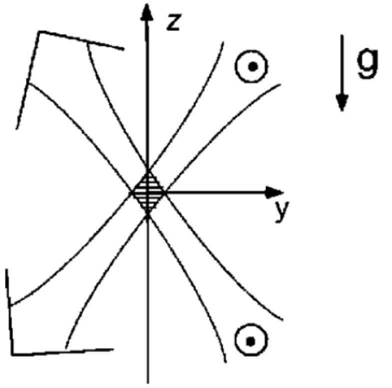
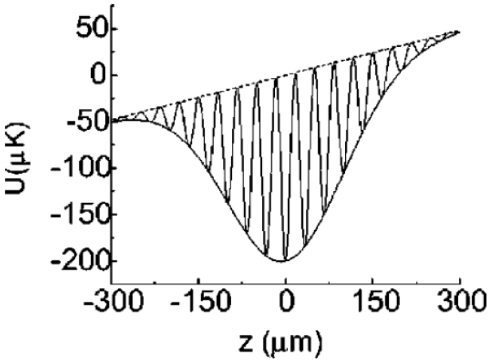
Cold trapped atoms

Experimental configuration

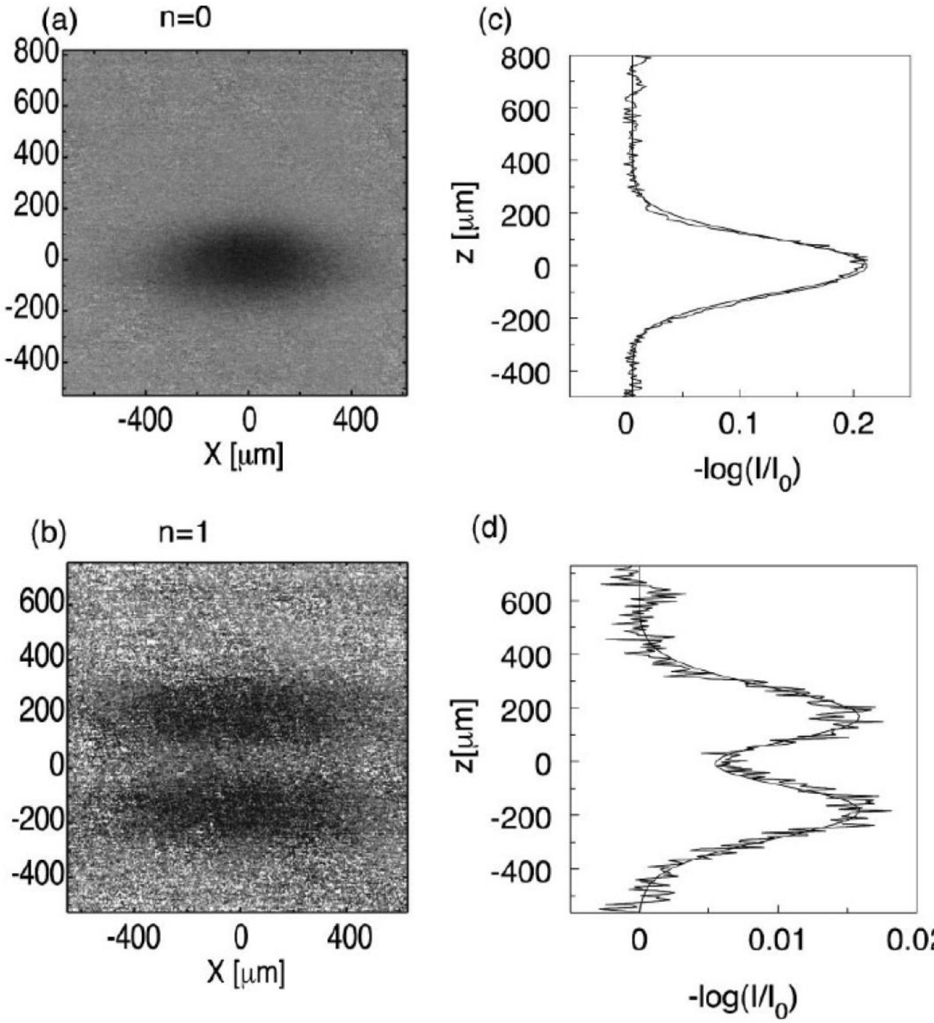


Potentiel energy U



Cold Cs atoms
trapped in a crossed dipolar trap
Oscillation frequency in the 100 kHz range
→ requires T in the μK range
(Raman cooling)

Fock states, Time-of-flight mapping of the momentum distribution



Neutral atoms prepared in Fock states of a one-dimensional harmonic potential, I. Bouchoule *et al.*, Phys. Rev. A **59**, R8 (1999)

