Title: Optomechanics and Filters with Micromirrors

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URL: http://pirsa.org/18060054

Abstract:

ARC Centre of Excellence for Gravitational Wave Discovery

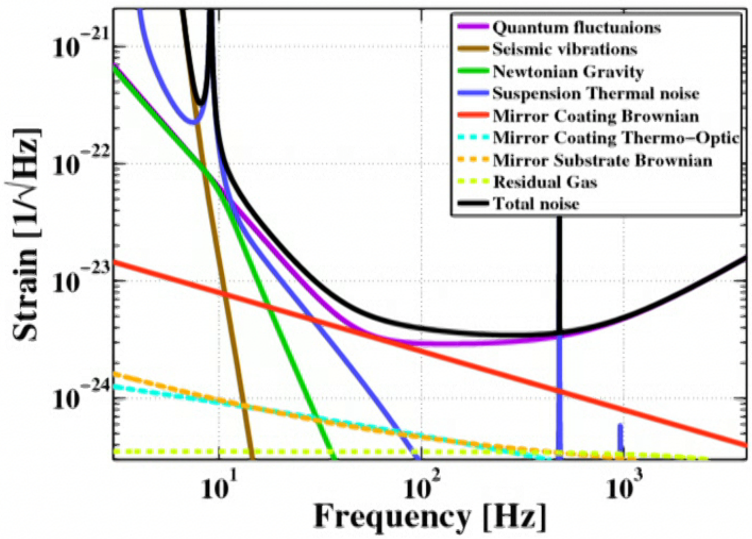
Parametric Instabilities
&
Development of mechanical resonators

Chunnong Zhao, Jue Zhang, Jian Liu, Vladimir Bossilkov, Vahid Jaberian Hamedan, Li Ju, David Blair,

THE UNIVERSITY OF WESTERN AUSTRALIA

Motivation

- Resonant optical cavities act like a low pass filter because of the light travel time
- Would like to increase the gain, or number of rounds trips, to increase SNR
- Low pass filter is already at 1 kHz with a finesse of about 40
- Problem for kHz GWs



$$\gamma = \frac{Tc}{4L}$$

Background

- Would like to cancel time delay from light travel time

Enhancing the bandwidth of gravitational-wave detectors with unstable optomechanical filters

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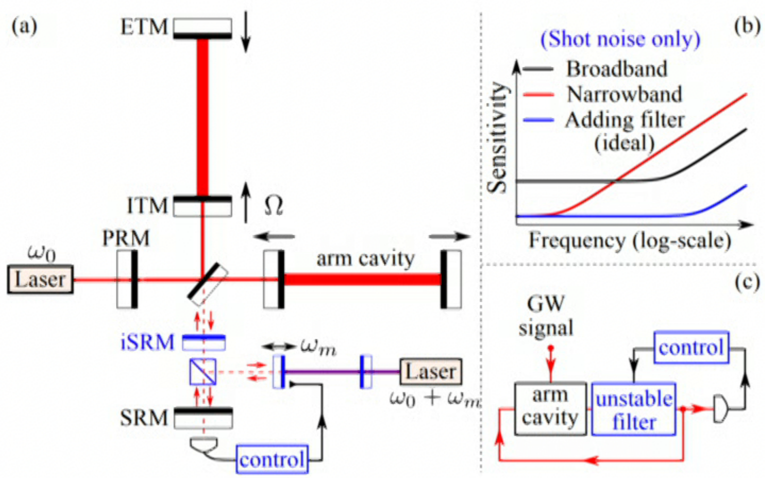
[3]Theoretical Astrophysics 350-17, California Institute of Technology, Pasadena, CA 91125, USA

For gravitational-wave interferometric detectors, there is a tradeoff between the detector bandwidth and peak sensitivity when focusing on the shot noise level. This has to do with the frequency-dependent propagation phase lag (positive dispersion) of the signal. We consider embedding an active unstable filter—a cavity-assisted optomechanical device operating in the instability regime—inside the interferometer to compensate the phase, and using feedback control to stabilize the entire system. We show that this scheme in principle can enhance the bandwidth without sacrificing the peak sensitivity. However, there is one practical difficulty for implementing it due to the thermal fluctuation of the mechanical oscillator in the optomechanical filter, which puts a very stringent requirement on the environmental temperature and the mechanical quality factor.

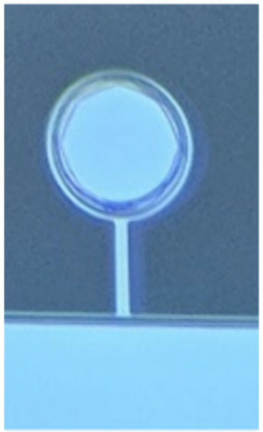


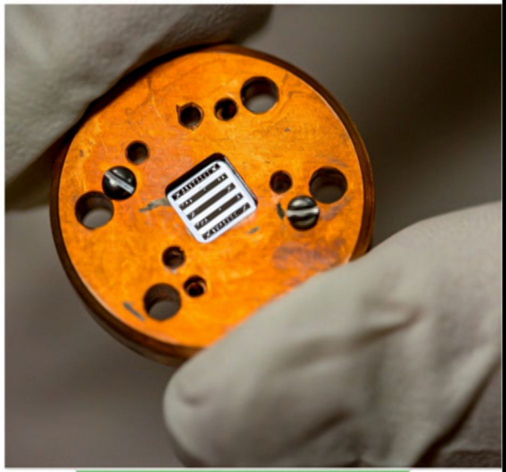
$$\frac{T_{\rm envir}}{Q_m} \lesssim 6\times 10^{-10}{\rm K}\left(\frac{\gamma_{\rm SRM}/2\pi}{100{\rm Hz}}\right)$$

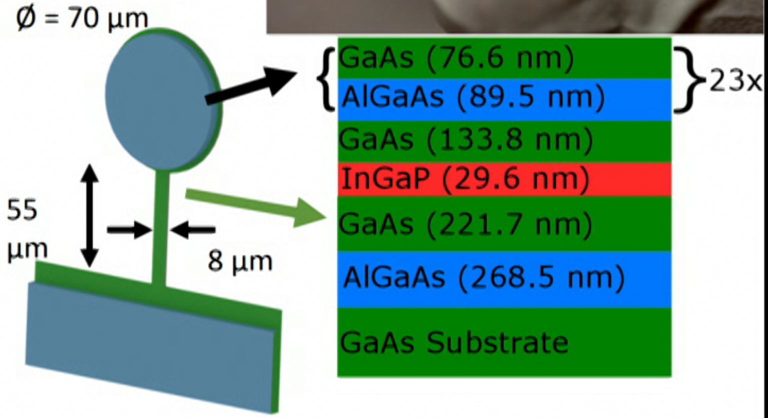
Phys. Rev. Lett. **115**, 211104 (2015).

Our devices

- Cantilever mirror
  - Fabricated by Garrett Cole
  - T = 250 ppm
  - Mirror diameter: 70 µm
  - Cantilever dimensions:
    55 µm long by 8 µm wide
  - Mass: 50 ng
  - Fundamental frequency: 876 Hz
  - Q = 17,000
  - T/Q = 0.017 K (room temperature)
  - Missing about 8 orders of magnitude to meet requirement
- Crystalline coatings are being considered for future GW detectors because of their low mechanical loss

