# Cavity optomechanics using microresonators

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**&**
**2) Independent Max Planck Junior Research Group Leader**
**MPQ, (Division of T. W. Hänsch)**

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MPQ

**College de France, Paris, 18th January 2010**

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R. Holtzwarth (Menlo System)

MAX-PLANCK-GESELLSCHAFT
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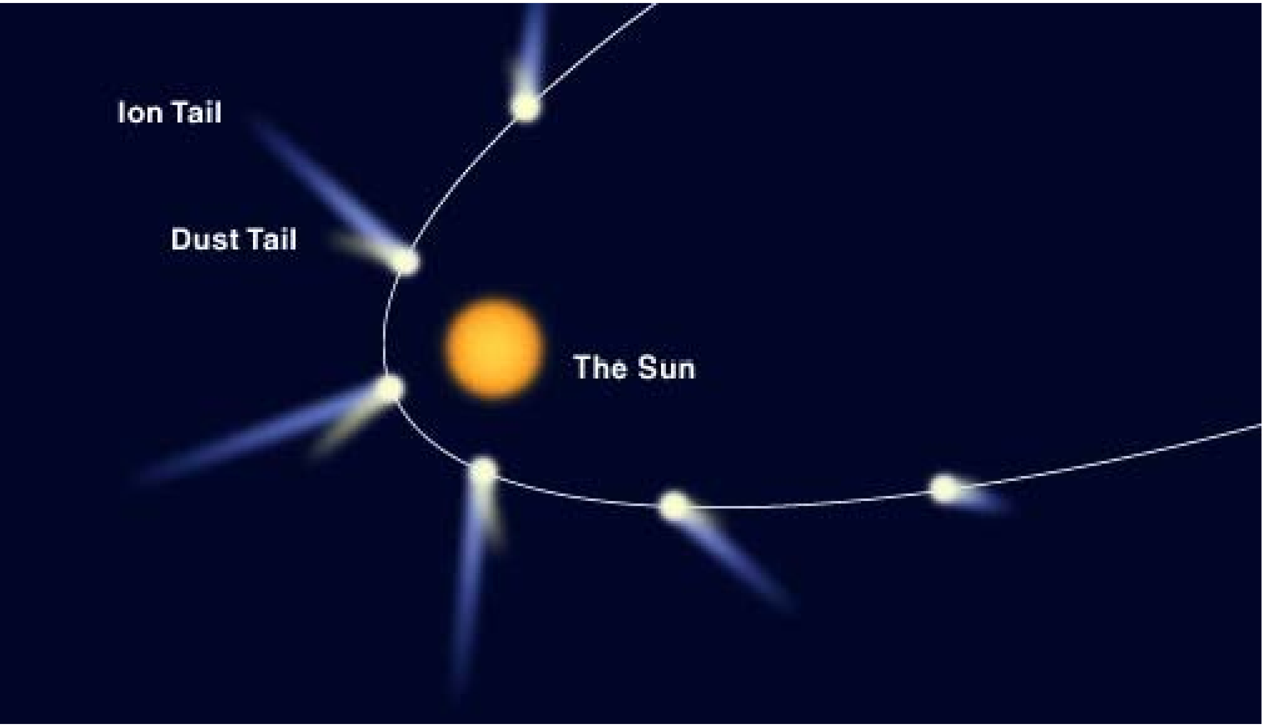
DFG
Nanosystems Initiative Munich
nanoscience Europe NanoSci-ERA

**MP-IJRG** **ERC StG** **MC-EXT** **DFG-NIM** **GSC** **MC-IRG/IEF** **NanoSci-ERA**

# Mechanical Effects of Light




**Photons carry momentum which leads to *radiation pressure***

$$p = \hbar \cdot k$$

**In the 16th century Keppler proposed that radiation pressure is responsible for comet tails pointing away from the sun**

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# Mechanical Effects of Light on Atoms

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

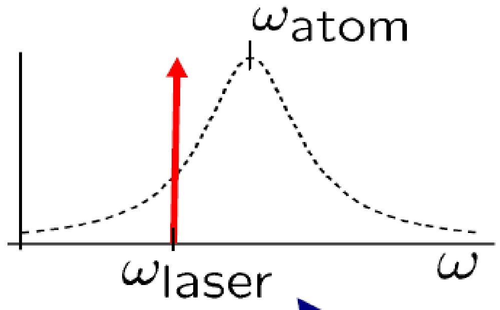
**1950: Kastler "Effet luminorefrigorifique et luminocalirofique"**

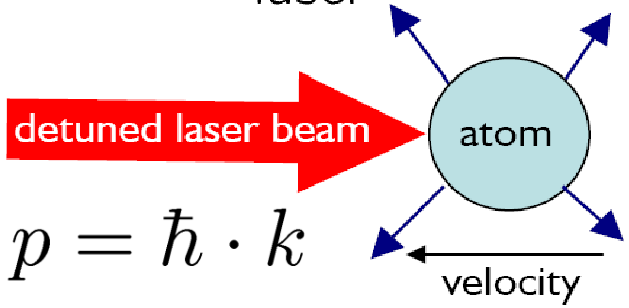
**1970: Ashkin Trapping of Particles in Laser Light**

**1975 Hänsch and A. Schwalow, Dehmelt and Wineland "Cooling gases by laser radiation"**

**1989: "Laser Cooling to the Zero Point Energy of Motion" (Wineland)**

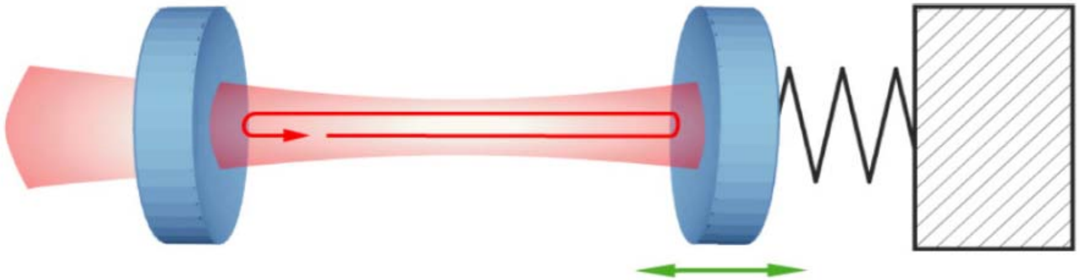
**.....**




$$p = \hbar \cdot k$$

**Is it also possible observe radiation pressure effects on mesoscopic system?**



Studied first by Braginsky, Manukin (1967)

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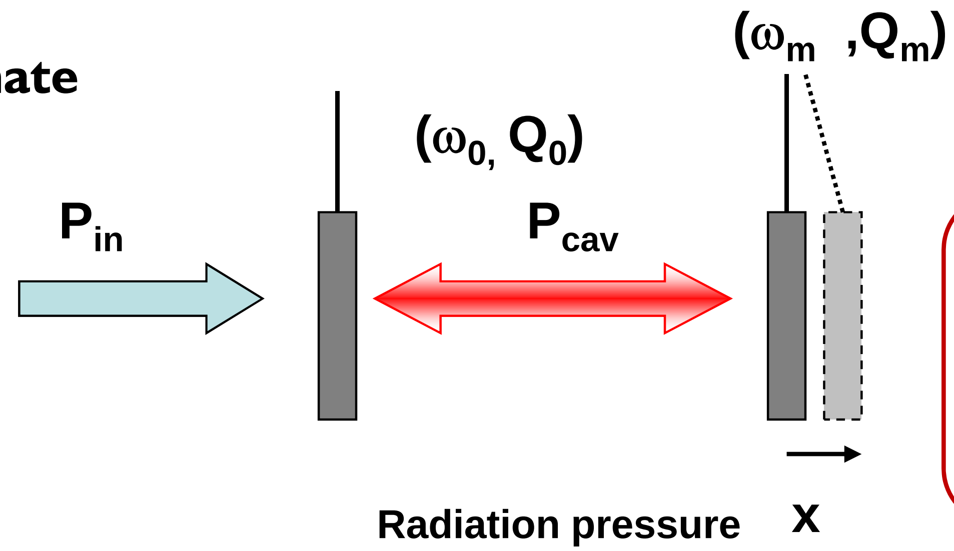
Braginsky, Manukin: *Measurement of Weak Forces in Physics Experiments* (1977)

# Principle of parametric motion transduction

**Radiation pressure determines the ultimate sensitivity of an interferometer**

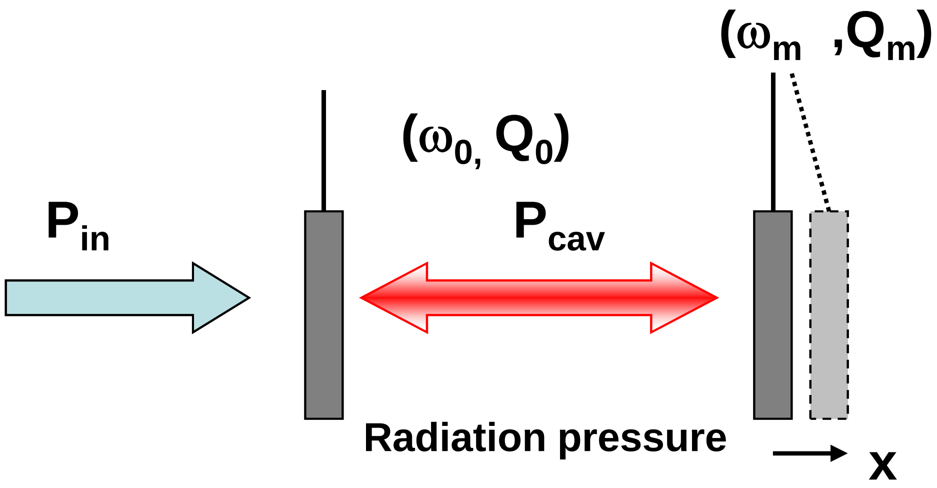


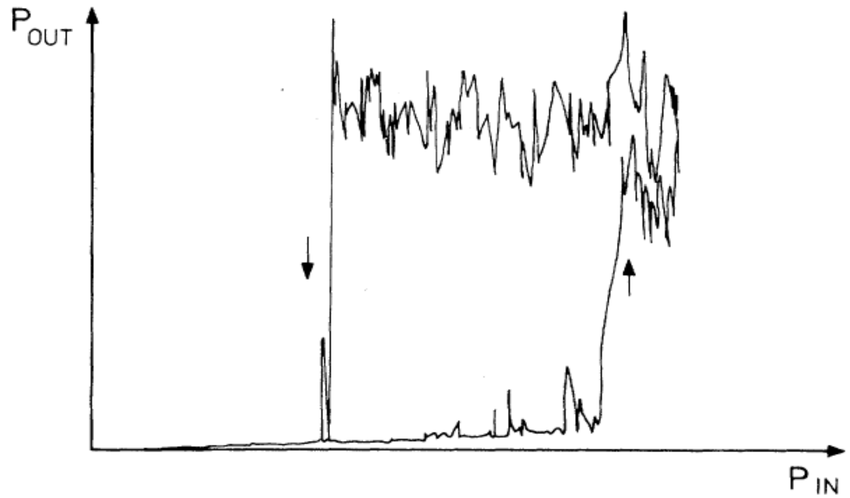

$$H_{int} = -\frac{\hbar\omega}{L} a^\dagger a x$$

$$F_{RP} = \frac{\hbar\omega}{L} a^\dagger a$$

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

# Observation of Radiation Pressure




MPQ 1983:

There is a discernible effect of radiation pressure in a high-finesse cavity with a suspended mirror.

$$H_{int} = \frac{\hbar\omega}{L} a a^\dagger x$$

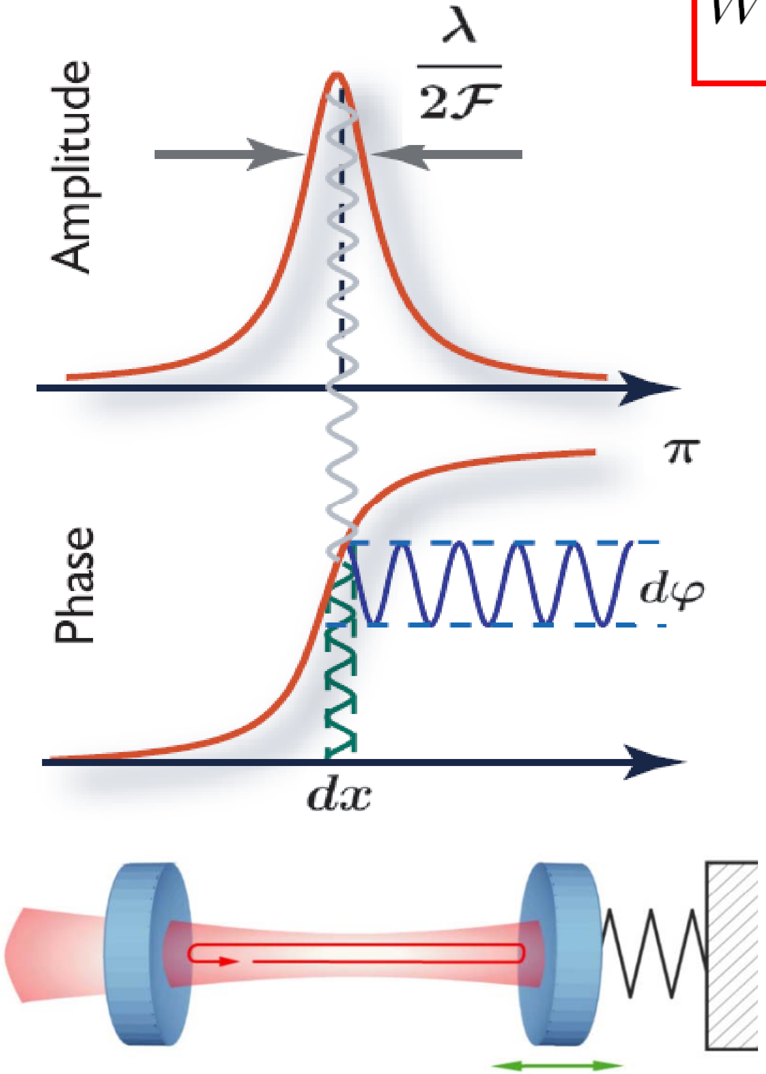
Dorsel, Meystre, Walther *et al.*, PRL **51,** 1550 (1983)

Radiation Pressure Limits Position Sensitivity: *Standard Quantum Limit*

$$S_{SQL} = \sqrt{\frac{\hbar}{2m\Omega_m\gamma}}$$

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

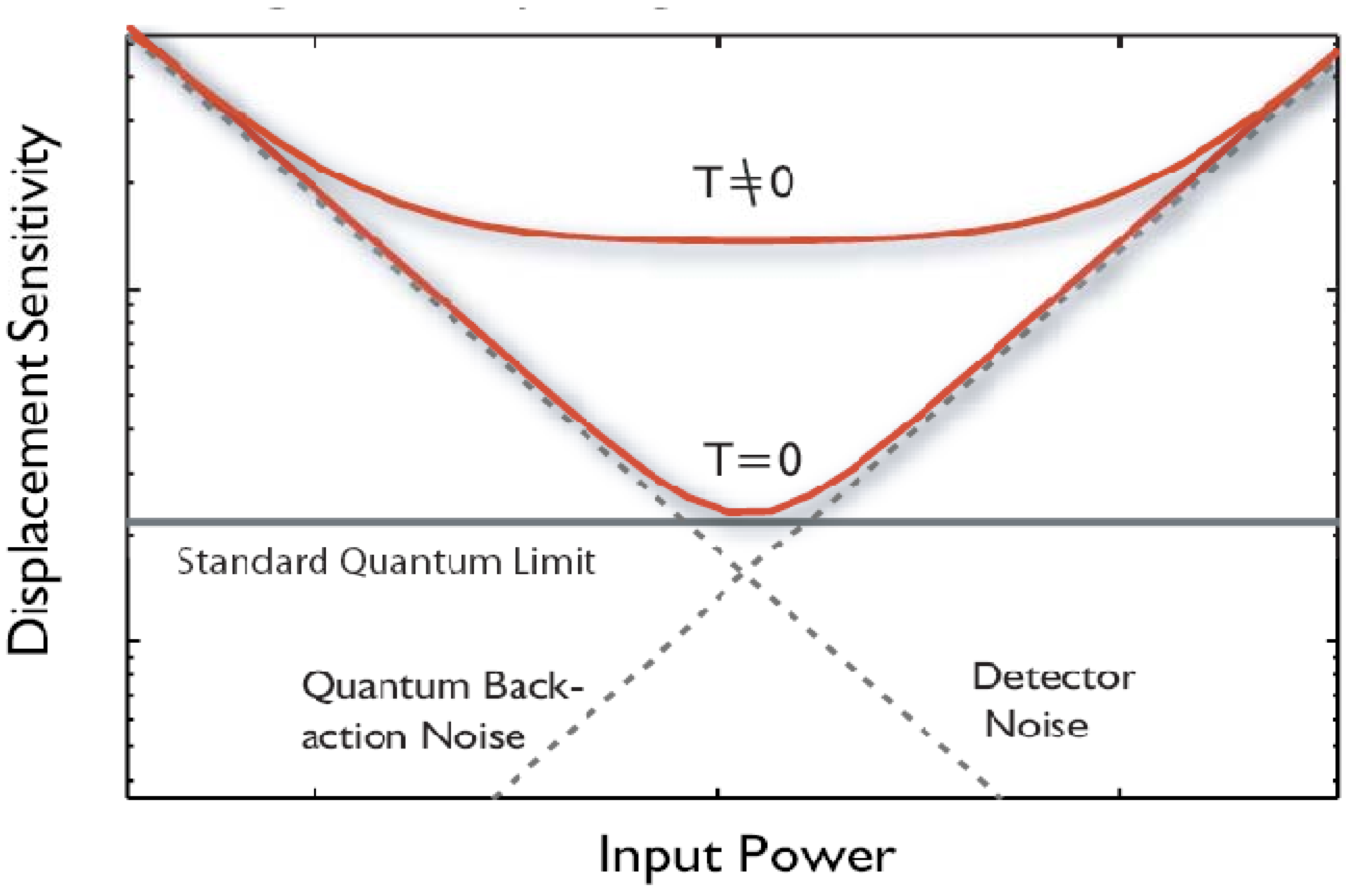
# Standard Quantum Limit of Motion Detection




$$W_{interaction} = -\frac{x}{L}|a_p|^2$$

$$\Rightarrow \quad \ddot{x} = \frac{|a_p|^2}{mL}$$

$$\Rightarrow \quad \dot{a_p} = -i\omega_o \frac{x}{L} a_p$$

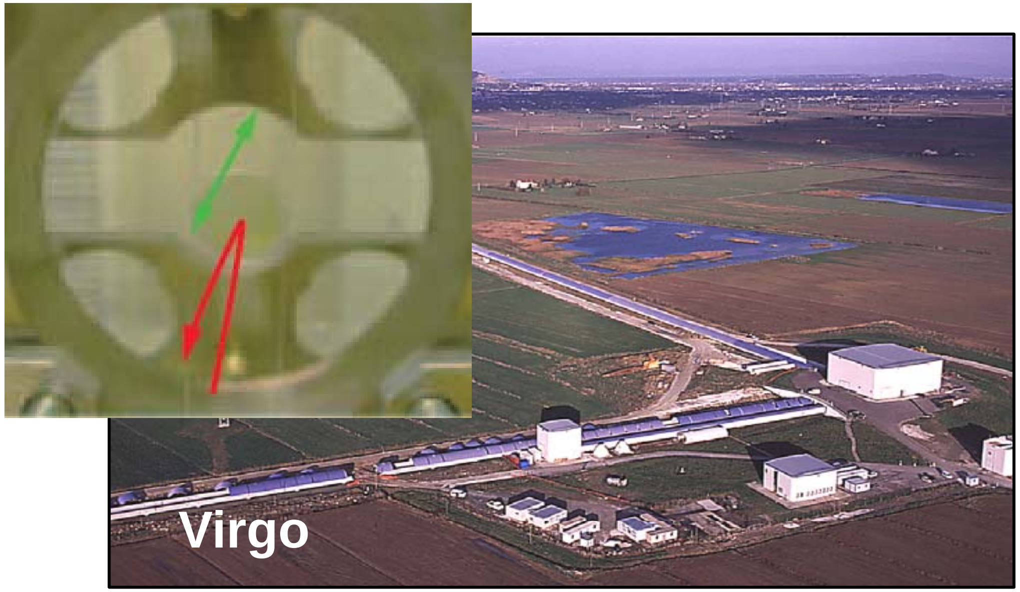




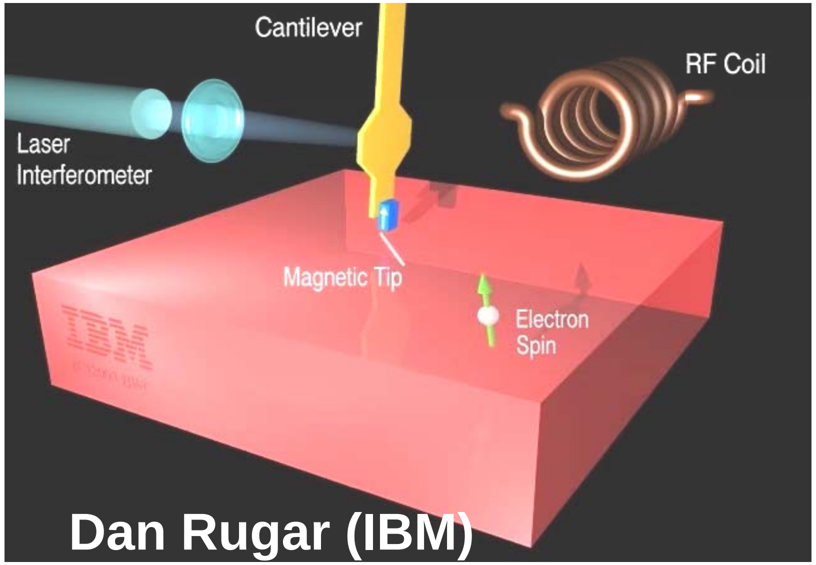
Caves, Phys. Rev. D (1980)

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

# Coupling light with mechanical oscillators




Gravitational wave interferometric Detection (VIRGO)




Weak force detection (IBM, San Jose)

Radiation Pressure Quantum Fluctuations limit Position Sensitivity:

***Standard Quantum Limit***

$$S_{SQL} = \sqrt{\frac{\hbar}{m\Omega_m \gamma_m}}$$

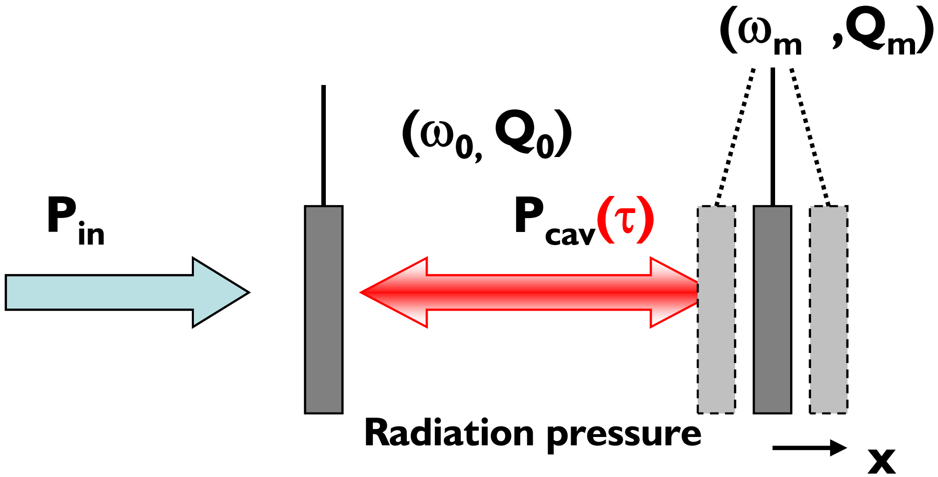
⇨ Quantum effects with macroscopic mechanical oscillators ?

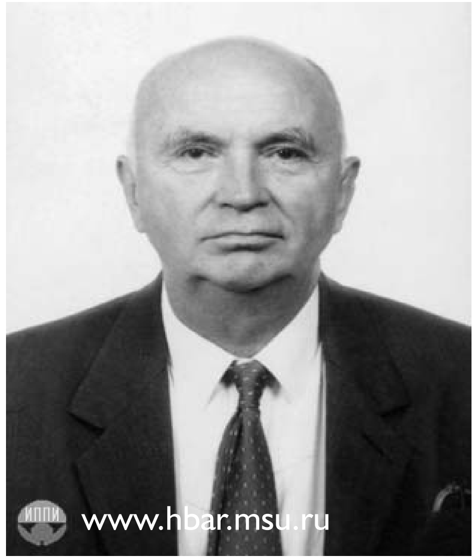
$$n = \frac{k_B T}{\hbar \Omega} \quad \Omega = 1MHz, T_Q = 50\mu K$$

# Dynamical Backaction



**The mutual coupling of optical and mechanical modes was first theoretically studied by V.B. Braginsky, "Measurement of Weak Forces"**




V.B. Braginsky

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

***Taylor Expansion yields:***

$$\Delta\omega = \frac{\frac{d}{dx}F_{rp}(x)}{m_{eff}}$$

***Position dependent term***

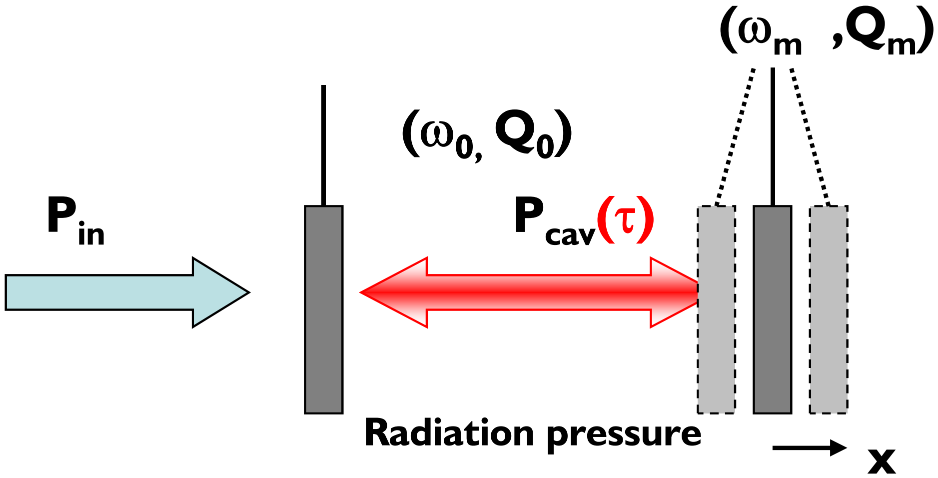
$$\Delta\beta = -\tau\frac{\frac{d}{dx}F_{rp}(x)}{m_{eff}}$$

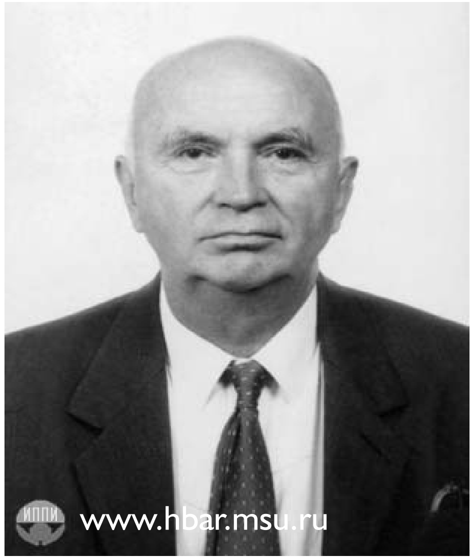
***Velocity dependent term***

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

# Dynamical Backaction

**The mutual coupling of optical and mechanical modes was first theoretically studied by V.B. Braginsky, "Measurement of Weak Forces"**




V.B. Braginsky

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

SOVIET PHYSICS JETP VOLUME 31, NUMBER 5 NOVEMBER 1970

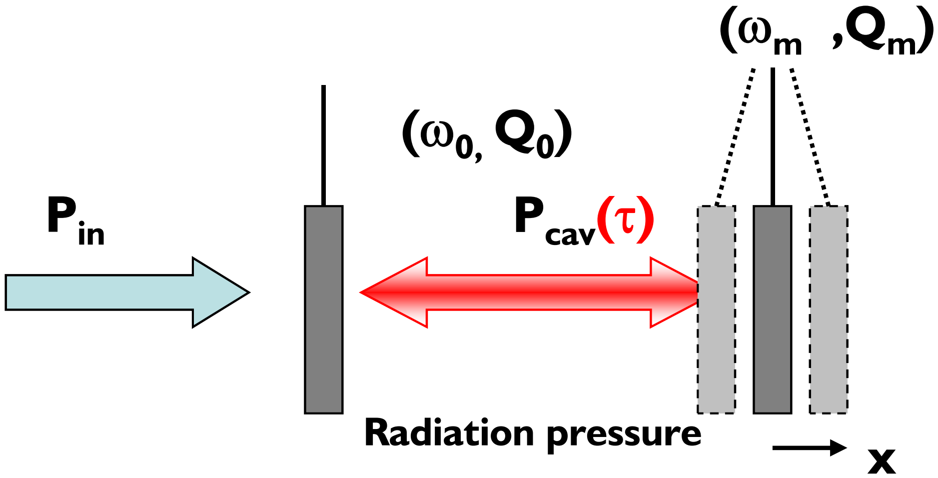
*INVESTIGATION OF DISSIPATIVE PONDEROMOTIVE EFFECTS OF ELECTROMAGNETIC RADIATION*

V. B. BRAGINSKIĬ, A. B. MANUKIN, and M. Yu. TIKHONOV
Moscow State University

Submitted October 17, 1969

# Dynamical Backaction

The mutual coupling of optical and mechanical modes was first theoretically studied by V.B. Braginsky, "Measurement of Weak Forces"





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

dent term

dent term;
Blue detuning
etuning

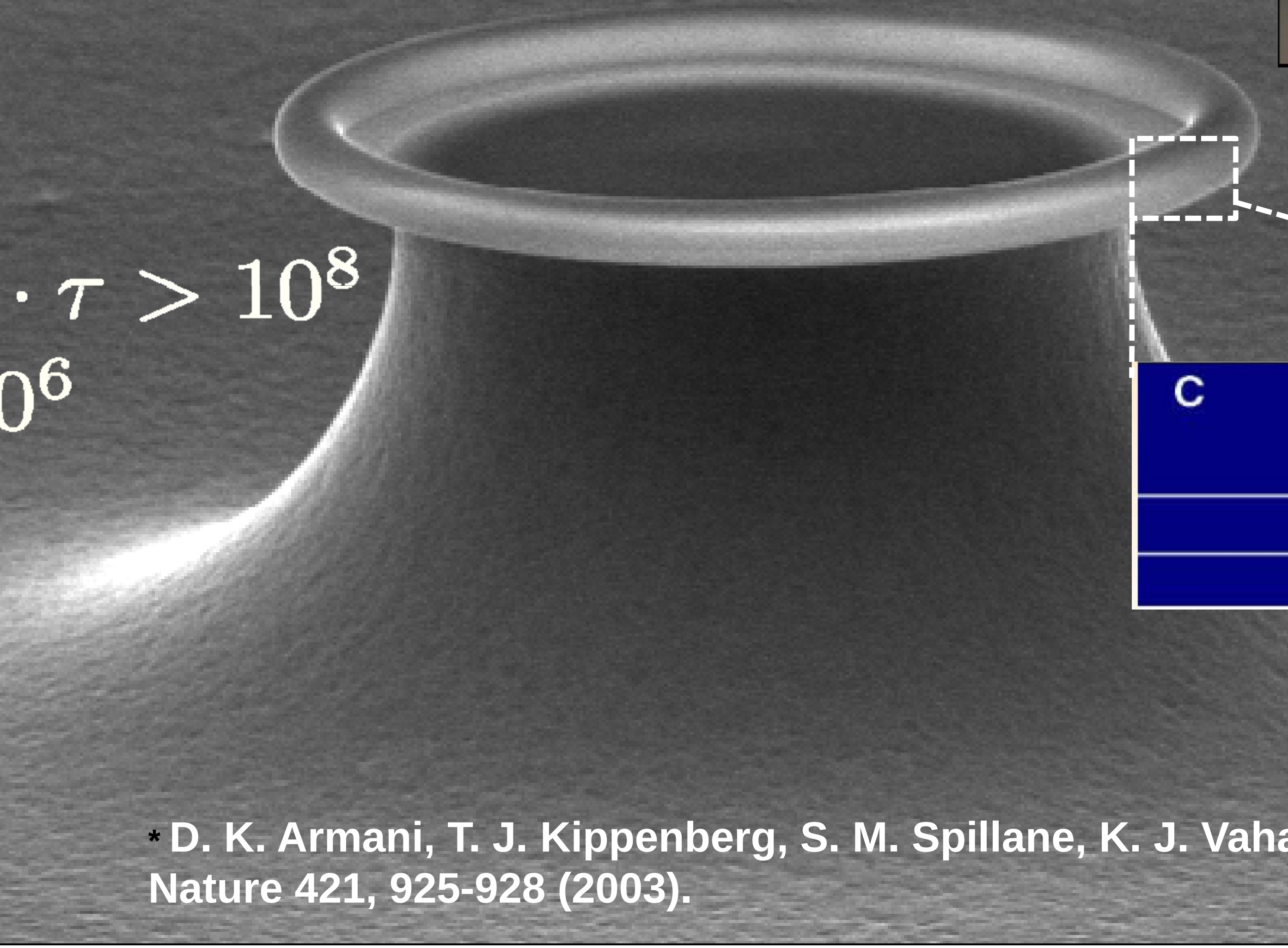
periments (1977)

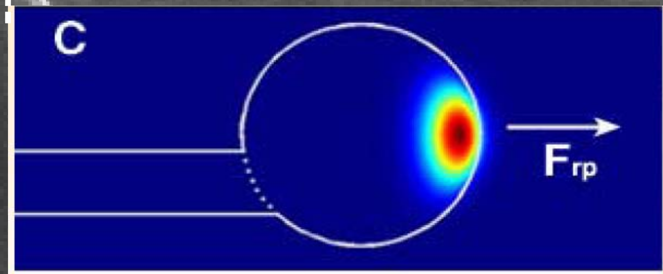
**Predicted for more than 30 years, but only recently observed.**

$\Delta\gamma < 0 \Rightarrow$ Amplification

$\Delta\gamma > 0 \Rightarrow$ Cooling

## Structures Fabricated at CMI-EPFL



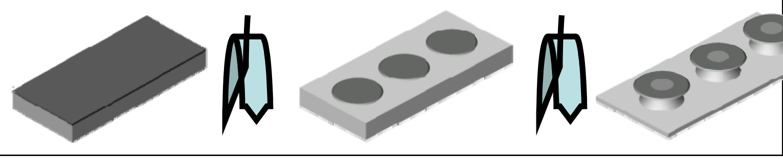



$$Q = \omega \cdot \tau > 10^8$$

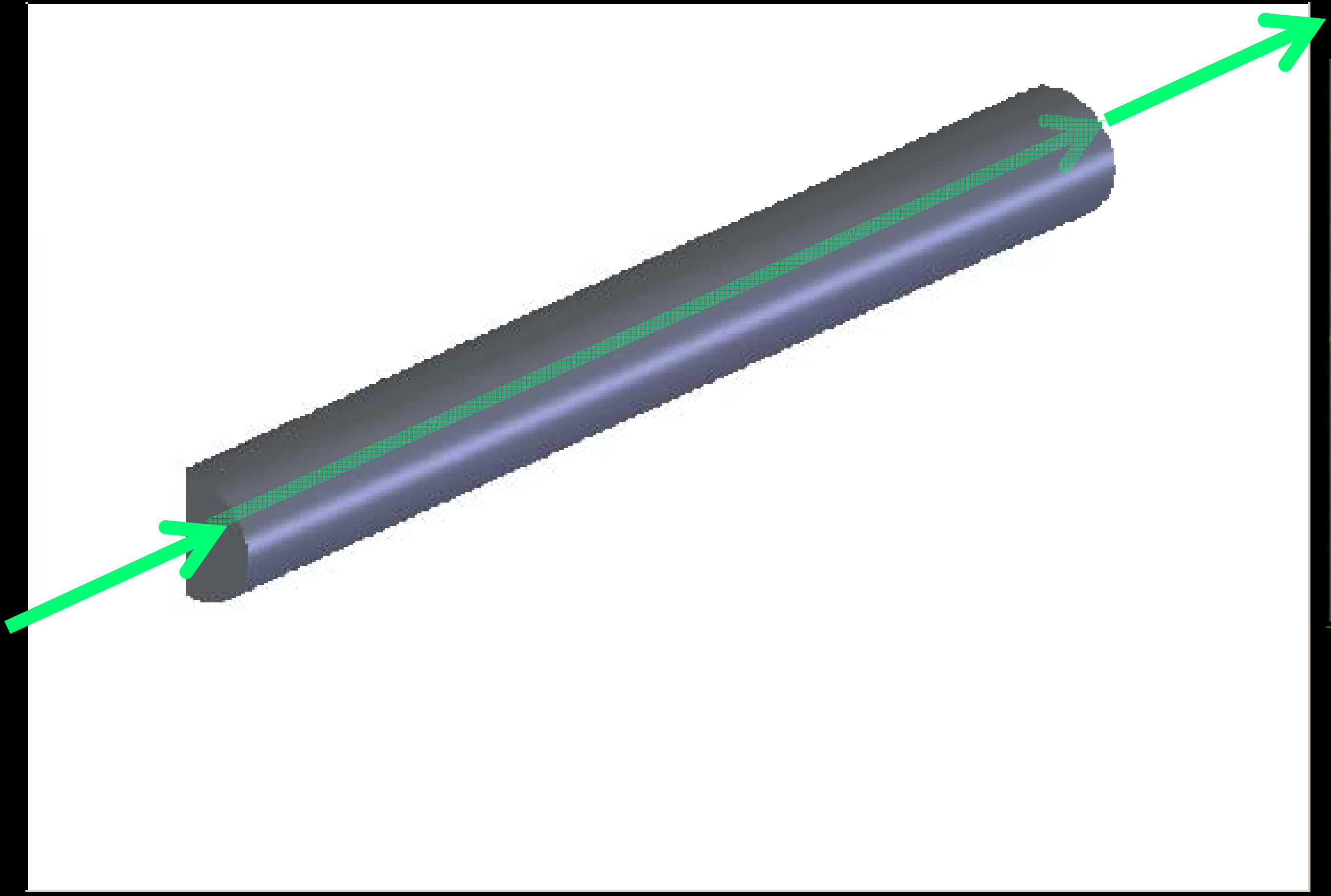
$$F > 10^6$$

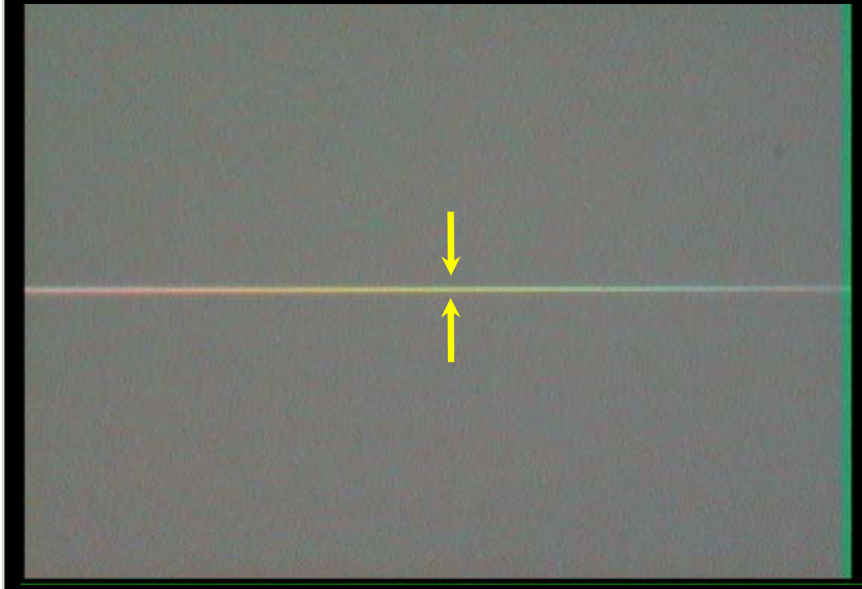
* D. K. Armani, T. J. Kippenberg, S. M. Spillane, K. J. Vahala. Nature 421, 925-928 (2003).

→ **Optical Finesse can exceeds 1 million**



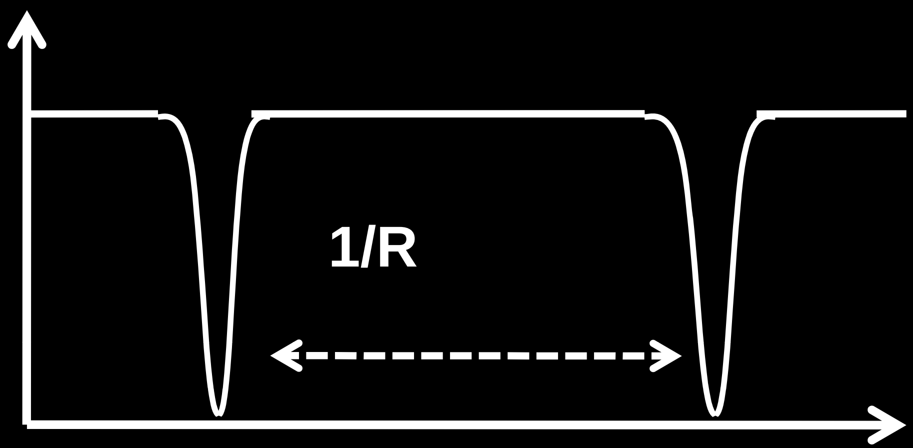
# Optical fiber coupling

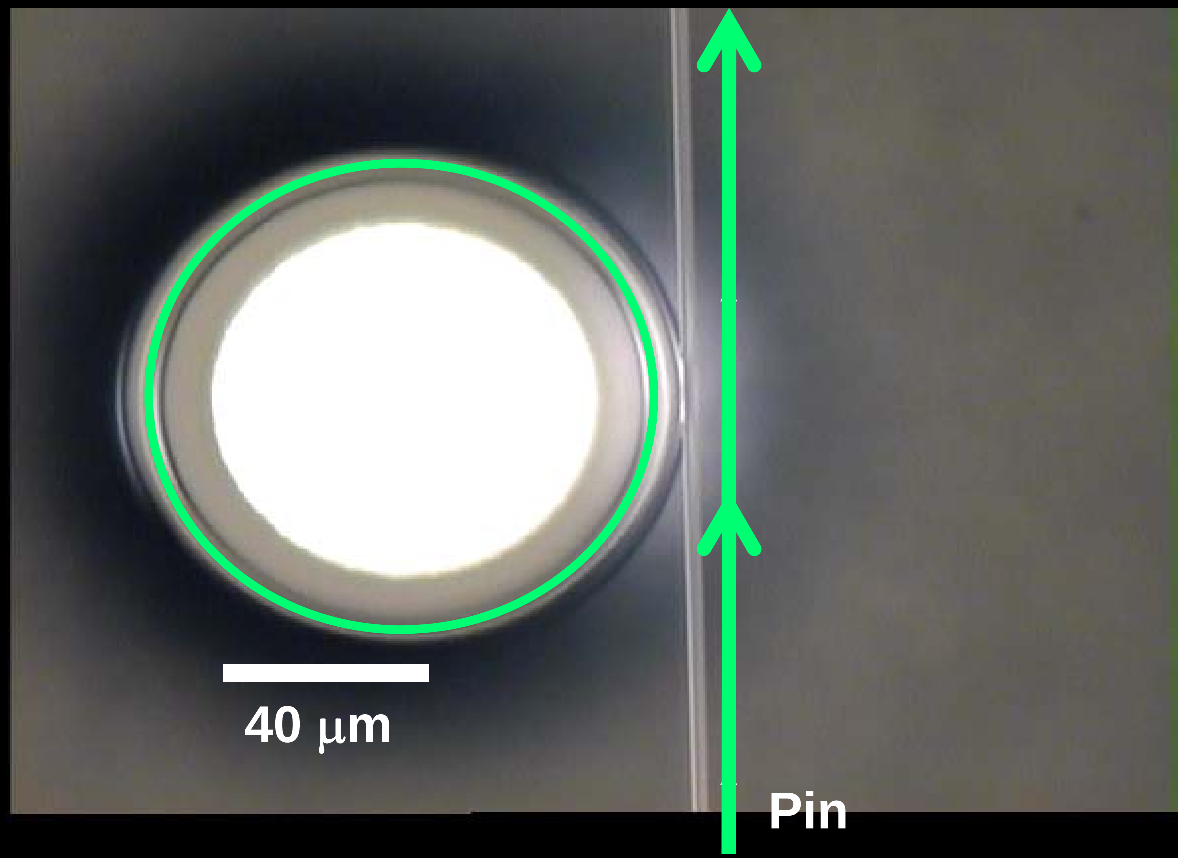




M. Cai, O.J. Painter, K. J. Vahala. *Phys. Rev. Lett.* (2002).

# Optical Microresonators with Giant Photon Lifetimes

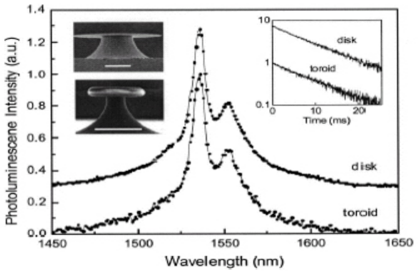



S. M. Spillane, T. J. Kippenberg, O.J. Painter, K. J. Vahala. Phys. Rev. Lett. (2003).
T.J. Kippenberg, S.M. Spillane, K.J. Vahala, Optics Letters, (2002).

# Ultra-high Q Physics

## Narrow Linewidth Laser sources




## Nonlinear Optics at ultra low power

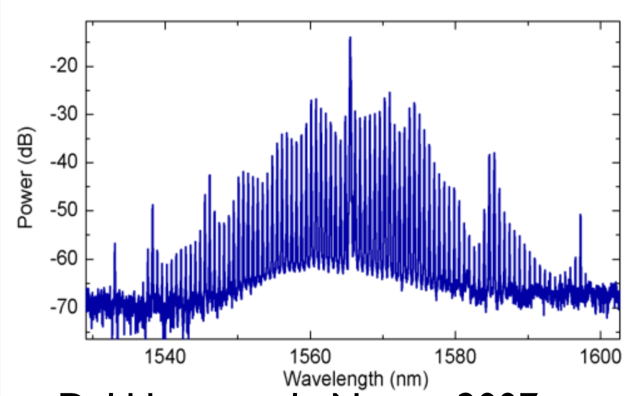
Kippenberg, Spillane, Vahala. **Phys. Rev. Lett.** (2004).

Spillane, Kippenberg, Vahala. **Nature,** 621-623 (2002).

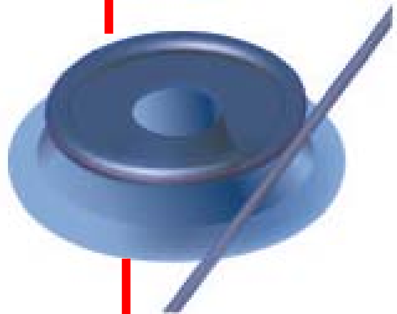
….

## Cavity QED strong coupling

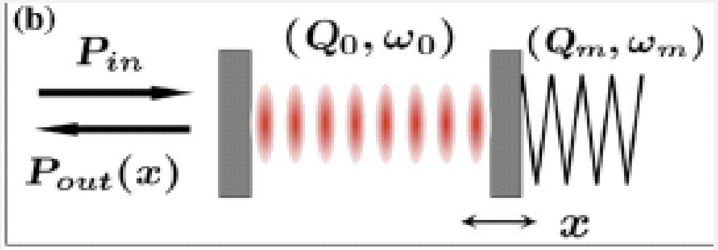

## Frequency Combs on a Chip




Del Haye, et al. Nature 2007



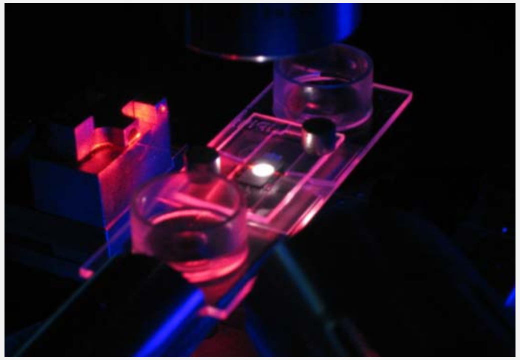
## Cavity Optomechanics




Kippenberg, Vahala **Science** (2008)

## Applications in Science, Technology, Metrology

## Molecule Sensing



## Fundamental Research

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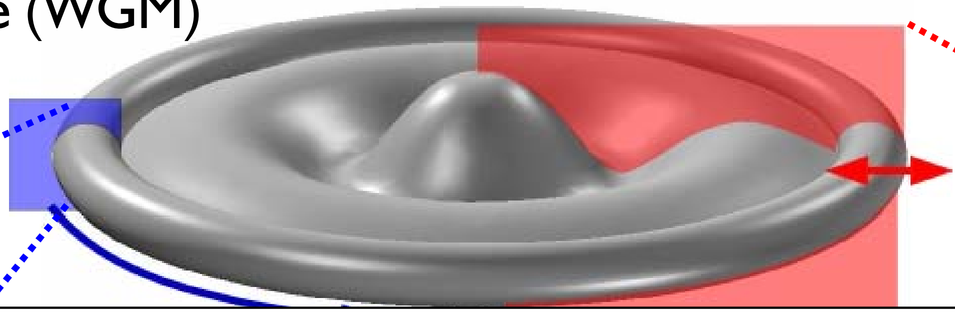
**optical**
whispering-gallery-mode (WGM)
„meter“

**mechanical**
radial-breathing-mode (RBM)
„oscillator“



$$\hat{H} = \hbar\omega_L \hat{a}_p^\dagger \hat{a}_p + \hbar\omega_m \hat{a}_m^\dagger \hat{a}_m + \hbar g_m \hat{a}_p^\dagger \hat{a}_p \left(\hat{a}_m + \hat{a}_m^\dagger\right)$$

$$g_m = \frac{x_0}{L}\omega_0$$

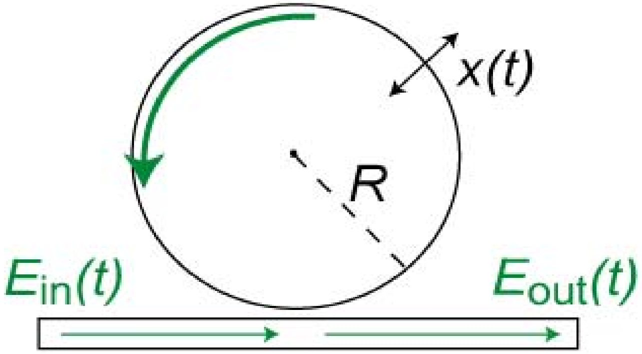
**Coupling strength**

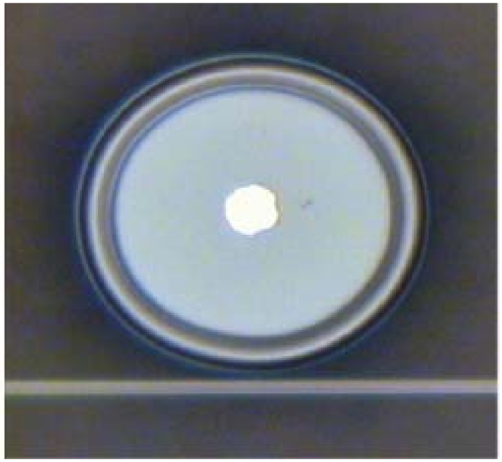
$$x_0 = \sqrt{\frac{\hbar}{2m\omega}}$$

**Zero point motion**

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

# Optomechanical Coupling



$$H_{int} = \hbar\omega a^\dagger a(1 - g_m x)$$

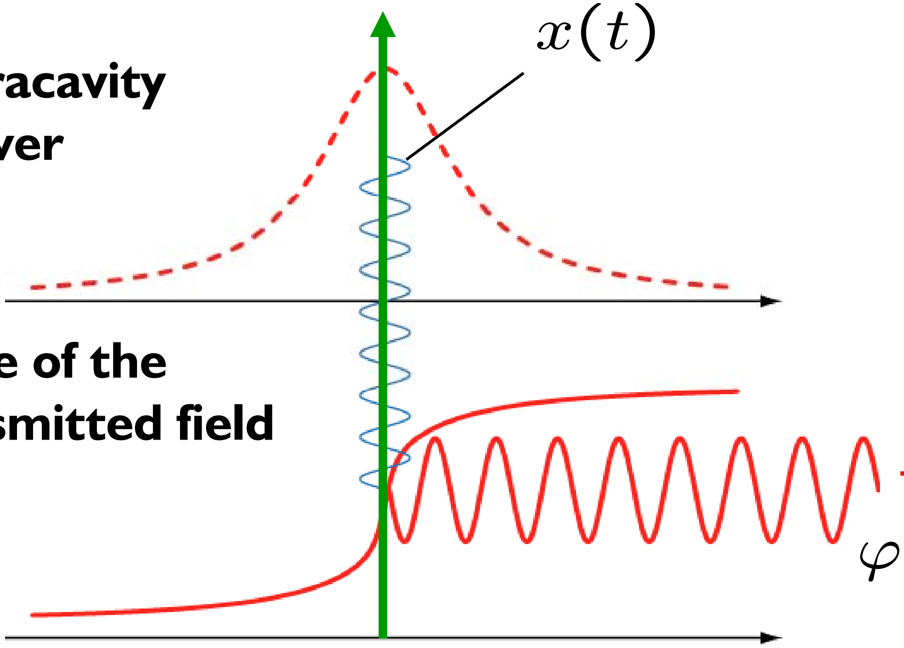
$$g_m = \frac{\omega}{R} \approx 10\mathrm{GHz/nm}$$

$$F_{rad} = \hbar \cdot g_m$$

$$T_{eff} = \frac{1}{k_B}\int m_{eff}\delta\Omega \cdot x[\Omega]^2 \cdot \Omega^2$$

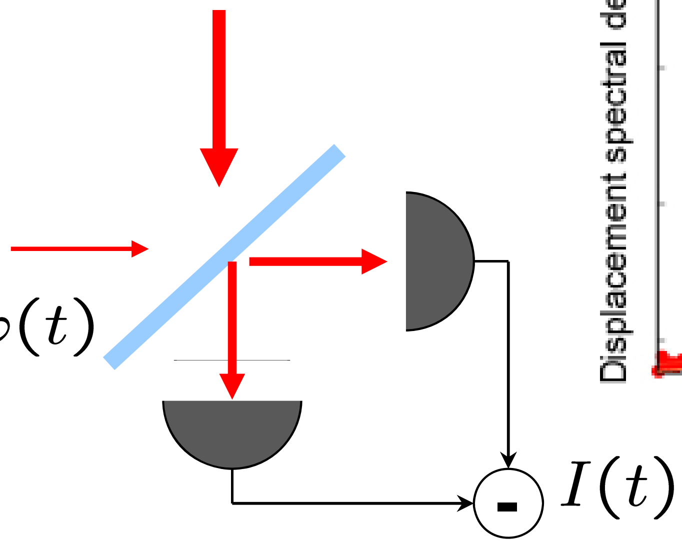
**Intracavity power**

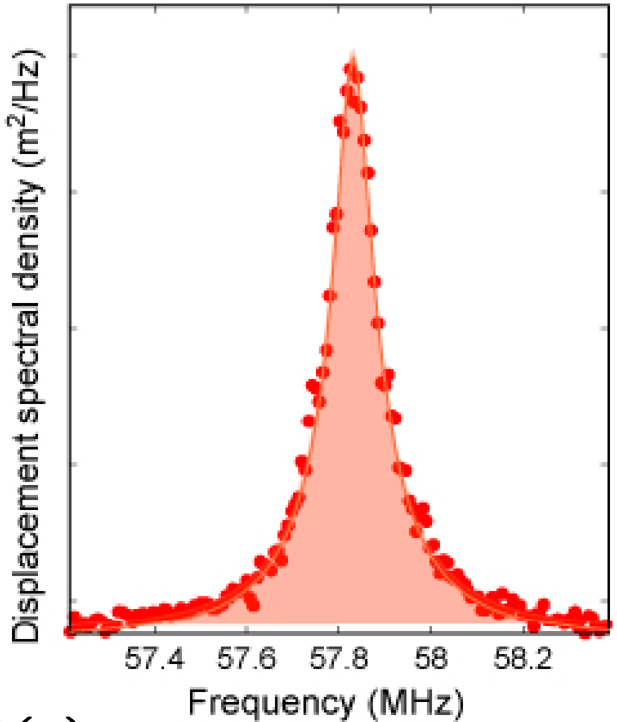
**Phase of the Transmitted field**




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

**Homodyne Detection**



# Quantitative Analysis of Noise Spectra

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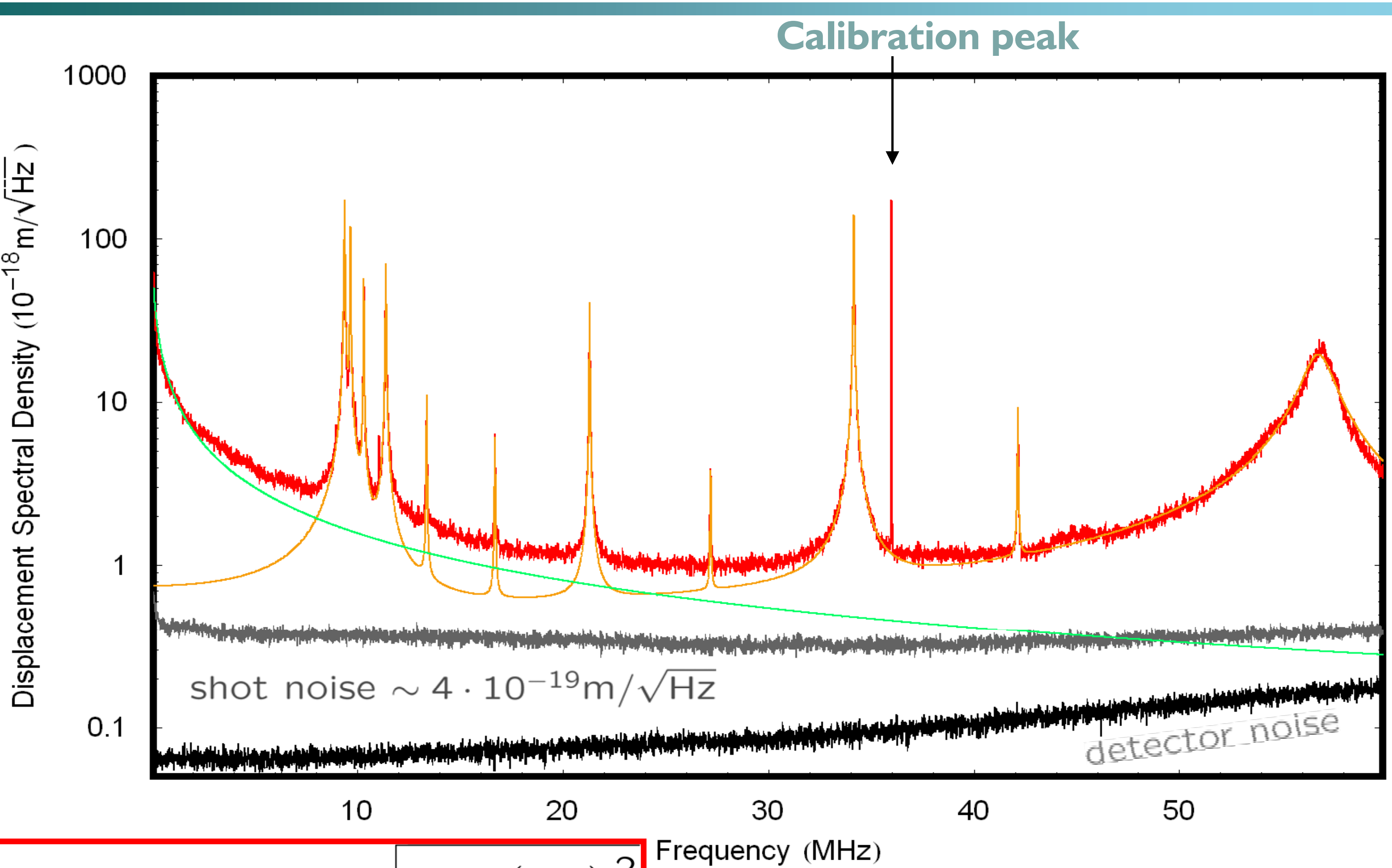
MPQ

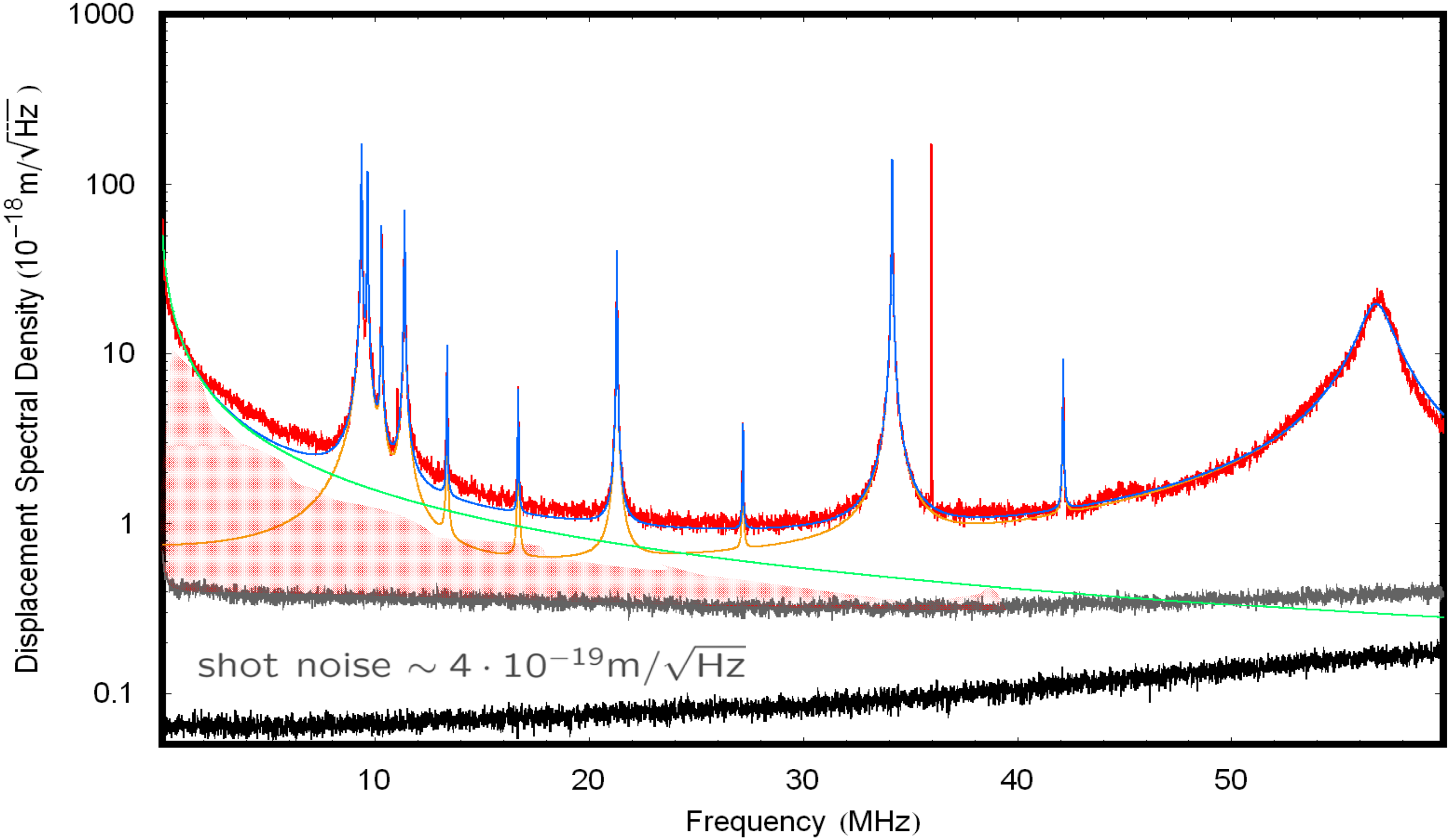



$$\sqrt{S_x^{\text{shot}}(\Omega)} \approx \frac{\lambda}{16\pi\eta_c\mathcal{F}} \cdot \sqrt{\frac{1+\left(\frac{\Omega}{\kappa/2}\right)^2}{P_{\text{in}}/\hbar\omega}}$$

Schliesser, Anetsberg, Riviere, Arcizet, Kippenberg NJP, 10, 095007

# Quantitative Analysis of Noise Spectra

MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK GARCHING
MPQ




**Thermorefractive noise caused by temperature fluctuations**


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

**V. B. Braginsky, M. L. Gorodetsky, and S. P. Vyatchanin, "Thermodynamical fluctuations and photo-thermal shot noise in gravitational wave antennae," Phys. Lett. A 264, 1–10 (1999).**

Schliesser, Anetsberg, Riviere, Arcizet, Kippenberg NJP, 10, 095007 (focus issue)

# Mechanical Modes

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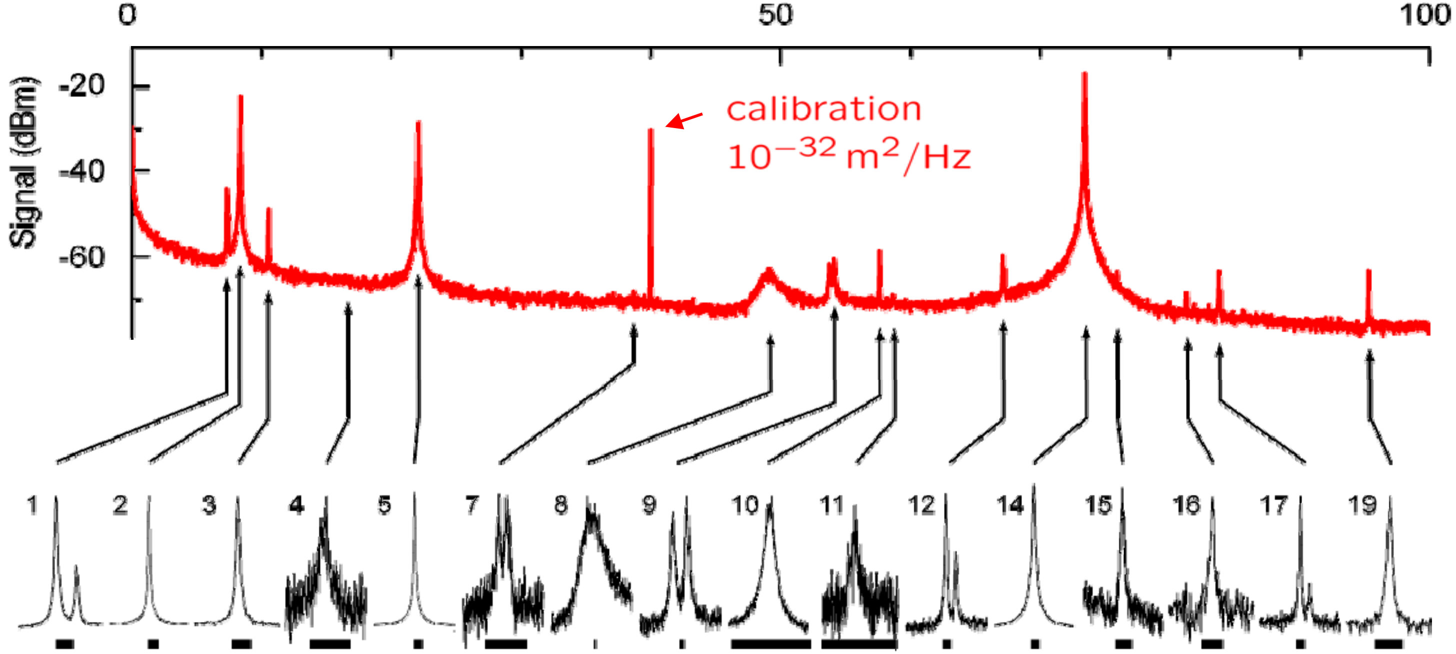
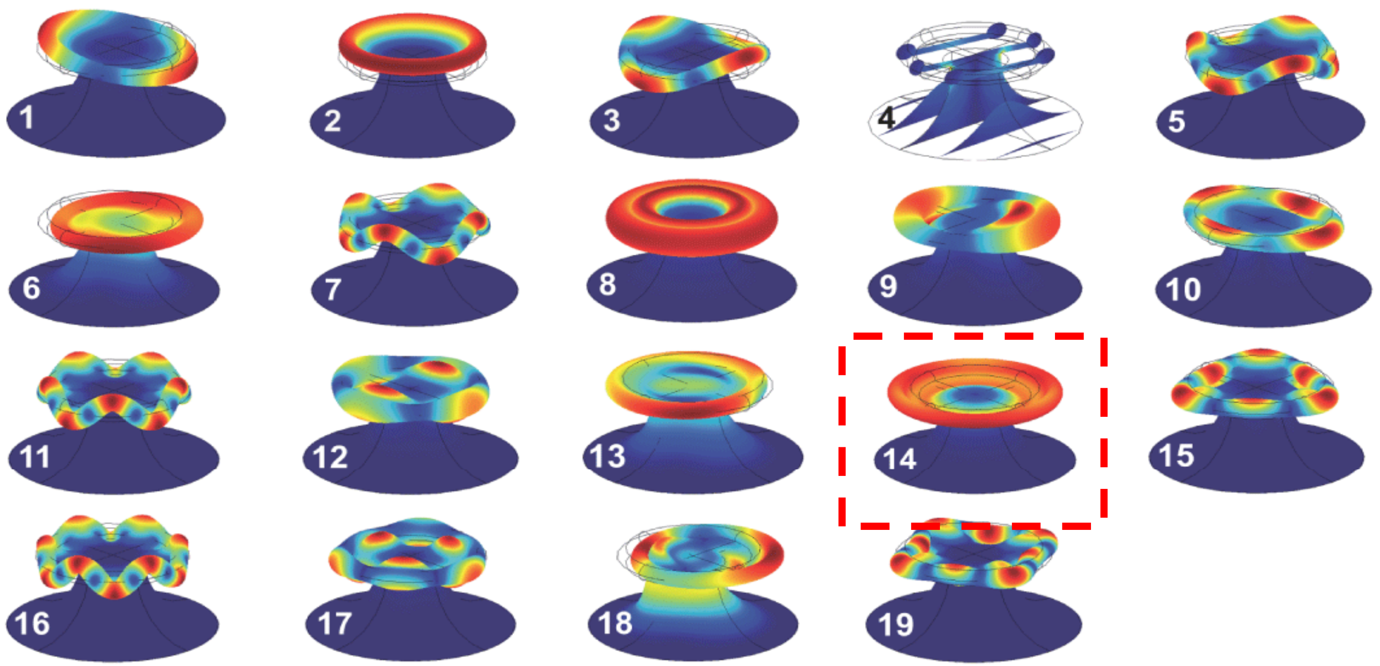



measured mechanical spectrum

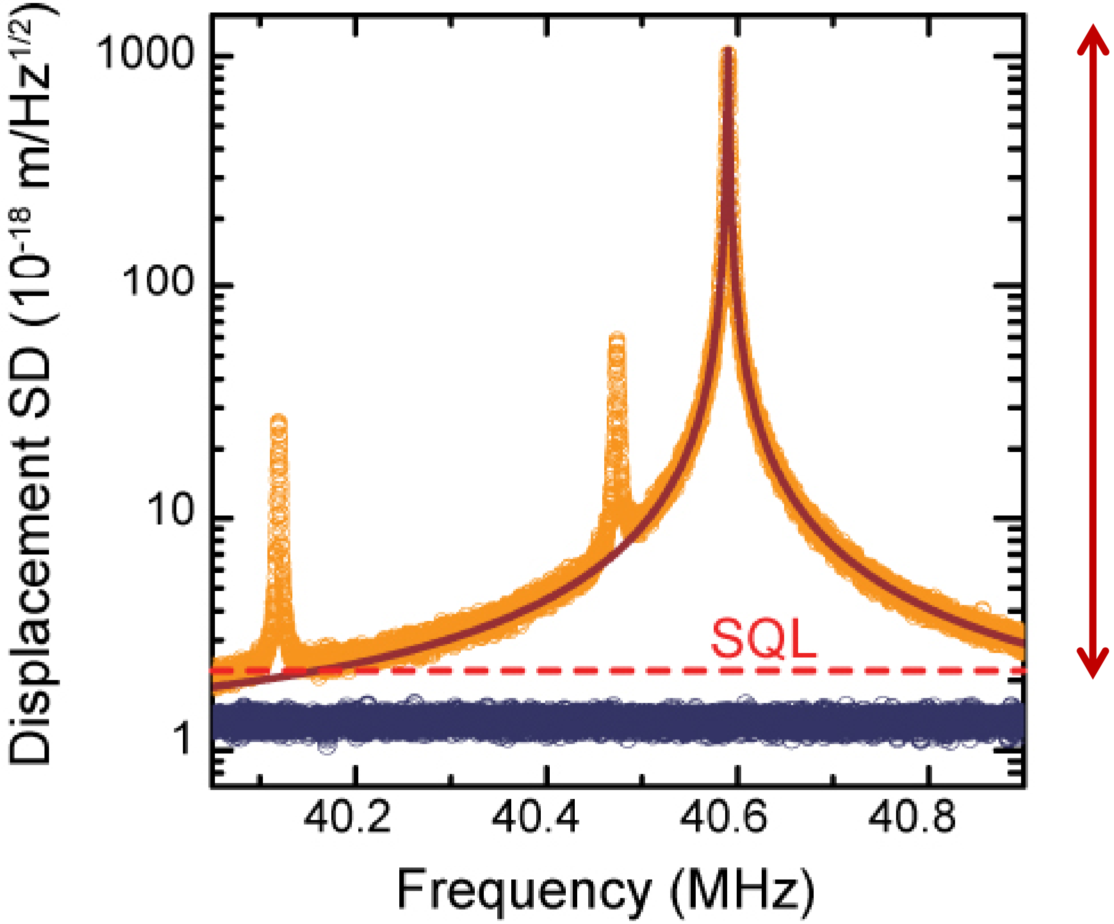
zoom on individual peaks




mode patterns obtained from finite element modeling

# Sensitivity of the Displacement Measurement






$$n \approx \frac{k_B T}{\hbar \Omega_m}$$

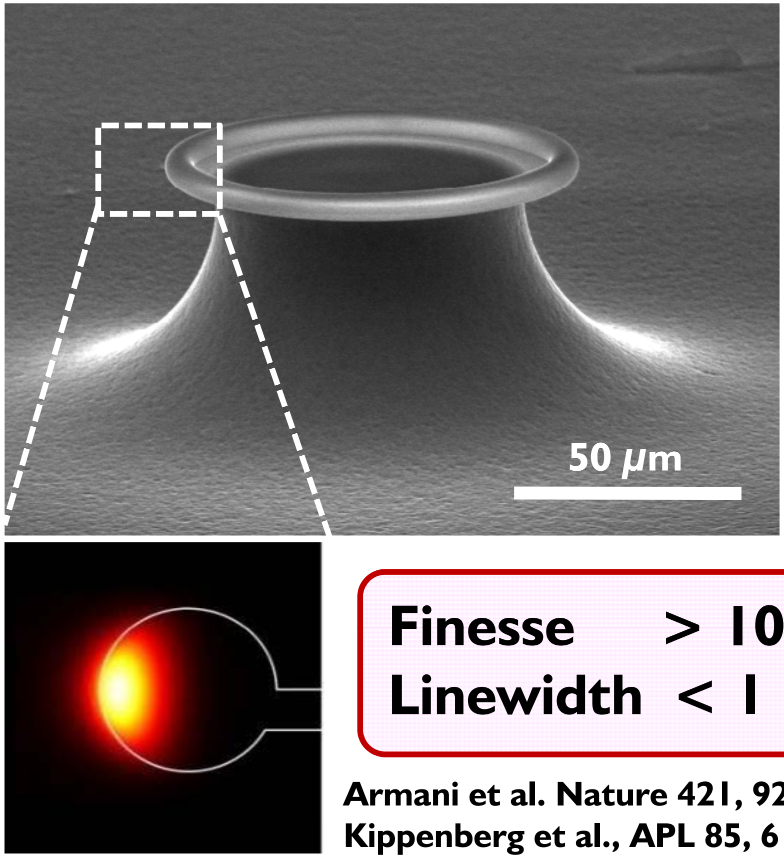
$$\sqrt{\frac{S_{th}}{S_{sql}}} > \sqrt{2n}$$

$$\frac{\sqrt{S_x^{sig}[\Omega_m]}}{\sqrt{S_x^{zpm}[\Omega_m]}} = \sqrt{2n}$$

**From signal to background one can deduce that the sensitivity is *below* the SQL**

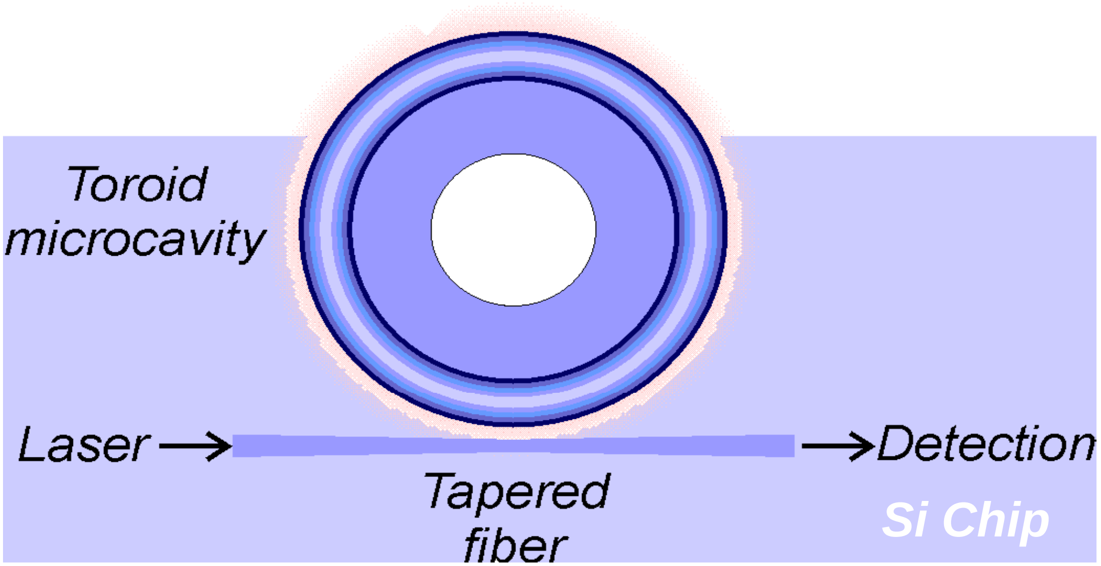
# Nano-Optomechanics

## Toroid microcavity:


**Finesse > $10^6$**
**Linewidth < 1 MHz**

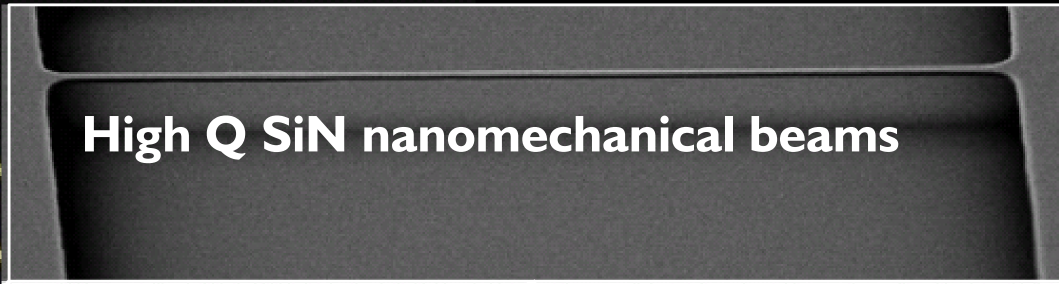
**Armani et al. Nature 421, 925 (2003).**
**Kippenberg et al., APL 85, 6113 (2004)**

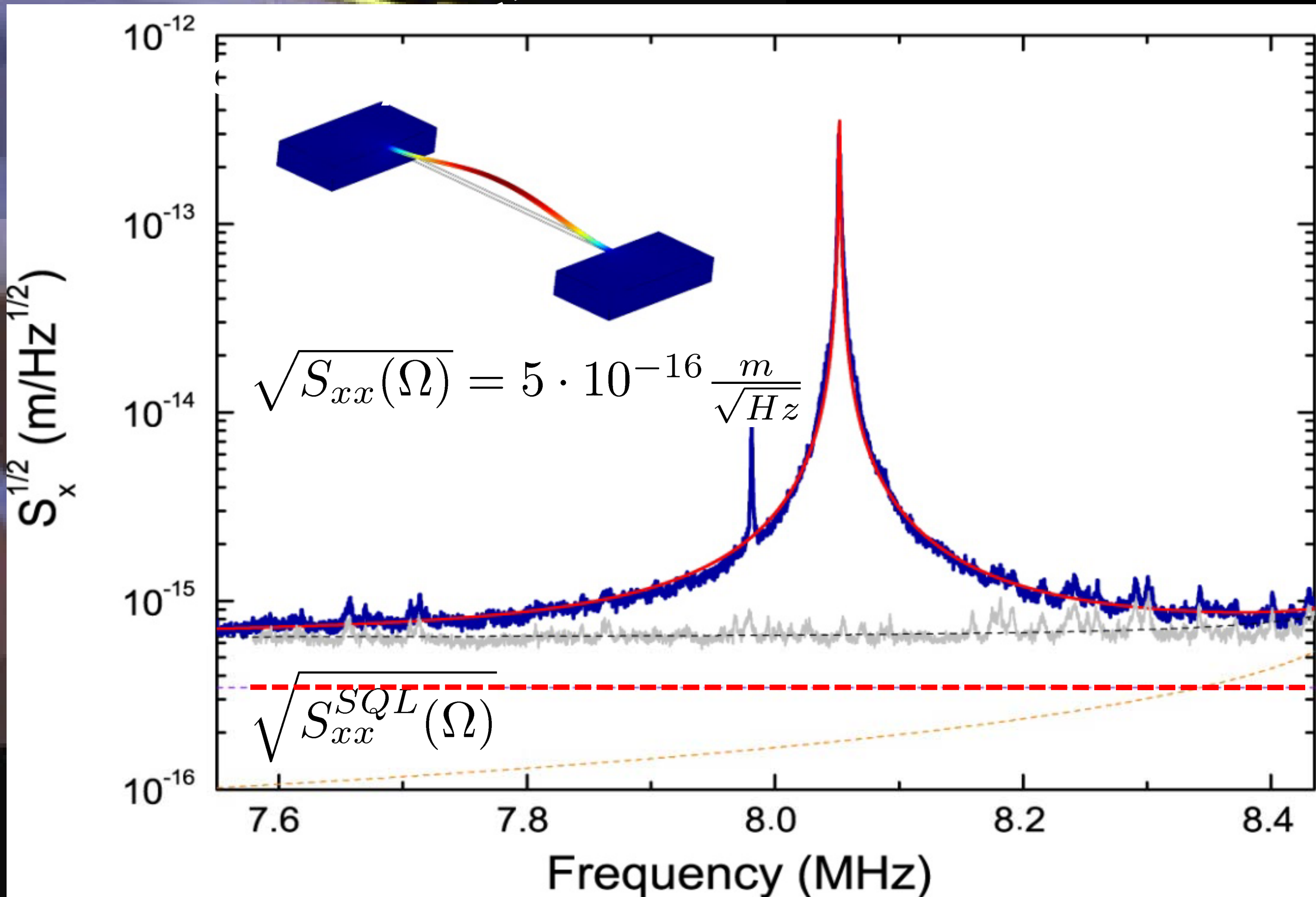



**Optomechanical near-field interaction**

Anetsberger, Arcizet, Weig, Unterreithmeyer, Kotthaus, Kippenberg,
arXiv:0904.4051 **(Nature Physics Dec. 2009)**

Anetsberger, Arcizet, Weig, Unterreithmeyer, Kotthaus,Kippenberg, arXiv:0904.4051 (Nature Physics Dec. 2009)




Parameters

$g_m = \frac{d\omega}{dx} \approx 10\text{MHz/nm}$

$m_{\text{eff}} \approx 1\text{pg}$

$Q_{\text{m}} > 100,000$

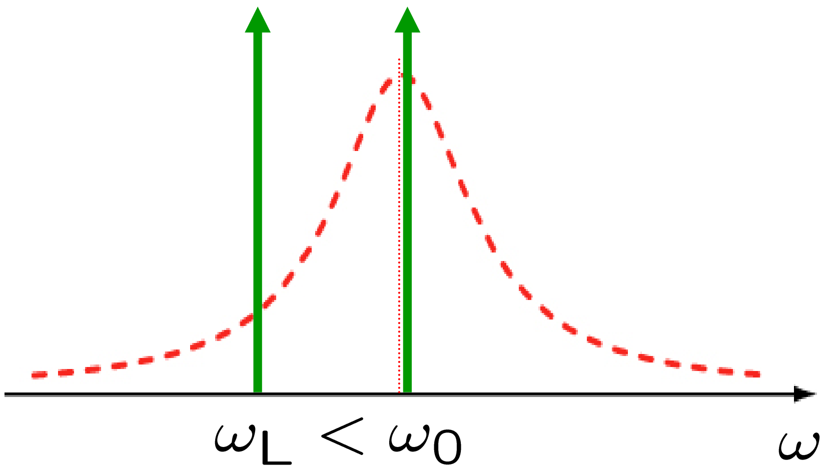
$\Omega_m \approx 10\text{MHz}$

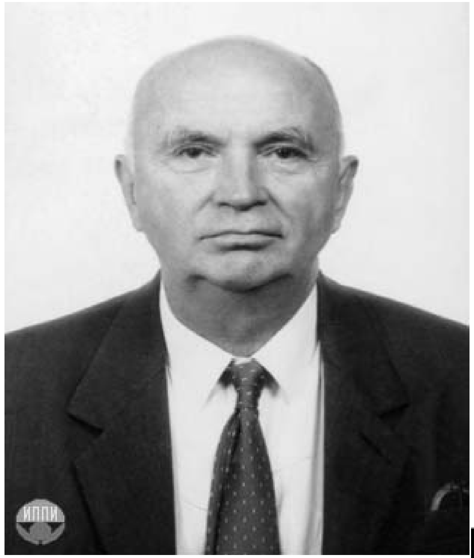
$\kappa < 10\text{MHz}(\text{F} > 250,000)$

# Cooling by Dynamical Backaction at MPQ

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

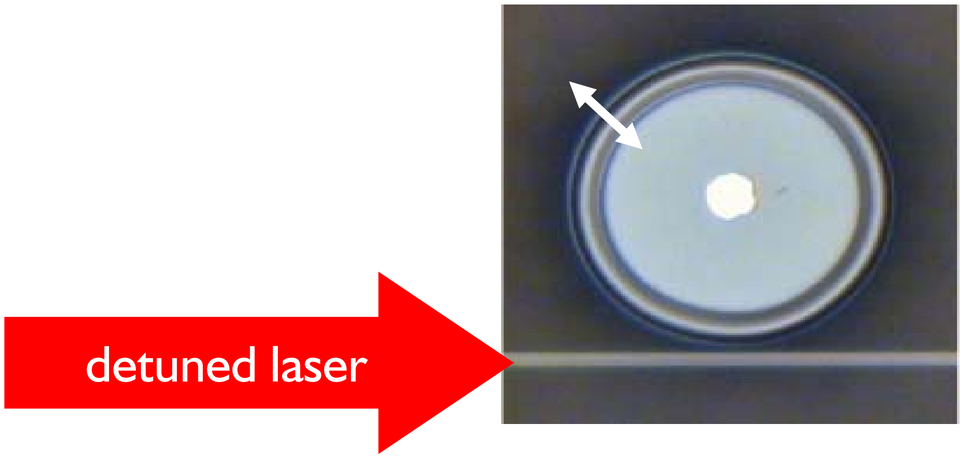
detuned laser induces viscous force on cavity boundary

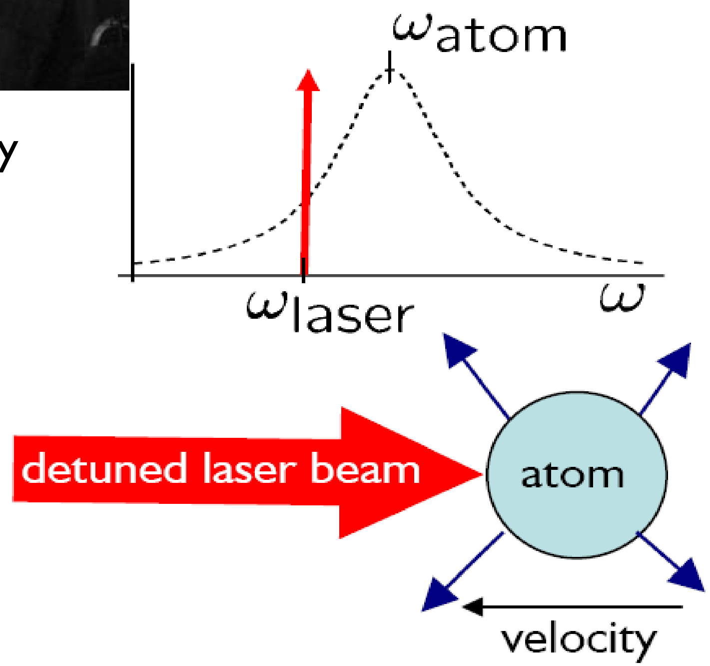


V.B. Braginsky

.... similar to laser cooling of atoms





**Braginsky, Manukin, "Ponderomotive effects of electromagnetic radiation", JETP Letters 52, 986 (1967)**
**Hänsch, Schawlow, "Cooling of gases by laser radiation", Opt. Commun. 13, 68 (1975)**
**Wineland, Dehmelt, "Proposed $10^{14}\Delta\nu < \nu$ laser fluorescence spectroscopy on $Tl^{+}$ ion mono-oscillator, Bull APS 20, 637 (197**

# Demonstration of Backaction Cooling @ MPQ

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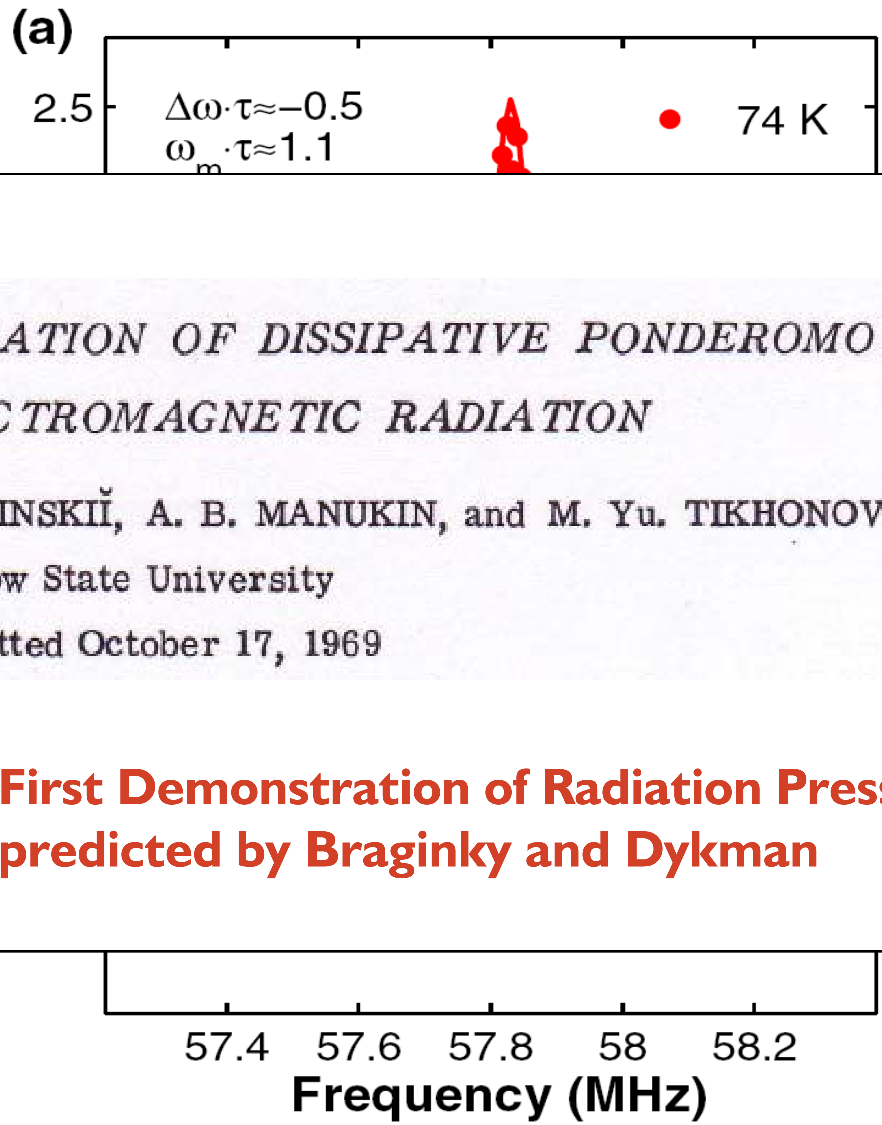
**Key Parameters:**

- Mechanical fr
of the cooled r
**57.8 MHz**

- Initial temper
**300 K**

- Final effective
temperature **1**




*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

→ **First Demonstration of Radiation Pressure Cooling as predicted by Braginky and Dykman**

l'Haye,. Nooshi,
Rev. *Lett*. **97**

don, Briant,
**444**, 71

, *Nature* **444**,

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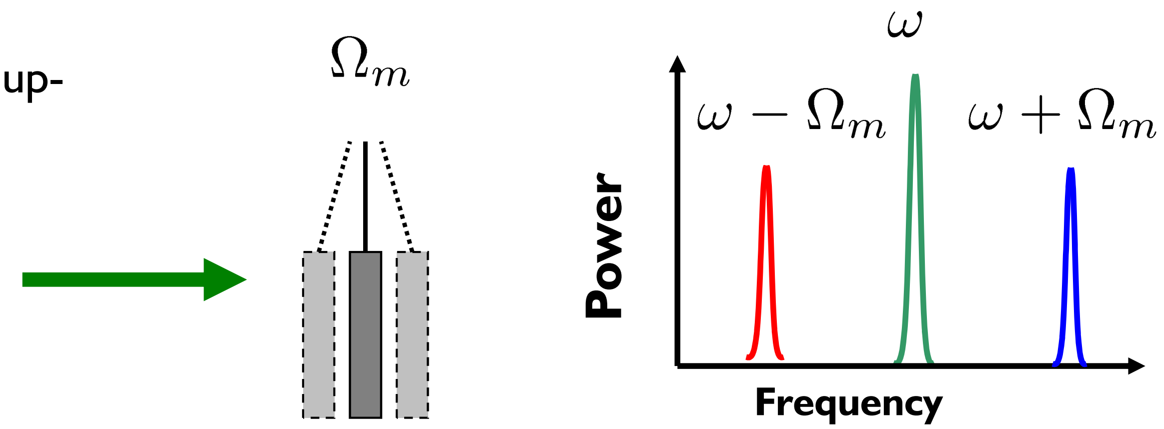
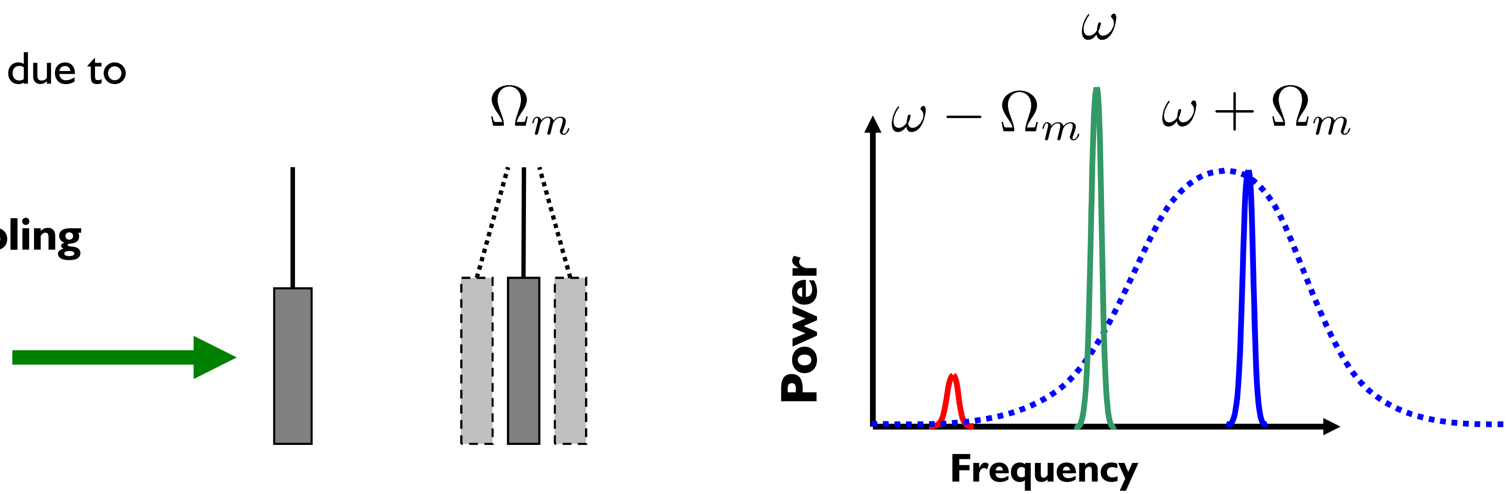
# Sideband interpretation

An oscillating mirror will cause Doppler up- and down-shifted fields.




A cavity can create an imbalance due to resonant buildup

Excess anti-Stokes photons: **Cooling**




***Similar mechanism to cavity cooling of atoms and molecules (coherent scattering)***

V. Vuletic, S. Chu, *Phys. Rev. Lett.* , Vol. 84, No. 17 (2000)

P. Maunz, Puppe, Schuster, Syassen, Pinkse, Rempe, *Nature* (2004)

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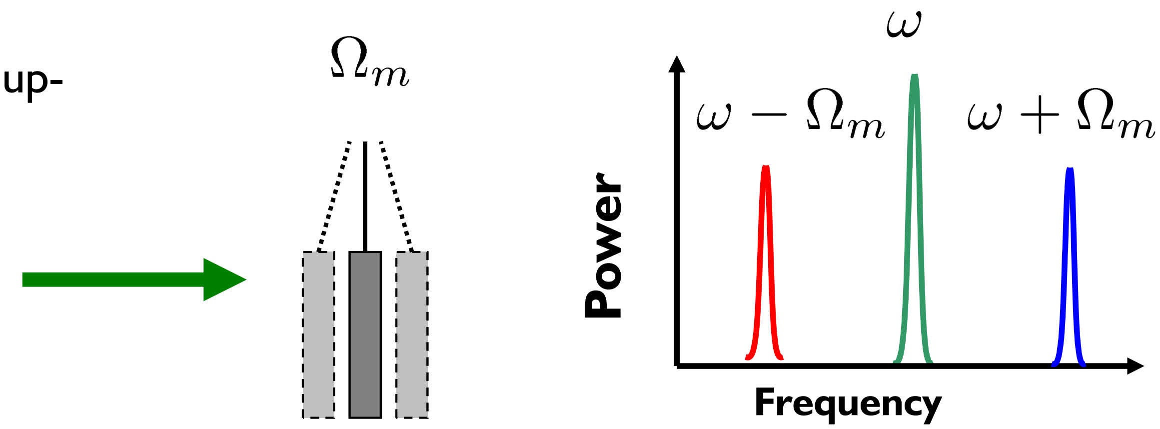
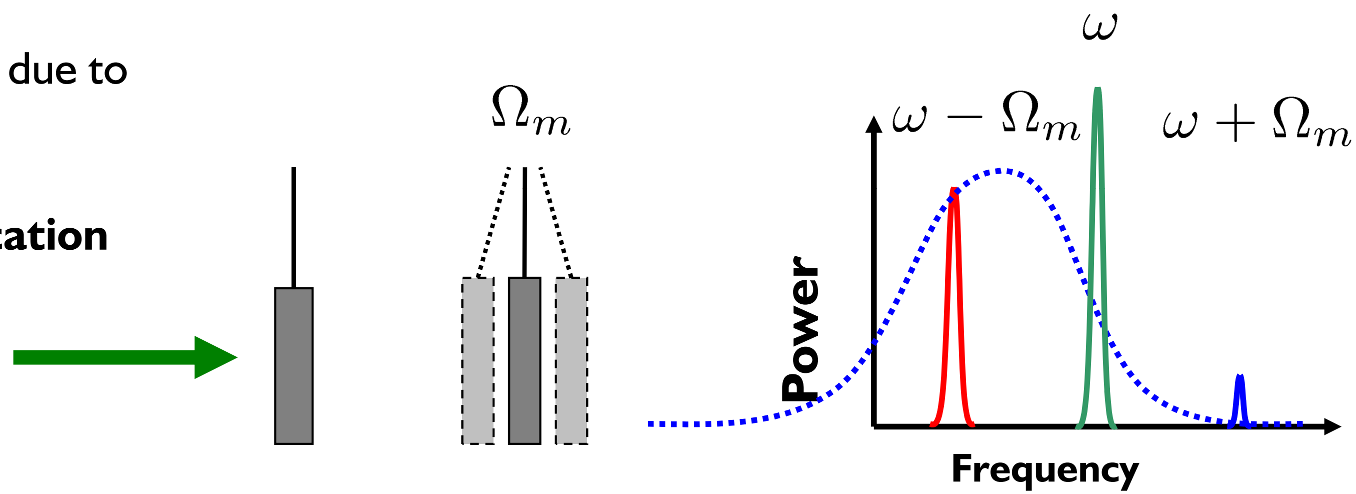
# Sideband interpretation

An oscillating mirror will cause Doppler up- and down-shifted fields.




A cavity can create an imbalance due to resonant buildup

Excess Stokes photons: **amplification**

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P. Maunz, Puppe, Schuster, Syassen, Pinkse, Rempe, *Nature* 428, 50 (2004).

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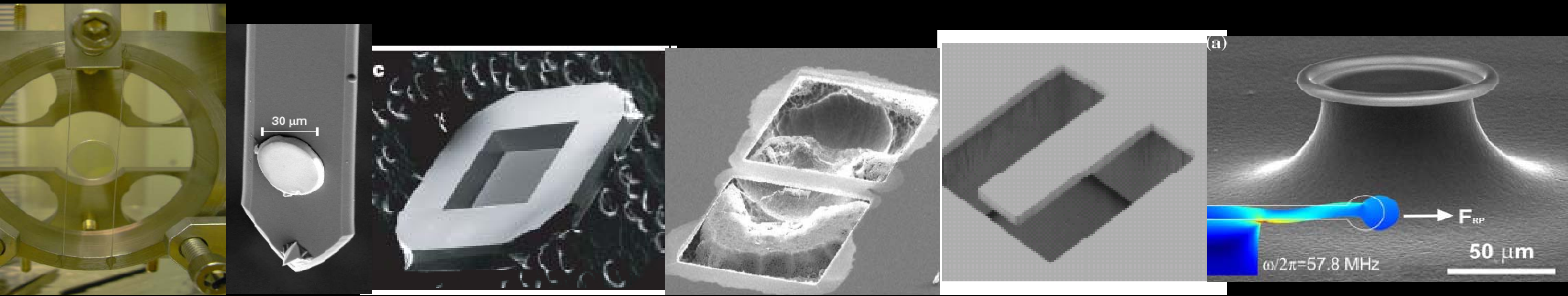
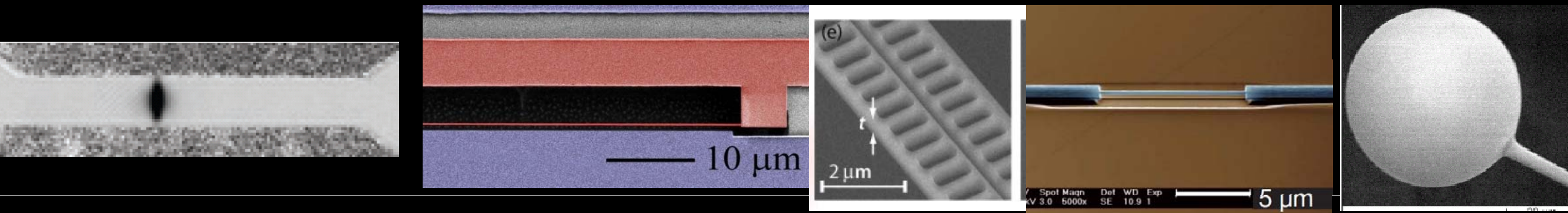
# Recent Experiments in cavity Optomechanics (2006-2009)

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




MIT/LIGO Paris | UCSB | Yale | Vienna | Paris | MPQ/Caltech/EPFL

$1Hz$ — $1kHz$ — $1MHz$ — $1GHz$




Berkeley/ETHZ | JILA, USA | Caltech | Ghent IMEC, Yale | Oregon

T. J. Kippenberg and K. J. Vahala, "Cavity Opto-Mechanics: Backaction at the Mesoscale," ***Science*, 321, 1172** (2008)

# Quantum regime of mechanical oscillators

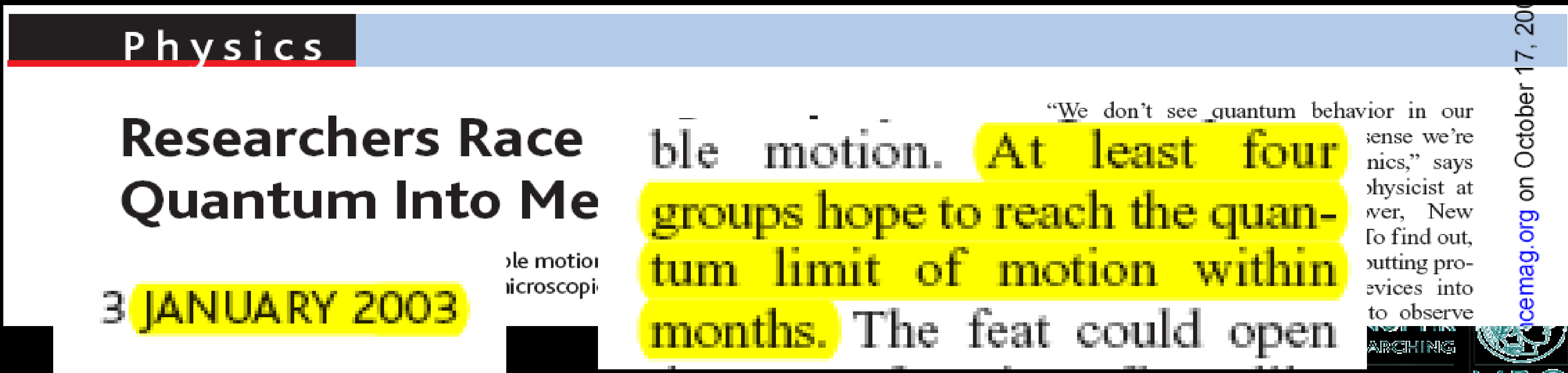
**Prerequisites to be able observe e.g. zero point motion or quantum back-action of the measurement**

- **Imprecision at the zero point motion level** $S_{SQL} = \sqrt{\frac{\hbar}{m\Omega_m \gamma_m}}$

- **Mechanical oscillators in which thermal noise is sufficiently reduced (close to quantum ground state)**

$$n \approx \frac{k_B T}{\hbar \Omega} \qquad \Omega_m = 1\text{MHz}, \mathrm{T_Q} = 50\mu\text{K}$$

**Difficult!** **e.g. Science Magazine, A. Cho:**


Physics

Researchers Race Quantum Into Me

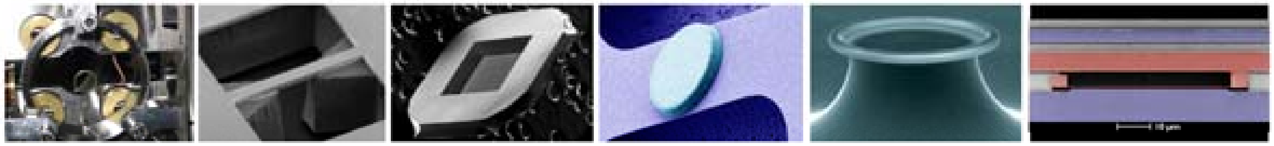
3 JANUARY 2003

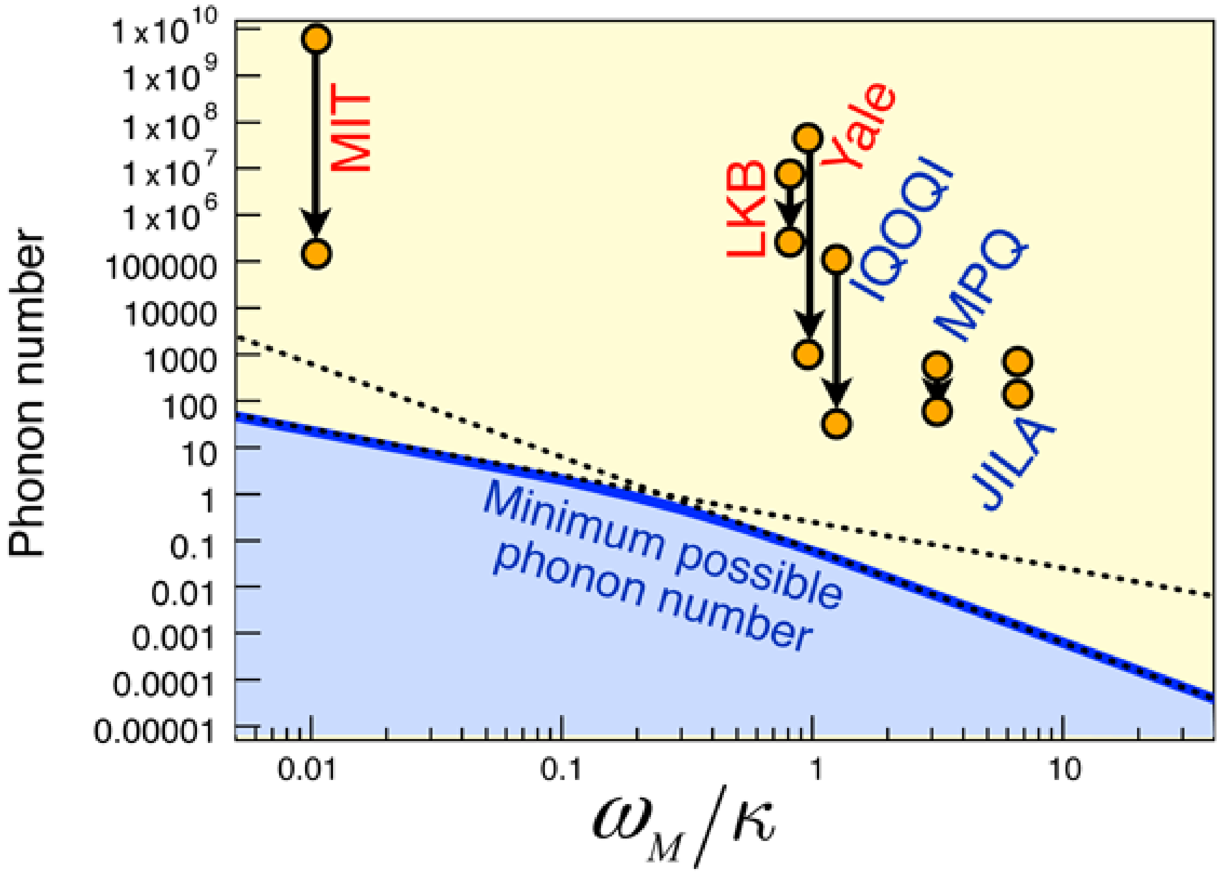
ble motion. At least four groups hope to reach the quantum limit of motion within months. The feat could open

"We don't see quantum behavior in our


cemag.org on October 17, 20

# Demonstration of Backaction Cooling

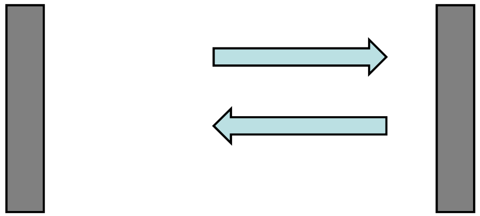





**Physics 2, 40 (2009)**
**DOI: 10.1103/Physics.2.40**
**F. Marquardt, Girvin, Optomechanics**

# Quantum Limits of Radiation Pressure Cooling

**Quantum Limits of radiation pressure cooling – <u>photon shot noise perspective</u>**



$$\Delta p = 2\hbar \cdot k$$

$$F_{RP} = < F_{RP} > + \delta F(t)$$

$$S[\Omega]_{NN} = n \cdot \frac{\kappa}{\frac{\kappa^2}{4} + (\Omega - \Delta)^2}$$

**Spectrum of Photon Number Fluctuations**

$$S_{FF}[\Omega] = \left(\frac{2\hbar k}{T_{rt}}\right)^2 S_{NN}[\Omega]$$

**Spectrum of Radiation Pressure Fluctuations**

$$n_f = \frac{1}{\hbar \Omega_m} \int_{-\infty}^{\infty} S_{FF}[\Omega] \cdot \chi(\Omega)^2 \Omega^2 m_{eff} d\Omega$$

**Final temperature due to Radiation Pressure Fluctuations**


I. Wilson-Rae, Nooshi, Zwerger, T.J. Kippenberg, PRL **99**, 093901 (2007)

F. Marquardt, Chen, Clerk, Girvin, PRL **99**, 093902 (2007)

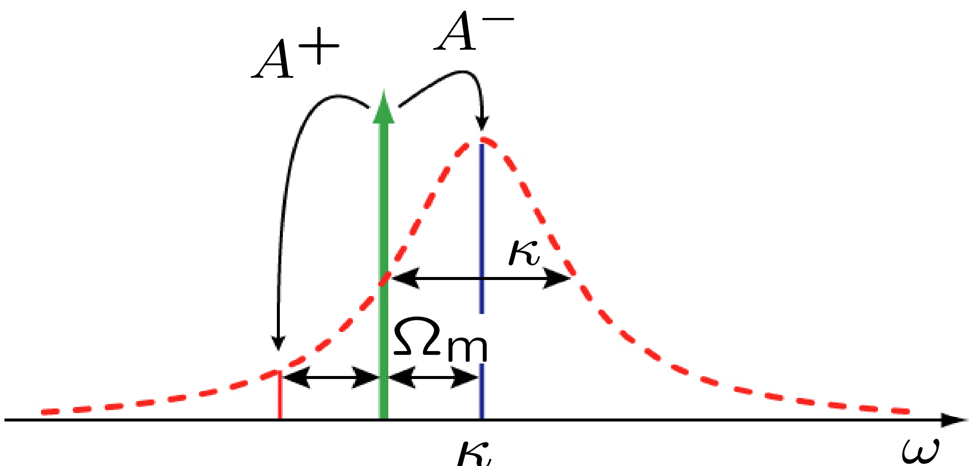
# Quantum Limits of Radiation Pressure Cooling



$$n_\mathrm{f} \approx \frac{\Gamma_\mathrm{m}}{\Gamma_\mathrm{cool}} n_\mathrm{i} + \frac{A_+}{A_- - A_+}$$

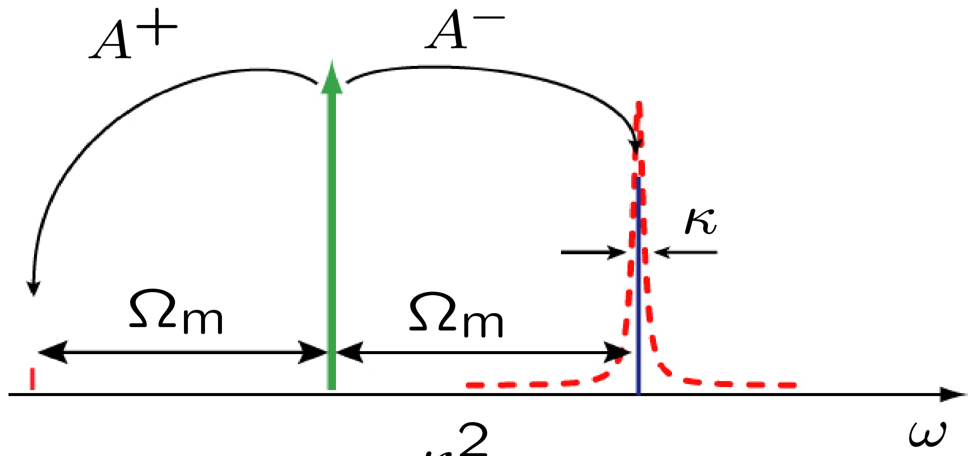
**Reservoir heating**

**Quantum Backaction** $\tilde{n}_\mathrm{qba}$




$$\tilde{n}_\mathrm{f} \approx \frac{\kappa}{4\Omega_\mathrm{m}} \gg 1$$

**„Doppler" limit**
**ground-state cooling impossible**

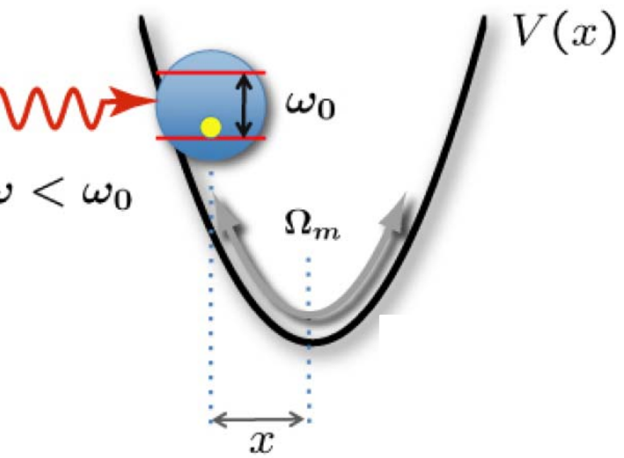


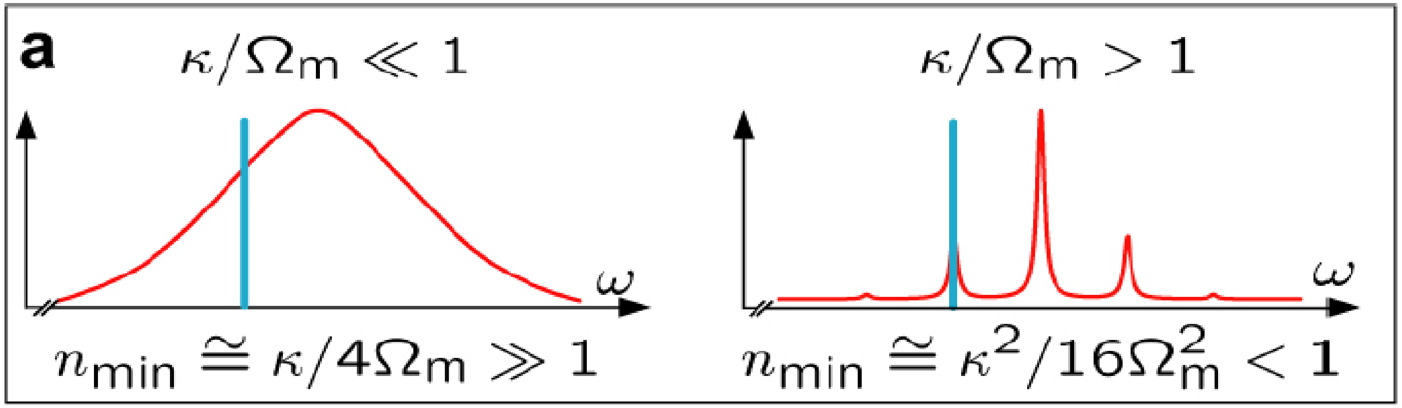

$$\tilde{n}_\mathrm{f} \approx \frac{\kappa^2}{16\Omega_\mathrm{m}^2} \ll 1$$

**resolved sideband cooling**
**ground-state cooling possible**

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

# Resolved Sideband Cooling




EL 9 Proposed $10^{14}\Delta\nu<\nu$ Laser Fluorescence Spectroscopy on $Tl^{+}$ Mono-Ion Oscillator III.
D. WINELAND and H. DEHMELT, U. of Washington.--The pulsed


EL 9 Proposed $10^{14}\Delta\nu<\nu$ Laser Fluorescence Spectroscopy on $Tl^{+}$ Mono-Ion Oscillator III.
D. WINELAND and H. DEHMELT, U. of Washington.--


oscillation parallel the $\lambda_2$ beam. Then the MIO predominantly absorbs $(\nu_2-\nu_v)$ photons. As it emits photons at all side band frequencies $\nu_2 + n\nu_v$, $|n|=0,1,2\cdots$, but of average energy $h\nu_2$ the balance $h\nu_v$ has to come from the oscillatory motion. The maximum cooling rate is $\sim h\nu_v/2\tau_2 \approx .2eV/s$! This only drops off for $v_m << v_m^*$, promissing oscillatory temperatures $h\nu_v/2k \approx 10^{-4}°K \leq T_i << M v_m^{*2}/2k \approx .004°K$, $-\delta_D << 7mHz$, $-\delta_S << 3mHz$ and no Doppler side bands on the $\lambda_0$ resonance! Directing the $\lambda_2$ beam along $(-\hat{i} + \hat{j} + \hat{k})$ makes the cooling 3-dimensional[1].--H.D. thanks H. Walter and coworkers for stiumlating discussions. We thank the National Science Foundation for it's generous support.

[1]Dehmelt, Bull. APS 18, 1521 (1973) & 20, 60 (1975).

**Lead to ground state cooling of ions:**

F. Diedrich, J. C. Bergquist, W. M. Itano, D. J. Wineland, *Physical Review Letters* 62, 403 (Jan, 1989).

D. Wineland, H. Dehmelt, *Bulletin of the American Physical Society* **20, 637 (1975).**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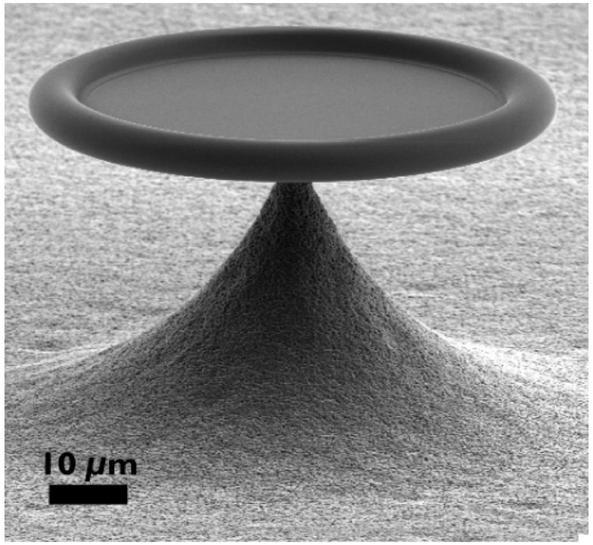
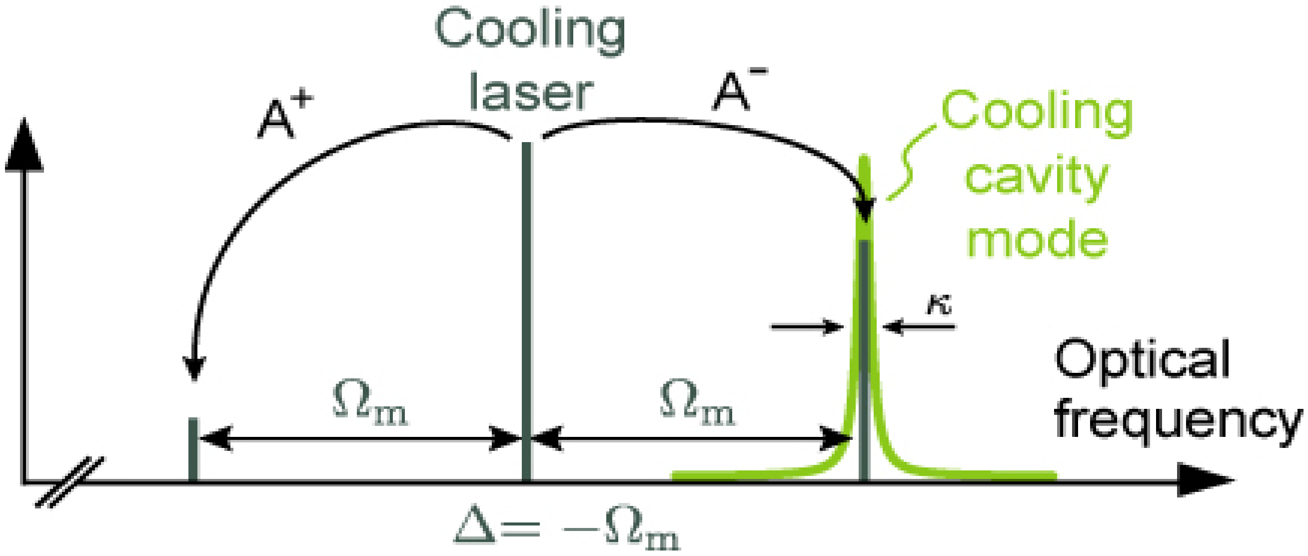
MPQ

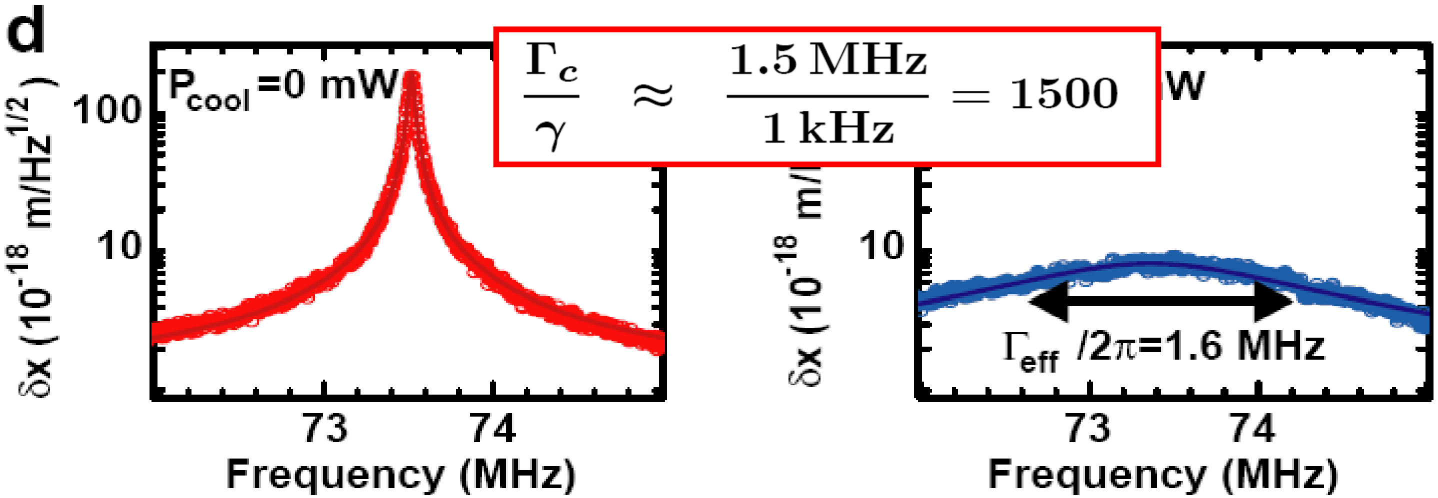
# Demonstration of Resolved Sideband Cooling

$$\kappa \ll \Omega_m$$




$\Omega_m/2\pi = 73.5\,\text{MHz}$
$\kappa/2\pi = 3.2\,\text{MHz}$
$\mathcal{F} = 440000$
$\Omega_m/\kappa \approx 22$




$$\frac{\Gamma_c}{\gamma} \approx \frac{1.5\,\text{MHz}}{1\,\text{kHz}} = 1500$$

A. Schliesser, Rivière, Anetsberger, Arcizet, T.J.Kippenberg, *Nature Physics* 4, 415-419 (2008)

# The challenge of ground state cooling

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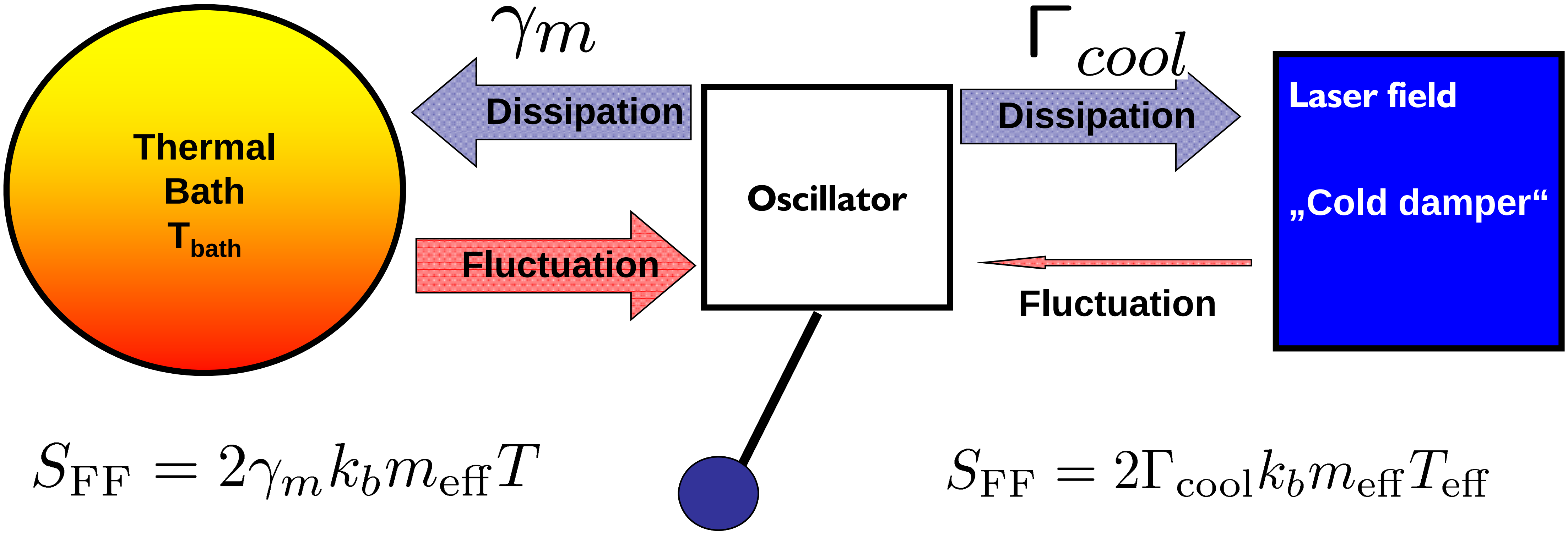


$$S_{\mathrm{FF}} = 2\gamma_m k_b m_{\mathrm{eff}} T$$

$$S_{\mathrm{FF}} = 2\Gamma_{\mathrm{cool}} k_b m_{\mathrm{eff}} T_{\mathrm{eff}}$$

$$T_{eff} = \frac{\hbar\Omega_m}{2k_b}\left(1 + \frac{A^+}{A^+ - A^-}\right)$$

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

$$T_{\mathrm{f}} \approx \frac{\gamma_{\mathrm{m}}}{\gamma_m + \Gamma_{\mathrm{cool}}} \cdot T_{\mathrm{i}}$$

Improving mechanical Q

Cryogenics....

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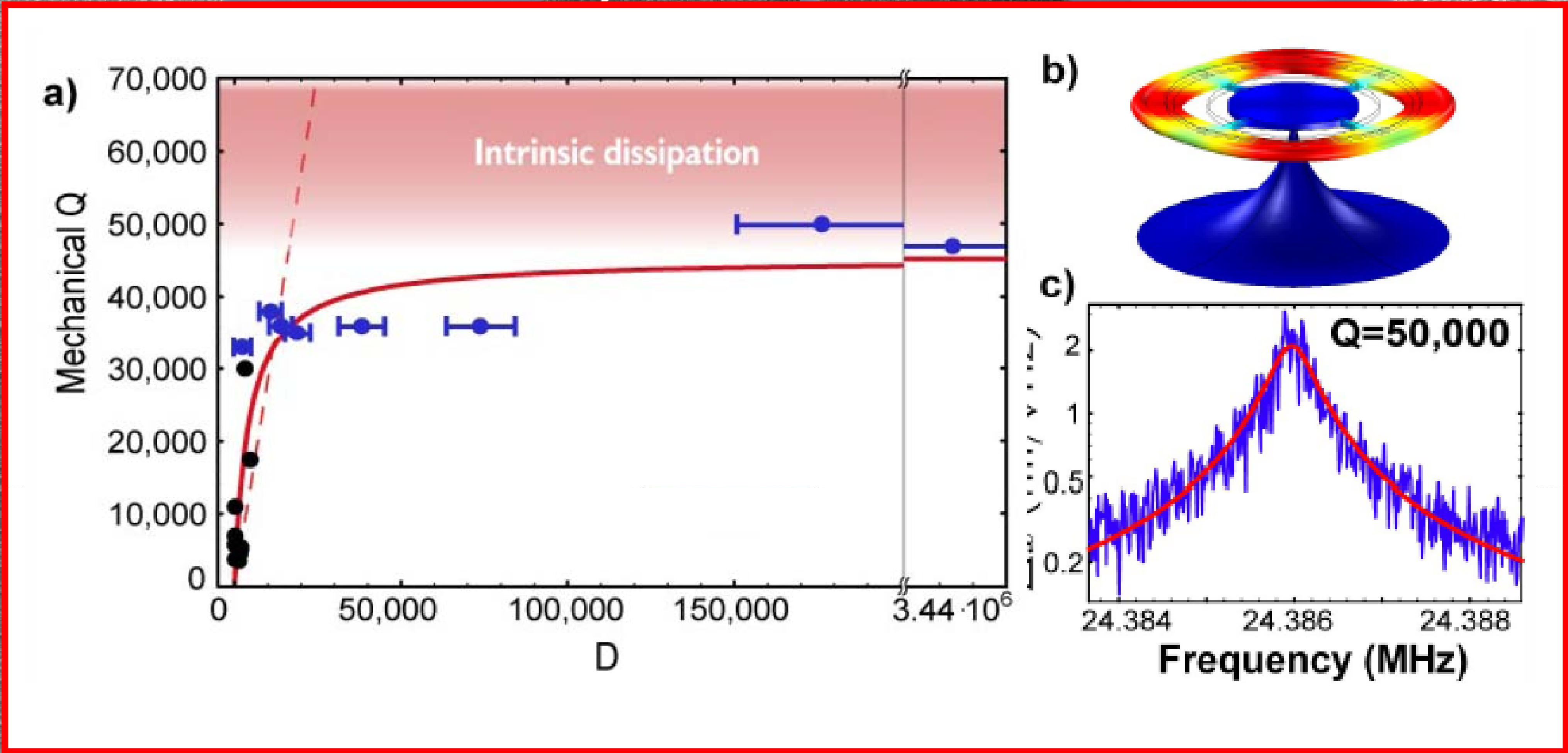
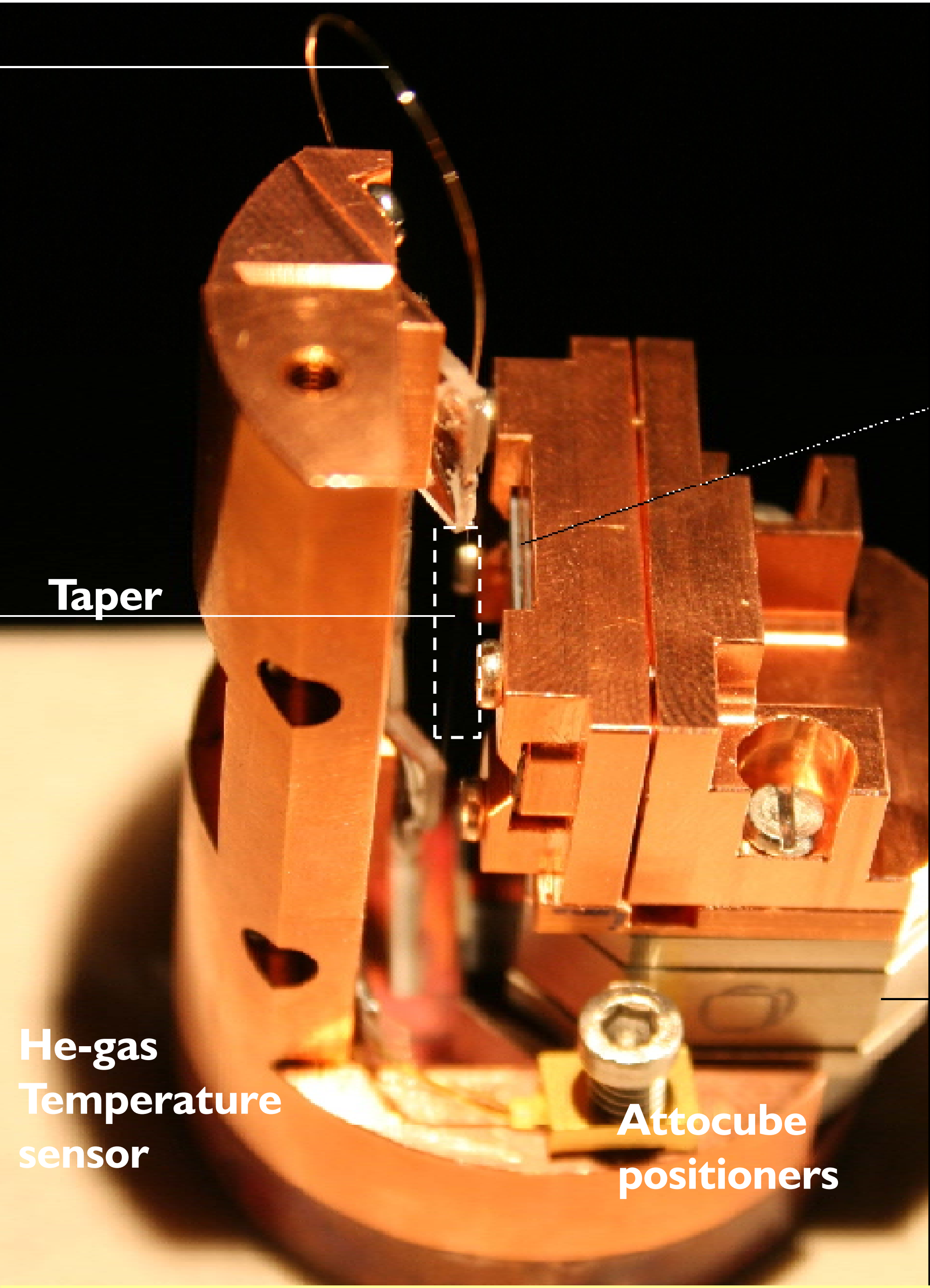
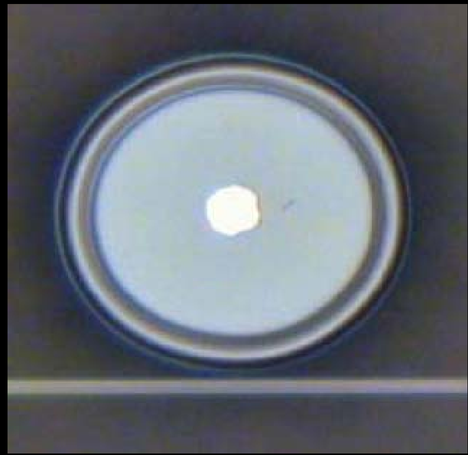
Anetsberger et. al *Nat. Photon.* 2, 627 (2008)

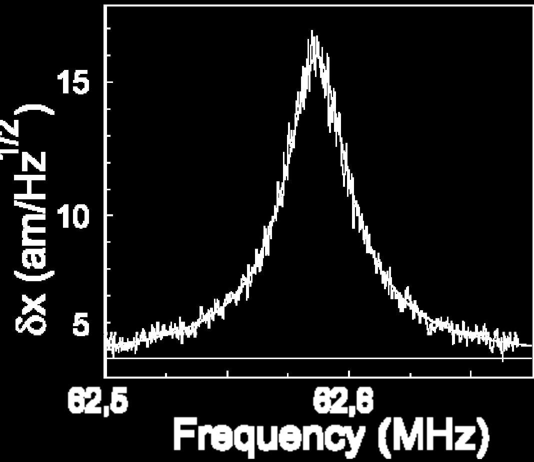
$$\nu_i = \frac{i^2\pi}{2L^2}\sqrt{\frac{Ehw^3}{12\rho A}}$$




**High Finesse and Mechanical Q factor in *<u>one and the same device</u>***





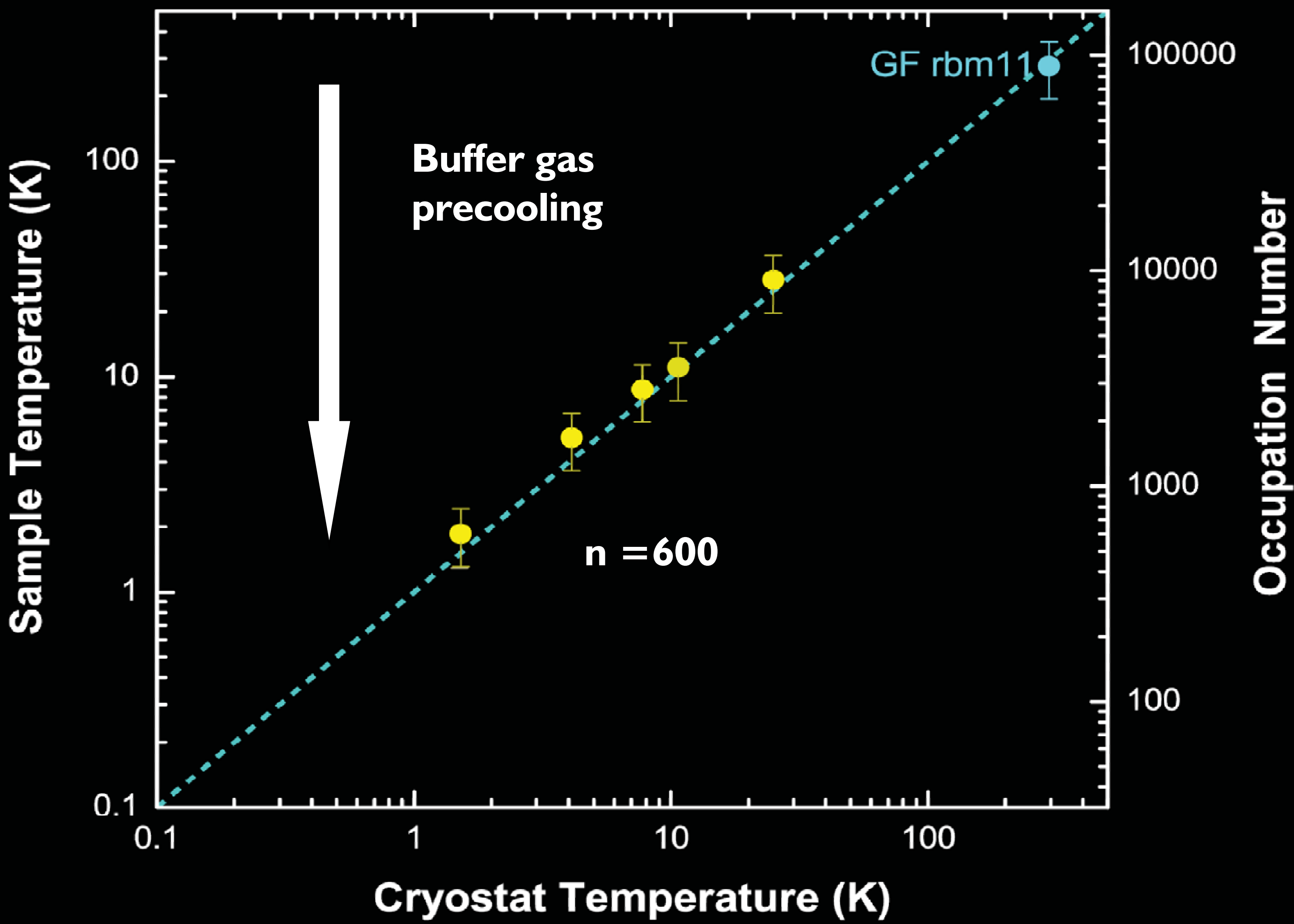

**Characteristics He Buffer gas cooling**

$$\Omega_m = 62\text{MHz} \qquad T = 1.6K$$

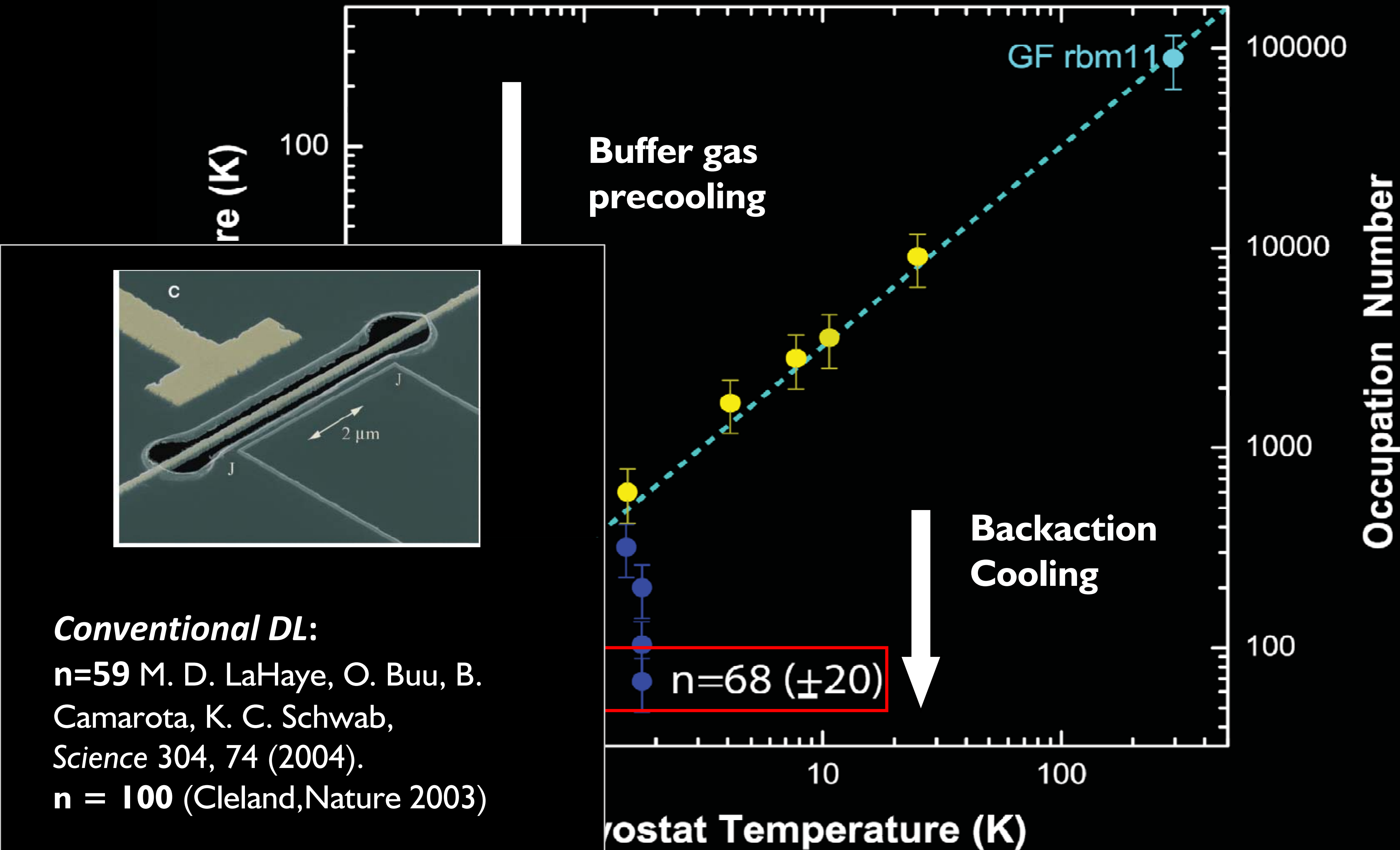
$$n = \frac{k_B T}{\hbar \Omega} \approx 500$$

http://arxiv.org/abs/0901.1292 Arcizet,Riviere, Schliesser, TJK (Phys. Rev. A ).

# Cryogenic Cavity Optomechanics @ MPQ



# Cryogenic Cavity Optomechanics @ MPQ

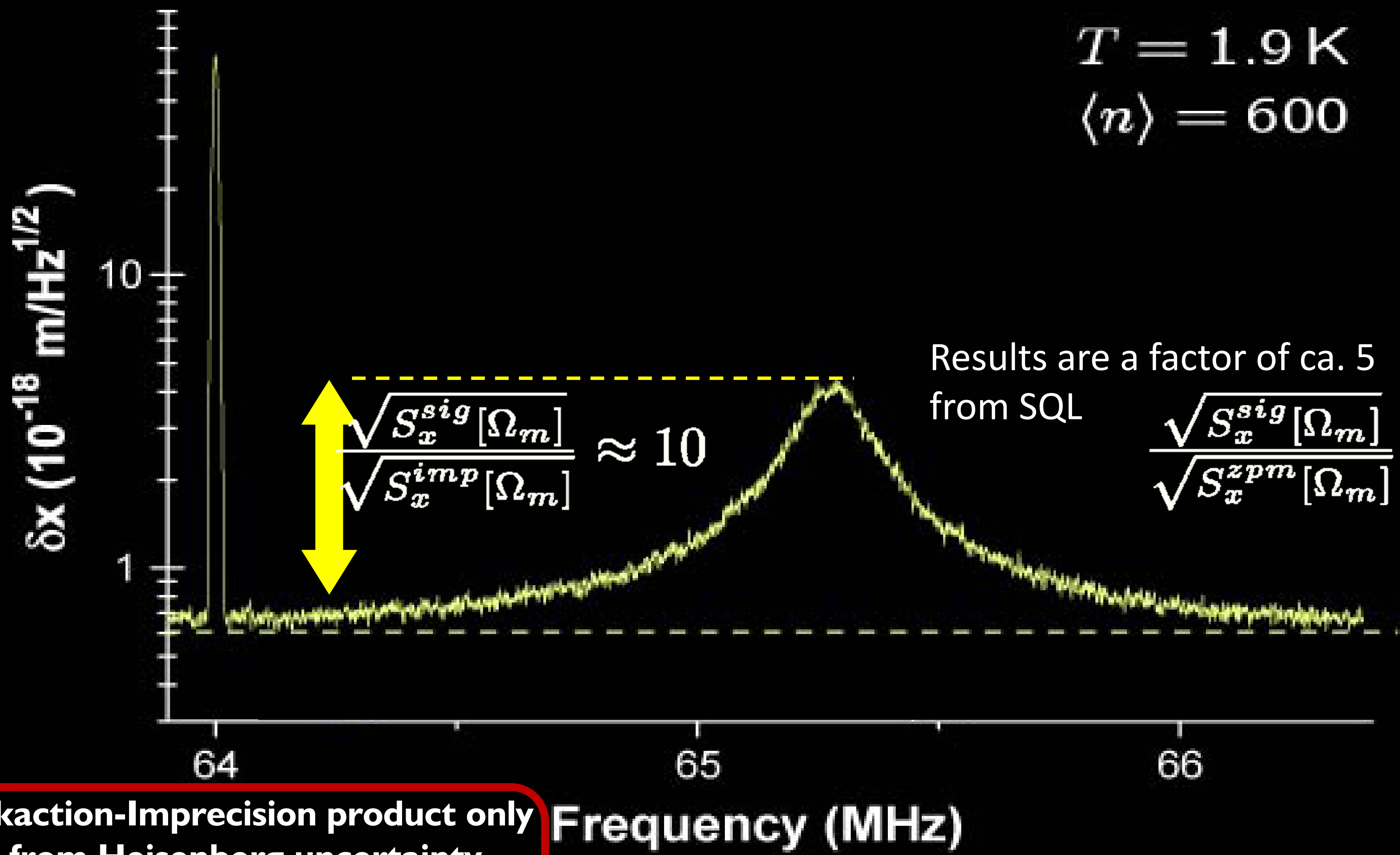



***Conventional DL*:**
**n=59** M. D. LaHaye, O. Buu, B. Camarota, K. C. Schwab, *Science* 304, 74 (2004).
**n = 100** (Cleland,Nature 2003)

Schliesser at al. Nature Physics 2009

# Approaching the SQL using a cryogenic microresonator

Schliesser, et al. Nature Physics (2009)




$$\frac{\sqrt{S_x^{sig}[\Omega_m]}}{\sqrt{S_x^{imp}[\Omega_m]}} \approx 10$$

Results are a factor of ca. 5 from SQL

$$\frac{\sqrt{S_x^{sig}[\Omega_m]}}{\sqrt{S_x^{zpm}[\Omega_m]}} = \sqrt{2n}$$

**-Backaction-Imprecision product only x100 from Heisenberg uncertainty limit**

$$\sqrt{S_x S_F} \approx \frac{\hbar}{2} \cdot 100$$

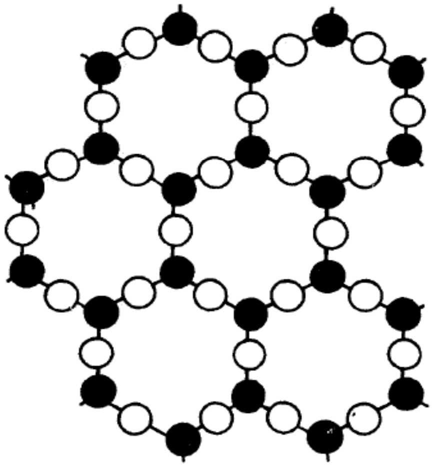
# Low Temperatures: Two level fluctuators (TLS)



**Anomalous Low-temperature Thermal Properties of Glasses and Spin Glasses**

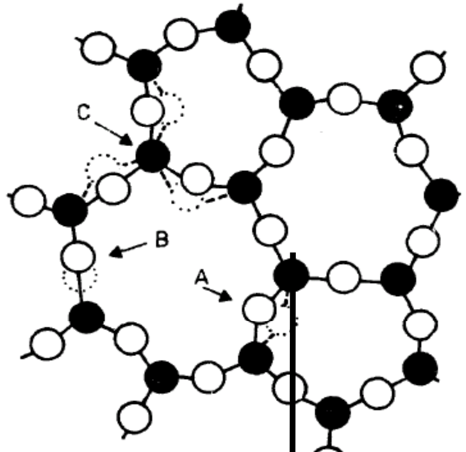
By P. W. ANDERSON†, B. I. HALPERIN and C. M. VARMA
Bell Laboratories, Murray Hill, New Jersey 07974

**Crystalline structure**



" QUARTZ- CRYSTAL"

[2]



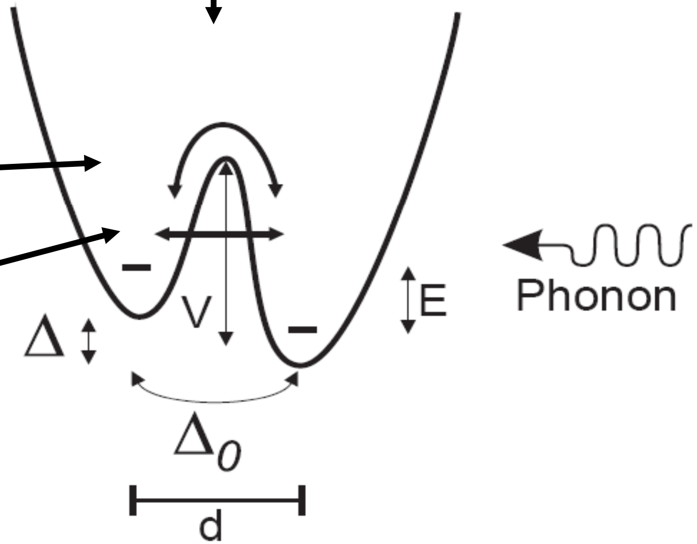

"QUARTZ-GLASS"

**Glassy structure: Different possible conformations**

**2-level system approximation [1]**

**Thermally activated process**

**Tunelling process**




[2]

**[1] Vacher, Courtens, Forêt, PRB 72 214205 (2005)**
**[2] Jäckle, Piché, Hunklinger, J. Non-Crys. Sol. 20 365 (1976)**

# Low Temperatures: Two level fluctuators (TLS)

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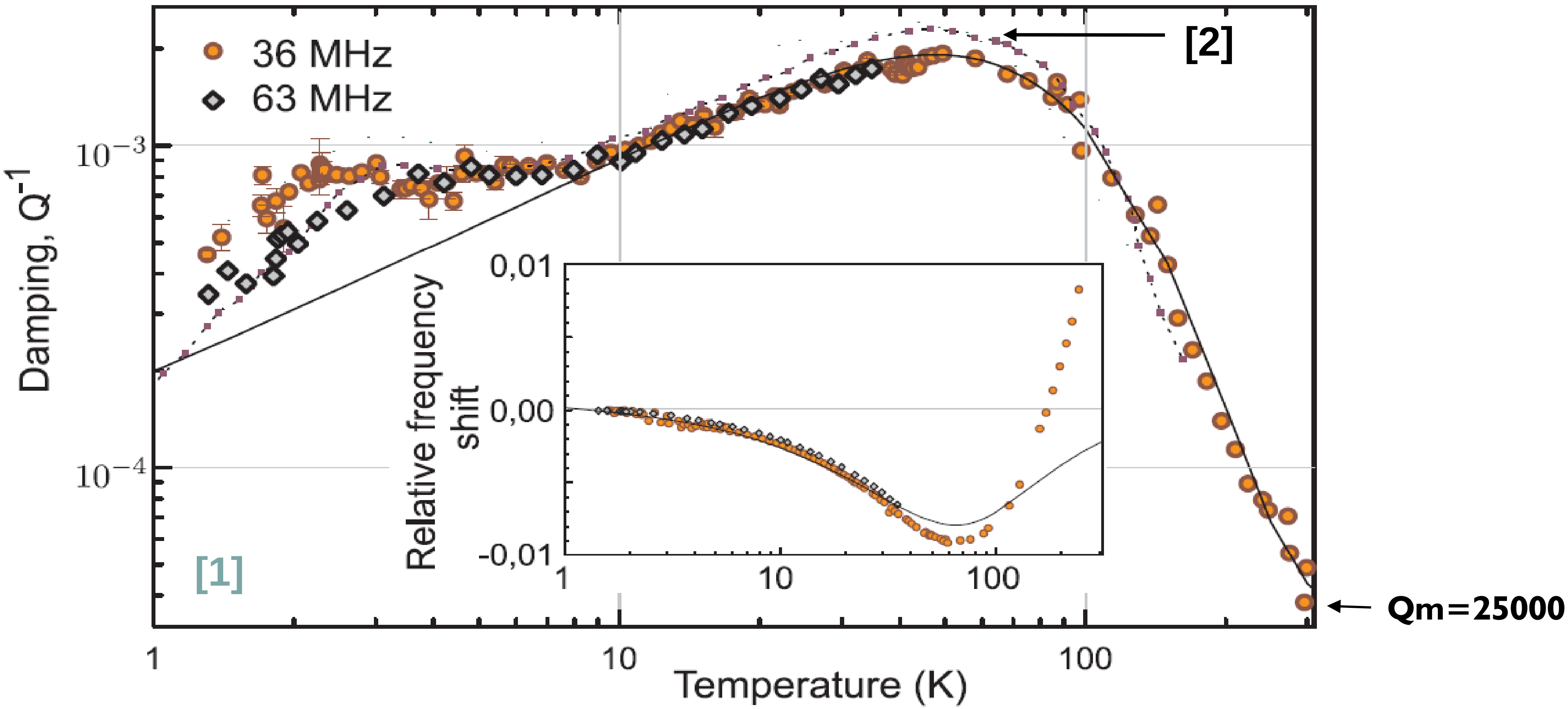


$$Q^{-1} = \mathcal{C}\,\mathrm{Erf}\left(\frac{\sqrt{2}T}{\Delta_C}\right)\frac{1}{T}\int_0^{\infty}\left(\frac{V}{V_0}\right)^{-\xi} e^{-\frac{1}{2}\frac{V^2}{V_0^2}} \frac{\Omega\tau_0 e^{V/T}}{1+\Omega^2\tau_0^2 e^{2V/T}}\,dV \quad [3]$$

[1] Arcizet, Rivière, Schliesser, Anetsberger, Kippenberg, PRA (2009)
[2] U. Bartell et al., J. Phys. (Paris) Colloq. 43, C9 (1982)11
[3] Vacher, Courtens, Forêt, PRB 72, 214205 (2005)

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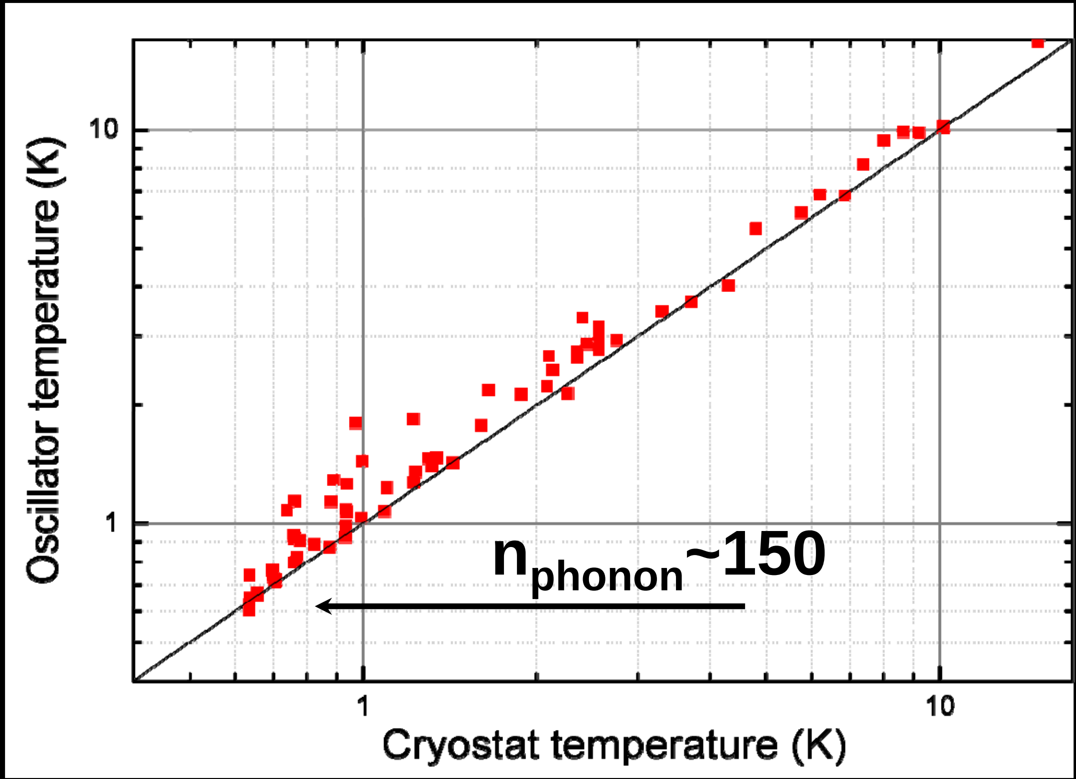
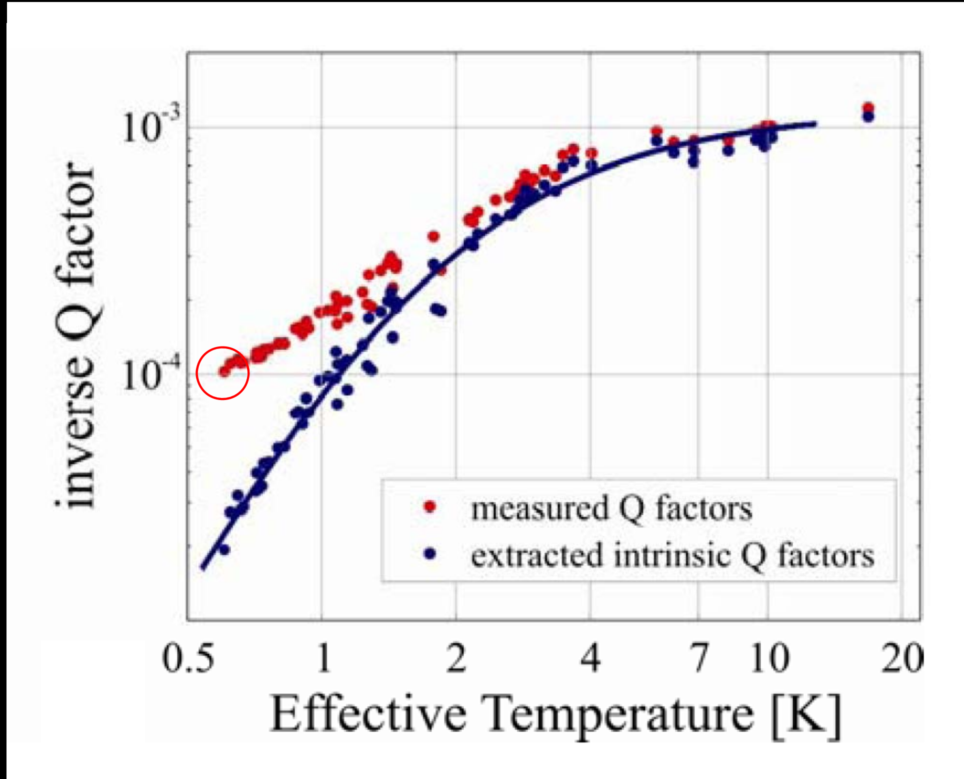
# Optomechanics at Helium-3 Temperatures (600 mK)




$$T_i = 600\text{mK} : \text{Q}_\text{m} > 10^4, \Omega_\text{m} = 75\text{MHz}$$

$$n_i = \frac{k_B T_i}{\hbar \Omega_m} \approx 150$$

**Experiments fulfills are prerequisites to achieve cooling to below n=10 and possess imprecision close to SQL.**

(O. Arcizet, S. Weis, R. Riviere unpublished)

# Evidence for direct phonon absorption (Quantum friction)

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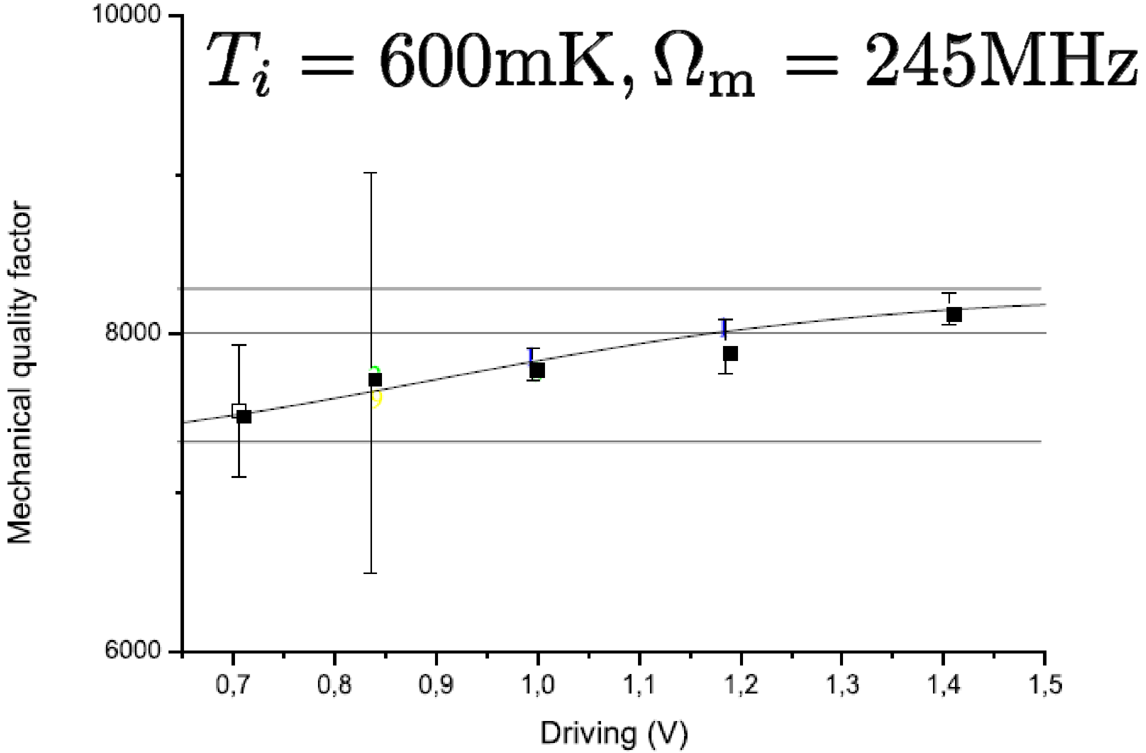
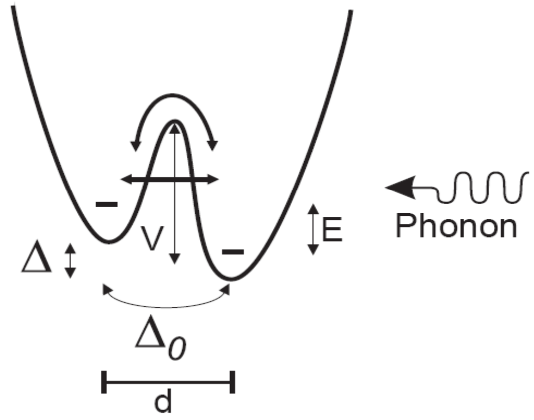
## $2^{nd}$ Order radial breathing mode




**Observation: Driving of mechanical oscillator (pm amplitudes) *increases* the mechanical Q factor**

**Explanation: Saturation of Two Level Systems due to mechanical oscillator also termed "Quantum friction"**

**L. G. Remus, M. P. Blencowe, Y. Tanaka Phys. Rev. B 80, 174103 (2009)**

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# Scientific Goals in cavity Optomechanics

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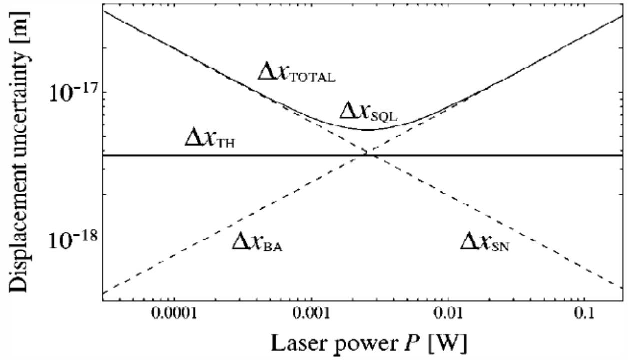
## Quantum Backaction –
## **how Nature enforces the Heisenberg uncertainty**

**Quantum-mechanical noise in an interferometer**

Carlton M. Caves
*W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, Califo*
(Received 15 August 1980)




## Ground-State Cooling – **true quantum *mechanics* of a macroscopic object**

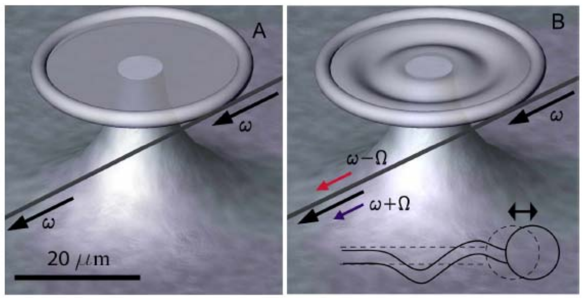
Analog to: Diedrich et al. PRL, 1989....

**Laser Cooling to the Zero-Point Energy of Motion**

F. Diedrich,[a] J. C. Bergquist, Wayne M. Itano, and D. J. Wineland
*Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80303*
(Received 28 July 1988)

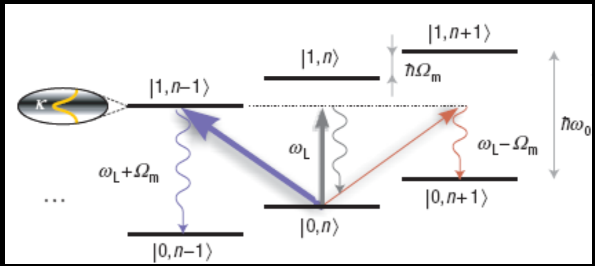
## **Applied Side:** Radiation Pressure Driven Quartz Oscillators–
## **Novel form of photonic oscillators for metrology and timekeeping**

..



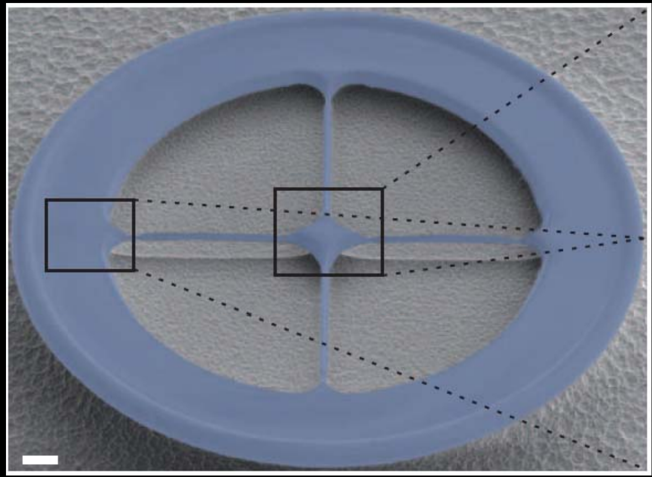
# Conclusions

## Sideband Cooling



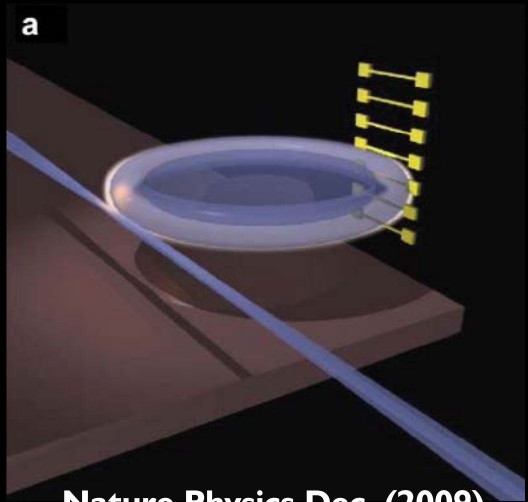

**PRL, Dec. 2008**
**Nature Physics 4, 415 - 419 (2008)**
**Nature Physics, 5, 509-514, (2009)**

## Low dissipation optomechanics



**Nature Photonics 2, 627 (2008)**

## SQL for Nanomechanics




**Nature Physics Dec. (2009)**

## Developed crystalline resonators

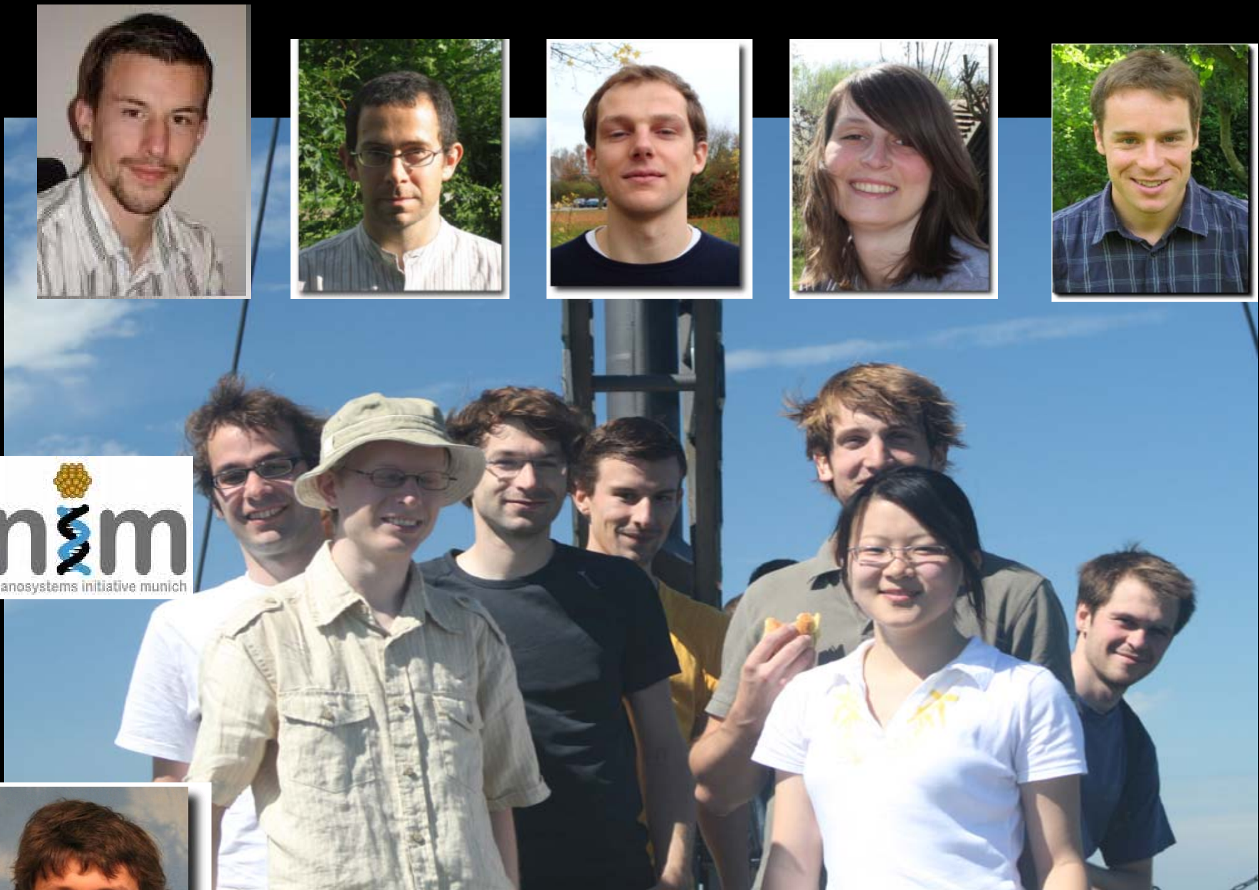

## Future Directions…

**Ground state cooling of a mechanical oscillator**

**Measurement of Zero Point Motion**

**Study of Quantum Friction**

# Acknowledgements




- **Prof. T. Hänsch**
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  (LMU, clean room access)
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  (EDFA and ESA support)


**Thank you for**
**your attention**
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