Substantial scattering of a Weak Coherent Beam by a Single Atom

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Centre for Quantum Technologies

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Atom-Photon interface

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Motivation:

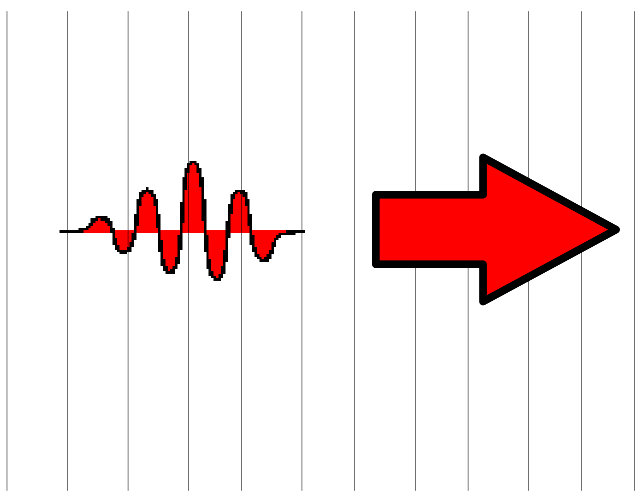
- Atoms and photons are good for different quantum information tasks – allow an exchange of quantum information between them
- Understand elementary interaction between flying qubits and single atoms
- Explore possibilities of controlled phase gates & friends for photonic qubits

Key idea:

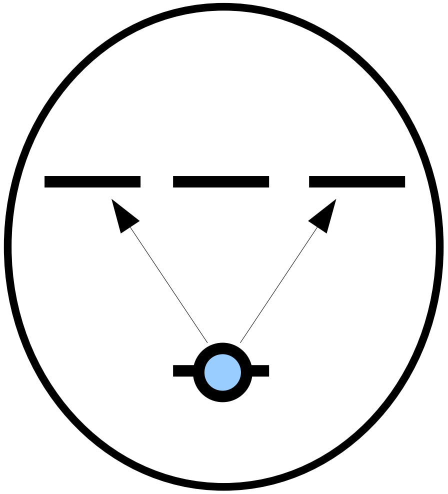
- Try to **mode-match** traveling qubit modes to field modes of spontaneous emission of a single atom

Why is this interesting?

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



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

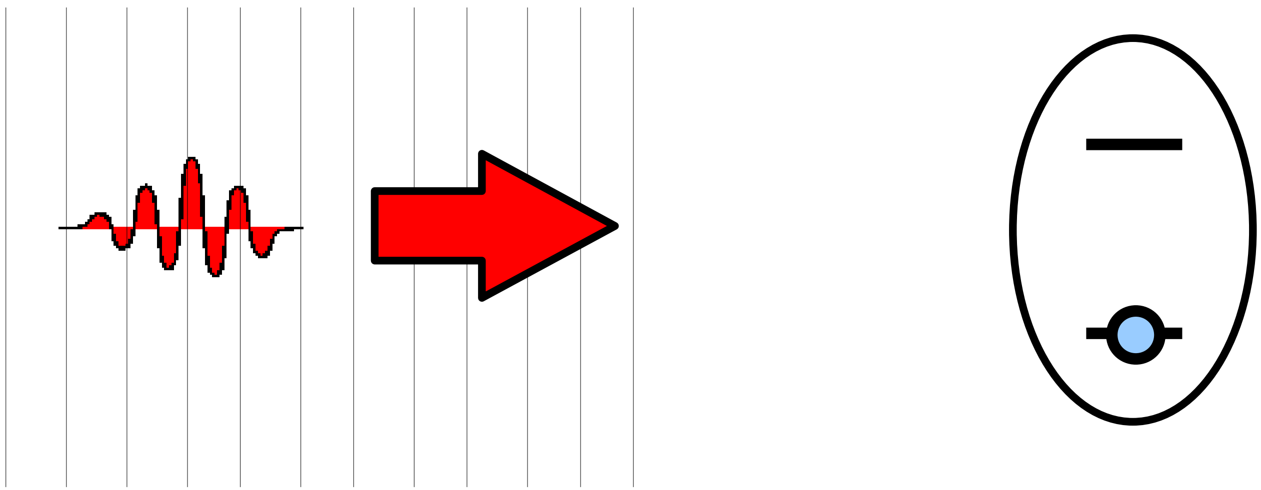


$$\left|\Psi_A\right\rangle = \alpha\left|m=-1\right\rangle + \beta\left|m=+1\right\rangle$$

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

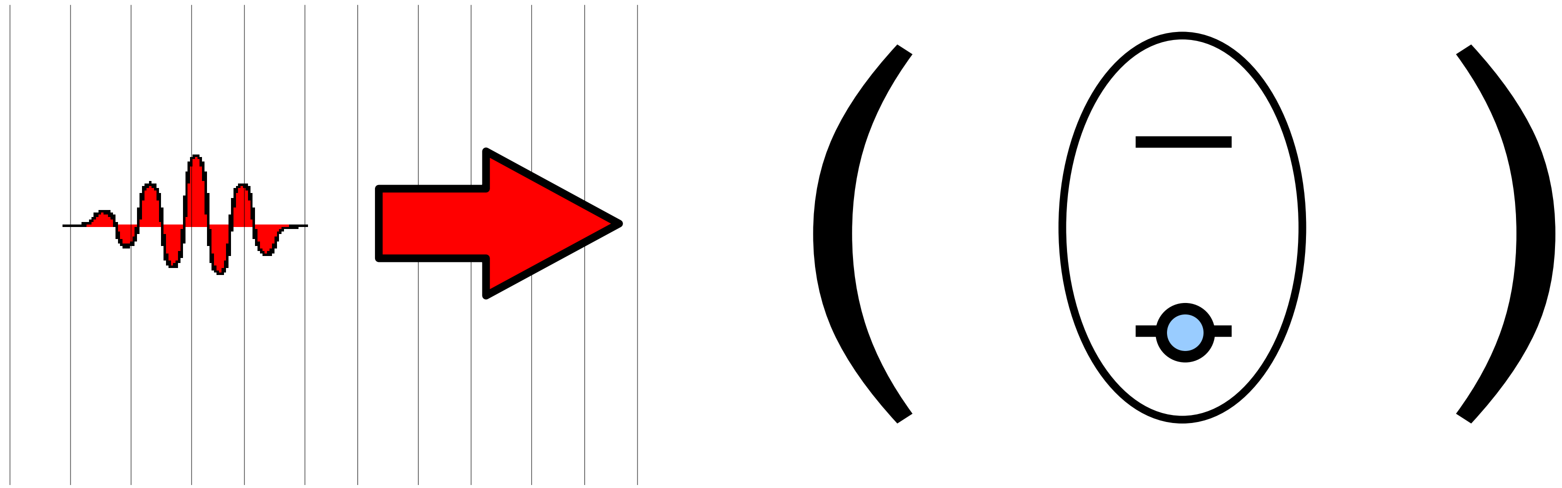
The basic problem

- 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

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

Electrical field operator (single freq):

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

mode function, e.g.

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

Atom in a cavity

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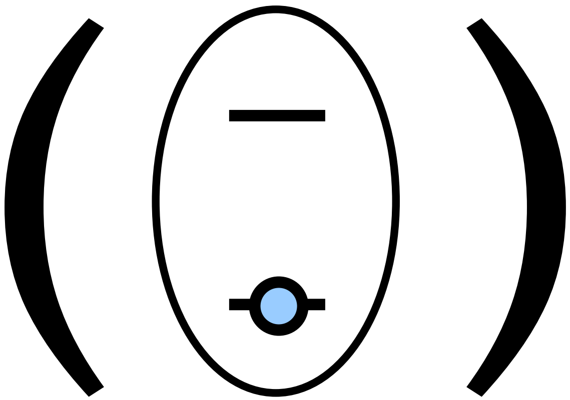


- atom Hamiltonian

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

- electric dipole interaction

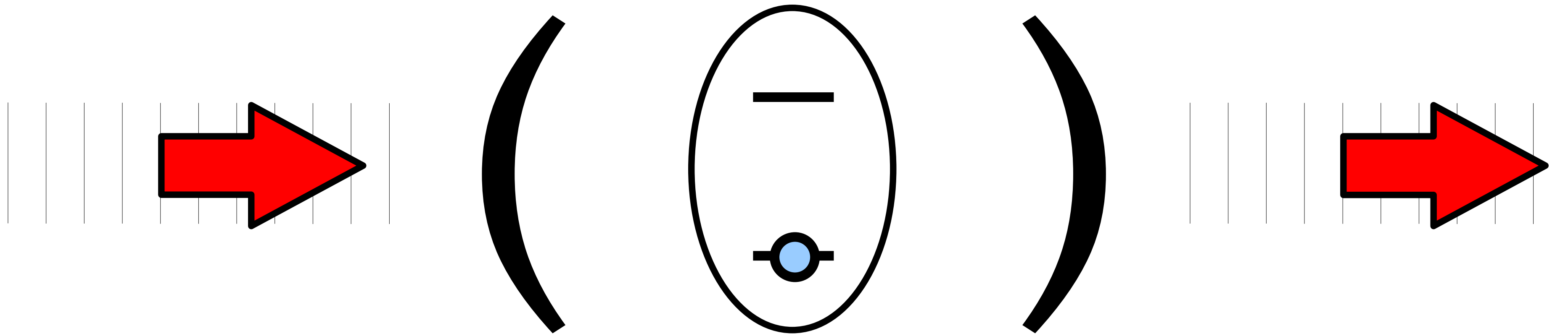
$$\hat{H}_I = \hat{\boldsymbol{E}} \cdot \hat{\boldsymbol{d}} \quad \text{with} \quad \hat{\boldsymbol{d}} = \boldsymbol{e}\, d_{eff} \left(|e\rangle\langle g| + |g\rangle\langle e| \right)$$

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

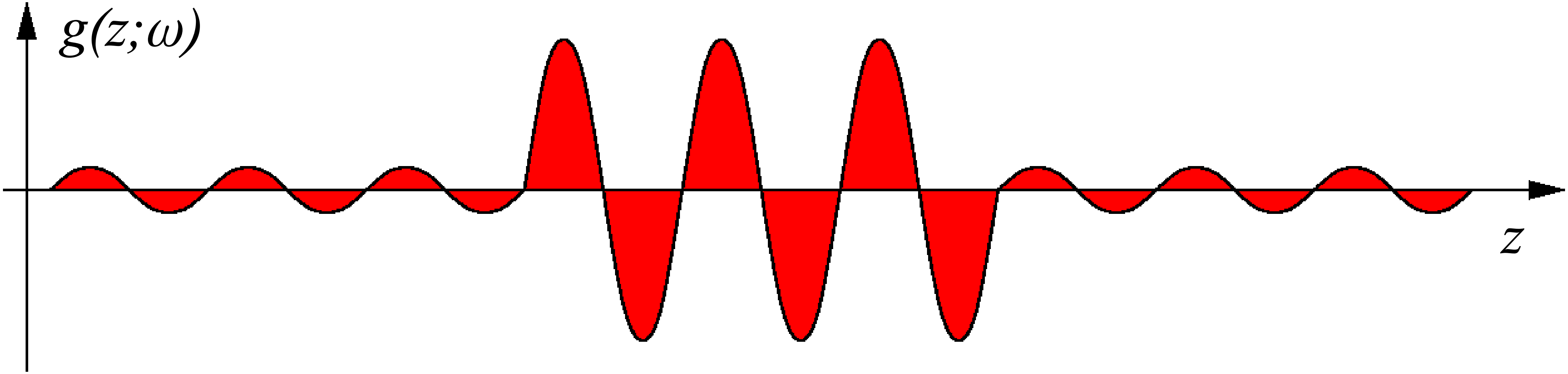
.....Jaynes-Cummings model with all its aspects

