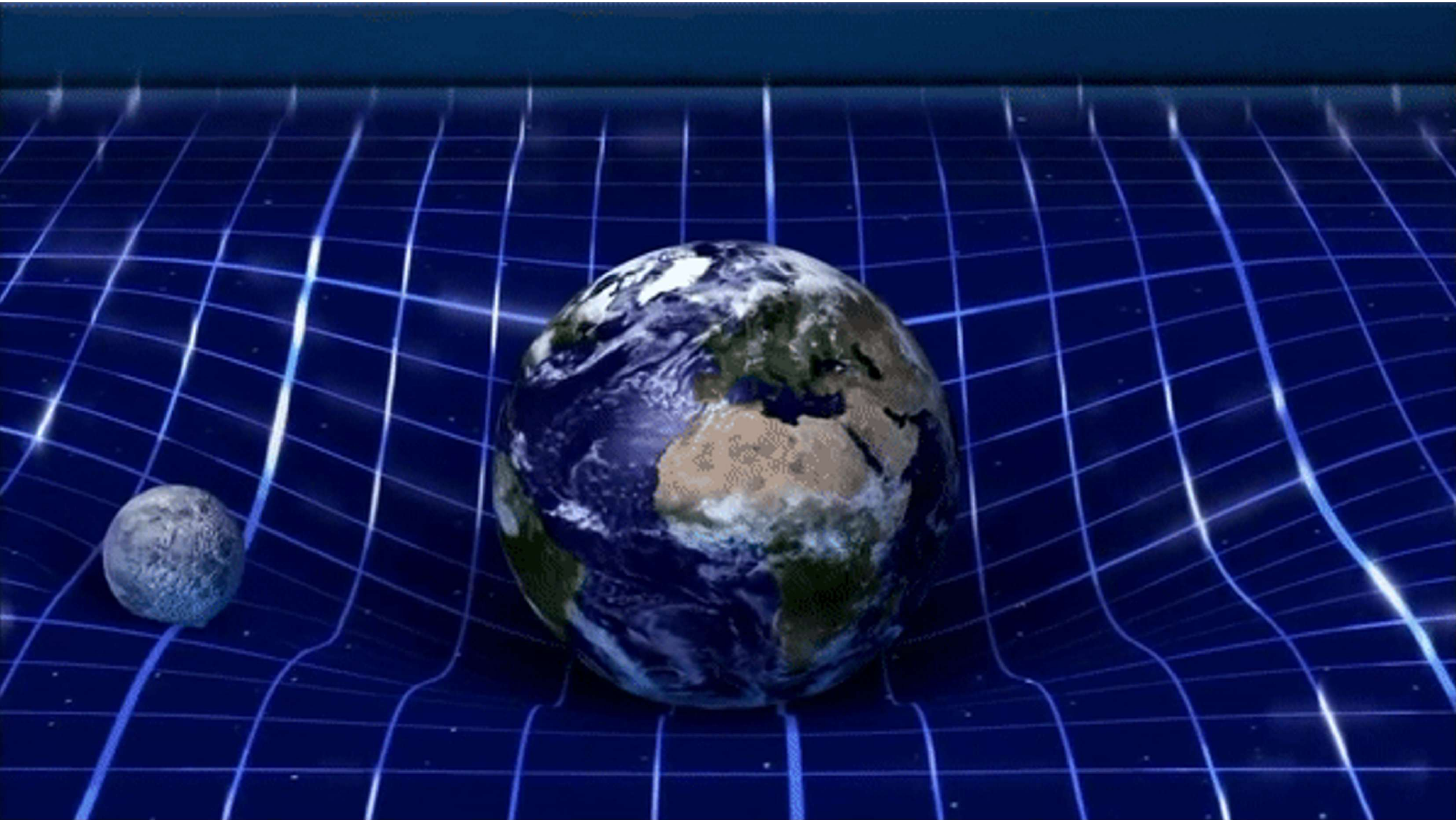
Laboratoire Kastler Brossel
Physique quantique et applications

ENS SORBONNE UNIVERSITÉ COLLÈGE DE FRANCE cnrs

Listening to the universe with quantum light:
Quantum technologies for gravitational-wave detection

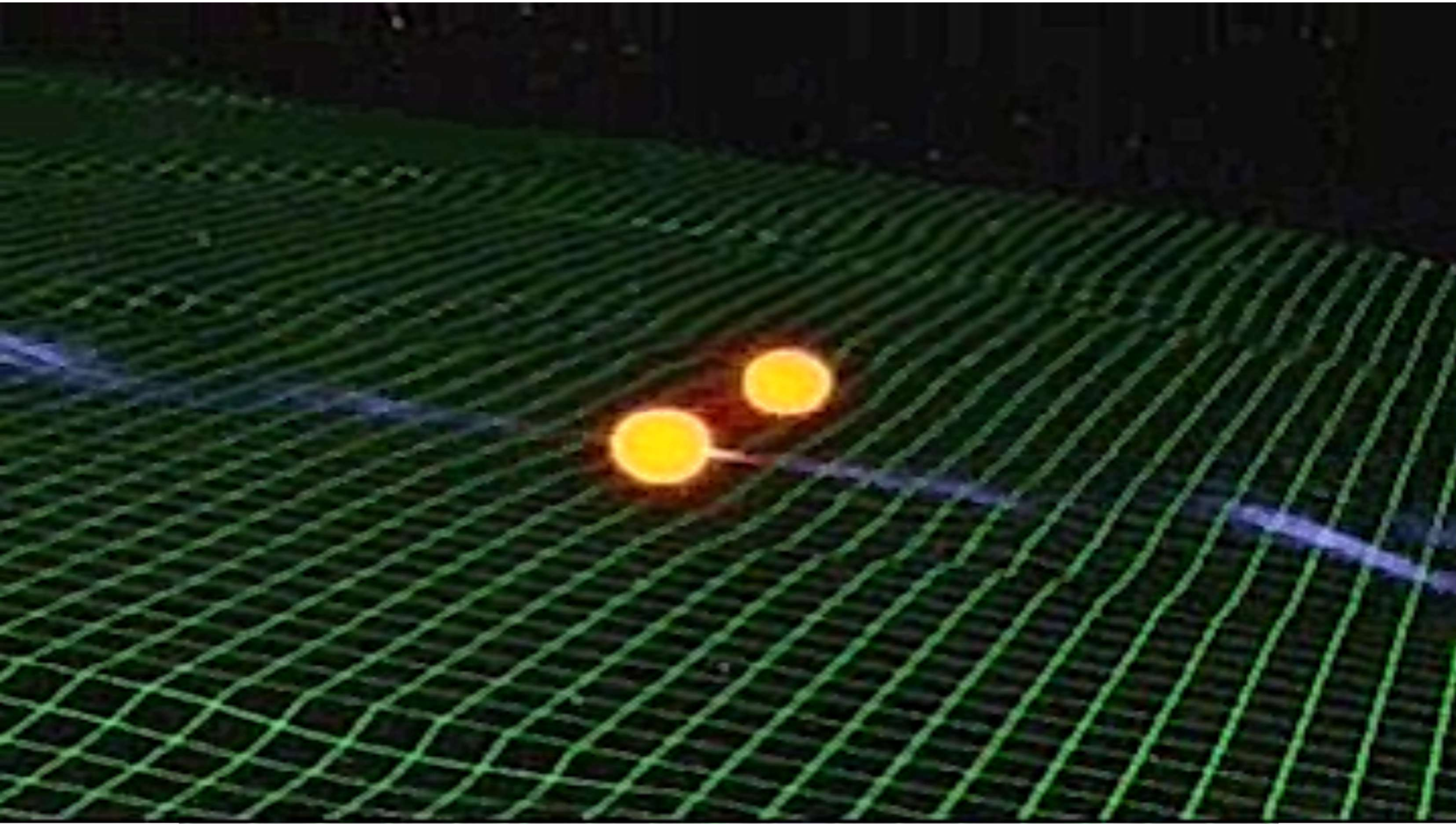
Antoine HEIDMANN
Optomechanics and Quantum Measurement group
Laboratoire Kastler Brossel

Gravitational waves:



a consequence of Einstein's General Relativity

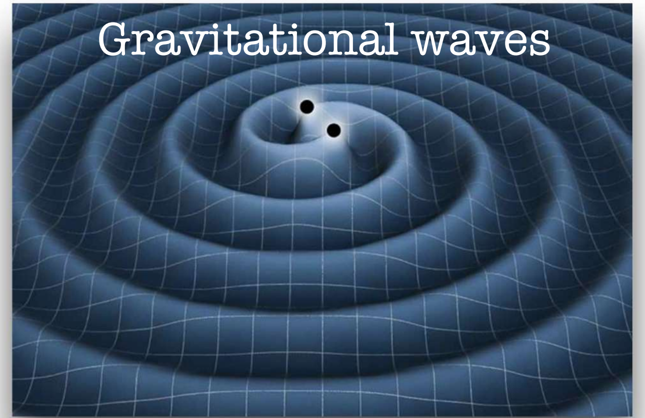
Gravitational waves:



a consequence of Einstein's General Relativity

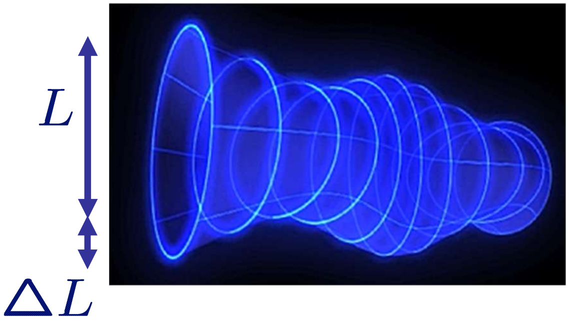
Effect of gravitational waves on earth

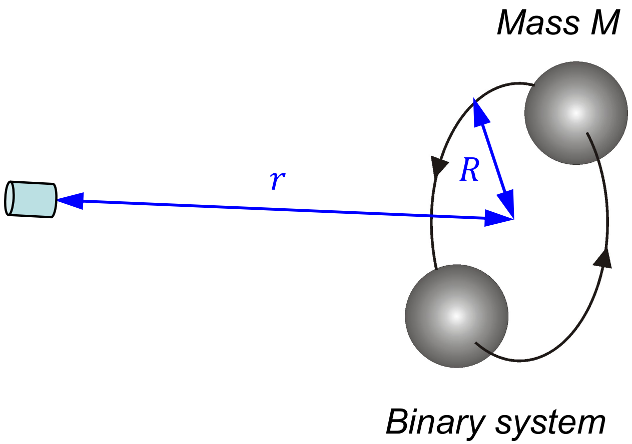
Ripples of space-time metric induce changes in distances between free-fall objects



→ Effect of a gravitational wave:

Alternative compression and expansion of distances (depend on polarization and direction of the wave)

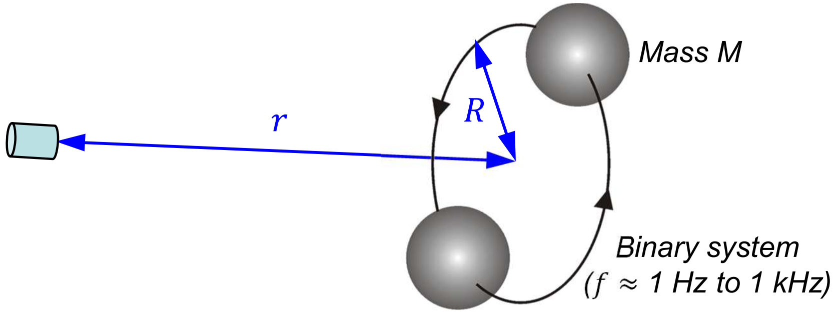




Gravitational-wave amplitude: $h = \Delta L / L$

Gravitational-wave amplitude (1)

$$h \simeq \Delta L/L \simeq \frac{GM}{rc^2}\left(\frac{v}{c}\right)^2$$



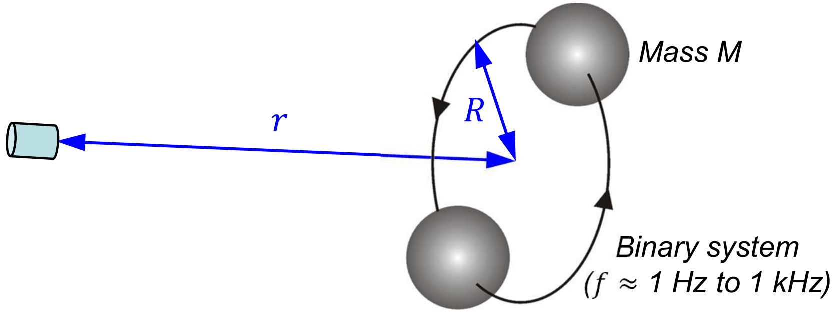
with $G = 6.67 \times 10^{-1}\ \ \mathrm{m^3/kg/s^2}$,
$c = 3 \times 10^8\ \mathrm{m/s}$,
radial velocity: $v = 2\pi f R$

- GW generated on earth: a 500-ton steel bar rotating on itself at 5 revolutions per second

$\rightarrow\ h \simeq 10^{-34}$ at $r = 1$ m

Gravitational-wave amplitude (2)

$$h \simeq \Delta L/L \simeq \frac{GM}{rc^2}\left(\frac{v}{c}\right)^2$$



with $G = 6.67 \times 10^{-11}\ \mathrm{m^3/kg/s^2}$,
$c = 3 \times 10^{8}\ \mathrm{m/s}$,
radial velocity: $v = 2\pi f R$

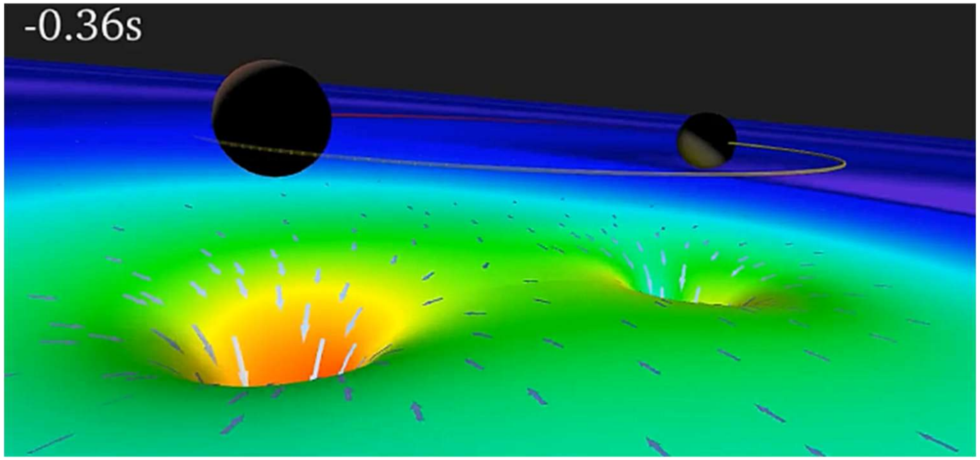
- GW generated on earth: a 500-ton steel bar rotating on itself at 5 revolutions per second

  $\rightarrow\ h \simeq 10^{-34}$ at $r = 1$ m

- A binary system made of 2 black holes:

  $M \simeq 30\ M_{\odot}$, $R \simeq 100$ km
  rotation at $f \simeq 100$ Hz

  $\rightarrow\ h \simeq 10^{-21}$ at $r = 400$ Mpc



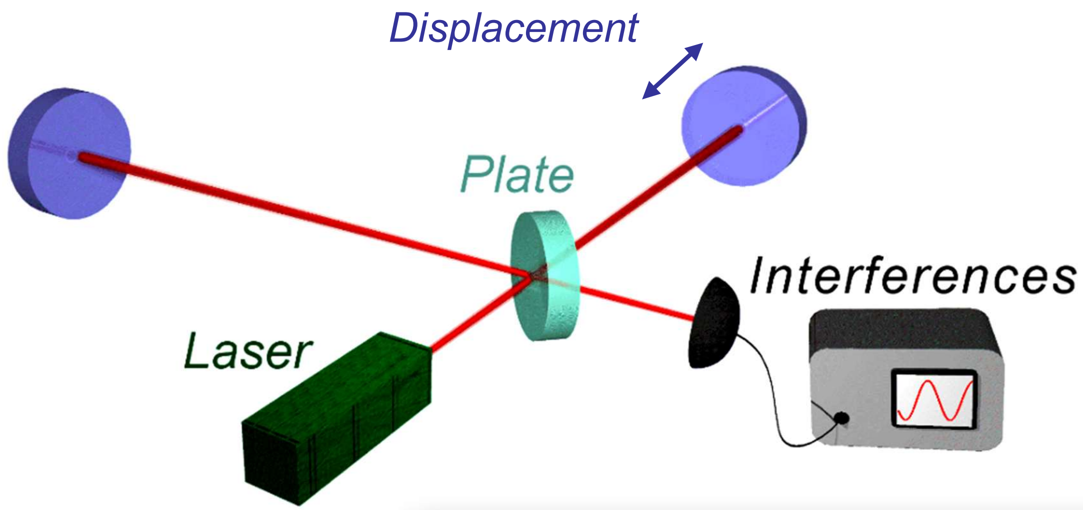
For the Earth ($L \simeq 10\ 000$ km), deformation
on the order of an atomic nucleus: $\Delta L \simeq 10^{-14}$ m !

