Ponderomotive Squeezing

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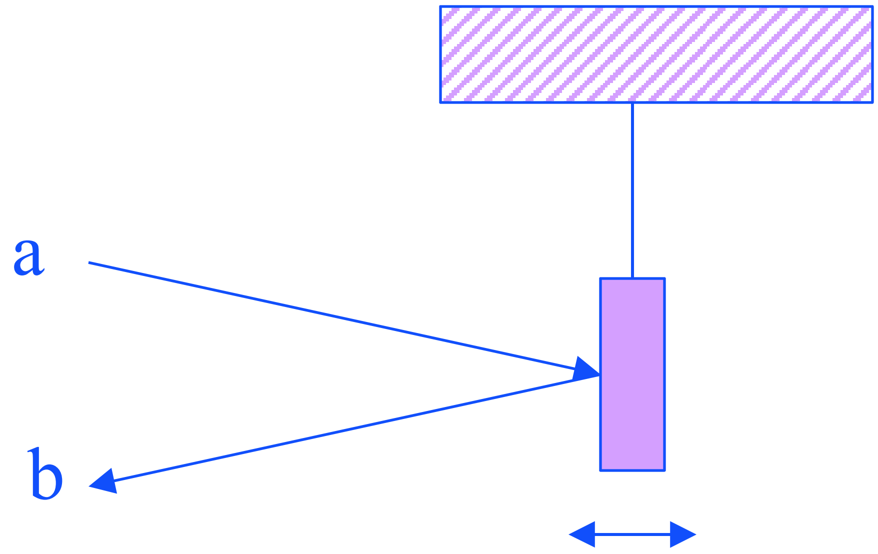
March 2004 LLO LSC Meeting

Introduction

- Crystal based squeezing is the only current possibility for generating squeezed light. Technical noise makes reaching low frequencies(100 Hz – the GW band) difficult. The lowest frequency reached to date is ~80kHz, although work is ongoing.
- We propose using a tabletop interferometer to generate squeezed light, using radiation pressure as the squeezing mechanism. We show that the expected noise sources in our configuration do not prohibit squeezing.

Radiation Pressure



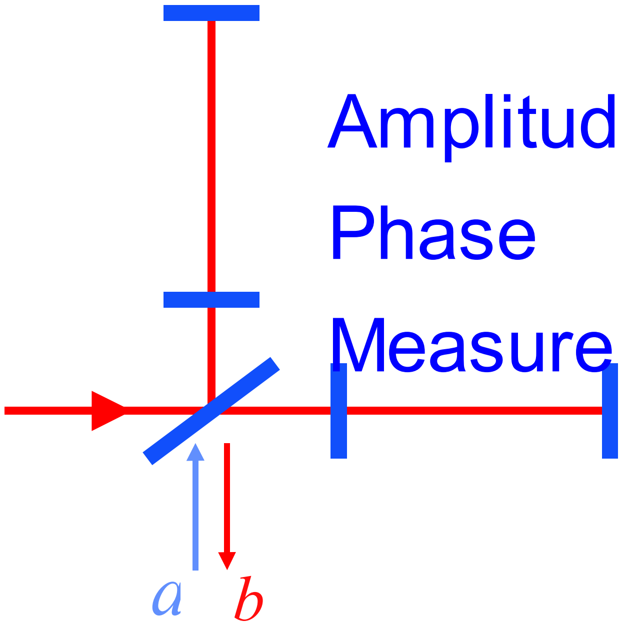
$$\Phi_b = \varphi_a + \kappa(\text{amplitude of a})$$

The frequency dependence of RP

$$-\Omega^2 x = -w_0^2 x + F \longrightarrow x = F / (w_0^2 - \Omega^2)$$

We consider suspensions with low resonant frequencies, so $x = -F/\Omega^2$. This means that the displacements of the mirror will be frequency dependent. Therefore, the magnitude of the squeezing will also be frequency dependent.

