Substantial scattering of photons by a Single Atom

Syed Abdullah Aljunid, Meng Khoon Tey,
Brenda Chng, Zilong Chen, Jianwei Lee, Timothey Liew,*
Gleb Maslennikov, Valerio Scarani, Christian Kurtsiefer*

SPW 2009, 6. November 2009 @ NIST, Boulder

Centre for Quantum Technologies

NUS National University of Singapore

Atom-Photon interface

Motivation:

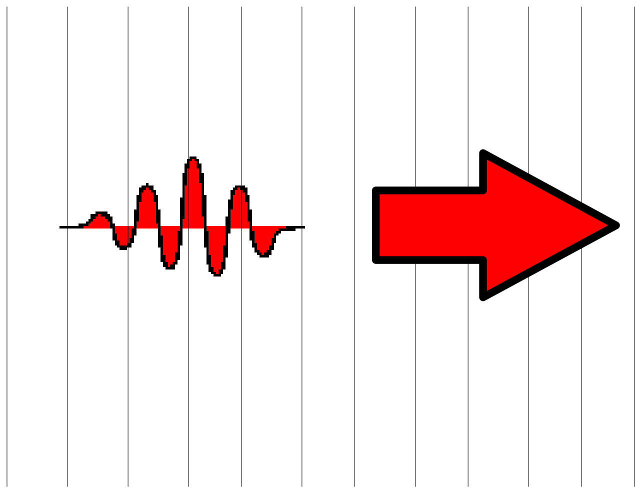
- Atoms and photons are good for different quantum information tasks – allow an exchange of quantum information between them
- Understand elementary interaction between flying qubits and single atoms
- Explore possibilities of controlled phase gates & friends for photonic qubits

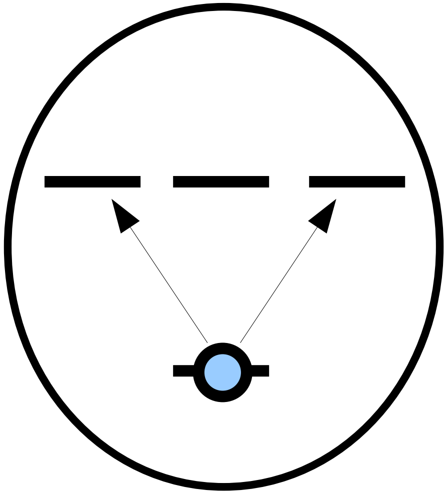
Key idea:

- 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





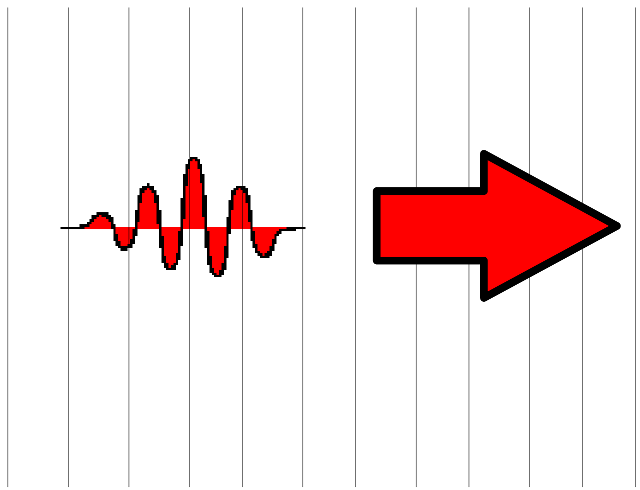
$$|\Psi_L\rangle = \alpha|L\rangle + \beta|R\rangle$$

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

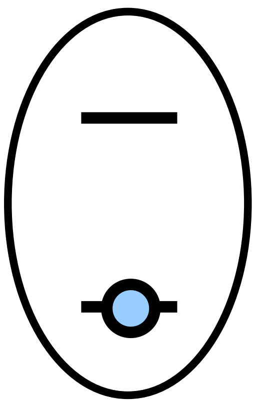
- requires internal states of atom and an **absorption process**

The basic problem

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

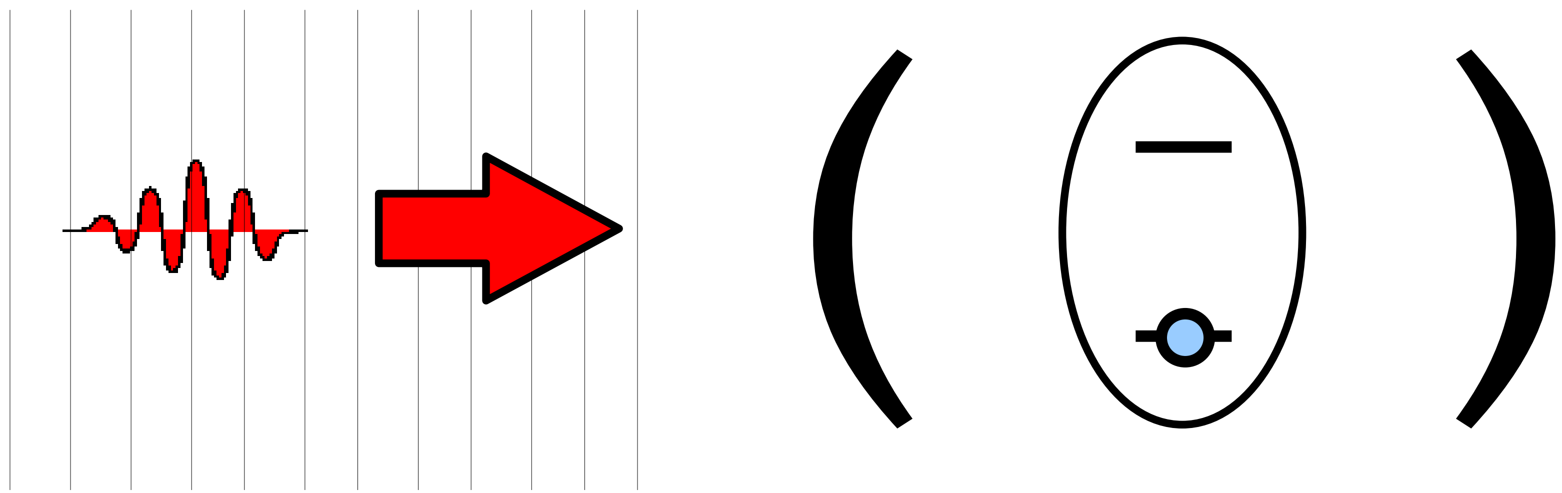


electromagnetic field / photon



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

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

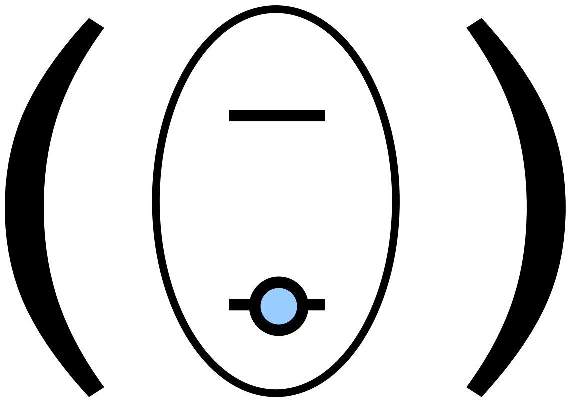
Electrical field operator (single freq):

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

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



- atom Hamiltonian

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

- electric dipole interaction

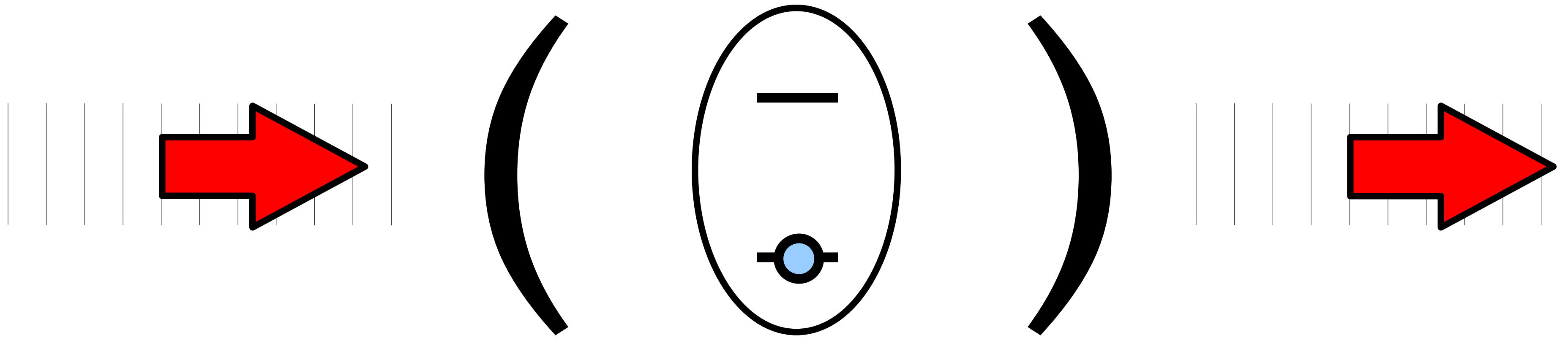
$$\hat{H}_I = \hat{\boldsymbol{E}} \cdot \hat{\boldsymbol{d}} \quad \text{with} \quad \hat{\boldsymbol{d}} = \boldsymbol{e}\, d_{eff} \left(|e\rangle\langle g| + |g\rangle\langle e| \right)$$

