Development of a Stable Low-Frequency Squeezed Vacuum Source for Gravitational Wave Interferometers

Keisuke Goda, Eugeniy Mikhailov, Thomas Corbitt,
Christopher Wipf, David Ottaway, Stan Whitcomb, Nergis Mavalvala
Quantum Measurement Group, LIGO Laboratory
Kavli Institute for Astrophysics and Space Research
Massachusetts Institute of Technology

Collaborators
Kirk McKenzie, Ping Koy Lam, Mal Gray, David McClelland
The Australian National University

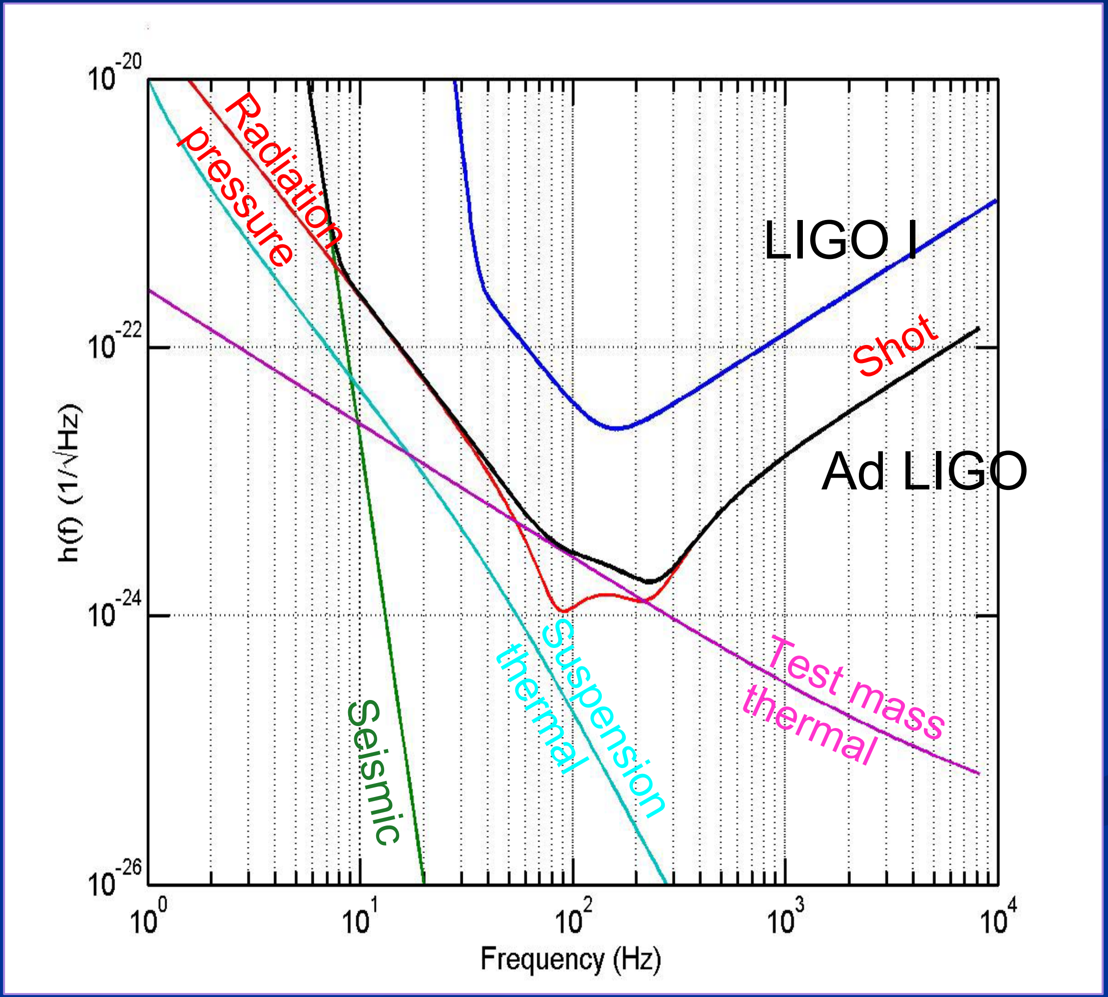
Caltech Special LIGO Seminar
July 29, 2005

Outline/Agenda

- Motivation and Goal
- Introduction to Quadrature Squeezing in OPO/OPA
- Some Results
- Requirements for Squeezing in GW Interferometers
- Work so far (by me, the group, and collaborators)
- Summary and Future Plans

Motivation and Goal

- The sensitivity of the next generation GW interferometers will be limited by **quantum noise** (and thermal noise).
- To go beyond that, must reduce the quantum noise
- Quantum noise:
  - **Radiation pressure noise** at low frequencies (below ~100Hz)
  - **Shot noise** at high frequencies (above ~100Hz)



Quantum Noise in GW Interferometers

- The sensitivity of next generation GW interferometers will be limited by **quantum noise**.
- **Shot Noise**

$$h(f) \propto \sqrt{\frac{1}{P_{bs}}}$$

  - Uncertainty in number of photons detected ⇨
  - Higher input power P_{bs} ⇨ need low optical losses
  - Frequency dependence ⇨ depends on light (GW signal) storage time in the interferometer
  - **Important at high frequencies (>100Hz)**
- **Radiation Pressure Noise**

$$h(f) \propto \sqrt{\frac{P_{bs}}{Mf^4}}$$

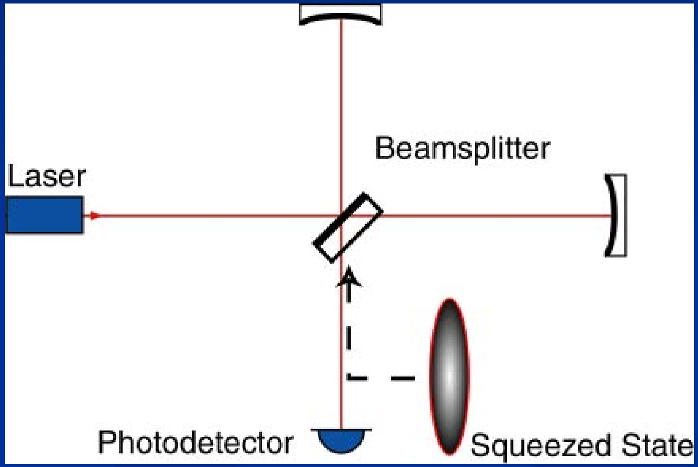
  - Photons impart momentum to cavity mirrors
  - Fluctuations in the number of photons ⇨
  - Lower input power, P_{bs}
  - **Important at low frequencies (<100Hz)**

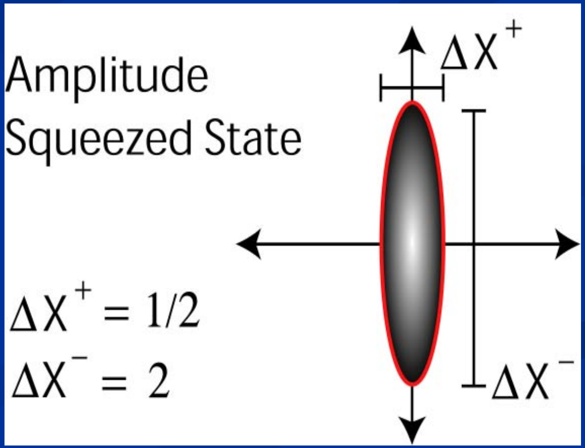
Squeezed State in a Michelson

How to increase the sensitivity of GW interferometers?

- **Inject** a squeezed field into the **dark port** of a Michelson interferometer to replace vacuum noise

C.M. Caves, Phys. Rev. D **23**, 1693 (1981)





K. McKenzie

Before going into the details of the issues..

Introduction to Quadrature Squeezing in Optical Parametric Oscillation/Amplification (OPO/OPA)

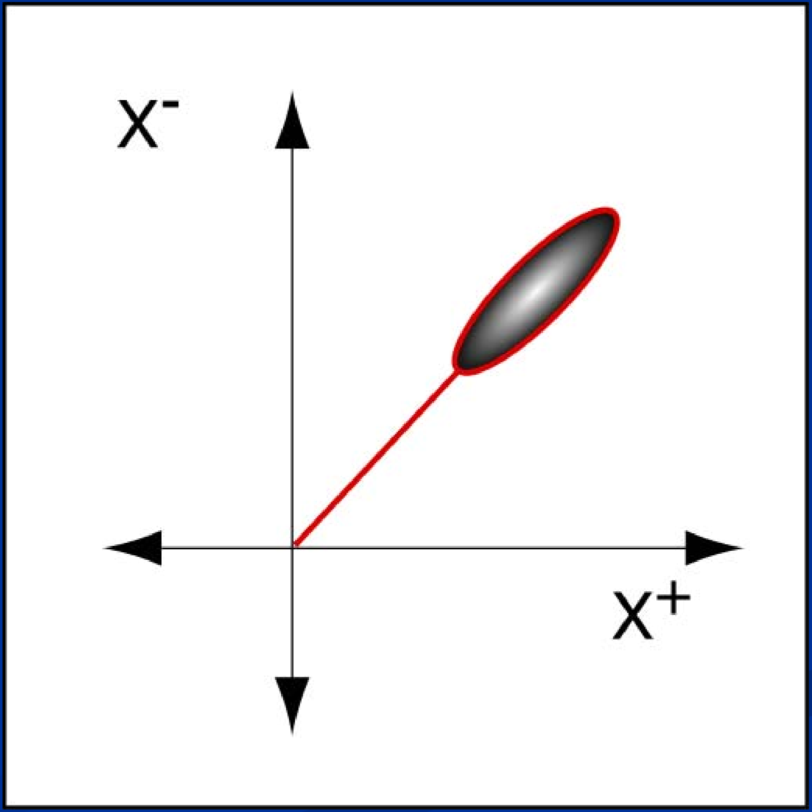
Quantum States of Light/Vacuum

- Analogous to the phasor diagram
- Stick → dc term
- Ball → fluctuations
- Common states
  - **Coherent state**
  - **Vacuum state**
  - **Amplitude squeezed state**
  - **Phase squeezed state**

