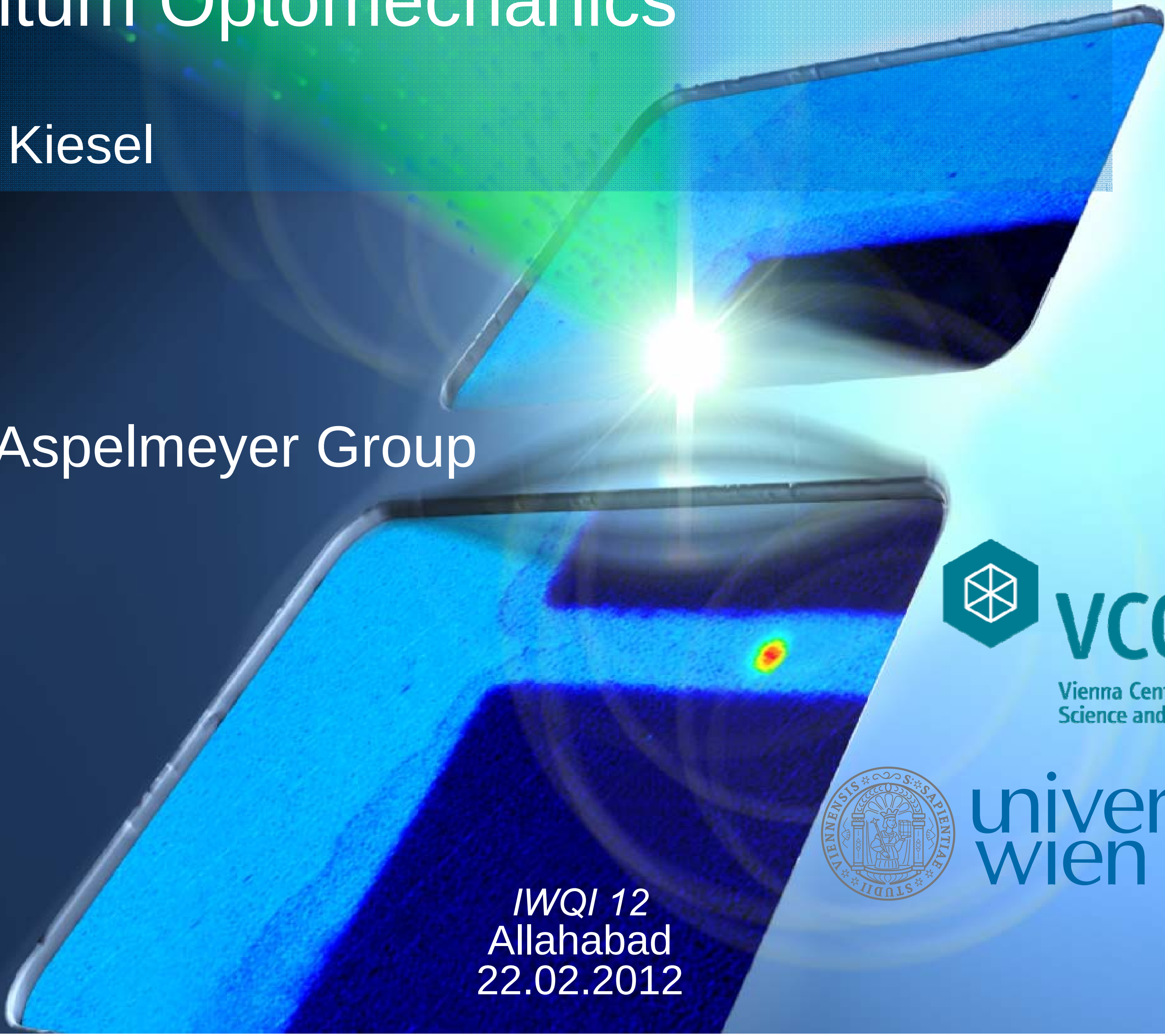
Quantum Optomechanics

Nikolai Kiesel

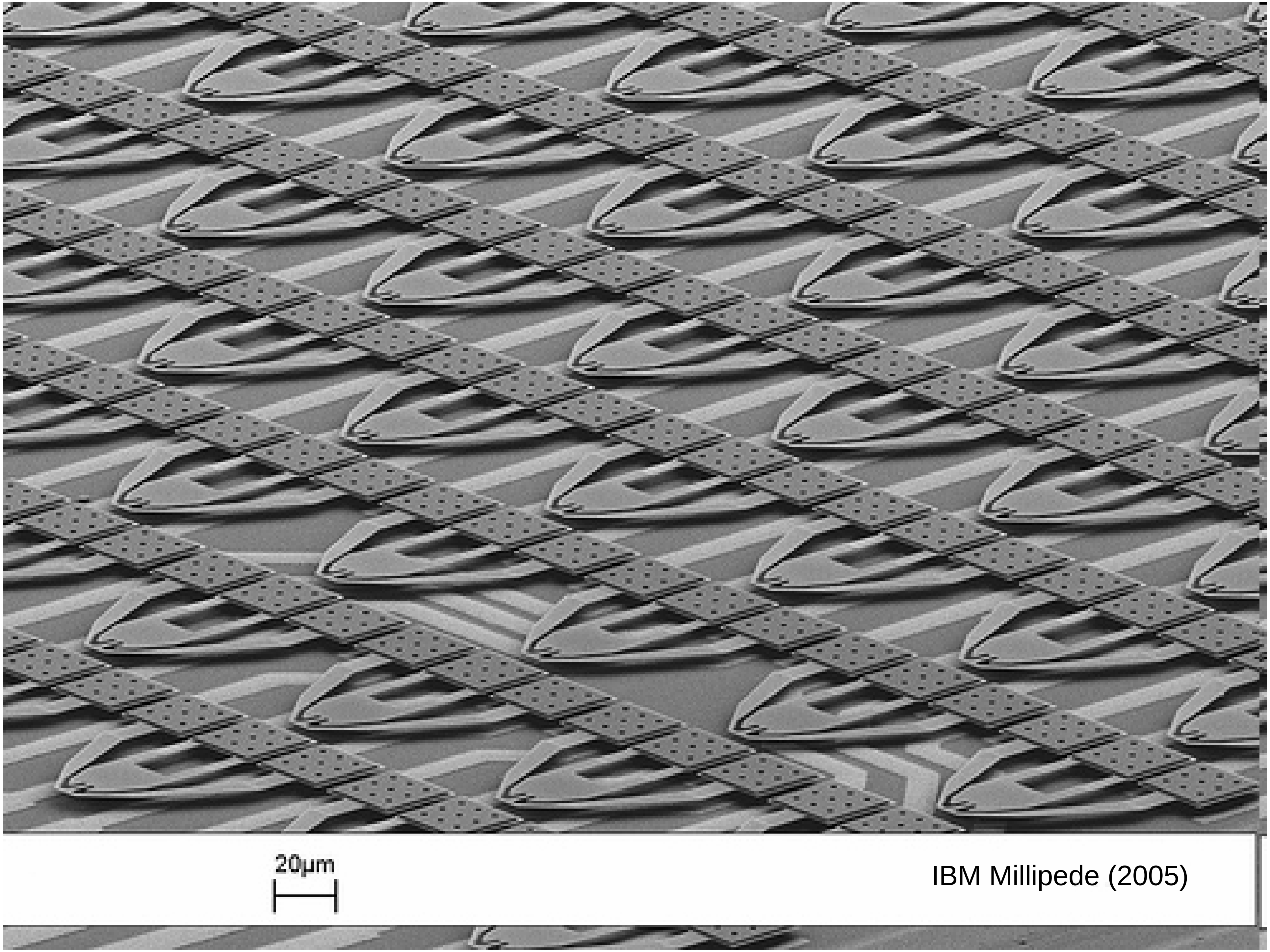


The Aspelmeyer Group

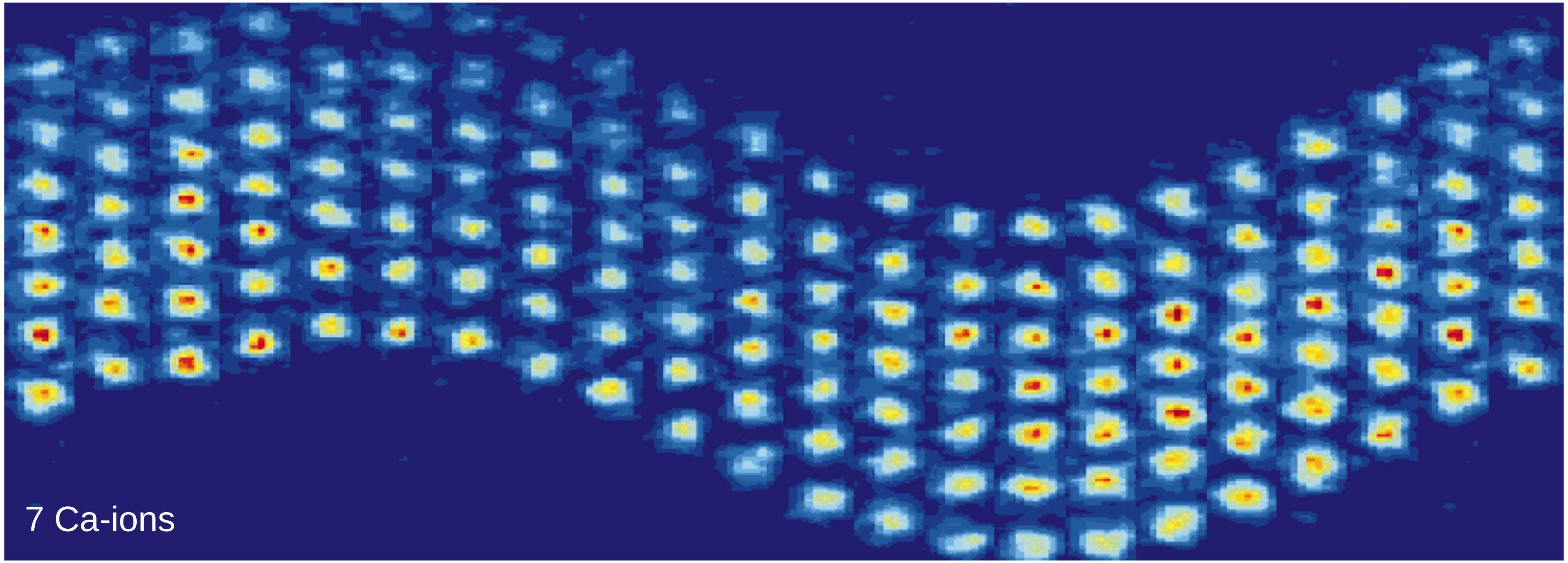
IWQI 12
Allahabad
22.02.2012

VCQ
Vienna Center for Quantum Science and Technology

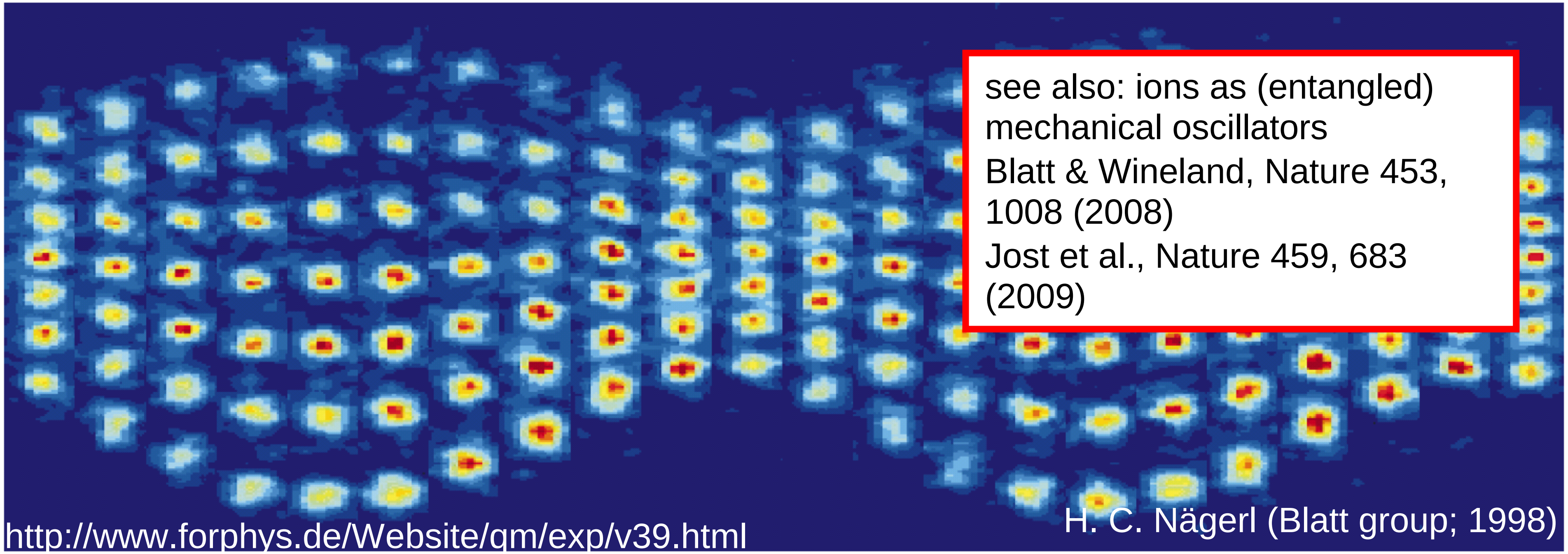
universität wien

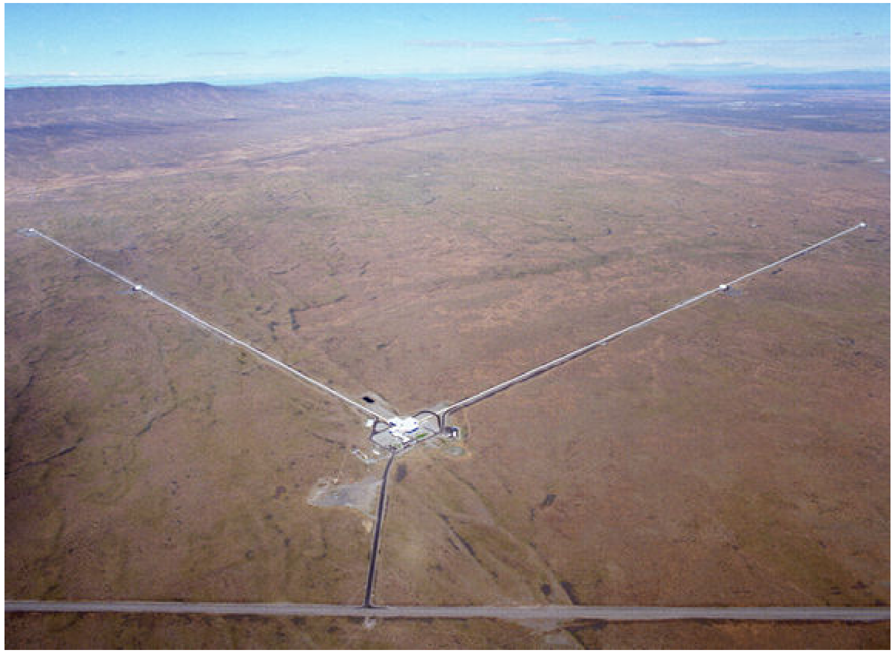


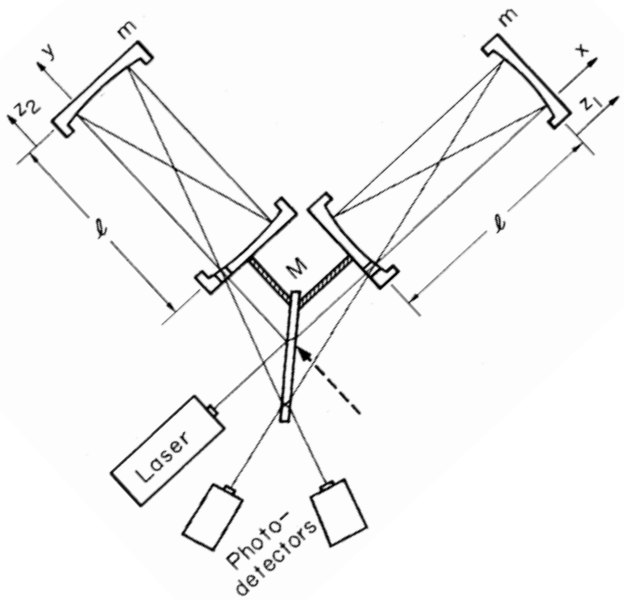
IBM Millipede (2005)



