Photons refrigerating phonons

Optomechanics is a promising route towards the observation of quantum effects in relatively large structures.

Three papers, each discussing a different implementation, now combine optical sideband and cryogenic cooling to refrigerate mechanical resonators to fewer than 60 phonons.

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Three Optomechanical Resonators

- Andrew Cleland, Nat-Phys., 5 (2009) p. 458
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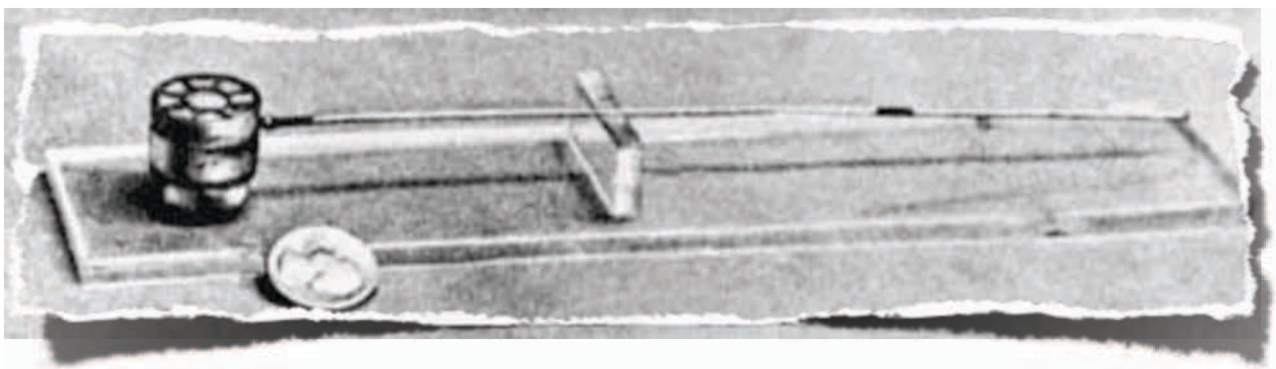
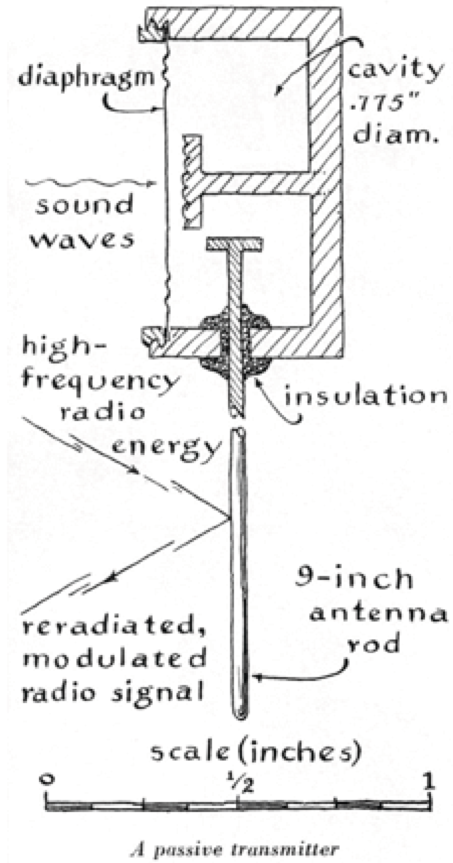
Review

- 1946: Mechanical modulation of resonators (the Great Seal Bug)
- 2004: Quantized vibrations: Phonons in a cold "nano-beam"
- 1989: Laser cooling of ions (and Wineland's Nobel Prize 2012)

“The Thing”

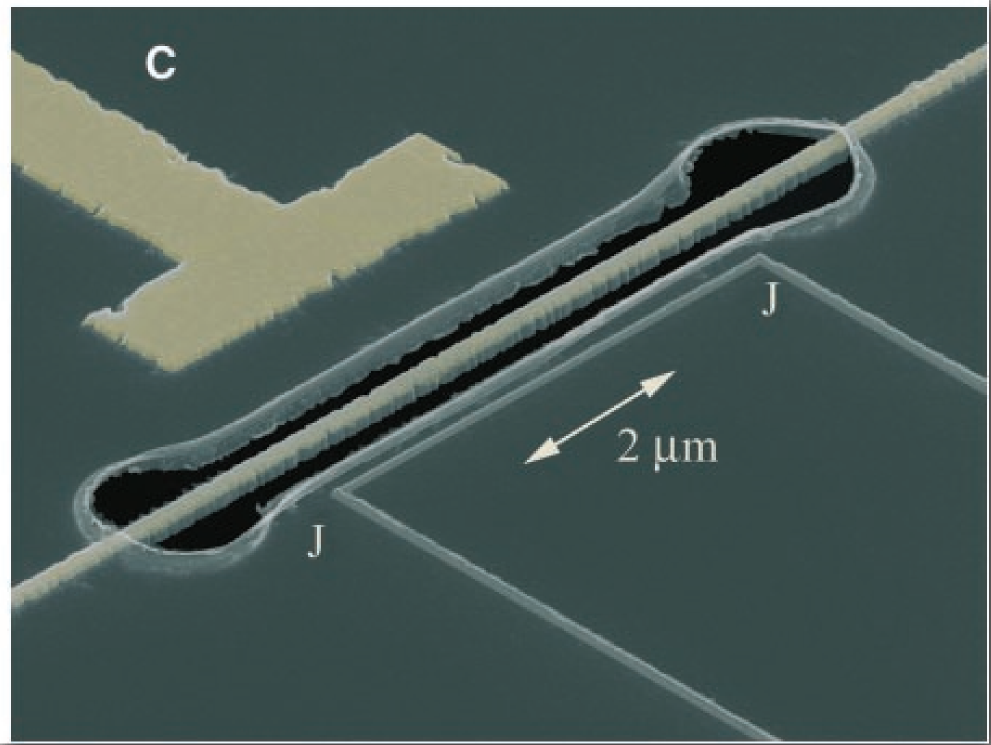




(from Scientific American, 1968)

19.7 MHz Nanomechanical Resonator

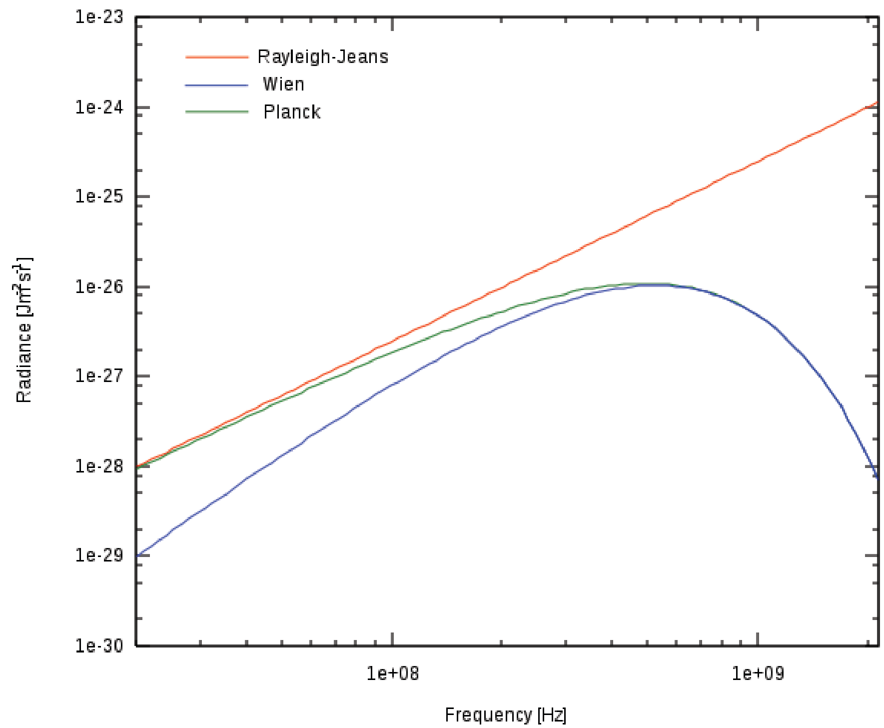
(C) Details of the 19.7-MHz nanomechanical resonator (**200 nm wide, 8 μm long, coated with 20 nm of Au atop 100 nm SiN**), defined by the regions in black where the SiN has been etched through. The SSET island (5 μm long and 50 nm wide) is positioned 600 nm away from the resonator. Tunnel junctions, marked "J," are located at corners. A 70-nm-thick gold gate is positioned to the right of the resonator and is used both to drive the resonator and to control the bias point of the SSET.