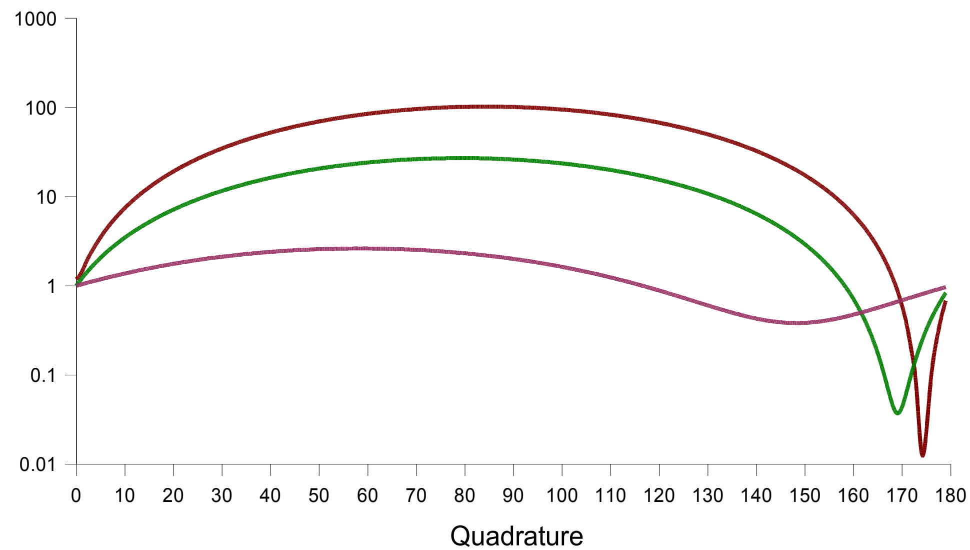
Squeeze angle



Amplitude $\Rightarrow b_1 = a_1$

Phase $\Rightarrow b_2 = -\kappa a_1 + a_2 + \text{Signal}$

Measure $\Rightarrow b_\zeta = \cos\zeta\, b_1 + \sin\zeta\, b_2$



Squeeze angle

Amplitude $\Rightarrow$ $b_1 = a_1$

Phase $\Rightarrow$ $b_2 = -\kappa a_1 + a_2 +$ Signal

Measure $\Rightarrow$ $b_\zeta = \cos\zeta\, b_1 + \sin\zeta\, b_2$

An arbitrary quadrature may be squeezed, so that the quantity $a_\zeta = \cos\zeta\, a_1 + \sin\zeta\, a_2$ is minimized, but the noise in the orthogonal quadrature will be increased.

Frequency dependent squeeze angle is needed, and a frequency dependent squeeze angle is also produced, but it has the wrong frequency dependence.

Requirements for squeezer

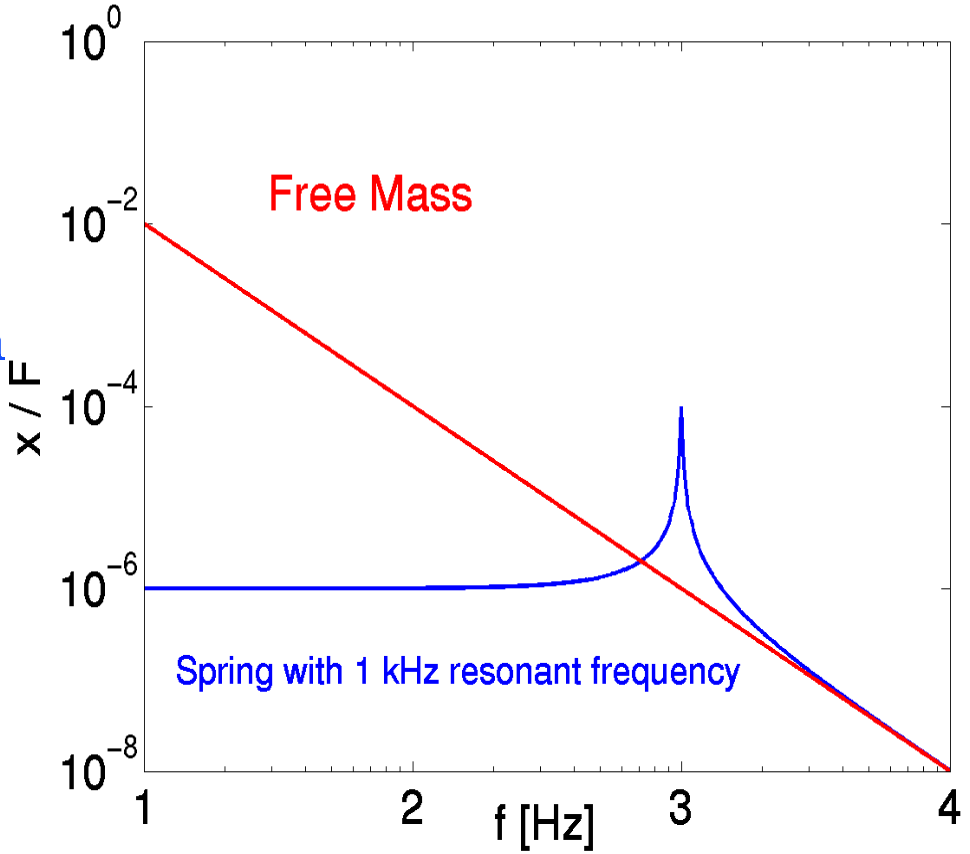
- Need to address frequency dependence.
- Need squeezing (RP) to ~10kHz.
  - » Small mass
  - » High power
    - – High finesse cavities with large power buildups.
  - » These lead to a high power density(~1 MW/cm^2).
- Need to control other noise sources to be below the optical quantum limit.
  - » Low thermal noise
  - » Low laser noise.