Trapped ions: **quantum physics with phonons** (Cirac & Zoller, PRL 74, 4091 (1995))







Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

A mechanical system in the quantum regime

See also Teufel et al., arxiv 1103.2144 (2011)

ARTICLES

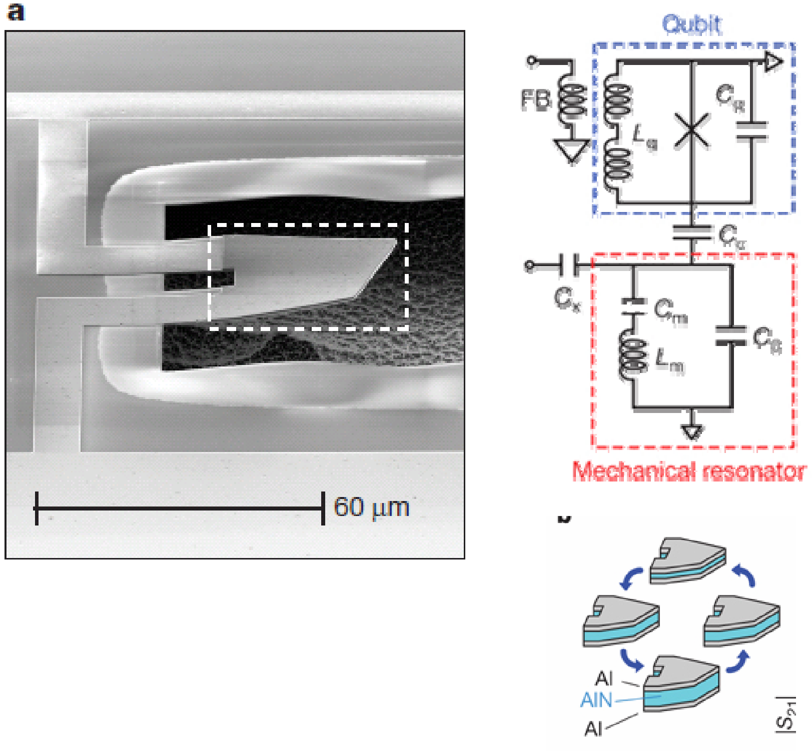
Quantum ground state and single-phonon control of a mechanical resonator

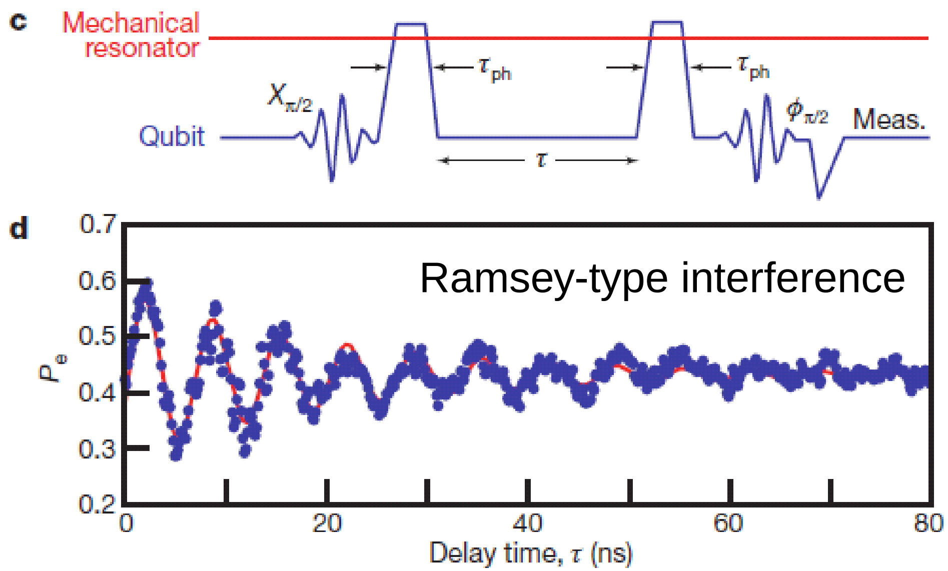
A. D. O'Connell[1], M. Hofheinz[1], M. Ansmann[1], Radoslaw C. Bialczak[1], M. Lenander[1], Erik Lucero[1], M. Neeley[1], D. Sank[1], H. Wang[1], M. Weides[1], J. Wenner[1], John M. Martinis[1] & A. N. Cleland[1]

6 GHz piezo vibration → n ~ 0.07 @ 20 mK

Cleland/Martinis groups (UCSB); April 2010

a

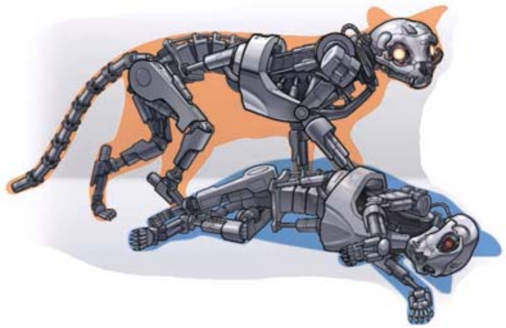




O'Connell, et al. *Nature*.464, 697 (2010)

Quantum regime of massive resonators

Cho , Science 327, 516 (2010)

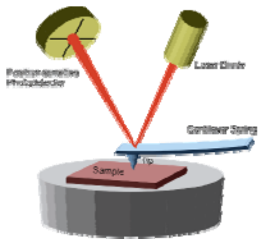


Access a new realm of experimental physics

Quantum Foundations

macroscopic quantum superposition involving up to 10^{20} atoms

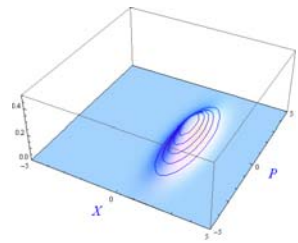
→ *<u>Is there a limit to the size/mass of Schrödinger cats?</u>*

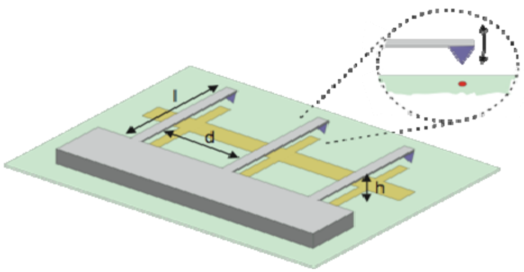


Mechanical Sensing

present performance: zeptogram, zeptonewton, attometer, etc.

→ *<u>What are the quantum limits to mechanical sensing?</u>*





*Rabl et al.,
Nature Physics 6, 602 (2010).*

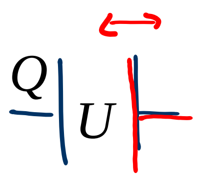
Quantum Information

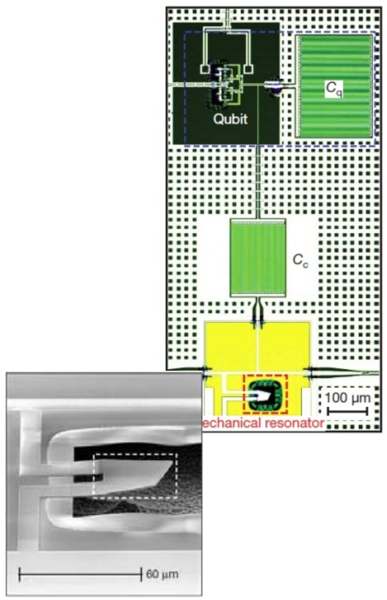
e.g. potential for hybrid quantum information architectures on a chip

→ *<u>Can mechanical systems serve as universal quantum bus?</u>*

Coupling to mechanics

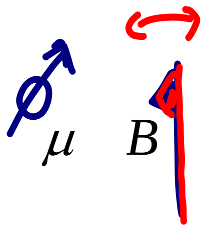
charge

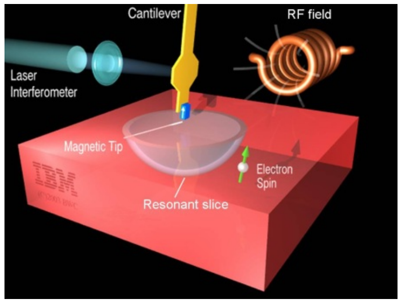




O. Connell et al.,
Nature 464 (10)

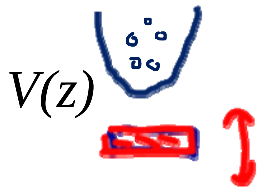
spin

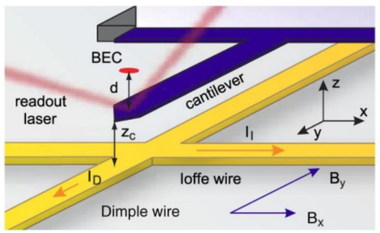




D. Rugar et al.,
Nature 430 (04)

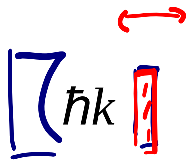
atoms

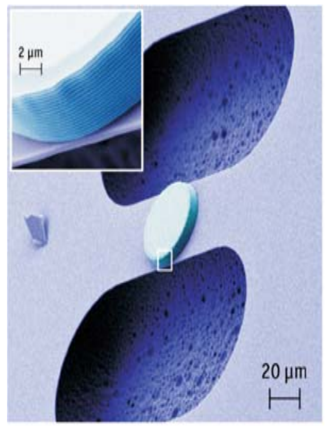




D. Hunger et al.,
PRL 104 (10)

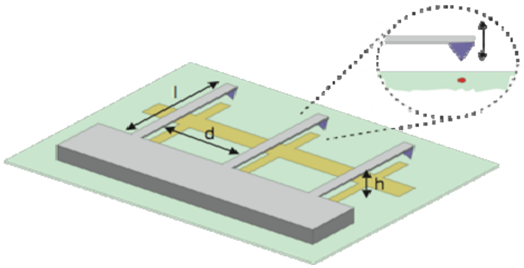
photon momentum





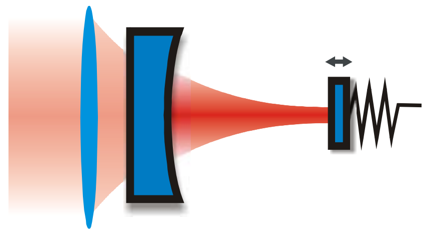
S. Gröblacher et al.,
Nature Phys. 5 (09)

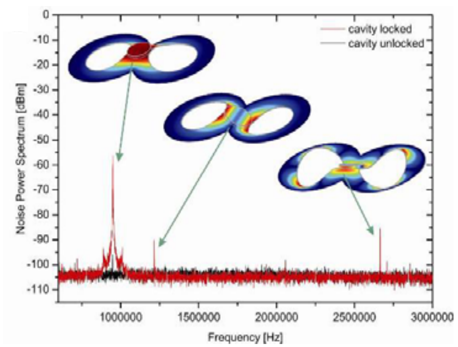
Cavity Optomechanics



Large mechanics in the quantum regime ?

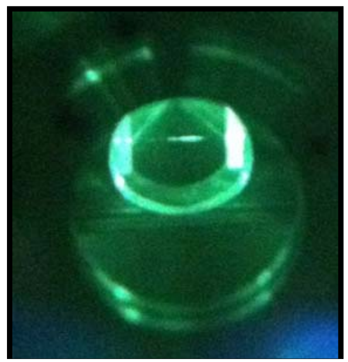
Contol of mechanical resonators with light



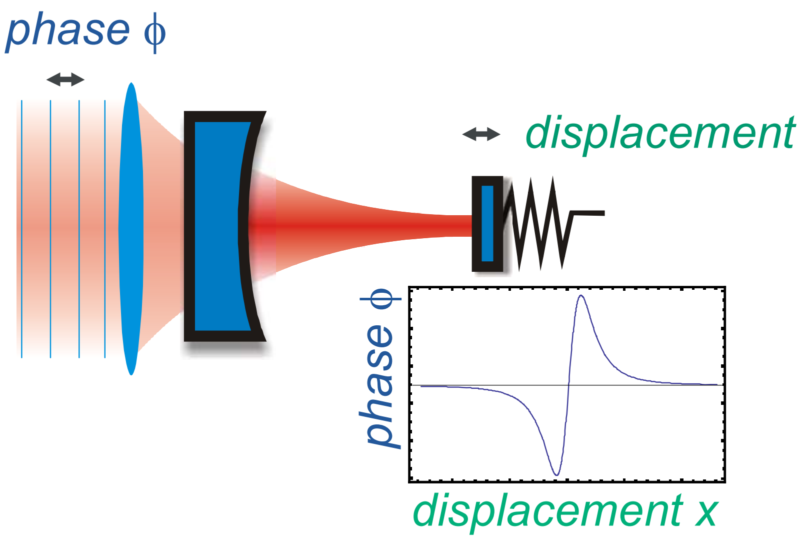


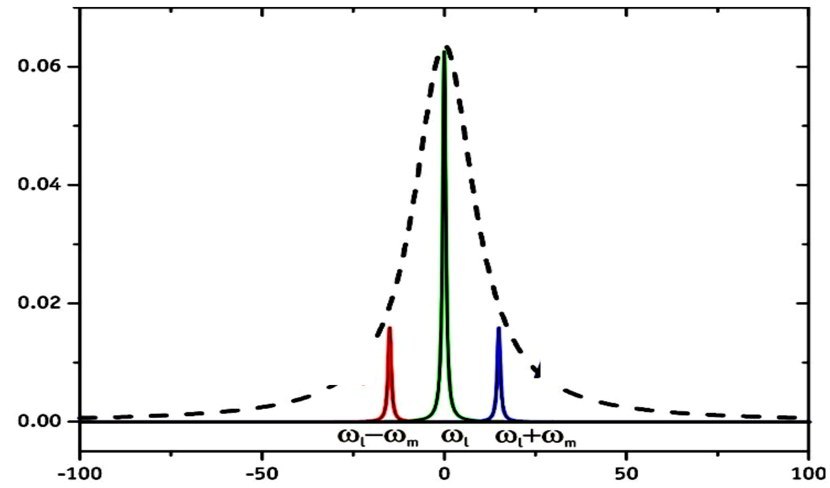
Towards Quantum Optomechanics - Experiments

New ideas, future plans and a famous cat

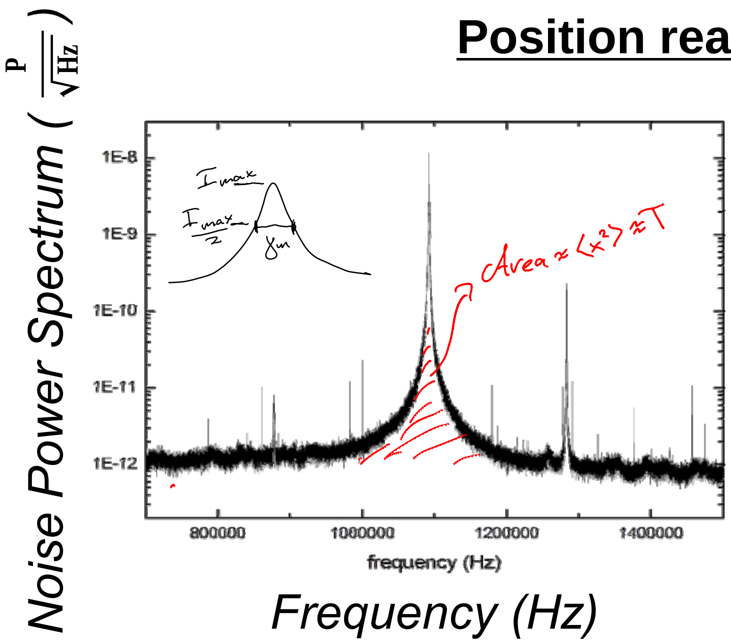


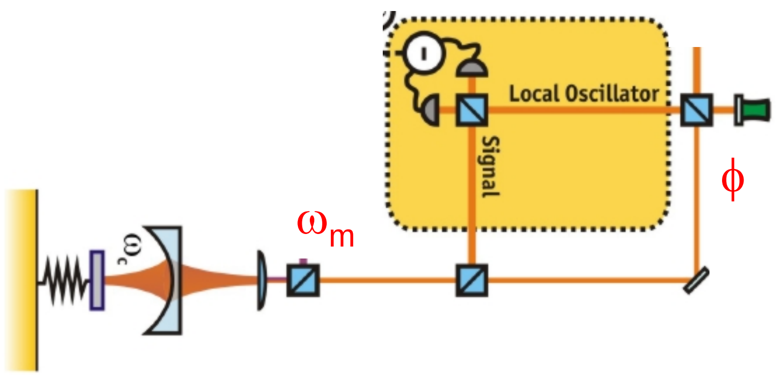
Mechanics acting on light



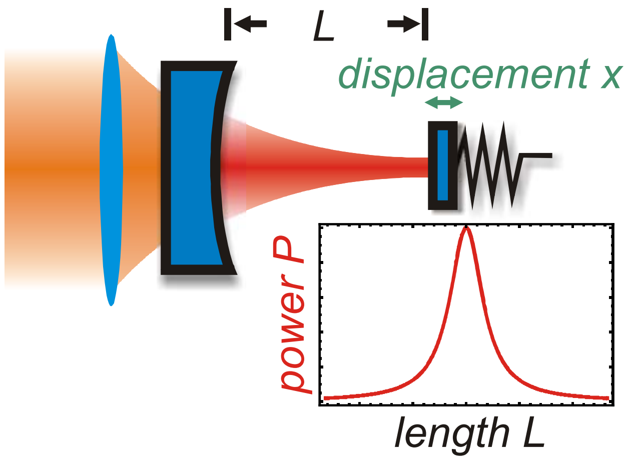


Position readout by Homodyne Detection





Cavity Optomechanics



Intracavity power responsible for force acting on the mirrors

$$F_1(x) = \frac{2P(x)}{c} \approx \frac{2}{c}\frac{\mathrm{d}P(x)}{\mathrm{d}x}x.$$

