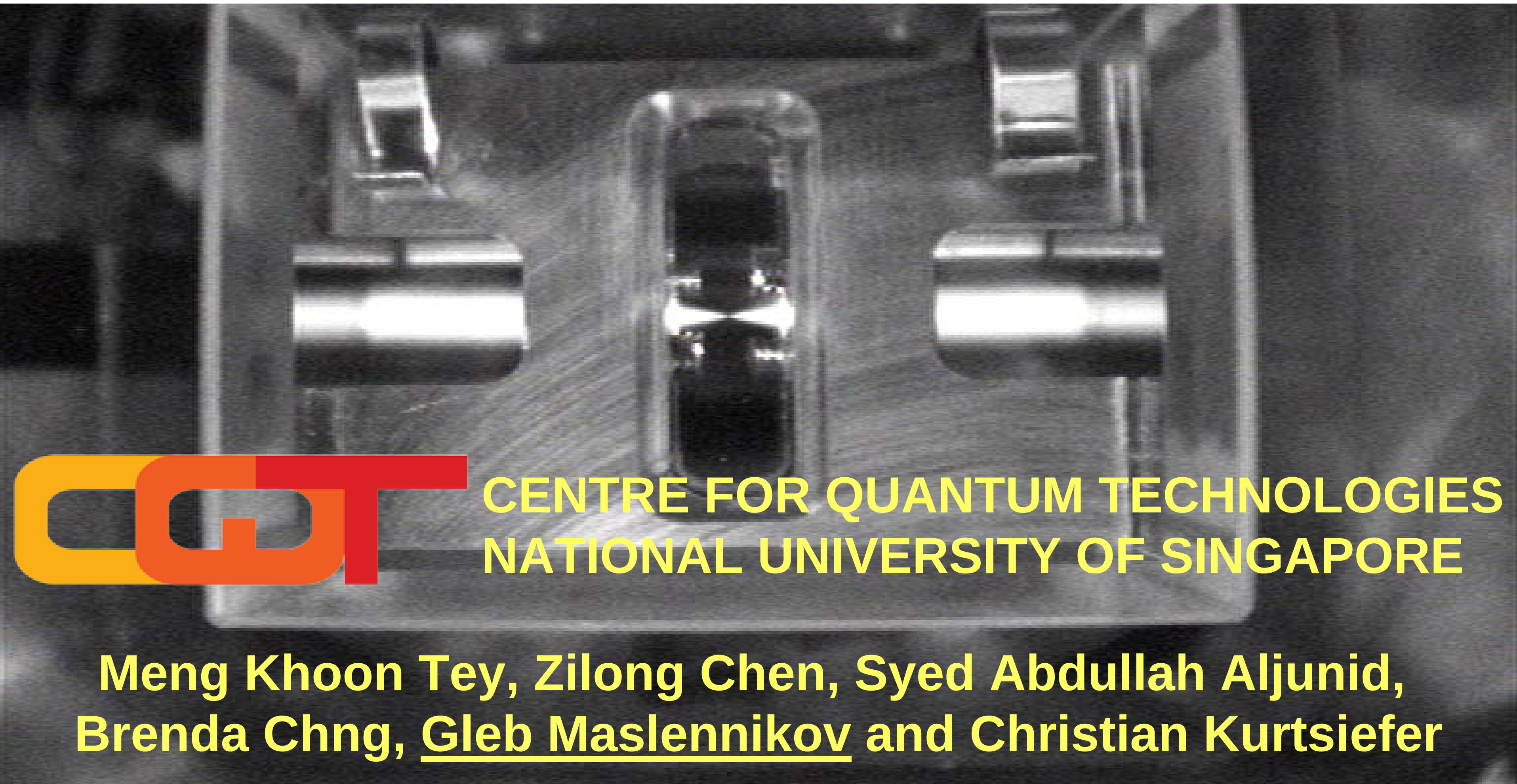
STRONG INTERACTION BETWEEN LIGHT AND SINGLE TRAPPED ATOM WITHOUT A CAVITY



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Motivation

Light-Atom Interface for Quantum Information

quantum repeaters & quantum memory

(J. I. Cirac et. al, *PRL*, 78, 3221, L. M. Duan et. al, *Nature*, 414, 413)

conditional phase gates on photonic qubits

(S. M. Savage et. al, *Opt.Lett, 15, 628*)

Precision Spectroscopy with Cold Atoms

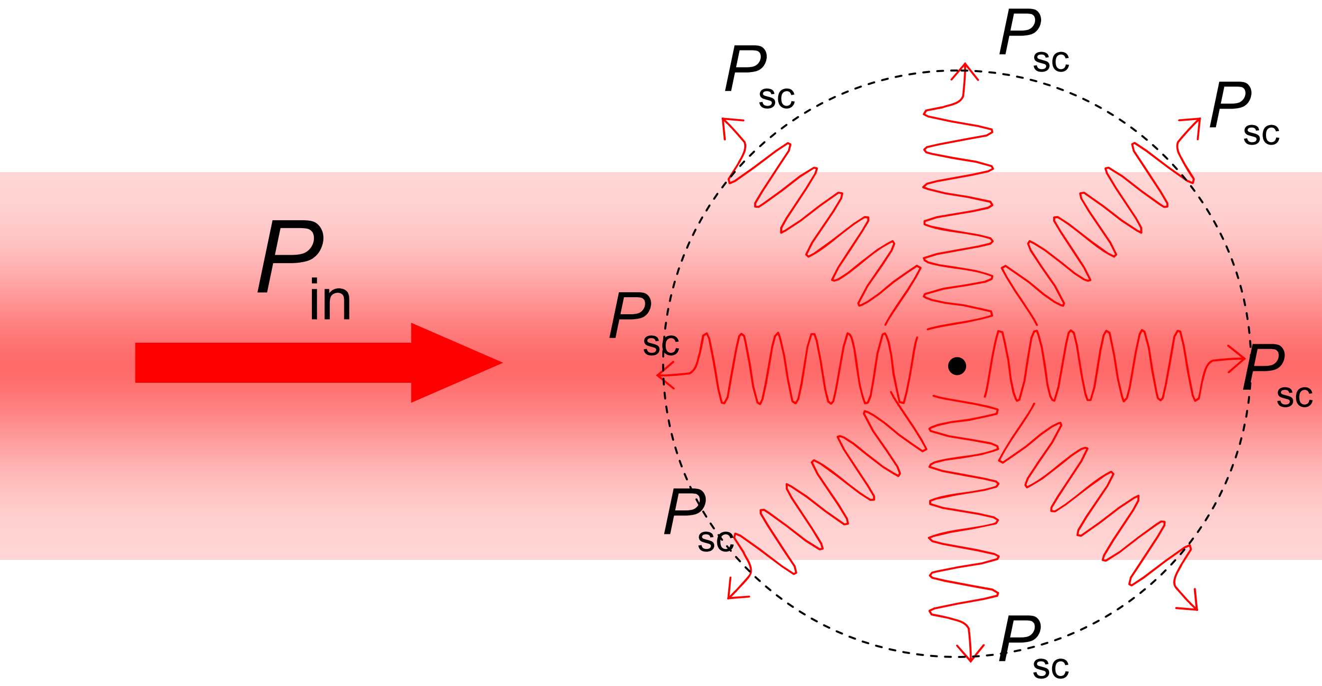
determination of atomic polarizabilities