Quanta of Oscillations

(19.7 MHz Phonons)

T	n_i
1.4 mK	1
2.3 mK	2
47.7 mK	50



$$n_i = \frac{1}{\exp(\hbar\omega/kT) - 1} \rightarrow \frac{kT}{\hbar\omega} \text{ for } kT \gg \hbar\omega$$

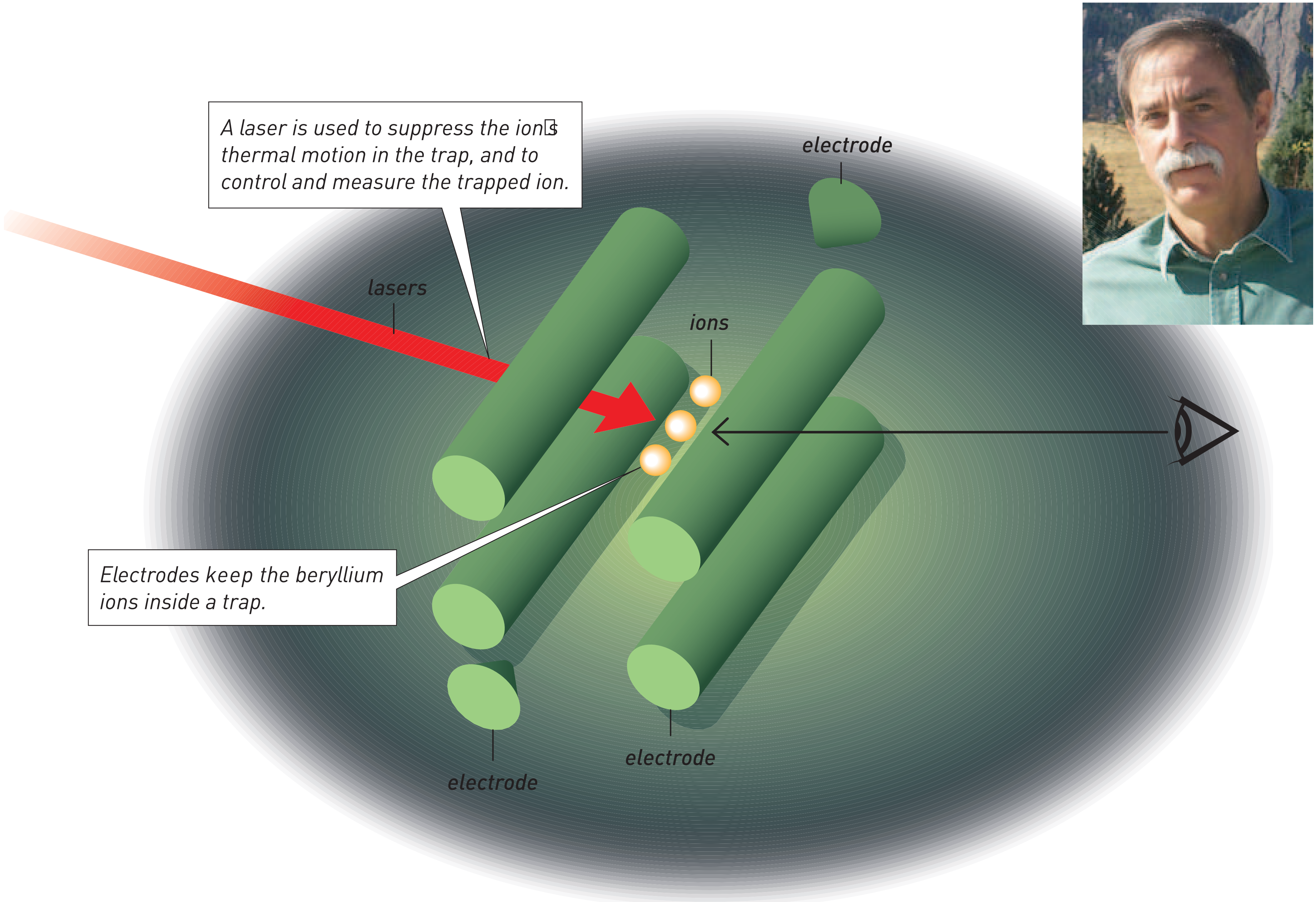


Figure 2. In David Wineland's laboratory in Boulder, Colorado, electrically charged atoms or ions are kept inside a trap by surrounding electric fields. One of the secrets behind Wineland's breakthrough is mastery of the art of using laser beams and creating laser pulses. A laser is used to put the ion in its lowest energy state and thus enabling the study of quantum phenomena with the trapped ion.

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Laser cooling of atoms

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(Received 16 May 1979)

Various aspects of the laser cooling of atoms are investigated theoretically. More generally, the authors investigate a process through which the kinetic energy of a collection of resonant absorbers can be reduced by irradiating these absorbers with near-resonant electromagnetic radiation. The process is described here as anti-Stokes spontaneous Raman scattering. Cooling mechanisms, rates, and limits are discussed for both free and bound atoms.

B. Laser cooling of free atoms

Assume that we have an unbound gas of atoms (or resonant absorbers in general) which possess a resonant electric dipole transition (frequency, ν_0) in some convenient spectral region with radiative linewidth $\gamma/2\pi$ (full width at half-intensity points). Now suppose that we irradiate these atoms with monochromatic, directed, low intensity radiation tuned near, but slightly lower than, the resonance frequency. We assume that the in-

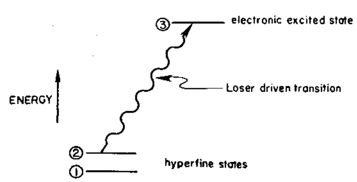

FIG. 1. Levels of interest in a hypothetical alkali-like atom. Optical pumping into state 1 occurs while driving the 2 ⟶ 3 transition with a laser.