Squeezed states of cold trapped atoms

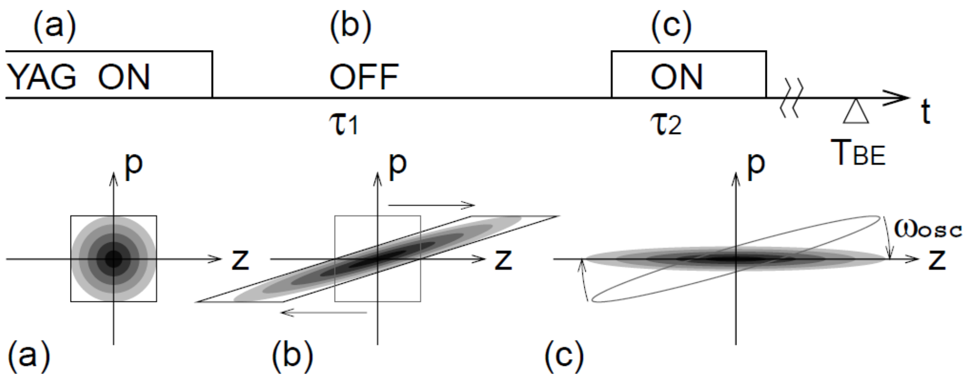
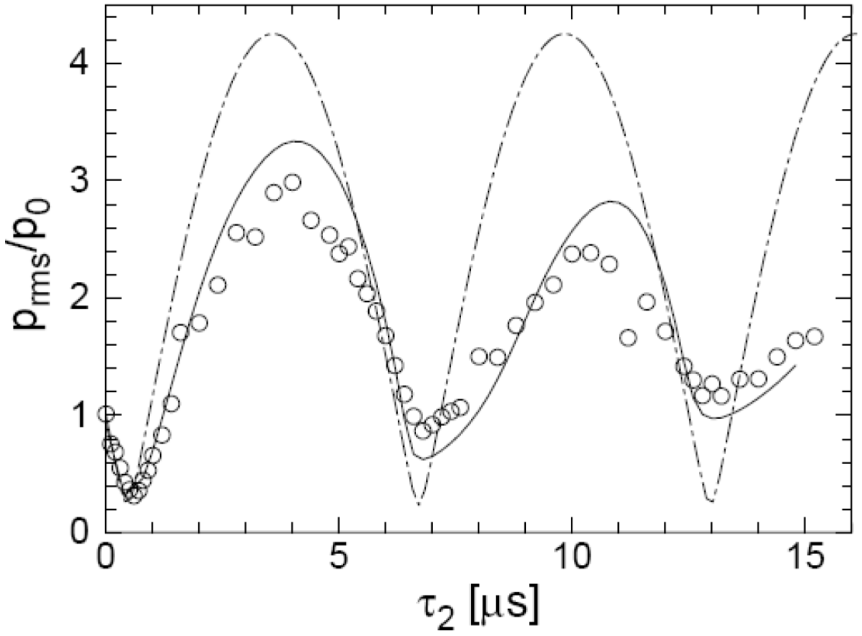


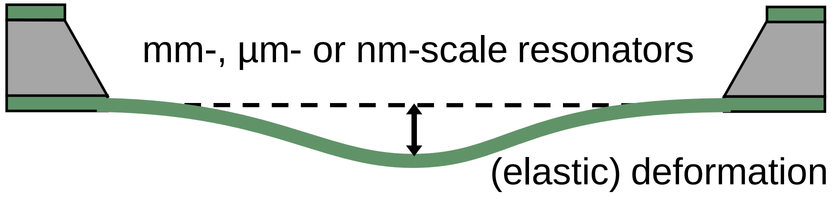
FIG. 1. Experimental time sequence and evolution of the phase space distribution. (Wigner function !!)

Experimental results



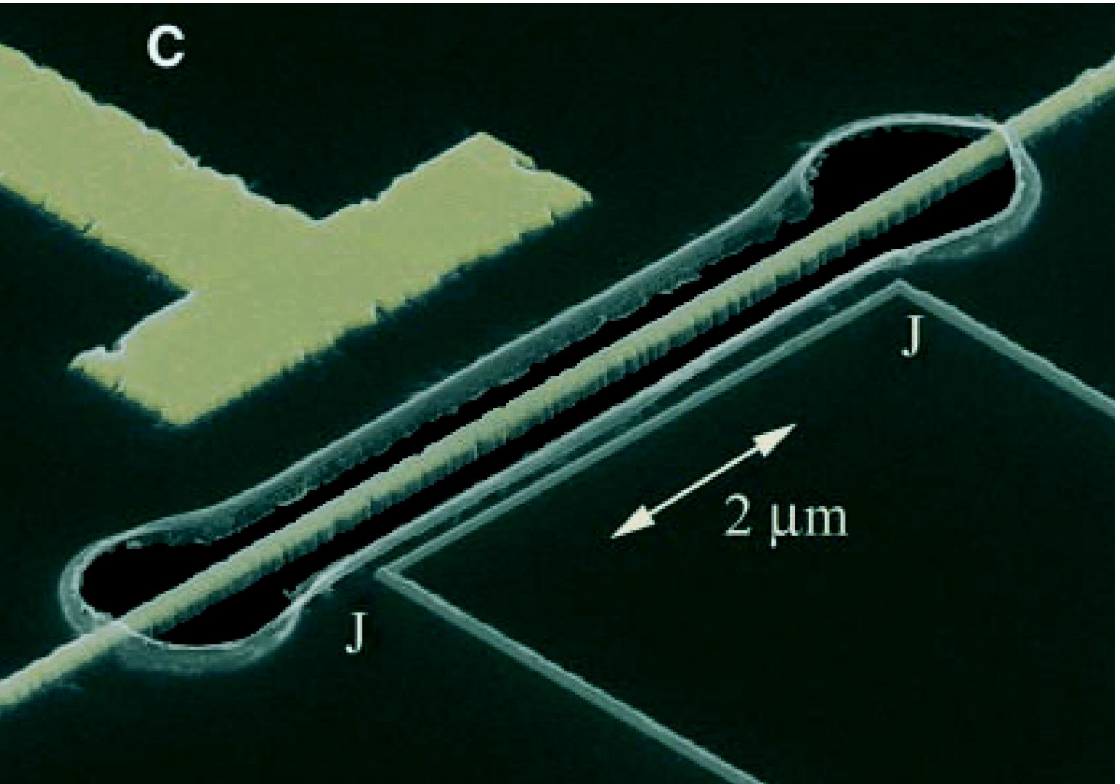
Manipulation of Motional Quantum States of Neutral Atoms,
M. Morinaga *et al., Phys. Rev. Lett.* ***83****, 4037 (1999)*

