The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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International Atomic Energy Agency

2164-7

Workshop on Nano-Opto-Electro-Mechanical Systems Approaching the Quantum Regime

6 - 10 September 2010

Cavity Optomechanics with Microresonators

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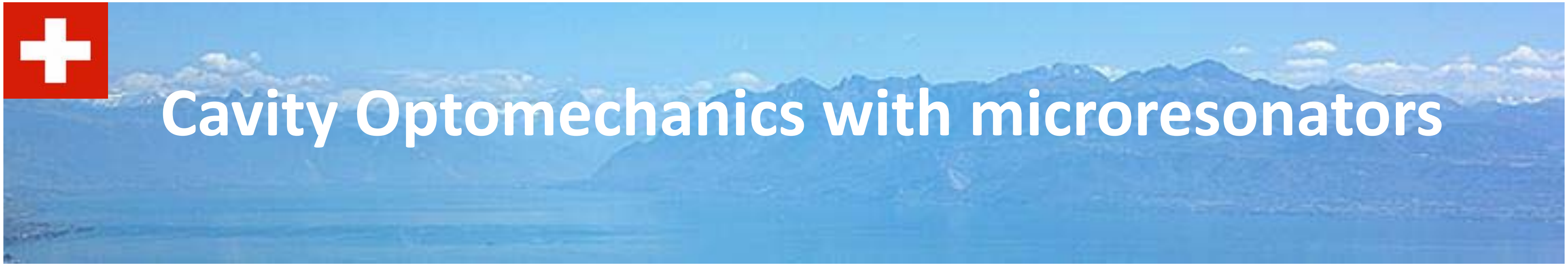

Cavity Optomechanics with microresonators

Stefan Weis, Samuel Deleglise, Pierre Verlot, Remi Riviere, A. Schliesser, Georg Anetsberger, Ewold Verhagen and Emanuel Gavartin

Tobias J. Kippenberg

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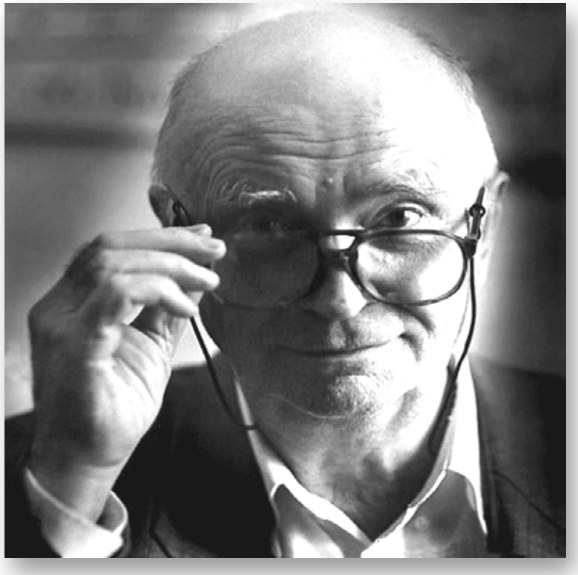
I. Wilson-Rae
A. Marx
J. Raedler
R. Holtzwarth (Menlo System)

Miramar, Italy
7th September 2010

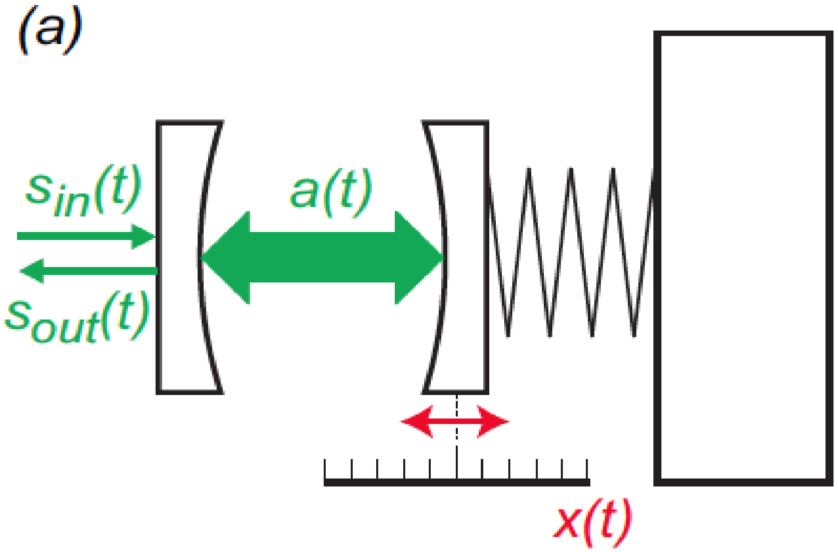
SEVENTH FRAMEWORK PROGRAMME
erc European Research Council
MARIE CURIE ACTIONS
BRIDGING THE GAP DARPA 1958 2008 50 YEARS POWERED BY IDEAS
nim Nanosystems Initiative Munich
FNSNF Fonds National Suisse Schweizerischer Nationalfonds Fondo Nazionale Svizzero Swiss National Science Foundation
EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

PhD thesis available

Parametric transducer as canonical optomechanical system



V.B. Braginsky

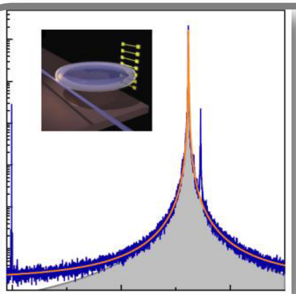


$$\omega = \omega_0 + Gx(t)$$

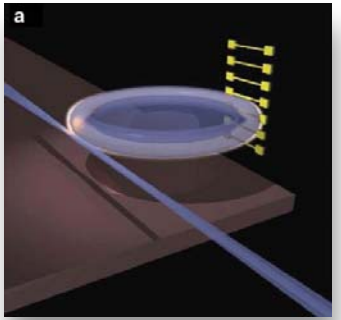
$$\boxed{\hat{H}_{int} = -\hbar\omega\frac{\hat{x}}{L}(\hat{a}^\dagger\hat{a}) = -\hat{F}_{RP}\hat{x}}$$

Braginsky, Manukin: *Measurement of Weak Forces in Physics Experiments* (1977)
Dykman, M. I., 1978. Heating and cooling of local and quasilocal vibrations by a nonresonance field. Soviet Physics Solid State 20, 1306–1311.
Braginskii, V. B., Manukin, A. B., Tikhonov, M. Y., 1970. Investigation of dissipative ponderomotive effects of electromagnetic radiation. Soviet Physics JETP 31, 829–830.

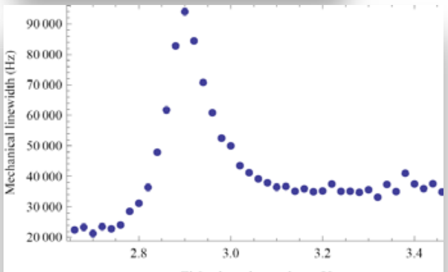
Outline



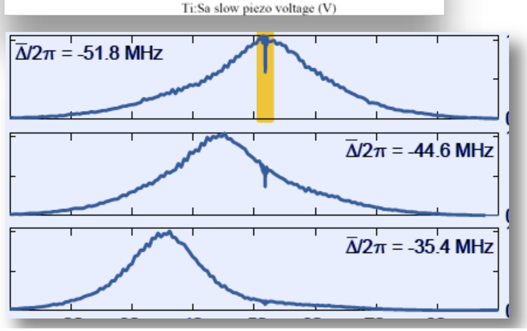
Toroid microresonators and measurement of optomechanical coupling strength



Measurement imprecision below that at The Standard Quantum Limit

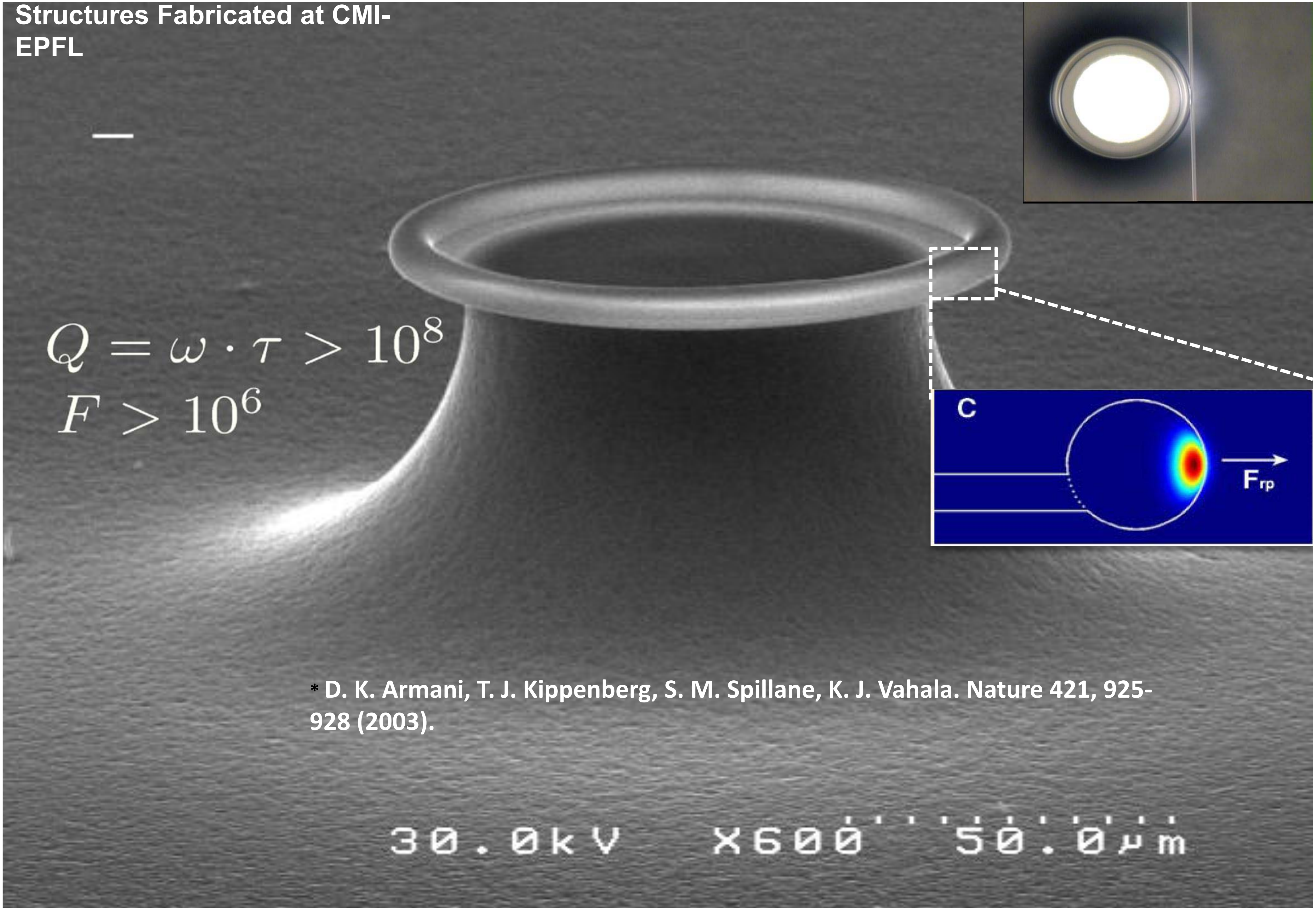


Thermometry of an optomechanically cooled Microresonator in a Helium-3 cryostat



Optomechanically induced transparency

Structures Fabricated at CMI-EPFL

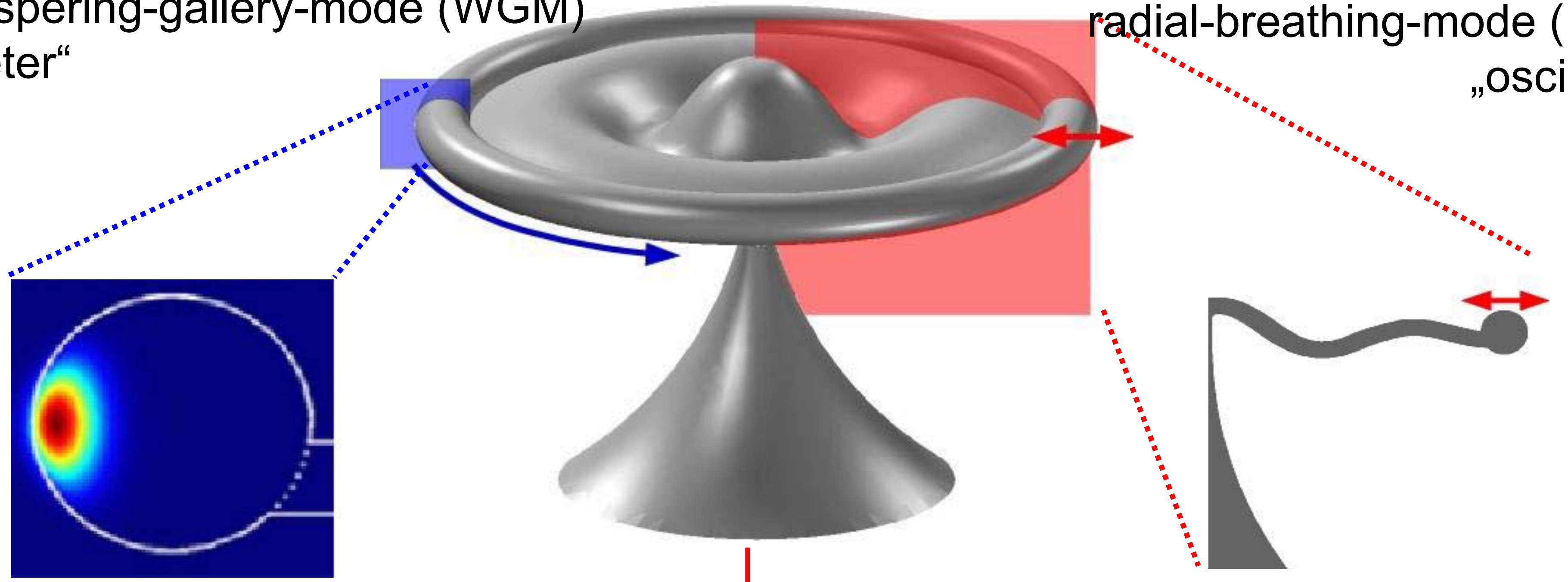


$$Q = \omega \cdot \tau > 10^8$$

$$F > 10^6$$

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

Natural optomechanical coupling in microresonators



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

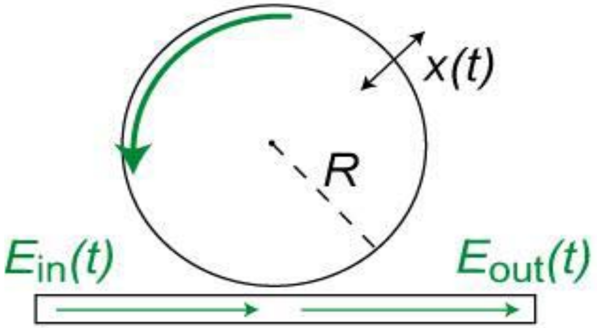
mechanical
radial-breathing-mode (RBM)
„oscillator“

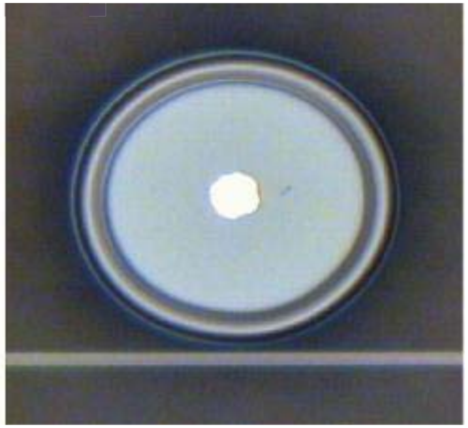
Linewidth	κ	$\gtrsim 1\,\mathrm{MHz}$
Quality factor	Q	$\lesssim 3 \cdot 10^8$
Finesse	$\mathcal{F}$	$\lesssim 10^6$
free spectral range	FSR	$\approx 1\,\mathrm{THz}$

Resonance frequency	$\Omega_\mathrm{m}/2\pi$	$\approx 50\,\mathrm{MHz}$
Quality factor	Q_m	$\lesssim 50000$
Effective mass	m_eff	$\approx 10^{-11}\,\mathrm{kg}$
RMS displacement @ RT	Δx	$\approx 50\,\mathrm{fm}$

T. J. Kippenberg, H. Rokhsari, T. Carmon, A. Scherer and K.J. Vahala *Phys. Rev. Lett.* 95, Art. No. 033901 (2005)

Optomechanical Coupling





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

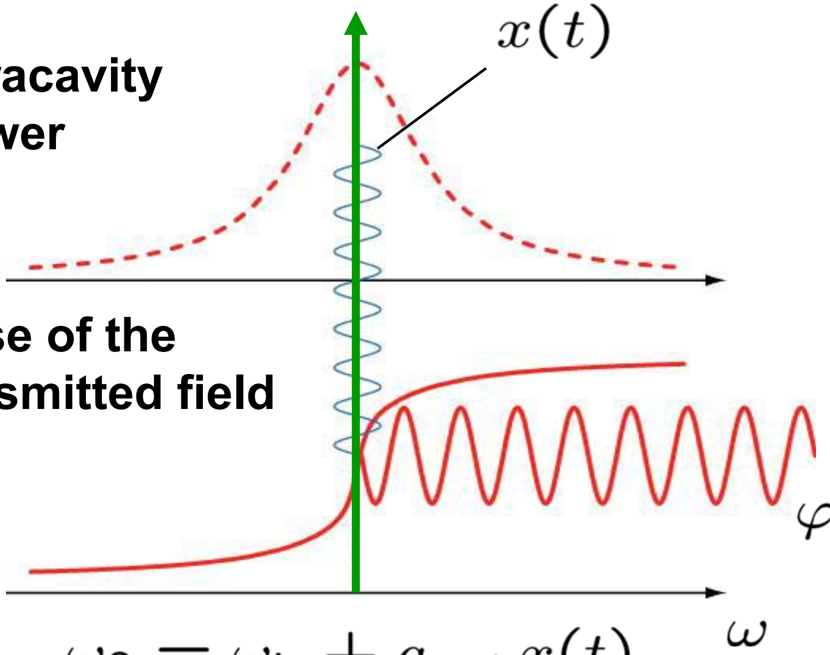
$$g_m = \frac{\omega}{R} \approx 10\mathrm{GHz/nm}$$

