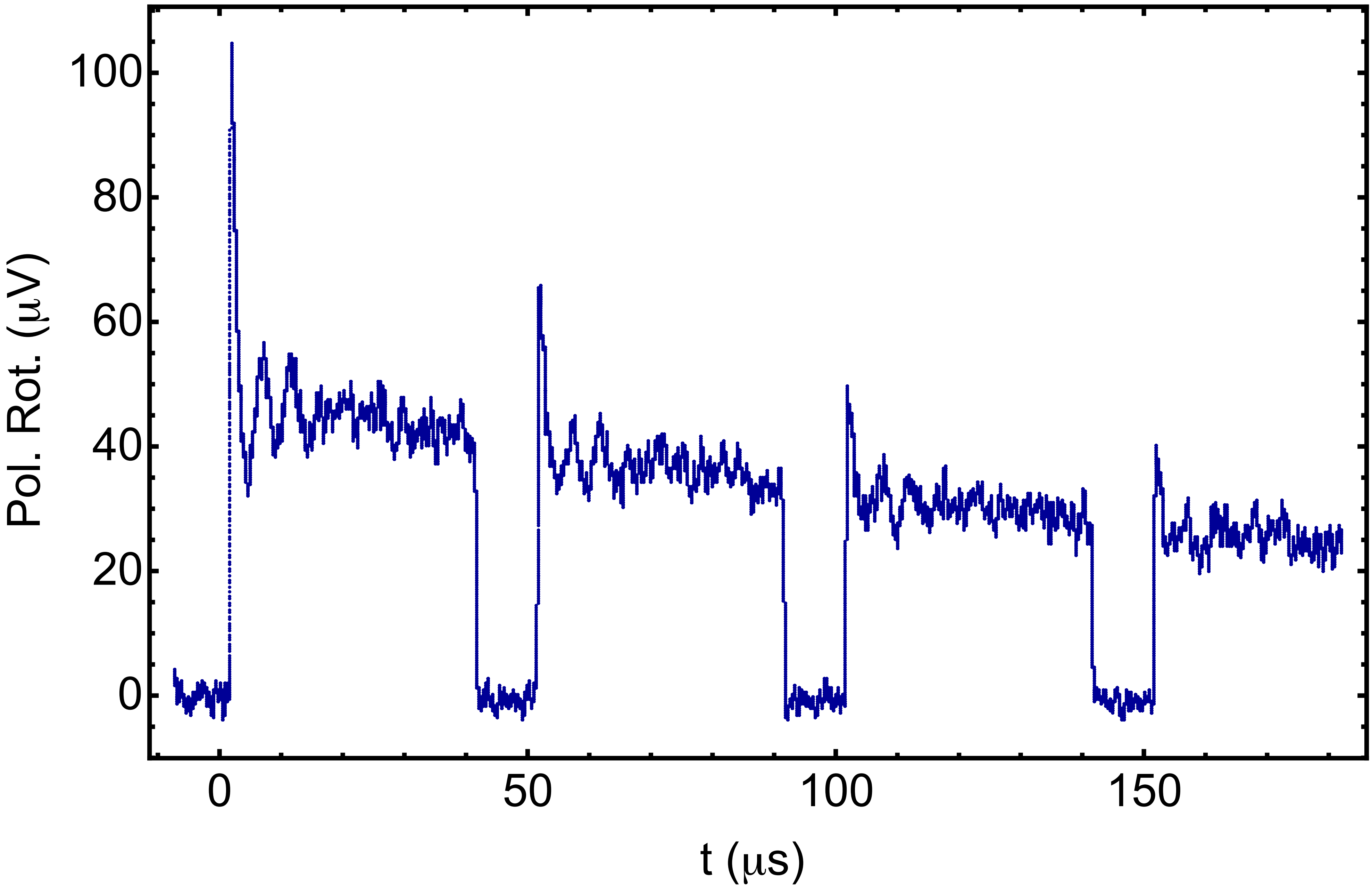


Atoms moving in the trap

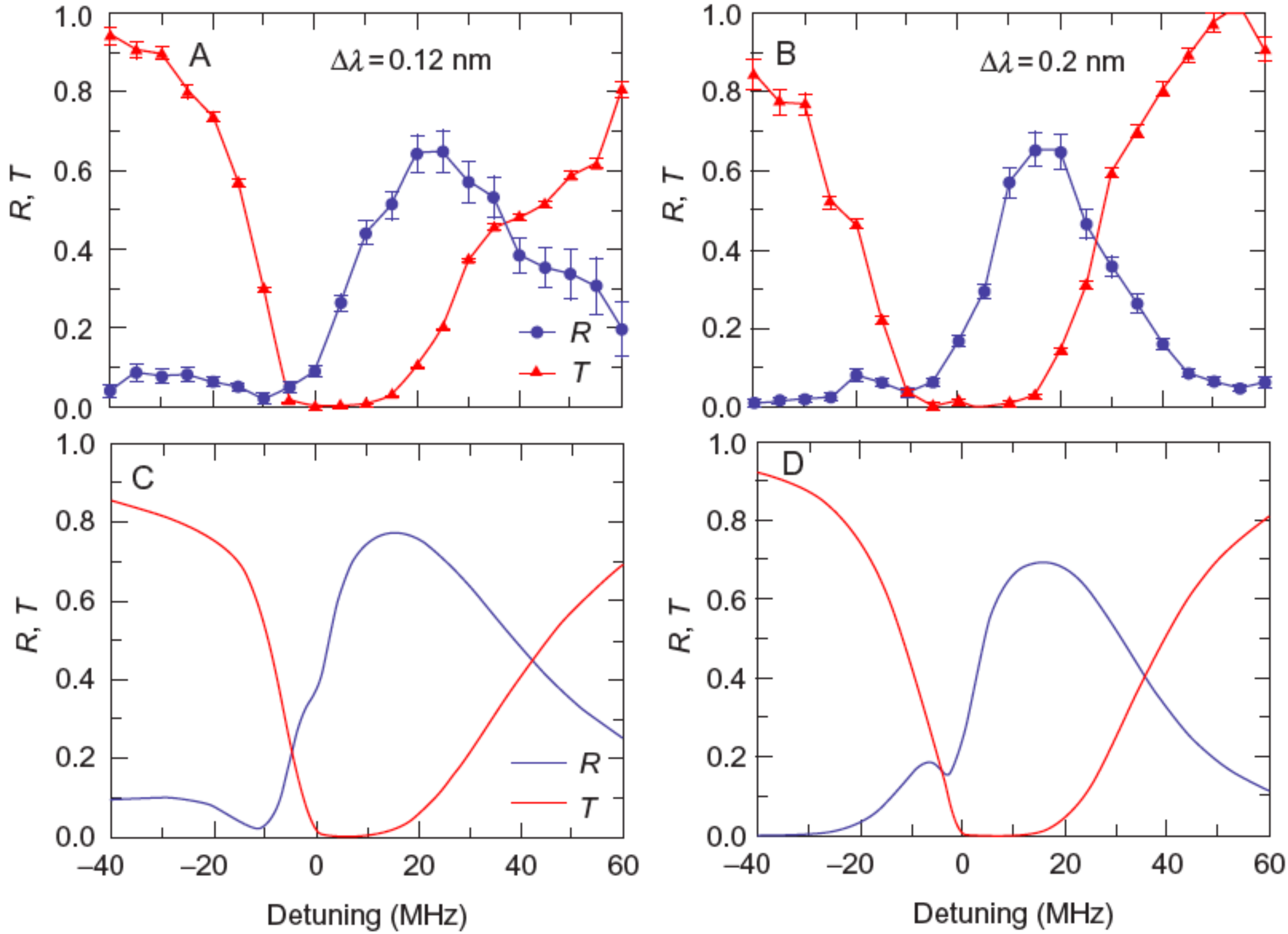


The frequencies agree with the simulation within a 10%

Atoms moving in the trap



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



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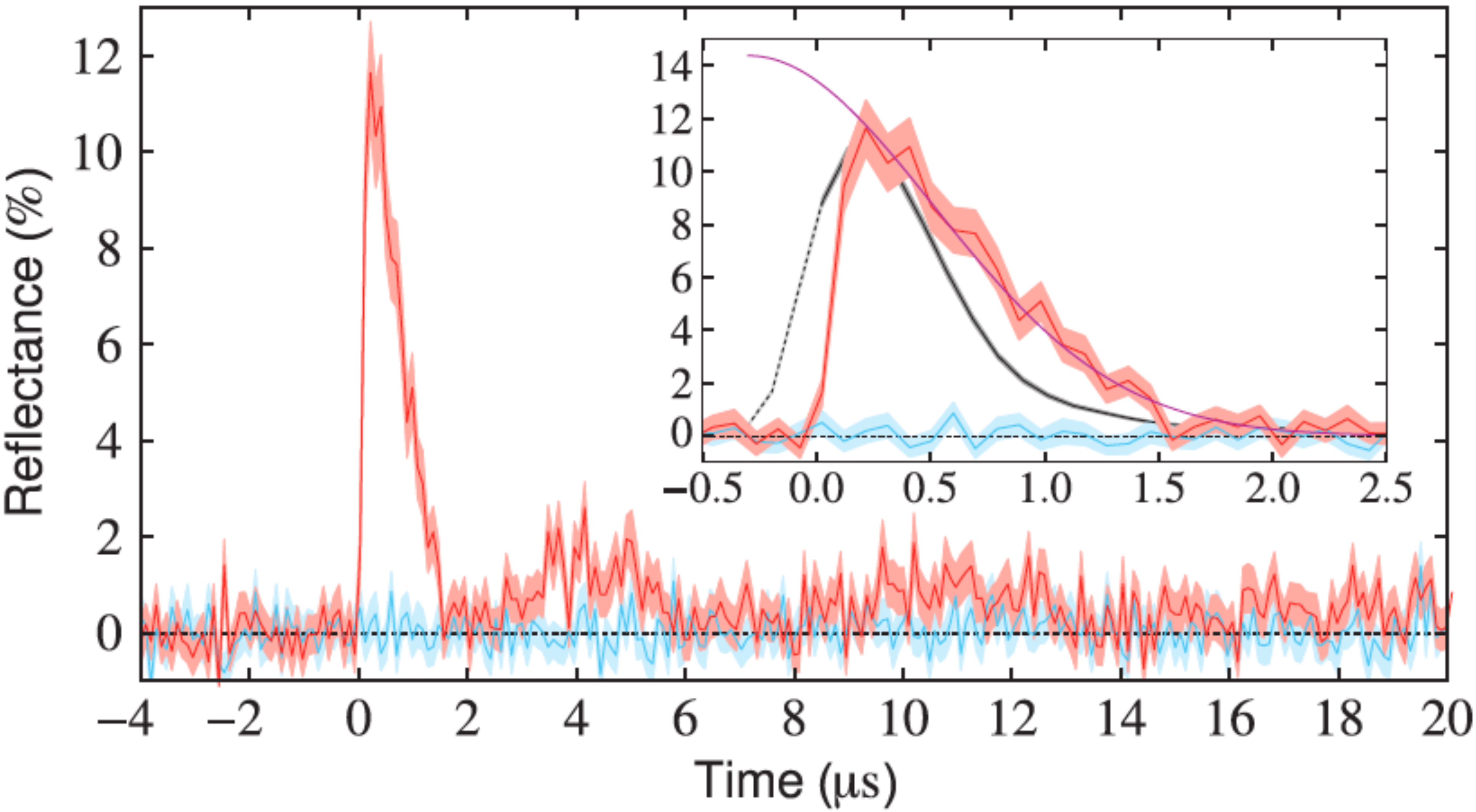

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Collective effects in waveguides

Superradiance for Atoms Trapped along a Photonic Crystal Waveguide

A. Goban,[1,2] C.-L. Hung,[1,2,†] J. D. Hood,[1,2] S.-P. Yu,[1,2] J. A. Muniz,[1,2] O. Painter,[2,3] and H. J. Kimble[1,2,*]
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[2]*Institute for Quantum Information and Matter, California Institute of Technology, Pasadena, California 91125, USA*
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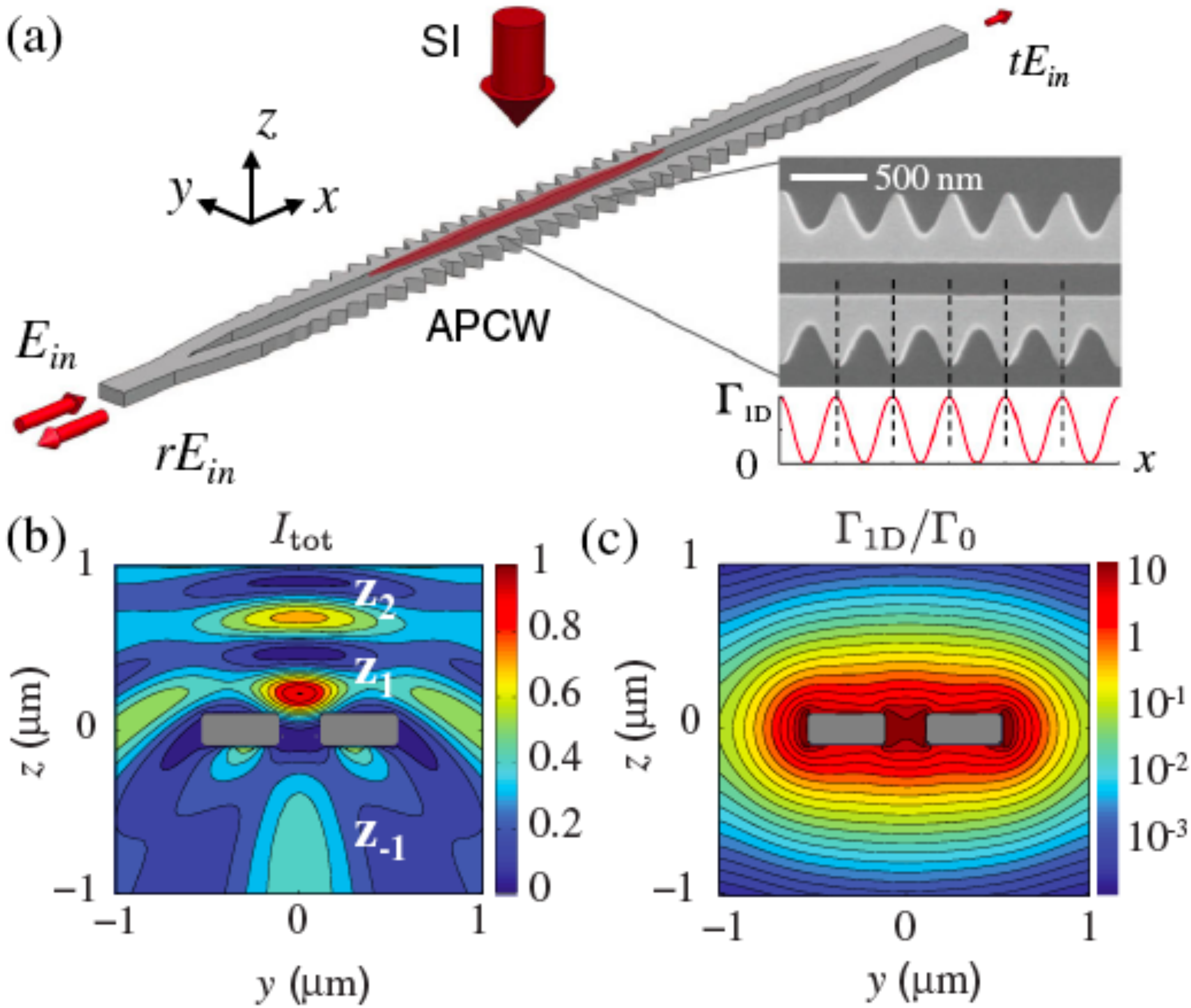
(Received 14 March 2015; published 5 August 2015)

We report observations of superradiance for atoms trapped in the near field of a photonic crystal waveguide (PCW). By fabricating the PCW with a band edge near the D_1 transition of atomic cesium, strong interaction is achieved between trapped atoms and guided-mode photons. Following short-pulse excitation, we record the decay of guided-mode emission and find a superradiant emission rate scaling as $\bar{\Gamma}_{\rm SR} \propto \bar{N}\Gamma_{\rm 1D}$ for average atom number $0.19 \lesssim \bar{N} \lesssim 2.6$ atoms, where $\Gamma_{\rm 1D}/\Gamma' = 1.0 \pm 0.1$ is the peak single-atom radiative decay rate into the PCW guided mode, and Γ' is the radiative decay rate into all the other channels. These advances provide new tools for investigations of photon-mediated atom-atom interactions in the many-body regime.

