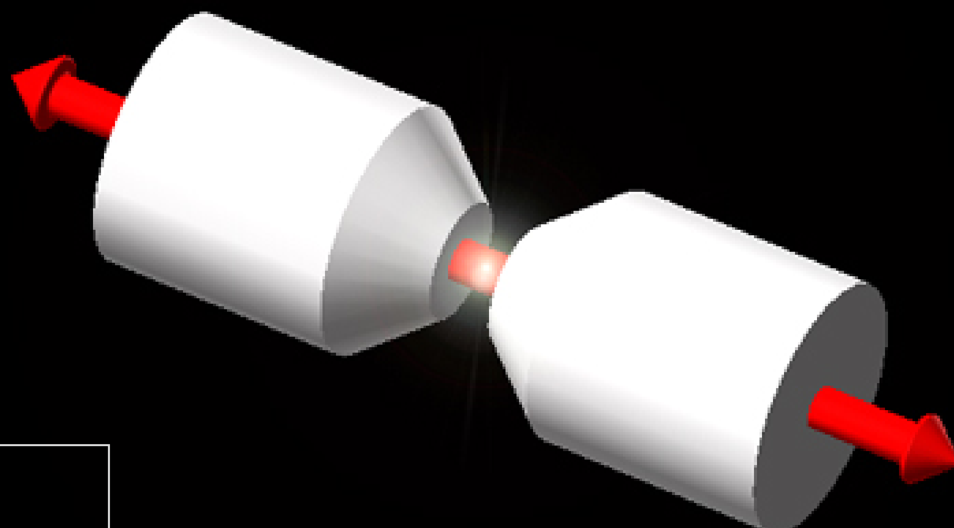
Trapped Atoms in Cavity QED for Quantum Optics and Quantum Information

Jason McKeever
Quantum Optics Group, Caltech
QUEST Summer Workshop
August 9, 2004



Sponsors:
Caltech MURI for
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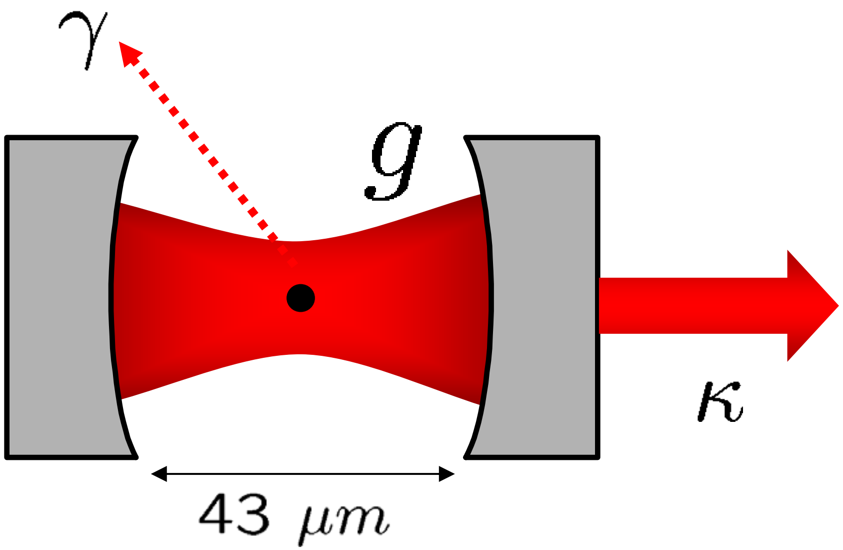
Quantum Optics

Outline

1. Introduction and motivation: Why trap an atom in a cavity?
2. State-insensitive cooling and trapping of a single atom in an optical cavity
3. Cavity QED "By The Numbers" (*briefly*)
4. A One-Atom Laser in the Regime of Strong Coupling
5. Deterministic Generation of Single Photons
6. Summary and Outlook

Strong Coupling in Cavity QED



g = dipole interaction strength between atom and cavity mode (of volume V)

$$g \propto \sqrt{\frac{\hbar\omega}{V}}$$

Strong Coupling Condition:

$$g \gg (\gamma, \kappa)$$

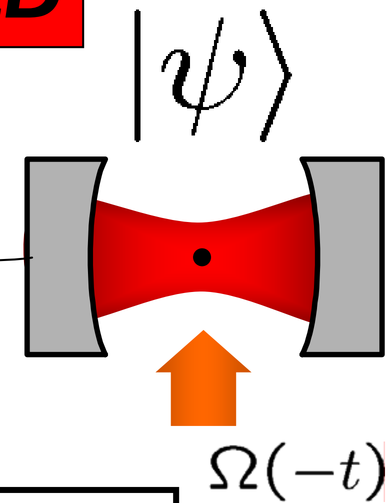
$$g = 2\pi \times 32\ \text{MHz}$$
$$\gamma = 2\pi \times 2.6\ \text{MHz}$$
$$\kappa = 2\pi \times 4.2\ \text{MHz}$$

2g = Rabi Frequency of a Single Photon

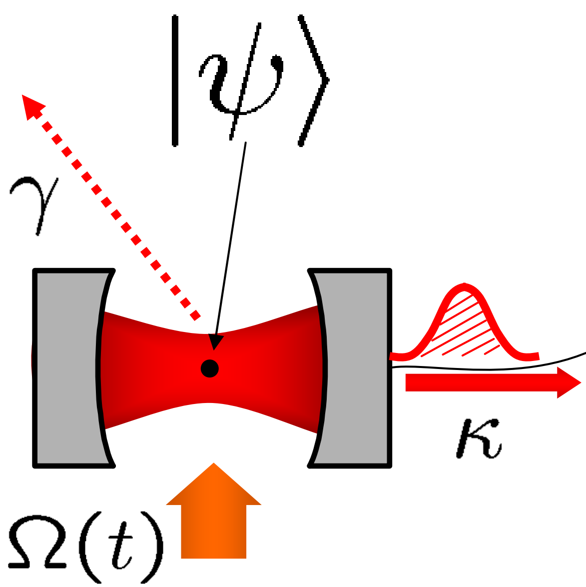
Rate of **coherent exchange** between excitation of ***atom*** and ***field***

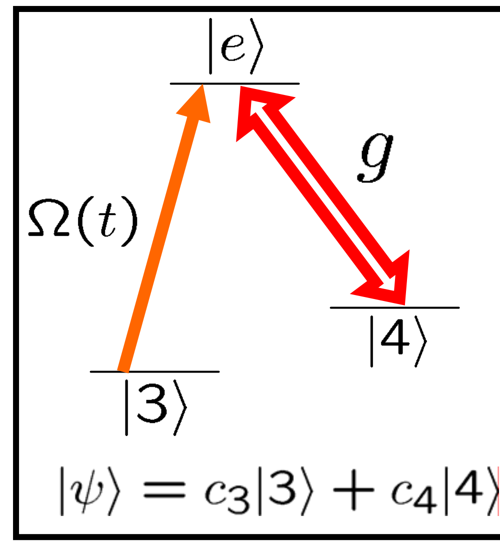
Quantum Networks Enabled by Cavity QED

Cirac *et al* PRL **78**, 3221 (1997)
van Enk *et al* PRL **78**, 4293 (1997)



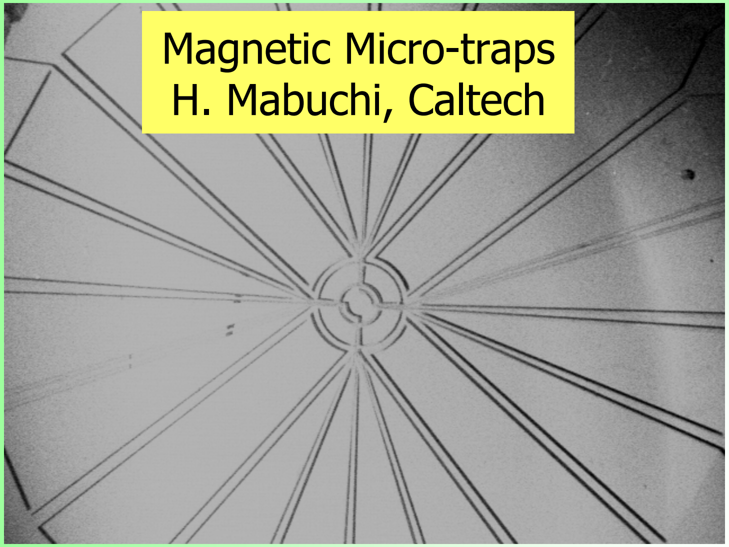
Atomic internal states store quantum information locally, Cavity used for atom-field interaction

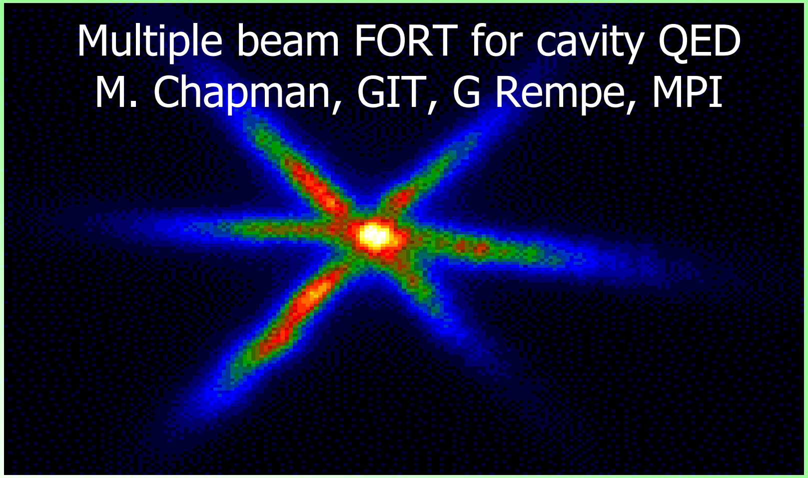


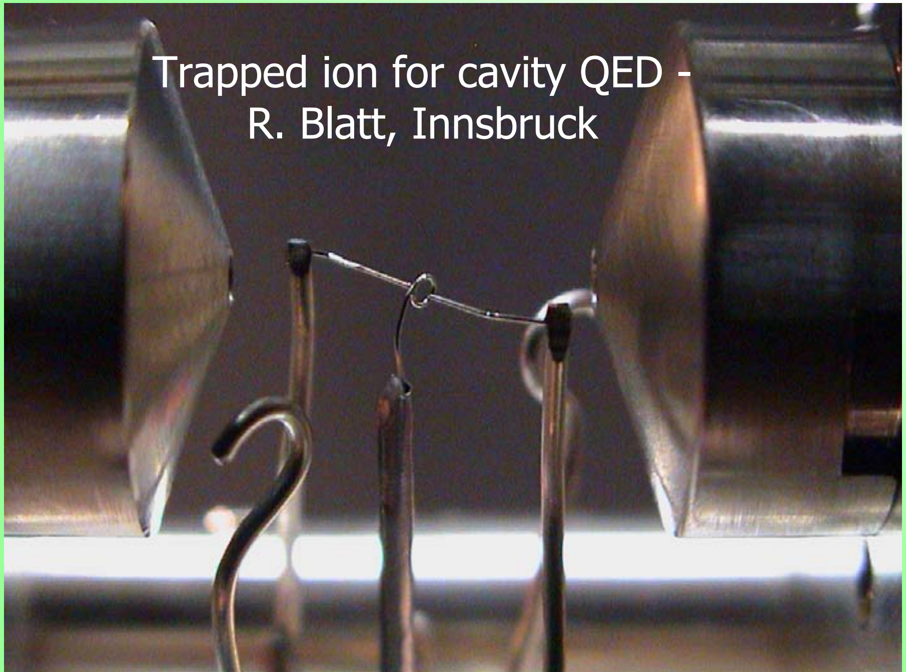


Heart of the scheme:
Single photon generation
from one atom trapped in a cavity.

Cavity QED with Trapped Atoms: Various Approaches

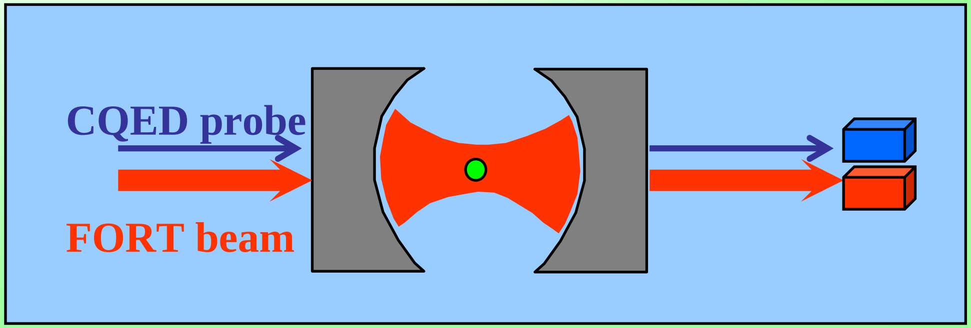






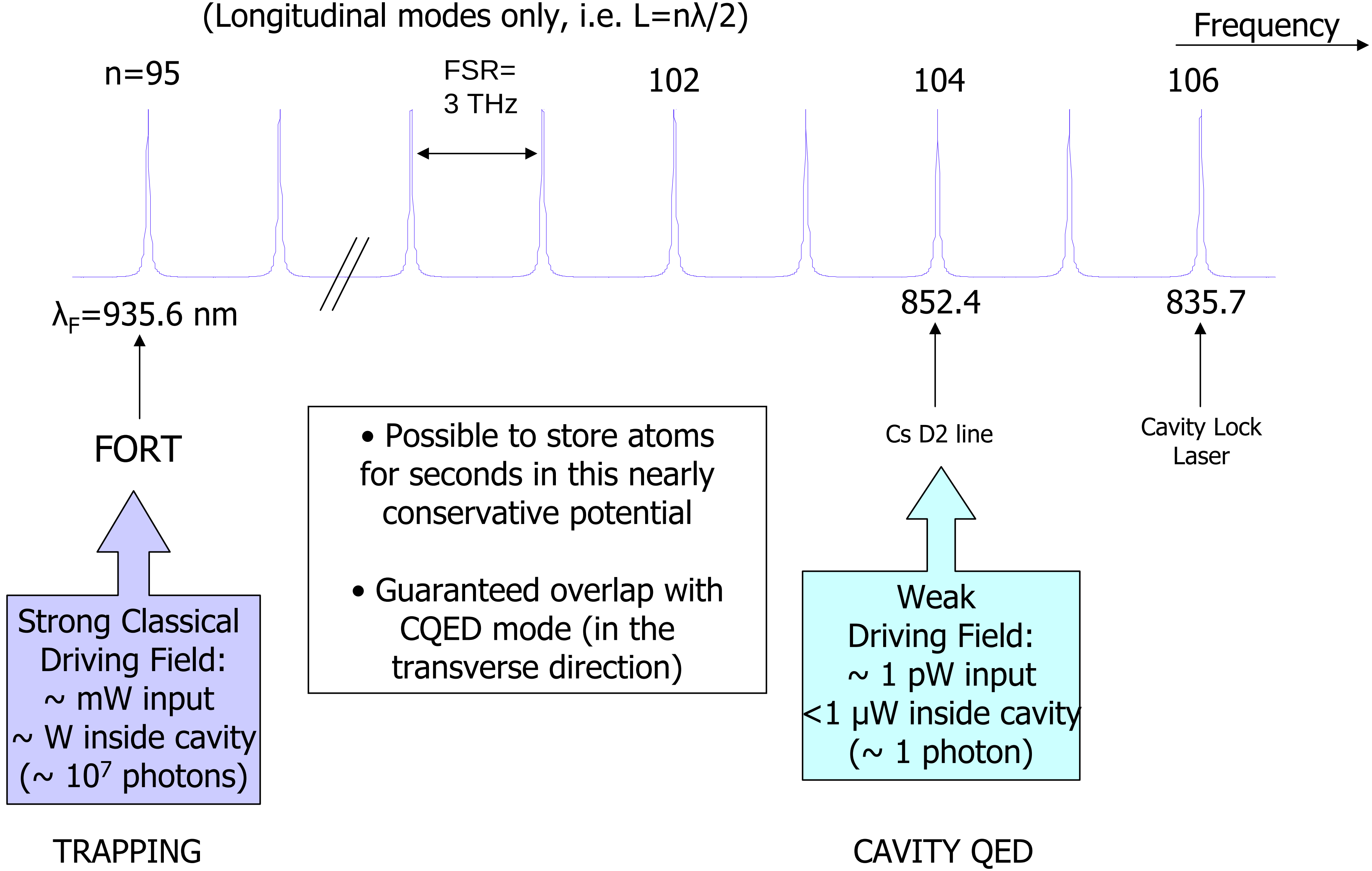
Conveyor Belt for Single Atoms:
D. Meschede, Bonn

