# Cold Atomic Ensembles in the Strong Coupling Regime of Cavity QED

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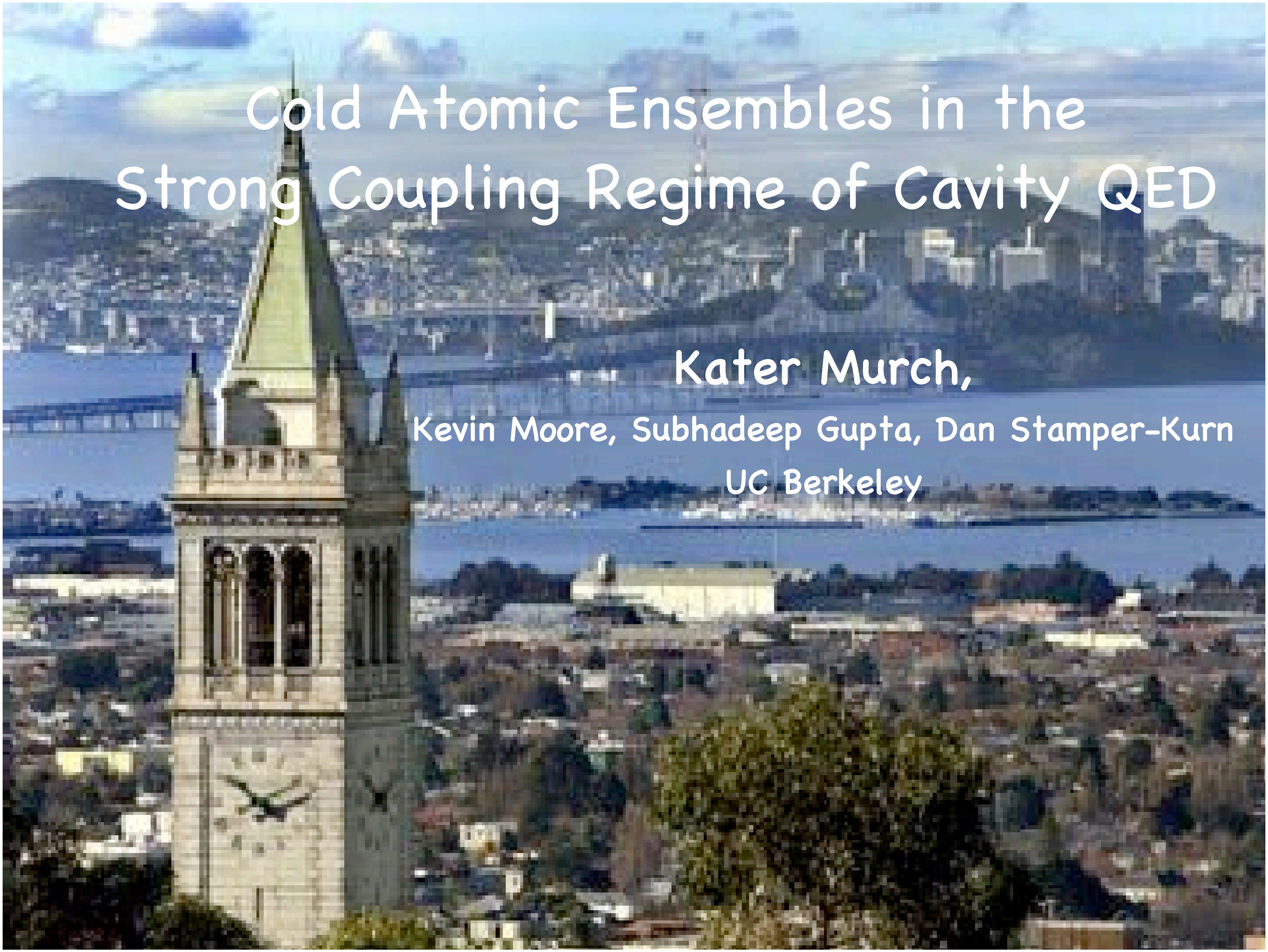
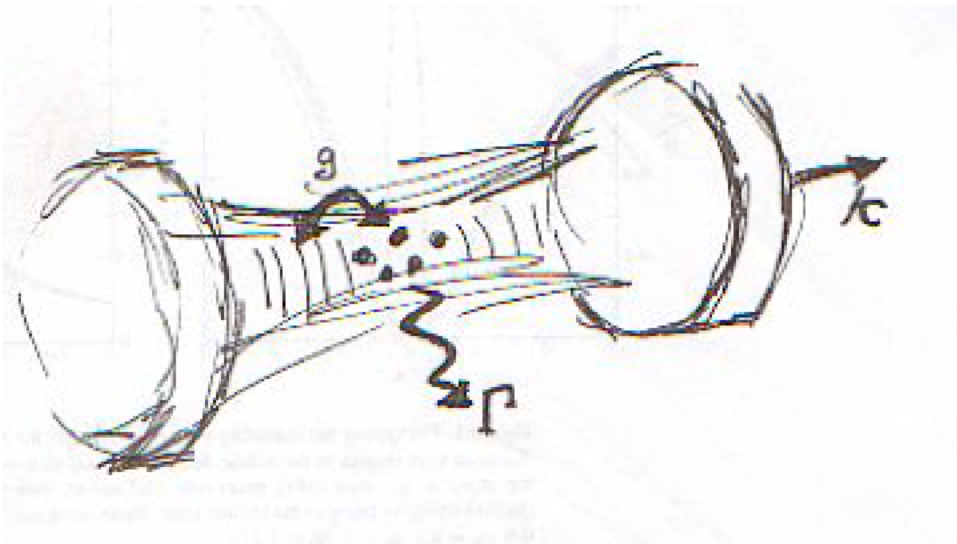
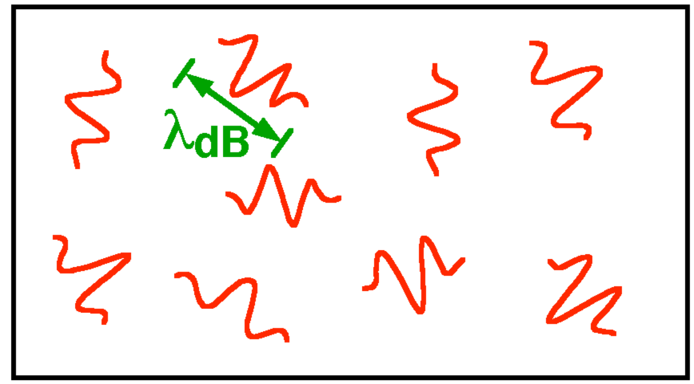
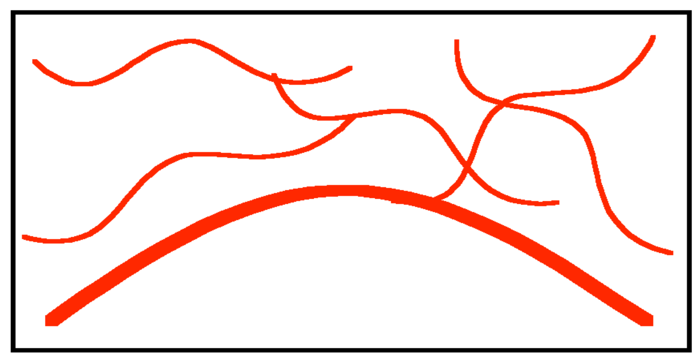


# Cavity QED meets Ultracold



# Cavity QED+ Cold atoms

What new physics and capabilities do we see having introduced long lived motional coherence?

- Storage of quantum information
- Much longer (and slower) timescales
- Tunable Nonlinear material

# Cold Atoms:
# New sources of long lived coherence

What new physics and capabilities do we see having introduced long lived motional coherence?

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- Fragility of states
- Tunable Nonlinear material

## Demonstration and Development of New techniques

- Limitations of Squeezing
- Feedback and Quantum control

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Demonstration and Development of New techniques

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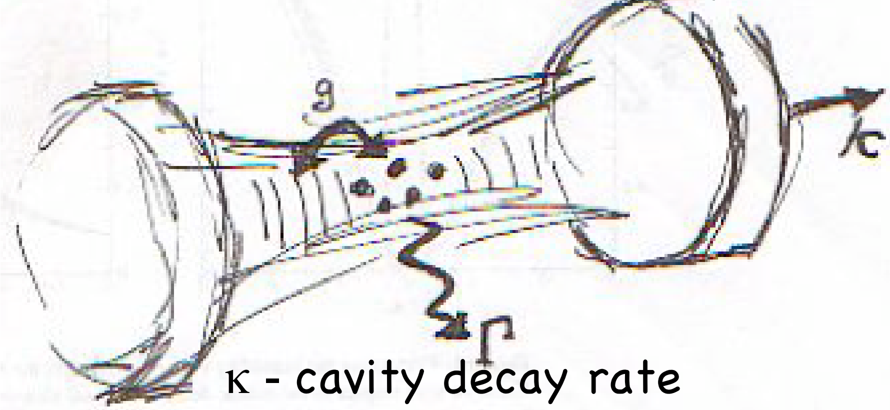
## Fundamental questions and surprises

- BEC in a Cavity?
- Nature of Light Quanta:
  (Fock/Coherent States, Quantum and
  Classical fields)

# Cavity QED: Strong Coupling
# Nonlinear Phenomena



$\kappa$ - cavity decay rate

$\Gamma$ - atomic decay rate

g - atom cavity coupling

Critical photon number

$$n_o = \gamma^2 / 2 g_o^2 = .02$$

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:

