A ponderomotive squeezing experiment

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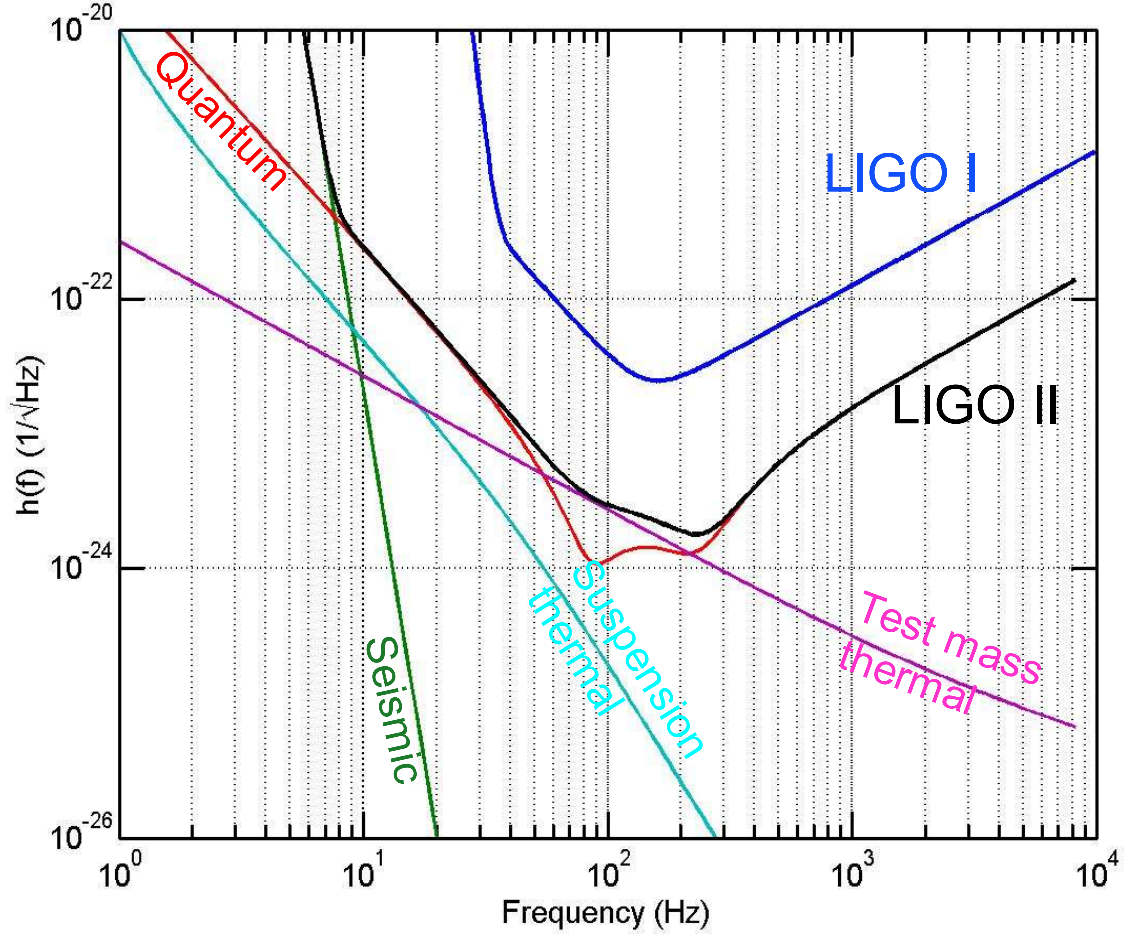
Caltech Seminar, March 23, 2004

Outline

- Motivation
  - Squeezing lowers the quantum noise floor
    - Ponderomotive squeezing offers an alternative to crystal based squeezing
  - Test quantum limited radiation pressure effects
- Ponderomotive Squeezing
  - Frequency dependent squeezing
- Experimental design
  - Small mass, high power
  - Optical spring
  - Noise sources
  - Difficulties

