Interaction of Photons with Single Atoms - a complementary approach to cavity QED

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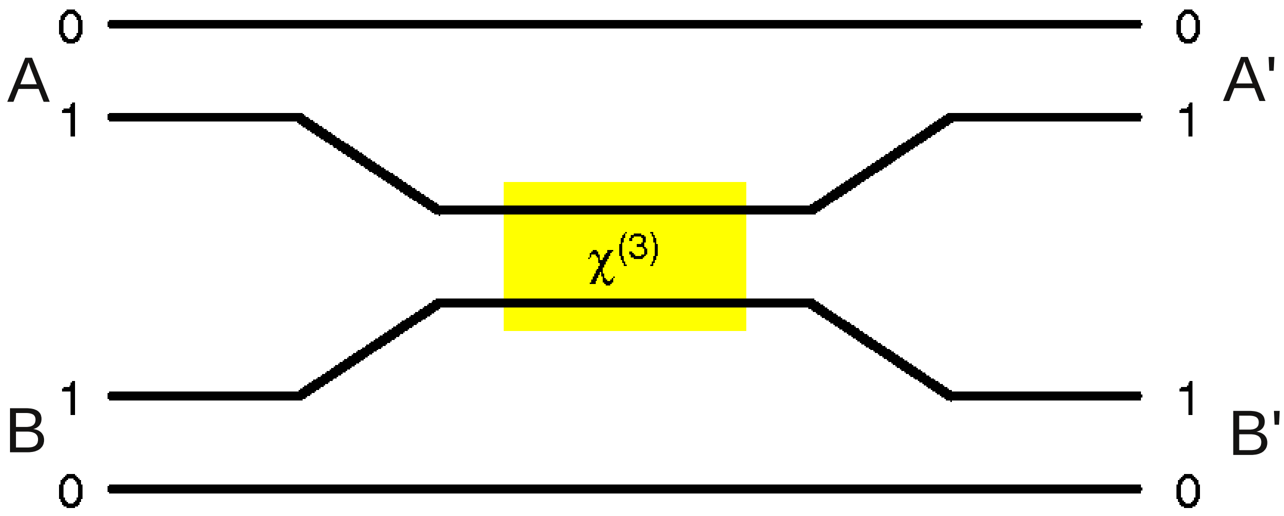
Atoms and quantum comm?

Motivation:

- Advanced quantum communication schemes (q repeater etc) will require universal gates between photonic qubits
- Bulk optical materials (LiNbO3 etc) have too low nonlinearity
- Atoms and photons are good for different quantum information tasks – allow an exchange of quantum information
- Explore possibilities of controlled phase gates & friends for photonic qubits

Photonic Phase Gate Concept

- universal 2-qubit operations, require large optical nonlinearity



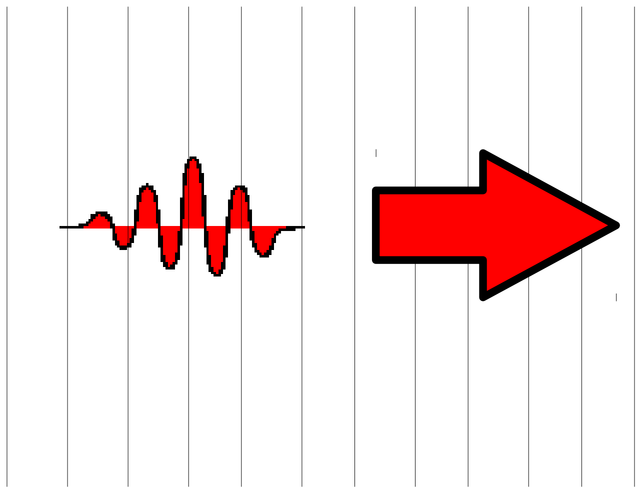
A, B	A', B'
0,0	0,0
0,1	0,1
1,0	1,0
1,1	(1,1) $e^{i\varphi}$

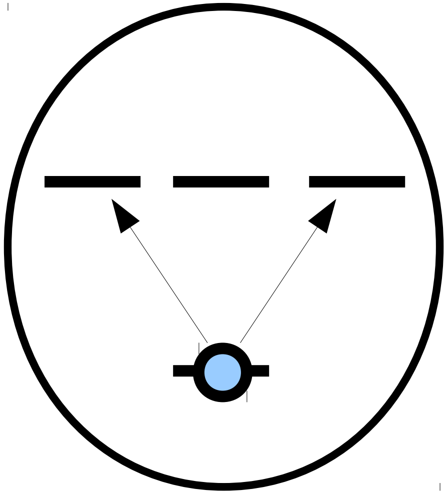
- hopeless with typical bulk nonlinearities
- possible with atoms close to resonance:

S. Harris & team, Stanford: atomic clouds
M. Lukin & team, Harvard: atoms in fibers

Atom-Photon interface

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





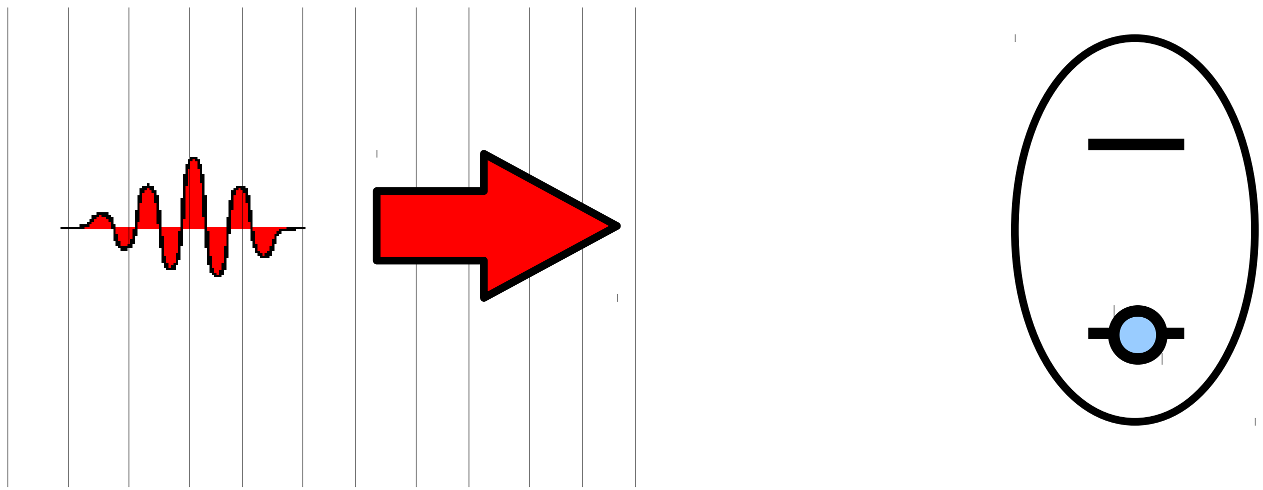
$$|\Psi_L\rangle = \alpha|L\rangle + \beta|R\rangle$$

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

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

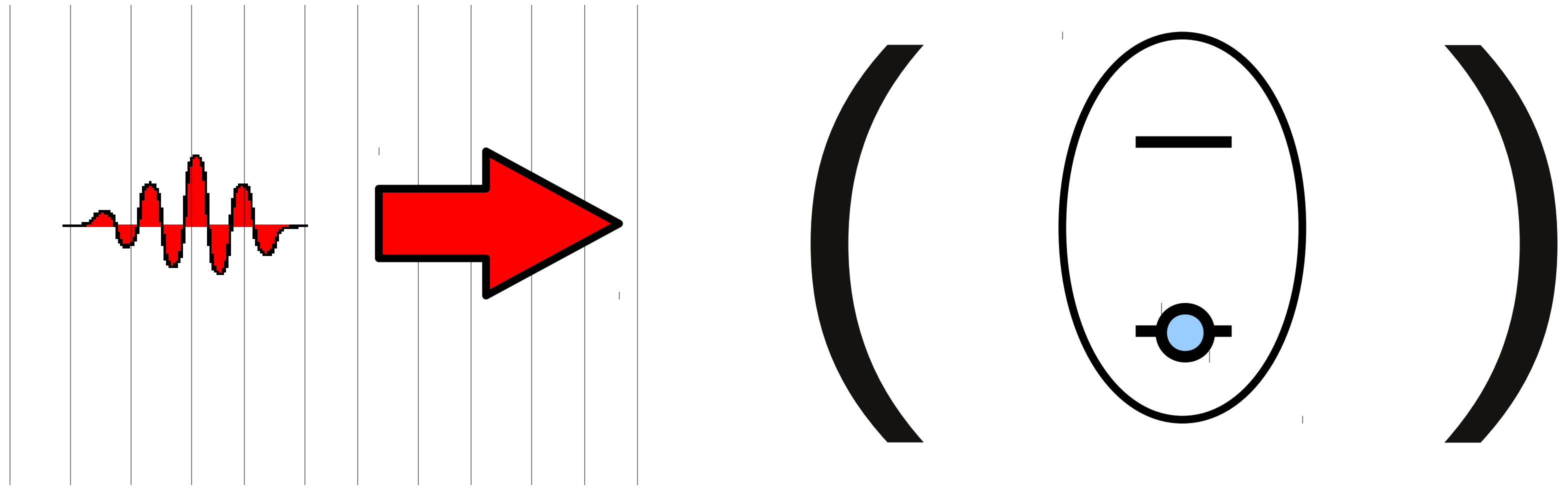
The basic problem

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



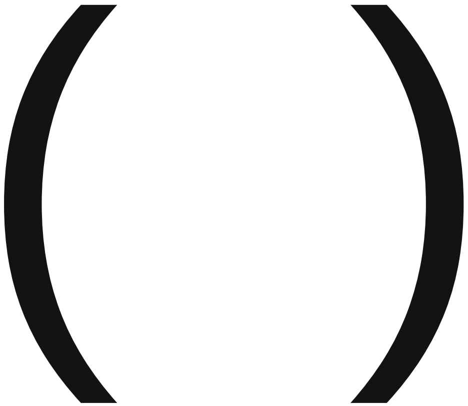
electromagnetic field / photon **2-level atom**

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



- discrete mode spectrum
- 'textbook' field energy eigenstates

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

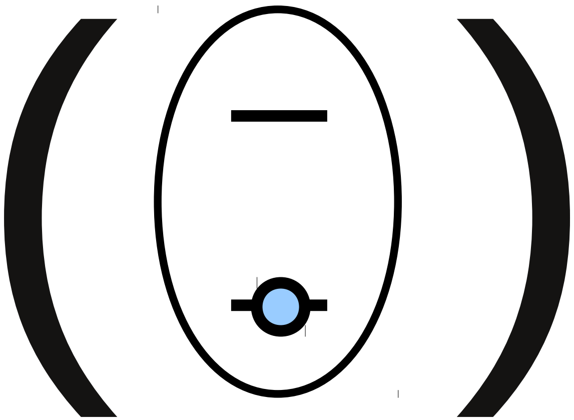
Electrical field operator (single freq):

