Measurement of Intracavity Quantum Fluctuations Using an Atomic Fluctuation Bolometer

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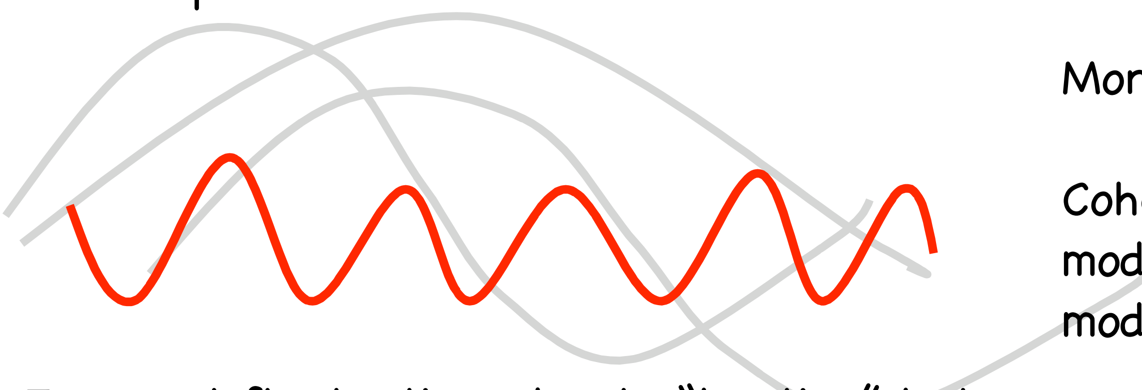
K. W. Murch, K. L. Moore, S. Gupta, and D. M. Stamper-Kurn, quant-ph/0706.1005 (June 2007)

Temporal fluctuations

Free space:

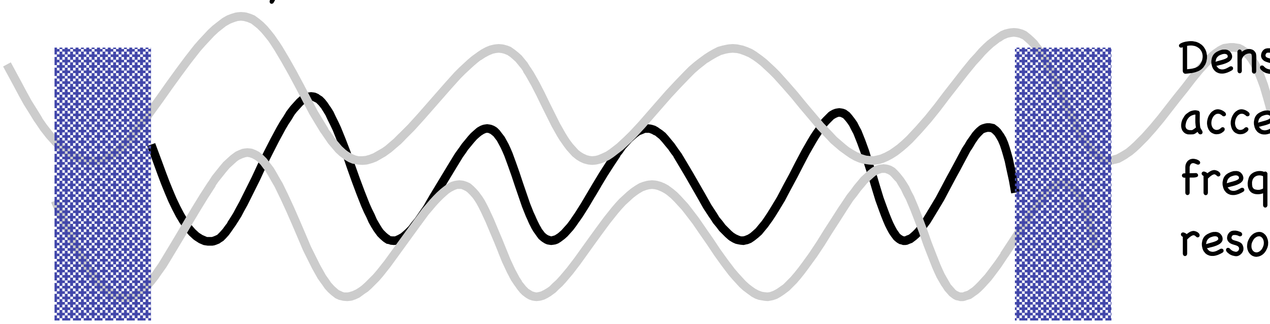


Monochromatic Beam:

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



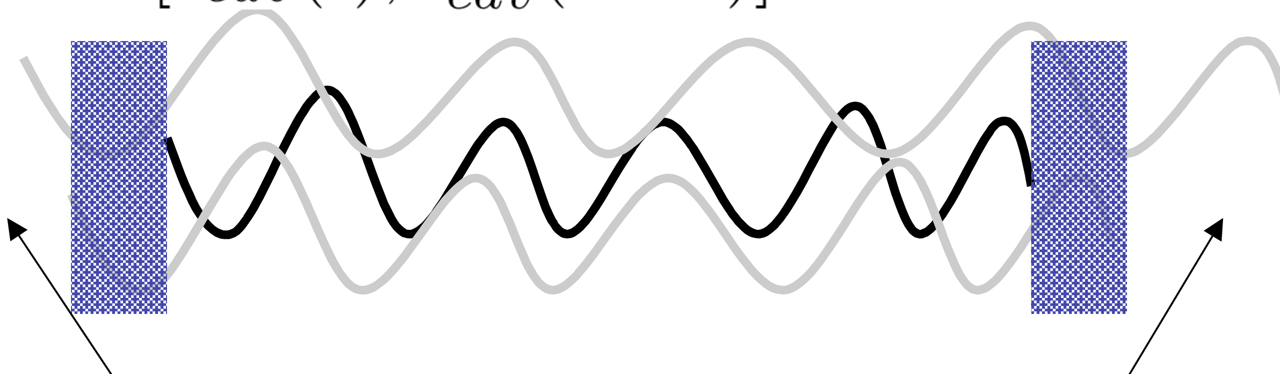
Density of states is accentuated at frequencies near cavity resonance

