Sub kHz Squeezing for Gravitational Wave Detection

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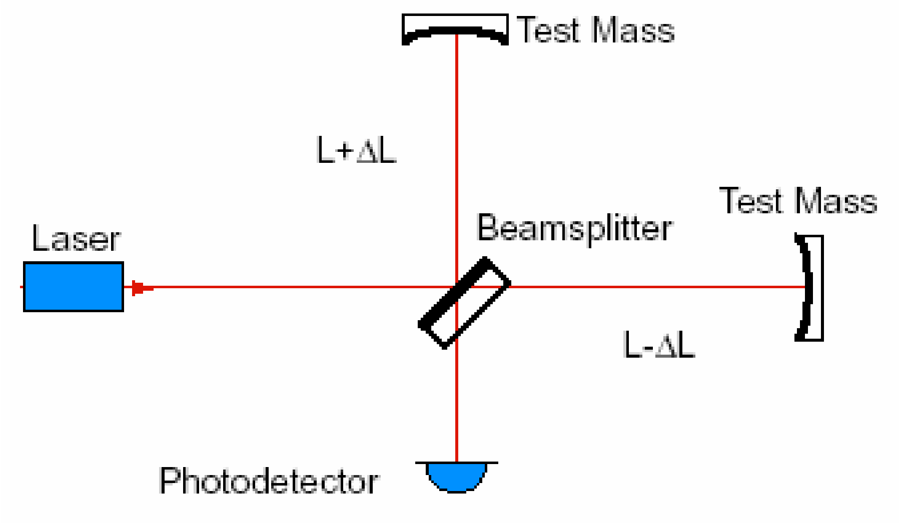
Kirk McKenzie, Nicolai Grosse, Warwick Bowen, Stanley Whitcomb[†], Malcolm Gray, David McClelland and Ping Koy Lam

The Center for Gravitational Physics,
The Australian National University

[†]**Californian Institute of Technology**

Interferometic GW Detectors

Michelson Interferometer



LIGO (USA), L=4km

Strength of GW given by Strain, *h;*

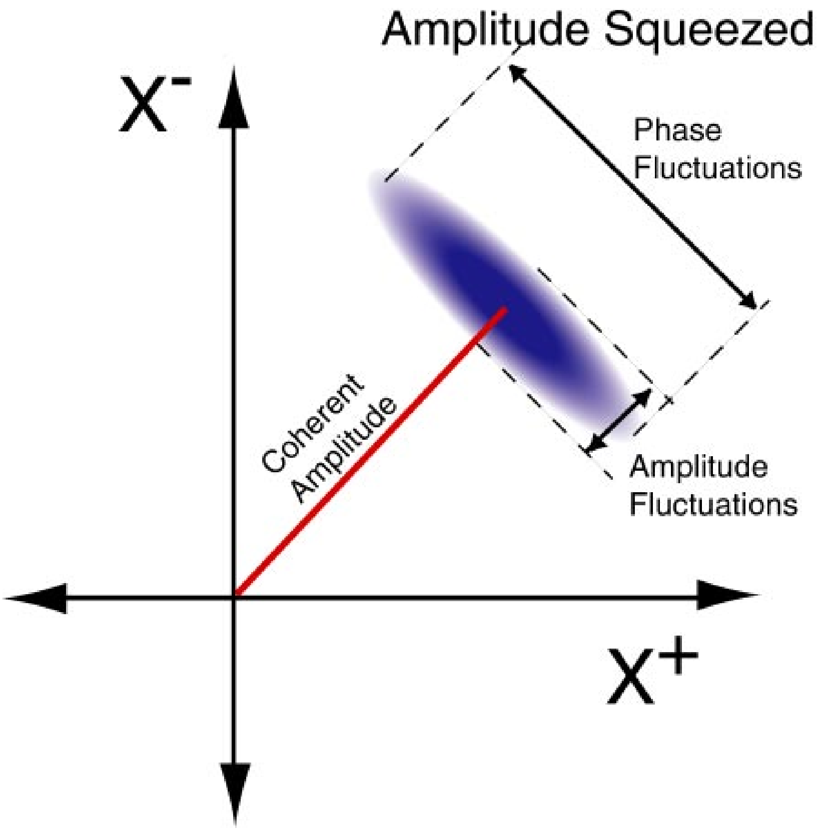
$$\frac{\Delta L}{L} = \frac{h}{2} < 10^{-22}\left(\frac{1}{\sqrt{Hz}}\right)$$

Quantum Mechanical Noise

- The EM field has quantum mechanical fluctuations

- The HUP relation for the EM field.