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

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

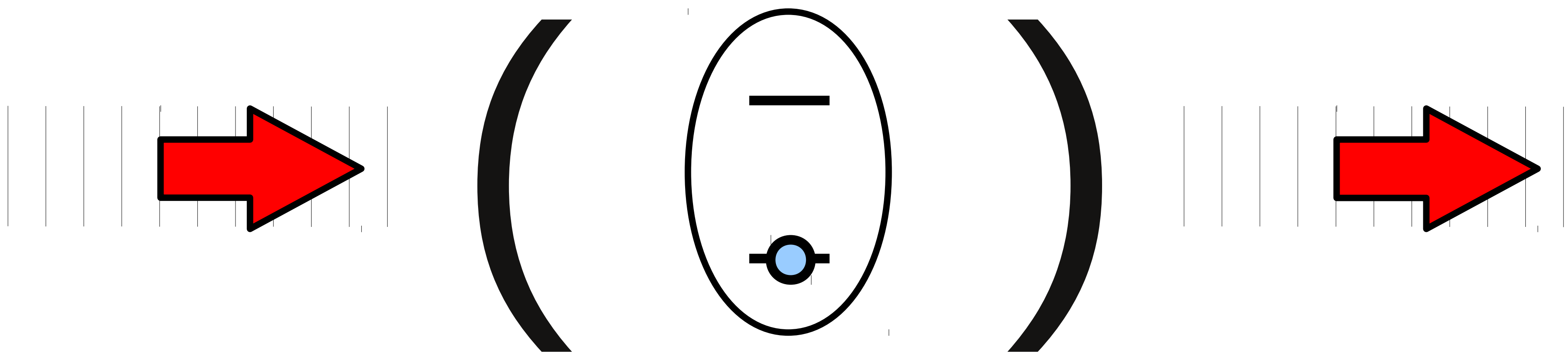
$$\hat{H}_I = \hat{\boldsymbol{E}} \cdot \hat{\boldsymbol{d}} \quad \text{with} \quad \hat{\boldsymbol{d}} = \boldsymbol{e}\, d_{eff} \left(|e\rangle\langle g| + |g\rangle\langle e|\right)$$

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

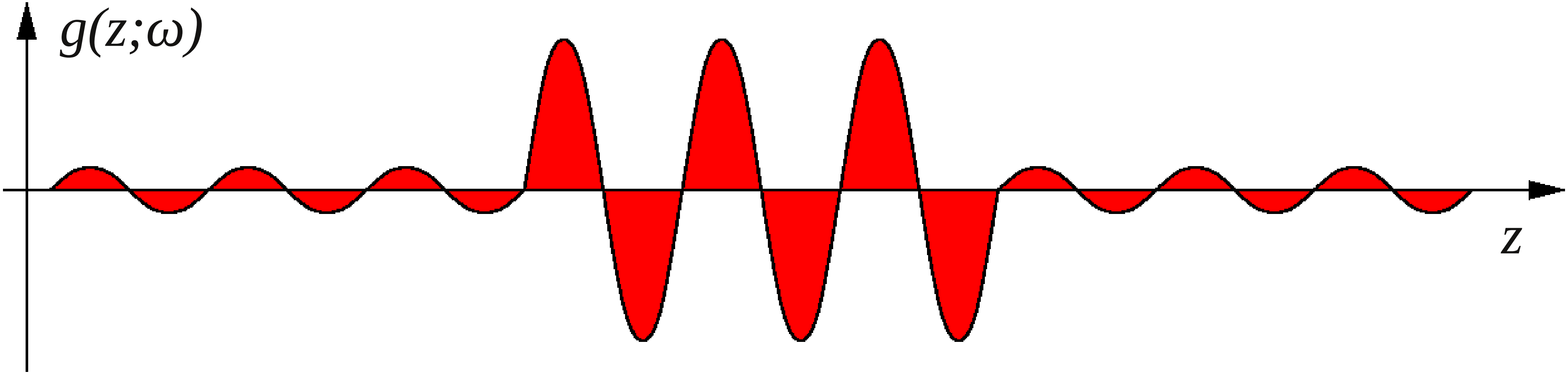
.....Jaynes-Cummings model with all its aspects

- treat external fields as perturbation/spectator of internal field

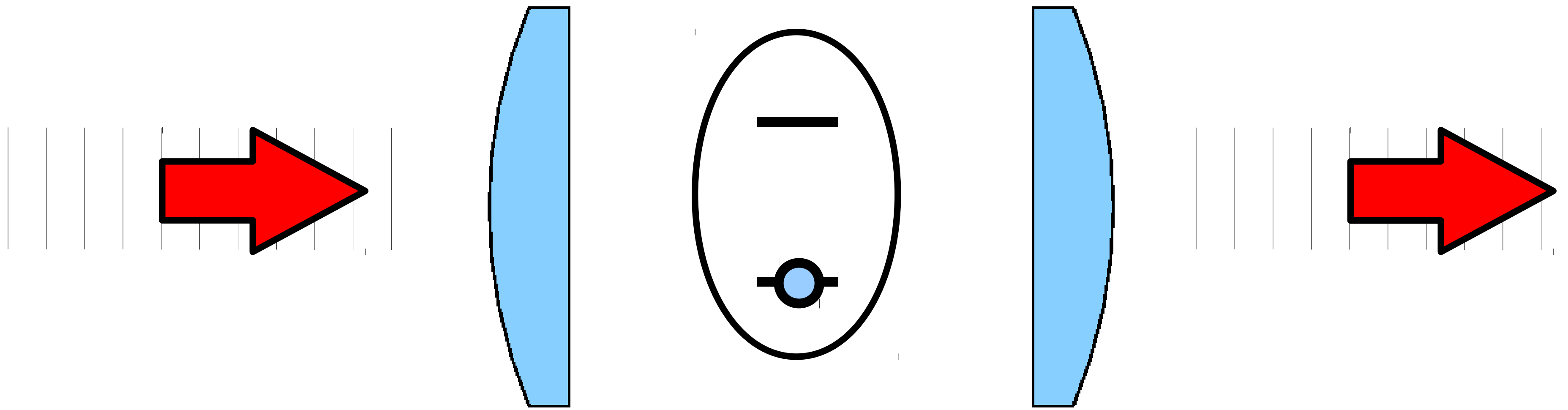
External view of cavity+atom



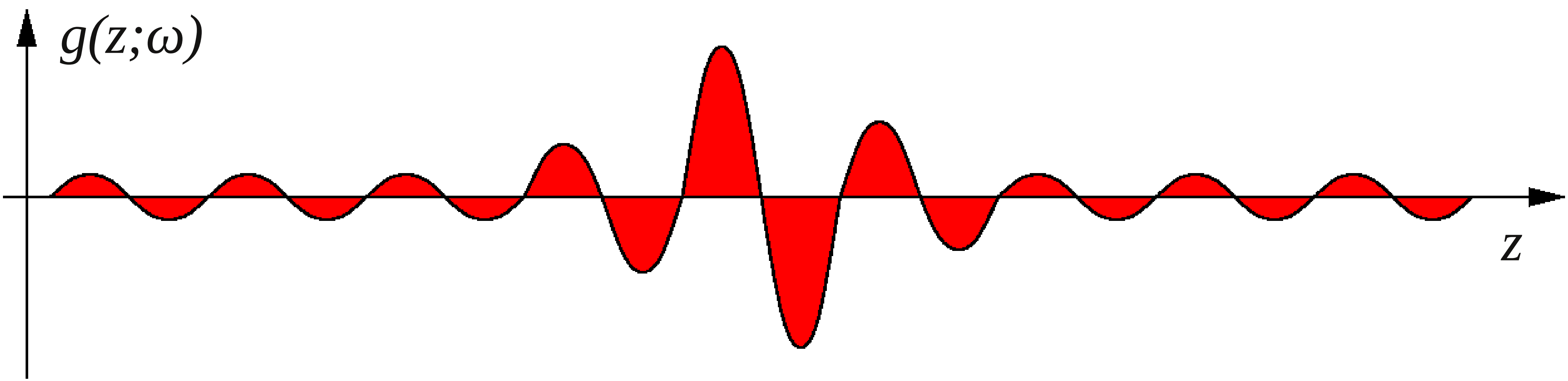
- continuous mode spectrum with enhanced/reduced field mode function:



An alternative approach

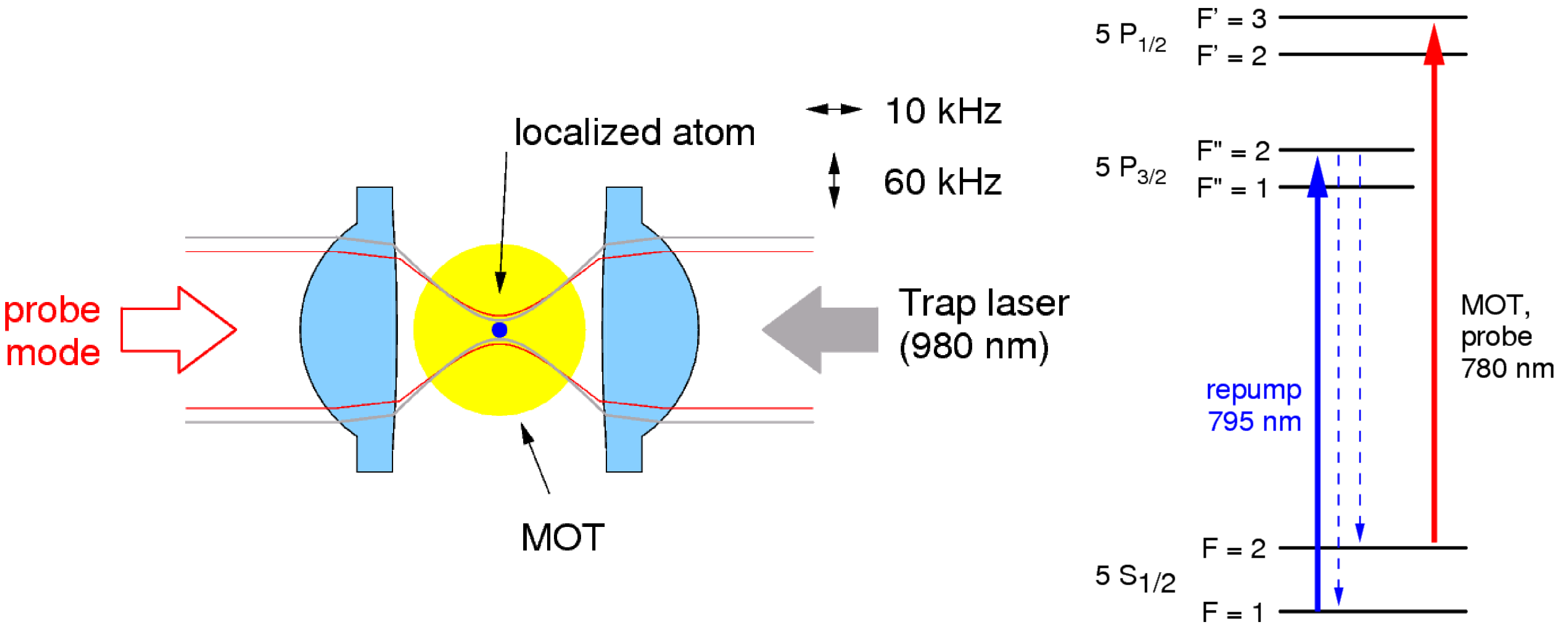


- use a **focusing lens pair** to enhance center mode function:



Experiment

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

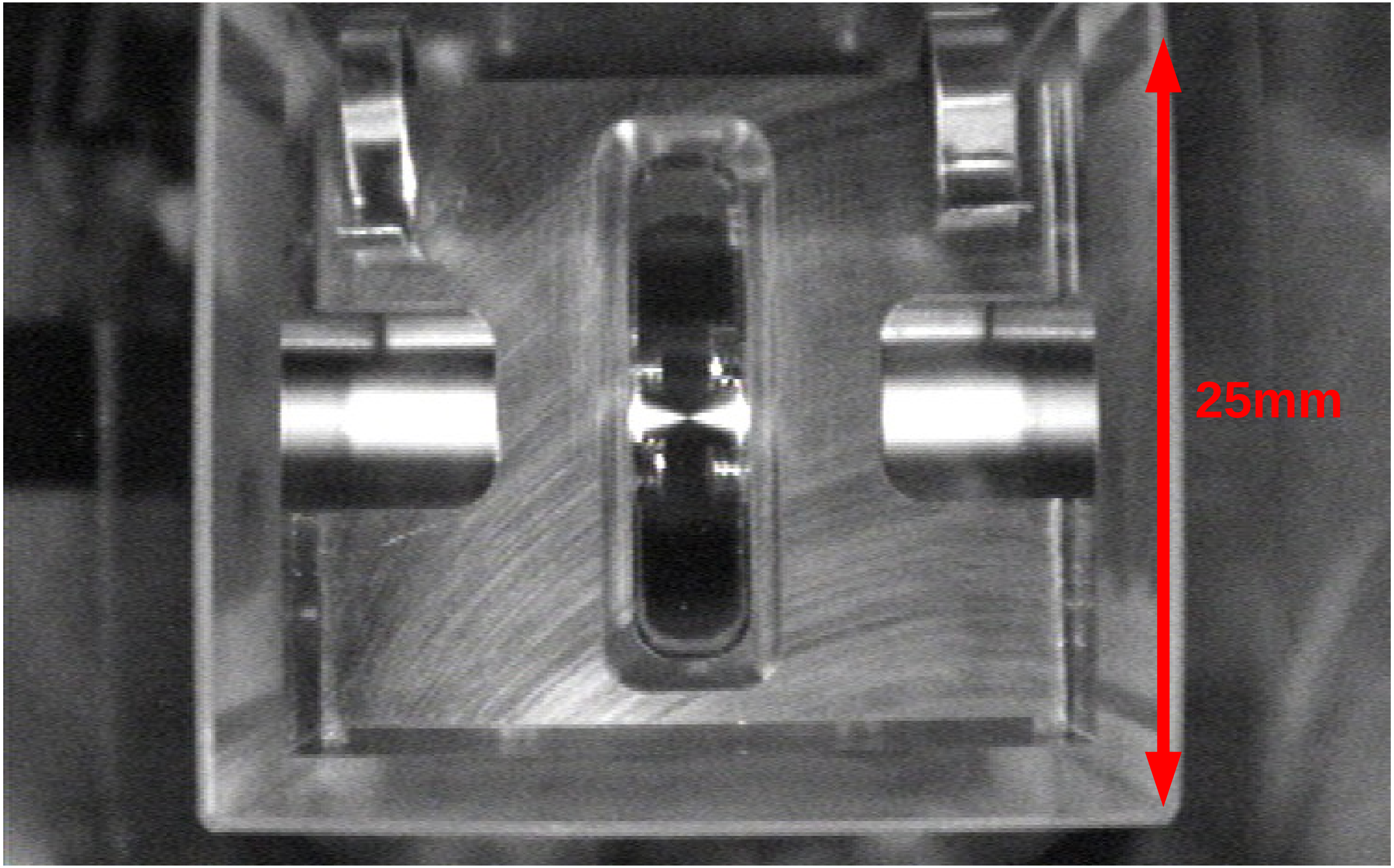


- use Rubidium-87 atom because it is convenient

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

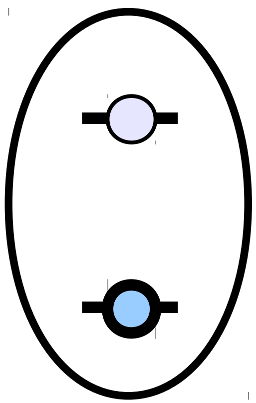
Focusing geometry...

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



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 scattering rate $\rho_e \Gamma$ leads to

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

Field at focus (simple)

paraxial approximation

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

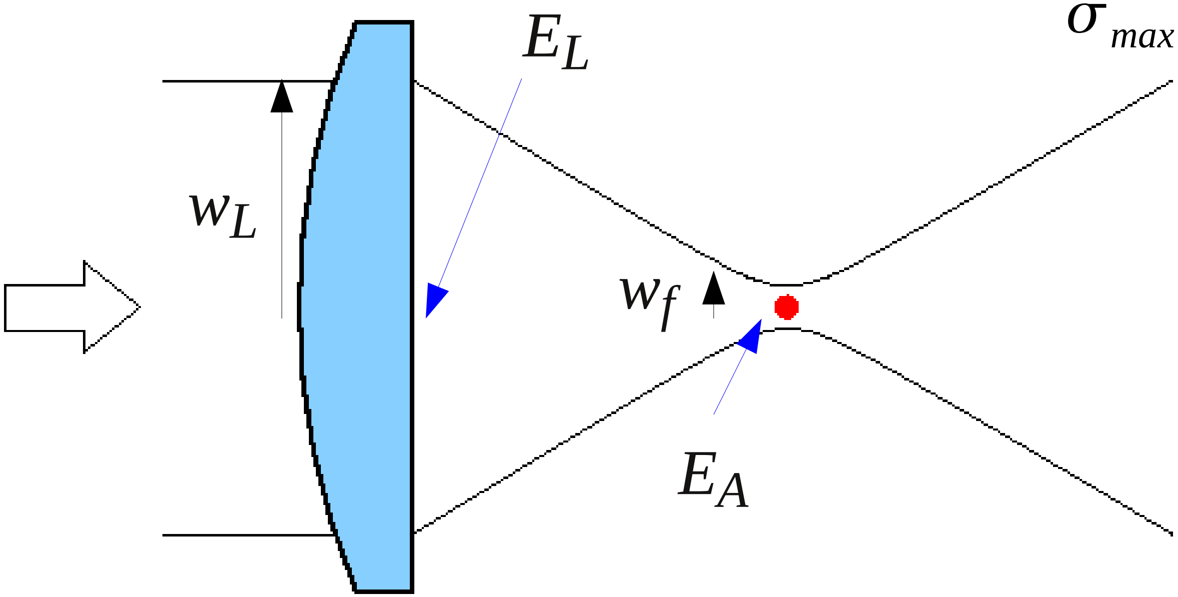
focal area

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

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

Field to focus (exact)

Exact propagation to focus:

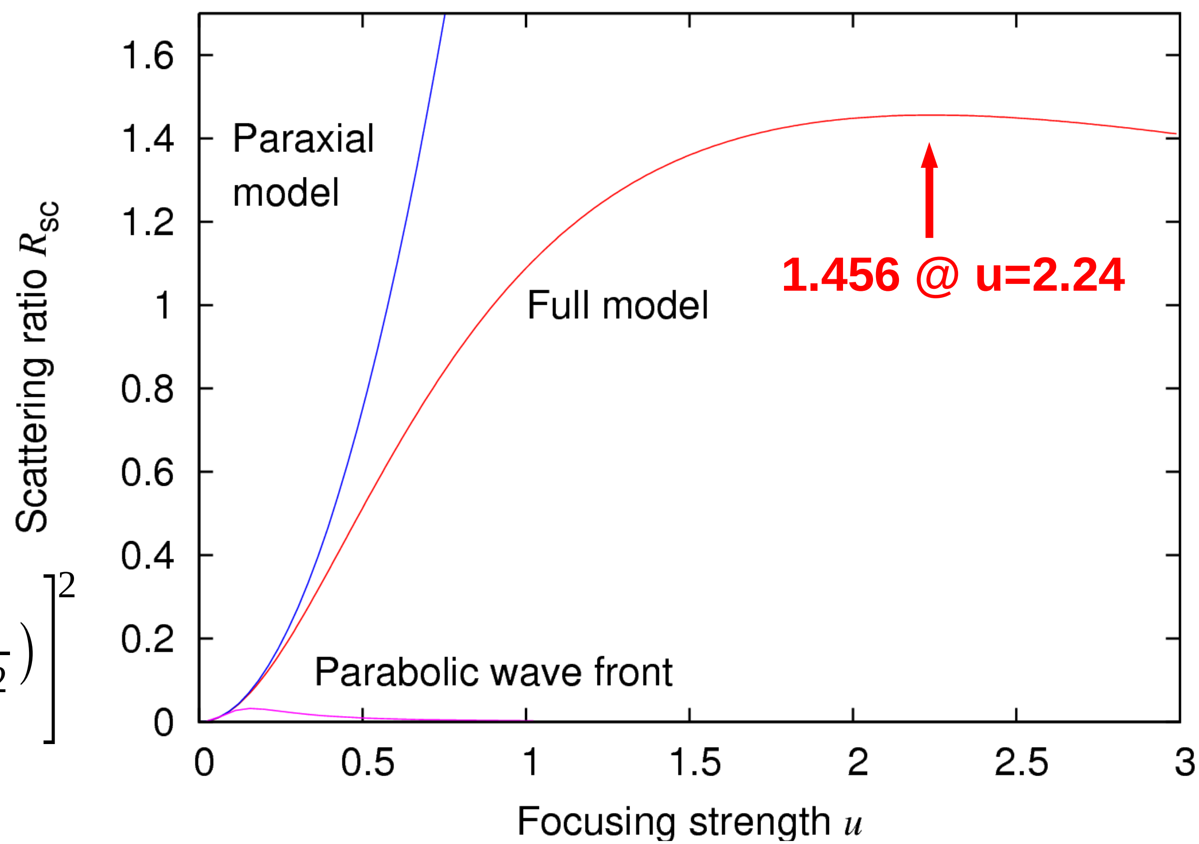
$$\boldsymbol{E}_A(z=f,\rho=0)=\sqrt{\frac{\pi P_{in}}{\epsilon_0 c\lambda^2}}\cdot\frac{1}{u}e^{1/u^2}\left[\sqrt{\frac{1}{u}}\Gamma\left(-\frac{1}{4},\frac{1}{u^2}\right)+\sqrt{u}\,\Gamma\left(\frac{1}{4},\frac{1}{u^2}\right)\right]\hat{\epsilon}_+,$$

leads to "scattering ratio"