DOI: 10.1103/PhysRevLett.115.063601 PACS numbers: 42.50.Ct, 37.10.Gh, 42.70.Qs



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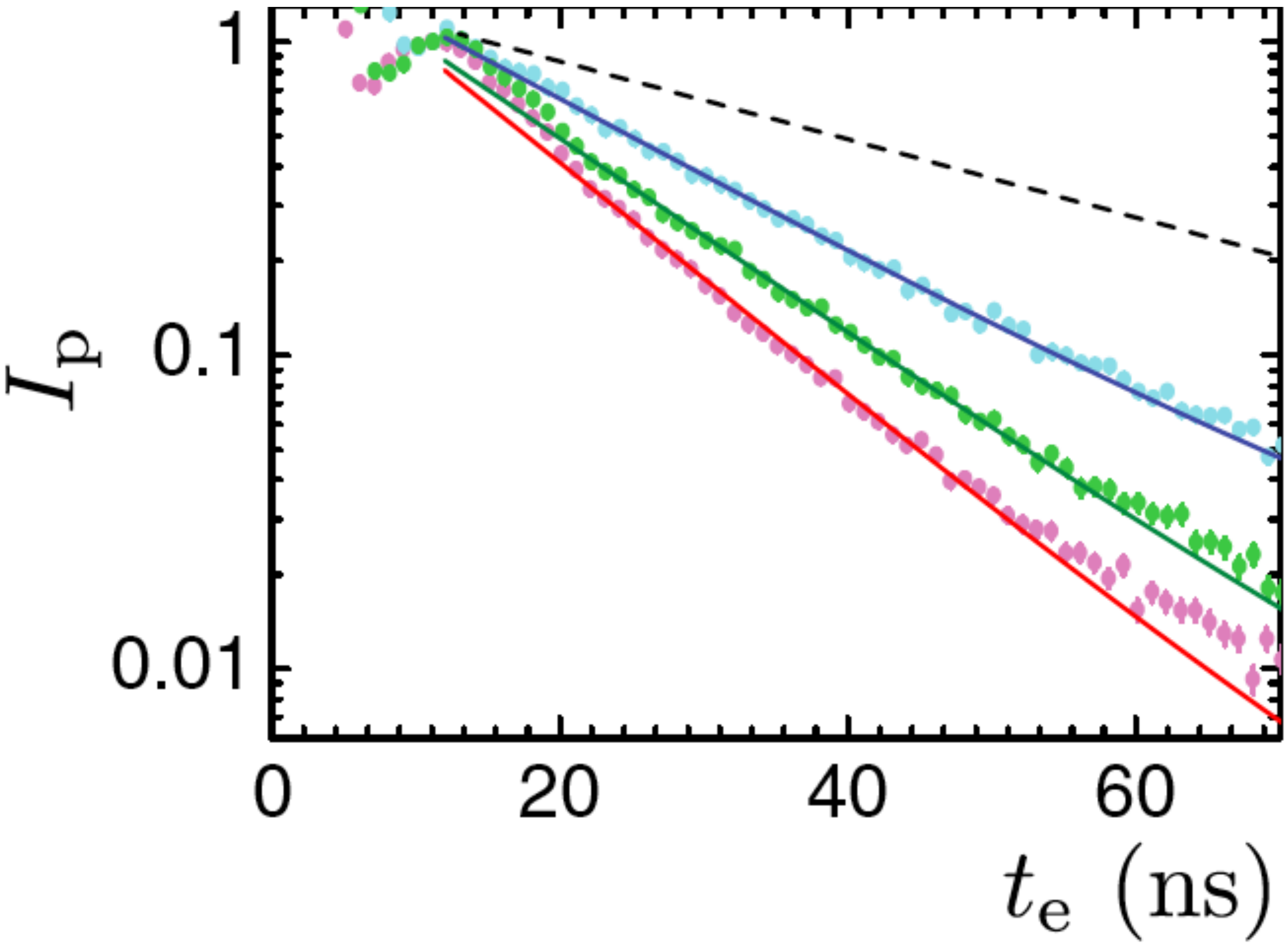
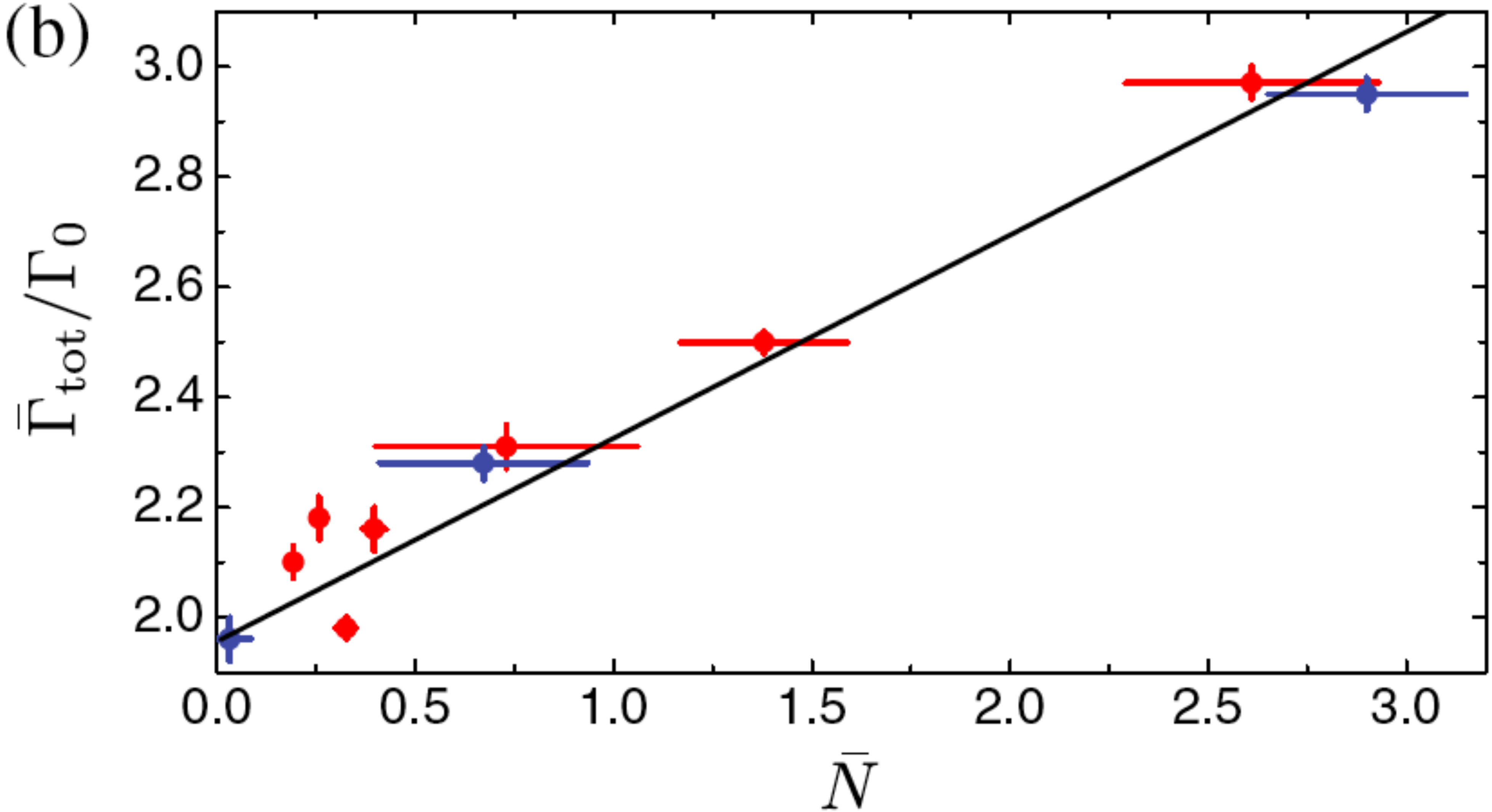


1
0.1
0.01
I_p
0
20
40
60
t_e (ns)


(b)
3.0
2.8
2.6
2.4
2.2
2.0
$\bar{\Gamma}_{\mathrm{tot}}/\Gamma_0$
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\bar{N}$

Some bibliography:

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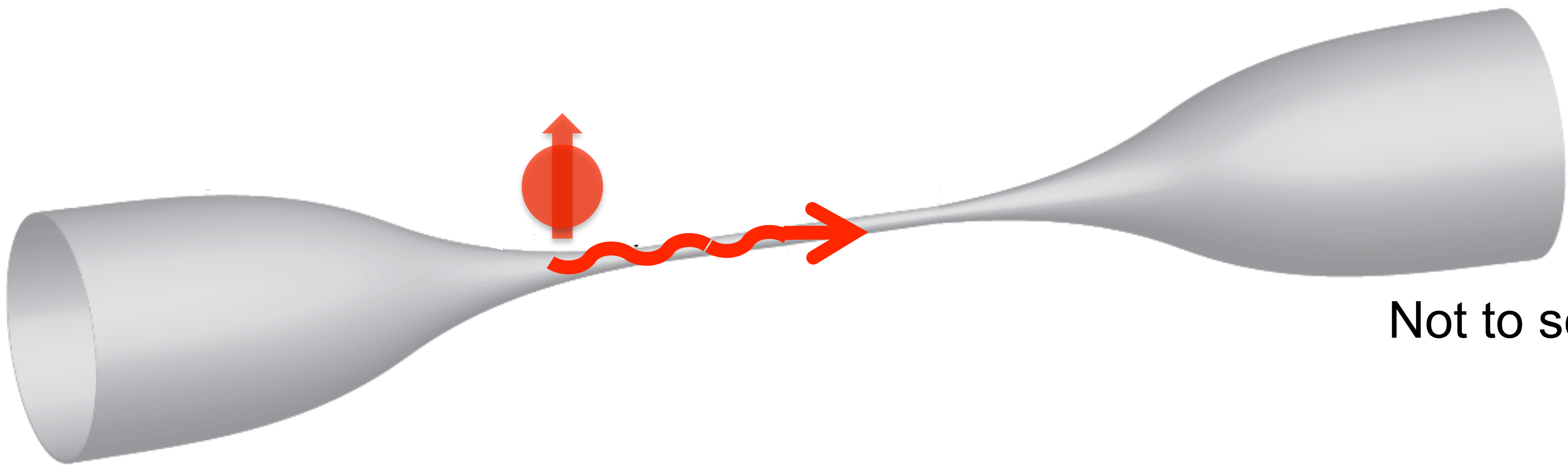
谢谢

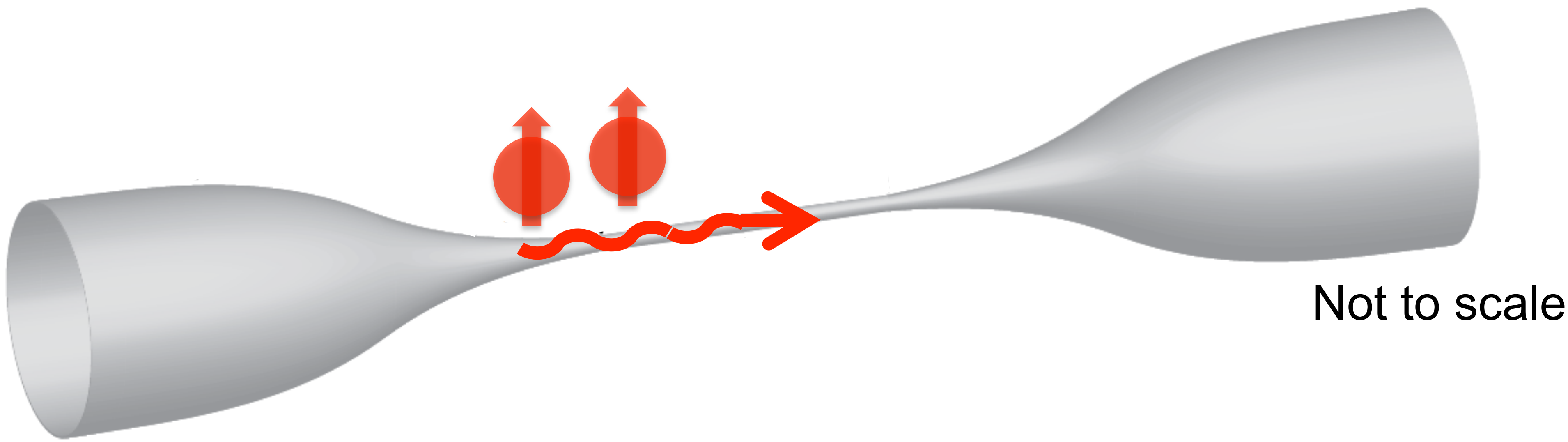
Long Range Interactions
Bonus

Infinite Range Interactions

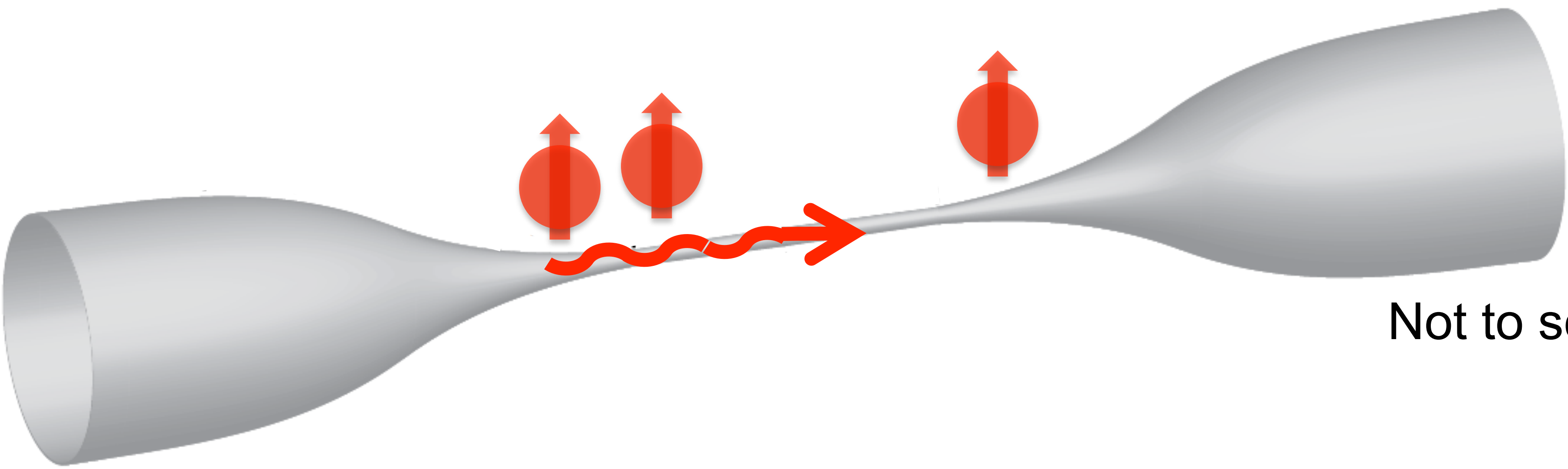


Not to scale

Infinite Range Interactions

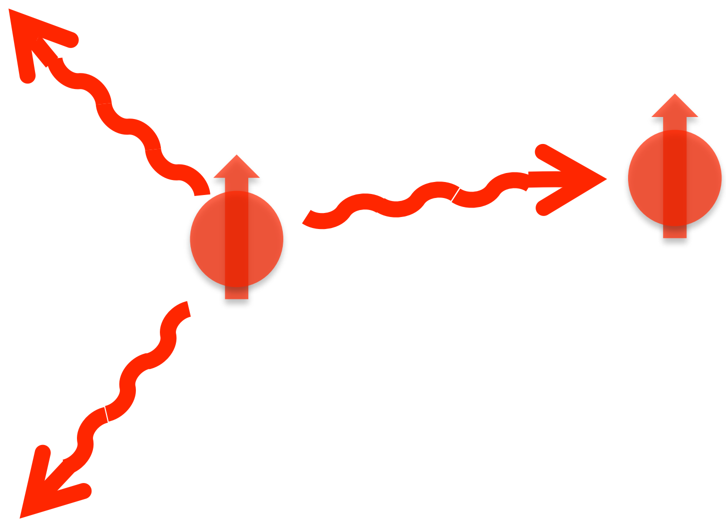


Infinite Range Interactions



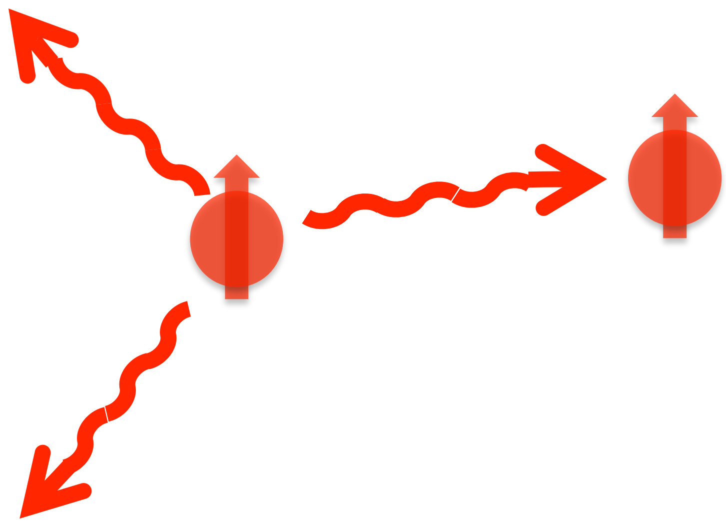
Not to scale

Infinite Range Interactions

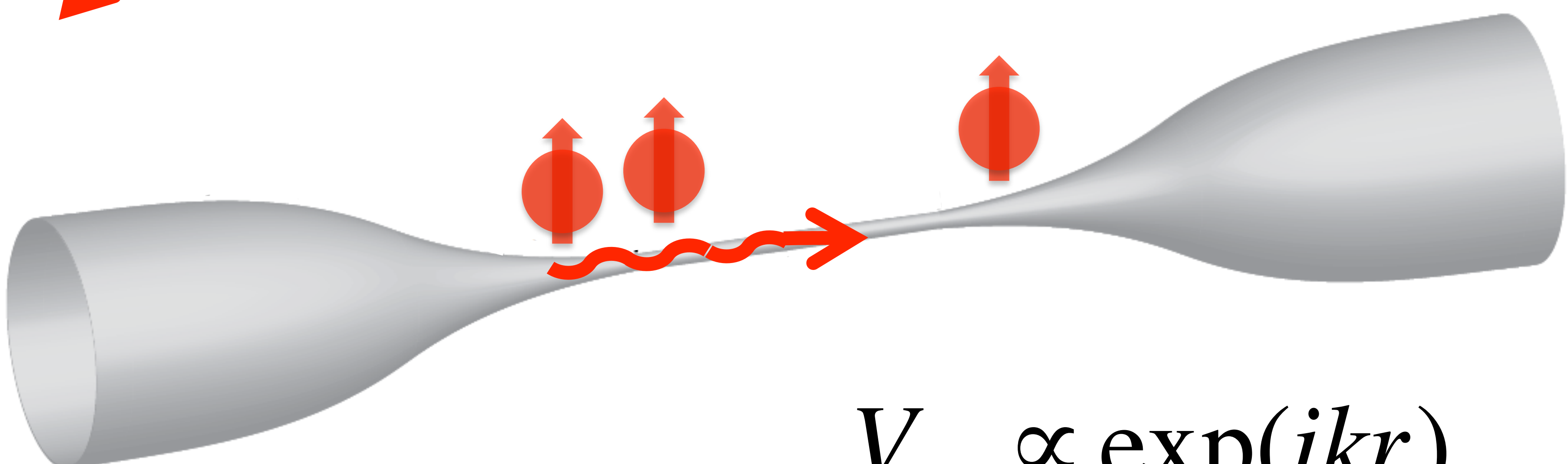


$$V_{free} \propto \frac{\exp(ikr)}{kr}$$

Infinite Range Interactions

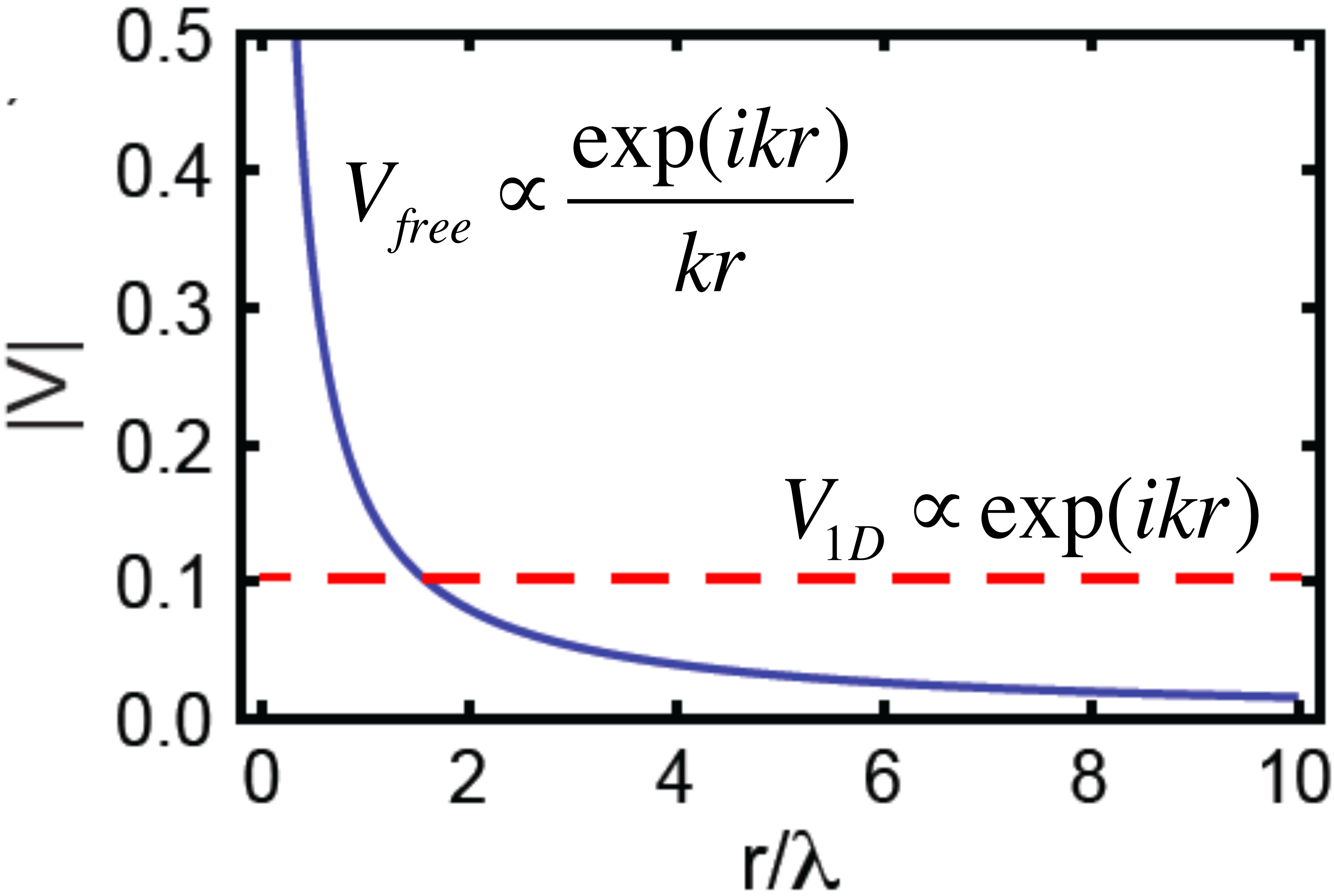


$$V_{free} \propto \frac{\exp(ikr)}{kr}$$



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

Infinite Range Interactions



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:

$$\ddot{a}_1 + \gamma_0 \dot{a}_1 + \omega_0^2 a_1 = \frac{3}{2}\omega_0 \gamma_0 \hat{d}_1 \cdot \vec{\mathcal{E}}_2(\vec{r}) a_1,$$

