Quantum Optomechanics Outside the GW Community

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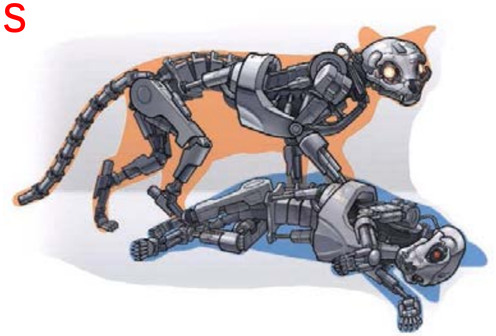
Quantum Regime of Microsystems

Motivation: investigation of complex quantum systems



Quantum Foundations

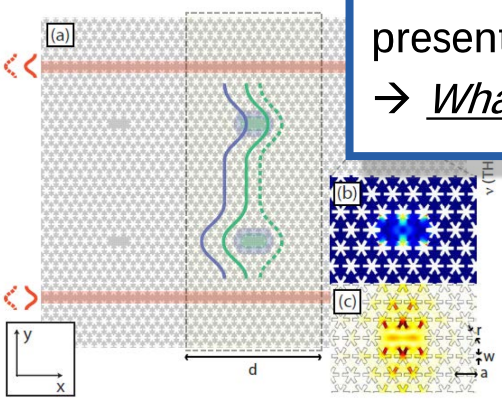
macroscopic quantum superposition involving up to 10^{20} atoms

→ *Is there a limit to the size of Schrödinger cats?*

Mechanical Sensing

present performance: zeptogram, zeptonewton, attometer, etc.

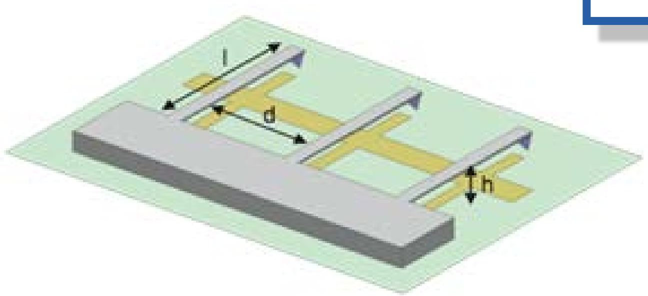
→ *What are the quantum limits to mechanical sensing?*



Quantum Information

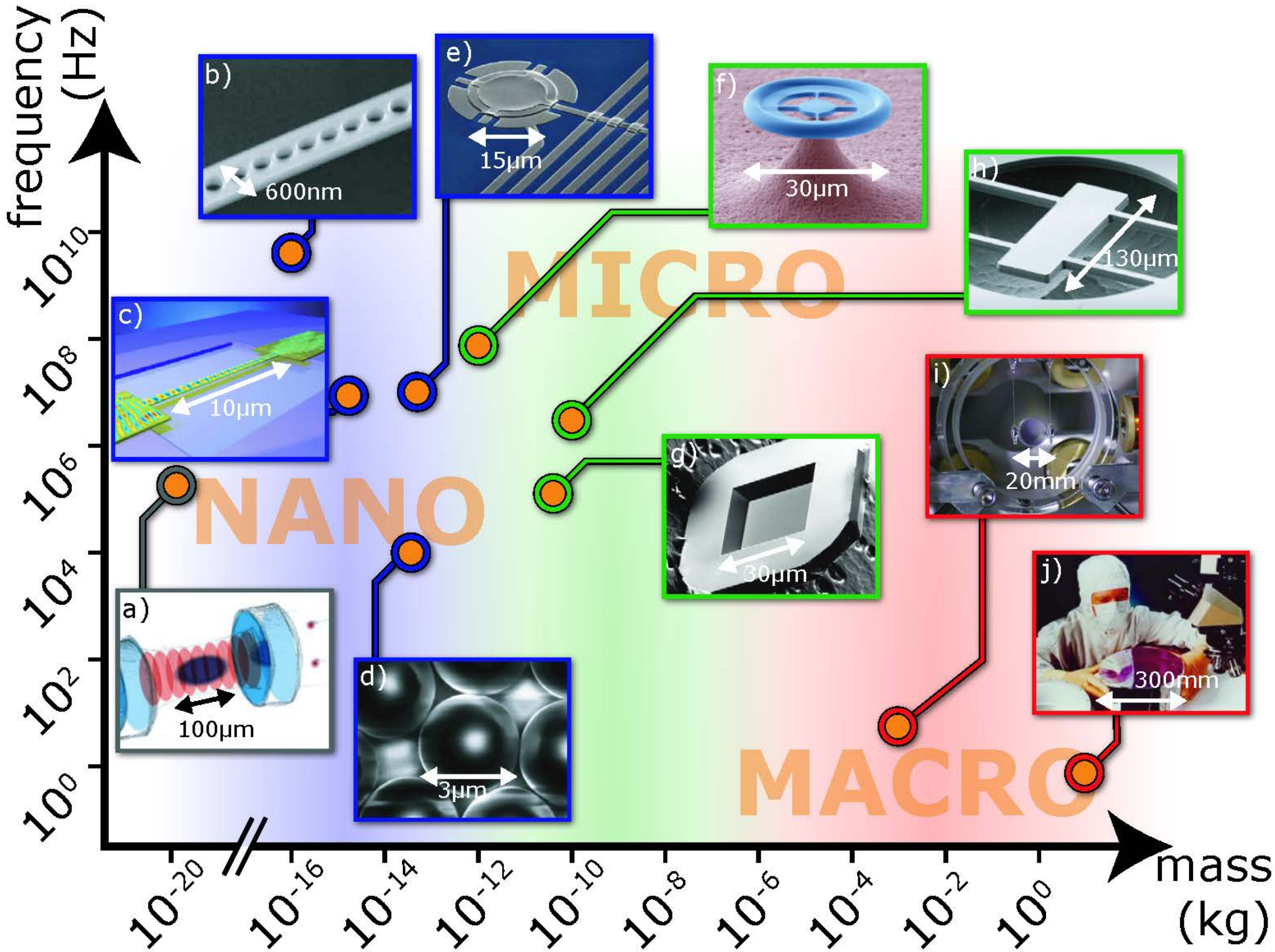
potential hybrid quantum information architectures on a chip

→ *Can mechanical systems serve as a universal quantum bus?*

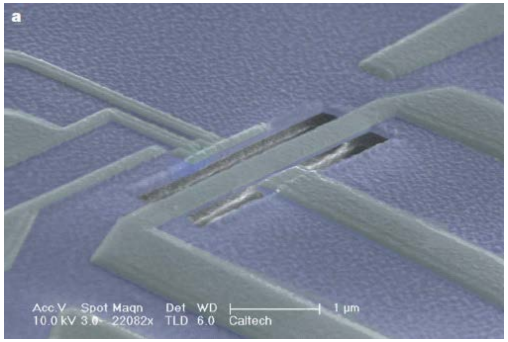


Approach: combine quantum optics with high-performance micro and nanomechanics

Optomechanical Systems



Progress Towards Quantum Control



Mechanical coupling to quantum systems

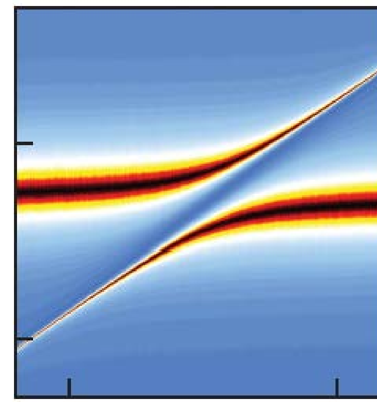
- Resonator probes a quantum system
- LaHaye 2009: Dispersive coupling with a CPB qubit

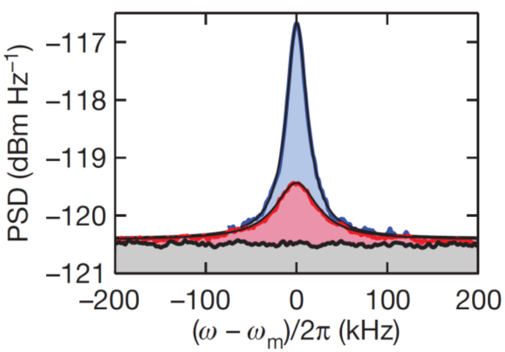
→ *first step towards quantum control of mechanics*

Strong optomechanical coupling

- Coupling strength exceeds individual dissipation rates
- Gröblacher 2009, Teufel 2011, Verhagen 2012...

