Quantum Micro-mechanics with Ultracold Atoms

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Motivation : Toward the Quantum

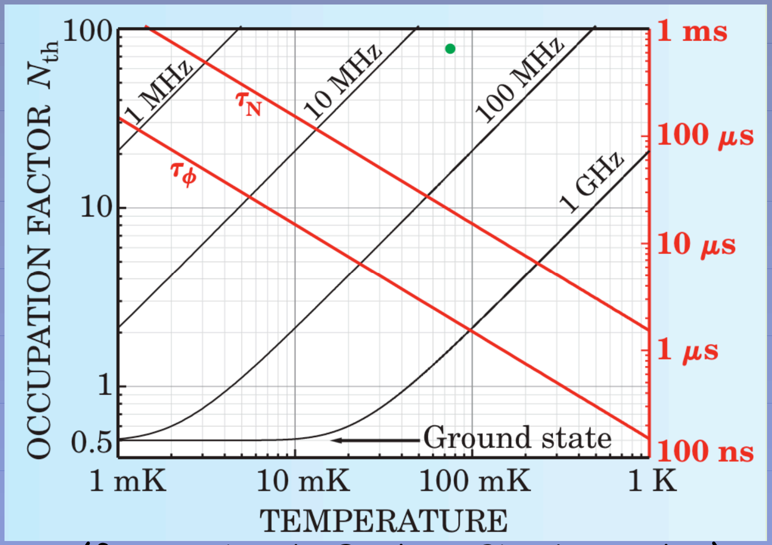
Pursuit of ground state mechanical oscillators:

Very high resonance frequencies (Roukes, Kippenberg, Schwab)

Cooling:
Cryogenics:
(Roukes...

Active feedback
(Rugar)

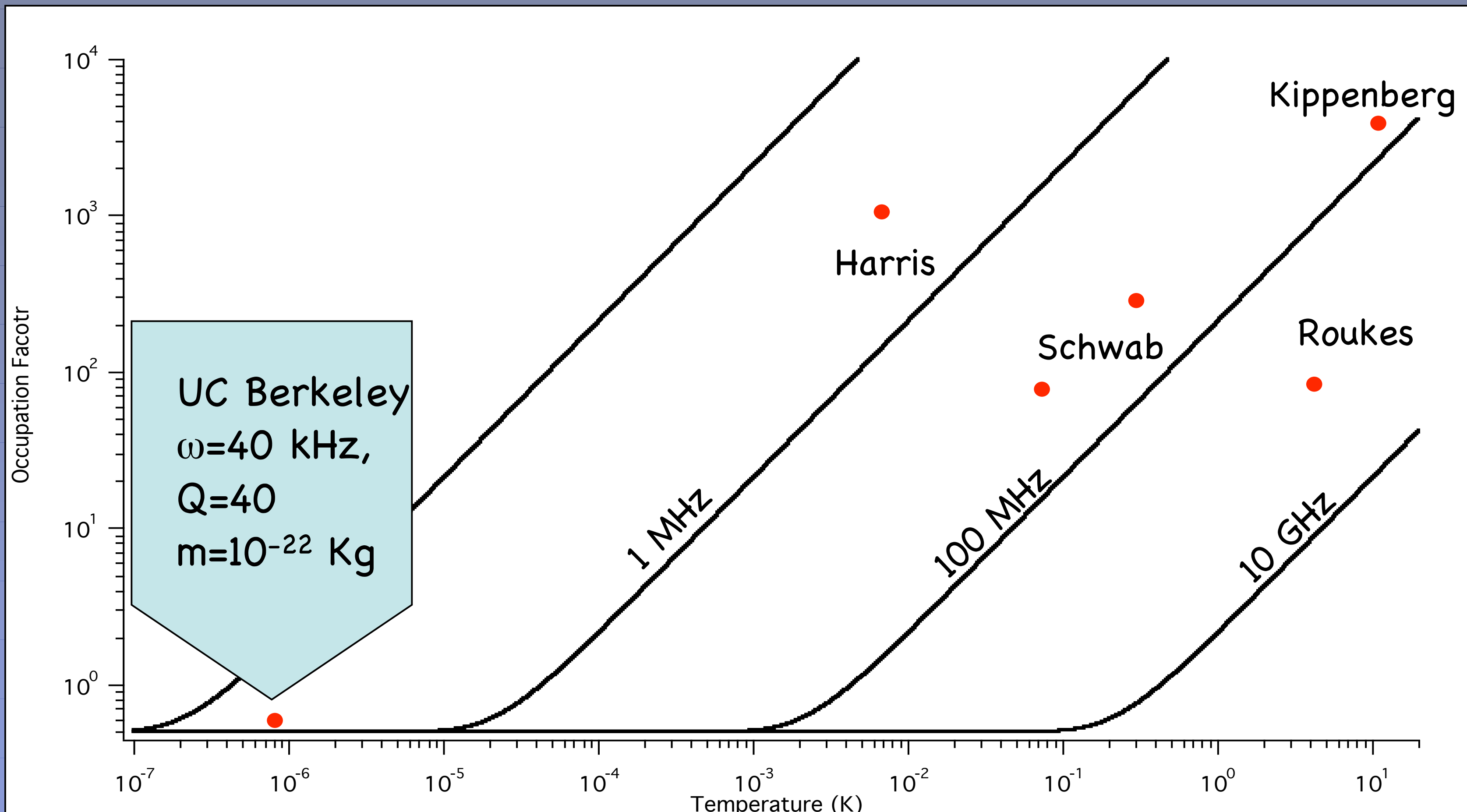
Passive Feedback:
Dynamical Backaction/
Cavity Cooling
(Ritsch, Vuletic & Chu,
Rempe) (Bouwmeester,
Zeilinger, Mavalvala...



(from Schwab, Roukes, Physics Today)