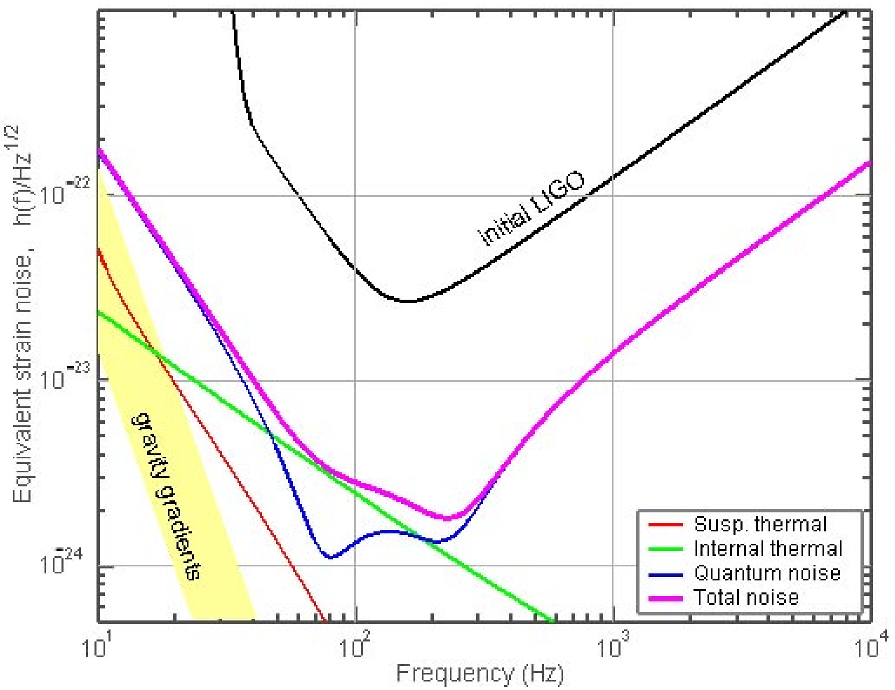
$$\Delta \hat{X}^{+} \Delta \hat{X}^{-} \geq 1$$



Low Frequency Squeezing?

- Applications
  - **Gravitational Wave Detectors**
  - Position sensing
  - Atomic Force Microscopy
  - Other quantum noise limited applications

Advanced LIGO target sensitivity



http://www.ligo.caltech.edu/advLIGO/

Previous Low Frequency Results

- Recent CW LF Results include
  - 220kHz -W.P. Bowen *et al.* [1]
  - 80kHz - R. Schnabel *et al*. [2]
  - 50kHz - J. Laurat *et al.* [3]

All experiments used common mode noise cancellation!

