Optomechanical sensing beyond quantum limits

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Quantum sensing

Quantum sensing is typically used to describe one of the following:

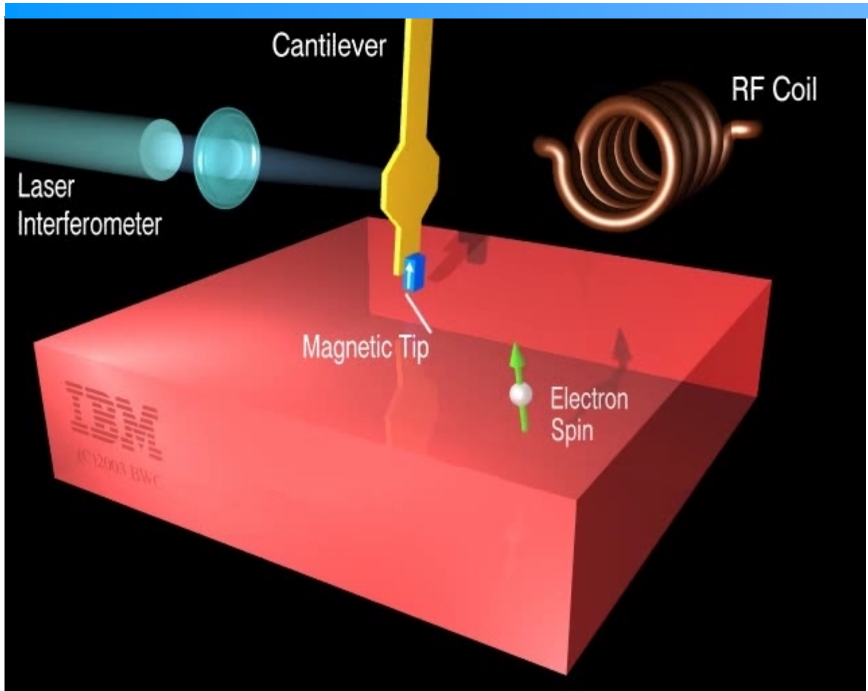
- Use of a **quantum object** to measure a physical quantity (classical or quantum)
- Use of **quantum coherence** to measure a physical quantity
- Use of **quantum entanglement** to improve the sensitivity or precision of a measurement

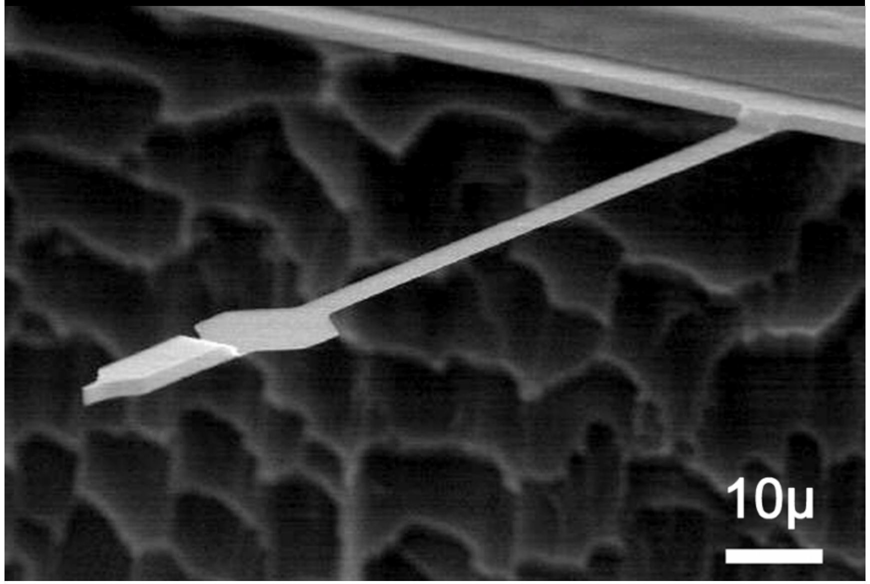
Degen *et al.*, RMP 2017

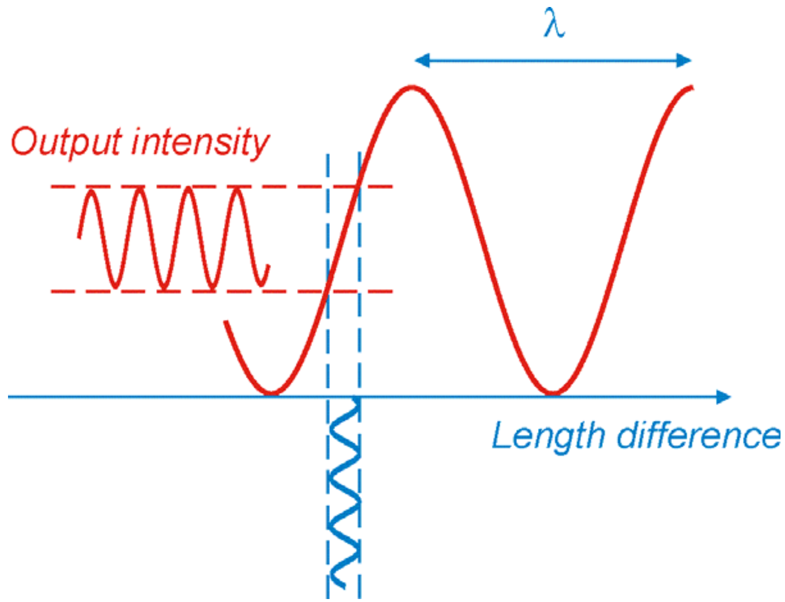
atomic magnetometers
NMR
NV centers
SQUIDs
SETs...

Mechanical systems (not quantum yet!) probed by (quantum) laser light

The beginning (or the end?) of the story







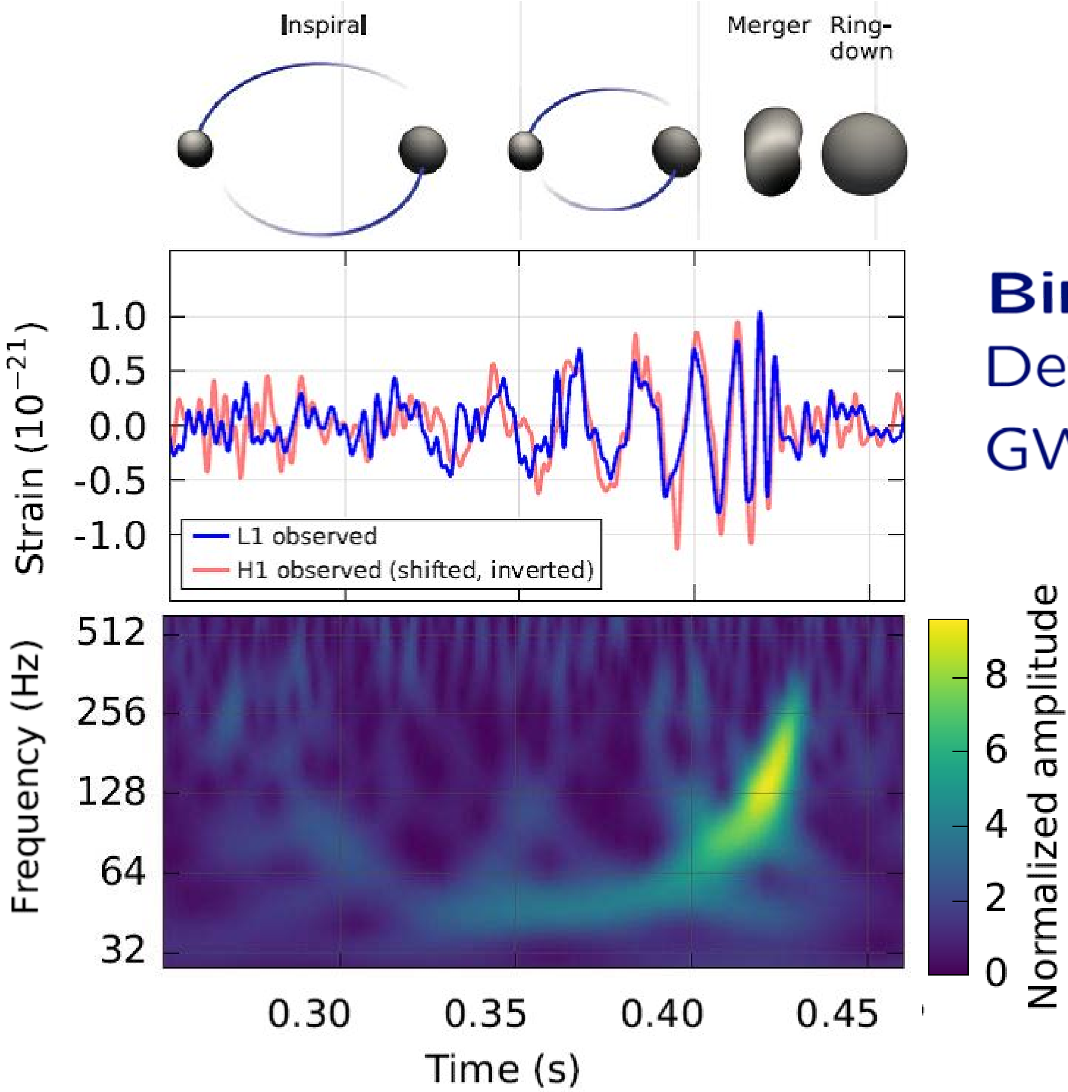
Displ. sensitivity better than 10^{-10} m

Force sensitivity better than 1 aN

(1 aN $= 10^{-18}$ N)

(D. Rugar, IBM San Jose, 2004)

September 14th, 2015, around 9h50 UTC



Binary black hole merger!