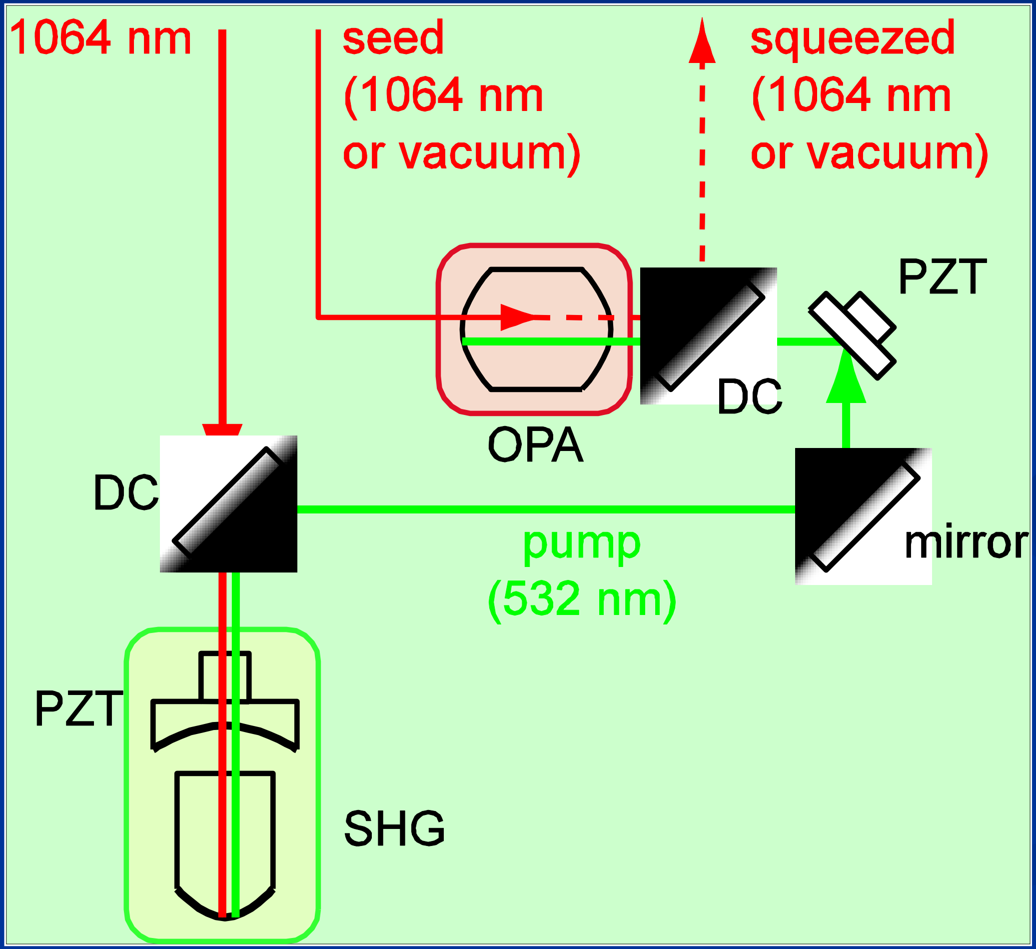
$$\begin{cases} X_1 = a + a^{+} \\ X_2 = i(a - a^{+}) \end{cases}$$

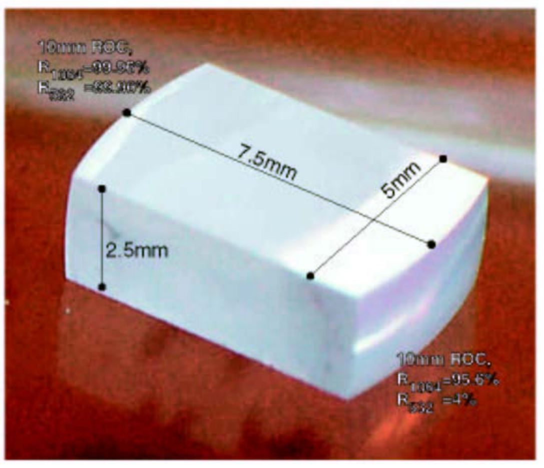
1 or + = amplitude

2 or - = phase



Generation of Squeezed States in Optical Parametric Amplification (OPA)





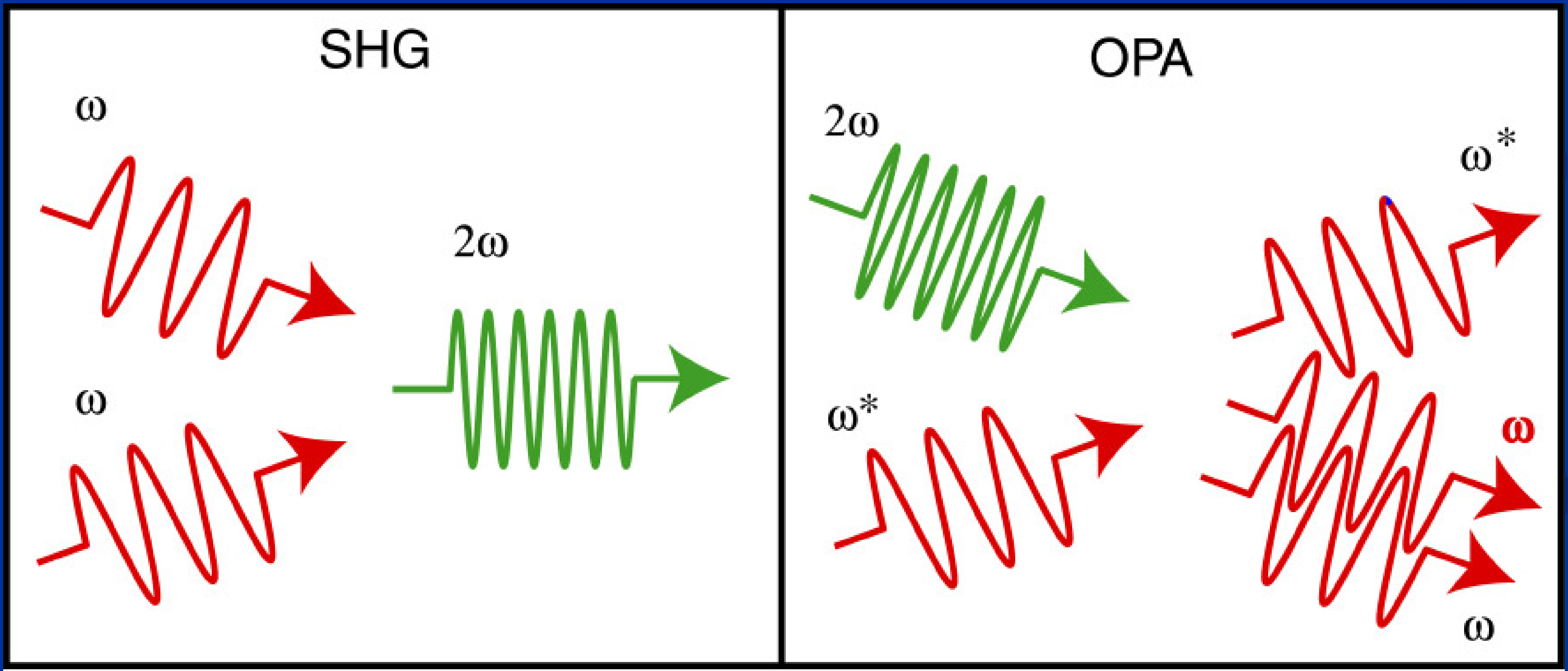
OPA crystal ($MgO:LiNbO_3$)

