# *Atom-Light Interface in Strong Focusing Geometry*

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*CLEO 2011, Europe, Munich   EA 9.2*

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# Atom-Photon Interface

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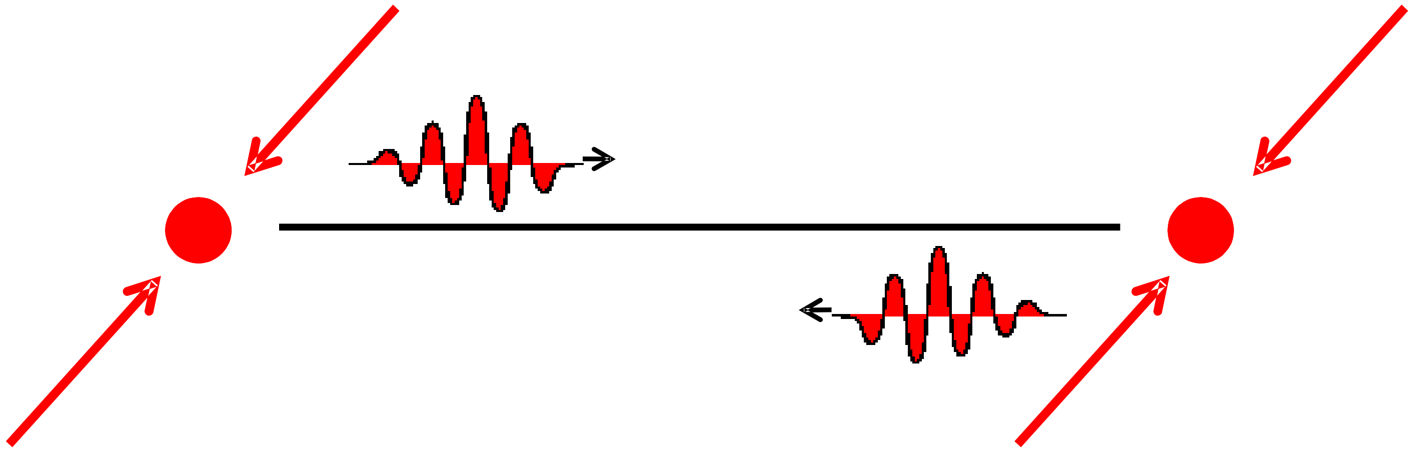
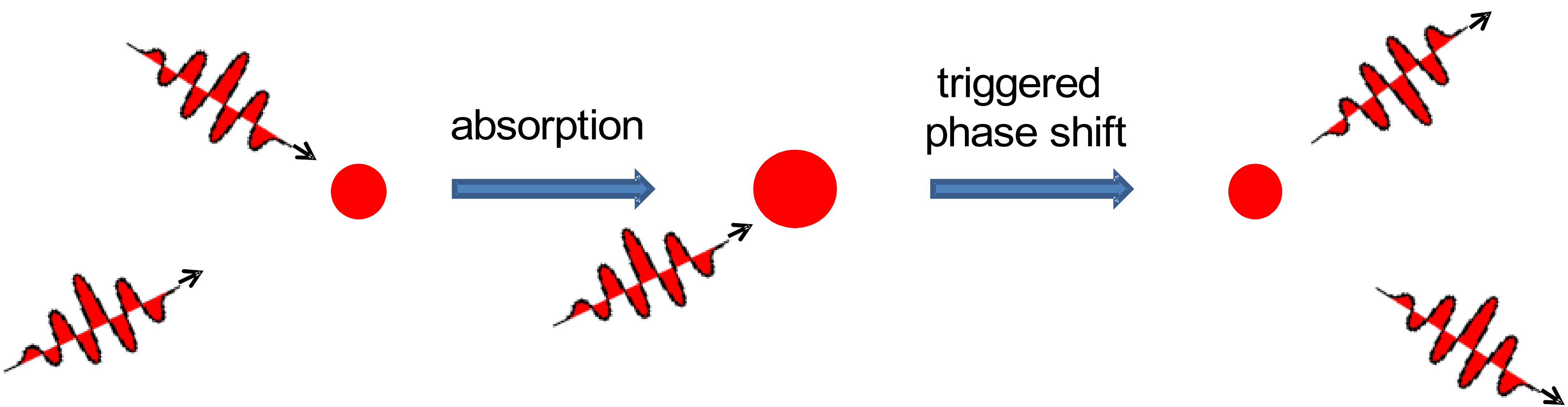
- Quantum Information and Communication protocols