Detected by km-scale GW interferometers

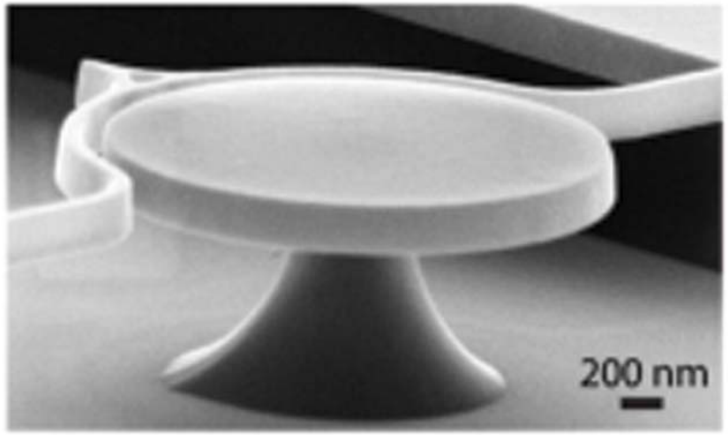
$h_{\text{max}} \simeq 10^{-21}$

Distance $\simeq$ 450 Mpc

Duration $\simeq$ 0.2 s

(over Myears???)

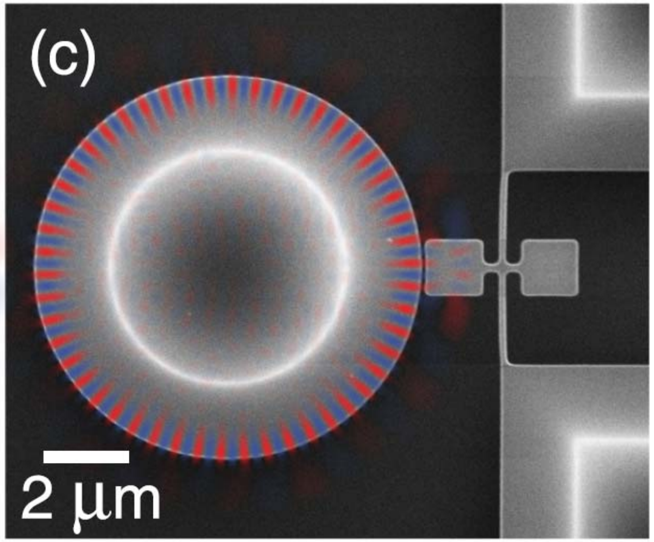
Optomechanical sensing

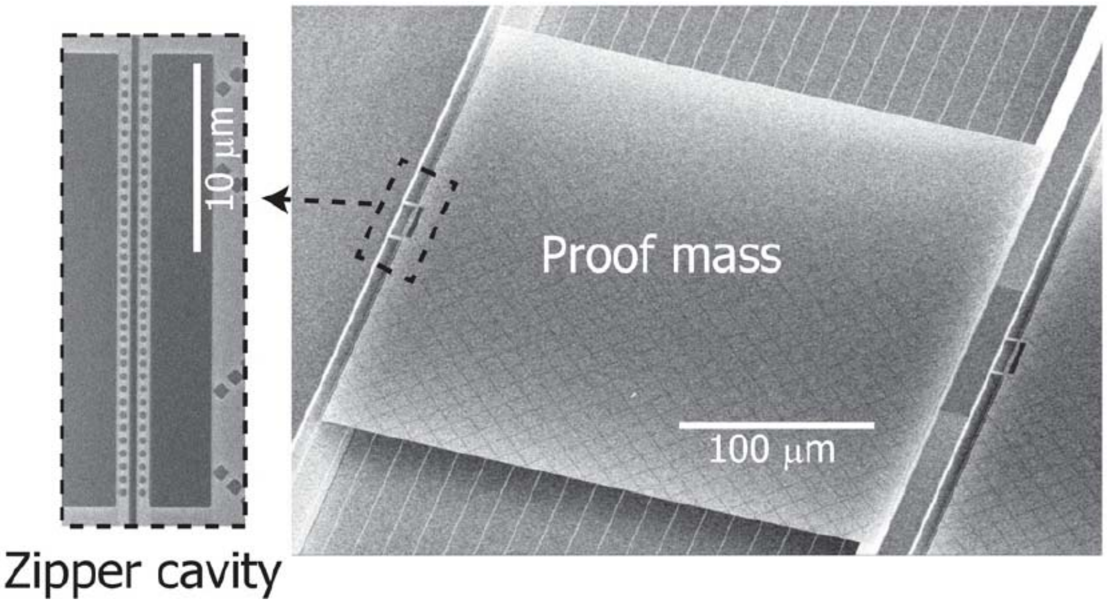


AFM

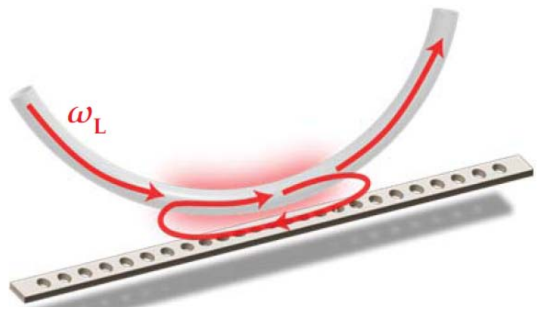
← WGM →

torsion sensor

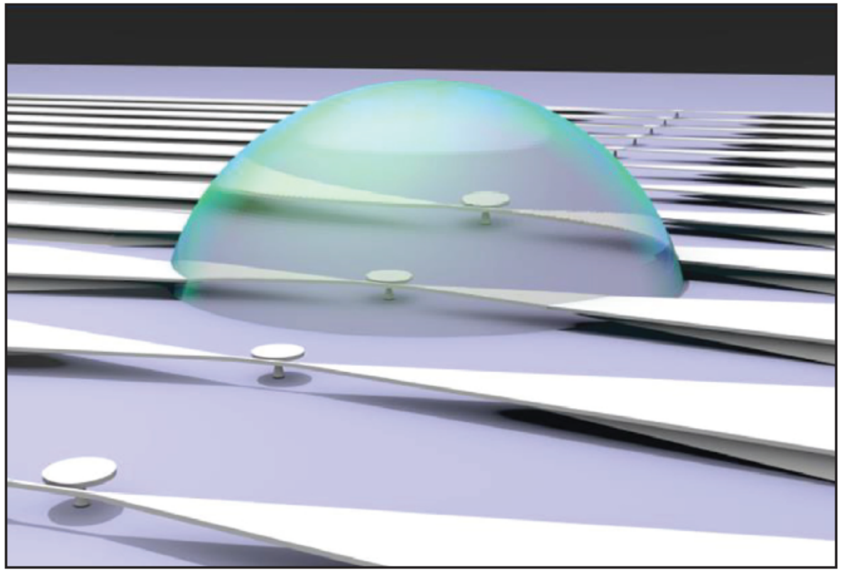




accelerometer with photonic-crystal cavity

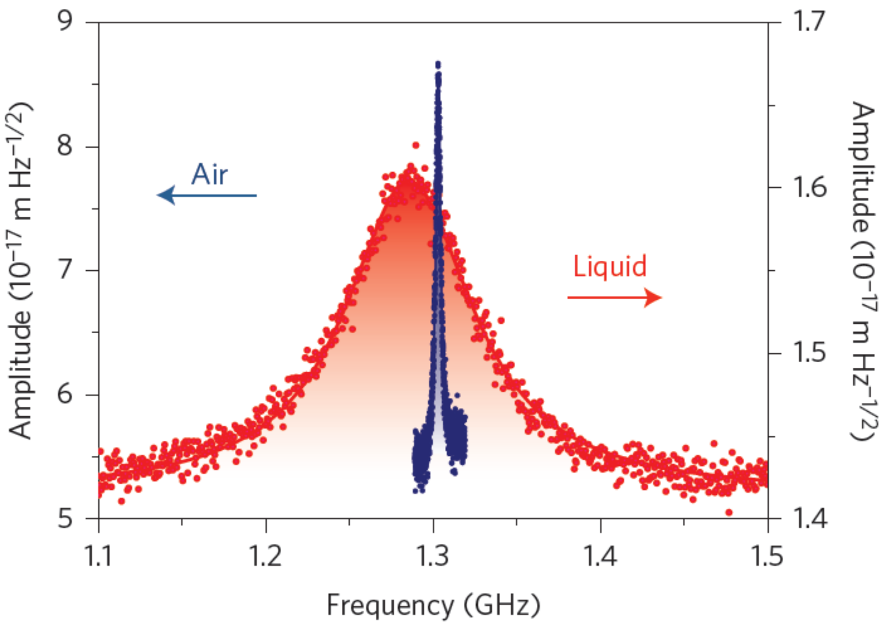


Optomechanical sensing in liquids



Optical and mechanical properties depend on the environment (T, pressure...)

