Quantum-Coherent Coupling of a Mechanical Oscillator to an Optical Cavity Mode

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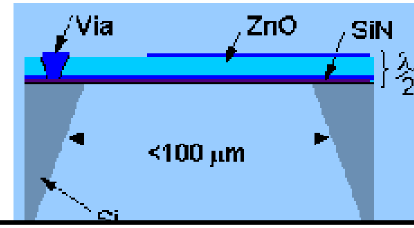
19th June 2012

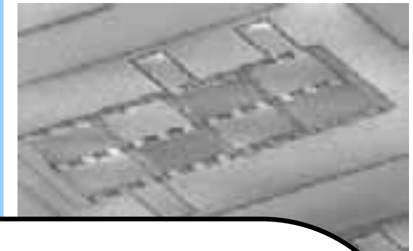
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Marie Curie ITN
SEVENTH FRAMEWORK PROGRAMME

Mechanical oscillators as probe for nanoscale phenomena

Quartz tuning f





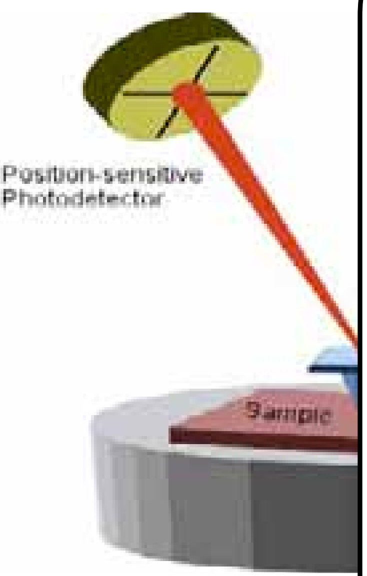
Control of the quantum state of mechanical systems is challenging

High environmental occupation

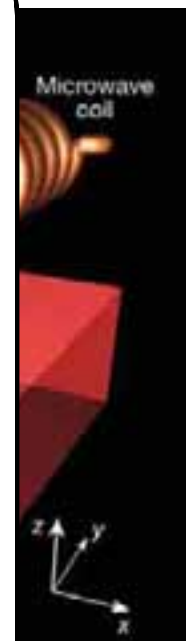
$$\bar{n}_m = \frac{k_B T}{\hbar \Omega_m} \gg 1$$

Sensitive readout required

$$\Delta x_{ZPF} = \sqrt{\frac{\hbar}{2 m \Omega_m}}$$



Atomic forc

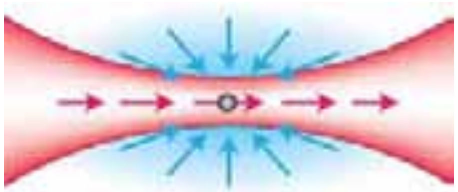


San Jose)

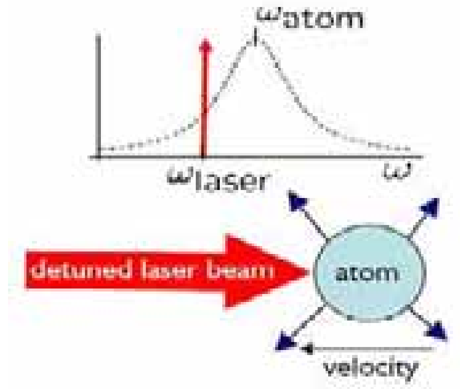
Image: NIST

D. Rugar (Nature)

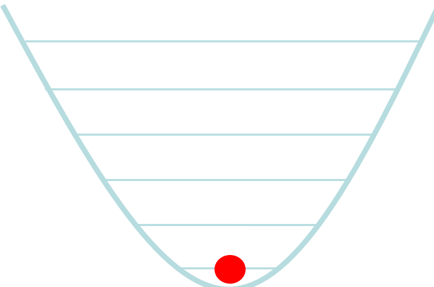
Quantum control in Atomic Physics



1970: Arthur Ashkin demonstrated radiation pressure trapping of dielectric particles

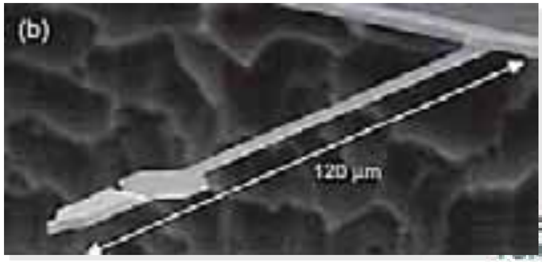


1975: Hänsch et Schawlow, Dehmelt et Wineland "Laser Cooling by Radiation Pressure"



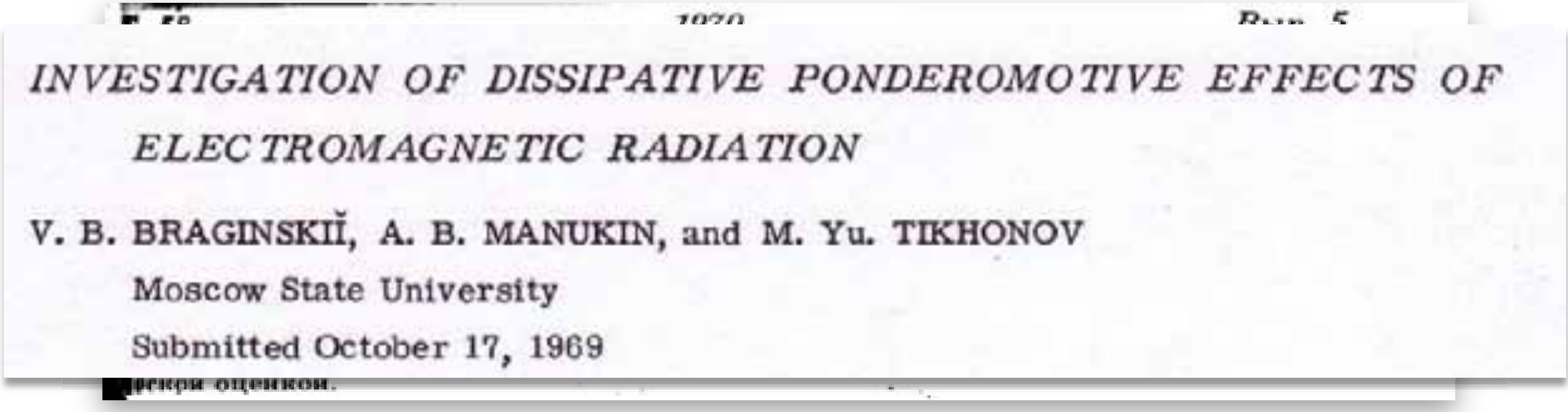
1989: Ground state cooling of ions (Wineland)

Can quantum control be extended to NEMS / MEMS?



Parametric transducers – optomechanical coupling

V.B. Braginsky

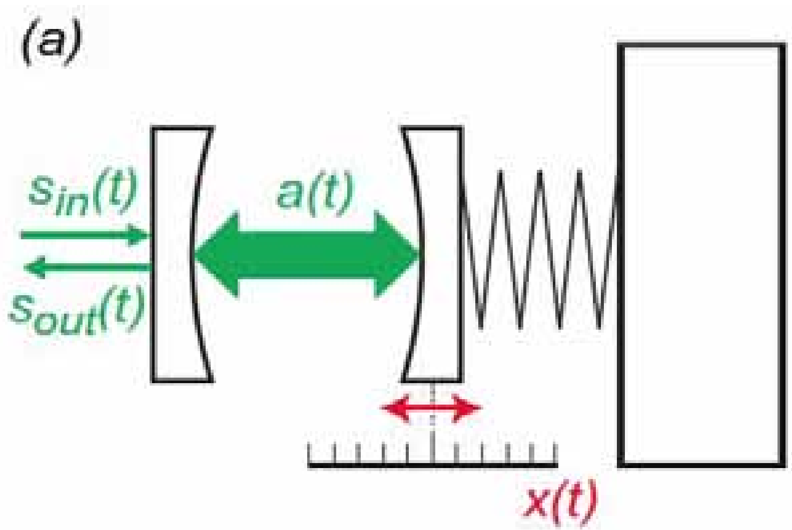


INVESTIGATION OF DISSIPATIVE PONDEROMOTIVE EFFECTS OF ELECTROMAGNETIC RADIATION

V. B. BRAGINSKIĬ, A. B. MANUKIN, and M. Yu. TIKHONOV

Moscow State University

Submitted October 17, 1969



Parametric, optomechanical coupling

$$\omega = \omega_c + G\, x(t)$$

$$G = \frac{d\omega}{dx} = -\frac{\omega_0}{L}$$

Hamiltonian description (K.C. Law)

$$\hat{H}_{int} = \hbar G\, \hat{a}^\dagger \hat{a} \cdot \hat{x}$$

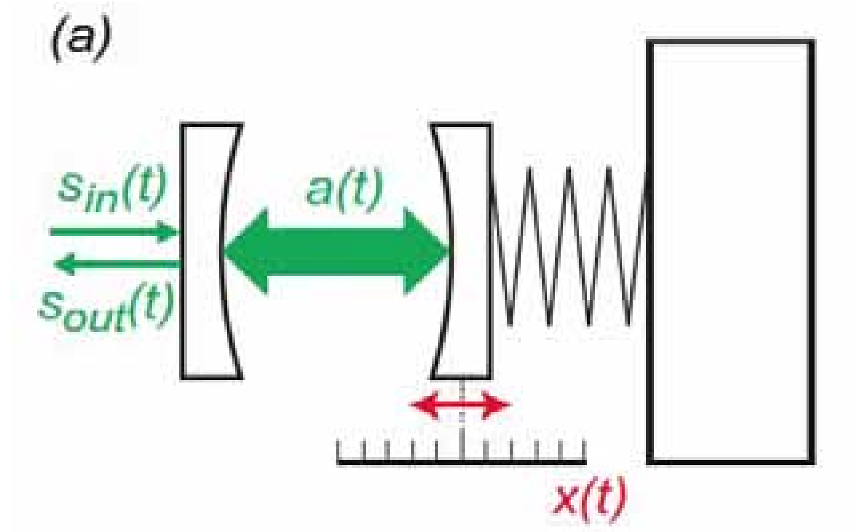
Braginsky, Manukin, Tikhonov, JETP 1970

Braginsky, Manukin: Measurement of Weak Forces in Physics Experiments (1977)

Radiation pressure dynamical backaction

$$\frac{d^2x}{dt^2} + \frac{1}{2\tau_m}\frac{dx}{dt} + \omega_m^2 x = \frac{F_{rp}(x(t-\tau))}{m_{eff}}$$

(ω_m, Q_m)



$F_{RP}(x(t-\tau))$

Predicted for more than 30 years,
but only recently observed.

$\Delta\gamma < 0 \Rightarrow$ Amplification

$\Delta\gamma > 0 \Rightarrow$ Cooling

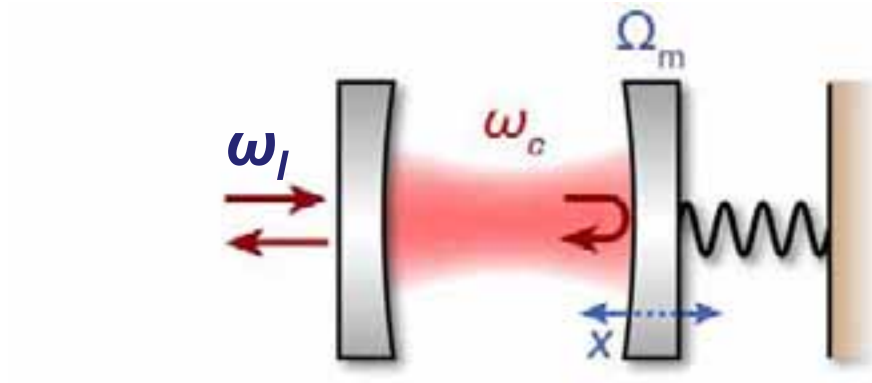
Velocity dependent term

Amplification: Blue detuning

Cooling: Red Detuning

Br ... 77)

Radiation pressure effects on test masses



For a Fabry Perot:

$$G = \frac{d\omega}{dx} = -\frac{\omega_0}{L}$$

$$\boxed{\hat{H} = \hbar\omega_c \hat{a}^\dagger\, \hat{a} + \hbar\Omega_m \hat{b}^\dagger\, \hat{b} + \hbar G\hat{x}\, \hat{a}^\dagger \hat{a}}$$

Optical readout:

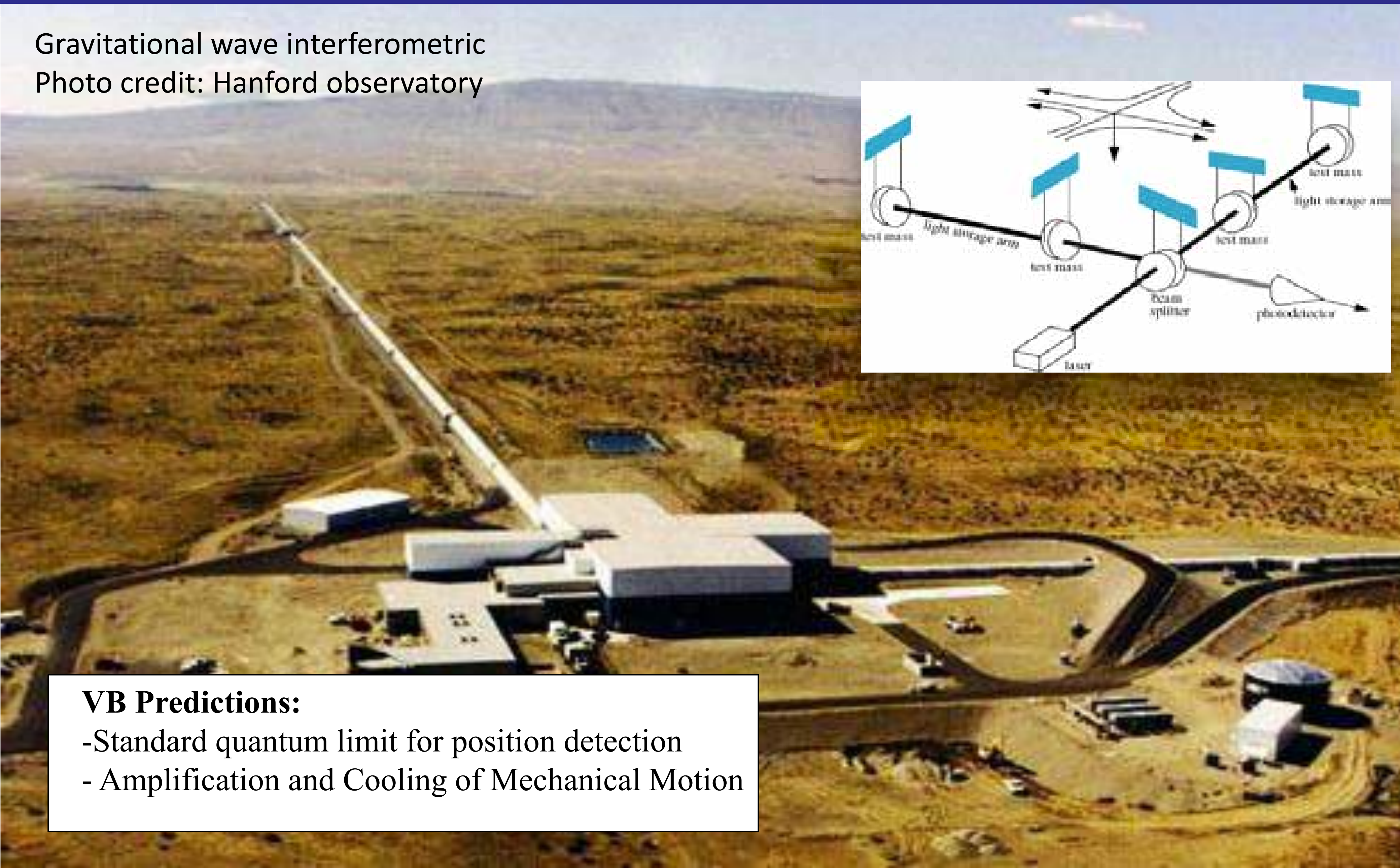
$$\frac{d}{dt}\hat{a} = \frac{i}{\hbar}[\hat{H}, \hat{a}] = i(\omega + G\hat{x})\hat{a}$$

Radiation pressure back-action:

$$\frac{d}{dt}\hat{p} = \hat{F} = \frac{i}{\hbar}[\hat{H}, \hat{p}] = -\hbar G\hat{a}^\dagger \hat{a}$$

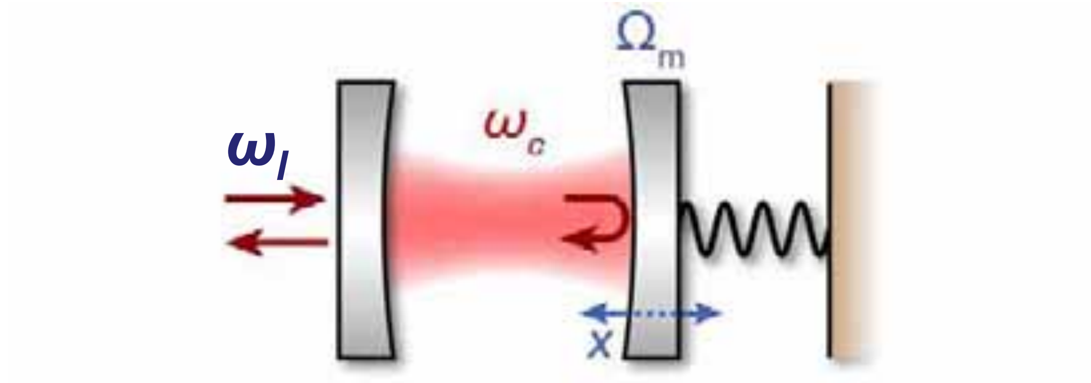
Parametric transducer – optomechanical coupling

Gravitational wave interferometric
Photo credit: Hanford observatory



VB Predictions:
-Standard quantum limit for position detection
- Amplification and Cooling of Mechanical Motion

Linearized optomechanical Hamiltonian



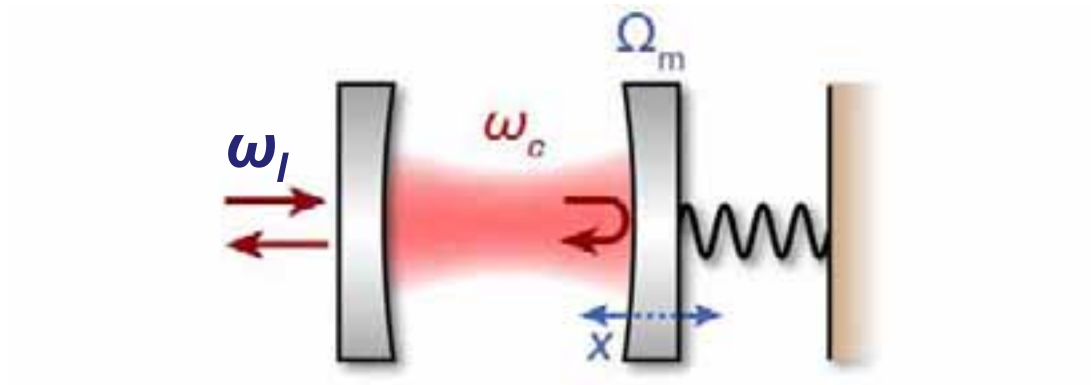
$$\hat{H} = \hbar\omega\hat{a}^\dagger\,\hat{a} + \hbar\Omega_m\hat{b}^\dagger\,\hat{b} + \underbrace{\hbar G\hat{x}\,\hat{a}^\dagger\hat{a}}_{\hat{H}_{int}}$$

Linearization around the driven cavity

linearization: $\begin{cases} \hat{a} = \bar{a} + \delta\hat{a} \\ \hat{x} = \bar{x} + x_{zpm}(\delta b + \delta b^\dagger) \end{cases}$

<u>Quantum theory of optomechanical cooling and strong coupling:</u>
I. Wilson-Rae, Nooshi, Zwerger, Kippenberg, PRL **99**, 093901 (2007)
J. Dobrindt, Wilson-Rae, Kippenberg, PRL, **101**, 263602 (2008)
F. Marquardt, Chen, Clerk, Girvin, PRL **99**, 093902 (2007)

Linearized optomechanical Hamiltonian



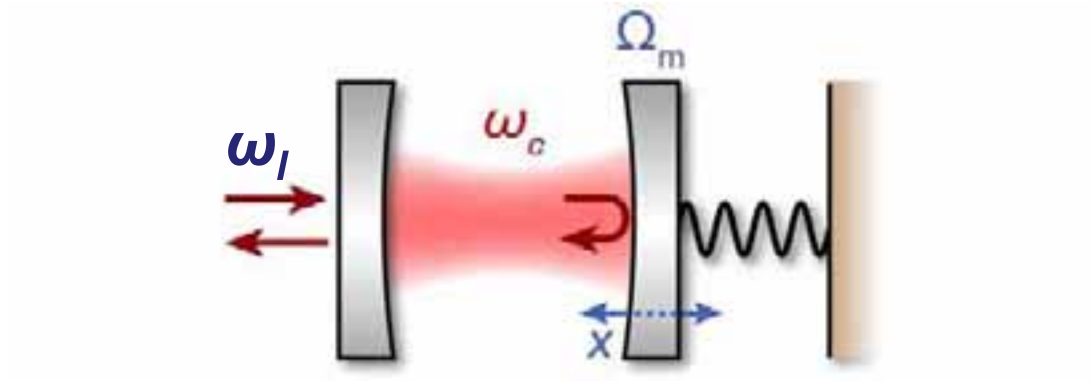
$$\hat{H} = \hbar\Delta\delta\hat{a}^\dagger\,\delta\hat{a} + \hbar\Omega_m\delta\hat{b}^\dagger\,\delta\hat{b}$$
$$+\hbar G x_{ZPF}\bar{a}(\delta\hat{b} + \delta\hat{b}^\dagger\,)(\delta\hat{a} + \delta\hat{a}^\dagger\,)$$

Resolved sideband regime, $\Delta = -\Omega_m$:

$$\boxed{\begin{gathered}\hat{H}_{int} = \hbar\Omega_c/2(\hat{a}^\dagger\,\hat{b} + \hat{a}\hat{b}^\dagger\,) \\ \Omega_c/2 = G x_{ZPF}\bar{a}\end{gathered}}$$

Corresponds to *state swapping* between optical and mechanical mode

Linearized optomechanical Hamiltonian



$$\hat{H} = \hbar\omega\hat{a}^\dagger\,\hat{a} + \hbar\Omega_m\hat{b}^\dagger\,\hat{b} + \underbrace{\hbar G\hat{x}\,\hat{a}^\dagger\hat{a}}_{\hat{H}_{int}}$$

Resolved sideband regime, $\Delta = -\Omega_m$:

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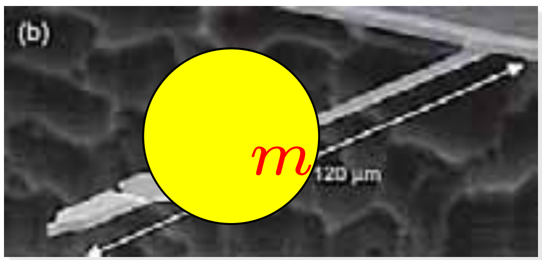
Corresponds to *state swapping* between optical and mechanical mode

Weak coupling: optomechanical cooling

$$\hat{H}_{int} = \hbar \frac{\Omega_c}{2} \left(\delta\hat{a}^\dagger \, \delta\hat{b} + \delta\hat{a}\delta\hat{b}^\dagger \right)$$

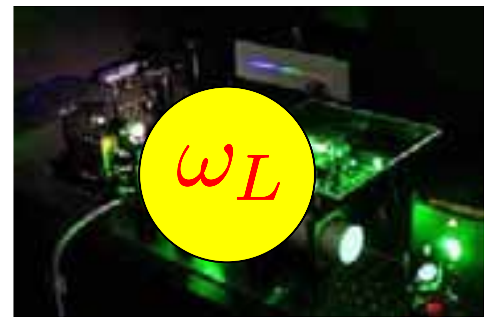
$$\Omega_m \gg \kappa$$

Mechanical oscillators



$$\Omega_c$$

Optical fields



$$\Omega_c = 2 g_0 \sqrt{\bar{n}_p}$$ Coupling rate between light and mechanical oscillator

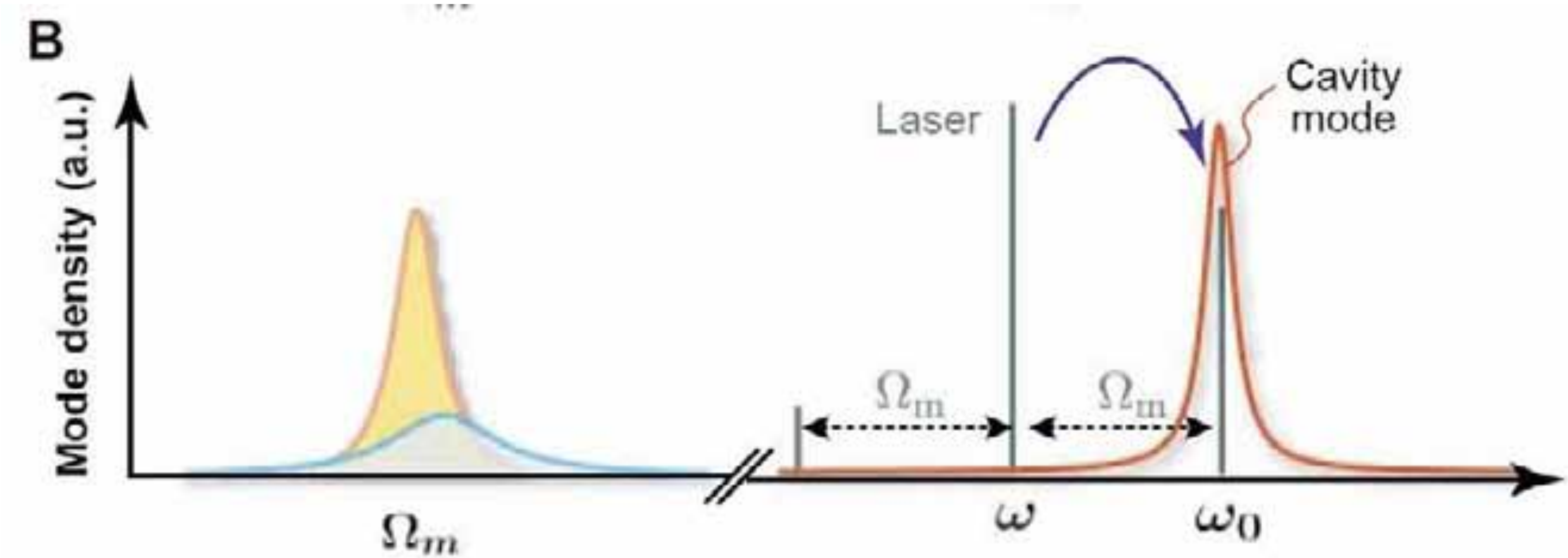
Weak coupling $\Omega_c < \kappa$ Cooling occurs if $\kappa \gg \Gamma_m$

$$\Gamma_{eff} = \Omega_c^2 / \kappa$$

Quantum theory :
I. Wilson-Rae, Nooshi, Zwerger, Kippenberg, PRL **99**, 093901 (2007)
F. Marquardt, Chen, Clerk, Girvin, PRL **99**, 093902 (2007)