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



# Strong Coupling

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Interaction

$$\hat{V} = \langle \hat{d}_{eff} \cdot \hat{E}_A \rangle$$

Electric field operator (single mode)

$$\hat{E}(\vec{x},t) = i E \left[ g(\vec{x}) \hat{a}(t) + g^*(\vec{x}) \hat{a}^\dagger(t) \right]$$

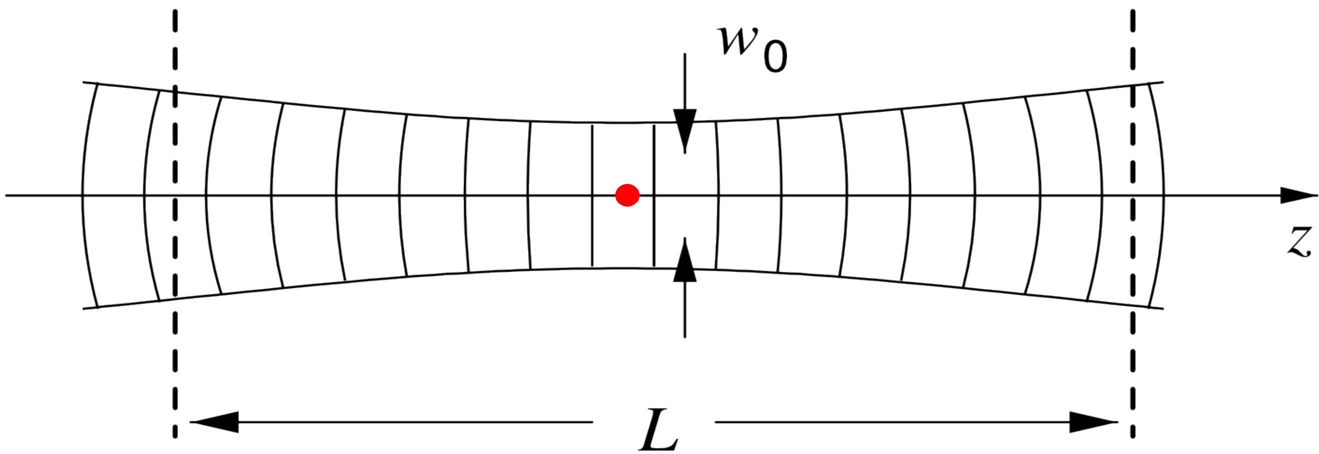
normalization

mode function

$$E = \sqrt{\frac{\hbar \omega}{2 \epsilon_0 V_m}}$$

mode volume

$$V_m = \int d\vec{x} |g(\vec{x})|$$




paraxial beams with gaussian mode function

$$V_m = \frac{\pi L w_0^2}{2}$$

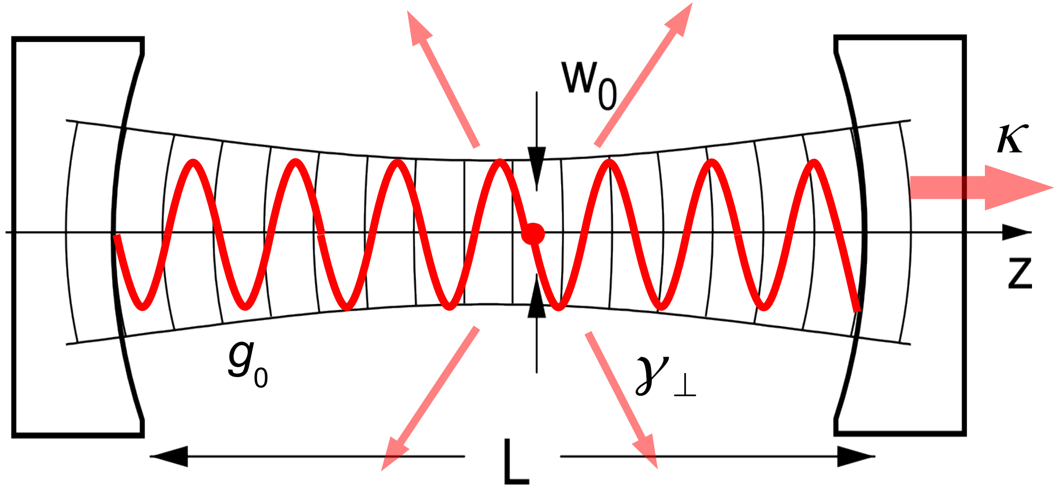
$$E = \sqrt{\frac{\hbar \omega}{\pi w_0^2 L \epsilon_0}}$$

Strong coupling in a Jaynes-Cummings model

$$g_0 = d_{eff} \cdot E = \hbar \sqrt{\frac{3 \lambda^2 c}{\pi \tau w_0^2 L}} \gg LOSSES$$

