Phase shift of a Weak Coherent Beam by a Single Atom

Syed Abdullah Aljunid, Meng Khoon Tey,

Brenda Chng, Timothy Liew, Gleb Maslennikov,

Valerio Scarani, Christian Kurtsiefer

Laser Physics 2009, Barcelona, Spain

Centre for Quantum Technologies

National University of Singapore

Motivation

ATOM-PHOTON INTERFACE

- Quantify interaction of a two-level atom with light
- Strong interaction without a cavity.
- Appropriate measurement

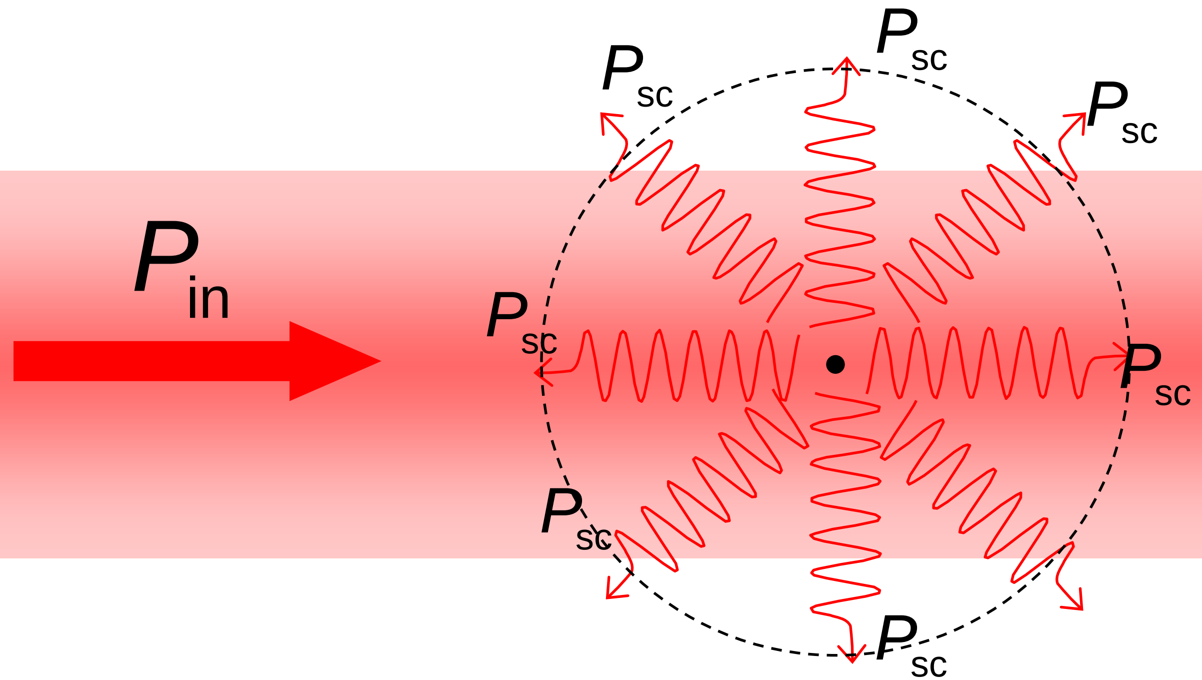
Key idea for high efficiency:

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

Centre for Quantum Technologies

Quantification

NUS National University of Singapore

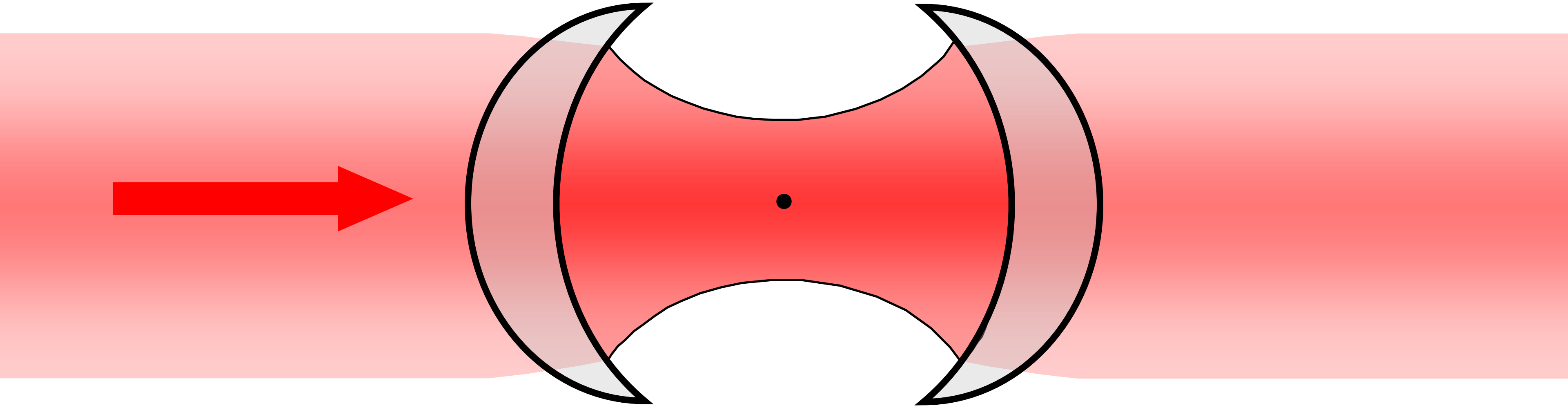


The scattering ratio $R_{sc} = \frac{P_{sc}}{P_{in}}$

Concentration of the incoming field
at the position of the atom is necessary!