Environmental sensor by monitoring frequency and damping shifts



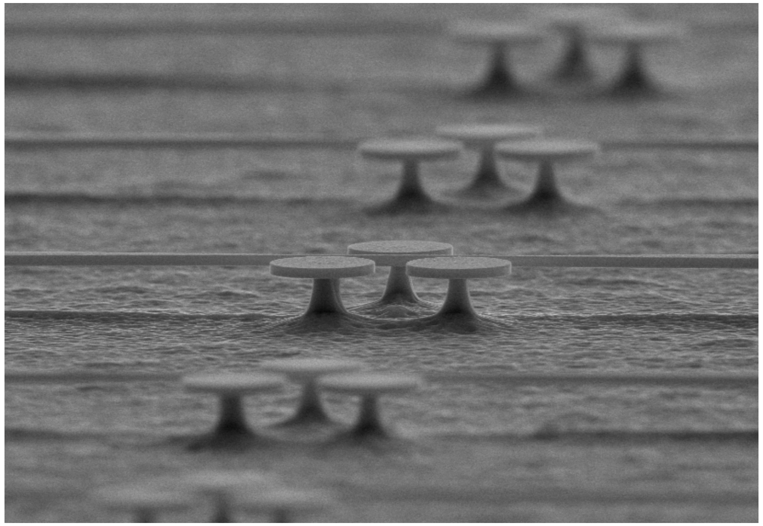
I. Favero, MPQ

A few assets of optomechanical sensing

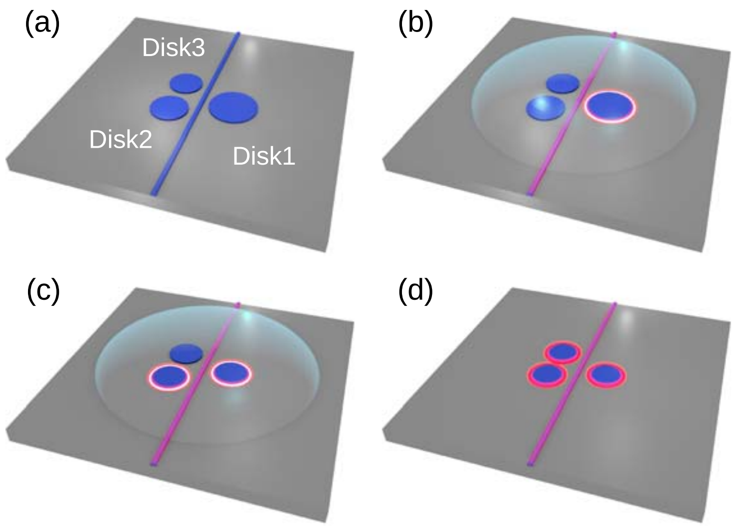
Sensitivity can be increased
by optomechanical auto-oscillation
(↓ linewidth)

I. Favero, MPQ

Network of sensors:
flow or force field imaging,
spatial correlations...



Sub-picometer nanophotonic
wavelength tuning
(scalable technique)



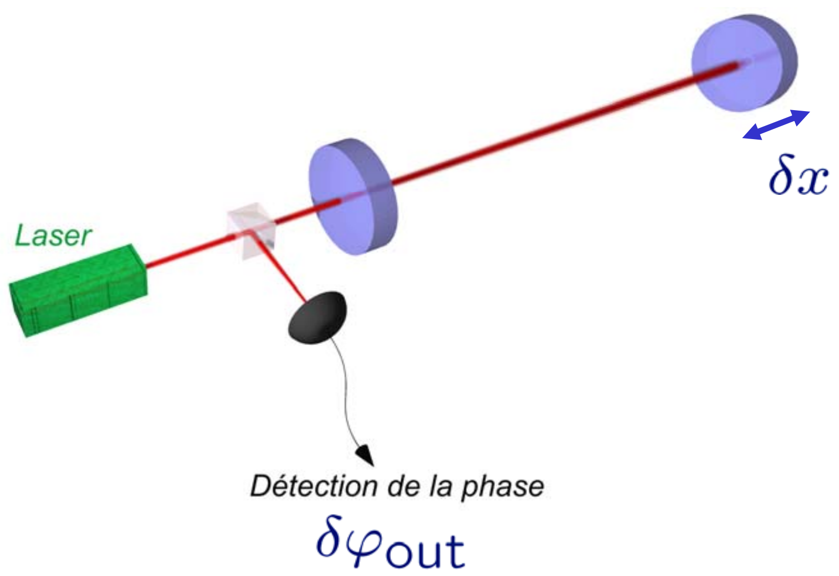
Interferometric measurements and quantum limits