# Cavities

Cavity to compensate for losses $g_0 \gg \kappa, \gamma_\perp$




State of art values

| $g_0$ $(2\pi)\cdot MHz$ | $\kappa$ $(2\pi)\cdot MHz$ | *Finesse* | *Reference* |
|---|---|---|---|
| 15 | 1.5 | $2x10^5$ | M. Koch et. al., Phys. Rev. Lett. **105**, 173003 (2010) |
| 12 | 0.4 | $10^6$ | T. Kampschulte et. al.,Phys. Rev. Lett. **105**, 153603 (2010) |
| 215 | 53 | $4x10^4$ | R.Gehr et. al., Phys. Rev. Lett. **104**, 203602 (2010) |

? can we go for even lower finesse to achieve strong coupling ?

$$E = \sqrt{\frac{\hbar\omega}{\pi w_0^2 L \epsilon_0}}$$

Focusing !?

S.E. Morrin et al., Phys.Rev. Lett **73,** 1489 **(1994)**

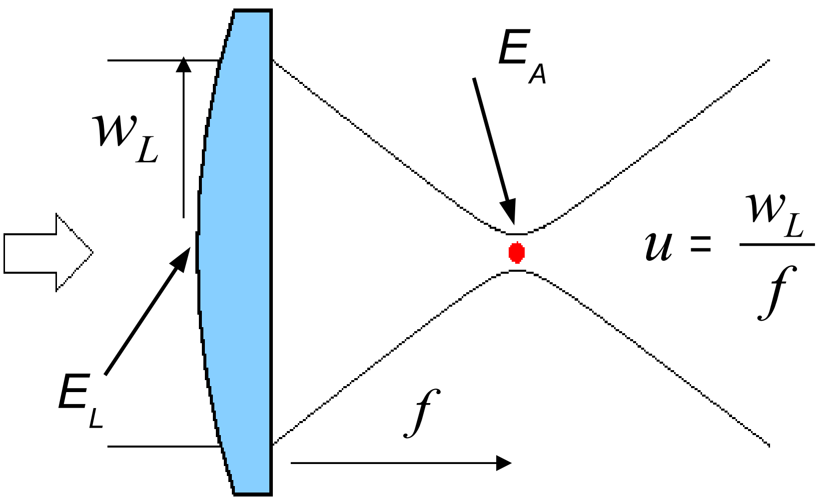
- *Finesse* $= 4.5, \kappa = (2\pi)\cdot 540\, MHz$
- Confocal cavity with $w_0 \approx \lambda$
- $g_0 = (2\pi)\cdot 32\, MHz$

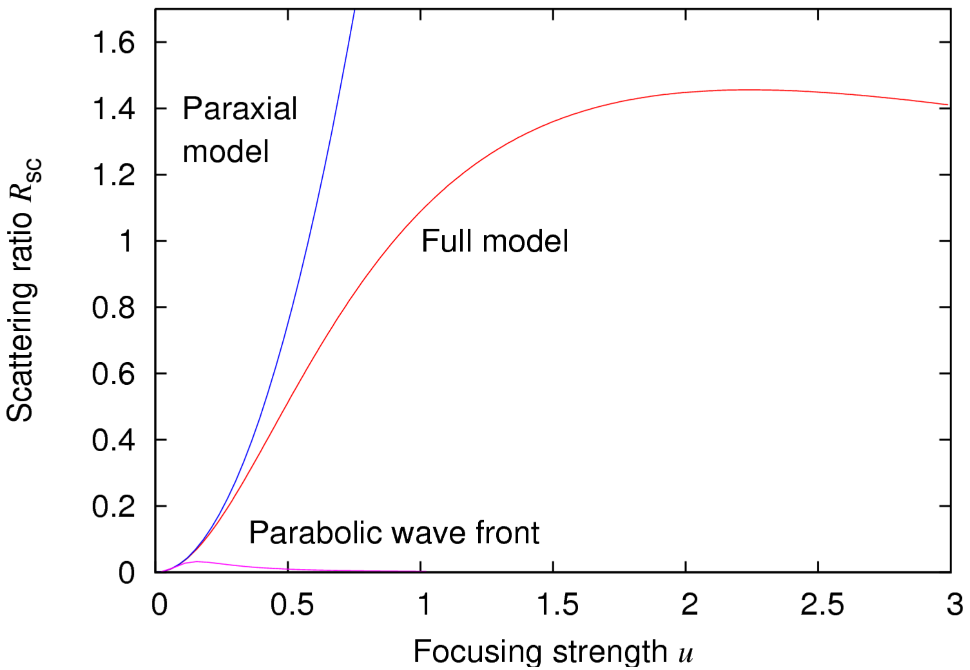
Finesse enough to observe cavity mediated changes in spontaneous emission

# Strong Focusing

? what is the maximal coupling one can achieve with strong focusing ?