Those atoms of a particular velocity class moving against the radiation are Doppler shifted toward the resonant frequency ν_0 and scatter the incoming light at a higher rate than those atoms moving with the radiation which are Doppler shifted away from resonance. For each scattering event, the atom receives a momentum impulse $\hbar\vec{k}$ ($\vec{k}$ is the photon wave vector) in the absorption process. For an atom which is moving against the radiation, this impulse retards its motion. This retardation can also be described in terms of radiation pressure.[1,10] The average momentum per scattering event transferred to the atom by the reemitted photons is zero, because of the randomness of the photons' directions (if we neglect terms of second order in $|\vec{v}|/c$, where $\vec{v}$ is the atom velocity and c is the speed of light). The average net effect then is that the atomic velocity is changed by an amount $\Delta\vec{v} \cong \hbar\vec{k}/M$ per scattering event, where M is the atomic mass. When $\vec{v}$ and $\vec{k}$ are antiparallel, this leads to a net cooling, provided $|\vec{v}+\Delta\vec{v}| < |\vec{v}|$.[1] (See Fig. 2.) In a practical cooling experiment it would be desirable to irradiate the atoms from all sides with radiation that covered the entire lower half of the Doppler profile.[1] Alternatively, nar-

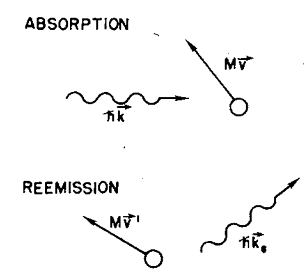

FIG. 2. Qualitative description of radiation-pressure cooling. In the absorption process, the atomic velocity is changed (reduced for $\vec{k}\cdot\vec{v}<0$) by an amount $\Delta\vec{v}=\hbar\vec{k}/M$. In the reemission process, the average change in velocity is zero. Therefore in the overall scattering process, the kinetic energy can be reduced.

Laser Cooling to the Zero-Point Energy of Motion

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(Received 28 July 1988)

A single trapped $^{198}Hg^{+}$ ion was cooled by scattering laser radiation that was tuned to the resolved lower motional sideband of the narrow $^2S_{1/2}$-$^2D_{5/2}$ transition. The different absorption strengths on the upper and lower sidebands after cooling indicated that the ion was in the ground state of its confining well approximately 95% of the time.

PACS numbers: 32.80.Pj, 32.30.Jc, 35.10.−d

ta. Therefore, for the y and z degrees of freedom, the ion is in the $n_v = 0$ state 95% of the time. The corresponding temperature given by[8] $k_B T = \hbar\omega_v / \ln(1 + 1/\langle n_v \rangle)$ is $T = 47 \pm 3\ \mu K$. For any other energy partition, $\langle n_v \rangle$ and T for one degree of freedom would be less than these values. Independent of the energy distribution, for

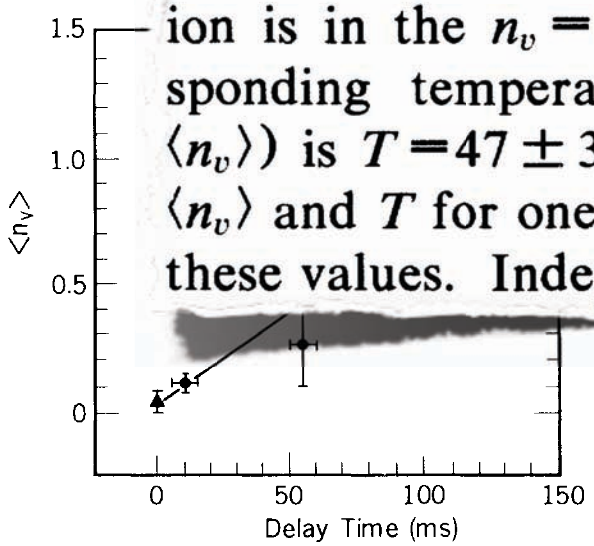
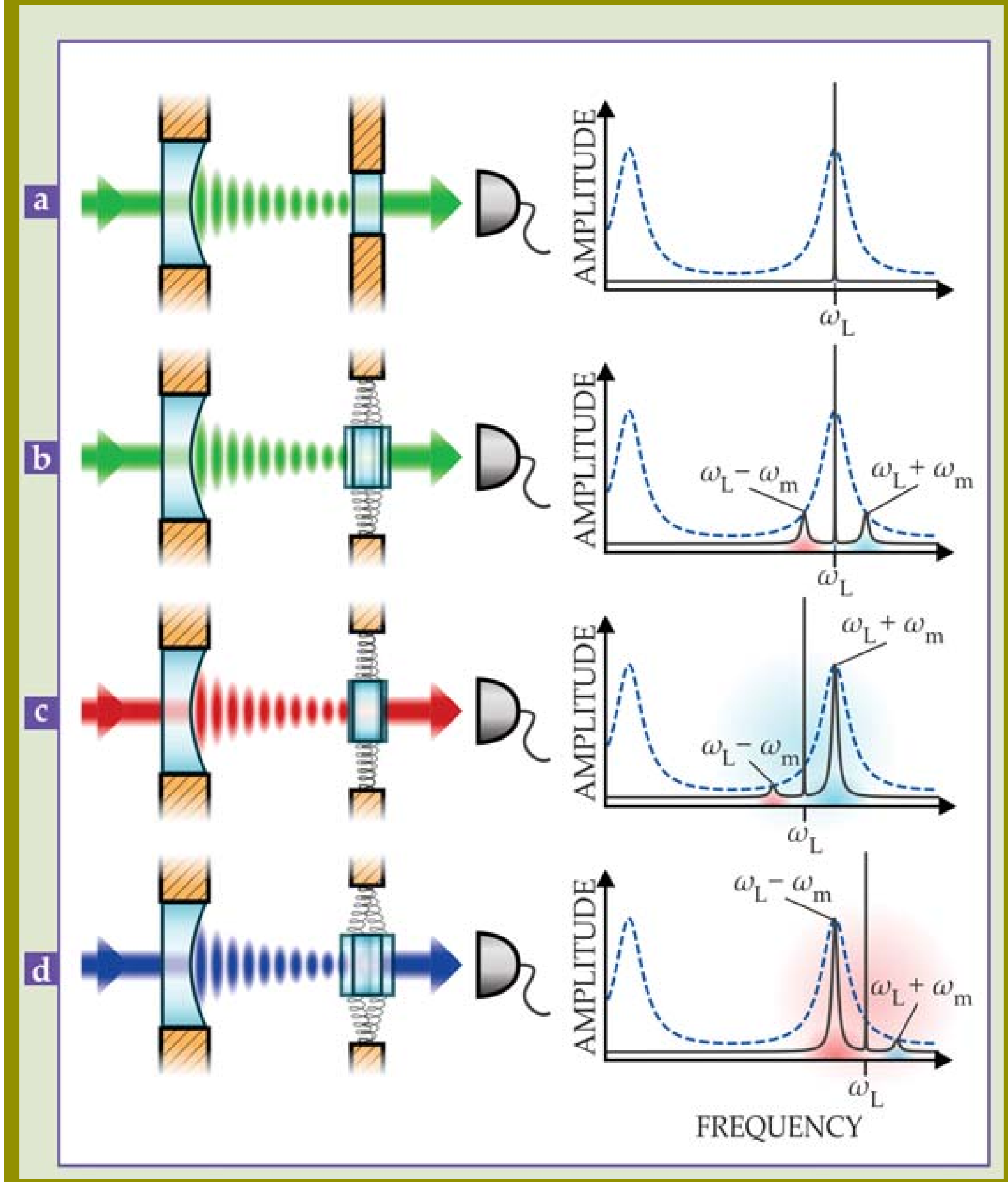


FIG. 3. Vibrational quantum number $\langle n_v \rangle$ for the axial motion ($\omega_v/2\pi = 4.66$ MHz) as a function of time delay between the end of the sideband cooling and probing. A linear extrapolation of the data points (circles) to zero delay time yields $\langle n_v \rangle$ (triangle) consistent with the theoretical expectation.

er cooling in the
time. The kinetic
educed to a value
ground-state level
at the ion is in the
is realizes for the
aser cooling for a
ated atomic particle at rest to within the quantum-mechanical limits imposed by the surrounding apparatus.