Our Scheme: Intracavity FORT



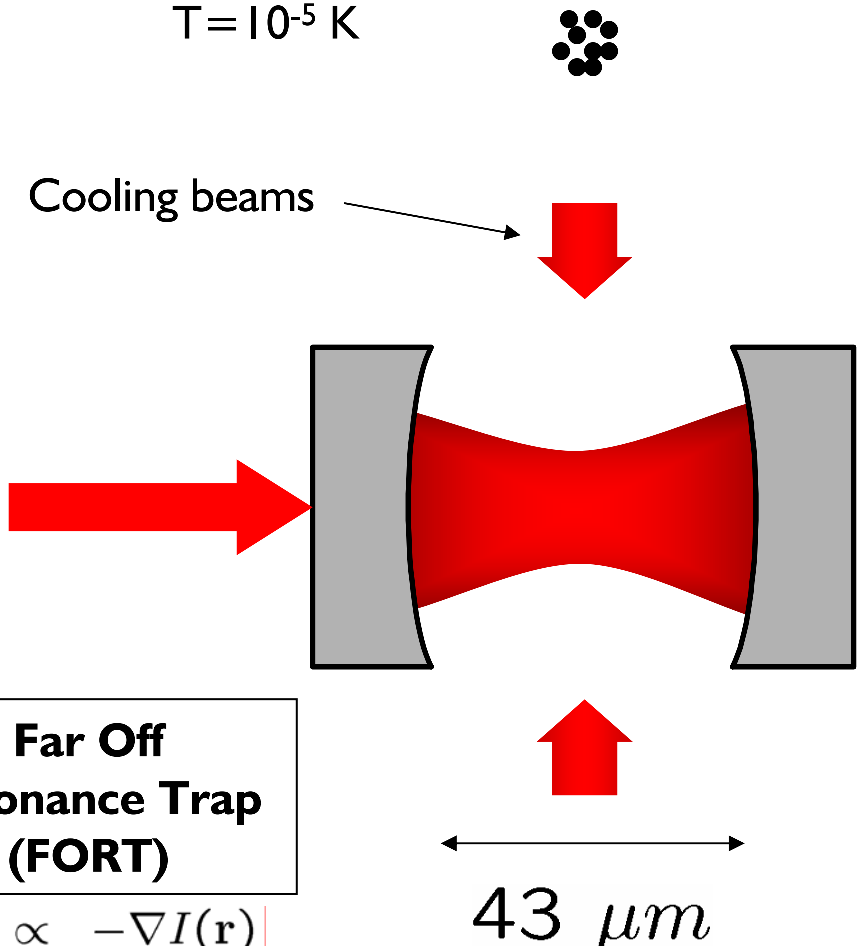
Intracavity Far-Off-Resonance Trap (FORT)

Transmission Spectrum of a Fabry-Perot Cavity (Length=43 μm)
(Longitudinal modes only, i.e. $L=n\lambda/2$)



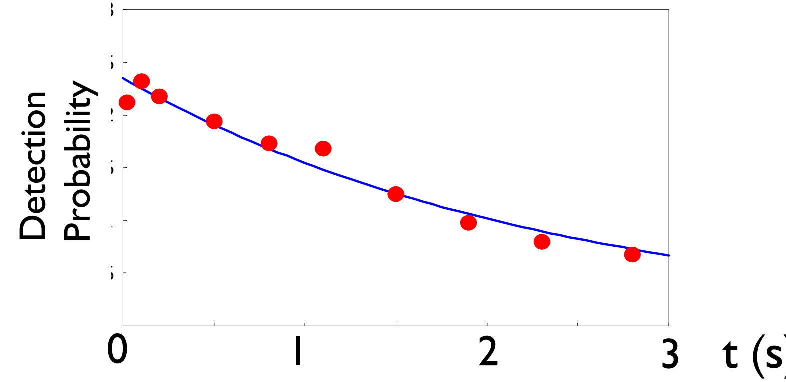
Trapping One Atom in the Cavity

Cloud of
$\sim 10^5$ cesium atoms
$T = 10^{-5}$ K



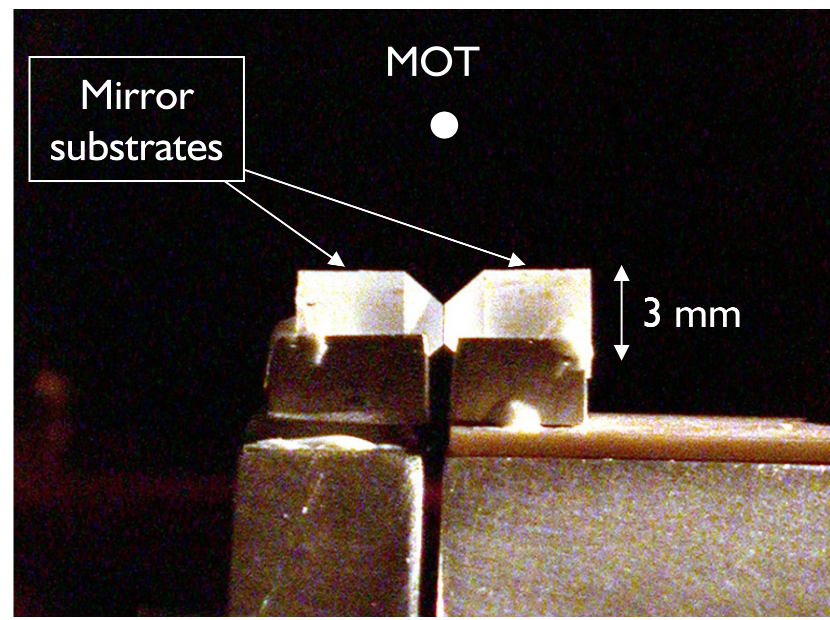
Far Off Resonance Trap (FORT)

$$\mathbf{F} \propto -\nabla I(\mathbf{r})$$
$$\lambda_F = 936\ nm$$



Single-atom storage time:
2 to 3 seconds

Phys. Rev. Lett **90**, 133602 (2002)



Dipole Trap Overview for a Two Level Atom

a.k.a. Far-Off-Resonance-Trap (FORT)

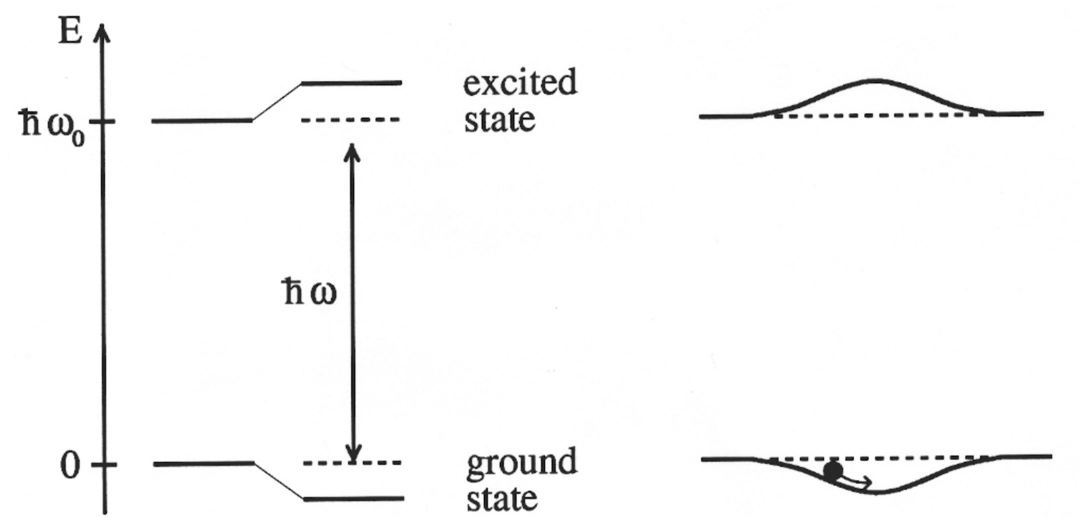
Classical picture: A dipole moment is induced in atom by optical field E

Atom then sees a dipole force toward higher intensities I(r) (attractive for red detuning)

$$U(\vec{r}) = \frac{3\pi c^2}{2\omega_0^3}\frac{\gamma}{\Delta}I(\vec{r})$$

$$\hbar\Gamma_{sc}(\vec{r}) = \frac{\gamma}{\Delta}U(\vec{r})$$

where $\Delta = \omega - \omega_0$



Detailed calculation of Excited State Stark shifts: The picture is a bit more complicated…

218   7. Spectroscopic Characteristics of Neutral Atoms

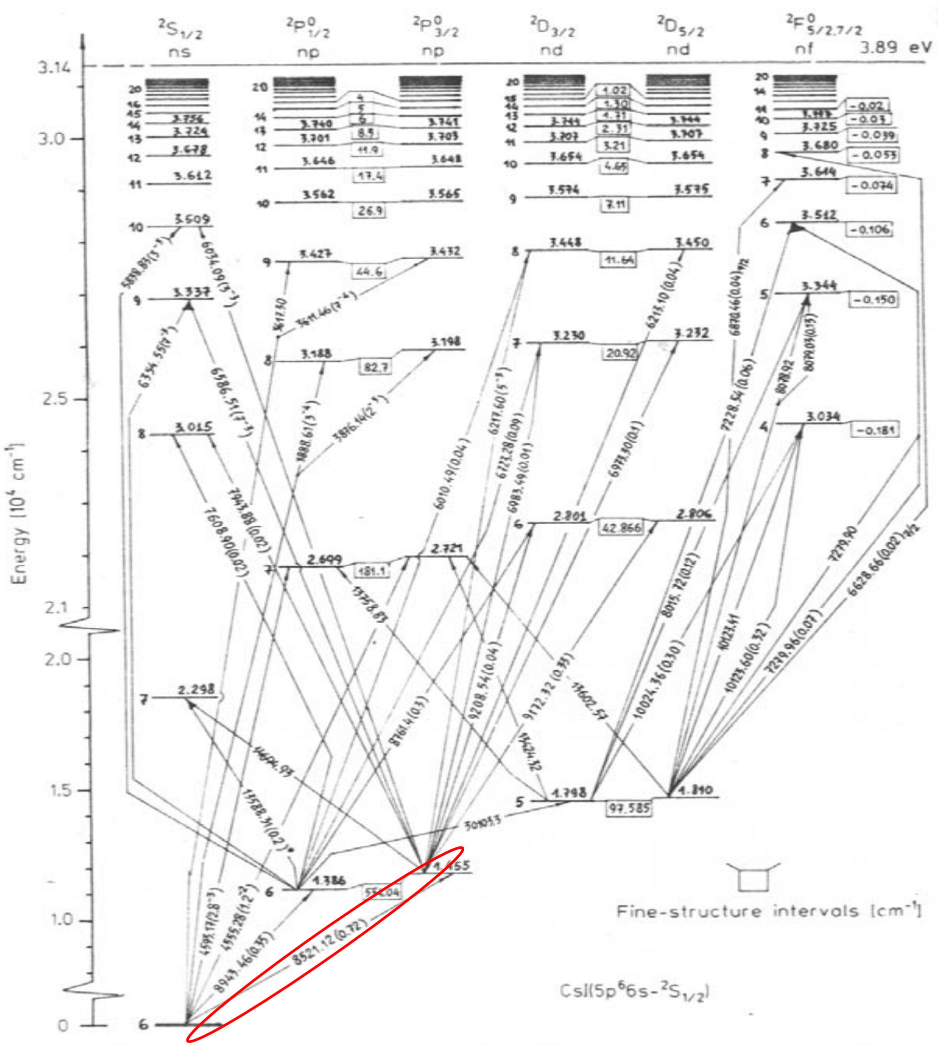


Fig. 7.40. Combined partial energy-level – Grotrian diagram with absorption oscillator strengths for caesium

$$\hat{U} = \vec{E}^* \cdot \hat{\alpha} \cdot \vec{E}$$

$$\hat{\alpha} = \sum_e \frac{\hat{d}|e\rangle\langle e|\hat{d}}{\hbar \Delta_{ge}}$$

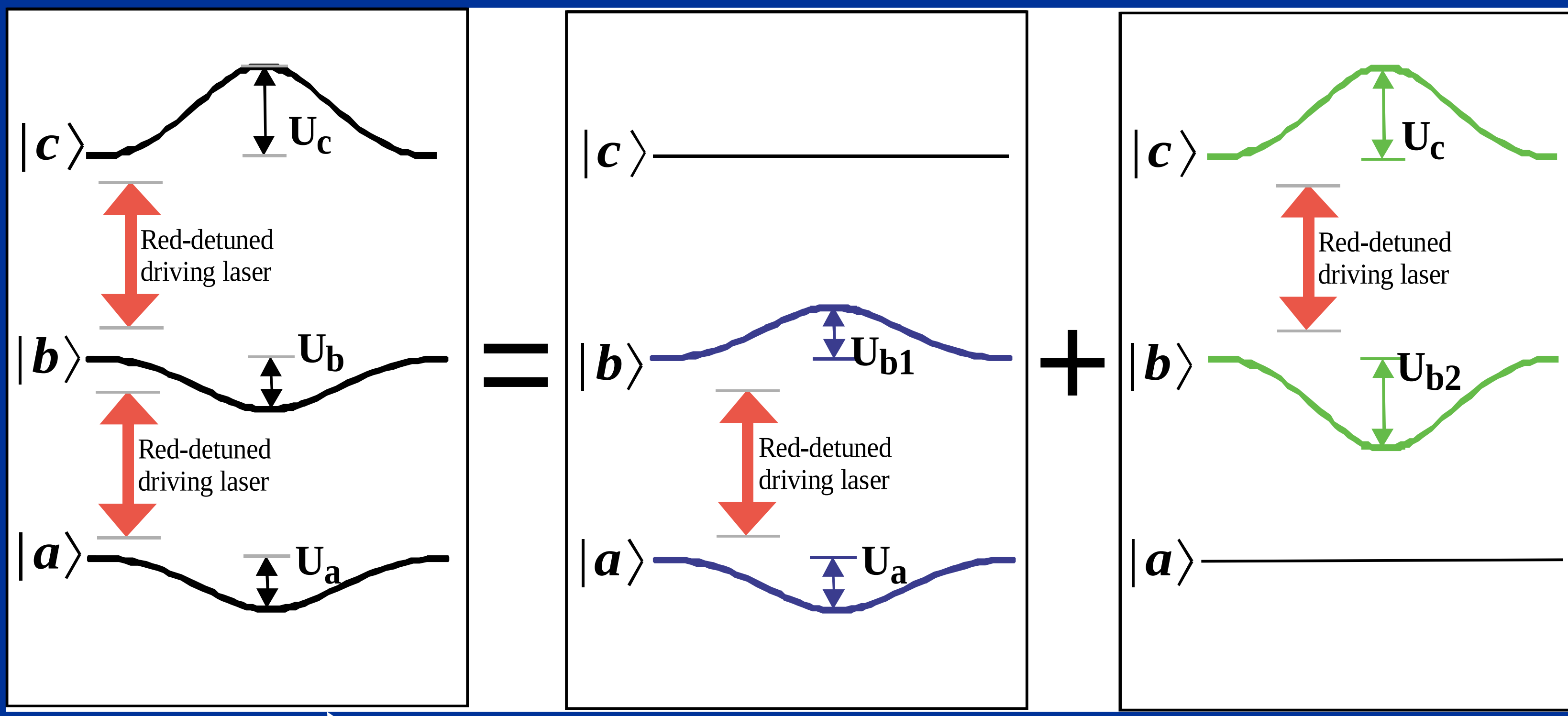
$$U = \langle g | \hat{U} | g \rangle$$

$$U(\vec{r}) = |E(\vec{r})|^2 \sum_{J'} \frac{|\langle J' \| d \| J \rangle|^2}{\hbar \Delta_{J'J}}$$

$$\sum_{F'} (2J'+1)(2F+1) \left| \begin{Bmatrix} F' & I & J' \\ J & 1 & F \end{Bmatrix} \right|^2 (c_{F,m}^{F',m+q})^2$$

But… we can get some Interesting answers.

