Nonlinear Optics of Ultracold Atoms in an Optical Cavity

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UC Berkeley

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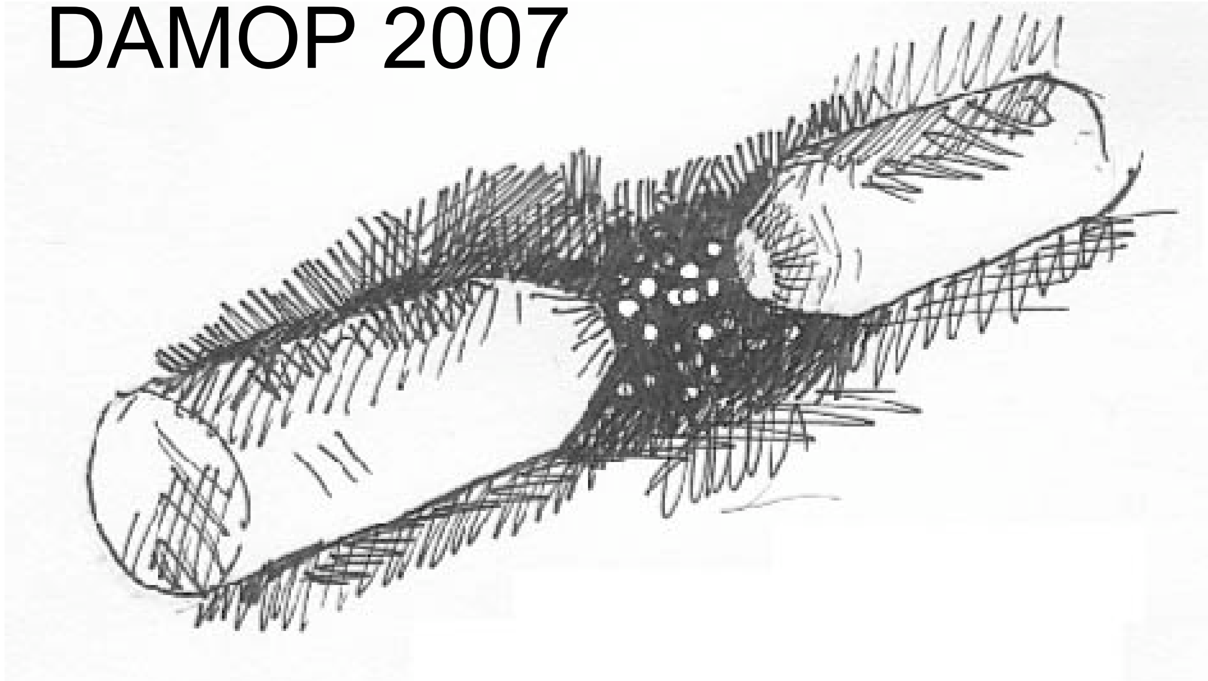
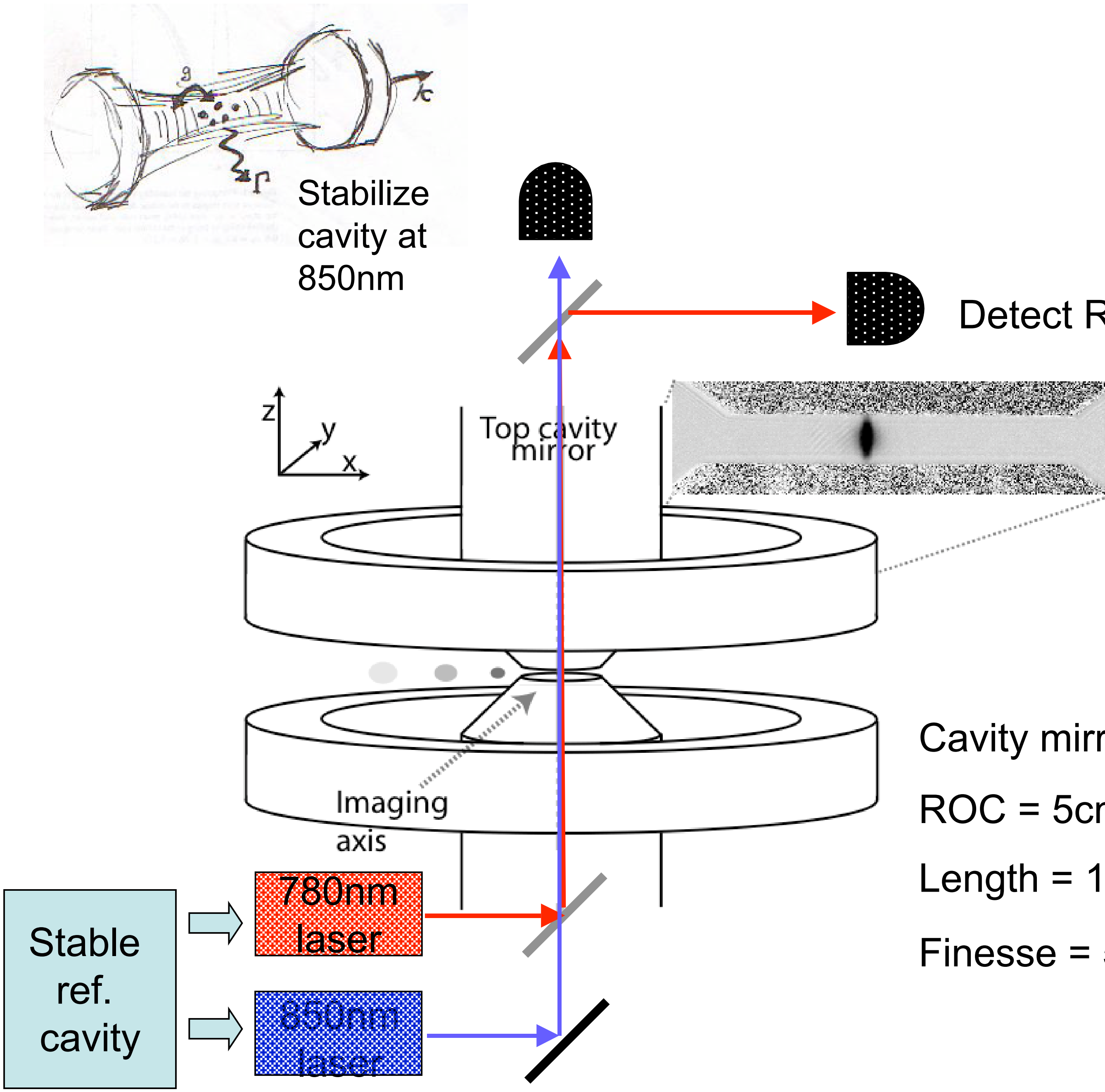




Detect Rb at 780nm

Quantify transmission as the average intracavity photon number: $\bar{n}$

Detection efficiency:

$\eta = 0.05$

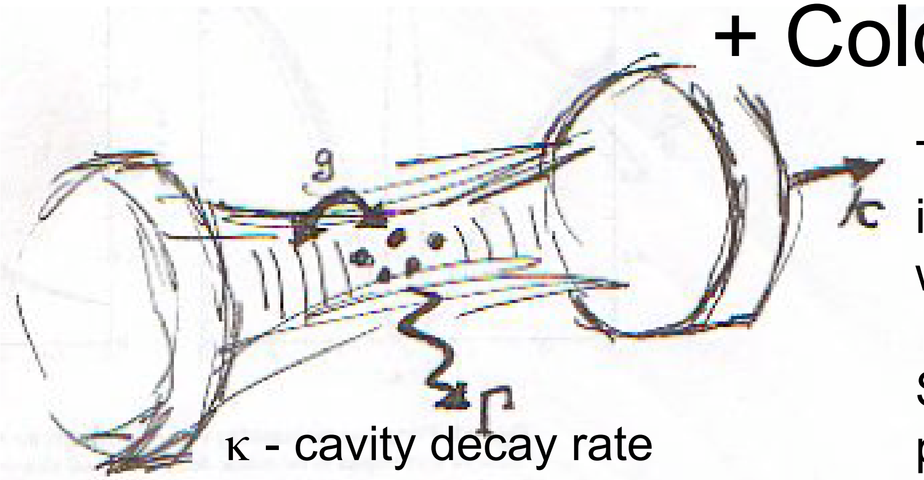
Cavity mirrors: Vital statistics

ROC = 5cm

Length = 194 μm

Finesse = 584,000

Cavity QED: Strong Coupling + Cold Atoms



κ - cavity decay rate

Γ - atomic decay rate

g - atom cavity coupling

Critical photon number
$n_o = \gamma^2/2g_o^2 = .02$

Critical atom number
$N_o = 2\gamma\kappa/g_o^2 = .02$

Single atom cooperativity
$C = g_o^2/ 2\gamma\kappa = 50$

Typically Nonlinear optics occurs at high intensities as conventional materials mediate weak coupling between light and matter