Detection of

gravitational waves

Sensitive optical measurement of displacements

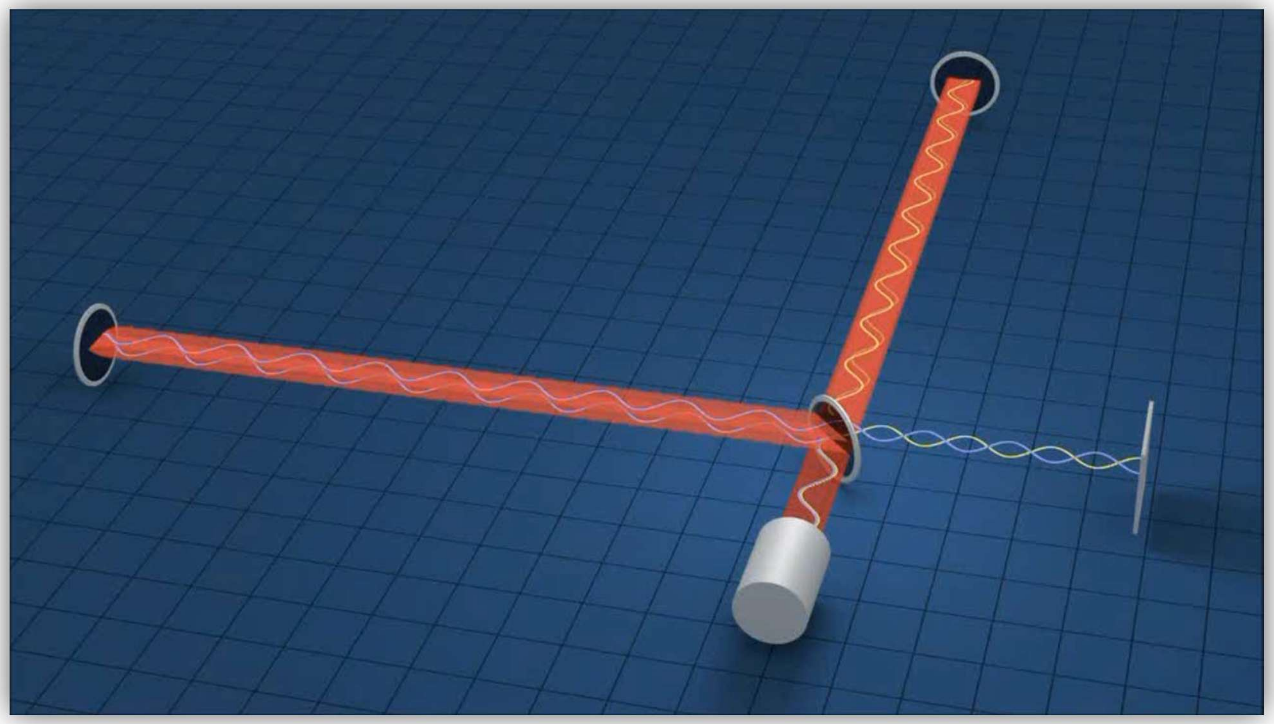
Michelson interferometer: measurement of relative lengths between 2 arms



Variation of the output intensity:

$$\delta I_{out}/\bar{I}_{in} \simeq \delta L/\lambda$$

$$\simeq L/\lambda \times \underbrace{\delta L/L}_{h}$$



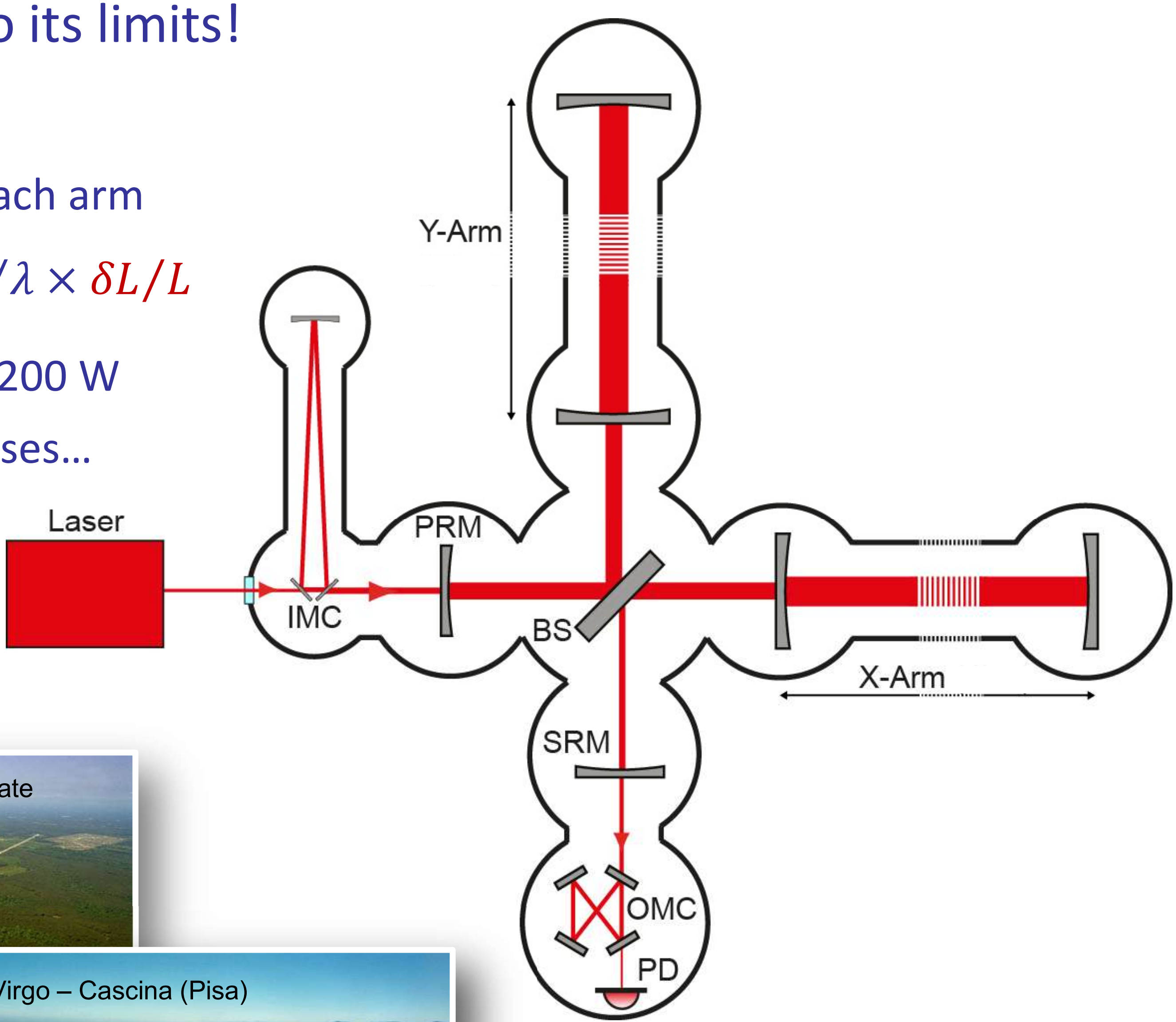
LIGO and Virgo interferometers

Interferometry pushed to its limits!

- Arms of km length
- Fabry-Perot cavities in each arm

$$\delta I_{out}/\bar{I}_{in} \simeq \mathcal{F} \times L/\lambda \times \delta L/L$$

- Incident power 10 W to 200 W
- Control/reduction of noises…



LIGO and Virgo interferometers

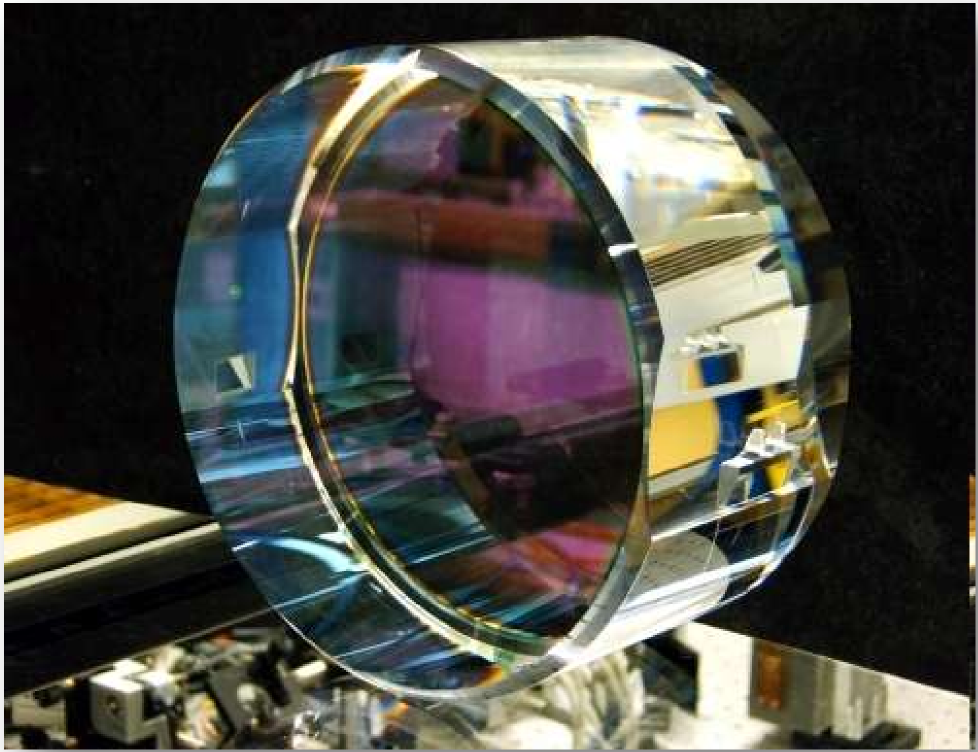
Interferometry pushed to its limits!

Europe's largest ultra-high vacuum system:

$6{,}800\ m^3$ at 10^{-9} mbar!

LIGO and Virgo interferometers

Unique high-quality mirrors!



- 35-cm-diameter and 40 kg silica mirrors
- Surface roughness corrected in situ < 1 nm
- Optical loss < 1 ppm

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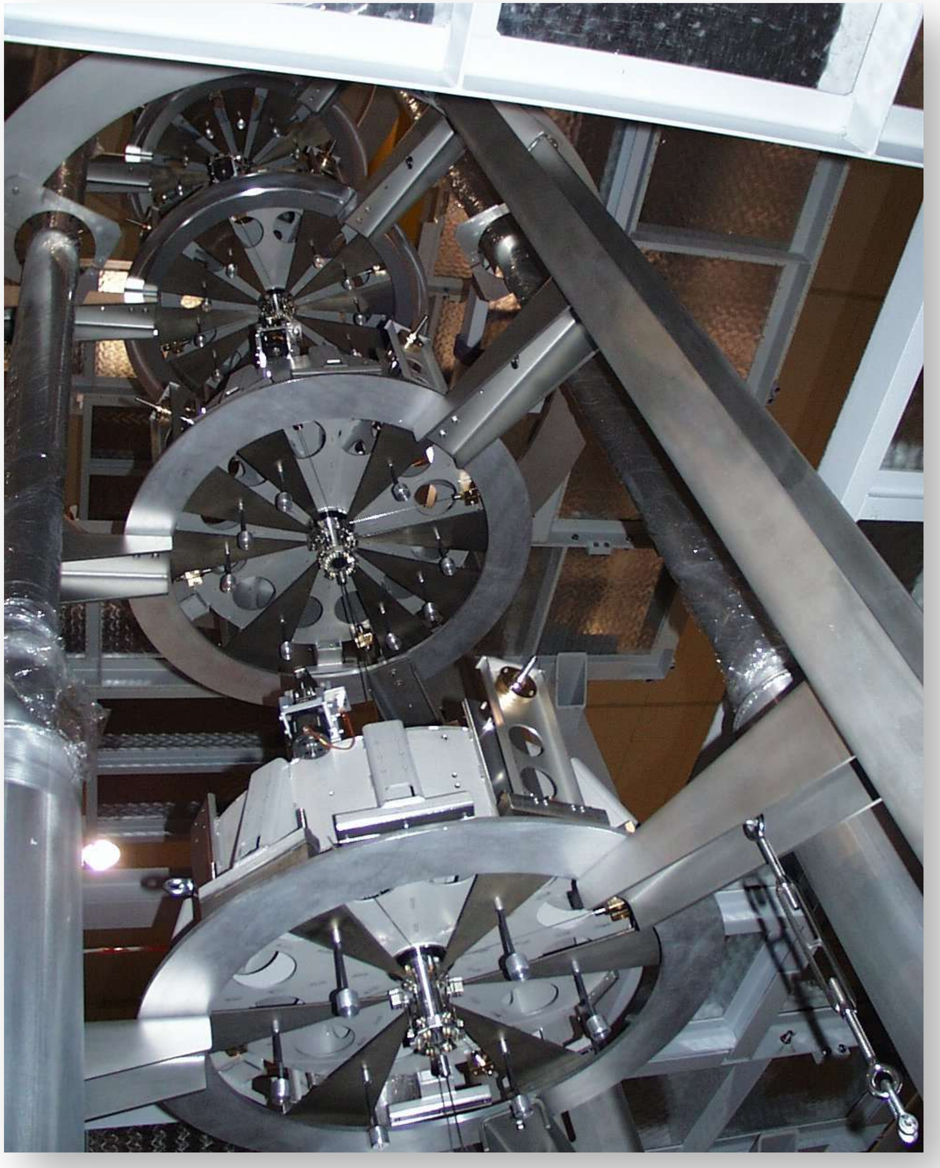
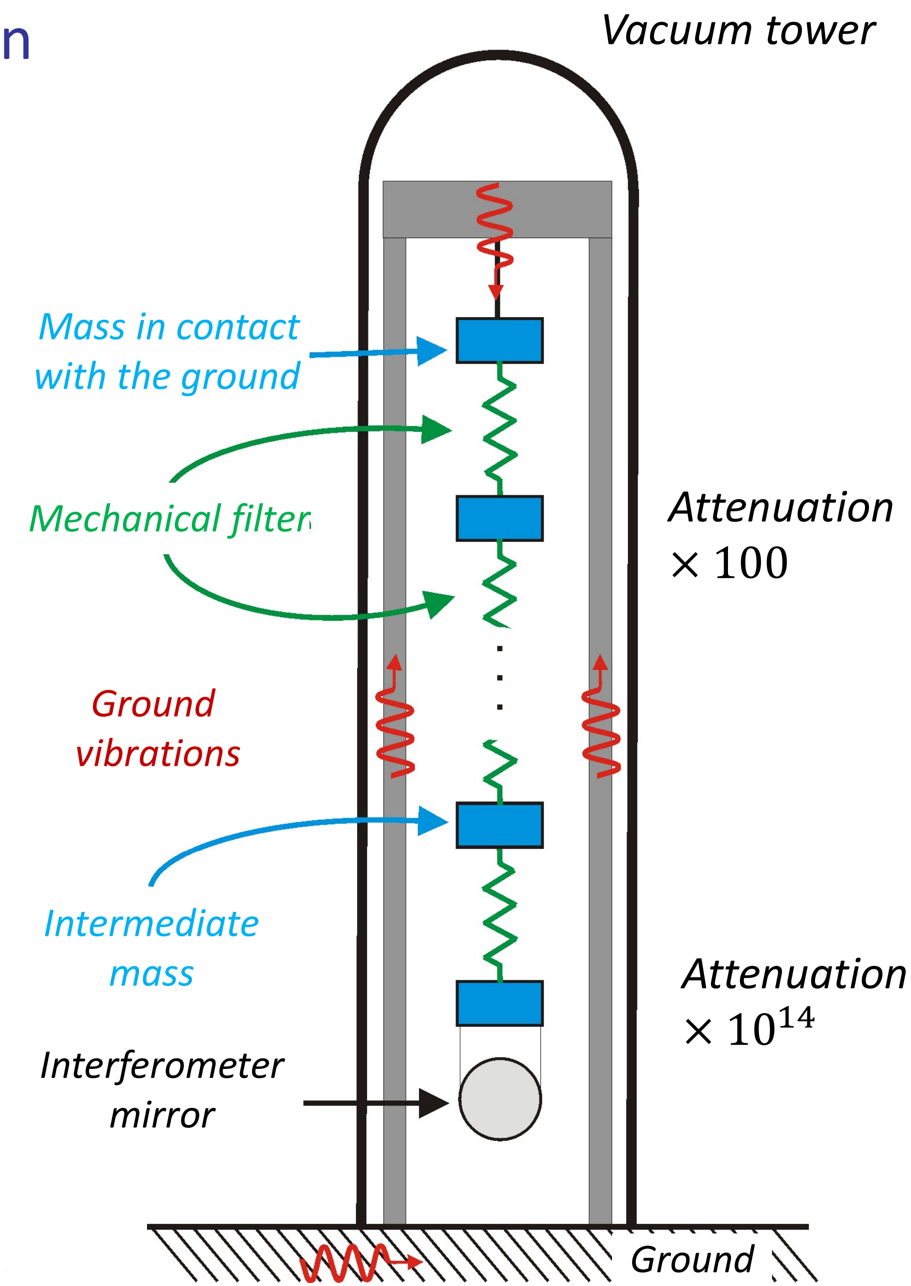
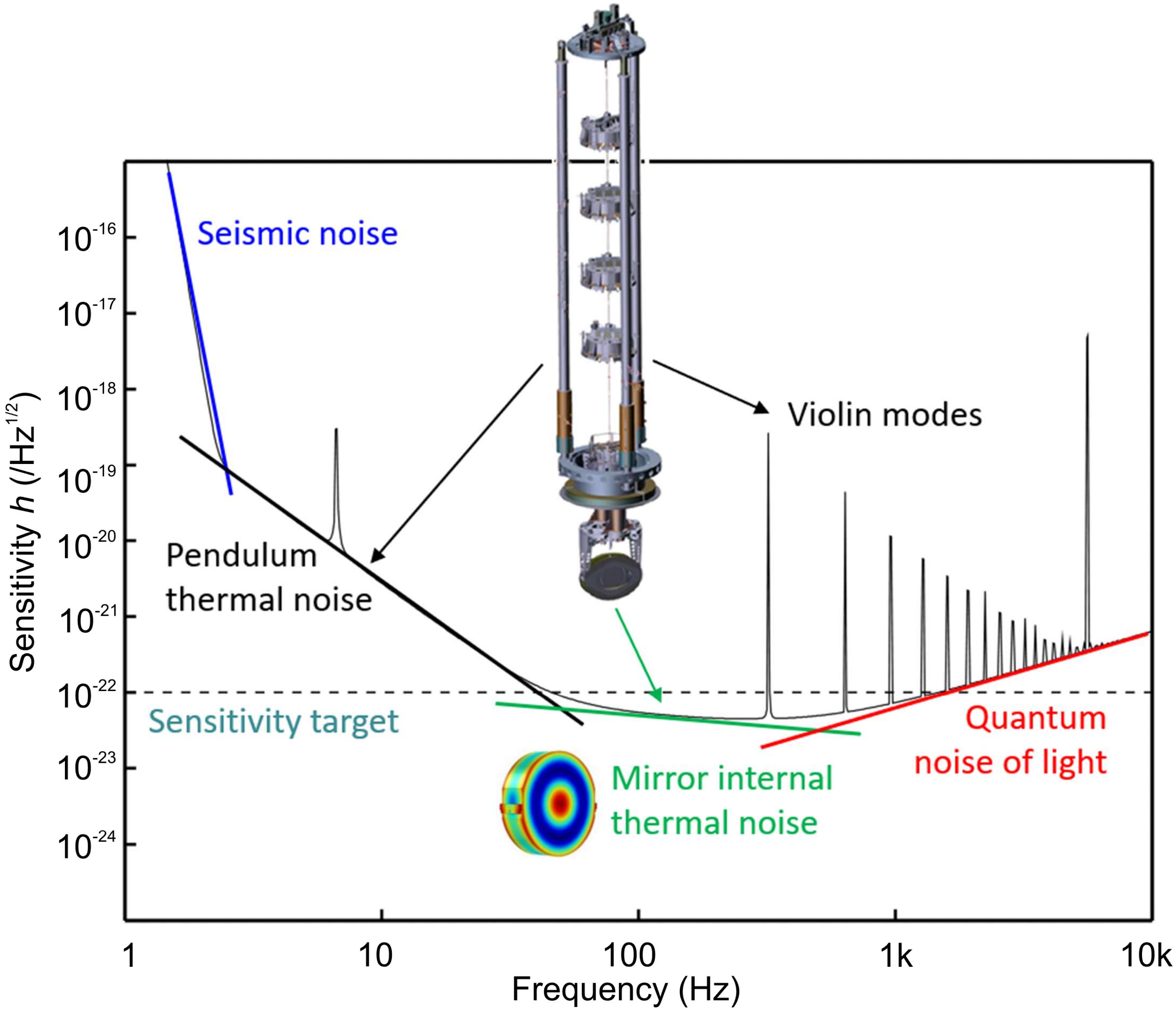
LIGO and Virgo interferometers

