# Experiments towards beating quantum limits

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The **ANU**
Centre of Gravitational Physics

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THE AUSTRALIAN NATIONAL UNIVERSITY

# Overview

I. **Squeezing in the GW detection band**

**Kirk McKenzie**, Malcolm Gray, Ping Koy Lam, David McClelland

II. **Off-resonant thermal noise and the Standard Quantum Limit**

**Conor Mow-Lowry**, **Stefan Goßler**, Jeff Cumpston, Malcolm Gray, David McClelland

# Squeezing...

## ...in the gravitational wave detection band:

- Squeezed states
- Noise sources
- Results from the 2004 experiment
- The 2005 experiment
- Current results and limitations
- Summary

# Squeezed states of light

The EM field has QM fluctuations:

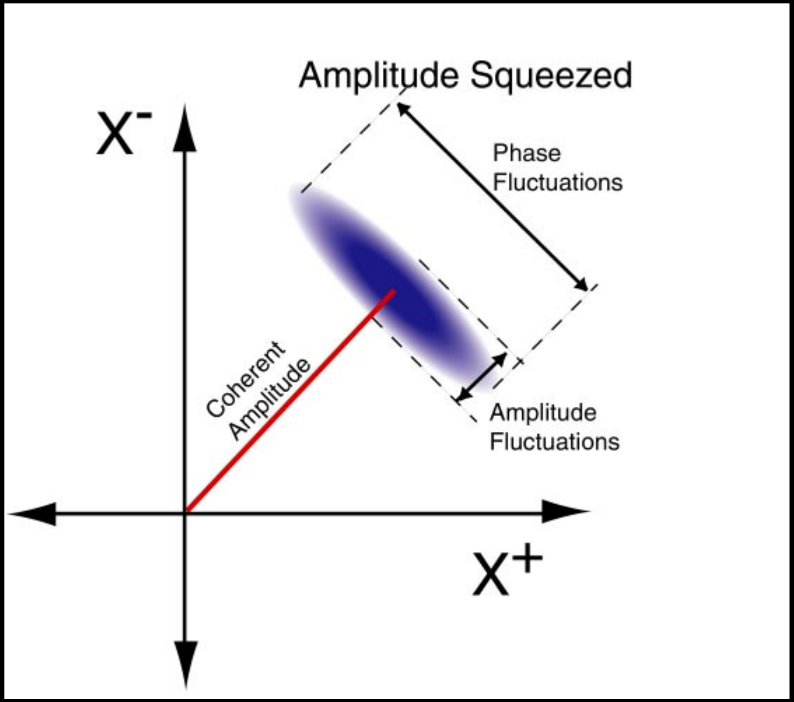
$$\Delta \hat{X}^{+} \Delta \hat{X}^{-} \geq 1$$

The production of squeezed states requires a non-linear process:

Optical Parametric Oscillators (OPO)

or

Optical Parametric Amplifier (OPA)




Use of squeezed states in Interferometric GW detectors first proposed in 1980 by Caves.

**Requires squeezing in the GW detection band!**

# OPO/OPA noise budget

Variance in the frequency domain for the squeezed output:

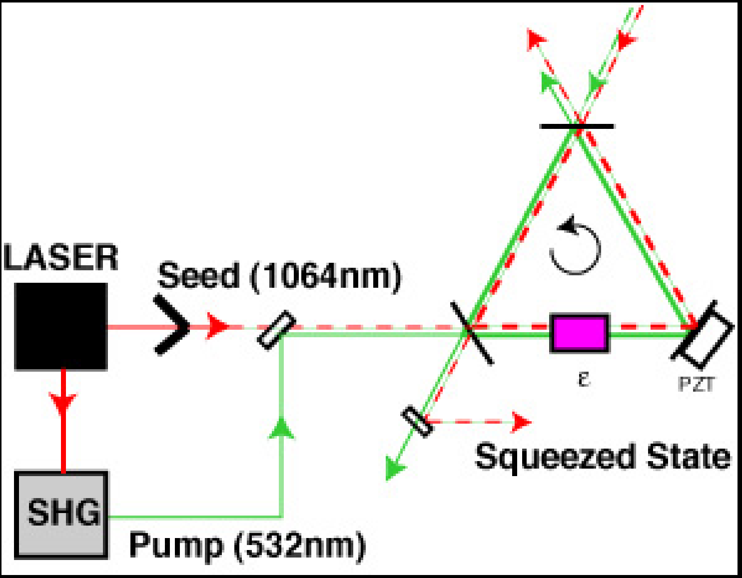
**Intra-cavity photon number@1064nm**

$$V_{OUT}^{\pm}(\omega) = C_s^{\pm} V_s^{\pm}(\omega) + C_l V_l^{\pm}(\omega) + \bar{n}\left(C_p V_p^{\pm}(\omega) + C_\Delta^{\pm} V_\Delta^{-}(\omega)\right)$$

↑ Sqz. ∝ ↑ Seed ↑ Loss ↑ Pump ↑ Detuning

For below threshold OPO (without power in the seed beam):
***n = 0*** and $V_s^{\pm} = 1$

$$V_{OPO}^{\pm}(\omega) = C_s^{\pm}(\omega) + C_l$$

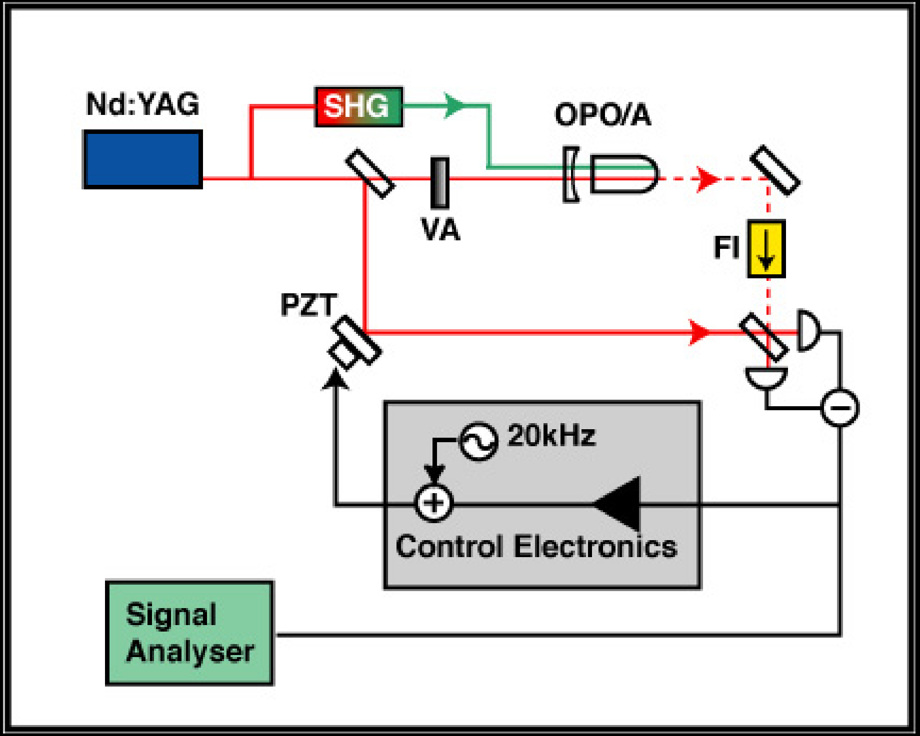



**Below threshold OPO is immune to laser noise, pump noise and detuning noise!**

(to first order)

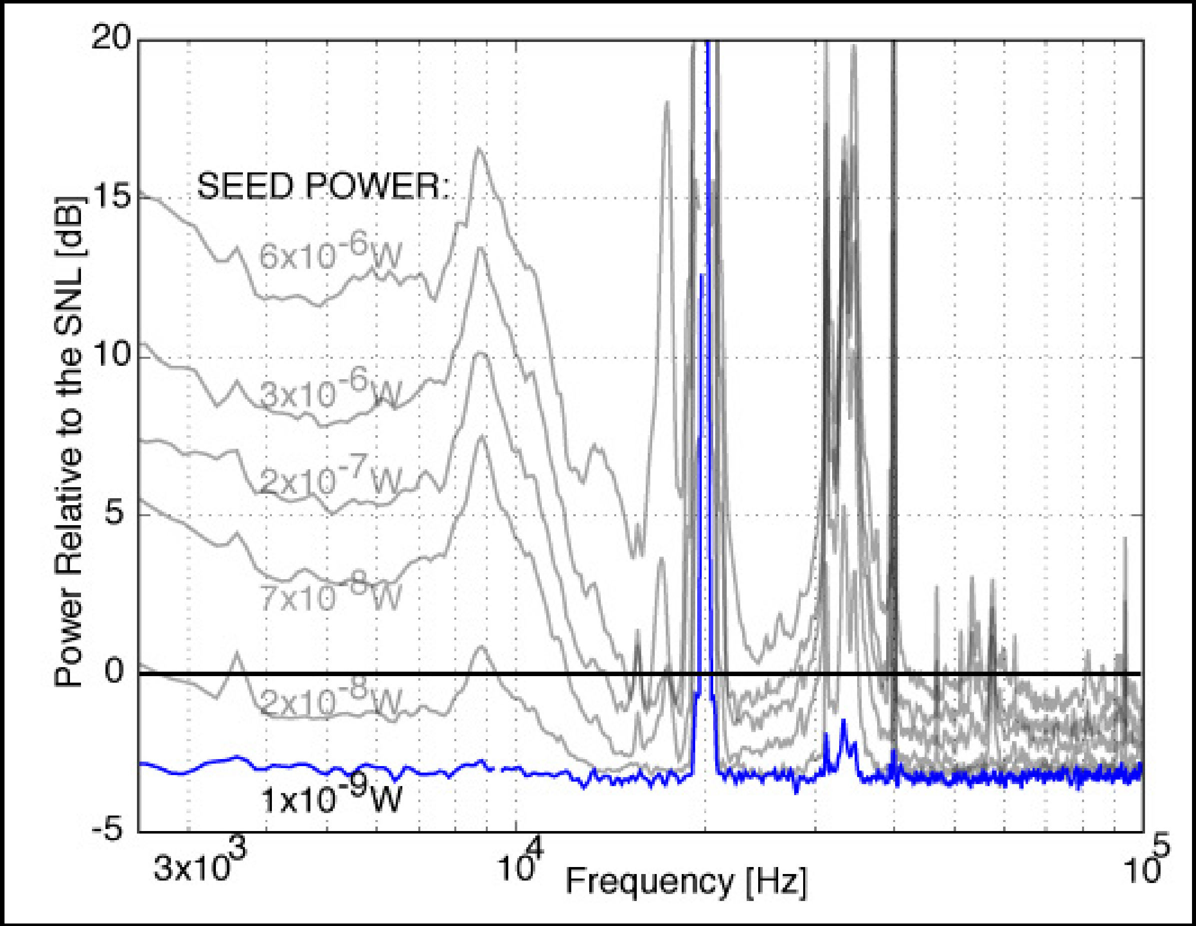
# 2004 Experiment

- Seed power was varied - transition from OPA to OPO
- OPO/OPA cavity locked to 1064 nm
- Homodyne phase locked using **noise power locking [3][5].**
  - Noise power locking **can be used to lock a vacuum state.**
- Backscatter from PD reduced using a Faraday Isolator




