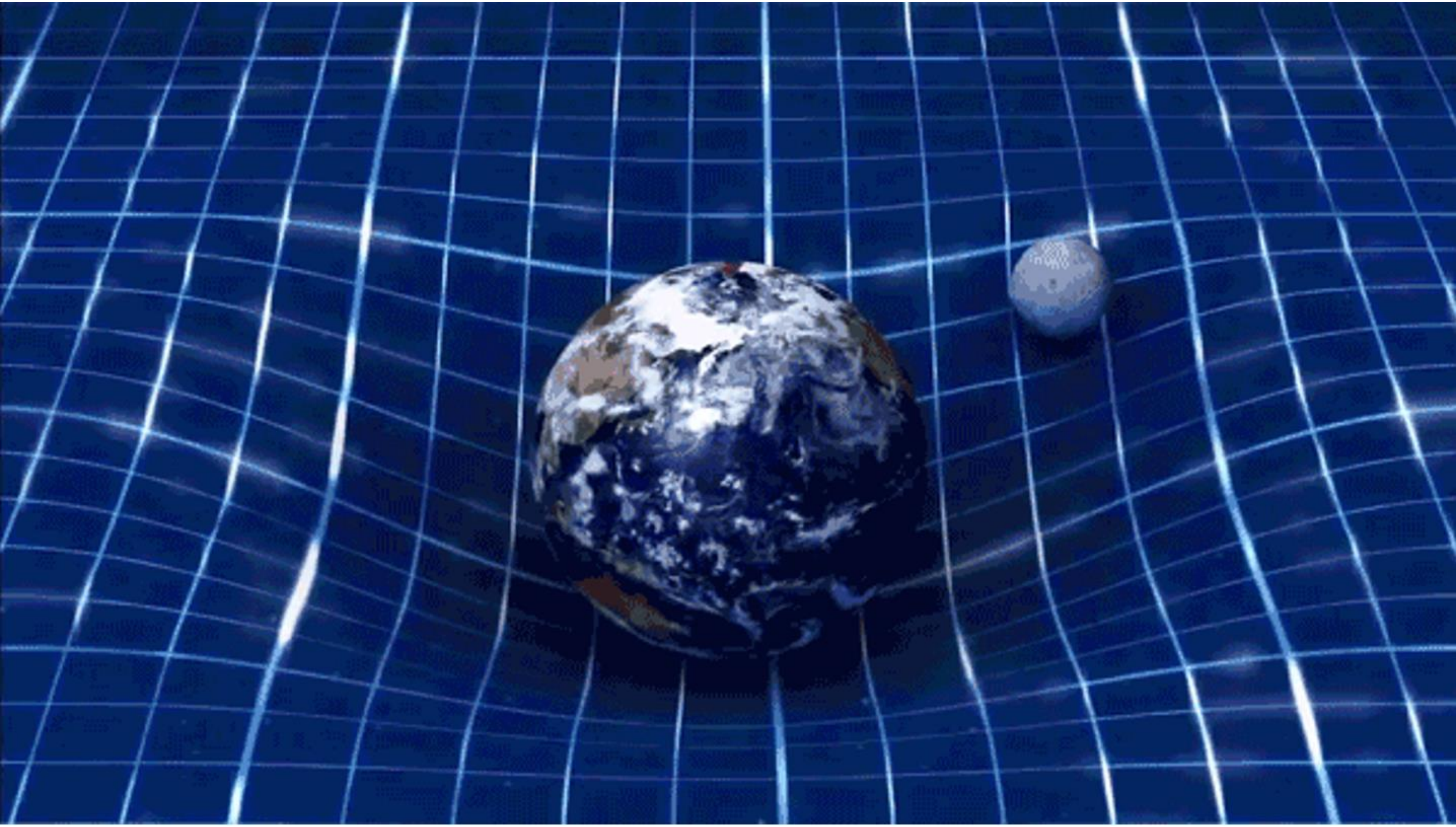
Laboratoire Kastler Brossel
Physique quantique et applications

L'optique quantique au service des ondes gravitationnelles

Quand la mécanique quantique aide à observer l'univers

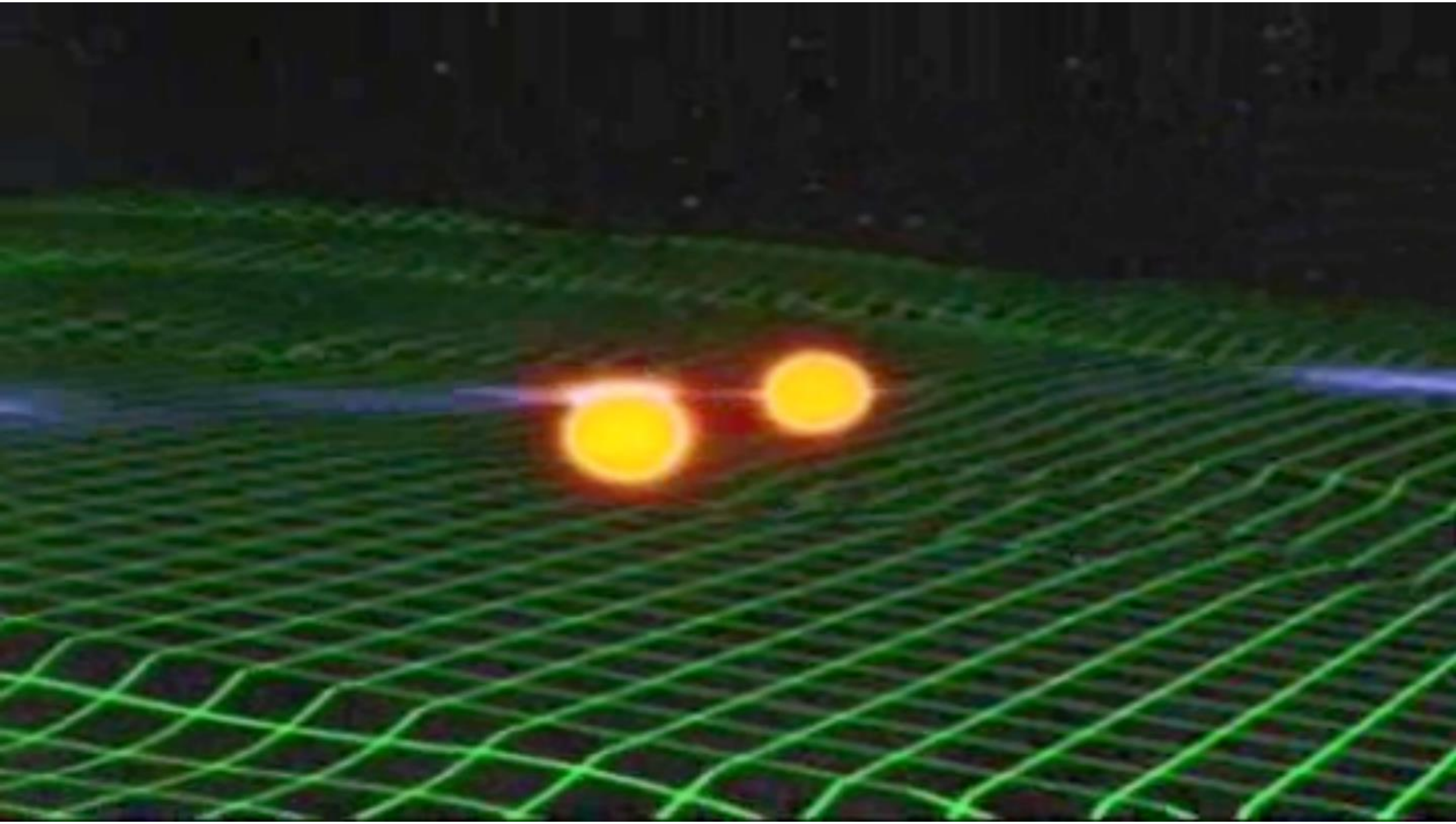
Antoine HEIDMANN
Laboratoire Kastler Brossel
Ecole Normale Supérieure, Sorbonne Université, Collège de France - Paris

Gravitational waves:



a consequence of Einstein’s General Relativity

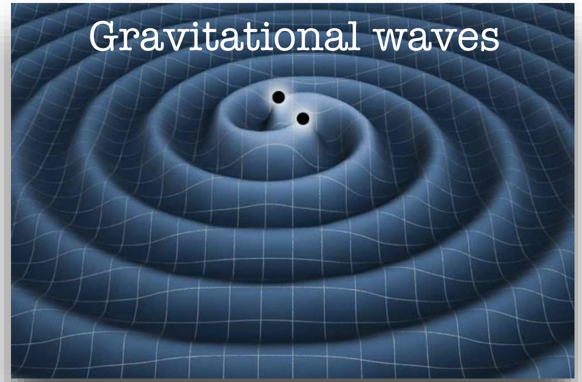
Gravitational waves:



a consequence of Einstein’s General Relativity

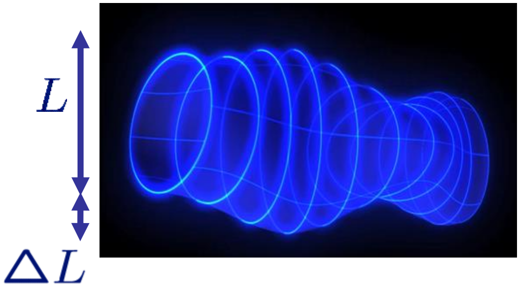
Effect of gravitational waves on earth

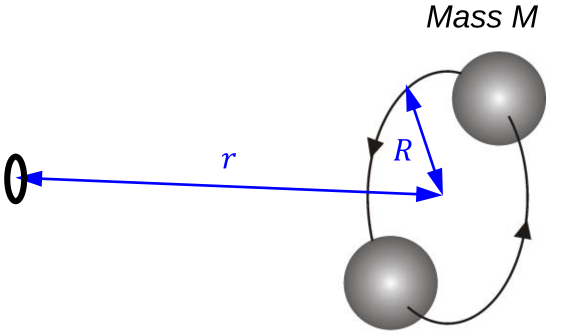
Ripples of space-time metric induces changes in distances between free-fall objects



→ Effect of gravitational wave:

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





Binary system
(f ≈ 1 Hz to 1 kHz)

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

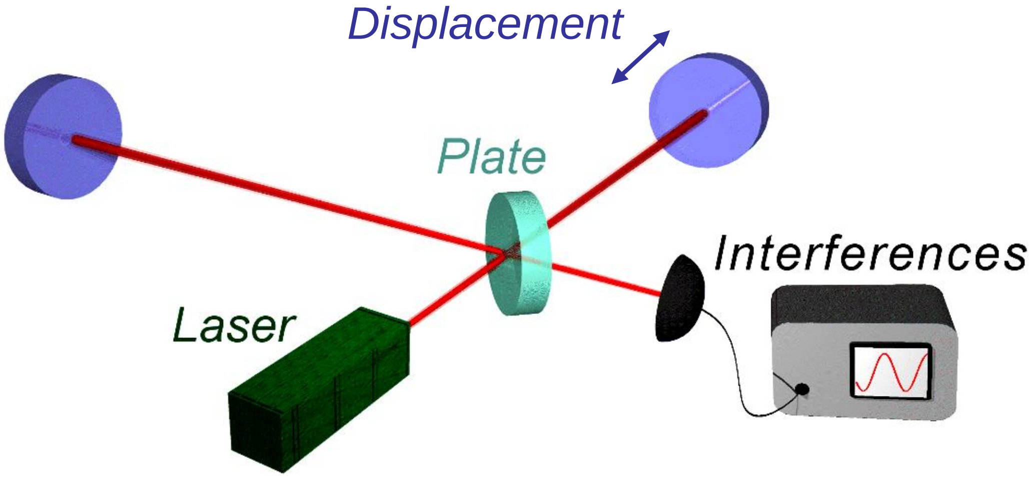
$R \simeq 100$ km, $M \simeq 30\ M_\odot$
rotation at $f \simeq 100$ Hz $\rightarrow$ $h \simeq 10^{-21}$ at $r = 400$ Mpc