Temporal fluctuations of an input coherent state is now colored.

Temporal fluctuations

Intracavity Temporal Fluctuations are not discernable outside the cavity

$$[\hat{b}_{cav}(t), \hat{b}^{\dagger}_{cav}(t+\tau)] = e^{-i\omega_0\tau - \kappa|\tau|}$$



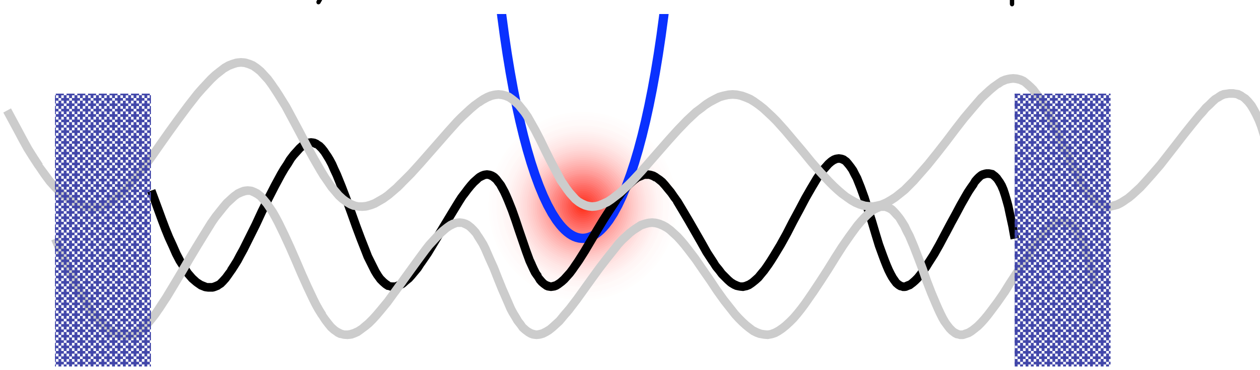
$$[\hat{b}_{in/out}(t), \hat{b}^{\dagger}_{in/out}(t+\tau)] = \delta(\tau)$$

Temporal fluctuations

To sense these fluctuations we introduce an ultracold gas into the cavity.

