LIGO-G030368-00-Z

Quantum locking of mirrors in interferometric measurements

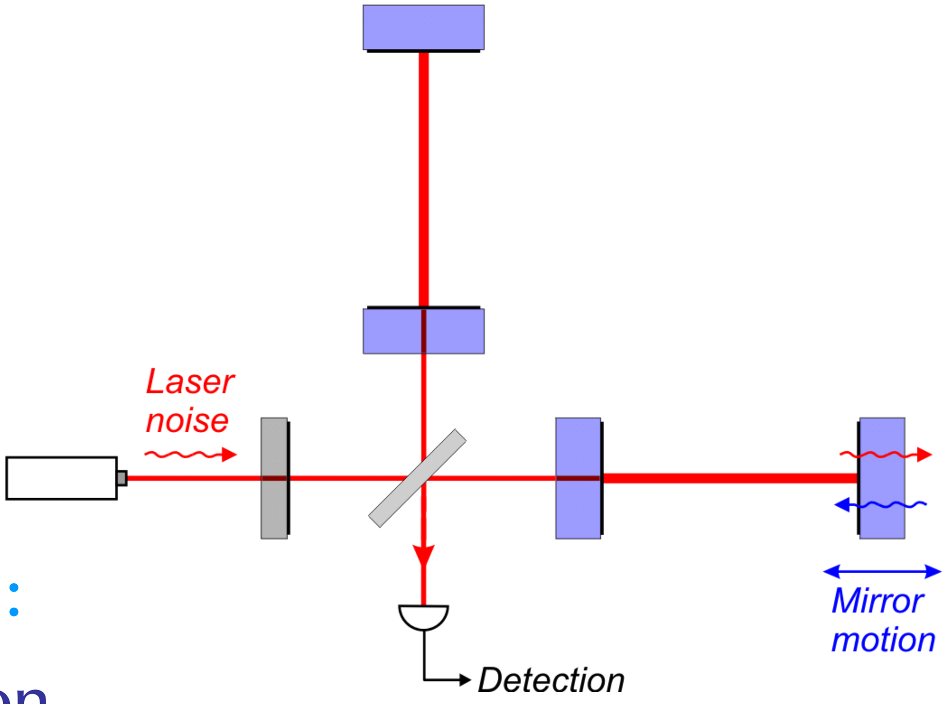
Antoine HEIDMANN
Jean-Michel COURTY
Michel PINARD

Laboratoire Kastler Brossel, Paris
CNRS
Ecole Normale Supérieure
Université Pierre et Marie Curie

Quantum noises in interferometers

Two quantum noises:

- Laser noise
- Mirror motion due to radiation pressure



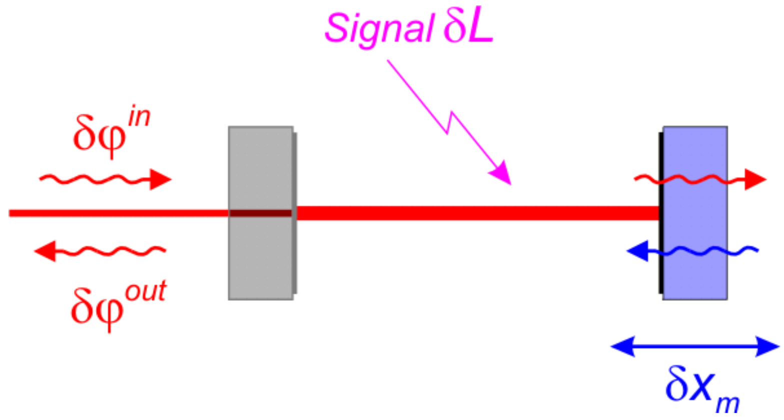
Reduction of noise by quantum optics techniques:

Squeezing, QND detection

Quantum locking of mirrors:

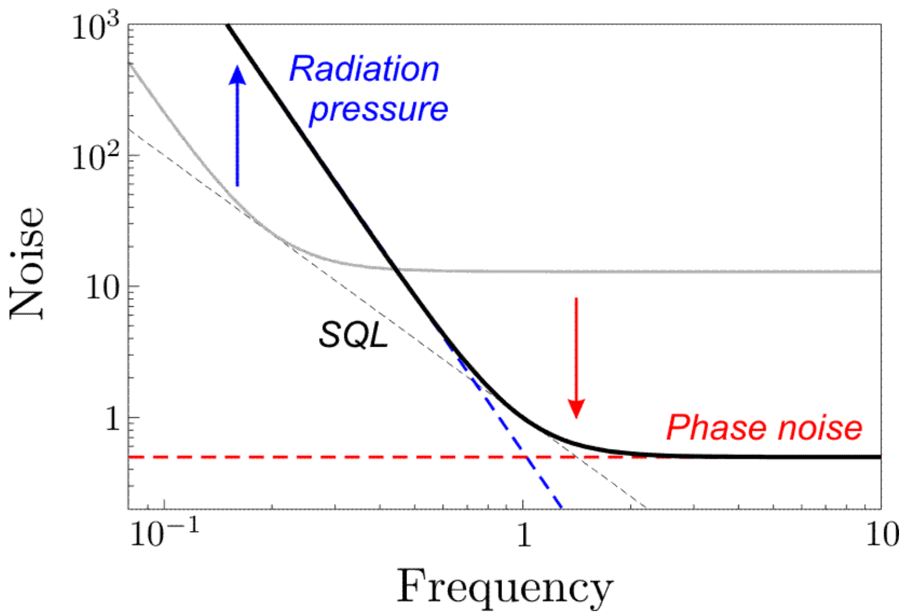
Local control of mirror motion

Quantum noises in interferometers



Output phase-shift:

$$\delta\varphi^{out} \approx \delta\varphi^{in} + \frac{\mathcal{F}}{\lambda}\left(\delta L + \delta x_m\right)$$

