Atelier “Technologies quantiques des deux infinis”

Quantum technologies in GW detectors: theory and state of the art

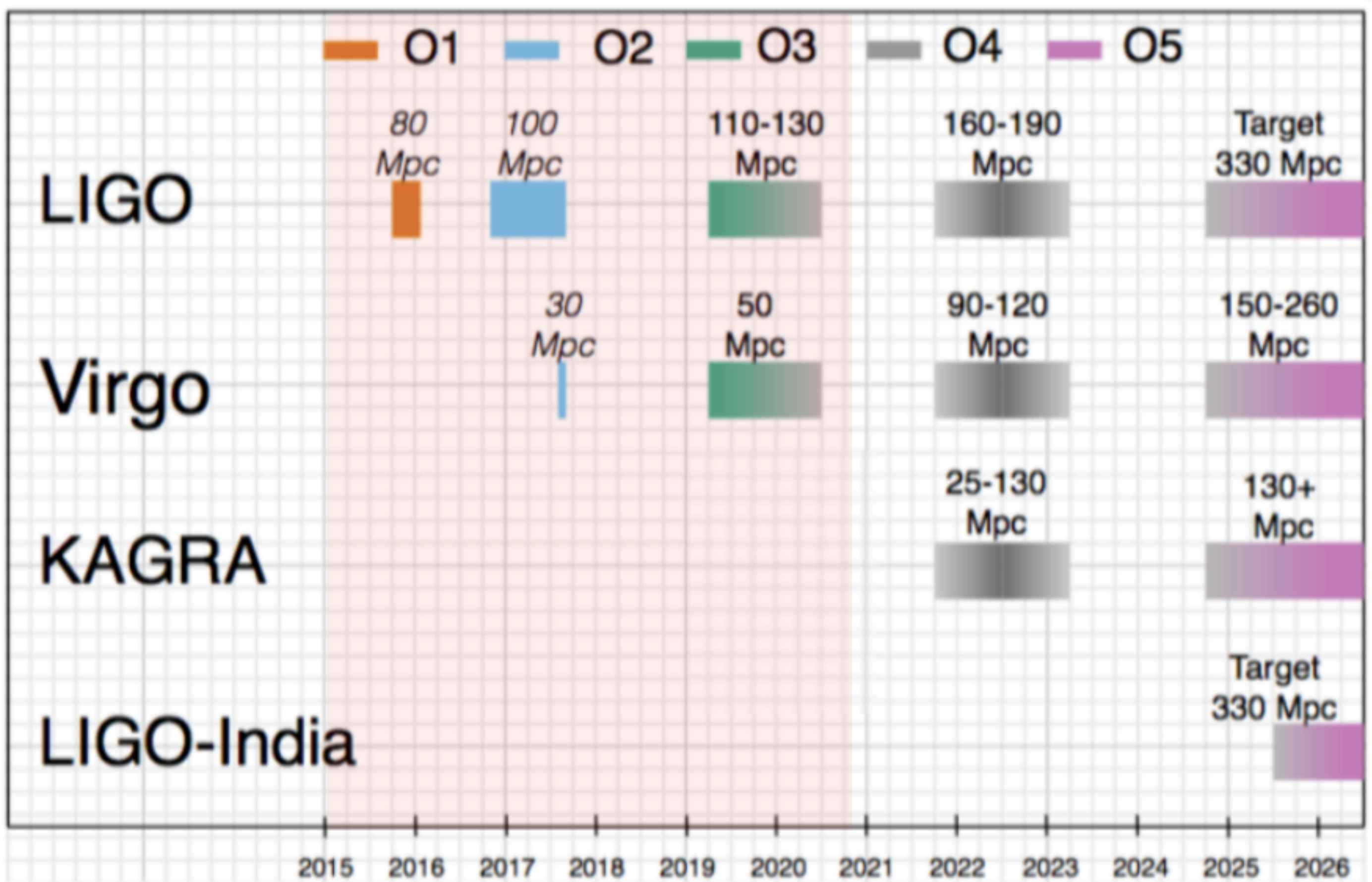
Eleonora Capocasa

on behalf of the Virgo groups APC, Artemis, IJCLab, IPHC, IP2I, LAPP, LKB, g-MAG

VIRGO

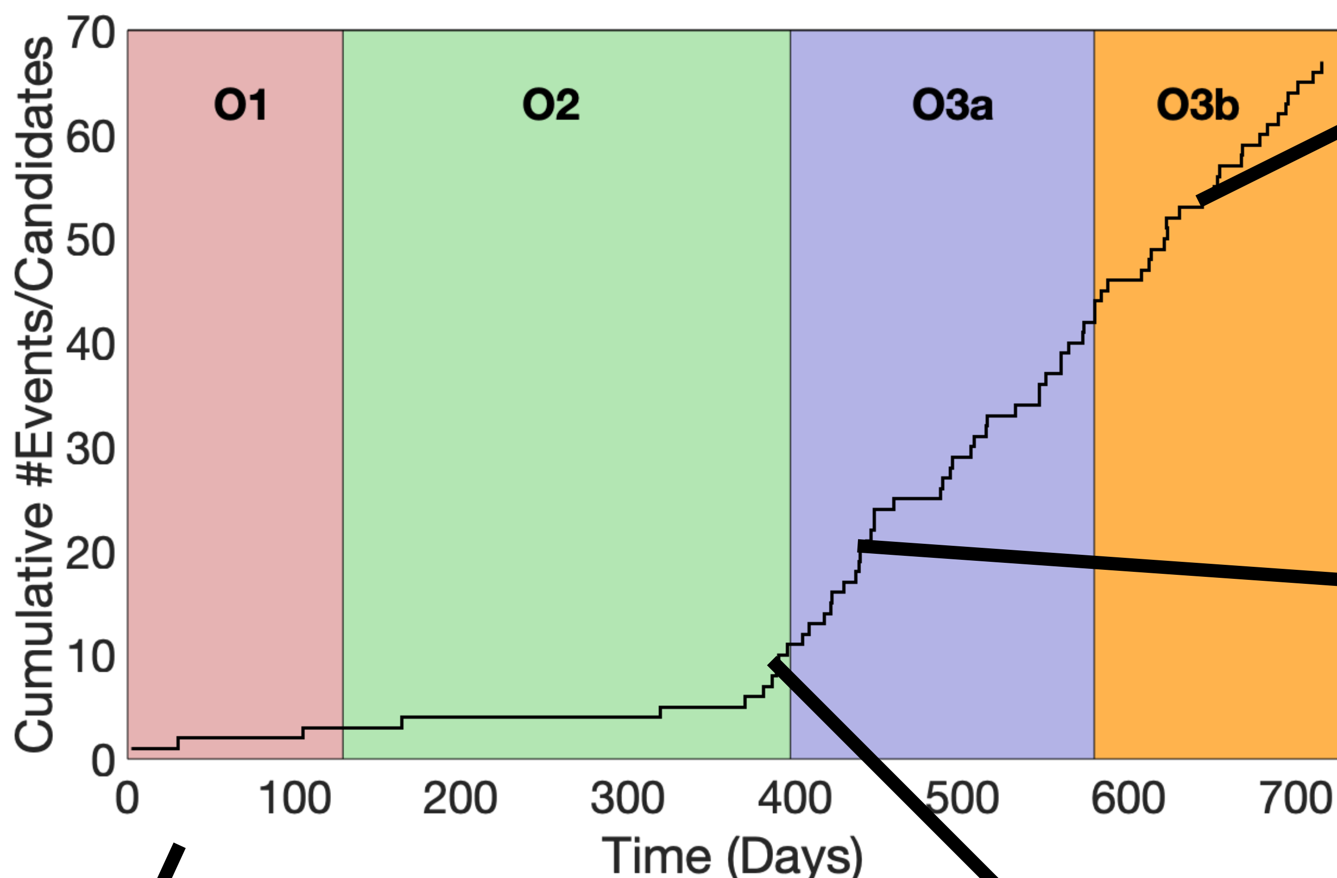
Marseille, 30/07/2021

GW detector network: state of the art



- 2G network: Virgo, LIGO and KAGRA
- 3 observation runs performed
- 50 detections

Some remarkable detection



GW200105
GW200115

First BH-NS mergers observed

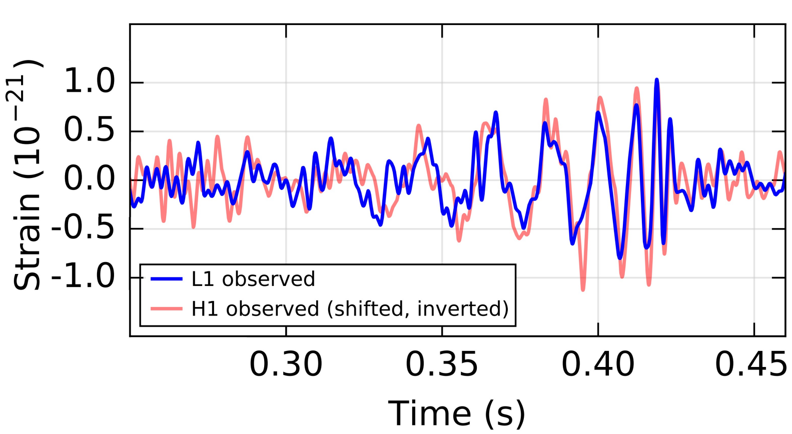
Announced yesterday! [Link]

GW190521

First intermediate mass BH observed

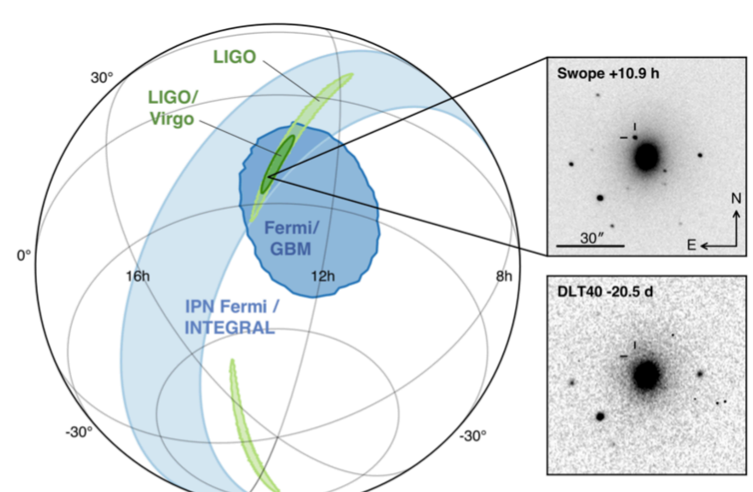
GW150914

First detection



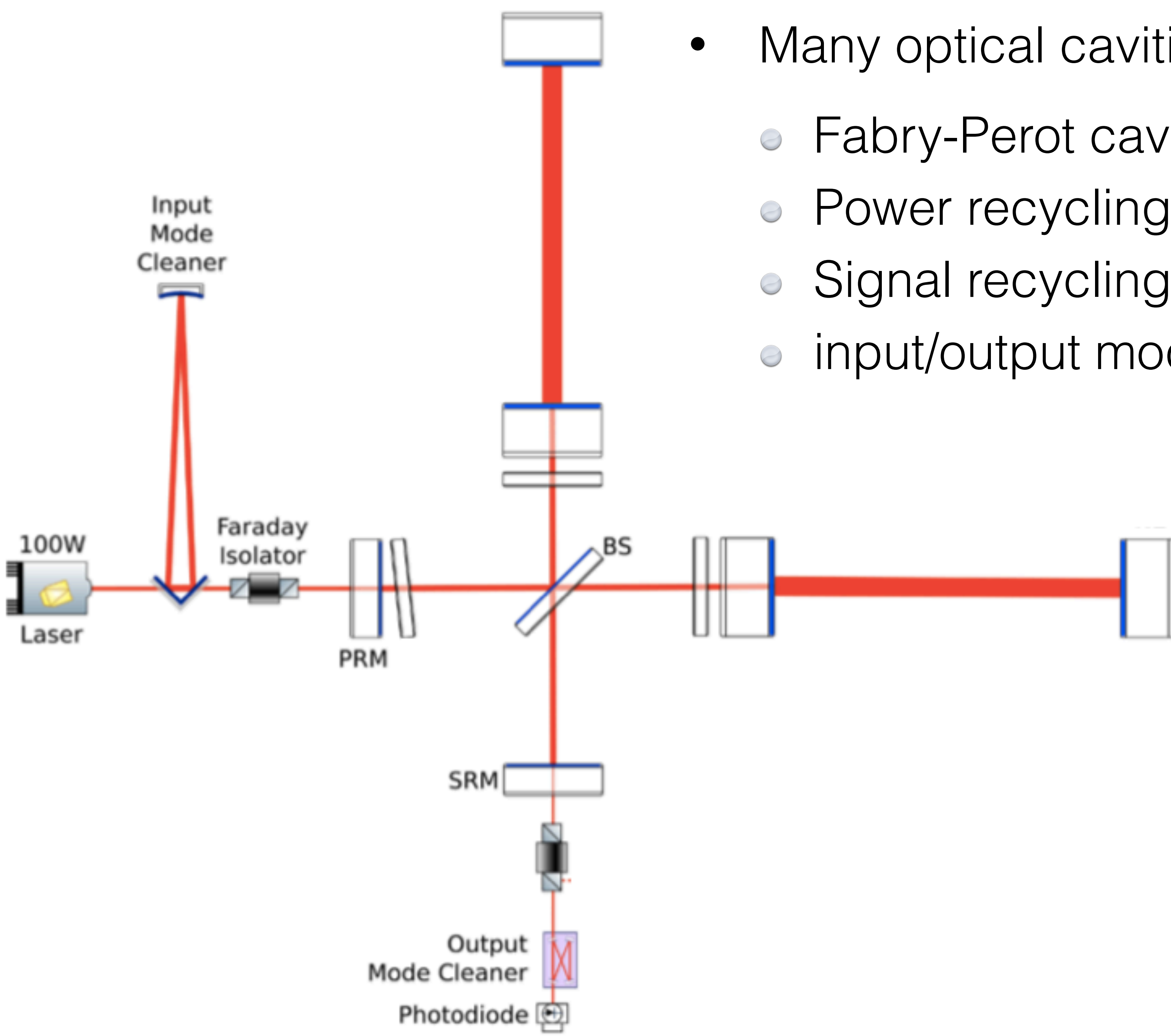
GW170817

NS-NS merger, multimessenger observation



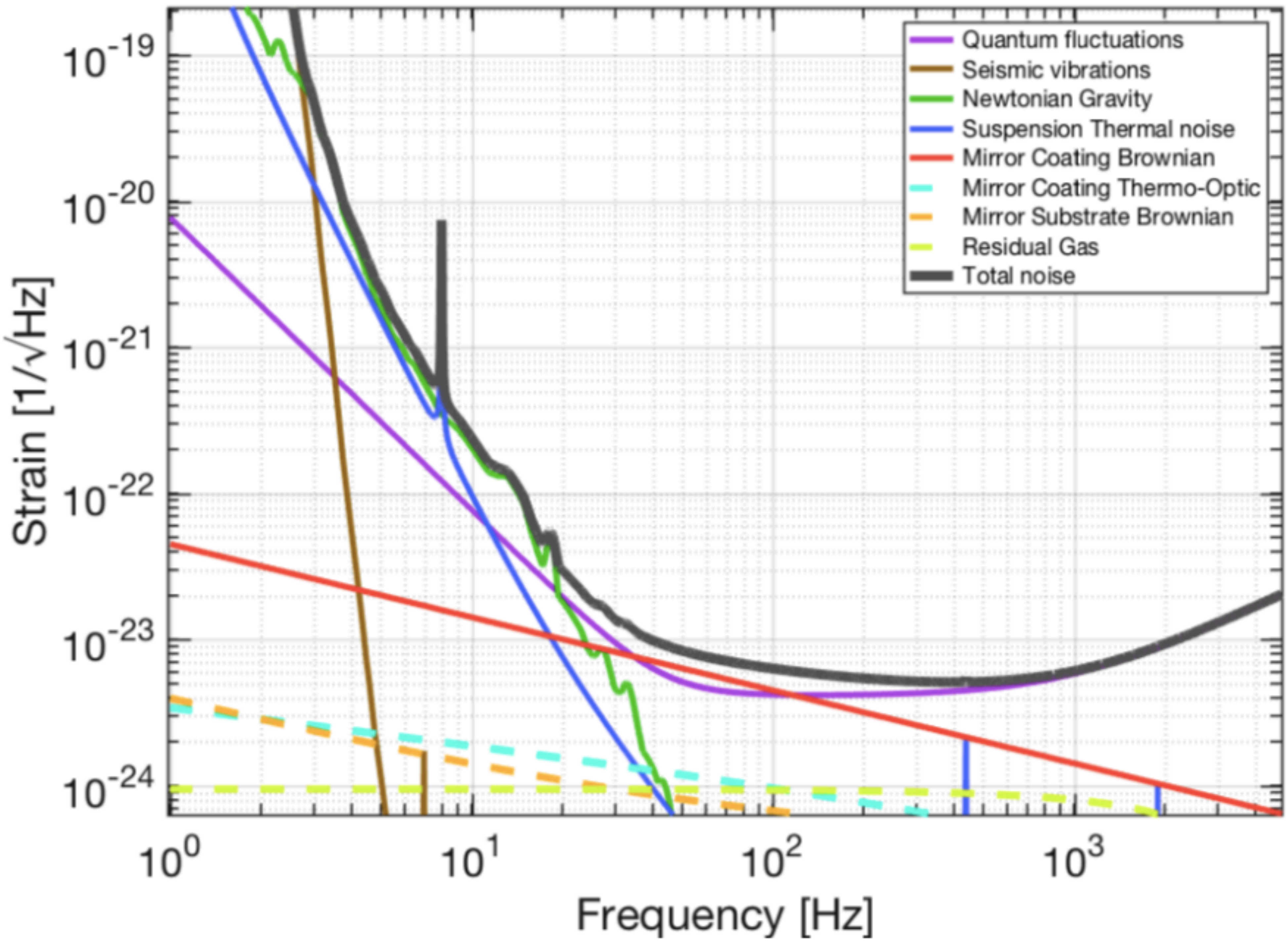
Detection principle: modified michelson interferometers

- Many optical cavities to improve the performances
  - Fabry-Perot cavities in the arms
  - Power recycling
  - Signal recycling
  - input/output mode-cleaner

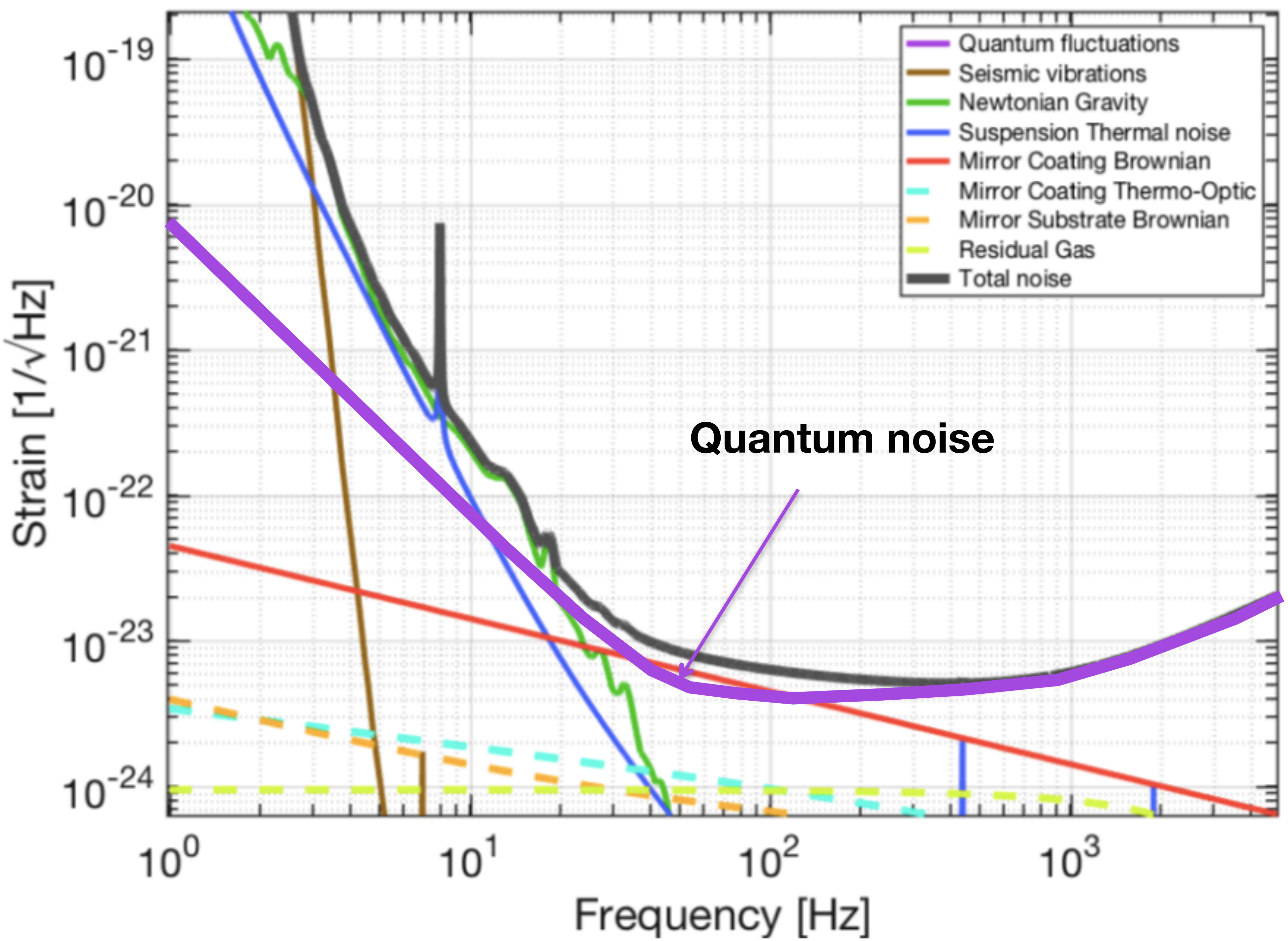


AdVirgo optical scheme

Advanced Virgo noise budget



Advanced Virgo noise budget



How does quantum mechanics affect GW detection?