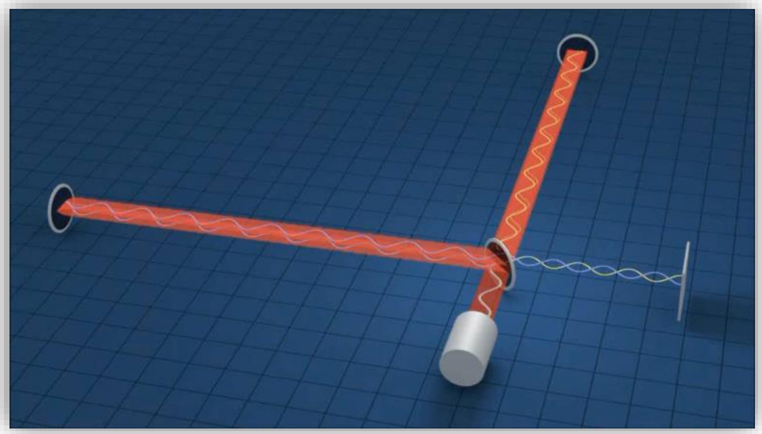
Detection of

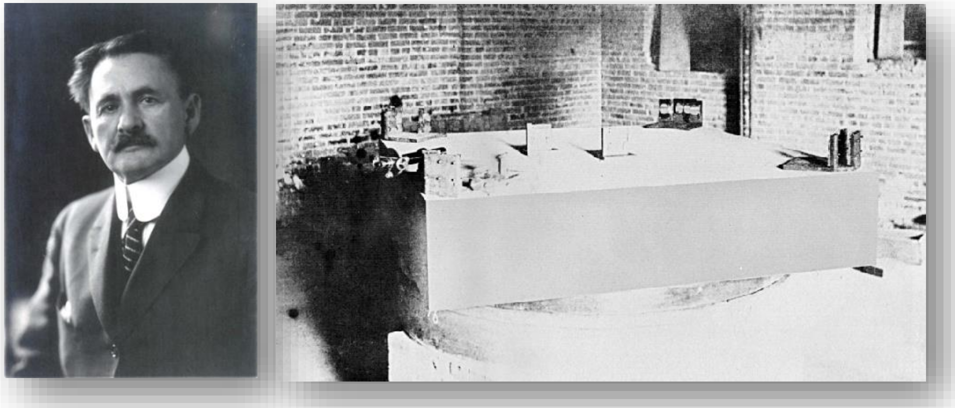
gravitational waves

Sensitive optical measurement of displacements

Interferometer: measurement of relative lengths between 2 arms





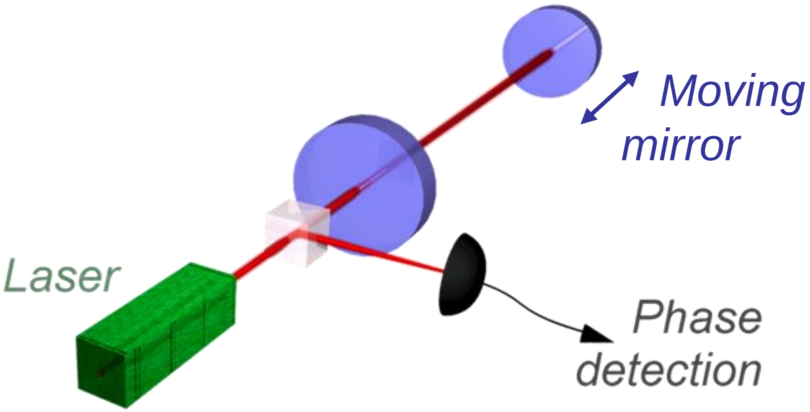


Michelson – Morley interferometer

Sensitivity $\sim 1\ \text{Å} = 10^{-10}\ \text{m}$

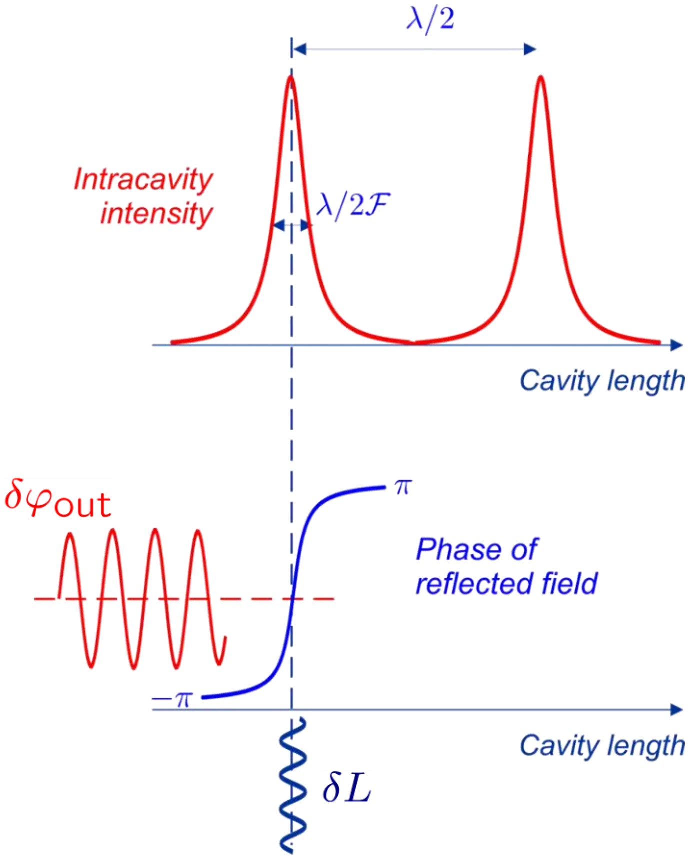
Ultra-sensitive displacement sensor

Use of a high-finesse cavity:



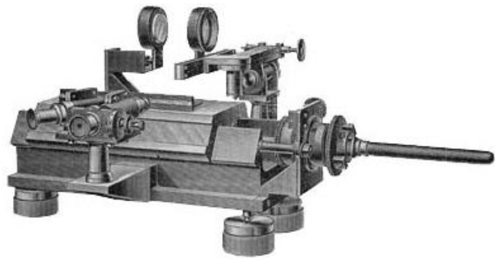
Resonance width: $\lambda/2\mathcal{F}$ ($\mathcal{F}$: cavity finesse)

Phase of the reflected light: $\delta\varphi_{\text{out}} \simeq \mathcal{F}\,\dfrac{\delta L}{\lambda}$



Sensitivity $\sim 10^{-20}$ m

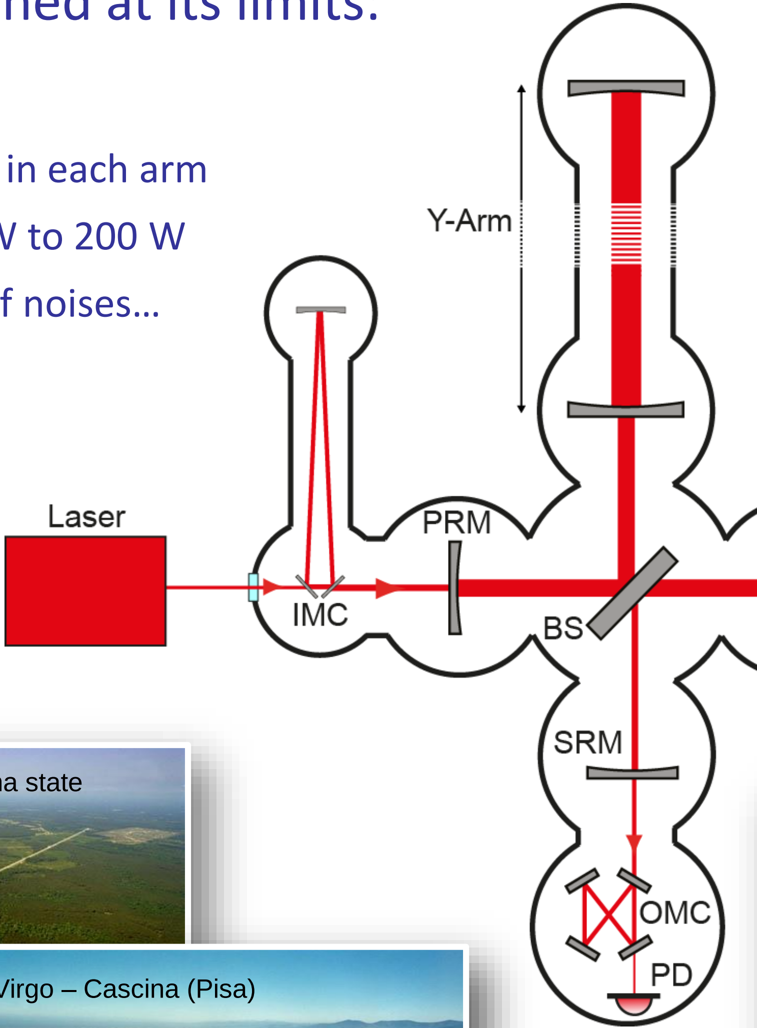
Fabry – Perot cavity



Advanced LIGO and Virgo interferometers

Interferometry pushed at its limits:

- Arms of km length
- Fabry-Perot cavities in each arm
- Incident power 10 W to 200 W
- Control/reduction of noises…



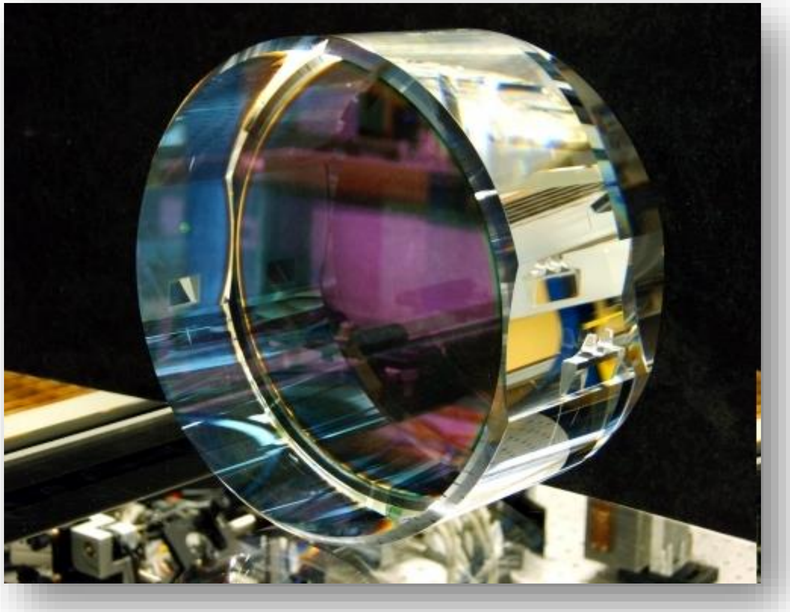

H1- Hanford – Washington state


L1- Livingston – Louisiana state


Virgo – Cascina (Pisa)

Drastic technological advances in many domains

Unique high-quality mirrors!



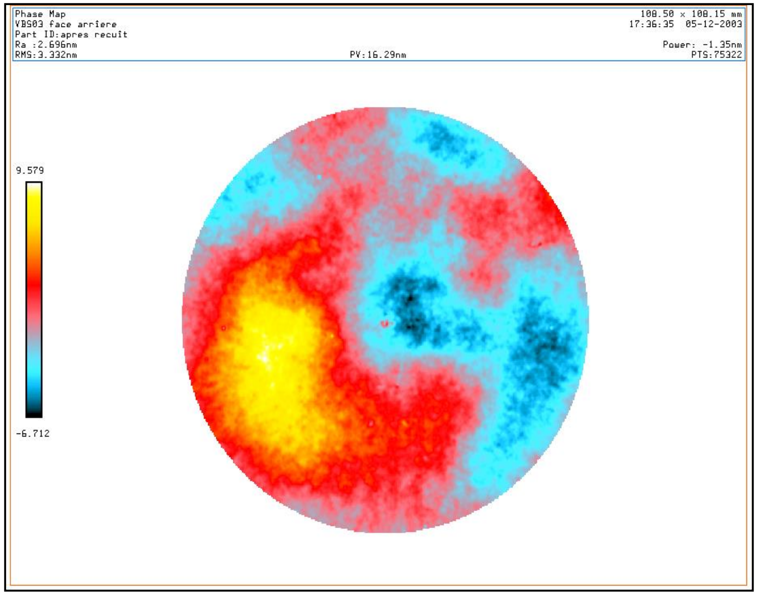
Silica mirrors $\phi = 35$ cm

Roughness corrected in situ < 1 nm

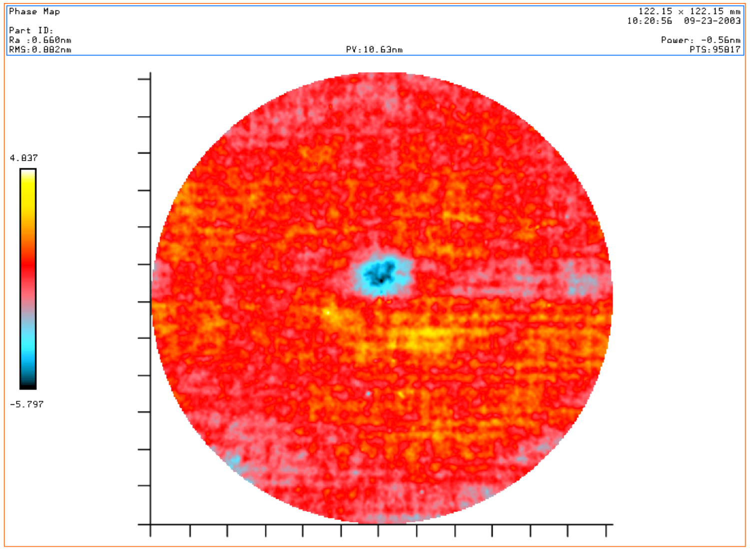
Optical losses < 1 ppm

Optical coatings made at Lyon (LMA)

LABORATOIRE
MATÉRIAUX
AVANCÉS

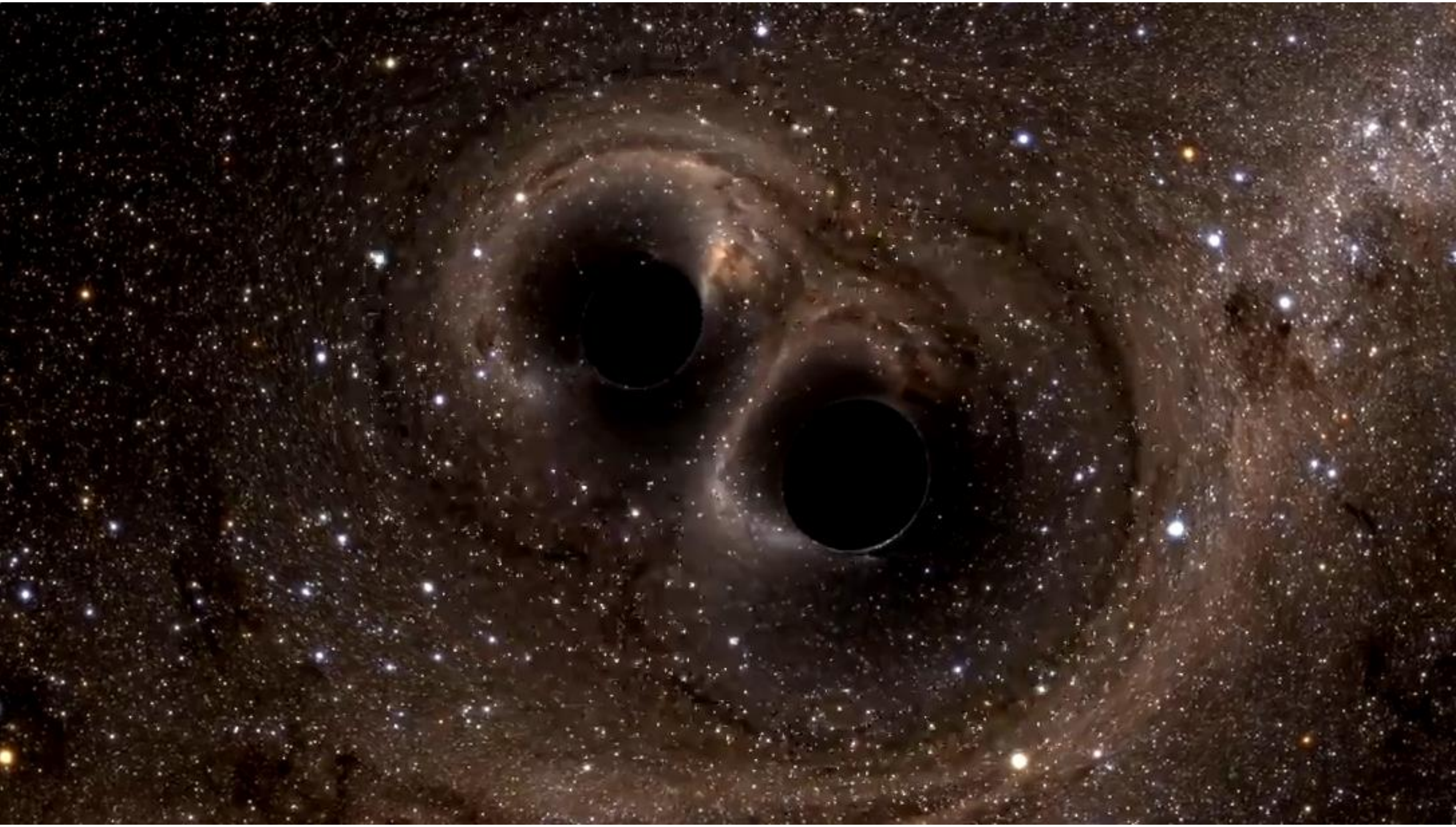


```
Phase Map                                          108.50 x 108.15 mm
VBS03 face arriere                                17:36:35  05-12-2003
Part ID:apres recuit
Ra :2.696nm                                             Power: -1.35nm
RMS:3.332nm                  PV:16.29nm                      PTS:75322
```



```
Phase Map                                          122.15 x 122.15 mm
                                                  10:20:56  09-23-2003
Part ID:
Ra :0.660nm                                             Power: -0.56nm
RMS:0.882nm                  PV:10.63nm                      PTS:95817
```