(B. Arora et. al, *PRA*, 76, 052616, M. Safronova, et. al, *PRA*, 73, 022505)

atomic response to the excitation profile

(P.V. Elyutin, arXiv:quant-ph/0802.0913, E. S. Kyoseva et al, *PRA,* 73, 023420)

Physical System: Atom in a Light Field

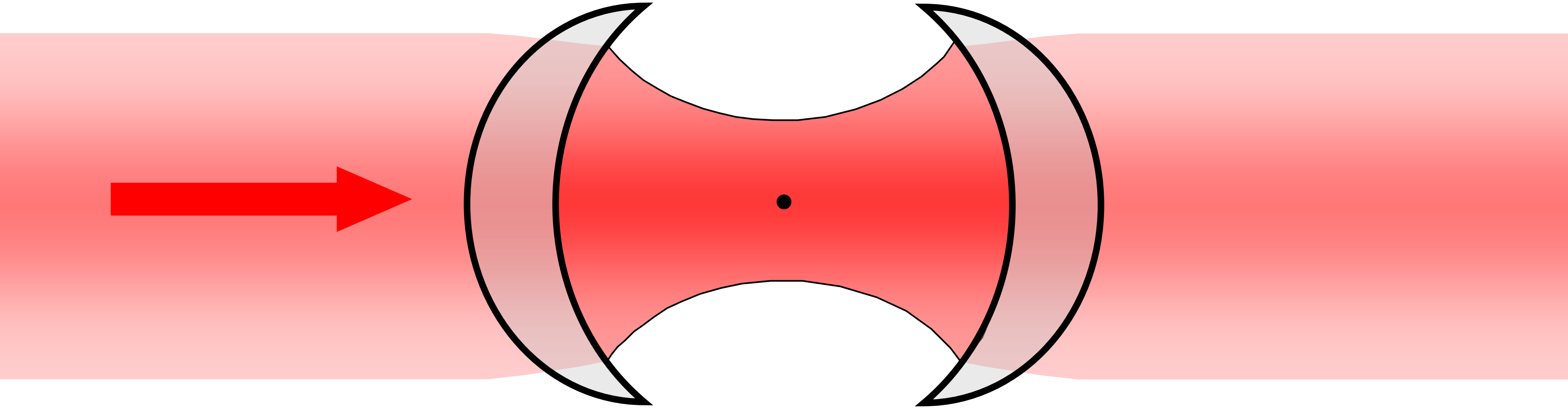


The scattering probability $p_{sc} = \dfrac{P_{sc}^{tot}}{P_{in}}$

Concentration of the incoming field
at the position of the atom is necessary!

