SQUEEZED LIGHT -

YESTERDAY – TODAY – TOMORROW

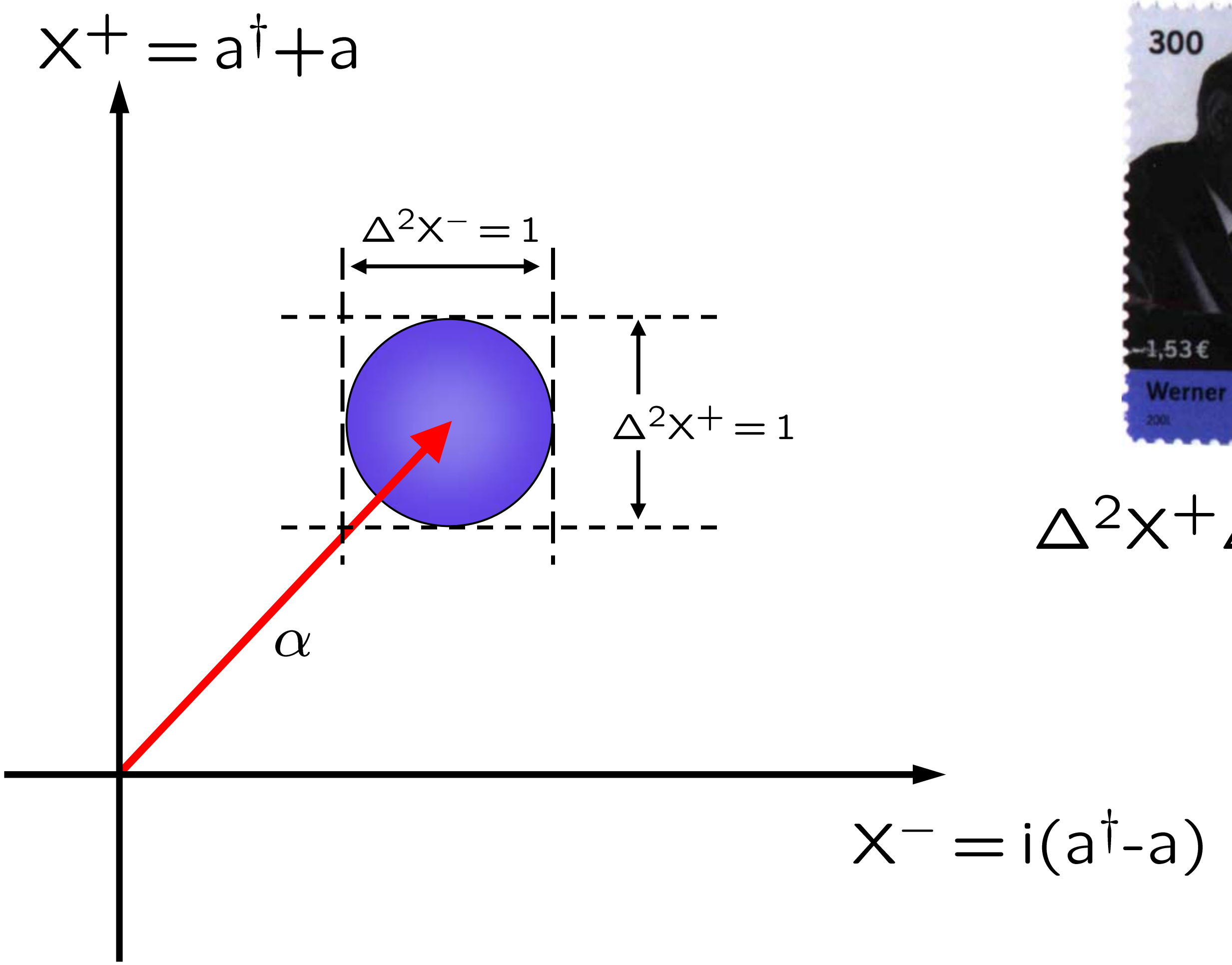
Alexander Khalaidovski for the AEI squeezing group (R. Schnabel)

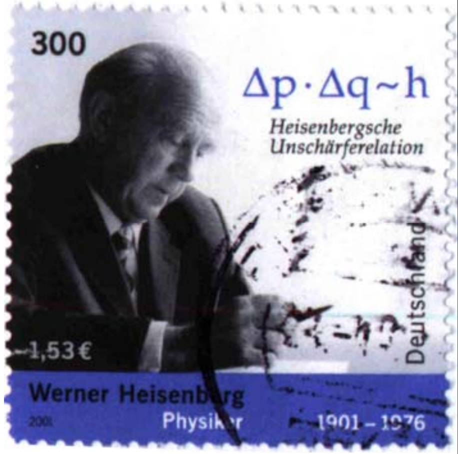
AEI Hannover

OUTLINE

- SQUEEZING? WHAT'S THAT?
- HOW CAN IT HELP US?
- „HISTORICAL" RESULTS
- RECENT AND ONGOING WORK
- OUTLOOK – FUTURE POSSIBILITIES

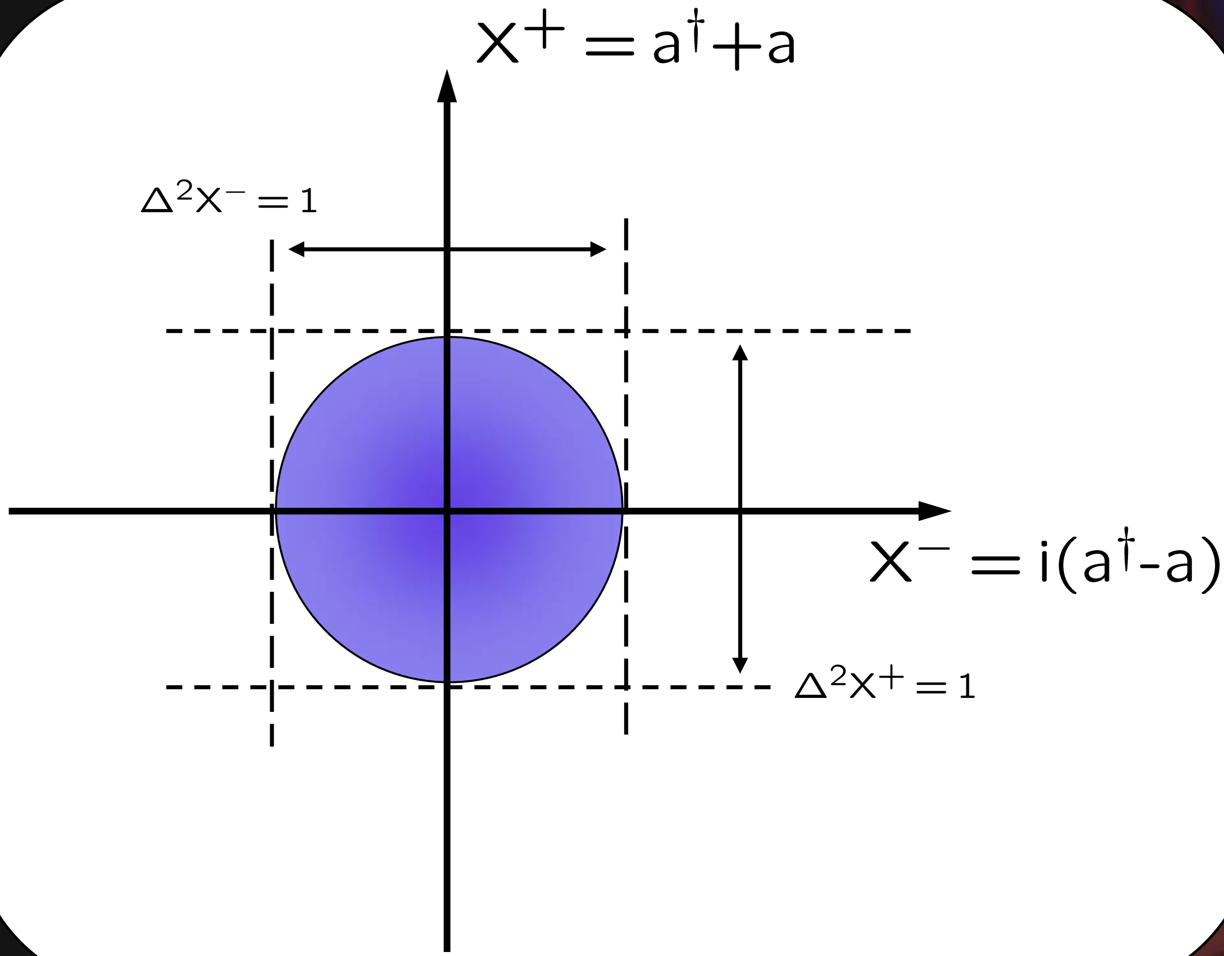
COHERENT STATE





$$\Delta^2 X^+ \Delta^2 X^- \geq 1$$

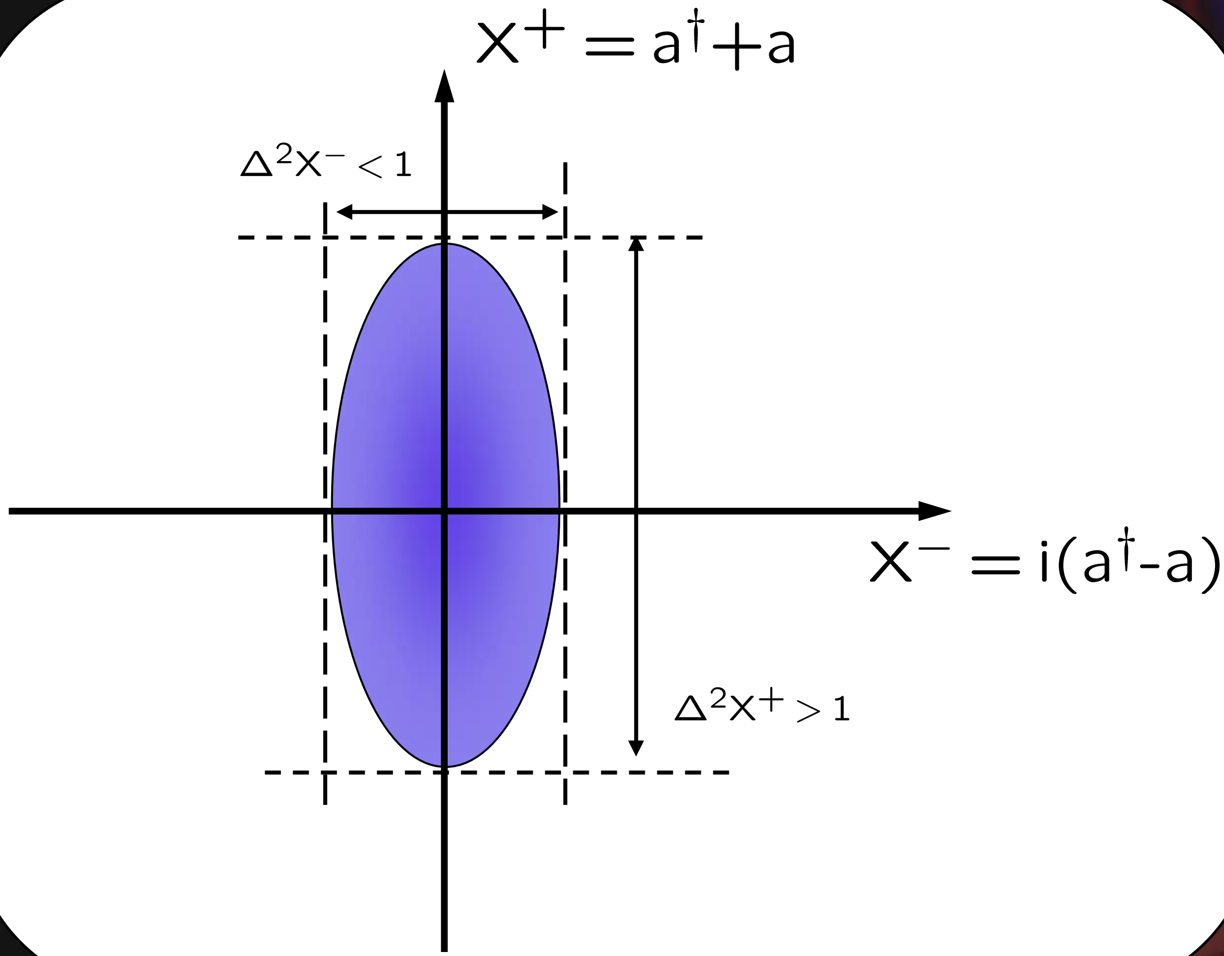
VACUUM STATE



$$\Delta^2 X^+ \Delta^2 X^- \geq 1$$

$$< n > = 0$$

SQUEEZED VACUUM STATE

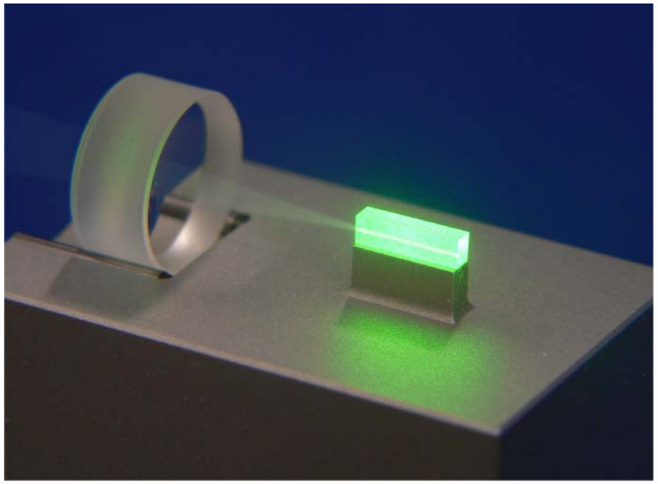


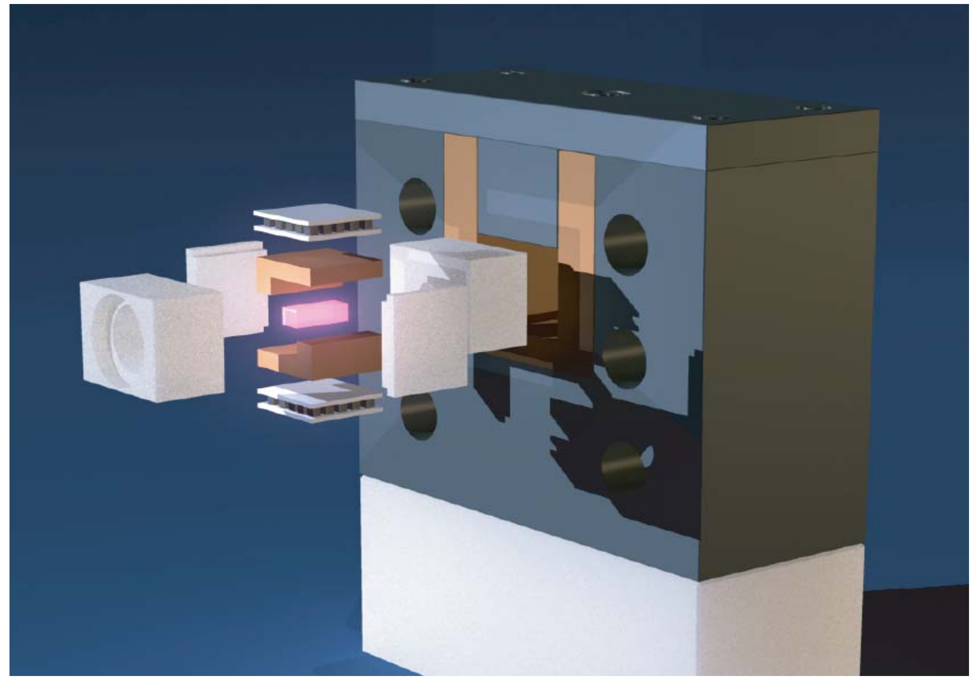
$$\Delta^2 X^+ \Delta^2 X^- \geq 1$$

$$< n > \neq 0$$

EXPERIMENTAL GENERATION

BASED ON OPTICAL PARAMETRIC AMPLIFICATION (OPA)





χ_2- nonlinear crystal

(7% MgO: $LiNbO_3$ / PPKTP)

