Experimental Demonstration of a Squeezing-Enhanced Laser-Interferometric Gravitational-Wave Detector

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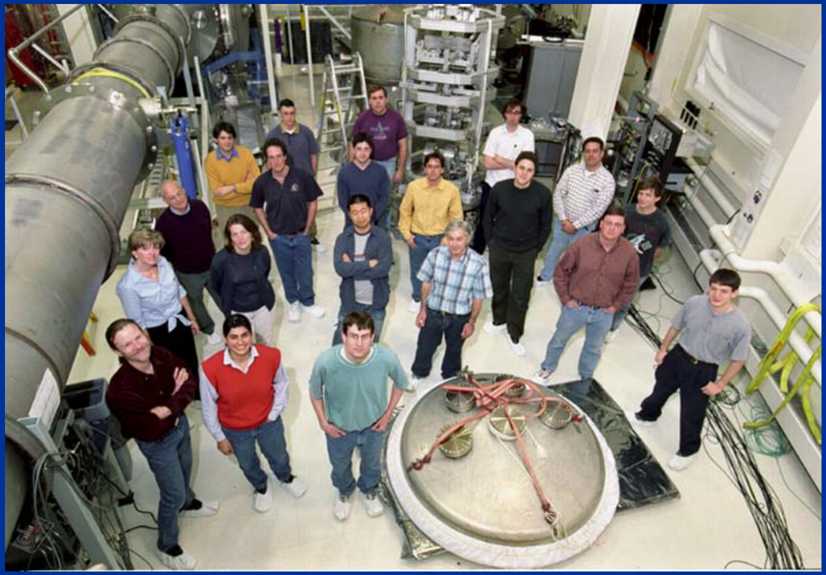

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  The College of William and Mary
- Shailendhar Saraf
  Rochester Institute of Technology
- Kirk McKenzie, Ping Koy Lam, Malcolm Gray, David McClelland
  Australian National University

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Technical Plenaries

Outline

- Motivation and Goal
- Squeezing Project at 40m
- Experimental Apparatus
- Results
- Summary and Future Work

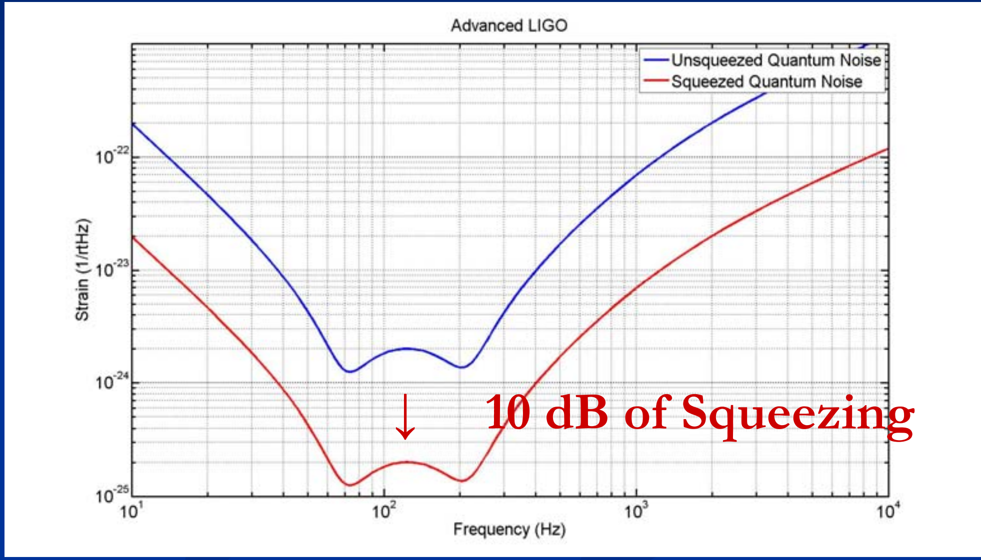
Quantum-Noise-Limited Detectors

- The sensitivity of the next generation GW detectors such as Advanced LIGO will be mostly limited by **quantum noise** in the GW band (10Hz – 10kHz).
- Quantum noise:
  - **Shot Noise** at high frequencies (above ~100Hz)

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

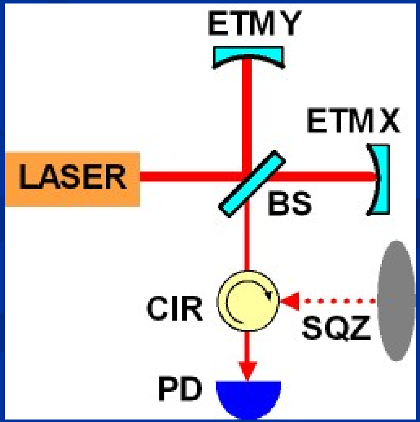
  - **Radiation Pressure Noise** at low frequencies (below ~100Hz)

$$h(f) \propto \frac{\sqrt{P}}{mf^2}$$



The sensitivity can be improved by the **injection of squeezed states** to the dark port with a proper squeeze angle.

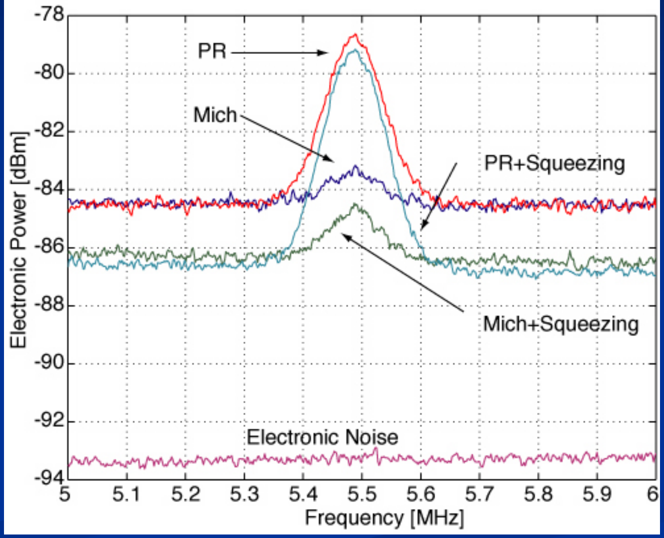
C. M. Caves, Phys. Rev. D 23, 1693 (1981)

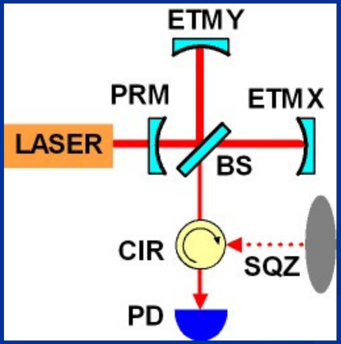


Squeezing-Enhanced Table-Top Interferometers

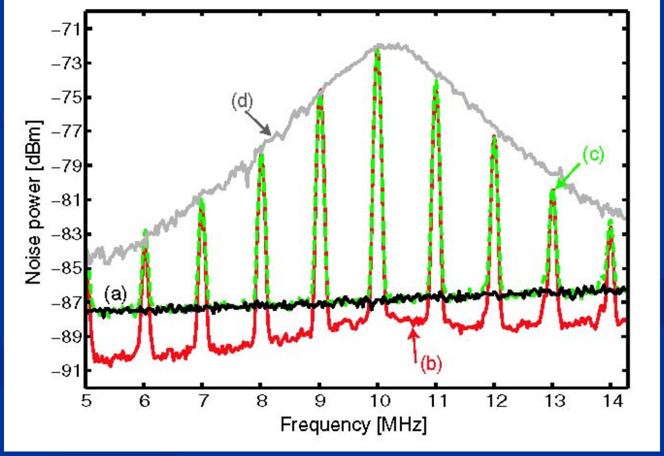
1. **Squeezing-Enhanced Mach-Zehnder Interferometer**
   M. Xiao, L-A Wu, and H. J. Kimble, Phys. Rev. Lett. 59, 278 (1987)
   - First demonstration of squeezing-enhanced interferometry

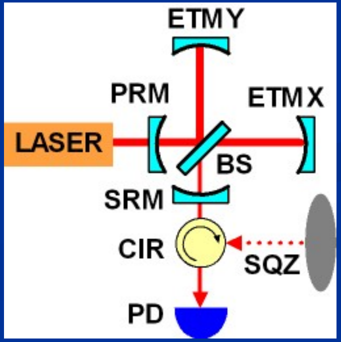
2. **Power-Recycled Michelson Interferometer**
   K. McKenzie, B.C. Buchler, D.A. Shaddock, P.K. Lam, and D.E. McClelland, Phys. Rev. Lett. 88, 231102 (2002)
   - Demonstrated squeezing-enhancement at MHz and an increase in S/N
   - Used squeezed light





3. **Dual-Recycled Michelson Interferometer**
   H. Vahlbruch, S. Chelkowski, B. Hage, A. Franzen, K. Danzmann, and R. Schnabel, Phys. Rev. Lett. 95, 211102 (2005)
   - Demonstrated squeezing-enhancement at MHz and an increase in S/N
   - Implemented a filter cavity that rotates the squeeze angle at MHz
   - Used squeezed light





ULTIMATE GOAL

Implementation of **Squeezing-Enhancement** in Laser-Interferometric Gravitational-Wave Detectors in the Advanced LIGO Configuration