Physical System: Atom in a Light Field

One solution: use a high-finesse cavity around the atom

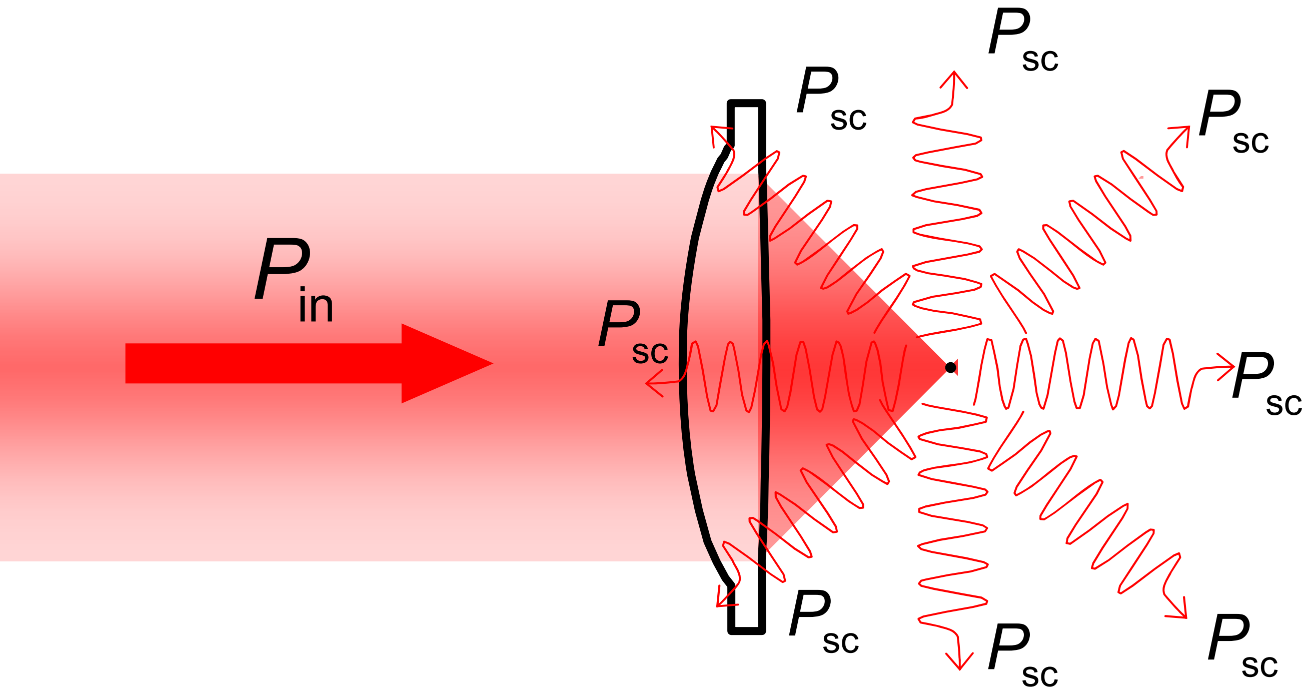


Many ongoing experiments

CalTech, Univ. of Georgia, Max-Planck-Institute, etc…

Physical System: Atom in a Light Field

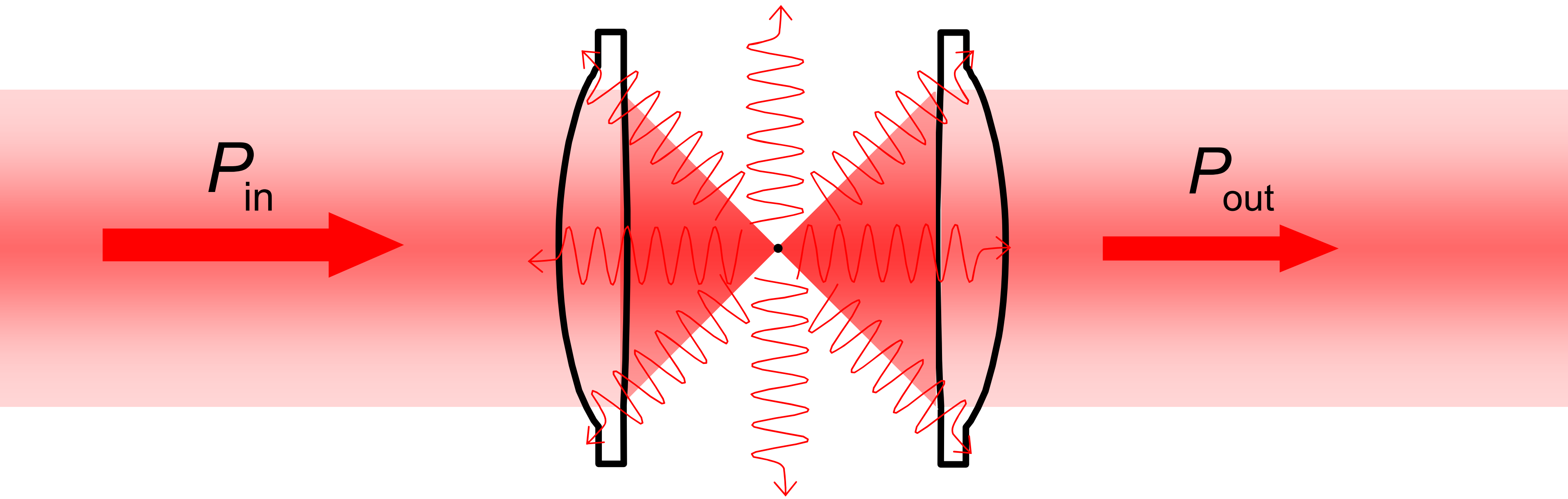
Or just use a lens to focus the beam to the atom