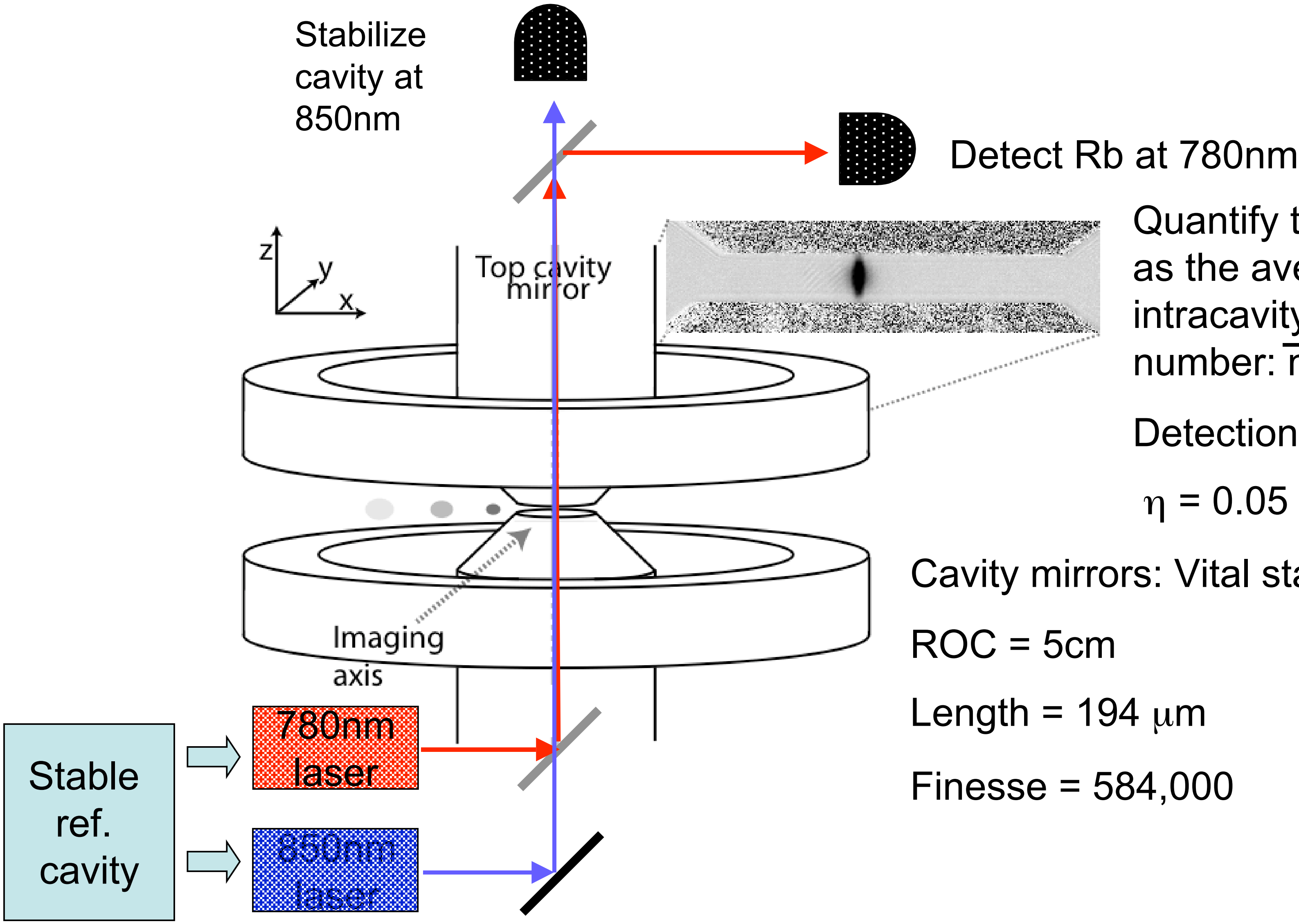
Optical bistability, cross phase modulation, photon blockade

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)

# Heart of the Cold Atom-Cavity Machine




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

Detection efficiency:

$\eta = 0.05$

Cavity mirrors: Vital statistics

ROC = 5cm

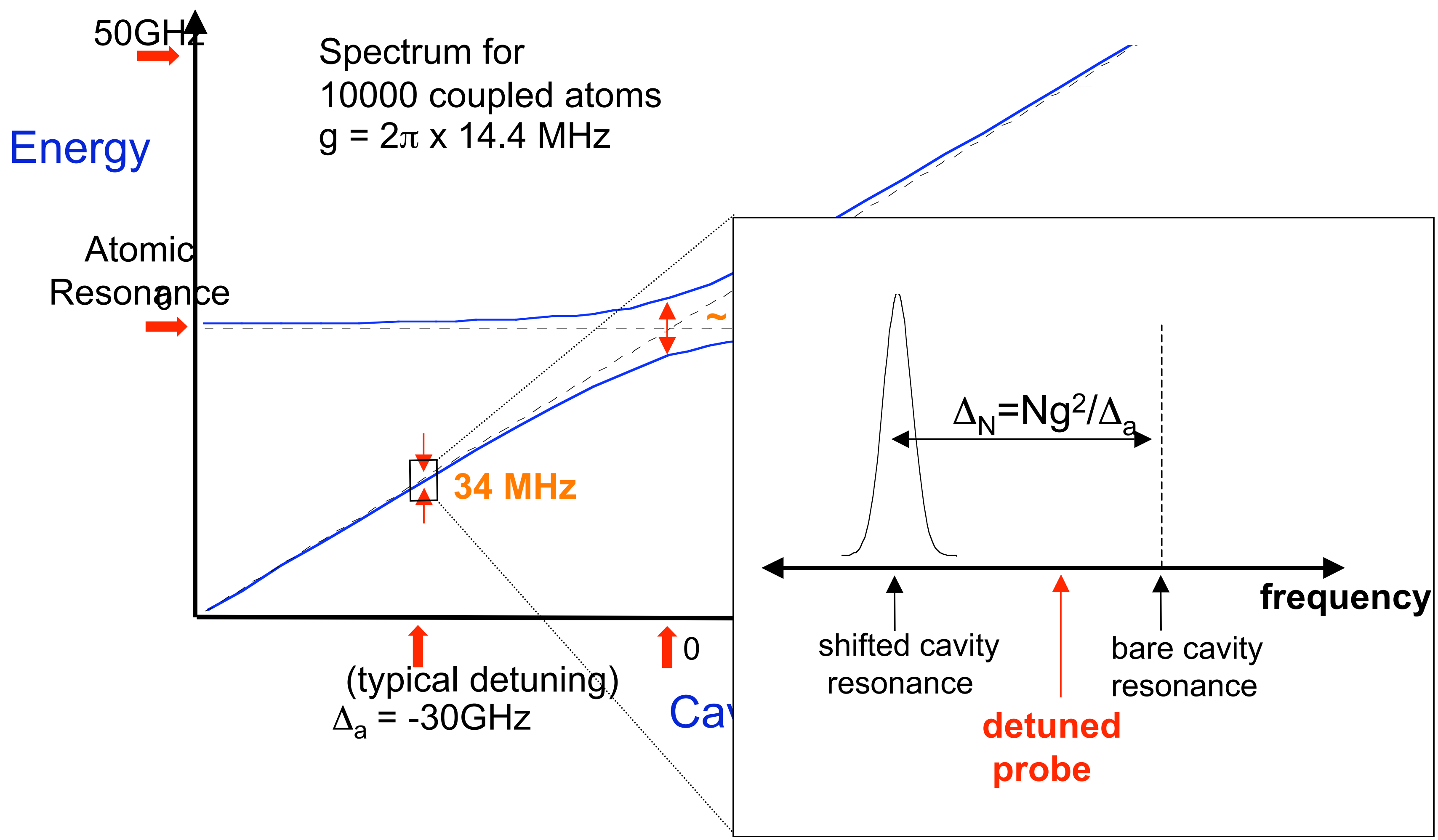
Length = 194 $\mu$m

Finesse = 584,000

# Dispersive Cavity QED
# (far from atomic resonances)

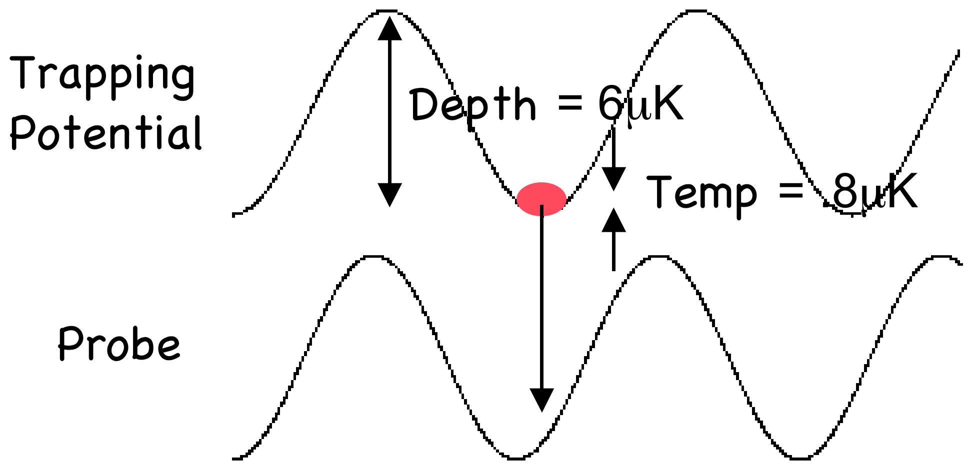
Presence of atoms basically changes the index of refraction in the cavity

Each atom shifts the cavity resonance by an amount: $g^2/\Delta_a$



# Details of the Lattice

Atoms occupy a 1D lattice in the cavity




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

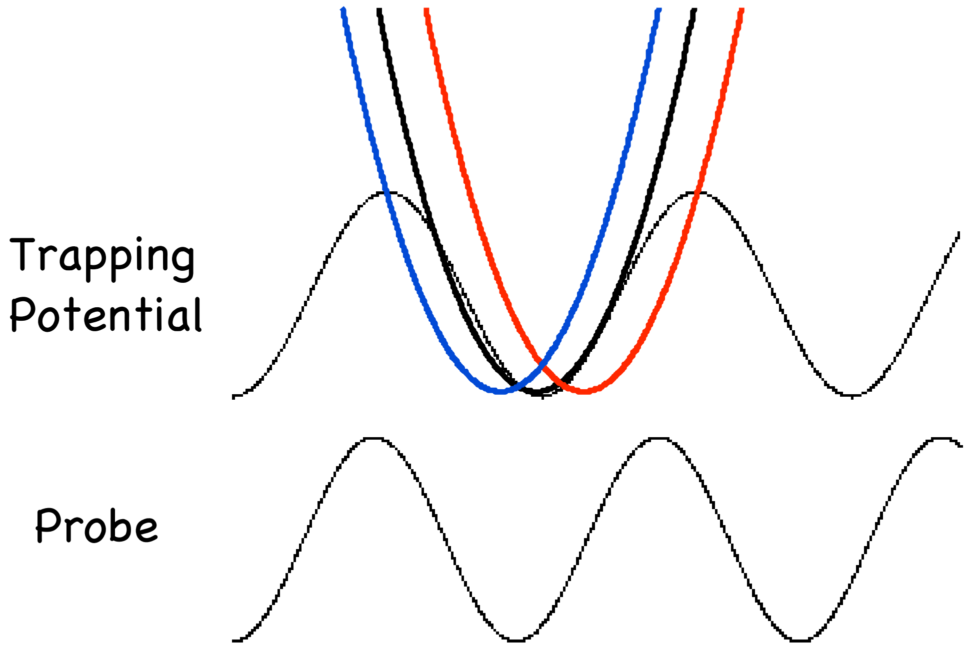
Cavity is stabilized to this wavelength

Varies depending on detuning from cavity resonance

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

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

# Probe induced spatial shift




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

Cavity is stabilized to this wavelength

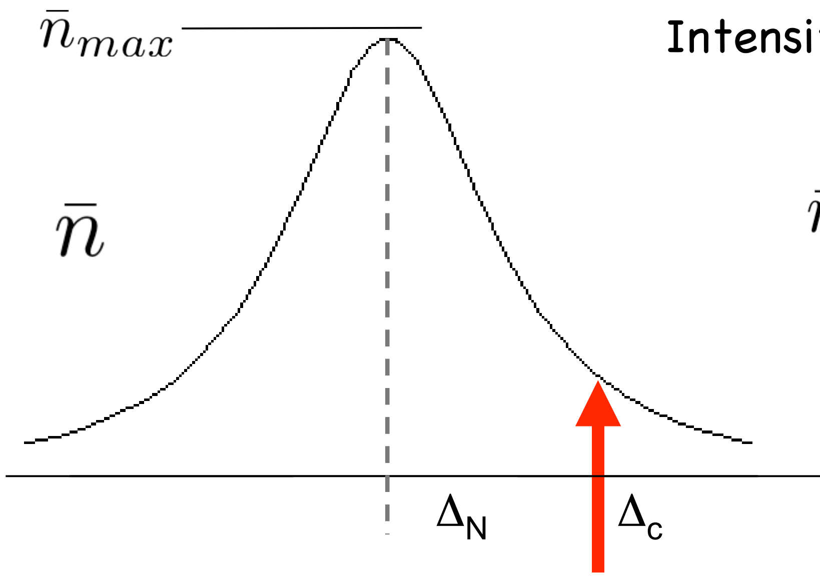
Varies depending on detuning from cavity resonance