Dynamical backaction cooling

$$\hat{H}_{int} = \hbar \frac{\Omega_c}{2} \left(\delta\hat{a}^\dagger \, \delta\hat{b} + \delta\hat{a}\delta\hat{b}^\dagger \right)$$



Resolved sideband cooling $\quad \Gamma_{eff} = \Omega_c^2/\kappa$

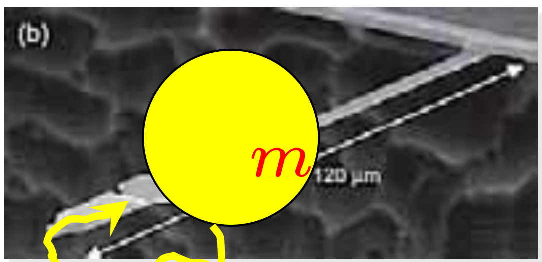
<u>**Quantum theory :**</u> $\quad n_f = \kappa^2/16\Omega_m^2 \quad$ Only for: $\quad \Omega_m \gg \kappa$

Wilson-Rae, Nooshi, Zwerger, Kippenberg, PRL **99**, 093901 (2007)
Marquardt, Chen, Clerk, Girvin, PRL **99**, 093902 (2007)

Coupling mechanical motion to an optical field

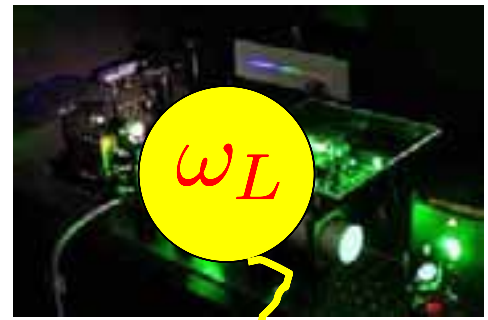
$$\hat{H}_{int} = \hbar \frac{\Omega_c}{2} \left(\delta\hat{a}^{\dagger}\,\delta\hat{b} + \delta\hat{a}\delta\hat{b}^{\dagger}\right)$$

Mechanical oscillators



Ω_c

Optical fields



$\Gamma_m(\bar{n}_m)$

$$\gamma = \Gamma_m(\bar{n}_m + 1) \sim \Gamma_m \bar{n}_m$$

$$\kappa(\bar{n}_p + 1) \sim \kappa$$

Environment

$$\bar{n}_m = \frac{k_B T}{\hbar \Omega_m} \gg 1$$

Quantum coherent coupling

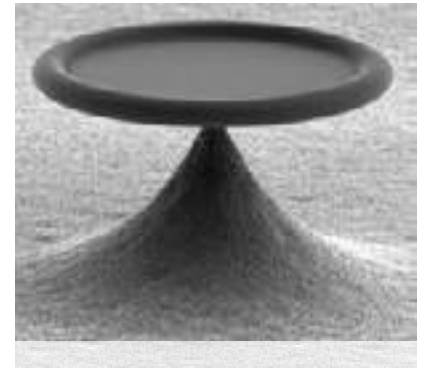
Environment

$$\bar{n}_p = \frac{k_B T}{\hbar \omega_l} \sim 0$$

$$\Omega_c > (\gamma, \kappa)$$

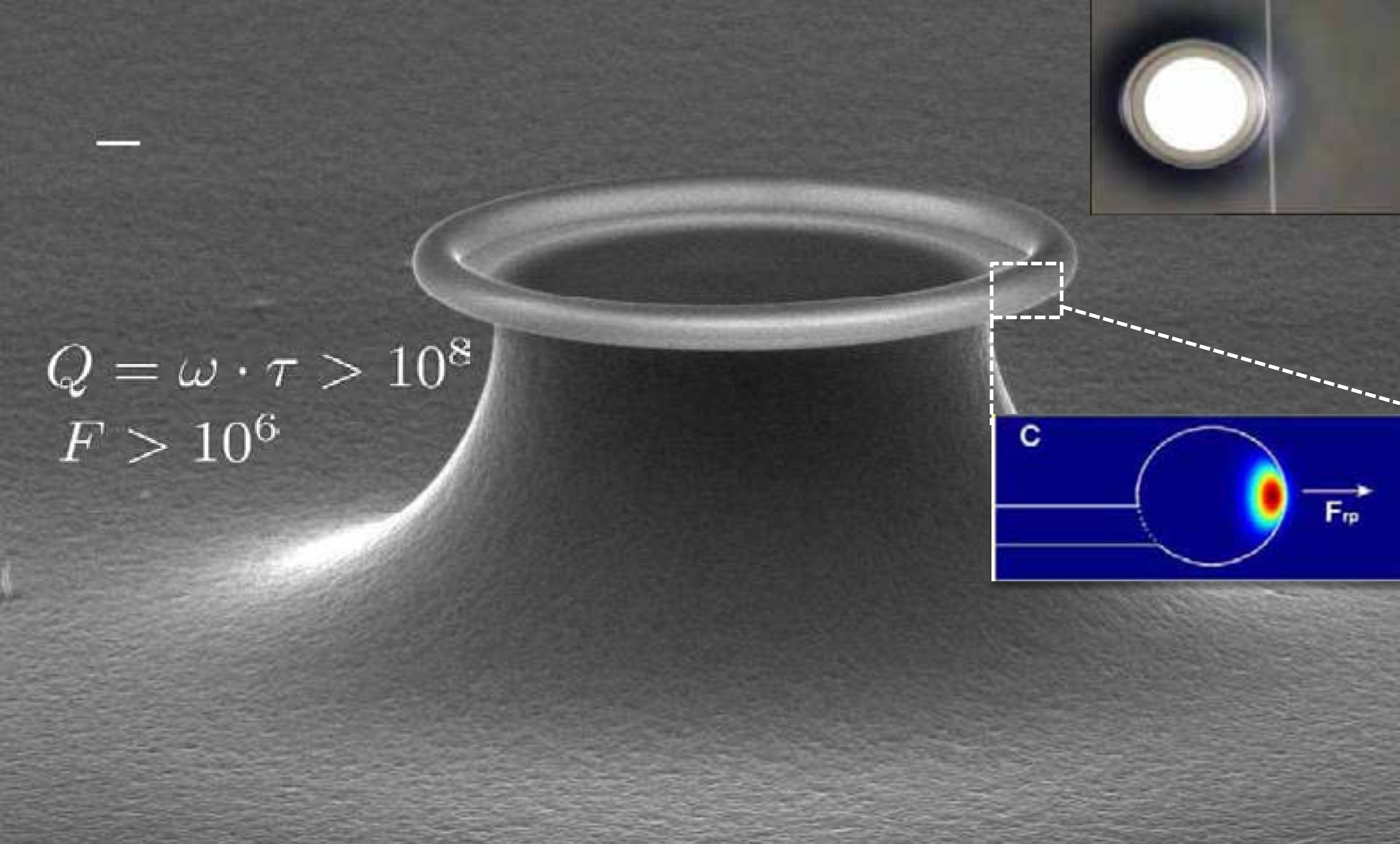
Outline

- Exploring cavity optomechanics with microresonators



- Optomechanically Induced Transparency

- Quantum-coherent coupling of mechanical and optical modes



D. K. Armani, T. J. Kippenberg, S. M. Spillane, K. J. Vahala.
Nature 421, 925-928 (2003).

Optomechanical coupling in optical microresonators

Insight: Mechanical vibrations also apply to the microscale* optical microresonators

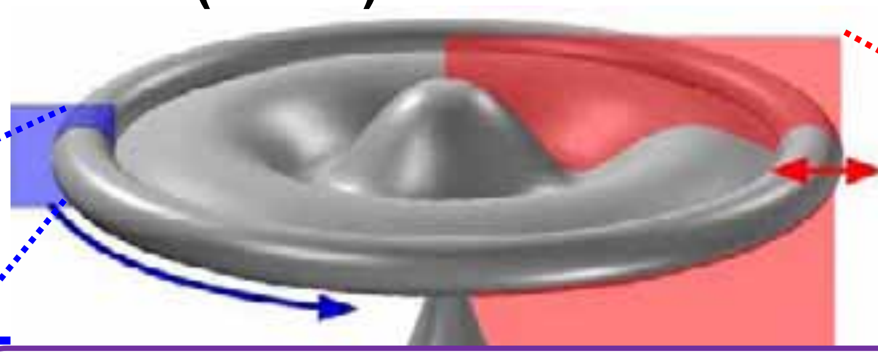
-> Enabled a new class of cavity optomechanical devices

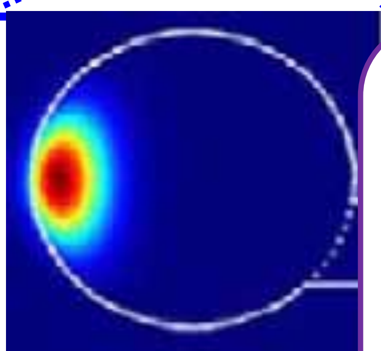
*T. J. Kippenberg, H. Rokhsari, T. Carmon, A. Scherer and K.J. Vahala *Physical Review Letters* 95, Art. No. 033901 (2005)

Optomechanical coupling in microresonators

optical
whispering-gallery-mode (WGM)

mechanical
radial-breathing-mode (RBM)





$$\hat{H}_{int} = \hbar G x_{ZPF} \hat{a}^\dagger \hat{a} (\hat{b}^\dagger + \hat{b}) \qquad \Omega_m \gg \kappa$$

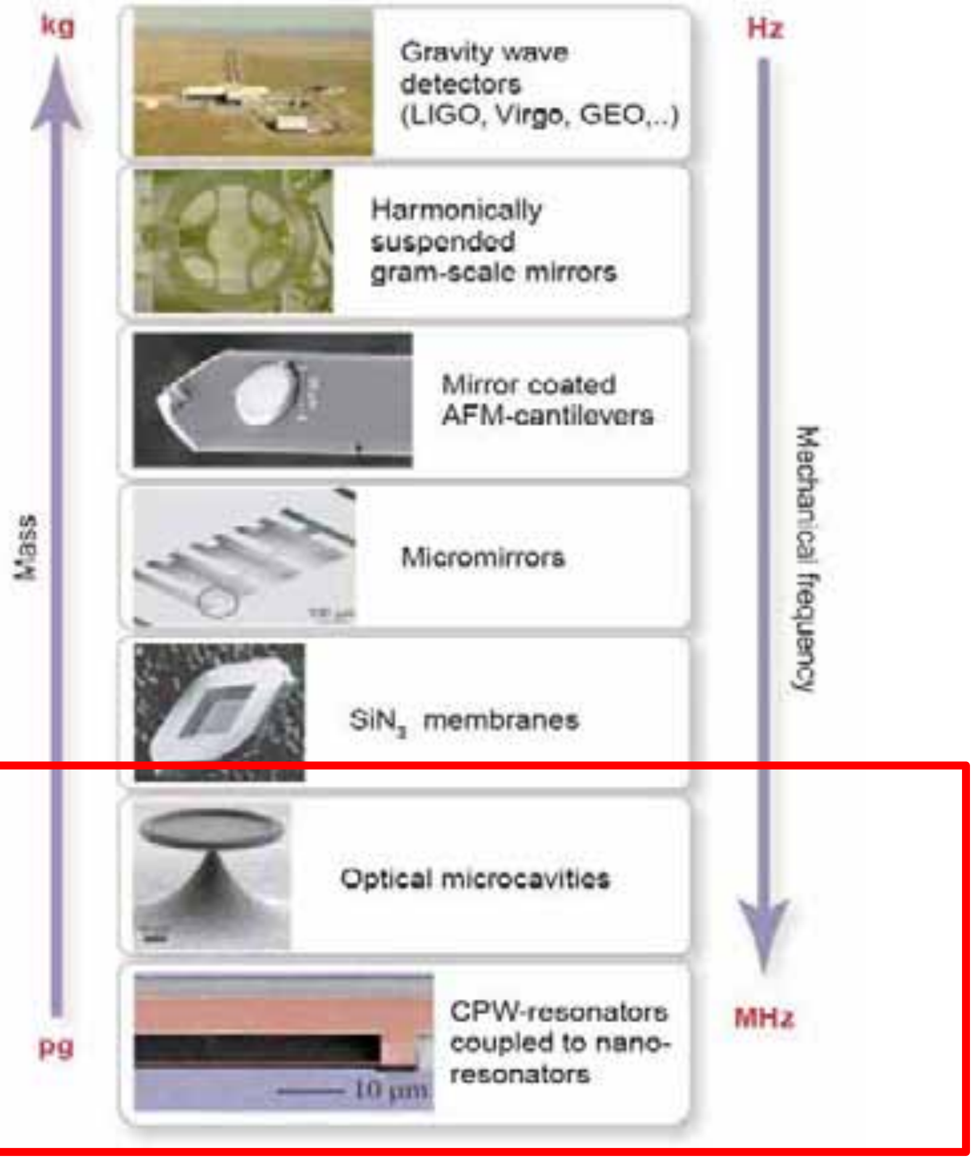
$$g_0 = G x_{ZPF} \Leftrightarrow \Omega_0/2$$

Linewidth		
Quality factor	Q	$\lesssim 3 \cdot 10$
Finesse	$\mathcal{F}$	$\lesssim 10^6$
free spectral range	FSR	≈ 1 THz

		MHz
Quality factor	Q_m	$\lesssim 50000$
Effective mass	m_{eff}	$\approx 10^{-11}$ kg
zero-point fluctuations	Δx	≈ 150 am

T.J. Kippenberg, Rokhsari, Carmon, Scherer, K.J. Vahala, PRL 95, 033901(2005)

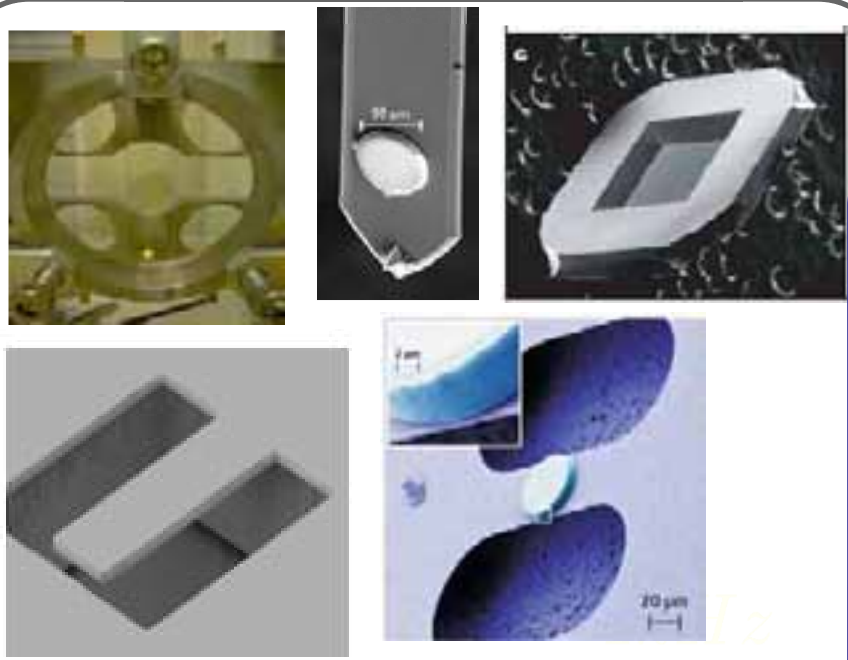
Examples of optomechanical devices



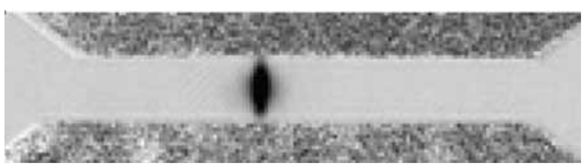
Cavity optomechanics in micro and nano-optical systems

Kippenberg, Vahala Science (2008) «Cavity Optomechanics»

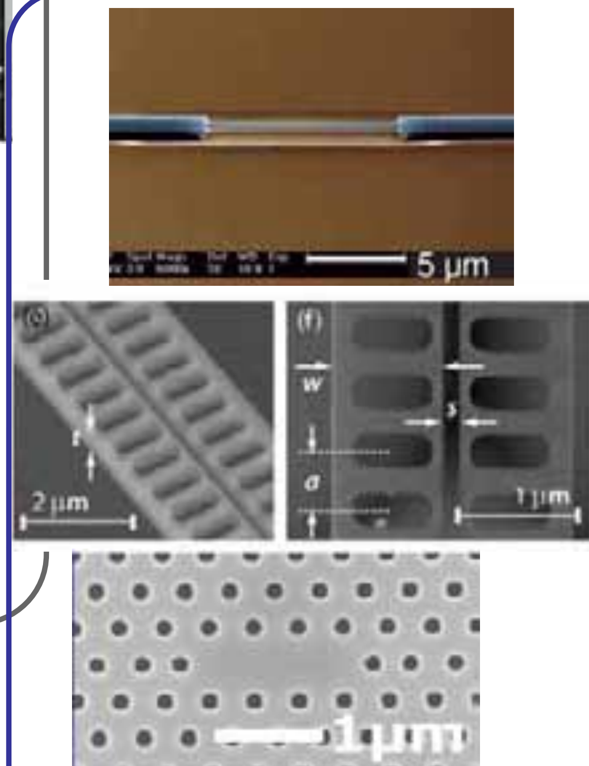
Cavity optomechanical systems (2011)



Movable mirrors and membranes:
Caltech, MIT, Paris, UCSB, Vienna, Yale



Cold atoms (simulators):
Berkeley, ETHZ, MIT



Nanophotonic systems:
Caltech, Ghent, EPFL

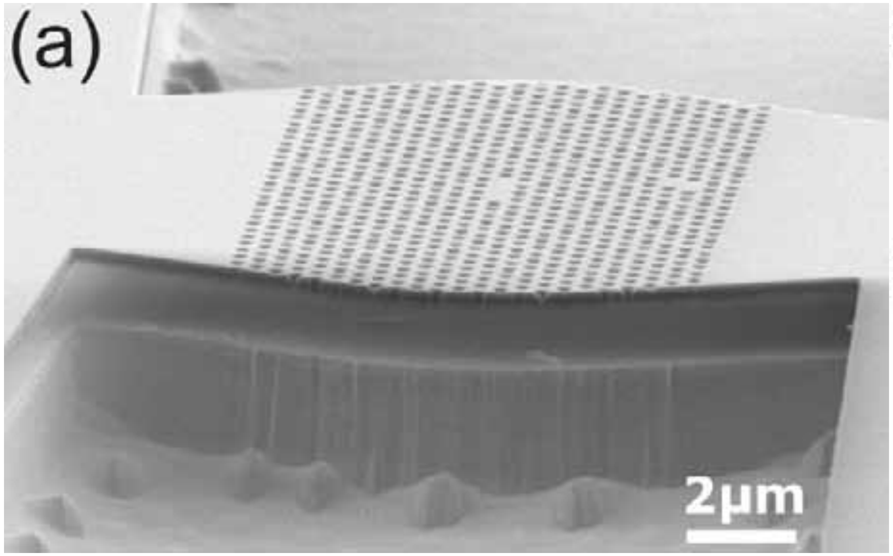
Whispering-gallery-mode resonators:
Caltech, EPFL, MPQ

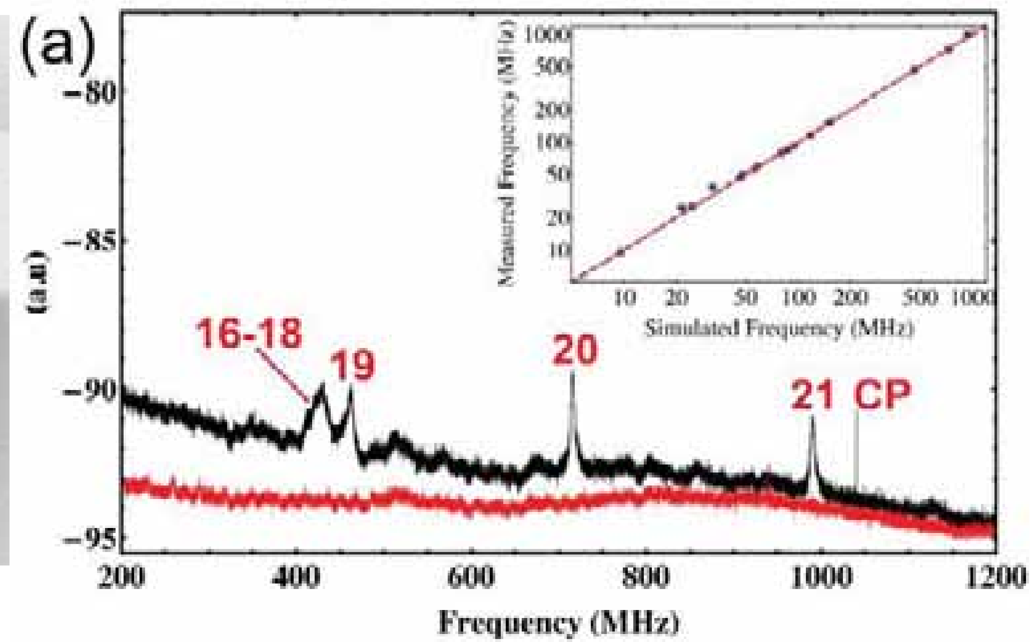
Microwave systems:
Caltech, JILA, NIST, UCSB

Reviews: Kippenberg, Vahala, Science 321, 1172 (2008) "Cavity Optomechanics"
Marquardt, Girvin, Physics 2, 40 (2009)

$$H_{int} = g_0 \hbar a^\dagger a (a_m^\dagger + a_m)$$

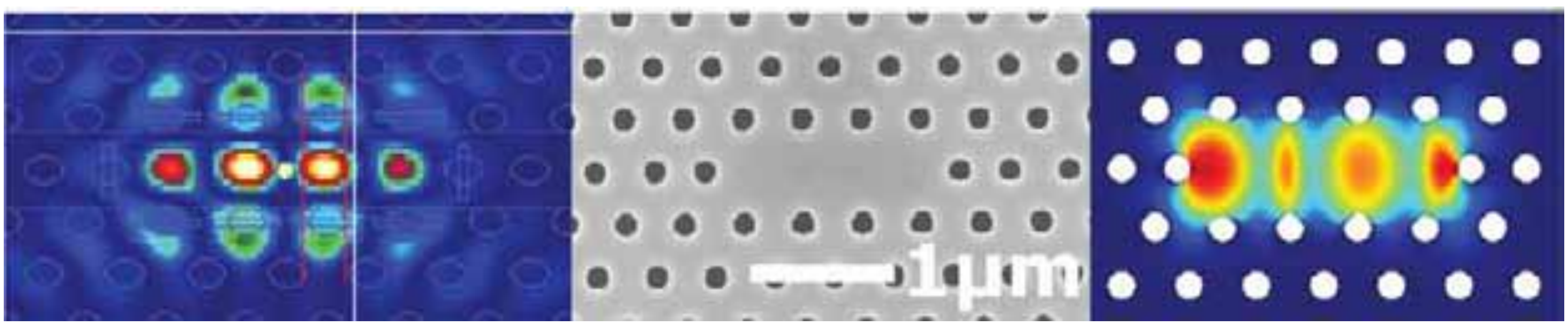
Optomechanical coupling in 2 D photonic crystal cavities





2-D defect cavity

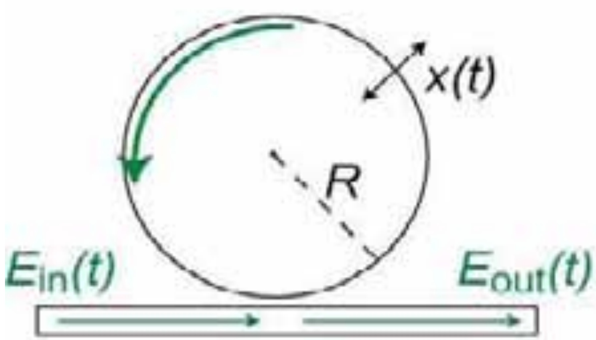
Optical mode **Photonic crystal cavity** **Mechanical mode**