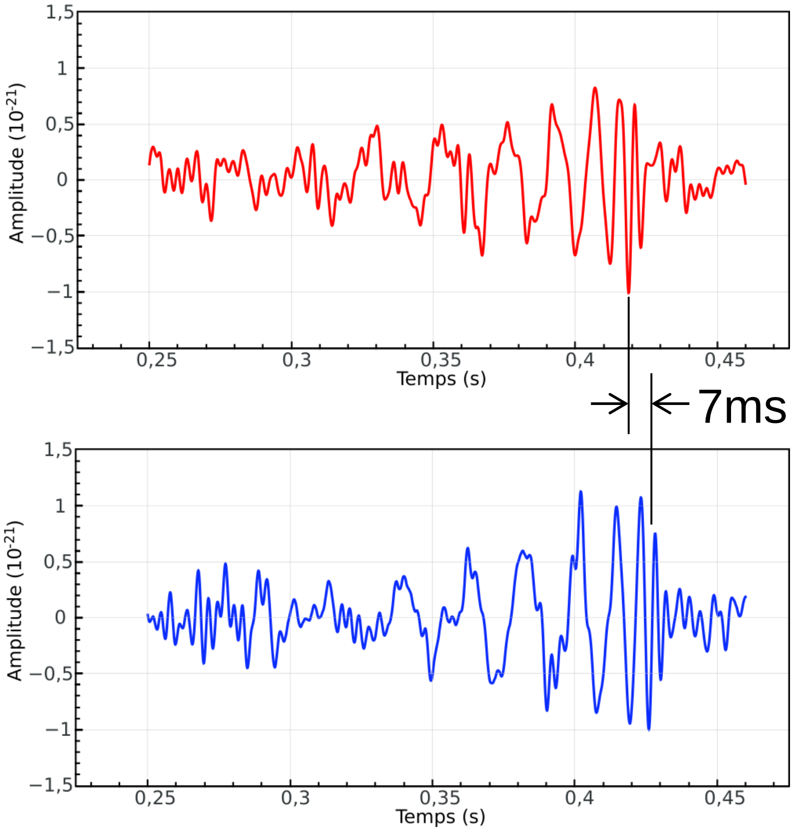
Observation of



gravitational waves

First observation September 14th, 2015

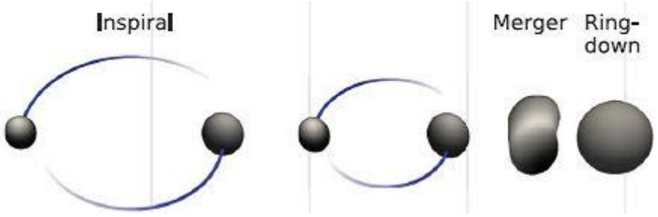
2 signals observed with both LIGO detectors



LIGO Hanford
Washington

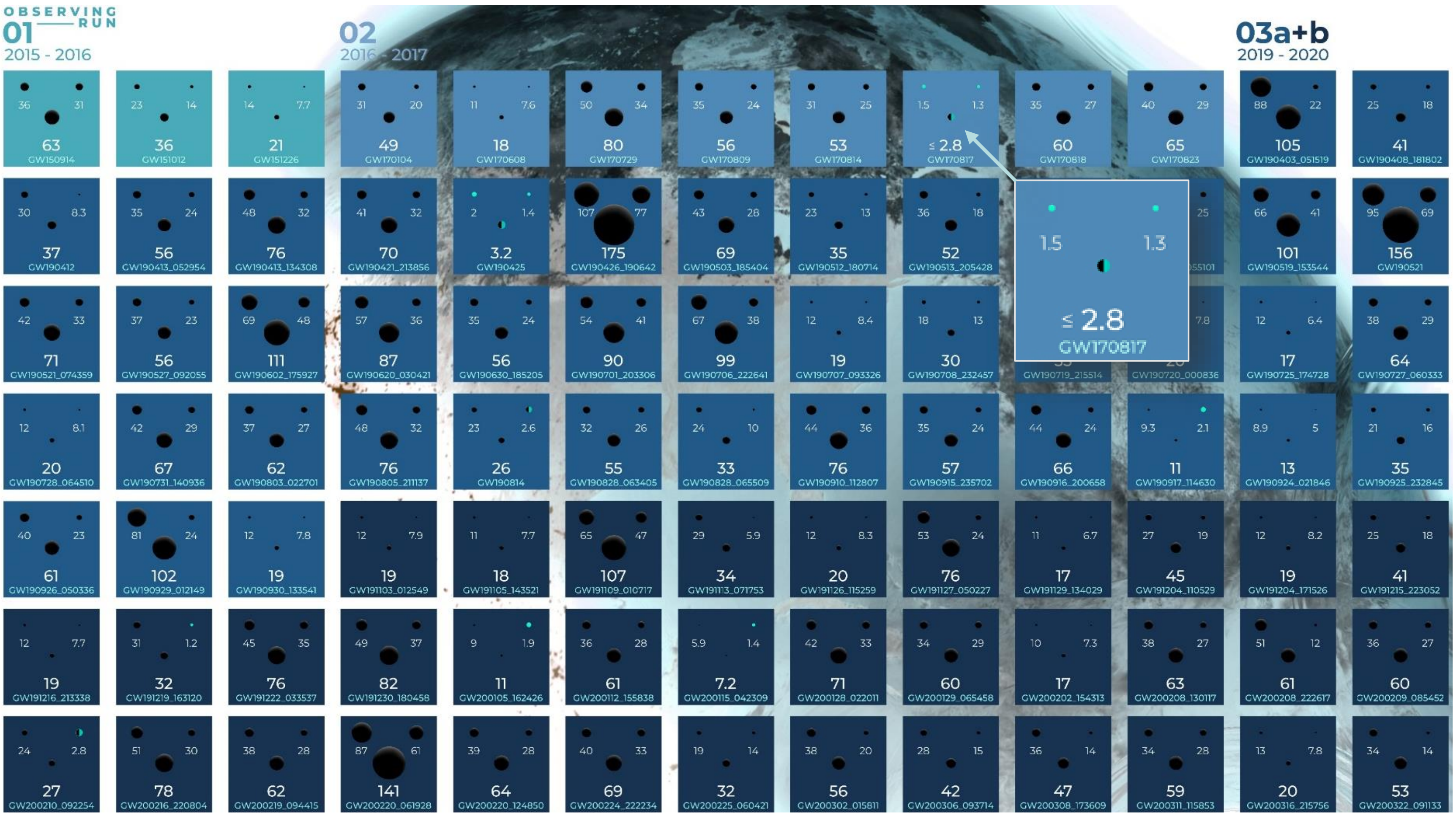
$\simeq$ 3,000 km
(10 ms)

LIGO Livingston
Louisiana



Binary black hole merger!

Summary of the 90 detections (2015 to 2020)

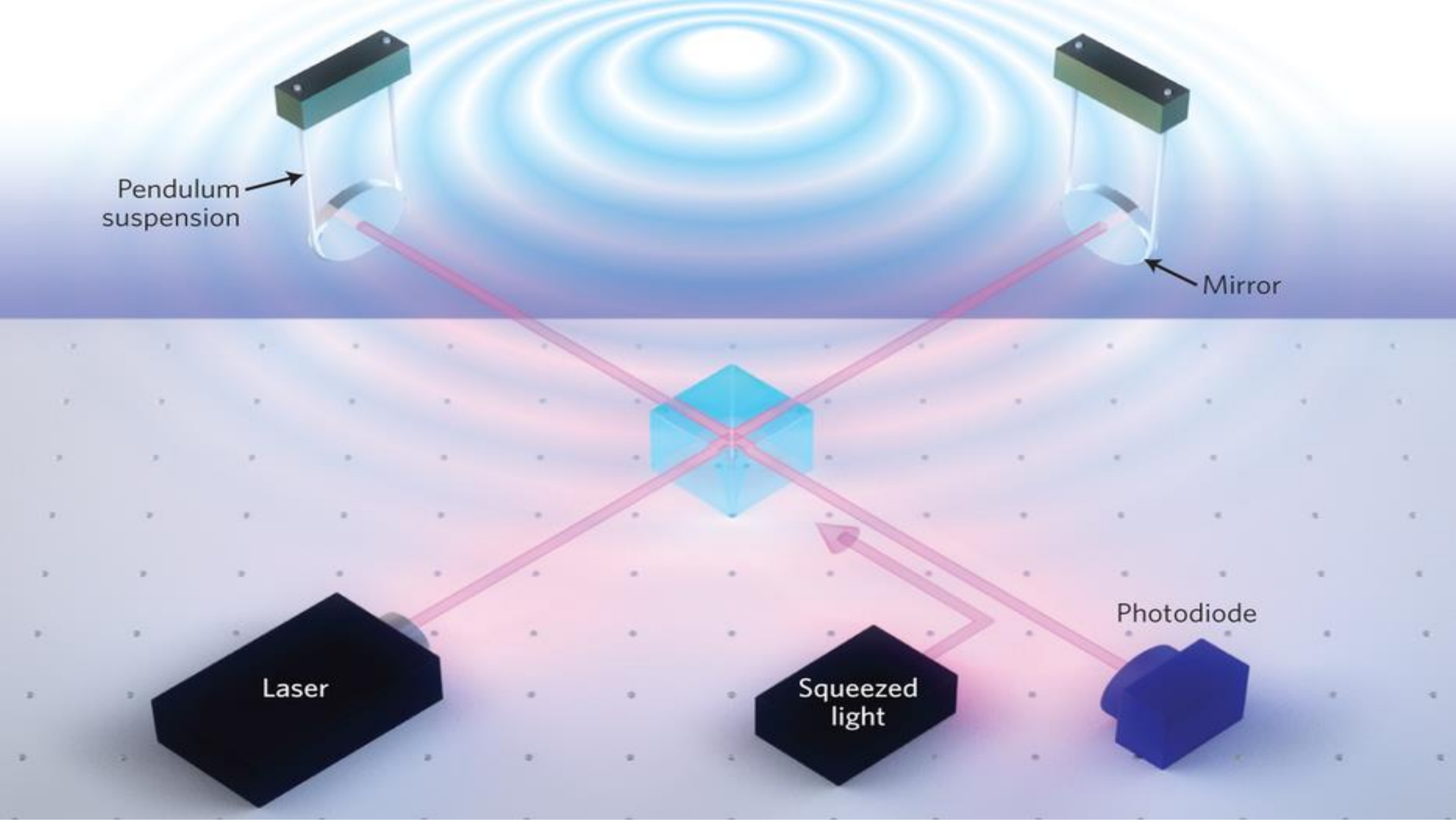


90 events detected since 2015

- 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 real gravitational astronomy!*

Gravitational-wave detection



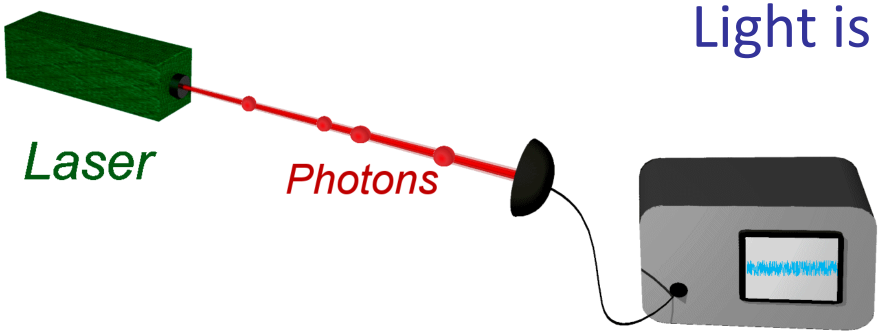
and quantum mechanics…

Gravitational-wave detection

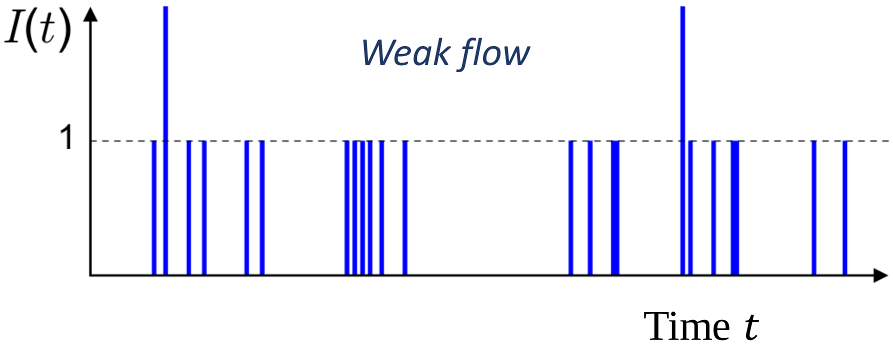
and quantum mechanics…

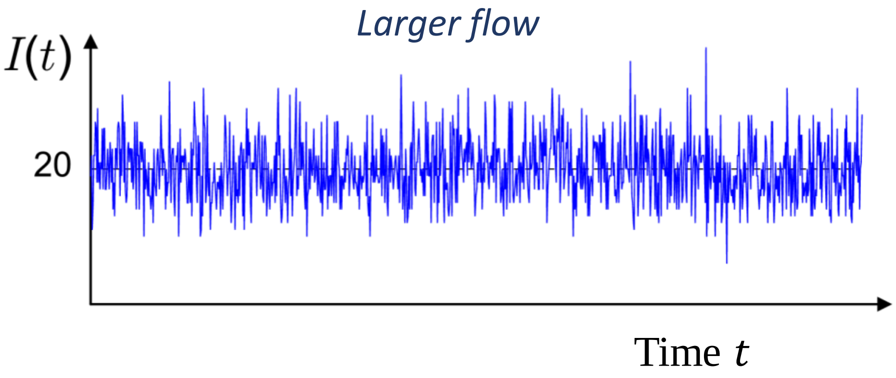
Quantum noise of light

Light is subject to quantum fluctuations



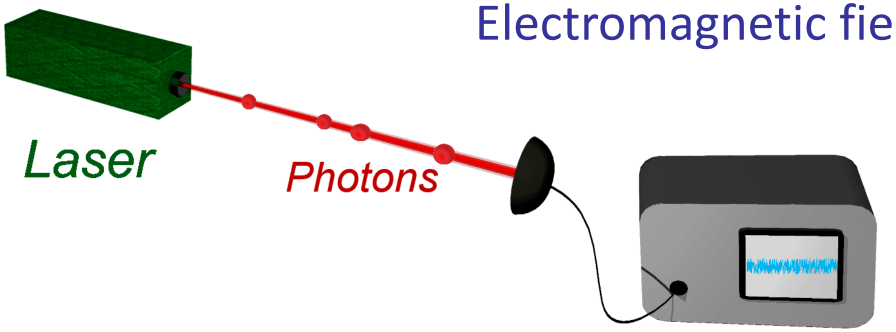
Photons emitted by a laser have a random distribution in time
(Poisson law $\Delta N = \sqrt{N}$)