$$p_{sc} = \frac{P_{sc}^{tot}}{P_{in}}$$

Hard to obtain P_{sc}^{tot}, need a detector, covering 4π solid angle

Physical System: Atom in a Light Field



Relate P_{sc} to the transmission of the probe through the atom

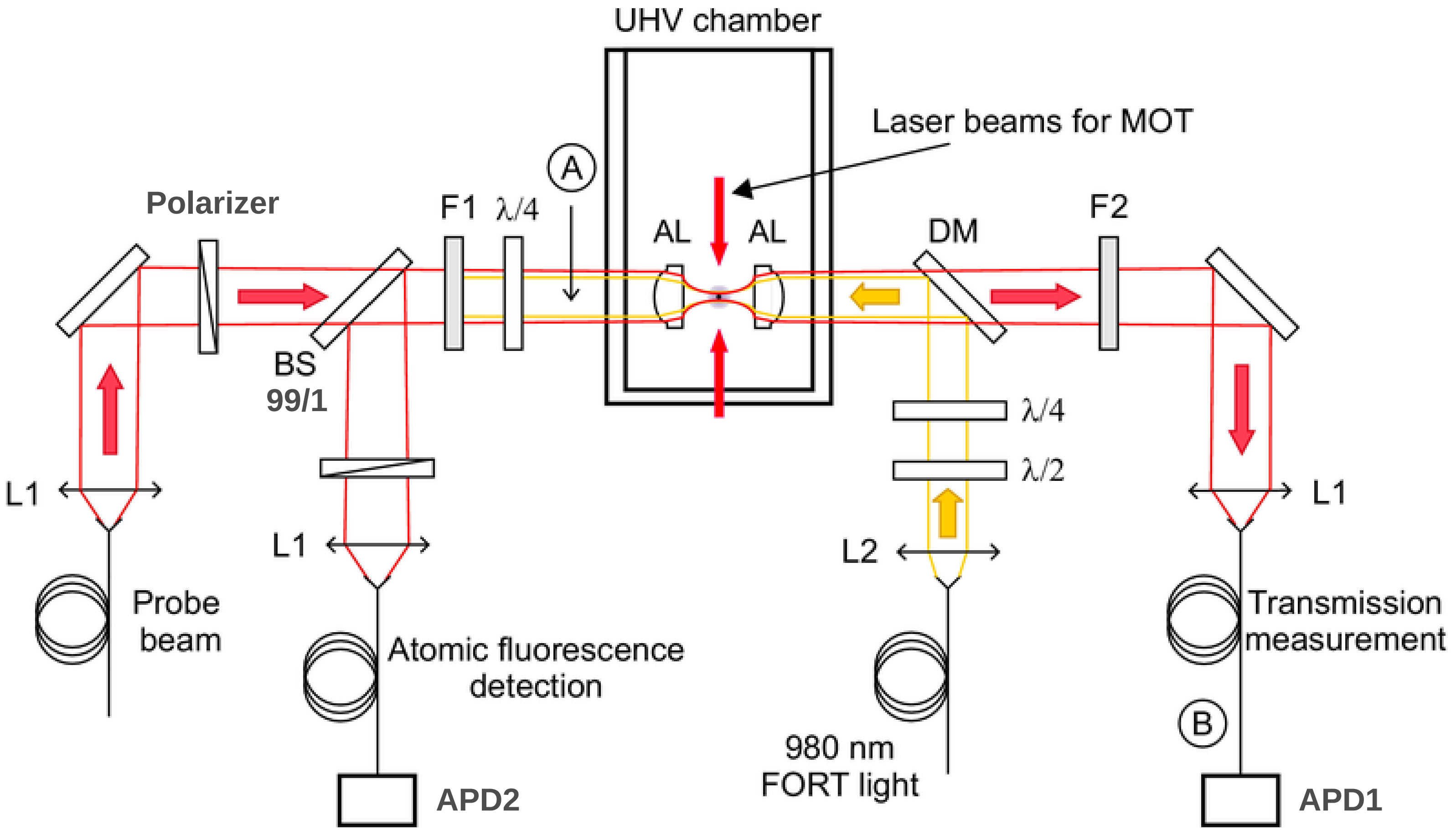
$$T = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_{sc} + \alpha P_{sc}}{P_{in}}$$