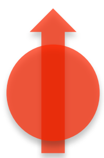
$$\gamma = \gamma_0 + \frac{3}{2}\gamma_0 \mathrm{Im}\left\{\hat{d}_1 \cdot \vec{\mathcal{E}}_2(\vec{r})\right\}, \quad \text{with} \left|\hat{d}_1 \cdot \vec{\mathcal{E}}_2(0)\right| = \frac{2}{3}$$

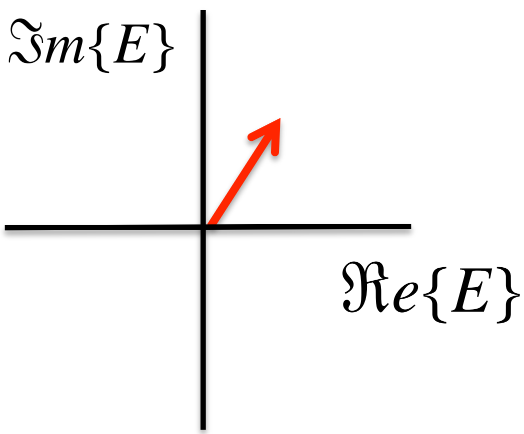
$$\omega = \omega_0 - \frac{3}{4}\gamma_0 \,\mathrm{Re}\left\{\hat{d}_1 \cdot \vec{\mathcal{E}}_2(\vec{r})\right\}$$

Super- and Sub-radiance

(a classical explanation)

Normal radiance





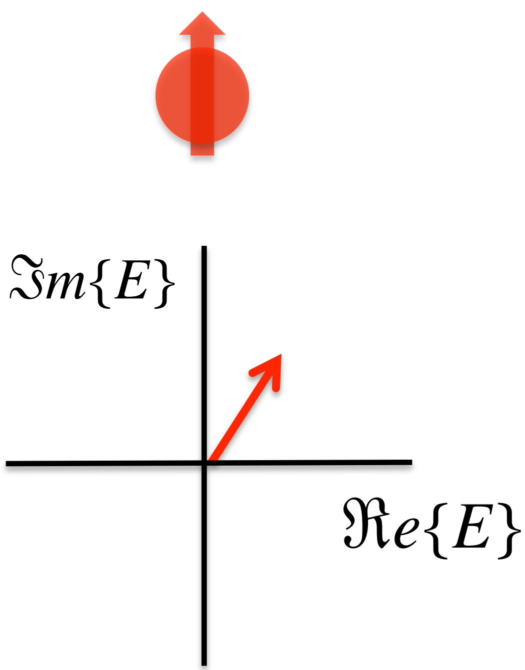
$$I = \left|E_0\right|^2 = I_0$$

$$\Delta t = \tau_0$$

Super- and Sub-radiance

(a classical explanation)

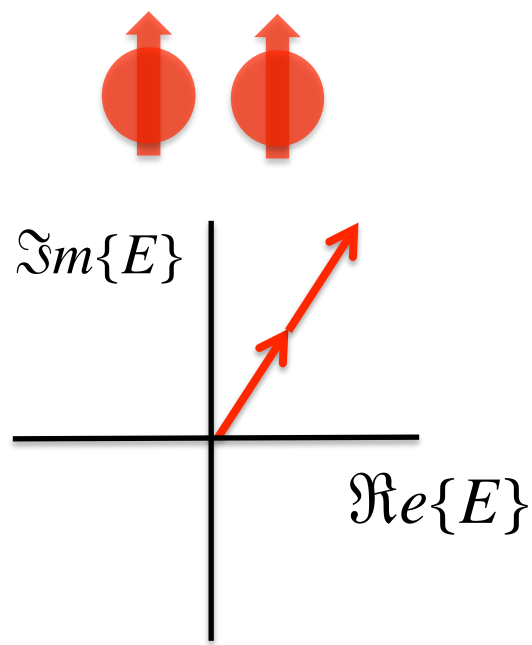
Normal radiance



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

$$\Delta t = \tau_0$$

Super-radiance



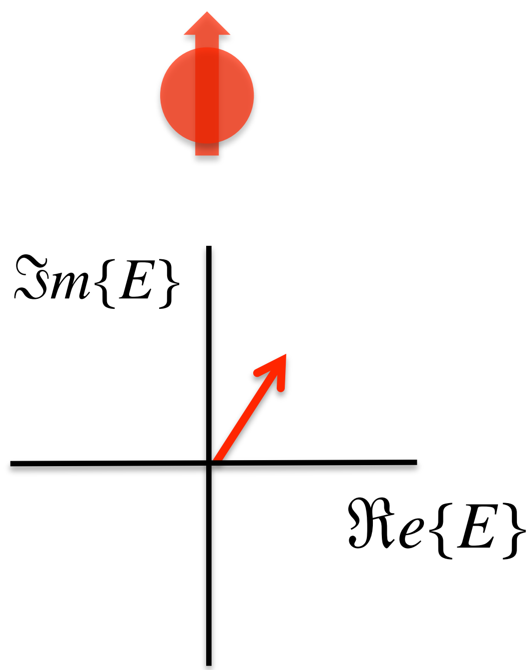
$$I = 4I_0$$

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

Super- and Sub-radiance

(a classical explanation)

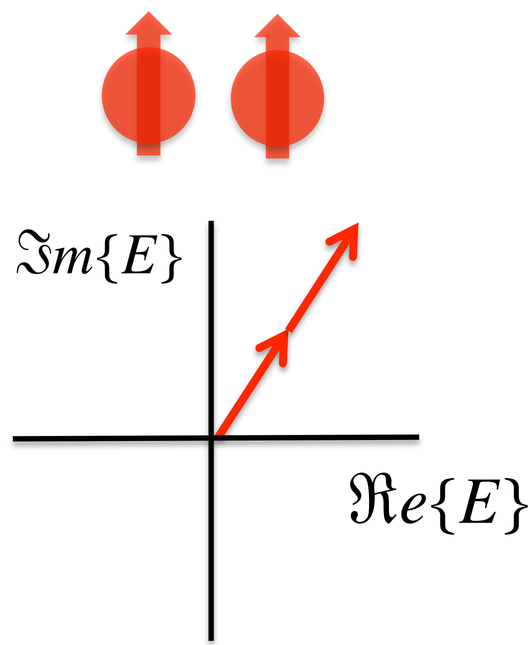
Normal radiance



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

$$\Delta t = \tau_0$$

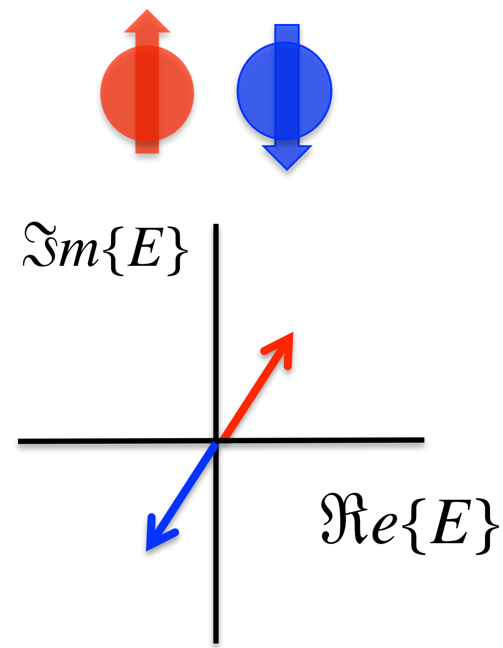
Super-radiance



$$I = 4I_0$$

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

Sub-radiance



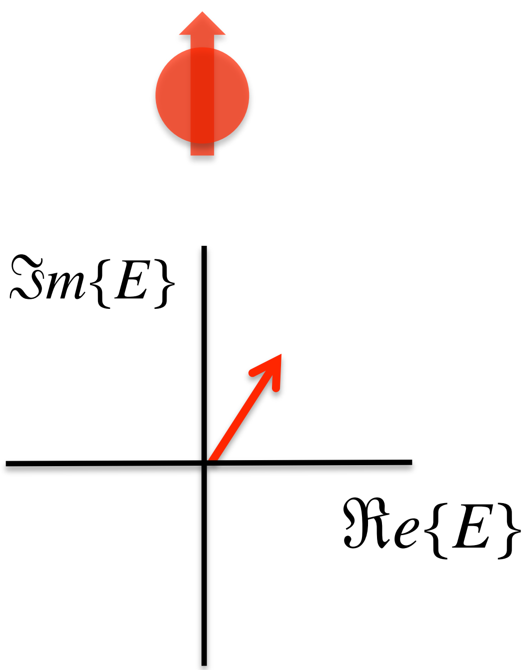
$$I = 0$$

$$\Delta t = \infty$$

Super- and Sub-radiance

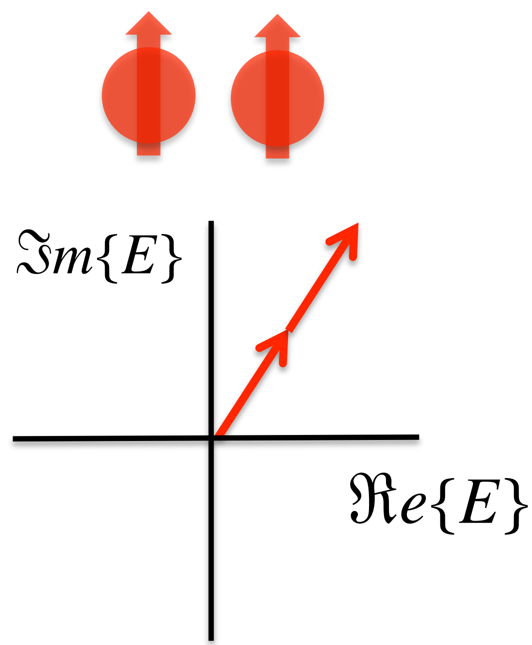
(a classical explanation)

Normal radiance



$$\Delta t = \tau_0$$

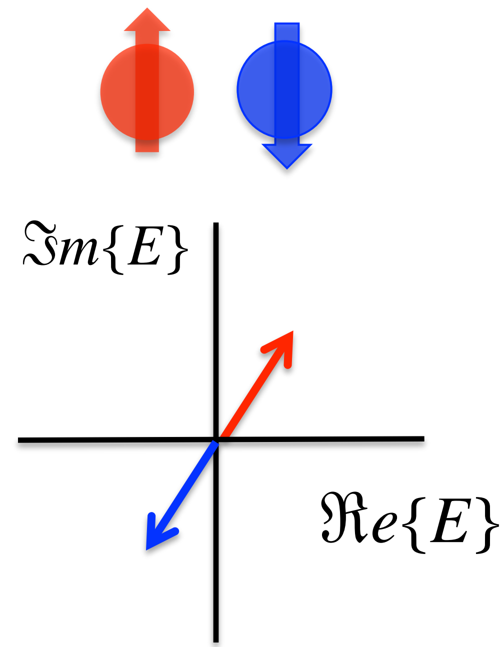
Super-radiance



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

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

Sub-radiance



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

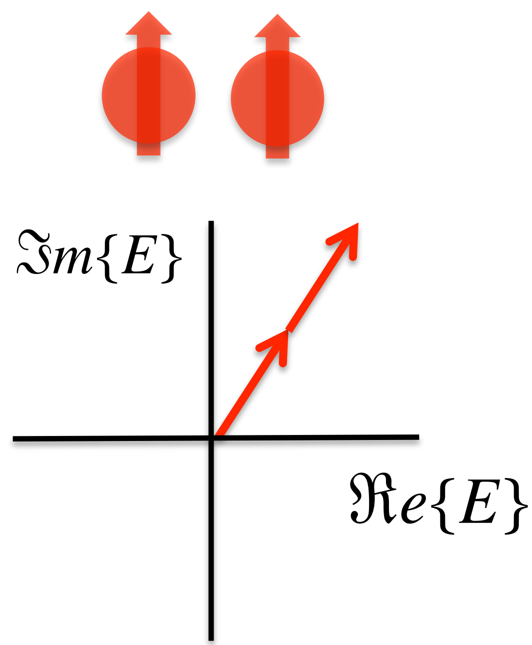
$$\Delta t = \infty$$

Super- and Sub-radiance

(a classical explanation)