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

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

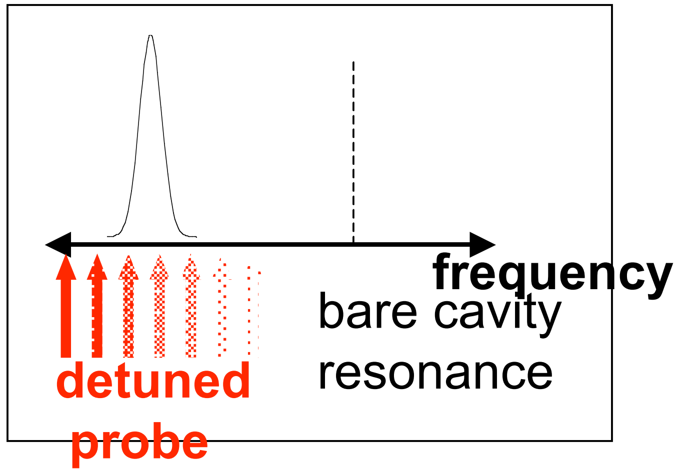
But now, $\Delta_N$ depends on the intensity,

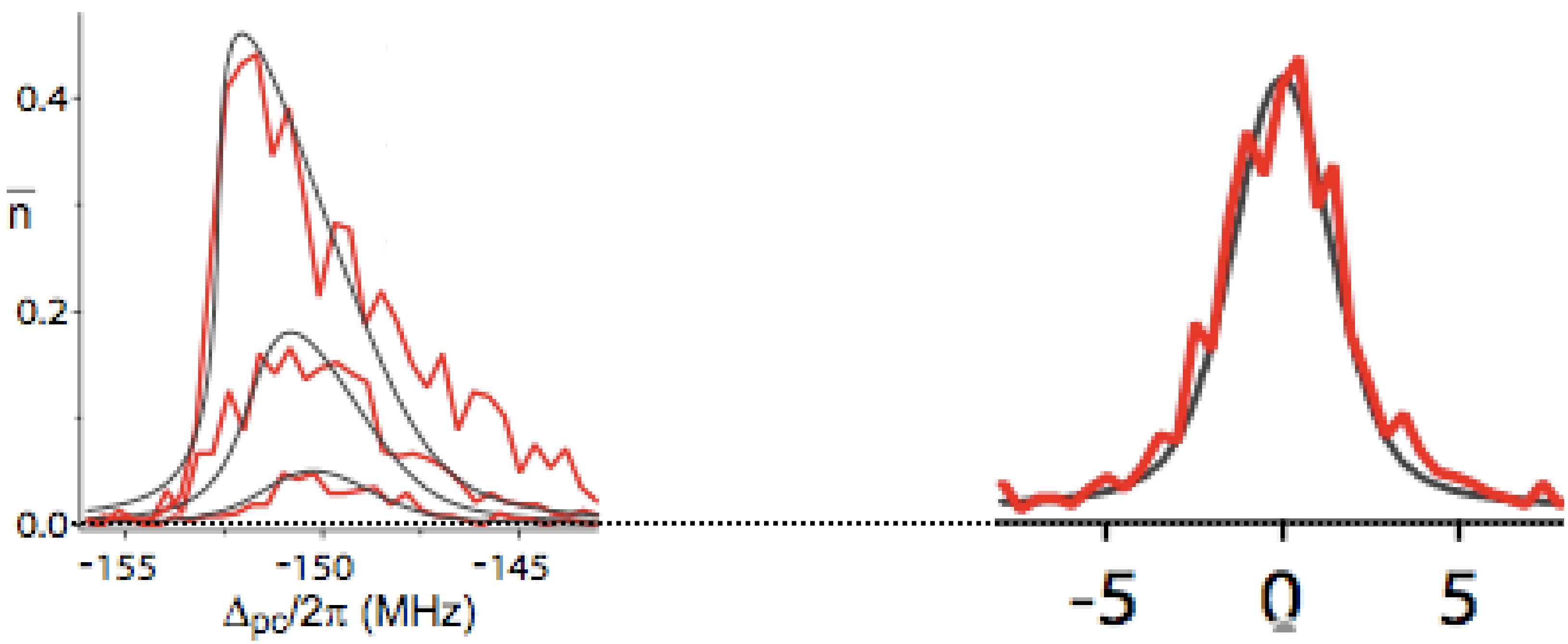
$$\bar{n} = \frac{\bar{n}_{max}}{1 + (\frac{\Delta_c - \Delta_N (1+\epsilon \bar{n})}{\kappa})^2}$$