- 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

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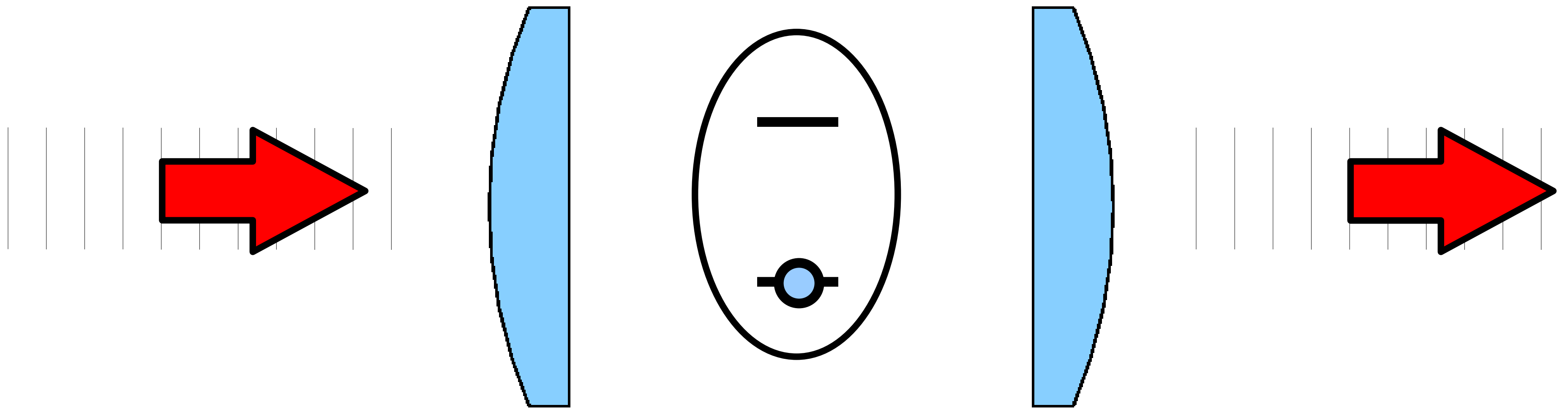
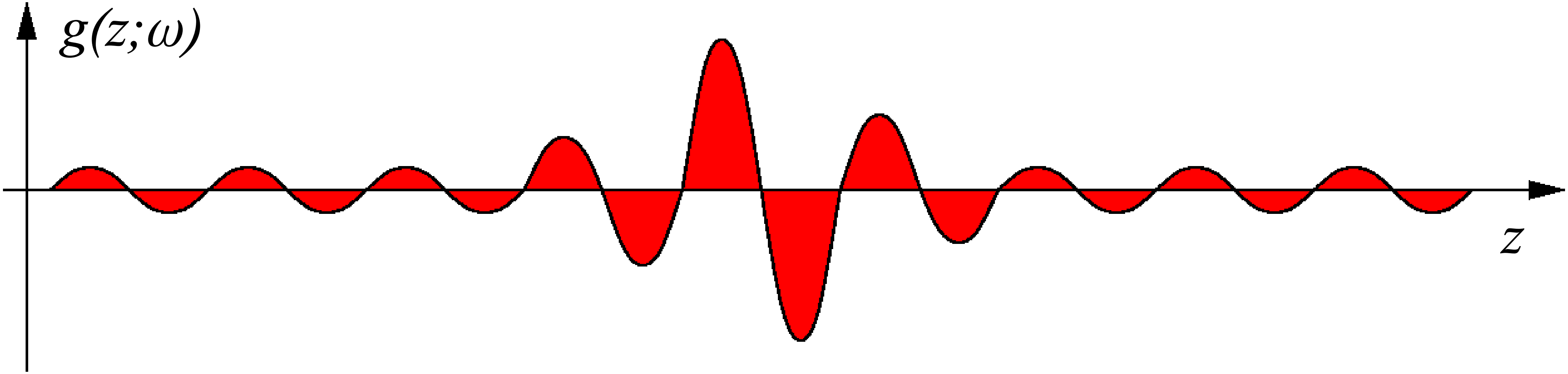
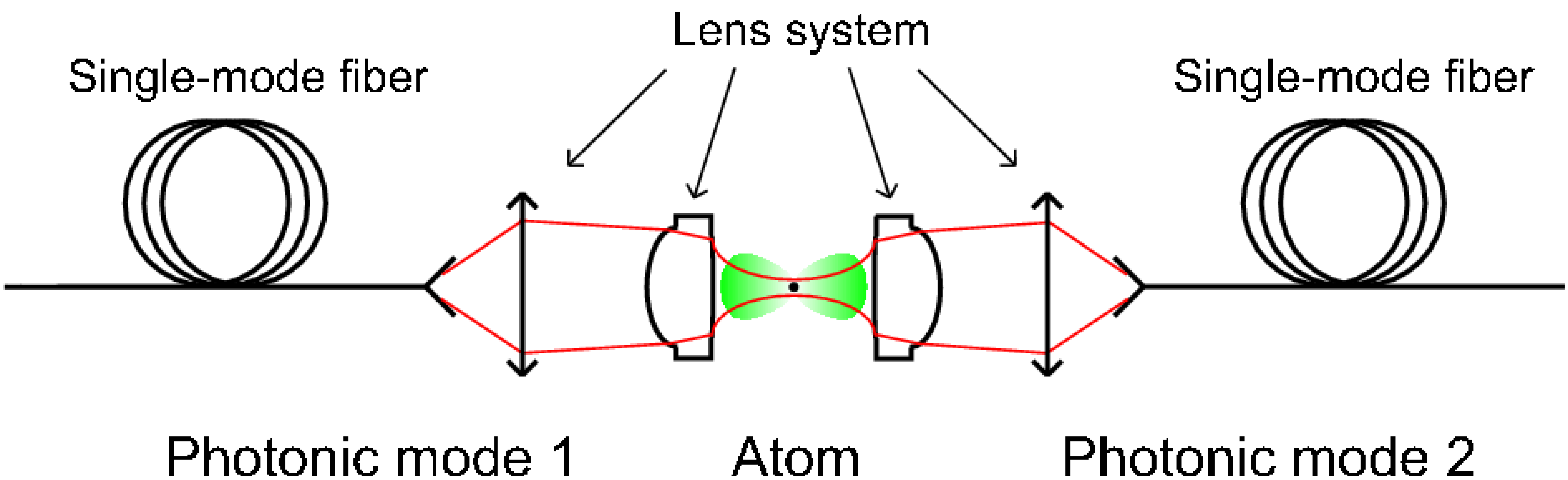


- use a **focusing lens pair** to enhance center mode function:



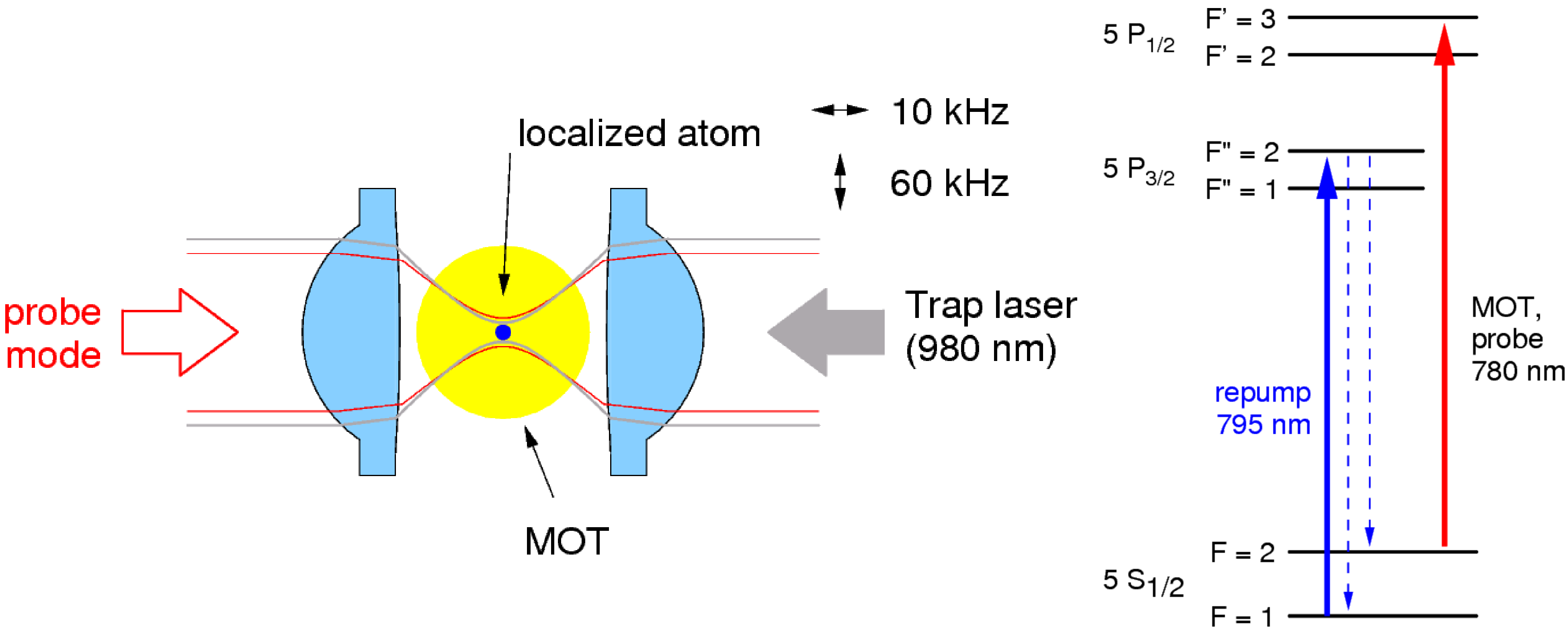
Concept of an experiment



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

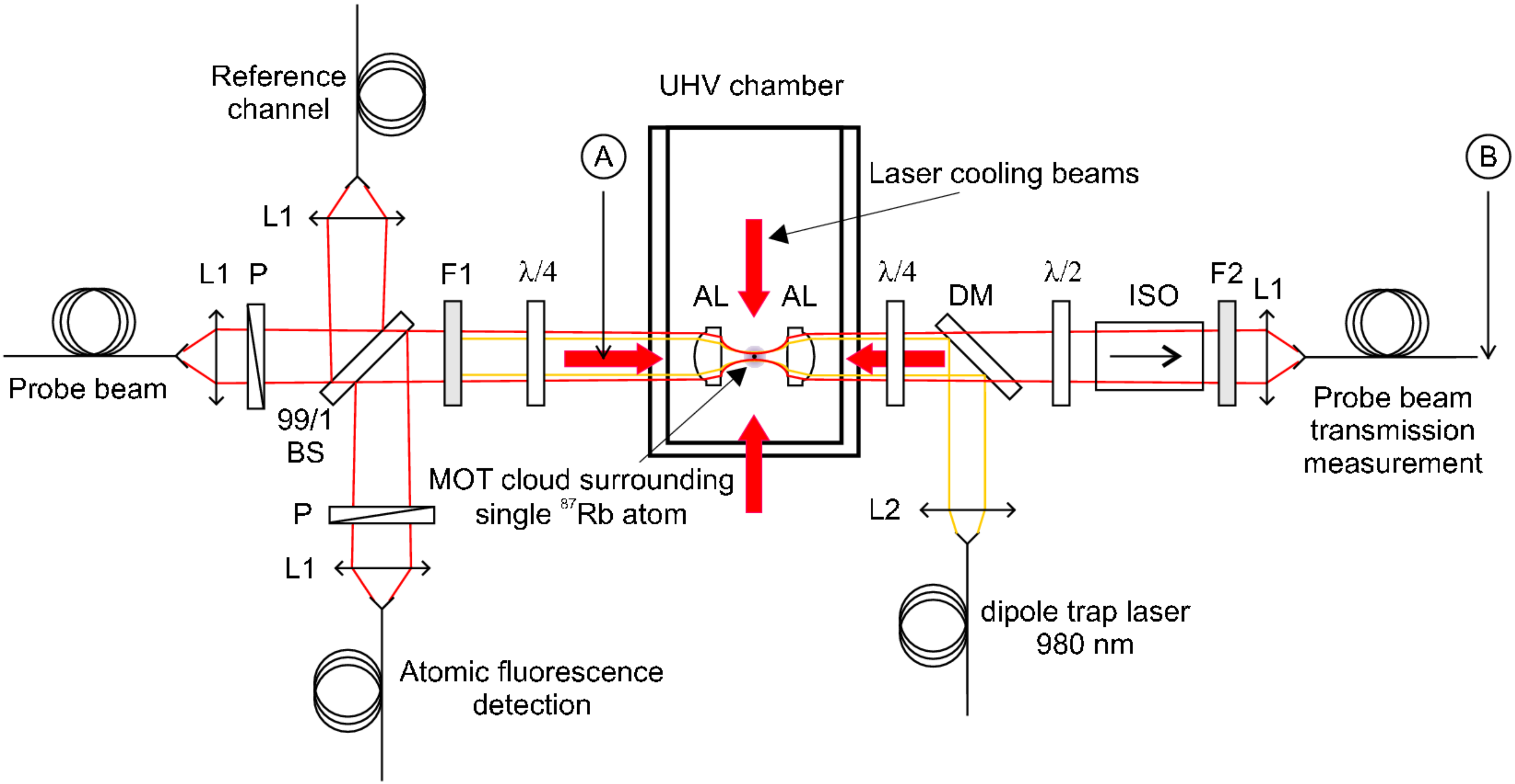
More technical details

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...

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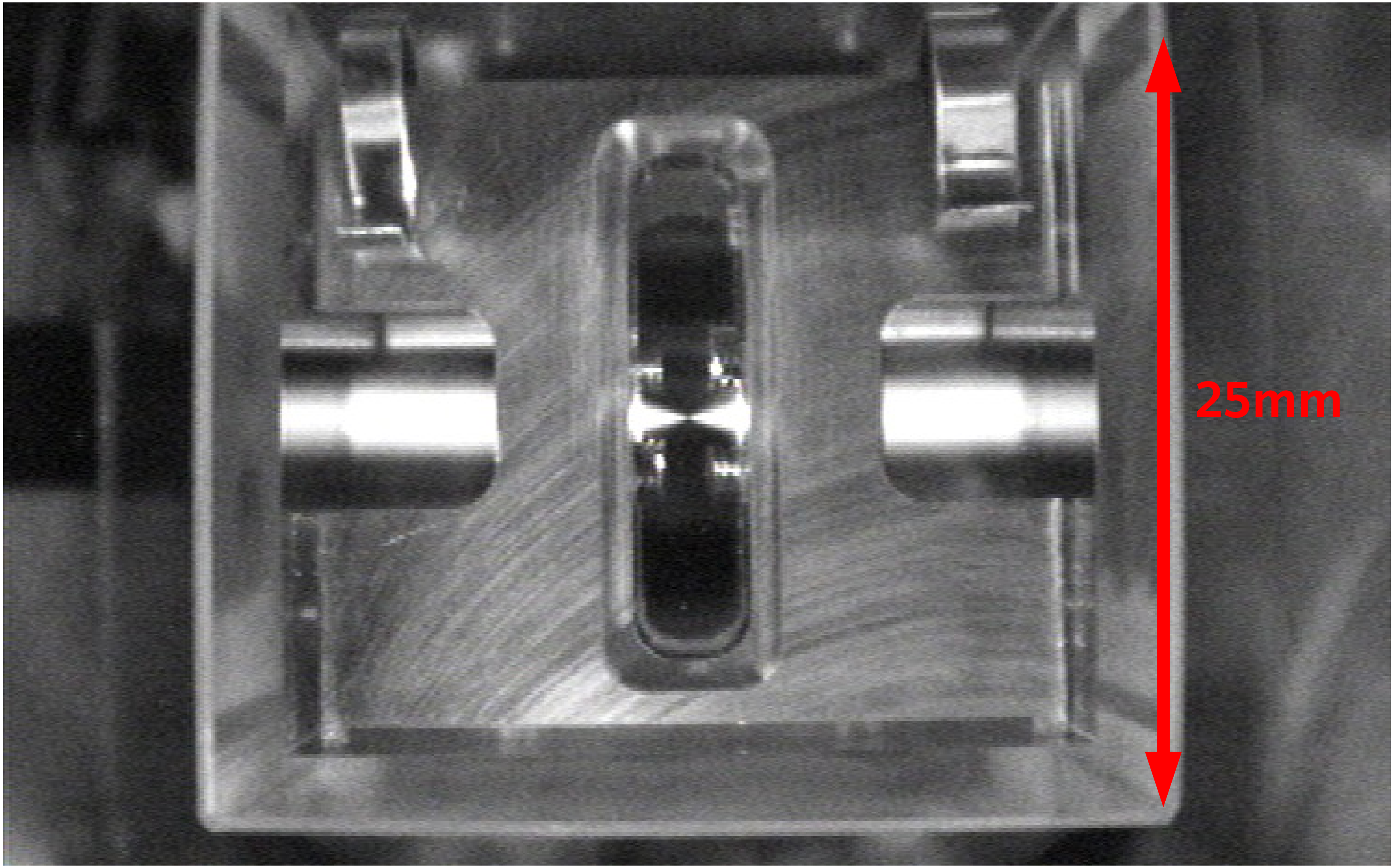
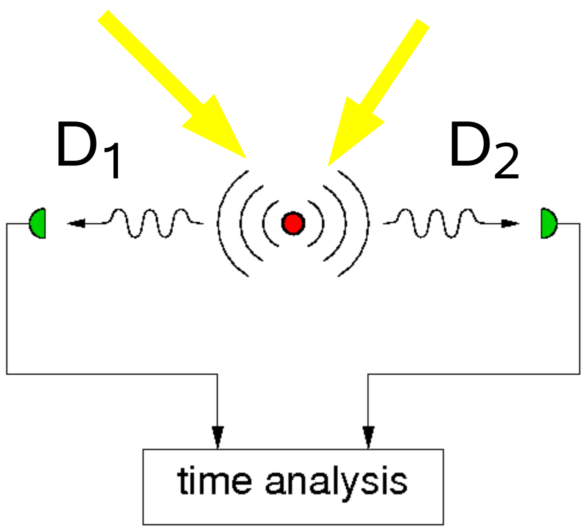
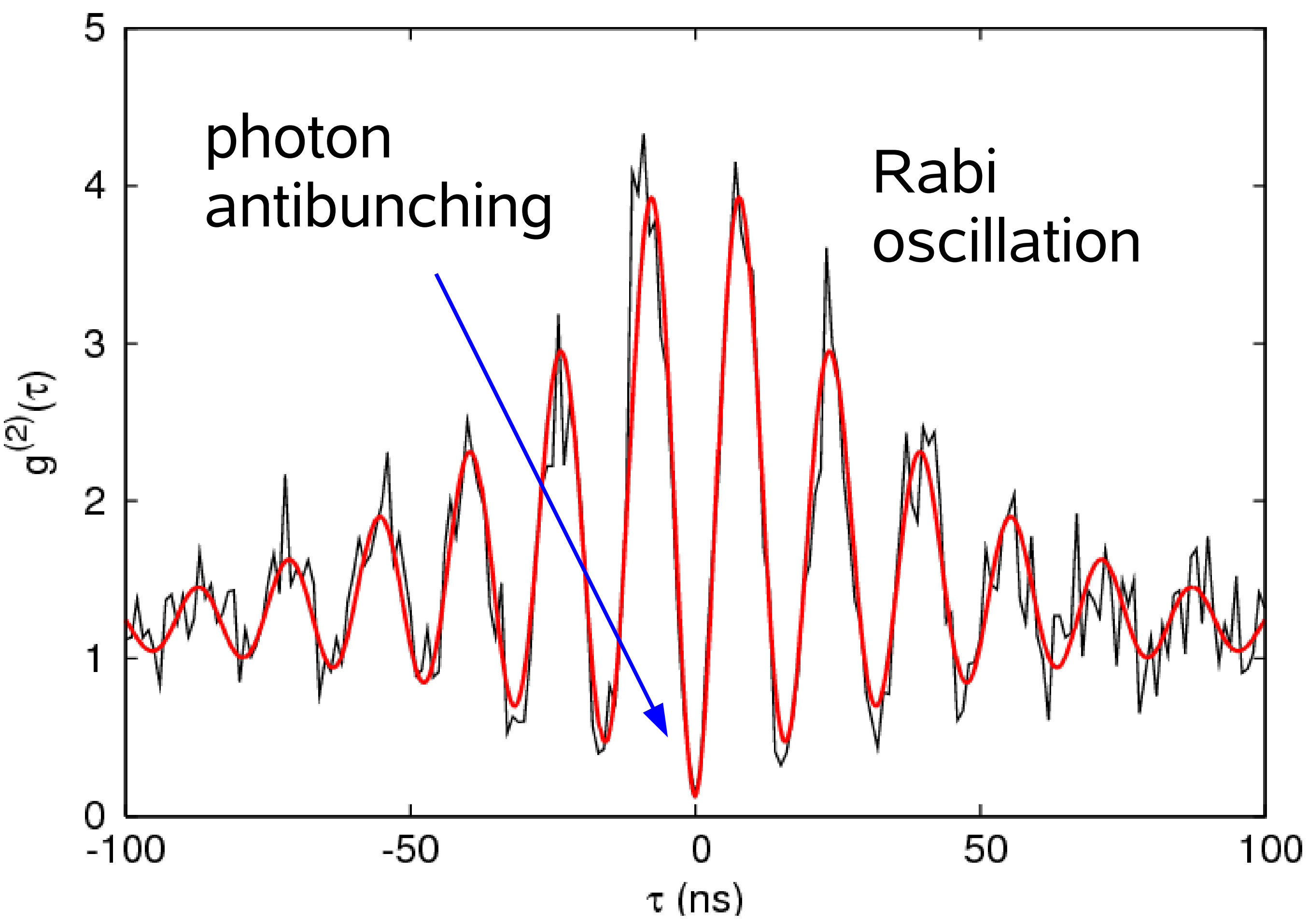
...as seen by a CCTV camera at high Rb pressure