- Quantum nature of the light used for the measurement
- Test mass quantization

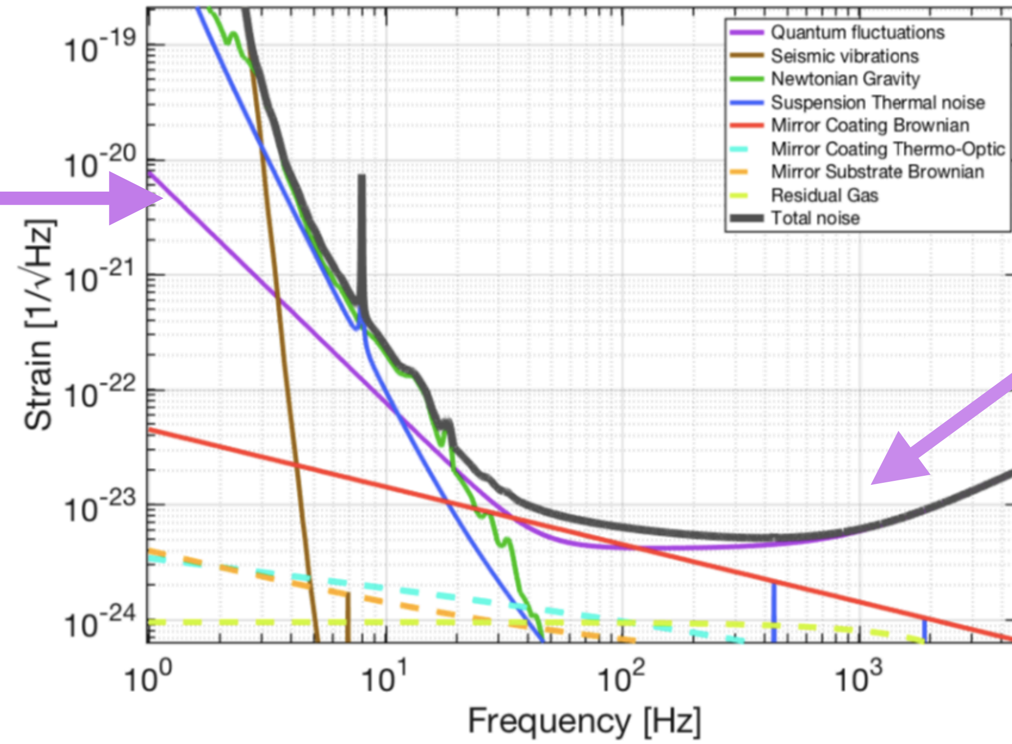
PHYSICAL REVIEW D **67**, 082001 (2003)

Noise in gravitational-wave detectors and other classical-force measurements is not influenced by test-mass quantization

Vladimir B. Braginsky,[1] Mikhail L. Gorodetsky,[1] Farid Ya. Khalili,[1] Andrey B. Matsko,[2] Kip S. Thorne,[3] and Sergey P. Vyatchanin[1]
[1]*Physics Faculty, Moscow State University, Moscow, Russia*
[2]*Department of Physics, Texas A&M University, College Station, Texas 77843-4242*
[3]*Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125*
(Received 2 September 2001; published 7 April 2003)

Quantum noise: a semiclassical picture

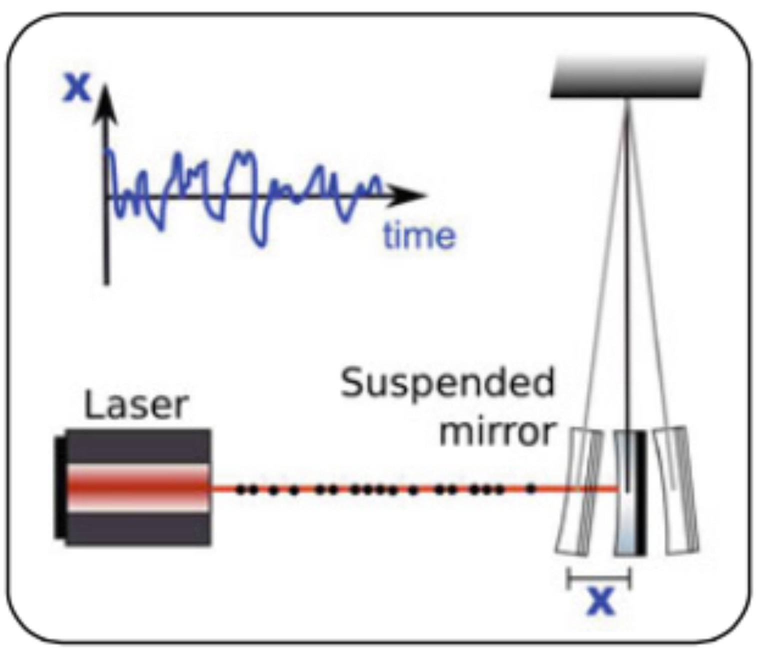
Radiation pressure noise

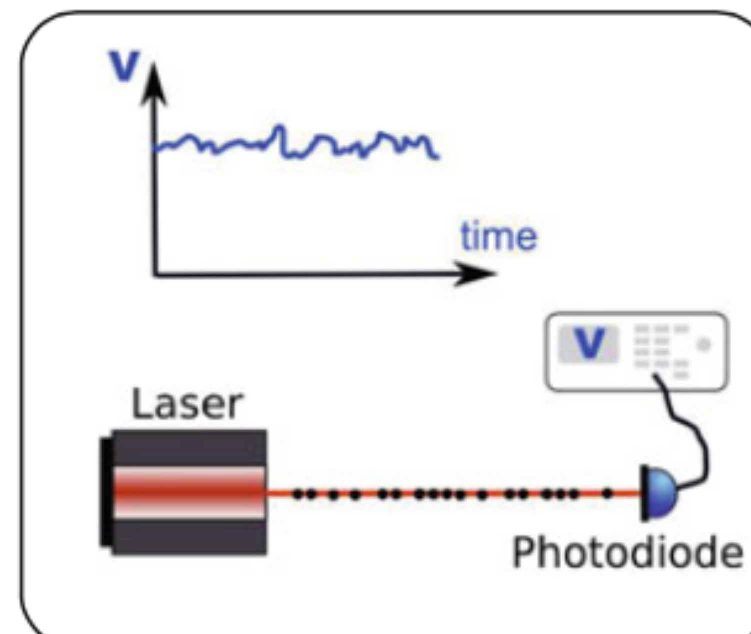


Shot noise

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

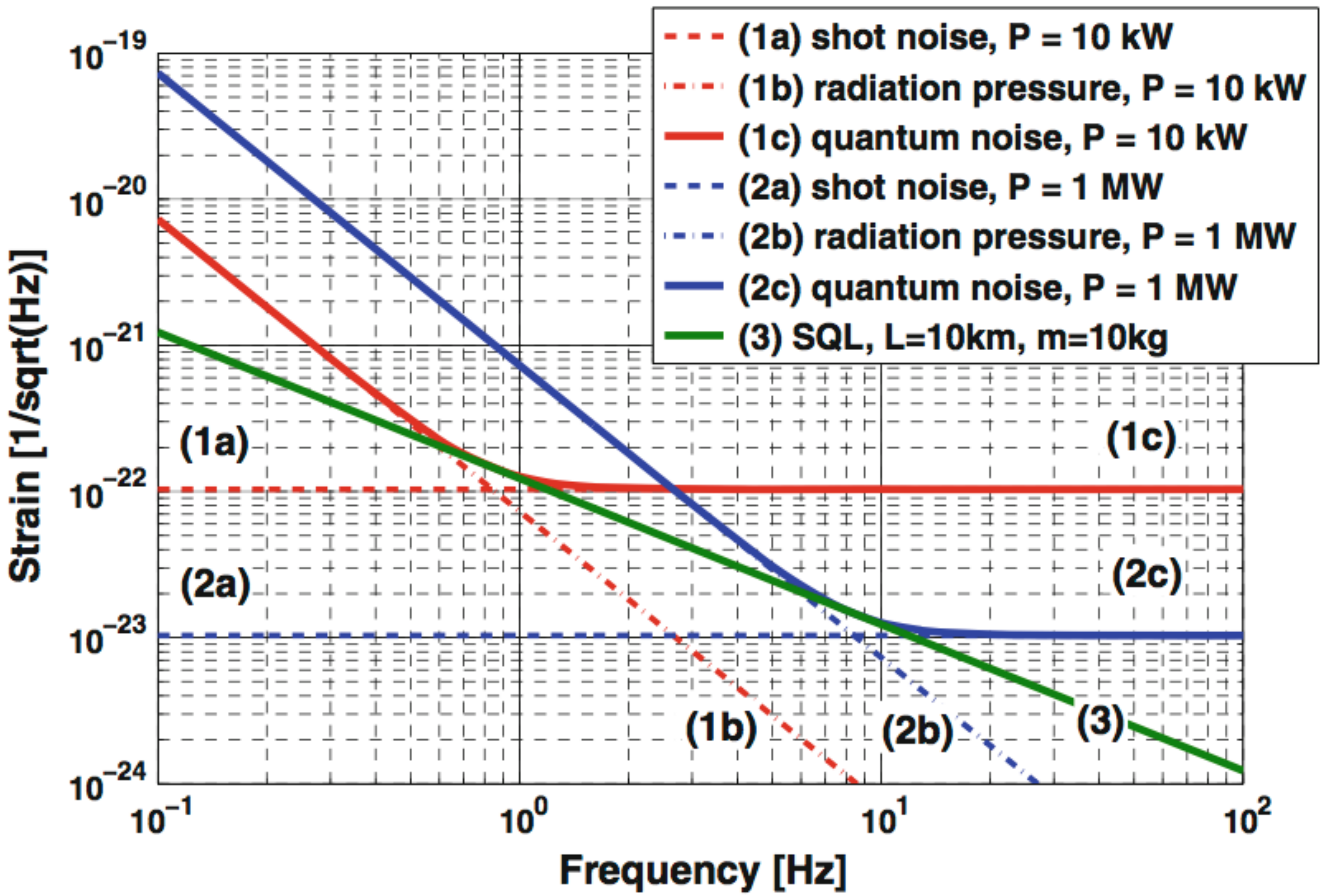
$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c\lambda}{2\pi P}}$$





- 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

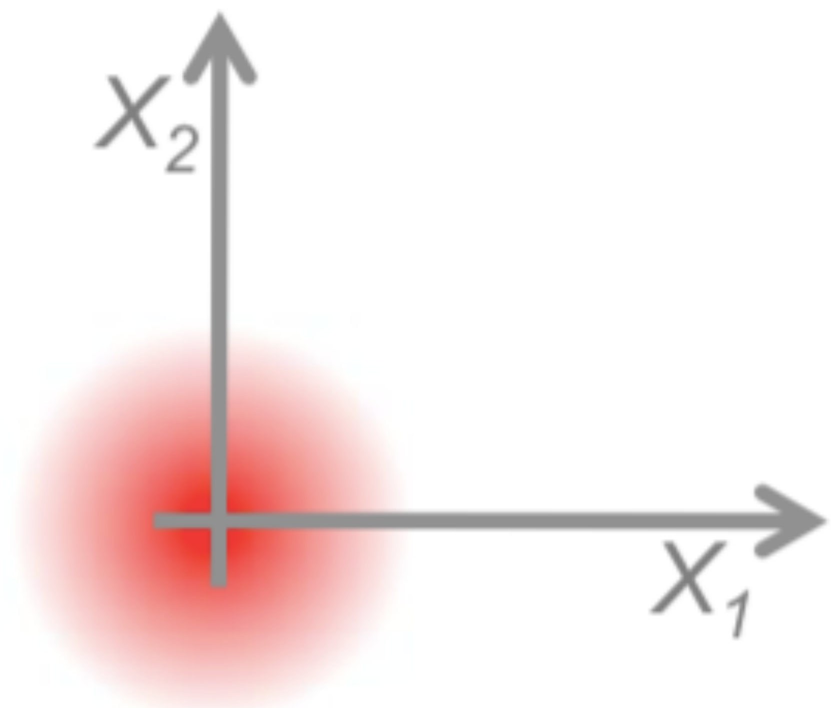
VOLUME 45 | 14 JULY 1980 | NUMBER 2

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

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

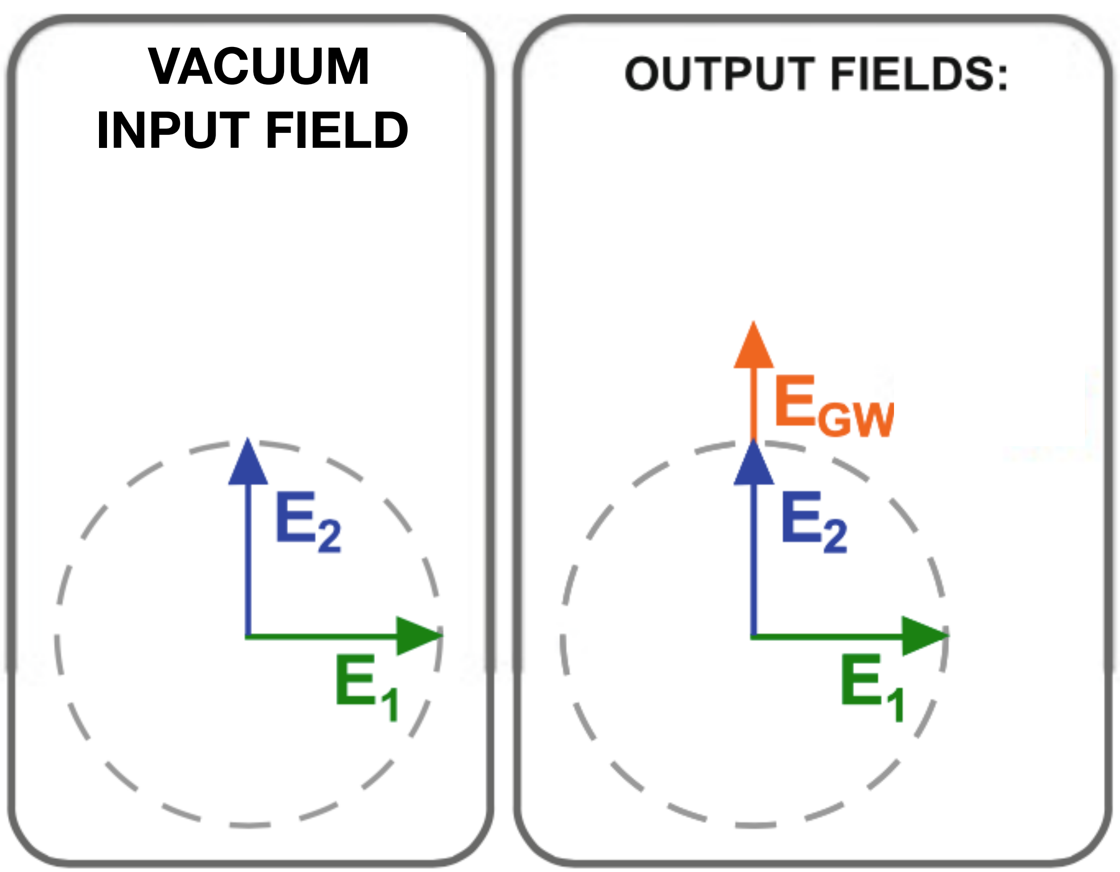
- Laser (and vacuum) are described by coherent states

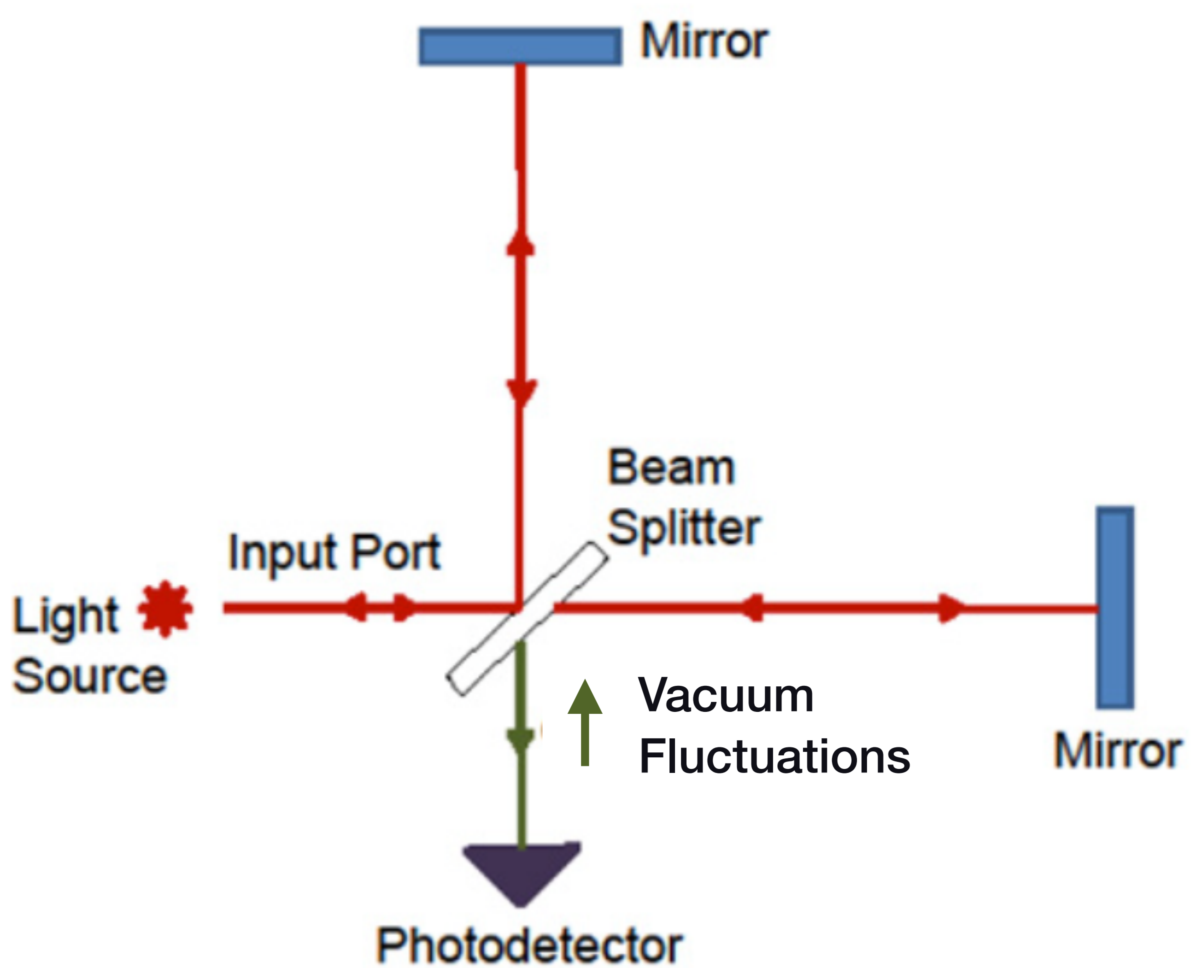
- Amplitude and phase fluctuations equally distributed and uncorrelated