? what is the maximum field at the focus $E_A$, related to input field $E_L$?




analytical solution for field at the focus gives (M.K.Tey et.al., NJP, 11, 043209 (2011))

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

# Strong Focusing

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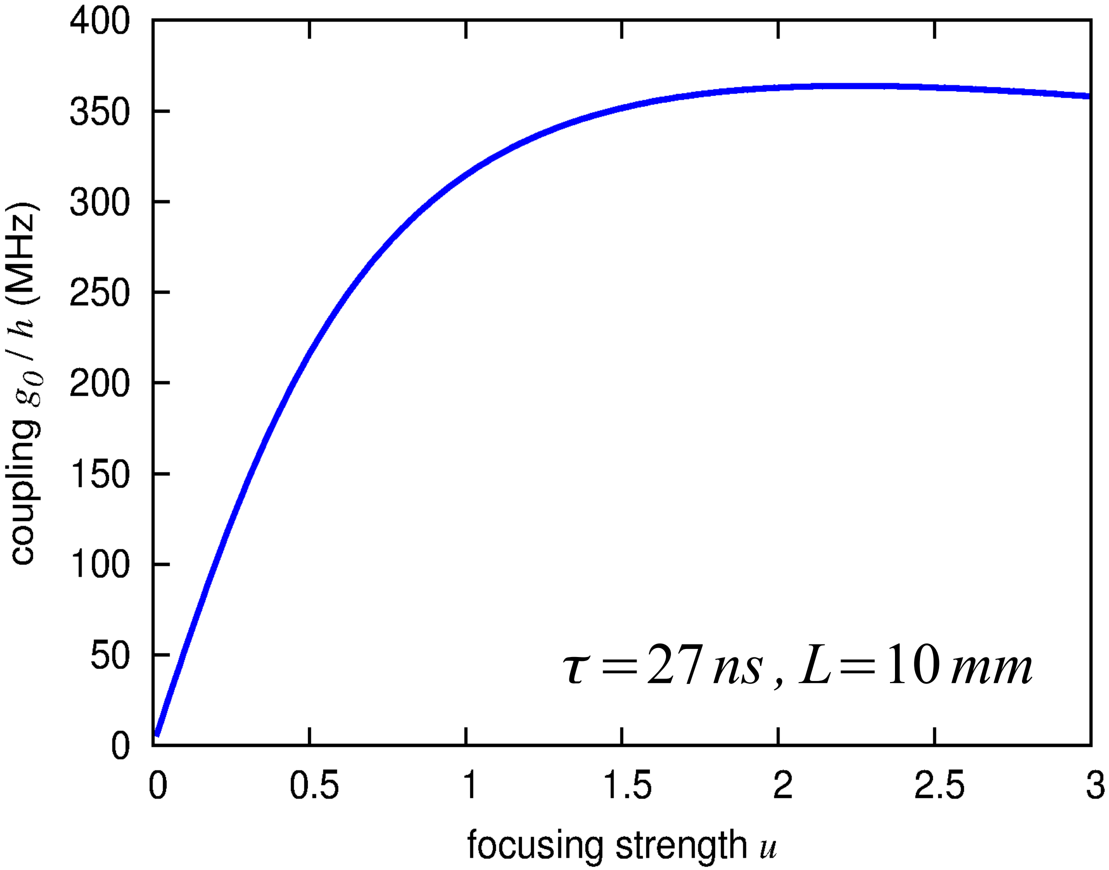
The normalization constant for a strongly focused mode becomes

$$E = \sqrt{\frac{\pi \hbar \omega R_{sc}(u)}{3 \lambda^2 L \epsilon_0}}$$

and the coupling strength for an atom in an antinode of cavity's standing wave is

