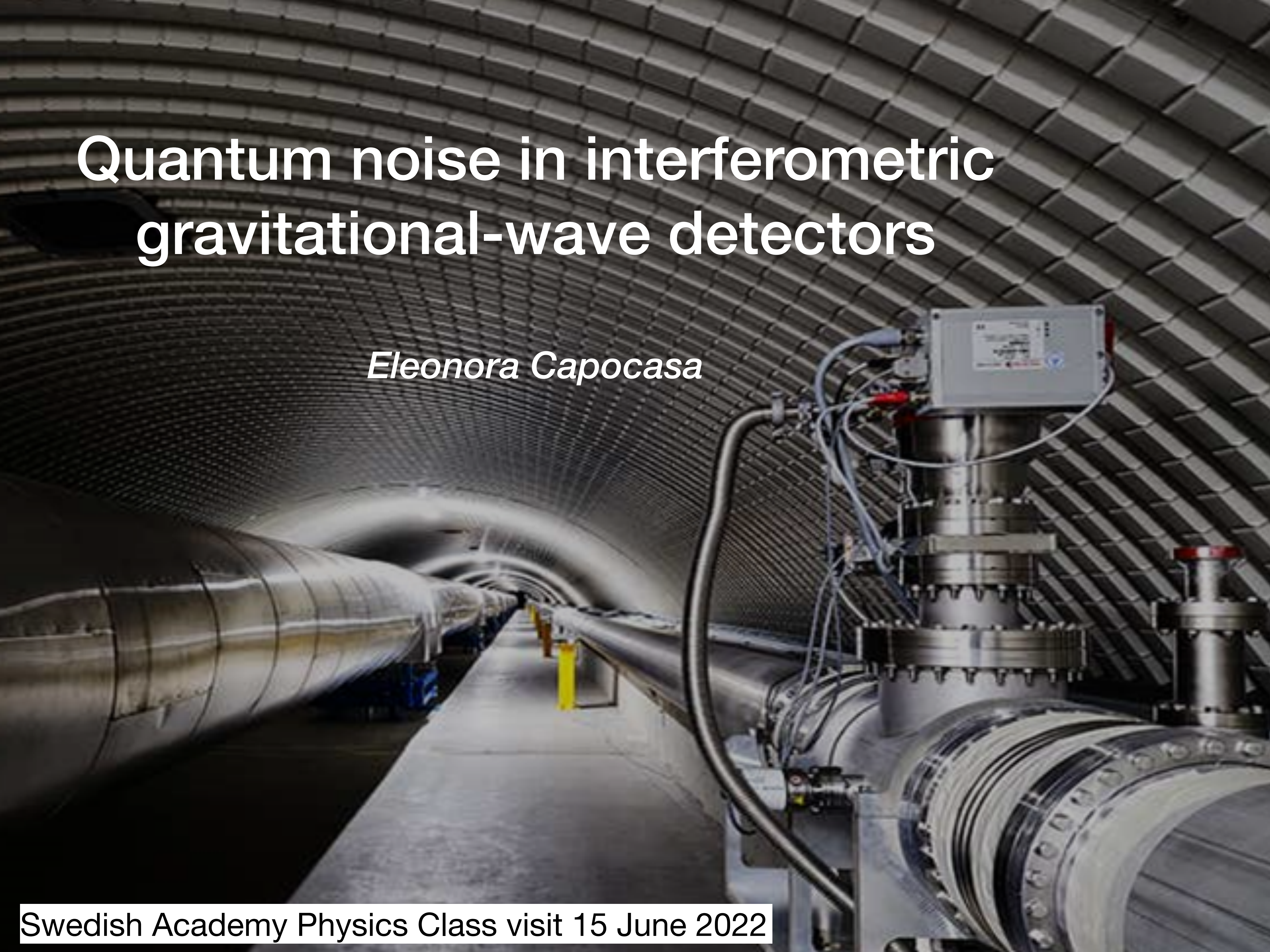


Quantum noise in interferometric gravitational-wave detectors

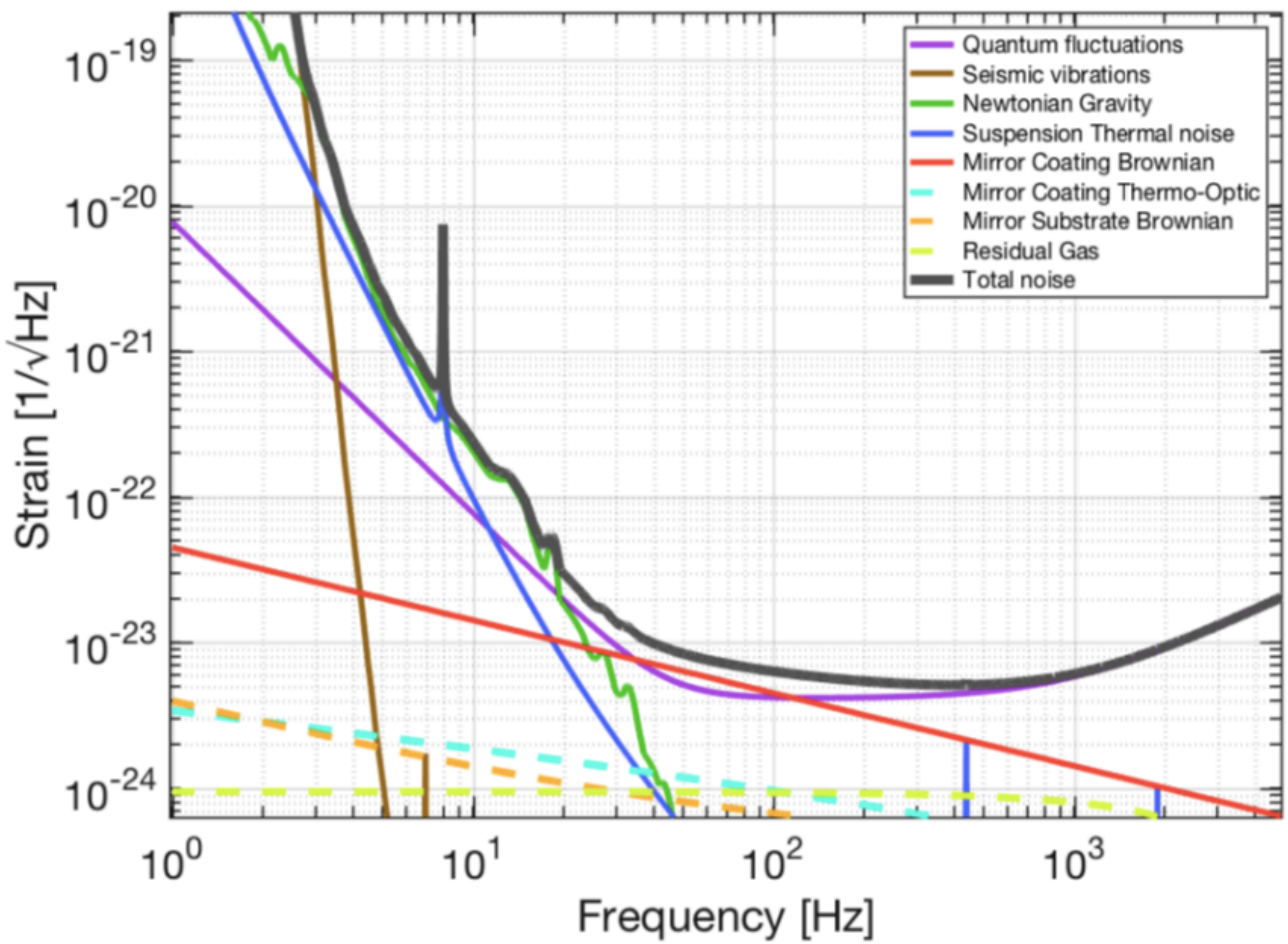
Eleonora Capocasa

Swedish Academy Physics Class visit 15 June 2022

Quantum noise

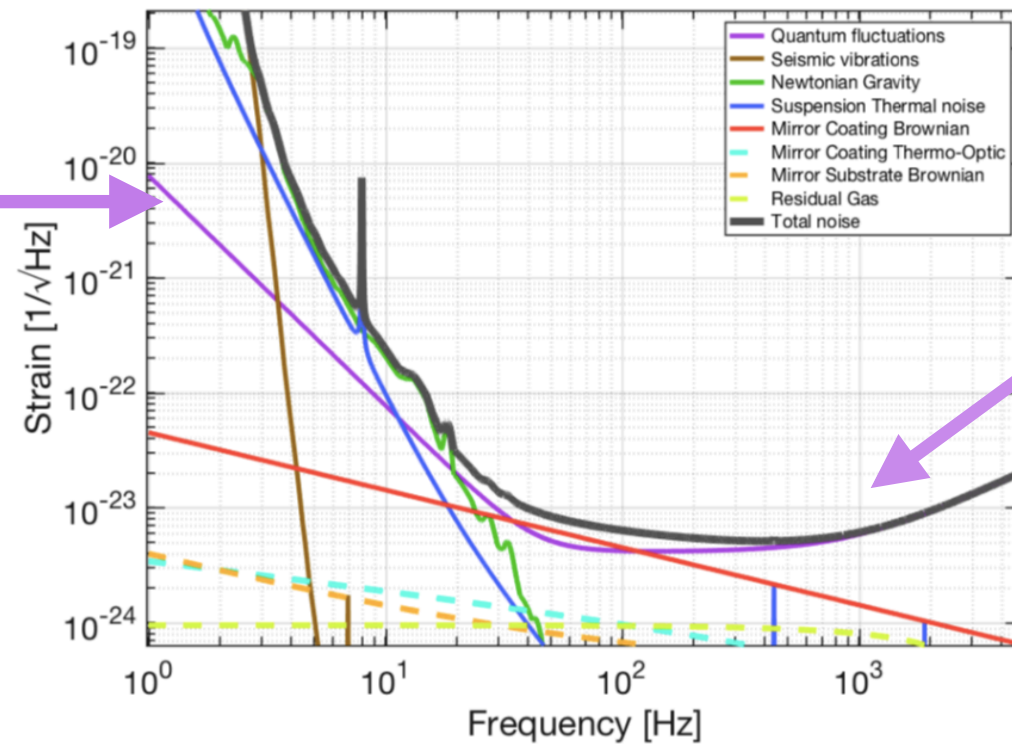
- Main limiting noise of current and future GW detectors
- Intrinsic limitation of the interferometric measurements

AdVirgo noise budget



Quantum noise: a semiclassical picture

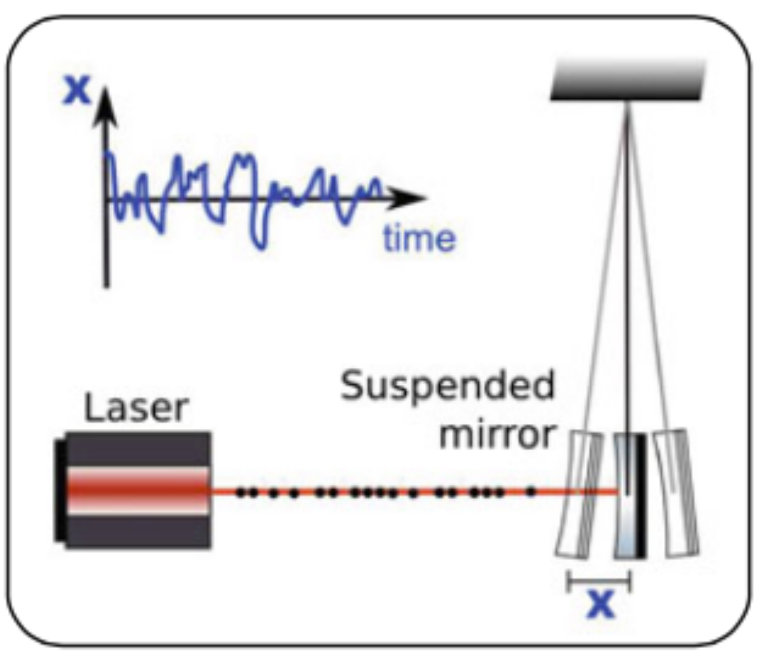
Radiation pressure noise

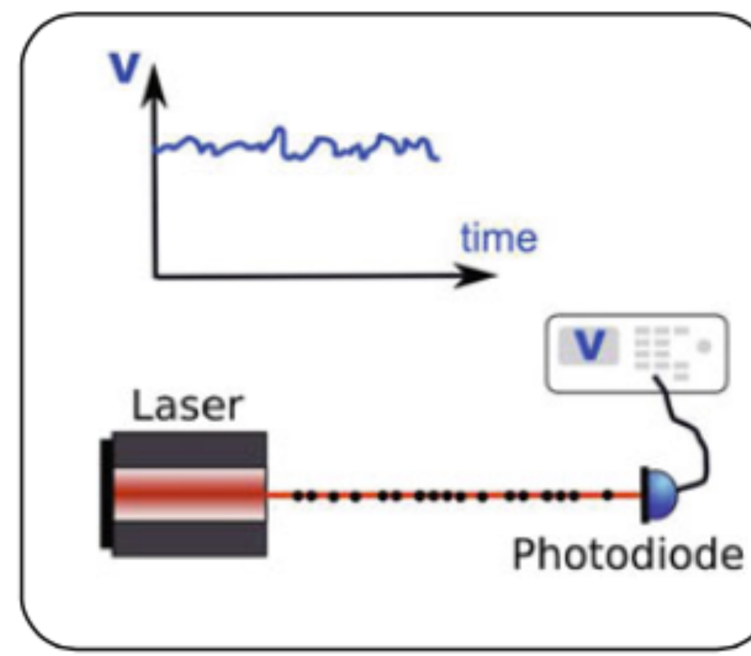


Shot noise

$$h_{\rm rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c\lambda}}$$

$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$

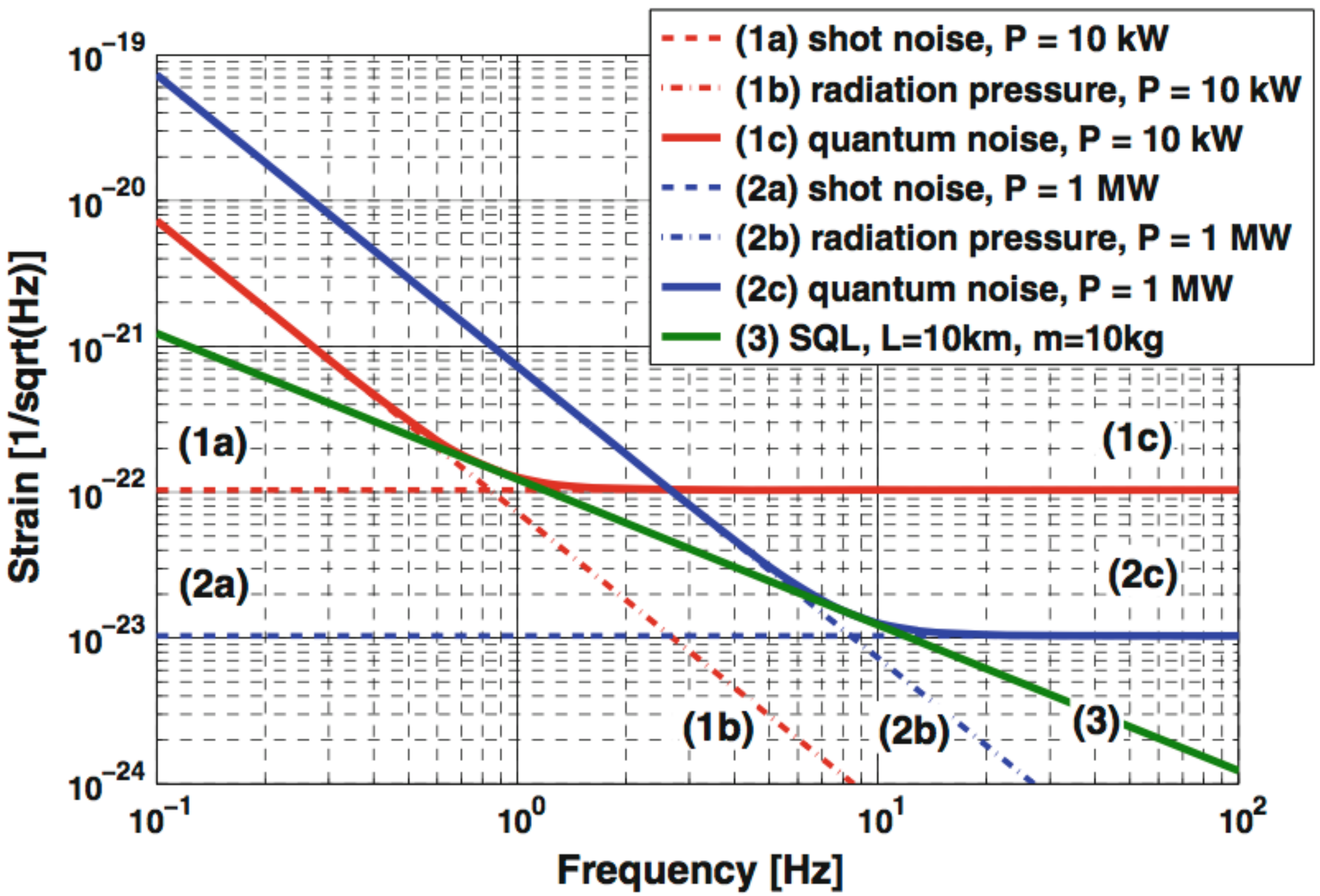




- Fluctuation in the momentum transferred to the mirror

- Poissonian statistics on the photon arrival time

The standard quantum limit (SQL)