11

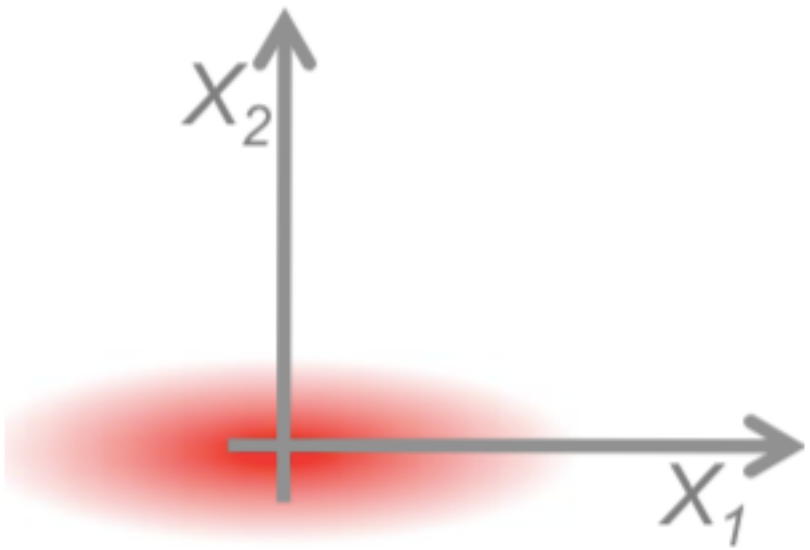
Quantum noise in GW interferometers

- If the cavities are symmetric, only vacuum fluctuations are responsible for quantum noise
- Standard quantum limit can be circumvented introducing vacuum states with modified noise features





Squeezed states

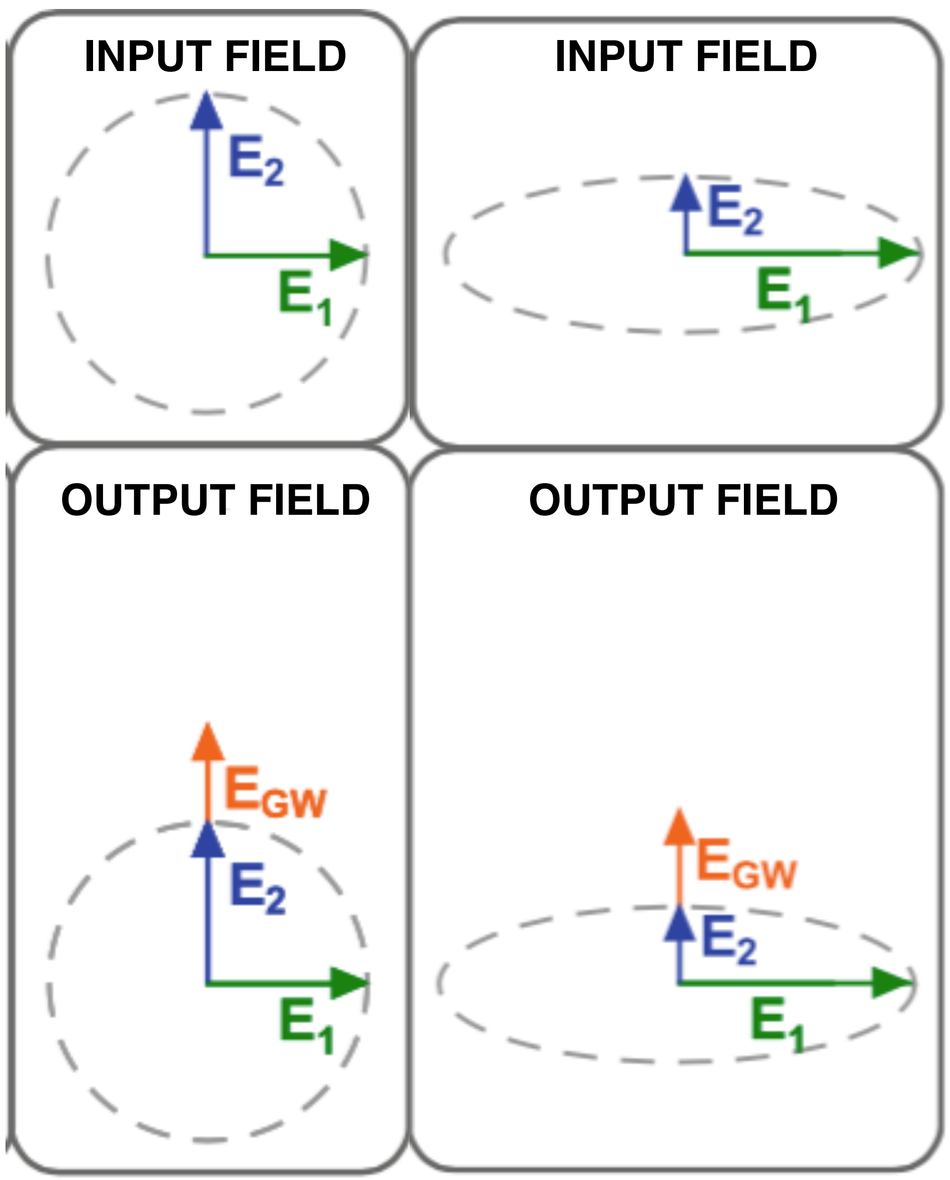


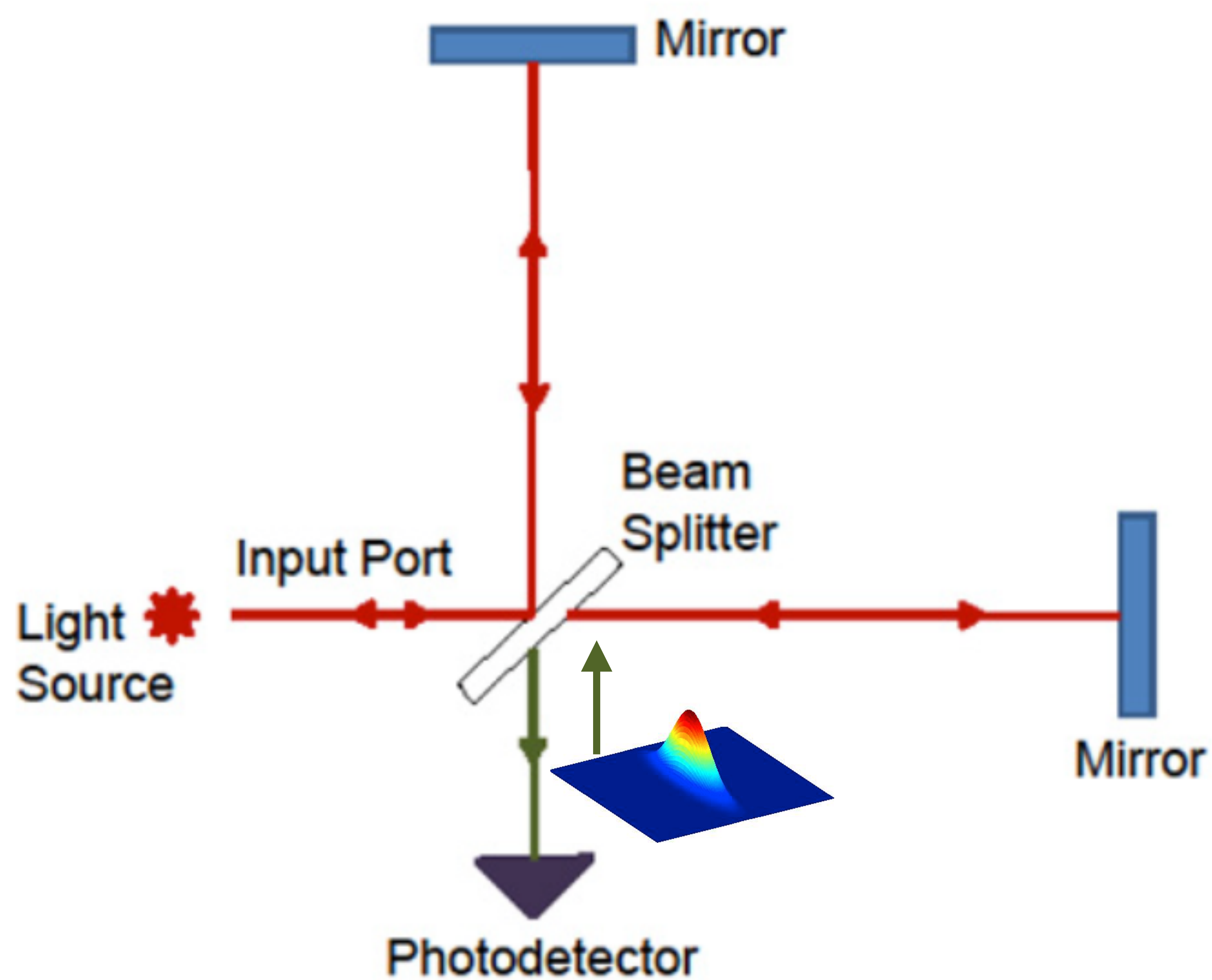
- Non classical light state
- Noise in one quadrature is reduced with respect to the one of a coherent state

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 in GW interferometers

PHYSICAL REVIEW D 15 APRIL 1981

Quantum-mechanical noise in an interferometer

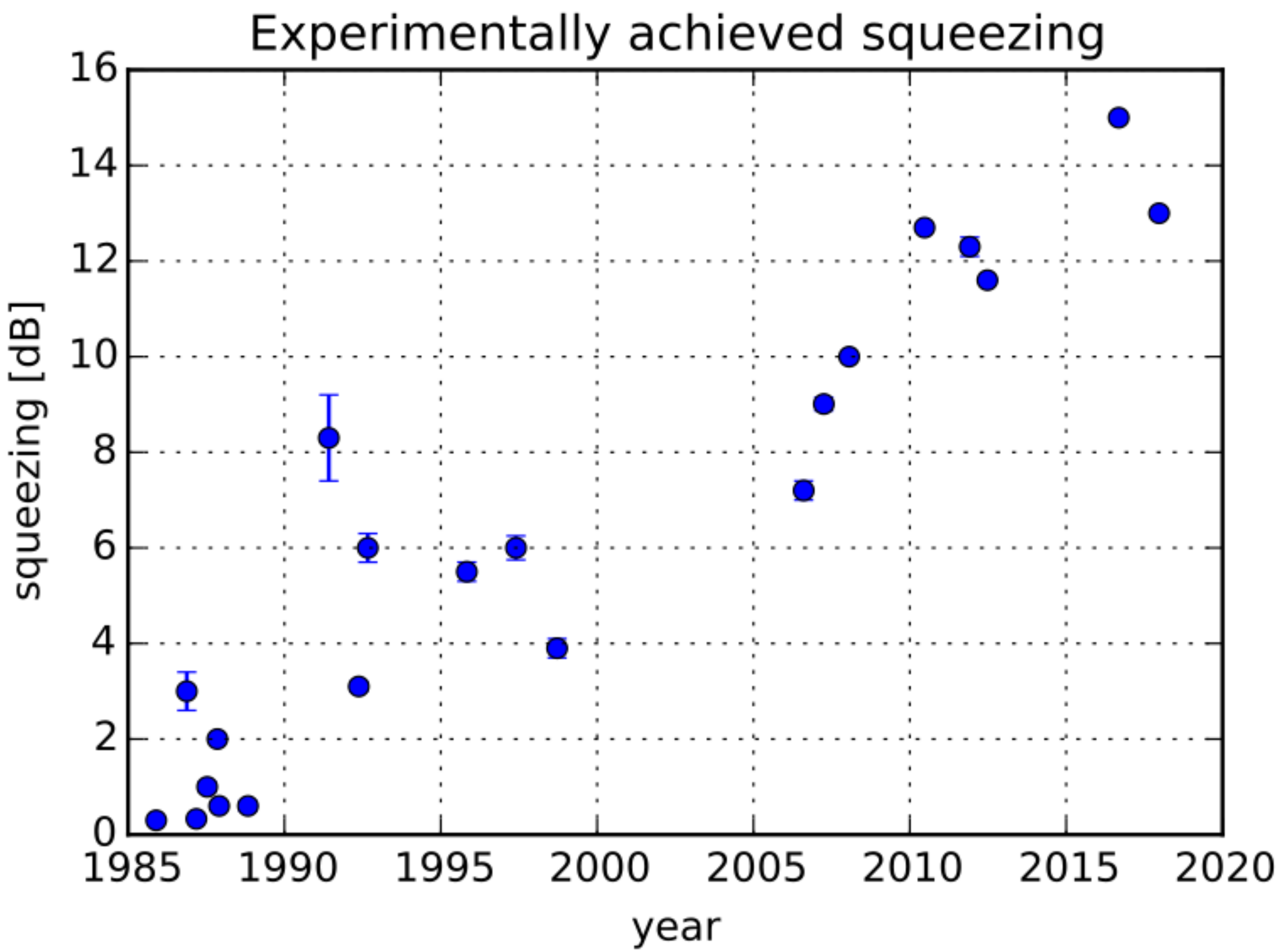
Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

VOLUME 23, NUMBER 8

IV. CONCLUSION

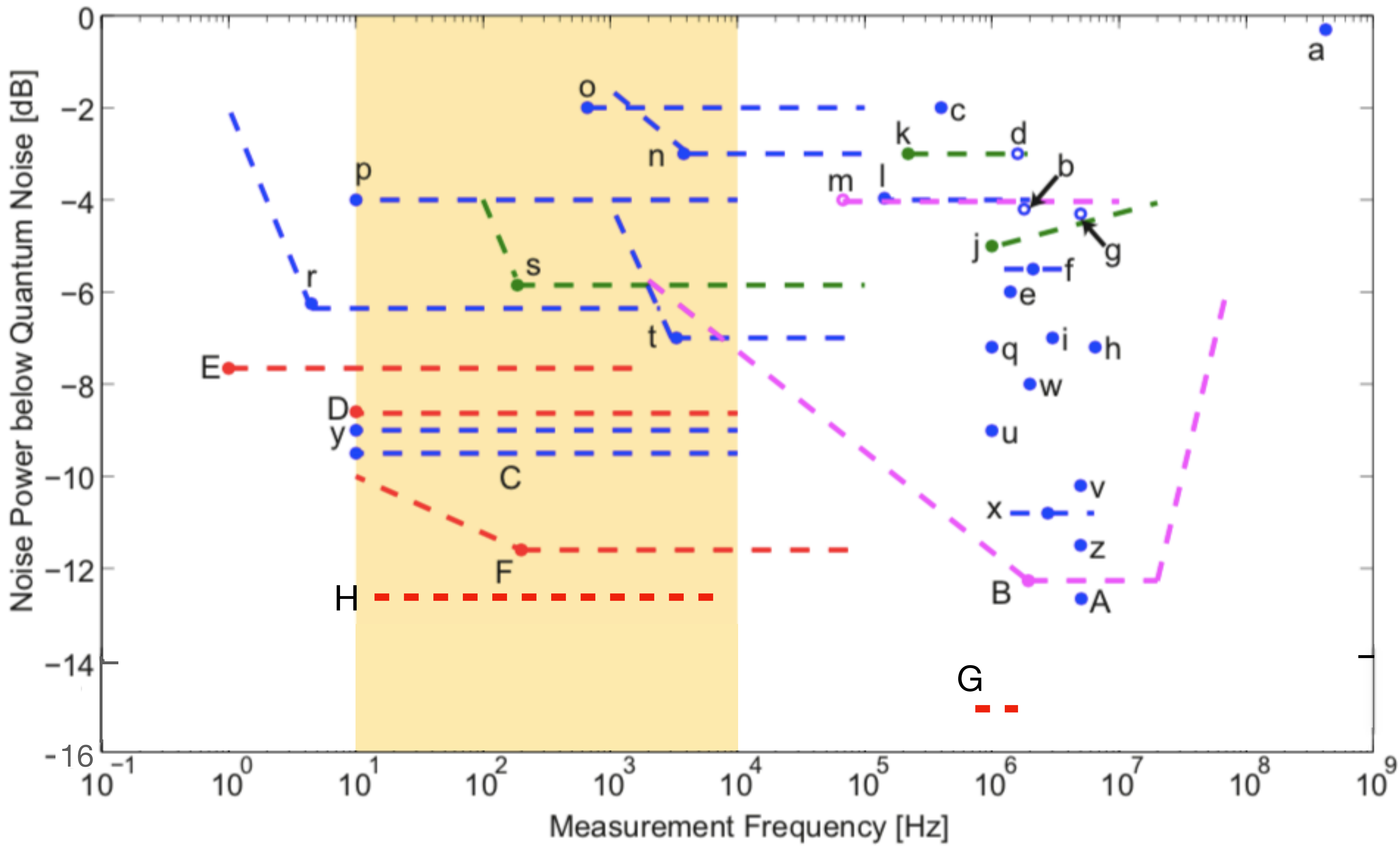
The squeezed-state technique outlined in this paper will not be easy to implement. A refuge from criticism that the technique is difficult can be found by retreating behind the position that the entire task of detecting gravitational radiation is exceedingly difficult. Difficult or not, the squeezed-state 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

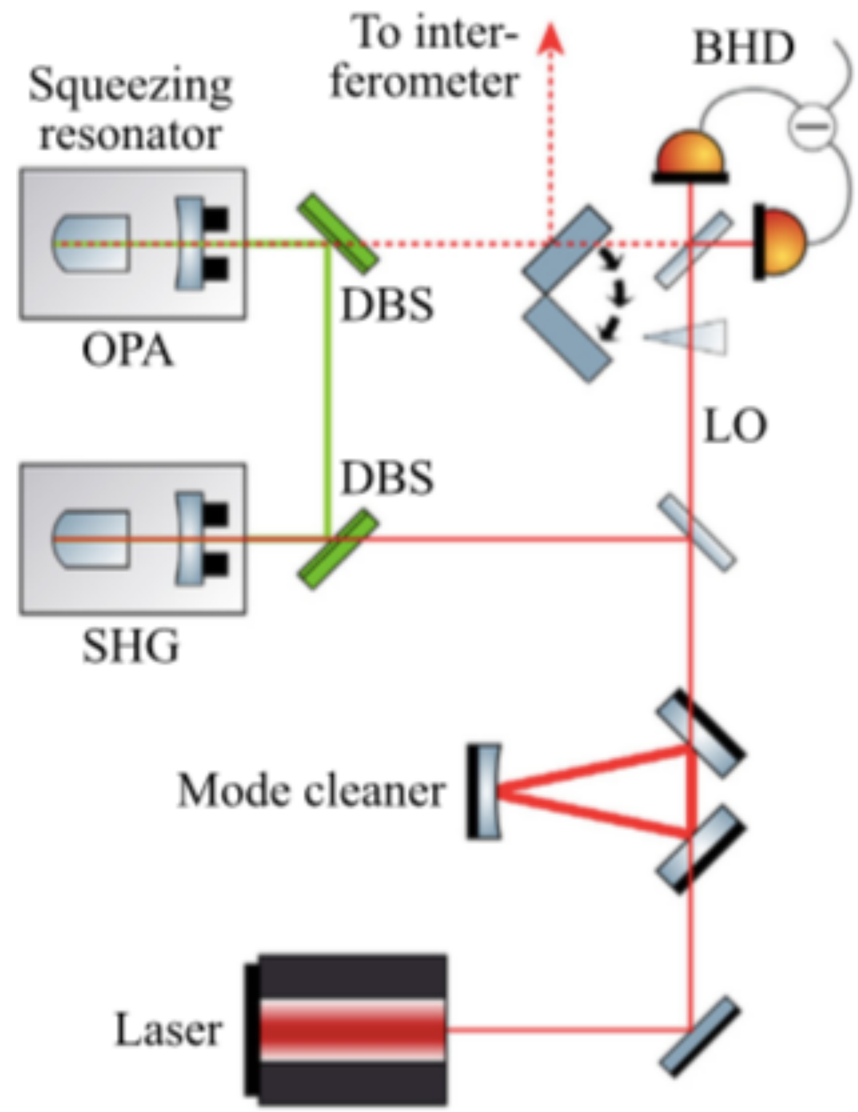


Adapted from S. Chua PhD Thesis

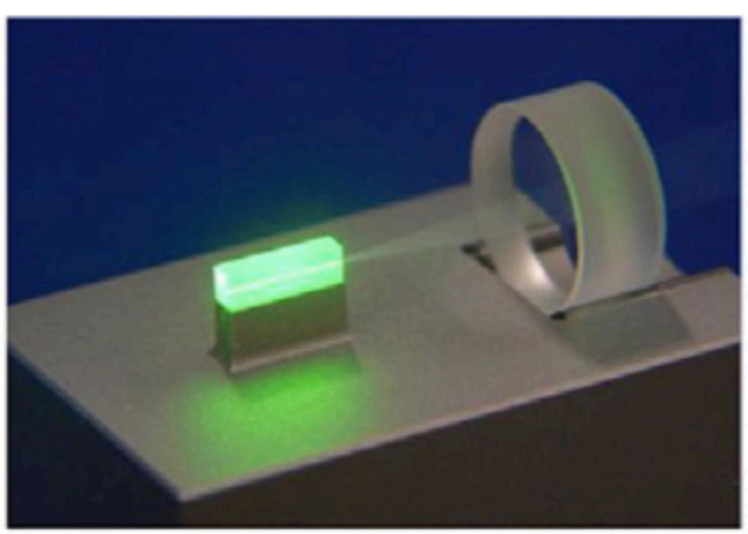
How to generate a squeezed state: non linear interaction

- The most effective way to generate squeezing is a optical parametric oscillator (OPO)

