

Interfacing light and single atoms with a lens

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Atom-Photon interface



Motivation:

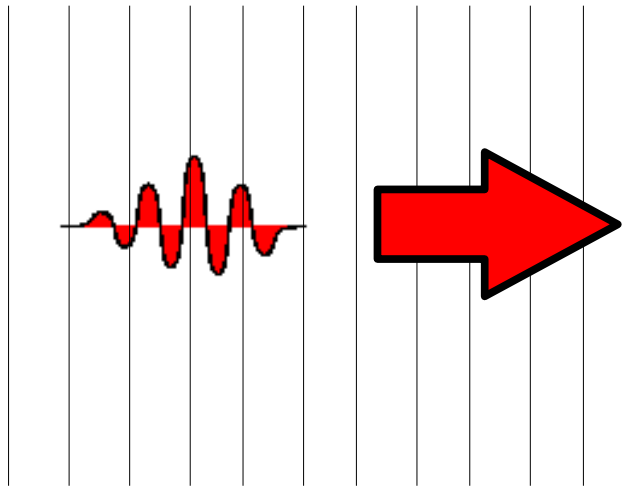
- Atoms and photons are good for different quantum information tasks – allow an exchange of quantum information between them
- Understand elementary interaction between flying qubits and single atoms
- Explore possibilities of controlled phase gates & friends for photonic qubits

Key idea:

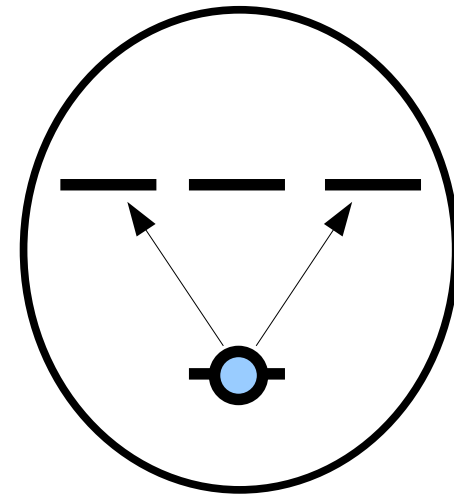
- Try to **mode-match** traveling qubit modes to field modes of spontaneous emission of a single atom

Why is this interesting?

- e.g. transfer of information from flying qubits into a quantum memory



$$|\Psi_L\rangle = \alpha|L\rangle + \beta|R\rangle$$

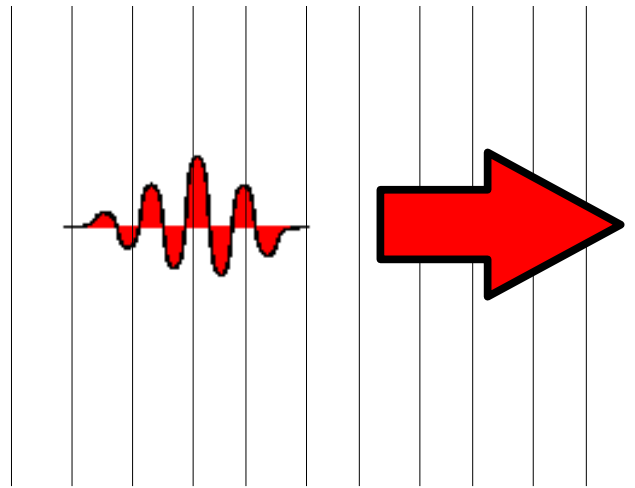


$$|\Psi_A\rangle = \alpha|m=-1\rangle + \beta|m=+1\rangle$$

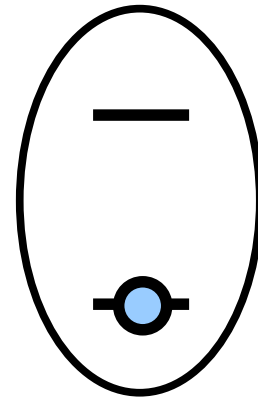
- requires internal states of atom and an **absorption process**

The basic problem

- Get strong coupling between an atom and a light field on the single photon level

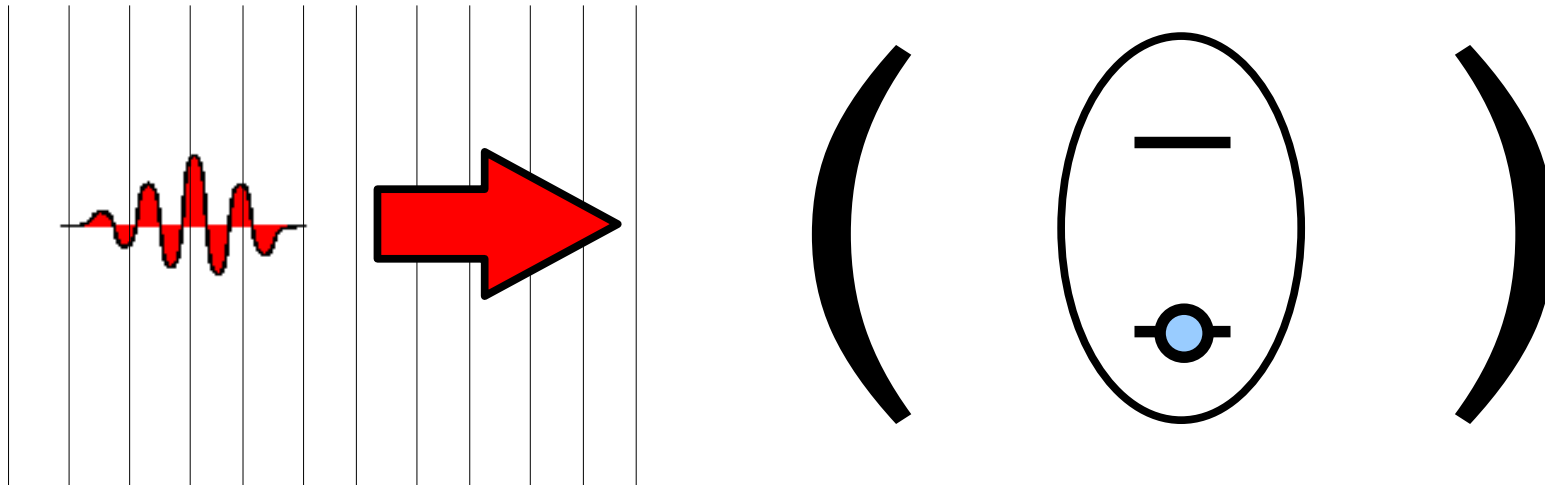


electromagnetic field / photon



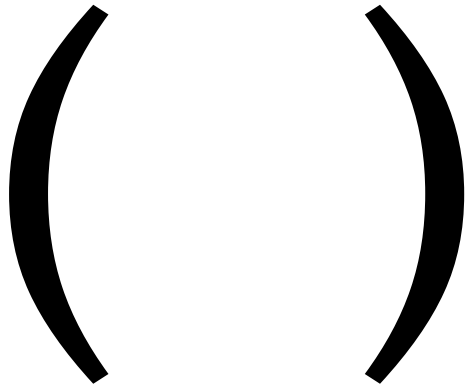
2-level atom

One solution: Use a cavity



- High electrical field strength even for a single photon
- Preferred spontaneous emission into the cavity mode
- A cavity can enhance the interaction between a propagating external mode and an atom

Why cavities are nice



- It's clear what photons in a cavity are
discrete mode spectrum, 'textbook' energy eigenstates for the electromagnetic field

$$\hat{H}_{field} = \frac{\epsilon_0}{2} \int (\hat{\mathbf{E}}^2 + c^2 \hat{\mathbf{B}}^2) dV = \hbar \omega (\hat{n} + \frac{1}{2})$$

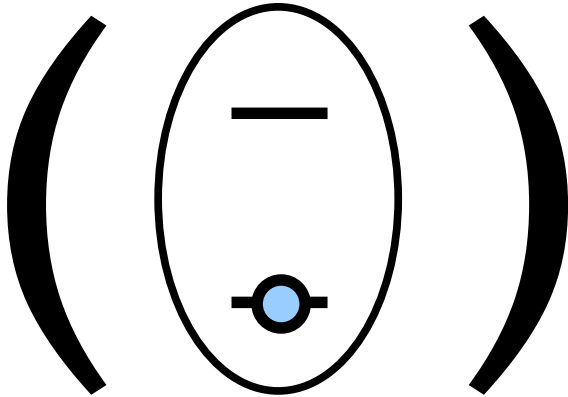
Electrical field operator (single freq):

$$\hat{\mathbf{E}}(x, y, z) = i \sqrt{\frac{\hbar \omega}{2\pi \epsilon_0 V}} (\mathbf{g}(x, y, z) \hat{a}^+ - \mathbf{g}^*(x, y, z) \hat{a})$$

mode function, e.g.

$$\mathbf{g}(x, y, z) = \mathbf{e} \sin kz e^{-\frac{x^2 + y^2}{w^2}}$$

Atom in a cavity



- atom Hamiltonian

$$\hat{H}_{atom} = E_g |g\rangle\langle g| + E_e |e\rangle\langle e|$$

- electric dipole interaction

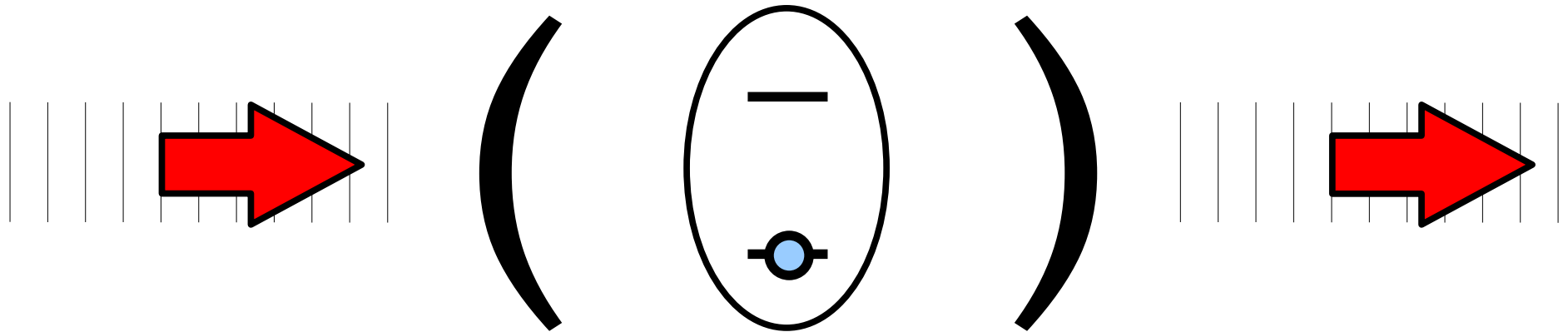
$$\hat{H}_I = \hat{\mathbf{E}} \cdot \hat{\mathbf{d}} \quad \text{with} \quad \hat{\mathbf{d}} = \mathbf{e} d_{eff} (|e\rangle\langle g| + |g\rangle\langle e|)$$

- (treat other field mode as losses)...