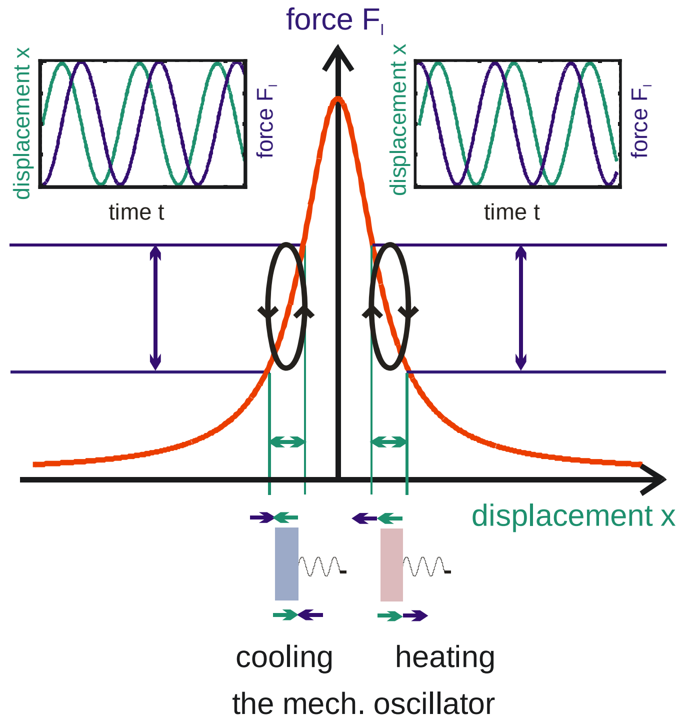
⟶ Position Dependent Force creates an additional harmonic potential

$$\ddot{x} + \gamma_m \dot{x} + \left(\omega_m^2 - \frac{2}{c \cdot m}\frac{\mathrm{d}P(x)}{\mathrm{d}x}\right)x = \frac{F_B}{m}$$

OPTICAL SPRING

A change in cavity length leads to a change in resonance frequency and therefore in intra-cavitypower

The decay time of the cavity results in a delay – for detuned operation heating or cooling of cantilever



Cavity Optomechanics

1983 Walther group: “Optical bistability and mirror confinement induced by radiation pressure“ , Dorsel et al. PRL 51, 1550 (1983)

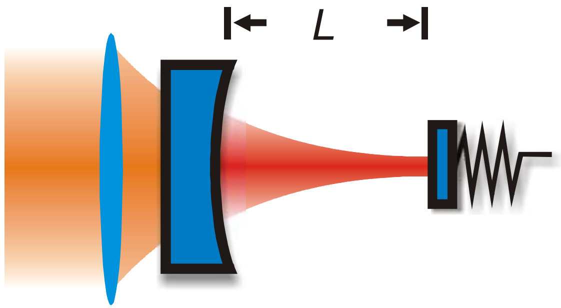
2003 Karrai group: „Optically tunable mechanics of microlevers“

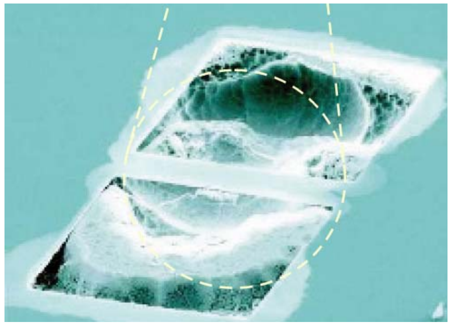
Favero et al.,APL 83,1337 (2003)

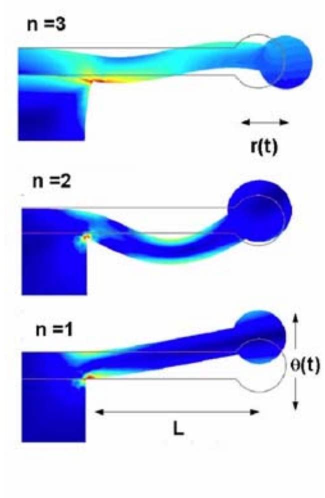
2005 Vahala group: “Kerr-Nonlinearity Optical Parametric Oscillation in an Ultrahigh-Q Toroid Microcavity“ Kippenberg et al.,PRL 93, 83904 (2004)

2006 Aspelmeyer and Kippenberg group, Selfcooling by Radiation Pressure

S. Gigan et al. Nature 444, 67–70 (2006), O. Arcizet et al. Nature 444, 71–74 (2006).



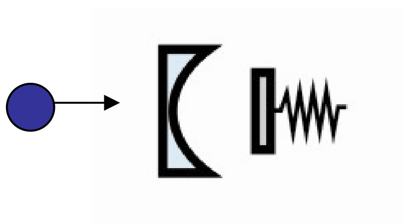




Overview Articles

T. J. Kippenberg and K. Vahala, Science 321, 1172–1176 (2008).
I. Favero and K. Karrai, Nat. Photonics 3, 201–205 (2009).
F. Marquardt and S. M. Girvin, “Optomechanics,” Phys. 2, 40 (2009).
Aspelmeyer M et al., JOSA B 27, A189 (2010)
M. Aspelmeyer and K. Schwab, New J. Phys. 10, 095001 (2008).

Quantum - Cavity Optomechanics



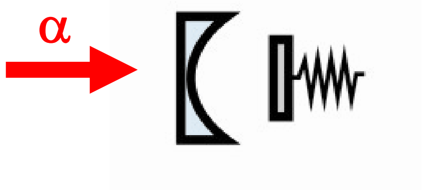
$$H_{\text{int}} = -\hbar g_0 n_c X_m$$

single-photon cavity frequency shift

$$g_0 = \frac{\omega_c}{L}\sqrt{\frac{\hbar}{m\omega_m}}$$

0.1...100 Hz
with most current systems
(too small!!)

Solution: strongly driven optomechanics



$$a \rightarrow \alpha + \bar{a}$$

$$H_{\text{int}} = \hbar g_0 \alpha X_c X_m$$

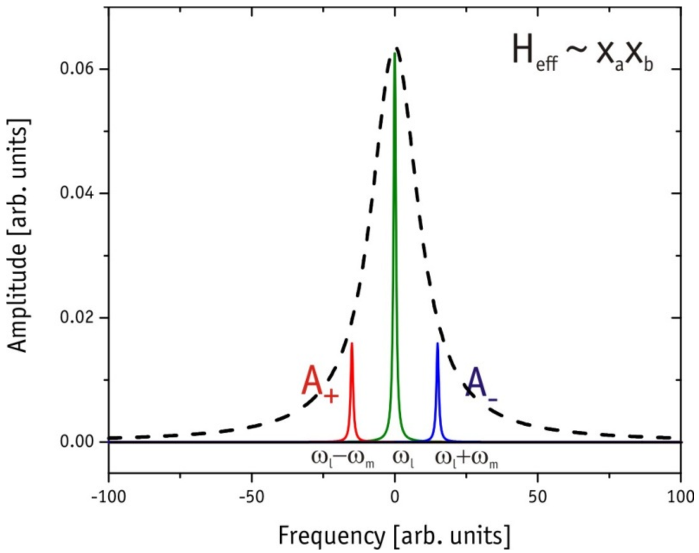
enhancement by α

$$\alpha = \sqrt{n_c} \approx \theta\left(10^5\right)$$

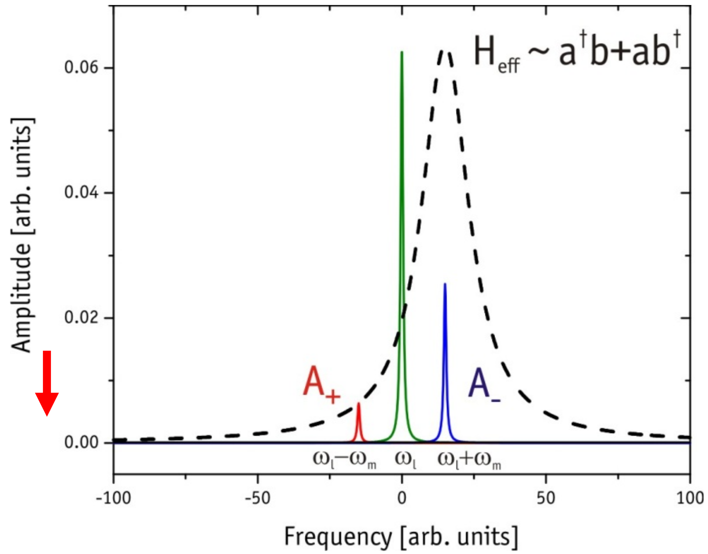
→ strong coupling

Trade-off: only linear coupling... BUT...

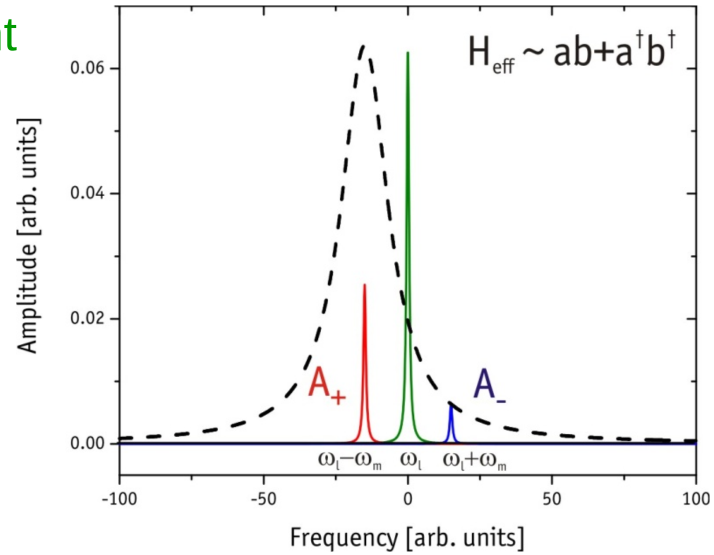
Linear coupling is sufficient



QND Measurement

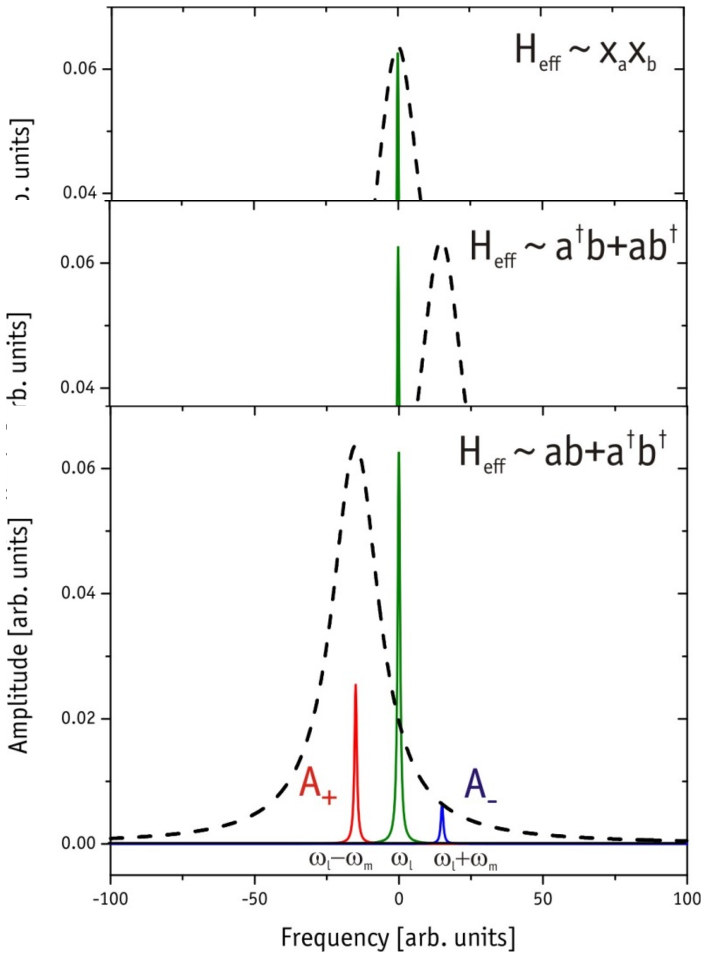


Beamsplitter Interaction



Squeezing Interaction

Linear coupling is sufficient



full **quantum optics toolbox** to prepare and control **mechanical quantum states** via photonic quantum states

Requires:

Minimum entropy mechanics (e.g. ground state)

+

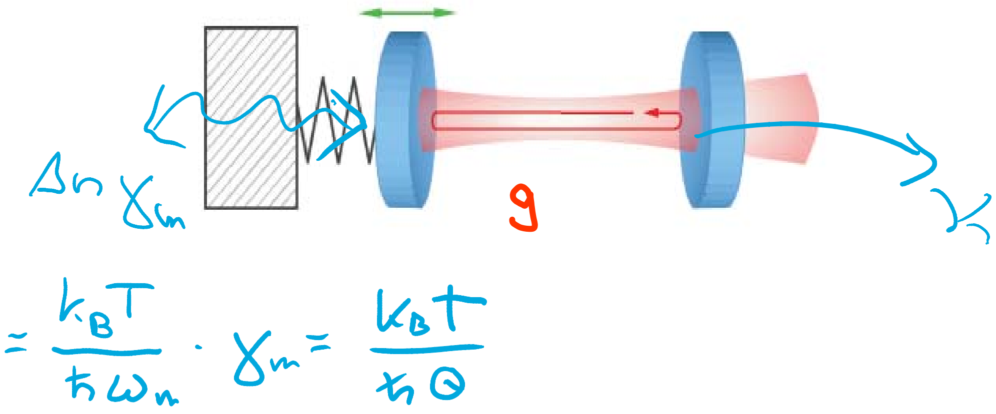
Strong optomechanical coupling (coupling rate > decoherence rate)

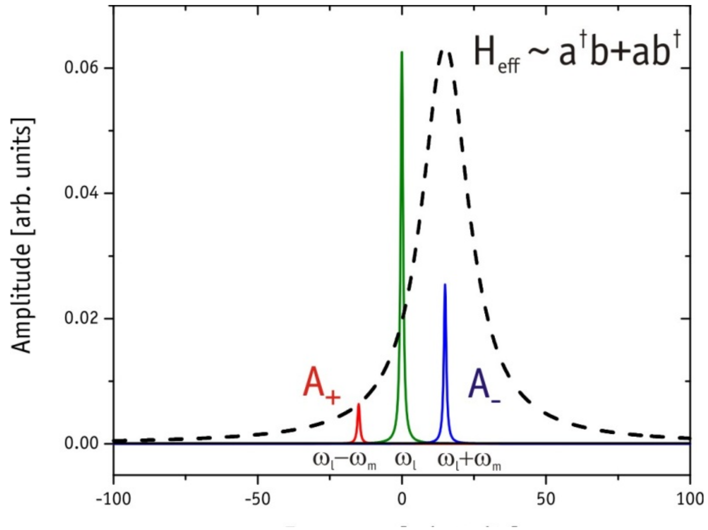
$$\frac{k_B T}{\hbar Q} << \kappa << \omega_m, g$$