Cavity

One solution: use a high-finesse cavity around the atom

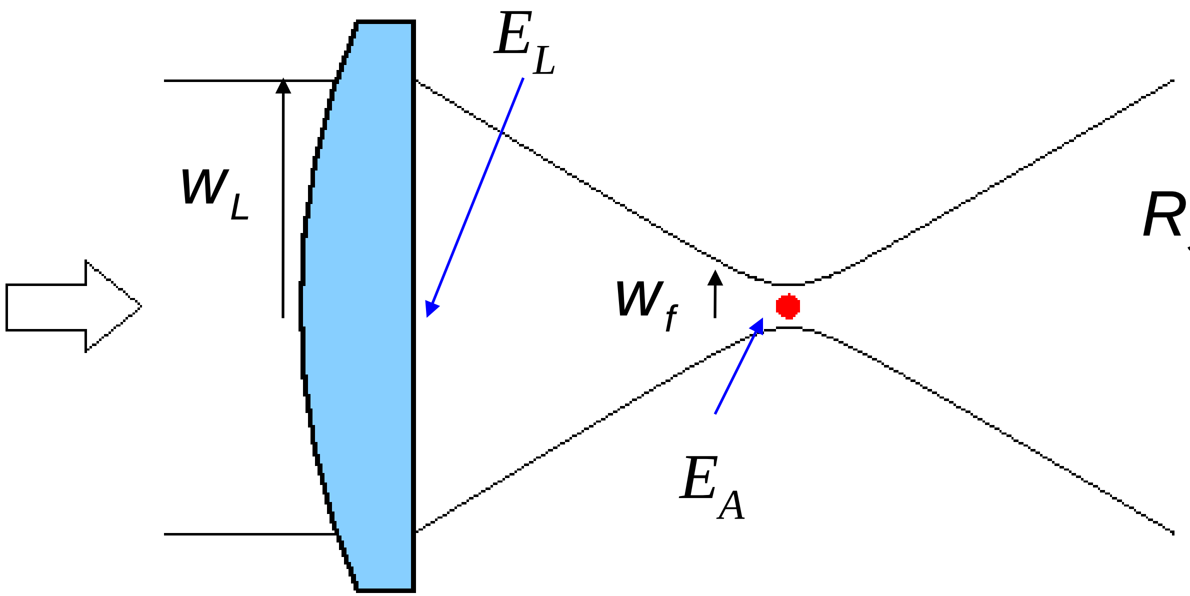


Many ongoing experiments
CalTech, Univ. of Georgia, Max-Planck-Institute, etc…

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



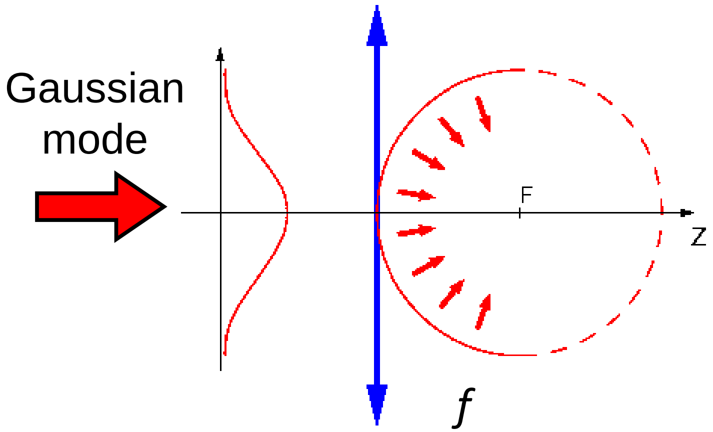
paraxial approximation

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

$$\approx \frac{3\lambda^2}{\pi w_f^2} \approx \sigma_{\max}/A$$

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

Modelling



- 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,

spherical wavefront: M.K. Tey et al., 2009.