Typically, the OPA is a cavity at 1064nm and single/double pass at 532nm

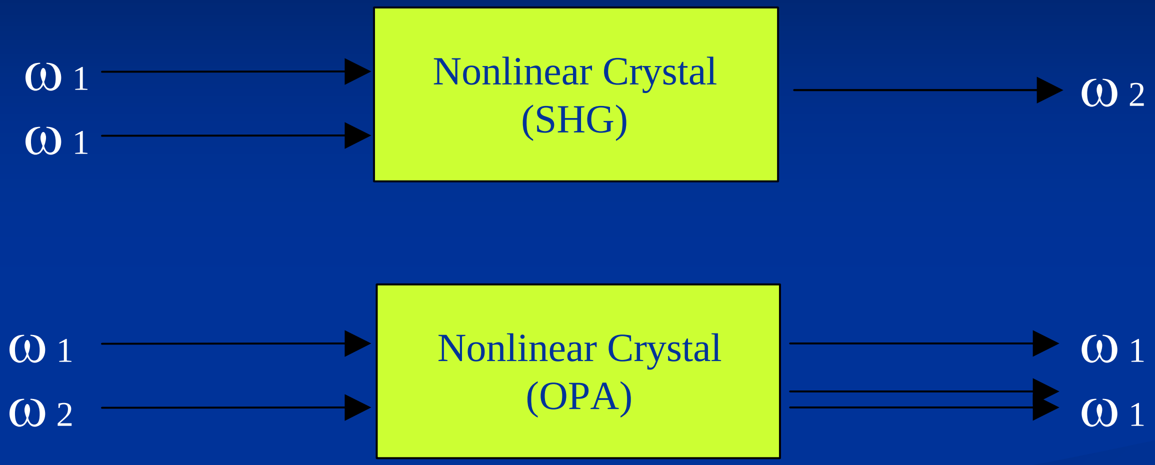
Before Squeezing, A Little Introduction to Nonlinear Optics

- Optical parametric amplification (OPA)
- Seed (1064nm): field "a"
- Pump (532nm): field "b"

$$H = \hbar\omega_1 a^+ a + \hbar\omega_2 b^+ b + \frac{1}{2} i\hbar\kappa (b a^{+2} - b^+ a^2)$$



Required Conditions



ω 1
ω 1
Nonlinear Crystal (SHG)
ω 2

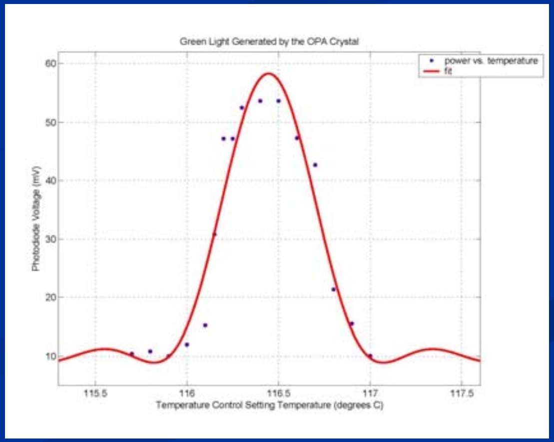
ω 1
ω 2
Nonlinear Crystal (OPA)
ω 1
ω 1

- Energy conservation

$$2\omega_1 = \omega_2$$

- Momentum conservation (phase-matching condition)

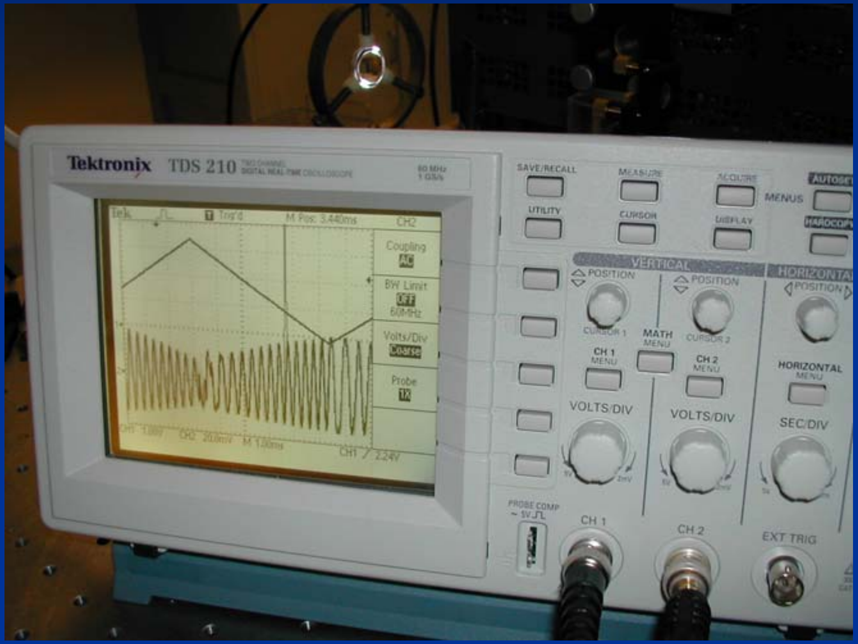
$$2k_1 = k_2$$

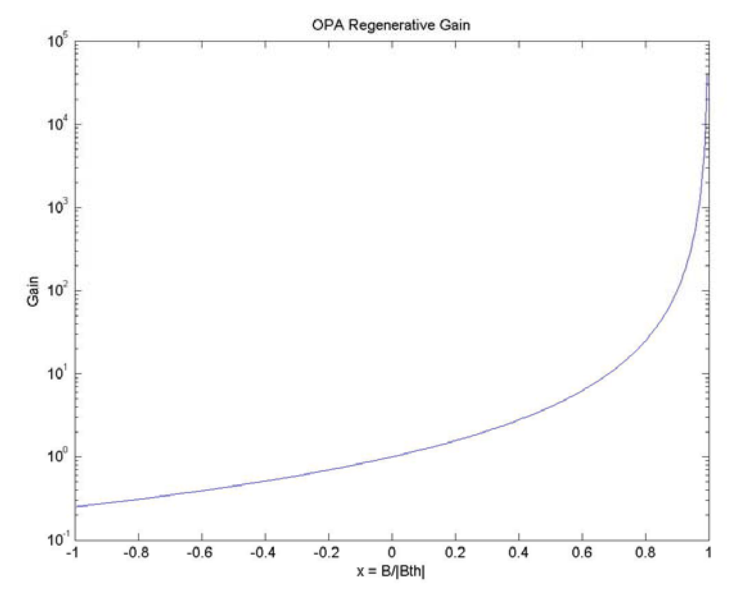


K. Goda

The phase-matching parameter is temperature-dependent, and therefore the crystal requires temperature control.

Parametric Amplification/De-amplification





- Ramp signal driving the phase-matching PZT (upper)
- Parametric amplification and de-amplification of the seed beam (lower)
- Parametric amplification or deamplification is determined by the relative phase between the seed and pump

$$G=\frac{P^{out}_{(\varepsilon)}}{P^{out}_{(\varepsilon=0)}}=\left(\frac{1+x}{1-x^{2}}\right)^{2},\ where\ \ x=\frac{B_{in}}{\left|B^{threshold}_{in}\right|}$$

Simple Model of Squeezing 1

$$H = \hbar\omega_1 a^+ a + \hbar\omega_2 b^+ b + \frac{1}{2} i\hbar\kappa(b a^{+2} - b^+ a^2)$$

In the Heisenberg picture, using

$$\frac{d}{dt}O(t) = \frac{i}{\hbar}[H, O(t)]$$

and

$$[a(t), a^+(t)] = 1$$

The Heisenberg equations of motion for the signal mode:

$$\begin{cases} \dfrac{d}{dt}a(t) = -i\kappa\beta a^+(t) - \dfrac{\Gamma}{2}a + N(t) \\ \dfrac{d}{dt}a^+(t) = i\kappa\beta a(t) - \dfrac{\Gamma}{2}a^+ + N^+(t) \end{cases}$$

Γ= the cavity decay rate, N(t) = the associated noise operator.

Simple Model of Squeezing 2

For the signal initially in a vacuum state, the expectation values in the steady state are

$$\langle a(t)\rangle_{ss} = \langle a^{+}(t)\rangle_{ss} = 0$$

$$\langle a^{2}(t)\rangle_{ss} = \langle a^{+2}(t)\rangle_{ss} = \frac{-\Gamma\kappa\beta}{2(\Gamma^{2}-(\kappa\beta)^{2})}$$

$$\langle a(t)a^{+}(t)+a^{+}(t)a(t)\rangle_{ss} = \frac{\Gamma^{2}}{2(\Gamma^{2}-(\kappa\beta)^{2})}$$

The field amplitudes in the amplitude and phase quadratures are defined by X1 and X2 (1 = amplitude, 2 = phase). The noise variances of the field amplitudes in the steady state are given by