RWA approximation: $g \ll \omega_m$

Zhang et al., PRA 68, 13808 (2003)

Sideband Cooling





Cooling into the quantum ground state possible

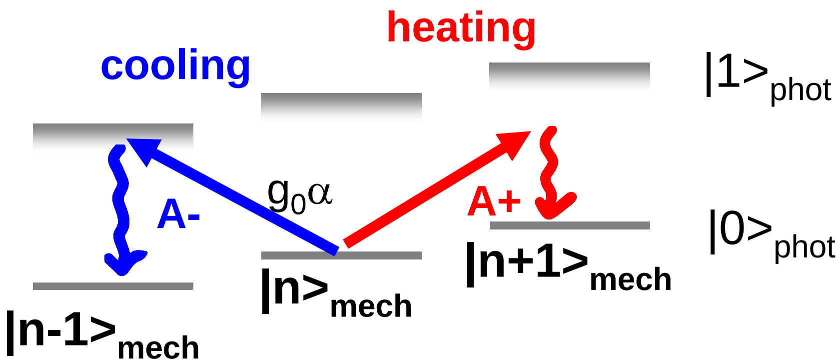
Analogue: sideband-resolved cooling of ions

Cooling rate $\Gamma = A_- - A_+ \approx \frac{(g_0 \alpha)^2}{\kappa}$

Thermal coupling / decoherence) rate $\Gamma_{thermal} = \frac{k_B T}{\hbar Q}$

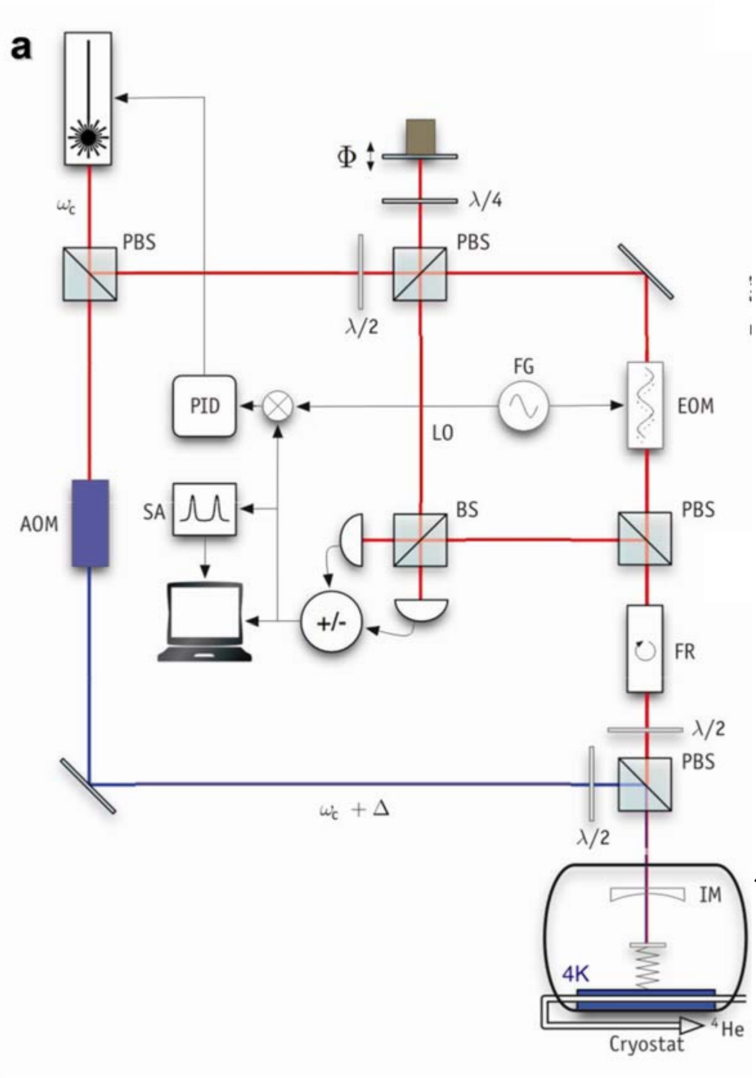
Effective mode occupation $\langle n \rangle_{mech} = \frac{\Gamma_{thermal} + A_+}{\Gamma}$

$\langle n \rangle_{mech}^{min} \approx \left(\frac{\kappa}{4\omega_m}\right)^2$ <<1 for sideband-resolved regime

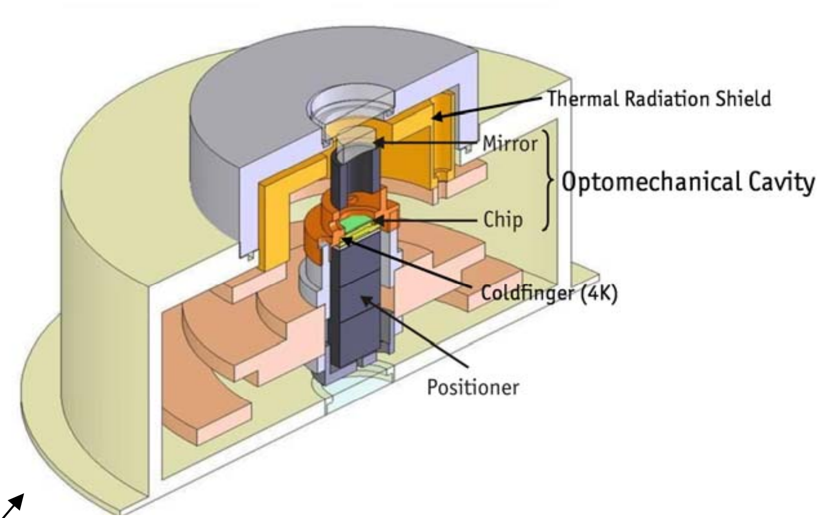


F. Marquardt et al. PPRL 99, 093902 (2007)
I. Wilson-Rae et al., PRL 99, 093901 (2007)
C. Genes et al., PRA 77, 033804 (2008)

Vienna Cooling Experiment



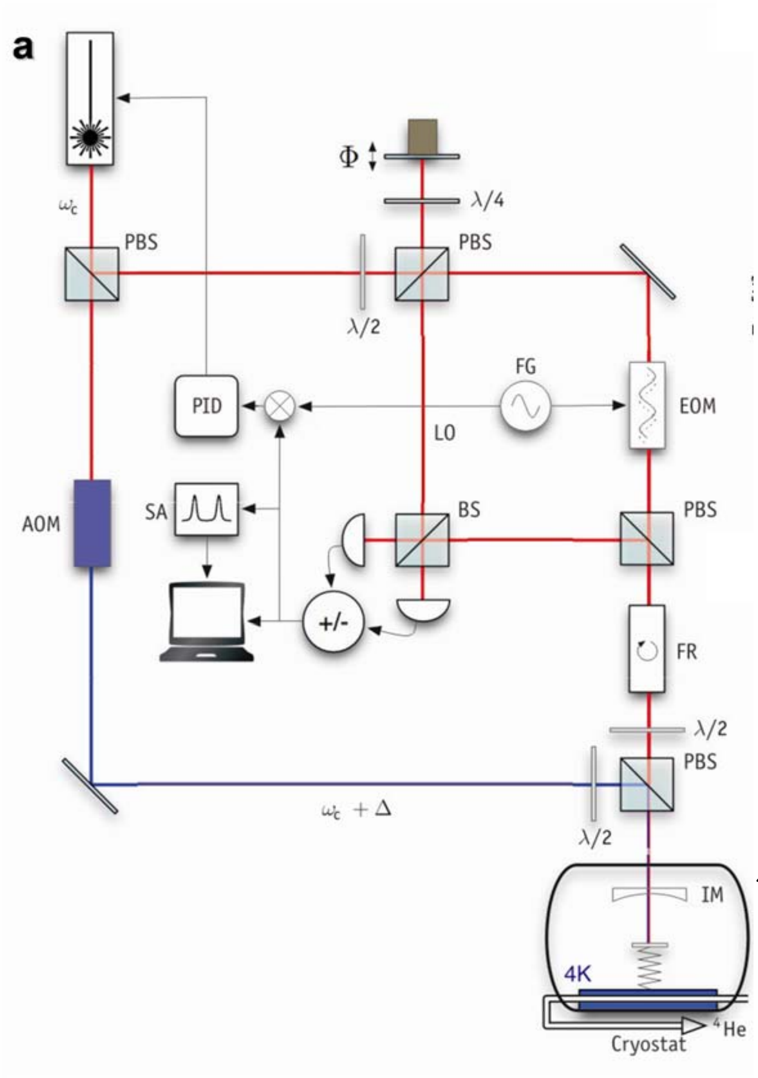
Kryostat holding the cavity with the sample

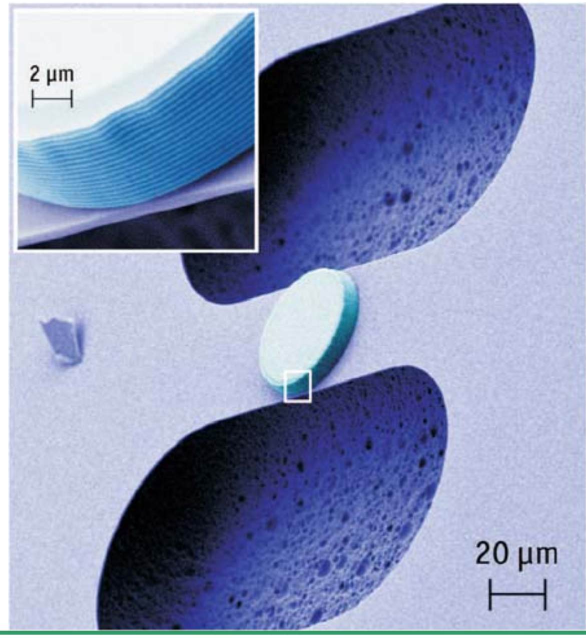


F=3800
$\kappa = 2\pi \times 793$ kHz
$\omega_m = 2\pi \times 945$ kHz

Gröblacher et. al, Nature Physics, 5, 2009

Vienna Cooling Experiment





dielectric mirror pad (Ta_2O_5/ SiO_2) on SiN_x

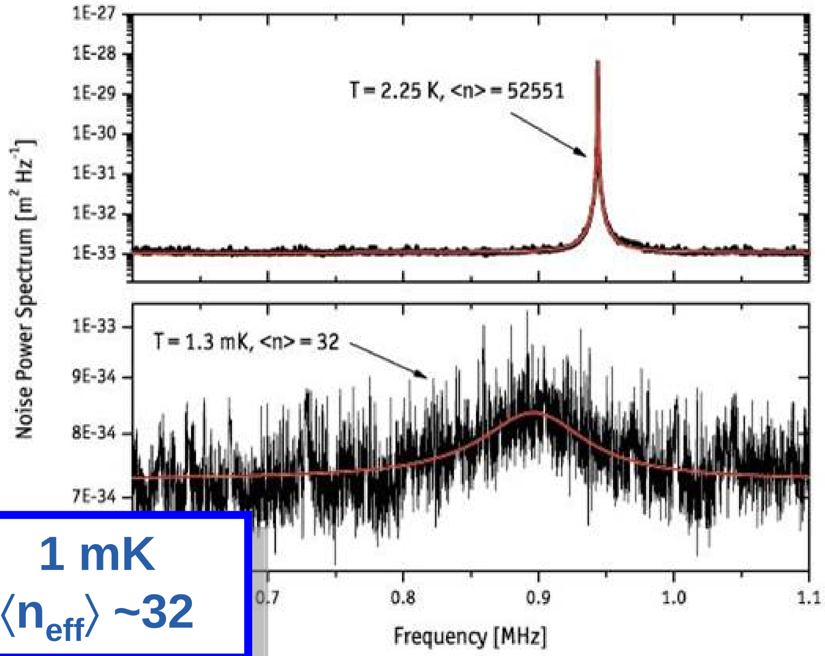
dimensions: 100s x 50 x 6 μm^3

Quality factor: Q=30000 @ 5.3 K

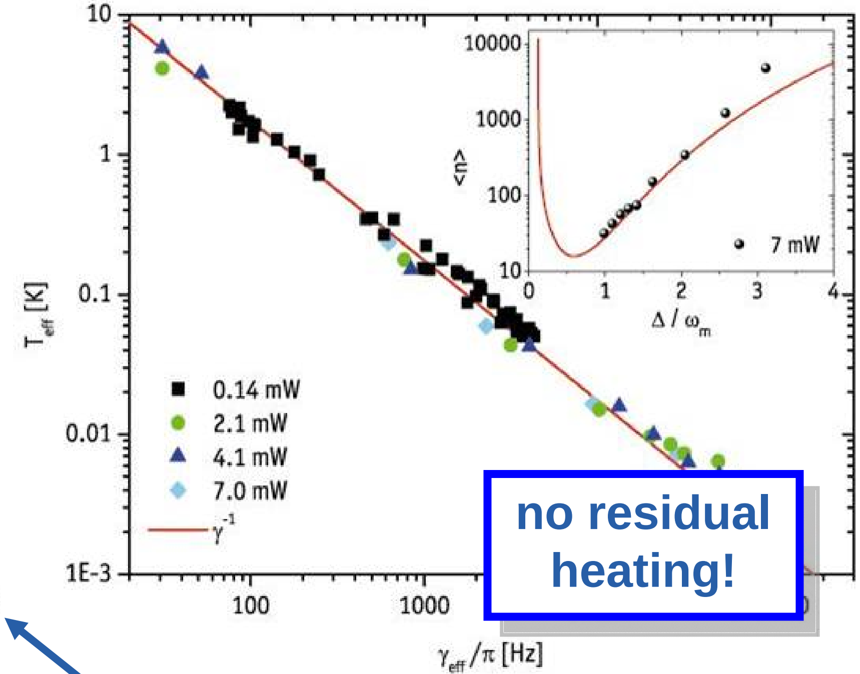
Reflectivity > 0.9999

Gröblacher et. al, Nature Physics, 5, 2009

Ultracold optomechanical systems

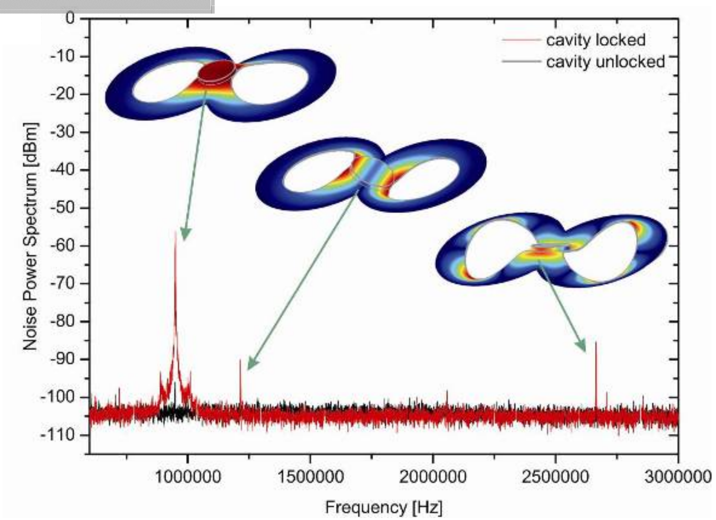


1 mK
⟨n_{eff}⟩ ~32



no residual heating!