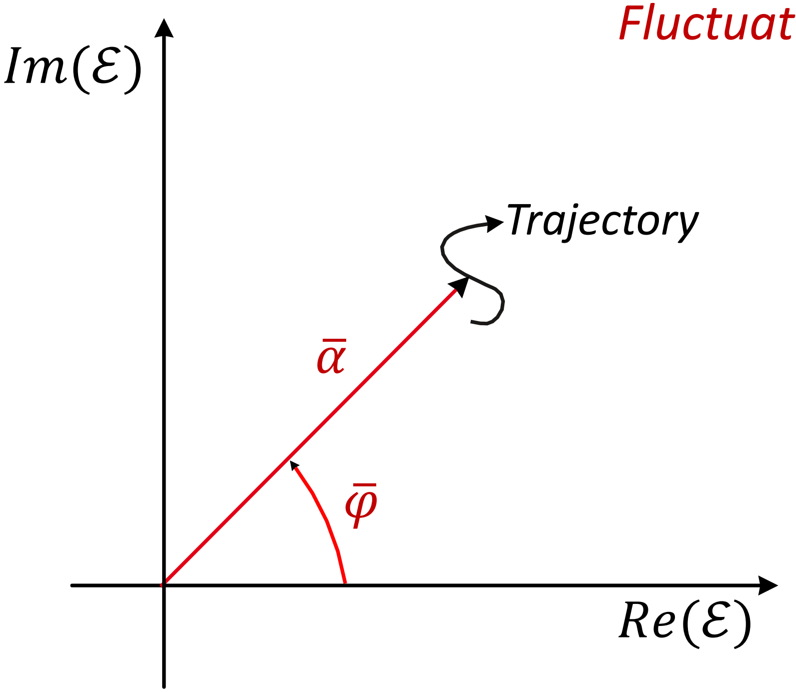
Quantum noise of light: representation in phase space

Electromagnetic field: $\mathcal{E}(t) = \alpha(t)\, e^{i(\omega_0 t + \varphi(t))}$



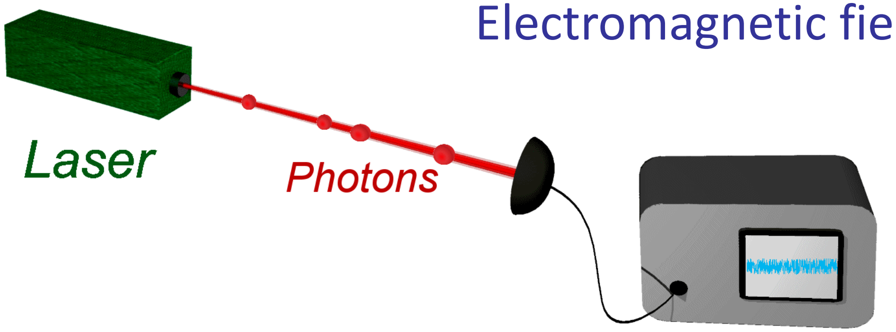
Intensity: $I(t) = |\alpha(t)|^2$

Fluctuations: $\delta I(t) \simeq \bar{\alpha}\, \delta\alpha(t)$



Quantum noise of light: coherent state

Electromagnetic field: $\mathcal{E}(t) = \left(\bar{\alpha} + \delta\alpha(t)\right) e^{i\left(\omega_0 t + \bar{\varphi} + \delta\varphi(t)\right)}$

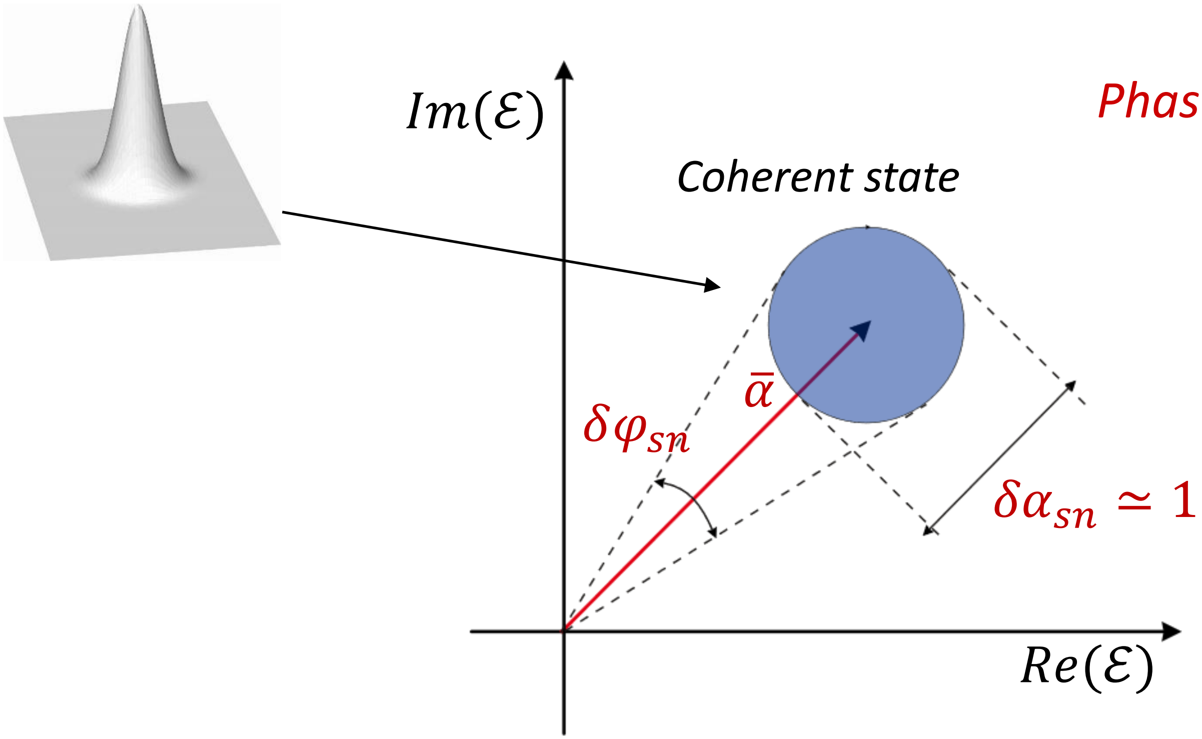


Intensity fluctuations:

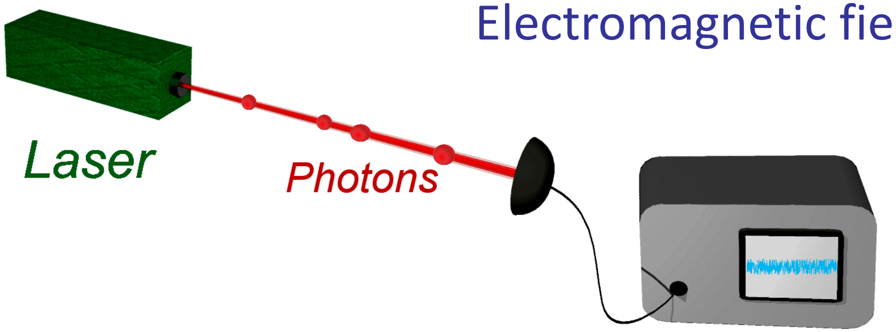
$$\delta I_{sn} \simeq \bar{\alpha}\ \delta\alpha_{sn} \simeq \sqrt{\bar{I}}$$

Phase noise:

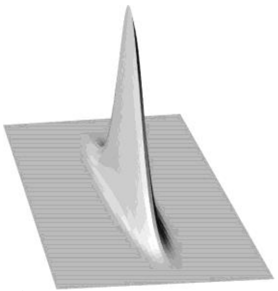
$$\delta\varphi_{sn} \simeq 1/\bar{\alpha} \simeq 1/\sqrt{\bar{I}}$$

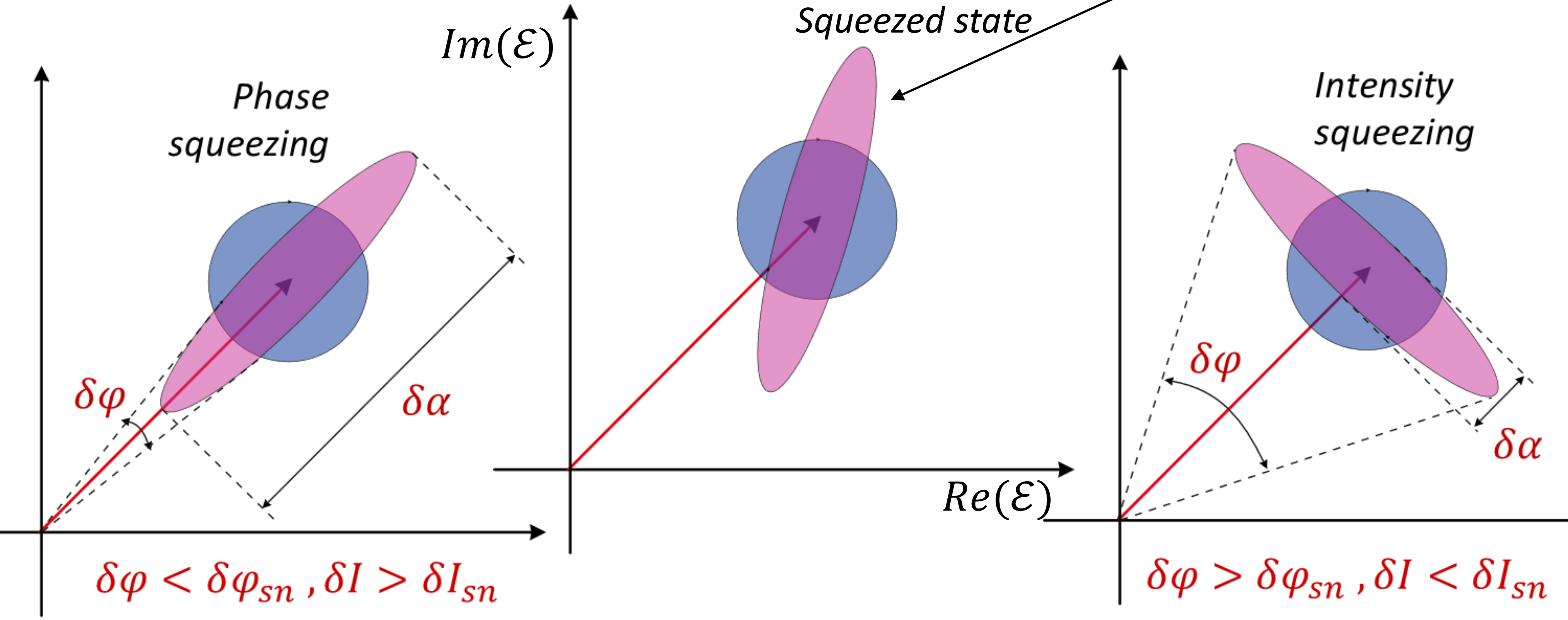


Quantum noise of light: squeezed states



Electromagnetic field: $\mathcal{E}(t) = \left(\bar{\alpha} + \delta\alpha(t)\right)\, e^{i(\omega_0 t + \bar{\varphi} + \delta\varphi(t))}$

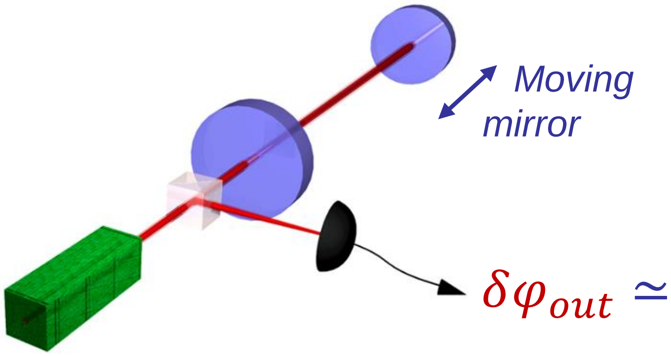




$\delta\varphi < \delta\varphi_{sn}\, , \delta I > \delta I_{sn}$

$\delta\varphi > \delta\varphi_{sn}\, , \delta I < \delta I_{sn}$

Quantum noise in displacement sensor



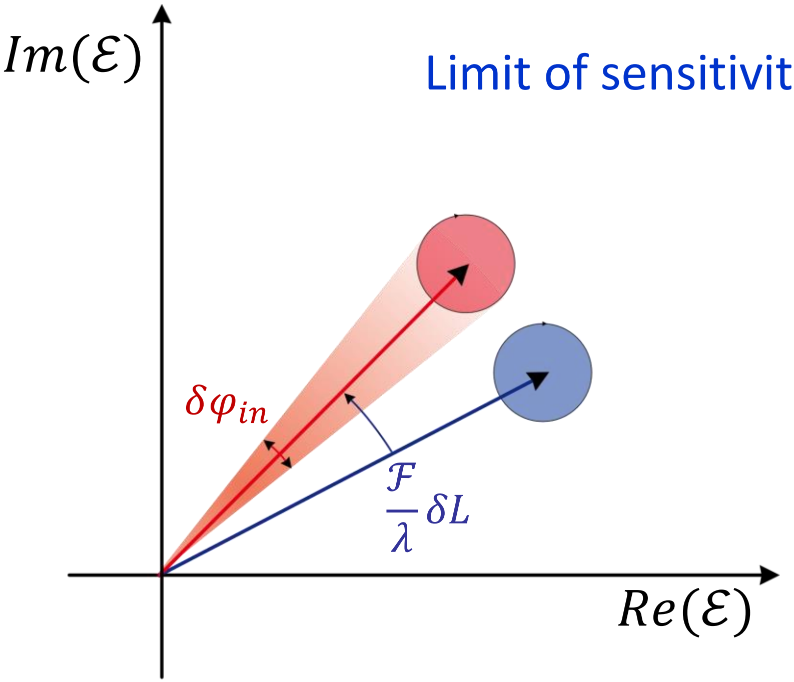
Noise in the reflected phase:

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

Input phase noise

Signal

Classical noise



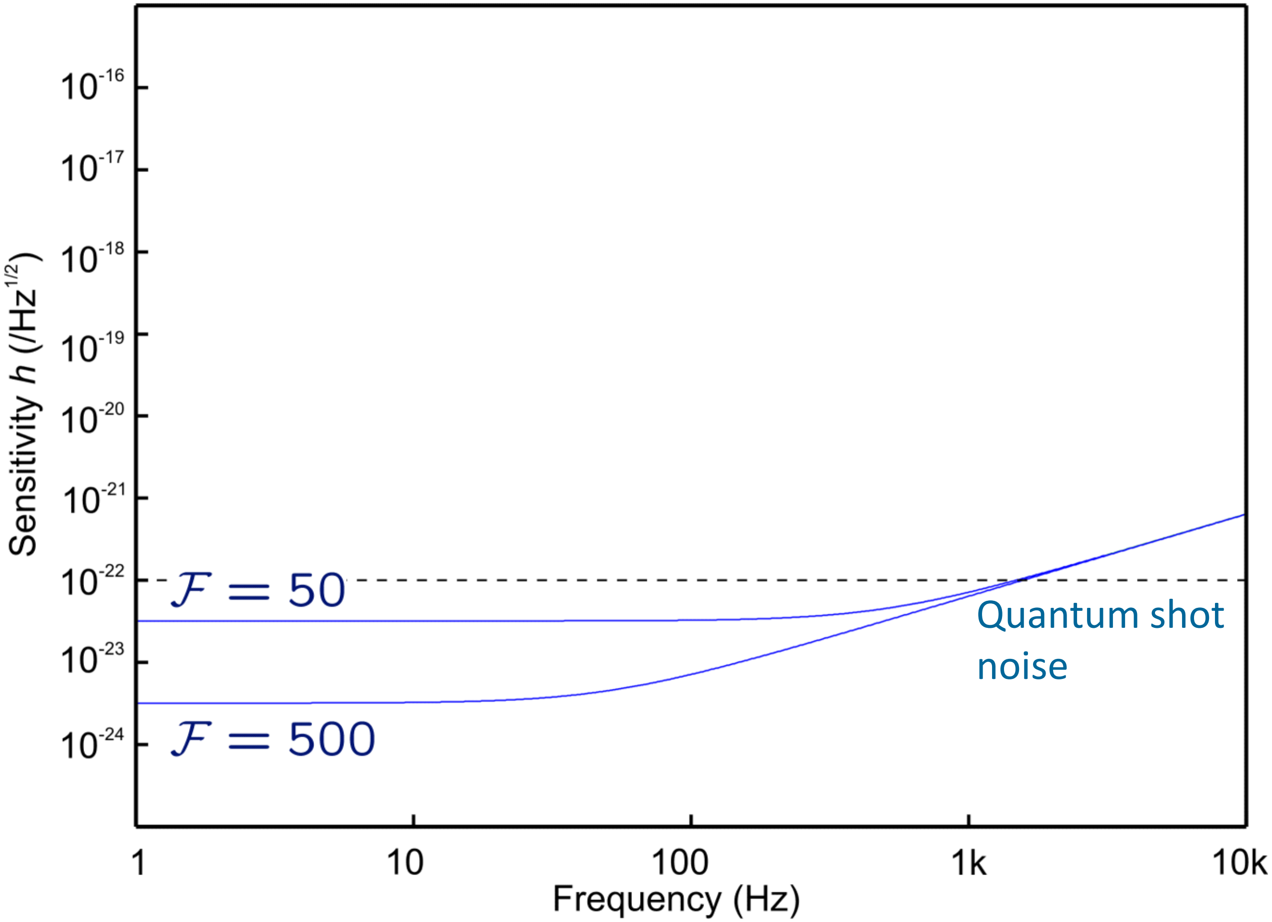
Limit of sensitivity induced by the quantum noise:

$$\delta L_{shot} \simeq \frac{\lambda}{\mathcal{F}\sqrt{\bar{I}}}\sqrt{1+\left(\frac{\Omega}{\Omega_{cav}}\right)^2}$$

Effect of finite cavity bandwith

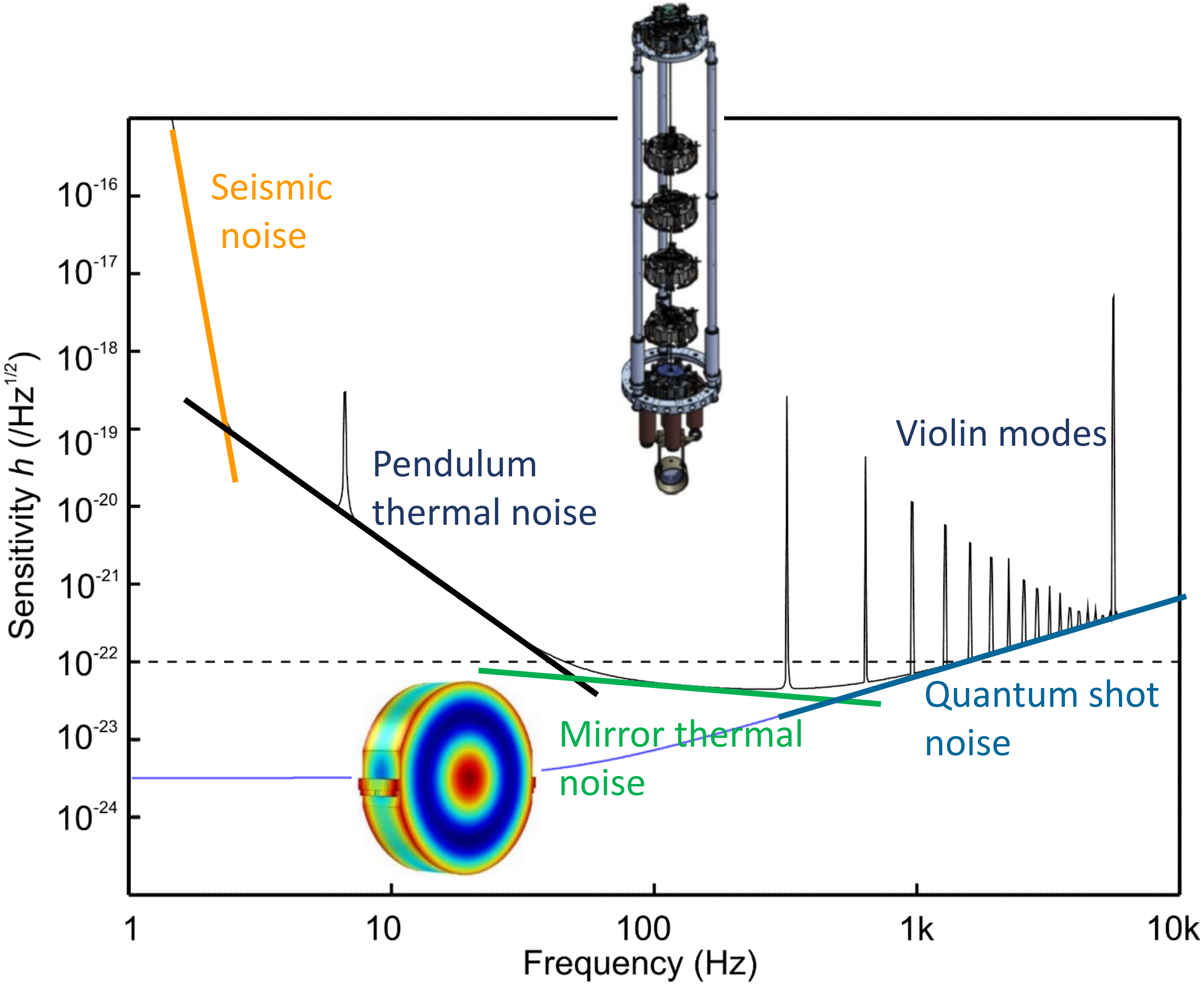
Virgo sensitivity (2007 - 2010)

$$h_{shot} \simeq \frac{1}{L}\frac{\lambda}{\mathcal{F}\sqrt{\bar{I}}}\sqrt{1+\left(\frac{\Omega}{\Omega_{cav}}\right)^2}$$

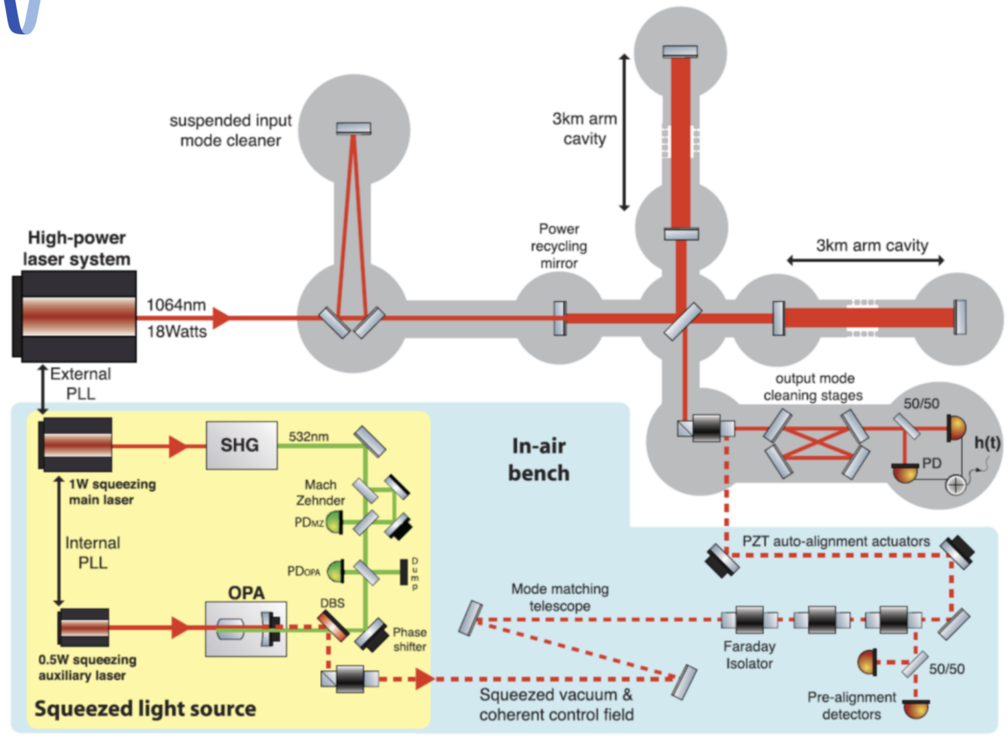


Computed for 1 kW

Virgo sensitivity (2007 - 2010)



