Single Atom-Photon Interface with Strongly Focused Optical Modes

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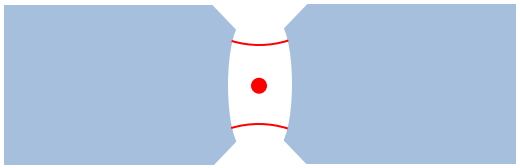
Theory support:
Yimin Wang, Colin Teo, Lana Sheridan, Valerio Scarani

DPG 2011, 14 March, Dresden

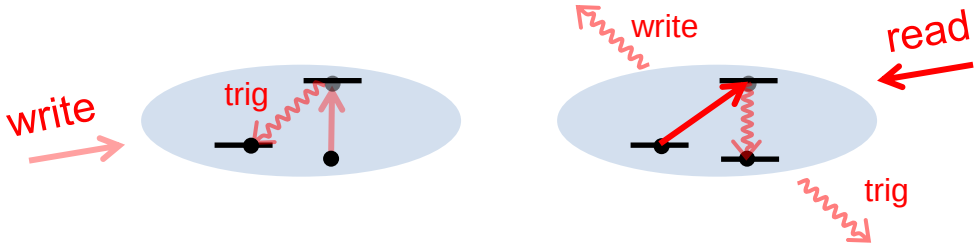
Centre for Quantum Technologies

Atom-Photon Interface

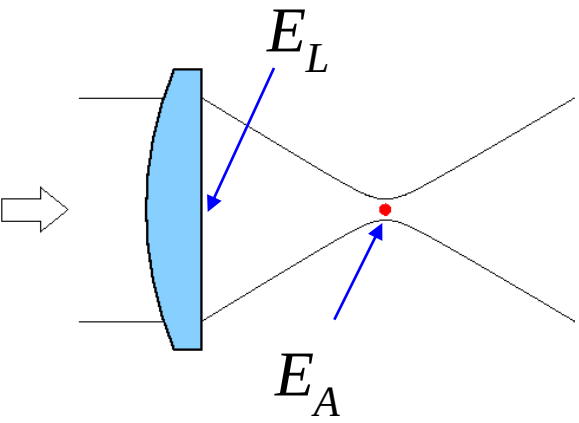
Cavity QED



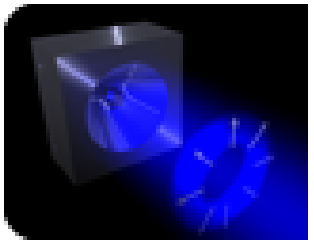
Atomic ensembles



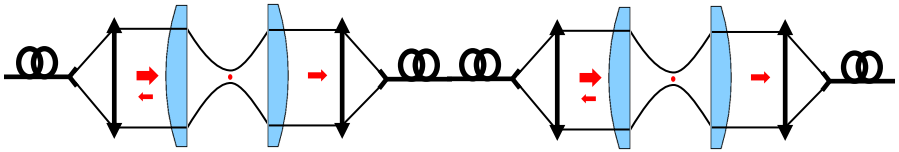
Focused light beams in free space



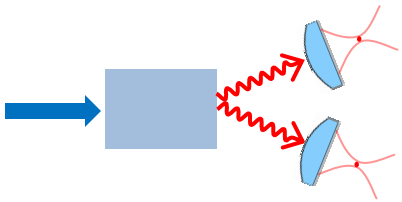
strong coupling (mode overlap) ✓



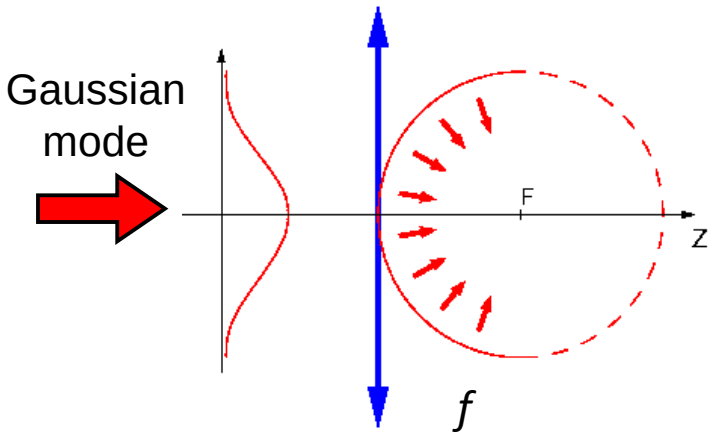
scalability ✓



coupling to non-classical light ✓



Modelling (coherent light)