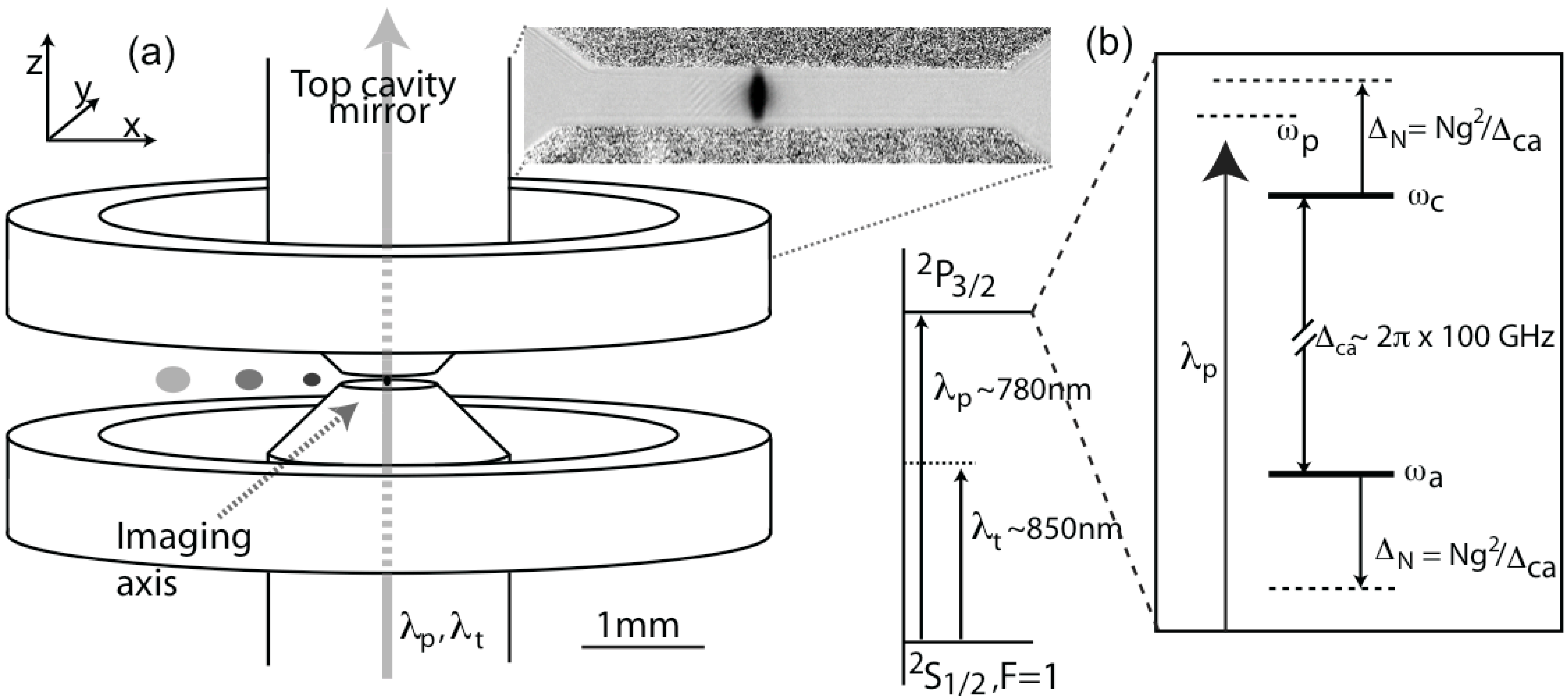
The atoms sense the intracavity field as an AC stark shift.

Atoms are buffeted by these fluctuations and heat up.