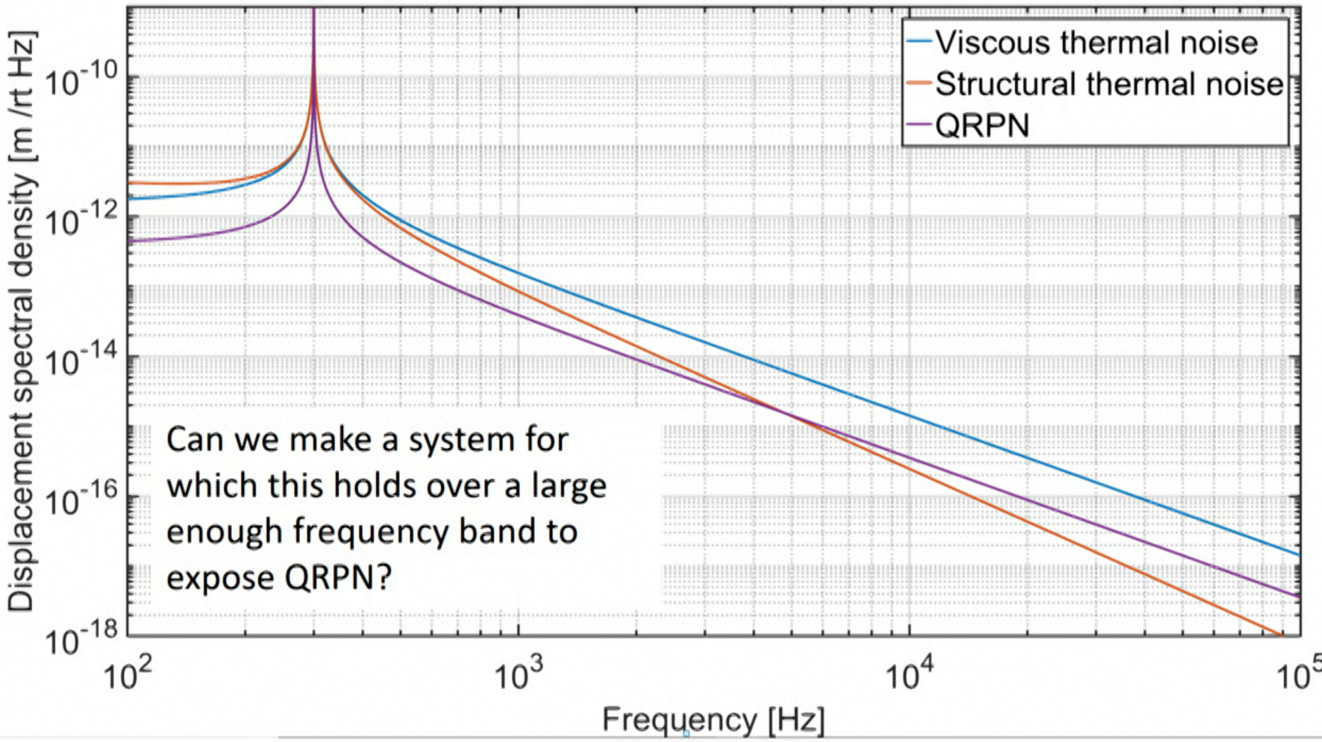






The trap of measuring QRPN / why did we design it this way

Thermal noise from structural damping falls off more rapidly than quantum radiation pressure noise (QRPN) -> use low frequency mechanical oscillator.



Cantilever Mirror Design Considerations

Goals: Low thermal noise, low mass, high reflectivity

Parameter	**Advantages for decreasing**	**Disadvantages for decreasing**
Fundamental frequency	Structural thermal noise starts to fall off sooner	More higher order modes between 10 kHz and 100 kHz
Mass	Increase ratio of QRPN to structural thermal noise	Increase fundamental frequency, worse higher order modes
Mirror transmission	Increases cavity finesse	Increases thickness of mirror and mass

Making up some ground

Optical dilution and feedback cooling of a gram-scale oscillator to 6.9 mK

Thomas Corbitt,[1] Christopher Wipf,[1] Timothy Bodiya,[1] David Ottaway,[1]
Daniel Sigg,[2] Nicolas Smith,[1] Stanley Whitcomb,[3] and Nergis Mavalvala[1]

[1]*LIGO Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
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[3]*LIGO Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*

(Dated: May 30, 2018)

We report on use of a radiation pressure induced restoring force, the *optical spring effect*, to optically dilute the mechanical damping of a 1 gram suspended mirror, which is then cooled by active feedback (cold damping). Optical dilution relaxes the limit on cooling imposed by mechanical losses, allowing the oscillator mode to reach a minimum temperature of 6.9 mK, a factor of ∼ 40000 below the environmental temperature. A further advantage of the optical spring effect is that it can increase the number of oscillations before decoherence by several orders of magnitude. In the present experiment we infer an increase in the dynamical lifetime of the state by a factor of ∼ 200.

Phys. Rev. Lett. **99**, 160801 (2007).

For structural damping, the thermal noise PSD is:

$$S_{\mathrm{x,structural}} = 4k_bT\frac{\Omega_m^2}{\Omega Q}\frac{1/m}{(\Omega_m^2-\Omega^2)^2+\Omega_m^4/Q^2}$$

$$S_{\mathrm{x,structural,OS}} = 4k_bT\frac{\Omega_m^2}{\Omega Q}\frac{1/m}{(\Omega_{OS}^2-\Omega^2)^2+\Omega_{OS}^4/Q_{OS}^2}$$

$$= 4k_bT\frac{\Omega_{OS}^2}{\Omega Q_{\mathrm{eff}}}\frac{1/m}{(\Omega_{OS}^2-\Omega^2)^2+\Omega_{OS}^4/Q_{OS}^2}, Q_{\mathrm{eff}} = Q\left(\frac{\Omega_{OS}}{\Omega_m}\right)^2$$

For structural damping, effective quality factor is enhanced by the square of the ratio of the optical spring to the mechanical frequency

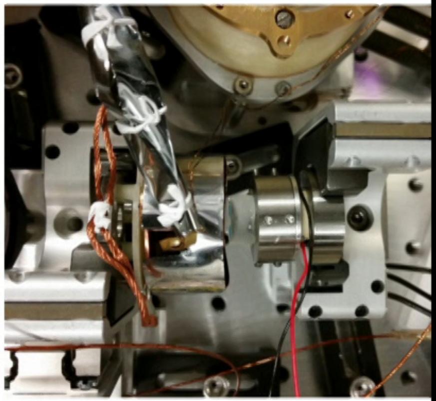
Stiff optical springs

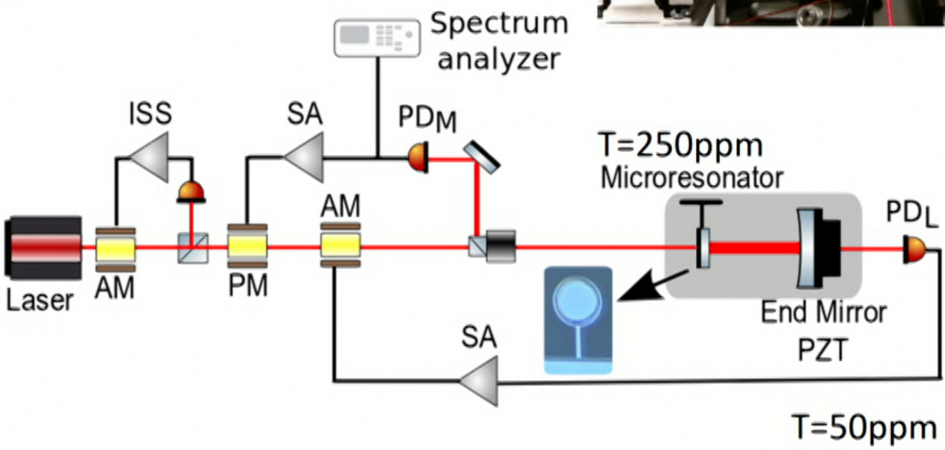
- To reach the desired T/Q for the filter cavity, we have about 8 orders of magnitude of make up:
  - Let's suppose that we can operate at 5 K. Given the required power levels and absorption levels, this is reasonable. That gives us about 2 orders of magntiude.
  - To make up the remaining 6 orders of magntiude, we need only make an optical spring a million times stiffer than the mechanical system (while not doing anything to spoil the noise performance).
    - Stiff optical springs like this were demonstrated over 10 years ago (but not without extra noise).
- So how close are we?

Experimental Setup

- Optomechanical cavity
  - 1-cm long
  - Finesse = 13,000
  - Detuned 0.6 linewidths to get large optical spring
- PD_L fed back to AM to acquire lock using optical spring (OS)
- PD_M loop maintains lock after PD_L loop is disconnected
- Intensity stabilization servo (ISS)
- Only 100 microWatts input needed to reach 150 kHz OS.

