Взаимодействие одиночных атомов с сильно сфокусированным световым полем

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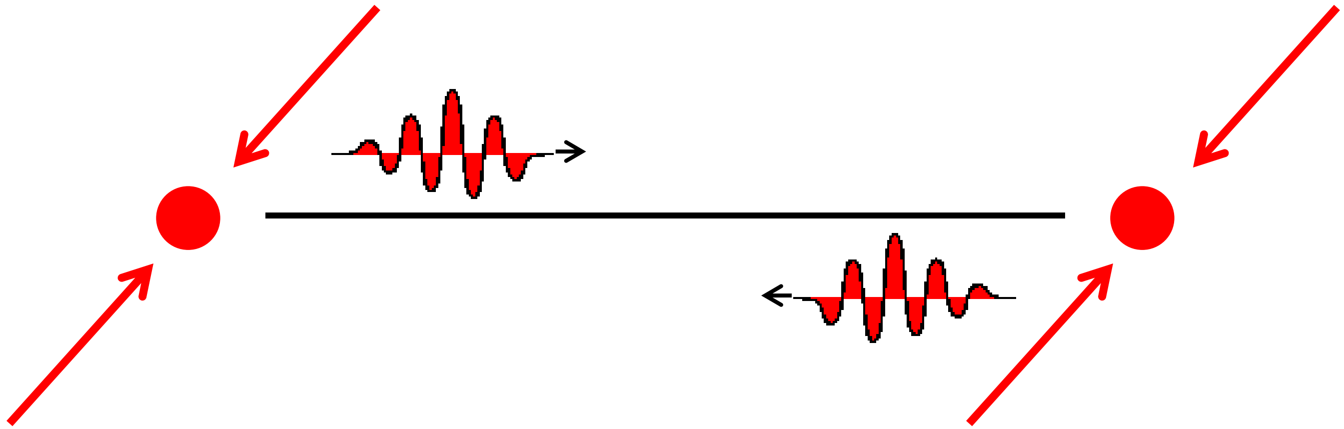
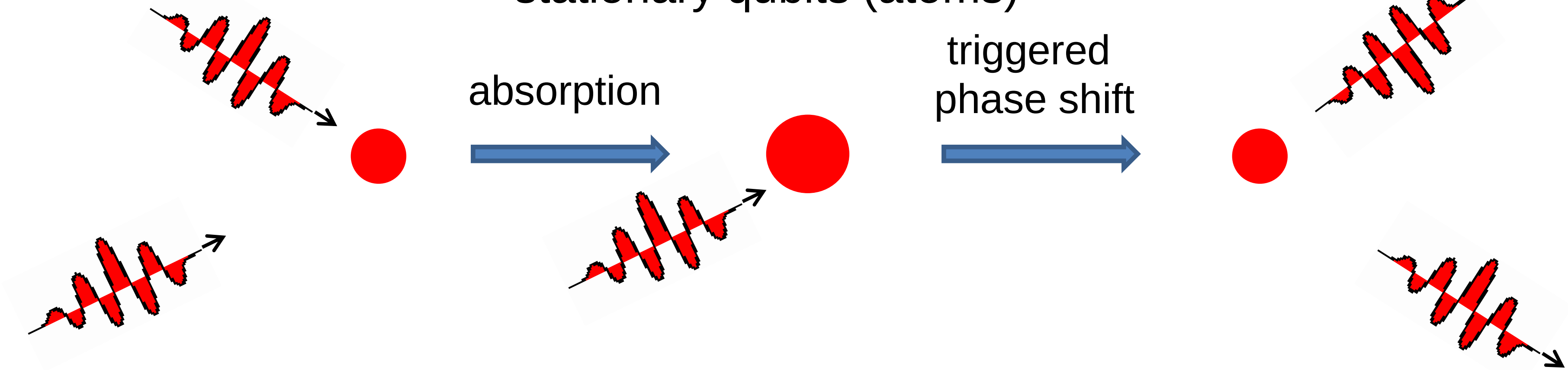
Motivation

- Quantum Information and Communication protocols



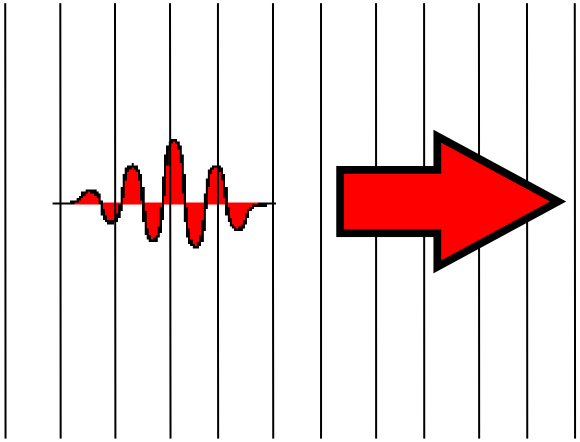
information exchange between “flying” qubits (photons) and stationary qubits (atoms)



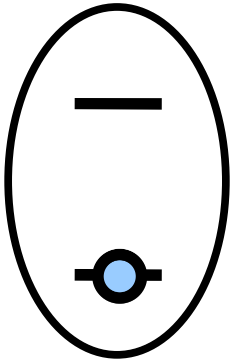
EFFICIENCY OF ATOM-PHOTON INTERFACE

Basic Problem

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



electromagnetic field / photon



2-level atom

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Use a cavity

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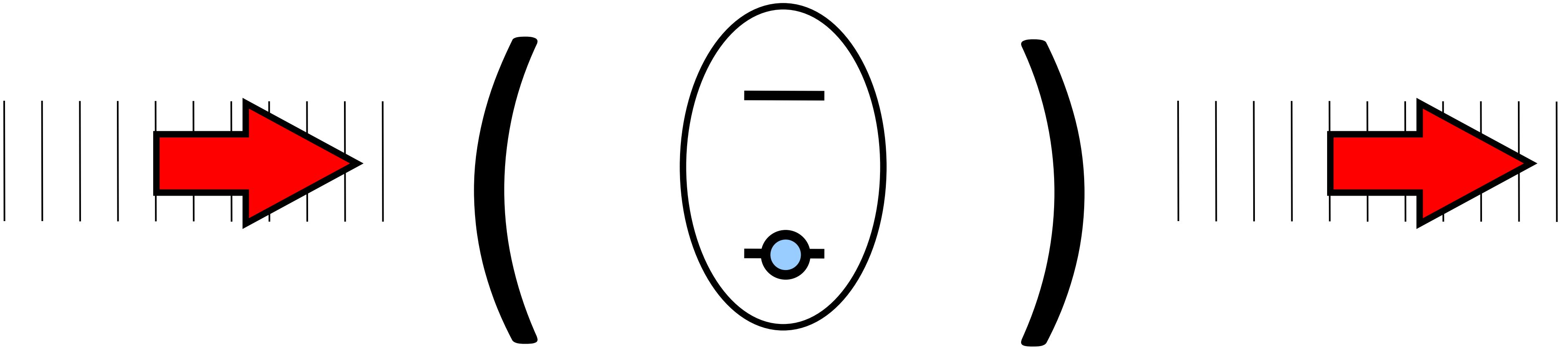