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

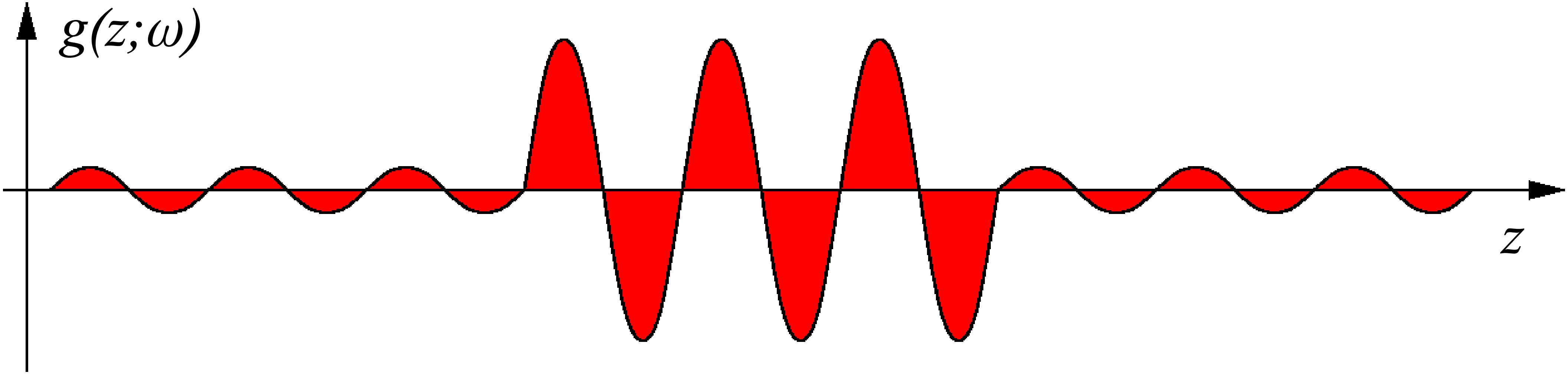
.....Jaynes-Cummings model with all its aspects

- treat external fields as perturbation/spectator of internal field

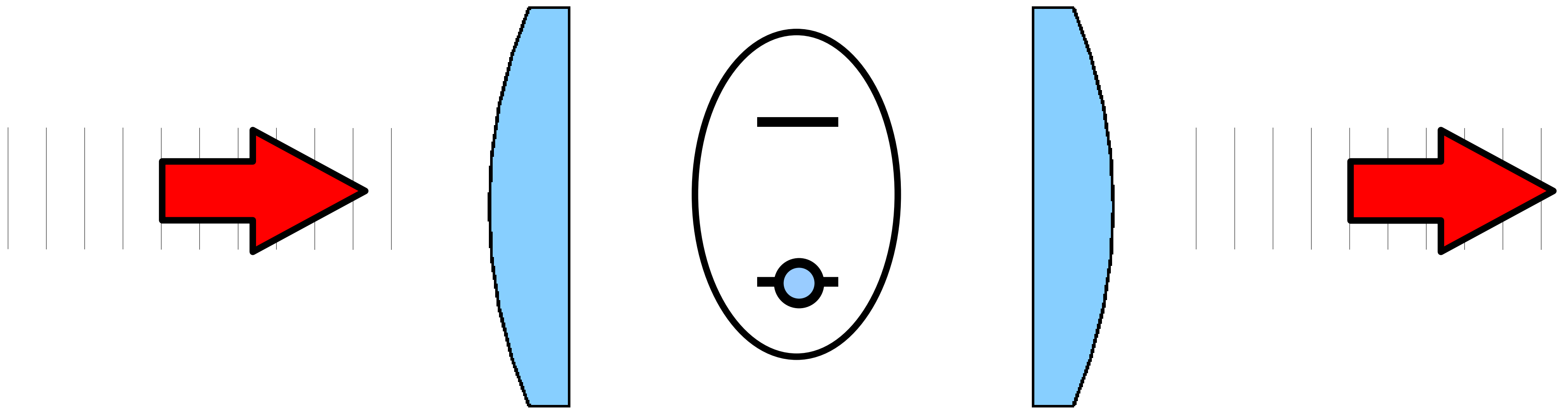
External view of cavity+atom



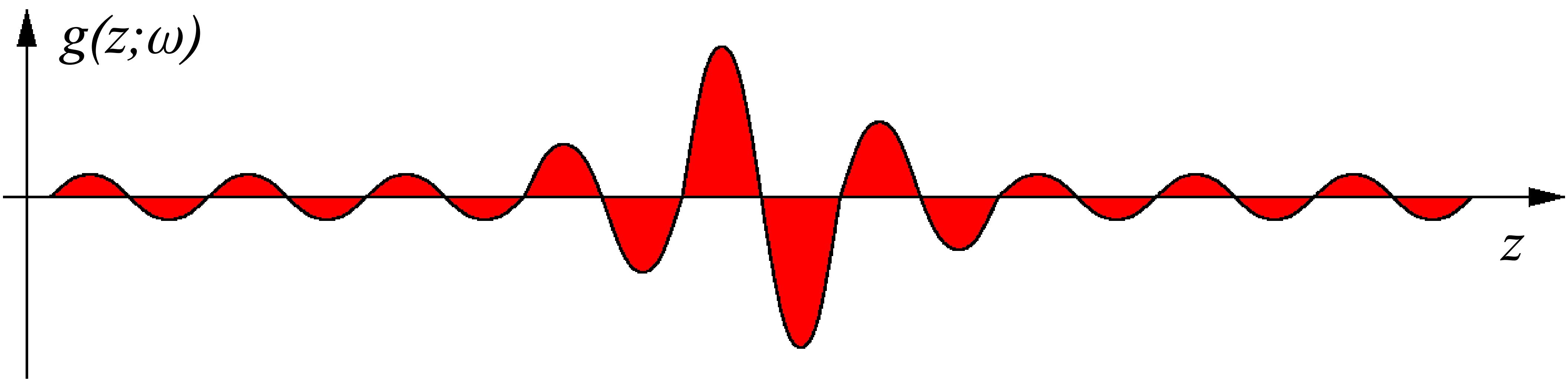
- continuous mode spectrum with enhanced/reduced field mode function:



An alternative approach

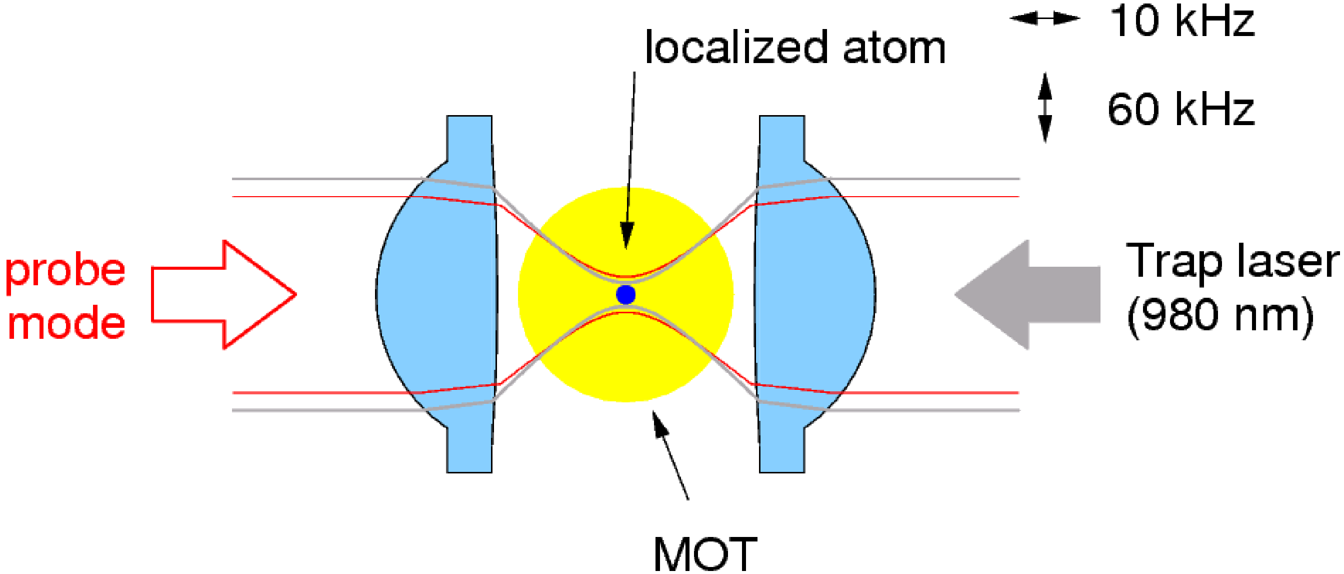


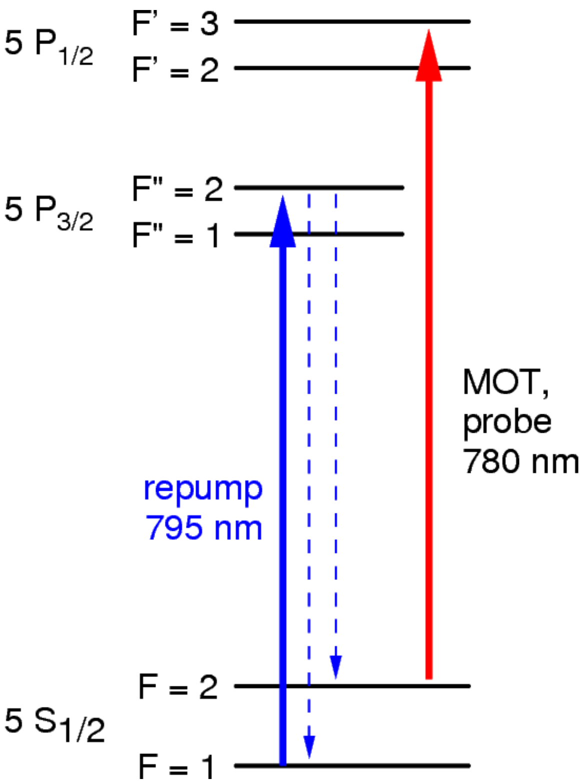
- use a **focusing lens pair** to enhance center mode function:



Experiment

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

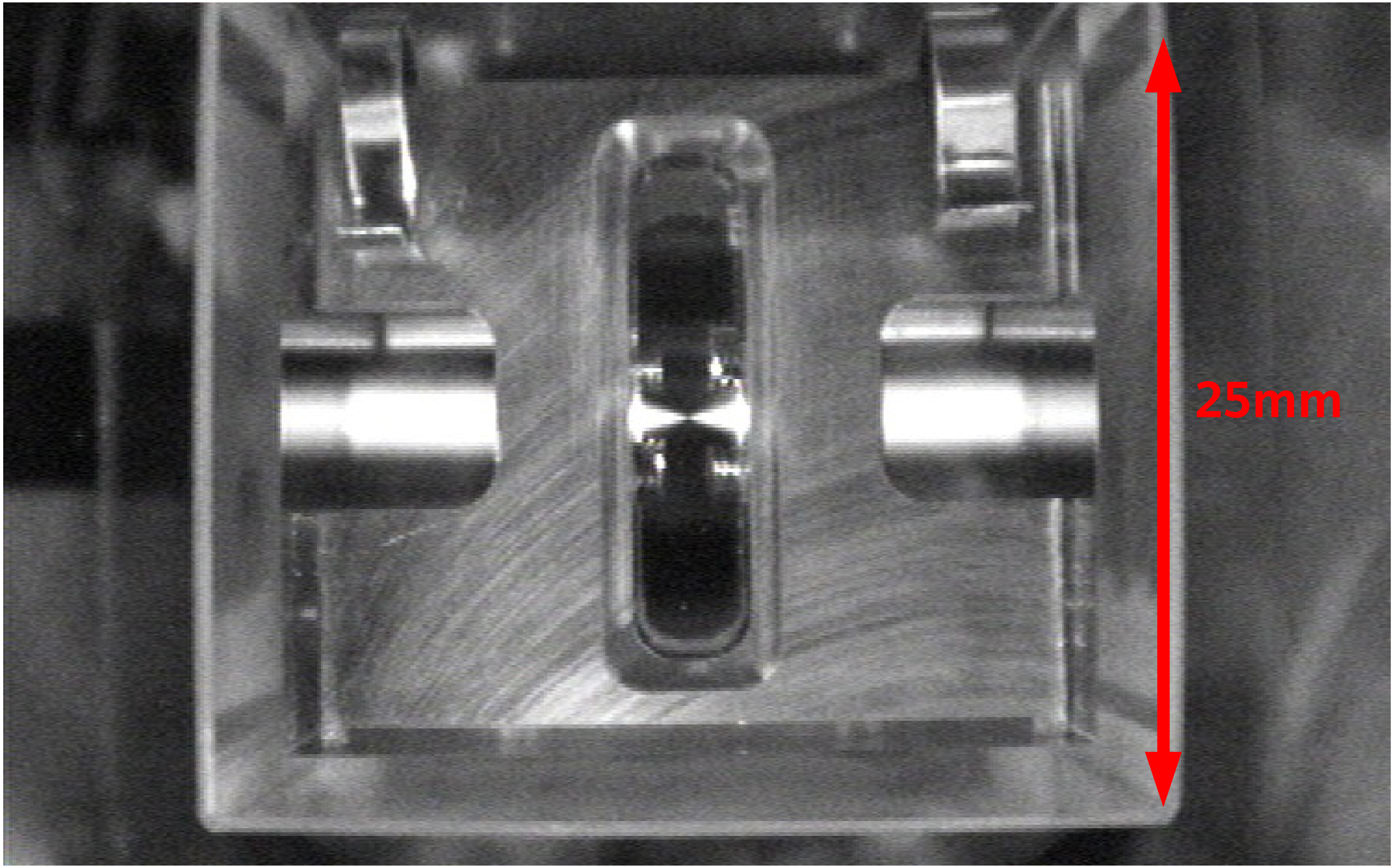




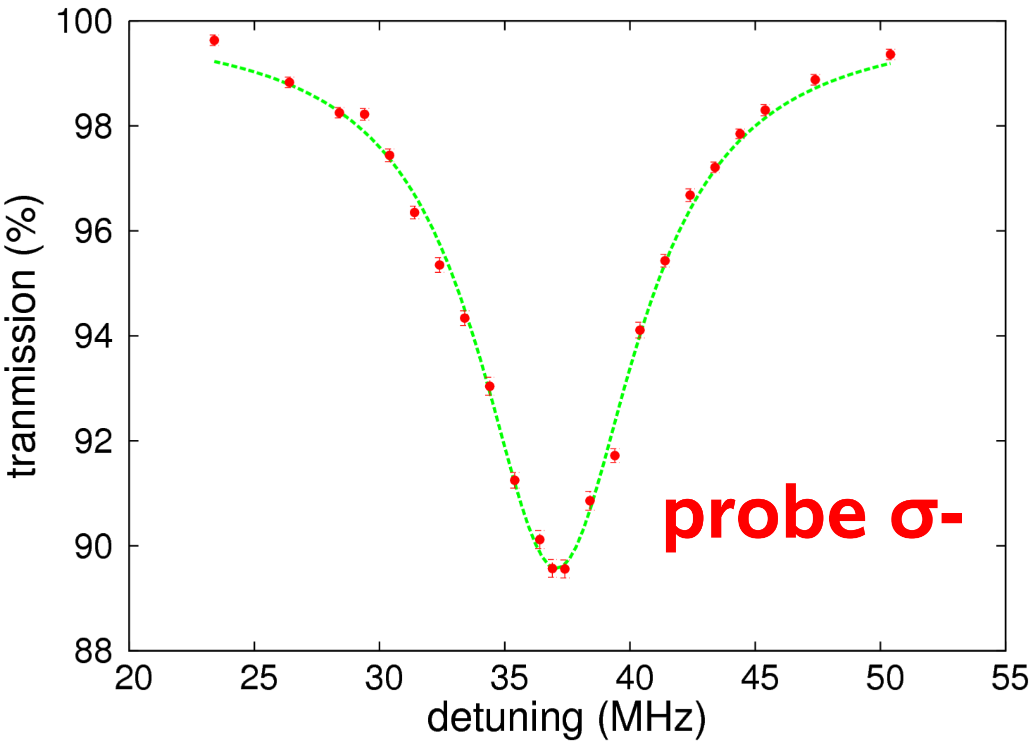
- use Rubidium-87 atom because it is convenient

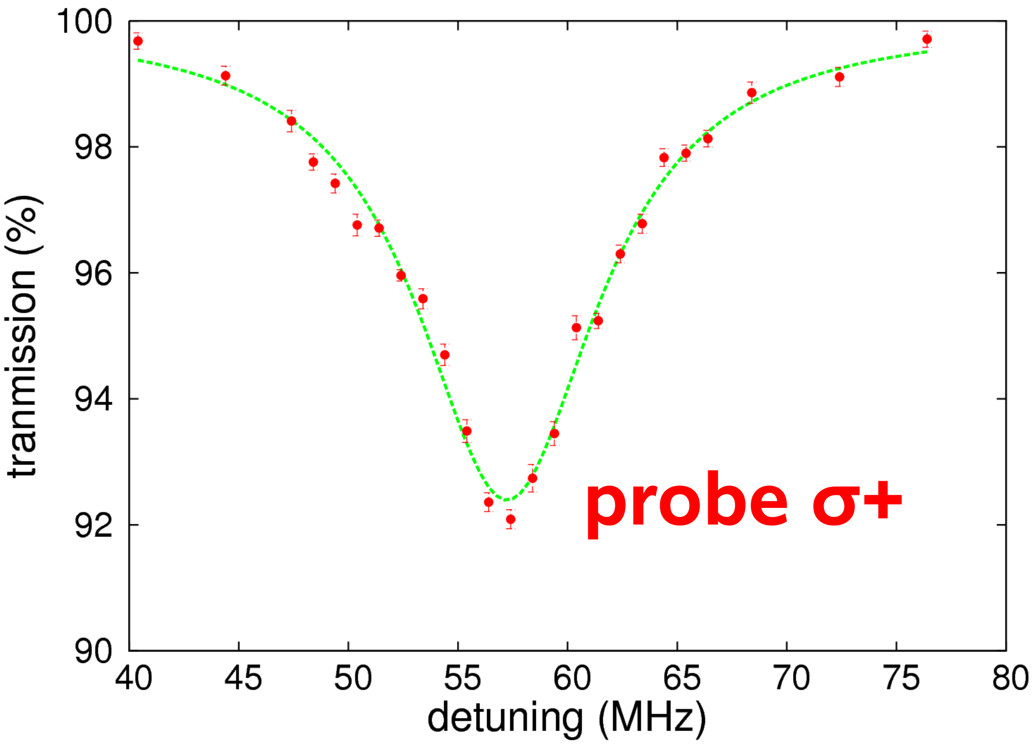
Focusing geometry...