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

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

Intracavity power

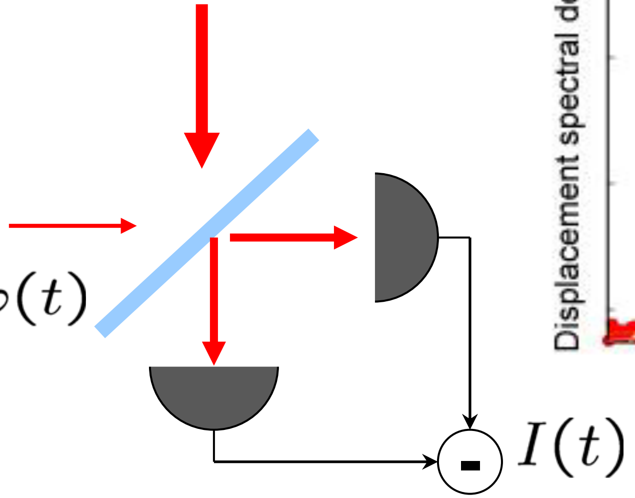
Phase of the Transmitted field

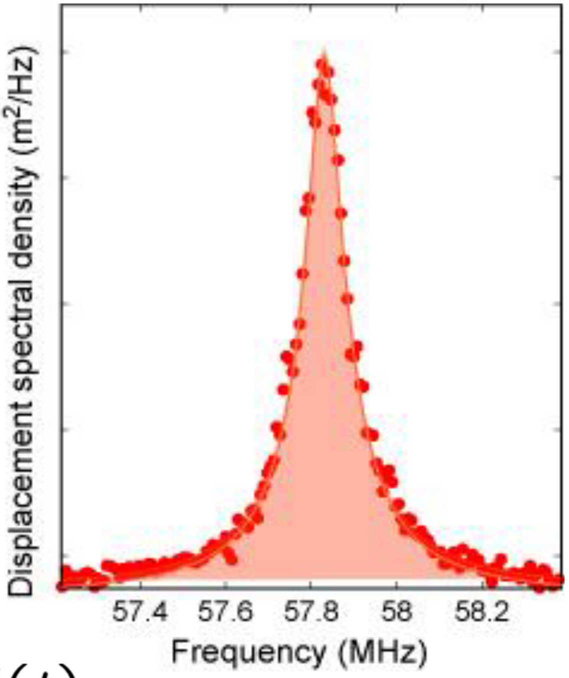


$$\omega_0 = \omega_L + g_m \cdot x(t)$$

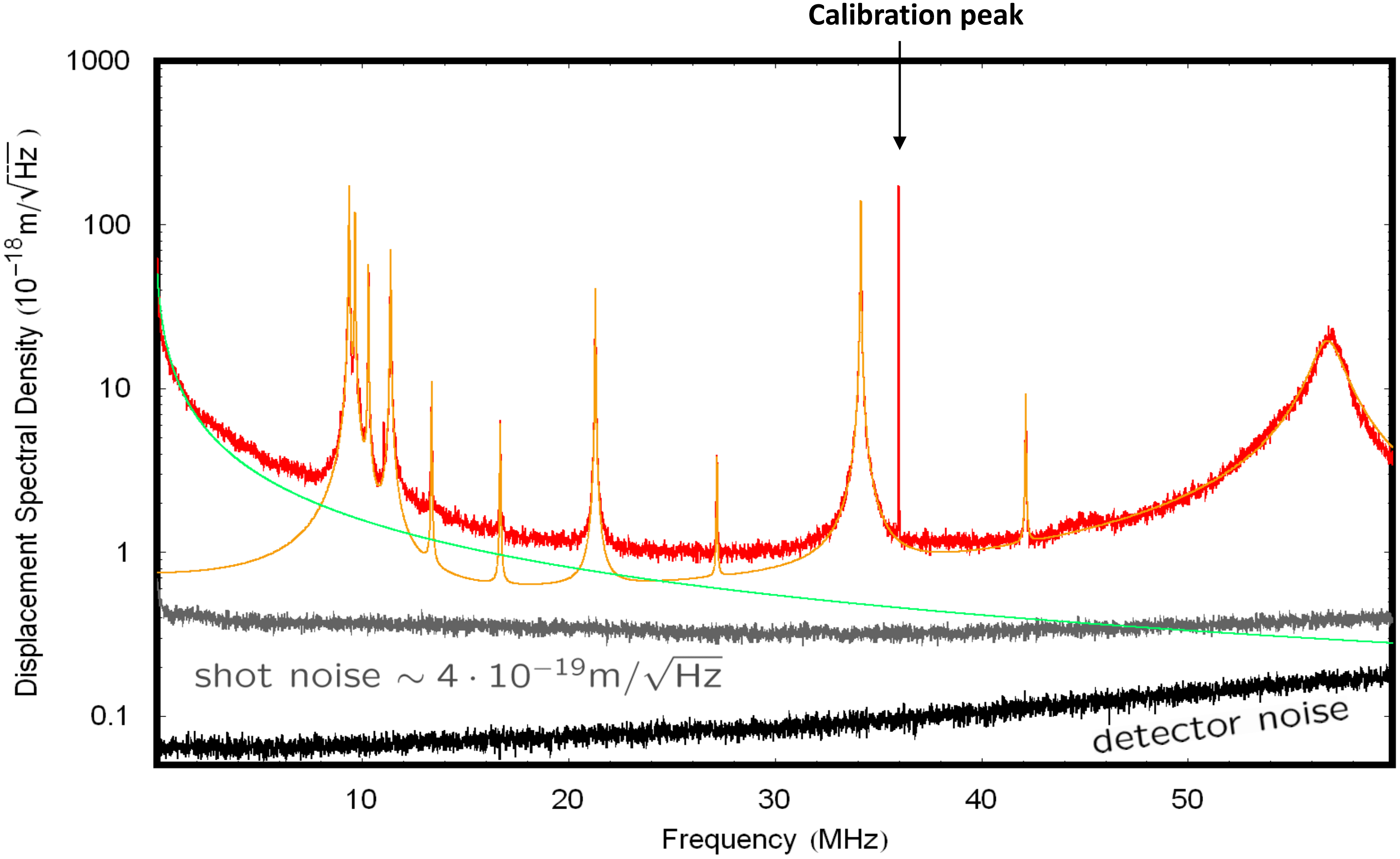
Quantum limited Homodyne Detection

LO





Quantitative Analysis of Noise Spectra



Schliesser et al., New Journal of Physics 10, 095015 (2008)

Determining the strengh of optomechanical coupling

$$\hat{H} = G x_{zpm} \cdot \hat{a}_p^\dagger \hat{a}_p (\hat{a}_m + \hat{a}_m^\dagger)$$

- **Optomechanical coupling G (Hz/nm)** $G \equiv \frac{d\omega(x)}{dx}$ $G = \frac{\omega}{L}$

- **The overlap of mechanics and optics is given by: Effective mass (*meff*)**

- **What is *Leff* and what is the amplitude *x*?**

[Eichenfeld et al. Nature]


Accordion mode

physically significant parameter is the *vacuum optomechanical coupling parameter*

$$g_0 \equiv G x_{zpm}$$

Determining the strengh of optomechanical coupling

$$\boxed{g_0 \equiv G x_{zpm}}$$

How to ***measure*** the *vacuum optomechanical coupling parameter* in an experiment directly?

Interesting relation

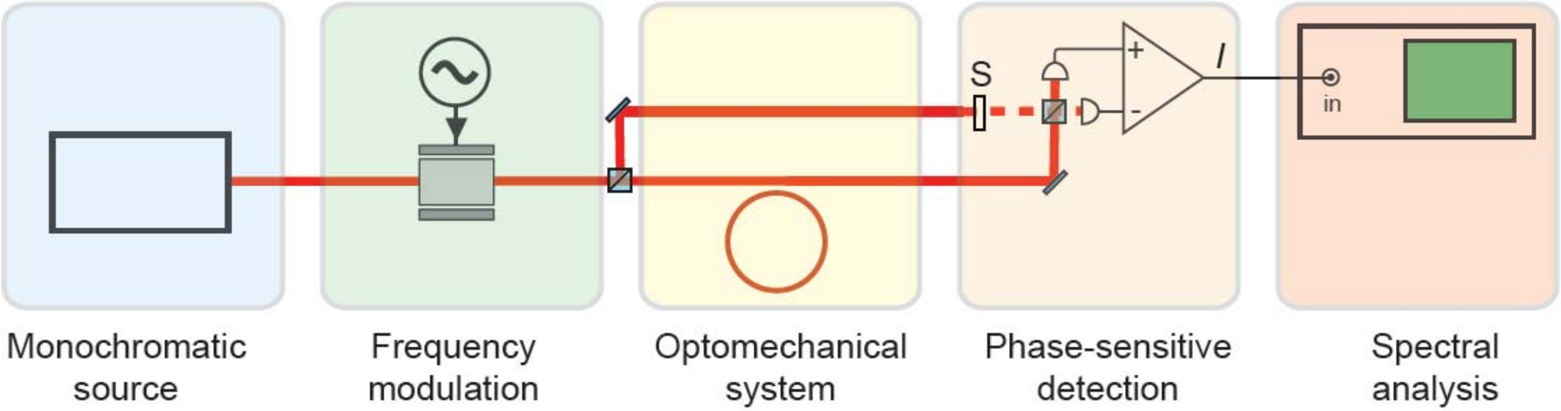
$$\int_{-\infty}^{\infty} S_{\omega\omega}(\Omega)\frac{\mathrm{d}\Omega}{2\pi} = S_{\omega\omega}(\Omega_m)\,\Gamma_\mathrm{m}/2 = 2\langle n\rangle g_0^2$$

Cavity frequency noise gives directly the vacuum optomechanical coupling strength. *No finite element simulation needed.*

$$\boxed{g_0 = \sqrt{\frac{1}{2\langle n\rangle}\int_{-\infty}^{\infty} S_{\omega\omega}(\Omega)\frac{\mathrm{d}\Omega}{2\pi}}}$$

Anetsberger, ML Gorodetsky, Schliesser, Kippenberg (to appear arXiv 2010)

Measuring the cavity frequency noise spectrum



- **Scheme to calibrate the cavity frequency (phase) noise**

$$S_{\phi\phi} = 2\pi\frac{1}{2}(\delta(\Omega-\Omega_{\mathrm{mod}})+\delta(\Omega+\Omega_{\mathrm{mod}}))\cdot\frac{\phi_0^2}{2}$$

- **Transduction of mechanical motion and phase modulation is the same (*)**

$$S_{II} = K(\Omega,\kappa,\Delta)(S_{\phi\phi}^{mod}(\Omega)+S_{\phi\phi}^{cav}(\Omega))$$

Photocurrent SD

Transduction

Calibration phase modulation SD

Phase noise SD of the cavity

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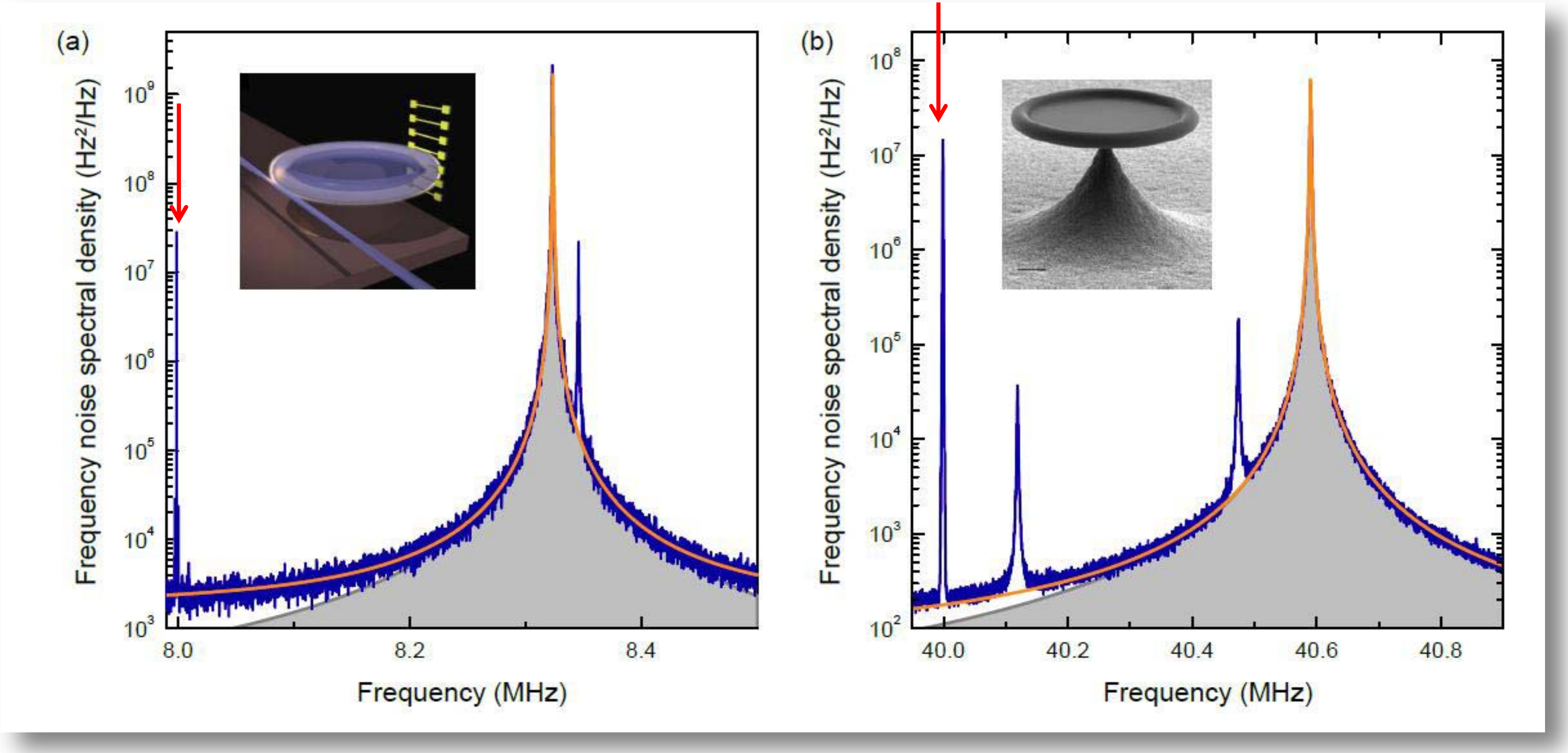
* Anetsberger, ML Gorodetsky, Schliesser, Kippenberg (to appear: arXiv 2010)

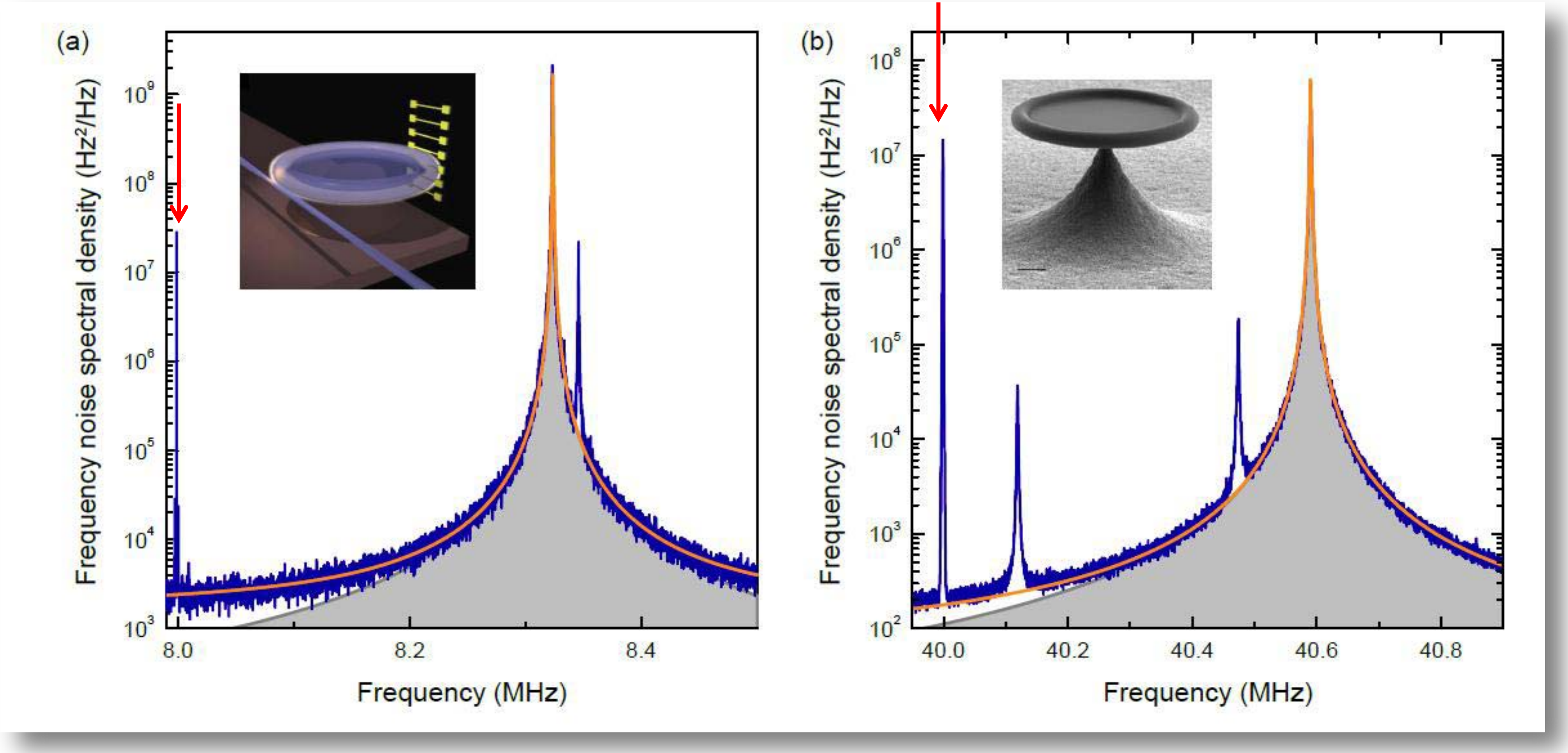
Determining the strengh of optomechanical coupling