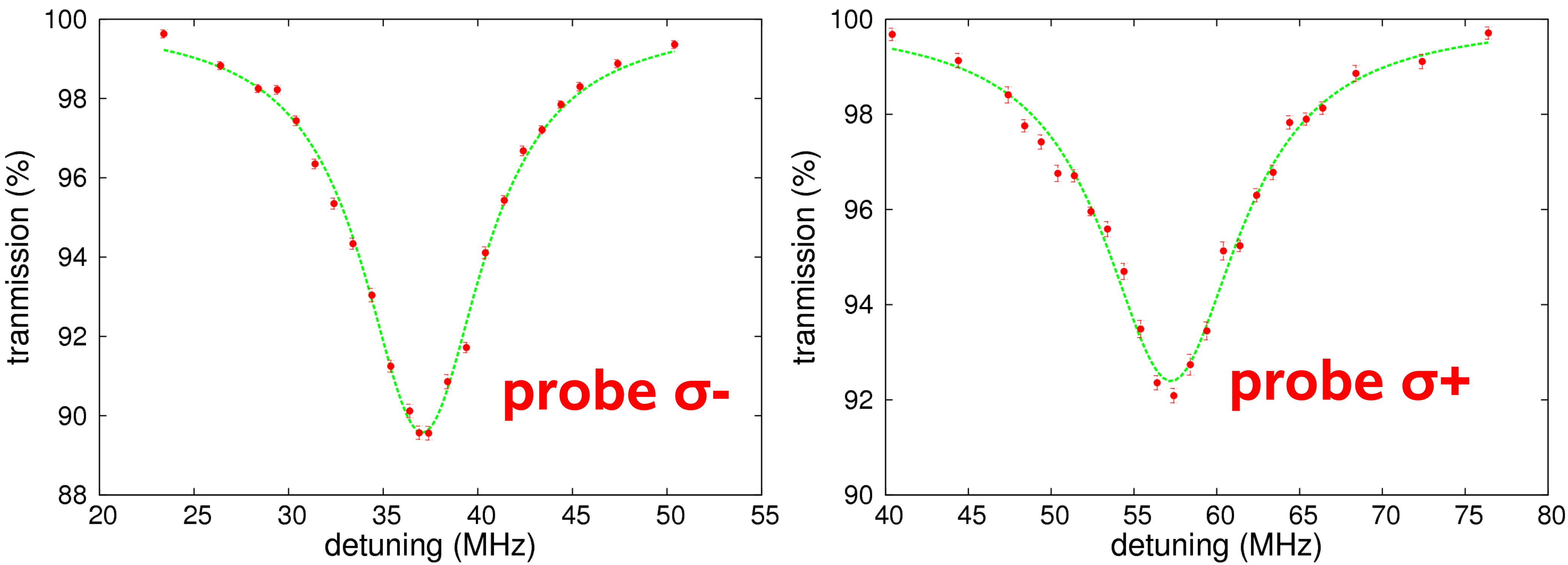
Single atom evidence

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





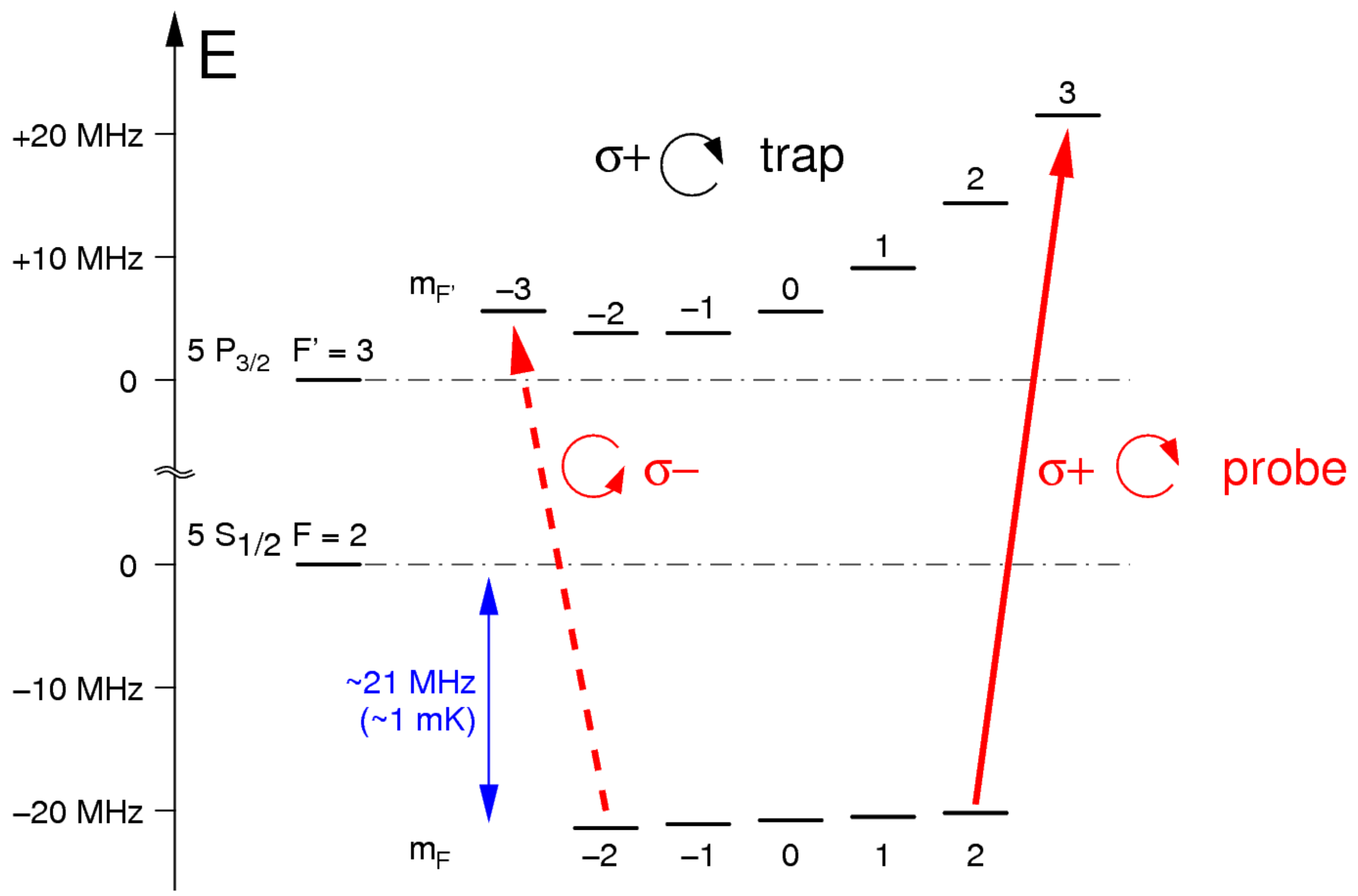
Transmission results



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

M. K. Tey, Z. Chen, S.A. Aljunid, B. Chng, F. Huber, G. Maslennikov,C. K.
nature physics ***4****, 924 (2008)*

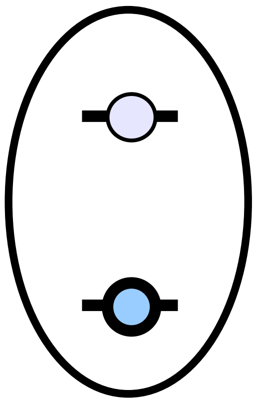
Atomic levels in a dipole trap



- 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:

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

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

$$\Gamma = \frac{\omega_{12}^3 d_{12}^2}{3\pi\epsilon_0 \hbar c^3}$$ 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

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

- 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

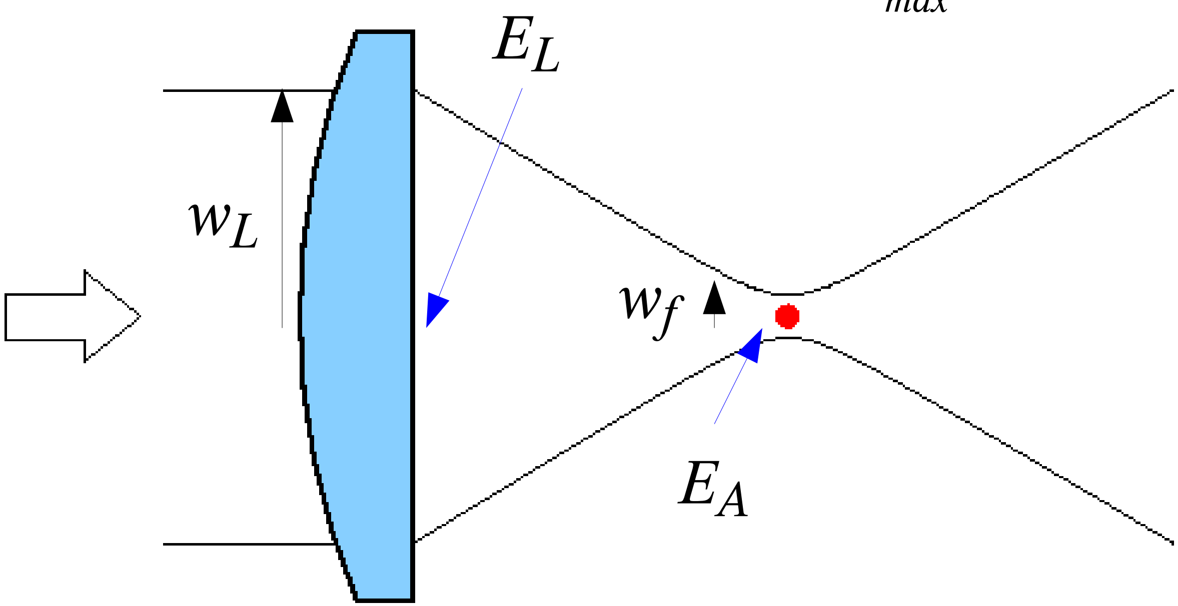
$$R_{sc} = \frac{P_{sc}}{P_{in}} = \frac{3\lambda^2}{\pi w_L^2}\left(\frac{E_A}{E_L}\right)^2 \approx \frac{3\lambda^2}{\pi w_f^2} \approx \sigma_{max}/A$$