→ *enables coherent energy exchange (OM polariton)*



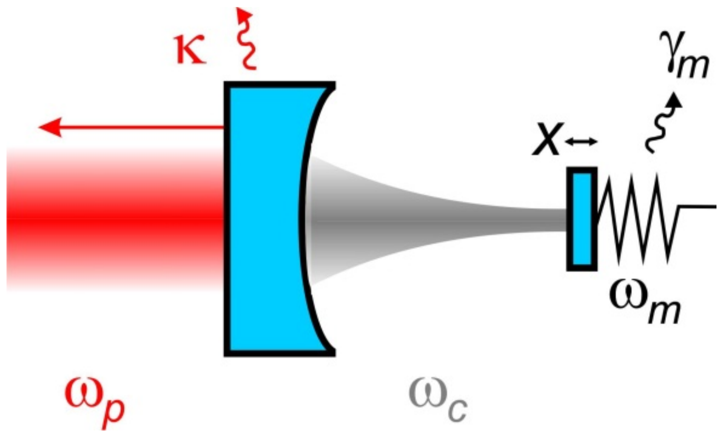


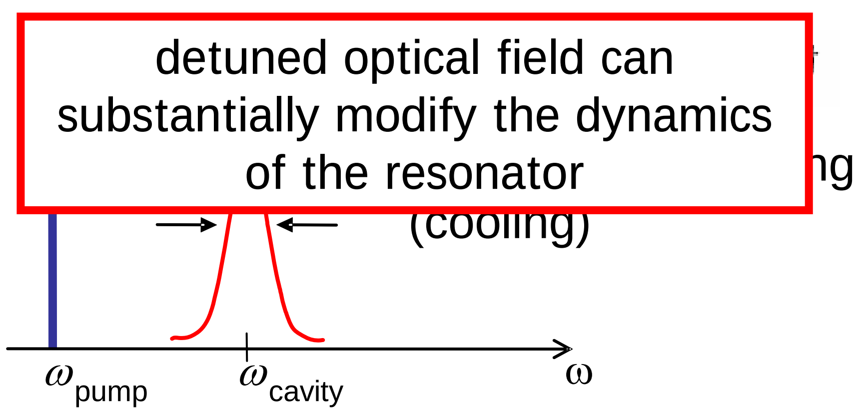
Ground state cooling

- Freezing out thermal fluctuations, <n> below 1
- Demonstrated in both optical and microwave systems

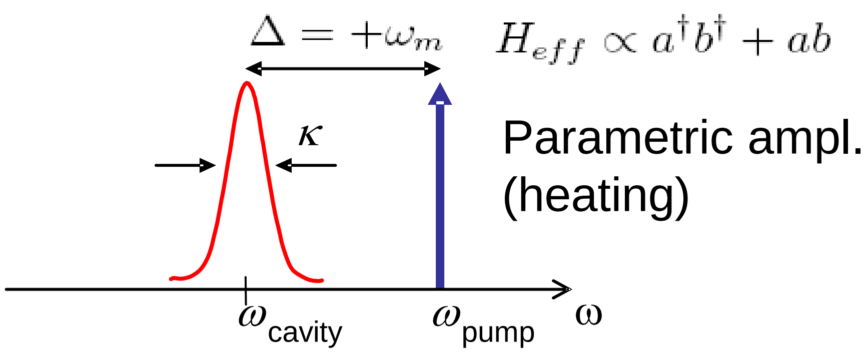
→ *+strong coupling: full control of mech quantum state*

Coupling Mechanics with Light





detuned optical field can substantially modify the dynamics of the resonator



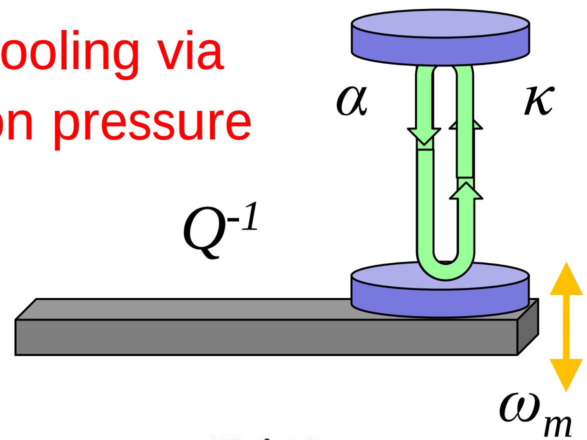
<u>Radiation pressure interaction:</u>

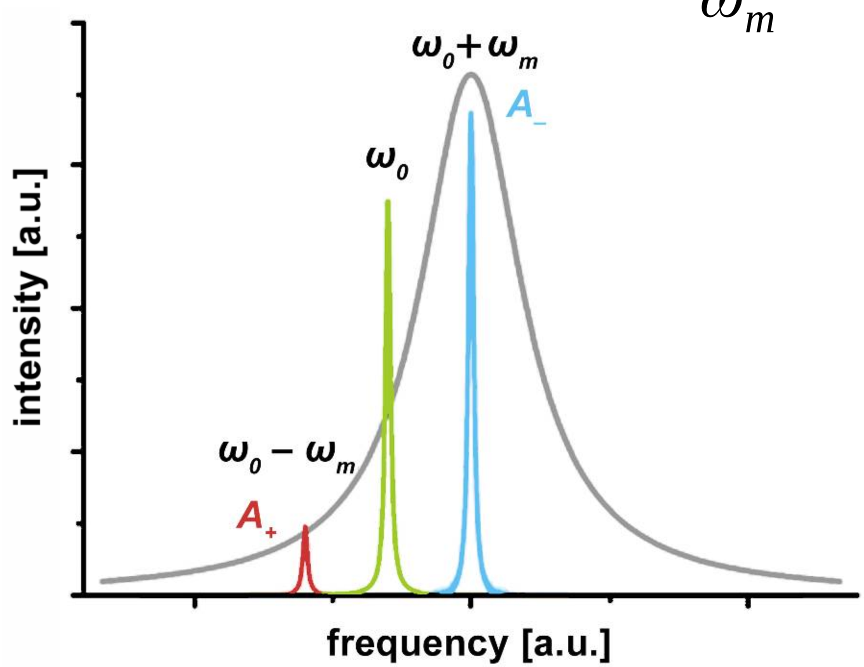
- Intensity-dependent mirror displacement (optical bistability)
- Intensity-dependent phase shift (Kerr-like interaction)
- Retarded forces (modification of the mechanical susceptibility)
- Doppler-shift of reflected light due to mirror motion

Rokhsari et al., OpEx 13 5293 (2005)
Gigan et al., Nature 444, 67 (2006)
O. Arcizet et al., Nature 444 71 (2006)

Cavity-Assisted Laser Cooling

Laser-cooling via radiation pressure





Requirements

- *resolved sideband: $\langle n\rangle_{min}=(\kappa/4\omega_m)^2$
- absence of optical absorption
- shot-noise limited optical pump
- weak coupling to environment
  - → cryogenic cavity (mK temp.)
  - → large Q (minimal dissipation)

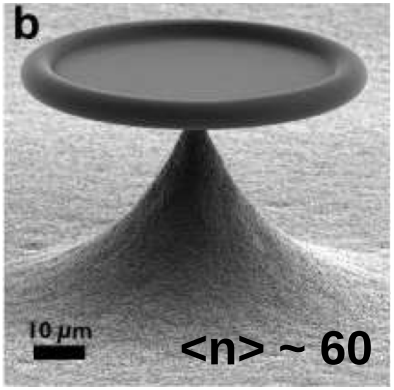
To achieve full quantum control:

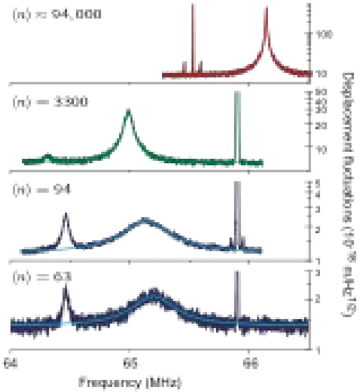
$$k_BT/\hbar Q \ll \kappa \ll \omega_m, g_0\alpha$$

zero entropy mechanics | strong coupling

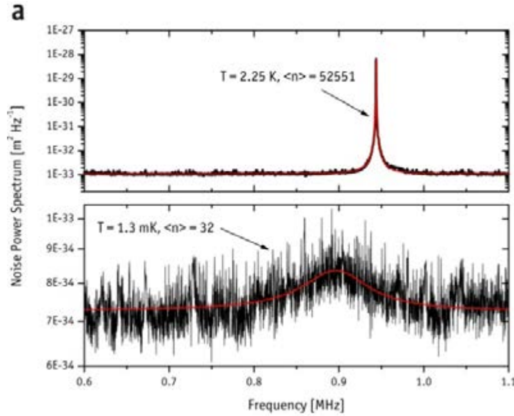
Ultra-Cold Mechanical Systems

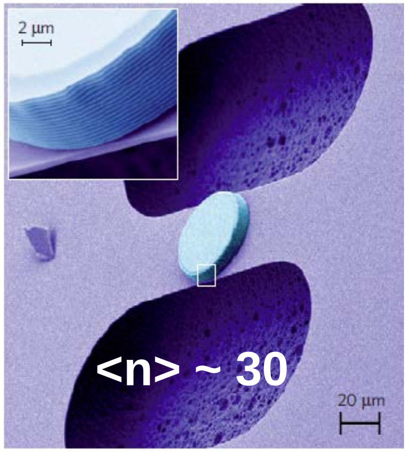
Optomechanical Devices





Schliesser et al., Nature Physics 5, 509 (2009)





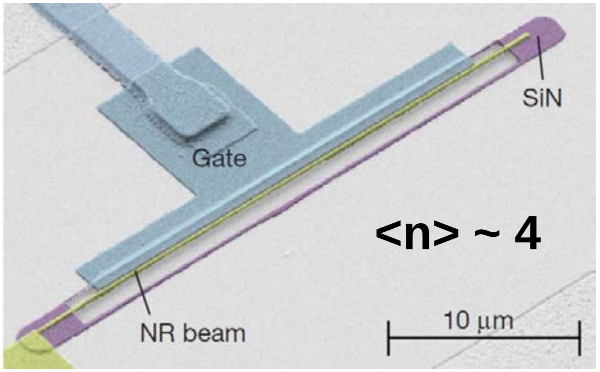
Gröblacher et al., Nature Physics 5, 485 (2009)