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

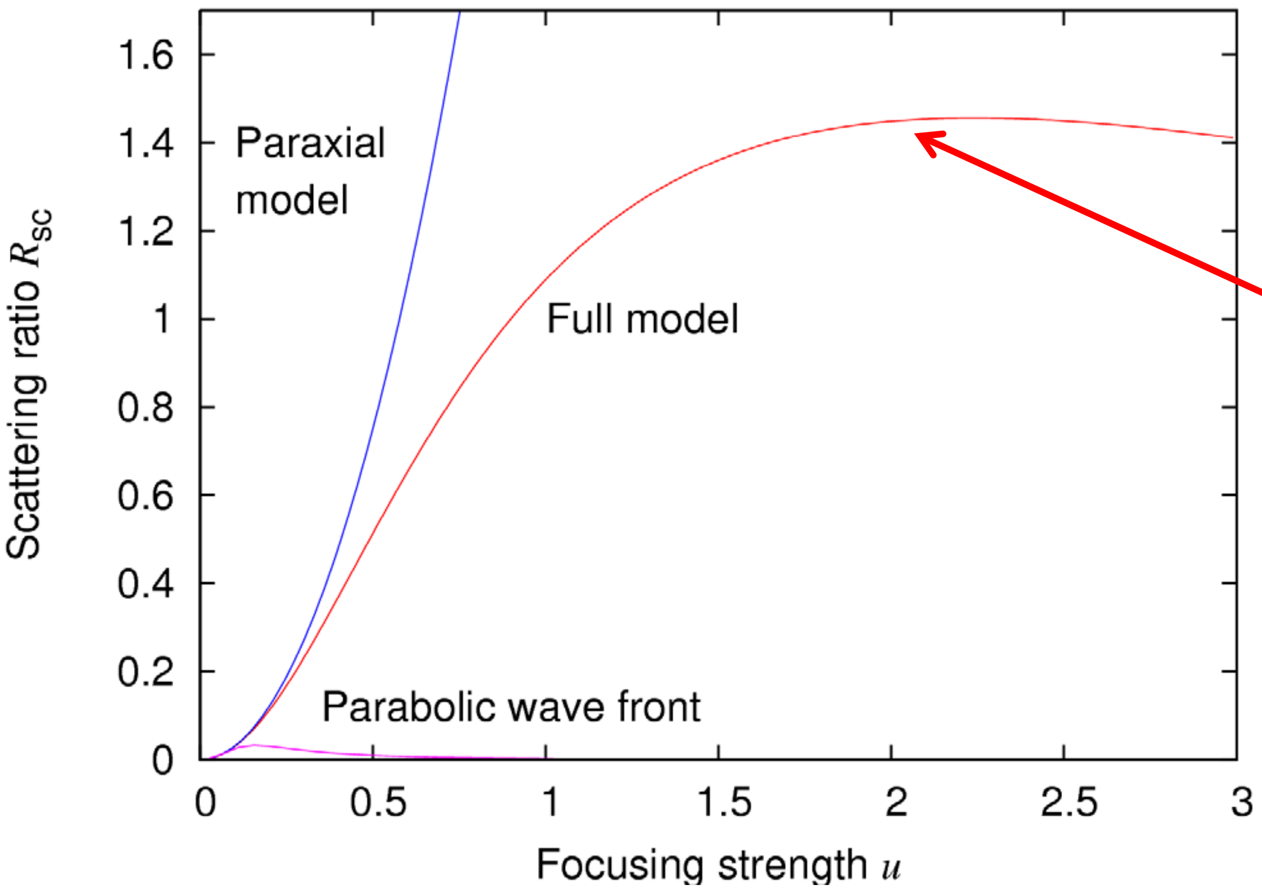
- determine atom response from semiclassical excitation probability for a given field

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

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

Modelling results

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



focusing strength

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

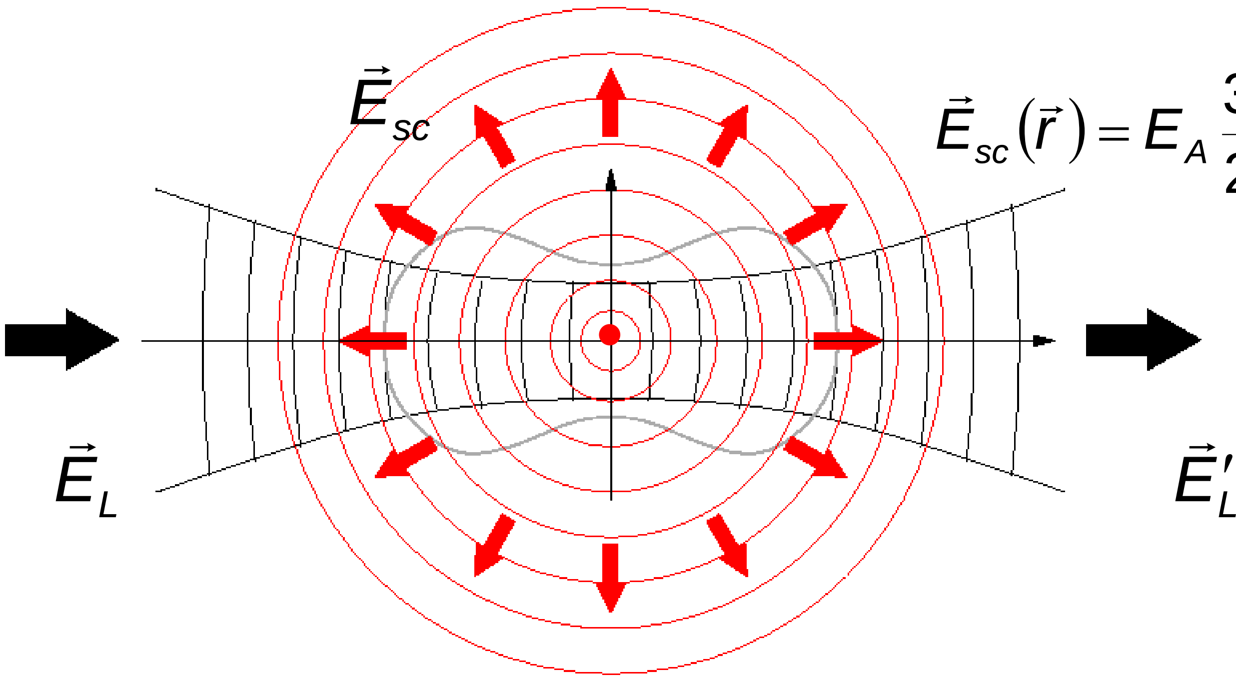
$R_{sc} > 1$!!!