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



Transmission results

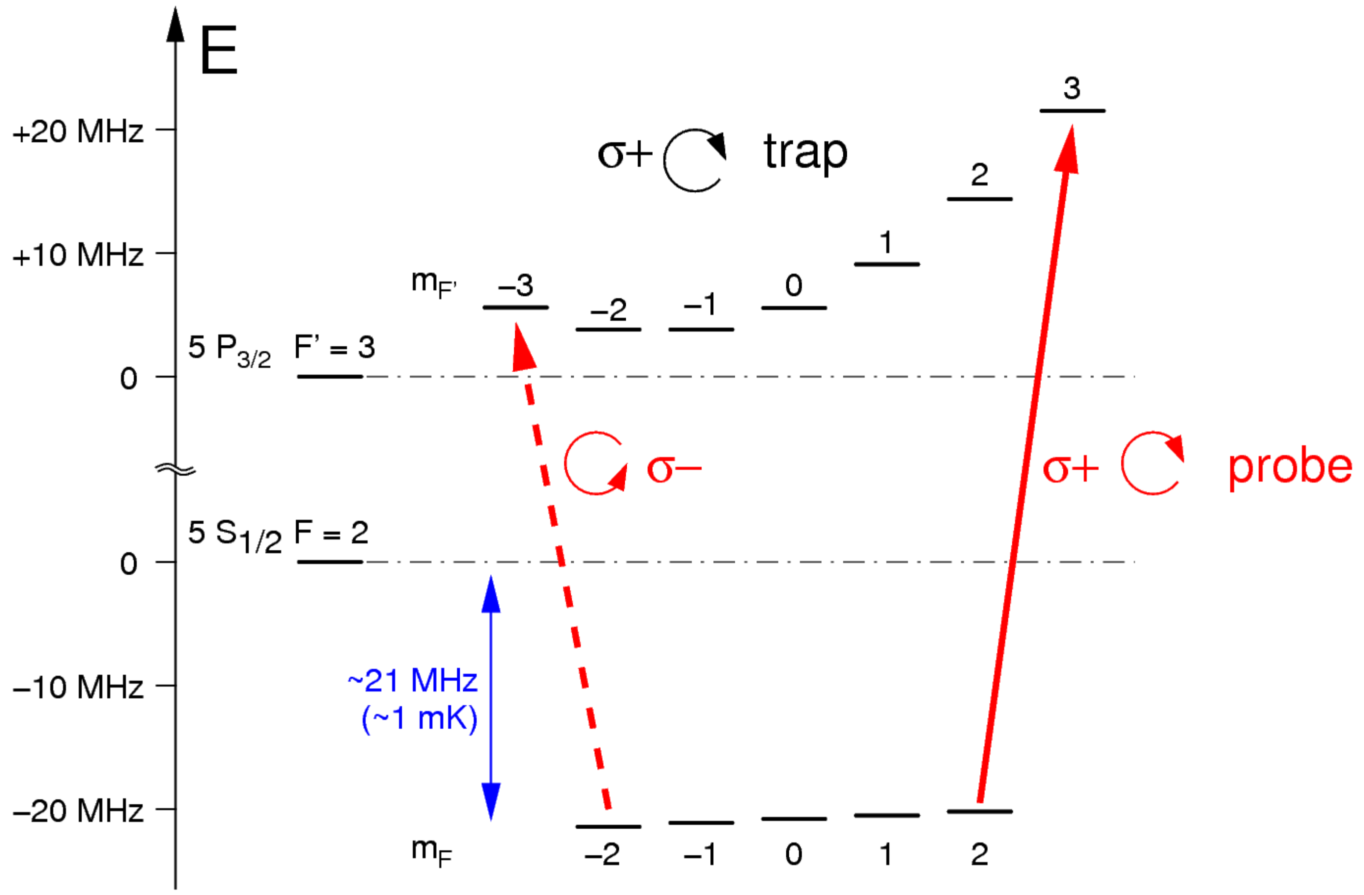




- almost natural line width of atomic transition
- different resonances for different probe polarizations

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

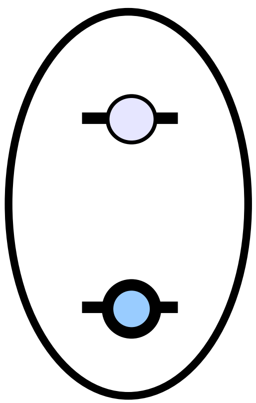
Atomic levels in a dipole trap



- 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 scattering rate $\rho_e \Gamma$ leads to

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

Simple model II

paraxial approximation

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

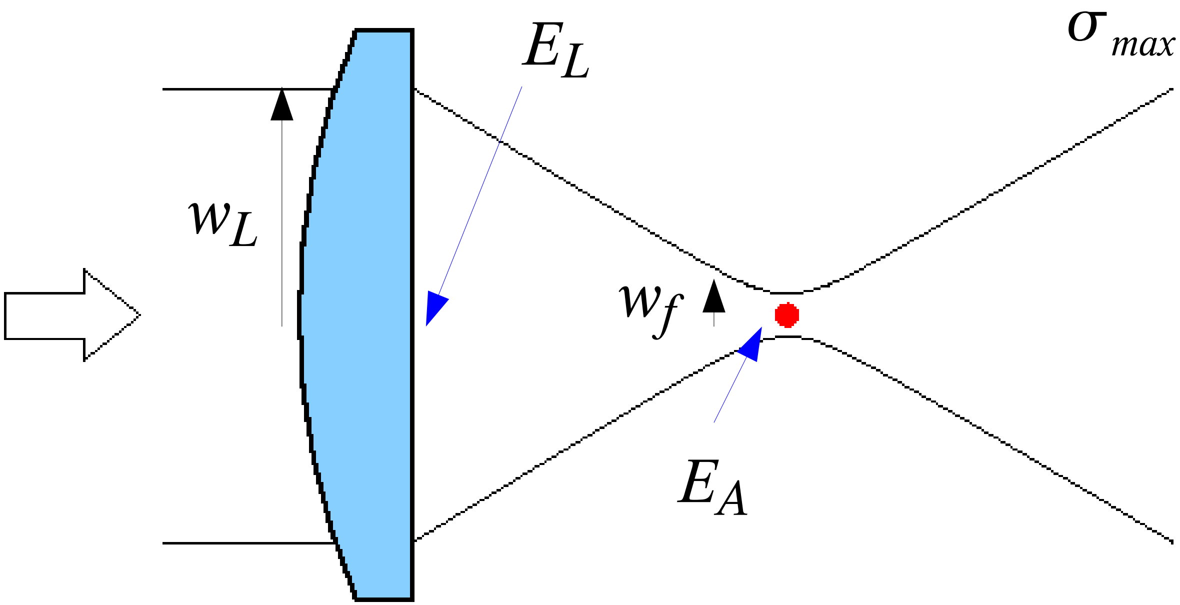
focal area

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

focusing strength $u := w_L / f$

atomic scattering cross section

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

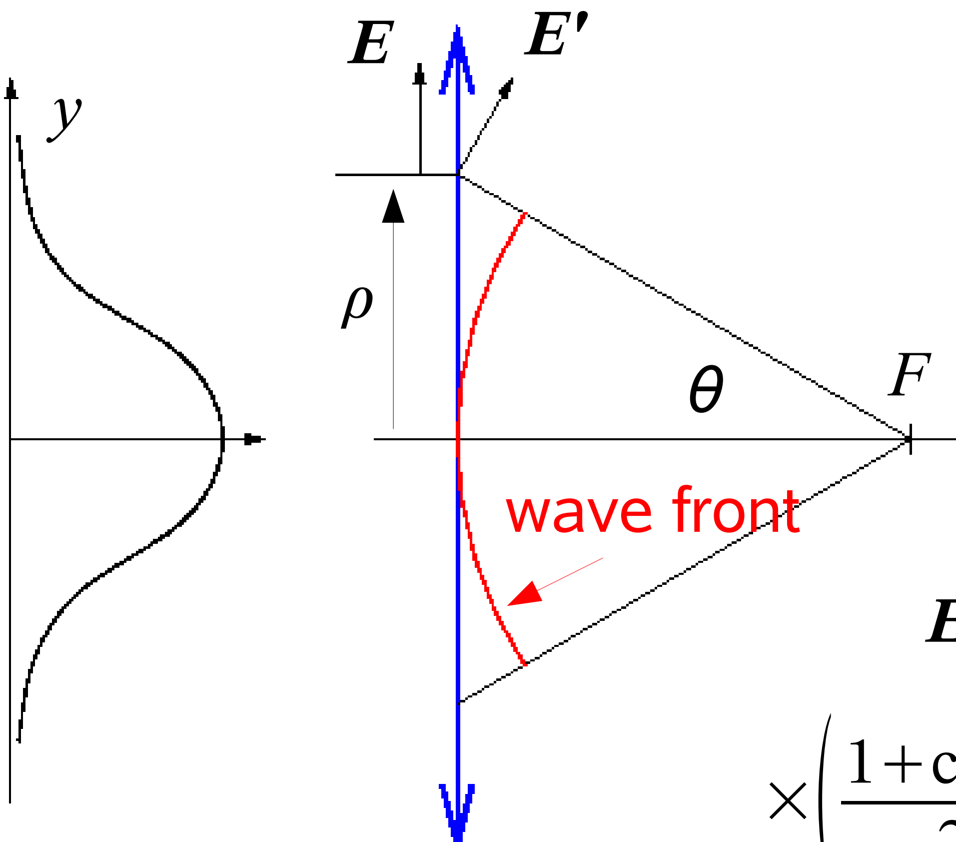


E_A diverges, use full expression for field

Step 2: Get exact field in focus

Circularly polarized Gaussian beam.....

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



....transformed by an ideal lens:

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

(Richardson/Wolf criteria, ~1950)

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

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

Propagate field to focus

Exact propagation to focus:

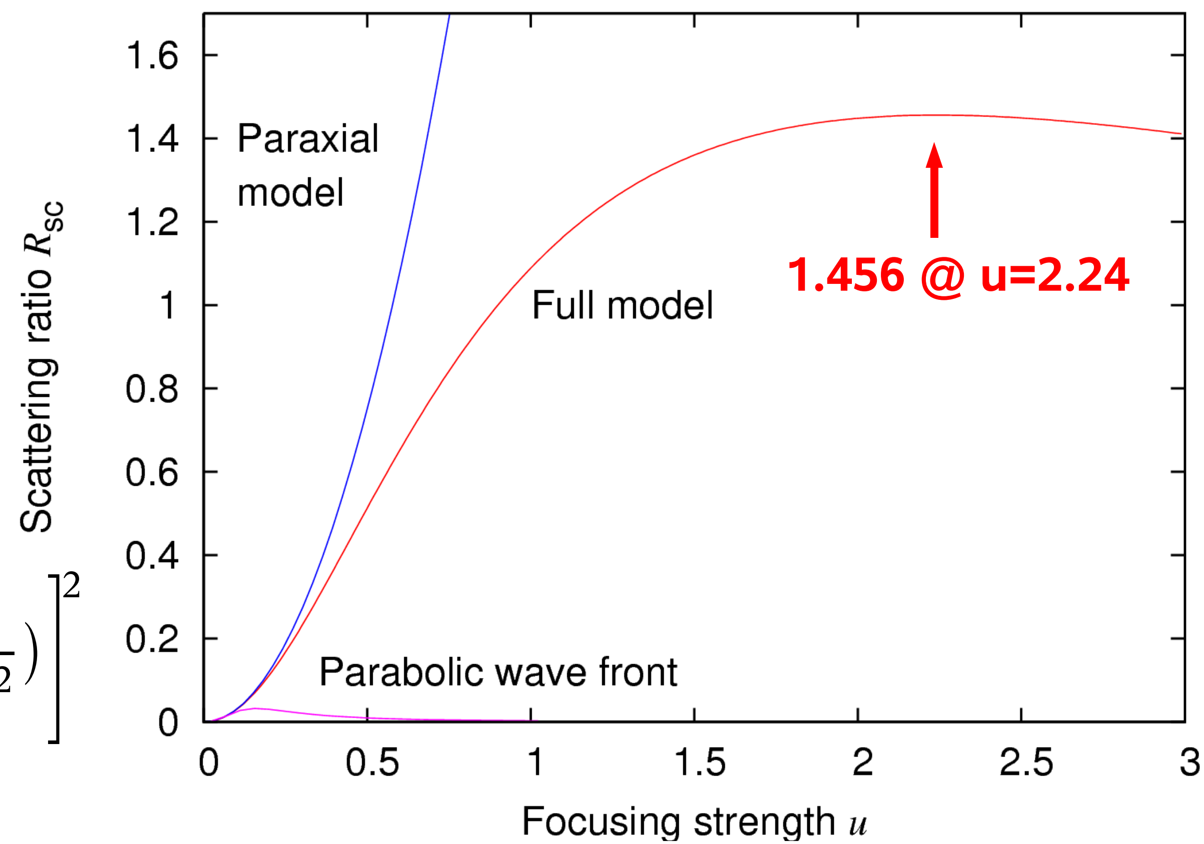
$$\boldsymbol{E}_A(z=f,\rho=0)=\sqrt{\frac{\pi P_{in}}{\epsilon_0 c\lambda^2}}\cdot\frac{1}{u}e^{1/u^2}\left[\sqrt{\frac{1}{u}}\Gamma\left(-\frac{1}{4},\frac{1}{u^2}\right)+\sqrt{u}\,\Gamma\left(\frac{1}{4},\frac{1}{u^2}\right)\right]\hat{\epsilon}_+,$$

