A GW Observatory Operating Beyond the Quantum Shot-Noise Limit: Squeezed Light in Application

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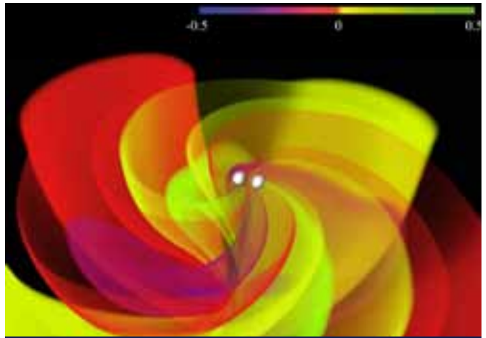
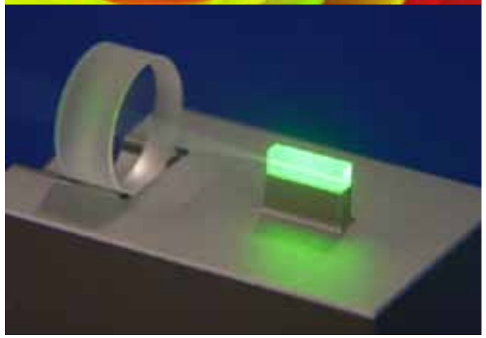
Outline

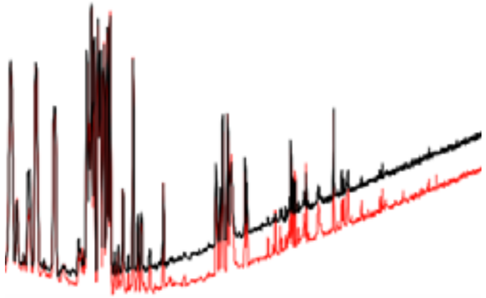
- Gravitational Waves





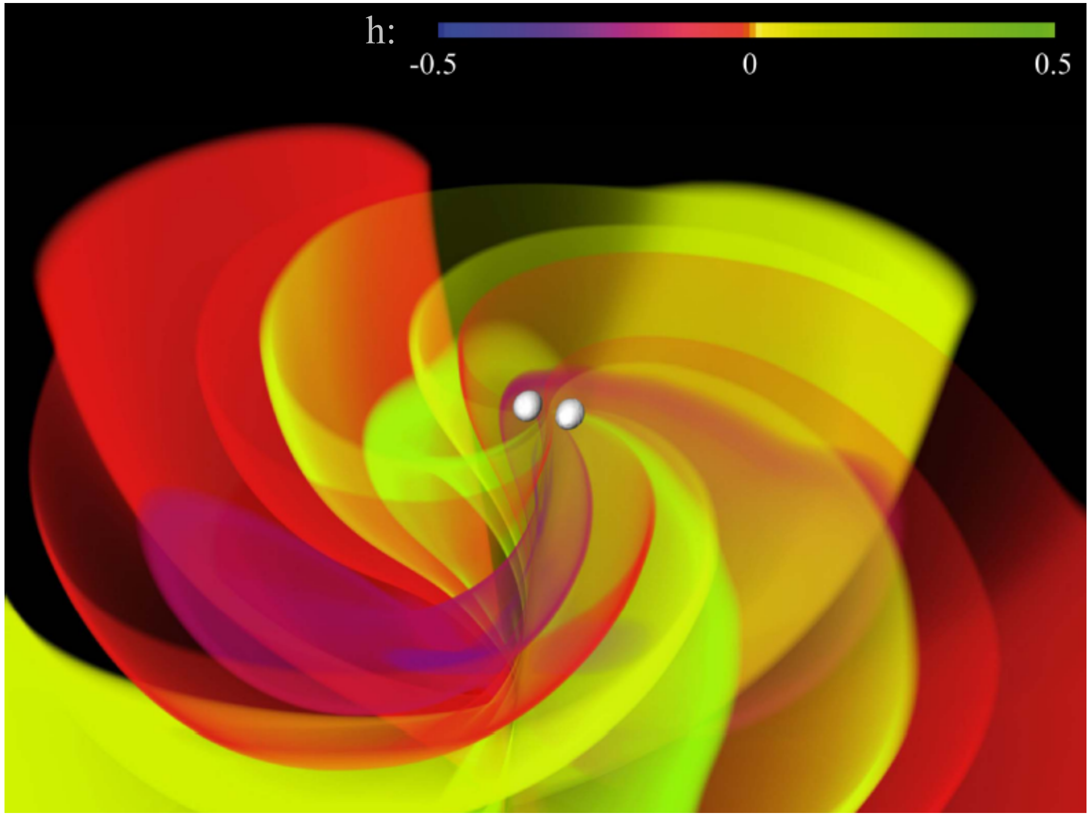
- Squeezed Light generation

- Sensitivity improvement of GEO600 with squeezed light

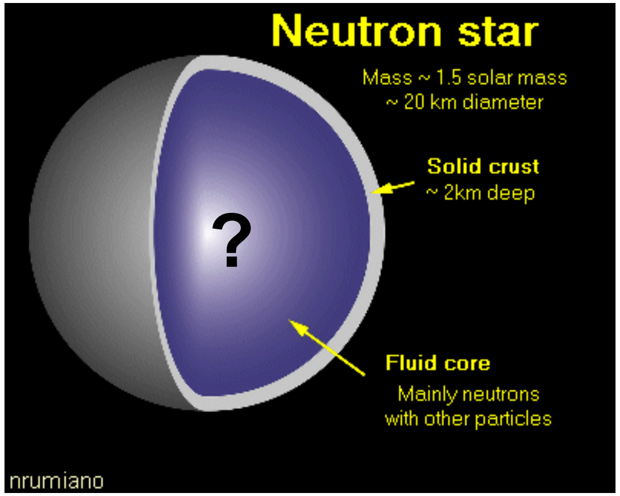


- Squeezed light as a key-technology for GW astronomy…

Merging Neutron Stars



Merging neutron stars. Numerical relativity simulation of the gravitational wave amplitude emitted from two neutron stars which are about to merge in 4 ms [Rezzolla, AEI].

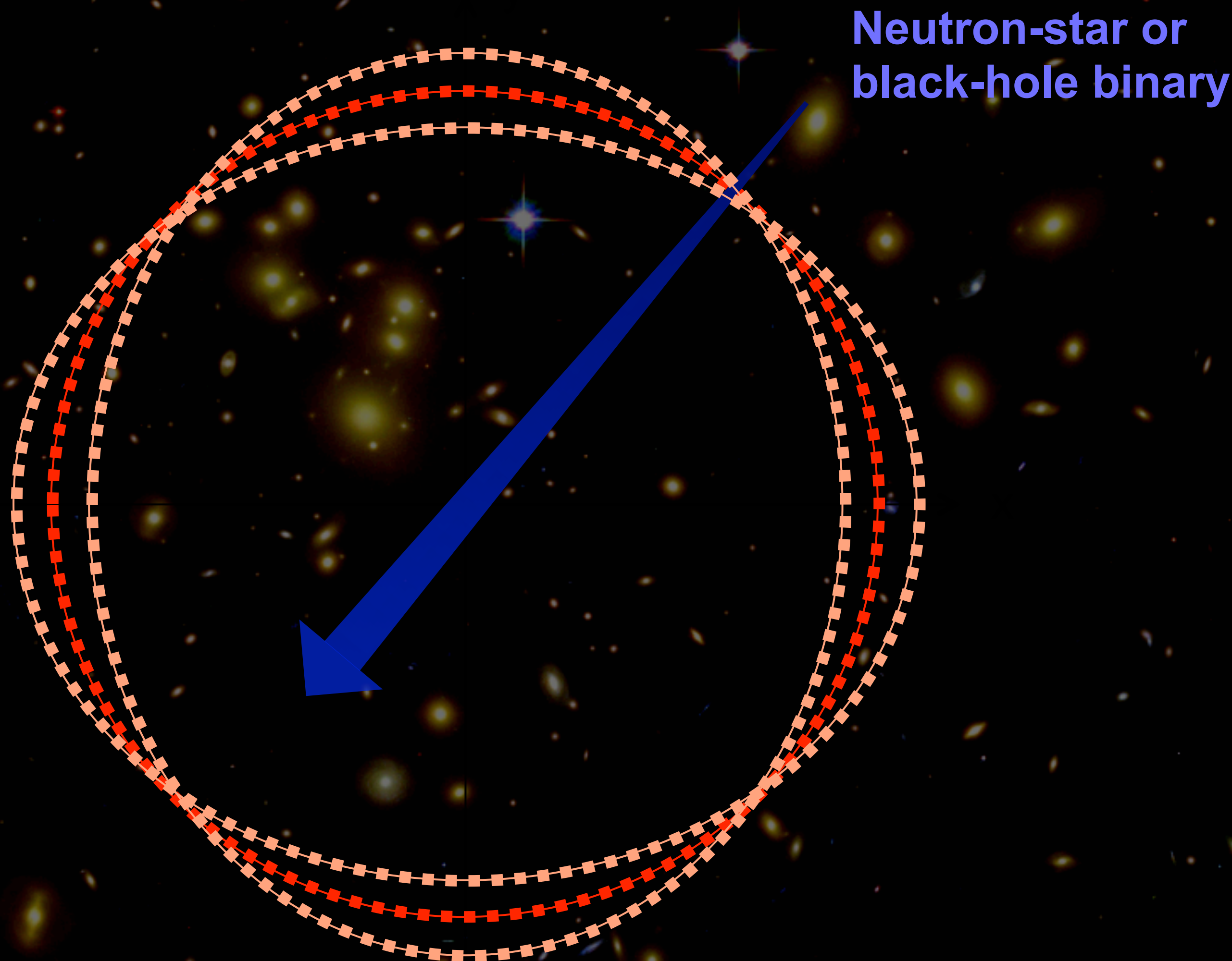


Gravitational wave astronomy requires observatories that can detect

$h < 10^{-23}$

(over a band from e.g. 100Hz - 200Hz)