noise floor ~ 2.6×10^{-17} $mHz^{-1/2}$
4x above the shot noise limit

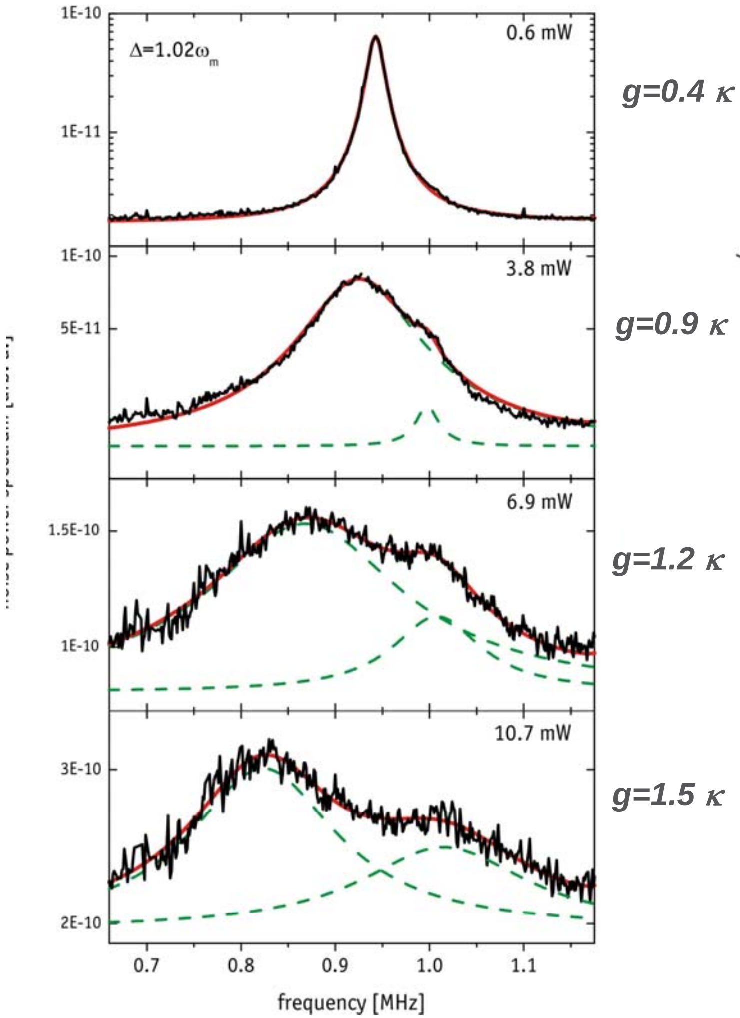


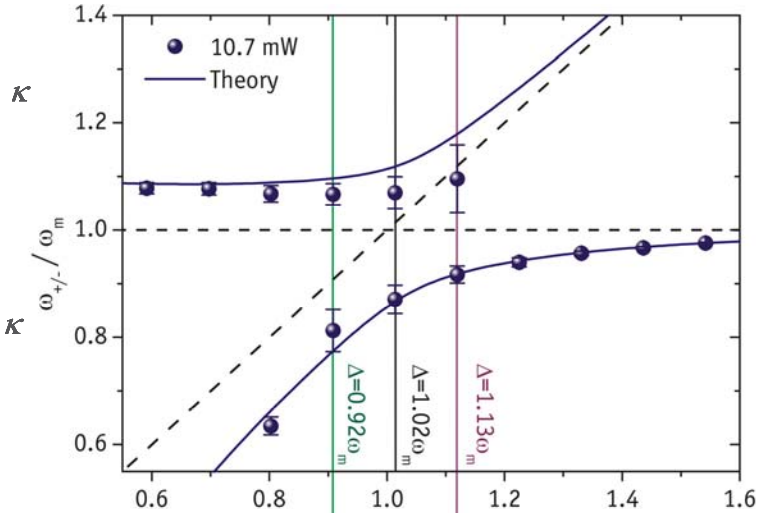
relevant modes identified via FEM

Gröblacher et. al, Nature Physics, 5, 2009

Optomechanical strong coupling

optomechanical normal mode splitting





avoided level crossing = normal mode spectrum of hybrid optomechanical states

strong coupling = reversible energy exchange large compared to systems' decoherence rate

$g > \kappa, \gamma_m$

$g \approx 2\pi \times 325$ kHz
$\kappa = 2\pi \times 215$ kHz
$\gamma_m = 2\pi \times 140$ Hz

S. Gröblacher et al., Nature 460, 724-727 (2009)

GS-Cooling and Strong coupling achieved

Quantum regime of mechanical oscillator

minimum entropy mechanical states (e.g. ground state via cooling)

S. Gröblacher et al., Nature Phys. 5 (09)
A. Schliesser et al., Nature Phys. 5 (09)
Y. Park et al., Nature Phys. 5 (09)

$\langle n \rangle \sim 30$

J. Teufel et al., arXiv:1103.2144 (11)
J. Chan et al., Nature 478 (11)

$\langle n \rangle < 1$

+

coherent photon-phonon exchange (strong optomechanical coupling)

S. Gröblacher et al., Nature Phys. 5 (09)
O'Connell et al., Nature 464 (10)
J. Teufel et al., Nature 471 (11)

$$\Gamma_m \ll \kappa \ll \omega_m, g$$

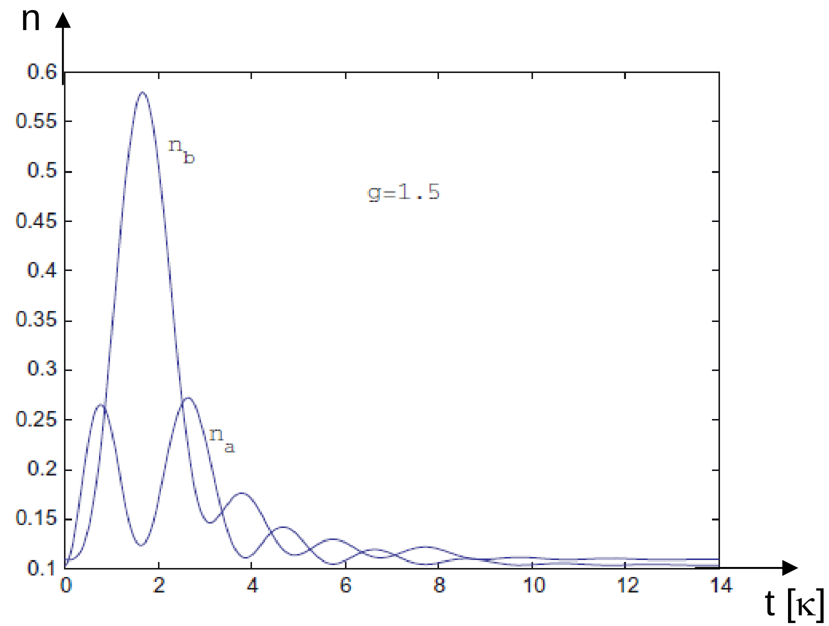
RWA approximation: $g \ll \omega_m$

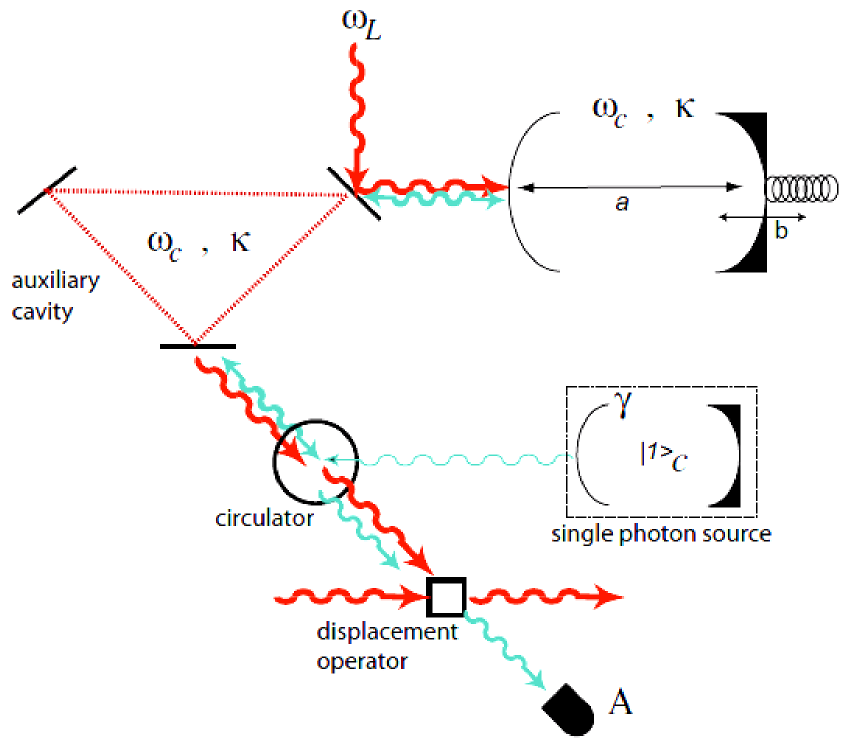
Single Photon Optomechanics ?

Akram U, Kiesel N, Aspelmeyer, M, Milburn G, NJP 12, 083030 (2010)

Single photon optomechanics enabled by strong driving

Optomechanical Rabi Oscillations

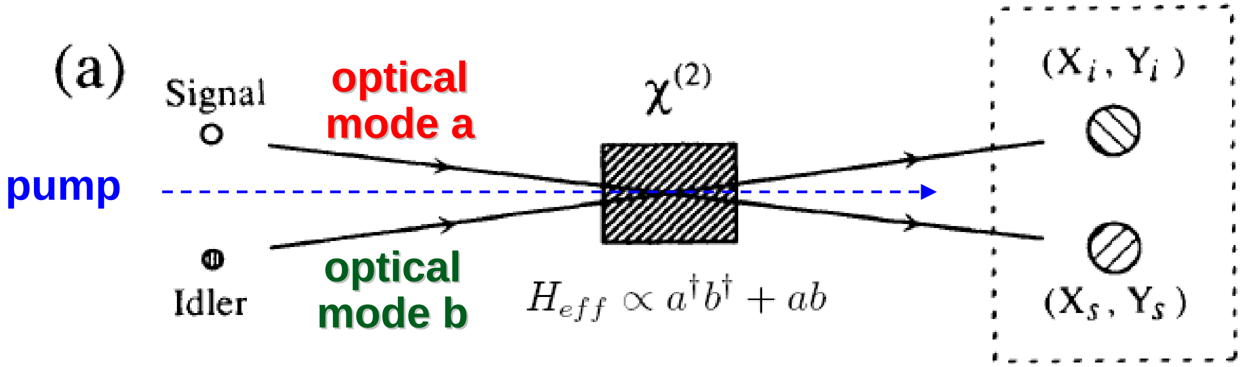




Closely related – Mechanical Storage of Light:
S. Weis et al., Science 330, 1520 (2010) (OM induced tranparency)
D.E. Chang et al., Nature 472, 69 (2011) (OM - Slowing Light)

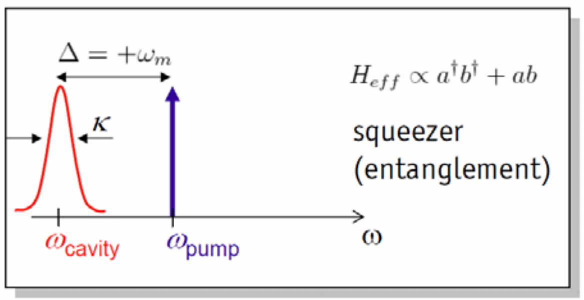
Towards Quantum-Optomechanical Entanglement

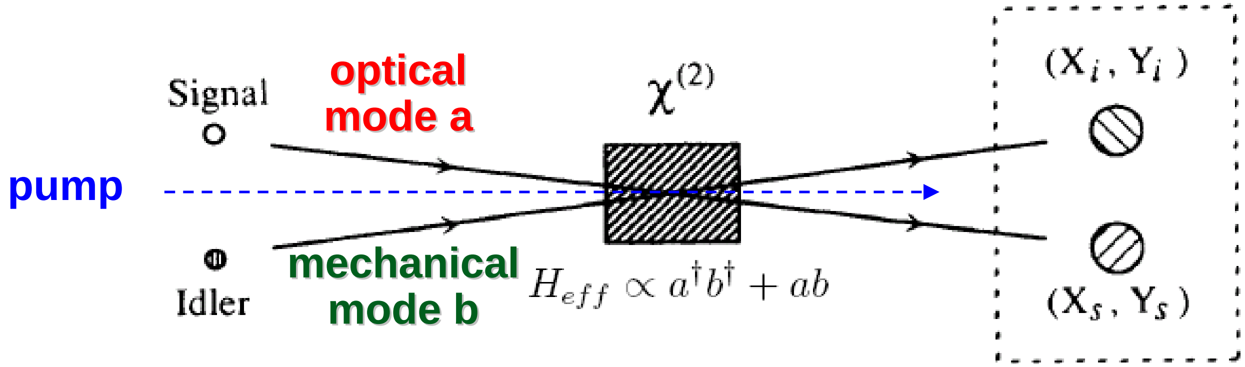
EPR Entanglement in parametric downconversion



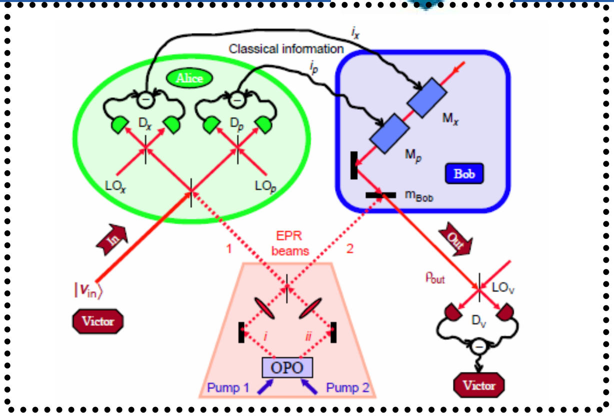
Realization of the Einstein-Podolsky-Rosen Paradox for Continuous Variables
Ou, Pereira, Kimble, Peng, PRL 68, 3663 (1992)

EPR Entanglement in „optomechanical parametric downconversion"





Teleportation



With light fields: Furusawa et al., Science 282, 707 (1998)

EPR-Entanglement between two light fields

Optomechanical correlations: towards EPR entanglement

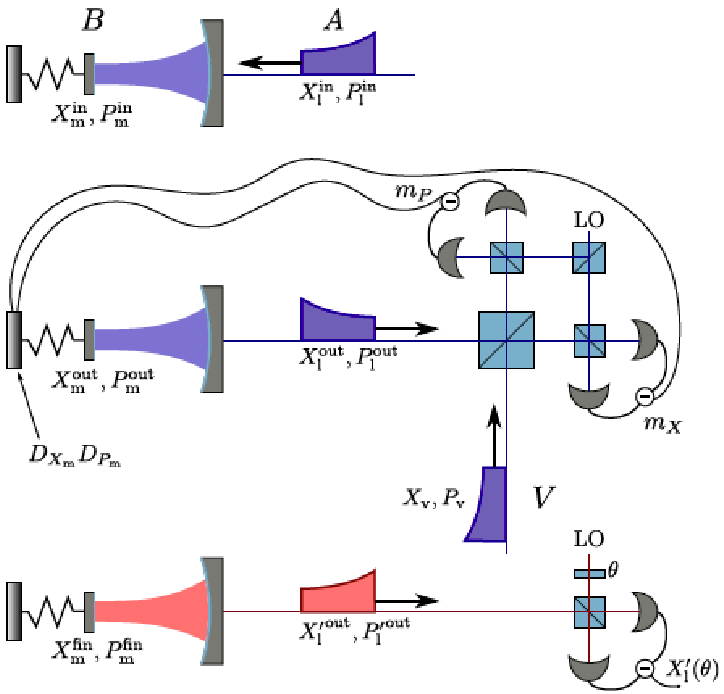
$$\Delta_{\mathrm{EPR}} = \Delta(x_1 - x_2)^2 + \Delta(p_1 + p_2)^2 \rightarrow 0(< 2)$$

requires:

$$x_- = x_1 - x_2 \rightarrow 0$$

$$p_+ = p_1 + p_2 \rightarrow 0$$

use entanglement for optomechanical teleportation



Entanglement schemes

Bose, Jacobs, Knight, PRA 56, 4175 (1997)

D. Vitali et al. PRL 98, 030405 (2007)

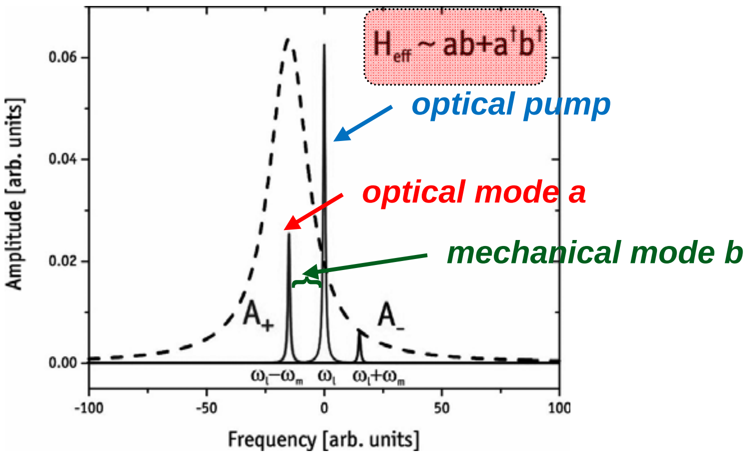
M. Paternostro et al.PRL 99, 250401 (2007)

Romero-Isart O, Phys. Rev. A. 83, 013803 (2011).

and many others...

