Light Sources and Interferometer Topologies

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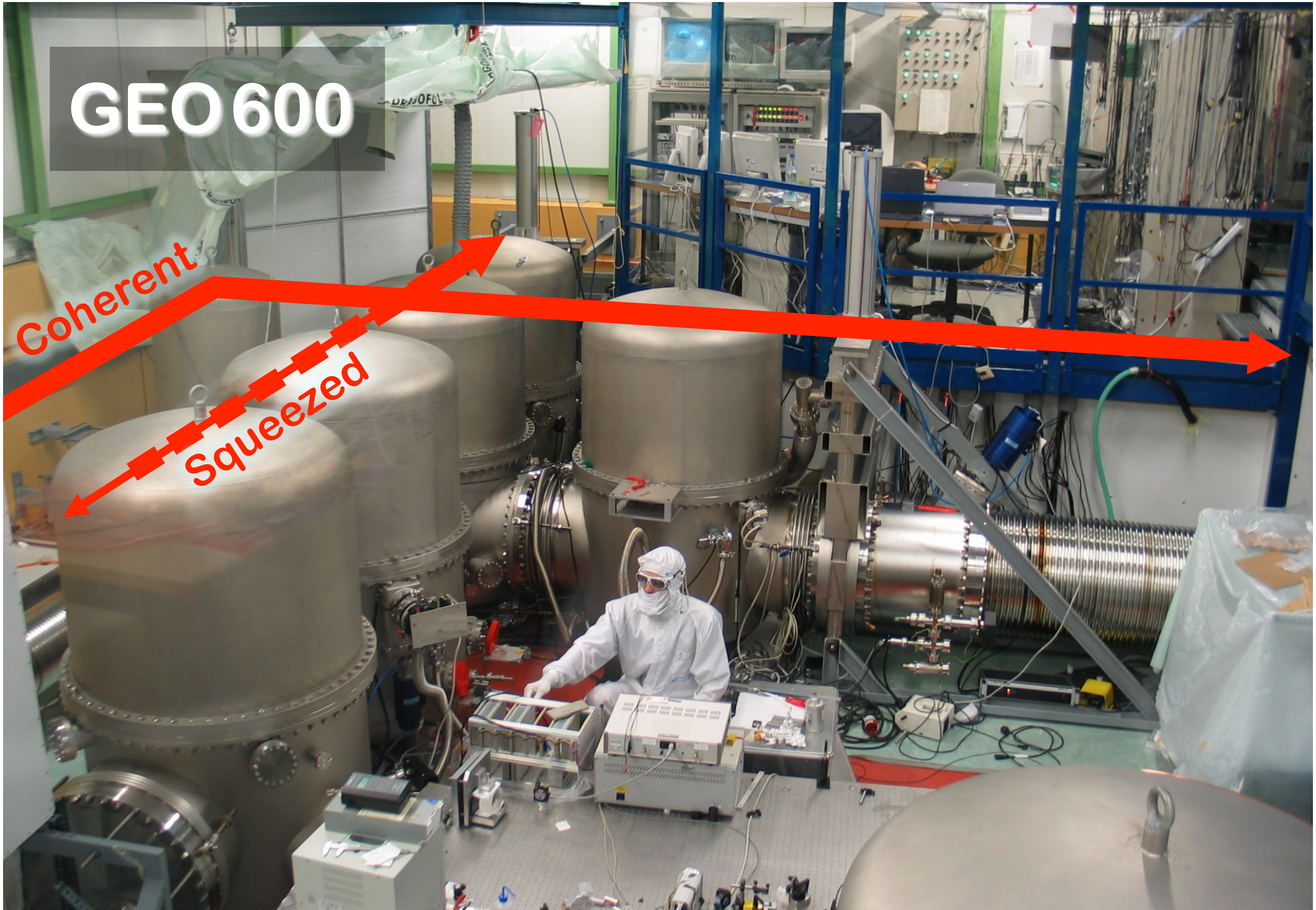
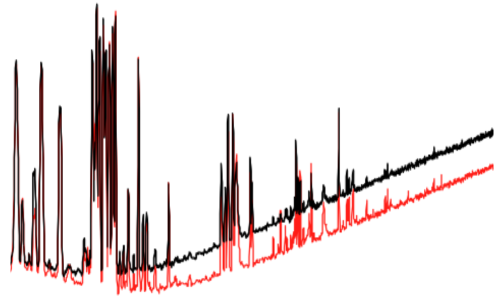
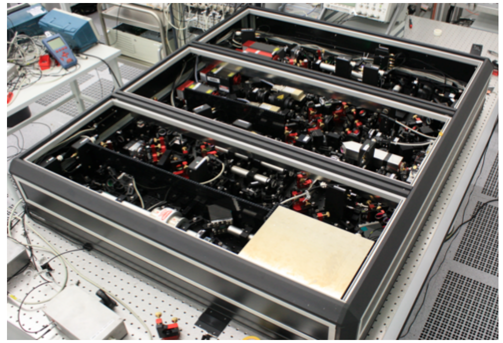
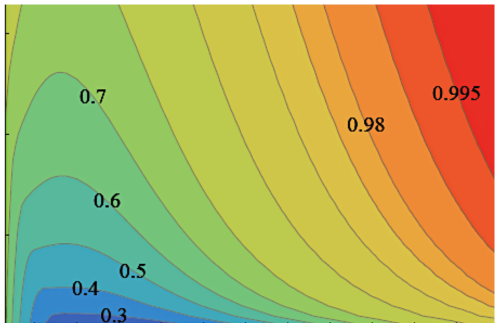

GEO 600
Coherent
Squeezed

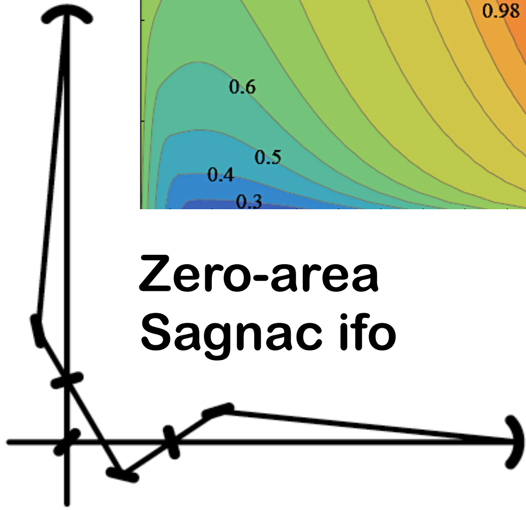
Outline





- Optimality of the "coherent state – squeezed state approach"
- Further aspect: radiation pressure noise
- Ponderomotive Squeezing
- Squeezed vacuum generation
  @ 1064nm, @ 1550nm, @ 532nm
- Avoiding radiation pressure noise:
  Sagnac interferometer
- Dynamic back-action and optical springs





Zero-area
Sagnac ifo

PHYSICAL REVIEW D VOLUME 23, NUMBER 8 15 APRIL 1981

Quantum-mechanical noise in an interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 15 August 1980)

The interferometers now being developed to detect gravitational waves work by measuring the relative positions of widely separated masses. Two fundamental sources of quantum-mechanical noise determine the sensitivity of such an interferometer: (i) fluctuations in number of output photons (photon-counting error) and (ii) fluctuations in radiation pressure on the masses (radiation-pressure error). Because of the low power of available continuous-wave lasers, the sensitivity of currently planned interferometers will be limited by photon-counting error. This paper presents an analysis of the two types of quantum-mechanical noise, and it proposes a new technique—the "squeezed-state" technique—that allows one to decrease the photon-counting error while increasing the radiation-pressure error, or vice versa. The key requirement of the squeezed-state technique is that the state of the light entering the interferometer's normally unused input port must be not the vacuum, as in a standard interferometer, but rather a "squeezed state"—a state whose uncertainties in the two quadrature phases are unequal. Squeezed states can be generated by a variety of nonlinear optical processes, including degenerate parametric amplification.

Introduction of „squeezed states“ to electro-magnetic fields:

H. P. Yuen, *Two-photon coherent states of the radiation field*,
Phys. Rev. A **13,** 2226–2243 (1976)

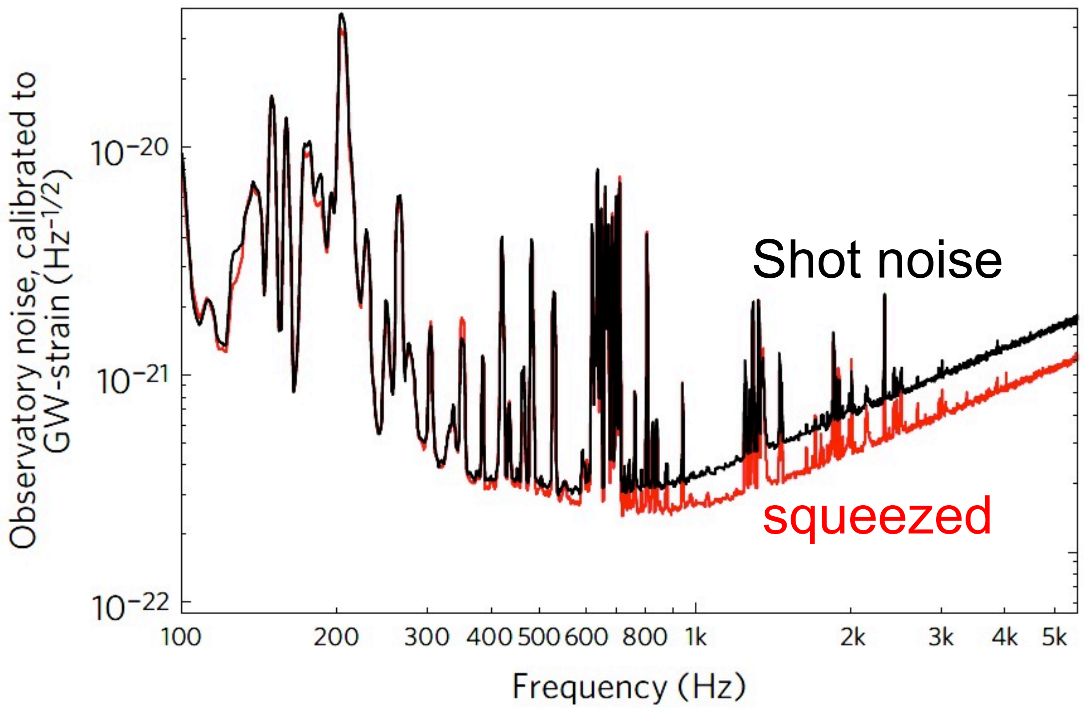
nature physics

LETTERS

PUBLISHED ONLINE: 11 SEPTEMBER 2011 | DOI: 10.1038/NPHYS2083

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

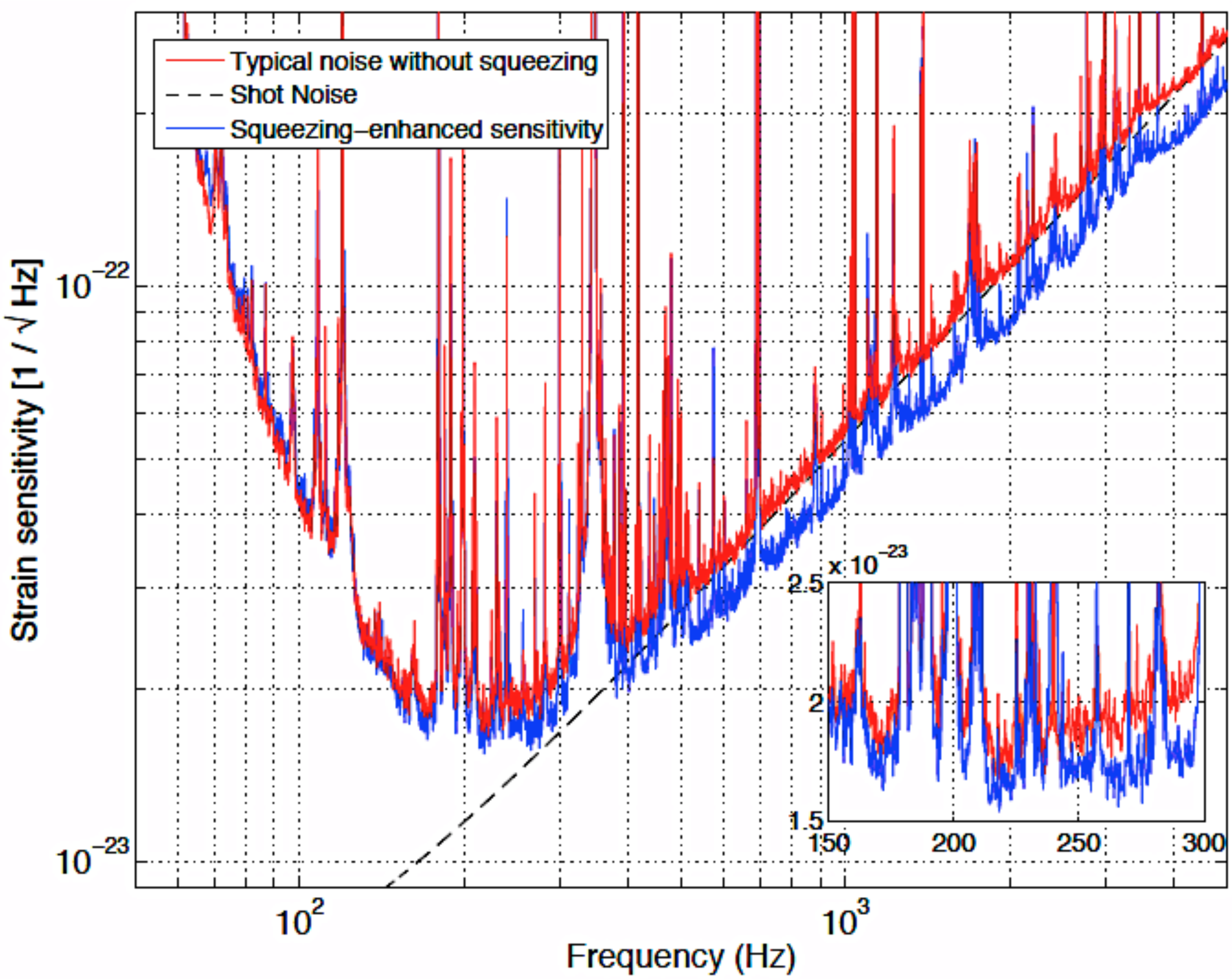
The LIGO Scientific Collaboration †*



GEO600 now regularly uses squeezed light and has acquired 205 days of squeezed science data.