Laser Cooling? **Evaporation?**

Motivation : Toward the Quantum



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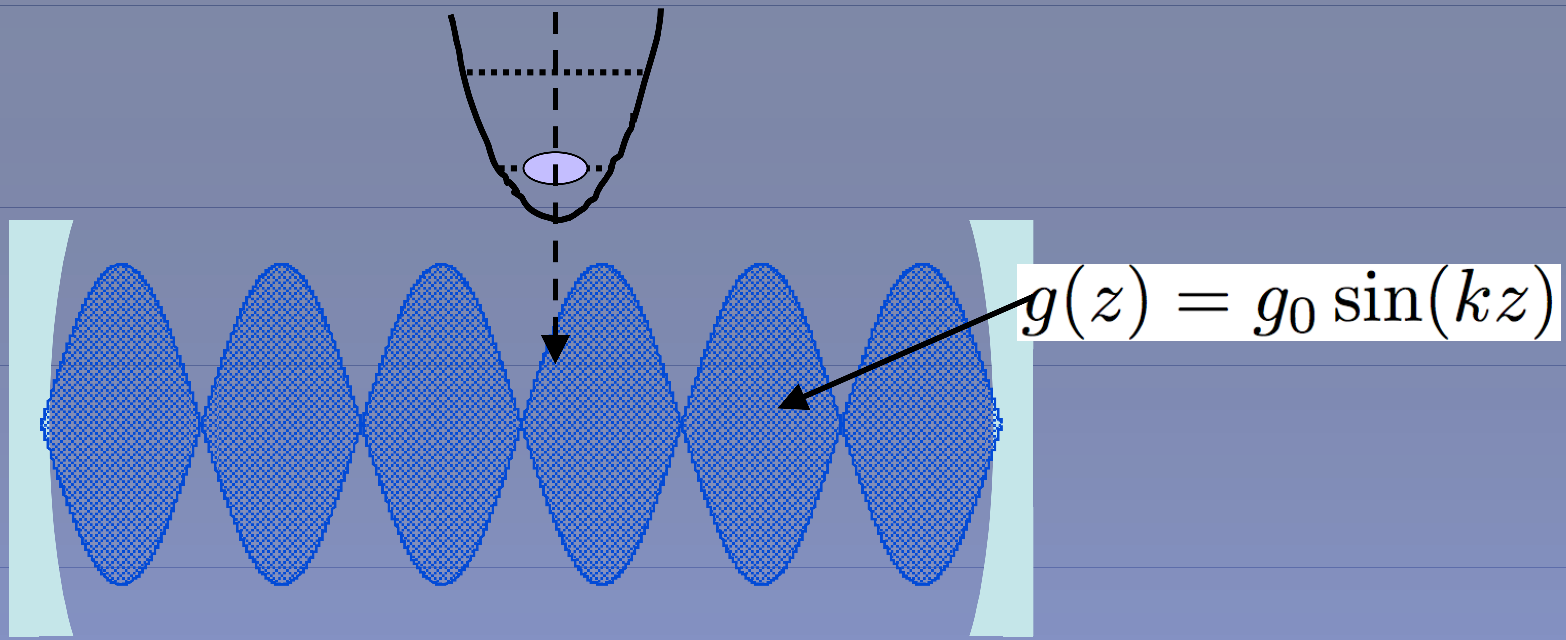
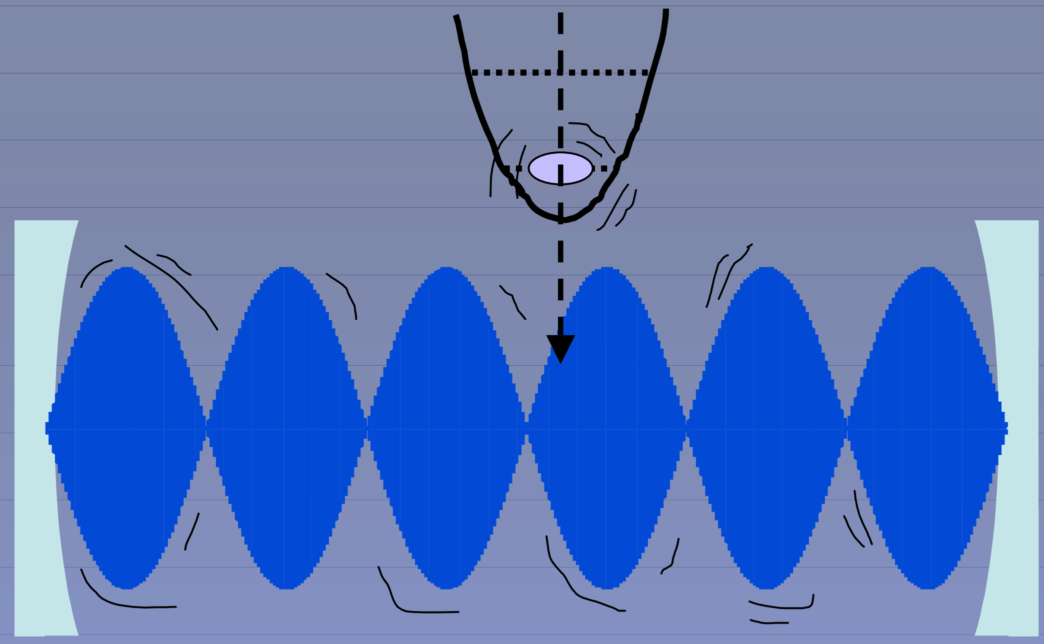
Laser Cooling? **Evaporation?**



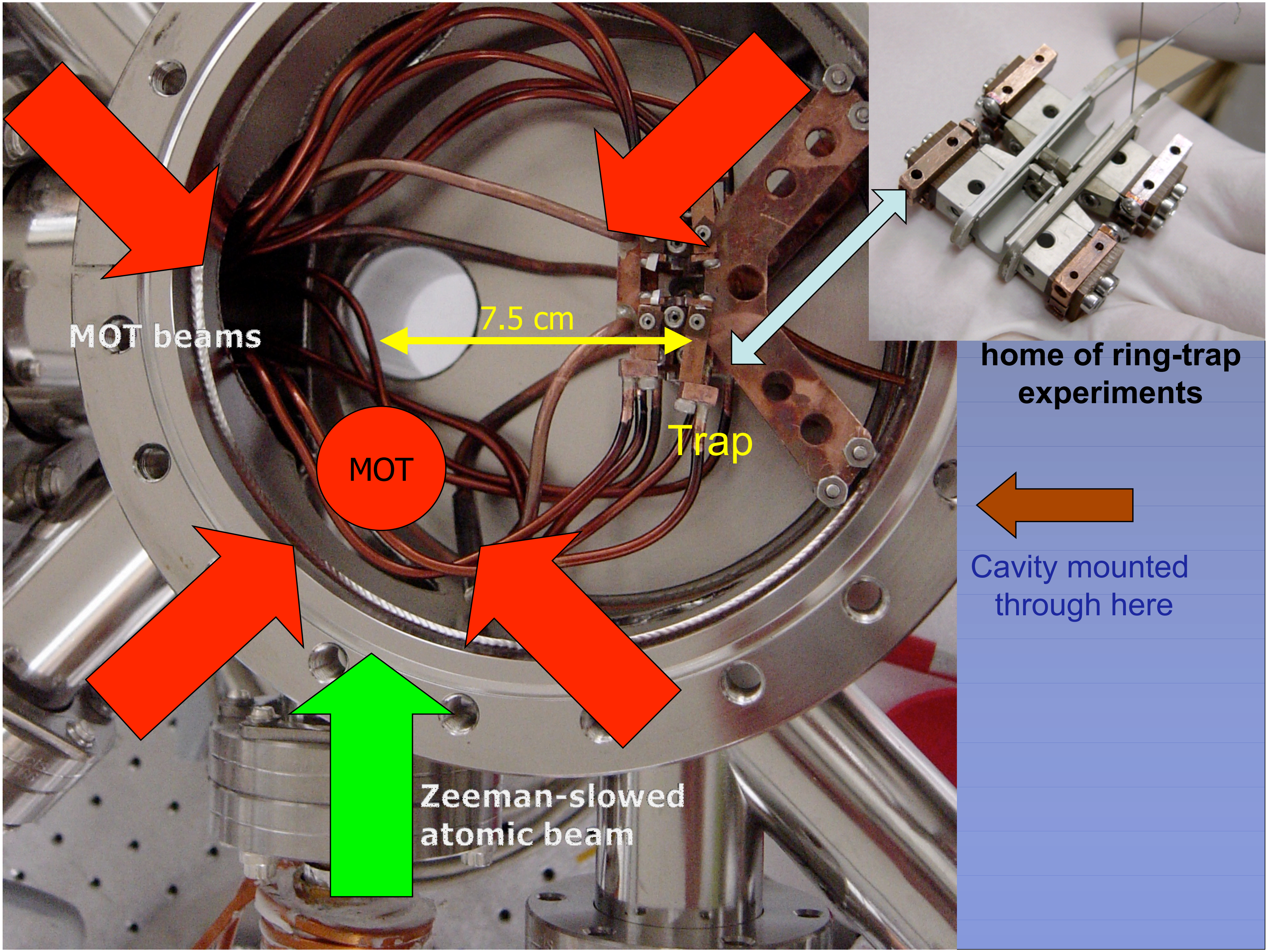
"Coherent" effect: probing the cavity displaces trapped atoms
Probing the cavity shifts the cavity resonance -> nonlinear cavity optics