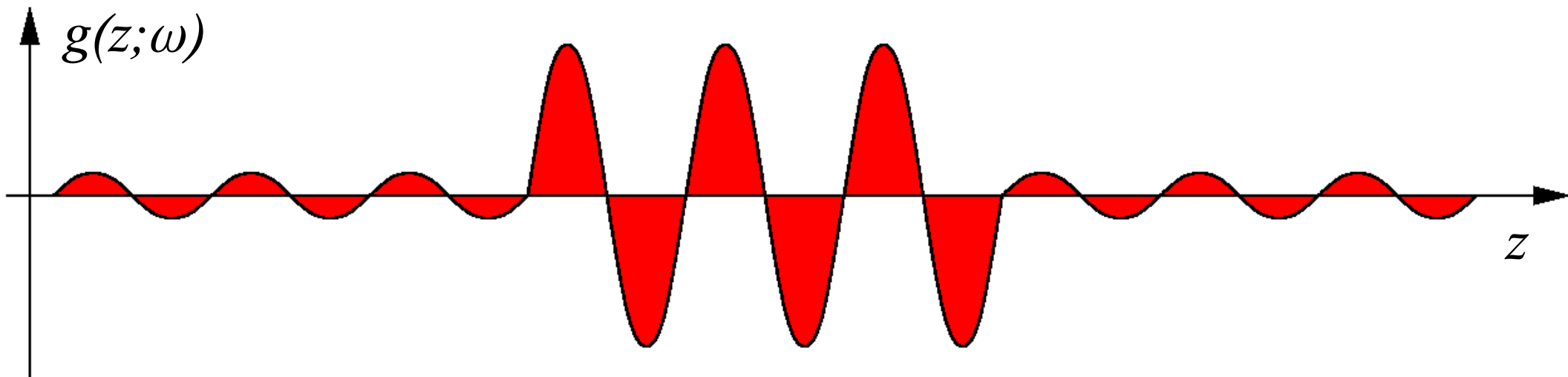
.....Jaynes-Cummings model with all its aspects

- treat external fields as perturbation/spectator of internal field

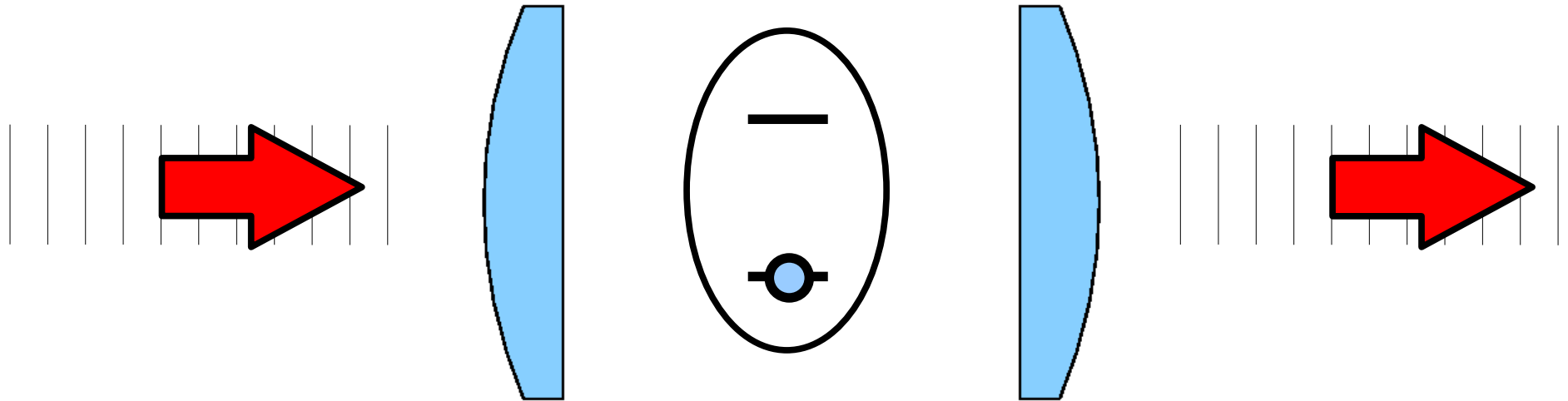
External view of cavity+atom



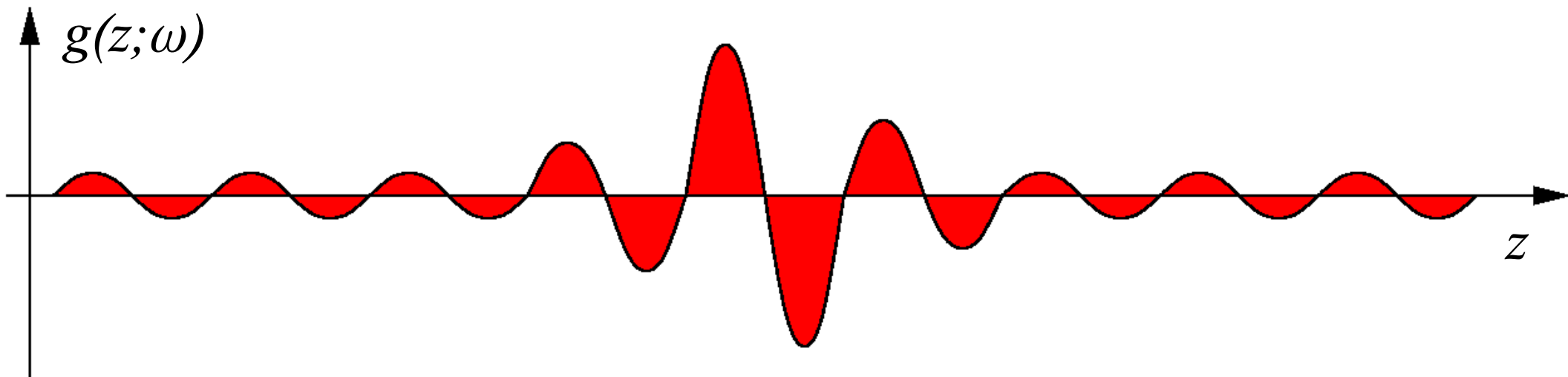
- continuous mode spectrum with enhanced/reduced field mode function:



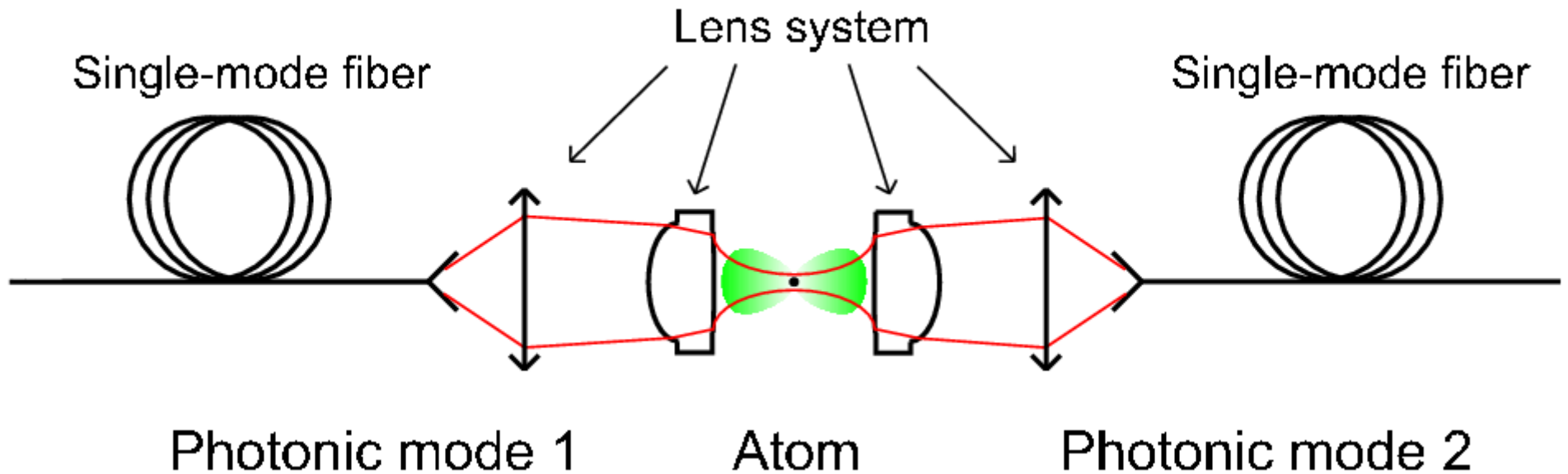
An alternative approach



- use a **focusing lens pair** to enhance center mode function:



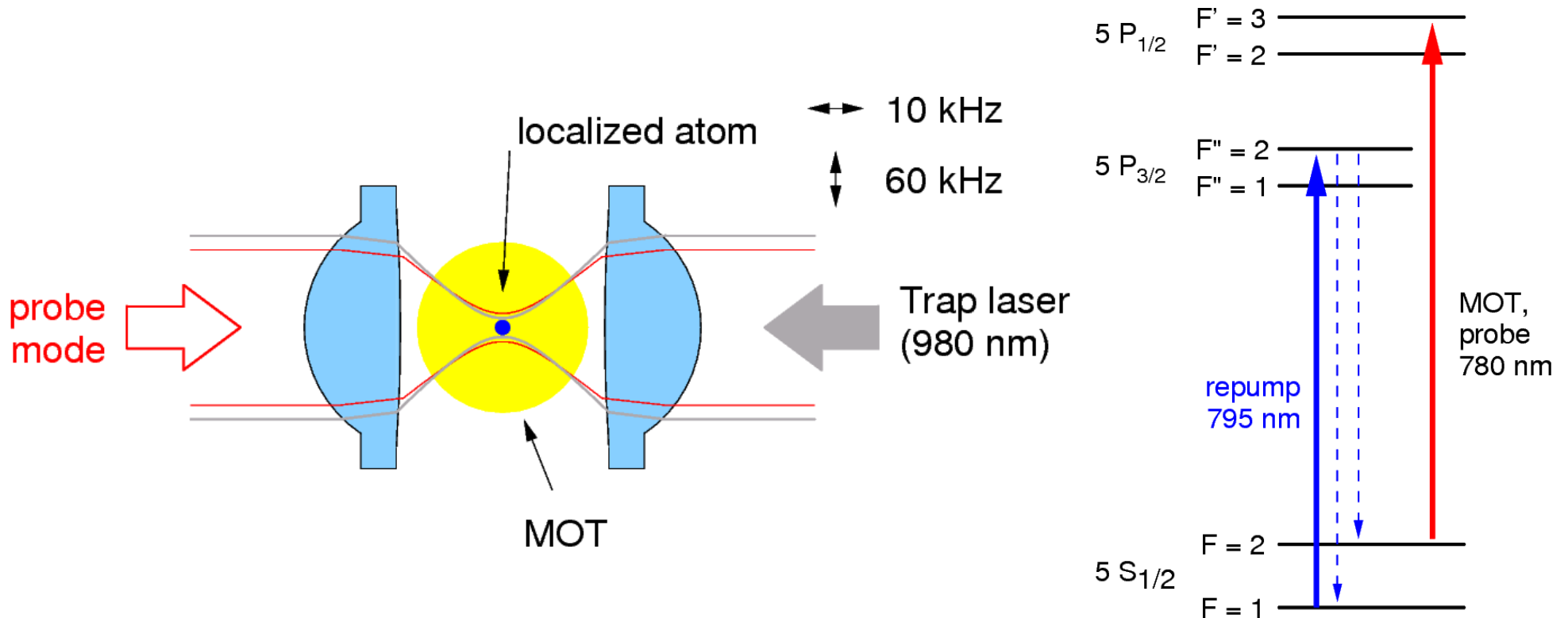
Concept of an experiment



- achieve a small focal spot
- = high central field amplitude
- = good mode match between atomic emission mode and propagating light field

