

# Observation of a kilogram-scale oscillator near its quantum ground state

**Abstract.** We introduce a novel cooling technique capable of approaching the quantum ground state of a kilogram-scale system—an interferometric gravitational wave detector. The detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) operate within a factor of 10 of the standard quantum limit (SQL), providing a displacement sensitivity of  $10^{-18}$  m in a 100 Hz band centered on 150 Hz. With a new feedback strategy, we dynamically shift the resonant frequency of a 2.7 kg pendulum mode to lie within this optimal band, where its effective temperature falls as low as  $1.4 \mu\text{K}$ , and its occupation number reaches about 200 quanta. This work shows how the exquisite sensitivity necessary to detect gravitational waves can be made available to probe the validity of quantum mechanics on an enormous mass scale.

LIGO Scientific Collaboration – B Abbott et al.

**Michael Sprague**

# Overview

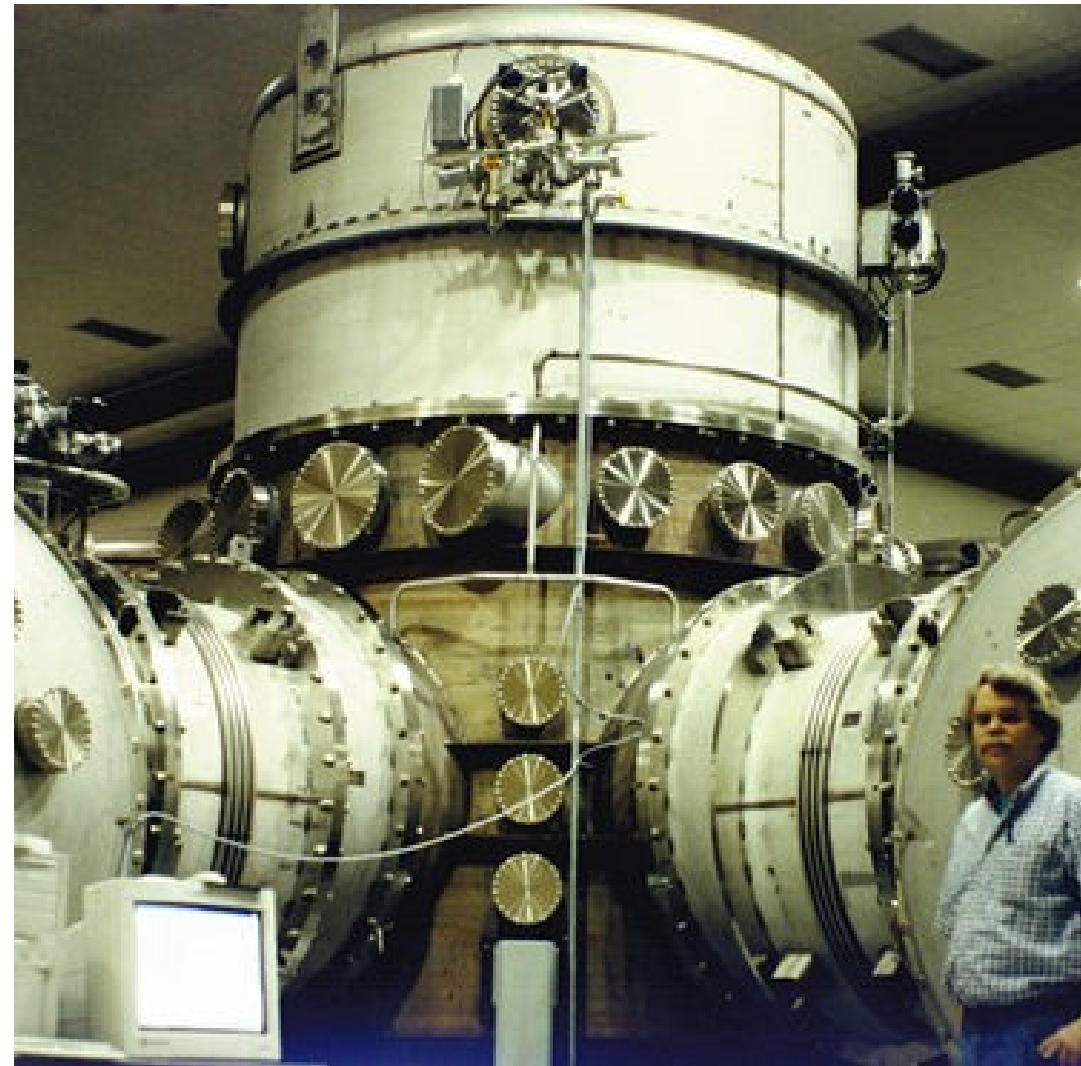
Details of LIGO

Signal and noise performance

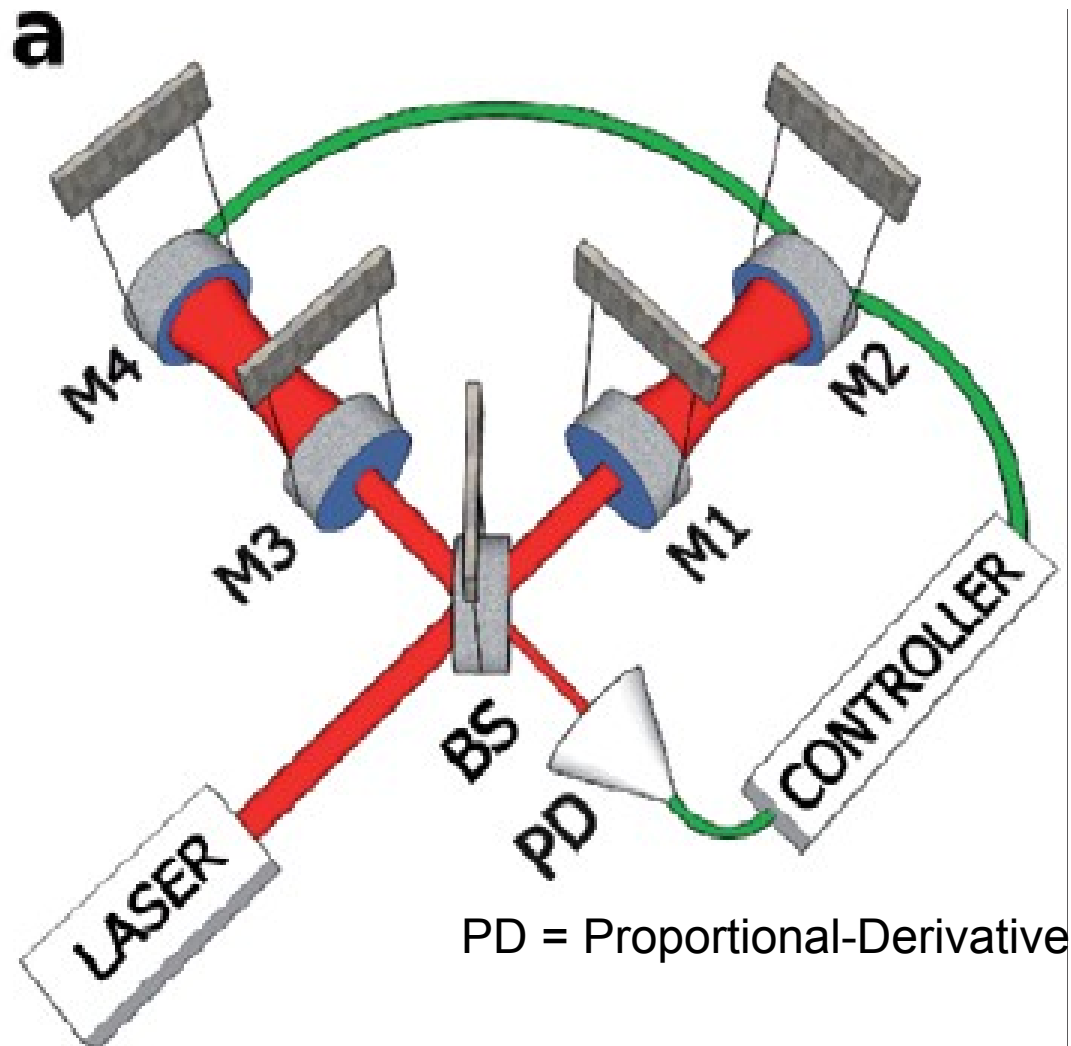
Cold damping

Damped harmonic oscillator, control system

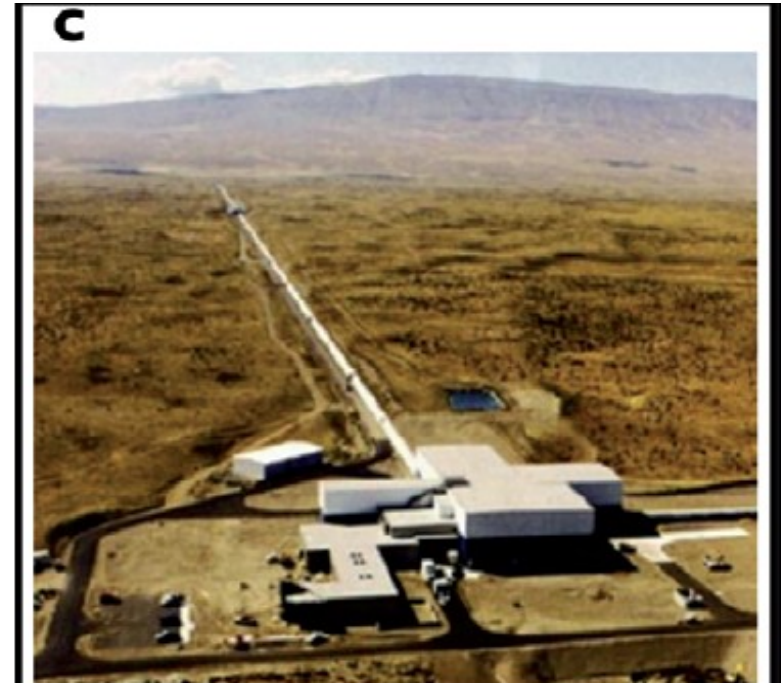
Cooling to quantum limit