Cesium + 935 nm = A State-Insensitive Trap

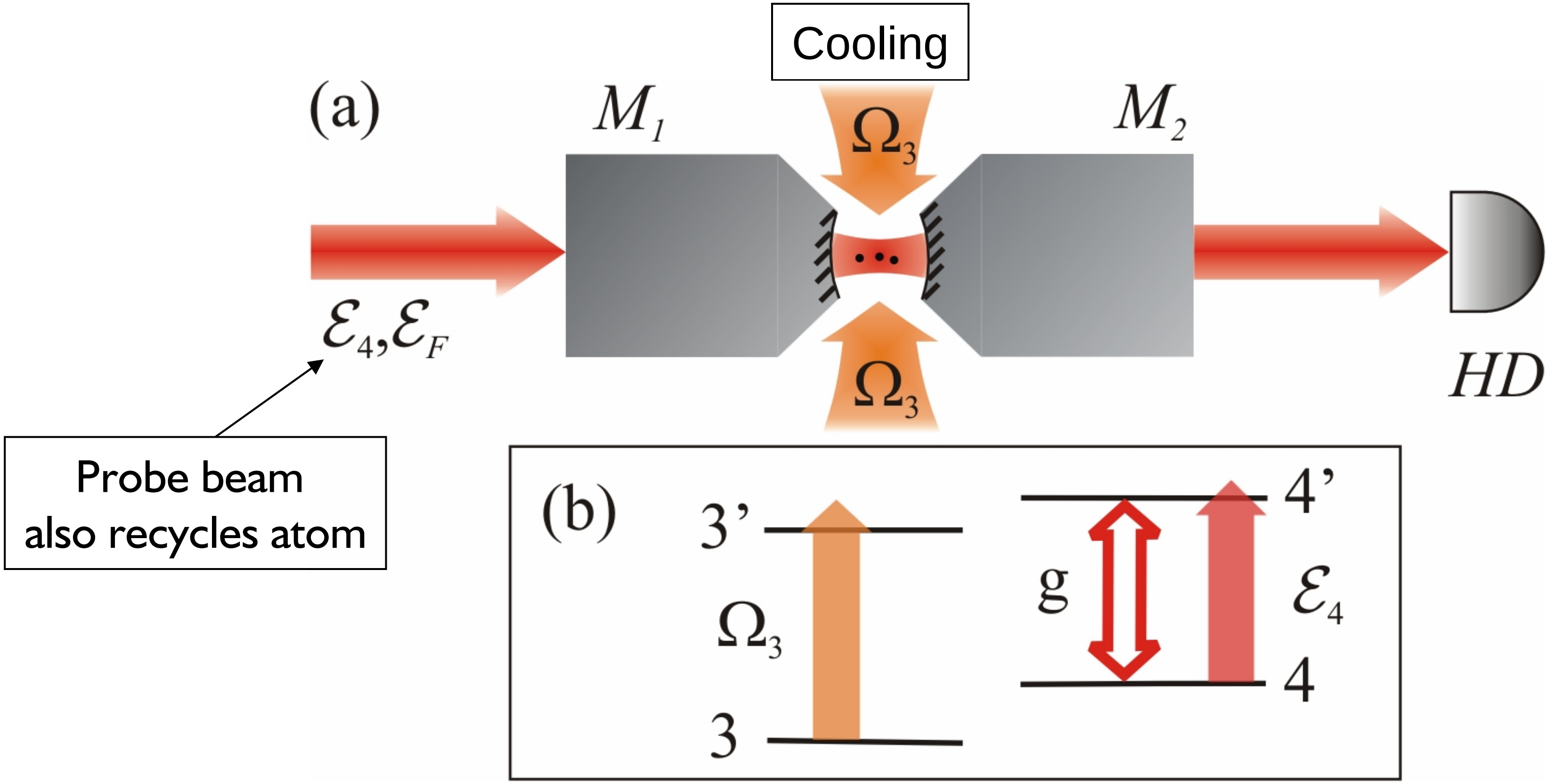


Transition of interest nearly unshifted by trap:

Cavity QED is then unperturbed by Stark shifts, which otherwise cause unwanted effective detunings

Cavity QED "By the Numbers"

J. McKeever, J. R. Buck, A. D. Boozer and H. J. Kimble, quant-ph/0403121



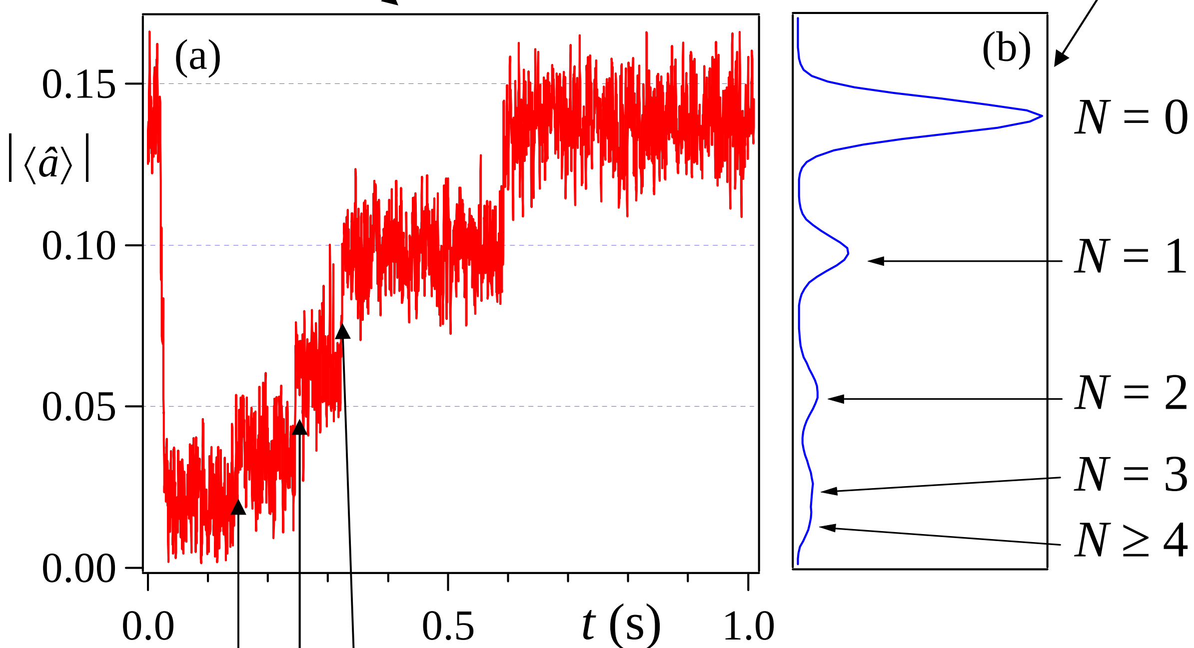
- Atoms dropped into cavity with probe, side beams and FORT continuously on
- Leads to interesting and useful effect

Demonstrated ability to resolve intracavity atom number in real time

See quant-ph/0403121 for details

Typical trace (one event)

Histogram built up from 500 events



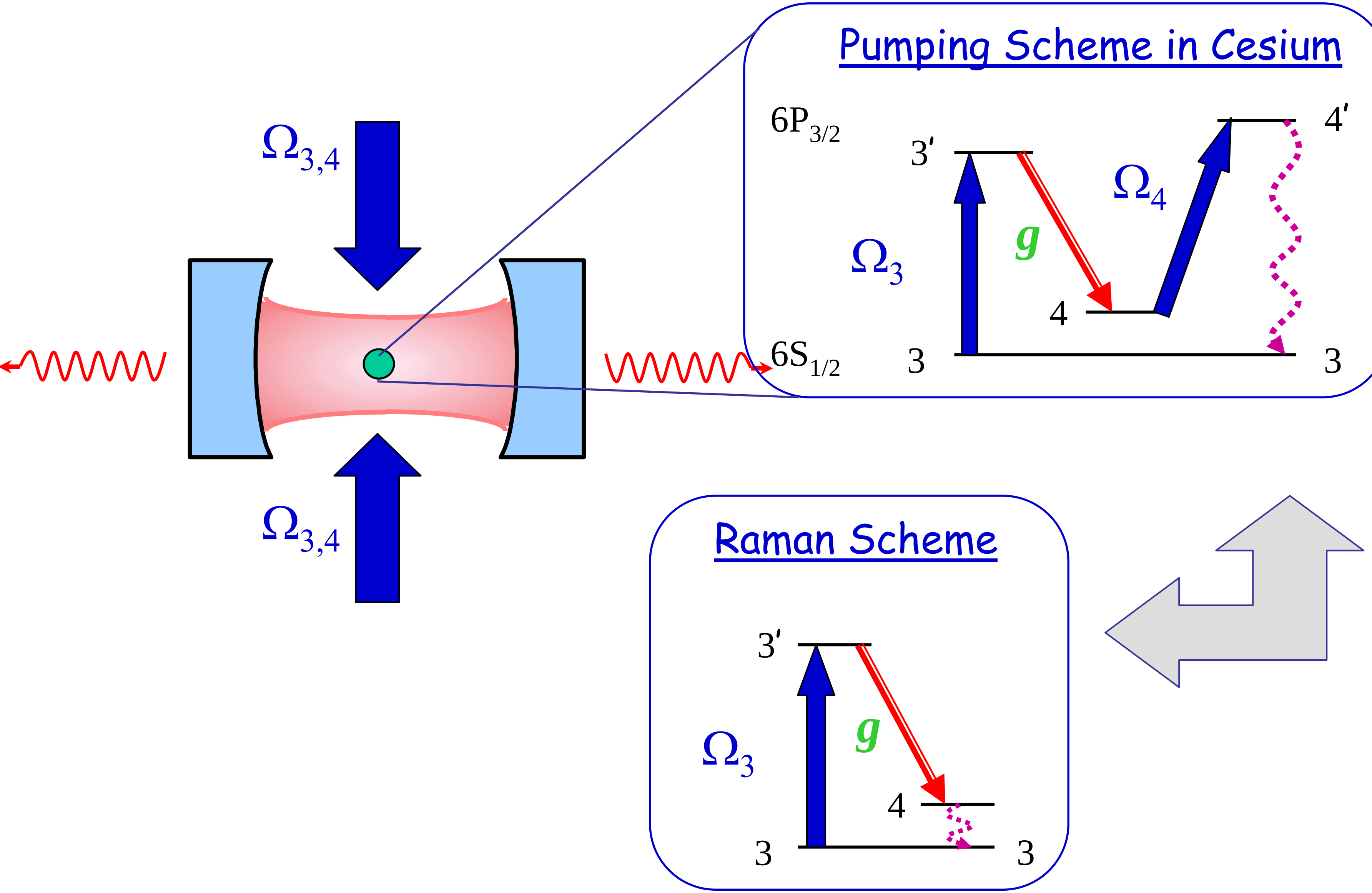
Scheme can be used to *prepare* specific atom number (although loading still probabilistic)

Steps in transmission always increase in time

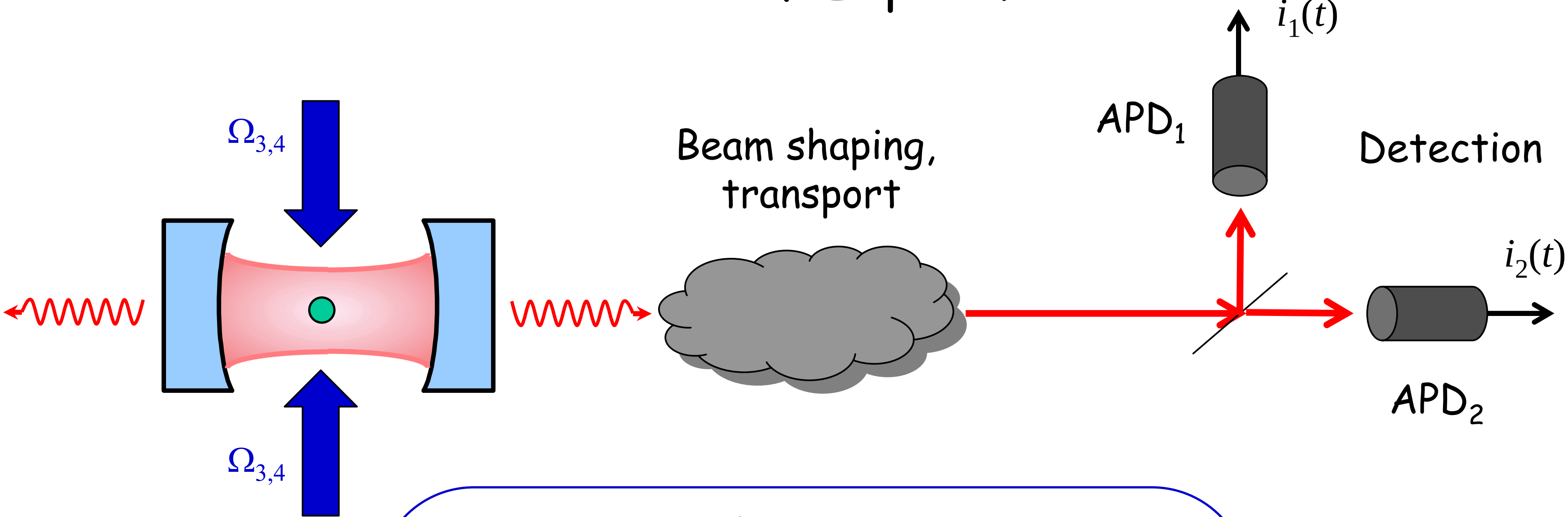
A One-Atom Laser in a Regime of Strong Coupling

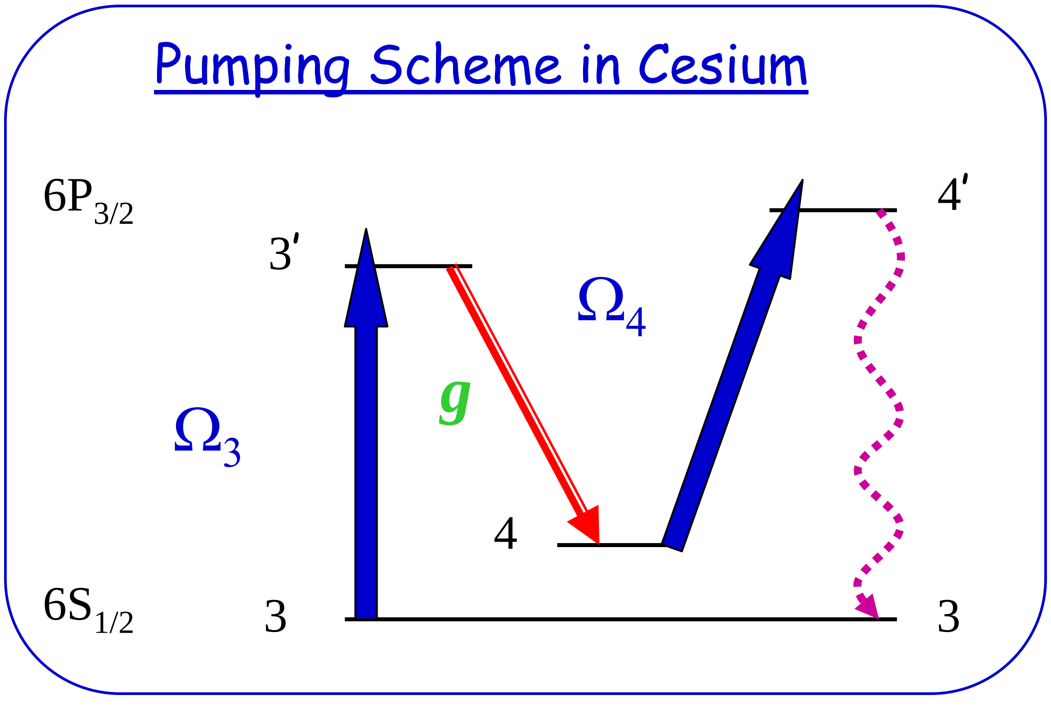
J. McKeever, A. Boca, A. D. Boozer, J. R. Buck, and H.J. Kimble

