The Abdus Salam
International Centre
for Theoretical Physics

2445-09

Advanced Workshop on Nanomechanics

9 - 13 September 2013

Optomechanics with micro and nano-mirrors

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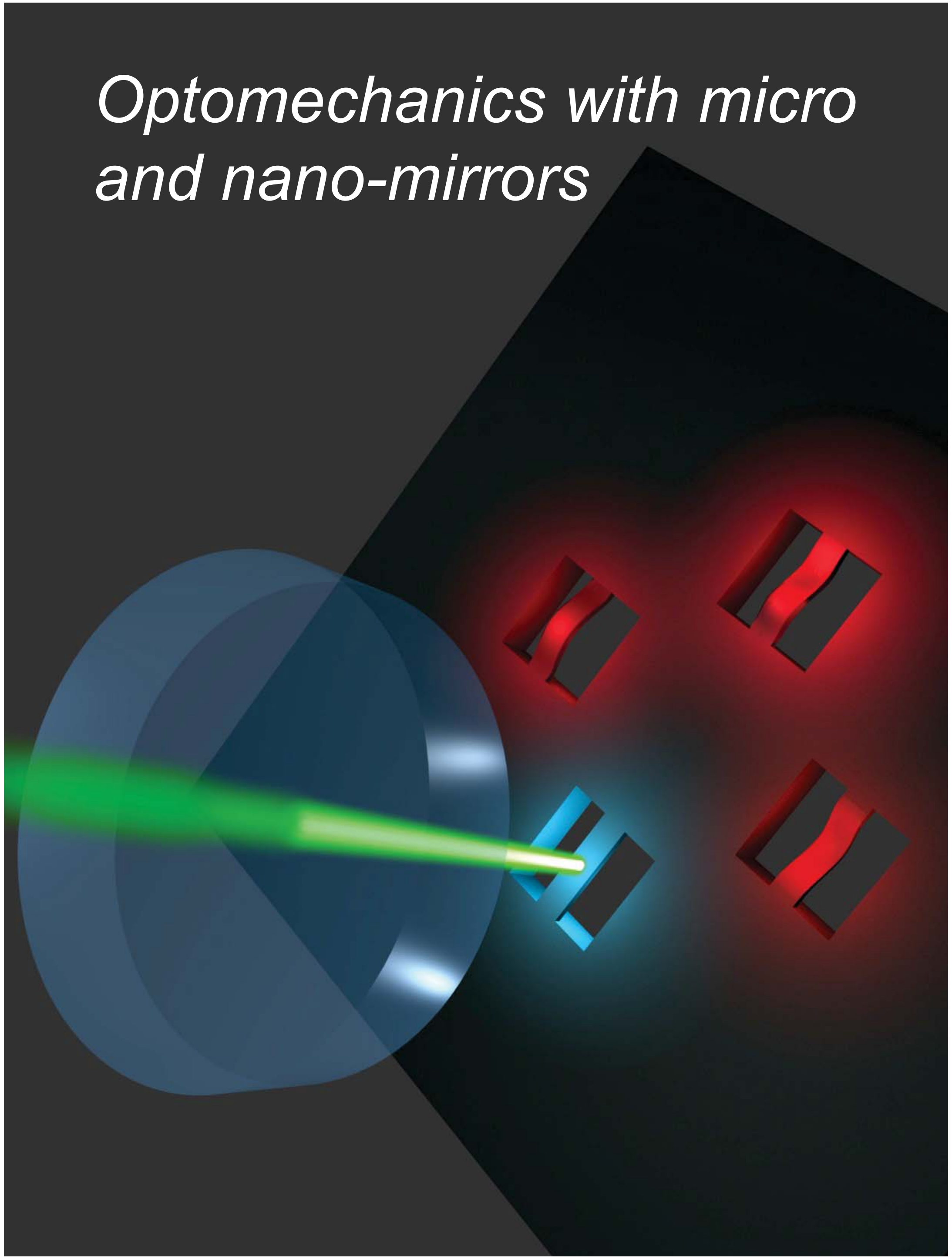
Laboratoire Kastler Brossel
Universite P. et M. Curie

Optomechanics with micro and nano-mirrors



PhD: A. Kuhn, L. Neuhaus, K. Makles, S. Zerkani, T. Karassouloff , A. Tavernerakis P. Verlot

Post-docs: T. Antony, J. Teissier, D. Garcia-Sanchez

Permanents: S. Deléglise, T. Briant, P.-F. Cohadon, A. Heidmann

Collaborations: I. Robert (LPN), O. Le Traon (ONERA), V. Dolique (LMA), J. Reichel (LKB), J. Laurat (LKB)

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Physique quantique et applications

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The origins of cavity optomechanics

Frontiers of nano-mechanics
Trieste, September 2013

Interferometric measurements and quantum limits

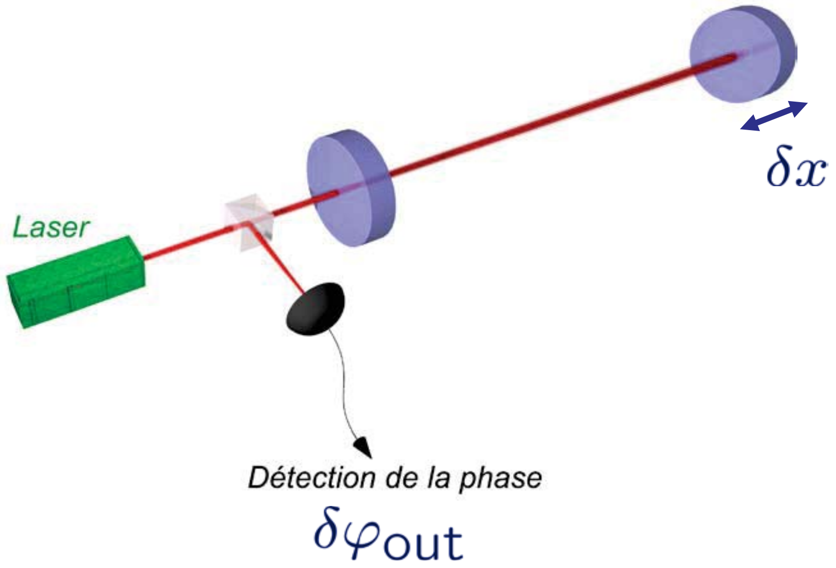
thermal noise

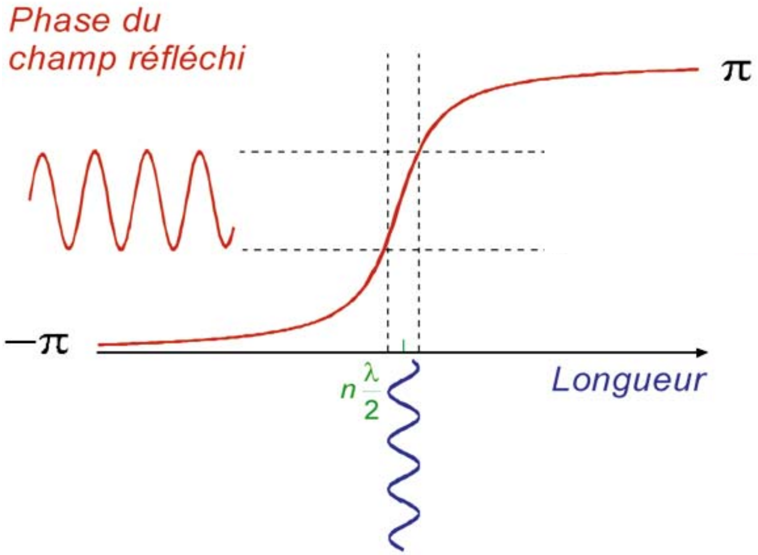
$$\delta\varphi\delta\varphi_{\text{in}} + \frac{8\mathcal{F}}{\lambda}(\delta x + \delta x_{\text{cl}} + \delta x_{\text{rad}}$$

phase noise

signal

radiation pressure noise

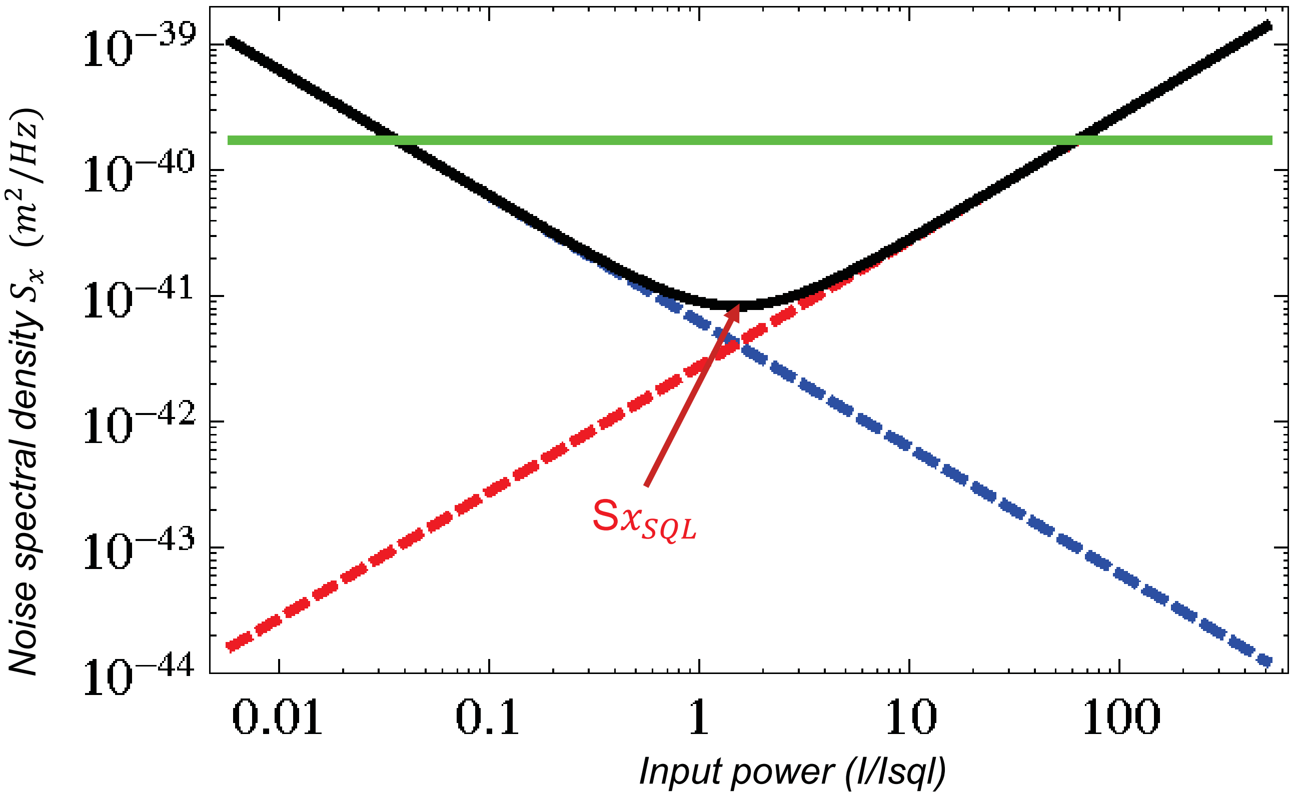




Standard quantum limit

$$\delta\varphi_{\text{out}} = \delta\varphi_{\text{in}} + \frac{8\,n\,\mathcal{F}}{\lambda}(\delta x + \delta x_{\text{cl}} + \delta x_{\text{rad}})$$

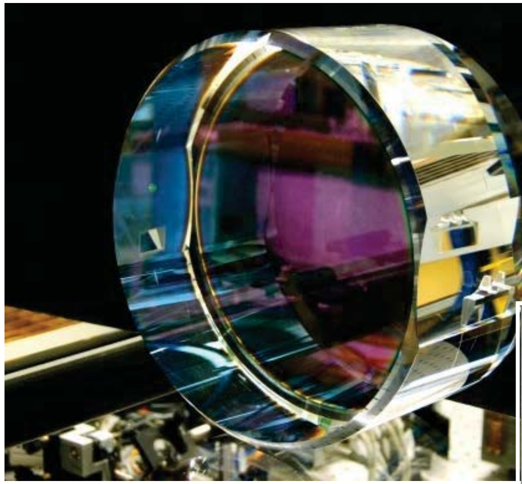
$\delta\phi_{in} \propto \frac{1}{\sqrt{I_{in}}}$ $\delta x_{rad} \propto \sqrt{I_{in}}$



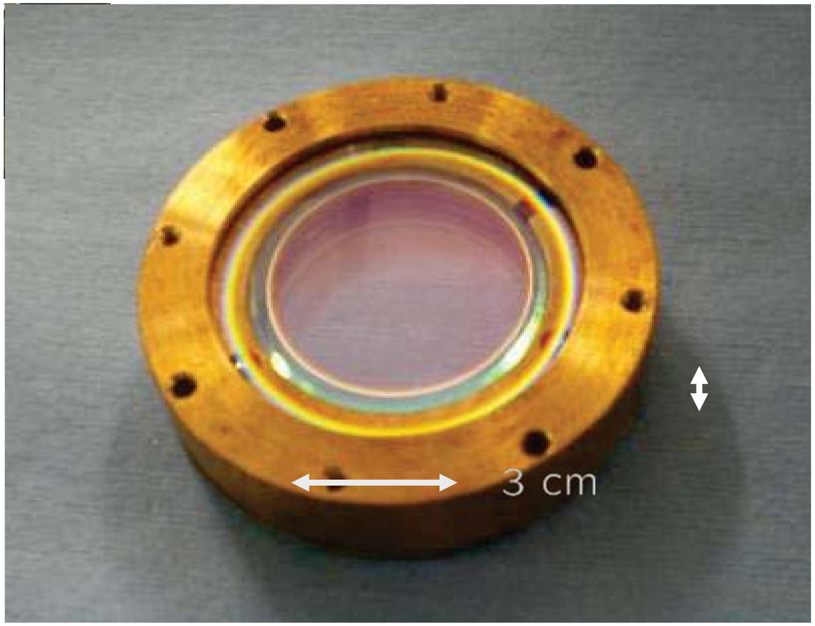
(quantum) compromise

$$\delta x_{\text{LQS}}[\Omega] = \sqrt{\hbar\chi[\Omega]}$$

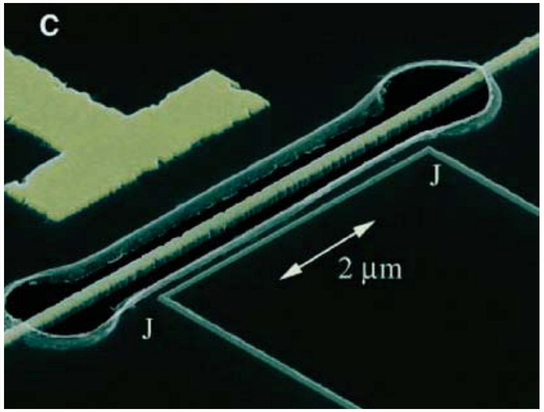
Optomechanical resonators

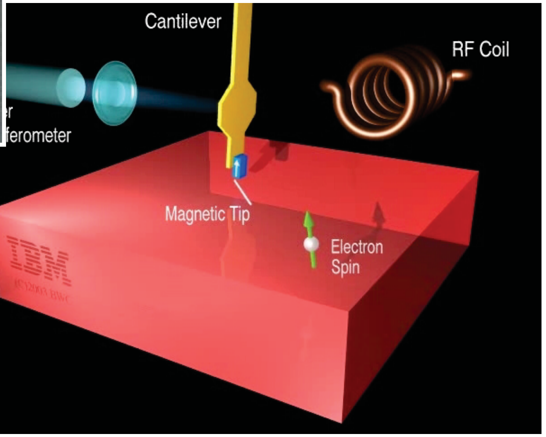


GW interferometer mirror :
high optical quality



Schwab 2004





AFM cantilever or nanoresonator:
high mechanical susceptibility

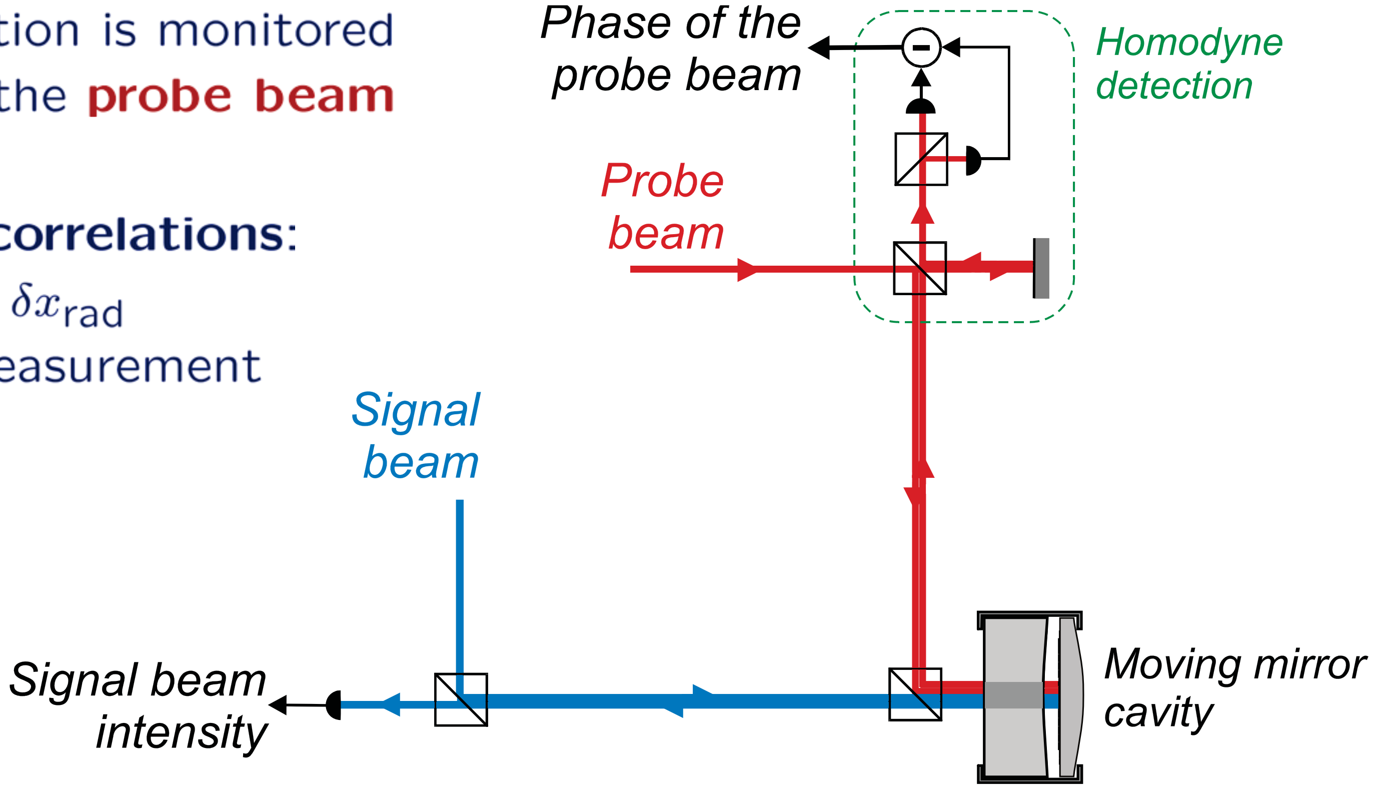
A twin-beam experiment

Two beams into one moving mirror cavity:

- intensity fluctuations of the **signal beam** drive the mirror into motion
- the resulting motion is monitored with the phase of the **probe beam**

Optomechanical correlations:

- demonstration of δx_{rad}
- QND intensity measurement



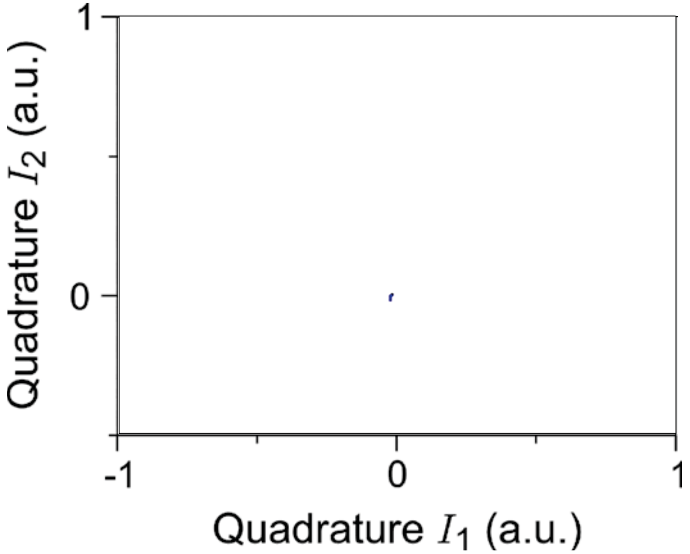
A **moving mirror** cavity is very similar to a **nonlinear** cavity: optical length $n(I)L \leftrightarrow$ length $L(I)$

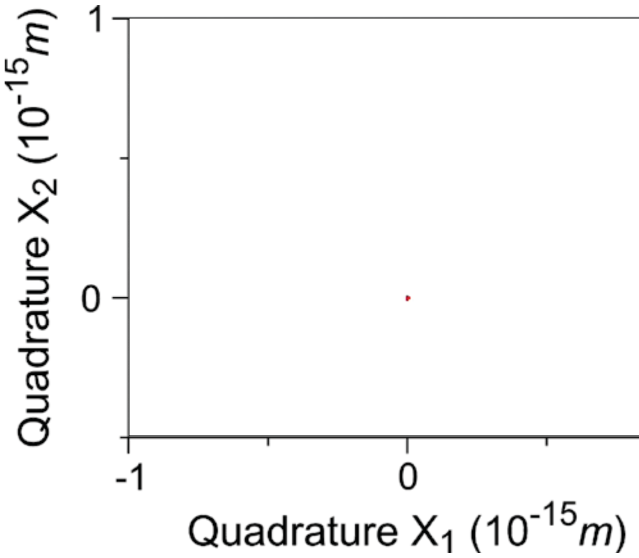
Verlot et al. PRL (2009)
but also Heidmann et al. APB (1997)

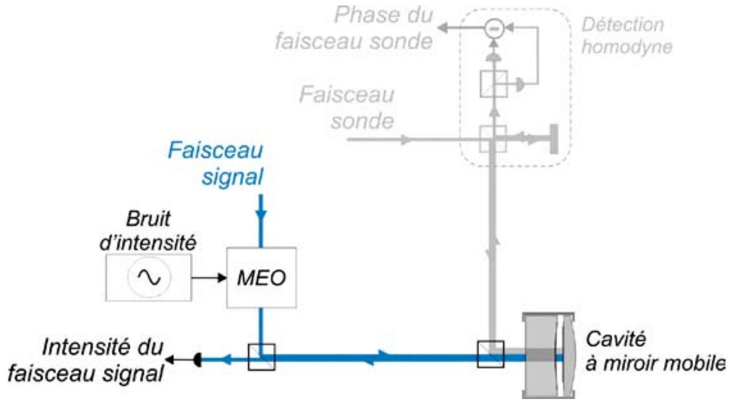
Optomechanical correlations in phase space

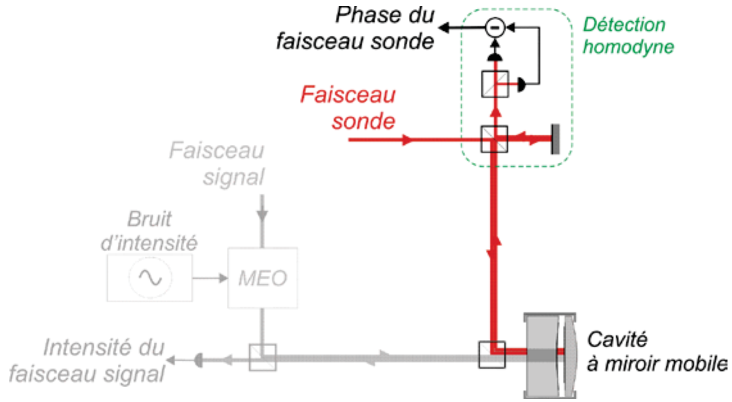
Intensity noise: $\delta I_{\mathrm{out}}(t) = I_1(t)\cos(\Omega_0 t) + I_2(t)\sin(\Omega_0 t)$

Phase noise: $\delta\varphi_{\mathrm{out}}(t) = X_1(t)\cos(\Omega_0 t) + X_2(t)\sin(\Omega_0 t)$









Optomechanical correlations in phase space

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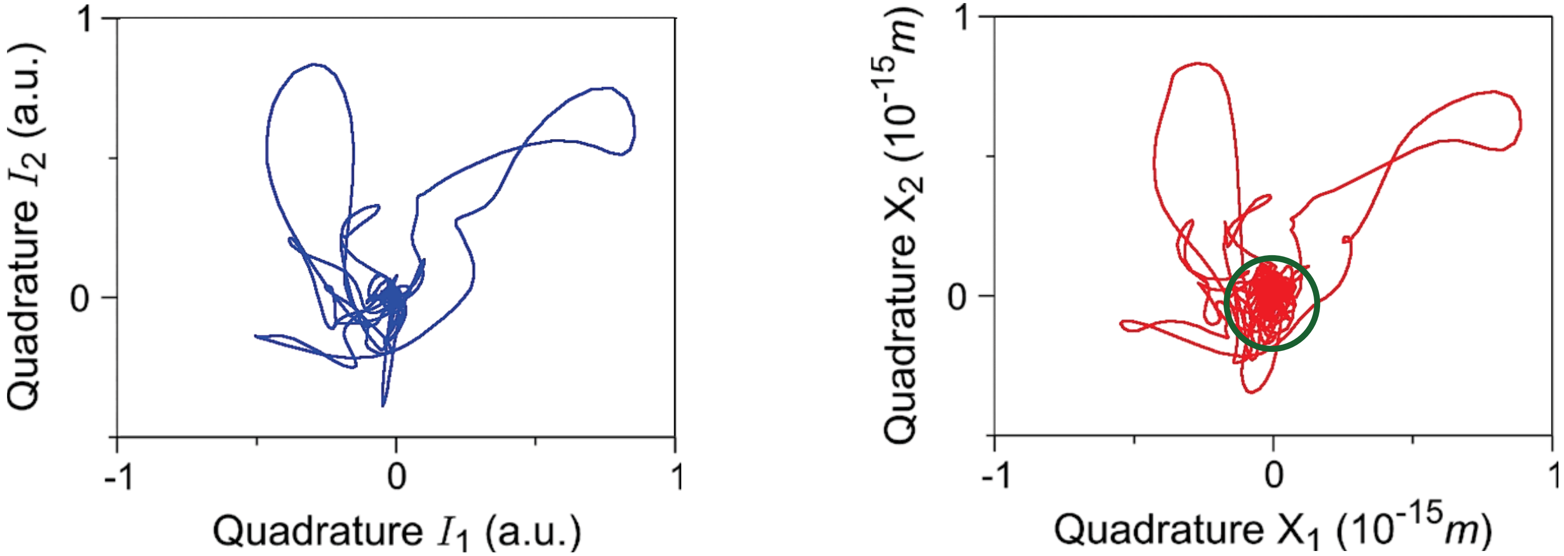


Strong correlations between noise channels:

$$\frac{\delta x_{\text{rad}}}{\delta x_t} \simeq 5 \quad \rightarrow \quad C_{I,\varphi} = \frac{|\langle \delta I_{\text{out}}\, \delta\varphi^{\star}_{\text{out}} \rangle|}{\Delta I_{\text{out}} \Delta\varphi_{\text{out}}} = 0{,}96$$

(limited by thermal noise)

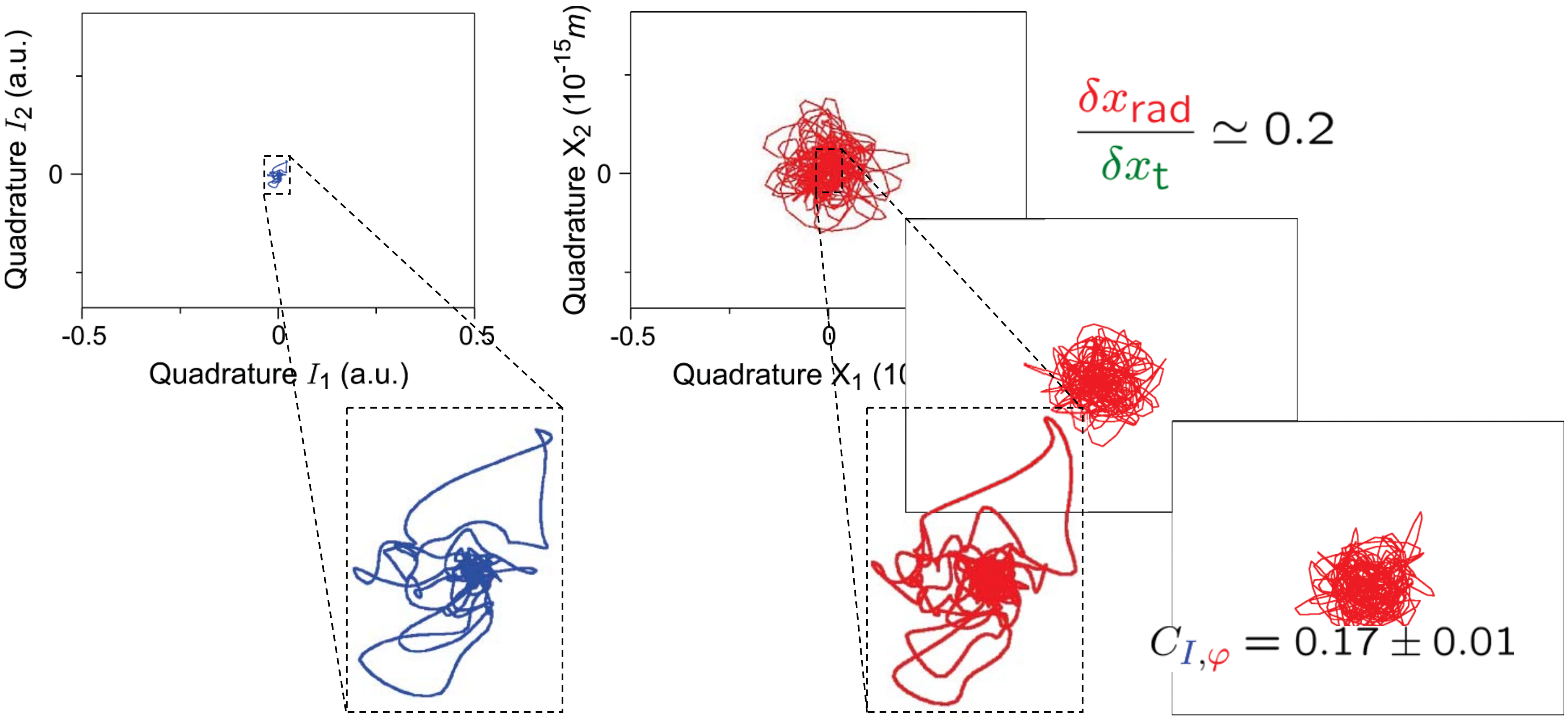
Can one detect quantum-radiation pressure noise?

For quantum noise: $\delta x_{\text{rad}} < \delta x_{\text{t}}$

Averaging however allows to recover quantum correlations:

$$\langle \delta\varphi_{\text{out}} \cdot \delta I_{\text{out}} \rangle \simeq \frac{\mathcal{F}}{\lambda} \left(\langle \delta x_{\text{rad}} \cdot \delta I_{\text{out}} \rangle + \underbrace{\langle \delta x_{\text{t}} \cdot \delta I_{\text{out}} \rangle}_{\longrightarrow 0} \right)$$

Can one detect quantum-radiation pressure noise?



$$\frac{\delta x_{\text{rad}}}{\delta x_{\text{t}}} \simeq 0.2$$

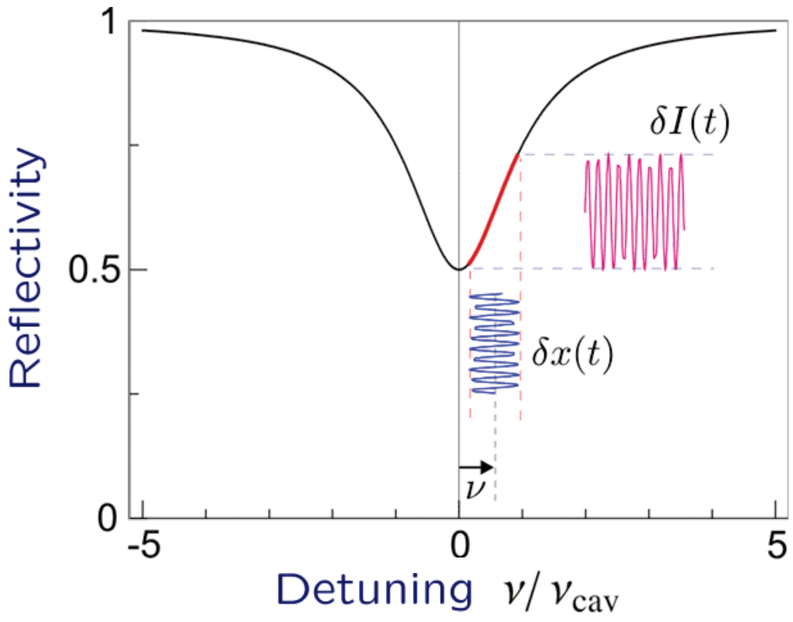
$$C_{I,\varphi} = 0.17 \pm 0.01$$

Consecutive runs

500 averages:

Quantum noise: $\frac{\delta x_{rad}}{\delta x_T} \approx 10^{-3} - 10^{-4}$

(Big) Issues still pending



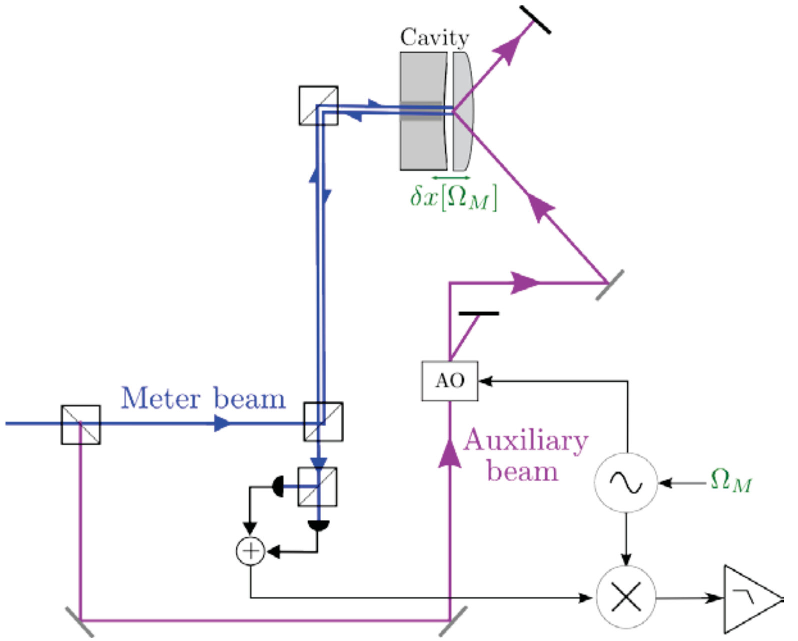
Losses and non-zero detuning:
contamination of beam by (thermal) motion

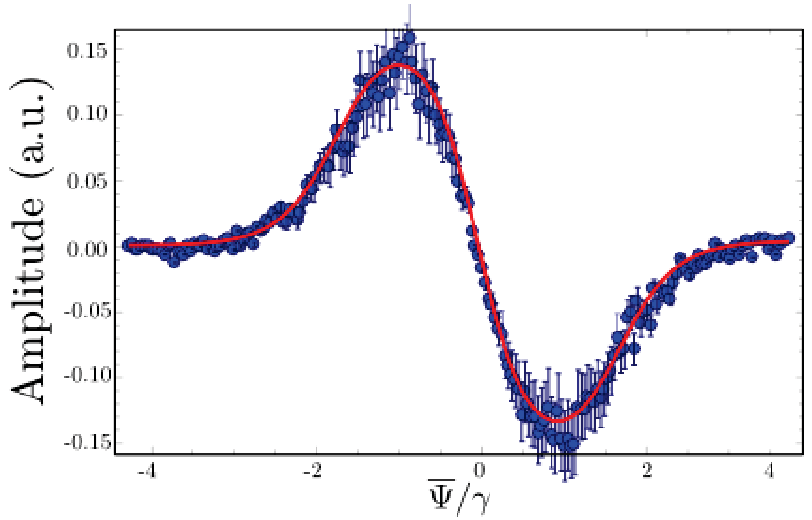
$$\langle \delta I_{\text{out}}\, \delta\varphi_{\text{out}}\rangle \simeq \frac{\mathcal{F}}{\lambda}\left(\underbrace{\langle \delta I_{\text{out}}\, \delta x_{\text{t}}\rangle}_{C_T \neq 0} + \underbrace{\langle \delta I_{\text{out}}\, \delta x_{\text{rad}}\rangle}_{\text{Quantum correlations}}\right)$$

Current improvements:

- Increase of optical power
- Decrease of laser frequency noise

Contamination-based locking

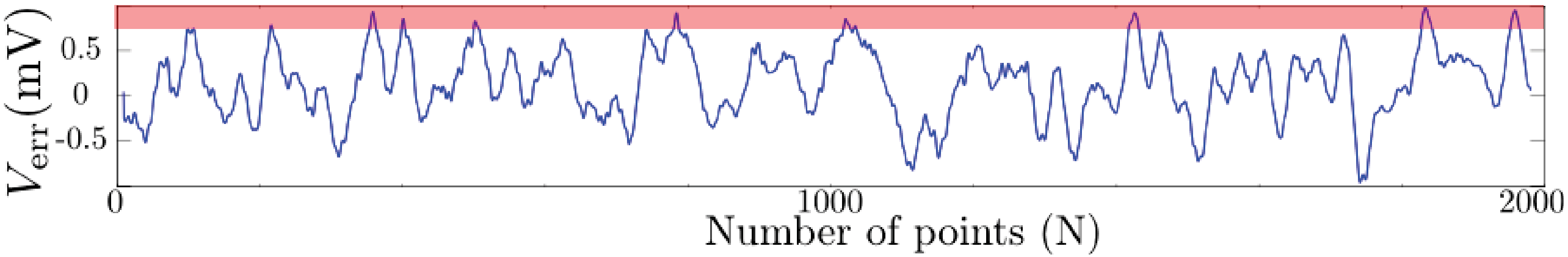




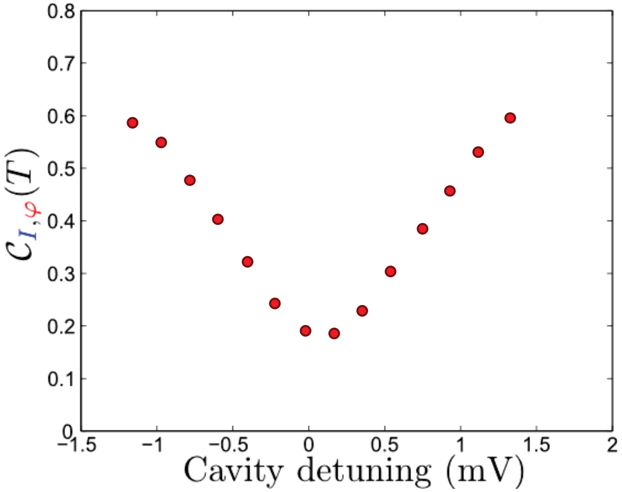
Use of the contamination effect
to create a laser frequency locking signal

Data post-selection

Error signal provides us with a
real-time monitoring of the cavity detuning

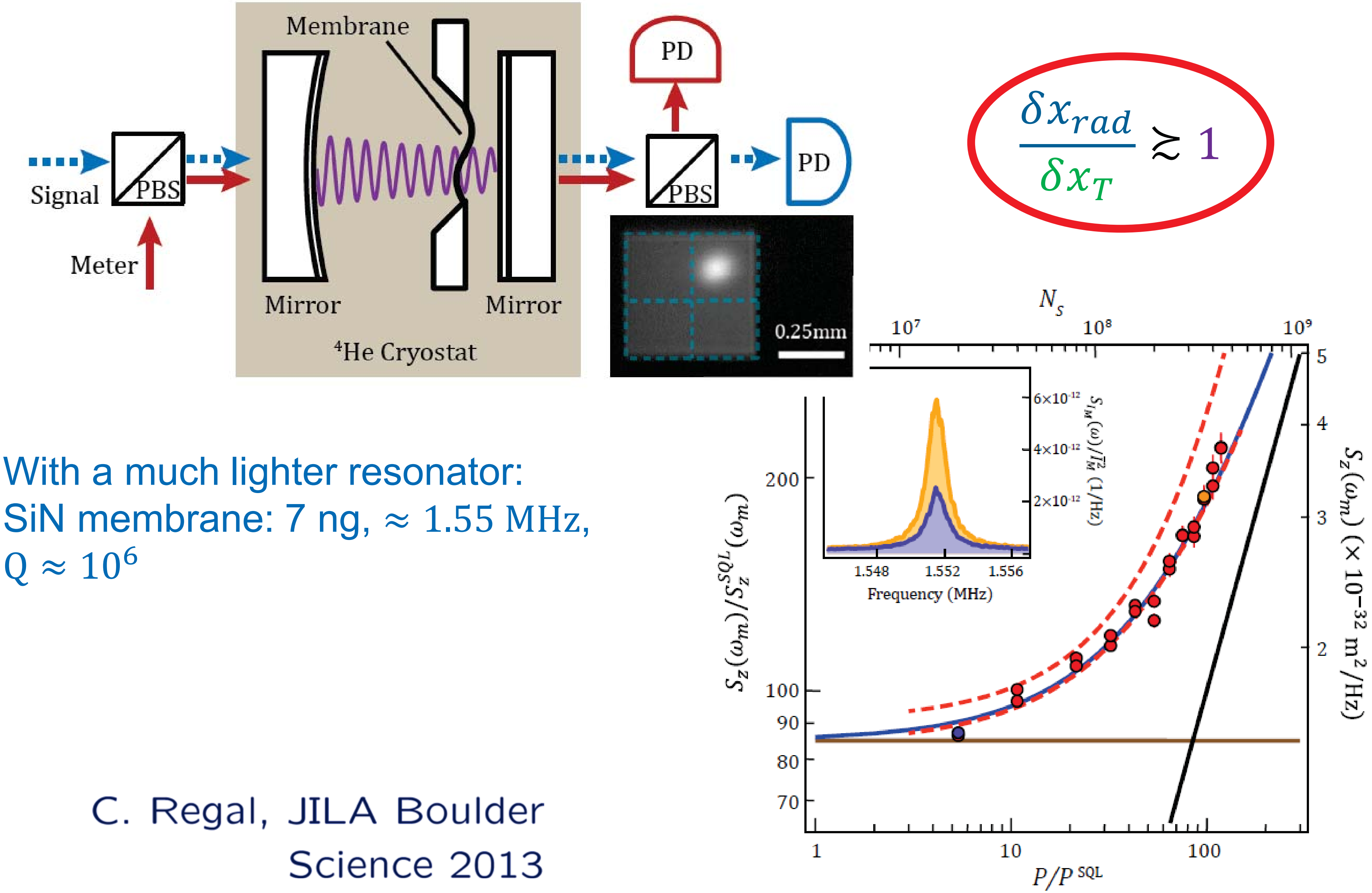


Post-selection



← but lower level of correlation
still not related to quantum noise...

Some actually managed to do it…

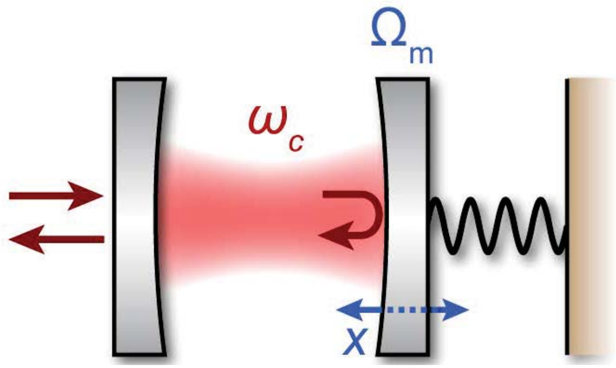


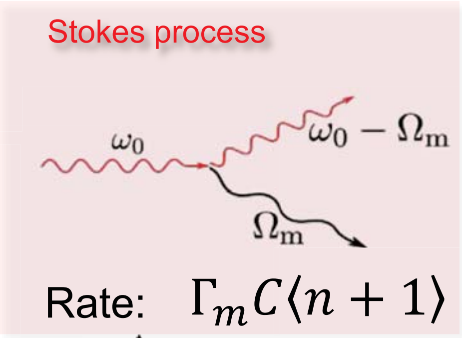
$$\frac{\delta x_{rad}}{\delta x_T} \gtrsim 1$$

With a much lighter resonator:
SiN membrane: 7 ng, ≈ 1.55 MHz,
Q $\approx 10^6$

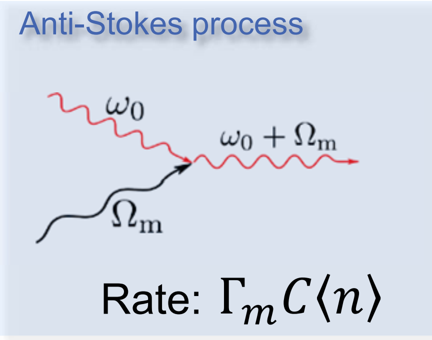
C. Regal, JILA Boulder
Science 2013

1. Radiation-pressure noise, scattering picture

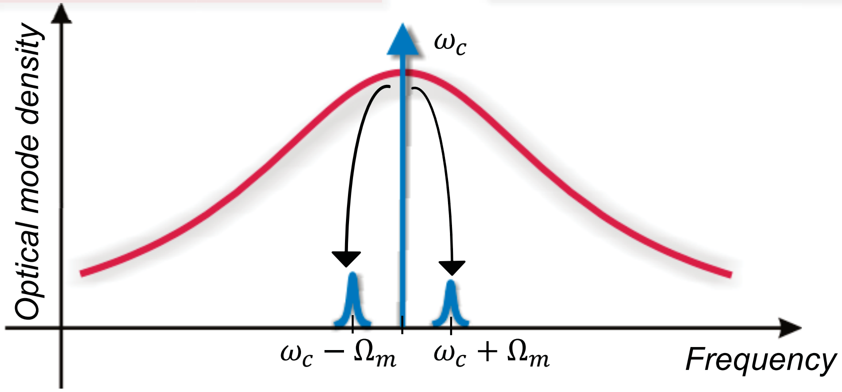


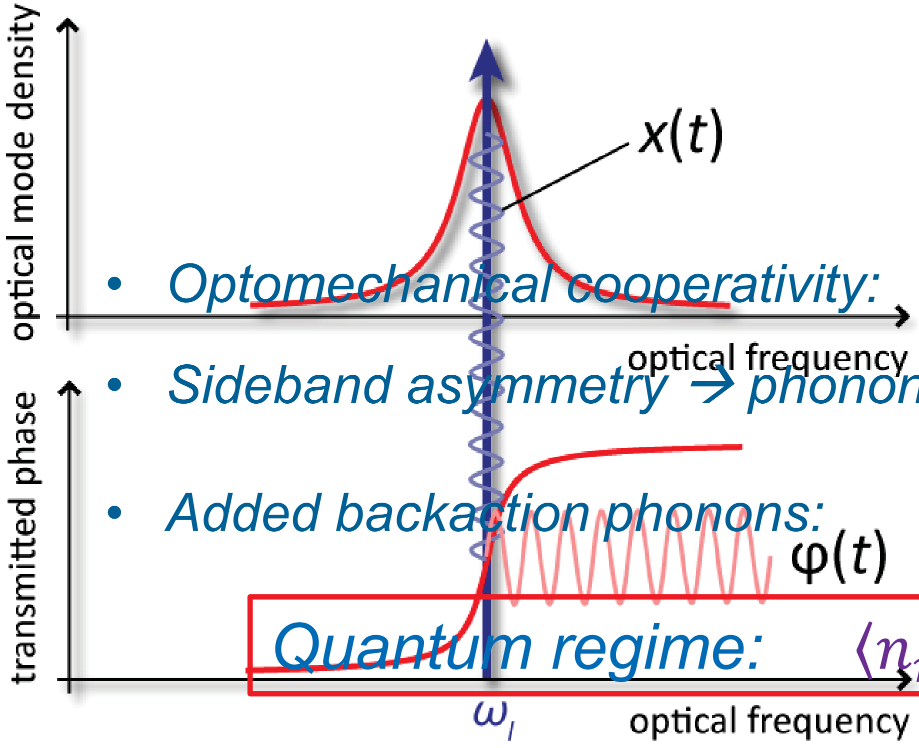

Stokes process

Rate: $\Gamma_m C\langle n+1\rangle$


Anti-Stokes process

Rate: $\Gamma_m C\langle n\rangle$



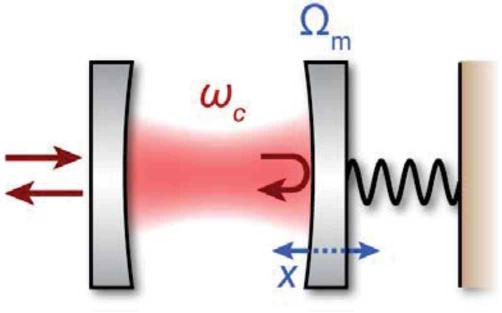


- *Optomechanical cooperativity:* $C = \dfrac{8}{\lambda c}\dfrac{\mathcal{F}P}{\Gamma_m M\Omega_m}$
- *Sideband asymmetry → phonons emitted in the resonator at a rate* $\Gamma_m C$
- *Added backaction phonons:* $\langle n_{rad}\rangle = C$

Quantum regime: $\langle n_{rad}\rangle > \langle n_T\rangle \Rightarrow C > \langle n_T\rangle$

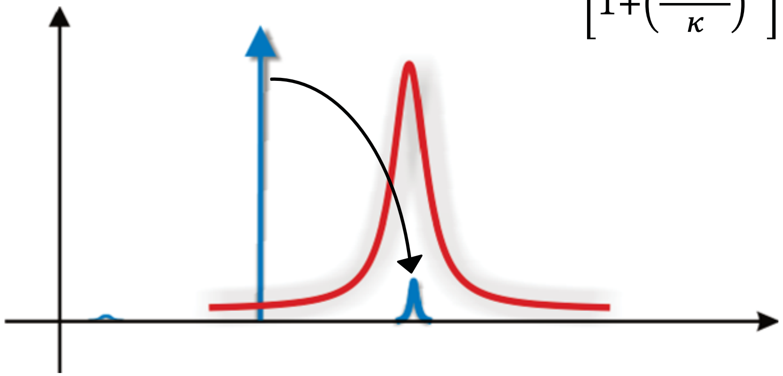
2. Laser cooling of a micro-resonator

In a detuned cavity, radiation pressure is sensitive to mirror displacements:



Anti-Stokes rate: $\mathrm{r_{as}} = \Gamma_m C\langle n\rangle$

Stokes rate: $\mathrm{r_s} = \Gamma_m C\langle n+1\rangle \frac{1}{\left[1+\left(\frac{4\Omega_m}{\kappa}\right)^2\right]}$

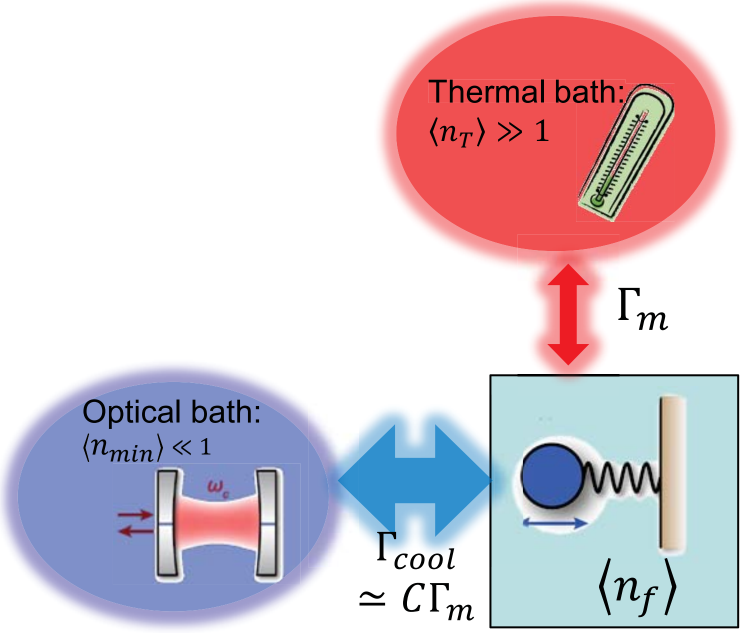


- *Minimum occupation number (laser bath temperature):*

$$r_{as} = r_s \Longrightarrow \langle n_{min}\rangle \simeq \frac{\kappa^2}{16\Omega_m^2}$$

- *Competition between thermal bath and laser cooling:*

$$\boxed{\langle n_f\rangle = \frac{\langle n_T\rangle}{C}}$$



Thermal bath: $\langle n_T\rangle \gg 1$

Γ_m

Optical bath: $\langle n_{min}\rangle \ll 1$

$\Gamma_{cool} \simeq C\Gamma_m$

$\langle n_f\rangle$

F. Marquardt, *PRL* (2007)
I. Wilson-Rae, PRL (2007)

Towards quantum optomechanics

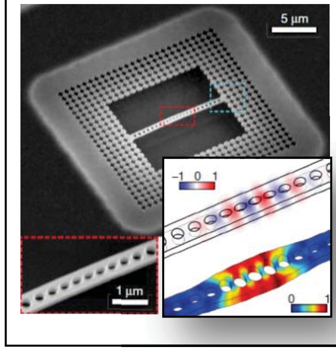
$$\frac{C}{\langle n_T \rangle} \simeq \left(\frac{\mathcal{F}}{300000}\right)\left(\frac{P}{100\ W}\right)\left(\frac{1\ MHz}{\Omega_m/2\pi}\right)\left(\frac{1\ mg}{M}\right)\left(\frac{Q}{10^6}\right)\left(\frac{1\ K}{T}\right)$$

Micro-toroid

$\Omega_m/2\pi = 75\,\text{MHz}$
$M = 3\,\text{ng}$
1.7 phonons
$C \approx 150$

T. Kippenberg (Lausanne), 2011

Silicon nanobeam

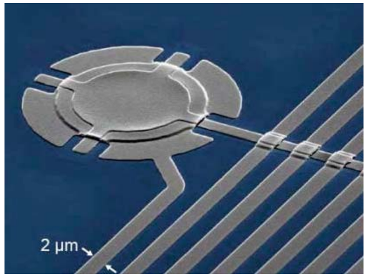


$\Omega_m/2\pi = 3.7\,\text{GHz}$
$M = 300\,\text{fg}$
0.8 phonon
$C \approx 150$

0. Painter (Caltech), 2011

Can we reach this regime with more massive mechanical resonators (planck's mass: 22 µg)?

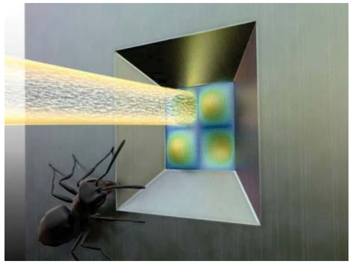
Microresonator coupled to a microwave



$\Omega_m/2\pi = 10\,\text{MHz}$
$M \simeq 50\,\text{pg}$
0.3 phonon
$C \approx 5000$

K. Lehnert (Boulder), 2011

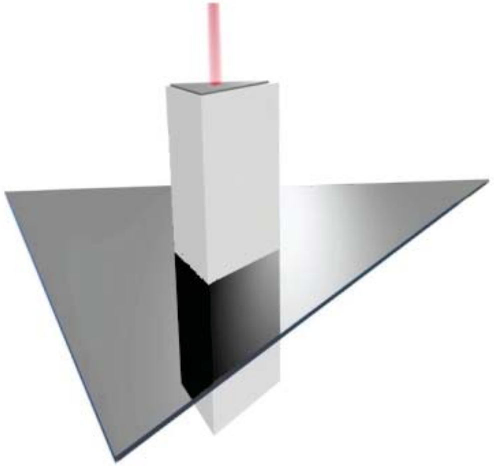
Optomechanical membrane



$_m/2\pi = 1MHz$
$M = 7\ \text{ng}$
$\frac{\langle n_{rad} \rangle}{\langle n_T \rangle} = 5$
$C \approx 10^6$

C. Regal (Boulder), 2012

An optomechanical micropillar



Clamping to a vibration node

→ no clamping loss

No strain at the coating location

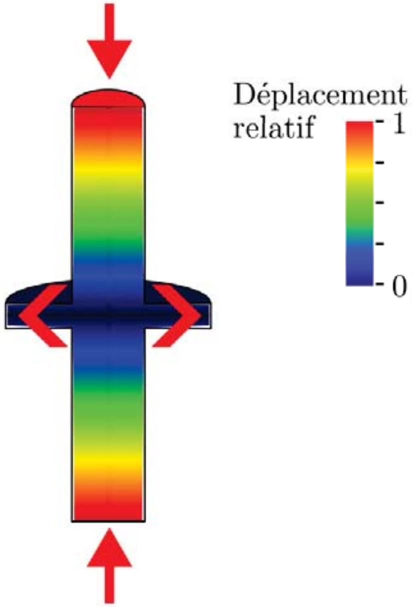
→ no coating losses

1-mm long quartz micropillar

$M \simeq 100\ \mu\mathrm{g}$

$\Omega_\mathrm{m}/2\pi \simeq 3{,}6$ MHz

$Q \simeq 10^6$ to 10^8



ONERA

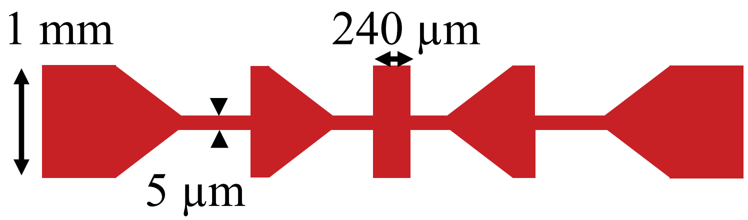
THE FRENCH AEROSPACE LAB

A. G. Kuhn, *APL* (2011)

Micro-fabrication issues

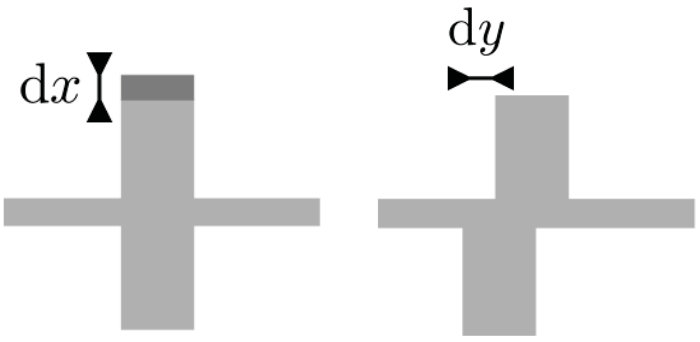
Geometry:

- triangular section(quartz)
- etching slopes (not so steep)
- Membrane roughness: a few μm rms



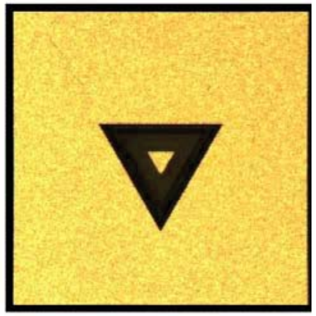
Symmetry requirements:

- Chemical etching: a few μm imbalance
- Standard alignment: a few μm
- HF etching constraints



Micro-fabrication

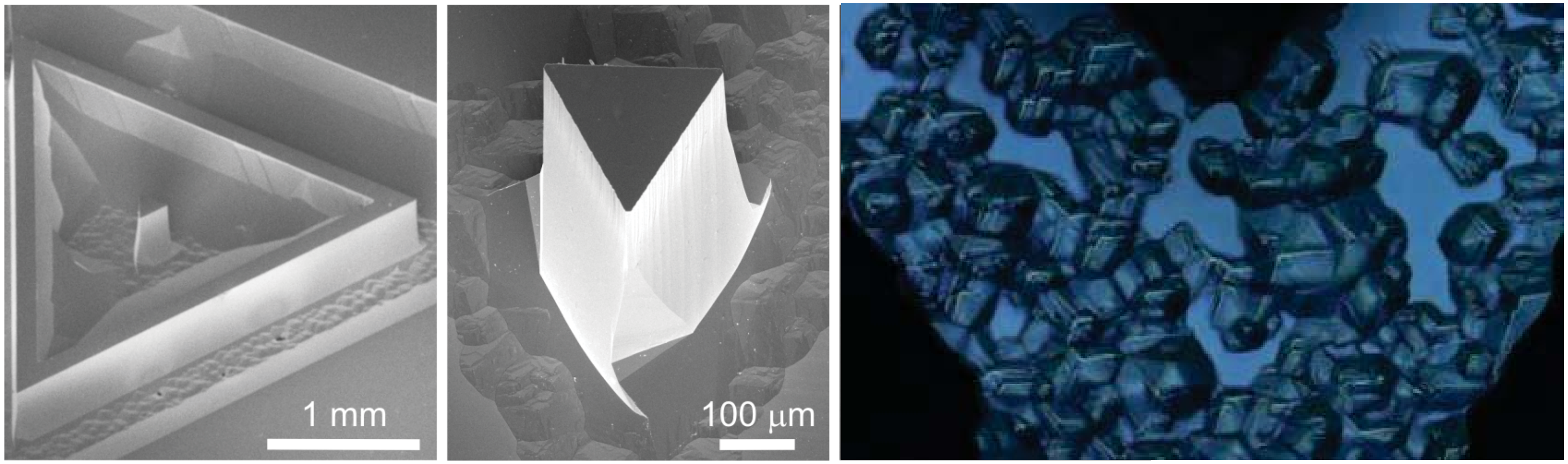
$Q \simeq 10\ 000$



$Q \simeq 1\ 000\ 000$

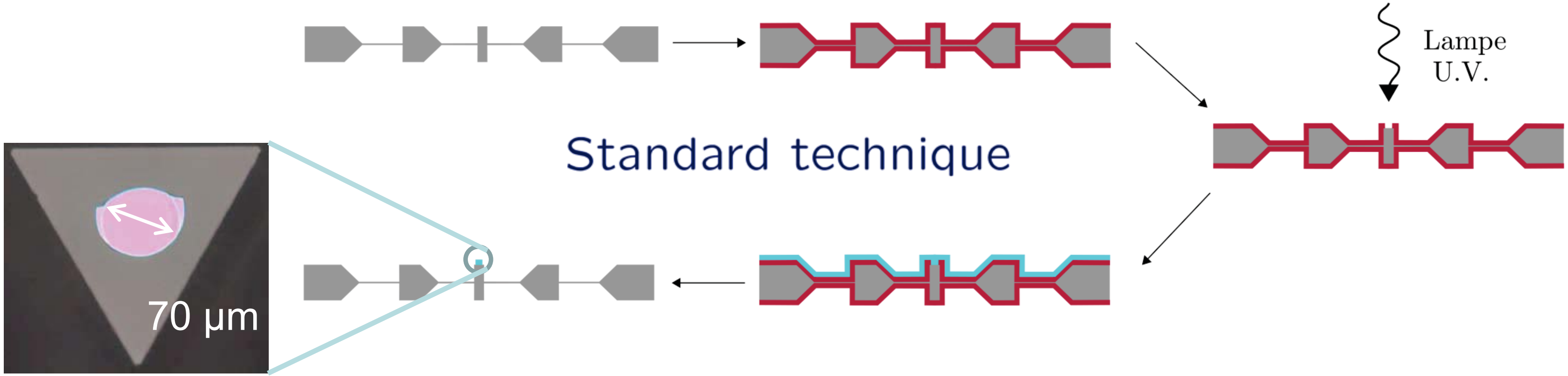
$Q \simeq 100\ 000$

Membrane



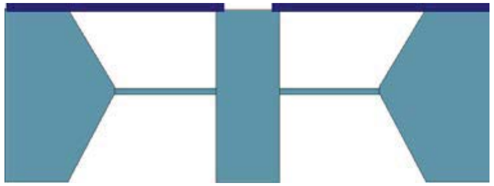
App. Phys. Lett. (2011)

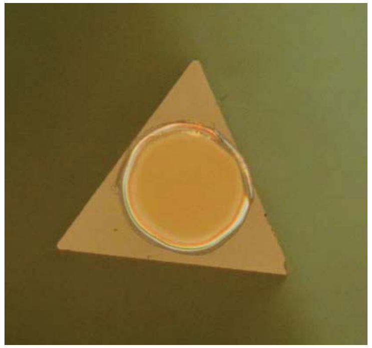
Optical coating



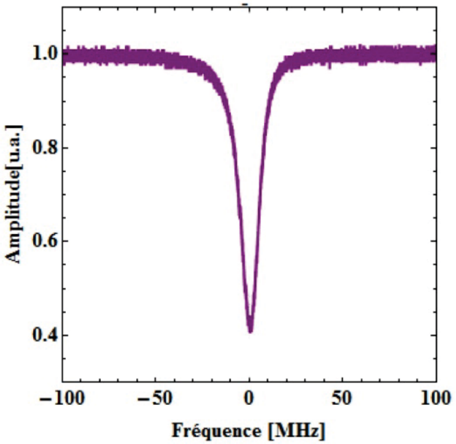
Standard technique

Polymer film mask,
resistant to coating conditions

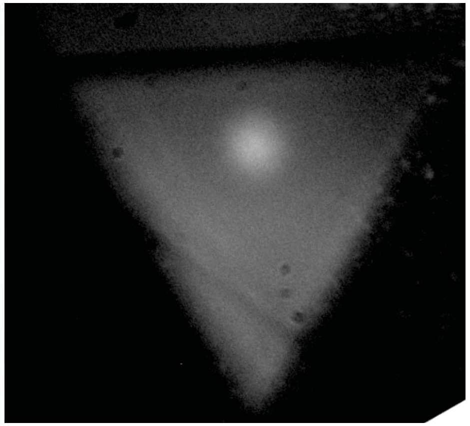




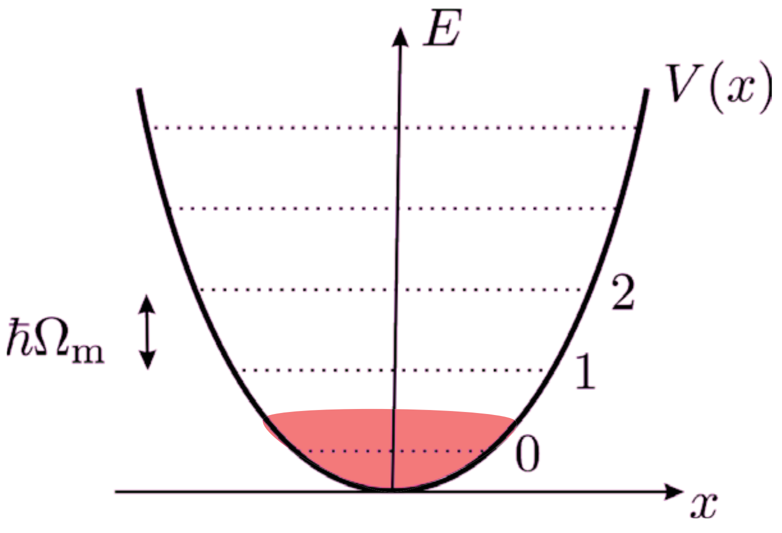
Mode-matching inside a dilution fridge



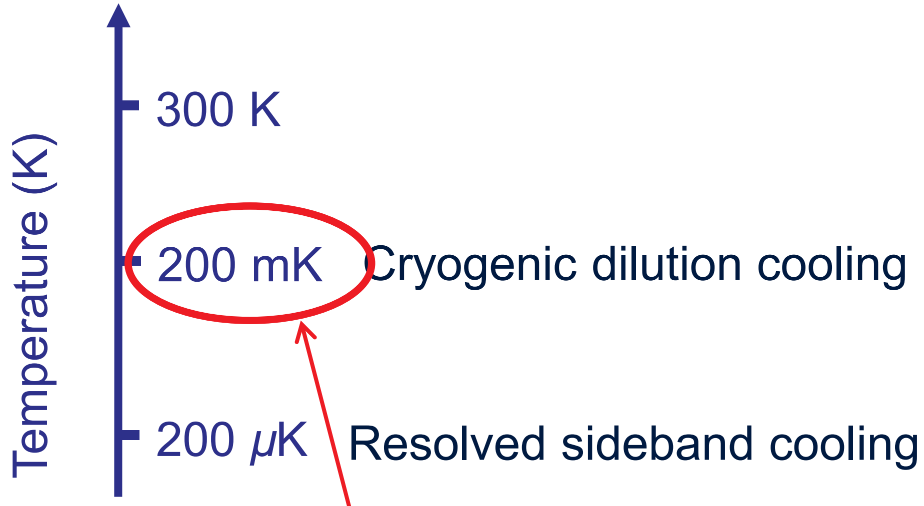
- Finesse: $40\,000 @ 200mK$
- Mode matching $\eta = 80\,\%$
- No misalignement during cooldown



Towards the quantum regime of a massive resonator



$T_\mathrm{QGS} \approx 200\,\mu\mathrm{K}$
(@ 4 MHz)


Temperature (K)

300 K

200 mK Cryogenic dilution cooling

200 μK Resolved sideband cooling

Requires: $C \simeq 10^3$

?

Current parameters:

$$\begin{cases} \mathcal{F} = 40\,000 \\ P = 100\ W \\ Q = 2\,000\,000 \\ M = 100\ \mu g \\ \Omega_m = 2\pi \cdot 4\ MHz \end{cases}$$

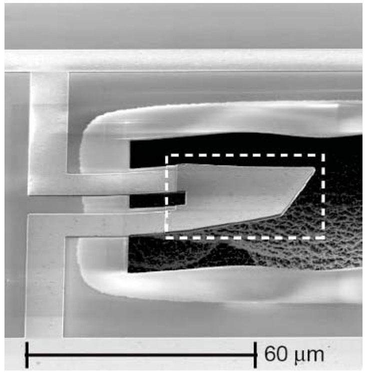
$\Rightarrow \quad C \approx 3000$

Hybrid optomechanical systems

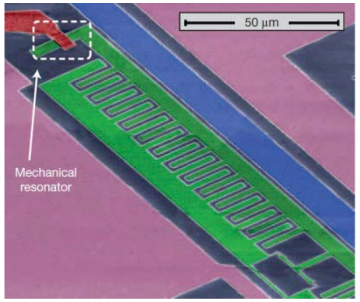
Couple a mechanical resonator to another well-controlled quantum device

Control and measure the quantum state of a macroscopic mechanical system using the toolboxes of the other system

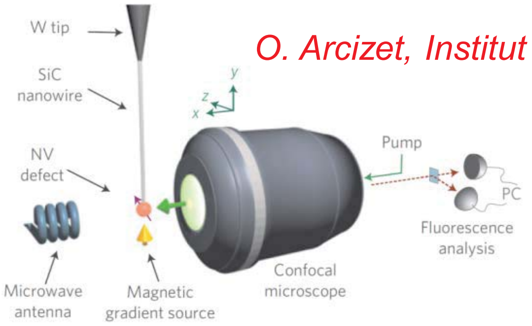
Use entanglement for the transfer and storage of quantum information in hybrid systems



A. Cleland, UC Santa Barbara

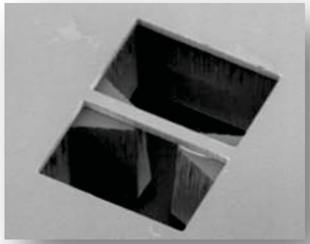


P. Hakonen, Aalto Univ



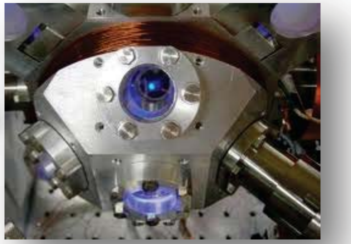
O. Arcizet, Institut Néel

Couple cold atoms to a mechanical resonator



Resonator

Laser link



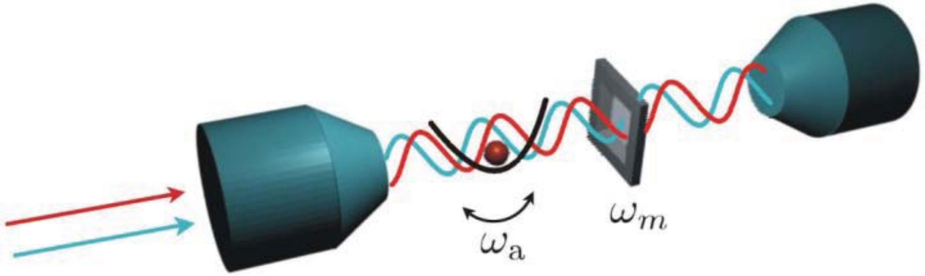
Cold atoms

- *Efficient quantum control*
- *Comprehensive atomic toolbox*
- *Long atomic coherence time*
- *Access to external and internal degrees of freedom*

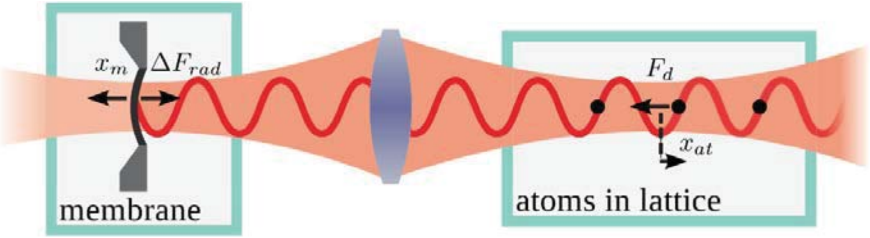
Atoms and mechanical resonators : state of the art

Currently 2 experiments in this domain:

Atom and membrane in a high-finesse cavity (H.J. Kimble, Caltech)



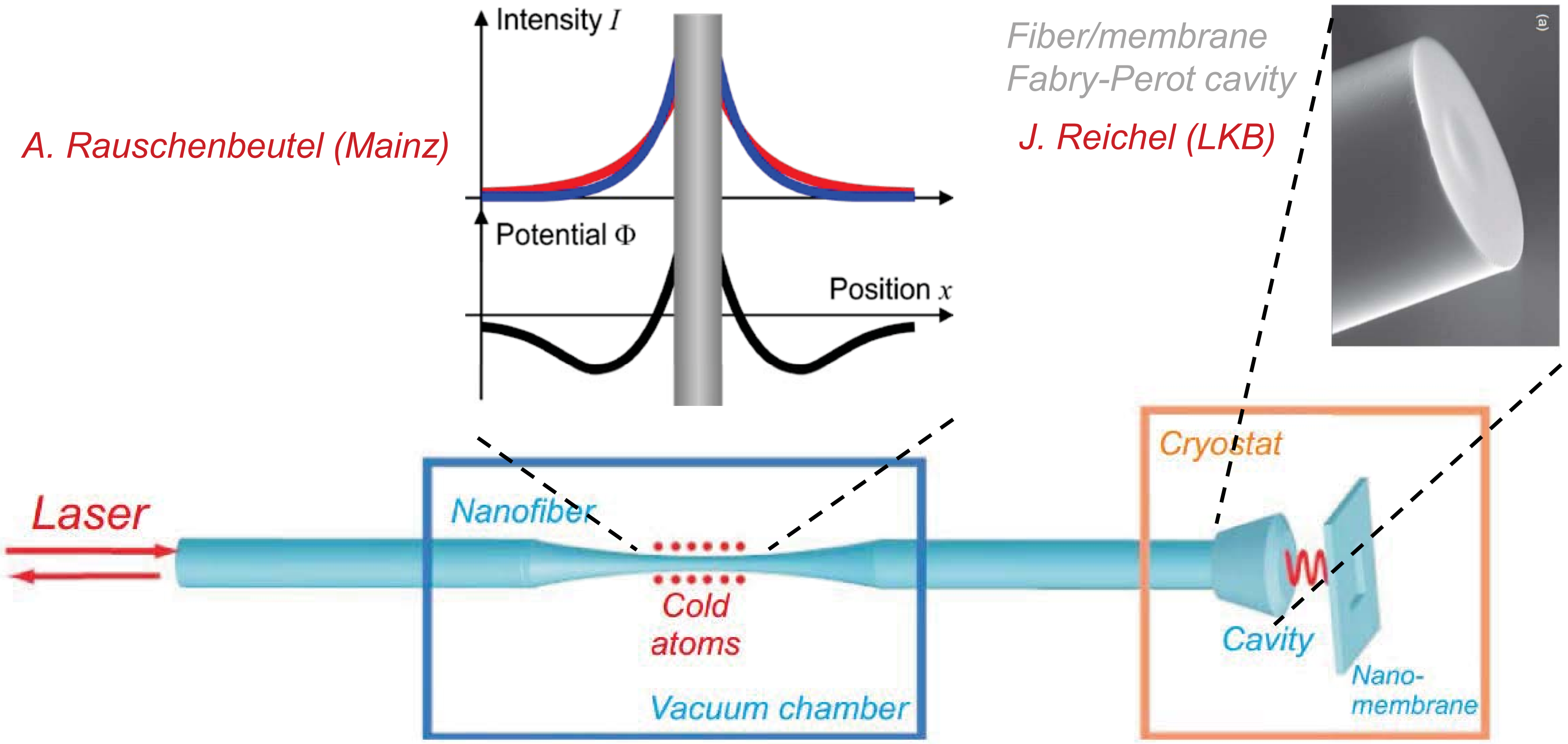
Atoms in the field reflected by a membrane (P. Treutlein, Basel)



- *Possibility of different environments*
- *No cavity but large number of atoms* $(N \sim 10^6)$

Recent observation of atom heating when the membrane is actuated

Coupling a nanomembrane to cold atoms



A. Rauschenbeutel (Mainz)

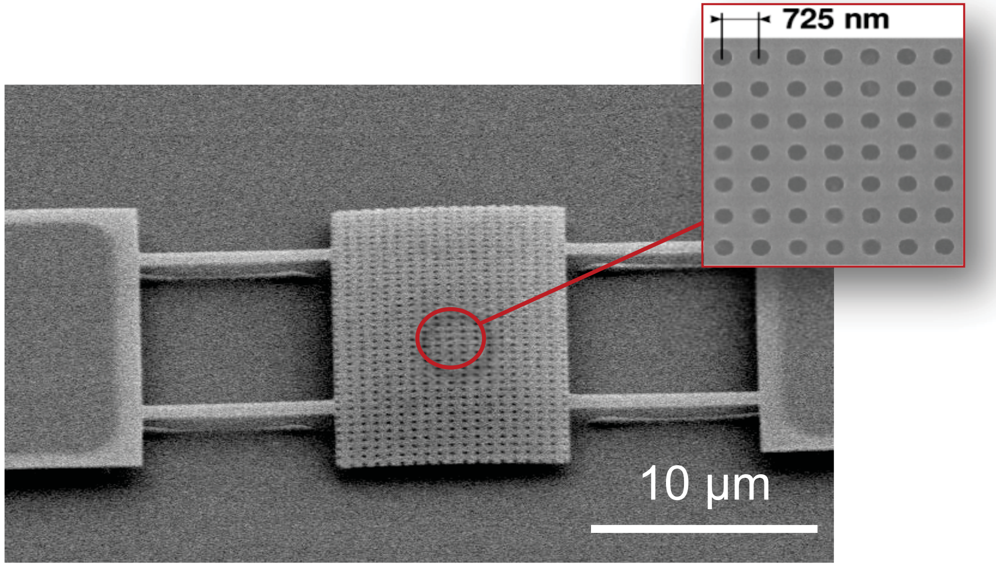
Fiber/membrane Fabry-Perot cavity

J. Reichel (LKB)

- Atoms trapped in the evanescent field of a tapered optical fiber (Collaboration: J. Laurat LKB)
- Coupling to a nano-membrane enhanced by the cavity finesse (see *Vogell et al. PRA 2013*)

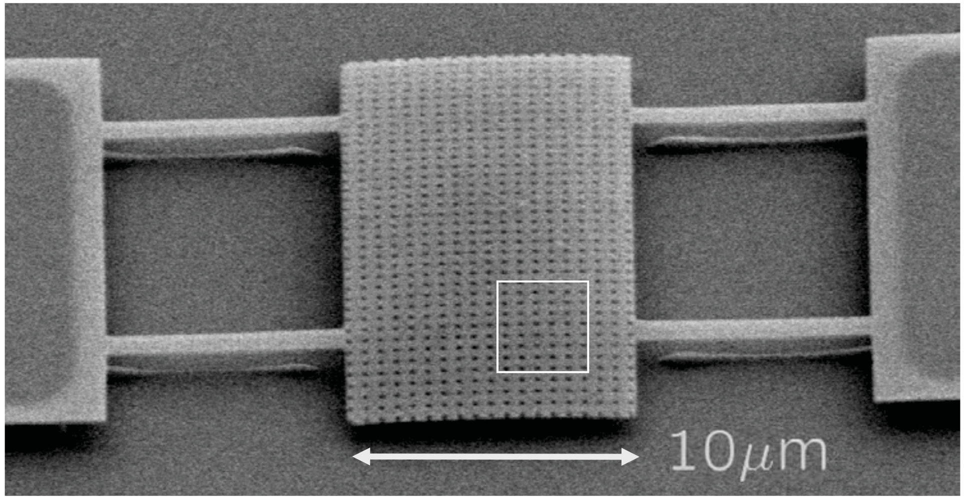
A photonic crystal nano-cavity

- Mirror coatings are strongly limiting the resonator design
  - Dielectric layers are thick and heavy
  - Poor mechanical properties



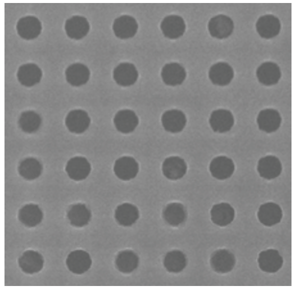
Opt. Lett. **36**, 17 (2011)

A photonic-crystal membrane



InP membrane

$20\ \mu m \times 10\ \mu m \times 200\ nm$

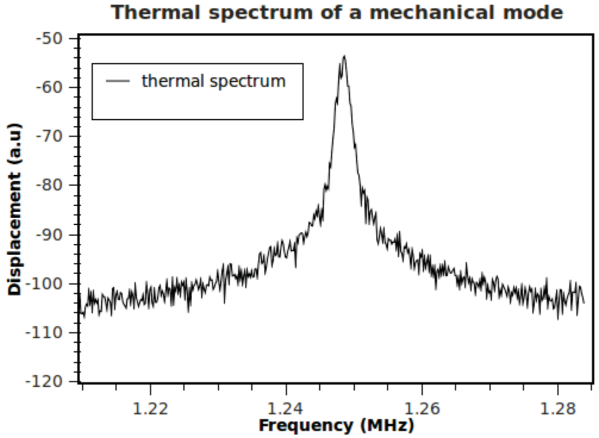


$\simeq 725$ nm

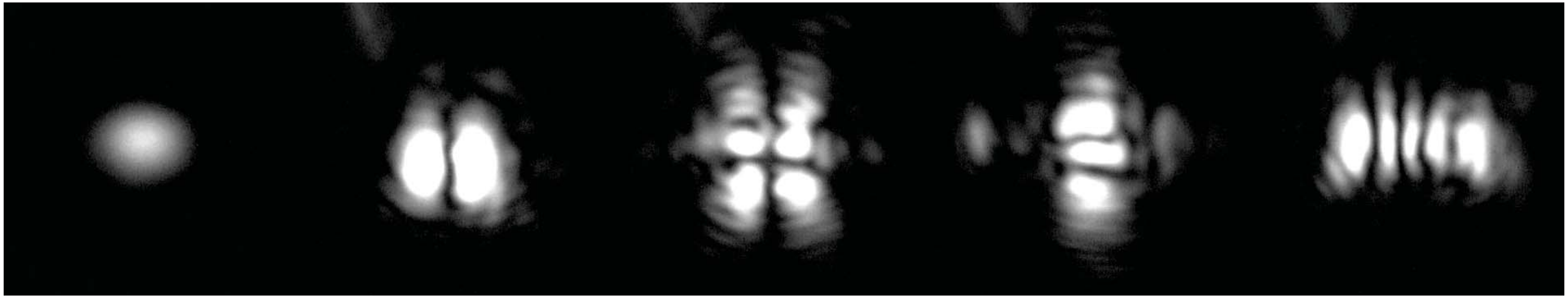
Photonic crystal:

$R \simeq 95\%$

Opt. Lett. (2011)

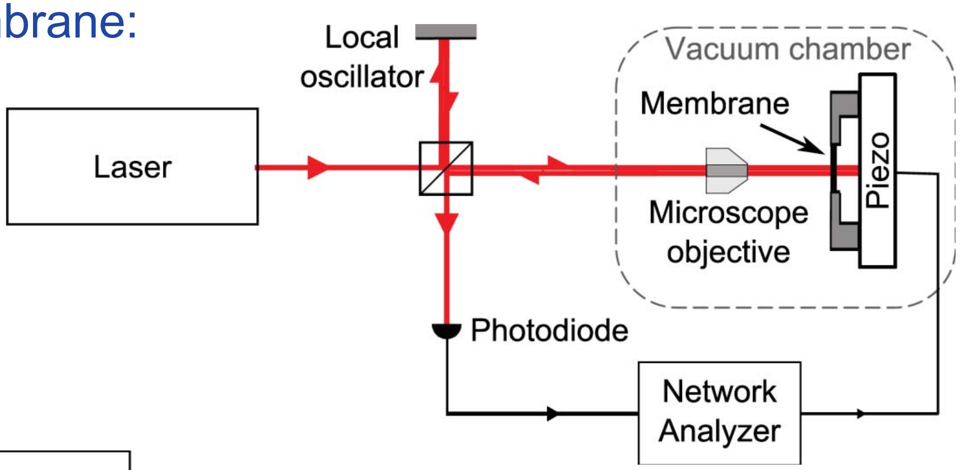


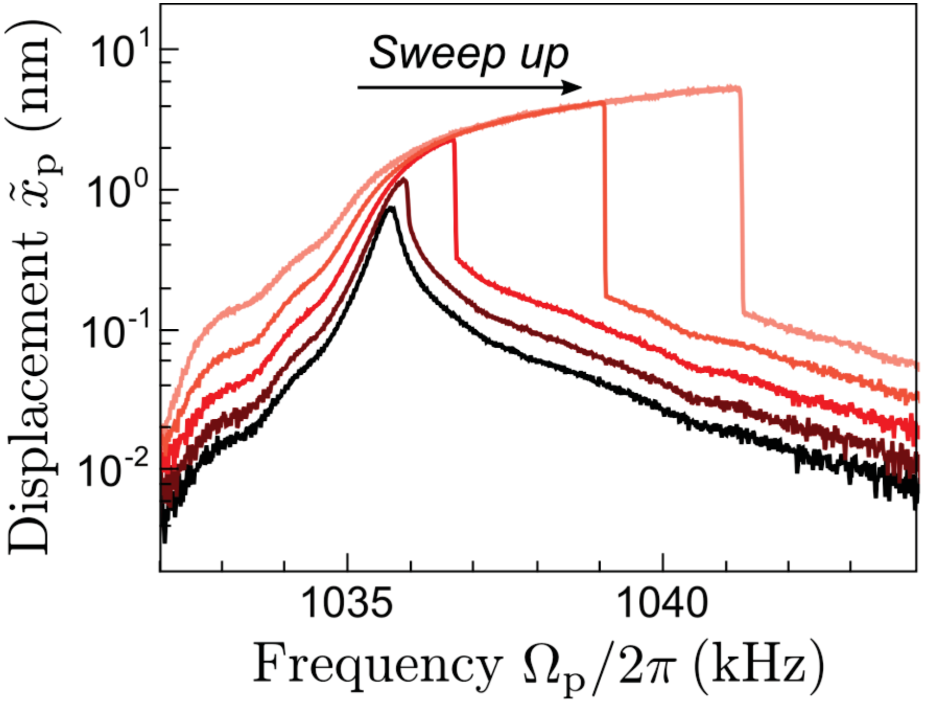
Cavity: $w_0 \simeq 2-3\ \mu m$ $\mathcal{F} \simeq 100$



Nonlinear regime of the nanomembrane

Piezoelectric actuation of the membrane:



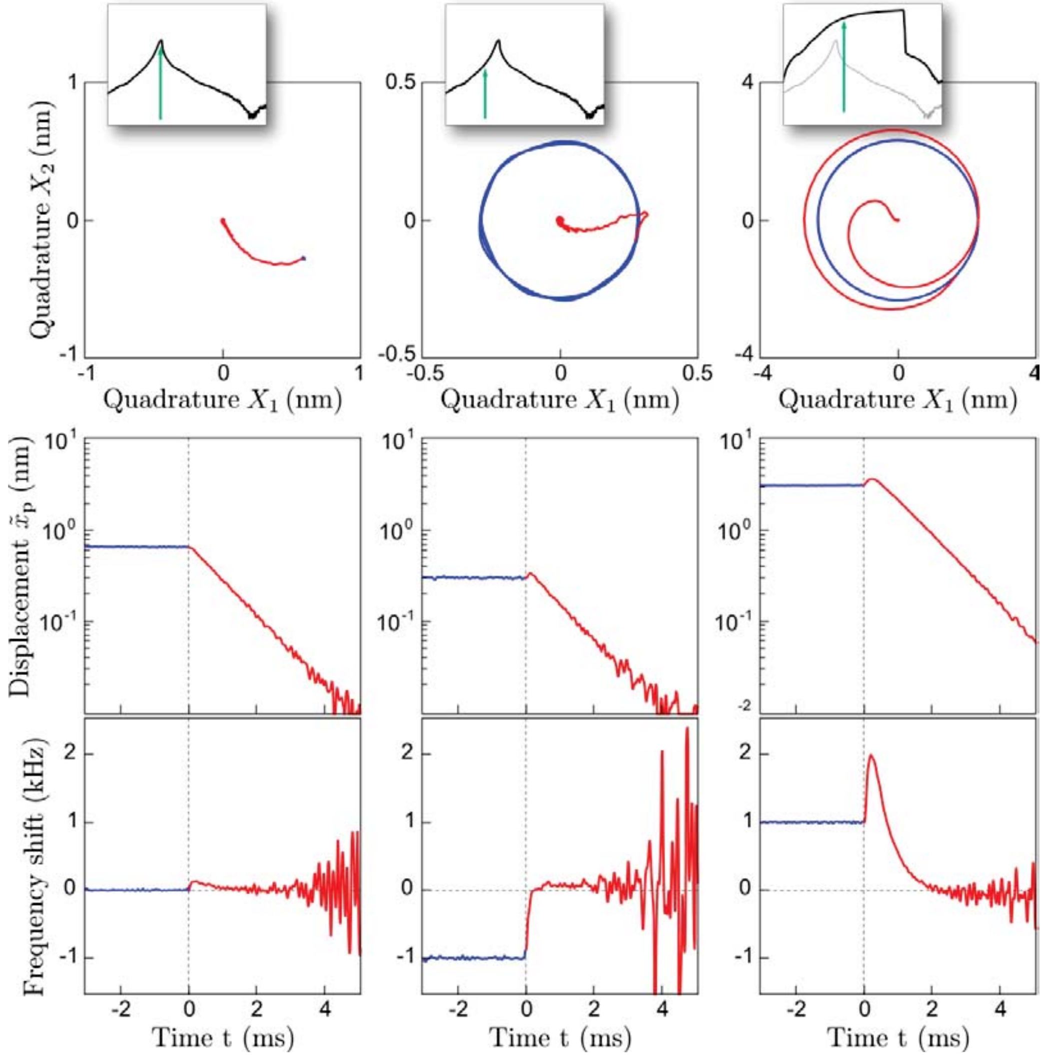


➔ Duffing equation:

$$\ddot{x}(t) + \Gamma\dot{x}(t) + \omega_0^2[1 + \beta x^2(t)]x(t) = \alpha(t)$$

Nonlinear dynamics

➔ Ring-down evolution in phase space



➔ Resonant linear response

➔ Out-of-resonance:

Same time decay

Instantaneous jump to resonance frequency

➔ Nonlinear response:

Same time decay

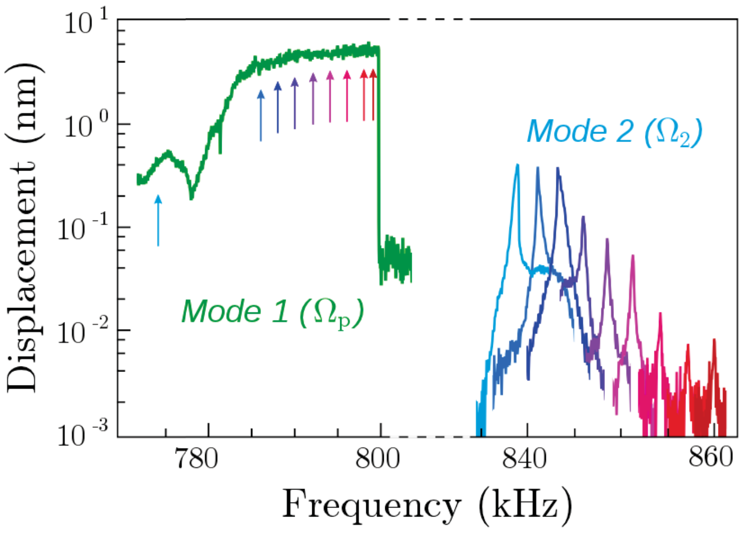
Frequency jump to the top of the upper branch

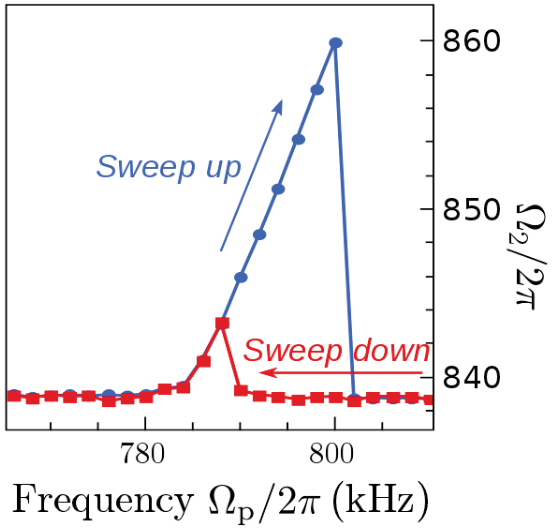
➔ Nonlinearity pushes the resonance frequency upwards

T. Antony et al. EPL (2012)

Non-locality of the nonlinearity

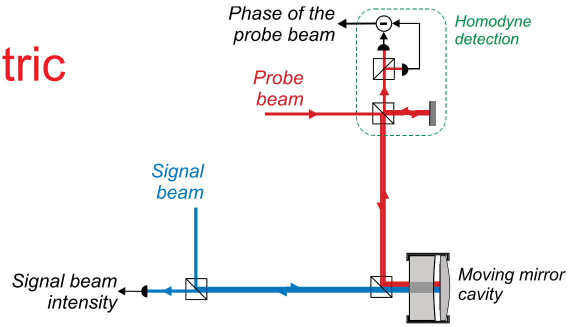
Driving of mode 1 in the non-linear regime also affects the frequency of mode 2





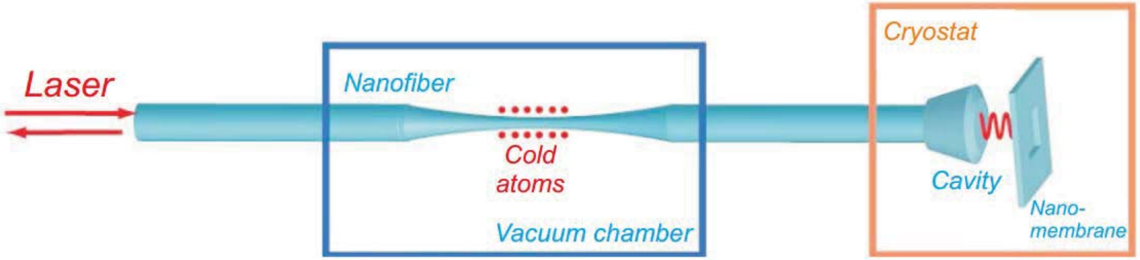
Summary

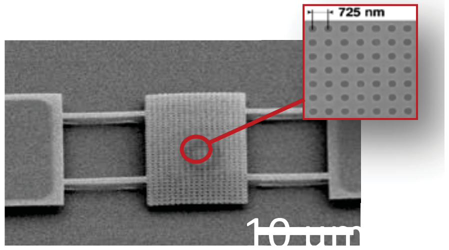
Effects of radiation pressure noise in an interferometric measurement at room temperature



Quantum behaviours of massive resonators

Development of an hybrid optomechanical system





The team

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