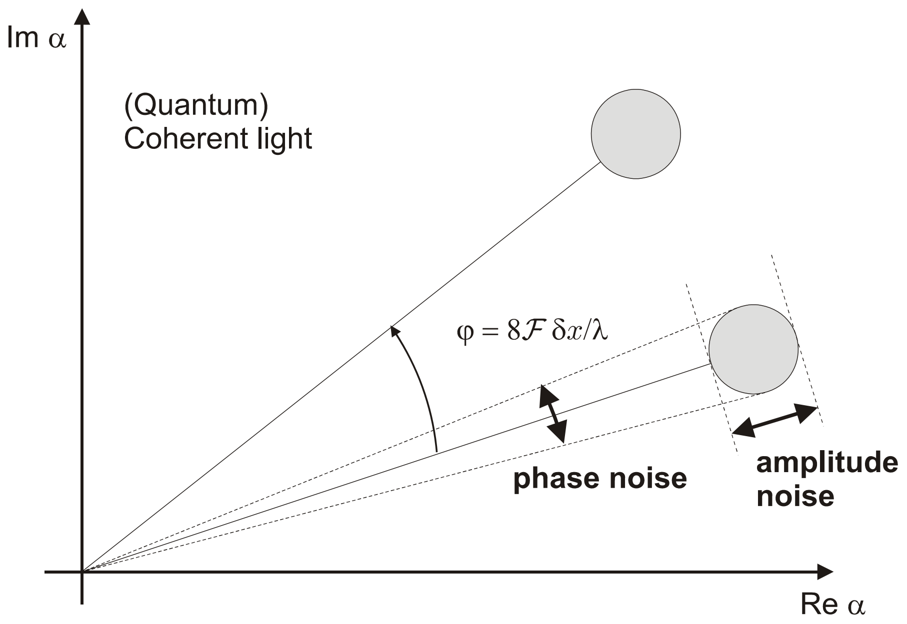
thermal noise

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

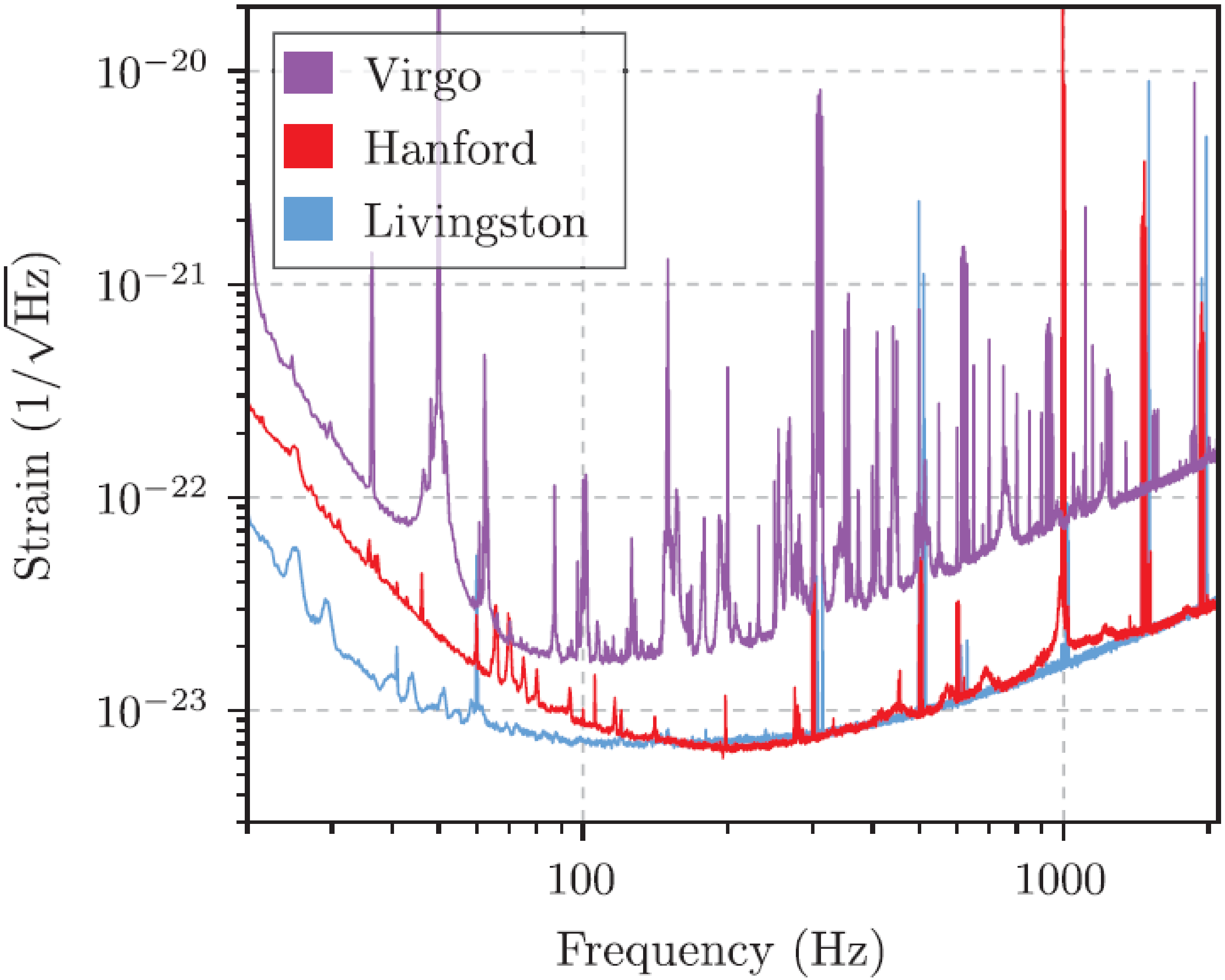
phase noise

signal



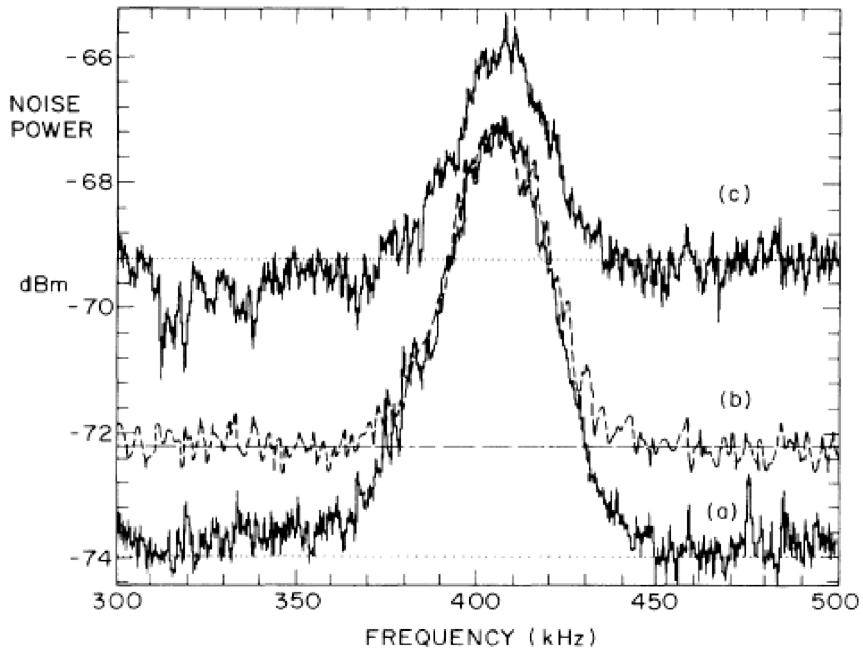


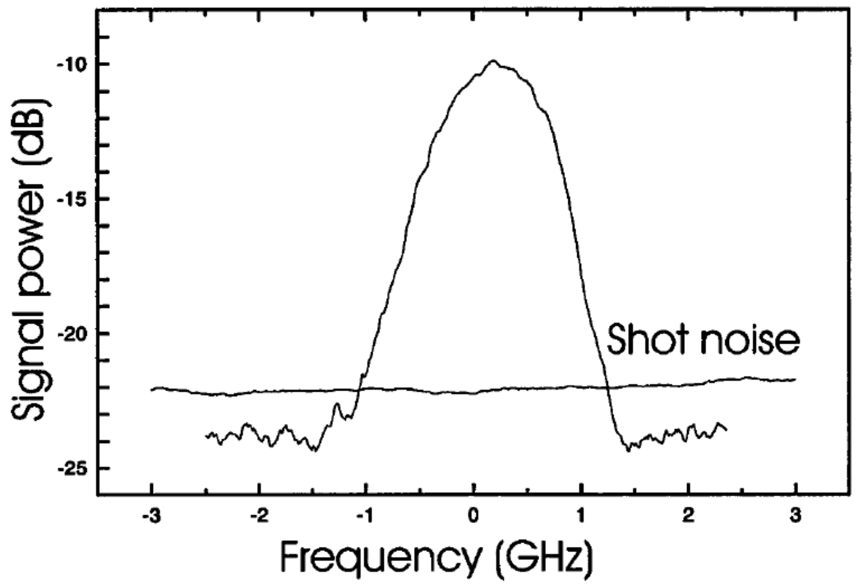
Advanced GWI sensitivity (as of Aug. 14th, 2017)



Early sub-shot-noise measurements

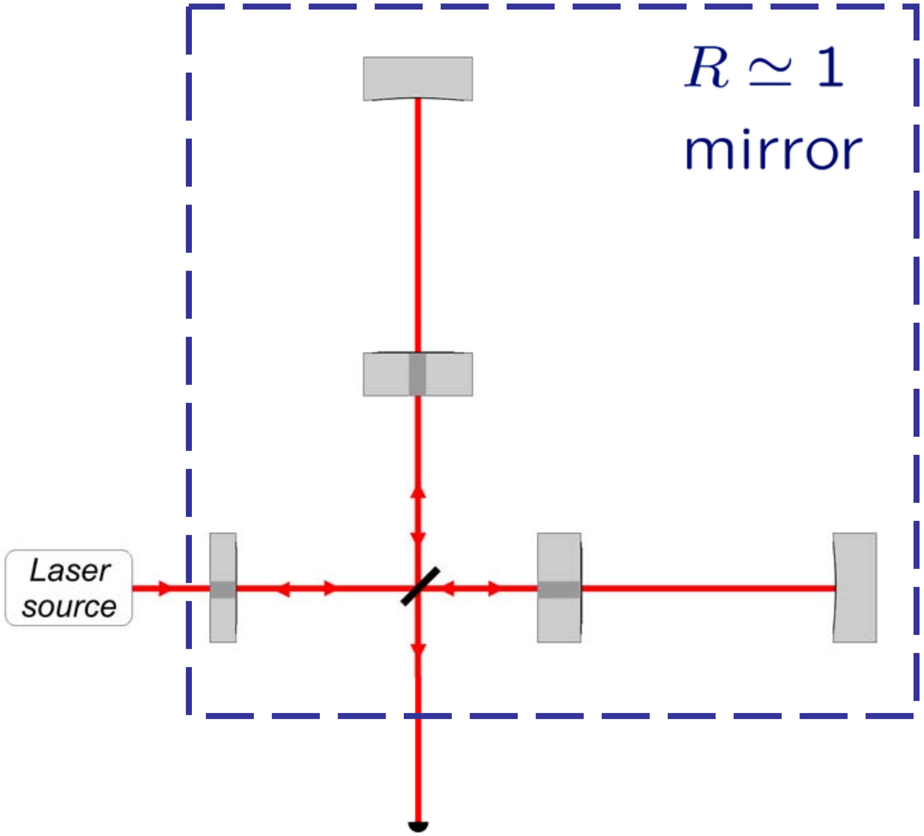
Squeezed-light-enhanced polarization interferometer
Grangier *et al.*,
Phys. Rev. Lett. 1987





Two-photon absorption with twin beams
Fabre *et al.*,
Opt. Lett. 1998

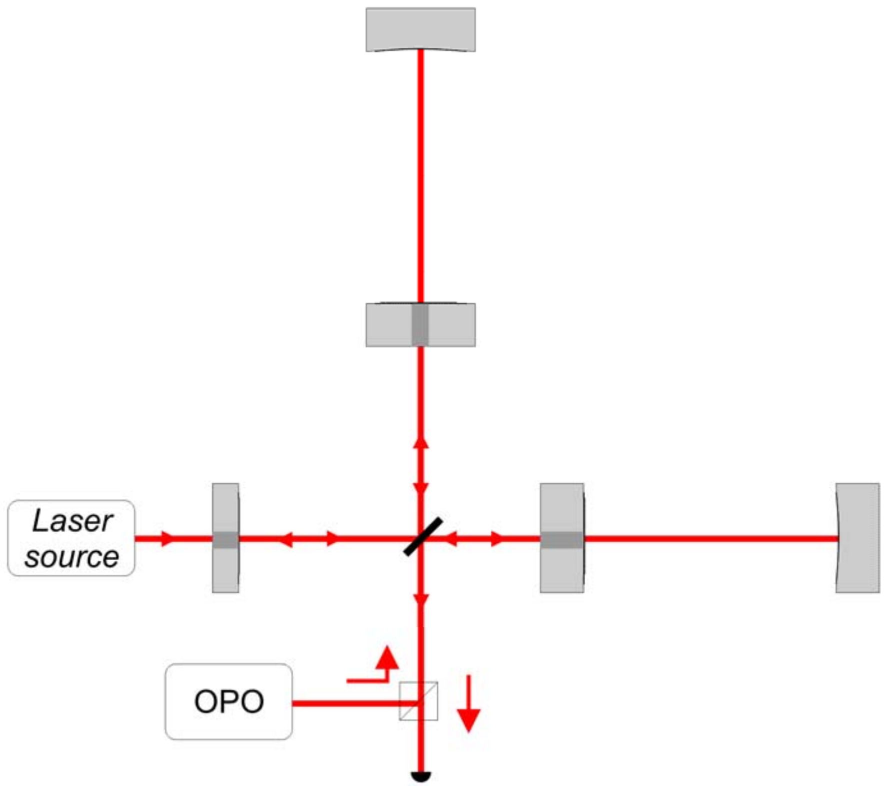
Measurements below the Q phase noise limit