[3] Laurat *et al* PRA. **70** 042315(2004), [5] McKenzie *et al* J.Opt B, accepted (2005)

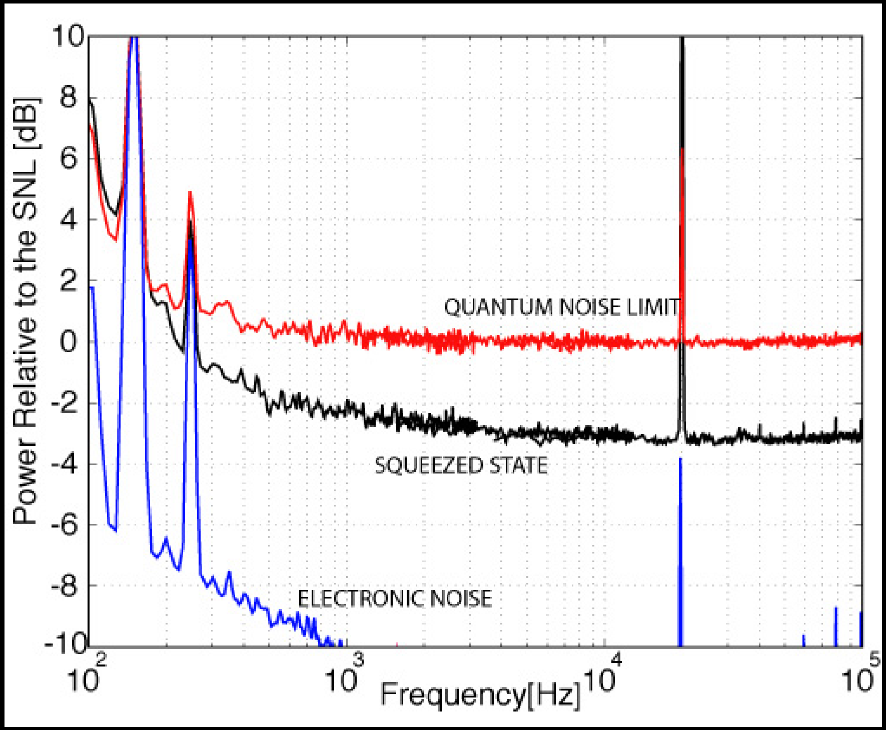
# Reducing the seed power




McKenzie, Grosse, Bowen,Whitcomb, Gray, McClelland, Lam PRL. **93** 161105 (2004)

# Zero Seed Power

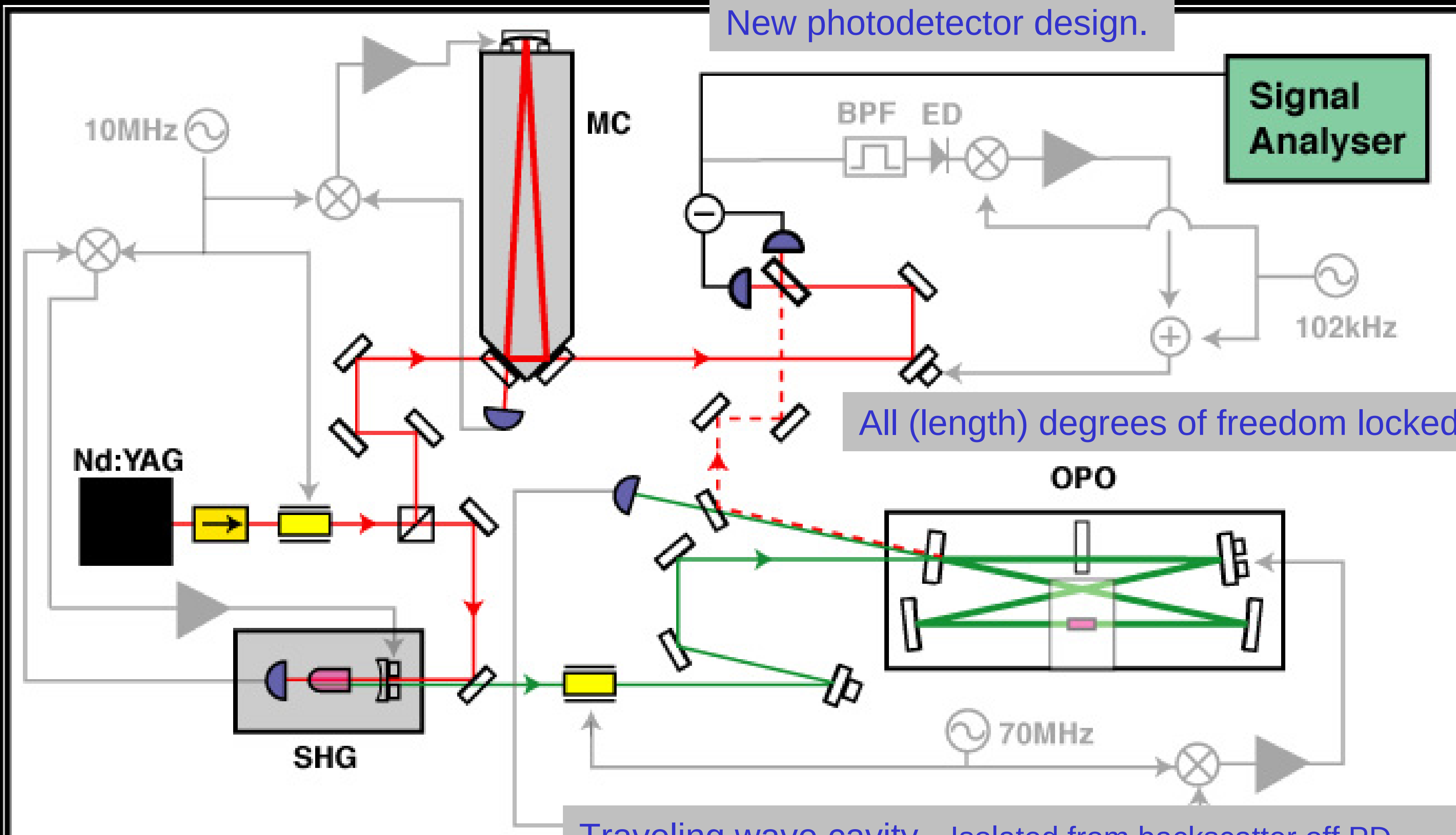
- Was the lowest frequency squeezing result to date - at 300 Hz.
  - (previous lowest was 50 kHz, Laurat *et al* PRA. **70** 042315(2004))




- Covers SNL frequencies of first generation detectors

- Measurement limited at low frequencies by the stability of the unlocked OPO and homodyne ‘roll up’

# New layout 2005



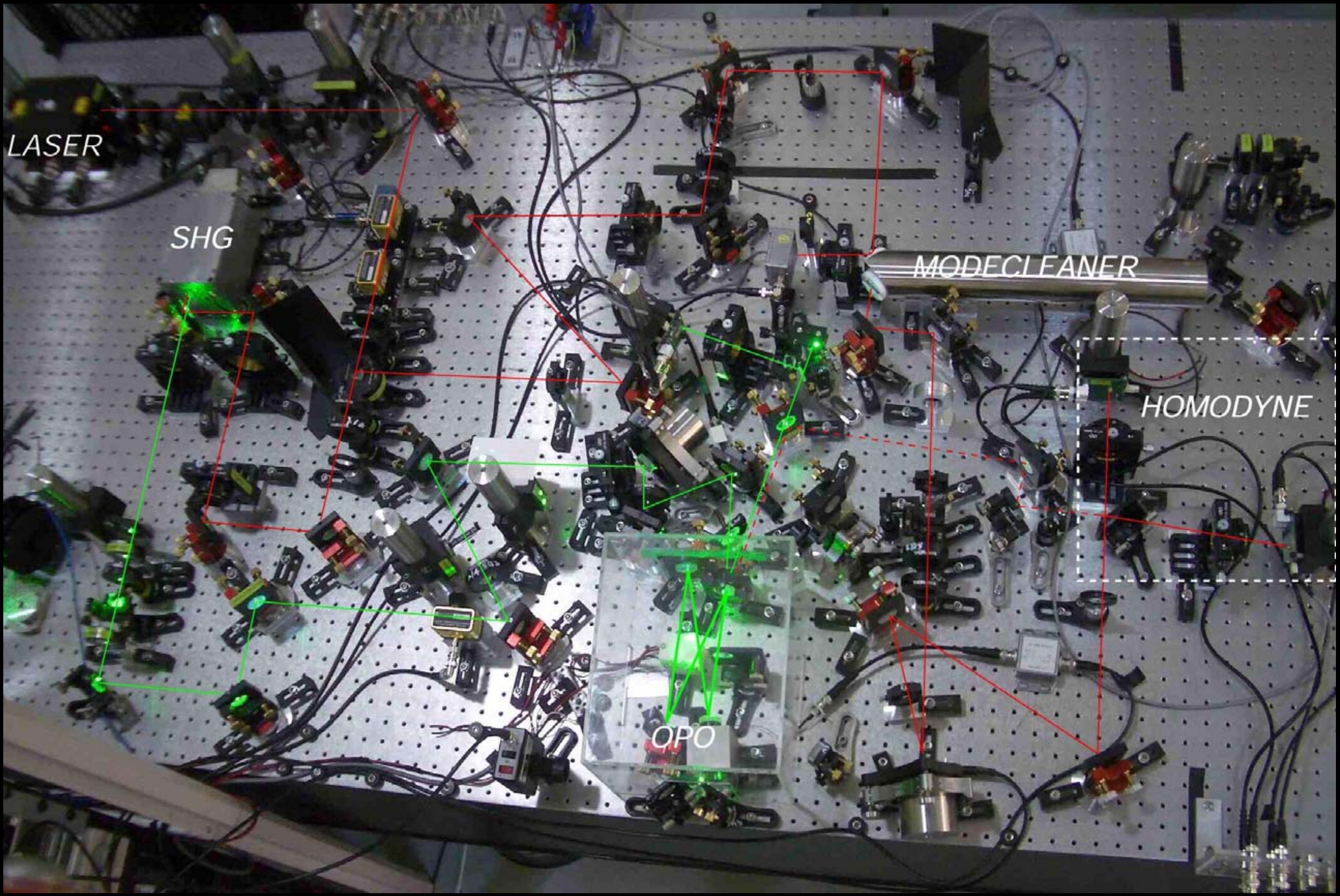

New photodetector design.