$$g_0 = \hbar \sqrt{\frac{\pi c R_{sc}(u)}{\tau L}}$$




Current experiments on strong focusing

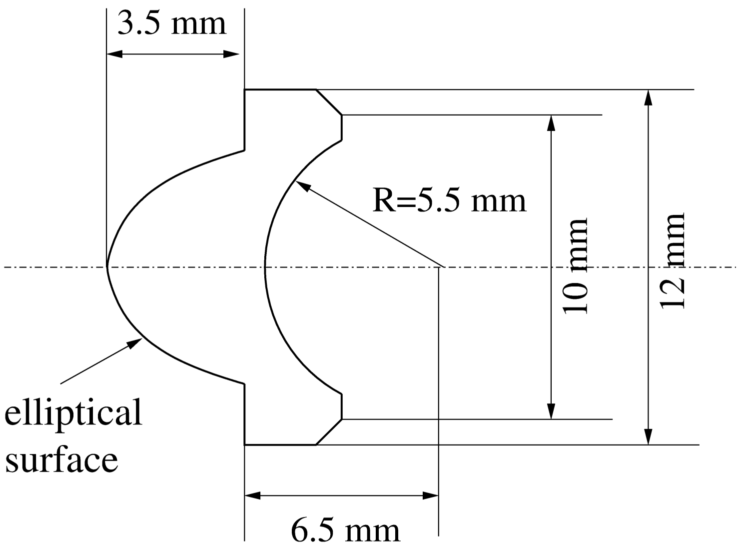
$$u \approx 0.35\, L = 6\,mm,\, g_0 \approx (2\pi) \cdot 40\,MHz$$

Strong coupling expected for

$$\kappa \approx (2\pi) \cdot 10\,MHz \Rightarrow R \approx 0.99$$

# Cavity lenses






NA = 0.35

$$\frac{f\,n}{n+1}$$ longitudinal half-axis

$$f\sqrt{\frac{n-1}{n+1}}$$ transverse half-axis

I. Sahl, *On burning mirrors and lenses* (Publisher unknown, Baghdad, 984)

prototype lens turned from PMMA by SYNTEC OPTICS

surface irregularity < 100 angstrom

sag error (spherical surface) ± 300 nm

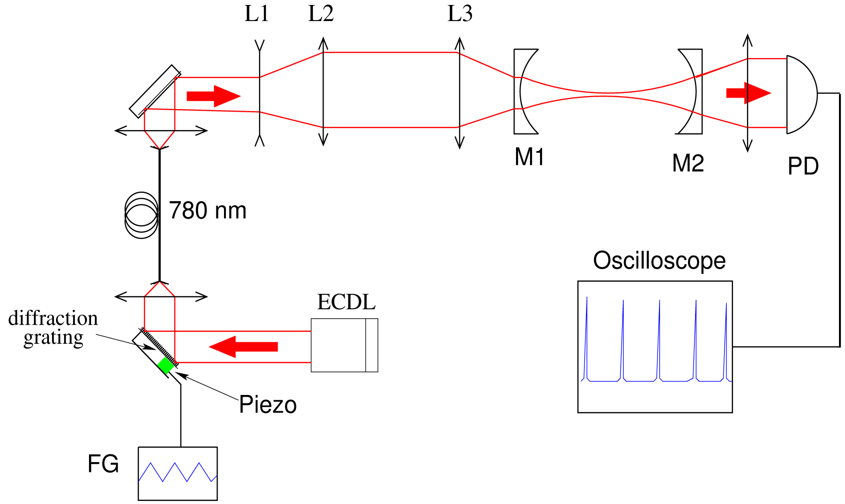
wavefront deviations ~ $\lambda$/10 PV

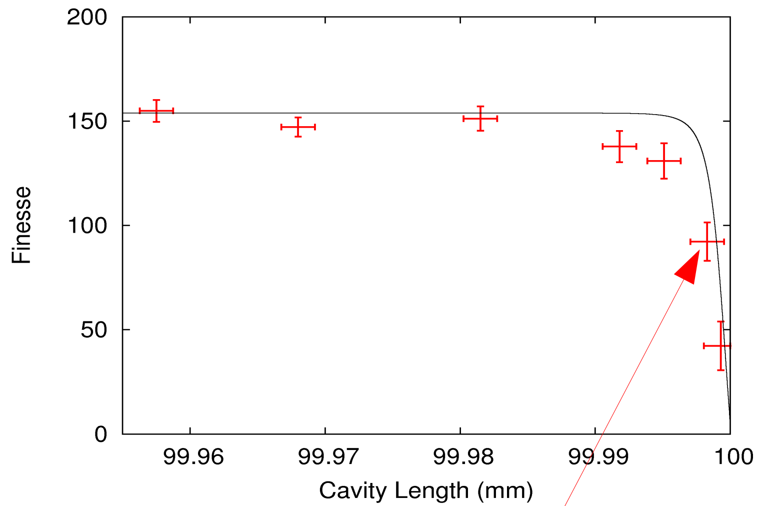
Work in progress!