$S_{SQL} = 8\hbar/(m\Omega^2 L^2)$

- It comes from Heisenberg uncertainty principle
- It is not a fundamental limit for our measurements

Radiation pressure noise origin

- In the '80 Caves solves the controversy on the radiation pressure effect
- It proposes a new picture to explain quantum noise in interferometers

PHYSICAL REVIEW LETTERS

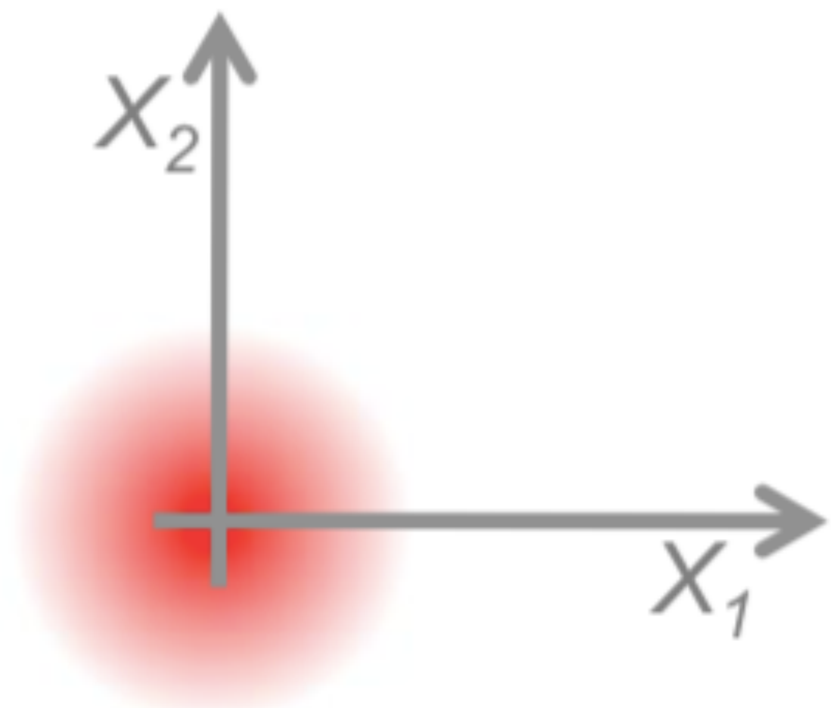
VOLUME 45 | 14 JULY 1980 | NUMBER 2

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.

Quantum representation: the quadrature picture



- Quantization of the EM field

$$\hat{E}(t) = \left[E_0 + \hat{E}_1(t)\right] \cos \omega_0 t + \hat{E}_2(t) \sin \omega_0 t$$

- Laser (and vacuum) are described by coherent states

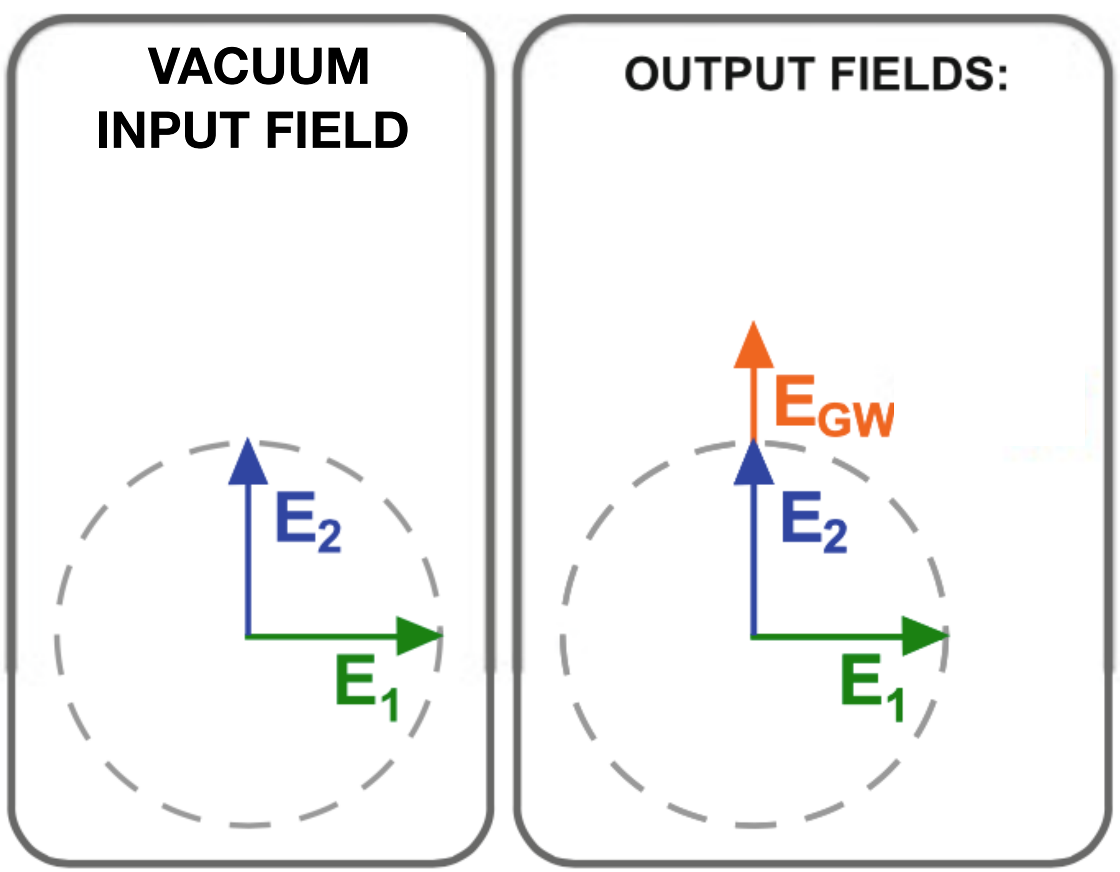
- Amplitude and phase fluctuations equally distributed and uncorrelated

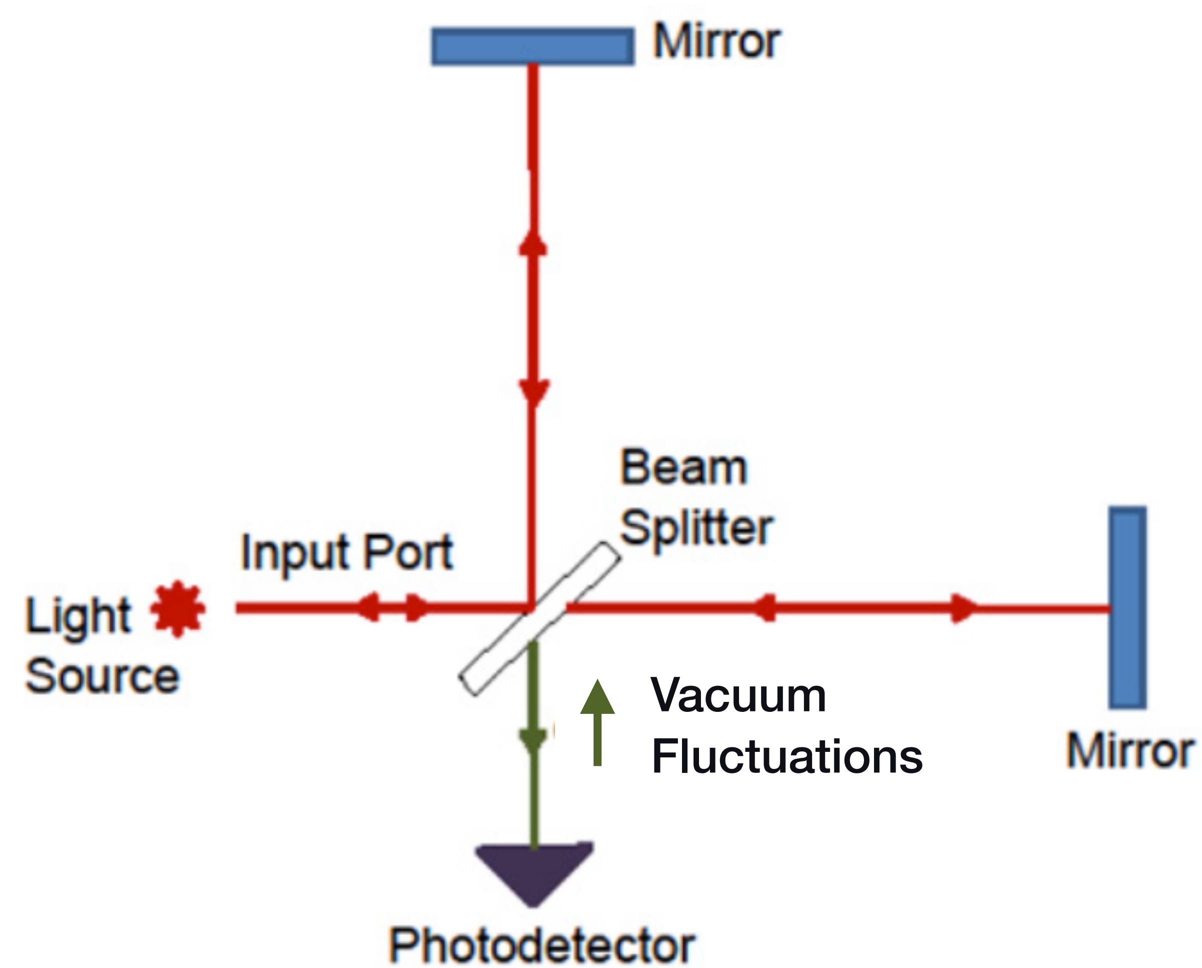
- In frequency domain is described by two quantum operators accounting for quantum fluctuation in each quadrature

$$\vec{a}(\Omega) = \begin{pmatrix} a_1(\Omega) \\ a_2(\Omega) \end{pmatrix}$$

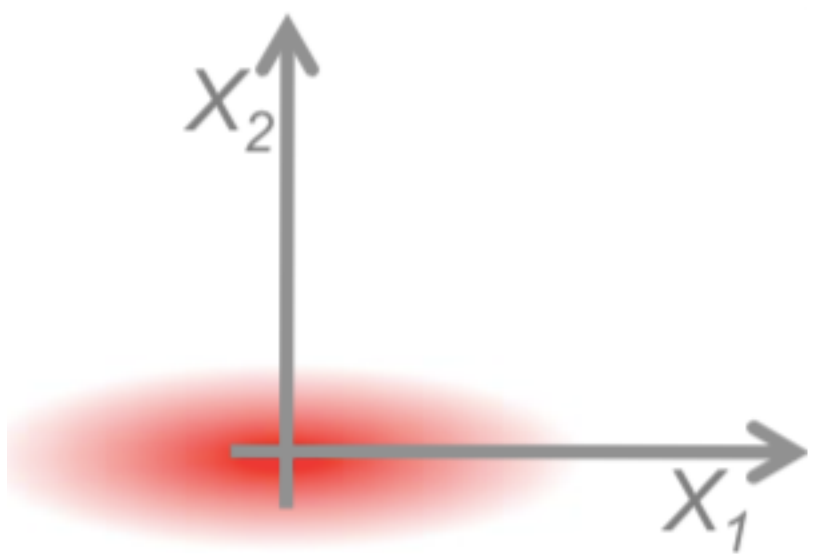
Quantum noise in GW interferometers

- If the cavities are symmetric, only vacuum fluctuations are responsible for quantum noise
- Standard quantum limit can be circumvented introducing correlation between vacuum fluctuations





Squeezed states

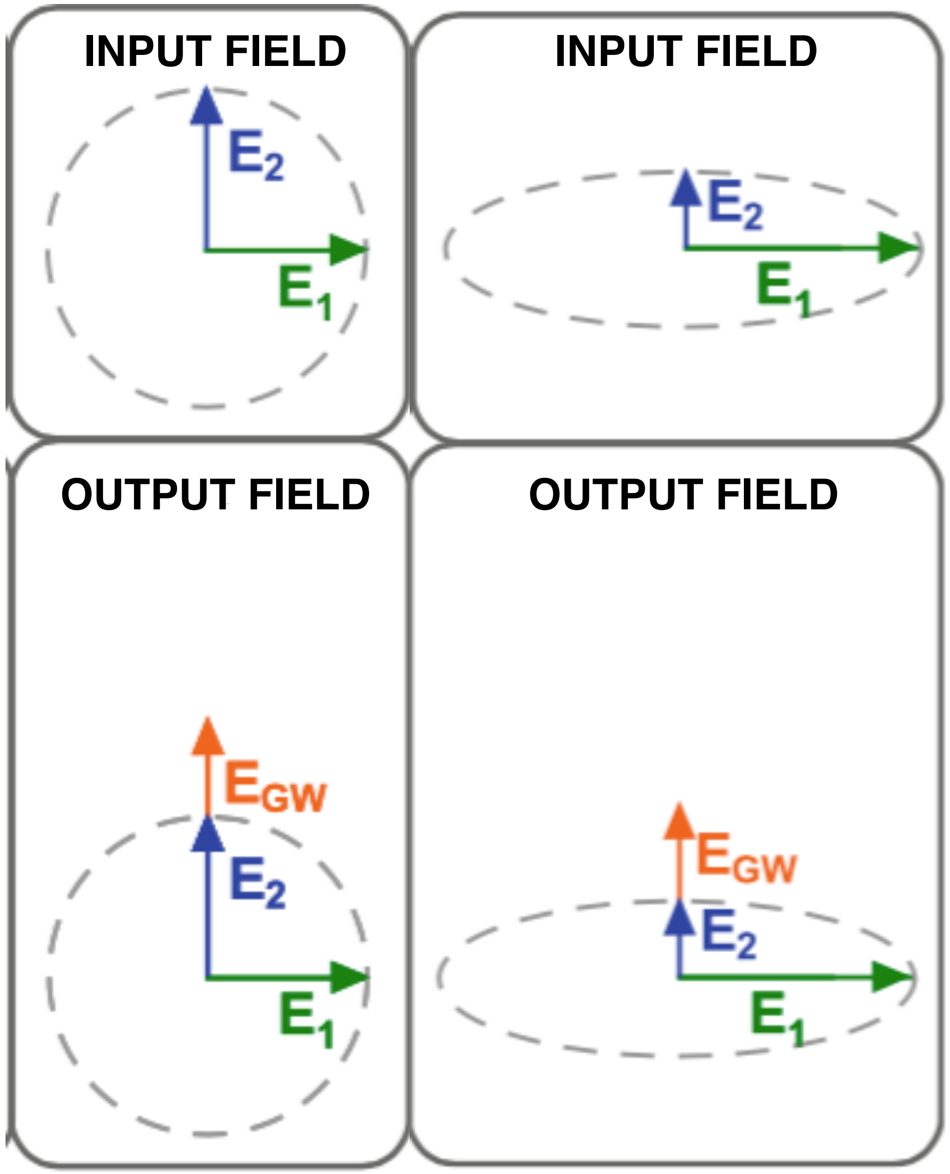


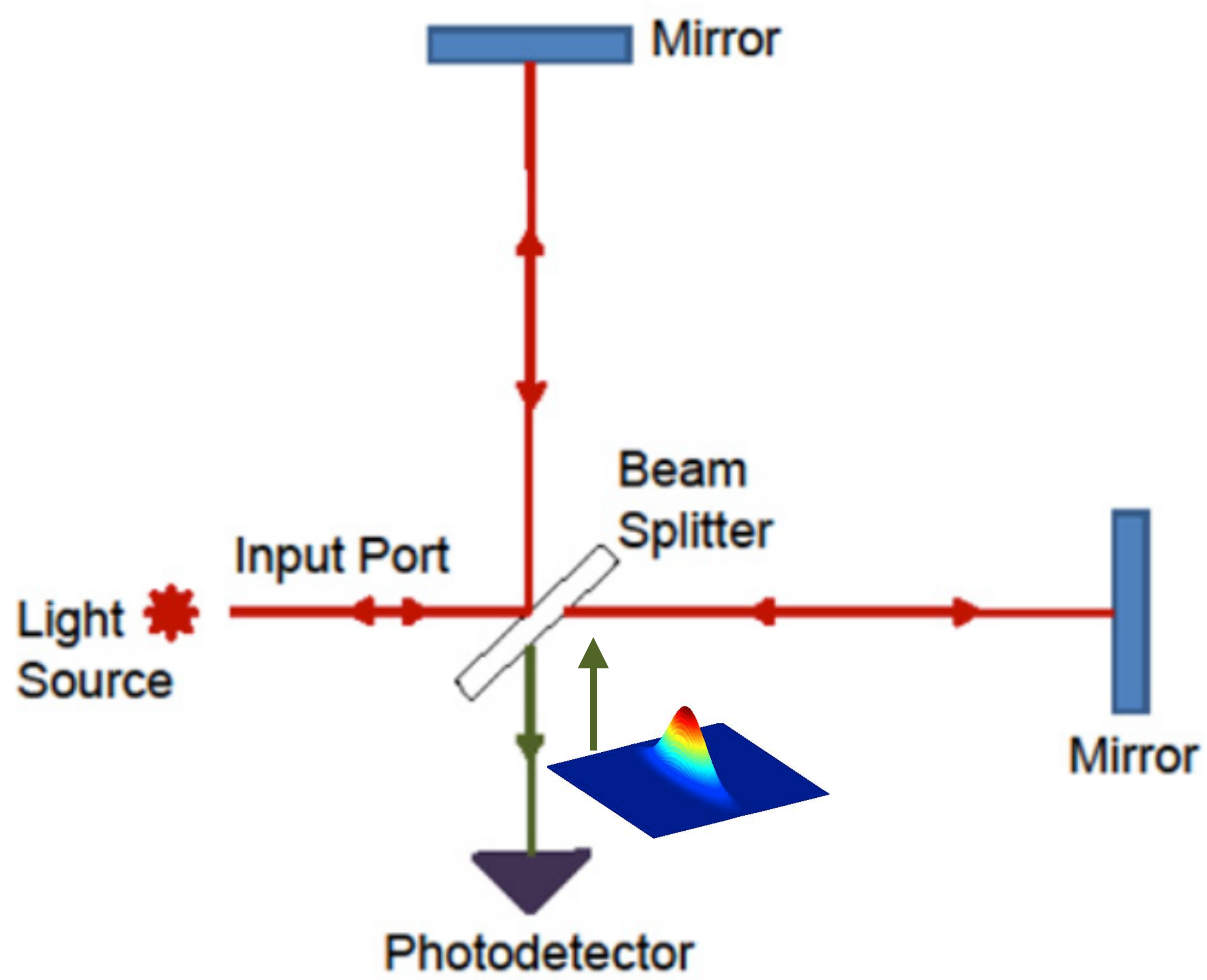
- Non classical light state
- Noise in one quadrature is reduced with respect to the one of a coherent state