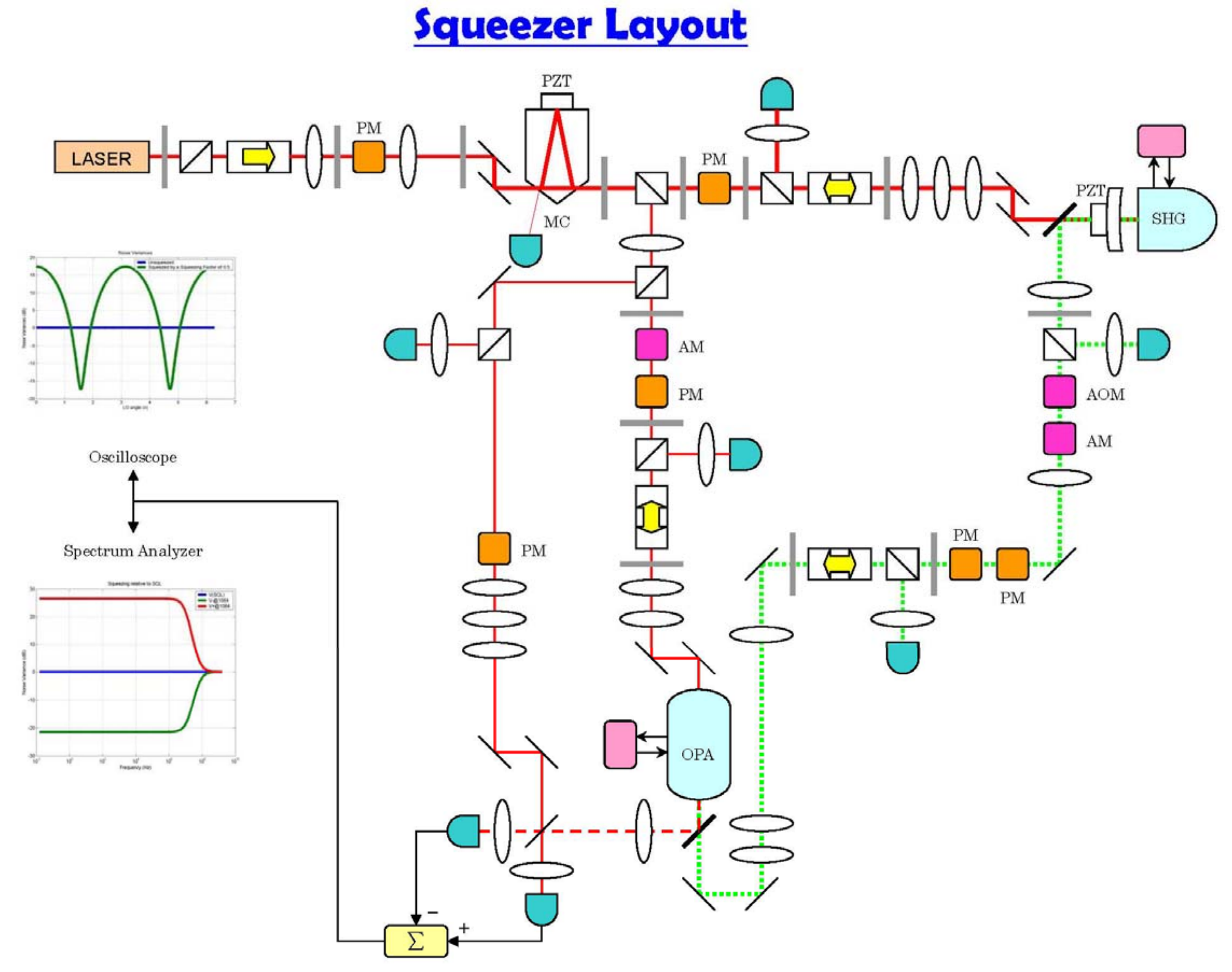
$$\begin{cases} X_1 \equiv a + a^{+} \\ X_2 \equiv i(a - a^{+}) \end{cases}$$

$$\begin{cases} \Delta X_1 \equiv \sqrt{< X_1^2 > - < X_1 >^2} = \sqrt{\dfrac{\Gamma}{\Gamma+\kappa\beta}} < 1 \\ \Delta X_2 \equiv \sqrt{< X_2^2 > - < X_2 >^2} = \sqrt{\dfrac{\Gamma}{\Gamma-\kappa\beta}} > 1 \end{cases}$$

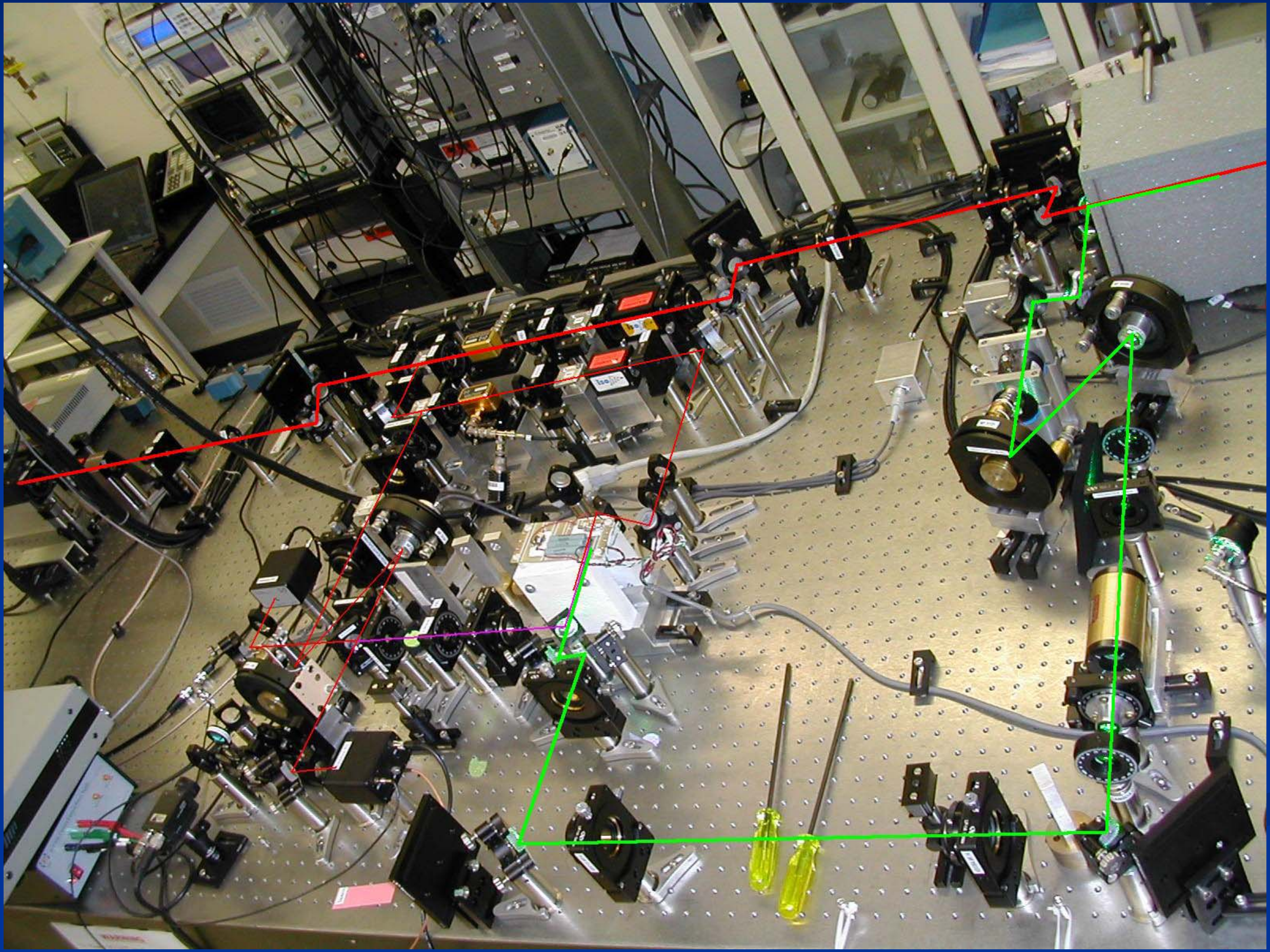
ΔX_1 squeezed!!

The level of squeezing increases with the coupling constant, k.

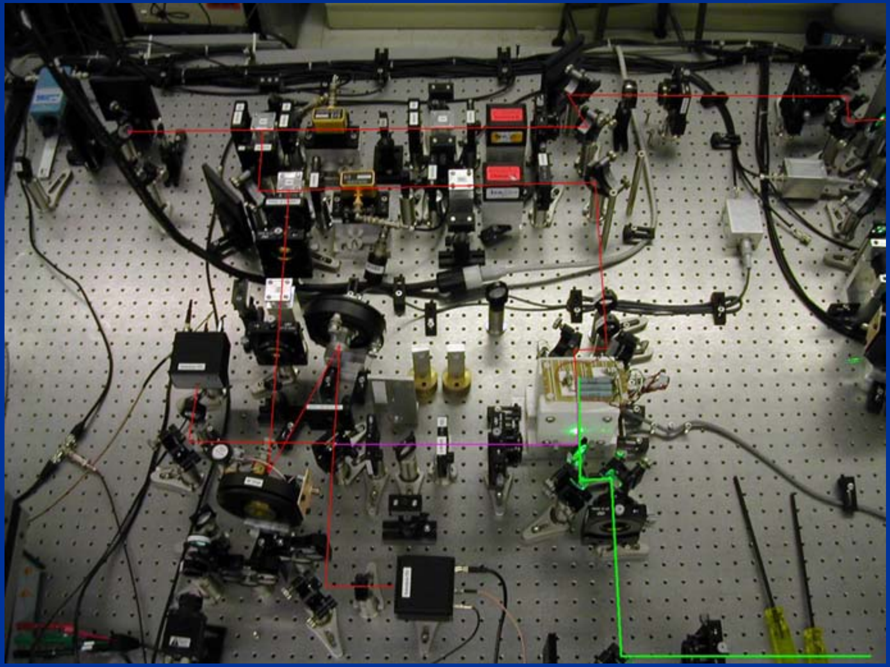
Squeezer Layout



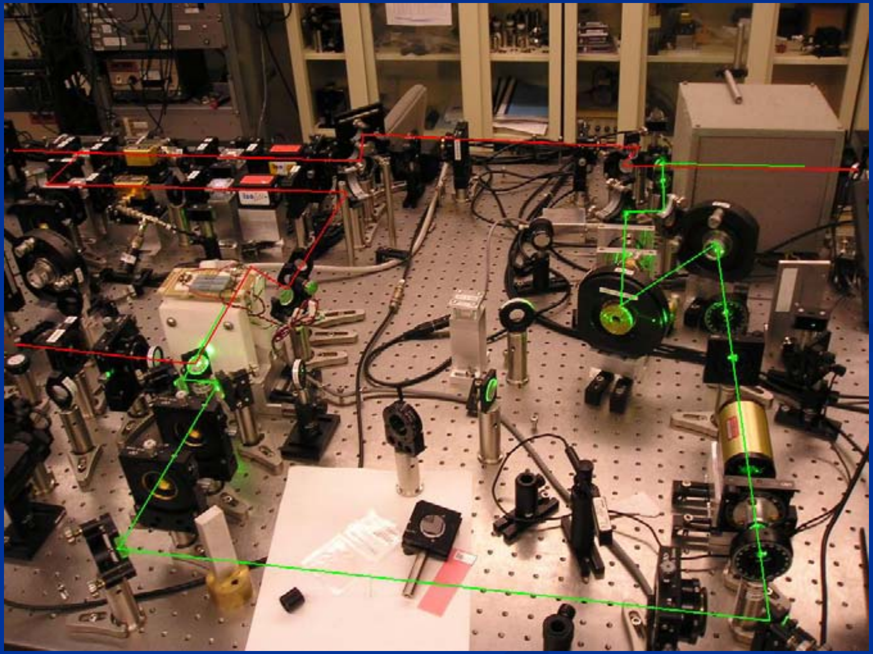
Squeezer @ MIT



Squeezer @ MIT

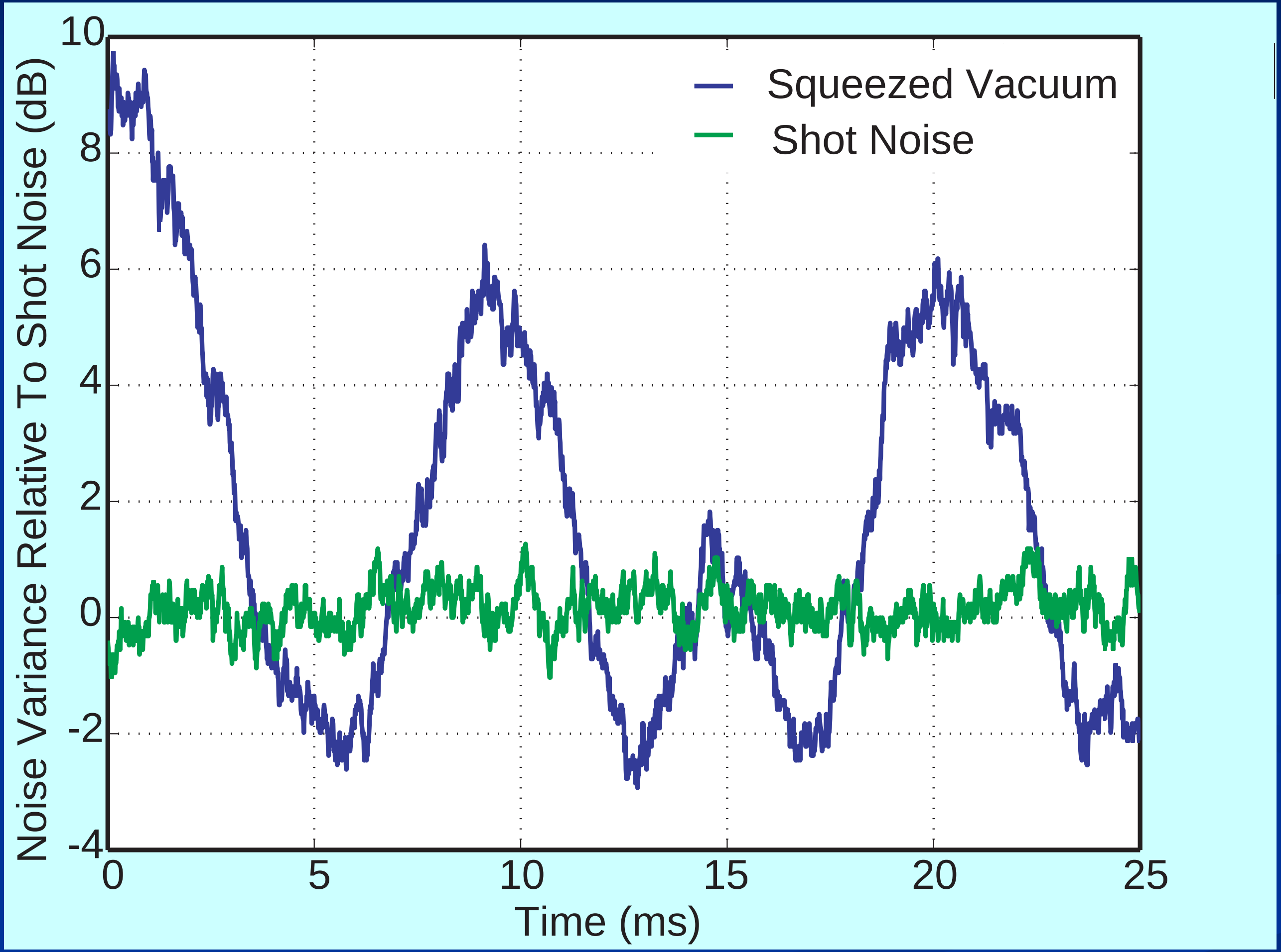


Homodyne Detector



OPA and SHG

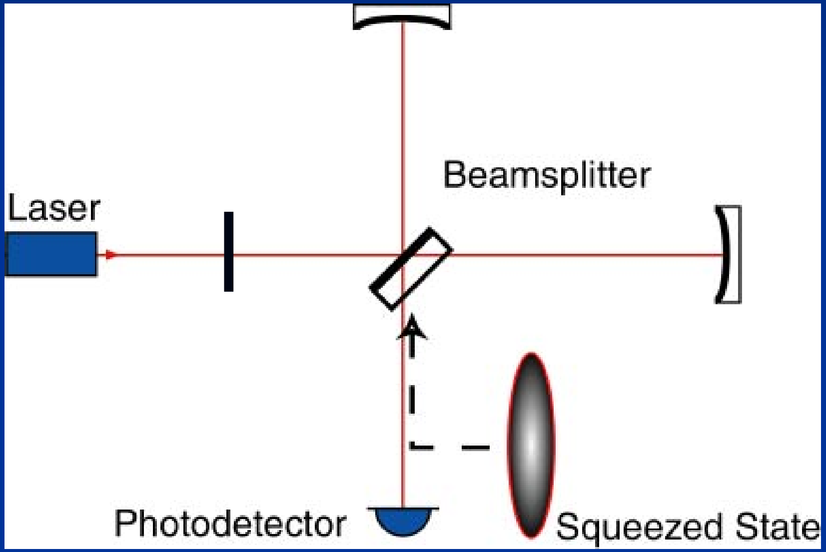
Squeezing Result



K. Goda

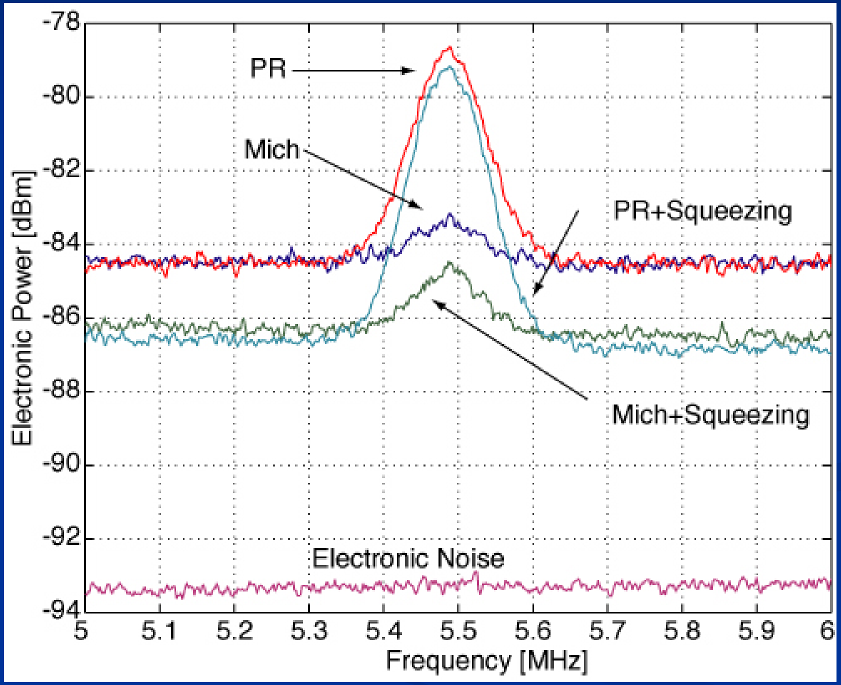
Roughly 10dB of squeezing was created in the OPO cavity, but it was reduced down to 3dB of squeezing due to losses.