GWI on a dark fringe

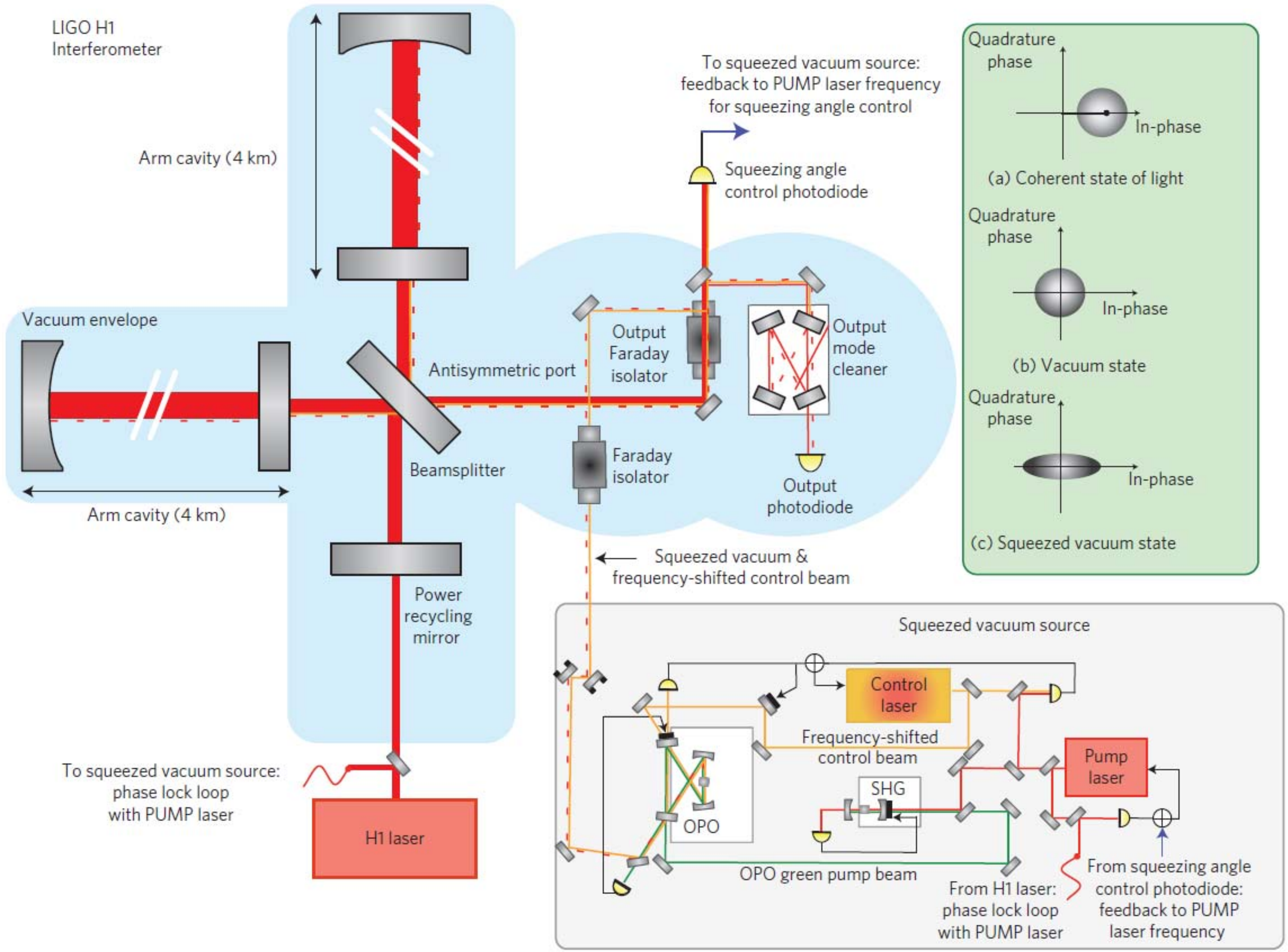
$\Longrightarrow$ sensitive to vacuum noise

Measurements below the Q phase noise limit

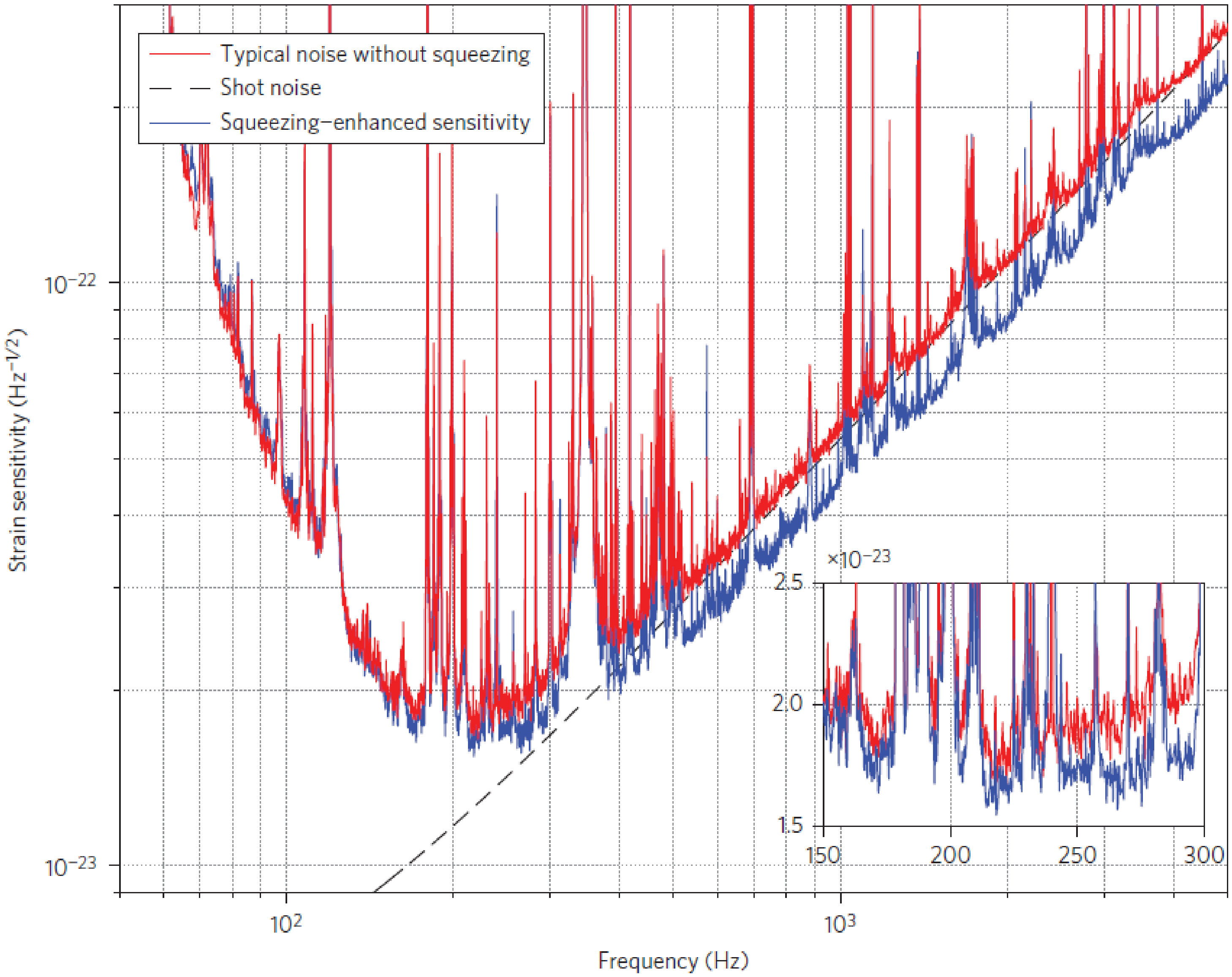


Squeezed vacuum injection
to increase the sensitivity

Experiment at LIGO Hanford (2011)



Experimental results at LIGO (2011)



Measurement back-action

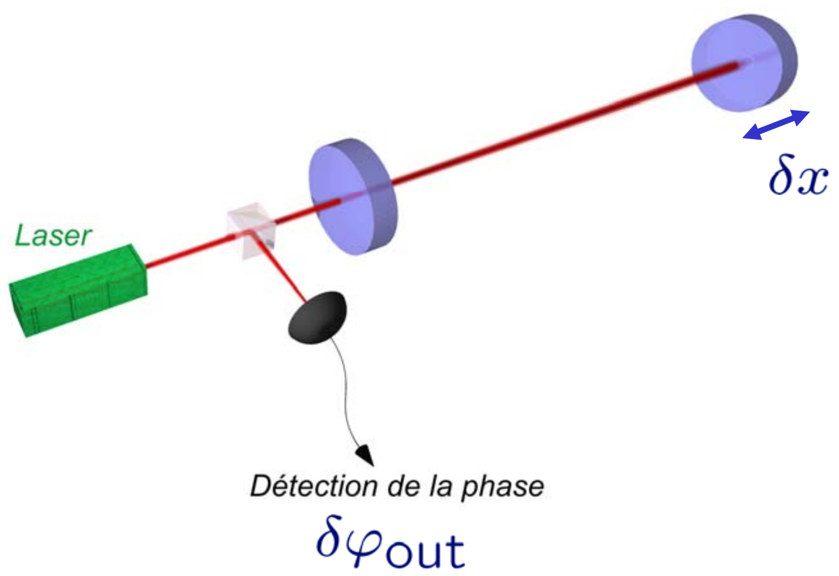
$$\delta\varphi_{\text{out}} = \delta\varphi_{\text{in}} + \frac{8\mathcal{F}}{\lambda}(\delta x + \delta x_{\text{cl}} + \delta x_{\text{rad}})$$