leads to "scattering ratio"

$$R_{sc}:=\frac{P_{sc}}{P_{in}} =$$

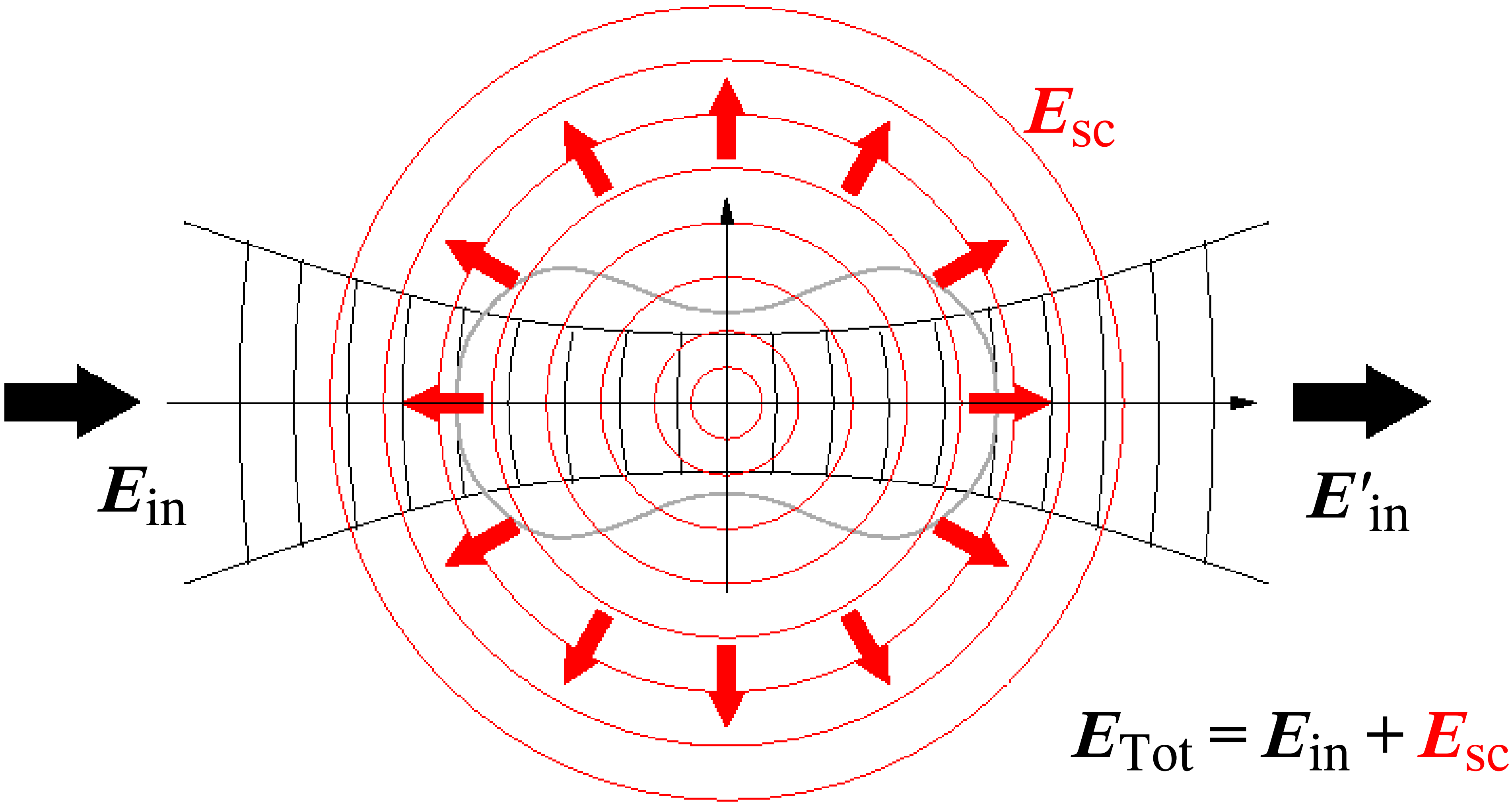
$$=\frac{3}{4u^3}e^{-2/u^2}\times$$

$$\times\left[\Gamma\left(-\frac{1}{4},\frac{1}{u^2}\right)+u\,\Gamma\left(\frac{1}{4},\frac{1}{u^2}\right)\right]^2$$



Step 3: Combine with probe

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



Collection into Gaussian mode

- Project total field onto Gaussian mode of collection fiber

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

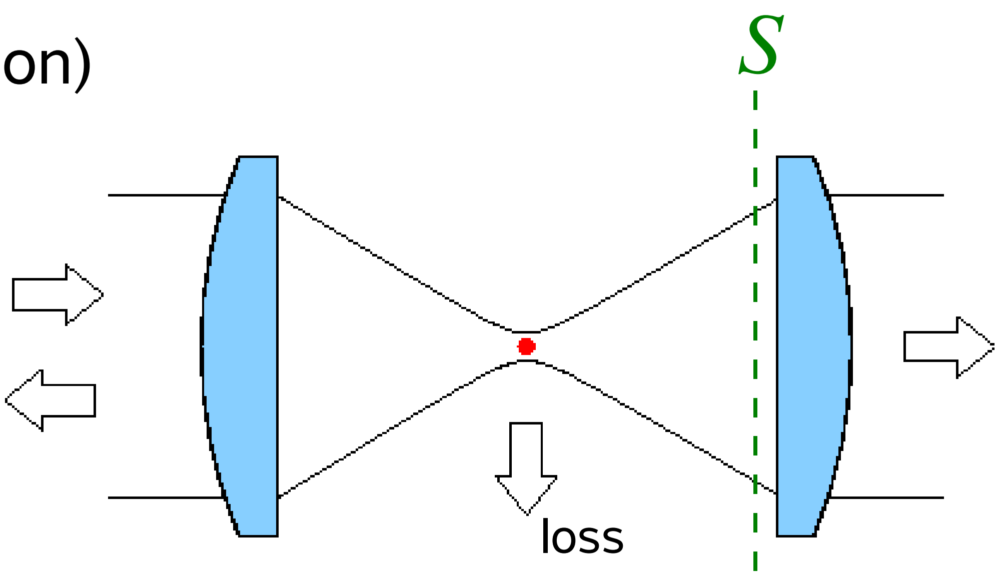
cross section　　fiber mode

- Forward transmission:

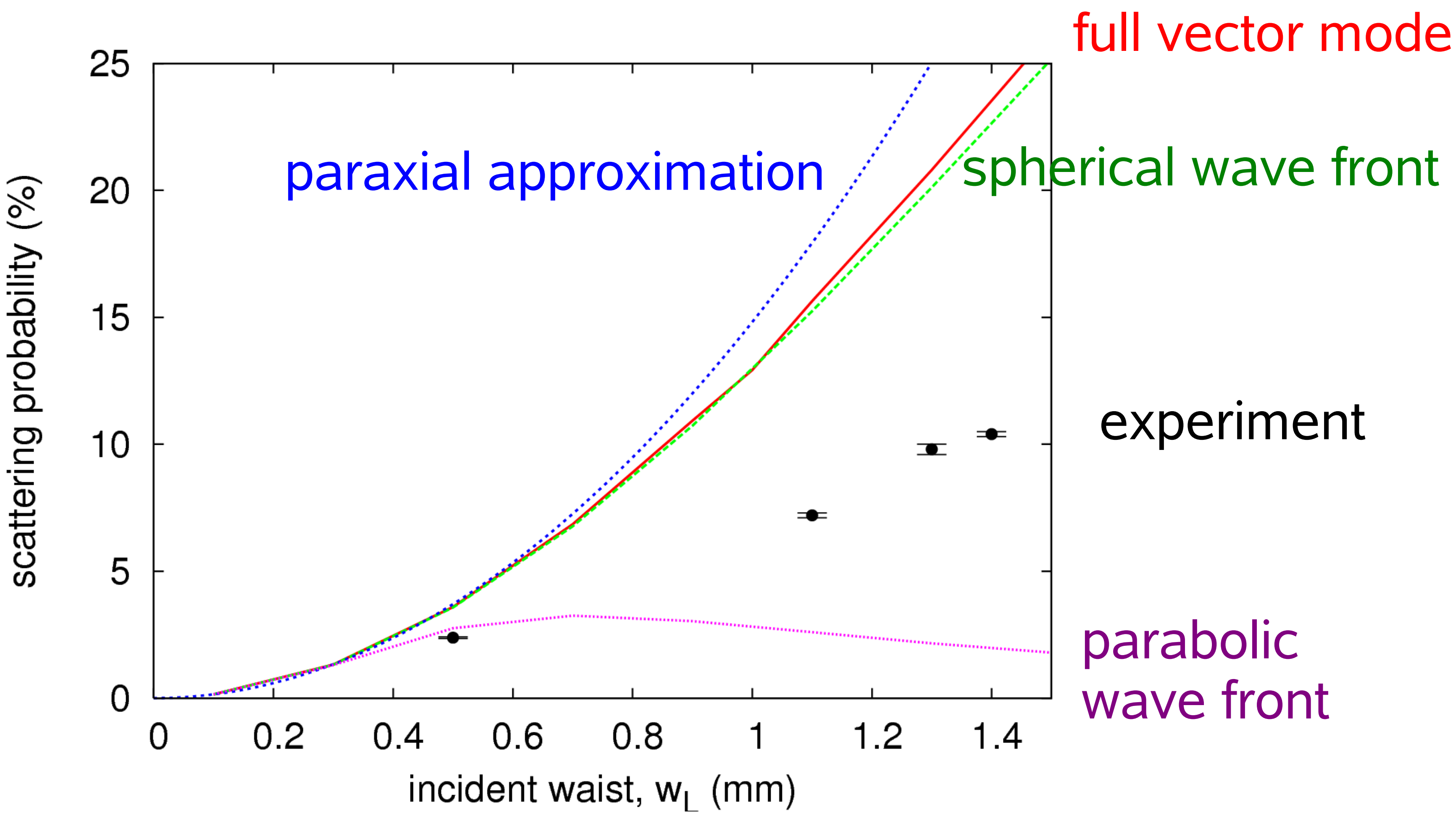
$$1 - \epsilon = \frac{P_{out}}{P_{in}} = \left| 1 - \frac{P_{sc}/P_{in}}{2} \right|^2$$