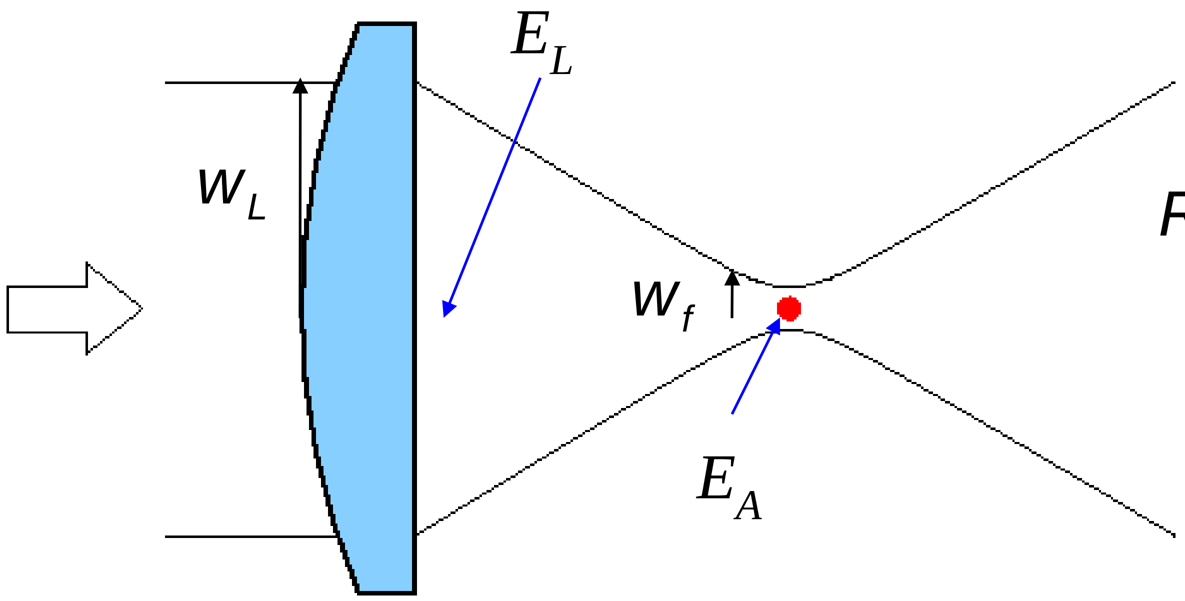
- High electrical field strength even for a single photon
- Preferred spontaneous emission into the cavity mode
- A cavity can enhance the interaction between a propagating external mode and an atom

Many ongoing experiments
CalTech, Univ. of Georgia, MPQ, etc…

Lens-based

Or just use a (good) lens to focus light to an atom

Take a Gaussian beam (laser, single-mode fiber) and do estimation



paraxial approximation

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

Oversimplified model --- doesn't apply for strong focusing

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Modelling

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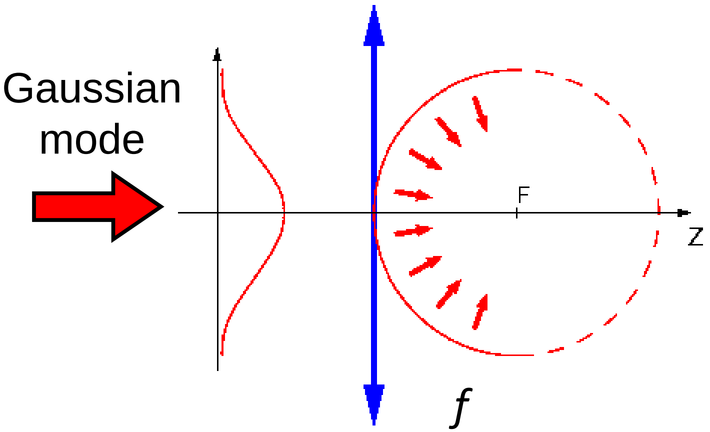


- Let the field have a spherical wave front after the lens and write it in vectorial form compatible with Maxwell equations

- Propagate field to the focus

✓ mode decomposition

parabolic wavefront: S. van Enk et al., 2001, (Phys.Rev.A **63**, 023809)

spherical wavefront: M.K. Tey et al., 2009. (NJP, **11**, 043011)

✓ use Green theorem for a closed expression for field at focus E_A

- determine atom response from semiclassical excitation probability for a given field

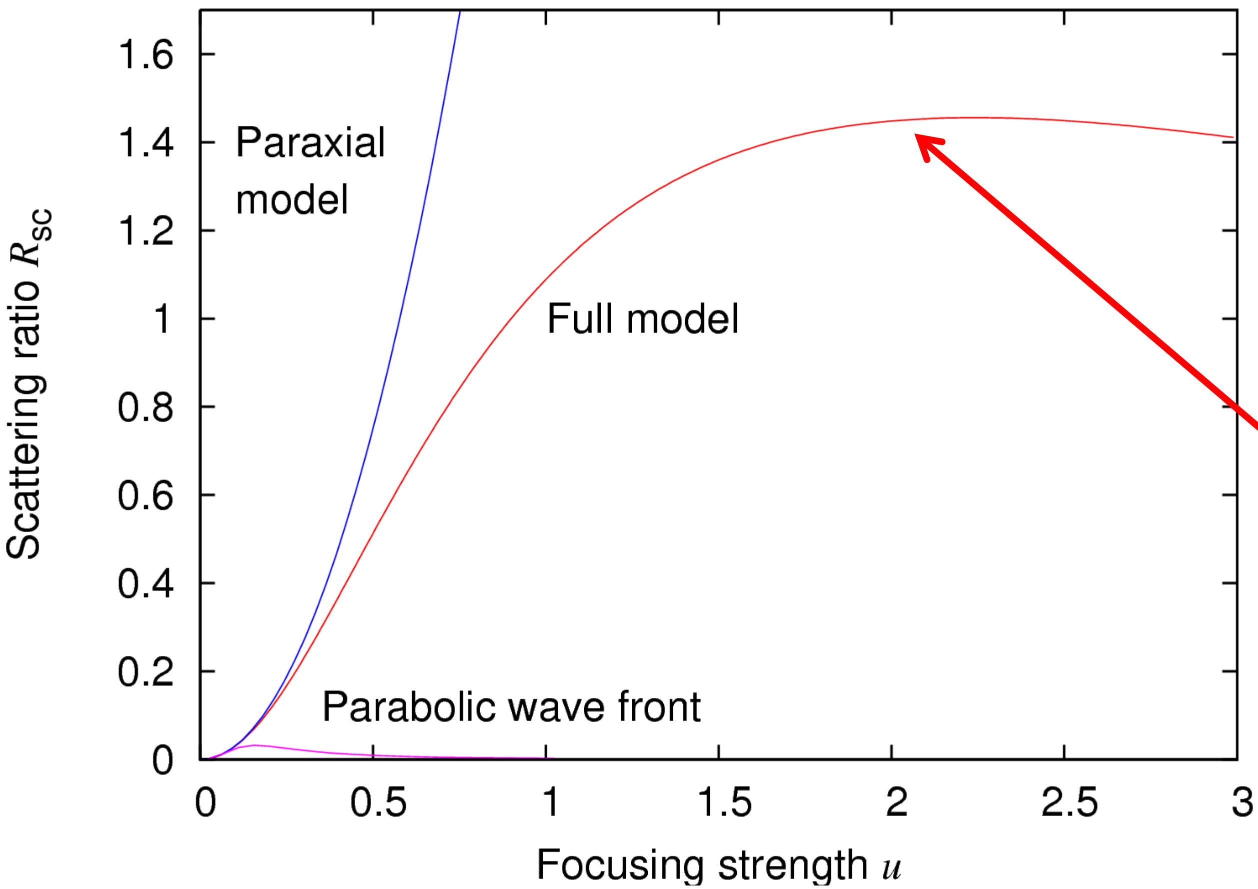
for weak, on-resonant excitation $P_{sc} = \dfrac{3\lambda^2 \varepsilon_0 E_A^2}{4\pi}$