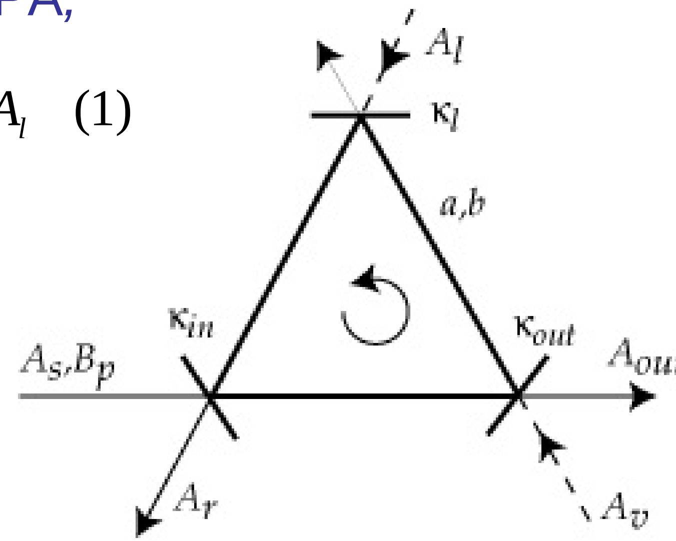
- We chose to investigate OPO

[1] W.P. Bowen *et al*. J. Opt. B **4** 421 (2002)
[2] R. Schnabel *et al*. arXiv quant-ph/0402064 (2004)
[3] J. Laurat *et al* arXiv:quant-ph/0403224 (2004)

OPA/OPO Theory

Equations of motion for a singly resonant OPO/OPA;

$$\dot{a} = -(\kappa_a + i\delta\Delta)a + \varepsilon a^\dagger b + \sqrt{2\kappa_{in}^a}A_s + \sqrt{2\kappa_{out}^a}A_v + \sqrt{2\kappa_l^a}A_l \quad (1)$$



B.Buchler PhD Thesis ANU 2002

a - fundamental field mode

b - harmonic (pump) field

κ_j - decay constants

$\delta\Delta$ - fluctuating detuning

ε - nonlinear coupling strength

A_j,*B* - fields entering the cavity

The linearized equation of motion for the fluctuations is given by;

α - coherent amplitude of fundamental field, β - coherent amplitude of pump field

$$\delta\dot{a} = -\kappa_a\delta a - i\alpha\delta\Delta + \varepsilon(\alpha^*\delta b + \beta\delta a^\dagger) + \sqrt{2\kappa_{in}^a}\delta A_s + \sqrt{2\kappa_{out}^a}\delta A_v + \sqrt{2\kappa_l^a}\delta A_l \quad (2)$$

OPA/OPO Theory II

The variances in the frequency domain for the OPA/OPO output are;

$$V_{OUT}^{\pm}(\omega) = \left[C_s V_s^{\pm}(\omega) + C_l V_l^{\pm}(\omega) + C_v^{\pm}(\omega) V_v^{\pm}(\omega) + \alpha^2 \left(C_p V_p^{\pm}(\omega) + C_\Delta^{\pm} V_\Delta^{-}(\omega) \right) \right] / \left| D^{\pm}(\omega) \right|^2 \quad (3)$$

↑	↑	↑	↑	↑
Seed	Loss	Vacuum	Pump	Detuning
(f < 2MHz)			(f < 2MHz)	(f < 50kHz)

For below threshold OPO $\alpha = 0$ and $V_s^{\pm} = 1$;

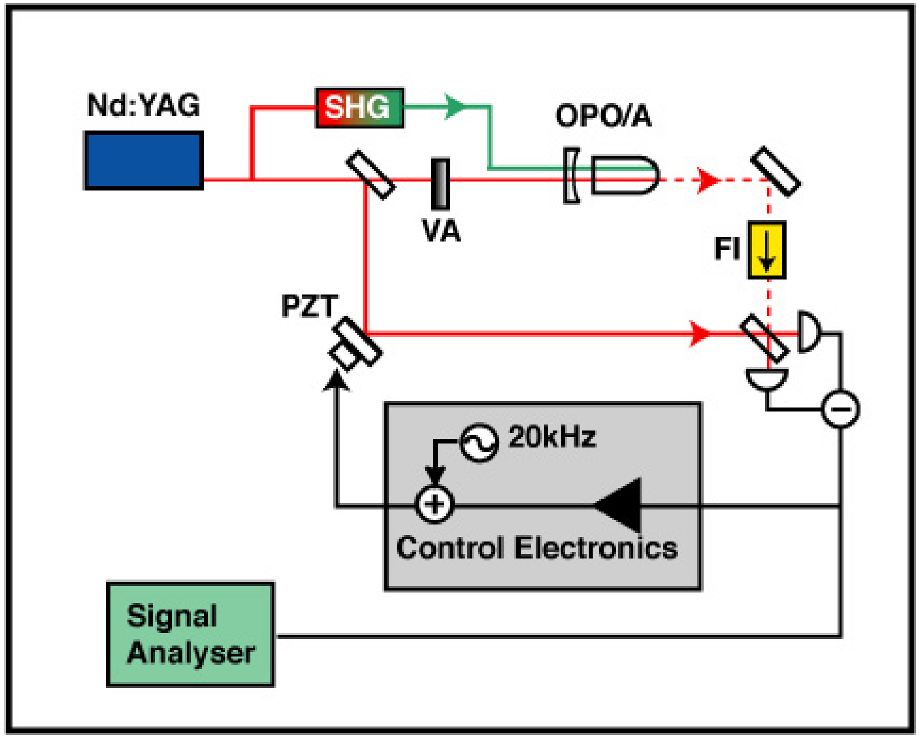
$$V_{OPO}^{\pm}(\omega) = \left[C_s + C_l + C_v^{\pm}(\omega) \right] / \left| D^{\pm}(\omega) \right|^2 \qquad (4)$$