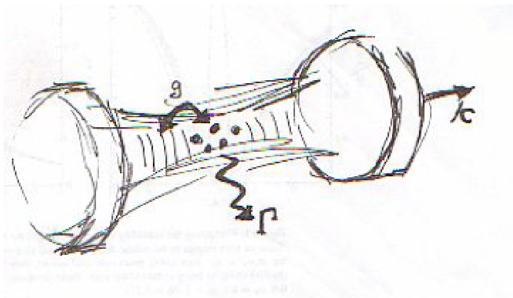
Strong Coupling allows access to nonlinear phenomenon at very low average photon number:

Optical bistability, cross phase modulation, photon blockade

Cold atoms introduce long lived motional coherence, hence, nonlinearities resulting form collective atomic motion may occur at very low average photon number:

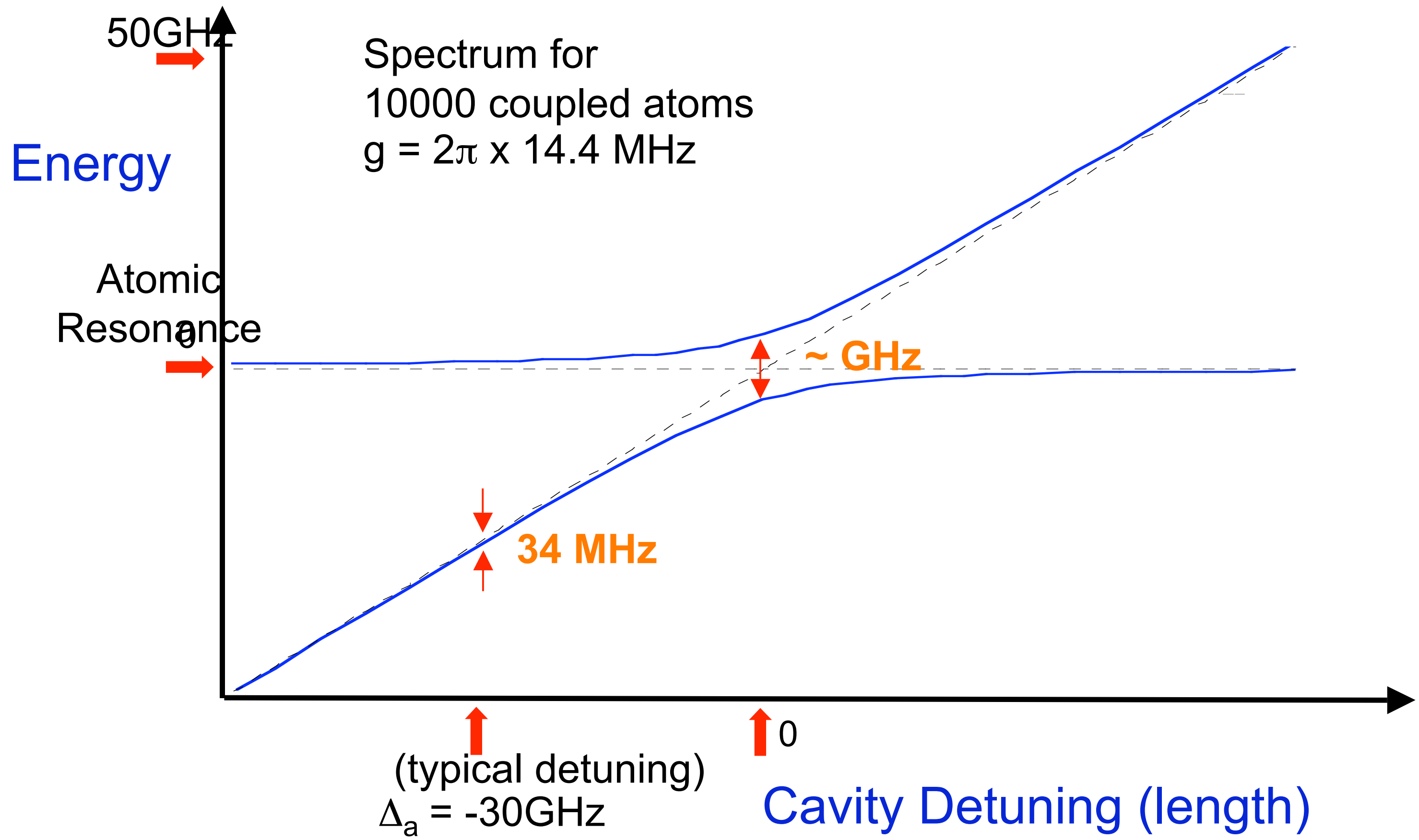
$\bar{n} \sim \Gamma_m/\kappa$

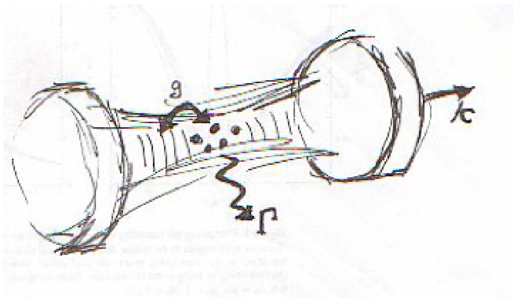
(Rempe ‘91, Gripp ‘96, Stauer ‘04, Turchette ‘95, Birnbaum ‘05)



Dispersive Cavity QED (far from atomic resonances)

Presence of atoms basically changes the index of refraction in the cavity
Each atom shifts the cavity resonance by an amount: g^2/Δ_a