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

Anetsberger, ML Gorodetsky, Schliesser, Kippenberg (arXiv,2010)

Determining the strengh of optomechanical coupling



$$g_0 = 2\pi \cdot 500\text{Hz}$$

$$g_0 = 2\pi \cdot 1\text{kHz}$$

$$g_0 = 2\pi \cdot 5\text{kHz}$$

Estimate for coupling strength in optomechanical systems

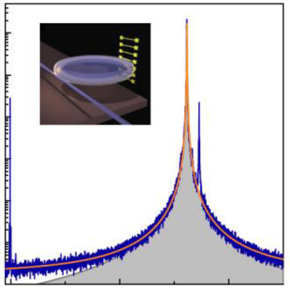
$$g_0 \equiv G x_{zpm}$$

- Microwave coupled nanobeams ~ 10-100 Hz [~ 1 kHz Teufel]
- Cantilever based systems g_0~10-100 Hz
- Toroid microcavities g_0~ 1 kHz
- Near field optical beams g_0~ 1-10 kHz
- Photonic crystals (predicted) g_0~ 100-500 kHz

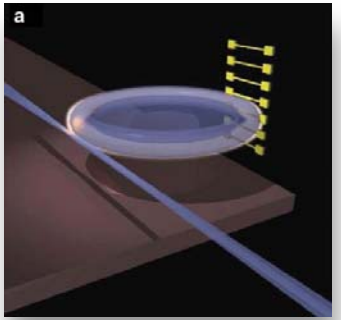
Some relevant formulas:

$$\Gamma_{cool} \approx g_0 \frac{g_0}{\kappa} \bar{n}_c \quad \Gamma_{cool} \approx \frac{4g_0^2}{\Omega_m^2} \frac{P_{in}}{\hbar \omega_L} \qquad P_{in}^{\mathrm{SQL}} = \frac{\kappa^2}{16 g_0^2} \Gamma_m [1 + \frac{4\Omega_m^2}{\kappa^2}]$$

Outline



Measuring the vacuum optomechanical coupling strength



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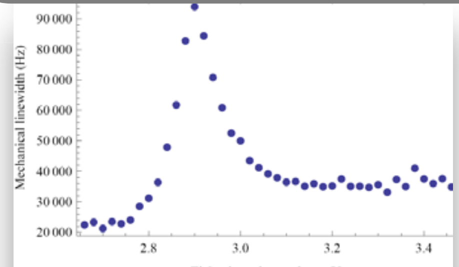

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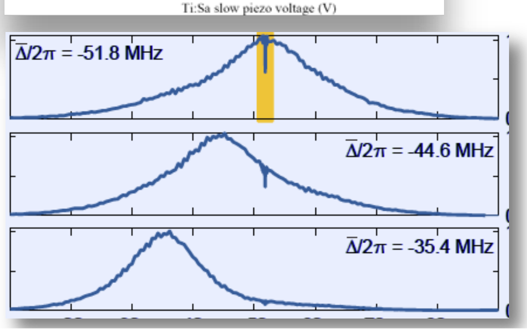
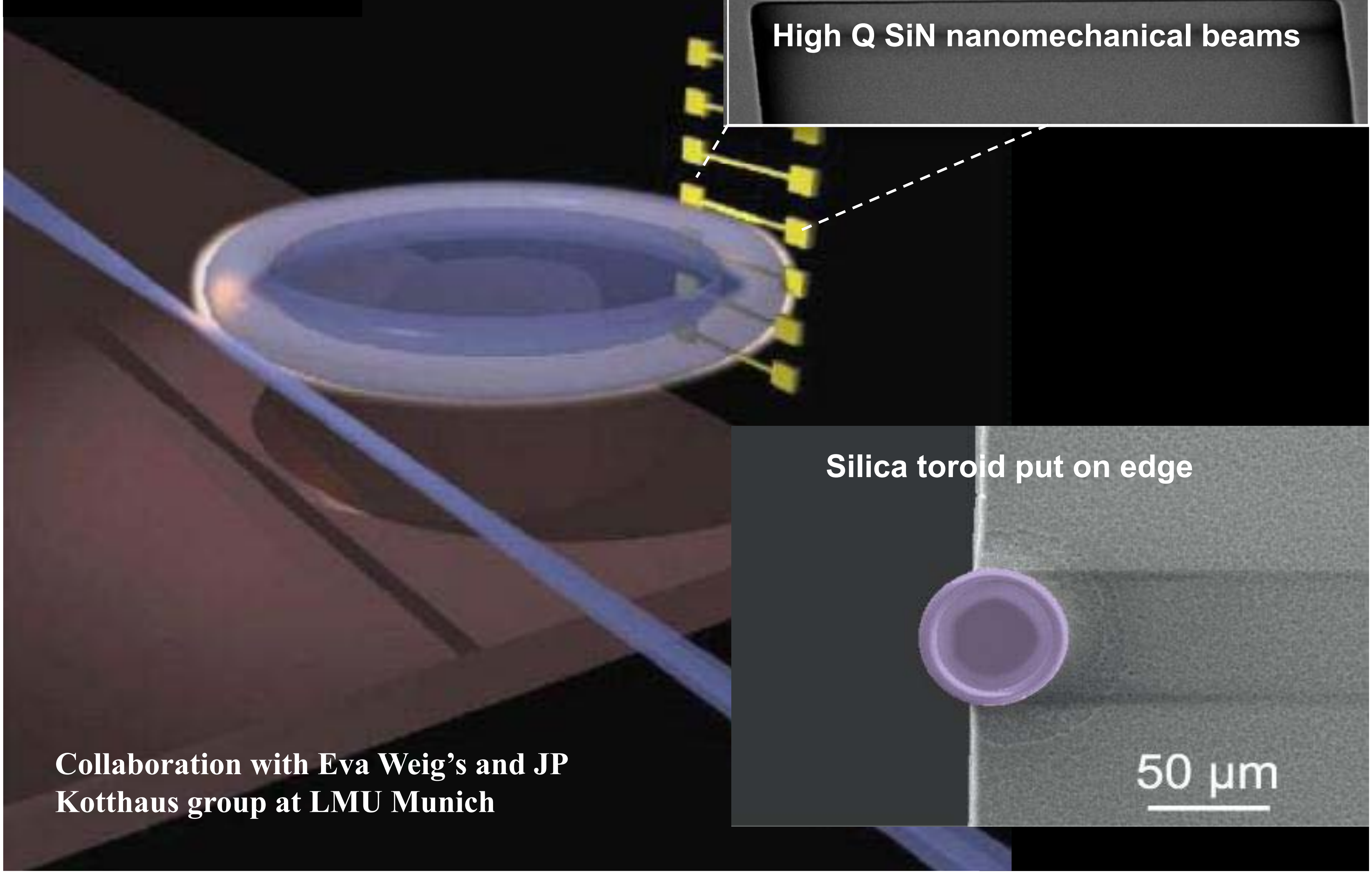


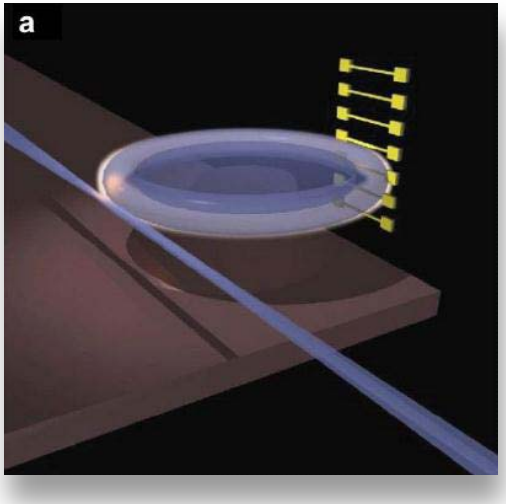
Optomechanically induced transparency

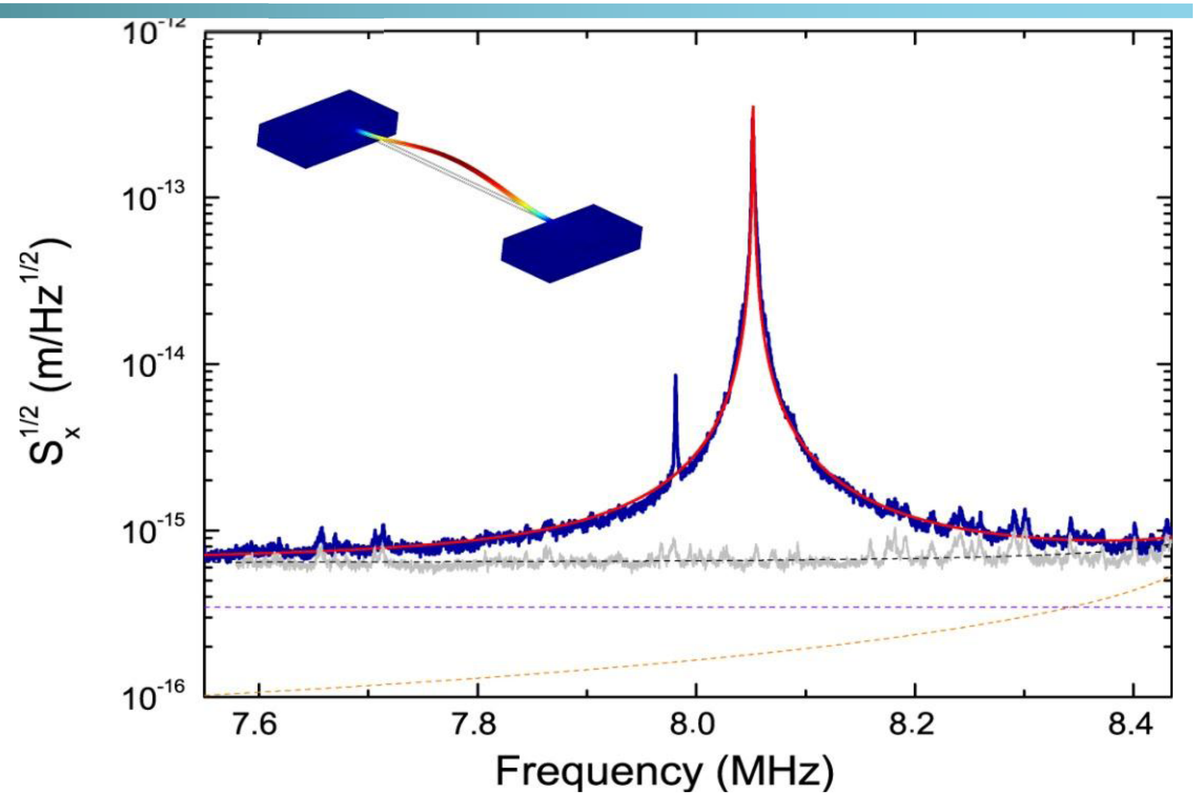
Evanescent sensing

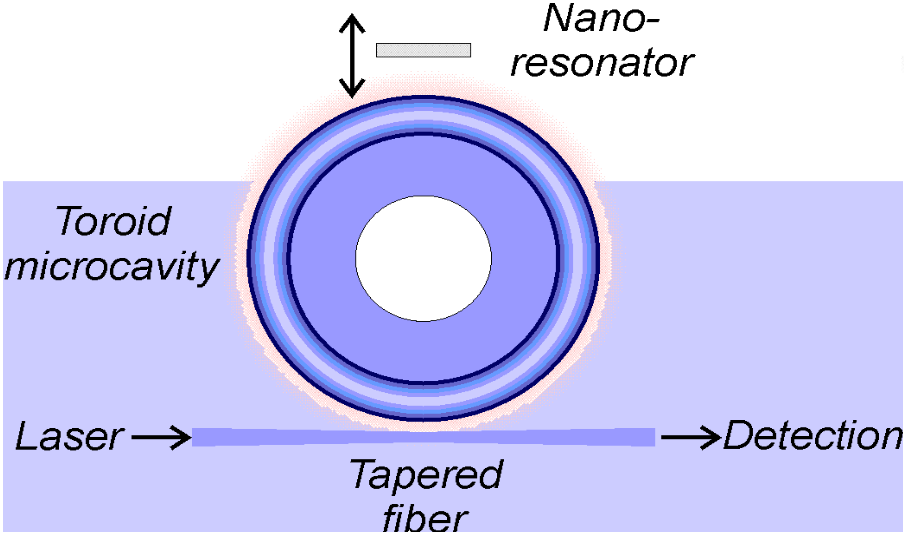


Collaboration with Eva Weig’s and JP Kotthaus group at LMU Munich

Near field displacement transduction







Parameters

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

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

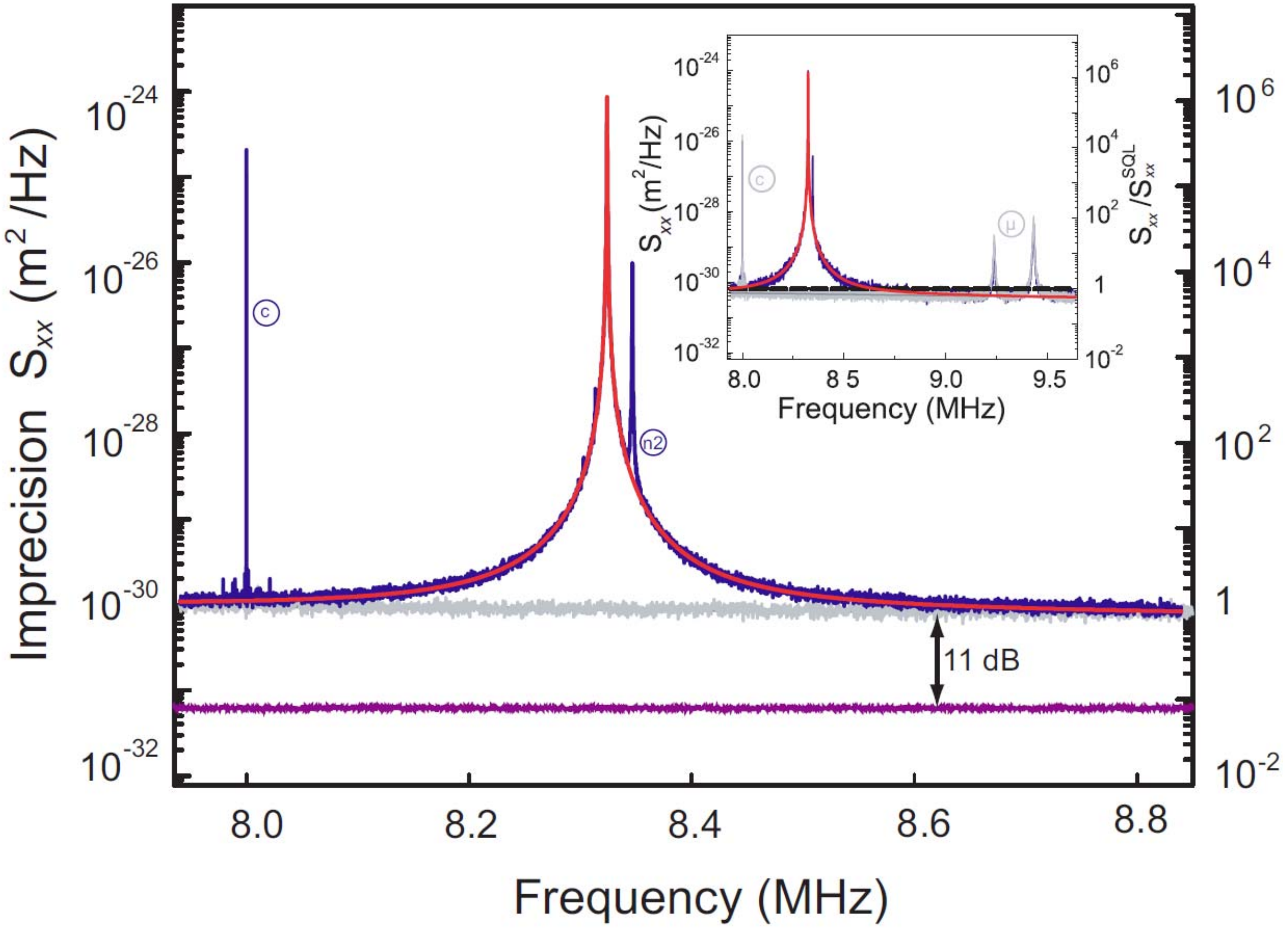
$Q_{\mathrm{m}} > 100,000$

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

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

Anetsberger, Weig, Kotthaus, Kippenberg *et al.*, Nature Physics 5, 909 (2009)