Very efficient seismic vibration isolation





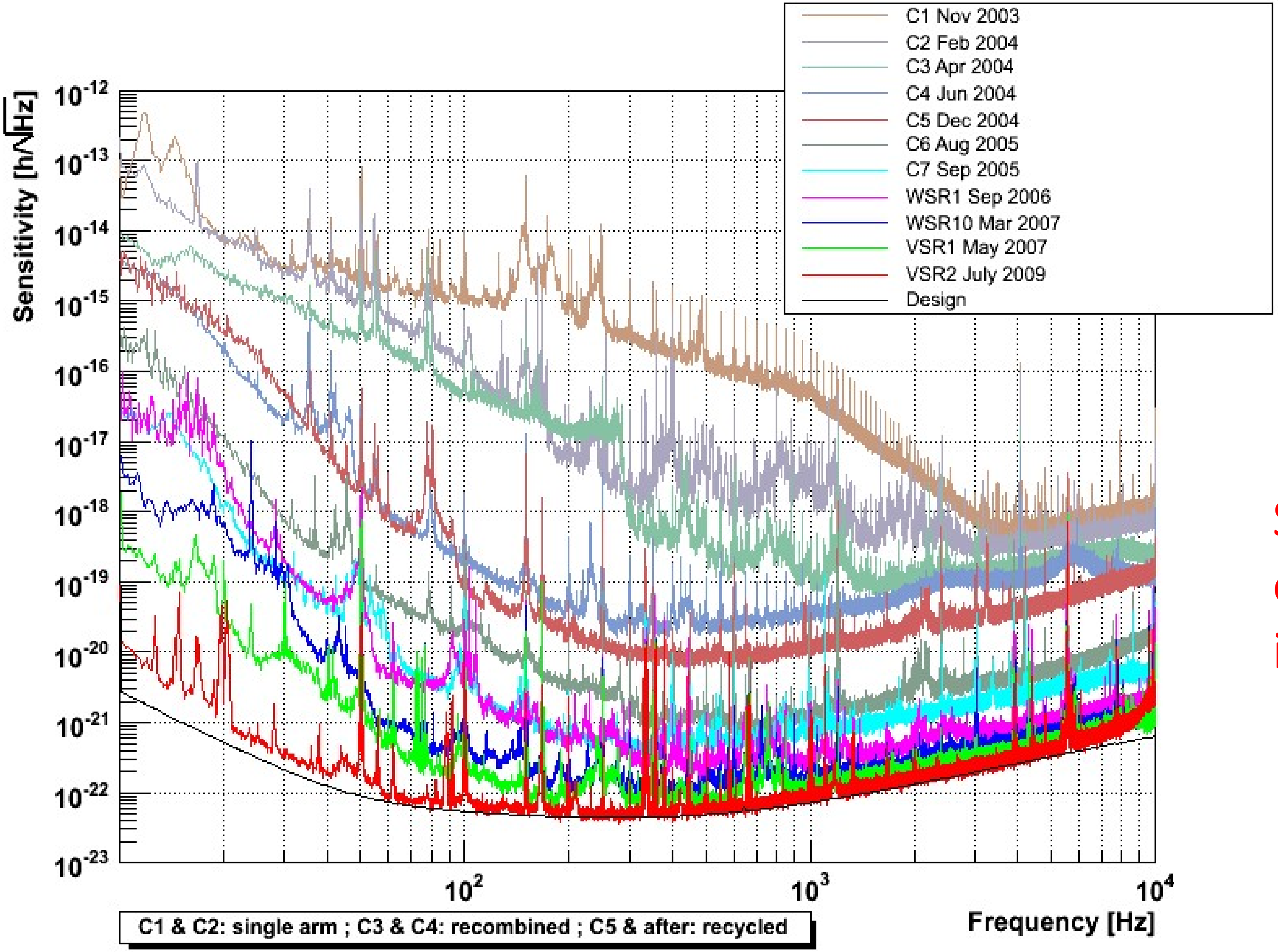
Sensitivity of Virgo 1 (2003 – 2010) (1)



Main noise sources:

- Mirror and suspension
- Attenuated seismic noise
- Quantum noise of light

Sensitivity of Virgo 1 (2003 – 2010) (2)

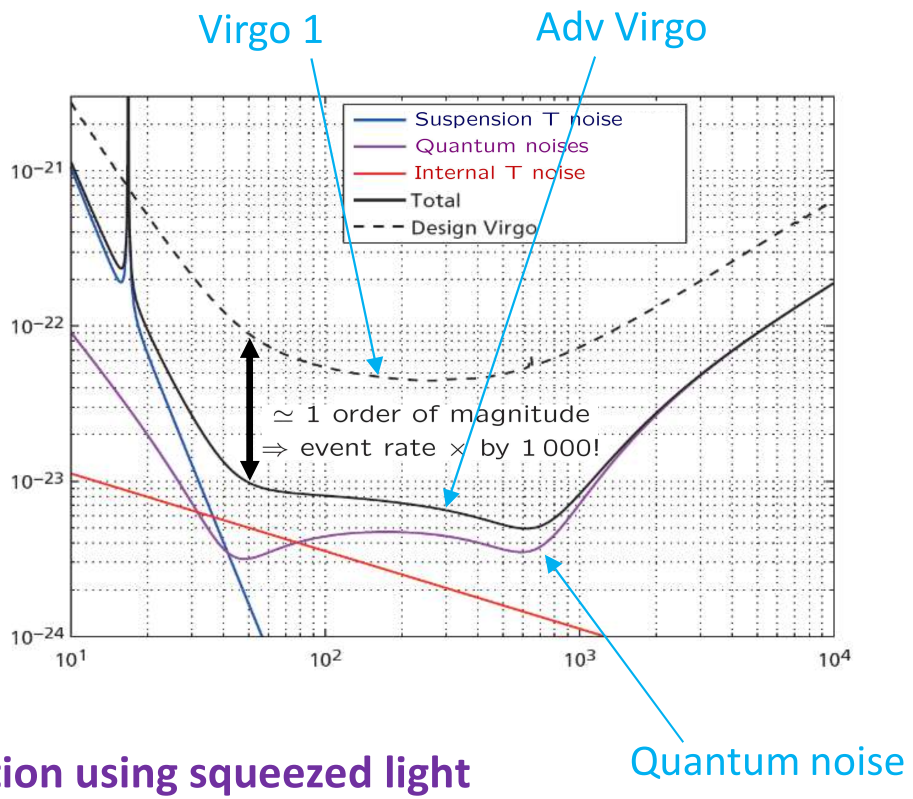


Seven years
of continuous
improvements!

A brief history of gravitational-wave detectors

- **1980 – early 2000s**: design, feasibility, construction of km-scale interferometers
- **2006 – 2011**: first science runs (initial LIGO and Virgo 1)

  (no detection)

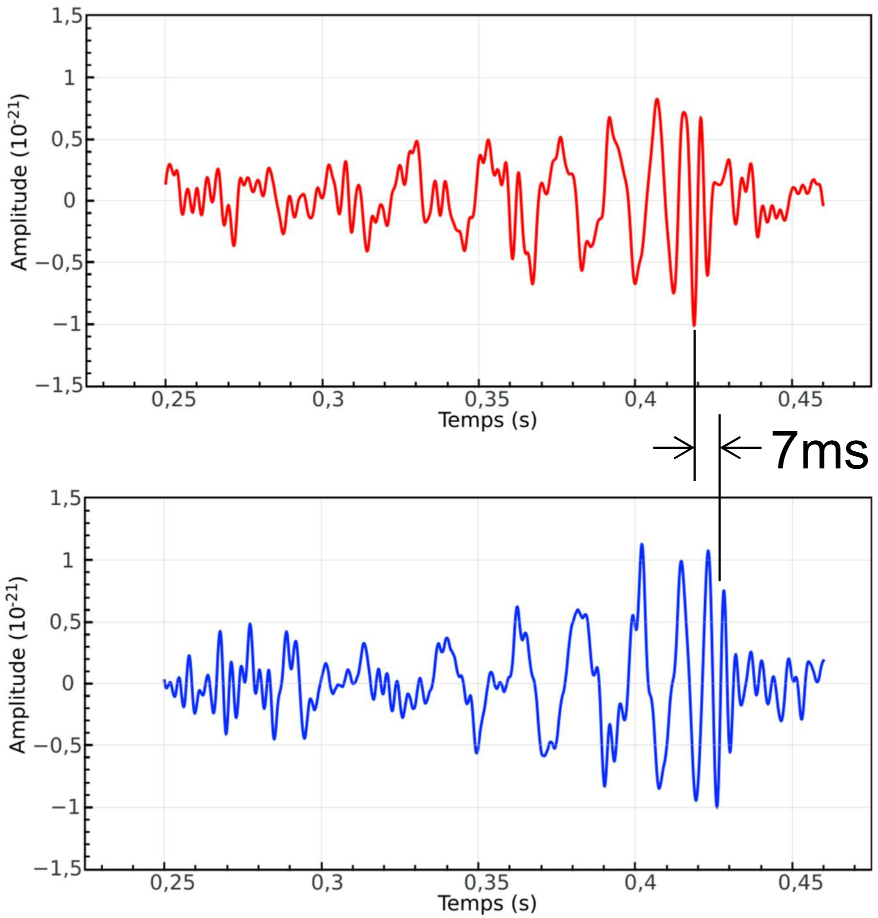


- **2012 – 2015**: construction of Advanced detectors

  (∼10× sensitivity improvement)
- **2015**: first direct detection of gravitational waves
- **2019 – 2020: run O3**, increasing detection rate, first population studies
- **Since 2019**: implementation of **quantum noise reduction using squeezed light**
- **2023 – 2025: run O4**, highest sensitivity and detection rate so far
- **Towards O5 (2027–)**: improved stability and **broadband quantum noise reduction**

First observation: September 14th, 2015

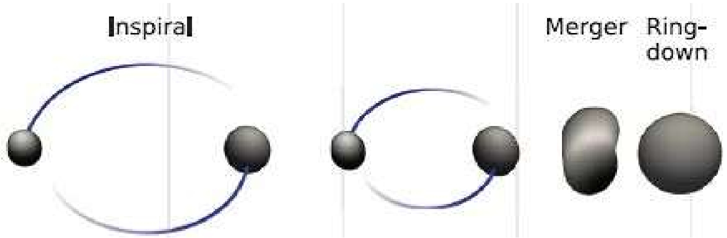
Signal observed on both LIGO detectors



LIGO Hanford
Washington

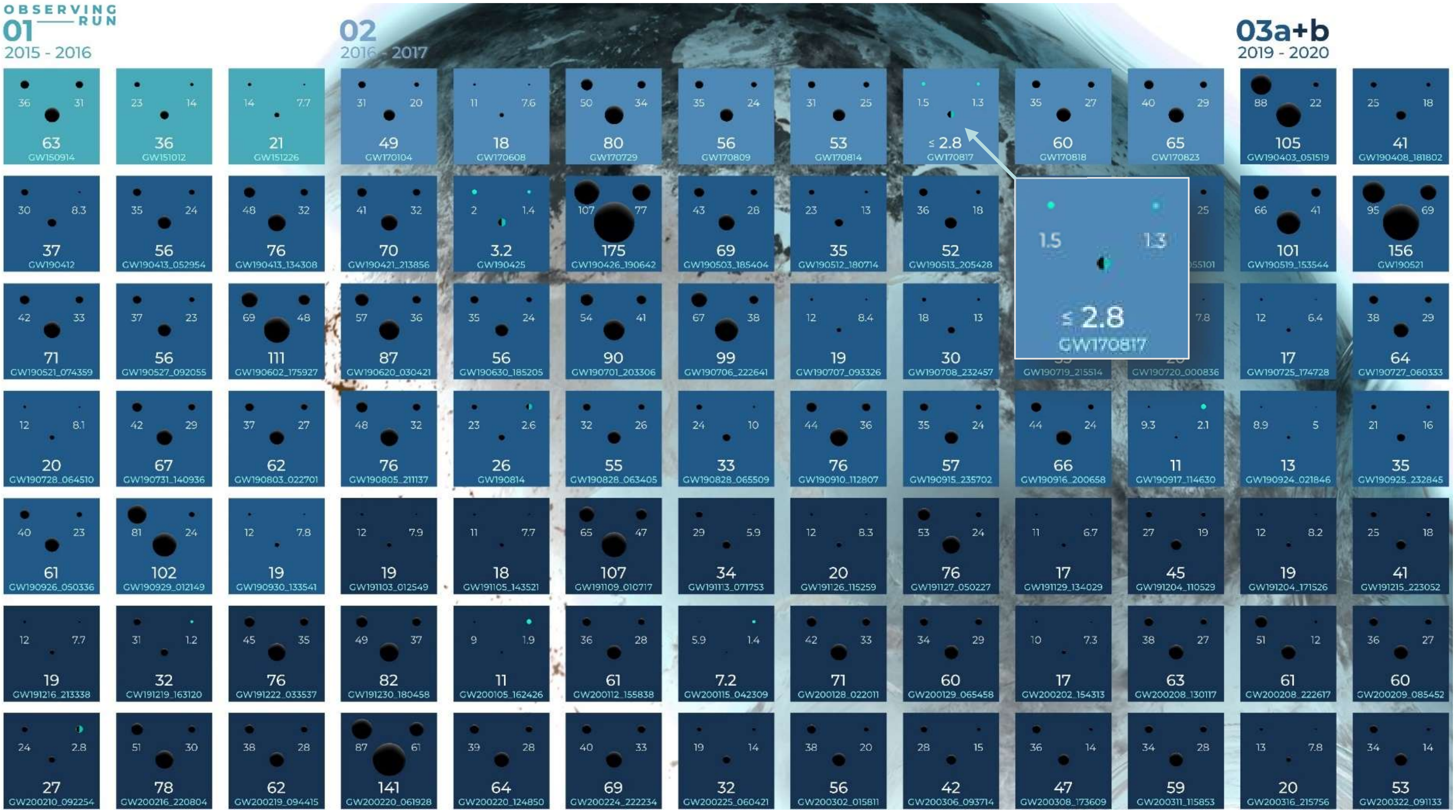
$\simeq 3,000$ km
(10 ms)

LIGO Livingston
Louisiana



Binary black hole merger of 30 $M_\odot$ at 400 Mpc!

Summary of the 90 detections (2015 to 2020)



90 events detected during runs O1 to O3

- Almost only binary black holes (BBH), way more than initially predicted!
- 2 binary neutron stars (BNS), including one with electromagnetic counterpart

→ *The beginning of a new era of gravitational-wave and multi-messenger astronomy!*

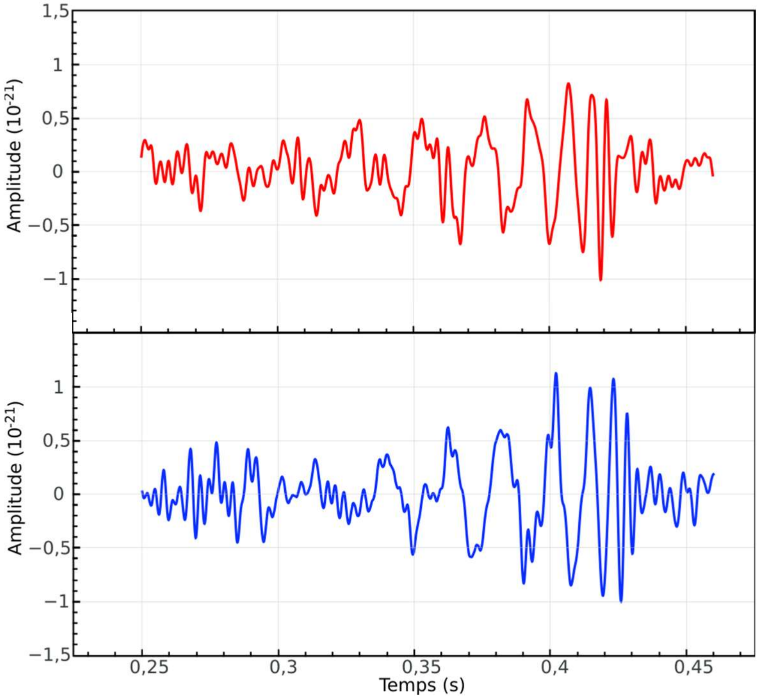
Ten years later: run O4 (2023-2025)

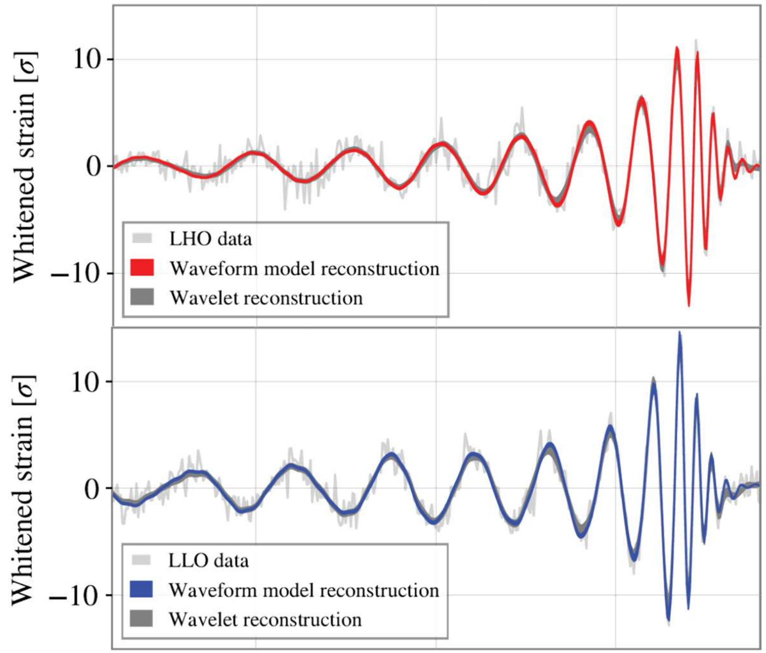
Drastic improvement in signal quality!