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

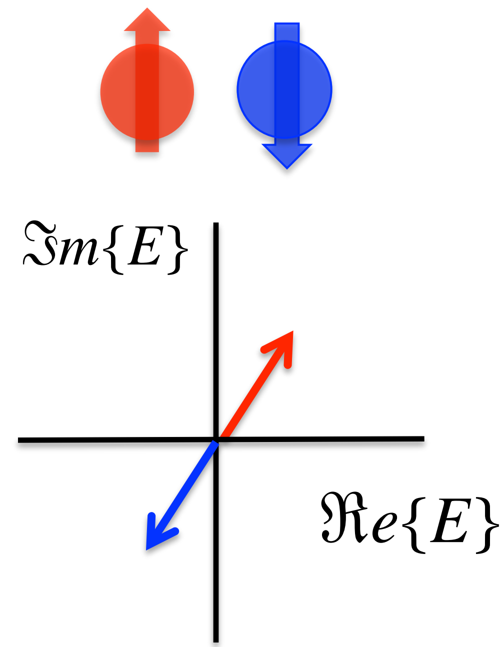
Super-radiance



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

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

Sub-radiance

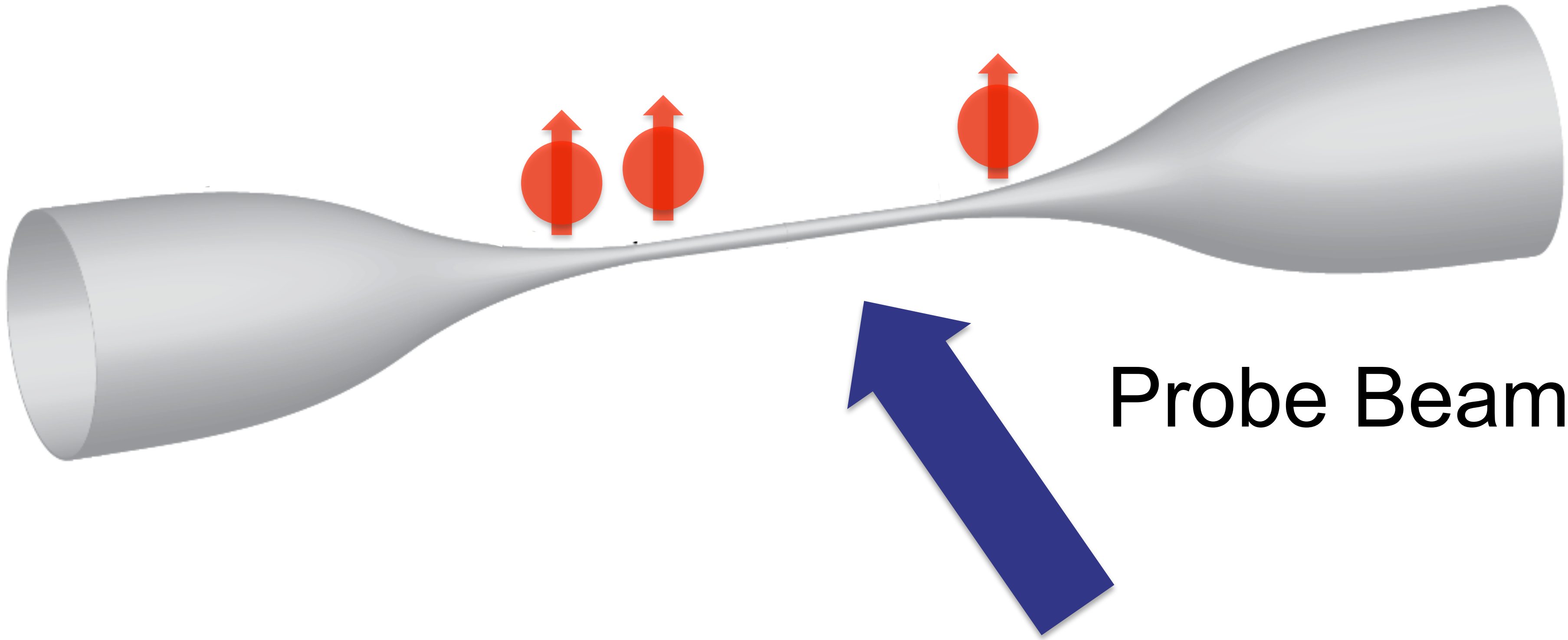


$$|ge\rangle - |eg\rangle$$

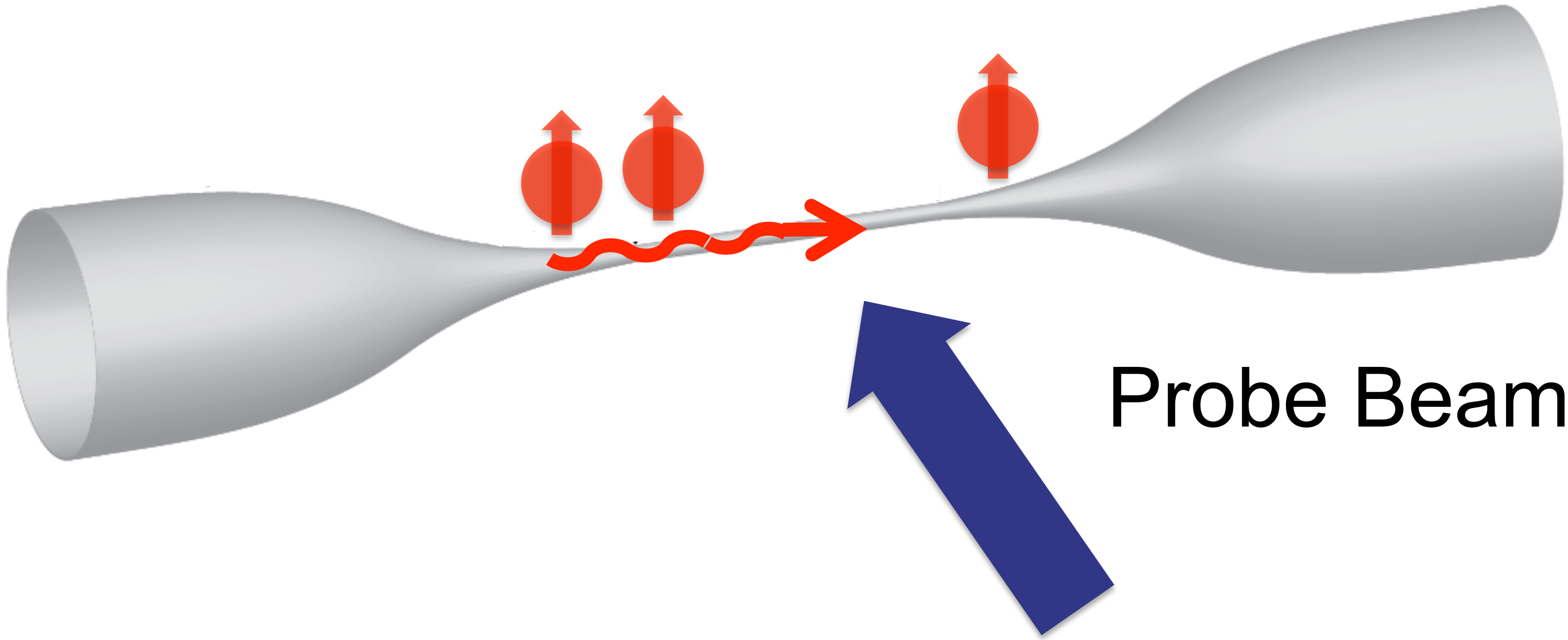
$$\Delta t = \infty$$

Observation of infinite-range interactions

The idea behind the experiment

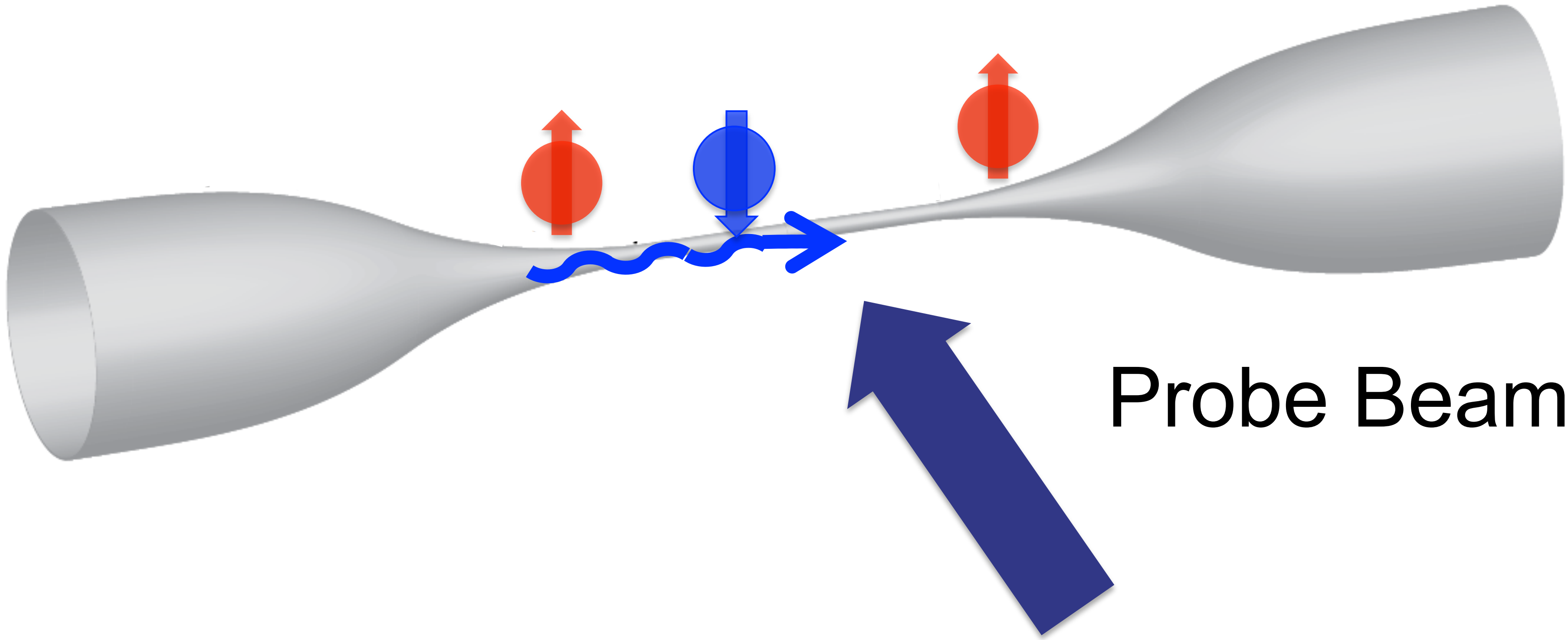


The idea behind the experiment



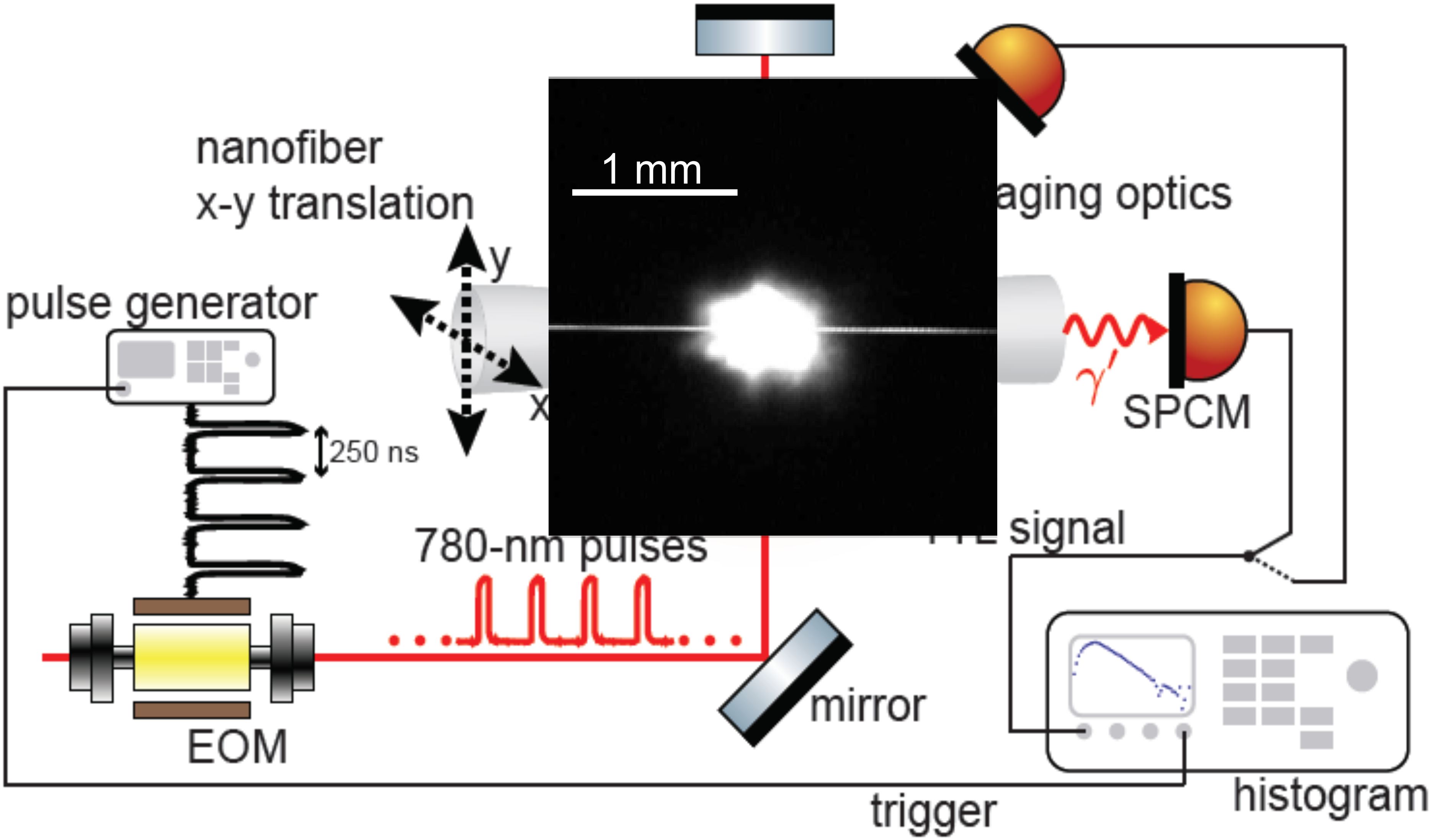
We look for modifications of the radiative lifetime of an ensemble of atoms around the ONF.

The idea behind the experiment

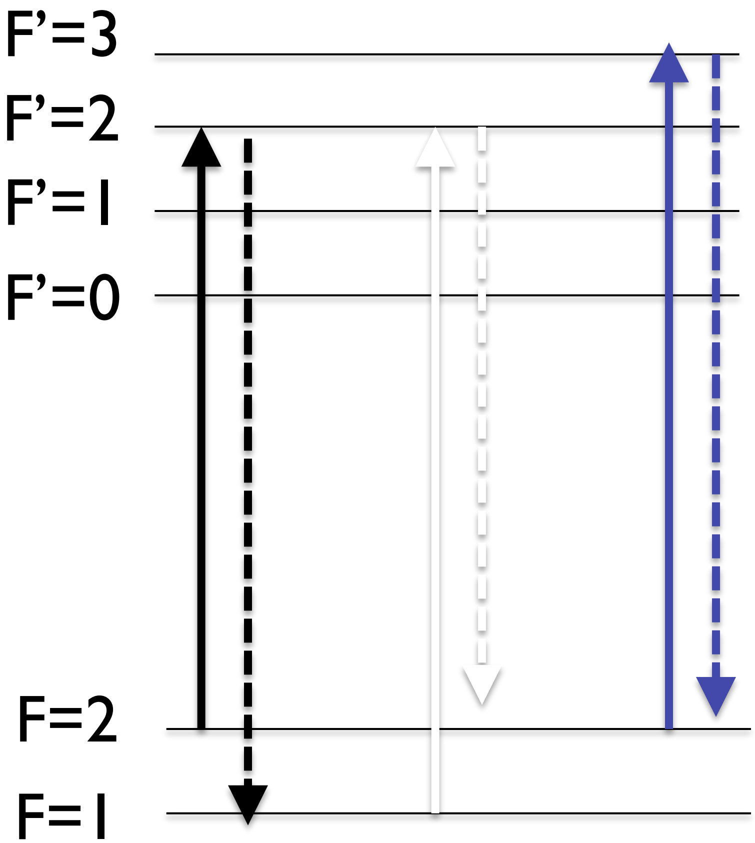


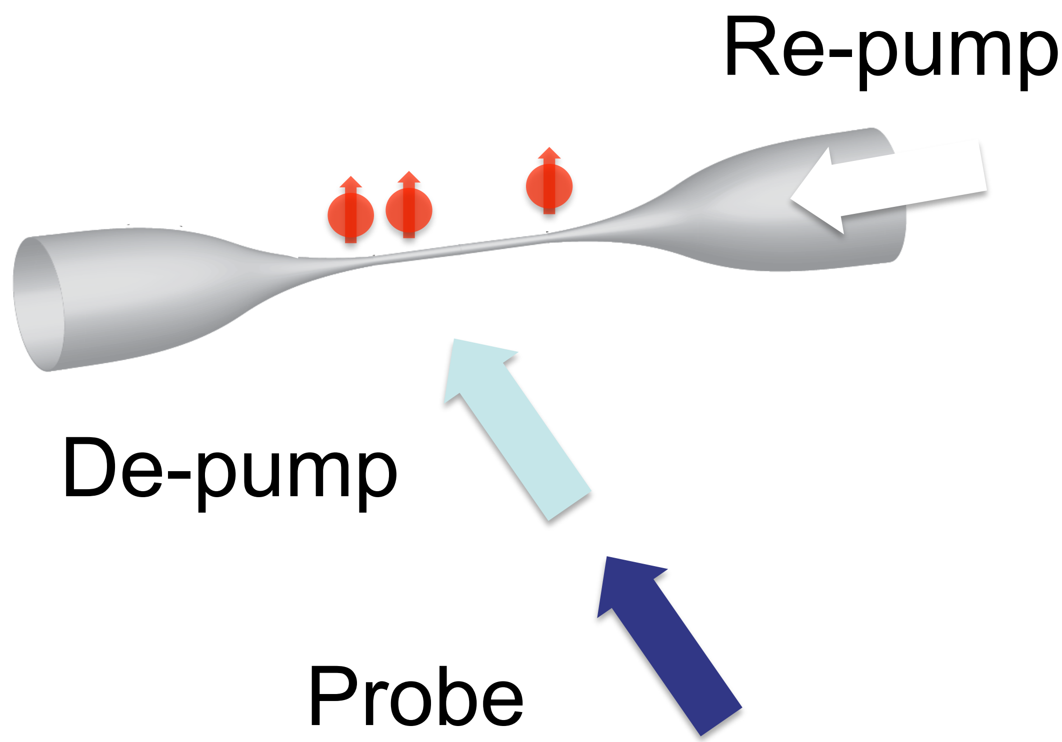
The sub- and super-radiant behavior depend on the phase relation of the atomic dipoles along the common mode