Collaboration LPN (CNRS)/EPFL

E. Gavartin, Braive, T.J. Kippenberg, I. Robert (*Physical Review Letters* 2011)

Optomechanical coupling in a toroidal microcavity

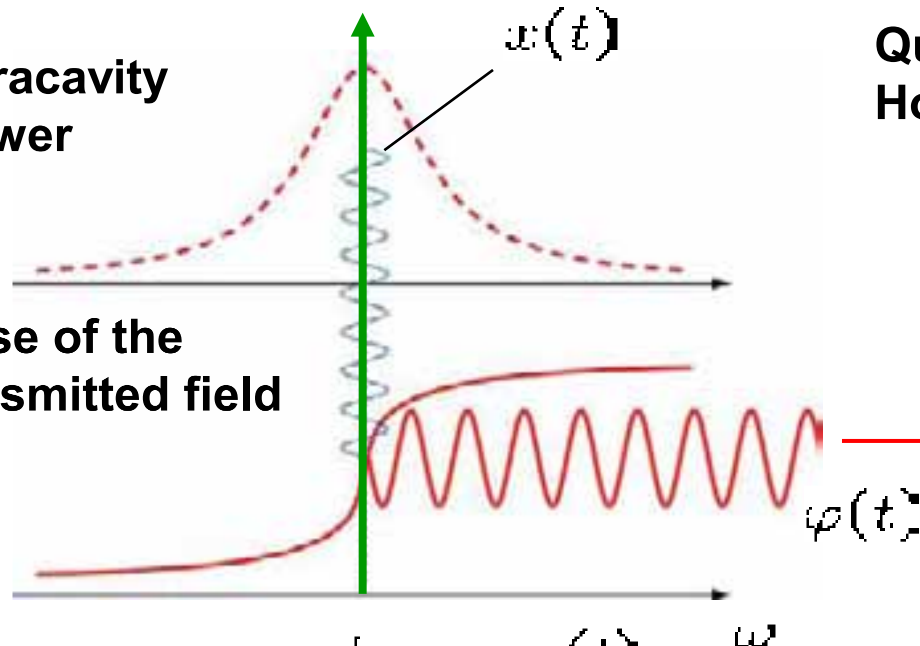


$$G/2\pi = 10^9 GHz/nm$$

Critical coupling $\kappa_{ex} = \kappa_0$

Intracavity power

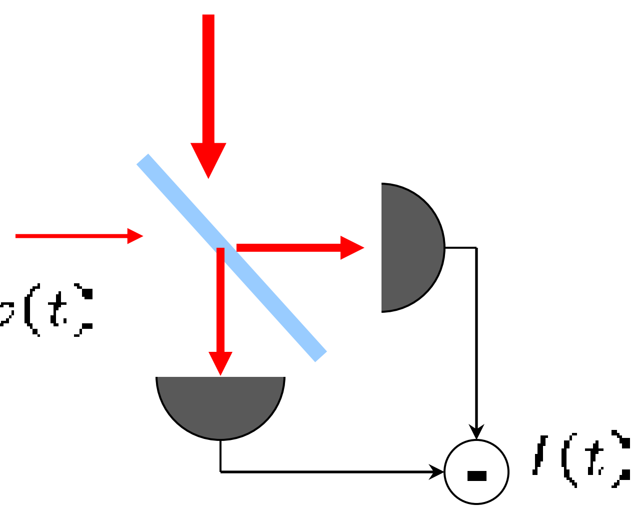
Phase of the Transmitted field



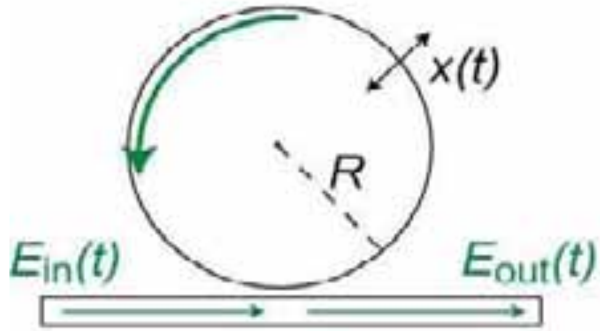
$$\omega_0 = \omega_L + g_m \cdot x(t)$$

Quantum limited Homodyne Detection

LO

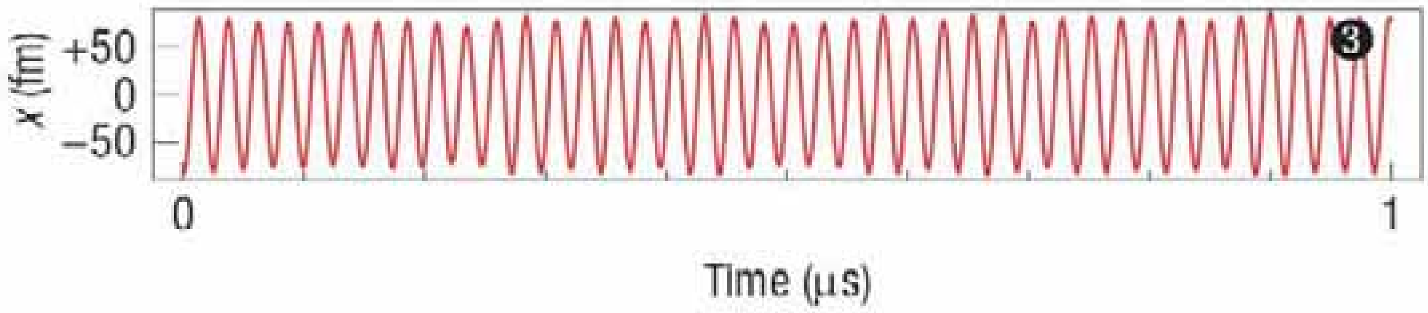


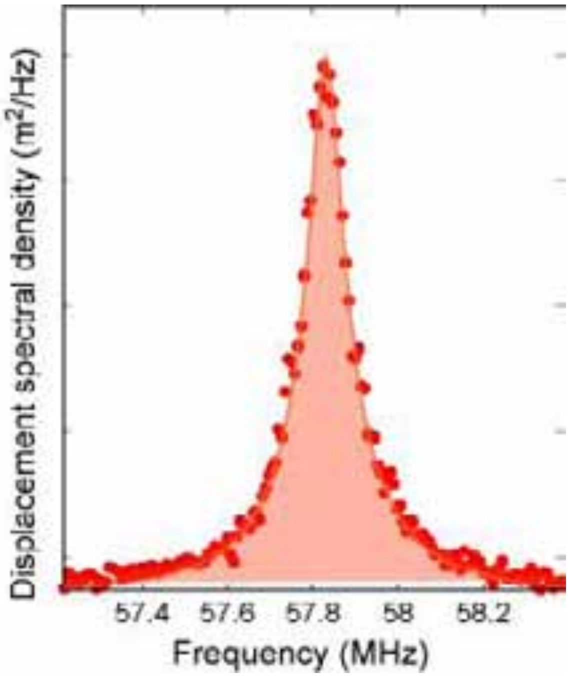
Optomechanical coupling in a toroidal microcavity



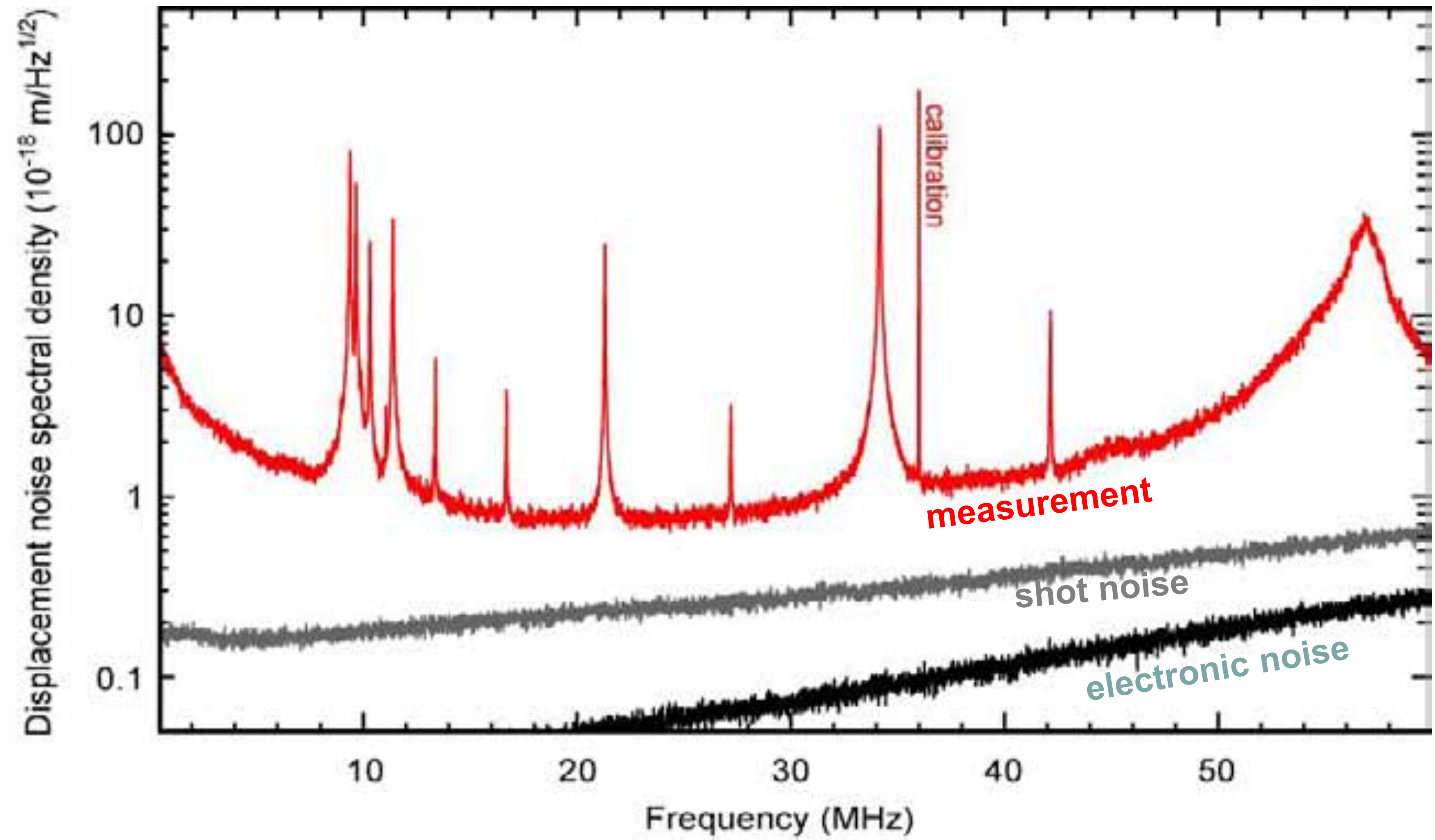
$$G/2\pi = 10^9 GHz/nm$$

$$k_B T_{eff} = \int m_{eff} |x[\Omega]|^2 \Omega^2 d\Omega$$



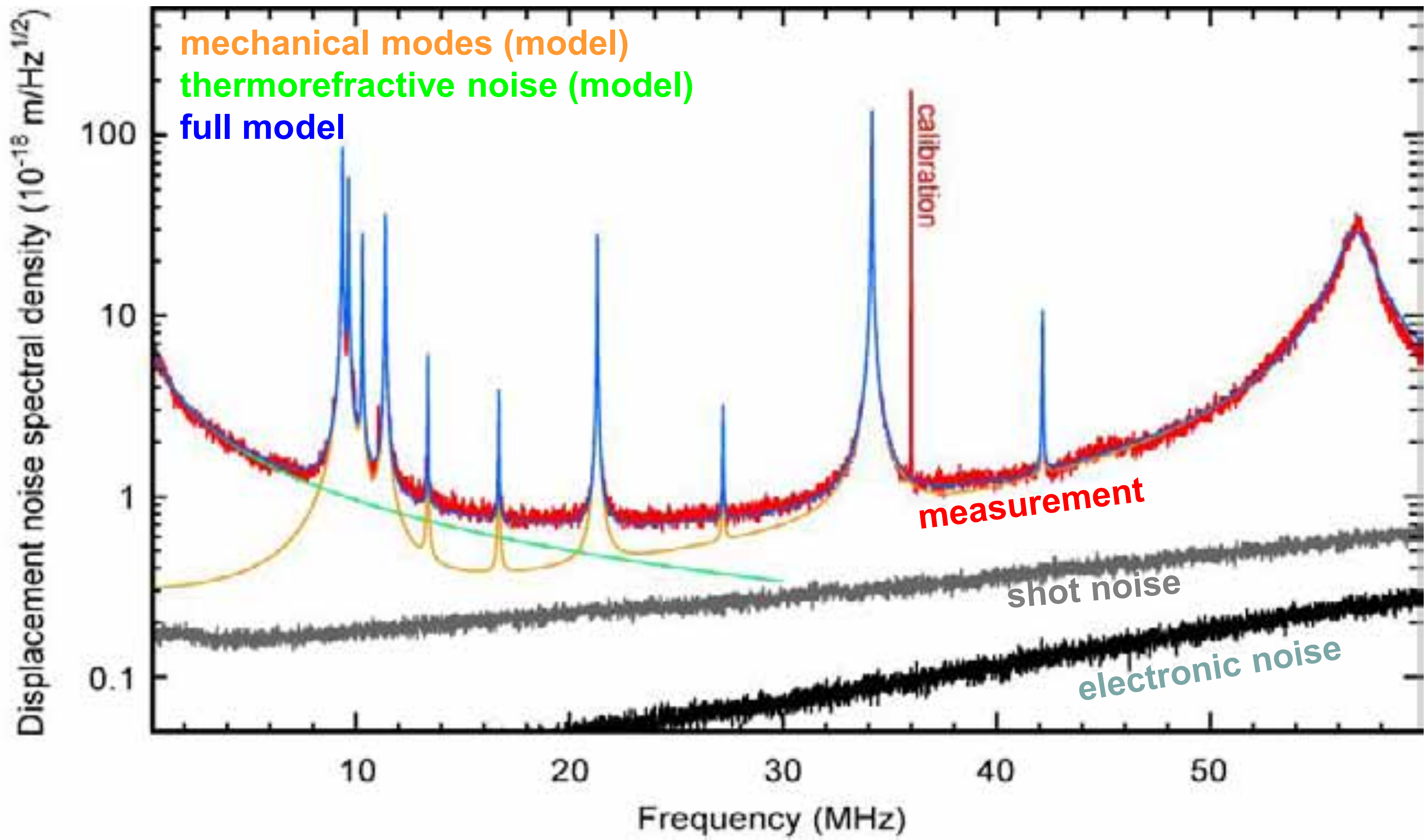


Example: noise spectral density of a toroid microresonator



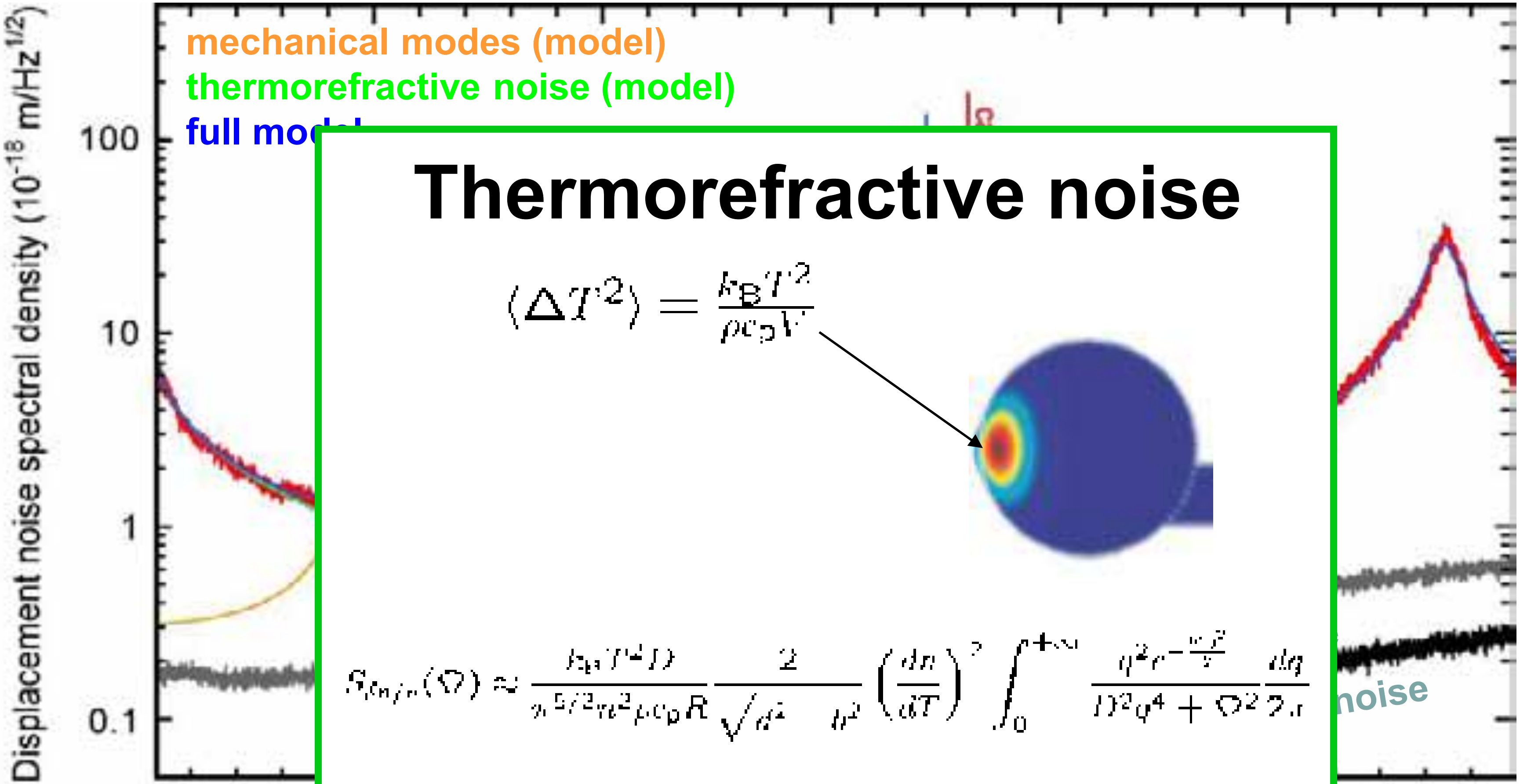
A. Schliesser et al. NJP 2009

Example: noise spectral density of a toroid microresonator



A. Schliesser et al. NJP 2009

Example: noise spectral density of a toroid microresonator



Thermorefractive noise

$$\langle \Delta T^2 \rangle = \frac{k_B T^2}{\rho c_p V}$$

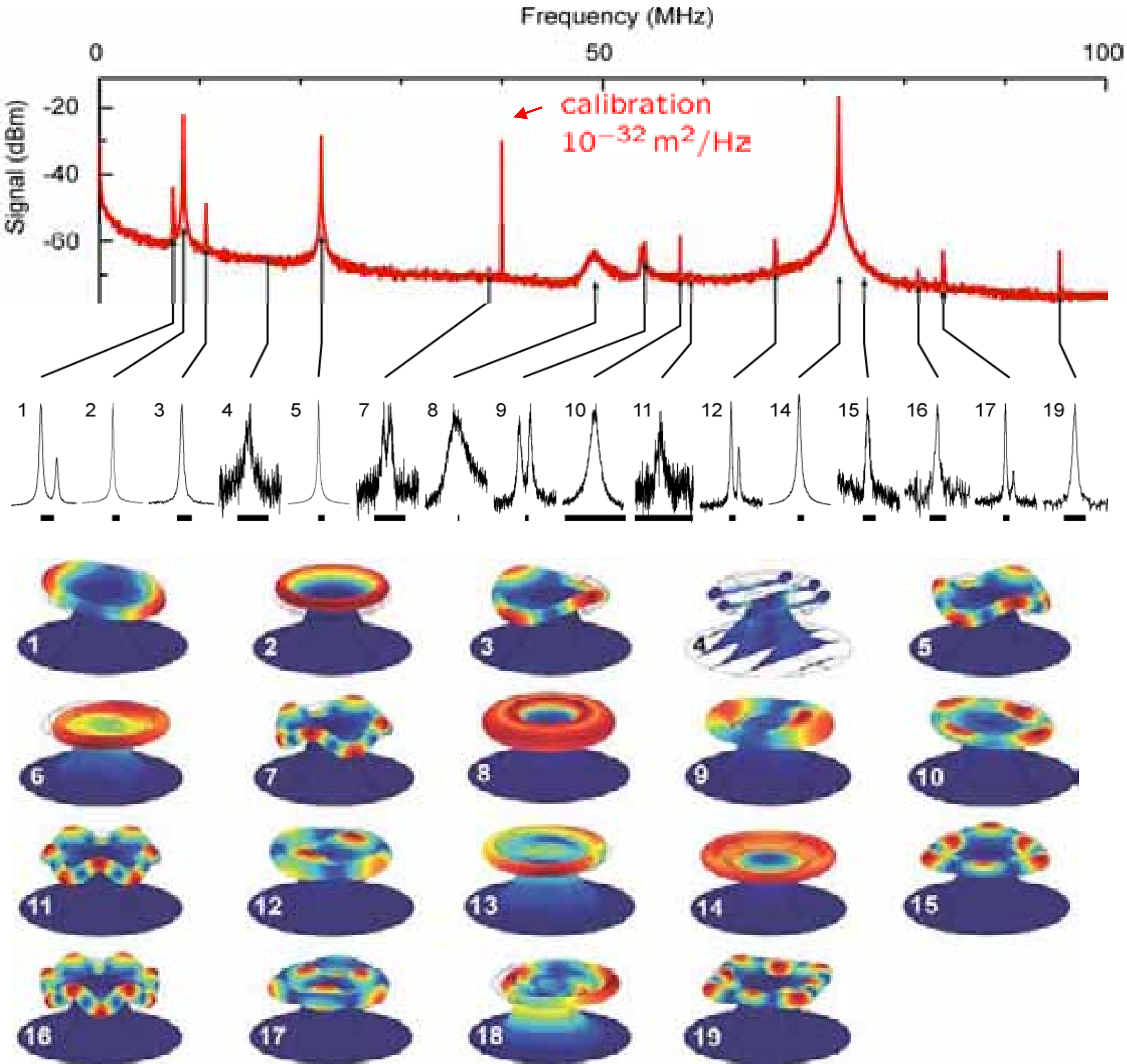
$$S_{\delta n/n}(\Omega) \approx \frac{k_B T^2 D}{\pi^{5/2} n^2 \rho c_p R} \frac{2}{\sqrt{d^2 - b^2}} \left(\frac{dn}{dT}\right)^2 \int_0^{+\infty} \frac{q^2 e^{-\frac{q^2}{2}}}{D^2 q^4 + \Omega^2} \frac{dq}{2\pi}$$

Landau, Lifshitz, *Statistical Physics*, Pergamon Press (1980)
Gorodetsky, Grundinin, JOSA B, 21, 697 (2004)

A. Schliesser et al. NJP 2009

MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK GARCHING

Observing Brownian motion of toroid microresonators



measured mechanical spectrum

zoom on individual peaks

mode patterns obtained from finite element modeling

Displacement sensitivity below that at the SQL

- **Vacuum coupling strength**

$$\langle \delta\omega^2 \rangle = \int_{-\infty}^{\infty} S_{\omega\omega}(\Omega)\frac{d\Omega}{2\pi} = 2\langle n \rangle g_0^2$$

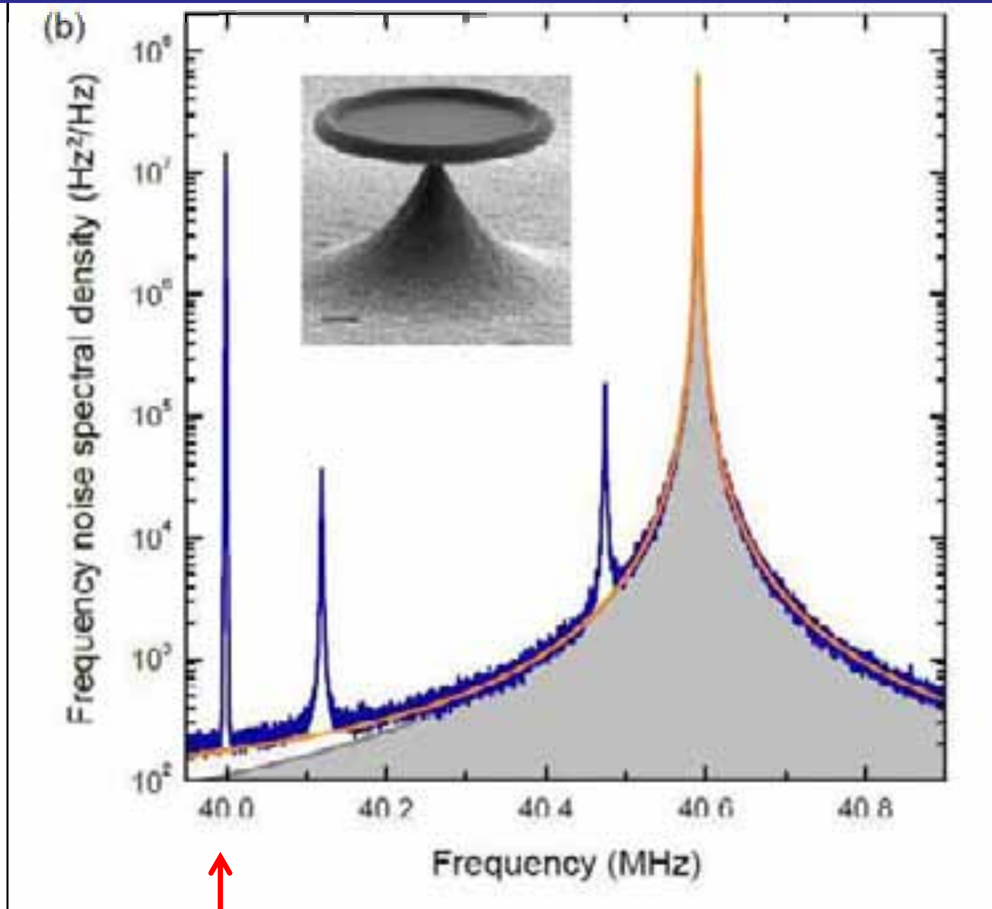
- **Peak displacement spectral density**

$$S_{xx} = 2\bar{n}_m S_{xx}^{zpm}$$

- **spectral density of Zero Point Motion**

$$S_{xx}^{zpm} = \frac{\hbar}{2m\Omega_m\Gamma_m}$$

$$\boxed{\frac{S_{xx}^{th}[\Omega_m]}{S_{xx}^{zpm}[\Omega_m]} > \sqrt{2\bar{n}} \qquad \bar{n}_m \approx \frac{k_B T}{\hbar\Omega_m}}$$