Gravitational Waves



Gravitational Wave Detection

1) Test masses

2) Laser light

3) Interference

4) Photo-electric effect

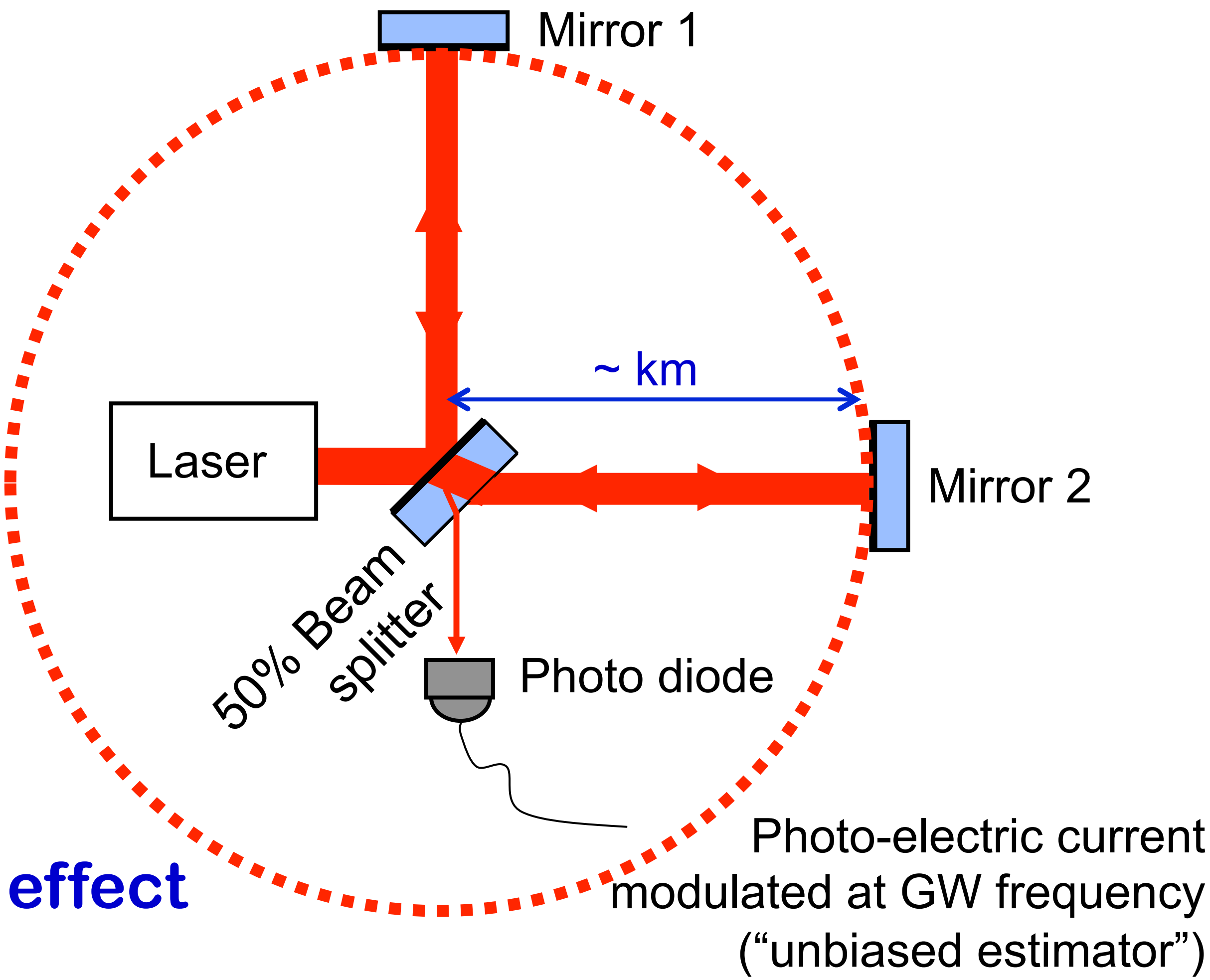


Photo-Electric Current

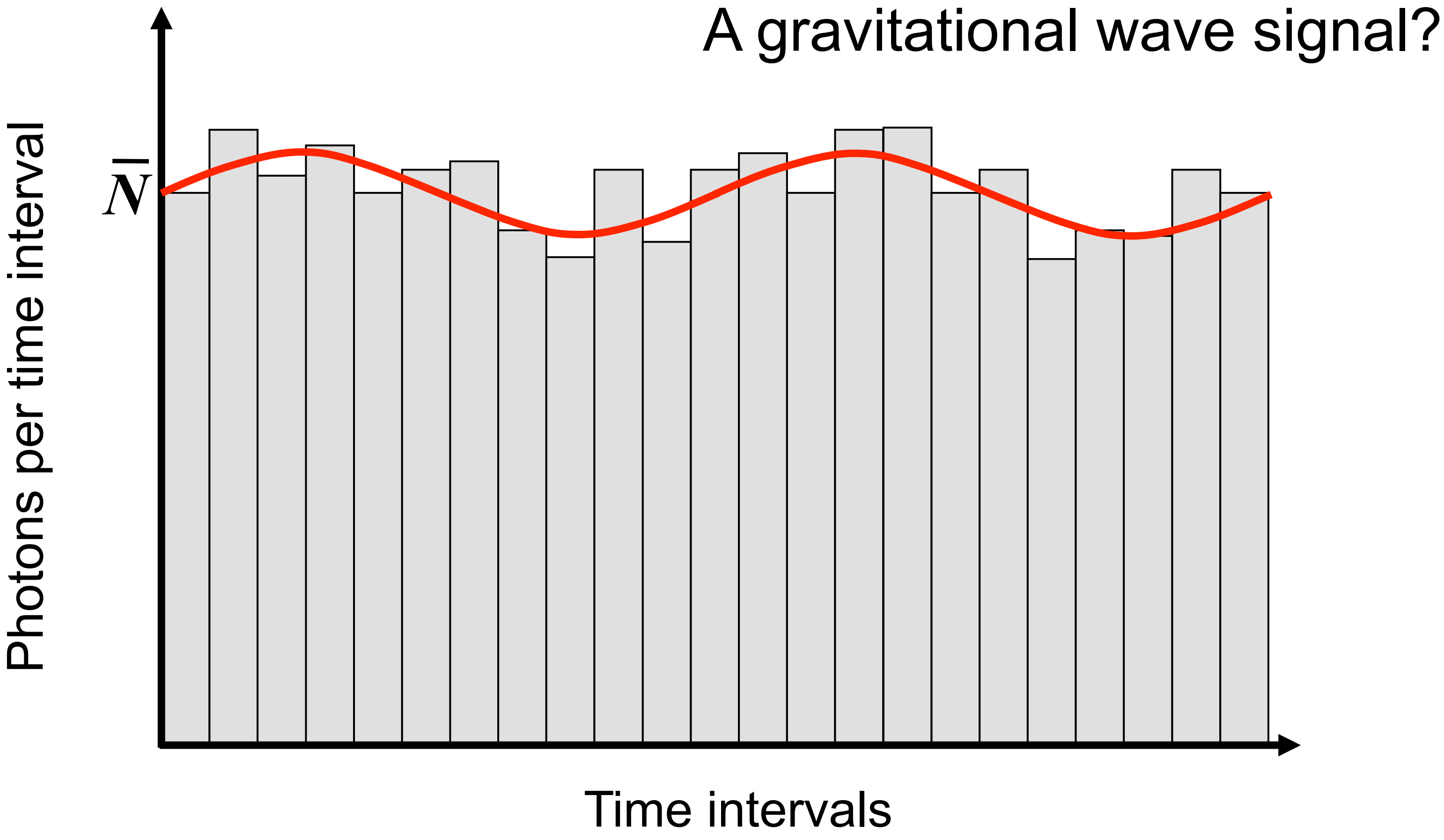
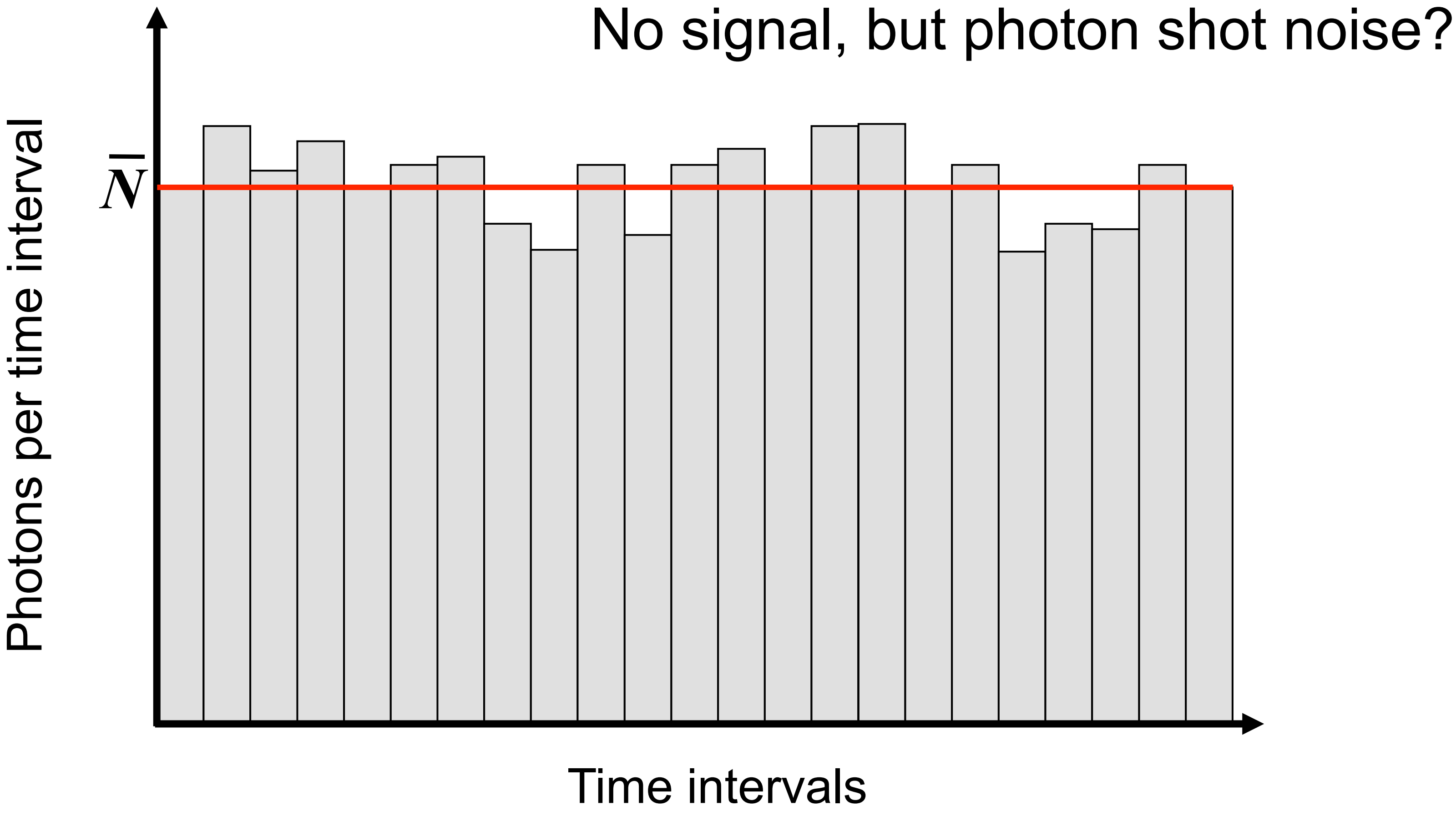
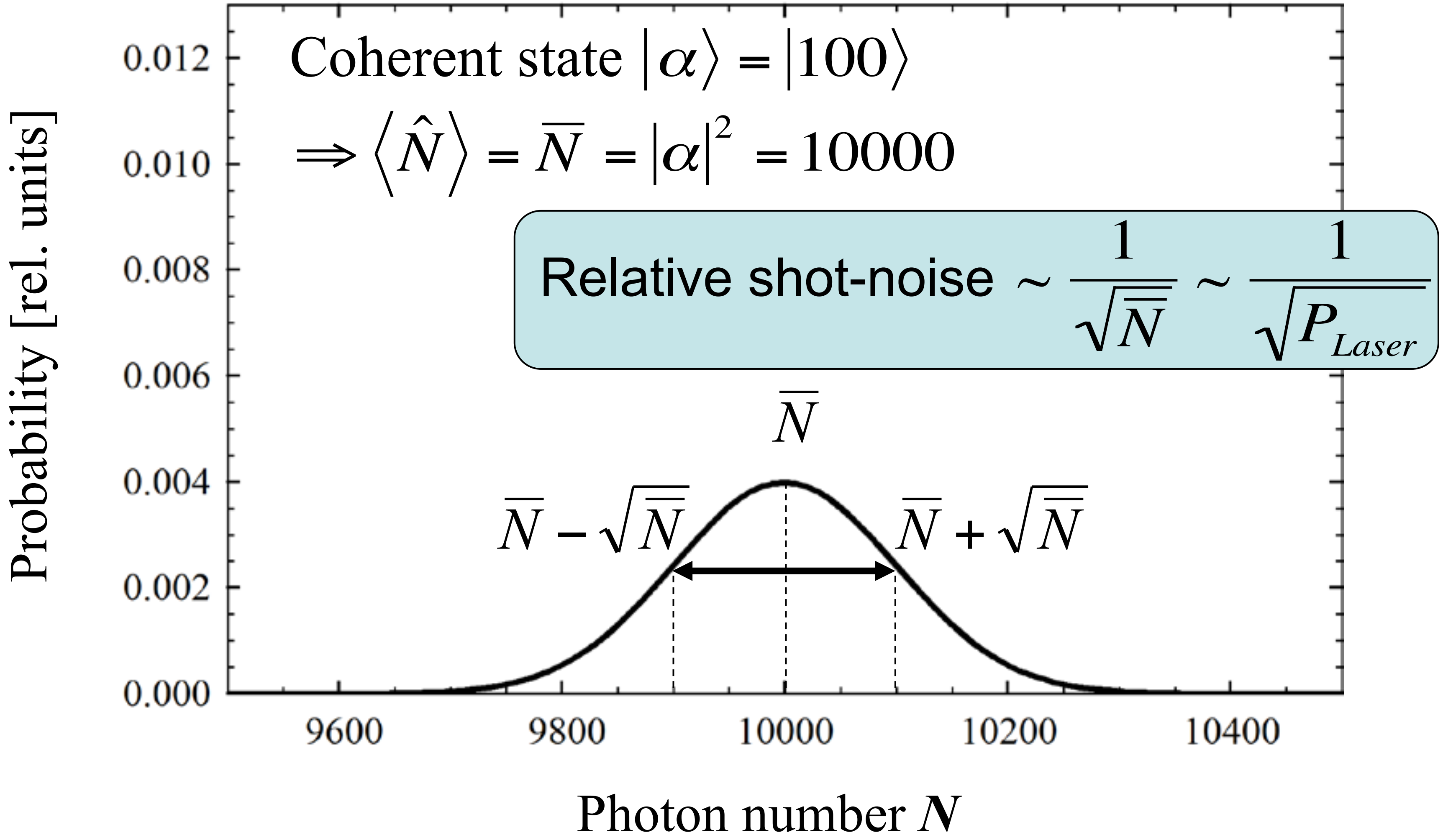


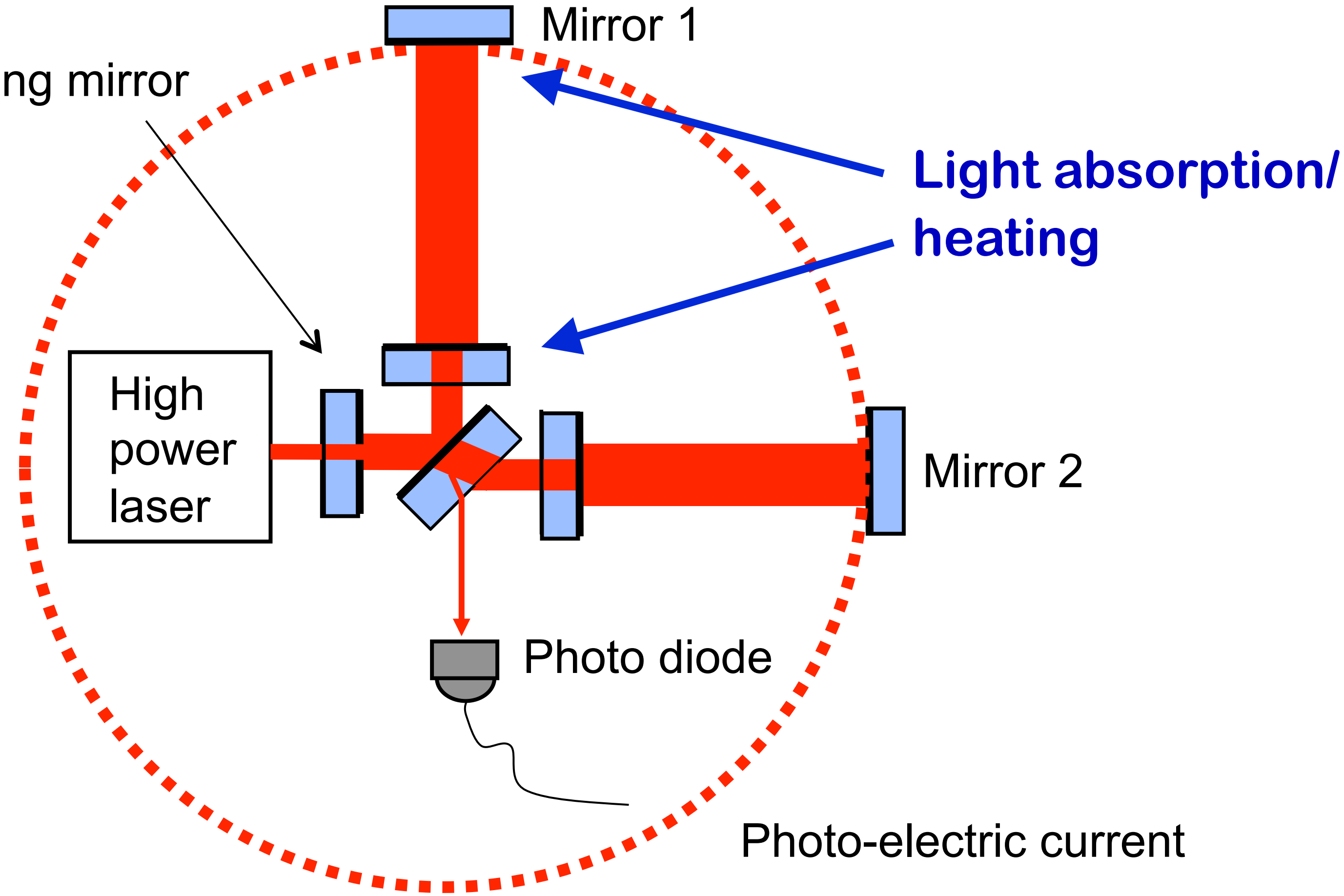
Photo-Electric Current



Photon Counting Statistics



Increasing the Light Power

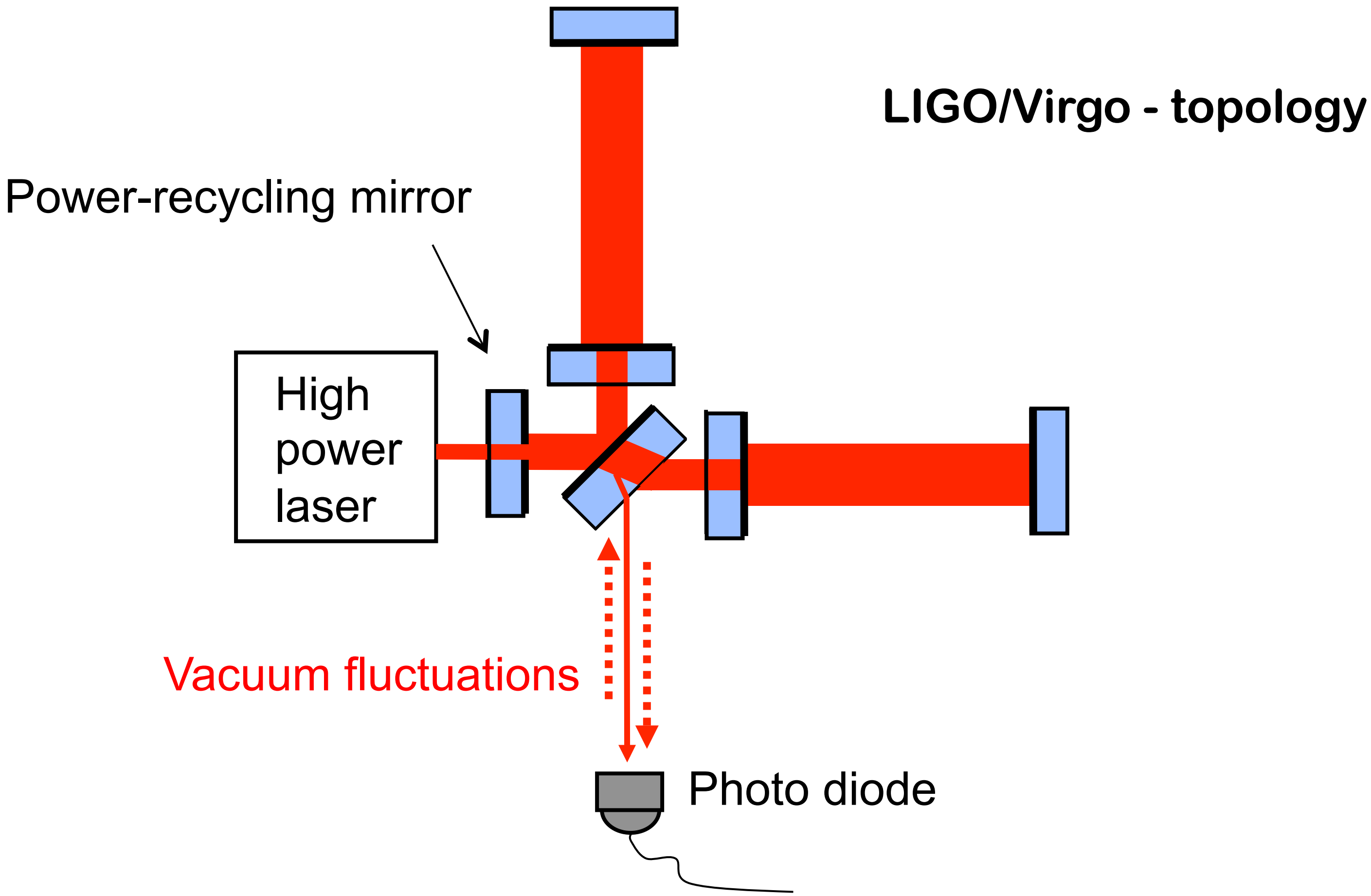


Is there a possibility to increase the signal/quantum noise–ratio without increasing the laser power?