[Grote, Danzmann, Dooley, Schnabel, Slutsky, Vahlbruch, Phys. Rev. Lett. 110, 181101(2013)]

LIGO

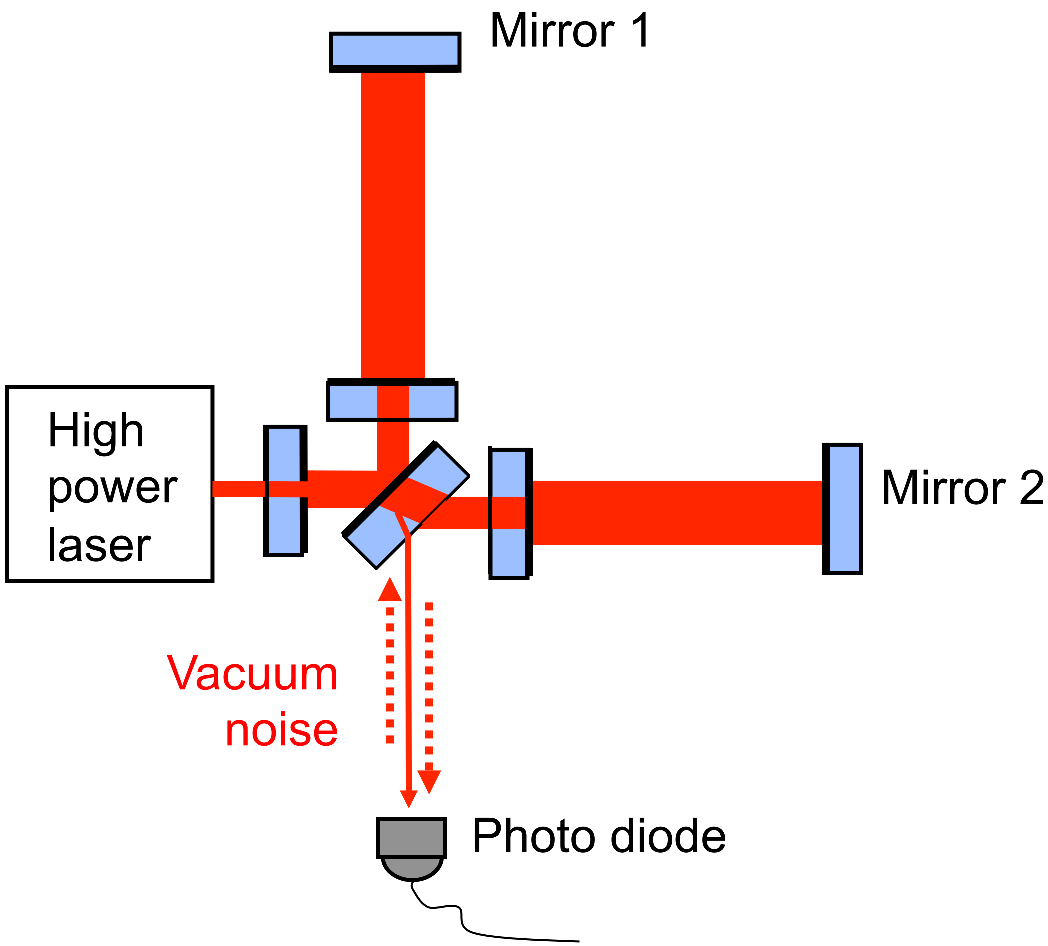


Typical noise without squeezing
Shot Noise
Squeezing–enhanced sensitivity
Strain sensitivity [1 / √Hz]
10^-22
10^-23
10^2
10^3
Frequency (Hz)
x 10^-23
2.5
2
1.5
150
200
250
300

Shot Noise / Vacuum Noise

C. M. Caves (1981):

Vacuum noise that enters at the dark port is responsible for shot-noise on photo diode

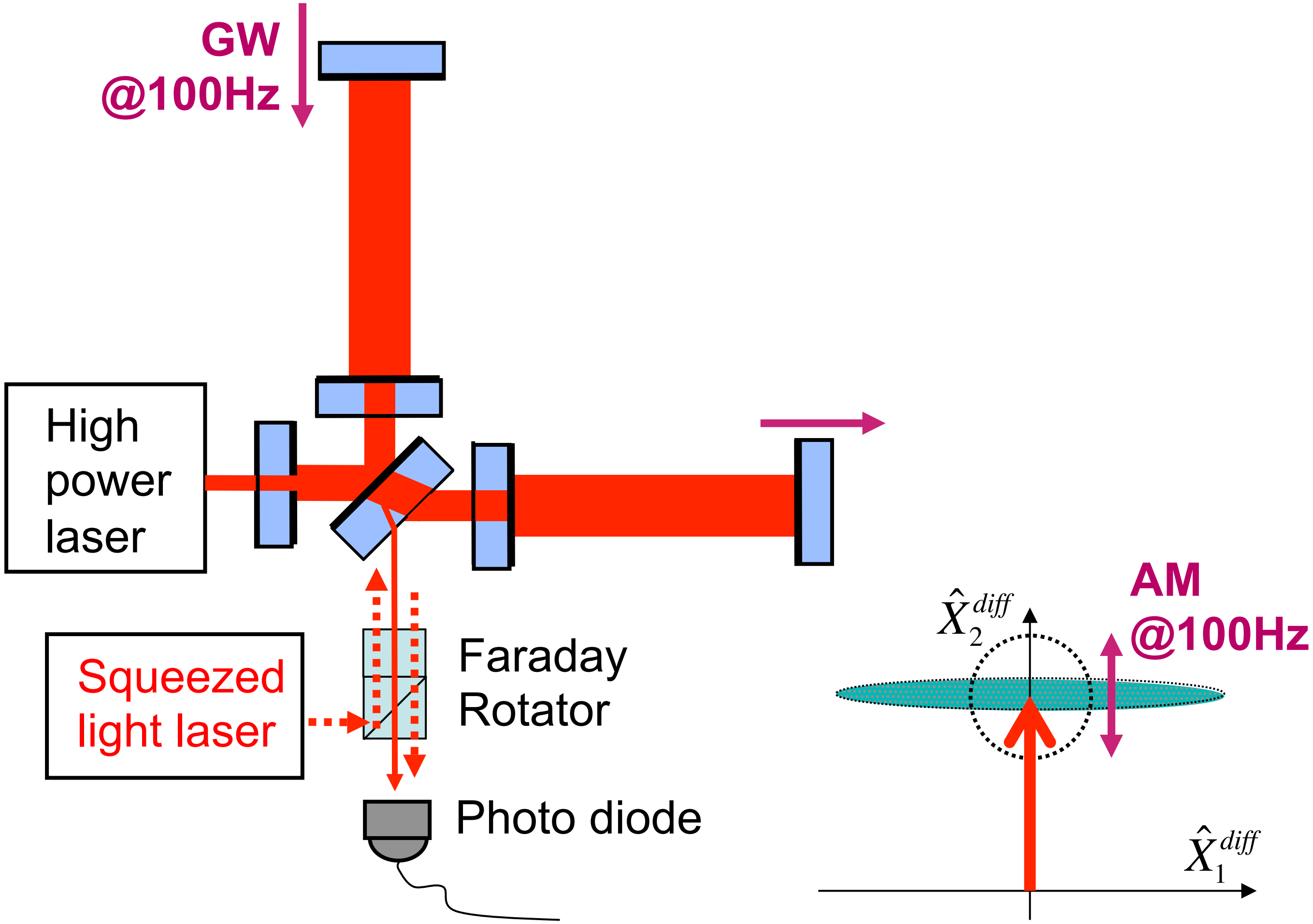


[Caves, Phys. Rev. D 23, 1693 (1981)]

Squeezing the Shot-Noise: "Optimal"?

C. M. Caves (1981):

Vacuum noise that enters at the dark port is responsible for shot-noise on photo diode



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

Optimality of Phase Sensing

Well-known: “Light power should be high and optical loss low! (And radiation pressure noise needs to be evaded.)”

What is the optimum approach to measure a small phase $\Delta\Phi$ for a given photon rate and for a given decoherence rate (loss)?

For just a few photons (per integration time) and low optical loss, Fock states (N00N-states) are optimal:

$$\Delta\Phi_{|N00N\rangle} = \frac{1}{N} \qquad \Delta\Phi_{|\alpha\rangle} = \frac{1}{\sqrt{N}} \qquad \Delta\Phi_{|\alpha,r\rangle} \approx \frac{e^{-r}}{\sqrt{N}}$$

“Heisenberg Scaling”

[J. Rarity *et al.*, *Two-photon interference in a Mach-Zehnder interferometer*, Phys. Rev. Lett. 65, 1348 (1990)]
[M. Mitchell *et al.*, *Superresolving phase measurements with a multiphoton entangled state,* Nature 429, 161 (2004)]

Optimality of Phase Sensing

For many photons ($N > 10^{12}$ per second) and some optical loss $(1-\eta) > 1\%$, the combination of bright coherent states and squeezed vacuum states is optimal !
(Current GW detectors: $N \approx 10^{22}$/s, $(1-\eta) \approx 40\%$)

Cramér–Rao bound, $\eta < 1$:
$\Rightarrow$

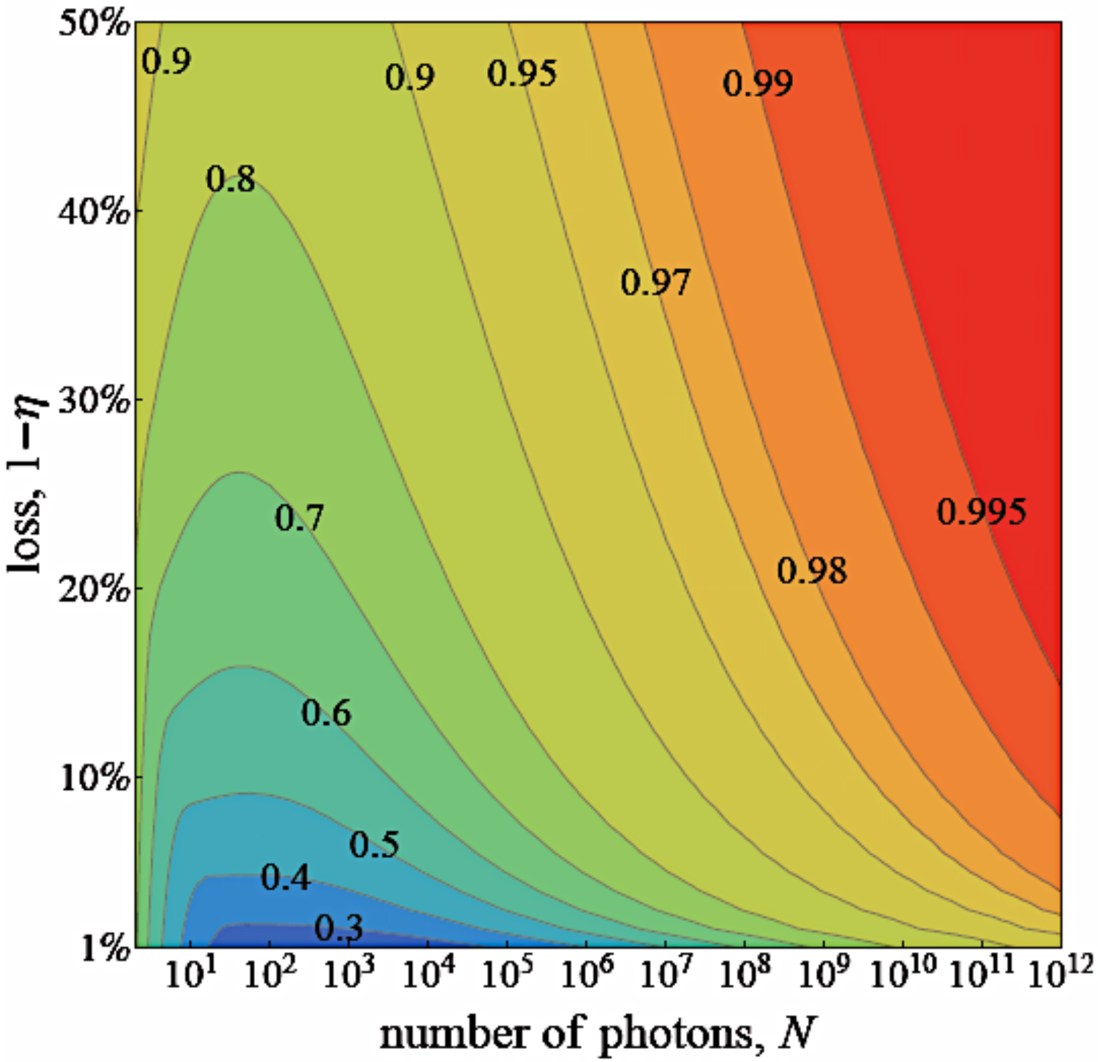
$$\Delta\Phi_{|\psi\rangle} \geq \sqrt{\frac{1-\eta}{\eta N}}$$

Caves 1981:

$$\Delta\Phi_{|\alpha,r\rangle} \approx \sqrt{\frac{1-\eta+\eta e^{-2r}}{\eta N}}$$

[R. Demkowicz-Dobrzanski, K. Banaszek, R.S., *Fundamental quantum interferometry bound for the squeezed-light-enhanced GW detector GEO600*, **LIGO-P1300059**-v2]

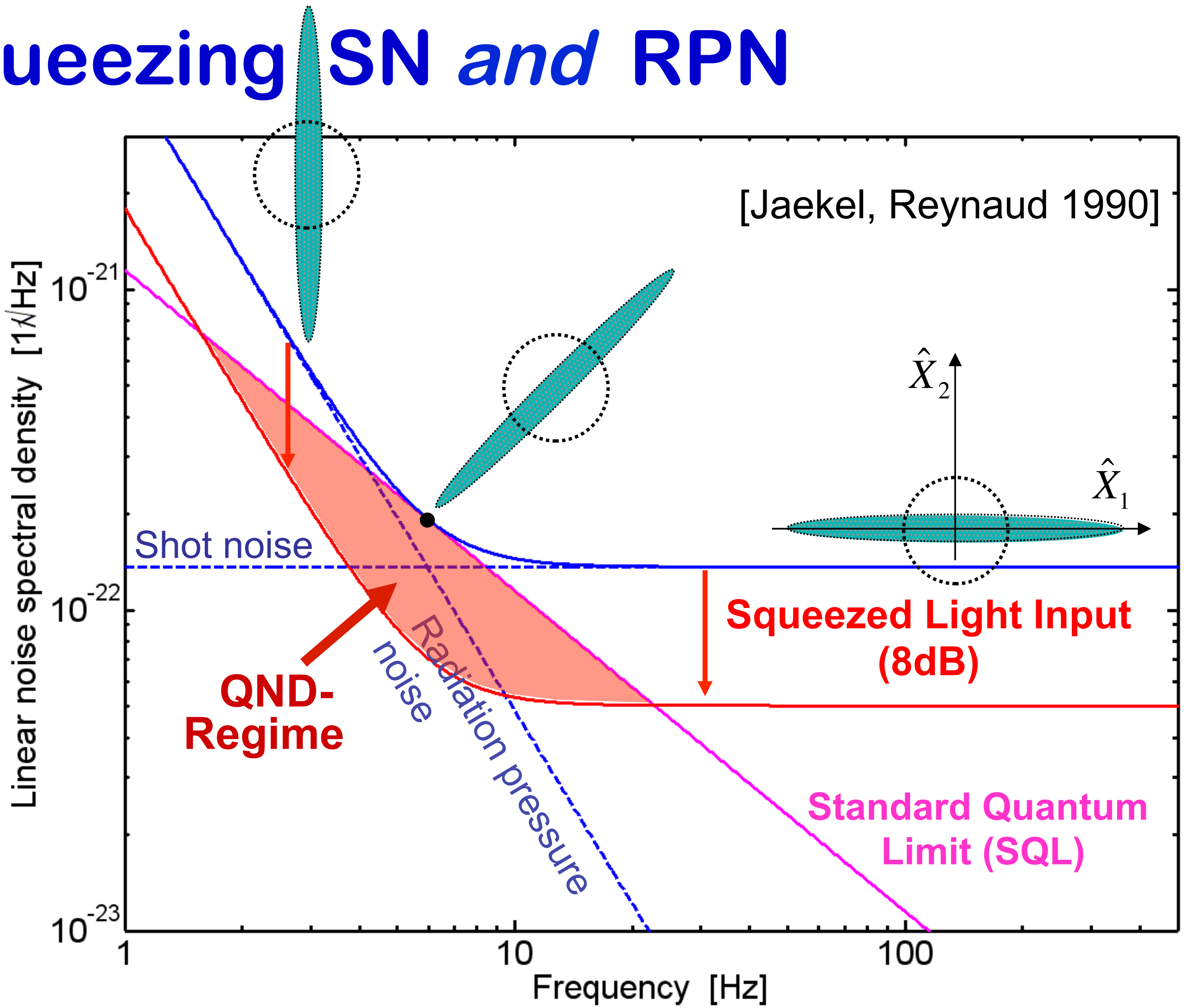
Optimality of Phase Sensing



For N ≈ 10^{22}/s and 40% loss, 16 dB instead of the currently used 10 dB of input squeezing would achieve 99.9996% of the ultimate phase sensitivity.

→ "No need for other than coherent and squeezed states in GW detection!"

Squeezing SN *and* RPN



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

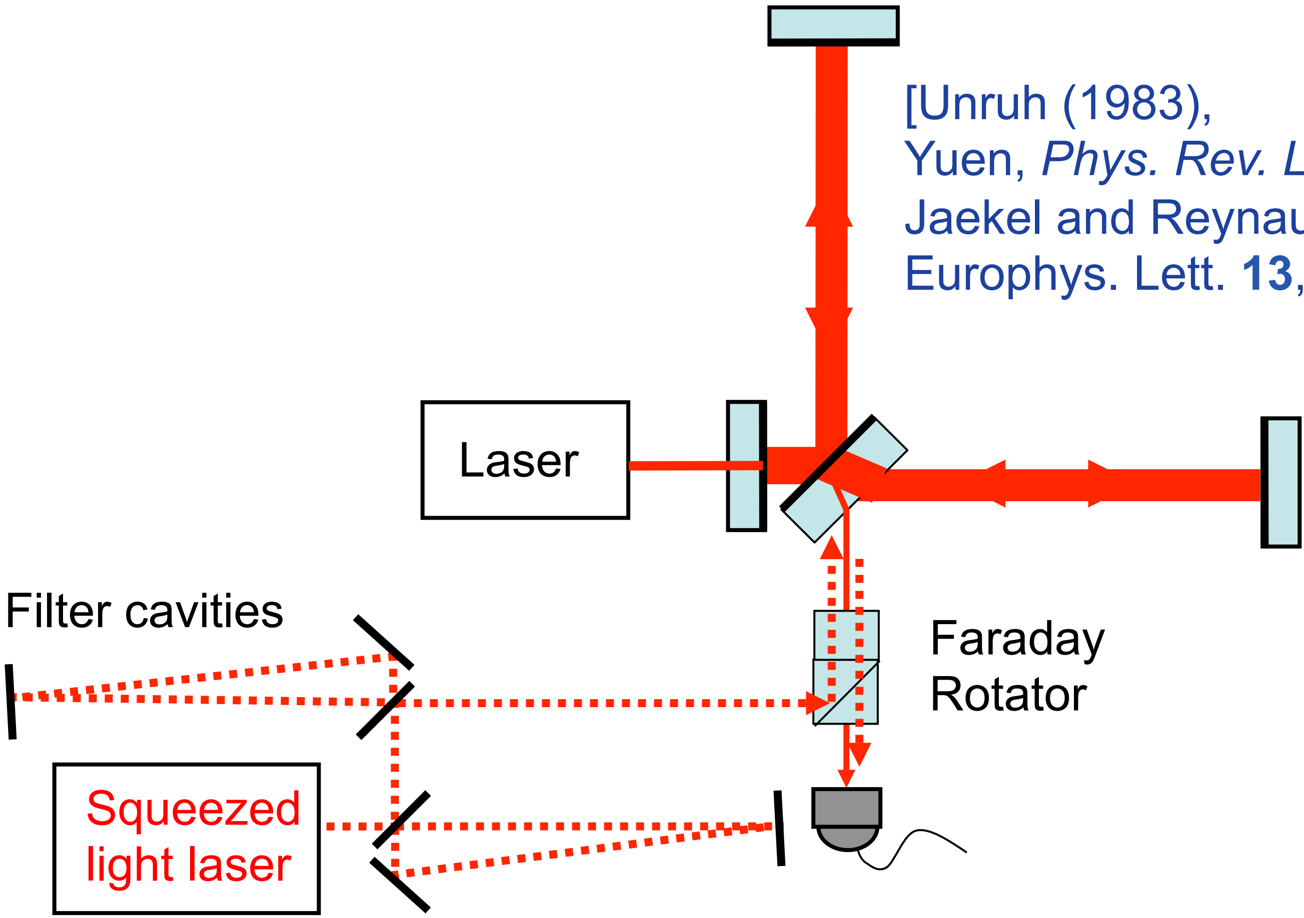
"Photon counting noise and radiation pressure noise in a GW detector can ***both*** be squeezed!"

First doubts on the free-mass SQL as the ultimate limit:

W. G. Unruh, in *Quantum Optics, Experimental Gravitation, and Measurement Theory* 647–660 (Plenum, 1983),

H. P. Yuen, Phys. Rev. Lett. **51,** 719 (1983)

Squeezing SN *and* RPN: Filter cavities

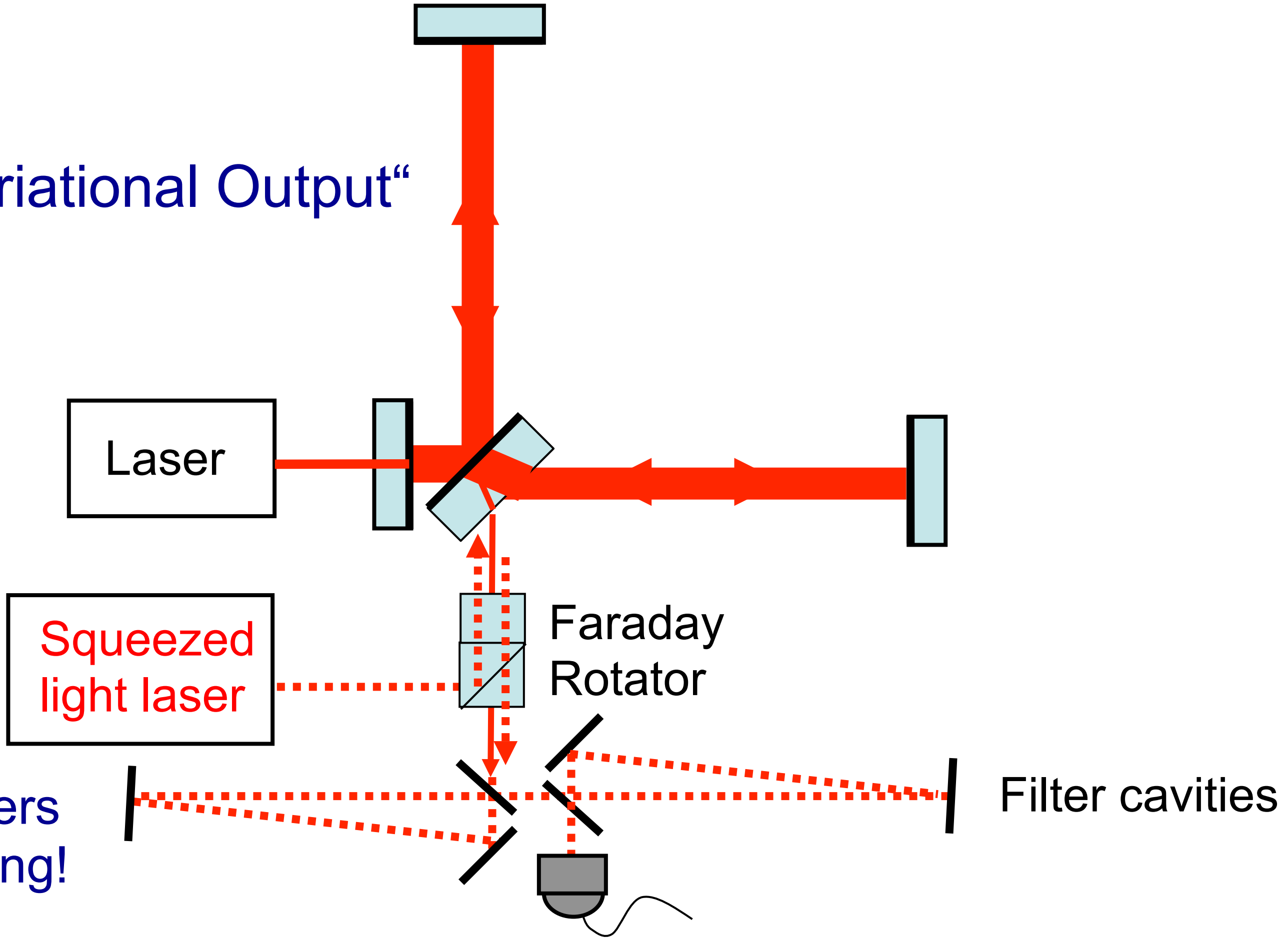


[Unruh (1983),
Yuen, *Phys. Rev. Lett.* **51,** 719 (1983);
Jaekel and Reynaud,
Europhys. Lett. **13**, 301 (1990)]

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

Squeezing and Full Evasion of RPN

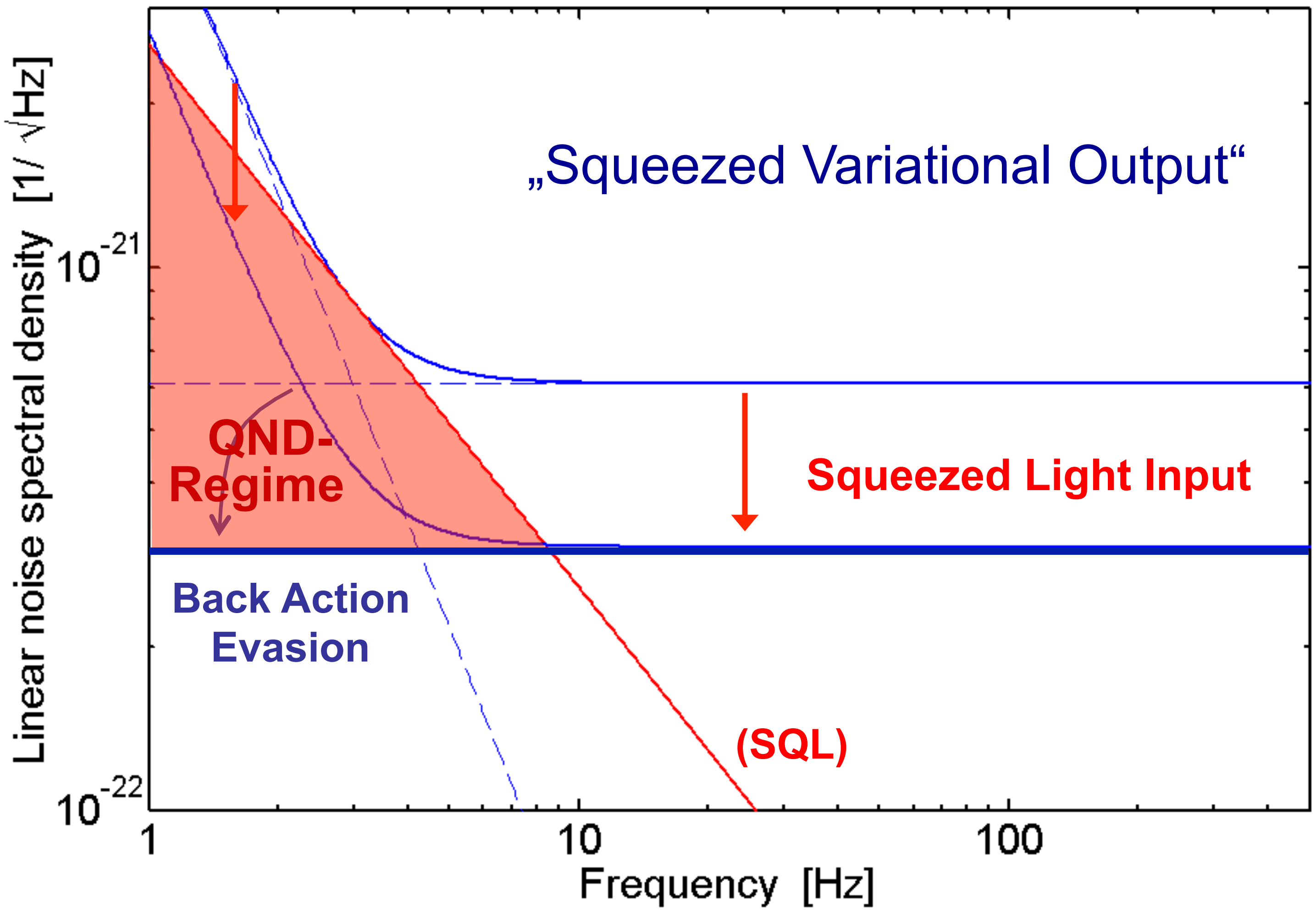
„Squeezed Variational Output“



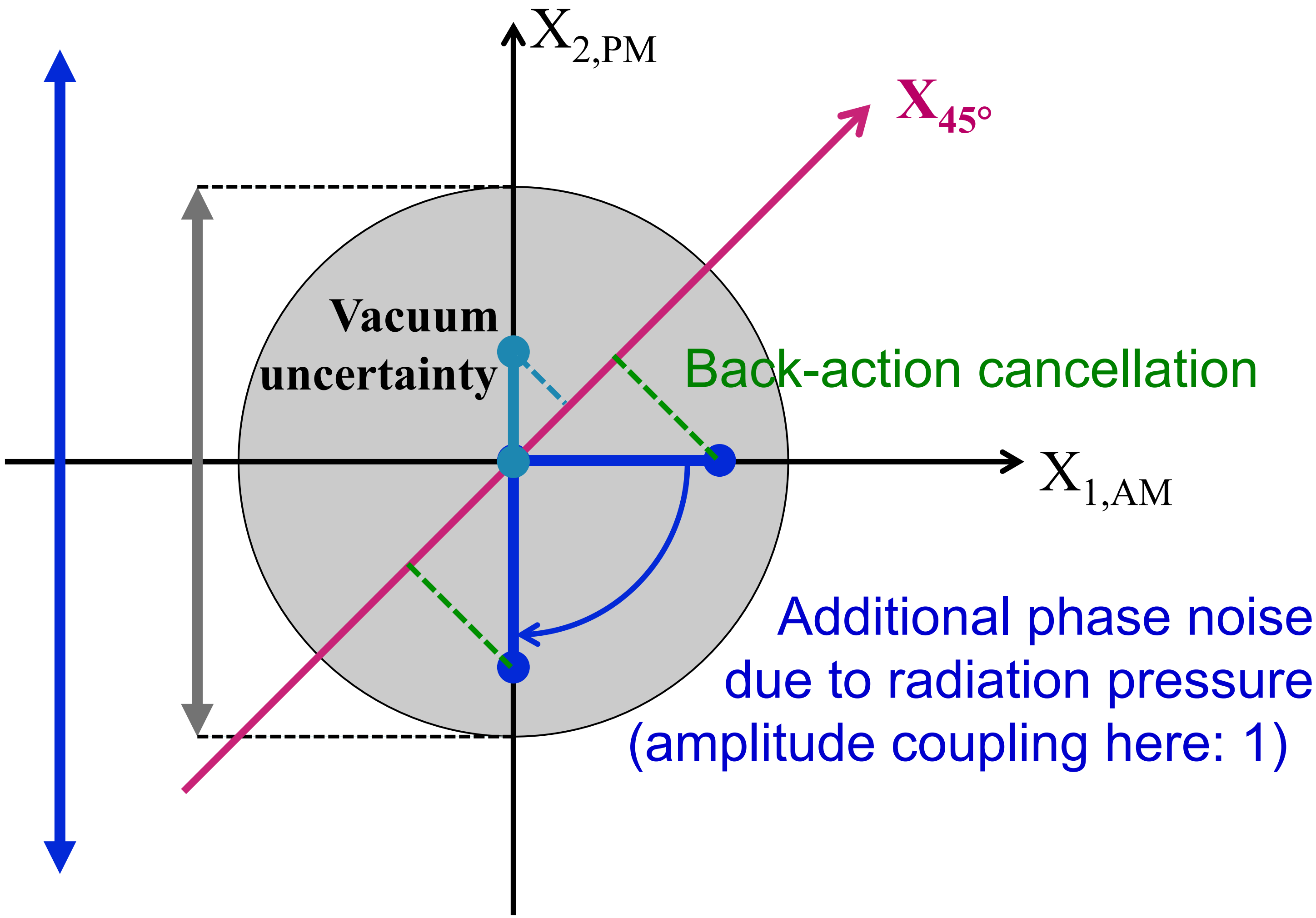
Optical quality of filters even more demanding!

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

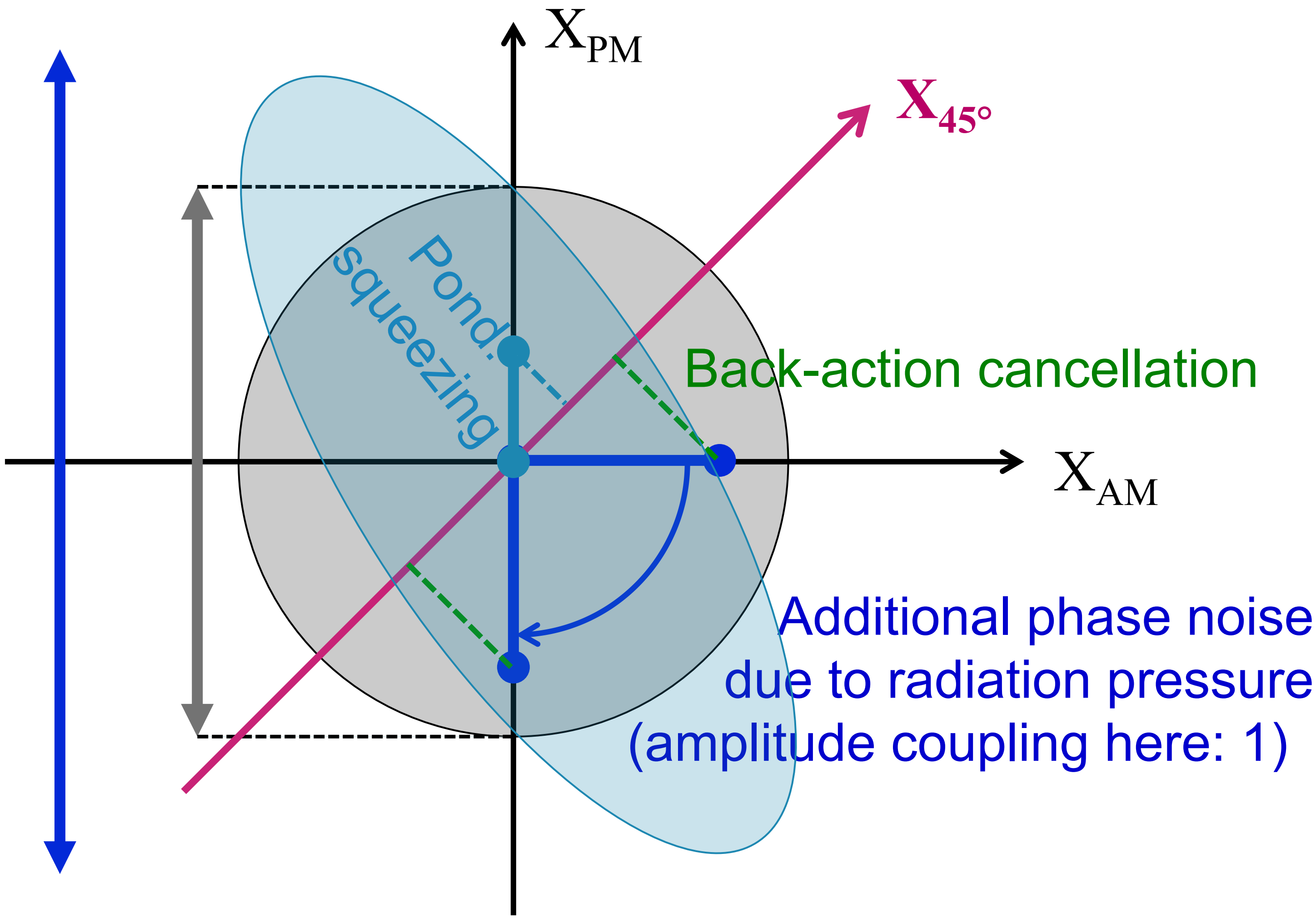
Squeezing and Full Evasion of RPN



Ponderomotive Squeezing



Ponderomotive Squeezing



Ponderomotive Squeezing

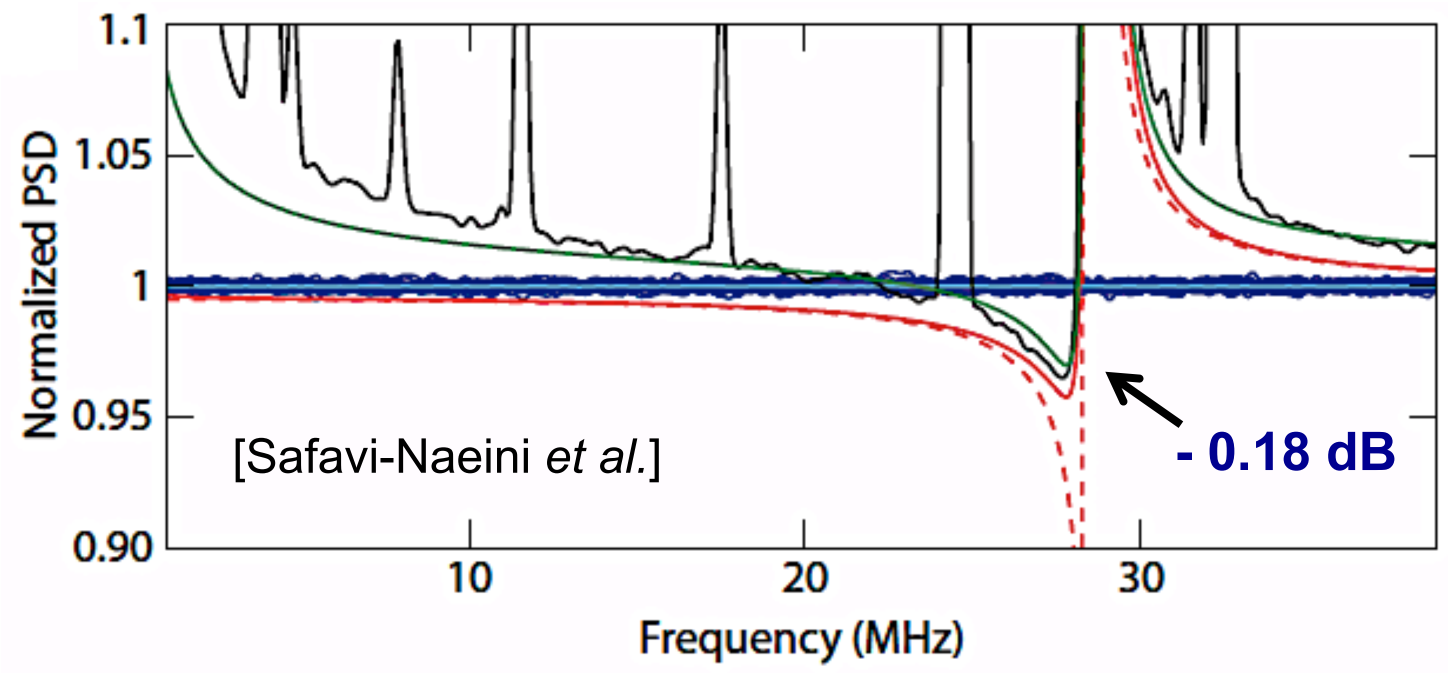
- Is of limited strength (requires an increasingly dominating RPN)
- Has a frequency dependent angle (and strength)
- Good to cancel back-action (less good as a squeezing source)

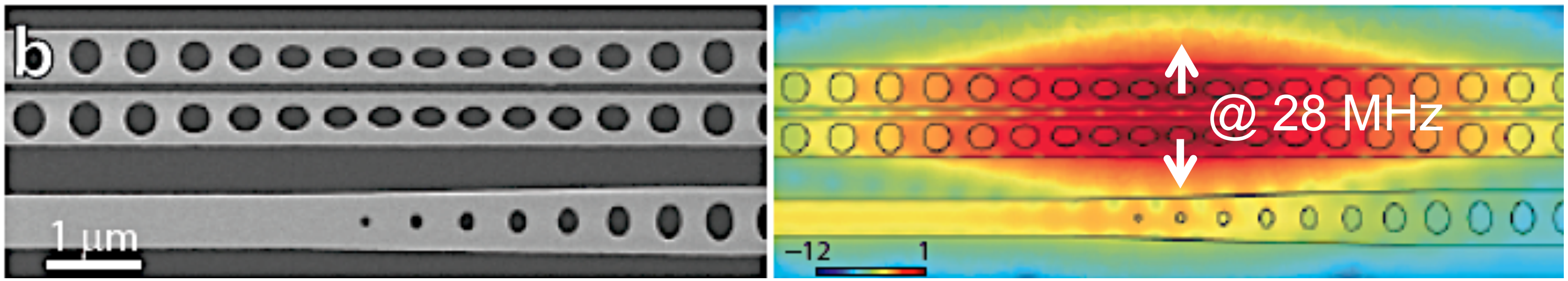
Recent experiments:

- Observation of radiation pressure noise on a membrane at NIST
  [T. P. Purdy, R. W. Peterson, C. A. Regal, Science **339**, 801 (2013)]

- Observation of ponderomotive squeezing at Caltech
  [A.H. Safavi-Naeini, S. Gröblacher, J.T. Hill, J. Chan, M. Aspelmeyer, O. Painter, arXiv:1302.6179]

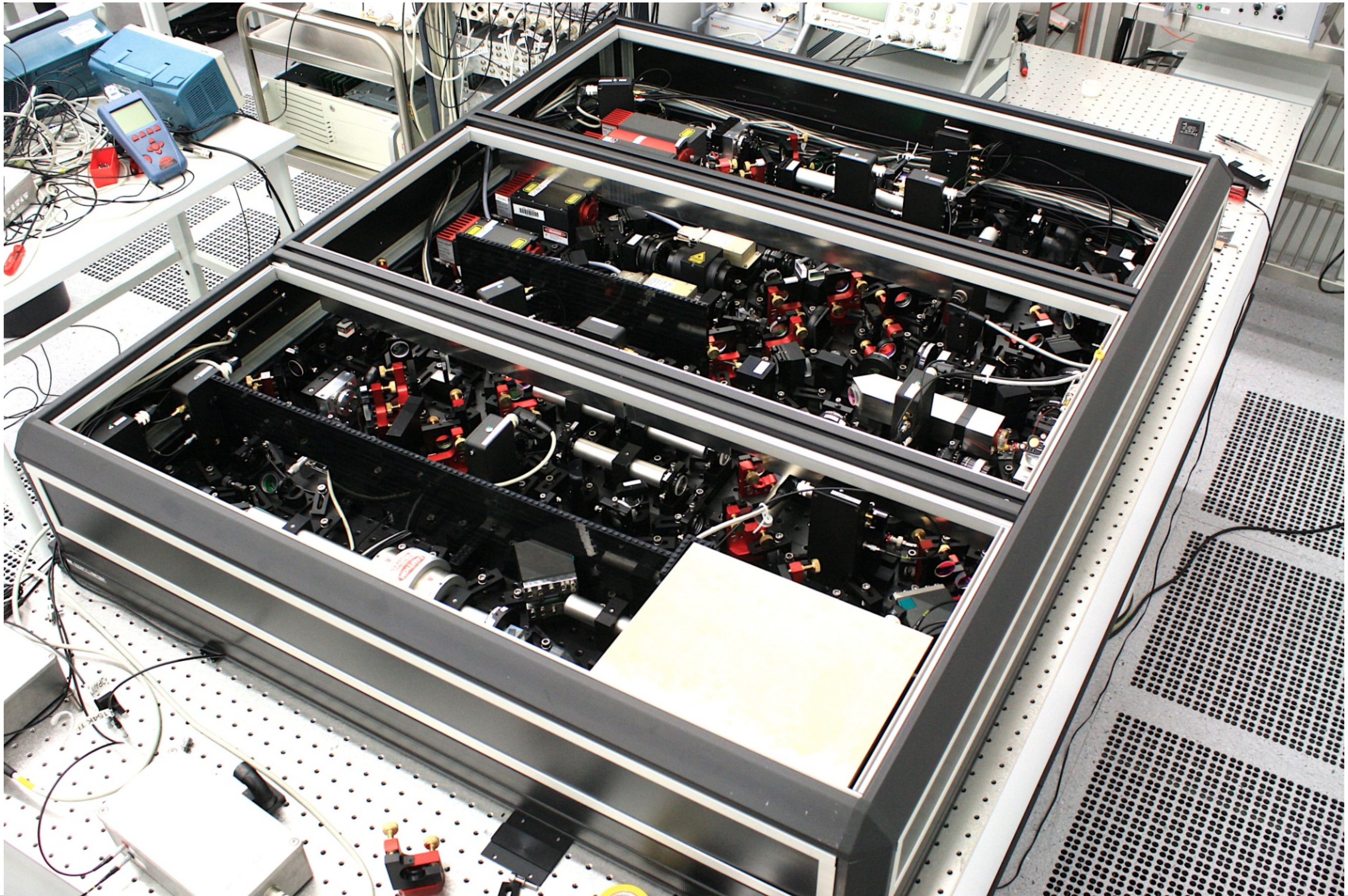
Ponderomotive Squeezing: Experiment



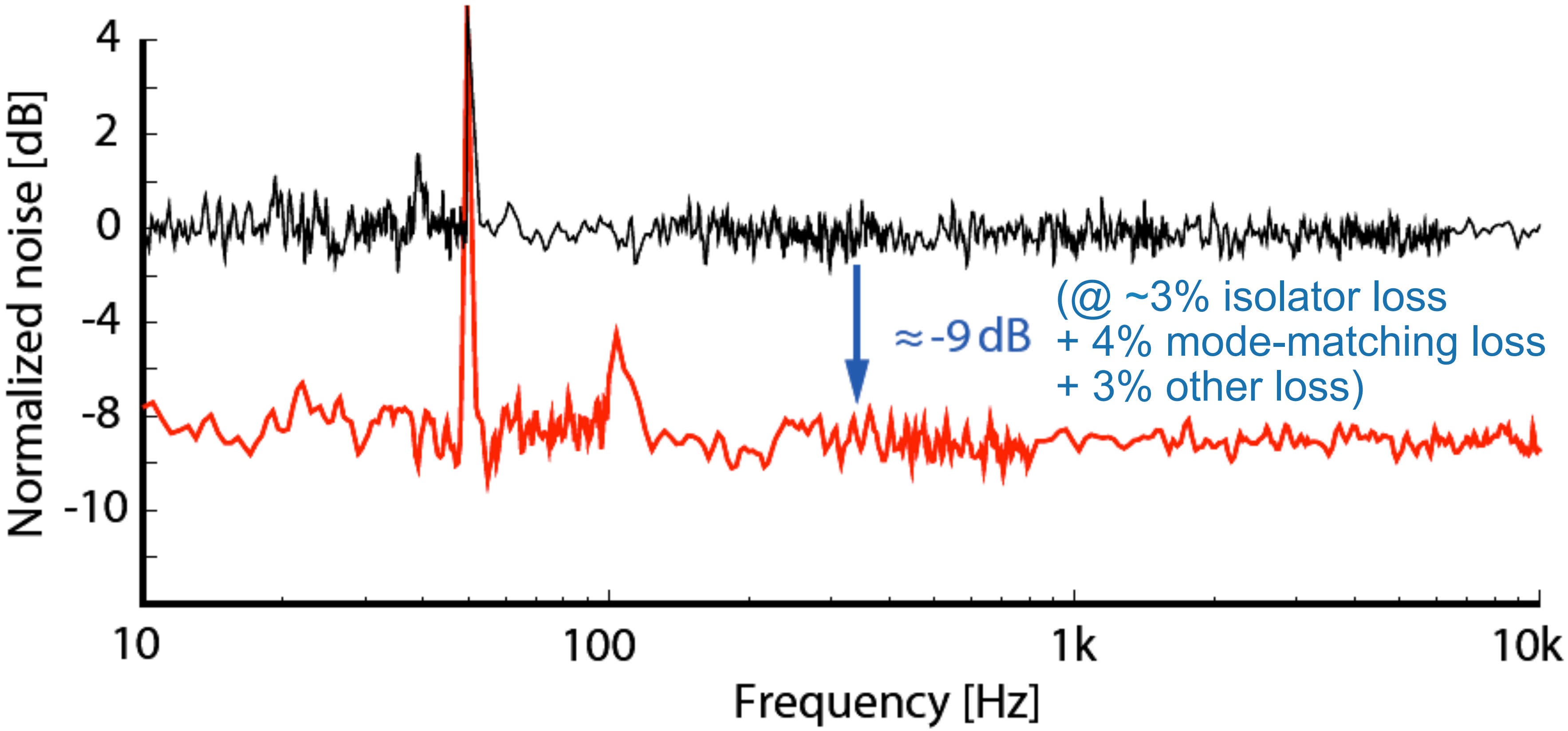


Waveguide coupled opto-mechanical cavity from Si, at 10 K

The GEO600 Squeezed Light Source

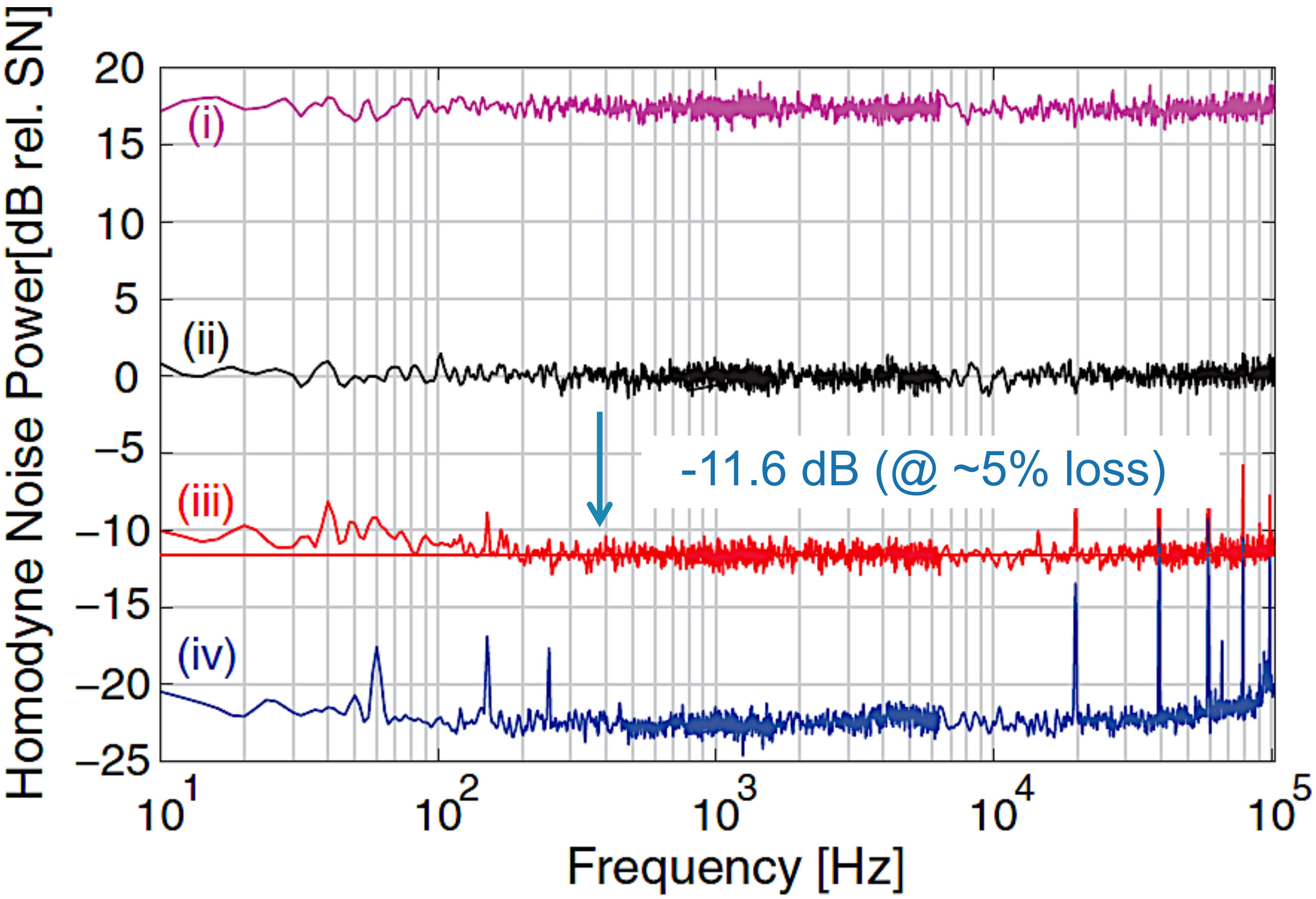


The GEO600 Squeezed Light Source



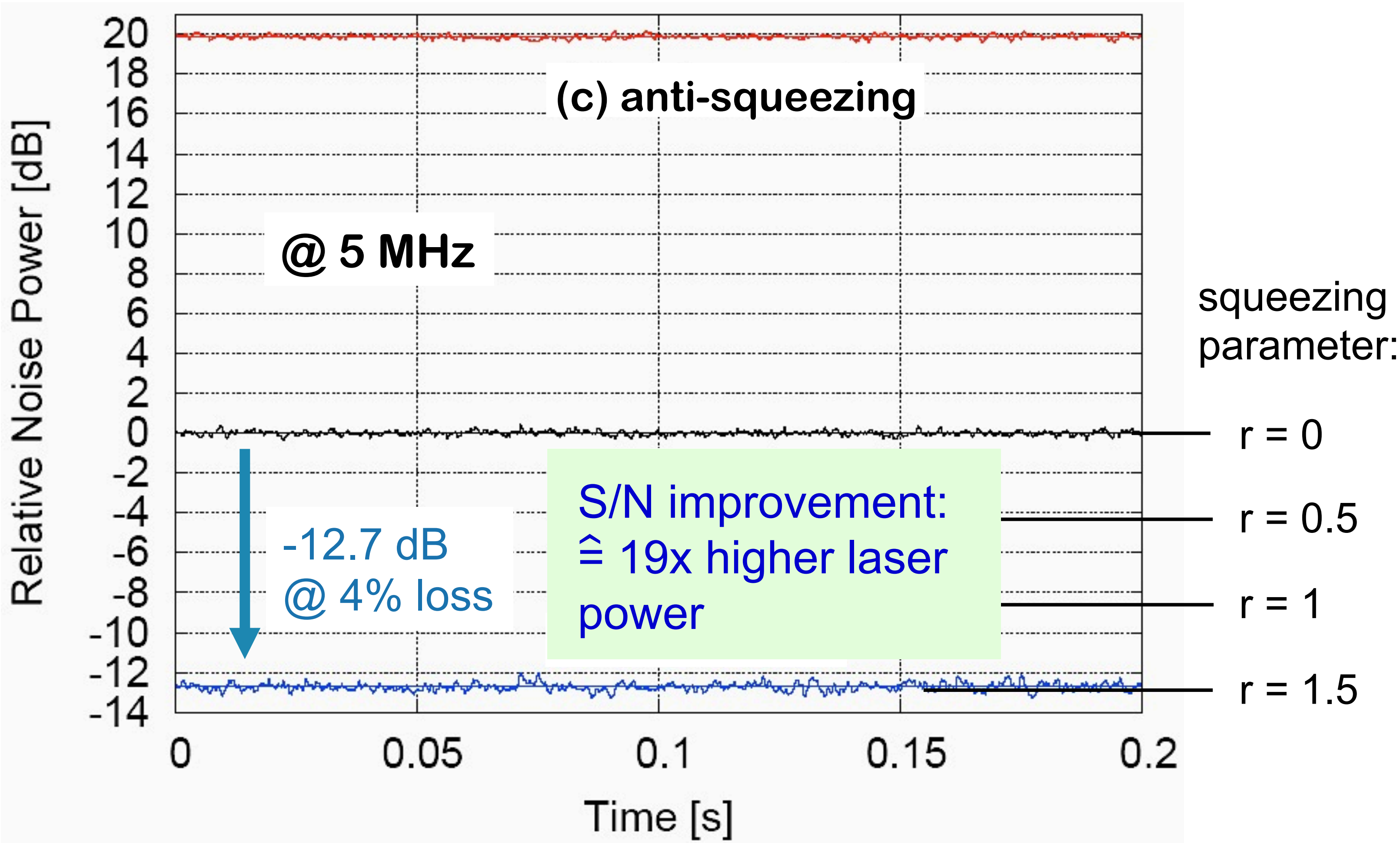
[H. Vahlbruch, A. Khalaidovski, N. Lastzka, C. Gräf, K. Danzmann, and R. Schnabel, *The GEO600 squeezed light source*, Class. Quantum Grav. **27,** 084027 (2010).]

ANU Squeezed Light Source



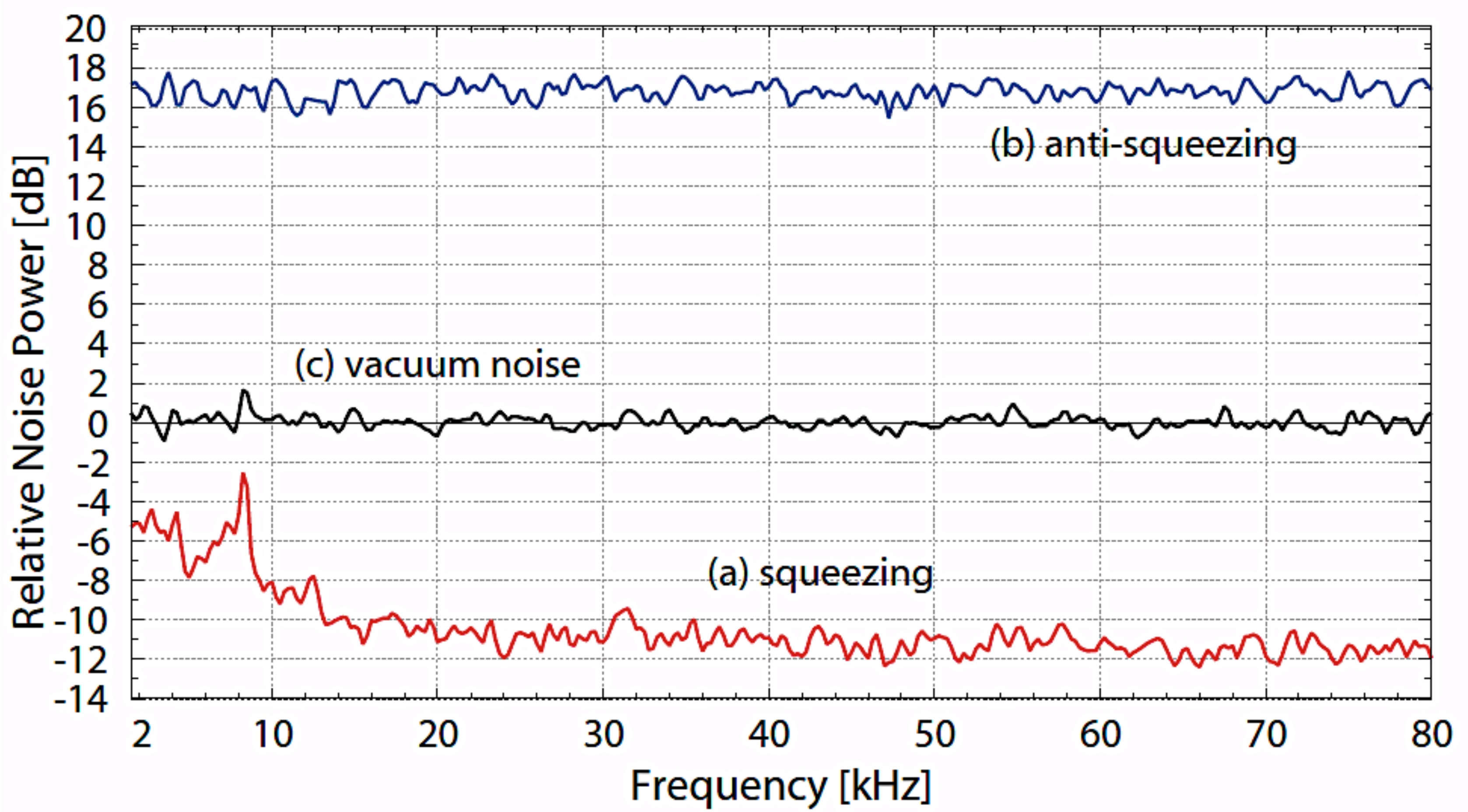
[M S Stefszky, C M Mow-Lowry, S S Y Chua, D A Shaddock, B C Buchler, H Vahlbruch, A Khalaidovski, R Schnabel, P K Lam, D E McClelland, CQG **29**, 145015 (2012)]

12.7 dB Squeezing @1064 nm



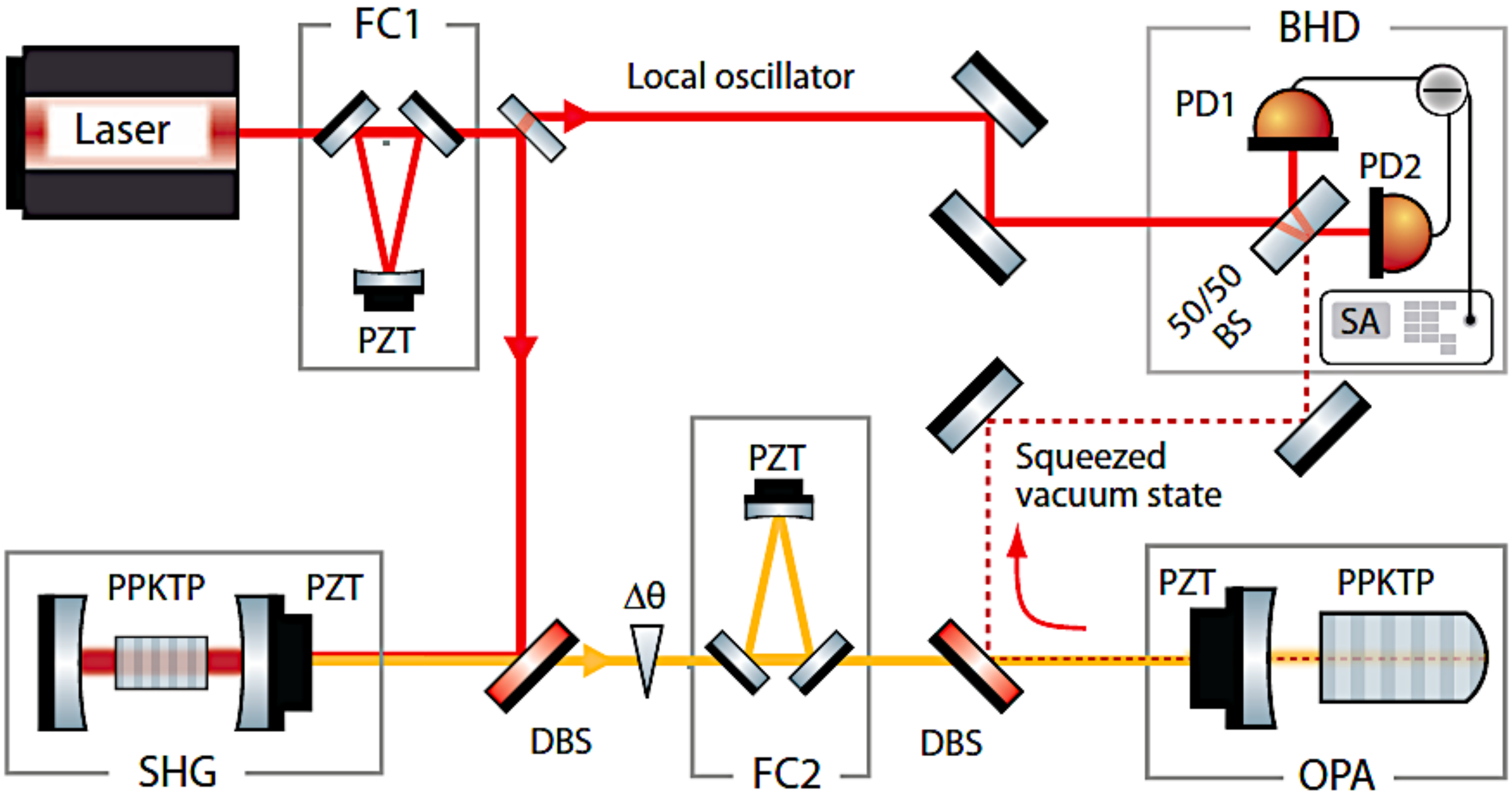
[T. Eberle *et al.*, PRL **104**, 251102 (2010)]

Squeezing Spectrum @1550 nm



[M. Mehmet *et al.*, Opt. Exp. **25**, 25763 (2011)]

Squeezed Light at 1064 nm / at 1550 nm



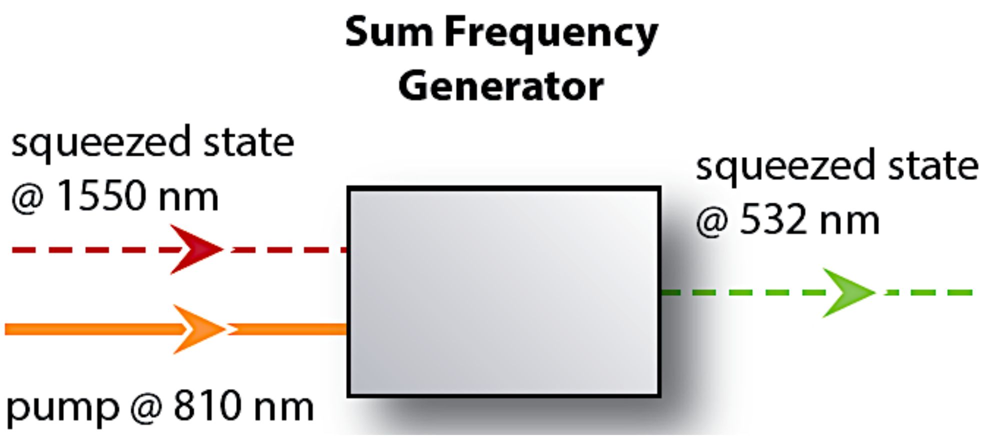
[M. Mehmet *et al.*, Opt. Exp. **25**, 25763 (2011)]

Squeezing Light at Visible Wavelengths

Strongly (audio-band) squeezed vacuum states at visible wavelengths have not yet been demonstrated.