2015 (GW150914) → **2025** (GW250914)

LIGO Hanford Washington

LIGO Livingston Louisiana

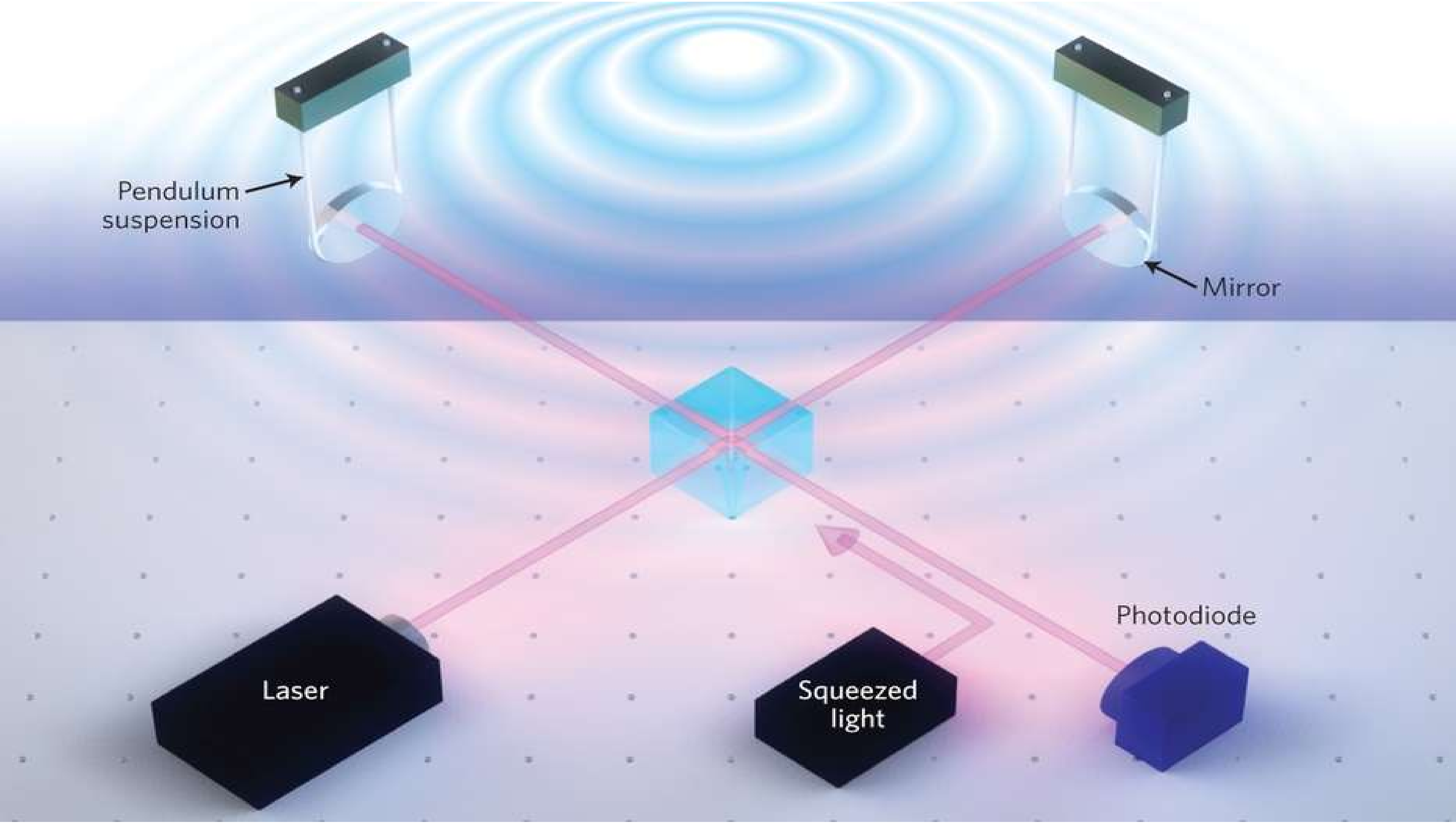




Main results:

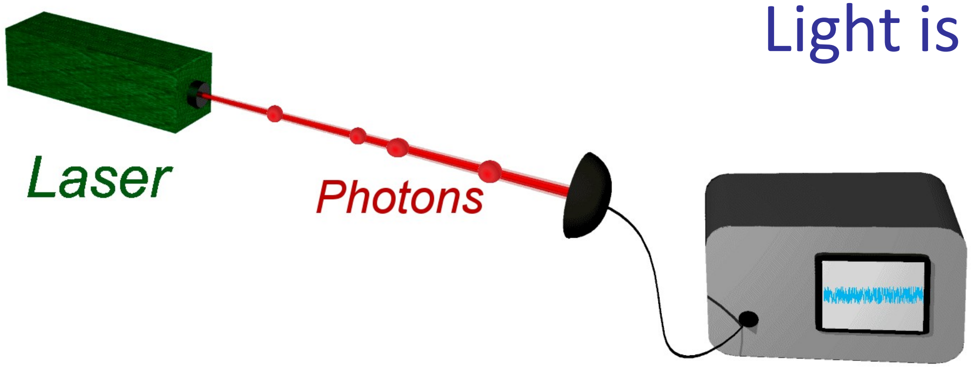
- The longest campaign (2½ years), 250 gravitational events observed
- Several rare astrophysical phenomena: very massive mergers (> 200 $M_\odot$), 2nd-generation mergers...
- In-depth tests of fundamental theory, in particular general relativity in highly nonlinear regimes (Stephen Hawking's black hole area theorem...)

Gravitational-wave detection



and quantum mechanics...

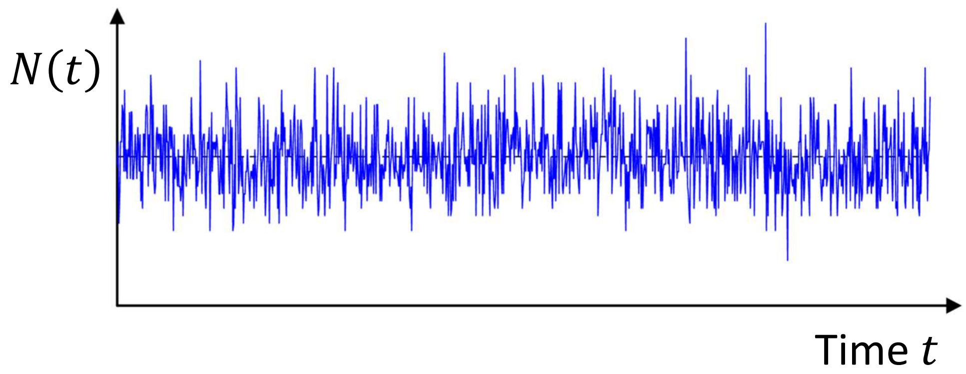
Quantum noise of light

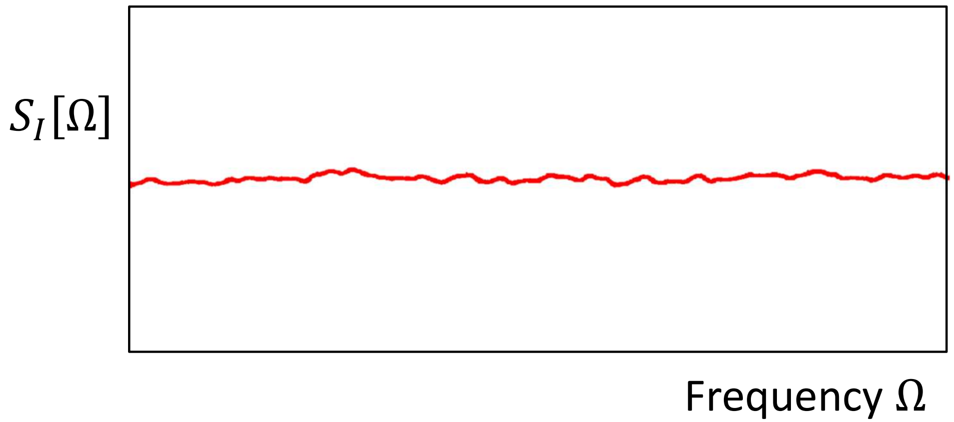


Light is subject to quantum fluctuations

Photons emitted by a laser have a random distribution in time:

Poisson distribution $\Delta N^2 = \bar{N}$ → Flat noise spectrum $S_I[\Omega] = \bar{I}$

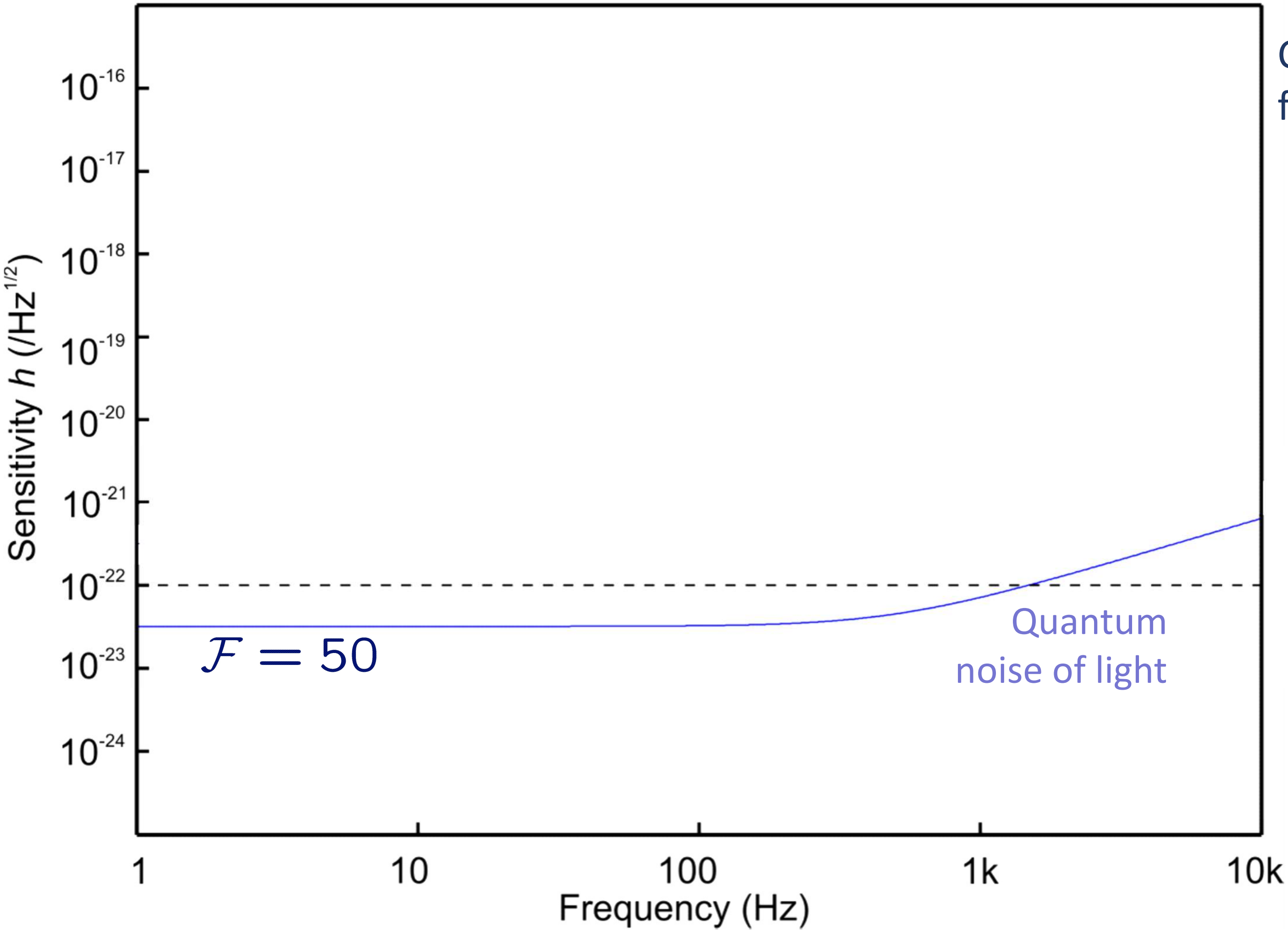




Quantum noise in gravitational-wave detectors (1)

Quantum limited sensitivity (cavity finesse $\mathcal{F}$ and bandwidth Ω_{cav}):

$$\delta I_{out}/\bar{I}_{in} \simeq \frac{\mathcal{F}L}{\lambda} \times \delta L/L \qquad \rightarrow \qquad h_{shot} \simeq \frac{\lambda}{\mathcal{F}L} \times \frac{1}{\sqrt{\bar{I}_{in}}} \times \sqrt{1+\left(\frac{\Omega}{\Omega_{cav}}\right)^2}$$

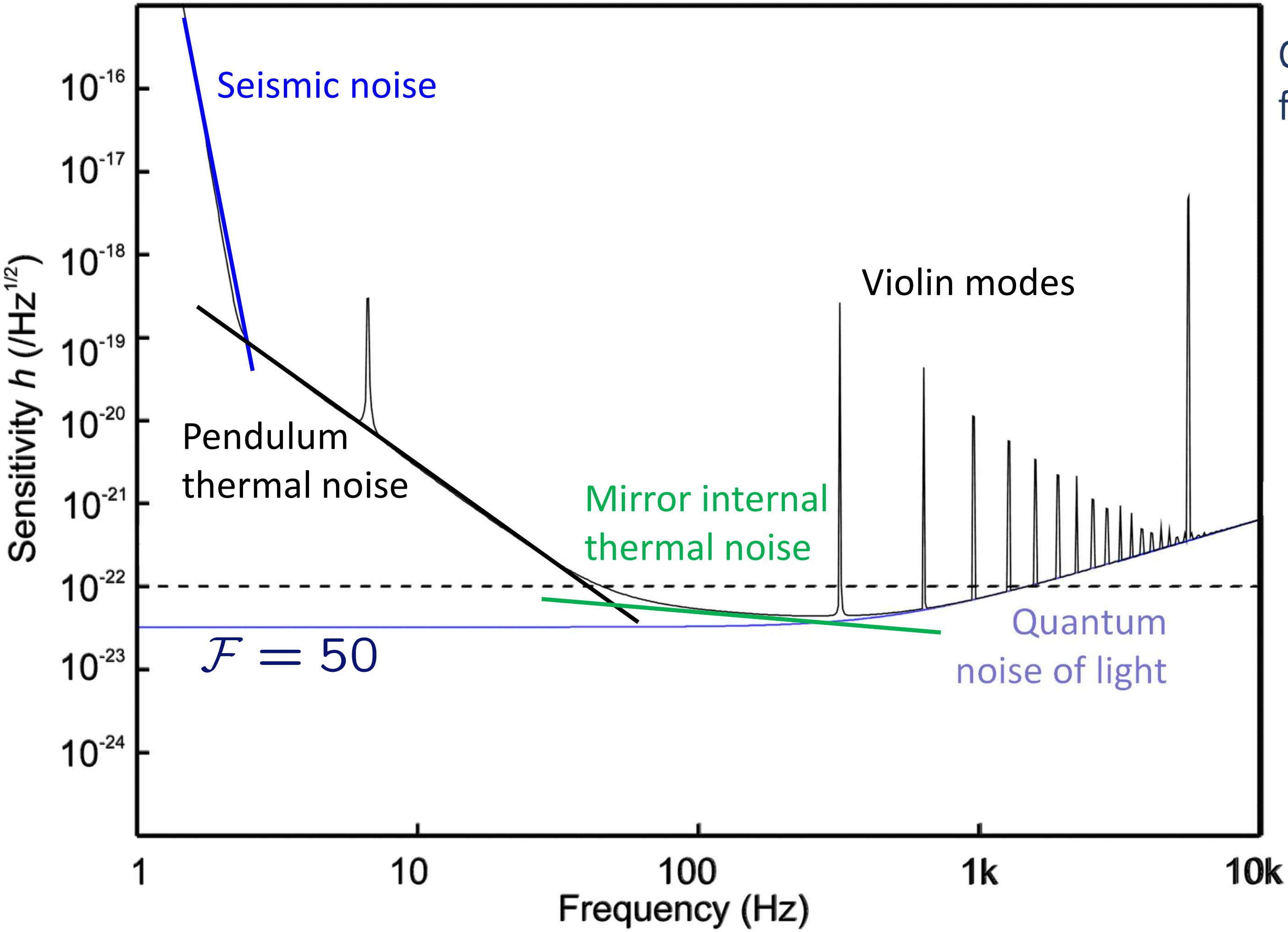


Computed for 1 kW

Quantum noise in gravitational-wave detectors (2)

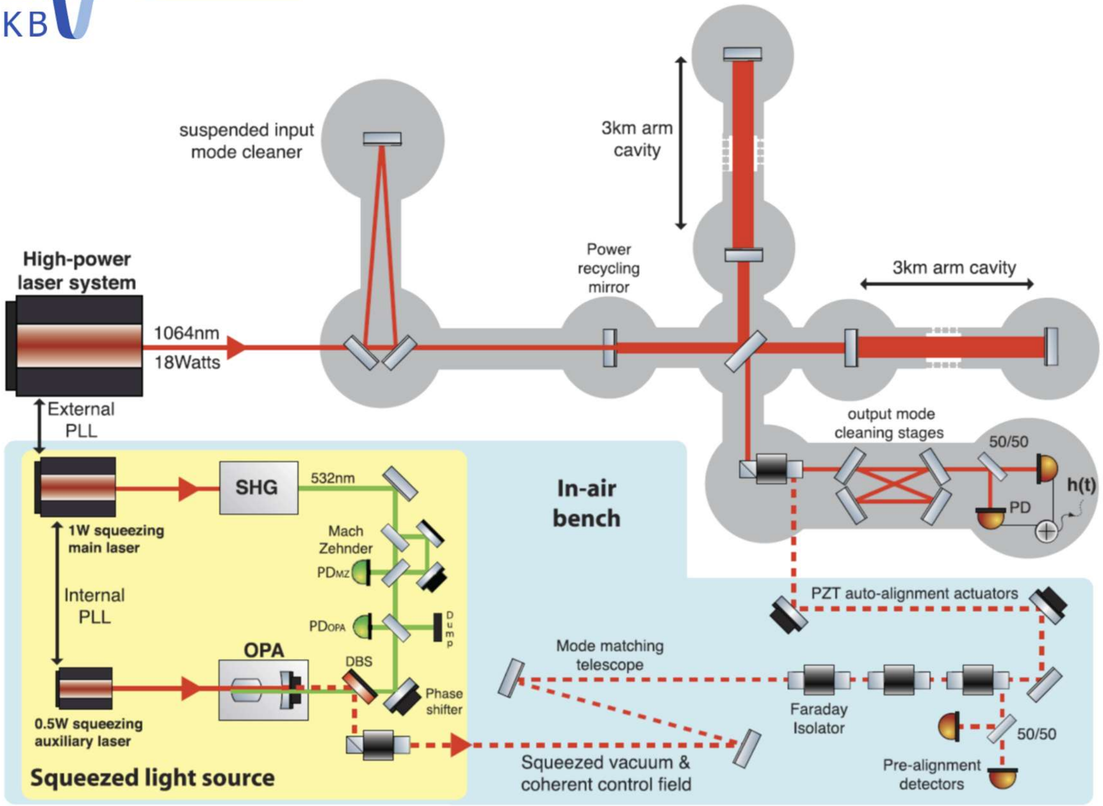
Quantum limited sensitivity (cavity finesse $\mathcal{F}$ and bandwidth Ω_{cav}):

$$\delta I_{out}/\bar{I}_{in} \simeq \frac{\mathcal{F}L}{\lambda} \times \delta L/L \qquad \rightarrow \qquad h_{shot} \simeq \frac{\lambda}{\mathcal{F}L} \times \frac{1}{\sqrt{\bar{I}_{in}}} \times \sqrt{1 + \left(\frac{\Omega}{\Omega_{cav}}\right)^2}$$