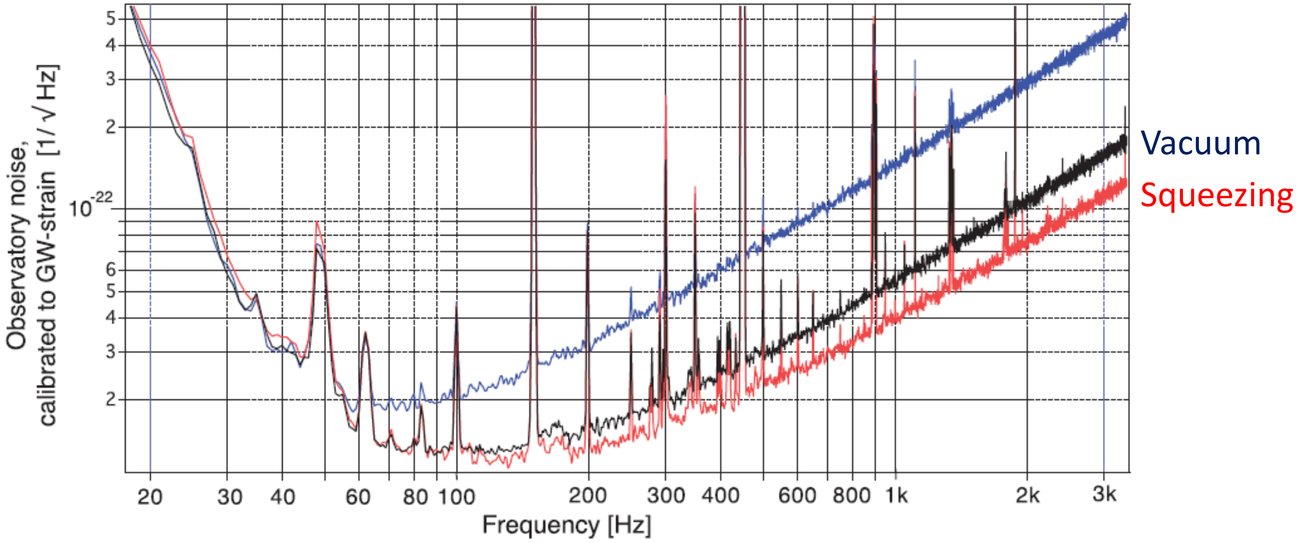
Squeezing in Advanced Virgo



Injection of a squeezed state via the output port

➙ Phase squeezing increases the sensitivity by **3 dB** at **high frequency**

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



Quantum

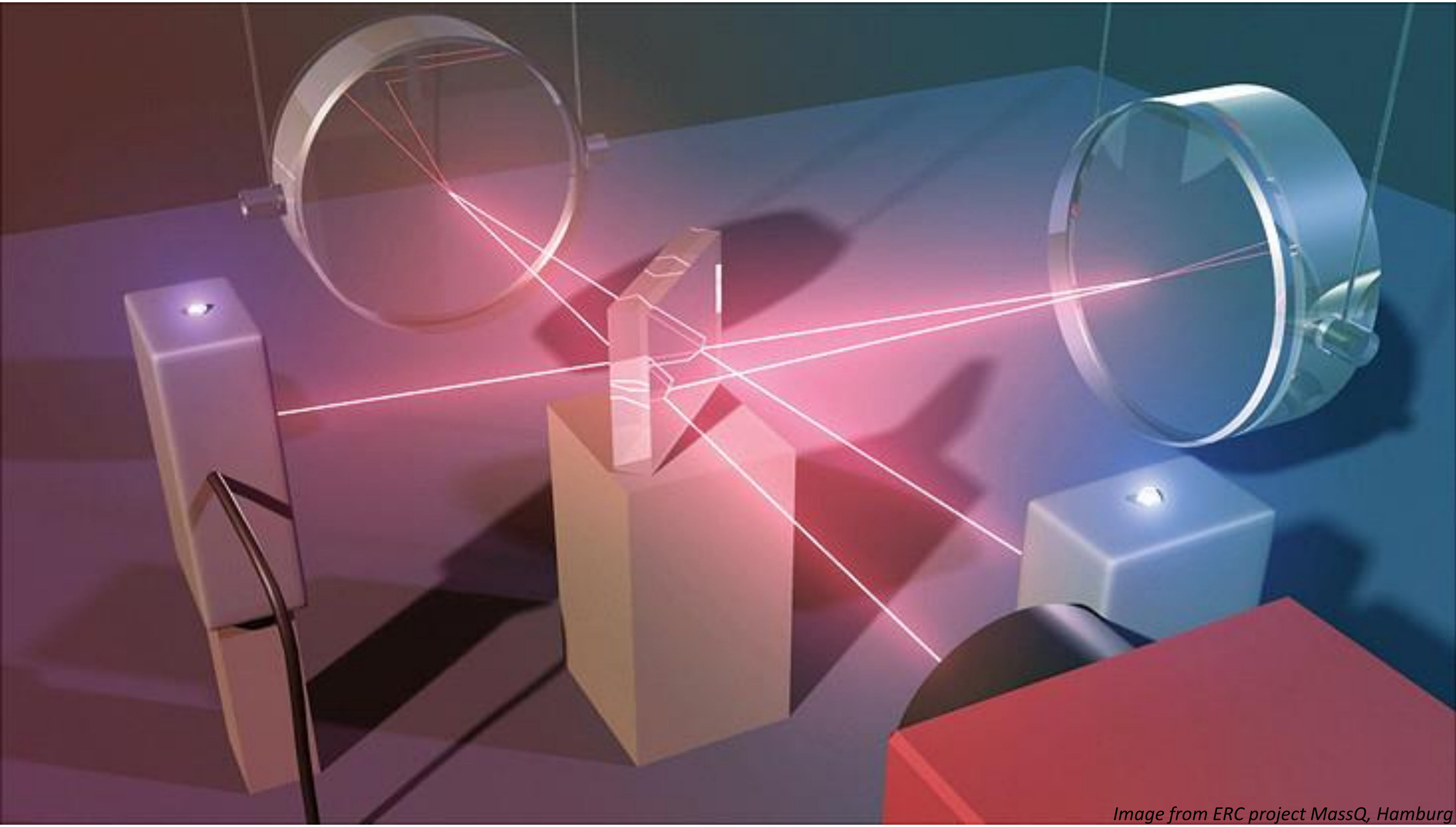
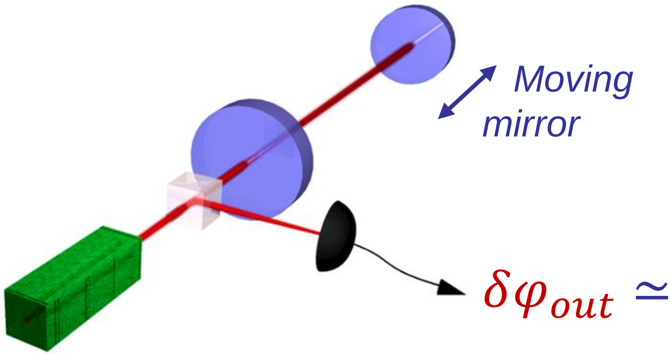


Image from ERC project MassQ, Hamburg

radiation pressure

Radiation pressure in displacement sensor

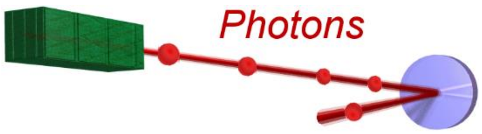


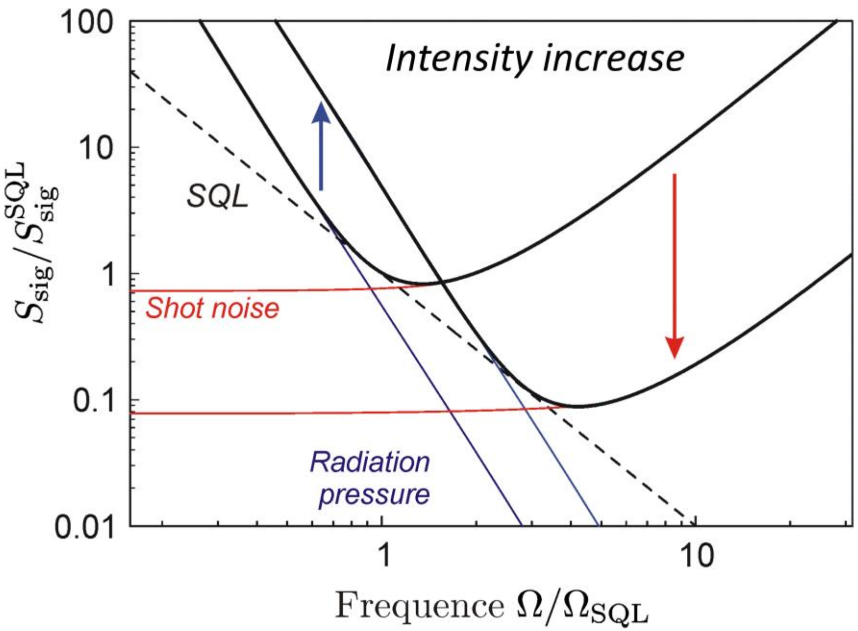
Noise in the reflected phase:

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

Input phase noise Signal Classical noise

Radiation pressure: $F_{rad} = 2\hbar k \times I$





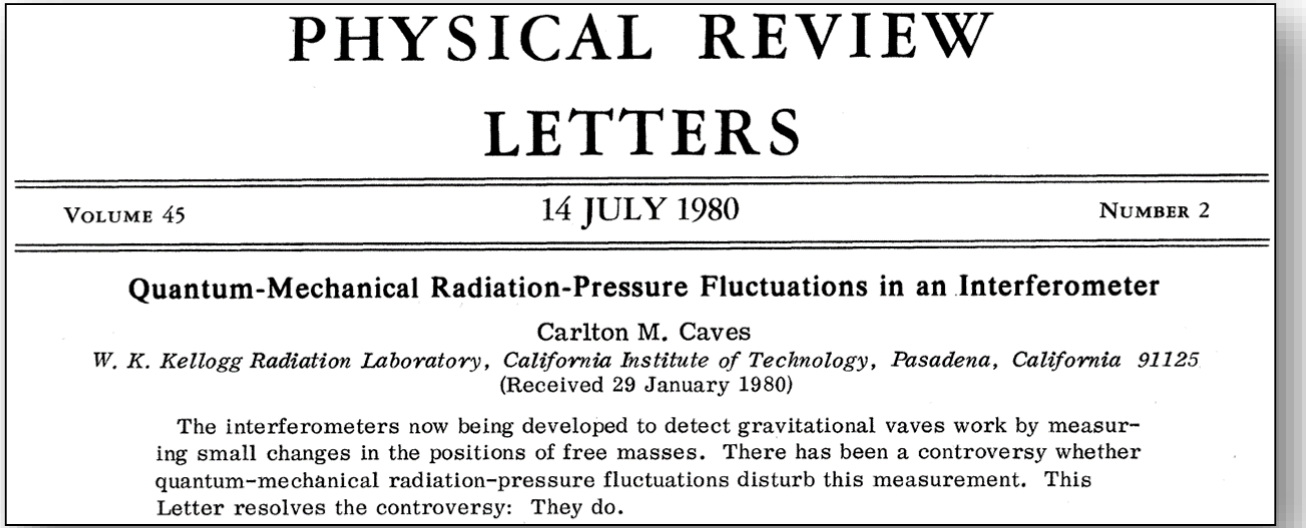
→ Fundamental principle of quantum measurement

The measurement ($\delta\varphi_{in}$, $\delta\alpha_{in}$) disturbs the system (δx_{rad})

Intensity increase: $\delta\varphi_{in} \propto 1/\sqrt{\bar{I}_{in}}$ but $\delta x_{rad} \propto \sqrt{\bar{I}_{in}}$

→ Standard quantum limit (SQL)

Quantum noises in interferometric measurements



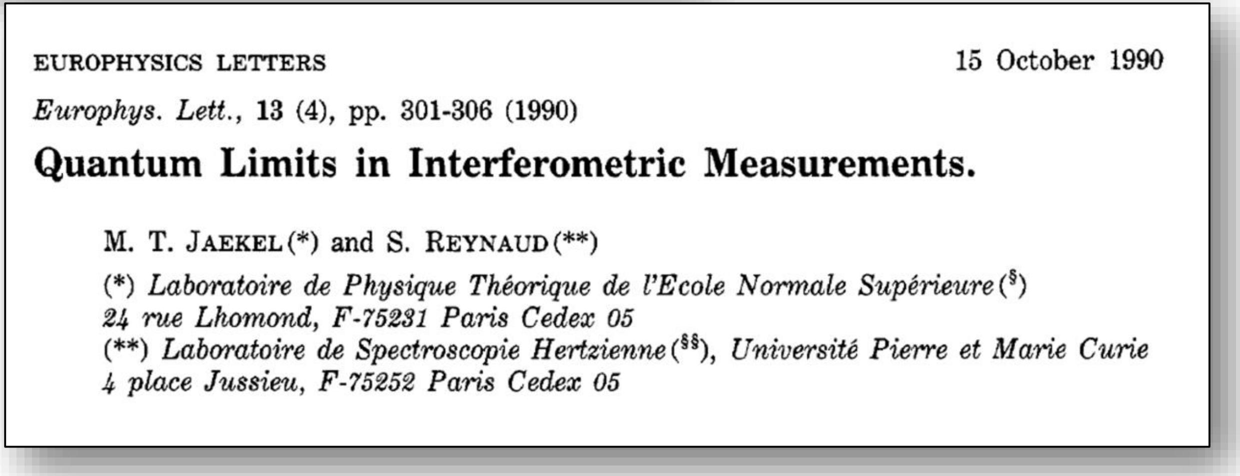
PHYSICAL REVIEW
LETTERS

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.



EUROPHYSICS LETTERS 15 October 1990

Europhys. Lett., 13 (4), pp. 301-306 (1990)

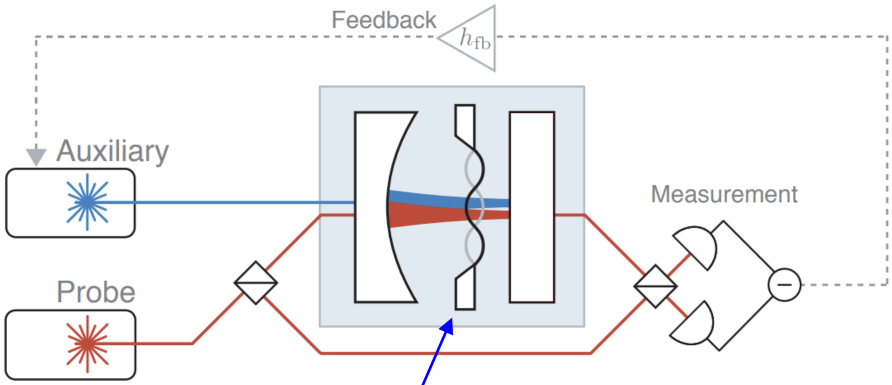
Quantum Limits in Interferometric Measurements.