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

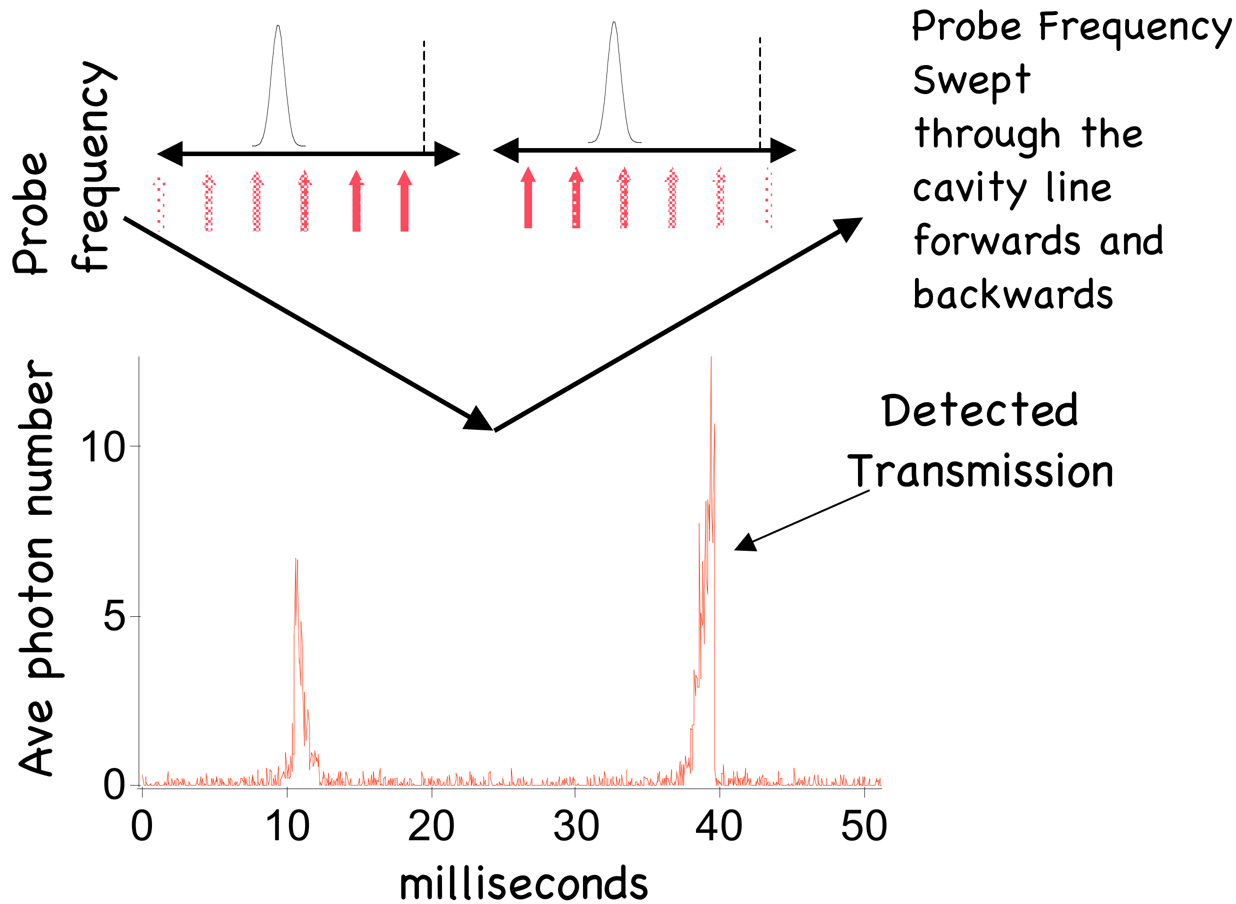
**Kerr Effect:** $n = n_0 + n_2 I$

# Asymmetric Line Shapes from Kerr Non-Linearity



# Dispersive/Refractive bistability



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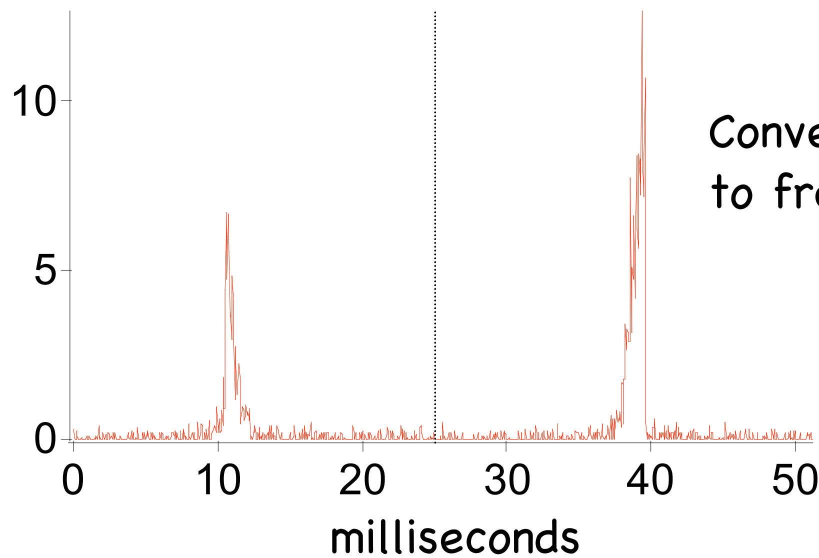
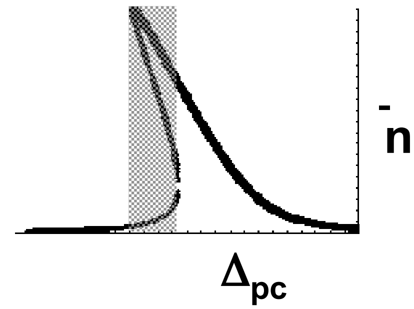
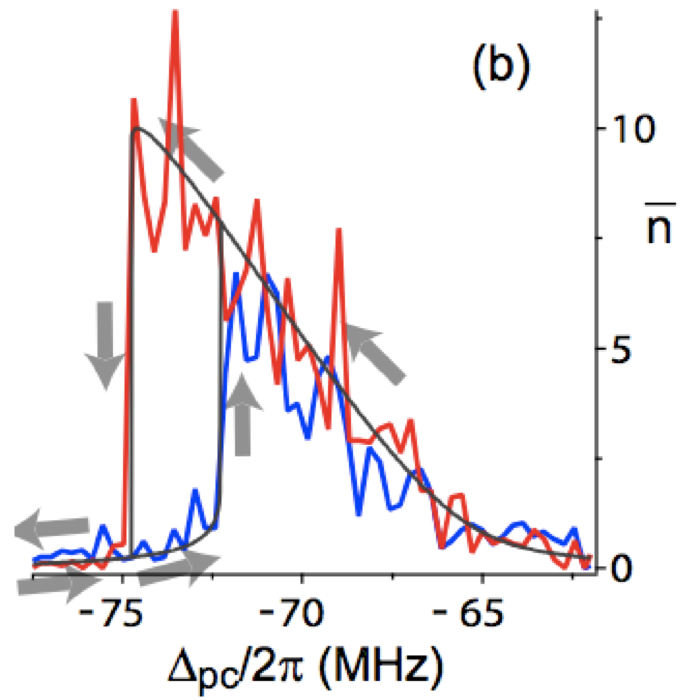


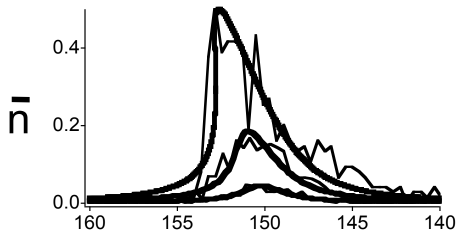

Convert
to frequency units



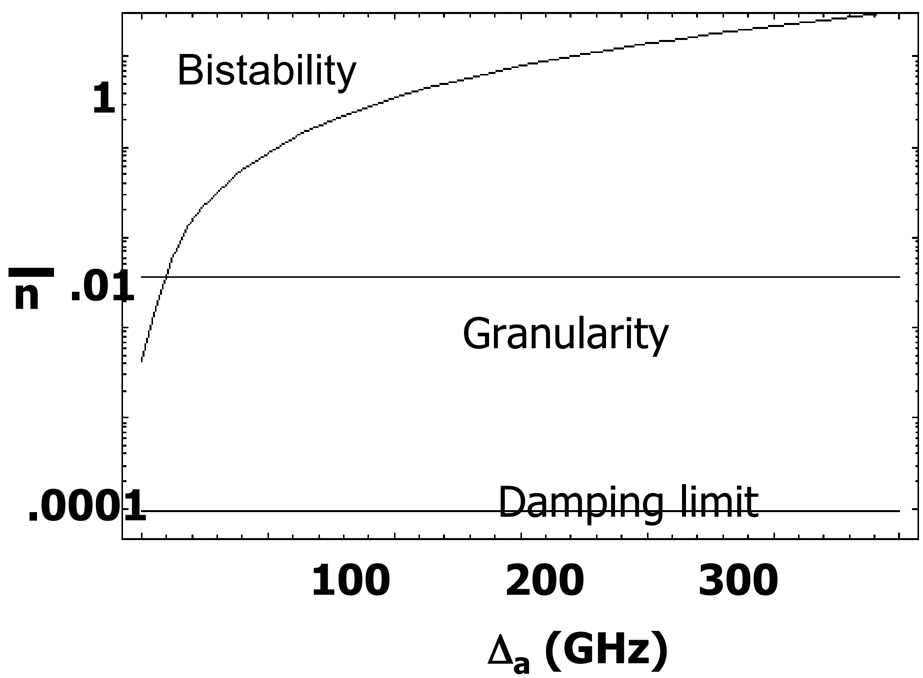

Probe-cavity detuning (MHz)

# Non-linearity at very low photon numbers



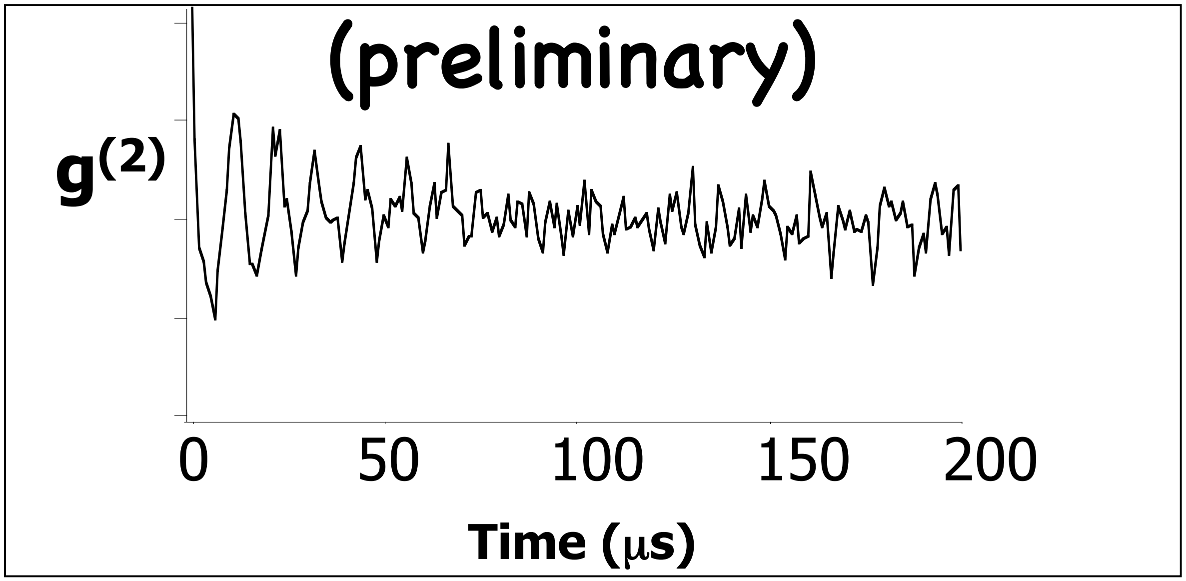

As we reduce the atomic detuning, fewer photons will suffice for bistability; nonlinearities at very low photon number are obtainable.

Nonlinearity "phase diagram"



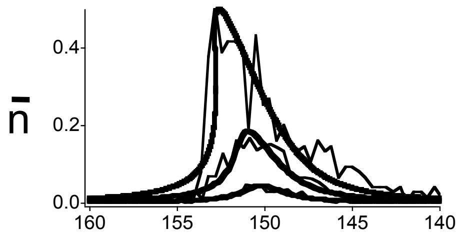

When photons arrive less frequently than the period of harmonic motion, granularity of individual photons becomes important.

# Photon correlations (preliminary)




In Granular regime, each photon's impulse excites a transient oscillation, evident in the cavity resonance, and the correlation of subsequent photons

# Non-linearity at very low photon numbers

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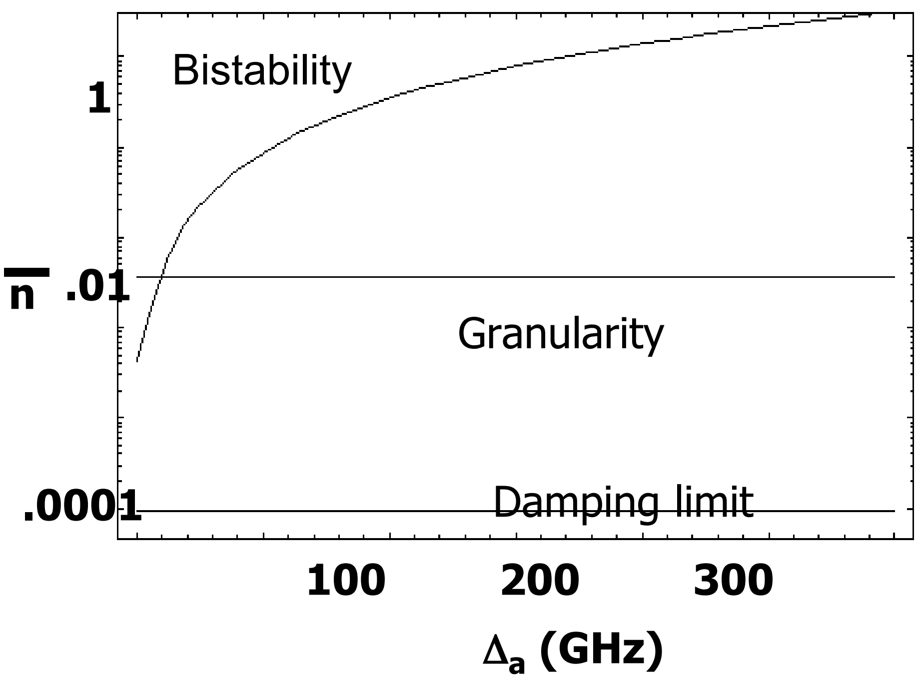
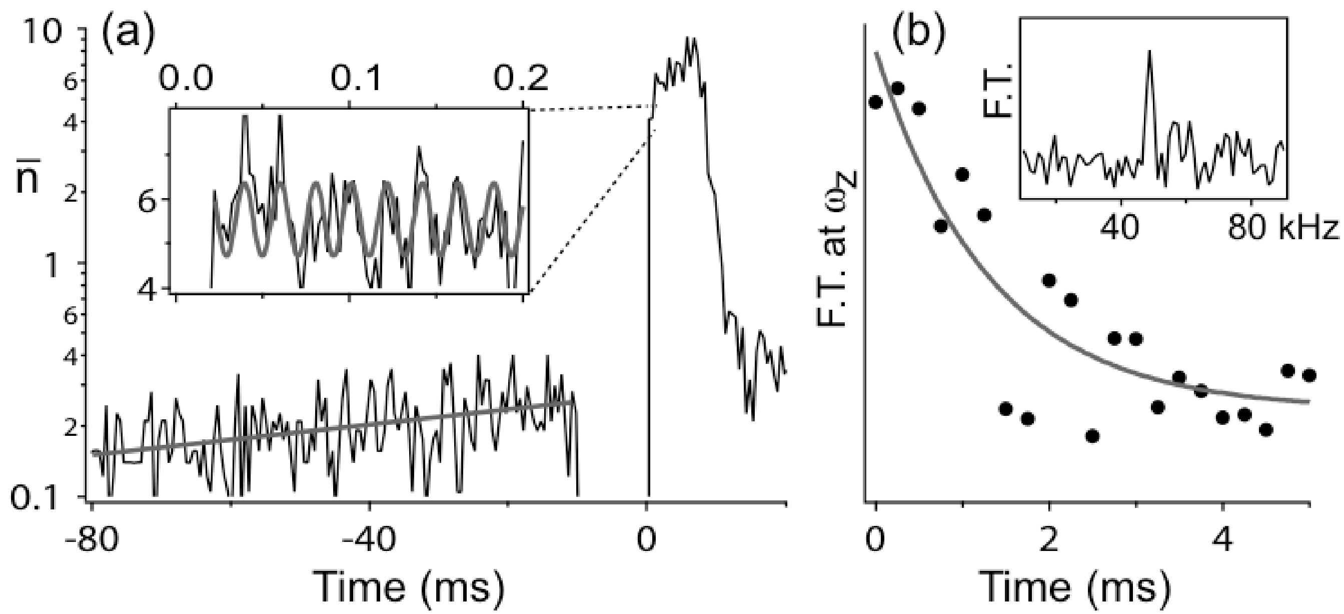