$$p_{sc} = \frac{1-T}{1-\alpha}$$

If α (collection efficiency) is small

$$p_{sc} \simeq 1 - T$$

Experimental Setup

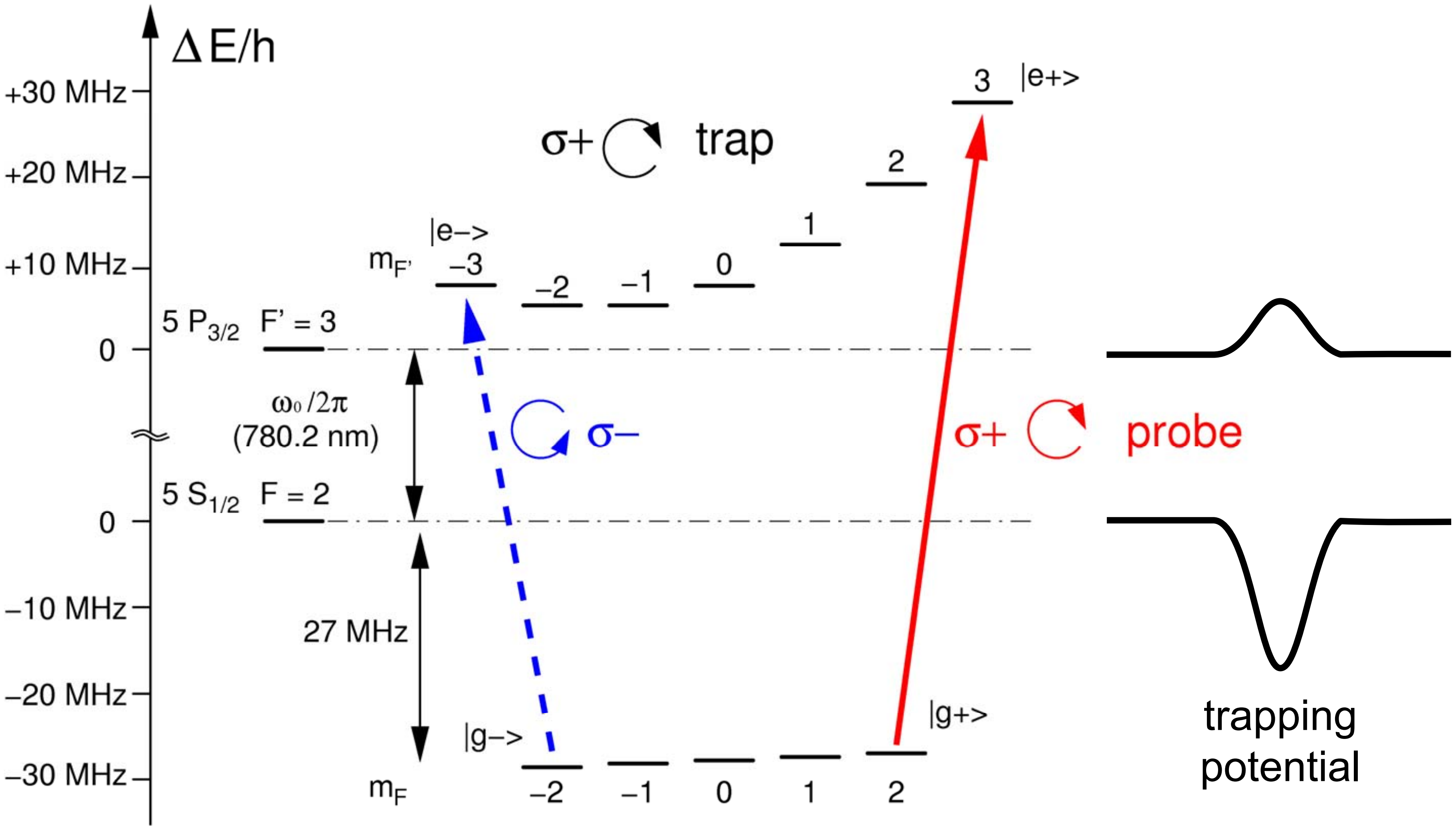


AL – aspheric lenses (*f* = 4.5 mm, full NA = 0.55),
DM – dichroic mirror, F1 – filters to block 980 nm light,

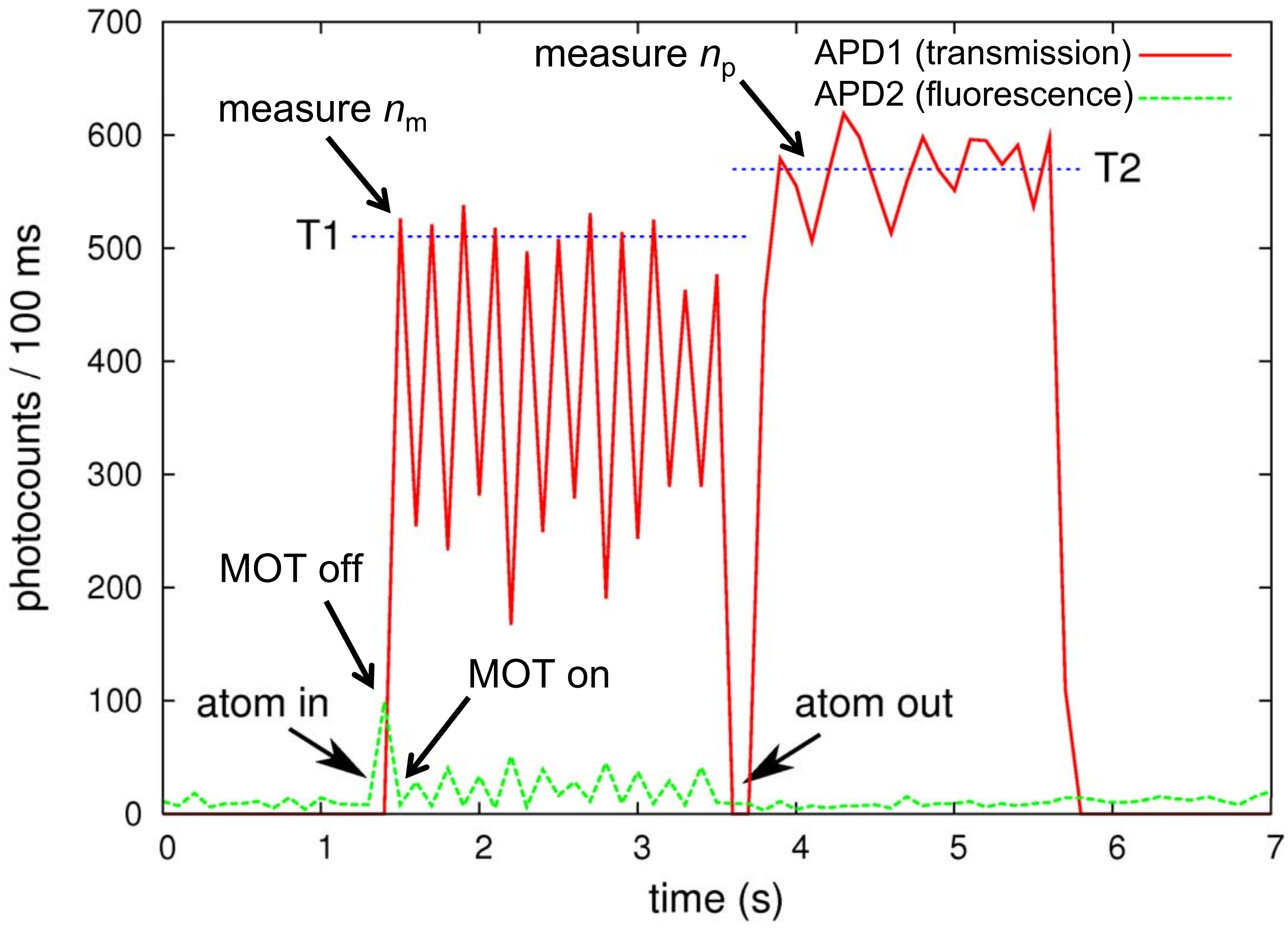
Losses: 55% transmission from Ⓐ to Ⓑ
dominated by reflection loss at optical surfaces