Frequency independent squeeze angle

- Ideally, the squeezer should produce the frequency dependent squeeze angle that's required by the GW detector.
- It is not known how to do this directly, instead -
  - » First produce frequency independent squeezing
    - – Filter this squeezing to produce the desired frequency dependence. (KLMTV and Harms reference).
    - – Or just make the best use of frequency independent squeezing.

Producing a Flat Squeeze Angle

- Frequency dependent squeeze angle is due to the frequency response (f^{-2}) of a free mass to a force.
- Modify the dynamics of the test mass by attaching it to a spring with a high resonant frequency – below the resonant frequency of the spring, the response is frequency independent.

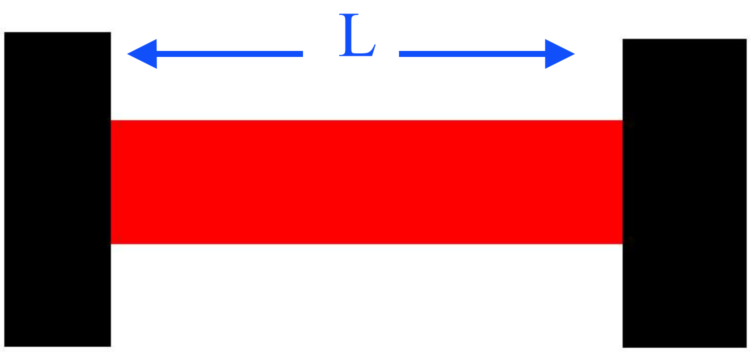


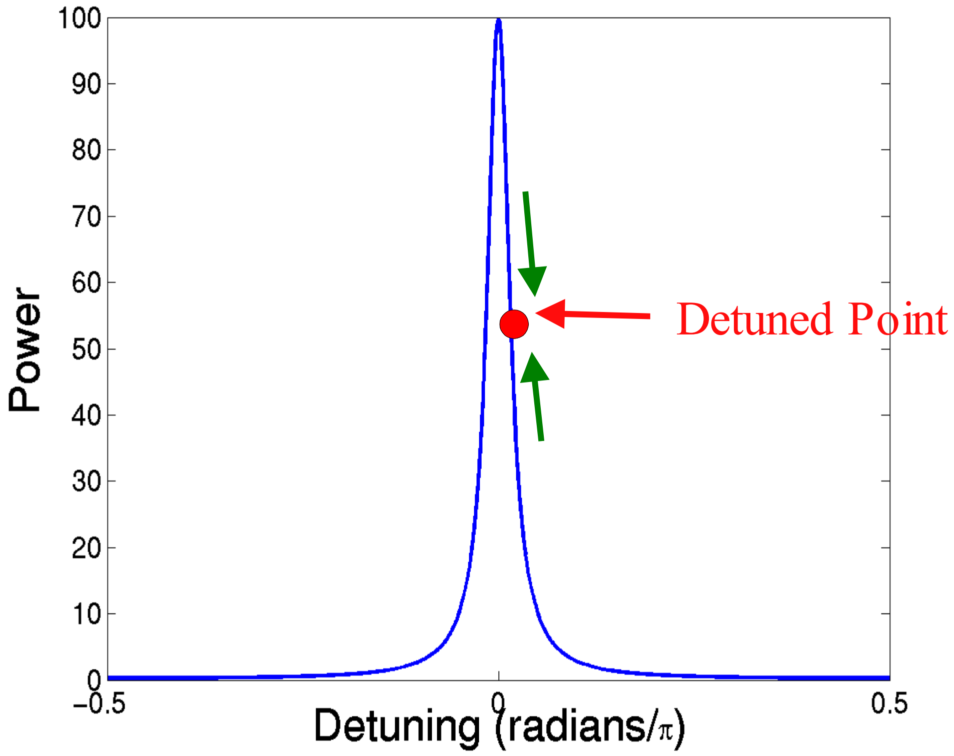
Thermal Noise in Springs

- Why not use a mechanical spring?
  - » The thermal noise introduced by the high frequency (mechanical) spring will wash out the effects of squeezing.
- Use optical spring instead -
  - » An optical spring with a high resonant frequency will not change the thermal force spectrum of the mechanical pendulum.
  - » A low resonant frequency mechanical pendulum may be used to minimize thermal noise, while the optical spring produces the flat response in our band.