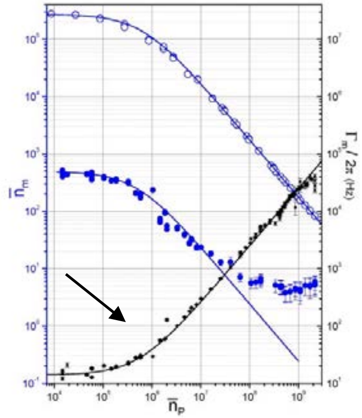
Nanoelectromechanical Systems

→ cooling via microwave photons

Mechanics capacitively coupled to a superconducting microwave resonator

Rocheleau et al., Nature 463, 72 (2010)



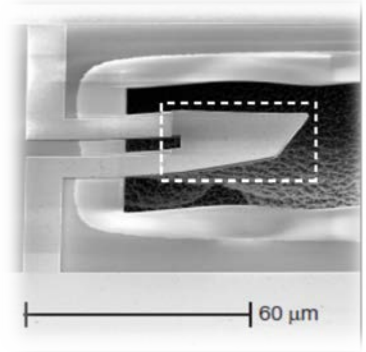


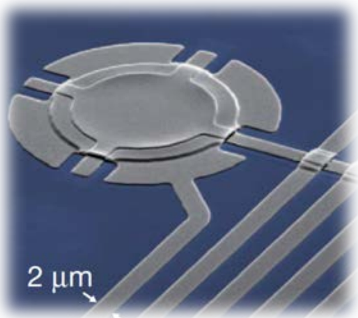
Mechanics in the Quantum Regime

Nature **464**, 697-703 (2010)

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]





Nature **475**, 359-363 (2011)

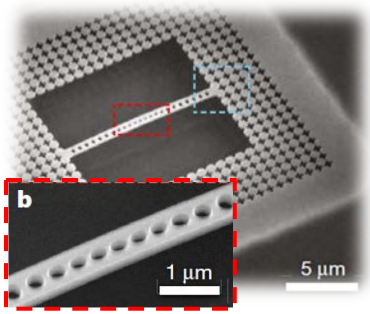
Sideband cooling of micromechanical motion to the quantum ground state

J. D. Teufel[1], T. Donner[2,3], Dale Li[1], J. W. Harlow[2,3], M. S. Allman[1,3], K. Cicak[1], A. J. Sirois[1,3], J. D. Whittaker[1,3], K. W. Lehnert[2,3] & R. W. Simmonds[1]

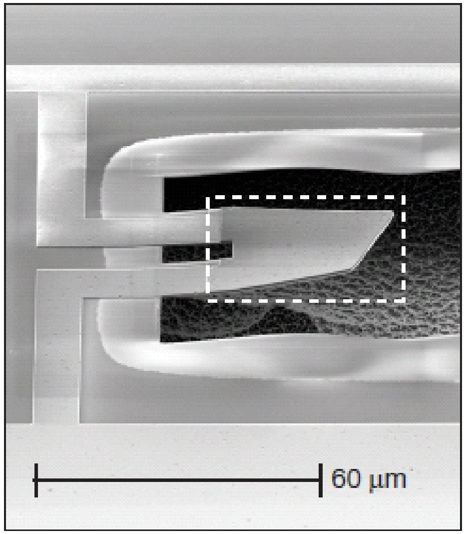
Nature **478**, 89-92 (2011)

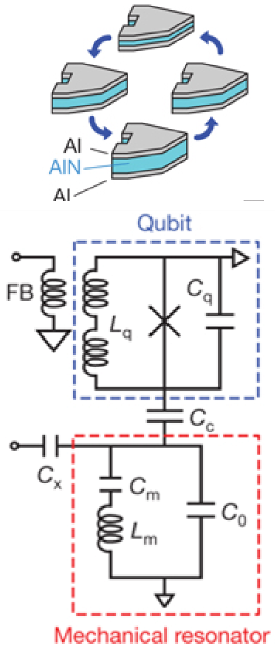
Laser cooling of a nanomechanical oscillator into its quantum ground state

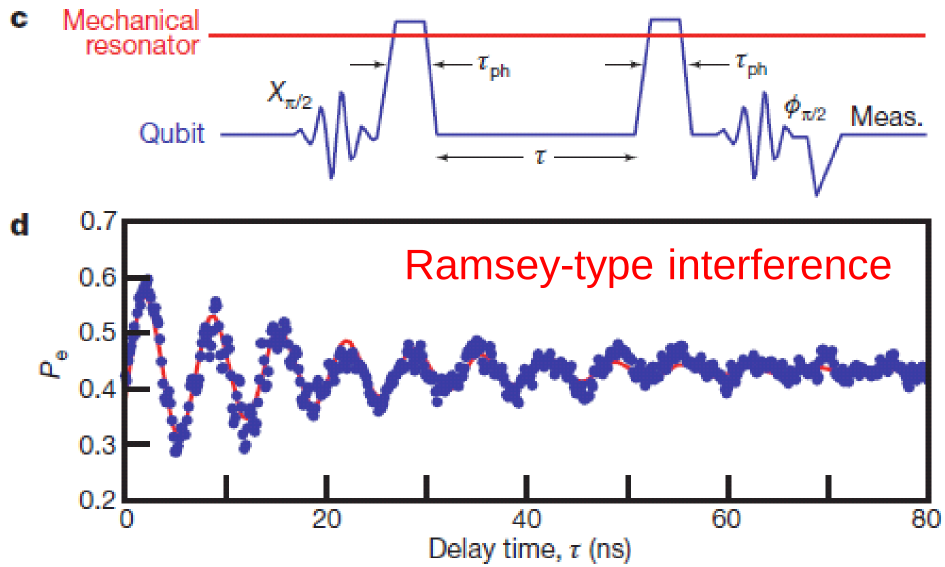
Jasper Chan[1], T. P. Mayer Alegre[1]†, Amir H. Safavi-Naeini[1], Jeff T. Hill[1], Alex Krause[1], Simon Gröblacher[1,2], Markus Aspelmeyer[2] & Oskar Painter[1]



Single-Phonon Control of a Resonator





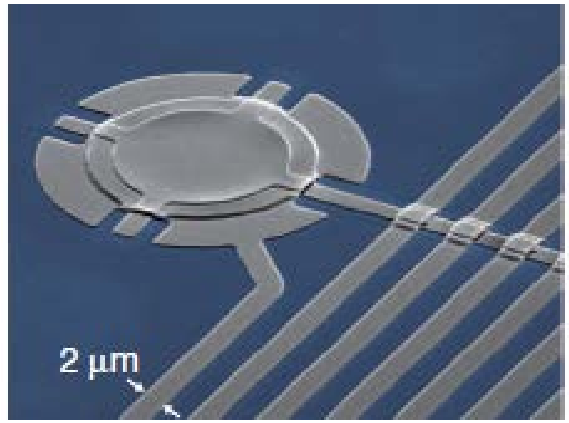


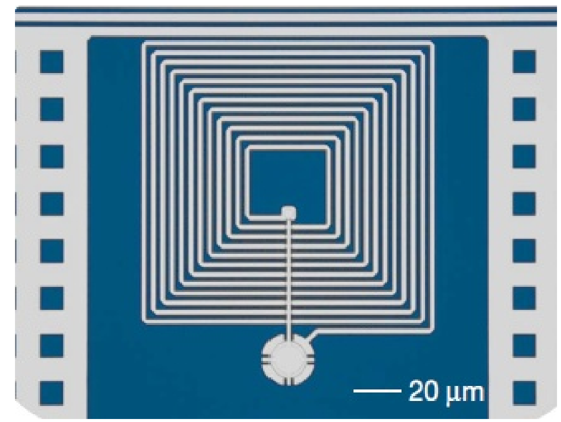
- Qubit-coupled 6 GHz piezoelectric bulk acoustic wave resonator
  - conventional cooling to reach ground state (<n> ~ 0.07 at 20 mK)
- Single-phonon readout and quantum control is the key advancement
  - verification of ground-state and qubit-resonator swap oscillations
  - generation of coherent phonon states in the resonator via the qubit

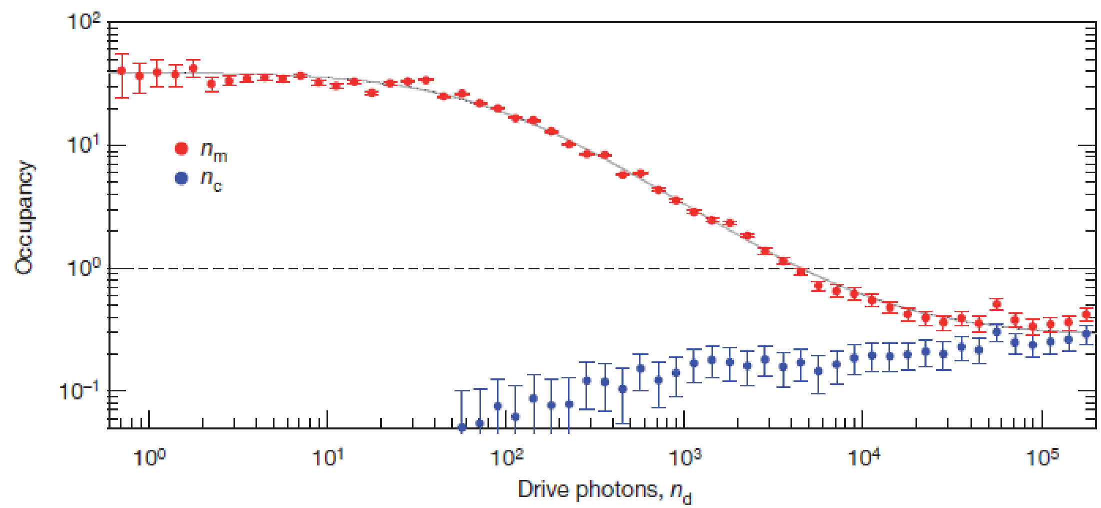
O'Connell, et al. Nature. 464, 697 (2010)