Measuring the Radiative Lifetime



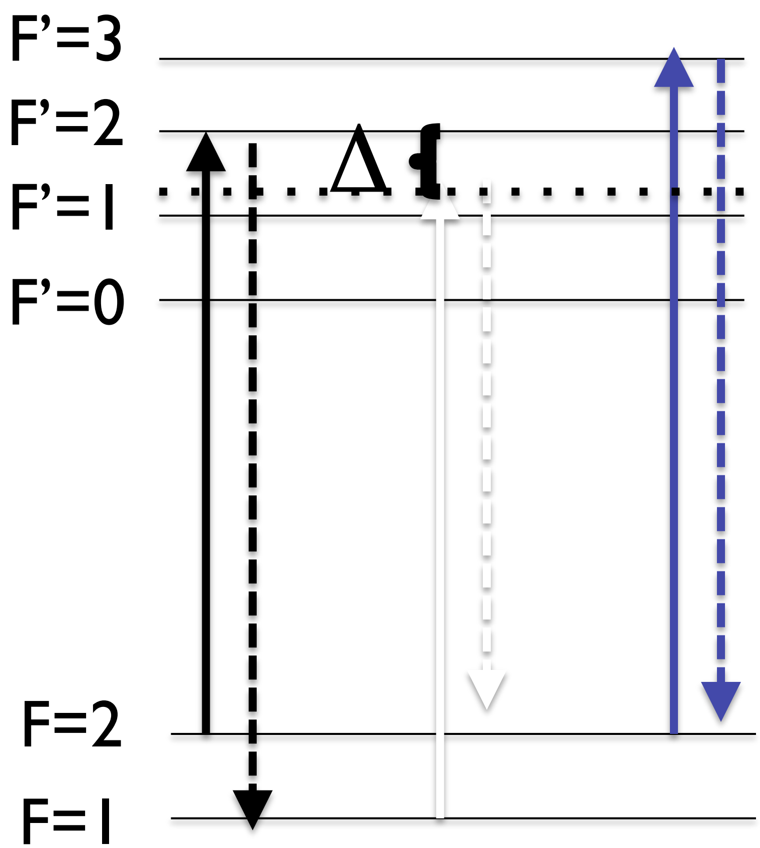
Preparing the Atoms

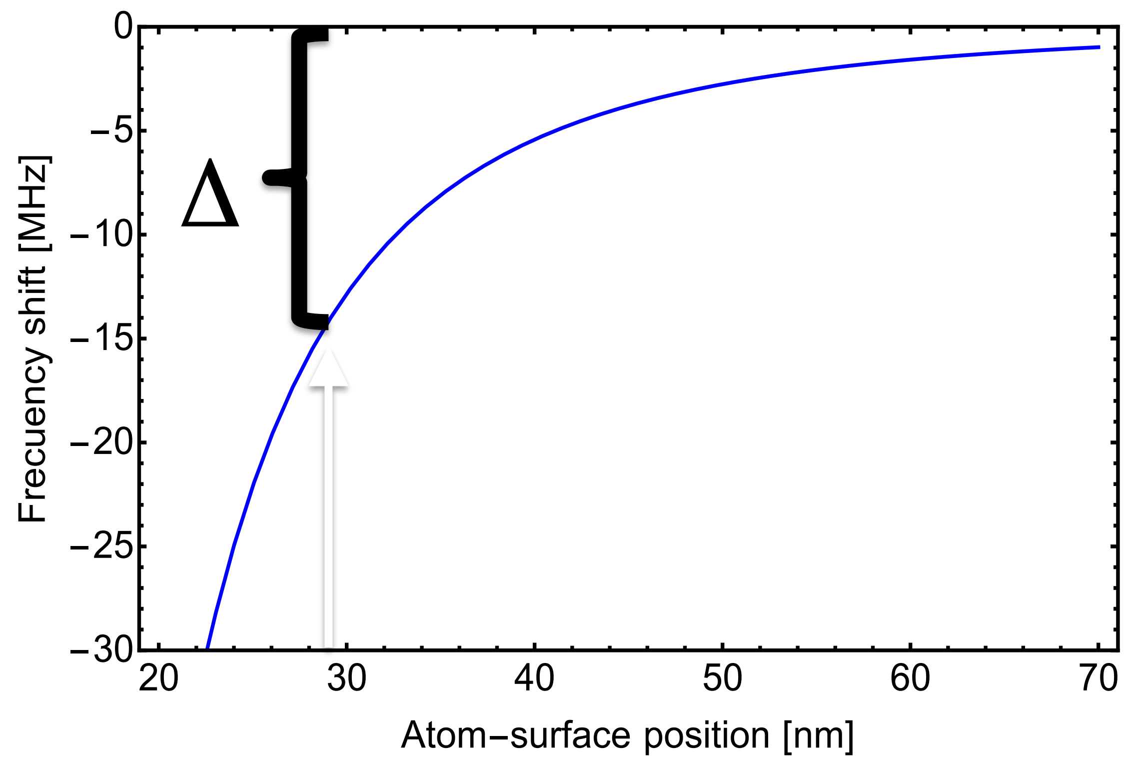




De-pump Re-pump Probe

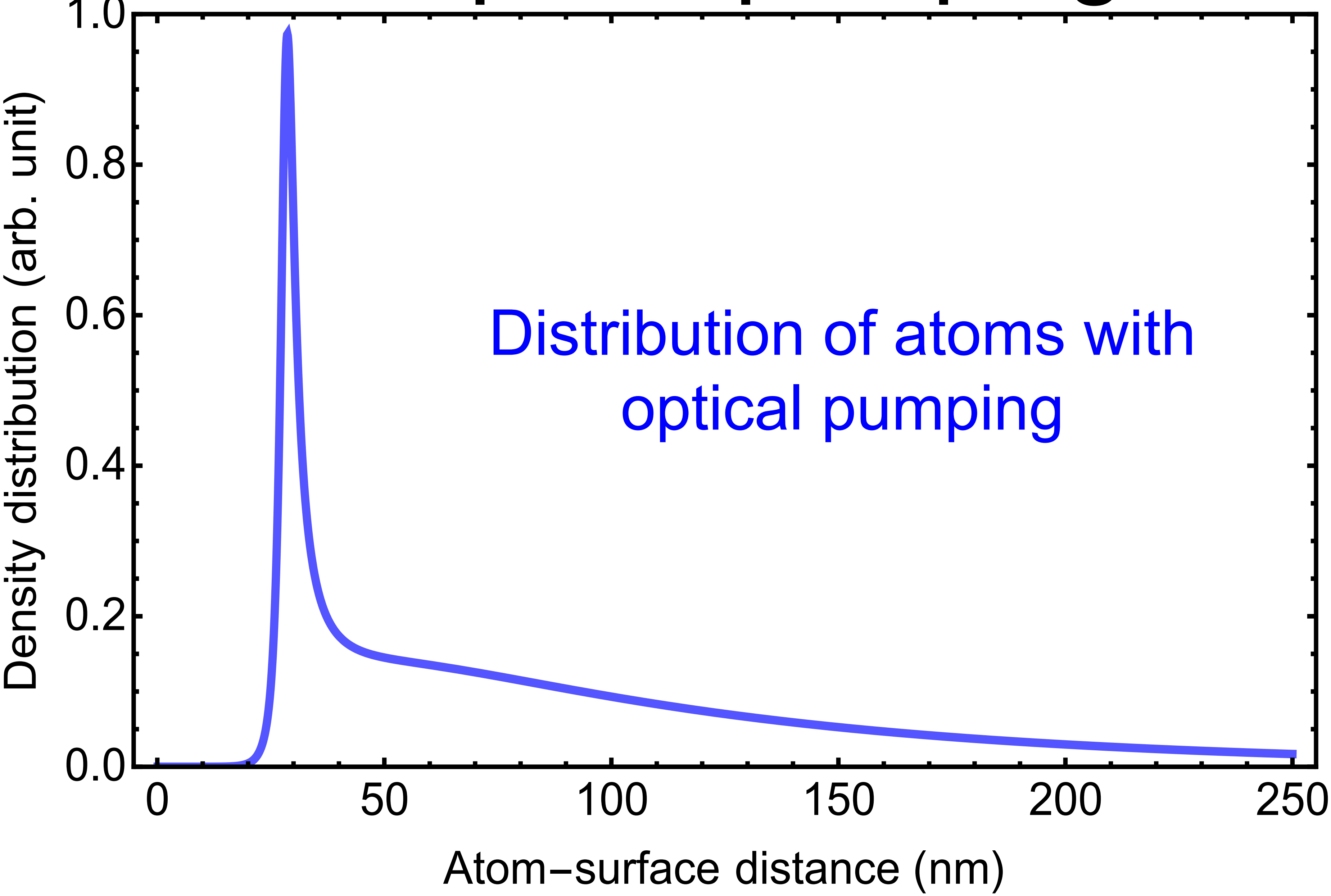
Preparing the Atoms



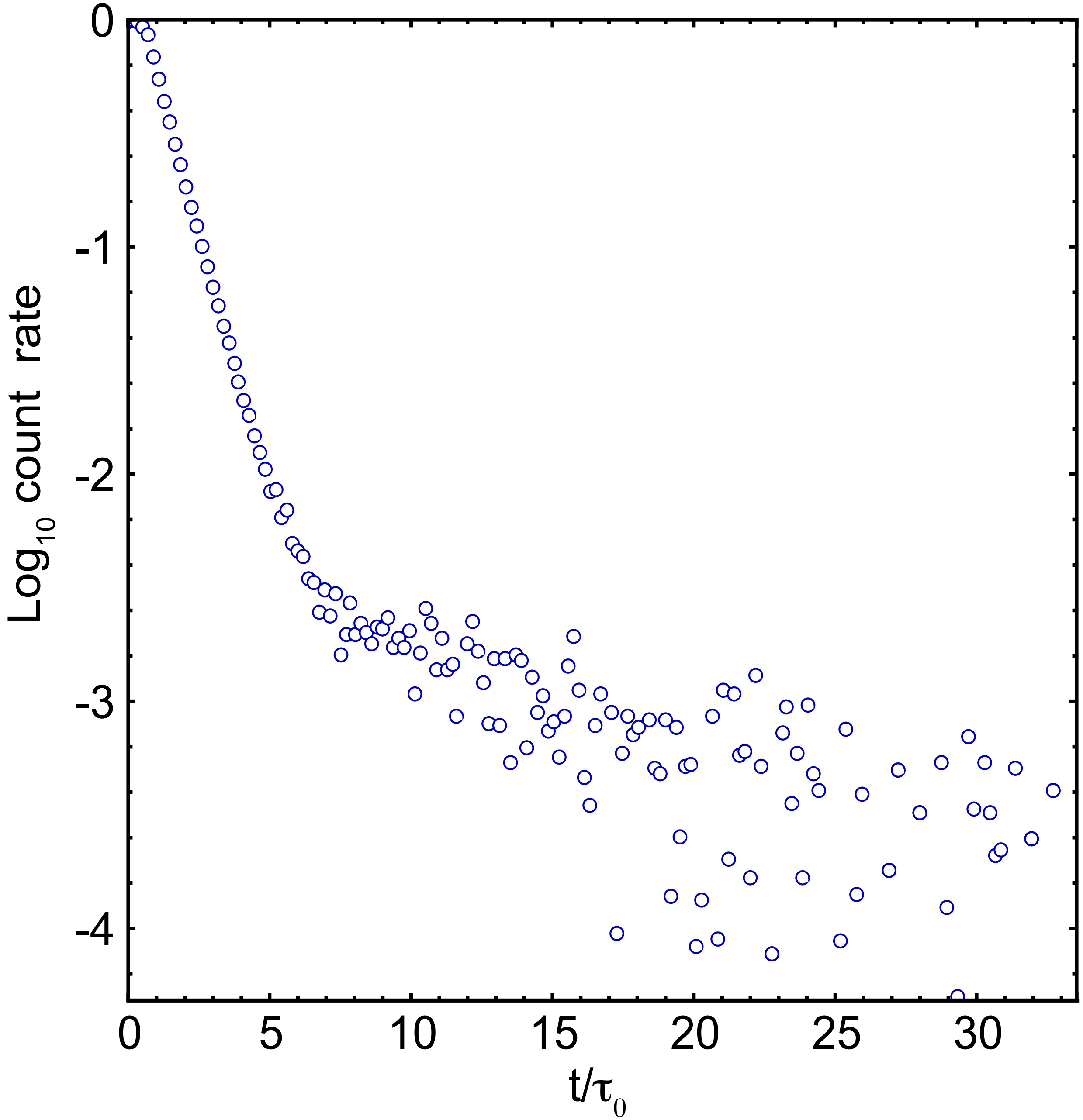


De-pump Re-pump Probe

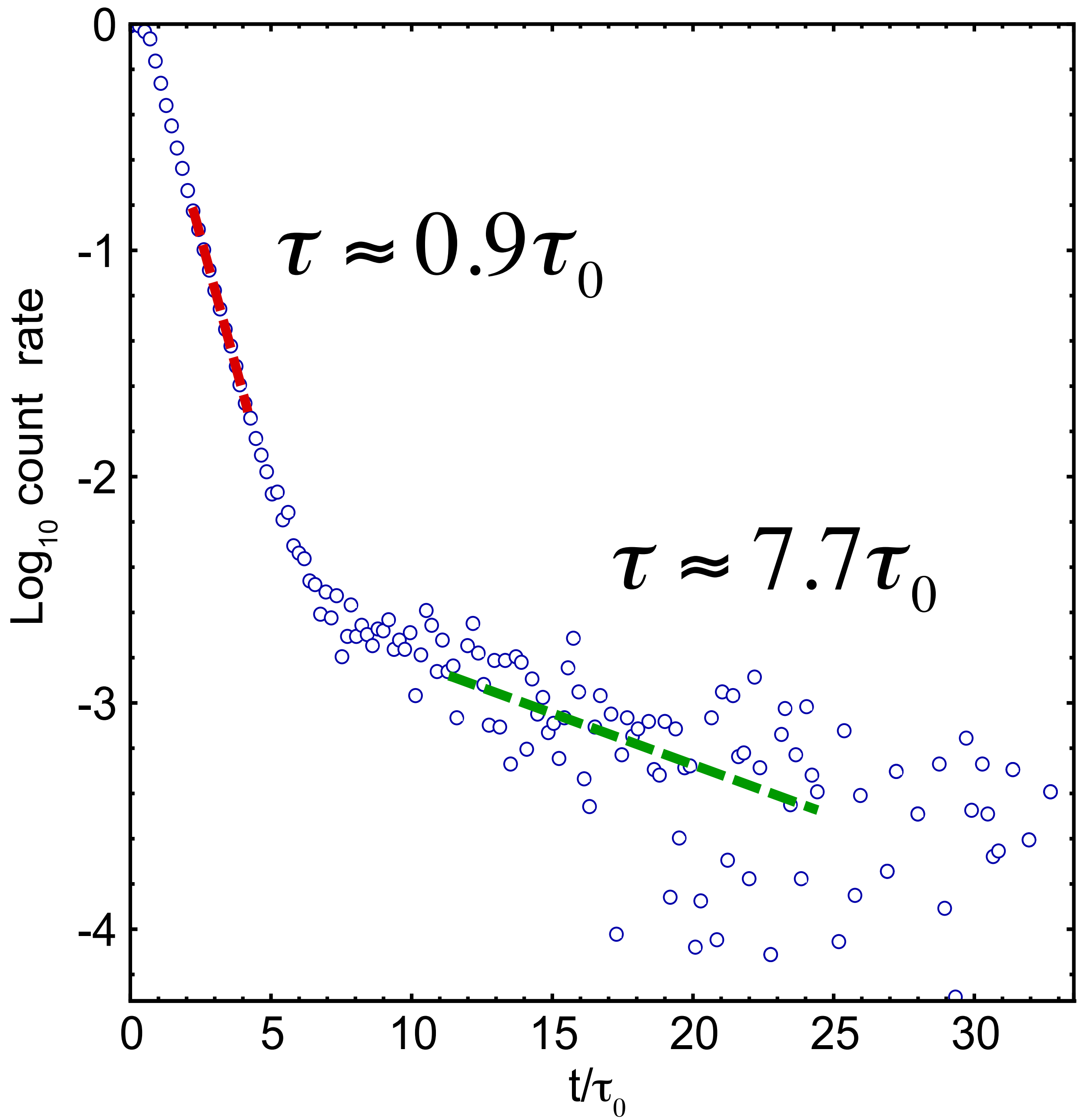
Atomic distribution with optical pumping