Table-Top Demonstration



K. McKenzie

table-top demonstration of squeezing in a Michelson interferometer with a power recycling mirror



K. McKenzie

Injection of squeezed **light** into the dark port

K. McKenzie, B.C. Buchler, D.A. Shaddock, P.K. Lam, and D.E. McClelland, Phys. Rev. Lett. 88, 231102 (2002)

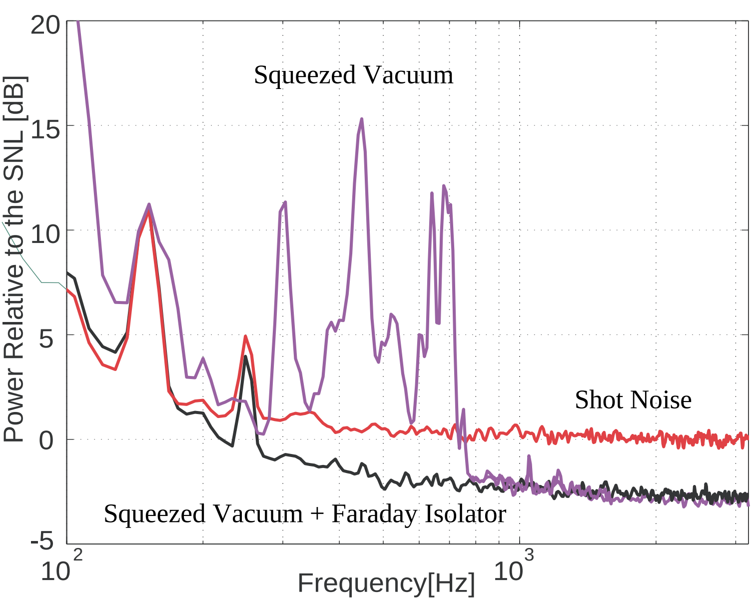
Requirements for Squeezing in GW Interferometers (practical issues and what has been achieved)

Requirements for Squeezing in GW Interferometers

- **Squeezing in the GW Band (10Hz – 10kHz)**
  - Squeezed vacuum preferred as opposed to squeezed light
  - Photothermal noise, laser excess noise, etc..
- **Increased Level of Squeezing (ideally 10dB or higher)**
  - Again, squeezed vacuum preferred to have a shot noise limited seed
  - Use better crystals, change the OPO cavity configuration, etc..
- **Long-Term Stability for Operation**
  - Control signal required for phase-locking squeezed vacuum
  - Noise-locking, frequency-shifted sub-carrier, etc..
- **Frequency-Dependent Squeeze Angle**
  - Phase-squeezing at high frequencies (<100Hz) and amplitude-squeezing at low frequencies (>100Hz) required
  - Long squeeze angle rotation cavities, squeeze amplitude filter cavities, etc..

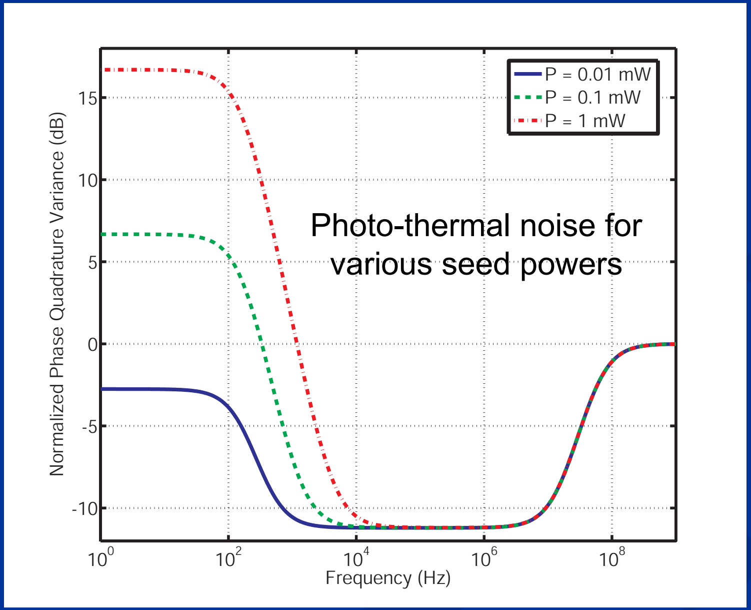
Squeezing in the GW Band (10Hz – 10kHz)

- Historically, squeezing has been done at ~MHz.
- Squeezed light has been used for applications.
- However, for application to GW interferometers, **squeezed vacuum** is preferred as opposed to squeezed light.



Noise-locked squeezed vacuum down to frequencies as low as 280Hz

K. McKenzie, Nicolai Grosse, W.P. Bowen, S.E. Whitcomb, M.B. Gray, D.E. McClelland, and P.K. Lam, Phys. Rev. Lett. **93**, 161105 (2004)



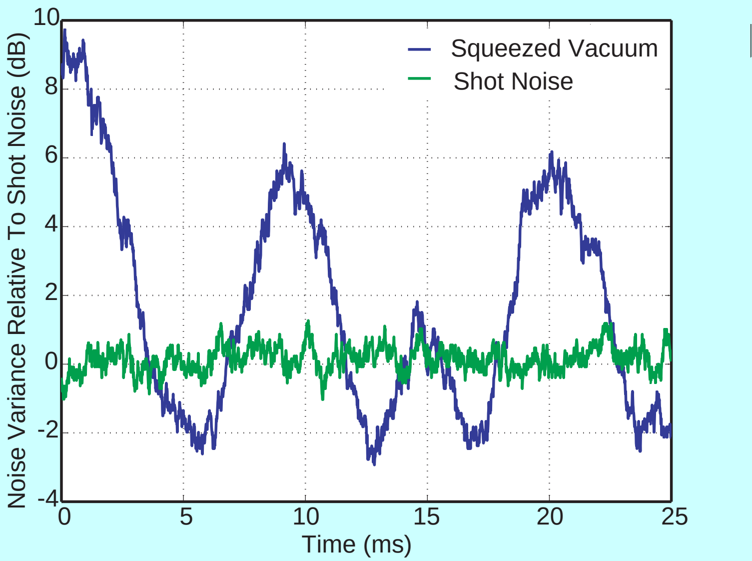
Limiting noise sources at low frequencies (photo-thermal noise, laser noise, etc..)

K. Goda, K. McKenzie, E. Mikhailov, P.K. Lam, D. McClelland, and N. Mavalvala, submitted to Phys. Rev. A, quant-ph/0505154

Phase-Locking Squeezed Vacuum for Long-Term Stability

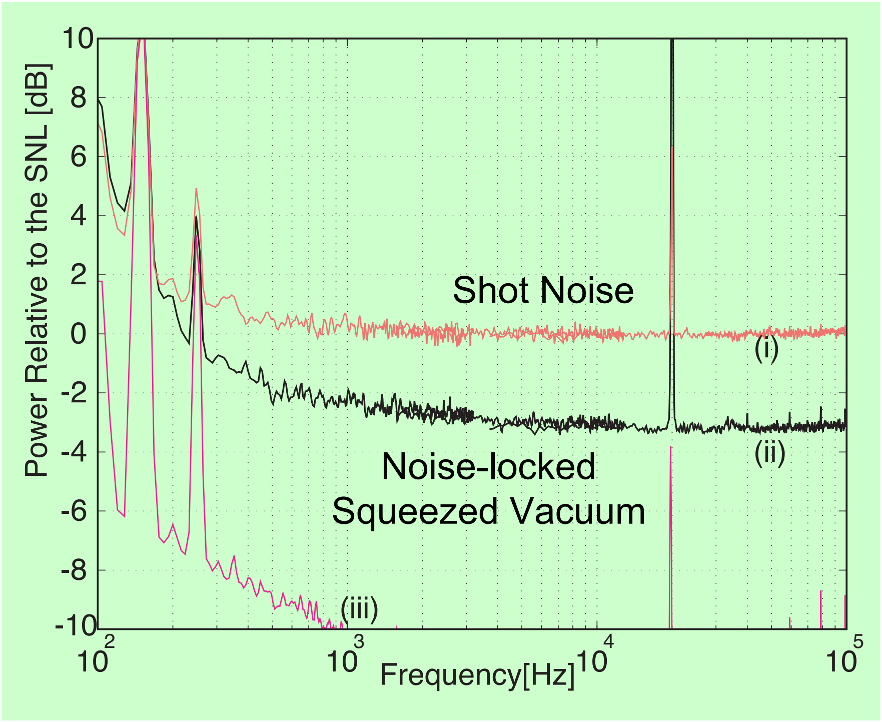
- Squeezed vacuum is hard to control since it has no carrier light.
- Noise-locking and/or frequency-shifted sub-carrier technique can be used

  K. McKenzie, E. Mikhailov, K. Goda, P.K. Lam, N. Grosse, M.B. Gray, N. Mavalvala, and D.E. McClelland, J. Opt. B: Quantum Semiclass. Opt., quant-ph/0505164



Unlocked squeezed vacuum..

If the squeezing spectrum itself is modulated to obtain a control signal..