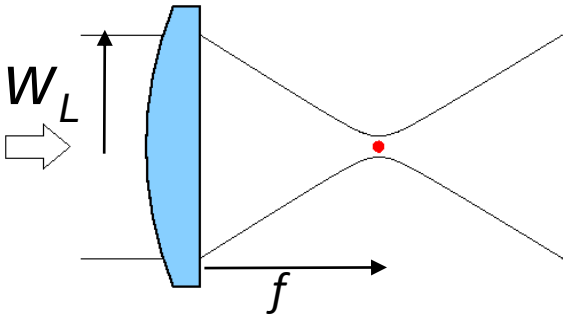


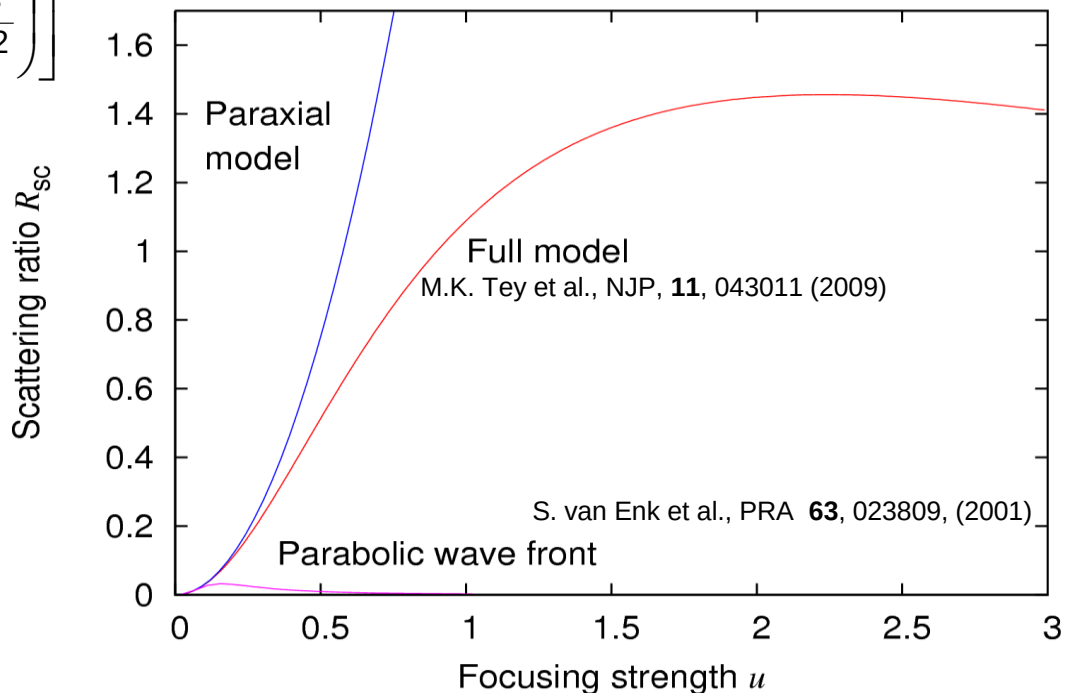
- vectorial light field after the lens with spherical wave front
- propagate field to focus (obtain E_A)
- obtain scattered power and scattering ratio

$$P_{sc} = \frac{3\lambda^2 \varepsilon_0 E_A^2}{4\pi} \qquad R_{sc} = \frac{P_{sc}}{P_{in}}$$