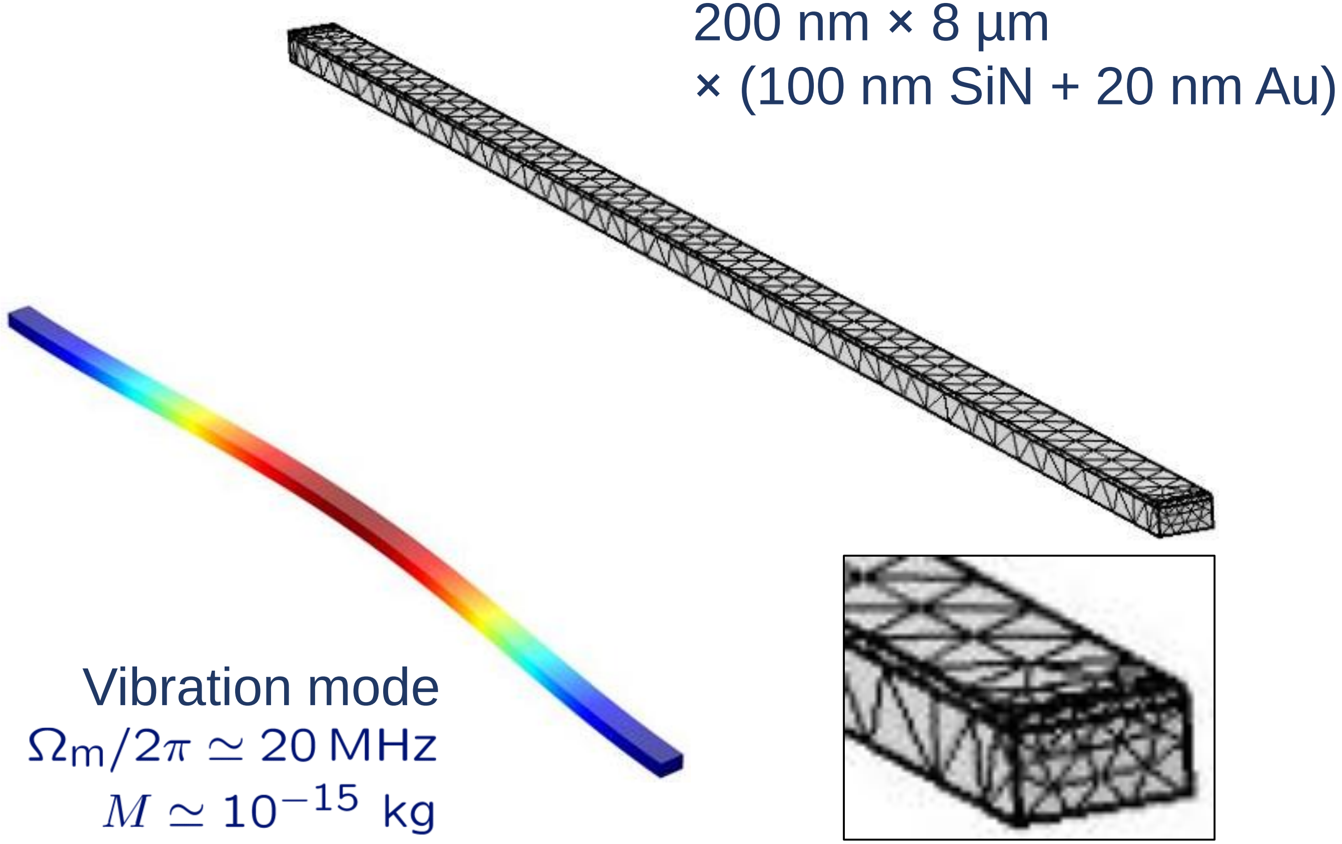
Mechanical resonators



Finite-element modelling
(elasticity equations)
developed for engineering (macroscopic systems)
but works fine with nm-scale objects

(Schwab, Science 2004)



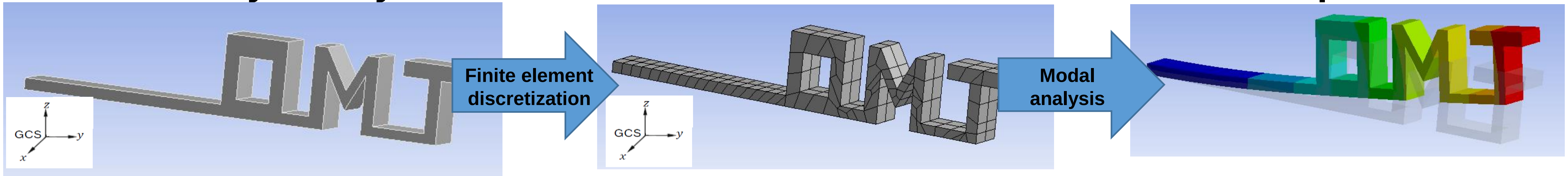


Finite-element modelling

Elasticity theory

FEM

Modal representation



Task: Solve partial differential equations for the field variable $\boldsymbol{u}(\boldsymbol{x},t)$ which denotes the time dependent displacement of every material point at position $\boldsymbol{x}$ from its position at rest.