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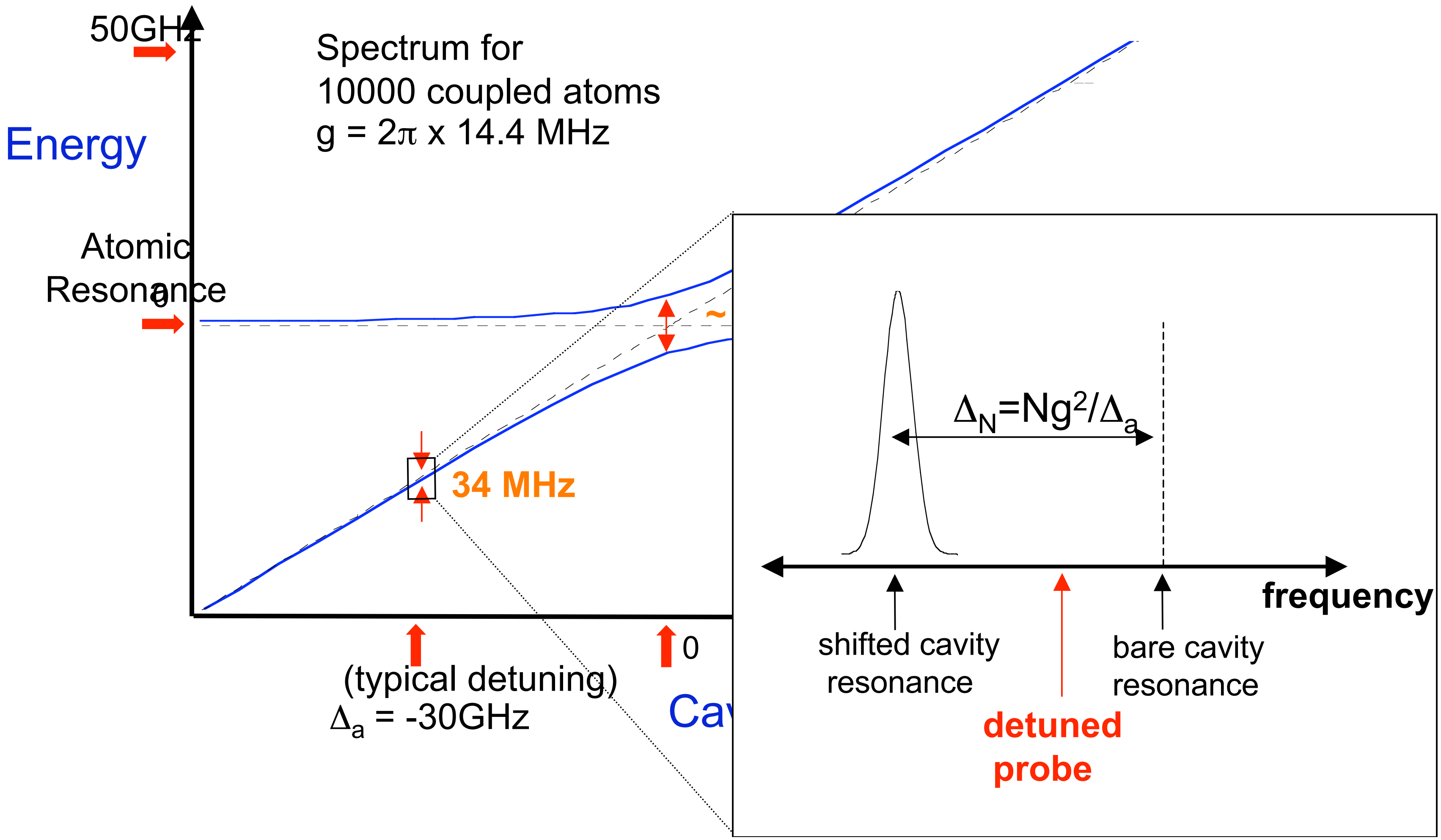
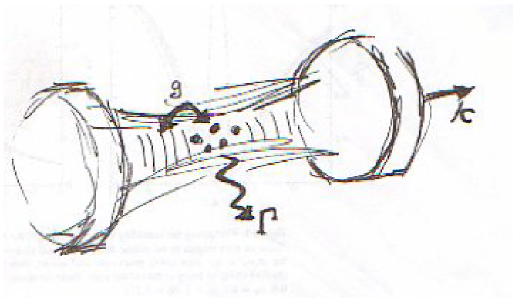
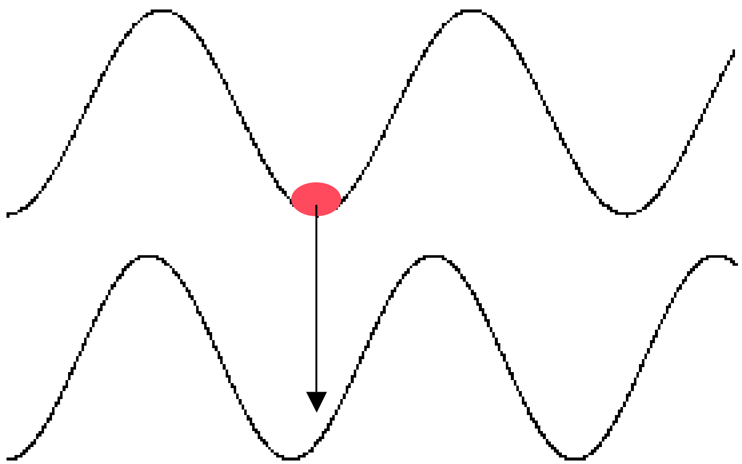




Atoms occupy a 1D lattice in the cavity

Trapping Potential



Probe

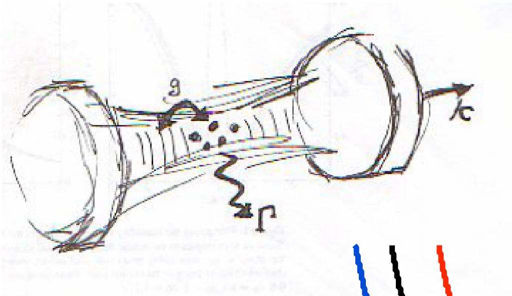
$U(z) = U_{850}(z) + U_{780}(z,t)$

Cavity is stabilized to this wavelength

Varies depending on detuning from cavity resonance

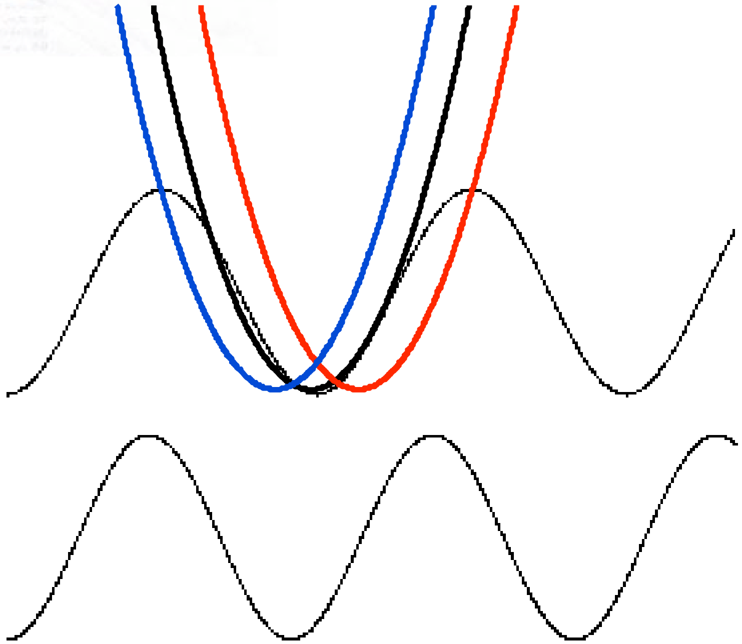
Interaction depends on intensity of the probe: this differs from well to well.

$$\Delta_N = \sum_{sites} \frac{N_i g_i^2}{\Delta_a} \simeq \frac{N g_0^2}{2\Delta_A}$$



Trapping Potential

Probe



$U(z) = U_{850}(z) + U_{780}(z,t)$

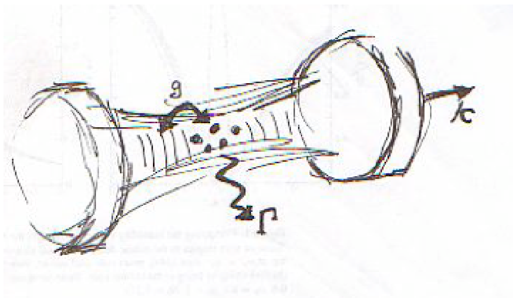
Cavity is stabilized to this wavelength

Varies depending on detuning from cavity resonance

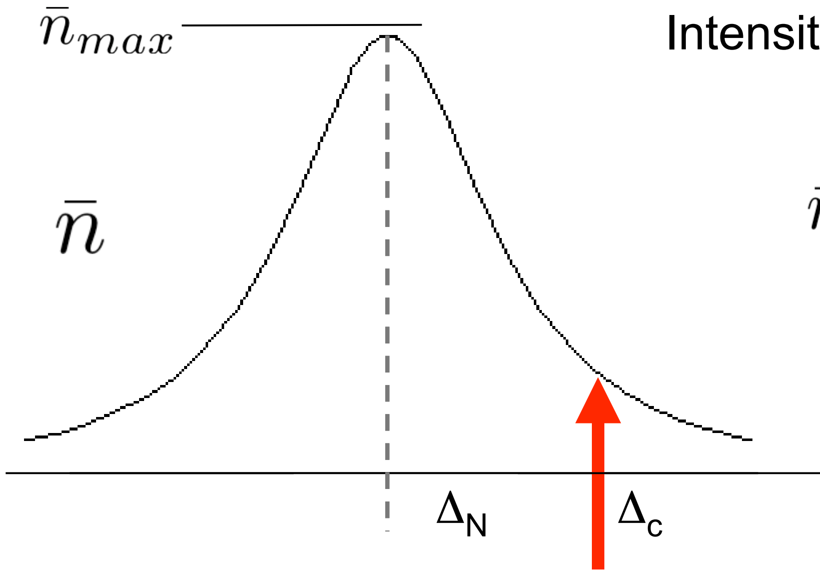
Presence of the probe shifts potential minimum.