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

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

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



Collection into Gaussian mode

- Project total field onto Gaussian mode of collection fiber

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

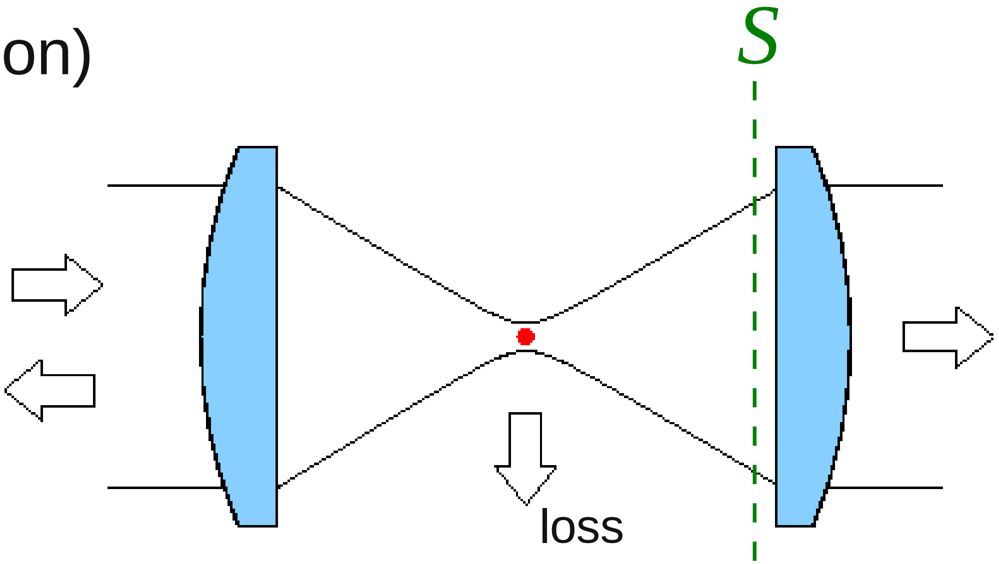
cross section   fiber mode

- Forward transmission:

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

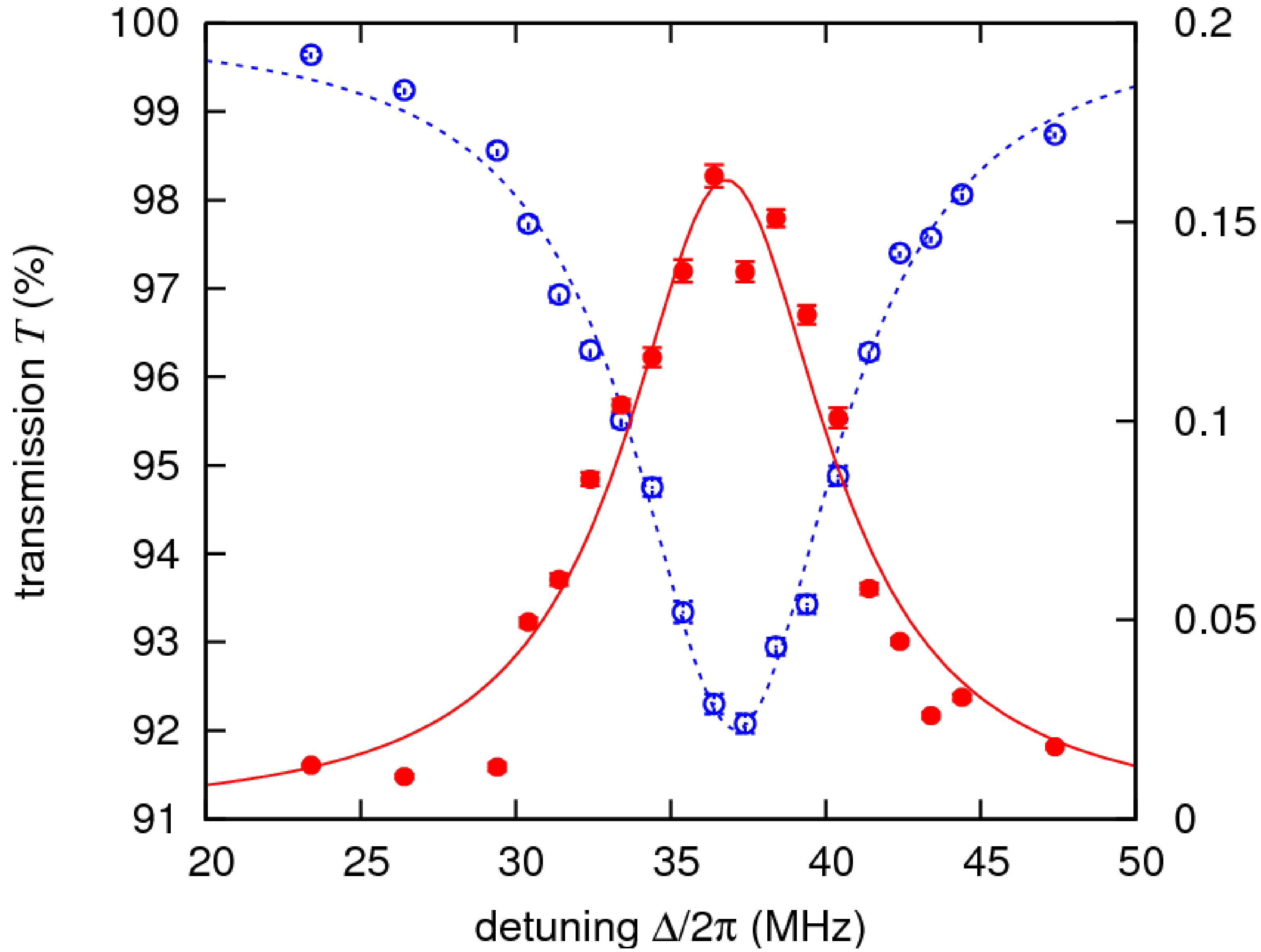
- Reflectivity (backward direction)

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

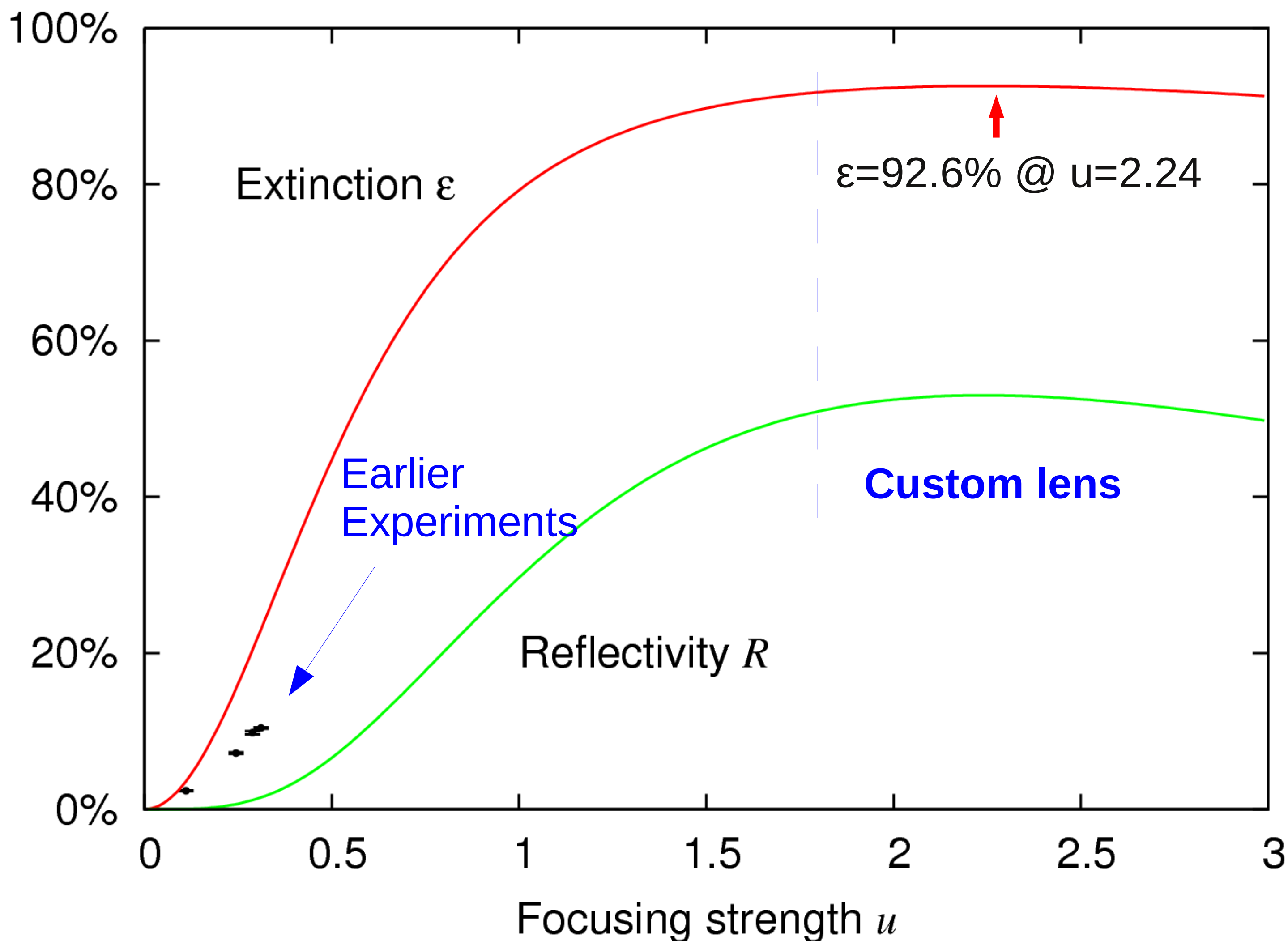


Reflection & Transmission

(σ- probe)