Navier-Cauchy equation:

$$\mu\nabla^2\mathbf{u} + (\mu+\lambda)\nabla(\nabla\cdot\mathbf{u}) + \mathbf{F} = \rho\frac{\partial^2\mathbf{u}}{\partial t^2}$$

Impossible to solve for arbitrary geometries and boundary conditions

Task: Solve ordinary differential equations for the vector-valued variable $\vec{u}(t)$ which denotes the time dependent displacement of every node of the FE mesh from its position at rest $\vec{x}$.

$$\boxed{M\,\ddot{\vec{u}} + D\,\dot{\vec{u}} + K\,\vec{u} = \vec{F}}$$

Solvable with numerical effort

Task: Solve ordinary differential equations for the scalar-valued variable $q_1(t)$ which denotes the time dependent modal amplitude.

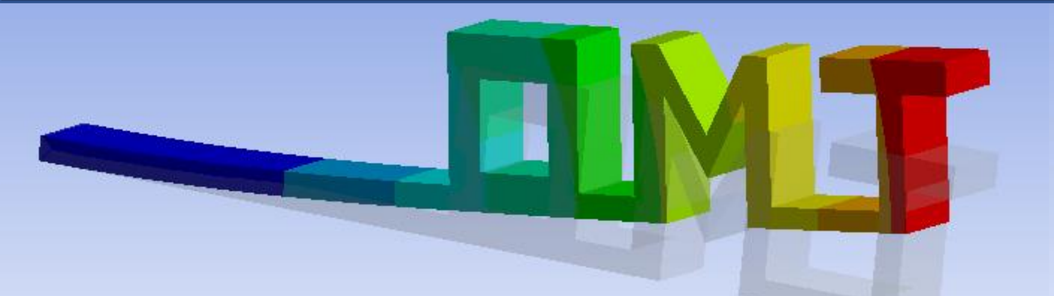
Extremely good appr. for high-Q oscillation

$$\boxed{\vec{u}(t) = \sum_{n=1}^{DOF} q_n(t)\vec{S}_n \approx q_1(t)\vec{S}_1}$$

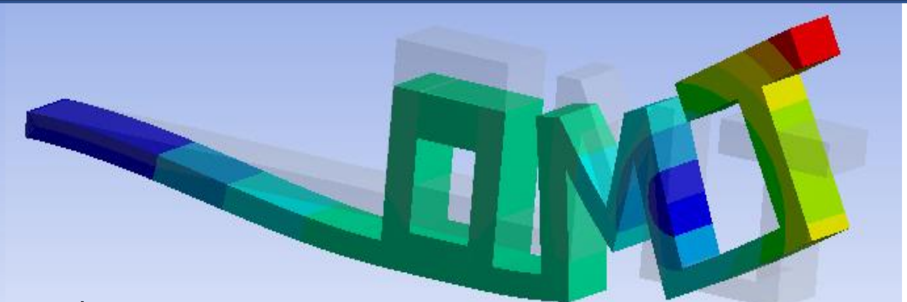
Few- or even one-mode problem solvable for both the classical and quantum domain

Slide by Peter Degenfeld-Schonburg
Robert Bosch GmbH

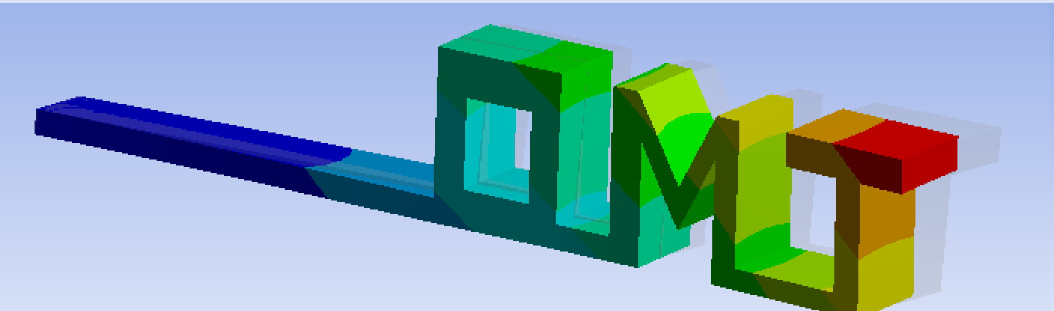
Finite-element modelling: results for a non-trivial geometry