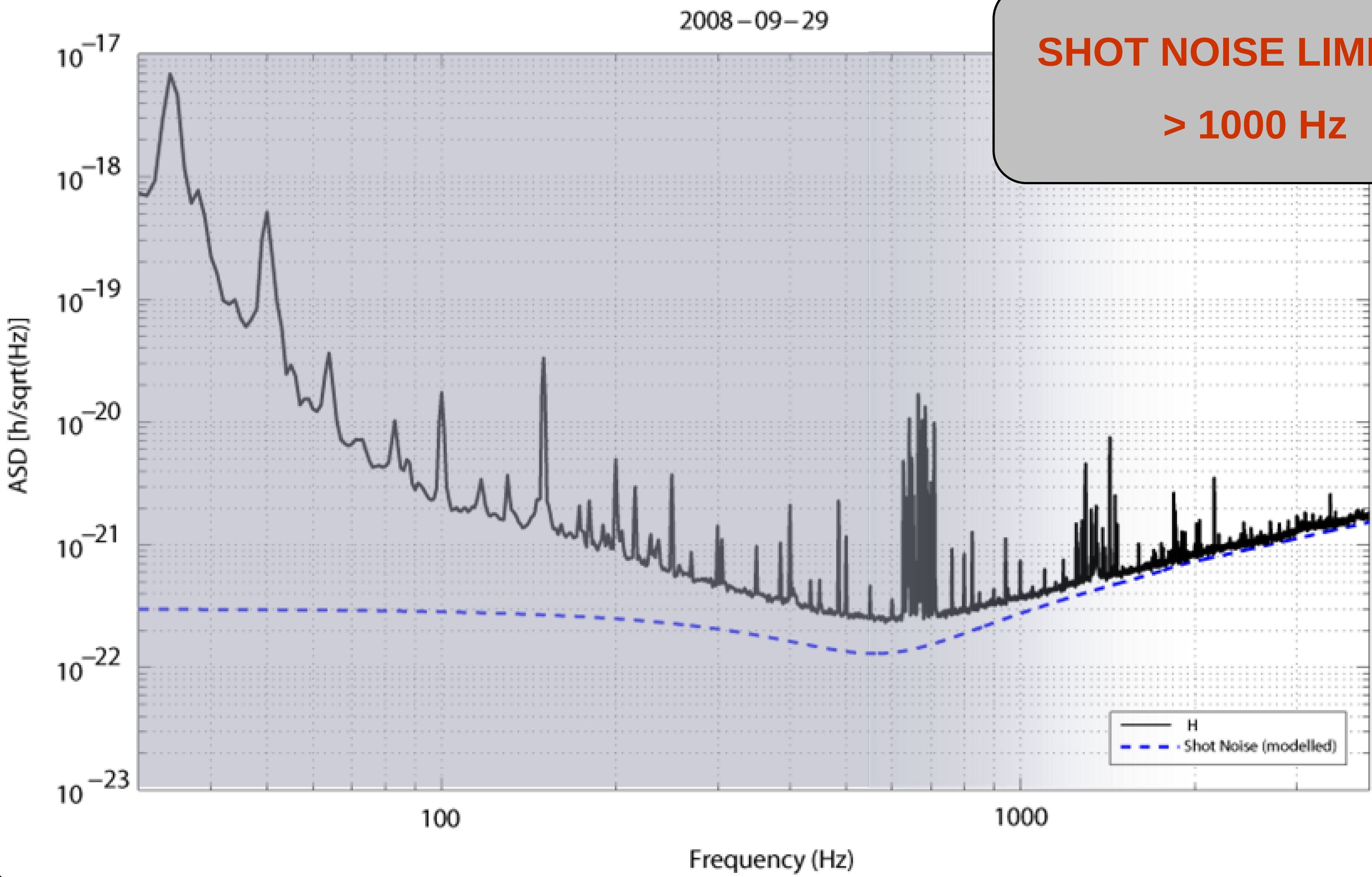
in standing wave cavity

pump field: cw, 532 nm

squeezed field: cw, 1064 nm

IMPLEMENTATION IN GRAVITATIONAL WAVE DETECTORS

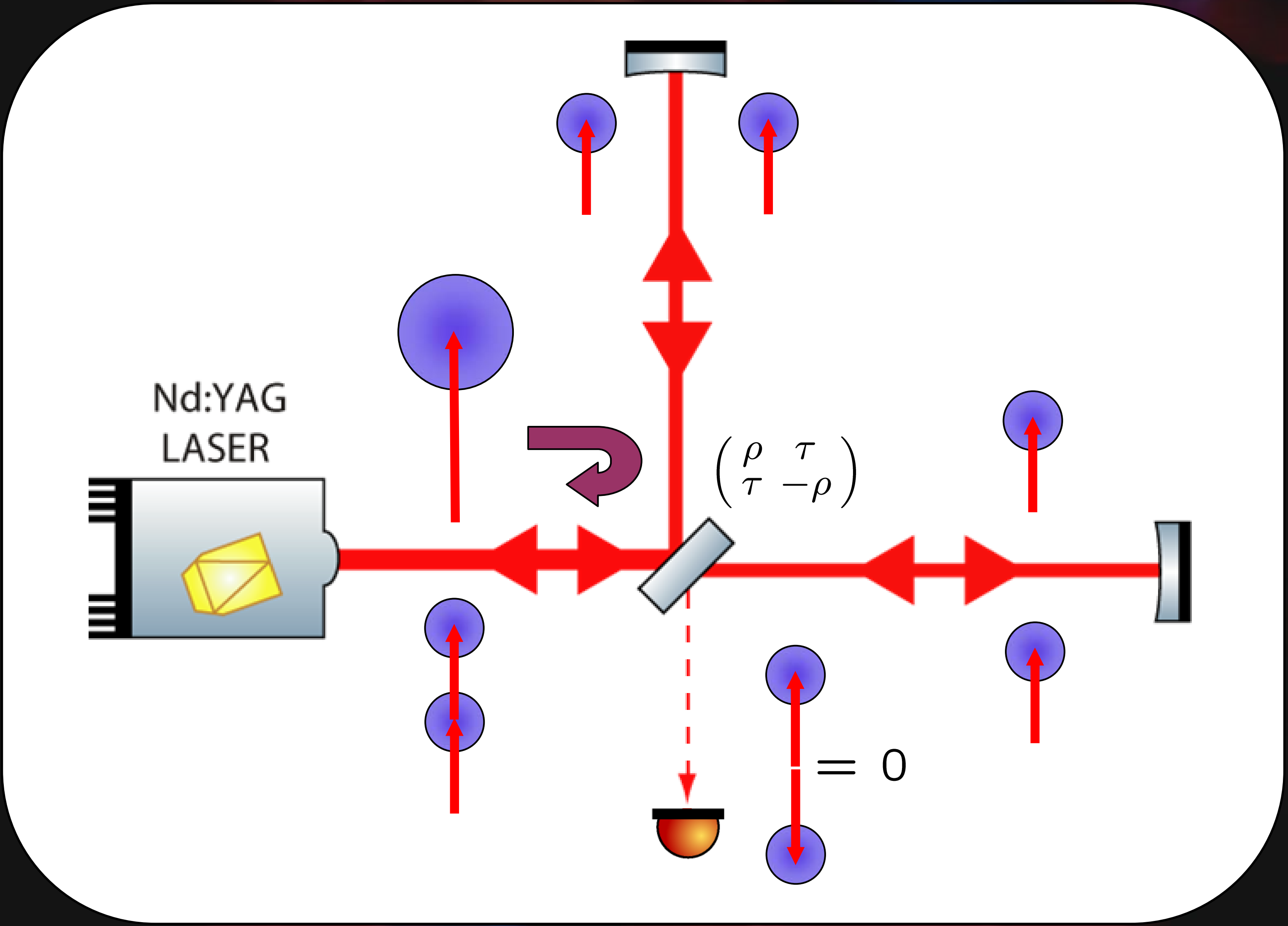
GEO 600 SENSITIVITY



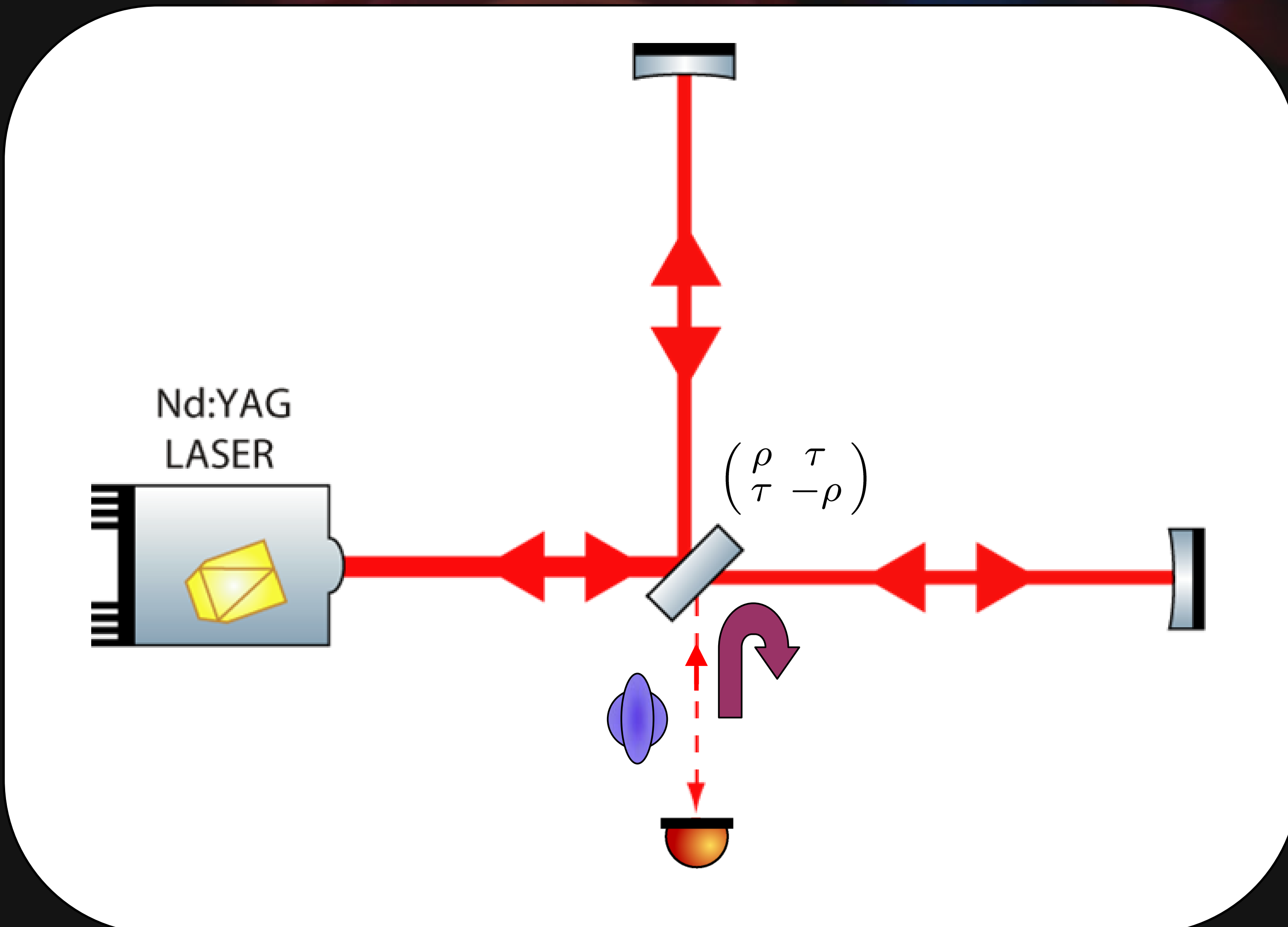
SHOT NOISE LIMITED

> 1000 Hz

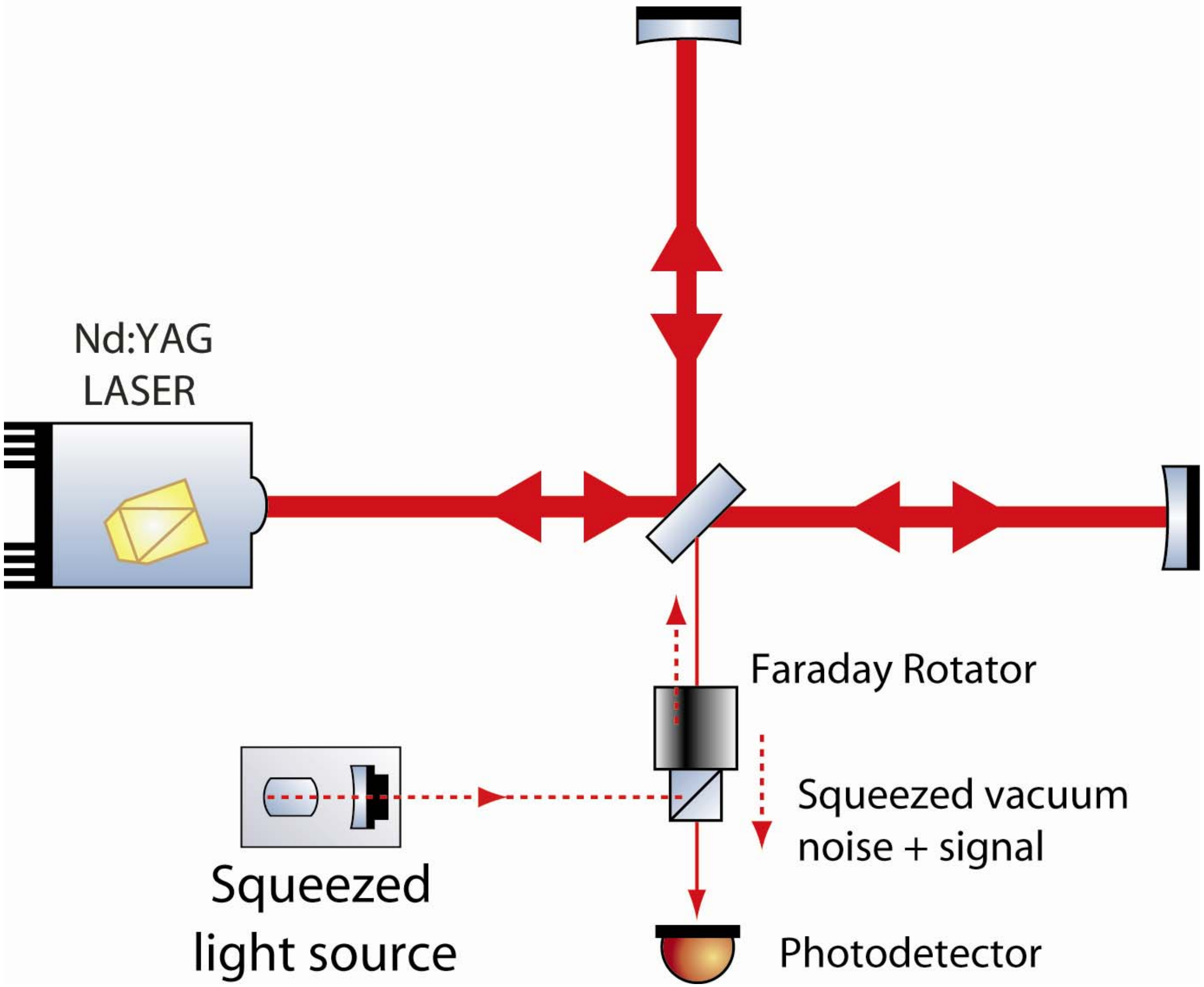
SHOT NOISE (DARK FRINGE OPERATION)



SHOT NOISE (DARK FRINGE OPERATION)



SQUEEZED INPUT



28 YEARS OF PREPARATION

1981 - FIRST PROPOSAL

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.

1985 - FIRST SQUEEZING RESULTS

VOLUME 55, NUMBER 22 PHYSICAL REVIEW LETTERS 25 NOVEMBER 1985

Observation of Squeezed States Generated by Four-Wave Mixing in an Optical Cavity

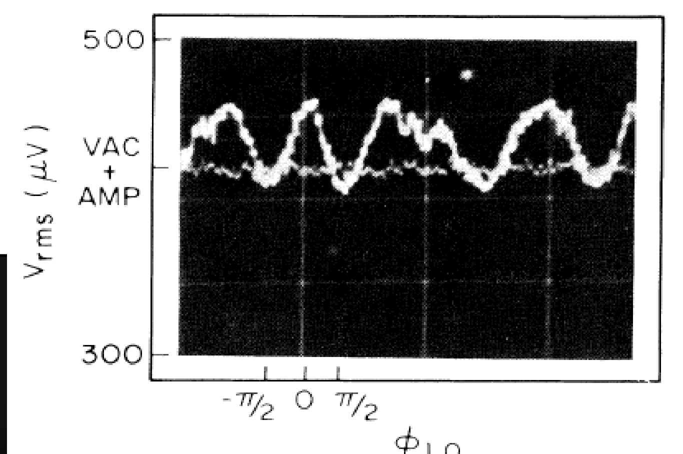
R. E. Slusher
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

L. W. Hollberg
AT&T Bell Laboratories, Holmdel, New Jersey 07733

and

B. Yurke, J. C. Mertz, and J. F. Valley[a]
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
(Received 27 August 1985)

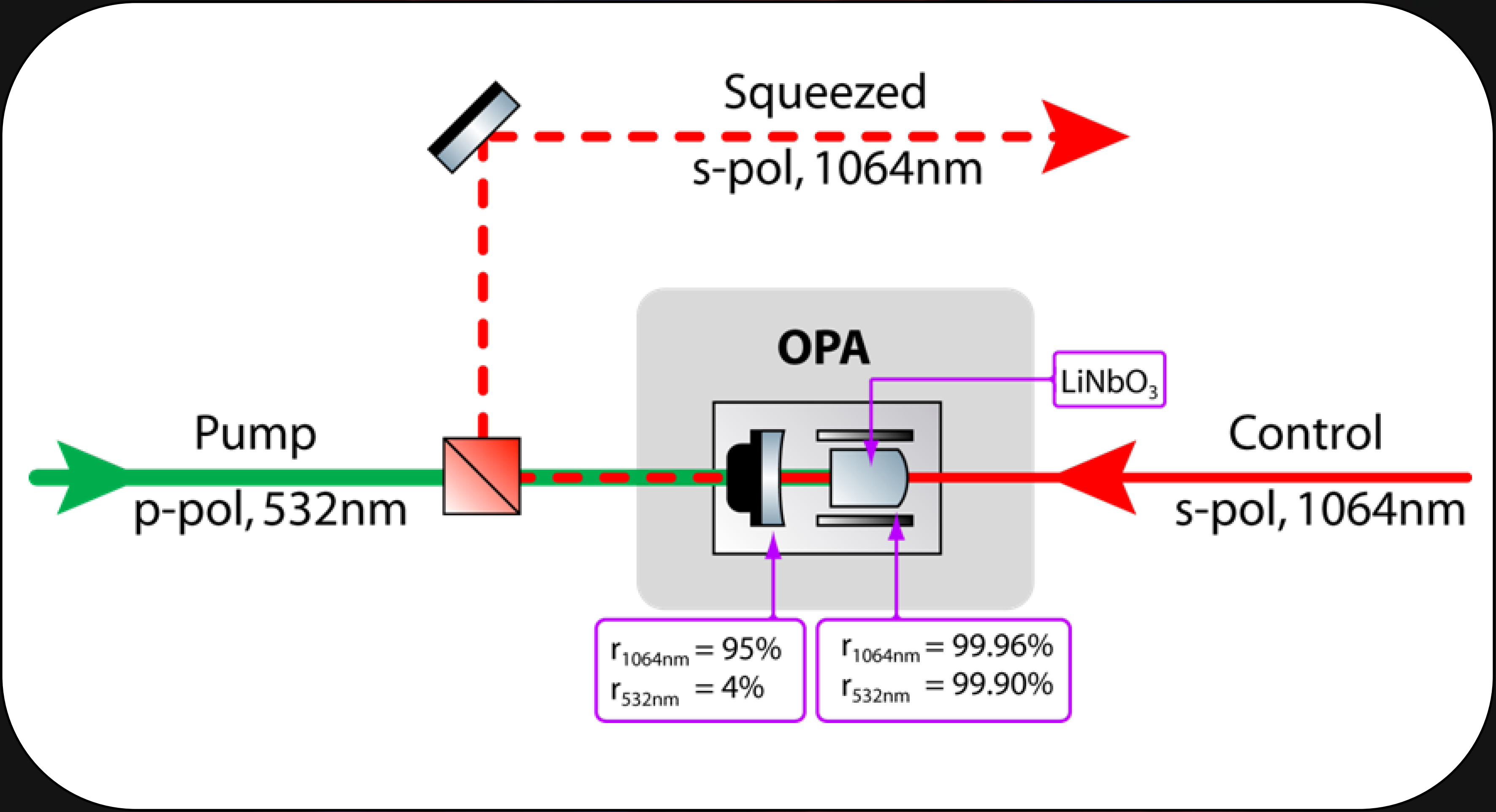
Squeezed states of the electromagnetic field have been generated by nondegenerate four-wave
The optical noise in the cavity, comprised of primarily
of spontaneous emission from the pumped Na atoms,
field and deamplified in the other quadrature. These
balanced homodyne detector. The total noise level in
acuum noise level.



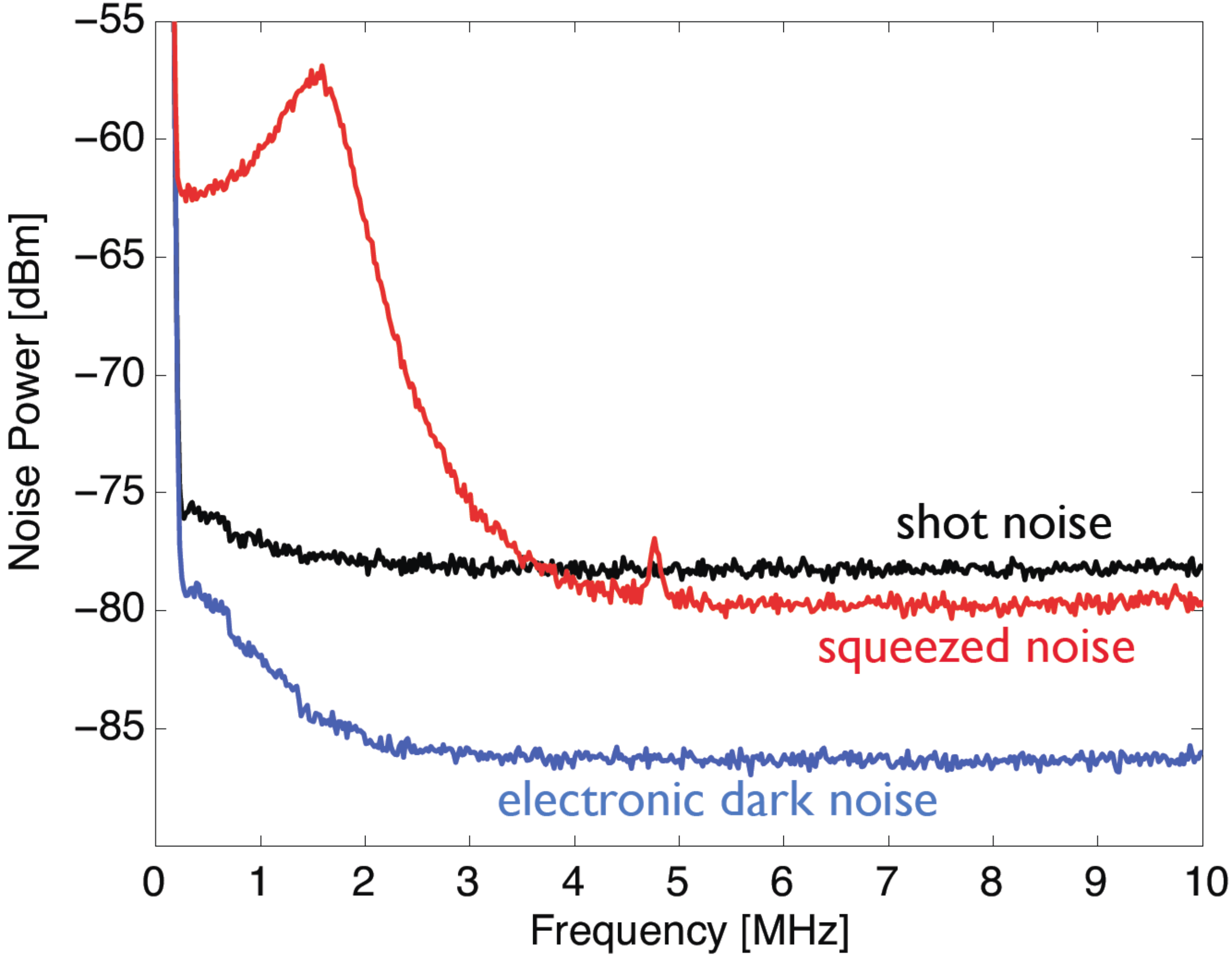
REQUIREMENTS

- SQUEEZING IN GW DETECTION BAND
  (10 Hz – 10 kHz)
- STABLE CONTROL SCHEME
  (allowing for long-term, independent operation)
- STRONG SQUEEZING