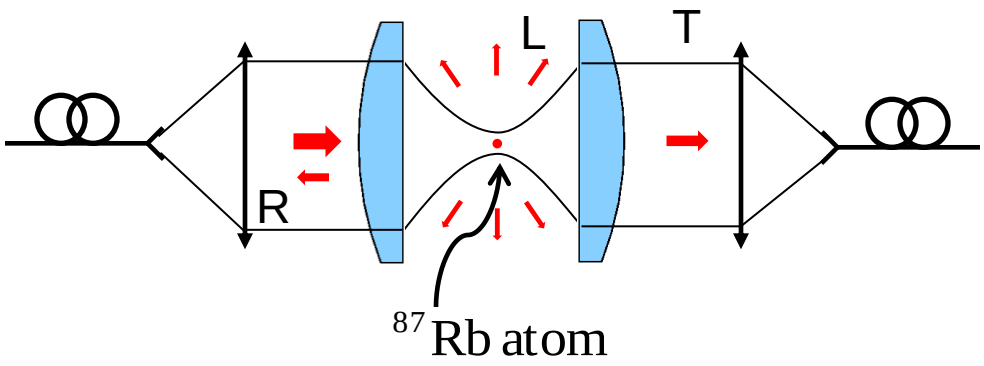
$$R_{sc} = \frac{3}{4u^3} e^{-2/u^2} \left[\Gamma\left(-\frac{1}{4}, \frac{1}{u^2}\right) + u\Gamma\left(\frac{1}{4}, \frac{1}{u^2}\right) \right]^2$$

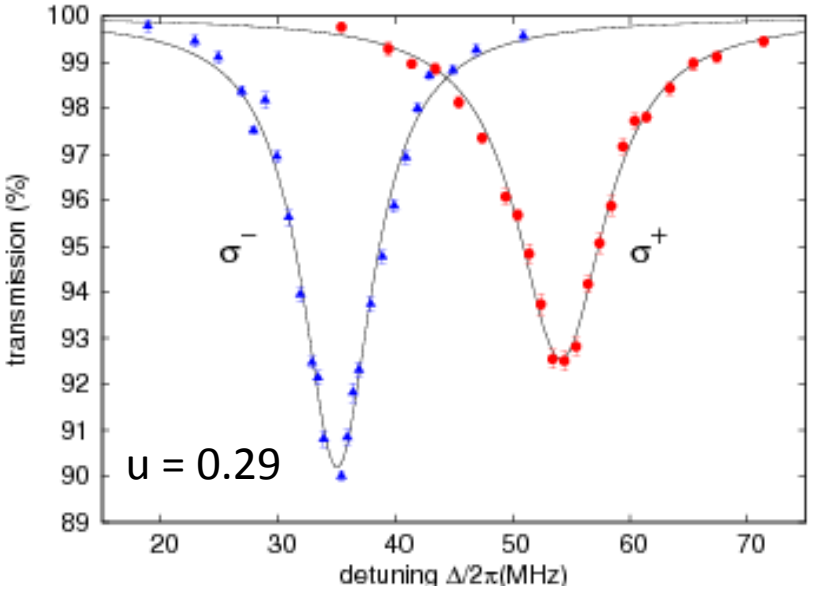
focusing strength $u = \frac{W_L}{f}$





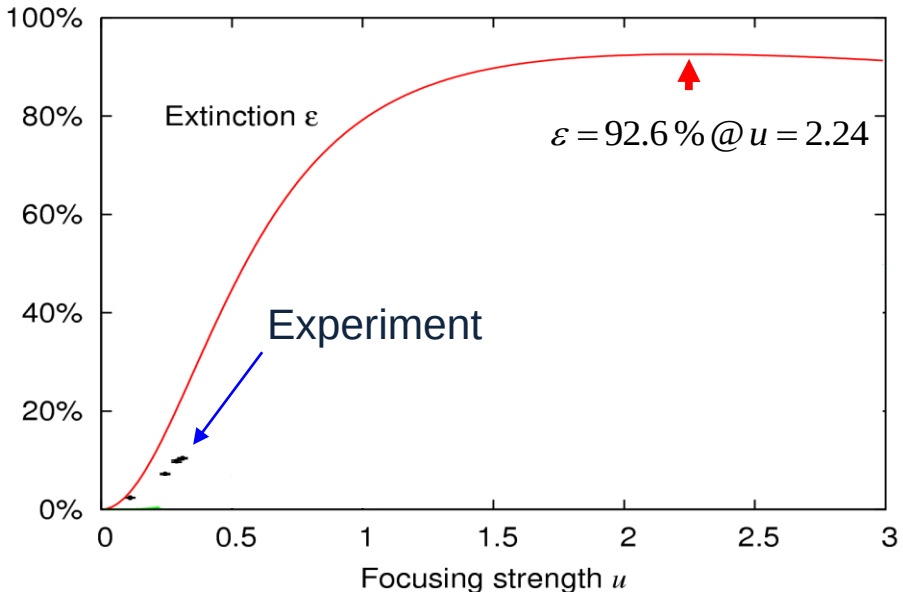
Experiment





M.K. Tey et al, Nat. Phys. **4** pp. 924 (2008)