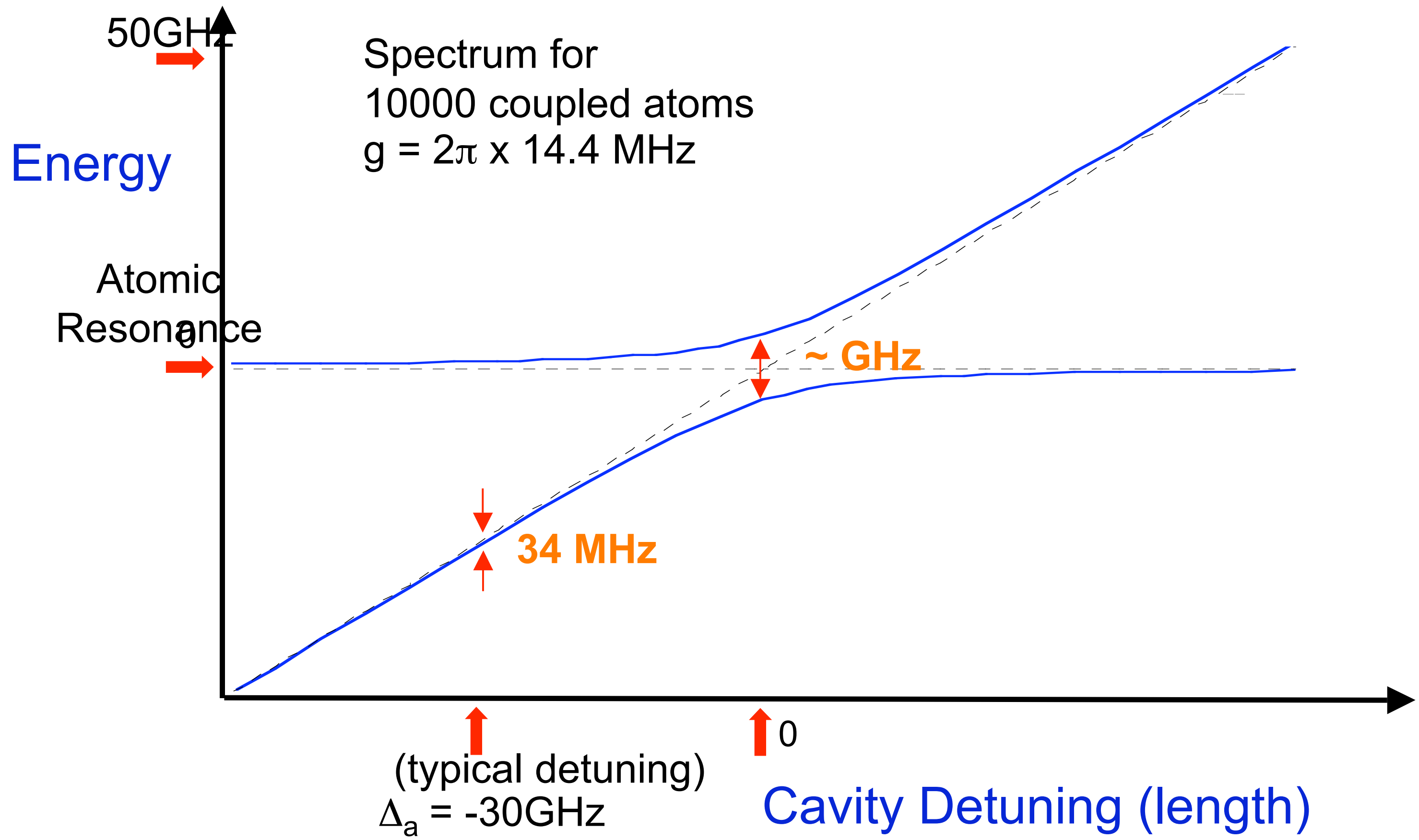
$$\mathcal{H}(t) = \hbar\omega_z\left(\hat{a}^\dagger(t)\hat{a}(t) + \frac{1}{2}\right) + \hbar\omega_0\left(\hat{b}^\dagger(t)\hat{b}(t) + \frac{1}{2}\right) - f\hat{b}^\dagger(t)\hat{b}(t)\hat{z}(t) + \mathcal{H}_{input}$$