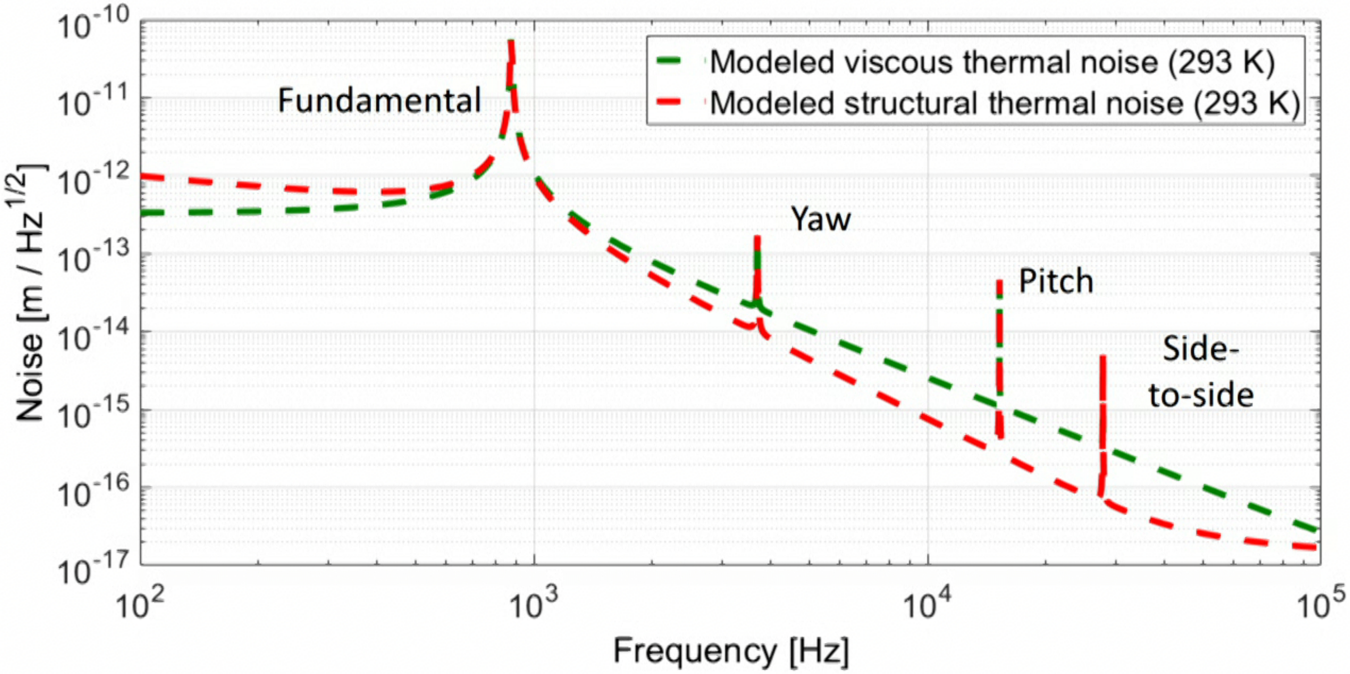
PRA **97**, 013827 (2018)