^{87}Rb Atom in the Optical Dipole Trap: AC Stark shift

Dipole trap laser wavelength: 980 nm

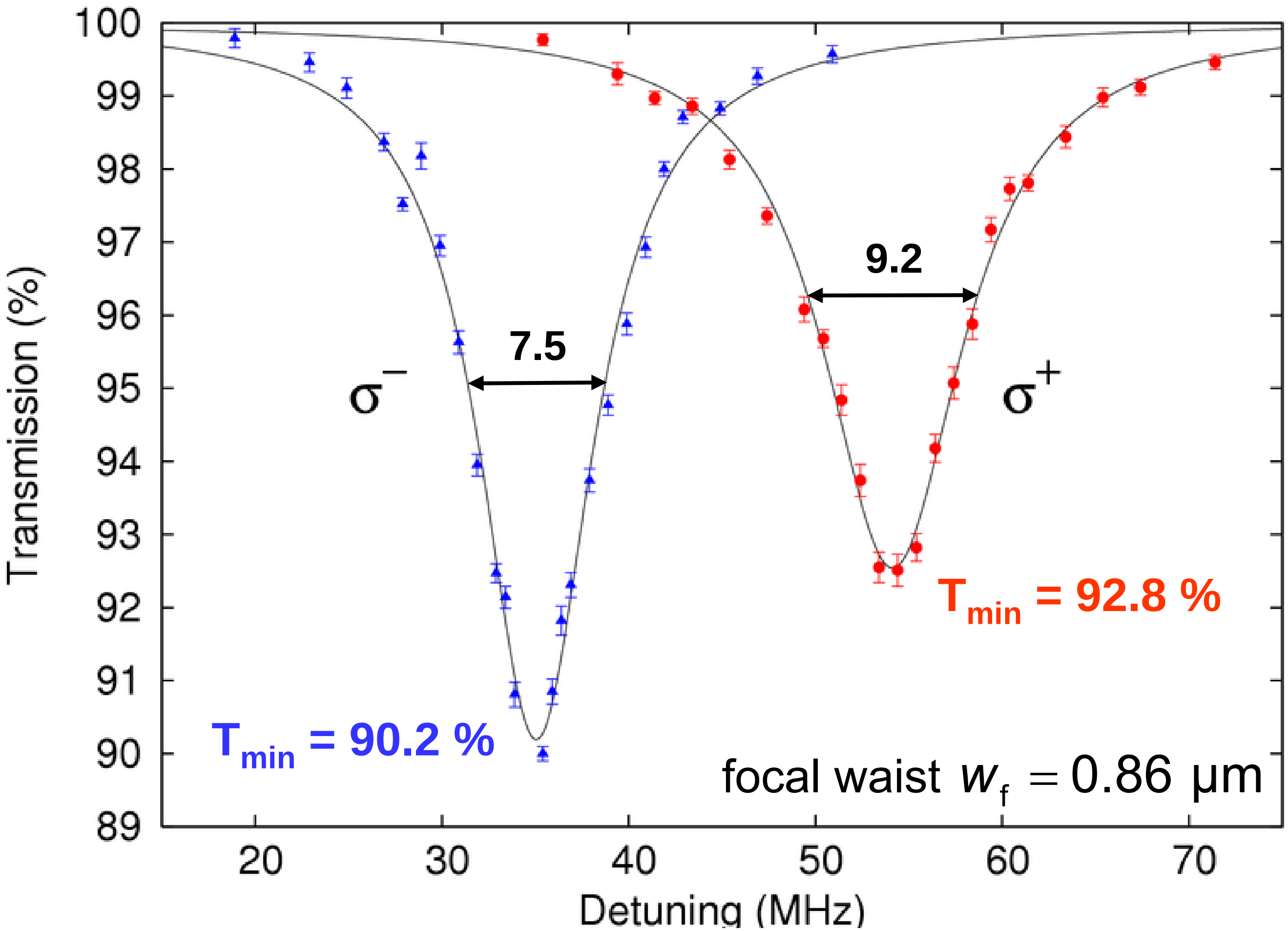


Experimental Procedure



$$T = \frac{T_1}{T_2} = \frac{\sum n_m}{\sum t_m} \frac{t_p}{n_p}$$

Experimental Results



Actual scattering rate

2500 photons s^{-1}

Natural linewidth

6 MHz

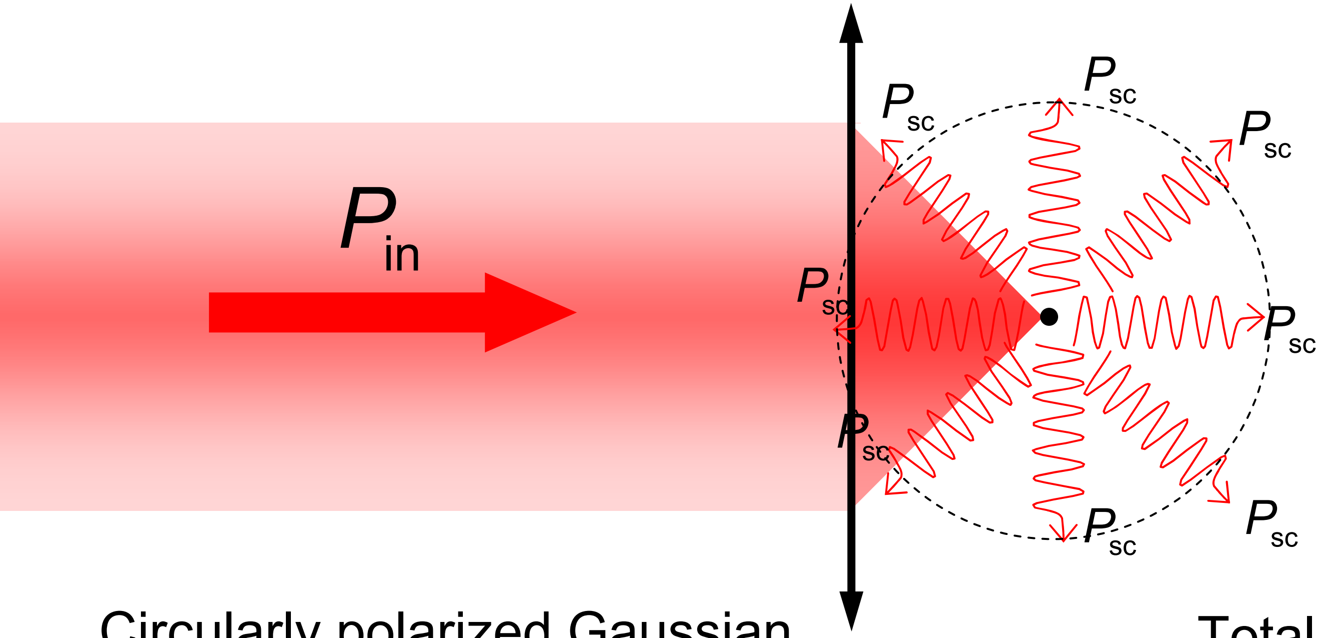
Collection efficiency

α ~ 5%, so p_{sc} ≈ 9.8%

Resonance frequency depends on the AC Stark shift of the energy level

Infer polarizability!

Theoretical model



Circularly polarized Gaussian beam at the lens

$$P_{in} = \frac{1}{4}\varepsilon_0 \pi c E_L^2 w_L^2$$

Total power scattered by a two-level atom

$$P_{sc} = \frac{3\varepsilon_0 c \lambda^2 E_A^2}{4\pi}$$

$$p_{sc} \equiv \frac{P_{sc}}{P_{in}} = \frac{3\lambda^2}{\pi^2 w_L^2}\left(\frac{E_A}{E_L}\right)^2$$

Theoretical model

$$p_{sc} = \frac{3\lambda^2}{\pi^2 w_L^2}\left(\frac{E_A}{E_L}\right)^2$$

1. Paraxial approximation $\left(\frac{E_A}{E_L}\right)^2 = \left(\frac{w_f}{w_L}\right)^2$ $\quad p_{sc} = \frac{3\lambda^2}{\pi^2 w_f^2}$

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Inappropriate for strong focusing regime

Theoretical model

$$p_{sc} = \frac{3\lambda^2}{\pi^2 w_L^2}\left(\frac{E_A}{E_L}\right)^2$$

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2. Decomposition of the field into modes with cylindrical symmetry and model the action of the lens as a local phase shifter of the wavefront curvature (S. J. van Enk and H. J. Kimble, PRA, **63**, 023809)

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Original paper

parabolic wave front after the lens

Allows analytical integration for field decomposition

Does not efficiently concentrate the incoming energy at the focus for strong focusing regime

Theoretical model

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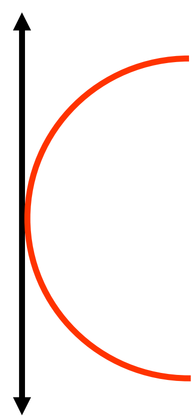
Our contribution

spherical wave front after the lens

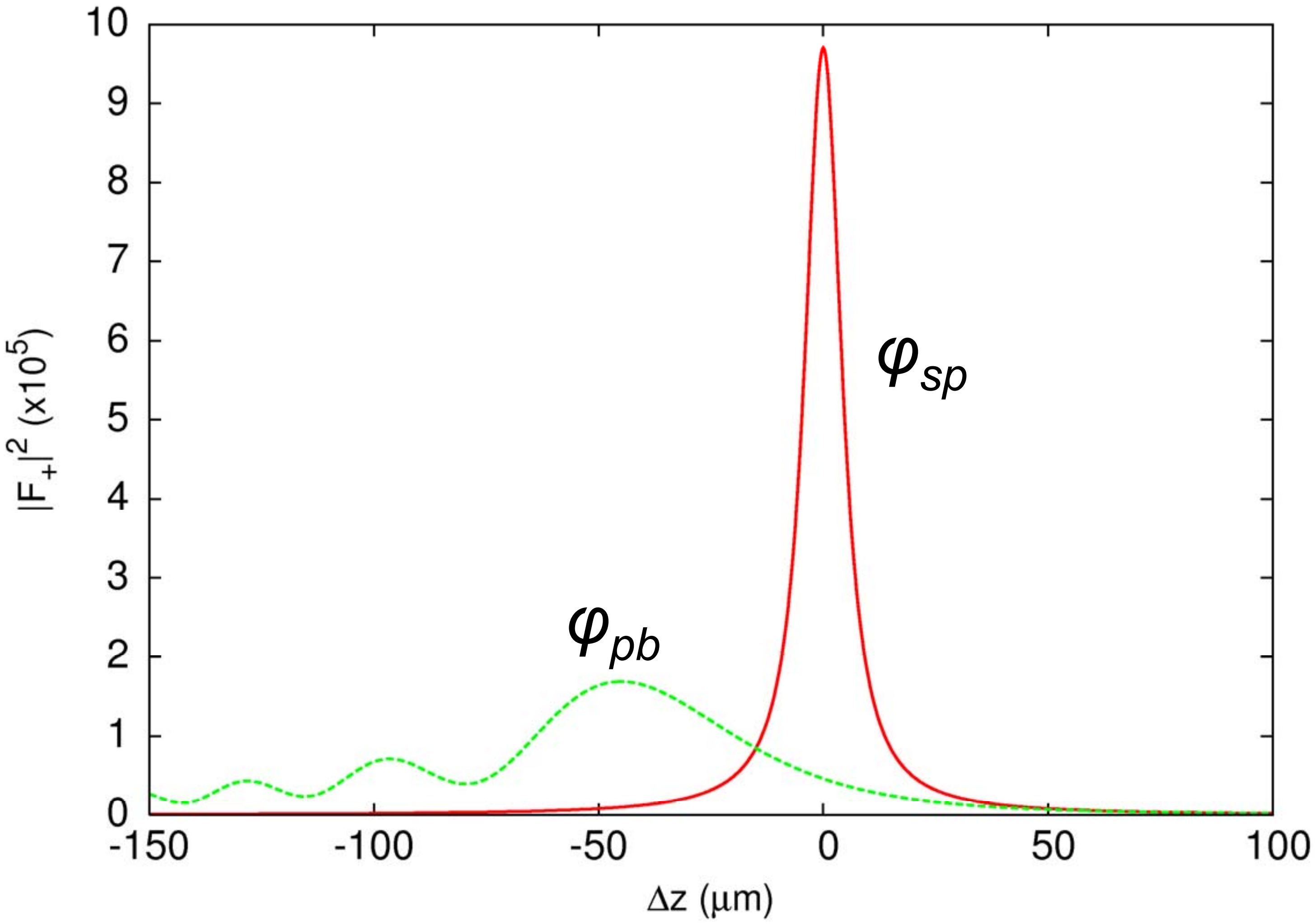


Numerical calculations required

Efficiently concentrates the incoming field at the focus

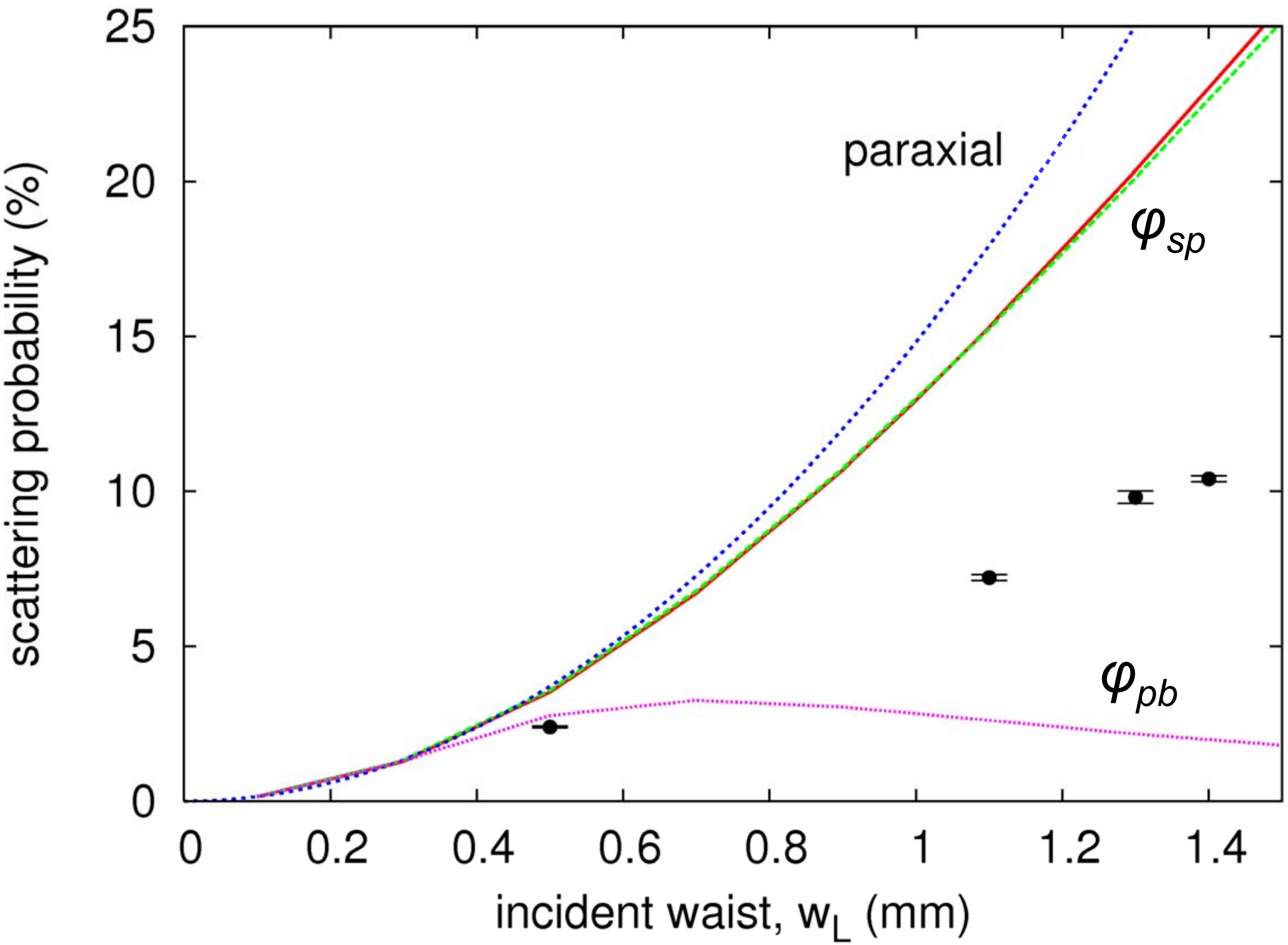
Theoretical model

Comparison of field strengths at the focus, calculated with parabolic (φ_{pb}) and spherical (φ_{sp}) phase factors for our experimental parameters