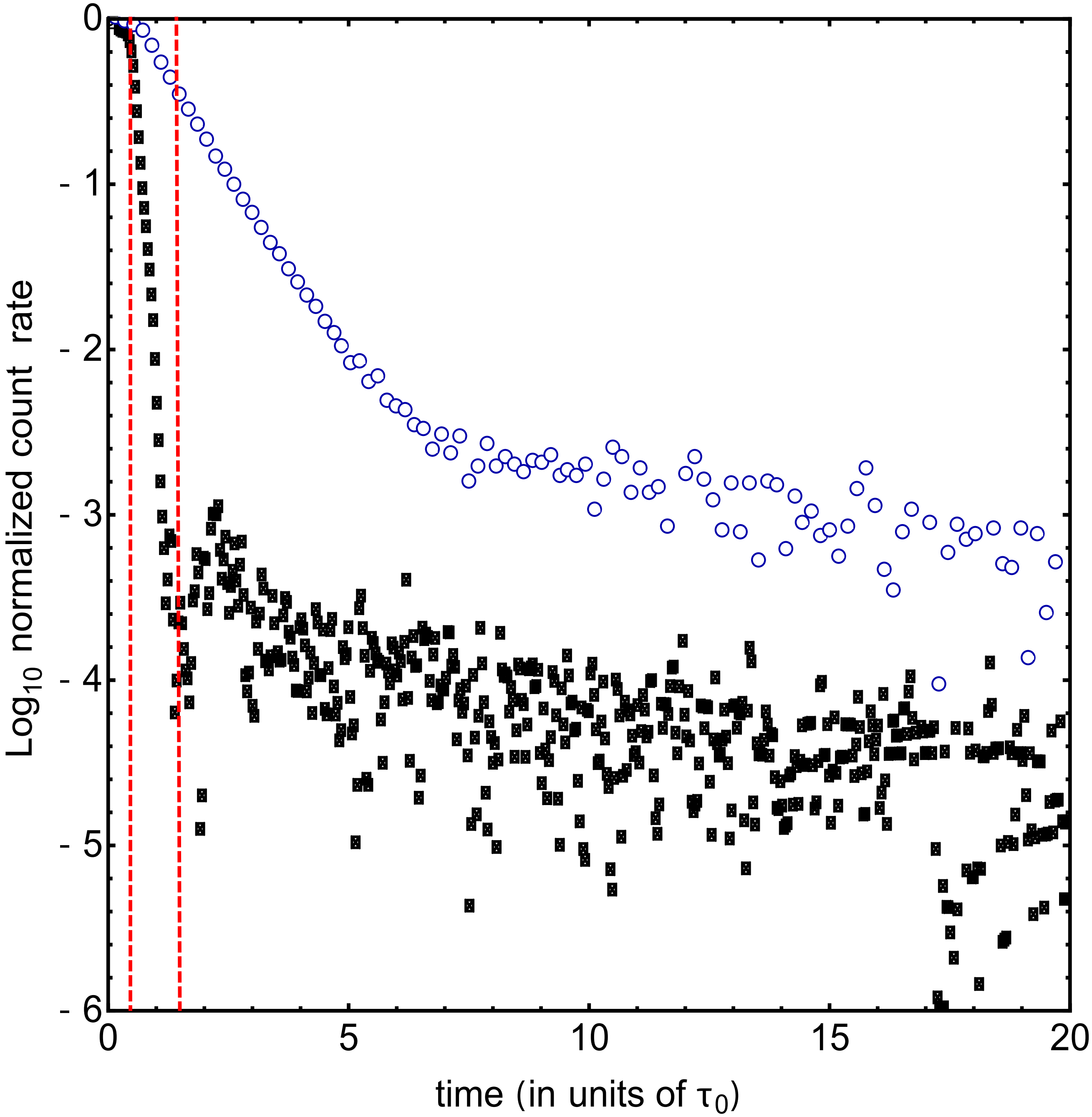
Two distinct lifetimes



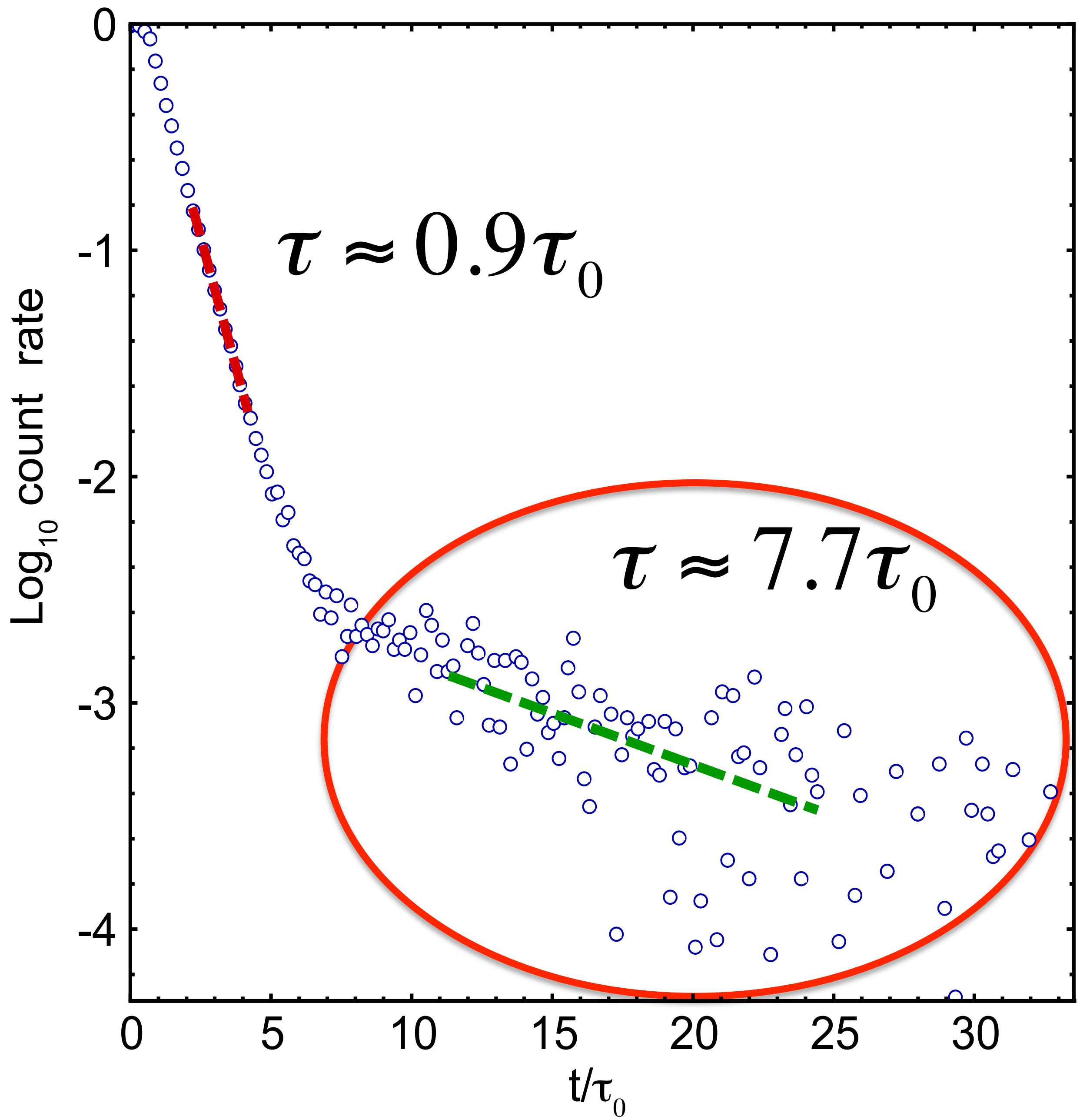
Two distinct lifetimes



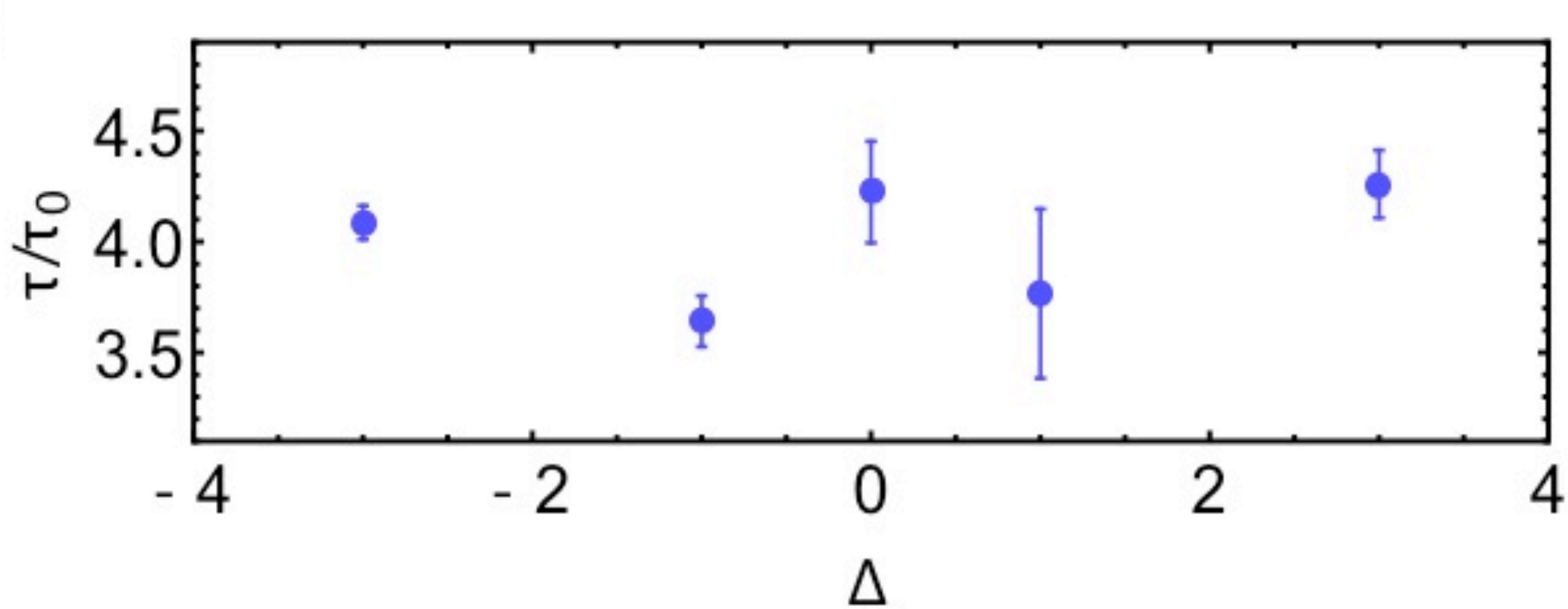
Pulse and signal



Two distinct lifetimes

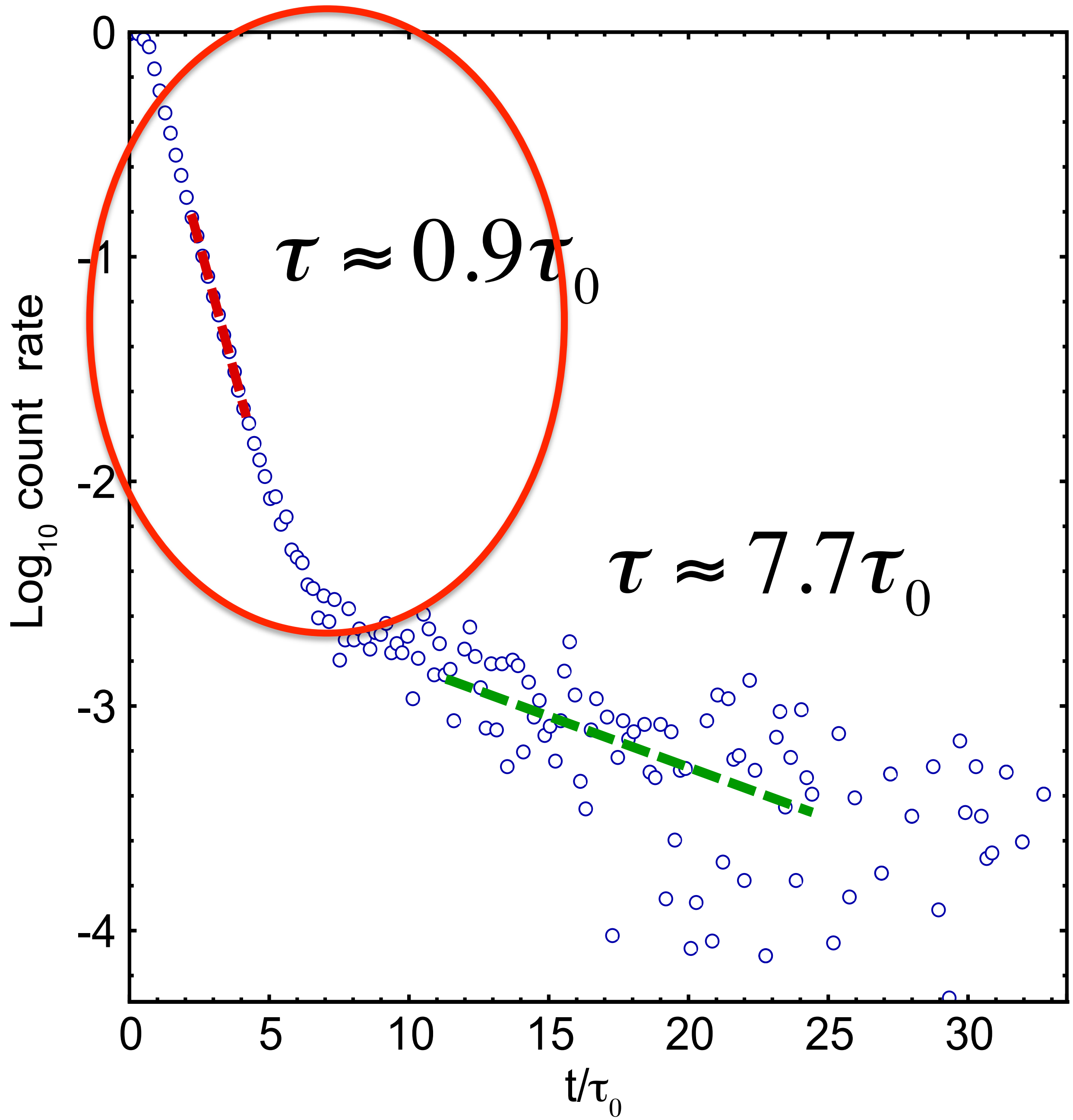


Decay time vs detunning

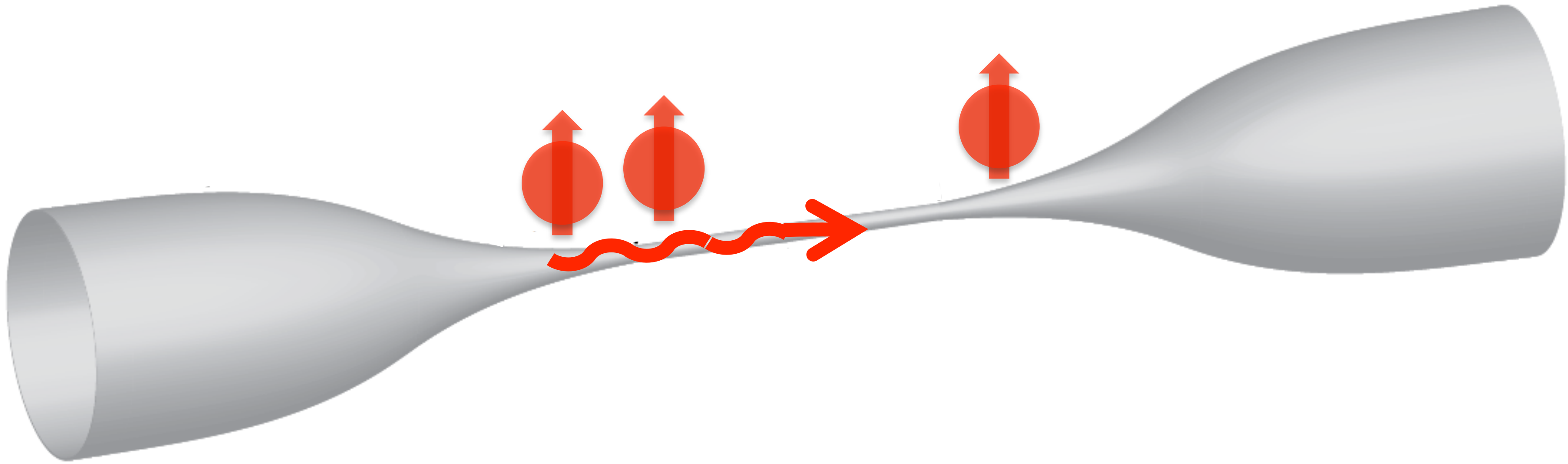


No radiation trapping for long lifetime

Two distinct lifetimes

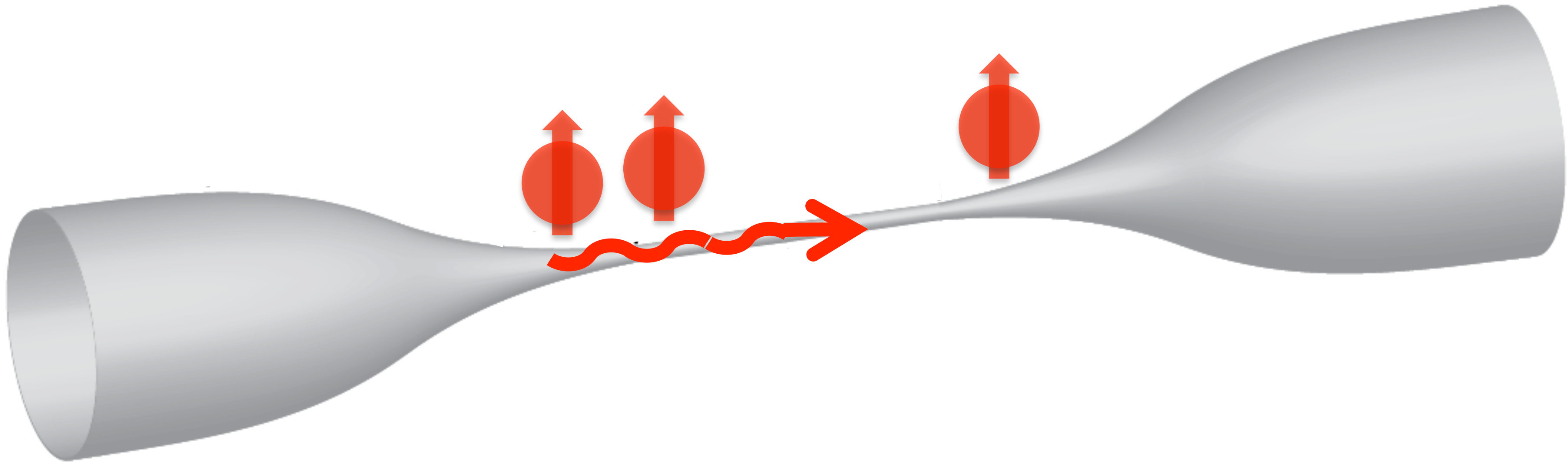


N dependence



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

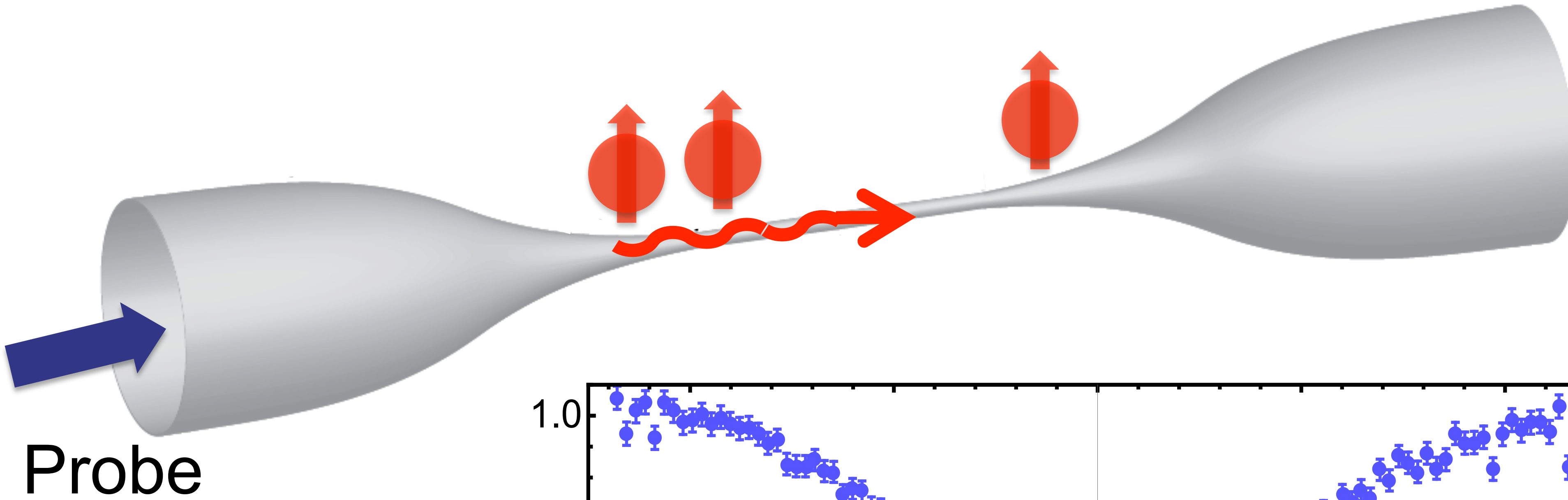
N dependence

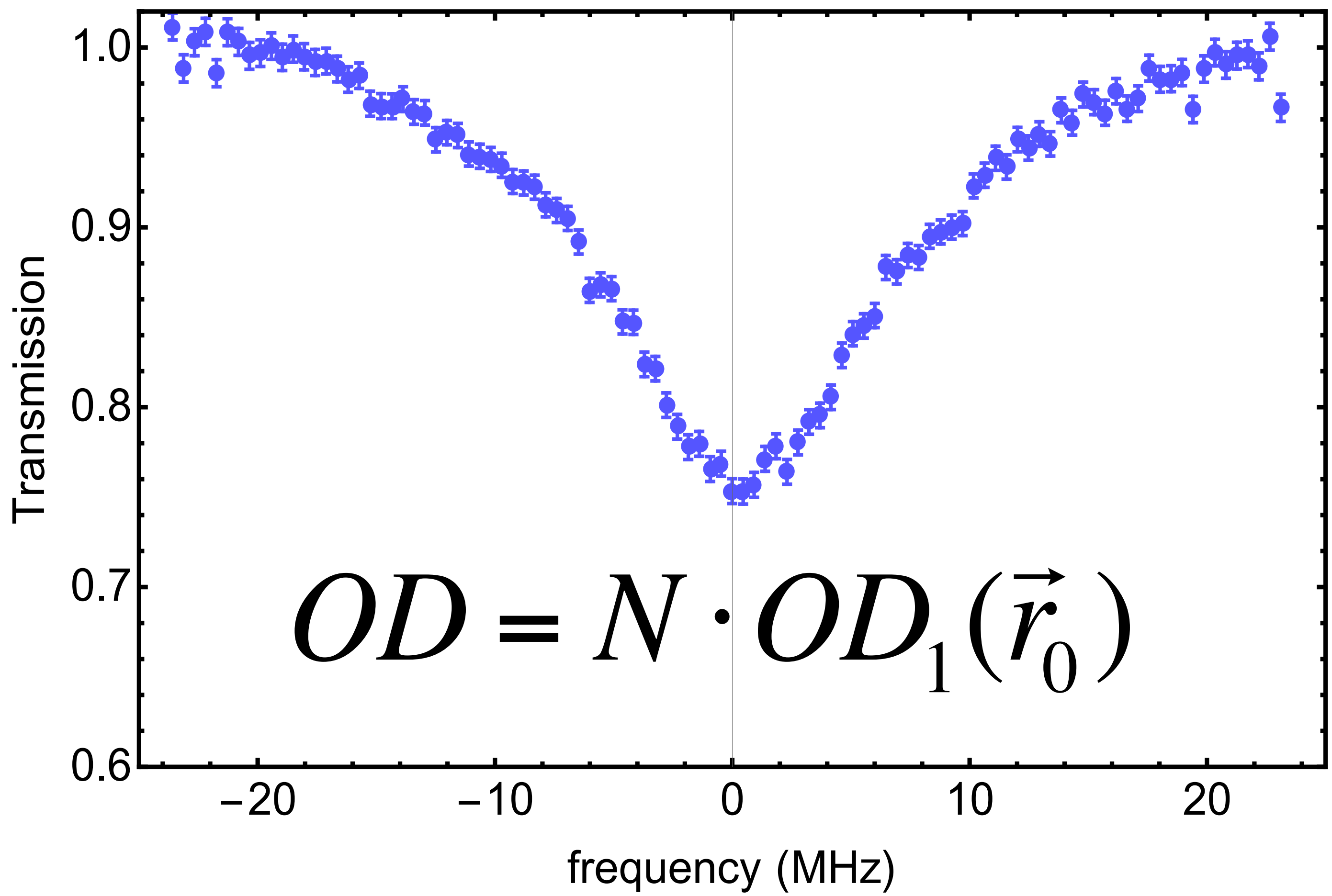


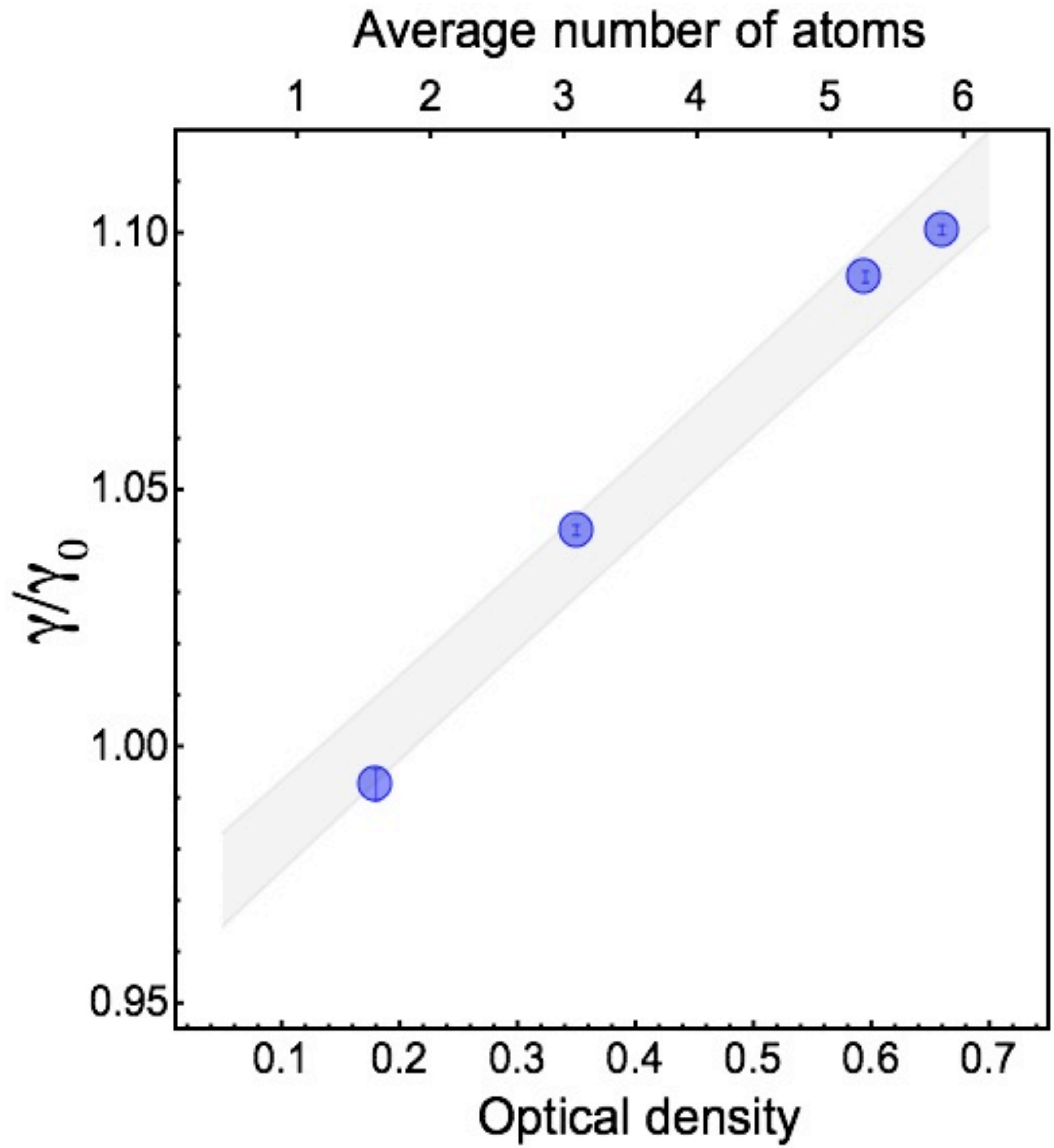
$$\gamma_{\text{sup}} = \gamma_{rad} + N\gamma_{1D}$$

Superradiance depends on the **atom number**!