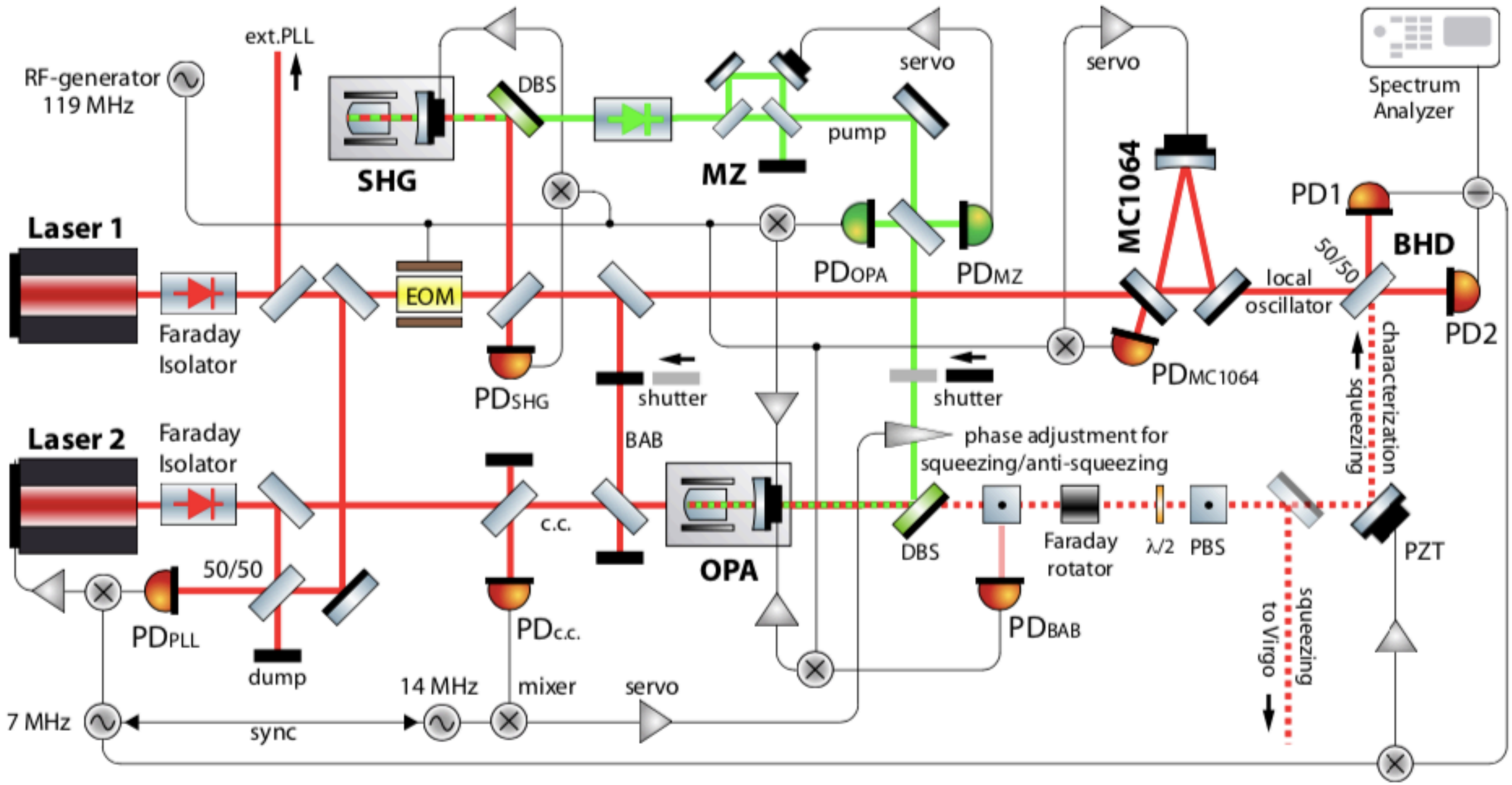
- OPO uses non linear crystal to create correlation between quadratures



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

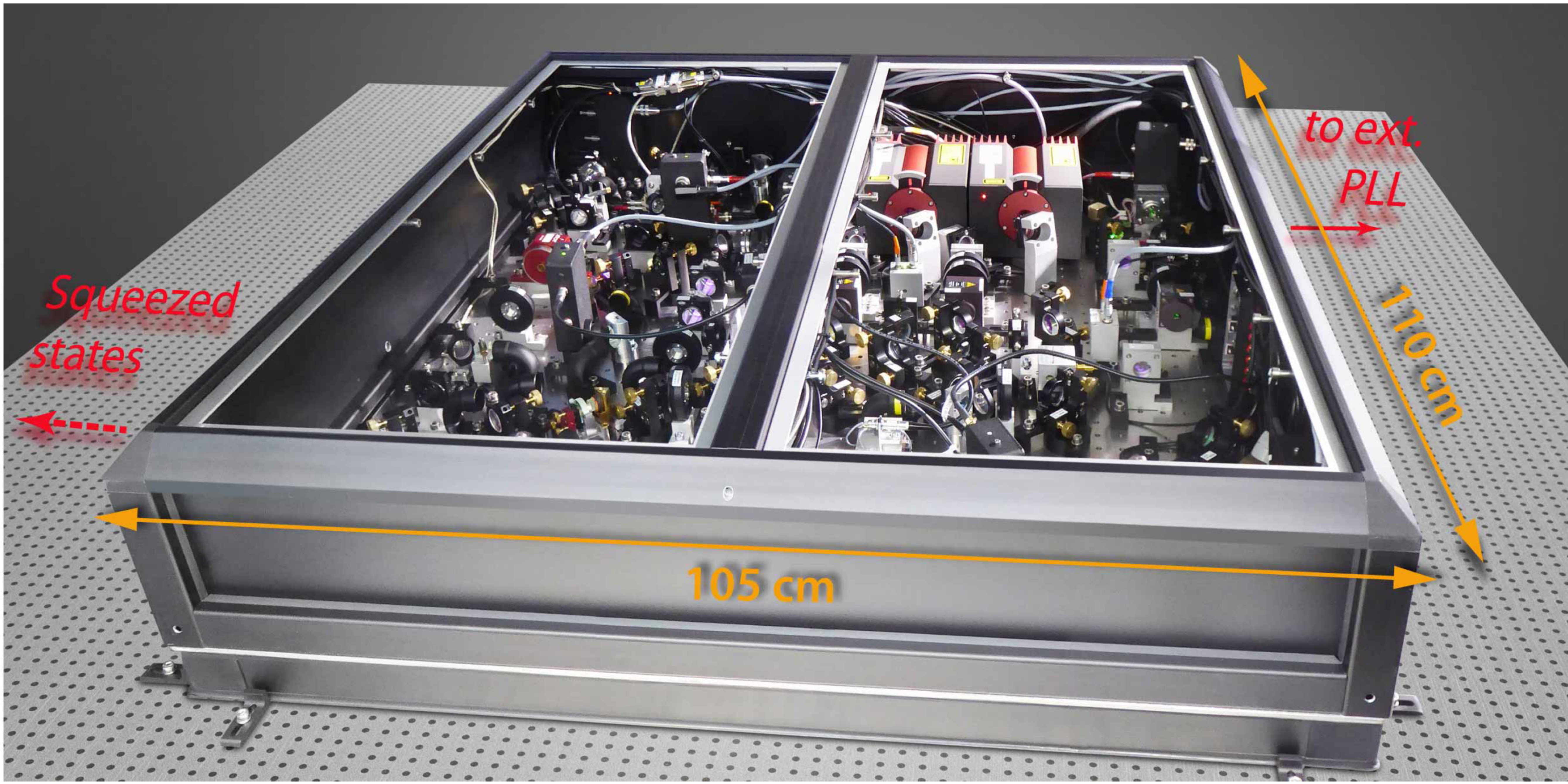


Vacuum squeezed source: optical scheme



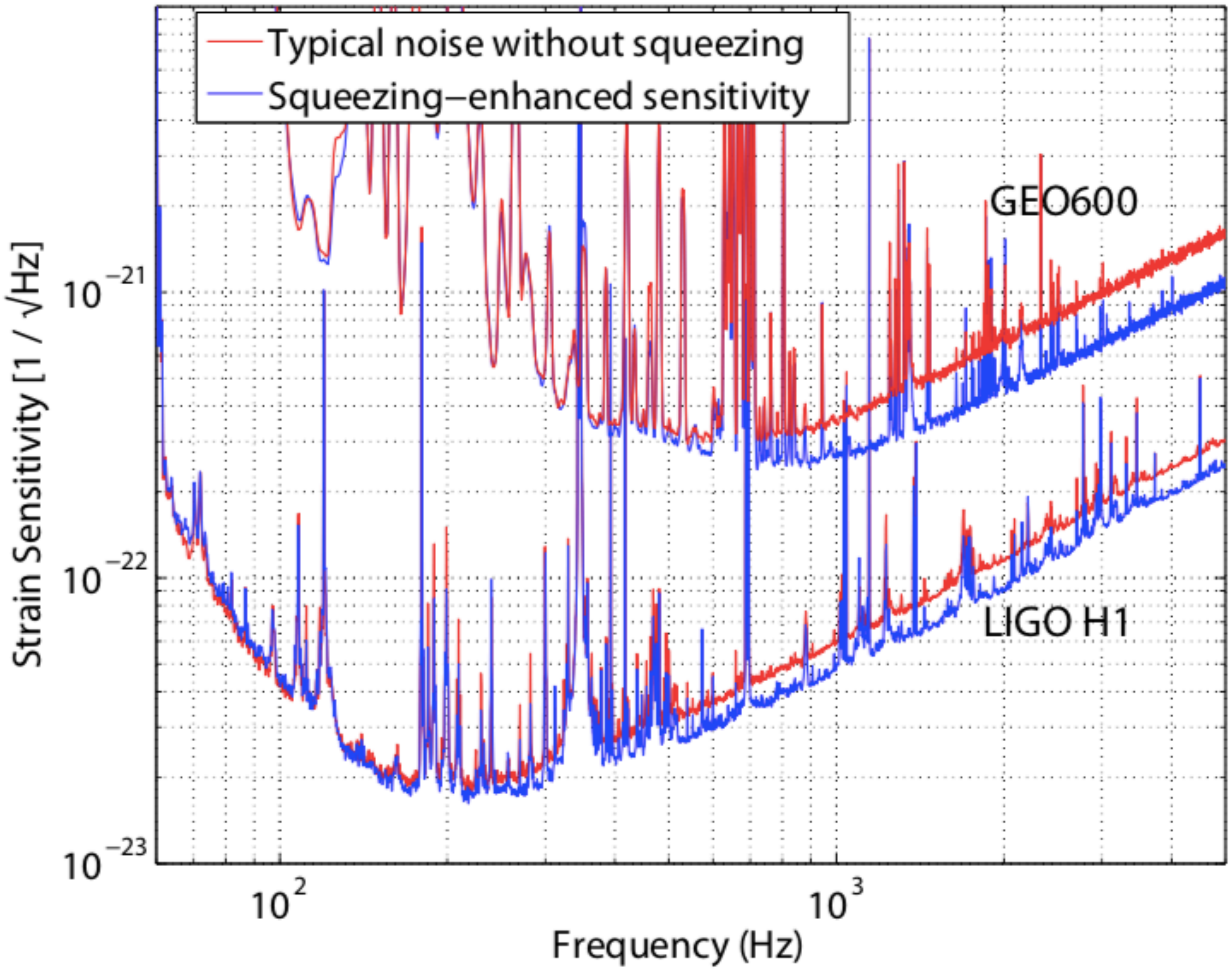
Mehmet, M.; Vahlbruch, H. The Squeezed Light Source for the Advanced Virgo Detector in the Observation Run O3. *Galaxies* **2020**, *8*, 79. https://doi.org/10.3390/galaxies8040079

Vacuum squeezed source



First applications to GW detectors

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



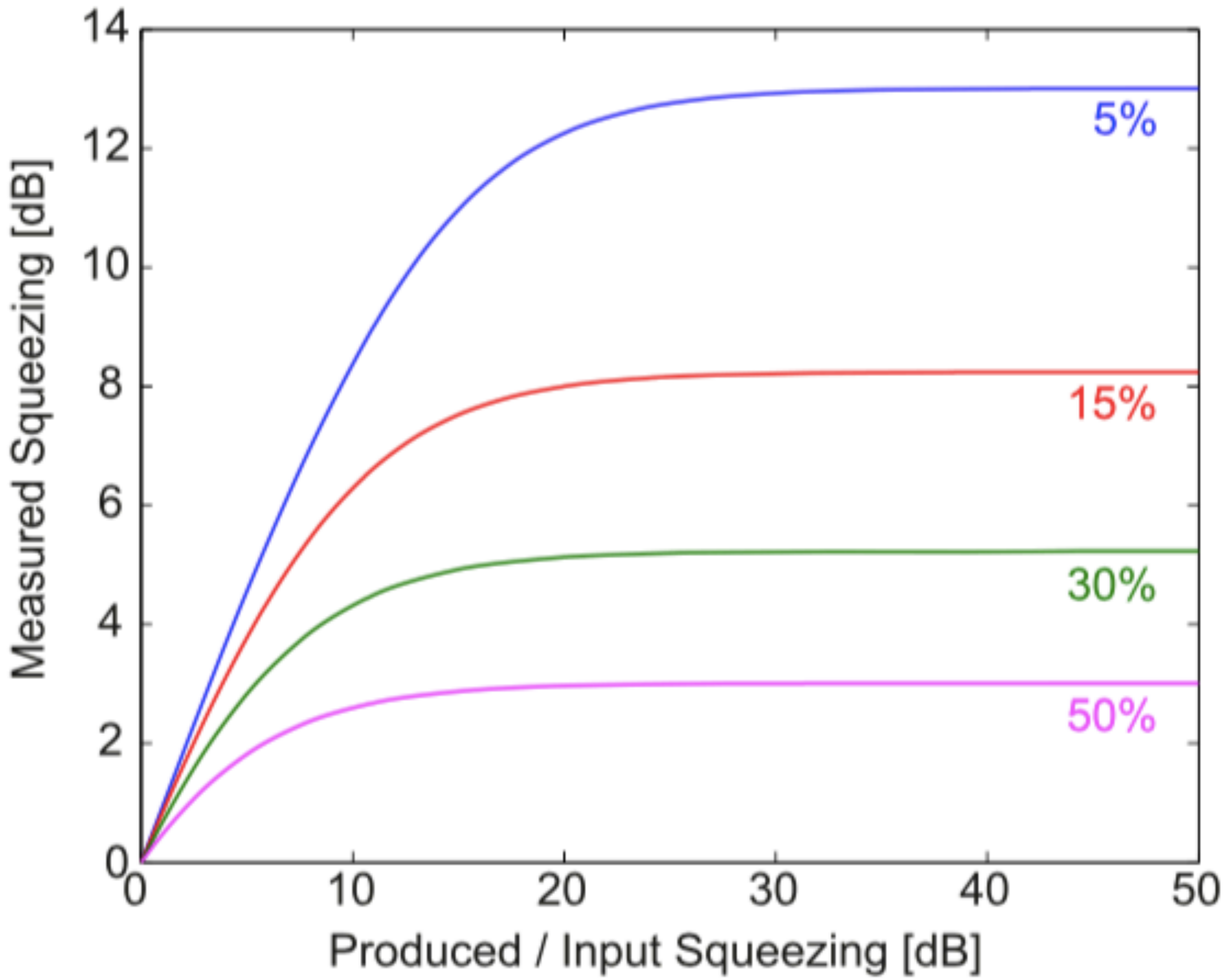
LIGO Scientific Collaboration, J. Aasi et al., "Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light", Nat Photon 7 no. 8, (Aug, 2013) 613–619.

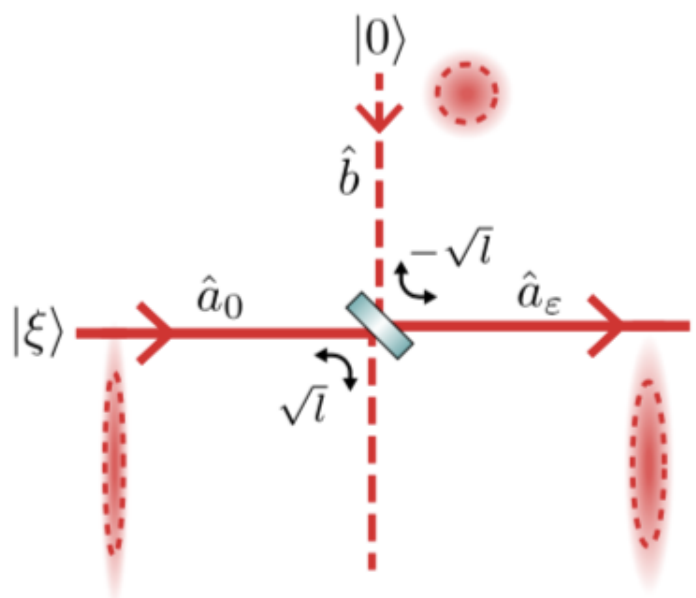
H. Grote et al. "First Long-Term Application of Squeezed States of Light in a Gravitational-Wave Observatory" Phys. Rev. Lett. 110, 181101 (2013)

Optical losses degrades squeezing

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

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



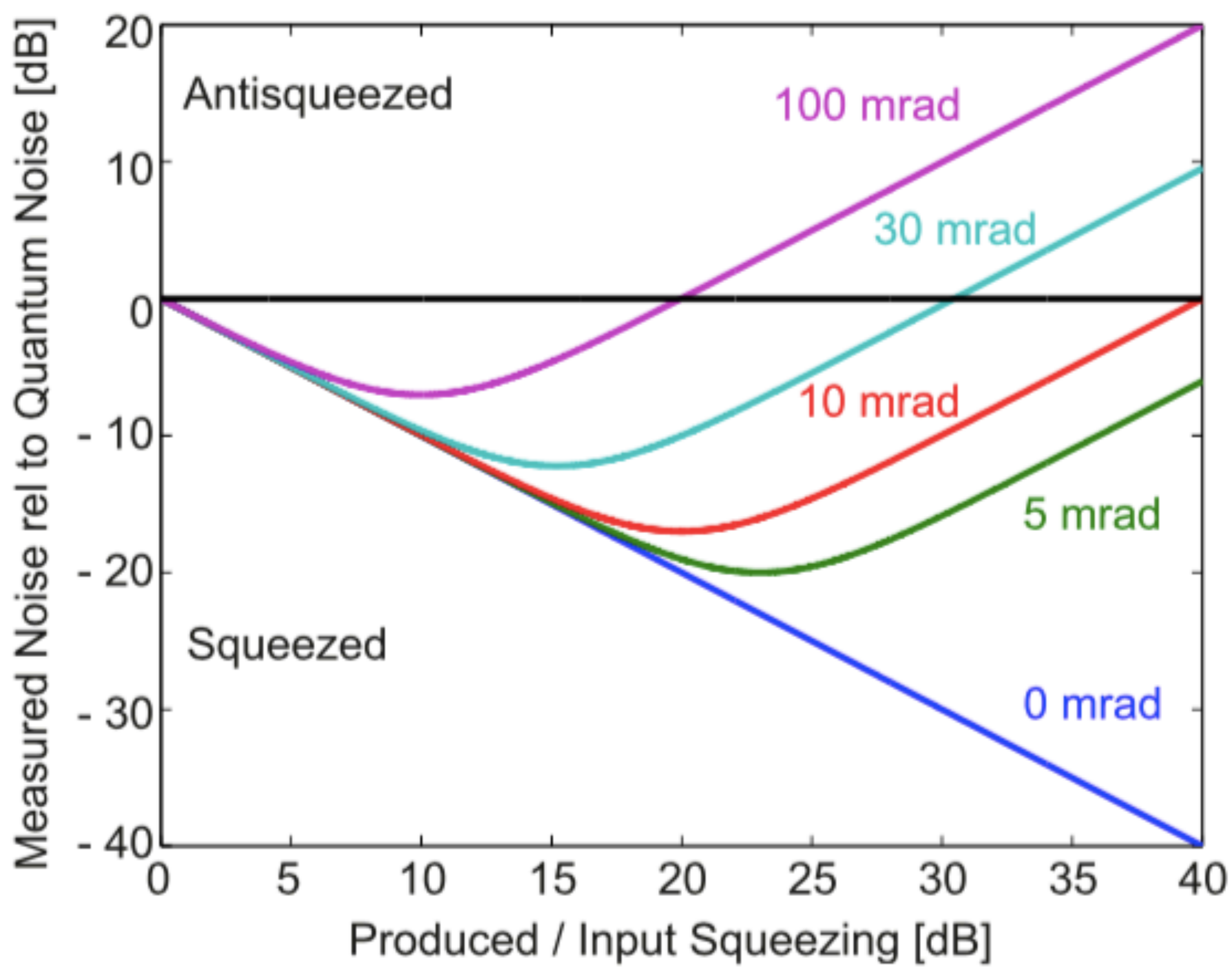


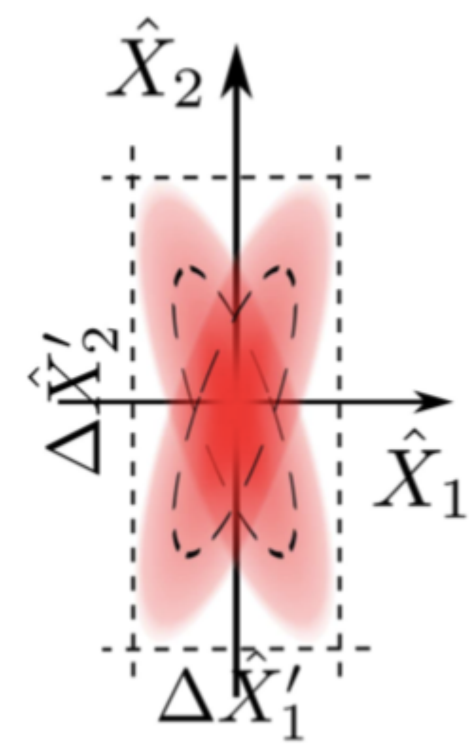
S. Chua et al. Class. Quantum Grav. 31 (2014)