All (length) degrees of freedom locked!

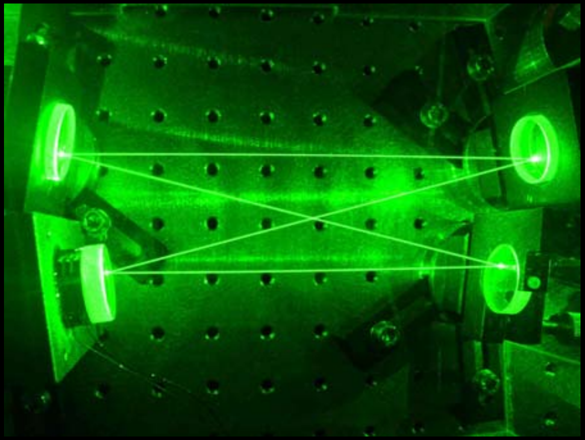
Traveling wave cavity - Isolated from backscatter off PD

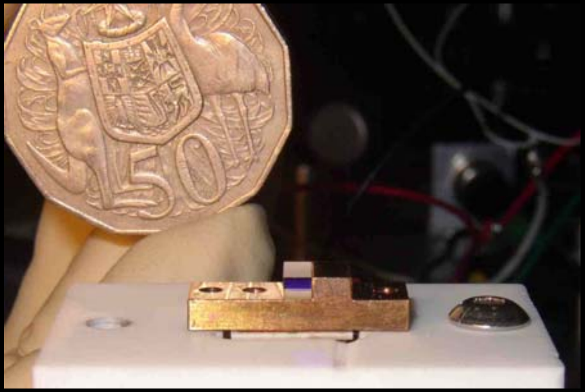
Resonant at pump frequency - effective pump power up to 12 W

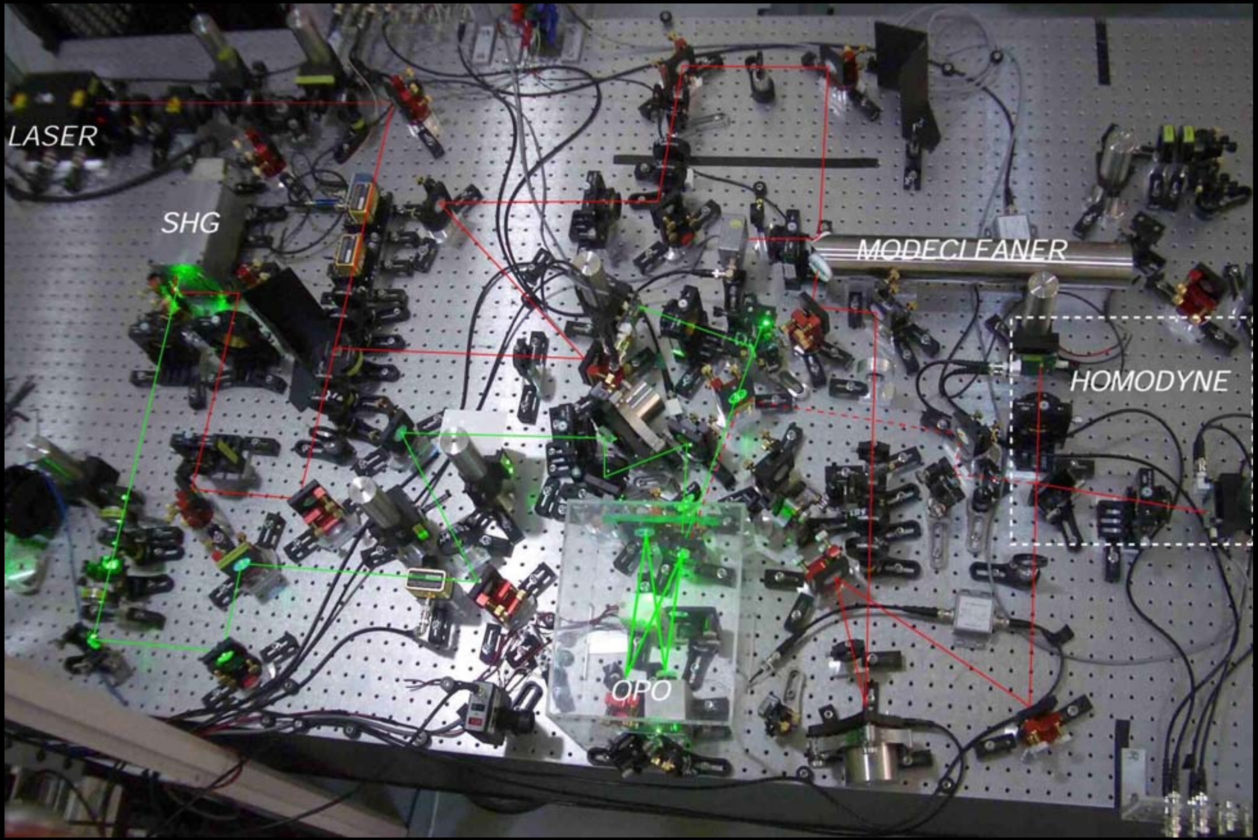
# In the Lab



# In the Lab





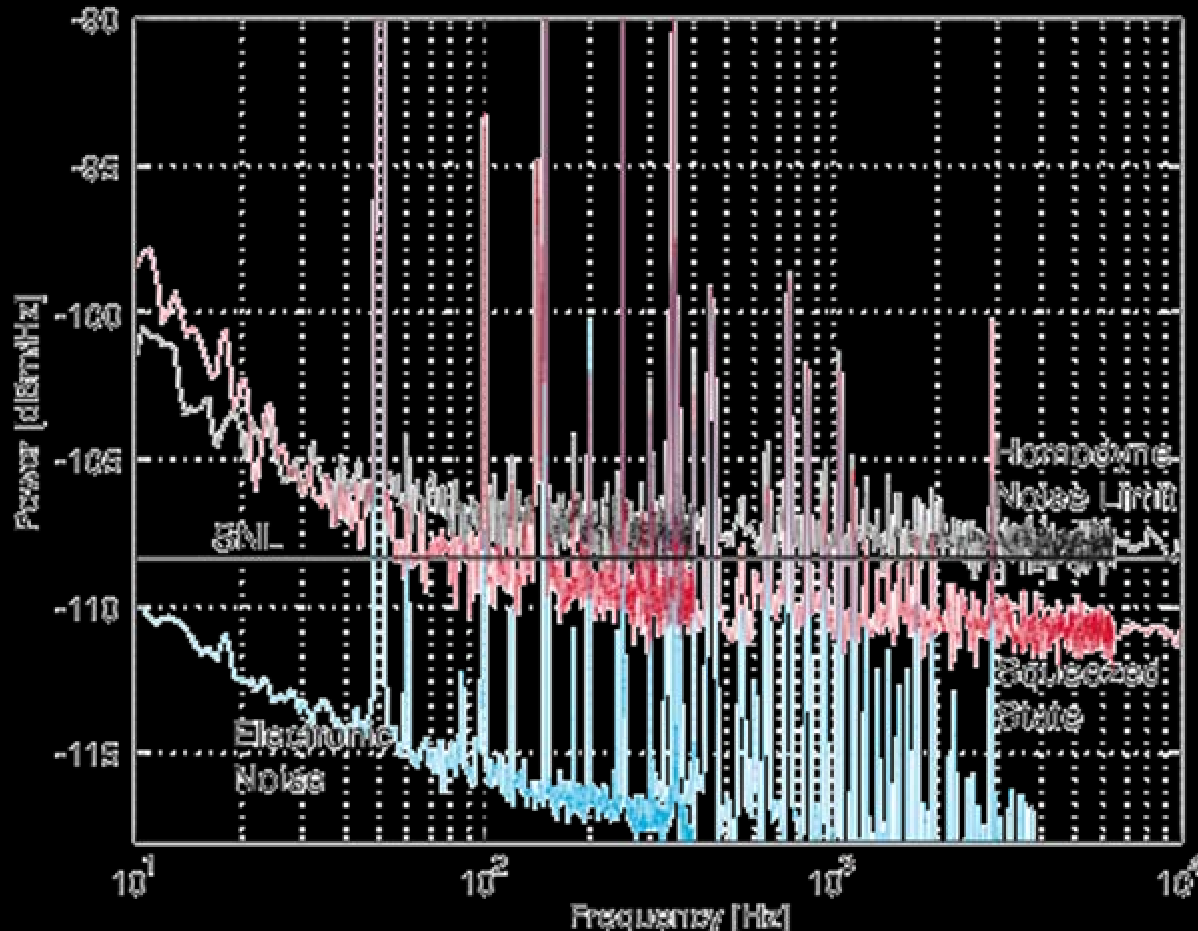


# Current Results

Squeezing down to ~100 Hz

Measured squeezing strength: ~3 dB at 500 Hz

Inferred squeezing strength: ~4.1dB at 500 Hz



# Current limitations

- Currently, only moderate pump power (130 mW) can be used due to cavity spatial mode instability
  - ➢ We need to adjust our cavity parameters (by a small amount) to ensure higher order spatial modes are not co-resonate with the $TEM_{00}$
- Noise locking used to lock homodyne phase - Noise locking stability is poor in comparison to standard (coherent) locking techniques
  - ➢ In the future we would like to phase lock a second laser with a frequency offset and use this to lock the harmonic - fundamental phase as well as the homodyne phase
- Beam pointing limits low frequency detection efficiency (coupling via inhomogenity of photo detectors)
  - ➢ Employ fast steering mirrors in front of homodyne detection