The experimental apparatus



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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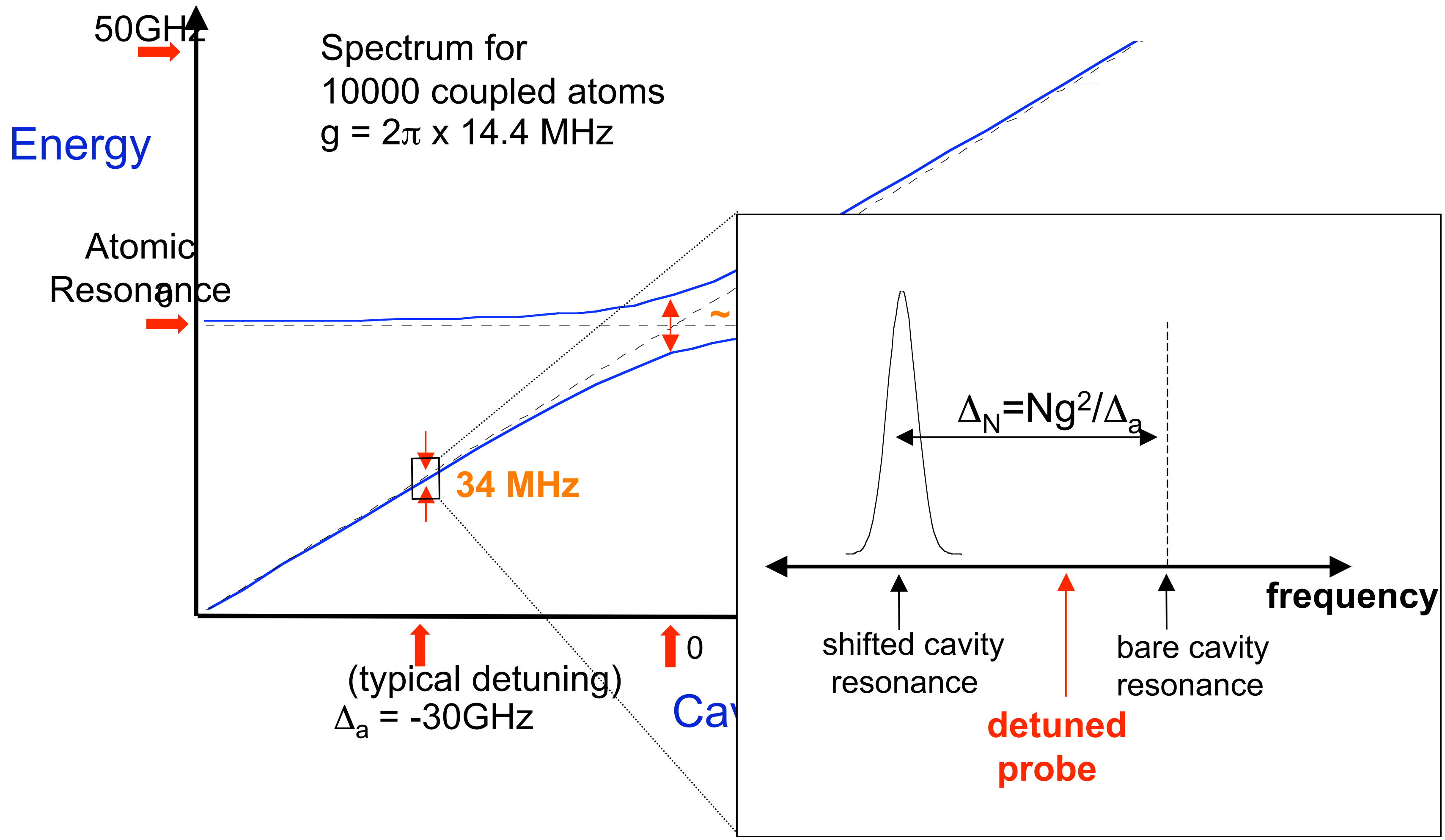


Atoms are simply passive observers of the field;
they only present a dispersive medium

Two features allow this simplifying assumption

(a) the atoms are and remain ultracold

$$k_B T \ll \hbar \kappa$$

(b) the atom cavity detuning is very large

$$g^2/\Delta_a \ll \kappa$$

Calculation of the heating rate

Cavity fluctuations lead to a heating rate:

$$R_c = (\pi f^2(z)/m)\, S_{nn}(-\omega_z)$$

Which is related to the spectrum of photon fluctuations,

$$S_{nn}(-\omega_z) = \frac{1}{\pi}\mathrm{Re}\left[\int_0^\infty d\tau\, e^{-i\omega_z \tau}\ \langle \hat{n}(\tau)\hat{n}(0)\rangle\right]$$

The total heating rate is a sum of "free space" heating terms and the contribution from cavity fluctuations:

$$R = R_{\mathrm{fs}}\left(1 + 2C\sin^2(2kz)\frac{1}{1+(\delta-\omega_z)^2/\kappa^2}\right)$$