Yes, by squeezed light!

[Caves, Phys. Rev. D 23, 1693 (1981)]

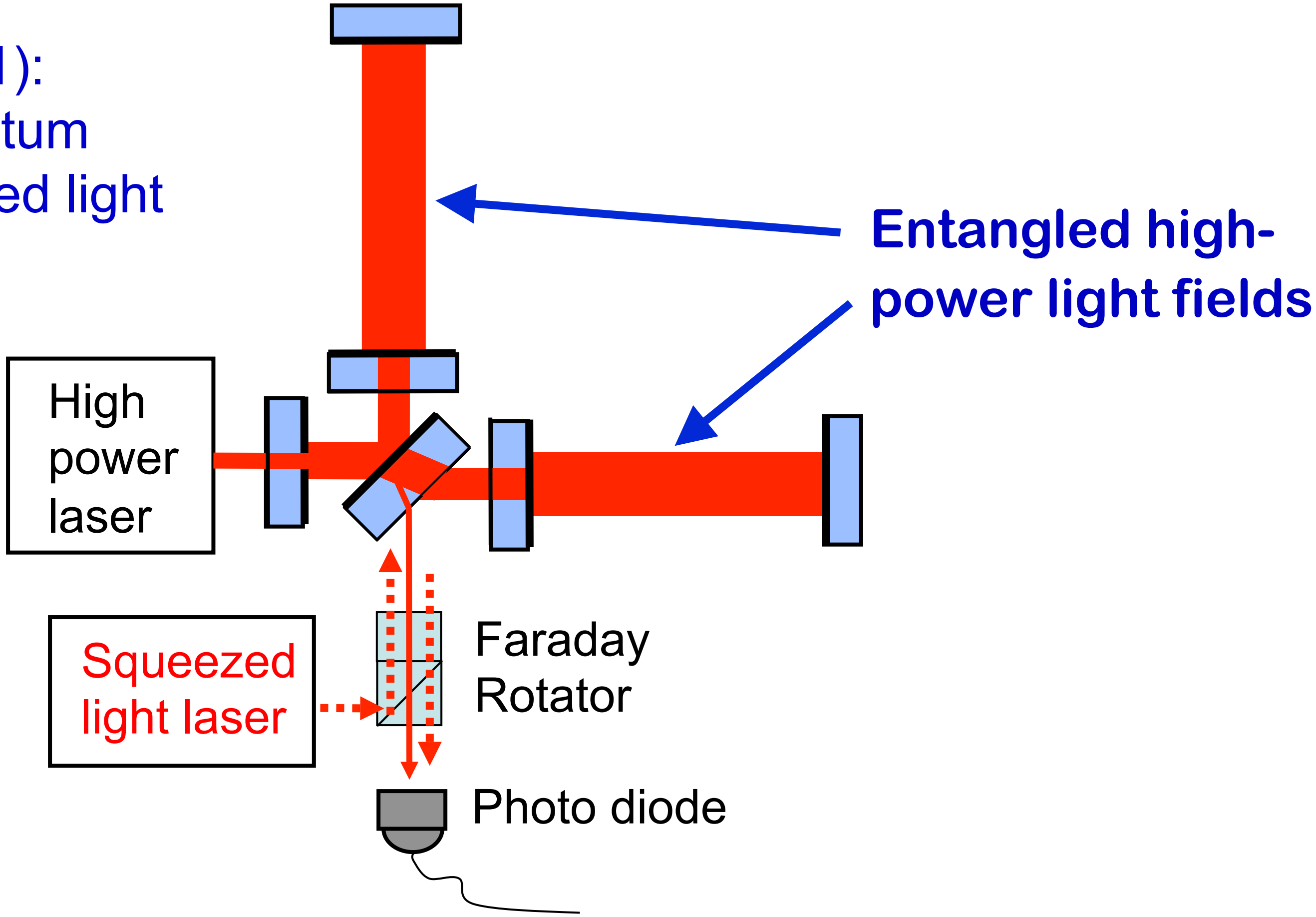
Shot-Noise / Vacuum Fluctuations



[Caves, Phys. Rev. D 23, 1693 (1981)]

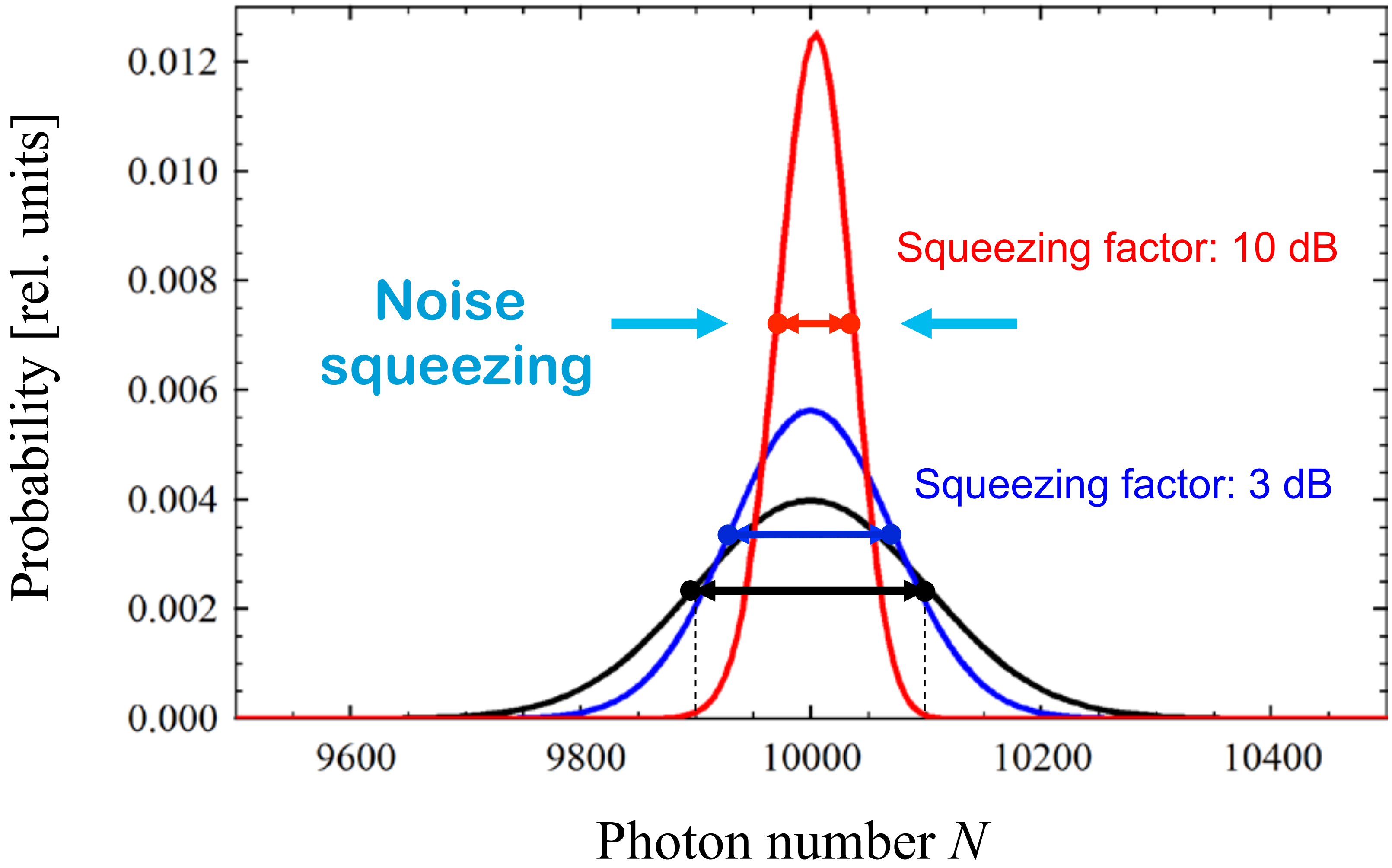
Squeezing the Shot-Noise

C. M. Caves (1981):
Reduction of quantum
noise with squeezed light



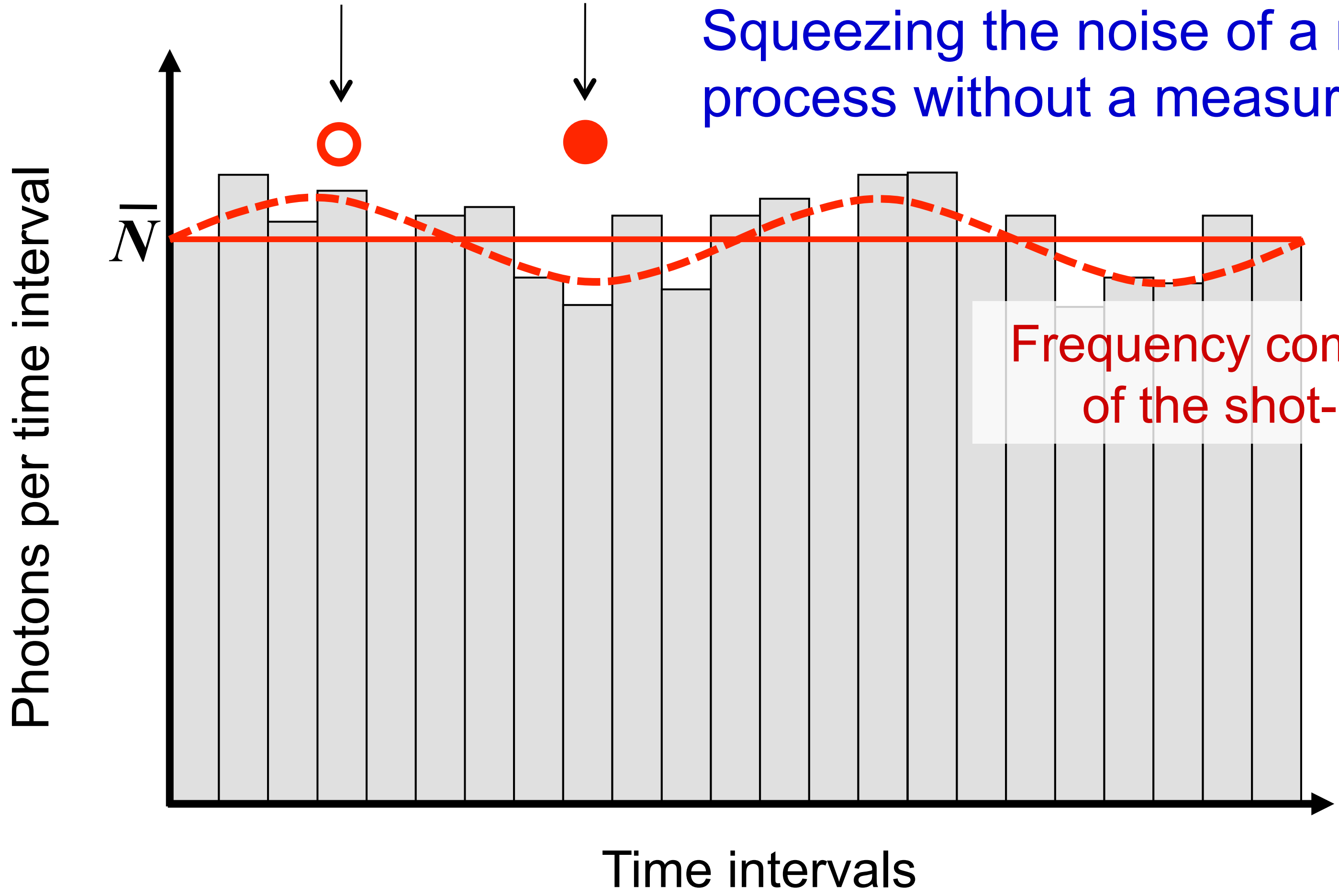
[Caves, Phys. Rev. D 23, 1693 (1981)]