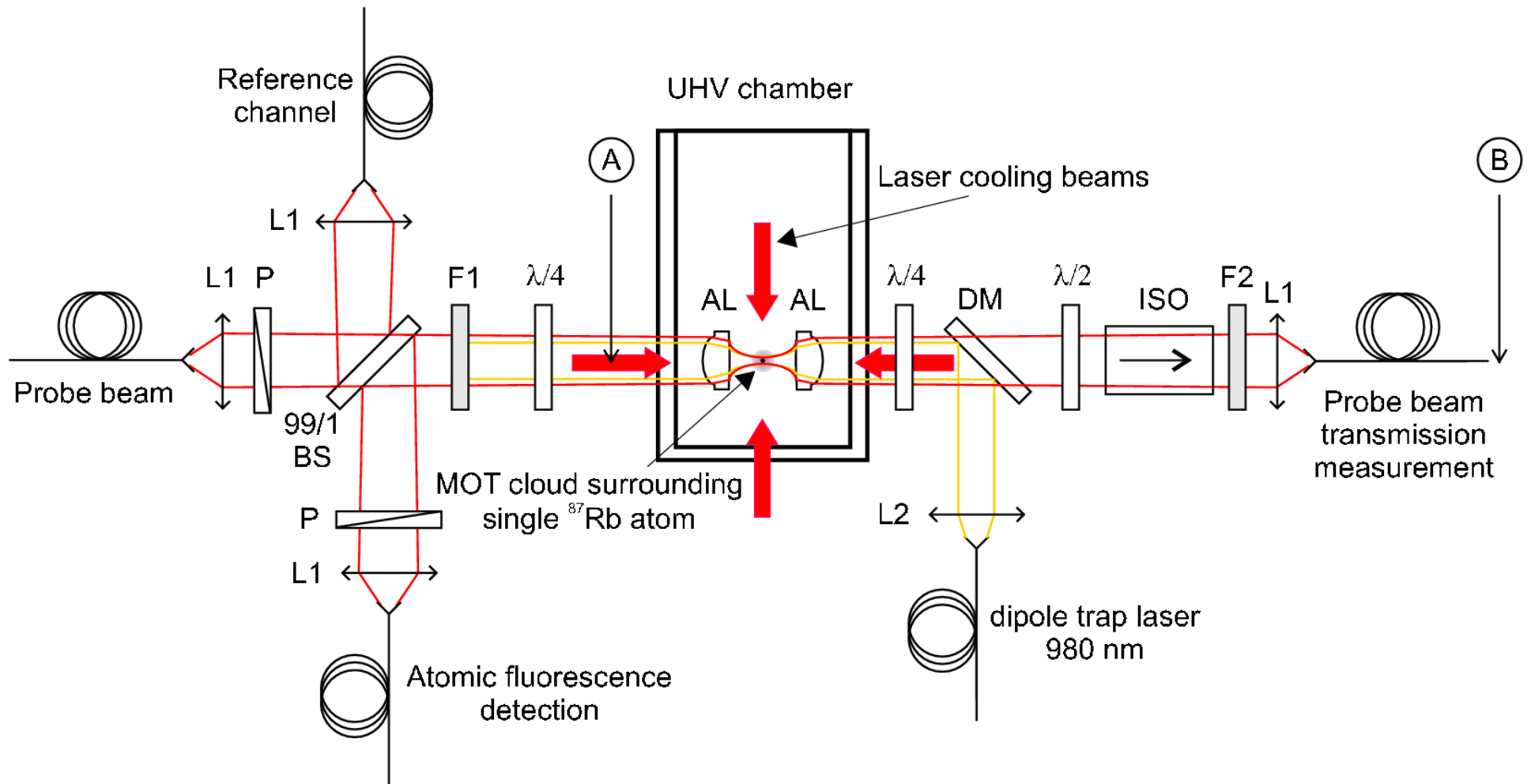
More technical details

One atom in an optical dipole trap, loaded from a MOT



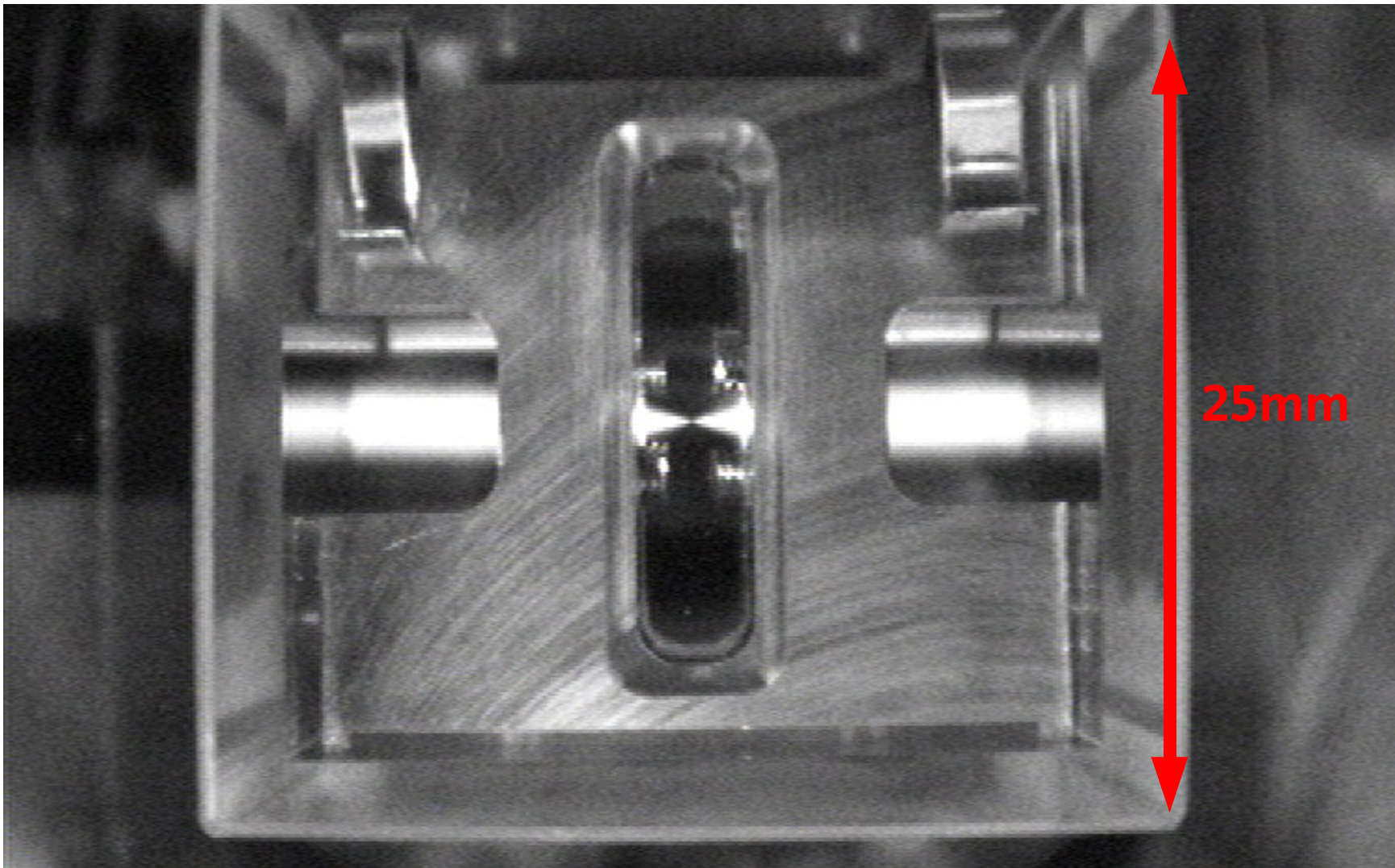
- use Rubidium-87 atom because it is convenient

Almost the real exp setup



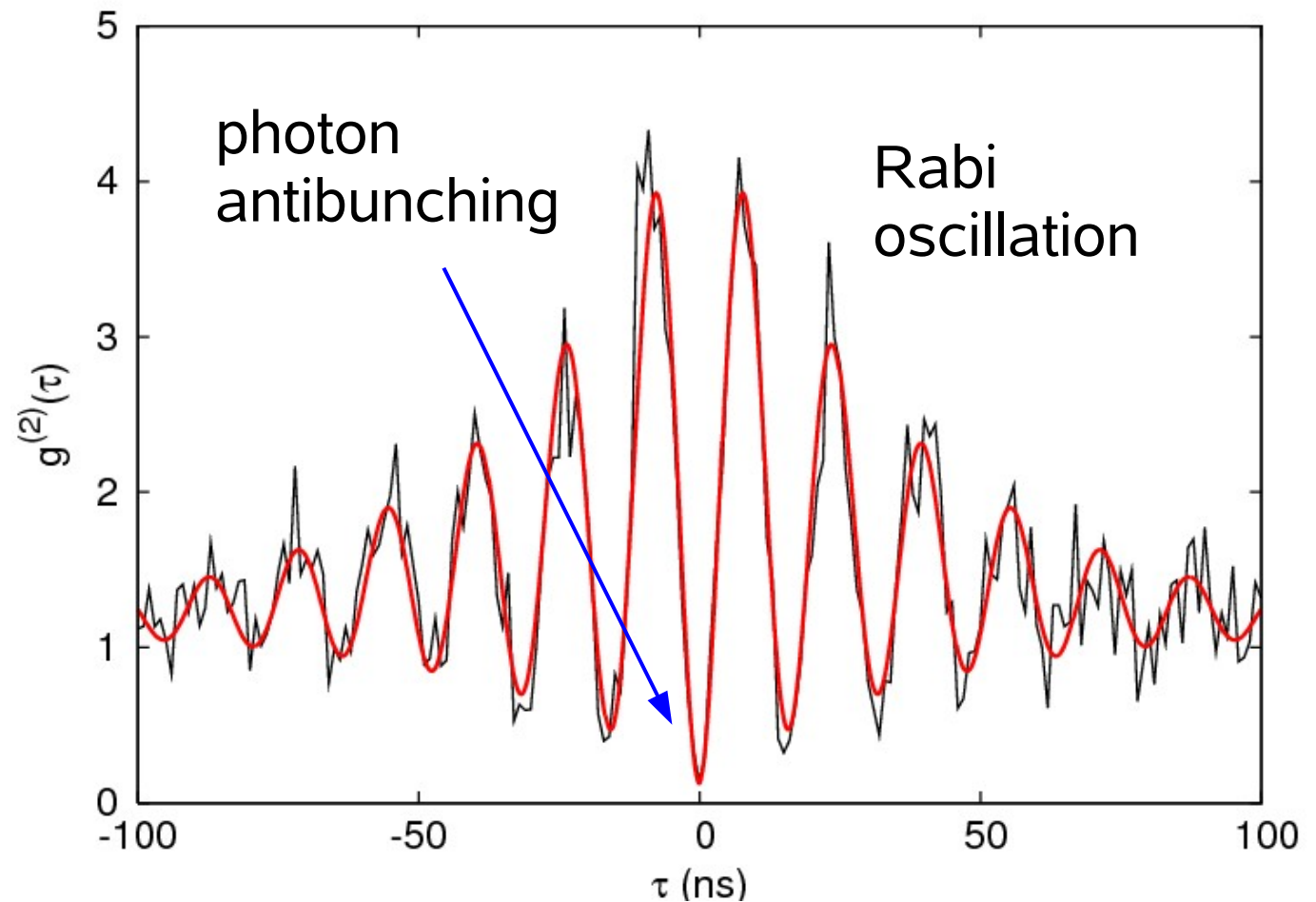
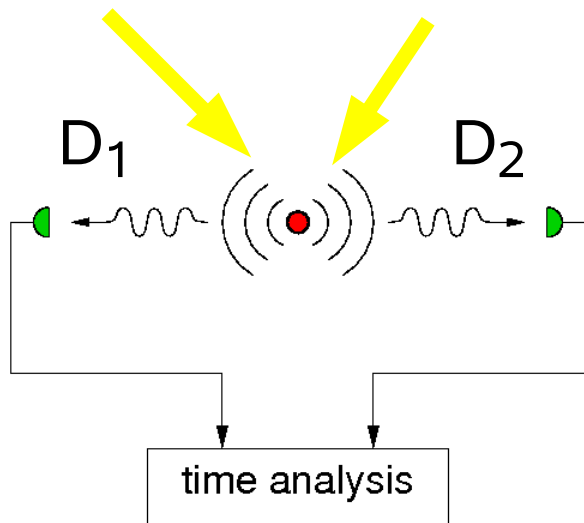
Focusing geometry...