Near field displacement transduction

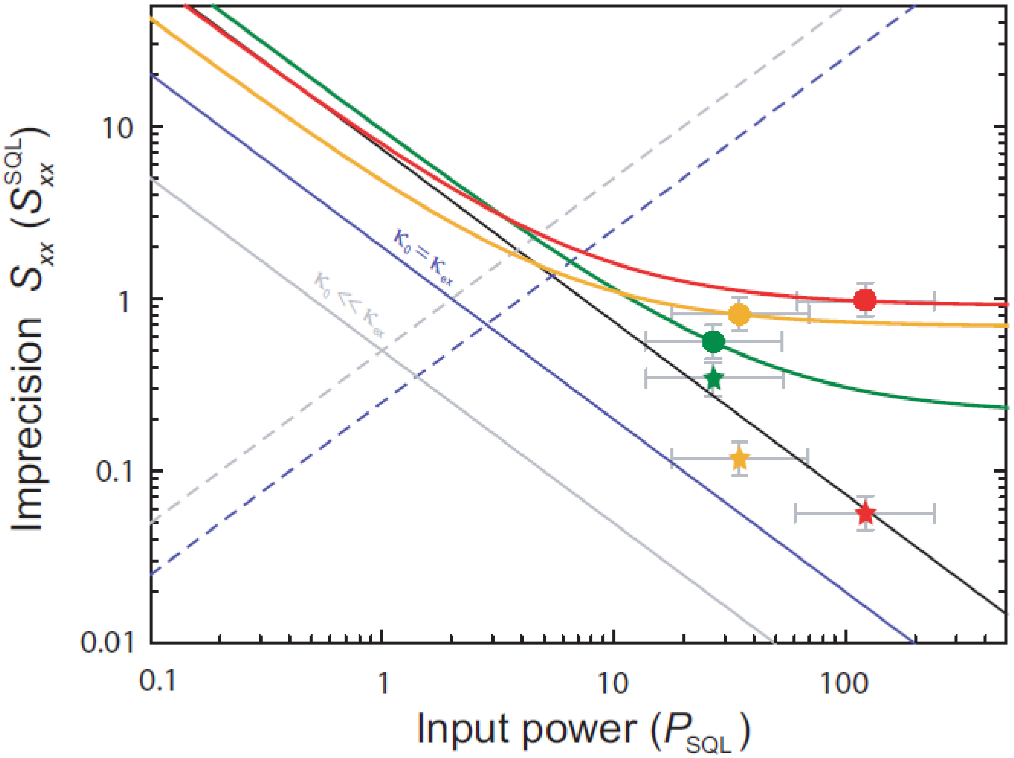


$$S_{xx} = 0.08 \times S_{xx}^{\mathrm{SQL}} \;\text{ or }\; (250\,\mathrm{am}/\sqrt{\mathrm{Hz}})^2$$

Optical fields: **Anetsberger et al. http://arxiv.org/ 1003.3752f**

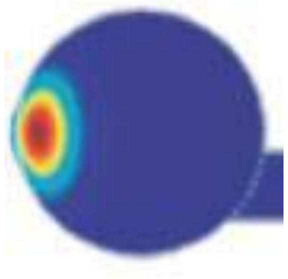
Microwave fields: **Teufel, Donner, Castellanos-Beltran, Harlow, Lehnert Nature Nanotechnology 4, 820 - 823 (2009)**

Near field displacement transduction

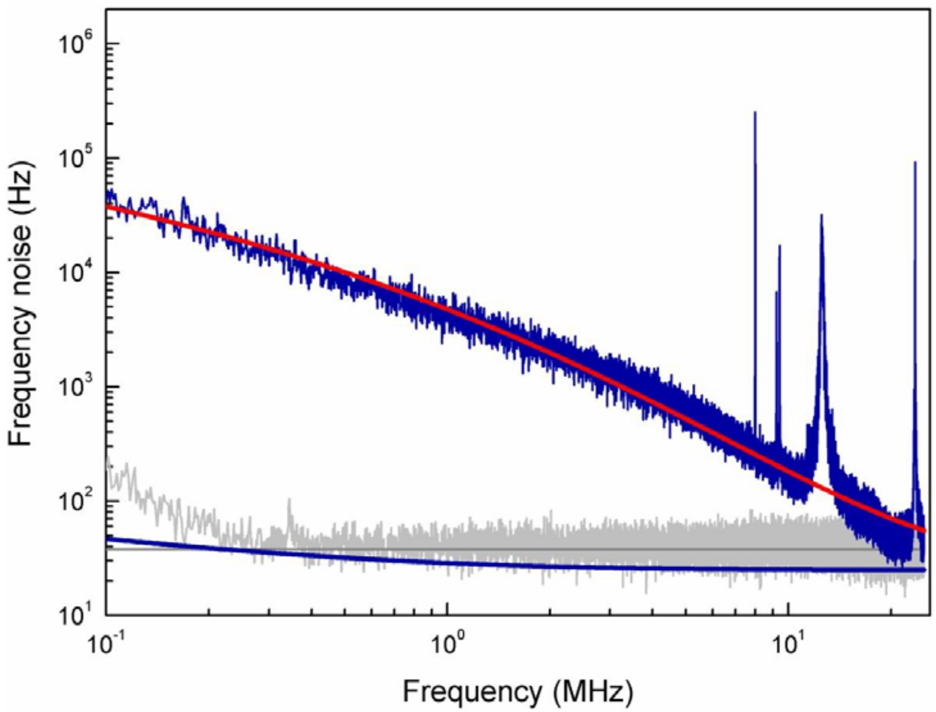


- **Imprecision limited by cavity frequency noise.**
- **Access to QBA dominated regime**

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



$$S_\omega^{\mathrm{thr}}[\Omega] = \omega^2 \left(\frac{dn}{dT}\right)^2 k_B T^2 \frac{\sqrt{l}}{\pi^{3/2} n^2 R^2 \sqrt{\Omega \lambda^2 / D}} \frac{1}{\sqrt{1-(b/d)^2}} \frac{1}{(1+(\Omega\tau)^{3/4})}$$



Anetsberger et al. http://arxiv.org/ 1003.3752f
Gorodetsky, Grudinin JOSA B, Vol. 21, Issue 4, pp. 697-705 (2004)

Quantum backaction

- **Quantum backaction[1] can reach values of unity even at *room temperature***

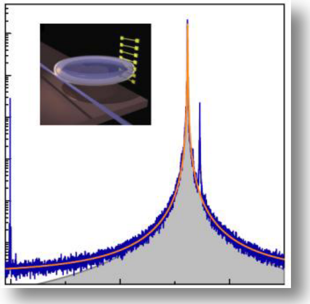
$$\frac{S^{\mathrm{qba}}}{S^{\mathrm{th}}} = \left(\frac{g/2\pi}{20\,\mathrm{MHz/nm}}\right)^2 \underbrace{\left(\frac{15\,\mathrm{pg}}{m_{\mathrm{eff}}}\right)\left(\frac{Q_{\mathrm{m}}}{10^6}\right)\left(\frac{1\mathrm{MHz}}{\Omega_{\mathrm{m}}/2\pi}\right)}_{\textbf{[2]}} \left(\frac{4\,\mathrm{MHz}}{\kappa/2\pi}\right)^2 \left(\frac{P}{100\,\mu\mathrm{W}}\right)\left(\frac{\lambda}{780\,\mathrm{nm}}\right)\left(\frac{300\,\mathrm{K}}{T}\right)$$

- **QBA dominated regime is prerequisite for *room temperature* Quantum Optomechanical Experiments.**

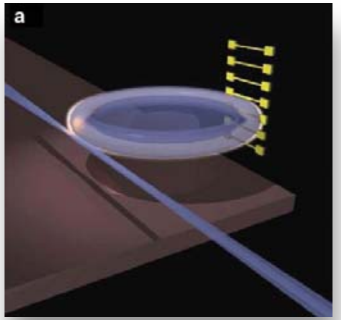
---

[1] Fabre *et al.* PRA 49, 1337 (1994), Heidmann et al. Applied Physics B 64, 173 (1997).
[2] Verbridge et al. APL 92, 013112 (2008).
[3] Verlot, P., Tavernarakis, A., Briant, T., Cohadon, P.-F. & Heidmann, Phys. Rev. Lett. 102, 103601 (2009)

Outline



Measuring the vacuum optomechanical coupling strength



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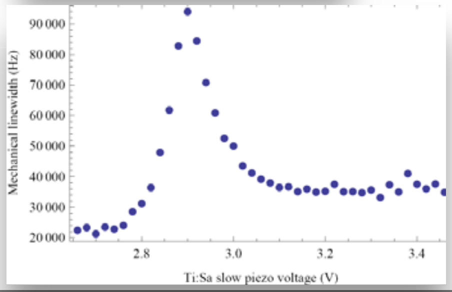
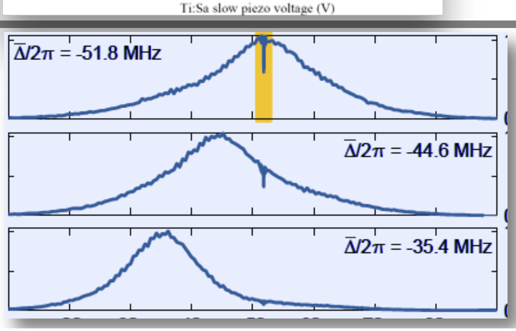
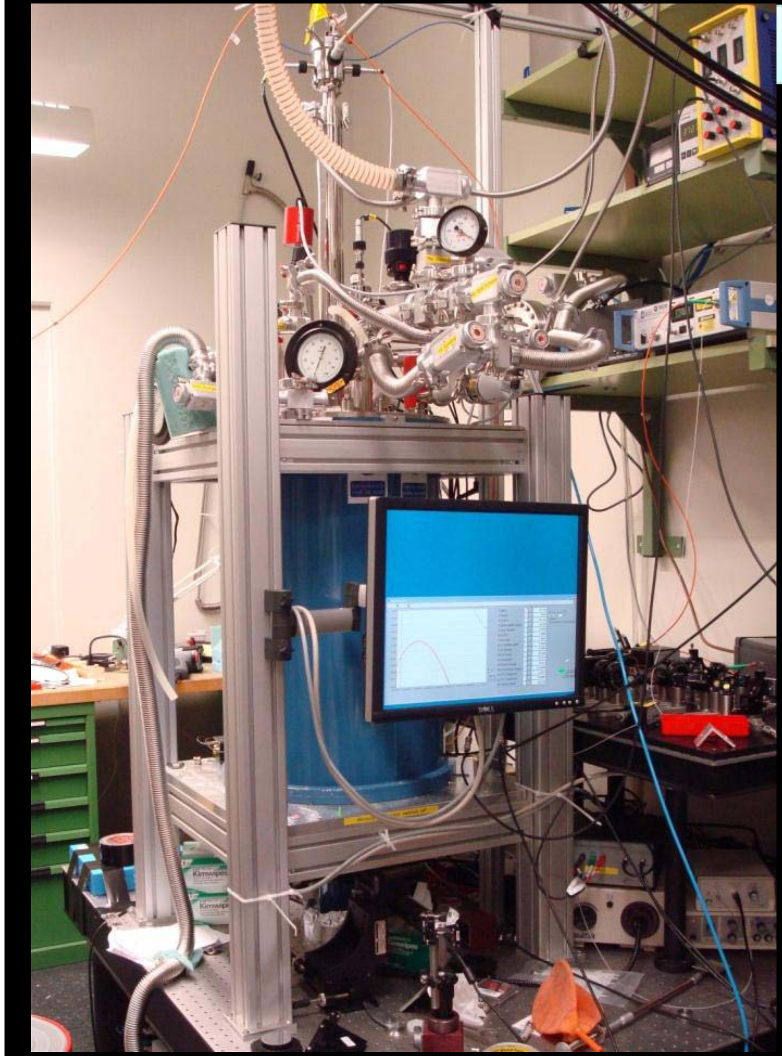


Thermometry of an optomechanically cooled Microresonator in a Helium-3 cryostat



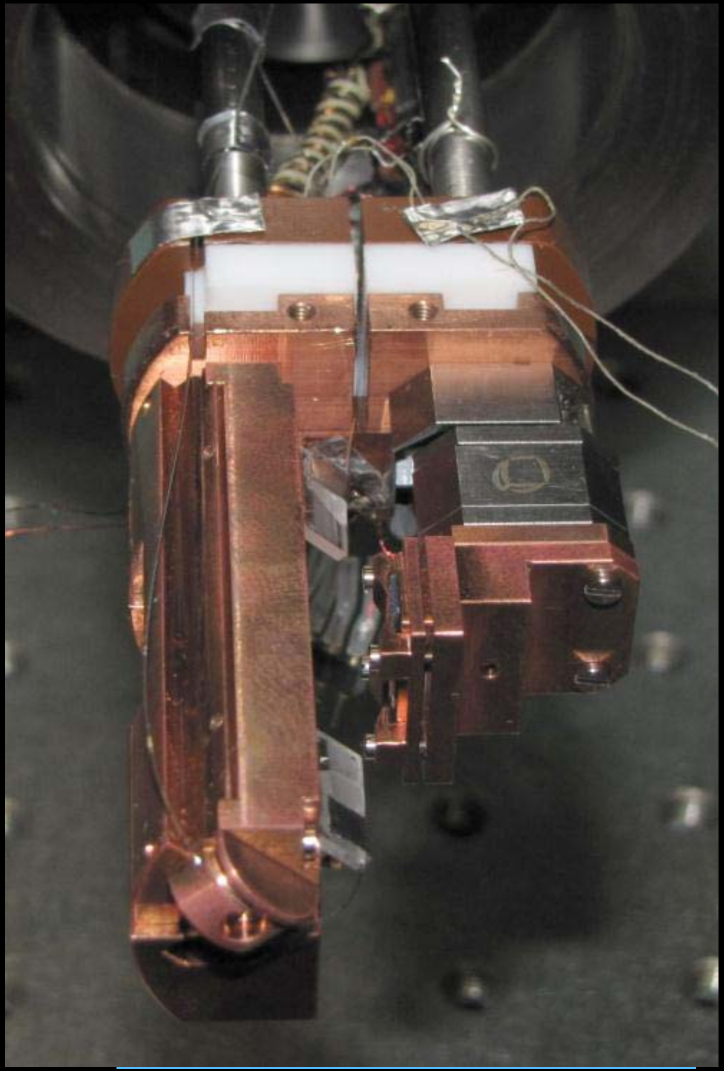
Optomechanically induced transparency

Optomechanics at Helium-3 Temperatures (600 mK)



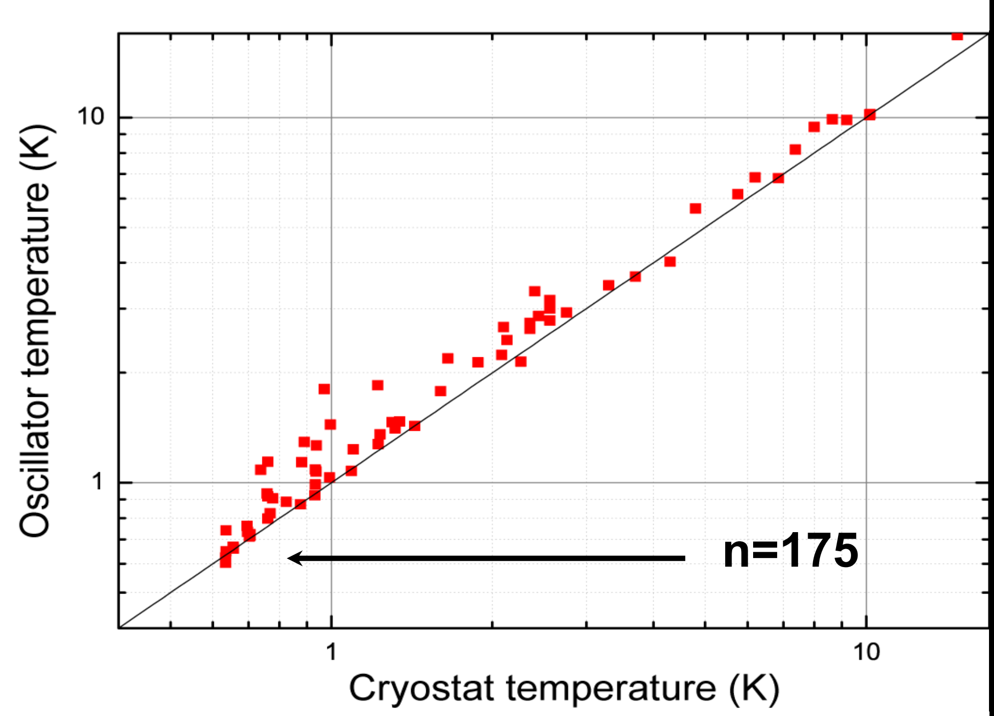
Holder for tapered fiber

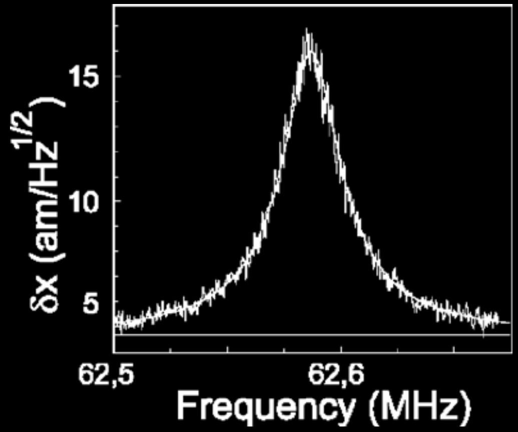
Piezo Positioners



38mm

Optomechanics at Helium-3 Temperatures (600 mK)





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

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

At low power excellent thermalization observed with the cryostat

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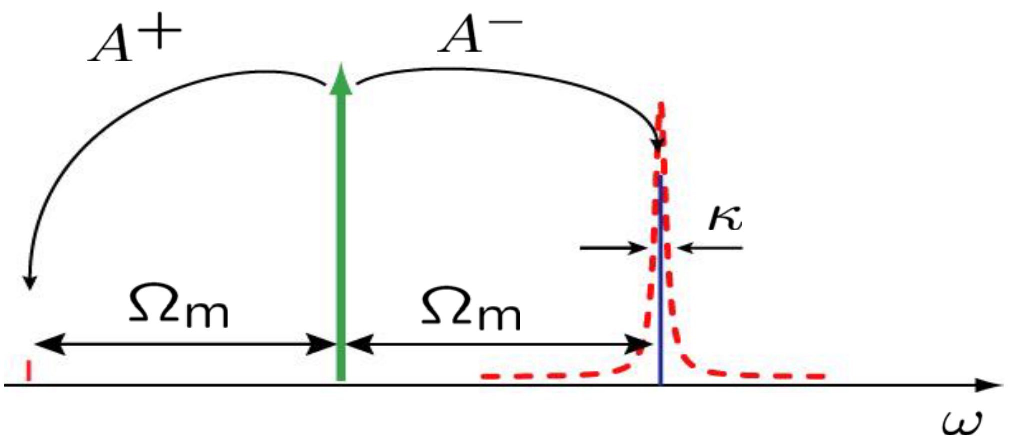
(S. Deleglise, O. Arcizet, S. Weis, R. Riviere unpublished)

Resolved sideband cooling in a cryostat



Resolved Sideband Limit and Cooling:

- **Suppresses direct excitation of the optical mode, i.e. reduces resonant heating**

$$n_f \approx \frac{\Gamma_m}{\Gamma_{cool}} n_i + \frac{A_+}{A_- - A_+}$$

Technical problem: relative detuning of the laser is not precisely known!

Reservoir heating

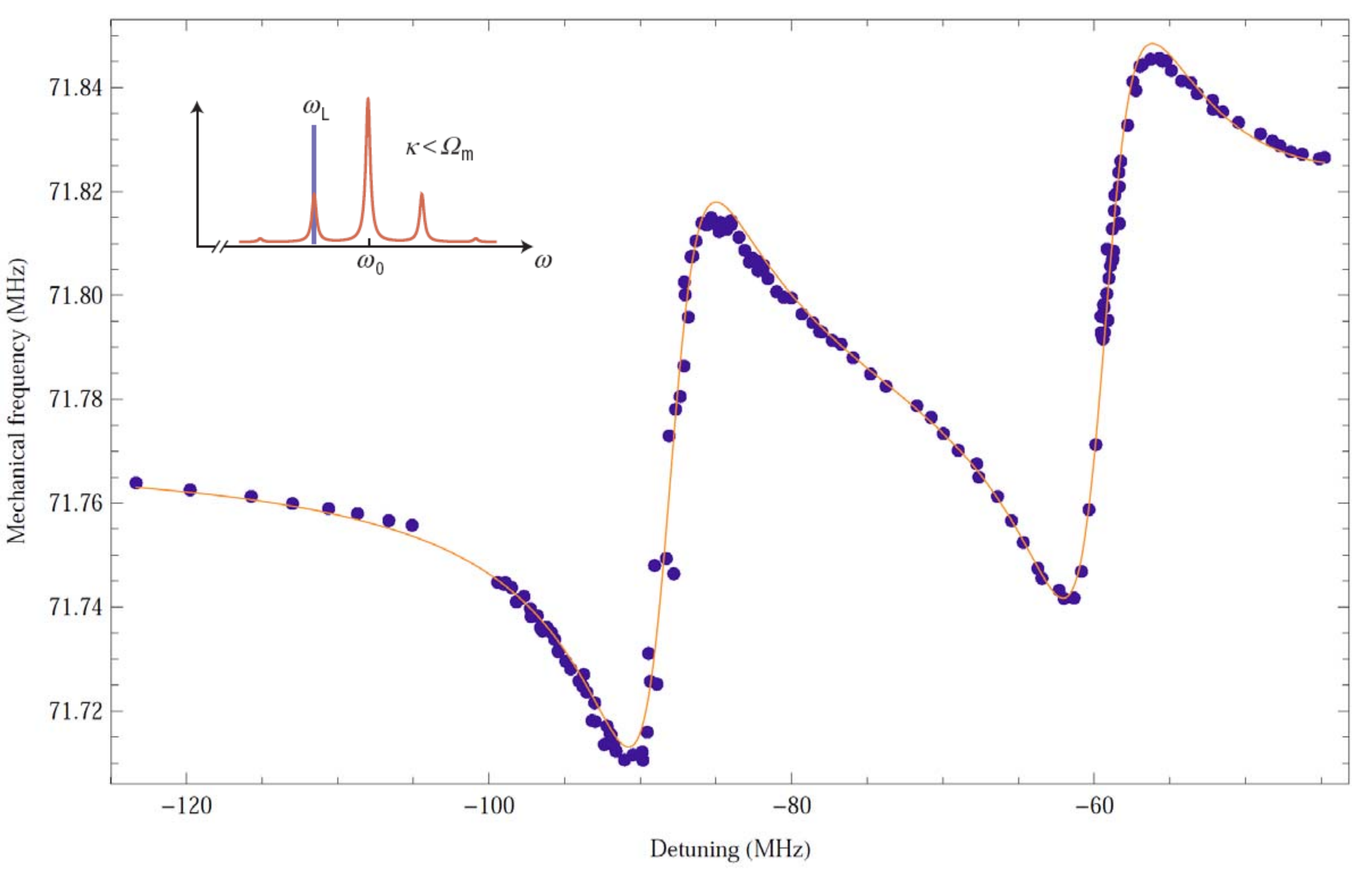
$$\Gamma_{cool} \approx \frac{4g_0^2}{\Omega_m^2} \frac{P_{in}}{\hbar\omega_L}$$

Quantum Backaction

$$n_b \approx \frac{\kappa^2}{16\Omega_m^2} \ll 1$$

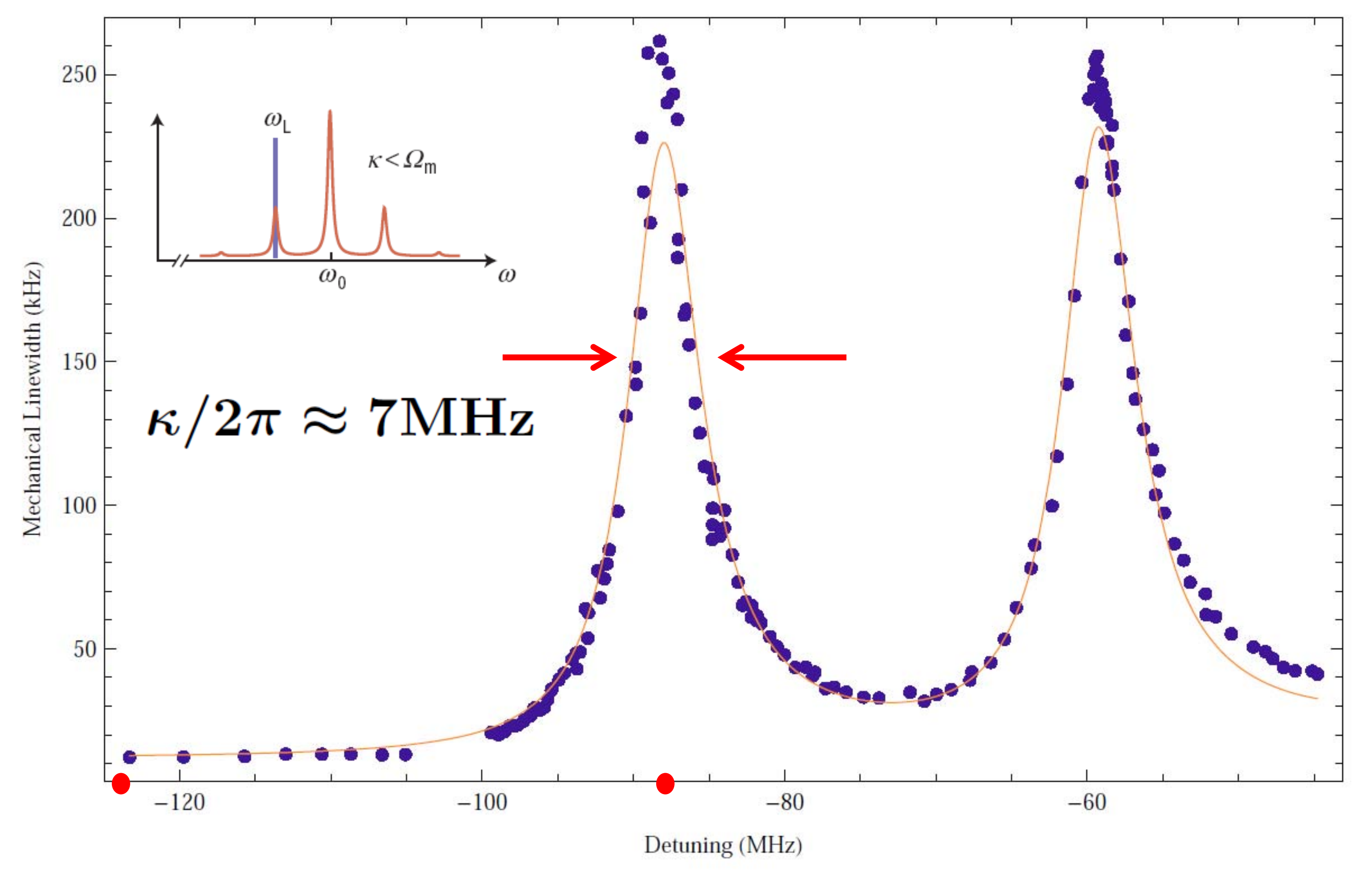
Schliesser et al., Nature Phys. 4, 415 - 419 (2008)

Mechanical frequency shift (in phase radiation pressure)



- **Excellent agreement with theory of Dynamical backaction cooling**
- **Frequency can be measured with high accuracy**

Damping rate (quadrature component of radiation pressure)



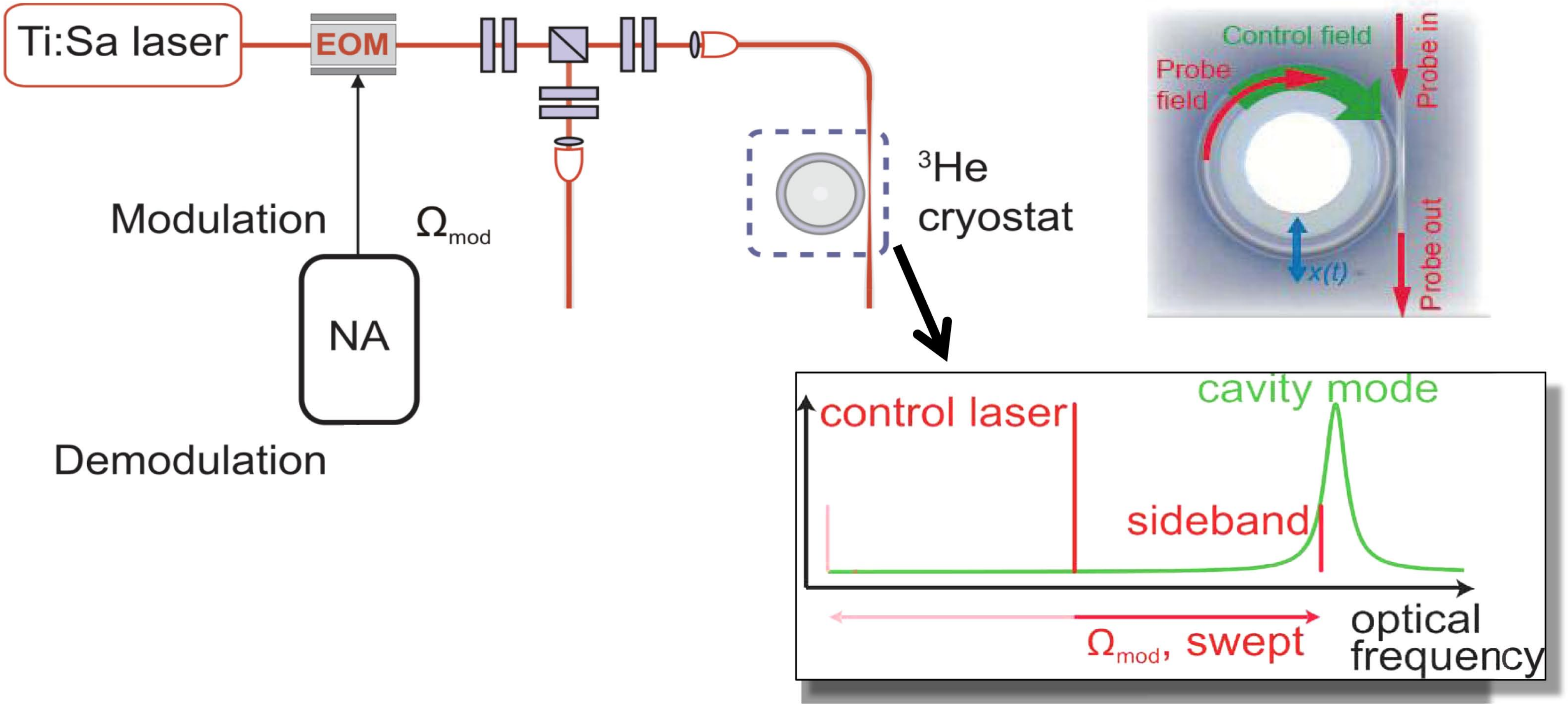
$\kappa/2\pi \approx 7\mathrm{MHz}$

- **Maximum cooling rate > 250 kHz**
- **Intrinsic mechanical damping 12 kHz**

$$\frac{\Omega_m}{\kappa} = 10$$

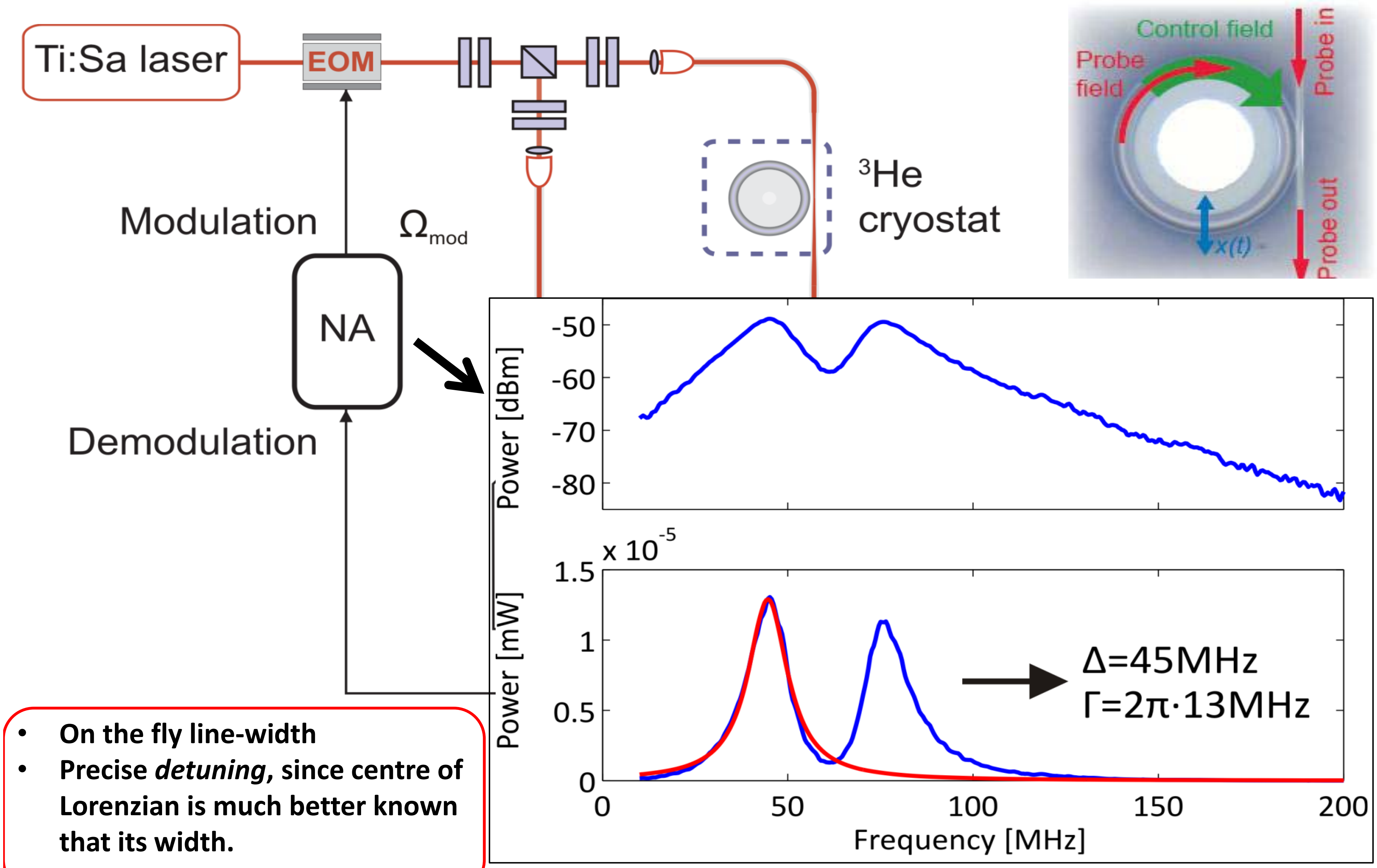
$$\Delta P_{abs} = P_{in} \cdot \frac{4\kappa^2}{\Omega_m^2}$$

Detuning calibration



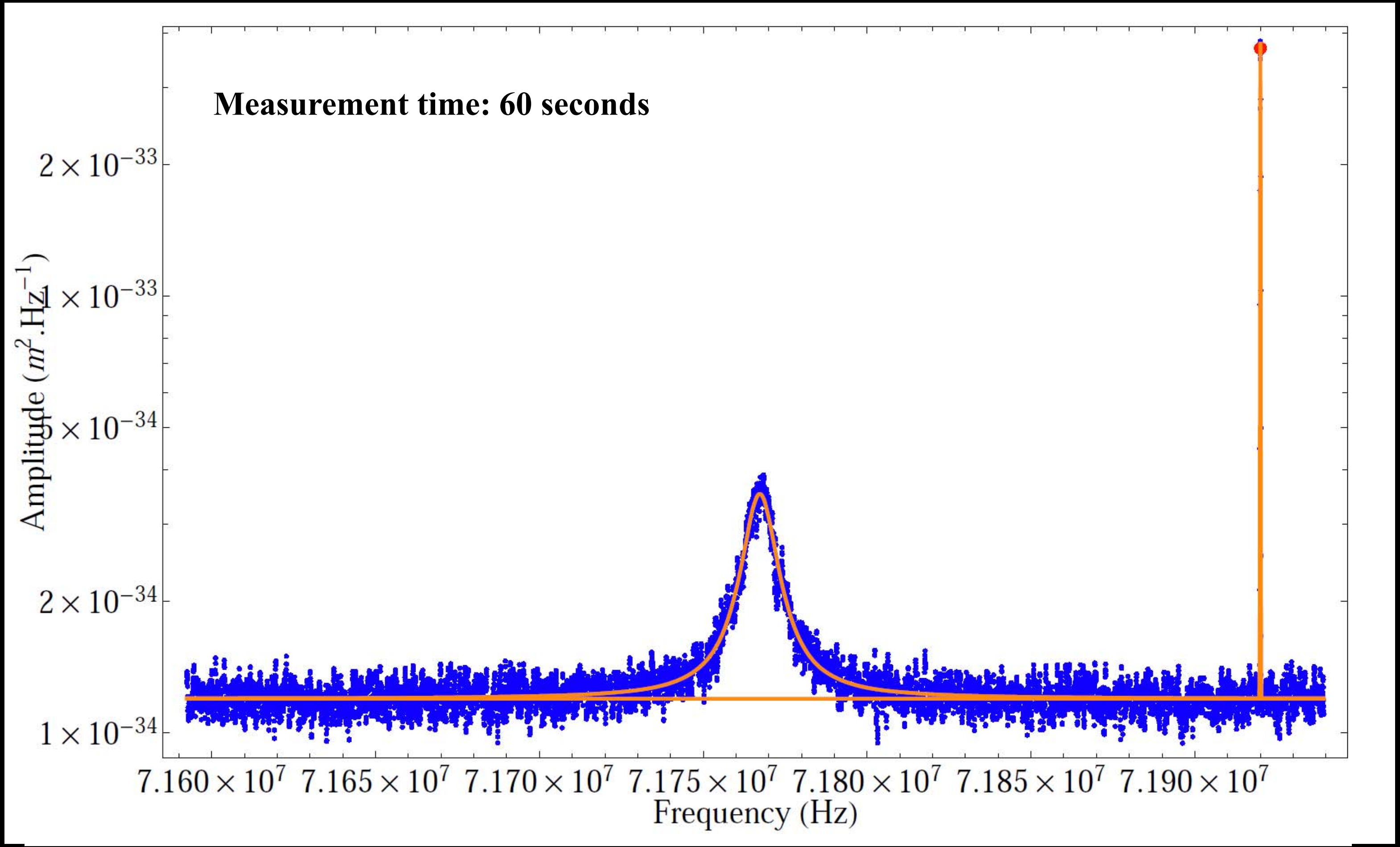
- On the fly line-width
- Precise detuning, since centre of Lorenzian is much better known that its width.

Detuning calibration



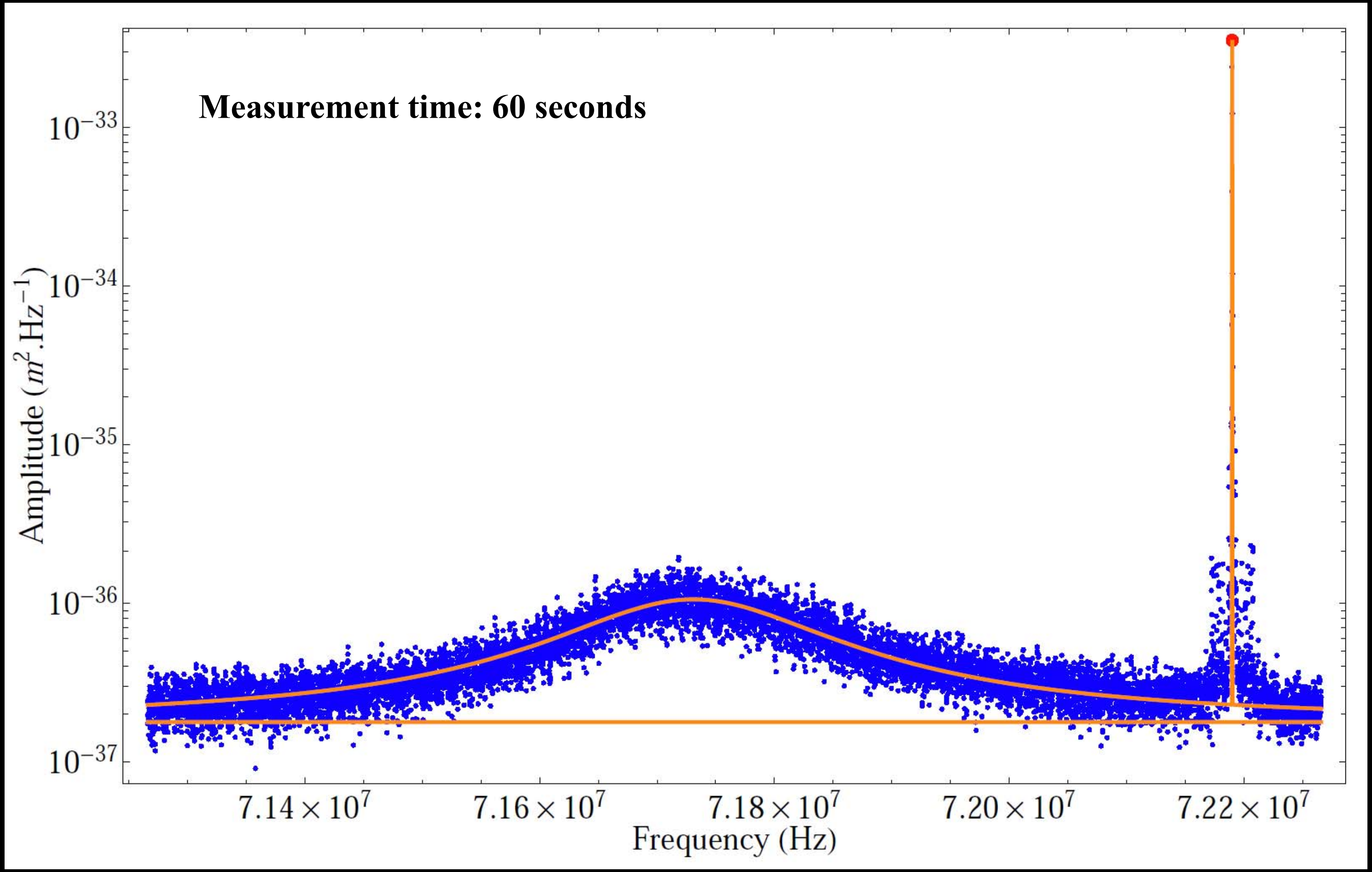
- **On the fly line-width**
- **Precise *detuning*, since centre of Lorenzian is much better known that its width.**

Displacement spectral density



- **Excellent agreement with theory of Dynamical backaction cooling** $\Gamma_{eff} = 12\text{kHz}$
- **Frequency can be measured with high accuracy**
- **Measurement time 60 seconds**

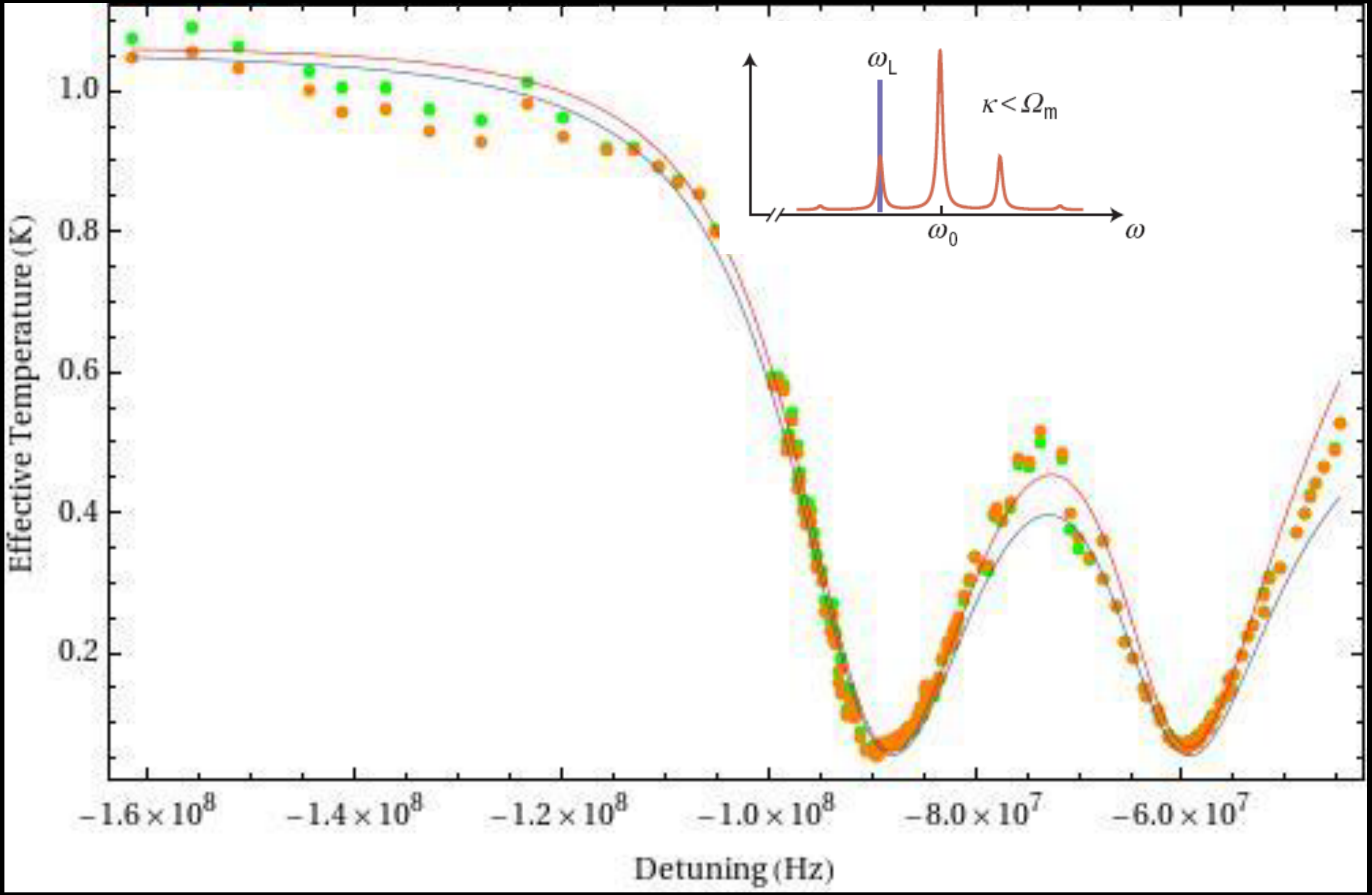
Displacement spectral density



$$\Gamma_{eff} \approx 250\text{kHz}$$

- **Excellent agreement with theory of Dynamical backaction cooling**
- **Frequency can be measured with high accuracy**

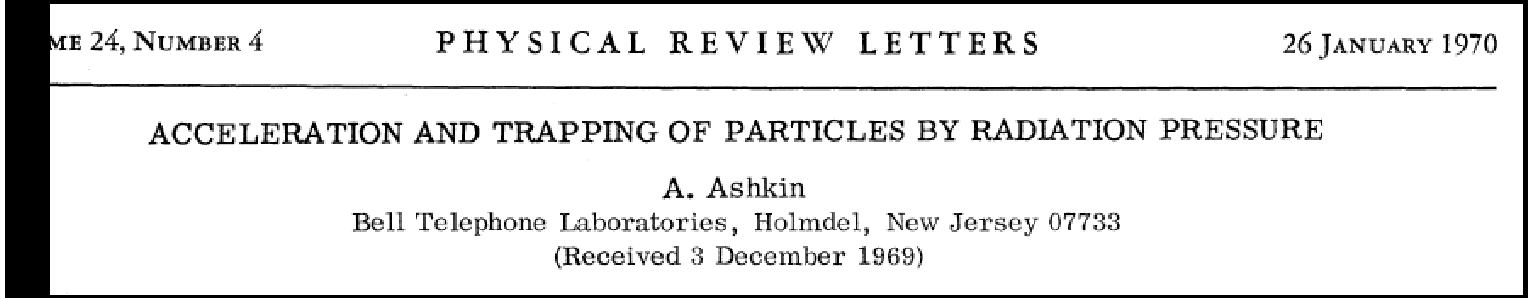
Resolved sideband in 3He cryostat



$$T_i = 1100\text{mK} : \text{Q}_\text{m} \approx 6100, \Omega_\text{m} = 71\text{MHz}, \kappa/2\pi = 7\text{MHz}$$

$$\bar{n}_i \approx 320 \qquad \bar{n}_f = \bar{n}_i \frac{\Gamma_m}{\Gamma_m + \Gamma_{opt}} \approx 15$$

S. Deleglise , S. Weis, R. Riviere, Kippenberg (unpublished)

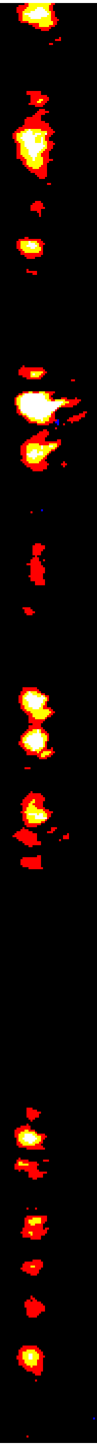


ME 24, NUMBER 4 PHYSICAL REVIEW LETTERS 26 JANUARY 1970

ACCELERATION AND TRAPPING OF PARTICLES BY RADIATION PRESSURE

A. Ashkin
Bell Telephone Laboratories, Holmdel, New Jersey 07733

(Received 3 December 1969)



Tapered fiber.

Low Temperatures: Two level fluctuators (TLS)

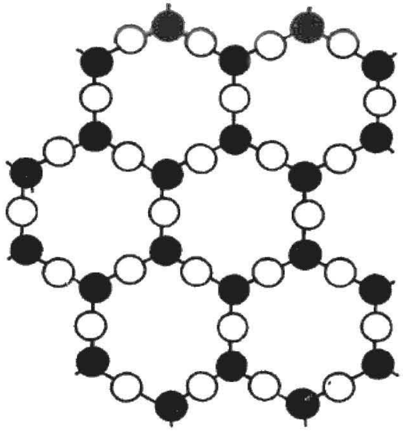
Anomalous Low-temperature Thermal Properties
of Glasses and Spin Glasses

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

Bell Laboratories, Murray Hill, New Jersey 07974

[2]

Crystalline structure



" QUARTZ-CRYSTAL"

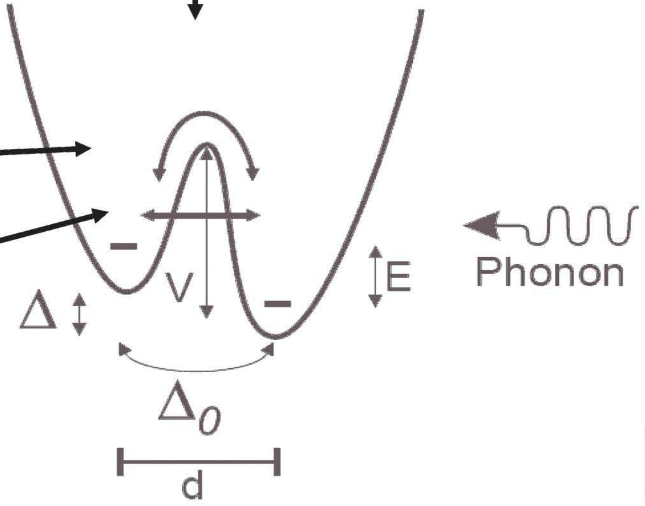
"QUARTZ-GLASS"

Glassy structure:
Different possible
conformations

2-level system approximation [1]

Thermally activated process

Tunelling process



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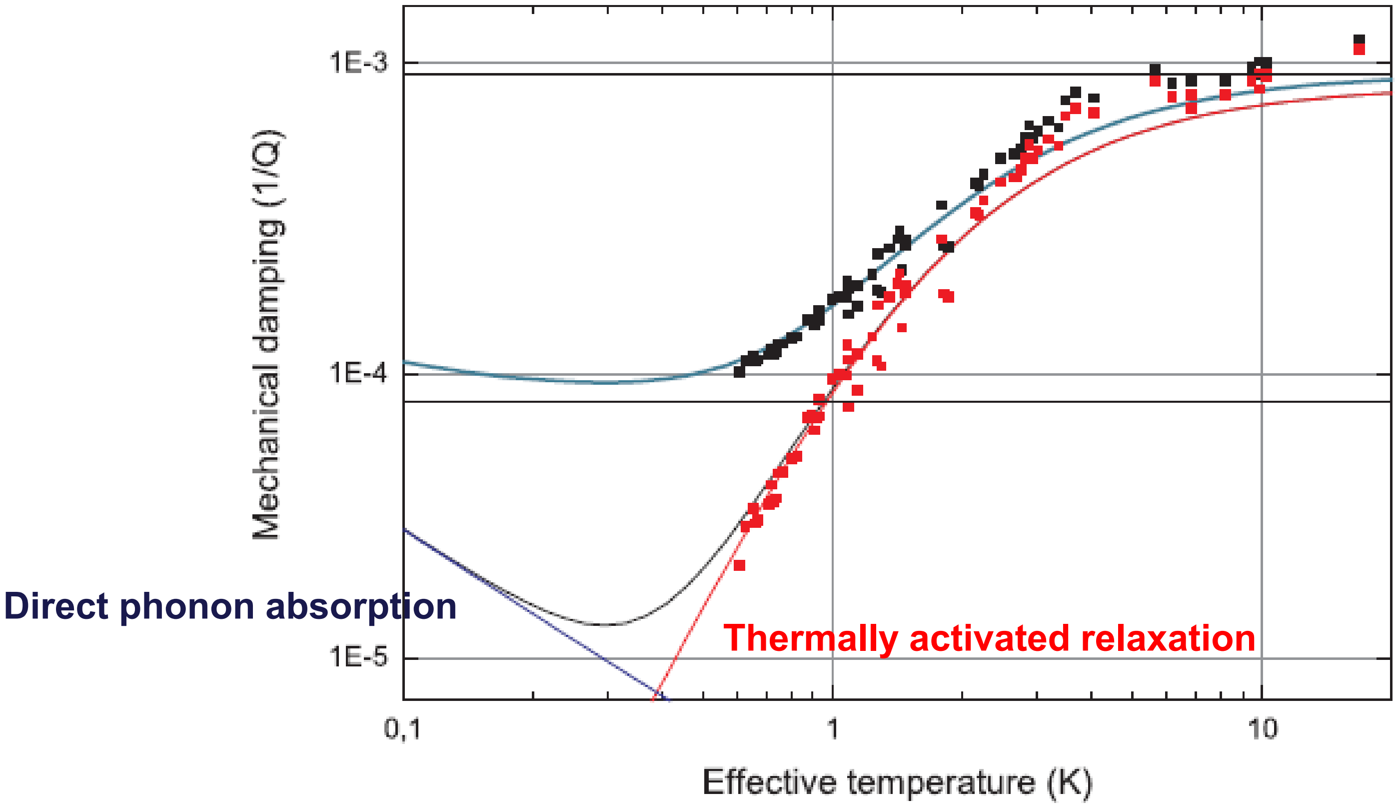
[1] Vacher, Courtens, Forêt, PRB 72 214205 (2005)
[2] Jäckle, Piché, Huncklinger, J. Non-Crys. Sol. 20 365 (1976)

Low Temperatures: Two level fluctuators (TLS)



$$Q_m \propto \frac{\Omega_m}{T^3}$$

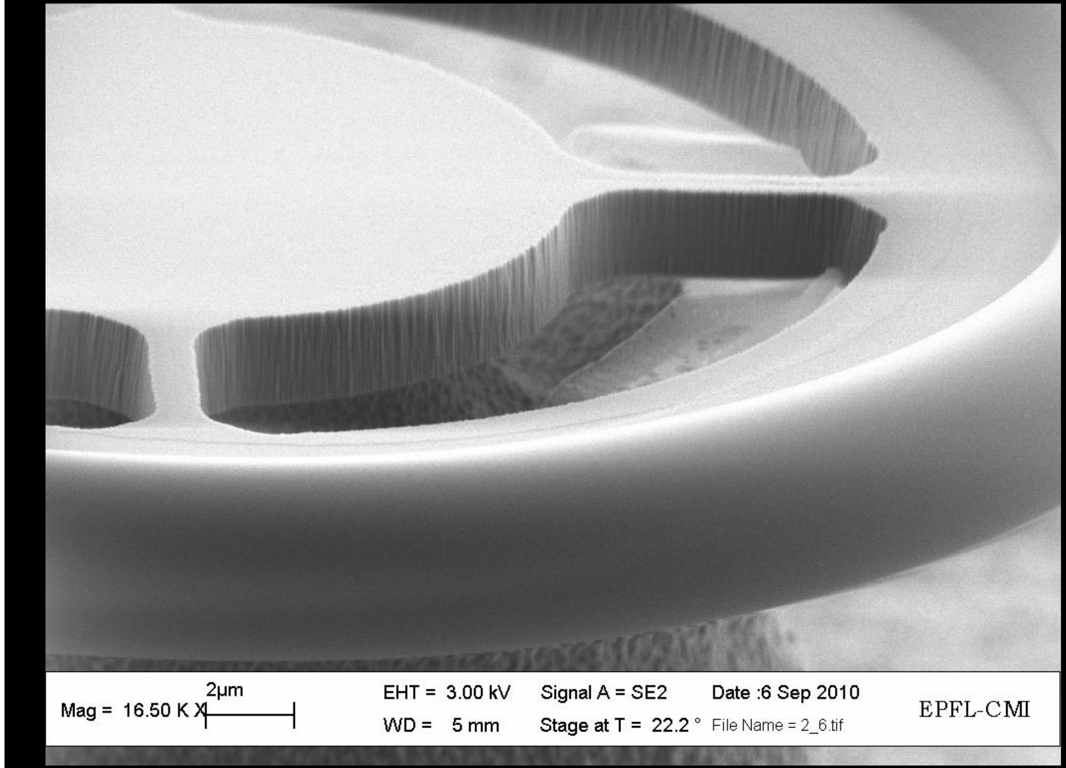
Thermally activated contribution

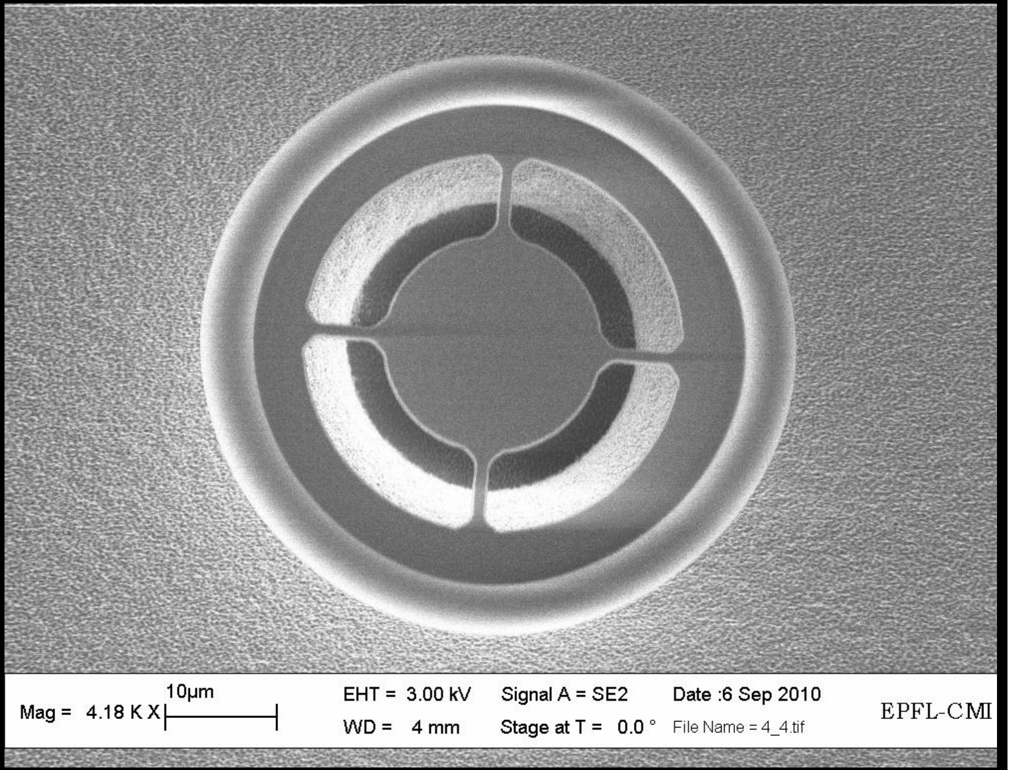
$$Q^{-1} = \mathcal{C}\,\mathrm{Erf}\left(\frac{\sqrt{2}T}{\Delta_C}\right)\frac{1}{T}\int_0^\infty \left(\frac{V}{V_0}\right)^{-\xi} e^{-\frac{1}{2}\frac{V^2}{V_0^2}}\,\frac{\Omega\tau_0 e^{V/T}}{1+\Omega^2\tau_0^2 e^{2V/T}}\,dV$$ **[3]**

---

[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)

Next steps .... Optomechanics@EPFL





Improved spoke resonators (using RIE processing)

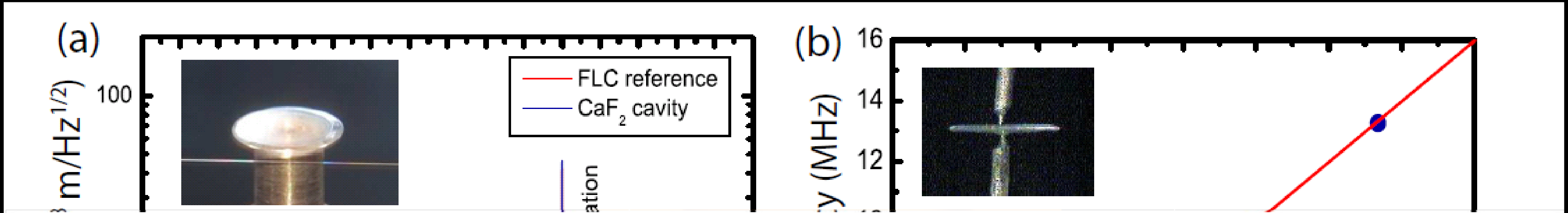
- **Reduced clamping losses**
- **Increased optomechanical coupling**

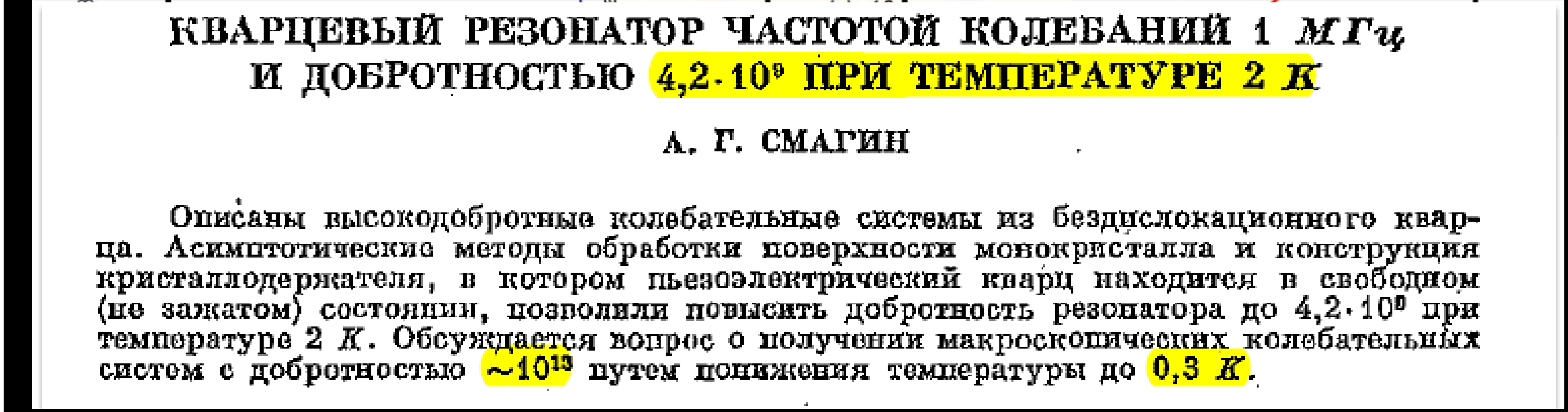
(Gavartin, Verhagen et al)

Anetsberger et. al *Nat. Photon. 2,* 627 (2008), see also: Nguyen Berkeley

Optomechanical coupling in crystalline microresonators

High Q mechanical modes observed coupled via radiation pressure





КВАРЦЕВЫЙ РЕЗОНАТОР ЧАСТОТОЙ КОЛЕБАНИЙ 1 *МГц* И ДОБРОТНОСТЬЮ $4{,}2\cdot10^9$ ПРИ ТЕМПЕРАТУРЕ 2 *К*

А. Г. СМАГИН

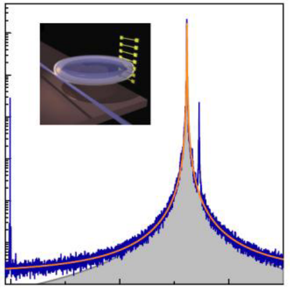
Описаны высокодобротные колебательные системы из бездислокационного кварца. Асимптотические методы обработки поверхности монокристалла и конструкция кристаллодержателя, в котором пьезоэлектрический кварц находится в свободном (не зажатом) состоянии, позволили повысить добротность резонатора до $4{,}2\cdot10^9$ при температуре 2 *К*. Обсуждается вопрос о получении макроскопических колебательных систем с добротностью $\sim10^{13}$ путем понижения температуры до 0,3 *К*.

$$\kappa < 20\mathrm{kHz}(\mathrm{Q} > 10^{10}) \rightarrow \mathrm{Im(n)} < 10^{-10}$$

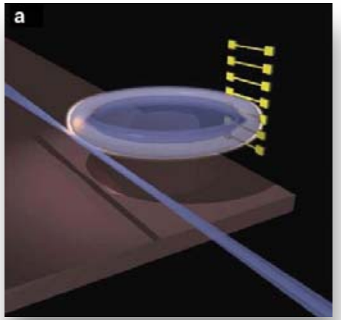
$$\Omega_m/\kappa > 100$$

Pioneering work on crystalline resonators: Maleki, Ilchenko, Matkso et al. JPL
J. Hofer, A. Schliesser, TJ Kippenberg (arXiv:1003.5922, to appear Phys. Rev. A.)

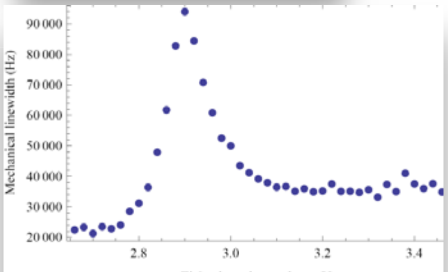
Outline



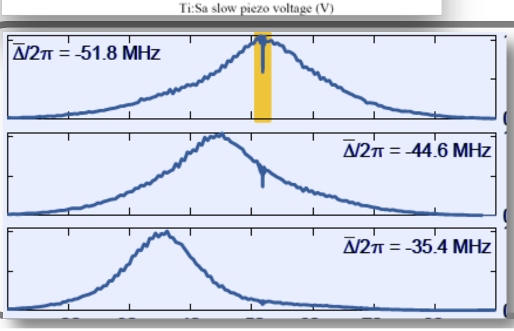
Measuring the vacuum optomechanical coupling strength



Measurement imprecision below that at The Standard Quantum Limit



Thermometry of an optomechanically cooled Microresonator in a Helium-3 cryostat



Optomechanically induced transparency

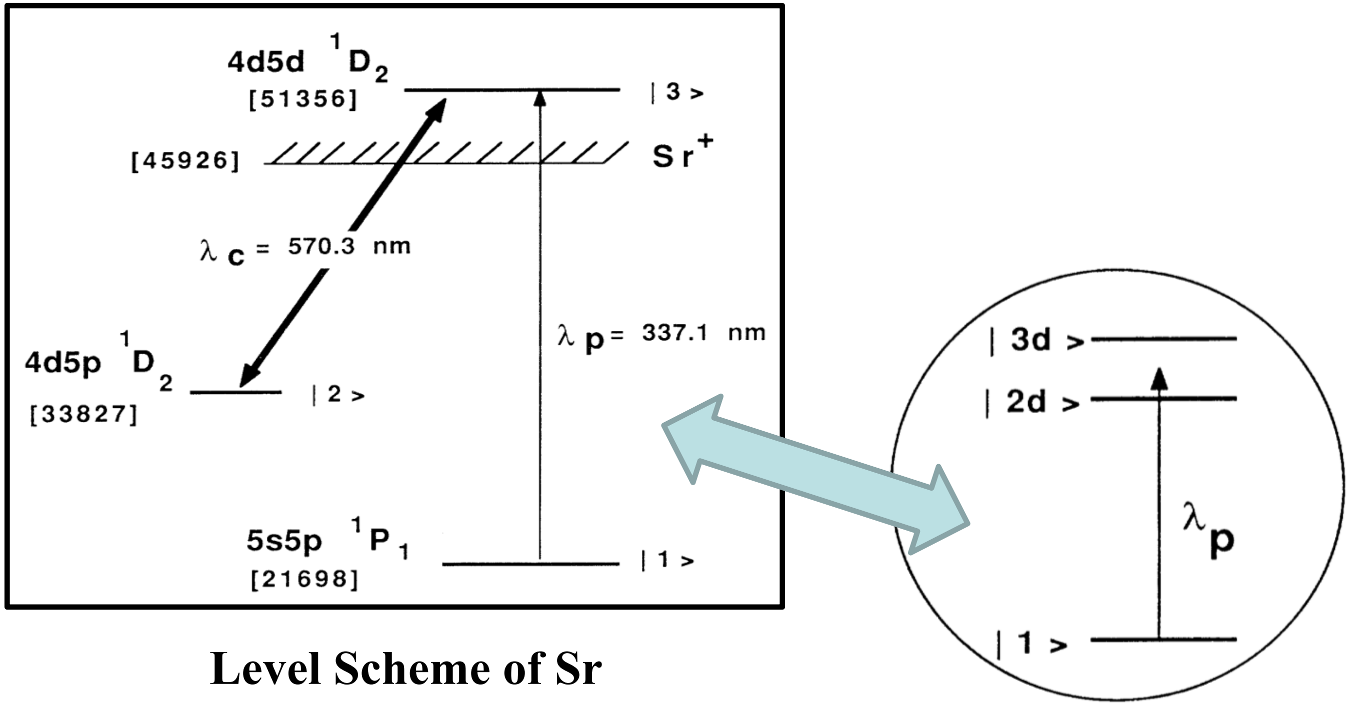
Optomechanical EIT

Observation of Electromagnetically Induced Transparency

K.-J. Boller, A. Imamoğlu, and S. E. Harris

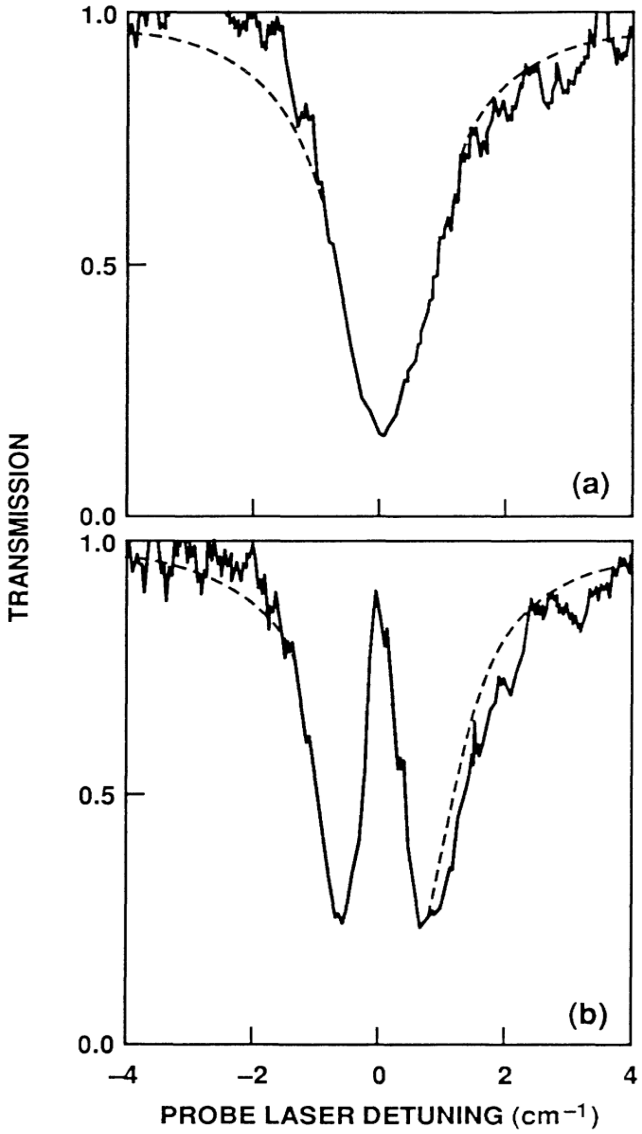
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

(Received 12 December 1990)



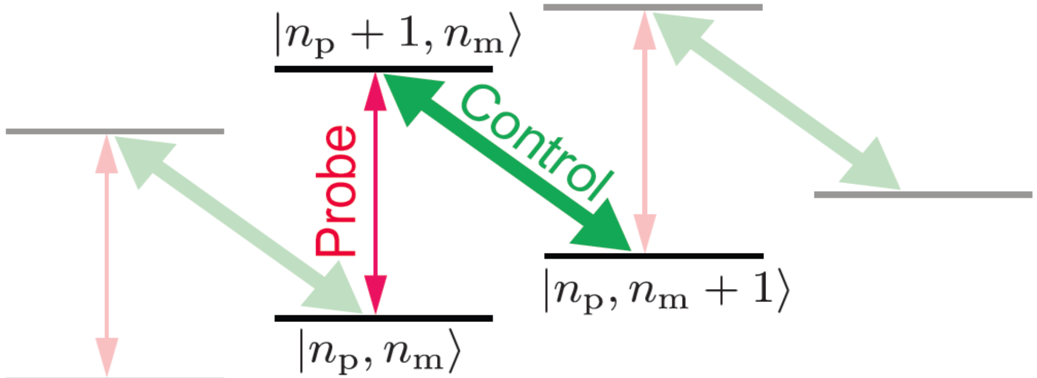
Level Scheme of Sr

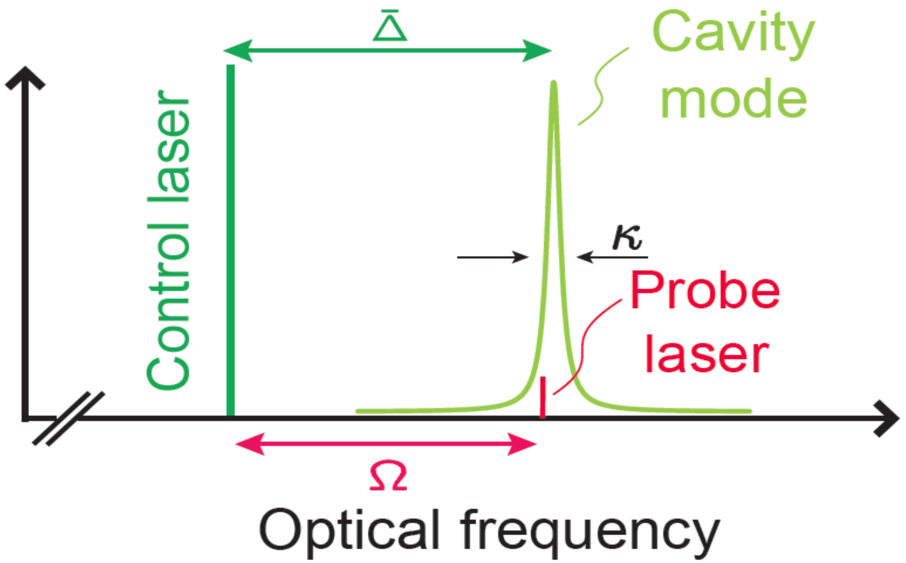
Dressed States Picture



- Light storage (Phillips, *PRL, 86 (2001)*); Slow light (Hau, *Nature, 97 (1999)*)

Optomechanical EIT





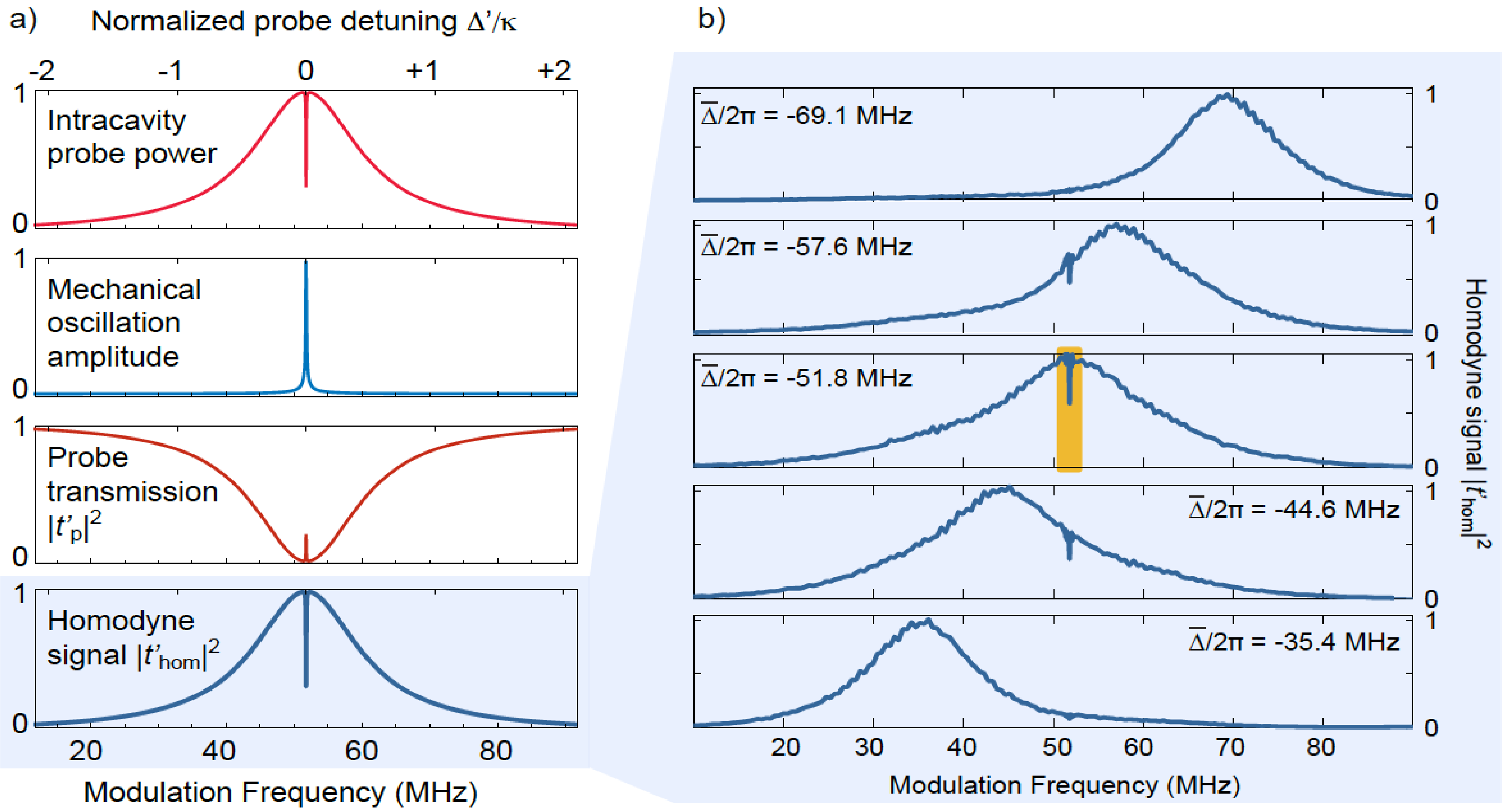
$$\left(-i(\bar{\Delta}+\Omega_m+\Delta')+\kappa/2\right)A^-(\Omega)=-ig_0\bar{a}X^-(\Omega)+\sqrt{\eta_c\kappa}s_p$$

$$2m_{\mathrm{eff}}\Omega_m(2\Delta'-i\Gamma_m)X^-(\Omega)=-\hbar g_0\bar{a}A^-(\Omega).$$

EIT	OMIT
projection operator σ_{13} (coherence ρ_{13})	intracavity field amplitude A^-
projection operator σ_{12} (coherence ρ_{12})	mechanical displacement amplitude X
energy difference between ground states $\hbar\omega_{21}$	phonon energy $\hbar\Omega_\mathrm{m}$
Rabi frequency $\mu_{23}\mathcal{E}_\mathrm{c}/\hbar$	optomechanical coupling rate $2g_0\bar{a}x_{\mathrm{zpf}}$

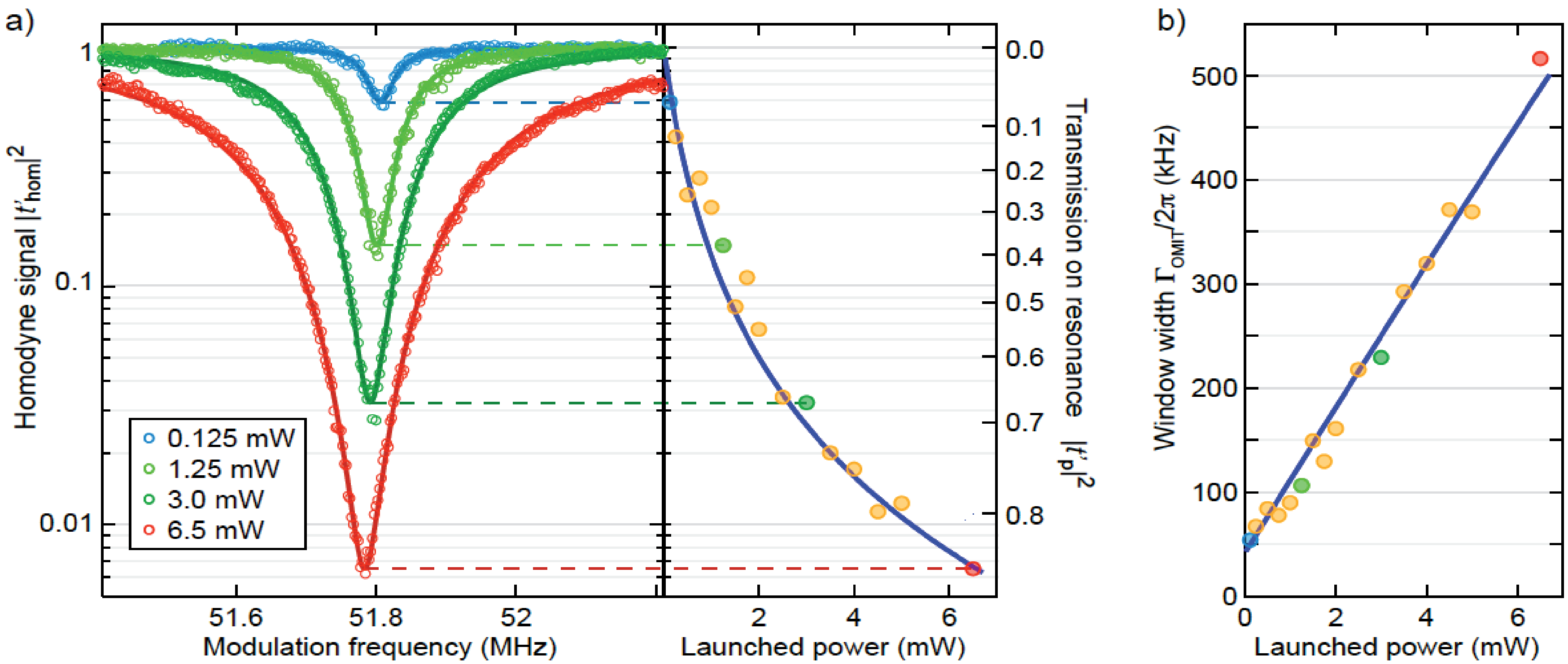
Schliesser, PhD thesis (Nov. 2009) http://edoc.ub.uni-muenchen.de/10940/
Agarwal Huang Phys. Rev. A 81, 041803(R) (2010)
S. Weis, R. Riviere, S. Deleglise, A. Schliesser&T.J. Kippenberg arXiv:1007.0565

Optomechanical EIT



S. Weis, R. Riviere, S. Deleglise, A. Schliesser&T.J. Kippenberg arXiv:1007.0565

Optomechanical EIT



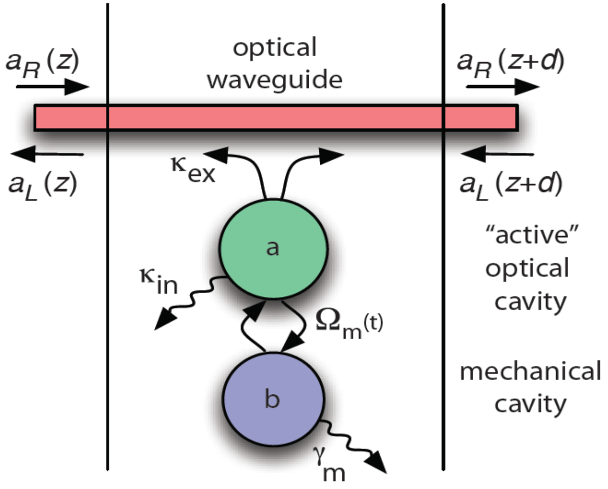
- **probe transparency window tunable by control as expected**
- **window width and depth can be continuously varied**
- “transparency” up to 81% achieved

S. Weis, R. Riviere, S. Deleglise, A. Schliesser&T.J. Kippenberg arXiv:1007.0565

Optomechanical EIT

Stopping and storing light in mechanical systems

- **Requires an array of optomechanical systems**
- **Tuning of probe transmission while light propagates through the array**

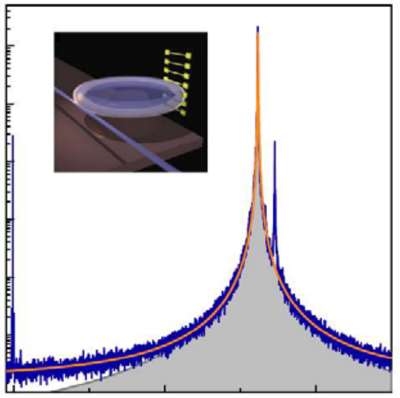


Chang, Safavi-Naeini, Hafezi, Painter, arXiv:1006.3829

S. Weis, R. Riviere, S. Deleglise, A. Schliesser&T.J. Kippenberg arXiv:1007.0565

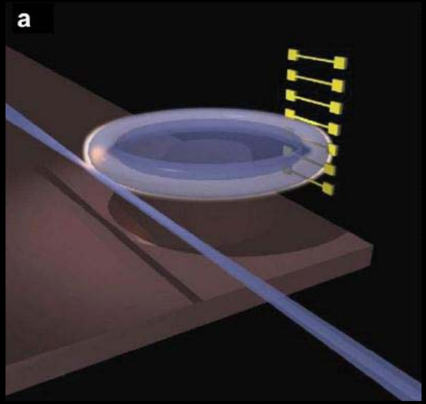
Summary

Vacuum optomechanical coupling calibration



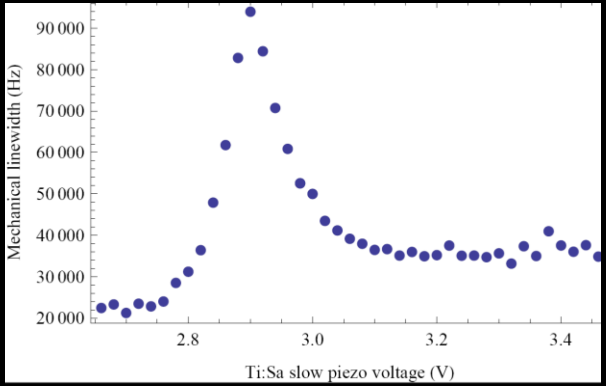
Anetsberger, ML Gorodetsky, Schliesser, TJK (*to appear:* arXiv)

Imprecision below that at the SQL for nanomechanical beams



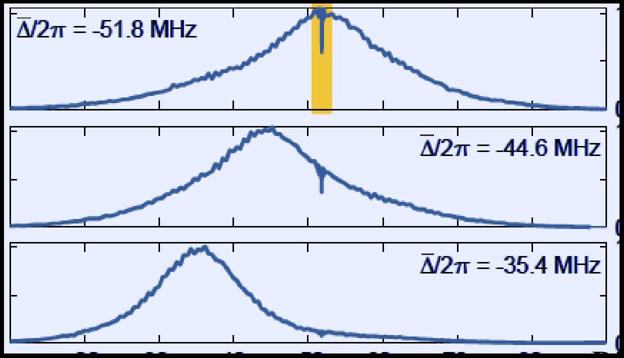
Anetsberger et al. arXiv (2009)

Optomechanical cooling in a He3 cryostat



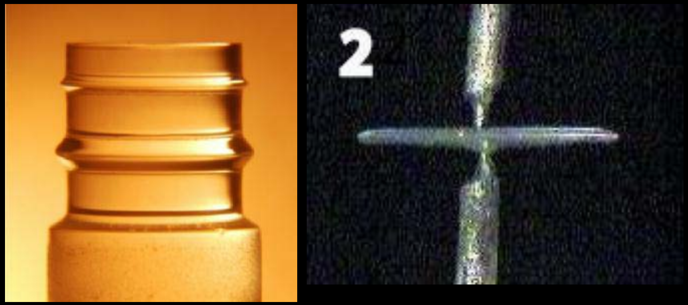
Unpublished (Weis, Riviere, Deleglise)

Observation of Optomechanical EIT



Weis, Riviere, Deleglise, Schliesser, TJK (arXiv)

Observation of Optomechanical EIT



Hofer et al. arXiv (*to appear: Phys. Rev. A.*)

Acknowledgements

Theodor Hänsch

Jörg Kotthaus

Wilhelm Zwerger

Ignacio Wilson-Rae

Achim Marx

MAX-PLANCK-GESELLSCHAFT

erc
European Research Council

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BRIDGING THE GAP
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