Nature, **425**, 268 (2003)

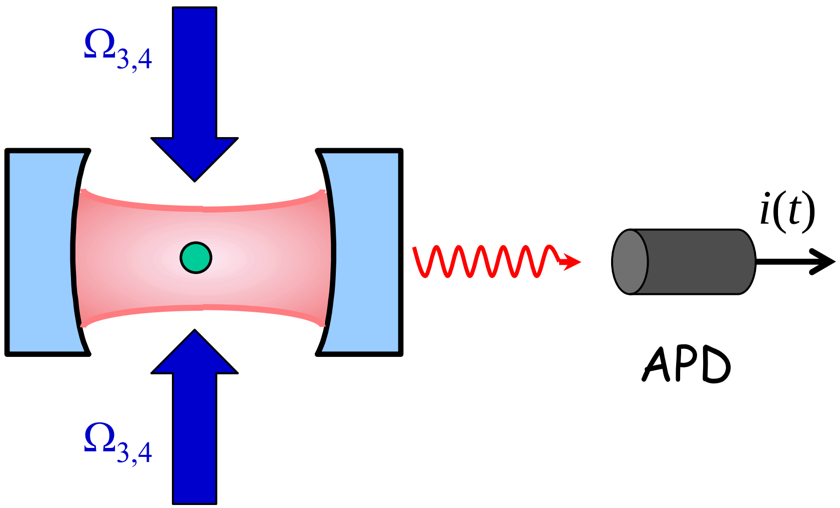


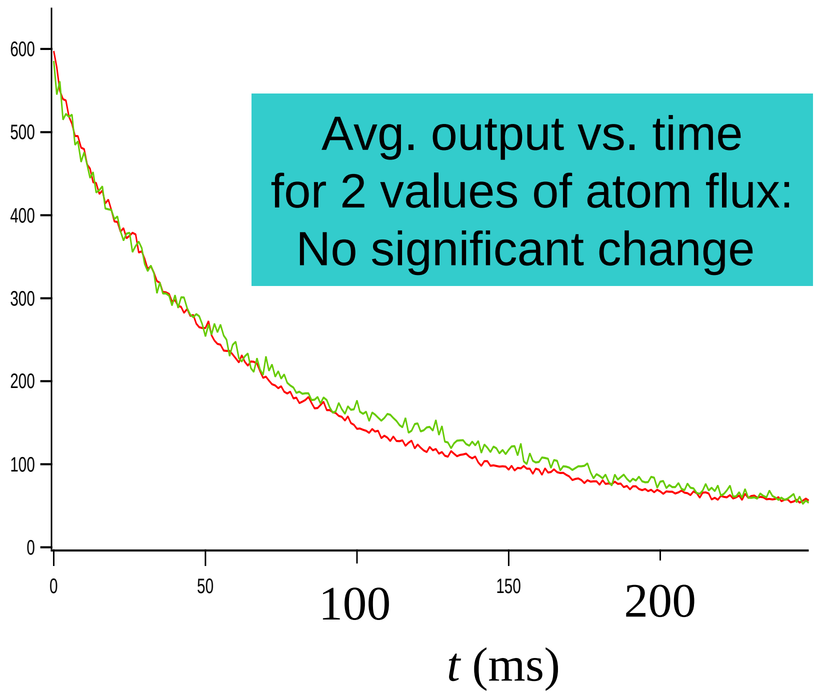
Overview of Experiment

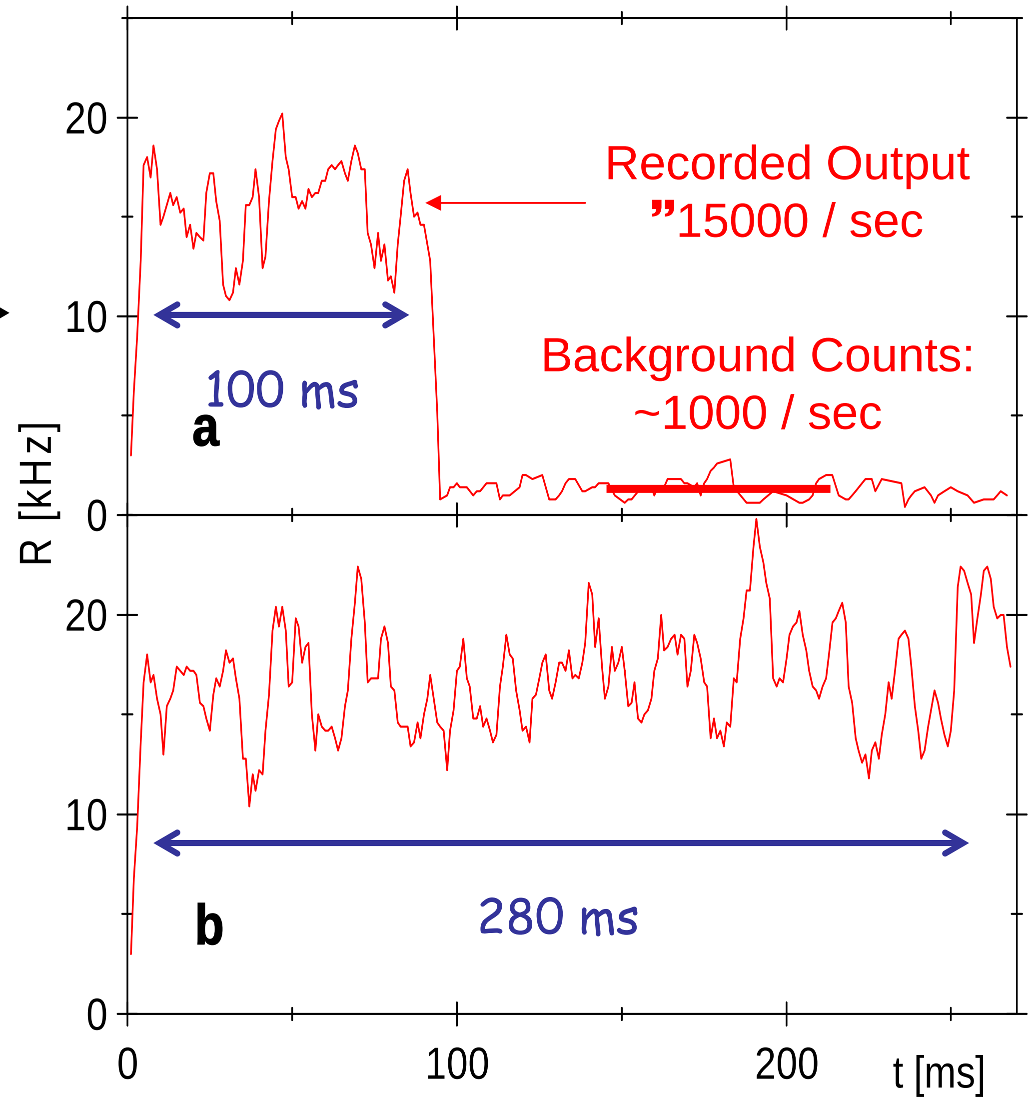




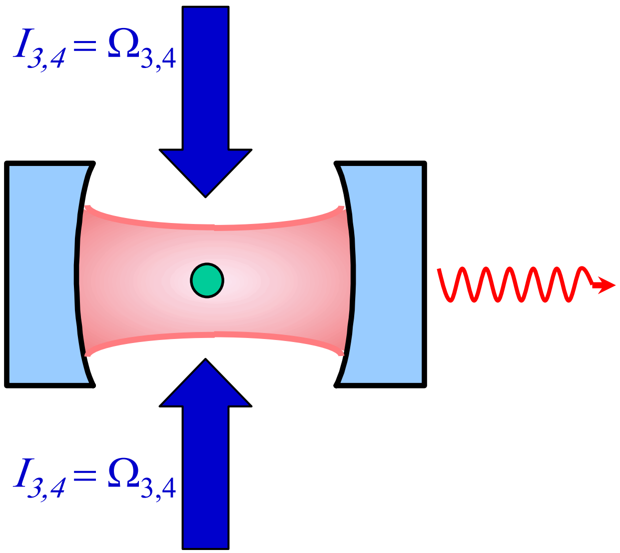
One-Atom Laser –
Observation of output vs. time

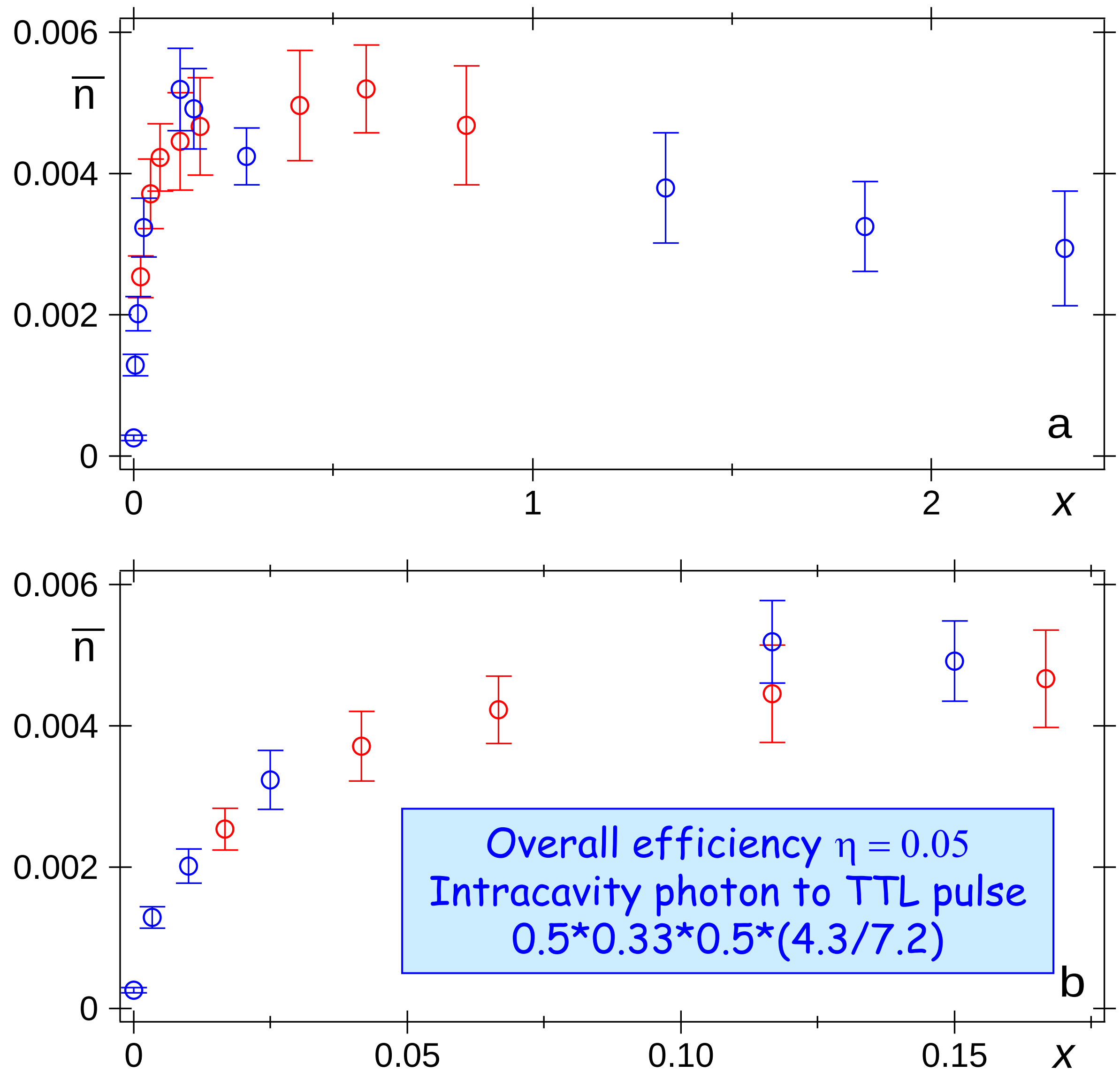






Experimental Data – Intracavity photon number <n> vs. pump I_3





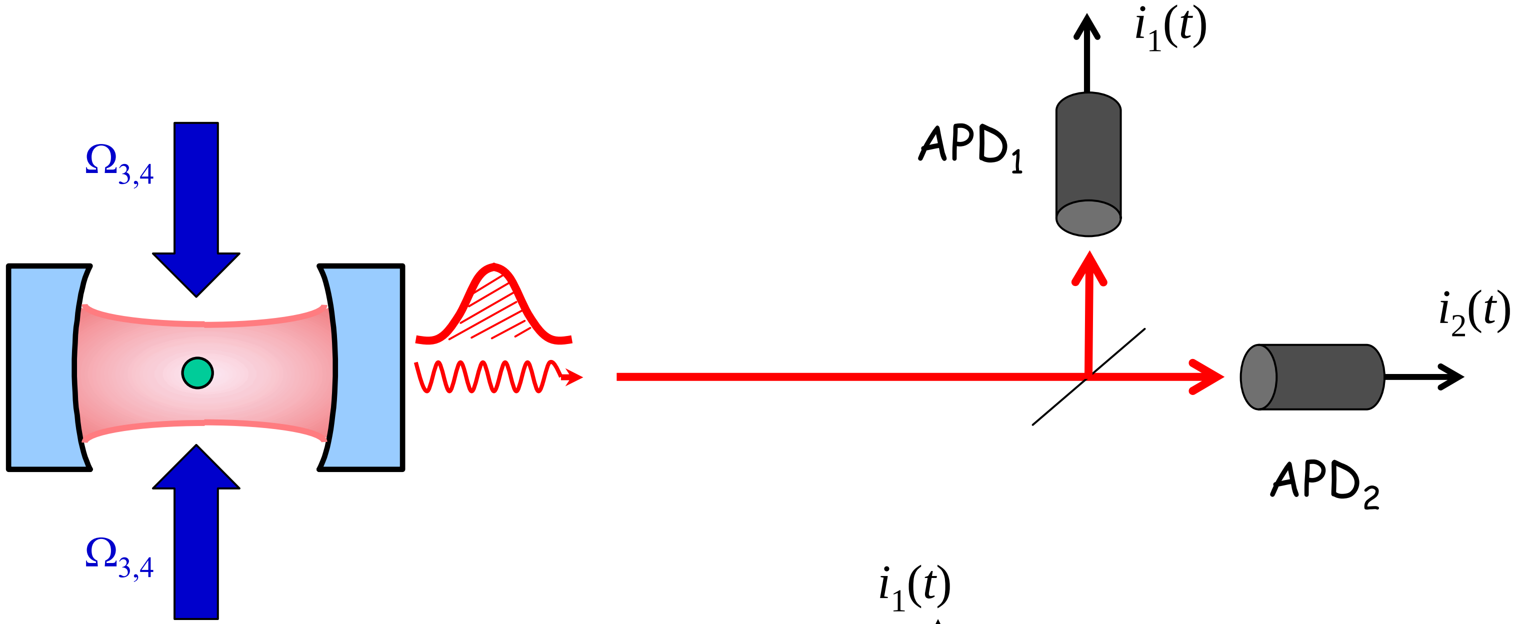
Fix $I_4 = \dfrac{\Omega_4^2}{\gamma^2} = 7.5$