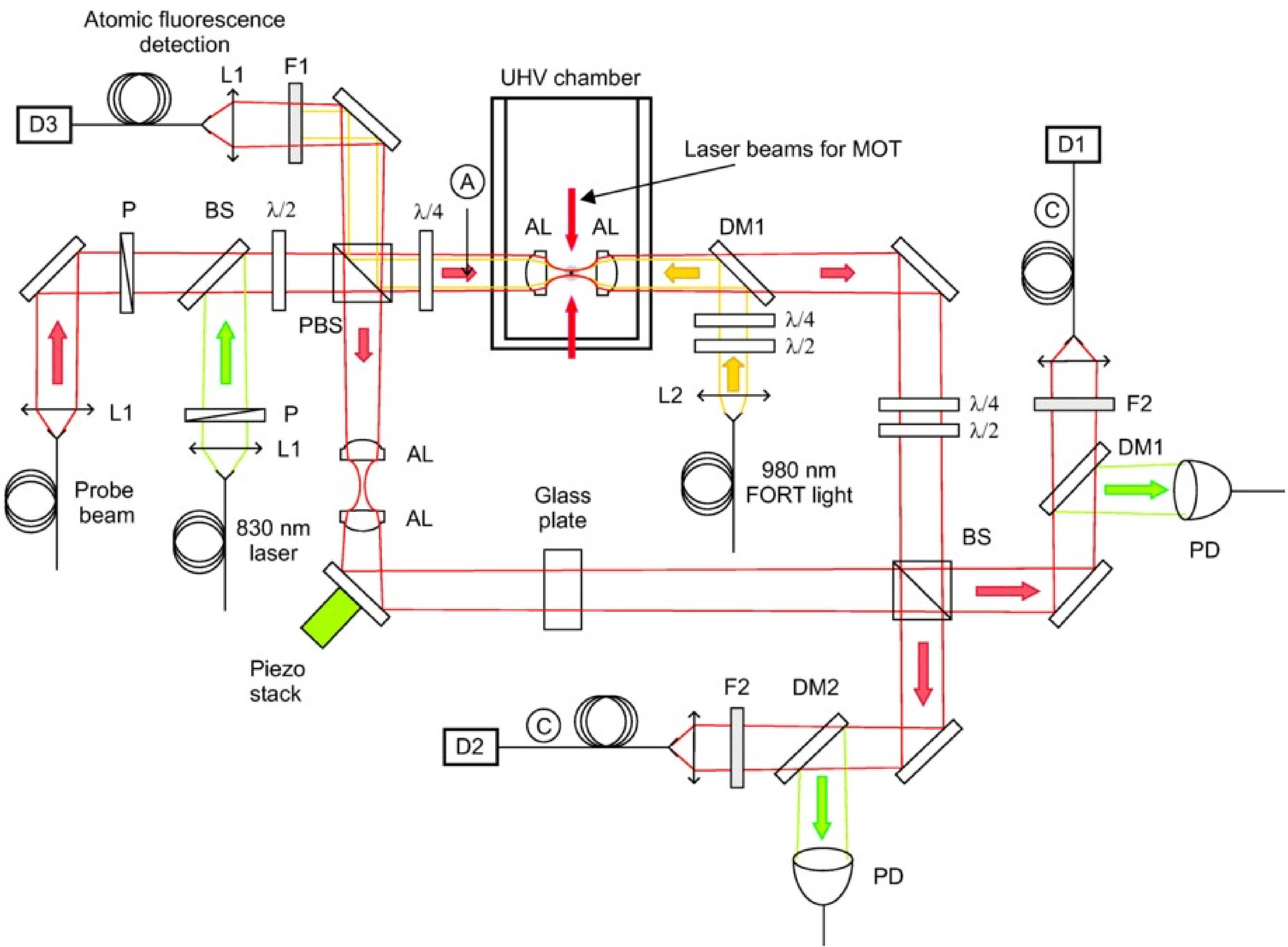
How far does this go?



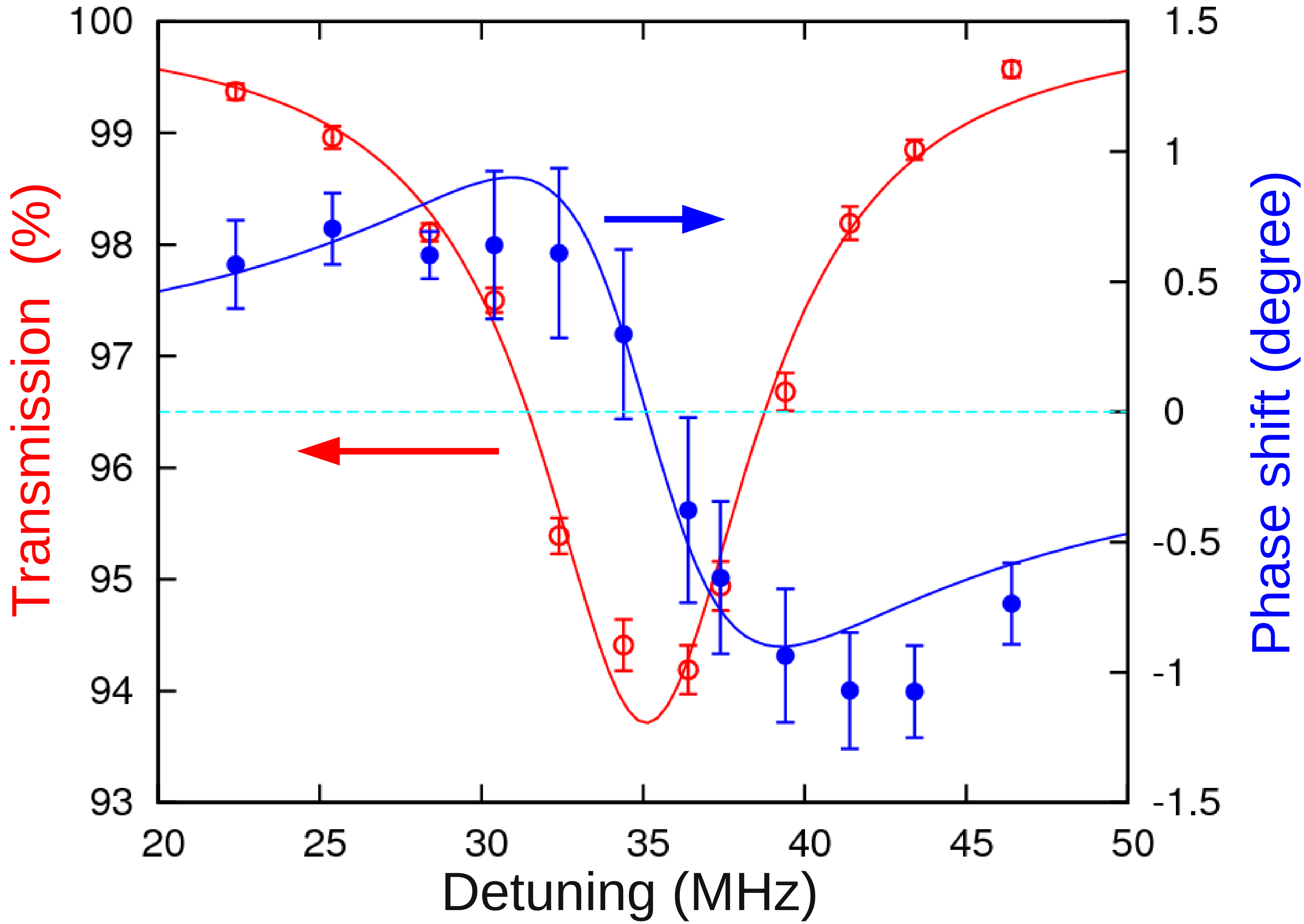
M.K. Tey, G. Maslennikov, T.C.H. Liew, et al., New J. Phys. ***11****, 040311 (2009)*

Phase shift measurement

Mach-Zehnder interferometer with one atom



Phase shift / Transmission

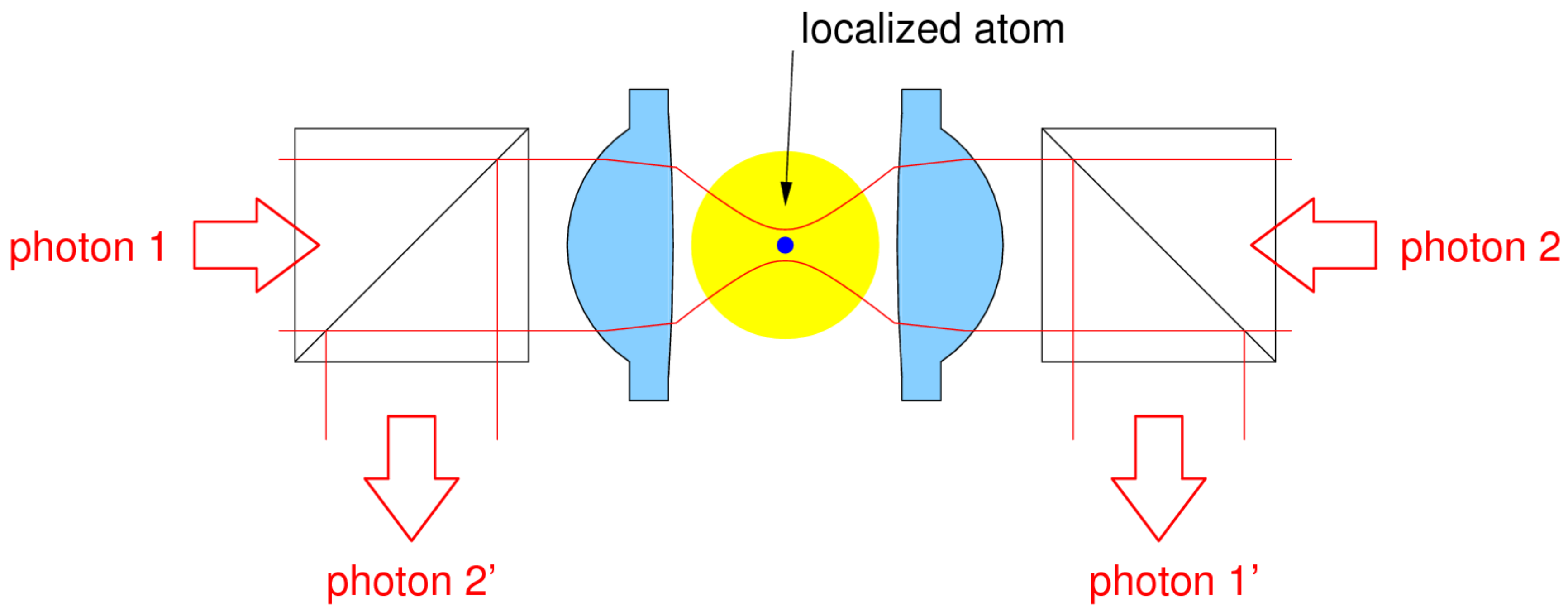


phase shift within factor 2..3 of prediction by stationary atom model!

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

Dreams...