"Cavity Nonlinear Optics at Low Photon Numbers from Collective Atomic Motion". Gupta et al PRL 99 213601 (2007)

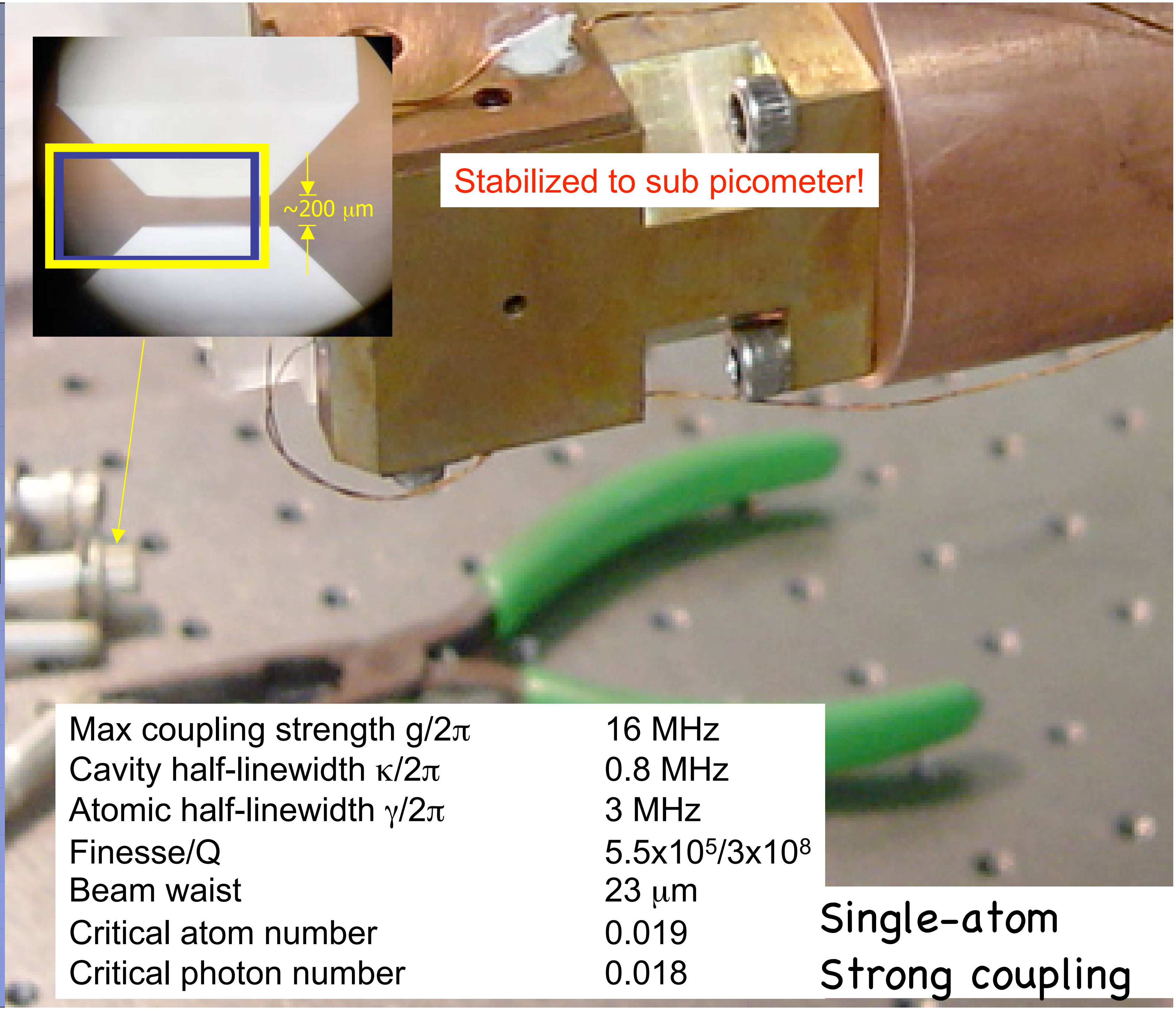


“Incoherent” effect: (quantum) fluctuations of the intracavity intensity cause momentum diffusion/diffusive heating.

The back-action of quantum measurement



MOT beams
7.5 cm
Trap
MOT
Zeeman-slowed
atomic beam
home of ring-trap
experiments
Cavity mounted
through here



Max coupling strength $g/2\pi$	16 MHz
Cavity half-linewidth $\kappa/2\pi$	0.8 MHz
Atomic half-linewidth $\gamma/2\pi$	3 MHz
Finesse/Q	$5.5\text{x}10^5/3\text{x}10^8$
Beam waist	23 μm
Critical atom number	0.019
Critical photon number	0.018