When photons arrive less frequently than the period of harmonic motion, granularity of individual photons becomes important.

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

# Diabatic excitation of collective oscillation



# Using atoms to measure aspects of the field

Brune et al 1995

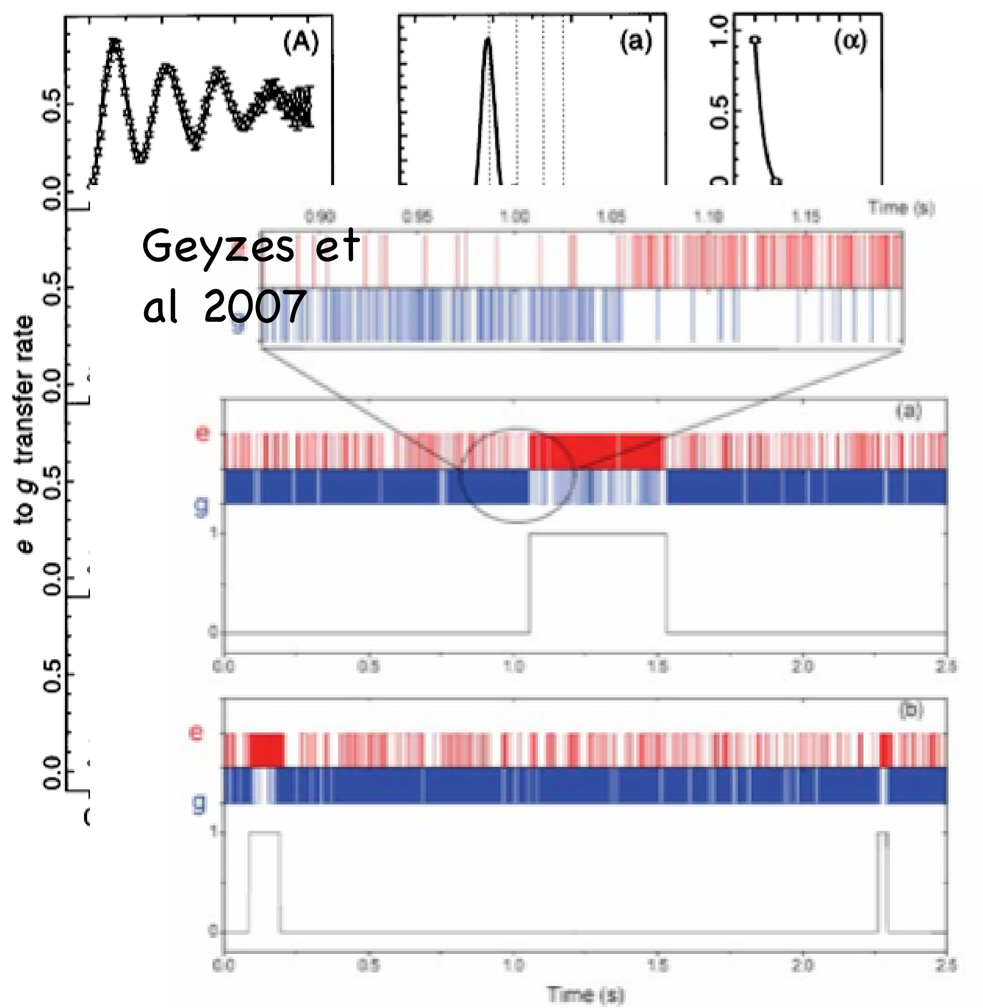


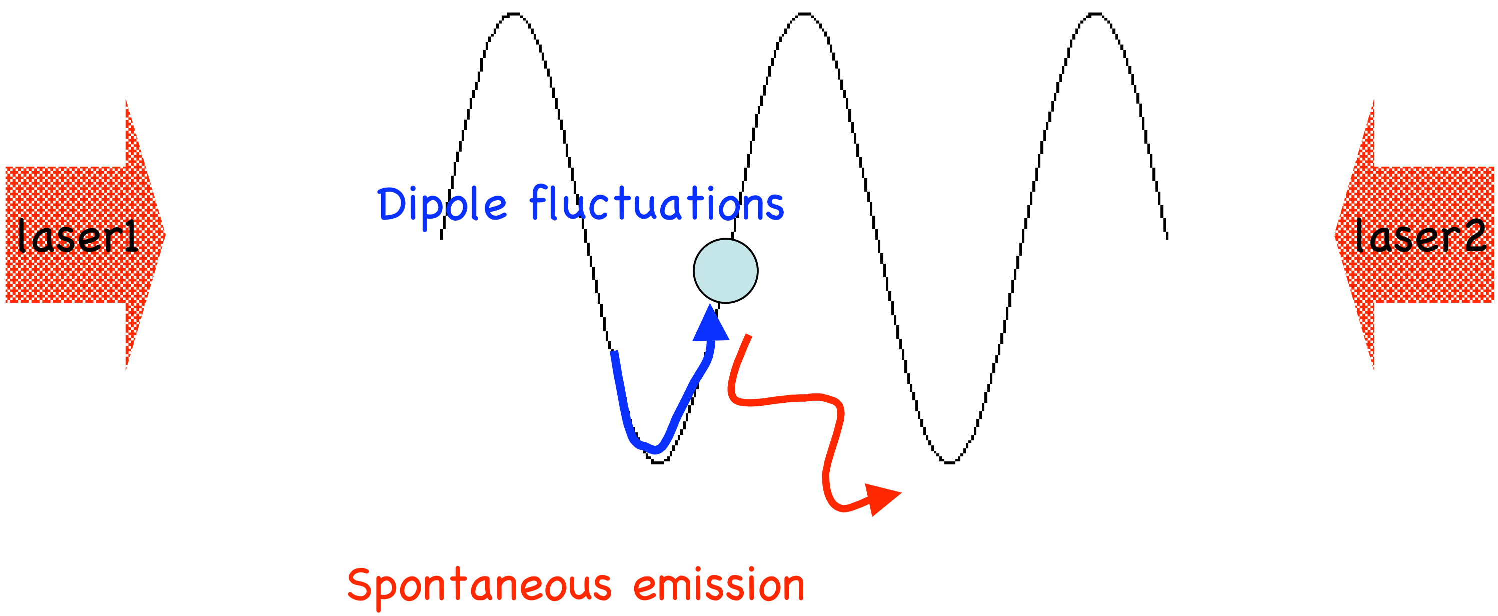

Figure 2: Birth, life and death of a photon: a QND Detection

Fluctuations of the cavity field?

Atoms are buffeted by quantum fluctuations in the intracavity field intensity and heat up..

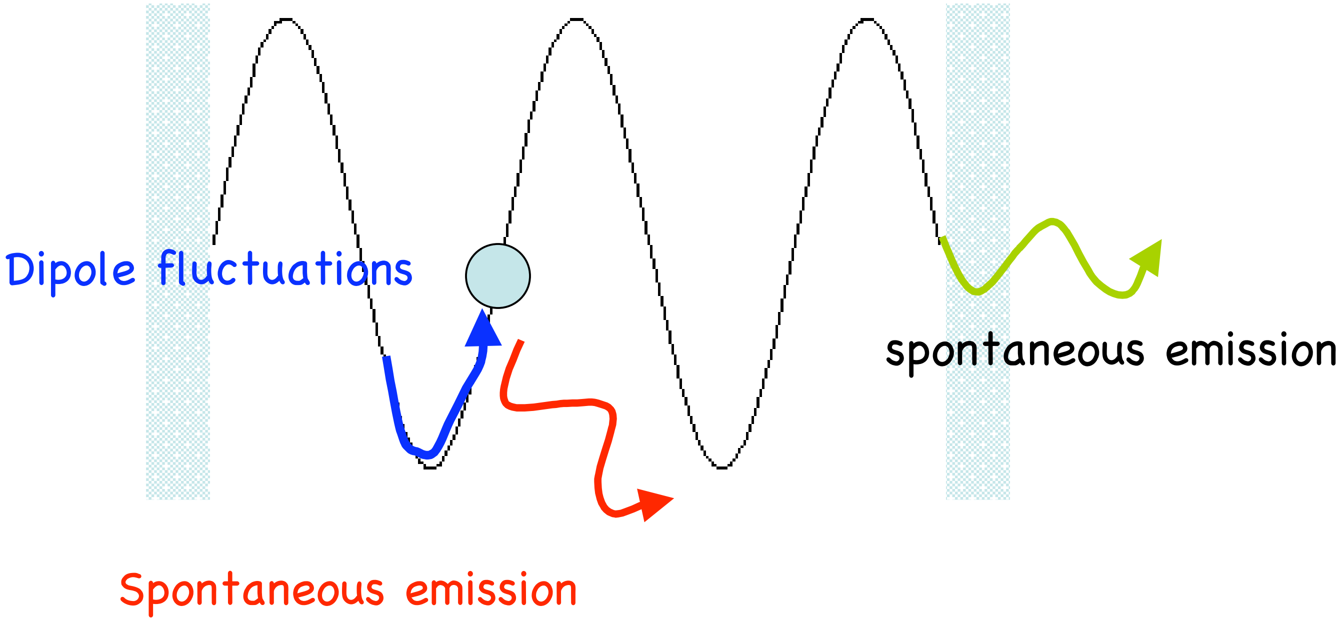
the atoms thus serve as a *fluctuation bolometer,* sensing the fluctuations of incident intensity by an increase in thermal energy.