Experiment	Theory
T_{min} = 89.7 ± 0.7 %	T_{min} = 79.6 %

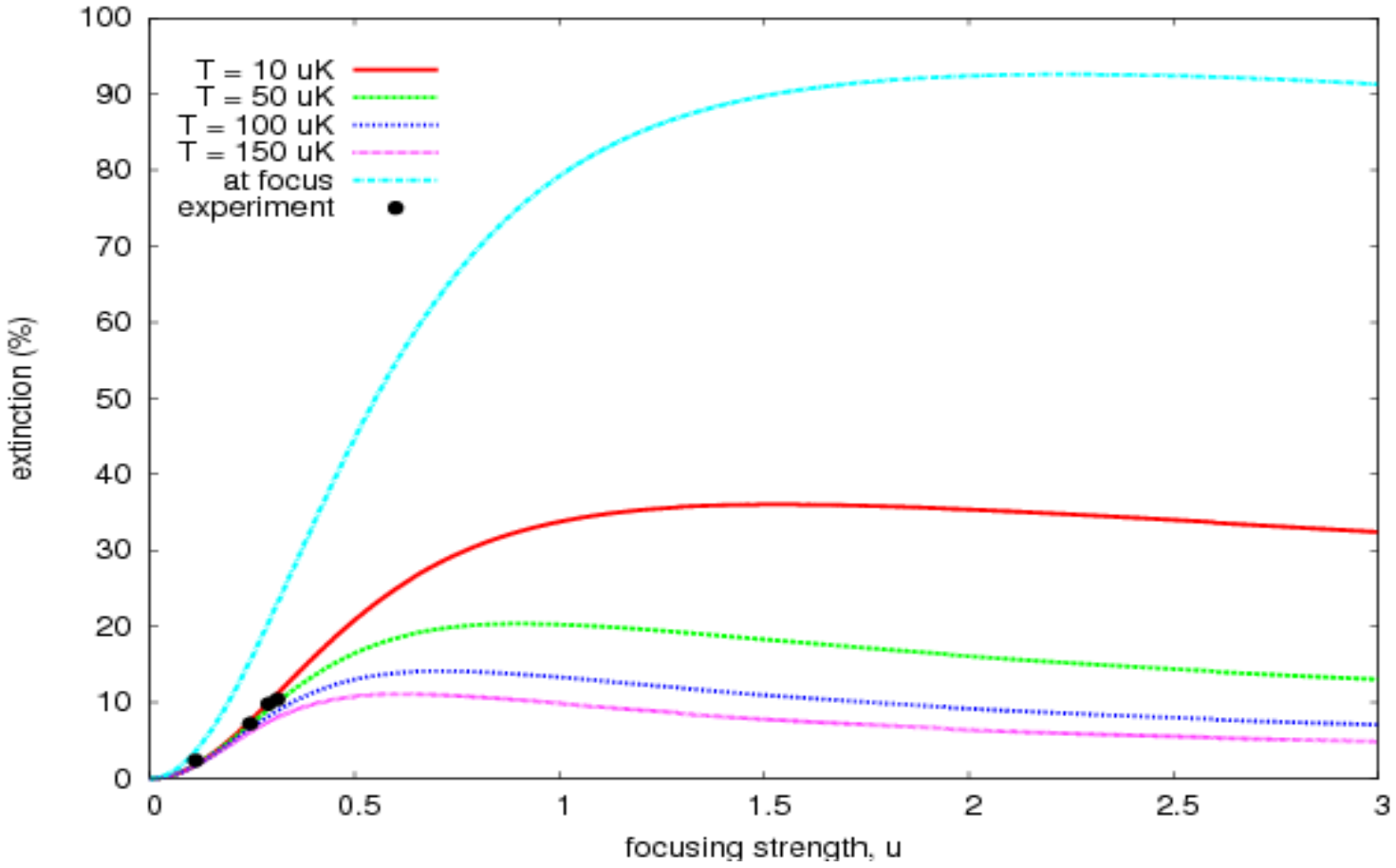


Two reasons
for discrepancy:

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

Temperature effects

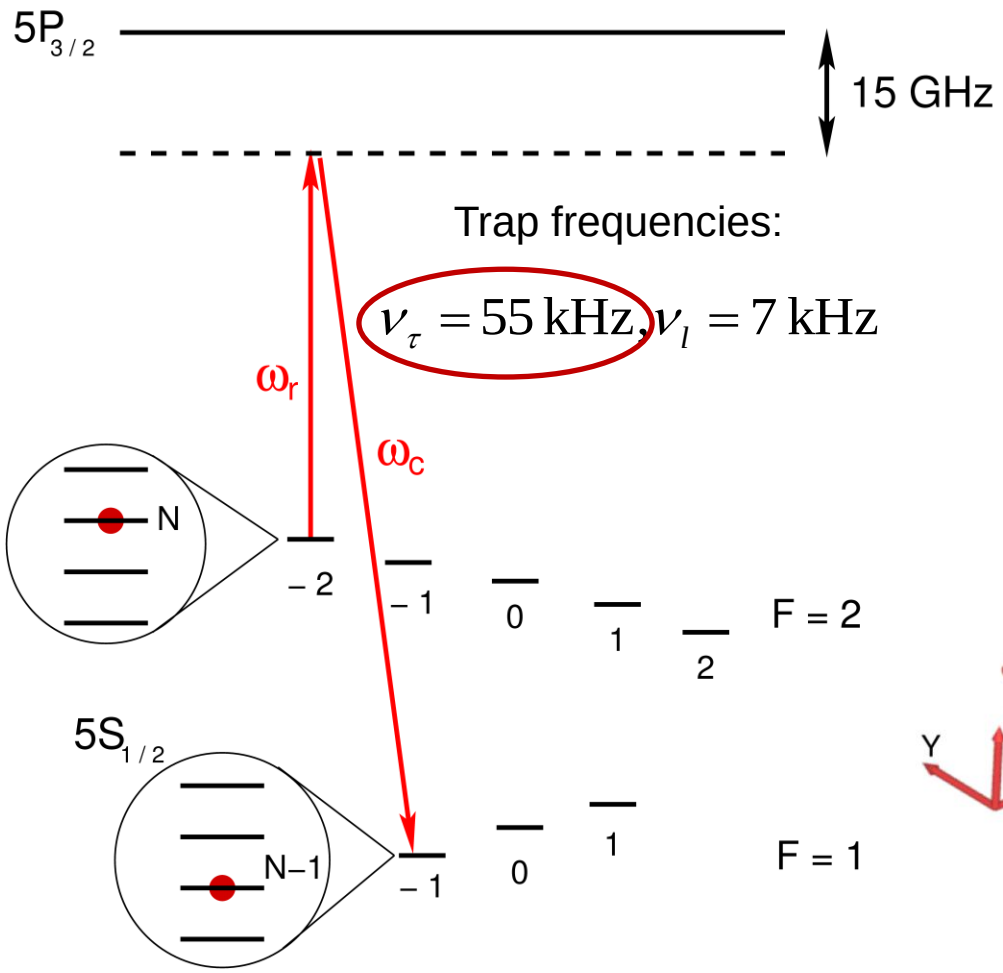
For our trap depth of 1.2 ± 0.1 mK, estimation of atomic motion gives