Phase noise effect

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

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

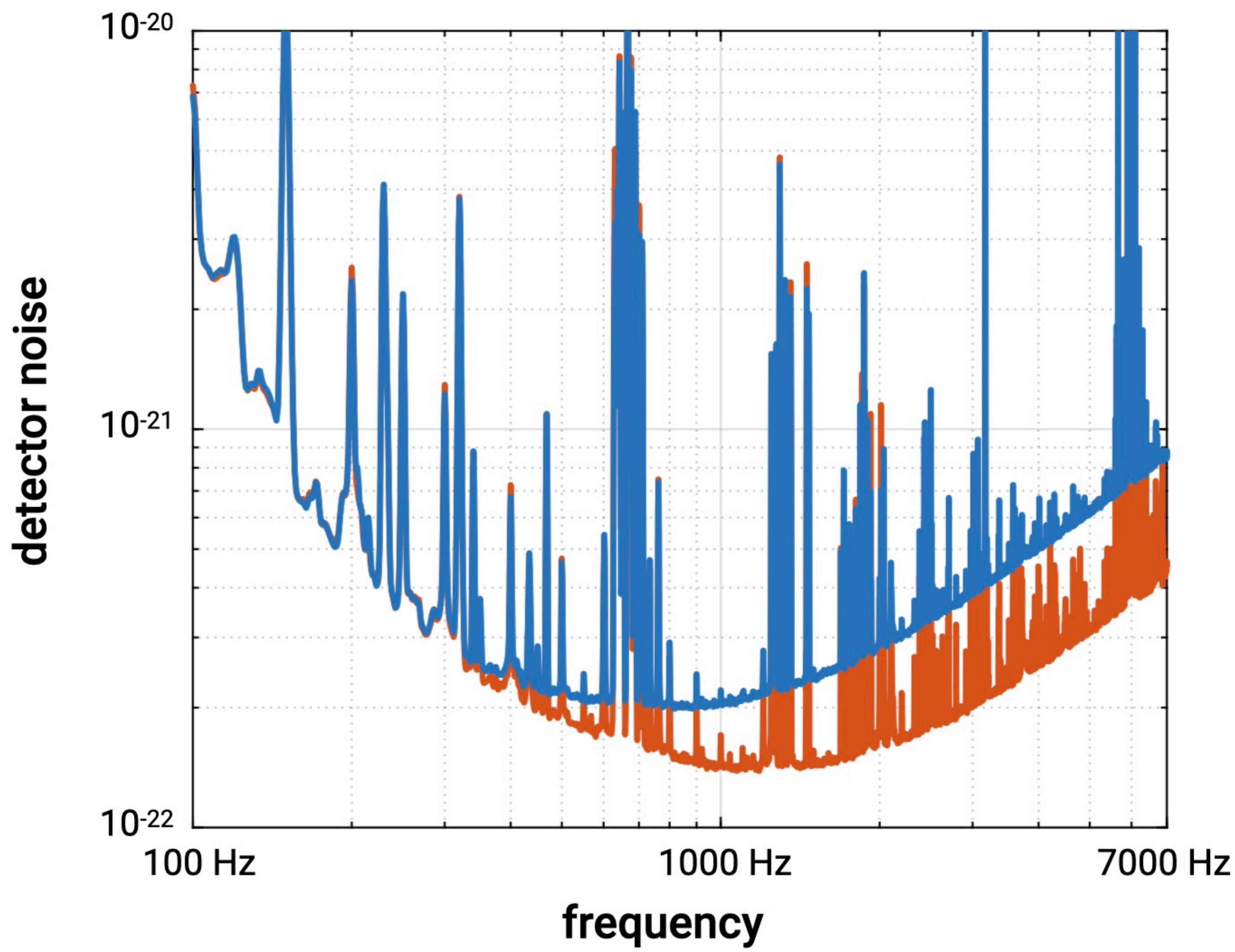




S. Chua et al. Class. Quantum Grav. 31 (2014)

GEO600 squeezing record

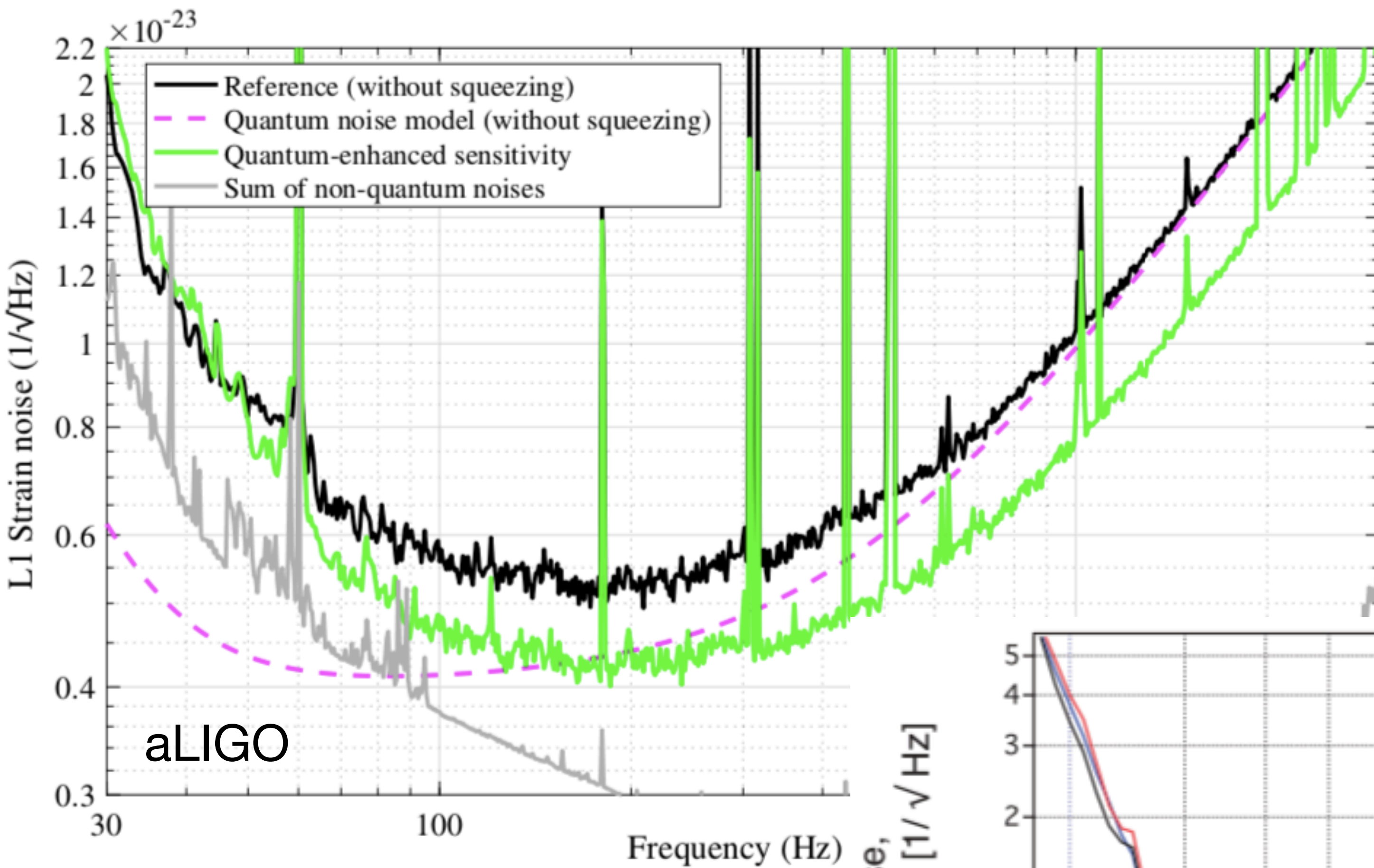
- 6dB achieved at high frequency



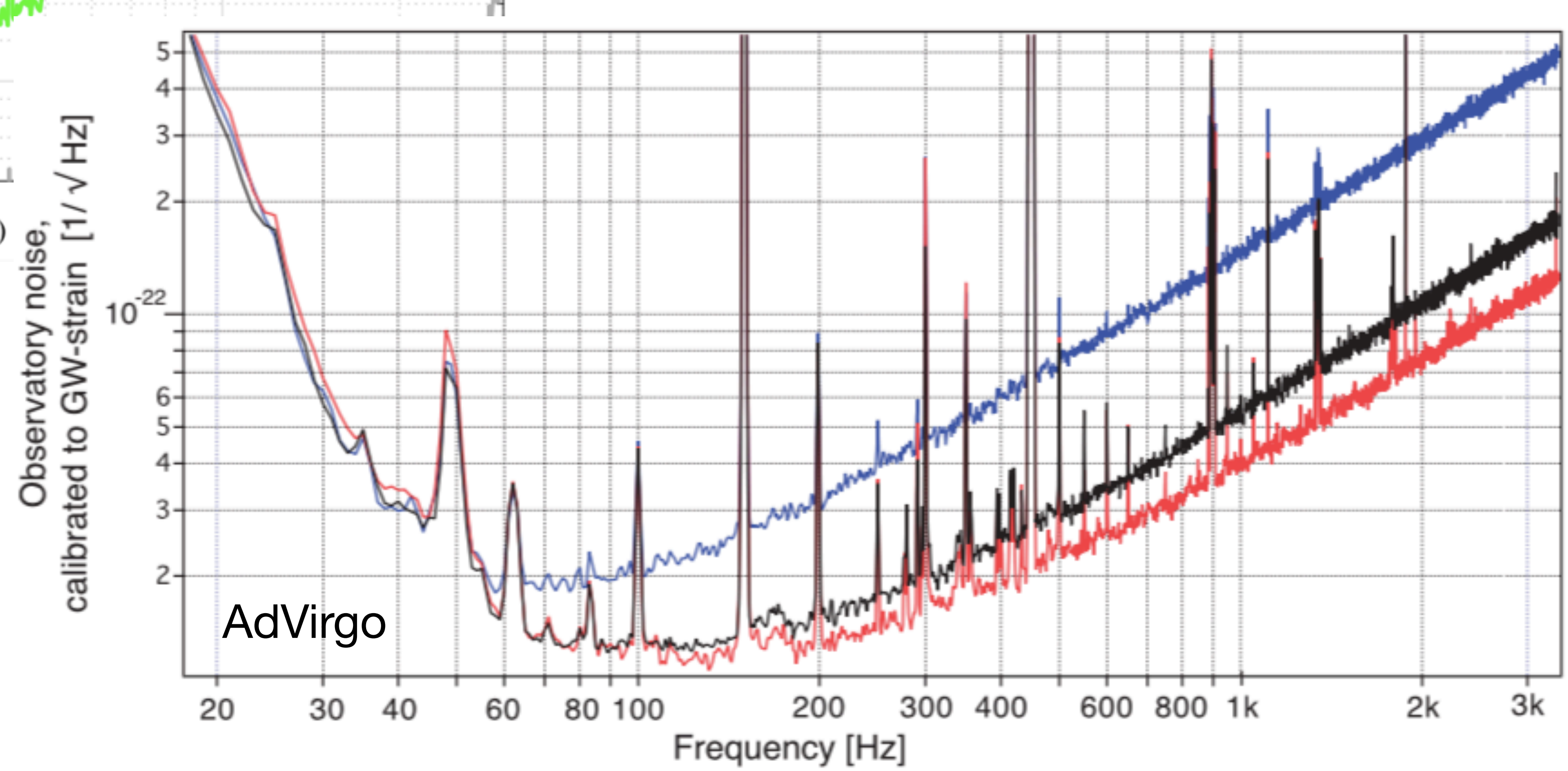
First Demonstration of 6 dB Quantum Noise Reduction in a Kilometer Scale Gravitational Wave Observatory, J.Lough et al.
Phys. Rev. Lett. 126, 041102 (2021)

Squeezed source integrated in 2G GW detectors

- Operating in both LIGO and Virgo since the beginning of O3 (2019)

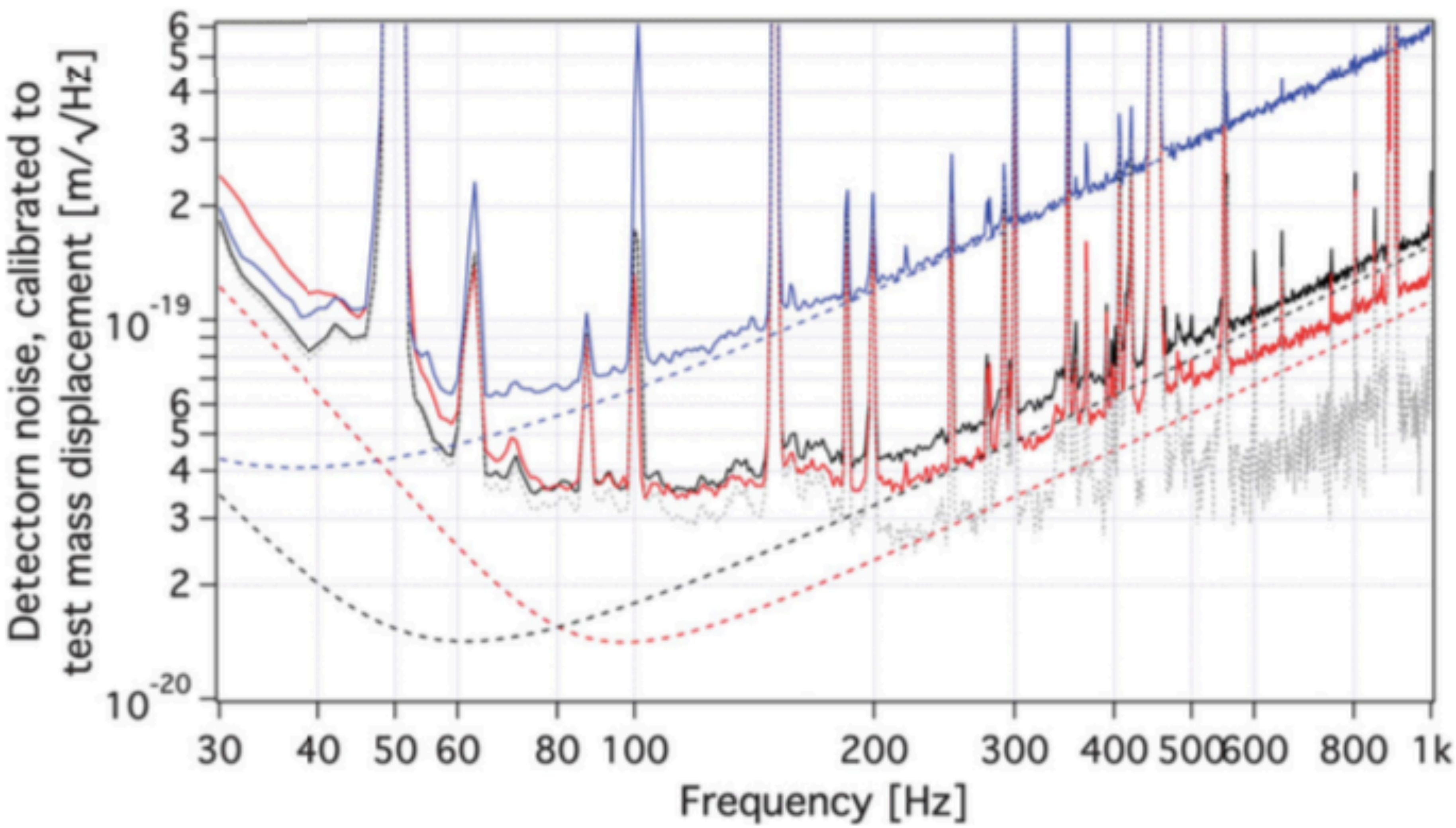


- About 3 dB of squeezing measured
- Between 25-40% of losses measured
- Detection rate improvement up to 50%



Broadband quantum noise reduction?

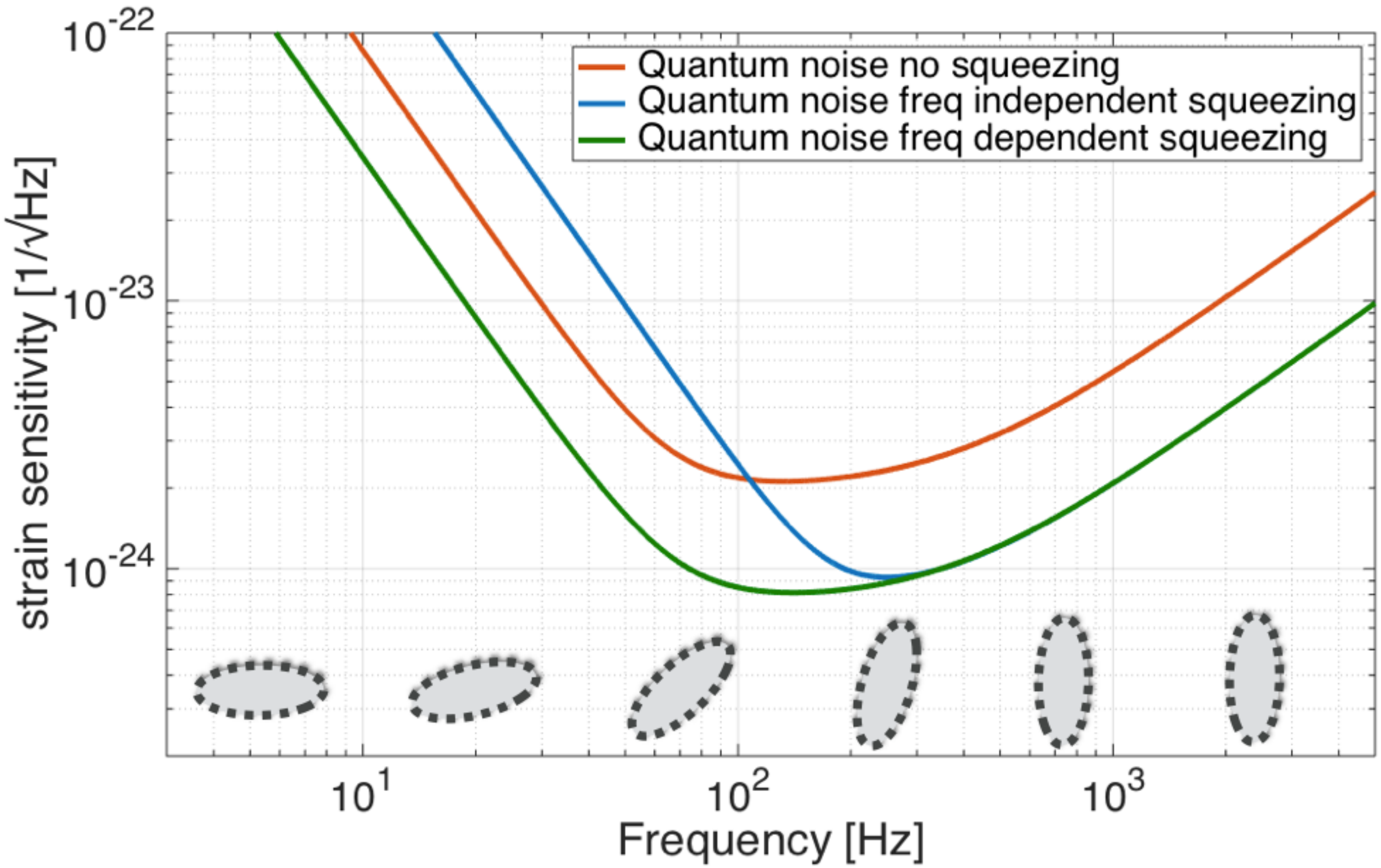
- Phase squeezed noise reduces shot noise but increase radiation pressure noise
- Effects already observed in O3