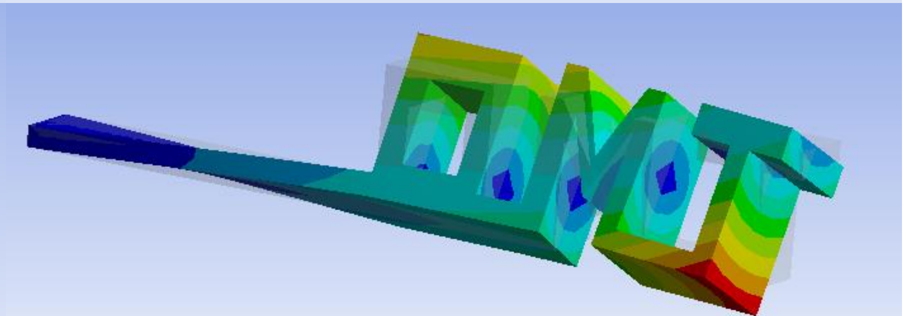
1st in-plane mode @ 113 kHz



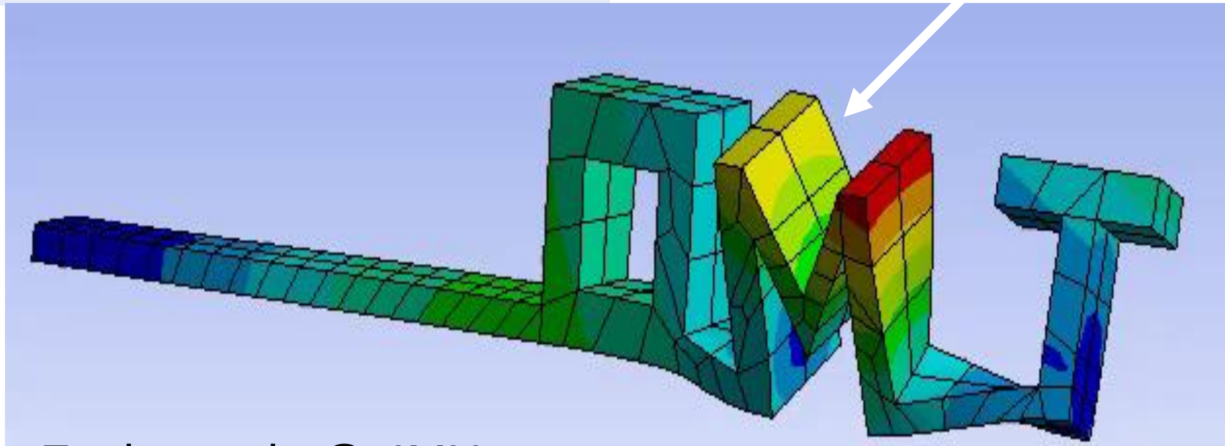
2nd in-plane mode @ 663 kHz



1st out-of-plane mode @ 353 kHz



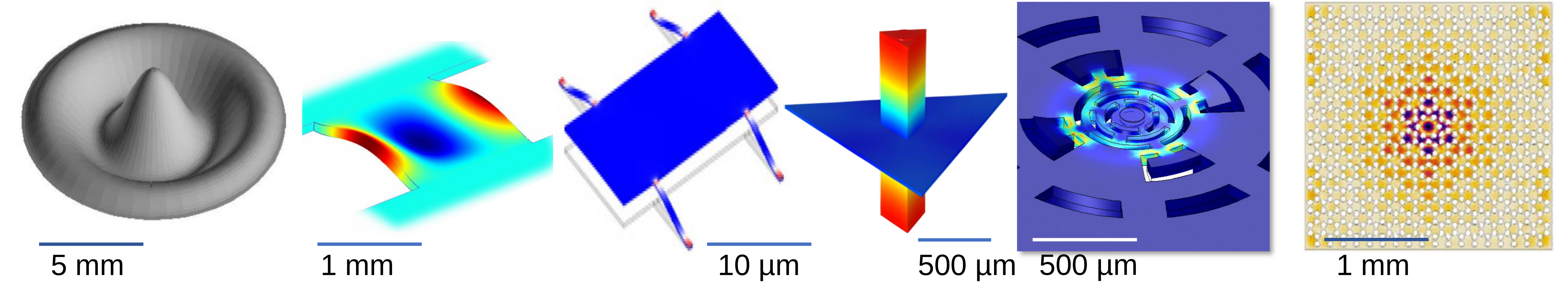
1st torsional mode @ 1.03 MHz



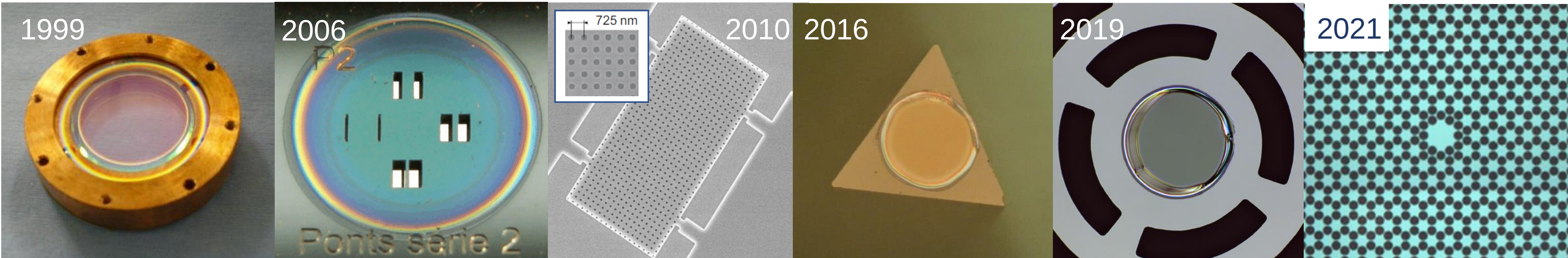
Funky mode @ 4MHz

Slide by Peter Degenfeld-Schonburg
Robert Bosch GmbH

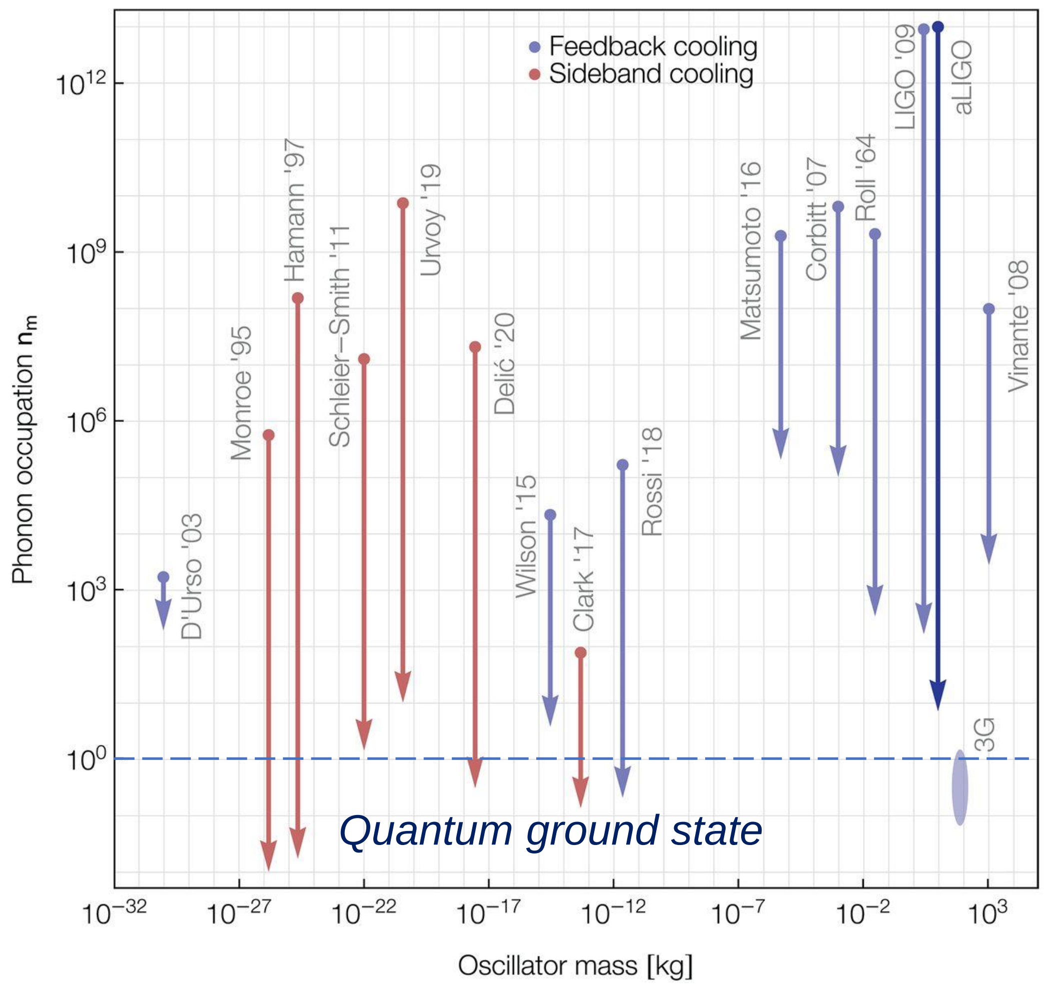
25 years of optomechanical resonators at LKB