"Squeezed" Counting Statistics

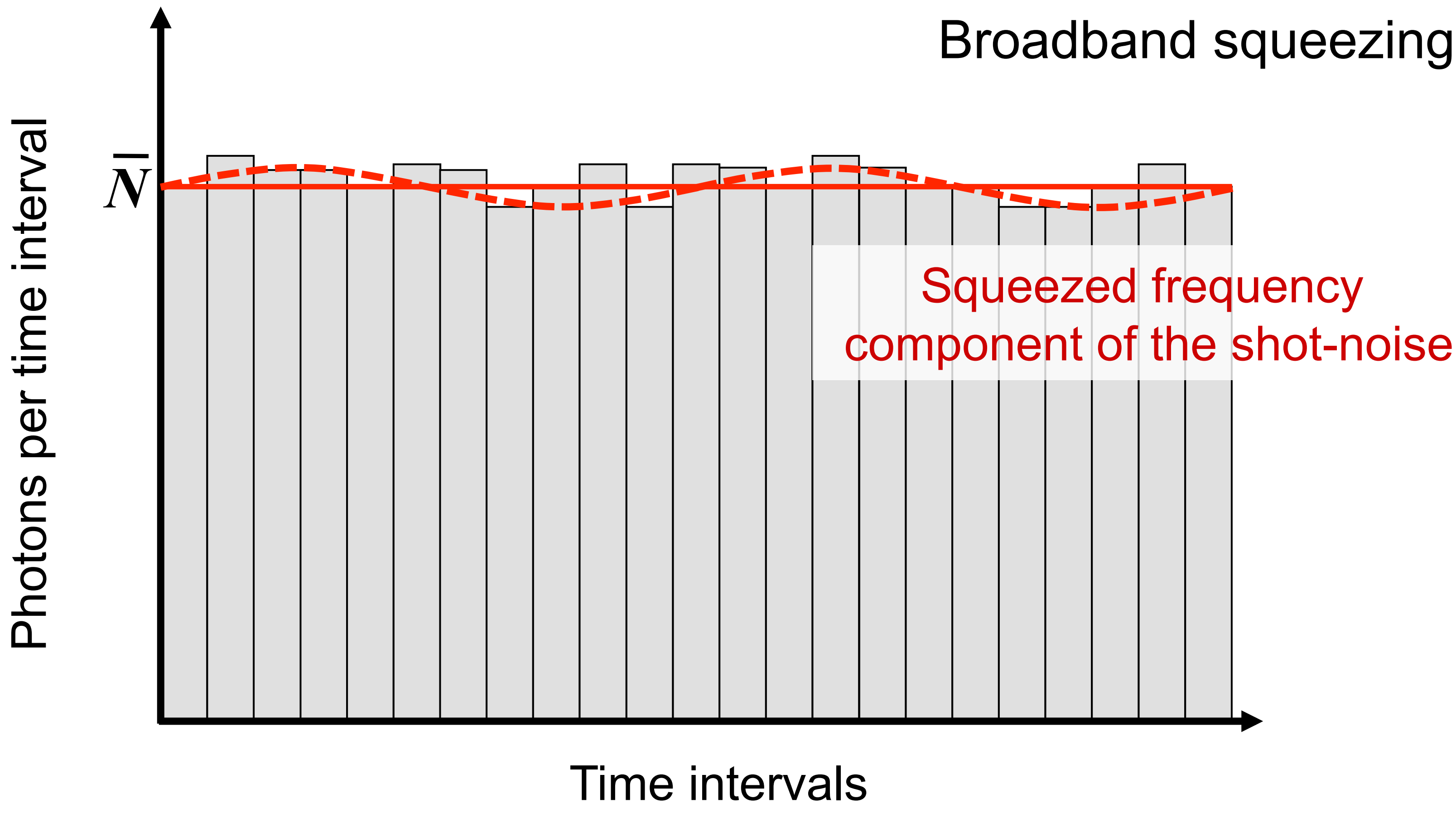


Shot-Noise / Vacuum Fluctuations

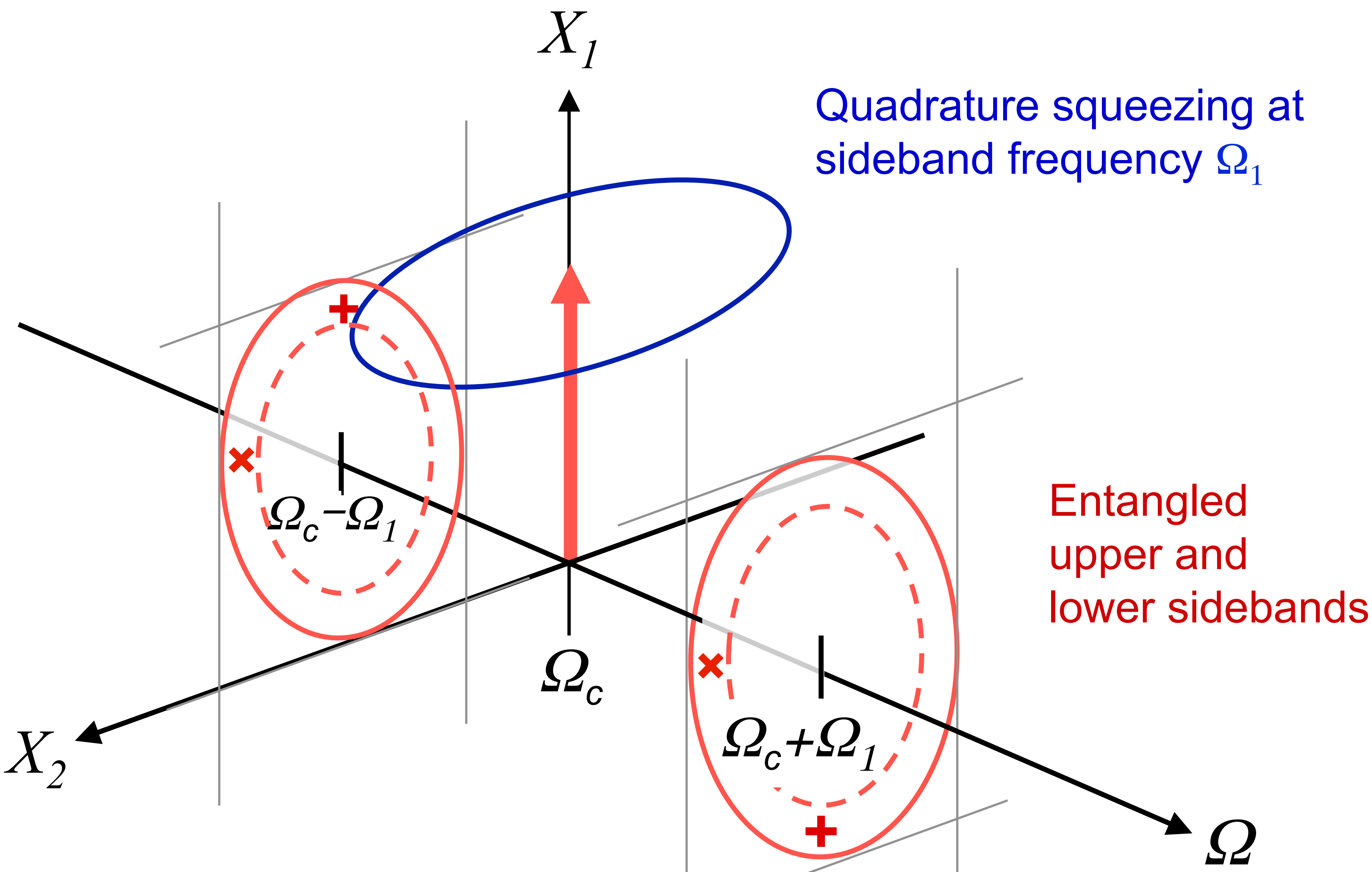
Squeezing the noise of a random process without a measurement!?



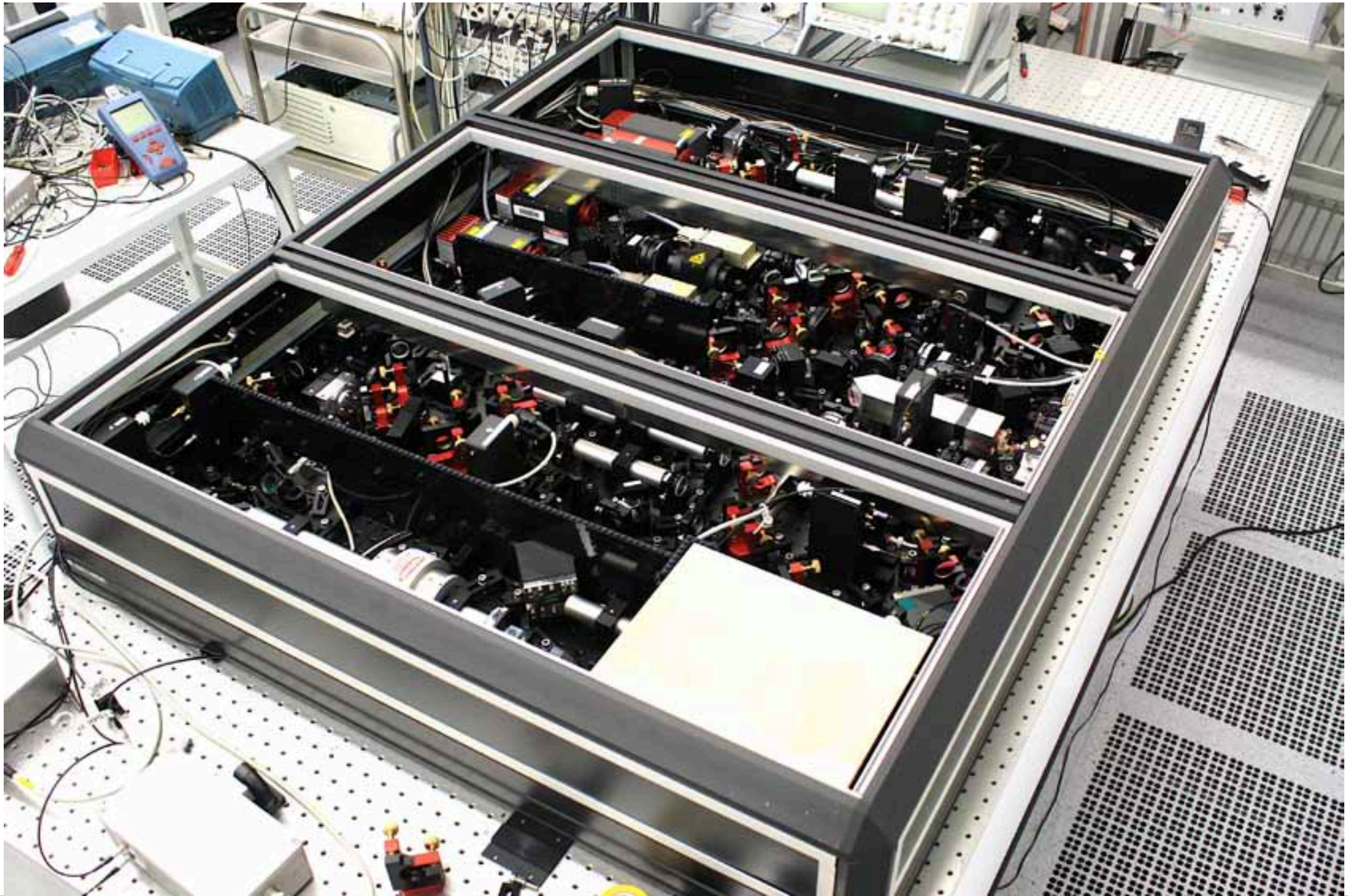
Squeezed Shot-Noise



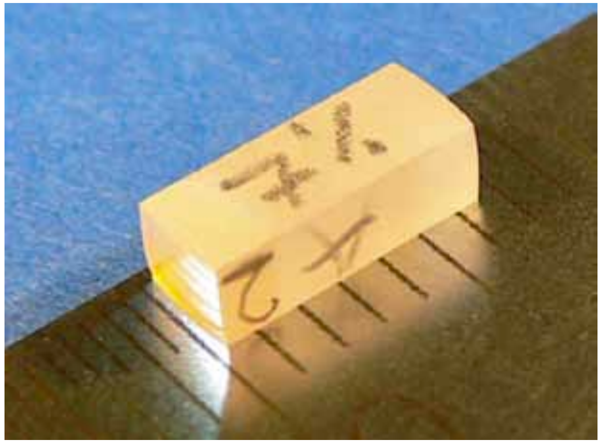
Squeezing in the Wave Picture



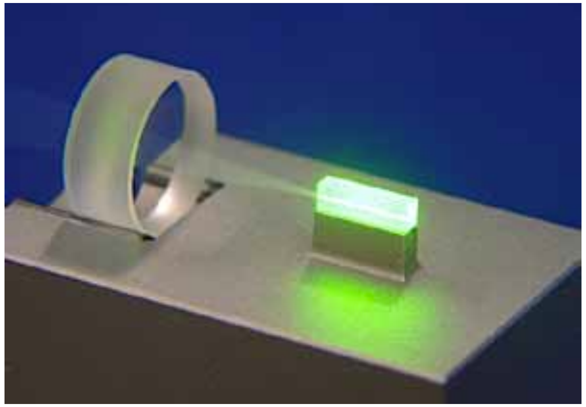
The GEO600 Squeezed Light Laser



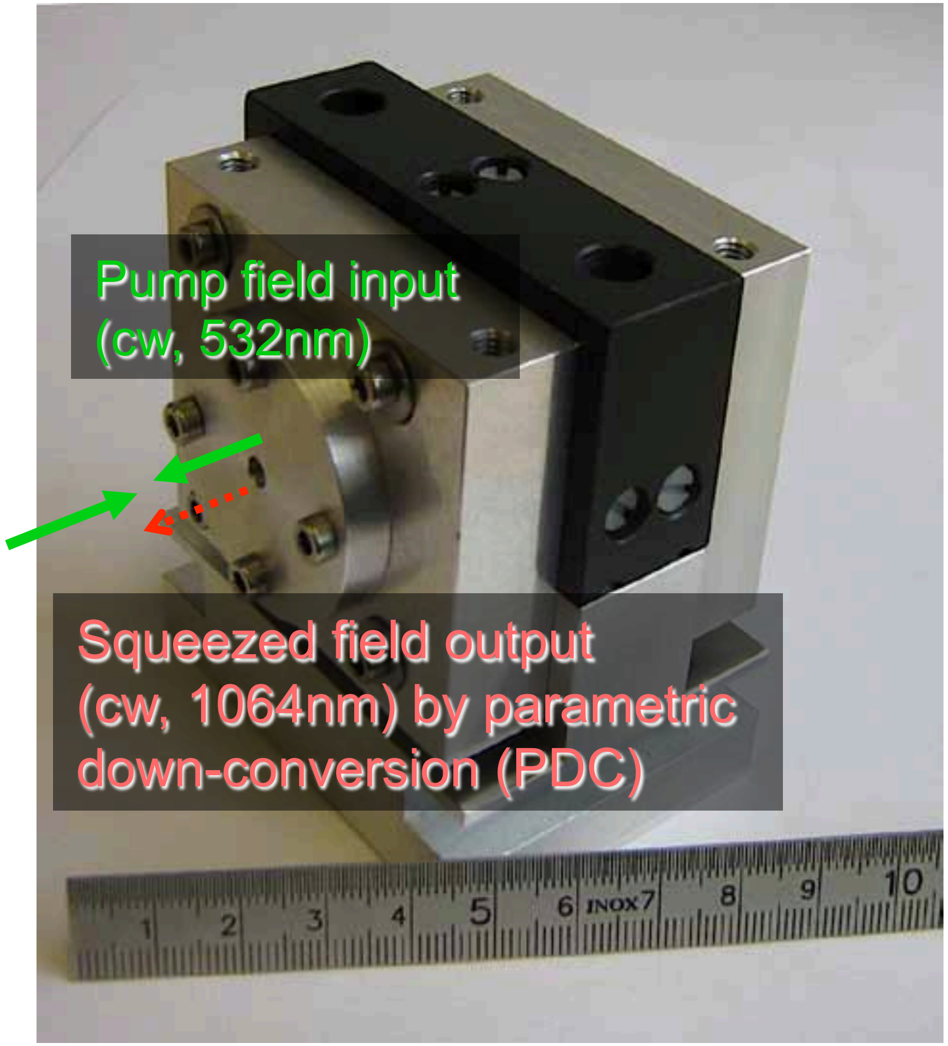
Generation of Squeezed Light (PDC)



χ_2-nonlinear crystal: $MgO{:}LiNbO_3$ or PPKTP



Standing wave cavity



History of Squeezed Light Generation

First squeezed light: [Slusher *et al.*, PRL **55**, 2409 (1985)]

Research labs with squeezed light (not complete):

- Kimble (CalTech): *teleportation*: [Furuzawa *et al.,* SCIENCE **282**, 706 (1998)]
- Grangier (Orsay); *kitten*: [Ourjoumtsev *et al.*, SCIENCE, **312**, 83 (2006)]
- Schiller and Mlynek (Konstanz): *tomography*: [Nature **387**, 471 (1997)]
- Bachor and Lam (Canberra): *6dB at 1064nm* [J. Opt. B **1**, 469 (1999)]
- Leuchs (Erlangen); *~7 dB pulsed* [Opt. Lett. **33**, 116 (2008)]
- Polzik (Copenhagen), [Neergaard-Nielsen *et al.*, PRL **97**, 083604 (2006)]
- Furusawa (Tokyo); *9 dB:* [Takeno *et al.*, Opt. Express **15**, 4321 (2007)]
- Fabre (Paris); Zhang, Peng (Shanxi); Andersen (Copenhagen); Mavalvala (MIT)
- Nussenzveig (Sao Paulo); Pfister (Virginia); ...

Squeezing Issues for GW Detection

Squeezing at frequencies in the GW detection band (10 Hz to 10 kHz)

- Control beam as noise source identified [Bowen, RS *et al.*, J. Opt. B **4**, 421 (2002)], [RS *et al.*, Opt. Comm. **240**, 185 (2004)]
- First Audioband squeezing [McKenzie *et al.*, PRL **93**, 161105 (2004)]
- New control scheme [Vahlbruch, RS *et al.*, PRL **97**, 011101 (2006)]
- 6 dB over complete band [Vahlbruch, RS *et al.*, NJP **9**, 371 (2007]

Compatibility with GW detector techniques

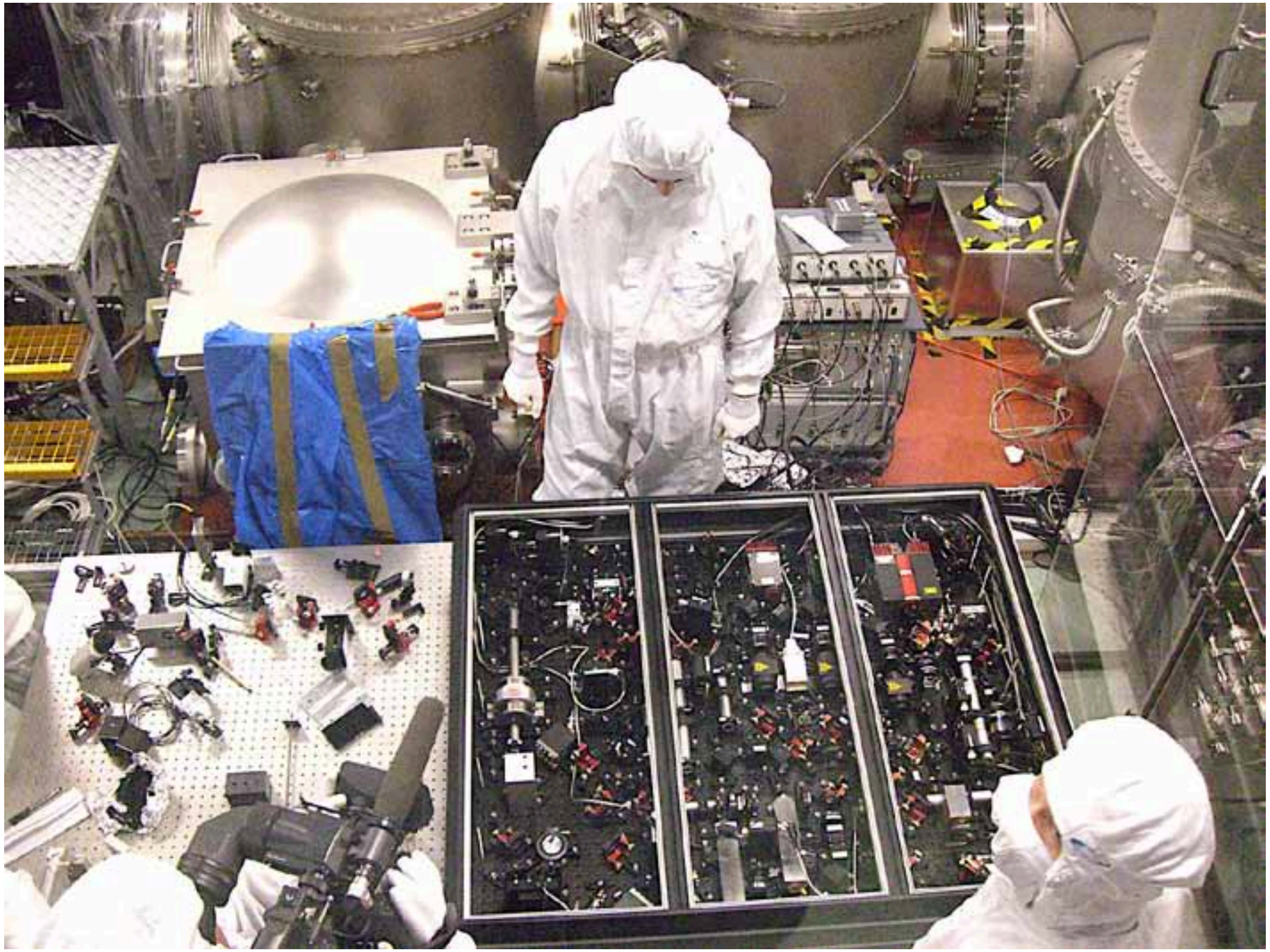
- Power-recycling [McKenzie *et al.*, PRL **88**, 231102 (2002).]
- Signal-recycling [Vahlbruch, RS *et al.*, PRL **95**, 211102 (2005)]
- Suspended interferometer [Goda *et al.*, Nat. Phys. **4**, 472 (2008).]