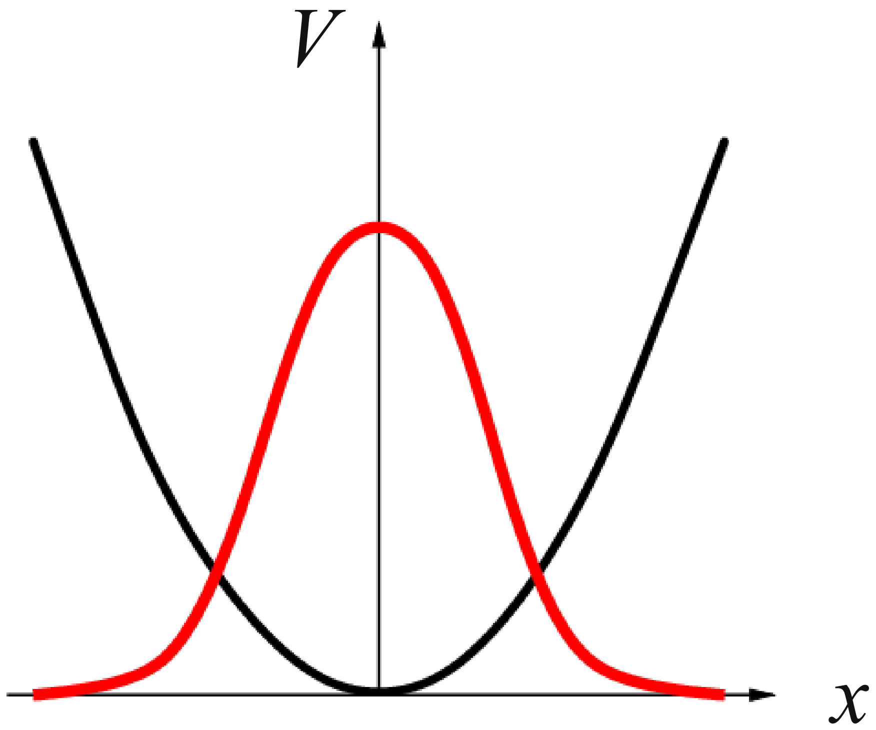
- Try to see conditional phase gate....



need photons with compatible bandwidth

Next steps in the real world

- Atom does not sit nicely in our trap:

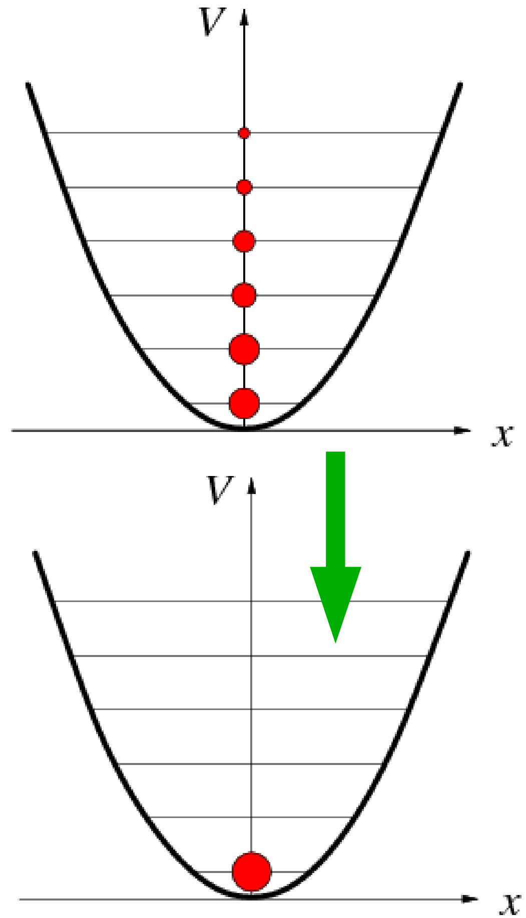


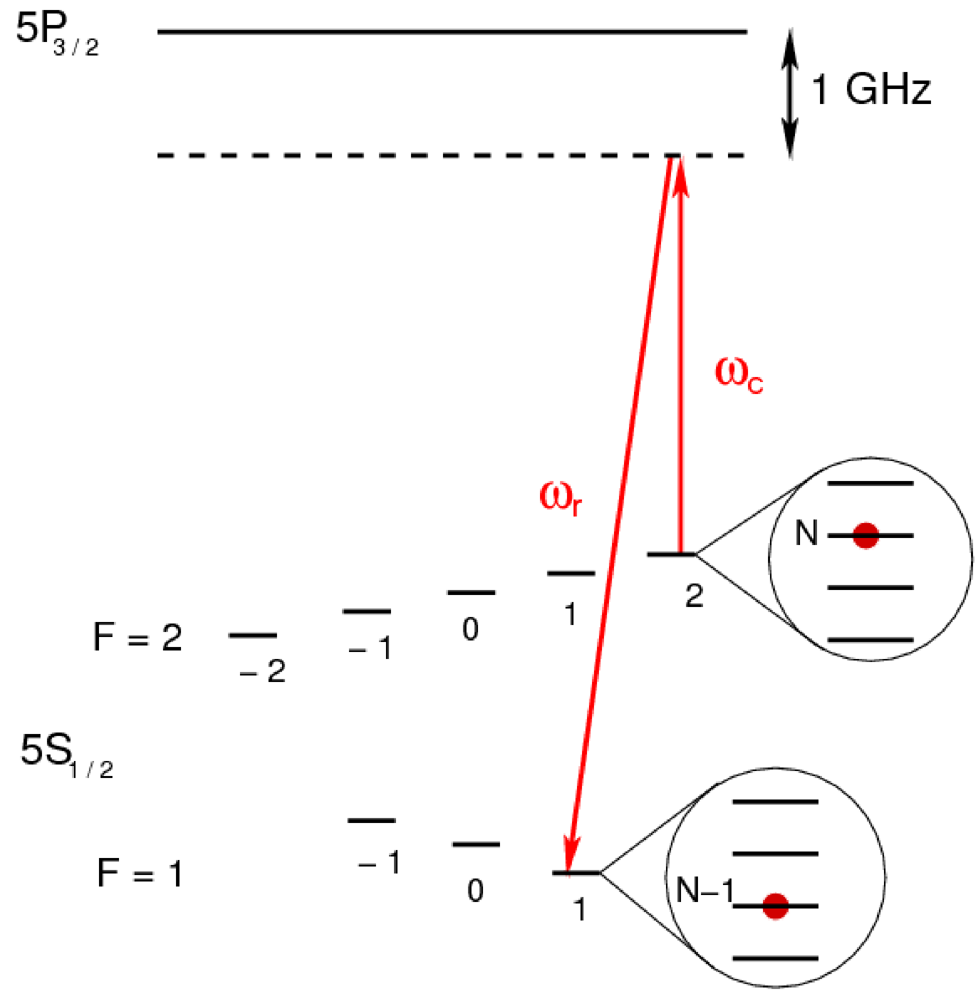
For T= 35 μK:

Δ x = 160 nm
Δ z = 1.3 μm

Raman Sideband Cooling

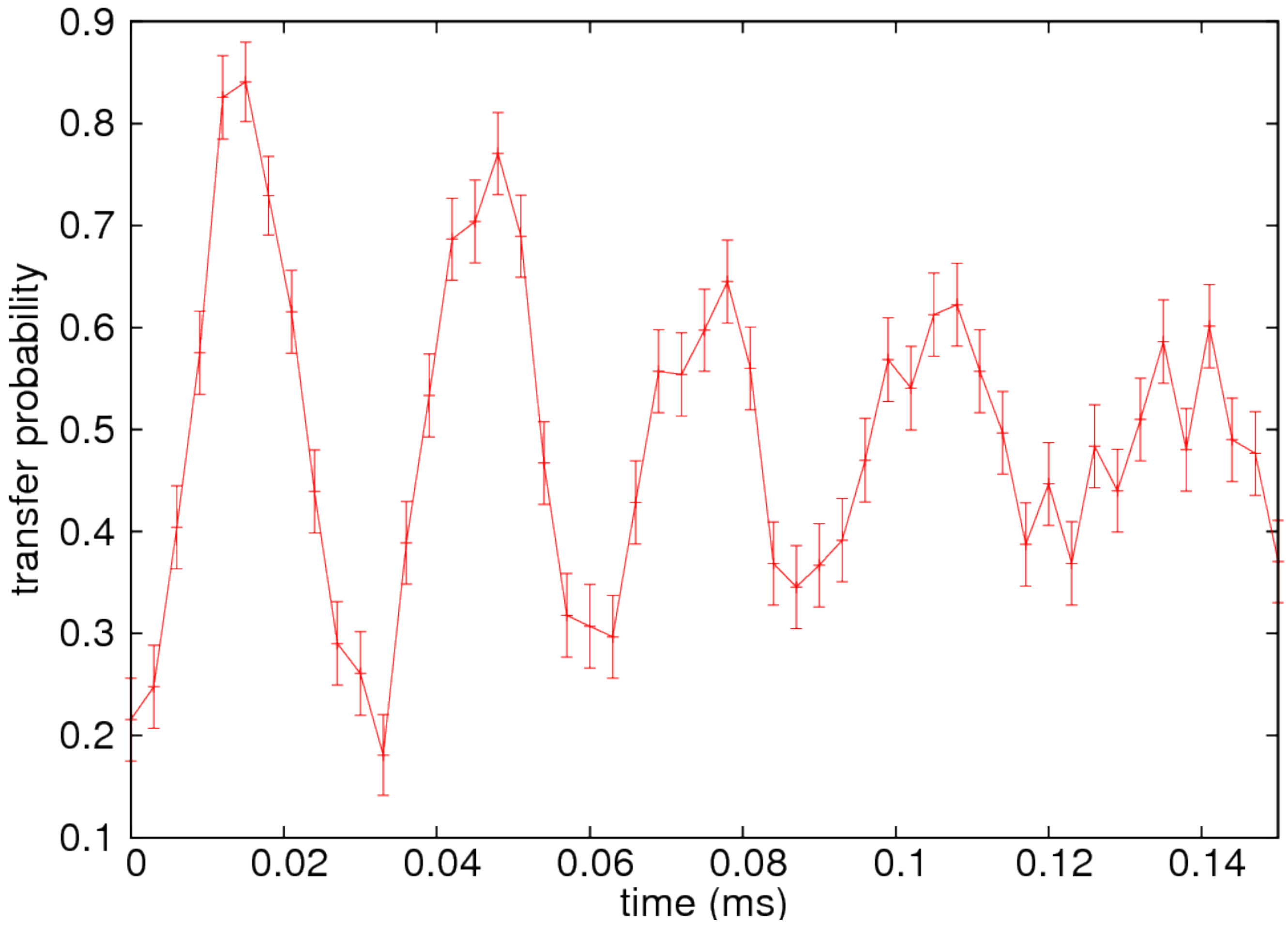
- Reduce vibrational quanta directly:





First steps: Raman transitions

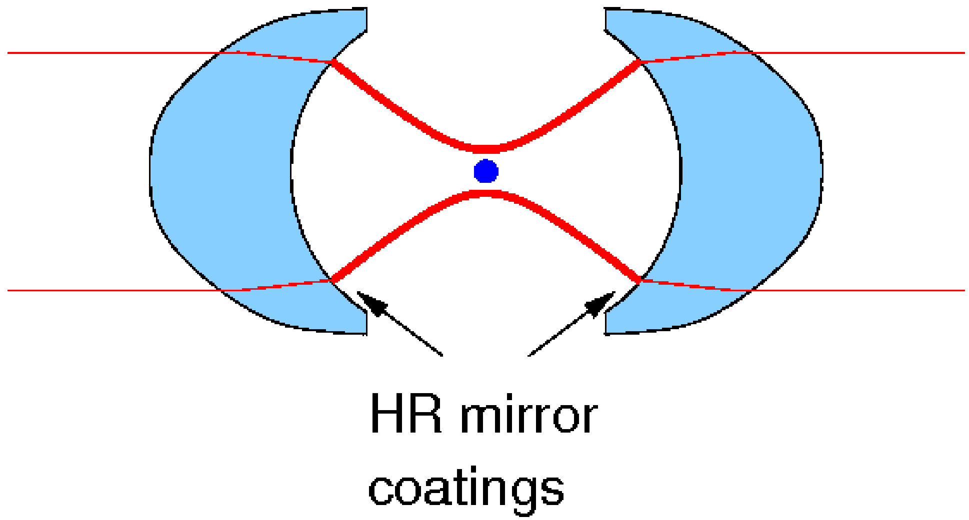
Atom state manipulation : Raman Rabi oscillations