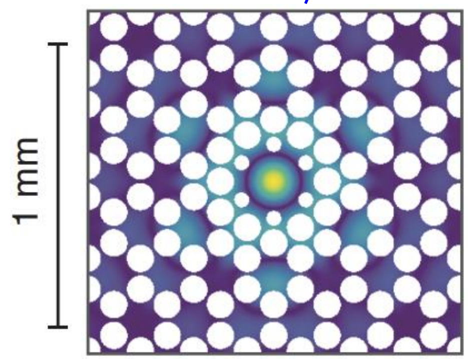
M. T. JAEKEL (*) and S. REYNAUD (**)

(*) *Laboratoire de Physique Théorique de l'Ecole Normale Supérieure* (§)
24 rue Lhomond, F-75231 Paris Cedex 05
(**) *Laboratoire de Spectroscopie Hertzienne* (§§), *Université Pierre et Marie Curie*
4 place Jussieu, F-75252 Paris Cedex 05

➙ Has motivated the emergence of quantum optics in the 80's and of quantum optomechanics in the 90's-2000's

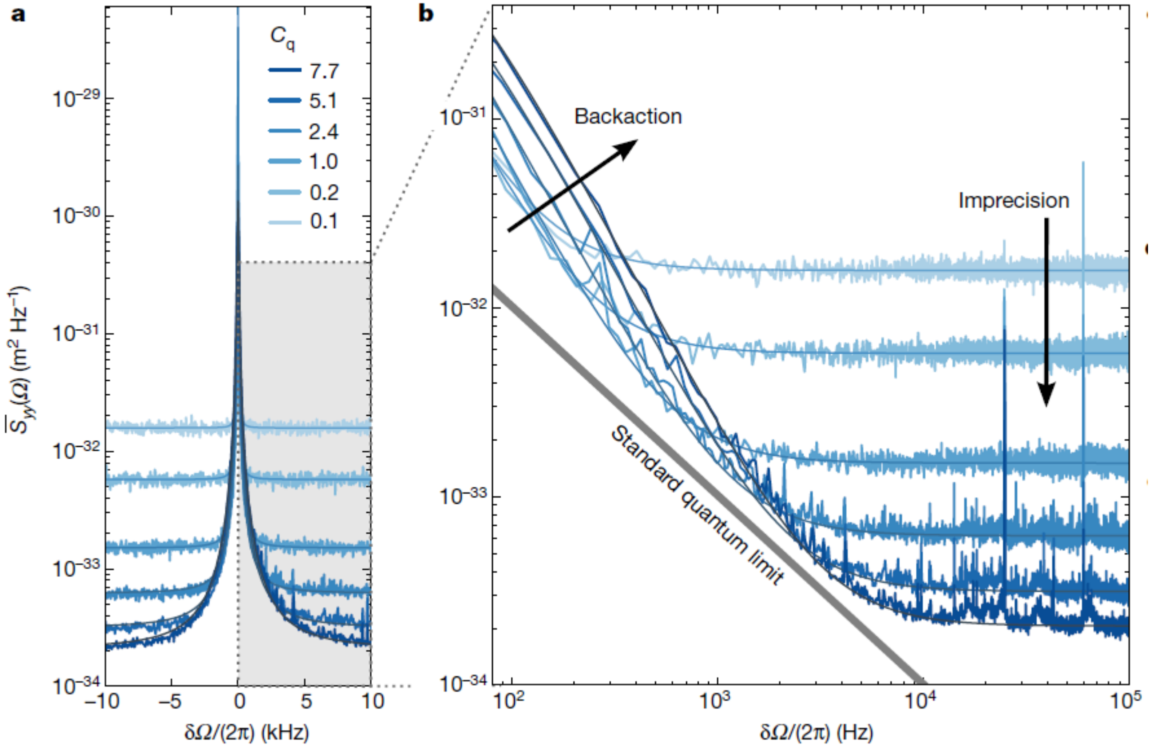
Demonstration of SQL with an optomechanical device





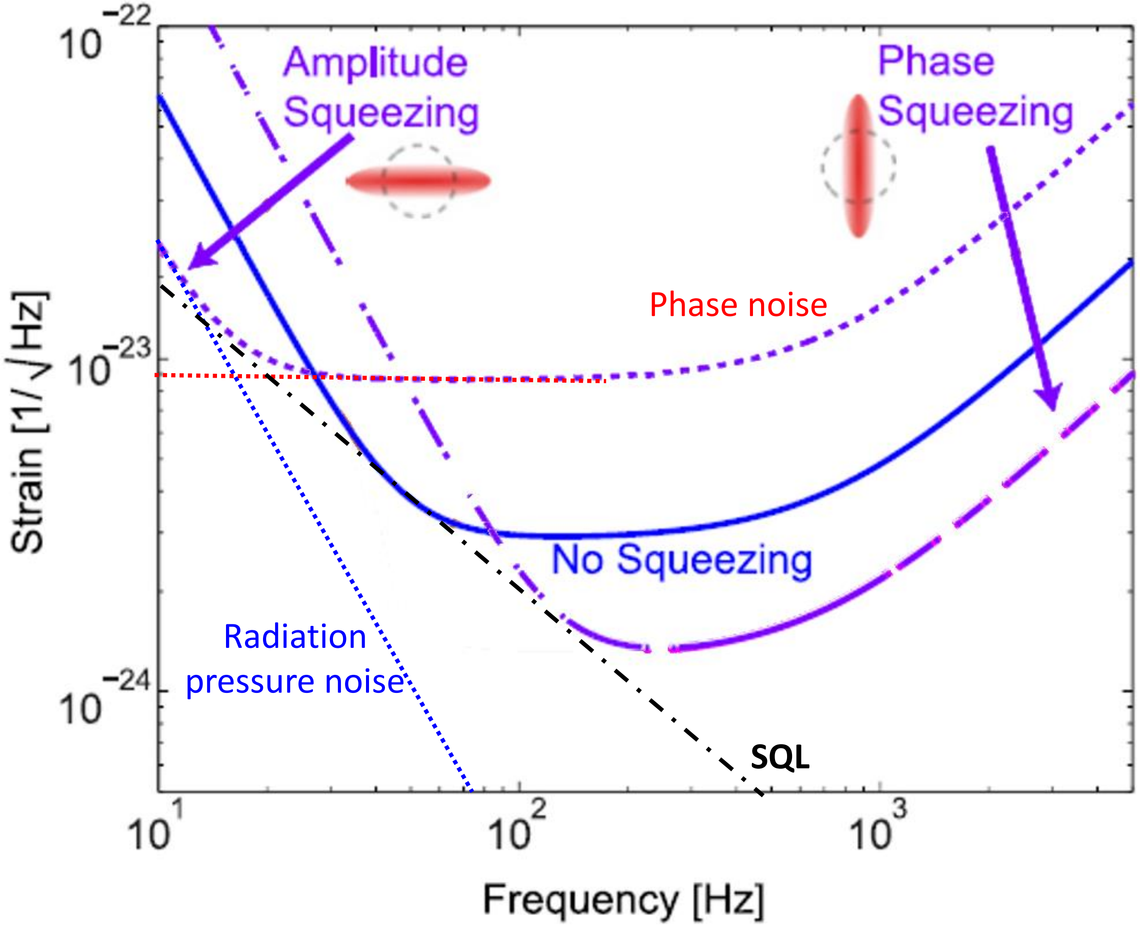
Very thin and light mechanical membrane in a high-finesse cavity

Schliesser, Nature (2018)



Beyond the SQL in gravitational-wave detectors

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



Beyond the SQL in gravitational-wave detectors

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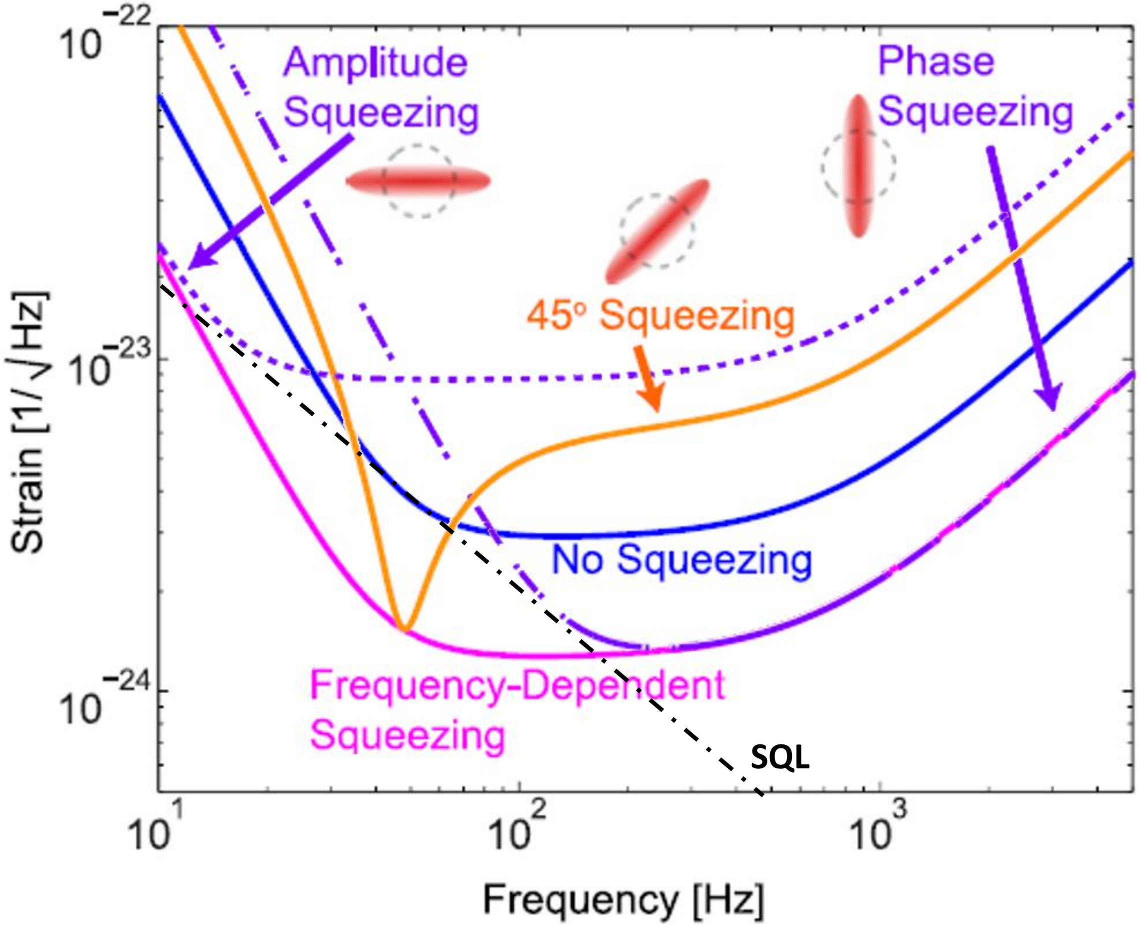


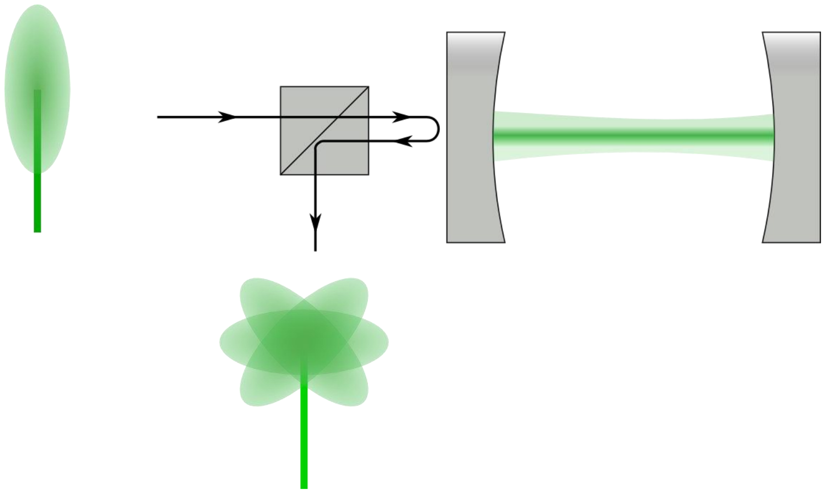
➙ Frequency dependent squeezing required!

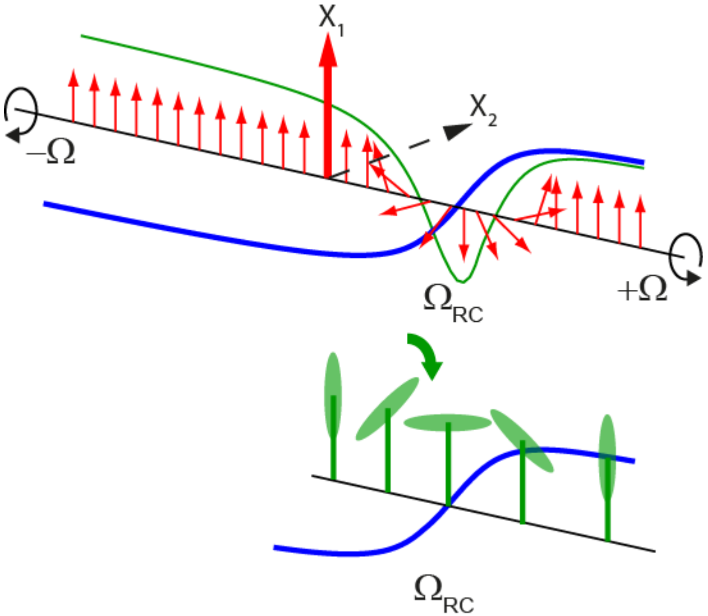
Frequency dependent squeezing

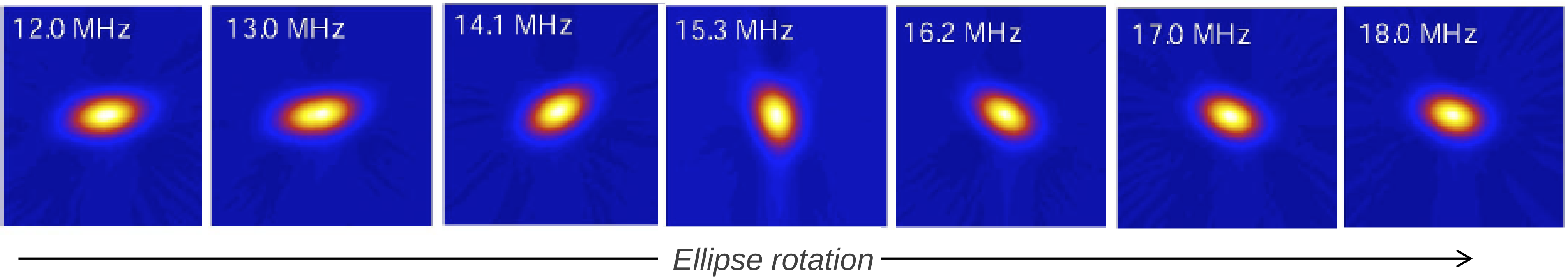
Rotate the squeezing ellipse with a detuned cavity