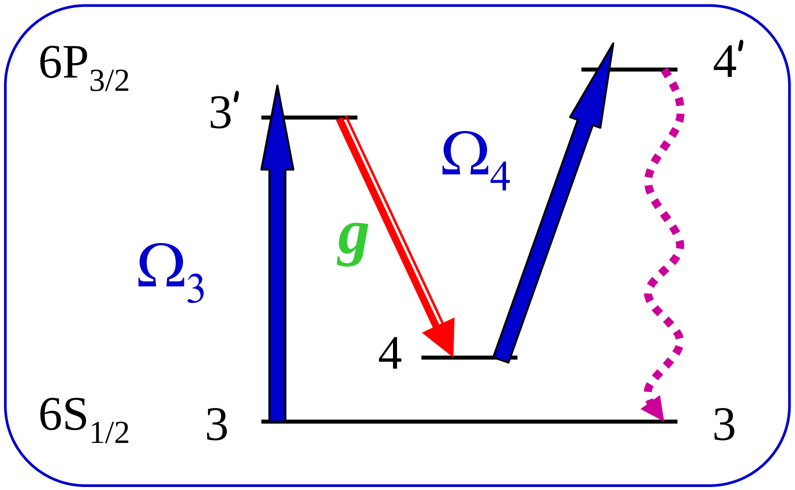
Vary $x = \dfrac{I_3}{I_4}$

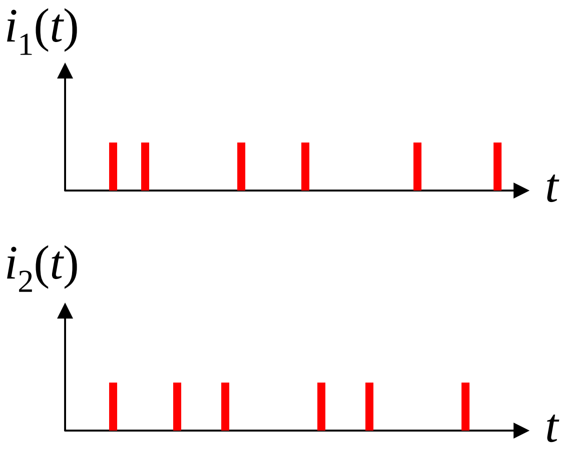
Coupling $g(\vec{r}) = g_0$

$$x = I_3 / I_4 = \Omega_3^2 / \Omega_4^2$$

Photon Statistics of the Emitted Light from the One-Atom Laser - Investigate via measurements of the joint probability of photoelectric detection





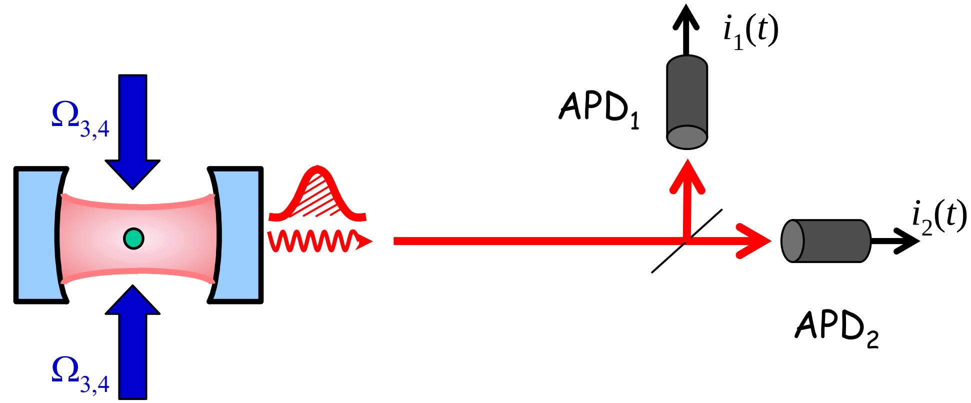


Time-resolved coincidence counts $n(\tau)$

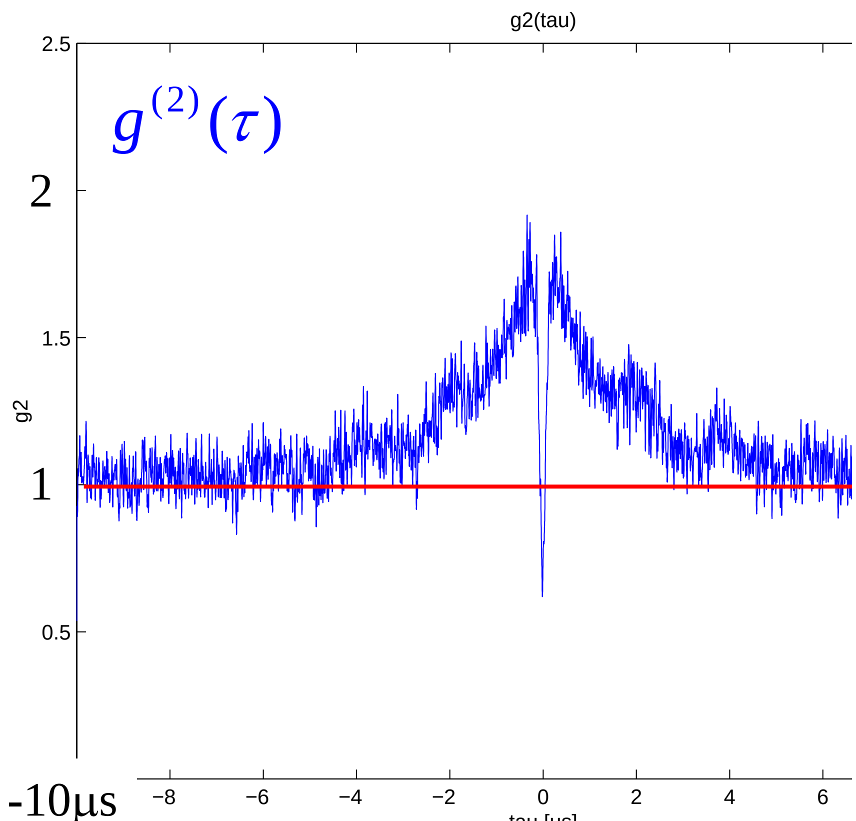
obtained from cross correlation $\langle i_1(t) i_2(t+\tau) \rangle$

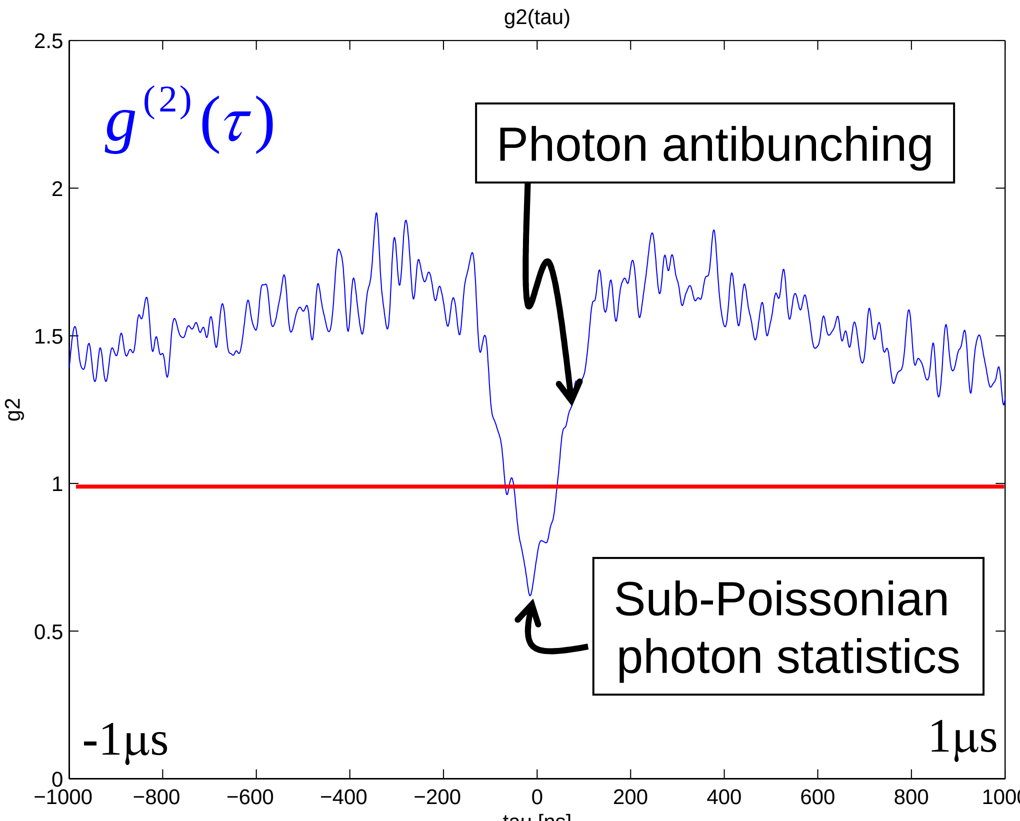
Intensity Correlation Function

$$g^{(2)}(\tau) = \frac{\langle : \hat{I}(t)\hat{I}(t+\tau) : \rangle}{\langle : \hat{I}(t) : \rangle \langle : \hat{I}(t+\tau) : \rangle}$$

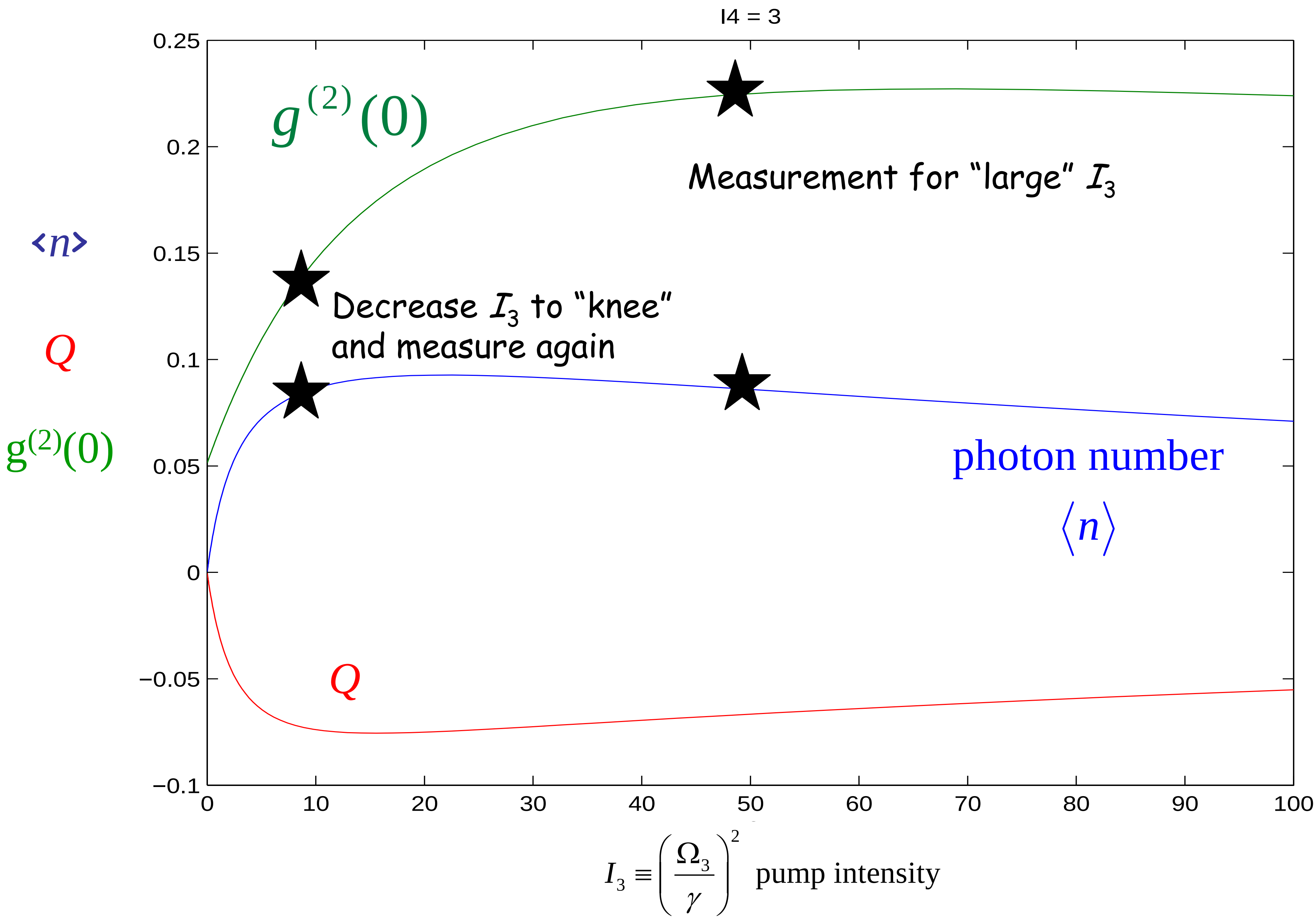


- Deduce $g^{(2)}(\tau)$ from time-resolved coincidence counts $n(\tau)$
- Set pump I_3 at "high" level well beyond "knee" for <n> vs. I_3