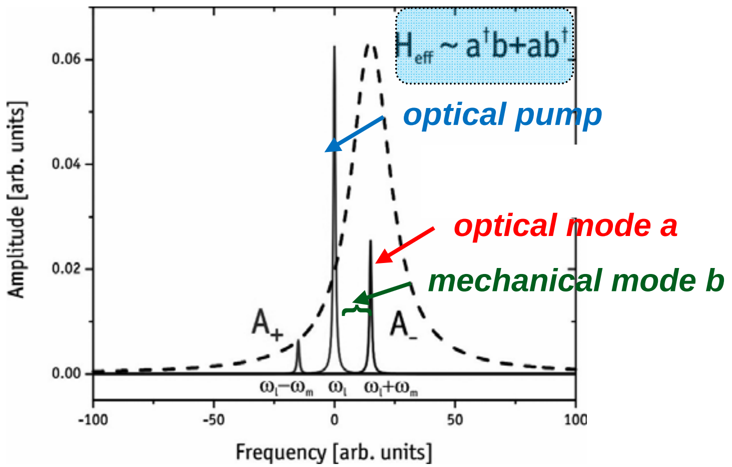
Hofer et al. arXiv:1108.2586.

Cooling + 2-mode squeezing



blue-detuned in resolved sideband:
two-mode squeezing

BUT:
cavity instability (system becomes nonlinear)
mechanical mode temperature increases



red-detuned in resolved sideband: cooling

„pure" beam splitter interaction only true in the RWA ($g \ll \omega_m$), full interaction:

$$\mathcal{H}_{rp} = \hbar g(a_c a_m^\dagger + a_c^\dagger a_m) + \hbar g(a_c^\dagger a_m^\dagger + a_c a_m)$$

$\sim g/\omega_m$

simultaneous „strong" cooling and „weak" squeezing

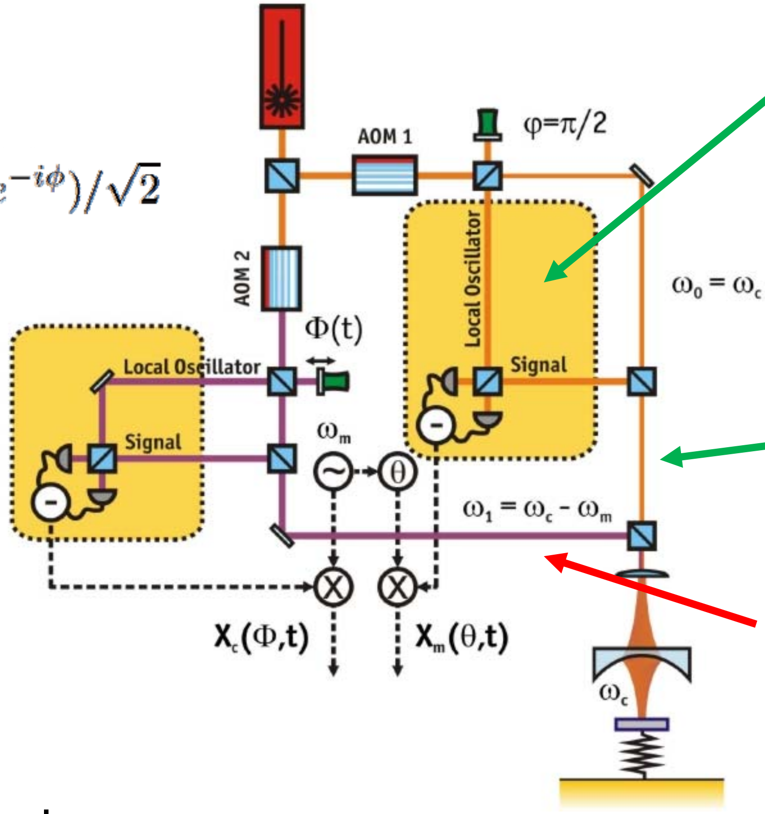
Experiment OM down conversion

homodyne detection:
read out optical field

$$\hat{X}_l(\phi) = (ae^{i\phi} + a^\dagger e^{-i\phi})/\sqrt{2}$$

homodyne detection:
read out resonant light
field to infer mechanics

$$\hat{X}_r(\gamma) = (a_r e^{i\gamma} + a_r^\dagger e^{-i\gamma})/\sqrt{2}$$



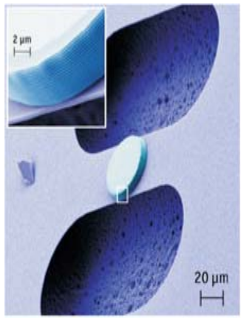
locking beam

$$g \ll \kappa < \omega_m$$

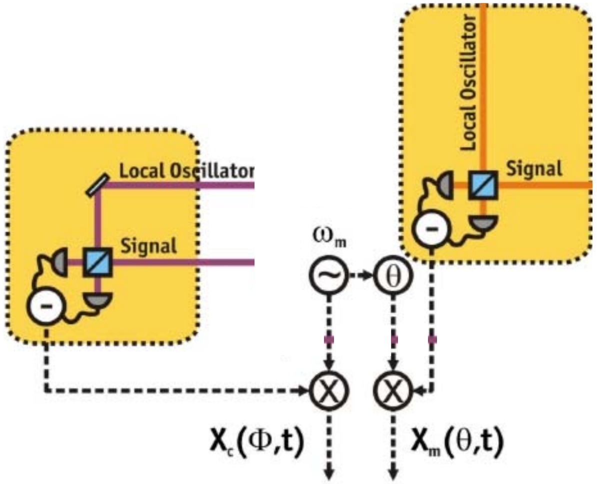
ω_m-detuned beam:
tunable g
for cooling and sqeezing

correlate time traces
of two independent
homodyne detections
to obtain optomechanical
correlation

Finesse 20000
Q_m ~ 2000 at RT (precooled)
m_{eff}=270ng



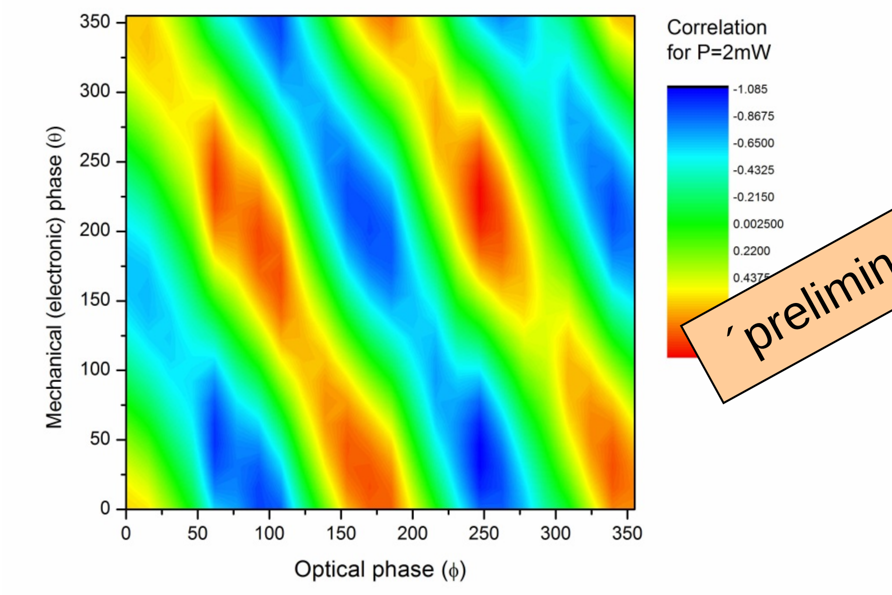
Correlation

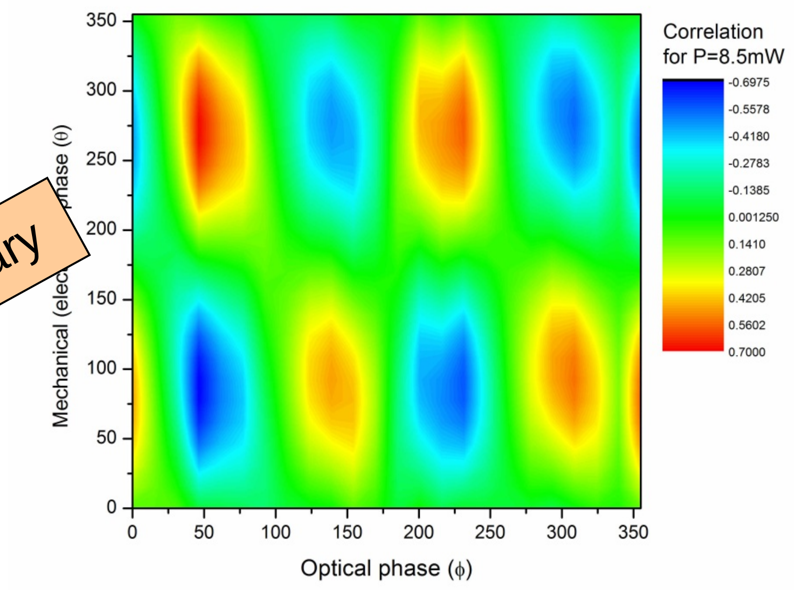


determination of correlations:

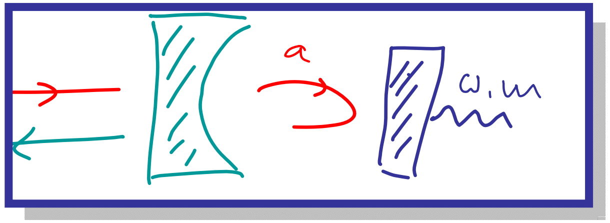
$$A = \hat{X}_l(\phi)$$
$$B = \hat{X}_m(\theta)$$

$$C(\phi,\theta) = \frac{\langle (A - \langle A \rangle)(B - \langle B \rangle) \rangle}{\sqrt{\langle (A - \langle A \rangle)^2 \rangle \langle (B - \langle B \rangle)^2 \rangle}}$$





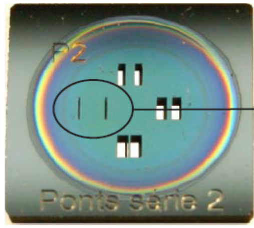
Opto-mechanical systems (a few examples)



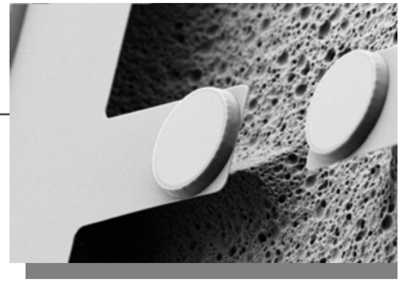
FP cavity

O(kg-ng)

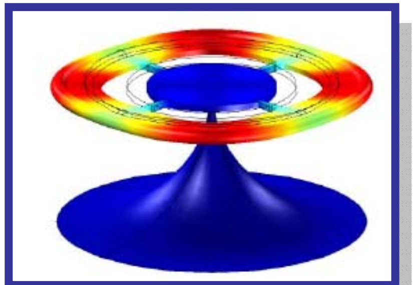
Mavalvala (LIGO, MIT)



Heidman (Paris)

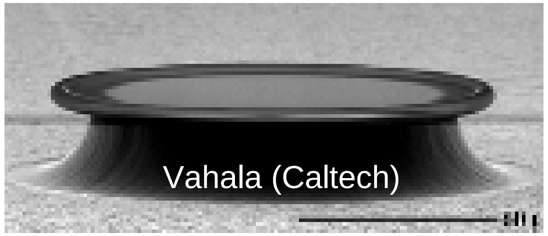


Aspelmeyer (Vienna)

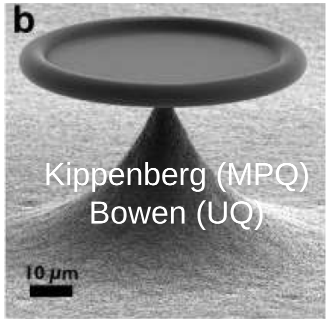


Toroidal microcavity

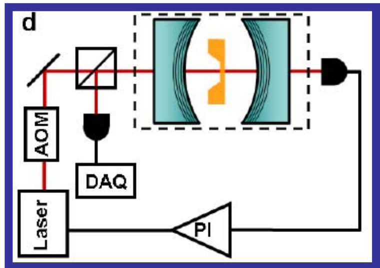
O(ng)



Vahala (Caltech)

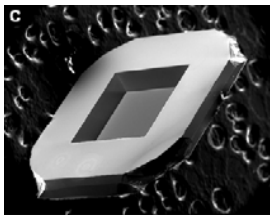


Kippenberg (MPQ)
Bowen (UQ)

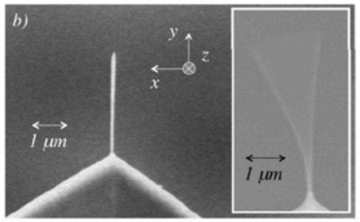


"Dispersive" coupling

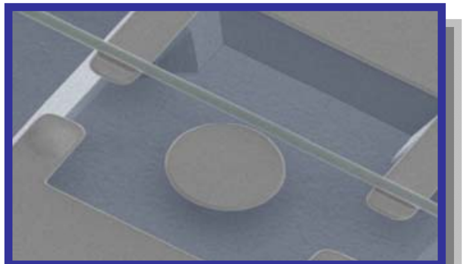
O(zg-ng)



Harris (Yale)
Kimble (Caltech)

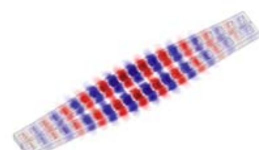


Favero (Paris)

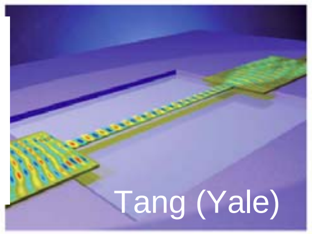


"Dipole" coupling

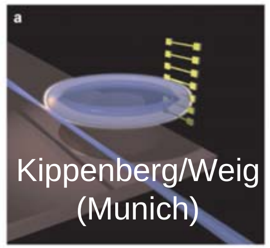
O(pg)



Painter (Caltech)

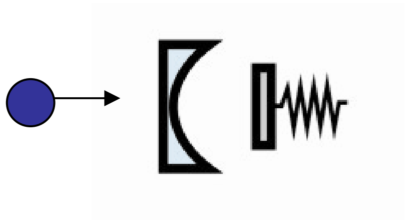


Tang (Yale)



Kippenberg/Weig
(Munich)

Nonlinear Single Photon Coupling?