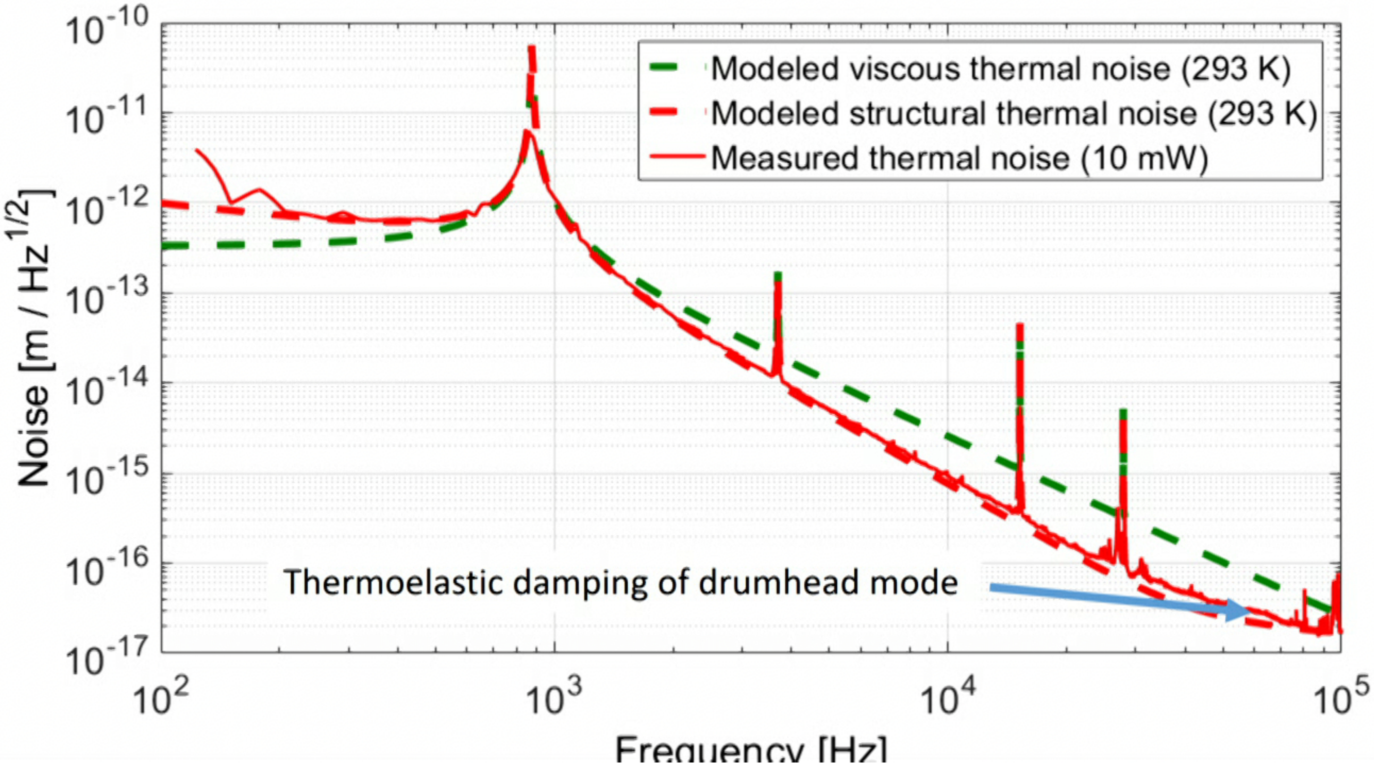
Thermal Noise Model

- Based on finite element model using measured frequencies



Thermal Noise Model

- Measured at low optical power to avoid QRPN

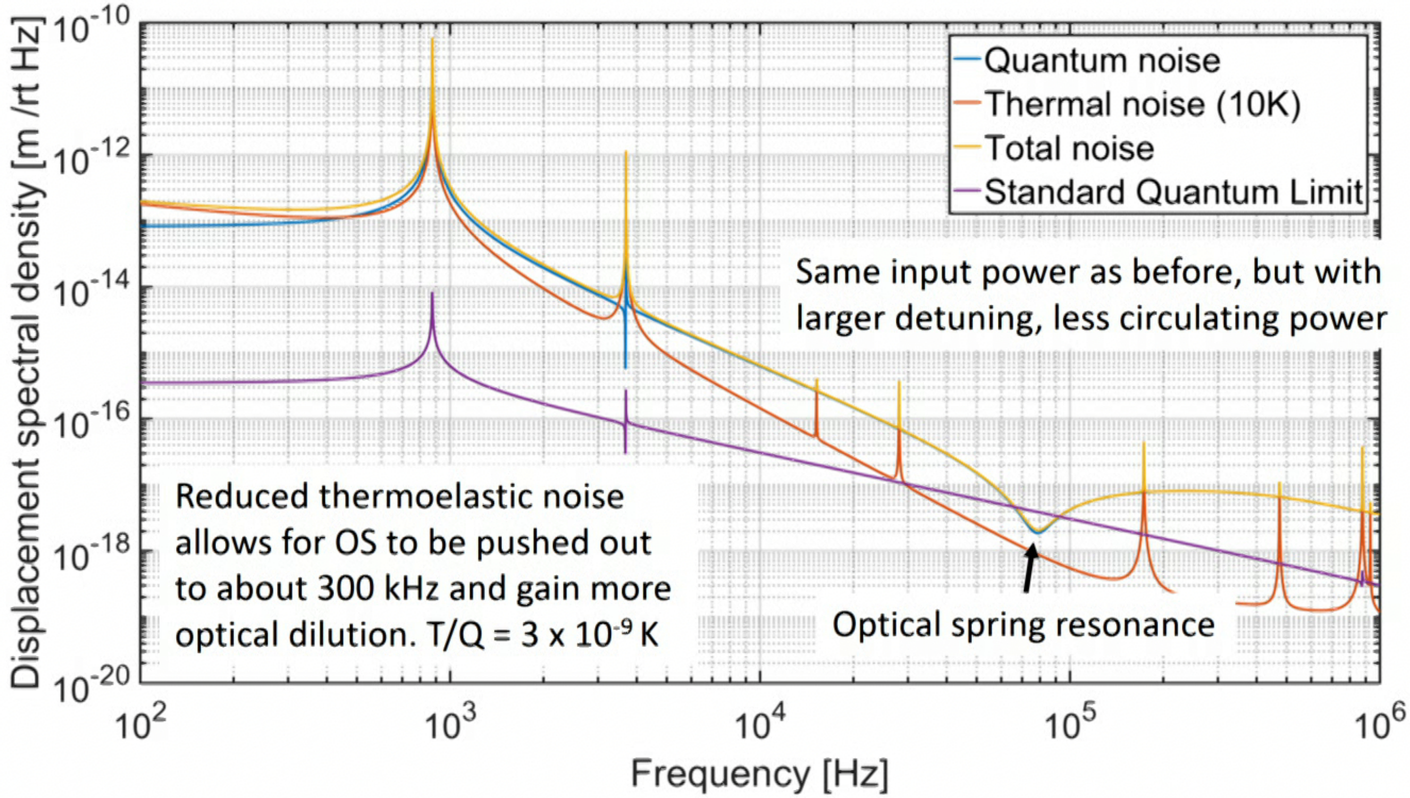


Cooling and the Standard Quantum Limit

- At room temperature:
  - Thermoelastic damping limits performance and optimal OS frequency. $T/Q = 5 \times 10^{-6}$ K
- SQL
  - Not really standard
  - Not really a limit
  - But… it still serves as a benchmark
  - Advanced LIGO currently within a factor of about 4 of SQL
  - This experiment is within a factor of about 4.5 at room temperature – limited by thermal noise

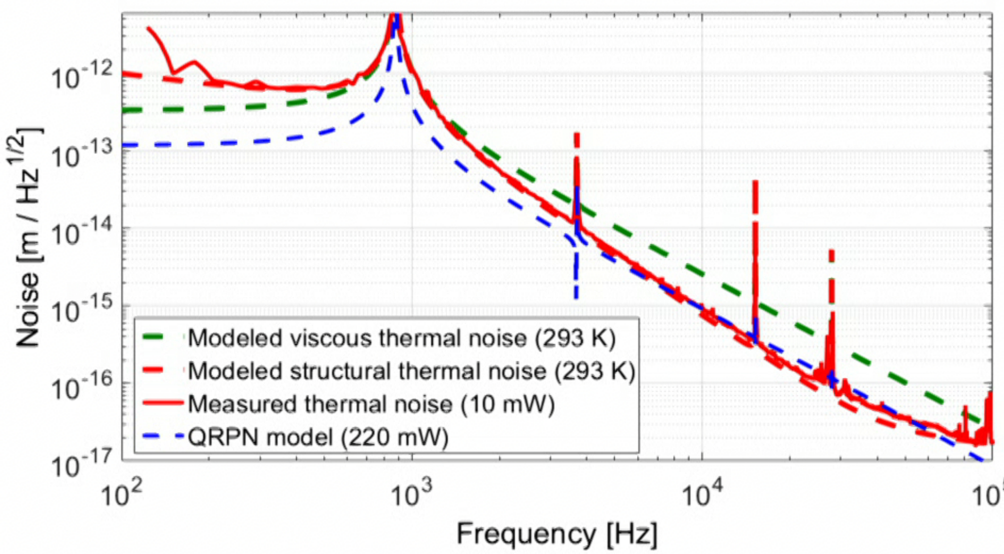
Cryogenic performance

Cryostat is installed and connected, allows for operation at 10 K. Need frequency stabilization

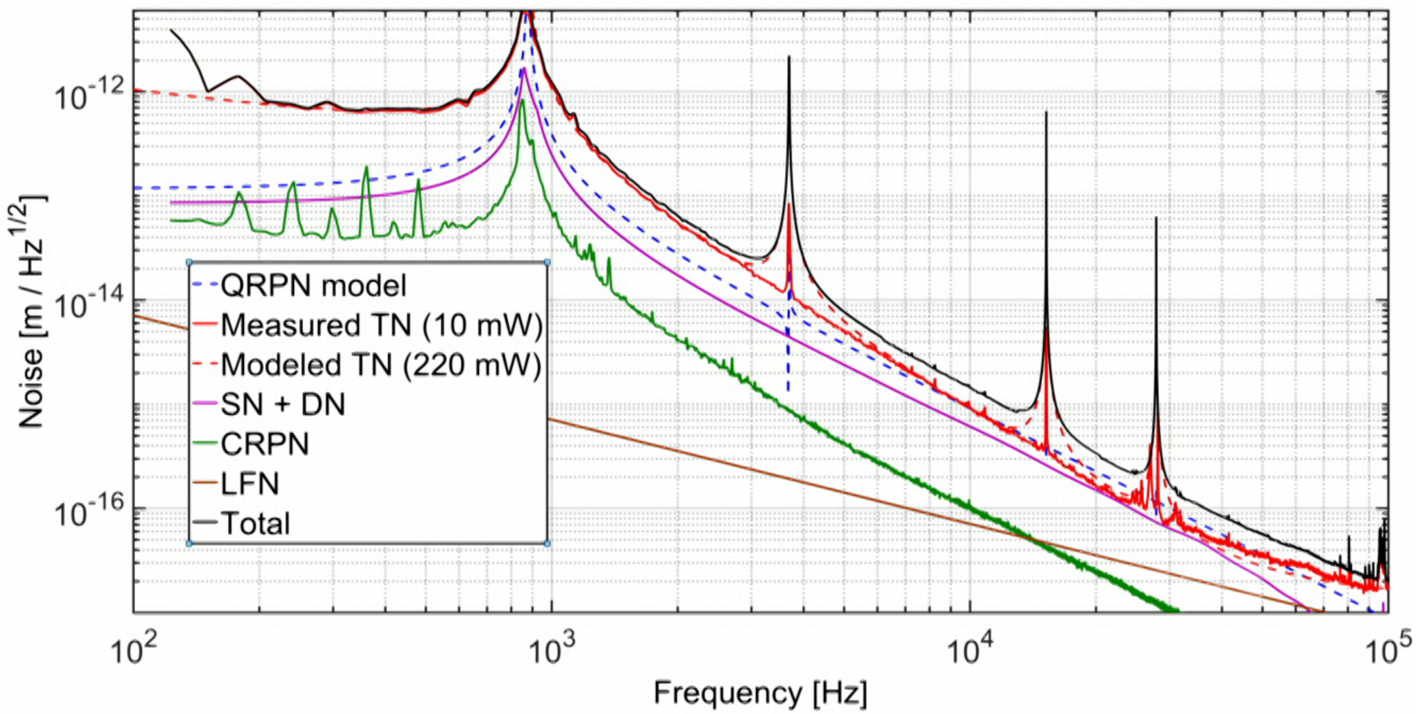


Quantum Noise Model

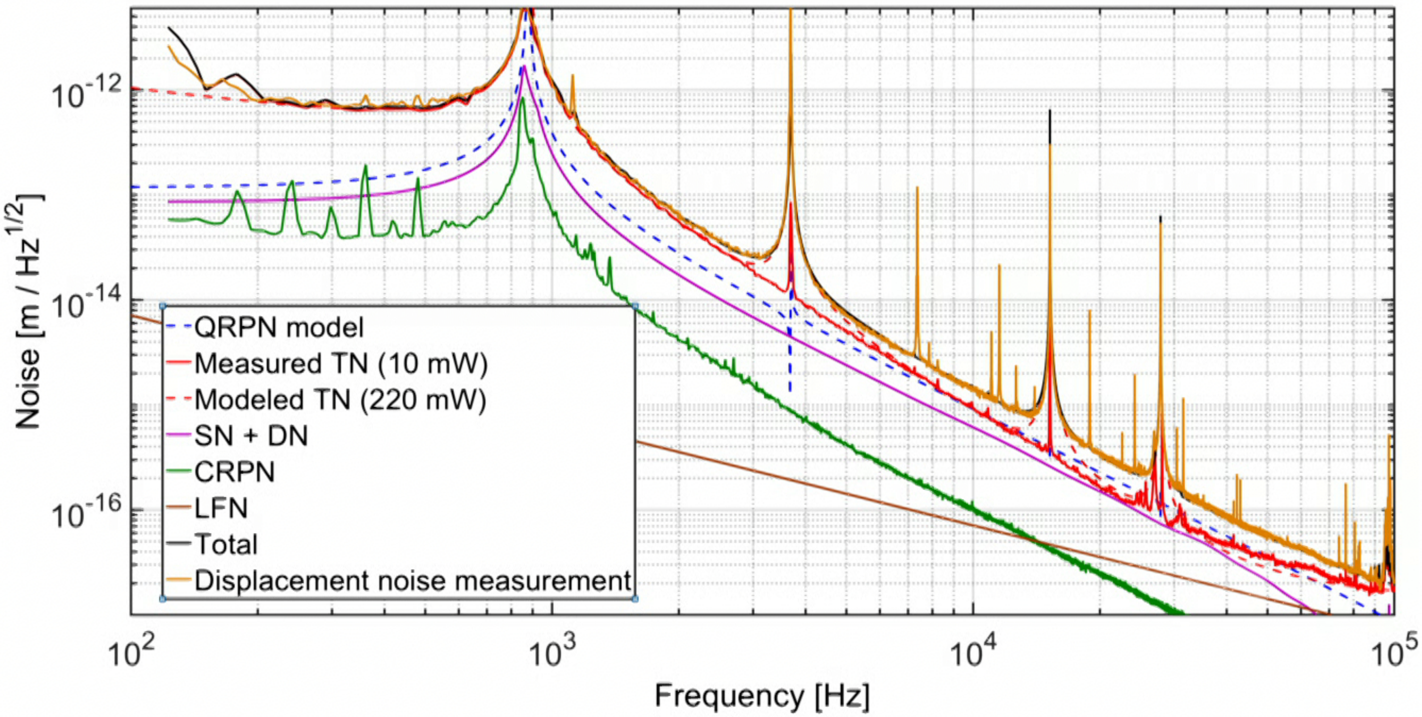
- Measurements of power, mode matching, optical spring frequency and linewidth to constrain parameters
- No free parameters used to calculate QRPN



Adding it up


Noise [m / Hz^1/2]
10^-12
10^-14
10^-16
10^2
10^3
10^4
10^5
Frequency [Hz]
QRPN model
Measured TN (10 mW)
Modeled TN (220 mW)
SN + DN
CRPN
LFN
Total

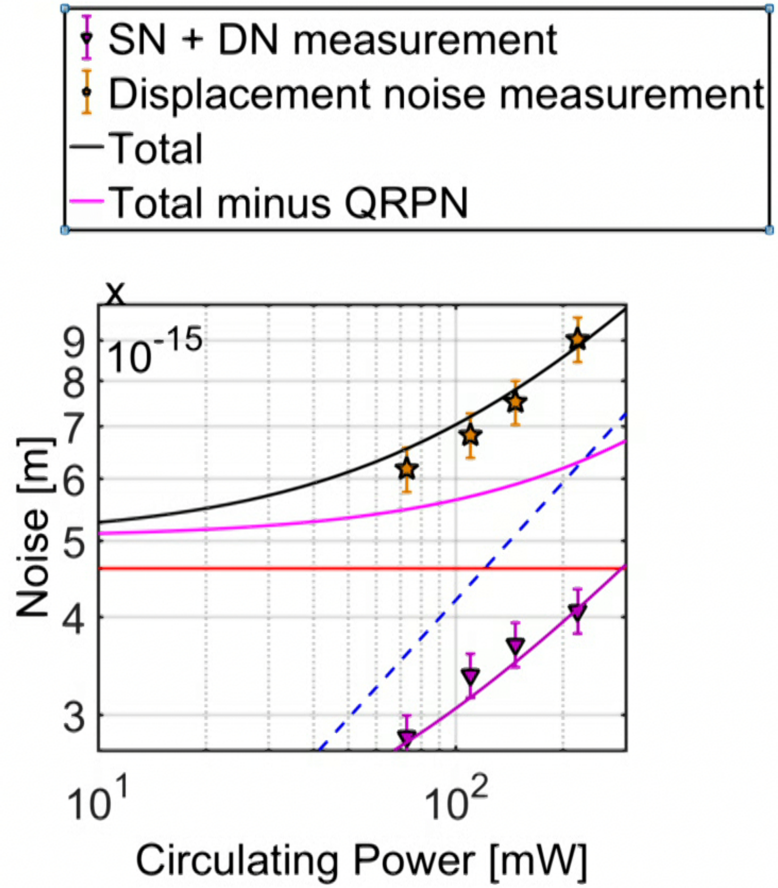
QRPN Measurement



arXiv:1802.10069

Noise Scaling with Power

- Integrate the noise between 21 kHz and 22 kHz to check if QRPN scales with the square root of power
  - Account for QRPN, thermal noise (TN), shot noise (SN), dark noise (DN), classical RPN

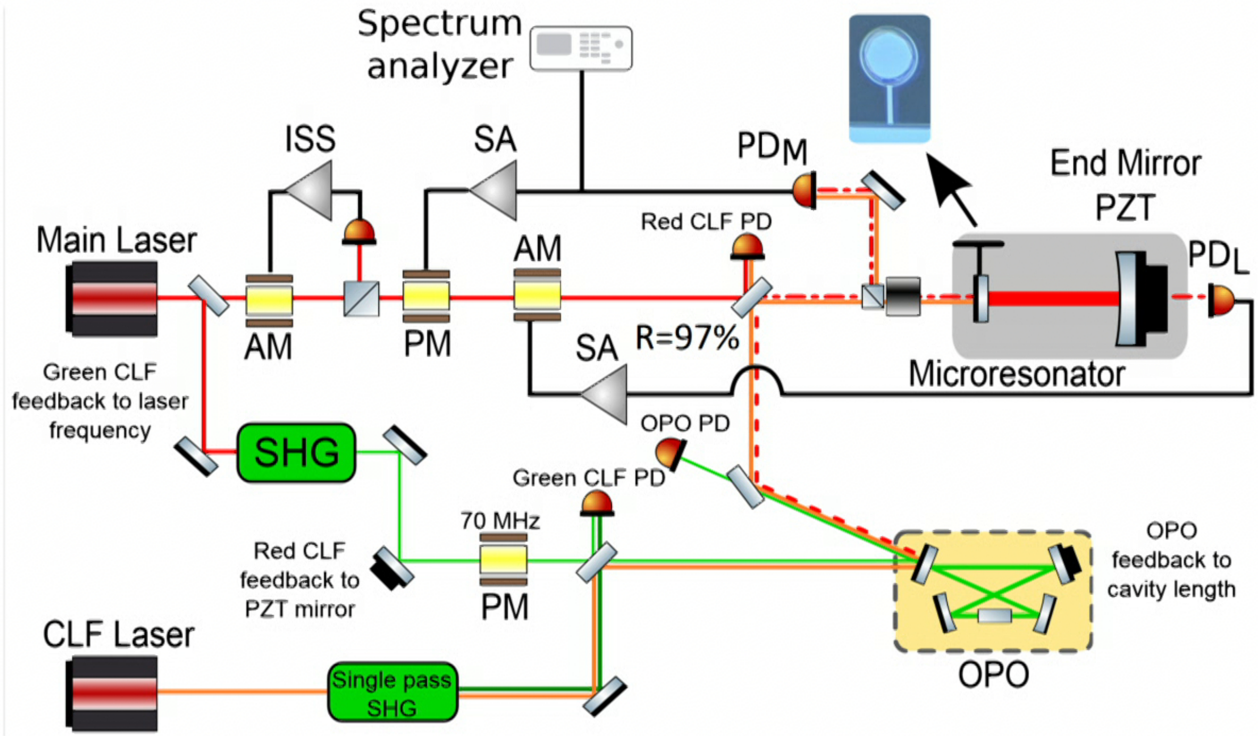


Manipulating QRPN

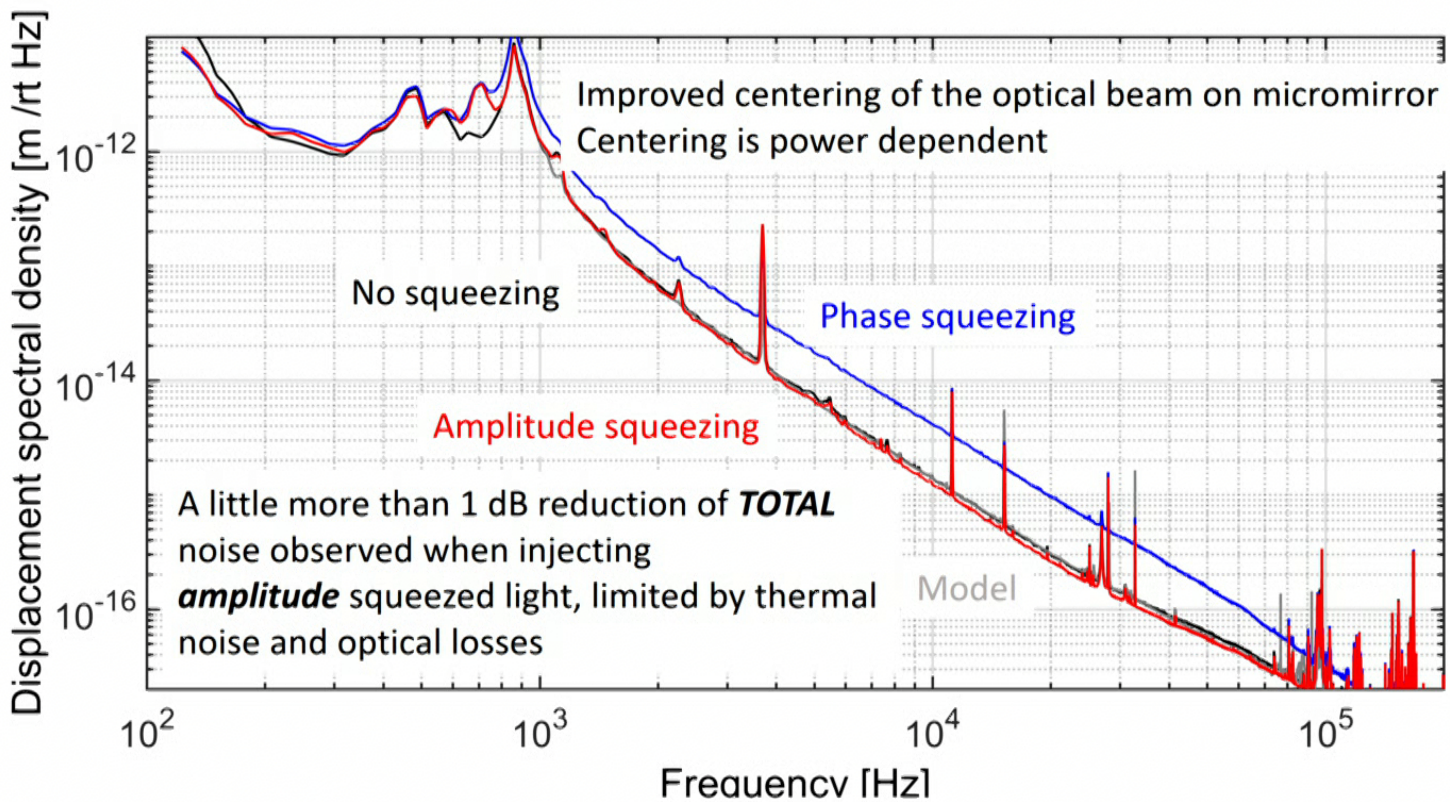
- What can be done about the QRPN?
- Squeezing
- Variational readout
- Other QND techniques

Squeezing the QRPN

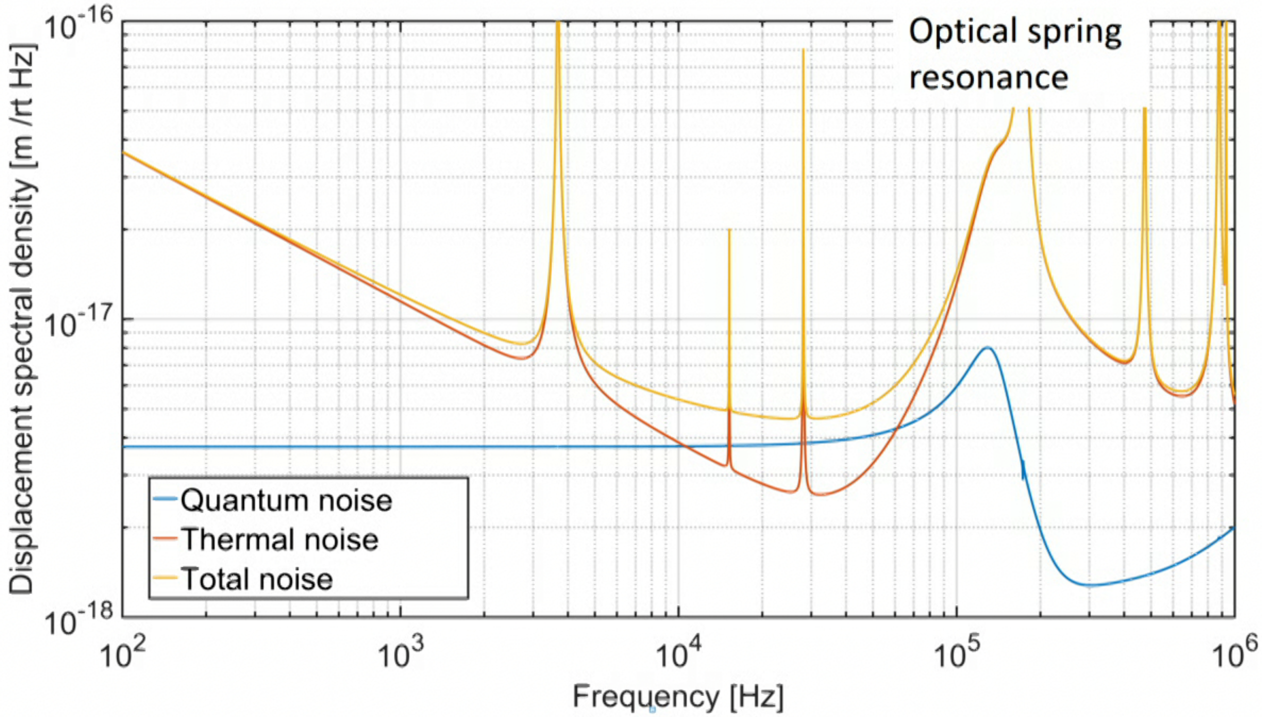
Need ***BRIGHT*** squeezing. Done with ANU.



Results of squeezing



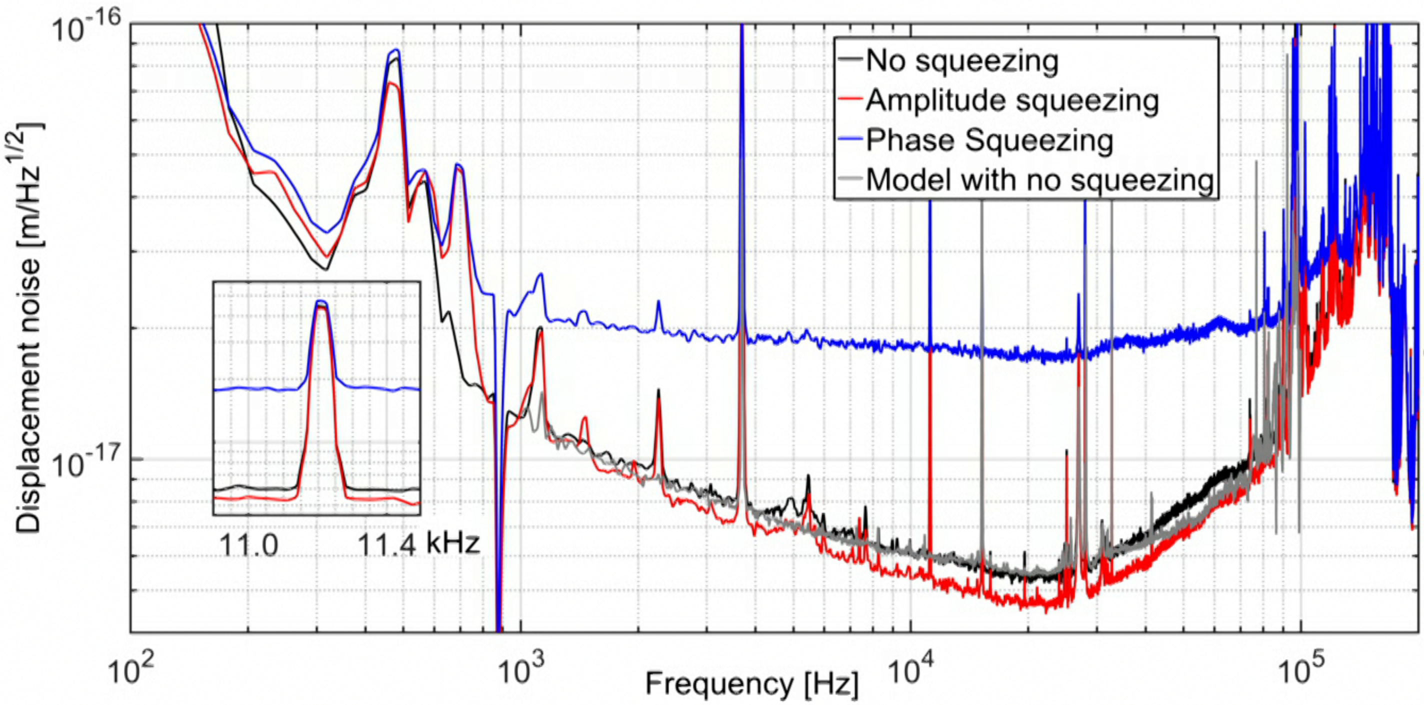
Leaving the optical spring in



Reshapes noise such that radiation pressure noise is frequency independent below resonance

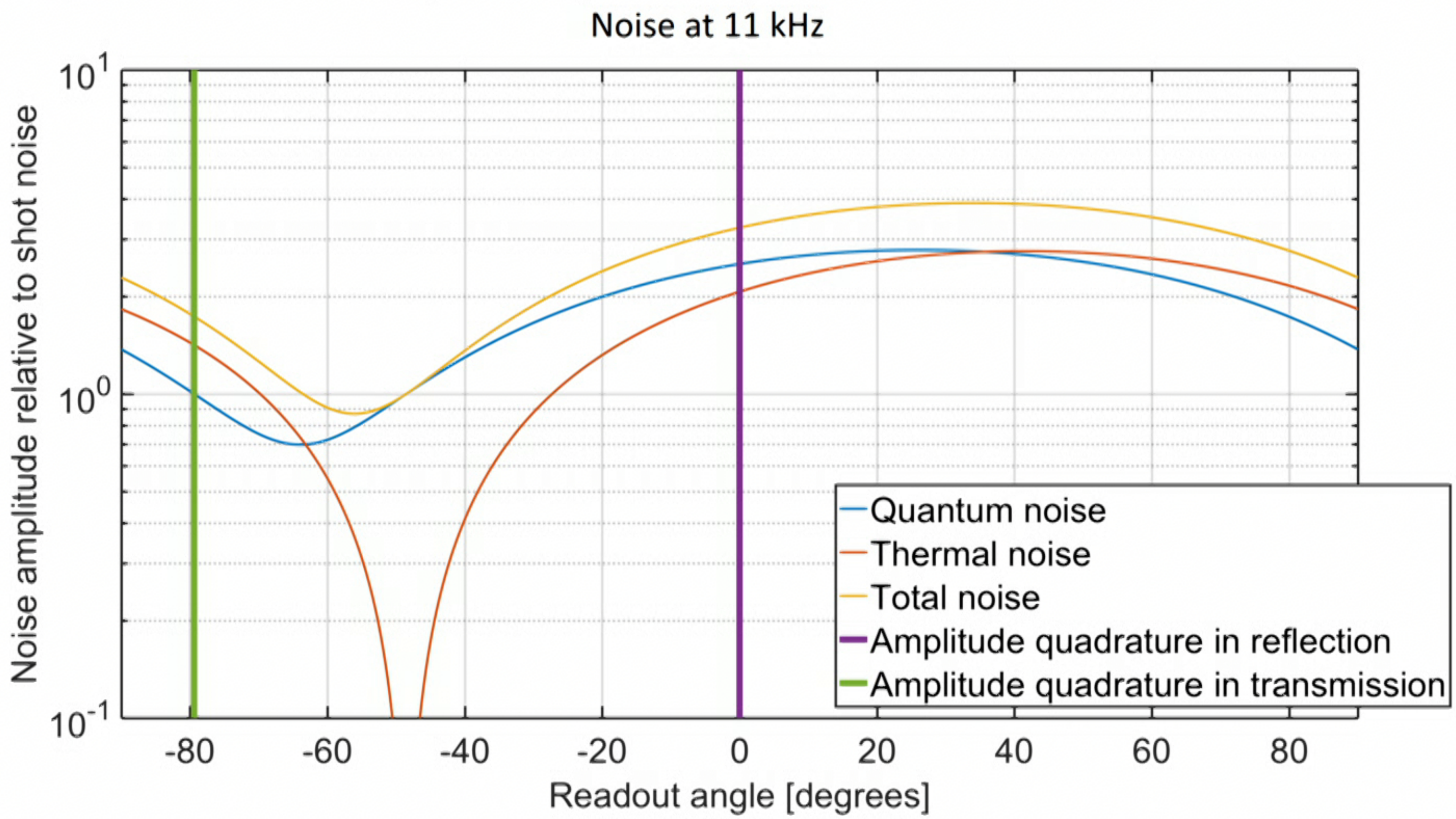
A different way to look at the same data