Rotate the squeezed sideband

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

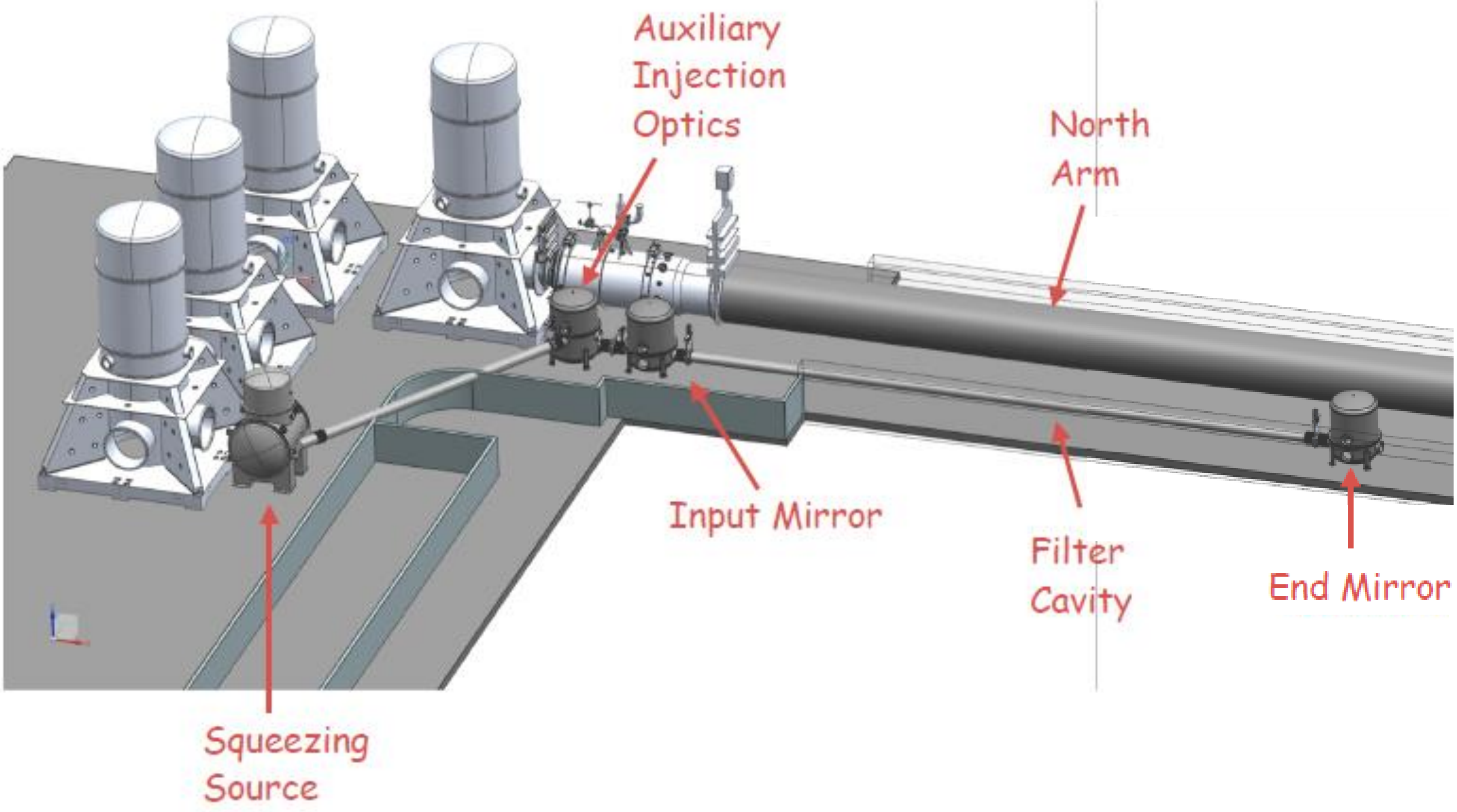






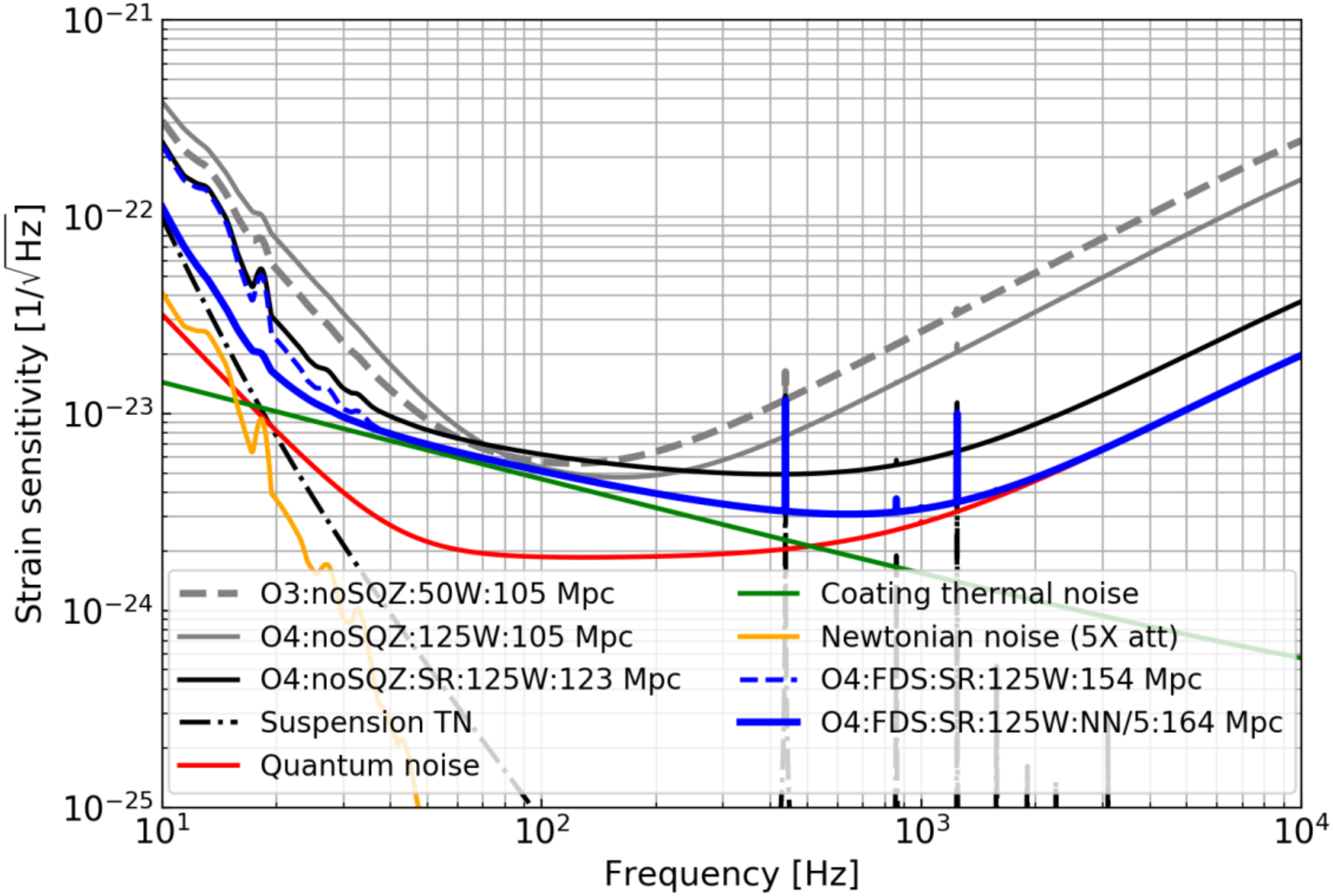
R. Schnabel et al., PRA (2005)

Installation in Advanced Virgo (run starting in 2023)



Installation in Advanced Virgo (run starting in 2023)

Expected sensitivity:

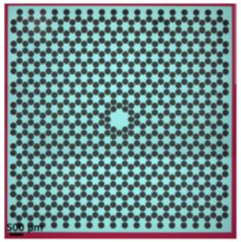


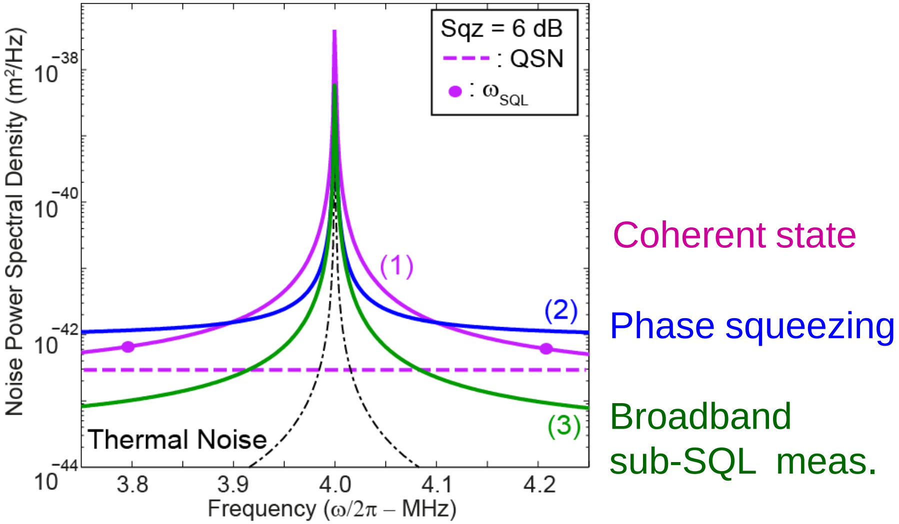
A. Bertolini (Nikhef)

Developments at LKB for Virgo

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

Use of a very high-quality nano-membrane



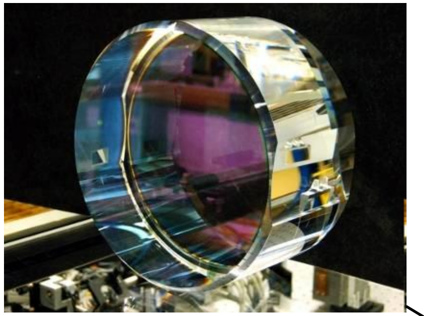


- Demonstration of frequency dependent squeezing with a corner frequency of 50Hz

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

CALVA group in Orsay

Conclusion: also 30 years of research on optomechanics!

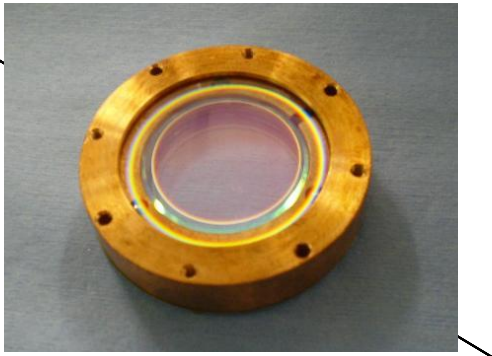


Gravitational interferometer mirror

High displacement sensitivity

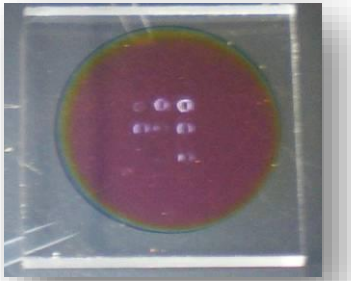
Mass ~ kg
Length ~ km
Frequency ~ Hz

Internal vibration modes
of cm-scale mirror



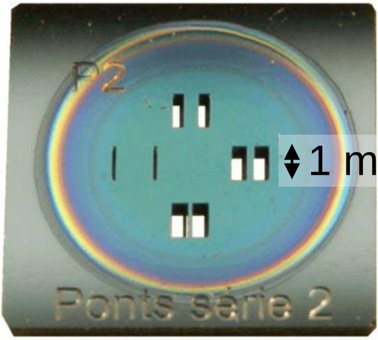
1999

Mass ~ g to µg
Length ~ mm
Frequency ~ kHz-MHz

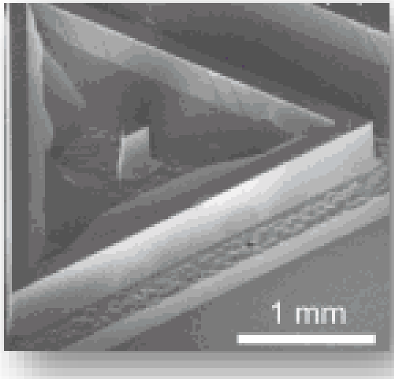


Small input mirrors

Micromirror
(MEMS)

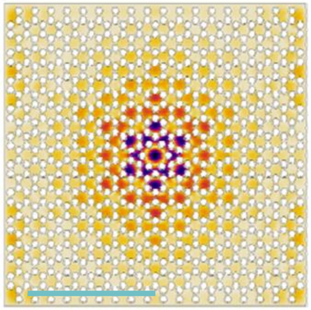


2006



Micro-pillars

Mass ~ pg
Length ~ nm
Frequency ~ MHz-GHz

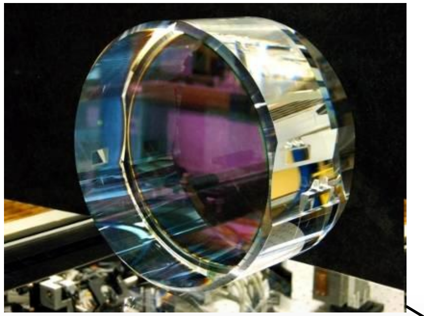


Nanoresonator

High mechanical response

2021

Conclusion: also 30 years of research on optomechanics!



Gravitational interferometer mirror

High displacement sensitivity

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Length ~ km

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of cm-scale mirror

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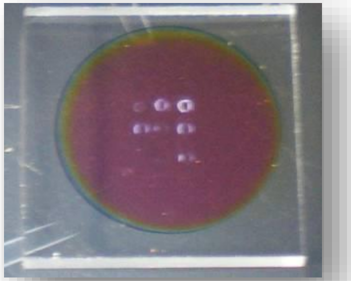


Small input mirrors

Mass ~ g to µg

Length ~ mm

Frequency ~ kHz-MHz

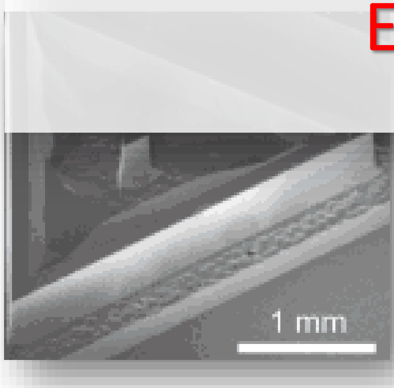
Merci au LMA pour toutes ces années de collaboration

Bon 30ème anniversaire !

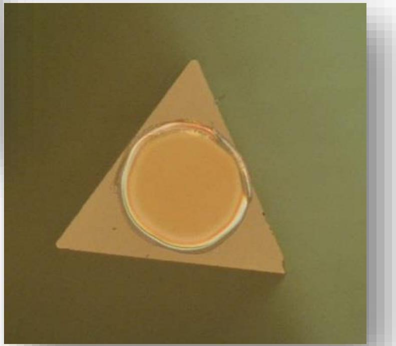
Et merci à tous pour votre attention

Micromirror
(MEMS)

2006



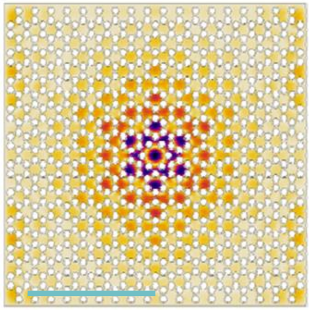
Micro-pillars



Mass ~ pg

Length ~ nm

Frequency ~ MHz-GHz



Nanoresonator

High mechanical response

2021