Sideband Cooling with Microwaves

- Mechanical resonator coupled to a μ-wave resonant circuit
  - superconducting (Al) vacuum gap capacitor
- Membrane motion modulates frequency
  - spiral inductor shunted by resonator
  - parametric interaction allows for cooling of the membrane motion
- <n> ~0.3 and strong coupling achieved

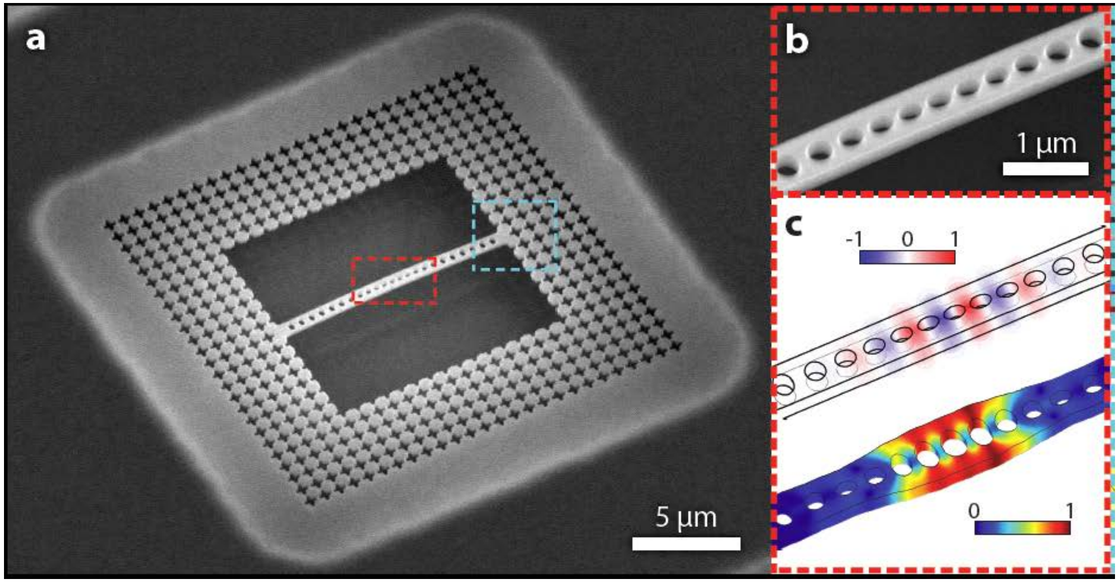


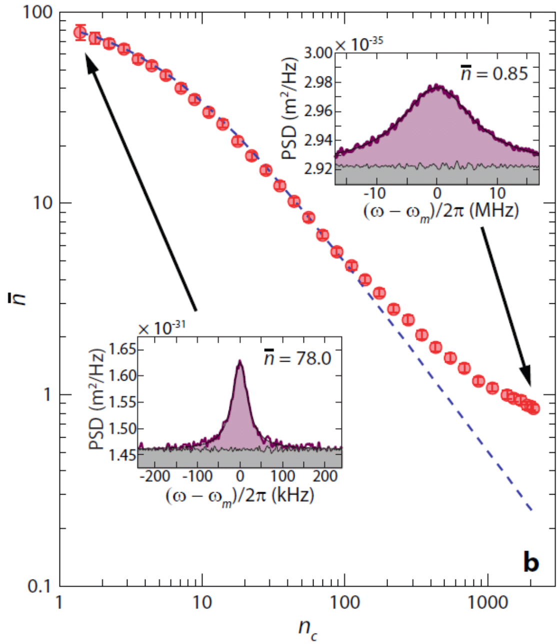




Teufel, et al., Nature, 475, 359 (2010)

Laser Cooling of an OM Crystal

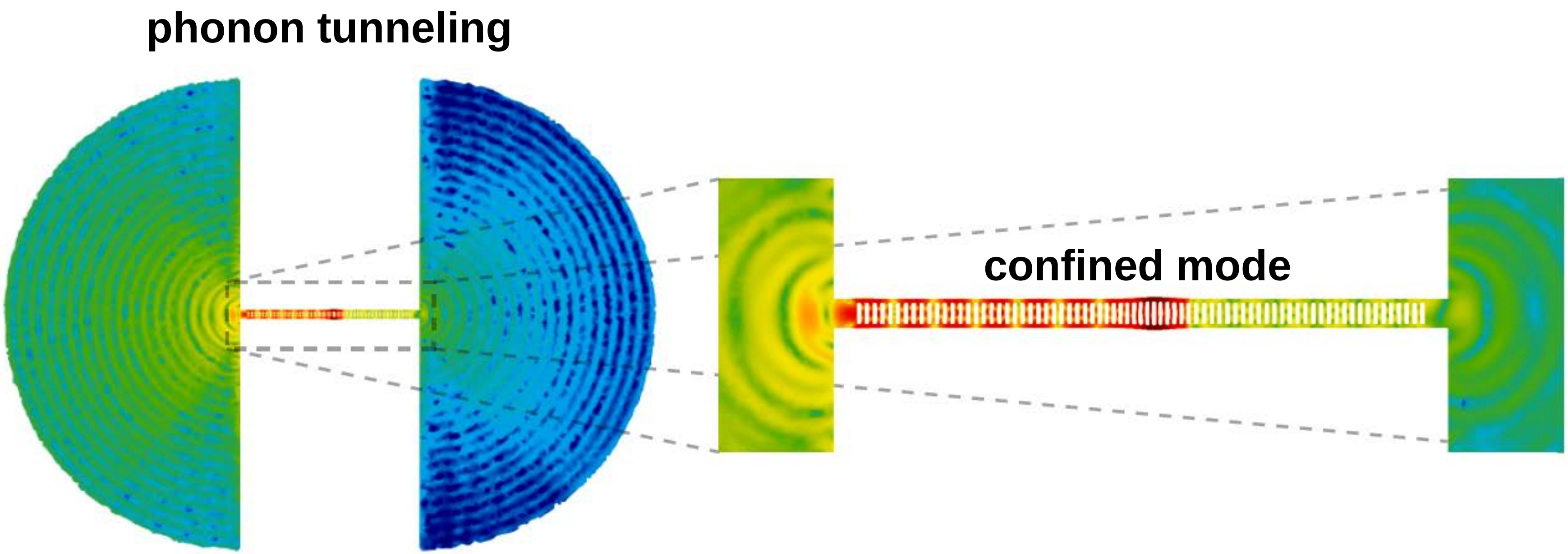




- Resonator: single-crystal-silicon-based optomechanical crystal
  - simultaneous photonic (1550 nm) and phononic (3.5 GHz) bandgap
- Laser-mediated ground-state cooling of a localized mechanical mode
  - m_{eff} of 311 fg; $Q_{optical}$ of 4×10^5 (500 MHz linewidth); Q_{mech} $\sim 1 \times 10^5$
  - current performance limited by absorption effects (TPA and FCA)

Chan, et al. Nature, 478, 89 (2011)

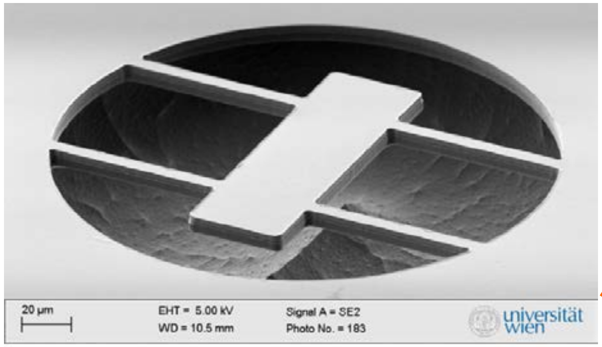
Dissipation: The Root of All Evil

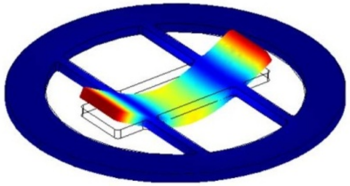


- Mechanical damping is currently the most significant roadblock
  - similar requirements as GW systems, particularly Fabry-Pérot implementation
- Cavity optomechanics enables exploration of alternatives
  - simultaneous high reflectivity and high Q: crystalline materials systems
  - eliminating support-induced losses: levitating resonators

