High sensitivity interferometric measurements in cryogenic environment: optmechanical correlations and laser cooling

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Physique quantique et applications

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Ens

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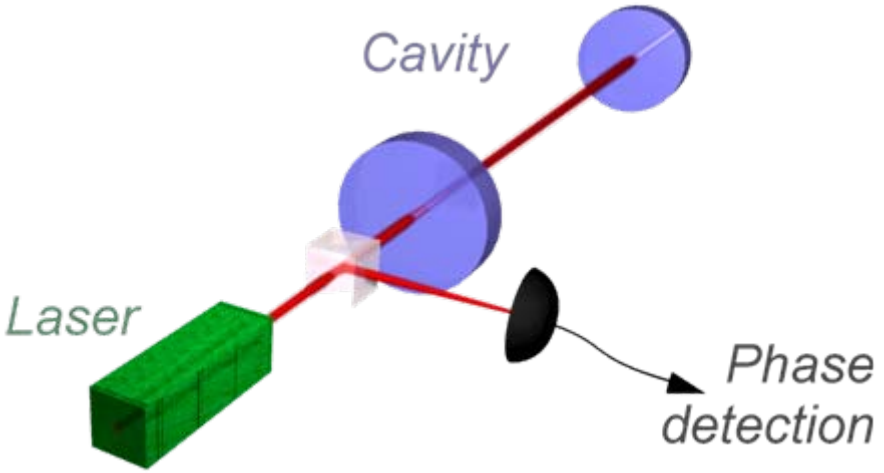
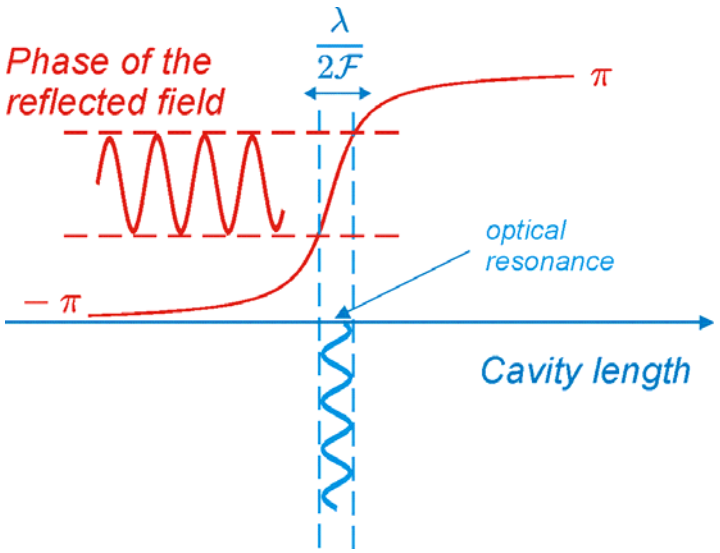
High-sensitivity displacement measurement





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

signal

(quantum) phase noise

index fluctuations

frequency noise

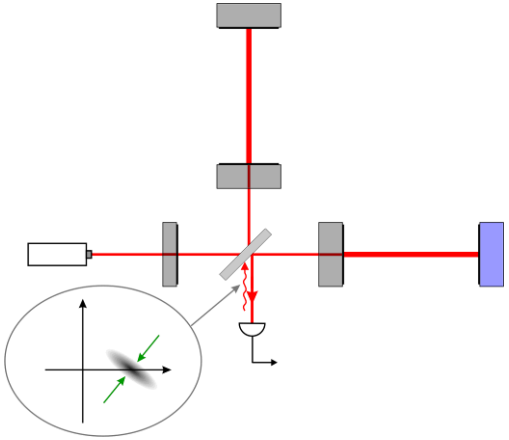
(classical) position noise

(quantum) radiation pressure noise

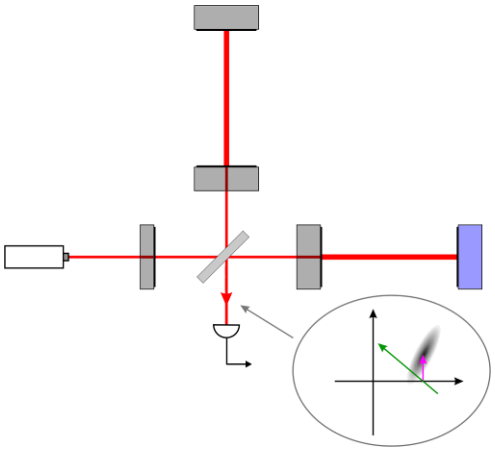
Quantum noise reduction

Many proposals to reduce quantum noises:

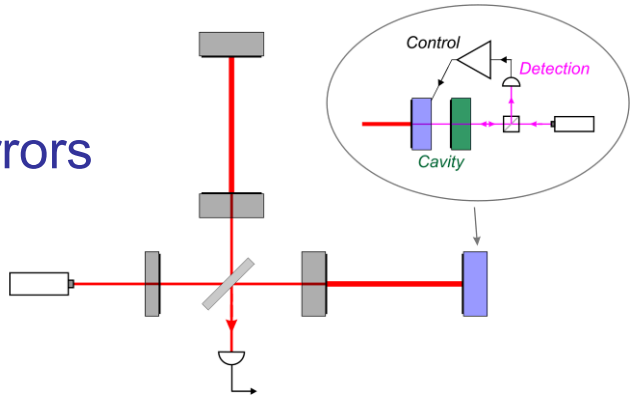
- Injection of squeezed states



- QND detection

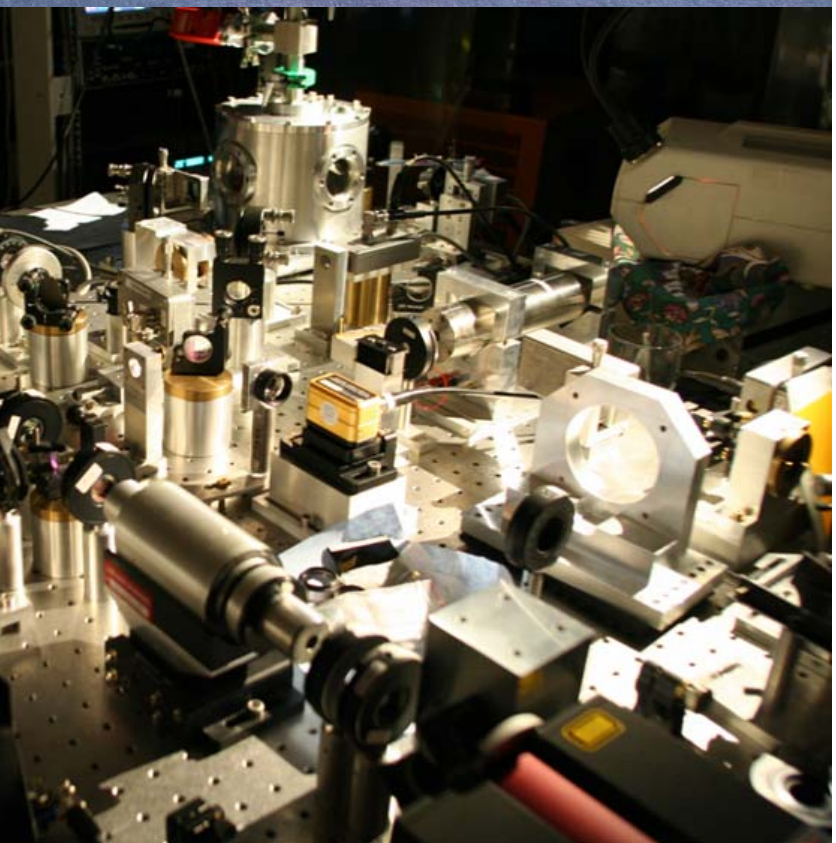


- Quantum locking of mirrors



Objectives:

- Define the constraints in real interferometers
- Find efficient and robust schemes
- Perform experimental tests of quantum noises



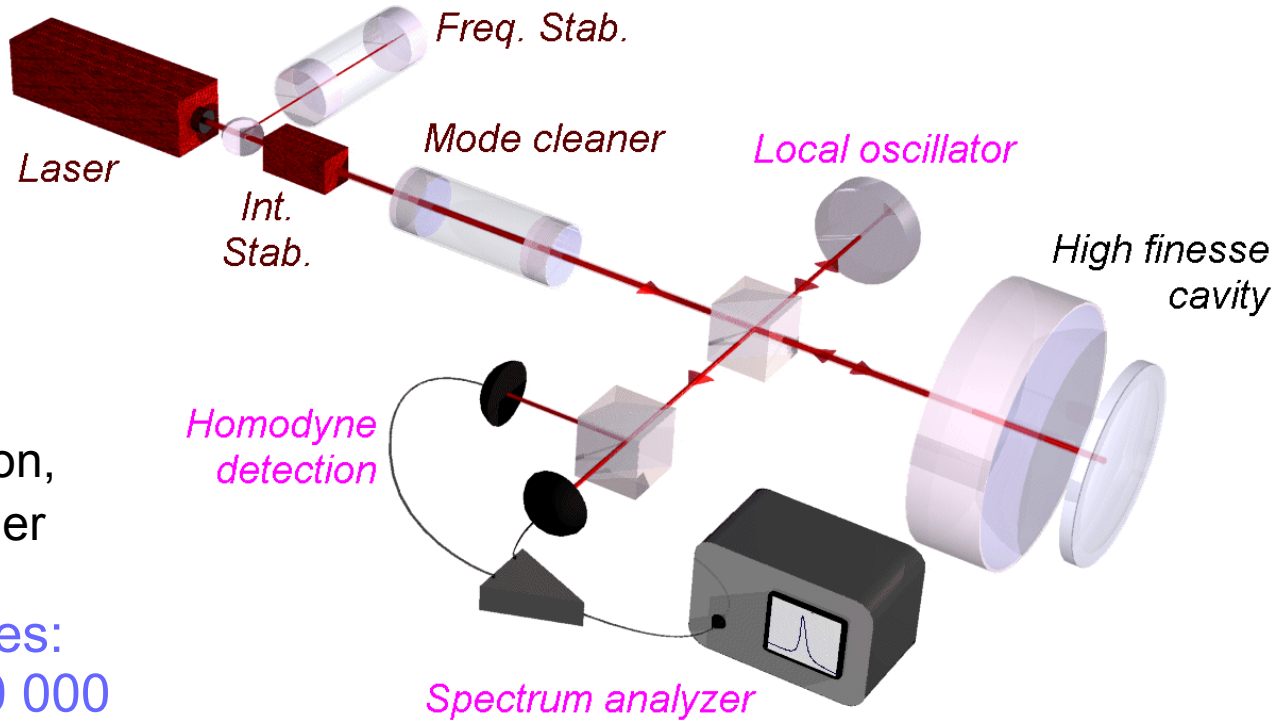
High sensitivity interferometric measurements

Toward a QND measurement

Laser cooling of a microresonator

Experimental setup

Measurement of mirror displacements with a high-finesse cavity



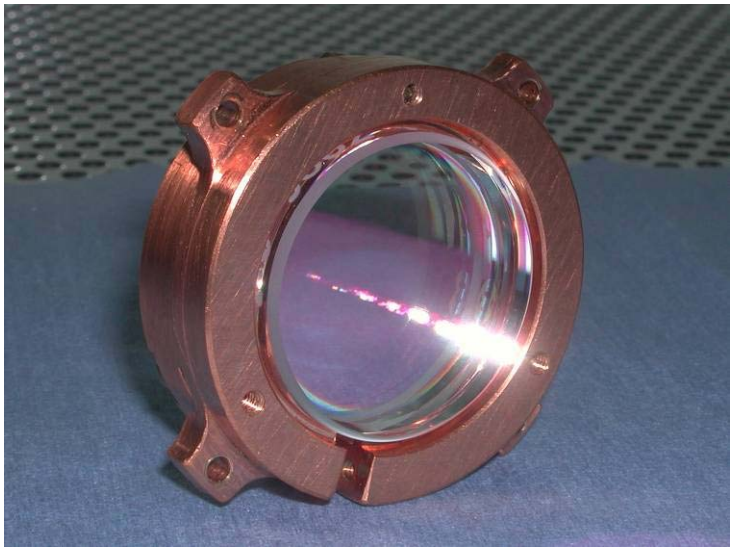
- Ultra stable laser source

  Frequency and intensity stabilization, spatial mode cleaner

- High-finesse cavities: from 30 000 to 230 000

- Homodyne detection working at the quantum level

Observation of thermal noise



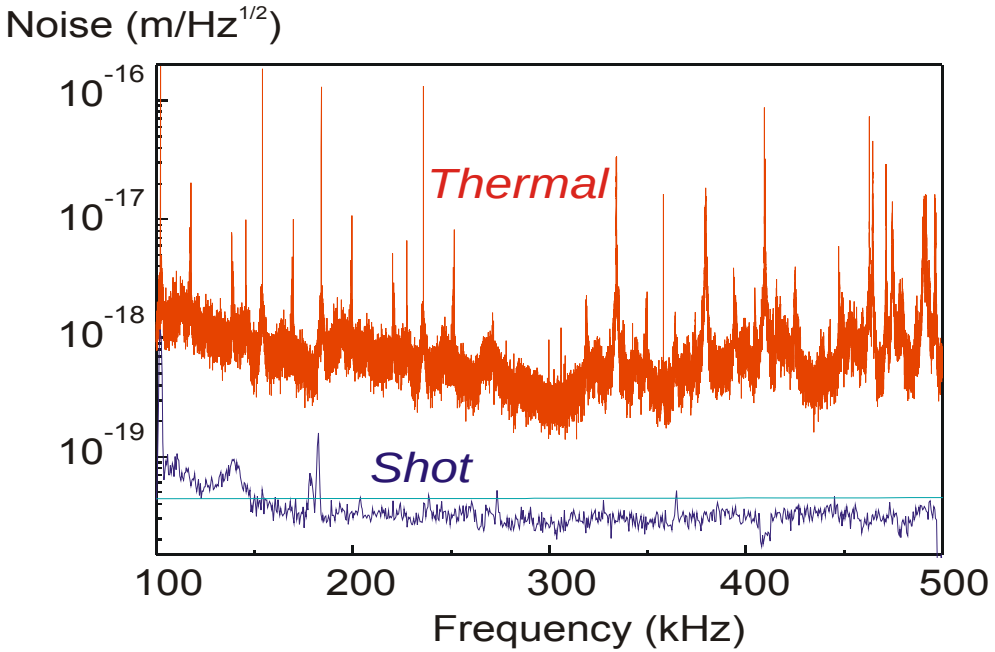
Optical coating made by the LMA

Cavity with a finesse 230 000

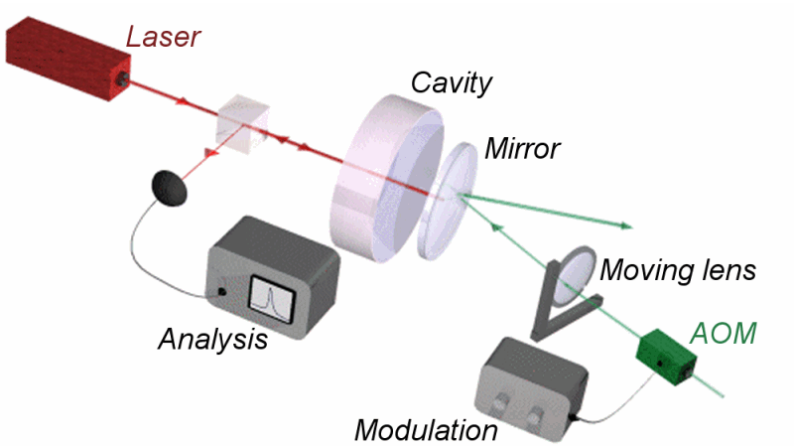
1 mW of incident power

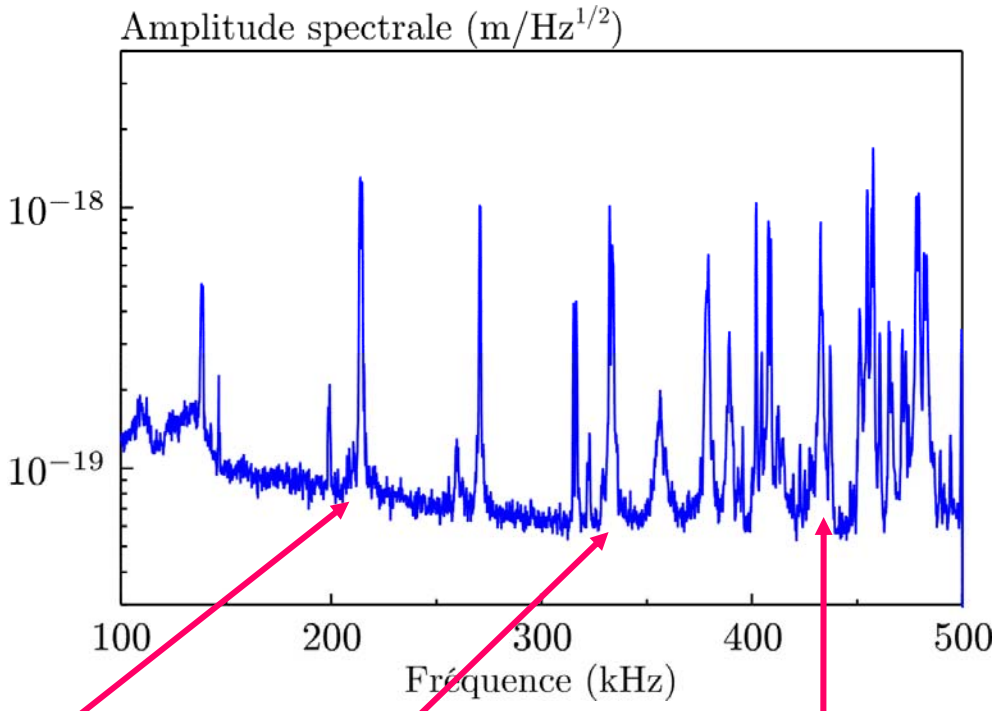
Current sensitivity:

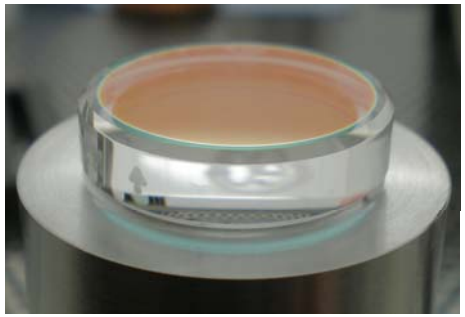
$$\delta x_{\mathrm{min}} = 3 \times 10^{-20}\, m/\sqrt{Hz}$$

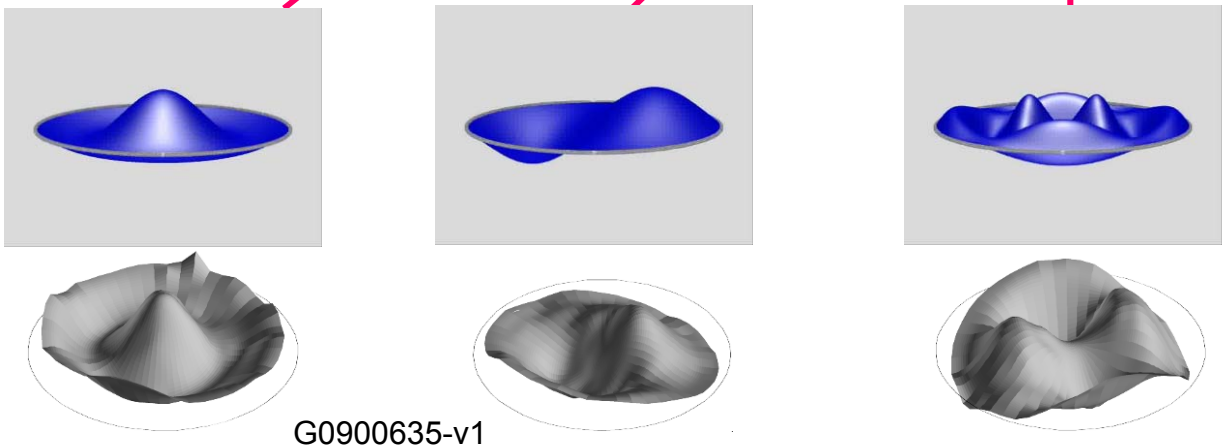


Characterization of internal modes



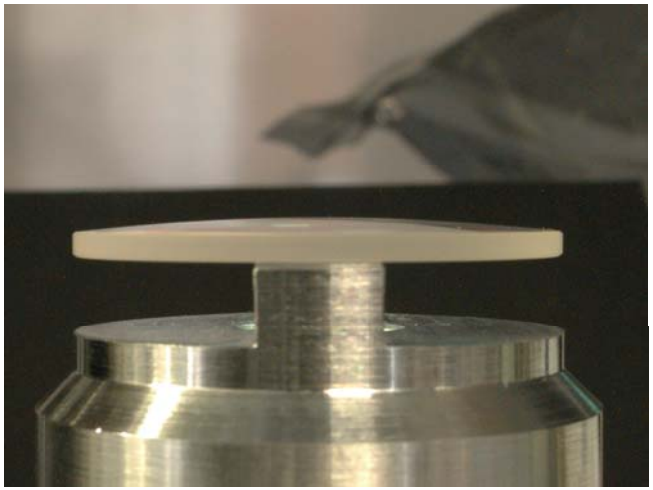




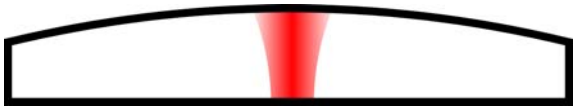


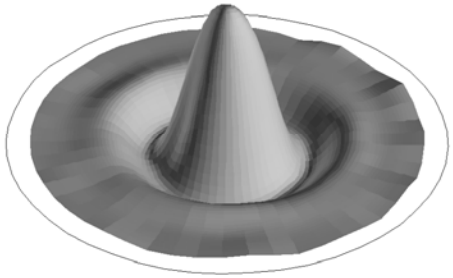
Characterization of internal modes

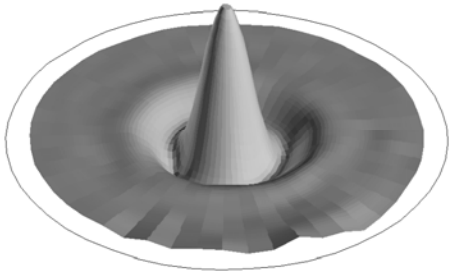
Plano-convex geometry



Gaussian structure of acoustic mode Confinement at the center



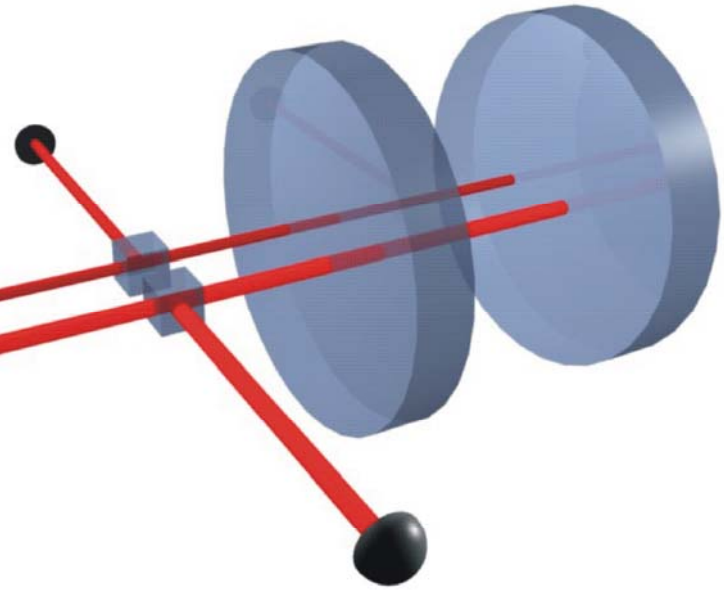


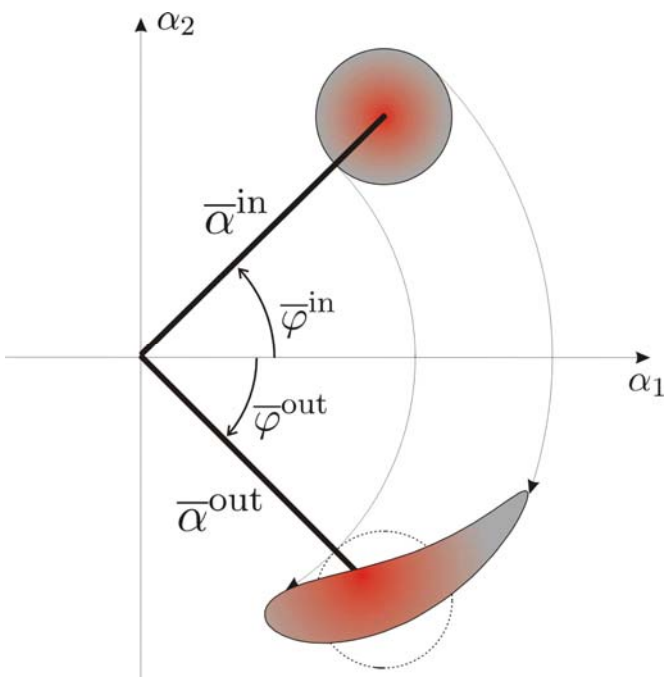


n p l = 100 200

Effective mass of 20mg < 1% of total mass

Mechanical Q factor up to 10^6





High sensitivity interferometric measurements

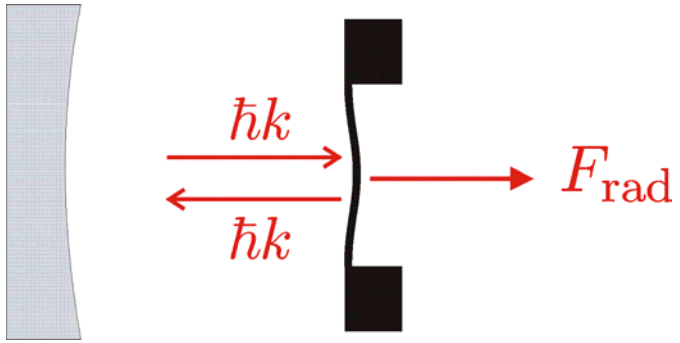
Toward a QND measurement

Laser cooling of a microresonator

Quantum optics and radiation pressure

Optomechanical effects in a cavity:

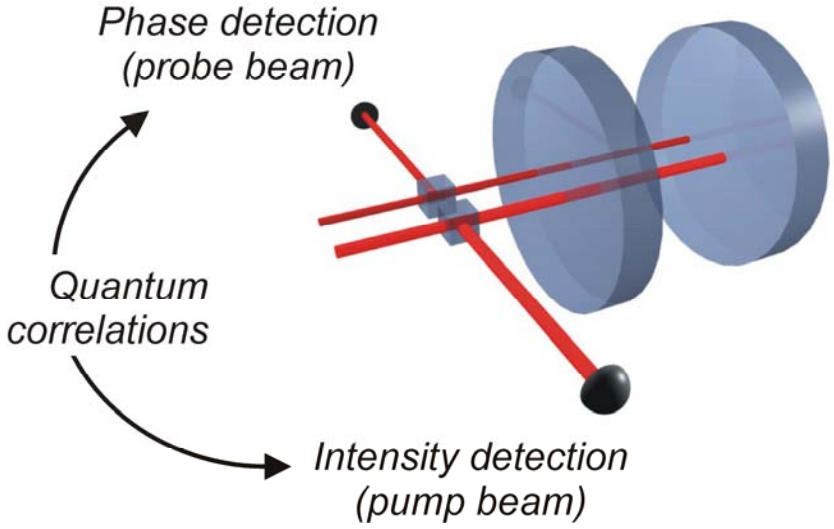
- Radiation pressure of light induces a mirror motion
- The mirror motion produces a phase-shift of the light



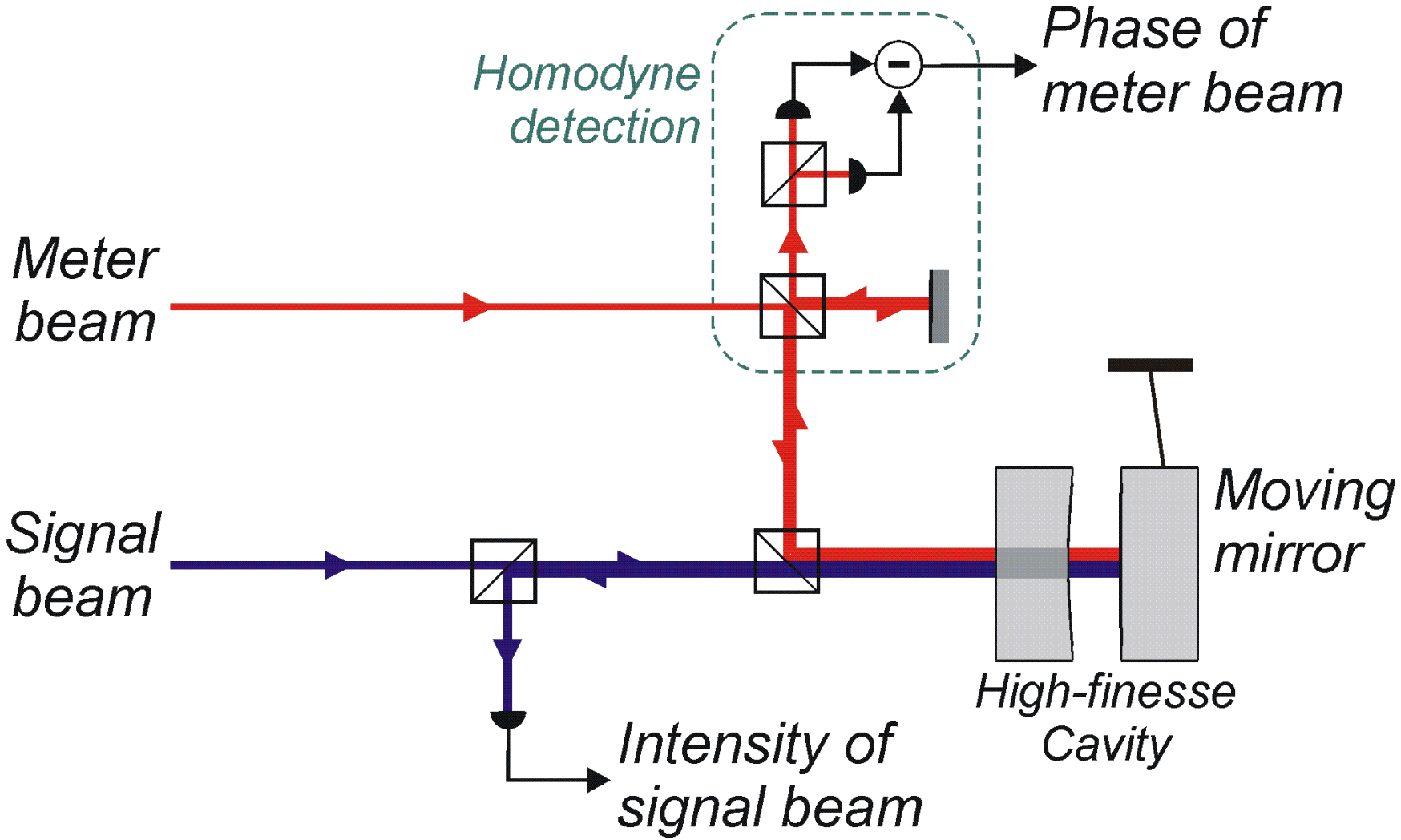
A moving mirror is equivalent to a nonlinear Kerr medium inserted in the cavity

→ Quantum optics experiments:

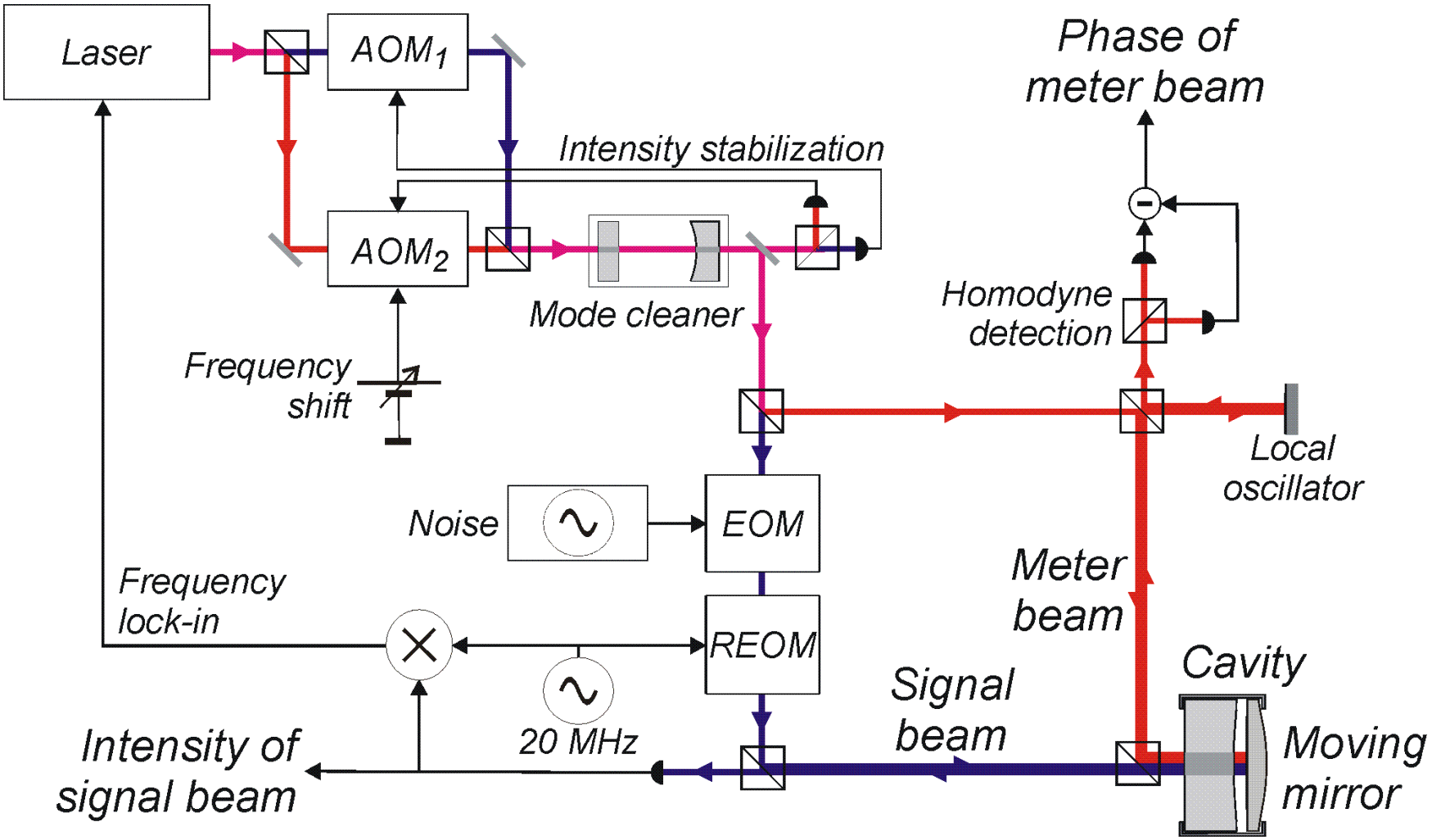
- Squeezed light generation
- Quantum Non Demolition measurement



Principle of the experiment



Experimental setup



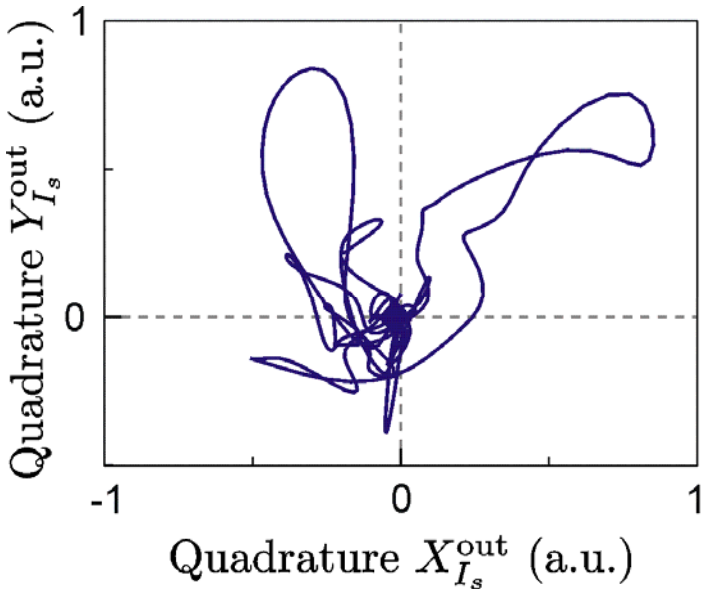
Experimental results

Intensity noise:

$$\delta I_s^{out}(t) = X_{I_s}^{out}(t)\cos(\Omega_c t) + Y_{I_s}^{out}(t)\sin(\Omega_c t)$$

Phase noise:

$$\delta \varphi_m^{out}(t) = X_{\varphi_m}^{out}(t)\cos(\Omega_c t) + Y_{\varphi_m}^{out}(t)\sin(\Omega_c t)$$

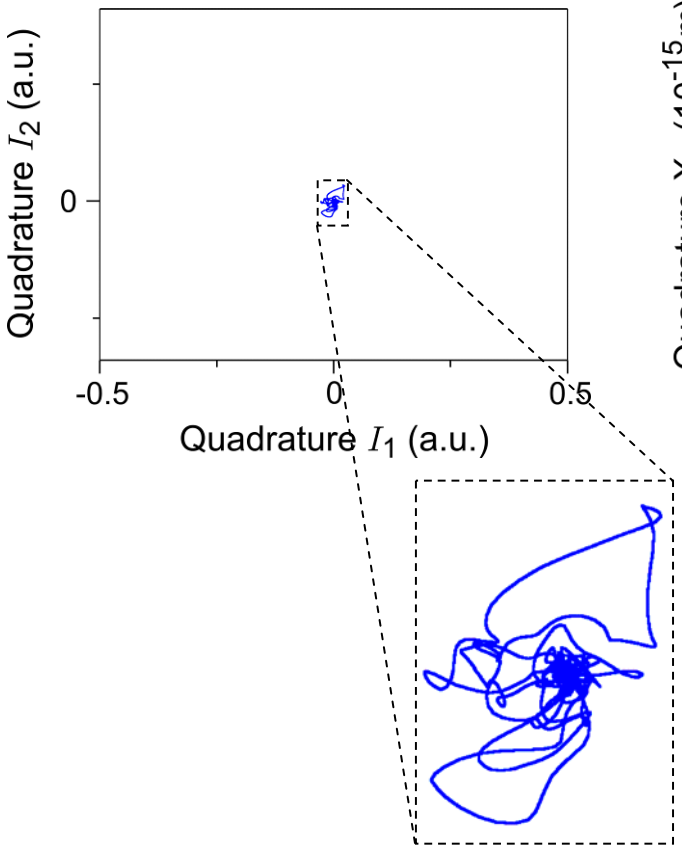


$$\delta x_{\mathrm{t}} \ll \delta x_{\mathrm{rad}} \rightarrow C_{I_s,\varphi_m} = \frac{|\langle \delta I_s^{out} \cdot \delta \varphi_m^{out\star} \rangle|^2}{\langle |\delta I_s^{out}|^2 \rangle \langle |\delta \varphi_m^{out}|^2 \rangle} = 0.96$$

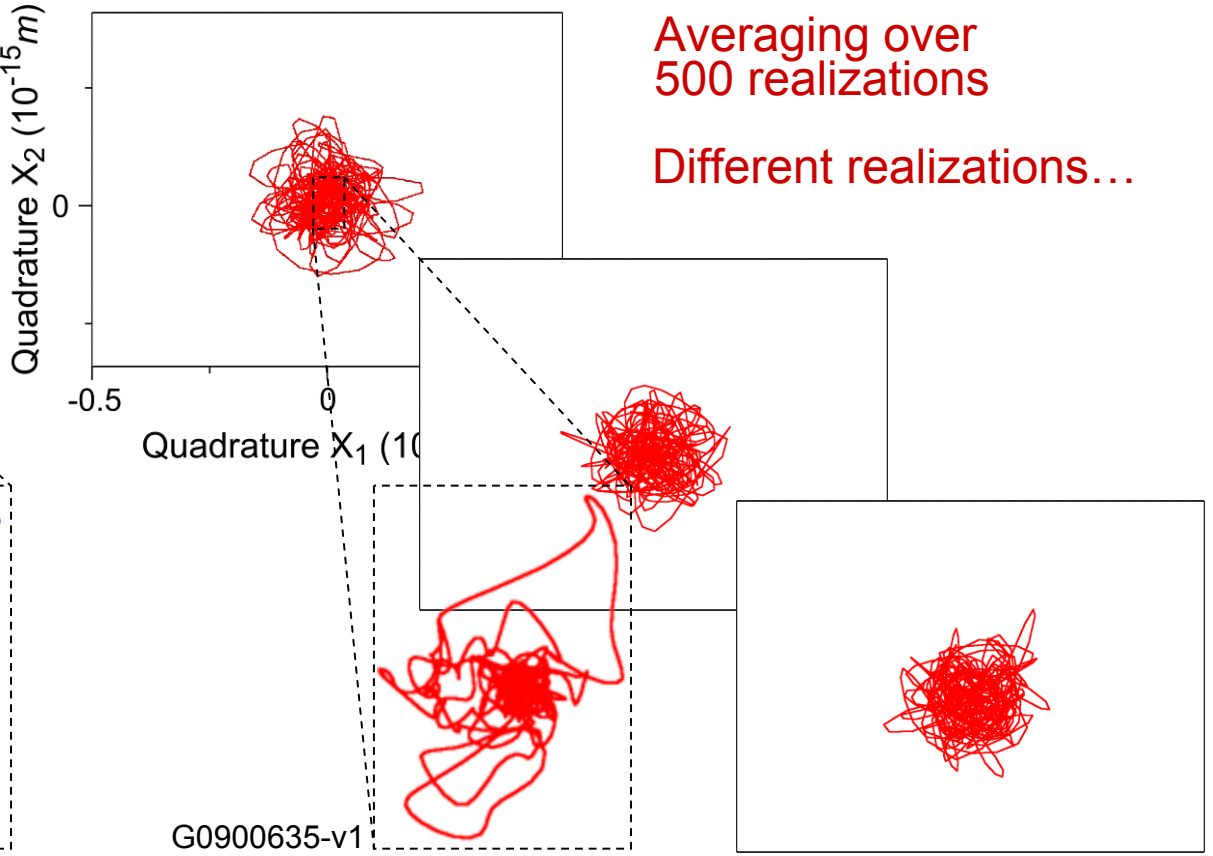
Observing quantum correlations?

$$\frac{\delta x_{\mathrm{rad}}}{\delta x_T} \simeq 0.2$$

Signal intensity:



Displacements :

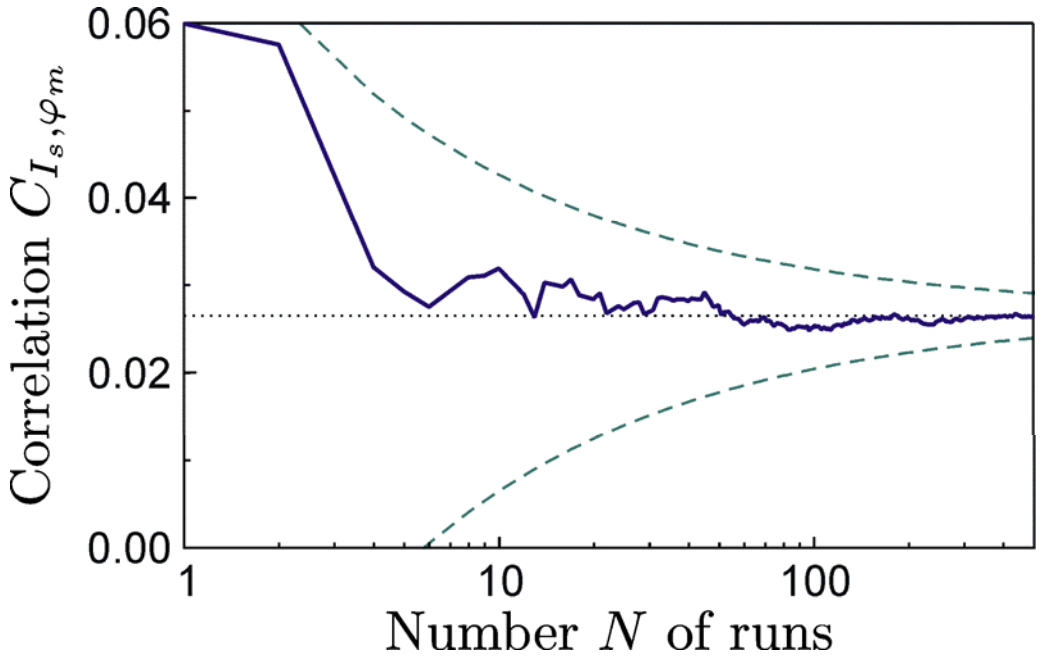


Averaging over
500 realizations

Different realizations…

Detecting quantum correlations ?

Correlation function: $C_{I,\varphi} \simeq 0.03$ for $\frac{\delta x_{\text{rad}}}{\delta x_T} \simeq 0.2$

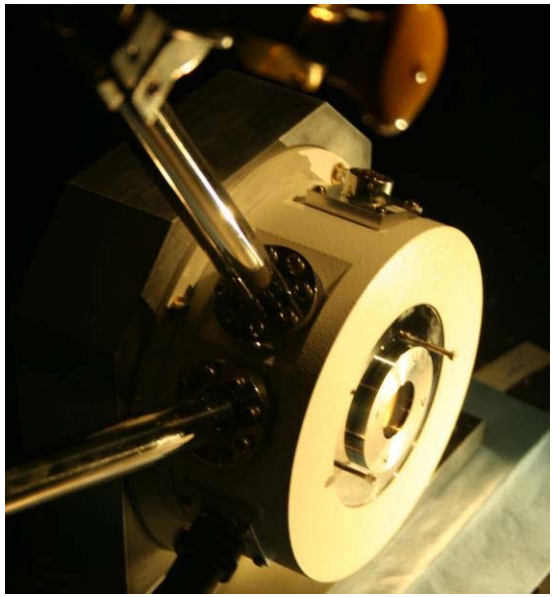


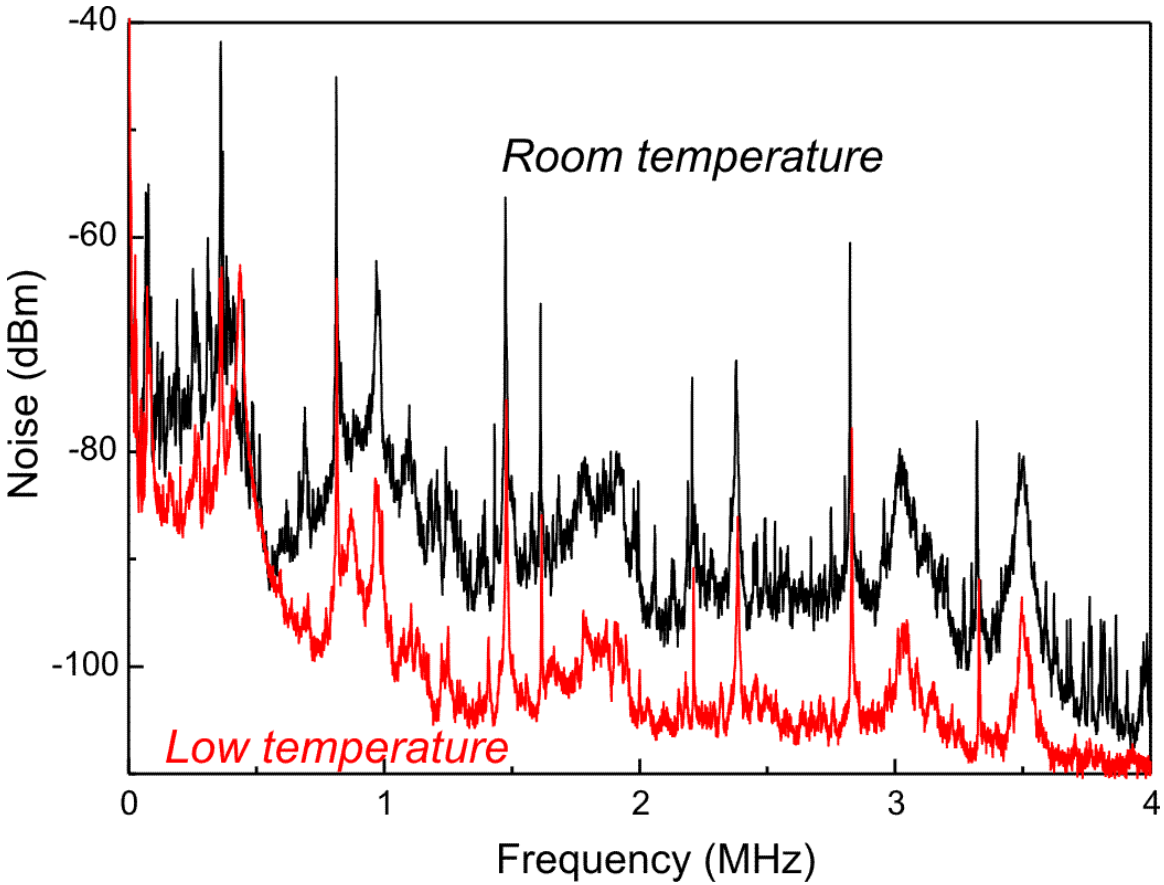
Quantum noise 2 orders of magnitude below but

$\frac{\delta x_{\text{rad}}}{\delta x_T} \simeq 0.1$ at 1 K

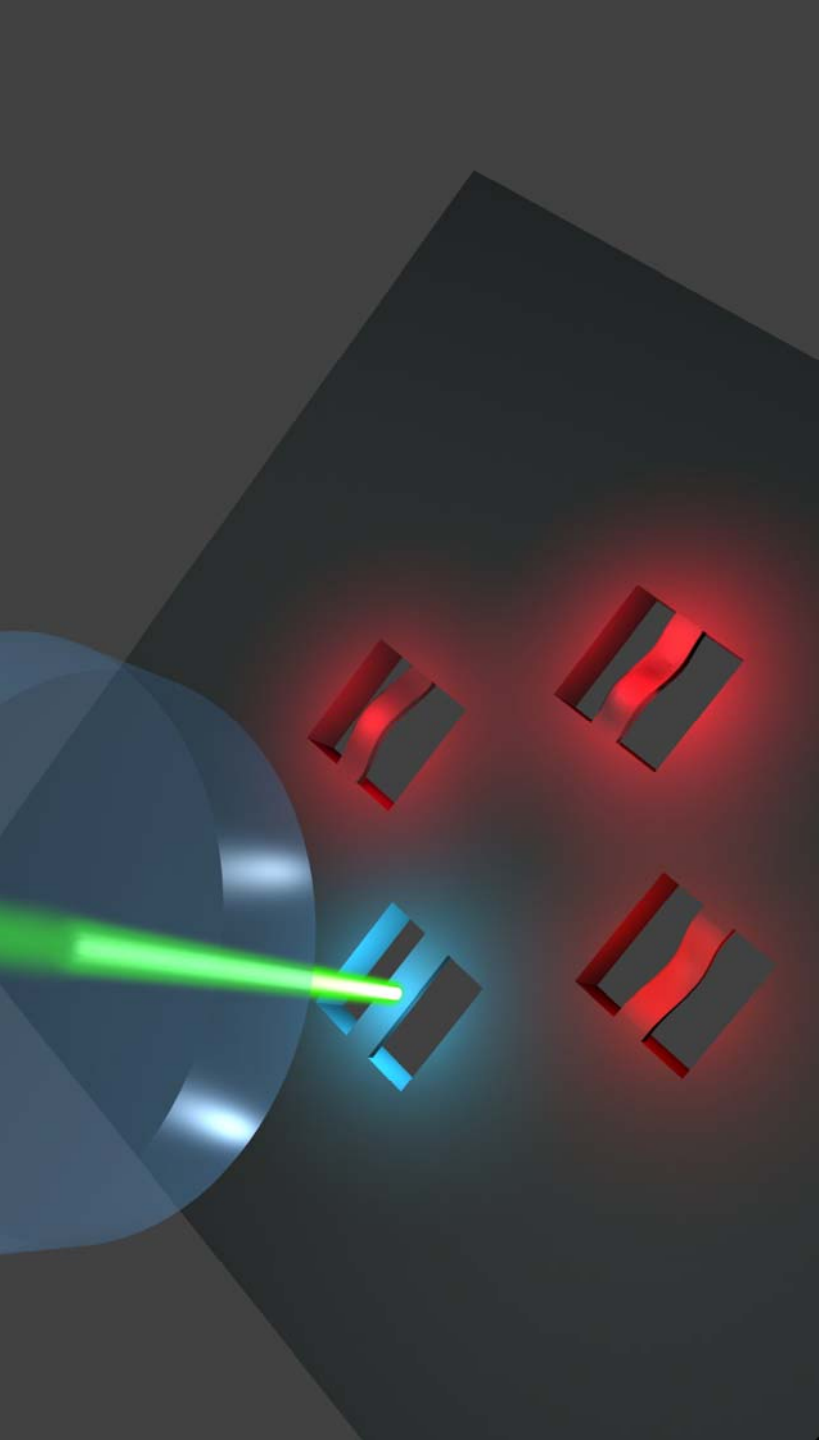
Toward the observation of quantum correlations

Cryogenic operation





Thermal noise at low temperature (cryostat at 3.5 K)
is reduced as compared to room temperature



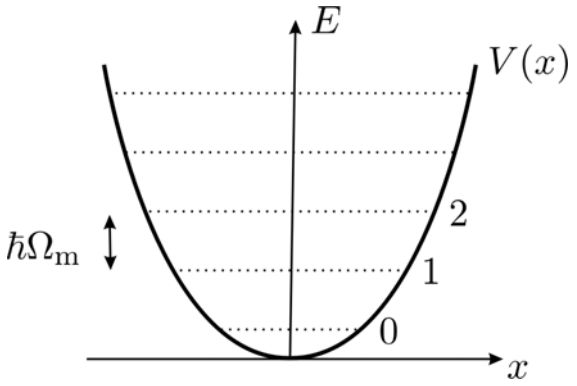
High sensitivity interferometric measurements

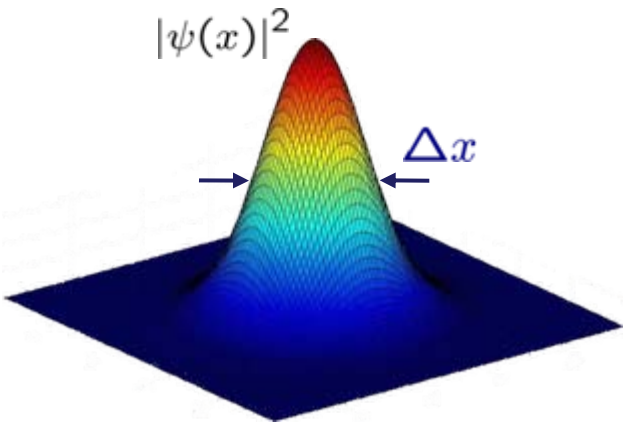
Toward a QND measurement

Laser cooling of a microresonator

Reach the quantum regime of microresonator ?

Use the optomechanical coupling to reach and observe the quantum fundamental state of of macroscopic mechanical resonator





- Observation of residual quantum fluctuations:

$$M\Omega_{\mathrm{m}}^2 \Delta x^2 = \frac{\hbar\Omega_{\mathrm{m}}}{2}$$

$$\Delta x \simeq 10^{-17}\,\mathrm{m}$$

$$(M \simeq 100\,\mu\mathrm{g},\ \Omega_{\mathrm{m}}/2\pi \simeq 1\,\mathrm{MHz})$$

- Reach the quantum regime:

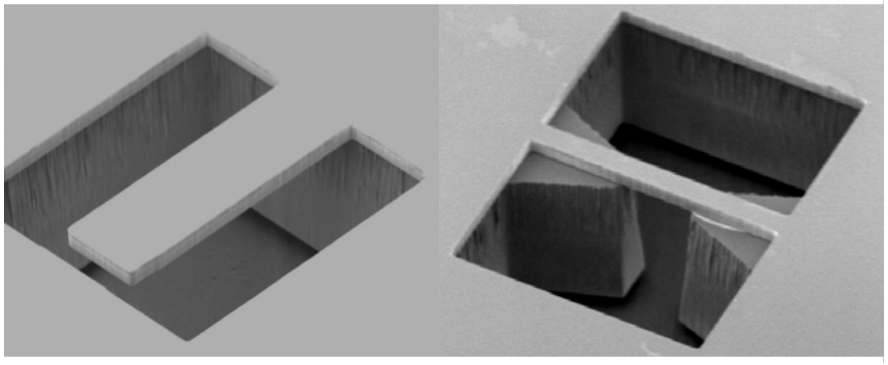
$$k_B T \leq \hbar\Omega_{\mathrm{m}}$$

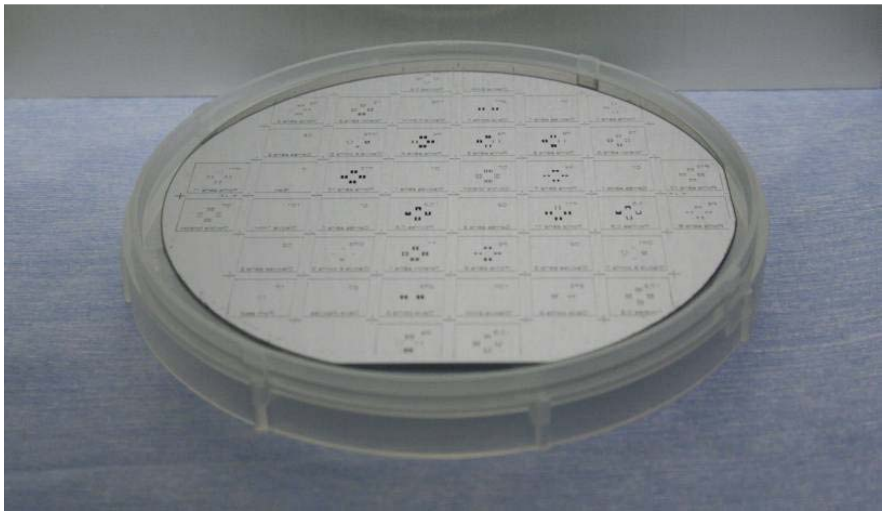
$1\,\mathrm{GHz} \leftrightarrow 50\,\mathrm{mK}$

$1\,\mathrm{MHz} \leftrightarrow 50\,\mu\mathrm{K}$

Cryogeny and laser cooling

Micro-resonator cavity

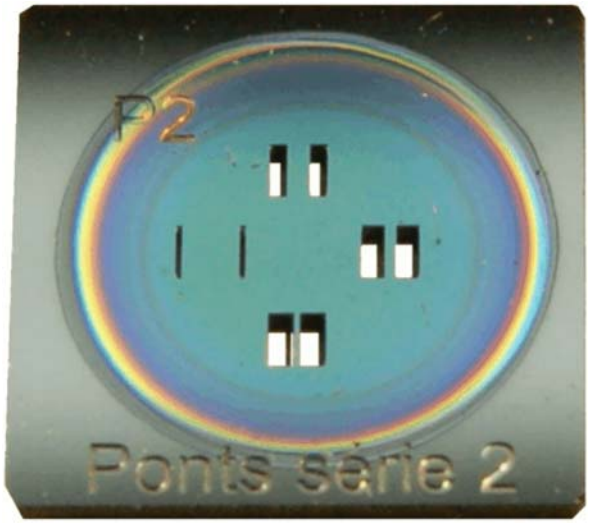




$1\ \mathrm{mm} \times 400\,\mu\mathrm{m} \times 60\,\mu\mathrm{m}$

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

Micro-fabrication at ESIEE

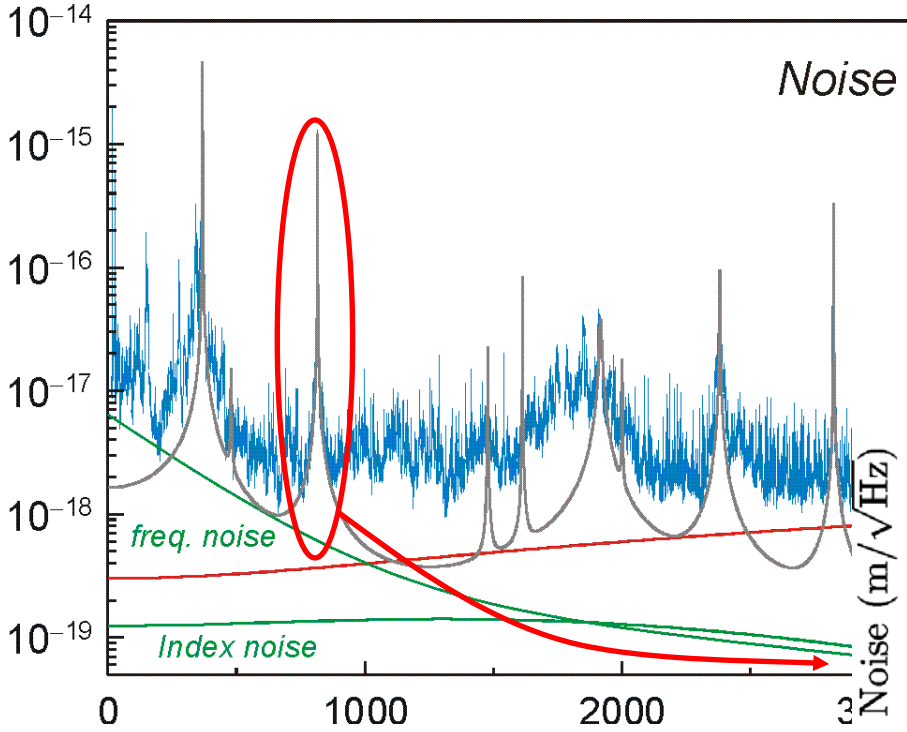


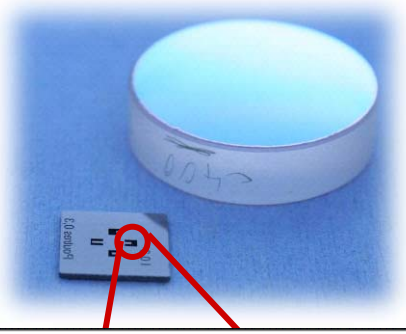
Optical coating at LMA (Virgo Lyon)

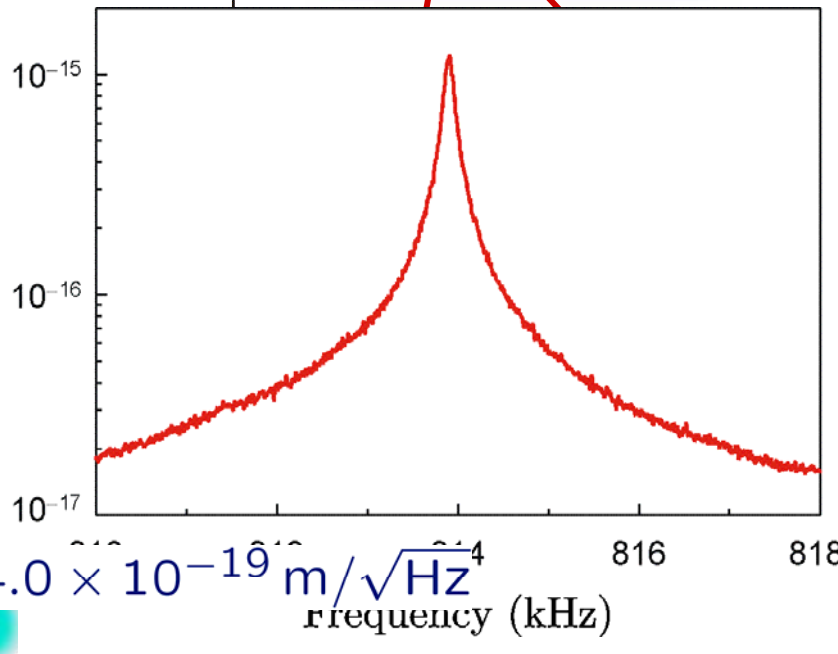
Optical metrology at ESPCI

Raw noise spectrum

Thermal noise at room temperature







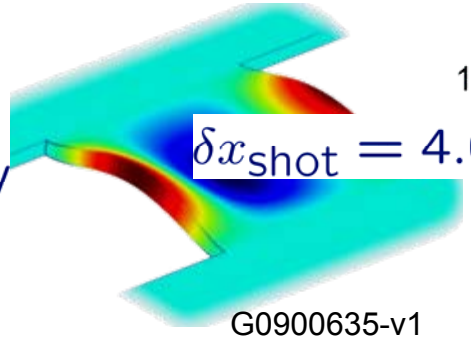
$\Omega_m/2\pi \sim 814\,\mathrm{kHz}$

$\mathcal{F} = 30\,000$

M

$P_{\mathrm{in}} = 1.5\,\mathrm{mW}$

Q

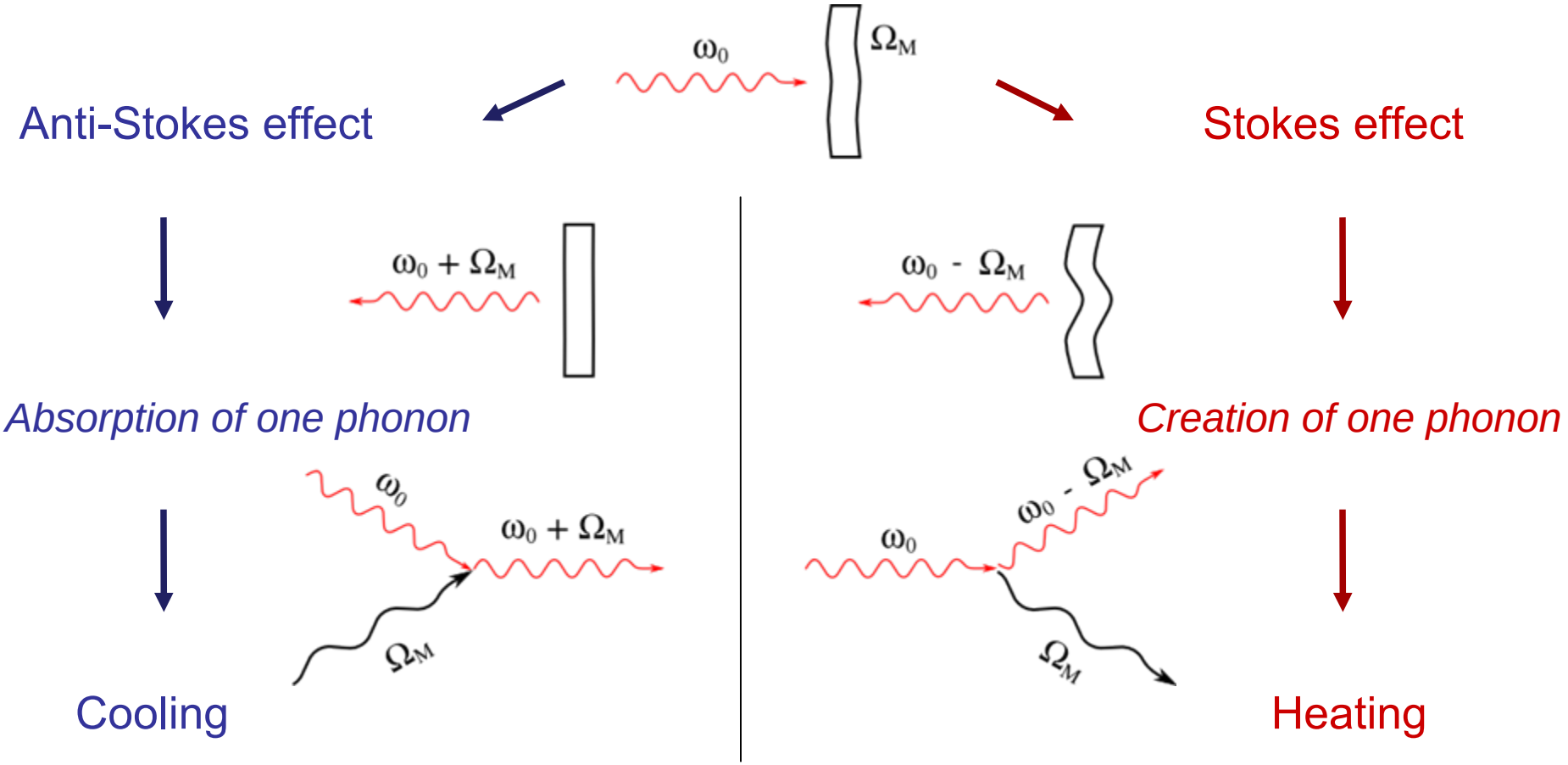


$\delta x_{\mathrm{shot}} = 4.0 \times 10^{-19}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$

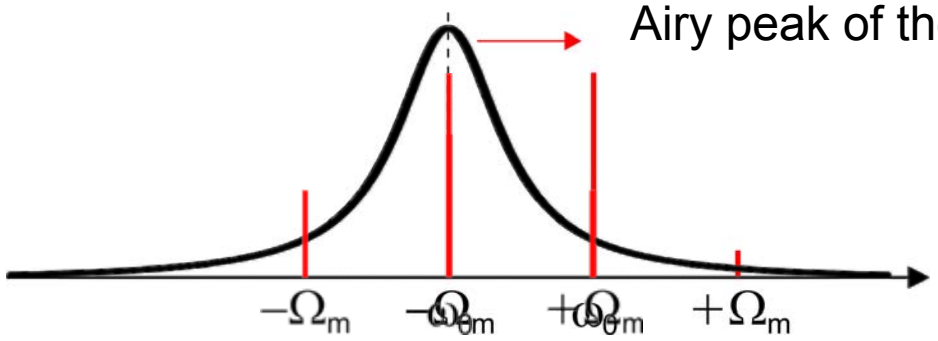
Phys. Rev. Lett. **97**, 133601 (2006)

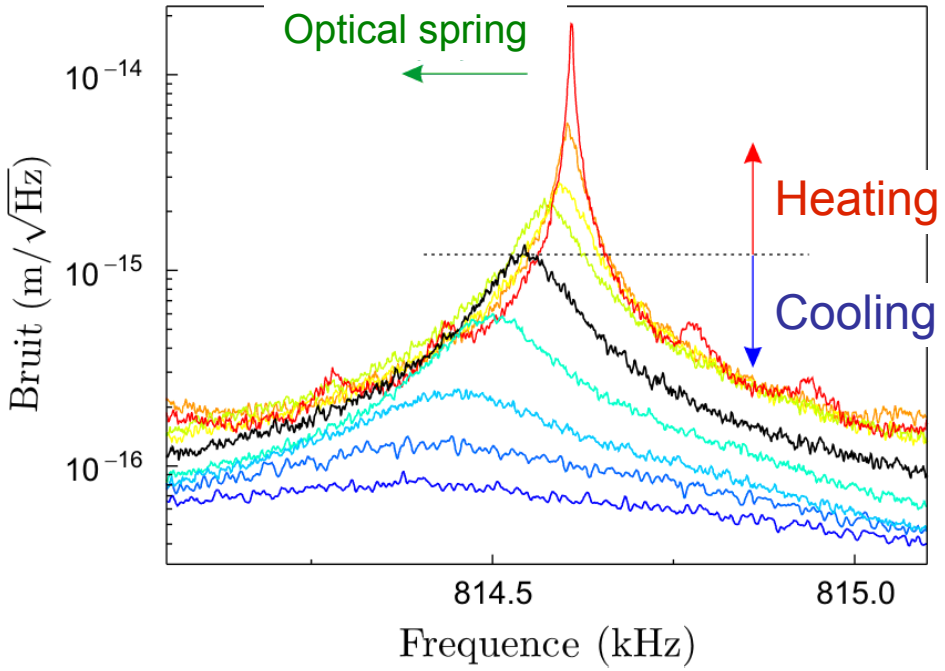
Laser cooling effect

Energy transfer between optical and mechanical modes via the radiation pressure:



Laser cooling





Thermal noise spectrum

Negative detuning:
Anti-Stokes process amplified

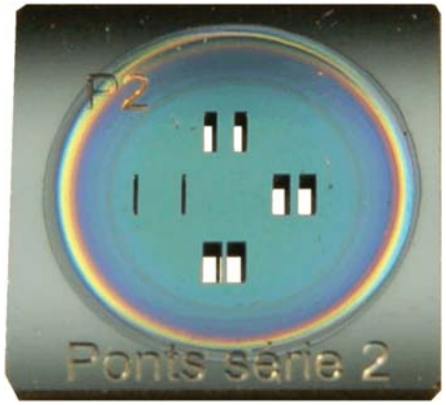
Positive detuning :
Stokes process amplified

Cooling down to 10 K, heating up to 2000 K

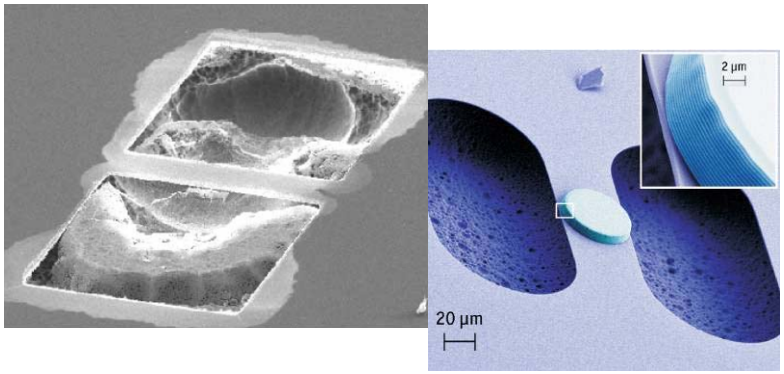
Nature **444**, 71 (2006)

Optomechanical system around the world

LKB

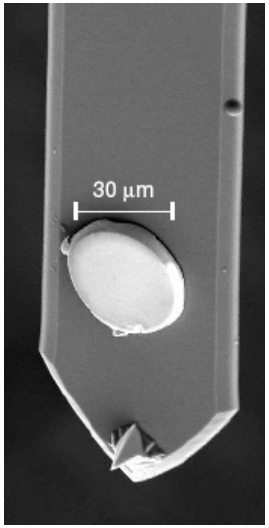


Vienna

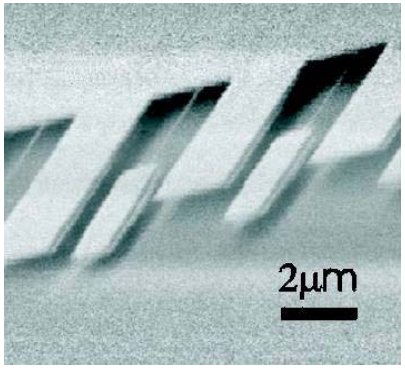


MIT - LIGO

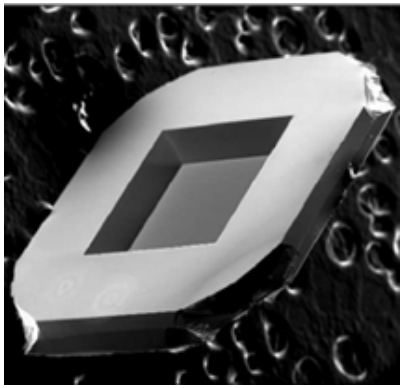
UCSB



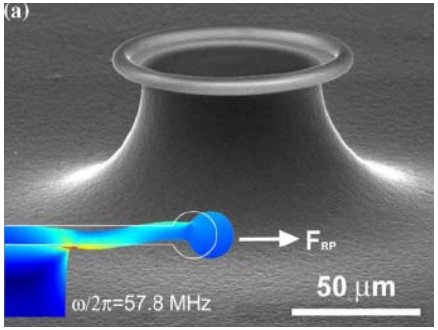
Munich



Yale



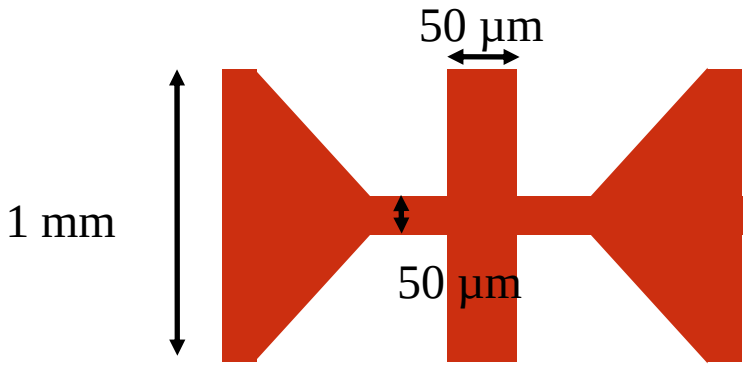
Garching / Caltech

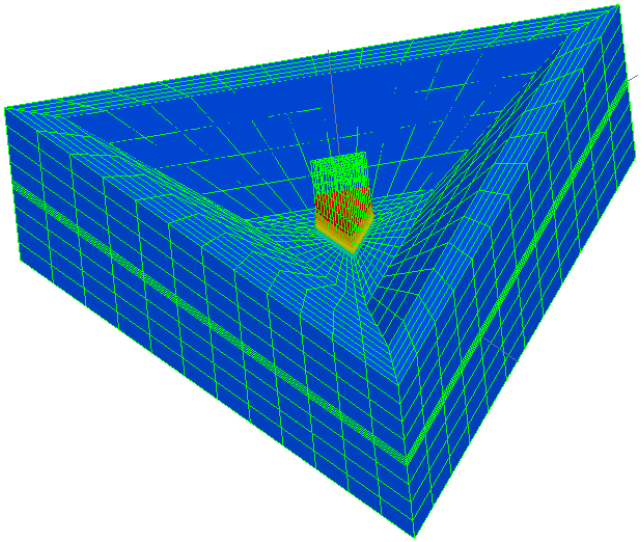


Cooling down to $k_B T/\hbar\Omega_m < 100$ phonons

New generation of micro-mirrors

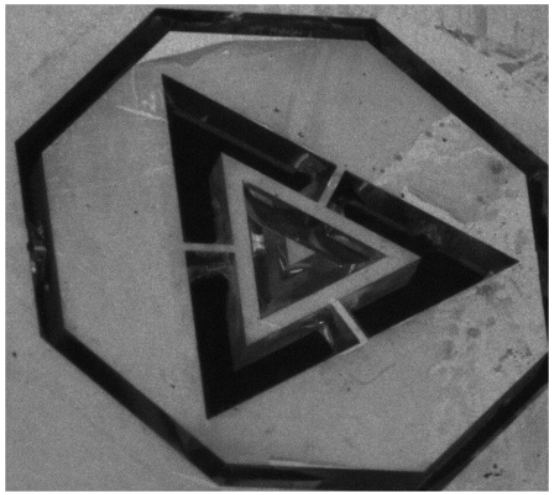
Symmetric pillar suspended by a thick membrane





Compression modes of the pillar

- *low mass, high mechanical isolation*
- *No stress in the coating area*
- *High mechanical Q factor*



Collaboration ANR with ONERA and LMA

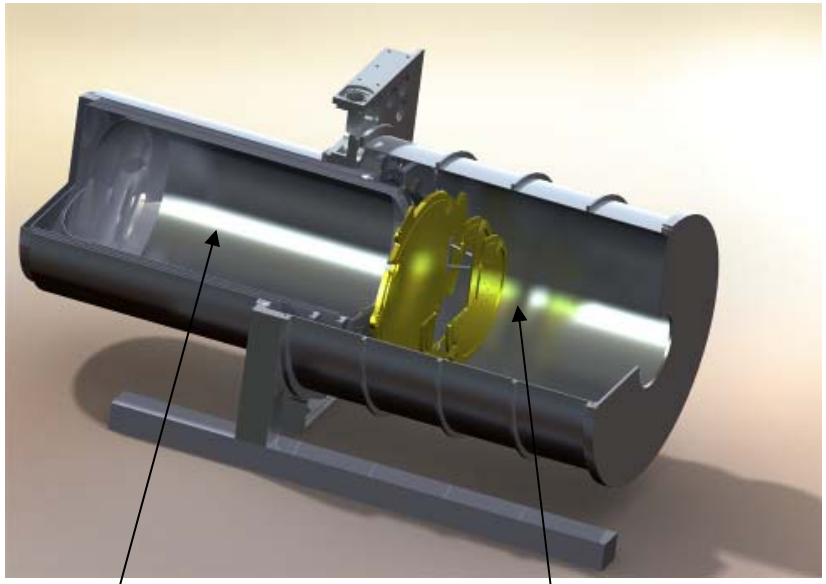
ONERA
THE FRENCH AEROSPACE LAB

LMA LABORATOIRE MATÉRIAUX AVANCÉS

Cryogeny

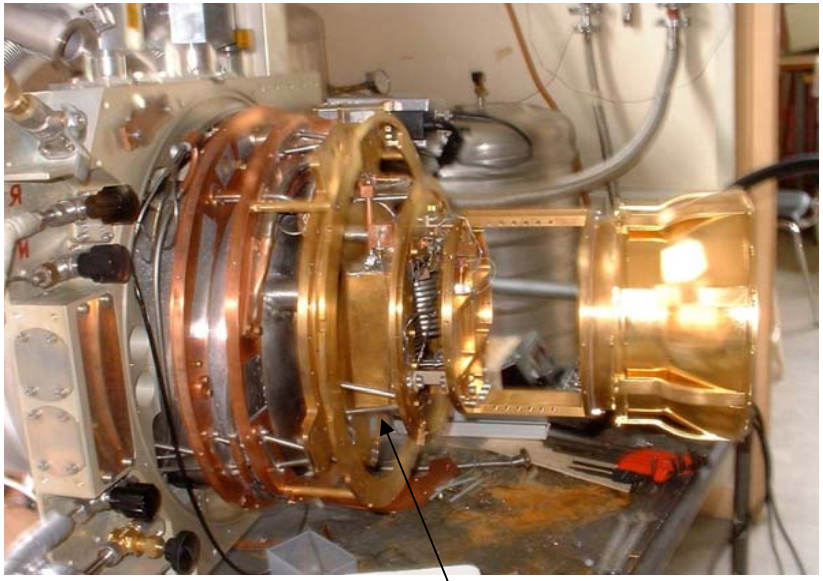
Conception of a dilution He_3/He_4 cryostat

limit temperature of 30 mK, horizontal configuration to achieve a good mechanical stability



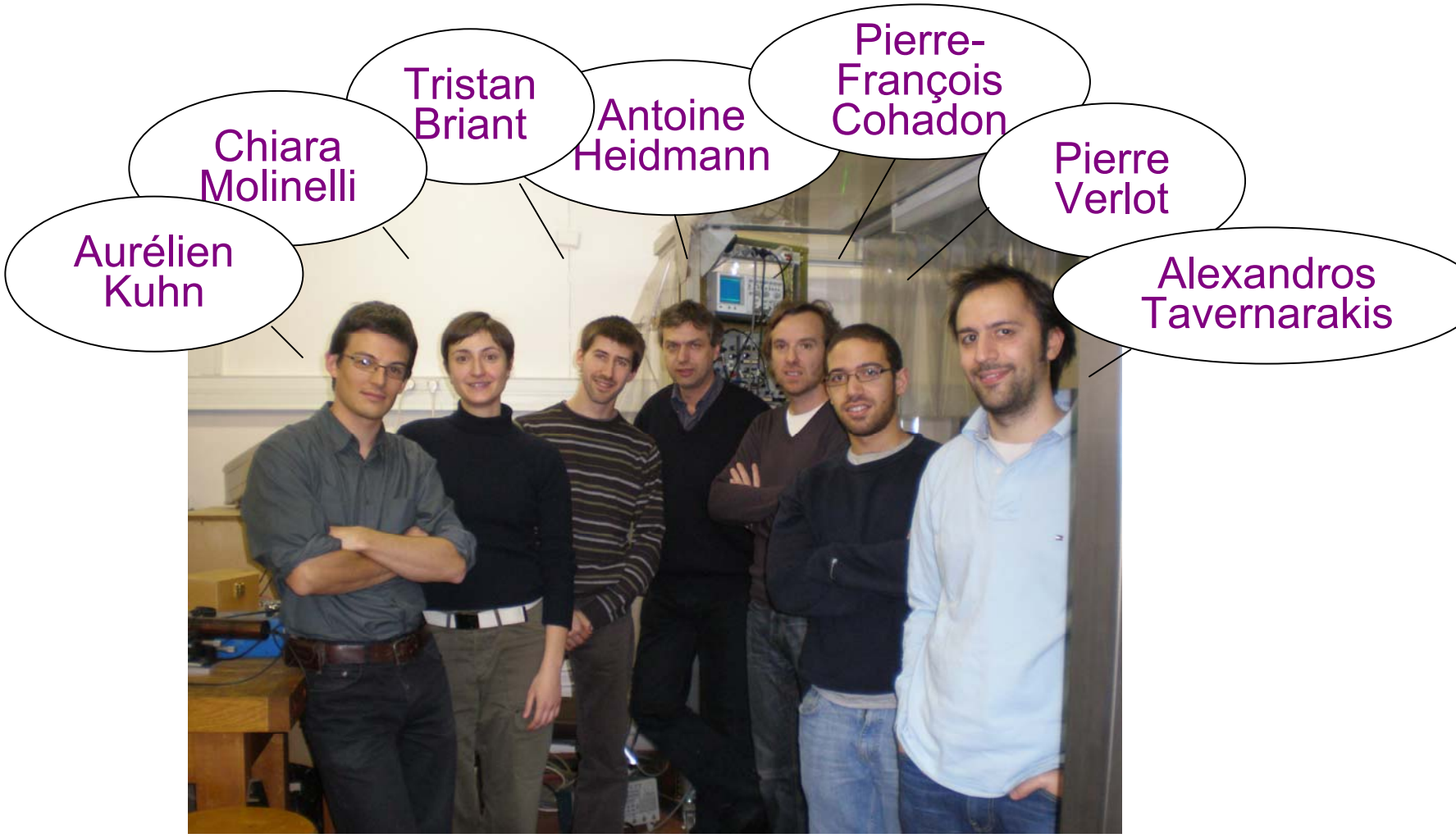
Helium tank

Sample chamber



Triangular suspensions

The « Mesure et bruits fondamentaux » team



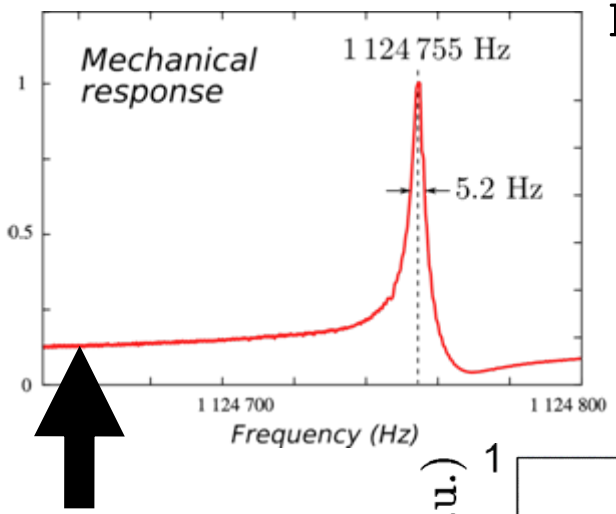
Detecting quantum correlations

For quantum radiation pressure noise: $\delta x_{\mathrm{rad}} < \delta x_{\mathrm{t}}$

but averaging should allow to uncover quantum correlations:

$$\langle \delta\varphi_m^{out} \cdot \delta I_s^{out} \rangle \simeq \frac{\mathcal{F}}{\lambda} \left(\underbrace{\langle \delta x_{\mathrm{t}} \cdot \delta I_s^{out} \rangle}_{\to 0} + \langle \delta x_{\mathrm{rad}} \cdot \delta I_s^{out} \rangle \right)$$

Experimental results

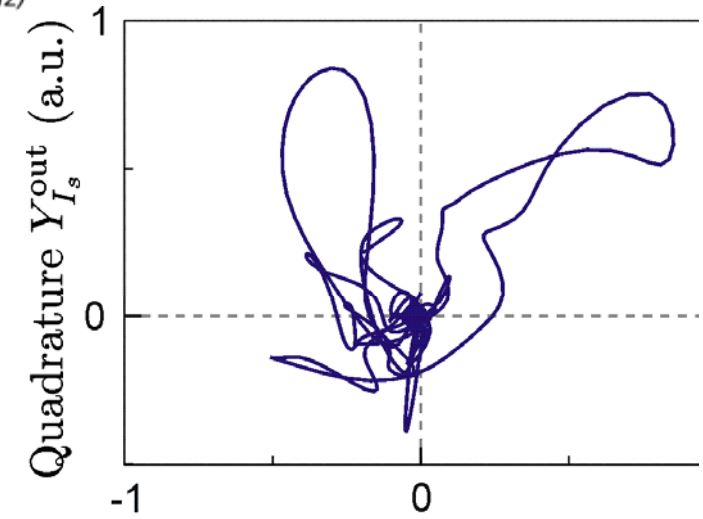


Intensity noise:

$$\delta I_s^{out}(t) = X_{I_s}^{out}(t)\cos(\Omega_c t) + Y_{I_s}^{out}(t)\sin(\Omega_c t)$$

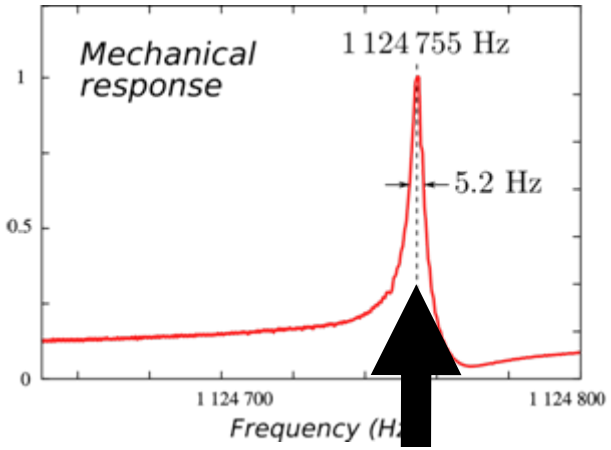
Phase noise:

$$\delta \varphi_m^{out}(t) = X_{\varphi_m}^{out}(t)\cos(\Omega_c t) + Y_{\varphi_m}^{out}(t)\sin(\Omega_c t)$$



$$\delta x_{\mathrm{t}} \ll \delta x_{\mathrm{rad}} \rightarrow {}^{\mathrm{Q}}C_{I_s,\varphi_m} = \frac{|\langle \delta I_s^{out} \cdot \delta \varphi_m^{out\star} \rangle|^2}{\langle |\delta I_s^{out}|^2 \rangle \langle |\delta \varphi_m^{out}|^2 \rangle} = 0.96$$

Correlations at resonance



The mechanical response has to be taken into account