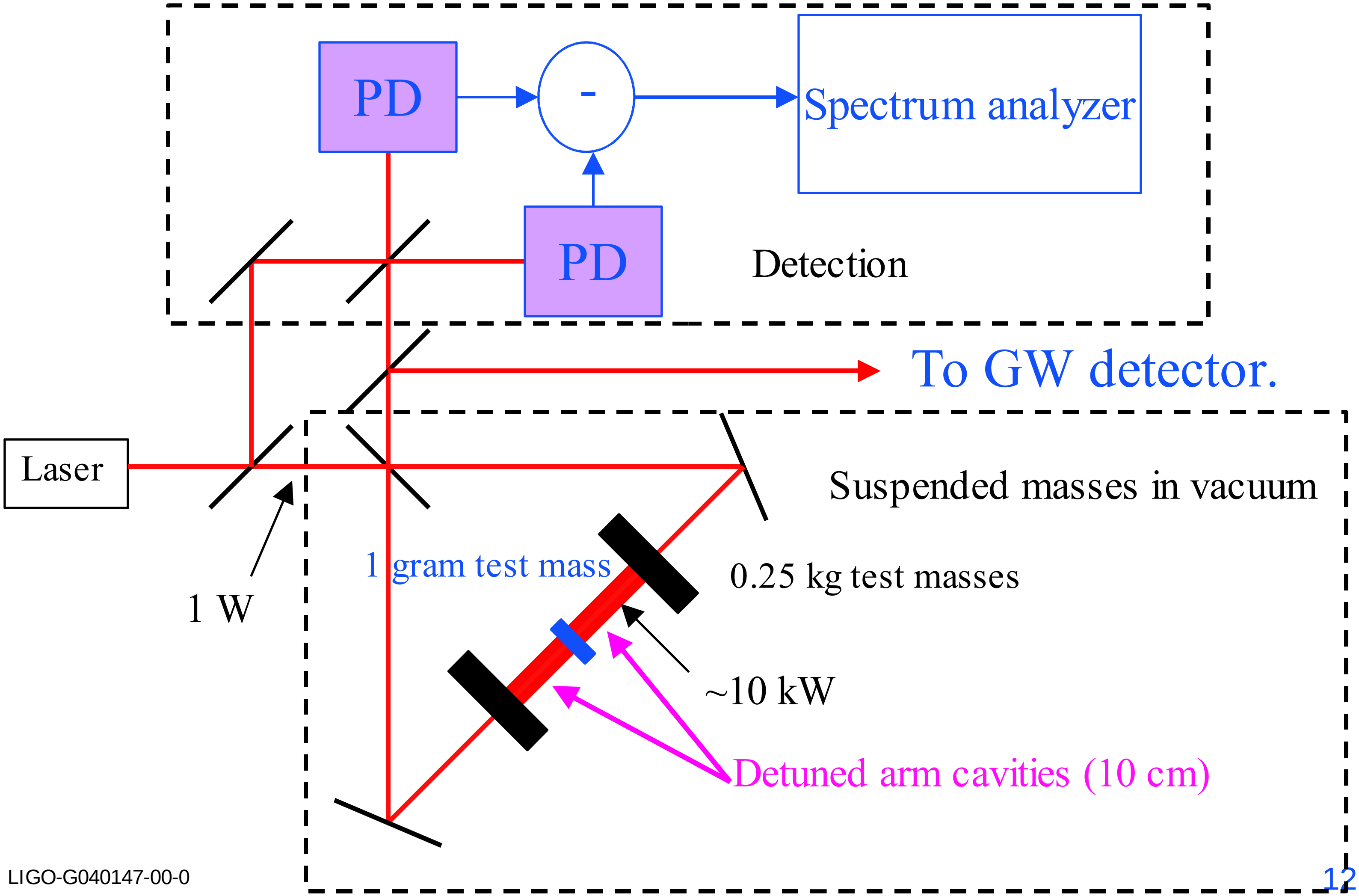
Optical Springs

If the detuning increases (cavity becomes longer) then the power in the cavity decreases, and the mirror is pushed back to the detuned point. If the detuning decreases, then the power in the cavity increases and the mirror is pushed back.





Design

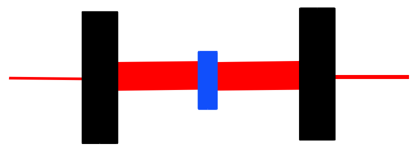


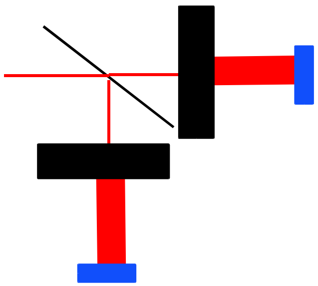
PD
-
Spectrum analyzer
PD
Detection
To GW detector.
Laser
Suspended masses in vacuum
1 gram test mass
0.25 kg test masses
1 W
~10 kW
Detuned arm cavities (10 cm)

The Test Mass

- ~1 cm diameter, 3mm thick
- Require low thermal noise.
  - » Use fused silica as the material and bond fused silica fibers to use as the suspension.
  - » Coating thermal noise could be an issue.
- Very high optical quality – losses ~ 5ppm per bounce.