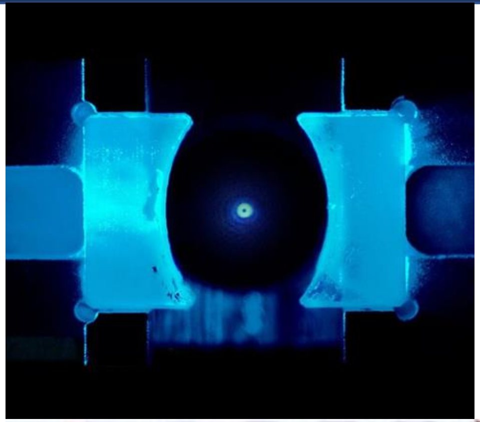


	Mirror	Chip	Membrane	Micropillar	Oscillator	Membrane
	silica	silicon	InP	quartz	silicon	SiN
m :	200 mg	µg	1 pg	30 µg	100 µg	10 ng
$\Omega_m/2\pi$:	1,8 MHz	800 kHz	800 kHz	3,6 MHz	300 kHz	1,4 MHz
Q :	40 000	15 000	5 000	7×10^7	3×10^6	3×10^8



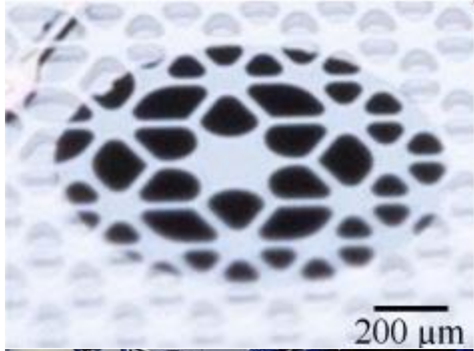
Quantum harmonic oscillators, over 33 decades in mass

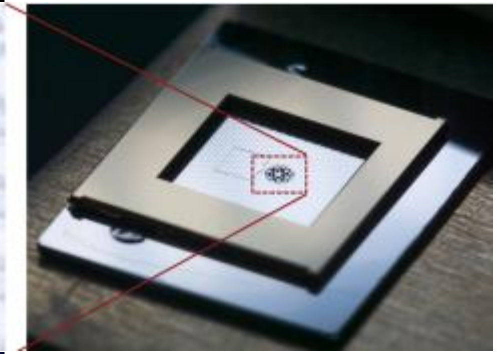




Trapped nanoparticle (≈ 10^{-17} kg)