- obtain the scattering ratio $R_{sc} = \dfrac{P_{sc}}{P_{in}}$

Modelling results

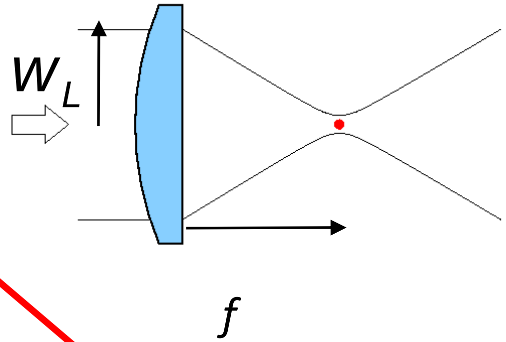
Scattering ratio for Gaussian beam

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



focusing strength

$$u = \frac{w_L}{f}$$



$R_{sc} > 1$!!!

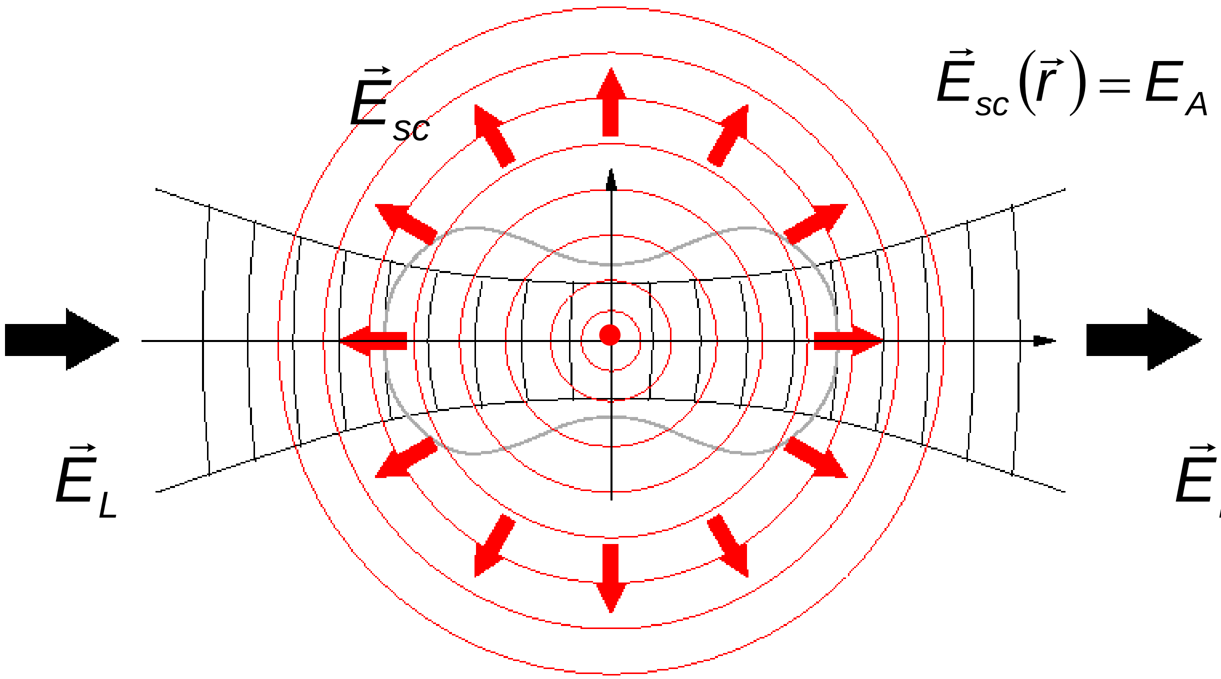
Energy conserved !?!?

Interference

The total field is a superposition of the excitation and scattered field

Zumofen, et al. Phys.Rev.Lett .**101**, 180404

$$\vec{E}_{Tot}(\vec{r}) = \vec{E}_{in}(\vec{r}) + \vec{E}_{sc}(\vec{r})$$



phase lag

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

dipolar σ_+ transition

assures no energy conservation violation

The outgoing power is defined up to a constant

$$P_{out} \equiv |E_{Tot}|^2 = P_{in} + P_{sc} + \int d\vec{r} \left[\left(\vec{E}_{in}(\vec{r}) \cdot \vec{E}^*_{sc}(\vec{r})\right) + \left(\vec{E}^*_{in}(\vec{r}) \cdot \vec{E}_{sc}(\vec{r})\right)\right]$$

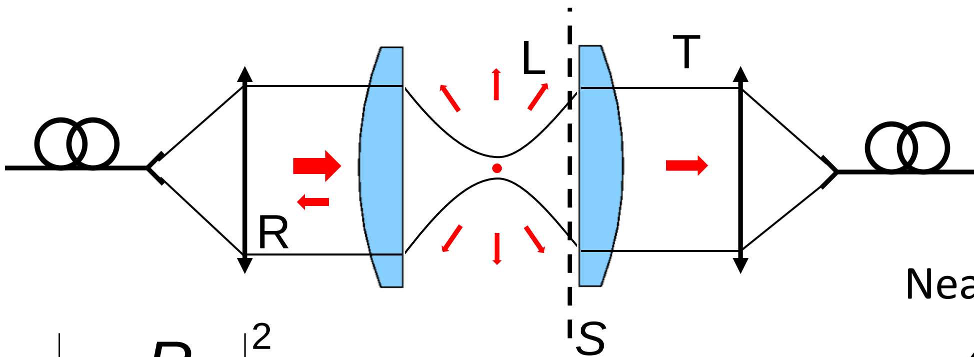
Projection into fiber

Since no detector covers the full solid angle, we only partially collect the outgoing power

✓ natural choice --- projection onto the same mode as excitation

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

Integration can be carried out and we obtain experimentally measured quantities



Transmission

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

Near-resonant phase shift

$$\delta\phi = \arg\left(1 - \frac{R_{sc}}{2} \frac{i\,\Gamma}{2\Delta + i\,\Gamma} \right)$$