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

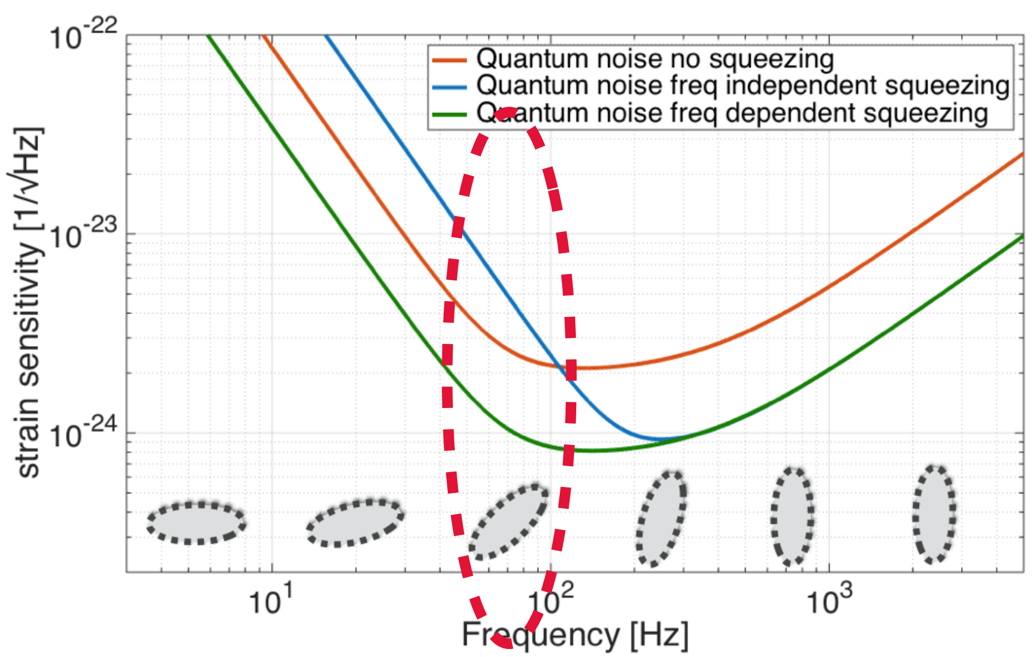
- Squeezing ellipse undergoes a rotation inside the interferometer
- Squeezing angle should change with the frequency for optimal noise reduction

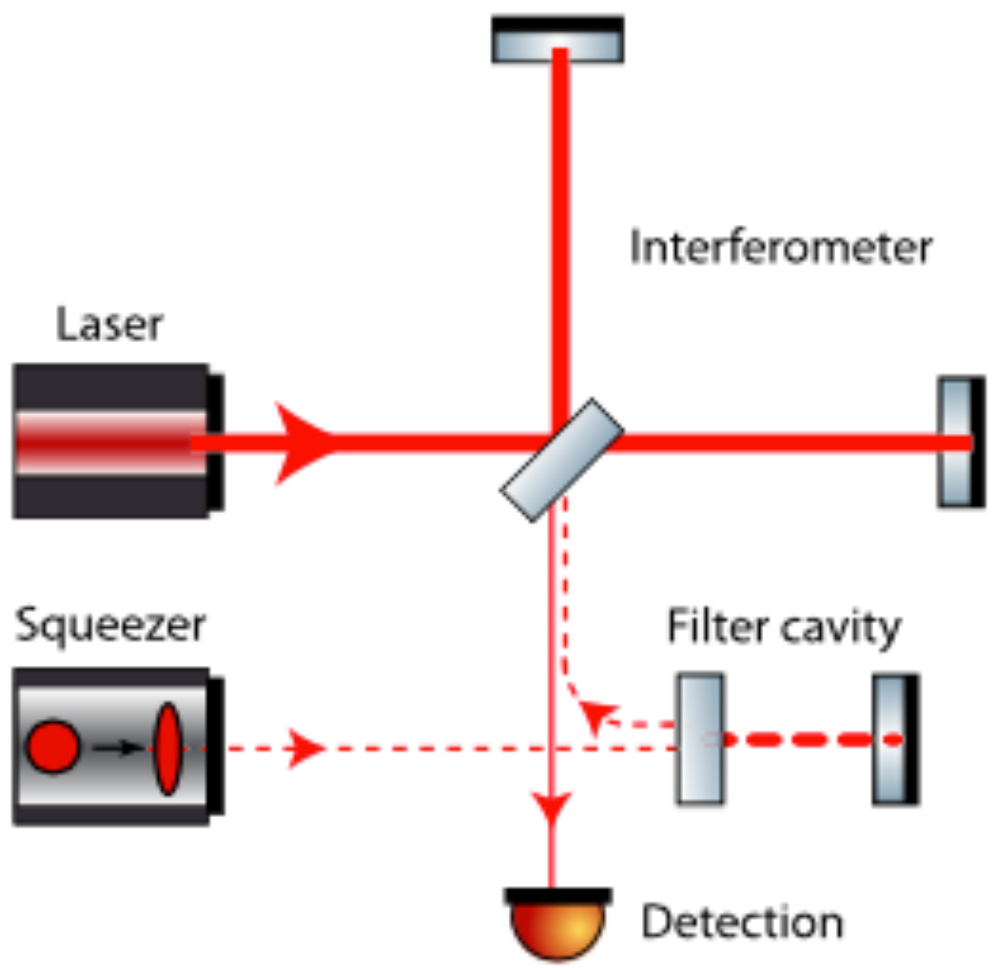


Frequency dependent squeezing via filter cavity

- Reflect frequency independent squeezing off a detuned Fabry-Perot cavity

- Rotation frequency depends on cavity linewidth

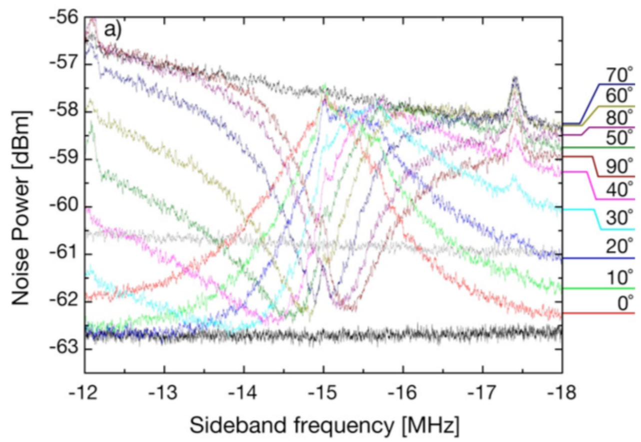




- Optimal rotation frequency between 40 and 70 Hz

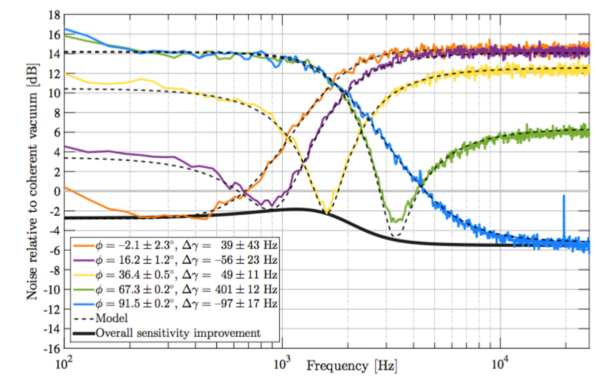
Squeezing angle rotation already realized

@ MHz frequency (2005)



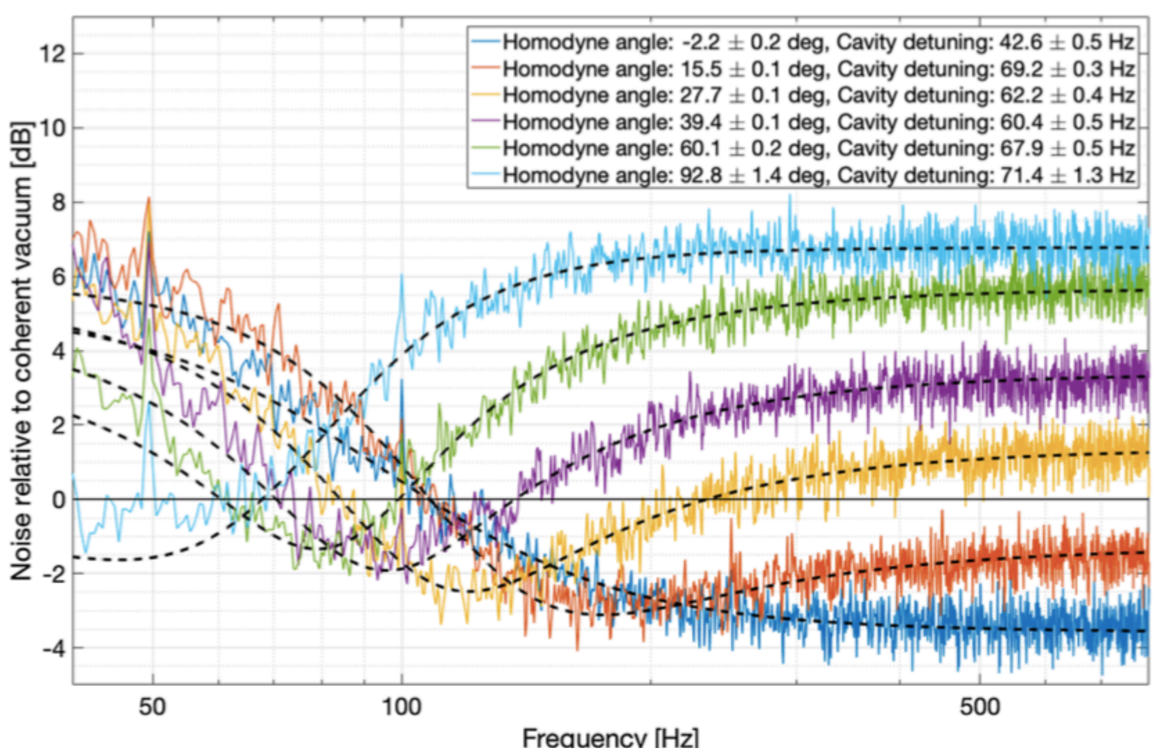
PHYSICAL REVIEW A **71**, 013806 (2005)

@ kHz frequency (2016)

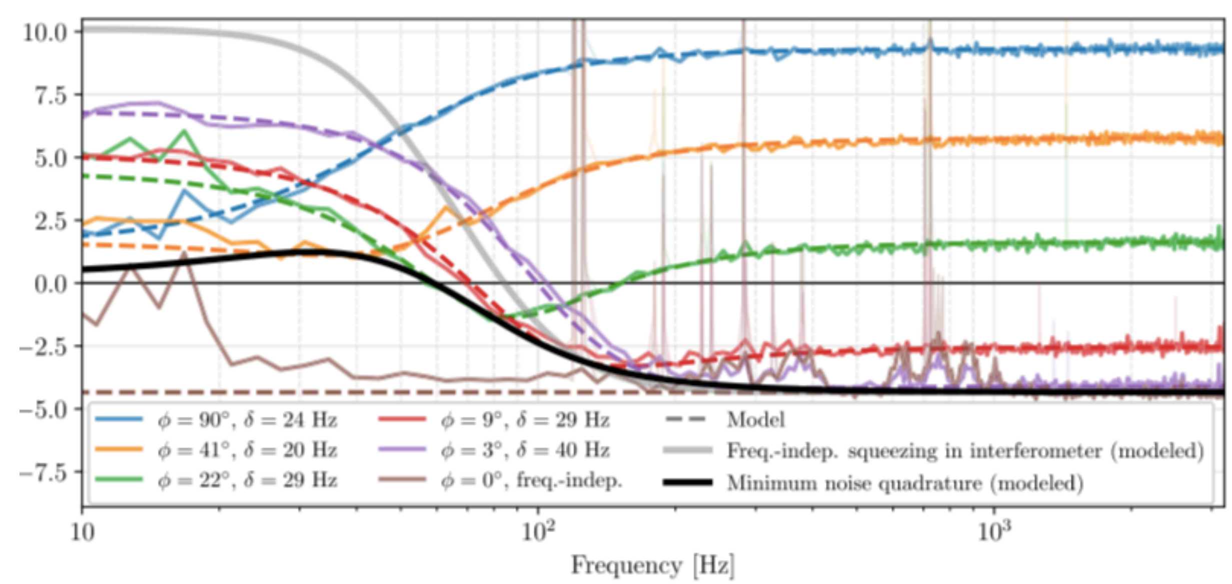


PRL **116**, 041102 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Below 100 Hz (2020)



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

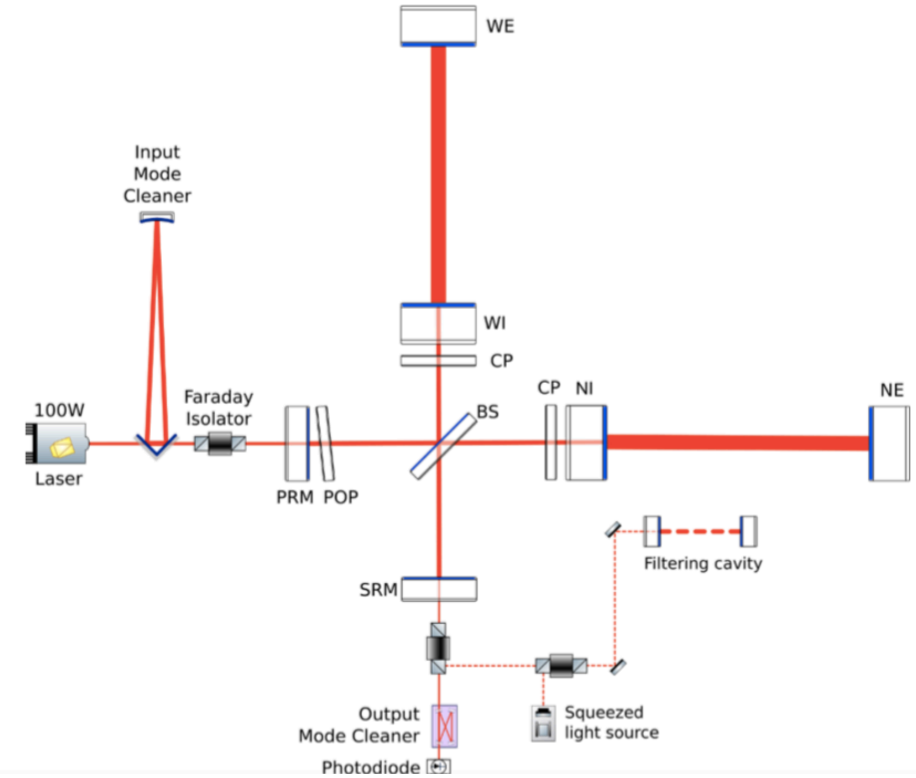


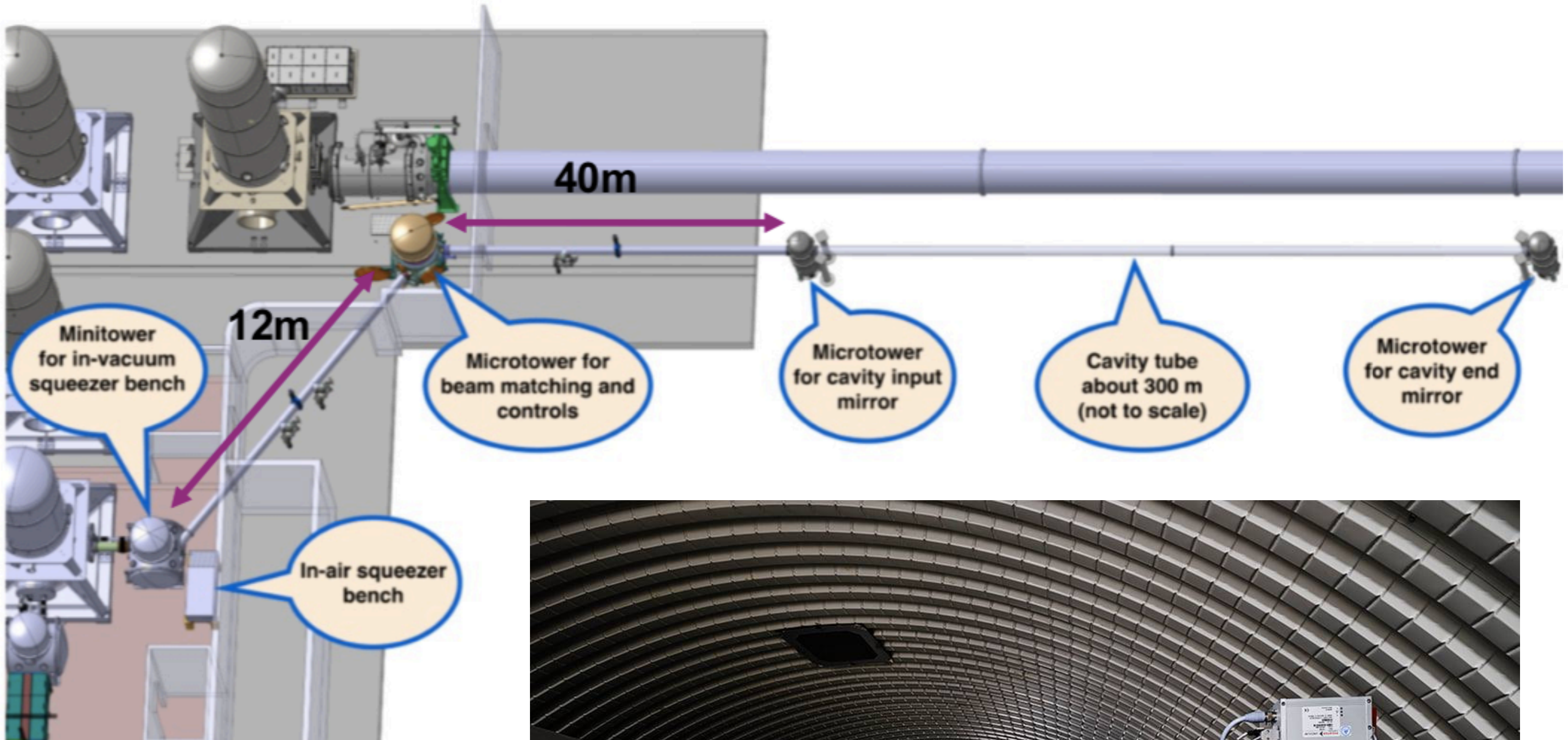
PHYSICAL REVIEW LETTERS **124**, 171102 (2020)

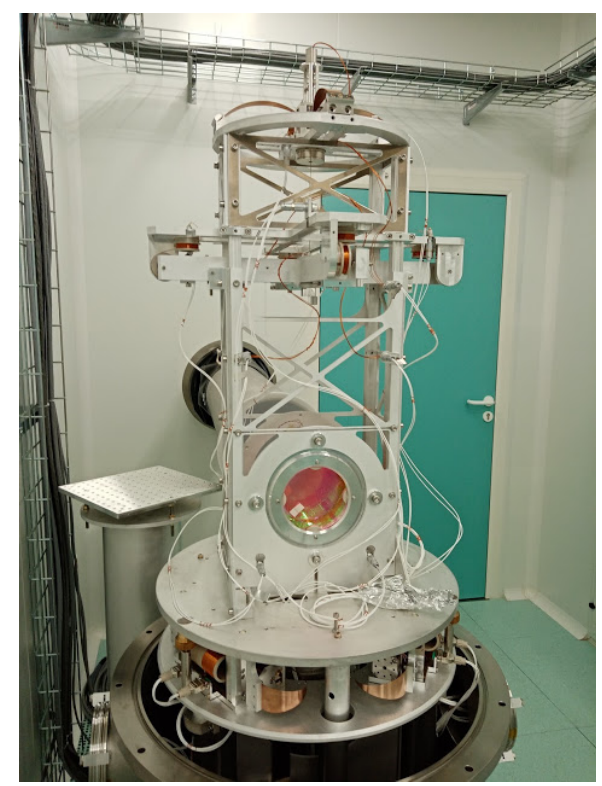
- See also N. Leroy's talk tomorrow

Filter cavity implementation for O4

- Same squeezed vacuum source used in O3
- Length: ~ 300 m
- Commissioning on-going: first lock achieved