...as seen by a CCTV camera at high Rb pressure

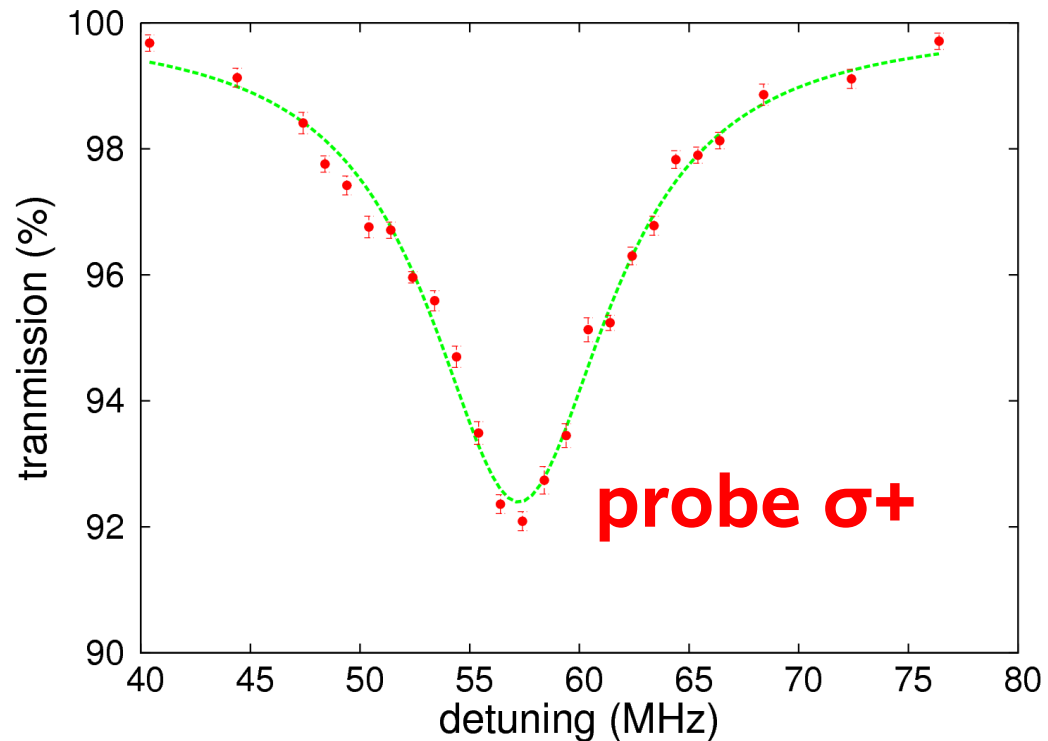
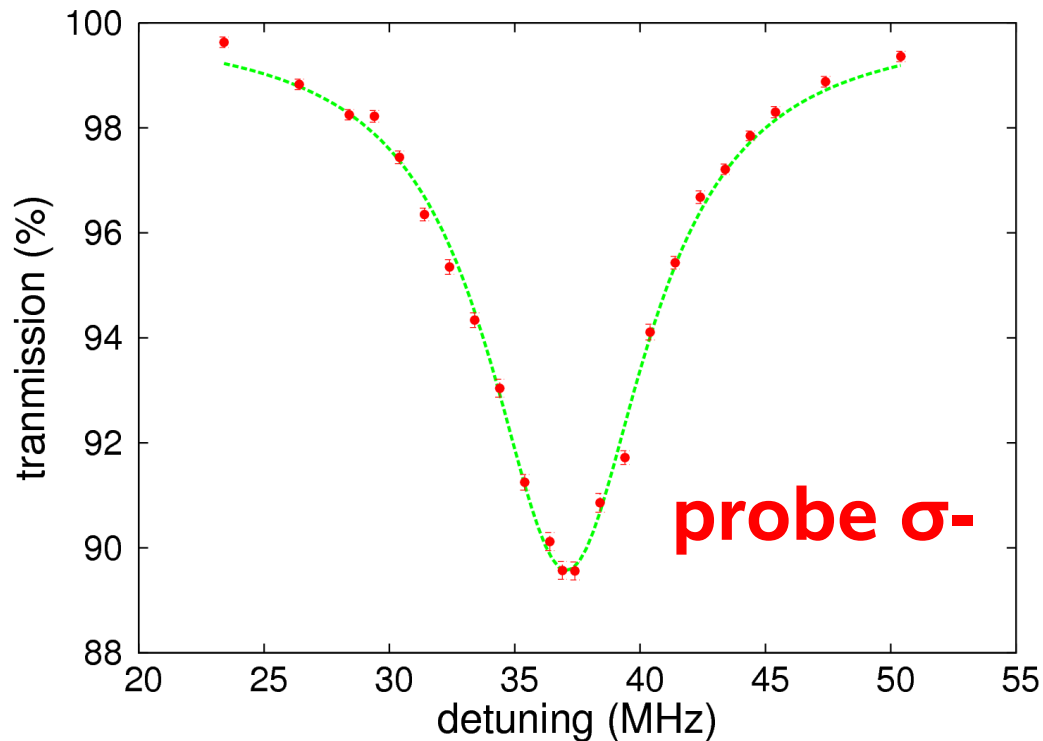


Single atom evidence

(almost) Hanbury-Brown—Twiss experiment on atomic fluorescence during cooling

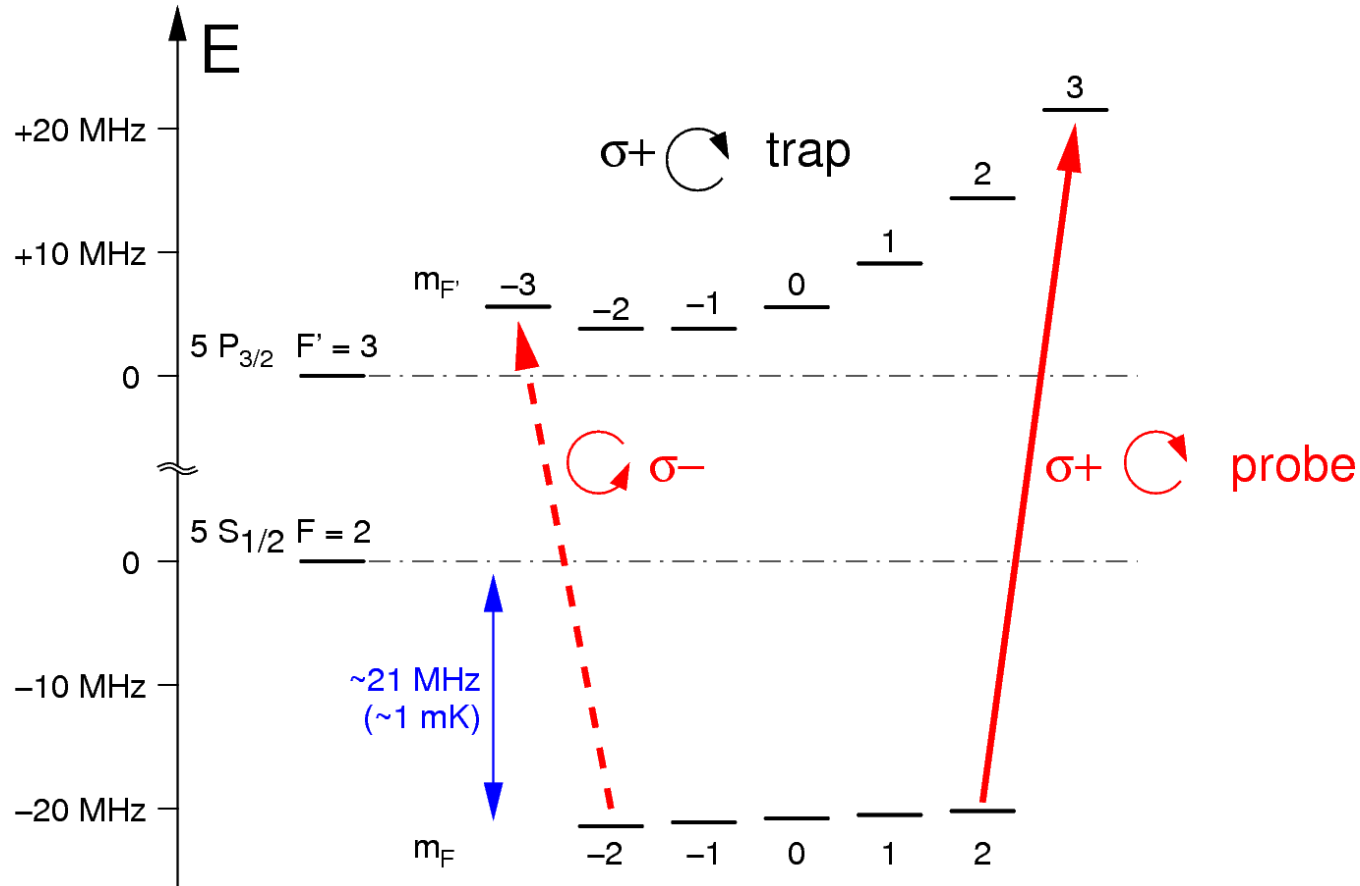


Transmission results



- almost natural line width of atomic transition
- different resonances for different probe polarizations

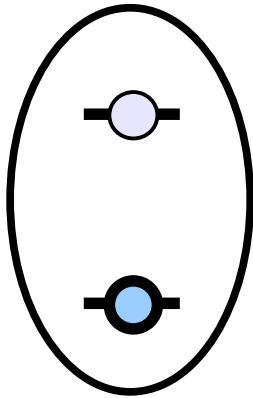
Atomic levels in a dipole trap



- optically pump with the probe beam into 2-level system

Step 1: Scattering from an atom

two - level atom in external driving field (quick & dirty)



- stationary excited state population:

$$\rho_{ee} = \frac{\Omega^2/4}{\delta^2 + \Omega^2/2 + \Gamma^2/4}$$

$$\Omega = E_A |d_{12}| / \hbar \quad \text{Rabi frequency}$$

$$\Gamma = \frac{\omega_{12}^3 d_{12}^2}{3\pi \epsilon_0 \hbar c^3} \quad \text{excited state decay rate}$$

- photon emission rate $\rho_e \Gamma$
- use this to obtain atomic susceptibility

A simple scattering model

- Electrical field in laser beam before lens

$$\mathbf{E} = E_L \frac{1}{\sqrt{2}} e^{-\frac{\rho^2}{w_L^2}} (\hat{x} \cos \omega t + \hat{y} \sin \omega t)$$