# Fluctuations of forces:
# Standing wave



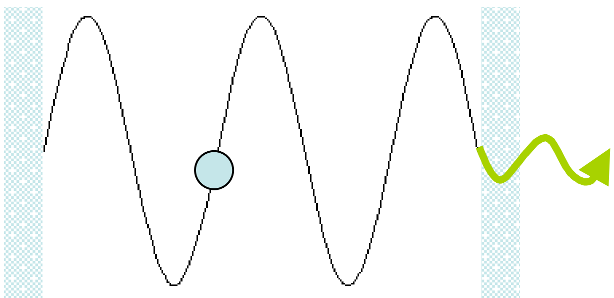

Gordon & Ashkin 1979, Dalibard & Cohen-Tannoudji 1985

# Fluctuations of forces
# Standing wave in a cavity



# The dipole force

"Dipole fluctuations"



The dipole force is:

$$F = -\hbar \partial_z \left[ g(z)(\sigma^+ a + a^\dagger \sigma^-) \right]$$

For large detuning from the
atomic resonances and weak drive

$$F = -\frac{\hbar \partial_z g^2(z)}{\Delta_a} \, \hat{n} = f(z)\hat{n}$$

The gradient of the AC stark shift

# Fluctuating force = momentum diffusion

An atom with a force history acquires momentum

$$p(t) = p_0 + \int_0^t dt' F(t')$$

diffusion is the change of the momentum variance

$$2D = \frac{d}{dt}(\langle p^2 \rangle - \langle p \rangle^2)$$

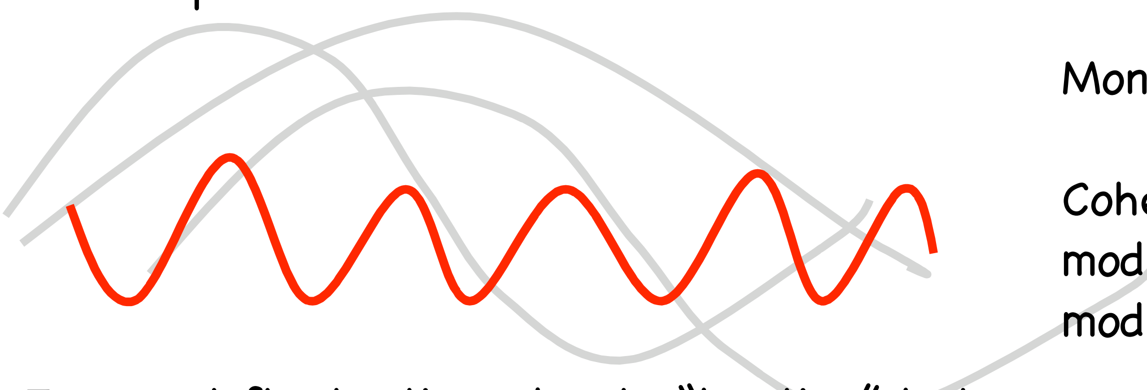
The momentum diffusion due to cavity fluctuations

$$2D_{cav} = f^2(z) \int_0^\infty d\tau \cos(\omega_t \tau) \boxed{(\langle \hat{n}(\tau)\hat{n}(0)\rangle - \langle \hat{n}(0)\rangle^2)}$$

Two-time correlation is quantum-optics property of cavity, independent of atoms

# Temporal fluctuations

Free space:

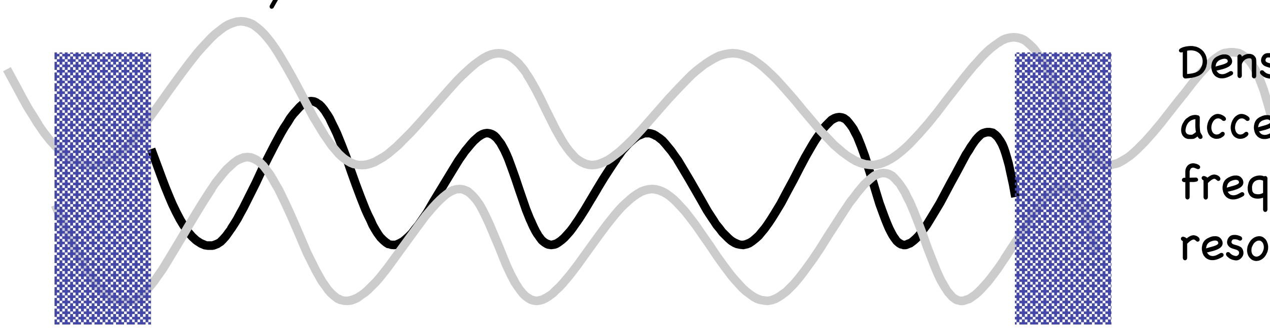


Monochromatic Beam:

Coherent state in single mode vacuum in other modes

Temporal fluctuations due to “beating” between coherent state and vacuum at other frequencies. White noise spectrum of fluctuations.

Cavity



Density of states is accentuated at frequencies near cavity resonance

Temporal fluctuations of an input coherent state is now colored.

# The fluctuation bolometer: momentum diffusion

The total diffusion is:

$$D = D_{fs}\left( \boxed{1} + \boxed{\pi C \sin^2(2kz)\left[\phi\left(\frac{\delta+\omega_t}{\kappa}\right) + \phi\left(\frac{\delta-\omega_t}{\kappa}\right)\right]} \right)$$

Free Space

$$\phi(x) = \frac{1}{\pi(1+x^2)}$$

Cavity Diffusion

$$D_{fs} = \hbar^2 k^2 s \Gamma/2$$

When single atom cooperativity is large diffusion is due primarily to cavity fluctuations

Hechenblaikner et al 1998, Fischer et al 2001, Murr et al 2006

# Spectrum of noise in a cavity

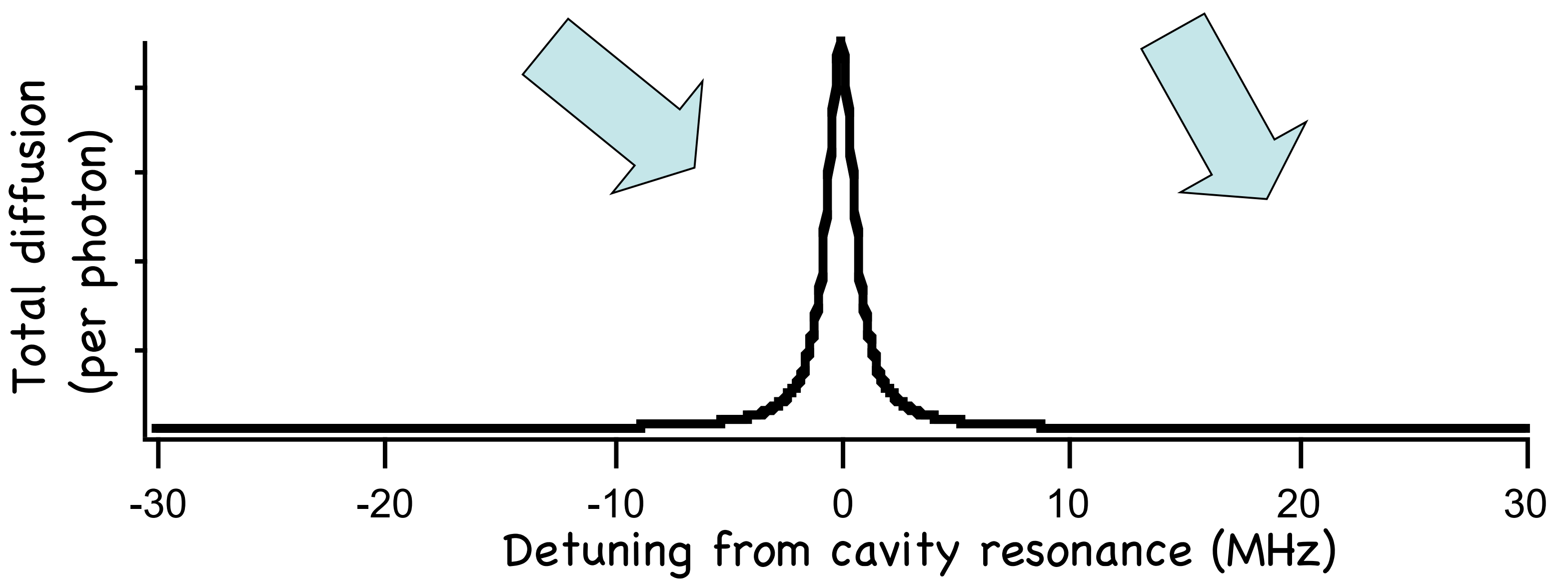
Cavity

Colored Spectrum of fluctuations.

Fluctuations are "concentrated" at cavity resonance.

Free Space

Away from the cavity resonance, the diffusion is the same as in free-space.

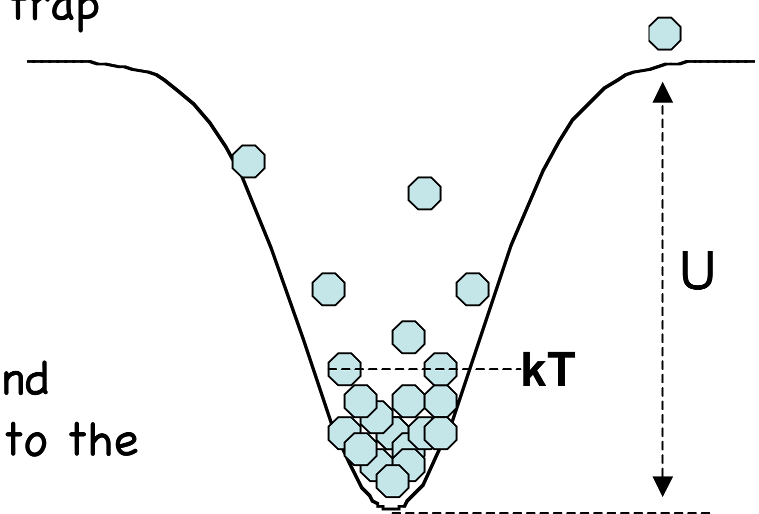


# The Bolometer

Diffusion leads to an increase in thermal energy

$$\frac{dE}{dt} = \frac{d}{dt}\frac{(\Delta p)^2}{2m} = \frac{D}{m}$$

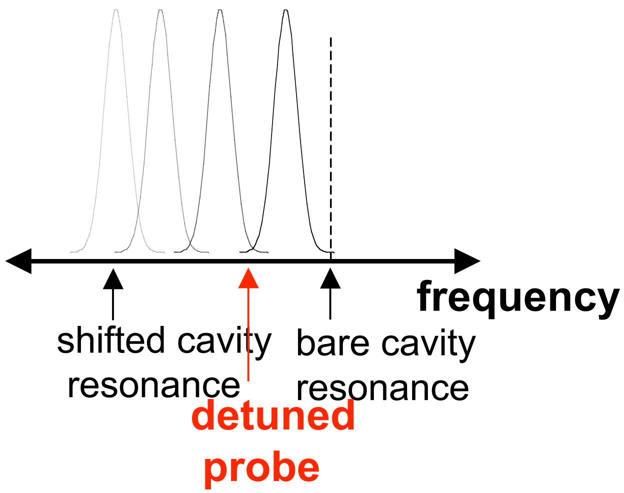
An increase in energy is sensed by a loss of atoms from the finite depth trap