OPO is immune to laser noise, pump noise and detuning noise!

ANU OPA/OPO Experiment

- Seed power was varied - transition from OPA to OPO
- OPO/OPA cavity not locked;
- Homodyne phase locked using **noise power locking [3]**
- Noise power locking requires no coherent amplitude in the squeezed beam - **can lock a vacuum state.**
- In OPO operation a Faraday Isolator was used to reduce backscatter from homodyne detector

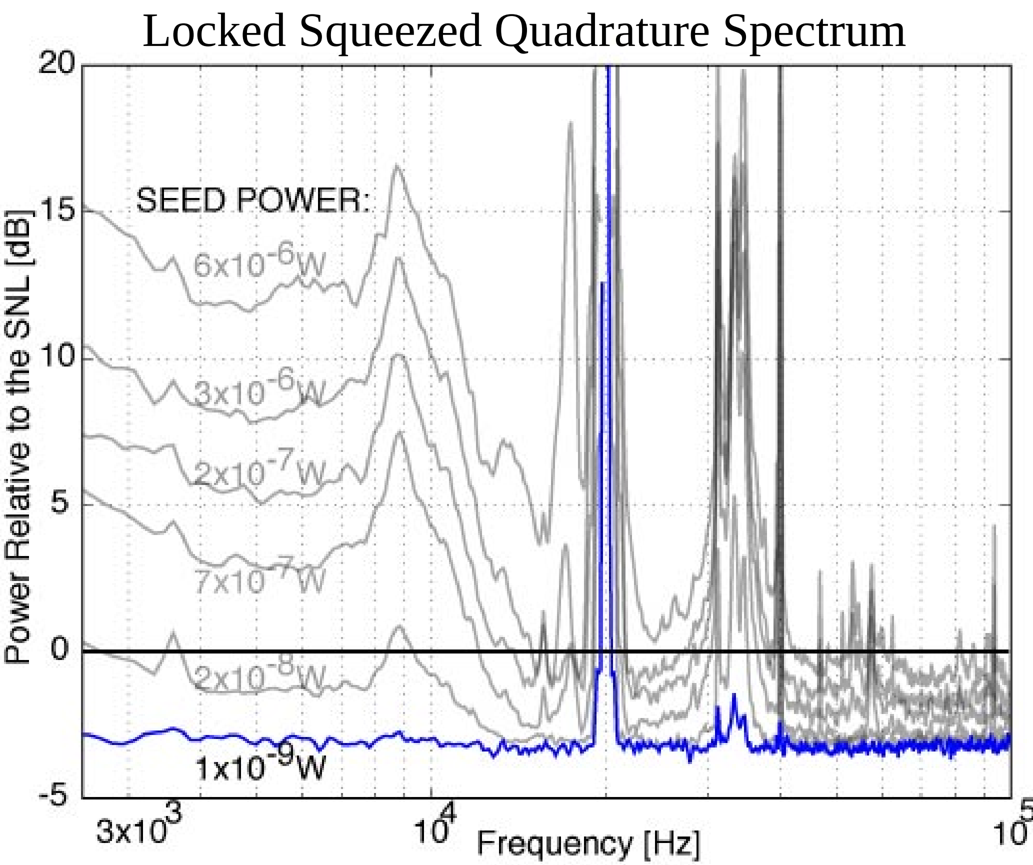
Experiment Schematic



[3] For example, J. Laurat *et al* arXiv:quant-ph/0403224

OPA Squeezed Quadrature Spectrum

- Transition from OPA to OPO made by reducing seed power.