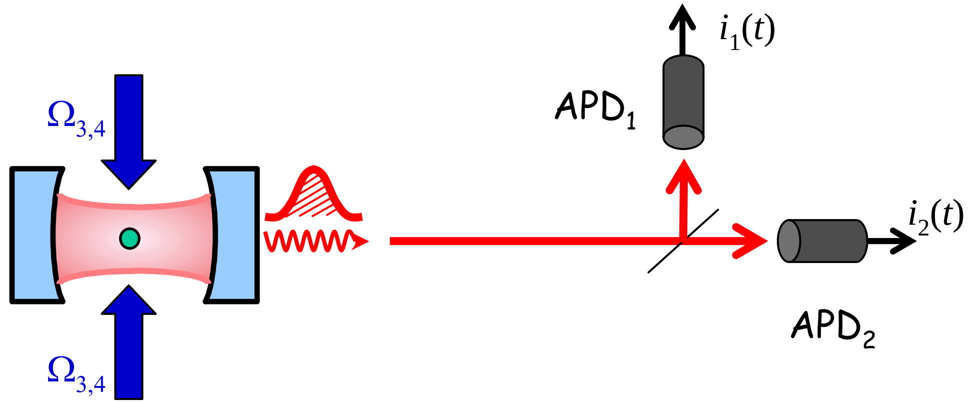


One-Atom Laser - Photon statistics from 4-state model

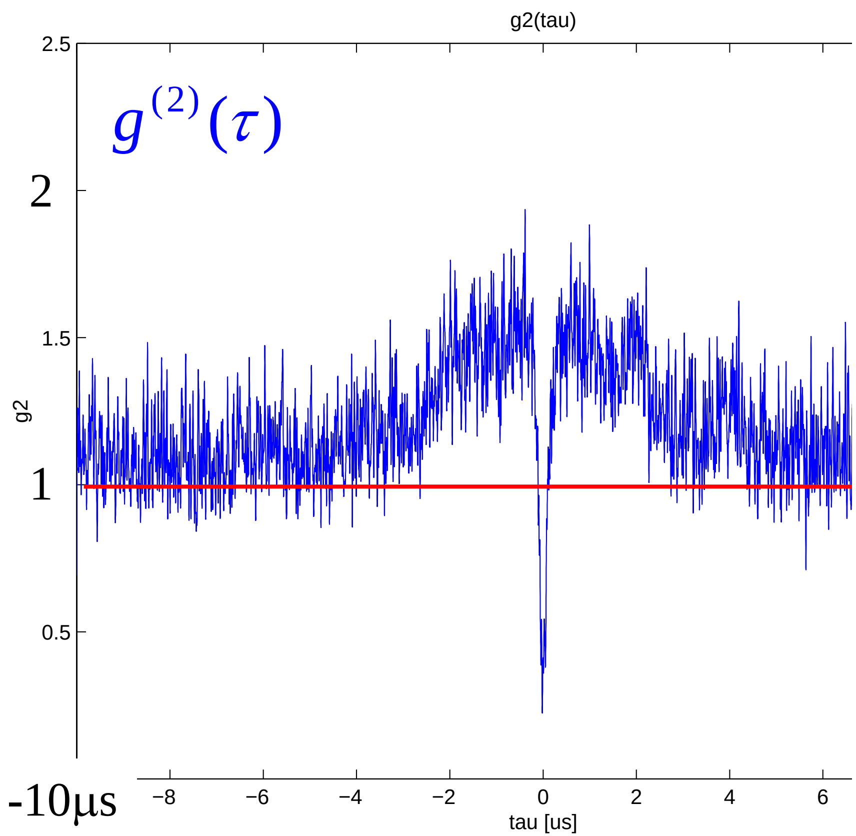


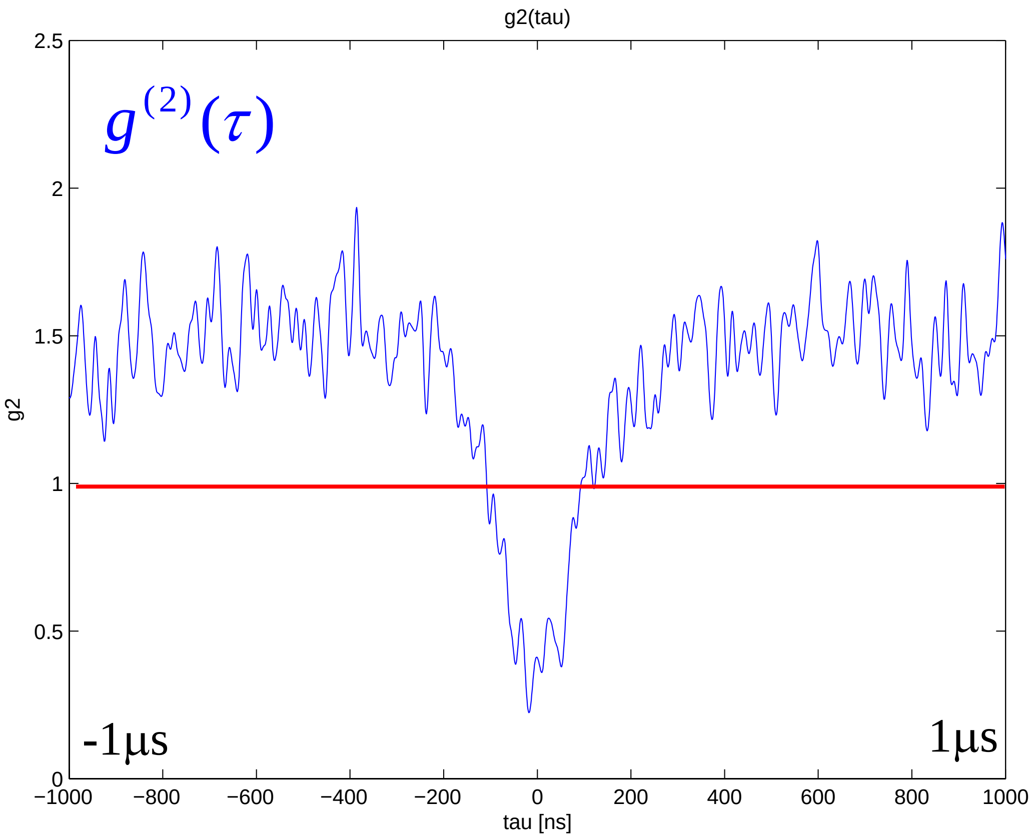
Intensity Correlation Function

$$g^{(2)}(\tau) = \frac{\left\langle : \hat{I}(t)\hat{I}(t+\tau) : \right\rangle}{\left\langle : \hat{I}(t) : \right\rangle \left\langle : \hat{I}(t+\tau) : \right\rangle}$$



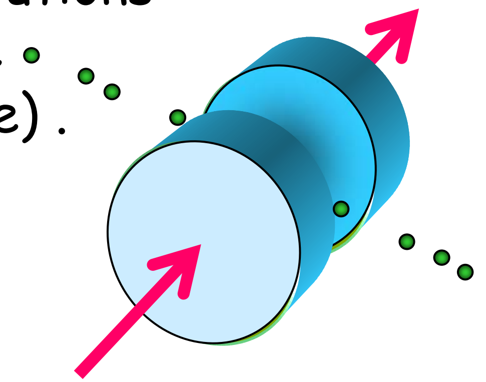
- Deduce $g^{(2)}(\tau)$ from time-resolved coincidence counts $n(\tau)$
- Set pump I_3 at approximate "knee" for <n> vs. I_3





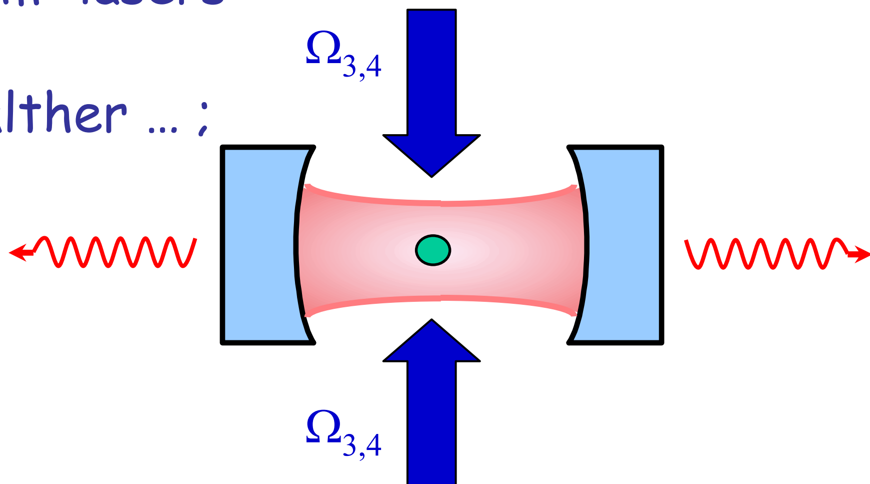
Distinctions from Prior Work

• "Single-atom" micro-masers and lasers – Walther, Haroche, Feld, …
Steady state is reached through the *incremental* contributions of many atoms that transit the cavity, even if one by one (in the microwave case) or few by few (in the optical case) .

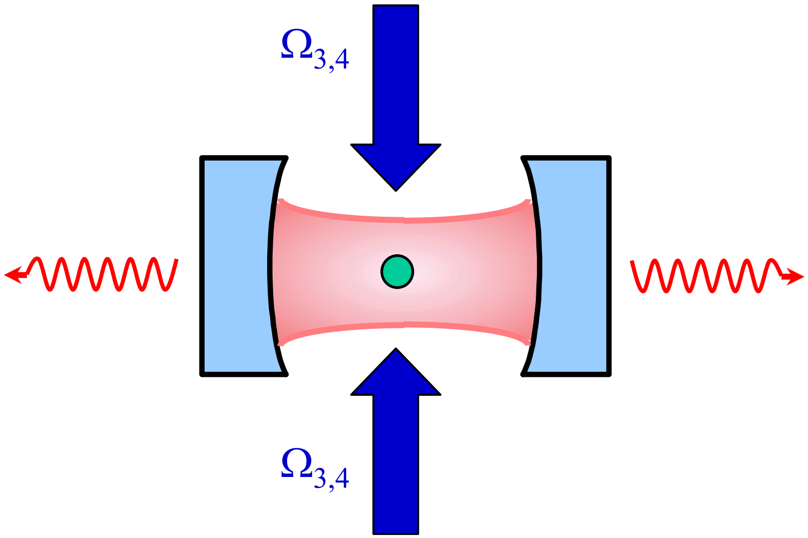


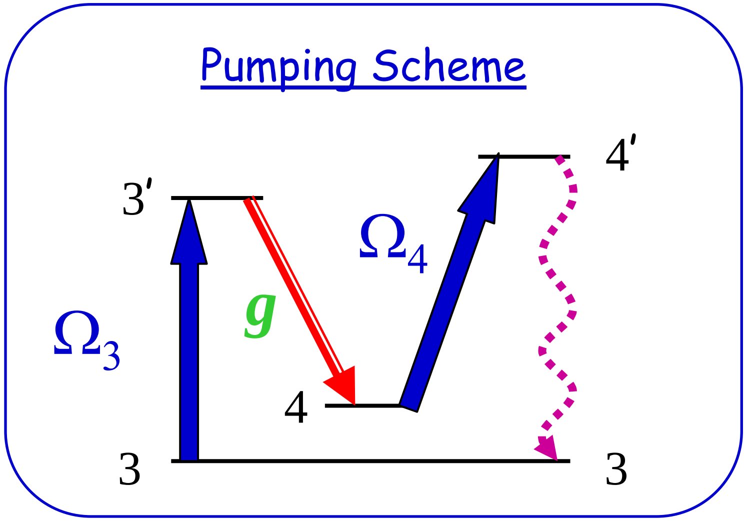
• A "one-and-the-same-atom" laser – Steady state achieved is reached with one atom in time $t \sim 10^{-7}$ sec as compared to trapping time $t \sim 10^{-1}$ sec.

• Large theoretical literature on "one-atom" lasers
- Mu and Savage 92
- H.-J. Briegel … ; H. Ritsch … ; H. Walther … ; P. R. Rice … ; Kilin and Karlovich 02; …



Summary – A One-Atom Laser in a Regime of Strong Coupling





• Measurements of photon statistics exhibit photon antibunching (with inference of sub-Poissonian statistics) and are in reasonable accord with theory

• Approximately stationary source of nonclassical light as a Gaussian beam

• Remaining issues –

• Measurements of optical spectrum of output

• Cooling of axial motion – new scheme "invented" by D. Boozer; implement in lab

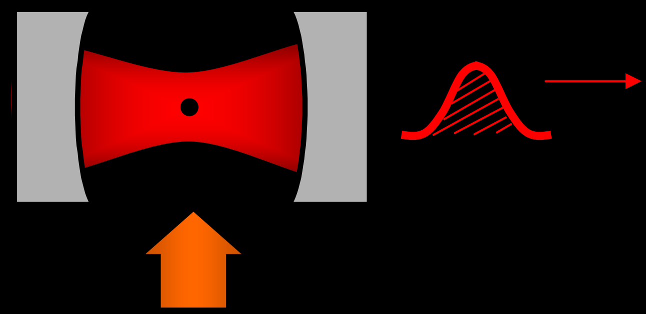
• Determine atomic location along axial standing waves of FORT and cavity QED

• …

•Comparison of theory & experiment: no time to discuss here, but there is reasonable agreement with data. See quant-ph/0309133, and Suppl. Info.

Deterministic Generation of Single Photons from One Atom Trapped in a Cavity

J. McKeever, A. Boca, A. D. Boozer, R. Miller, J. R. Buck, A. Kuzmich and H. J. Kimble, *Science* **303**, 1992 (2004)



Convert one-atom laser to a pulsed excitation scheme in order to realize the basic building block of a quantum network

Why Single Photons?

Advantages over classical light sources

Secure Quantum Cryptography

- Laser pulses containing nonzero multi-photon probability can leak information to an eavesdropper

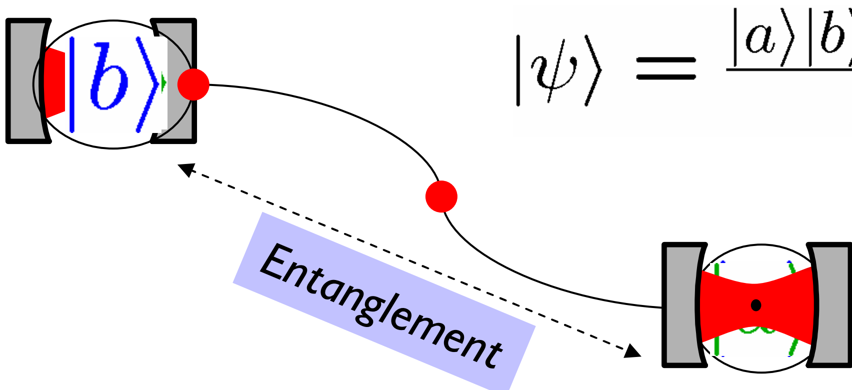
Linear Optics Quantum Computation

(Knill, Laflamme & Milburn, Nature **409**, 46 (2001))

- Scheme for universal quantum computation requires only **single-photon sources**, beamsplitters, phase shifters and detectors

Quantum Networks

Use photons as carriers of quantum information



$$|\psi\rangle = \frac{|a\rangle|b\rangle + |b\rangle|a\rangle}{\sqrt{2}}$$

Stationary qubits

Flying qubits

via

Single Photon Generation

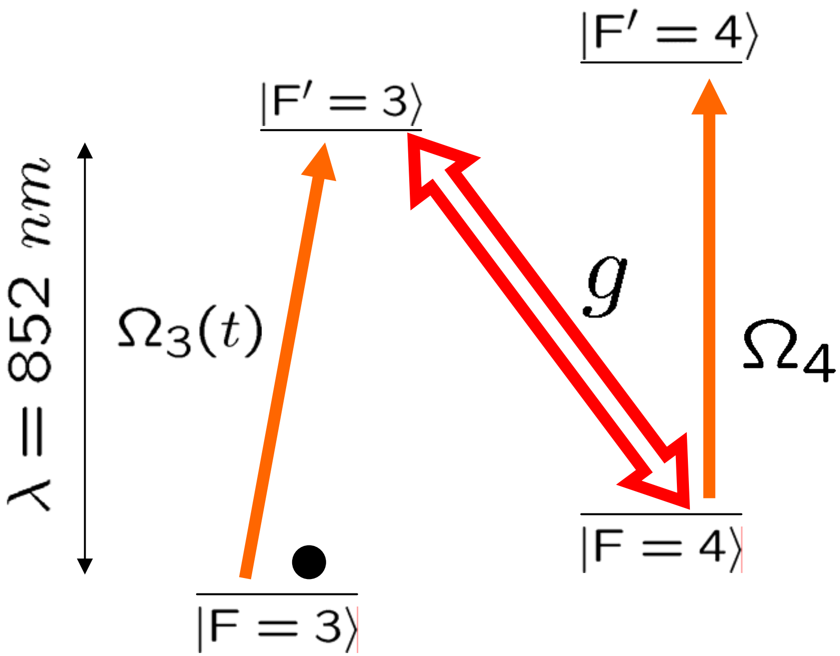
This requires more than just photon production:

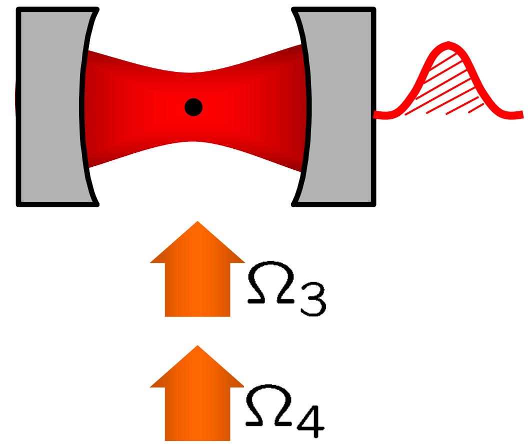
Need to transfer local quantum states onto the field, and back.