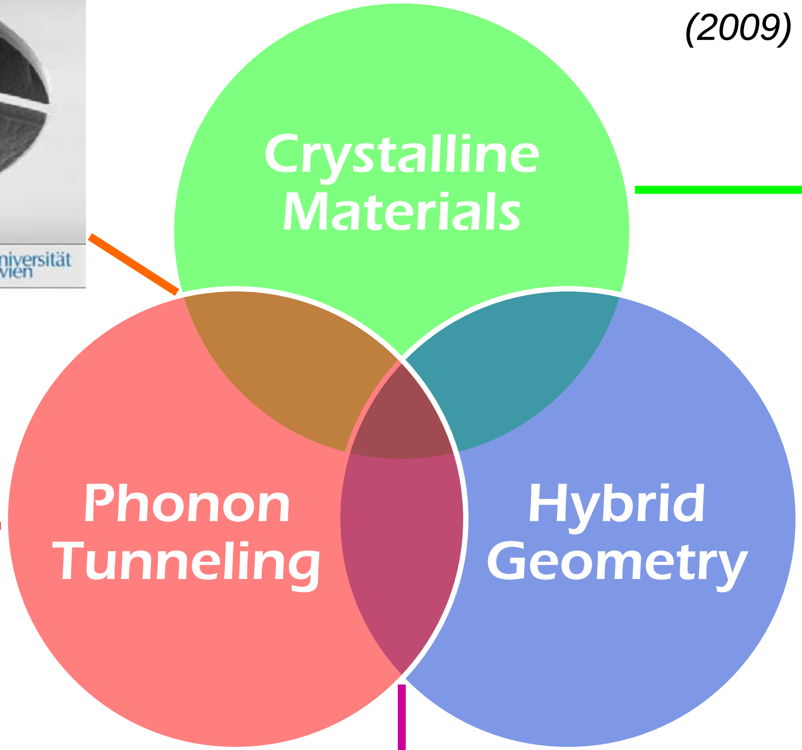
M. Eichenfield, J. Chan, R. M. Camacho, K. J. Vahala, O. Painter, Nature (2009)

Minimizing Mechanical Losses

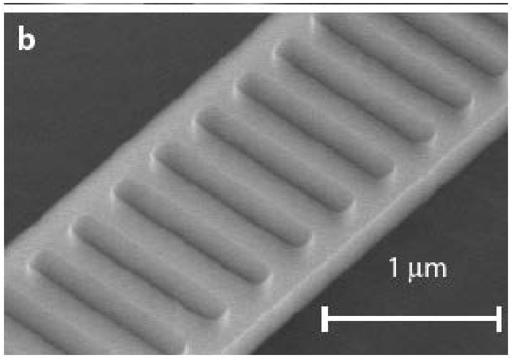


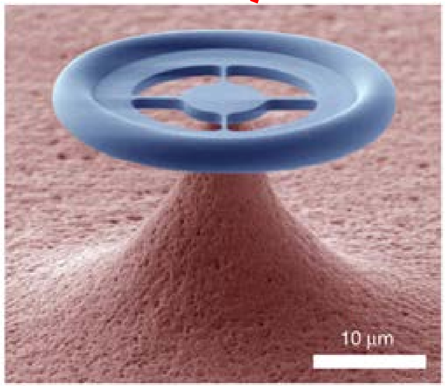


Cole (2011)

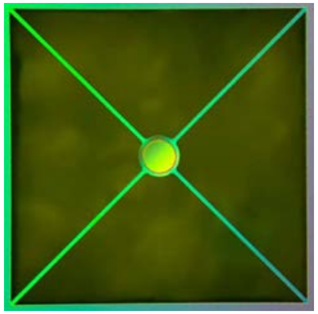


Eichenfeld (2009)



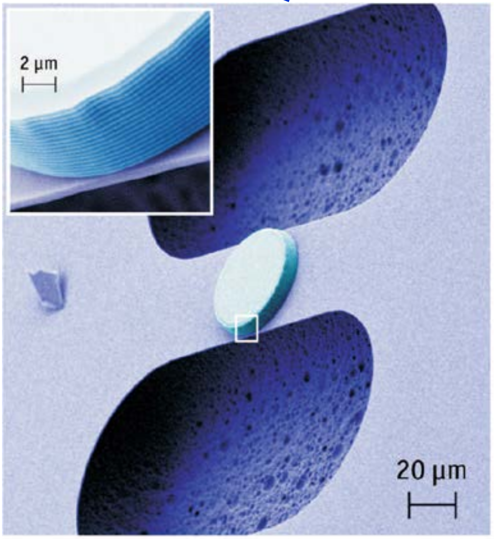


Anetsberger (2008)



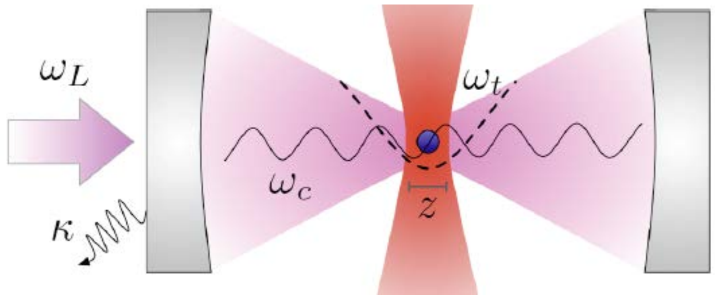
Kleckner (2011)

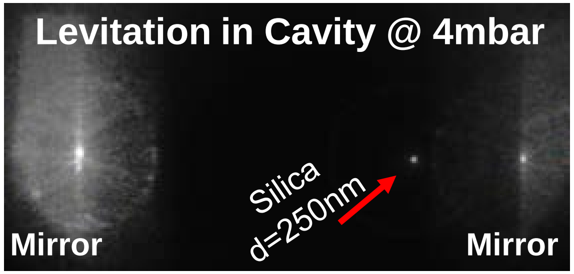
Gröblacher (2009)



Eliminating the Support Structure

Optically levitated nanospheres

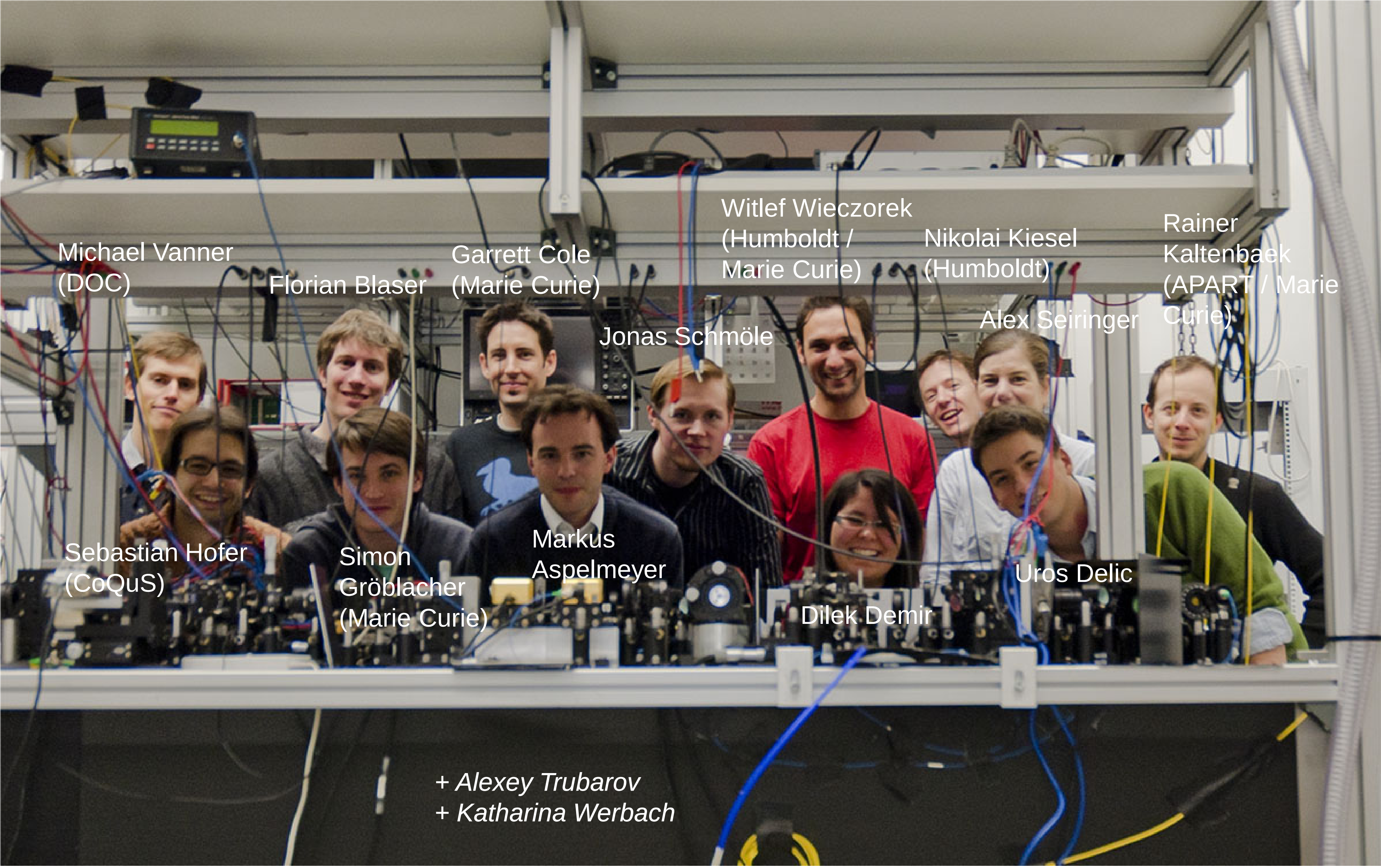




- Dielectric particle acts as harmonic oscillator in an all-optical potential
  - no anchor losses to degrade Q
- Dynamic control of spring constant
  - modulation of the confining potential
- Quantum-optical control via cavity optomechanics protocols
  - radiation pressure interaction for laser cooling, state transfer, etc.