Each state is characterized by:

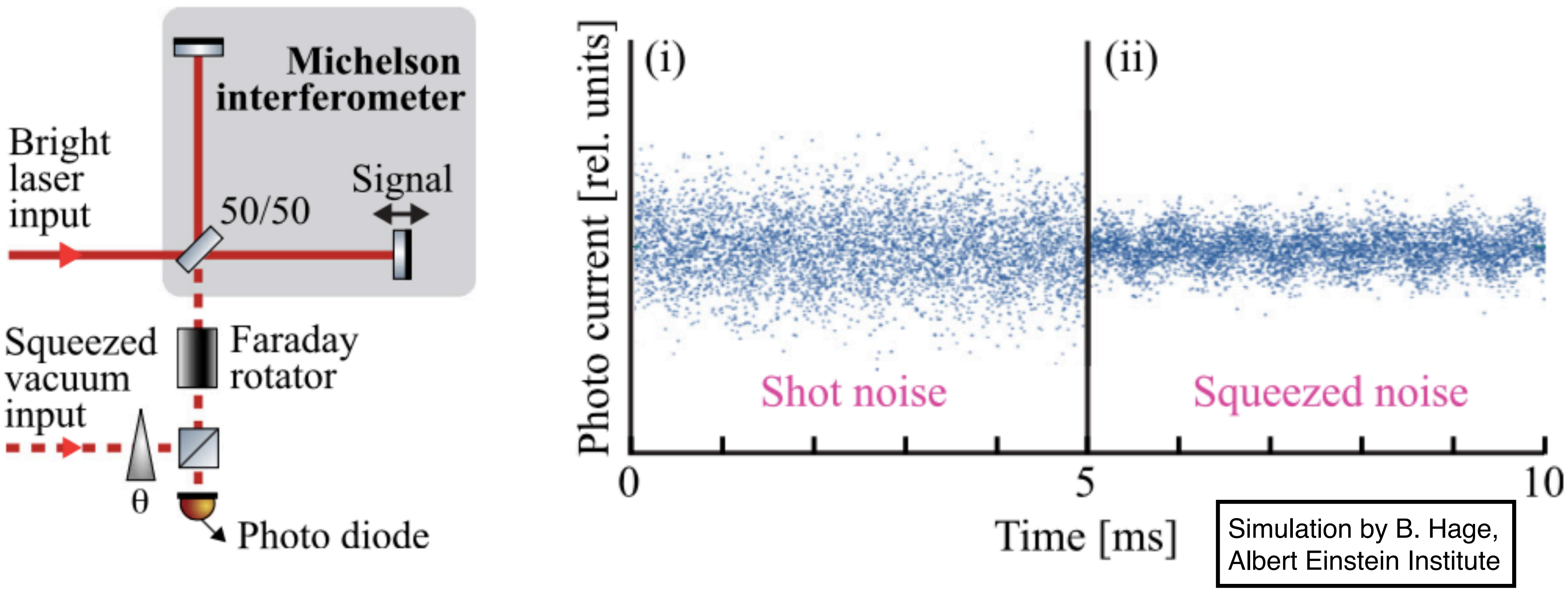
- Squeezing factor (magnitude of the squeezing)
- Squeezing angle (orientation of the ellipse)

Quantum noise reduction using squeezed light





Quantum noise reduction using squeezed light



- Simulated output of Michelson interferometer where a signal is produced by modulating the relative arm length
- With squeezing the shot noise is reduced and a sinusoidal signal is visible

Quantum noise in GW interferometers

PHYSICAL REVIEW D 15 APRIL 1981

Quantum-mechanical noise in an interferometer

Carlton M. Caves

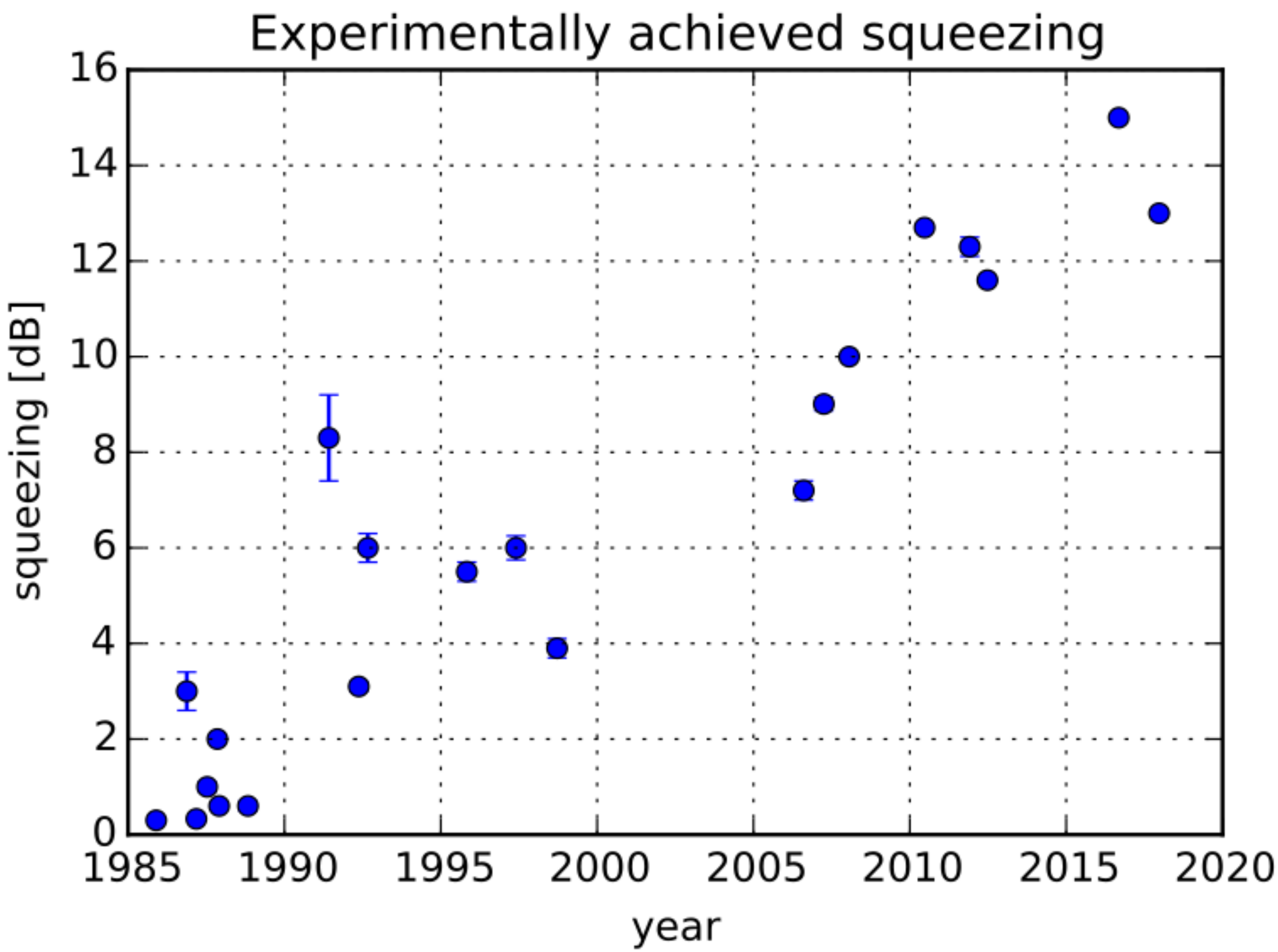
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

VOLUME 23, NUMBER 8

IV. CONCLUSION

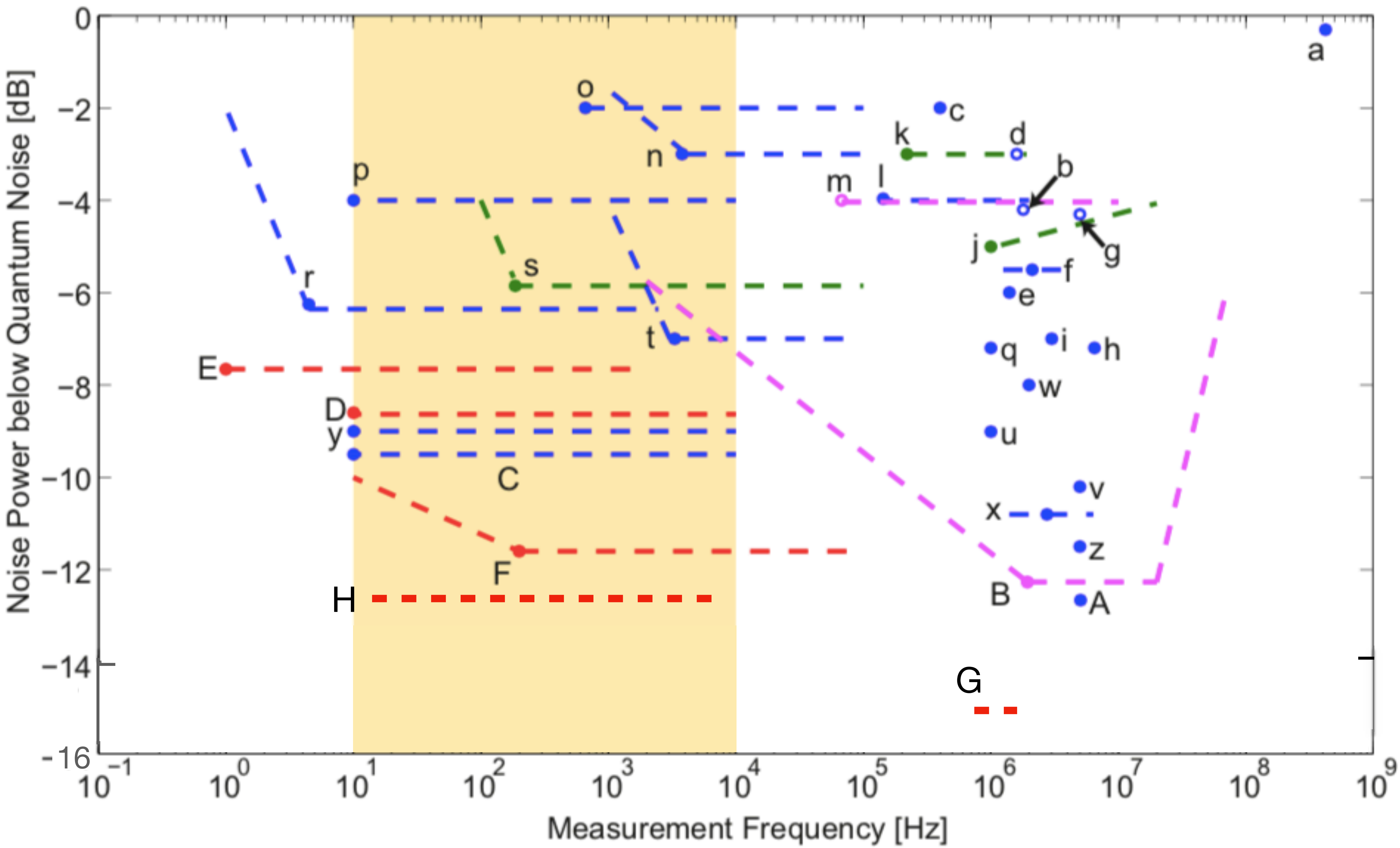
The squeezed-state technique outlined in this paper will not be easy to implement. A refuge from criticism that the technique is difficult can be found by retreating behind the position that the entire task of detecting gravitational radiation is exceedingly difficult. Difficult or not, the squeezed-state technique might turn out at some stage to be the only way to improve the sensitivity of interferometers designed to detect gravitational waves. As interferometers are made longer, their strain sensitivity will eventually be limited by the photon-counting error for the case of a storage time approximately equal to the desired measurement time. Further improvements in sensitivity would then await an increase in laser power or implementation of the squeezed-state technique. Experimenters might then be forced to learn how to very gently squeeze the vacuum before it can contaminate the light in their interferometers.

40 years of experimental developments



https://commons.wikimedia.org/wiki/File:Squeezed-light-timeline.svg

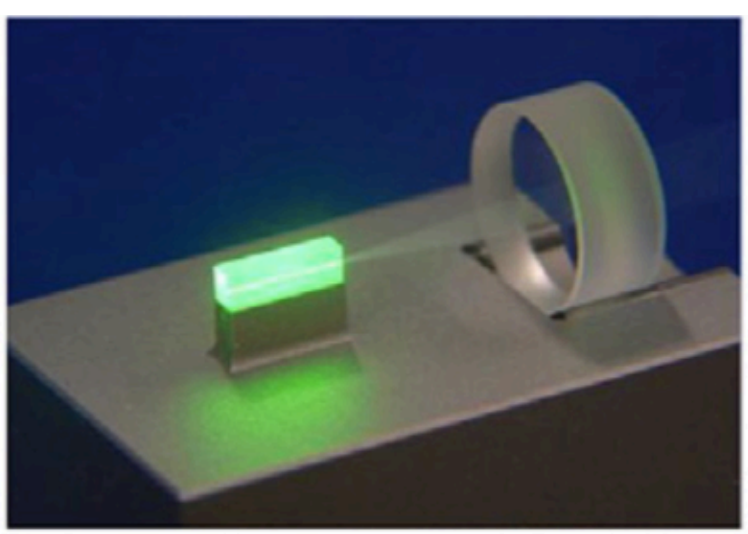
Goal: squeezing in the audio frequency bandwidth