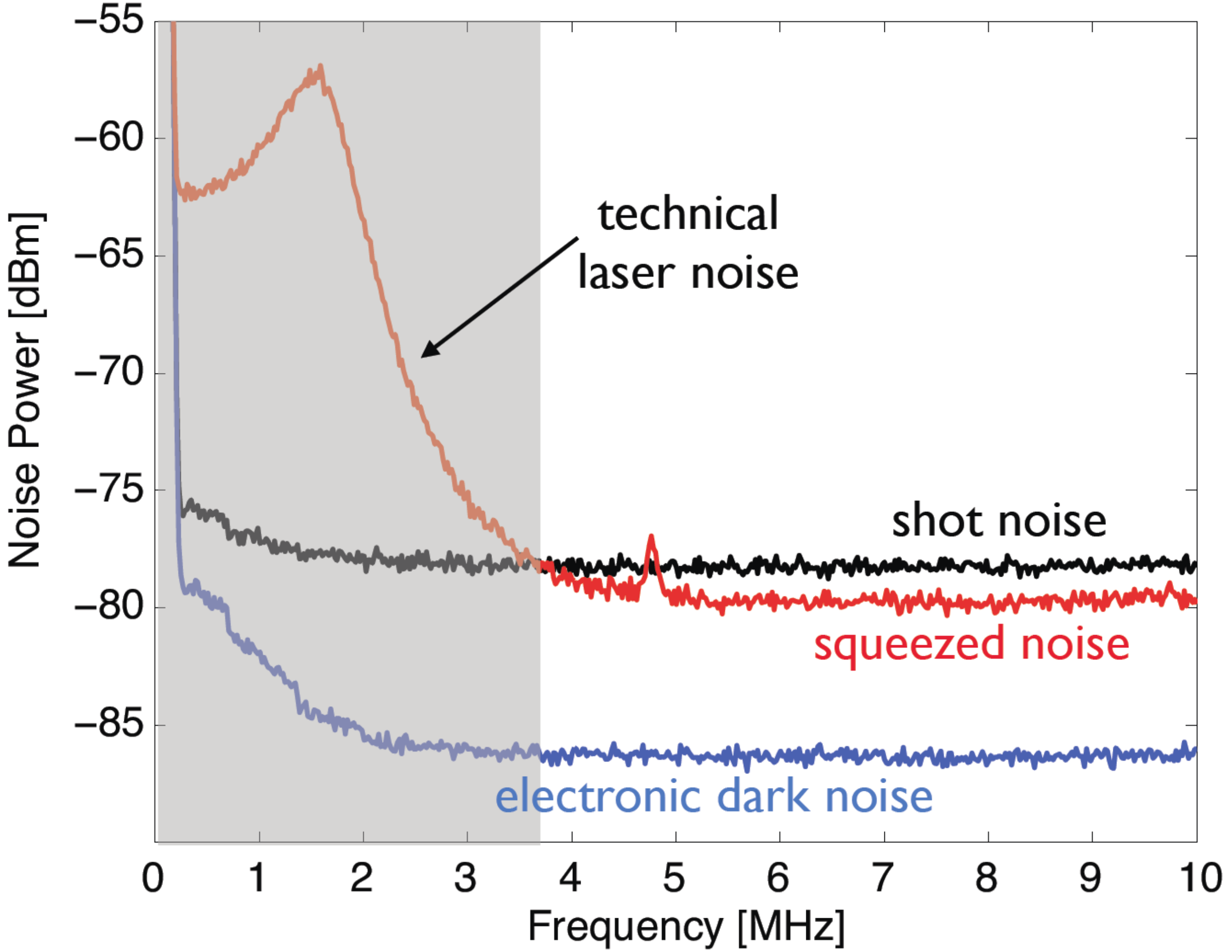
OLD EXPERIMENTAL APPROACH



RF SQUEEZING



RF SQUEEZING II



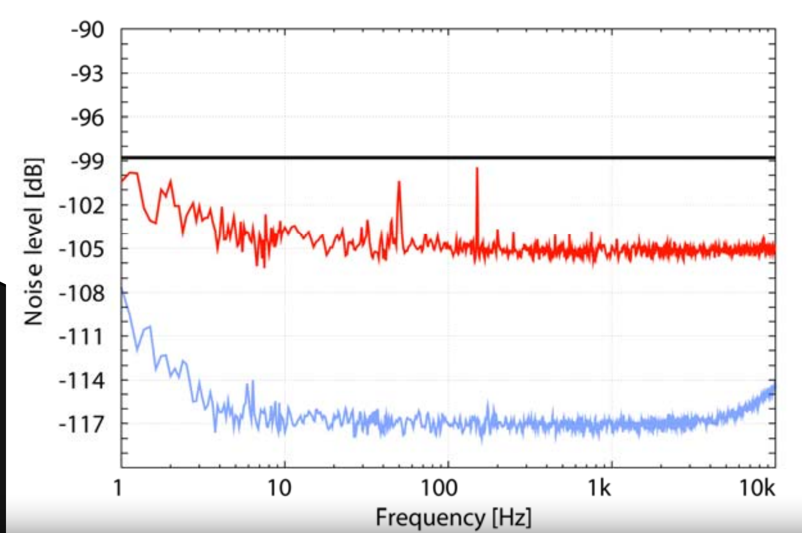
COHERENT CONTROL SCHEME

PRL 97, 011101 (2006) PHYSICAL REVIEW LETTERS week ending 7 JULY 2006

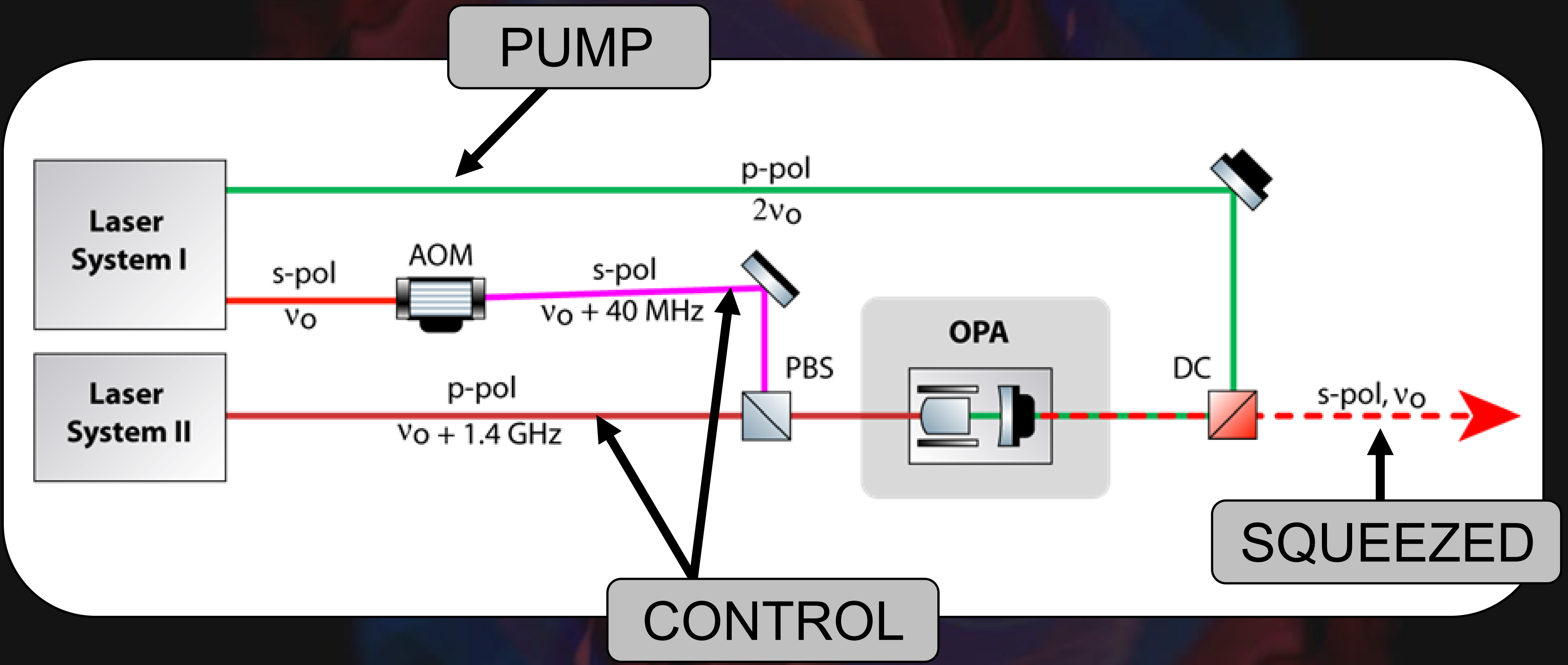
Coherent Control of Vacuum Squeezing in the Gravitational-Wave Detection Band

Henning Vahlbruch, Simon Chelkowski, Boris Hage, Alexander Franzen, Karsten Danzmann, and Roman Schnabel
Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Institut für Gravitationsphysik, Universität Hannover, Callinstraße 38, 30167 Hannover, Germany
(Received 5 April 2006; published 6 July 2006)

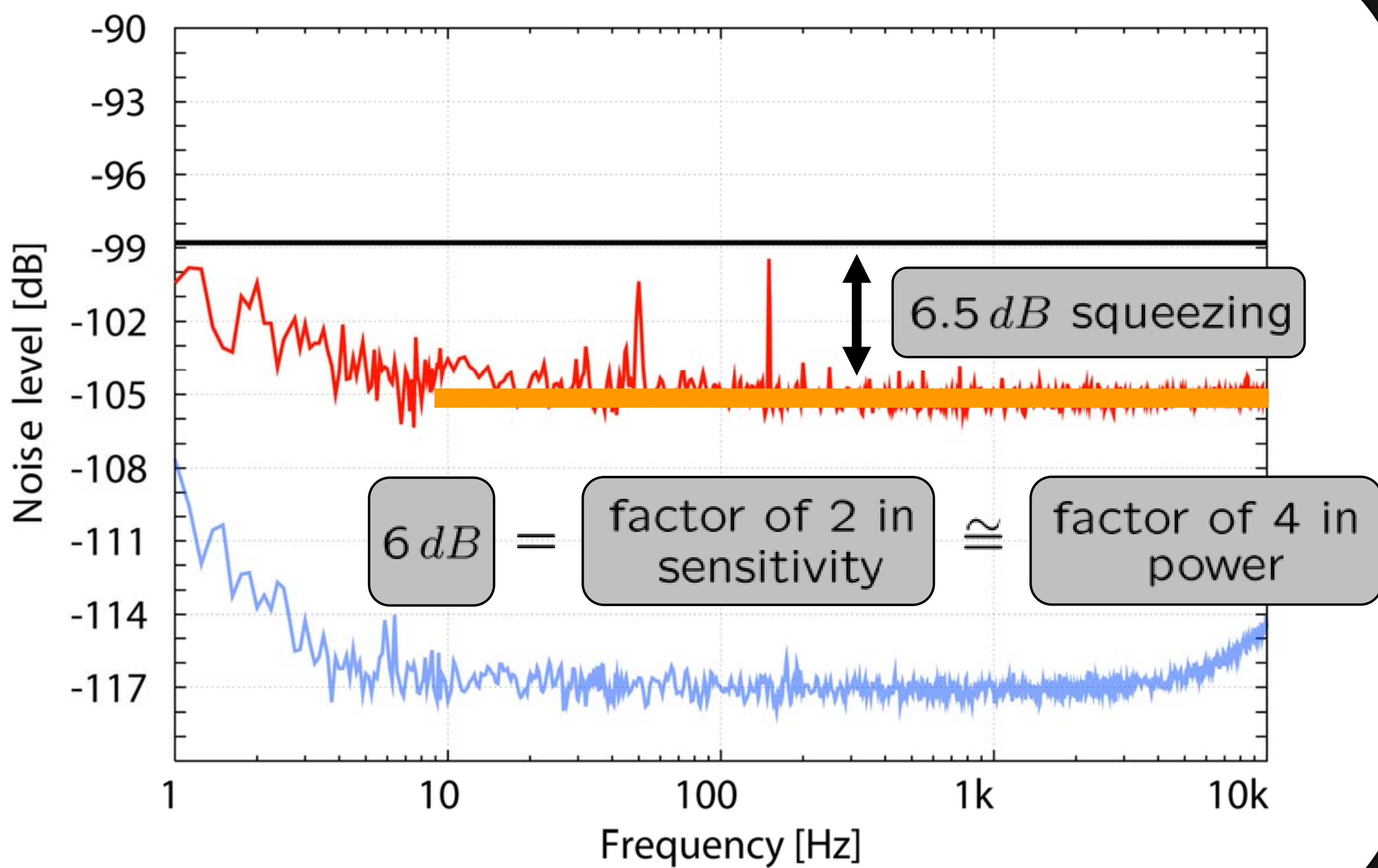
We propose and demonstrate a coherent control scheme for stable phase locking of squeezed vacuum fields. We focus on sideband fields at frequencies from 10 Hz to 10 kHz, which is a frequency regime of
and for which conventional control schemes have failed
; covering this entire band was produced using optical
alanced homodyne detection. The system was stably
rent but frequency shifted control fields. In order to
squeezed field was used for a nonclassical sensitivity
idio frequencies.



COHERENT CONTROL SCHEME II



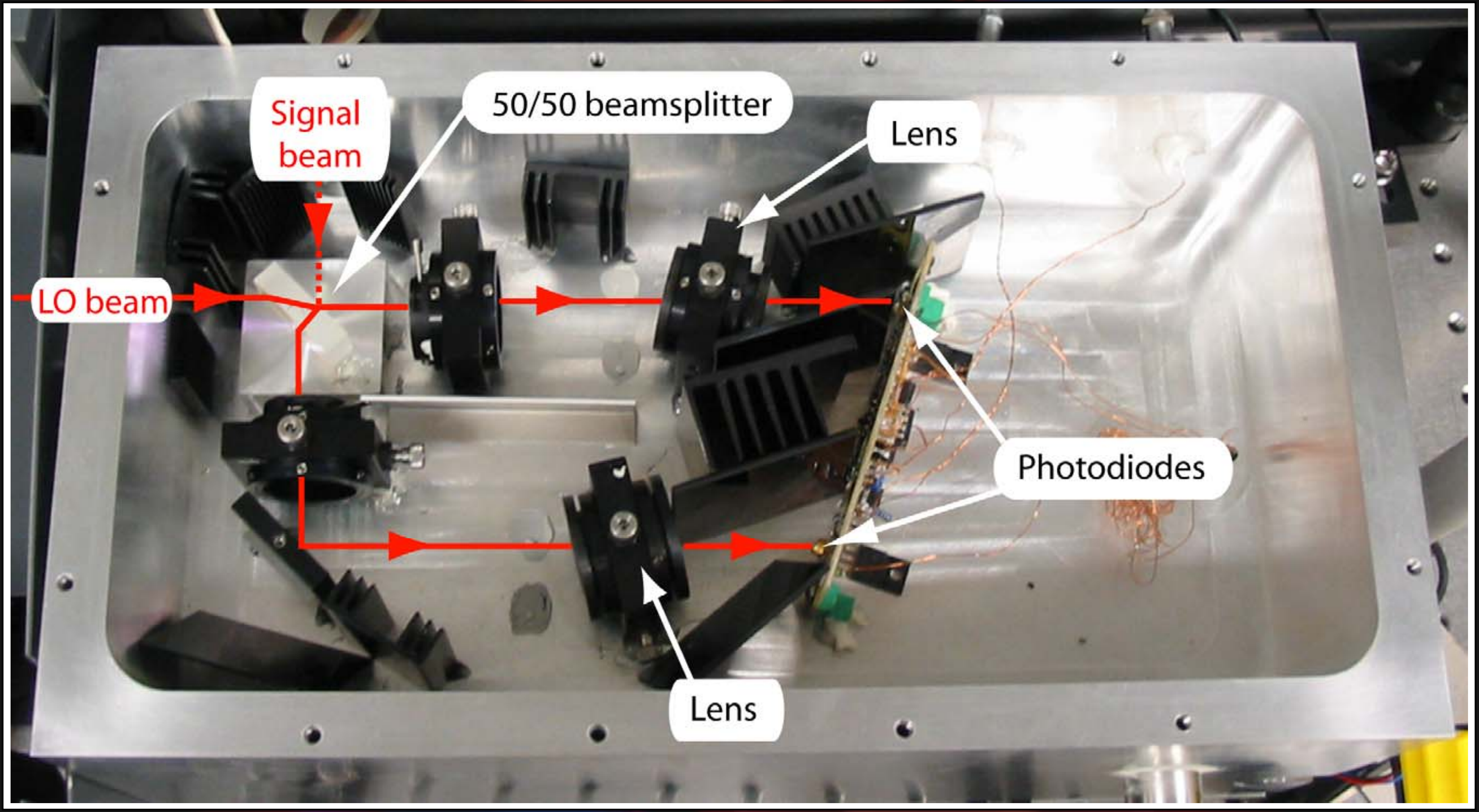
LOW FREQUENCY SQUEEZING



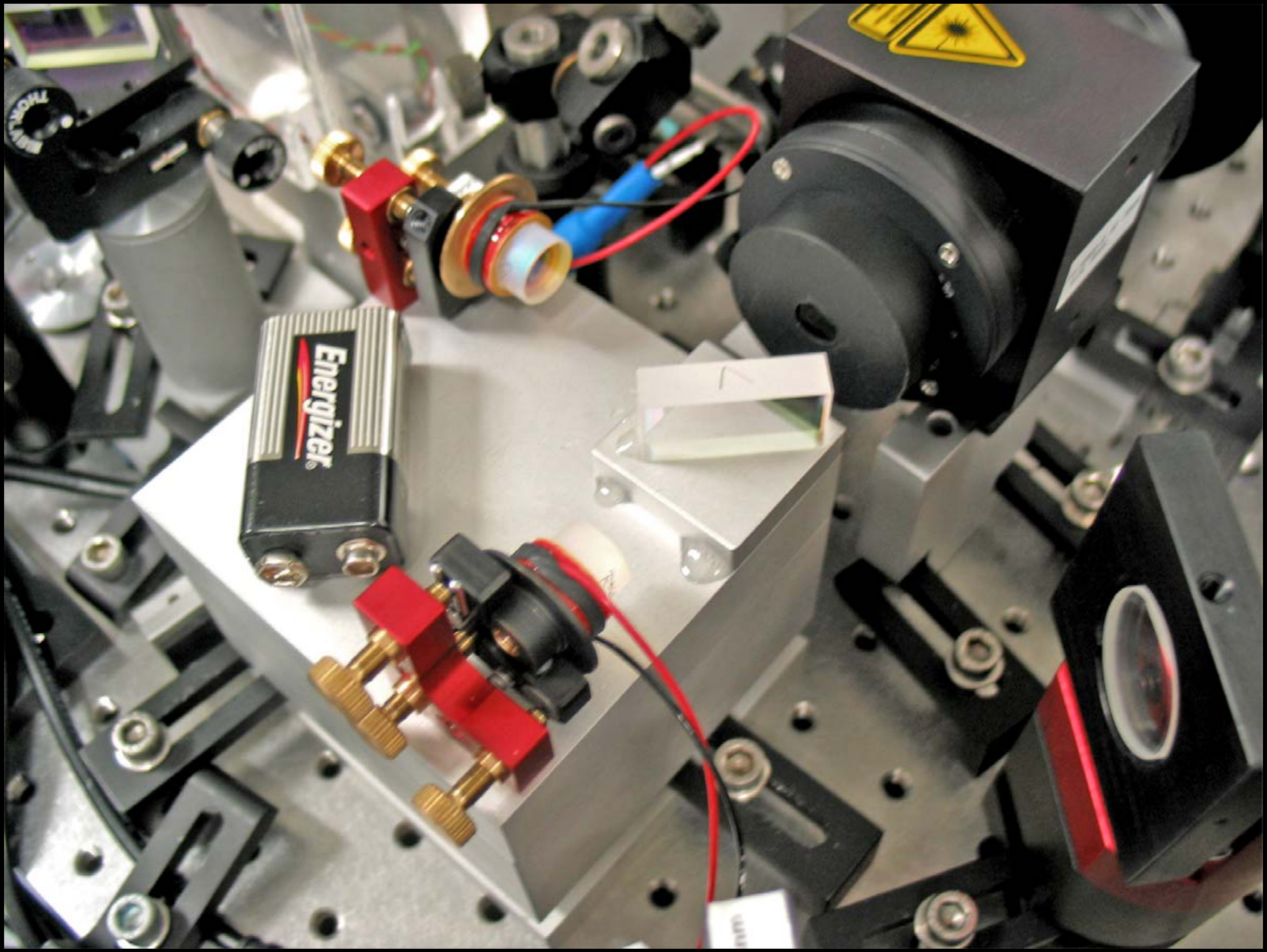
G0900615-v1

New J. Phys. 9 (2007) 371

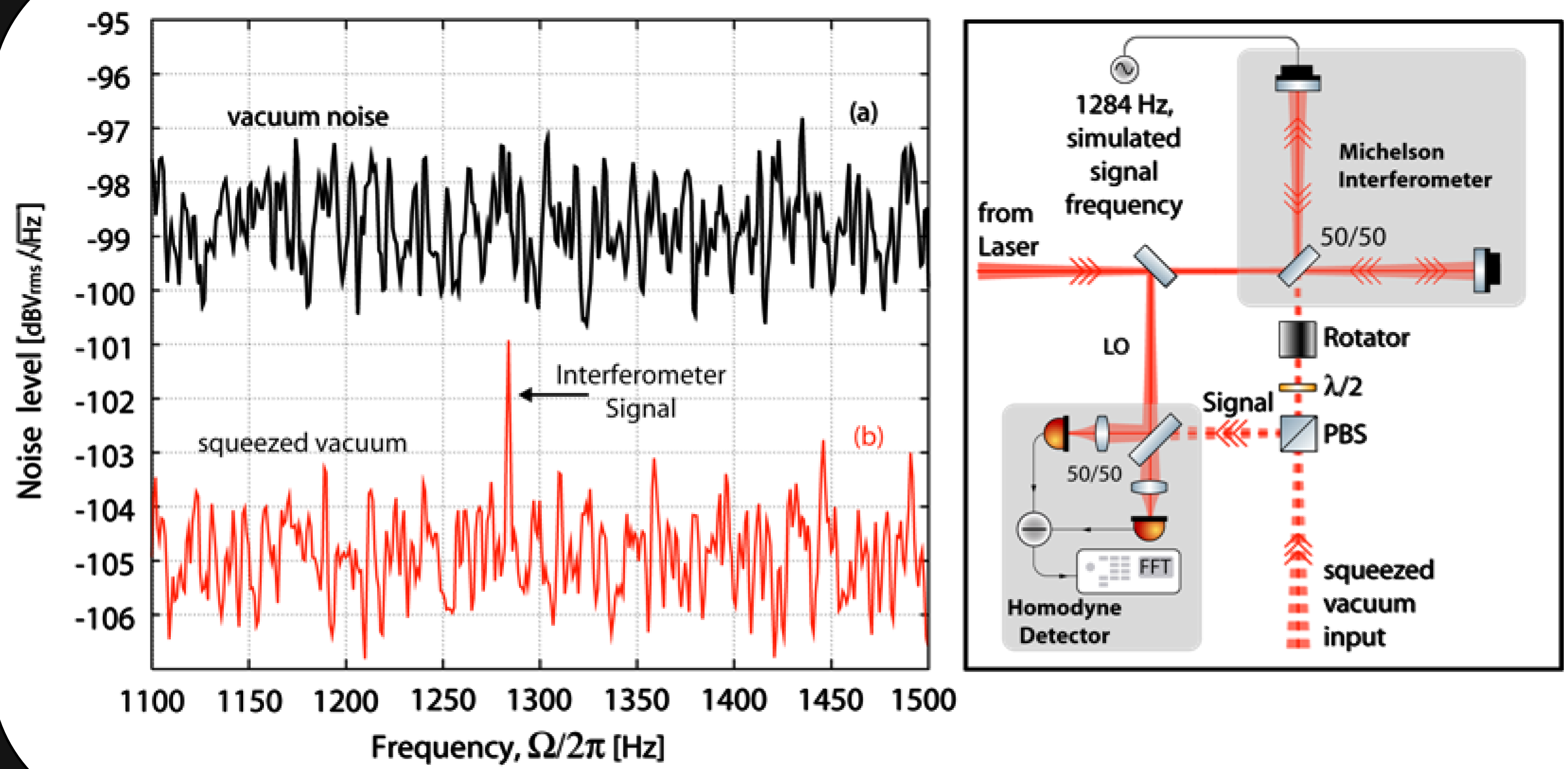
HOMODYNE DETECTOR



PROOF OF PRINCIPLE



RESULTS



unpublished

STRONG SQUEEZING

Observation of Squeezed Light with 10-dB Quantum-Noise Reduction

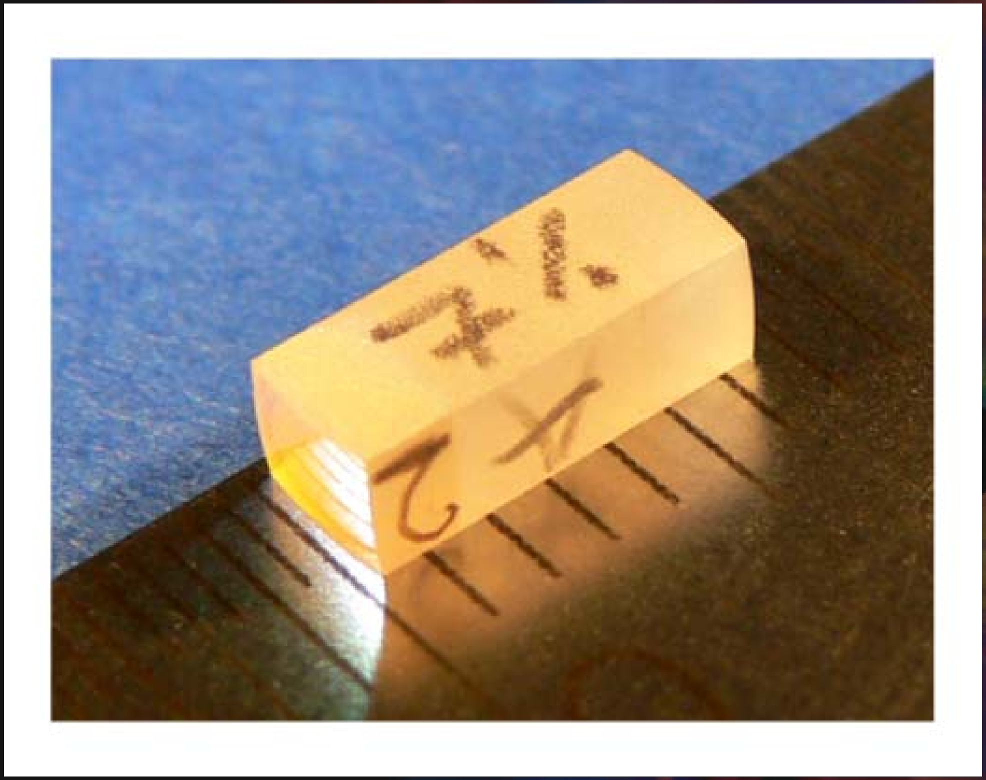
Henning Vahlbruch, Moritz Mehmet, Simon Chelkowski, Boris Hage, Alexander Franzen, Nico Lastzka, Stefan Goßler, Karsten Danzmann, and Roman Schnabel