From the results, shown in Fig. 3, we calculate $\langle n_v \rangle = 0.049 \pm 0.045$ at the end of the cooling period, consistent with the theoretical cooling limit. The confinement of the axial motion is given by the spread of the zero-point wave function $z(\mathrm{rms}) \approx 2.4$ nm.

Quantum Optomechanical Cavity



- **Quantum optomechanics: the basics**.
- (a) If both end mirrors of a Fabry-Perot cavity are fixed in place, pump-laser photons having frequency ω_L tuned to a cavity resonance arrive at a detector with no frequency modulation.
- (b) However, if one mirror is allowed to oscillate harmonically, pump photons are modulated by the oscillation frequency ω_m: A pump beam tuned to a cavity resonance will yield sidebands of equal amplitude at frequencies $\omega_L \pm \omega_m$. Each photon in the upper sideband acquires energy by extracting a phonon from the oscillator, and each photon in the lower sideband sheds energy by depositing a phonon.
- (c) By red-detuning the pump laser, one can enhance the upper sideband and thereby cool the oscillating mirror.
- (d) By blue-detuning the pump laser, one enhances the lower sideband and amplifies the mirror oscillations.

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Photons refrigerating phonons

Optomechanics is a promising route towards the observation of quantum effects in relatively large structures. Three papers, each discussing a different implementation, now combine optical sideband and cryogenic cooling to refrigerate mechanical resonators to fewer than 60 phonons.

Andrew Cleland

The experimental focus is on mechanical resonators, with resonance frequencies f_M typically **between a few kilohertz and a few hundred megahertz**. Cooling to the quantum ground state, which is one way to reach the quantum limit, requires reduction of the resonator's thermal energy $k_B T$ to below the energy quantum hf_M. **At 1 kHz, this requires temperatures below an astounding 50 nK**, whereas at 100 MHz this requires $T < 5$ mK. Conventional cryogenic techniques can be used to lower the resonator's physical temperature towards these values, **but typically further reduction is needed, especially for the lower resonator frequencies.**

http://web.physics.ucsb.edu/~clelandgroup/

Making Sideband Laser Cooling Effective...

- Reduce thermal leak back into mechanical resonator by increasing the mechanical quality factor (Q) of the resonator.
- The optical resonator needs to have very low optical absorption, which otherwise could cause heating from the illuminating laser.
- The laser can itself inject noise, so a stable, low-noise laser is needed.

➡ Effective sideband cooling therefore requires a long cavity lifetime, high mechanical Q, low optical absorption, and a low-noise laser.

Demonstration of an ultracold micro-optomechanical oscillator in a cryogenic cavity

Simon Gröblacher[1,2], Jared B. Hertzberg[3,4], Michael R. Vanner[1,2], Garrett D. Cole[1,5], Sylvain Gigan[6], K. C. Schwab[3]* and Markus Aspelmeyer[1]†

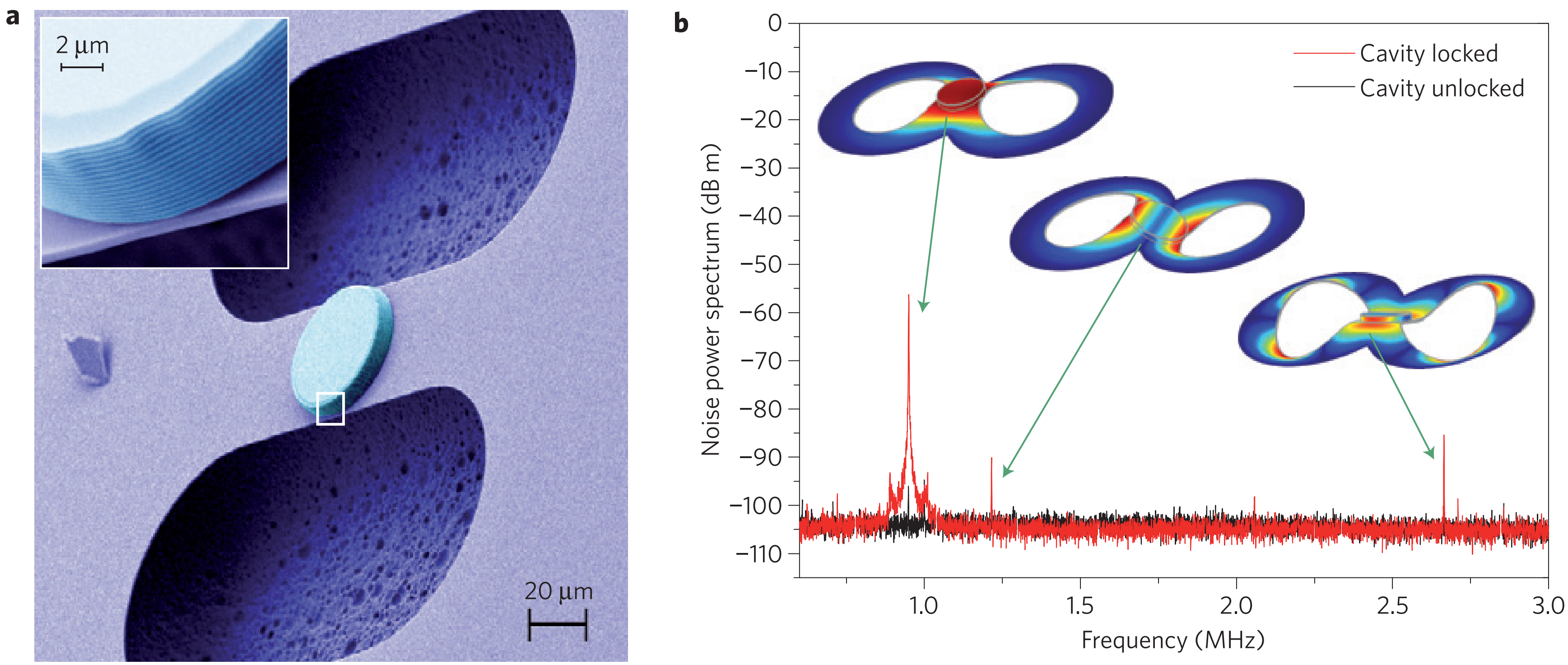

Figure 1 | High-quality micro-optomechanical resonator. a, Scanning electron micrograph of the basic mechanical system, which is formed by a doubly clamped Si_3N_4 beam. A circular, high-reflectivity Bragg mirror is used as the end mirror of a Fabry–Pérot cavity. The Bragg mirror is made of low-absorption, alternating dielectric stacks of Ta_2O_5/SiO_2. The magnified section in the inset shows the stacking sequence. **b**, Micromechanical displacement spectra shown as noise power spectra of the readout-beam phase quadrature for a locked and an unlocked cavity. The fundamental mode at $\omega_m = 2\pi \times 945$ kHz and all higher mechanical modes are identified by finite element simulation. For the cases that involve large Bragg mirror displacements, we provide the simulated mode profile.

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In summary, we have demonstrated optical cooling of the fundamental mode of a 100μm scale mechanical resonator in a cryogenic cavity to a thermal occupation of only 32 ± 4 quanta. This is comparable to the performance of state-of-the- art NEMS devices.