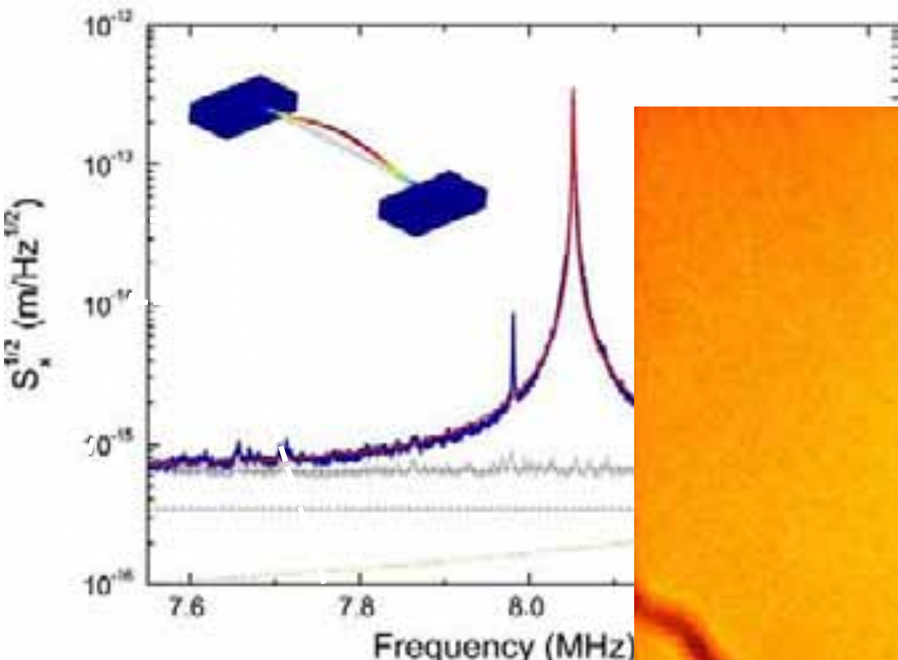


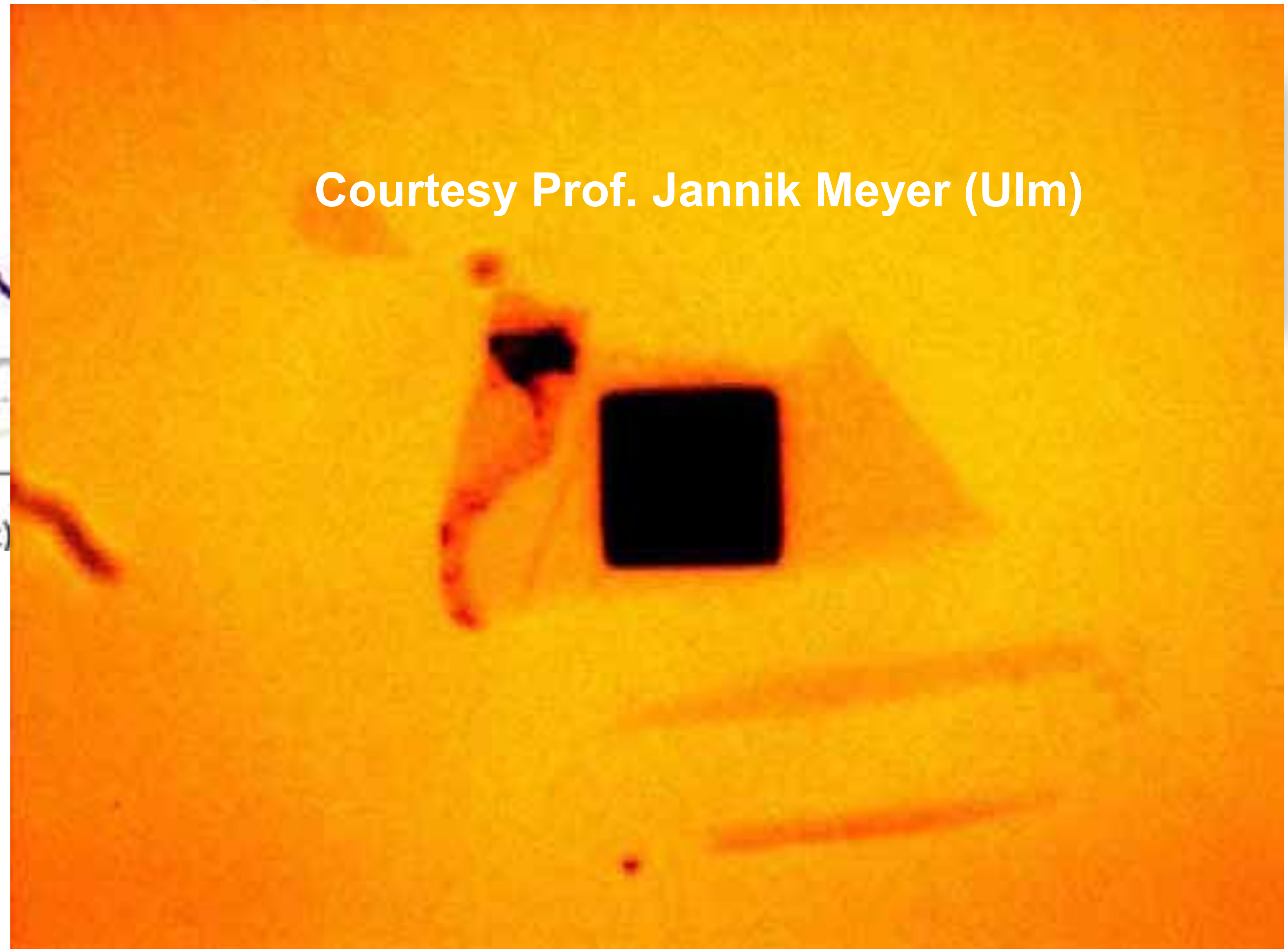
Applied phase modulation signal

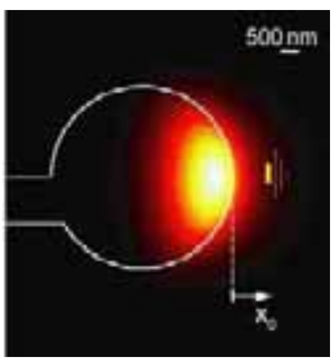
A. Schliesser et al. NJP (2008)

ML Gorodetsky, A. Schliesser, TJ Kippenberg (*Optics Express* 2010)

Displacement sensitivity below that at the SQL



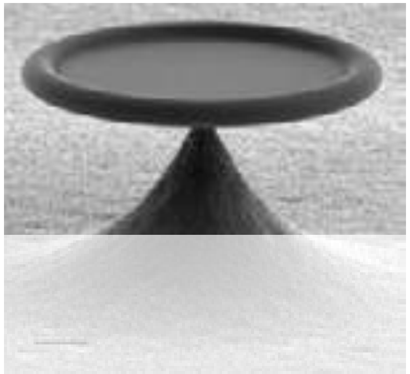




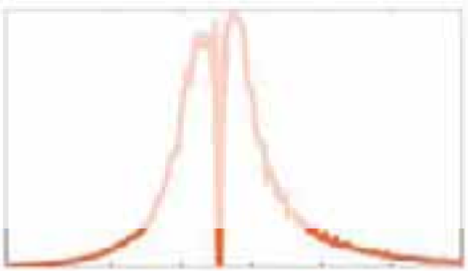
Anetsberger et al. *Nature Physics* (2009)
Collaboration: J.P. Kotthaus, E. Weig

Outline

- Cavity Optomechanics with silica microresonators

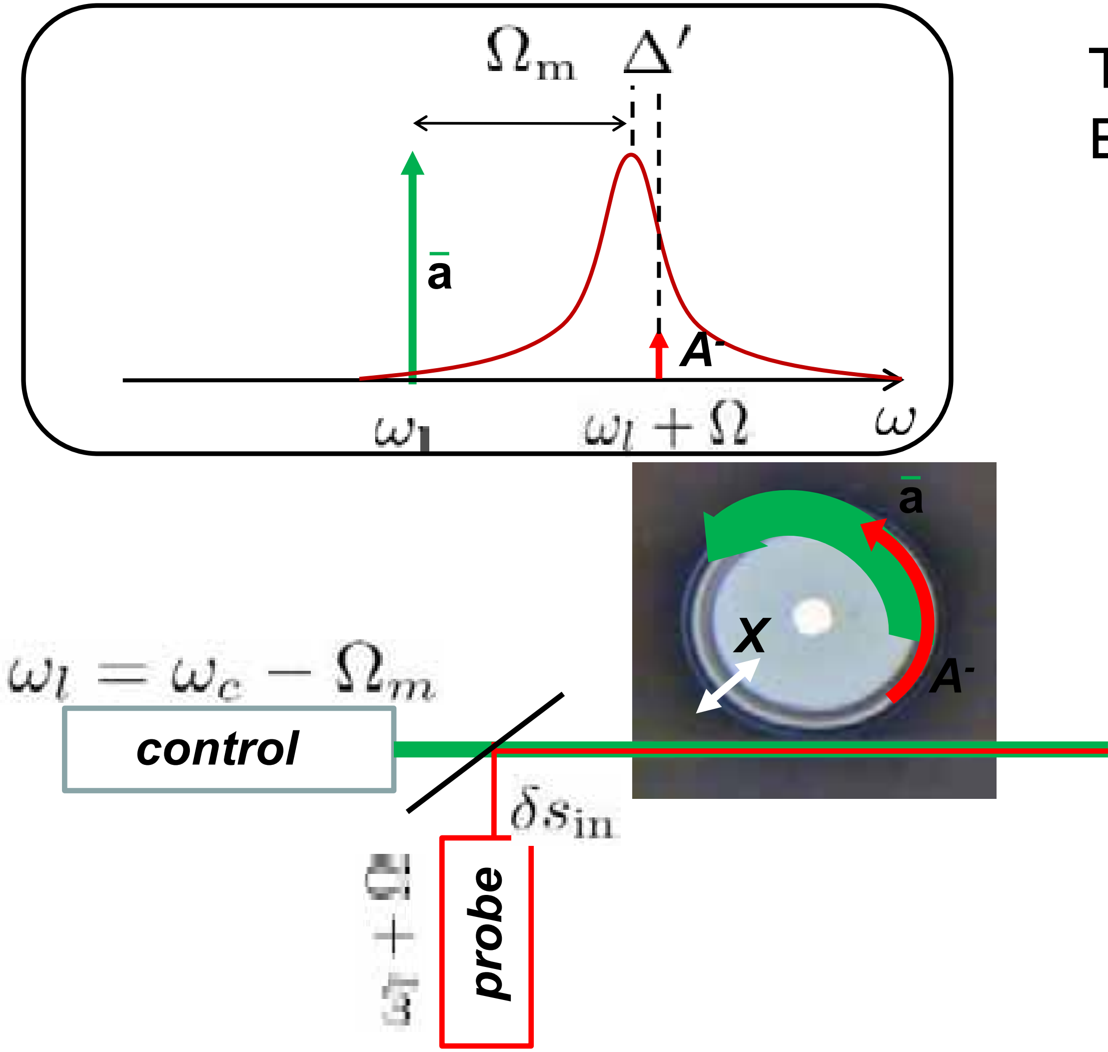


- Optomechanically Induced Transparency

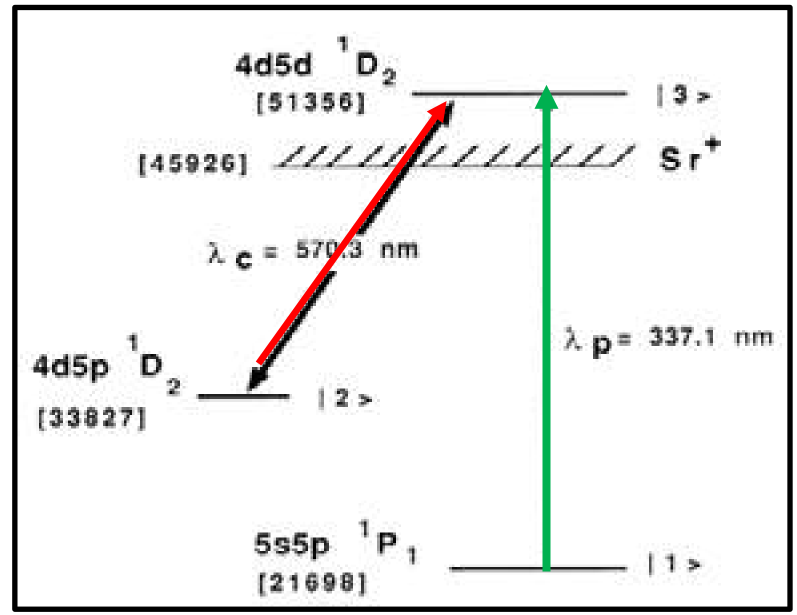


- Quantum-coherent coupling of mechanical and optical modes

Coherent probing: Optomechanically Induced Transparency



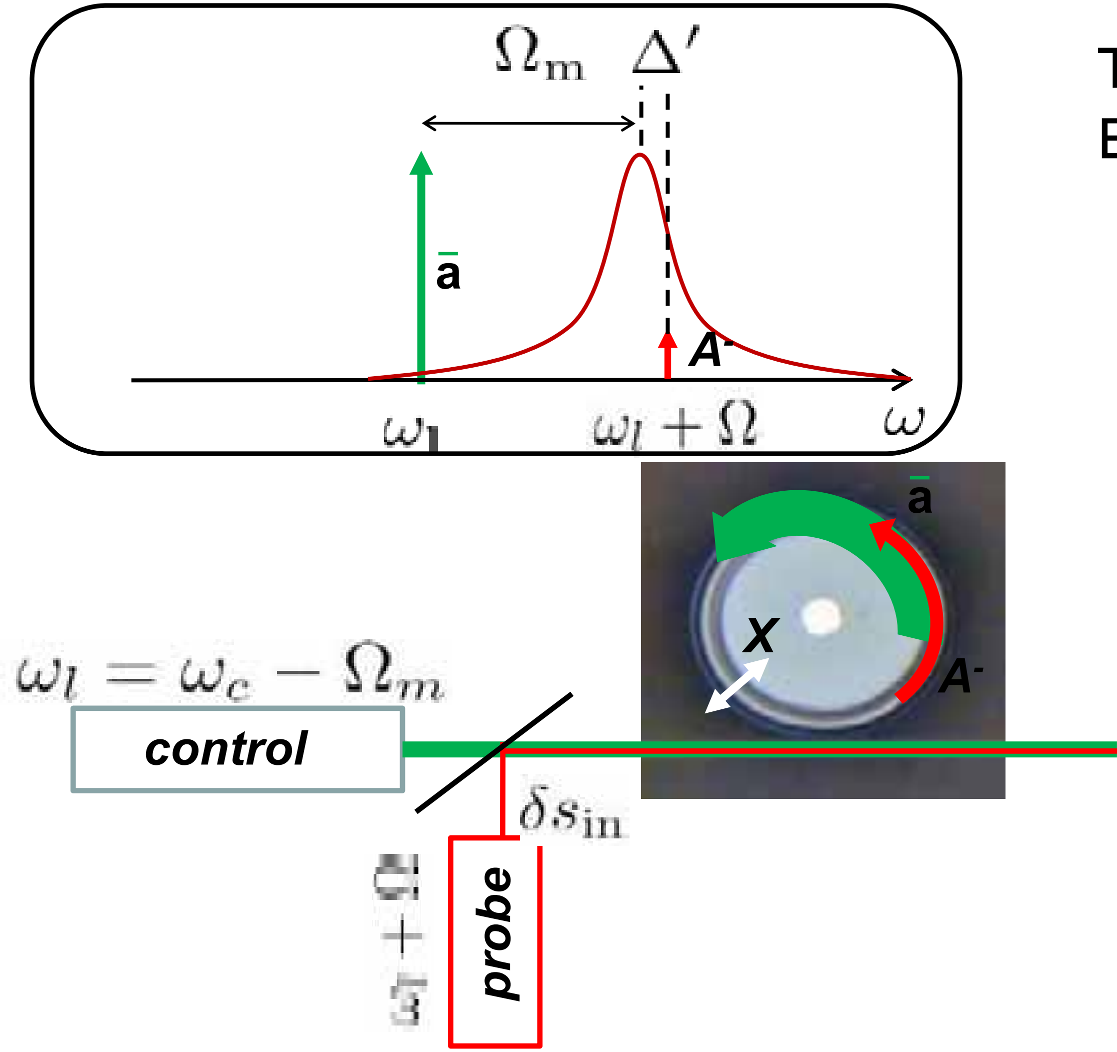
Two laser scheme is similar to atomic EIT



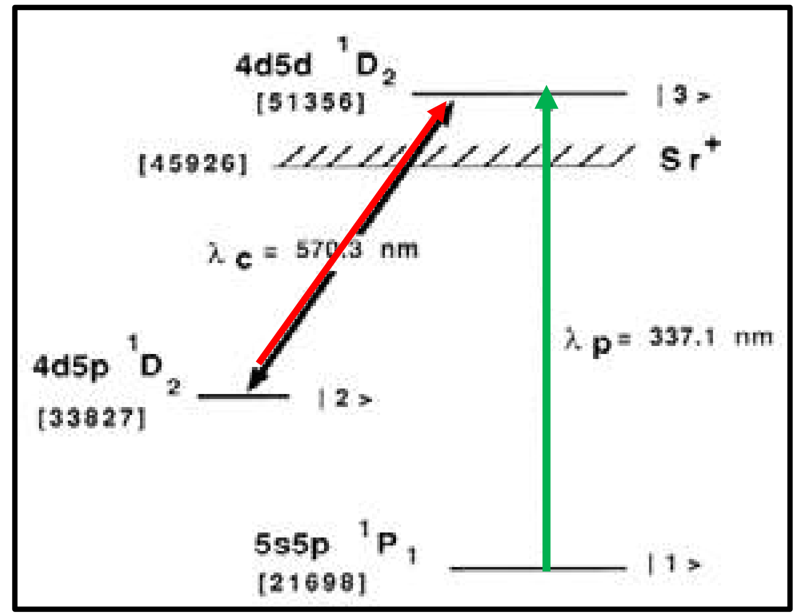
Harris, PRL

Zhang, Peng, Braunstein, PRA 68, 013808 (2003)
Schliesser, LMU PhD thesis (2009)
Agarwal, Huang, PRA 81, 041803 (2010)

Coherent probing: Optomechanically Induced Transparency



Two laser scheme is similar to atomic EIT



Harris, PRL

Zhang, Peng, Braunstein, PRA 68, 013808 (2003)
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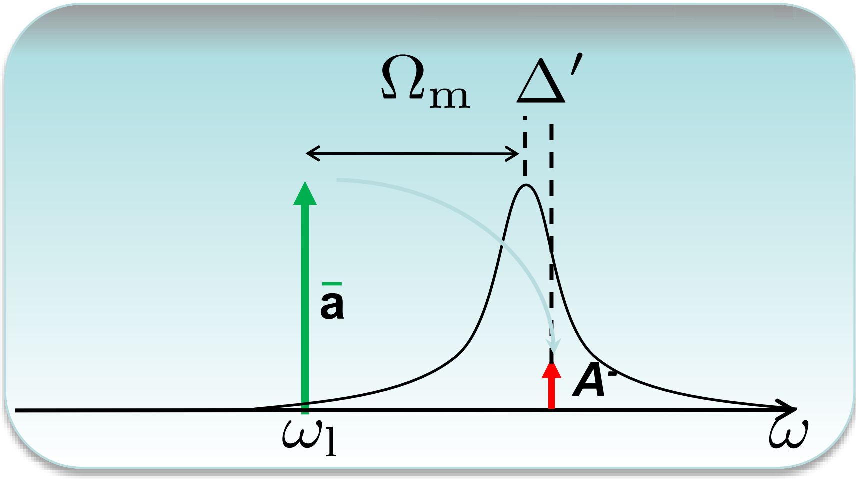
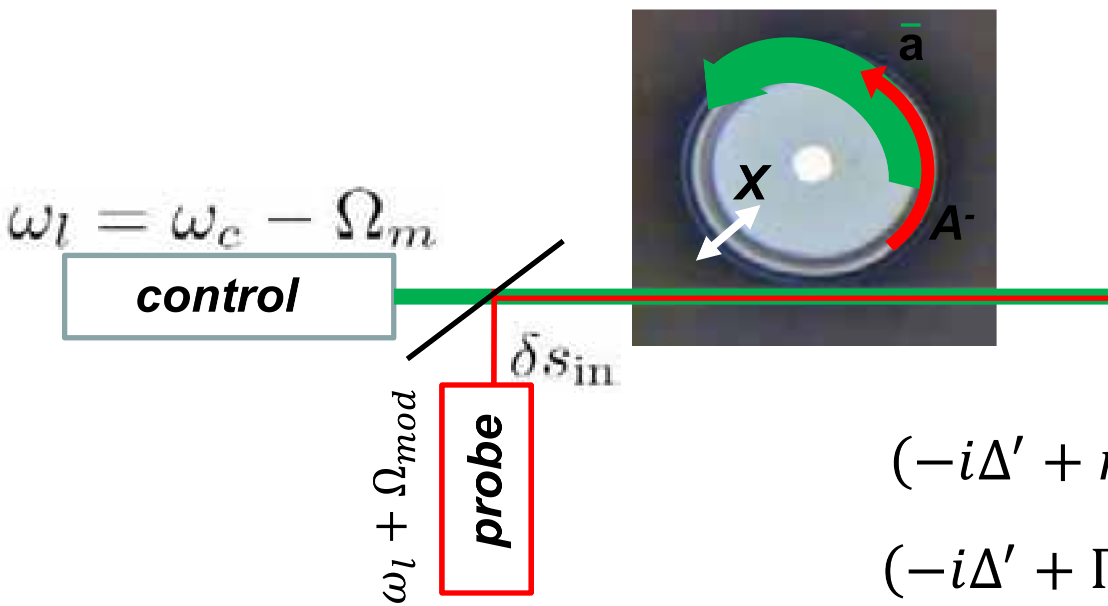
Optomechanically induced transparency



$$\hat{H}_{int} = \hbar \frac{\Omega_c}{2} \left(\delta\hat{a}^\dagger\, \delta\hat{b} + \delta\hat{a}\delta\hat{b}^\dagger\right)$$

$$\delta\hat{a}(t) = A^- e^{-i\Omega_{mod}t}$$

$$\delta\hat{b}(t) = X e^{-i\Omega_{mod}t}$$

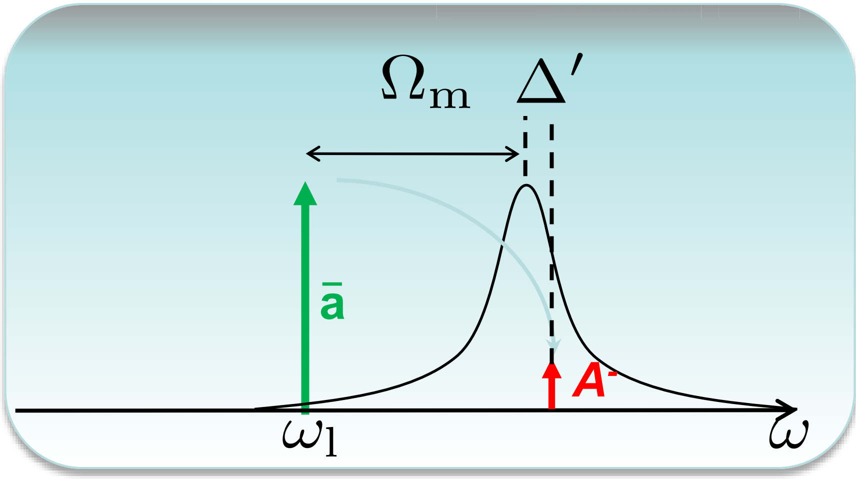


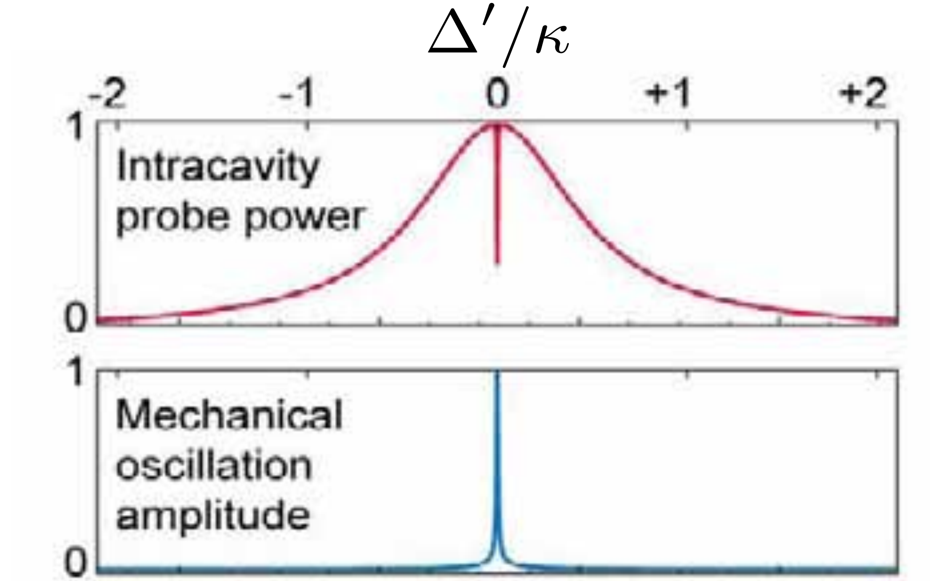
$$(-i\Delta' + \kappa/2)A^- = -i(\Omega_c/2)X + \sqrt{\kappa_{ex}}\delta s_{in}$$

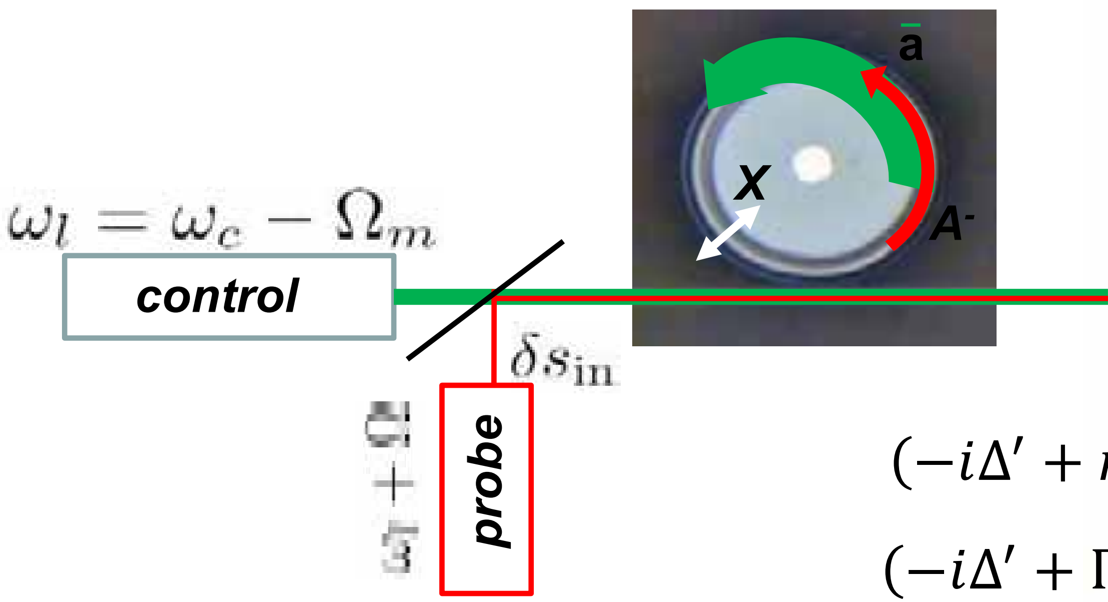
$$(-i\Delta' + \Gamma_m/2)X = -i(\Omega_c/2)X$$

Zhang, Peng, Braunstein, PRA 68, 013808 (2003)
Schliesser, LMU PhD thesis (2009)
Agarwal, Huang, PRA 81, 041803 (2010)