Institut für Gravitationsphysik, Leibniz Universität Hannover and Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Callinstr. 38, 30167 Hannover, Germany

(Received 13 August 2007; published 23 January 2008)

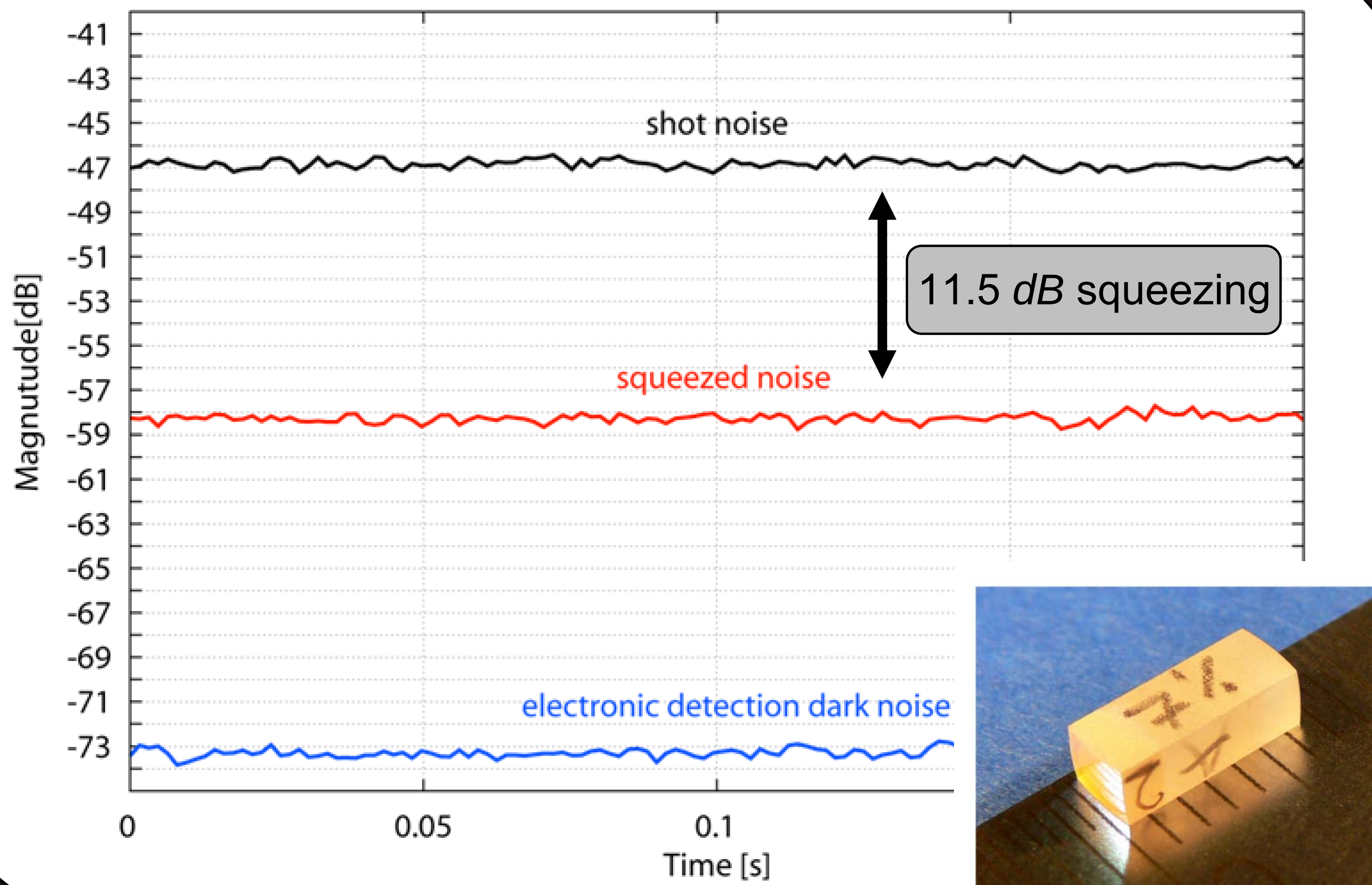
Squeezing of light's quantum noise requires temporal rearranging of photons. This again corresponds to creation of quantum correlations between individual photons. Squeezed light is a nonclassical manifestation of light with great potential in high-precision quantum measurements, for example, in the detection of gravitational waves [C. M. Caves, Phys. Rev. D **23**, 1693 (1981)]. Equally promising applications have been proposed in quantum communication [H. P. Yuen and J. H. Shapiro, IEEE Trans. Inf. Theory **24**, 657 (1978)]. However, after 20 years of intensive research doubts arose whether strong squeezing can ever be realized as required for eminent applications. Here we show experimentally that strong squeezing of light's quantum noise is possible. We reached a benchmark squeezing factor of 10 in power (10 dB). Thorough analysis reveals that even higher squeezing factors will be feasible in our setup.

MONOLITHIC SQUEEZED LIGHT SOURCE



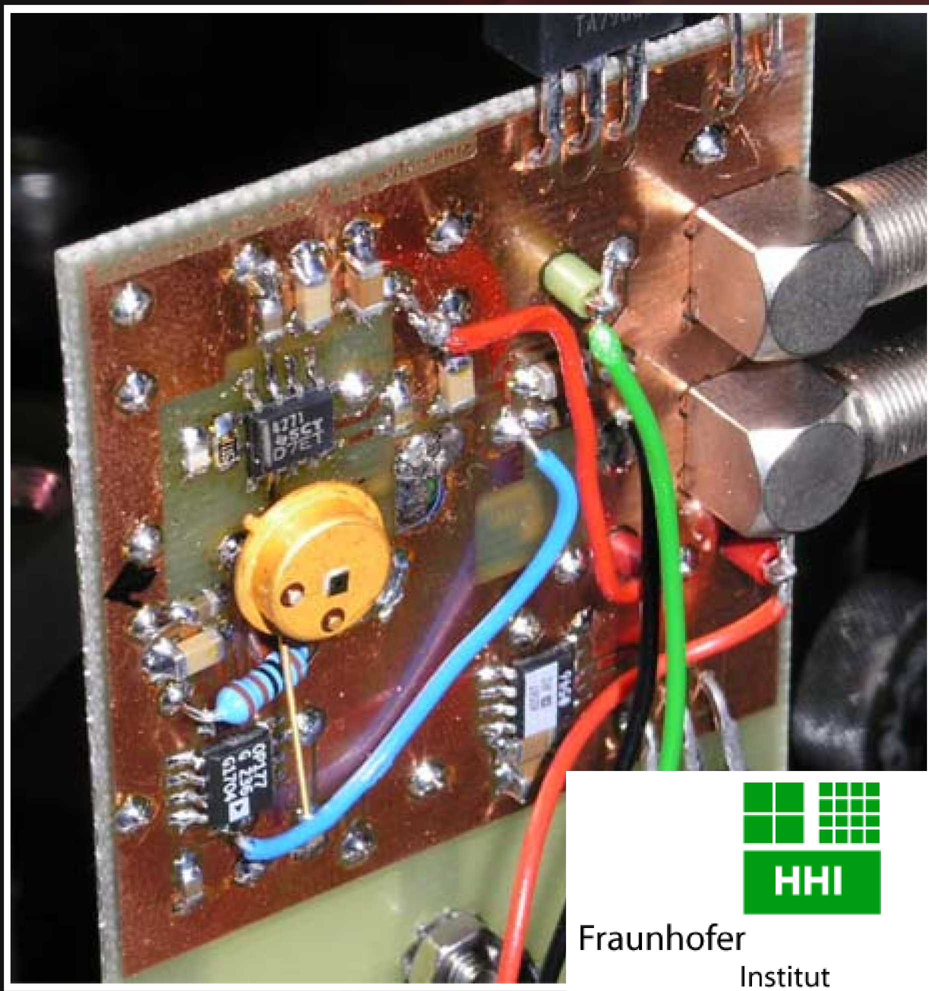
- Monolithic cavity
  - $\Rightarrow$ minimized losses
- Nonlinear medium:
  2×2.5×6.5 mm $LiNbO_3$ crystal
- Finesse of 50 @ 1064 nm
- High escape efficiency
- Free spectral range: 11 GHz

STRONG SQUEEZING @ 5 MHz



unpublished

LOW LOSS PHOTODETECTOR



- New custom made PD‘s
- AR coated @ 1064 nm
- Quantum efficiency = 99%
- 2% better than Epitaxx
- Active area 500 µm

HHI

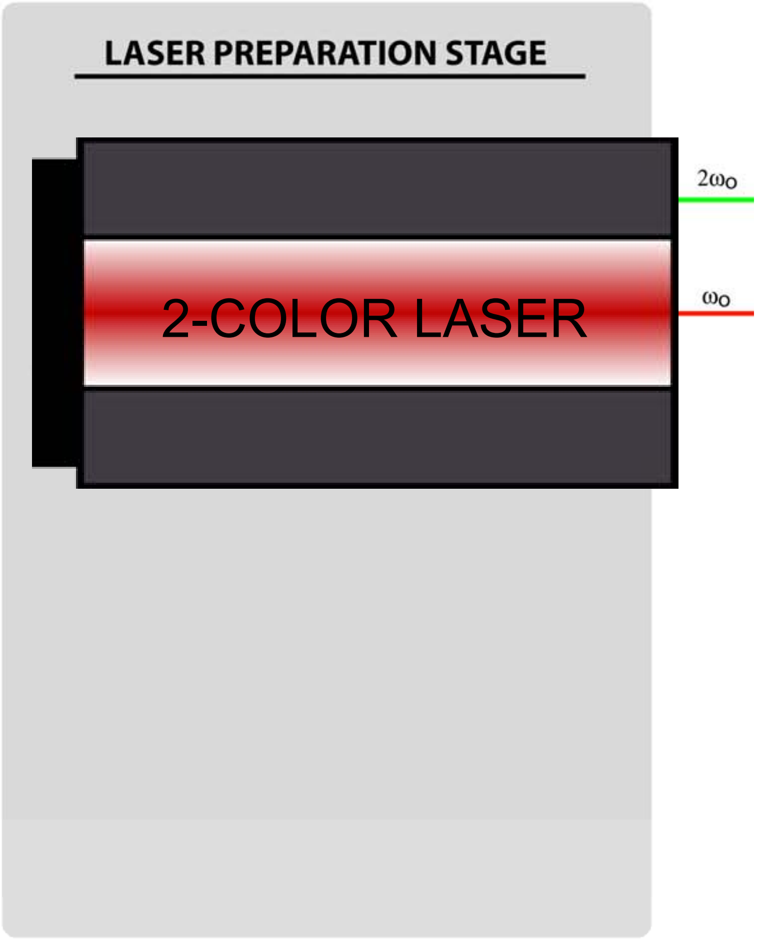
Fraunhofer
Institut
Nachrichtentechnik
Heinrich-Hertz-Institut


A SQUEEZED LIGHT SOURCE FOR
GEO 600

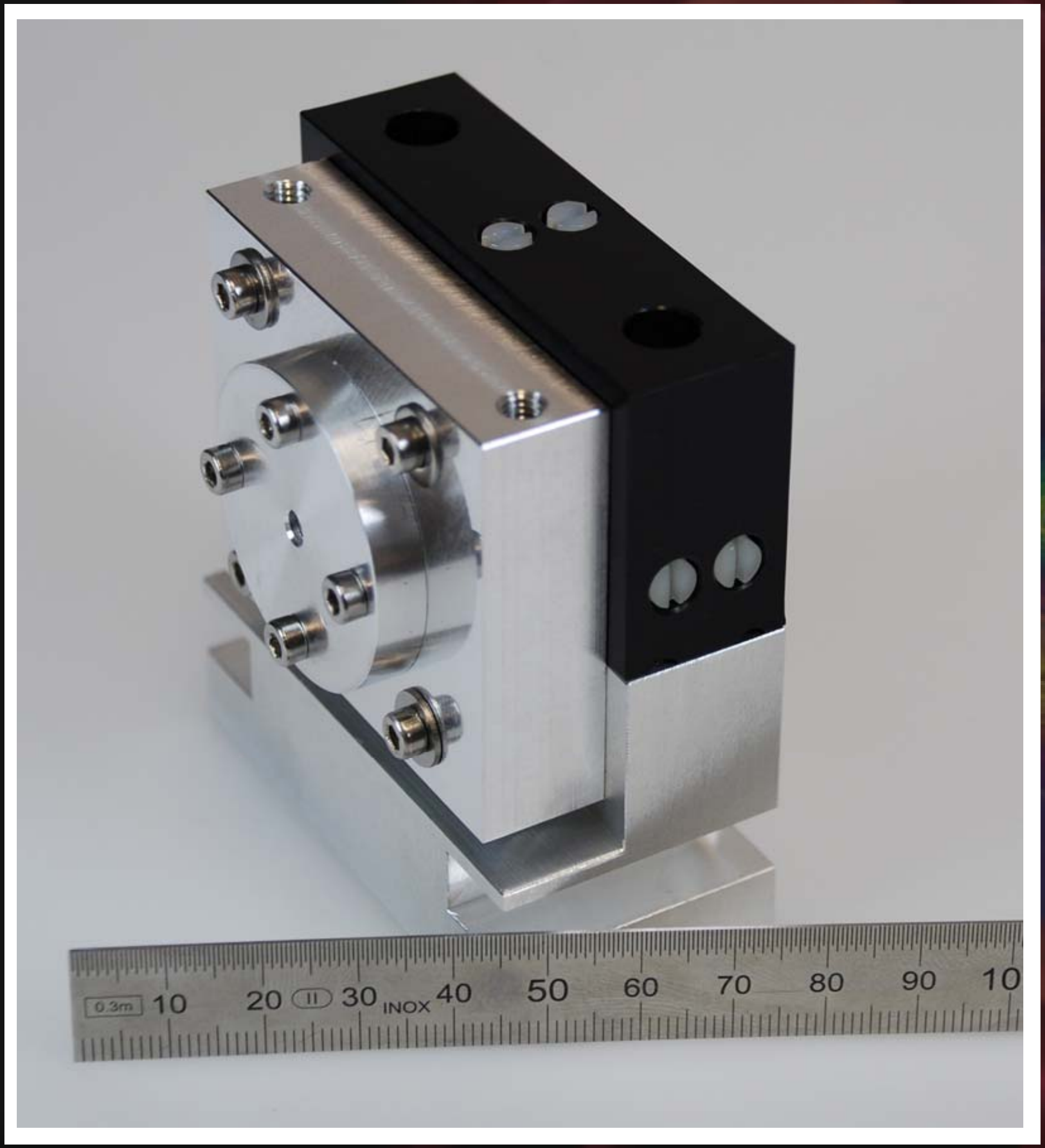
GOALS

- STRAY LIGHT REDUCTION
  - use superpolished optics
  - avoid polarization optics where possible
  - go into class 100 cleanroom
  - FIRST CONTACT – advanced cleaning technique
- LOSS REDUCTION
  - go for highest QE – 99%
- HIGHER NONLINEARITIES
  - less pump power ↔ smaller thermal effects
    ⇒ evaluate PPKTP
- DIGITAL REMOTE CONTROL SCHEME
  - allowing a permanent sensitivity improvement

EXPERIMENTAL LAYOUT SCHEME I

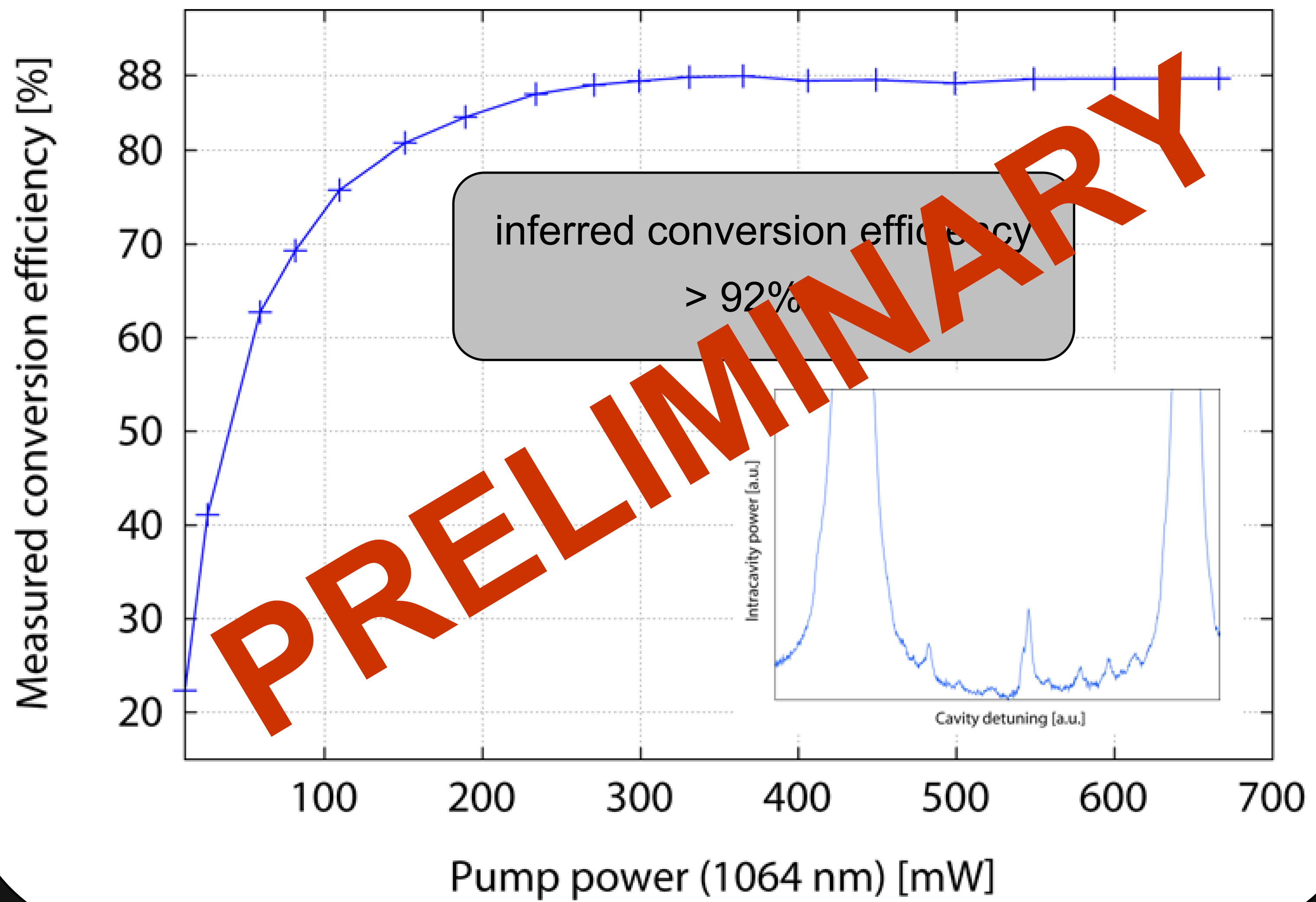


SECOND HARMONIC GENERATOR



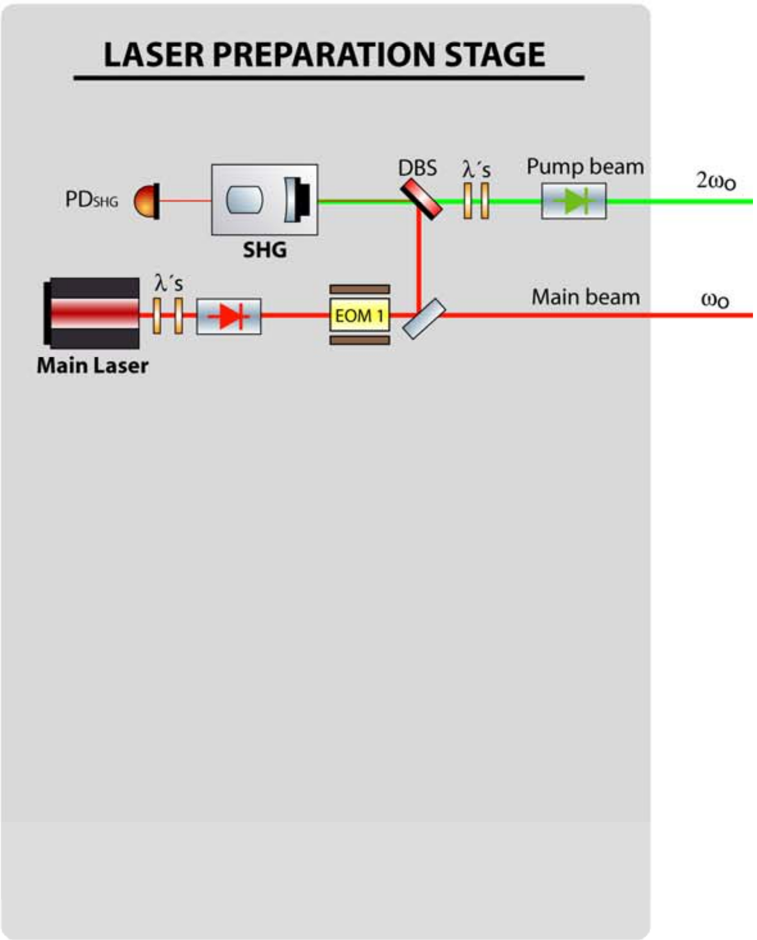
- Hemilithic cavity
- Nonlinear medium:
  1 x 1.5 x 9.3 mm PPKTP crystal
- Singly resonant at 1064 nm
- Coupling mirror: R = 92%
  $\Rightarrow$ Finesse $\approx$ 60
- Compact design
- High intrinsic mechanical stability

EFFICIENT SHG

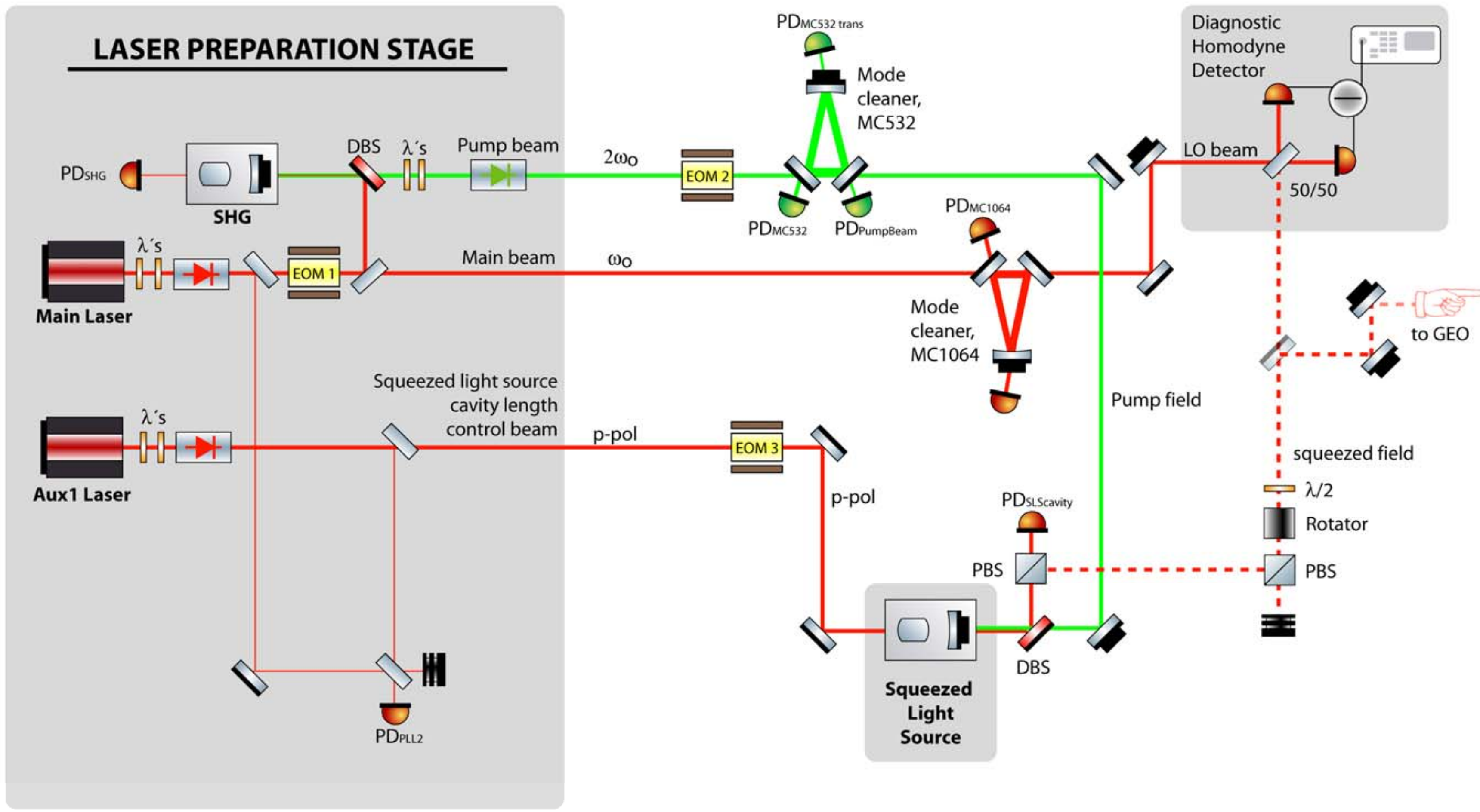


unpublished

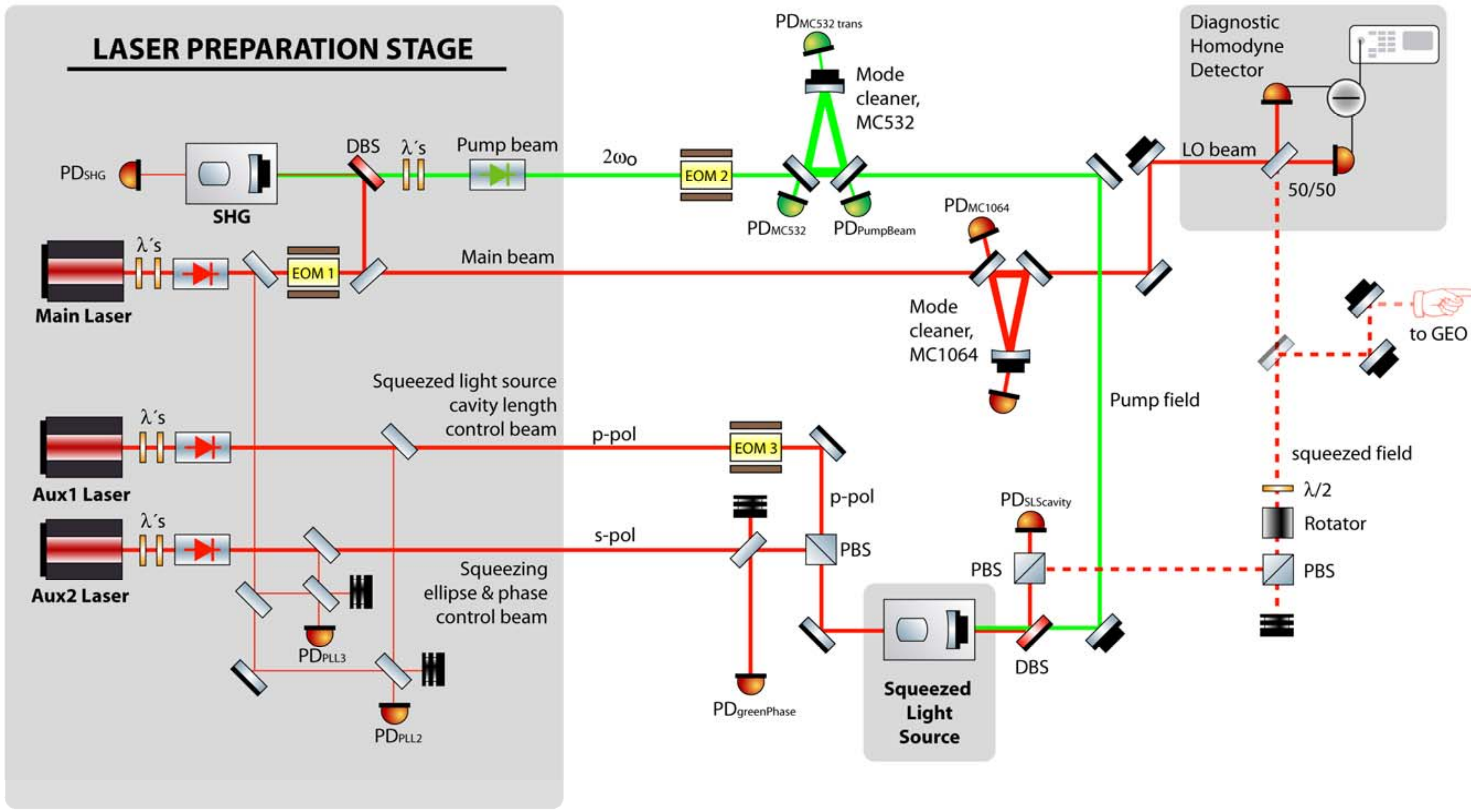
EXPERIMENTAL LAYOUT SCHEME II



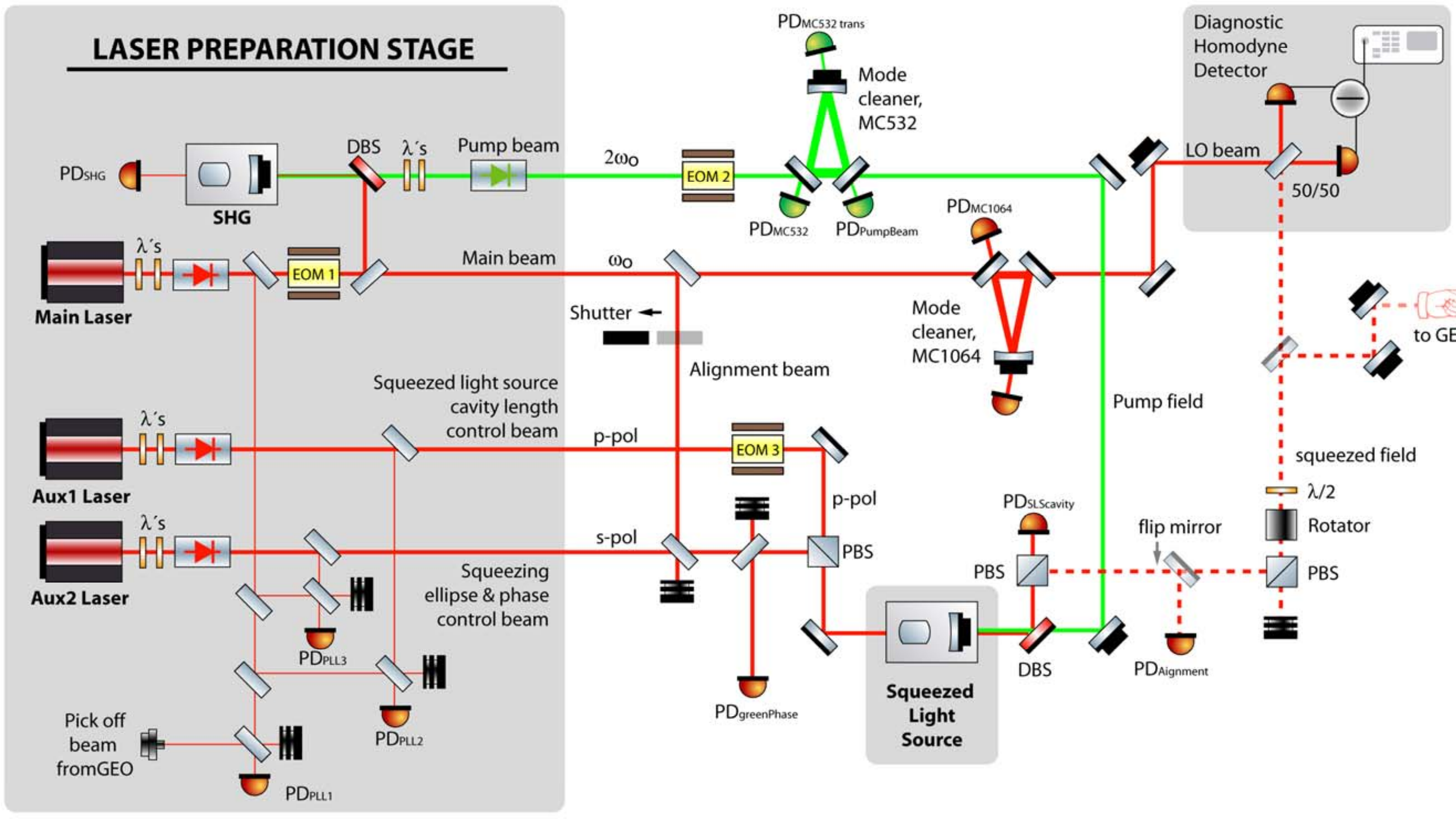
EXPERIMENTAL LAYOUT SCHEME III



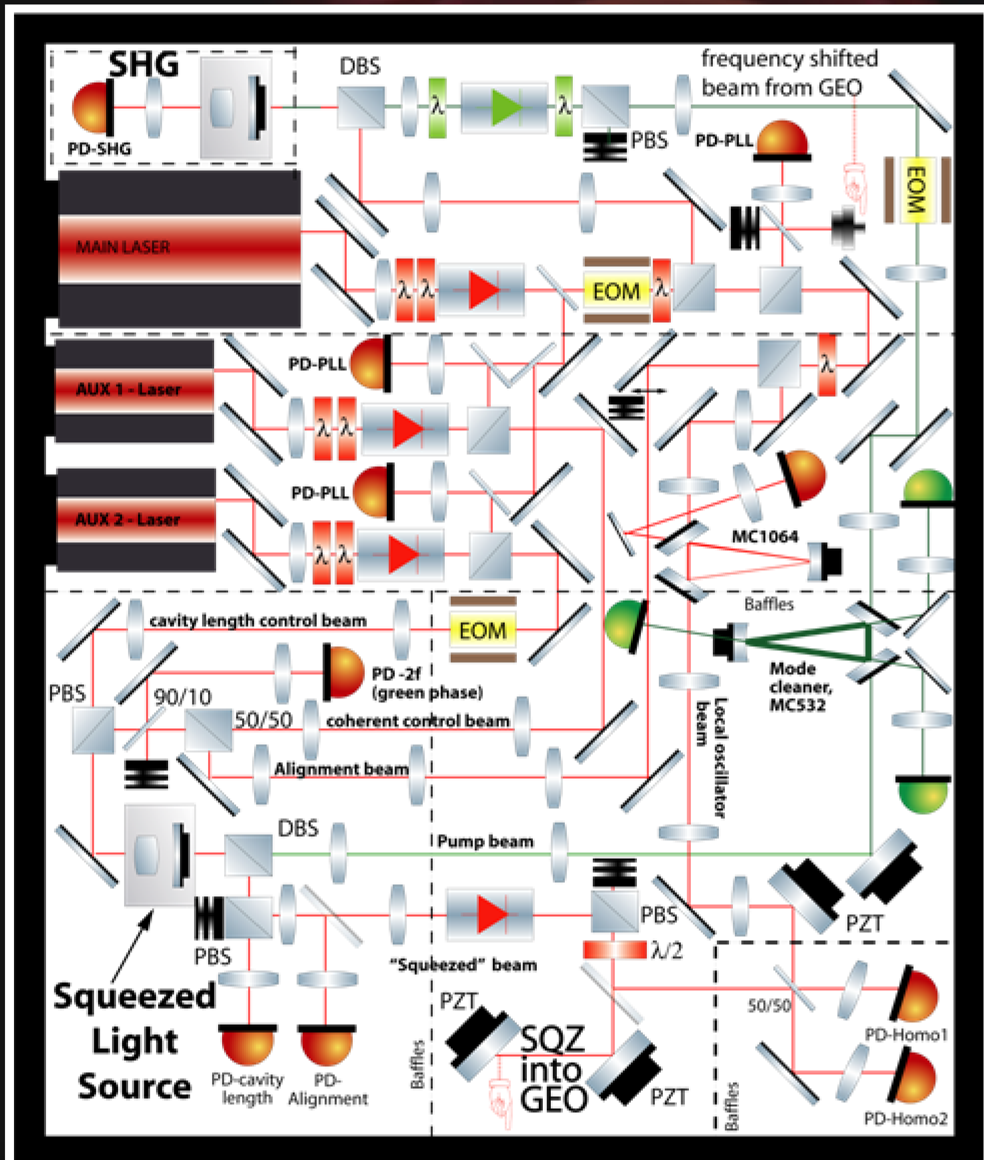
EXPERIMENTAL LAYOUT SCHEME IV



EXPERIMENTAL LAYOUT SCHEME V



GEO SQUEEZER BREADBOARD



Main Laser: InnoLight Mephisto

(Mephisto OEM in future)

Aux. Lasers: Mephisto OEM

Optics: ATF (superpolished)

Nonlinear medium: PPKTP

Breadboard: 113x135 cm

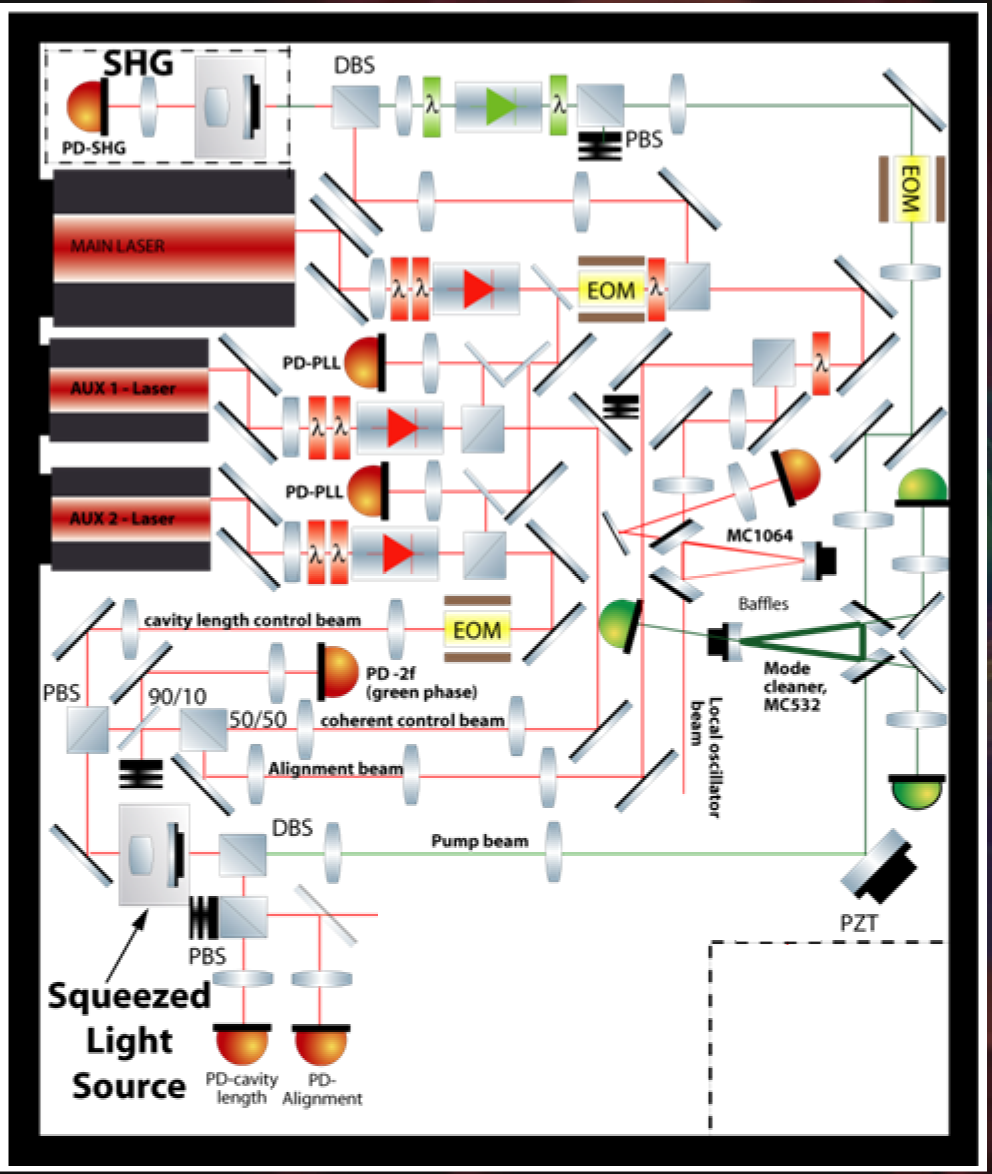
Beam height: 50mm

Compact design

> 120 opt. components

total weight ≈ 120 kg

STATUS OF THE EXPERIMENT I



SET-UP COMPLETED:

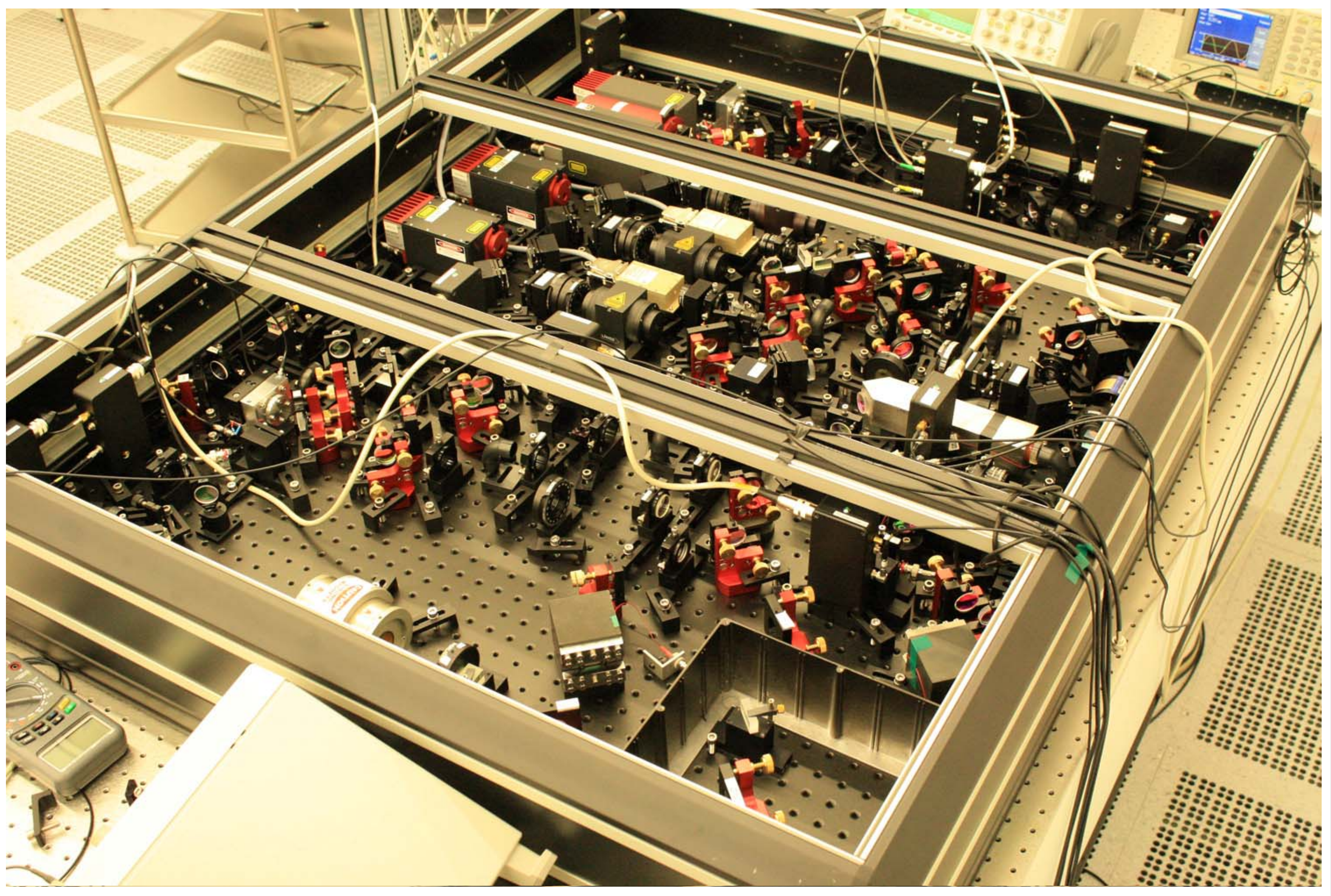
- second harmonic generator
- 2 phase-locking loops
- premodecleaner @ 532 and 1064
- squeezed light source

FUTURE WORK:

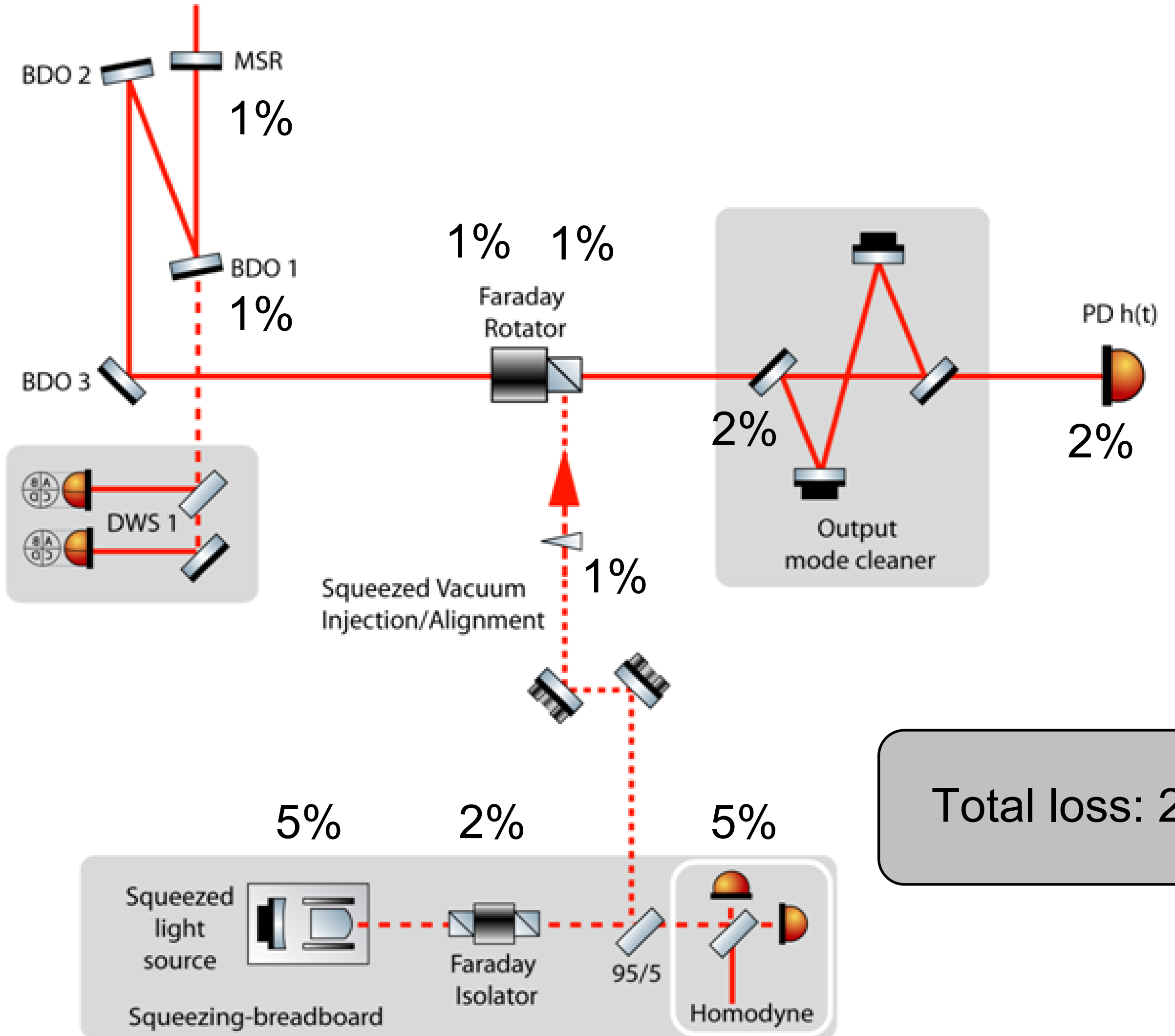
- homodyne detector
- injection into GEO 600

G0900615-v1

STATUS OF THE EXPERIMENT II

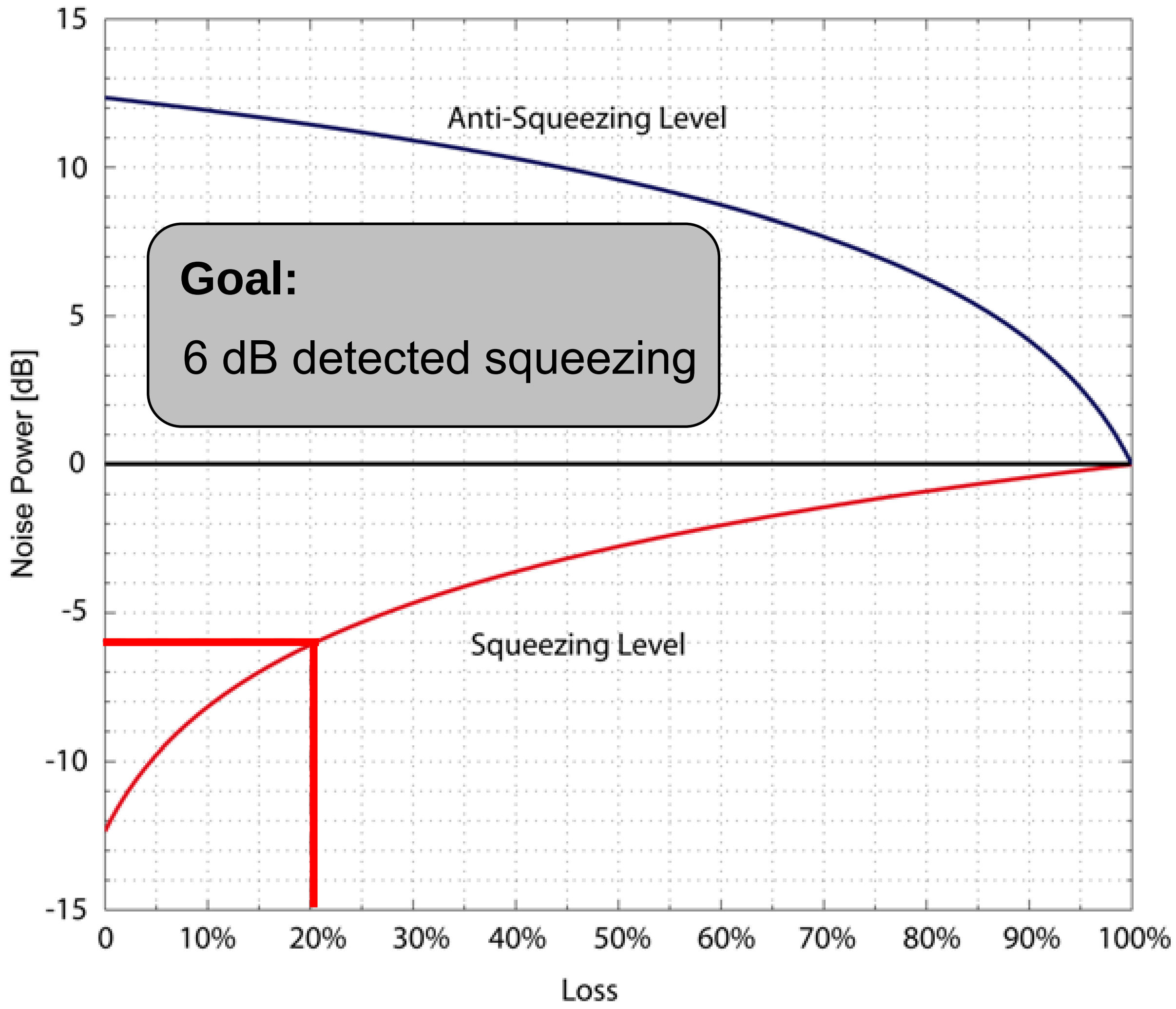


LOSS BUDGET



Total loss: 20%

LOSS BUDGET II



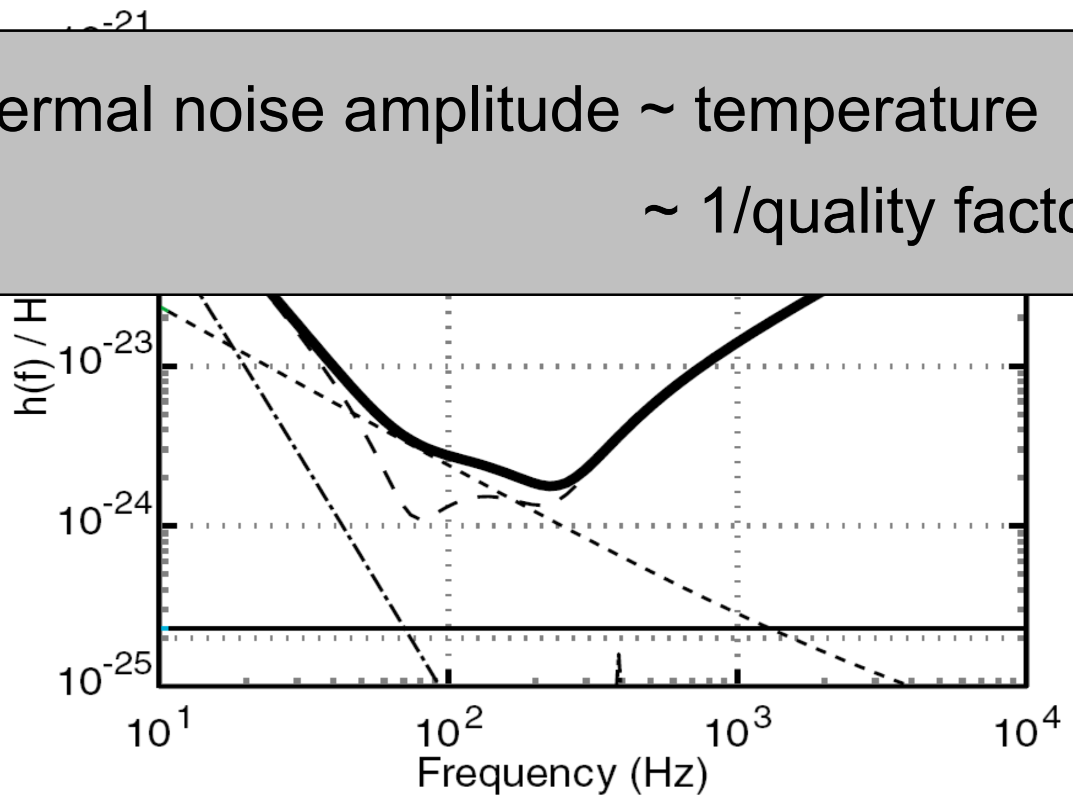
FUTURE WORK

THERMAL NOISE…

… will be one main problem in 2nd generation detectors

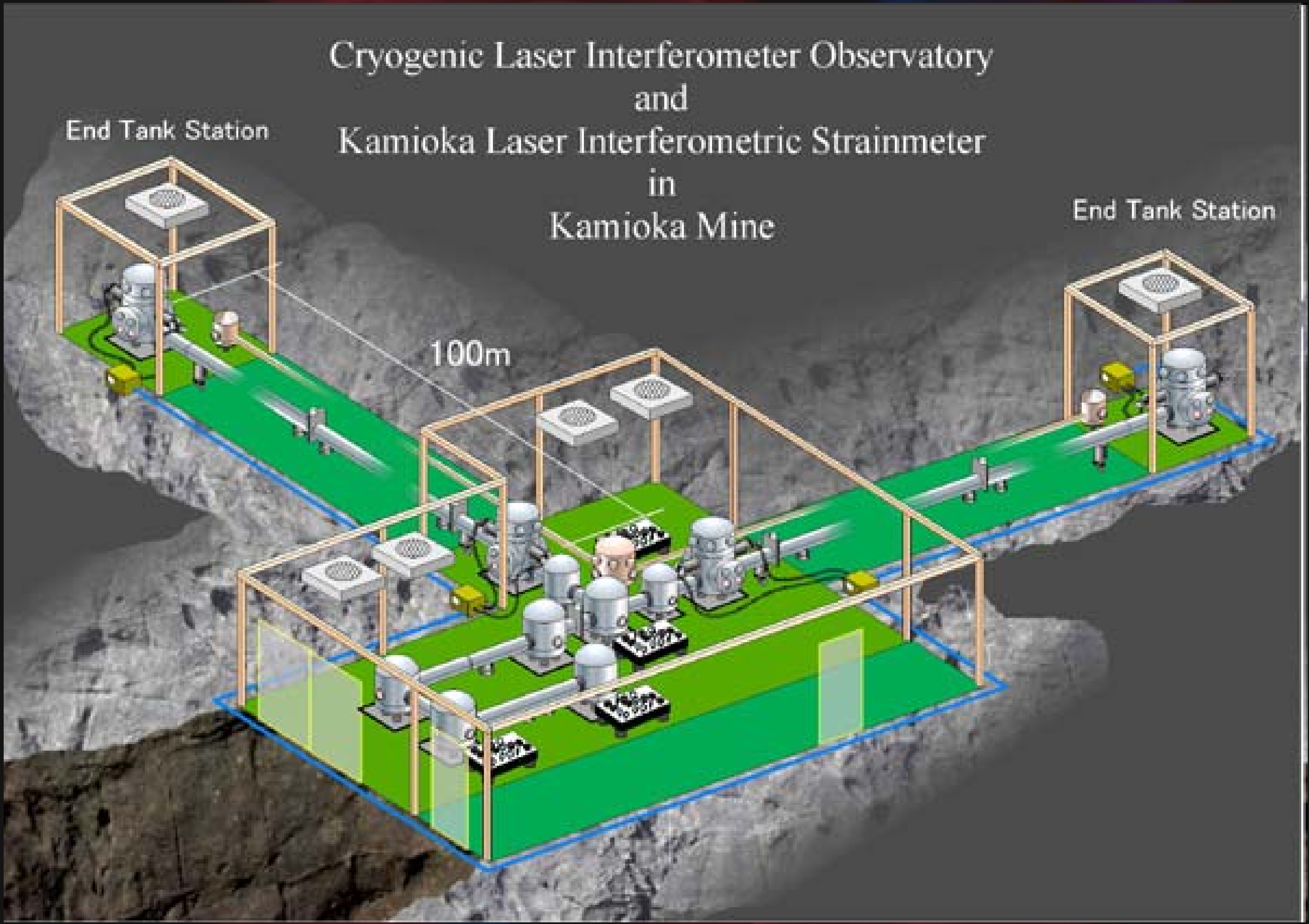
thermal noise amplitude ~ temperature

~ 1/quality factor



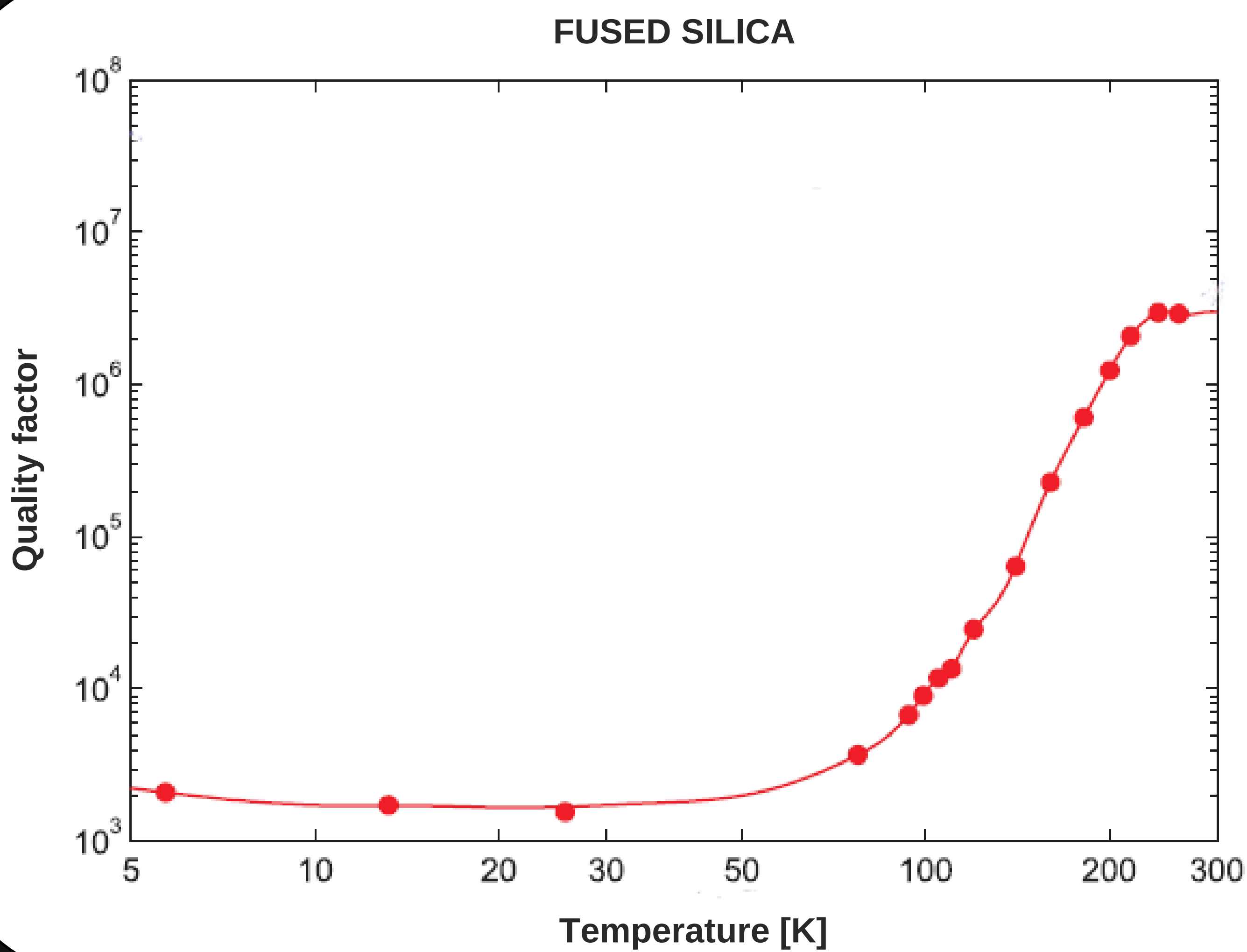
Abbott *et al*: Seismic isolation for advanced LIGO

CRYOGENIC SOLUTION



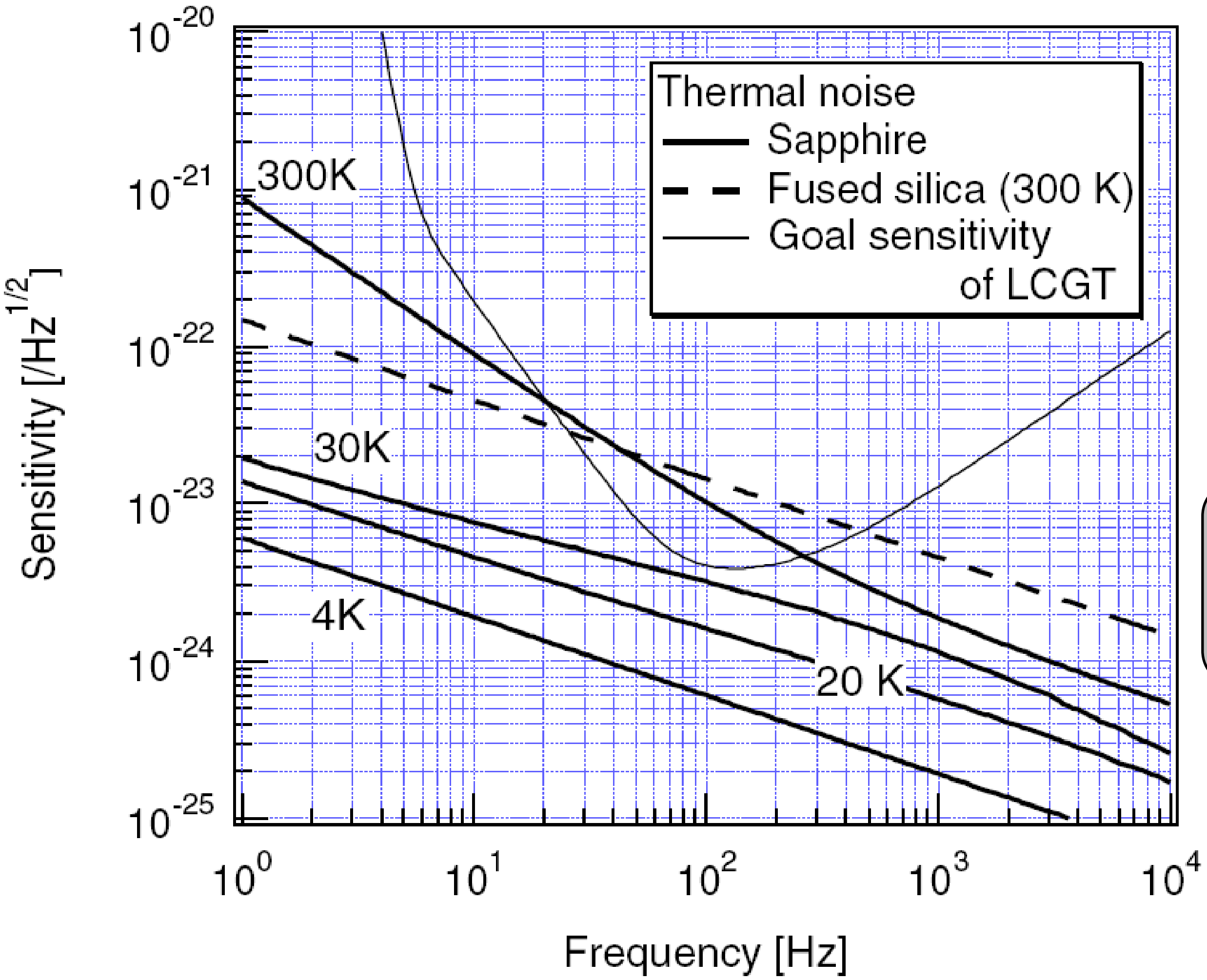
G0900615-v1 Kuroda *et al*: Introducing LCGT (2007)