Phononic-crystal nanomembrane (≈ 10^{-12} kg)

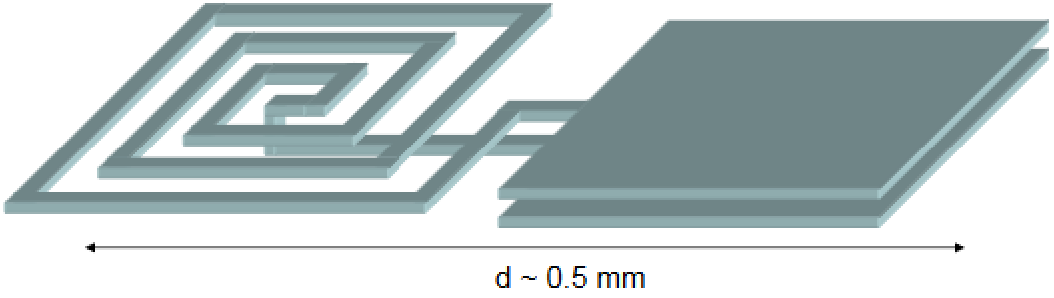




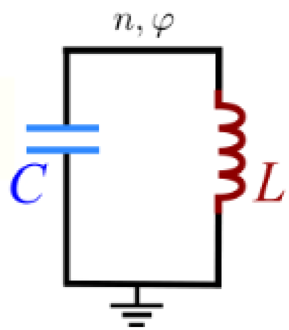
The AURIGA Weber bar (≈ 10^{3} kg)

Approaching the motional ground state of a 10-kg object,
C. Whittle *et al., Science* ***372****, 1333 (2021)*

Quantum LC circuits

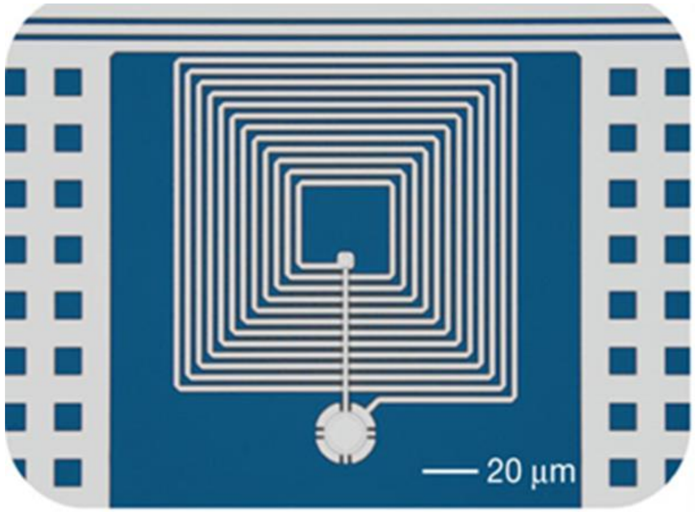


Microfabrication → $L \approx 3$ nH, $C \approx 1$ pF, $\omega_0/2\pi \approx 5$ GHz

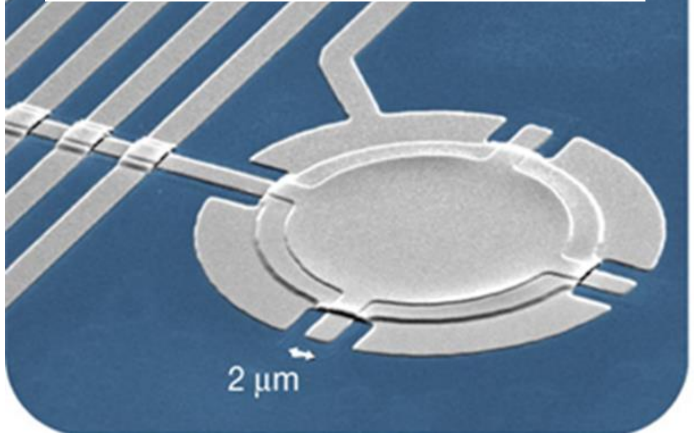


$$\hat{H}_{LC} = 4\,\frac{e^2}{2C}\,\hat{n}^2 + \left(\frac{\Phi_0}{2\pi}\right)^2 \frac{\hat{\varphi}^2}{2L}$$

See exercise with Alexandre next week
Also, nonlinear inductance → anharmonicity and TLS



Note the capacitor is **also** a mechanical resonator (vibrating at 10 MHz)