- Total excitation power

$$P_{in} = 1/4 \epsilon \pi c w_L^2 E_L^2$$

- Total power scattered by the atom

$$P_{sc} = 3 \epsilon_0 c \lambda^2 E_A^2 / 4 \pi$$

Simple model II

- “Scattering ratio”

paraxial approximation

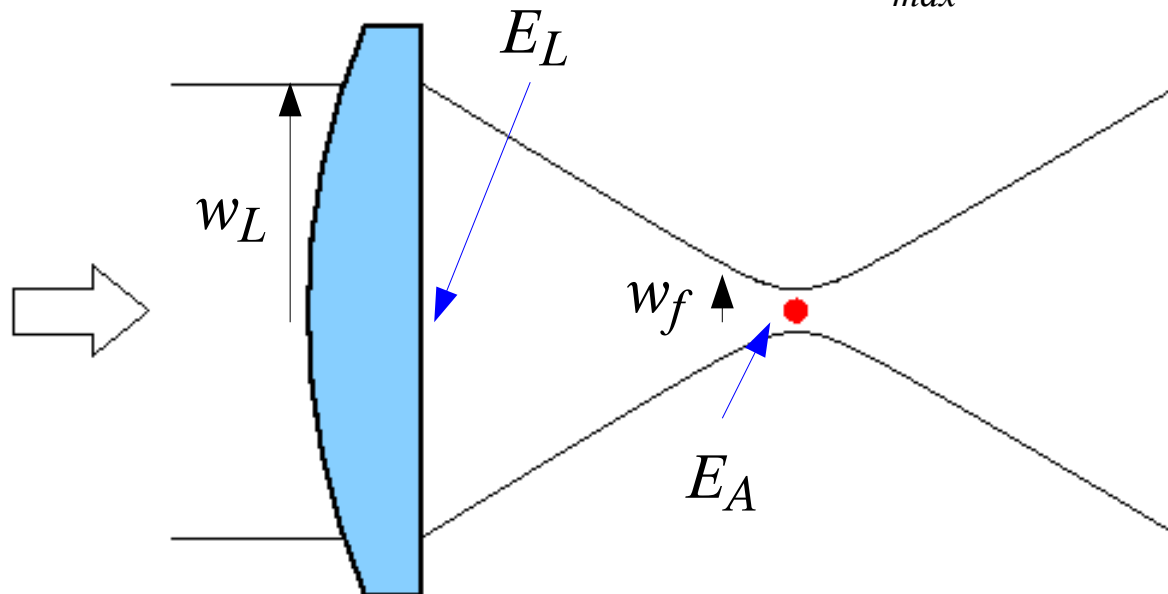
$$R_{sc} = \frac{P_{sc}}{P_{in}} = \frac{3\lambda^2}{\pi w_L^2} \left(\frac{E_A}{E_L} \right)^2 \approx \frac{3\lambda^2}{\pi w_f^2} \approx \sigma_{max} / A$$

focal area

$$A \approx \pi w_f^2 / 2$$

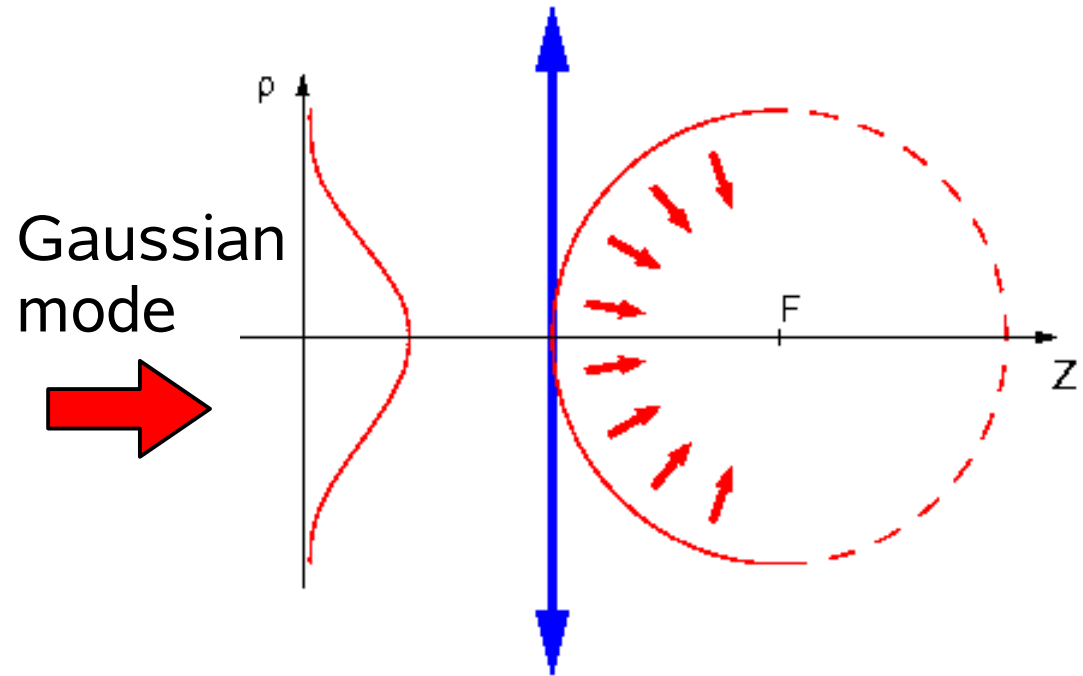
atomic scattering cross section

$$\sigma_{max} = 3\lambda^2 / 2\pi$$



A more careful model

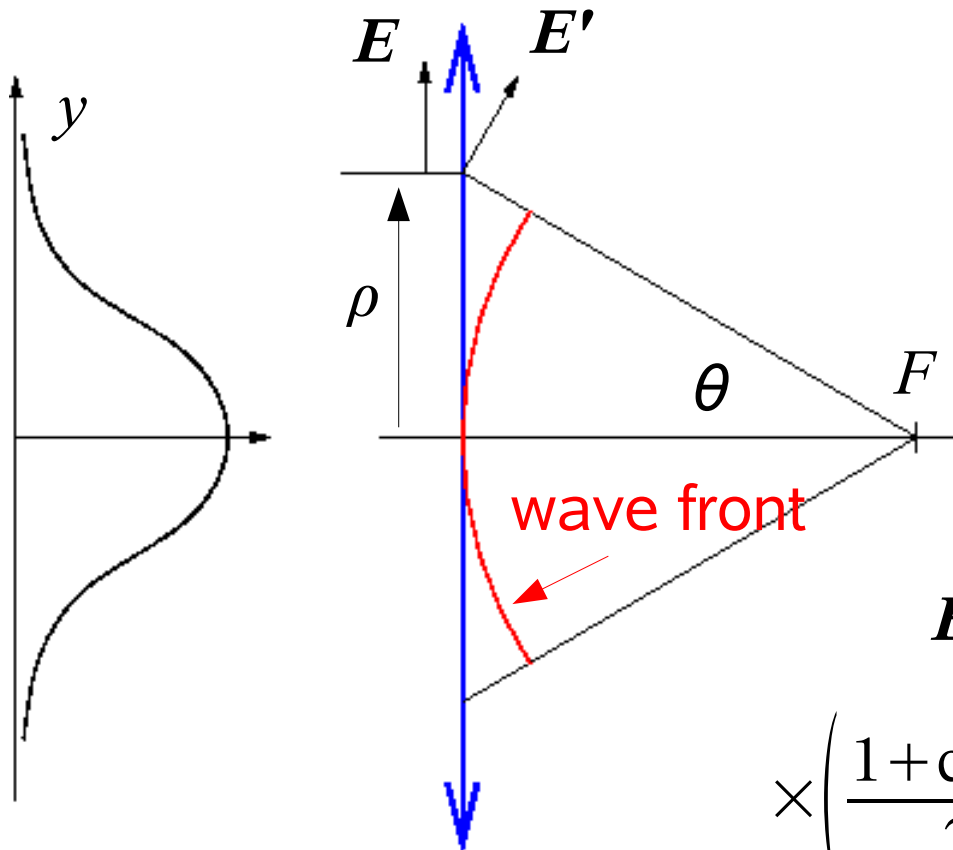
- assume spherical wave front and field compatible with Maxwell equations to get field at atom location
- determine atom response from semiclassical excitation probability for a given field
- combine atom response and original field



Step 2: Get field in focus

Action of an ideal lens on a collimated, circularly polarized Gaussian beam

$$\mathbf{E} = E_L \hat{\mathbf{e}}_+ e^{-\frac{\rho^2}{w_i^2}}$$



- spherical wave front
- locally transverse
- conserve power through each small area

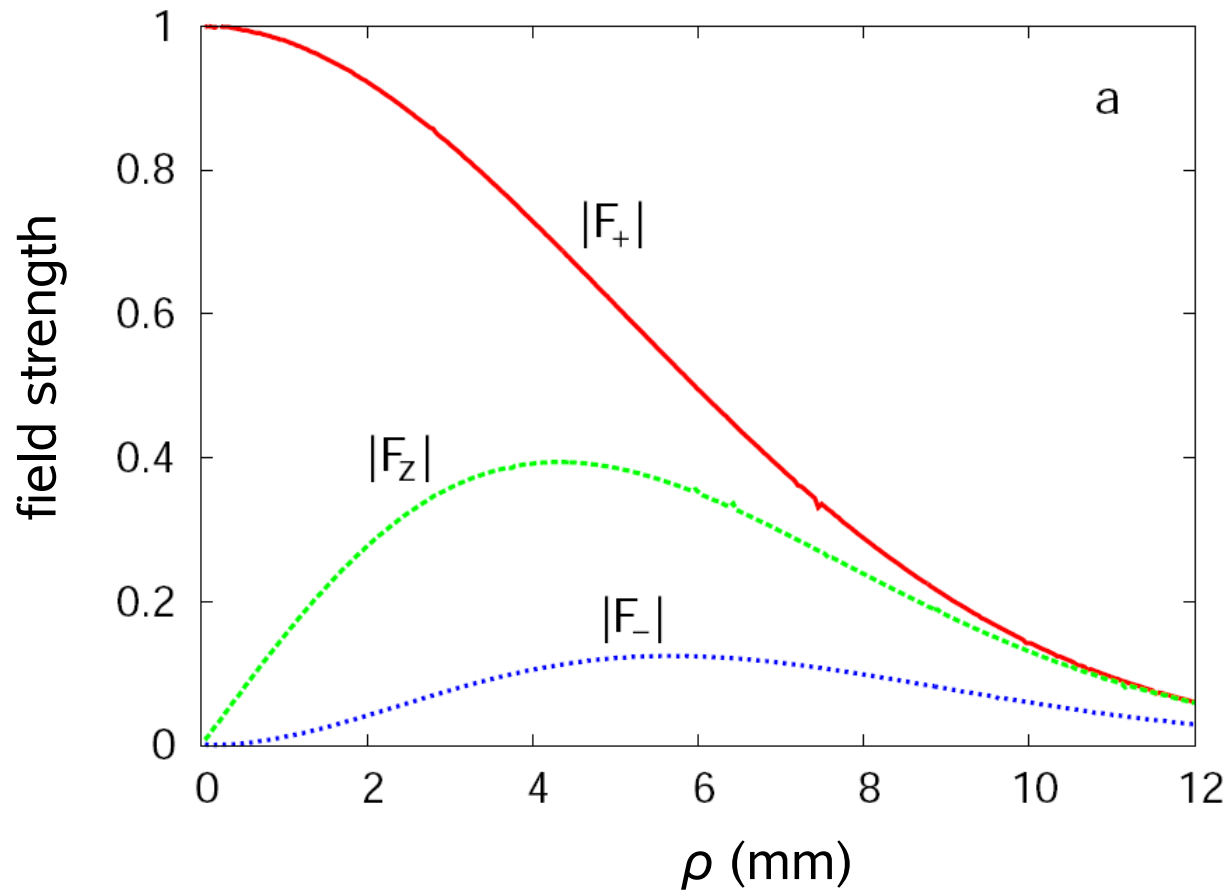
(cyl. coordinates)

$$\mathbf{E}' = E_L e^{-\frac{\rho^2}{w_i^2}} \frac{1}{\sqrt{\cos \theta}} \times e^{-ik\sqrt{\rho^2 + f^2}} \times$$

$$\times \left(\frac{1 + \cos \theta}{2} \hat{\mathbf{e}}_+ + \frac{\sin \theta e^{i\phi}}{\sqrt{2}} \hat{\mathbf{z}} + \frac{\cos \theta - 1}{2} e^{2i\phi} \hat{\mathbf{e}}_- \right)$$