Generating quantum states of the center-of-mass motion

- Laser cooling plus quantum state preparation and transfer
  - Barker, PRA 81, 023826 (2010); Chang, PNAS 107, 1005 (2010); Romero-Isart, PRA 83, 013803 (2011)
- Superposition, free fall experiments, and interferometry
  - Kaltenbaek et al., Exp. Astronomy (2012); Romero-Isart et al., PRL 107, 020405 (2011)



FWF Der Wissenschaftsfonds

SEVENTH FRAMEWORK PROGRAMME

erc European Research Council

fq(x) Foundational Questions Institute

ÖAW Österreichische Akademie der Wissenschaften

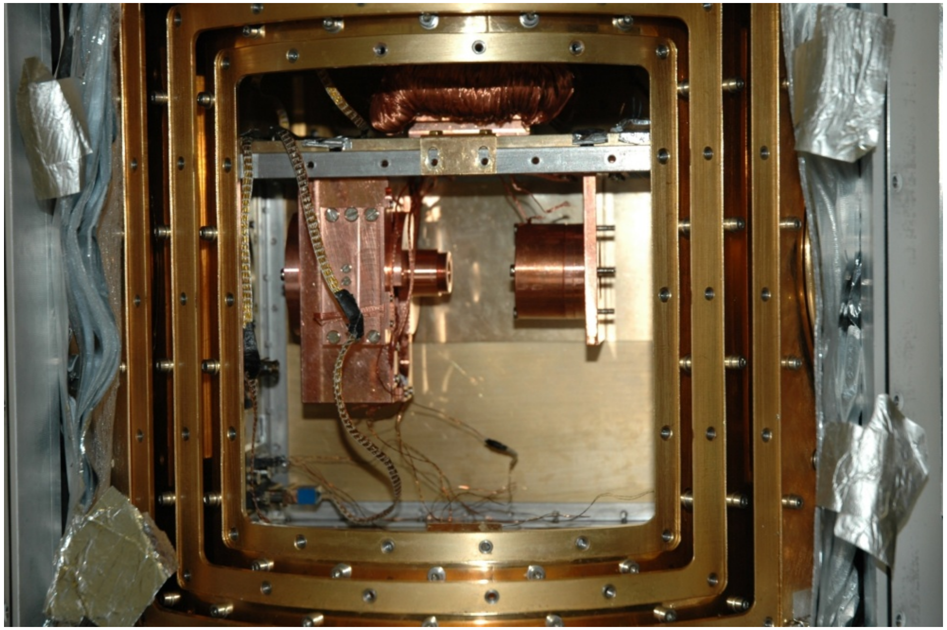
Alexander von Humboldt Stiftung/Foundation

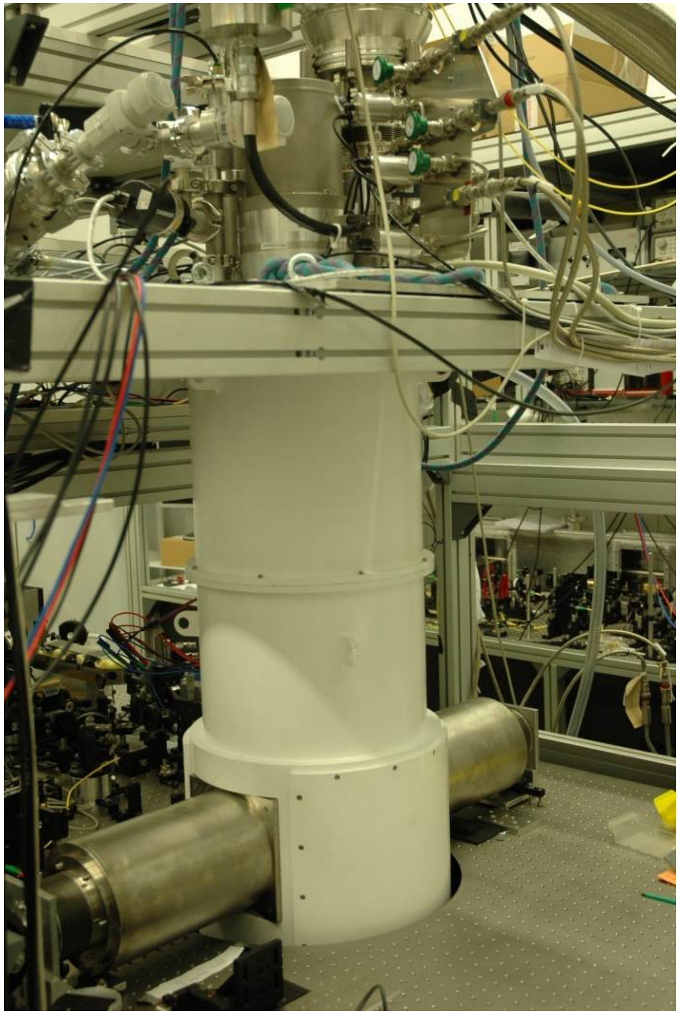
esa

Minimizing the Bath Temperature

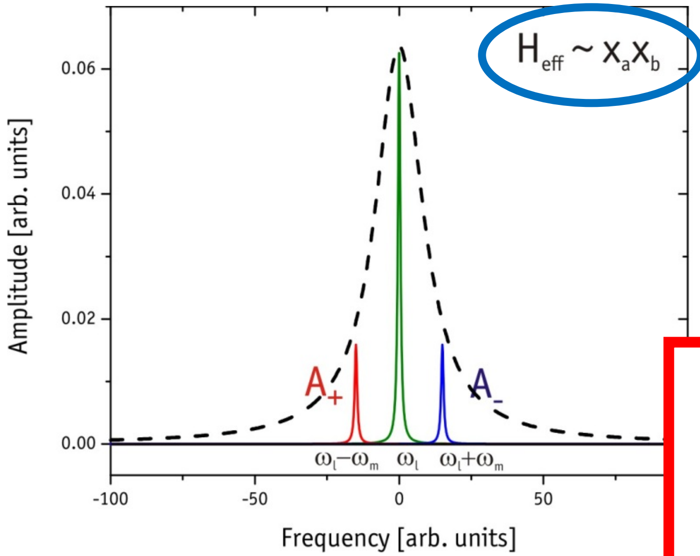
- Closed cycle dilution fridge with double-sided optical access
- Base temperature ~25 mK (no input laser), experiments @ 100 mK
- Stable operation of optomechanical cavity recently realized (*F* >10,000)