Summary

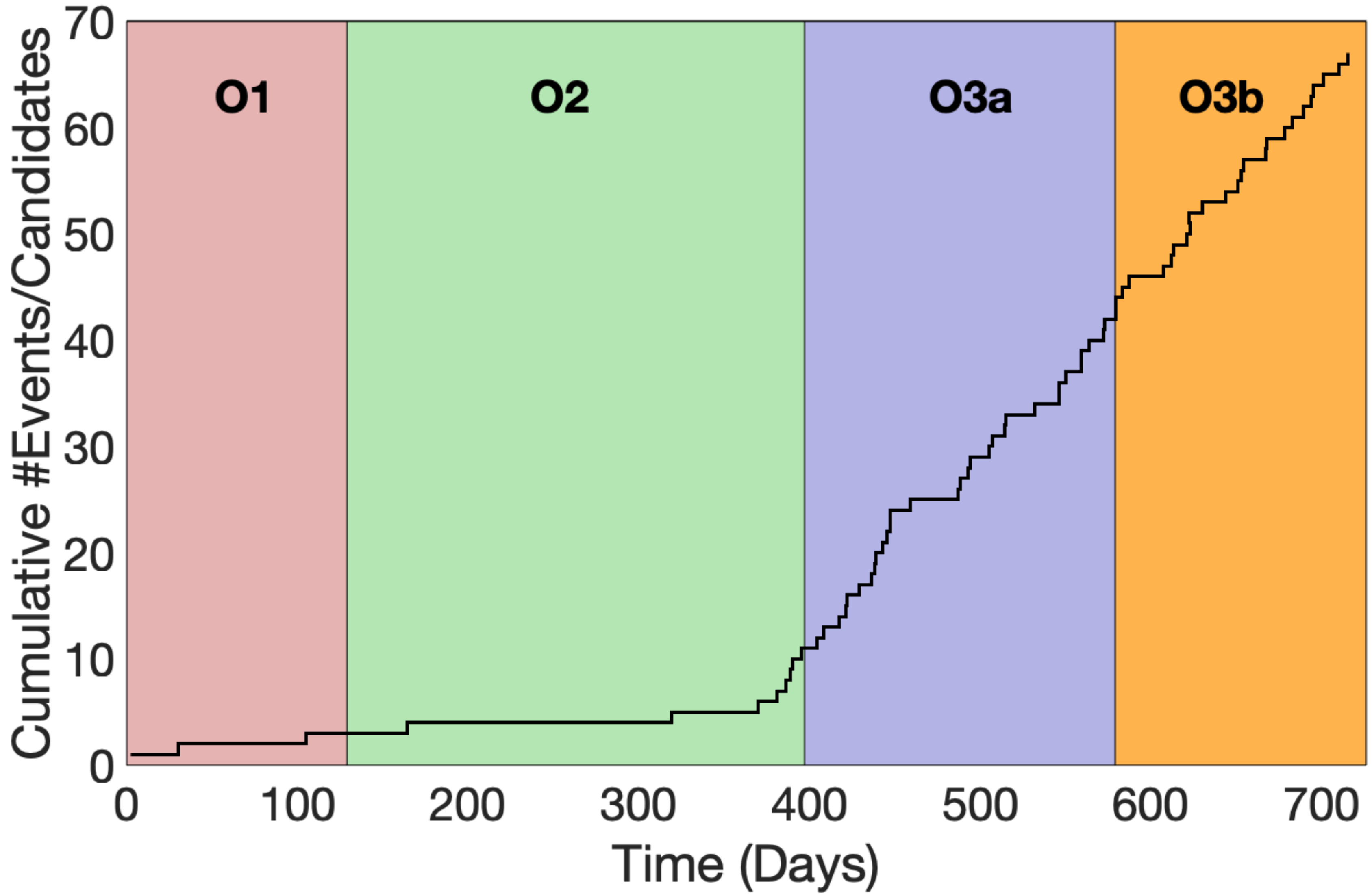
- Quantum noise is an intrinsic limitation of the interferometric measurement, originated by vacuum fluctuations. It limits the sensitivity in the whole bandwidth
- Standard quantum limit can be circumvented by injecting squeezed vacuum into the interferometer's output port
- After 40 year of developments squeezing is now a key technology for present and future GW detectors.
- Future prospective: See E. Tourefier's talk tomorrow

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

Observations summary



O1-O2 (2015 - 2017)

- 11 detections (10 BBH, 1 BNS)
- GWTC-1 first catalog of GW transient sources (2019)

O3a (2019)

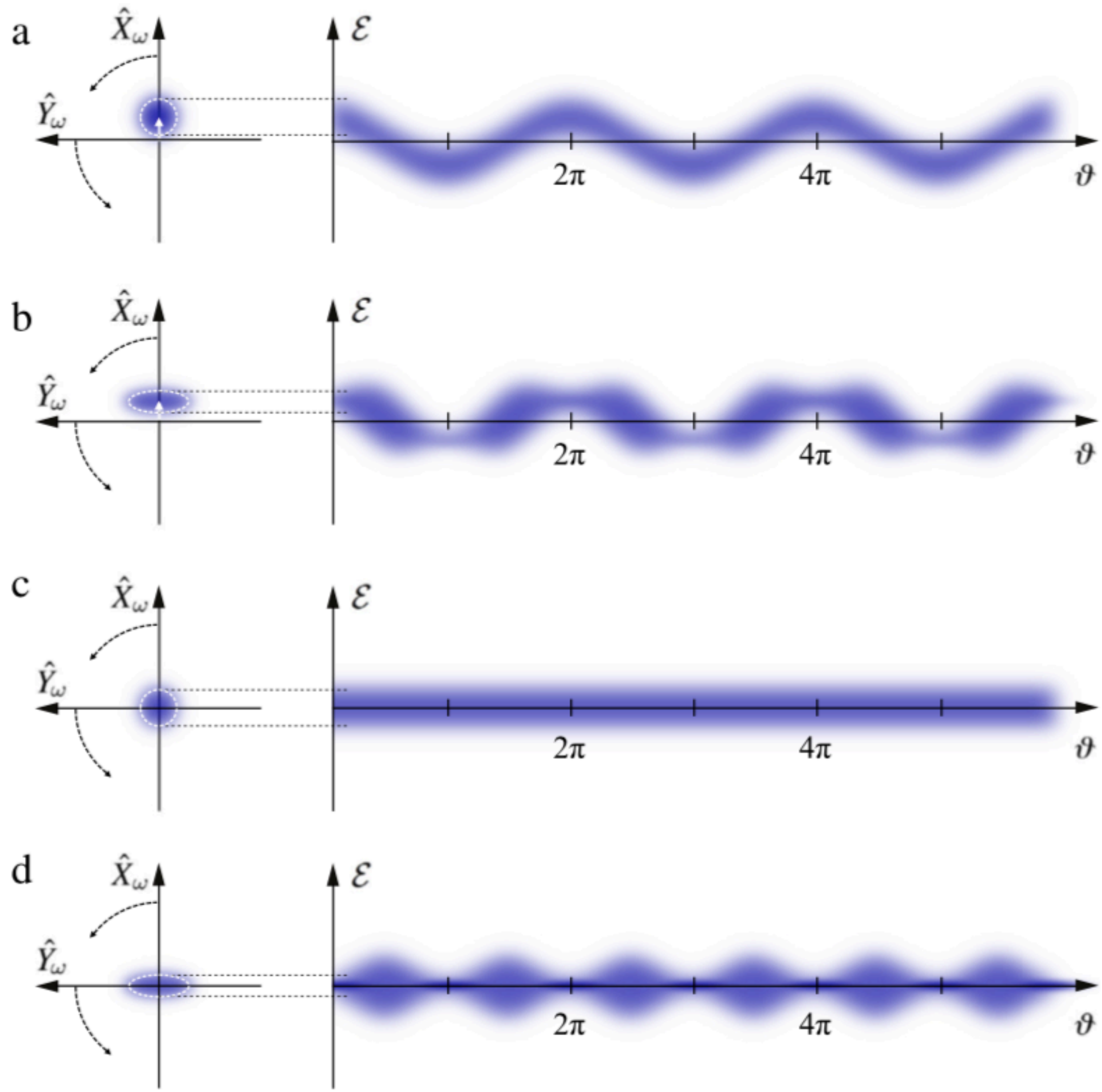
- 39 detections
- GWTC-2 second catalog of GW transient sources (2020)

O3b (2019 - 2020)

- 30 alerts
- Analysis on-going

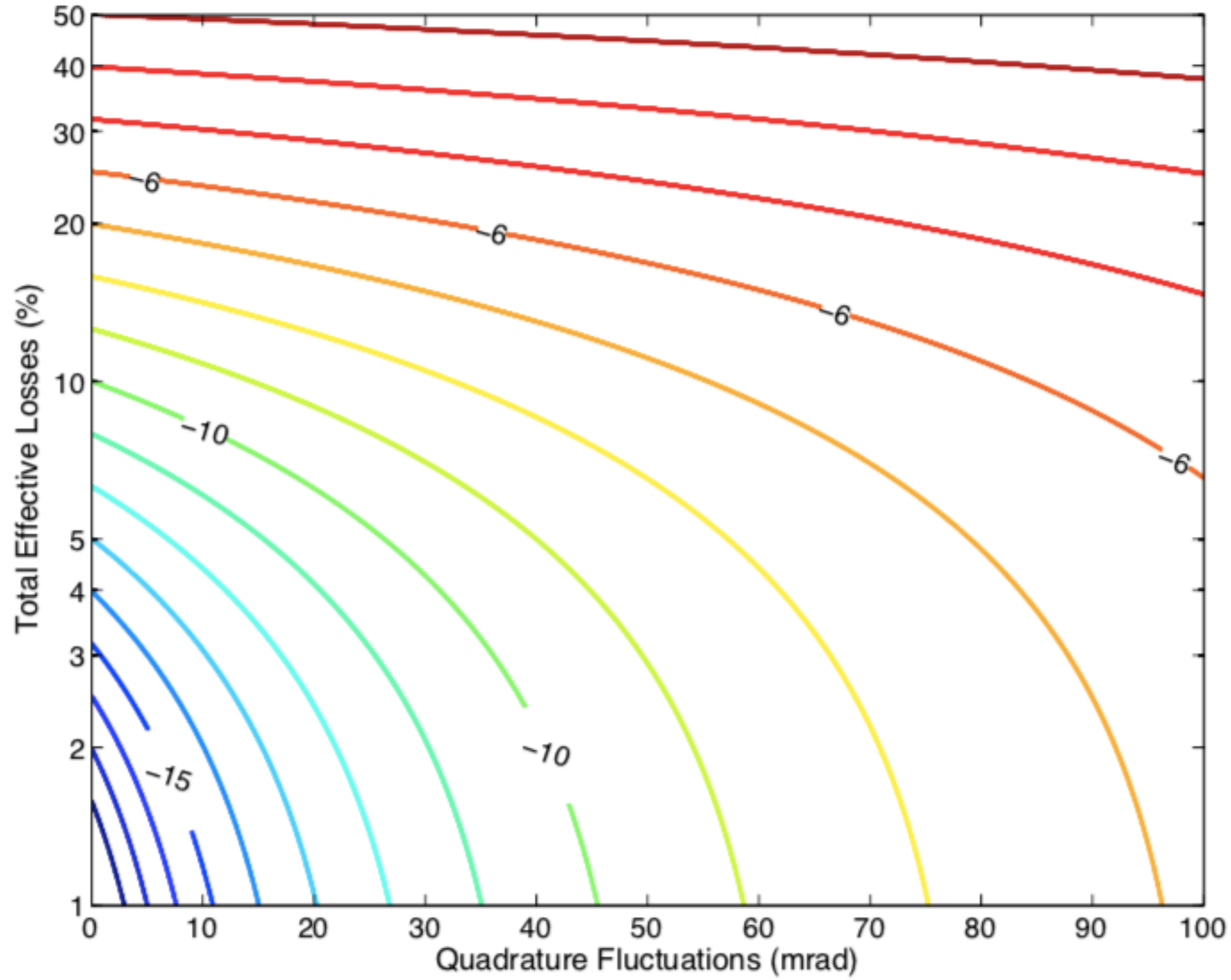
Squezeed states

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



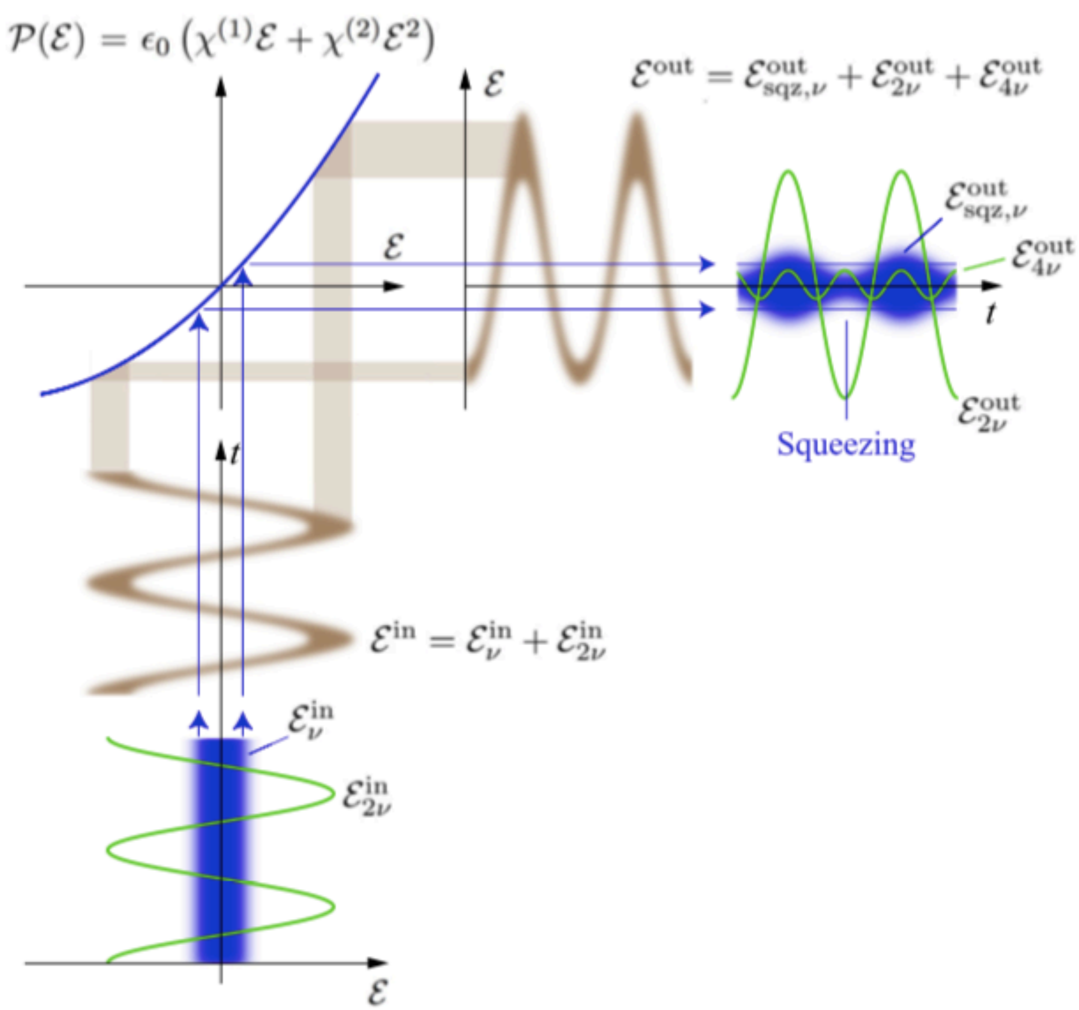
Optical losses and phase noise effect

- Measurable squeezing level in the presence of **optical losses** and **phase noise** (squeezed quadrature fluctuations)



Squeezed vacuum states of light for gravitational wave detectors
L. Barsotti, J. Harms and R. Schnabel
Reports on Progress in Physics, Volume 82, Number 1 (2018)

How to generate a squeezed state

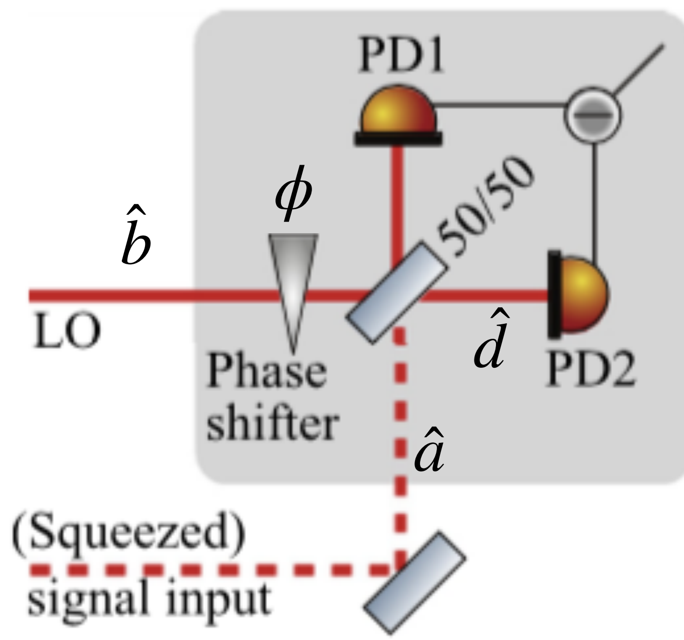


- Optical parametric amplification of a vacuum state
- The input field (vacuum and pump) is transferred into a time-dependent dielectric polarization that is the source of the output field

A graphical description of optical parametric generation of squeezed states of light
American Journal of Physics 81, 767 (2013)
J. Bauchrowitza), T. Westphal, R. Schnabel

How to measure a squeezed state

- Balanced Homodyne detector

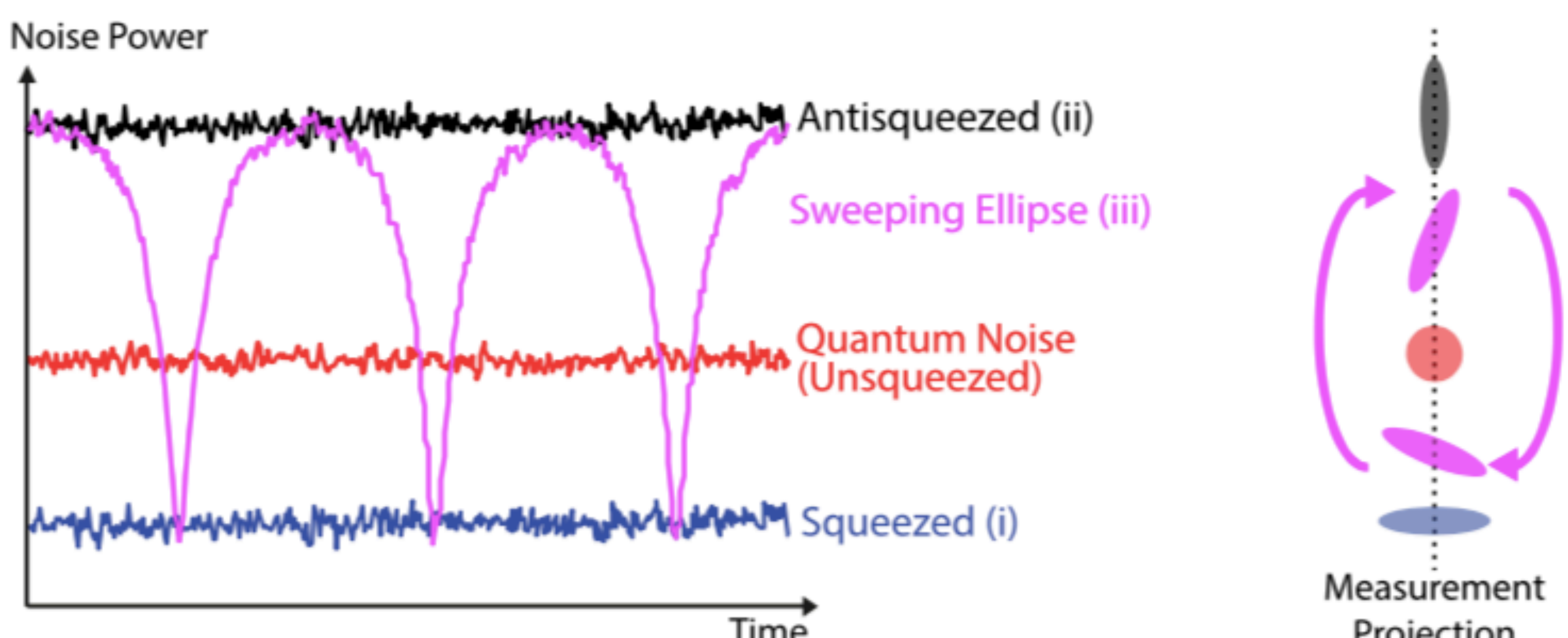


$$\hat{a} = \alpha + \delta\hat{a} \quad \hat{b} = (\beta + \delta\hat{b})e^{i\phi}$$

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

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

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



Noise in gravitational-wave detectors and other classical-force measurements is not influenced by test-mass quantization

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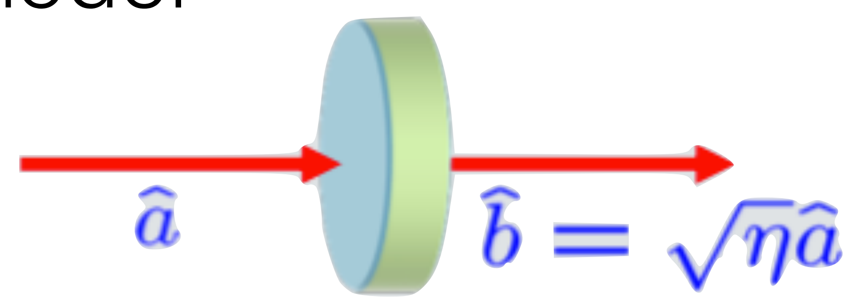
[3]*Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125*
(Received 2 September 2001; published 7 April 2003)

It is shown that photon shot noise and radiation-pressure back-action noise are the sole forms of quantum noise in interferometric gravitational wave detectors that operate near or below the standard quantum limit, if one filters the interferometer output appropriately. No additional noise arises from the test masses' initial quantum state or from reduction of the test-mass state due to measurement of the interferometer output or from the uncertainty principle associated with the test-mass state. Two features of interferometers are central to these conclusions: (i) The interferometer output [the photon number flux $\hat{\mathcal{N}}(t)$ entering the final photodetector] commutes with itself at different times in the Heisenberg picture, $[\hat{\mathcal{N}}(t),\hat{\mathcal{N}}(t')]=0$ and thus can be regarded as classical. (ii) This number flux is linear to high accuracy in the test-mass initial position and momentum operators $\hat{x}_o$ and $\hat{p}_o$, and those operators influence the measured photon flux $\hat{\mathcal{N}}(t)$ in manners that can easily be removed by filtering. For example, in most interferometers $\hat{x}_o$ and $\hat{p}_o$ appear in $\hat{\mathcal{N}}(t)$ only at the test masses' ~ 1 Hz pendular swinging frequency and their influence is removed when the output data are high-pass filtered to get rid of noise below ~ 10 Hz. The test-mass operators $\hat{x}_o$ and $\hat{p}_o$ contained in the unfiltered output $\hat{\mathcal{N}}(t)$ make a nonzero contribution to the commutator $[\hat{\mathcal{N}}(t),\hat{\mathcal{N}}(t')]$. That contribution is precisely canceled by a nonzero commutation of the photon shot noise and radiation-pressure noise, which also are contained in $\hat{\mathcal{N}}(t)$. This cancellation of commutators is responsible for the fact that it is possible to derive an interferometer's standard quantum limit from test-mass considerations, and independently from photon-noise considerations, and get identically the same result. These conclusions are all true for a far wider class of measurements than just gravitational-wave interferometers. To elucidate them, this paper presents a series of idealized thought experiments that are free from the complexities of real measuring systems.