Decoherence time ~ 100 μs

Combine focusing & cavity

- Get easier into “strong coupling” regime



Electrical field operator (single freq):

$$\hat{\boldsymbol{E}}(x,y,z)=i\sqrt{\frac{\hbar\omega\pi}{\epsilon_0 L 3\lambda^2}R_{sc}}\left(\boldsymbol{g}(x,y,z)\hat{a}^+-\boldsymbol{g}^*(x,y,z)\hat{a}\right)$$

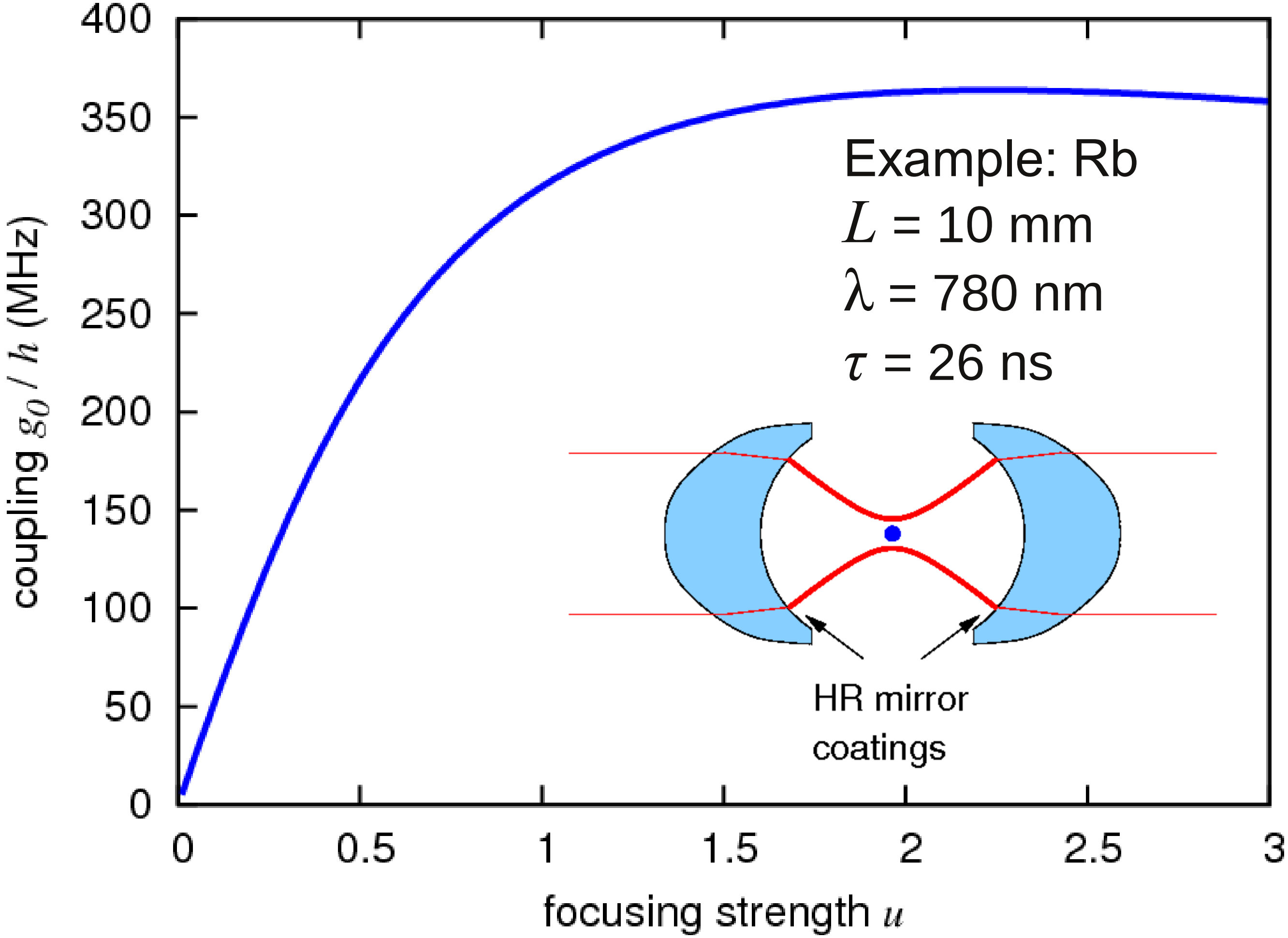
Scattering ratio, 0...2

mode function, g=1 at focus

Effective mode volume: $V=L\lambda^2/R_{sc}$

Weak cavity – strong coupling?

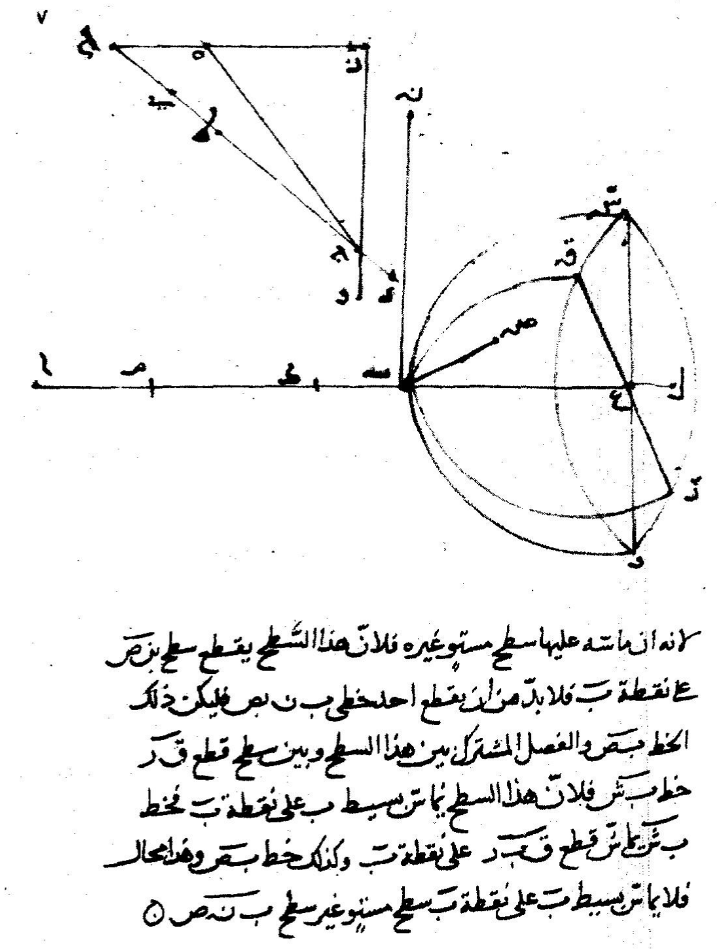
Coupling strength: $g_0 = \hbar \sqrt{\frac{\pi c R_{sc}}{\tau L}}$



S.A. Aljunid, B. chng, J. Lee, K. Durak, M. Paesold G. Maslennikov, CKArXiv: xxxx:2010

Not exactly a new idea...

- Ibn Sahl, ~ 984: optimal focusing



- Today's version of an anaclastic lens

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 by focusing
  can lower cavity finesse for a given coupling strength

- What is the balance of technical problems?

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

Thank you!