# Caveats I

Single-mode optical cavity with small waist --- need to work near stability threshold

testing with a different cavity, L = 10 cm, $R_c$ =- 5 cm, R = 0.97, F = 150




$$w_0^2 = \frac{\lambda}{2\pi}\sqrt{L(2R_c - L)}$$

$$w_0 = 7.5\mu m,\ g_0 = (2\pi)\cdot 5.3\ MHz,\ \kappa = (2\pi)\cdot 16\ MHz$$

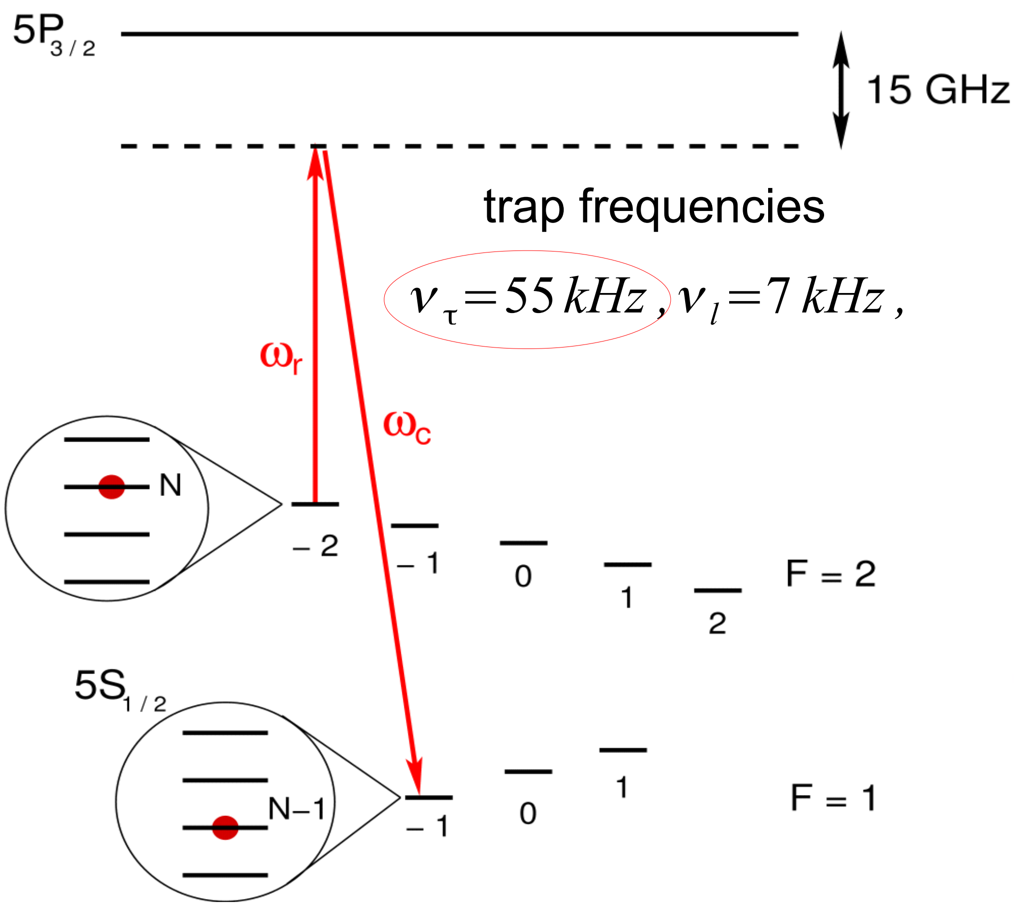
Ways to go: decrease L further, make more tests on stability in vacuum