# Summary squeezing

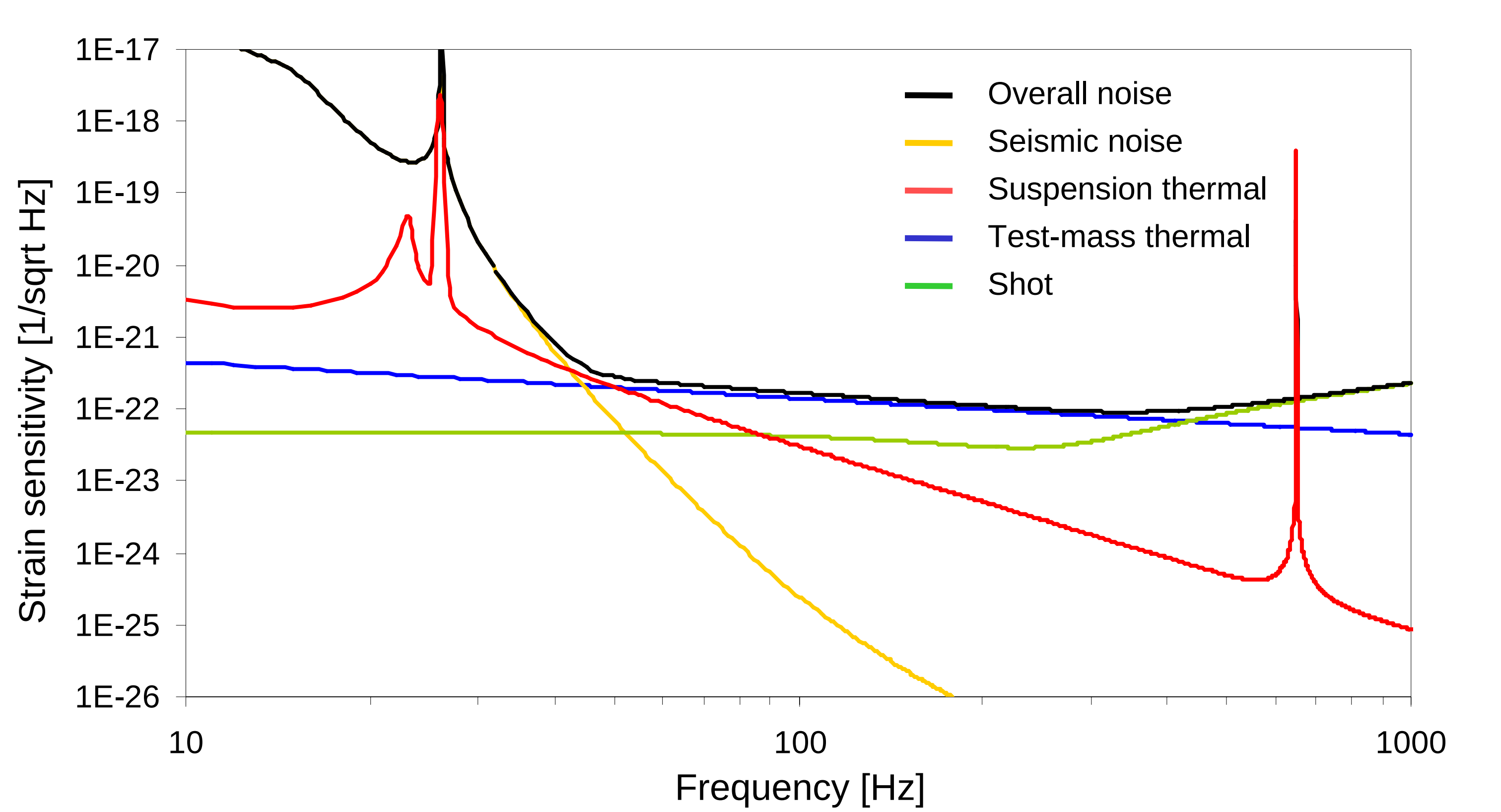
- Noise Coupling mechanism identified - the coherent fundamental field
- Below threshold OPO is immune to laser, pump and detuning noise to first order!
- All length degrees of freedom locked, OPO cavity locks indefinately.
- If this squeezed state (~3 dB measured at 500 Hz) could be implemented
  - Improve current LIGO SNL strain sensitivity increase by $\sqrt{2}$
  - Equivalent of turning up the laser power by a factor of 2

- Developing new generation of squeezer
  - Operate at higher pump power - to generate larger amounts of squeezing
  - Inject second laser to replace noise locking loop

# Thermal noise and SQL

- Thermal noise in gravitational wave detectors
- Niobium flexure membrane as an inverted pendulum mirror suspension
- Experimental layout
- Frequency stabilisation
- Seismic isolation
- Current results and limitations
- Summary

# Thermal noise

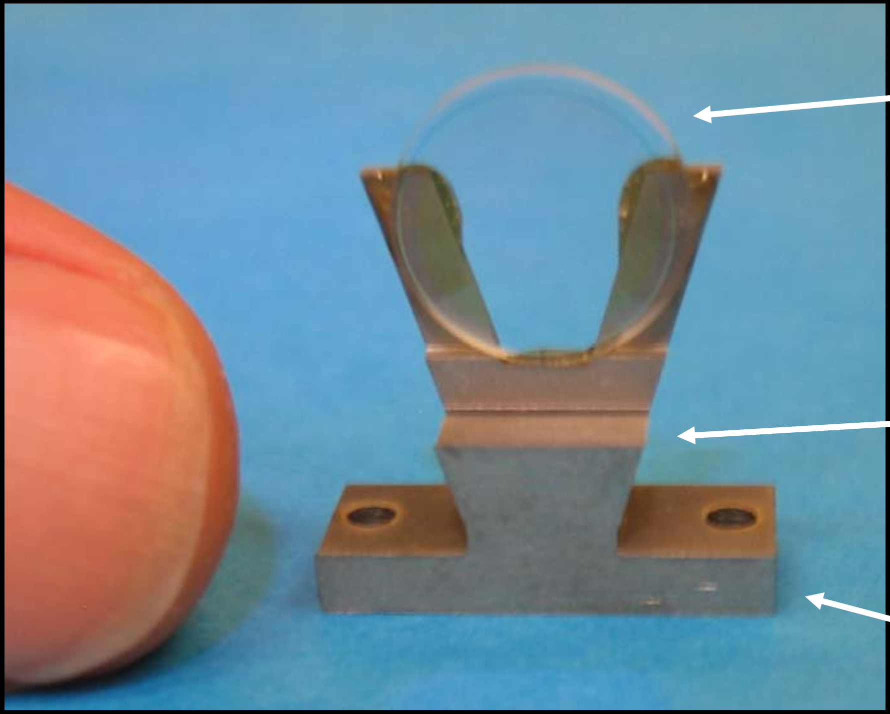



Thermal noise of mirrors and suspensions will eventually limit the sensitivity of gravitational wave detectors in their most sensitive frequency band

Thermal noise will also be a major impediment to reaching SQL sensitivity with a table-top experiment as is planned at the **ANU**