The Arm Cavities



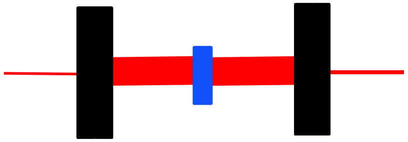


- Shared end mass
  - » Worse laser noise from common mode optical spring
  - » Easier to control
  - » The static forces from the light on the each side of the end mass balance
- Independent end masses
  - » Less laser noise
  - » The static forces from the light on the end mass displace it about 1mm from it's equilibrium.

Laser Noise

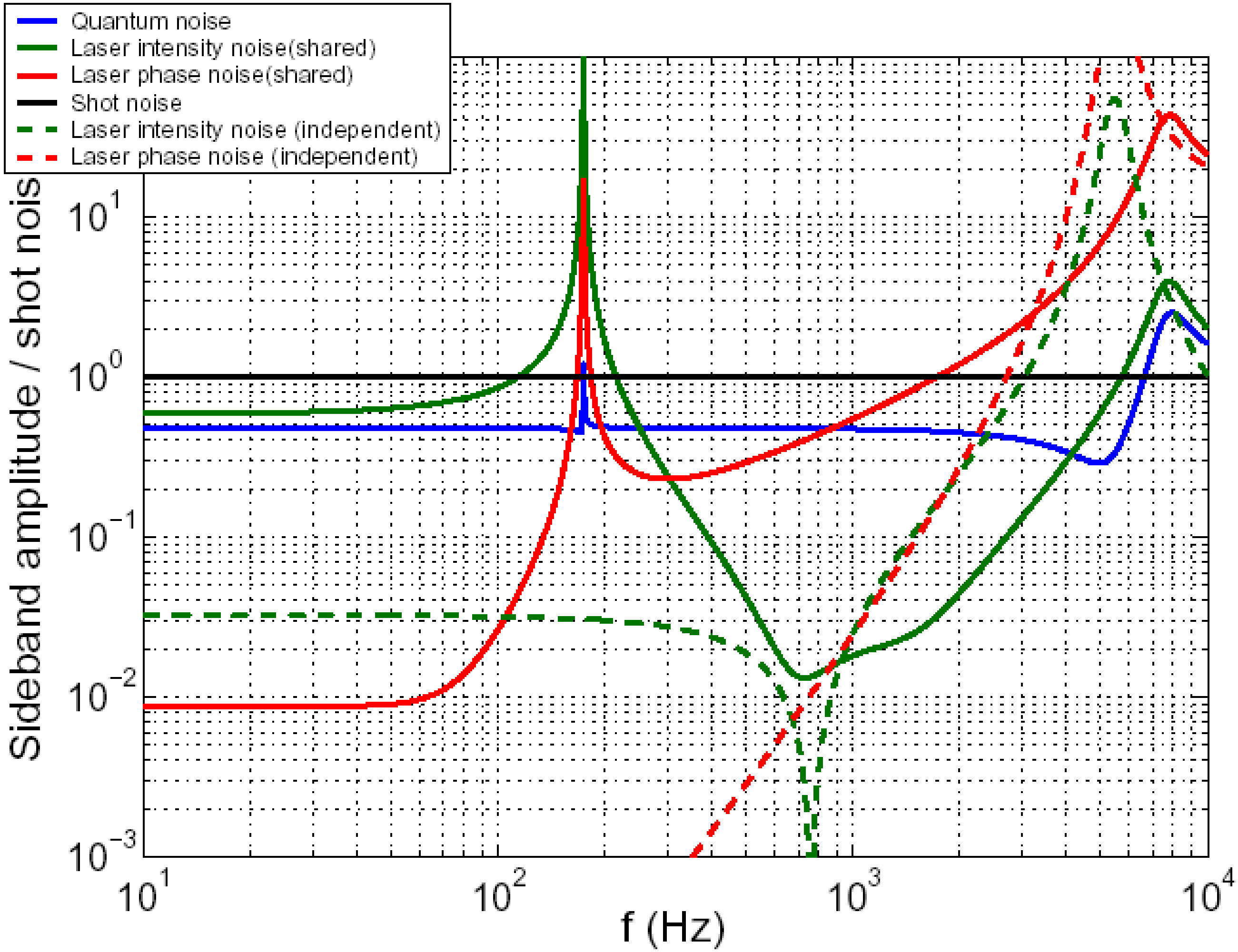
- Mismatches in the arm cavities at the 1% level are assumed
  - Beamsplitter ratio
  - Cavity detuning
  - Cavity losses
  - Cavity finesse
- Relative intensity noise at the level of 10^{-8} / rt Hz, and frequency noise of 10^{-4} Hz/rt Hz are assumed near 100 Hz. We think we can achieve this with a reasonable amount of work.