$$k_B T/\hbar Q \ll \kappa \ll \omega_m, g_0\alpha$$

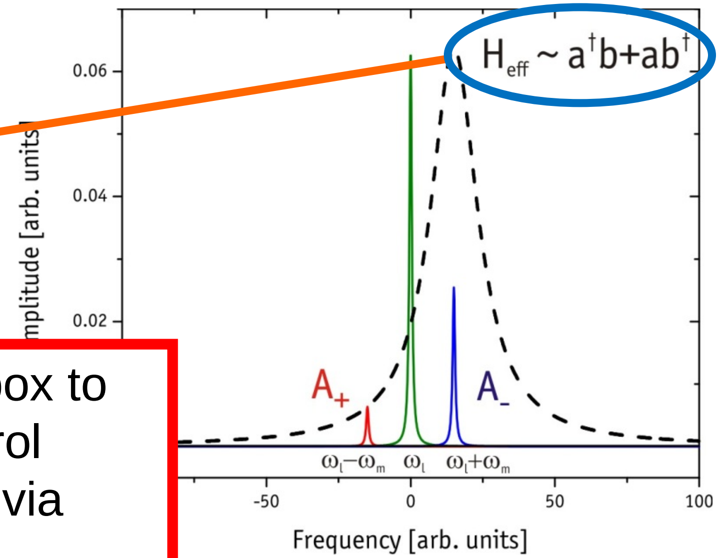




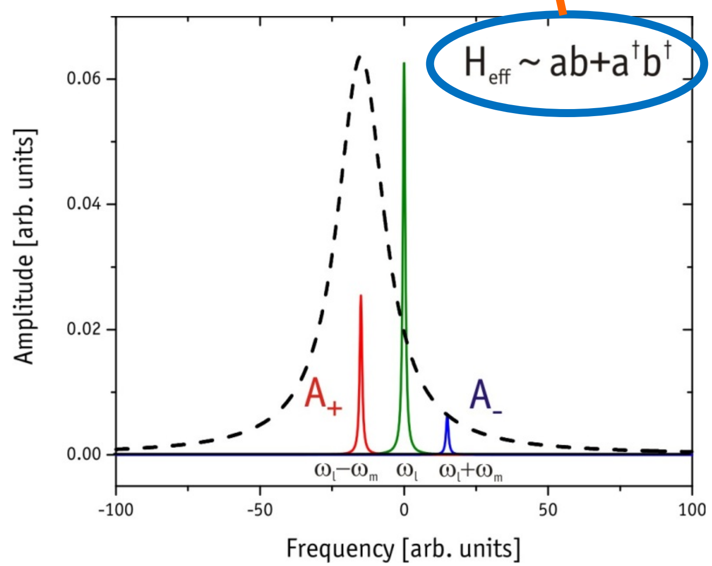
Detuning Driven Interactions



- QND
- Beamsplitter
- TM Squeezer



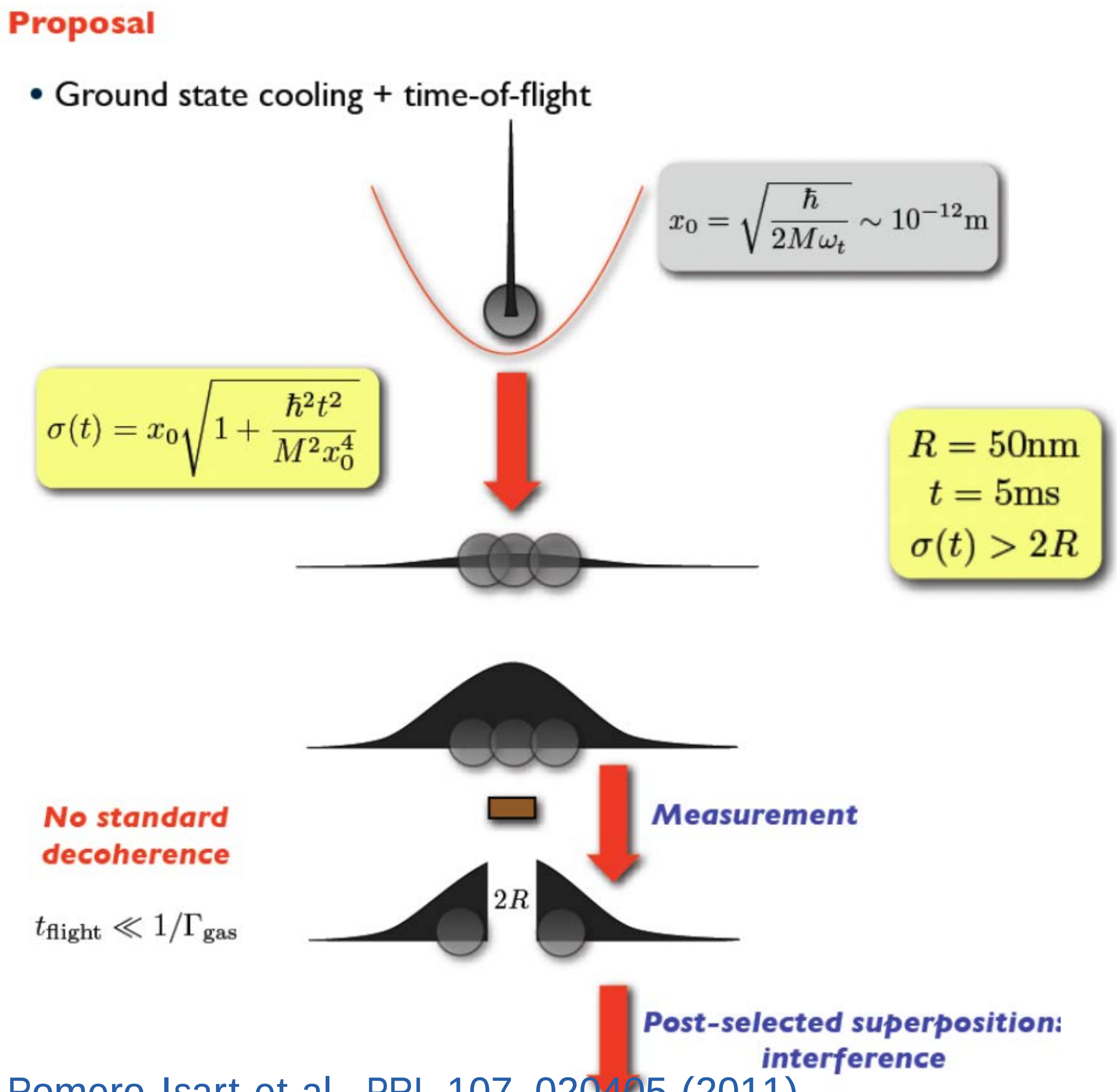
quantum optics toolbox to prepare and control mechanical states via photonic states



approximations:
-linearization
- $g \ll \omega_m$

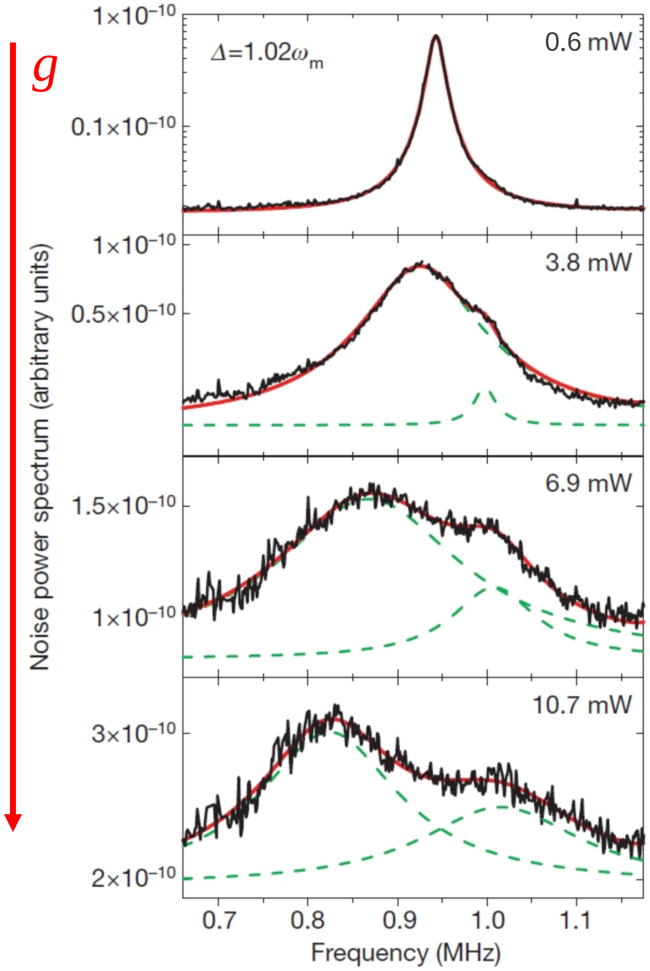
J. Zhang et al., PRA 68 (03)
M. Aspelmeyer et al., JOSAB 27 (10)

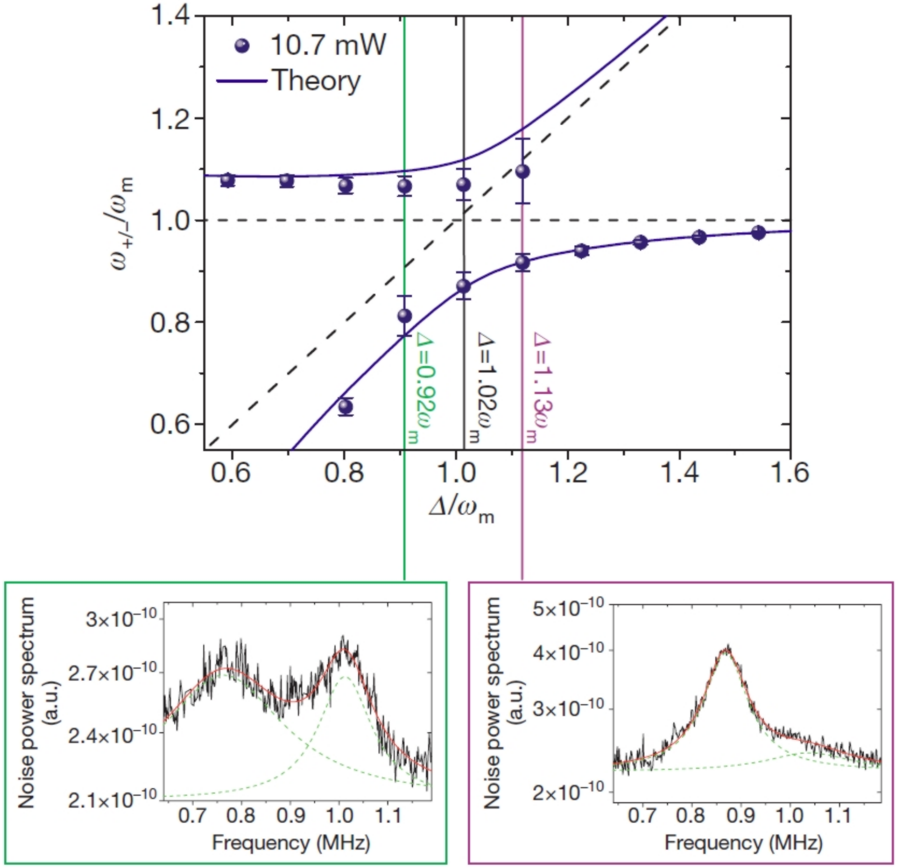
Large Quantum Superpositions



O. Romero-Isart et al., PRL 107, 020405 (2011)

Normal mode splitting





optomechanical normal mode splitting @ RT

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

first observation of strongly coupled micromechanics

S. Gröblacher et al., Nature 460 (09)

Optomechanical entanglement

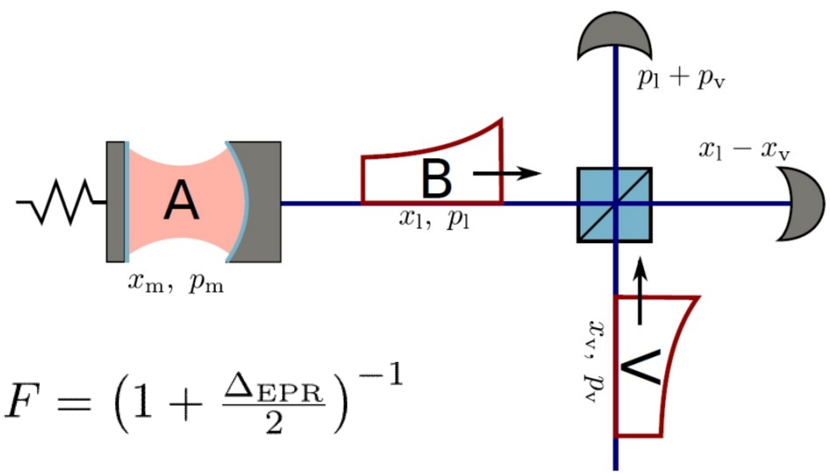
Optomechanical correlations: towards EPR