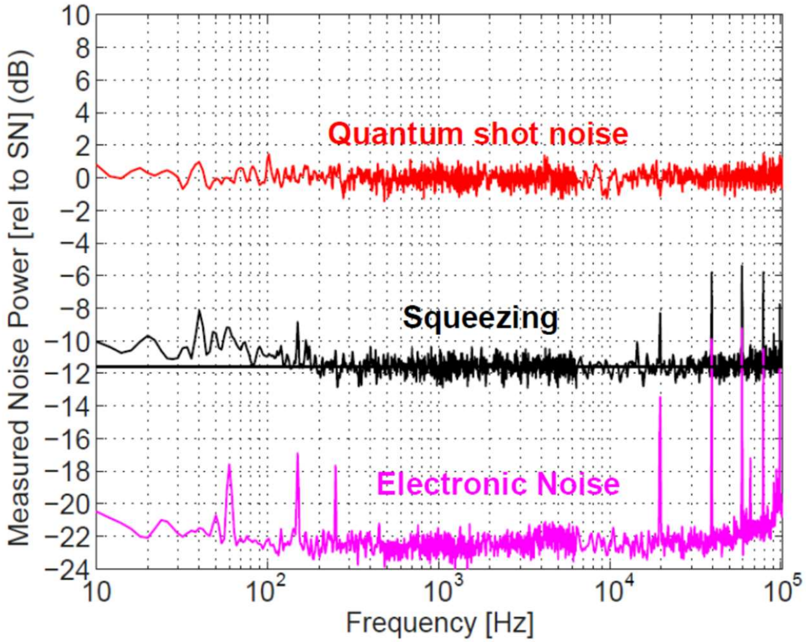
Computed for 1 kW

Squeezing in Advanced Virgo (2019) (1)

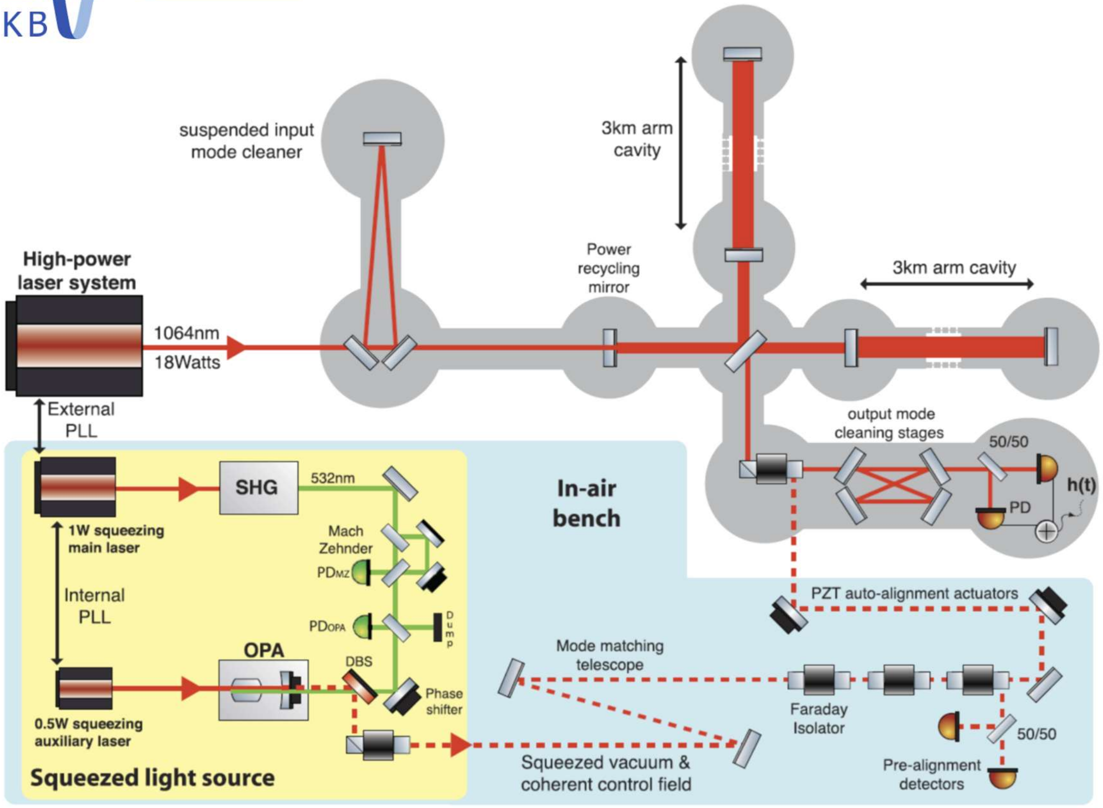


Injection of a squeezed state via the output port:

- Improved squeezer: 10 dB in the audio band (10 Hz – 100 kHz)



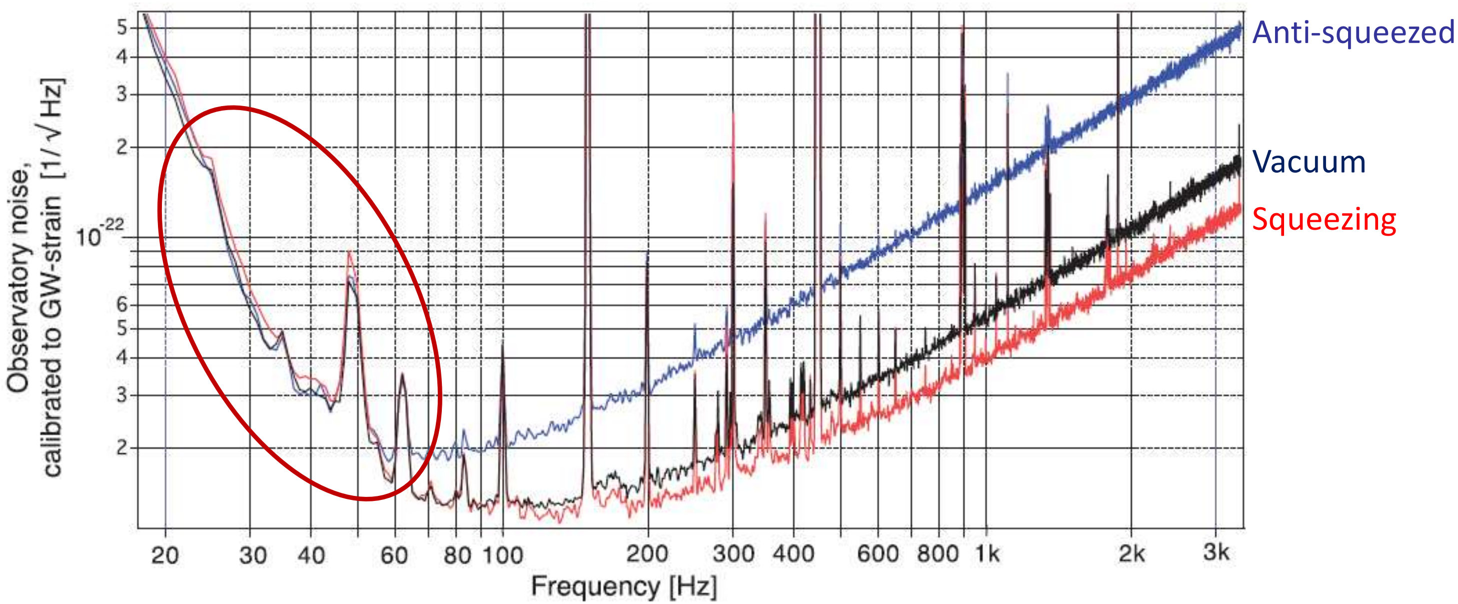
Squeezing in Advanced Virgo (2019) (2)



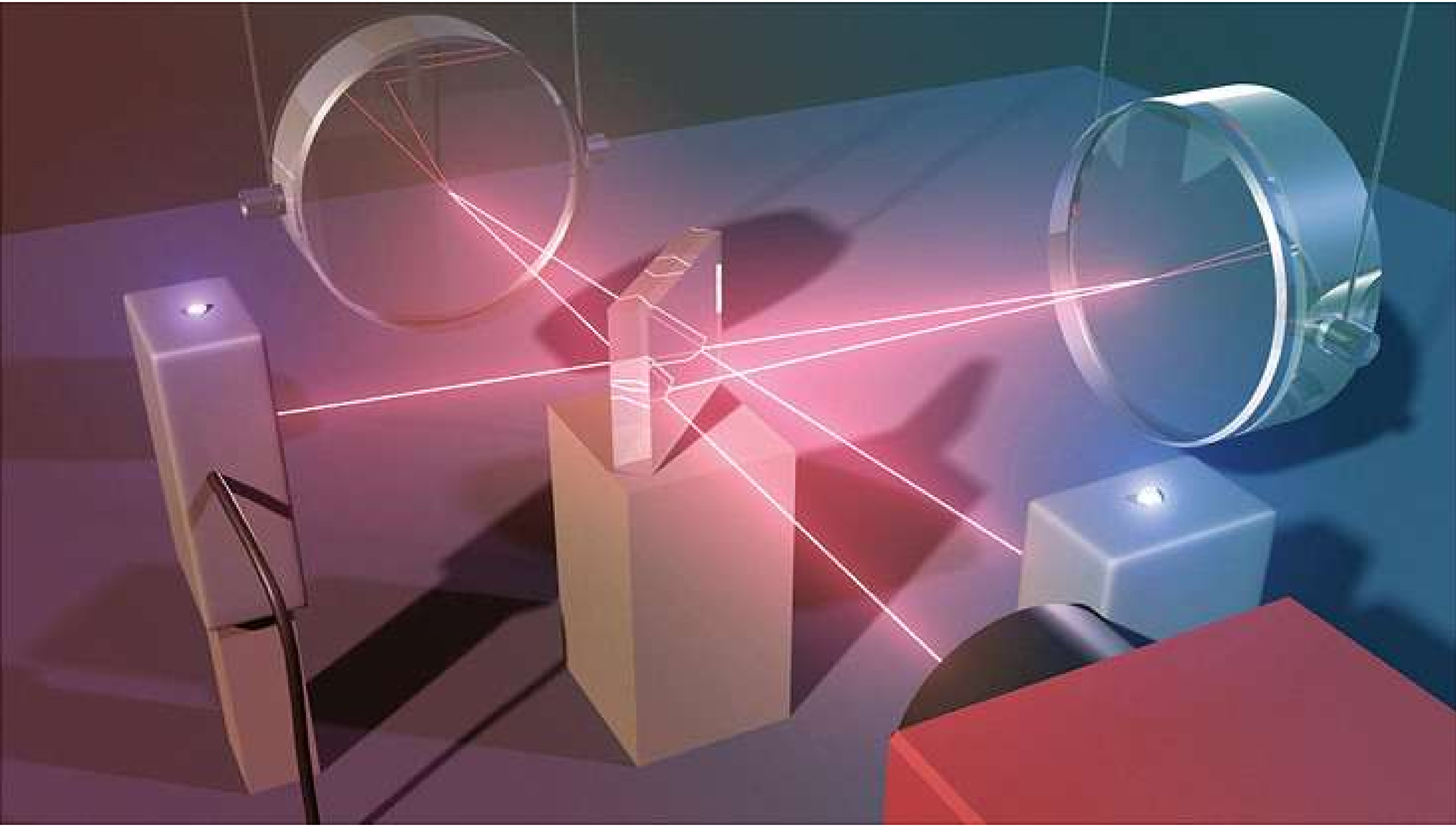
Injection of a squeezed state via the output port:

- Improved squeezer: 10 dB in the audio band (10 Hz – 100 kHz)
- Squeezing increases sensitivity by **3 dB at high frequency**
- Gain limited by **optical losses** (between 30 and 40%)

Phys. Rev. Lett. ***123****, 231108 (2019)*

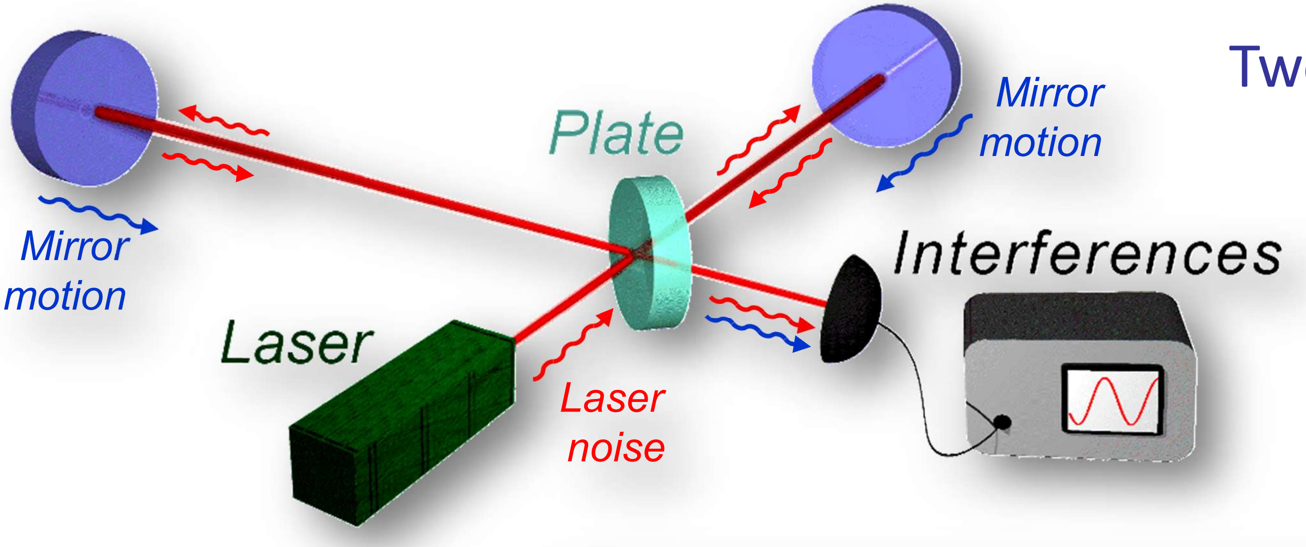


Quantum



radiation pressure

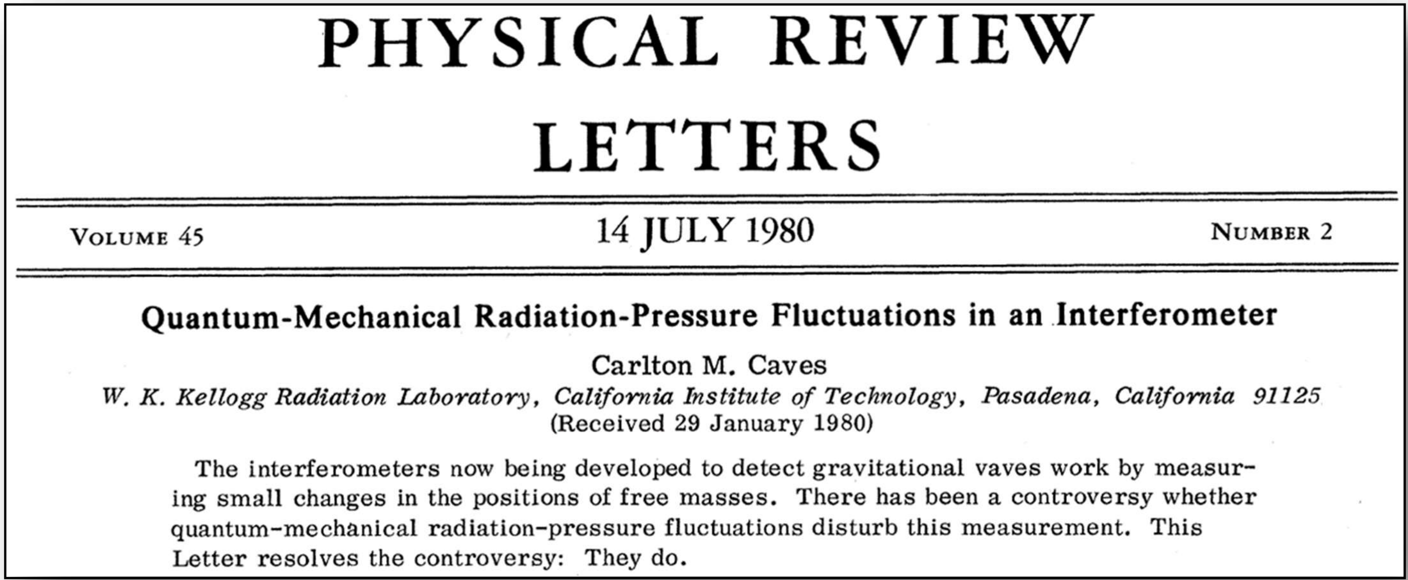
Quantum noises in interferometric measurements



Two conjugate quantum noises:

- Laser noise (shot noise)
- Mirror motion due to radiation pressure

First studies in the 80's



PHYSICAL REVIEW LETTERS

VOLUME 45 14 JULY 1980 NUMBER 2

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

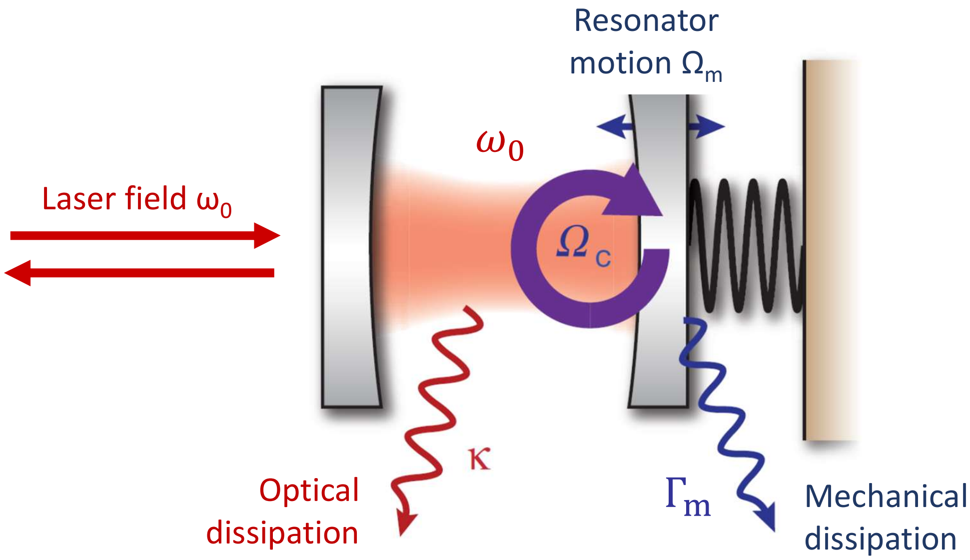
Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