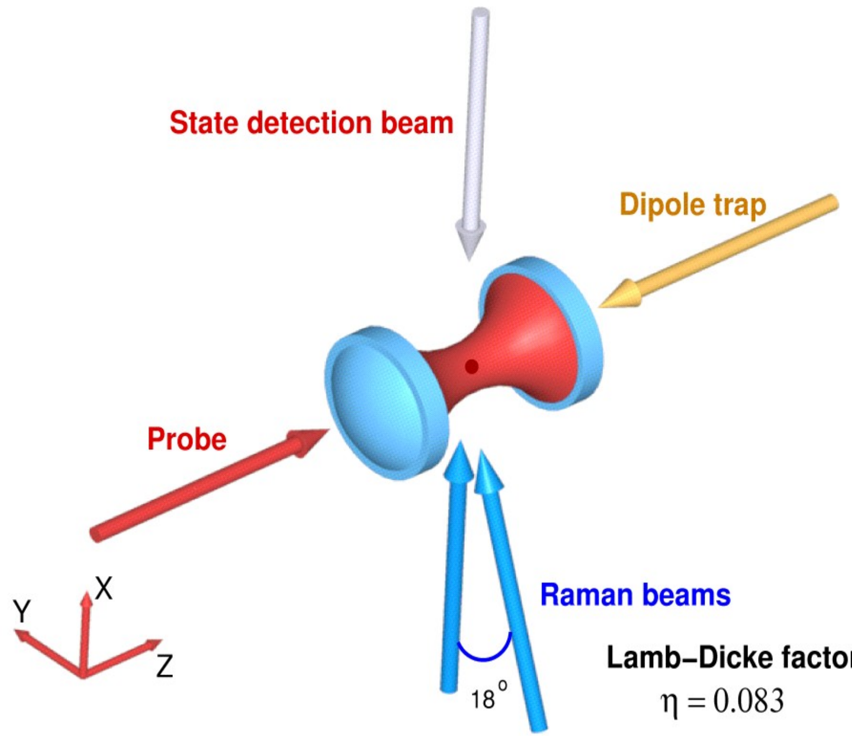
# Caveats II

Atom has to be well localized at the antinode of the standing wave

In our experiments we trap $^{87}$Rb atom in a tightly focused optical tweezer

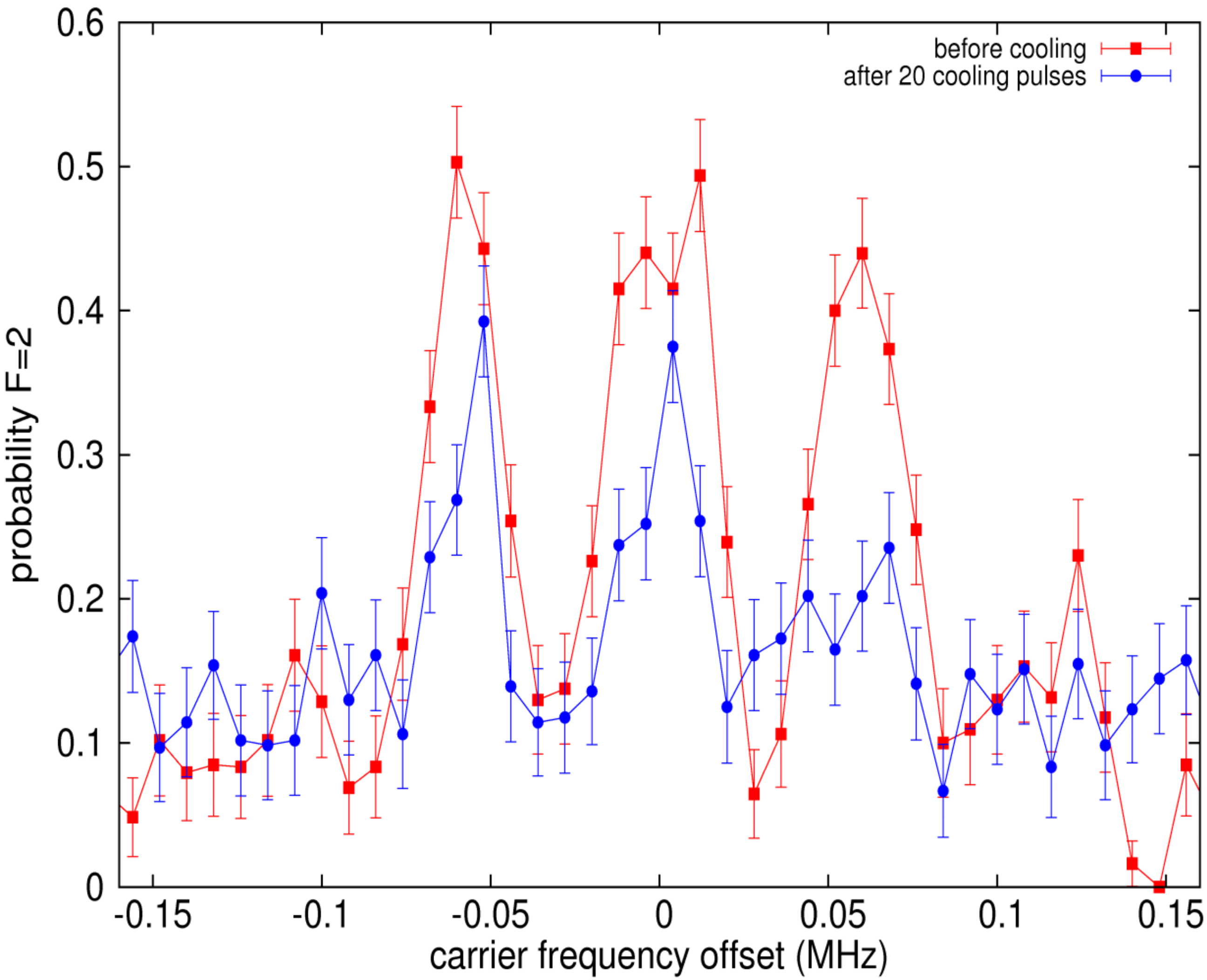
Raman cooling of an atom to the ground state of the trap can be performed



# Raman Cooling






average motional state after cooling

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

atomic delocalization

$$\Delta x_\tau \simeq 200\, nm$$

$$\Delta x_\tau < \frac{\lambda}{4}$$

# Conclusions

A model describing optical resonators with a strongly focused mode is proposed. An analytical expression is obtained for the coupling strength, beyond paraxial approximation.