Each atom leaves with and amount of energy equal to the trap depth on average

$$\frac{dE}{dt} = \frac{U}{N}\frac{dN}{dt}$$

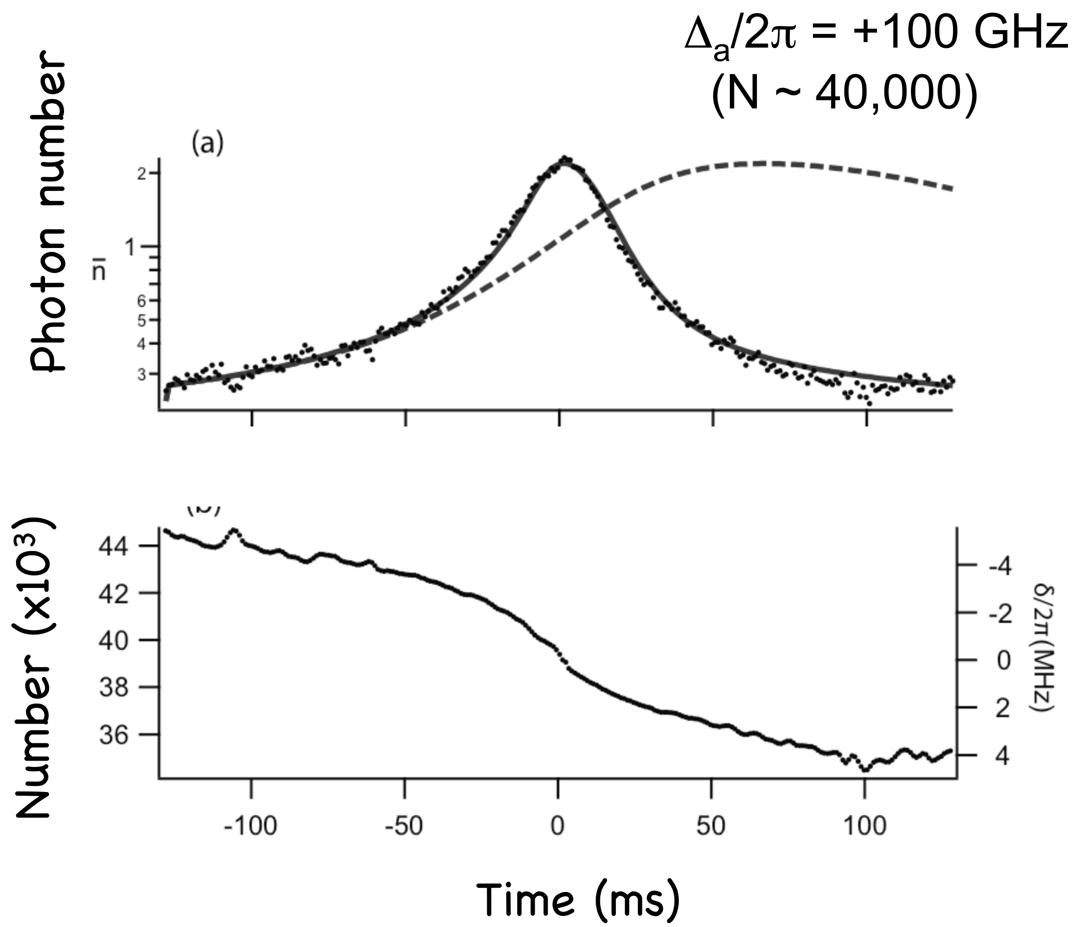
# Cavity heating



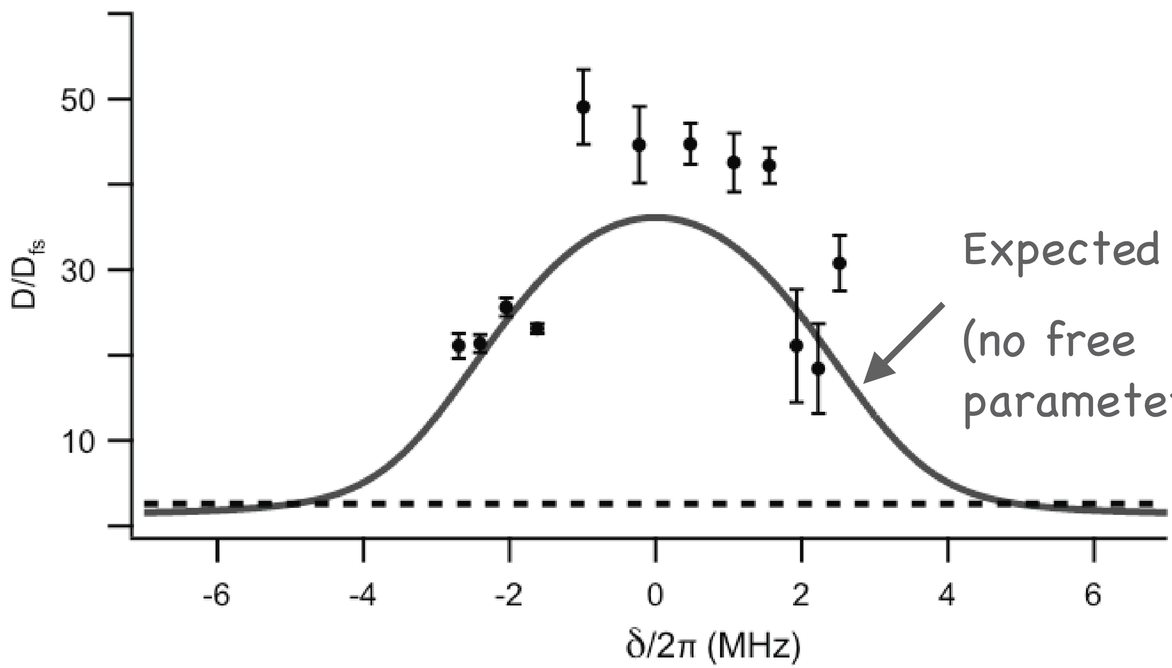

Simultaneous Measurements of N, and $\bar{n}$:

Overall timescale is long compared to evaporative timescale ~3ms

Temperature remains constant: 4ms TOF images



# Spectrum of noise in a cavity

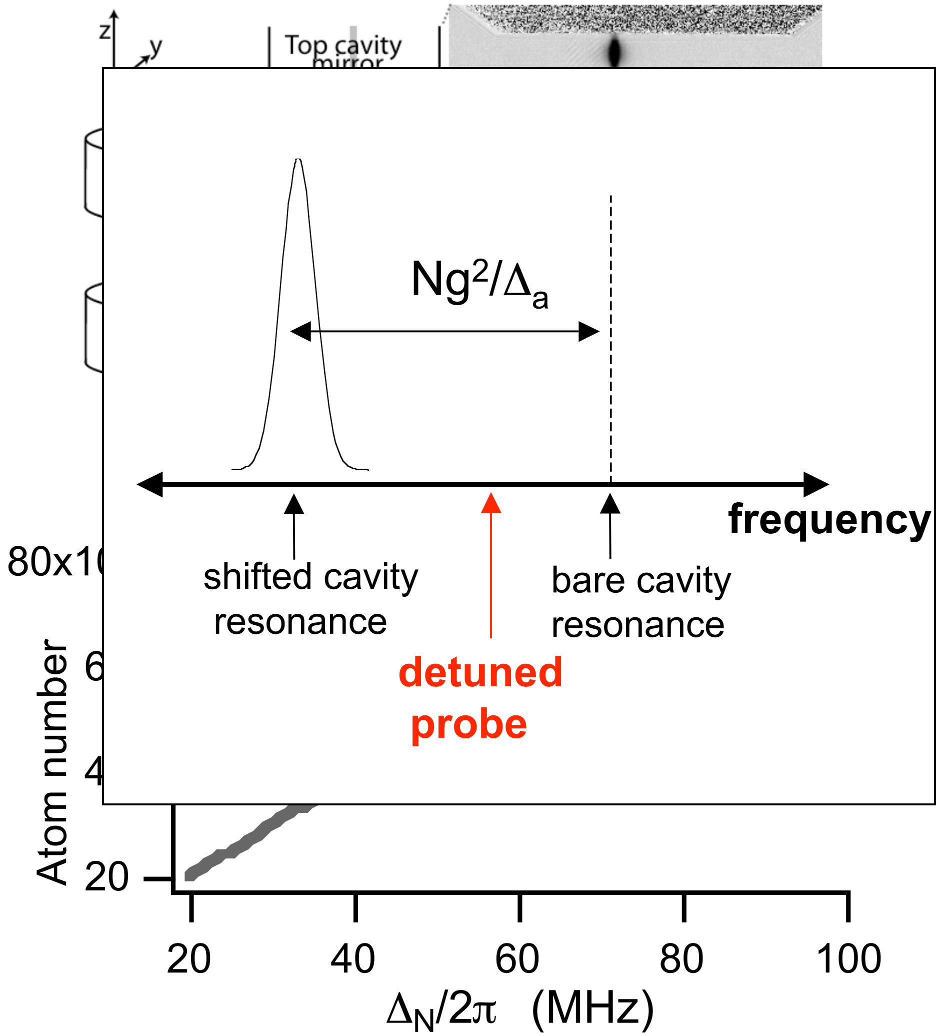



Expected Diffusion

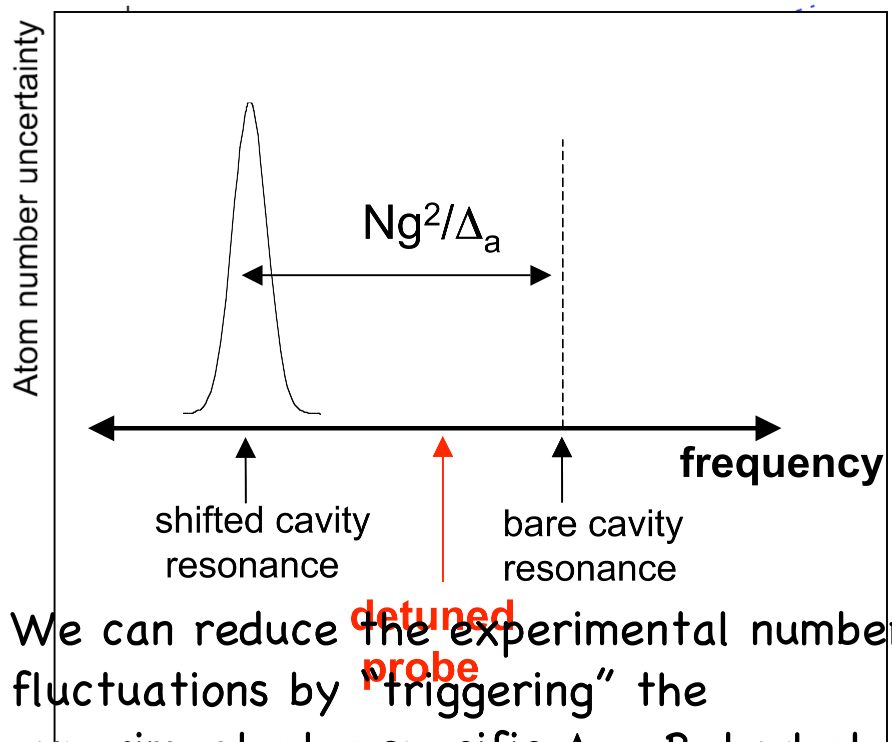
(no free parameters)

# Cavity measurements of number:

Resonant absorption image




How good is a purely cavity based measurement of number?