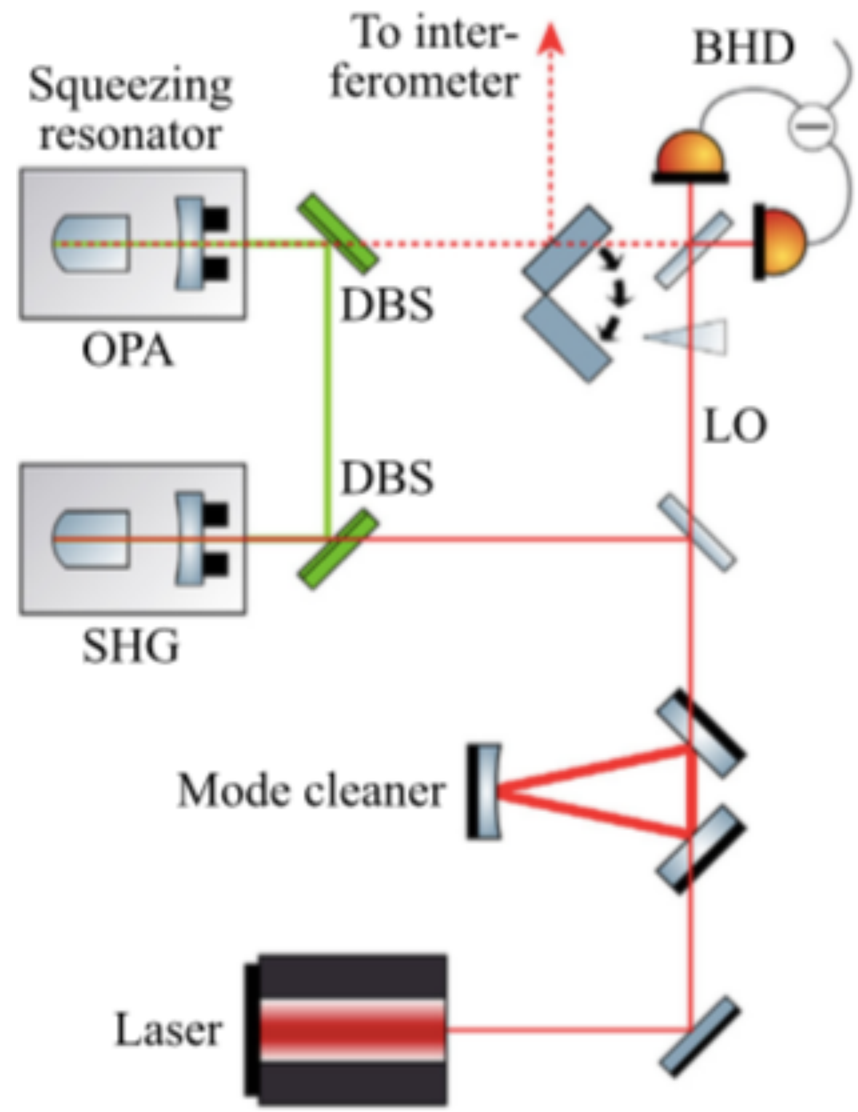


Adapted from S. Chua PhD Thesis

How to generate a squeezed state: non linear interaction

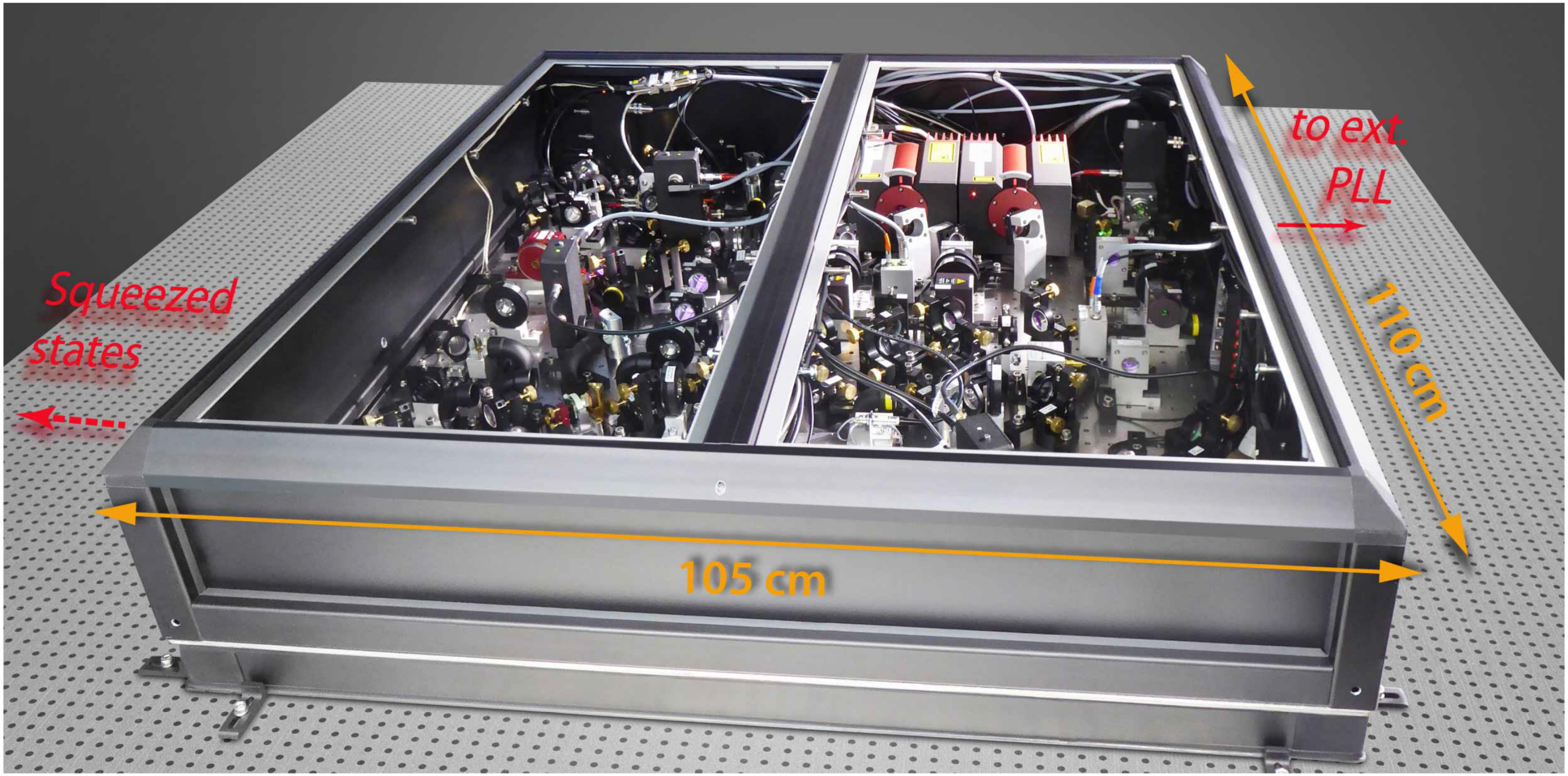
- Squeezing is produced inducing correlation between quantum fluctuations
- The most effective way to generate correlation is a optical parametric oscillator (OPO)
- OPO uses non linear crystal to create correlation between quadratures





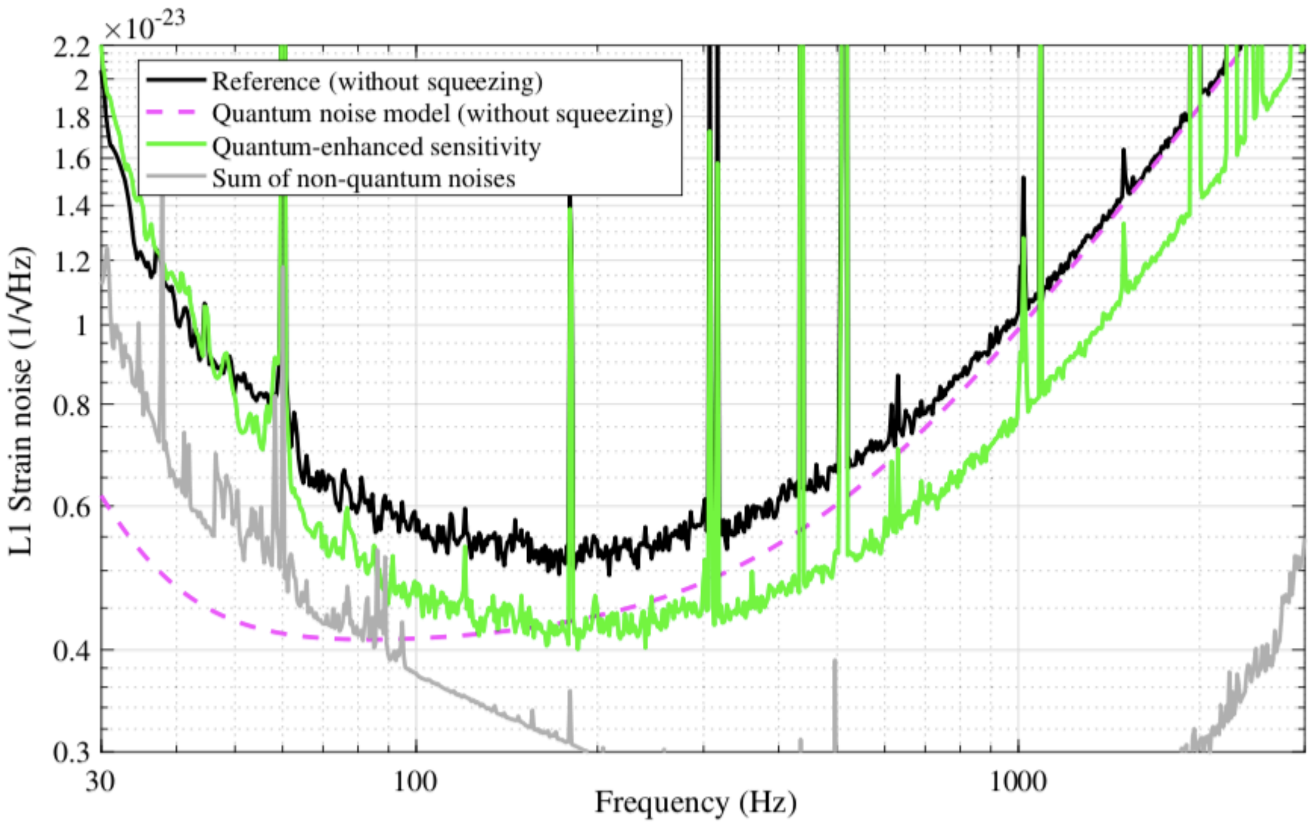
R. Schnabel- Physics Reports 684 (2017) 1–51

Vacuum squeezed source



Advanced Virgo squeezed vacuum source

Application to 2G detectors: results

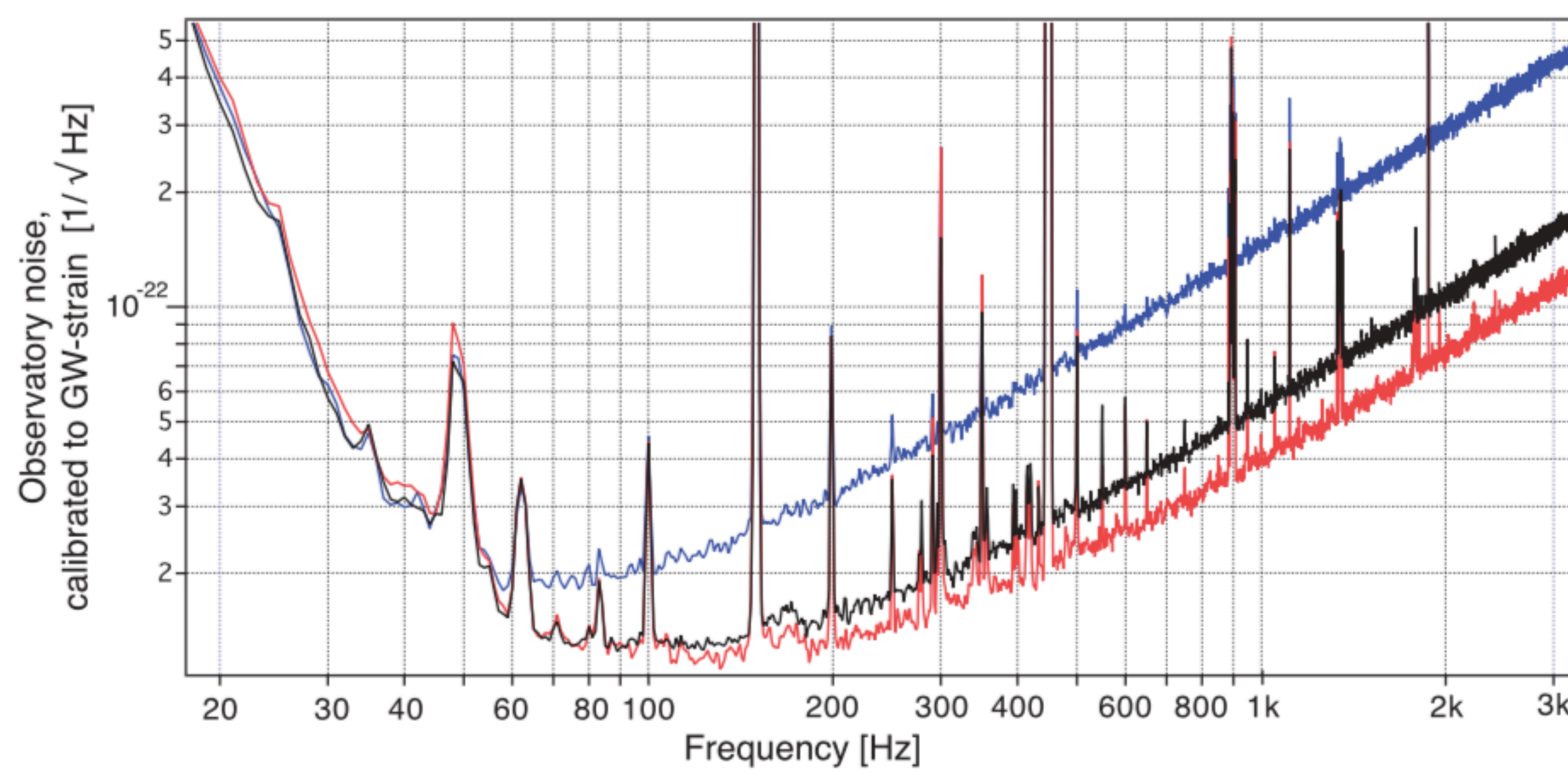


Advanced LIGO

- Best measured ~3 dB
- BNS Range improvement: 14%
- Detection rate improvement: 50%

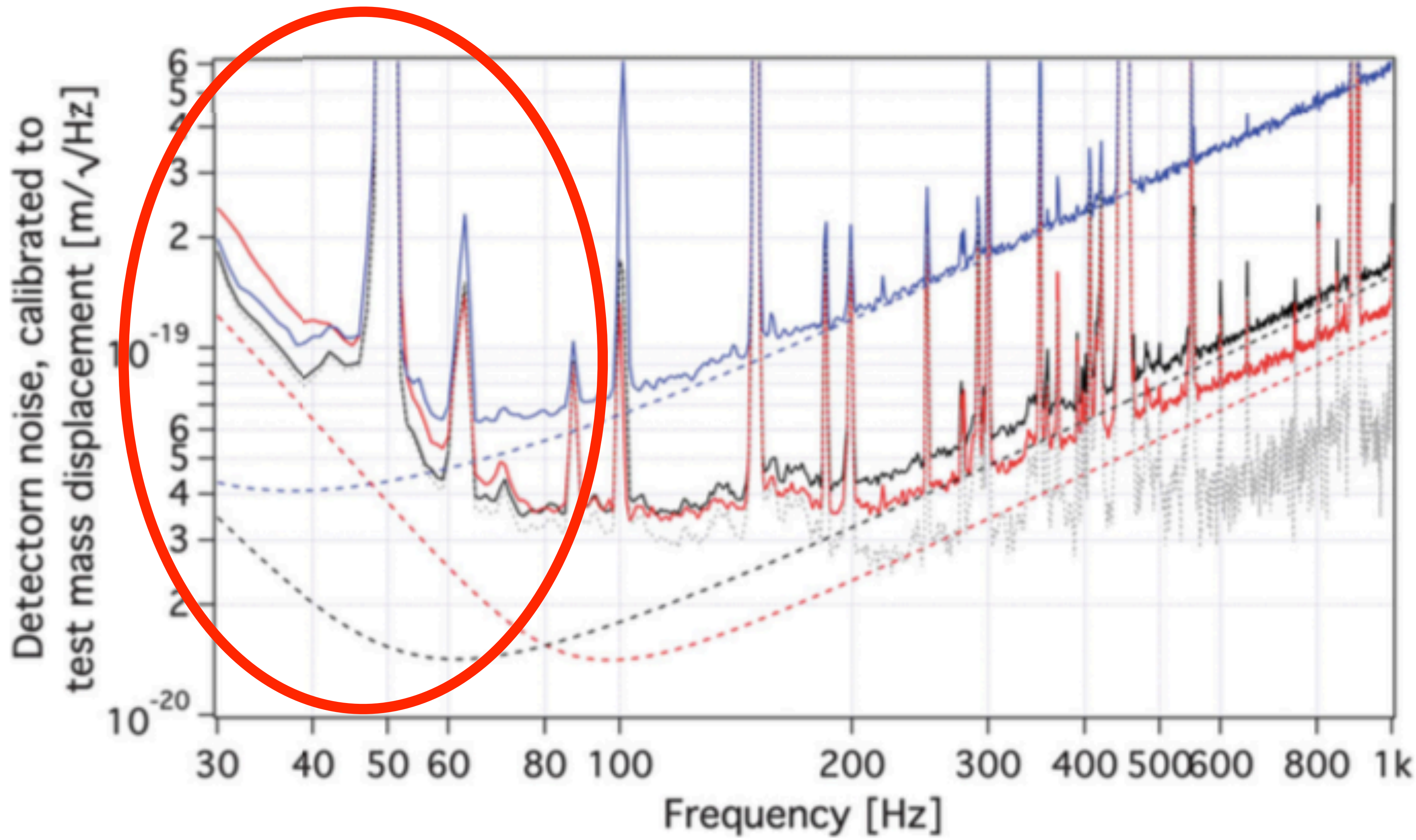
Advanced Virgo

- Best measured ~3dB
- BNS Range improvement: 5%-8%
- Detection rate improvement: 16-26%



Broadband quantum noise reduction?