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

requires: $x_- = x_1 - x_2 \rightarrow 0$ (correlated)

$p_+ = p_1 + p_2 \rightarrow 0$ (anticorrelated)

use entanglement for optomechanical teleportation

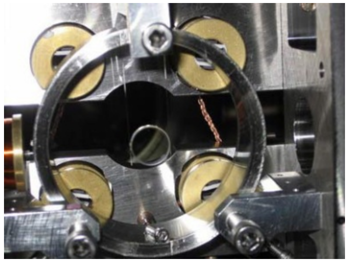


$$F = \left(1 + \frac{\Delta_{\mathrm{EPR}}}{2}\right)^{-1}$$

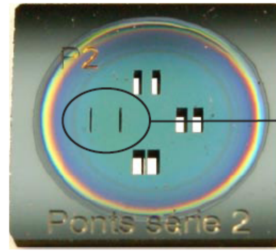
Example Optomechanical Systems

FP cavity

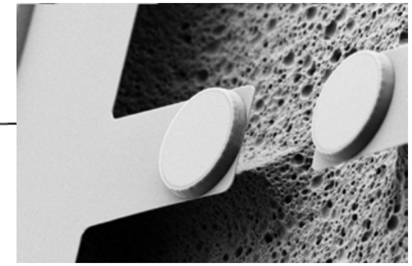
⚐(kg-ng)



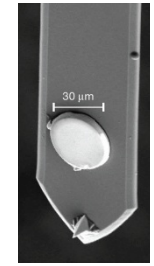
Mavalvala (LIGO, MIT)



Heidman (Paris)



Aspelmeyer (Vienna)

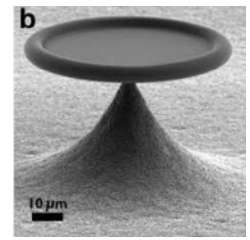


Bouwmeester (UCSB)

Toroidal microcavity

⚐(ng)

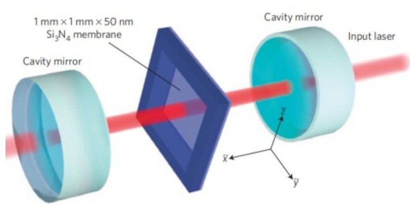
Vahala (Caltech)

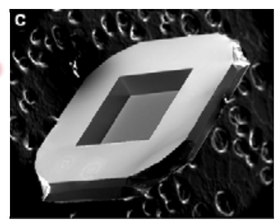


Kippenberg (Lausanne)
Bowen (UQ)

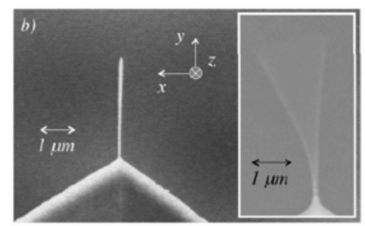
Dispersive coupling

⚐(zg-ng)





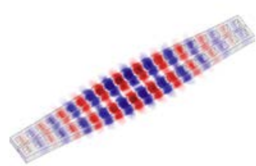
Harris (Yale), Kimble (Caltech)



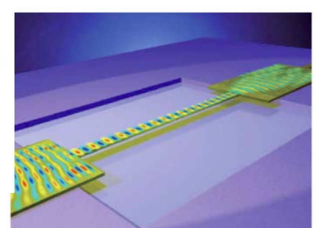
Karrai (Munich), Favero (Paris)

Gradient force

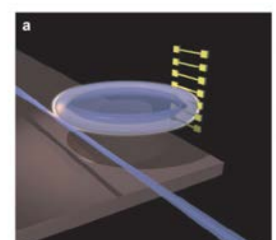
⚐(pg)



Painter (Caltech)



Tang (Yale)



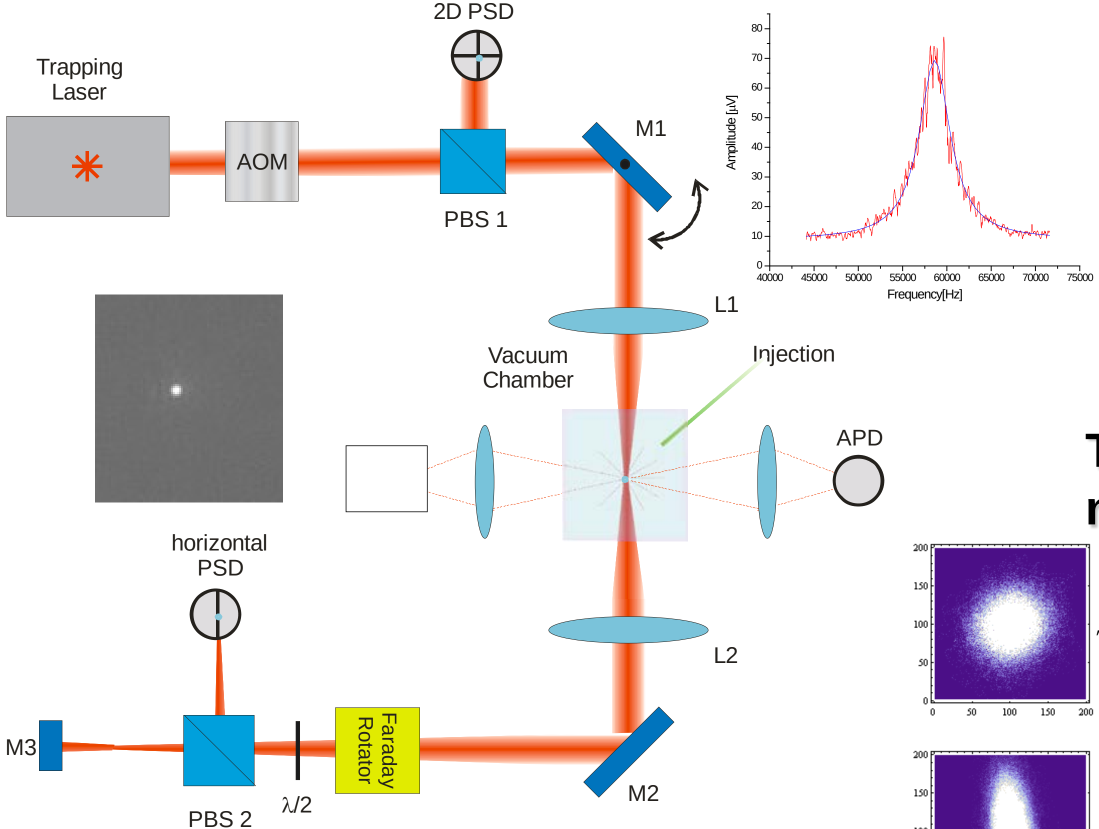
Kippenberg/Weig/Kotthaus (Munich)

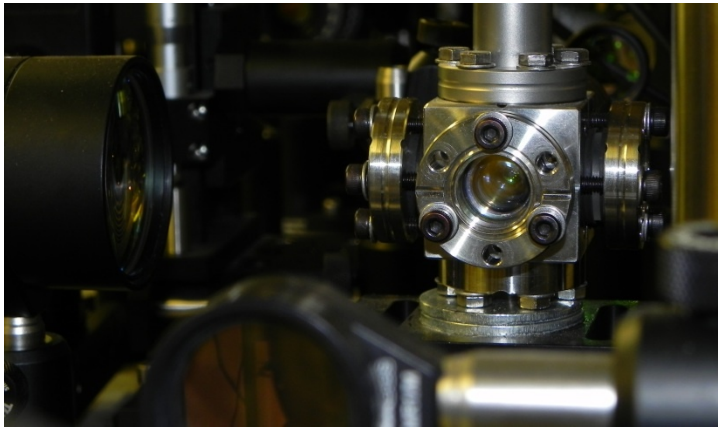
Trapped Nanoparticles in Vienna

Mechanical oscillator…

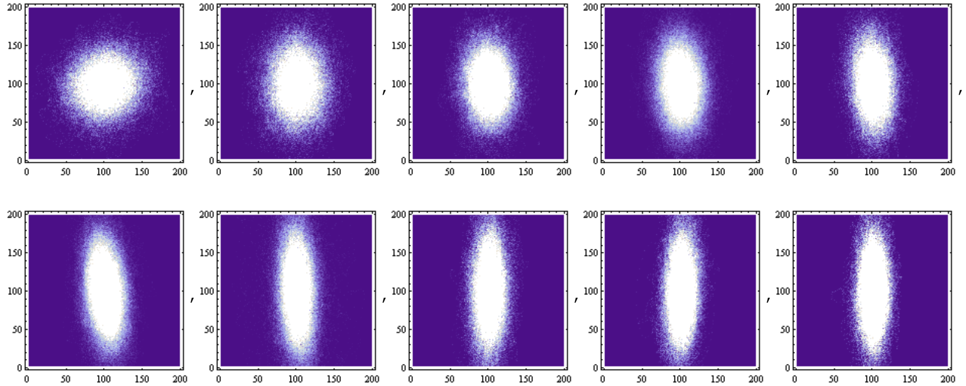
Ashkin since 1967
Raizen group, Science 2010

Optical trapping… (R~20nm – 2µm)





Thermal noise squeezing of a nanosphere in phase space…



N. Kiesel, F. Blaser, U. Delic, M. Aspelmeyer (unpublished)