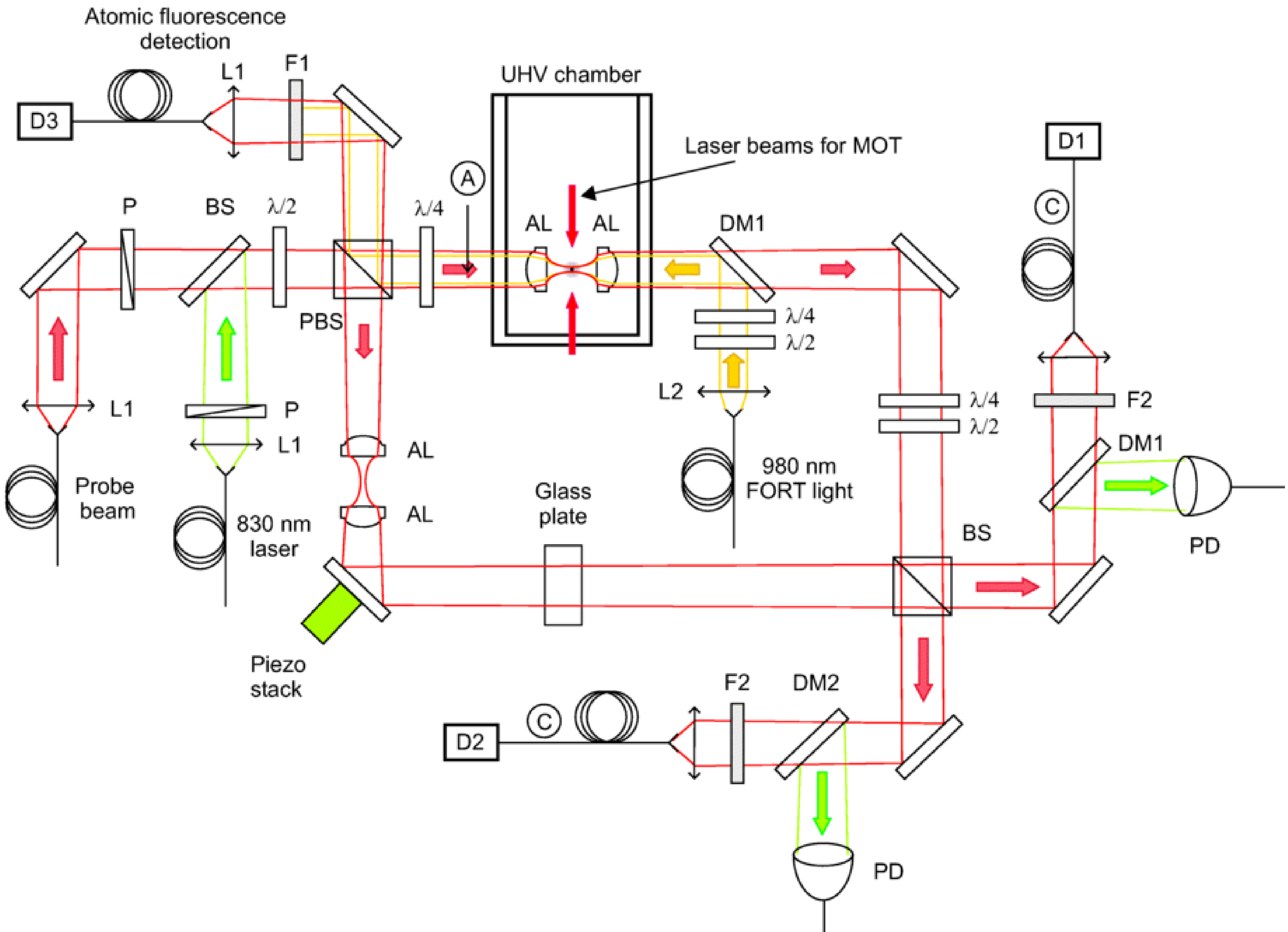
Reflectivity

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

Losses

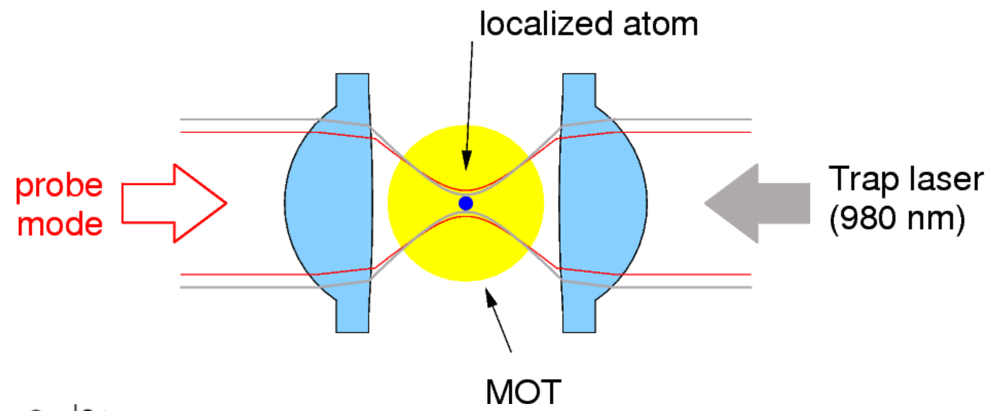
$$L = R_{sc} - \frac{R_{sc}^2}{2}$$

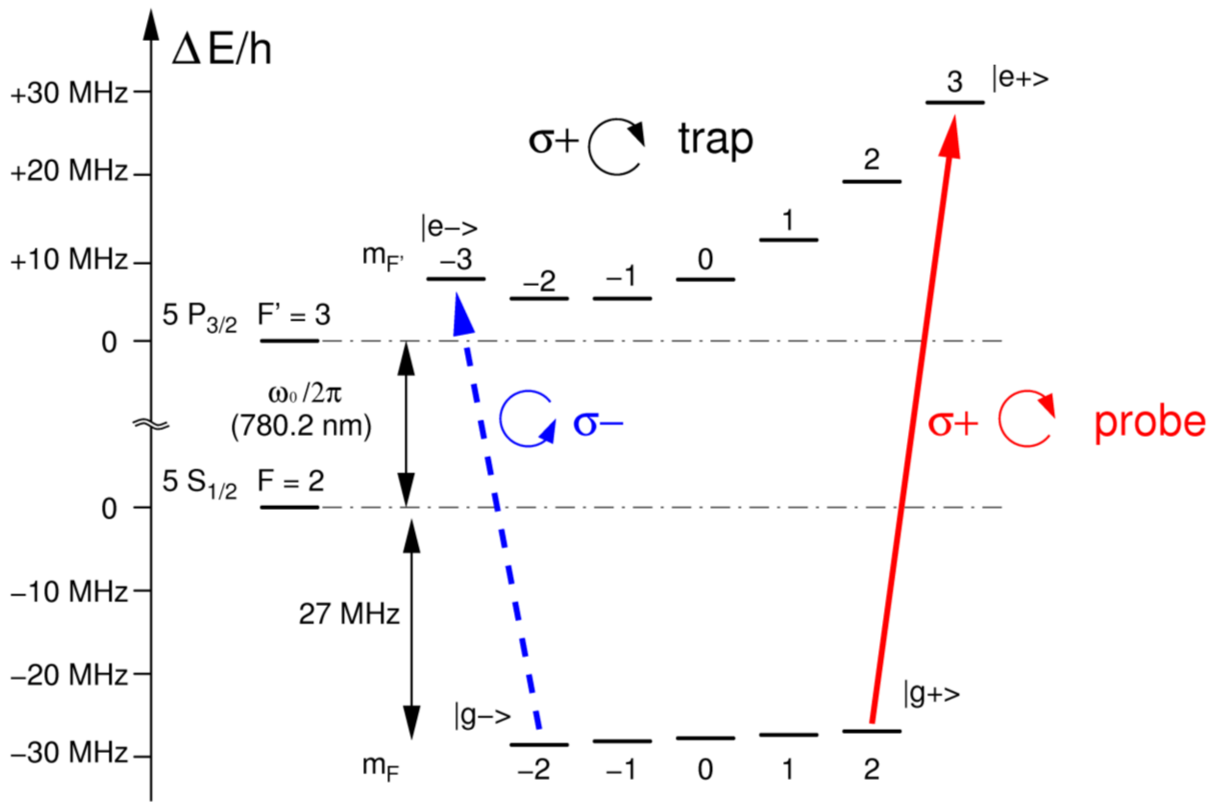
Experiment

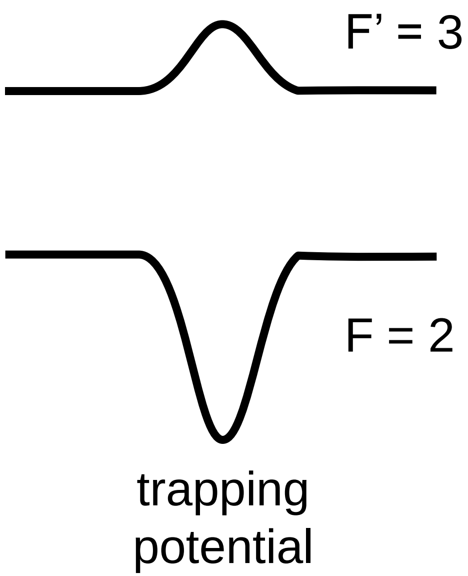

Atomic fluorescence detection
D3
L1
F1
UHV chamber