↑ Single atom cooperativity

Spectrum of noise in a cavity

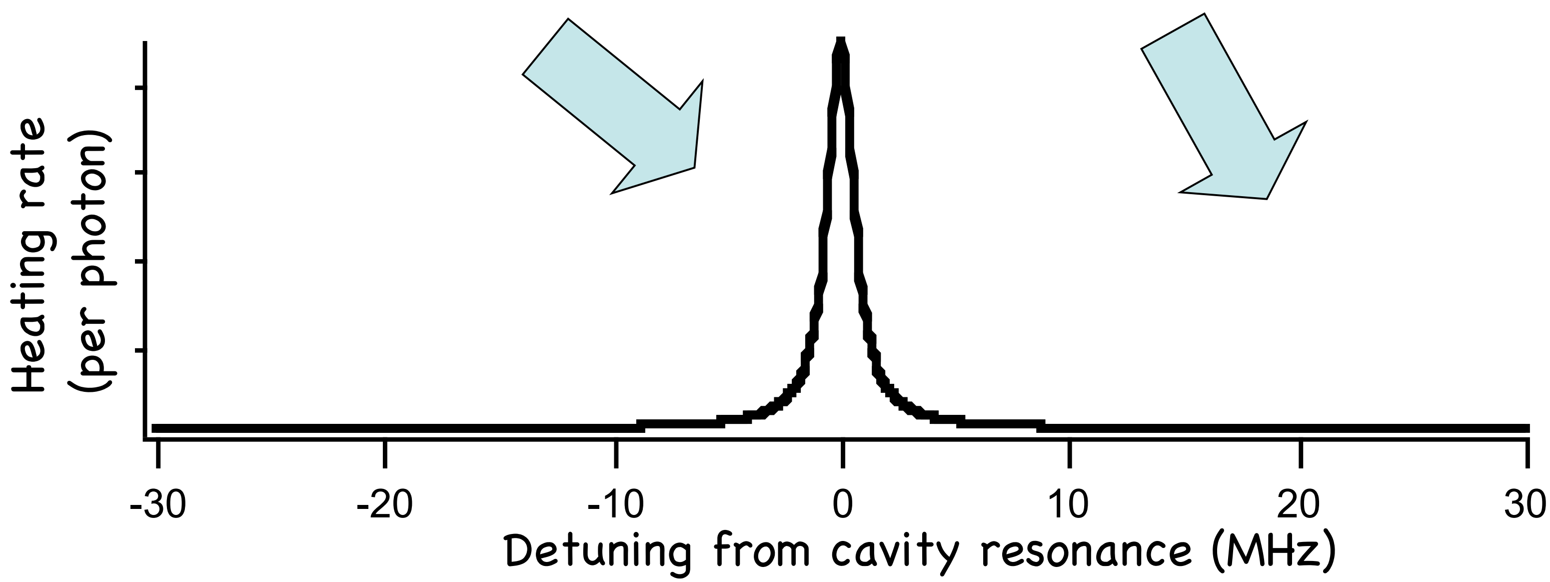
Cavity

Colored Spectrum of fluctuations.

Fluctuations are "concentrated" at cavity resonance.

Free Space

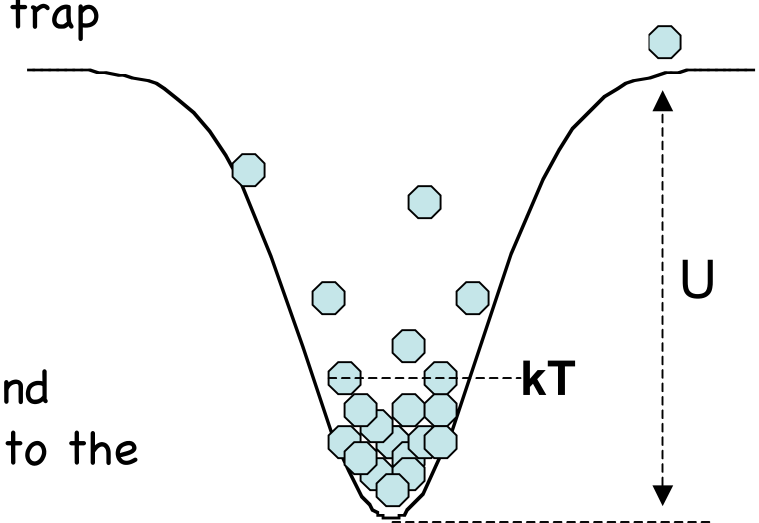
Away from the cavity resonance, the diffusion is the same as in free-space.