**Beam splitter**



1064 nm, 400W injected



4 km Fabry-Perot Interferometer

For  $\lambda = 4\text{km}$ ,  $f = 75\text{ kHz}$

Finesse = 220

Mass of mirror = 10.8 kg

## **Vacuum System**

1.2 m diameter tubing, 3mm thick stainless steel

$10^{-8}$  to  $10^{-9}$  torr,  $H_2$  limited. Ion pump and Cryo-trap.

## **Laser and Optics**

1064nm Nd:YAG,  $TEM_{00}$ , locked to reference cavity.

## **Interferometer Optics**

Fused Silica, 25cm dia. 10 cm thick, 1nm flatness.

## **Mirror Suspension**

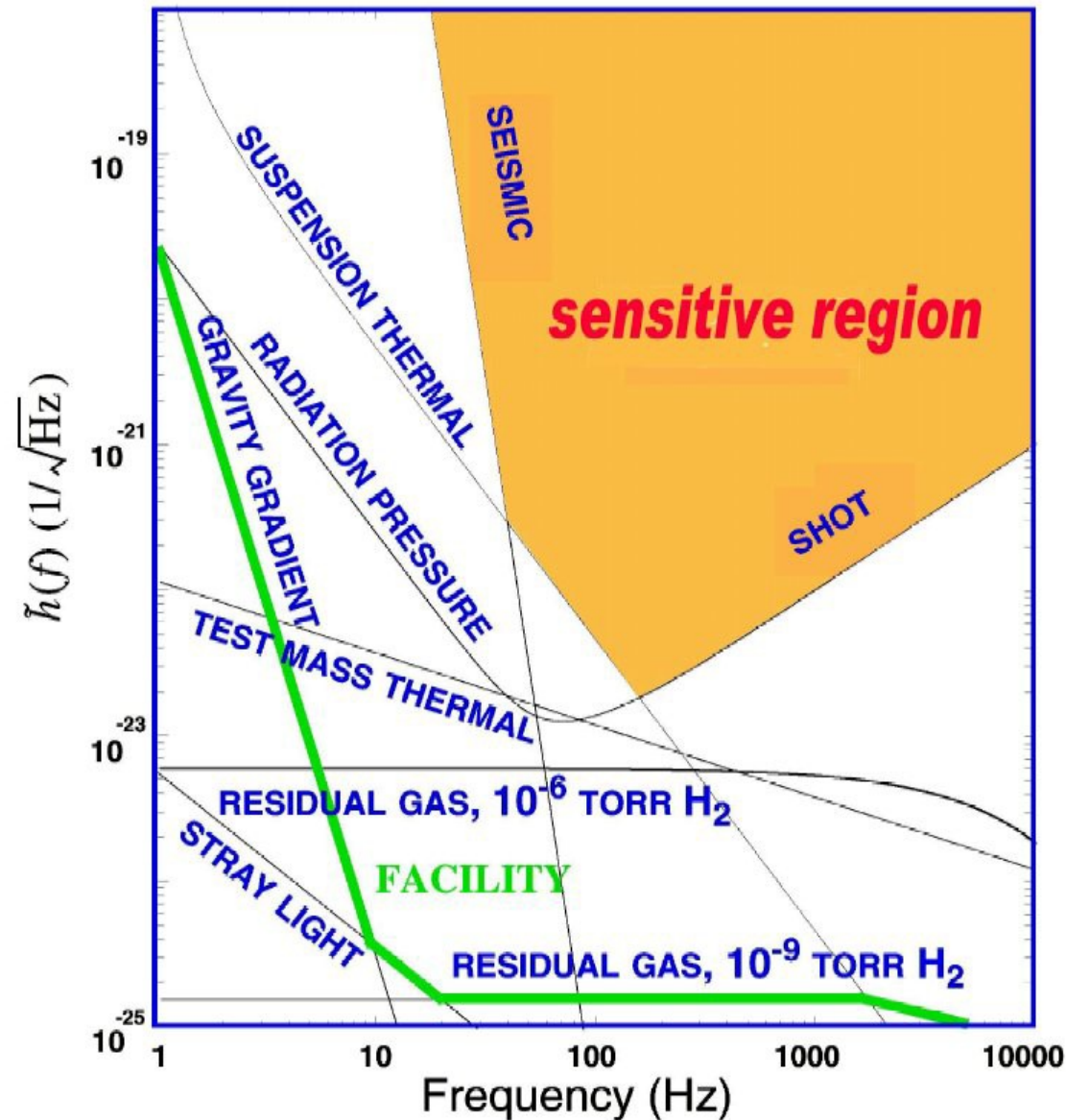
Steel piano wire. 4 Nd:Fe:B magnets alternating polarity, glued to mirror. Nearby coils provide force.