Laser beams for MOT
D1
A
C
P
BS
λ/2
λ/4
AL
AL
DM1
PBS
λ/4
λ/2
L2
λ/4
λ/2
F2
L1
P
L1
AL
AL
980 nm FORT light
DM1
Probe beam
830 nm laser
Glass plate
BS
PD
Piezo stack
F2
DM2
D2
C
PD

AC Stark shift

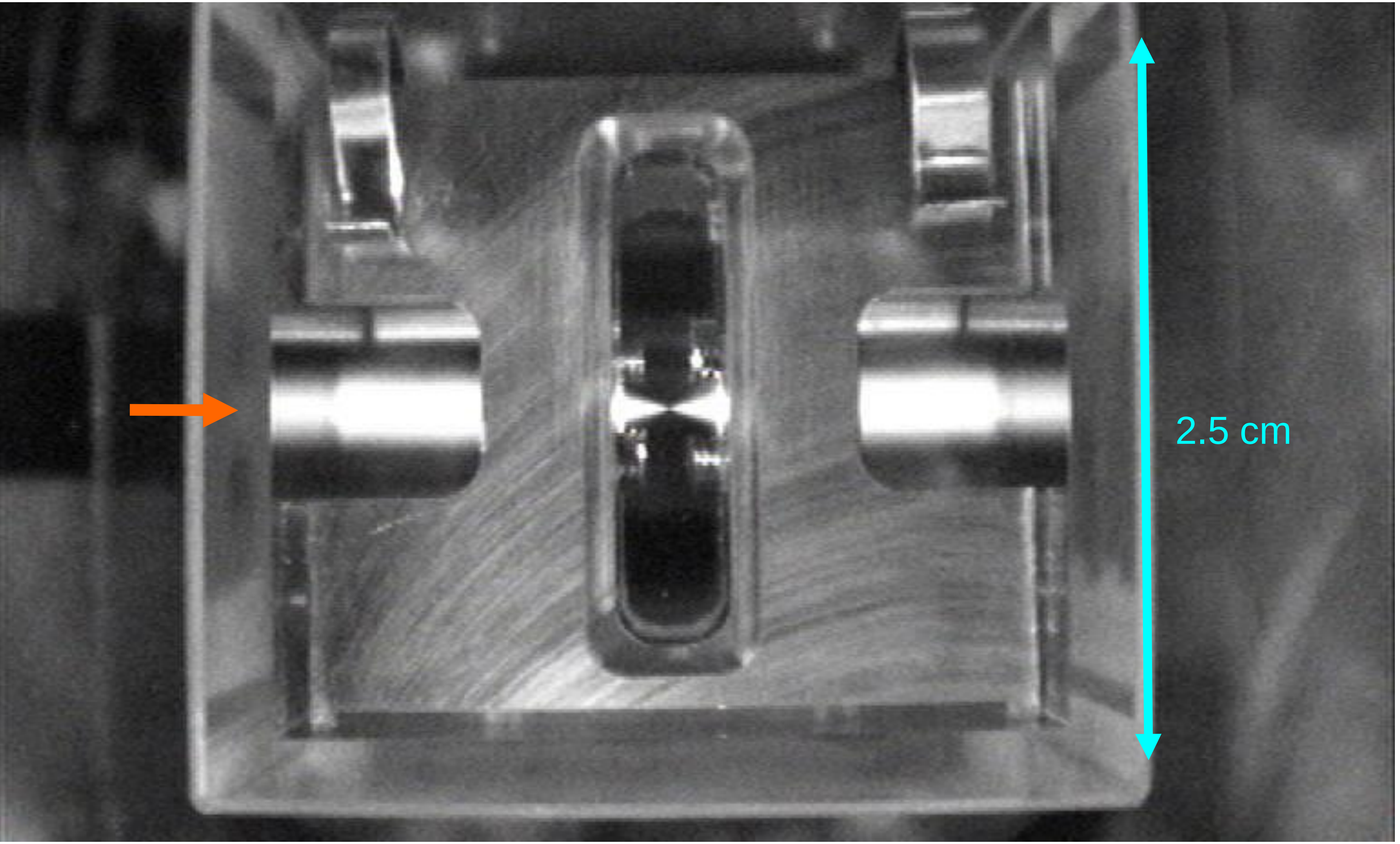
Circularly polarized dipole trap defines
the quantization axis and splits
the degeneracy of hyperfine states