focal area

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

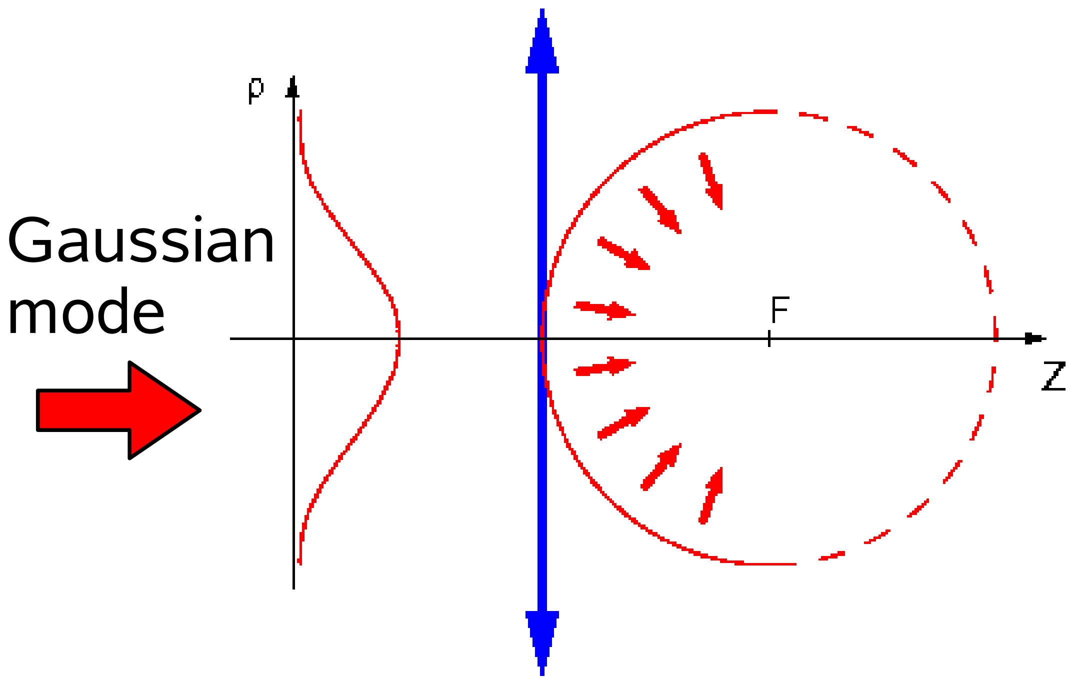
atomic scattering cross section

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



A more careful model

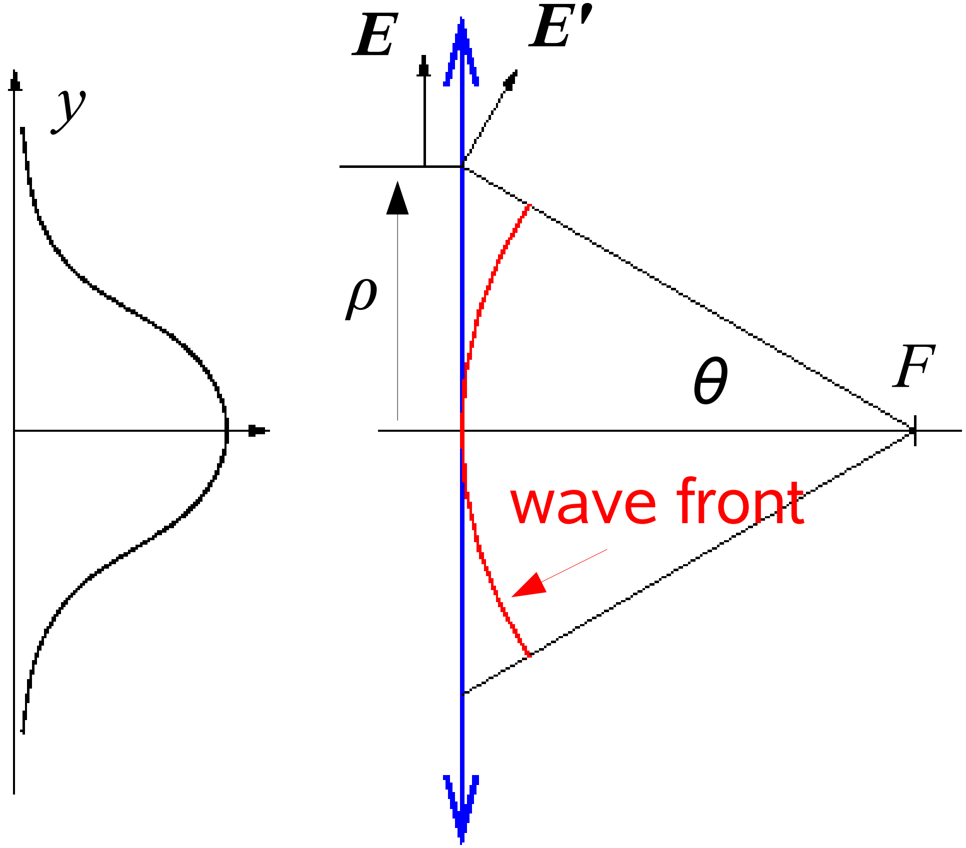
- assume spherical wave front and field compatible with Maxwell equations to get field at atom location
- determine atom response from semiclassical excitation probability for a given field
- combine atom response and original field



Step 2: Get field in focus

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

$$\boldsymbol{E} = E_L \hat{\epsilon}_+ e^{-\frac{\rho^2}{w_l^2}}$$



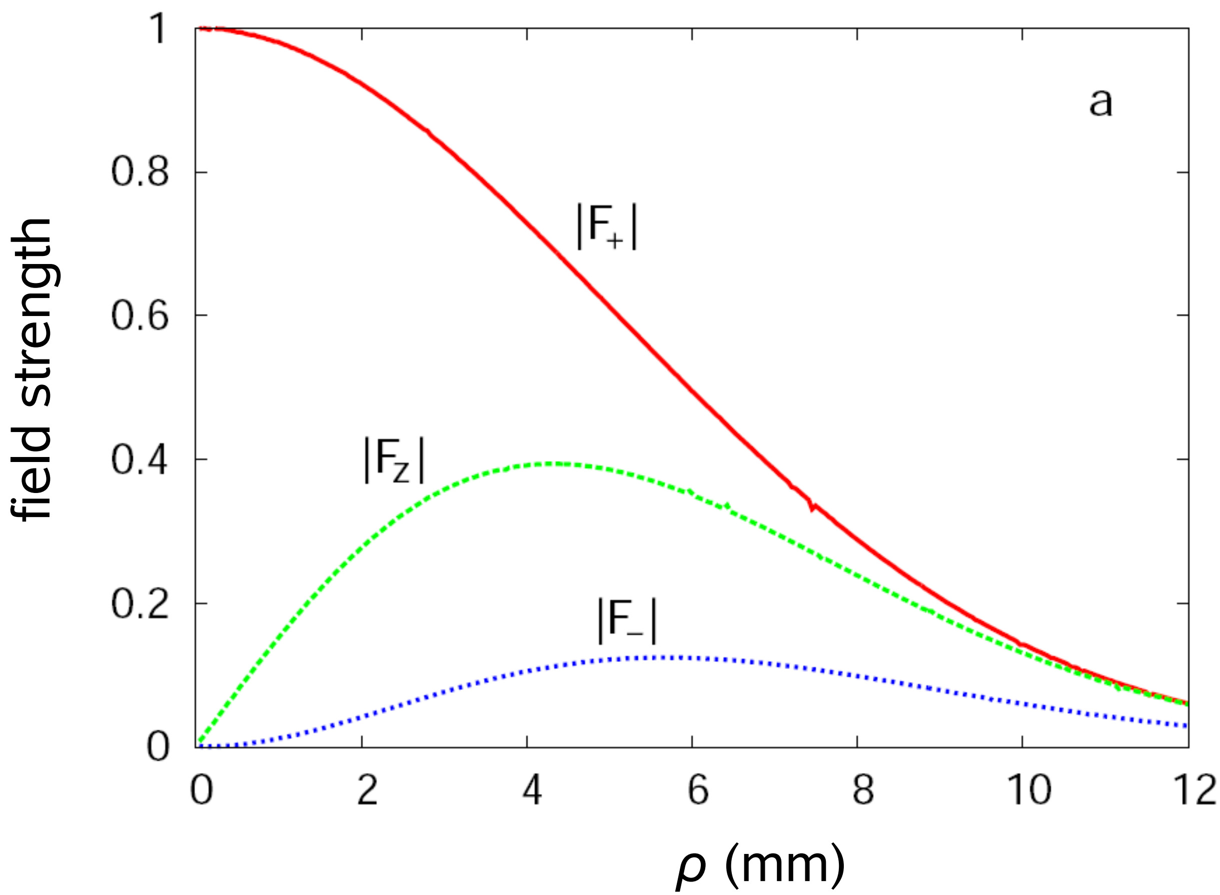
- spherical wave front
- locally transverse
- conserve power through each small area

(Richardson, Wolf, 1959)

(cyl. coordinates)

Directly after lens:

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



- 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

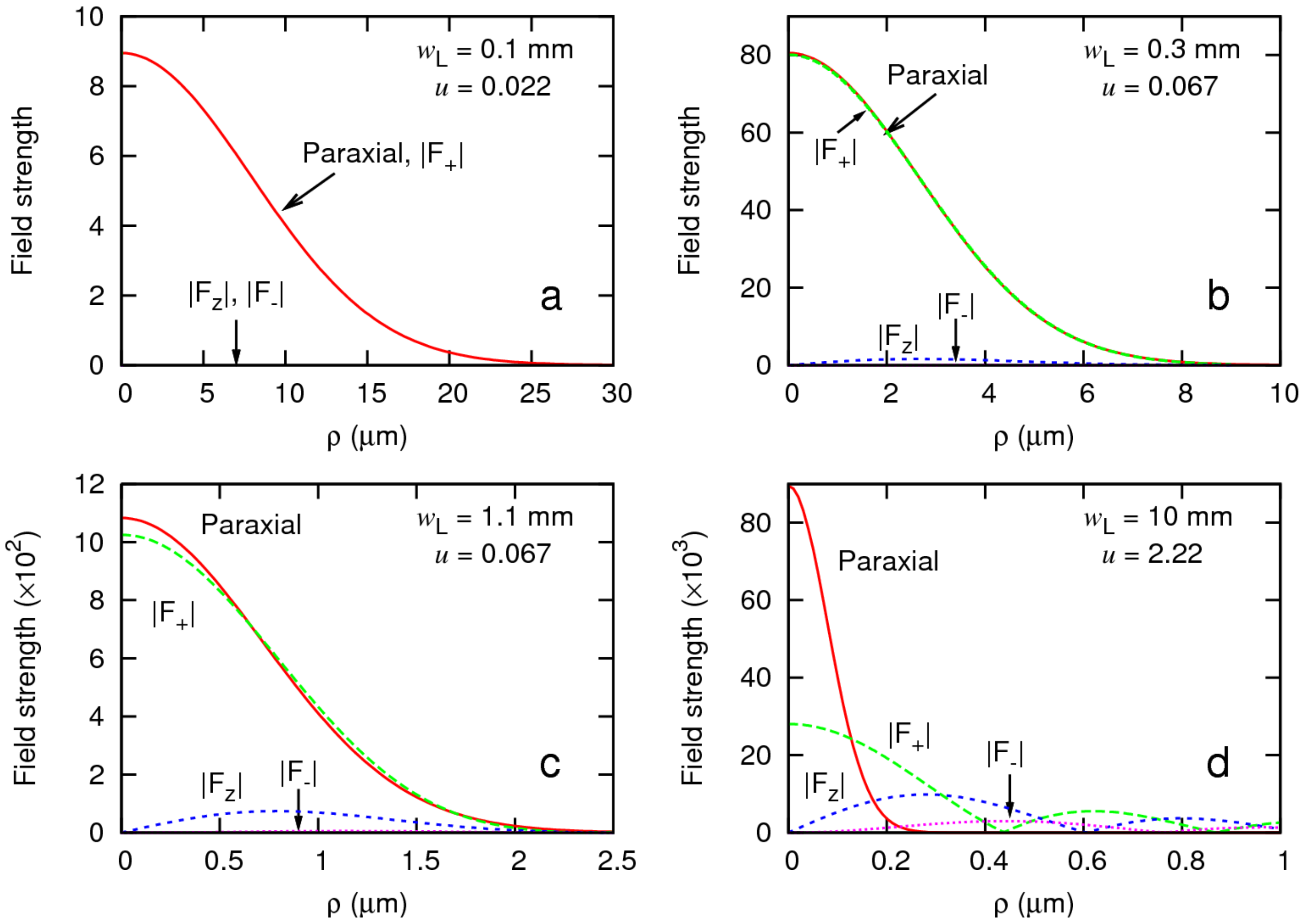
- closed expression for field at focus via Green theorem

$$\boldsymbol{E}(z=f,\rho=0)=\sqrt{\frac{\pi P_{in}}{\epsilon_0 c \lambda^2}}\cdot\frac{1}{u}e^{1/u^2}\left[\sqrt{\frac{1}{u}}\Gamma\left(-\frac{1}{4},\frac{1}{u^2}\right)+\sqrt{u}\,\Gamma\left(\frac{1}{4},\frac{1}{u^2}\right)\right]\hat{\epsilon}_+$$

with focusing strength $u:=w_L/f$

Focal fields for different w_L

- paraxial approximation starts to break down late...



(f = 4.5 mm)

Ooops...strange scattering?

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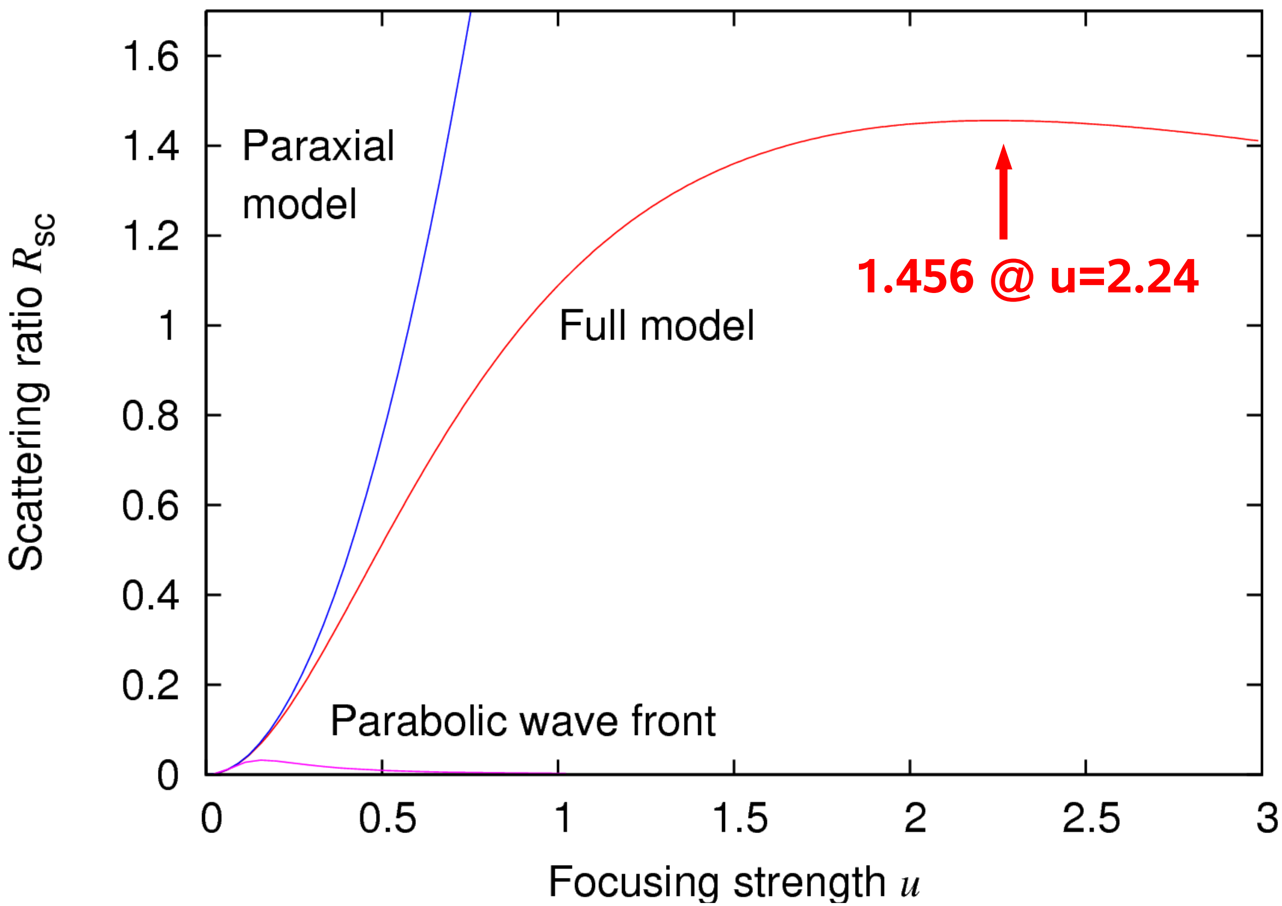
- scattering ratio like in plane wave excitation mode:

$$R_{sc}:=\frac{P_{sc}}{P_{in}}=\frac{3}{4u^3}e^{-2/u^2}\left[\Gamma\left(-\frac{1}{4},\frac{1}{u^2}\right)+u\,\Gamma\left(\frac{1}{4},\frac{1}{u^2}\right)\right]^2$$



???

Atomic response II

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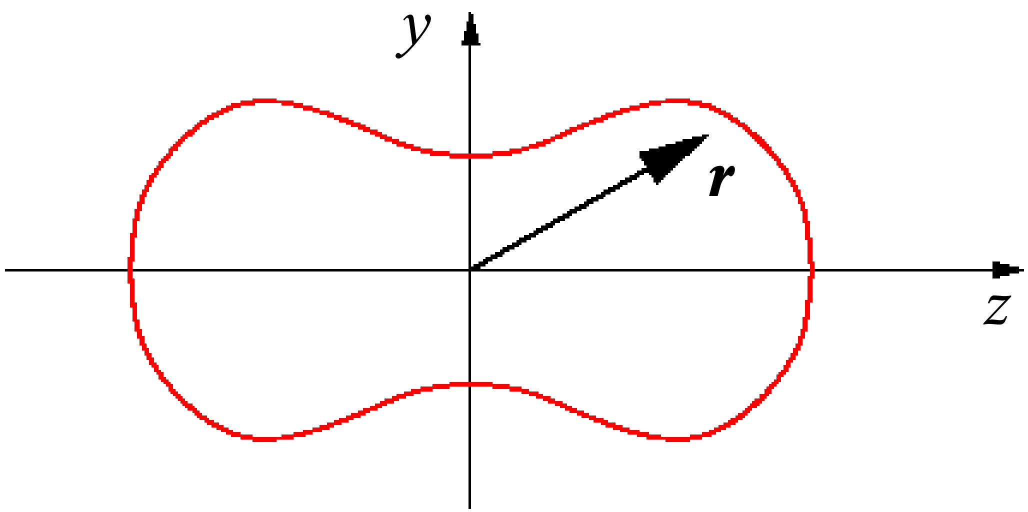
scattered field has electric dipole characteristic corresponding to σ+ transition