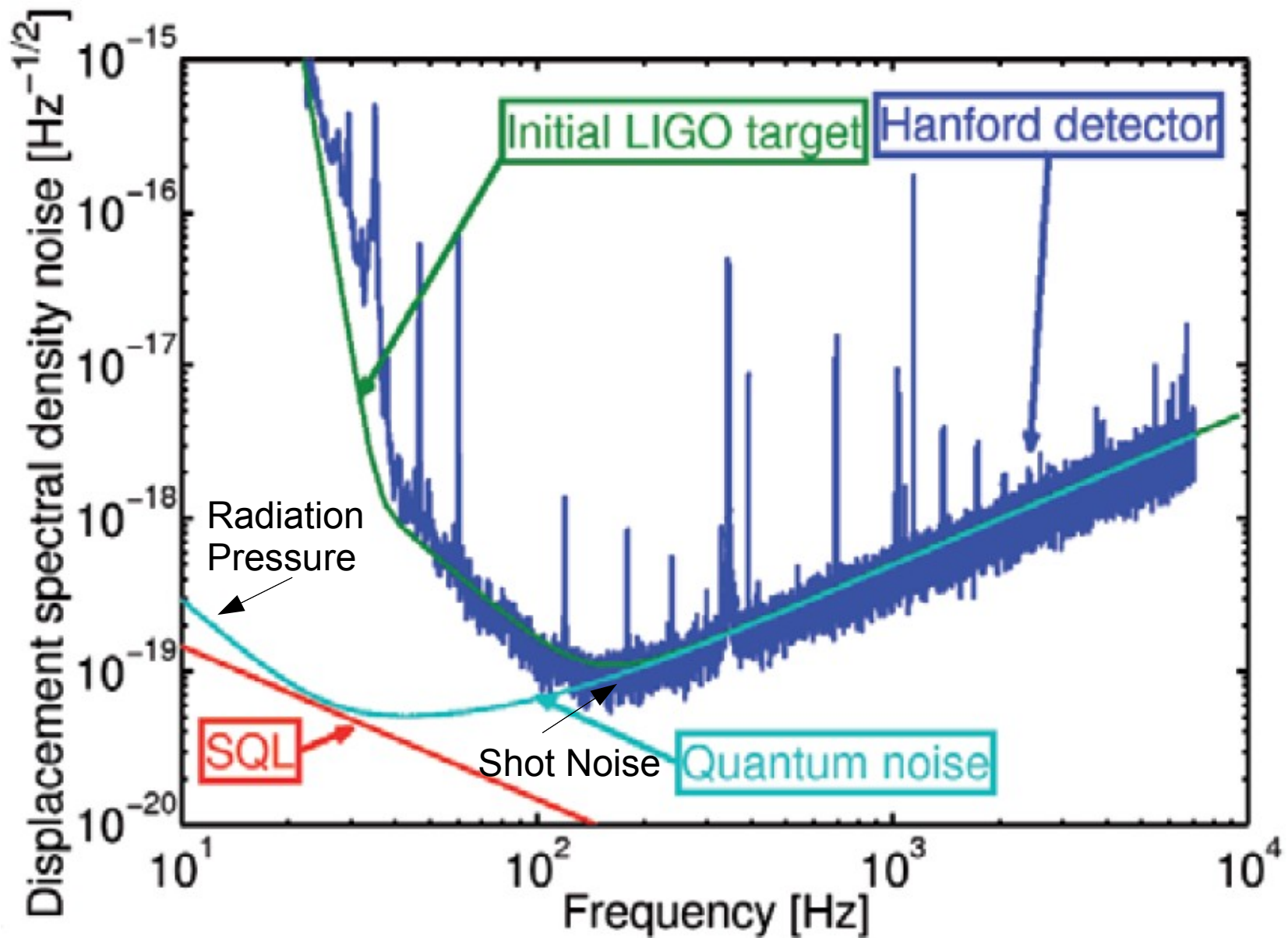
## **Detection**

Photodetector in dark port of beam splitter

# Noise Goals

SNR! Proportional to  $N^{-(1/2)}$





Based on sensitivity and estimates of likelihood astronomical events:  
 1 in 6 chance of detecting gravitational wave during one year.

**SQL** = Standard quantum limit = minimum noise level without squeezed state

**Shot noise** = noise from discrete photon statistics

**Radiation pressure** = random force depending on intensity of light

Want classical noise  $<$  quantum noise.

Classical noise = thermal noise, vibrations coupled to environment

# Cold-damping

First proposed by Mancini et al. PRL **80**, 688 (1998)

Couple to system with 'frictionless' force

- i.e. electromagnetically (optical, electronic feedback)

Cool below equilibrium temperature by feeding back position measurements

- Reduce position quadrature uncertainty
- Drives momentum quadrature
- Both quadratures can be reduced => refrigeration

Viscous frictionless force, 'correcting' back-action

$$X_{sensor} = X_{CM} + X_N \quad (1)$$

$$-M [\omega^2 - i\omega\omega_0\delta(\omega) - \omega_0^2] X_{CM} = F_N - K(\omega) X_s \quad (2)$$

$$\text{c.f. } \ddot{x} + \delta\omega_0\dot{x} + \omega_0^2 = F(t) \quad \omega_r = \omega_0\sqrt{1 - \frac{\delta^2}{4}}$$

$$-M [\omega^2 - i\omega\omega_0\delta(\omega) - \omega_0^2 - K(\omega)/M] X_{CM} = F_N - K(\omega) X_N \quad (3)$$

$$K(\omega)/M \approx \omega_{eff}^2 + i\omega\omega_{0,eff}\delta_{eff} \quad \text{and} \quad \delta_{eff} \gg \delta, \omega_{0,eff} \gg \omega$$

$$-M [\omega^2 - i\omega\omega_{0,eff}\delta_{eff}(\omega) - \omega_{eff}^2] X_{CM} = F_N - K(\omega) X_N$$