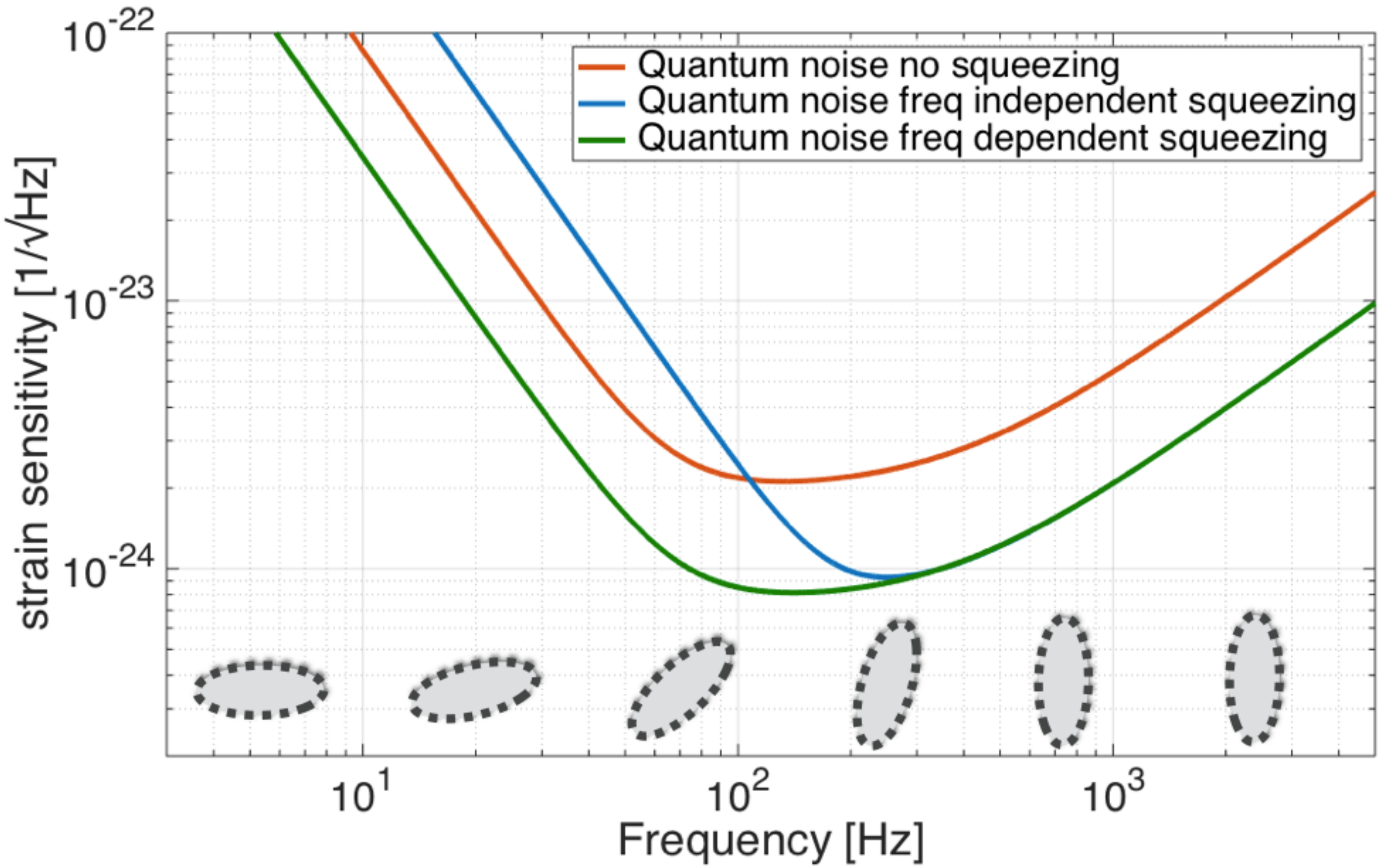
- Phase squeezed noise reduces shot noise but increase radiation pressure noise
- Effects already observed in O3



Quantum Backaction on kg-Scale Mirrors: Observation of Radiation Pressure Noise in the Advanced Virgo Detector
PHYSICAL REVIEW LETTERS 125, 131101 (2020)

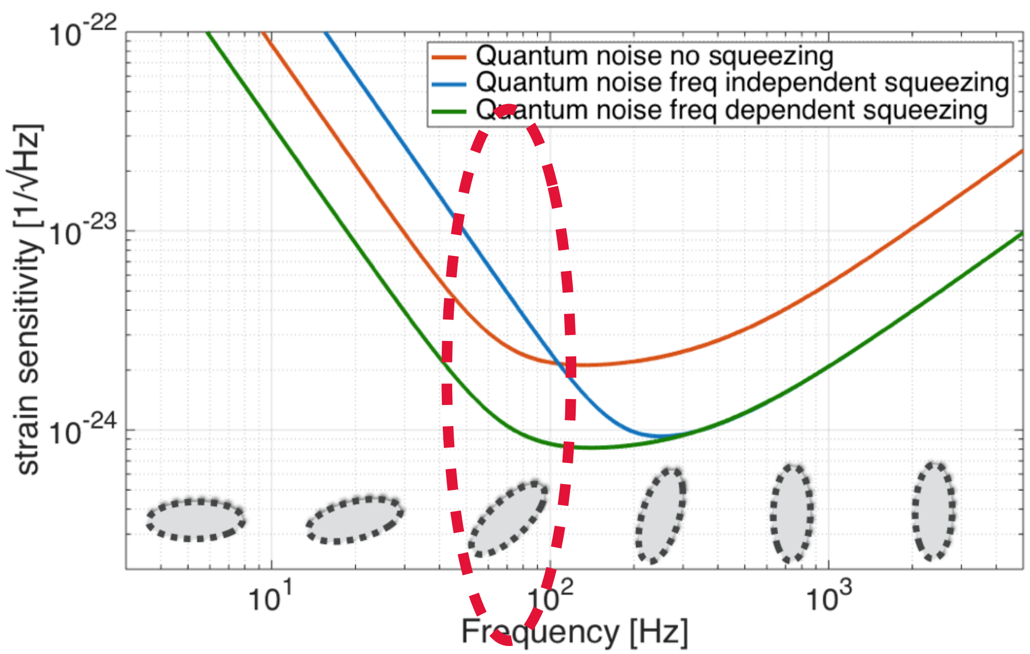
Broadband quantum noise reduction

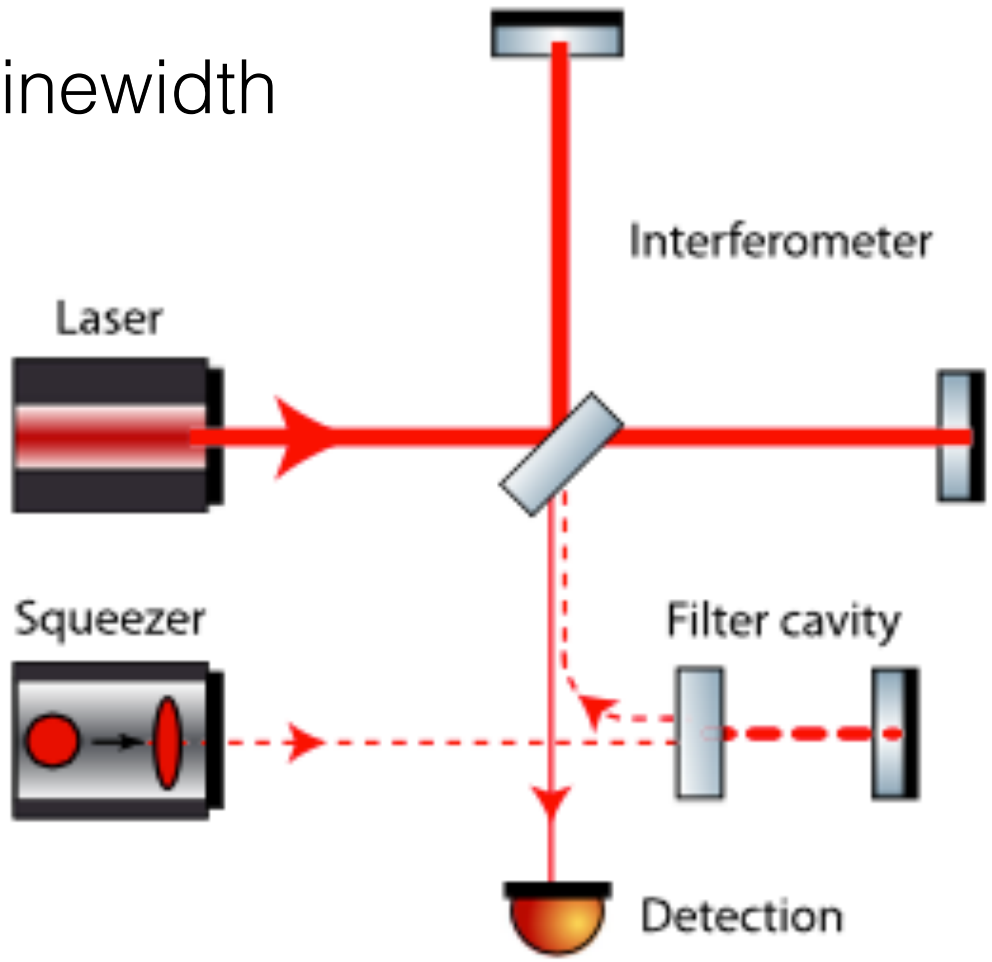
- Squeezing ellipse undergoes a rotation inside the interferometer
- Squeezing angle should change with the frequency for optimal noise reduction



Frequency dependent squeezing via filter cavity

- Reflect frequency independent squeezing off a detuned Fabry-Perot cavity
- Rotation frequency depends on cavity linewidth

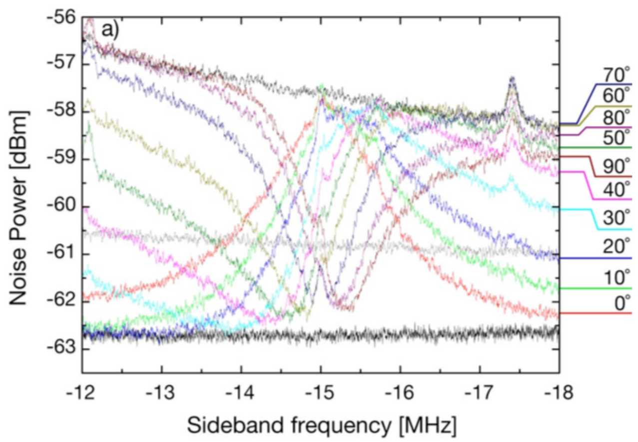




- Optimal rotation frequency around 25 Hz for Advirgo

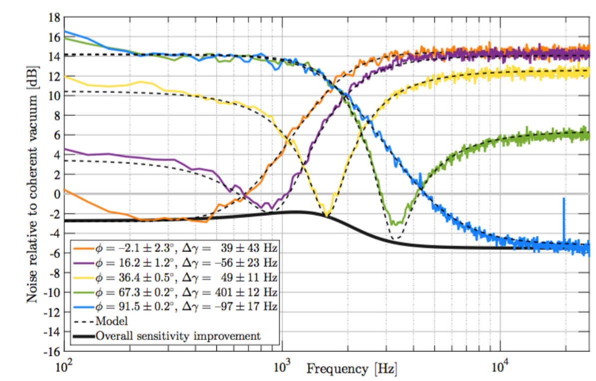
Squeezing angle rotation already realized

@ MHz frequency (2005)



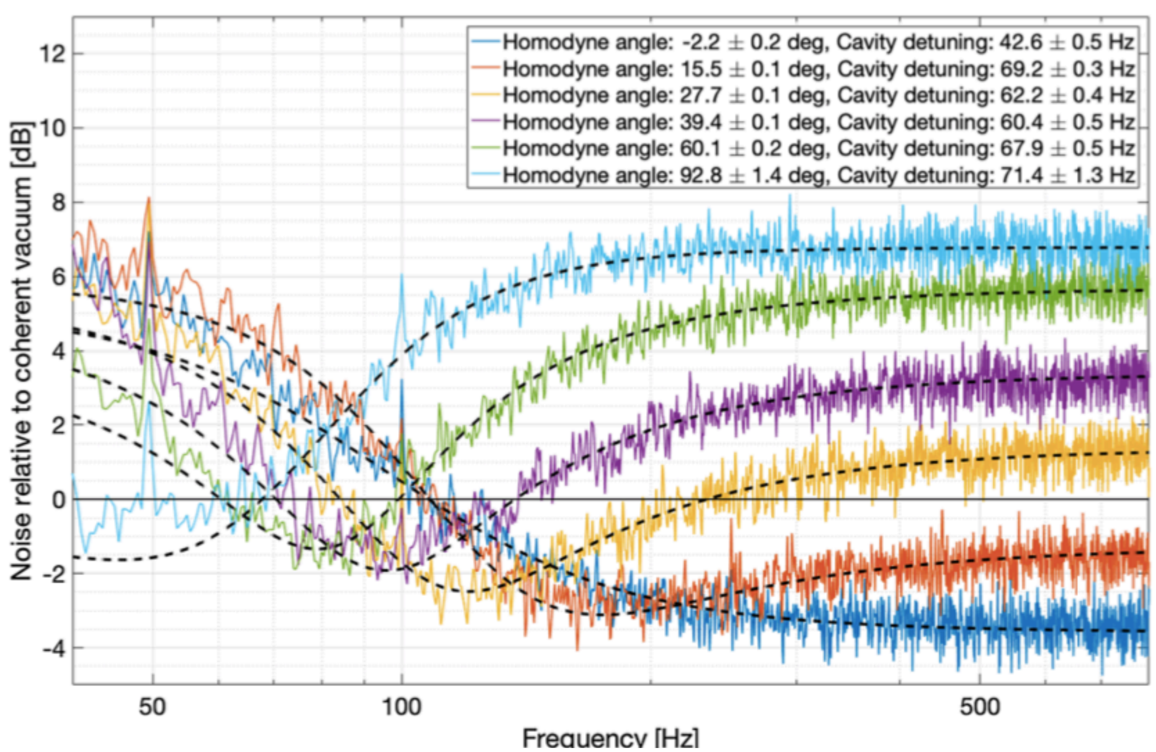
PHYSICAL REVIEW A **71**, 013806 (2005)

@ kHz frequency (2016)

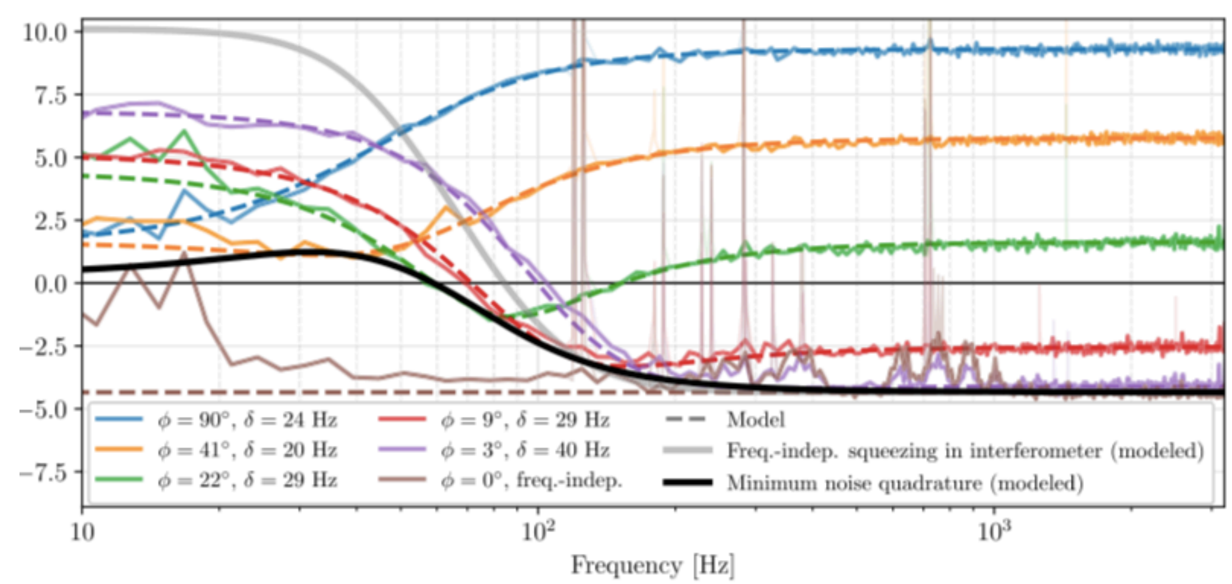


PRL **116,** 041102 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Below 100 Hz (2020)



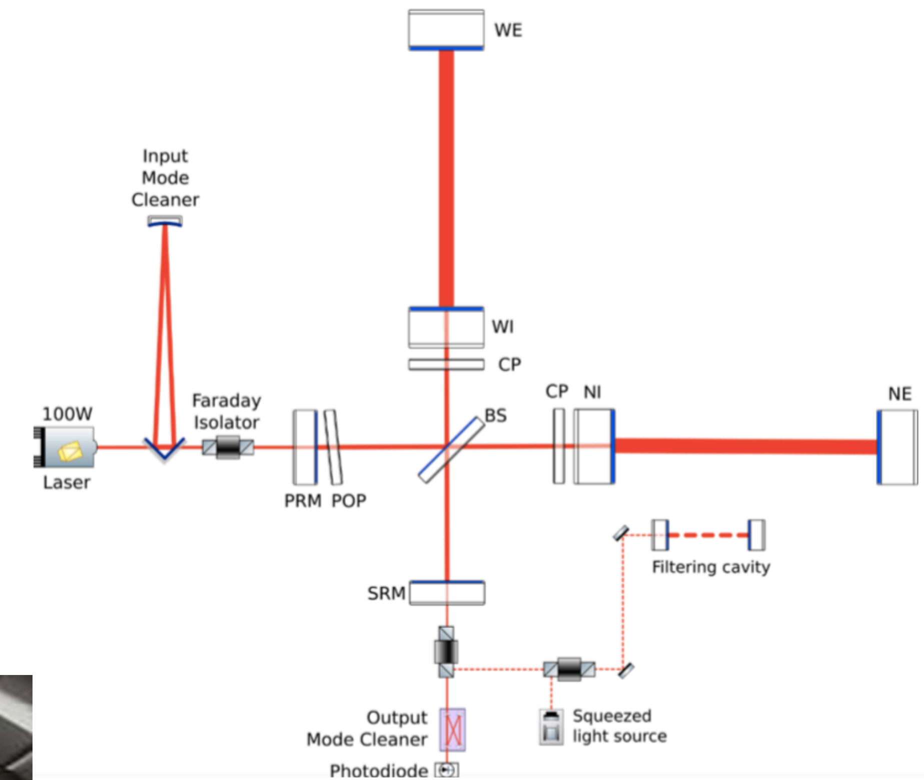
PHYSICAL REVIEW LETTERS **124,** 171101 (2020)