- Reflectivity (backward direction)

$$R = \frac{(P_{sc}/P_{in})^2}{4}$$



Scattering vs. focusing

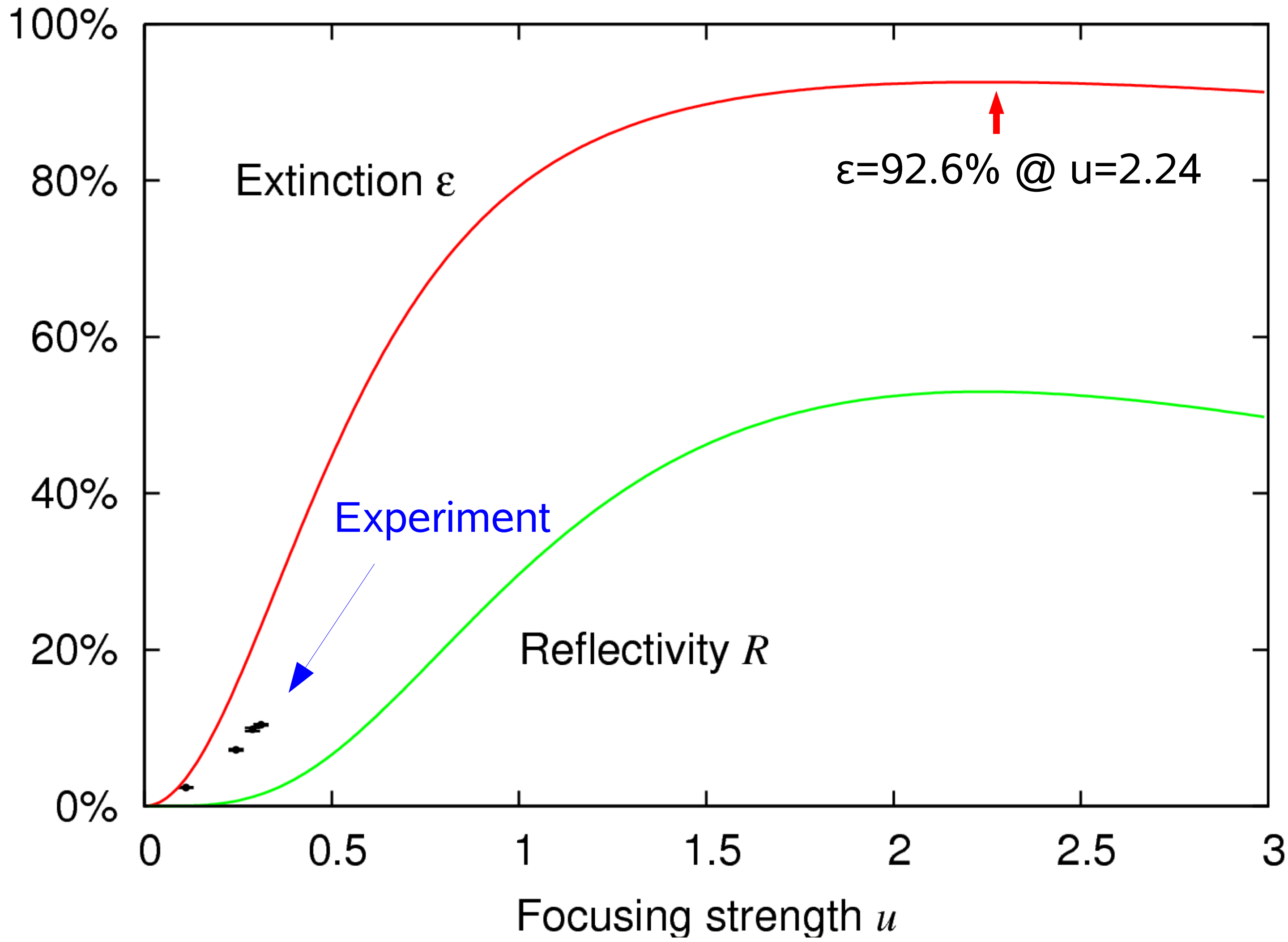


(experimental P_{sc} extracted out of transmission measurement)

(f = 4.5 mm)

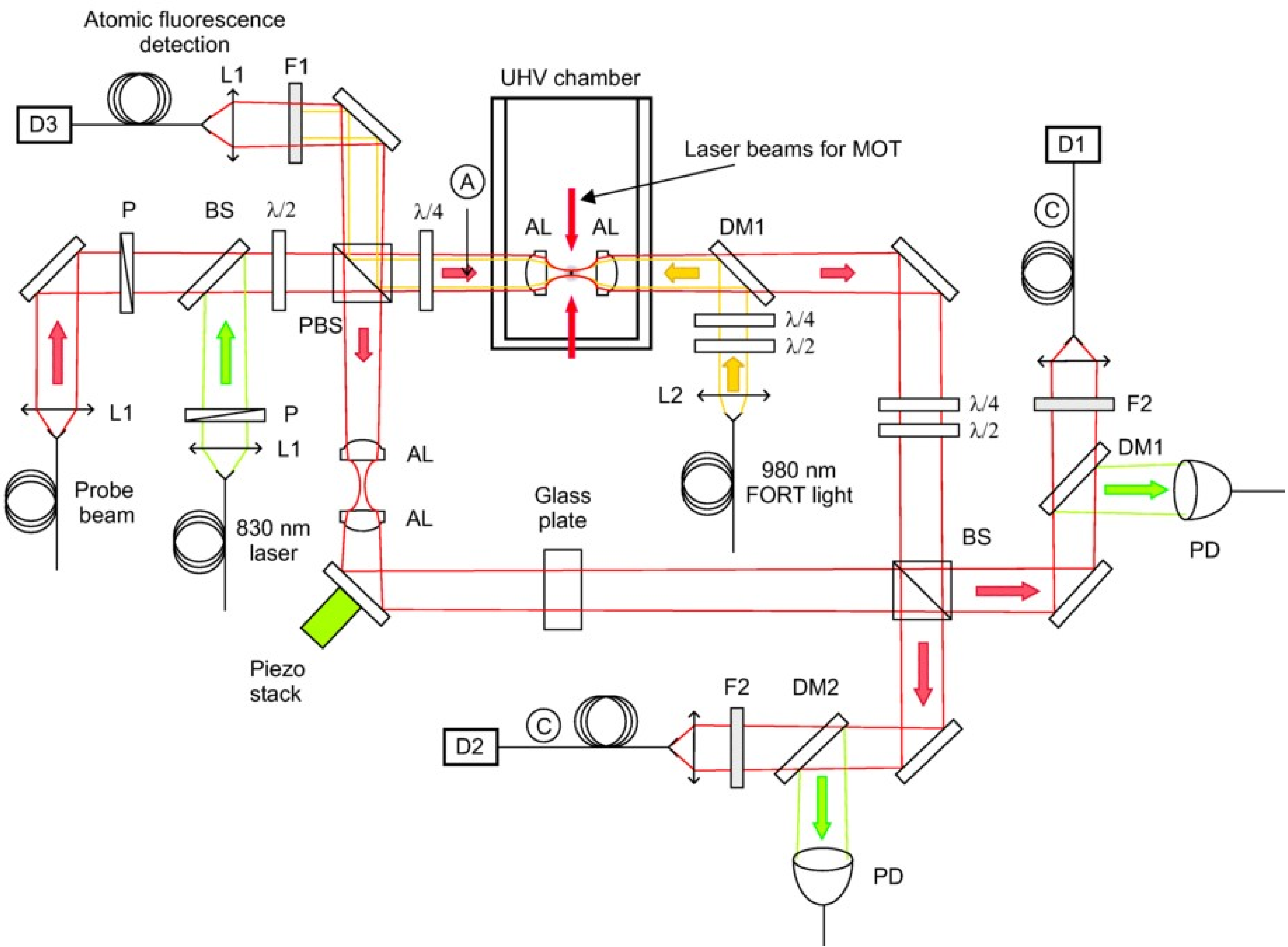
M.K. Tey, G. Maslennikov, T.C.H. Liew, et al., New J. Phys. ***11****, 040311 (2009)*

How far does this go?