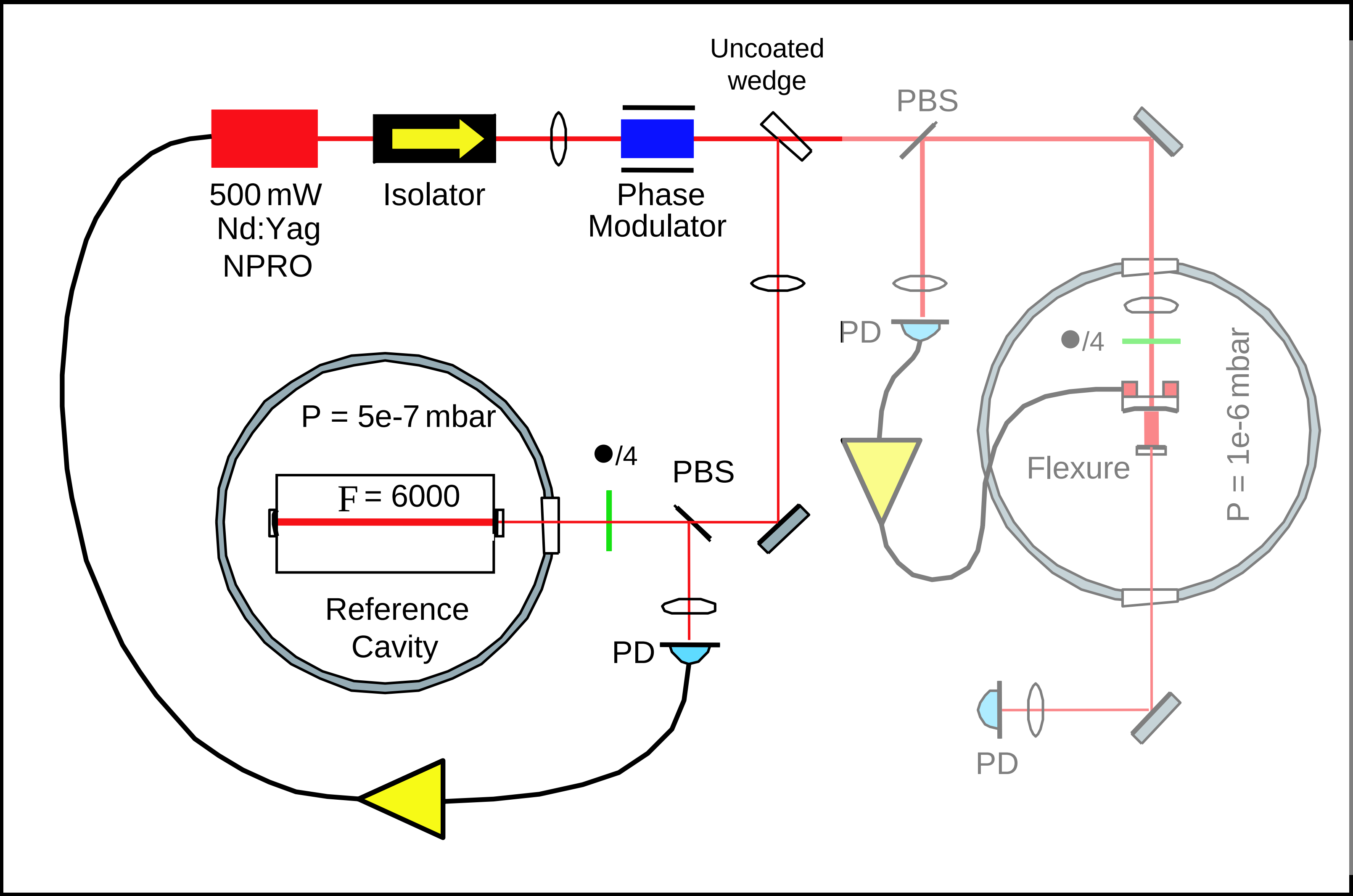
# Niobium Flexure Membrane

To investigate thermal noise
we use a niobium flexure membrane of 200 μm width
as an inverted pendulum to support a mirror of 0.25 g

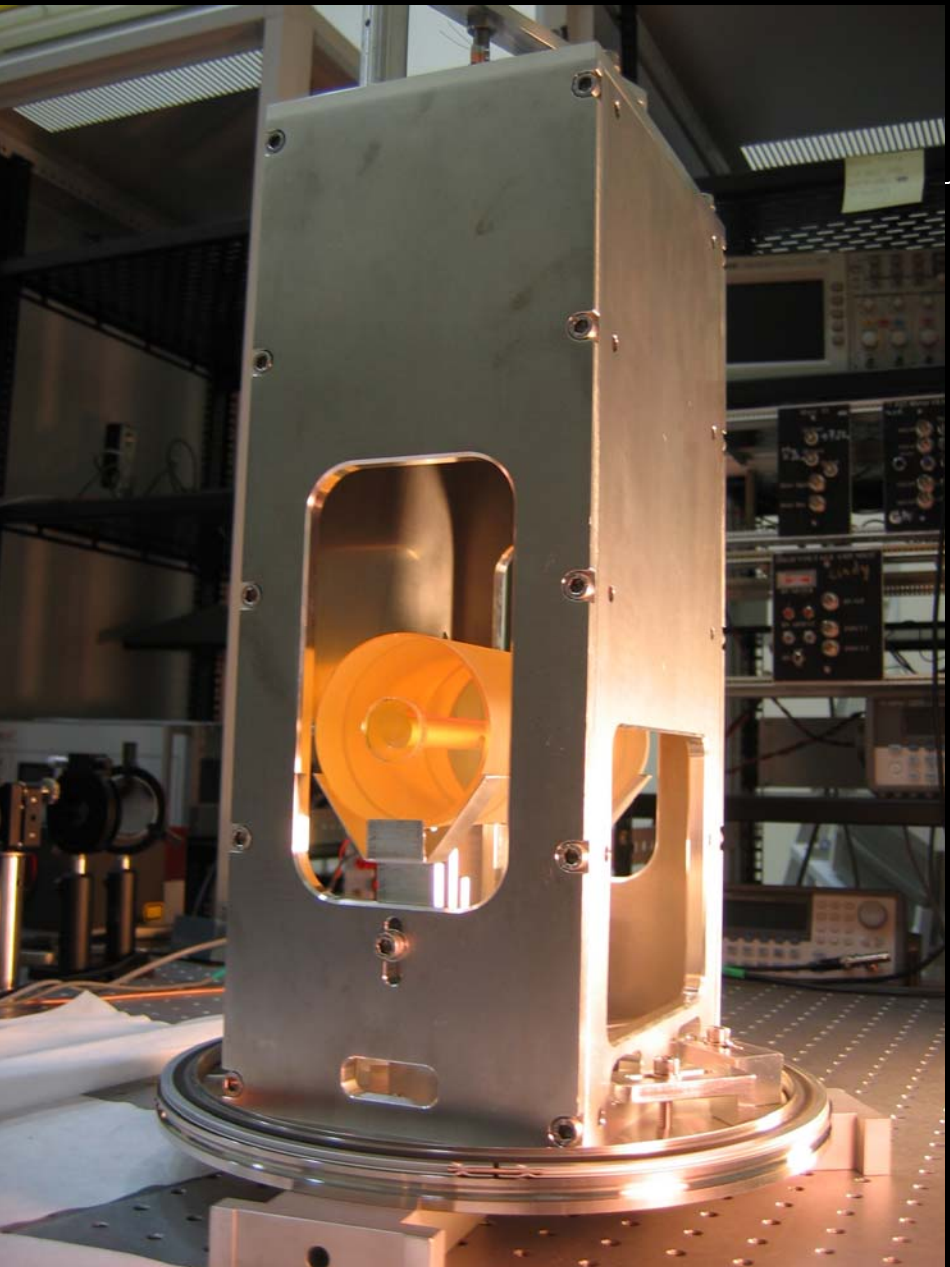


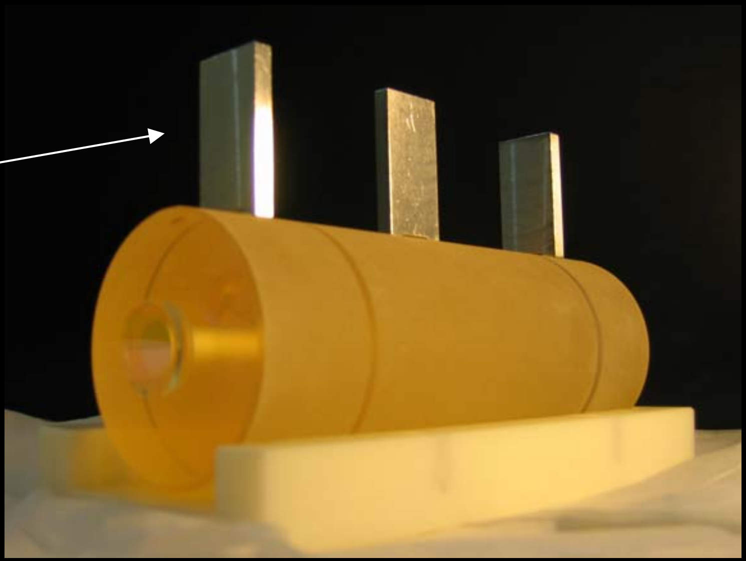

(Thanks to Ju Li from UWA for the help with niobium flexure!)