### Terms:

$\omega$  = frequency

$\omega_0$  = eigenfrequency =  $2\pi * 0.7$  Hz

$\omega_r$  = resonance frequency

$\delta$  = damping constant

$M$  = reduced mass of interferometer

$K$  = transfer function of controller

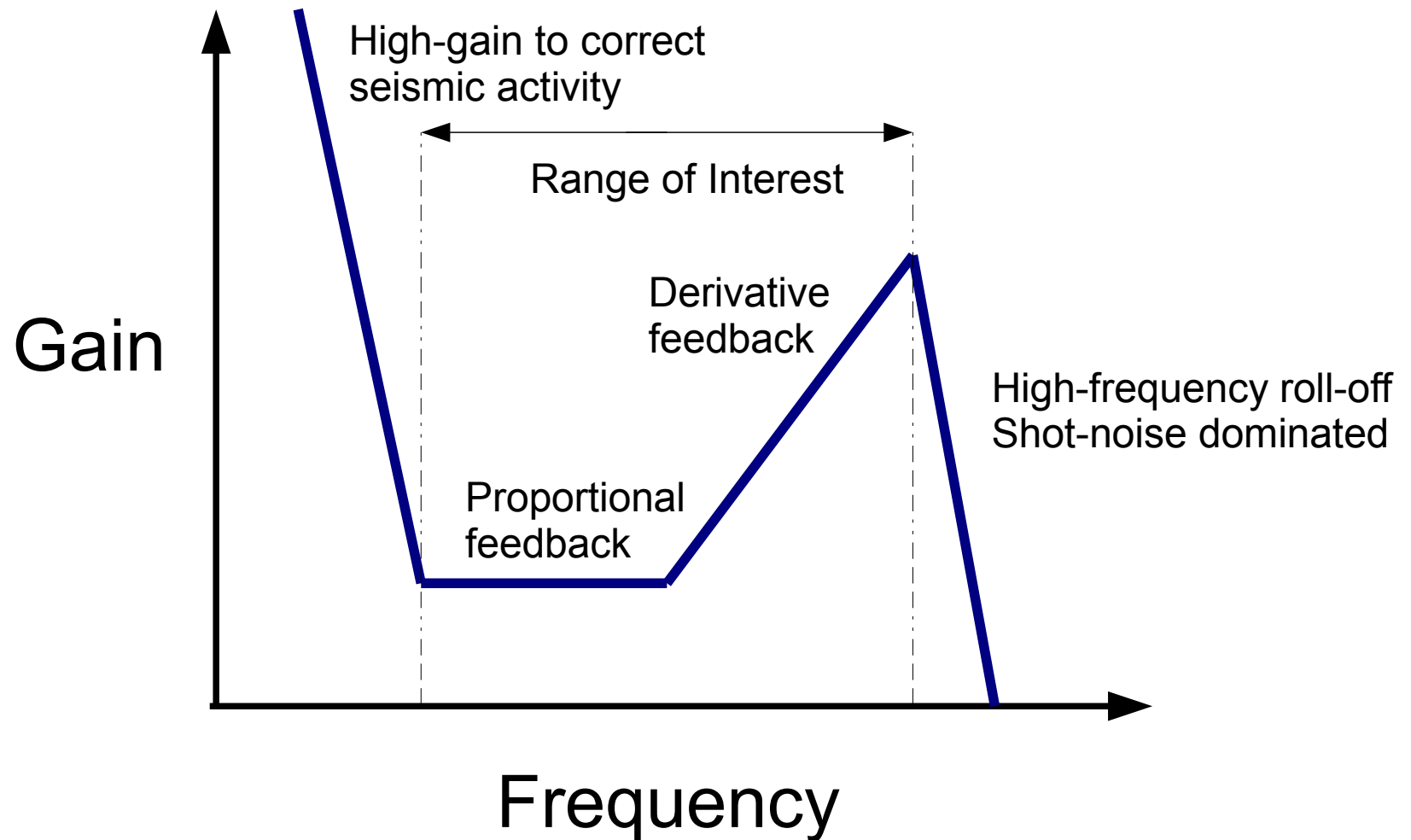
$F_N$  = noise force

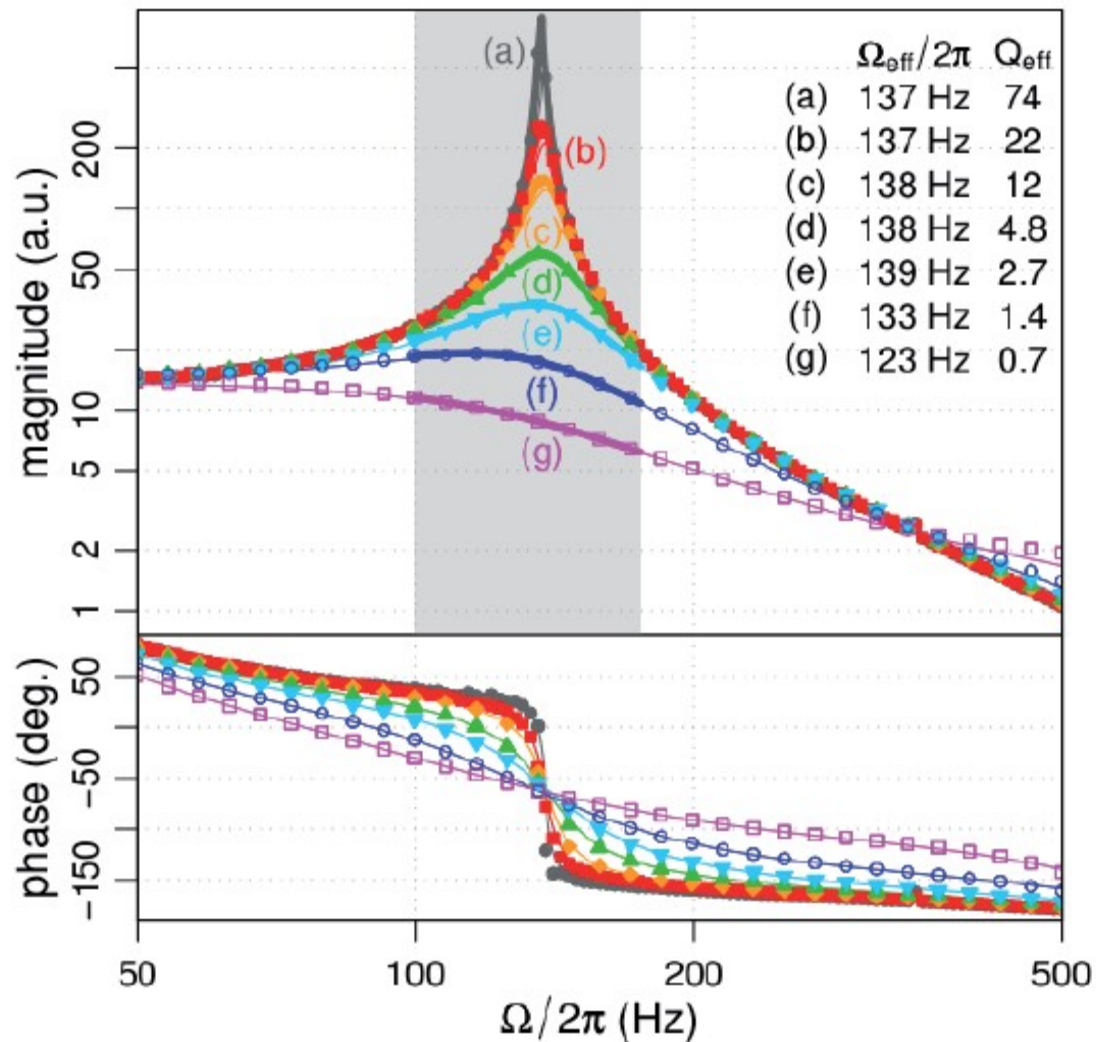
$X_{sensor}$  = measured mirror displacement

$X_{CM}$  = centre of mass displacement

$X_N$  = displacement due to noise

# Controller Transfer Function





**Figure 2.** Response function of mirror displacement to an applied force, for various levels of damping. The points are measured data, the thin lines are a zero fit parameter model of the complete feedback loop, and the thick lines spanning the resonance (shown in the shaded region) are fitted Lorentzians, from which the effective resonant frequency and quality factor are derived for each configuration.