IMMEDIATE GOAL

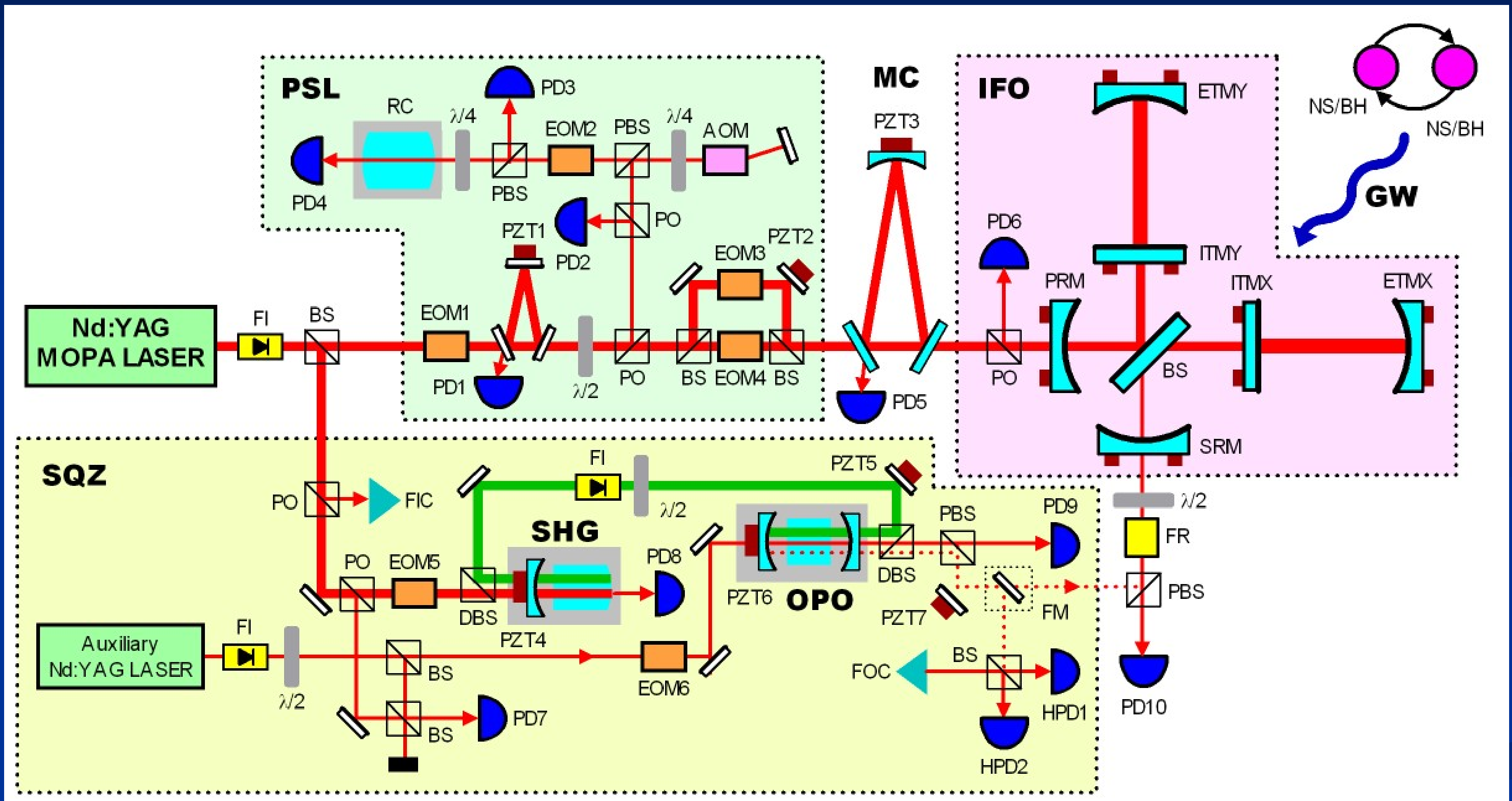
Demonstration of the technology necessary to reach the ultimate goal

↓ ↓ ↓

Squeezing Project @ Caltech 40m Lab

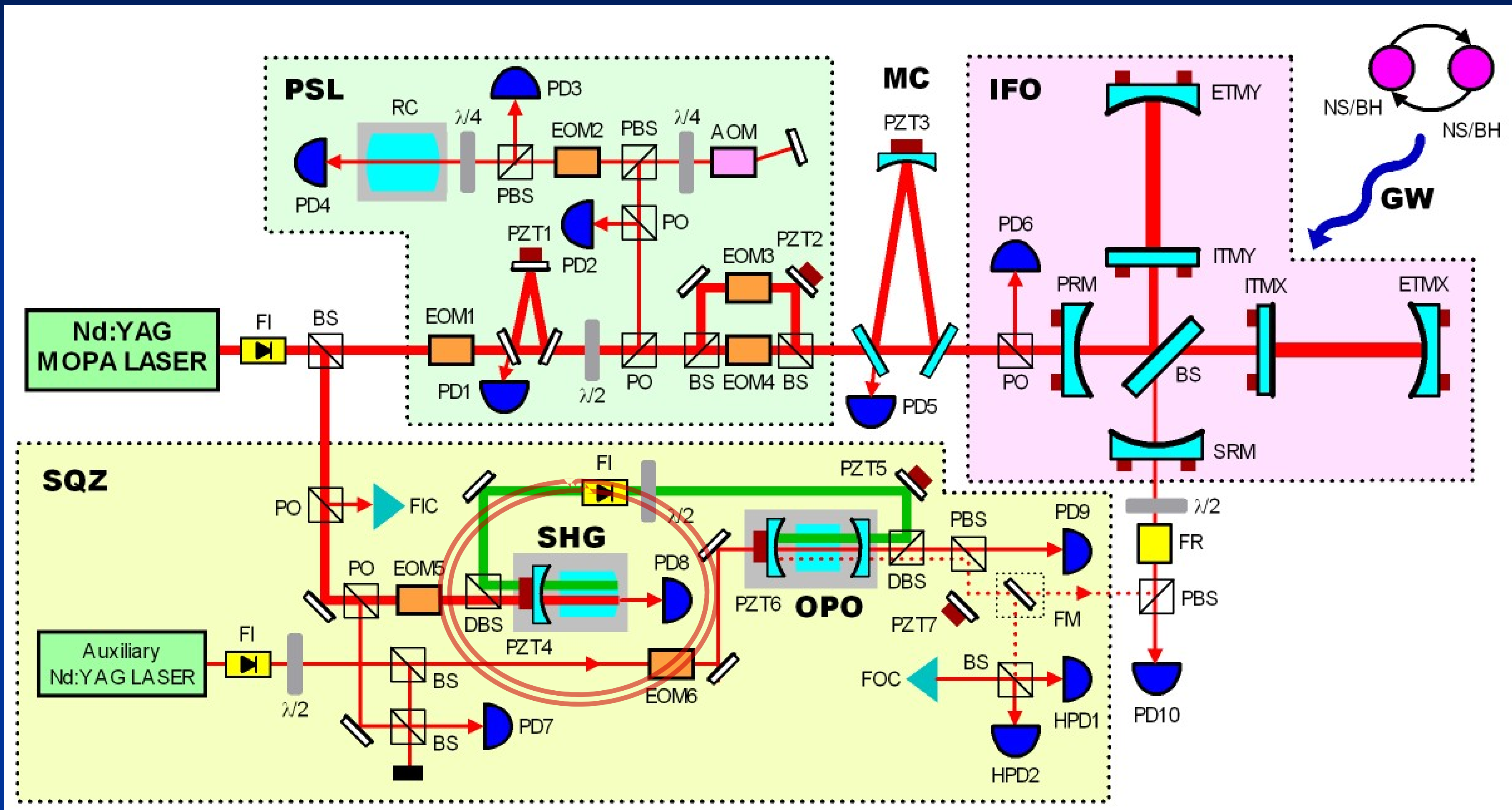
- Proposed a few years ago
- Started a year ago
- Initially without the output mode cleaner (OMC)
- People involved:
  - K. Goda, O. Miyakawa, E. E. Mikhailov, S. Saraf, A. Weinstein, and N. Mavalvala

40m Interferometer & Squeezer Interface



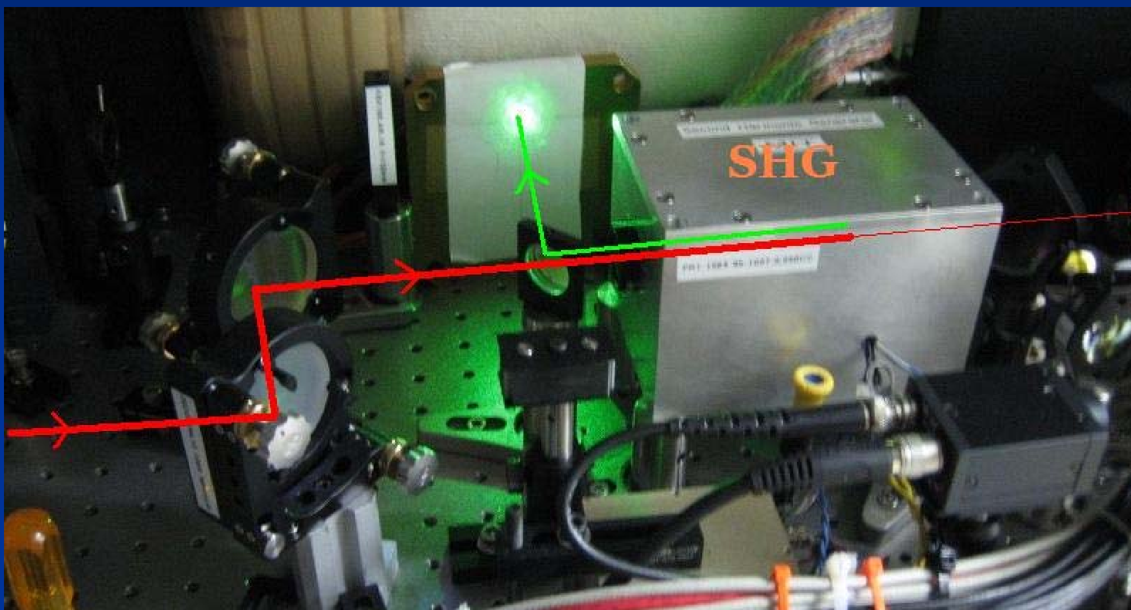
- PSL: pre-stabilized laser
- MC: mode-cleaner
- IFO: interferometer
- SQZ: squeezer
- PRM: power-recycling mirror
- SRM: signal-recycling mirror
- SHG: second-harmonic generator
- OPO: optical parametric oscillator