Optomechanically induced transparency







$$(-i\Delta' + \kappa/2)A^- = -i(\Omega_c/2)X + \sqrt{\kappa_{ex}}\delta s_{in}$$

$$(-i\Delta' + \Gamma_m/2)X = -i(\Omega_c/2)X$$

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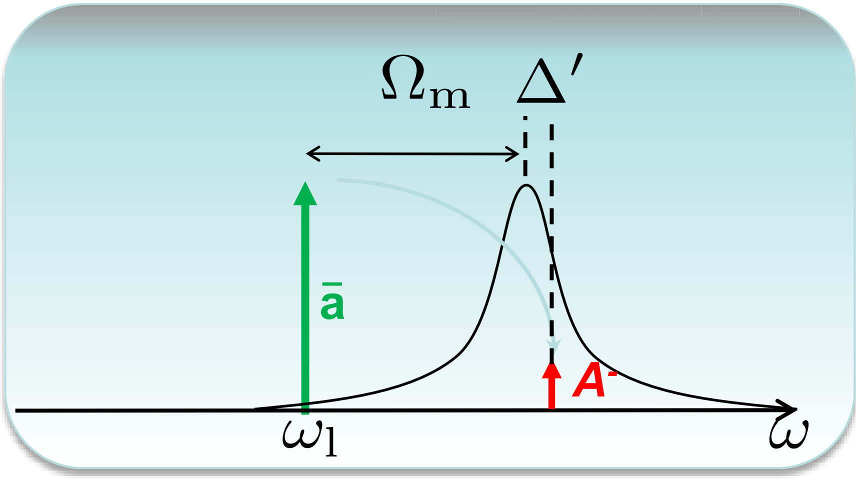
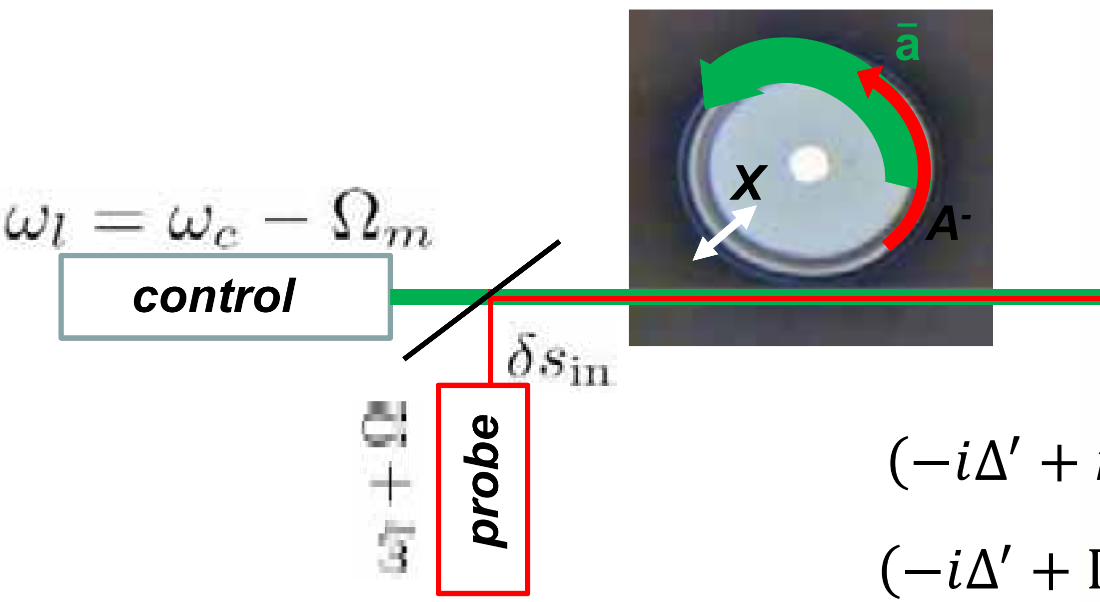
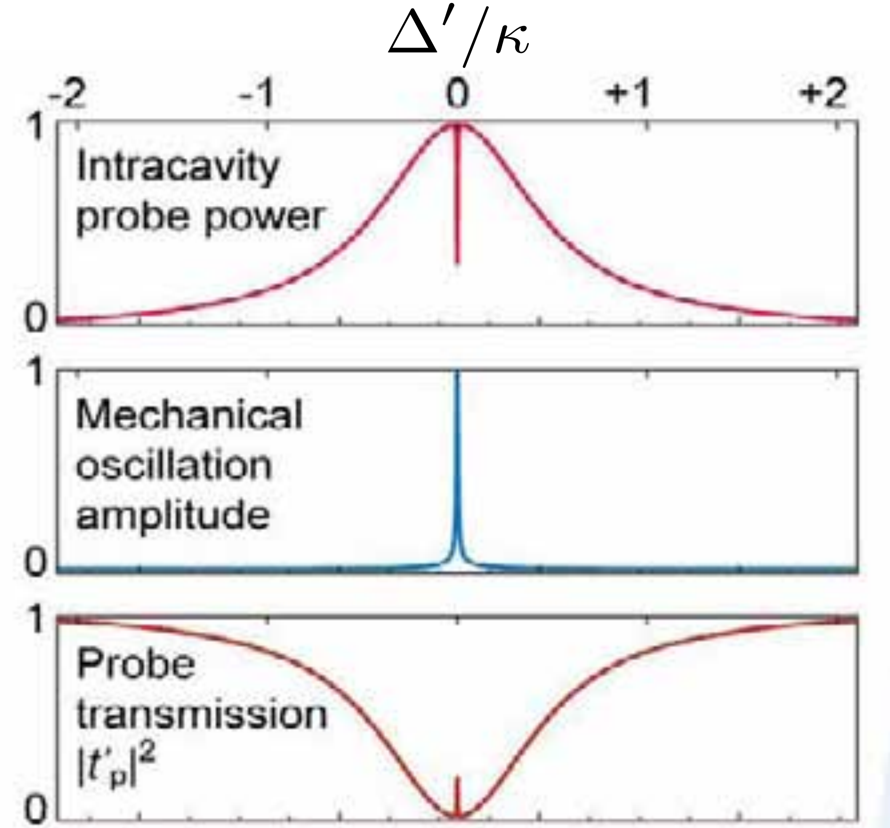
Optomechanically induced transparency





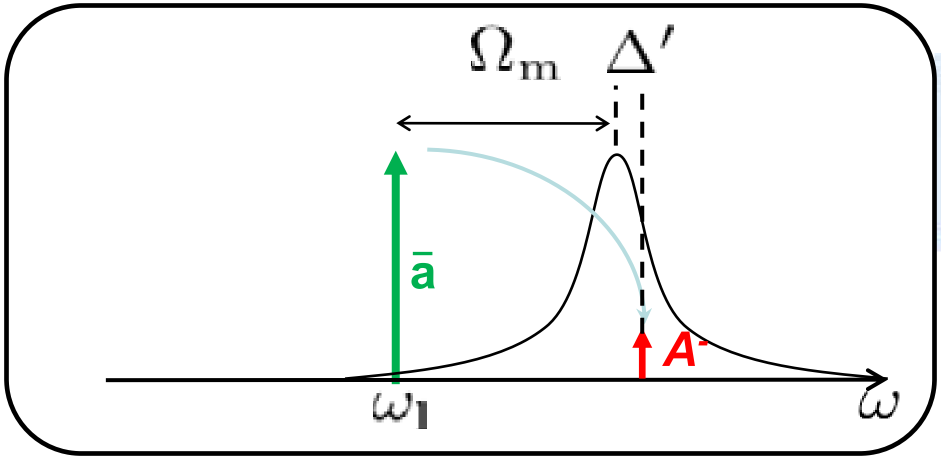


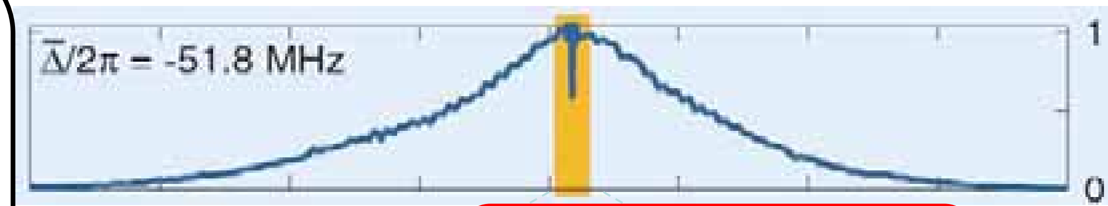
$$(-i\Delta' + \kappa/2)A^- = -i(\Omega_c/2)X + \sqrt{\kappa_{ex}}\delta s_{in}$$

$$(-i\Delta' + \Gamma_m/2)X = -i(\Omega_c/2)X$$

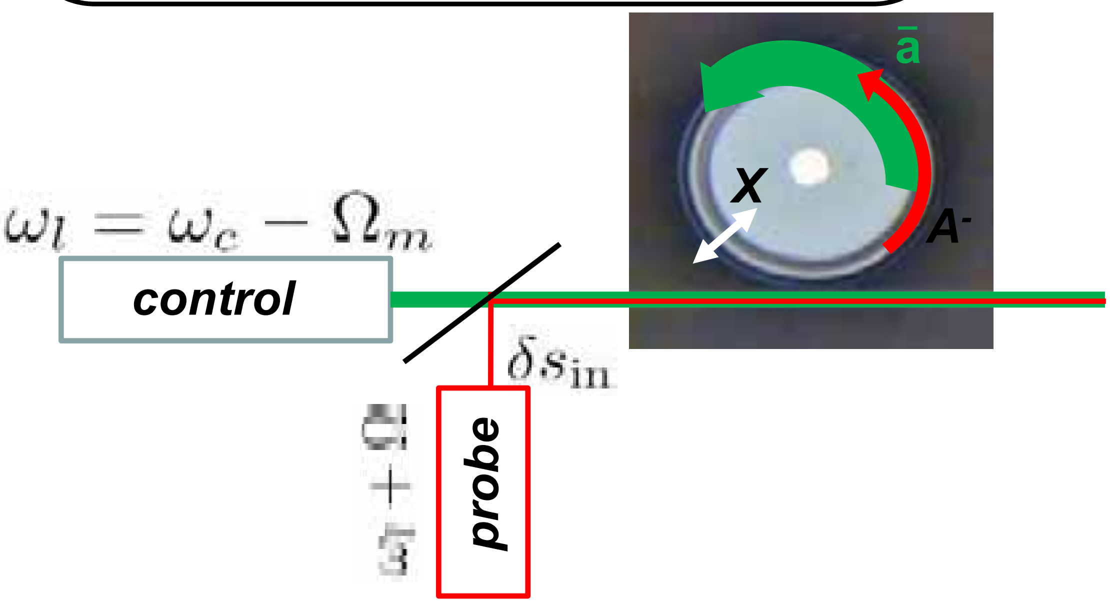
Zhang, Peng, Braunstein, PRA 68, 013808 (2003)
Schliesser, LMU PhD thesis (2009)
Agarwal, Huang, PRA 81, 041803 (2010)

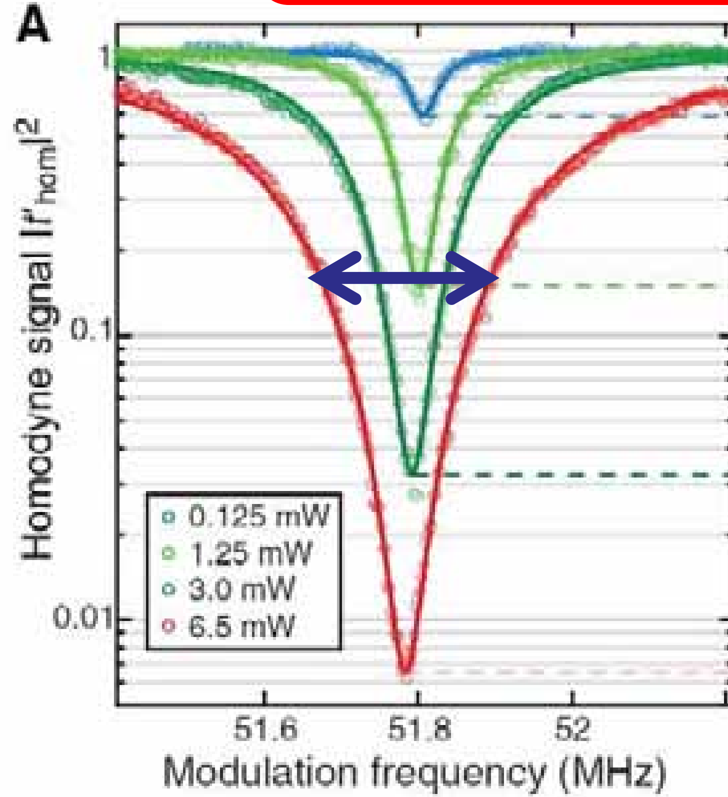
Optomechanically induced transparency (OMIT)





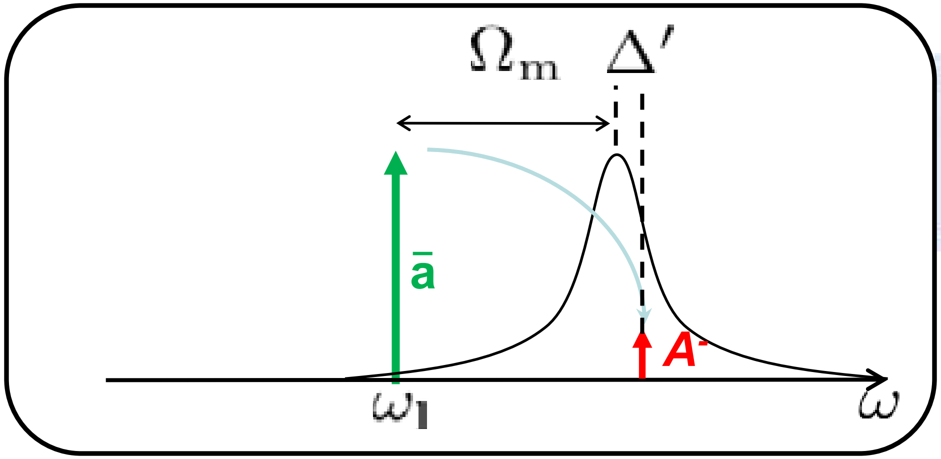
$$\Gamma_{eff} = \frac{(2g_0\bar{a})^2}{\kappa}$$

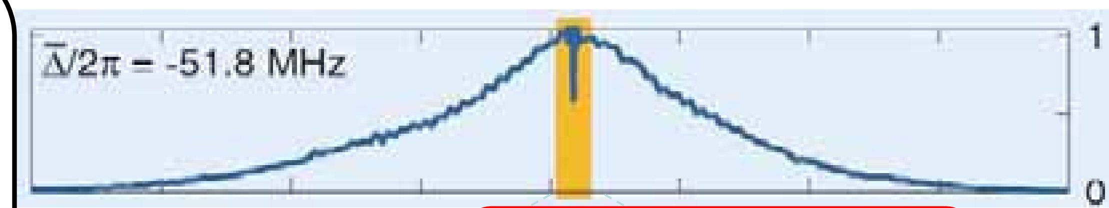




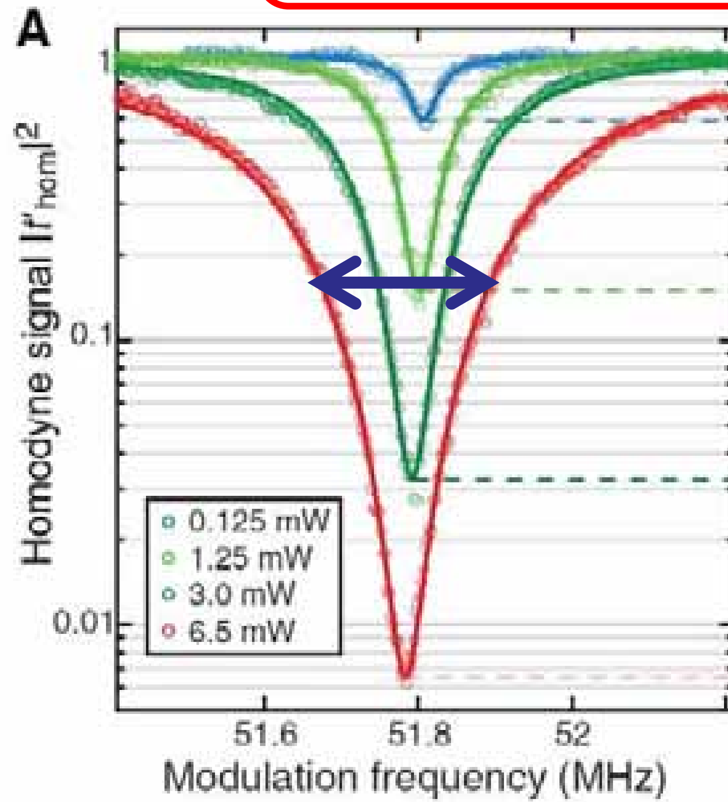
Zhang, Peng, Braunstein, PRA 68, 013808 (203)
Schliesser, LMU PhD thesis (2009)
Agarwal, Huang, PRA 81, 041803 (2010)
Weis et al. *Science* (2010)

Optomechanically induced transparency (OMIT)





$$\Gamma_{eff} = \frac{(2g_0\bar{a})^2}{\kappa}$$



Transmission

$$T(\omega = \omega_0) = \frac{C}{C+1}$$

Optomechanical cooperativity

$$C = \frac{4\,\bar{n}_p g_0^2}{\kappa\Gamma_m}$$

Zhang, Peng, Braunstein, PRA 68, 013808 (203)
Schliesser, LMU PhD thesis (2009)
Agarwal, Huang, PRA 81, 041803 (2010)
Weis et al. *Science* (2010)

Application of optomechanically induced transparency

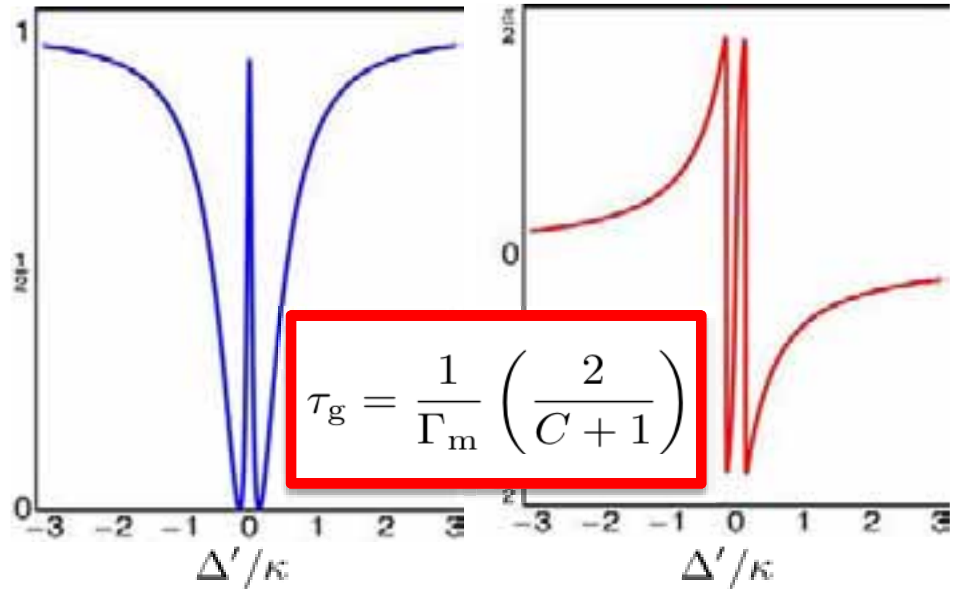
Strong nonlinearity, strong coupling

Intracavity pump photons required for *C*=1

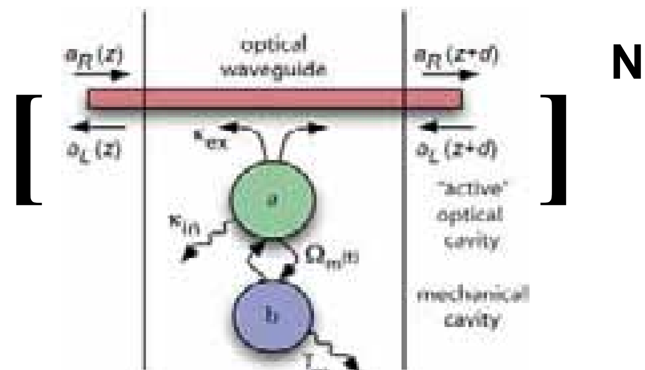
Reference	n
This work	20000
Optimized toroids*	1000
MW electromechanics	100
Integrated nanooptomechanics	10

See also
Gröblacher *et al.* Nature 460, 724 (2009)
Teufel *et al.* Nature 471, 204 (2011)

Tunable group delay



$$\tau_g = \frac{1}{\Gamma_m}\left(\frac{2}{C+1}\right)$$

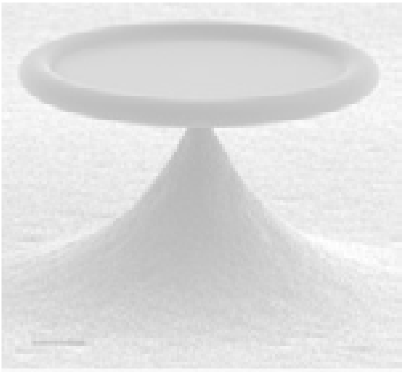


See also
Chang *et al.*, New Journal of Physics 13, 023003 (2011)
Safavi-Naeini *et al.*, Nature 472, 69 (2011)

Weis, Rivière, Deléglise, Gavartin, Arcizet, Schliesser, Kippenberg, *Science* 330, 1520 (2010)

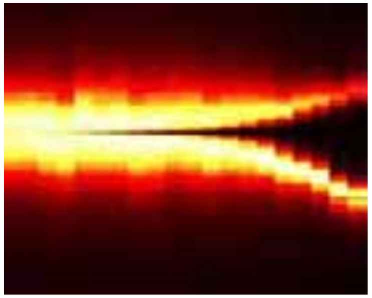
Outline

- Optomechanics with silica micro-toroids



- Optomechanically Induced Transparency

- Quantum-coherent coupling of mechanical and optical modes



Reaching the quantum coherent coupling regime

$$\gamma = \Gamma_m \bar{n}_m = \frac{k_B T}{\hbar Q}$$

<u>^{3}He cryostat</u>

- **Allows thermalization through** buffer gas
- **Reduced intrinsic losses below 1K**

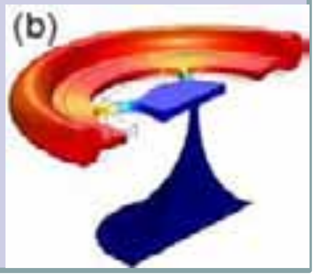
$$\Omega_c = 2 g_0 \bar{a}$$

$$g_0 = \frac{\omega}{R}\sqrt{\frac{\hbar}{2m\Omega_m}}$$

- **<u>Smaller structures:</u>**

  $\frac{\omega}{R}$ **increases, m is reduced but, increase of** Ω_m**, additional clamping losses**