Directly after lens:

$$\mathbf{E}' = E_L e^{-\frac{\rho^2}{w_l^2}} \frac{1}{\sqrt{\cos\theta}} \times e^{-ik\sqrt{\rho^2+f^2}} \times \left(\frac{1+\cos\theta}{2} \hat{\mathbf{e}}_+ + \frac{\sin\theta e^{i\phi}}{\sqrt{2}} \hat{\mathbf{z}} + \frac{\cos\theta-1}{2} e^{2i\phi} \hat{\mathbf{e}}_- \right)$$



- different polarization components appear

beam parameter:
 $w_l = 7$ mm

focal length:
 $f = 4.5$ mm

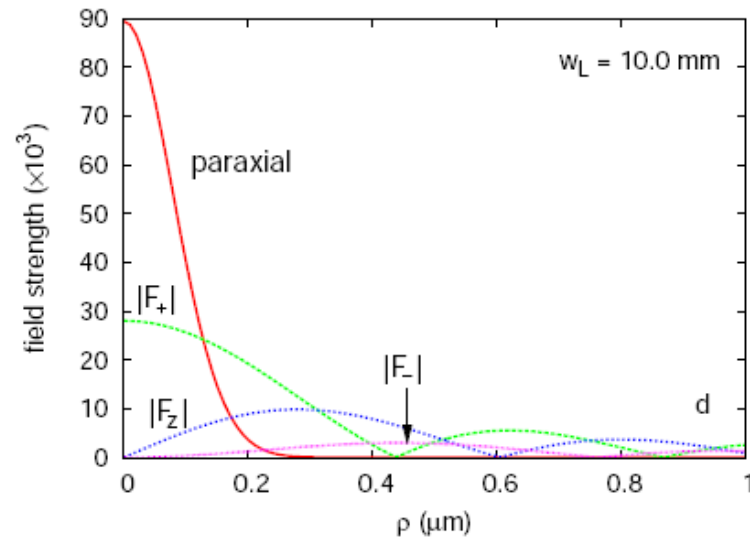
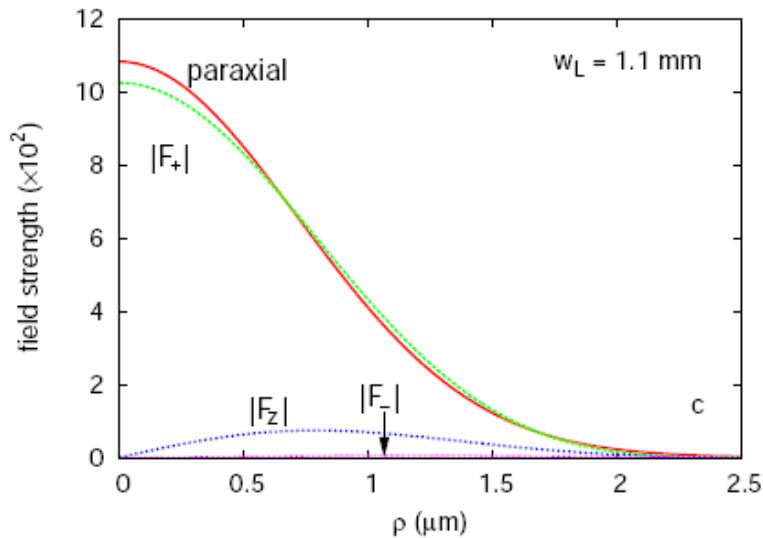
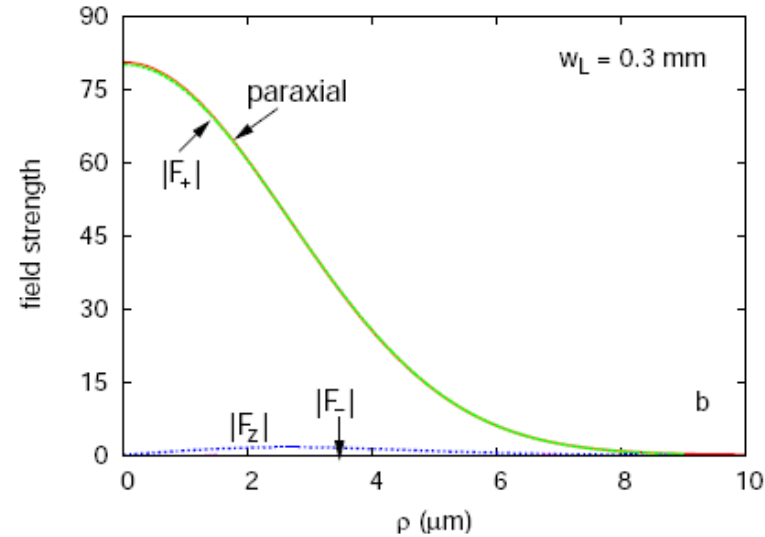
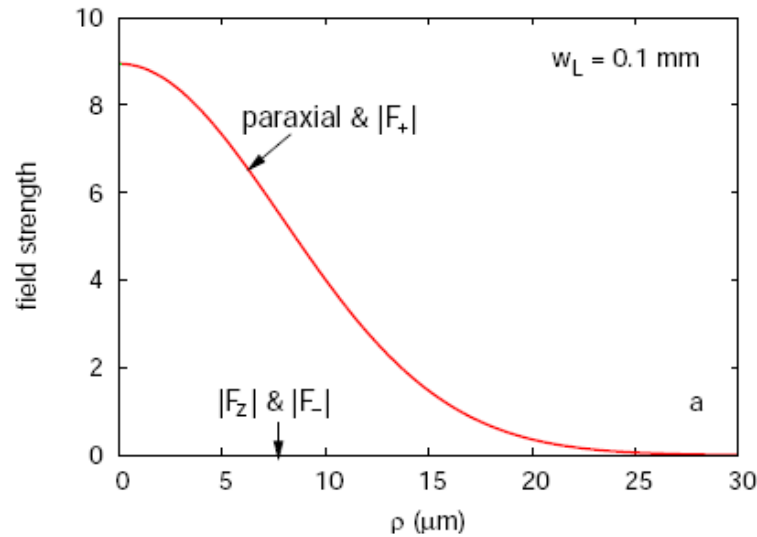
Propagate field to focus

- numerical method:
 - decompose initial field into cylindrical harmonics
 - analytically propagate to focus, allows to obtain field around focal point
- closed expression for field at focus via Green theorem

$$\begin{aligned} E(z=f, \rho=0) &= \\ &= E_L \frac{ikf}{4} e^{\frac{f^2}{w_L^2}} \left[\sqrt{\frac{f}{w_L}} \Gamma\left(-\frac{1}{4}, \frac{f^2}{w_L^2}\right) + \sqrt{\frac{w_L}{f}} \Gamma\left(\frac{1}{4}, \frac{f^2}{w_L^2}\right) \right] \hat{e}_+ \end{aligned}$$

Focal fields for different w_L

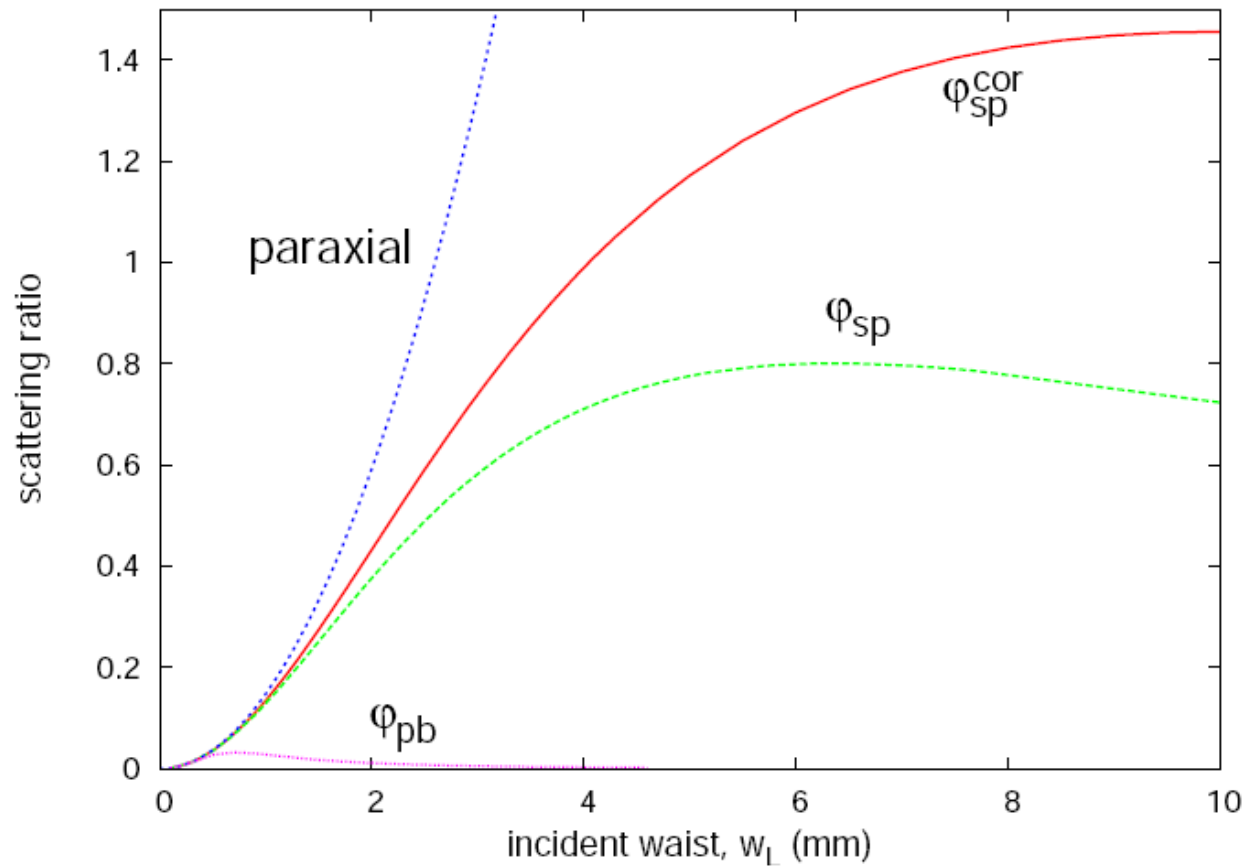
- paraxial approximation starts to break down late...



($f = 4.5$ mm)

Ooops...strange scattering?

- define scattering ratio as
$$R_{sc} = \frac{P_{sc}}{P_{in}} = \frac{\rho_{ee} \Gamma \cdot \hbar \omega}{1/4 \epsilon \pi c E_L^2 w_L^2}$$



???