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

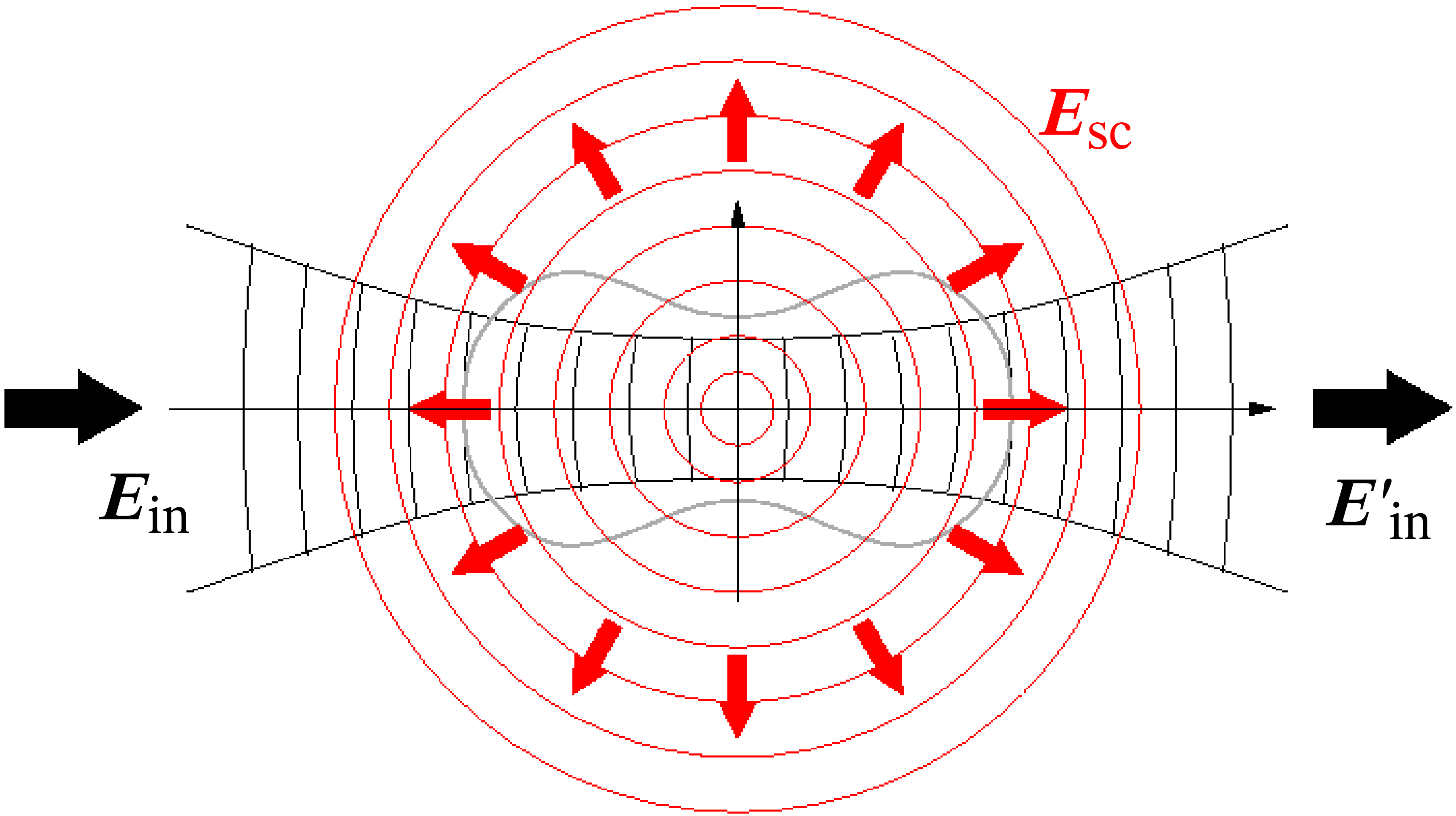
$$\hat{r} = \frac{1}{|\boldsymbol{r}|} \boldsymbol{r}$$ radial unit vector

$$\hat{\epsilon}_+ = \frac{\hat{x} + i\,\hat{y}}{\sqrt{2}}$$ circular unit vector



Step 3: Combine with probe

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



Collection into Gaussian mode

- Project total field onto Gaussian mode of collection fiber

$$P_{out} = \left| \langle \vec{g}, \vec{E}_{Tot} \rangle \right|^2 \qquad \langle \vec{g}, \vec{E} \rangle := \int_{\vec{x} \in S} \vec{E}_{Tot}(\vec{x}) \cdot \vec{g}(\vec{x}) (\vec{k}_g \cdot \vec{n}) \, dA$$

cross section   fiber mode

- Forward transmission:

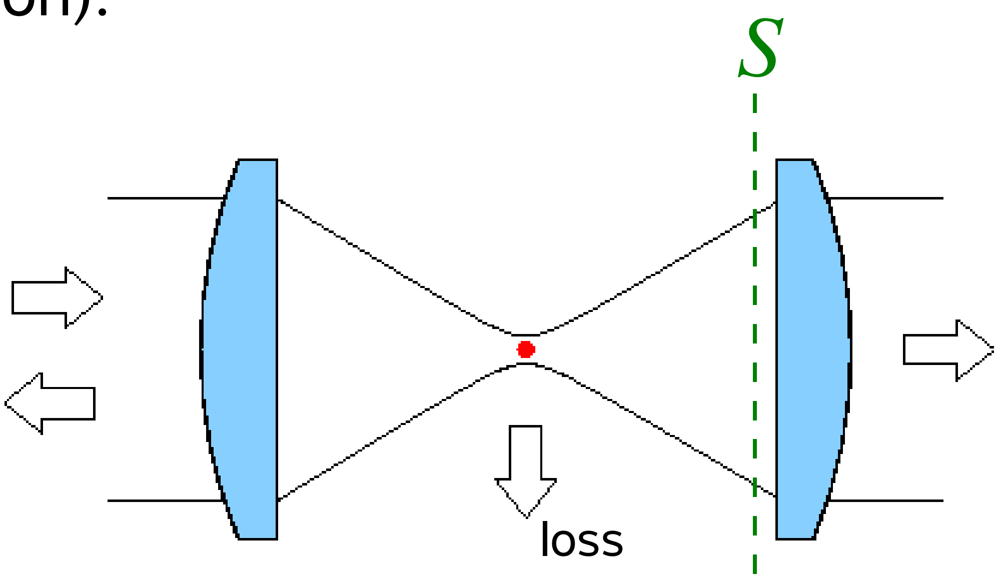
$$T = 1 - \epsilon = \frac{P_{out}}{P_{in}} = \left| 1 - \frac{R_{sc}}{2} \right|^2$$

- Reflectivity (backward direction):

$$R = \frac{R_{sc}^2}{4}$$

- Loss:

$$L = R_{sc} - \frac{R_{sc}^2}{2}$$



Scattering vs. focusing

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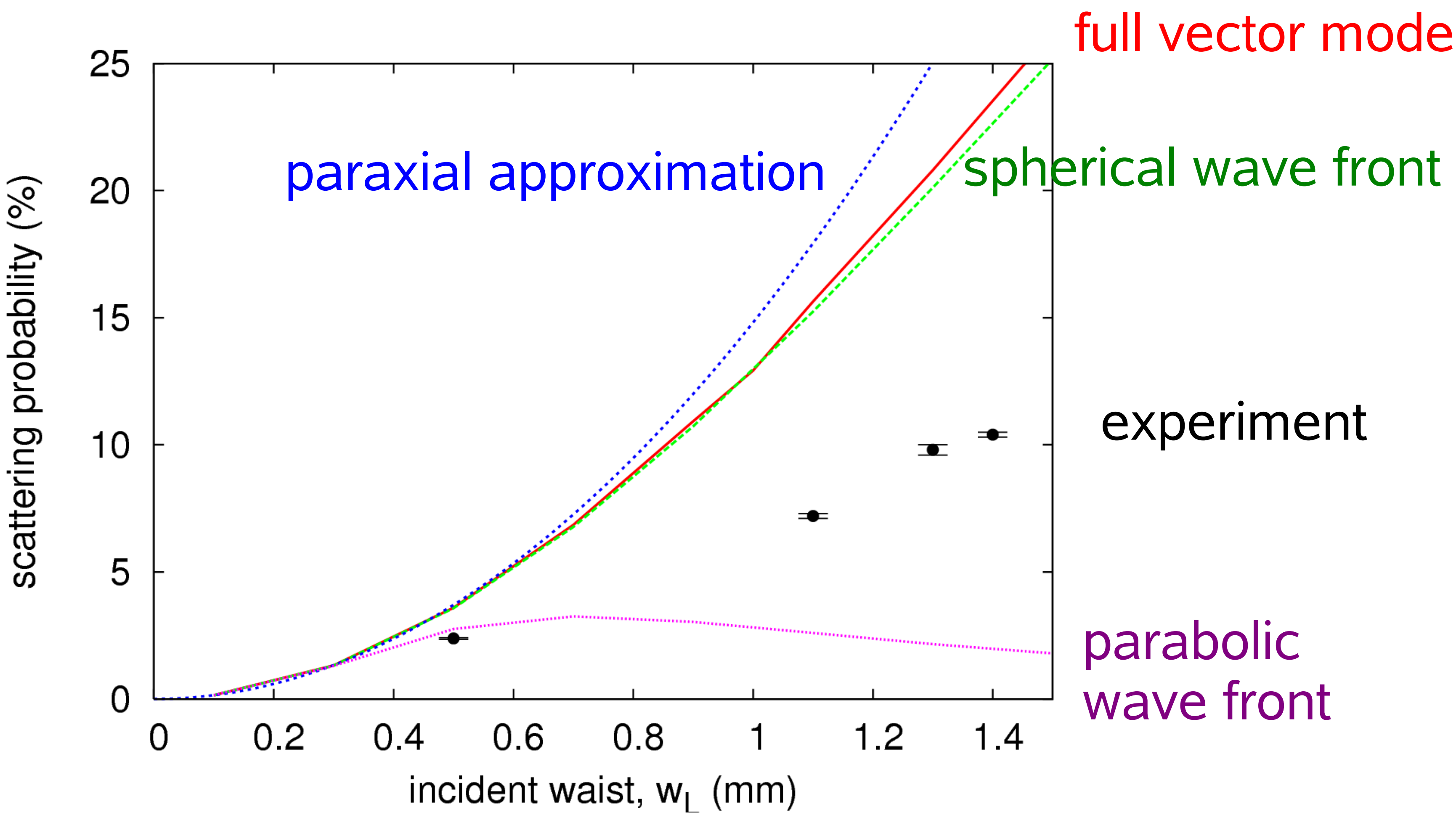
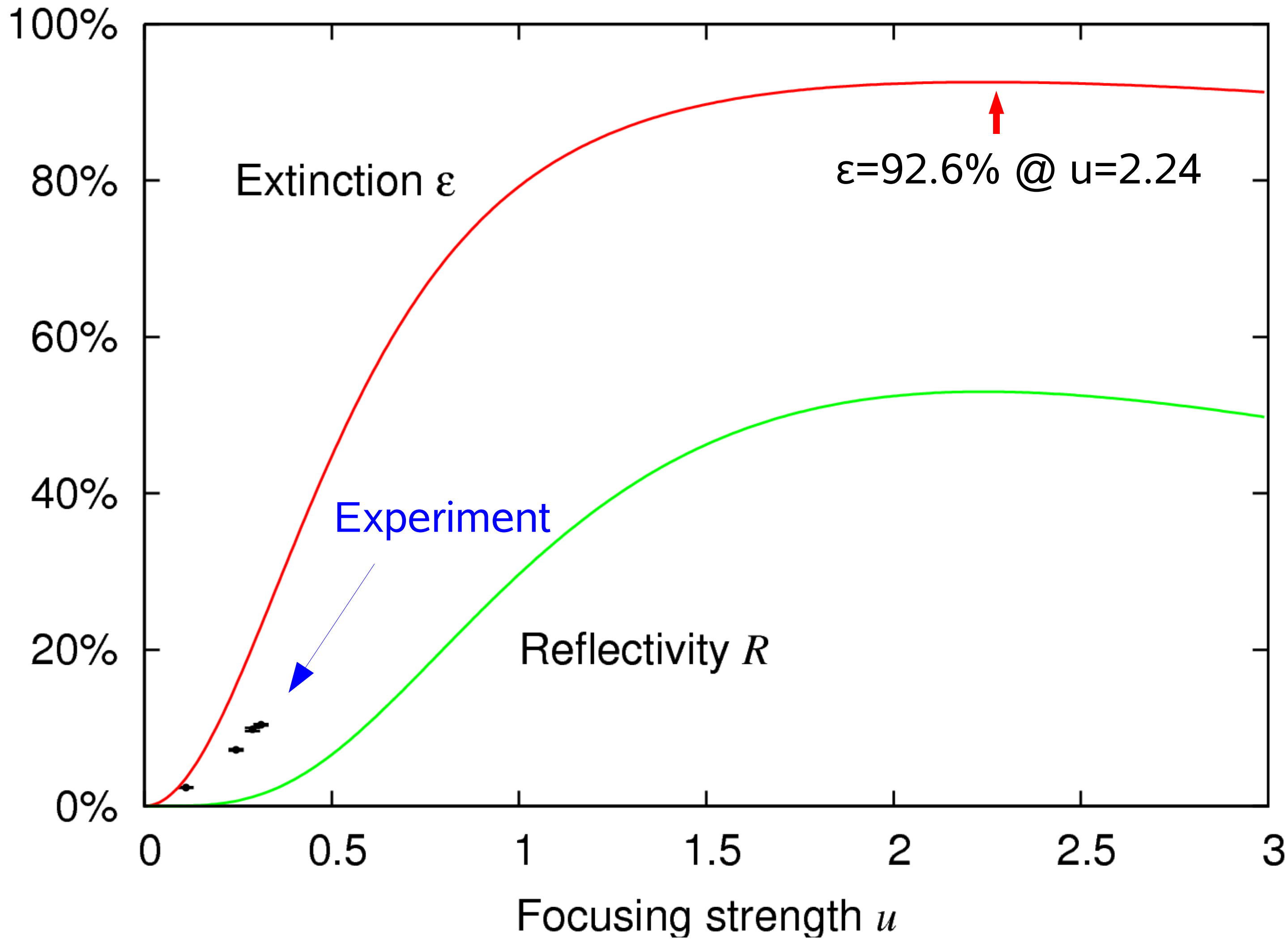