- Minimum noise quadrature was recorded.
- OPO immunity to noise sources
- Noise power locking modulation frequency peak at 20kHz

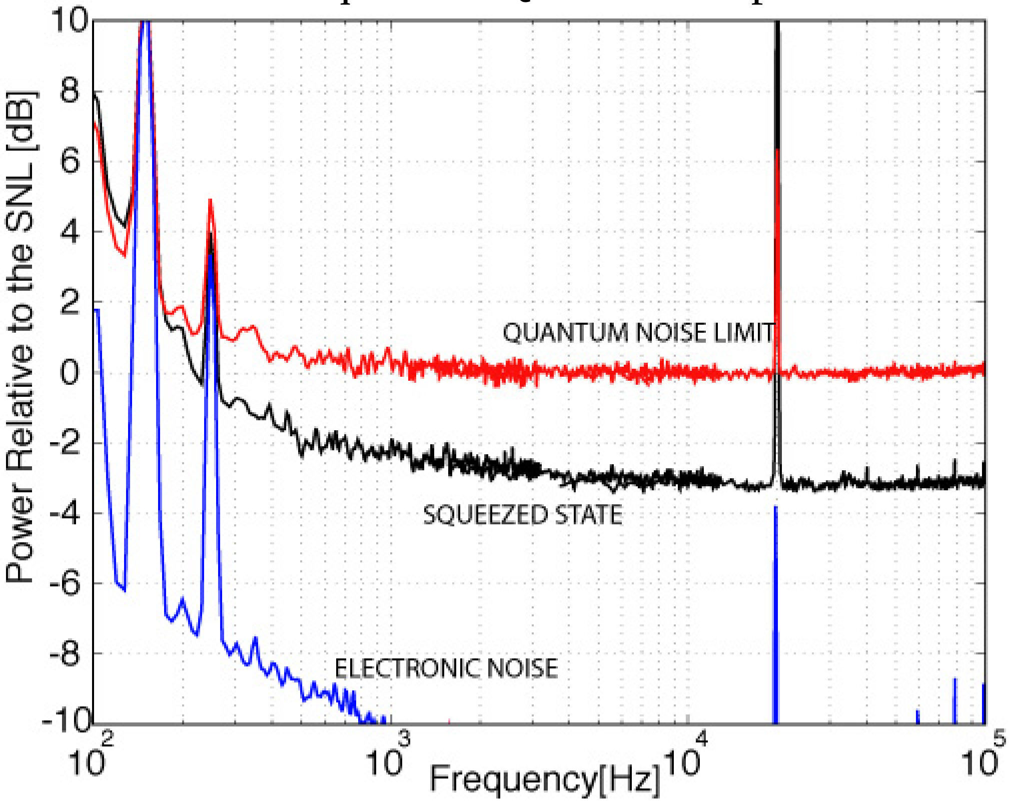


RBW = 128Hz, RMS averages = 1000, Electronic noise (at -12dB) subtracted from all traces

OPO Squeezed Quadrature Spectrum

- Lowest frequency squeezing result to date
- Covers SNL frequencies of LIGO
- Measurement limited at low frequencies by the stability of the unlocked OPO

Locked Squeezed Quadrature Spectrum



From 100Hz-3.2kHz: RBW = 8Hz, no. RMS ave = 500
From 1.6kHz-12.8kH: RBW = 32Hz, no. RMS ave = 1000
From 3.8kHz-100kHz: RBW = 128Hz, no. RMS ave = 2000