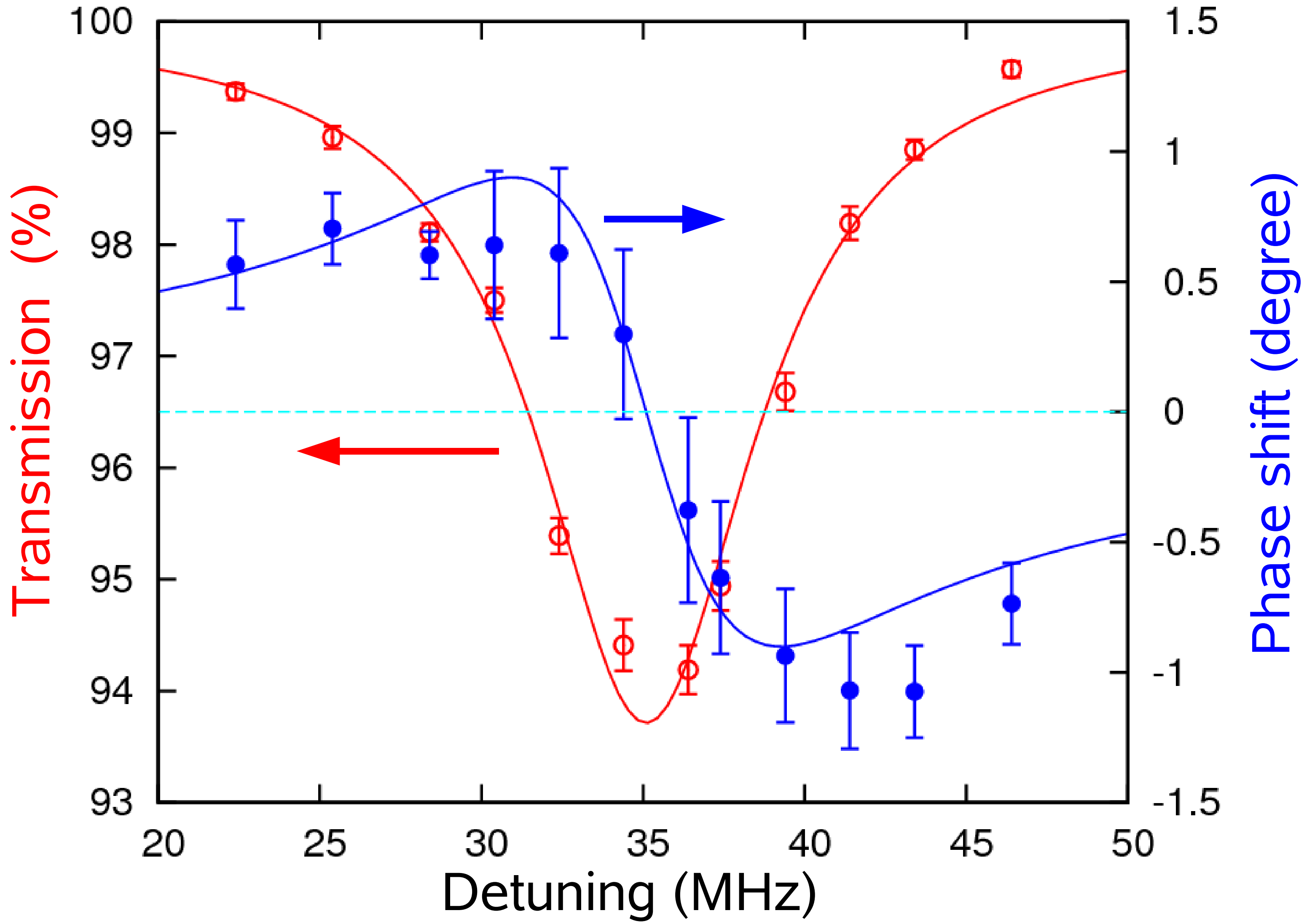


Phase shift measurement

Mach-Zehnder interferometer with one atom



Phase shift / Transmission

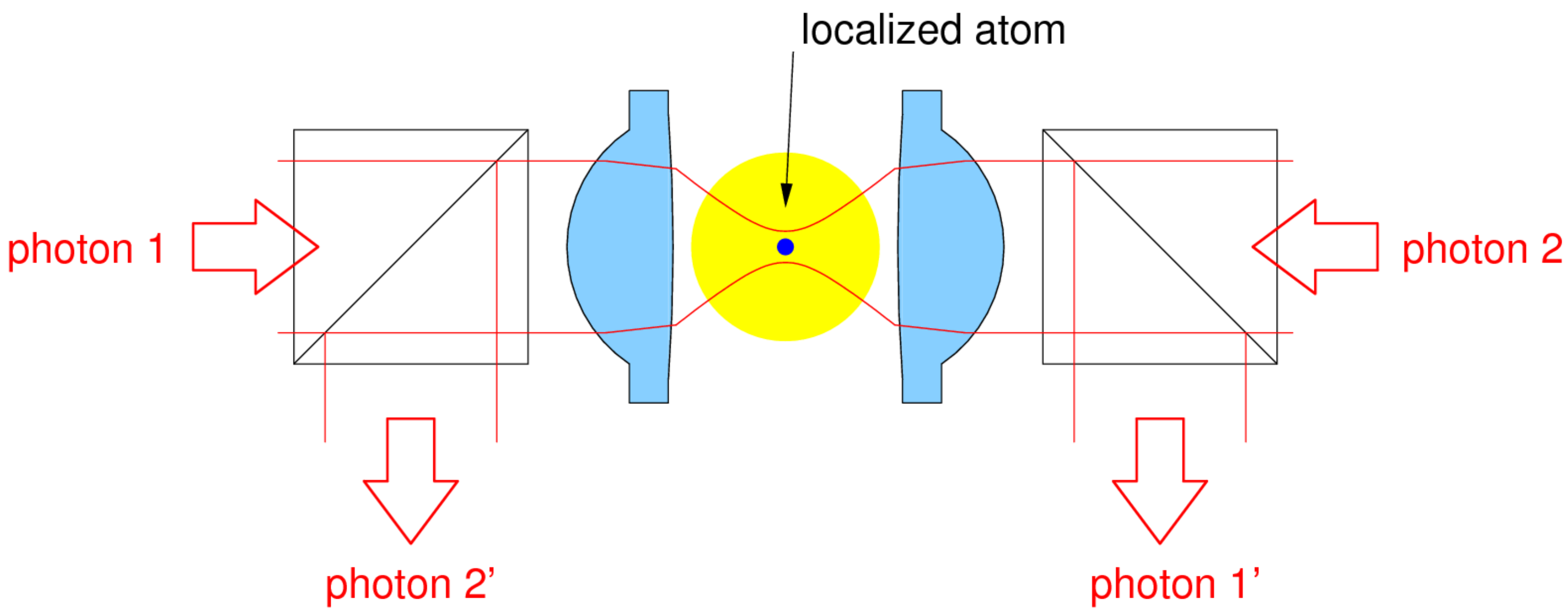


phase shift within factor 2..3 of prediction by stationary atom model!

*S.A. Aljunid et al. PRL **103**, 153601 (2009)*

Next steps

- Temperature & cooling:
  currently: 20 µK (tested; need to verify)...150 µK (MOT)
- Try larger numerical apertures (lenses are here..u ≈ 2)
- Sci-Fi? conditional phase gate....



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?)

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

Results (collect full NA)

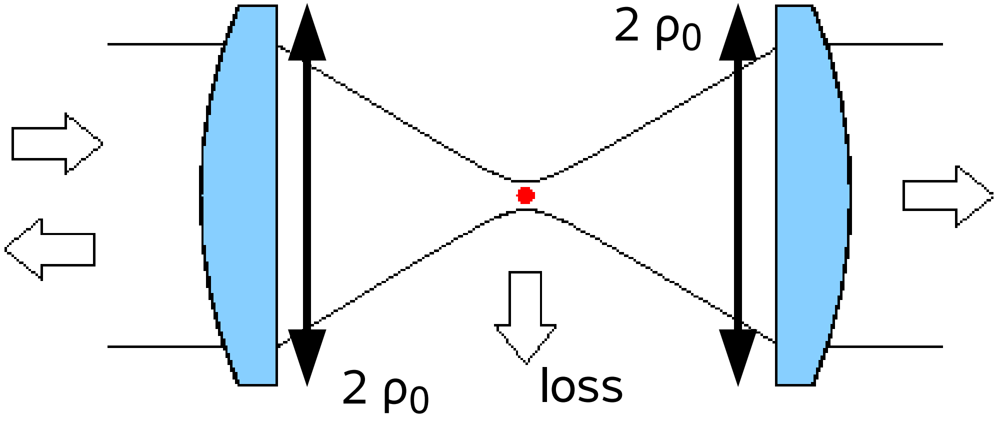
- Extinction

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

- Reflectivity (backward direction)