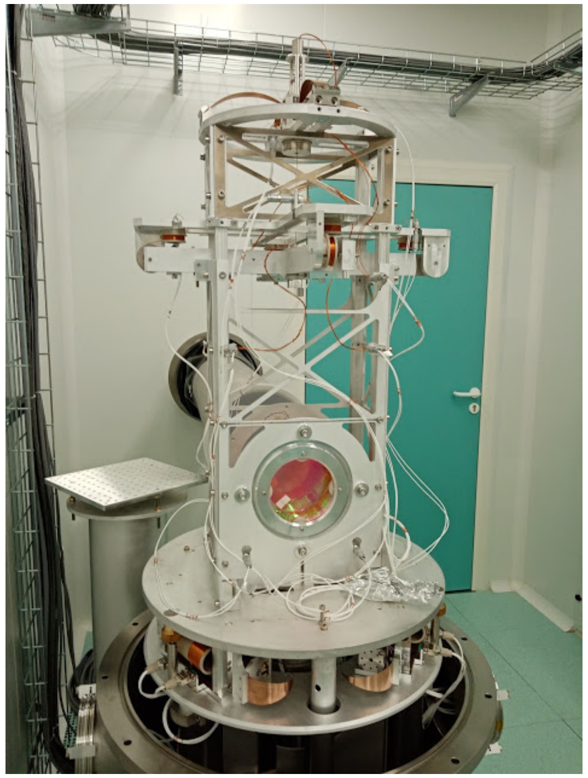


PHYSICAL REVIEW LETTERS **124,** 171102 (2020)

Filter cavity implementation for O4

- Same squeezed vacuum source used in O3
- Length: ~300 m
- Commissioning almost completed





Filter cavity implementation for O4

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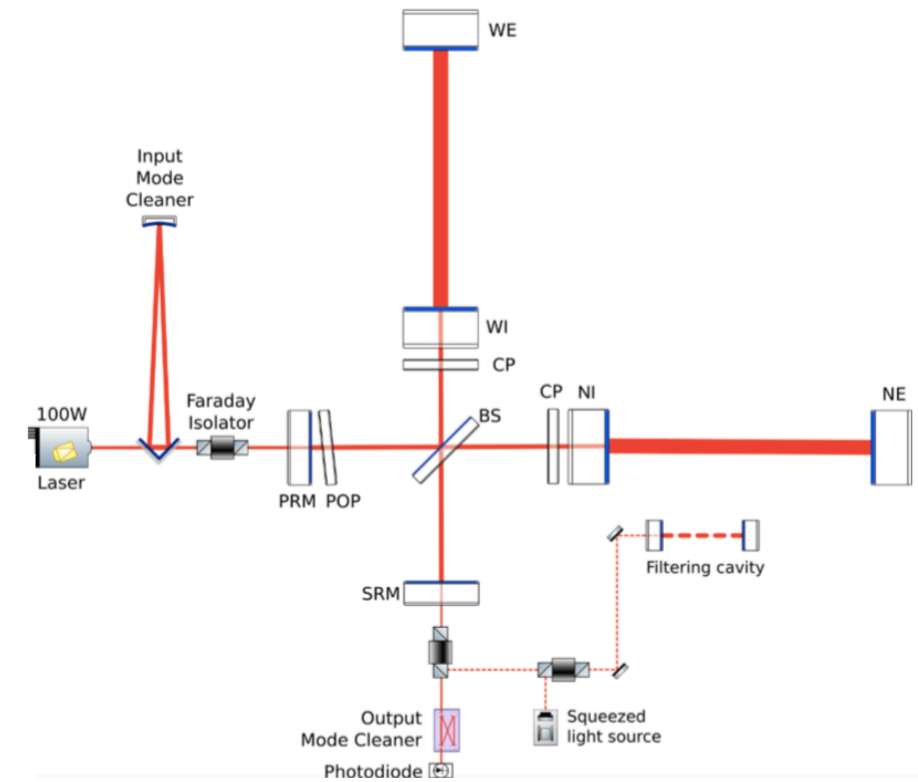
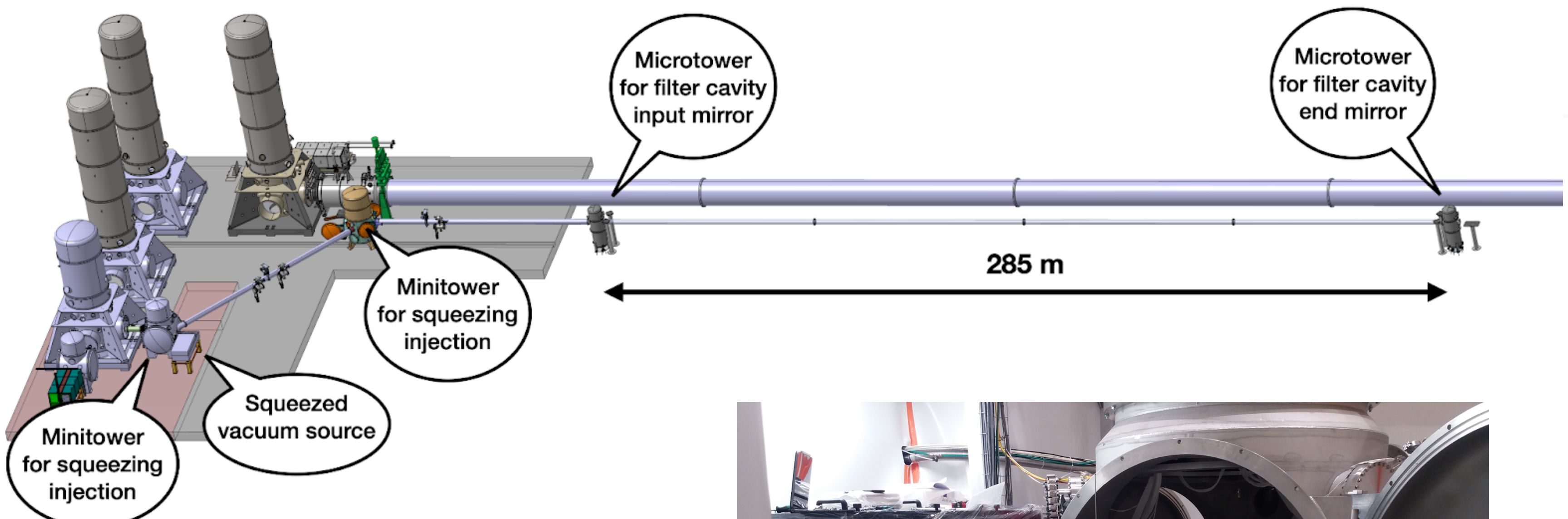
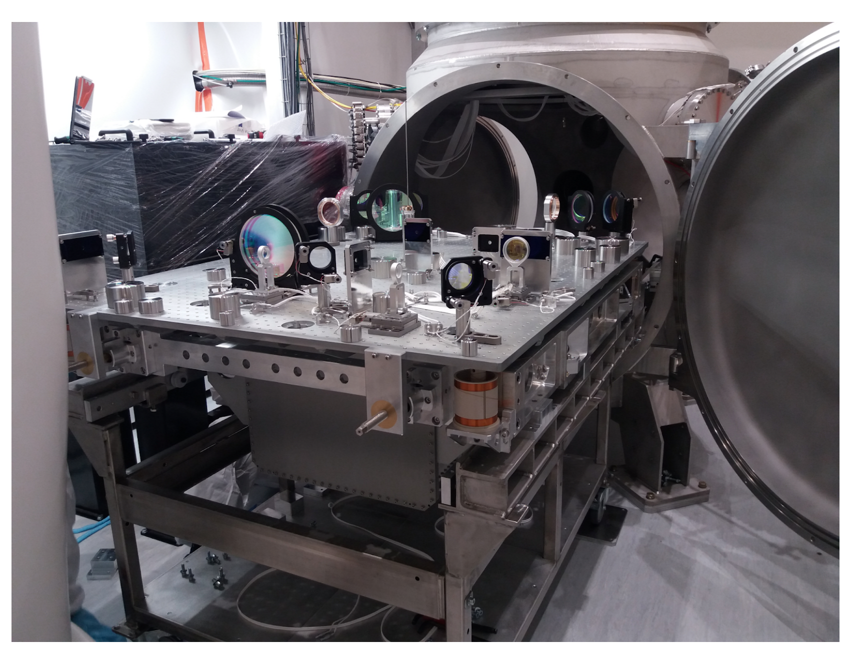
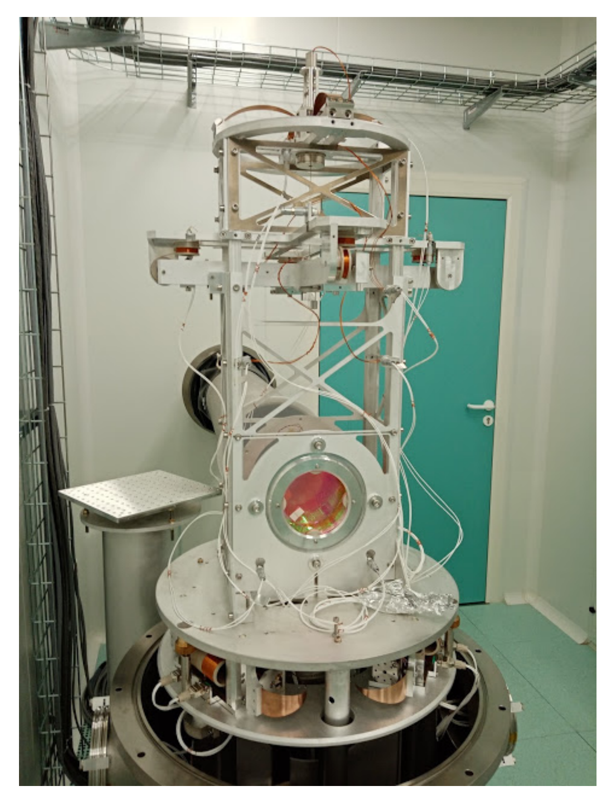


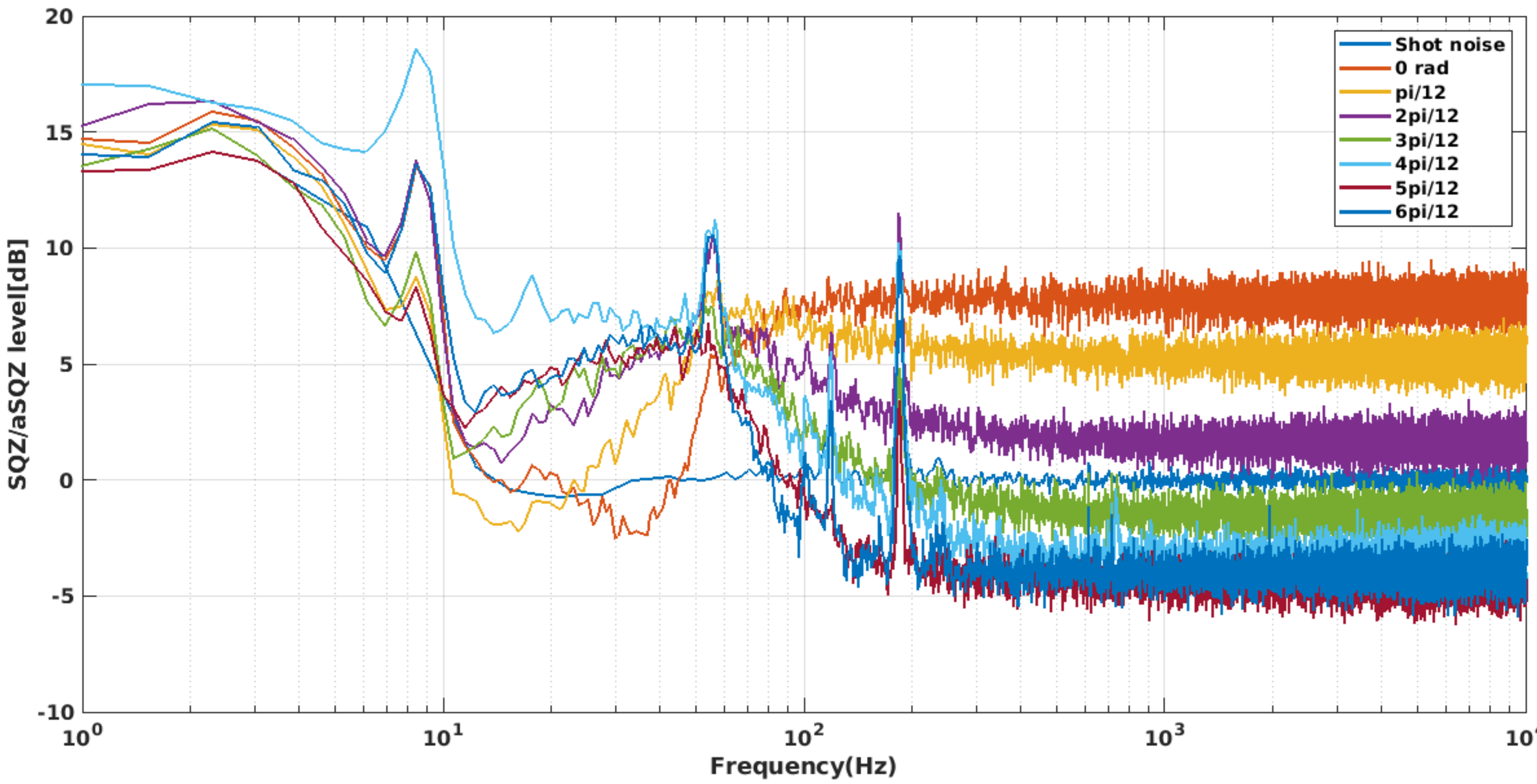






Frequency dependent squeezing measured at Virgo

- Latest measurement: 2dB of squeezing below 25 Hz
- Almost ready to inject it into the interferometer

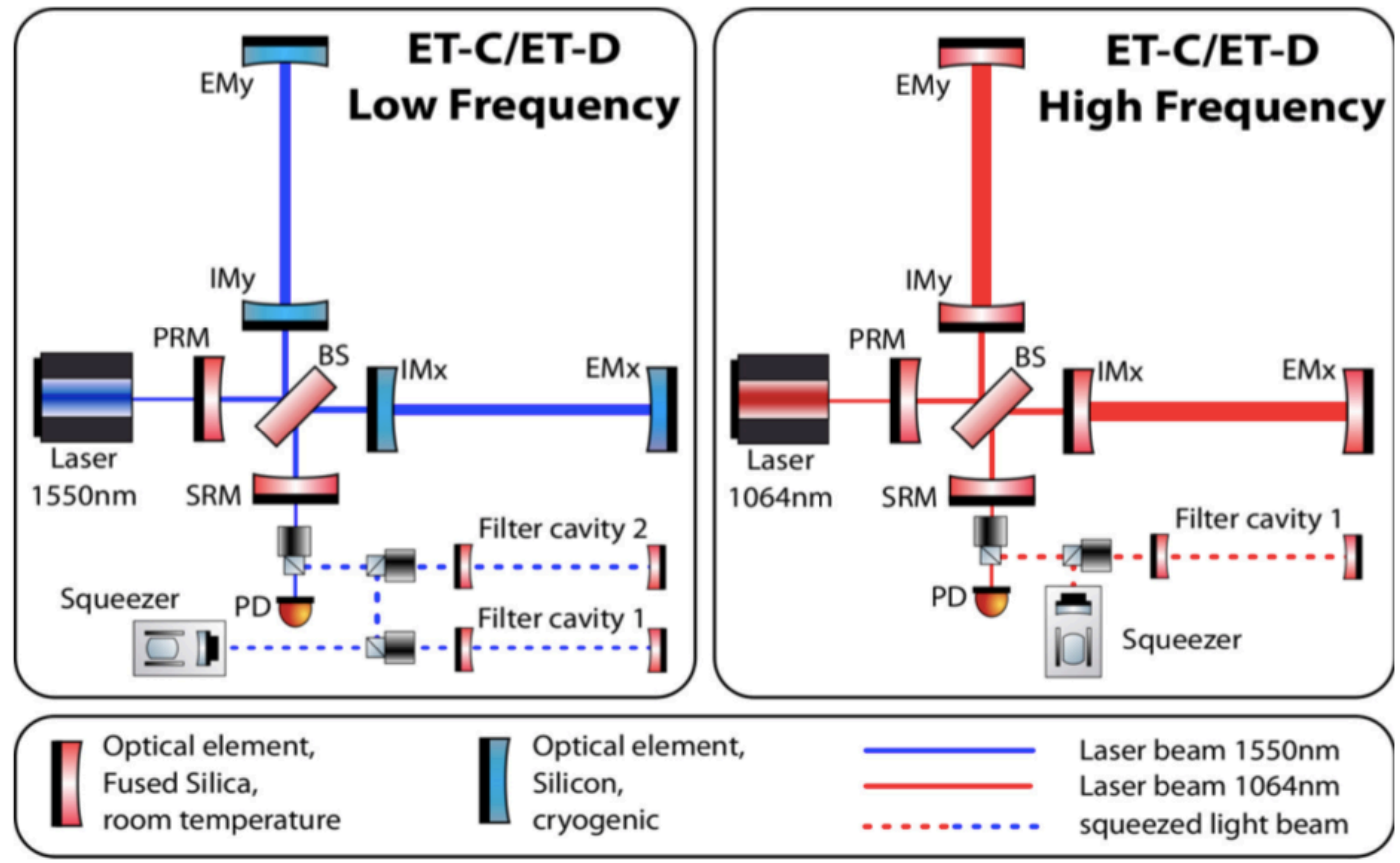


Squeezing for Einstein Telescope

- **Goal:** 10 dB of broadband quantum noise reduction

Challenges

- Squeezing source at different wavelength (e.g1550 nm)
- Very low total optical losses



Alternative quantum noise reduction schemes?