Energy conserved!?!?

Interference

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

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



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

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

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

Forward transmission

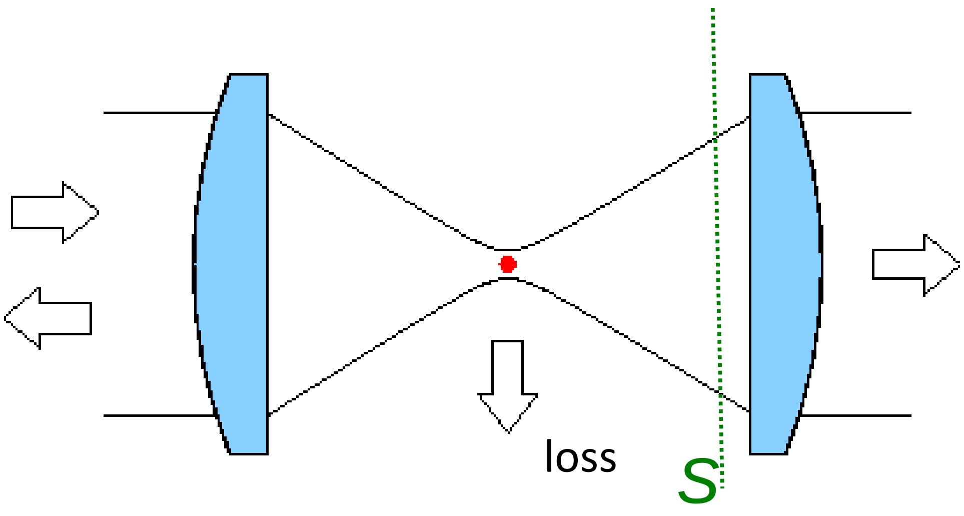
$$T = 1 - \varepsilon = \frac{P_{out}}{P_{in}} = \left|1 - \frac{R_{sc}}{2}\right|^2$$