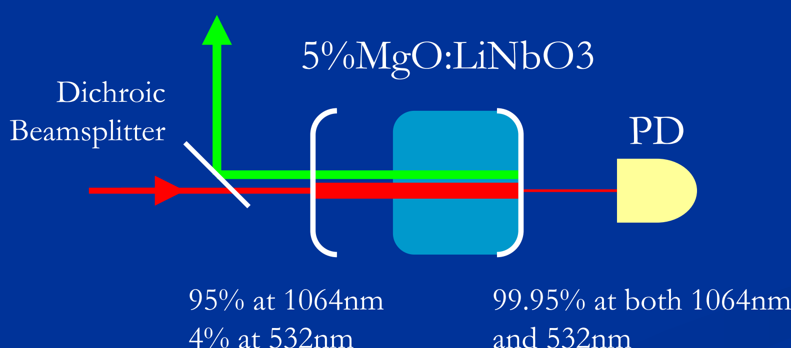
Second-Harmonic Generator (SHG)



Second-Harmonic Generator (SHG)

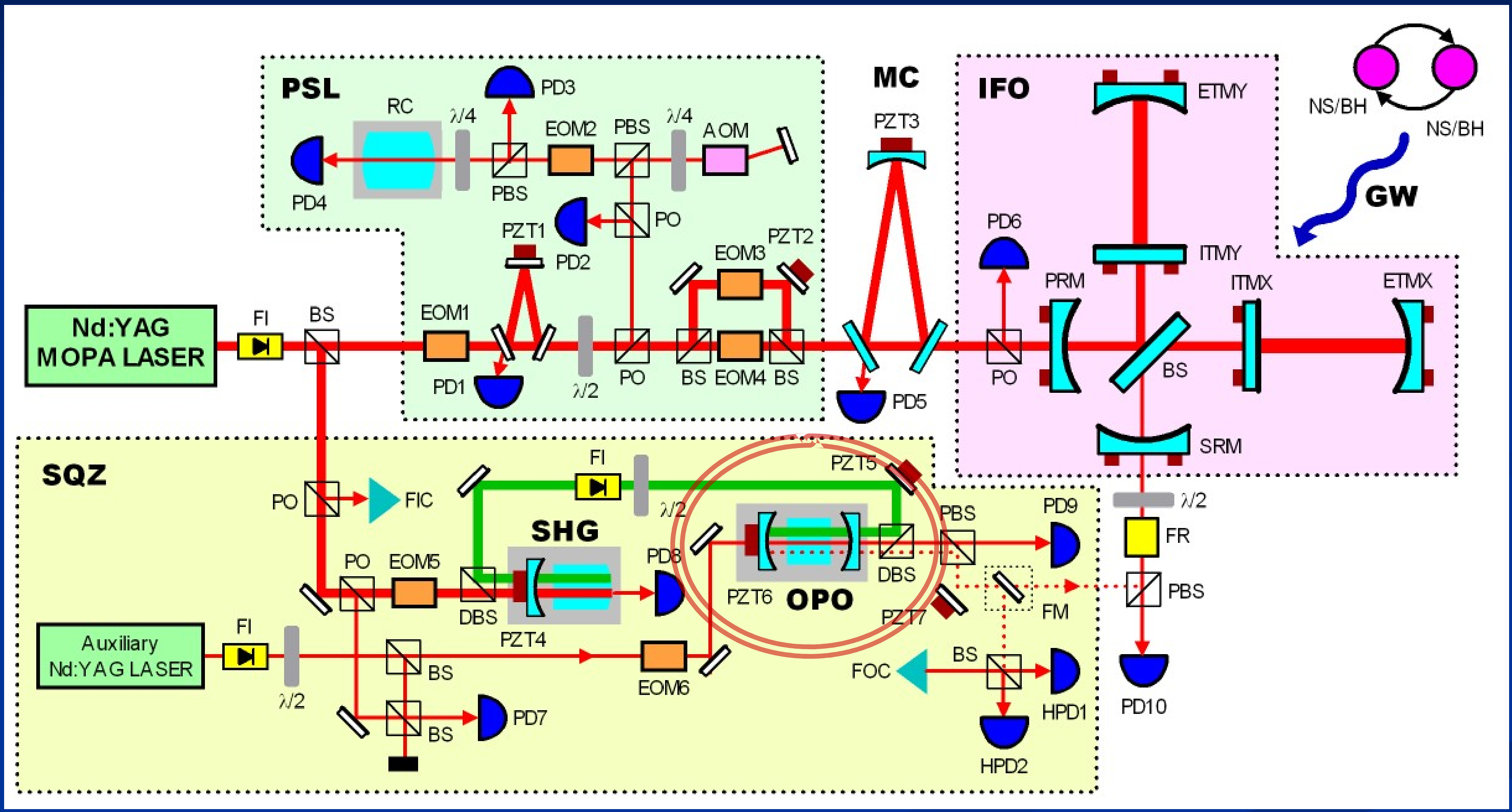
Role: to generate a second-harmonic field to pump the OPO cavity





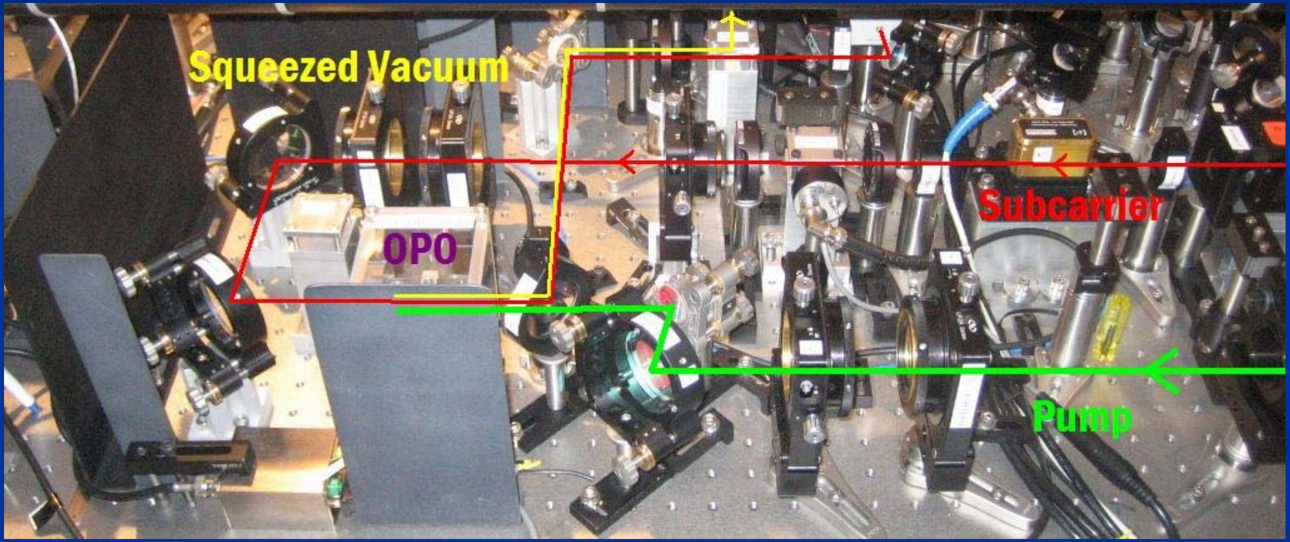
- The SHG is a cavity composed of a 5%MgO:LiNbO3 hemilithic crystal with ROC = 8mm and an output coupling mirror with ROC = 50mm.
- Crystal dimensions: 5mm x 2.5mm x 7.5mm
- The crystal is maintained at 114 deg C for phase-matching by temperature control.
- Uses type I phase-matching in which the pump and SHG fields are orthogonally polarized
  (S at 1064nm, P at 532nm)
- The SHG conversion efficiency = 30%

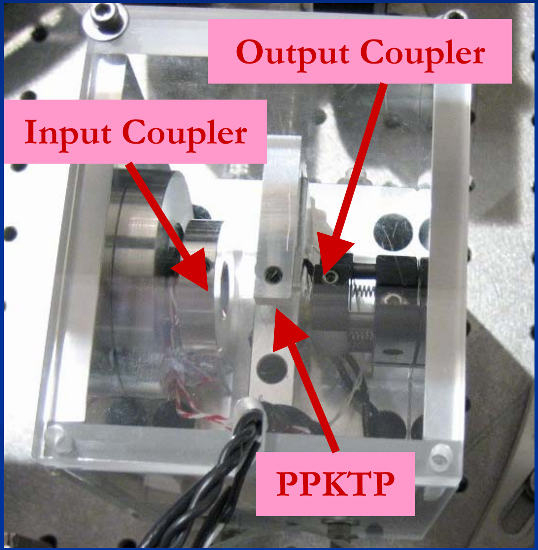
Squeezer/Optical Parametric Oscillator (OPO)



Squeezer/Optical Parametric Oscillator (OPO)