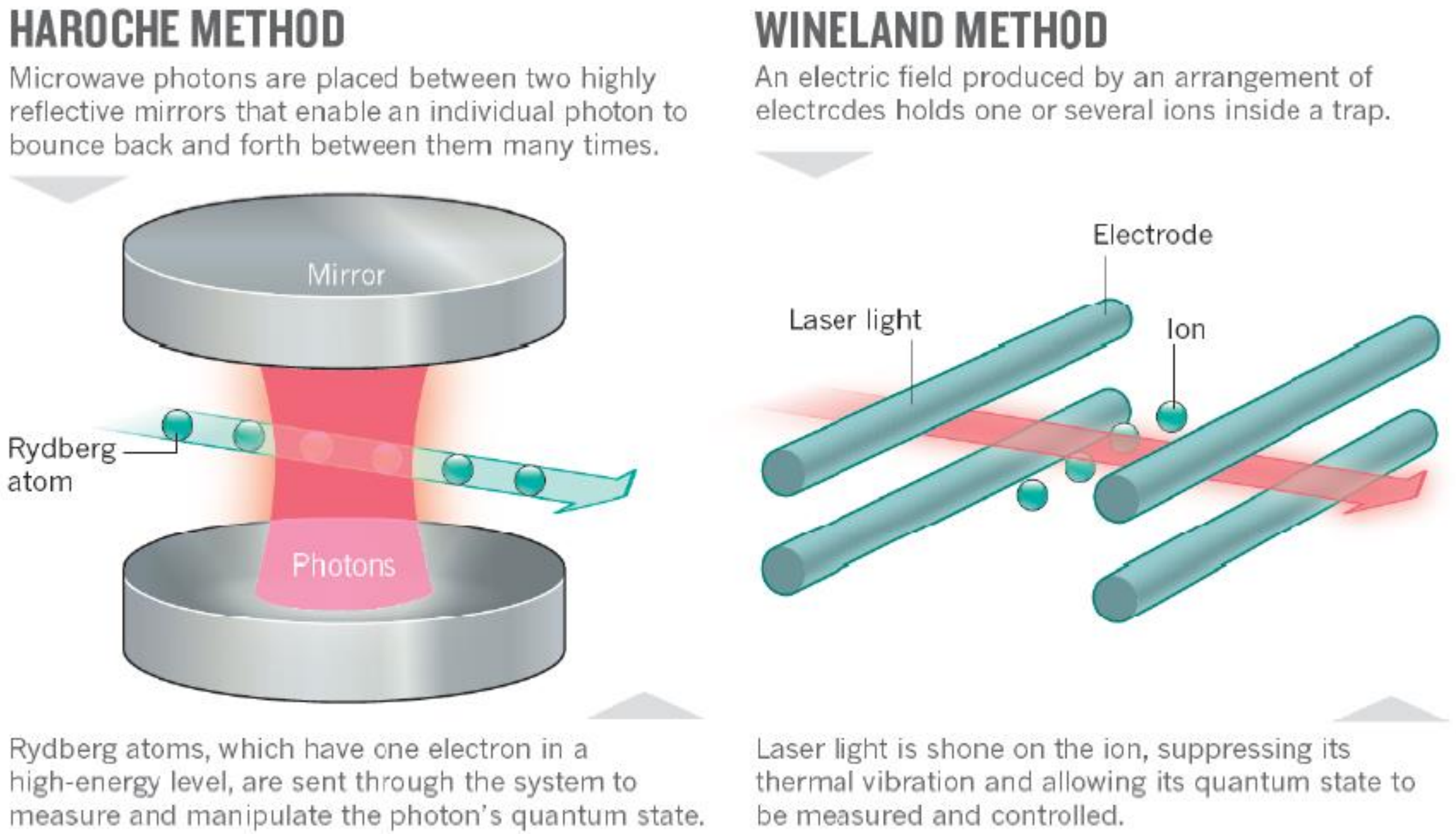
Sideband cooling of micromechanical motion to the quantum ground state, J. D. Teufel *et al.*, Nature **475**, 359 (2011)

Lectures by Michel Devoret at Collège de France
(slides, audio and video files available in english)
https://www.college-de-france.fr/fr/agenda/cours/signaux-et-circuits-quantiques/signaux-et-circuits-quantiques

Nobel Prize 2012

Serge Haroche and David Wineland

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"



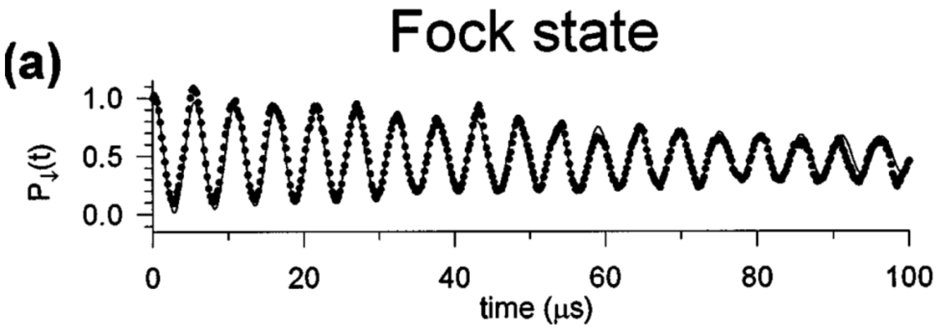
Similar timescales for 2 very different systems, developed at the exact same time

2 back-to-back “ground-breaking” papers in 1996

VOLUME 76, NUMBER 11 PHYSICAL REVIEW LETTERS 11 MARCH 1996

Generation of Nonclassical Motional States of a Trapped Atom

D. M. Meekhof, C. Monroe, B. E. King, W. M. Itano, and D. J. Wineland
Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303-3328
(Received 11 October 1995)



VOLUME 76, NUMBER 11 PHYSICAL REVIEW LETTERS 11 MARCH 1996

Quantum Rabi Oscillation: A Direct Test of Field Quantization in a Cavity

M. Brune, F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J. M. Raimond, and S. Haroche
Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, F-75231 Paris Cedex 05, France*
(Received 9 November 1995)