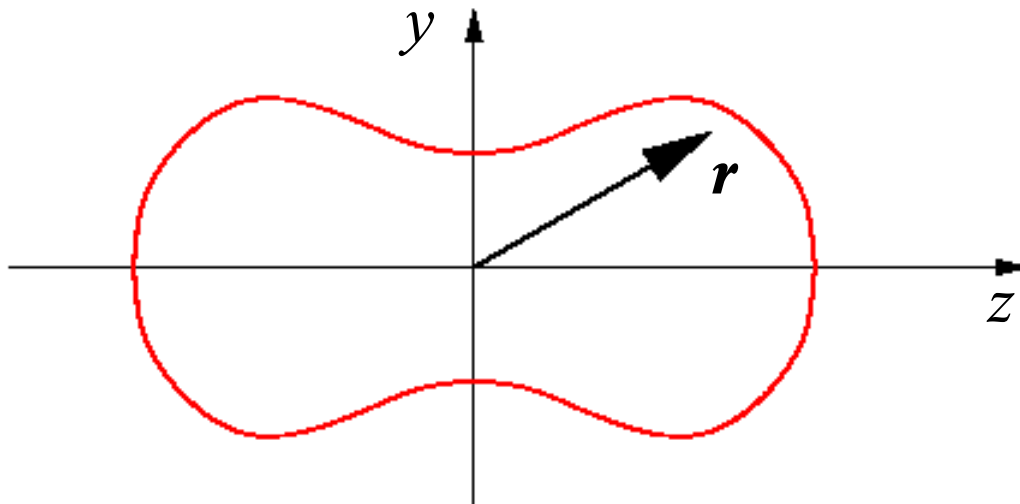
Atomic response II

scattered field has electric dipole characteristic
corresponding to $\sigma+$ transition

$$\mathbf{E}_{sc}(\mathbf{r}) = E_A \frac{3}{2} \frac{e^{ikr + \pi/2}}{kr} \left[\hat{\mathbf{e}}_+ - (\hat{\mathbf{e}}_+ \cdot \hat{\mathbf{r}}) \hat{\mathbf{r}} \right]$$

$$\hat{\mathbf{r}} = \frac{1}{|\mathbf{r}|} \mathbf{r} \quad \text{radial unit vector}$$

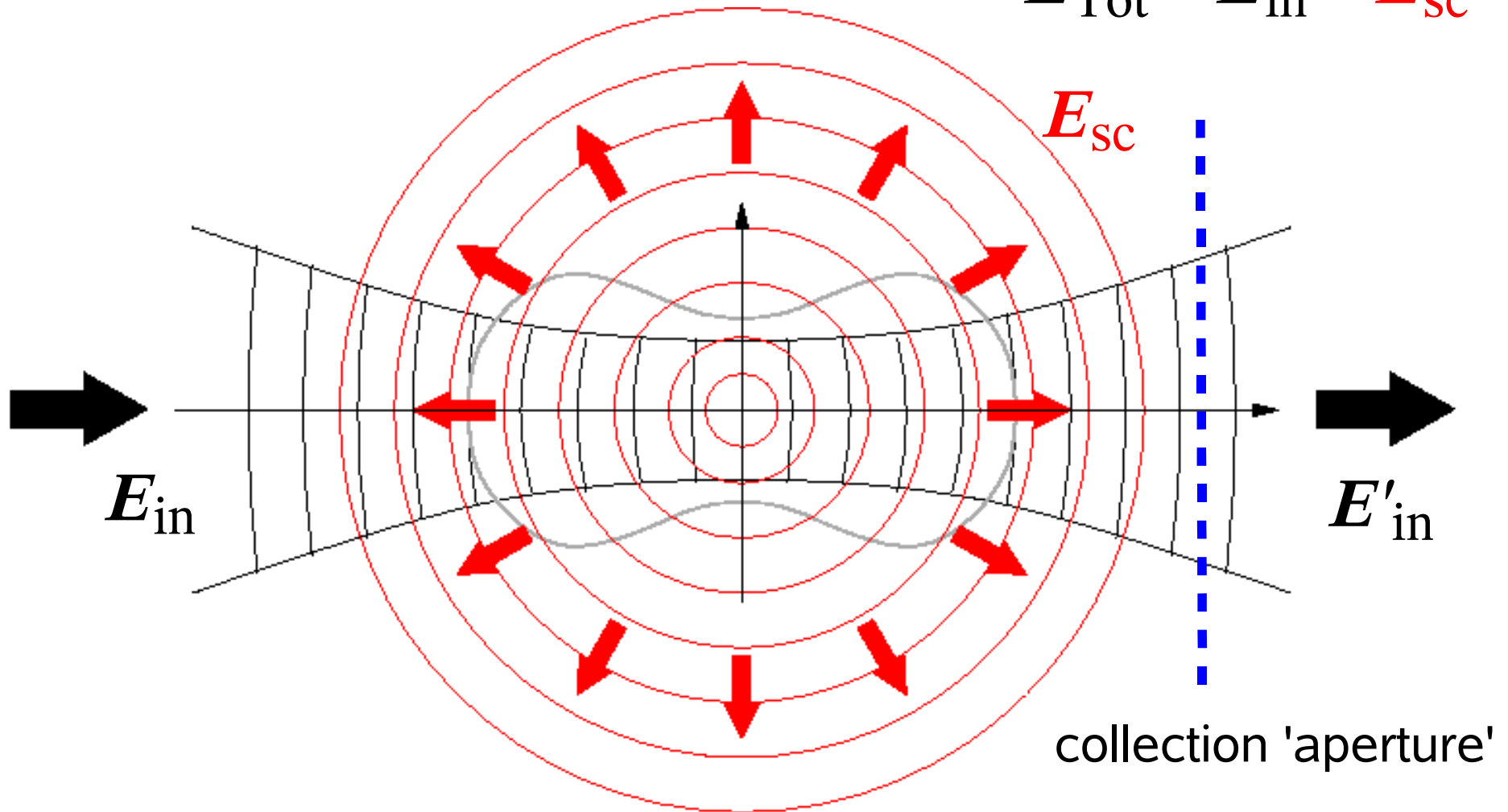
$$\hat{\mathbf{e}}_+ = \frac{\hat{x} + i\hat{y}}{\sqrt{2}} \quad \text{circular unit vector}$$



Step 3: Combine with probe

integrate combined field over collection aperture

$$E_{\text{Tot}} = E_{\text{in}} + E_{\text{sc}}$$



Results

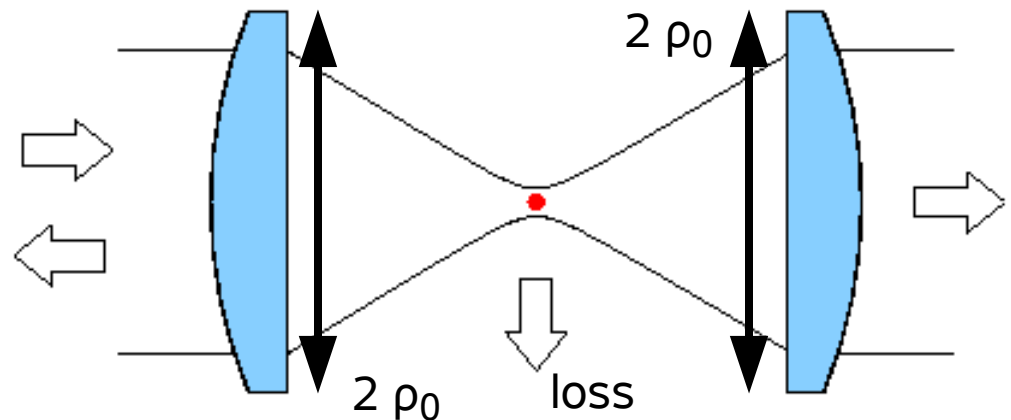
- Extinction

$$\epsilon = \frac{P_{sc}^{\rho_0}}{2 P_{in} (1 - e^{-2\rho_0^2/w_L^2})} \left[1 + \frac{4 f^3 + 3 f \rho_0^2}{4 (f^2 + \rho_0^2)^{3/2}} \right]$$

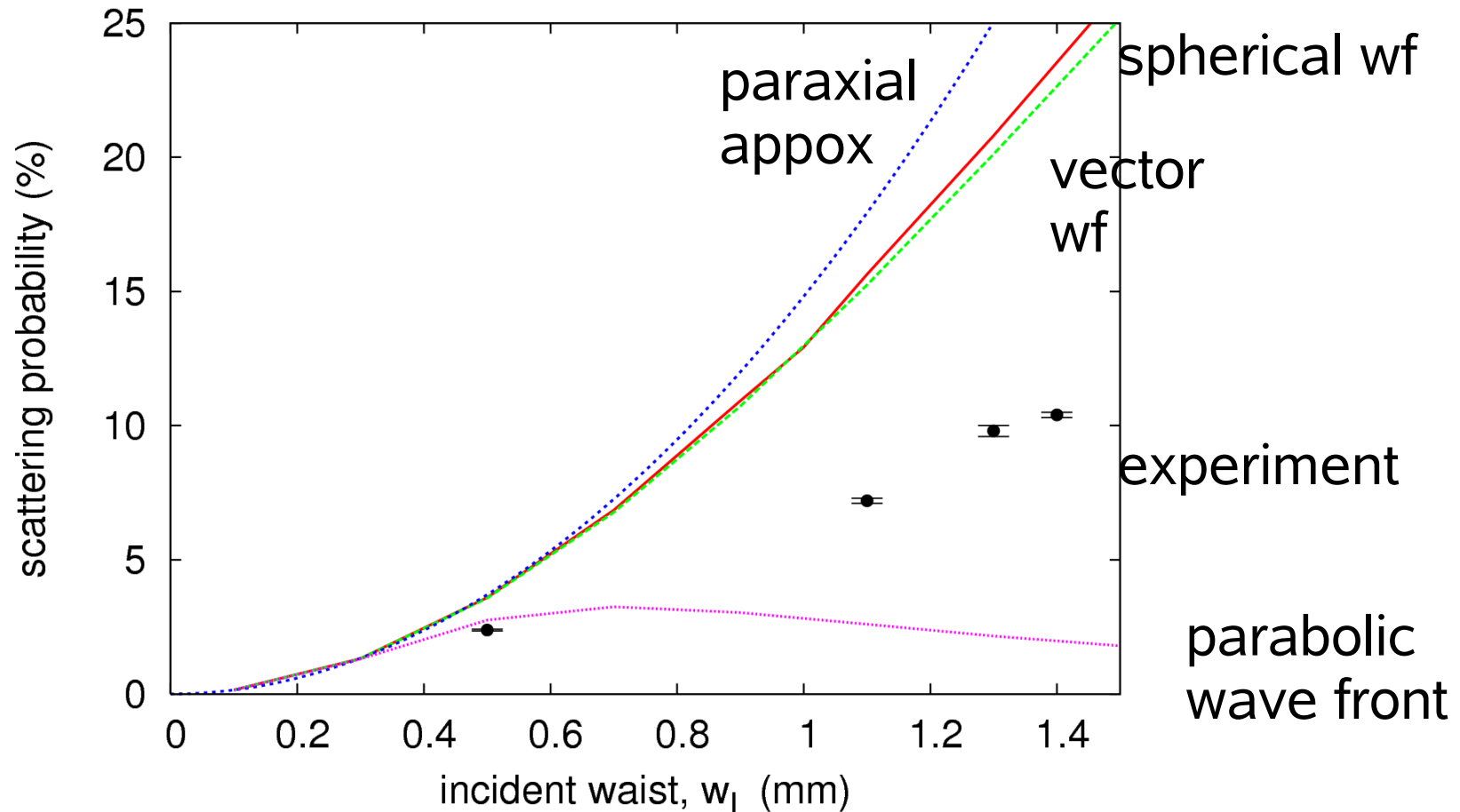
- Reflectivity (backward direction)

$$R = \frac{P_{sc}^{\rho_0}}{2 P_{in}} \left[1 - \frac{4 f^3 + 3 f \rho_0^2}{4 (f^2 + \rho_0^2)^{3/2}} \right]$$