Noise-locked squeezed vacuum

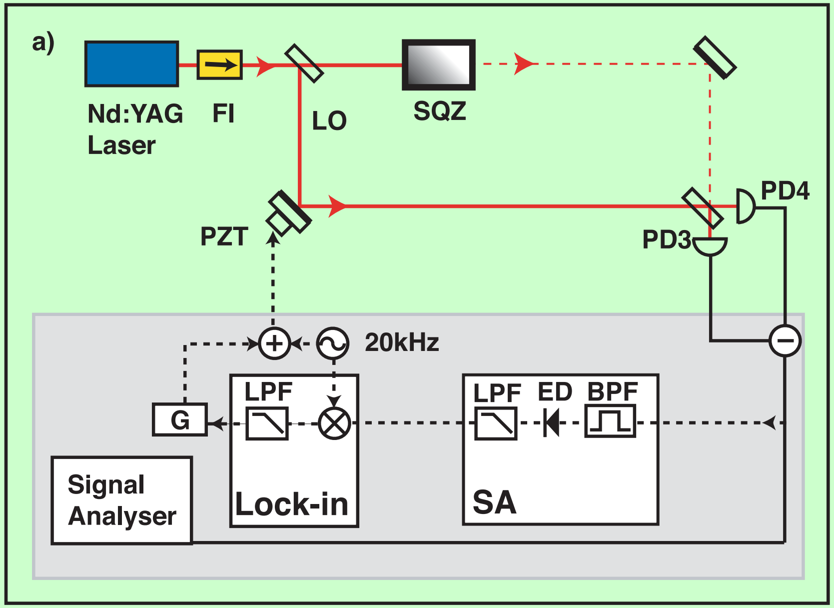
Stability of Noise-Locking

- The stability of noise-locking depends on the level of squeezing.
- The more squeezing you have, the more stable your noise-locking is.

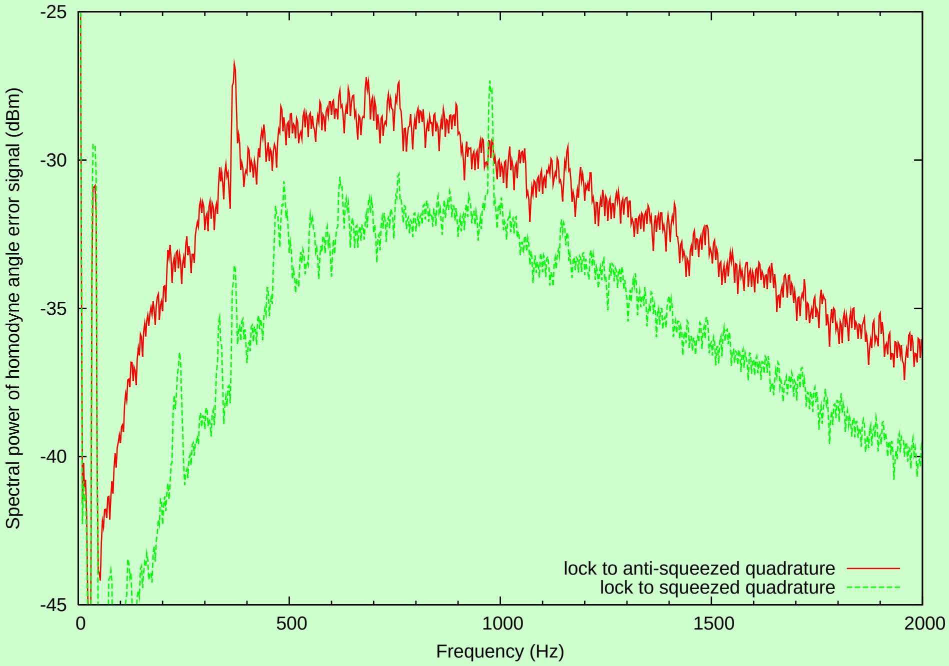
Instability or Fluctuations in Noise-Locked Angle

$$\Delta\theta \sim \frac{1}{\sqrt{e^{4R}-1}}\left(\frac{1}{\Delta\omega}\right)^{1/4}$$

$\Delta\omega$ = detection bandwidth
R = squeeze factor



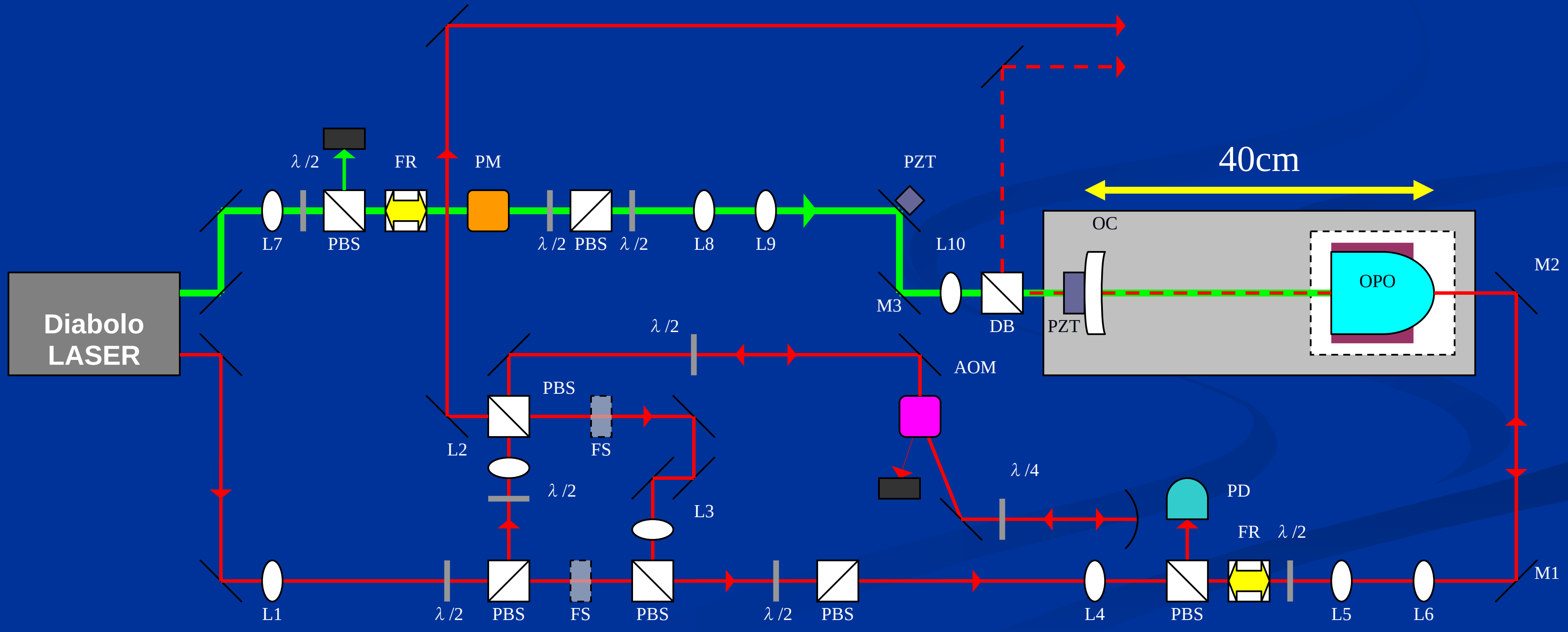
Schematic of the Noise-Locked Squeezer



Noise Power of the Noise-Locking Error Signal

Locking Squeezed Vacuum with Coherent Light

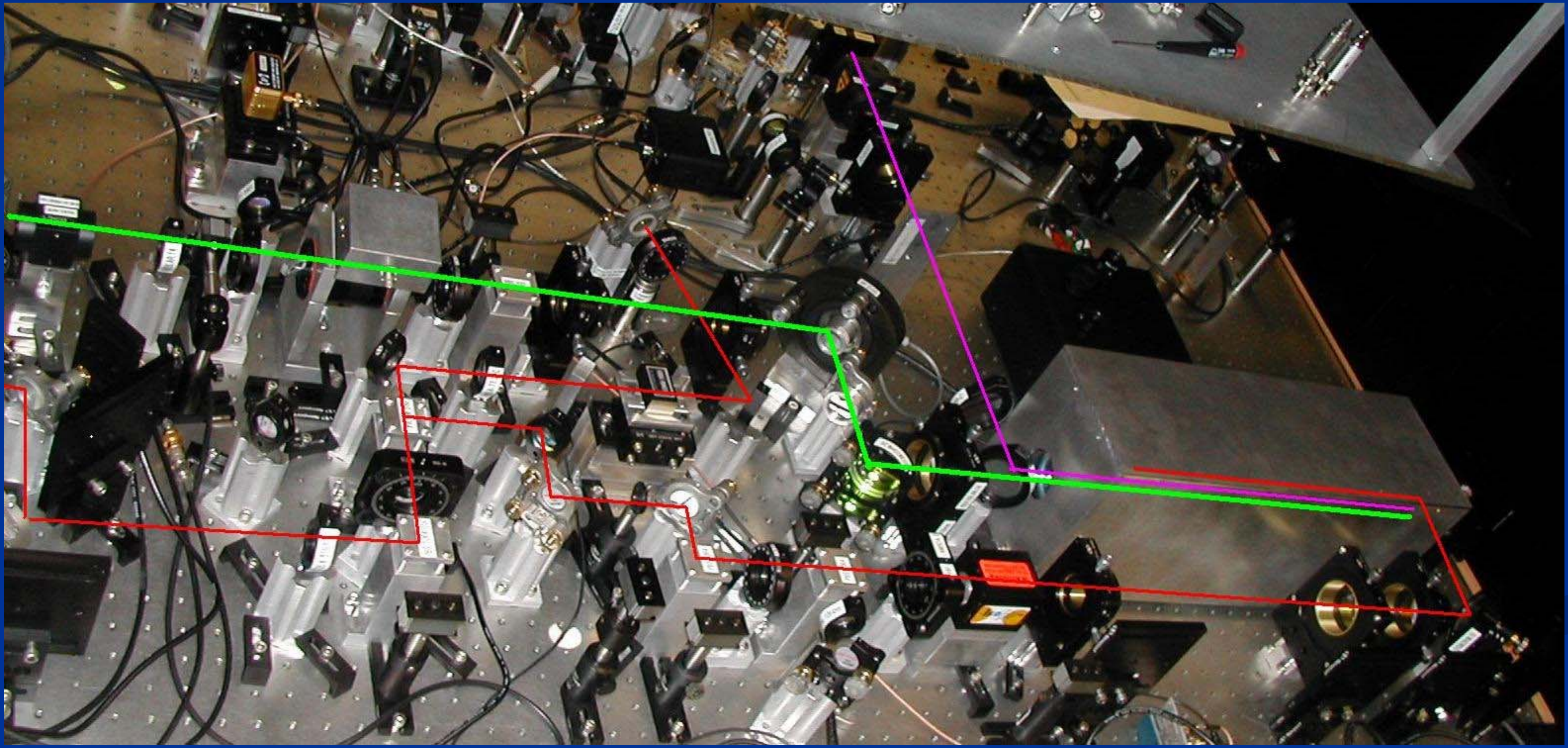
- Create bright sidebands on top of squeezed vacuum
- Extract the squeeze angle information by measuring the optical parametric amplification of the signal and idler beams which are at the carrier frequency ± FSR