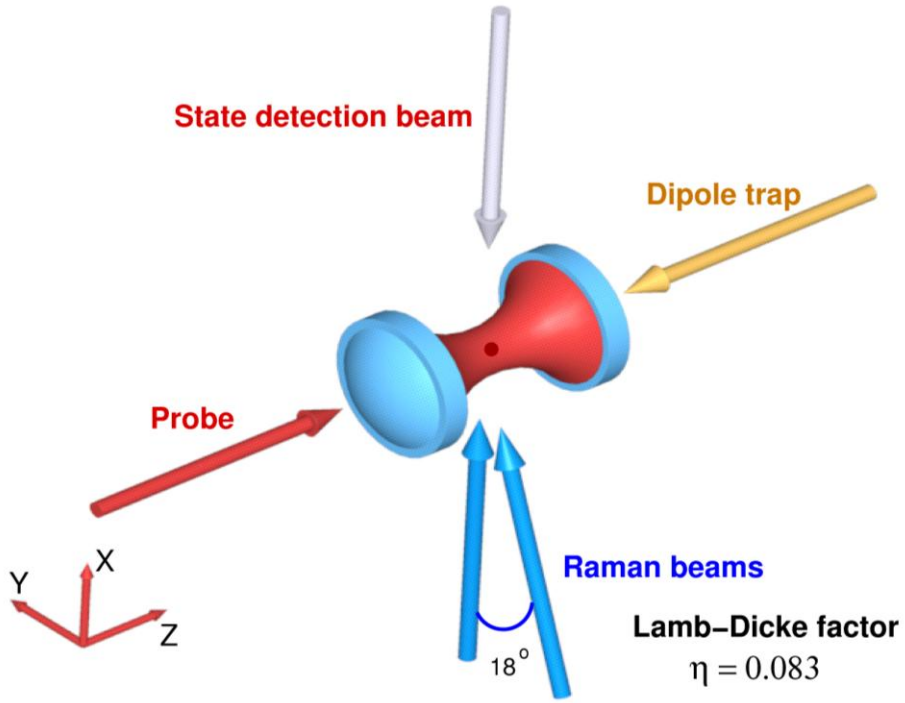
If we want to exploit strong focusing at full --- must cool atom to ground state of the trap

$$\Delta x \approx 50\,\mathrm{nm} << \lambda\ (\text{diffraction limited spotsize})$$