Strong continuous wave squeezing (>10 dB) at 1064nm

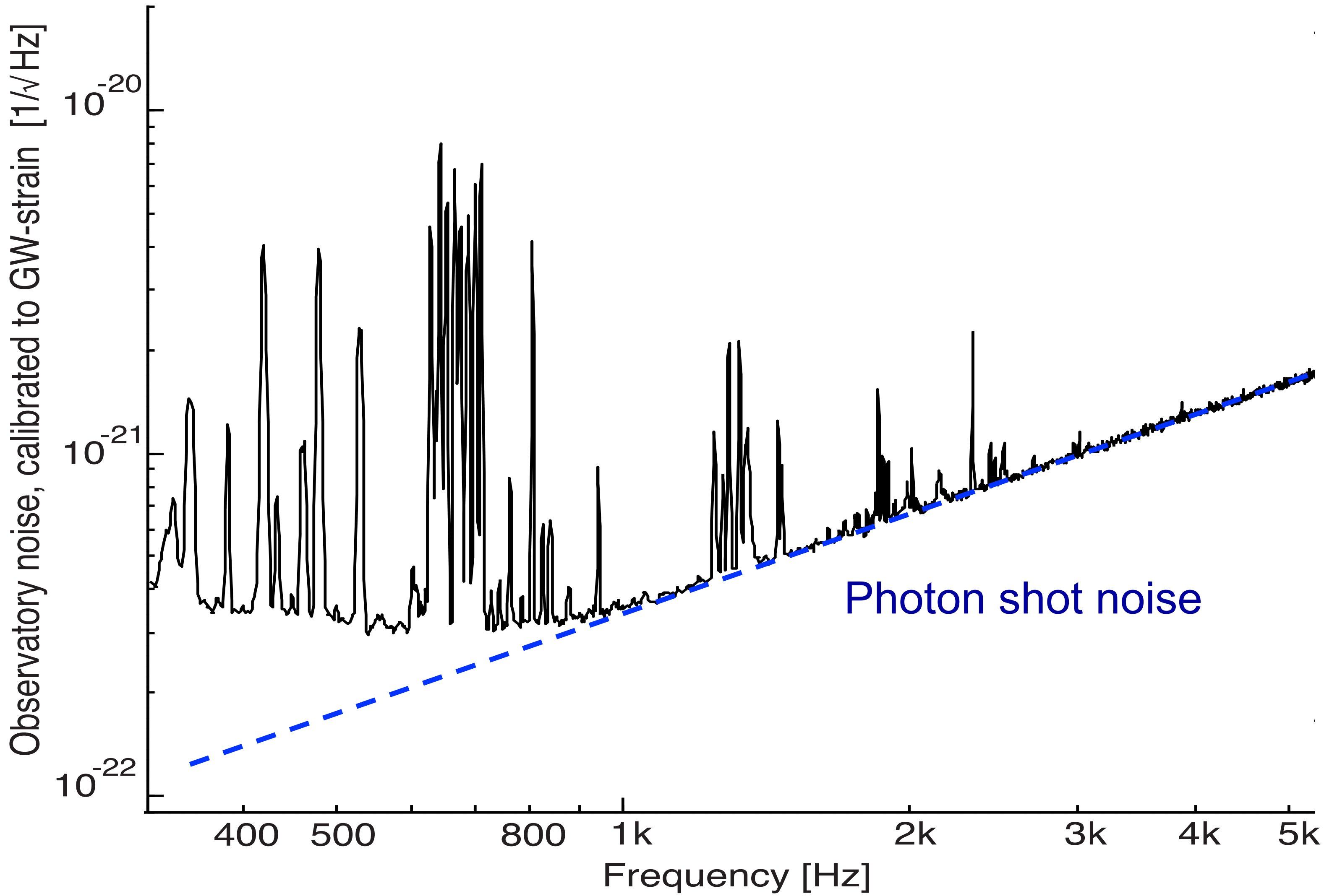
- [Vahlbruch, RS *et al.*, PRL **100**, 033602 (2008)]
- [M. Mehmet, RS *et al.*, PRA **81**, 013814 (2010)]

Review: [R.S. *et al.*, Nature Comm. 1:121 doi: 10.1038/ncomms1122 (2010)]

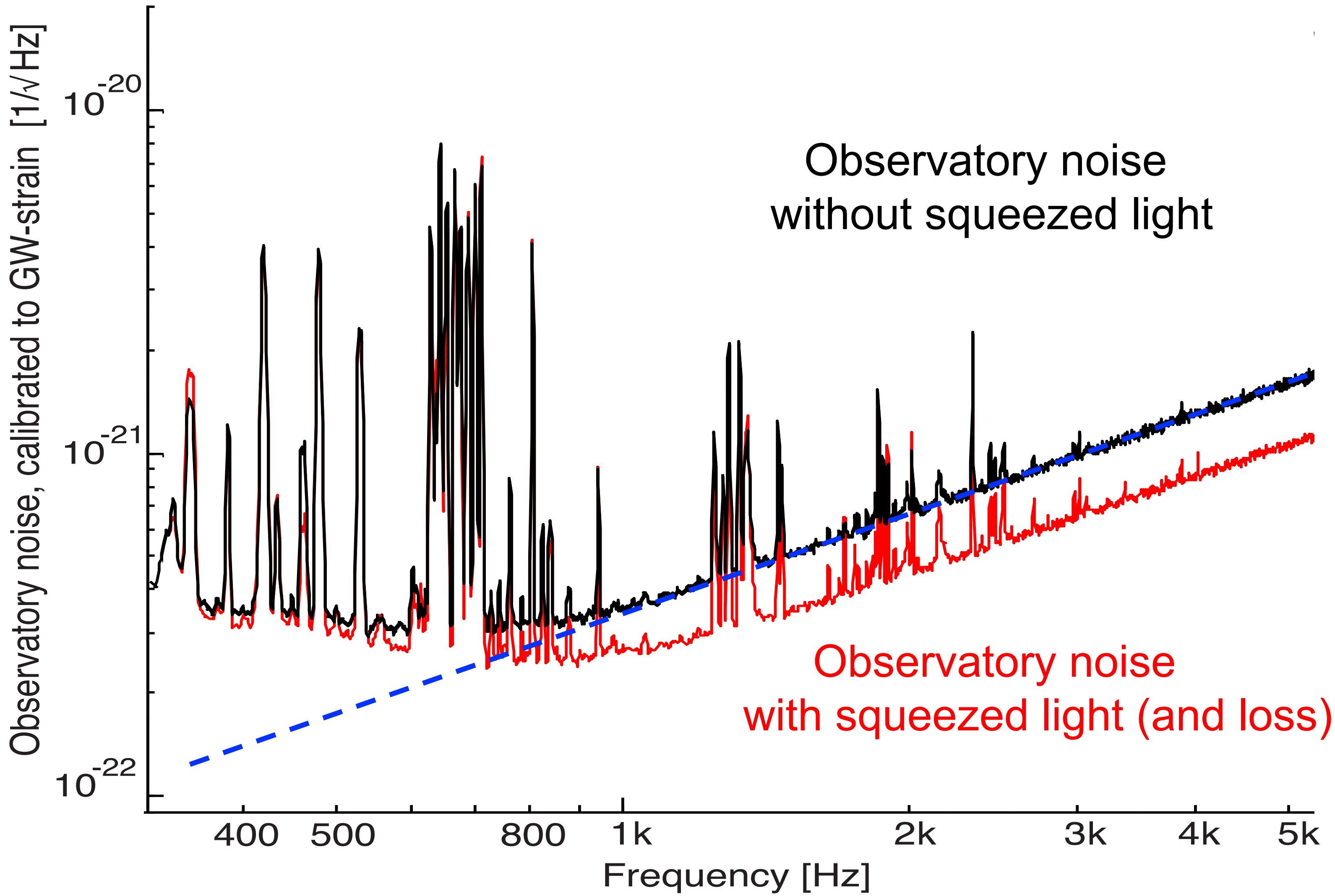
Transport to the GEO600 GW Detector



GEO600 Spectral Density 2010



GEO600: Squeezed Light in Application



nature physics

LETTERS

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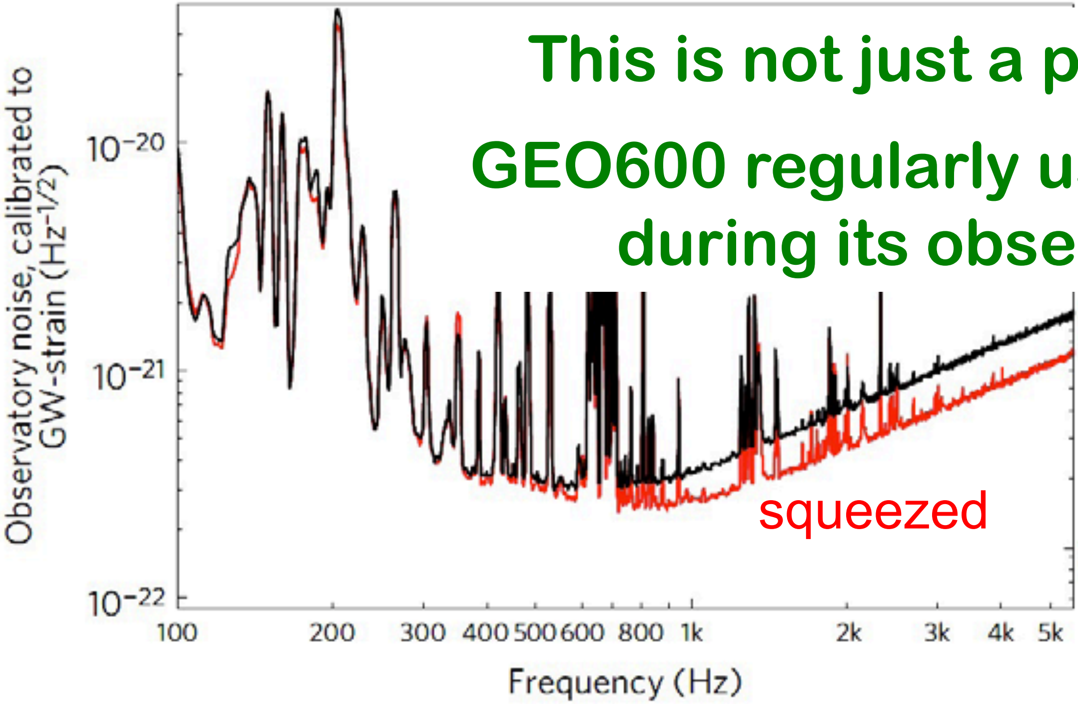
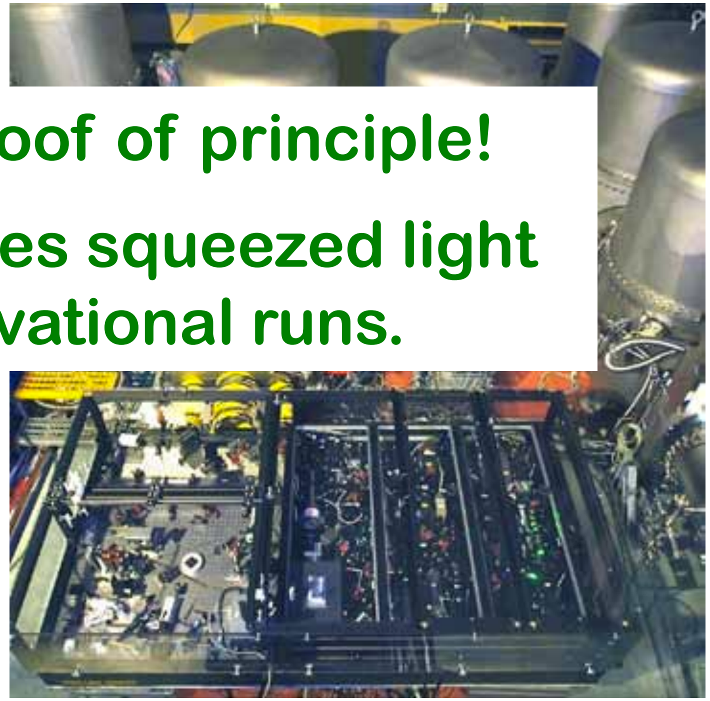
A gravitational wave observatory operating beyond the quantum shot-noise limit

The LIGO Scientific Collaboration †*

This is not just a proof of principle!

GEO600 regularly uses squeezed light during its observational runs.