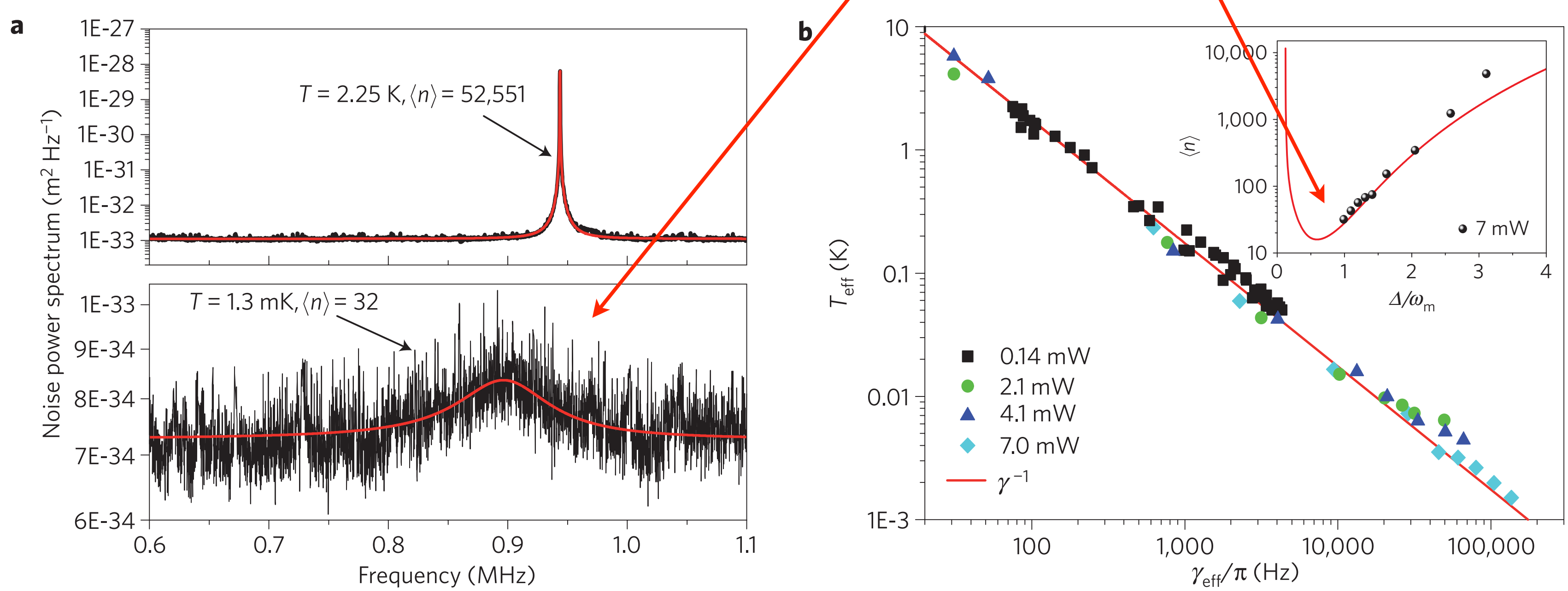


Figure 3 | Optomechanical laser cooling inside a cryogenic cavity. a, Calibrated noise power spectra for the fundamental mechanical mode at 5.3 K environmental temperature with small cavity cooling (top) and at maximum cooling (bottom). The thermal energy is reduced from ≈53,000 quanta at 7 μW laser power to 32 ± 4 quanta at 7 mW. The vertical axes in both plots are logarithmic. The change in the technical noise floor is due to different locking levels of the local oscillator phase Φ in the homodyne detection. **b**, Plot of the calibrated effective temperature T_{eff} versus the observed damping γ_{eff} for various power and detuning values of the cooling beam. No deviations from the theoretically expected power-law dependence (red solid line) can be observed. The inset shows the mean thermal occupation $\langle n \rangle$ as a function of detuning for maximal laser power. Cavity instability prevents detunings arbitrarily close to resonance. The red solid curve is a simulation based on ref. 16 that uses only experimentally obtained parameters.

Resolved-sideband and cryogenic cooling of an optomechanical resonator

Young-Shin Park and Hailin Wang*

Figure 1c shows a WGM transmission resonance obtained through free-space excitation for a silica microsphere with a diameter $d = 30$ μm and deformation less than 2%.

The transmission resonance features a cavity linewidth $\varkappa/2\pi = 26$ MHz, corresponding to an optical quality factor, $Q \sim 1.4\times10^7$.

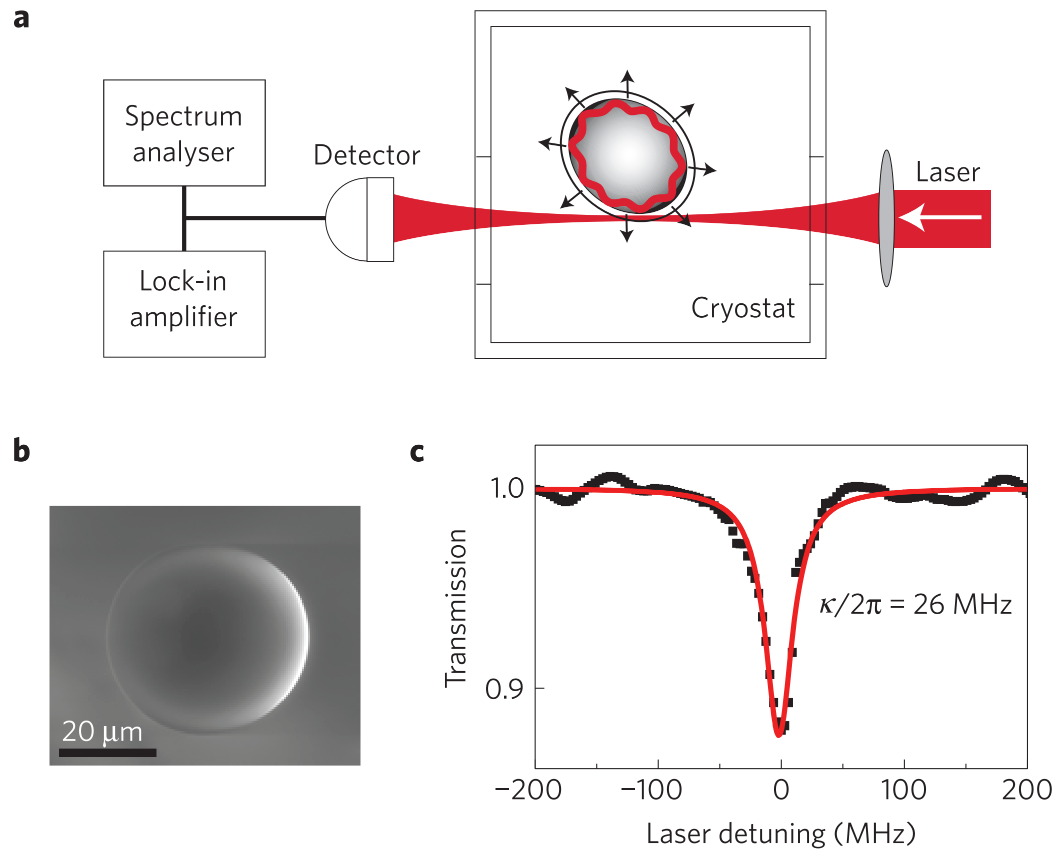
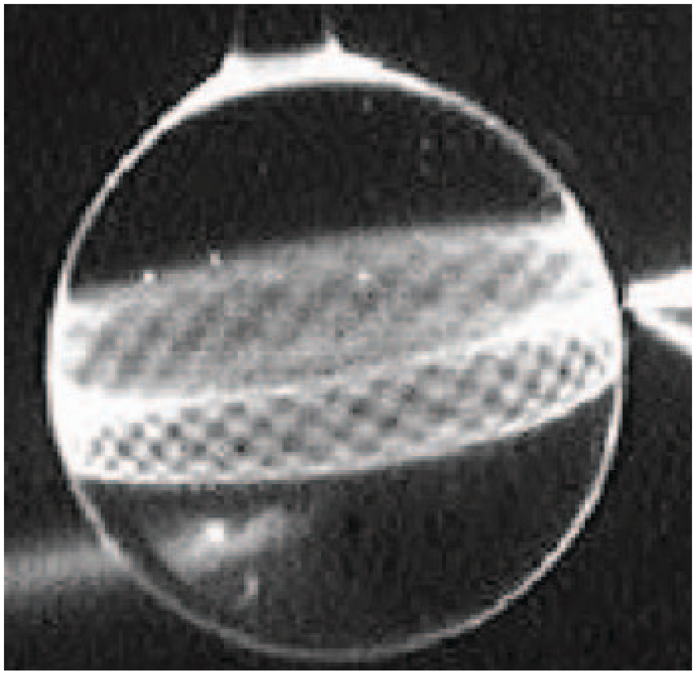