Reflection

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

Losses

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



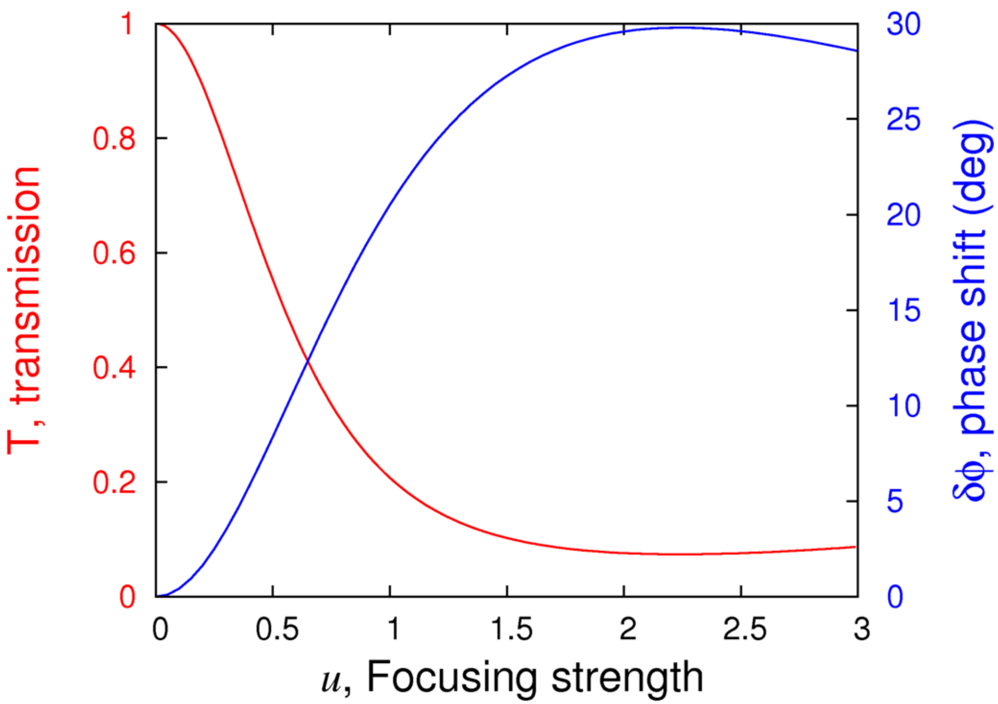
Phase shift

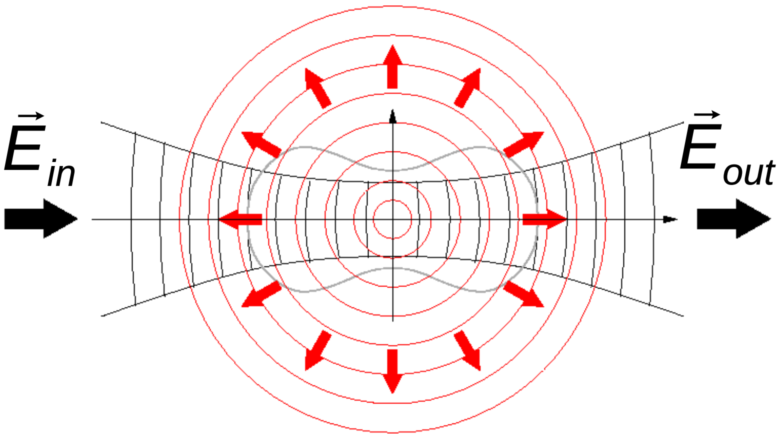
One also can estimate the phase shift that the atom imposes on a near-resonant light

$$\delta\phi = \arg\left(\vec{E}_{out}(\vec{r})\cdot\vec{E}^{*}_{in}(\vec{r})\right) = \arg\left(1 - \frac{R_{sc}}{2}\frac{i\,\Gamma}{2\Delta + i\,\Gamma}\right)$$