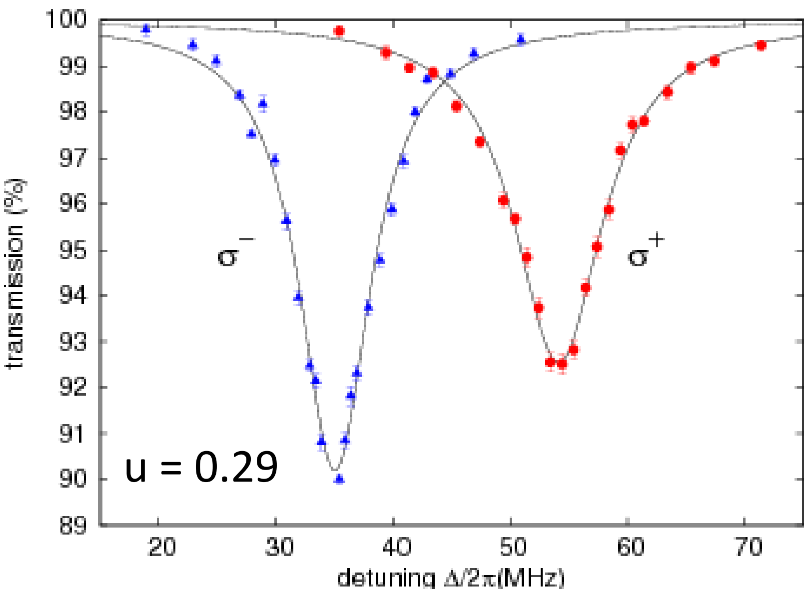


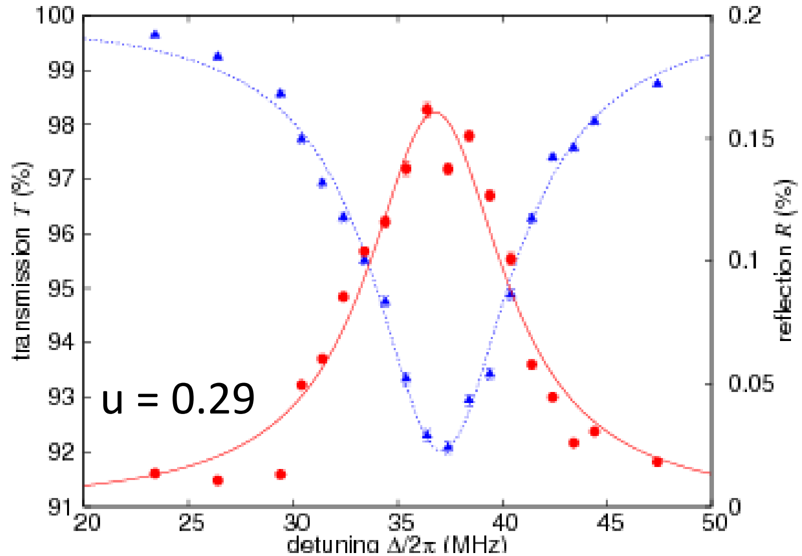


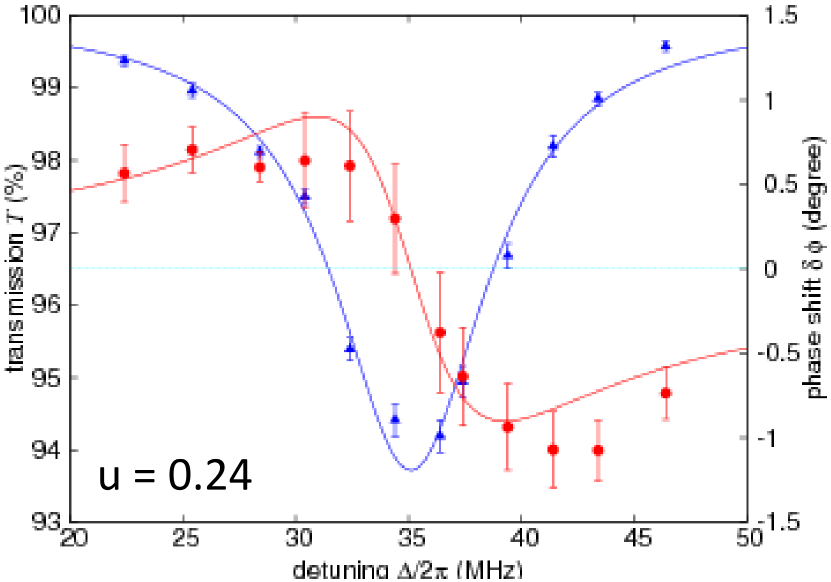
The real thing



Results

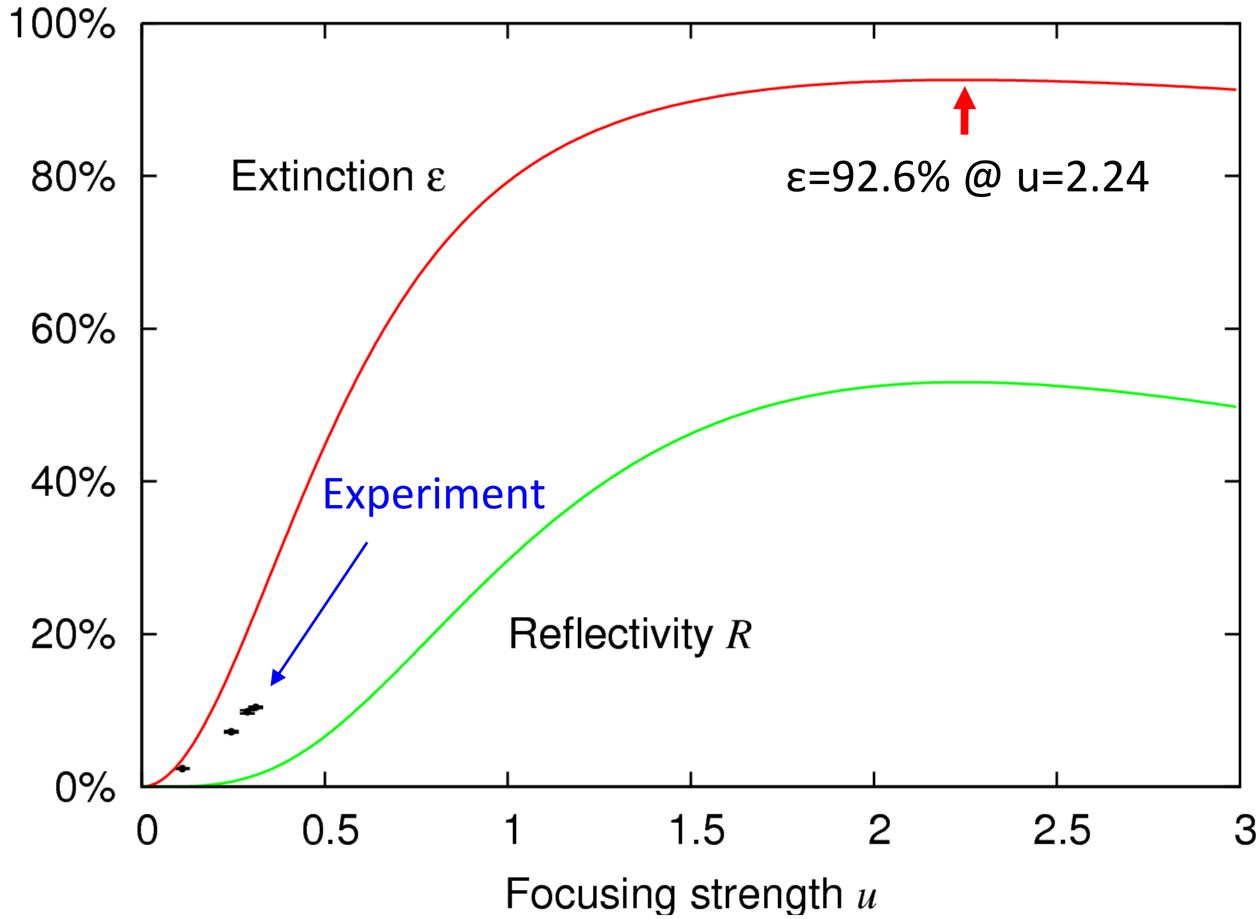






Experiment	Theory
T_{min} = 89.7 ± 0.7 %	T_{min} = 79.6 %
R_{max} = 0.17 ± 0.05 %	R_{max} = 0.29 %
$\delta\phi_{max}$ = 0.98 ± 0.07 ^{o}	$\delta\phi_{max}$ = 2.3 ^{o}