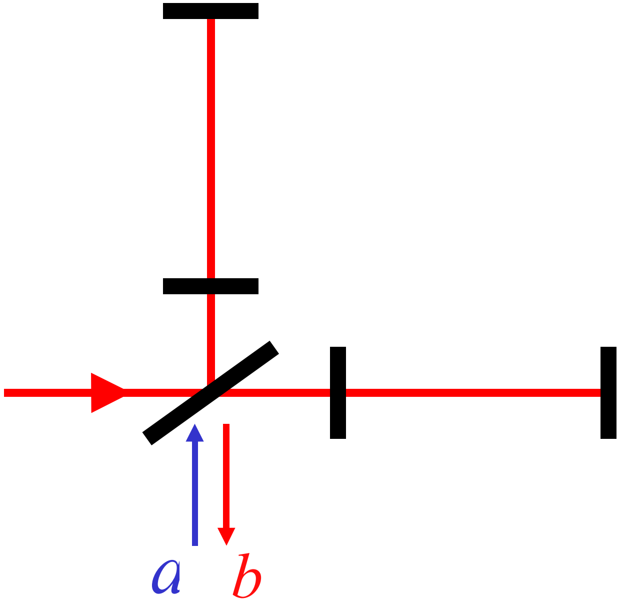
Quantum noise floor

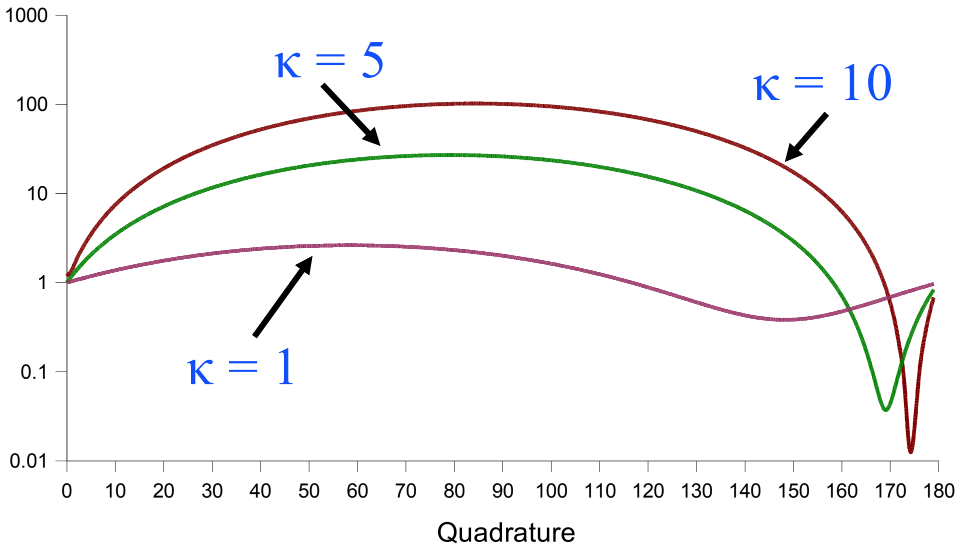


Quantum noise

- Measurement process
  - Interaction of light with test mass
  - Counting signal photons with a PD
- Noise in measurement process caused by vacuum fluctuations
  - Poissonian statistics of counting the photons
    ➔ shot noise
  - Poissonian statistics of force on test mass due to photon number uncertainty
    ➔ radiation pressure noise

Quantum noise





$$b_\varphi = b_1 \cos\varphi + b_2 \sin\varphi$$

Shot Noise

Amplitude → $b_1 = a_1$

Phase → $b_2 = \kappa a_1 + a_2$

Radiation Pressure

$\kappa \propto f^{-2}$ at frequencies below the cavity pole

Optimal squeeze angle

- If we squeeze a_2 *(phase squeezing)*
  - shot noise is reduced at high frequencies BUT
  - radiation pressure noise at low frequencies is increased
- If we could squeeze $\kappa\, a_1 + a_2$ instead
  - could reduce the noise at all frequencies
- "Squeeze angle" describes the quadrature being squeezed
- The noise exiting the dark port has a frequency dependence, but it's the wrong dependence!
  - Need to address this in order to use ponderomotive squeezing.

Experimental requirements

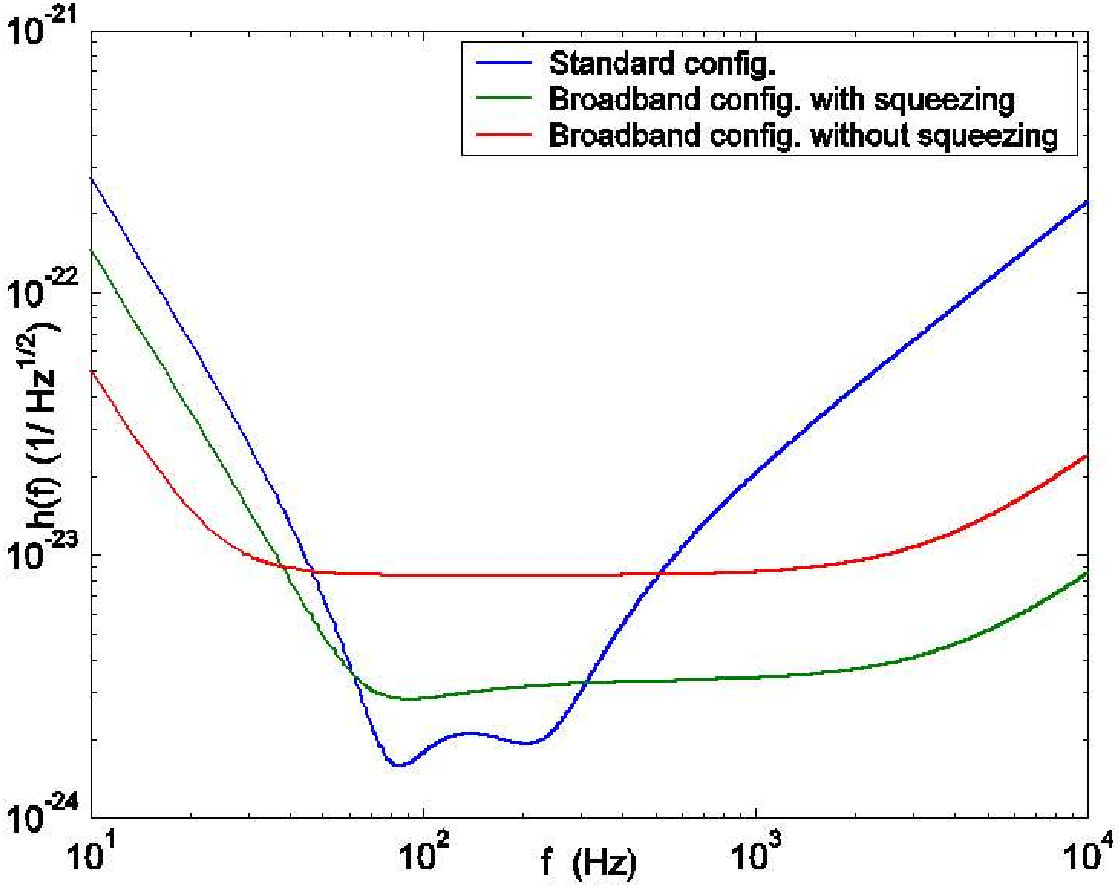
- Need to address frequency dependence
- Need squeezing (RP) at frequencies up to 10kHz
  - Small test mass
  - High power
  - High finesse cavities with large power buildups
- Need to control other noise sources to be below the optical quantum limit.
  - Low thermal noise
  - Low laser noise
  - Seismic isolation
  - Performed in vacuum

Frequency independent squeeze angle

- Ideally, the squeezer should produce the frequency dependent squeeze angle that's required by the GW detector.
- We don't know how to do this, instead we..
  - Produce frequency independent squeezing and..
    - Filter this squeezing to produce the desired frequency dependence (Kimble, Levin, Matsko, Thorne, and Vyatchanin, *Phys. Rev. D* **65**, 022002 (2001))
      - Requires long, low loss cavities – difficult!
    - Or just make the best use of frequency independent squeezing.