Figure 1 | Free-space coupling of WGMs. a, Schematic diagram of the experimental set-up for radiation-pressure cooling through free-space evanescent excitation of WGMs in a deformed silica microsphere. **b**, Scanning electron micrograph of a silica microsphere with deformation of 4.7%, taken on the side opposite to the attached fibre stem. **c**, Optical transmission spectrum, obtained with free-space excitation, of a WGM resonance near $\lambda = 800$ nm for a microsphere with $d = 30$ μm and deformation <2%. The solid line is a Lorentzian fit.

Whispering Gallery Modes



300 μm glass sphere

St. Paul's London

Resolved-sideband and cryogenic cooling of an optomechanical resonator

Young-Shin Park and Hailin Wang*

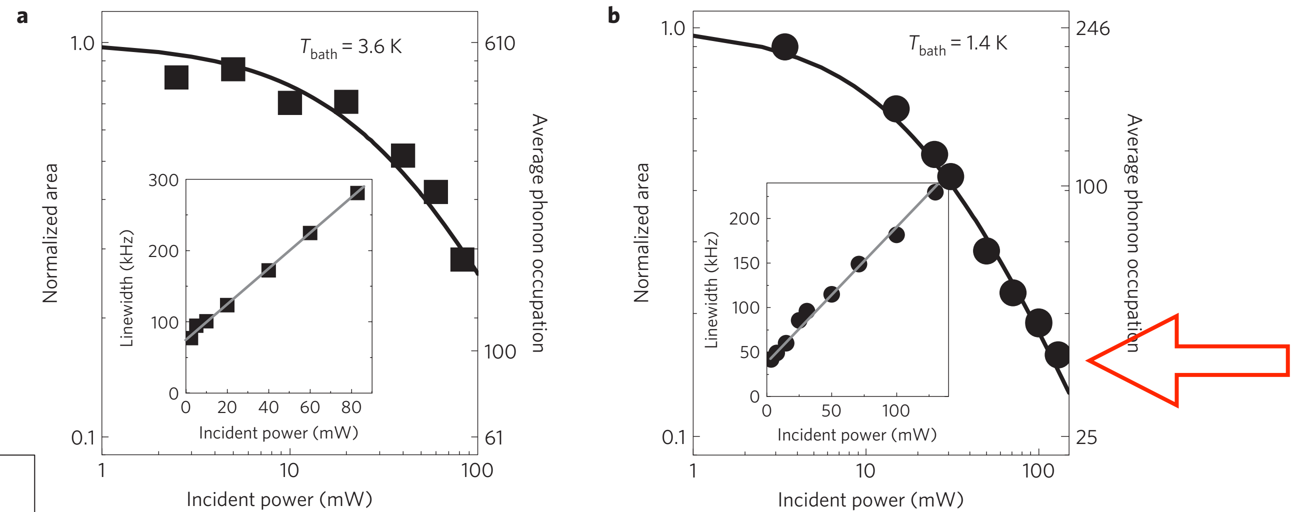
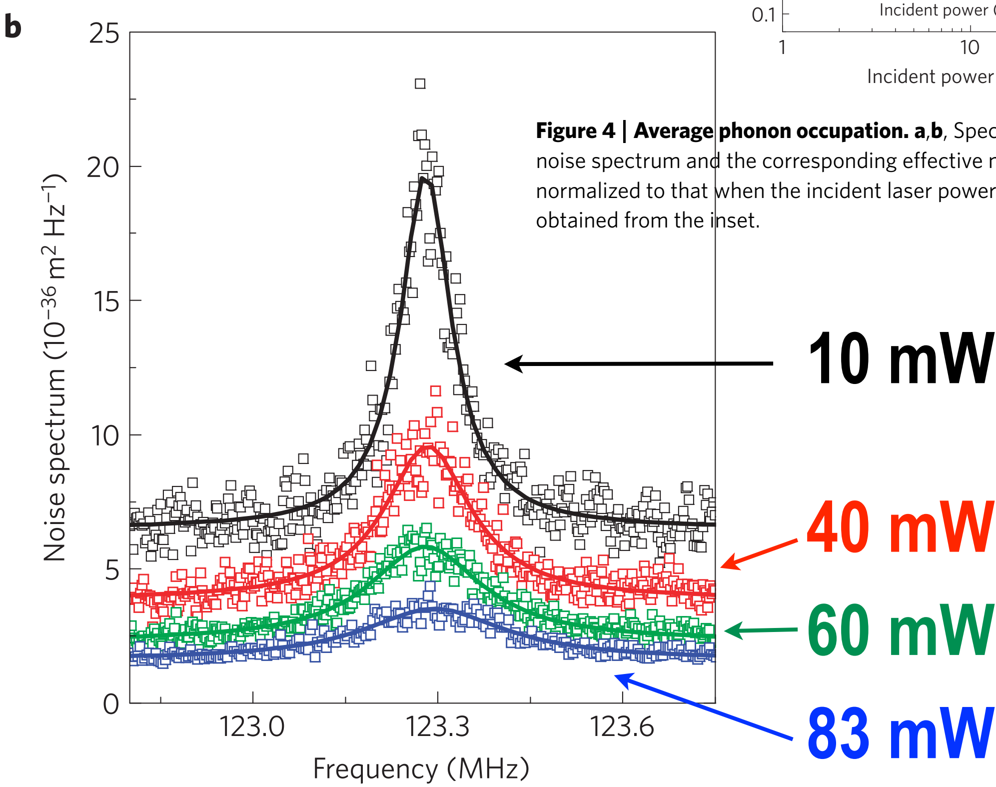