- No energy gets lost



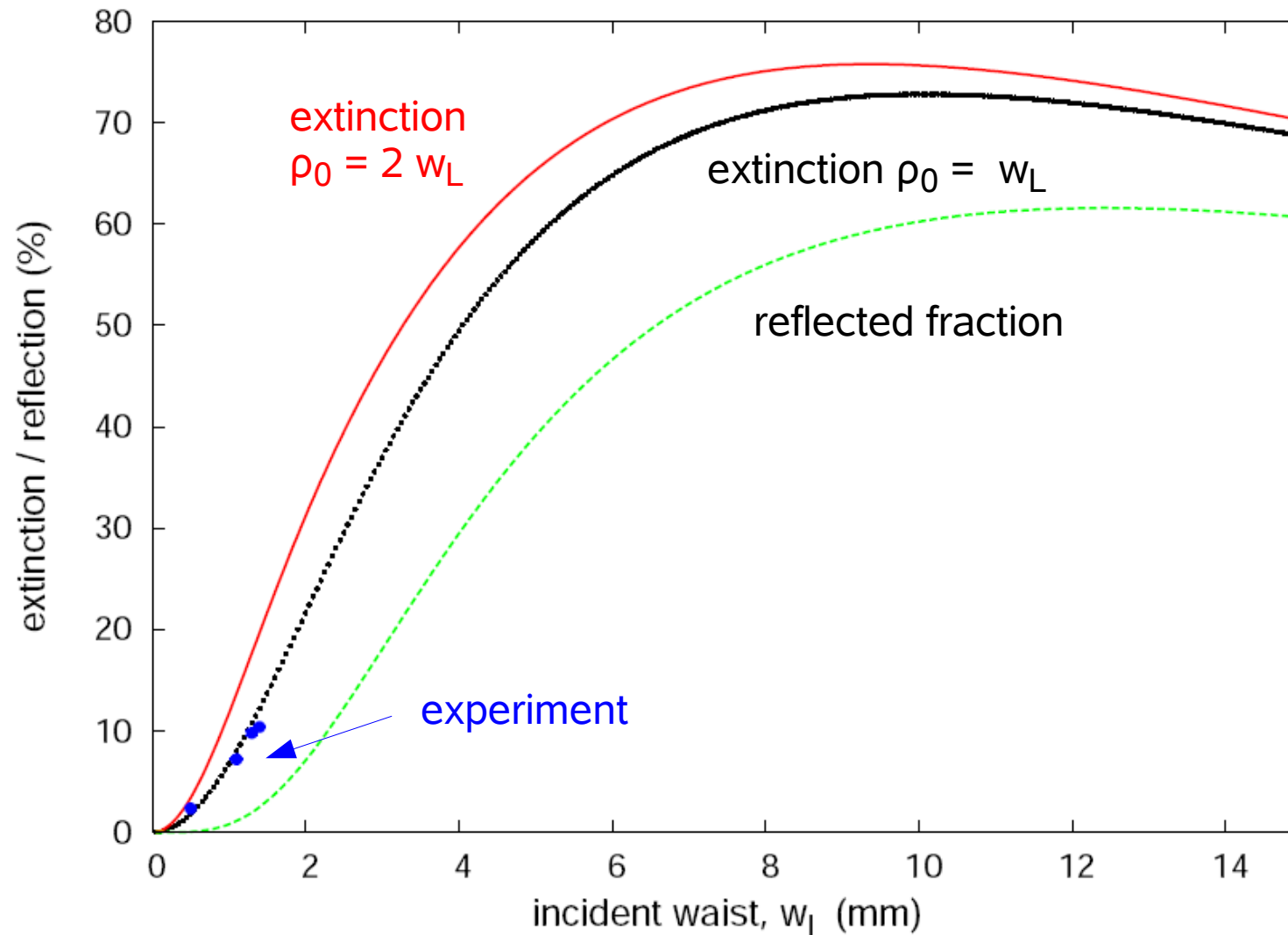
Scattering vs. focusing



(experimental P_{sc} extracted out of transmission measurement)

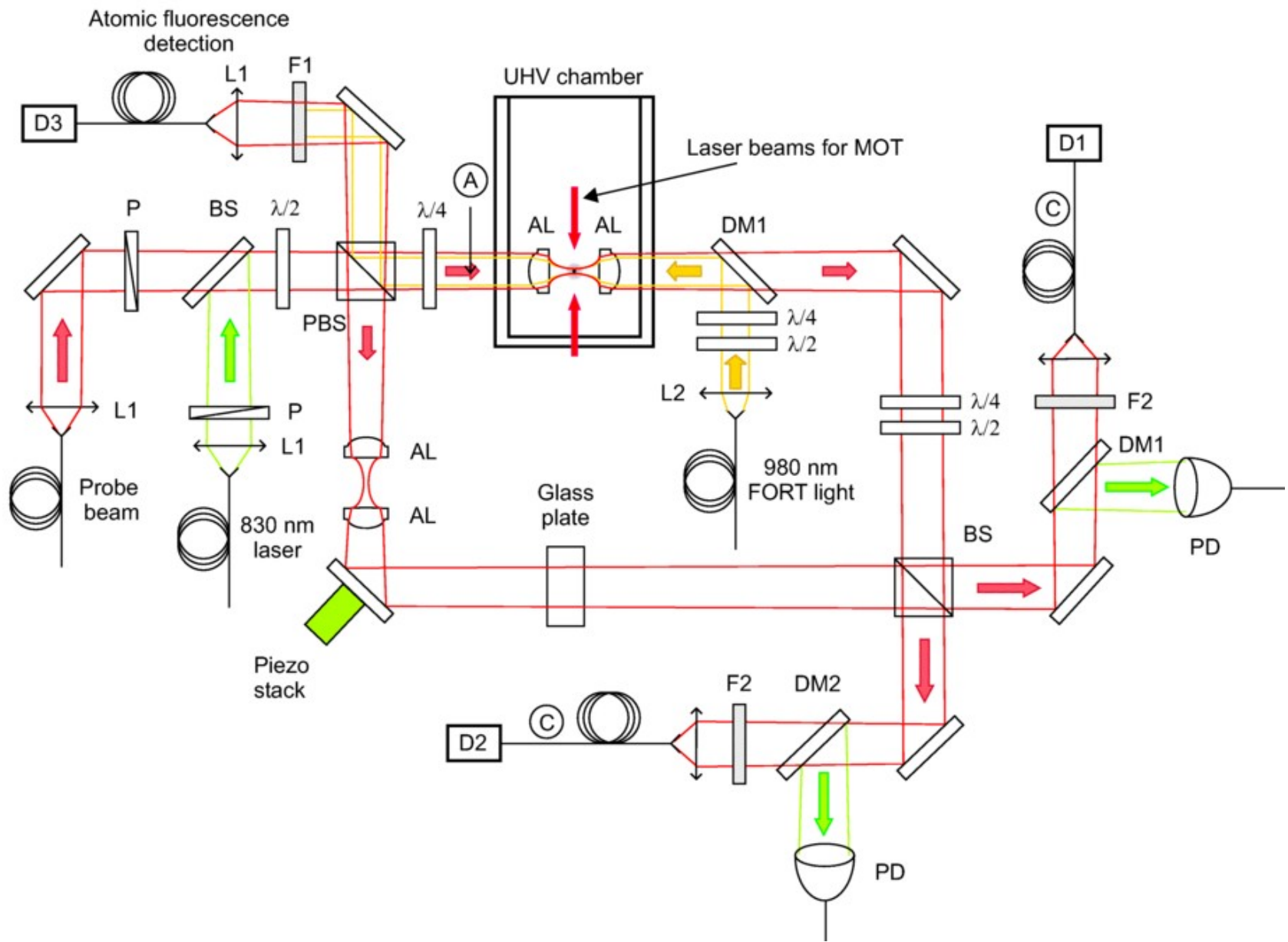
($f = 4.5$ mm)

How far does this go?

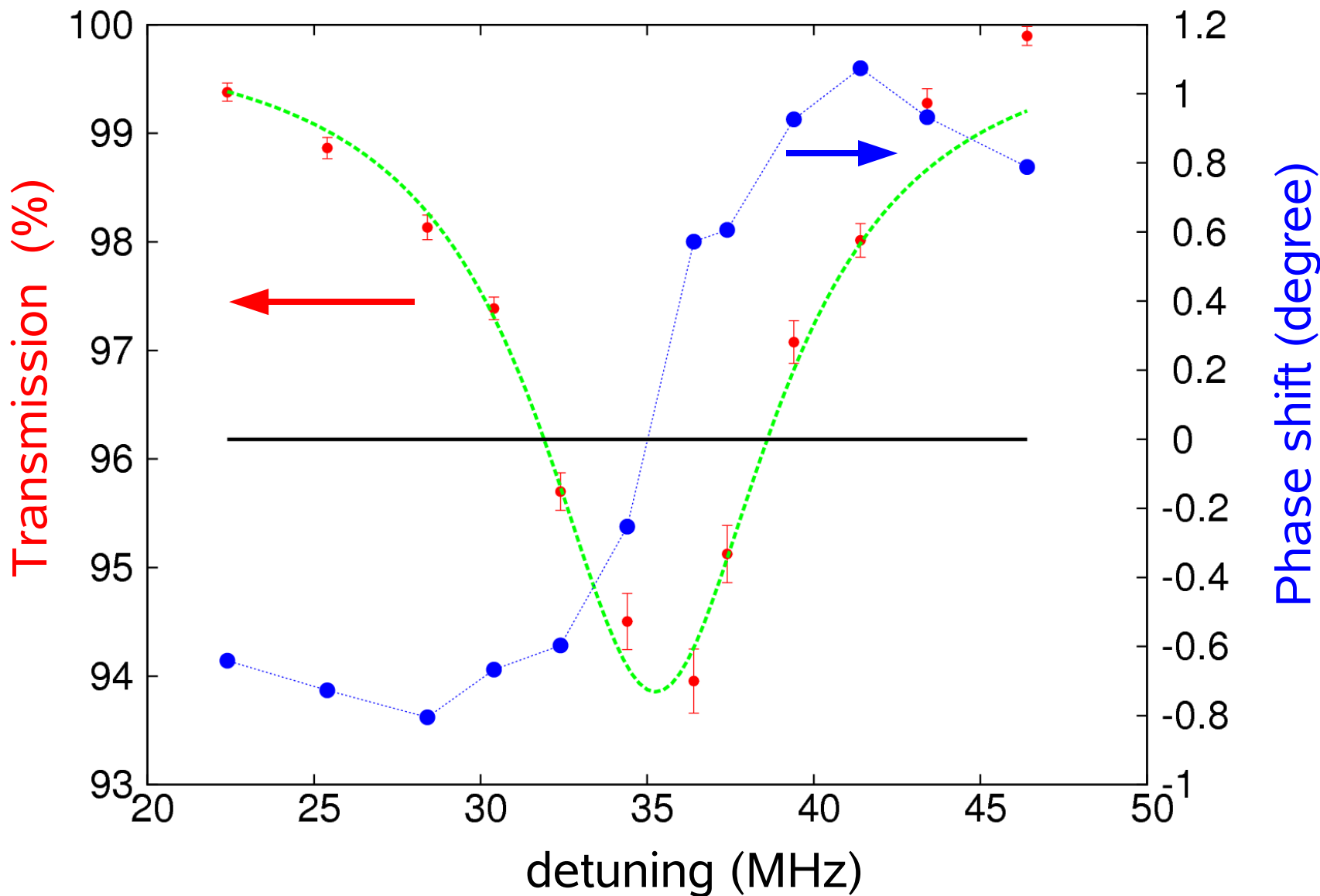


Single atom phase shift

Mach-Zehnder interferometer setup



Phase shift / Transmission



Comparison to cavity QED

- Could strong focusing replace cavities for strong coupling?

Probably not: imperfect mode match
Gaussian modes --- atomic dipole modes

- Can strong focusing help in cavity QED experiments?

Probably yes: field enhancement due to focusing
can lower cavity finesse

- What is the balance of technical problems?

high NA lenses vs. high finesse mirrors (similar effort?)

Next steps

- Improve laser cooling sequence
- Try larger numerical apertures
- Look for backscattered light
- Connect to nonclassical light sources....

Thank you!



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Zilong Chen
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Brenda Chng
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