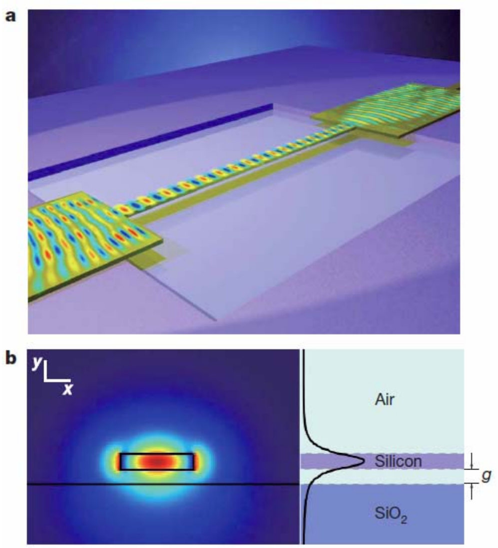


$$H_{\text{int}} = -\hbar g_0 n_c X_m$$

single-photon cavity frequency shift

$$g_0 = \frac{\omega_c}{L}\sqrt{\frac{\hbar}{m\omega_m}}$$

General requirement in Fabry-Perot geometry: **Finesse > λ/x_{ZP}** (O(10^6))



PROMISING APPROACH: Optical gradient forces

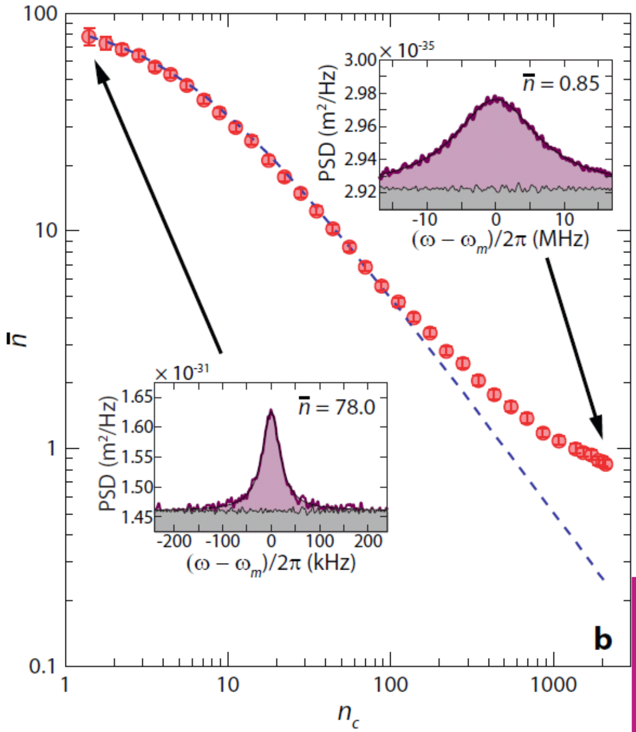
Idea: enhance cavity response $g_0 = d\omega_c/dx$ by **near-field effects in optical waiveguides**

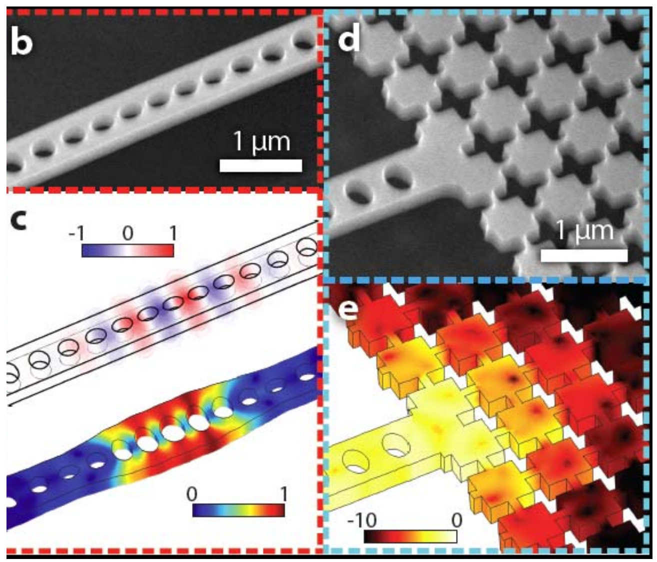
Advantage: low mass (pg), large g_0 (up to 10^5)
Current bottleneck: cavity decay too large ($\kappa > 10^8$)

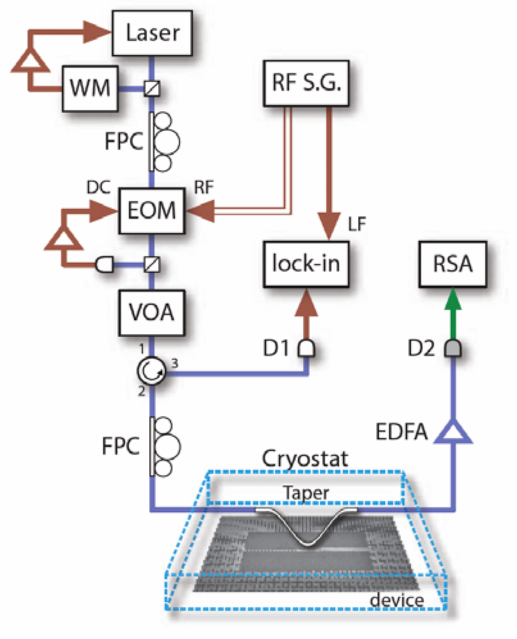
Tang group Nature 456, 480 (2008)
Painter group Nature 459, 550 (2009)

Ground-state laser cooling of a nanomechanical resonator

- **Optomechanical crystal** (photonic & phononic bandgap structure)
- **3.5 GHz mechanical mode** at 20 K (<n> ~ 100)
- m ~ O(pg), N ~ O(10^{10} atoms)
- currently limited by absorption effects, optical linewidth ~ 350 MHz







<n> ~ 0.8
Caltech/Vienna May 11

Note also:
Measurement of
Sideband Assymetry:
Safavi-Naeini et al..
arXiv 1108.4680 (2011)

J. Chan, T. P. M. Alegre, A. H. Safavi-Naeini, J. T. Hill,A. Krause,
S. Gröblacher, M. Aspelmeyer, O. J. Painter, *Nature, 478, 1* (2011)

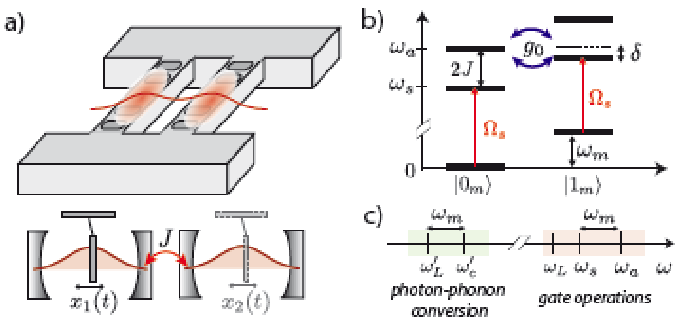
Most Recently:
Further ideas on QIPC with OM crystals

Optomechanical quantum information processing with photons and phonons

K. Stannigel[1,2], P. Komar[3], S. J. M. Habraken[1], S. D. Bennett[3], M. D. Lukin[3], P. Zoller[1,2], P. Rabl[1]
[1] *Institute for Quantum Optics and Quantum Information, 6020 Innsbruck, Austria*
[2] *Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria and*
[3] *Physics Department, Harvard University, Cambridge, Massachusetts 02138, USA*
(Dated: February 16, 2012)

We describe how strong resonant interactions in multimode optomechanical systems can be used to induce controlled nonlinear couplings between single photons and phonons. Combined with linear mapping schemes between photons and phonons, these techniques provide a universal building block for various classical and quantum information processing applications. Our approach is especially suited for nano-optomechanical devices, where strong optomechanical coupling on a single photon level is within experimental reach.

PACS numbers: 42.50.Wk, 03.67.Hk, 07.10.Cm

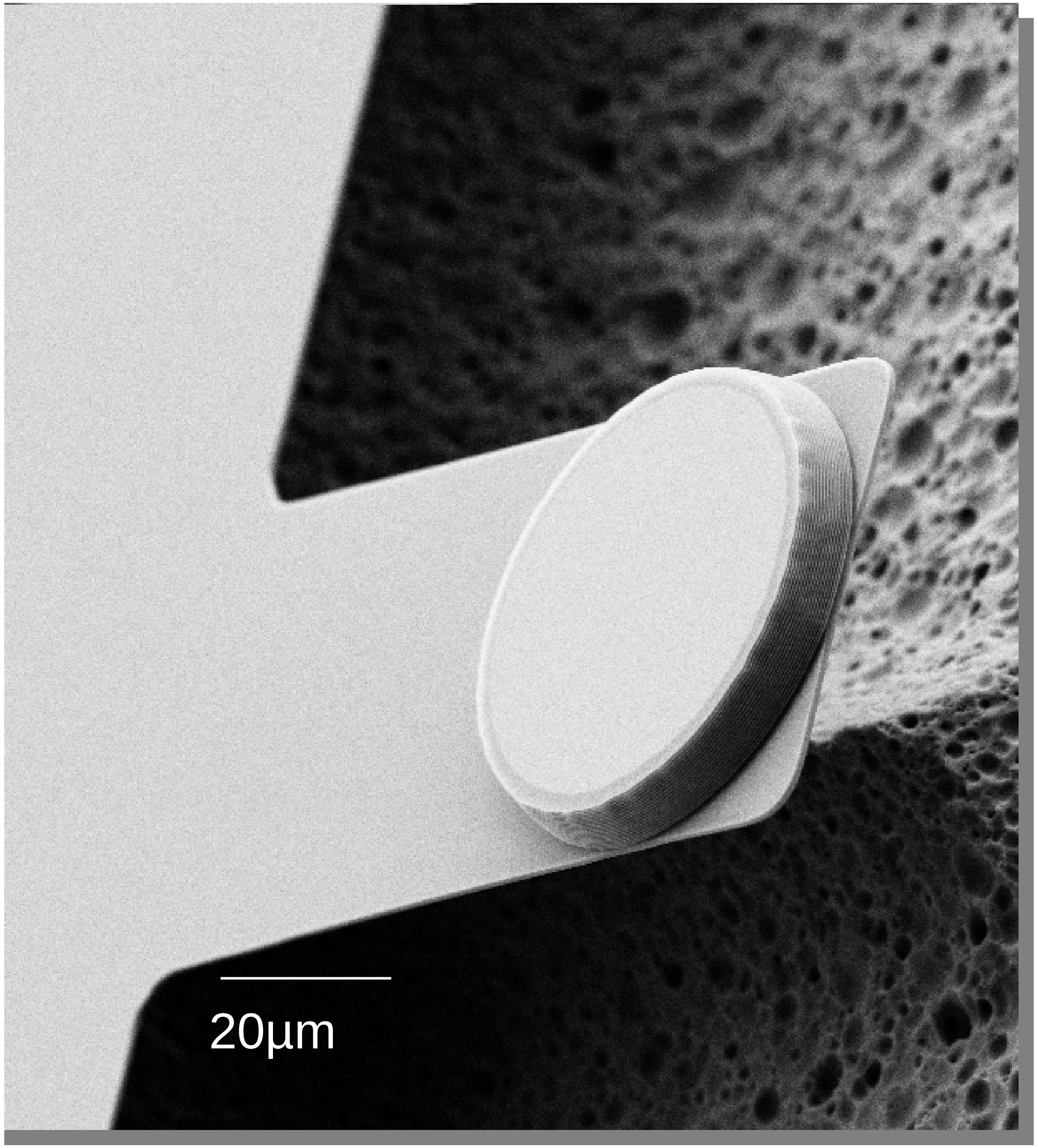


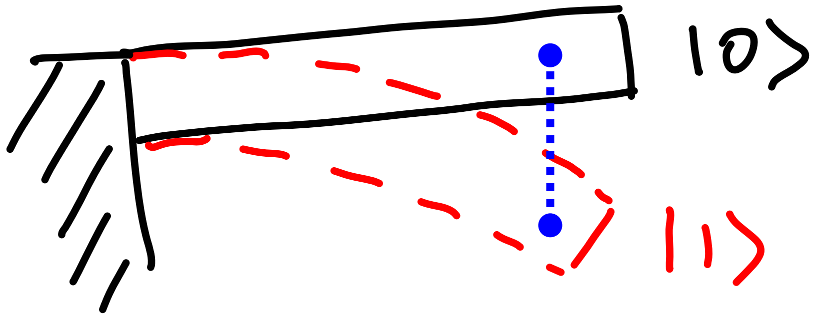
An OM single photon source

Single-phonon single-photon transistor

Phonon-phonon interactions

A mechanical cat? Schrödinger's mirrors?





Superposition of macroscopically distinct states?

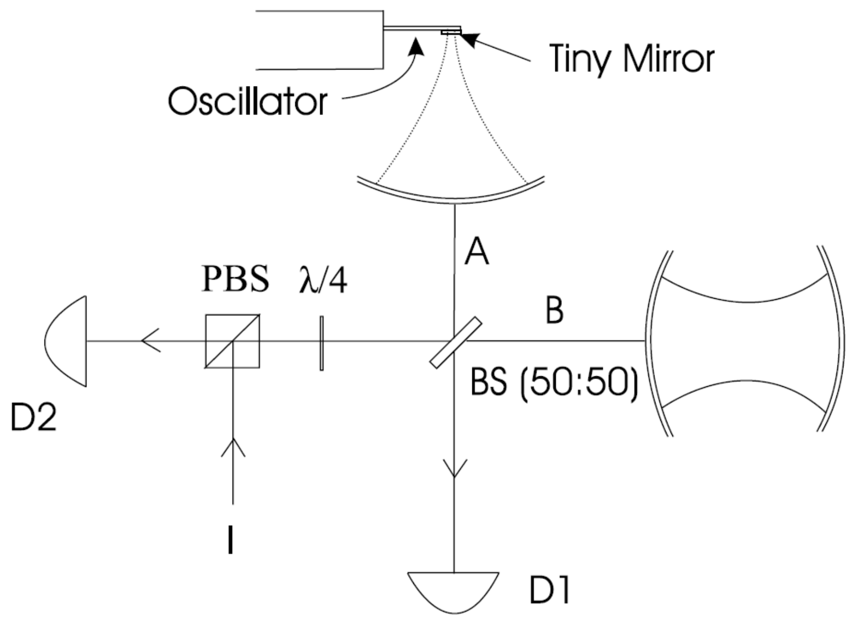
Tests of macrorealistic theories? (Collapse models, Leggett-Garg, …)

Tests of predictions of quantum gravity?

Short introduction to the subject:
Adler, Bassi, Science 325, 275 (2009)

A mechanical cat? Schrödinger's mirrors?

Marshall, Simon, Penrose, Bouwmeester, PRL 91, 130401 (2003)



also: A.D. Armour, M.P. Blencowe, and K. Schwab, PRL 88, 148301 (2002.)

A single photon – 2 paths

1. Path energy exchange
   with mechanical device
2. Path no interaction

Interference and projection of Photon: ½ excitation of mirror

Challenging:

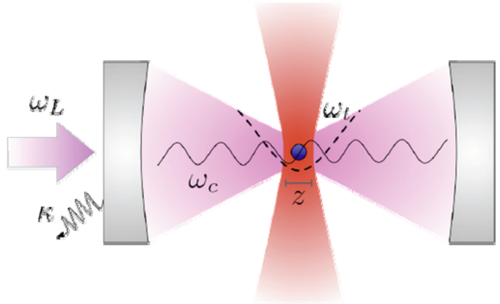
Single Photon Coupling
and
Low Frequencies
(for large displacement)

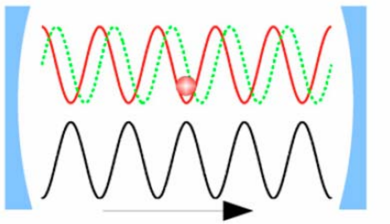
(high mechanical Q/T required)

High-Q by levitation

Optically levitated nanospheres

• Chang et al., quant-ph 0909.1548 (2009), PNAS 2010
• Romero-Isart et al., quant-ph 0909.1469 (2009), NJP 2010
• P. F. Barker et al., PRA 2010





→ **Harmonic oscillator in optical potential**
(no support loss, high Q
tunable optical frequency)

→ **Quantum control via cavity optomechanics**
(laser cooling, state transfer, etc.)