(experimental P_{sc} extracted out of transmission measurement)

(f = 4.5 mm)

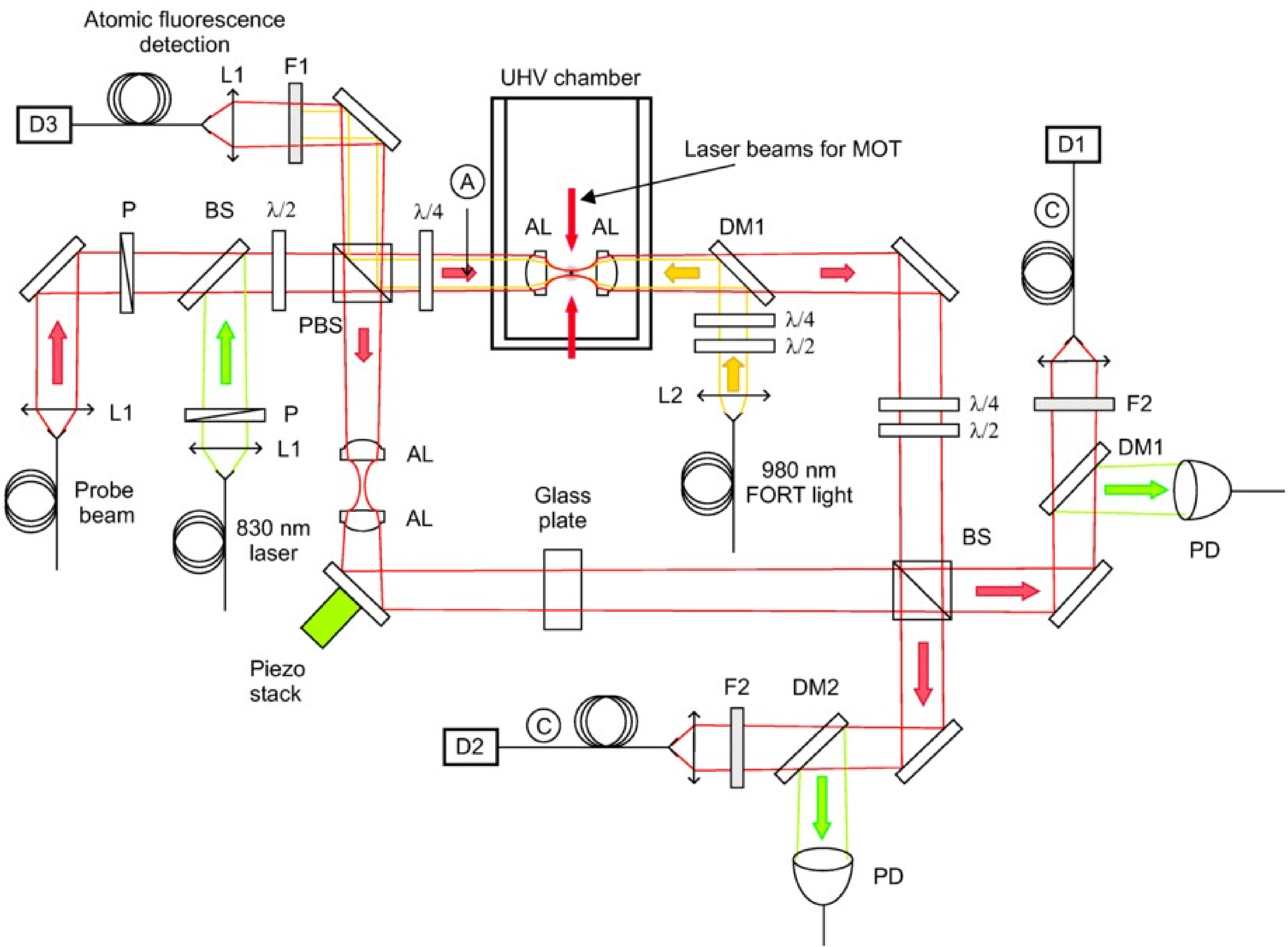
M.K. Tey, G. Maslennikov, T.C.H. Liew, et al., New J. Phys. ***11****, 040311 (2009)*

How far does this go?

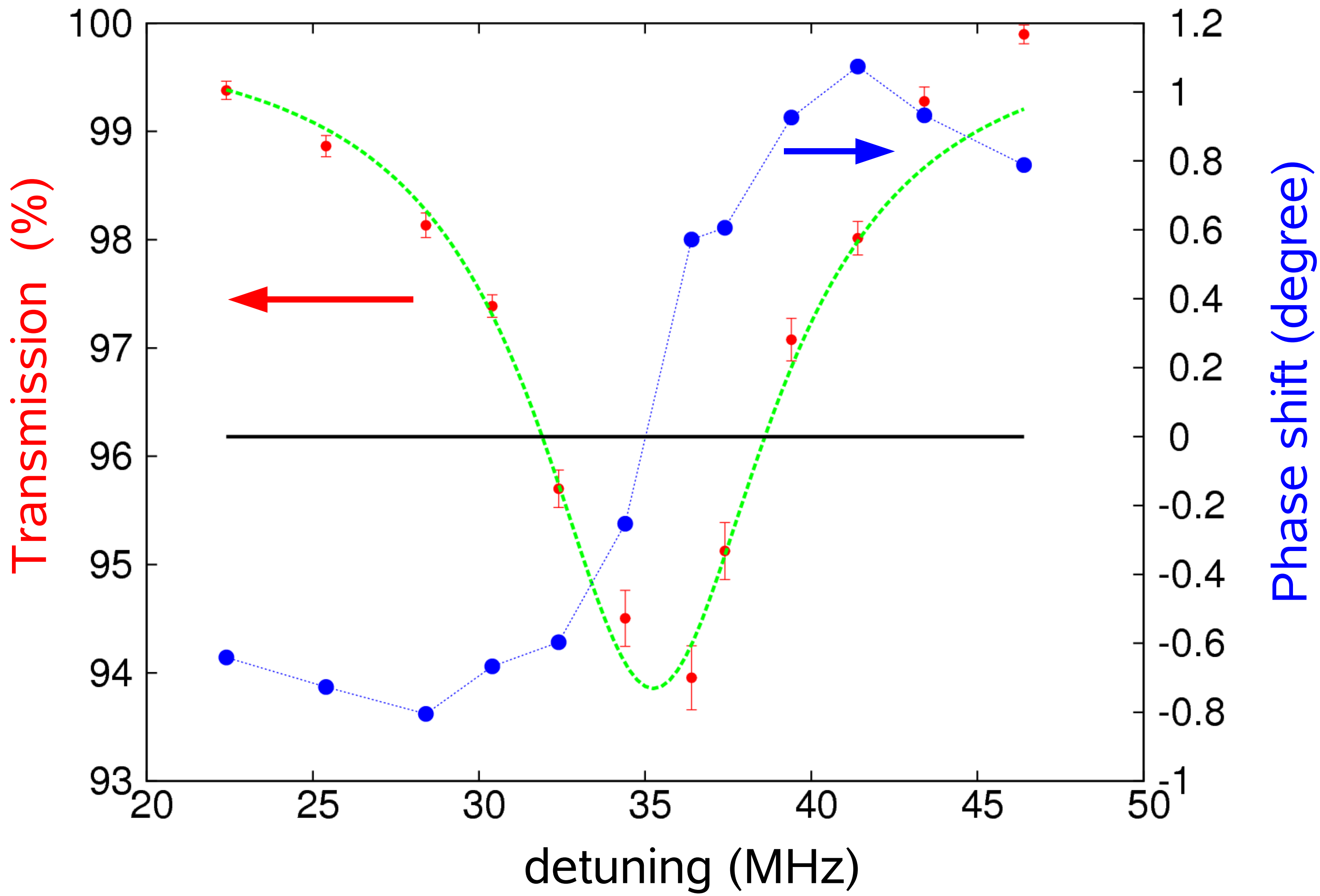


Single atom phase shift

Mach-Zehnder interferometer setup



Phase shift / Transmission



S.A. Aljunid, M.K. Tey, B. Chng,et al., arXiv:0905:3734

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
- Try larger numerical apertures
- Look for backscattered light
- Connect to nonclassical light sources....

Thank you!

Meng Khoon Tey (now UIBK)
Syed Abdullah Aljunid
Zilong Chen (now JILA)
Florian Huber (now Harvard)
Brenda Chng
Jianwei Lee

Timothey Liew
Gleb Maslennikov

Valerio Scarani
Christian Kurtsiefer

http://www.qolah.org
(has also this talk)

Results (collect full NA)

- Extinction

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

- Reflectivity (backward direction)

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

- No energy gets lost