Problems: The 2^{nd} harmonic (UV) pump field damages the crystal.
(The Kerr-effect requires a bright field having excess noise).

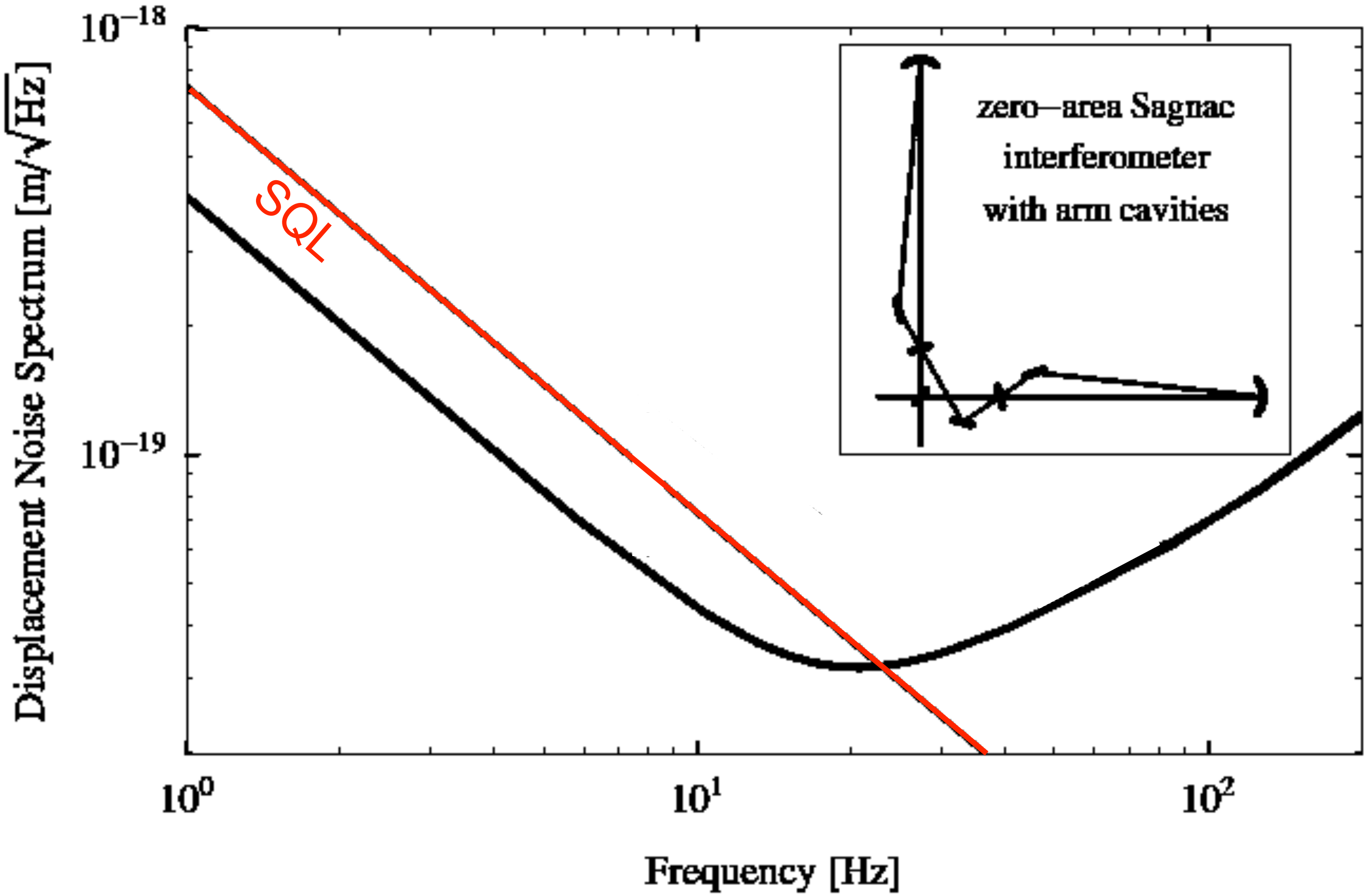
Solution: Up-conversion via sum frequency generation.



6 to 10 dB at visible wavelengths seem feasible.

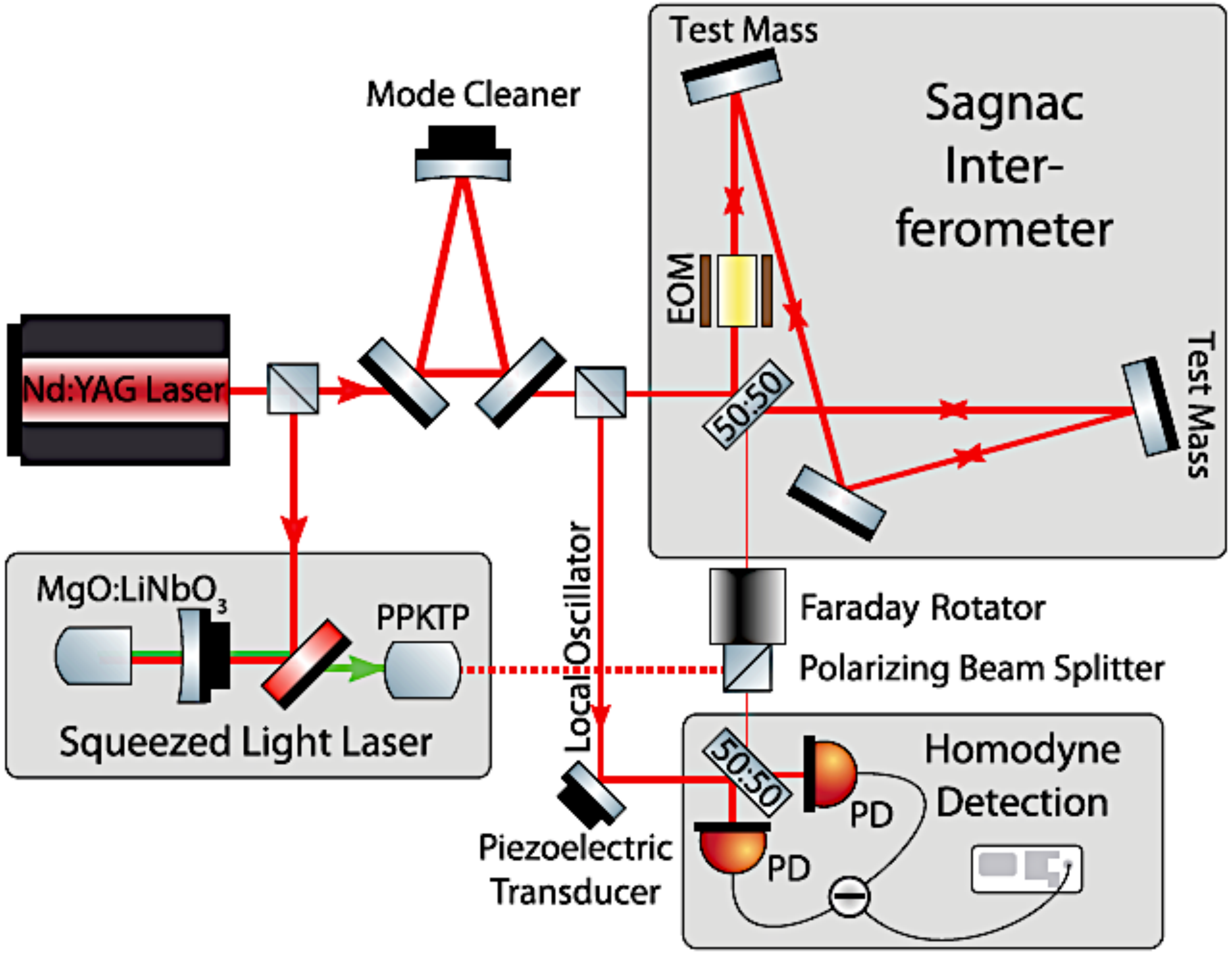
[C. Vollmer *et al.*, in preparation]

Evading RPN: Sagnac Interferometer



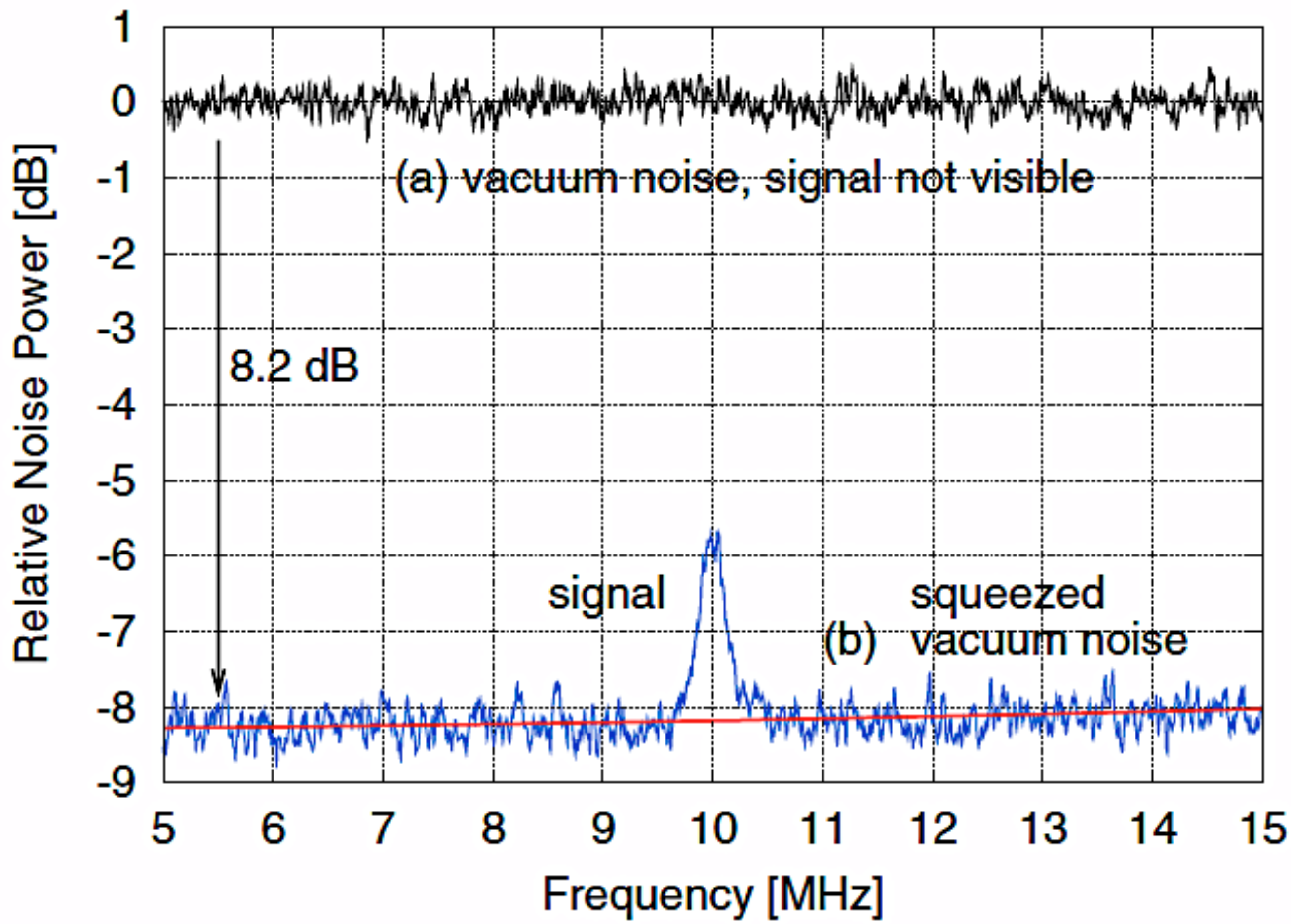
[Y. Chen, PRA **67**, 122004 (2003)]