SEARCH FOR NEW MATERIALS



Nawrodt: PhD thesis (2007)

CLIO/LCGT: SAPHIRE

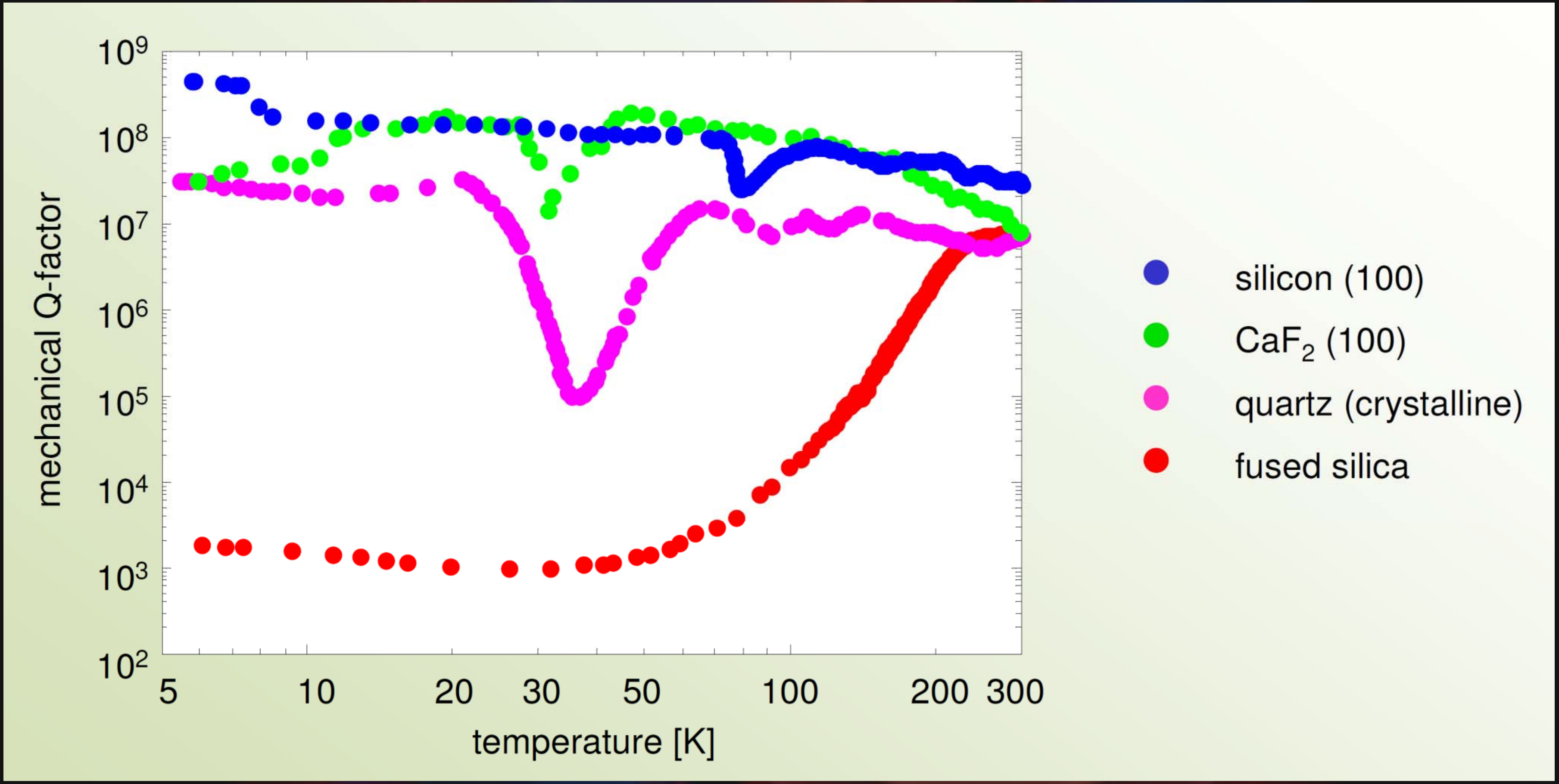


Bulk substrate:

$Q > 10^8$ @ $T < 20$ K

Yamamoto *et al*, (2006)

SILICON – QUALITY FACTOR



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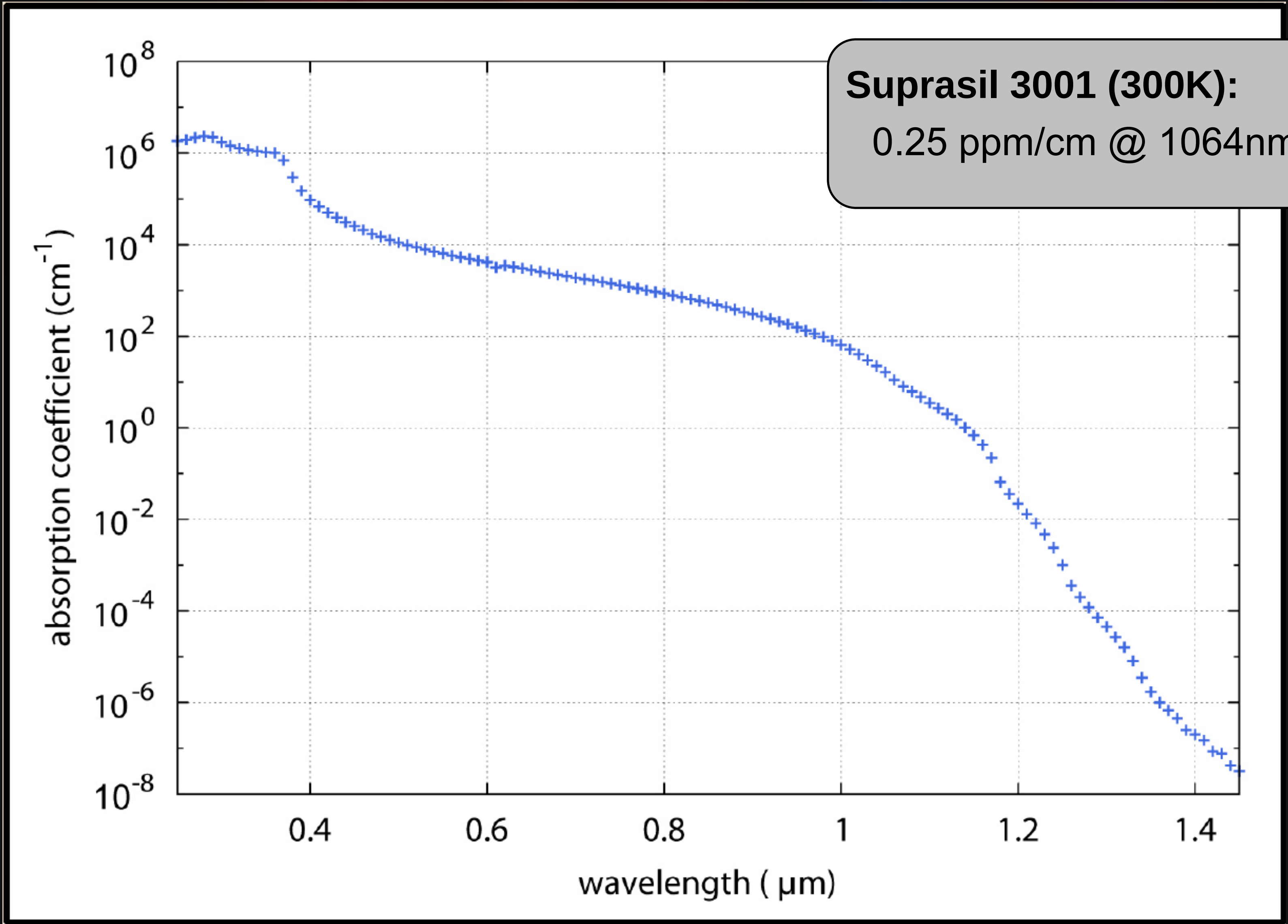
R. Nawrodt *et al*

SILICON - ABSORPTION

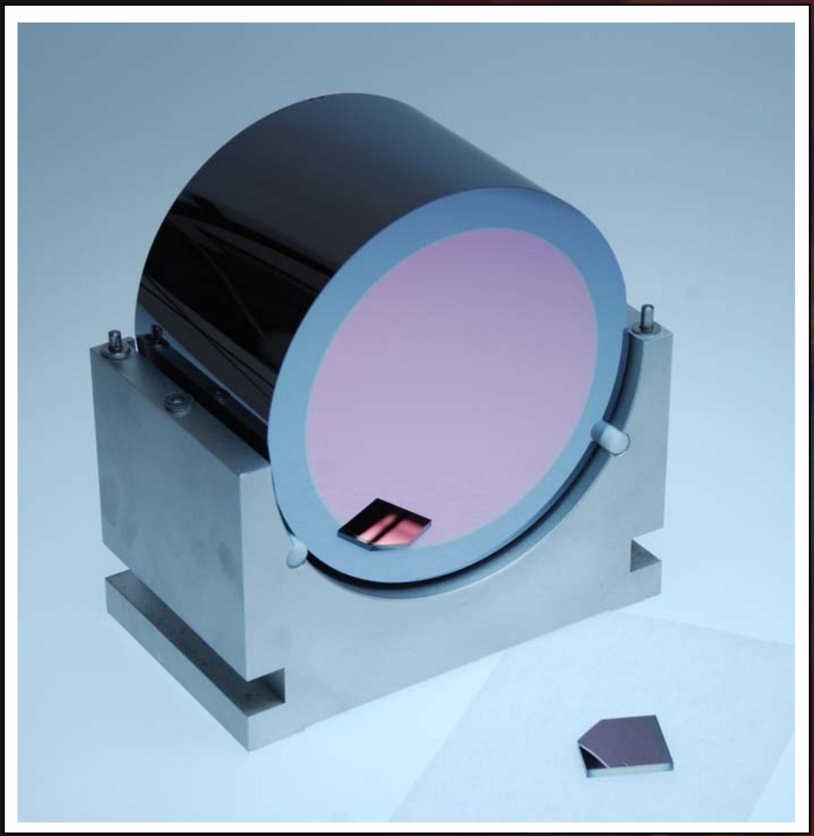


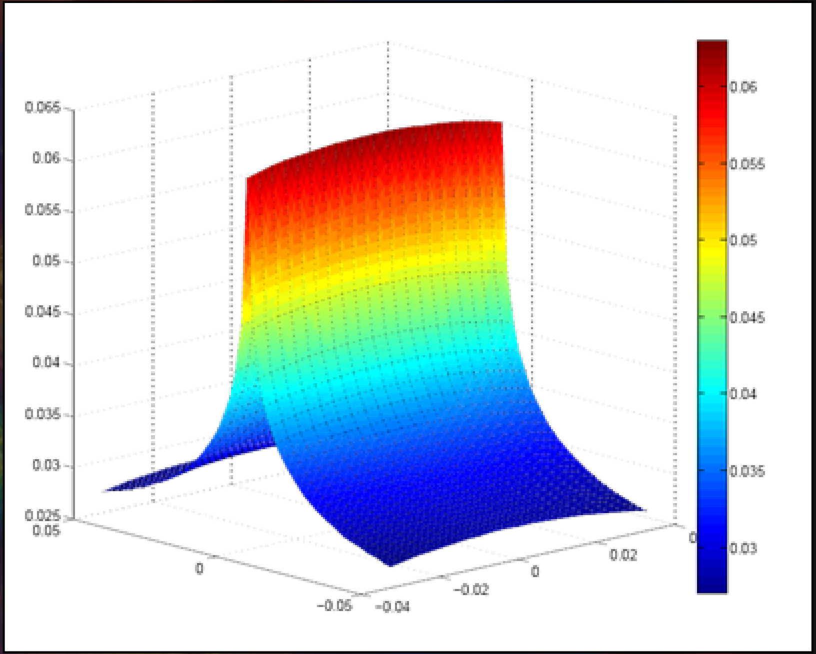
Suprasil 3001 (300K):

0.25 ppm/cm @ 1064nm

Green *et al* (1995)

MEASUREMENTS IN PREPARATION @ AEI





Measurement via temperature distribution in substrate

Monolithic silicon resonator (Finesse ≈ 20000)

Expected absorption coefficient: $< 3.2 \cdot 10^{-8}$/cm @ 1550 nm

ongoing experiment by J. Dueck

SQUEEZING @ 1550 nm

1060 OPTICS LETTERS / Vol. 34, No. 7 / April 1, 2009

Observation of cw squeezed light at 1550 nm

Moritz Mehmet,[1,2] Sebastian Steinlechner,[1] Tobias Eberle,[1] Henning Vahlbruch,[1] André Thüring,[1] Karsten Danzmann,[1] and Roman Schnabel[1,*]

[1]*Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Institut für Gravitationsphysik der Leibniz Universität Hannover, Callinstrasse 38, 30167 Hannover, Germany*

[2]*Centre for Quantum Engineering and Space-Time Research—QUEST, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover, Germany*

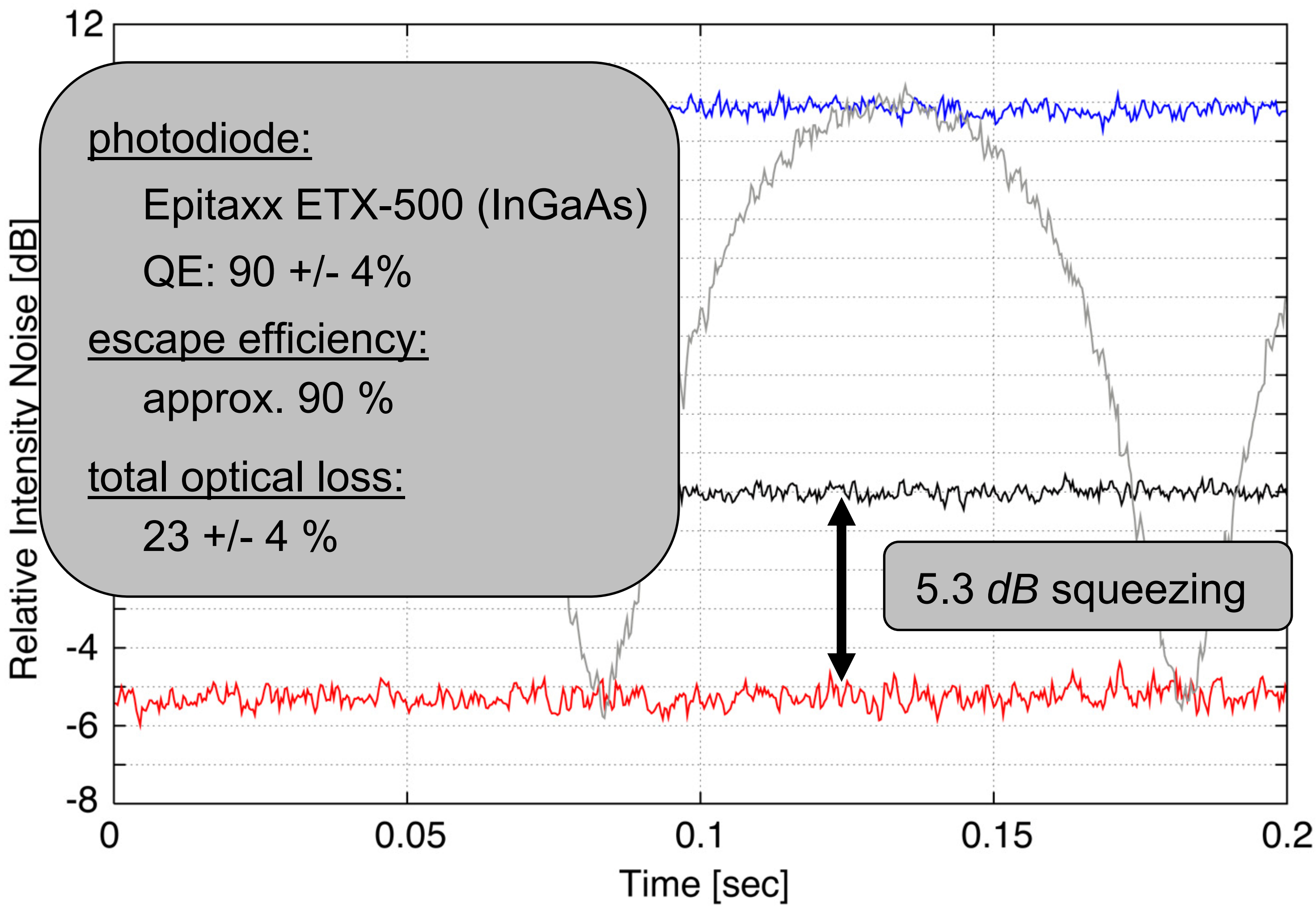
**Corresponding author: roman.schnabel@aei.mpg.de*

Received December 2, 2008; accepted February 1, 2009; posted February 23, 2009 (Doc. ID 104606); published March 25, 2009

We report on the generation of cw squeezed vacuum states of light at the telecommunication wavelength of 1550 nm. The squeezed vacuum states were produced by type I optical parametric amplification in a standing-wave cavity built around a periodically poled potassium titanyl phosphate crystal. A nonclassical noise reduction of 5.3 dB below the shot noise was observed by means of balanced homodyne detection.

OCIS codes: 270.0270, 270.6570, 190.4970.

SQUEEZING @ 1550 nm @ 5 MHz



G0900615-v1

Mehmet *et al*, Opt. Lett. 34 (2009)

THE FUTURE OF SQUEEZING

- SQUEEZING @ 1550 nm
  - optimize crystal coating, reduce detection losses
  - use of monolithic cavity possible
  - low frequencies:
    laser development/characterization required

  $\Rightarrow$ 10 – 15 dB feasible for the coming decade

- SQUEEZING IN GENERAL
  - evaluate materials with higher nonlinearities
    (less pump power $\leftrightarrow$ smaller thermal effects)

SQUEEZING IN FUTURE DETECTORS?