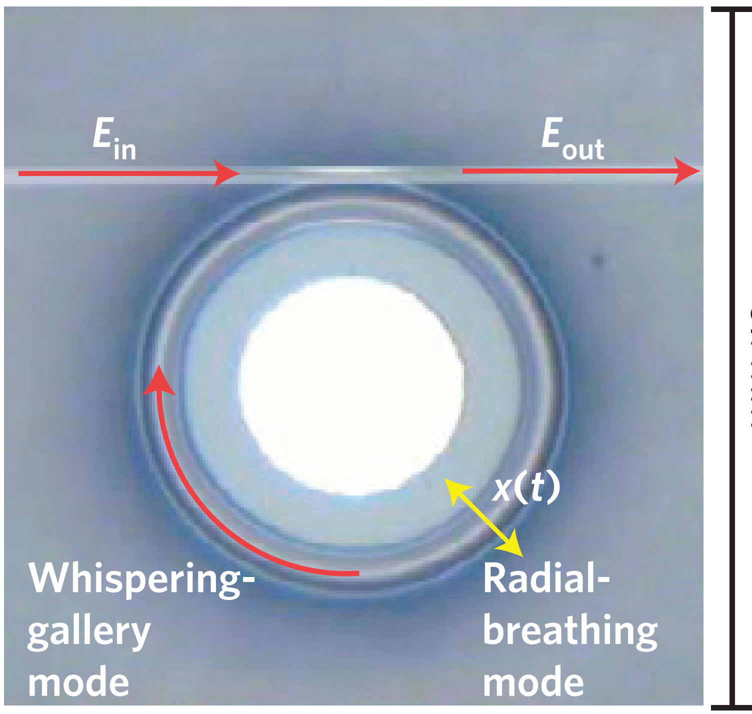
Figure 4 | Average phonon occupation. a,**b**, Spectrally integrated area of the (1, 2) mode obtained at different bath temperatures from the displacement noise spectrum and the corresponding effective mechanical linewidth (insets) as a function of the incident laser power with $\Delta\omega/\omega_m = -1$. The area is normalized to that when the incident laser power approaches zero. The solid curves are the calculated area using the slope of the linear power dependence obtained from the inset.



The spectrally integrated area of a mechanical resonance in the displacement power spectrum is proportional to the temperature of the mechanical mode.

Resolved-sideband cooling and position measurement of a micromechanical oscillator close to the Heisenberg uncertainty limit

A. Schliesser[1]*, O. Arcizet[1]*, R. Rivière[1]*, G. Anetsberger[1] and T. J. Kippenberg[1,2]†



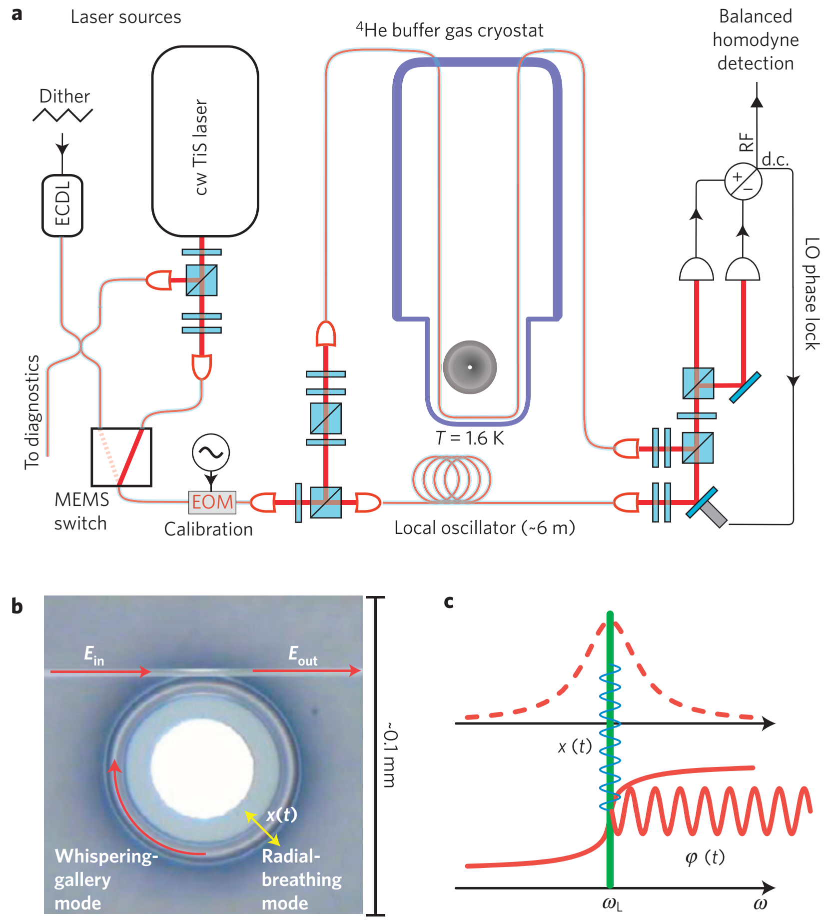


Figure 1 | Cryogenic cooling and displacement measurements of a micromechanical oscillator. a, A silica microtoroid is held in a 1.65 K-cold ^{4}He atmosphere. The toroid supports both high-Q optical WGMs and a mechanical RBM, parametrically coupled to an optical resonance frequency. High-Q optical resonances are identified using a frequency-agile external-cavity diode laser (ECDL). To probe the mechanical oscillator, the laser input is switched to a low-noise Ti:sapphire laser. **b**, A small fraction of the laser light is sent into the cryostat and evanescently coupled to the WGM by means of a tapered fibre placed in the near-field of the WGM. Balanced homodyne measurement of the laser phase as transmitted through the taper is implemented using a Mach–Zehnder fibre interferometer (phase plates and polarizing beam splitters are only schematically indicated). **c**, A modulation $x(t)$ of the radius of the cavity induces a modulation of the phase $\varphi(t)$ of the laser light emerging from the cavity. This phase shift is detected by comparison with a phase reference, derived from the same laser in a beam splitter followed by a balanced detector.

Resolved-sideband cooling and position measurement of a micromechanical oscillator close to the Heisenberg uncertainty limit[a]