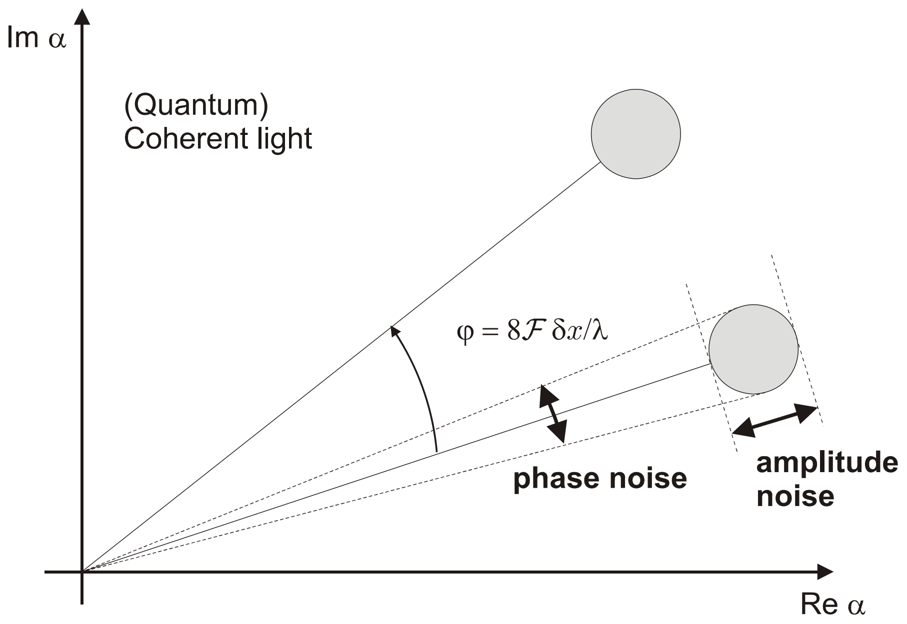
thermal noise

phase noise

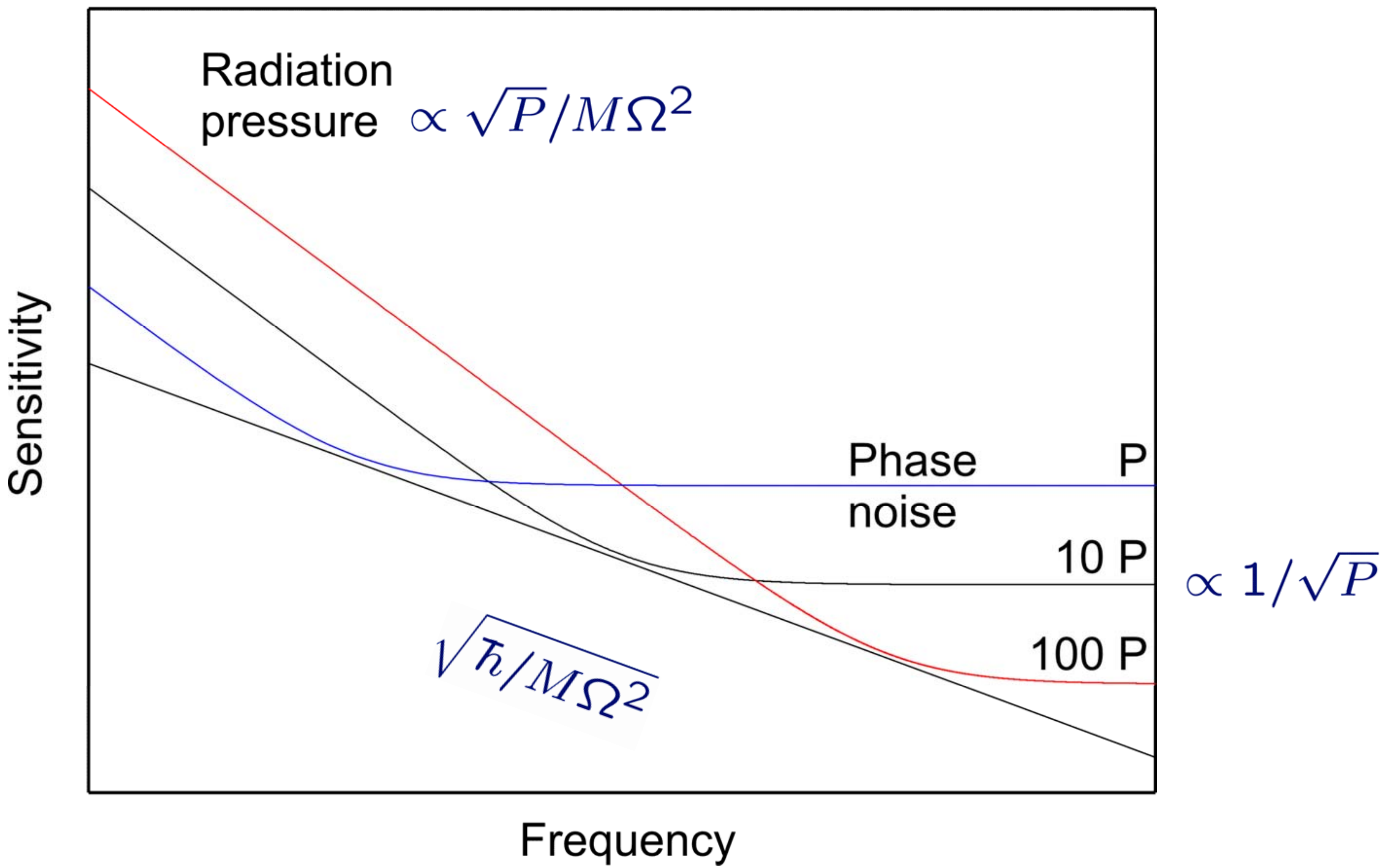
signal

radiation pressure noise

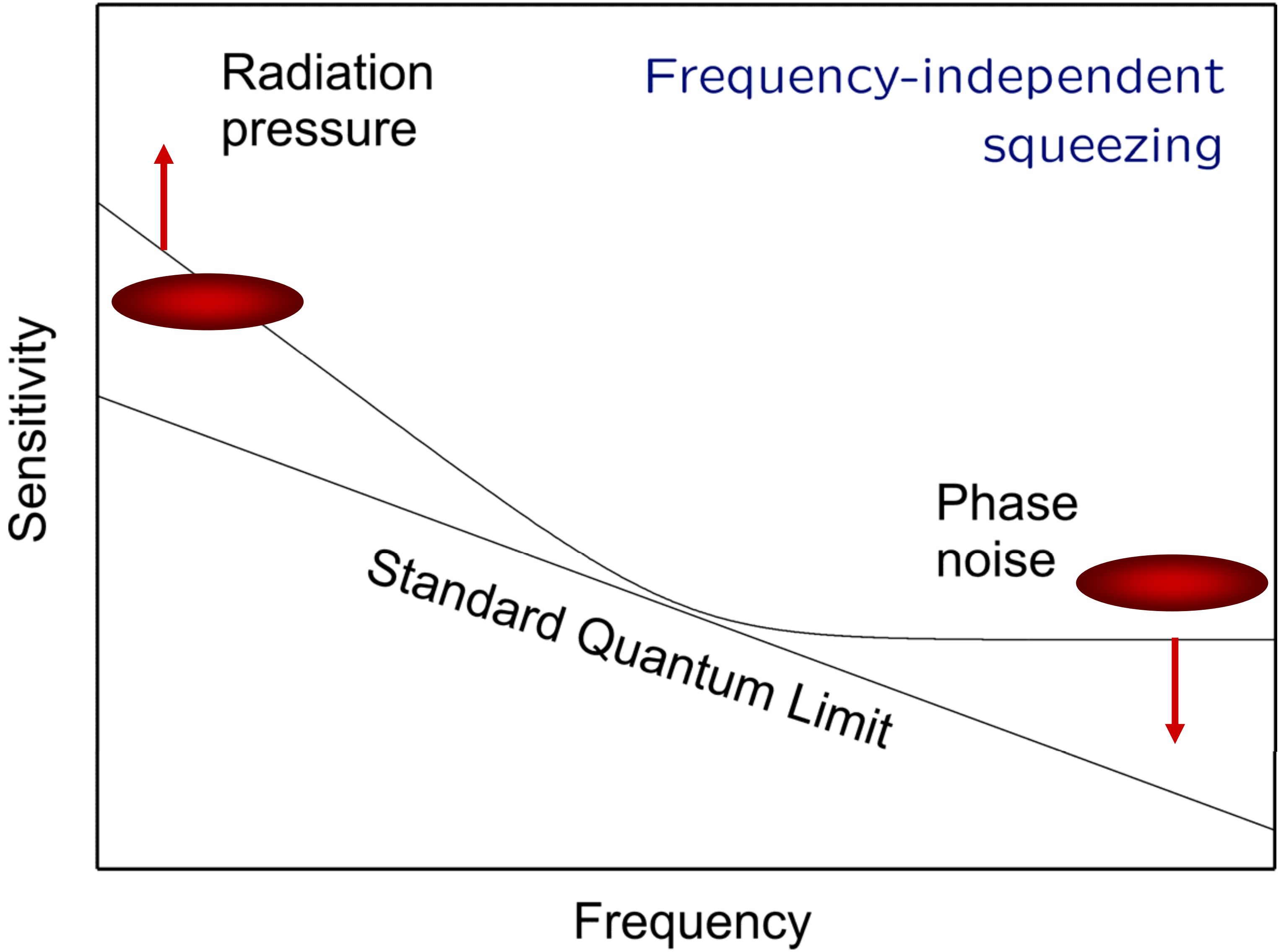




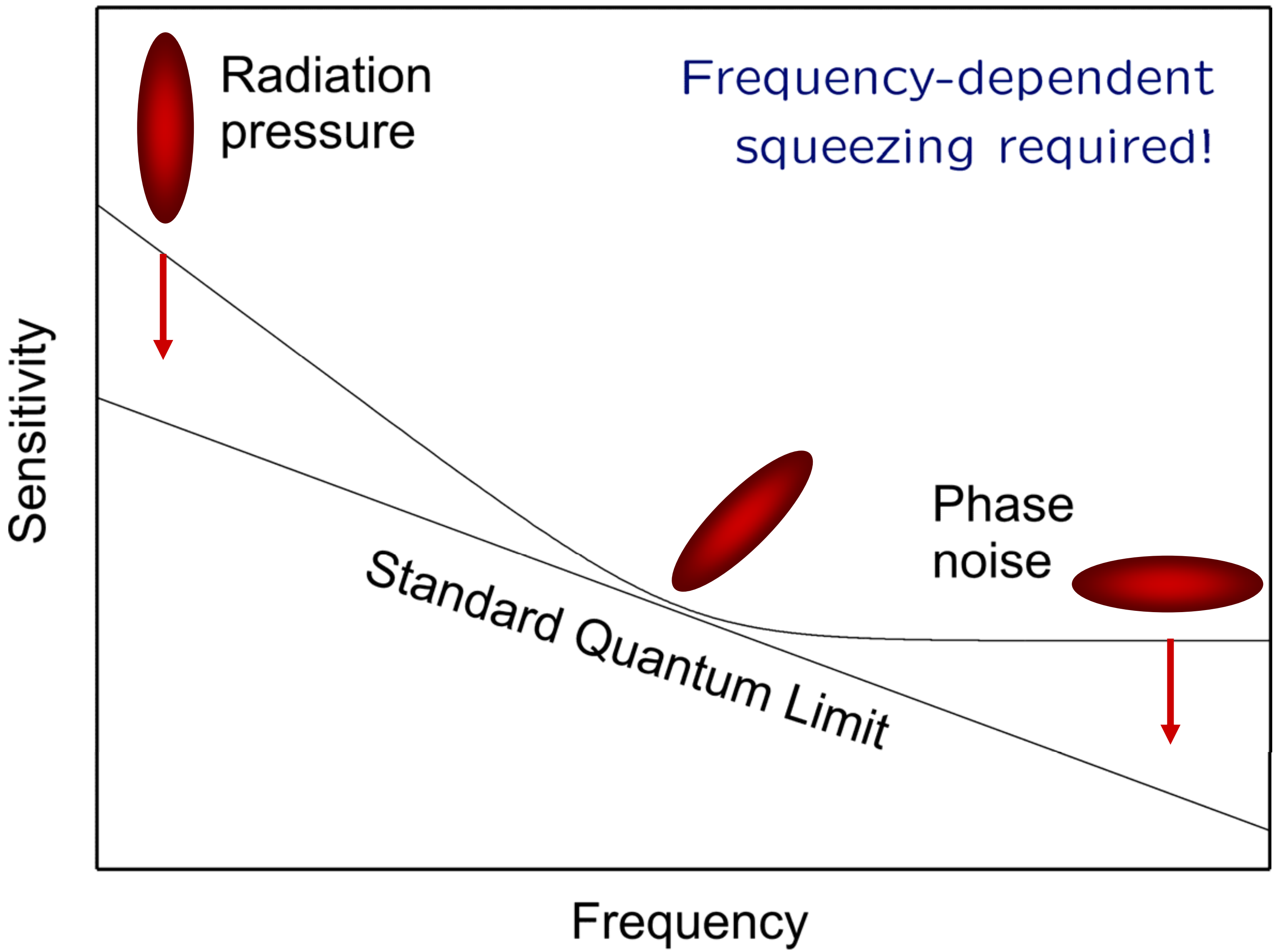
The Standard Quantum Limit (for a free mass)