Measurment of N

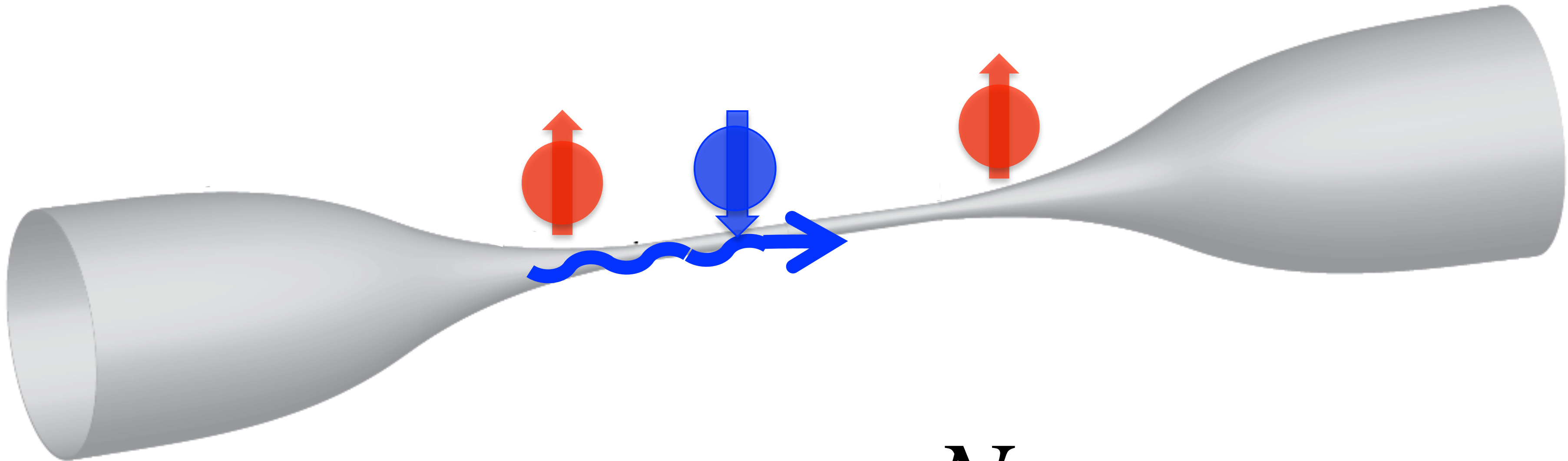






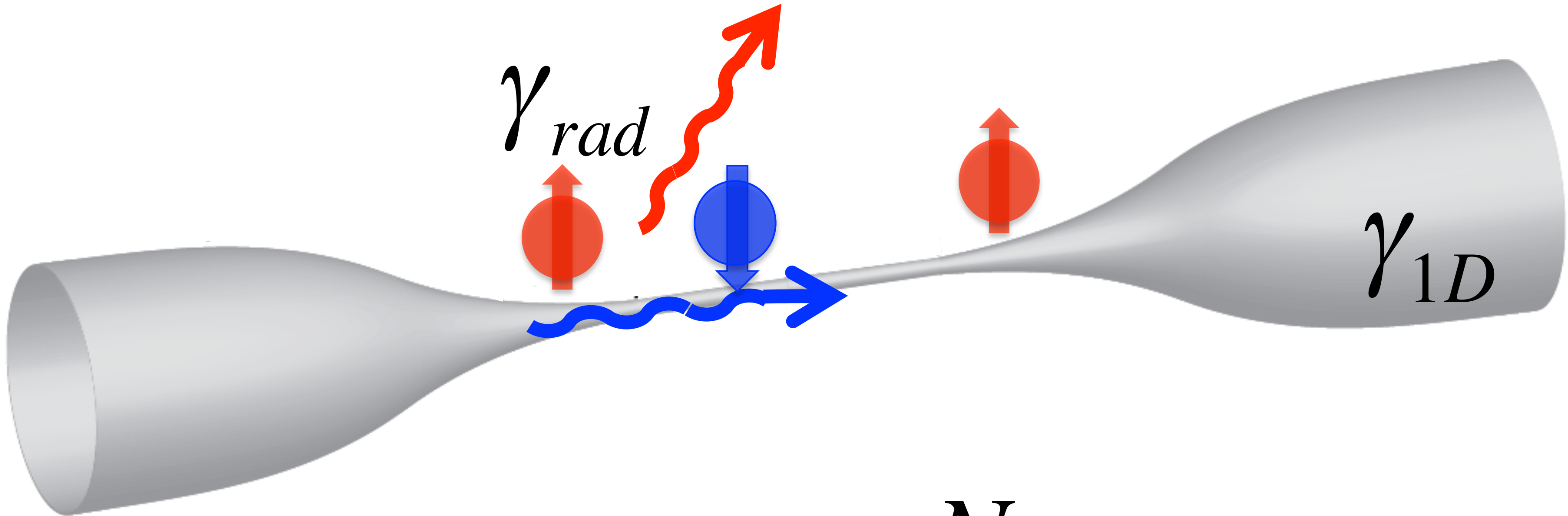
Average number of atoms
1
2
3
4
5
6
1.10
1.05
1.00
0.95
γ/γ_0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Optical density

Sub-radiance???



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

Subradiance???

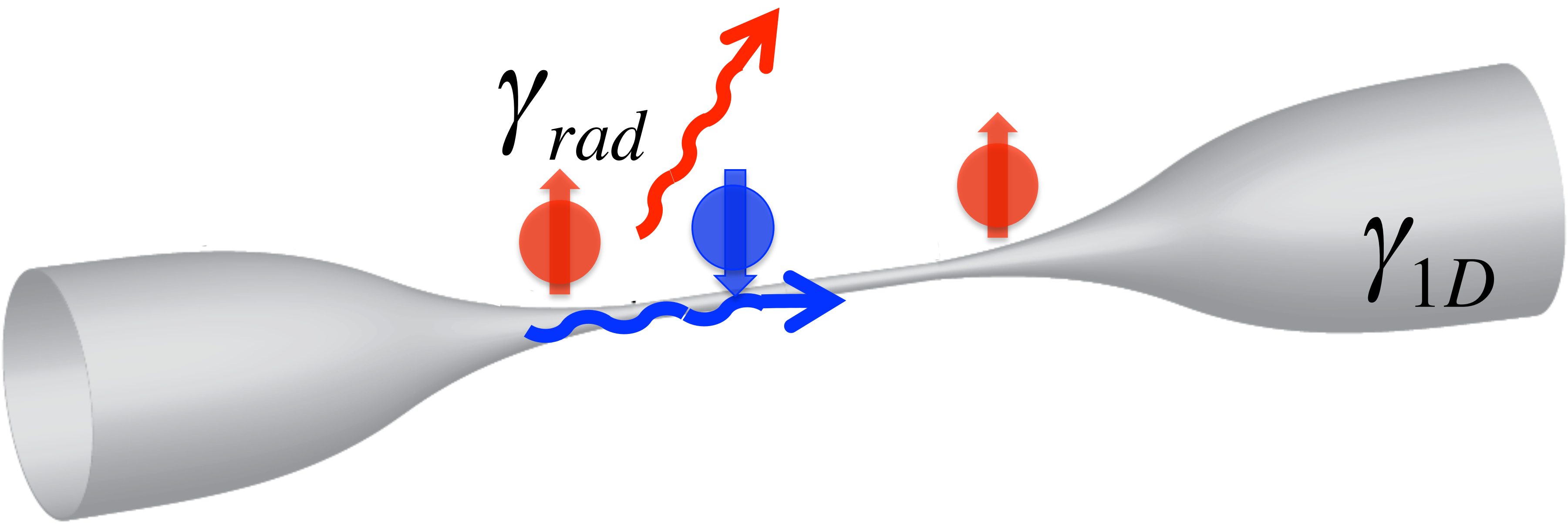


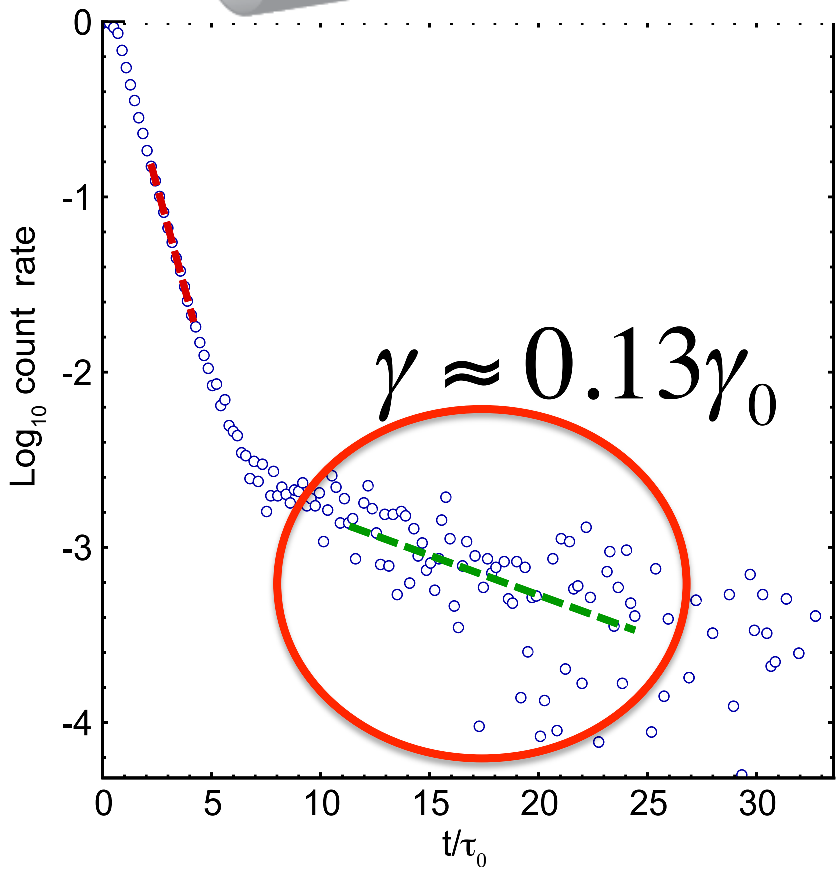
$$\gamma_{\sup} = \gamma_{rad} + N\gamma_{1D}$$

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

Infinite-range subradiance is **limited**!

Sub-radiance???



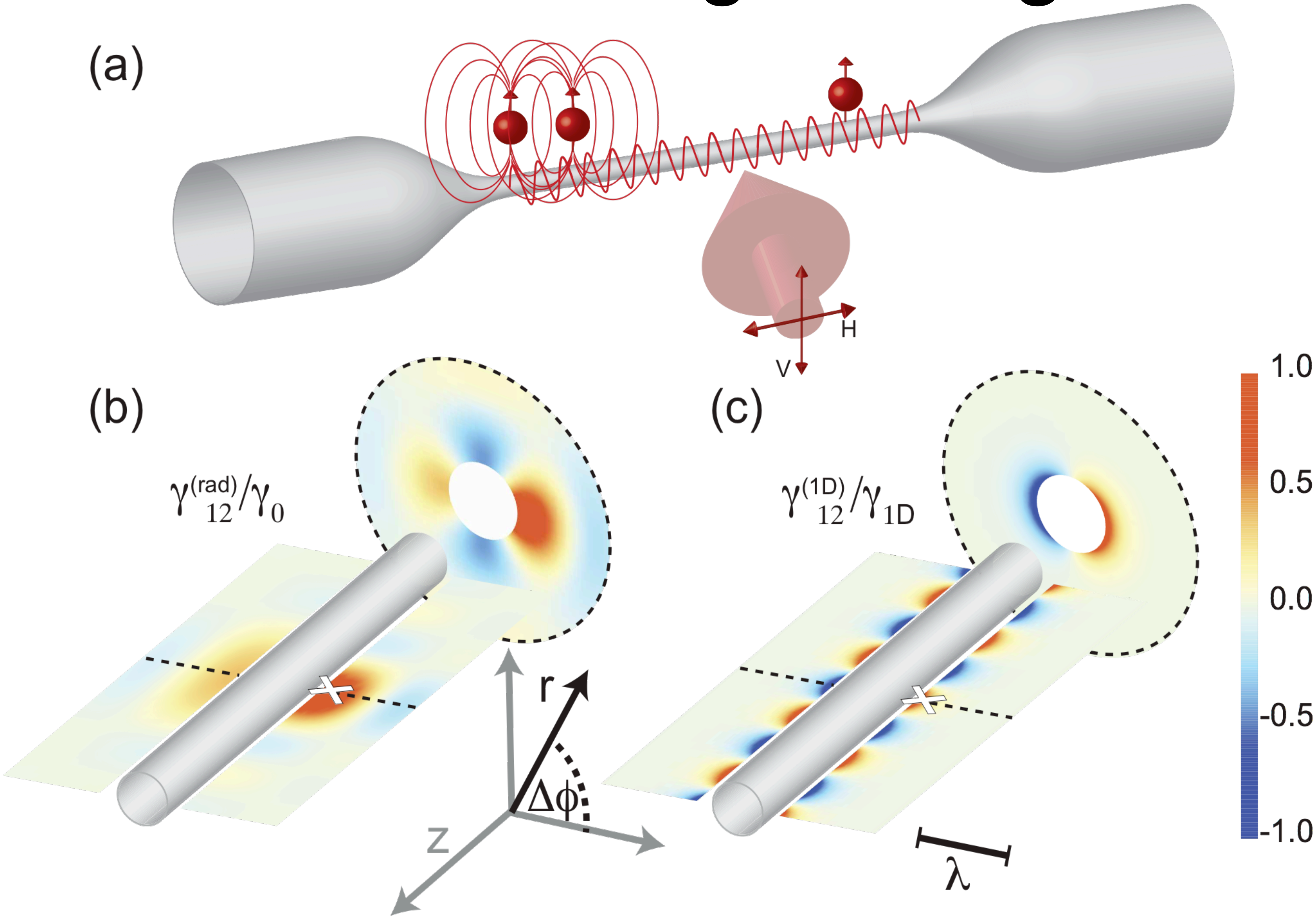


$$\gamma_{sub} = \gamma_{rad} - \gamma_{1D} \approx 0.9\gamma_0$$

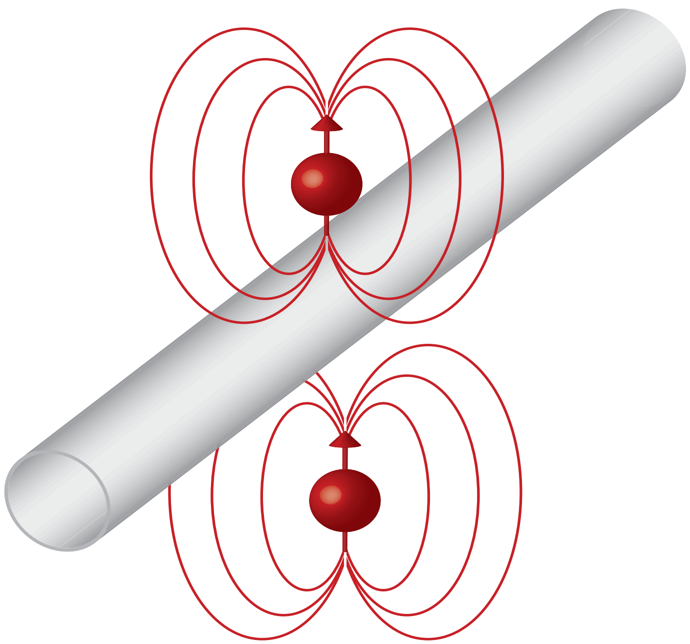
The subradiant decay rate we measure is **too slow**!

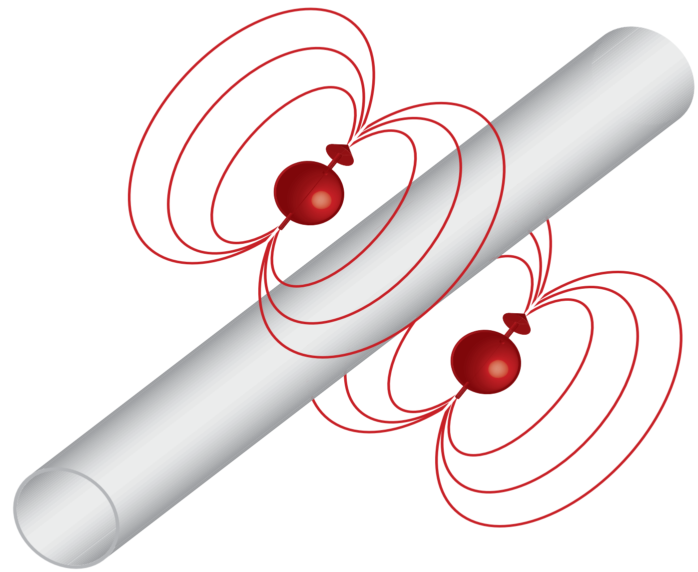
Understanding the Signal

Understanding the Signal



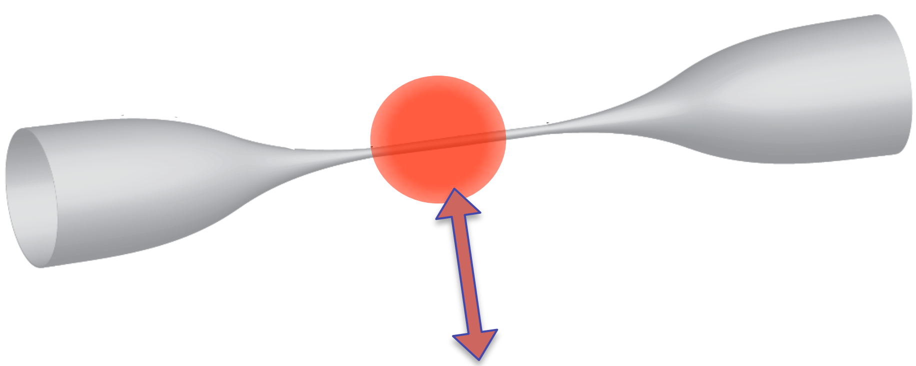
Polarization dependent signal

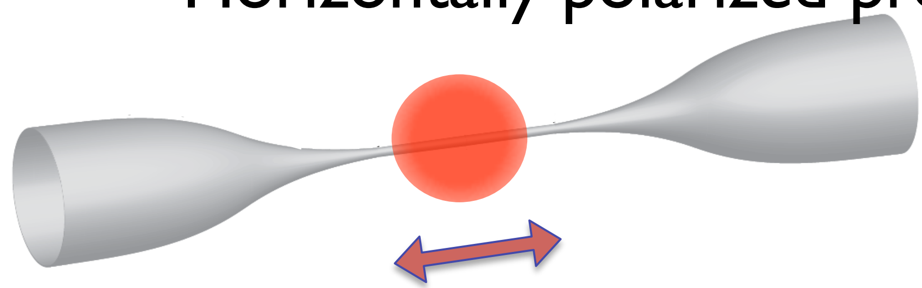




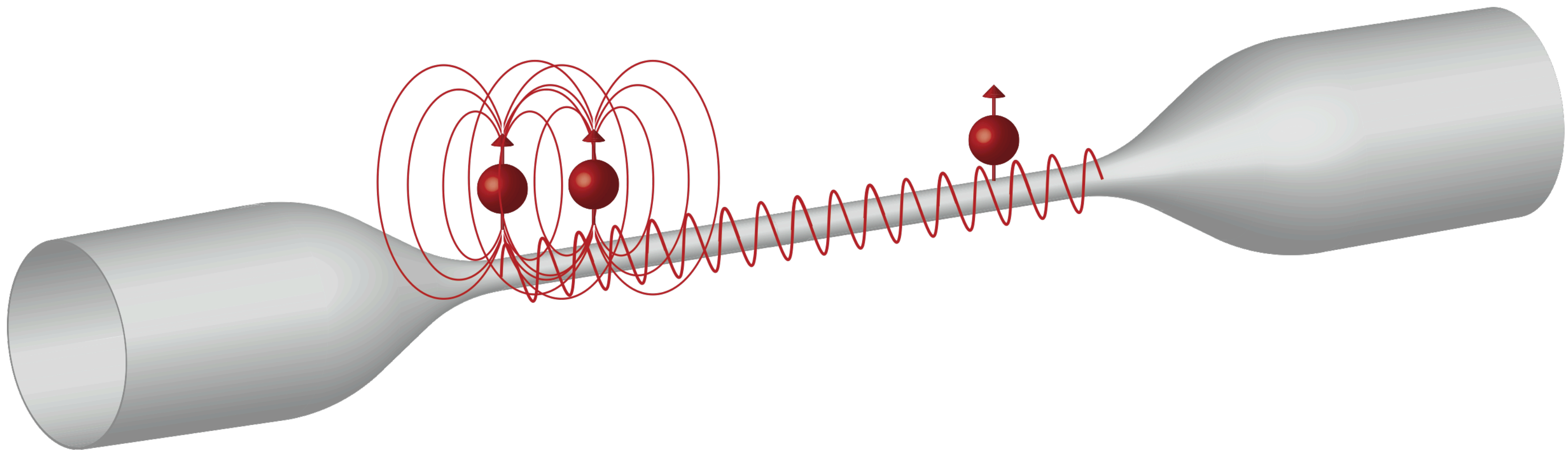
Vertically polarized probe

Horizontally polarized probe





Subradiant Signal



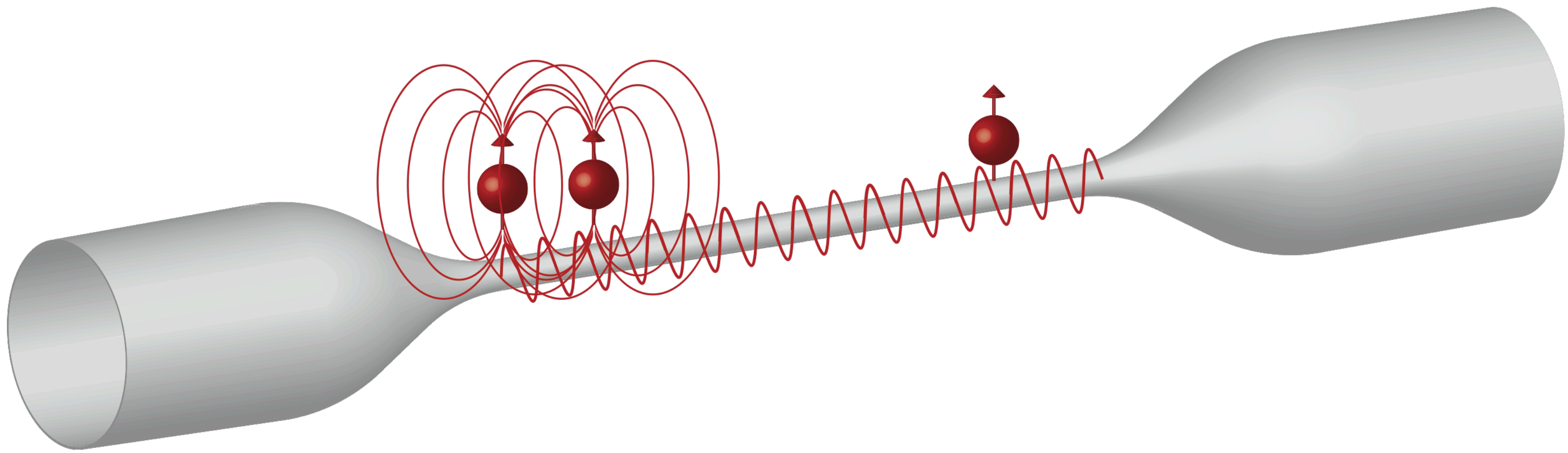
- Interaction distance smaller than λ: all modes get cancelled.
- Interaction distance greater than λ: only one mode gets cancelled