Common mode optical spring



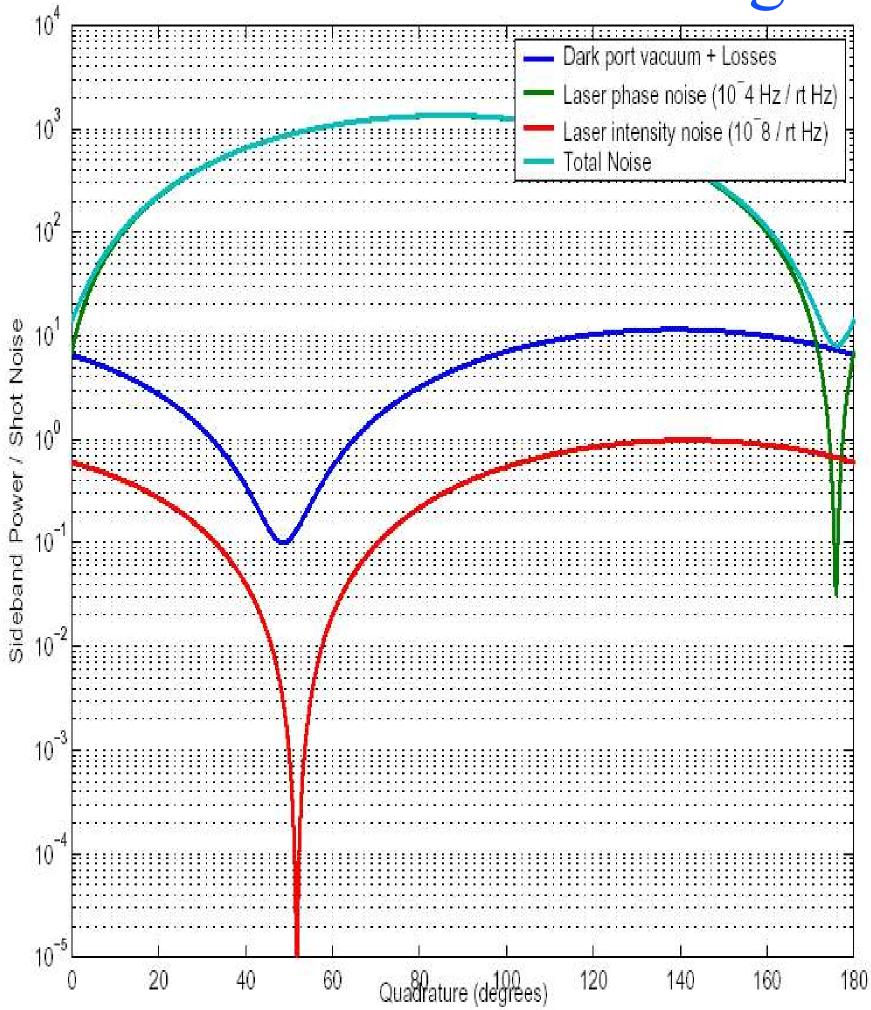
- Differential mode
  - » Primarily only moves the smaller end mass
- Common mode
  - » Insensitive to motions of the end mass
  - » Primarily moves the more massive input masses, so the resonant frequency of the common mode optical spring is much lower than the resonant frequency of the differential mode.