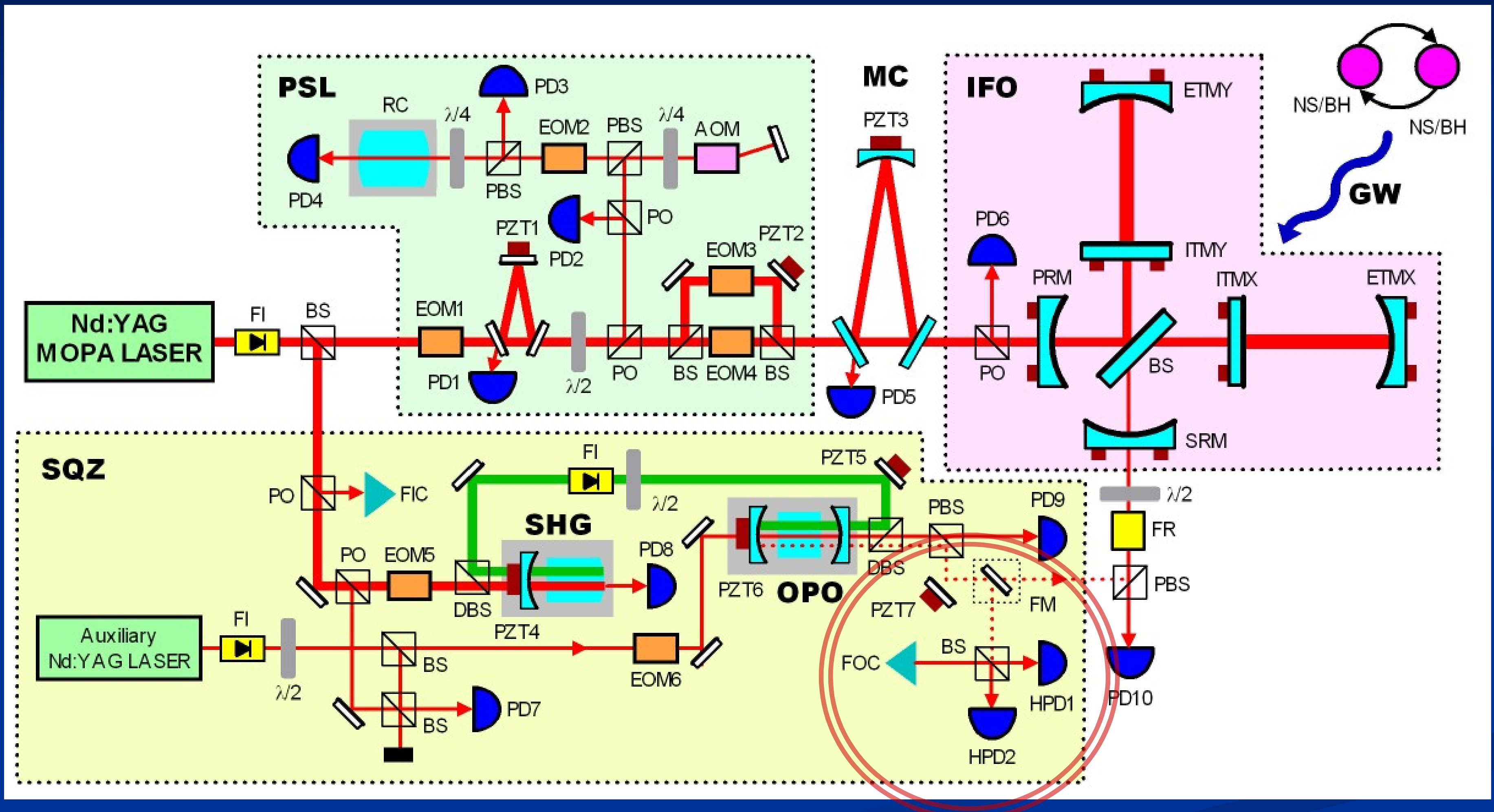
Role: to generate a squeezed vacuum field by correlating the upper and lower quantum sidebands around the carrier frequency





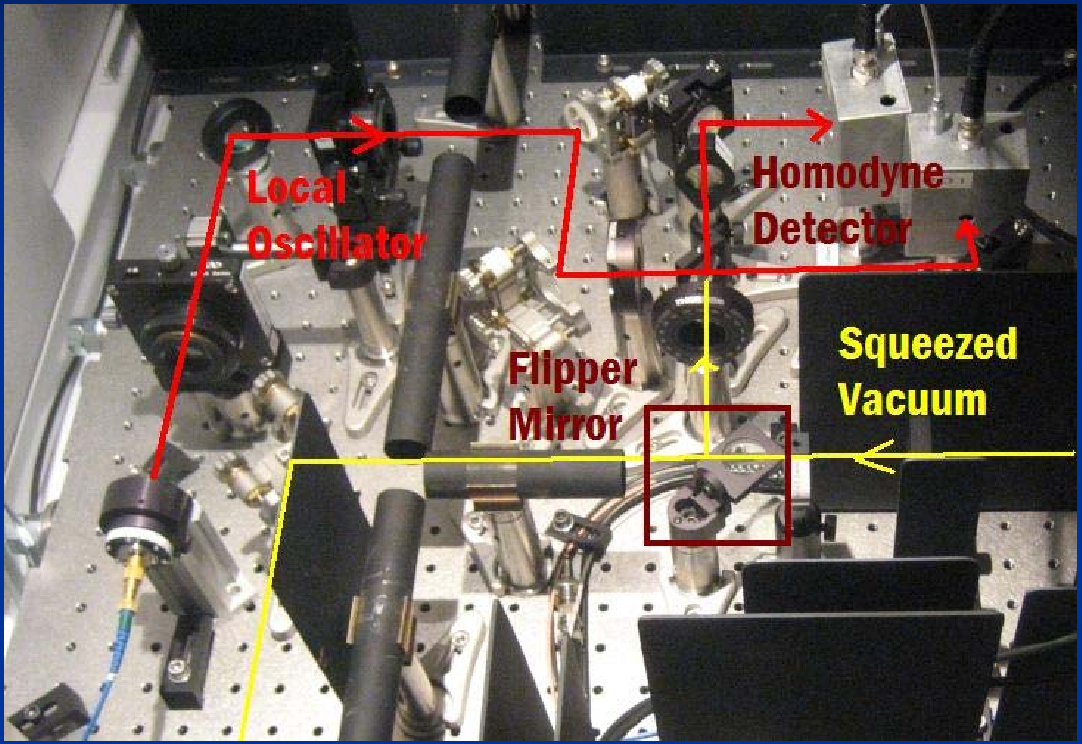
- The OPO is a 2.2 cm long cavity composed of a **periodically poled KTP (PPKTP)** crystal with flat/flat AR/AR surfaces and two coupling mirrors (R_{in} = 99.95% and R_{out} = 92%/4% at 1064/532nm).
- **PPKTP** offers the following **advantages** over $LiNbO_3$
  - Higher nonlinearity: d = 10.8 pm/V
  - Higher laser damage threshold
  - Higher resistance to photorefractive damage
  - Lower susceptibility to thermal lensing

Monitor Homodyne Detector before Injection



Monitor Homodyne Detector before Injection

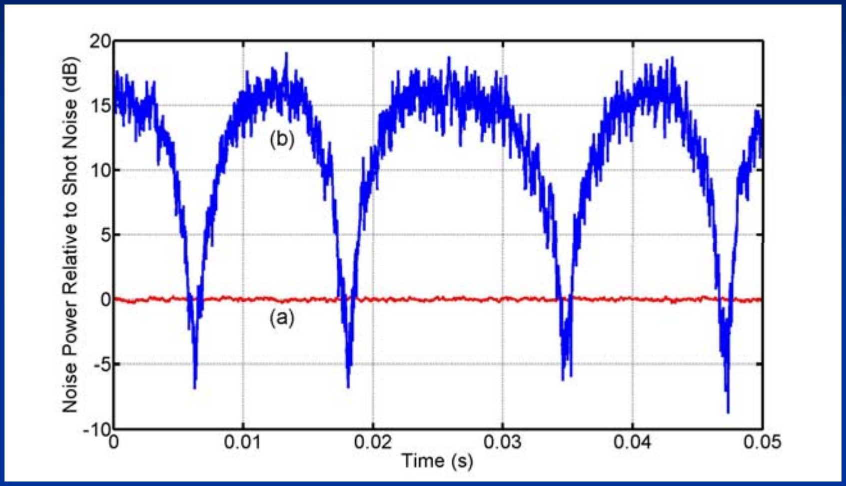
Role: to measure squeezing before injection to the interferometer

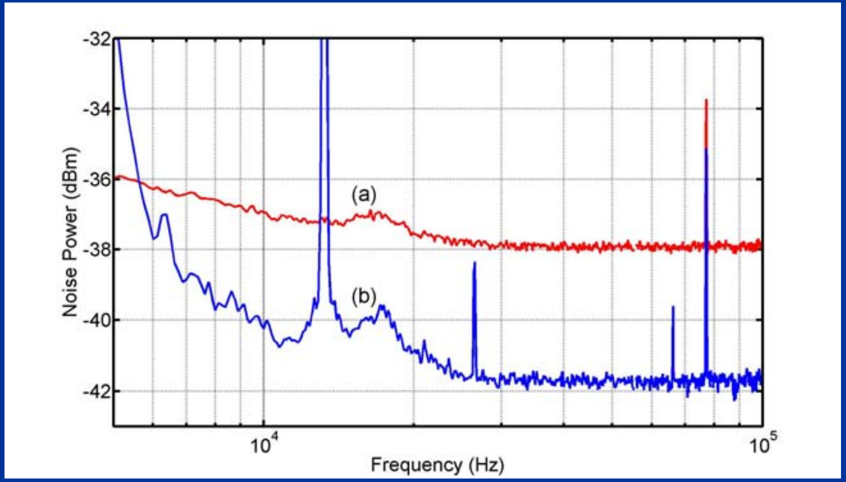


- **Homodyne detector** to measure squeezing
  - Composed of a 50/50 BS and a pair of home-made low-noise transimpedance photodetectors with high quantum efficiency photodiodes (JDS Uniphase ETX500T with QE = 93%)
  - The difference photocurrent is measured to **subtract uncorrelated** noise and **extract correlated** noise
  - And then sent to a spectrum analyzer to observe the effect of squeezing on the **local oscillator** (LO)