Beating the Standard Quantum Limit?



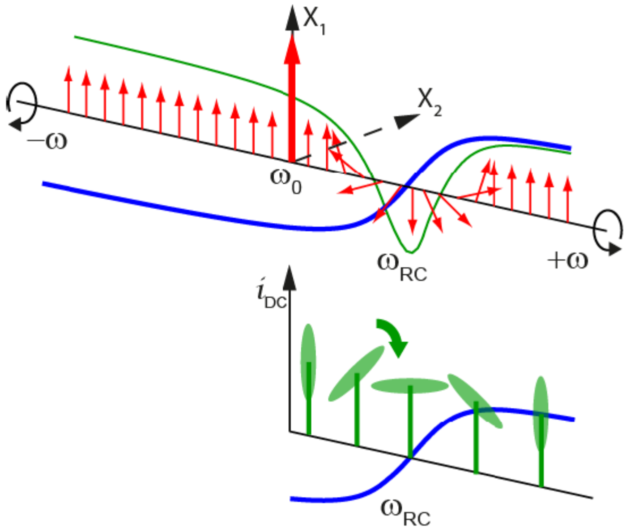
Beating the Standard Quantum Limit!

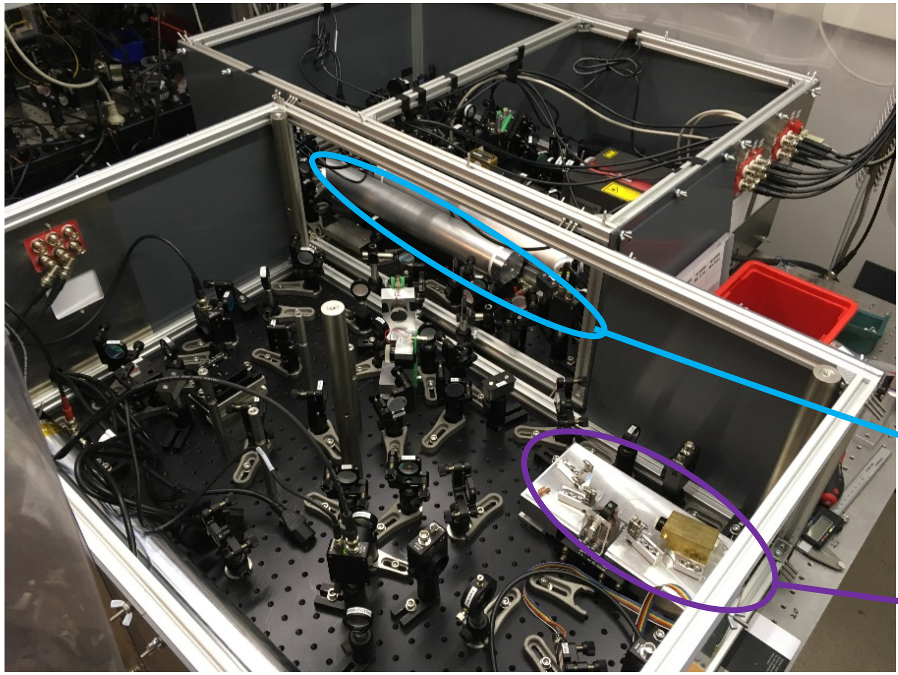


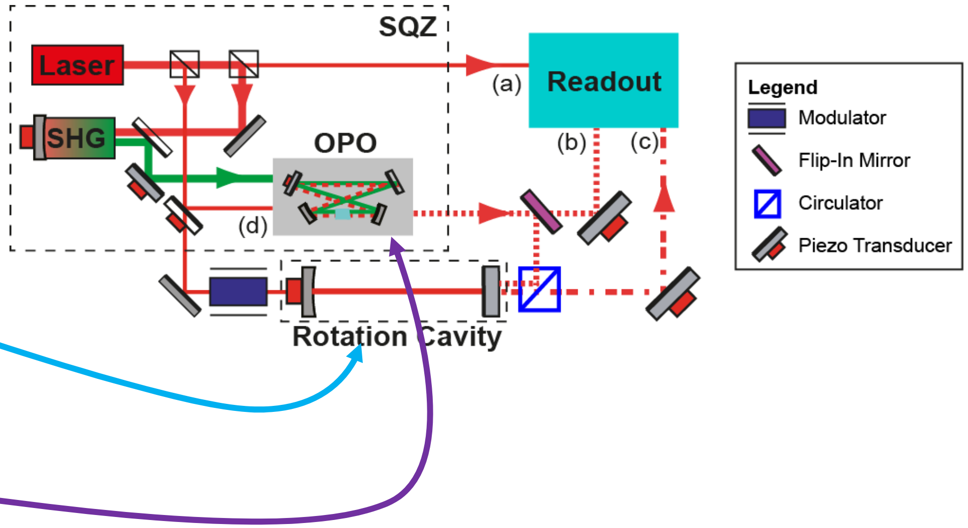
ExSqueez project (with ONERA and LMA)