# Quantum System (?)

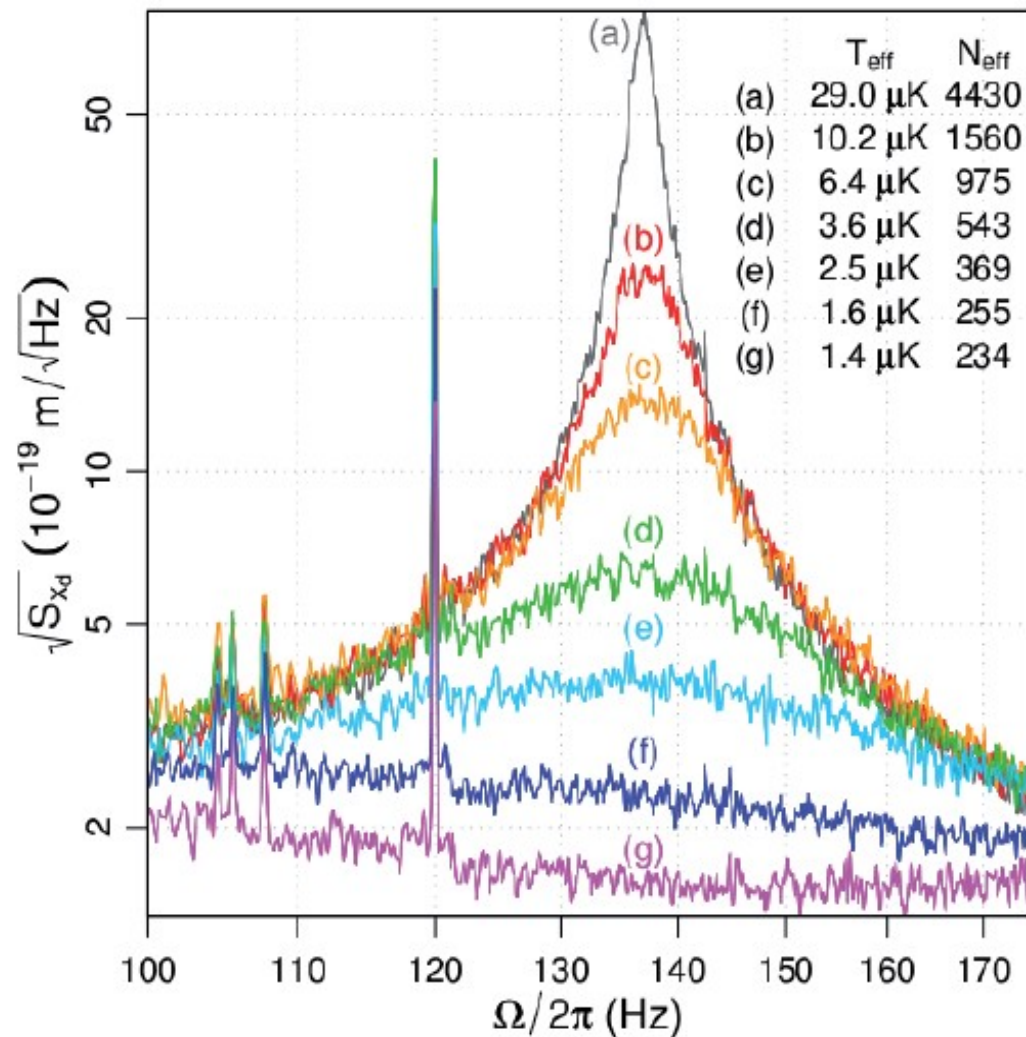
$$T_{eff} = \frac{M\omega_{0,eff} (\delta x_{rms}^2)}{k_B}, \quad \delta x_{rms}^2 = \int_0^\infty S_{x_d} d\omega$$

$$N_{eff} = \frac{k_B T_{eff}}{\hbar\omega_{eff}}$$

$S_{xd}$  = power spectral density of  
centre of mass motion

Is occupation number a good measure of quantum-like behaviour?

- What about squeezed states?



**Figure 3.** Amplitude spectral density of displacement in the frequency band of integration. The curves (from highest to lowest) were produced by applying increasingly strong cold damping to the oscillator, corresponding to the measurements of figure 2. The depression in the lowest curve is due to the shape of the background noise spectrum; the effects of the servo are corrected for according to equations (1)–(8). The narrow line features between 100 and 110 Hz are mechanical resonances of auxiliary subsystems, and a 120 Hz power line harmonic is also visible. The predominant noise is laser shot noise.

# Cooling to quantum limit

Lowest occupation has lowest Q-factor, highest damping

- Extrapolate that quantum limit could be reached for very 'bad' cavity...
- ...This would seemingly have high decoherence...
- ...likely that analytic framework would need to be changed (SHO analysis good only for  $\delta < 1$ ).

## Advanced LIGO

- Increase power by factor of 50, mass by factor 4, sensitivity x10.
- Ground state (?)

# Questions raised

- What is surprising?
  - 1) That a 2.7 kg mirror system cooled to ground state (technical)
  - 2) That 'classical' control can generate a quantum system (conceptual)
- What are conditions to reach quantum system with classical feedback?
- What about strong measurement?

## Creation of a quantum oscillator by classical control

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As a pure quantum state is being approached via linear feedback, and the occupation number approaches and eventually goes below unity, optimal control becomes crucial. We obtain theoretically the optimal feedback controller that minimizes the uncertainty for a general linear measurement process, and show that even in the absence of classical noise, a pure quantum state is not always achievable via feedback. For Markovian measurements, the deviation from minimum Heisenberg Uncertainty is found to be closely related to the extent to which the device beats the free-mass Standard Quantum Limit for force measurement. We then specialize to optical Markovian measurements, and demonstrate that a slight modification to the usual input-output scheme — either injecting frequency independent squeezed vacuum or making a homodyne detection at a non-phase quadrature — allows controlled states of kilogram-scale mirrors in future LIGO interferometers to reach occupation numbers significantly below unity.

## Does strong continuous position measurement produce decoherence?

Short answer: Yes, if classical noise below SQL

Possibly not otherwise (squeezing  
 and “optimal choice of measurement  
 strength”)