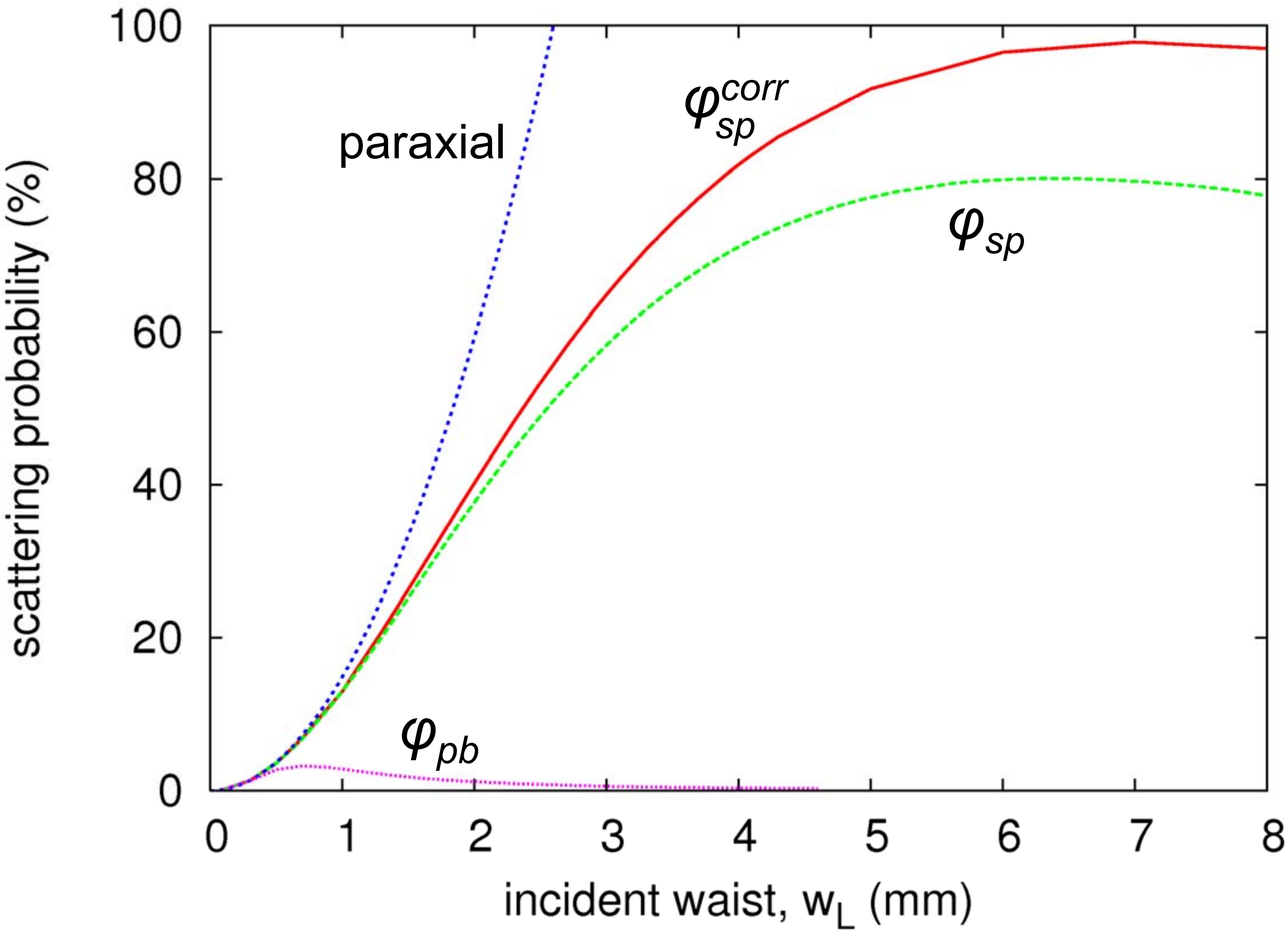
Comparison of experiment and theory

Scattering probability dependence on the input waist of the Gaussian beam for the lens used in our experiment



Theoretical model

If one focuses stronger….



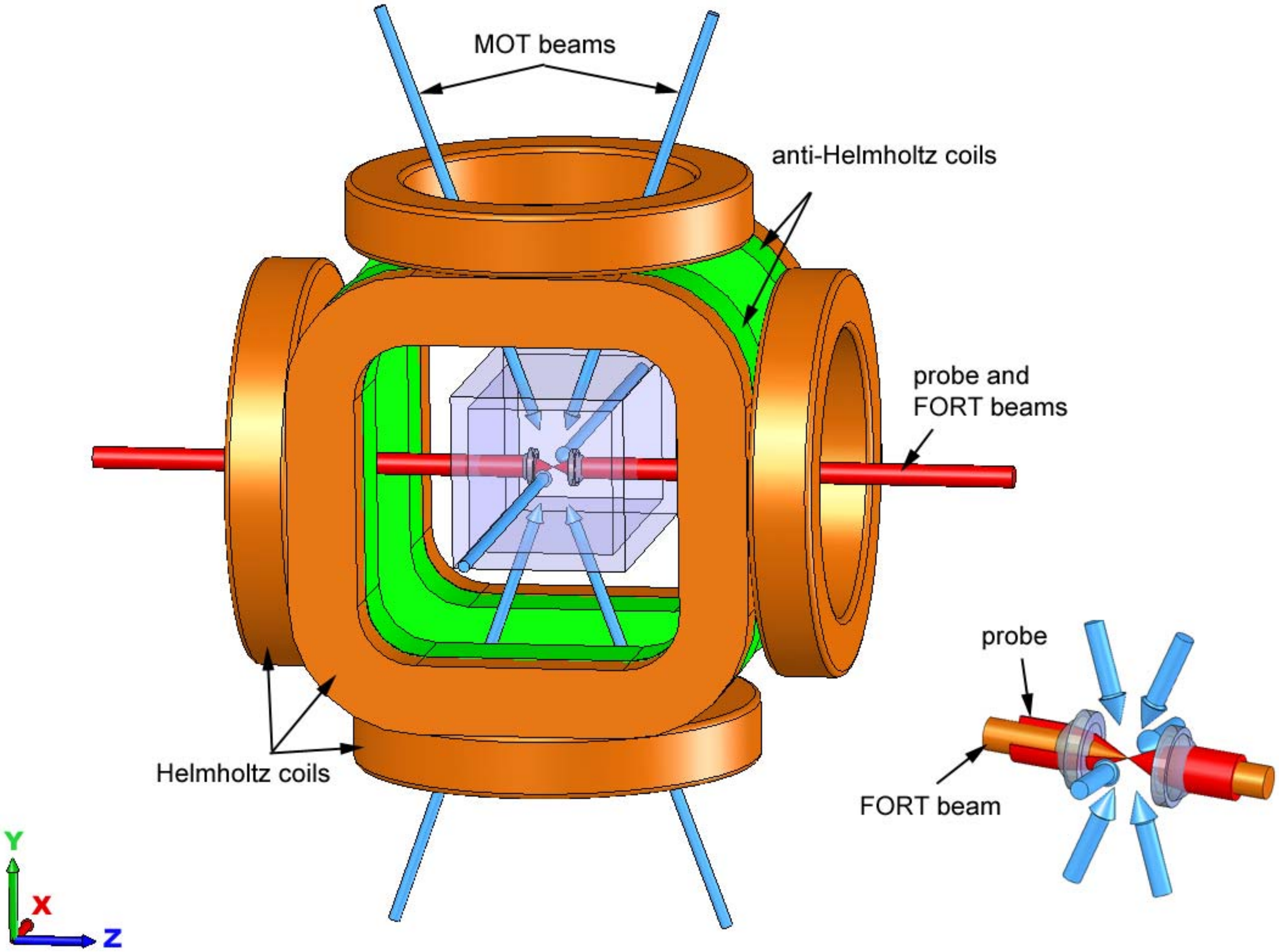
Conclusions

Substantial scattering probability can be achieved for a focused coherent light beam!

Experiment: scattering probability of 10.4 % was directly measured for the maximum focusing achievable with current lens setup.

Theory: scattering probability up to 98% is predicted for lenses with realistic focal length.

Thank you for your attention!



Antibunching in single atom fluorescence