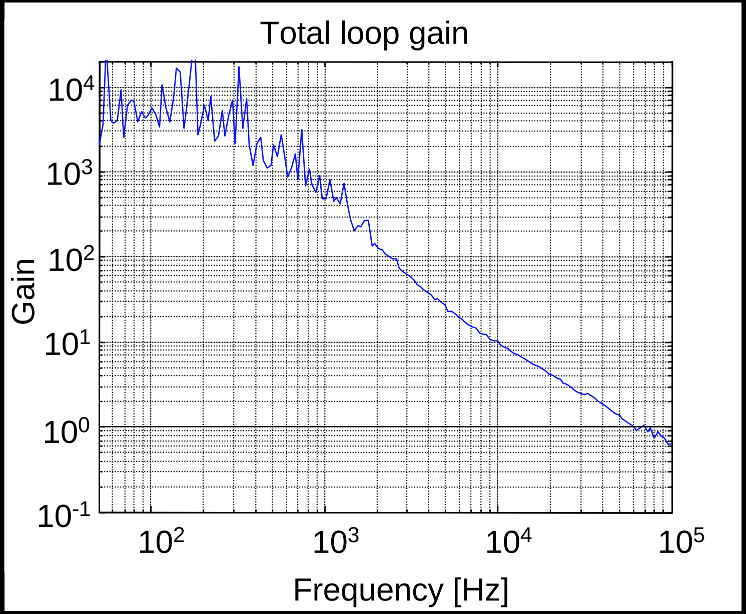
# Experimental layout



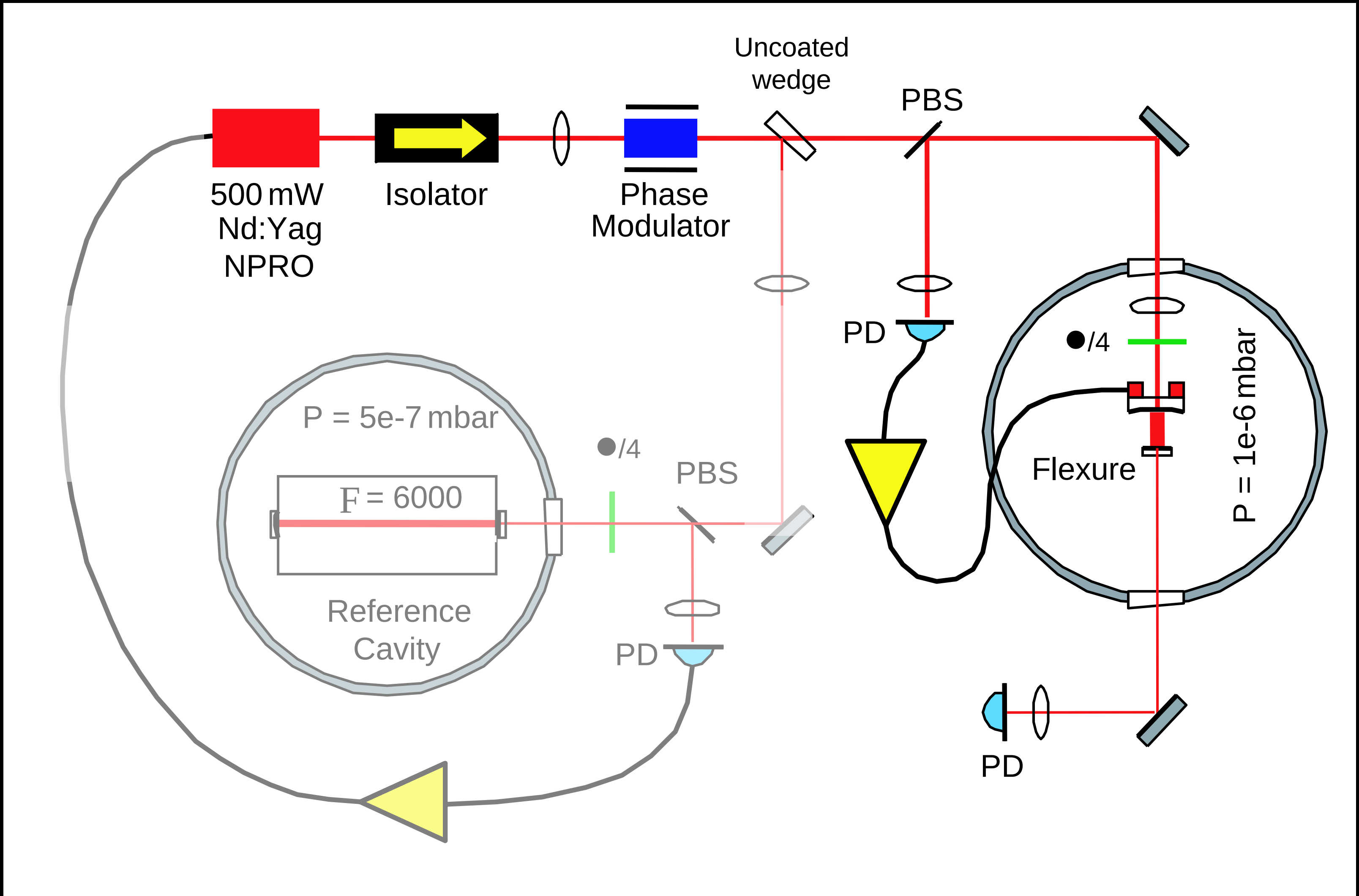
# Frequency stabilisation

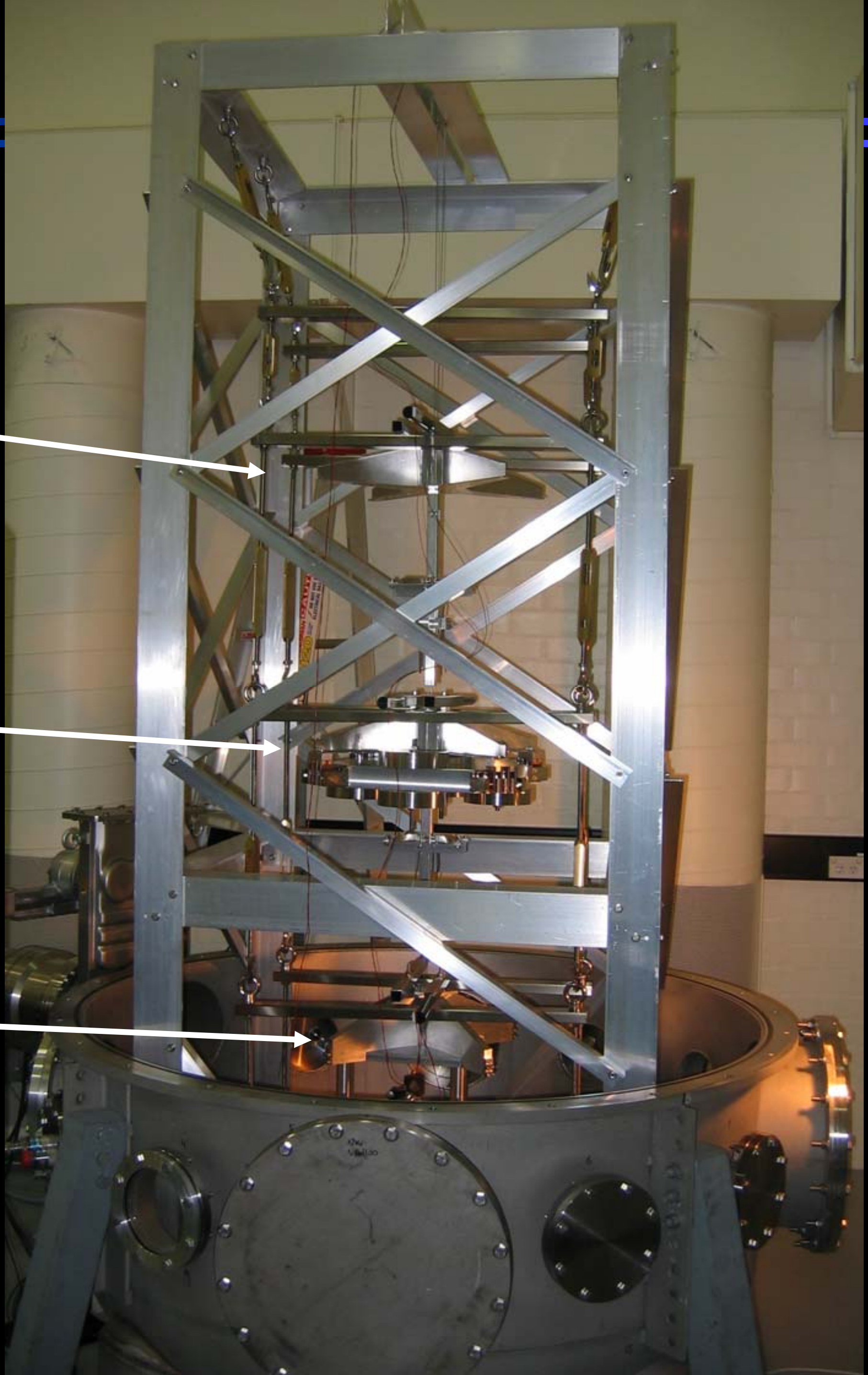




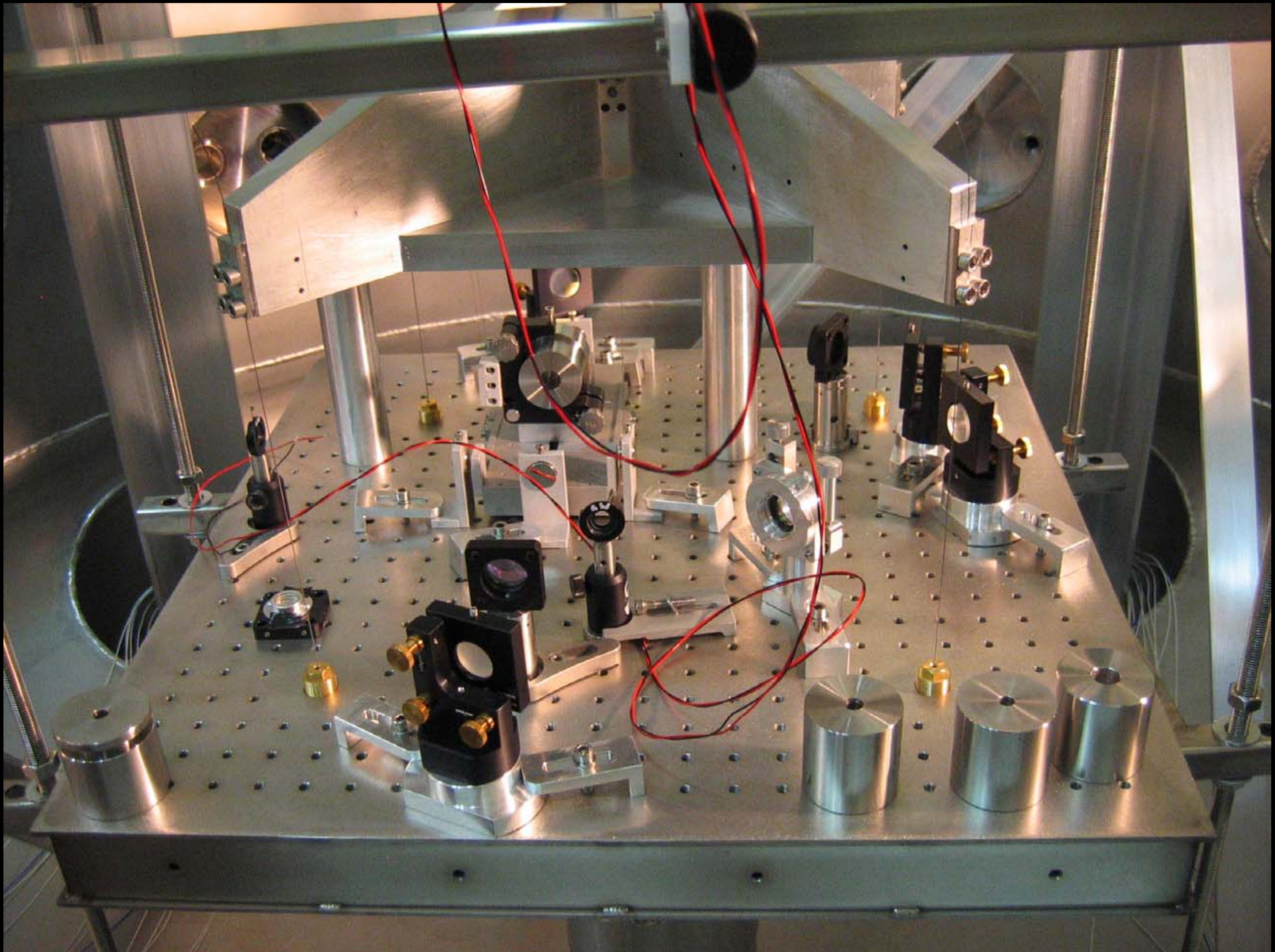