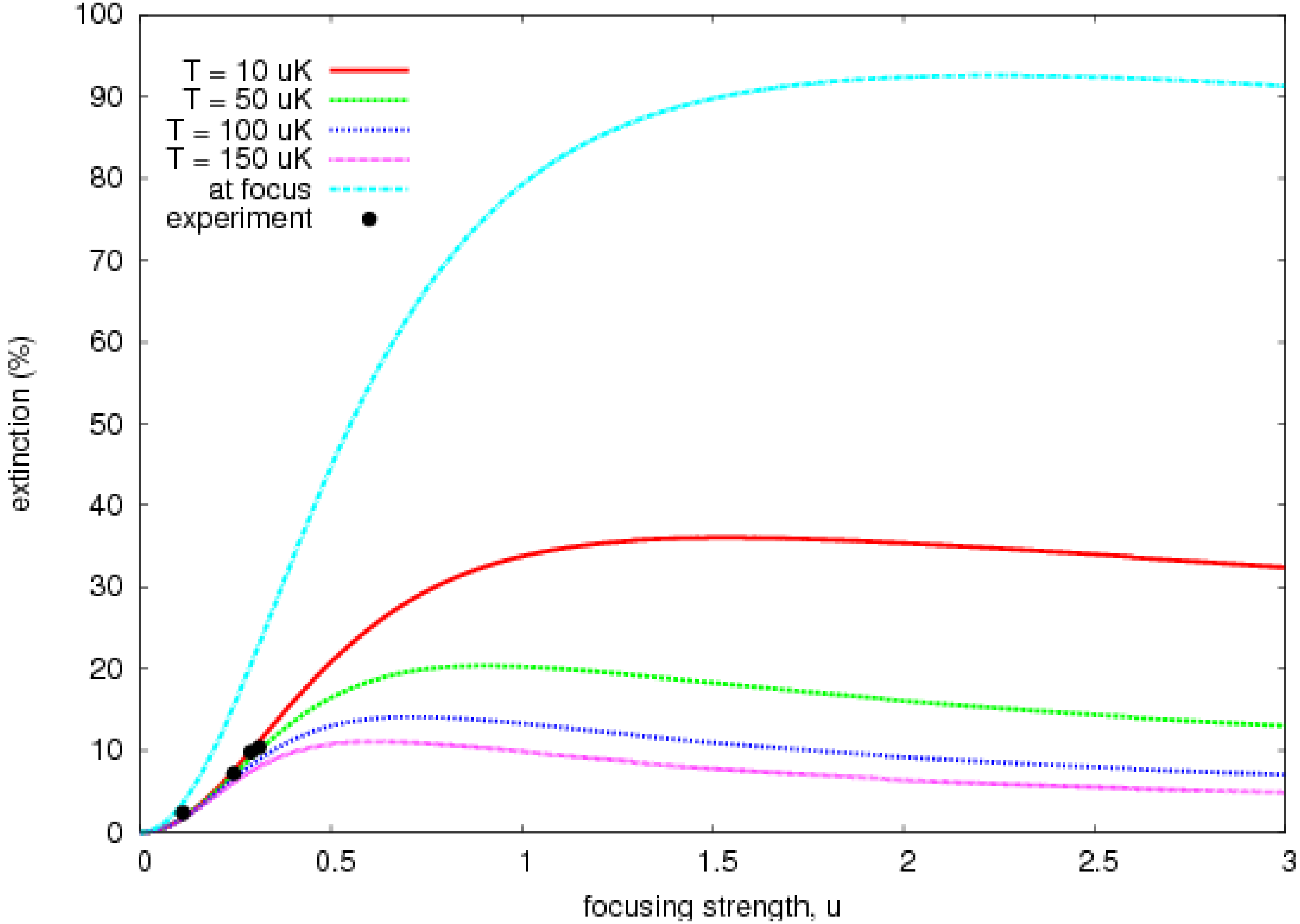
Theory vs Experiment



Two reasons for discrepancy:

- atomic motion around the focal point
- aberrations of the lens

Temperature



! MUST cool down the atom if high extinction values needed **!**

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Sideband cooling

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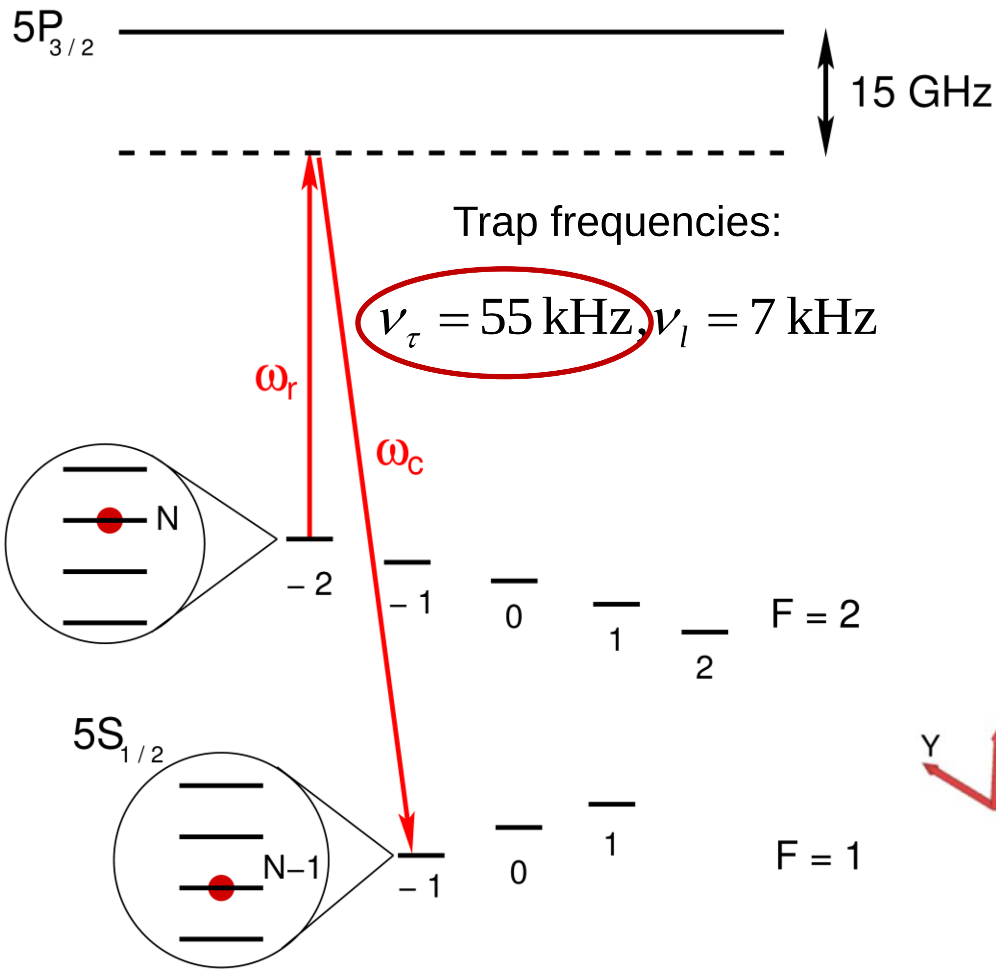
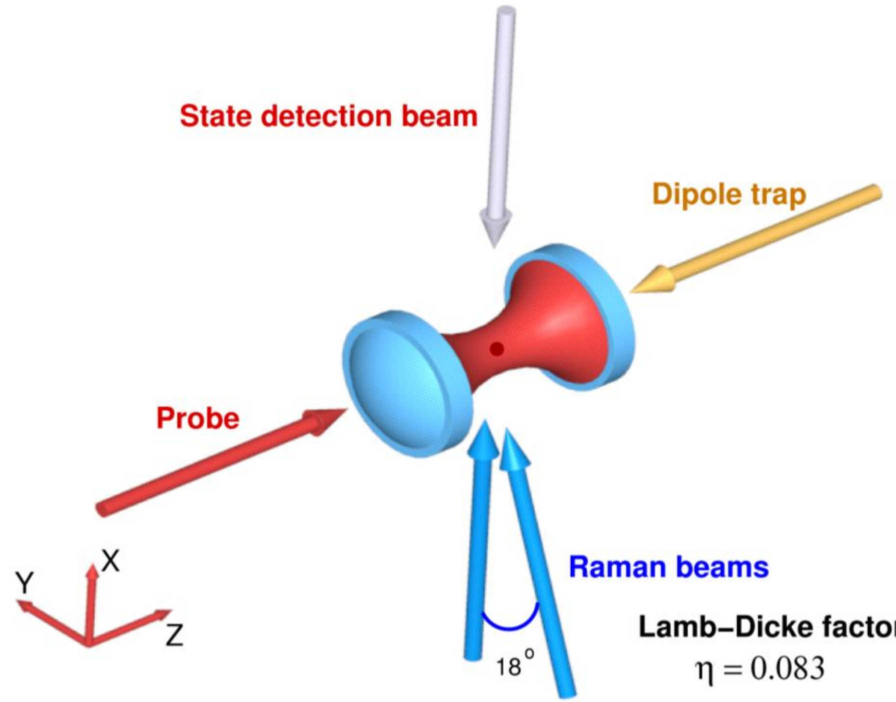
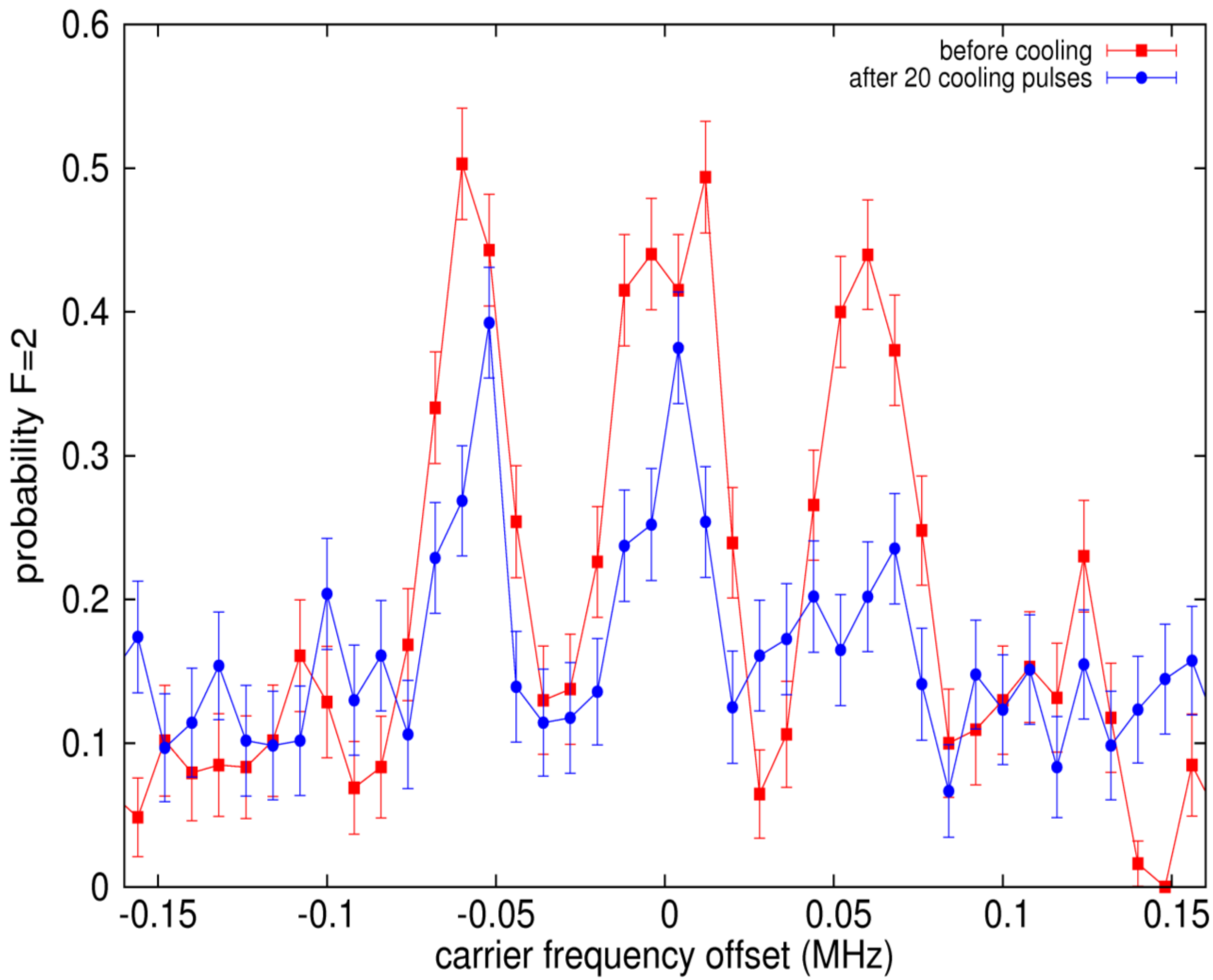


Beam geometry:



Sideband cooling



average motional state after cooling sequence

$$\langle n \rangle = 0.55 \pm 0.07$$

B-field sensitivity: ~ 2 kHz/mG
20 mG enough to shift the peak

active stabilization to mG level required.

Заключение

- Атом в сильно сфокусированном световом пучке, способен «сильно» рассеивать поле.
- Построена теоретическая модель, описывающая взаимодействие атома с сильно сфокусированными пучками света.
- За счет рамановского охлаждения, атом может быть охлажден до «почти» основного состояния ловушки

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Спасибо!

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http://www.qolah.org

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Gleb Maslennikov

Valerio Scarani
Christian Kurtsiefer

Single atom

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