This causes the overall interaction to either increase or decrease

$$\Delta_N = N\frac{g_0^2}{2\Delta_a}\left(1 + 0.6\frac{U_{780}}{U_{850}}\right)$$

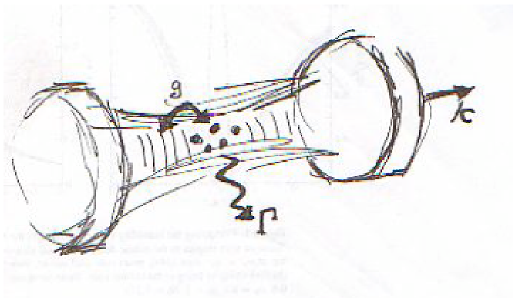


Modified cavity lineshape



Intensity in cavity is normally a lorentzian

$$\bar{n} = \frac{\bar{n}_{max}}{1 + (\frac{\Delta_c - \Delta_N}{\kappa})^2}$$



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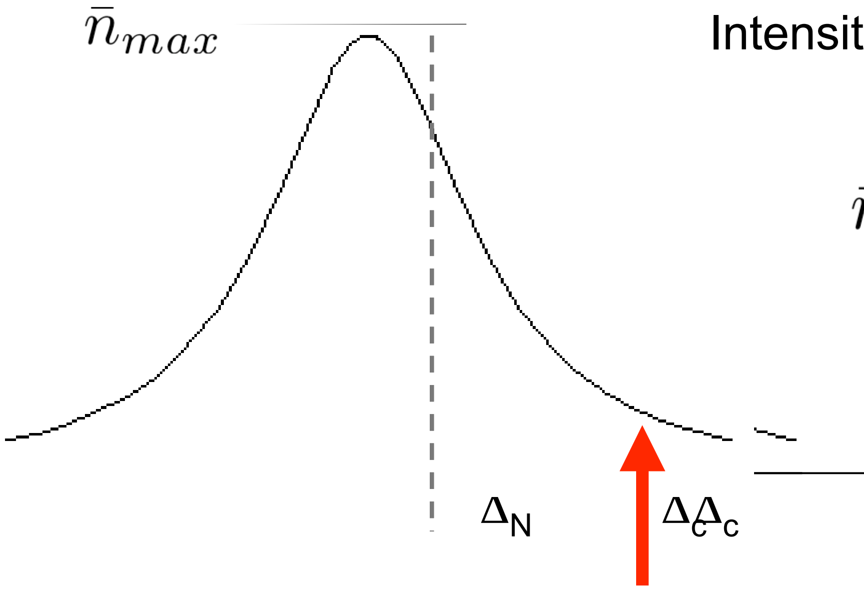


Intensity in cavity is normally a lorentzian

$$\bar{n} = \frac{\bar{n}_{max}}{1 + (\frac{\Delta_c - \Delta_N}{\kappa})^2}$$

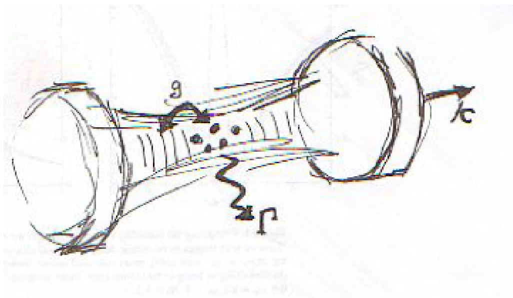
But now, Δ_N depends on the intensity,

$$\bar{n} = \frac{\bar{n}_{max}}{1 + (\frac{\Delta_c - \Delta_N(1+\epsilon \bar{n})}{\kappa})^2}$$

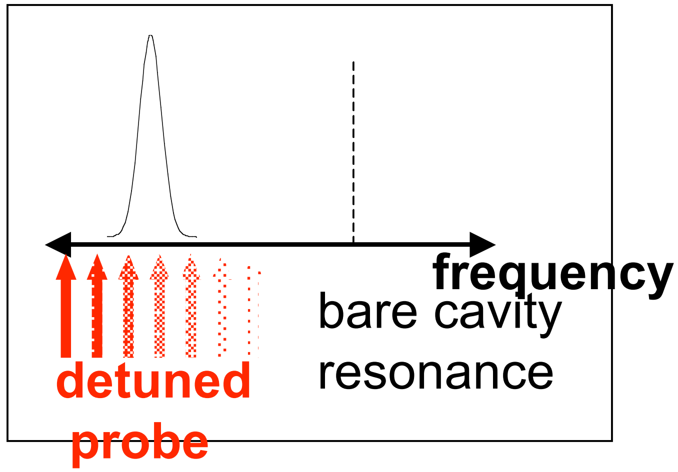
Index of refraction

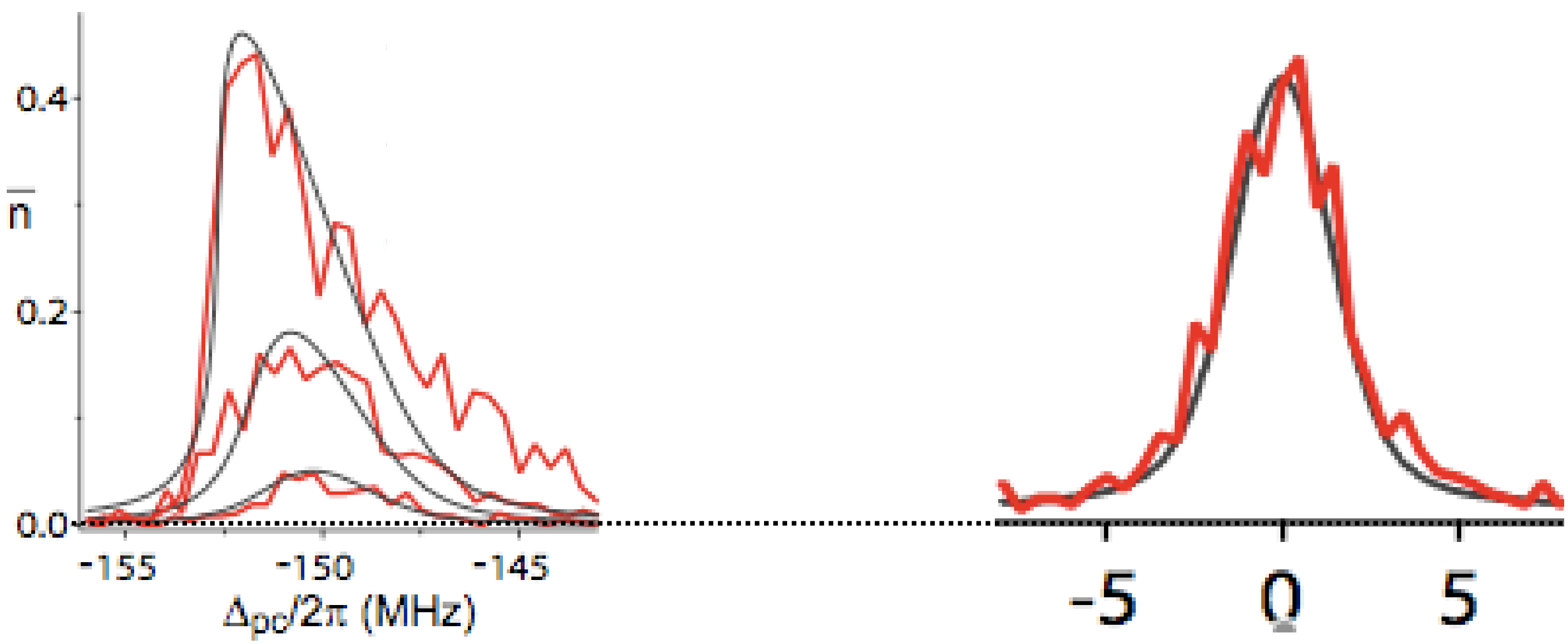
$$1 + \frac{N\langle g^2 \rangle}{\Delta_a \omega_p} = \left(1 + \frac{N g_0^2}{2\Delta_a \omega_p}\right) + \frac{N g_0^2}{2\Delta_a \omega_p}\, 0.6\, U_p/U_t$$

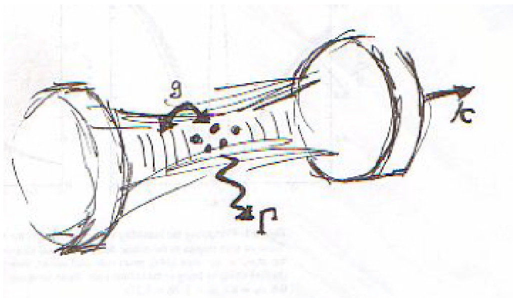
Kerr Effect



Asymmetric Line Shapes from Kerr Non-Linearity







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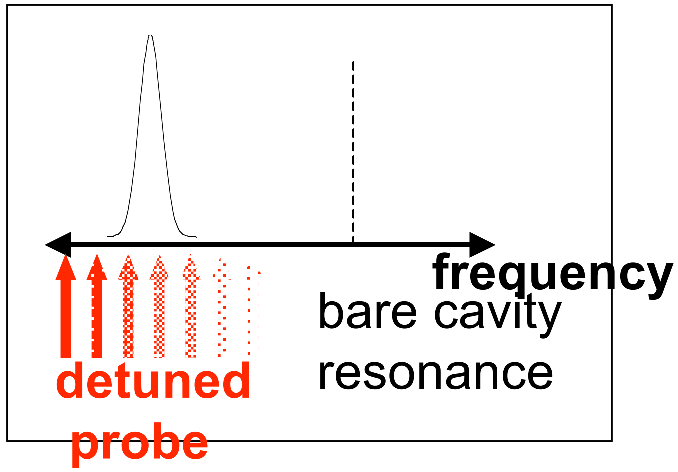
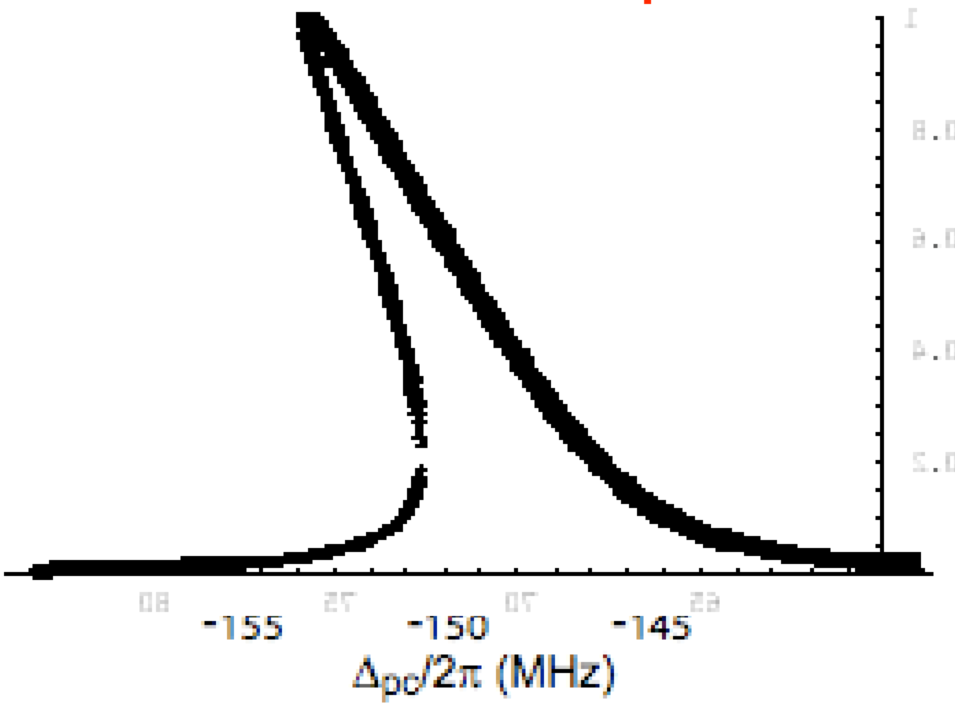
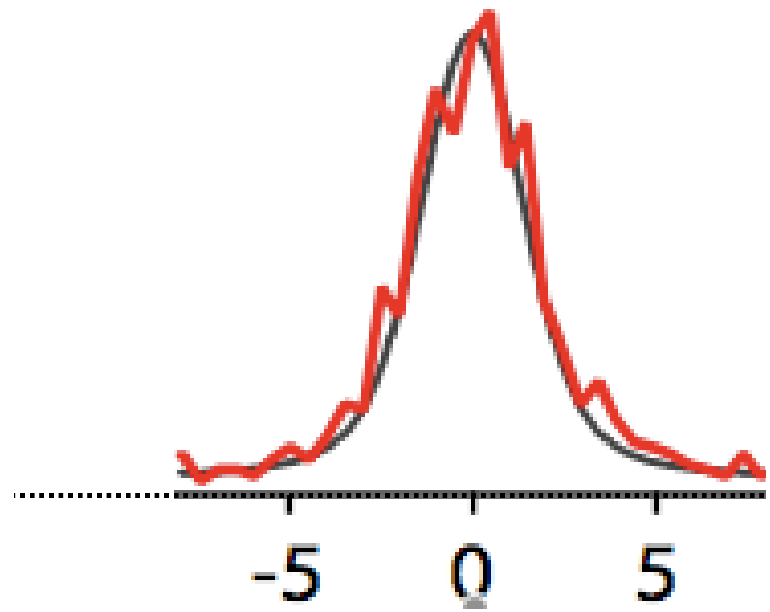
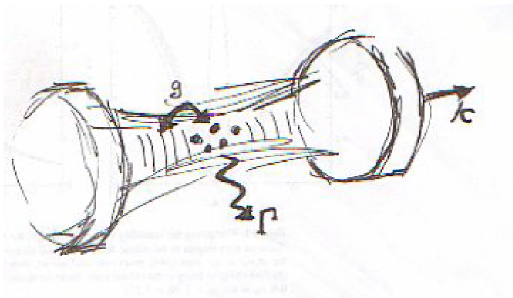
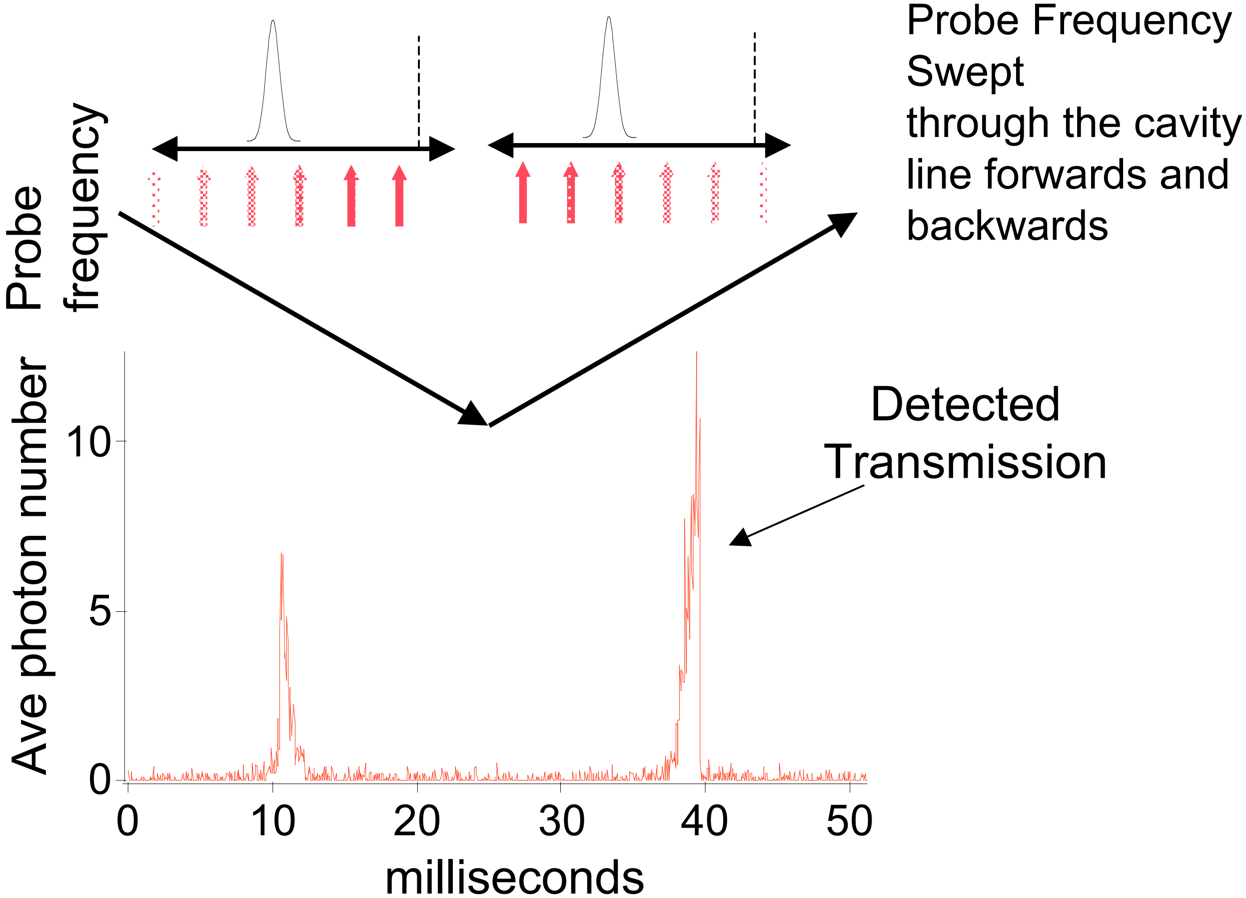


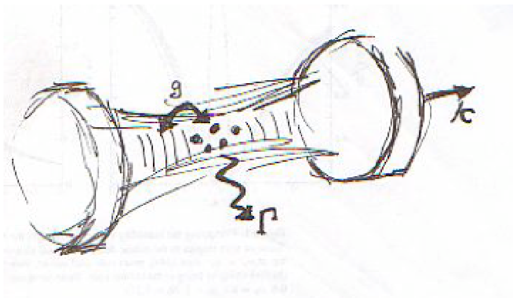






Dispersive/Refractive bistability





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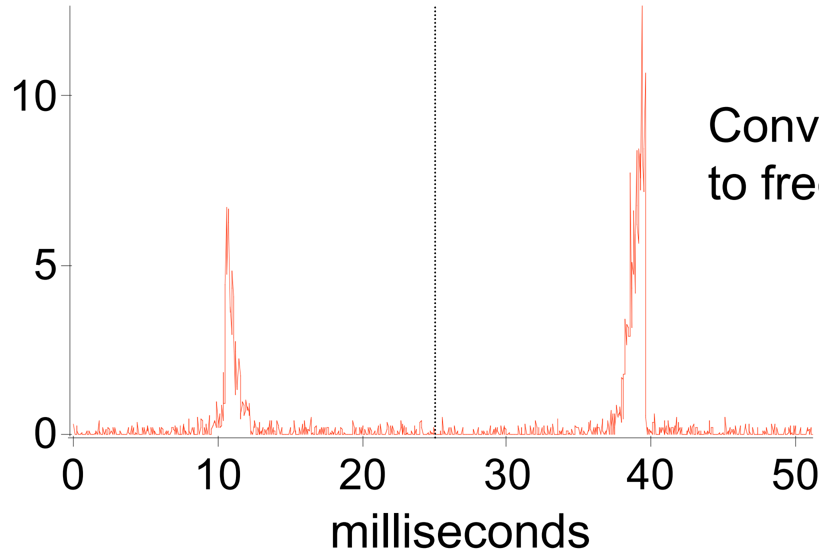
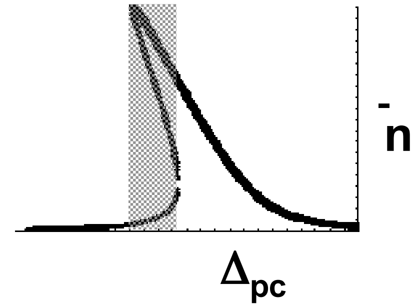
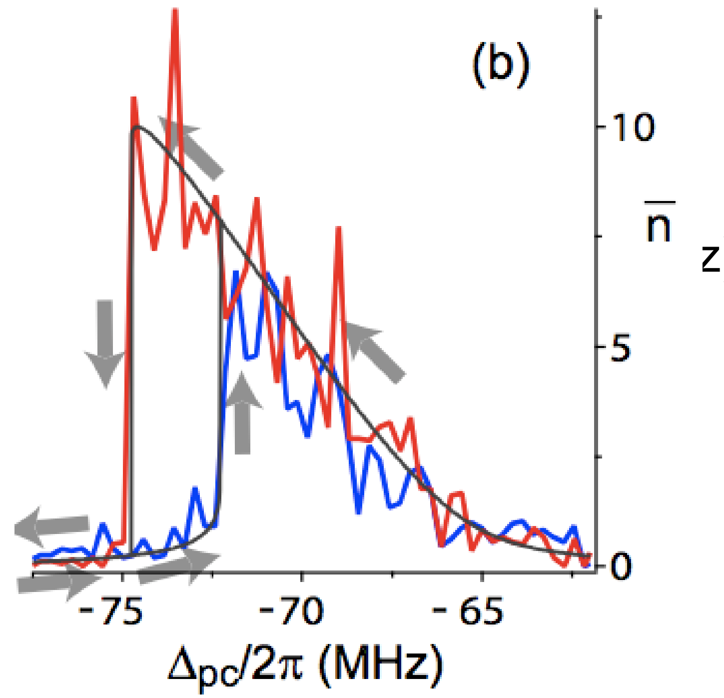
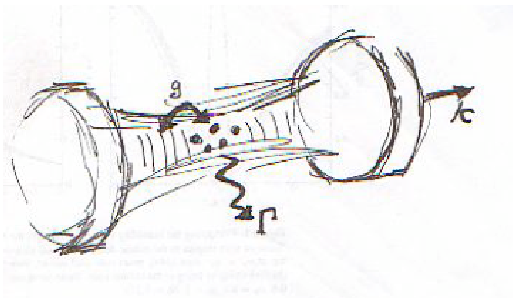


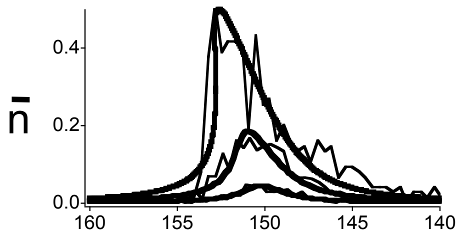
Convert
to frequency units





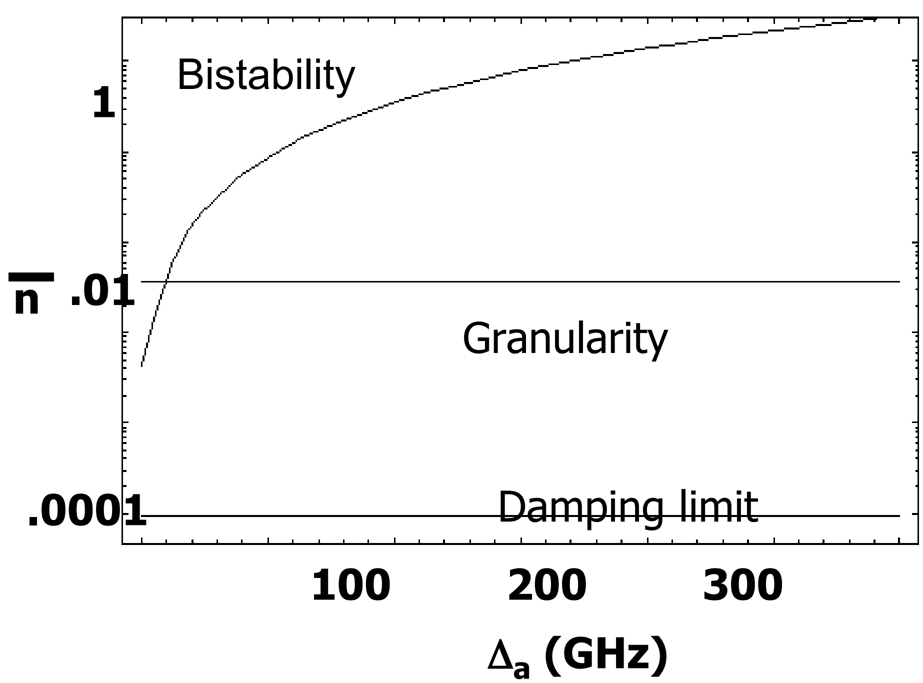
Non-linearity at very low photon numbers





As we reduce the atomic detuning, fewer photons will suffice for bistability; nonlinearities at very low photon number are obtainable.

Nonlinearity "phase diagram"



When photons arrive less frequently than the period of harmonic motion, granularity of individual photons becomes important.

Ultimately, the damping of atomic motion forces a technical limit on the nonlinearity.

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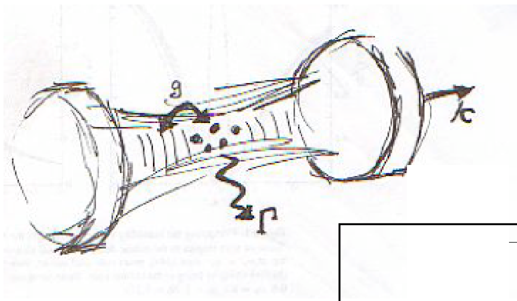
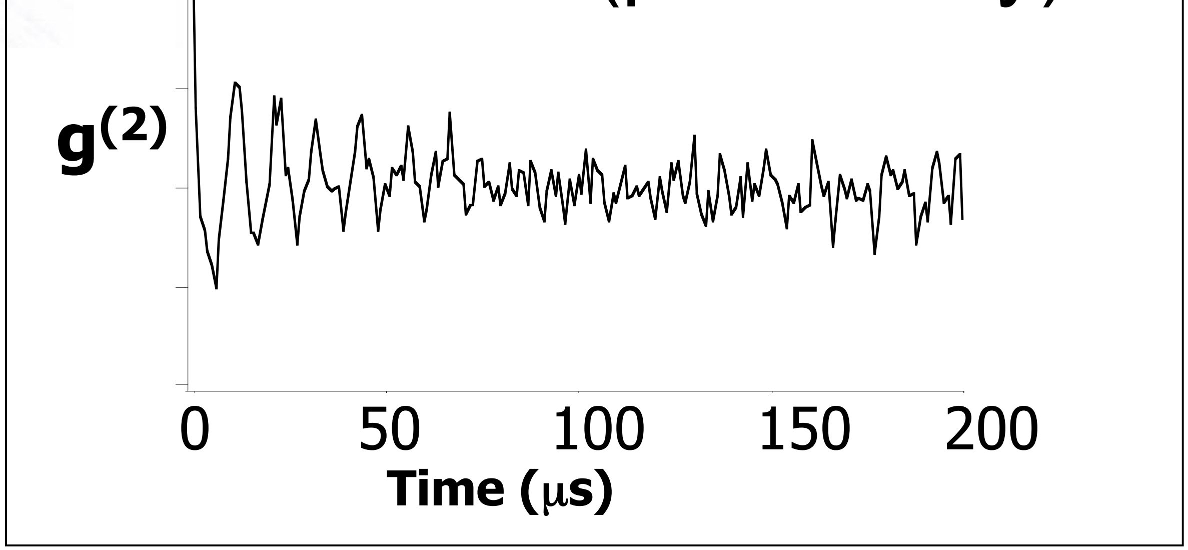
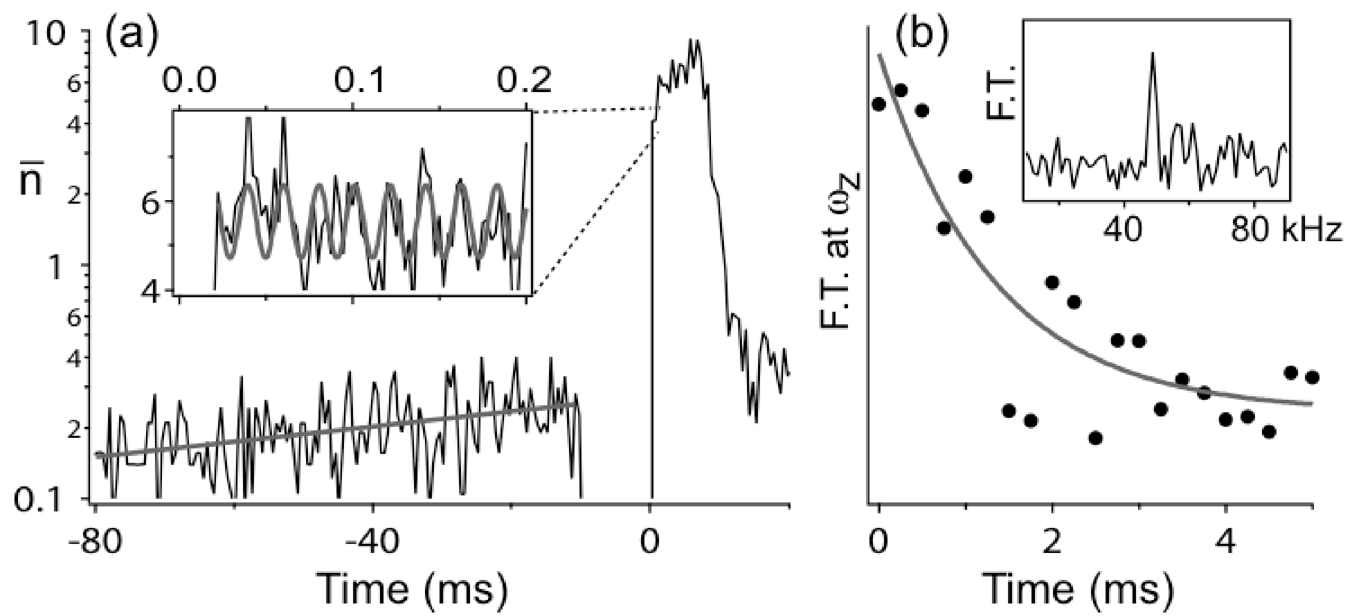
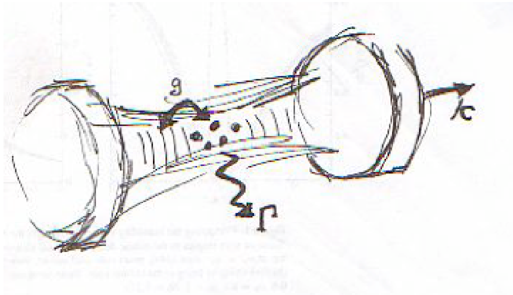


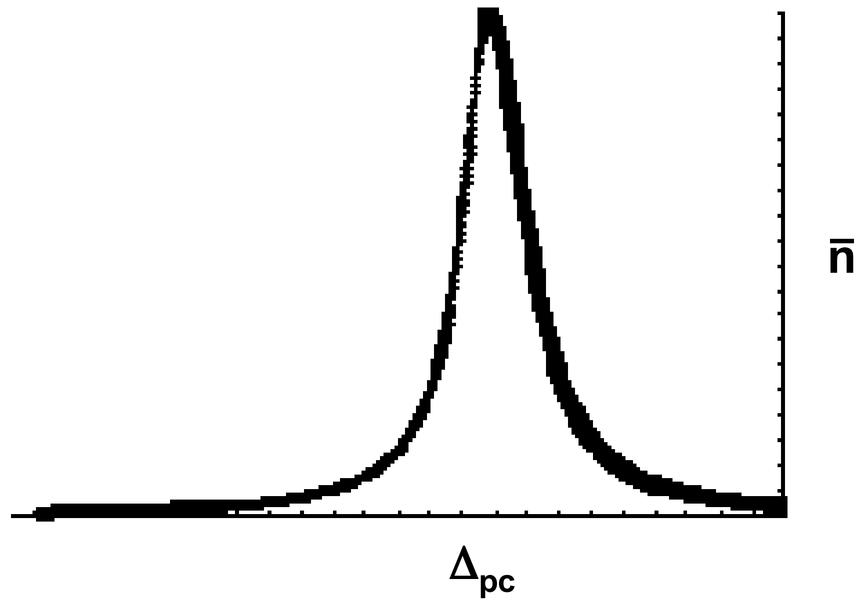
Photon correlations (preliminary)



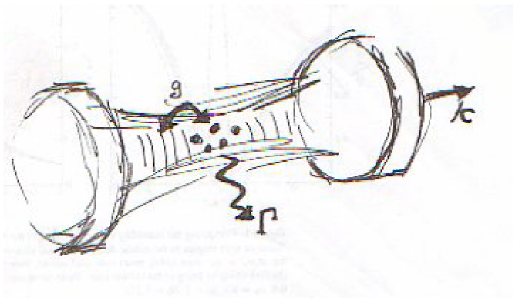




Varying the Kerr parameter



Kerr Parameter = 0.25



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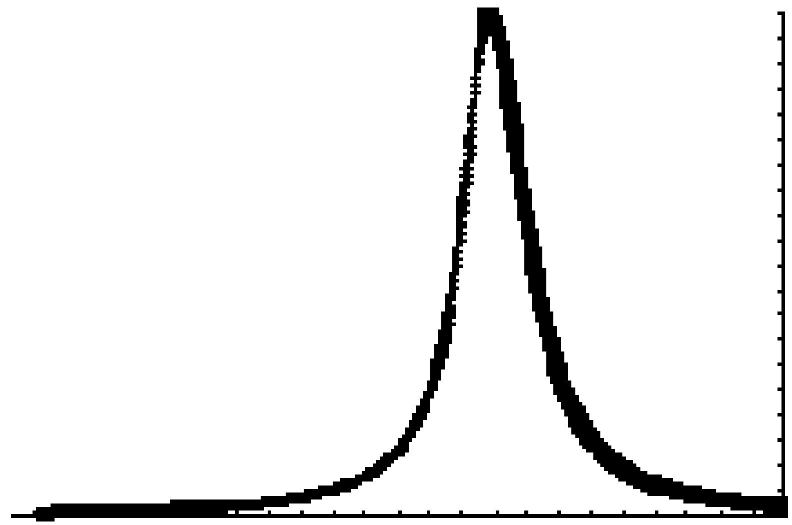
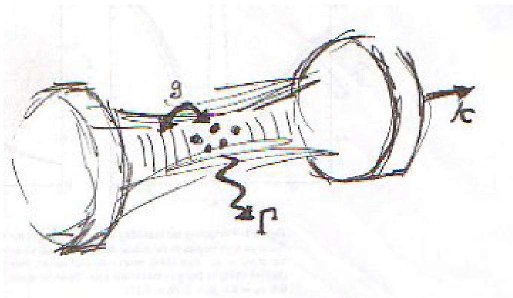