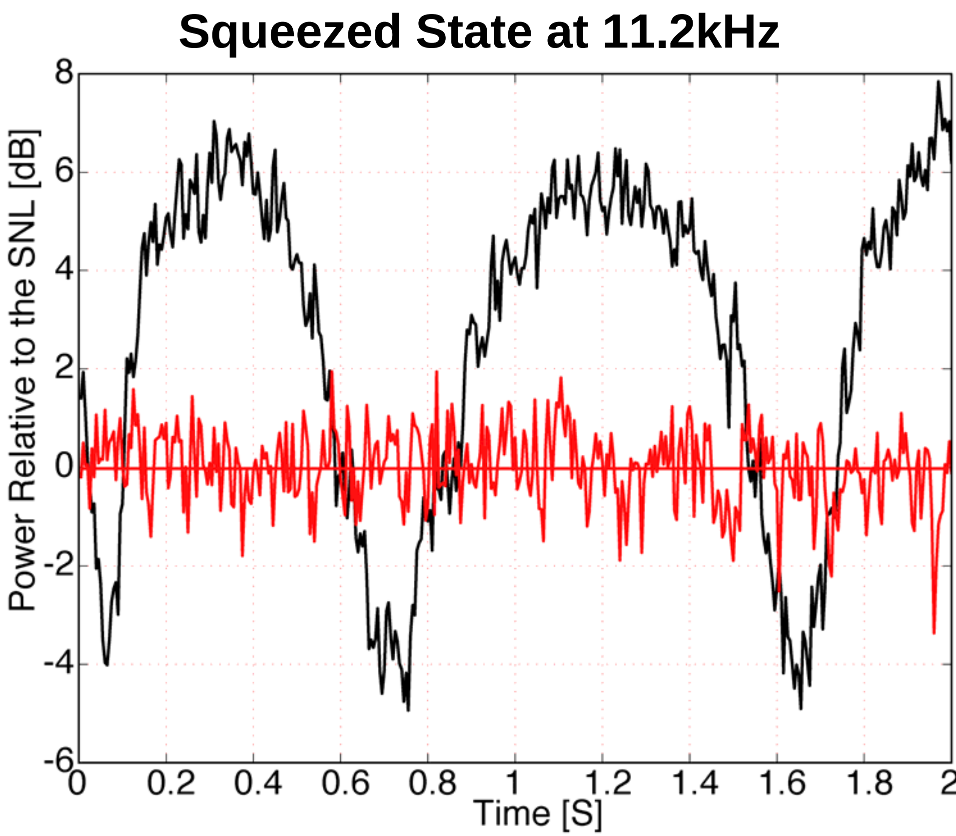
State Purity Results

- $V^{SQZ}_{MEASURED}$ = 3.5 dB ± 0.4dB
- Measured purity,

$$V^{+}V^{-}_{M} = 1.6 \pm 0.2$$

- $V^{SQZ}_{INFERRED}$ = 5.5 dB ± 0.6dB
- Inferred purity before detection

$$V^{+}V^{-}_{I} = 1.3 \pm 0.1$$



Squeezed State at 11.2kHz, RBW = 1kHz, VBW = 30Hz
Electronic noise was (9dB below SNL) was subtracted from traces

Conclusions & Future Work

Conclusions

http://arXiv:quant-ph/0405137 (2004)

- Coupling mechanism of noise sources identified - the coherent seed field
- Below threshold OPO is immune to laser, pump and detuning noise !
- OPO squeezing measured down to 200Hz - lowest to date
- Noise locking technique used for homodyne phase

Future Work

- Develop new generation of squeezer that can be locked in OPO operation
  - Generate larger amounts of squeezing
  - Probe lower frequencies
- Further investigation of noise locking technique