Optical losses degrades squeezing

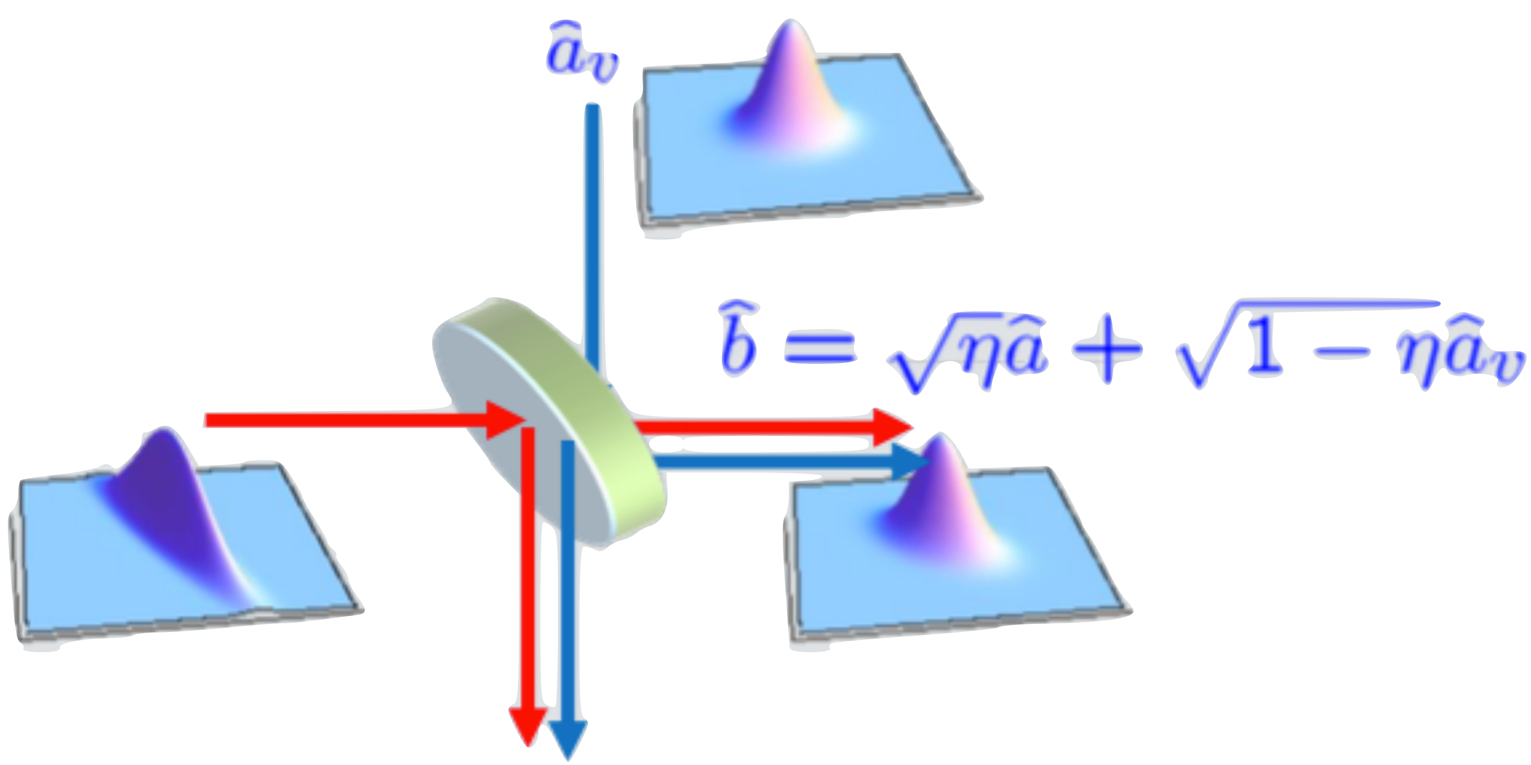
- Naive model



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

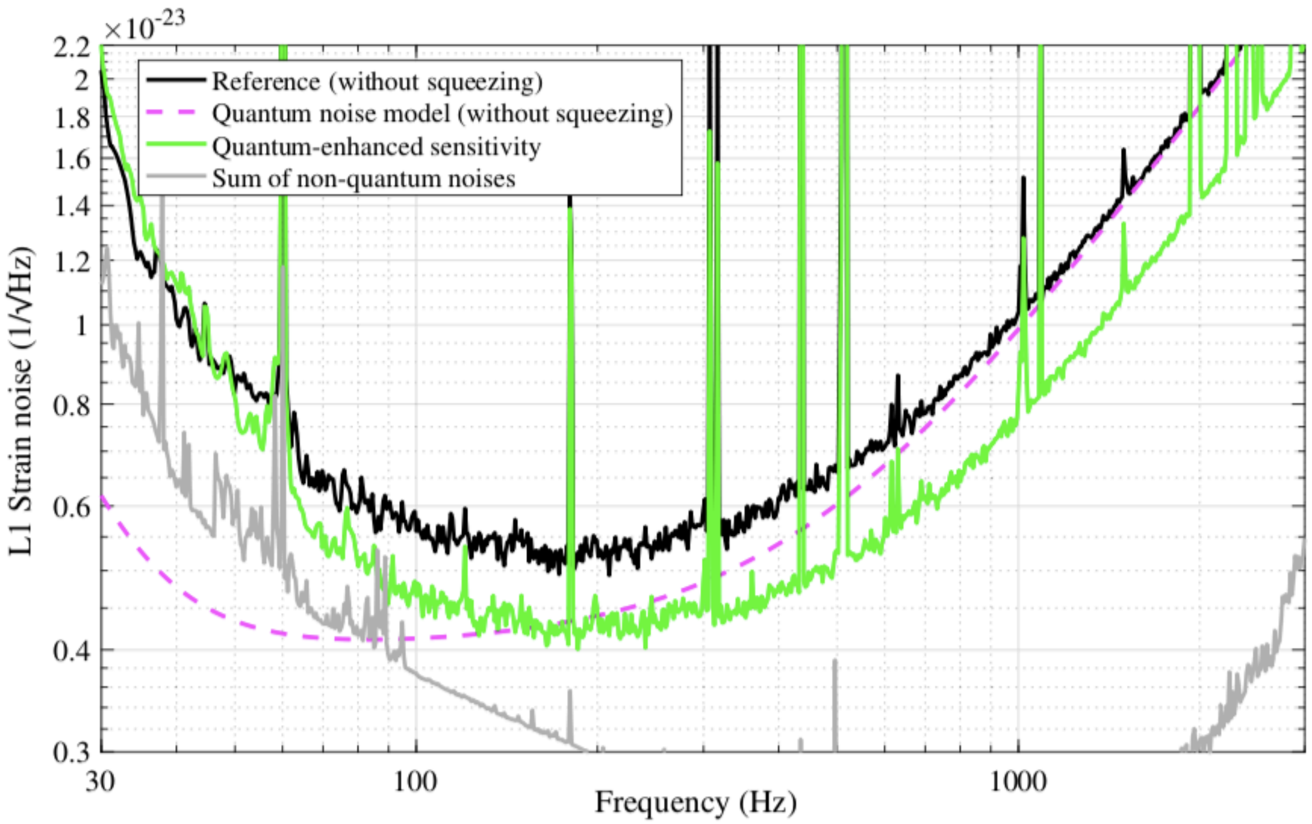
$$[\hat{b}, \hat{b}^{+}] = \eta \neq 1$$

- Consistent model



Squeezing deteriorated because of its recombination with non squeezed vacuum

Application to 2G detectors: results

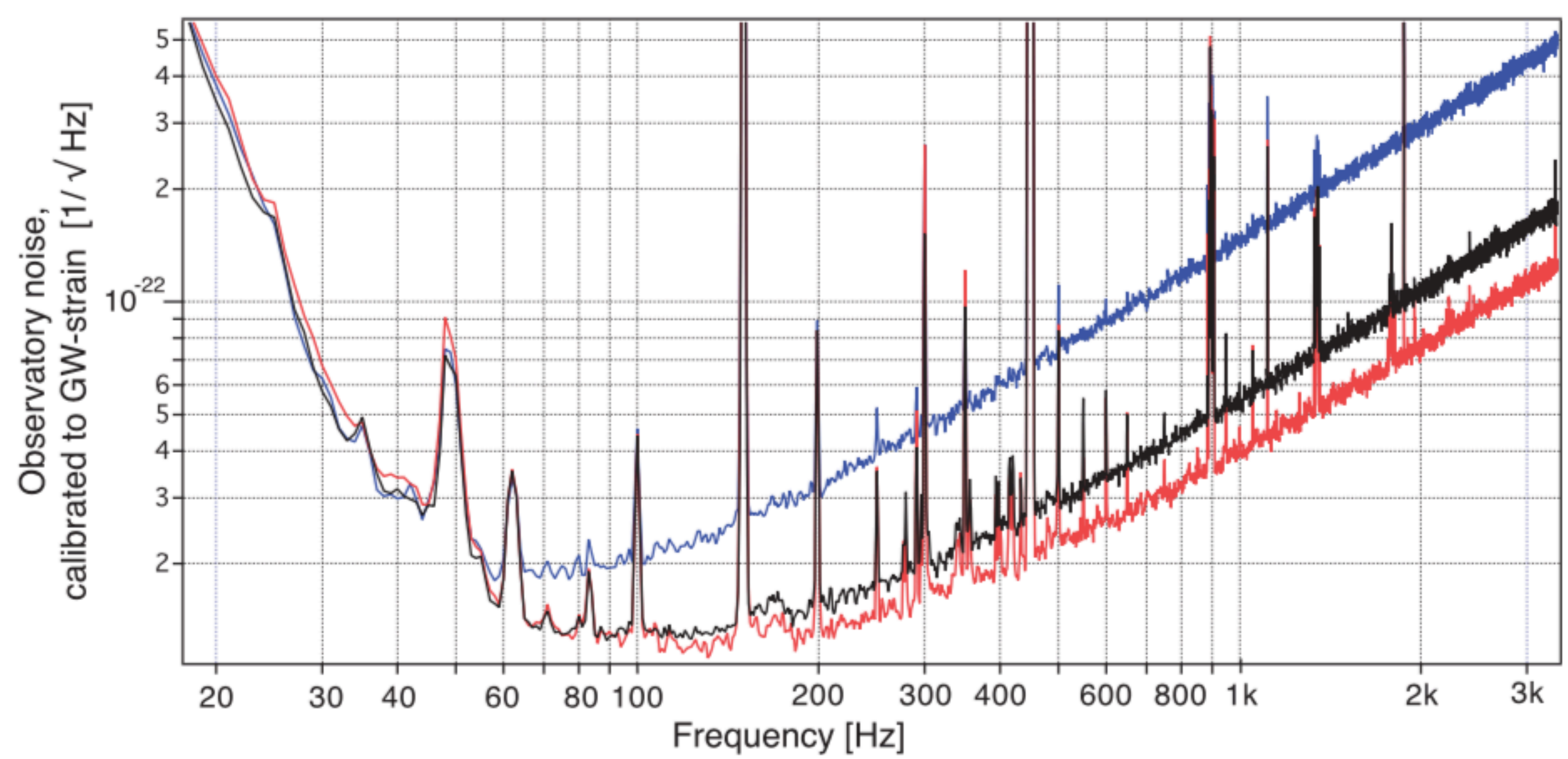


Advanced LIGO

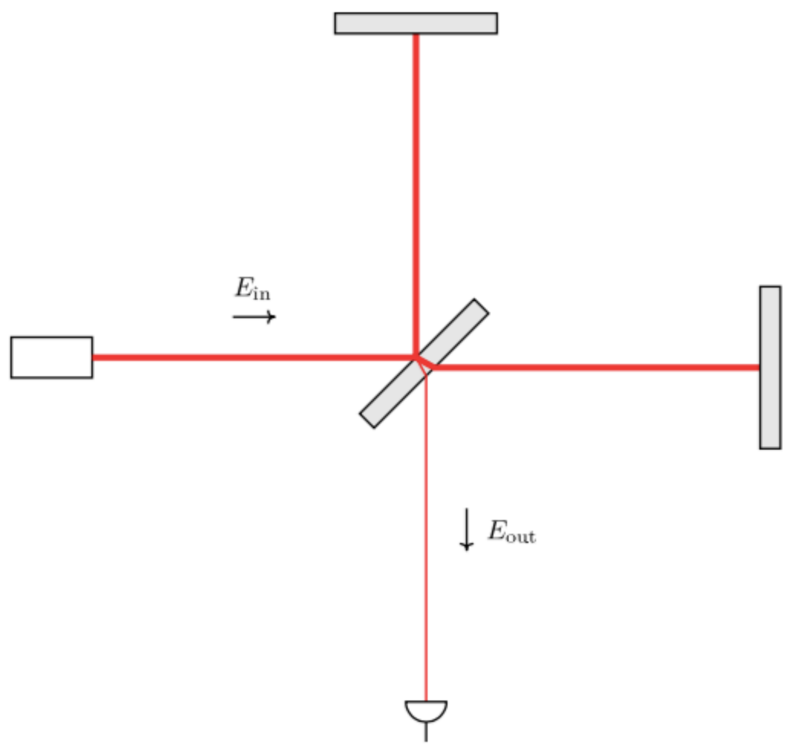
- Best measured 3.2 dB
- BNS Range improvement: 14%
- Detection rate improvement: 50%

Advanced Virgo

- Best measured 3.2 dB
- BNS Range improvement: 5%-8%
- Detection rate improvement: 16-26%



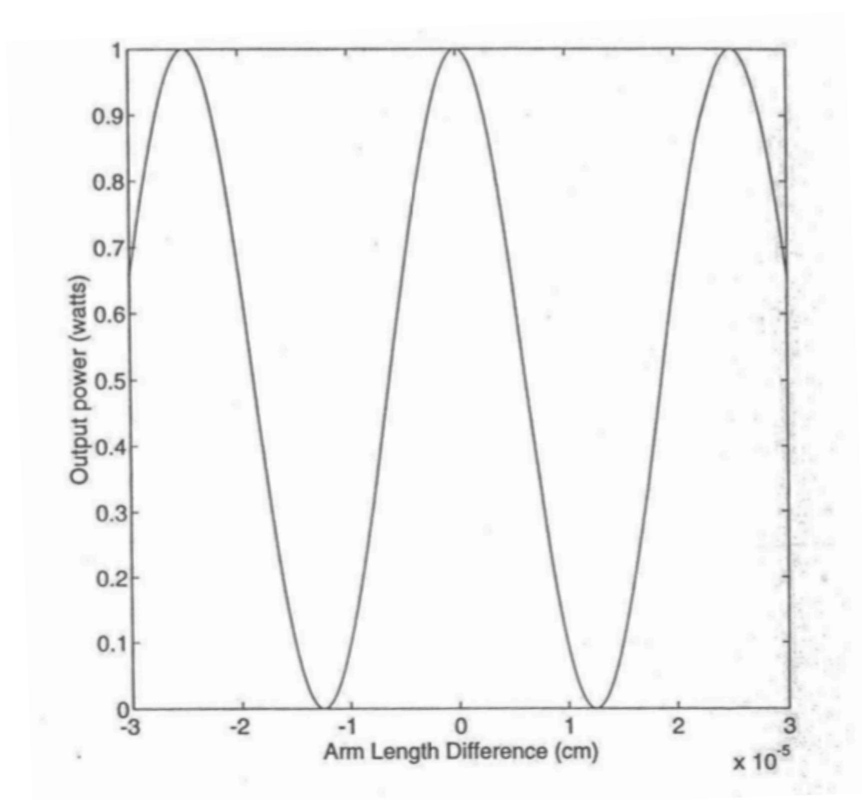
Shot noise derivation



$$P_{out} = \frac{P_{in}}{4}(R_1 + R_2)(1 + C\cos\phi)$$

Contrast $C = \dfrac{2r_1r_2}{R_1 + R_2}$

$$P_{out} = \frac{P_{in}}{2}[1 + C\cos(\phi_{sta}) - C\sin(\phi_{sta})\phi_{gw}]$$



$$\delta P_{gw} = \frac{P_{in}}{2}C\sin(\phi_{sta})\phi_{gw}$$

P. Saulson "Fundamentals Of Interferometric Gravitational Wave Detectors "

What is the minimum phase change we can measure?

- Arrival time of photon: poissonian process

$$P(N) = \frac{\bar{N}^N e^{-\bar{N}}}{N!}$$

$$\sigma = \sqrt{\bar{N}}$$

- Average number of impinging photons

$$\bar{N} = \frac{\eta P_{\text{out}} \delta T}{\hbar\omega}$$

$$\delta P_{\text{shot}} = \sqrt{\bar{N}} \frac{\hbar\omega}{\eta \delta T}$$

- Ratio between the power change due to GW and shot noise

$$\frac{\delta P_{\text{gw}}}{\delta P_{\text{shot}}} = \sqrt{\frac{\eta P_{\text{in}} \delta T}{\hbar\omega}} \frac{C \sin\phi}{\sqrt{(1 + C\cos\phi)}} \phi_{\text{gw}}$$

- It is maximized close to the dark fringe

What is the minimum phase change we can measure?

- Minimum detectable phase change

$$\delta P_{\mathrm{gw}} = \delta P_{\mathrm{shot}}$$

$$\downarrow$$

$$\delta\phi_{\mathrm{min}} = \sqrt{\frac{\hbar\omega}{\eta P_{\mathrm{in}}\delta T}}$$

- Shot noise amplitude spectral density

$$h_{\mathrm{shot}} = \frac{\lambda}{2\pi L}\sqrt{\frac{\hbar\omega}{\eta P_{\mathrm{in}}}} \simeq 5\cdot 10^{-21}\left[\frac{1}{\sqrt{\mathrm{Hz}}}\right]$$

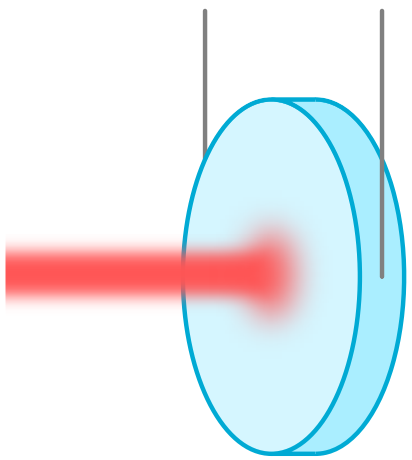
$$\lambda = 1064\,\mathrm{nm},\ L = 3\,\mathrm{km},\ P_{\mathrm{in}} = 20\,\mathrm{W}$$

Radiation pressure noise

- Variable force induced by power fluctuation acting on the mirrors

$$\delta F = \frac{2\delta P}{c}$$

$$F(f) = \sqrt{\frac{8\pi\hbar P}{c\lambda}}$$



- Corresponding displacement spectrum of each test mass

$$x(f) = \frac{F(f)}{M(2\pi f)^2} = \frac{1}{M(2\pi f)^2}\sqrt{\frac{2\pi\hbar P}{c\lambda}}$$

$$h_{\mathrm{rp}(f)} = \frac{2}{L}x(f)$$

- Total quantum noise

$$h_{\mathrm{qn}} = \sqrt{h_{\mathrm{shot}}^2 + h_{\mathrm{rp}}^2}$$