A. Schliesser[1]*, O. Arcizet[1]*, R. Rivière[1]*, G. Anetsberger[1] and T. J. Kippenberg[1,2†]

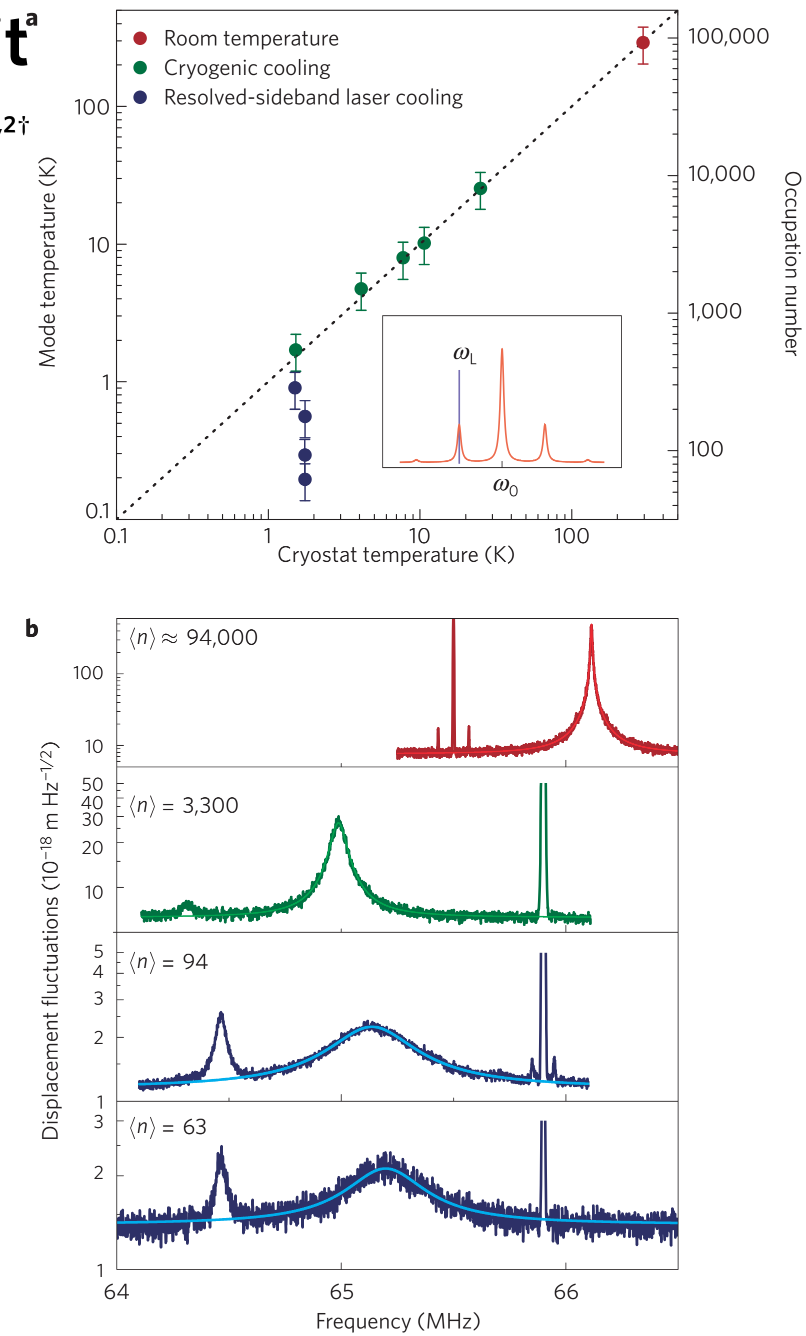
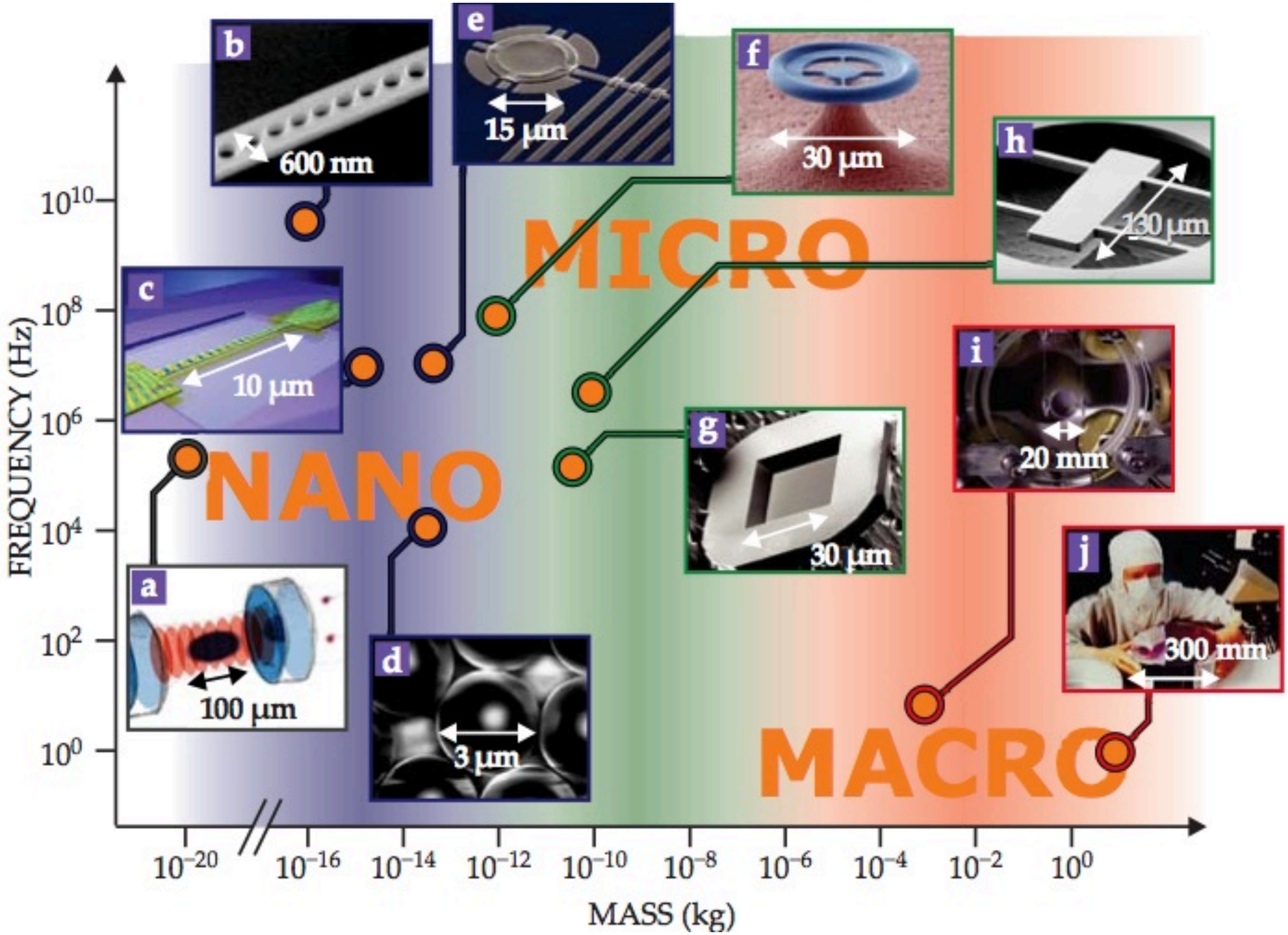


Figure 3 | Cryogenic precooling and resolved-sideband laser cooling. **a**, Mode temperature, derived from noise thermometry, compared with cryostat temperature, measured with a calibrated silicon diode close to the sample. Combined with precooling in the cryostat, resolved-sideband cooling reduces the occupation of the oscillator further to $\langle n \rangle = 63 \pm 20$ phonons. The inset illustrates the laser (blue line) detuned to the lower mechanical sideband of the cavity spectrum (red line). **b**, Displacement noise spectra of the RBM with four different average occupation numbers, together with a Lorentzian fit. The resonance frequency and intrinsic damping of the mode are modified under cryogenic cooling from room temperature (red curve) to 10 K (green curve) and 1.7 K (blue curves) owing to phonon coupling to structural defect states[27]. Extra resolved-sideband cooling (blue curves) induces extra damping and a small frequency shift. For the two traces shown, the launched laser powers were approximately 190 and 200 μW. The sharp calibration peak and a second mechanical mode (with a higher effective mass) at slightly lower frequency are also visible. It was verified that the contribution of the latter to the noise at the resonance frequency of the RBM is negligible.



Cavity optomechanical devices range from nanometer-sized structures of as little as 10^7 atoms and 10−20 kg to micromechanical structures of 10^{14} atoms and 10−11 kg to macroscopic, centimeter-sized mirrors comprising more than 10^{20} atoms and weighing several kilograms. They include (a) gases of ultracold atoms, (d) microspheres, and (g) micro-scale membranes, all of which have mechanical resonances that can couple with the light inside an optical cavity; (b, c) flexible, nanoscale waveguides that have both optical and mechanical resonances; (e) superconducting membranes that exhibit drum-like vibrations and can be integrated into microwave cavities; (f) microtoroidal waveguides having both optical and mechanical resonances; and mechanically compliant mirrors, which can range from the microscopic (h) to the macroscopic (i, j) and which introduce mechanical degrees of freedom to an optical cavity when incorporated as an end mirror.