K. Goda

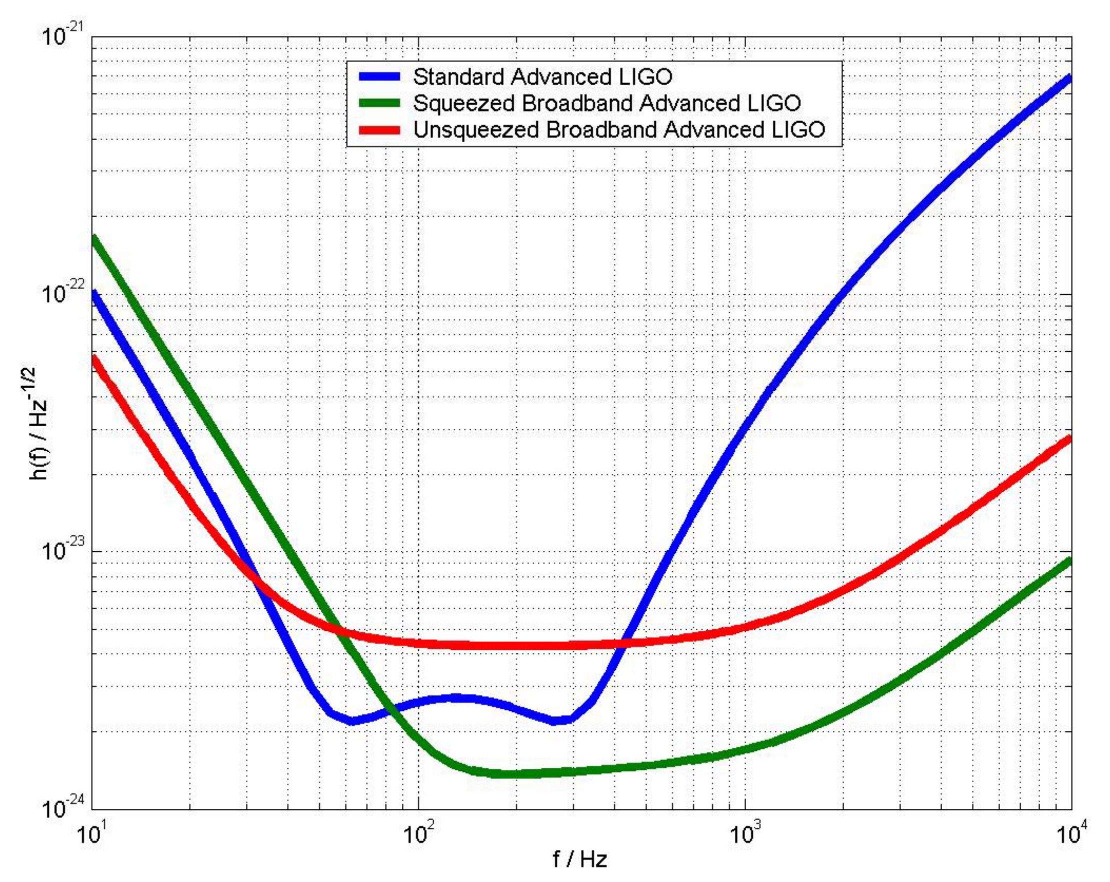
Squeezed Vacuum with Bright Sidebands

- ~10dB of squeezing (before detection)
- Bright sidebands used to control the squeeze angle



Advanced LIGO

(The need for Frequency-Dependent Squeeze Angle)

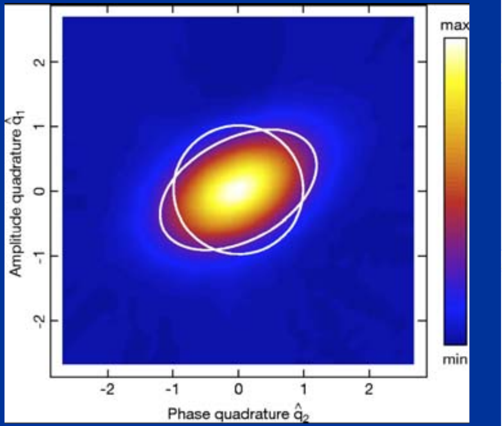


T. Corbitt

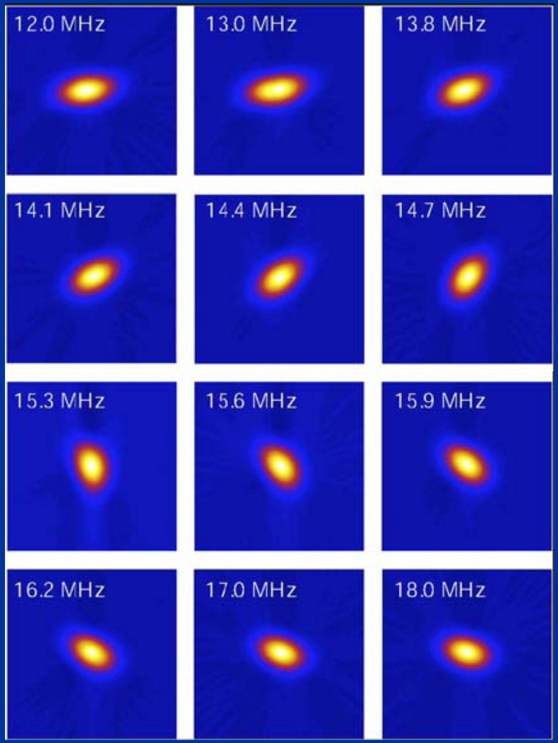
Frequency-Dependent Squeeze Angle

- For broadband Advanced LIGO, the detector sensitivity will be limited by **phase/shot noise at high frequencies** (>100Hz) and **amplitude/radiation-pressure noise at low frequencies** (<100Hz).

- Need frequency-dependent squeeze angle, i.e., phase squeezing at high frequencies and amplitude squeezing at low frequencies



Wigner function



- Squeeze angle rotated by a filter cavity

  S. Chelkowski, H. Vahlbruch, B. Hage, A. Franzen, N. Lastzka, K. Danzmann, and R. Schnabel, Phys. Rev. A **71**, 013806 (2005)

- However, this was done at ~MHz, not ideal for 10Hz – 10kHz for GW interferometers.

Summary and Future Work

- Low-frequency squeezing with the noise-locking technique achieved
  - K. McKenzie, Nicolai Grosse, W.P. Bowen, S.E. Whitcomb, M.B. Gray, D.E. McClelland, and P.K. Lam, Phys. Rev. Lett. **93**, 161105 (2004)
  - K. Goda, K. McKenzie, E. Mikhailov, P.K. Lam, D. McClelland, and N. Mavalvala, submitted to Phys. Rev. A, quant-ph/0505154
  - K. McKenzie, E. Mikhailov, K. Goda, P.K. Lam, N. Grosse, M.B. Gray, N. Mavalvala, and D.E. McClelland, J. Opt. B: Quantum Semiclass. Opt., quant-ph/0505164
- Experimental demonstration of noise-locking
  - K. McKenzie, E. Mikhailov, K. Goda, P.K. Lam, N. Grosse, M.B. Gray, N. Mavalvala, and D.E. McClelland, J. Opt. B: Quantum Semiclass. Opt., quant-ph/0505164
- A few different control schemes of squeezed vacuum under way
  - to be submitted to Phys. Rev. A
- Theoretical and experimental work on the increased level of squeezing under way
  - to be submitted to Phys. Rev. A or JOSA
- Theoretical work on frequency-dependent squeeze angle rotation and increased level of squeezing under way
  - to be submitted to Phys. Rev. Lett.

- **Future Plans**
  - Testing DC readout-compatible squeezing with 40M