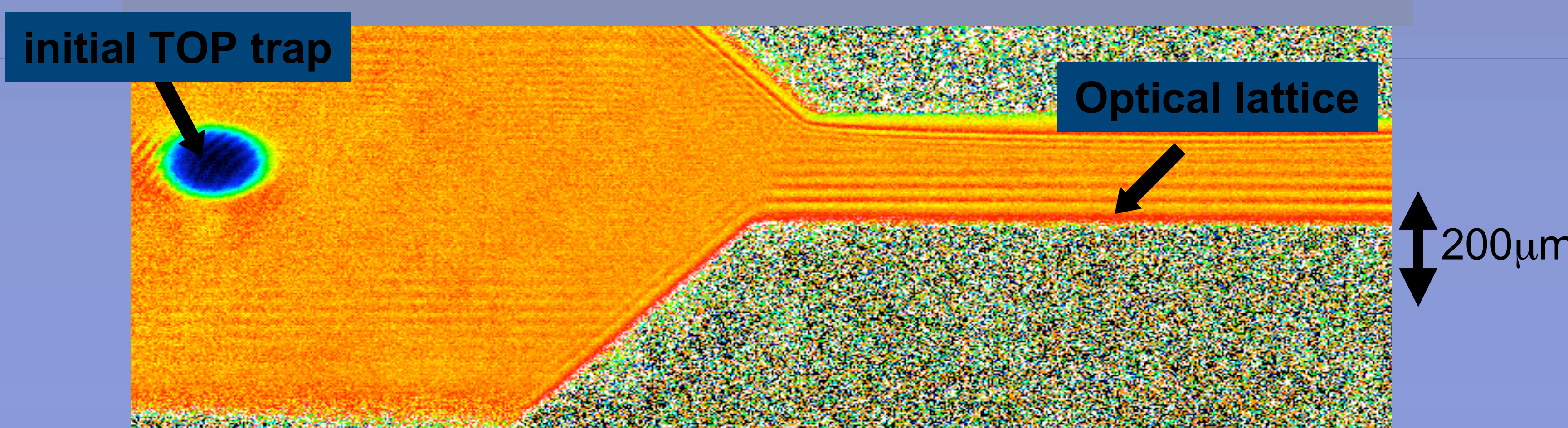
Single-atom
Strong coupling

"Building" a ground state resonator

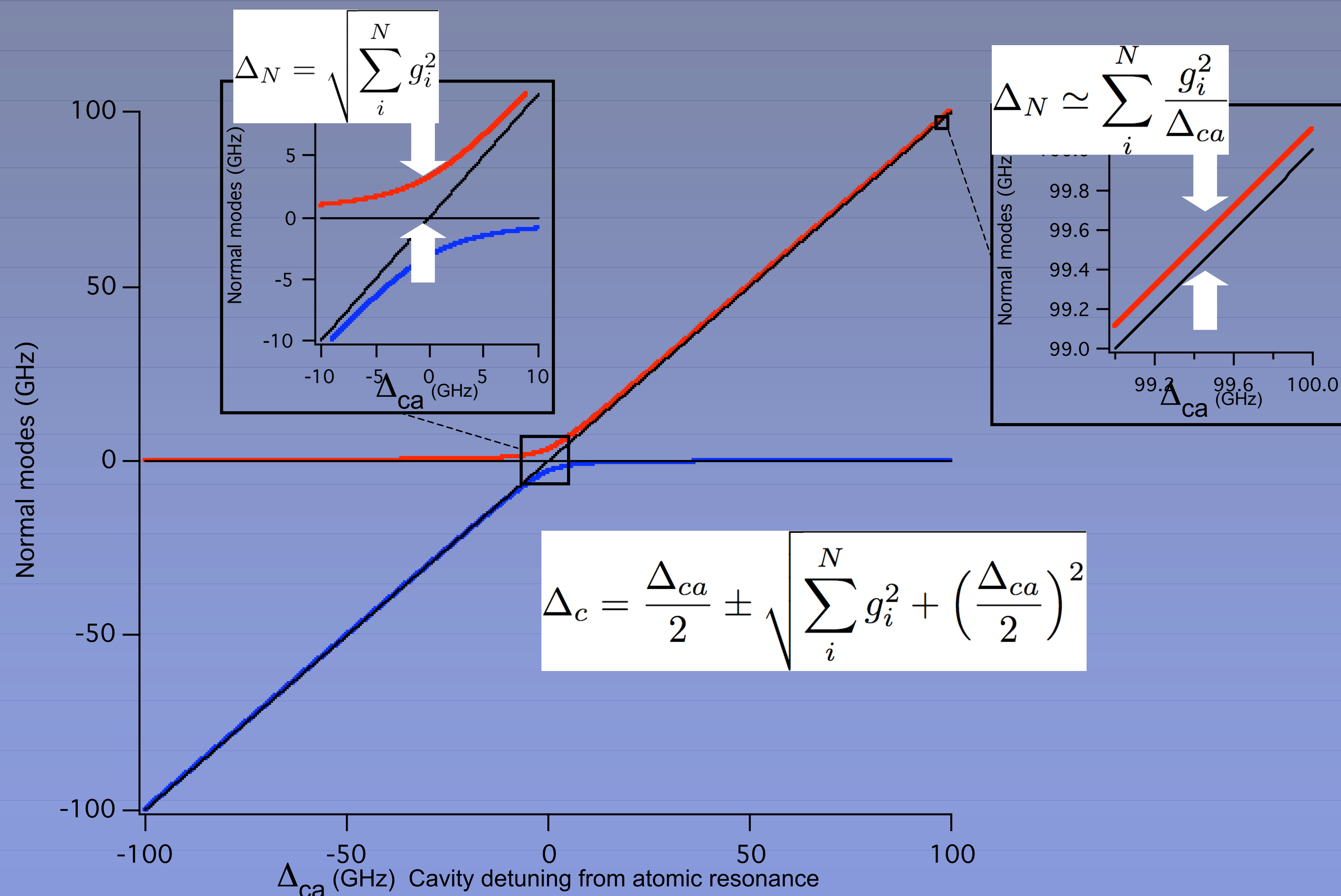
- Magnetic trapping outside cavity (TOP trap)
- Evaporative cooling
- Translation of the magnetic trap to within the cavity mode
- Transfer to 1D optical lattice inside cavity + turn off magnetic trap

  Result: ~50,000 atoms trapped in ~200 sites of the in-cavity standing wave trap, at T ~ 1 _K (20 kHz)

Note: Following the lead of Vuletic, Chapman, Zimmermann, Hemmerich, Esslinger, Reichel; Walther, Blatt



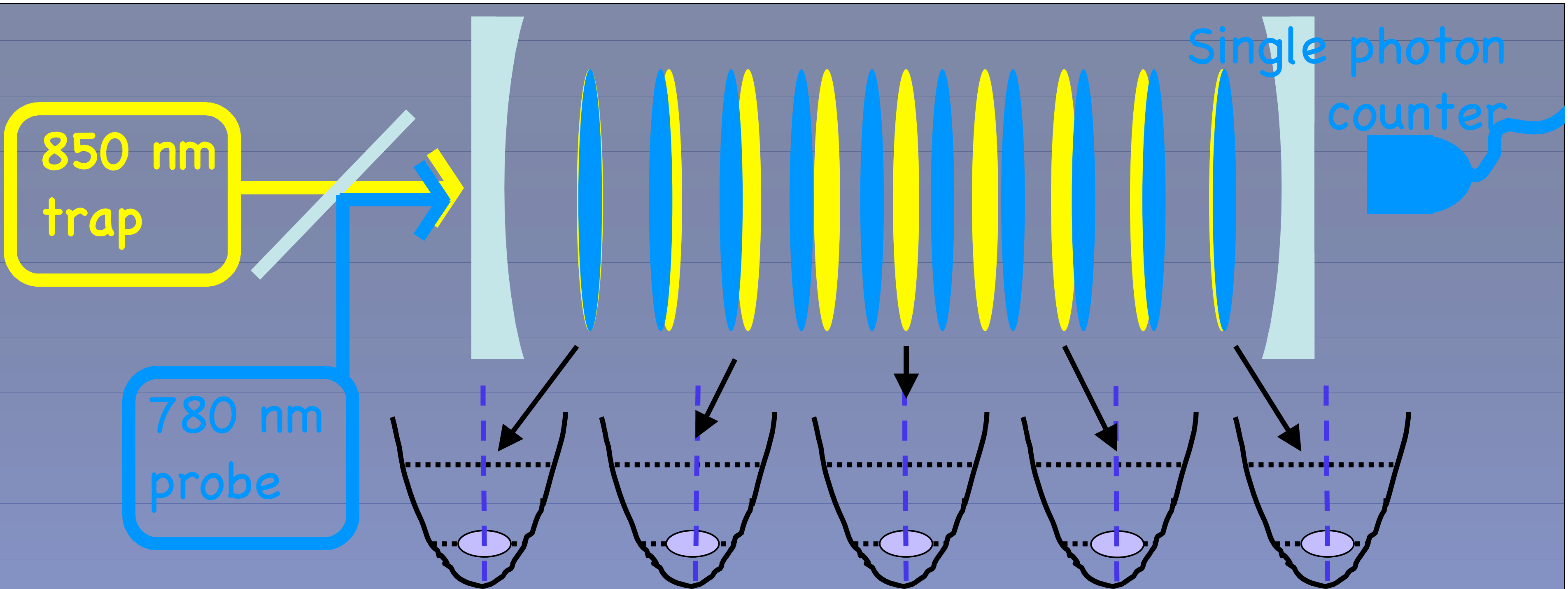
Normal Mode Spectrum



$$\Delta_N = \sqrt{\sum_i^N g_i^2}$$

$$\Delta_N \simeq \sum_i^N \frac{g_i^2}{\Delta_{ca}}$$

$$\Delta_c = \frac{\Delta_{ca}}{2} \pm \sqrt{\sum_i^N g_i^2 + \left(\frac{\Delta_{ca}}{2}\right)^2}$$

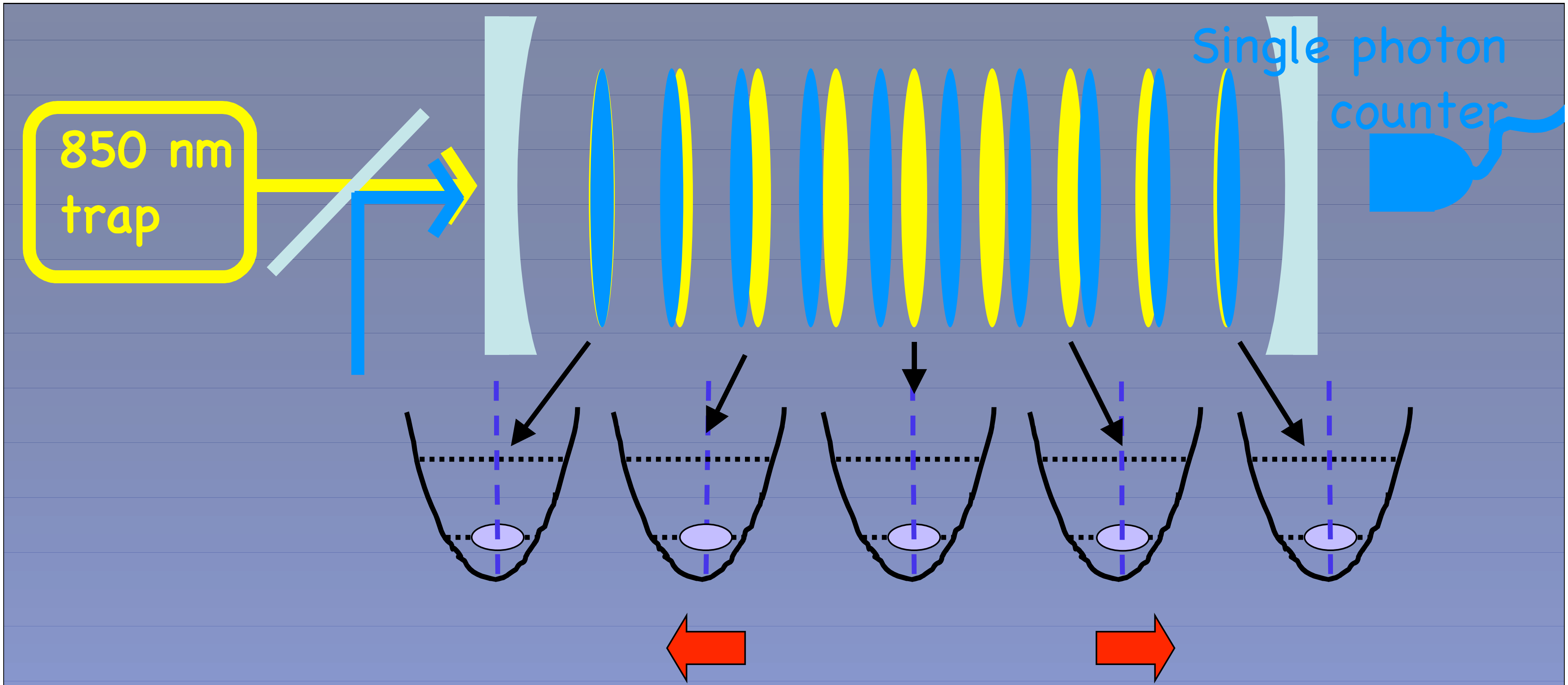


$$\Delta_N = \sum_i^N \frac{g_i^2}{\Delta_{ca}} \simeq \frac{g_0^2}{\Delta_{ca}} \sum_i^N \Big(\sin^2(k\bar{z}_i) + k \sin(2k\bar{z}_i)\Delta z_i \Big)$$

$$= \frac{N g_0^2}{2\Delta_{ca}} \Big(1 + kZ \Big)$$

Define collective position and momentum operators:

$$Z = \frac{2}{N} \sum \sin(2k\bar{z}_i)\Delta z_i \qquad P = \sum \sin(2k\bar{z}_i) p_i$$



Cavity based probe measures the collective position displacement Z

Single atom strong coupling: Granularity?

Does the "granularity" of individual photons matter?

Compare the impulse imparted to the collective motion due to the force of a single photon, $f_i = -\hbar\, \partial_z (g^2(z)/\Delta_{ca}) = f_0 \sin(2k\bar{z}_i)$

over the lifetime of a cavity photon $(2\kappa)^{-1}$

To the zero-point momentum fluctuations of the atomic ensemble

$$\epsilon = \frac{N f_0}{4\kappa} \Big/ \frac{\hbar}{2 Z_{ho}}$$

Collective Atom - Cavity dynamics

$$Z = Z_{ho}(c^\dagger + c)$$

$$\mathcal{H} = \hbar\omega_c' n - \hbar\epsilon\kappa(c^\dagger + c)(n - \bar{n}) + \hbar\omega_z c^\dagger c + \mathcal{H}_{in}$$

With $\epsilon \ll 1$ the energy of the collective mode changes as:

$$\frac{d}{dt}\langle c^\dagger c\rangle = \kappa^2\epsilon^2 \left[S_{nn}^{(-)} + \left(S_{nn}^{(-)} - S_{nn}^{(+)} \right) \langle c^\dagger c\rangle \right]$$

The spectral density of photon number fluctuations:

$$S_{nn}^{(\pm)} = \frac{2\bar{n}\kappa}{\kappa^2 + (\Delta \pm \omega_z)^2}$$

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Heating/Amplification

Cooling

Measurement Back-action

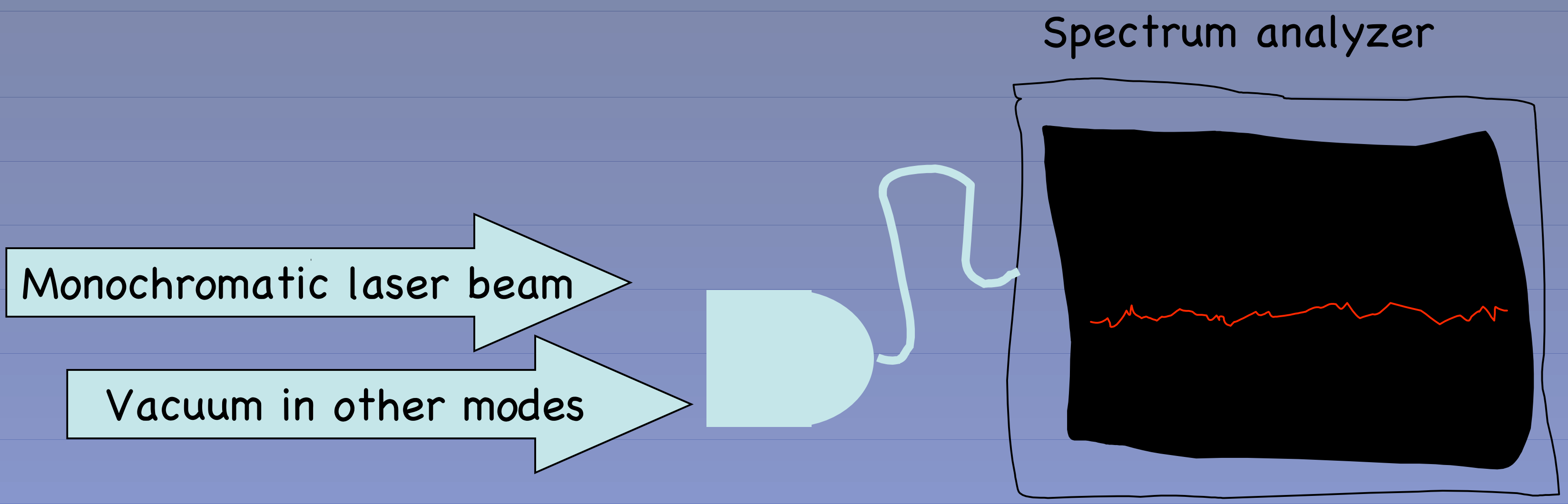
$$\frac{d}{dt}\langle c^\dagger c\rangle = \kappa^2\epsilon^2\left[S_{nn}^{(-)} + \boxed{\left(S_{nn}^{(-)} - S_{nn}^{(+)}\right)\langle c^\dagger c\rangle}\right]$$

"Dynamical Back-action"

The spectral density of photon number fluctuations:

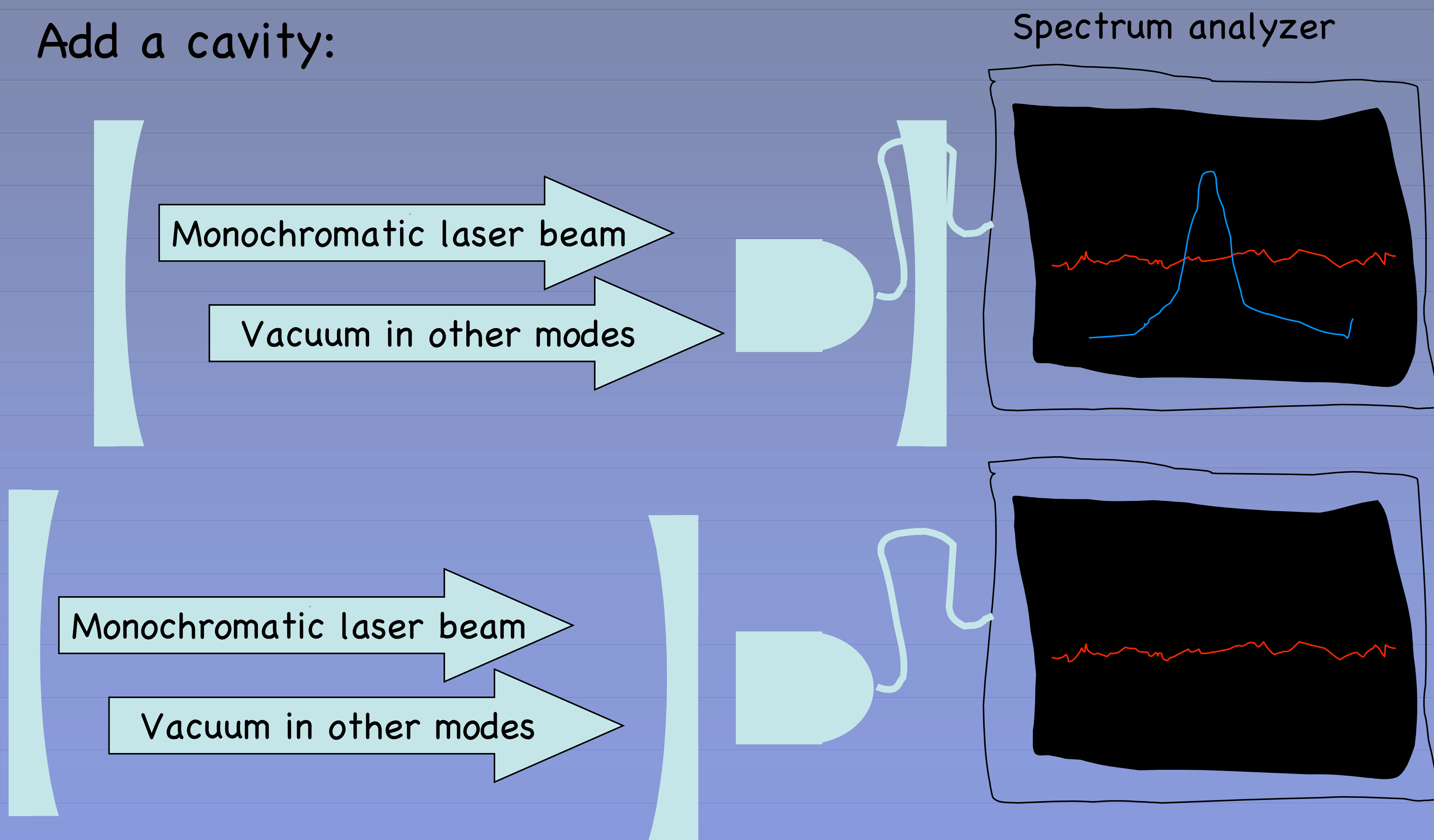
$$S_{nn}^{(\pm)} = \frac{2\bar{n}\kappa}{\kappa^2 + (\Delta \pm \omega_z)^2}$$

Spectrum of intensity fluctuations: White Noise

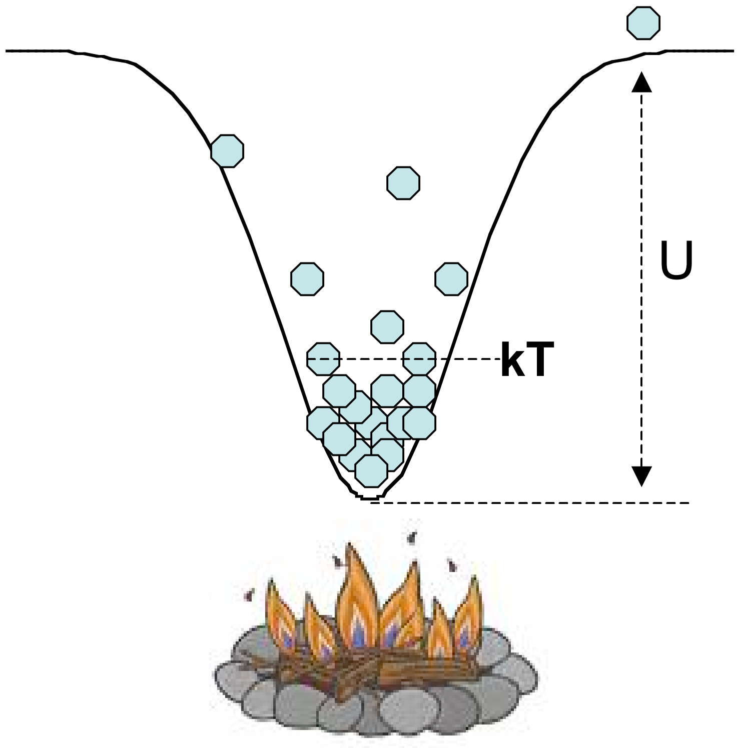


Spectrum of intensity fluctuations: Colored Noise

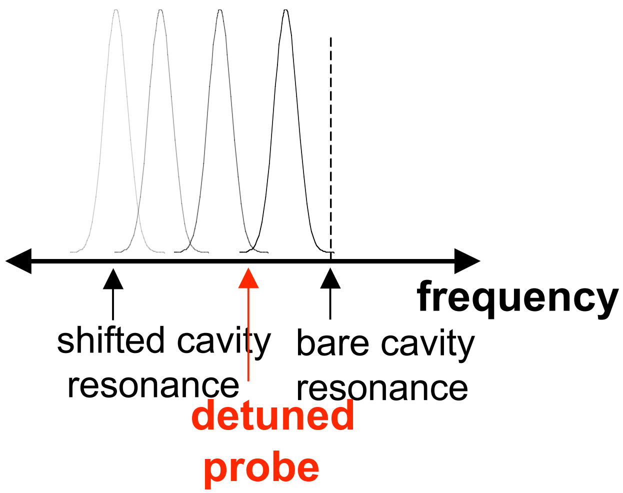
Add a cavity:

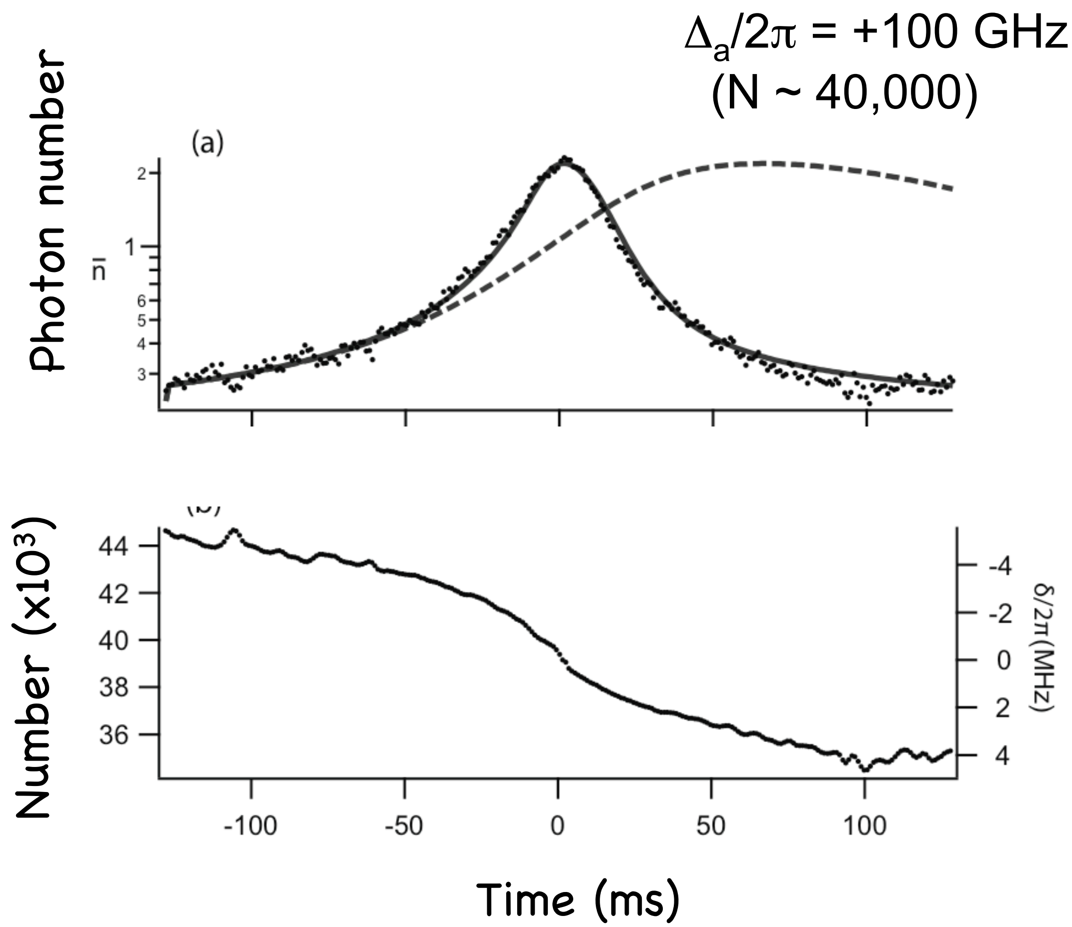


An Intracavity Atomic Flucutation Bolometer



Measurement of Backaction heating





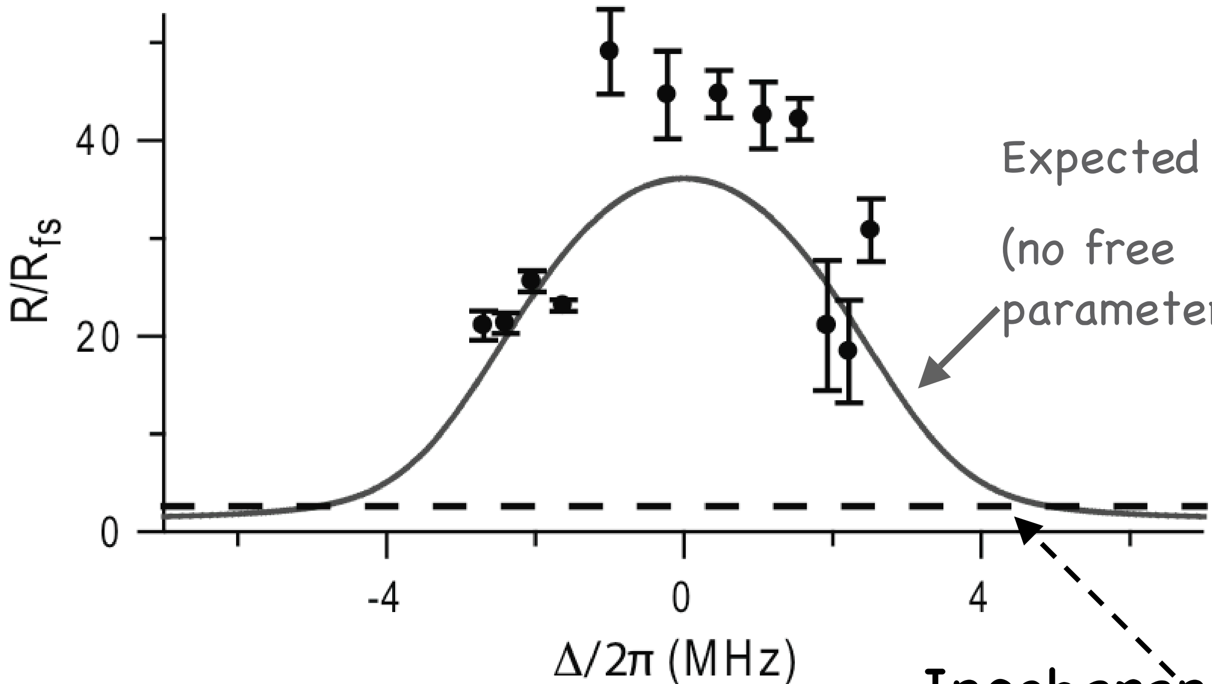
Simultaneous Measurements of N, and $\bar{n}$:

Overall timescale is long compared to evaporative timescale ~3ms

Temperature remains constant: 4ms TOF images

Back-action heating/Spectral density of photon number fluctuations in the cavity

$$R = \frac{\hbar\omega}{N}\frac{d}{dt}\langle c^\dagger c\rangle + R_{\text{fs}}$$



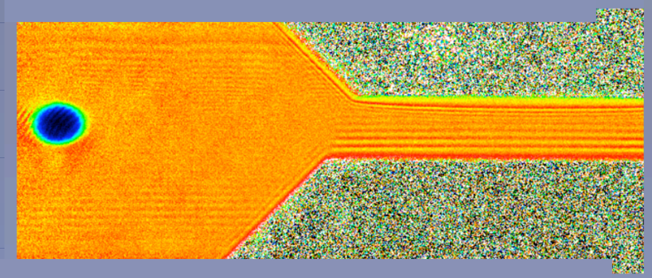
Expected Diffusion

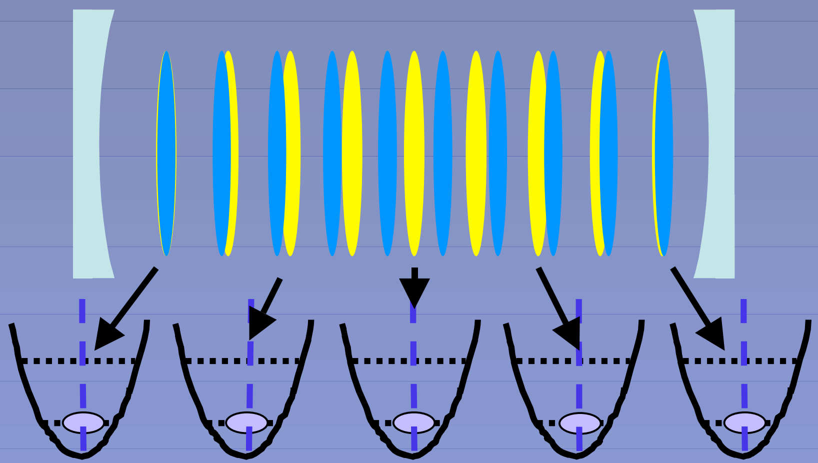
(no free parameters)

Incoherent "regular" light induced heating rate

Take home messages:

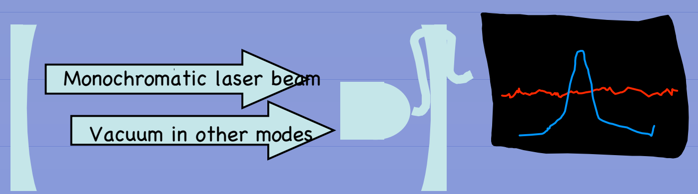
Using laser cooling and evaporation to construct a ground state resonator





Cavity mode structure selects a single collective mode that is measured, actuated by the optical field, and is subject to measurement backaction by quantum force fluctuations of the field.

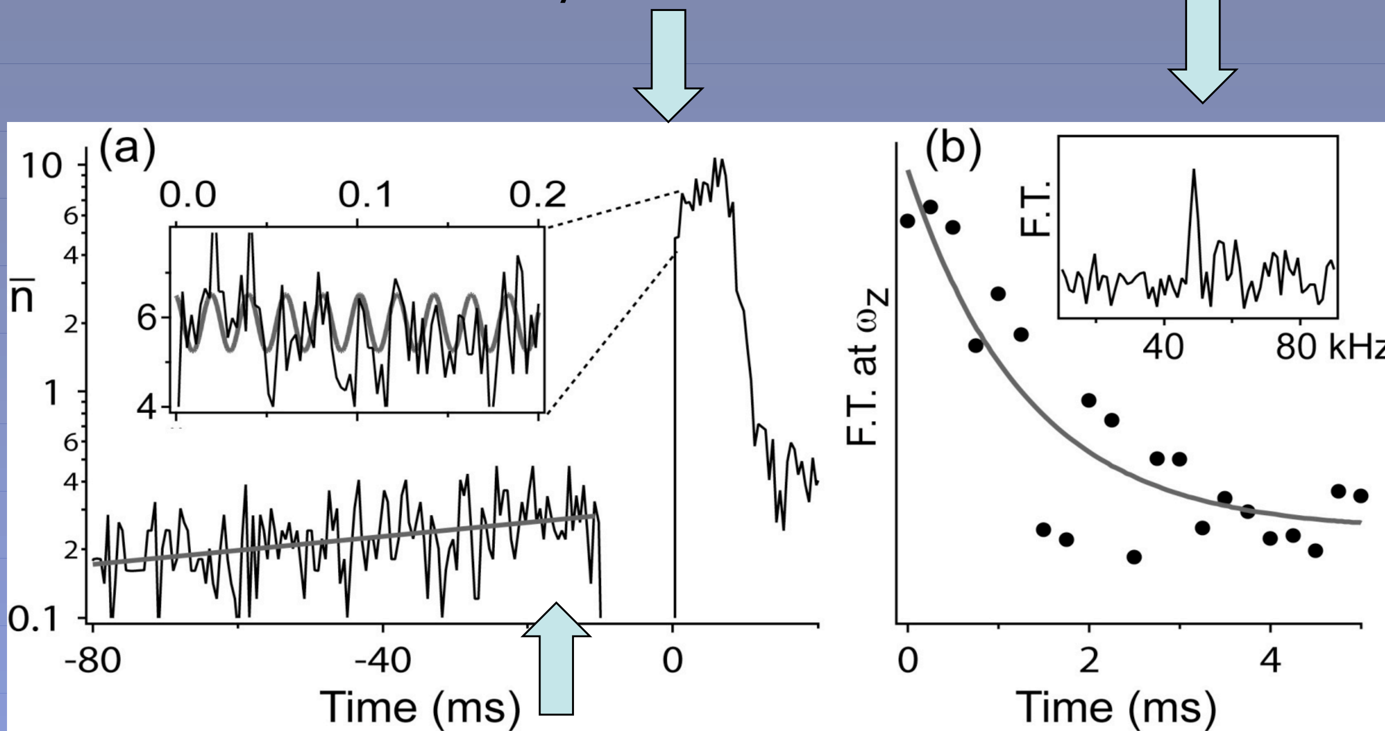
Relevance to Quantum optics colored spectrum of fluctuations is not visible in light transmitted through the cavity



Direct observation of collective motion

excite collective motion
diabatically and observe

single-shot detection



wait for cavity to come
into resonance

Observed motion has amplitude of ~2nm, Z_{ho}~0.2nm

(from Gupta et al PRL 99 213601 (2007))