The Bolometer

Heating leads to an increase in thermal energy

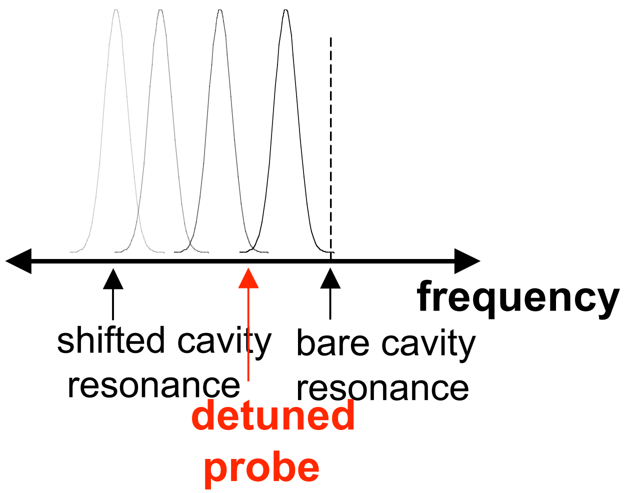
An increase in energy is sensed by a loss of atoms from the finite depth trap



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

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

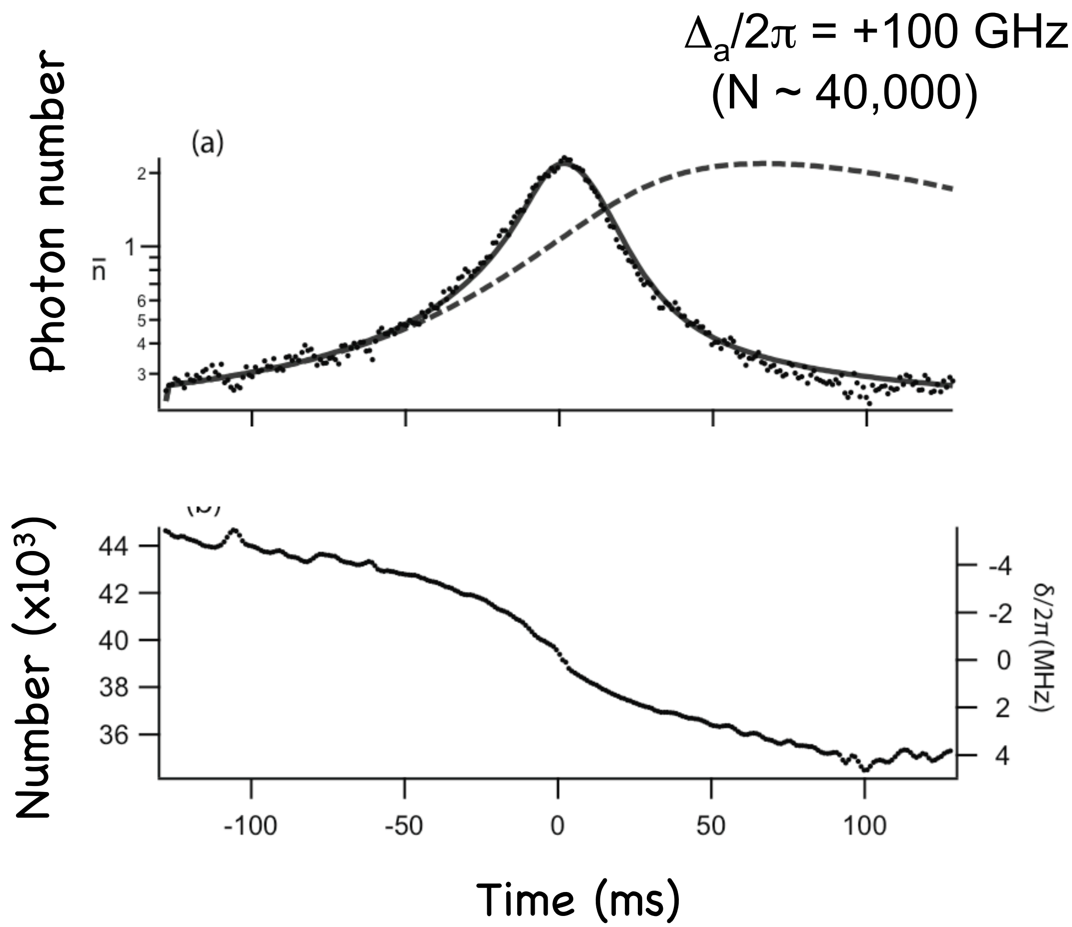
Cavity heating



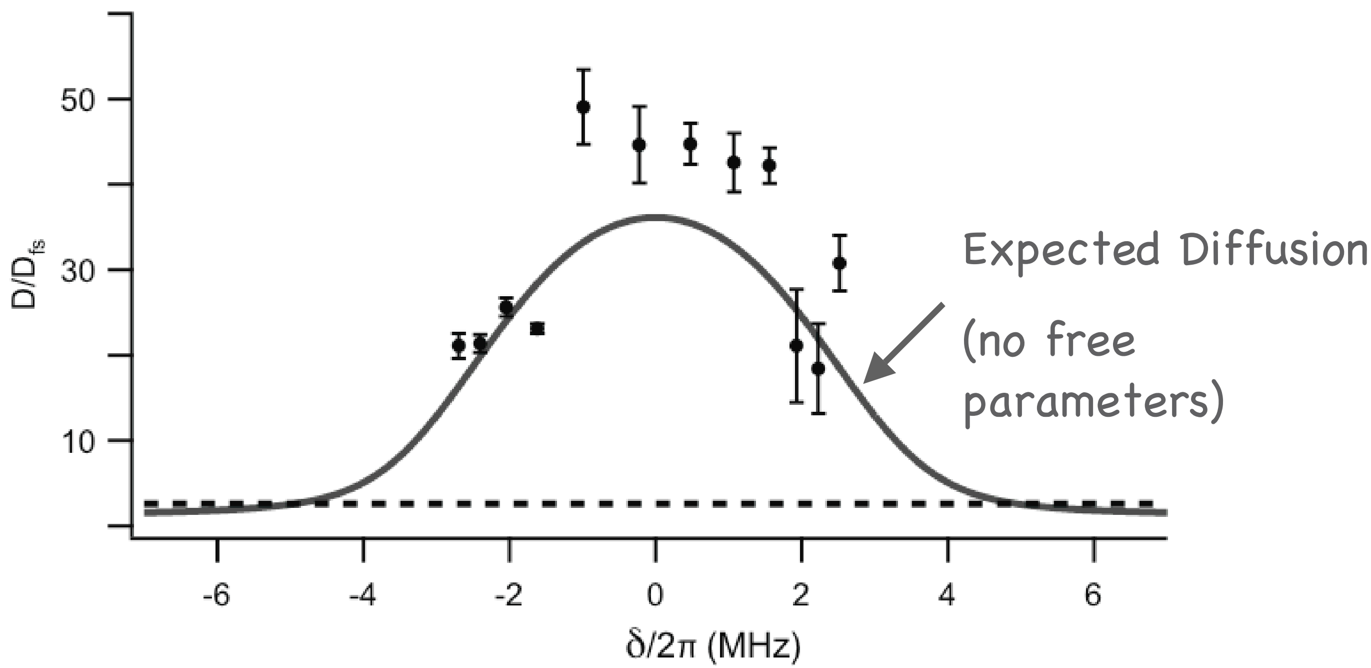
Simultaneous Measurements of N, and $\bar{n}$:

Overall timescale is long compared to evaporative timescale ~3ms

Temperature remains constant: 4ms TOF images



Spectrum of noise in a cavity



Outlook

Implications for cavity enhanced based measurement

Connections to micro-resonator/cooling work

New regime for Cavity QED

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