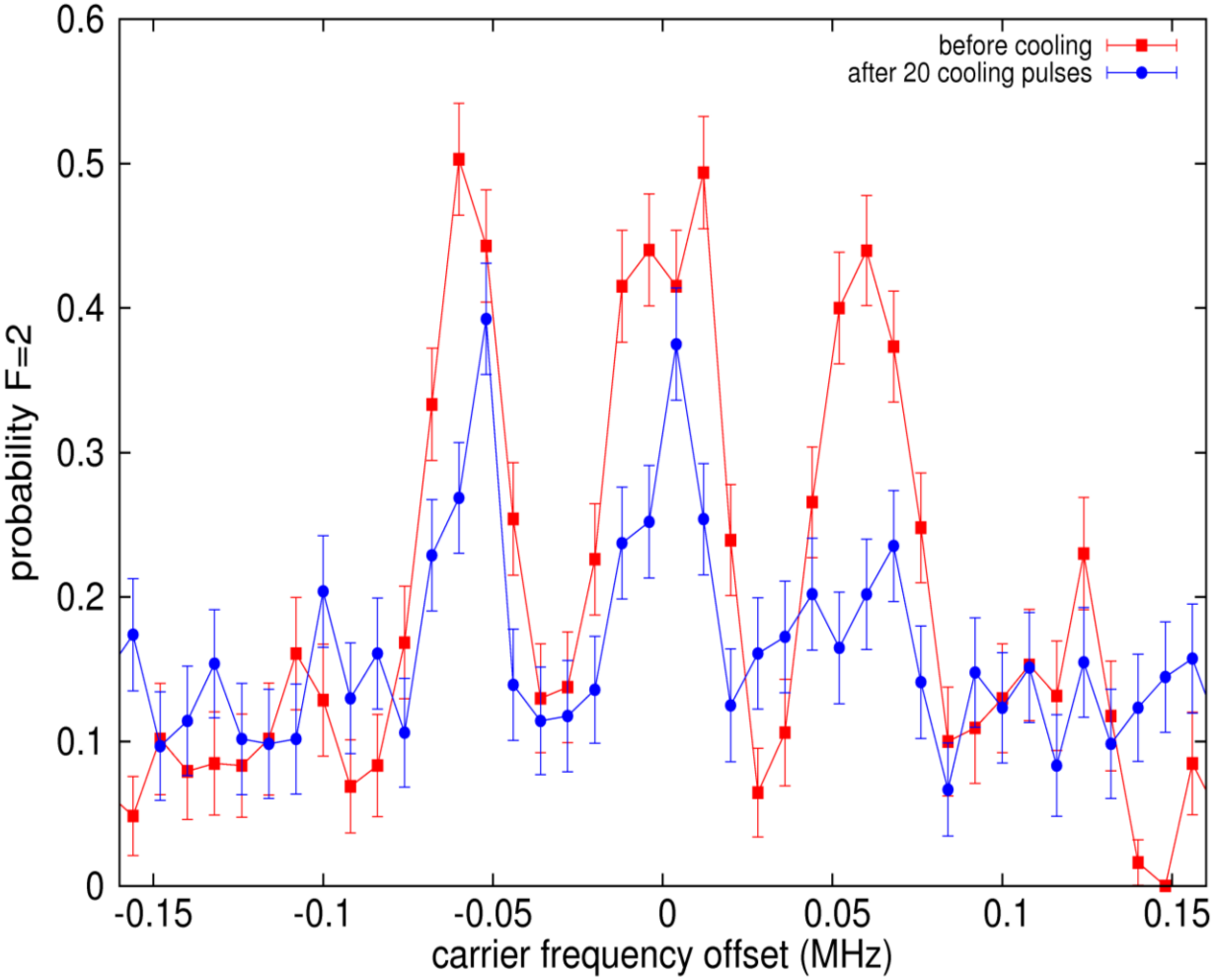
Sideband cooling



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.

see poster Q 57.54
by Syed Aljunid on Thursday

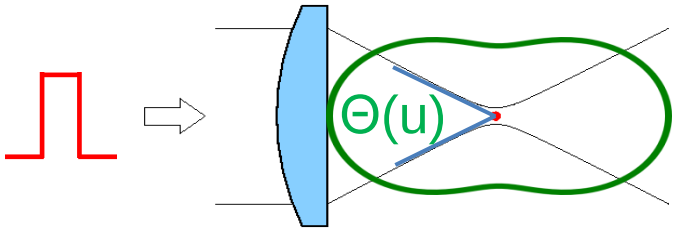
Excitation Probability

Coherent light beams so far --- what's our excitation probability?

In our experiment for ~ 6 fW (~20000 hν) of input power:

$$\text{Steady state: } \rho_{22} = \frac{r_{sc}}{\Gamma} \approx \frac{2.5\,\text{kHz}}{37\,\text{MHz}} = 6.7 \cdot 10^{-5}$$ ☹

Need to go for pulsed excitation!



P_e is set by the overlap between incoming light and atomic emission modes

	u=0.3	
Fock state (N=1)	0.223	0.274
Coherent state (N=1)	0.1823	0.2174

see poster Q 28.5 by Yimin Wang

For u = 2.2, Θ = 0.36 8π/3, P_e = 0.36 (lens limit)

(Y. Wang, et. al., arXiv:1010.4661)

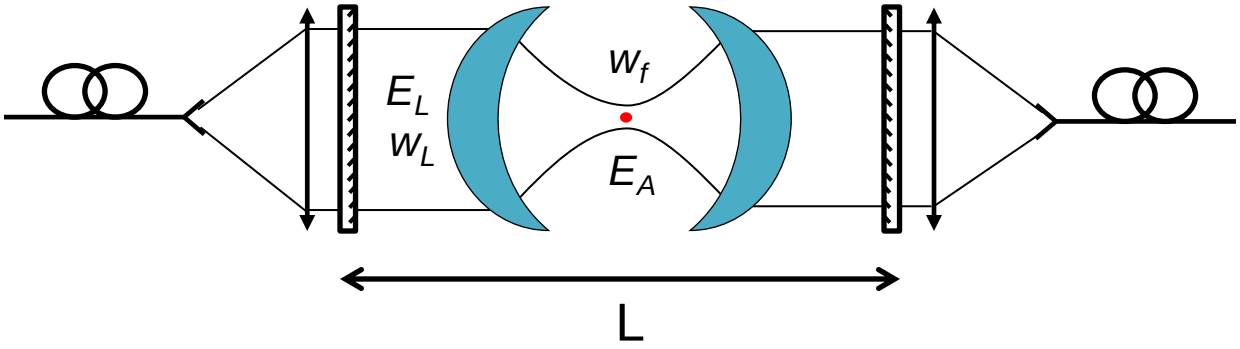
For Θ = 0.94 8π/3, P_e = 0.94

(M. Stobinska, et. al., Euro. Phys. Lett. 86, 14007 (2009).)