Conclusions

- Quantum noise is an intrinsic limitation of the interferometric measurement, originated by vacuum fluctuations
- Most effective mitigation strategy : squeezed vacuum injection
- After 40 year of developments squeezing is routinely used in GW detectors with relevant impact on sensitivity
- Key technology also for 3rd generation
- Alternatives quantum noise reduction strategies?

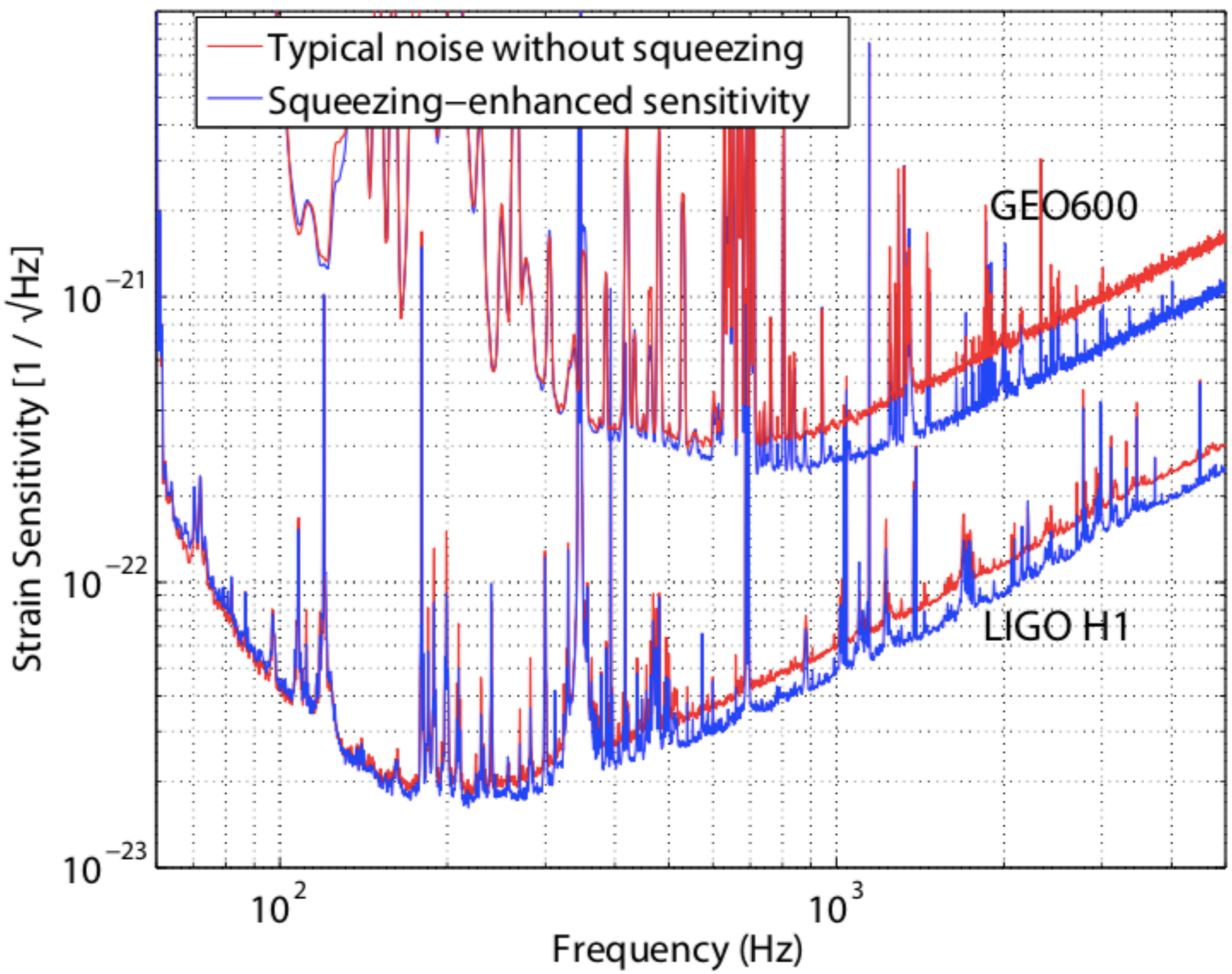
BACK UP SLIDES

Some of the plots and pictures in the slides are taken from:

- "A Basic Introduction to Quantum Noise and Quantum-Non-Demolition Techniques", (Lecture form 1st VESF school) S.Hild
- E.Schreiber PhD thesis

First applications to GW detectors

- Successfully tested also in GEO and initial LIGO
- Strongly limited by optical losses and phase noise



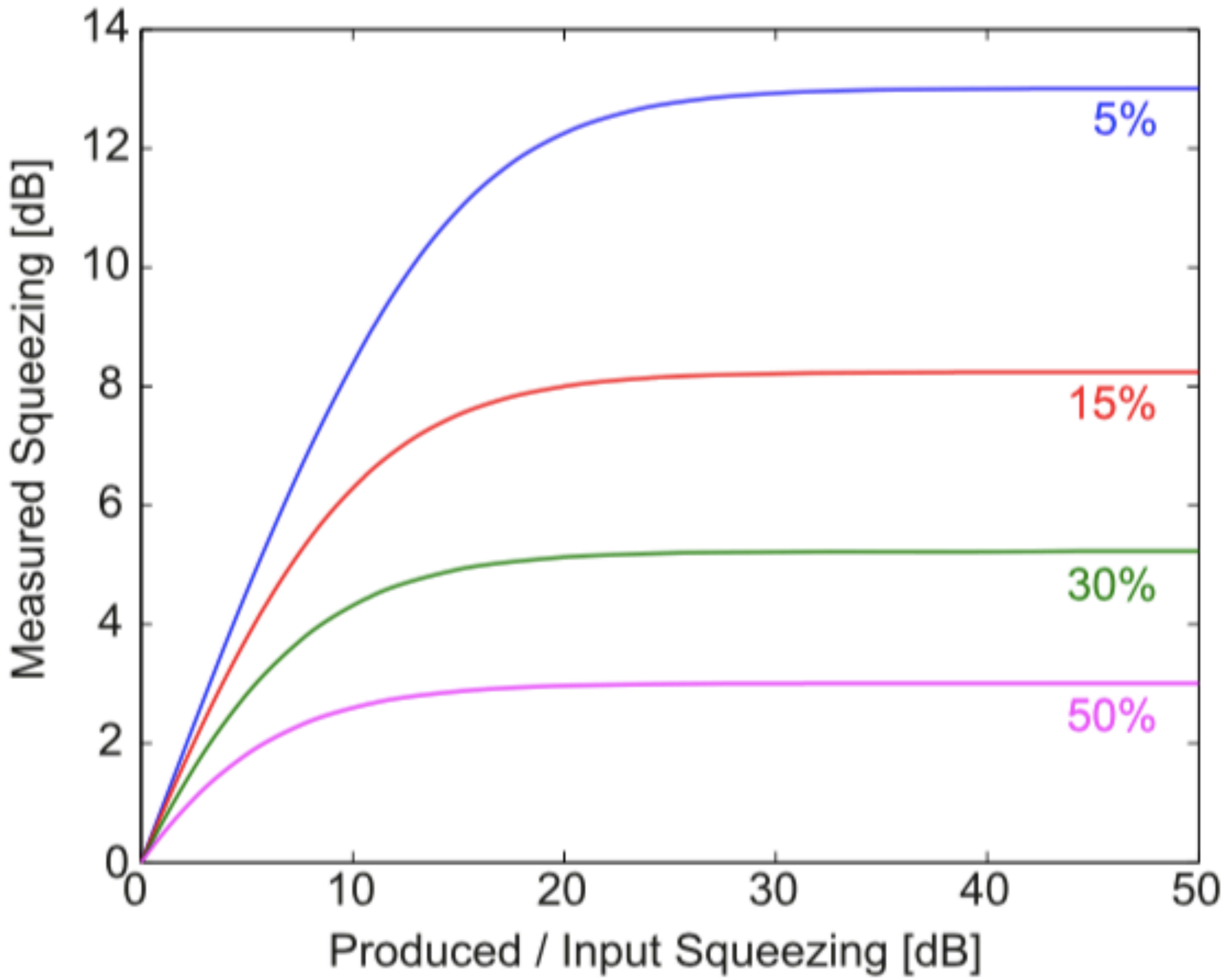
LIGO Scientific Collaboration, J. Aasi et al., "Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light", Nat Photon 7 no. 8, (Aug, 2013) 613–619.

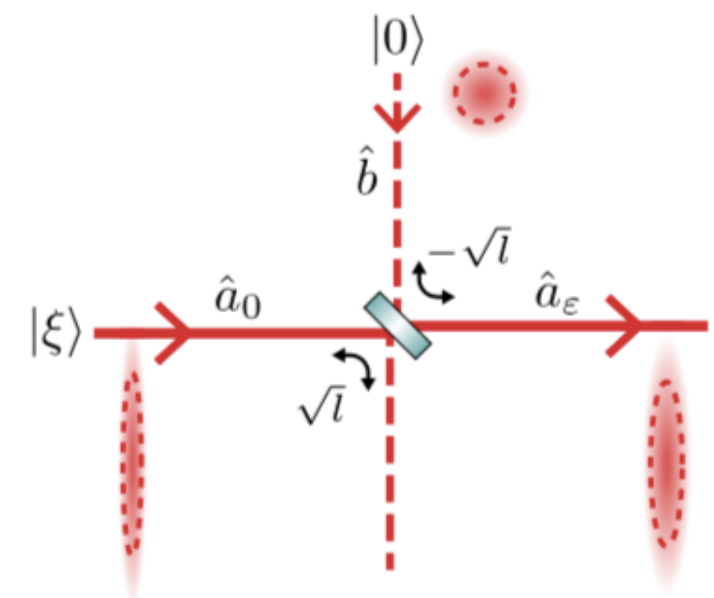
H. Grote et al. "First Long-Term Application of Squeezed States of Light in a Gravitational-Wave Observatory" Phys. Rev. Lett. 110, 181101 (2013)

Optical losses degrades squeezing

- Measured squeezing as a function of the input squeezing foe different loss levels

$$V_{\mathrm{sqz-m}} = \eta V_{\mathrm{sqz-in}} + (1 - \eta)$$



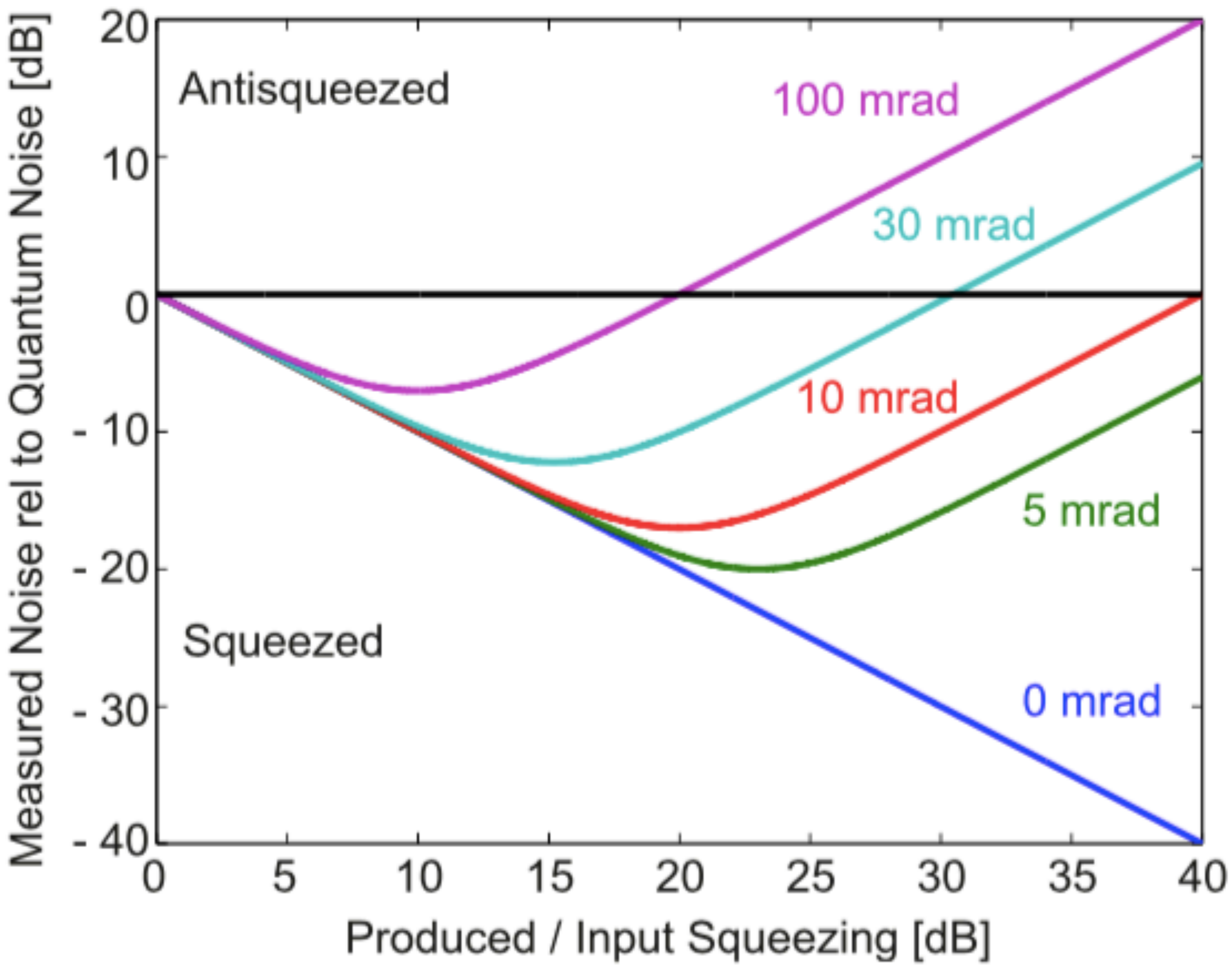


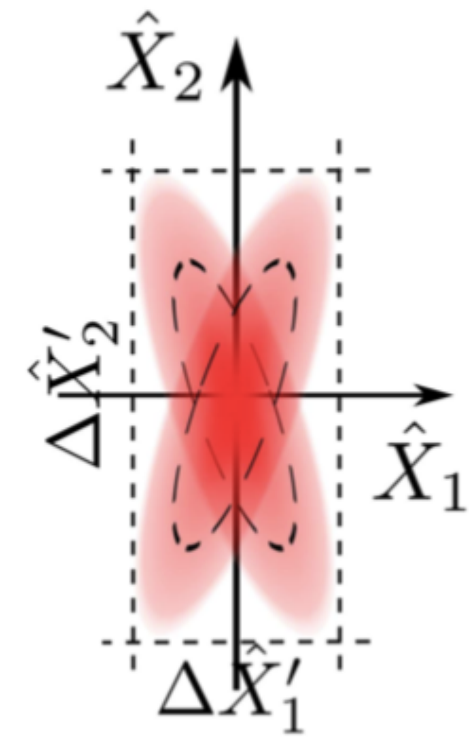
S. Chua et al. Class. Quantum Grav. 31 (2014)

Phase noise effect

- Measured squeezing as a function of the input squeezing for different phase noise levels