<u>Optimized spokes design:</u>



Anetsberger et al. Nature Photonics 2009

Spoke supported microtoroid resonators

$$\Omega_c = 2 g_0 \bar{a}$$

$$g_0 = \frac{\omega}{R}\sqrt{\frac{\hbar}{2m\Omega_m}}$$

$$\gamma = \Gamma_m \, \bar{n}_m = \frac{k_B T}{\hbar Q_m}$$

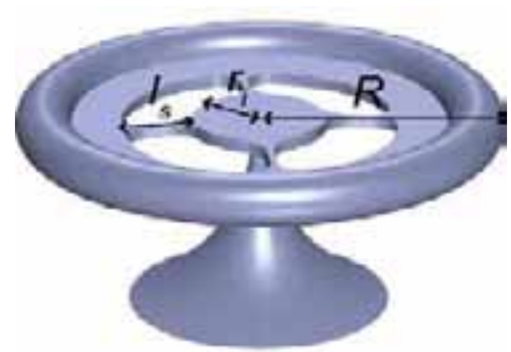
<u>Smaller structures:</u>

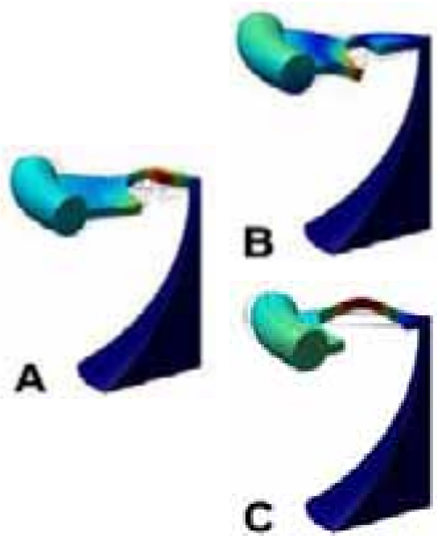
+ ω/R increases, m reduces

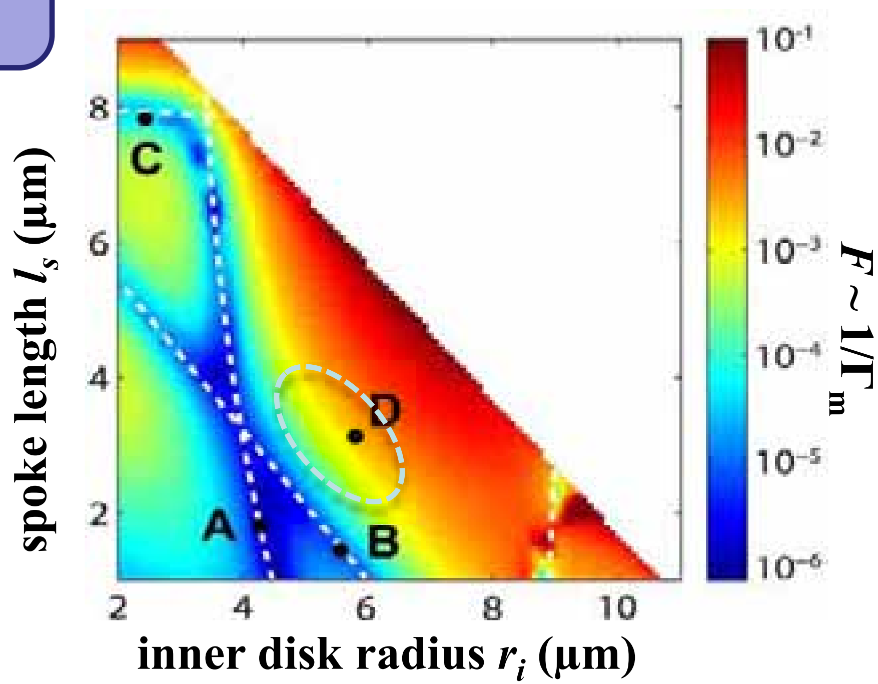
– Ω_m increases, larger clamping losses

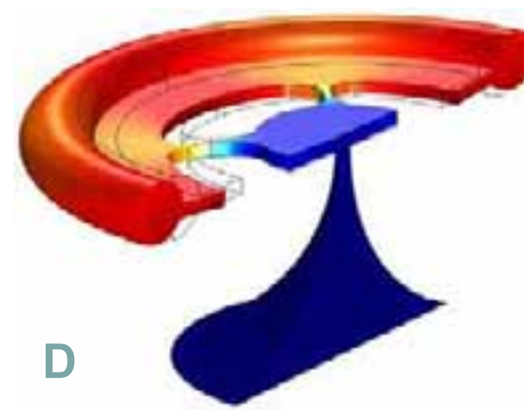
<u>Spokes-supported toroids:</u>

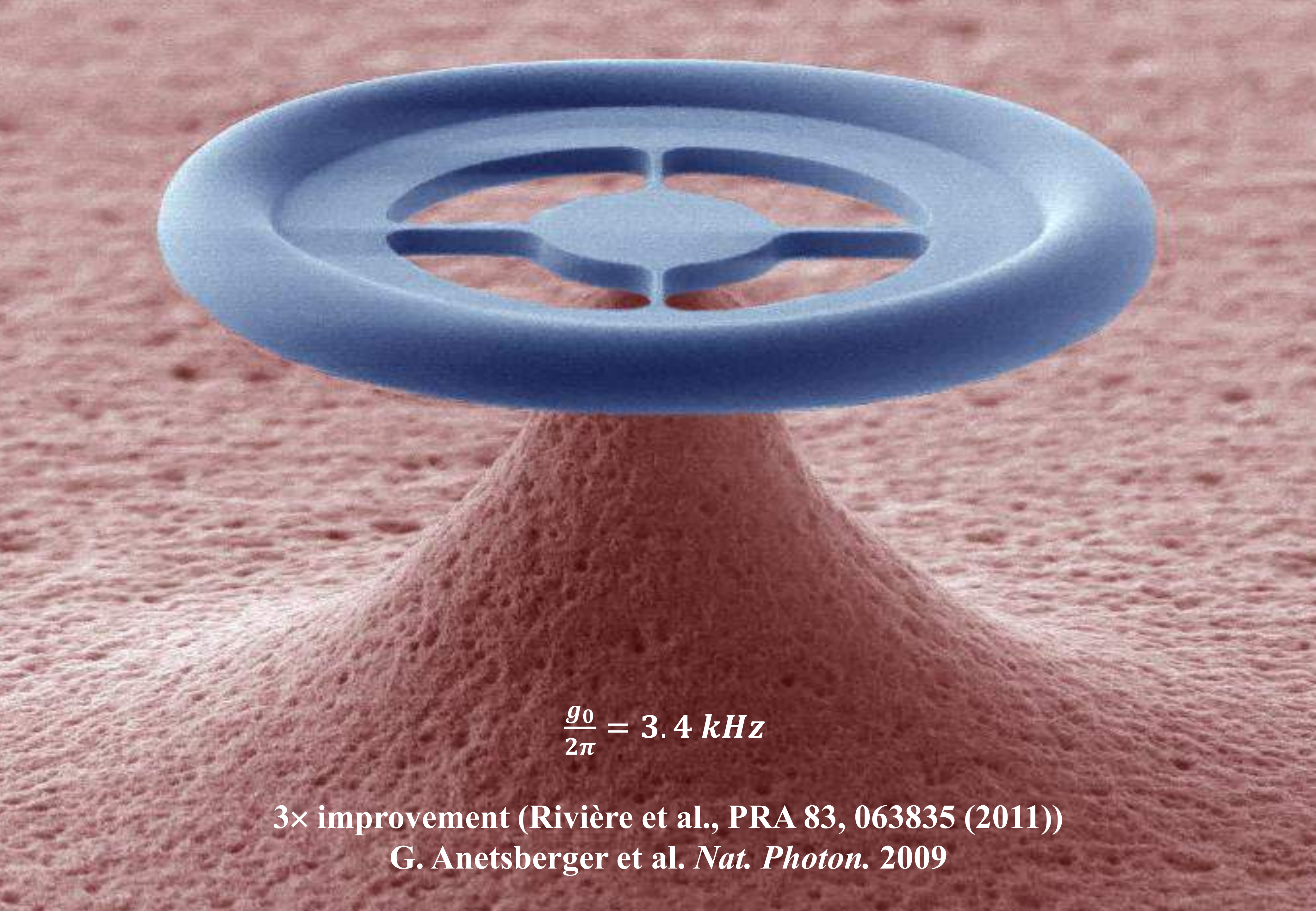
+ reduction of Ω_m and Γ_m

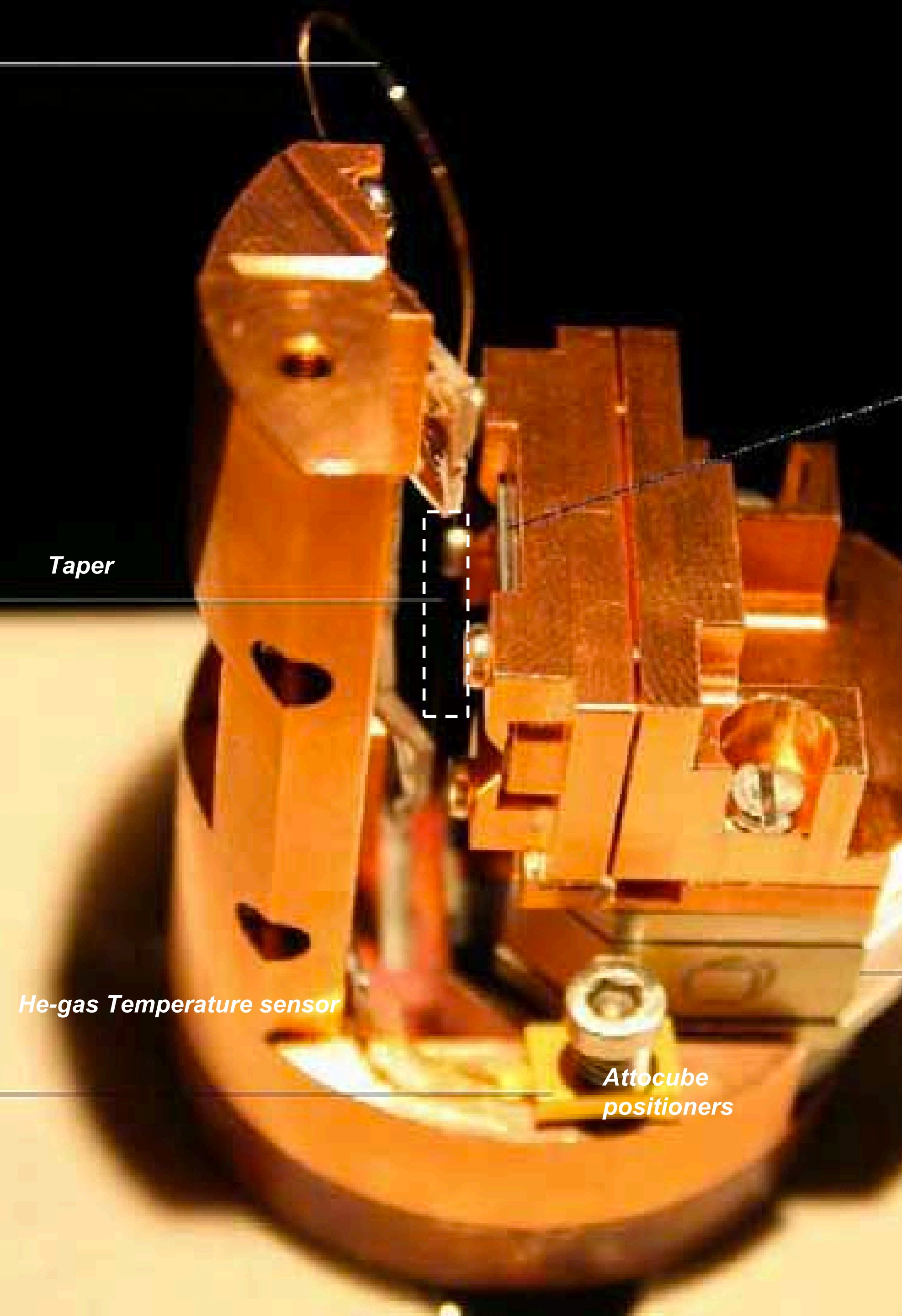


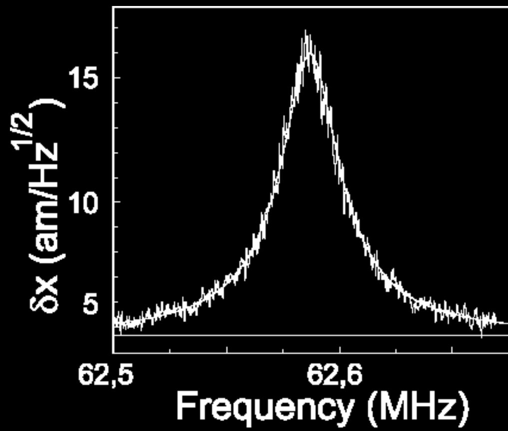







$\frac{g_0}{2\pi} = 3.4\ kHz$
3× improvement (Rivière et al., PRA 83, 063835 (2011))
G. Anetsberger et al. *Nat. Photon.* 2009

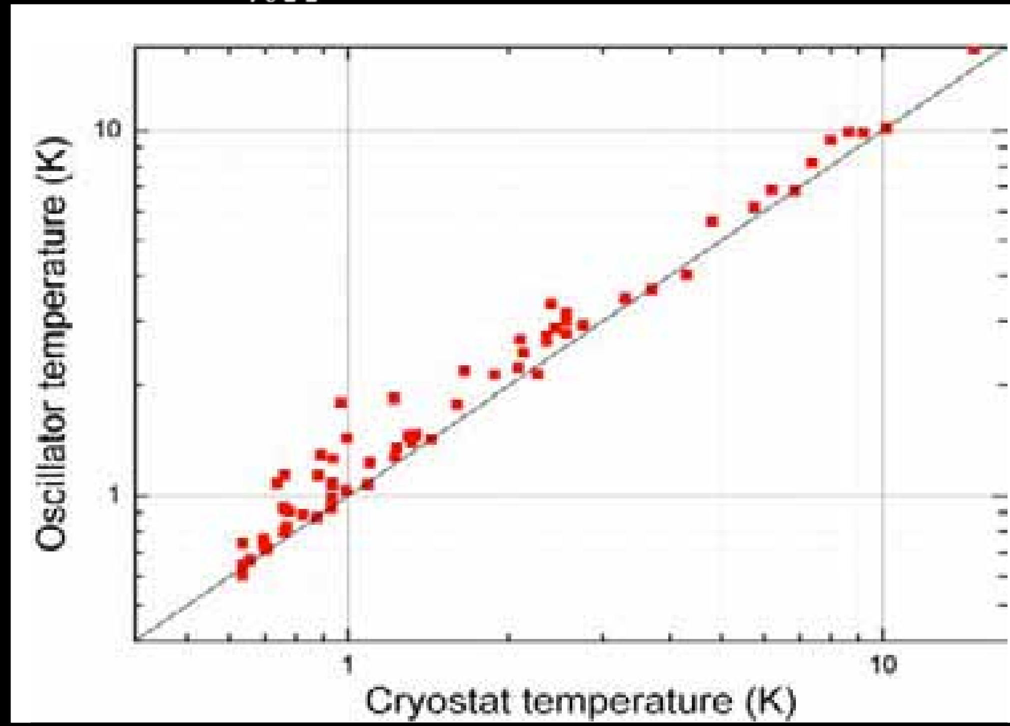




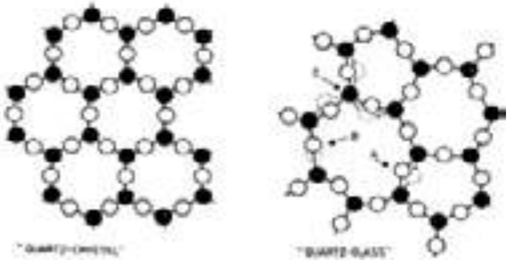
Characteristics Helium 3 Buffer gas cooling

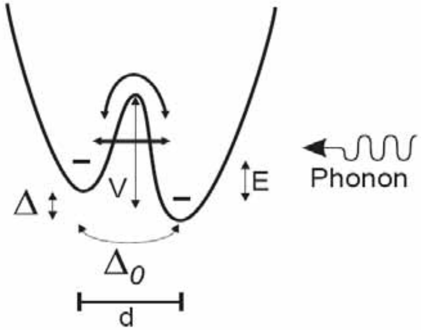
$$\Omega_m \approx 50 - 75\mathrm{MHz} \;\; T = 600\mathrm{mK}$$

$$n = \frac{k_B T}{\hbar\Omega} \approx 175 - 250$$



Dissipation due to two level systems (TLS)

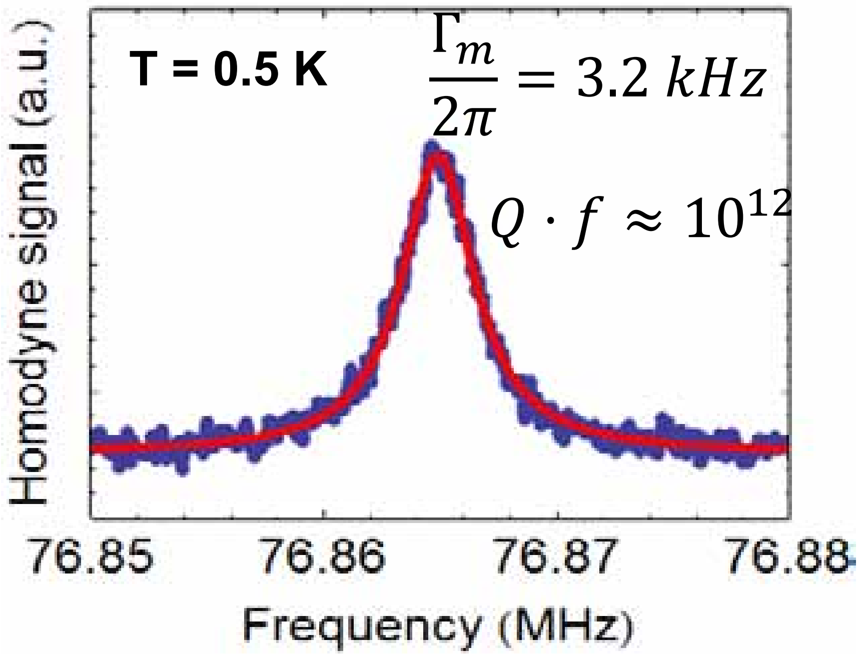


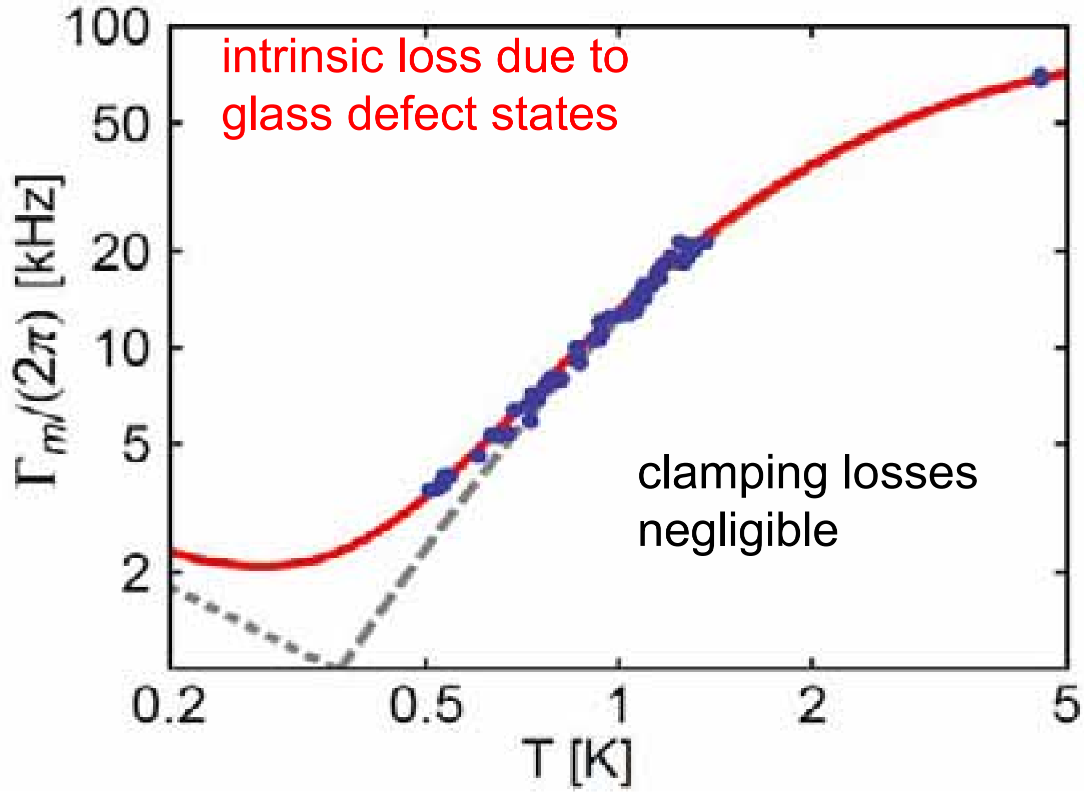


Anomalous Low-temperature Thermal Properties of Glasses and Spin Glasses

By P. W. Anderson†, B. I. Halperin and C. M. Varma

Bell Laboratories, Murray Hill, New Jersey 07974



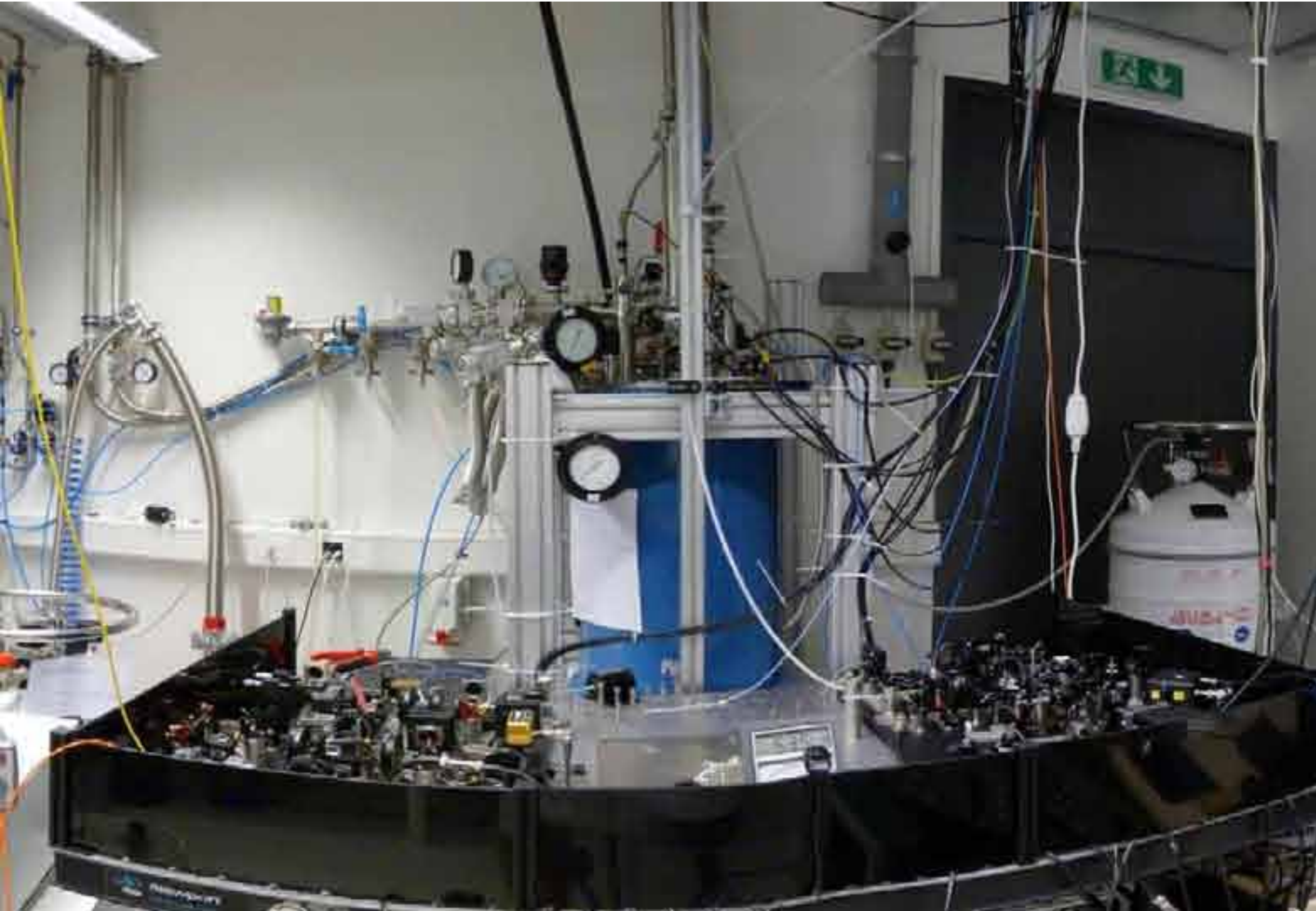


Observation of a purely TLS dominated losses in silica toroidal resonators

Vacher, Courtens, Forêt, PRB 72 214205 (2005)

Jäckle, Piché, Hunklinger, J. Non-Crys. Sol. 20 365 (1976)

O. Arcizet, R. Riviere, A. Schliesser, TJ Kippenberg PRA 2009

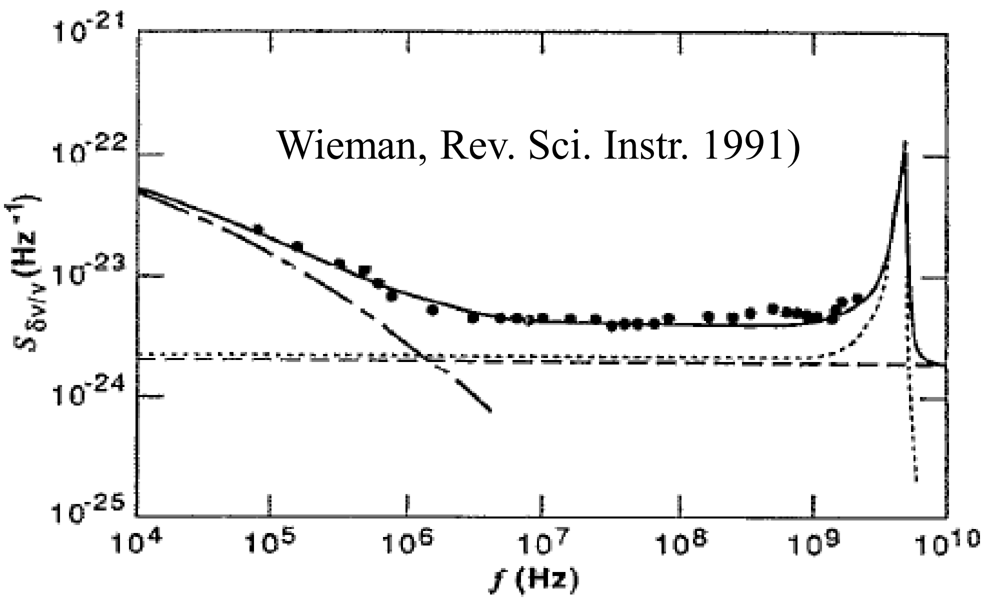


Achieving a „Cold“ photon bath: Laser phase noise

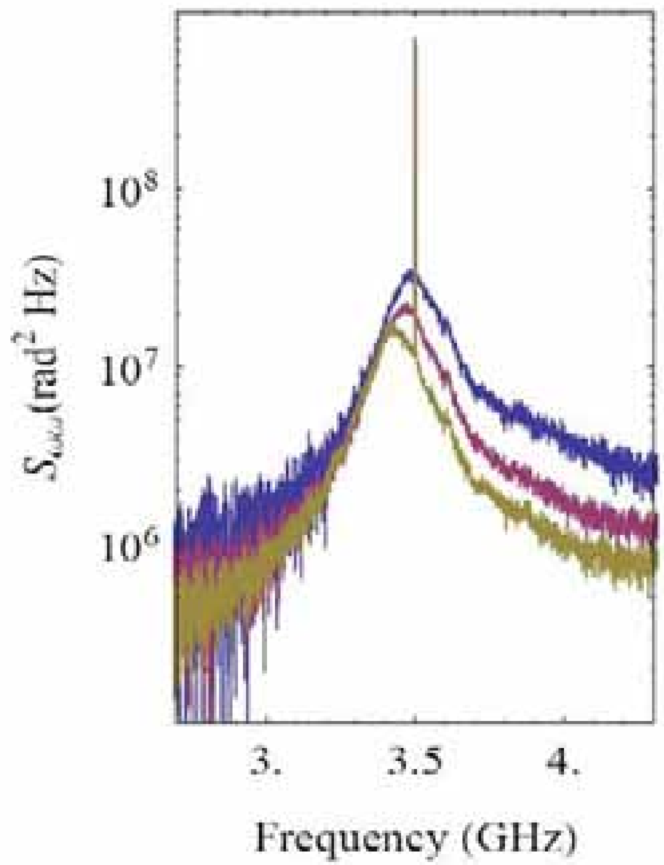
- Excess phase noise heats mechanical oscillator. The amount of tolerable phase noise for cooling to n=1

$$\boxed{S_{\omega\omega}[\Omega_m] = \frac{g_0^2}{\Gamma_m \bar{n}_m}}$$

- Chosen solution: TiSa laser system



New Focus *Diode Laser* frequency noise spectrum

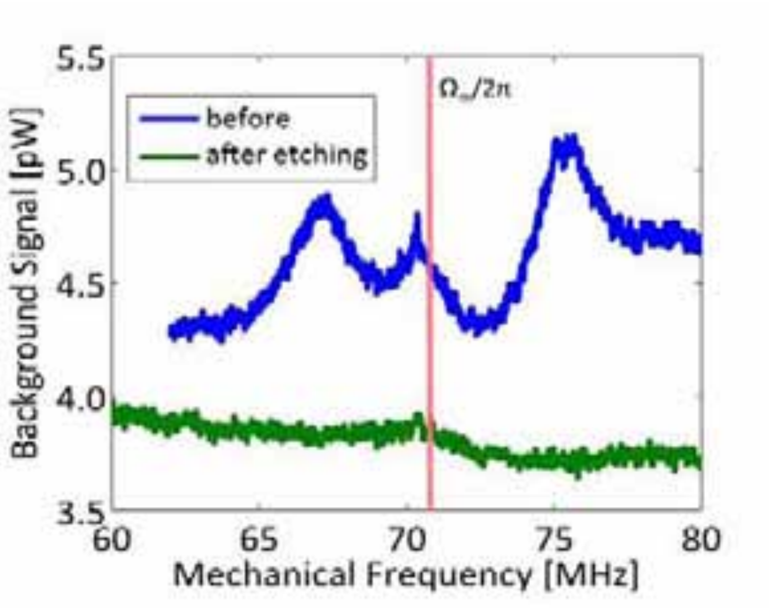


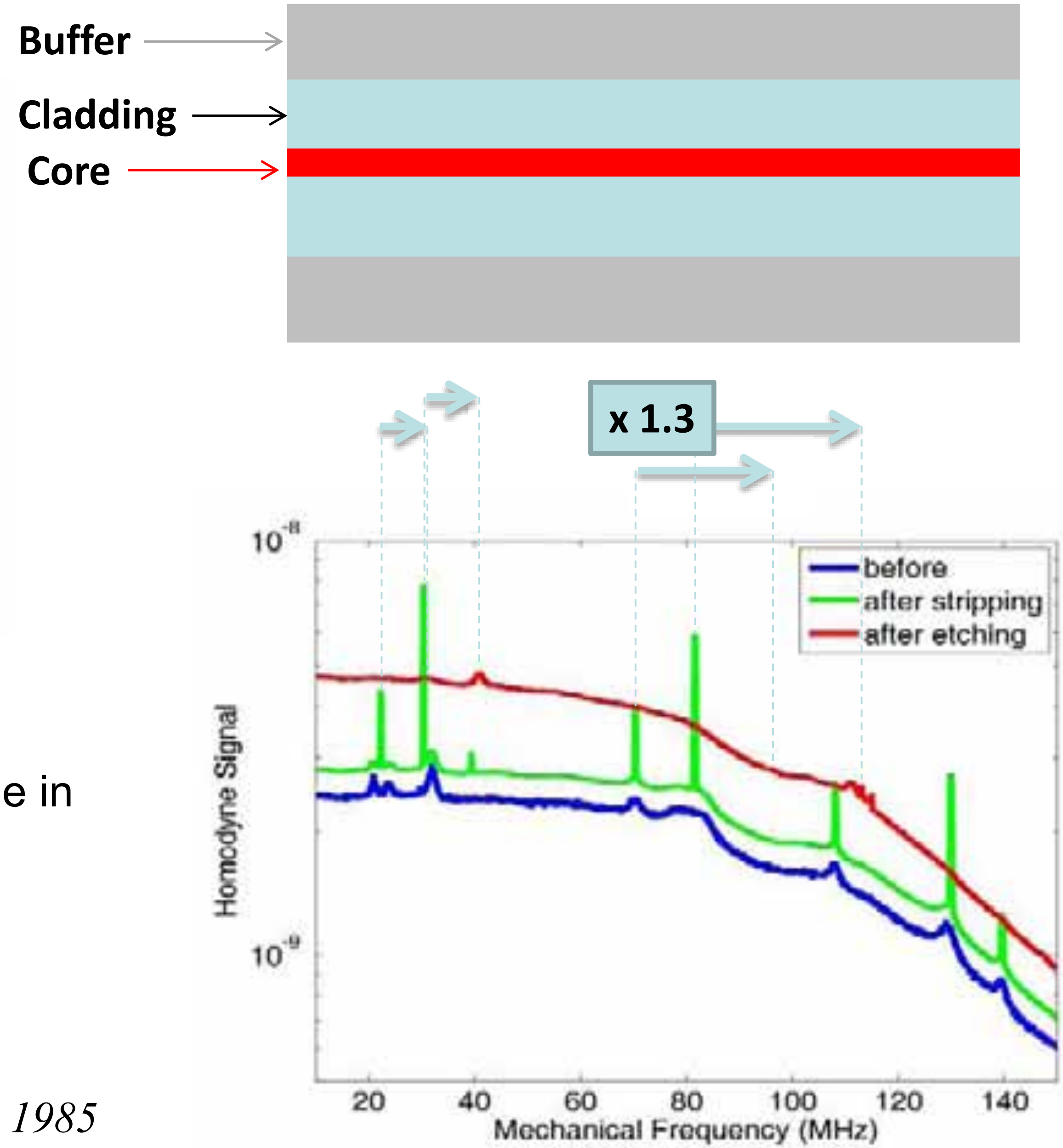
Kippenberg, Gorodetsky, Schliesser et al. arXiv:1112.6277

1. Schliesser, et al. Nature Physics 4, 415 (2008) [SUPPLEMENTARY INFO]
2. Diosi, PRA 78, 021801 (2008)
3. Rabl, Genes, Hammerer, Aspelmeyer, PRA 80, 063819 (2009)

Achieving a „Cold“ photon bath: Acoustic Modes of Fibers

- Homodyne signal

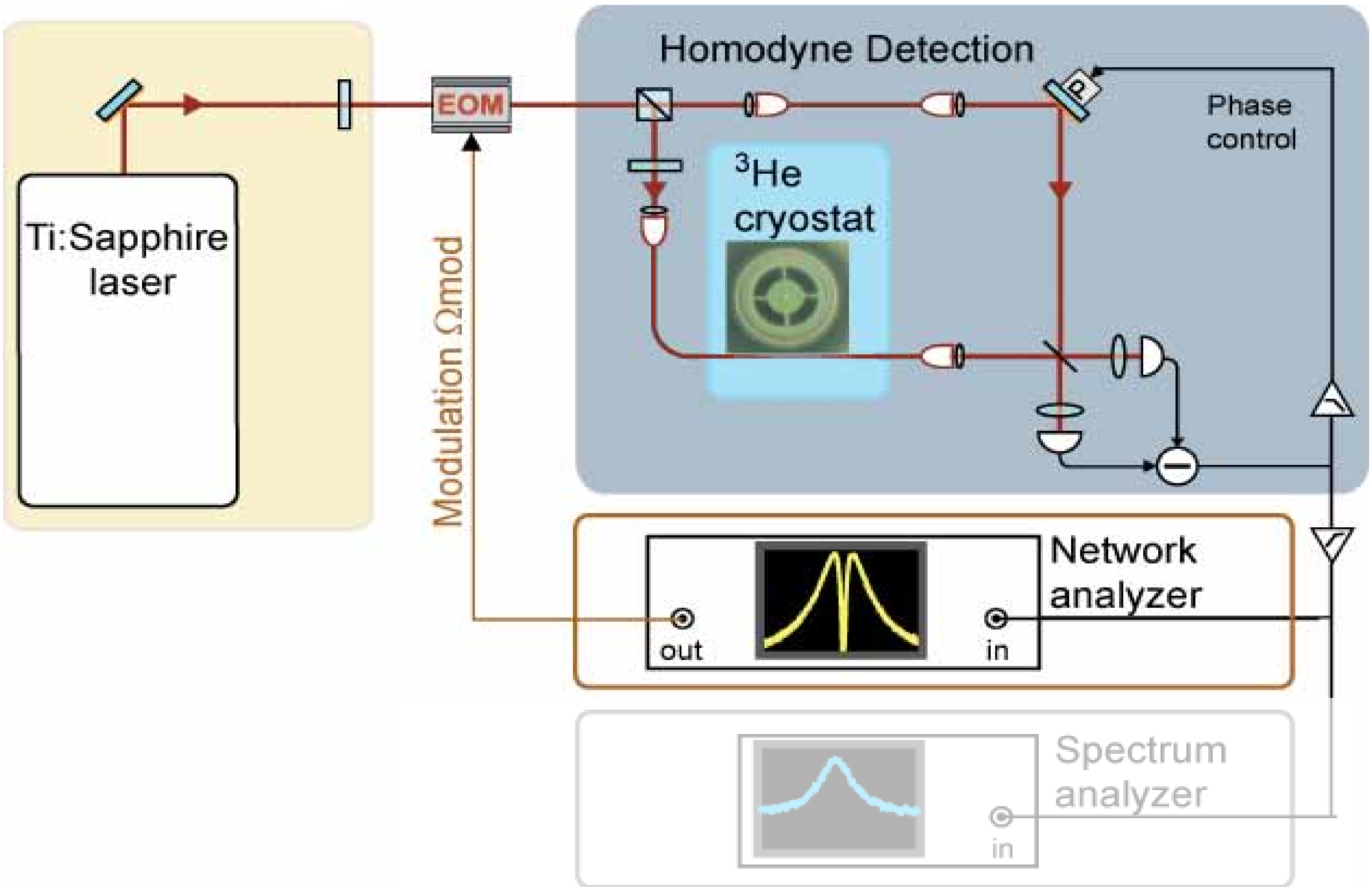




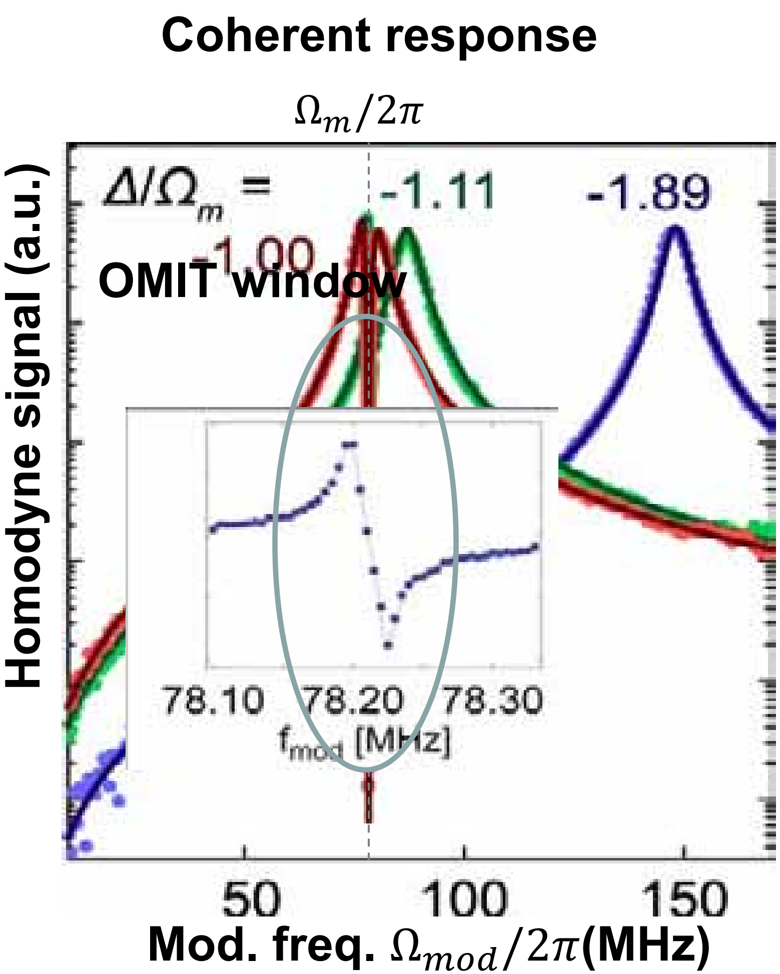
- Factor of 1.3 corresponds to change in diameter from 125µm to 95µm

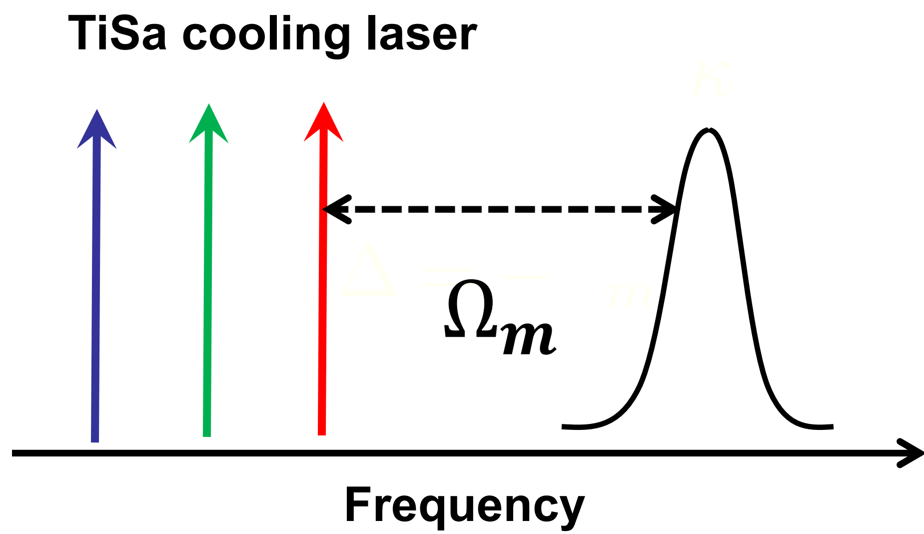
Shelby, Levenson, Bayer, *Phys. Rev. B 1985*

Experimental setup: coherent probing



Optomechanical cooling: coherent response



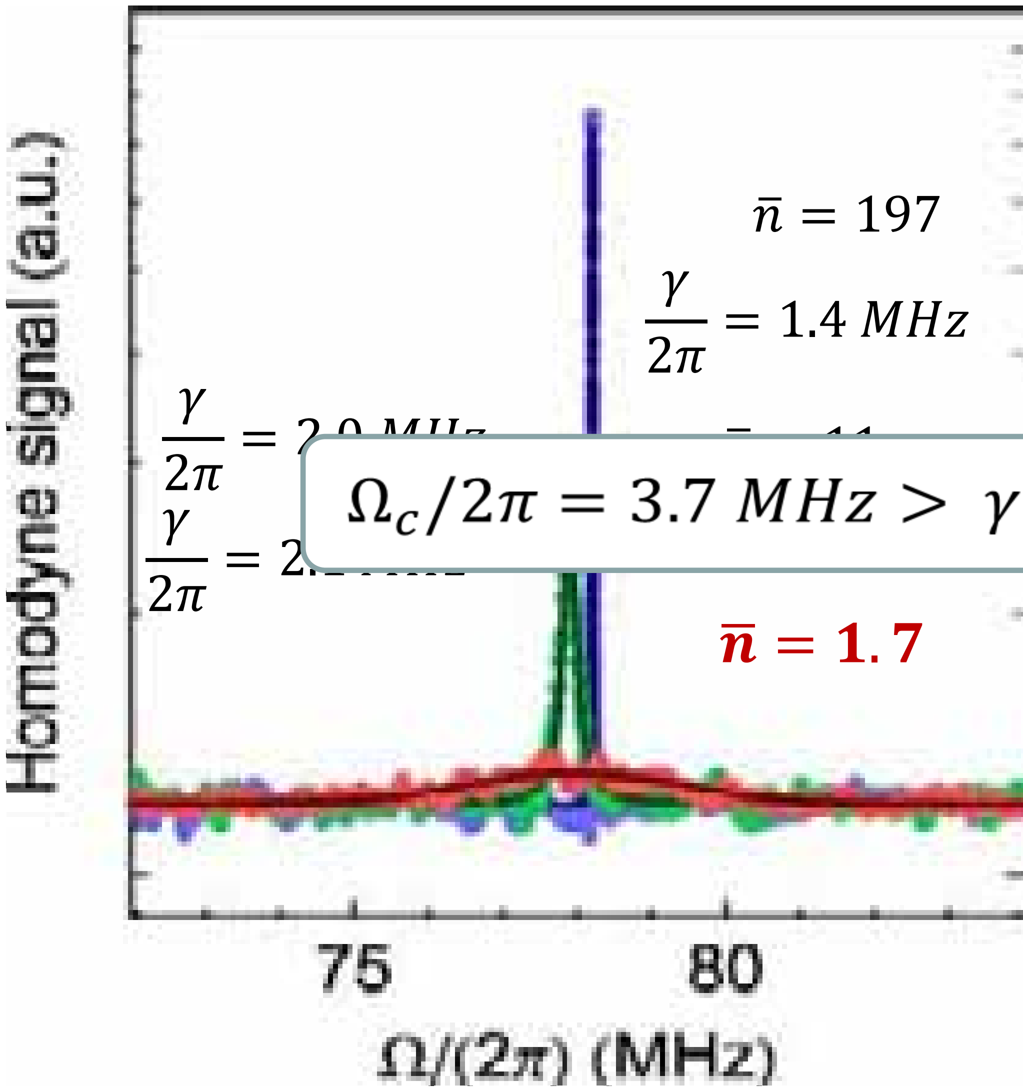


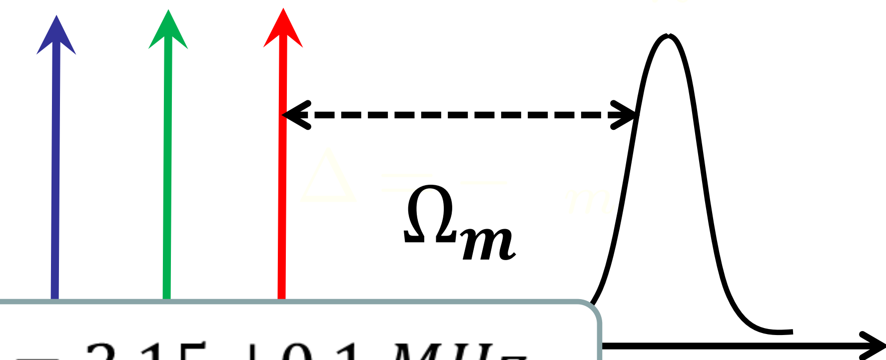
1) Determination of all parameters (Ω_c, κ, Δ ...)

2) Only amplitude of noise spectrum is used to derive the thermal fluctuations

(E. Verhagen et al. *Nature* 2012)

Optomechanical cooling: incoherent response



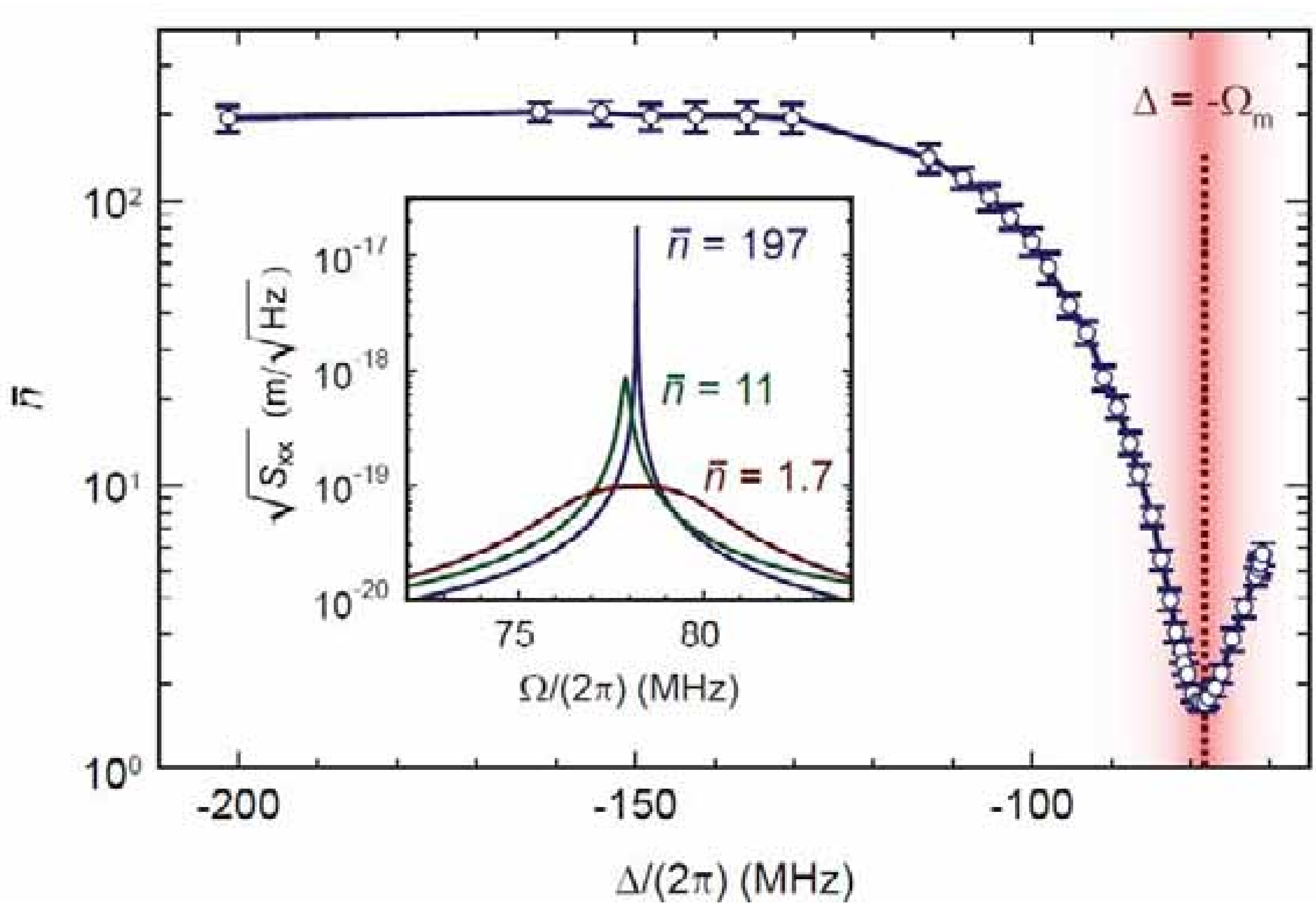


$$\Omega_c/2\pi = 3.7\ MHz > \gamma/2\pi = 2.15 \pm 0.1\ MHz$$

Laser Cooling of a macroscopic mechanical oscillator to ~37 % ground state occupation.

(E. Verhagen, S. Deleglise, S. Weis, A. Schliesser, TJK *Nature* 2012)

Optomechanical cooling: incoherent response

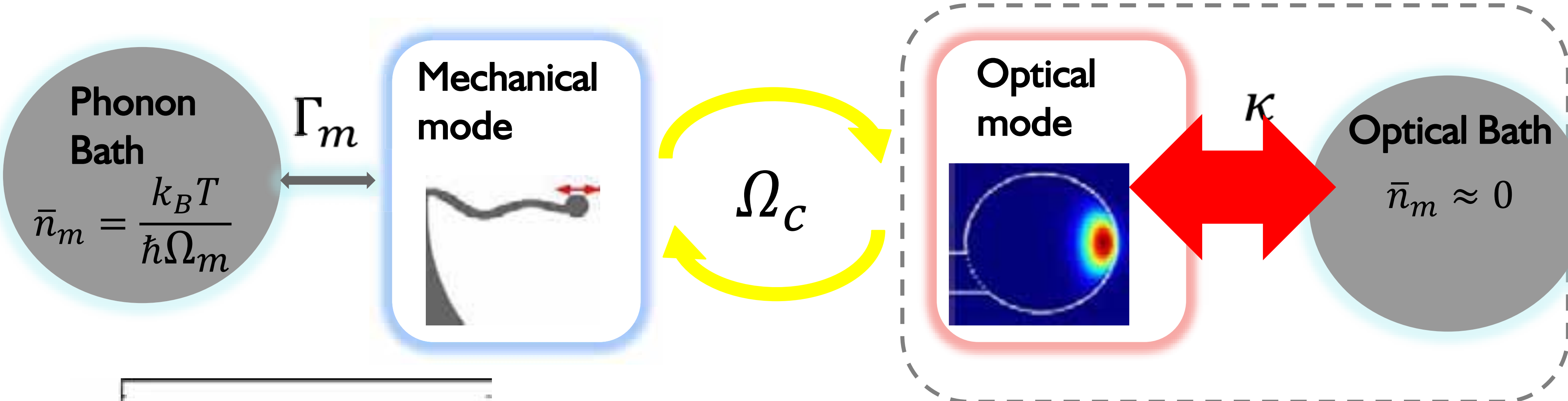


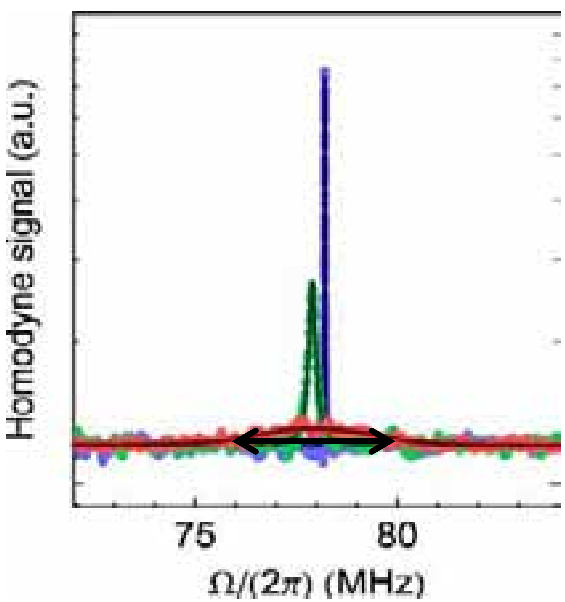
Laser Cooling of a macroscopic mechanical oscillator to ~37 % ground state occupation.

(E. Verhagen, S. Deleglise, S. Weis, A. Schliesser, TJK *Nature* 2012)

Optomechanical cooling in the weak coupling regime

$$\hat{H}_{int} = \hbar \frac{\Omega_c}{2} \left(\delta\hat{b}\delta\hat{a}^{\dagger} + \delta\hat{b}^{\dagger}\,\delta\hat{a} \right)$$





$$\Gamma_{eff} = \frac{4\Omega^2}{\kappa}$$

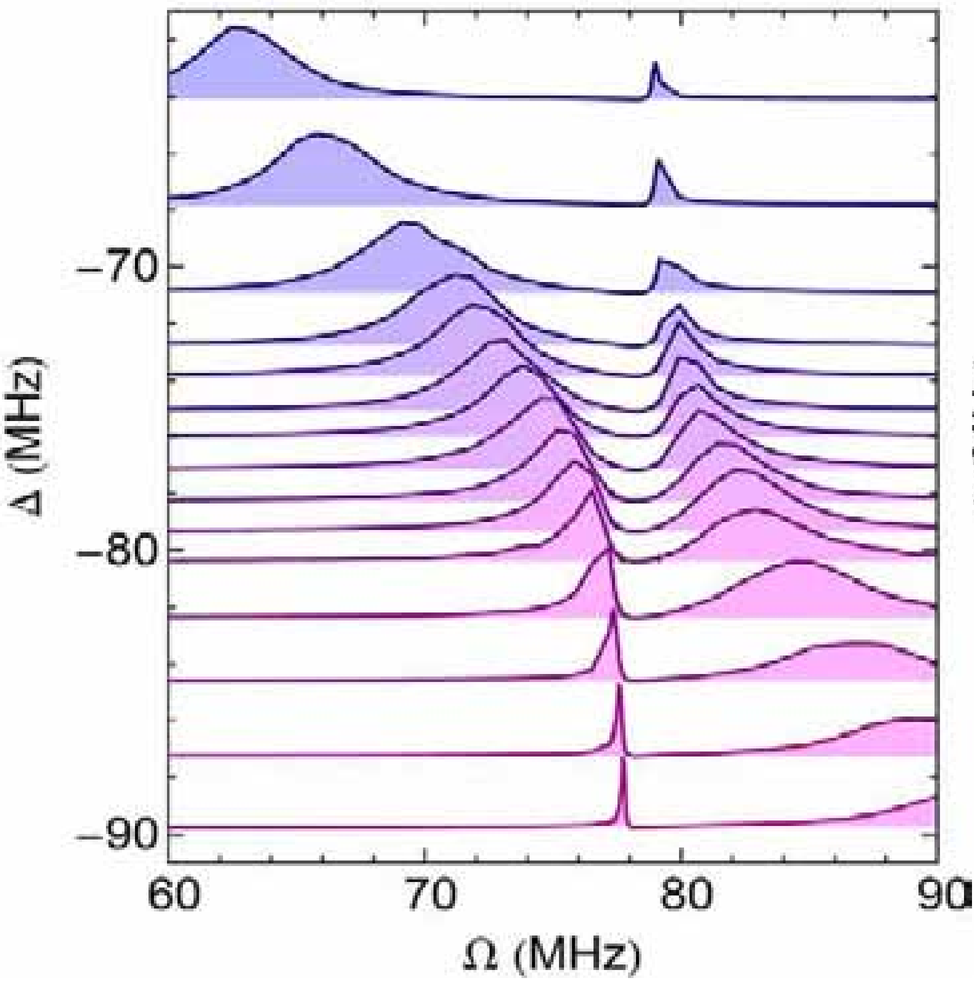
Optomechanical cooling rate

$\Gamma_{eff} = 2\pi \cdot 2.5\ MHz$ **yielding** $\bar{n} = 1.7$

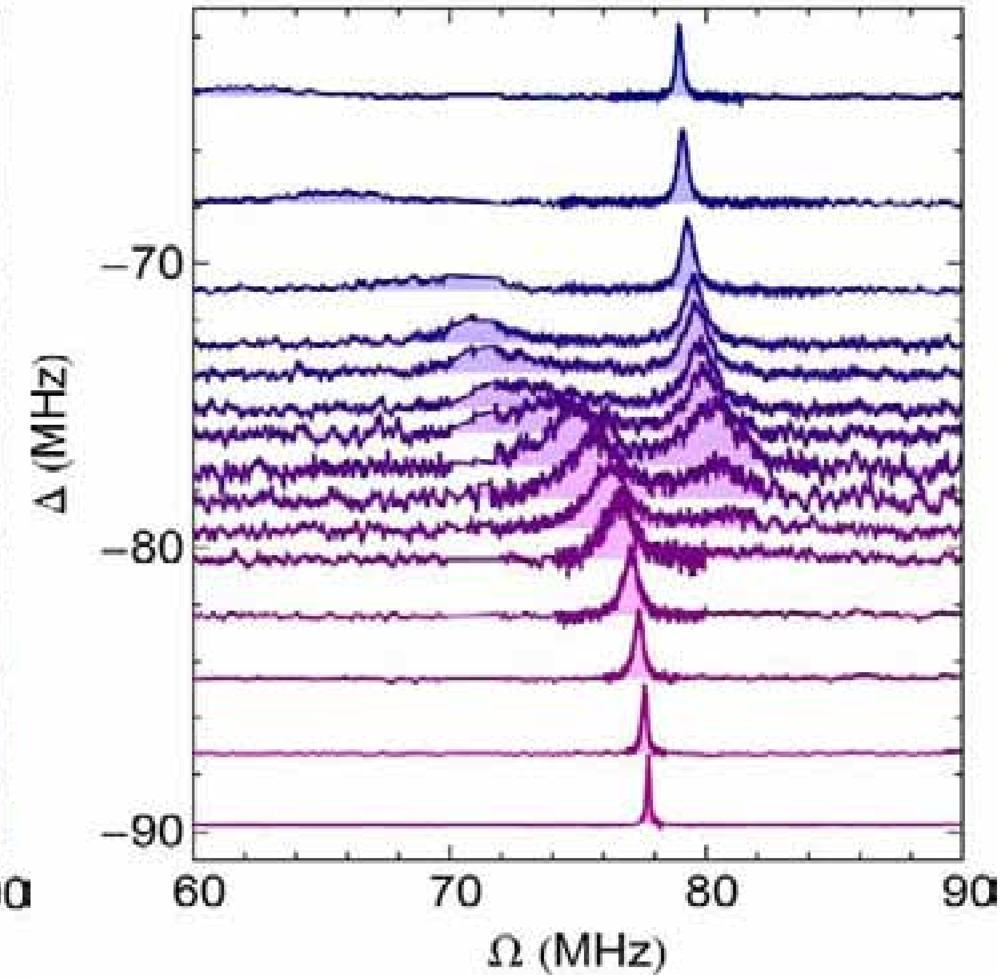
Wilson-Rae, Nooshi, Zwerger, Kippenberg, PRL 99, 093901 (2007)
Marquardt, Chen, Clerk, Girvin, PRL 99, 093902 (2007)

Quantum coherent coupling

- Optical domain:

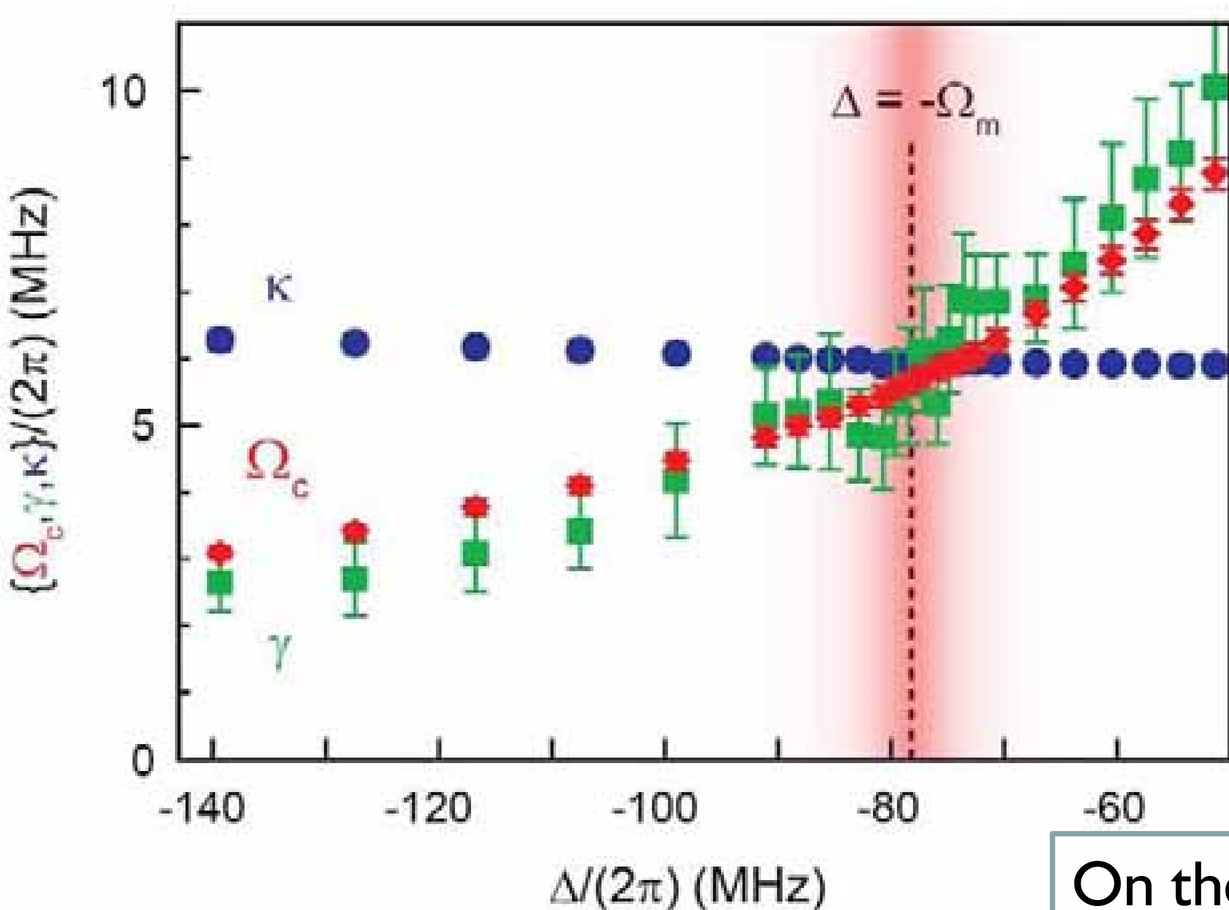


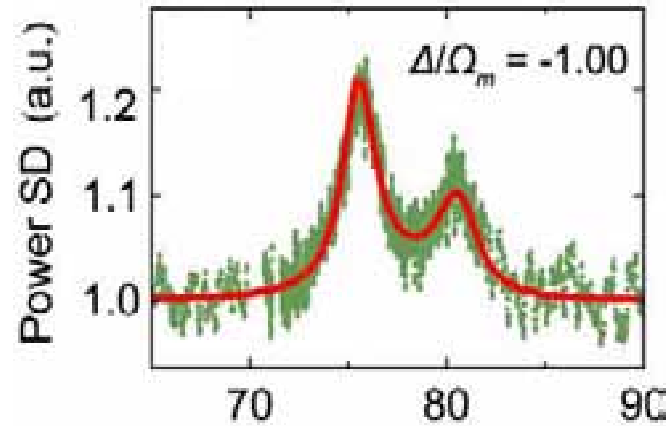
- Mechanical domain:



Verhagen, Deleglise, Weis, Schliesser et al. (*Nature*, 2012)

Quantum coherent coupling





On the lower mechanical sideband:

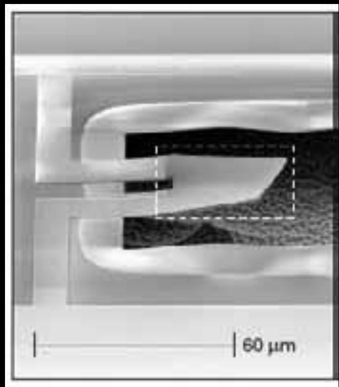
$$\Omega_c = 2\pi\ 5.7\ MHz$$
$$\gtrsim \gamma = 2\pi\ 5.6 \pm 0.9\ MHz$$

Quantum coherent coupling reached:

$$\Omega_c > (\gamma, \kappa)$$

Verhagen, Deleglise, Weis, Schliesser et al. (*Nature*, 2012)

Quantum Coherent coupling regime: $2g > \gamma, \kappa$



2010

$_m = 5\mathrm{GHz}$

Microwave piezo-mechanical oscillators

$\bar{n}_m << 1$

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

2011

$_m = 10\mathrm{MHz}$

Dynamical backaction *microwave* cooling

$\bar{n}_m \approx 0.34$

$2g > (\Gamma_m \bar{n}_m, \kappa)$

Teufel et al. (*Nature* 2011)

$_m = 75\mathrm{MHz}$

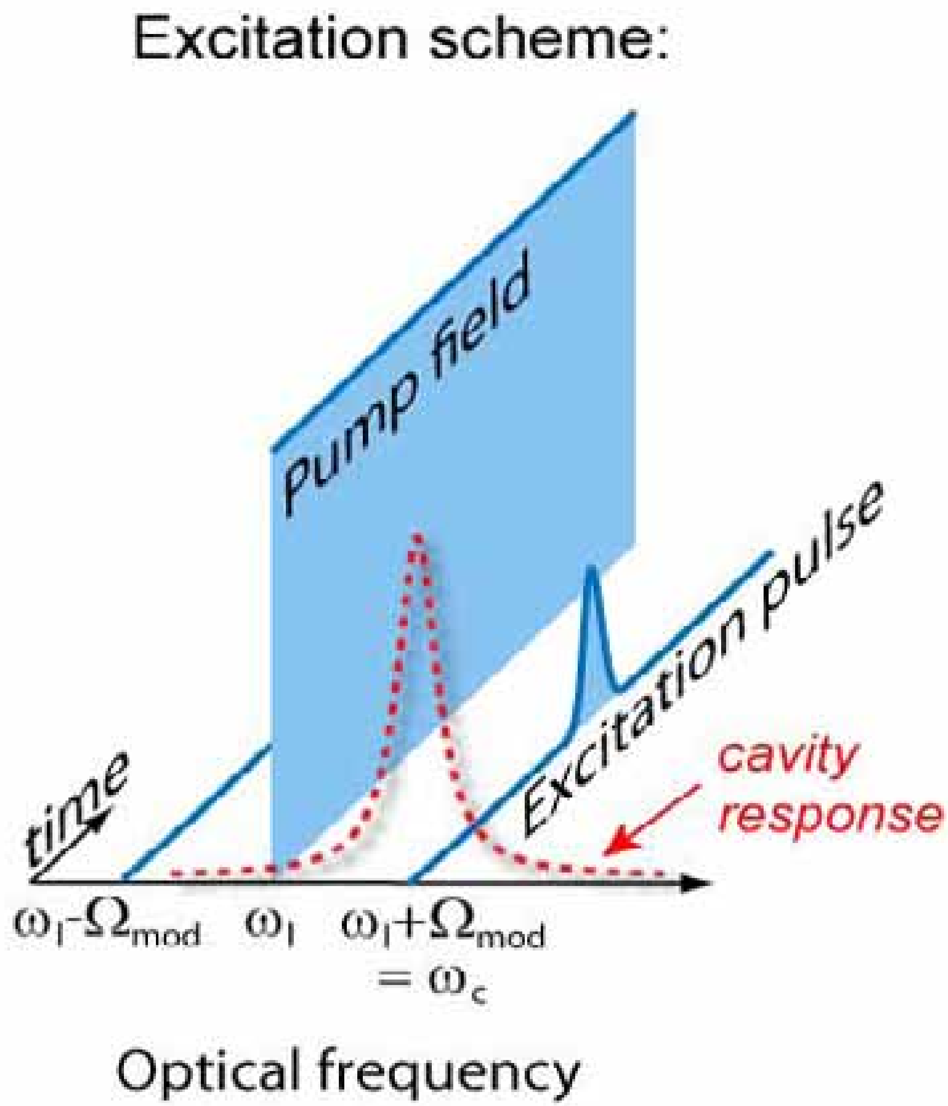
Dynamical backaction *optical* laser cooling

$\bar{n}_m = 1.7$

$2g \gtrsim (\Gamma_m \bar{n}_m, \kappa)$

Verhagen, Schliesser, Deleglise, Weis et al. (*Nature* 2012)

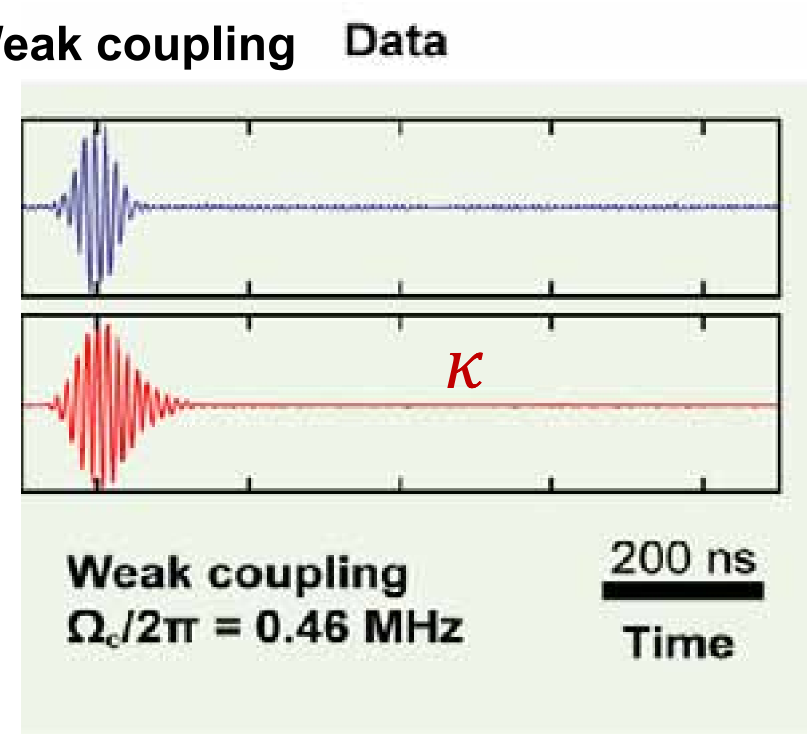
Energy exchange in time domain



Verhagen, Deleglise, Weis, Schliesser et al. *Nature* 2012

Energy exchange in time domain

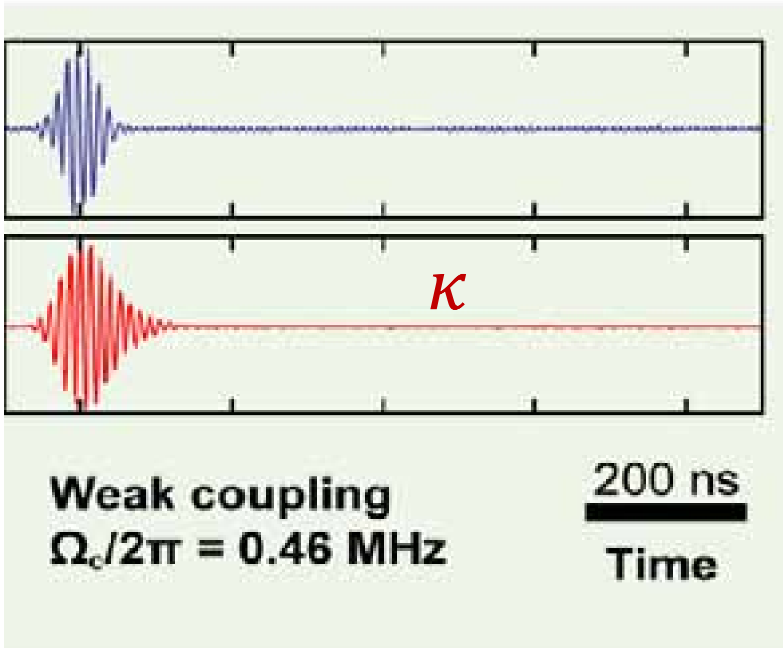
Weak coupling



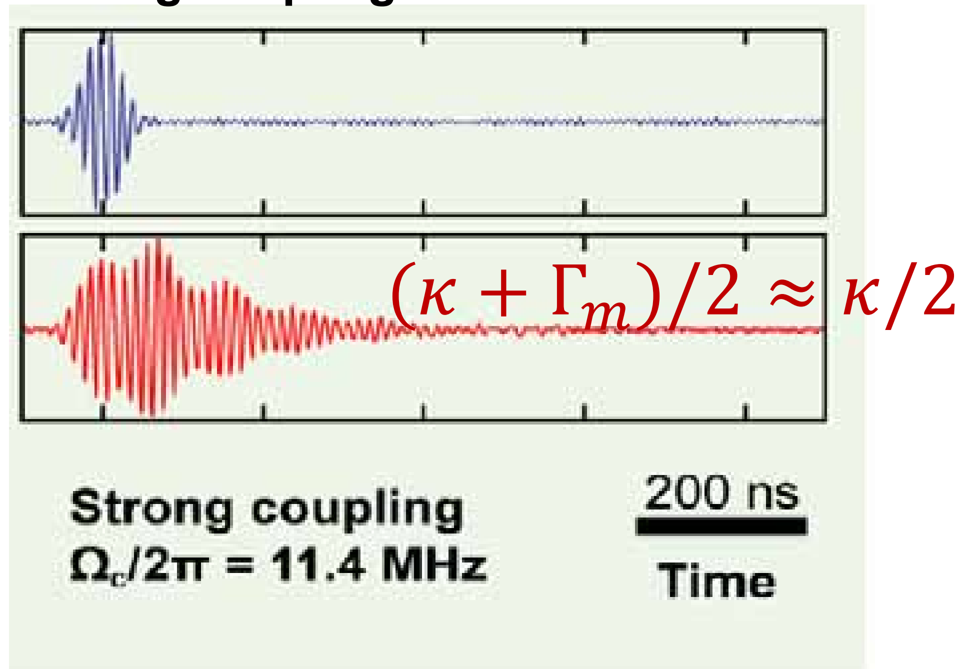
Verhagen, Deleglise, Weis, Schliesser et al. *Nature* 2012

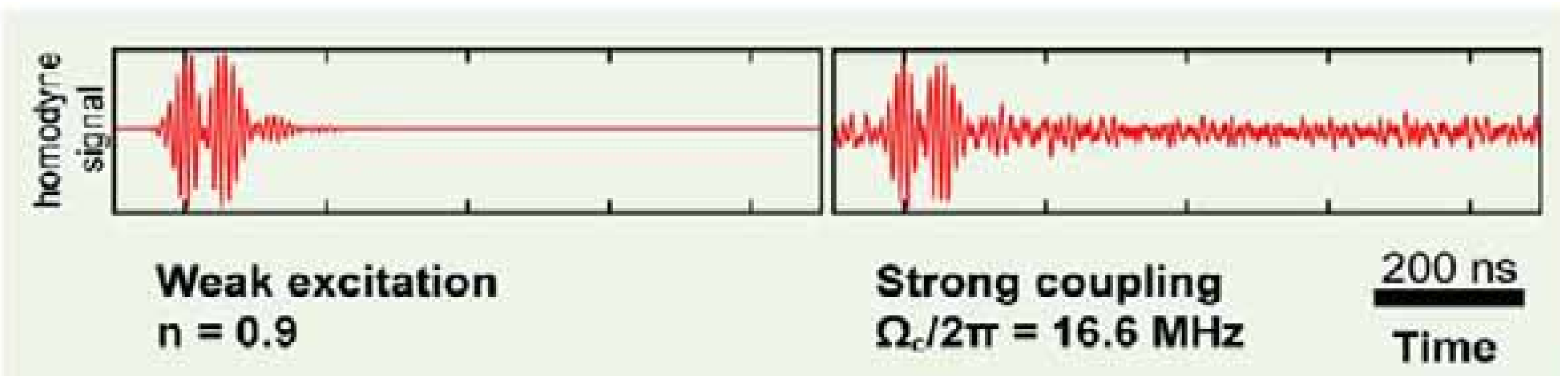
Energy exchange in time domain

Weak coupling Data



Strong coupling

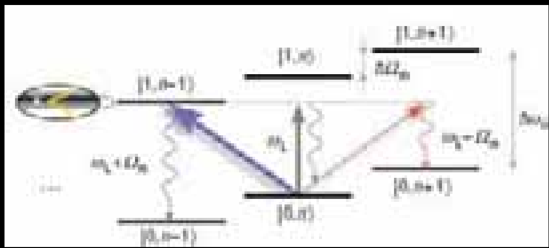




Verhagen, Deleglise, Weis, Schliesser et al. *Nature* 2012

Summary

Sideband Cooling

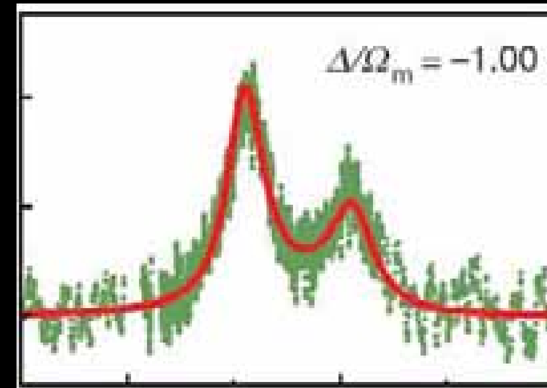


Schliesser et al. Phys. Rev. Let. 2006
Wilson-Rae, Phys. Rev. Lett. 2007
Schliesser et al. Nat. Phys. (2008)

Low dissipation optomechanics

Anetsberger et al. Nat. Phot. 2, 627 (2008)

Quantum coherent coupling

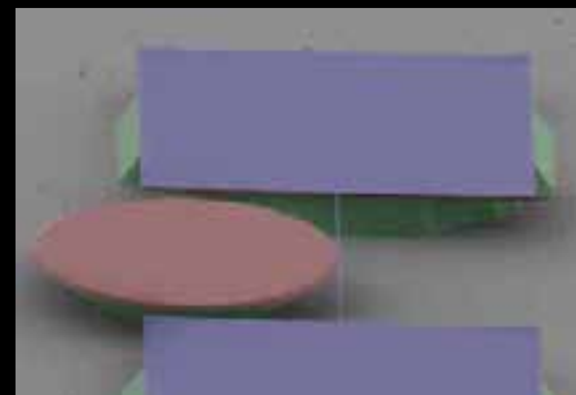


Verhagen, Deleglise, Weis, Schliesser, TJK Nature (2012)

Future directions of optomechanics

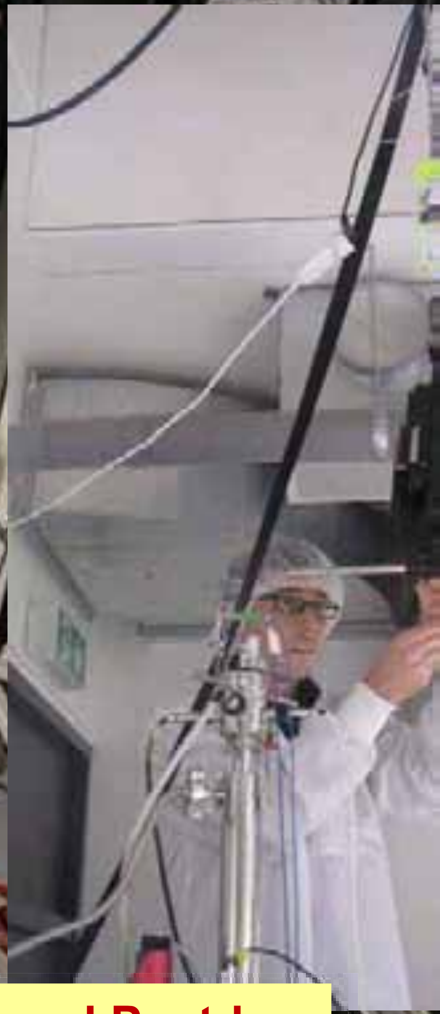
- **Quantum transducers between optical fields and other degrees of freedom**
- **Quantum measurements on a mechanical oscillator in the quantum regime**
- **Optomechanical transducers**

Transducers:



E. Gavartin, P Verlot TJK
http://arxiv.org/abs/1112.0797
Nat. Nanotech (in press)

Postdoc/ PhD position available at EPFL



He-3 Team: Ewold Verhagen, Vivishek Sudhir, Nicolas Piro

Former members: Samuel Deleglise, Olivier Arcizet, Albert Schliesser

ITN - PhD and Postdoc position available.