- LO as a trigger to observe either squeezed or anti-squeezed quadrature variance
- **Mode-cleaning fiber** to mode-match the LO to the squeezed vacuum
- When the **flipper mirror** is up, the squeezed vacuum is monitored by the homodyne detector. When the flipper is down, the squeezed vacuum is injected into the interferometer.
- Homodyne visibility of 99% achieved

Squeezing from the OPO with PPKTP

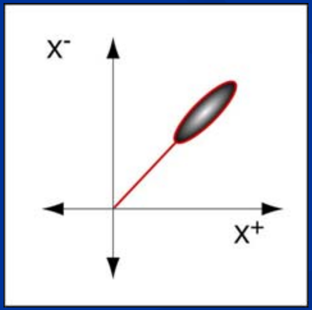


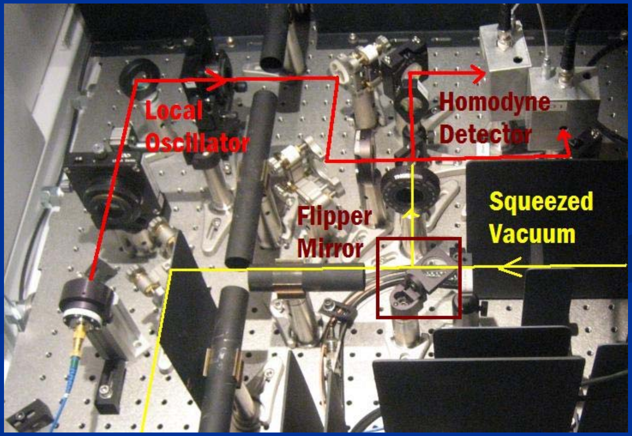


(a) Shot noise

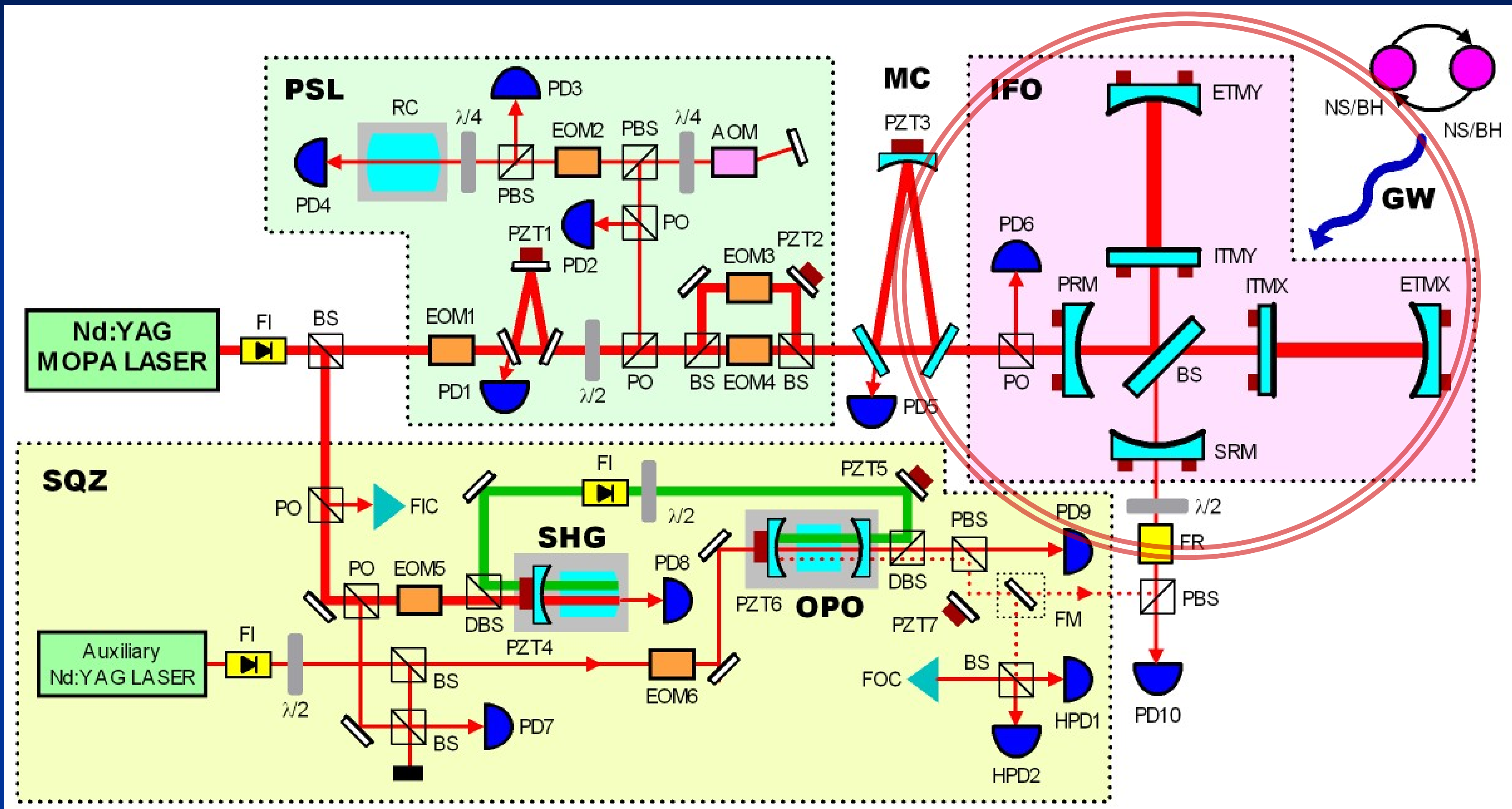
(b) Squeezed shot noise

- Measured by the squeezing **monitor homodyne detector**
  - About **6.5 dB** of scanned squeezing at MHz
  - About **4.0 dB** of phase-locked squeezing at frequencies down to a few kHz
- **The squeeze angle** is locked by the noise locking technique.
- More than 15dB of squeezing is created by the OPO, but losses kill most of it.



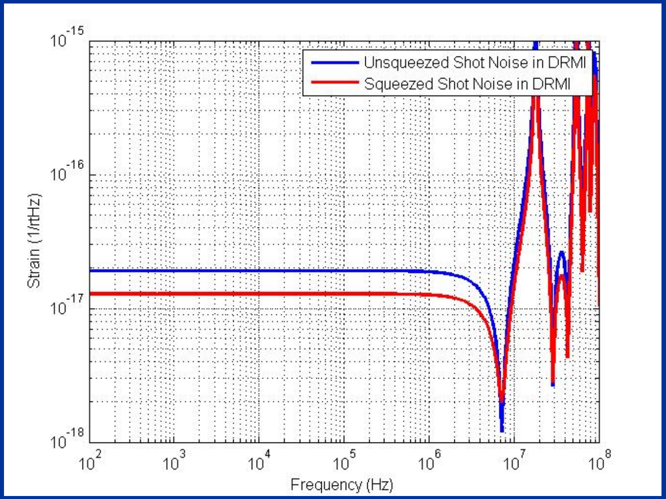


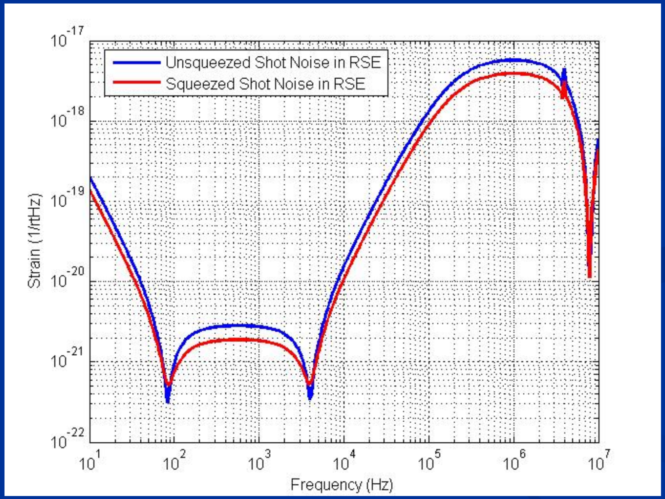
Interferometer



Interferometer Configurations

- Possible 40m Interferometer Configurations
  - **Signal-Recycled Michelson (SRMI) with DC Readout with/without the OMC**
  - **Resonant Sideband Extraction (RSE) with DC Readout with/without the OMC**
- **DC readout scheme**: local oscillator (LO) field necessary to beat squeezing against
  - Important step toward **squeezing-enhanced Advanced LIGO** with the DC readout scheme