# Experimental layout

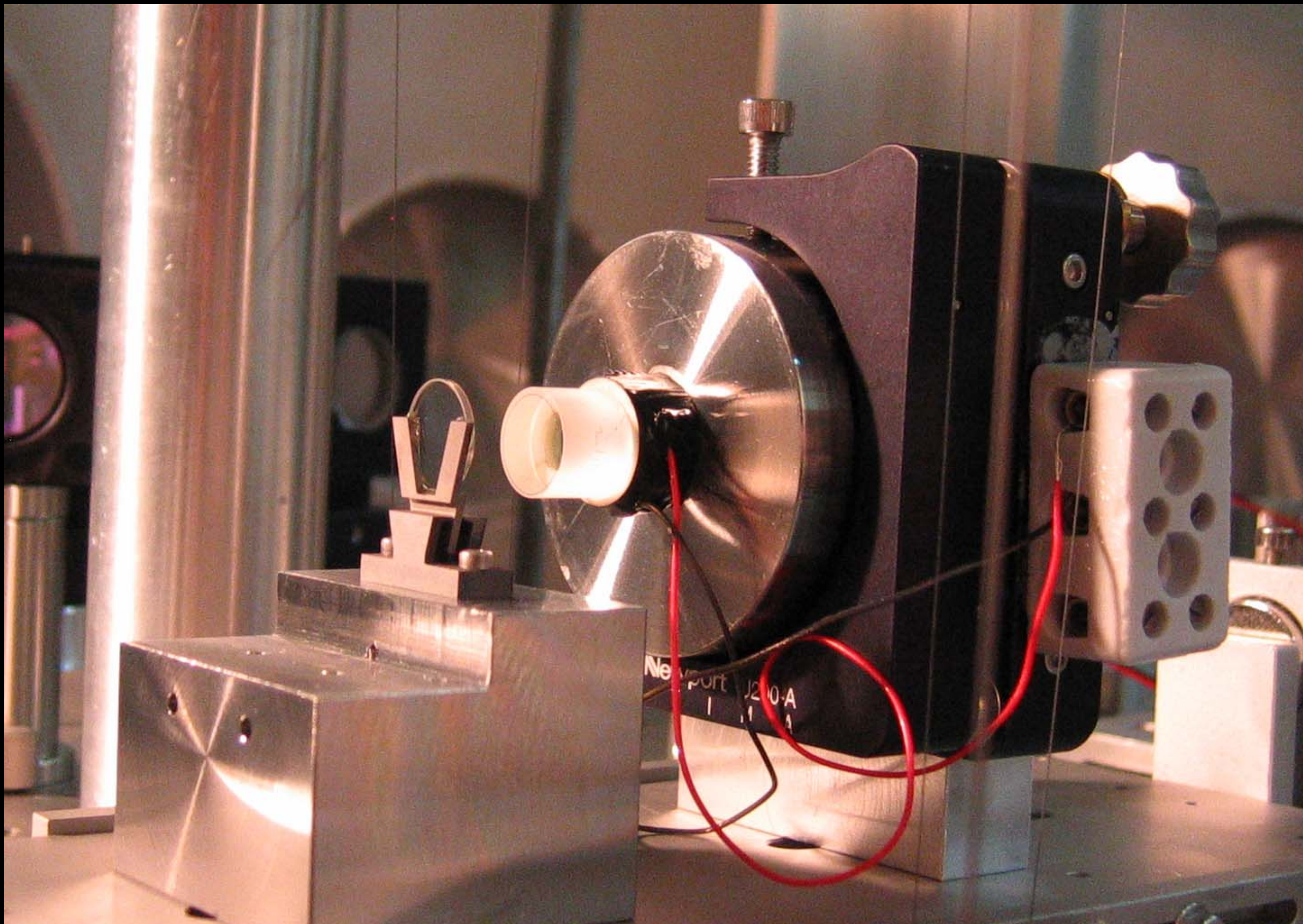



Upper mass
3 kg
Euler buckles
Rocking stage
50 kg
Euler buckels
Penultimate mass
9 kg
~3.5 m

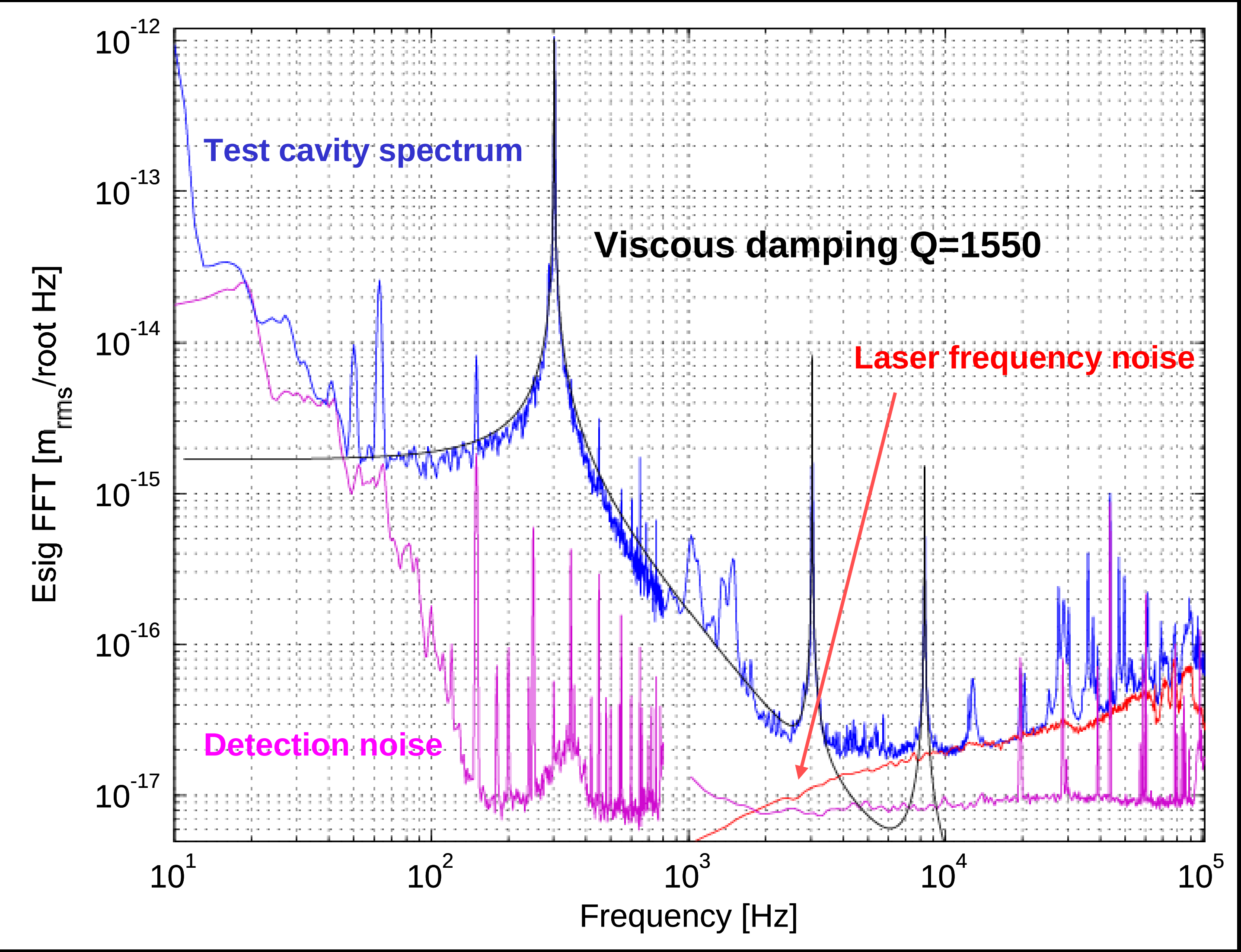
# Suspended breadboard (35 kg)