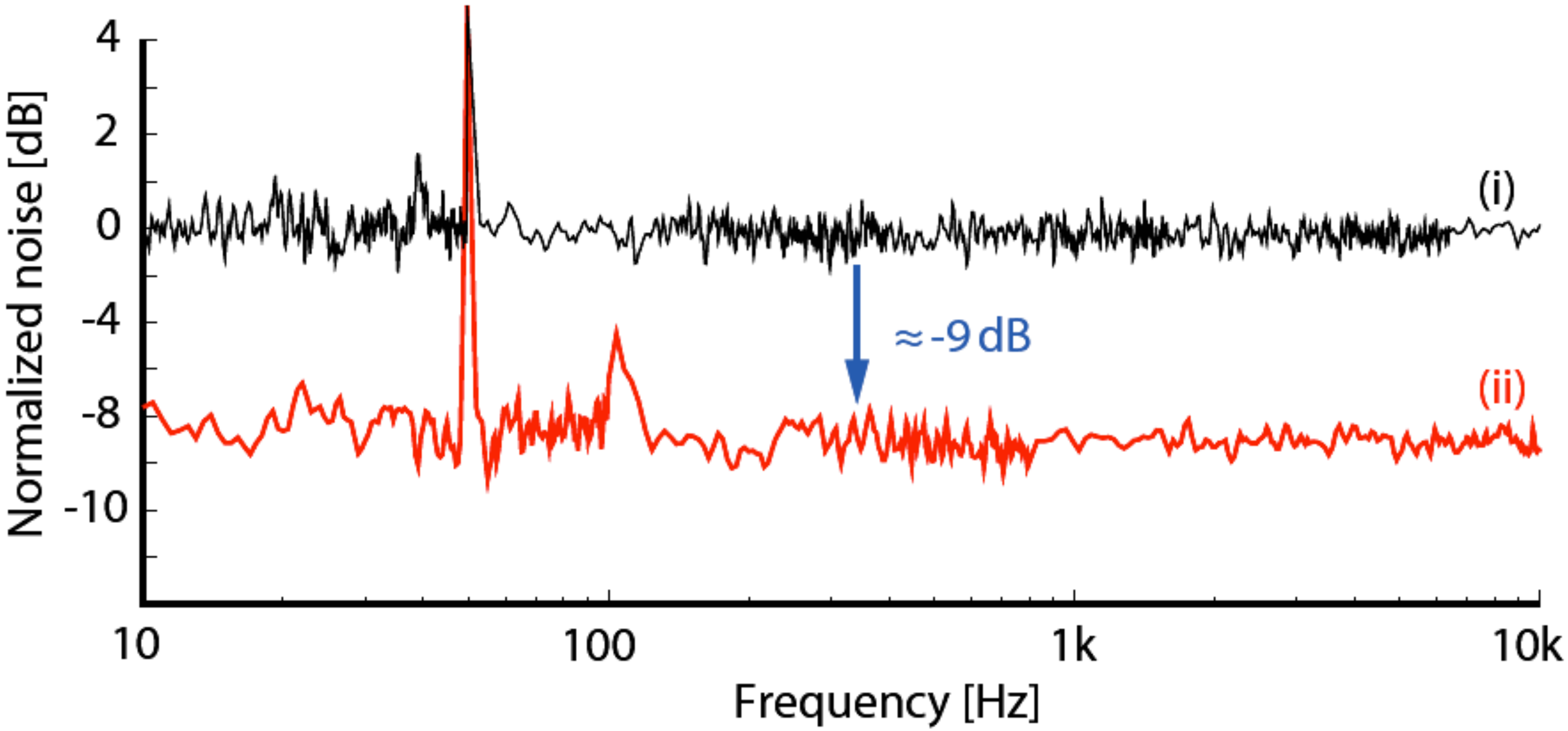




Squeezed Light Test @ LIGO Successful

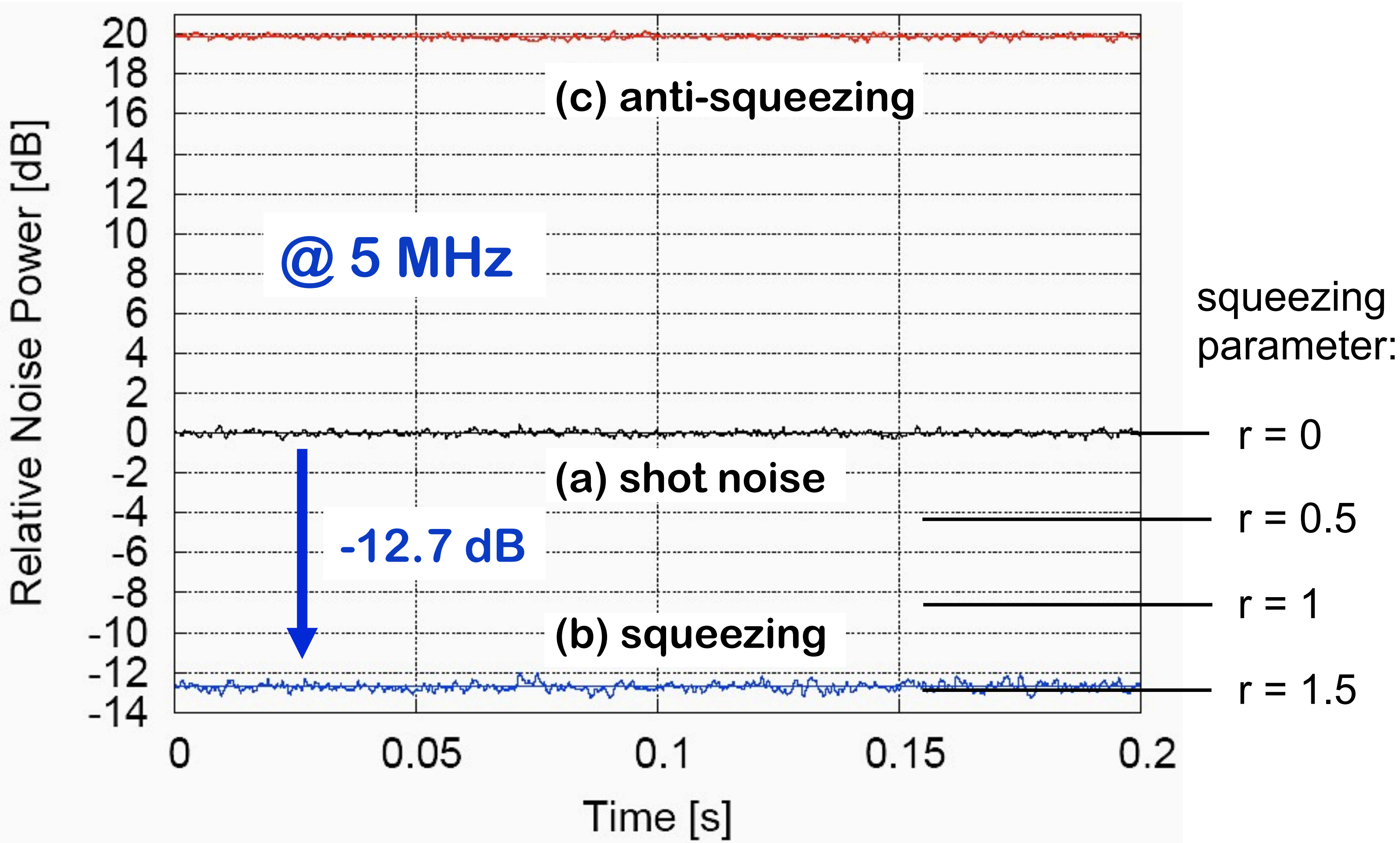
LIGO (arm length 4 km, Hanford, USA)

The GEO600 Squeezed Light Laser



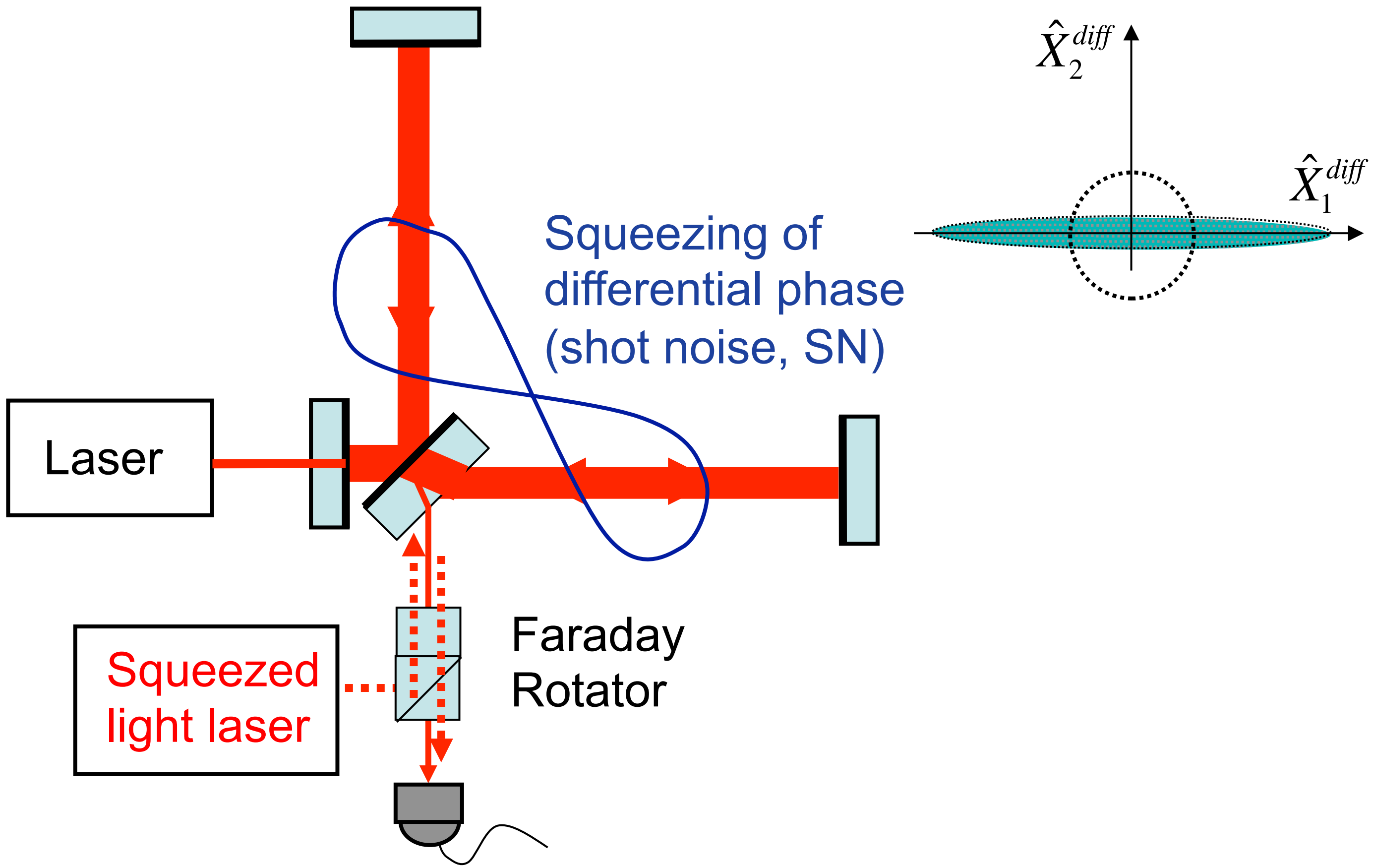
[H. Vahlbruch, A. Khalaidovski, N. Lastzka, C. Gräf, K. Danzmann, and R. Schnabel, ***The GEO600 squeezed light source***, Class. Quantum Grav. **27,** 084027 (2010).]

12.7 dB @1064 nm



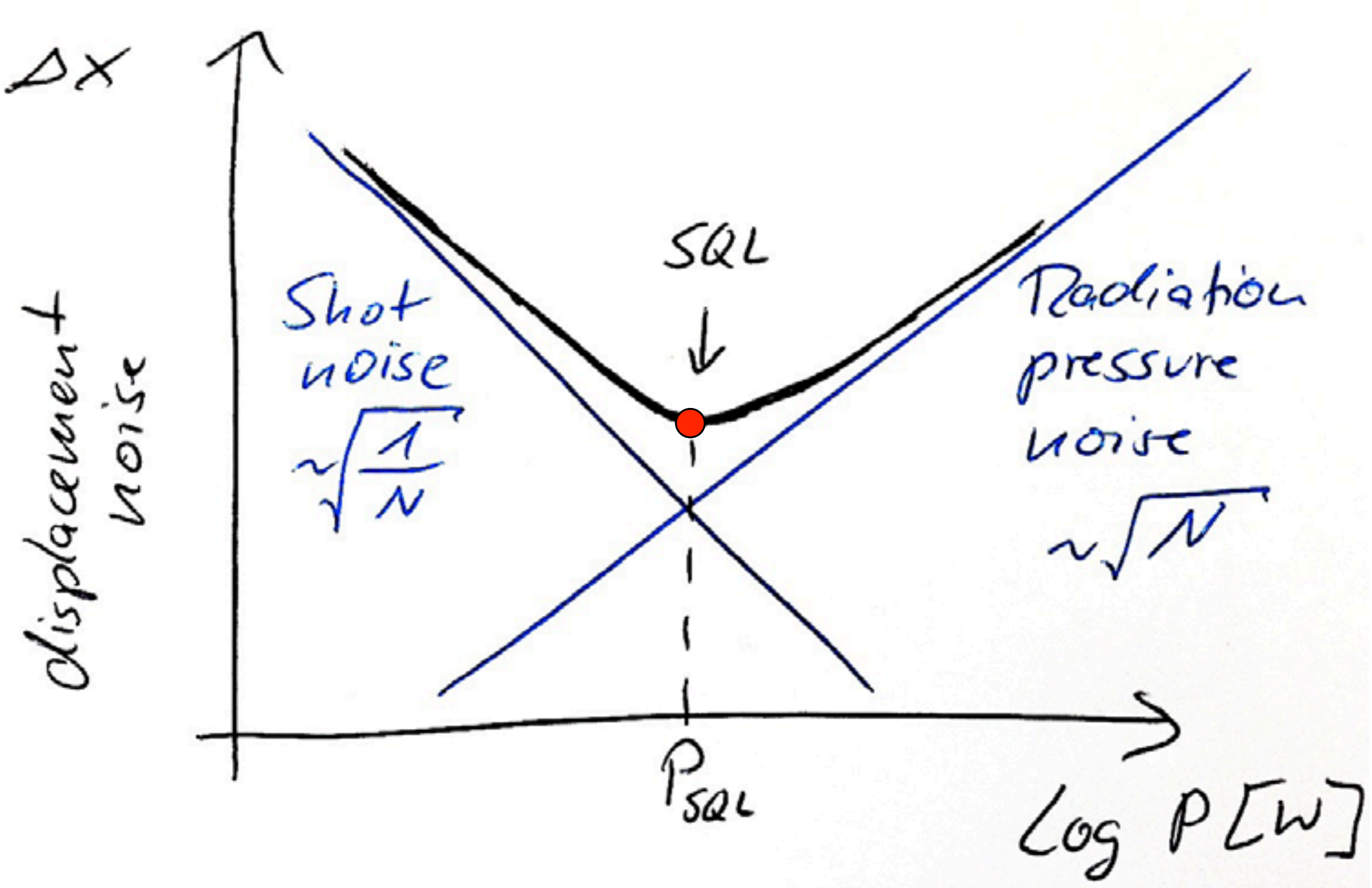
[T. Eberle *et al.*, PRL **104**, 251102 (2010)]

Shot Noise / Radiation Pressure Noise



Anti-squeezing the differential amplitude quadrature
= Anti-squeezing the (differential) radiation pressure noise (RPN)

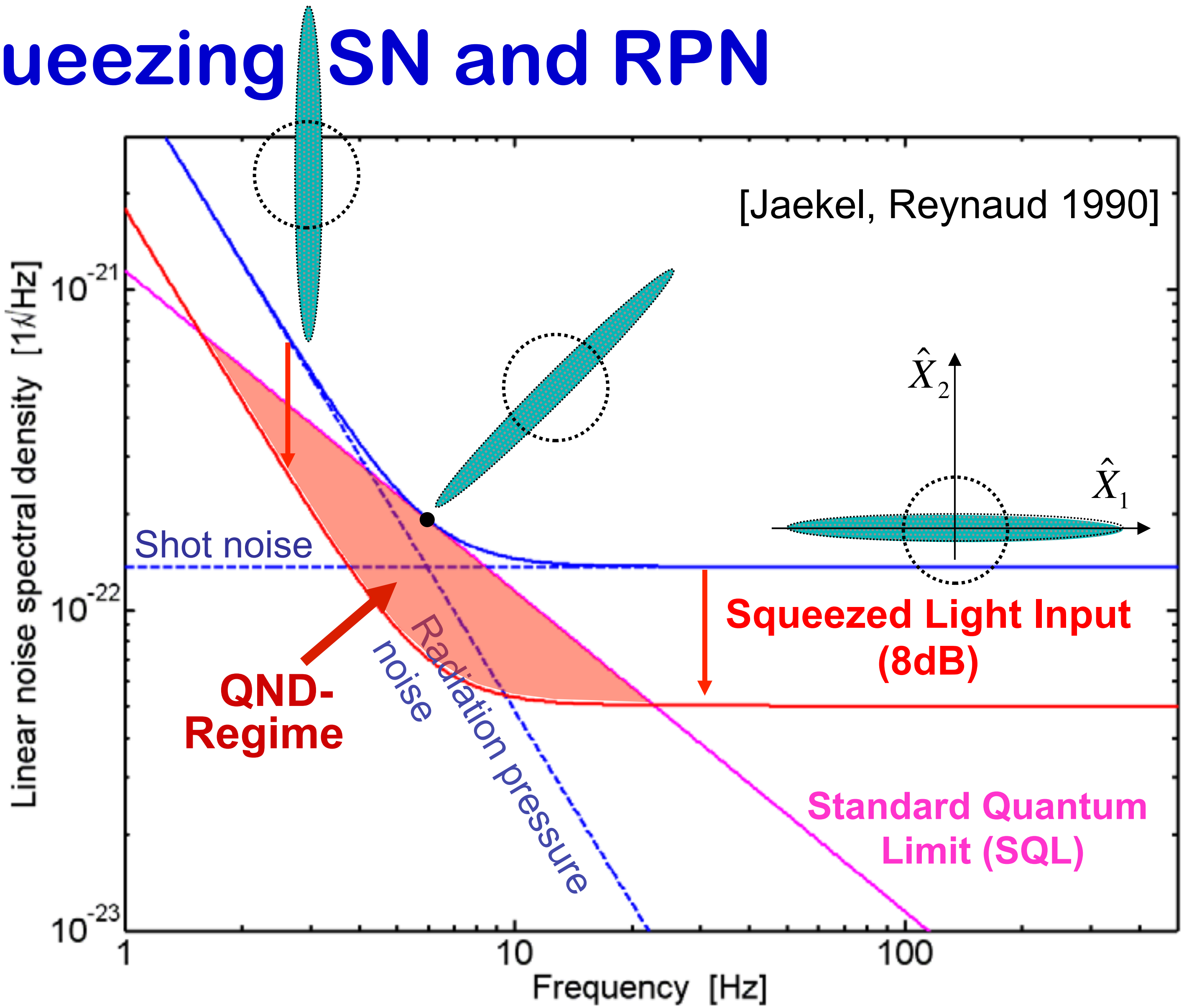
Standard Quantum Limit (SQL*)