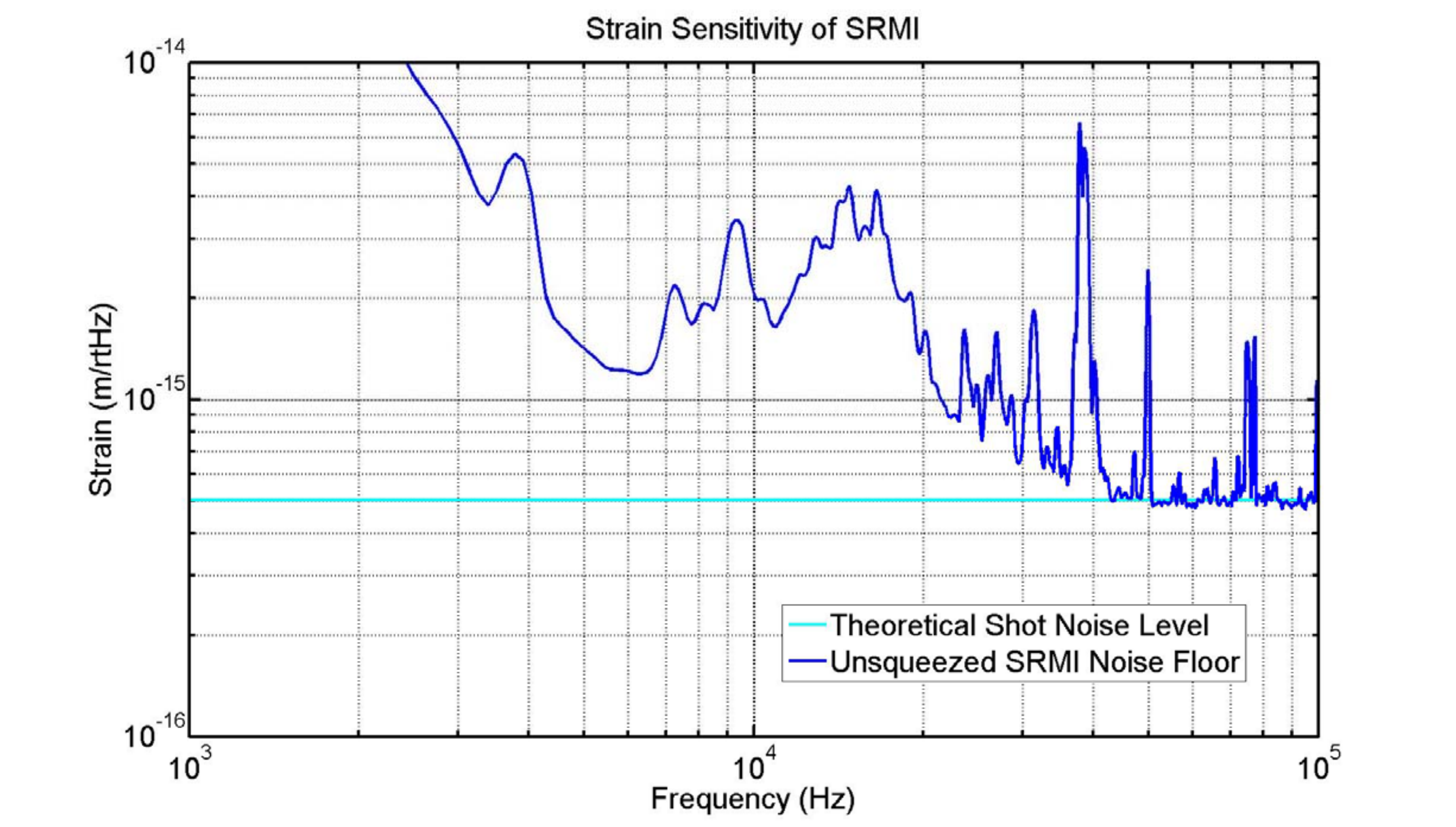
DRMI Quantum Noise Budget

- Input Power to BS = 50mW
- Homodyne Angle = 0
- Squeeze Angle = $\pi/2$
- Initial Squeezing Level = 5dB
- Injection Loss = 10%
- Detection Loss = 10%

RSE Quantum Noise Budget

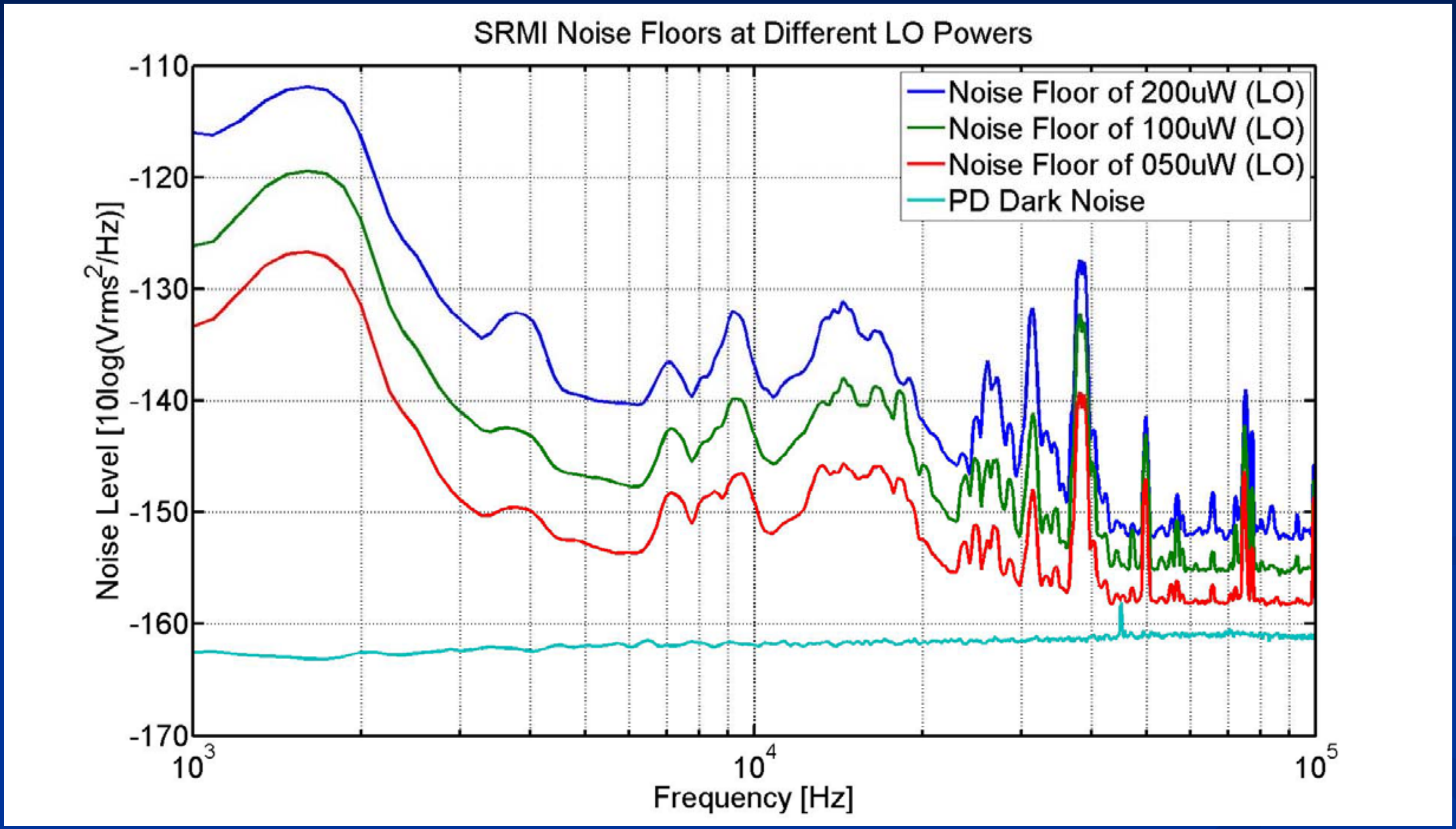
- Input Power to BS = 700mW
- Homodyne Angle = 0
- Squeeze Angle = $\pi/2$
- Initial Squeezing Level = 5dB
- Injection Loss = 10%
- Detection Loss = 10%

SRMI Noise Floor



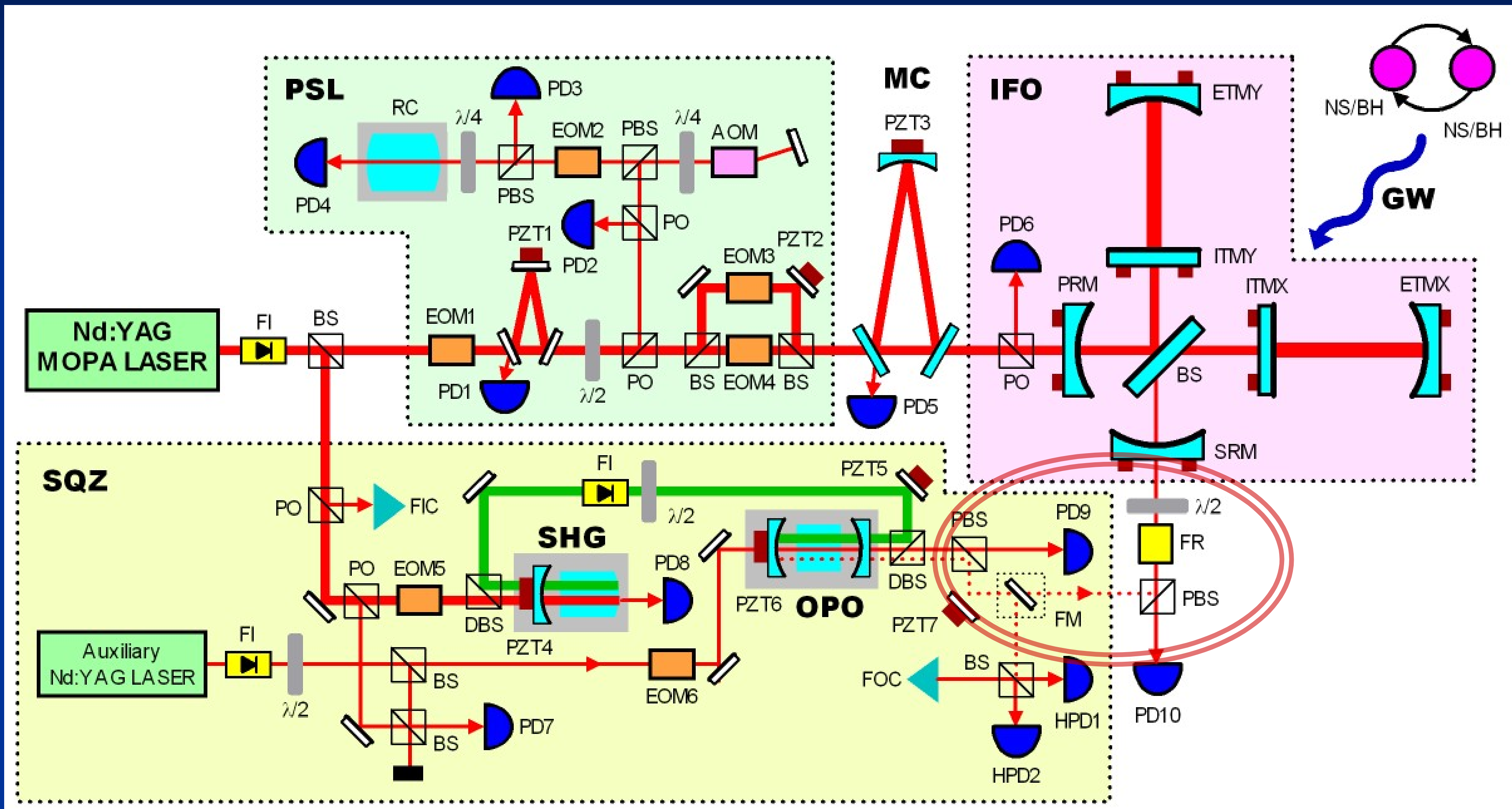
- The carrier field on resonance in the SRC
- Interferometer LO power from a Michelson offset: **100 μW** (the lower, the better)
- Ratio in power of the carrier to the 166MHz sidebands: at least **10 to 1**
- Mostly dominated by **laser (intensity) and interferometer noise** at low frequencies
- Shot noise limited at frequencies **above 40kHz**