Squeezed Light Enhanced Sagnac IFO



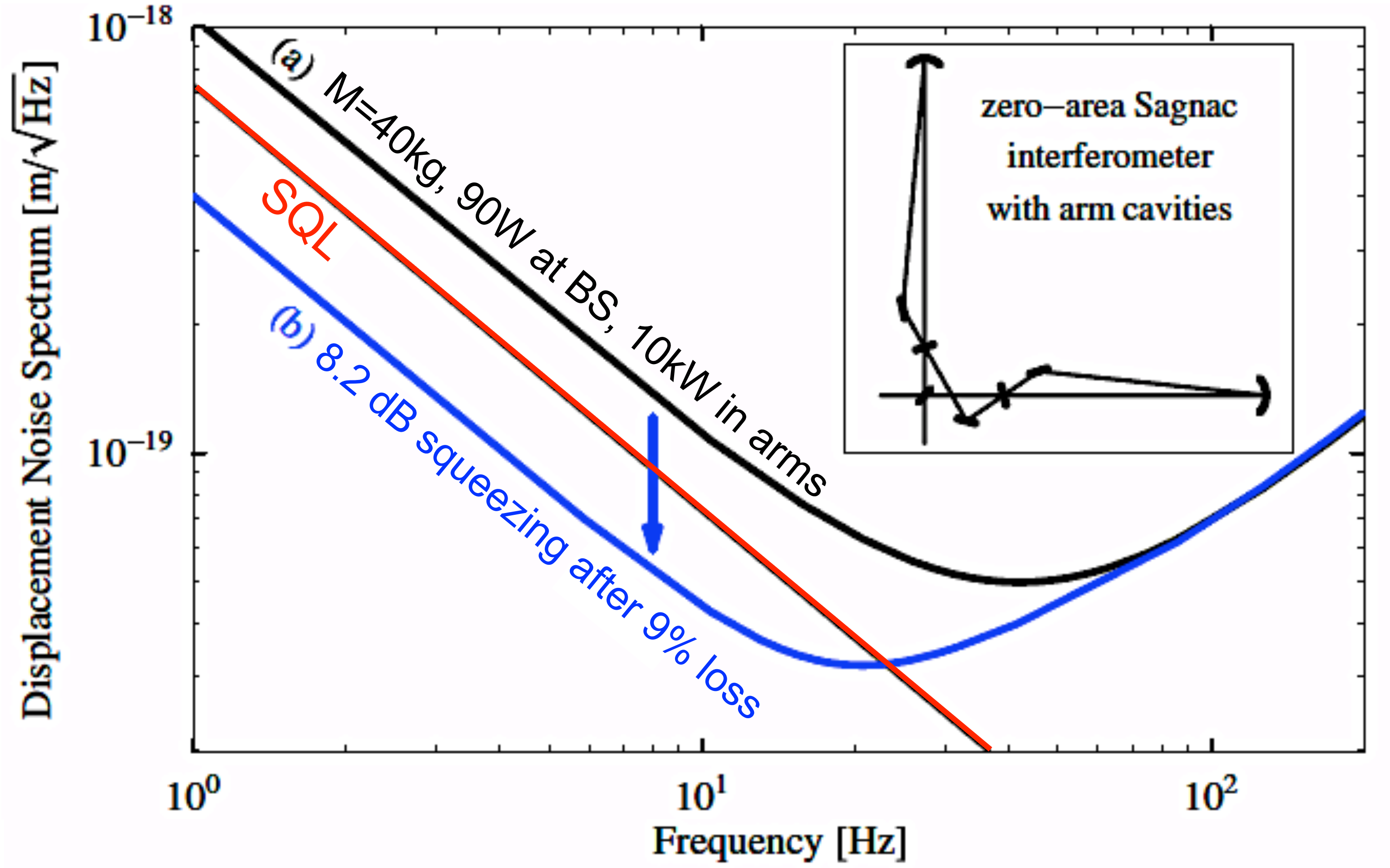
[T. Eberle *et al.*, PRL **104**, 251102 (2010)]

Squeezed Light Enhanced Sagnac IFO



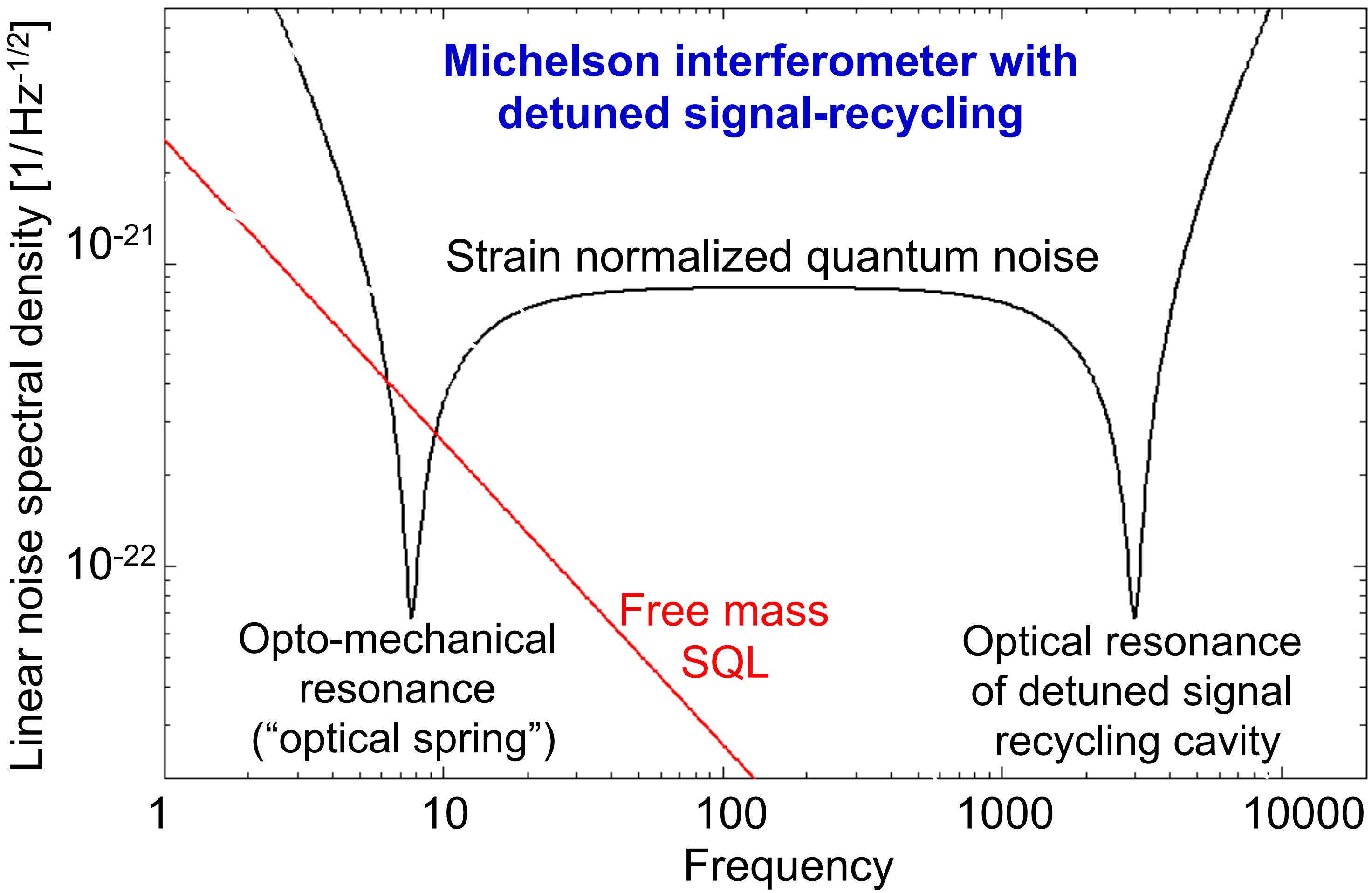
[T. Eberle *et al.*, PRL **104**, 251102 (2010)]

Squeezed Light Enhanced Sagnac IFO



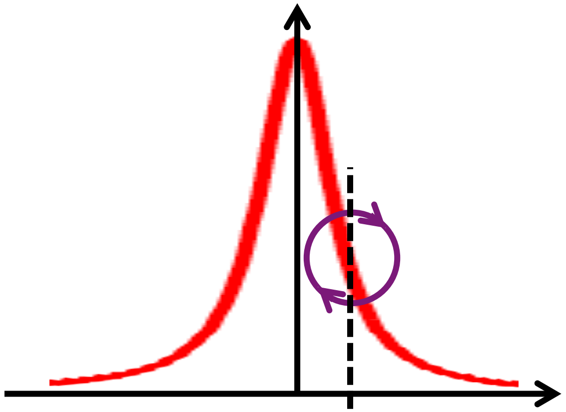
[T. Eberle S. Steinlechner, J. Bauchrowitz, V. Händchen, H. Vahlbruch, M. Mehmet, H. Müller-Ebhardt, R. Schnabel, PRL **104**, 251102 (2010)]

Dynamical Back-Action: Optical Spring



[A. Buonanno and Y. Chen, Phys. Rev. D 65, 042001 (2002)]

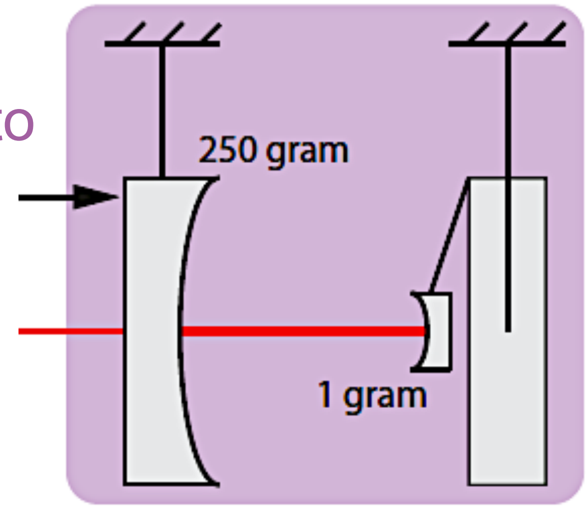
Dynamical Back-Action – Optical Spring

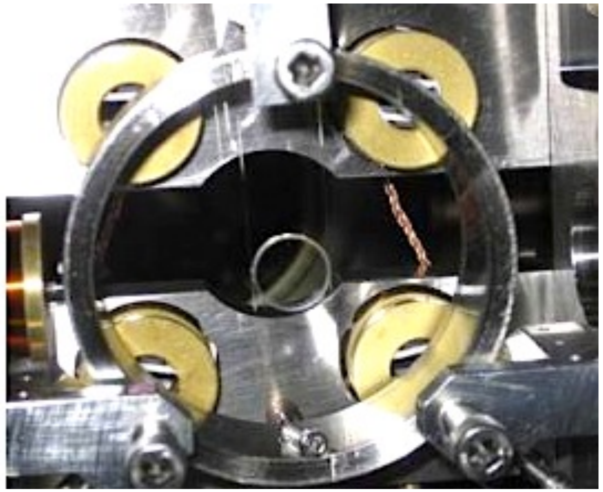


[B. S. Sheard, M. B. Gray, C. M. Mow-Lowry, D. E. McClelland, S. E. Whitcomb, Phys. Rev. A, 69, 051801 (2004)]

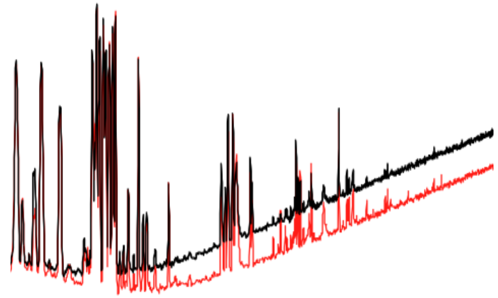
[T. Corbitt, C. Wipf, T. Bodiya, D. Ottaway, D. Sigg, N. Smith, S. E. Whitcomb, N. Mavalvala, Phys. Rev. Lett. 99, 160801 (2007)]

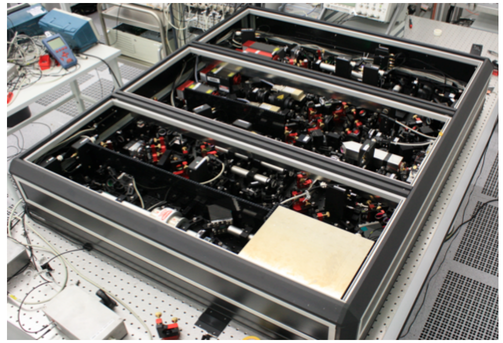
Feedback required to control instability

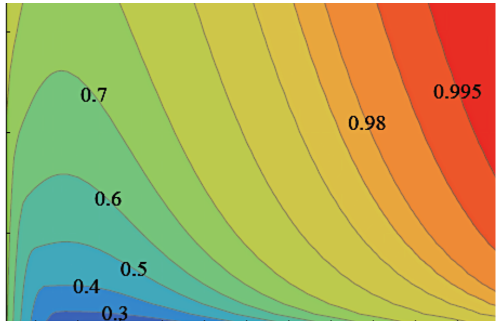




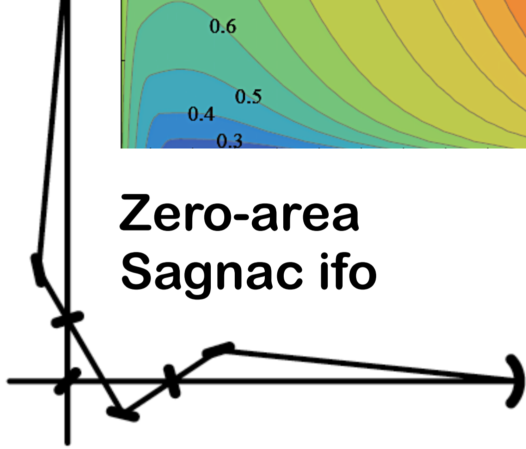
Summary







- The combination of intense coherent light and squeezed vacuum is and will remain the optimum quantum approach for GW detectors
- Quantum radiation pressure effects have recently been observed in micro-mechanical setups
- “Its time to experimentally explore back-action evading techniques and also the potential of dynamical back-action”



Zero-area Sagnac ifo

DFG SFB TR7

Light Sources and Interferometer Topologies

15:50	R. Schnabel	Introduction to the Session
16:30	S. Hild	Sagnac Interferometer for GW Detection
16:55	S. Danilishin	Broadband Sagnac Interferometer with short Filter Cavities
17:20	M. Wang	A polarizing Sagnac topology with DC readout for future GW detectors
17:45 *Break*		
18:15	S. Tarabrin	Anomalous Dynamical Back-Action in Michelson Interferometer
18:40	N. Gordon	Multiple optical springs in coupled resonator system