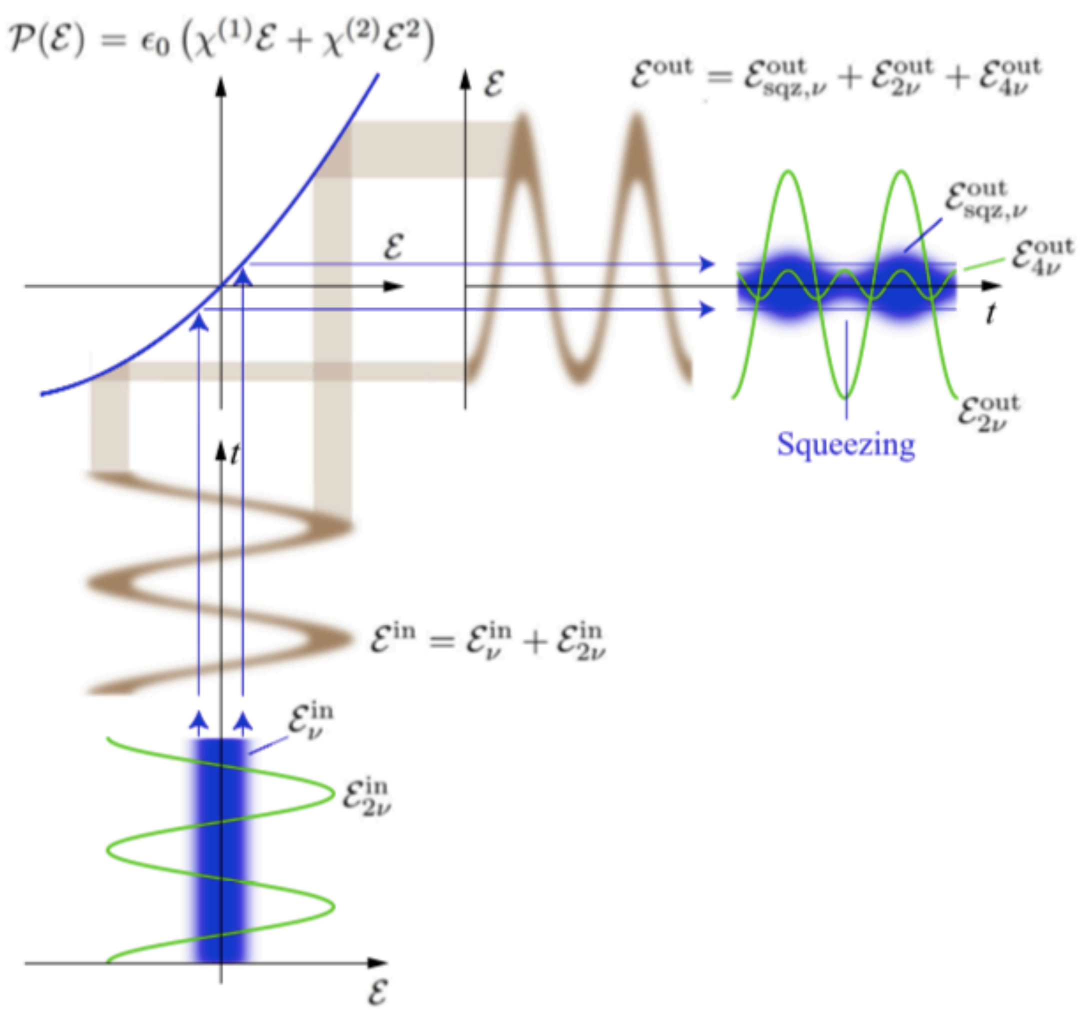
$$V_{\text{sqz-m}'} = V_{\text{sqz-in}} \cos^2\left(\tilde{\theta}\right) + V_{\text{asqz-in}} \sin^2\left(\tilde{\theta}\right)$$





S. Chua et al. Class. Quantum Grav. 31 (2014)

How to generate a squeezed state

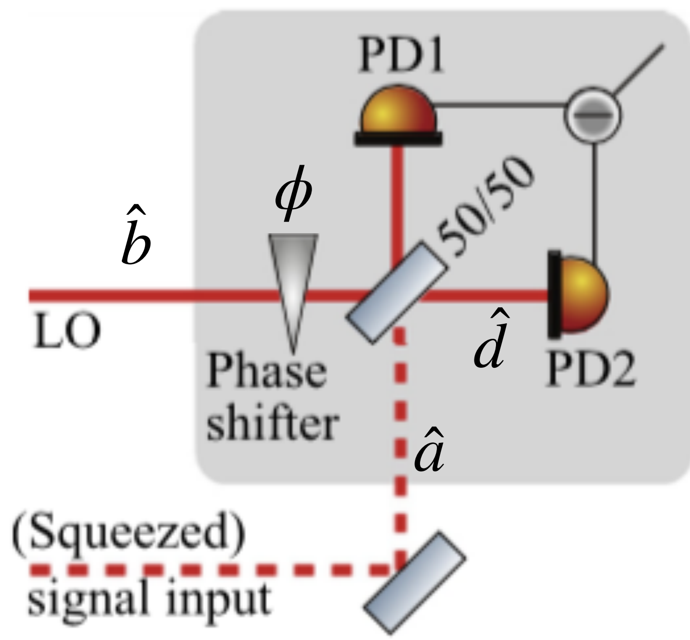


- Optical parametric amplification of a vacuum state
- The input field (vacuum and pump) is transferred into a time-dependent dielectric polarization that is the source of the output field

R. Schnabel- Physics Reports 684 (2017) 1–51

How to measure a squeezed state

- Balanced Homodyne detector

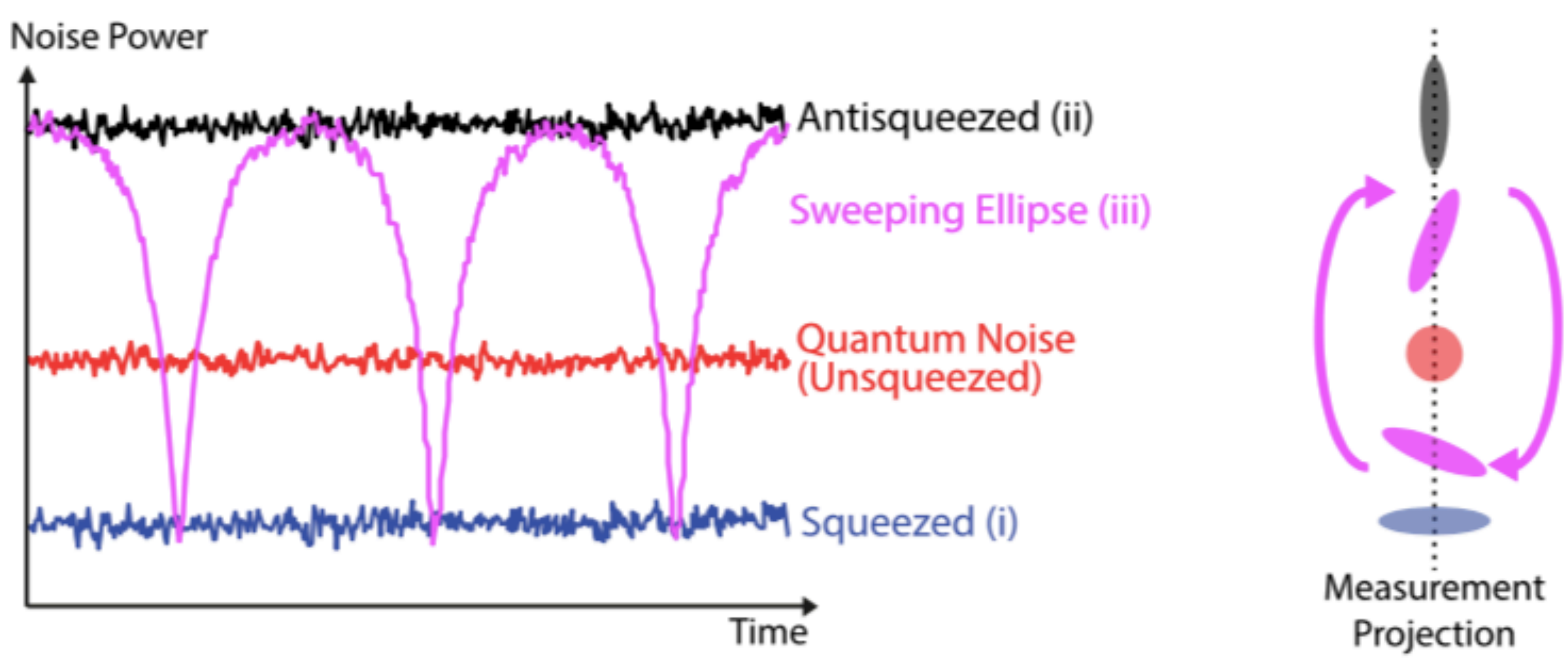


$$\hat{a} = \alpha + \delta\hat{a} \quad \hat{b} = (\beta + \delta\hat{b})e^{i\phi}$$

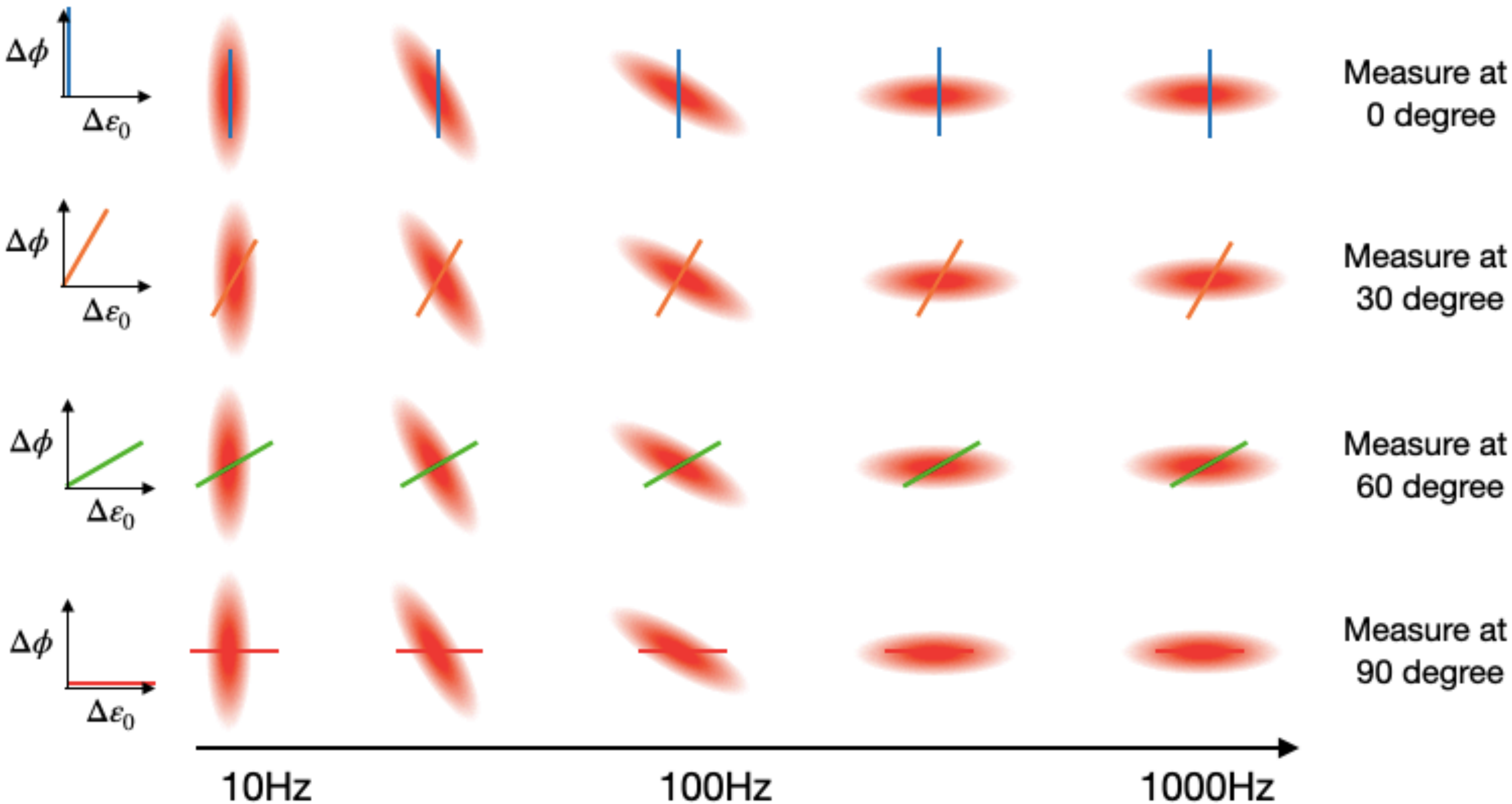
$$\hat{c} = \frac{1}{\sqrt{2}}(\hat{a} + \hat{b}) \quad \hat{d} = \frac{1}{\sqrt{2}}(\hat{a} - \hat{b})$$

$$\delta\hat{X}_1^a = \delta\hat{a}^\dagger + \delta\hat{a} \text{ and } \delta\hat{X}_2^a = i(\delta\hat{a} \dagger + \delta\hat{a}).$$

$$I_1 - I_2 \simeq \beta(\cos(\phi)\delta\hat{X}_1^a + \sin(\phi)\delta\hat{X}_2^a) = \beta\delta\hat{X}_\phi^a$$

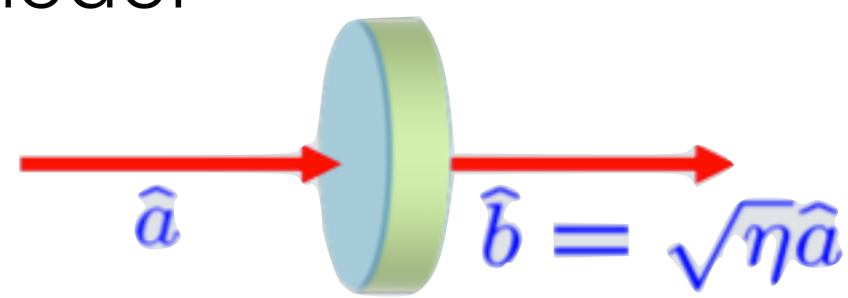


Frequency dependent squeezing measurement



Optical losses degrades squeezing

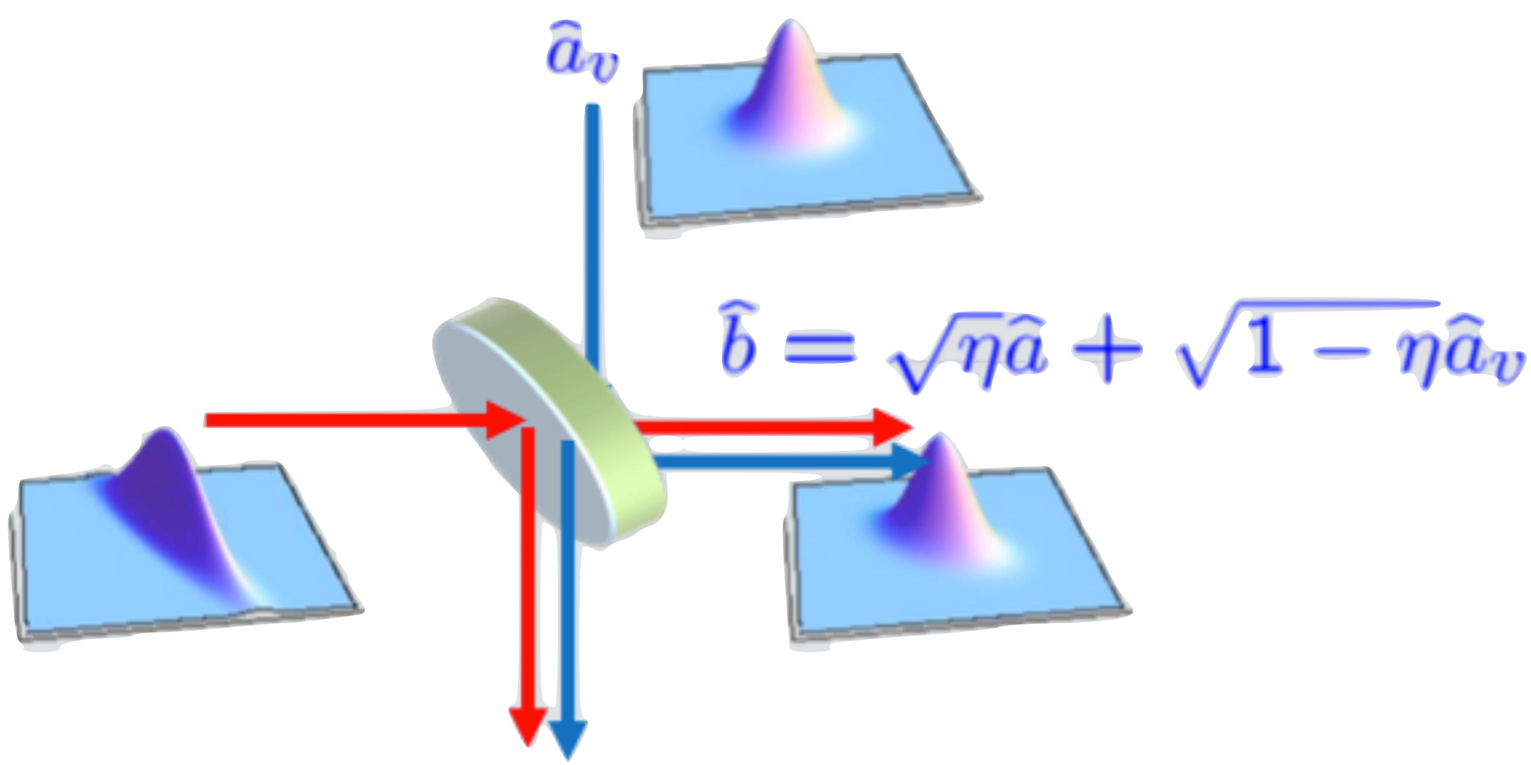
- Naive model



$$[\hat{a}, \hat{a}^{+}] = 1$$

$$[\hat{b}, \hat{b}^{+}] = \eta \neq 1$$

- Consistent model



Squeezing deteriorated because of its recombination with non squeezed vacuum

Sensitivity for O4