Laser Noise

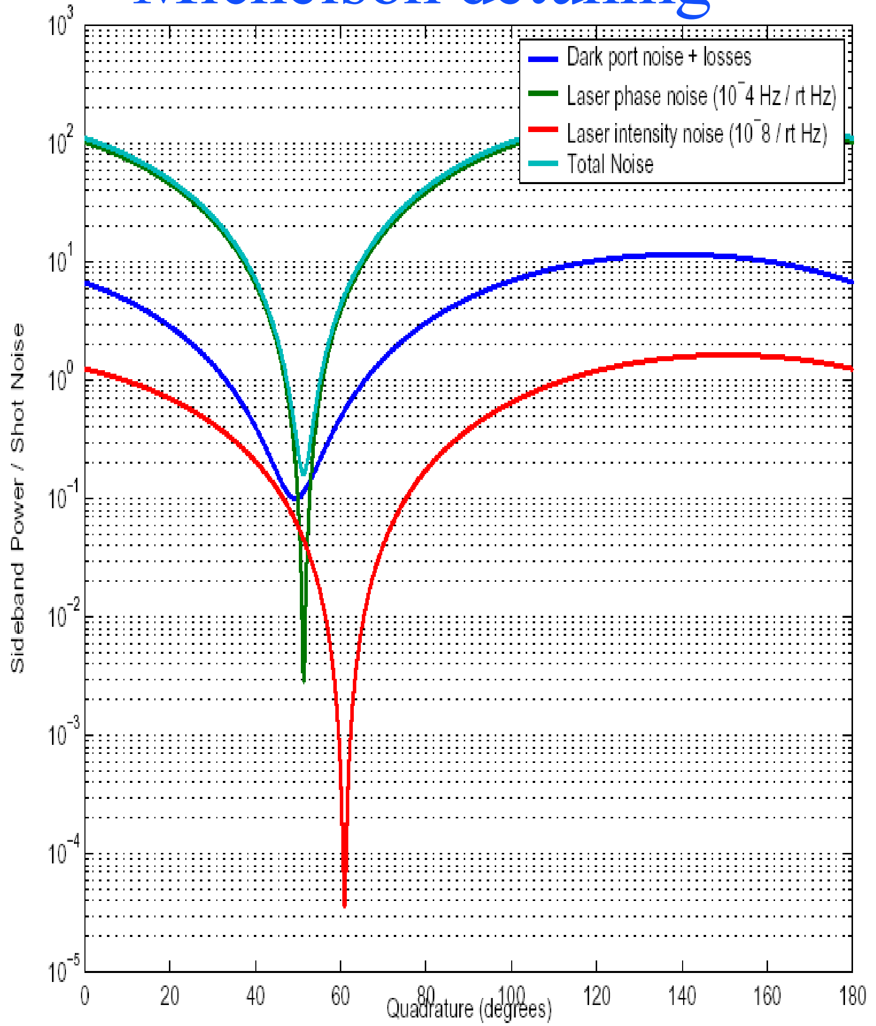

Quantum noise
Laser intensity noise(shared)
Laser phase noise(shared)
Shot noise
Laser intensity noise (independent)
Laser phase noise (independent)
Sideband amplitude / shot nois
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{1}
10^{2}
10^{3}
10^{4}
f (Hz)

Laser Noise Optimization (squeezing)