How to make exp. rising pulse: see poster by Syed Aljunid Q 23.56, Tuesday

Cavity to help

Can we use a low finesse cavity to enhance the interaction?



Field quantization

assume $|E| = |B|$, $L >> Z_R$

outside the cavity

$$E_L = \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}}, V = \frac{\pi}{2} w_L^2 L$$

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

To get field operator at the atom → use our model

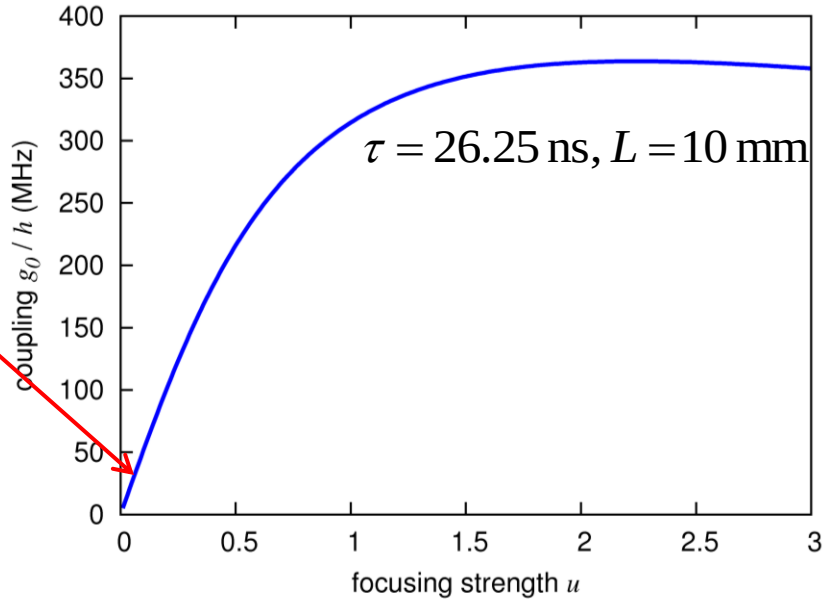
$$E_A = \sqrt{\frac{2\pi\hbar\omega}{3\varepsilon_0 L\lambda^2}} R_{sc},\ d_{\text{eff}} = \sqrt{\frac{3\varepsilon_0 h\lambda^3}{8\pi^2\tau}},\ g_0 = \hbar\sqrt{\frac{\pi c}{\tau L}} R_{sc}$$

$R_{sc} = 0.16$ (focusing NA ≈ 0.3)

$g_0 \approx 40$ MHz

strong coupling

$g_0 > (\Gamma, \kappa)$ $\kappa \approx 10$ MHz $\rightarrow$ $R \cong 99\%$



Stability of near-concentric cavity under test:
see poster by Kadir Durak Q 15.78, Monday

Conclusions

- Lenses are promising elements for single atom-photon interfaces. We have observed a substantial scattering of coherent light by a single atom in a simple transmission measurement with off-shelf elements.
- To achieve maximal coupling efficiency a thermal motion of atoms must be minimized. We have performed a Raman sideband cooling of single ^{87}Rb atom in a tightly focused optical trap to $\langle n \rangle = 0.55 \pm 0.07$
- To assess excitation probability of an atom by a single photon it is necessary to perform a pulsed excitation. For an optimal pulse shape the excitation probability is limited by mode overlap and reaches 0.36
- Strong focusing is useful in cavity QED experiments. One can substantially relax requirements on mirror coatings to enter a strong coupling regime. *S.E Morrin, et al*. *Phys. Rev. Lett.* **73** (11): 1489–1492. (1994)

Next steps

- Try larger numerical apertures lenses
- Improve Raman sideband cooling
- Cavity QED with strong focusing

Thank you

Syed Abdullah Aljunid
Brenda Chng
Jianwei Lee (now MOE, Singapore)
Martin Paesold (now ETH)
Dao Hoang Lan (now Univ. Of Twente)
Kadir Durak
Gleb Maslennikov
Christian Kurtsiefer

Yimin Wang
Teo Zhi Wei Colin
Lana Sheridan
Valerio Scarani

} *Theory*

http://www.qolah.org

New members are very welcome!!!

Single atom

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