We can reduce the experimental number fluctuations by "triggering" the experiment at a specific $\Delta_N$. But what does it take to make a number squeezed sample?

# GOAL: Non-destructive number counting below standard quantum limit

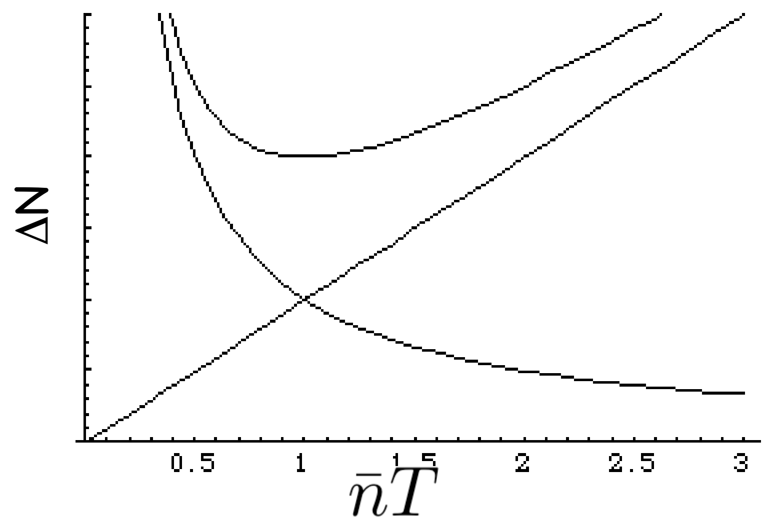
Need to non-destructively count number to squeeze: QND measurement.

Number measurement improves in time as;

$$(\Delta N)^2 = \frac{1}{4\bar{n}\kappa\eta T}\frac{\Delta_a}{g(z)^2}(\kappa(1+(\delta/\kappa)^2)^2$$

Heating process adds excitations to the system;

$$\frac{H(\Delta_a, z, \delta)\bar{n}T}{\hbar\omega_t} \Rightarrow (\Delta N)^2 = H\bar{n}T$$



# Minimum Uncertainty

On resonance,

$$(\Delta N)^2 = 2\Big(\frac{1}{\eta C\cos^2(kz)}\frac{\hbar^2 k^2}{\omega_t m}\Big(1 \qquad\qquad\qquad\qquad \Big)\Big)^{1/2}$$

Fluctuations in the cavity cancel the benefit of using a cavity to squeeze.

Except;

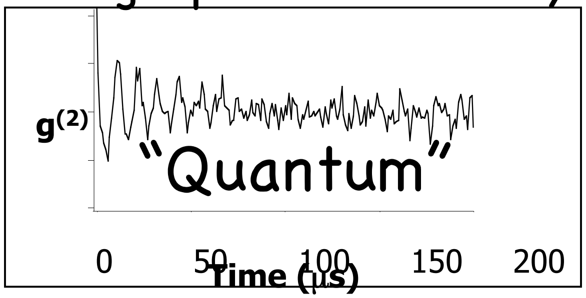
When $\omega_\tau > \kappa$

If sites where heating occurs are avoided

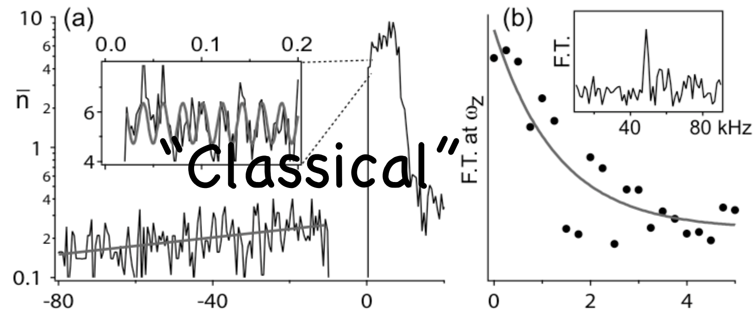
Our measurement of number was also sensitive to the position of the atoms. Heating can be avoided if atoms are only located where we are insensitive to the position.

# Review: applications and outlook

Single photon nonlinearity

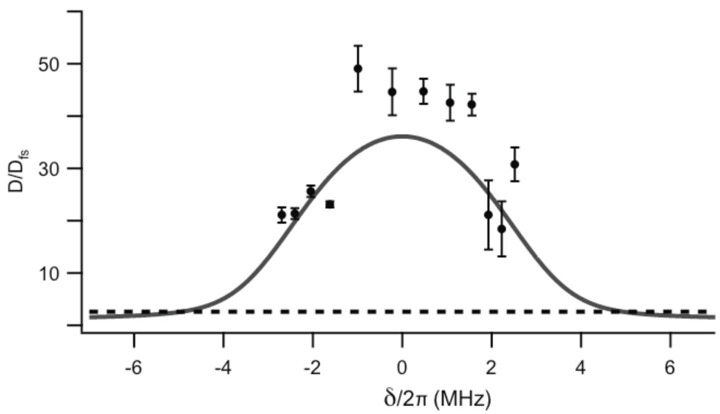



Diabatic excitation of collective oscillation



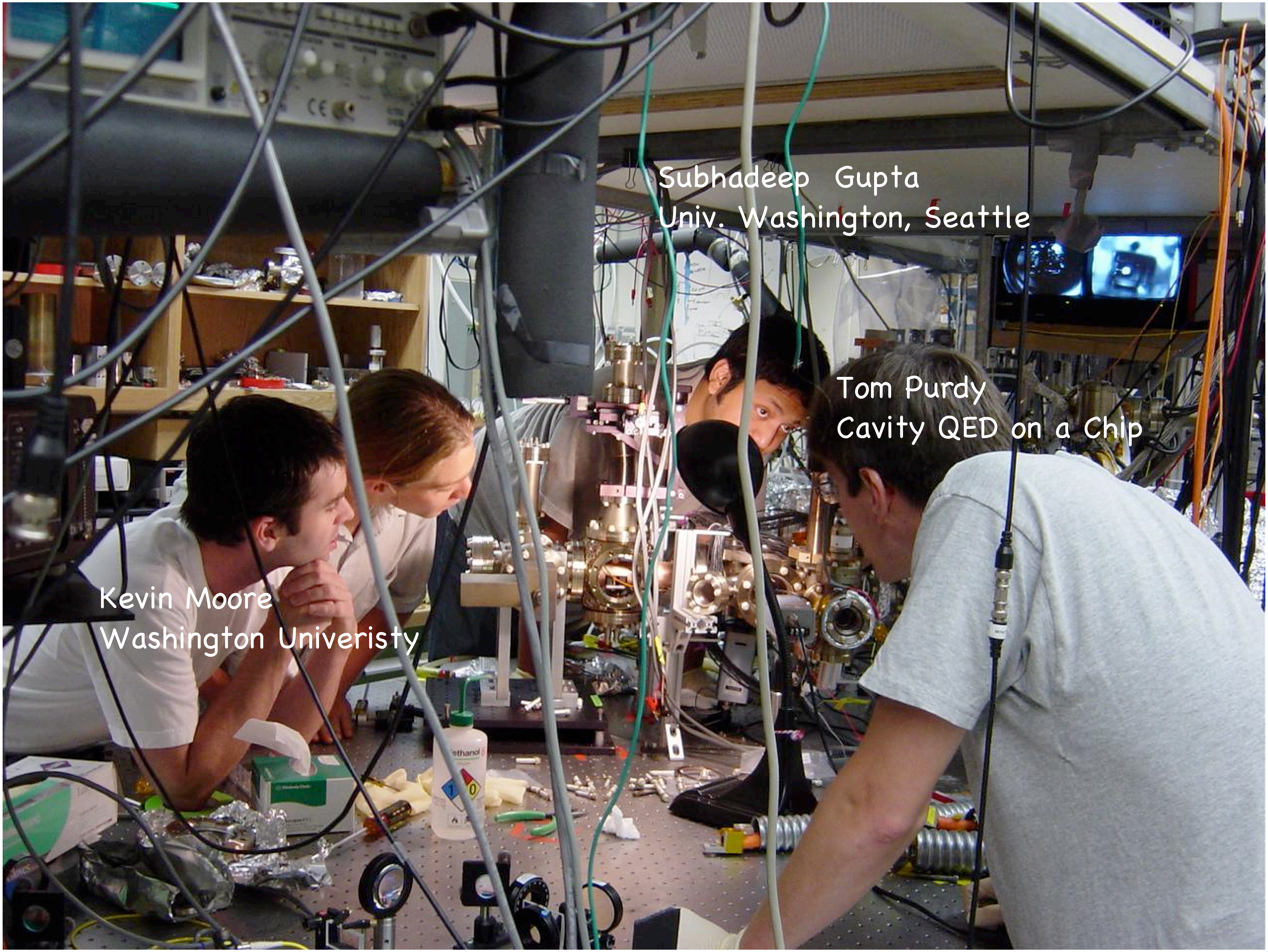

S. Gupta et al (2007) quant-ph/0706.1052

Fluctuation Bolometer




Able to detect properties of the field that cannot be detected outside of the cavity

K. Murch et al (2007) quant-ph/0706.1005


Subhadeep Gupta
Univ. Washington, Seattle
Tom Purdy
Cavity QED on a Chip
Kevin Moore
Washington Univeristy

Alfred P. Sloan Foundation

The David and Lucile Packard Foundation

Miller Institute

# Free Space diffusion

Away from the cavity resonance, the diffusion is the same as for free-space, and due to regular dipole fluctuations and spontaneous emission: