Group Meeting

Jan 14th, 2009

Alma Bardon

Cavity Optomechanics with a Bose-Einstein Condensate

Ferdinand Brennecke,* Stephan Ritter,* Tobias Donner, Tilman Esslinger†

Cavity optomechanics studies the coupling between a mechanical oscillator and the electromagnetic field in a cavity. We report on a cavity optomechanical system in which a collective density excitation of a Bose-Einstein condensate serves as the mechanical oscillator coupled to the cavity field. A few photons inside the ultrahigh-finesse cavity trigger strongly driven back-action dynamics, in quantitative agreement with a cavity optomechanical model. We approach the strong coupling regime of cavity optomechanics, where a single excitation of the mechanical oscillator substantially influences the cavity field. The results open up new directions for investigating mechanical oscillators in the quantum regime and the border between classical and quantum physics.

Dynamical Coupling between a Bose-Einstein Condensate and a Cavity Optical Lattice

Stephan Ritter[1,2], Ferdinand Brennecke[1], Christine Guerlin[1],
Kristian Baumann[1], Tobias Donner[1,3], Tilman Esslinger[1*]
[1] *Institute for Quantum Electronics, ETH Zürich, CH-8093 Zürich, Switzerland*
[2] *Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany*
[3] *JILA, University of Colorado and National Institute of Standards and Technology, Boulder CO 80309, USA*

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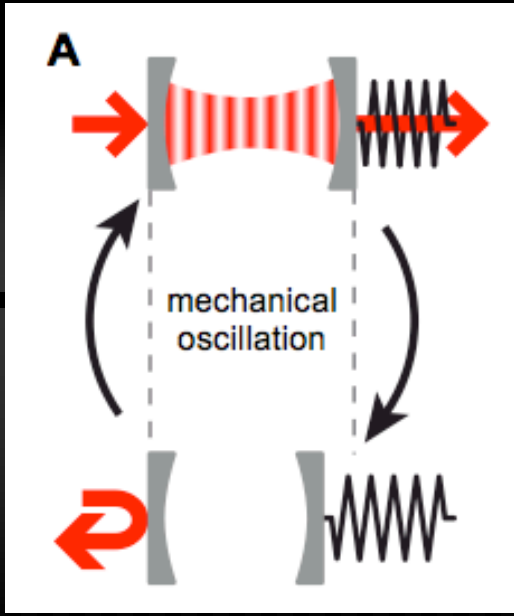
A Bose-Einstein condensate is dispersively coupled to a single mode of an ultra-high finesse optical cavity. The system is governed by strong interactions between the atomic motion and the light field even at the level of single quanta. While coherently pumping the cavity mode the condensate is subject to the cavity optical lattice potential whose depth depends nonlinearly on the atomic density distribution. We observe optical bistability already below the single photon level and strong back-action dynamics which tunes the coupled system periodically out of resonance.

Cavity Optomechanics

- Optomechanics
  - Light affects motional degree of freedom via exchange of momentum
    - "Radiation pressure force"
- Cavities
  - Increase coupling between photon mode and something else
    - Cavity photon makes many round trips ➔ increased interaction time
- Cavity optomechanics
  - Coupling between mechanical oscillator and a cavity field

Cavity mirror as mechanical oscillator

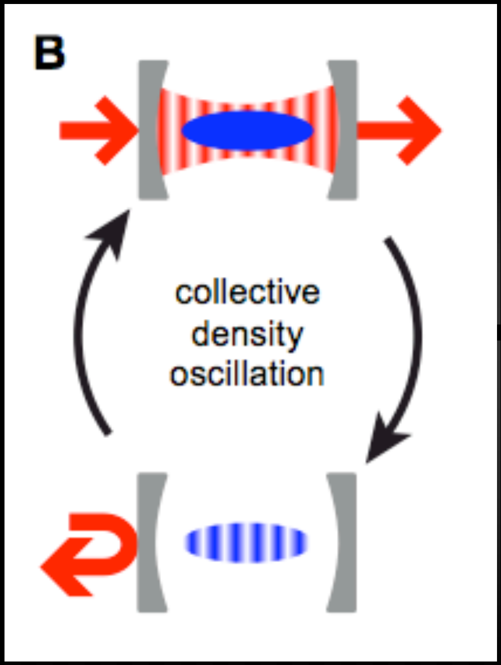


cavity length depends on displacement of oscillator

motion of oscillator affected by radiation pressure

n.b. Laser cooling of the mechanical mode

Collective density excitation of BEC as mechanical oscillator



field can excite collective density excitation

optical path length depends on atomic density distribution

Figure 1

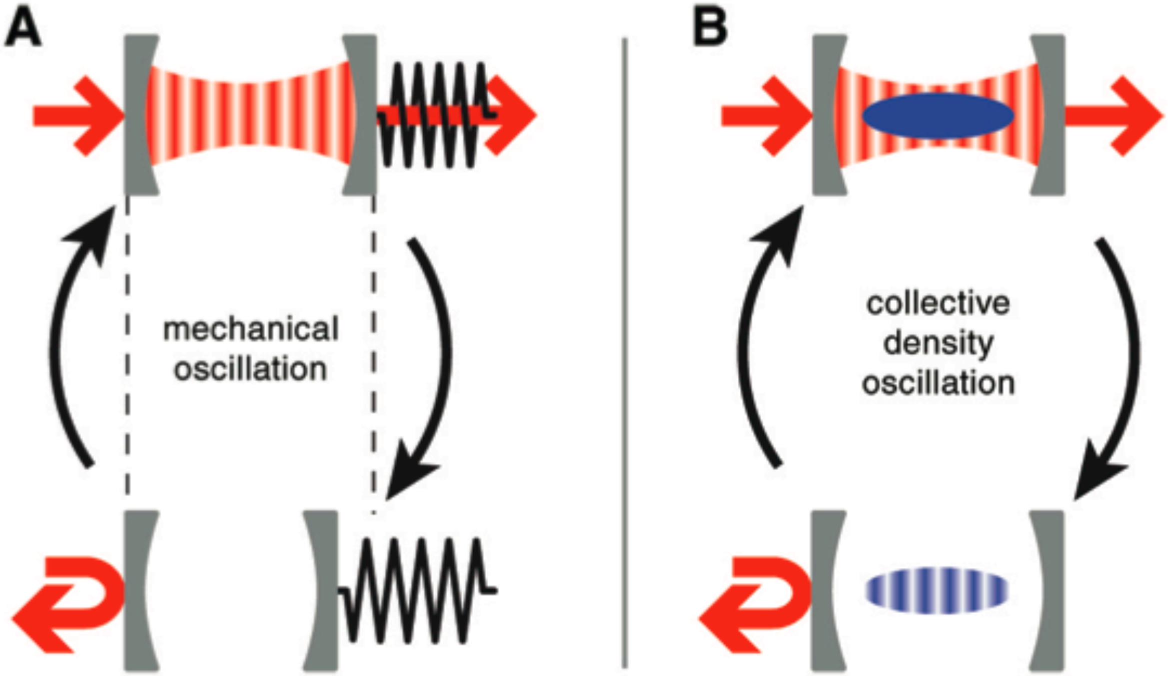
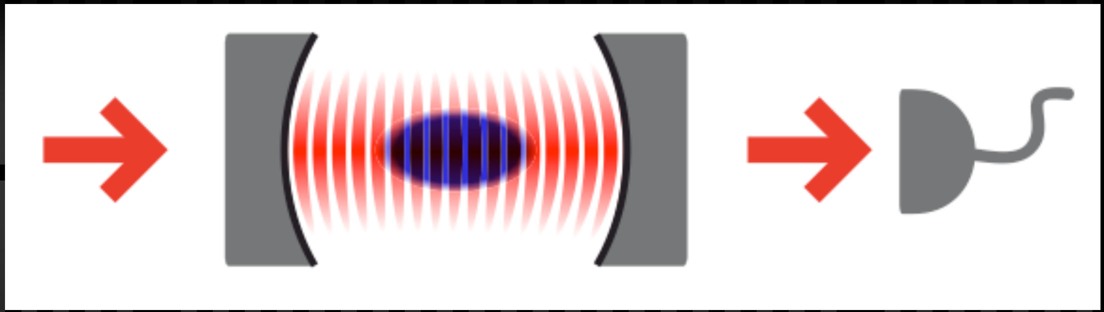


Fig. 1. (**A**) Cavity optomechanical model system. A mechanical oscillator, here one of the cavity mirrors, is coupled via radiation pressure to the field of a cavity whose length depends on the oscillator displacement. (**B**) Coupling a BEC dispersively to the field of an optical high-finesse cavity constitutes an equivalent system. Here, a collective density excitation of the condensate acts as the mechanical oscillator, which strongly couples to the cavity field. Feedback on the cavity field is accomplished by the dependence of the optical path length on the atomic density distribution within the spatially periodic cavity mode structure. In contrast to optomechanical systems presented so far, this mechanical oscillator is not based on the presence of an external harmonic potential (e.g., a spring); rather, it is provided by kinetic evolution of the condensate density excitation.

The Experiment

Weak pump



Single photon counter

$\Delta_a = \omega_p - \omega_a \geq 10^4\gamma$

➔ignore spontaneous emission

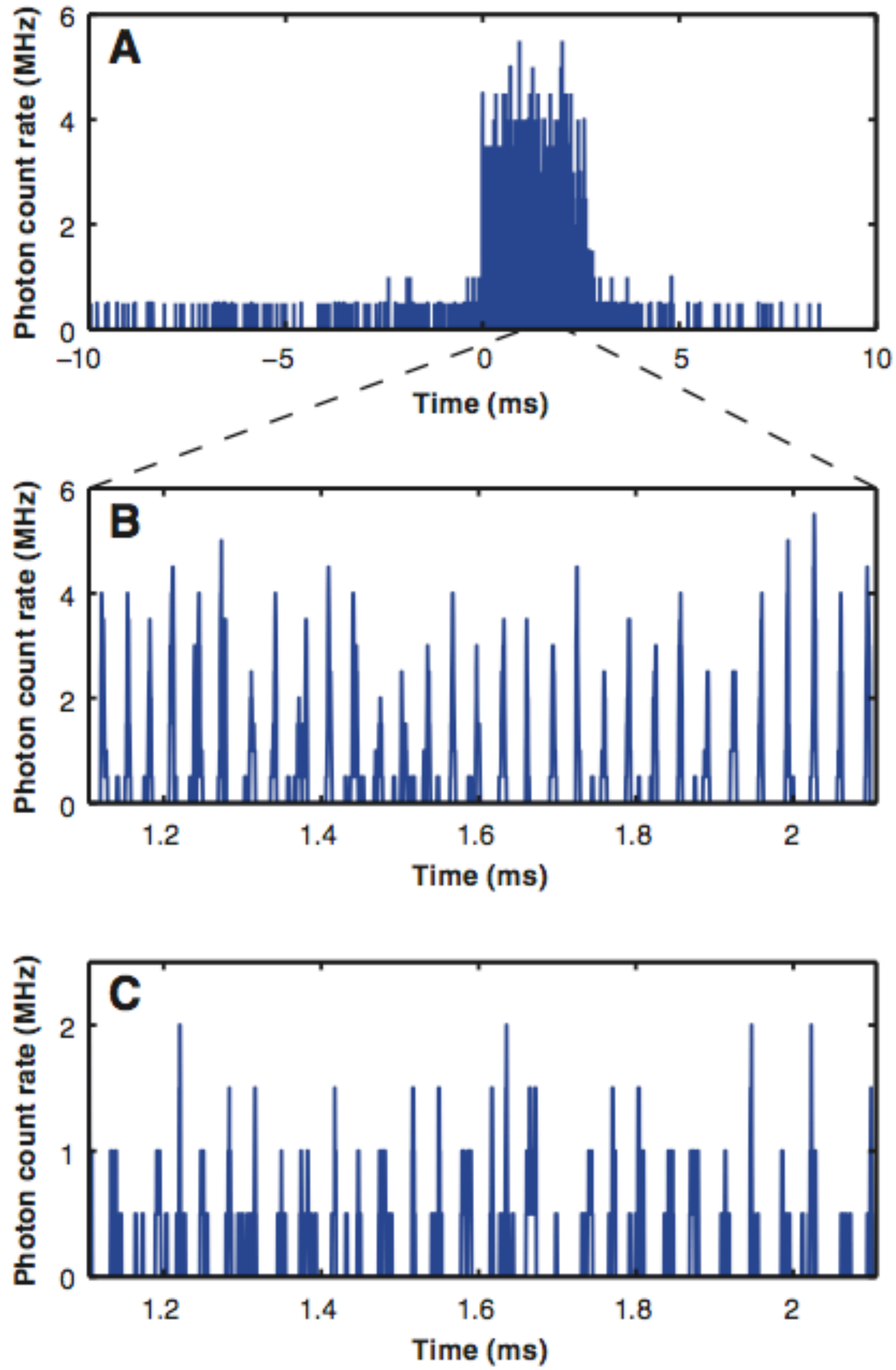
$\Delta_c = \omega_p - \omega_c$

ramp Δ_c across resonance

Experiment

- BEC of 1.2×10^5 ^{87}Rb in $|F,m_F\rangle = |1,-1\rangle$
  - Optically trapped
  - $\omega = 2\pi \times (222,37,210)$Hz
  - $R_{TF} = (3.3,20.0,3.5)\mu m$
- Ultrahigh finesse Fabry-Perot cavity
  - $g_0 = 2\pi \times 10.9$MHz
  - $\gamma = 2\pi \times 3.0$MHz (strong coupling regime)
  - $\kappa = 2\pi \times 10.9$MHz
  - Cavity length = $178\mu m$
  - TEM_{00} waist = $25\mu m$ (maximal overlap of mode and condensate)

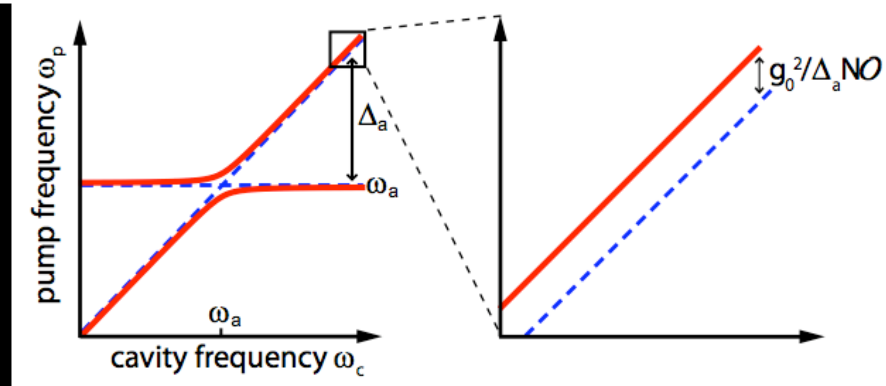
Fig. 2. (**A** to **C**) Response of the continuously driven BEC-cavity system. Shown is a single trace of the cavity transmission (averaged over 2 μs) while scanning the cavity-pump detuning at a rate of $+2\pi \times 2.9$ MHz/ms across its σ^- resonance (*17*). The pump rate corresponds to a mean intracavity photon number on resonance of 7.3 ± 1.8 [(A) and (B)] and 1.5 ± 0.4 (C). The photon count rate for one mean intracavity photon is 0.8 ± 0.2 MHz. The dead time of the single-photon counter is 50 ns, which leads to a saturation of high photon count rates. The pump laser was blue-detuned by $\Delta_a = 2\pi \times 32$ GHz with respect to the atomic resonance.



If they were not coupling to the atomic external degree of freedom, this would look Lorentzian

The Theory

1D mean-field



Equations of motion for the coupled system

$$i\hbar\dot{\psi}(x,t) = \Big(\frac{-\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + |\alpha(t)|^2\hbar U_0\cos^2(kx) + V_{\text{ext}}(x) + g_{1\text{D}}|\psi|^2\Big)\psi(x,t) \quad (1)$$

$$i\dot{\alpha}(t) = -(\Delta_c - U_0 N\mathcal{O} + i\kappa)\alpha(t) + i\eta. \quad (2)$$

frame rotating at ω_p

spatial overlap $\mathcal{O} = \langle\psi|\cos^2(kx)|\psi\rangle$.

$\lambda = 2\pi/k = 780$ nm.

$U_0 = g_0^2/\Delta_a$

$\Delta_c = \omega_p - \omega_c$

$\Delta_a = \omega_p - \omega_a$

Zero momentum state of BEC is coupled to ±2hk momentum states (absorption and emission of cavity photons)

$\psi(x,t) = c_0(t) + c_2(t)\sqrt{2}\cos(2kx)$

The Theory: Steady State

First look for steady-state solutions:

variational ansatz

$$\psi(x) = c_0 + c_2\sqrt{2}\cos(2kx)$$

$$\mathcal{O} = \frac{1}{2} - \frac{|\alpha|^2 U_0}{16\omega_{\mathrm{rec}}}.$$

$$|\alpha|^2 = \frac{\eta^2}{\kappa^2 + (\Delta_c - U_0 N\mathcal{O})^2},$$

$$n_{\mathrm{cr}} = \frac{8}{3\sqrt{3}} \frac{16\kappa\omega_{\mathrm{rec}}}{NU_0^2}.$$

Bistable at high pump strength

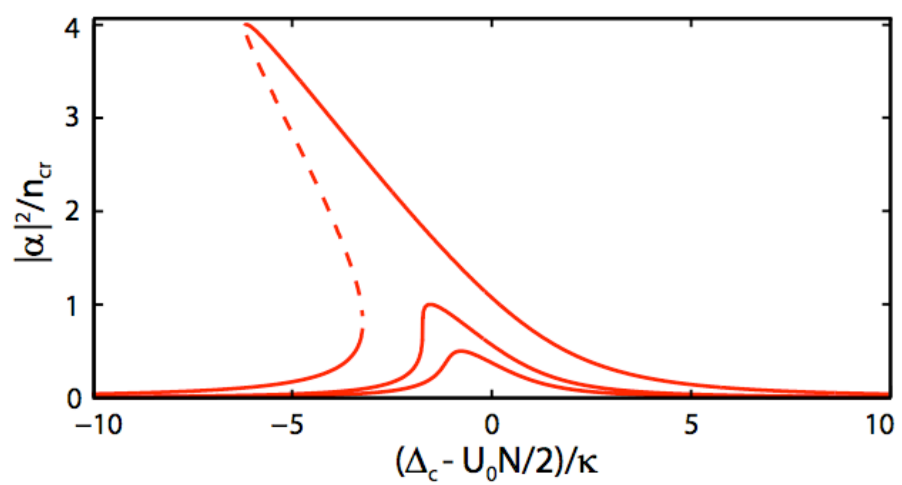


FIG. 2: Mean intracavity photon number $|\alpha|^2$ of the pumped BEC-cavity system versus the cavity-pump detuning Δ_c calculated for three different pump strengths $\eta = (0.7, 1, 2)\eta_{\mathrm{cr}}$ (bottom to top curve). The blue-detuned cavity light field pushes the atoms to regions of lower coupling strength which gives rise to bistability. The initially symmetric resonance curve centered around $\Delta_c = U_0 N/2$ develops above a critical pump strength η_{cr} a bistable region with two stable (solid lines) and one unstable branch (dashed).