Verification of Shot Noise

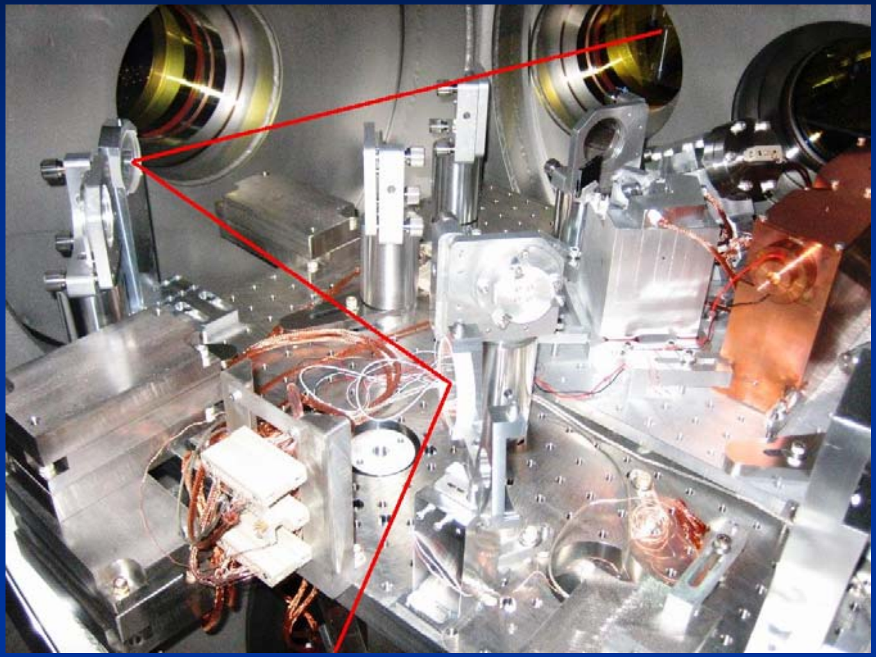


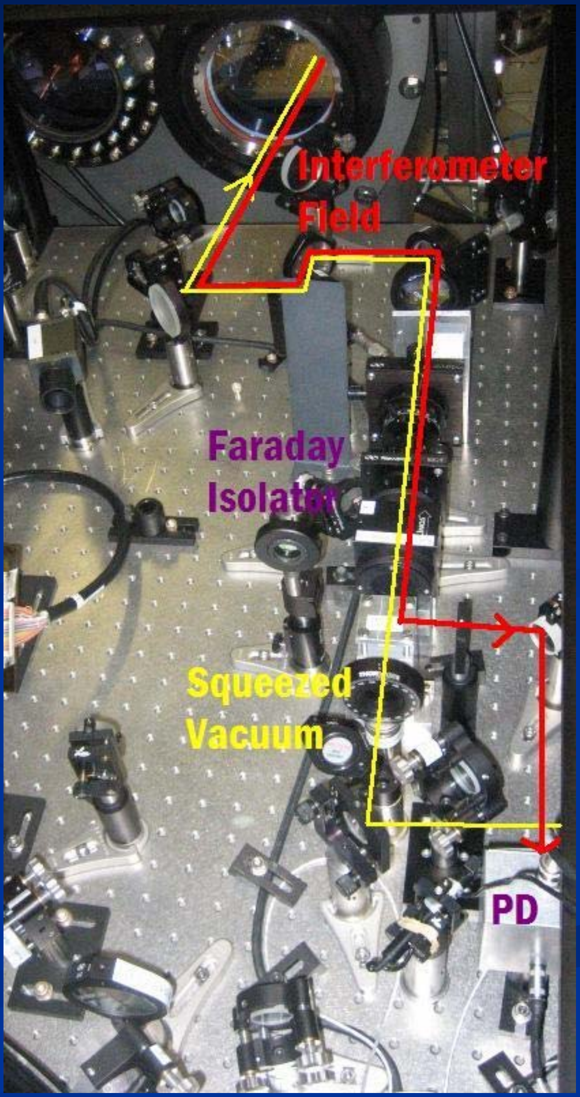
- Noise increase by **3dB** at frequencies above 40kHz » **Shot Noise**
- Noise increase by **6dB** at frequencies below 10kHz » **Laser (Intensity) Noise**
- Noise increase in between 10kHz and 40kHz » **Interferometer Noise**

Injection and Detection of Squeezing



Injection and Detection of Squeezing

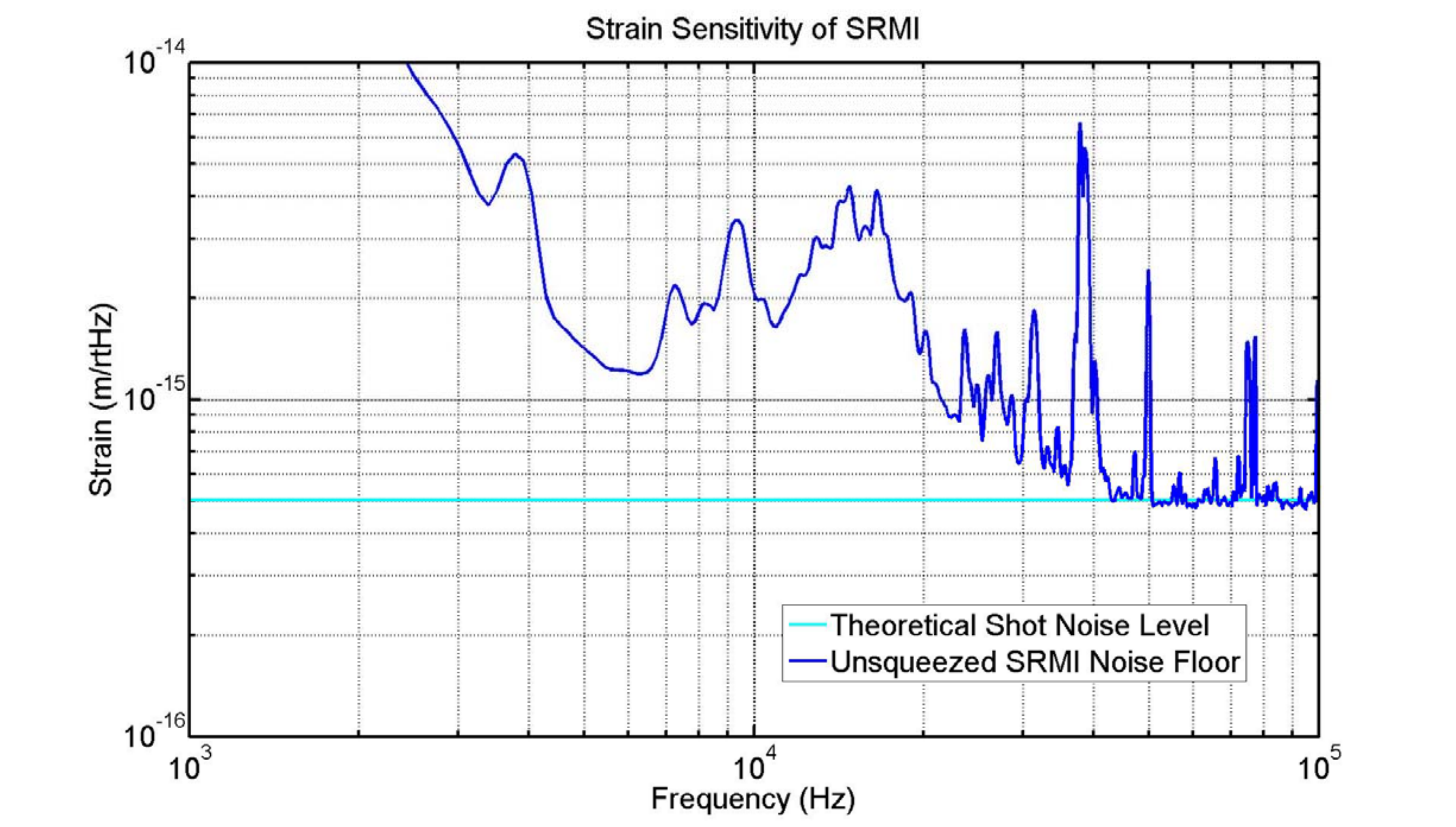




- **Mode-matching and alignment** of squeezed vacuum to the interferometer are done by a mode-matching telescope and steering mirrors.
- **Isolation of the squeezing-enhanced interferometer field** from the injection of squeezing is done by Faraday isolation.
- **An extra Faraday isolator** is installed to further reject the LO light from going into the OPO.
- Detection of the squeezing-enhanced interferometer field is done by a high transimpedance amplifier with a high quantum efficiency photodiode (JDS Uniphase ETX500T with QE: 93%)