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

We measure

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

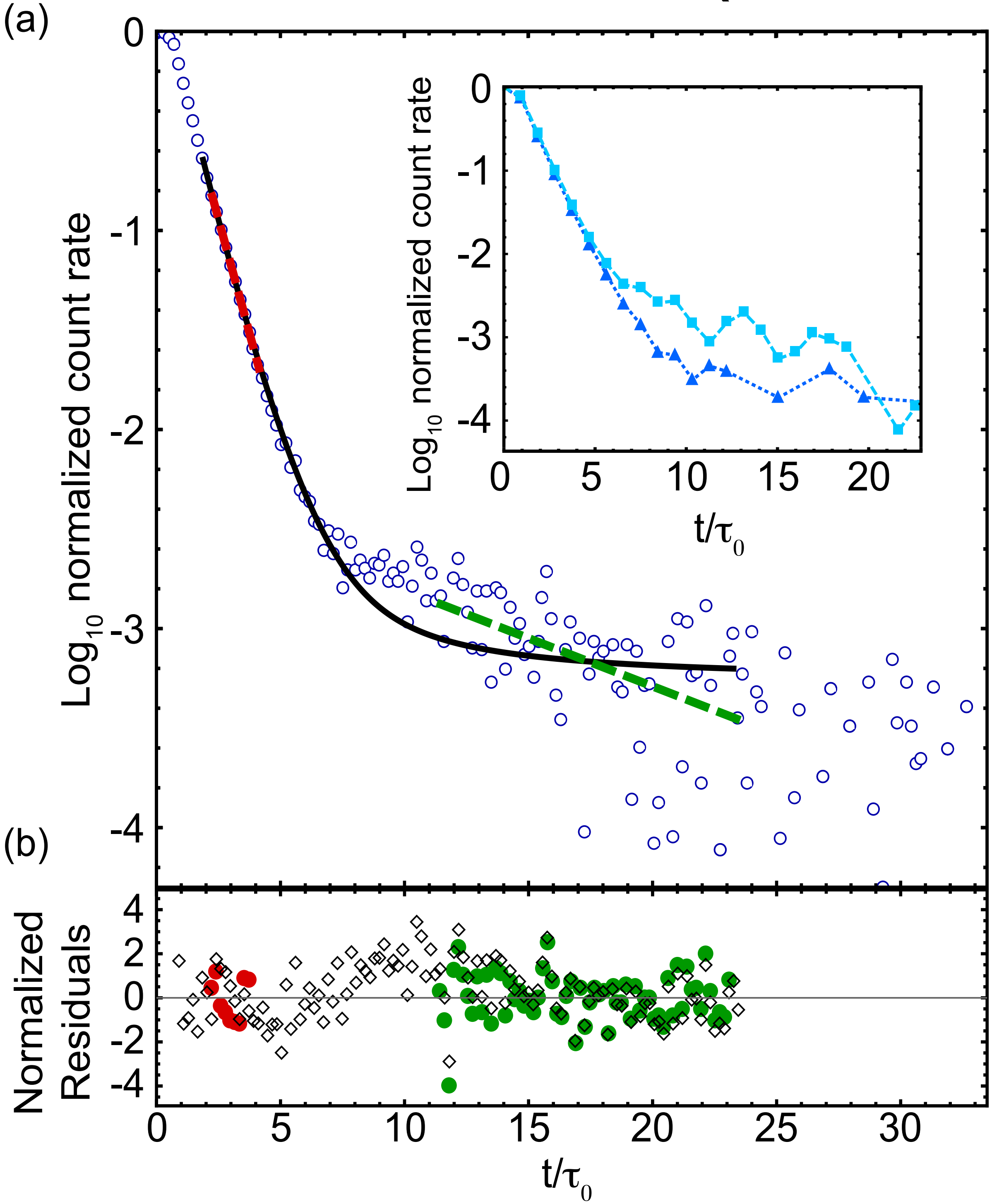
Super-radiant Signal



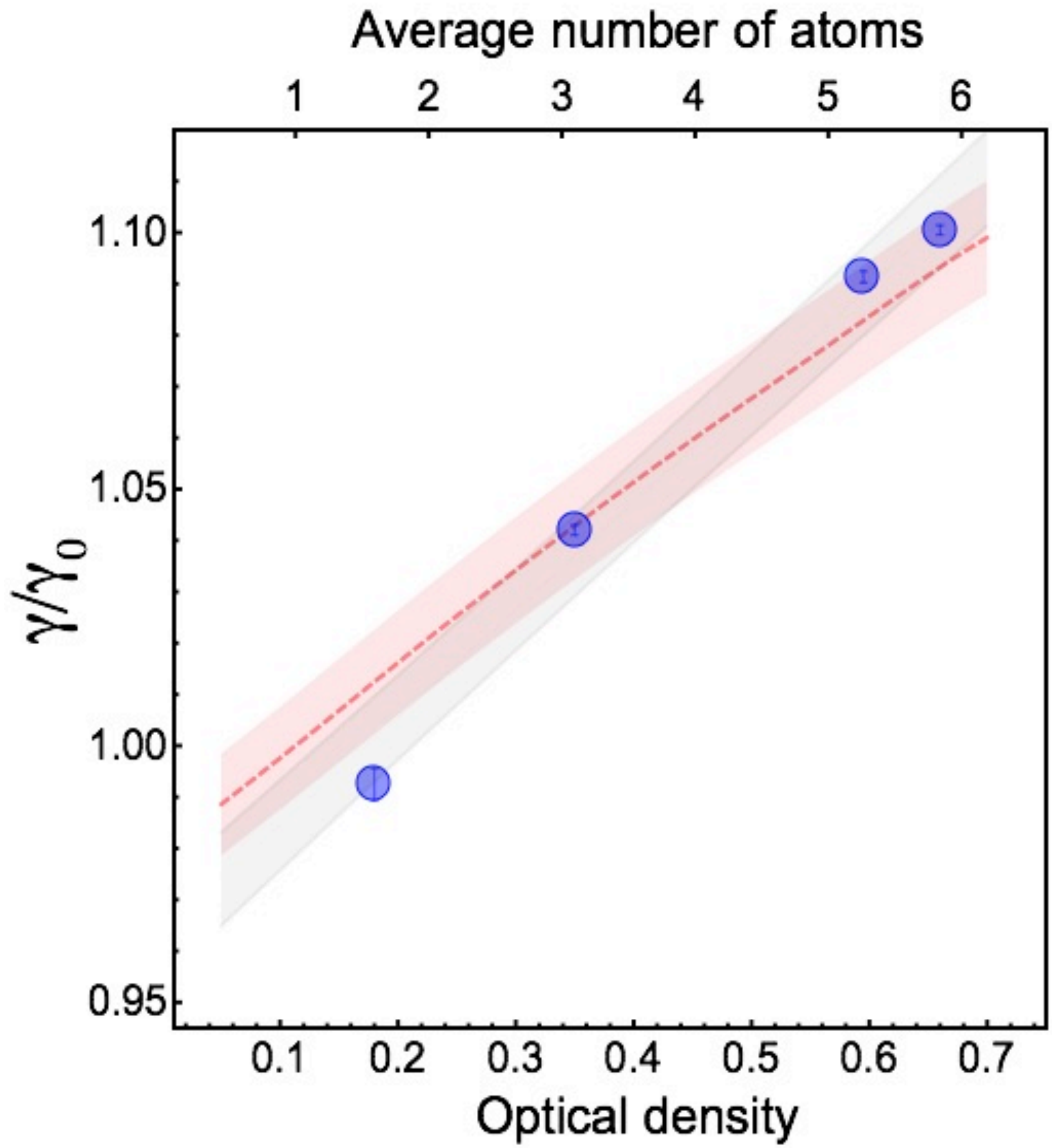
- Interaction distance smaller than λ: all modes get enhanced.
- Interaction distance greater than λ: only one mode gets enhanced $$\gamma_{\mathrm{sup}} = \gamma_{rad} + N\gamma_{1D}$$

We measure $$\gamma_{\mathrm{sup}} = 1.1\gamma_0$$

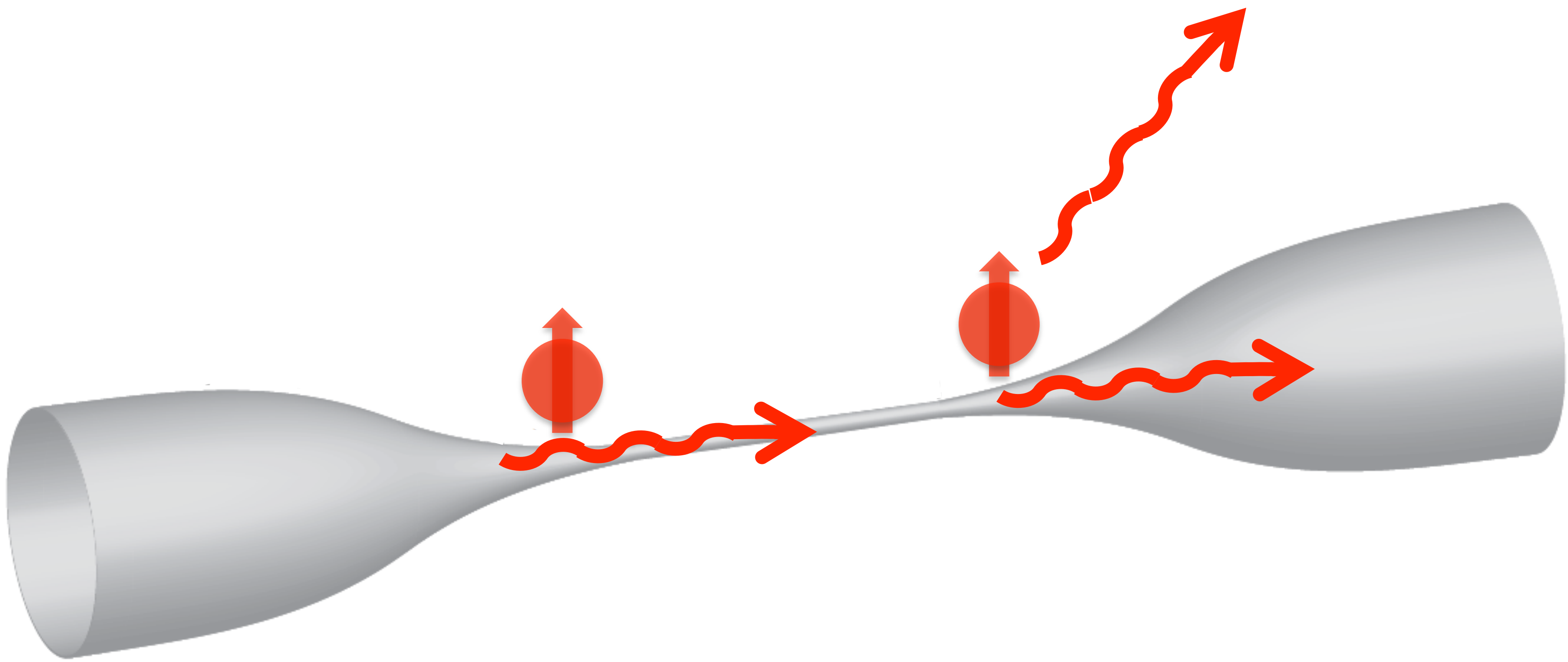
Fitting the Simulation (Monte Carlo)



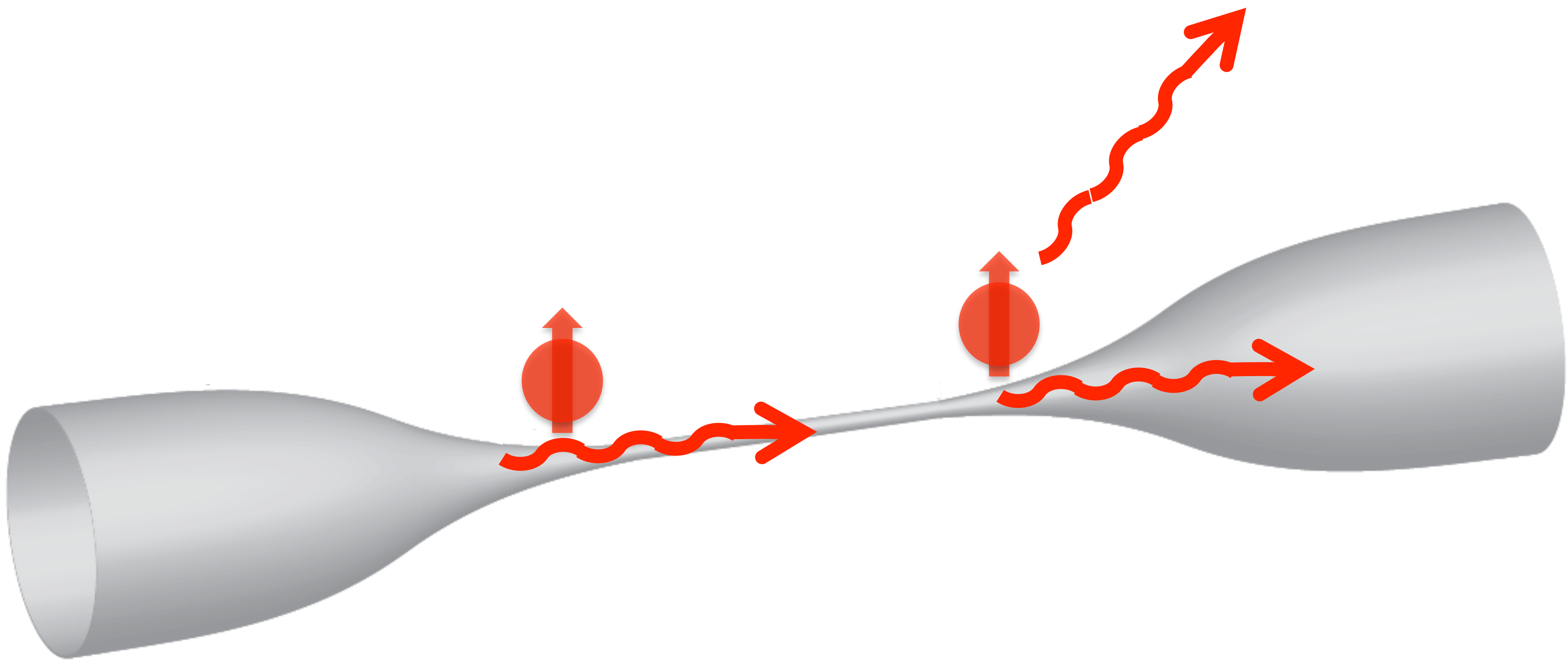
Fitting the Simulation



Long distance modification of the atomic radiation

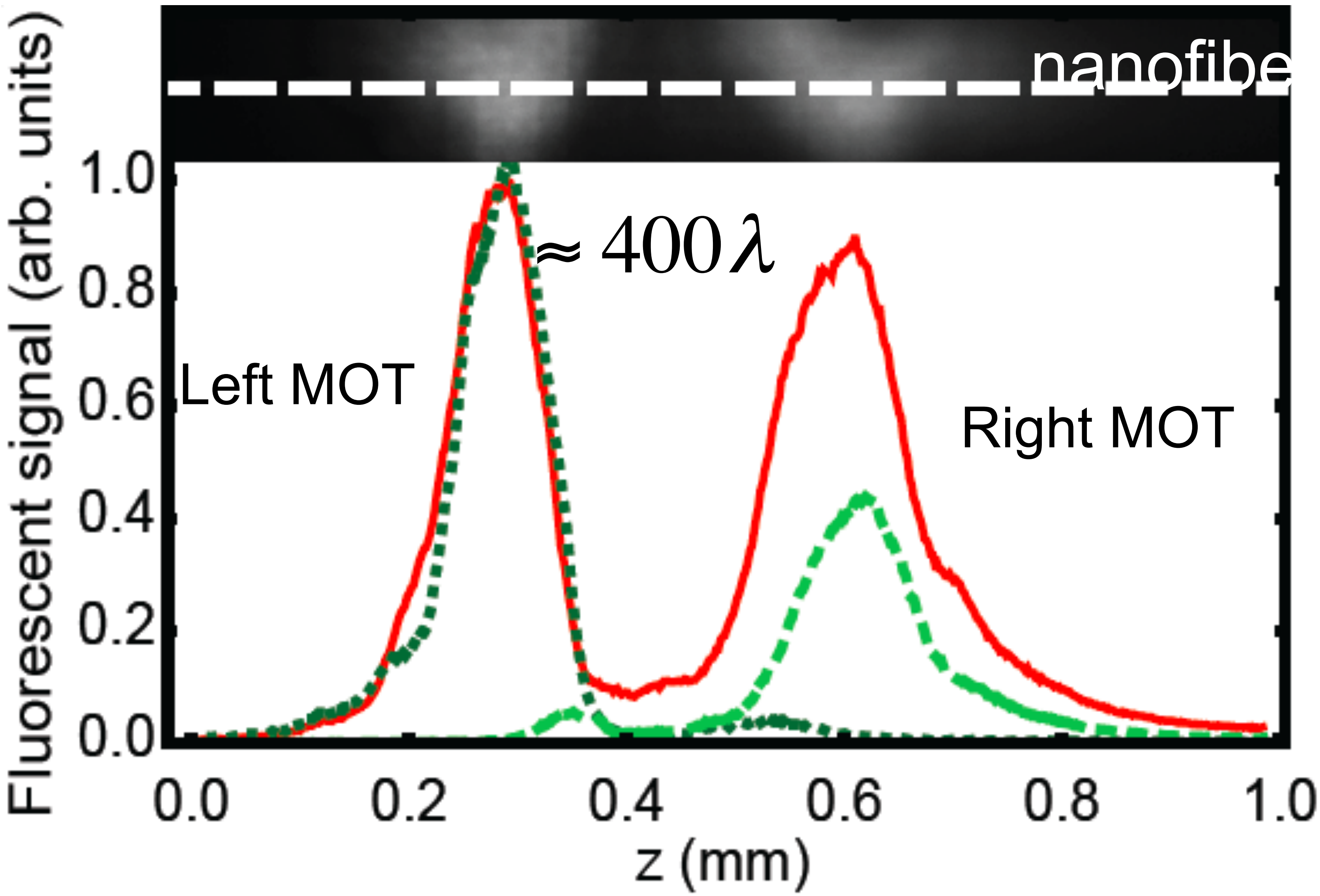


Long distance modification of the atomic radiation



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

Splitting the MOT in two



Evidence of infinite-range interactions