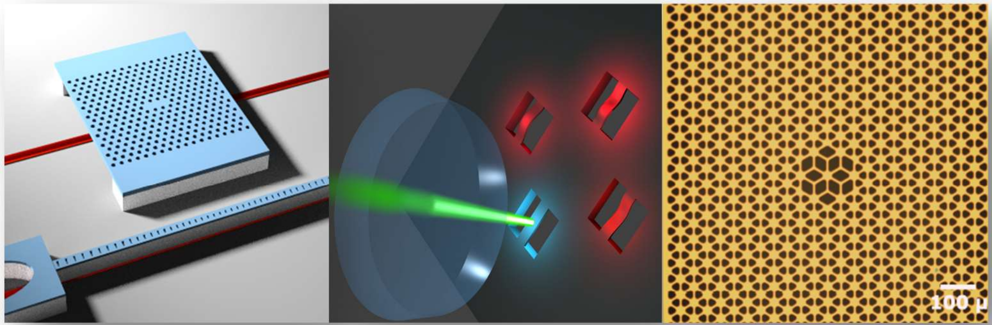
→ Has motivated the emergence of quantum optics in the 80's and of quantum optomechanics in the 90's

Quantum optomechanics

Optomechanics deals with the coupling between **mechanical motion** and **light** through **radiation pressure**



- **Quantum limits** in displacement measurements
  - Gravitational-wave interferometers
  - New miniaturized sensors
- **Quantum physics** of massive and macroscopic objects
  - Laser cooling
  - Frontier between classical and quantum worlds

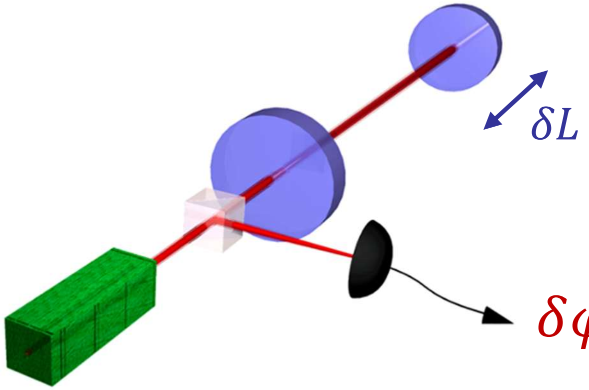


Philippe Tourrenc Alain Brillet Serge Reynaud

In France, fruitful exchanges with the gravitational-wave community

- Many discussions and meetings since the 80's *(GdR GREX)*

Quantum noises in a displacement sensor (1)



Reflected phase of a single cavity

(~1 arm of an interferometer)

$$\delta\varphi_{out} \simeq \delta\varphi_{in} + \frac{\mathcal{F}}{\lambda}(\delta L + \delta x_{rad})$$

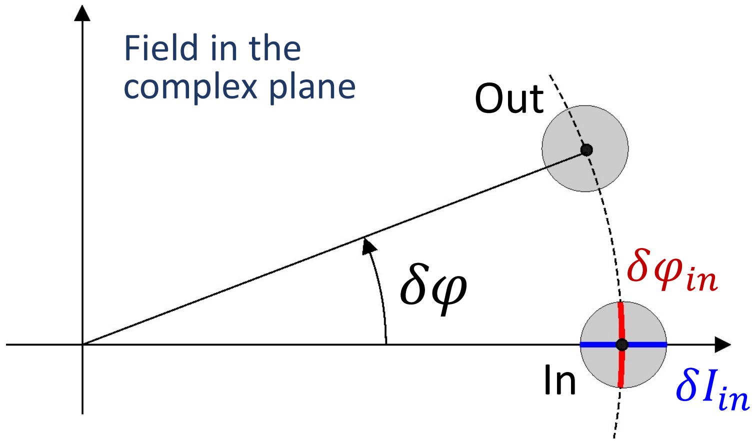
Input phase noise

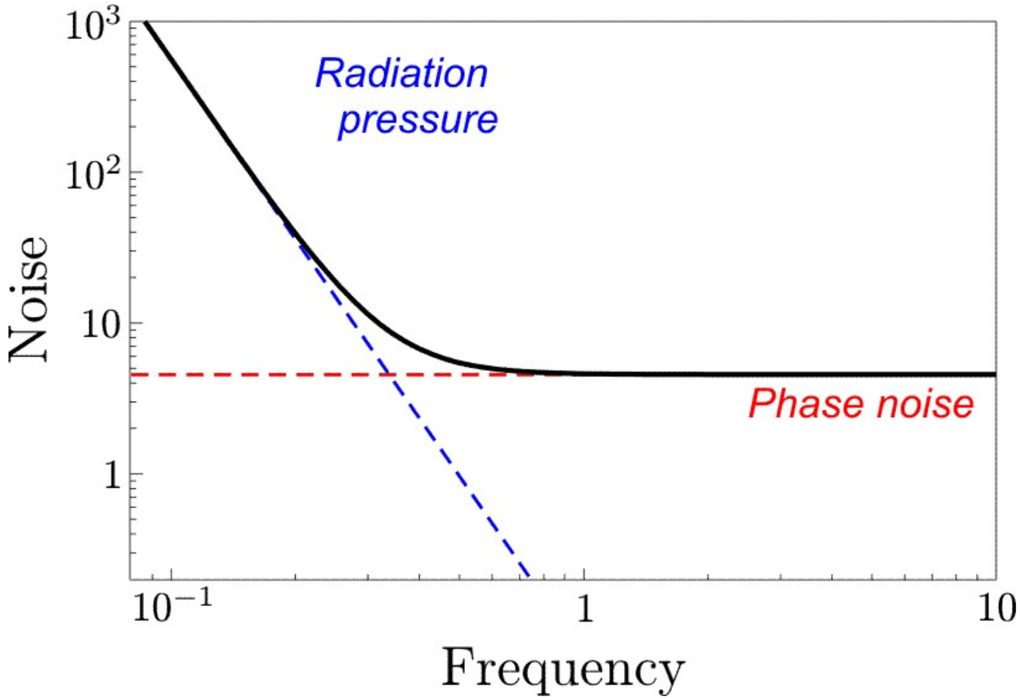
Signal

Radiation pressure:

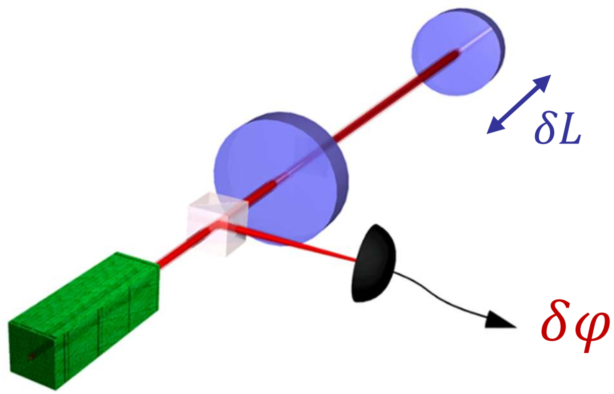
$\delta x_{rad} = \chi[\Omega]\ \delta I[\Omega]$

($\chi[\Omega]$: mechanical response)





Quantum noises in a displacement sensor (2)

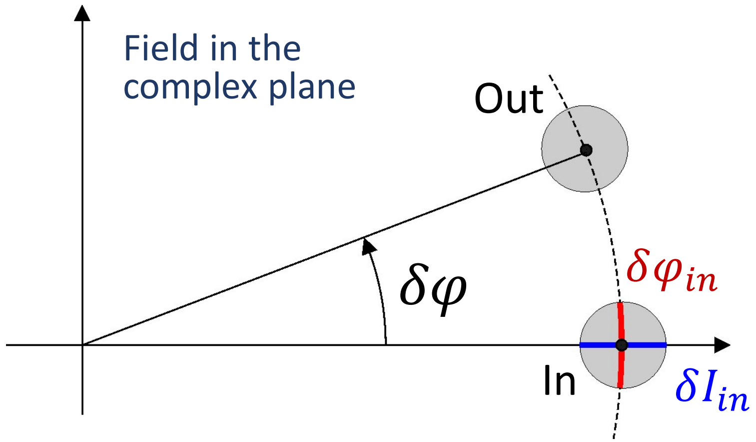


Reflected phase of a single cavity
(~1 arm of an interferometer)

$$\delta\varphi_{out} \simeq \delta\varphi_{in} + \frac{\mathcal{F}}{\lambda}(\delta L + \delta x_{rad})$$

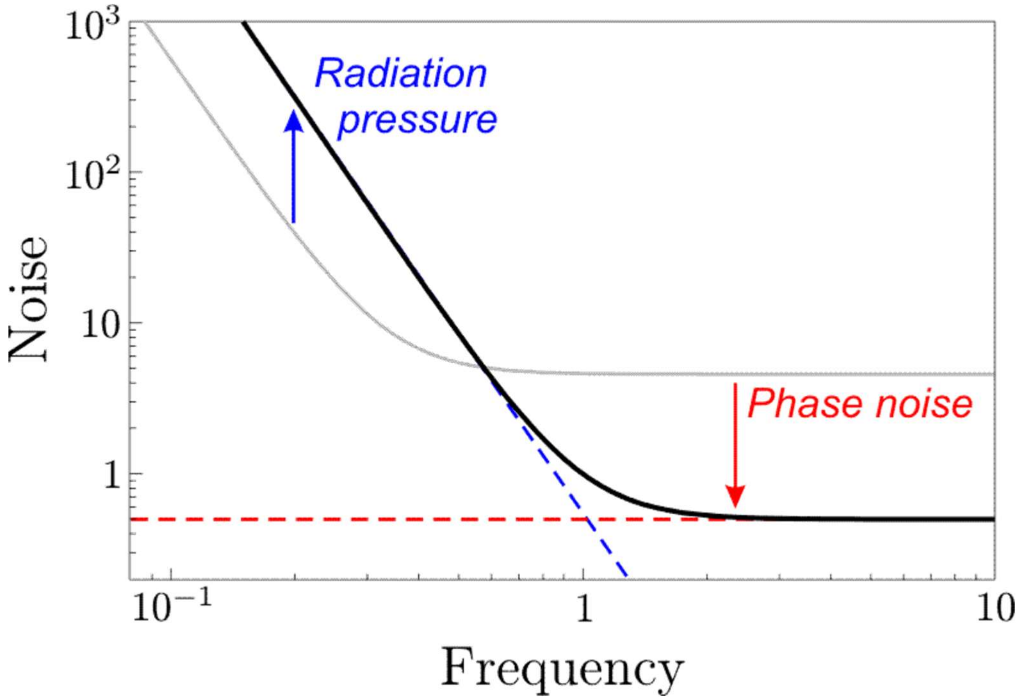
Input phase noise — Signal

Radiation pressure:
$\delta x_{rad} = \chi[\Omega]\ \delta I[\Omega]$
($\chi[\Omega]$: mechanical response)

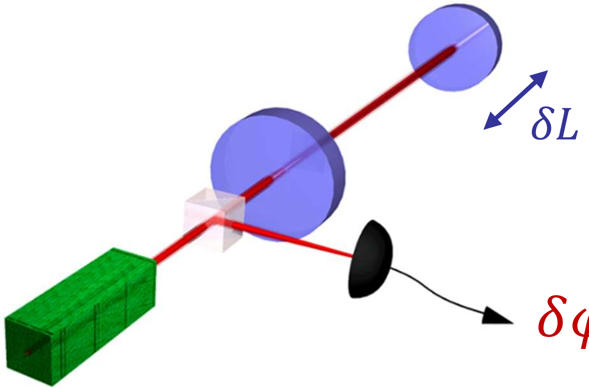


- Intensity increase:

$$\delta\varphi_{in} \propto 1/\sqrt{\bar{I}_{in}}\ ,\ \delta x_{rad} \propto \sqrt{\bar{I}_{in}}$$



Quantum noises in a displacement sensor (3)



Reflected phase of a single cavity

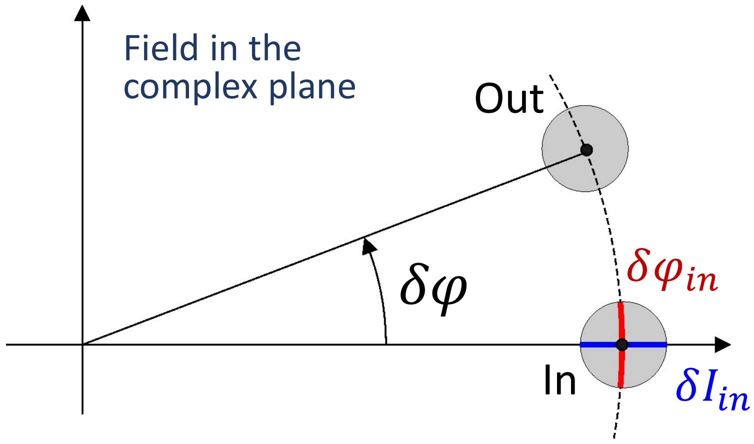
(~1 arm of an interferometer)

$$\delta\varphi_{out} \simeq \delta\varphi_{in} + \frac{\mathcal{F}}{\lambda}(\delta L + \delta x_{rad})$$

Input phase noise

Signal

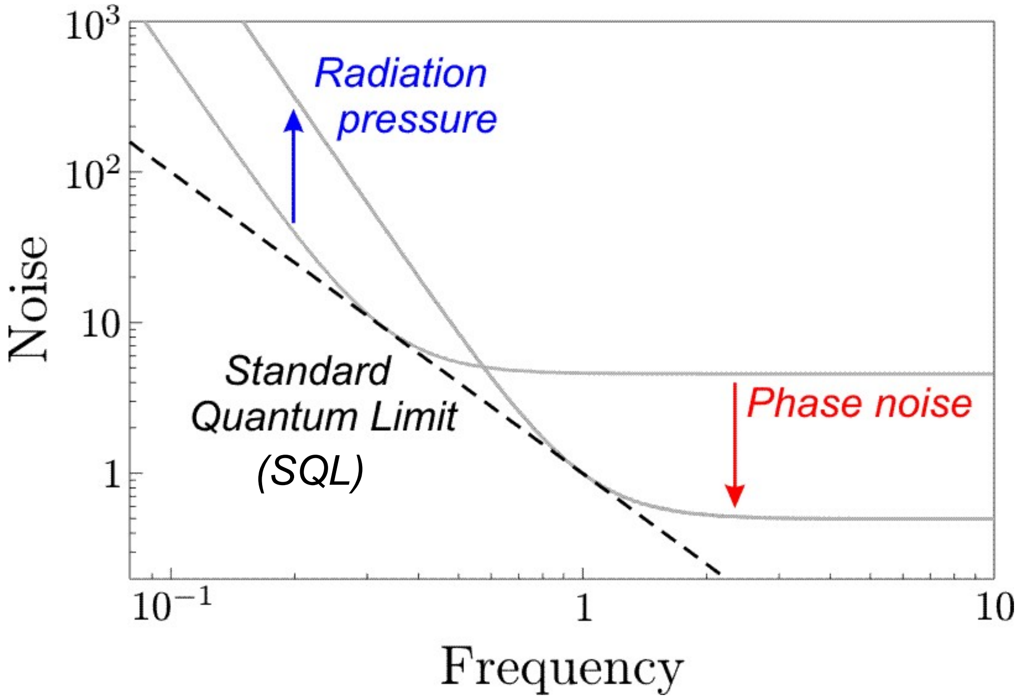
Radiation pressure:
$\delta x_{rad} = \chi[\Omega]\, \delta I[\Omega]$
($\chi[\Omega]$: mechanical response)



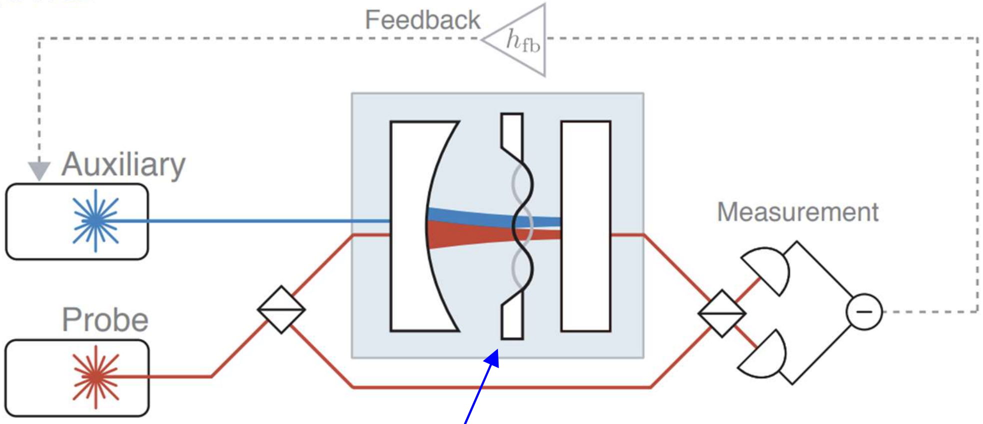
- Intensity increase:

$$\delta\varphi_{in} \propto 1/\sqrt{\bar{I}_{in}}\ ,\ \delta x_{rad} \propto \sqrt{\bar{I}_{in}}$$

➙ Standard quantum limit (SQL)