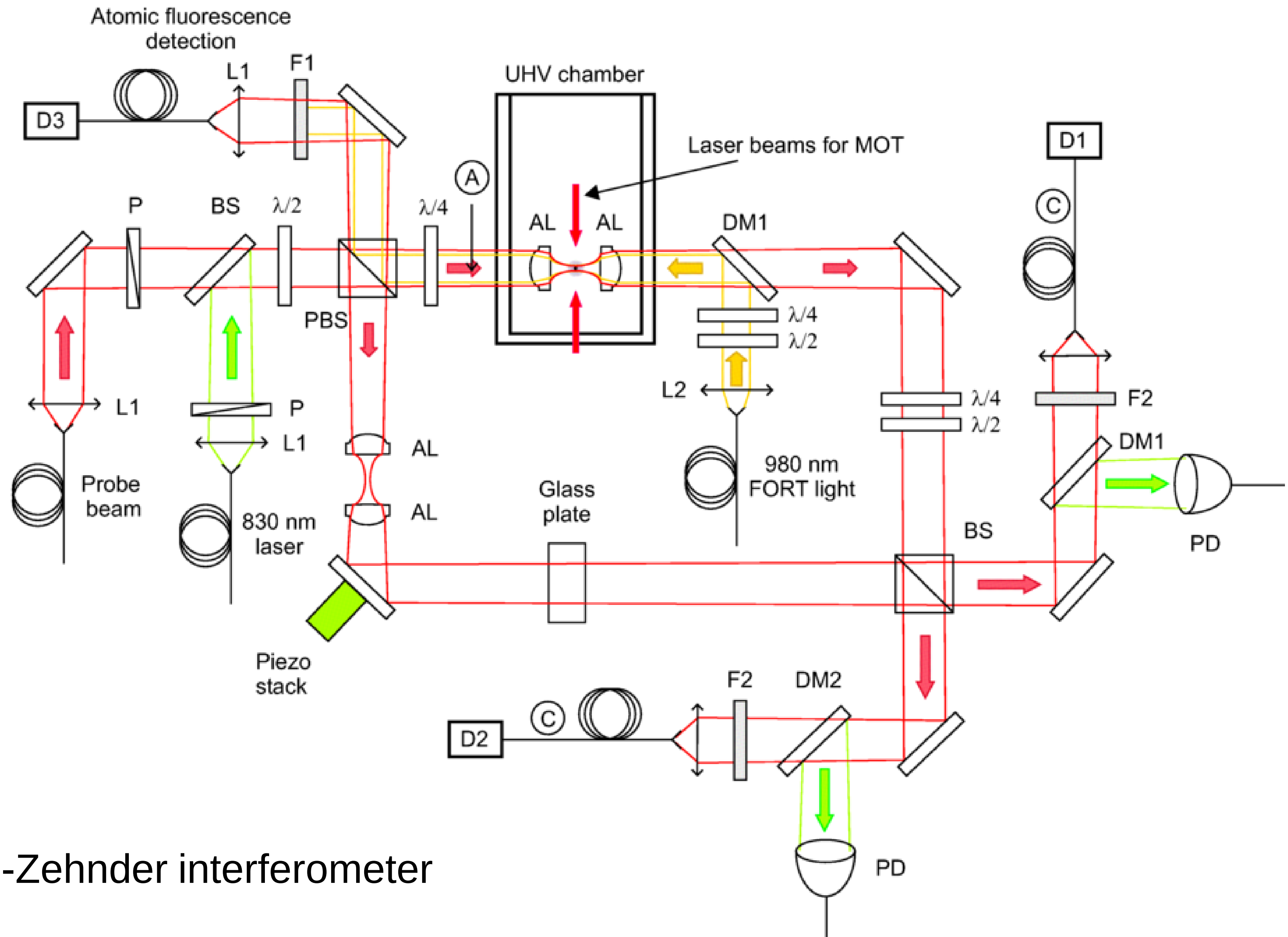
Lorentzian term

Gouy phase + “lag” of atomic response



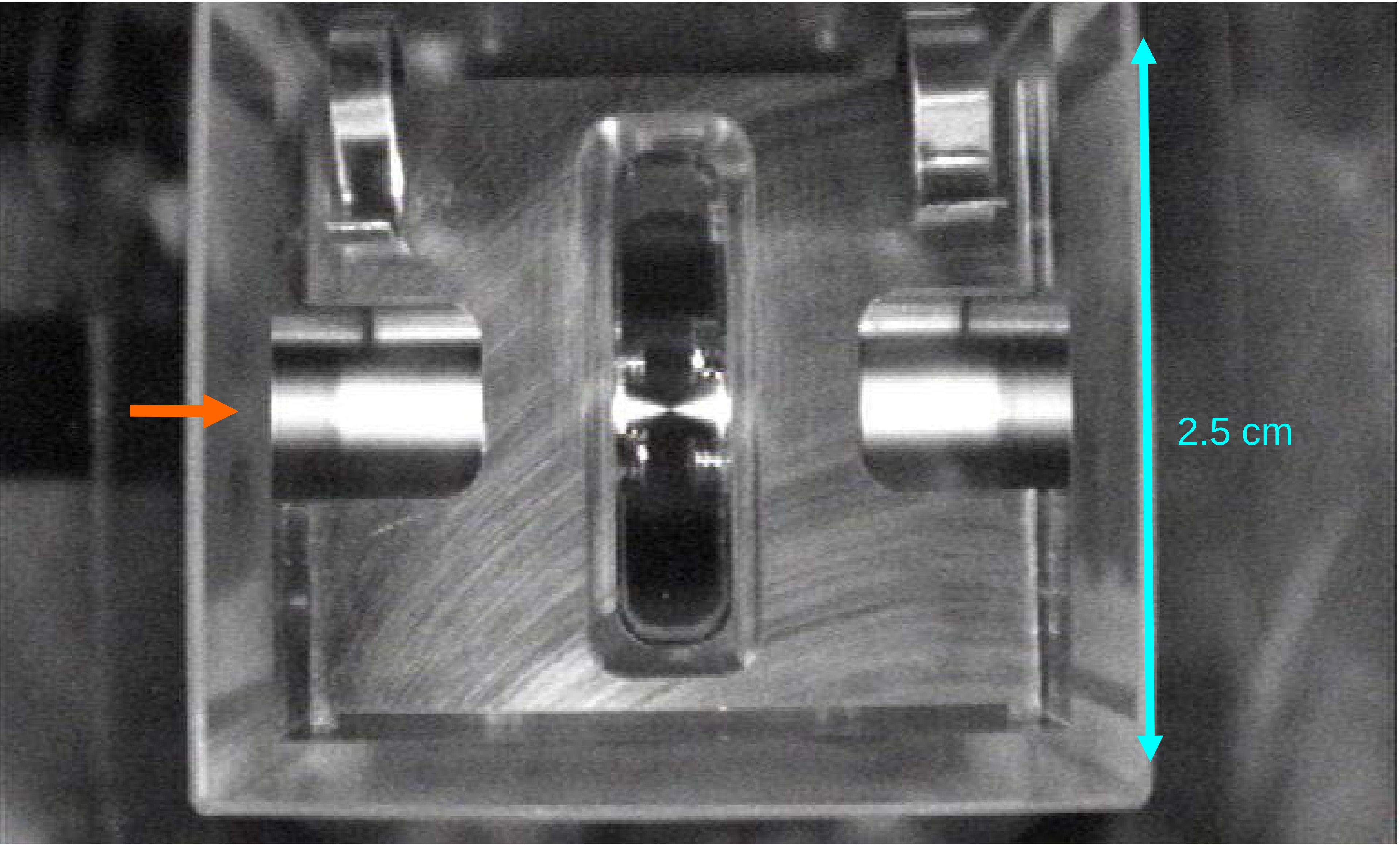


Experiment

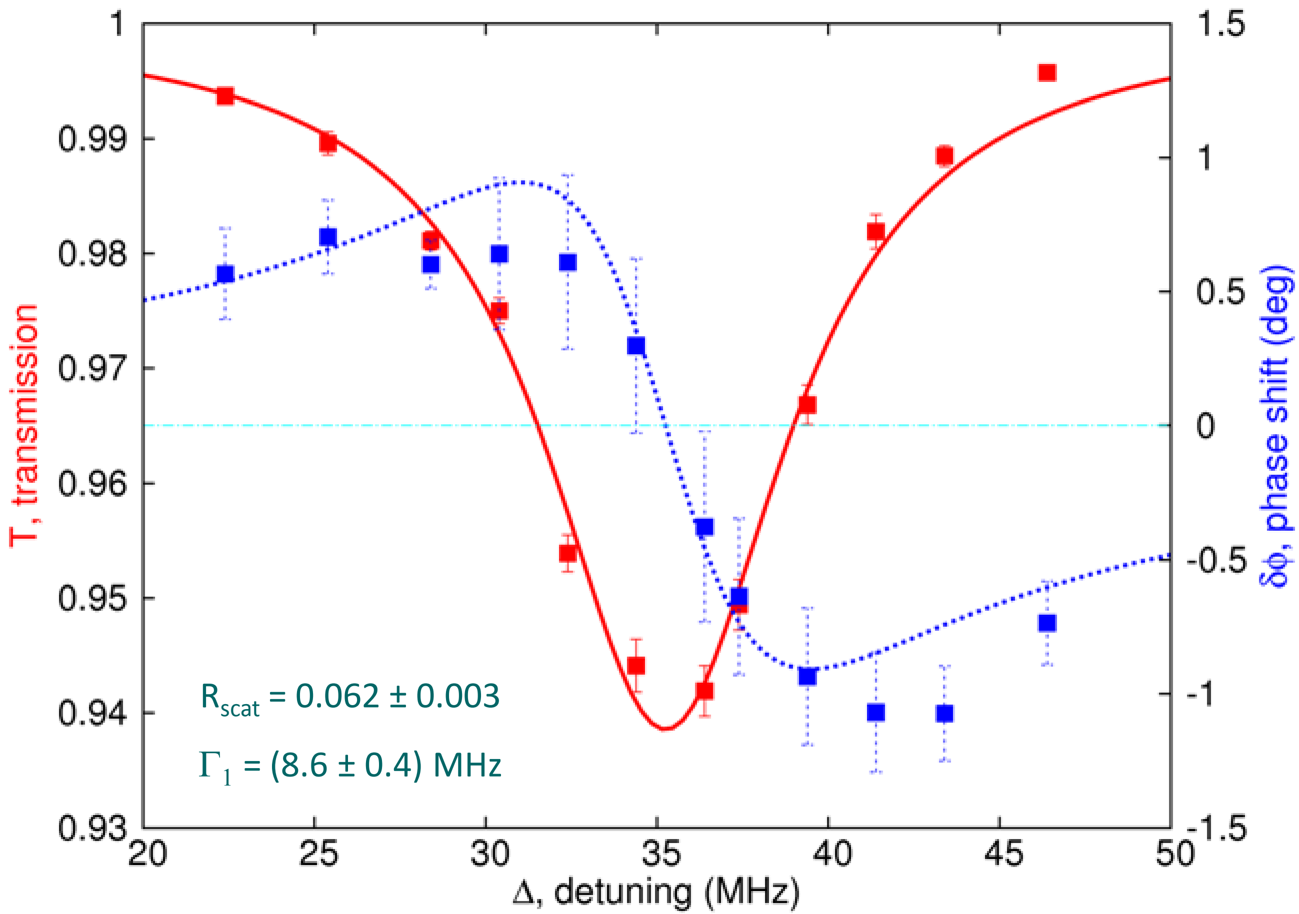


Mach-Zehnder interferometer

The real thing



Results



Transmission of

(95.9 ± 0.2)%

Max phase shift of (0.9 ± 0.2) ° at ~Γ/2

Theoretical

Transmission: 84%

max phase shift: 2.3°

$$\delta\phi = \arg(\vec{E}_{out} \cdot \vec{E}^{*}_{in}) = \arg\left(4\Delta^2 + \Gamma^2\left(1 - {R_{scat}}/{2}\right) + iR_{scat}\Gamma\Delta\right)$$

$$T = \frac{\left|\vec{E}_{out}\right|^2}{\left|\vec{E}_{in}\right|^2} = \frac{4\Delta^2 + \Gamma^2\left(1 - {R_{scat}}/{2}\right)^2}{4\Delta^2 + \Gamma^2}$$

Conclusion

- Strong interaction of light with a single atom can be observed by simple focusing.