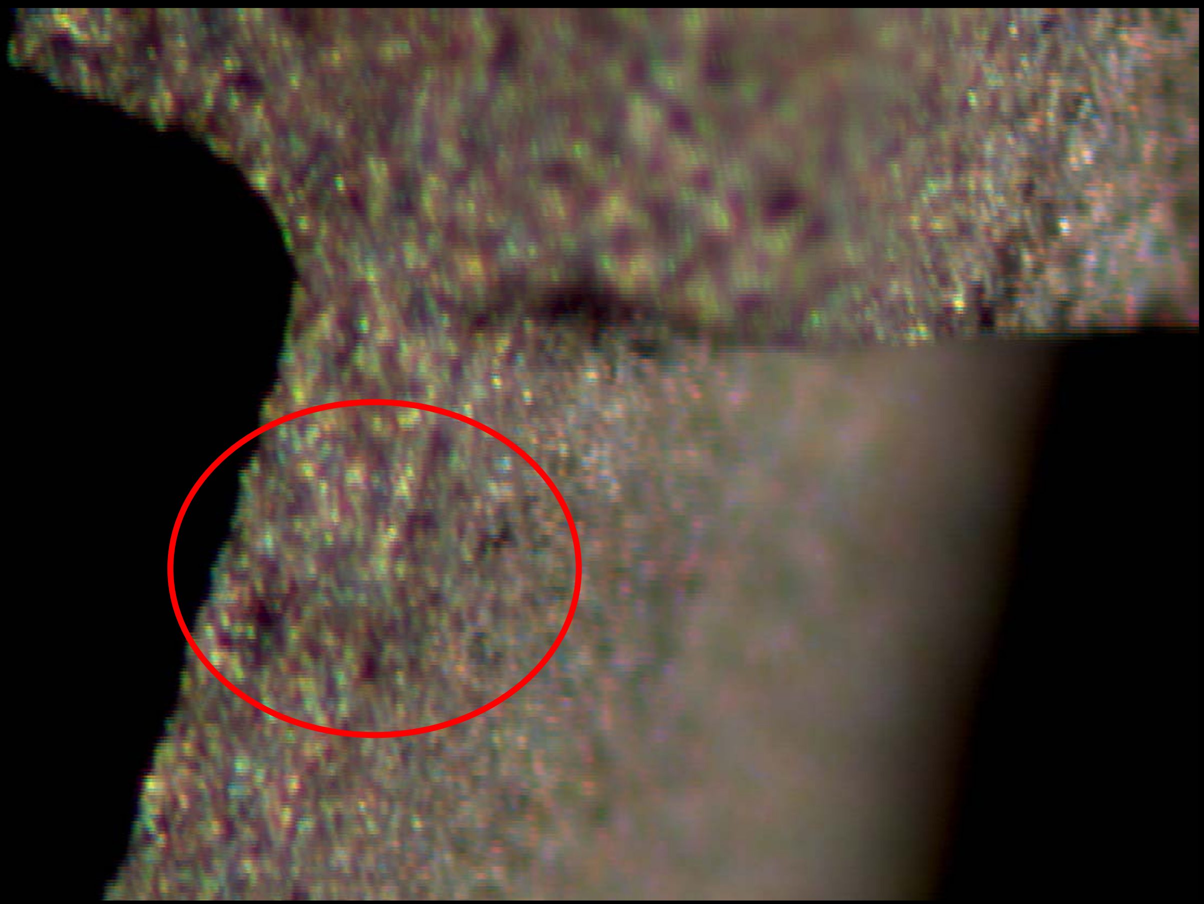
# Test cavity



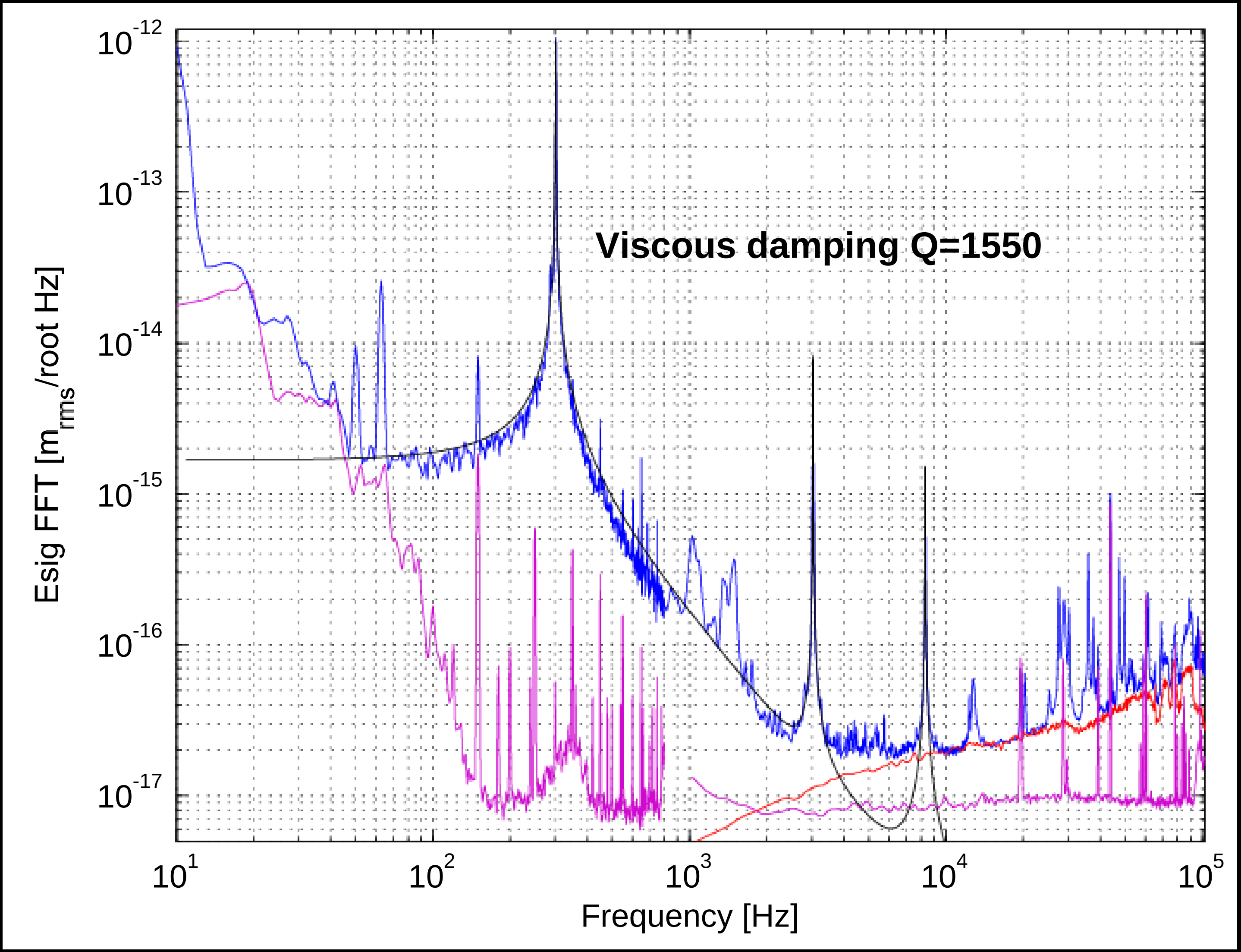
# Preliminary results



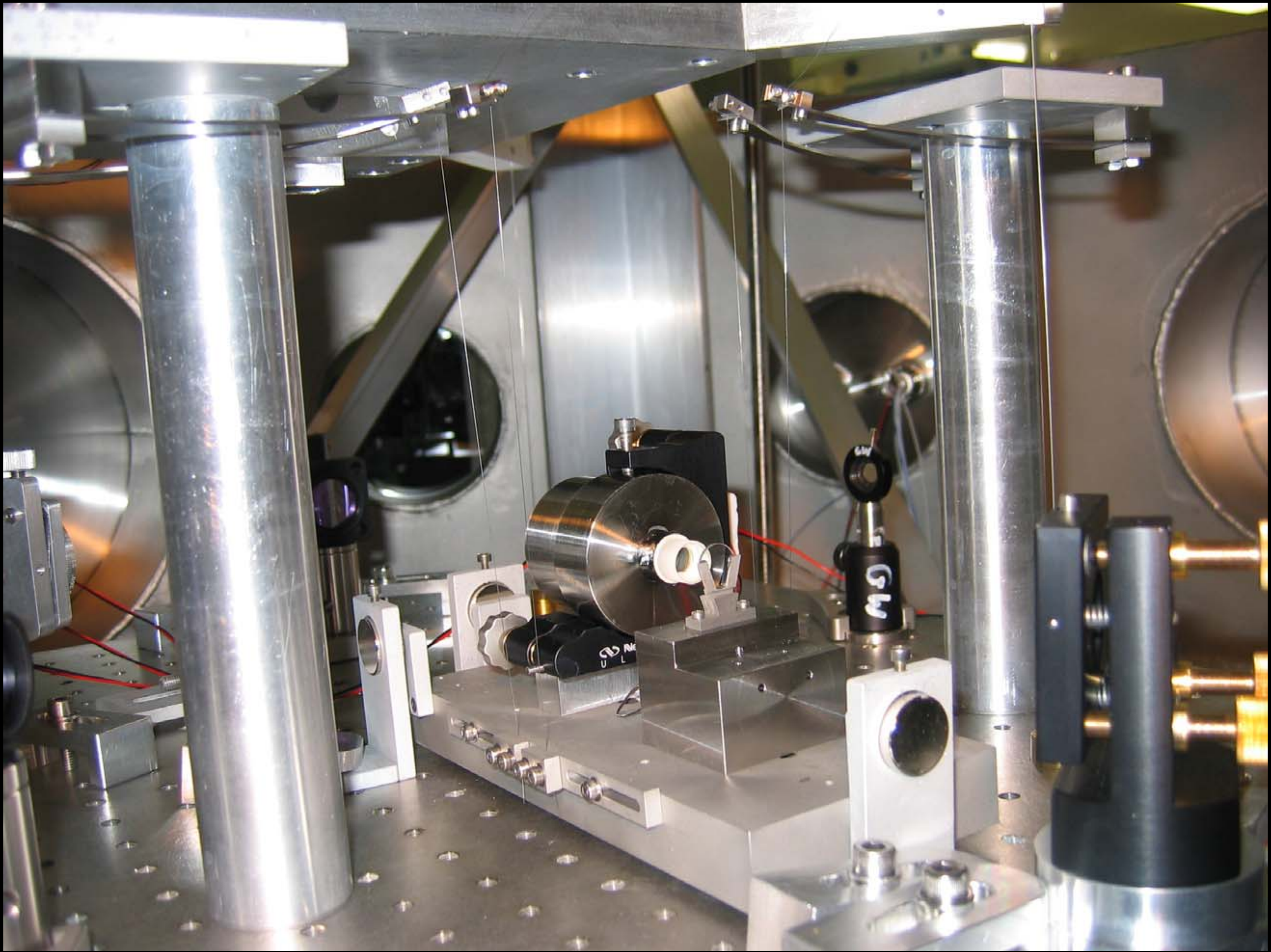
# Magnification 100 X



# Preliminary results



# New Suspension Stage

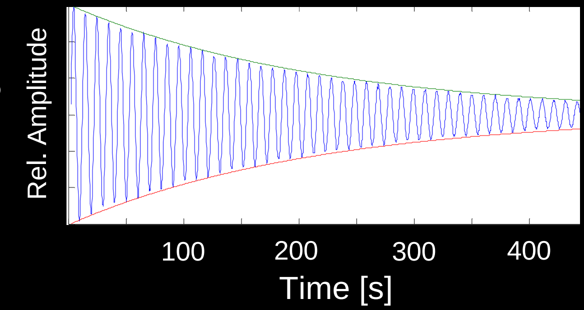


# Summary TN and SQL



• Measured thermal noise of a viscous damped system with Q=1550

• Move on to system with Q=45,000: structural damping?




**<u>Towards the SQL:</u>**

• Design of torsion balance of about 1g to couple optical fluctuations to displacement
This opto-mechanical coupler will be based on a thin fused silica fiber
Design study based on 100 µm steel wire

• Study of coating-free mirrors based on total internal reflection
to avoid coating thermal noise

•This torsion balance will be incorporated into arm-cavity Michelson interferometer

**SQL**