We have designed an anaclastic cavity lens with NA=0.3 that can be used in cavity QED experiments with strong focusing

To achieve maximal coupling strength a thermal Motion of atoms must be minimized.
We have performed a Raman sideband cooling of single $^{87}$Rb atom in a tightly focusing dipole trap to

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

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# Thank you!

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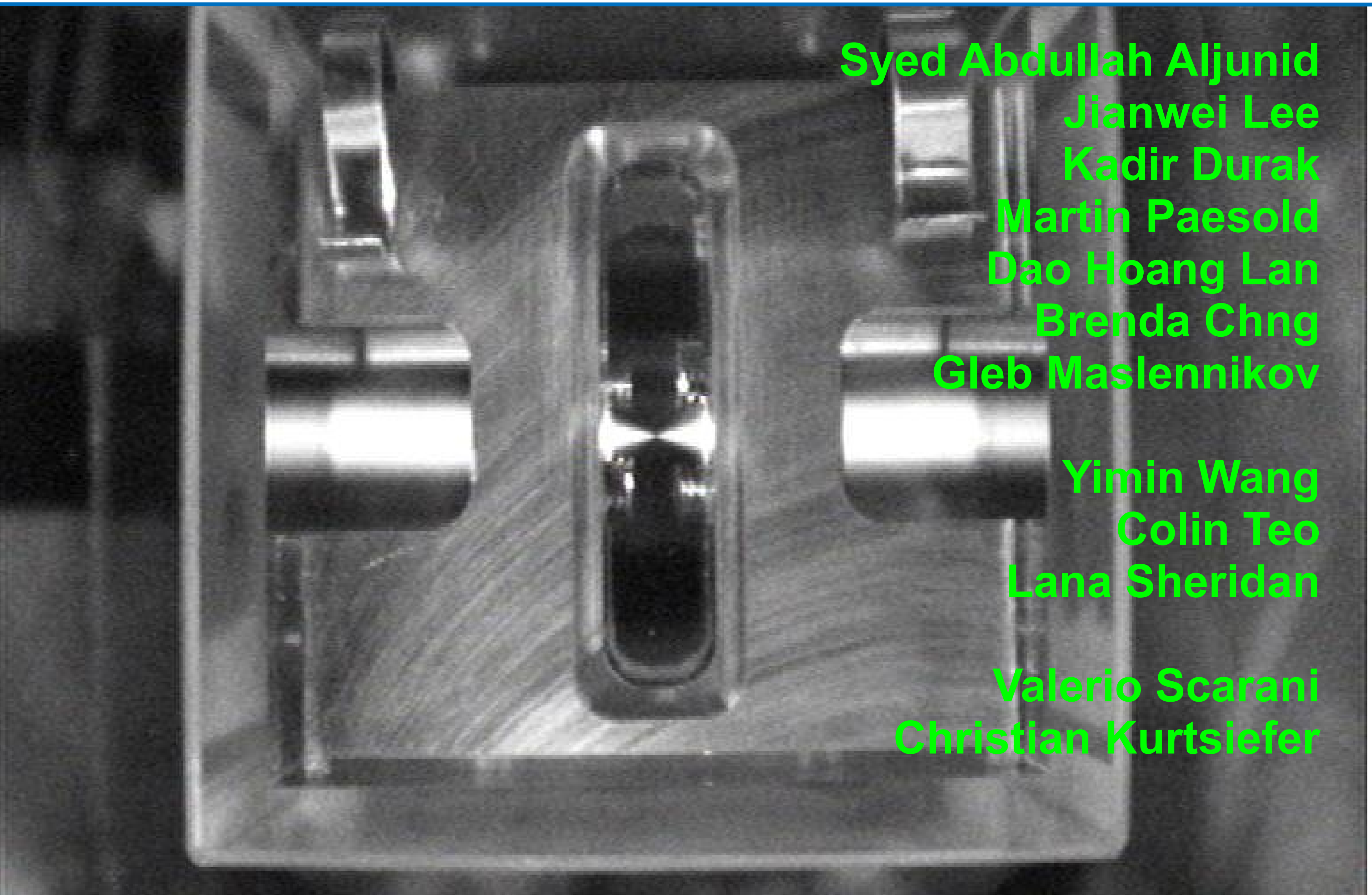

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# Single atom

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