Squeezing with OS

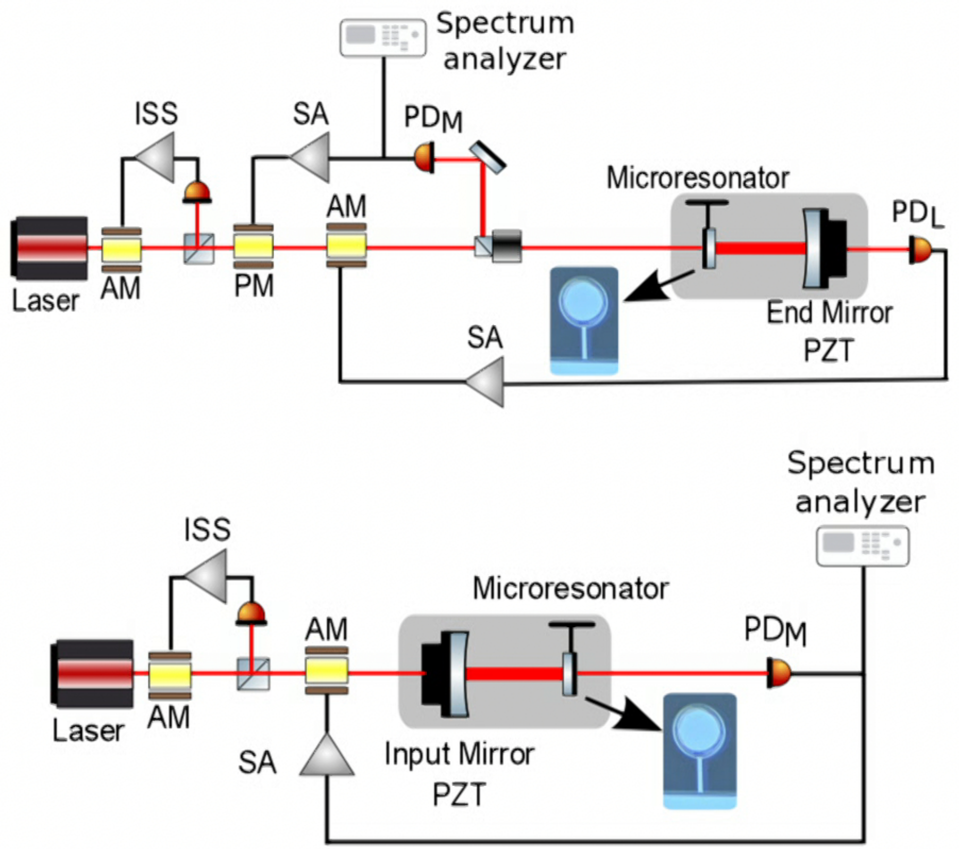


Variational readout

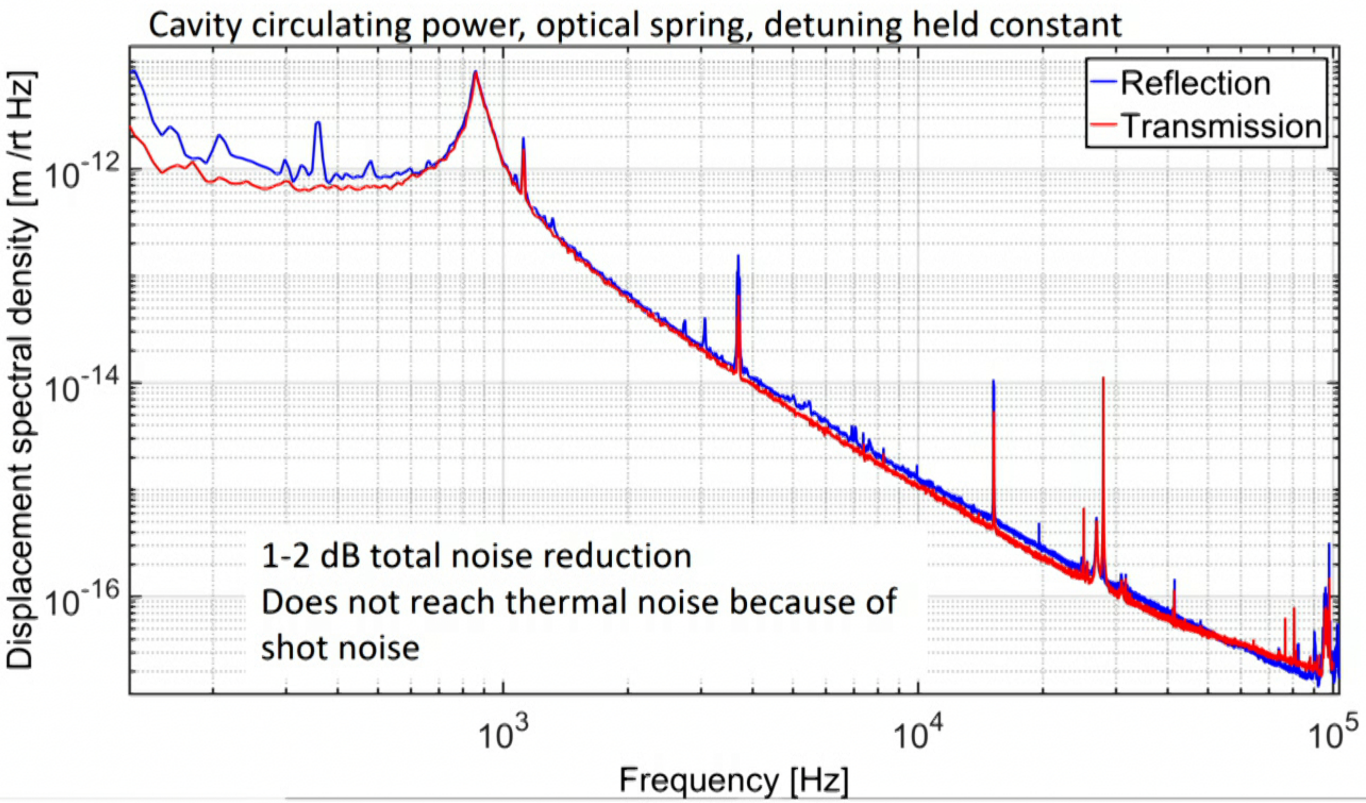
QRPN is not a purely a displacement noise.



Transmission vs reflection



Variational readout



What about the QRPN ruining the filter cavity?

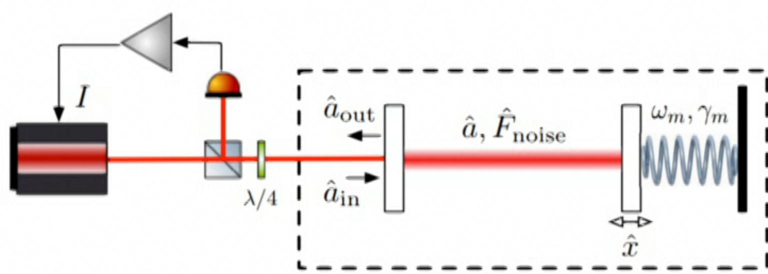
Towards the design of gravitational-wave detectors for probing neutron-star physics

Haixing Miao,[1] Huan Yang,[2,3,*] and Denis Martynov[4,1]

Optical spring	laser wavelength	1064 nm
	photodiode quantum efficiency	≥ 0.999
	cavity length	10 cm
	cavity bandwidth, detune	60 kHz, 0.9 MHz
	resonating power	680 W
	round-trip loss	≤ 1 ppm
	temperature	16 K

Suppression of quantum-radiation-pressure noise in an optical spring

W. Zach Korth,[1] Haixing Miao,[1,2] Thomas Corbitt,[3] Garrett D. Cole,[4] Yanbei Chen,[2] and Rana X. Adhikari[1]



Outlook

- Optical losses – total efficiency of our cavity is about 30% (99.9% needed for elimination of QRPN). This is mostly limited by optical losses due to diffraction around cantilever mirror – likely a technical issue and not a fundamental one.
  - Absorption in micromirror is in single digit ppm
- The current devices were optimized for radiation pressure and SQL measurements, and were not optimized for filter cavities. There is room for improvement in the mechanical design.
  - Thinner cantilevers, lower fundamental frequency
- Strong optical springs are achievable with modest optical power – simpler setup, compatible with cryogenics.
- Low noise cryogenic operation needs to be demonstrated.
- Worth considering these devices for filter cavities.