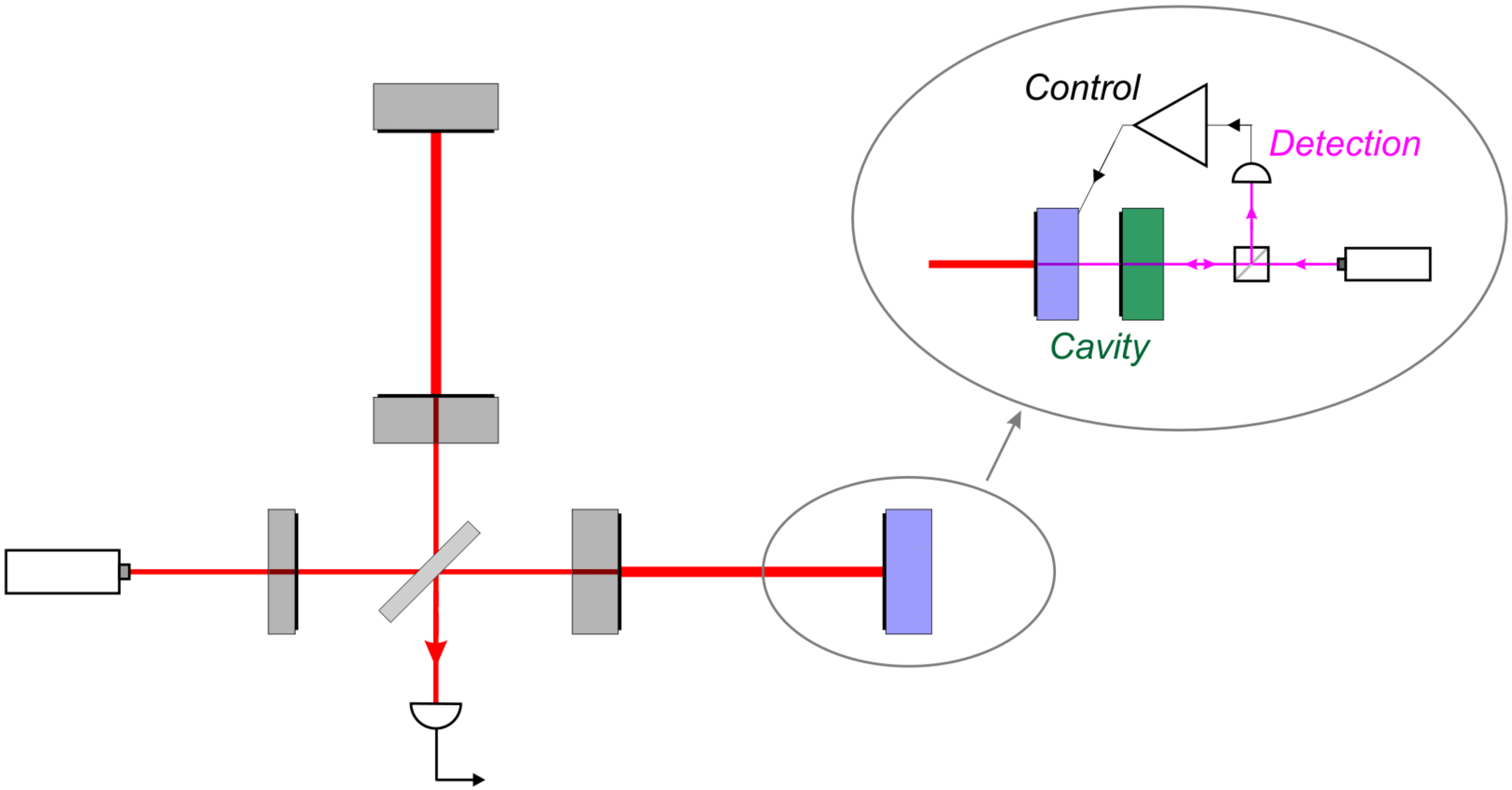


Quantum noises:

$$\delta\varphi^{in} \propto 1 / \sqrt{P^{in}}$$

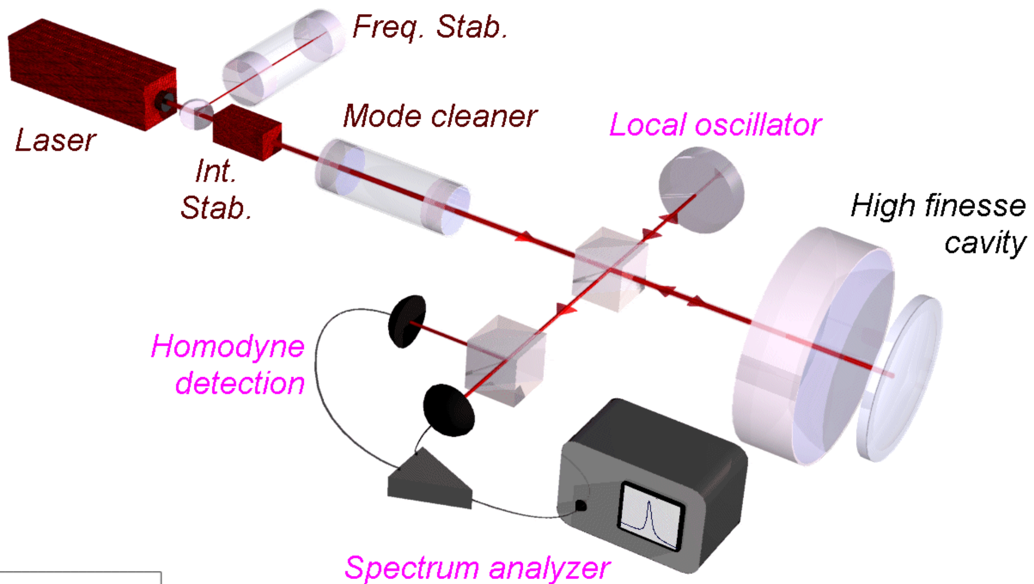
$$\delta x_m \propto \sqrt{P^{in}} / M\Omega^2$$

Quantum locking of mirrors

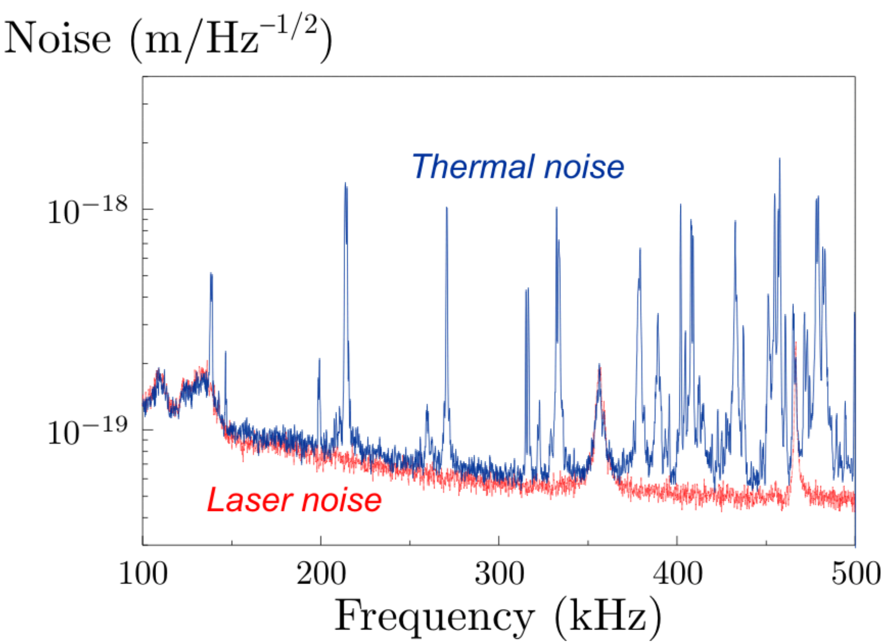


- Measurement of mirror motion with a high-finesse Fabry-Perot cavity
- Locking of mirror by active control

Experimental demonstration on thermal noise



Observation of mirror thermal noise with a high-finesse cavity

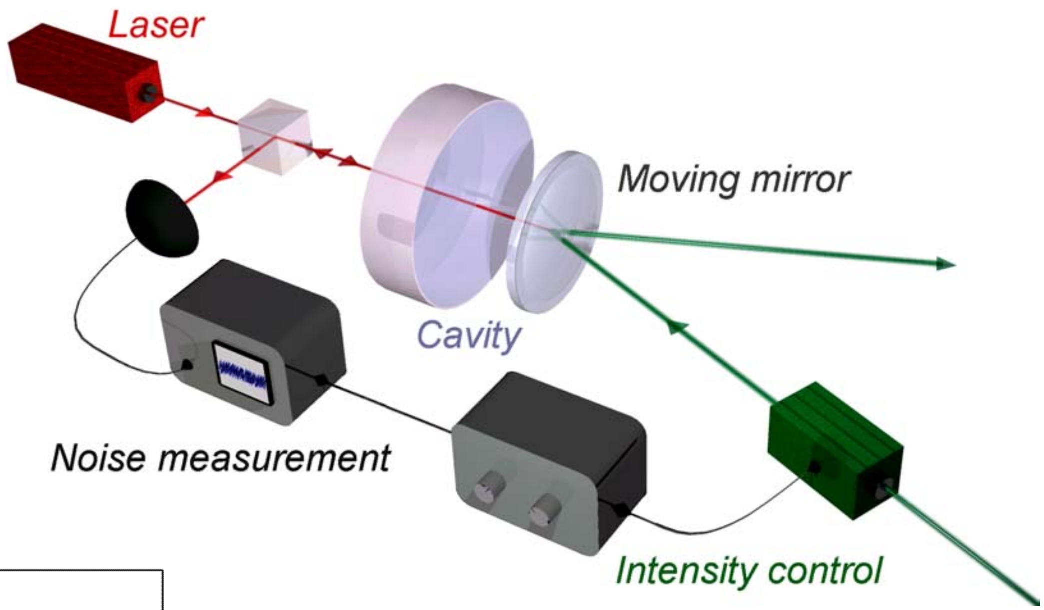


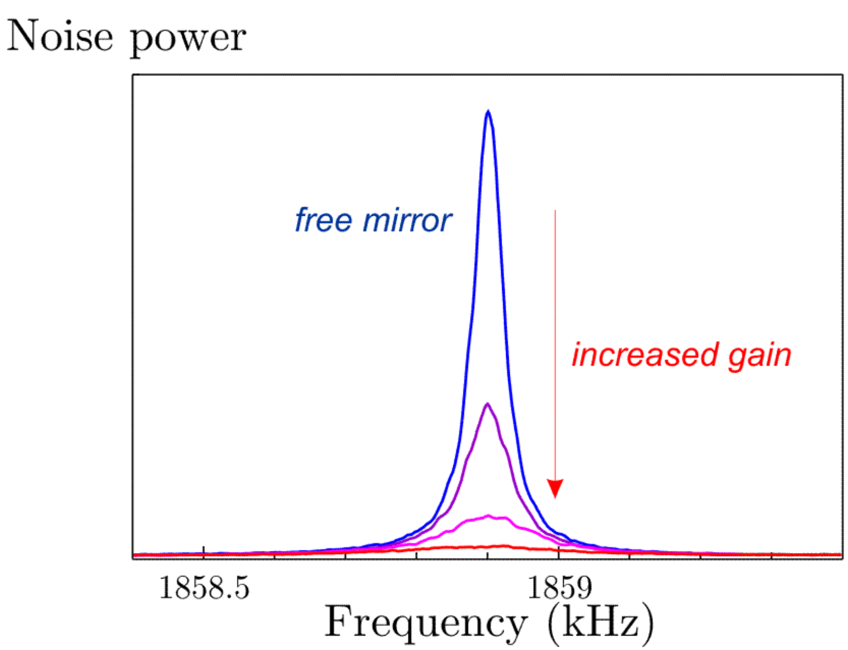
Very high sensitivity:

$$\delta x_{min} < 10^{-19}\ m/\sqrt{Hz}$$

Experimental demonstration on thermal noise

Active control
of thermal noise
by radiation pressure

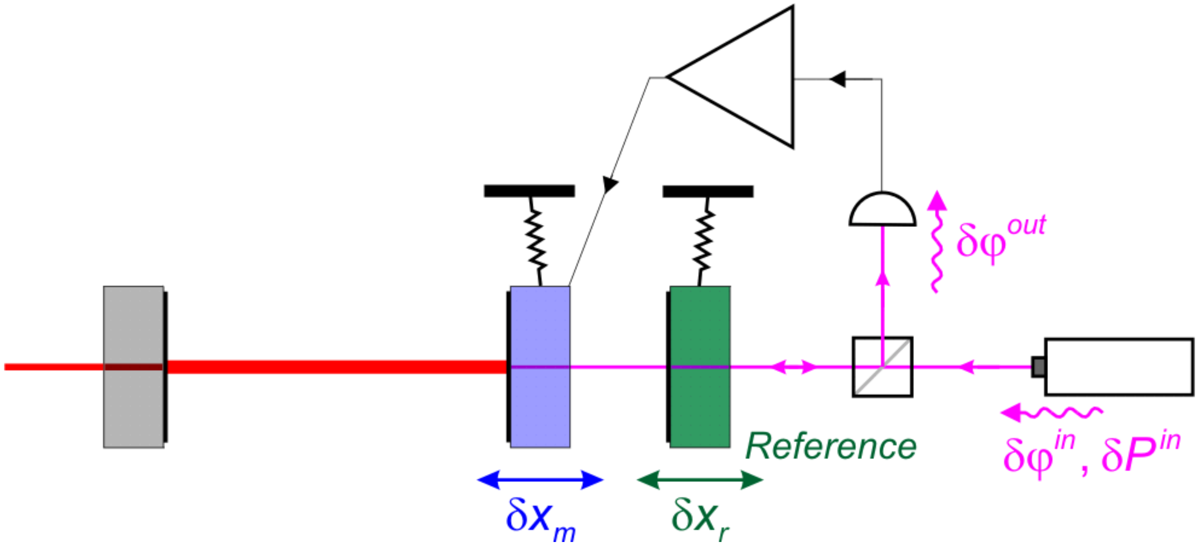




→ Freezing of the mirror motion

$T_{eff} < T/30$

Quantum locking of mirror



Active control in the quantum regime

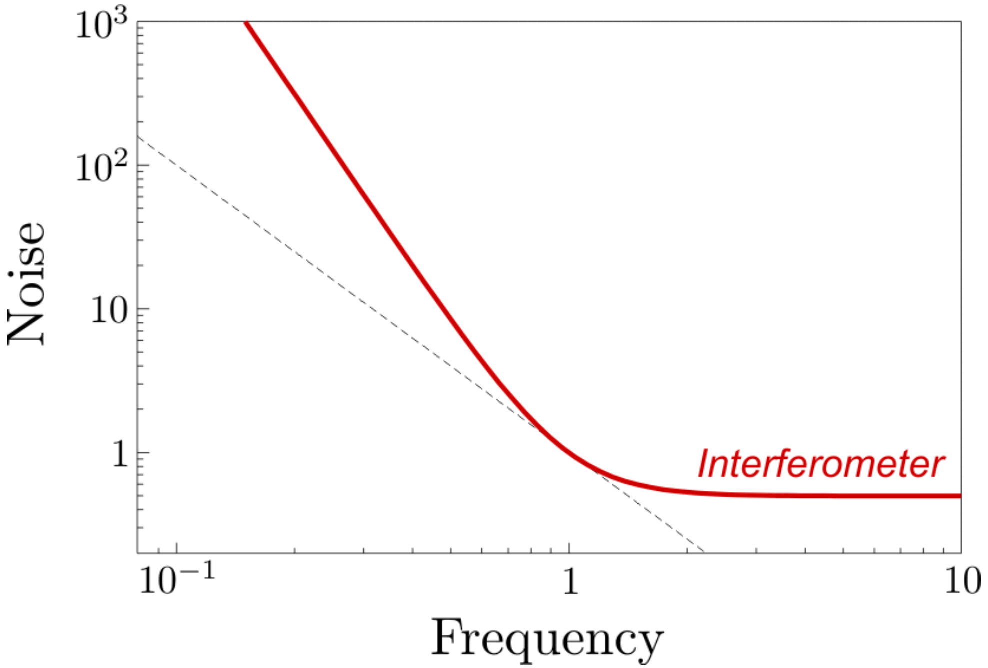
- Quantum noise in the measurement

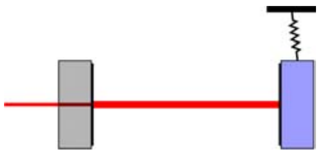
$$\delta\varphi^{out} \approx \delta\varphi^{in} + \frac{\mathcal{F}}{\lambda}\left(\delta x_m - \delta x_r\right)$$

- Radiation pressure on the reference mirror

$$\delta x_r \propto \delta P^{in}$$

Interferometer sensitivity



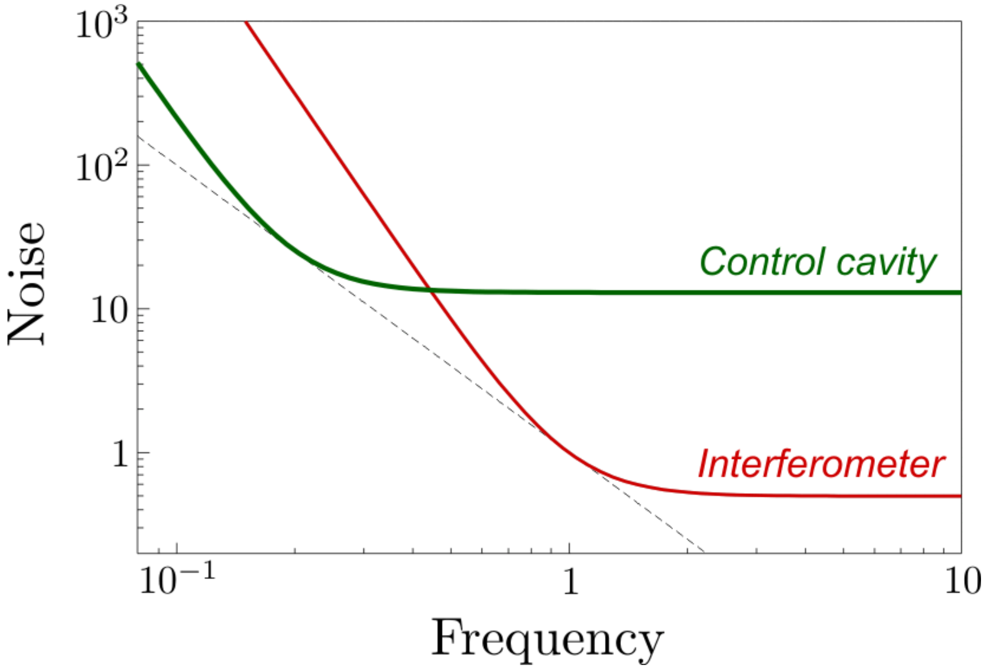


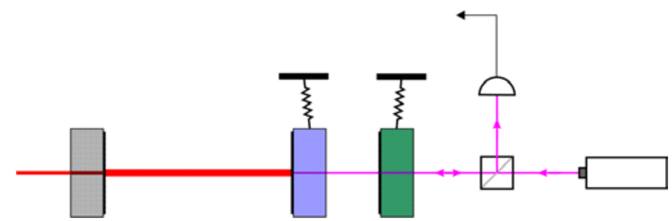
Interferometer:

Finesse = 600

Input = 20 W

Measurement of mirror motion





Control cavity:

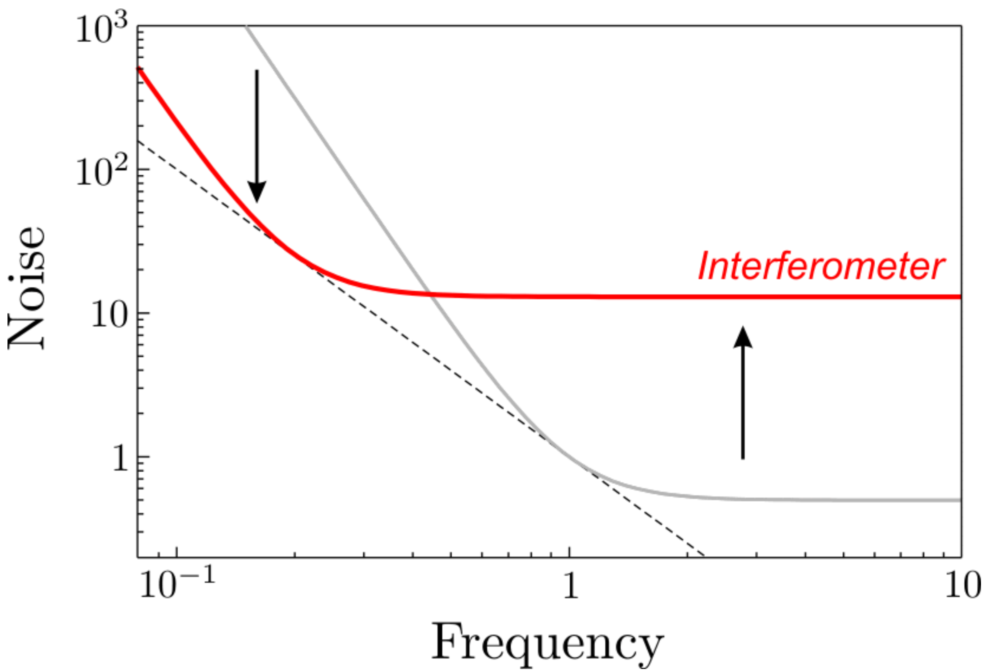
Finesse = 10 000

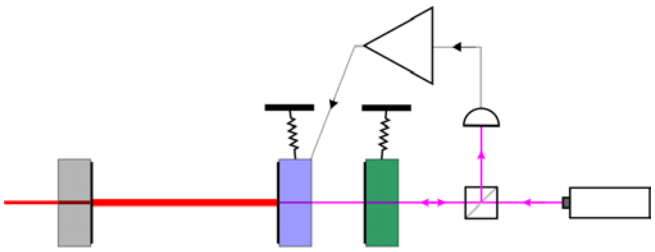
Input = 5 mW

$$\delta\varphi^{out} \approx \delta\varphi^{in} + \frac{\mathcal{F}}{\lambda}\left(\delta x_m - \delta x_r\right)$$

Measurement of δx_m limited by $\delta\varphi^{in}$ and δx_r

Control with an infinite gain



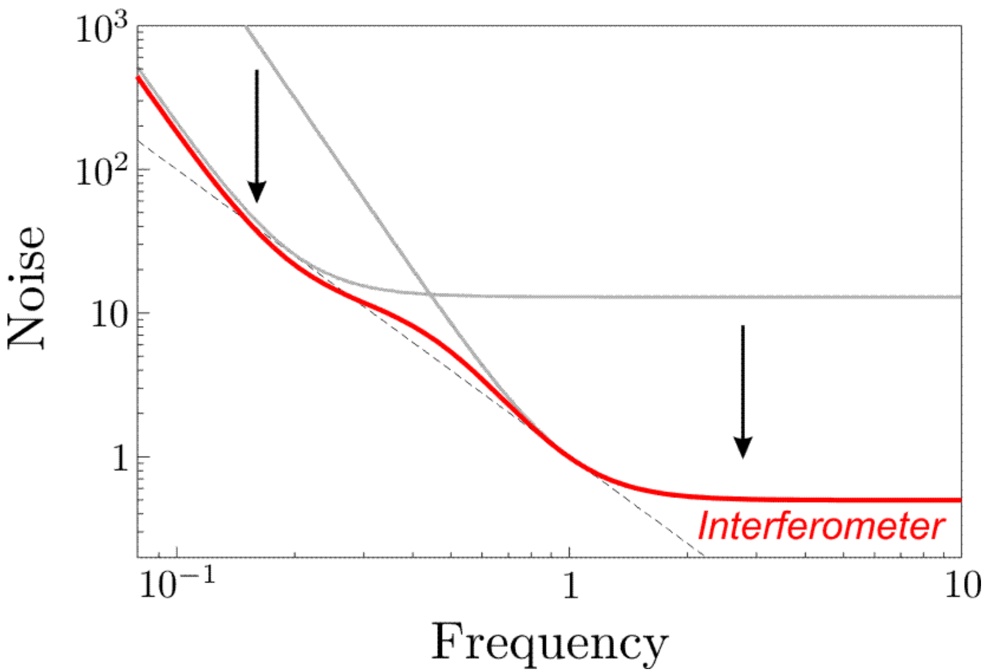


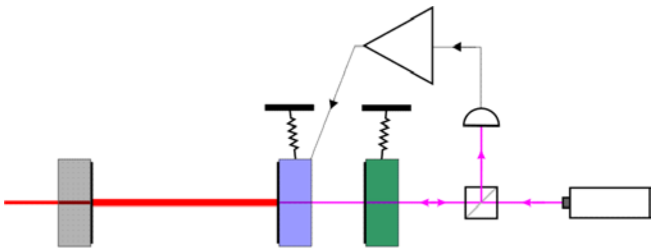
Infinite gain

$$\delta\varphi^{out} \approx \delta\varphi^{in} + \frac{\mathcal{F}}{\lambda}\left(\delta x_m - \delta x_r\right) \rightarrow 0$$

- Mirror is locked to the reference mirror
- Transfer of quantum noises

Control with an optimal gain

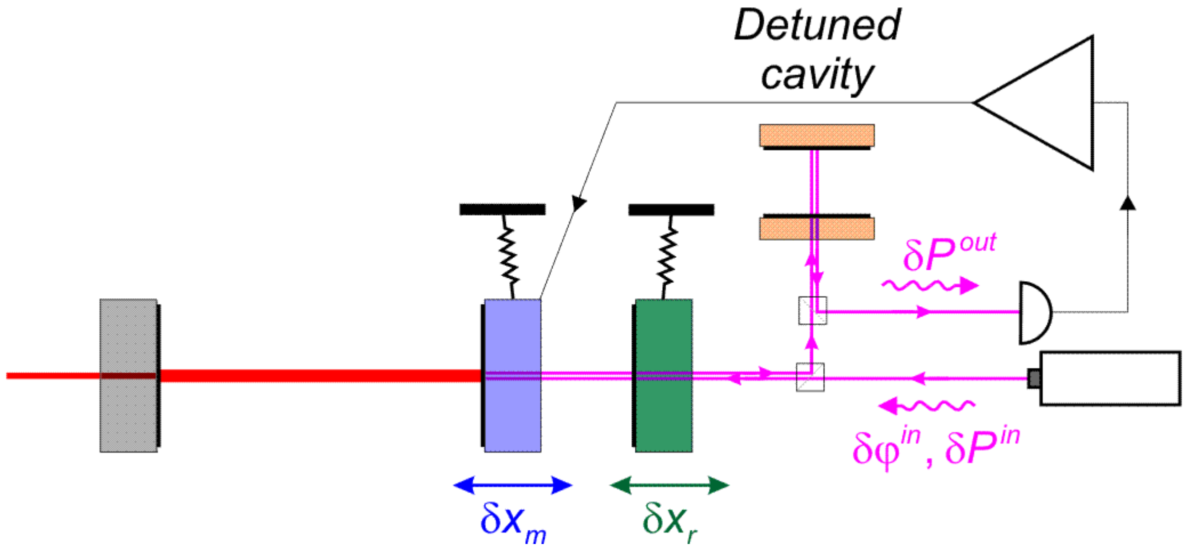




Optimal gain:
large at low frequency,
small at high frequency

- Reduction of radiation pressure noise
- Sensitivity preserved at high frequency

QND measurement of mirror motion

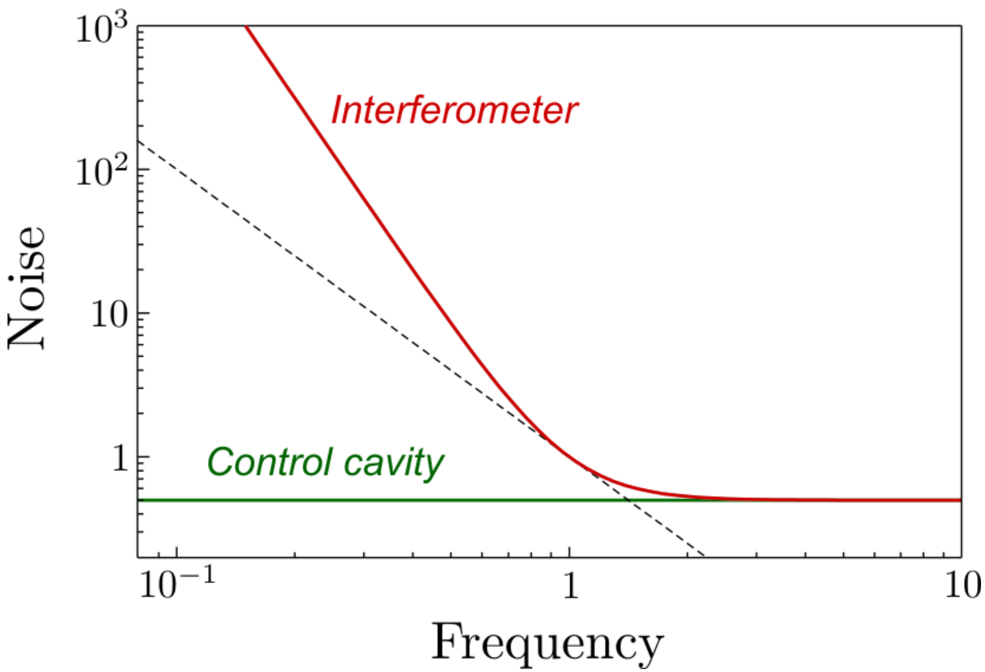


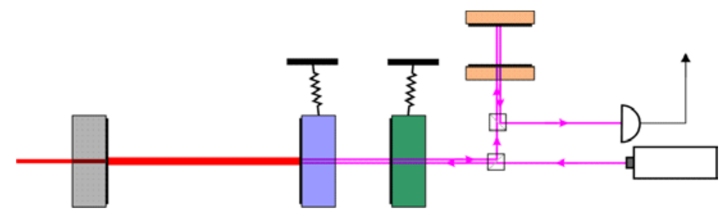
Intensity reflected by a detuned cavity

$$\delta x_r \propto \delta P^{in} \quad \rightarrow \quad \delta P^{out} \approx \delta\varphi^{in} + \frac{\mathcal{F}}{\lambda}\left(\delta x_m - f_{\Delta,\Omega}\,\delta x_r\right)$$

For a properly chosen detuning, $f_{\Delta,\Omega} = 0$

Sensitivity of QND measurement





Control cavity:

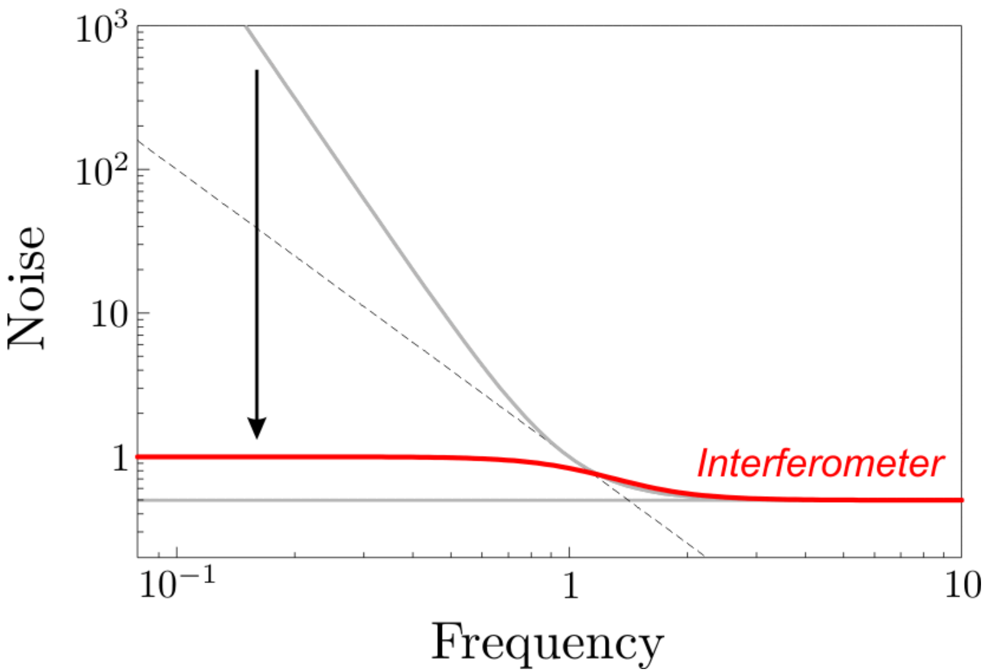
Finesse = 50 000

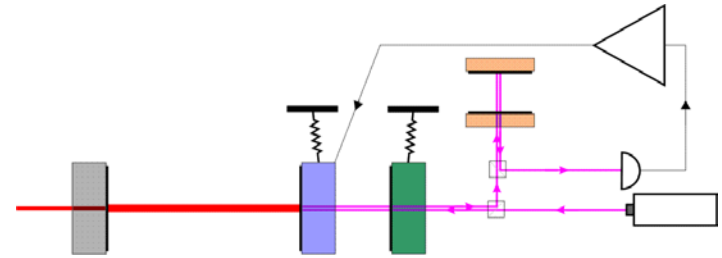
Input = 5 mW

$$\delta P^{out} \approx \delta\varphi^{in} + \frac{\mathcal{F}}{\lambda}\delta x_m$$

Measurement of δx_m only limited by $\delta\varphi^{in}$

Locking with QND measurement

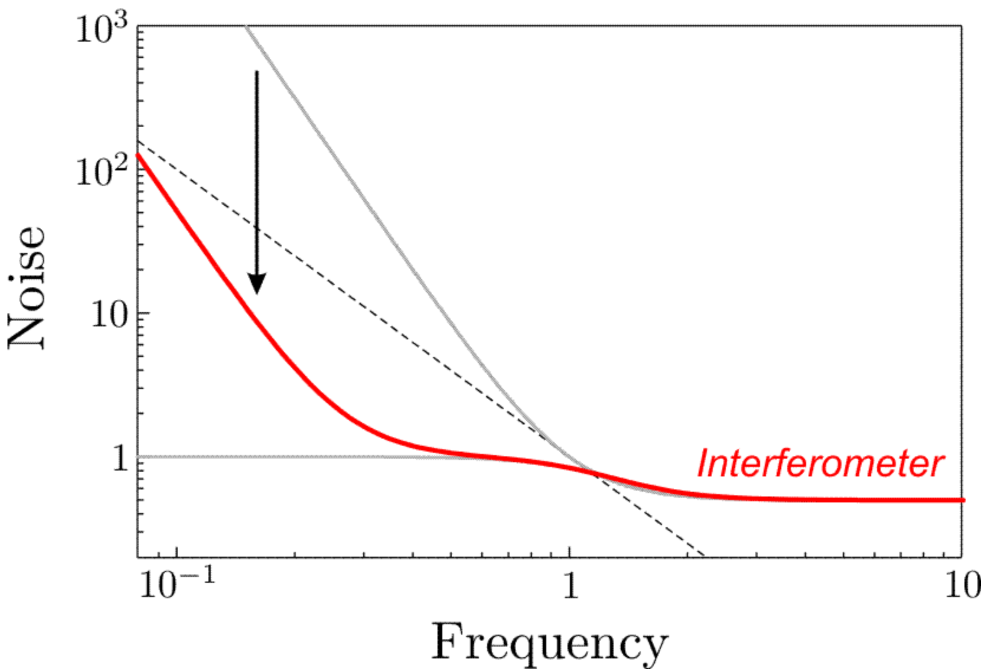


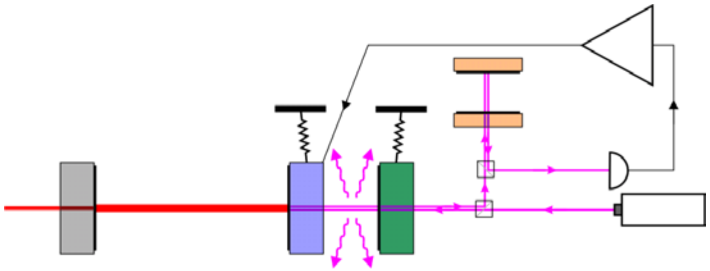


Optimal gain

Complete suppression of radiation pressure noise

Effect of losses



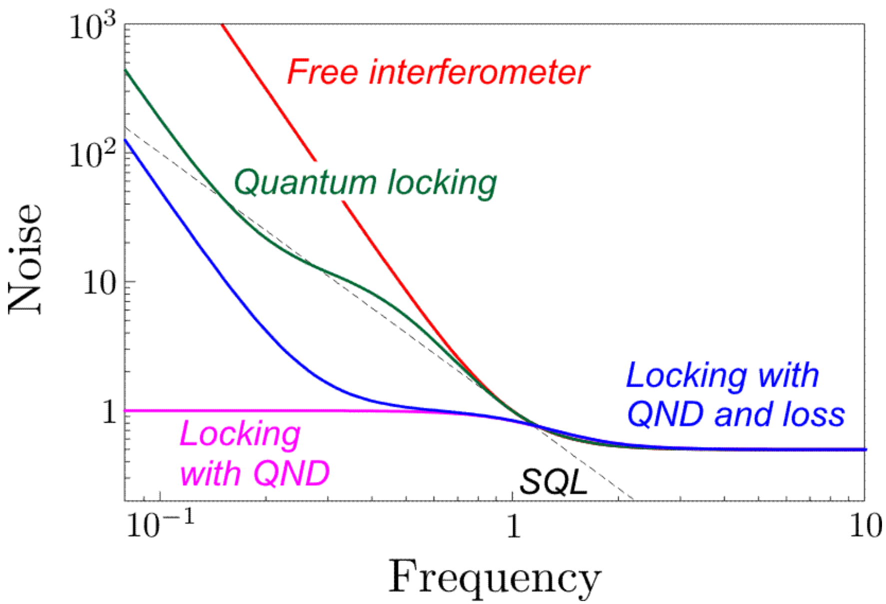


1% loss in control cavity

- Loss in interferometer:
  no impact on quantum locking
- Loss in detection:
  for 1% loss, sensitivity still increased by 100

Conclusion

- Active control techniques reduce quantum noise over a wide bandwidth



- Compatible with existing designs

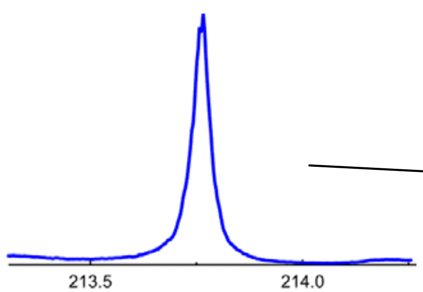
- Decouple quantum optics constraints from interferometer characteristics

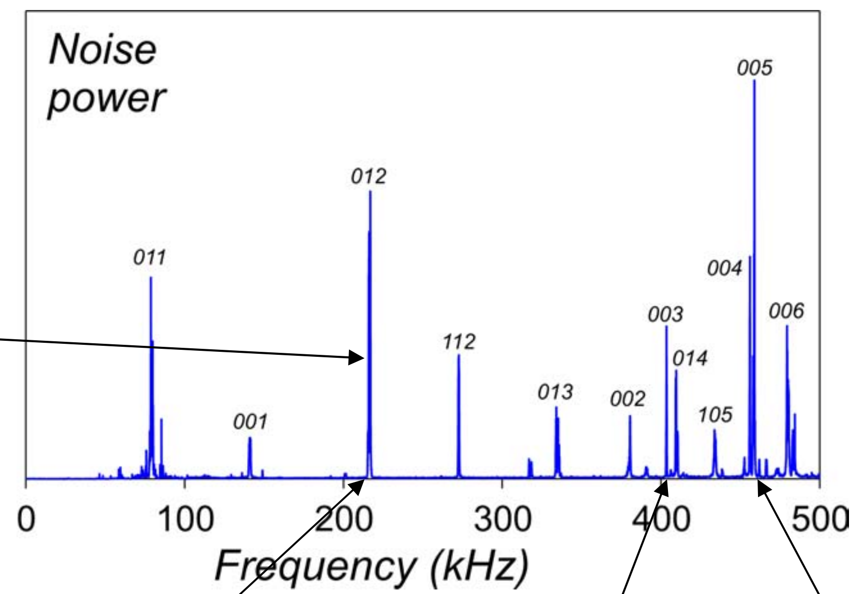
Insensitive to losses in the interferometer

Phys. Rev. Lett. 90, 083601 (2003) – Europhys. Lett. 63, 226 (2003)

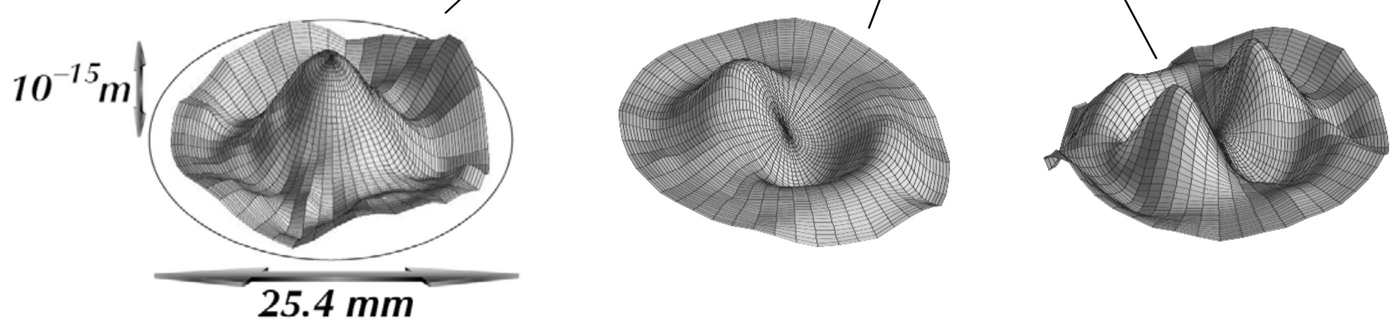
Characterization of internal modes

Noise spectrum:





Spatial profiles:



Determination of resonance frequencies, quality factors, masses, spatial profiles of internal acoustic modes