High-frequency experiment:
Create a HF squeezed-light source
with technologies compatible
with the injection inside a GWI

Demonstrate frequency-dependent squeezing
using a detuned filter cavity



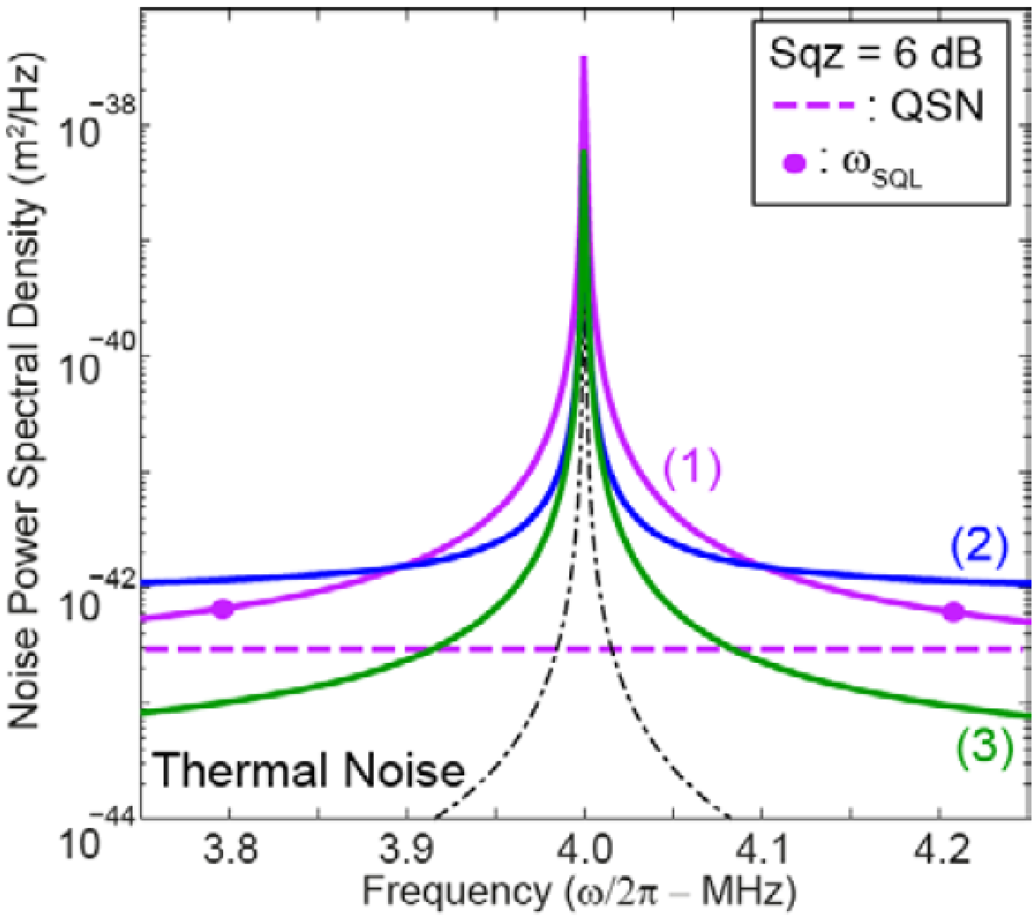


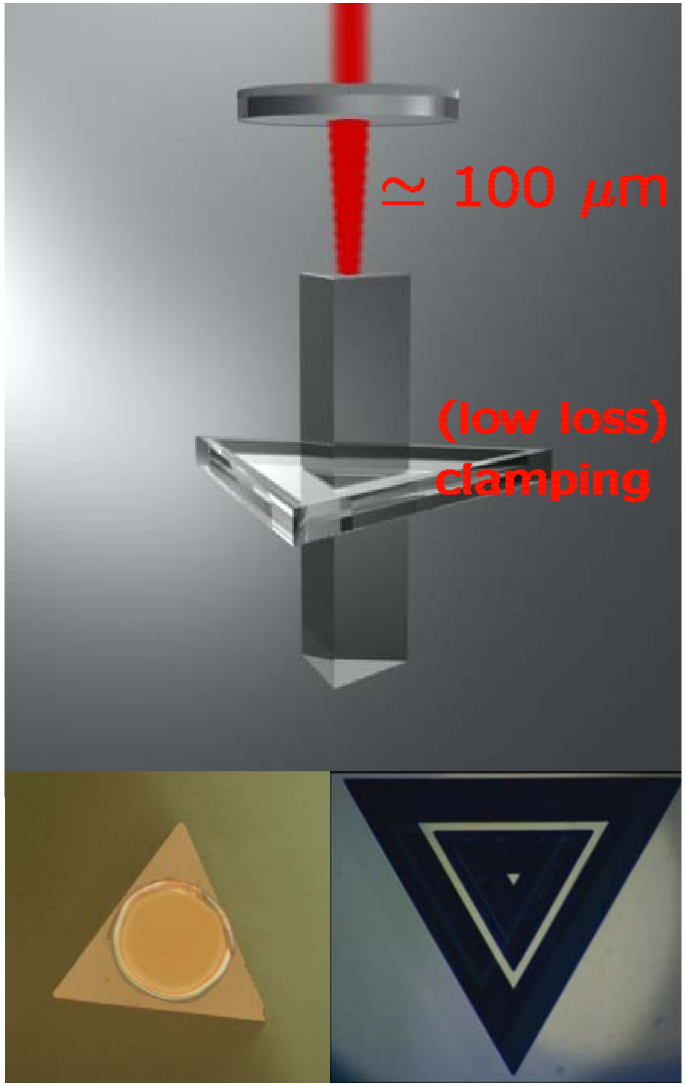


ExSqueez project (with ONERA and LMA)

1 mm, $40\ \mu$g, $Q \simeq 7 \times 10^7$, $T \simeq 1$ K

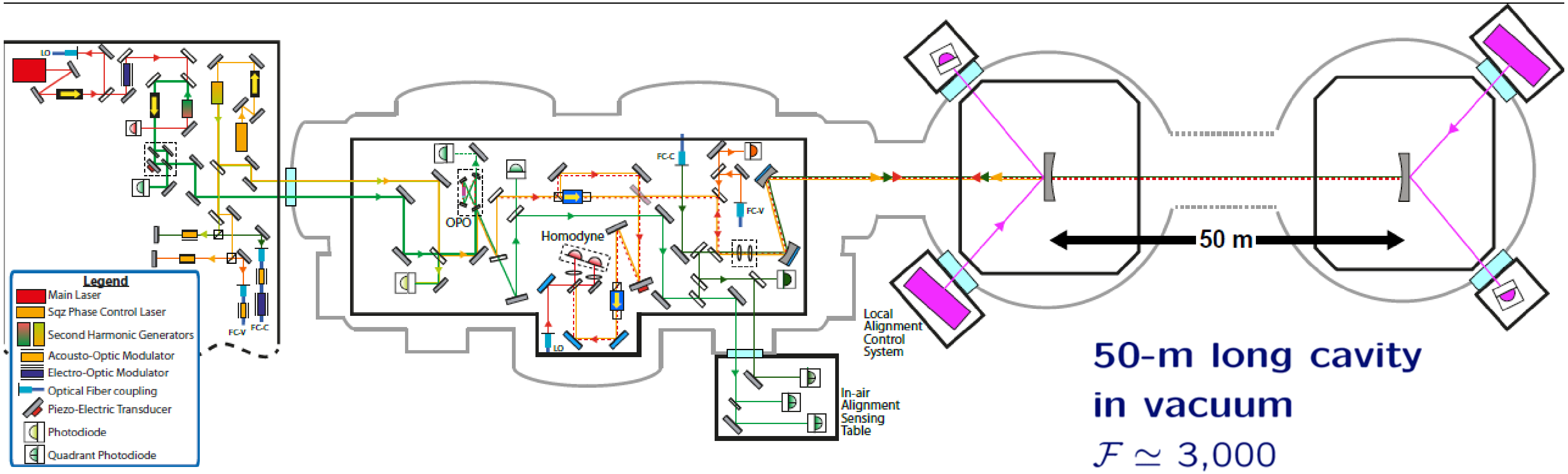
$\mathcal{F} = 10^5$, $P = 1$ mW





ExSqueez project (with LAL Orsay and LMA)

Low-frequency experiment:
Create a LF FD squeezed-light source with a corner frequency $\simeq$ 1 kHz (as a first step toward 50 Hz required for AdV)



50-m long cavity in vacuum

$\mathcal{F} \simeq 3{,}000$

Optomechanical sensing

Mechanical systems can be coupled
to any physical system
(atoms, spins, qbits, fields...)

Very fast progress on the squeezing front
- Adv LIGO and Adv Virgo will use
a (vacuum) **squeezed light source**
for their next scientifc run (03, end of 2018)
- **Frequency-dependent squeezing**
envisioned for 2020-21

Quantum behavior of macroscopic systems
can also be take advantage of
$\longrightarrow$ genuine **quantum sensing**