Sets our scheme apart from other photon sources

Single Photon Production

Adiabatic Passage via Dark States



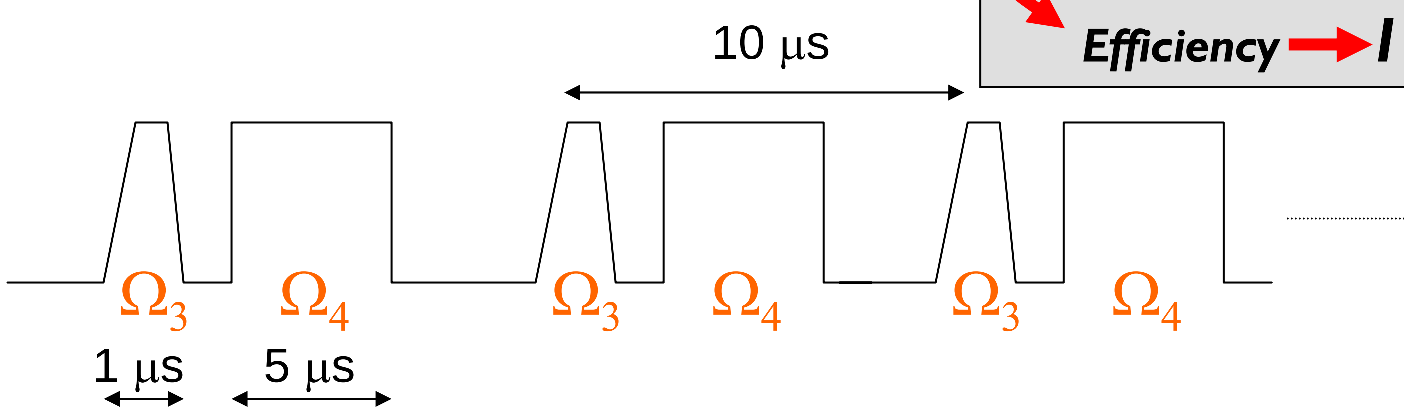


Gaussian Spatial Mode

User-controlled pulse shapes
≈ 100 ns

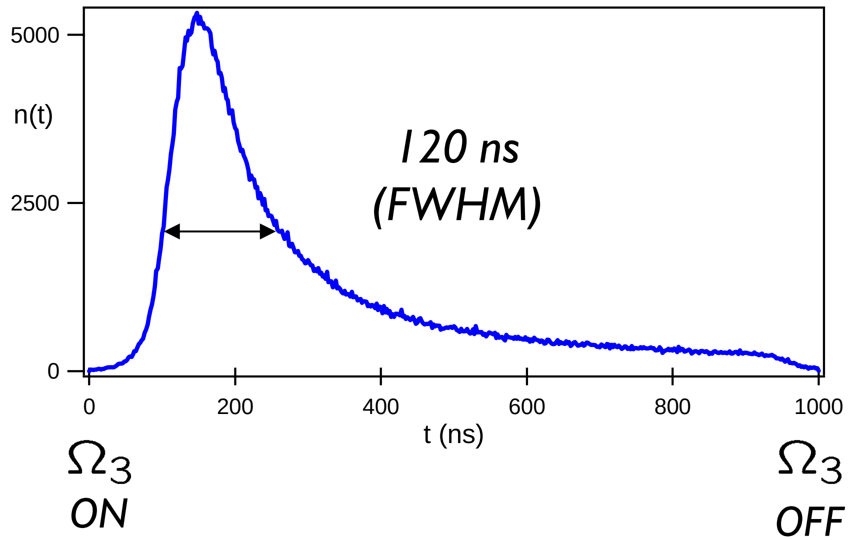
Strong coupling

Efficiency → 100%



Experimental Results: Pulse shape and Efficiency

Histogram of "click" times



14000 production attempts per trapped atom

Efficiency?

Inferred total cavity output:

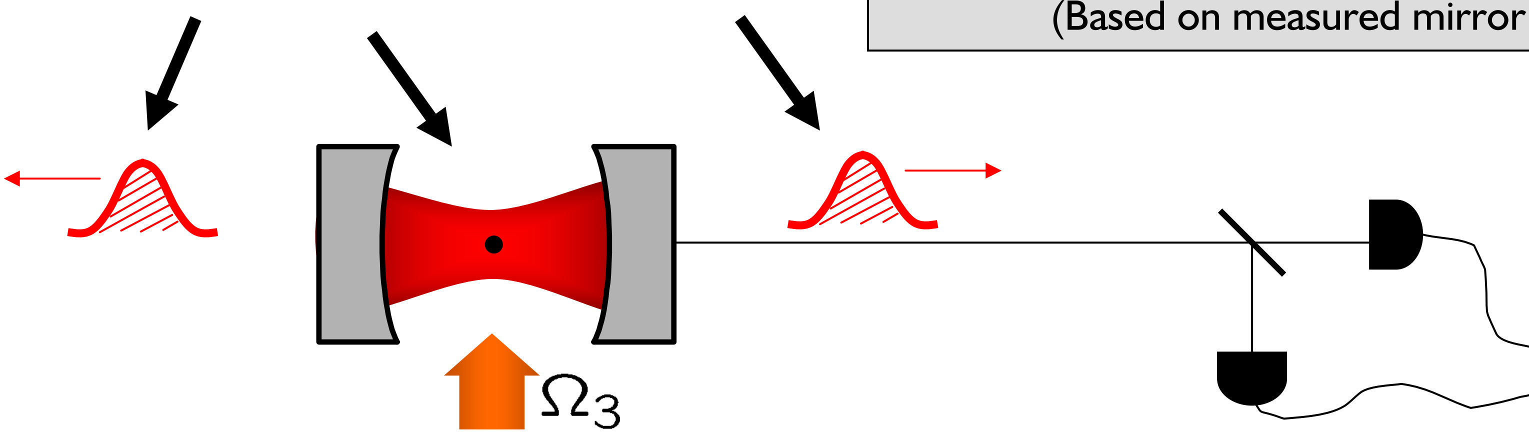
(69 ± 10)%

Consistent with

100 %

intracavity production (±18%)

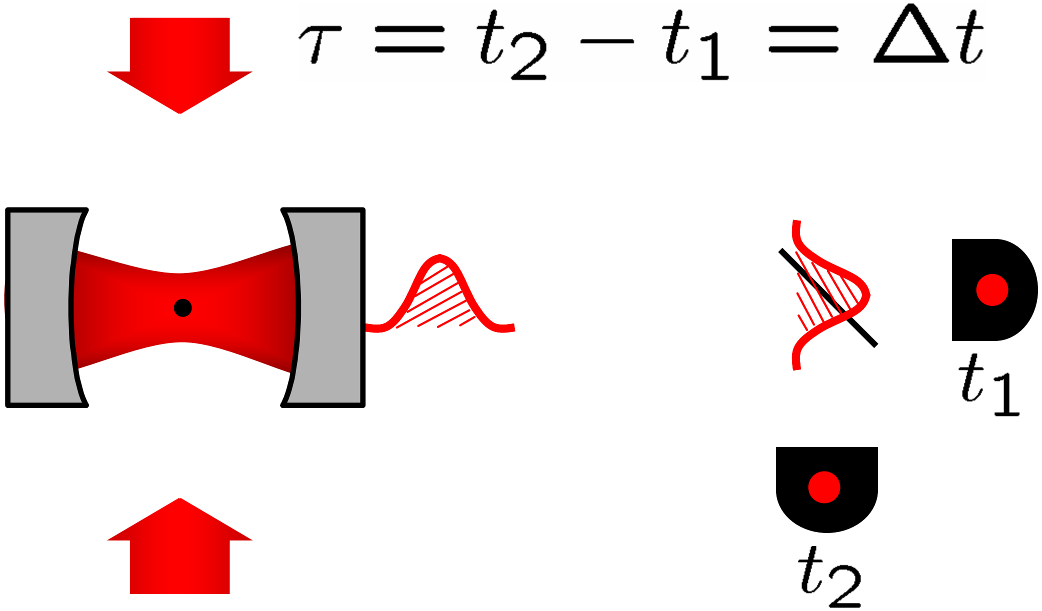
(Based on measured mirror losses.)

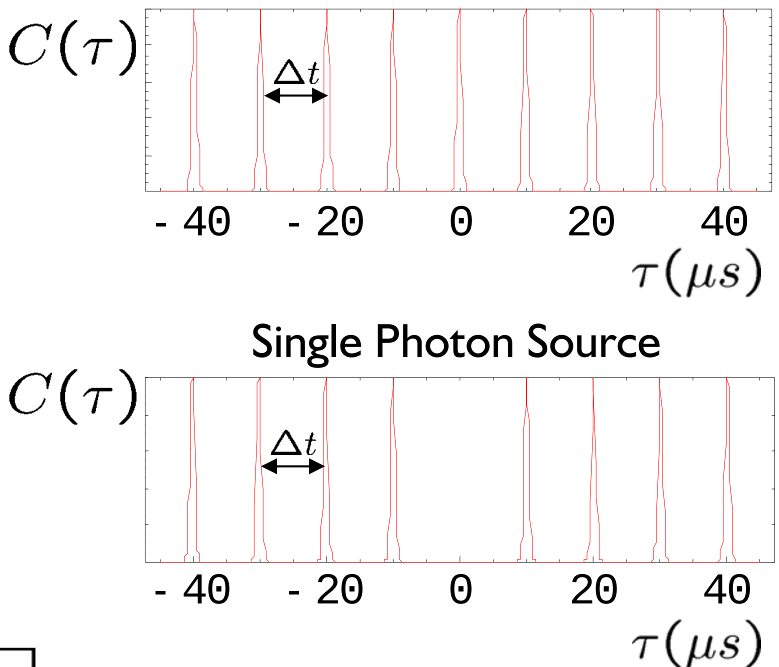


Final detection efficiency about 3%

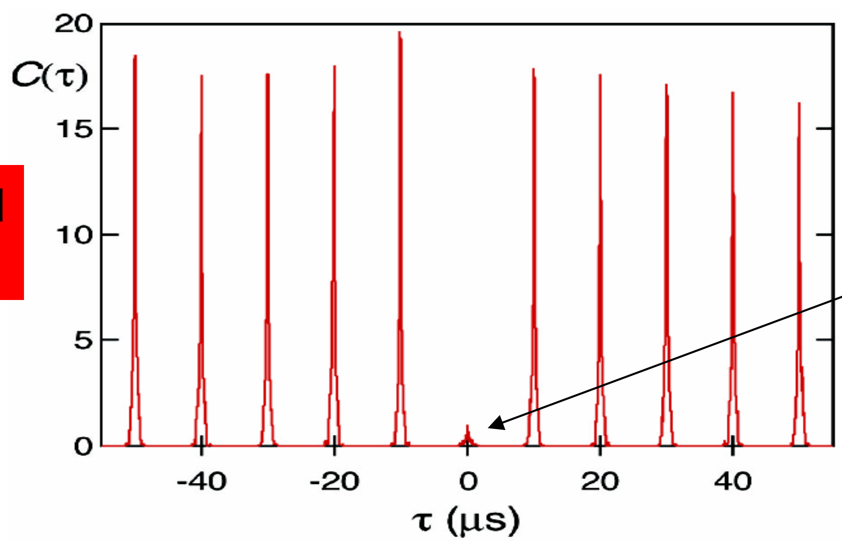
Correlation Functions and Time-Resolved Coincidences

$$\tau = t_2 - t_1 = \Delta t$$





Experimental Results



Suppression of two-photon events:

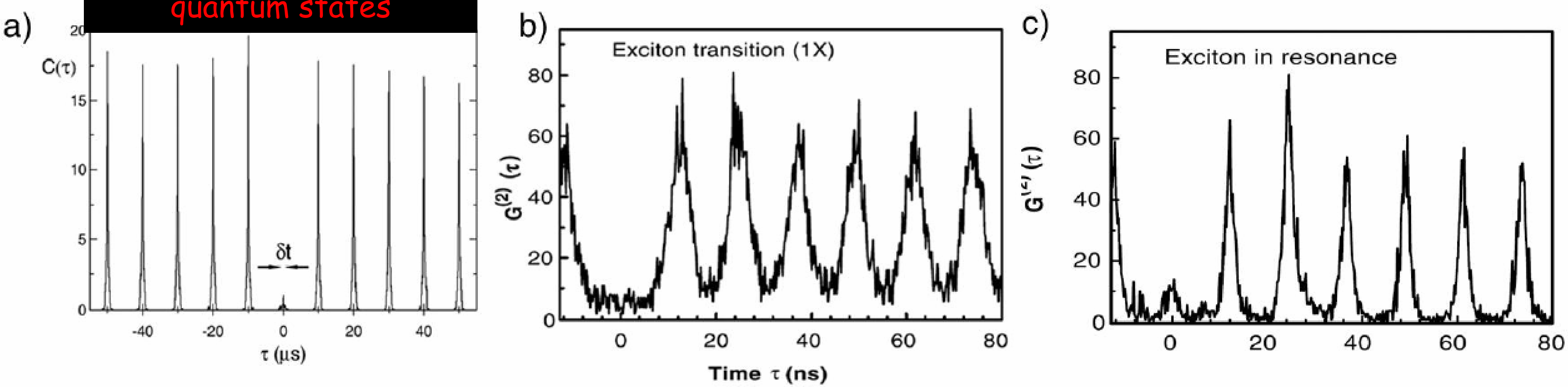
R=20.8 ±1.8

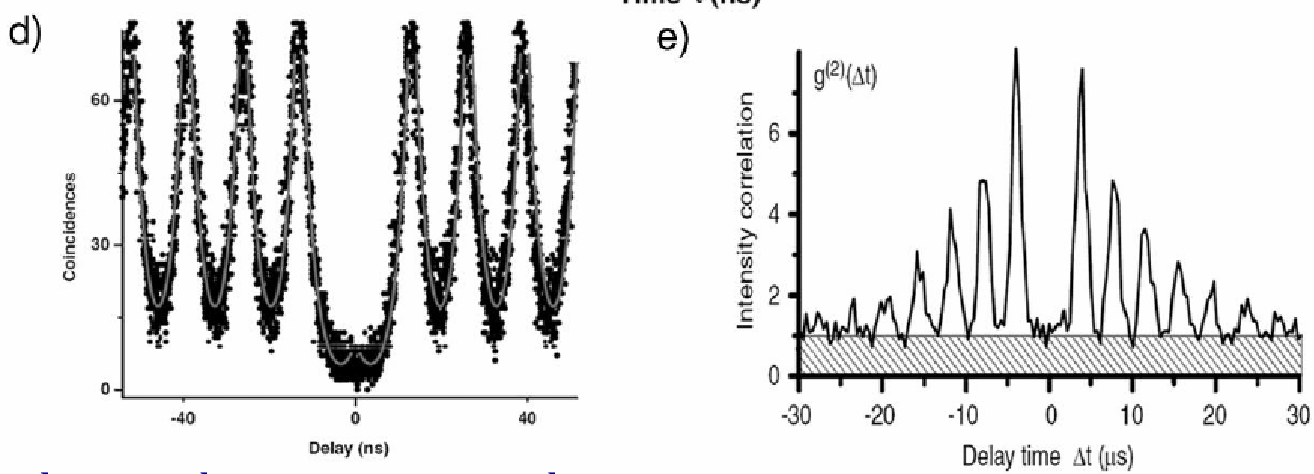
relative to a coherent state

But, worse than expected…

Comparison of Intensity Autocorrelation Functions for Several Single-Photon Sources

Inherently reversible for coherent transfer of quantum states





Our values of R and efficiency compare favorably with other sources.

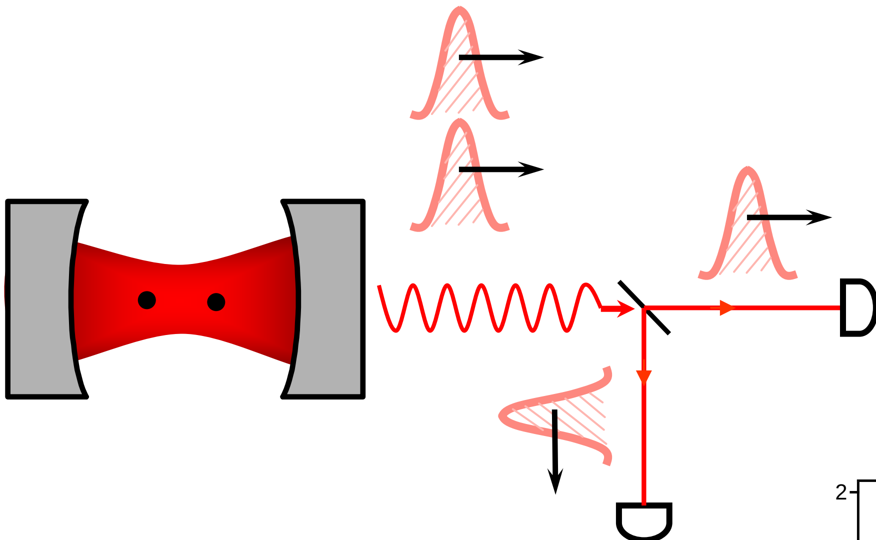
a) Single trapped atom – current work

b), c) Quantum dot coupled to disc resonator – P. Michler *et al.*, Science **290**, 2282 (2000).

d) Quantum dot coupled to vertical cavity – M. Pelton *et al.*, Phys. Rev. Lett. **89**, 233602 (2002).

e) Freely falling cold atoms – A. Kuhn *et al.*, Phys. Rev. Lett. **89**, 067901 (2002).