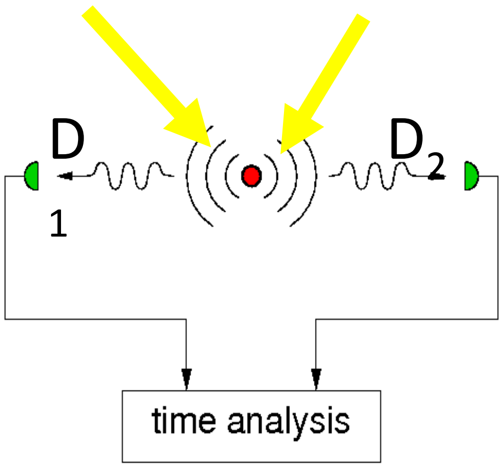
- 0.9° phase shift of a weak coherent beam observed together with 95.9% transmission.

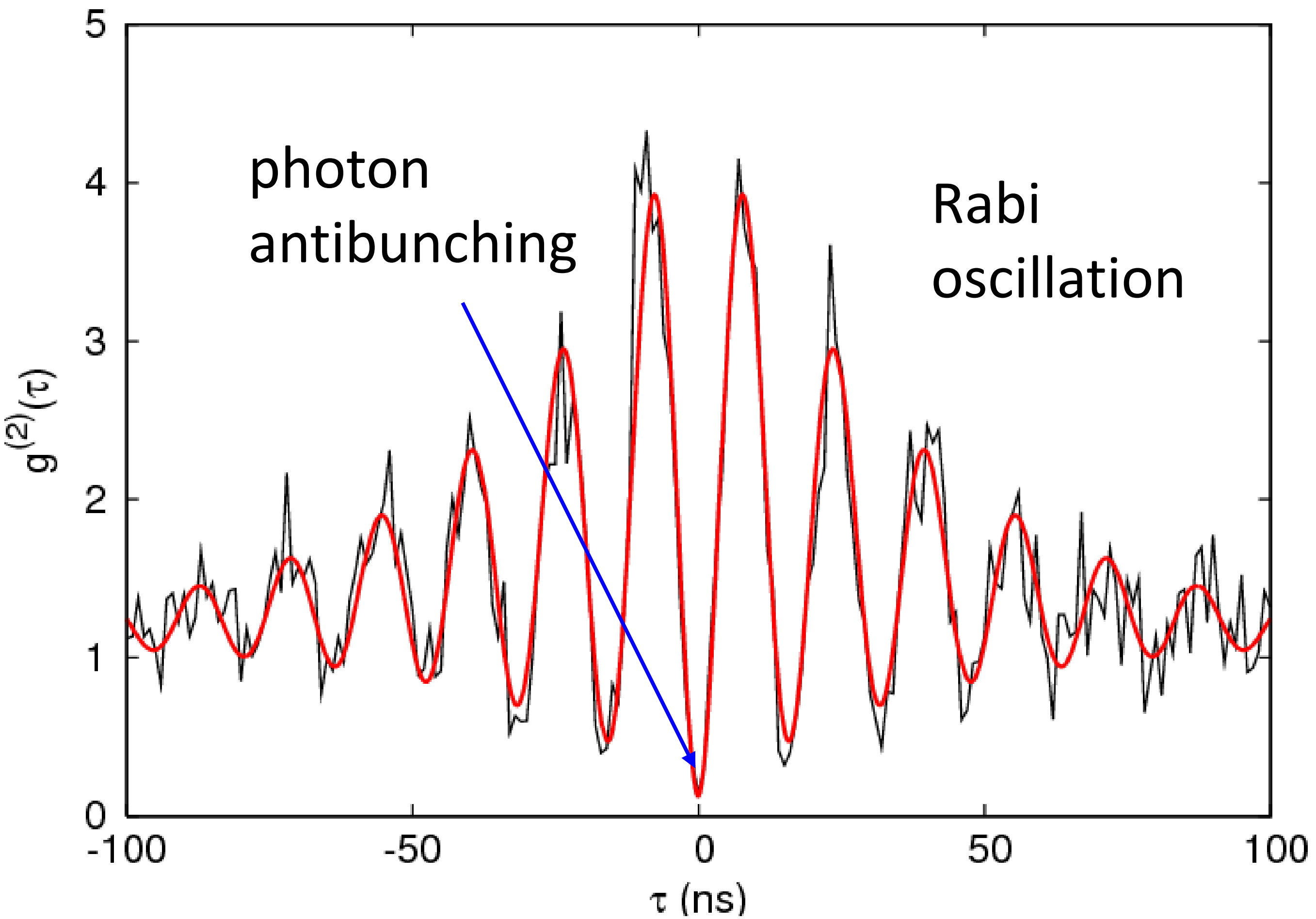
Next steps

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

Single atom

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





Centre for Quantum Technologies

Present state

NUS National University of Singapore