The Theory: Dynamic

$$\psi(x,t) = c_0(t) + c_2(t)\sqrt{2}\,\cos(2kx),$$

$$X = 2\sqrt{1/N}\,\mathrm{Re}(c_0{}^*c_2) \qquad P = \hbar\sqrt{1/N}\,\mathrm{Im}(c_0{}^*c_2).$$

$$|c_2|^2/|c_0|^2 << 1$$

Equations of motion now look like this:

$$\ddot{X} + (4\omega_{rec})^2 X = -\omega_{rec} U_0 \sqrt{8N}\langle\hat{a}^\dagger\hat{a}\rangle \qquad (3)$$

$$i\dot{\hat{a}} = -(\Delta + i\kappa)\hat{a} + i\eta \qquad (4)$$

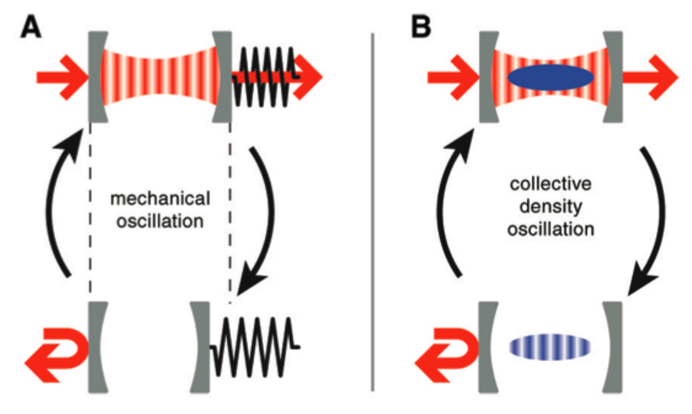
$$\Delta = \Delta_c - U_0 N/2 - U_0/2\sqrt{N/2}\,X$$

The Theory: Dynamic

$$\ddot{X} + (4\omega_{rec})^2 X = -\omega_{rec} U_0 \sqrt{8N} \langle \hat{a}^\dagger \hat{a} \rangle$$

$$i\dot{\hat{a}} = -(\Delta + i\kappa)\hat{a} + i\eta$$

$$\Delta = \Delta_c - U_0 N/2 - U_0/2 \sqrt{N/2}\, X$$



These equations describe a mechanical oscillator coupled via the radiation pressure force to the fields whose resonance frequency shift Δ depends linearly on the oscillator displacement X.

Now, numerically integrate…

Figure 3

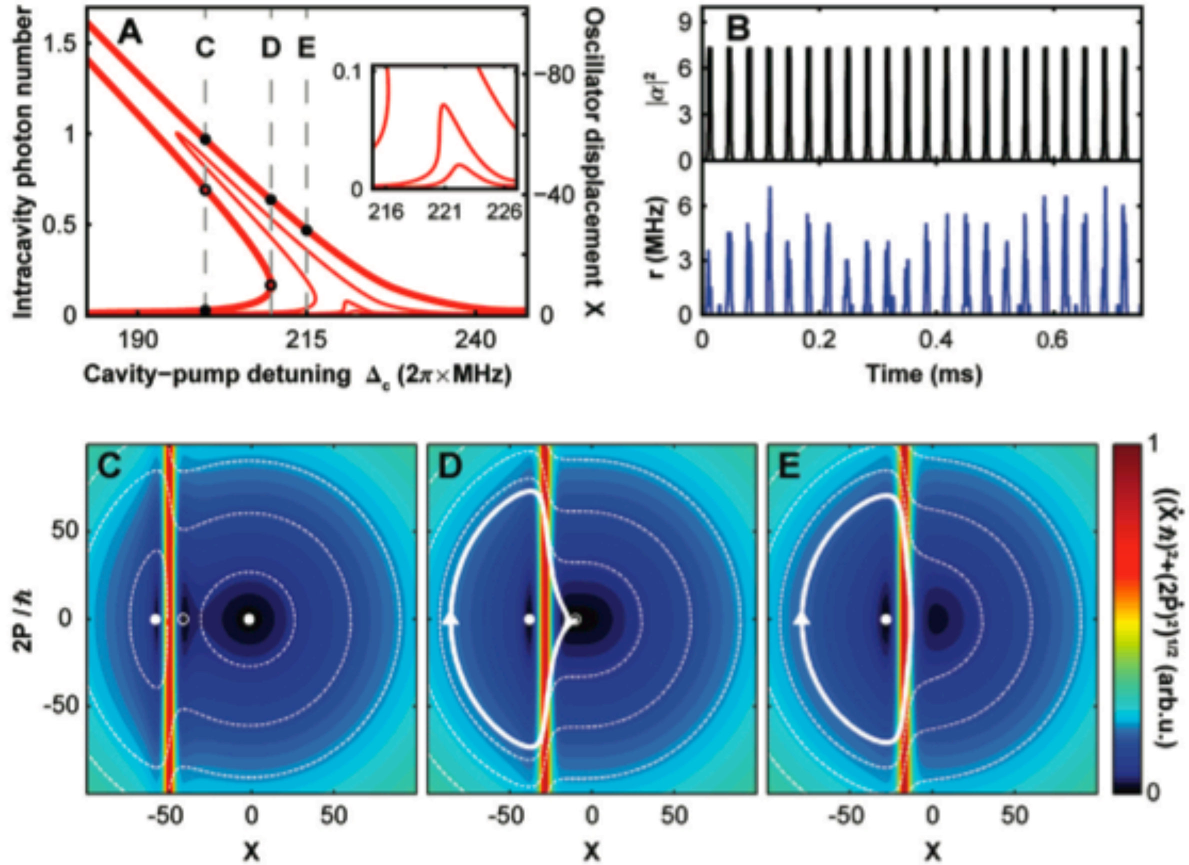


Fig. 3. Steady-state and dynamical behavior of the BEC-cavity system in the two-mode model. (**A**) Mean intracavity photon number and corresponding oscillator displacement X versus cavity-pump detuning Δ_c for the steady-state solutions of Eqs. 3 and 4. The curves correspond to mean intracavity photon numbers on resonance of $\eta^2/\kappa^2 = 0.02$, 0.07, 1, and 7.3, and a pump-atom detuning of $\Delta_a = 2\pi \times 32$ GHz. The inset highlights the bistable behavior for pump amplitudes larger than $\eta_{cr} \approx 0.27\kappa$. (**B**) Intracavity photon number $|\alpha|^2$ and corresponding transmission count rate r (including detection shot noise and averaging over 2 μs) for the system circling along the solid line in (E). For integration of the equations of motion, a coherent intracavity field α was assumed. (**C** to **E**) Evolution of the system in the mechanical phase space depicted for three subsequent situations [$\Delta_c = 2\pi \times (200, 209.7, 215)$ MHz] corresponding to the markers in (A) and $\eta^2/\kappa^2 = 7.3$. The stable and unstable steady-state configurations are displayed as solid and open circles, respectively. Dashed lines show representative evolutions for different starting conditions. Coloring indicates the modulus of the time evolution field ($\dot{X}$, $2\dot{P}/\hbar$). The solid lines in (D) and (E) correspond to the experimental situation in Fig. 2A and show the evolution of the system while scanning Δ_c at a rate of $2\pi \times 2.9$ MHz/ms across the resonance with the system initially prepared in the lower stable solution.

Figure 4

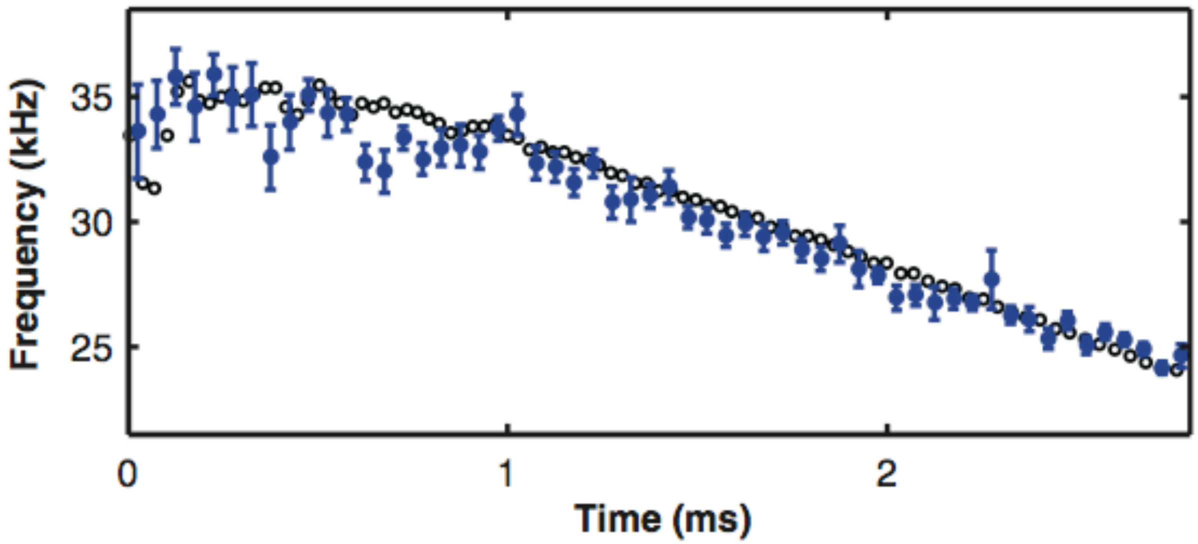
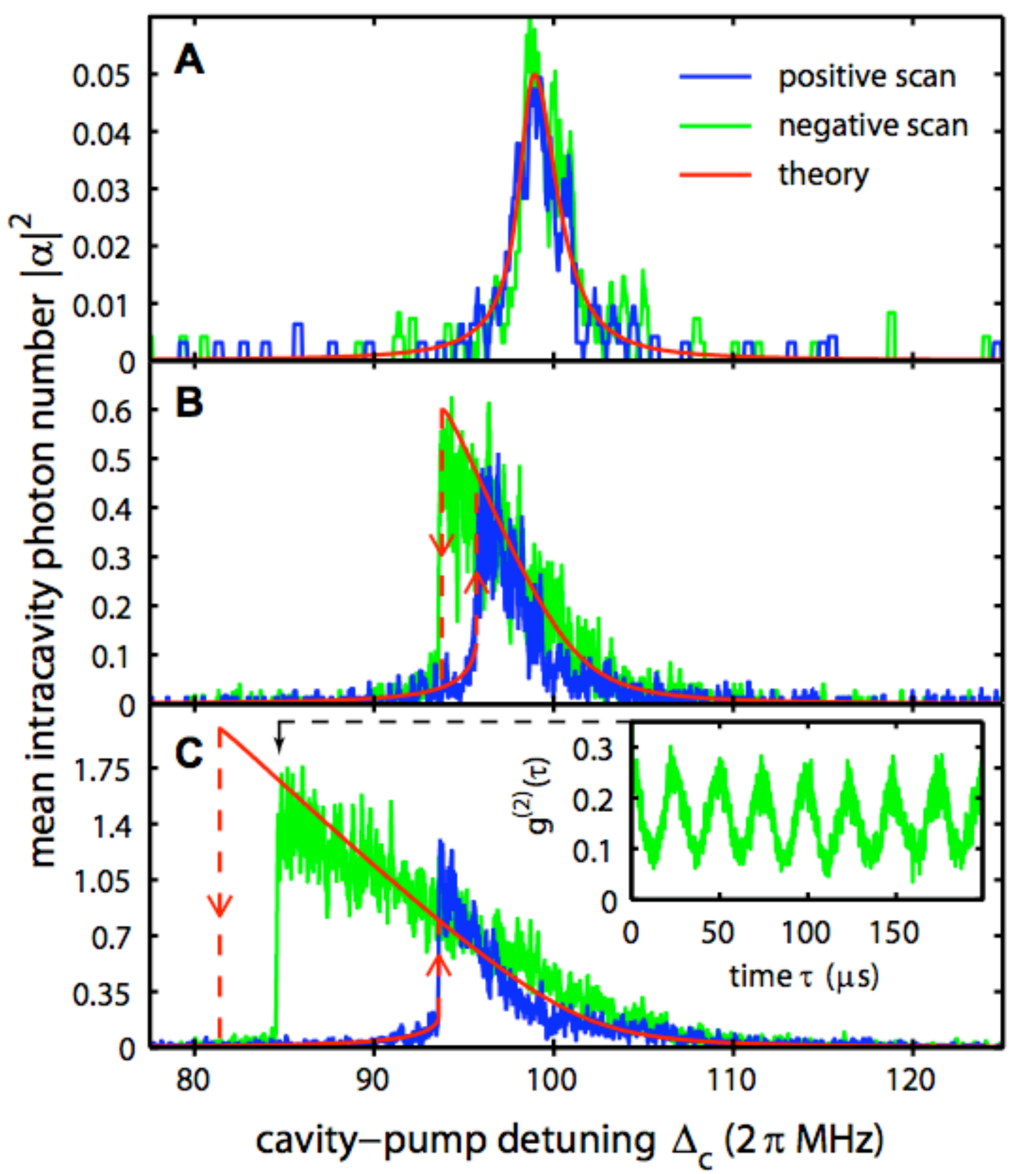


Fig. 4. Oscillation frequency while scanning over the resonance. The frequency within time bins of 50 μs was obtained from a peak-detection routine applied to the cavity transmission data averaged over 10 μs. The data (solid circles) are an average, ±SE, over 23 traces referenced to the start of the oscillations. Open circles show the result of a numerical integration of the one-dimensional system (Eqs. 1 and 2) taking atomic interactions and external trapping into account (*26*). The mean intracavity photon number on resonance was 3.6 ± 0.9. To fit the slope of the data, we added the effect of a dynamically induced atom loss during the time of oscillations of 1.5×10^3/ms to the experimental frequency chirp of $\dot{\Delta}_c = 2.9$ MHz/ms. The background rate of atom loss was measured to be 45/ms, and an atom number of $(116 \pm 18) \times 10^3$ was deduced from absorption images taken after the oscillations.

The newer paper measures the bistablilty…



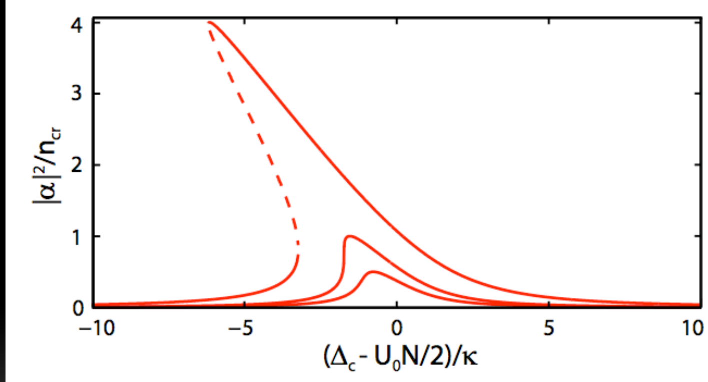


FIG. 3: Bistable behavior at low photon number. The traces show the mean intracavity photon number $|\alpha|^2$ versus the cavity-pump detuning Δ_c. Traces A, B and C correspond to pump strengths of $\eta = (0.22, 0.78, 1.51)\kappa$, respectively. The intracavity photon number is deduced from the detector count rate. Each graph corresponds to a single experimental sequence during which the pump laser frequency was scanned twice across the resonance, first with increasing detuning Δ_c (blue curve) and then with decreasing detuning (green curve). The scan speed was $2\pi \times 1\,\mathrm{MHz/ms}$ and the raw data has been averaged over 400 µs (A) and 100 µs (B and C). We corrected for a drift of the resonance caused by an atom loss rate assumed to be constant during the measurement. The theoretically expected stable resonance branches (red) have been calculated for 10^5 atoms taking a transverse mode overlap at maximum of 0.6 into account. The inset of C shows photon-photon correlations of the green trace calculated from the last 400 µs right before the system transits to the lower stable branch. Due to averaging these oscillations are not visible in the main graph.

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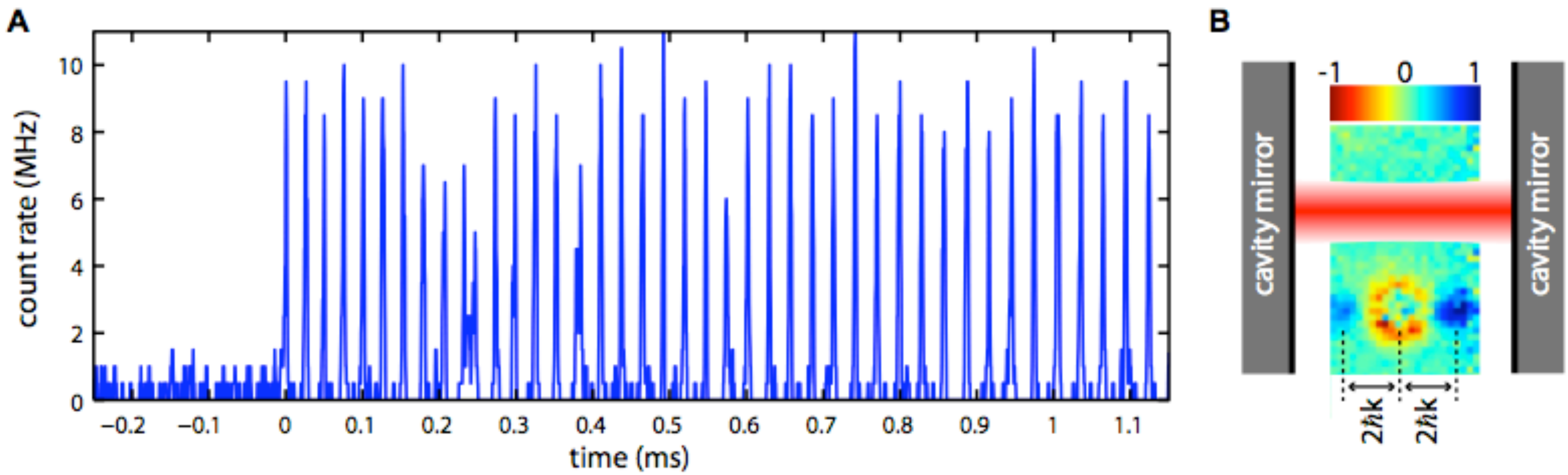

FIG. 4: **A.** Coherent dynamics of the BEC in the dynamical lattice potential. Shown is the count rate of the single photon detector while scanning with increasing cavity-pump detuning across the bistable resonance curve. The scan speed was set to $2\pi \times 2\,\mathrm{MHz/ms}$ with a maximum intracavity photon number of 9.5. The condensate is excited due to the non-adiabatic branch transition resulting in oscillations of the overlap $\mathcal{O}$ clearly visible in a periodic cavity output. **B.** Absorption image revealing the population in the $|p = \pm 2\hbar k\rangle$ momentum components during the coherent oscillations. Once the coherent dynamics was excited both trapping potential and pump laser were switched off and the cloud was imaged after 4 ms free expansion. To clearly detect the small $|p = \pm 2\hbar k\rangle$ population we averaged over 9 independent images and subtracted the average of 9 different images without excitation (taken after the oscillations had stopped [17]).

[redacted]

Summary

- ✓ They coupled a cavity mode to a collective density excitation of a BEC
- ✓ Bistable behavior, like a normal cavity optomechanical model
- ✓ "back-action" dynamics tune the system periodically out of resonance