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with;

$$\begin{aligned} D^{\pm}(\omega) &= i\omega + \kappa_a + \begin{bmatrix} 3 \\ 1 \end{bmatrix} \epsilon^2 \alpha^2 / (2\kappa_b) \mp \epsilon\beta \\ C_s &= 4\kappa_{in}^a \kappa_{out}^a \\ C_l &= 4\kappa_l^a \kappa_{out}^a \end{aligned}$$

$$\begin{aligned} C_v^{\pm}(\omega) &= |2\kappa_{out}^a - D^{\pm}(\omega)|^2 \\ C_p &= 4\kappa_{out}^a \kappa_{in}^b (\epsilon/\kappa_b)^2 \\ C_\Delta^{\pm} &= 8\kappa_{out}^a \begin{bmatrix} 0 \\ 1 \end{bmatrix} \end{aligned}$$

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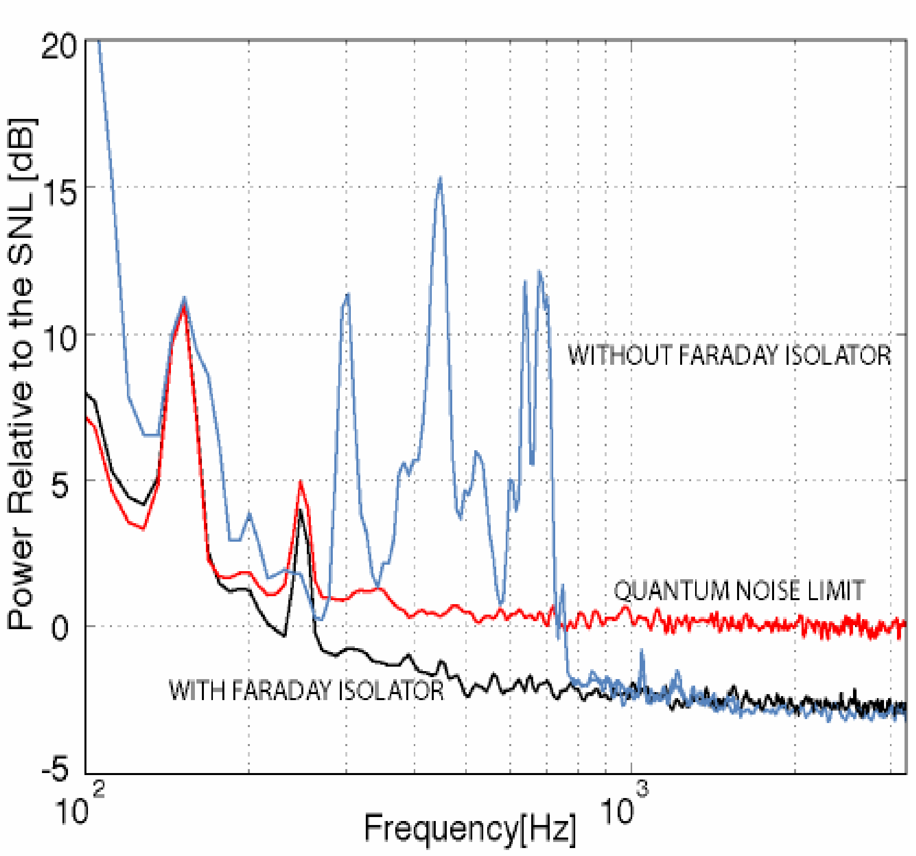
$$V_{OPO}^{\pm}(\omega) = \left[C_s + C_l + C_v^{\pm}(\omega) \right] / \left| D^{\pm}(\omega) \right|^2 \quad (4)$$

OPO is immune to laser noise, pump noise and detuning noise!

OPO Squeezing Without/With Isolator

- Light from the local oscillator beam backscattered from the photodetectors seeded our OPO cavity (~1pW)
- Undesired seed contributed to low frequency noise contamination.
- A Faraday Isolator between OPO cavity and homodyne detector to eliminated seed - **low frequency squeezing was recovered!**



RBW = 8Hz, No.RMS ave = 400 without isolator, 500 for QNL and with Isolator. Electronic noise (not shown) was not subtracted