Results

SRMI Noise Floor



- The carrier field on resonance in the SRC
- Interferometer LO power from a Michelson offset: **100 μW** (the lower, the better)
- Ratio in power of the carrier to the 166MHz sidebands: at least **10 to 1**
- Mostly dominated by **laser (intensity) and interferometer noise** at low frequencies
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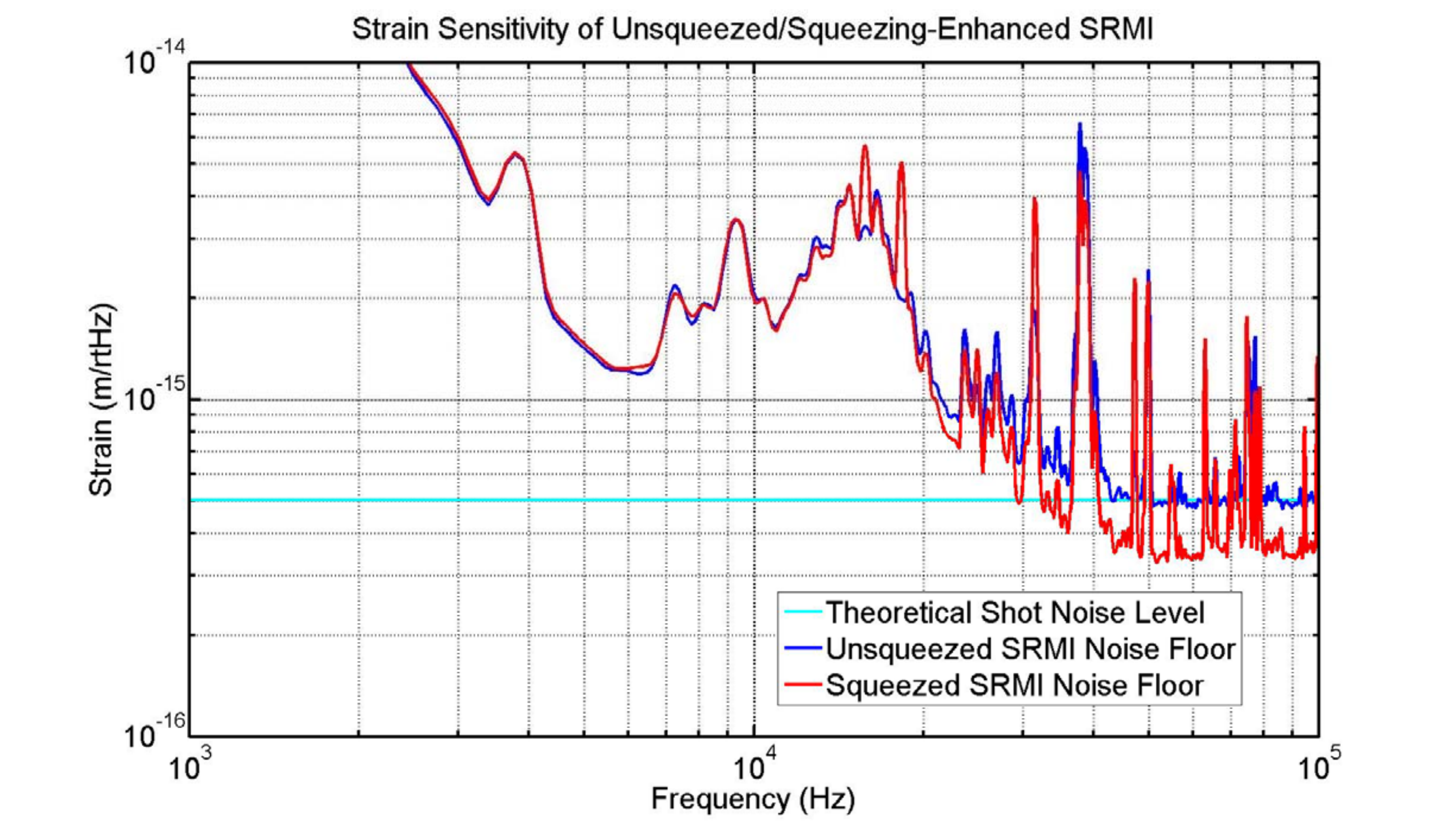
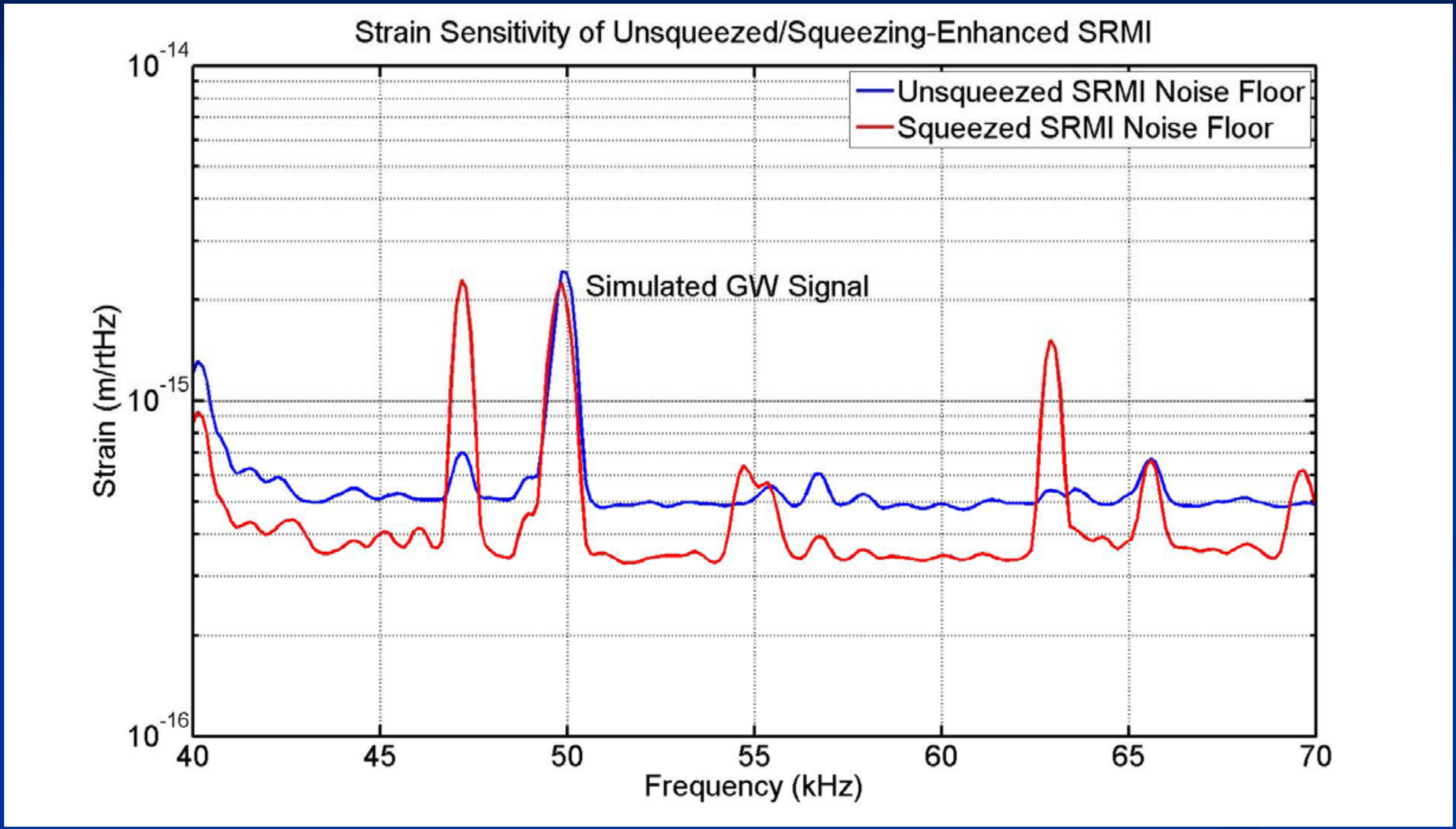
Squeezing-Enhanced SRMI



- **Broadband reduction of shot noise** by about 3dB at frequencies above 40kHz
- No squeezing effect on the SRMI in the laser-noise-dominant frequency band
- The squeeze angle is locked by the noise-locking technique with the modulation frequency at 18kHz.

Increase in S/N by Squeezing



- **Simulated GW Signal**: Excitation of BS at **50kHz**
- The noisy peaks in the squeezing spectrum are due to the **optical crosstalk** between the interferometer and OPO (imperfect isolation of the interferometer LO field from going into the OPO in spite of two Faraday isolators).

Summary and Future Work

- **SUMMARY**
  - We are developing **techniques** necessary for squeezing-enhanced laser-interferometric GW detectors
    - **GW detector-compatible squeezer**
    - **Squeezing injection scheme**
    - **Squeeze angle locking scheme**
    - **Interferometer locking scheme with squeezing**
  - With these techniques, we have demonstrated **squeezing-enhancement** (**an increase in S/N**) in the LIGO prototype interferometer by about 3dB in the shot-noise-limited frequency band (above 40kHz)
  - This squeezer is applicable to **any** interferometer configuration with DC readout.
- **FUTURE WORK**
  - Squeezing-enhanced RSE (full Advanced LIGO configuration)
  - Squeezing with the OMC
  - Coherent control of squeezing
  - Doubly-resonant OPO in a ring cavity
  - Noise-hunting for squeezing-enhanced interferometry in the GW band
  - Installation into Enhanced LIGO and then Advanced LIGO?

Acknowledgements

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- We also thank ANU for providing high quantum efficiency photodiodes
- We gratefully acknowledge support from NSF