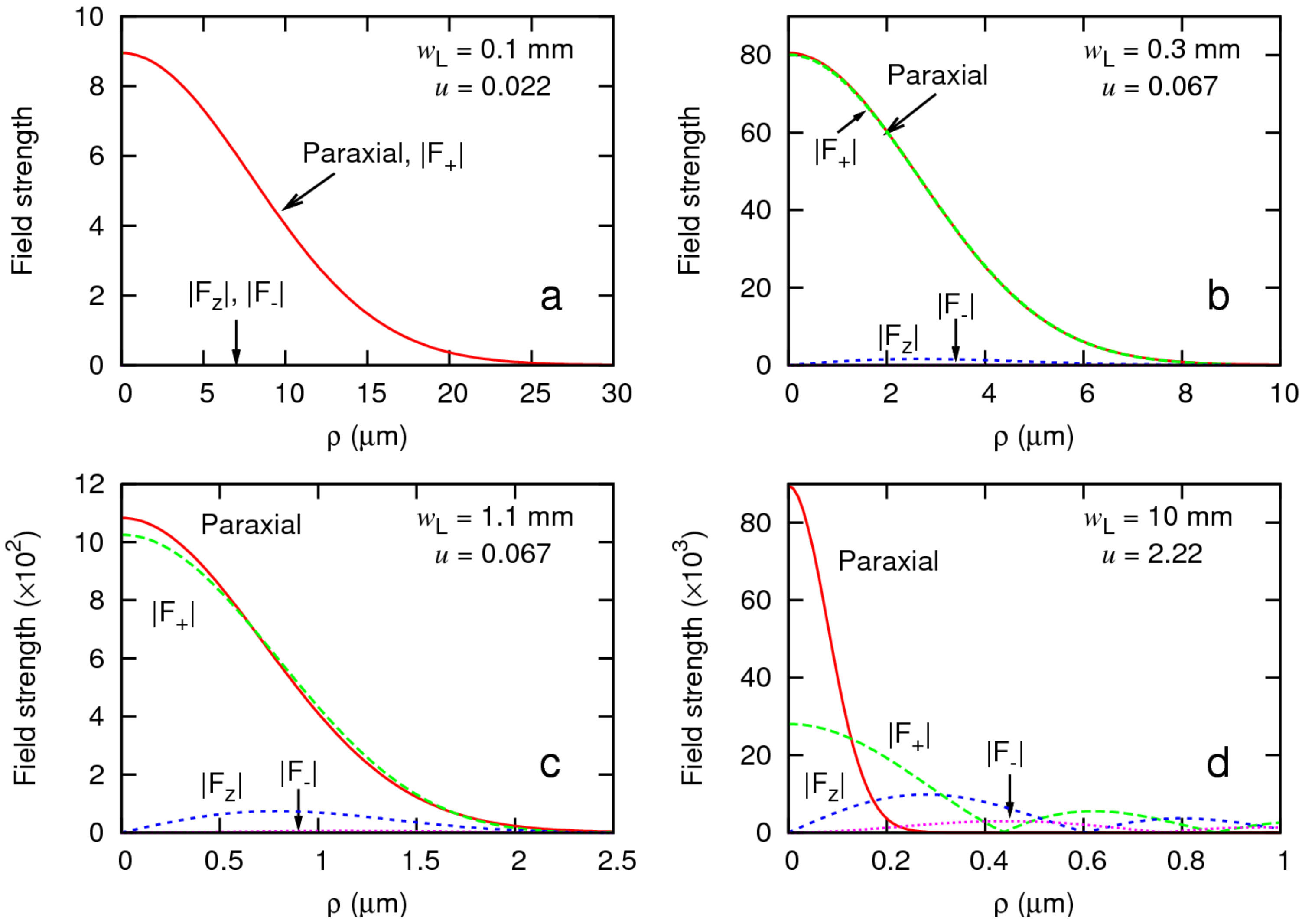
$$R = \frac{P_{sc}^{\rho_0}}{2P_{in}}\left[1-\frac{4f^3+3f\rho_0^2}{4\left(f^2+\rho_0^2\right)^{3/2}}\right]$$

- No energy gets lost



Focal fields for different w_L

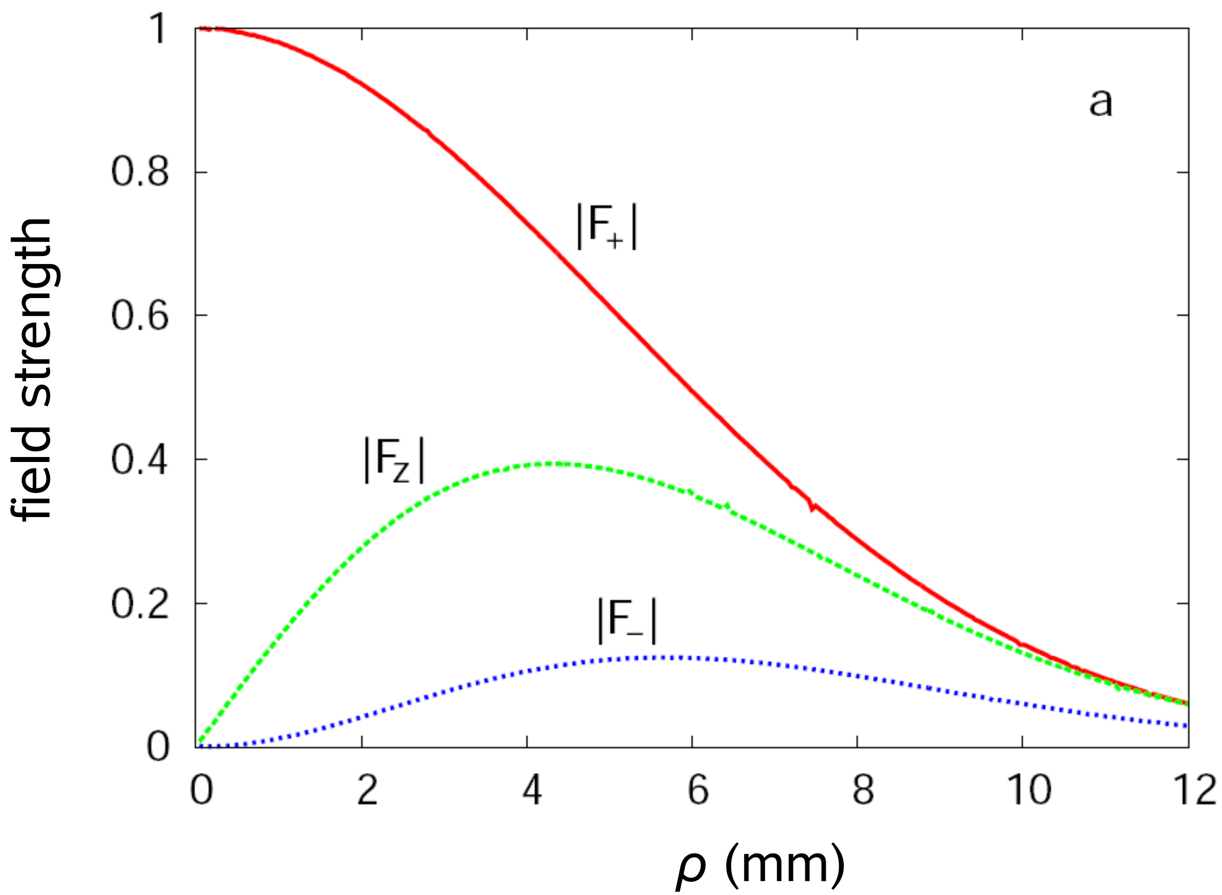
- paraxial approximation starts to break down late...



(f = 4.5 mm)

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

A simple scattering model

- Electrical field in laser beam before lens

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

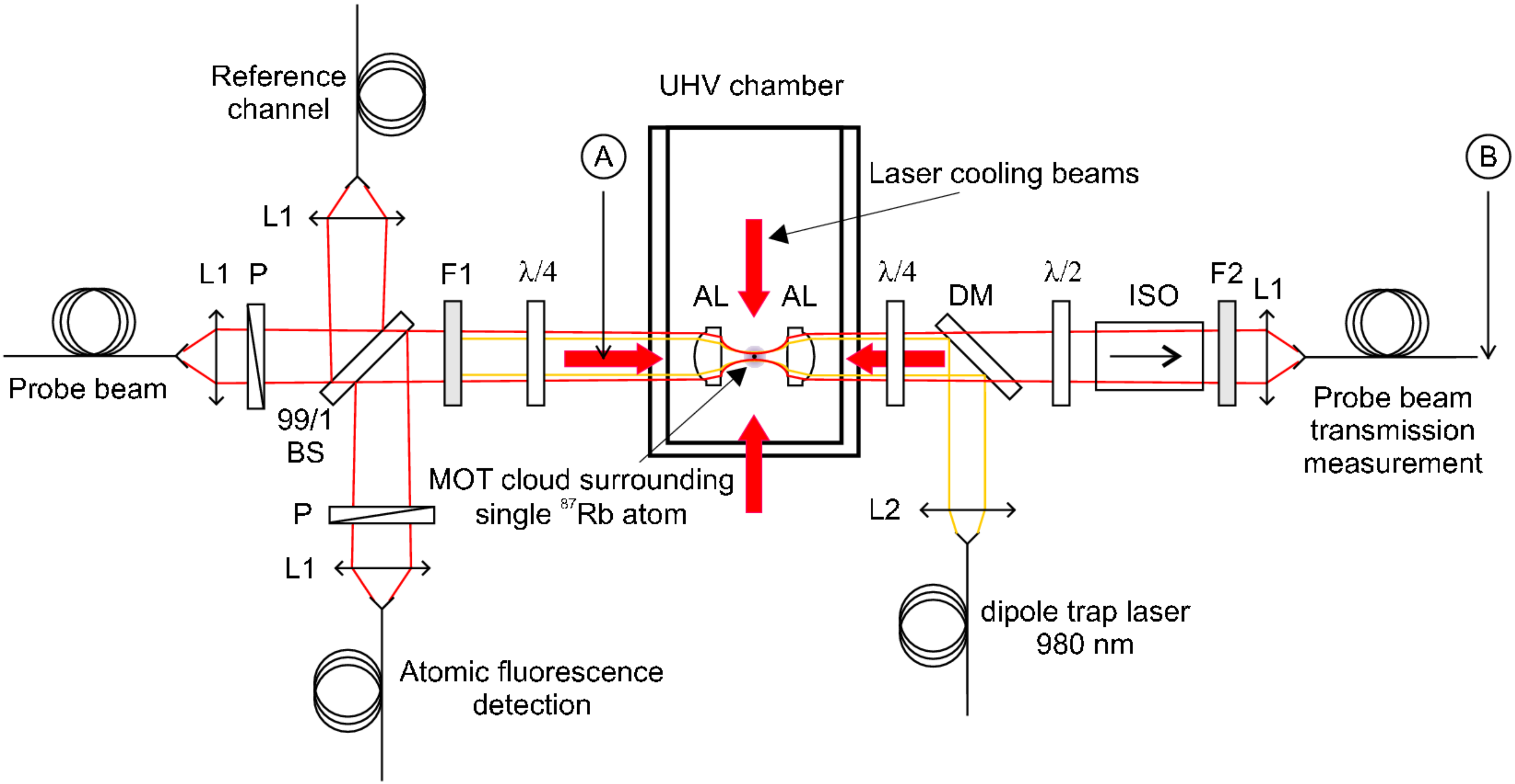
- Total excitation power

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

- Total power scattered by the atom

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

Almost the real exp setup



Single atom evidence

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