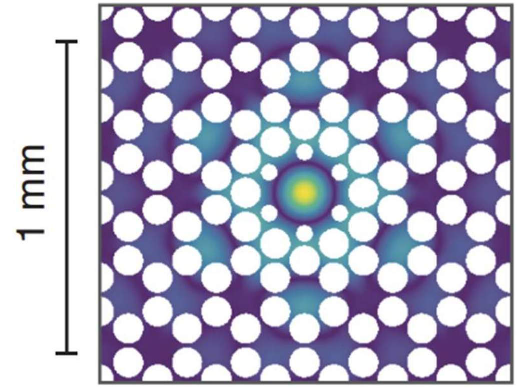


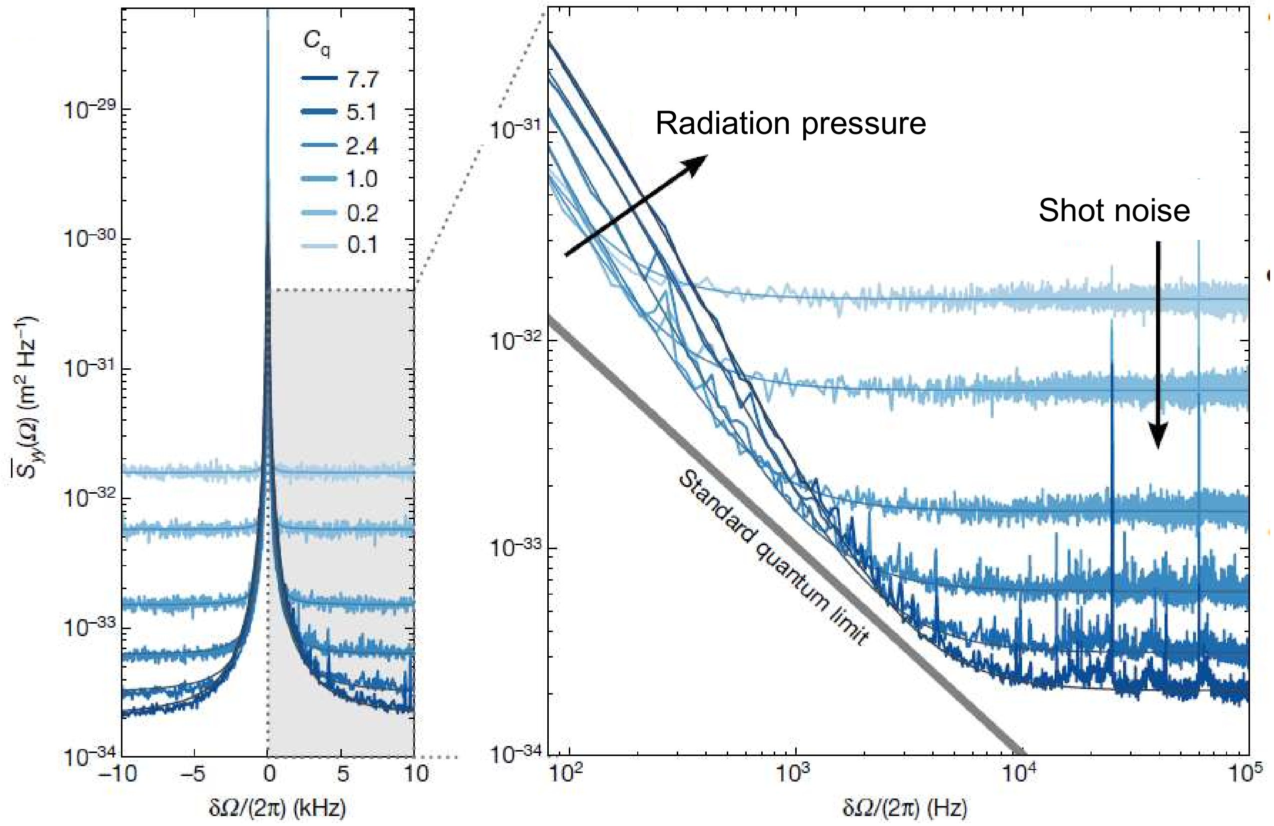
Demonstration of SQL with an optomechanical device



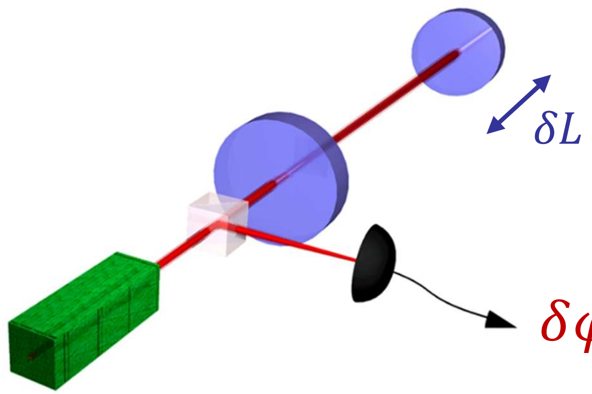
Very thin and light mechanical membrane in a high-finesse cavity

A. Schliesser, Nature (2018)





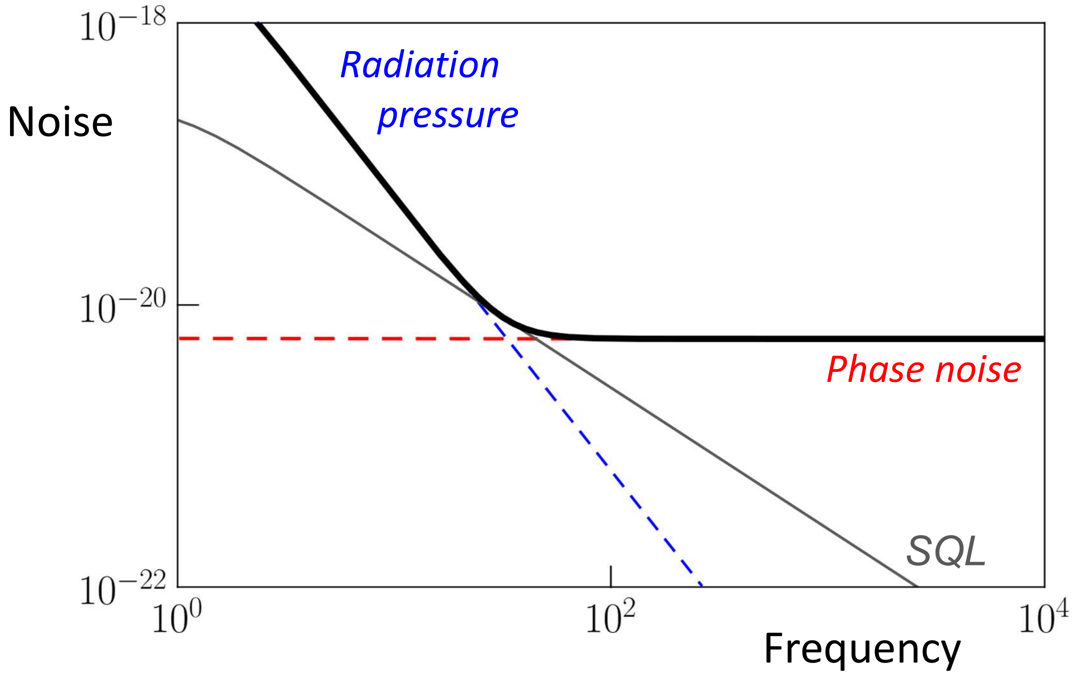
Beyond the SQL with squeezed states (1)



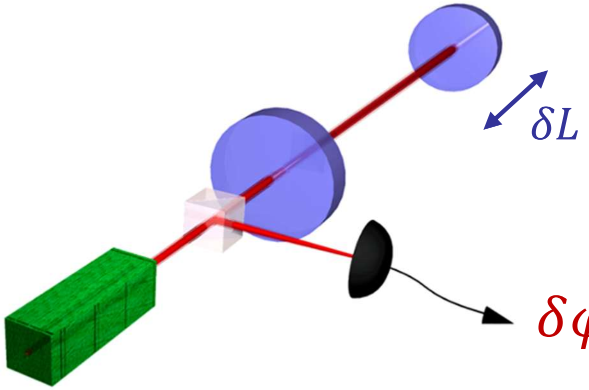
Input phase noise

Radiation pressure

$$\delta\varphi_{out} \simeq \delta\varphi_{in} + \frac{\mathcal{F}}{\lambda}(\delta L + \delta x_{rad})$$



Beyond the SQL with squeezed states (2)

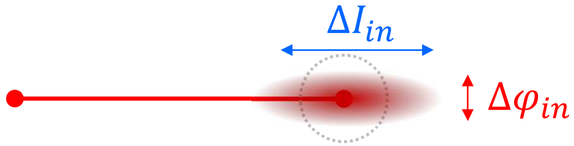


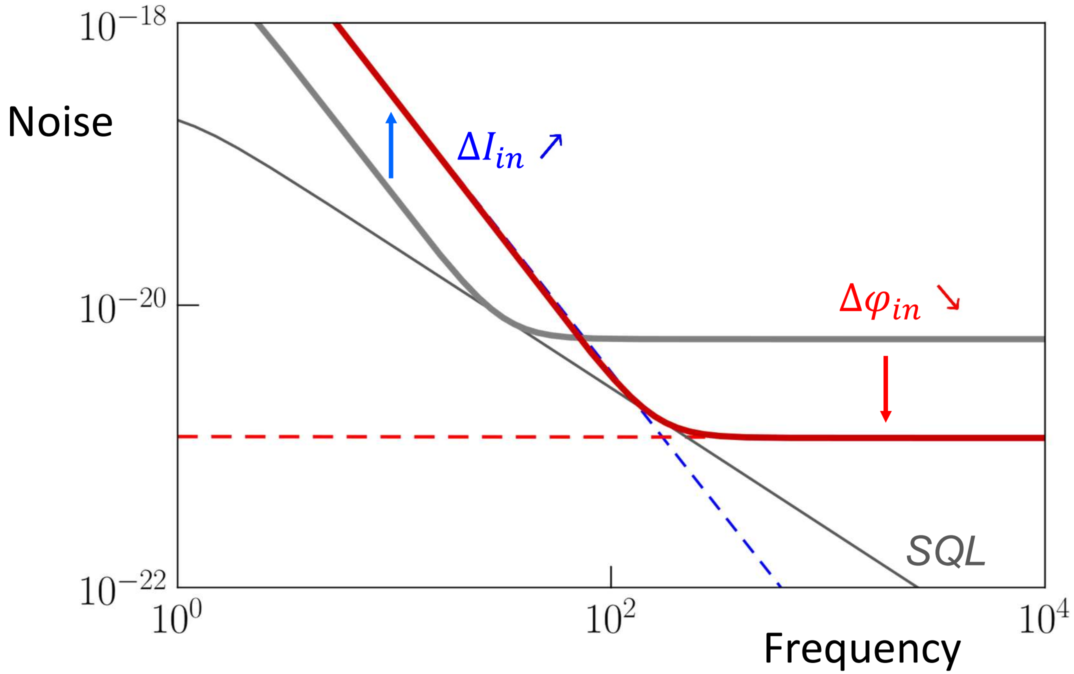
Input phase noise → $\delta\varphi_{in}$

Radiation pressure → δx_{rad}

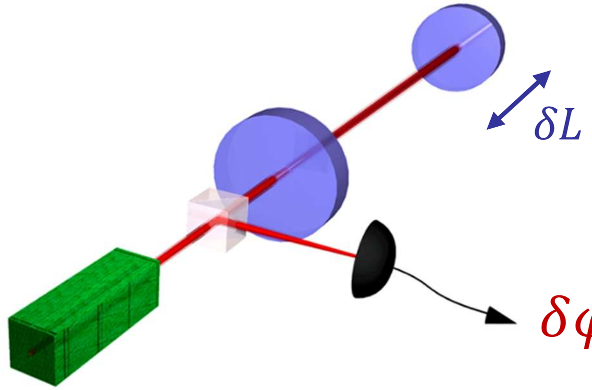
$$\delta\varphi_{out} \simeq \delta\varphi_{in} + \frac{\mathcal{F}}{\lambda}(\delta L + \delta x_{rad})$$

- A phase squeezed state reduces the phase noise at the expense of radiation pressure noise





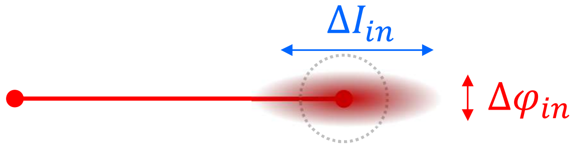
Beyond the SQL with squeezed states (3)

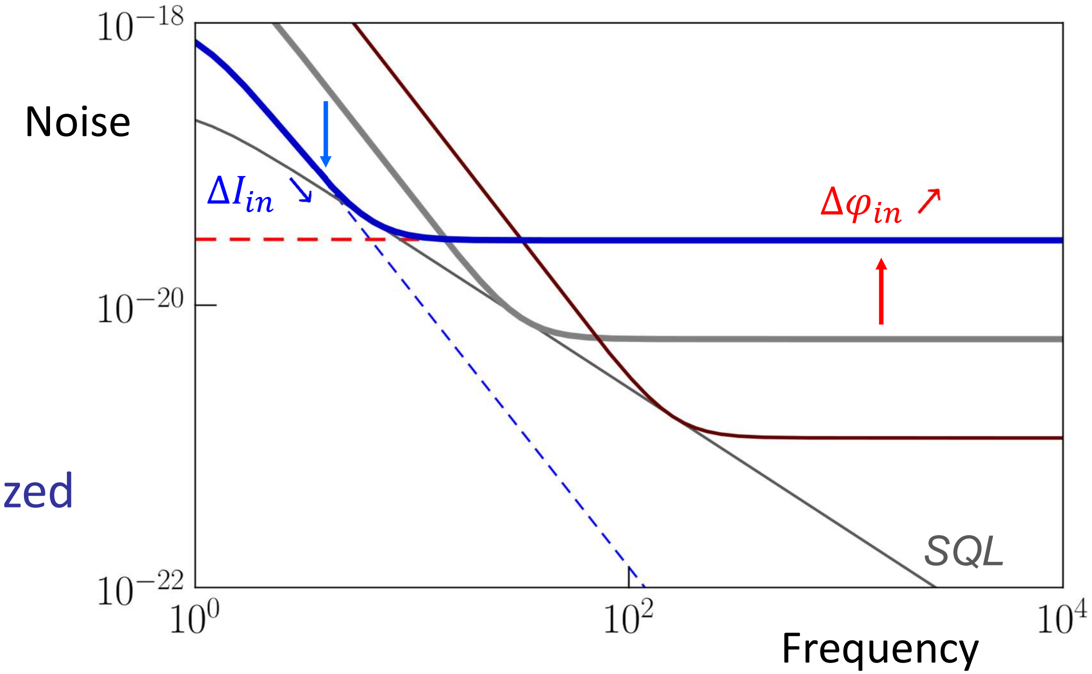


Input phase noise — Radiation pressure

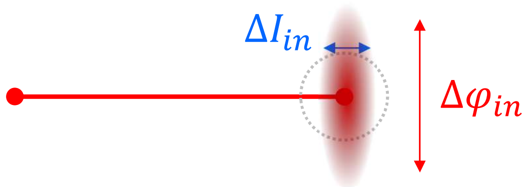
$$\delta\varphi_{out} \simeq \delta\varphi_{in} + \frac{\mathcal{F}}{\lambda}(\delta L + \delta x_{rad})$$

- A phase squeezed state reduces the phase noise at the expense of radiation pressure noise

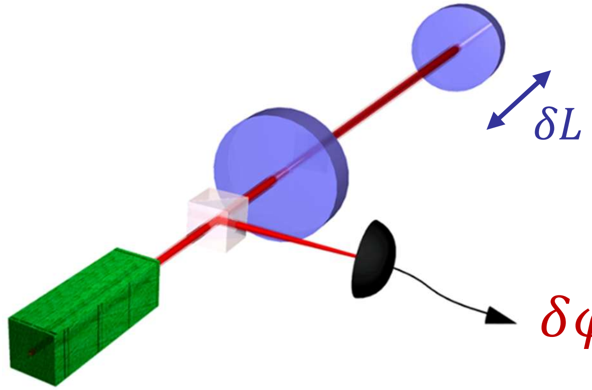




- Reverse effect for an intensity squeezed state



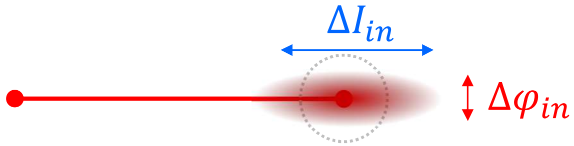
Beyond the SQL with squeezed states (4)



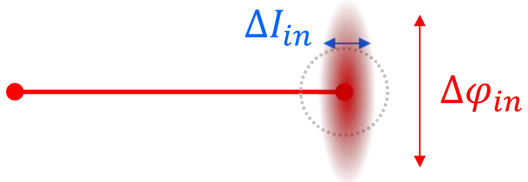
Input phase noise — Radiation pressure

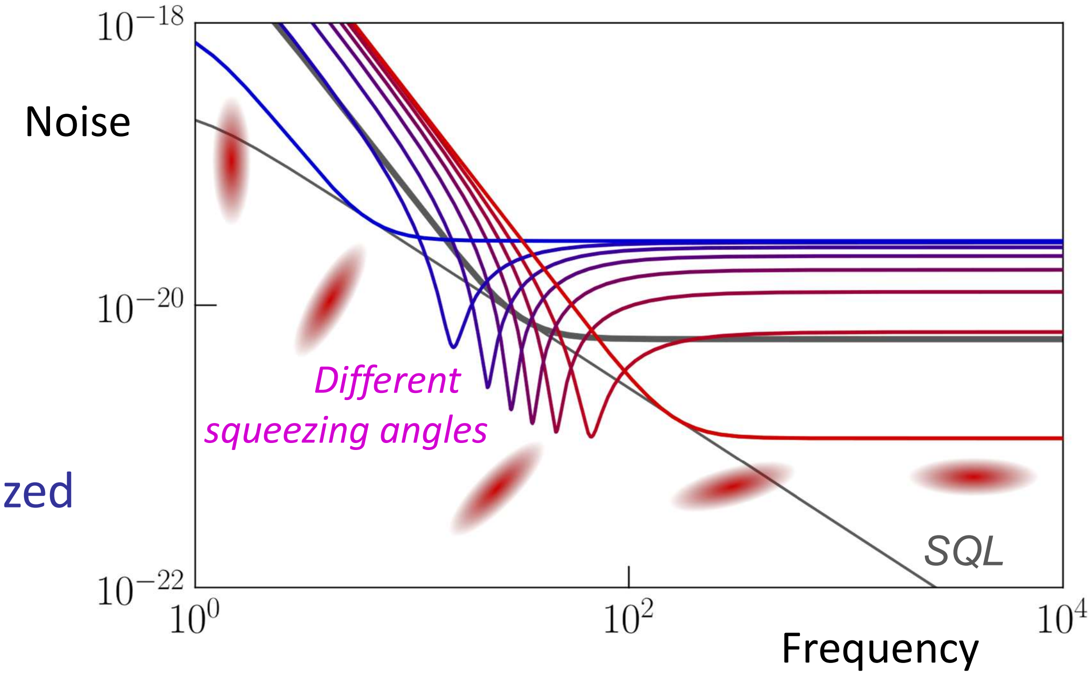
$$\delta\varphi_{out} \simeq \delta\varphi_{in} + \frac{\mathcal{F}}{\lambda}(\delta L + \delta x_{rad})$$