Kerr Parameter varied from 0.25 to 9.75

Strength of Nonlinearity controlled by Δ_a or atom number



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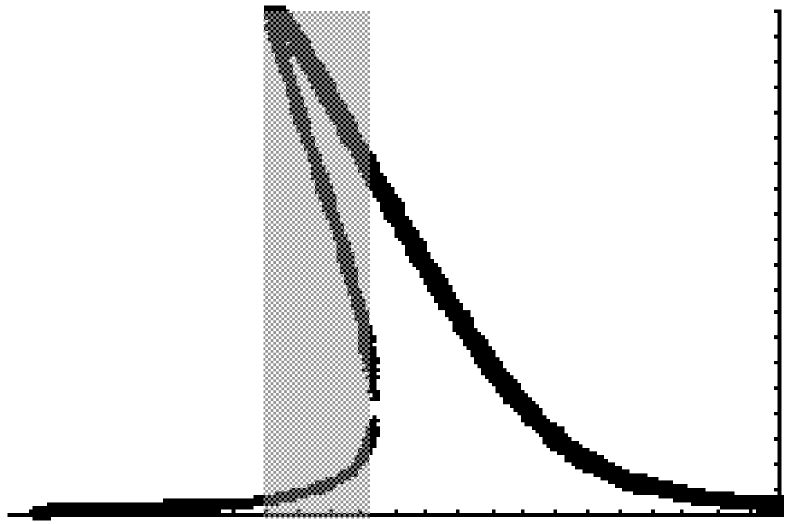
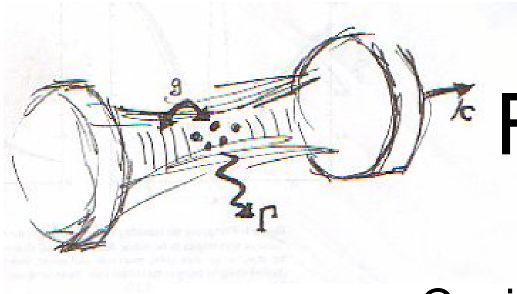


Three solutions to the cubic

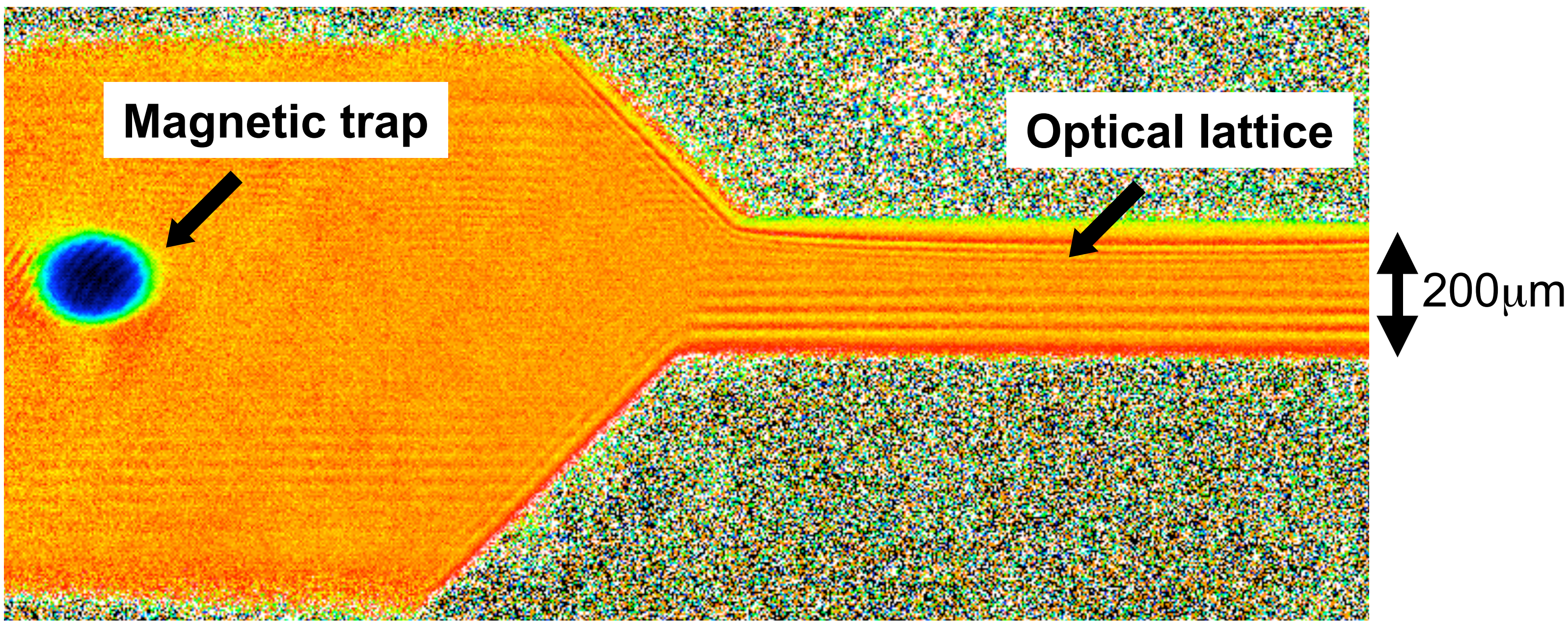
$$\bar{n} = \frac{\bar{n}_{max}}{1+\left(\frac{\Delta_c-\Delta_N(1+\epsilon(\bar{n}/\bar{n}_{max}))}{\kappa}\right)^2}$$

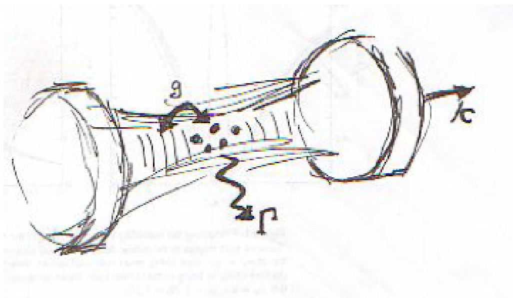
Kerr Parameter = 9.75
“Hysteresis”



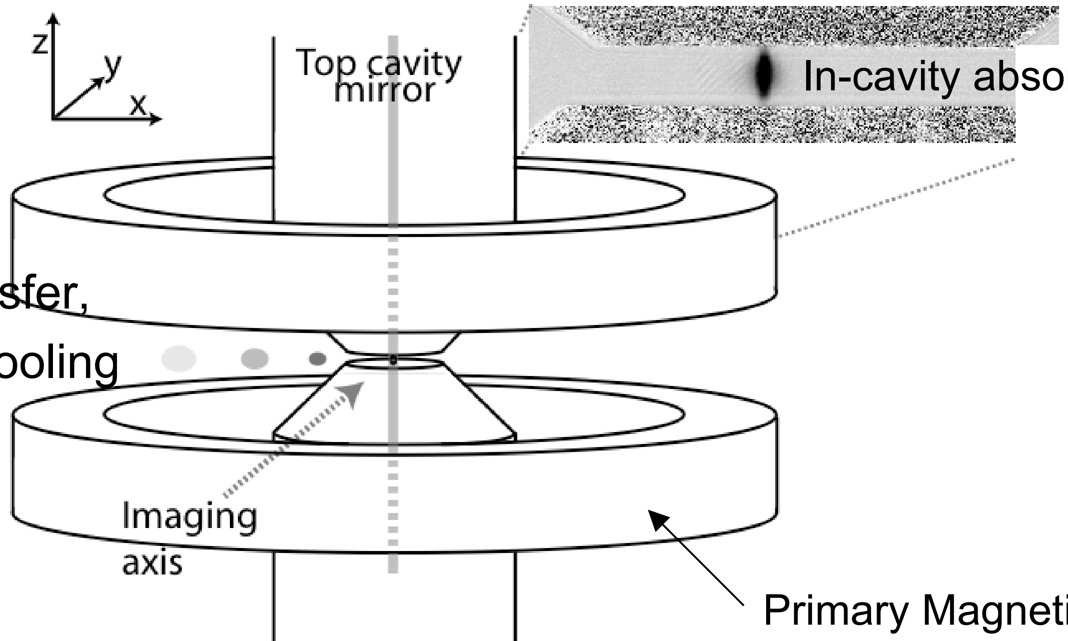
Far Off-Resonant optical Trap

Cavity stabilization laser at 851nm
forms an optical dipole trap





Cold atoms integrated with high finesse cavity



^{87}Rb MOT,
magnetic transfer,
evaporative cooling

Primary Magnetic trap coils form a TOP trap