1 -100 Hz

- low circulating power (< 1 kW)
- cryogenically cooled
- heavy test masses (100 – 200 kg)
- 15 dB squeezing-enhanced

100 Hz -10 kHz

- high circulating power (several MW)
- 15 dB squeezing-enhanced

BROADBAND DETECTOR WITH FILTER CAVITIES

SPARE SLIDES

PROOF OF PRINCIPLE II

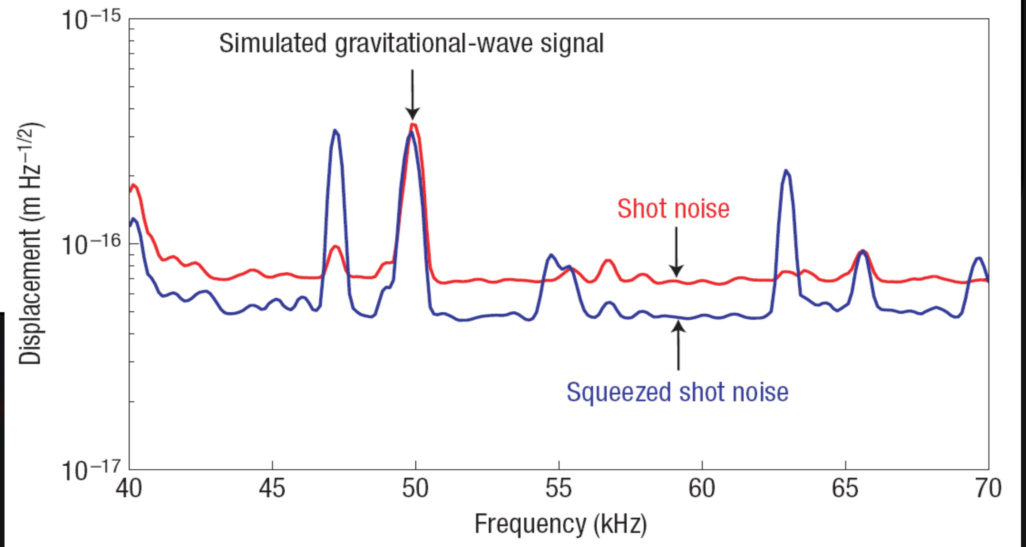
LETTERS

A quantum-enhanced prototype gravitational-wave detector

K. GODA[1], O. MIYAKAWA[2], E. E. MIKHAILOV[3], S. SARAF[4], R. ADHIKARI[2], K. McKENZIE[5], R. WARD[2], S. VASS[2], A. J. WEINSTEIN[2] AND N. MAVALVALA[1]*

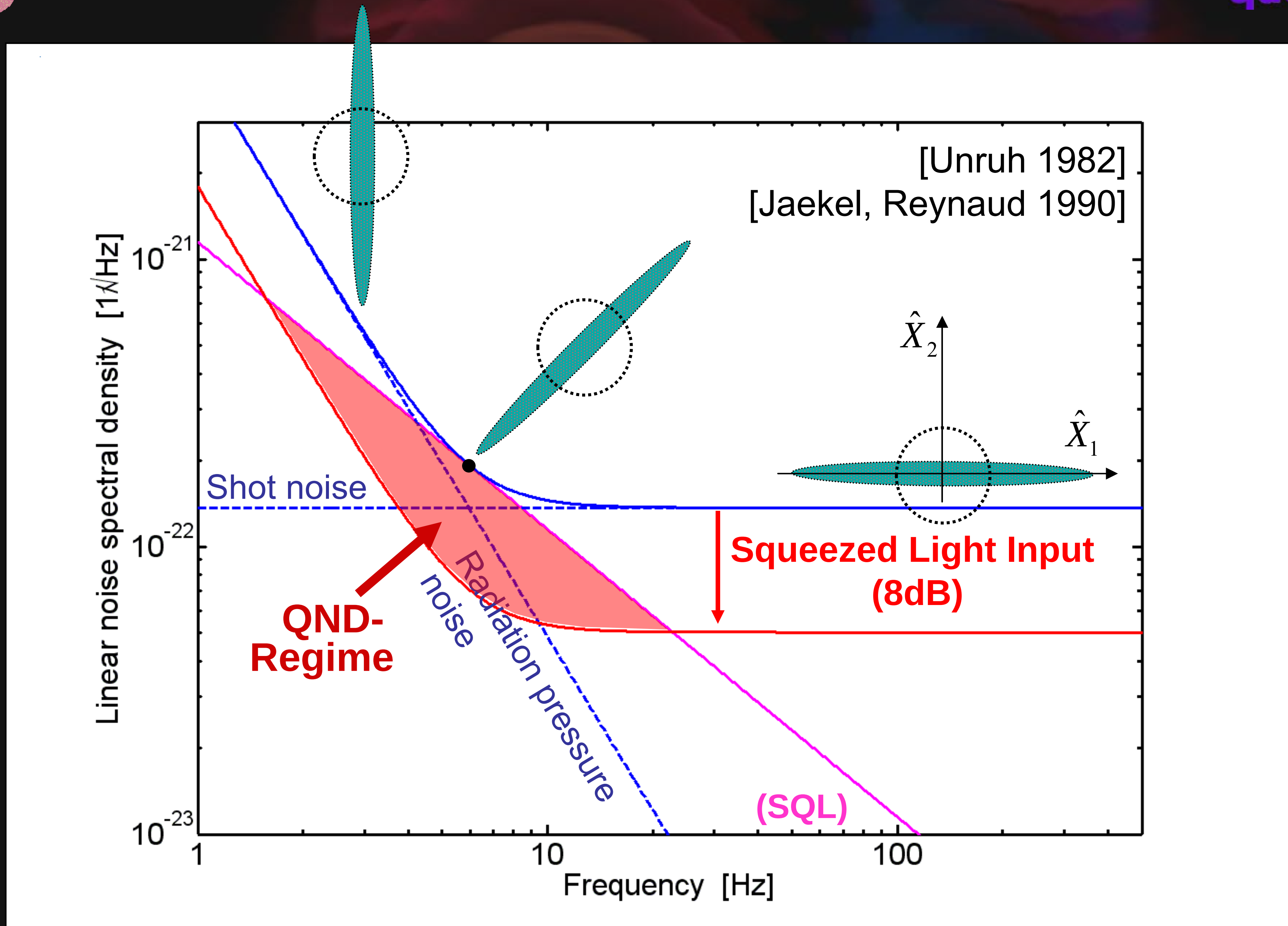
Result:

44 % increase in detector sensitivity

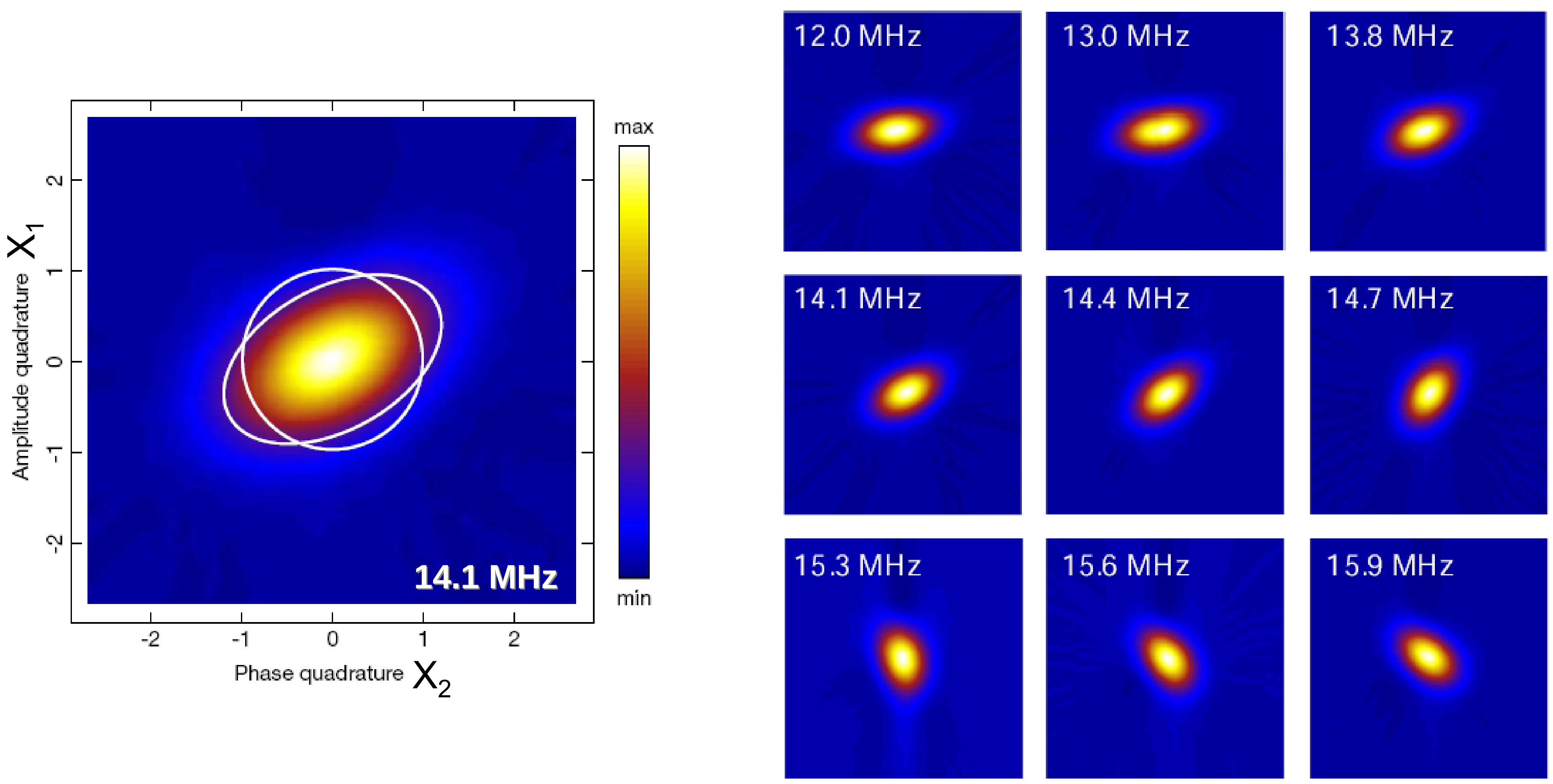


Nature Physics 4 (2008), 472

BACK-ACTION NOISE

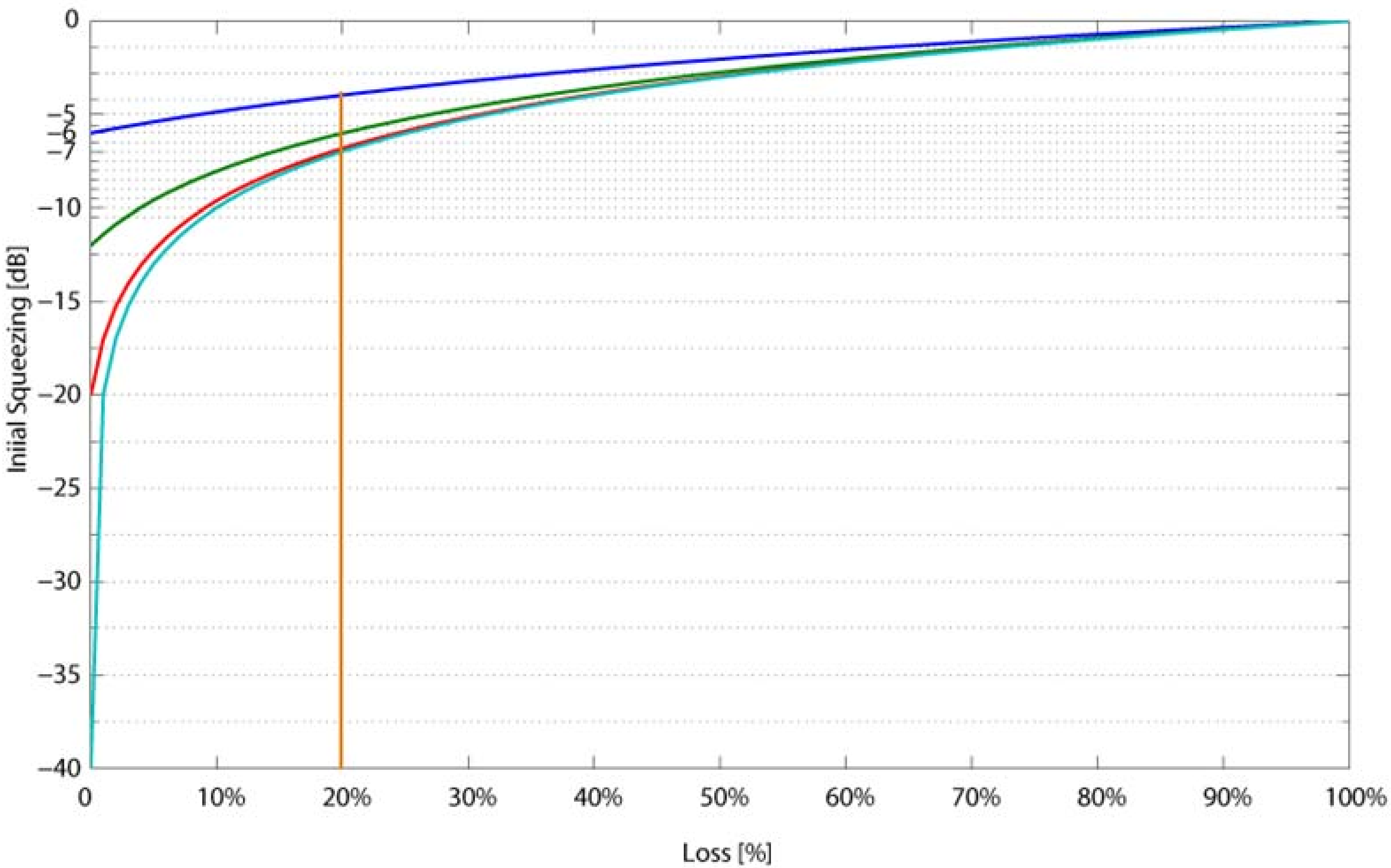


ROTATING THE SQUEEZING ELIPSE



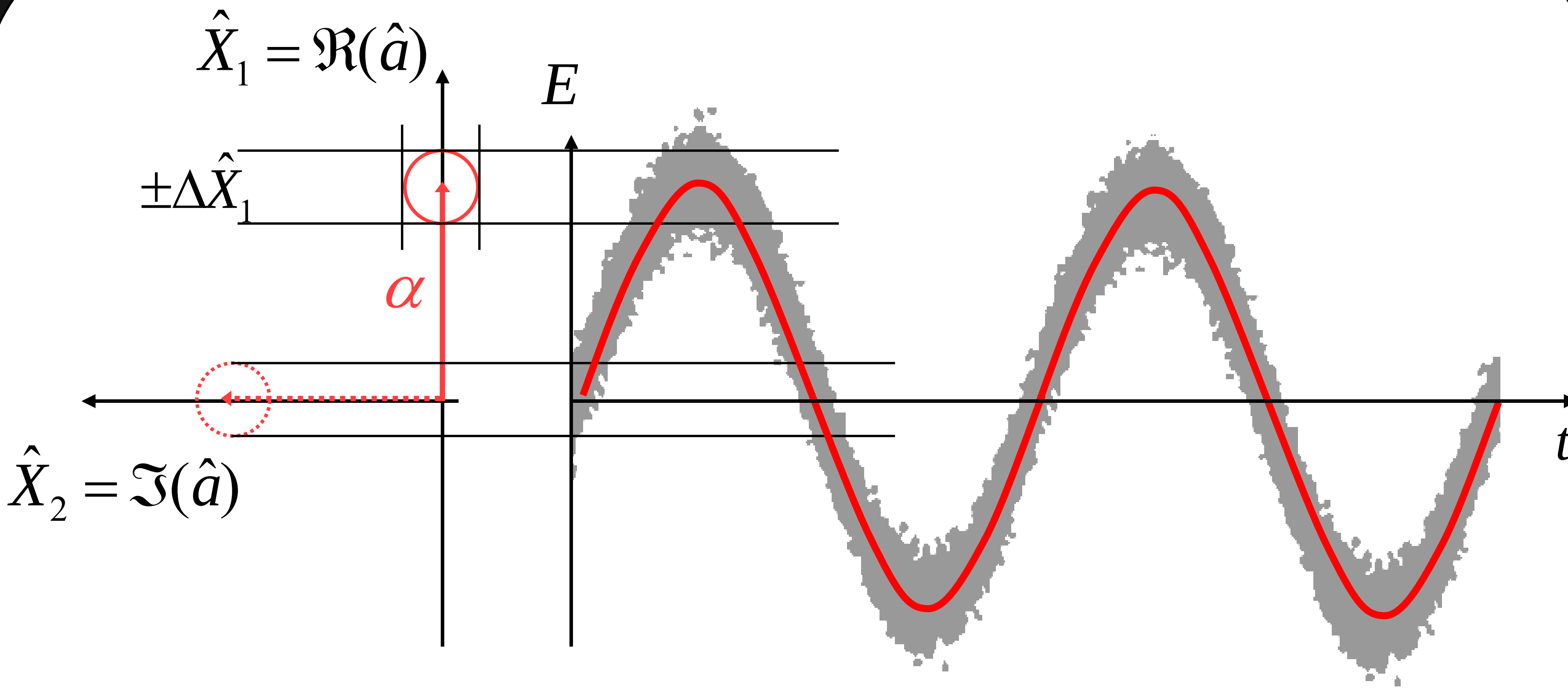
Chelkowski *et al*, PRA 71, 013806 (2005)

LOSS II



0
−5
−6
−7
−10
−15
−20
−25
−30
−35
−40
Inial Squeezing [dB]
0
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
Loss [%]

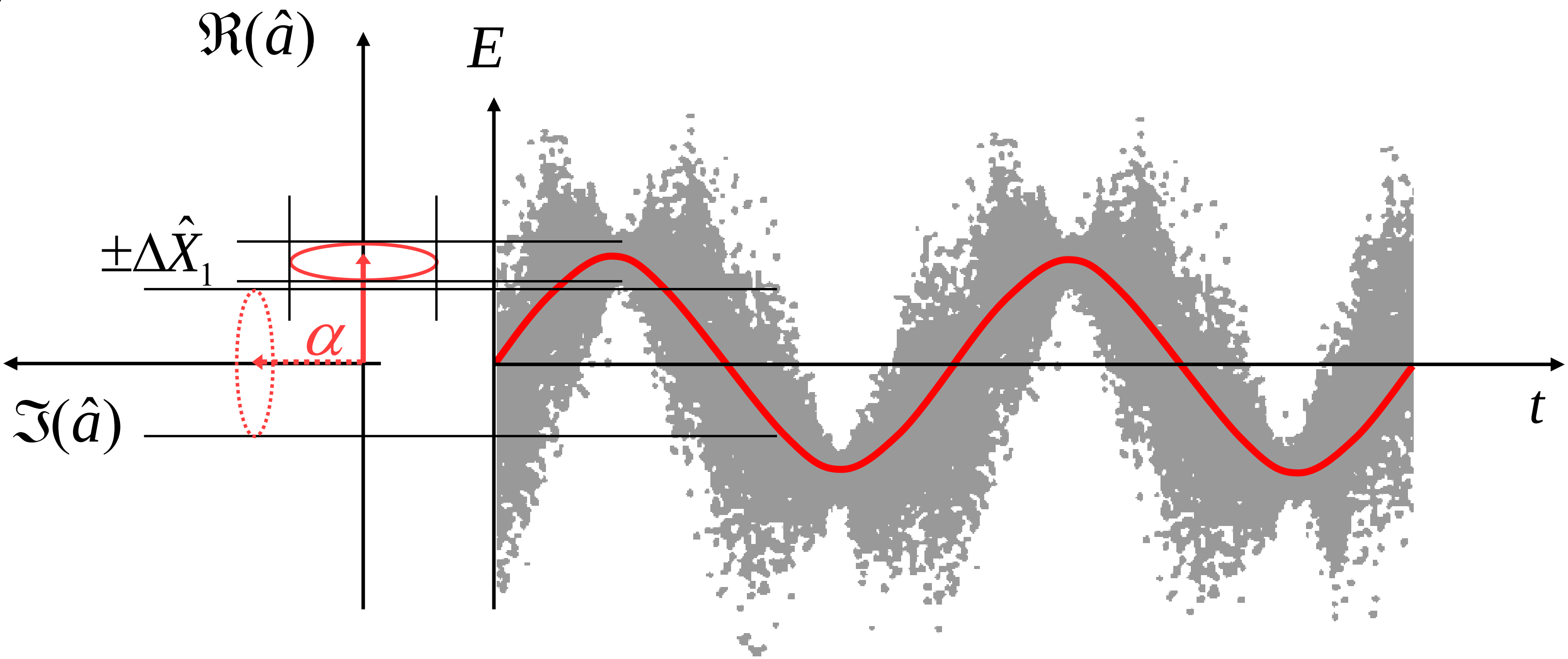
COHERENT STATE



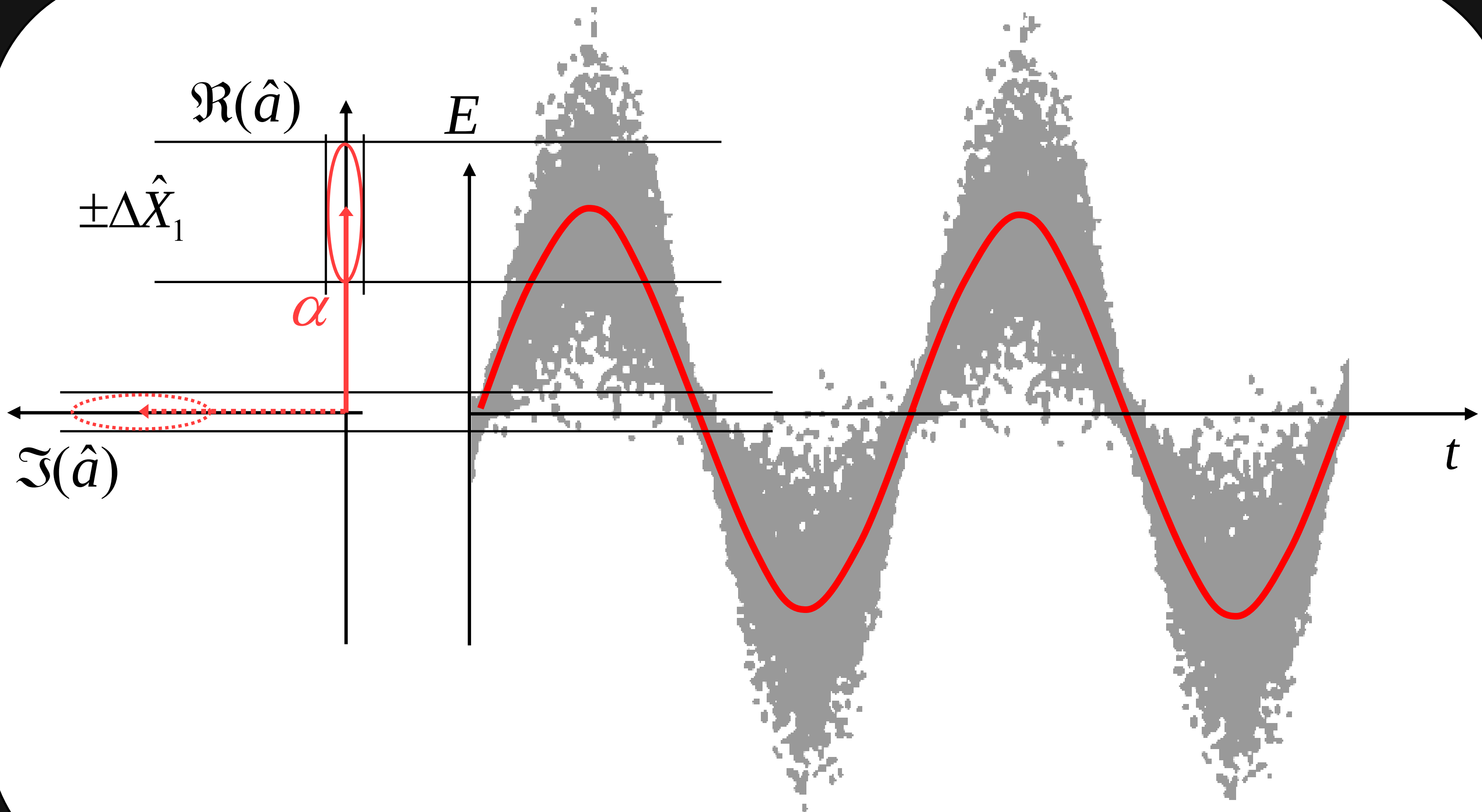
Coherent state $\Delta\hat{X}_1 = \Delta\hat{X}_2 = 1/4$

Coherent amplitude: $\alpha = \langle \hat{a} \rangle = \langle \alpha | \hat{a} | \alpha \rangle$

AMPLITUDE SQUEEZED LIGHT



PHASE SQUEEZED LIGHT



SQUEEZED VACUUM