http://www.qolah.org

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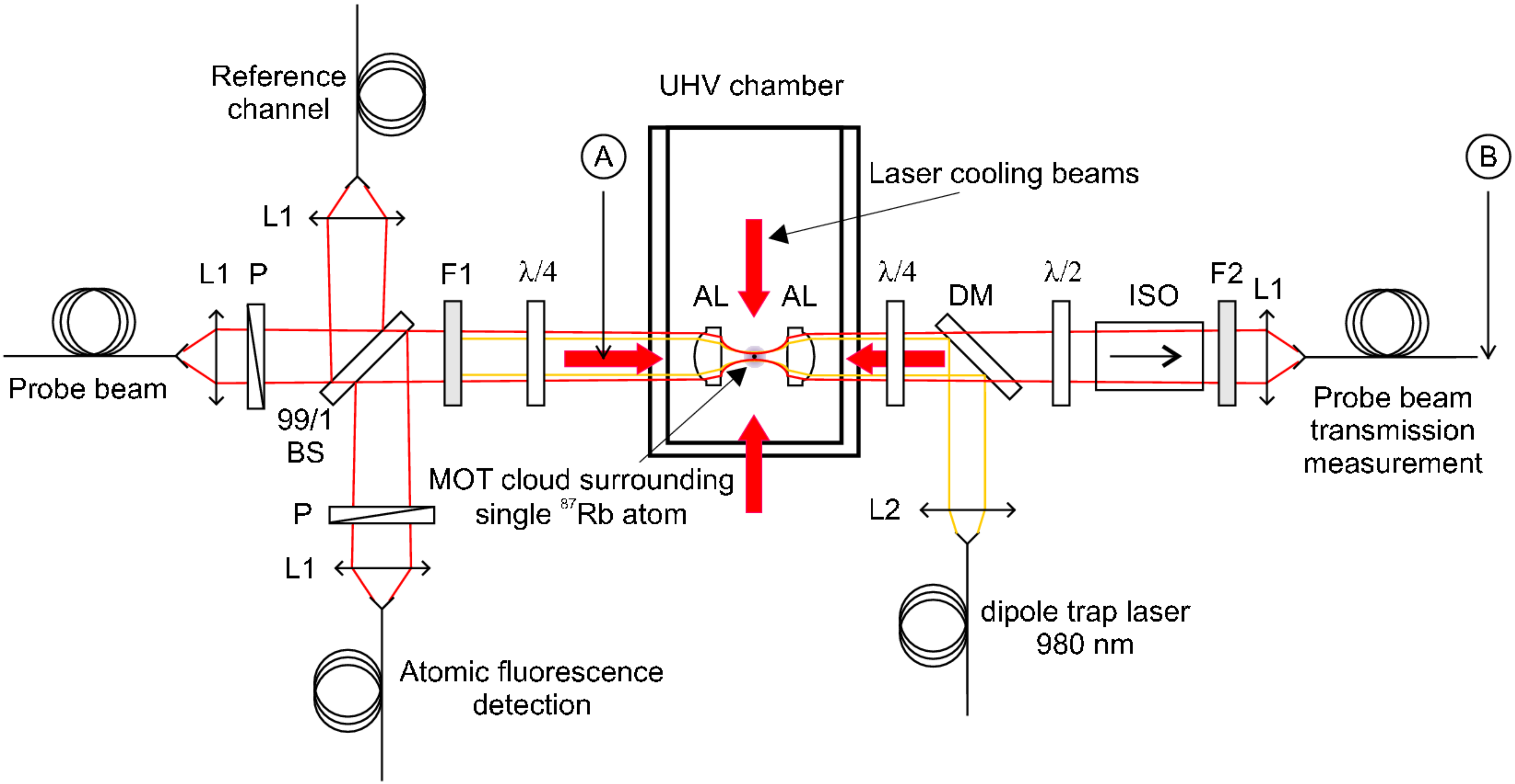
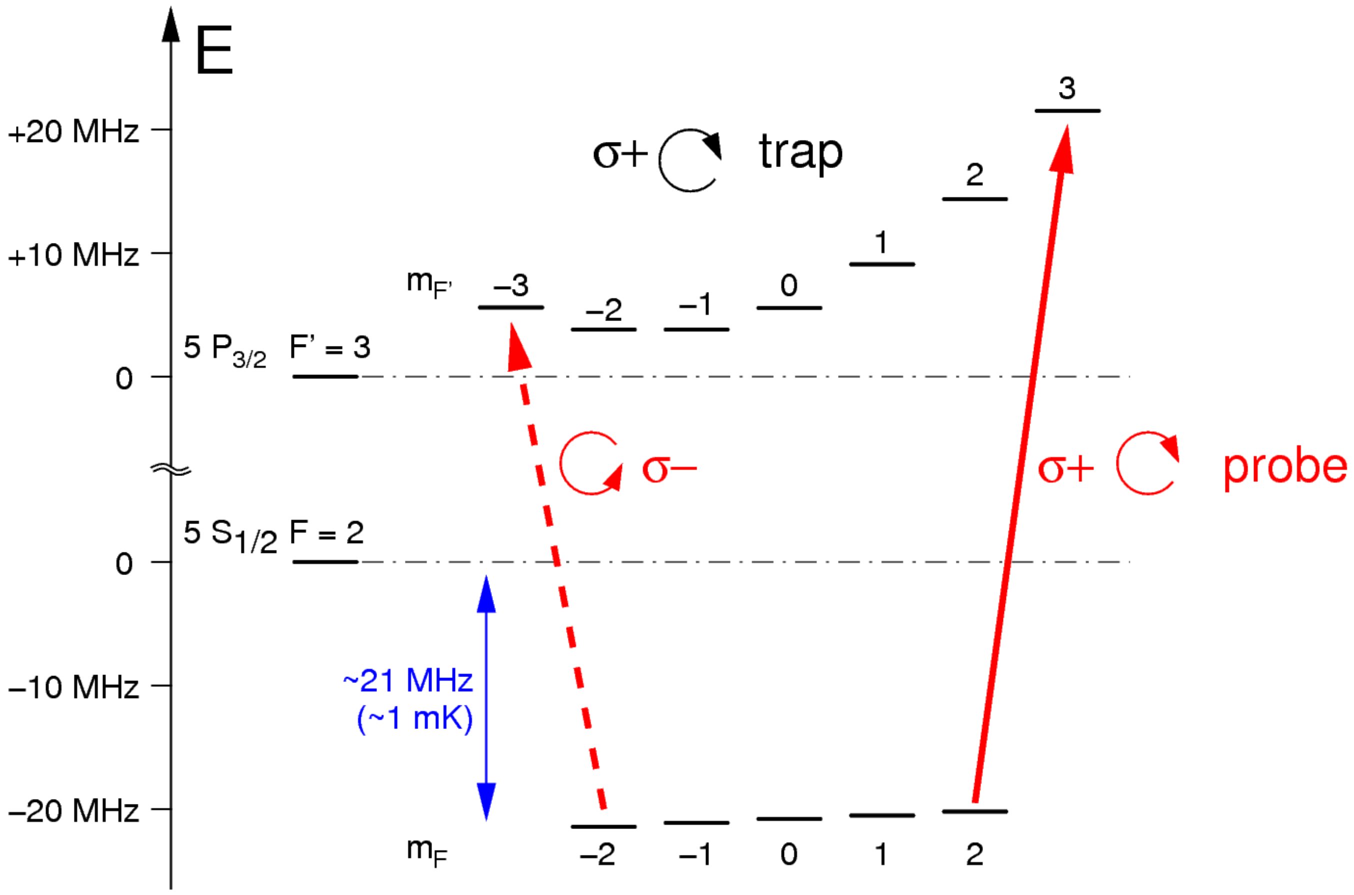
Experimental setup



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

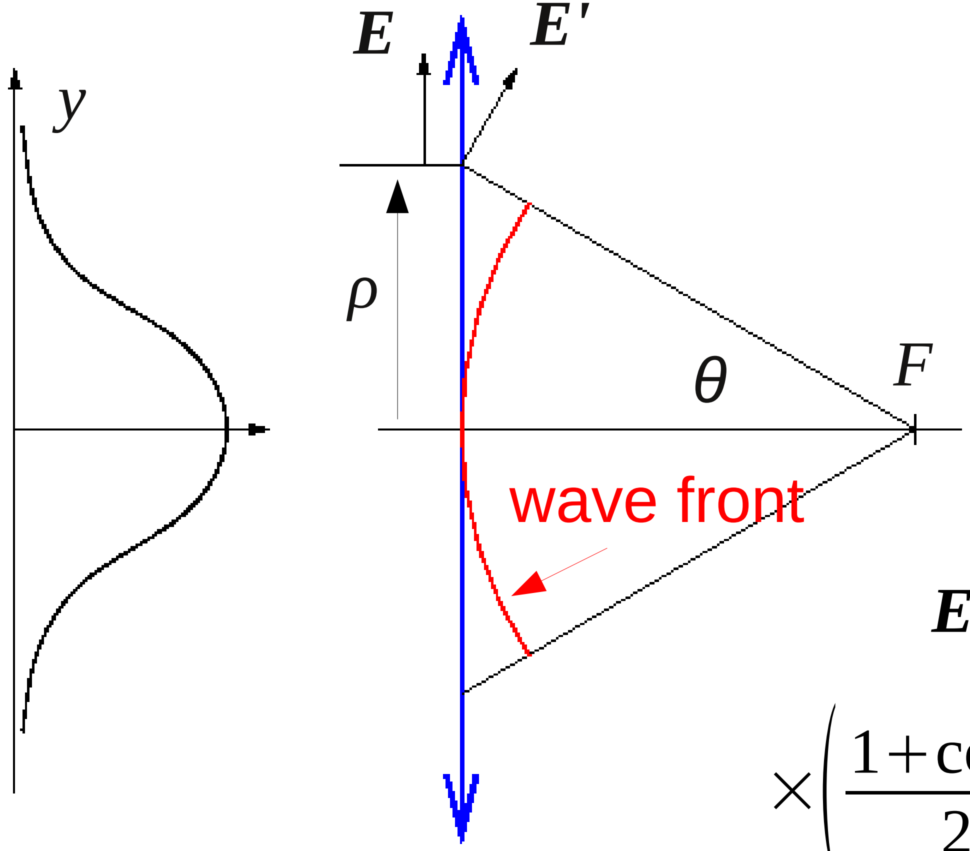


- optically pump with the probe beam into 2-level system

Step 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

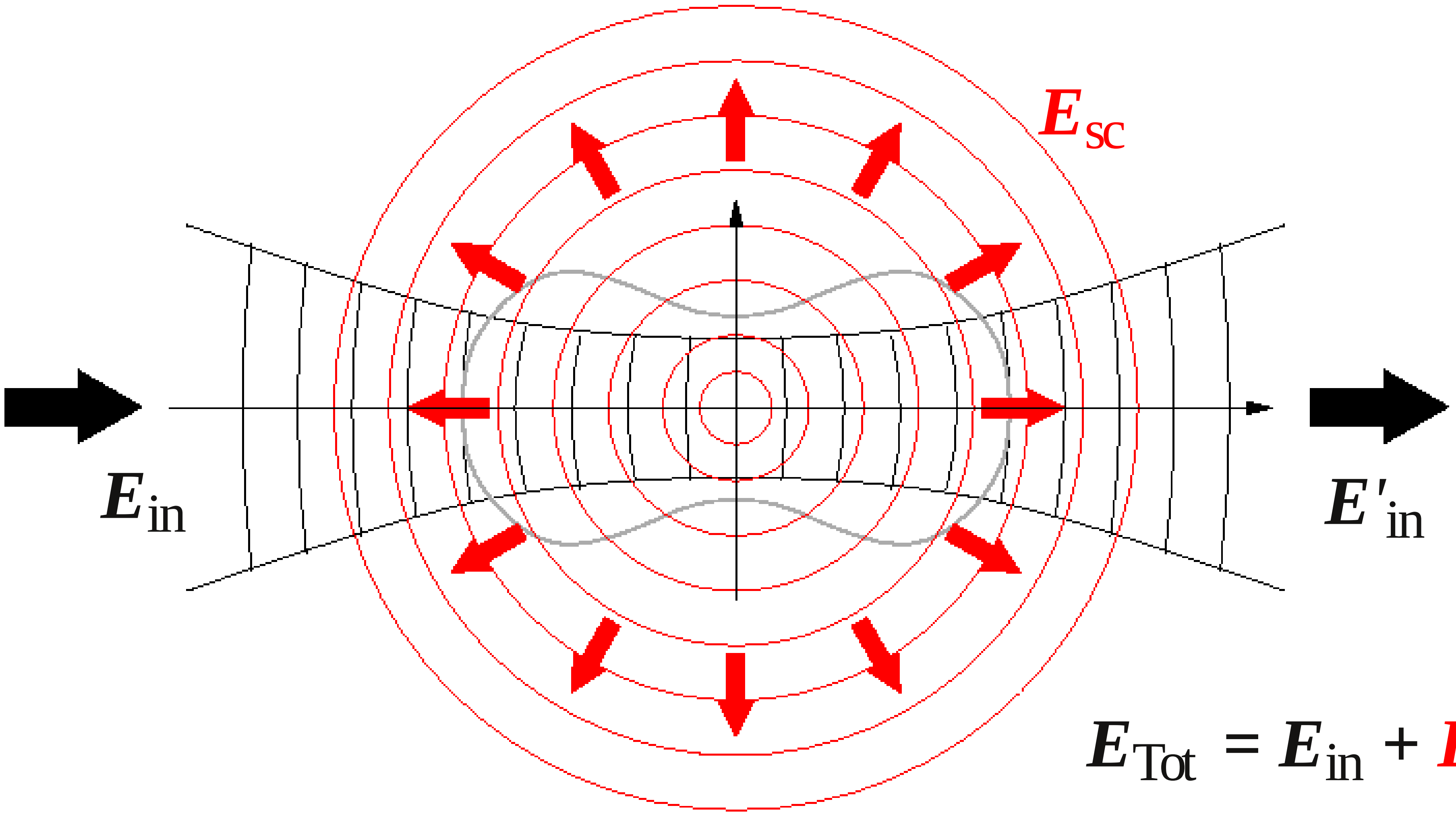
(Richardson/Wolf criteria, ~1950)

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

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

Step 3: Combine with probe

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



$\boldsymbol{E}_{Tot} = \boldsymbol{E}_{in} + \boldsymbol{E}_{sc}$

Single atom evidence

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