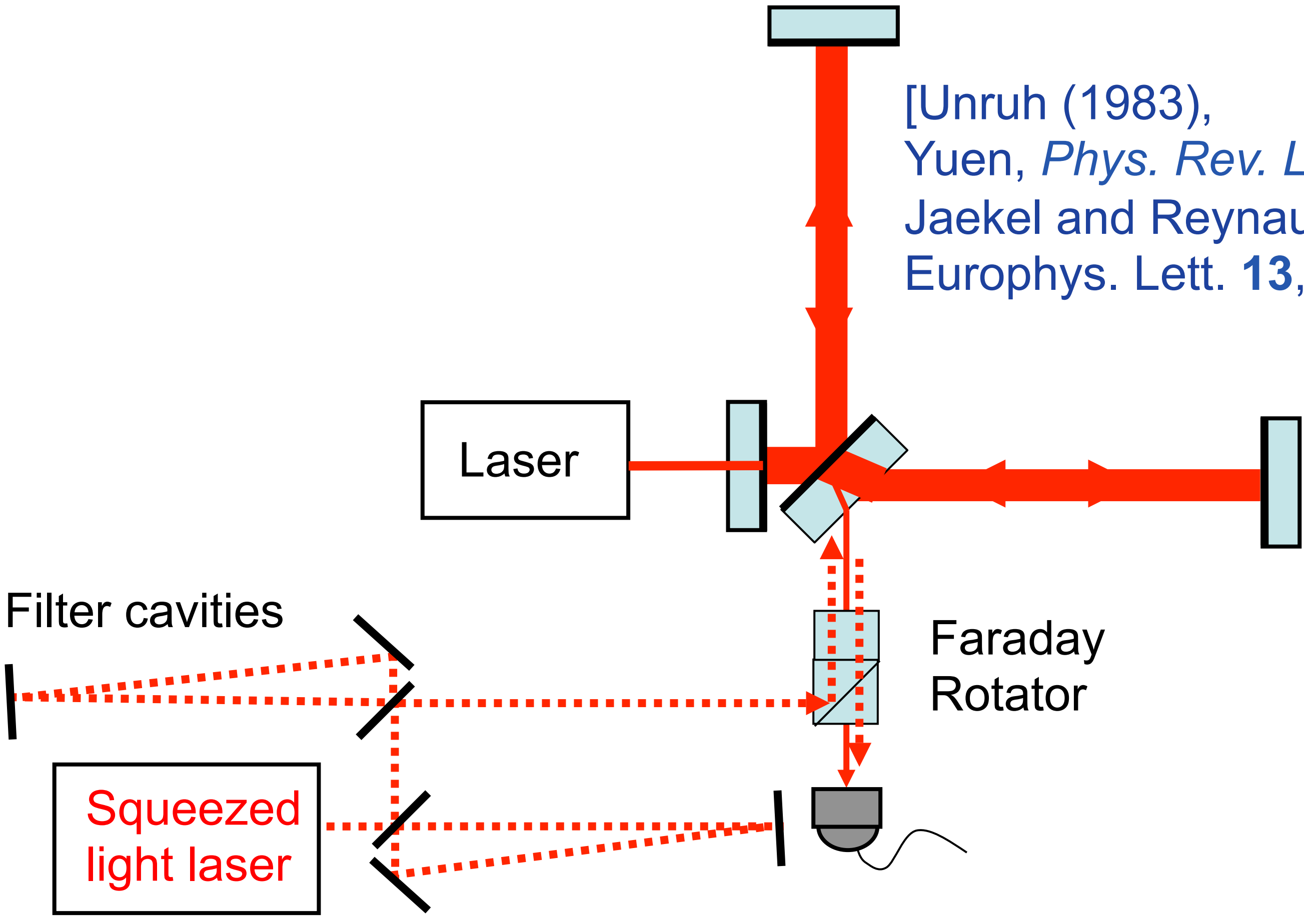
[Caves, Phys. Rev. D 45, 75 (1980)]

(Light power, coherent state)

Squeezing SN and RPN



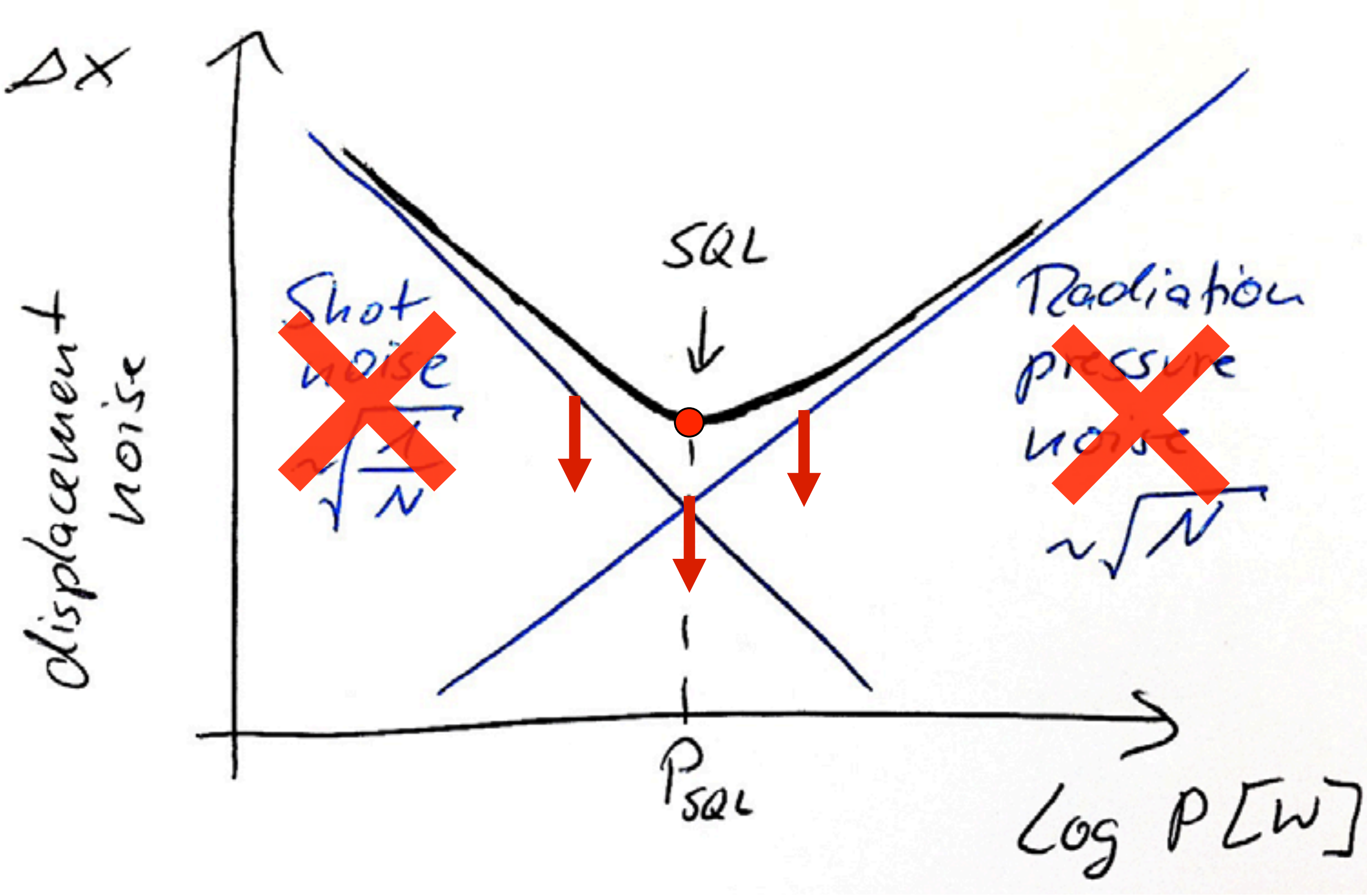
Squeezing the Shot-Noise (SN) *and* the Radiation Pressure Noise (RPN)



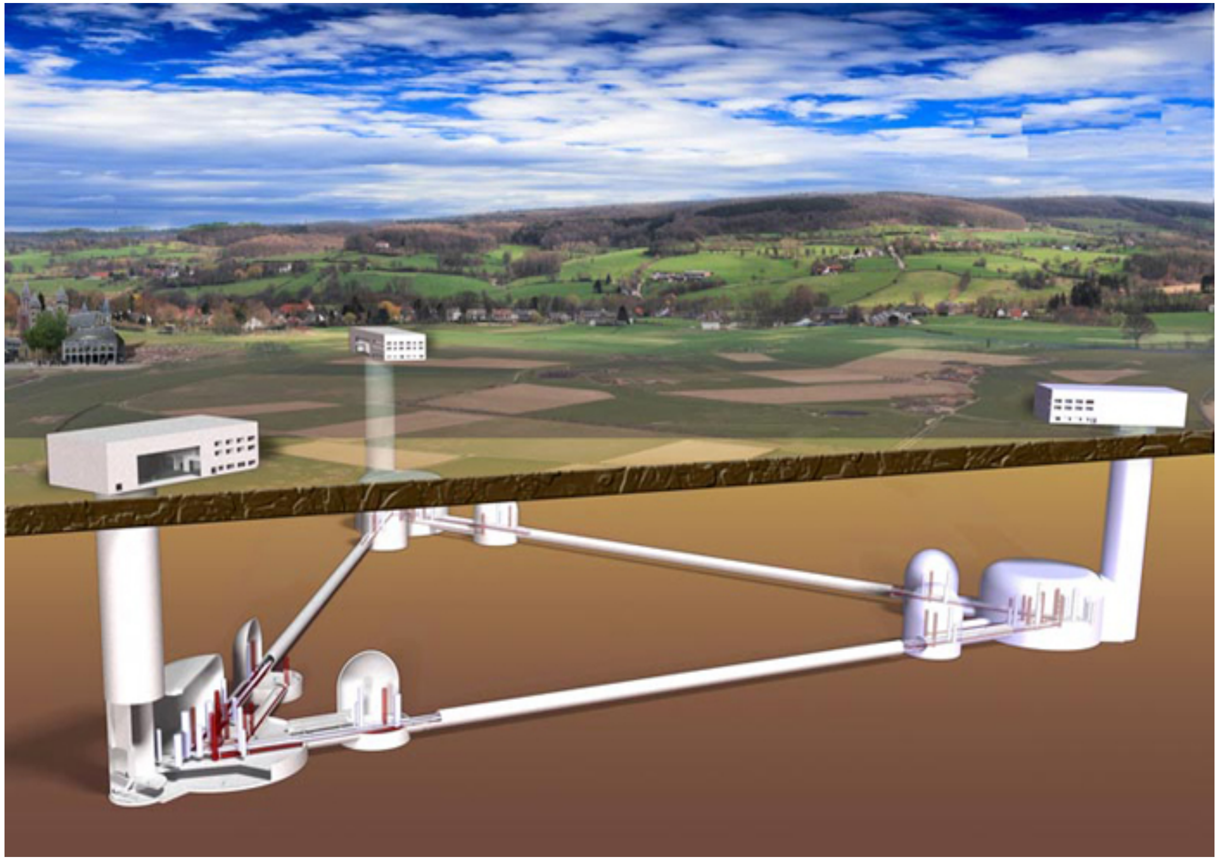
[Unruh (1983),
Yuen, *Phys. Rev. Lett.* **51,** 719 (1983);
Jaekel and Reynaud,
Europhys. Lett. **13**, 301 (1990)]

[Kimble *et al.*, Phys. Rev. D **65**, 022002 (2001)]

Standard Quantum Limit (SQL)



The Einstein Telescope

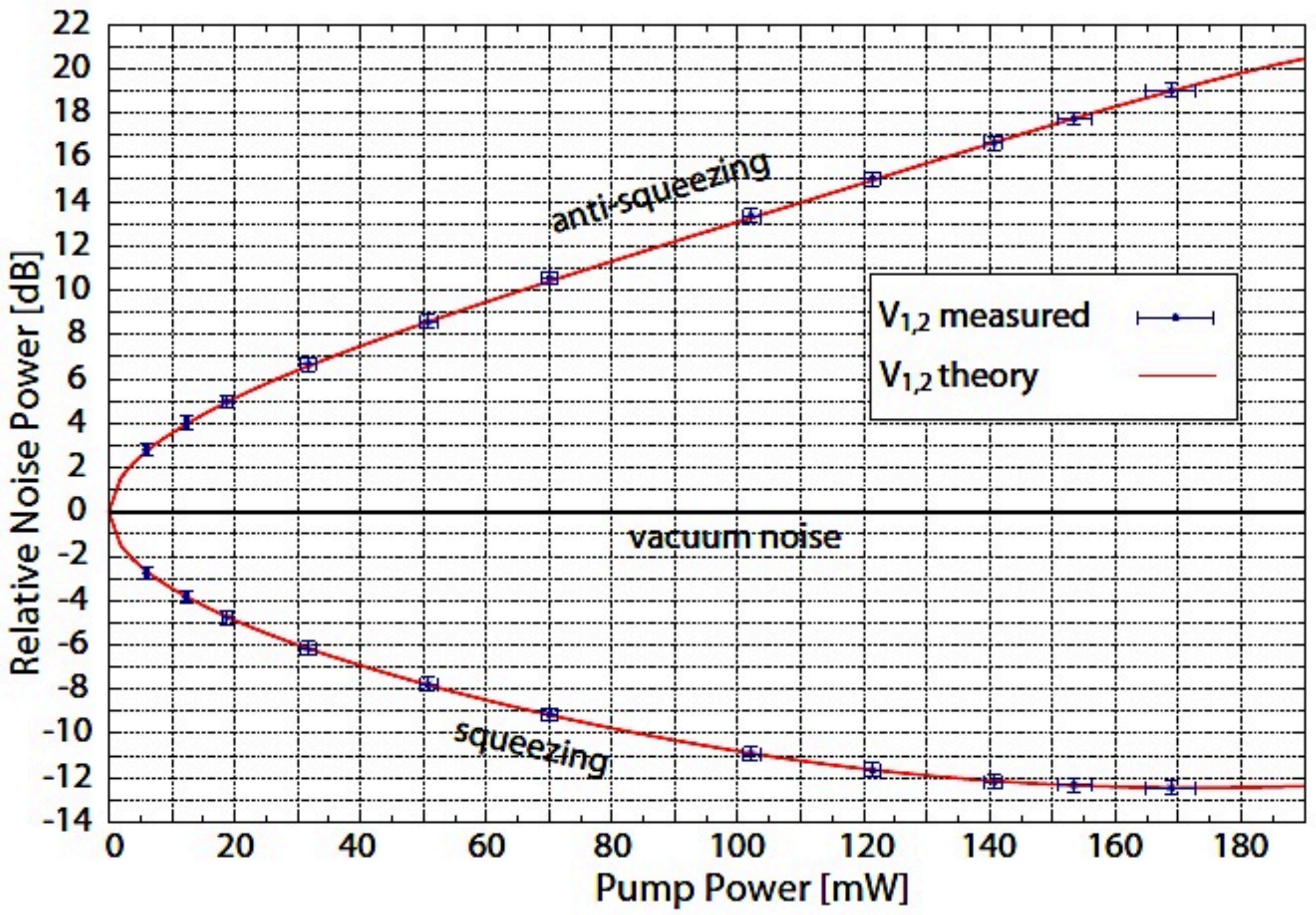


- **10 km arms**
- **under ground**
- **Cryo-cooled silicon mirrors**
- **Squeezed light at 1064 nm and 1550 nm (~10dB)**

[M. Punturo, R.S. *et al.*, Class. Quantum Grav. 084007 (2010)]

European conceptual design study, delivered May 2011

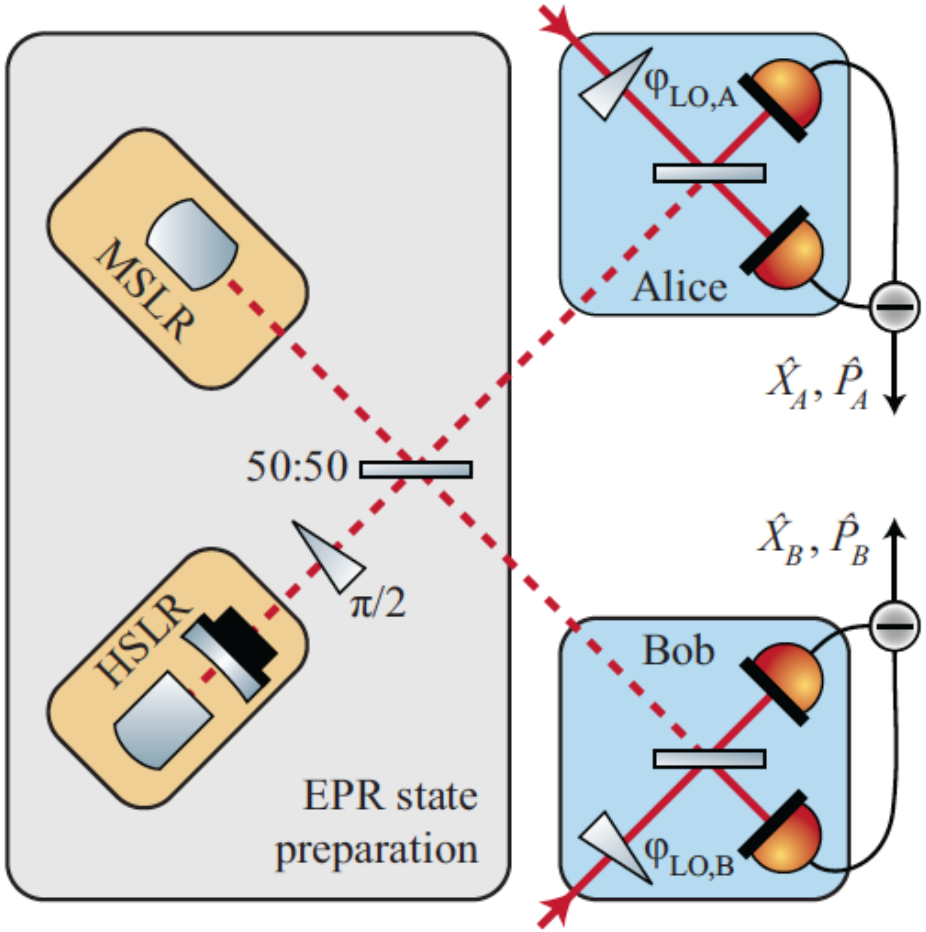
Squeezed Light @ 1550nm

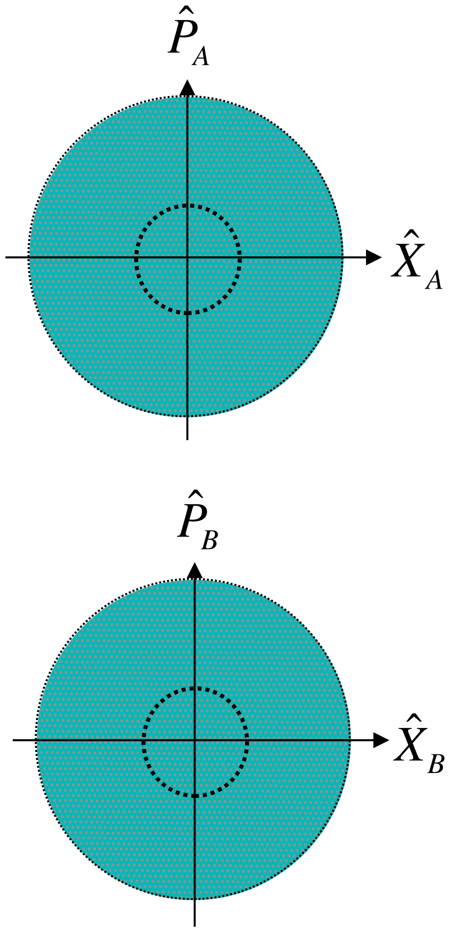


12.3 dB

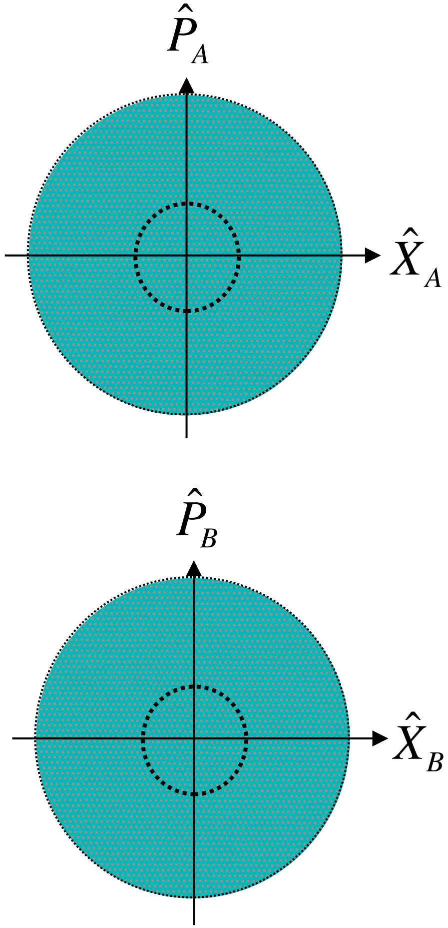
[M. Mehmet *et al.*, Opt. Exp. **19**, 25763 (2011)]

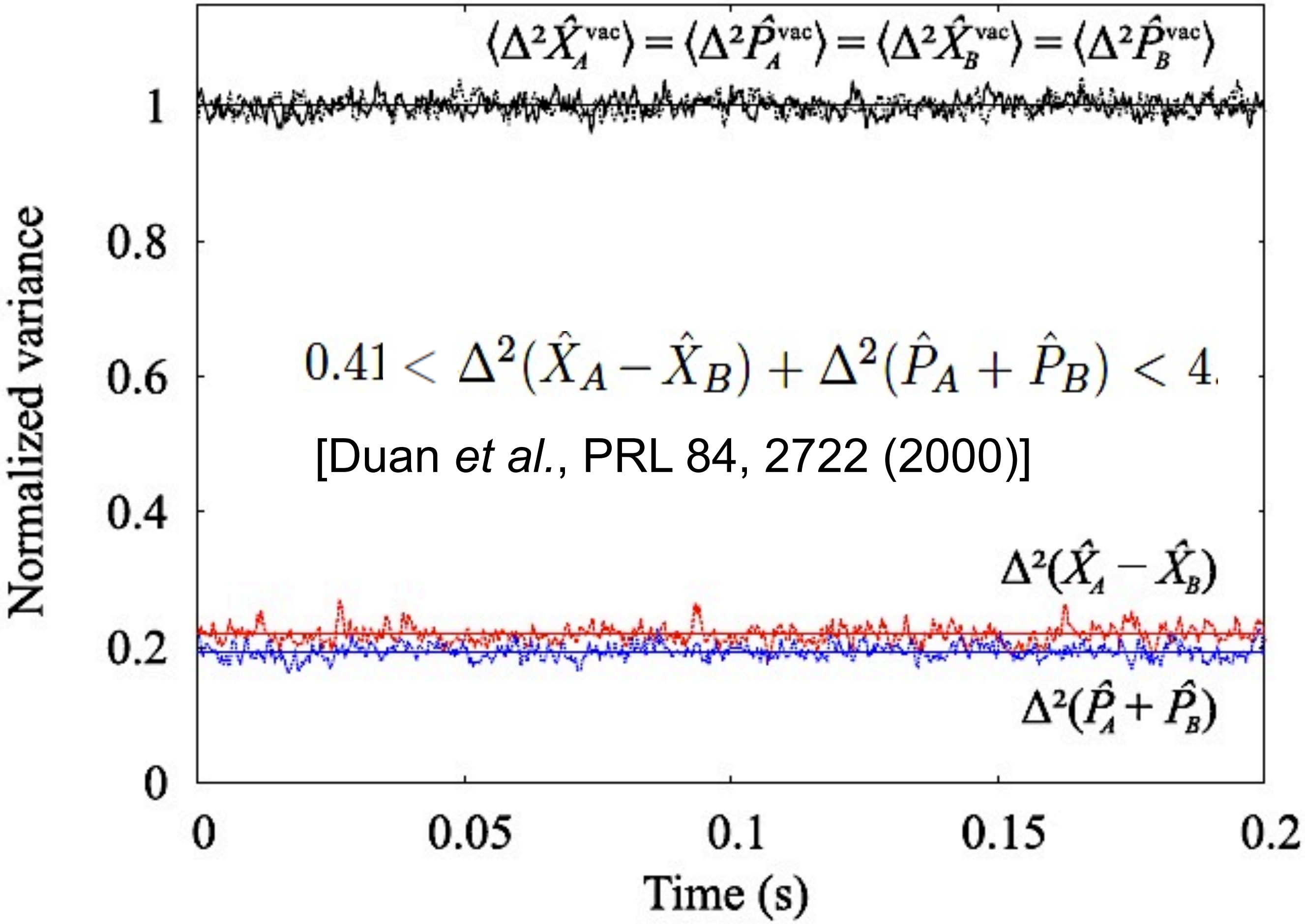
Two-Mode Squeezed Light





Two-Mode Squeezed Light





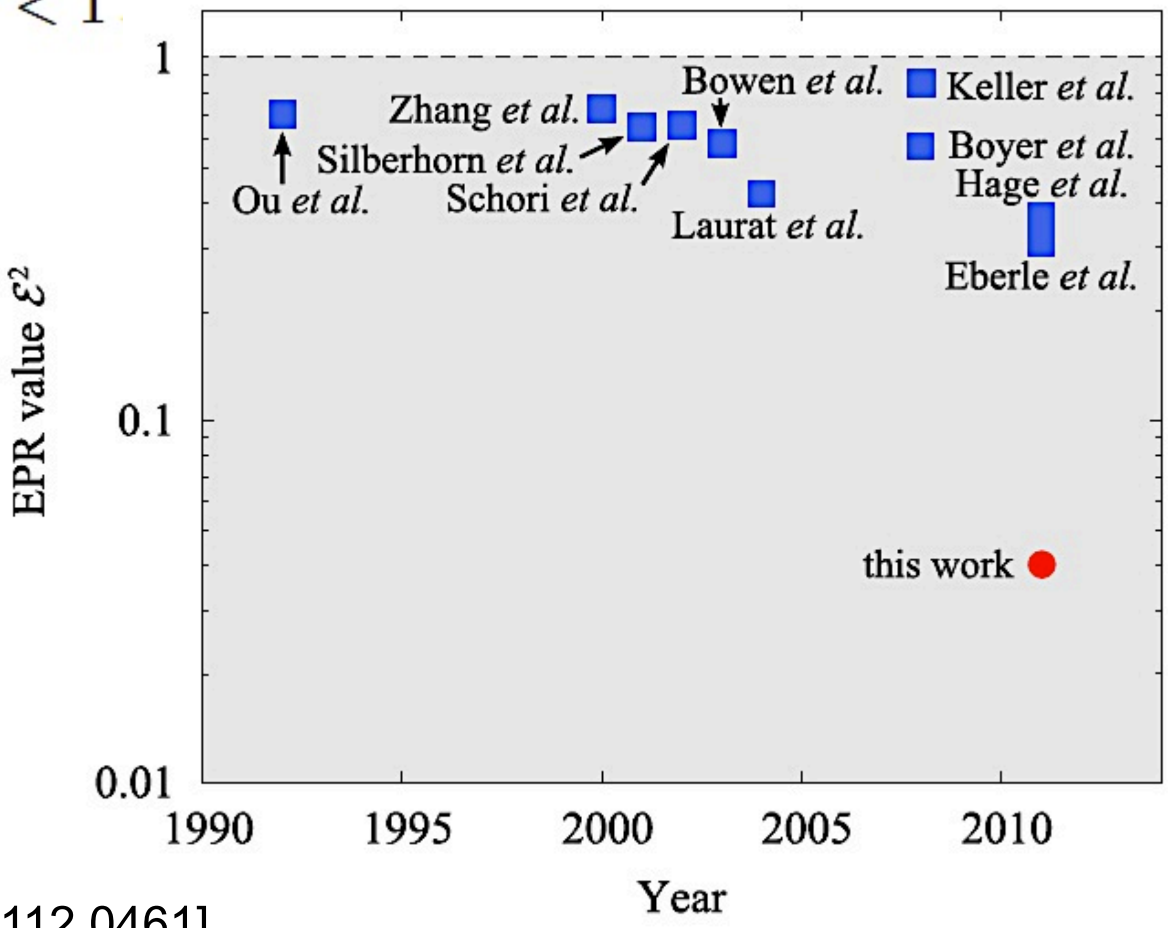
[S. Steinlechner, *et al.*, arXiv: 1112.0461]

EPR Entanglement

$$\mathcal{E}^2_{B|A} = \Delta^2_{B|A}\hat{X} \cdot \Delta^2_{B|A}\hat{P} < 1$$

[Reid, PRA 40, 913 (1989)]

Recent review:
[Reid *et al.*, Rev. Mod. Phys. 81, 1727 (2009).]



[S. Steinlechner, *et al.*, arXiv: 1112.0461]

Optical Squeezing Circuits / Motivation

LETTERS
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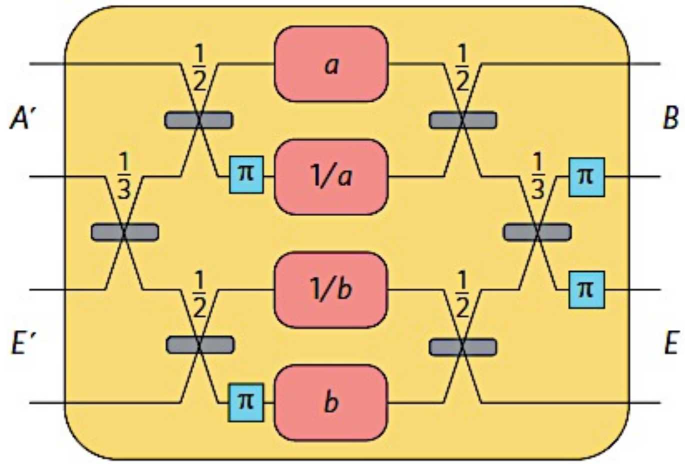
nature photonics

Quantum communication with Gaussian channels of zero quantum capacity

Graeme Smith[1]*, John A. Smolin[1] and Jon Yard[2]

As with classical information[1,2], error-correcting codes enable reliable transmission of quantum information through noisy or lossy channels[3-5]. In contrast to classical theory, imperfect quantum channels exhibit a strong kind of synergy: pairs of discrete memoryless quantum channels exist, each of zero quantum capacity, which acquire positive quantum capacity when used together[6]. Here, we show that this 'superactivation' phenomenon also occurs in the more realistic setting of optical channels with attenuation and Gaussian noise[7,8]. This paves the way for its experimental realization and application in real-world communications systems.



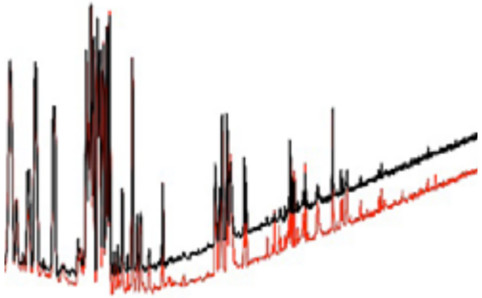
Requirement:
$3.1 < a < 5$ (9.6 dB – 14 dB)

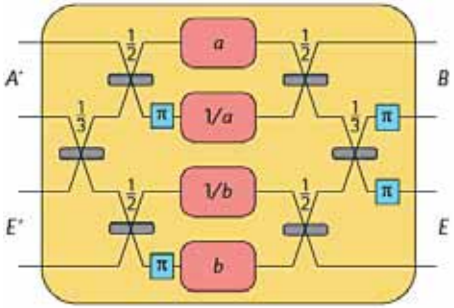
Summary

- **GEO600 uses squeezed light in observational runs and achieves its best ever sensitivity**
- **The improvement corresponds to 3.5 dB at shot-noise limited frequencies**
- **Up to 12.7 dB (12.3 dB) of squeezing has been generated at 1064nm (1550nm).**
- **“*Squeezed light will become a key-technology for GW detectors*”**

DFG SFB TR7

Centre of Excellence: quantum engineering and space time research





PhD Students and Postdocs