- A phase squeezed state reduces the phase noise at the expense of radiation pressure noise

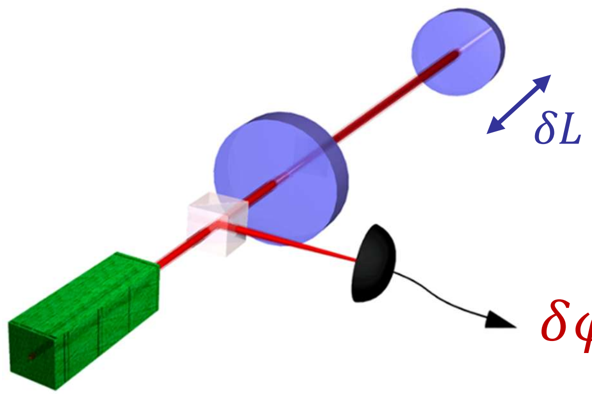


- Reverse effect for an intensity squeezed state



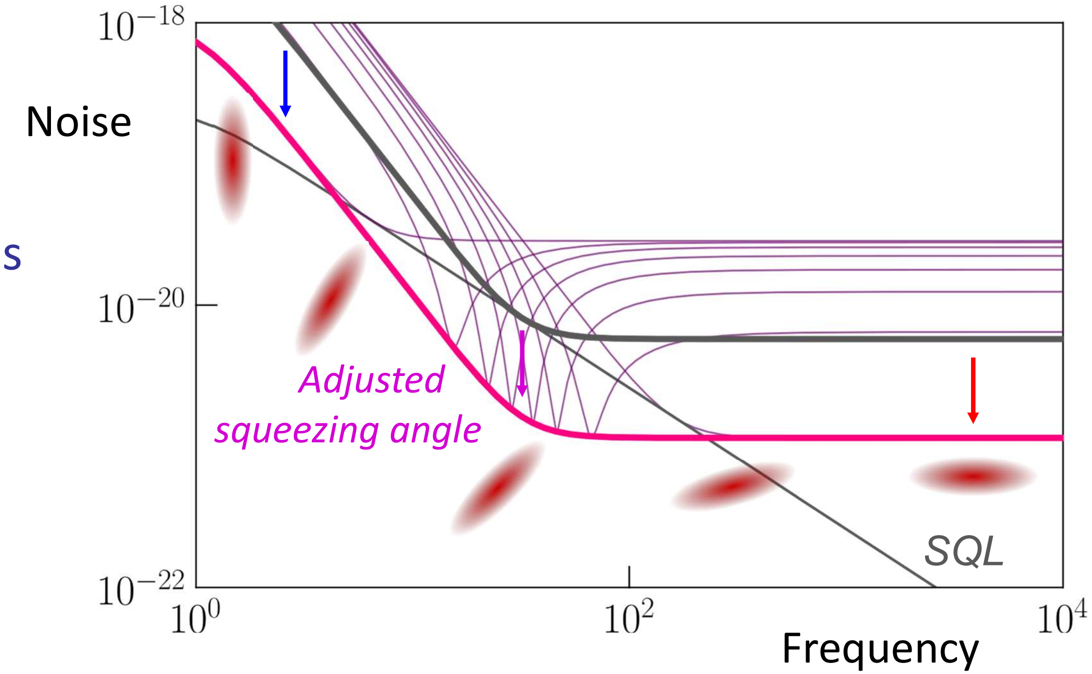


Beyond the SQL with squeezed states (5)



$$\delta\varphi_{out} \simeq \delta\varphi_{in} + \frac{\mathcal{F}}{\lambda}(\delta L + \delta x_{rad})$$

- An adjusted squeezing angle reduces the total noise below the SQL



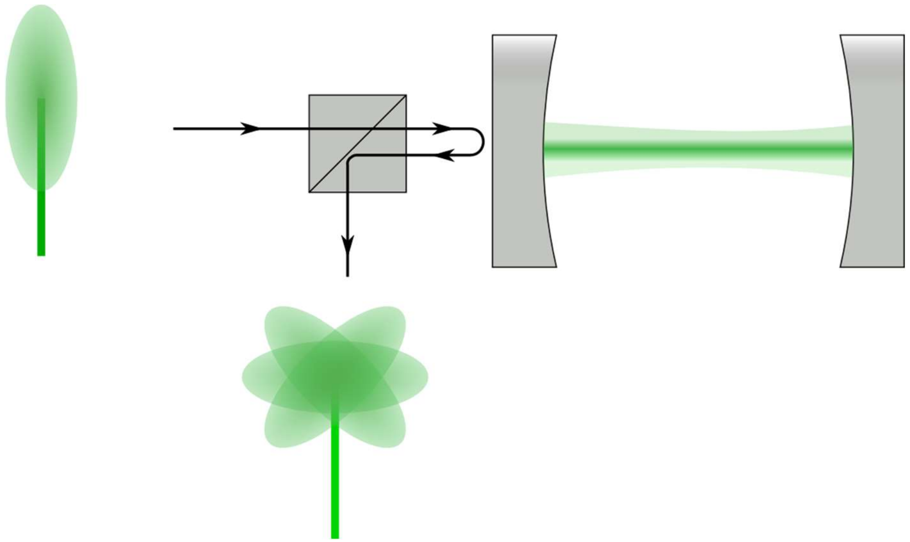
→ Sensitivity improvement over the whole bandwidth!

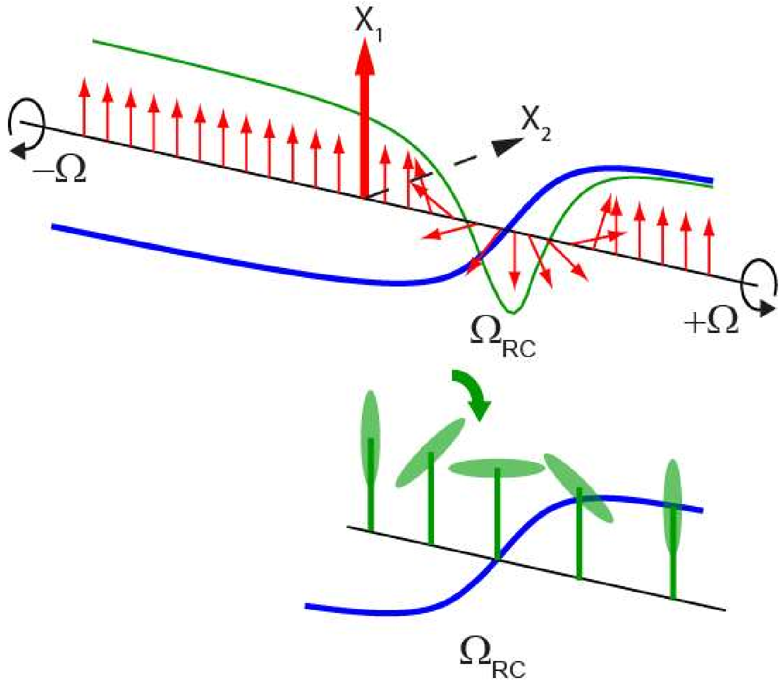
Frequency dependent squeezing

Rotate the squeezing ellipse with a detuned cavity

Rotate the squeezed sideband

Corner frequency and width given by the detuning and linewidth of the cavity

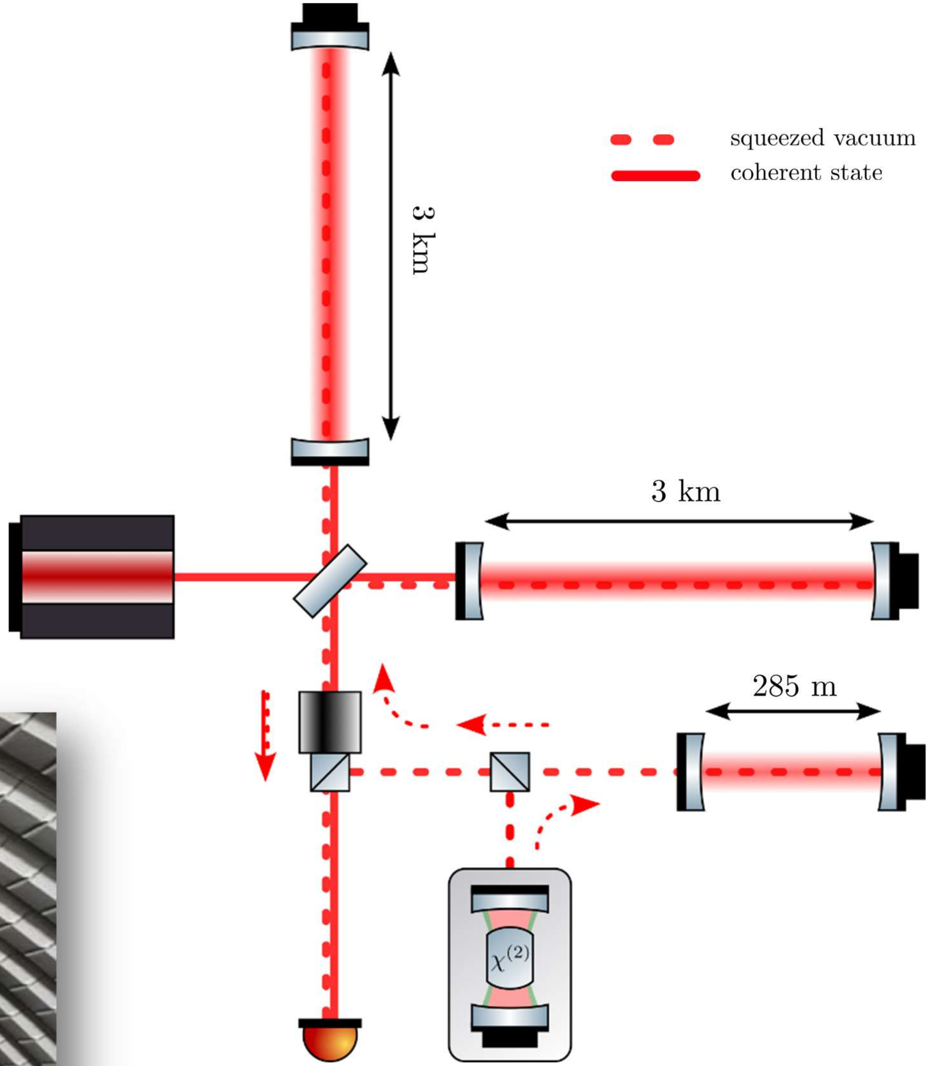




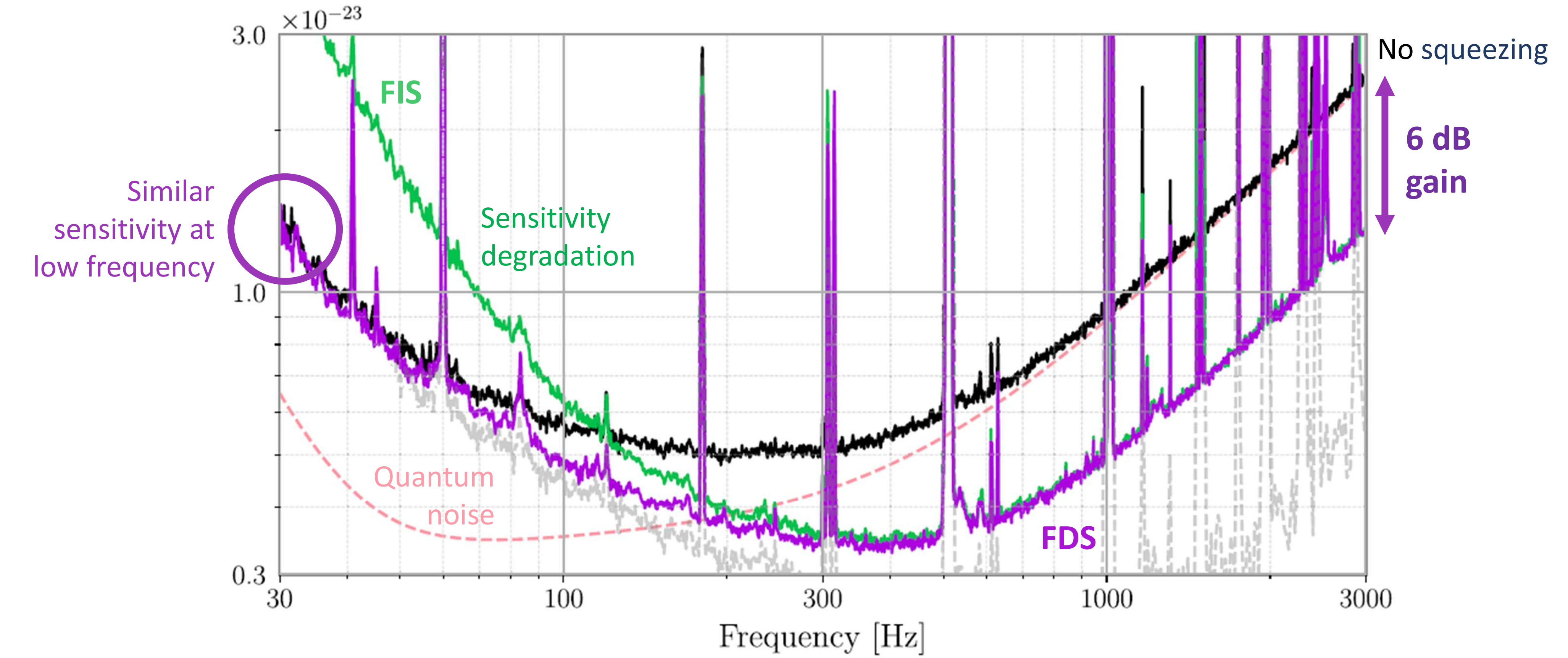
Implementation of frequency dependent squeezing in Virgo

Use of a ~300-m long detuned cavity

- The main challenge is to control the length of the cavity, as its bandwidth is very narrow (≈ 50 Hz)
- Work in progress!



Frequency dependent squeezing in Advanced LIGO



- Comparison between frequency dependent (**FDS**) and independent (**FIS**) squeezing

→ Sensitivity improvement over the whole bandwidth!

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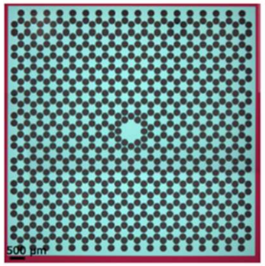
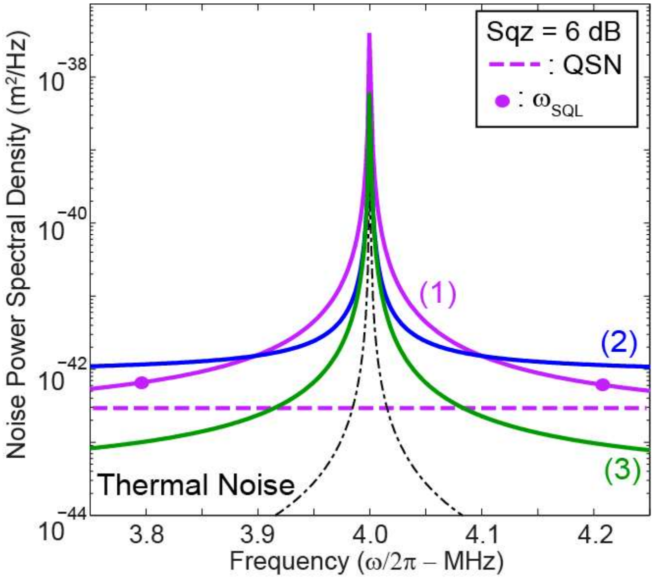
Developments at LKB for Virgo

- Demonstration of a sub-SQL measurement with a MHz-resonator

  Use of a very high-quality nano-membrane





Coherent state

Phase squeezing

Broadband sub-SQL meas.

- Collaboration with the CALVA group at IJCLab at Orsay

  Study of frequency dependent squeezing with a corner frequency of 50 Hz

Use of a long (50 m) and high-finesse (30 000) cavity

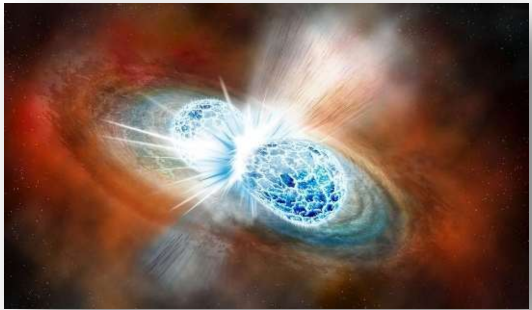
Conclusion and perspectives

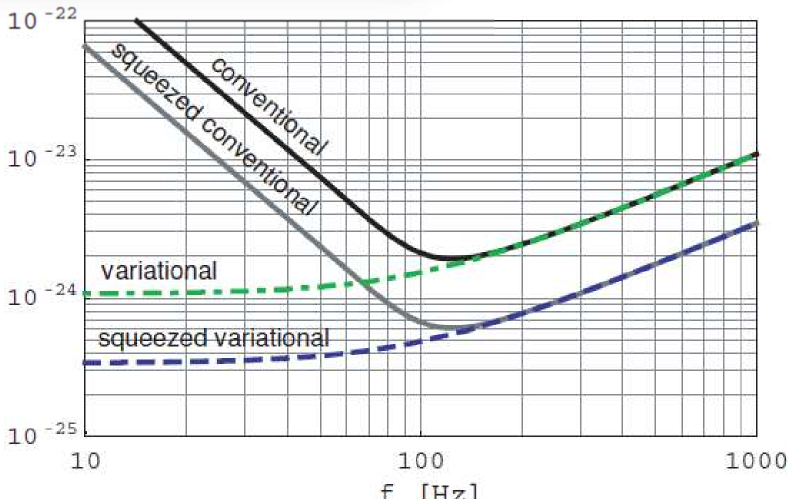
Quantum control is now essential in GW detectors

- GW detectors operate at the quantum limit
- Squeezed light is now routinely used

Towards broadband quantum noise reduction (FDS)

→ Increased sensitivity:
- *Improved detection range → more events*
- *Better low-frequency sensitivity → earlier detection and better parameter estimation*
- *Access to new sources and rare events*





Beyond current techniques

- Alternative approaches: variational readout
- Future detectors: Einstein Telescope, LISA

GW detectors are the largest quantum sensors ever built!

The *Optomechanics & Quantum Measurement* team at LKB

Thibaut Jacqmin **Samuel Deléglise**
Alice Desbois **Tristan Briant** Amin Lakhal Paul Manset Pierre-Edouard Jacquet Léo Balembois

Tatiana Steshchenko Katarzyna Lelonek Malte Kroj Himanshu Patange Rémi Rousseau **Pierre-François Cohadon** **AH** **Olga Kozlova**

Thanks you for your attention!