Michelson on dark fringe

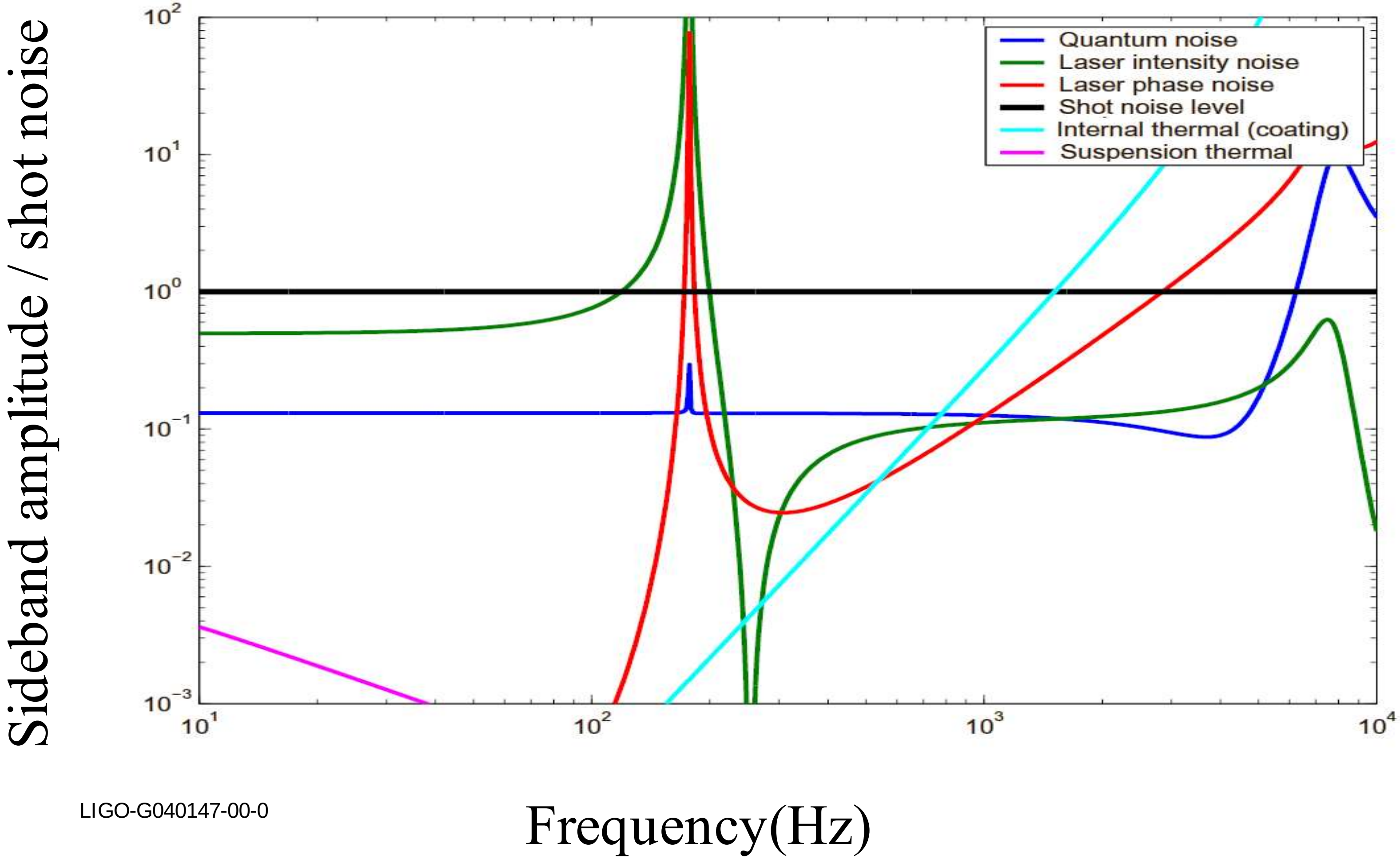


Michelson detuning



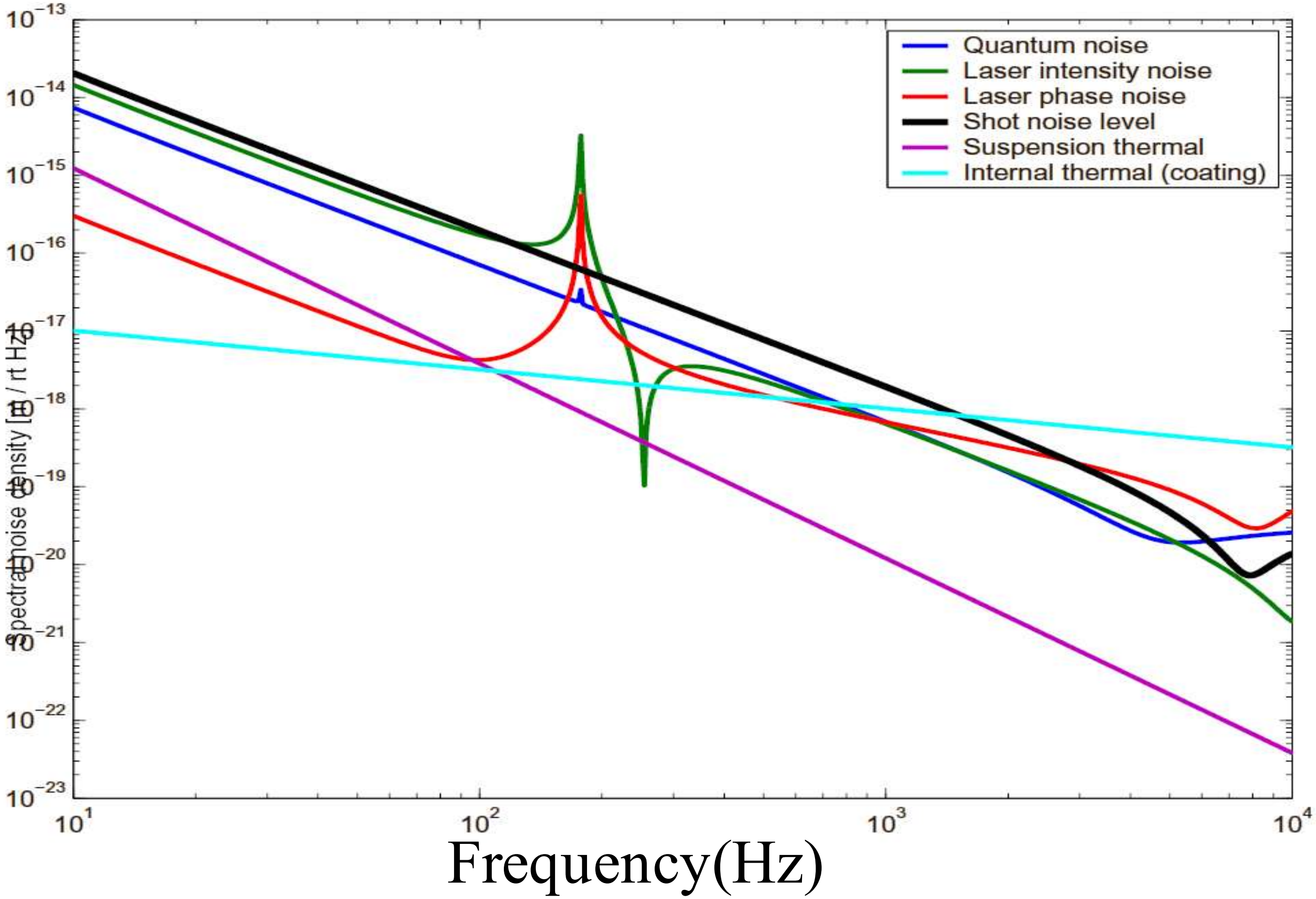
LIGO

Noise Sources



Noise Sources

Free mass equivalent displacement noise



Why is this interesting?

- Alternative to crystal squeezing at low frequencies
- Test quantum limited radiation pressure effects – gain confidence that the modeling is correct.
- Test noise cancellations of Michelson detuning.
- Squeezing may be produced while having a sensitivity far worse than the SQL due to the optical spring.
- Building to start soon.