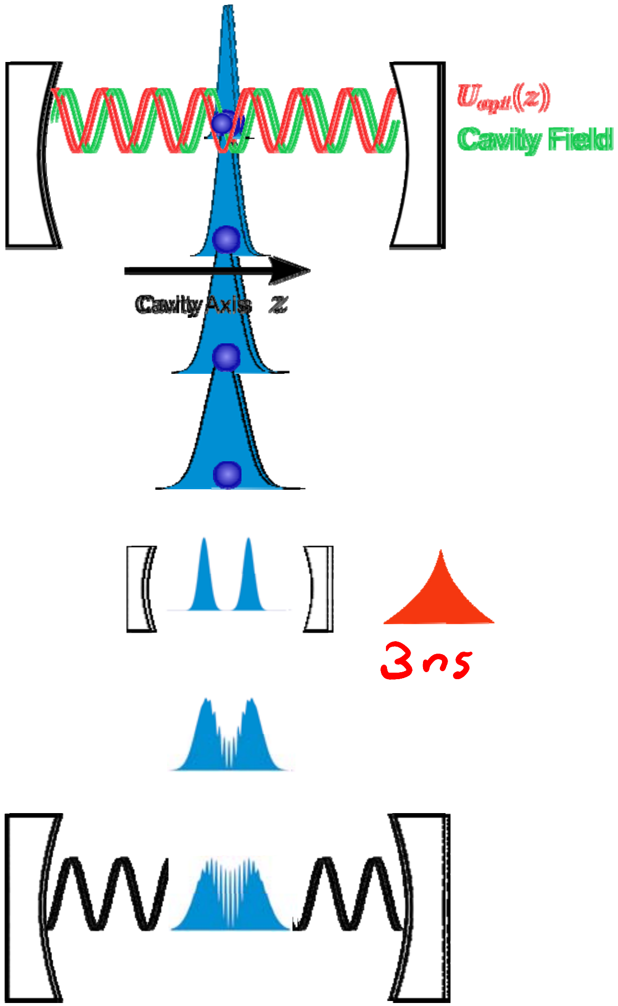
→ **More than just oscillator + OM control**
(e.g. optimized cooling Pender et al. , arXiv: 1107.0686)

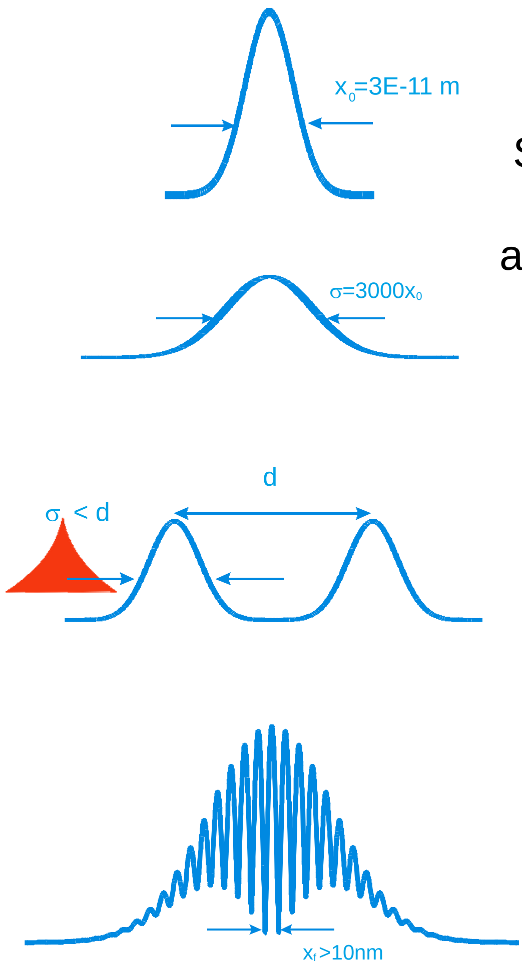
Generation of quantum superposition states

- single-photon quantum state transfer
- quantum state teleportation
- …
- ***free fall . . .***

•Khalili, Danilishin, Miao, Muller-Ebhardt, Yang, Chen, quant-ph 1001.3738 (2010)
• Romero-Isart, Pflanzer, Juan, Quidant, Kiesel, Aspelmeyer, Cirac, Phys. Rev. A 83, 013803 (2011)
• Akram, Kiesel, Aspelmeyer, Milburn, NJP 12, 083030 (2010)

Large quantum superpositions





Object: D=40nm
Silica Sphere

Sideband Cooling of Nanosphere
to 0.1 phonons
analogous to cooling of micromirror

↓ 3.3 ms

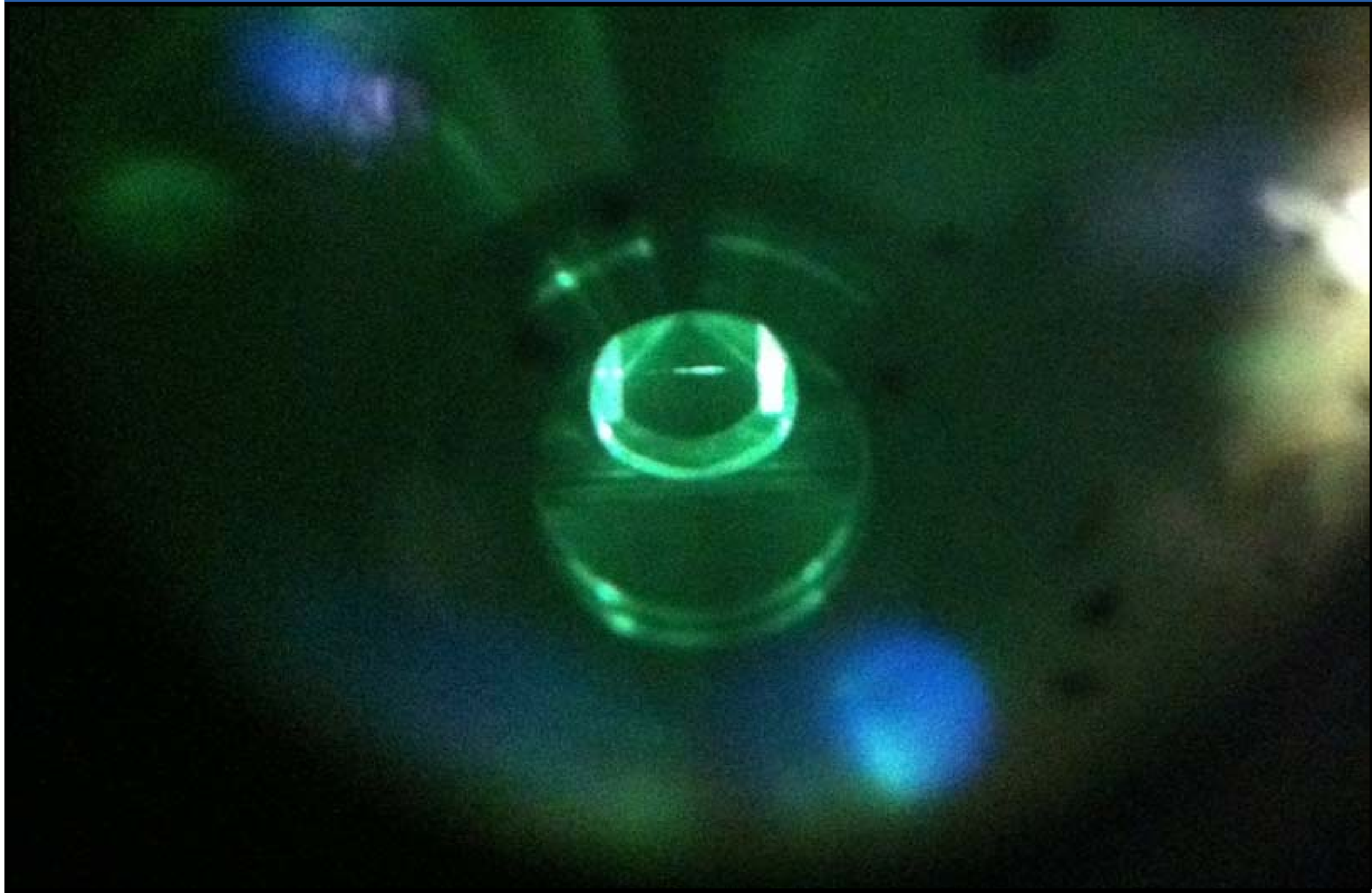
Short Pulse
x^2–readout Projection
on Cat-State $|x\rangle + |-x\rangle$
(Cavity: L=2μm, F=130000)

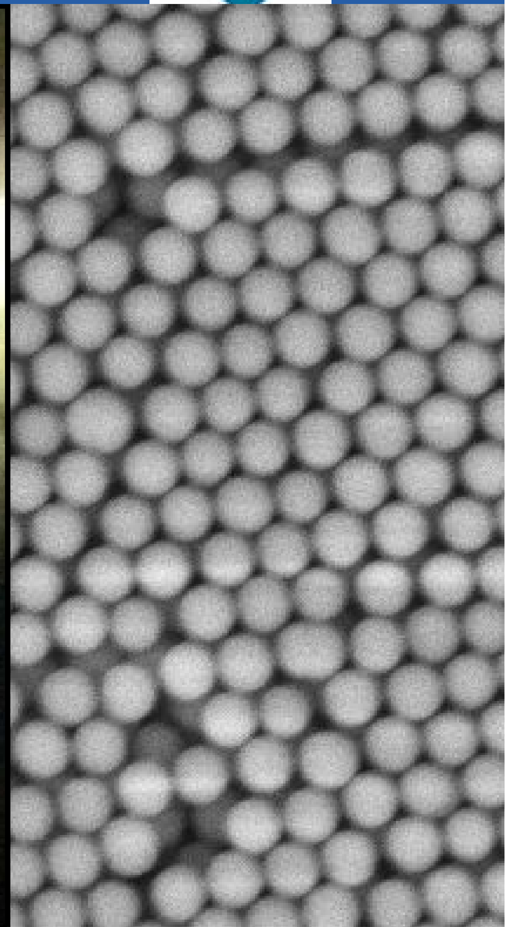
↓ 125 ms

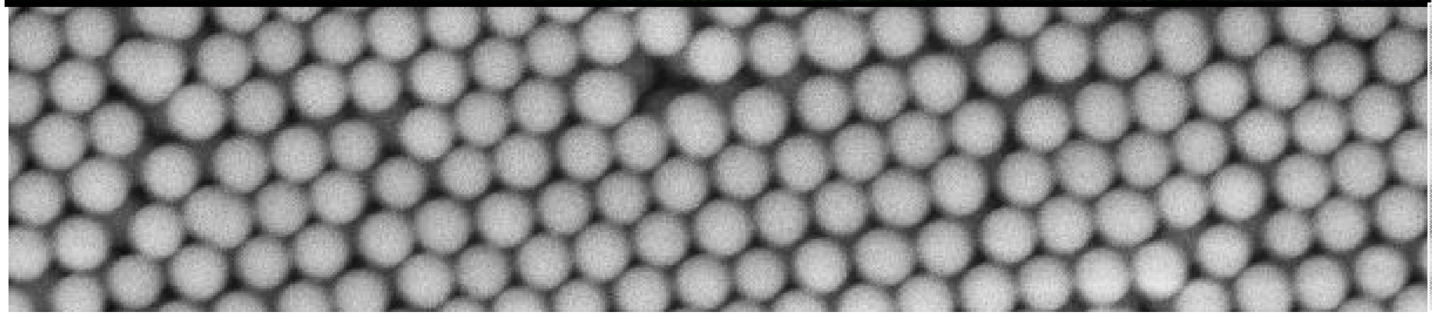
Position Detection
Precision: 10nm

O. Romero-Isart et al., PRL 107, 020405 (2011)
O. Romero-Isart , arXiv:1110.4495
Similar Approach: Kaltenbaek et al., arXiv: 1201.4756

Outlook: Optomechanics with Levitating Nanospheres

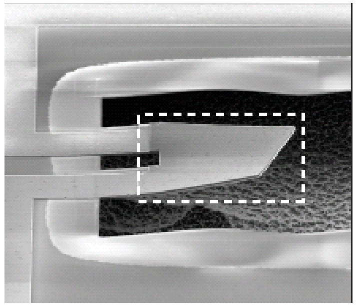




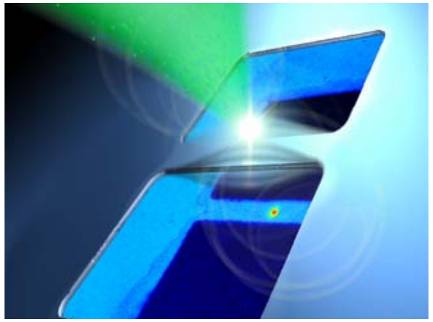


R=128 nm (+/- 10 %)
Silica

Summary

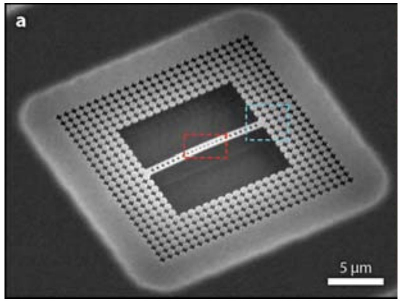


Mechanical Oscillators can serve as taylored quantum devices
In a completely new parameter regime in mass and size

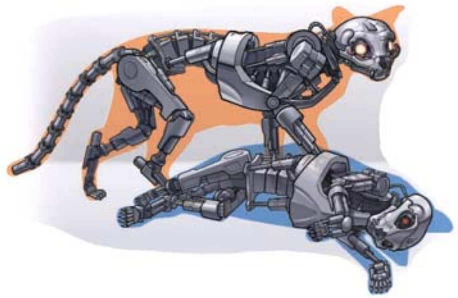


Experiments : cooling already
into the quantumground state and strong coupling
CW – QIPC possible

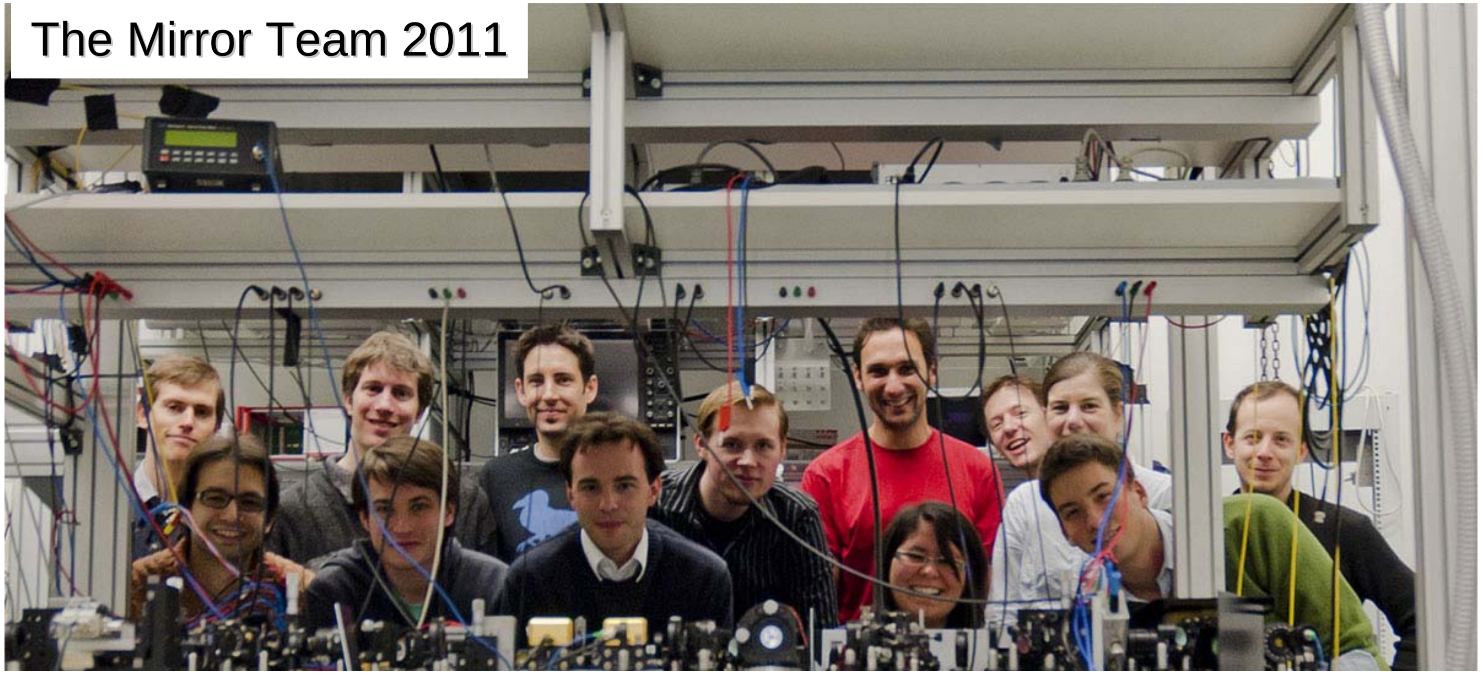
Exciting prospects
single photon optomechanics



Quantum information protocols and studies of coherence in extremely massive quantum systems envisioned



Quantum „mechanics“ in Vienna



M. Vanner (DOC fellow), F. Blaser, G. Cole (Marie Curie Fellow), J. Schmöle, W. Wieczorek (Humboldt Fellow), N. Kiesel (Humboldt Fellow), A. Seiringer, R. Kaltenbaek (Apart fellow), S. Hofer (CoQuS), S. Gröblacher (Marie Curie Fellow), M. Aspelmeyer (ERC Fellow), D. Demir , U. Delic, J. Hörsch

Former team members
M. Paternostro, H. Böhm, S. Gigan, T. Paterek, A. Trubarov

FWF START P15939 L426

STREP MINOS
IIF IQOS
ERC Starting Grant

Foundational Questions Institute (FQXI)

VCQ Vienna Center for Quantum Science and Technology

Alexander von Humboldt Stiftung/Foundation