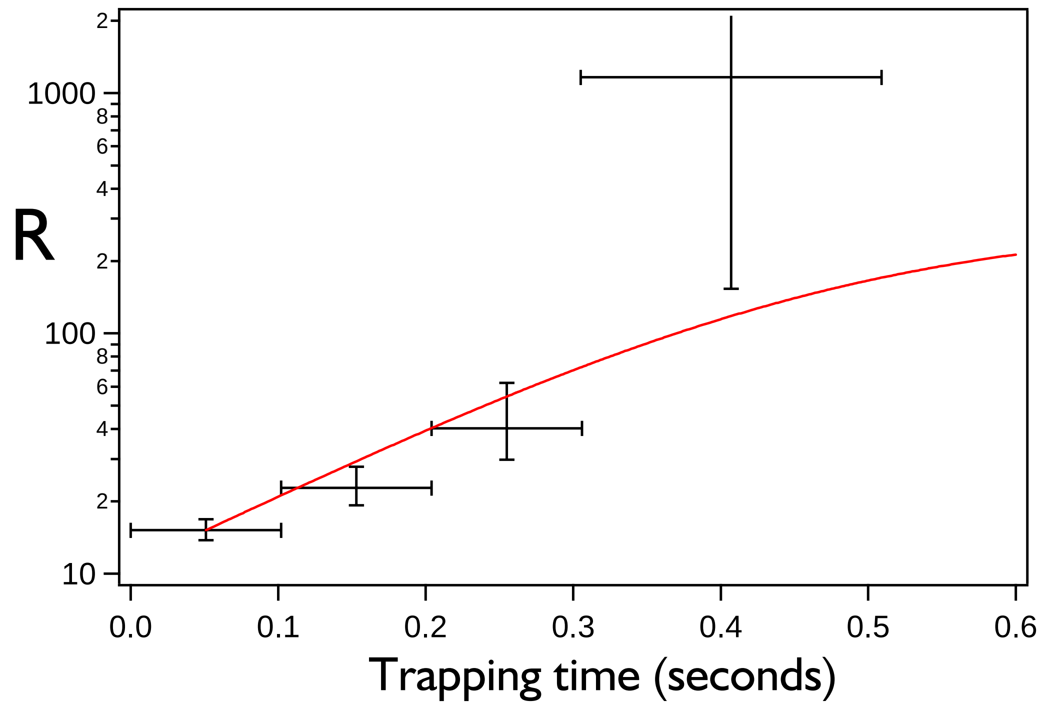
Two Atoms Can Make Two Photons



Two-photon "contamination" is limited by ***rare*** events (about 3%) in which two atoms are loaded into trap

R >150

at late times



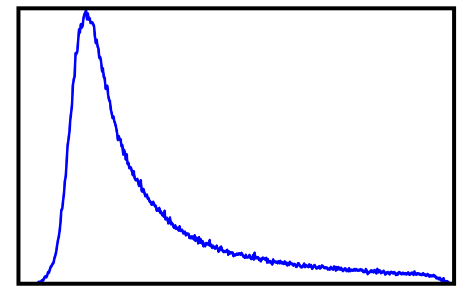
Measure dramatic improvement in suppression factor R at long trapping times

Using experimentally demonstrated scheme we can prepare **one atom** on demand. (quant-ph/0403121)

Single Photon Generation: Summary

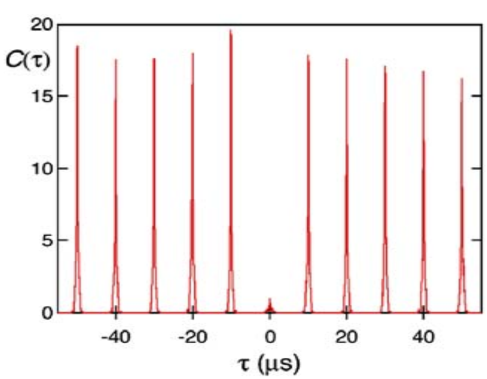
Single photons ***on demand*** with high efficiency
(consistent with 100% inside cavity)

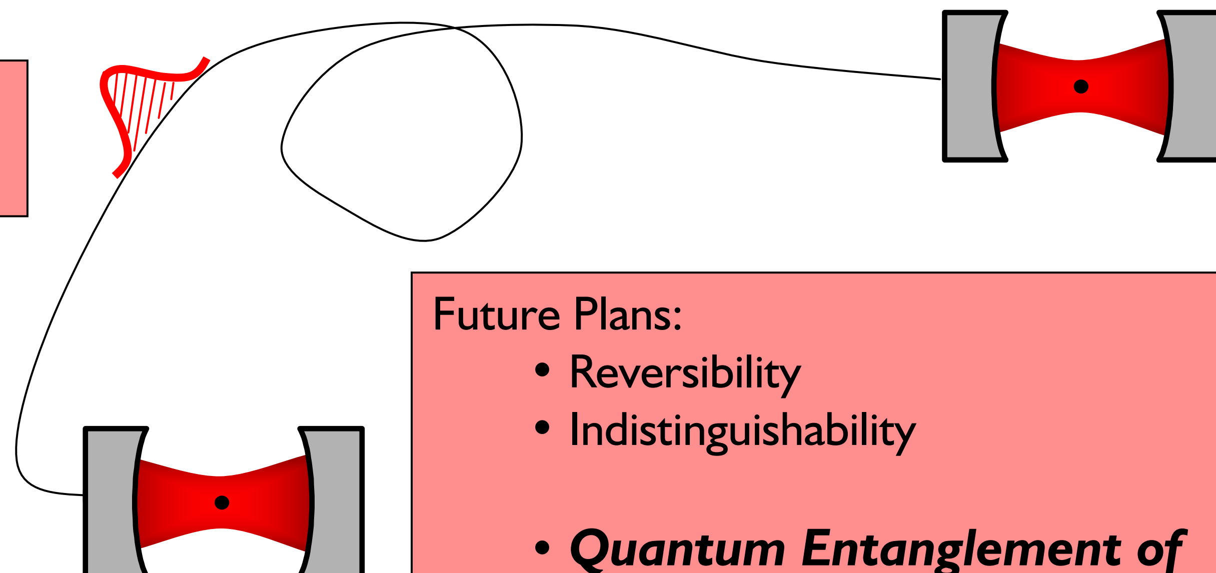
14000 photons per trapped atom
(improvements being made, **10^6** possible)



Scheme is ***coherent*** and ***reversible*** enabling implementation of ***quantum networks***

Output is highly non-classical:
R >150



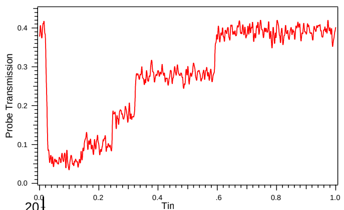


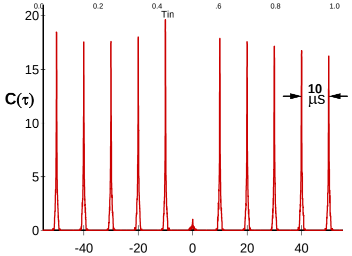
Future Plans:

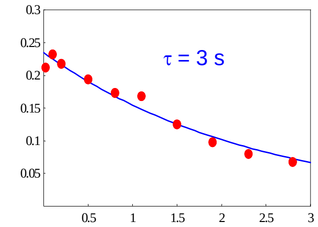
- Reversibility
- Indistinguishability
- ***Quantum Entanglement of Distantly Separated Atoms***

What Next?

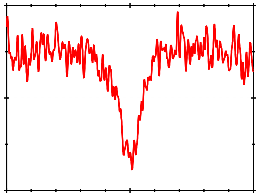
Already demonstrated:







- ✓ **trap atoms in the cavity for 2-3 s**
- ✓ **observe continuously and "count" atoms in real time**
- ✓ **produce a CW gaussian beam of nonclassical light**
- ✓ **efficiently create single photons on demand**



Still ahead:

Quantum schemes require control of all degrees of freedom

1. Internal state:

Control Zeeman sublevel via optical pumping and well-defined magnetic field

Should enable generation of polarized photons

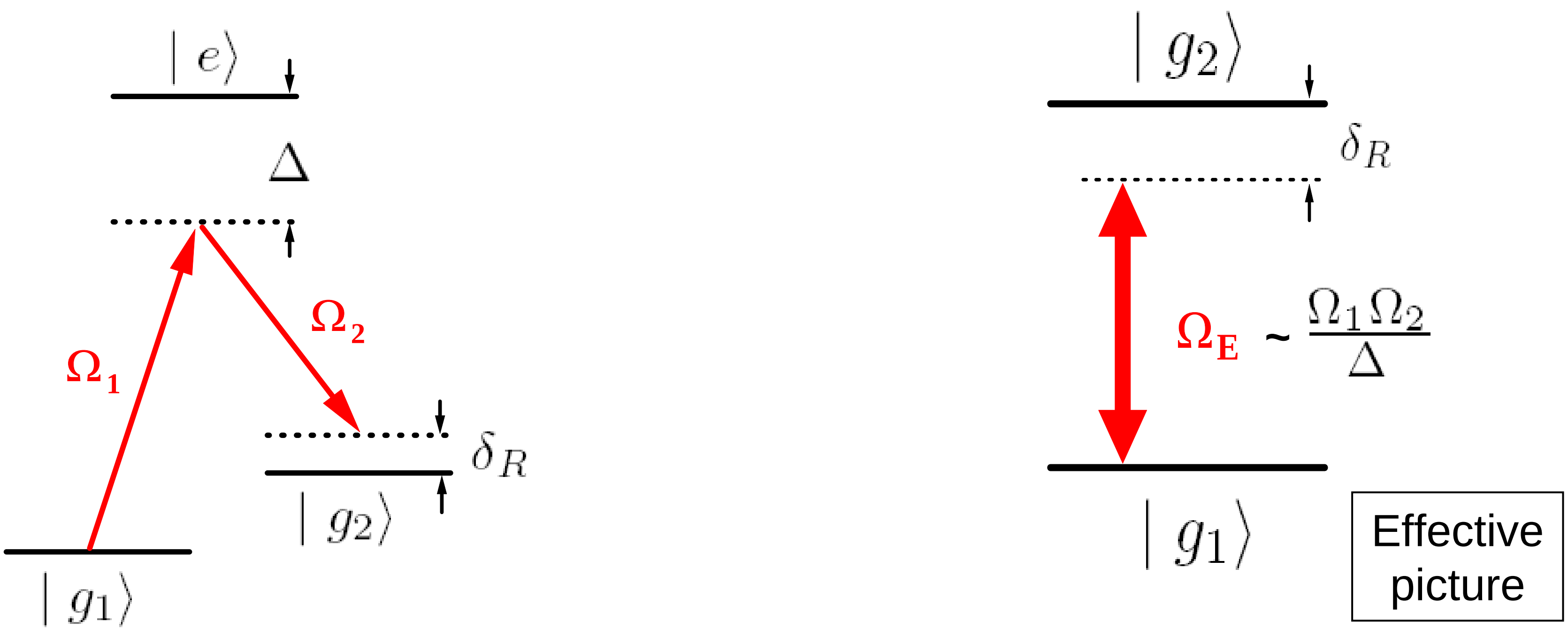
2. Atomic motion (temperature)

Ideally would like to cool to the ground state of the axial motion

Work in progress: Raman transitions

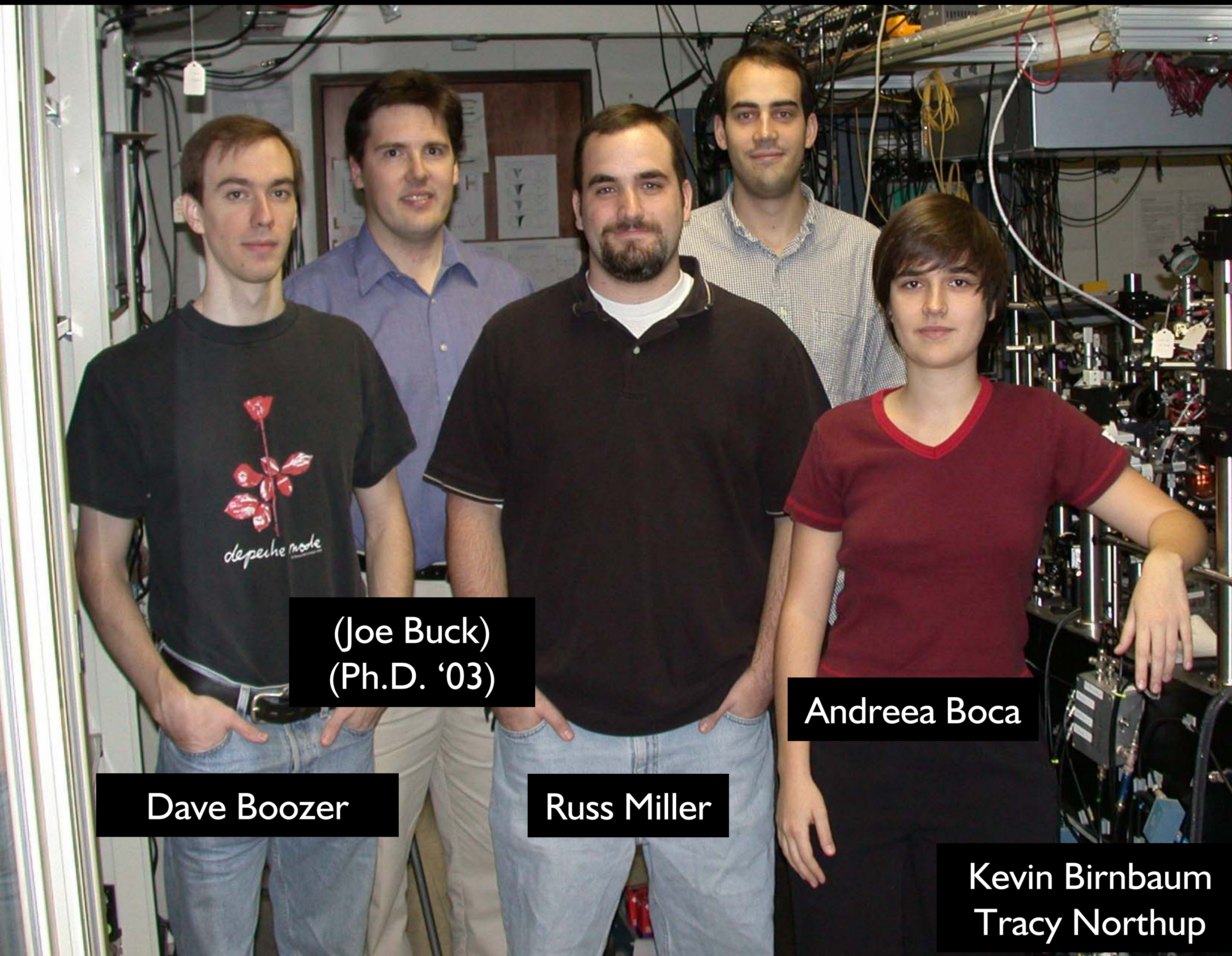
A. D. Boozer, A. Boca, R. Miller, H. J. Kimble

A tool for manipulating the internal state of an intracavity atom, and for implementing sideband cooling



- **g1, g2 can be hyperfine levels (Zeeman sublevels) of Cs ground state**
- **coherently drive transitions between hyperfine ground states, like a two-level atom with no spontaneous emission**

- **Ω_1 = Raman laser (on-axis)**
- **Ω_2 = FORT! 2-in-1 laser**



CALIFORNIA INSTITUTE OF TECHNOLOGY

Quantum Optics

(Jun Ye)
(David Vernooy)
(Alex Kuzmich)
(Dan Stamper-Kurn)
(Hanns-Christoph Nägerl)

H. Jeff Kimble