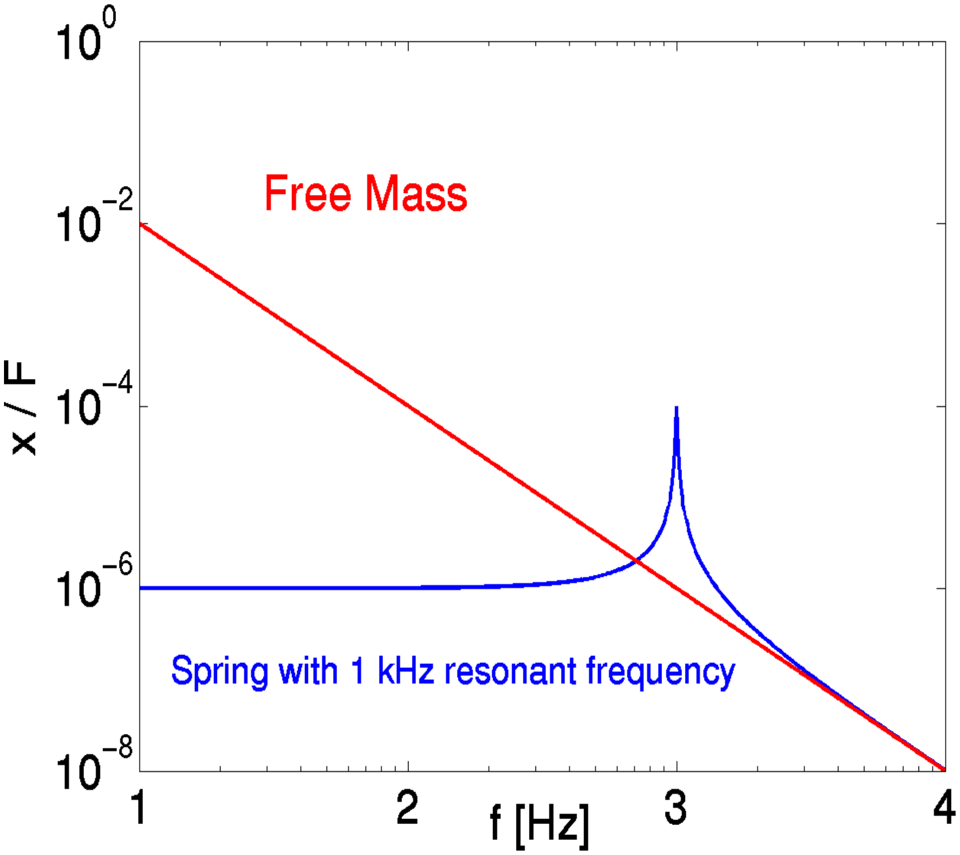
Frequency independent squeeze angle

Advanced LIGO quantum noise, assuming 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.

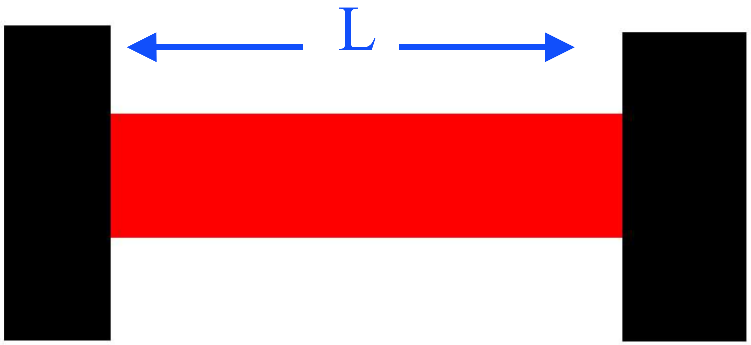


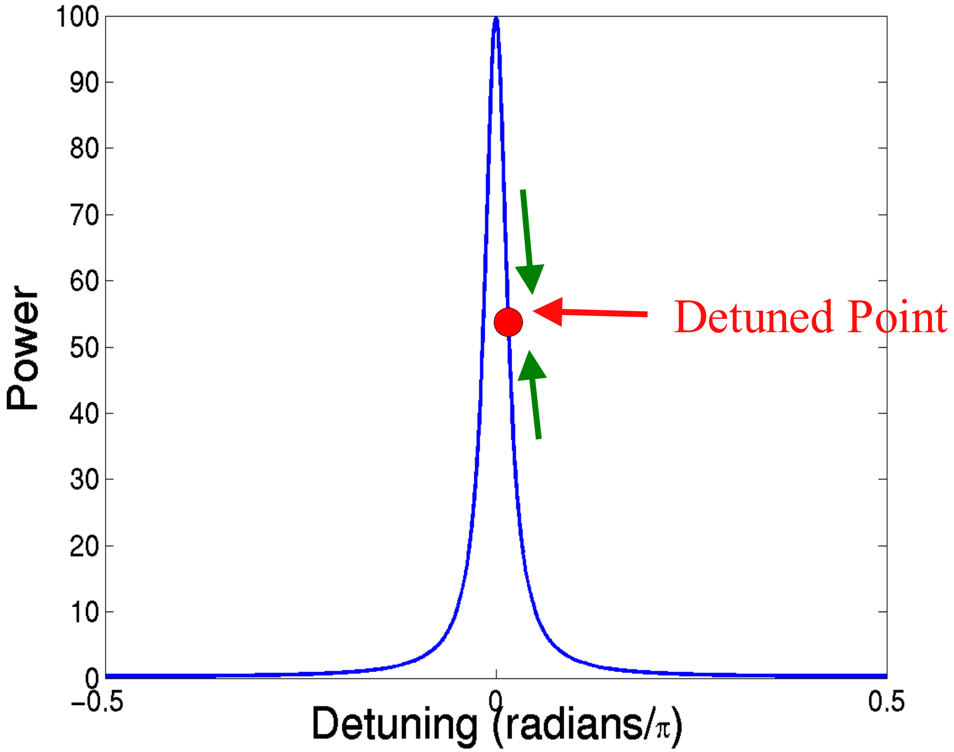
Thermal Noise in Springs

- 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 suspension.
  - » A low resonant frequency mechanical pendulum may be used to minimize thermal noise, while the optical spring produces the flat response in our frequency band.

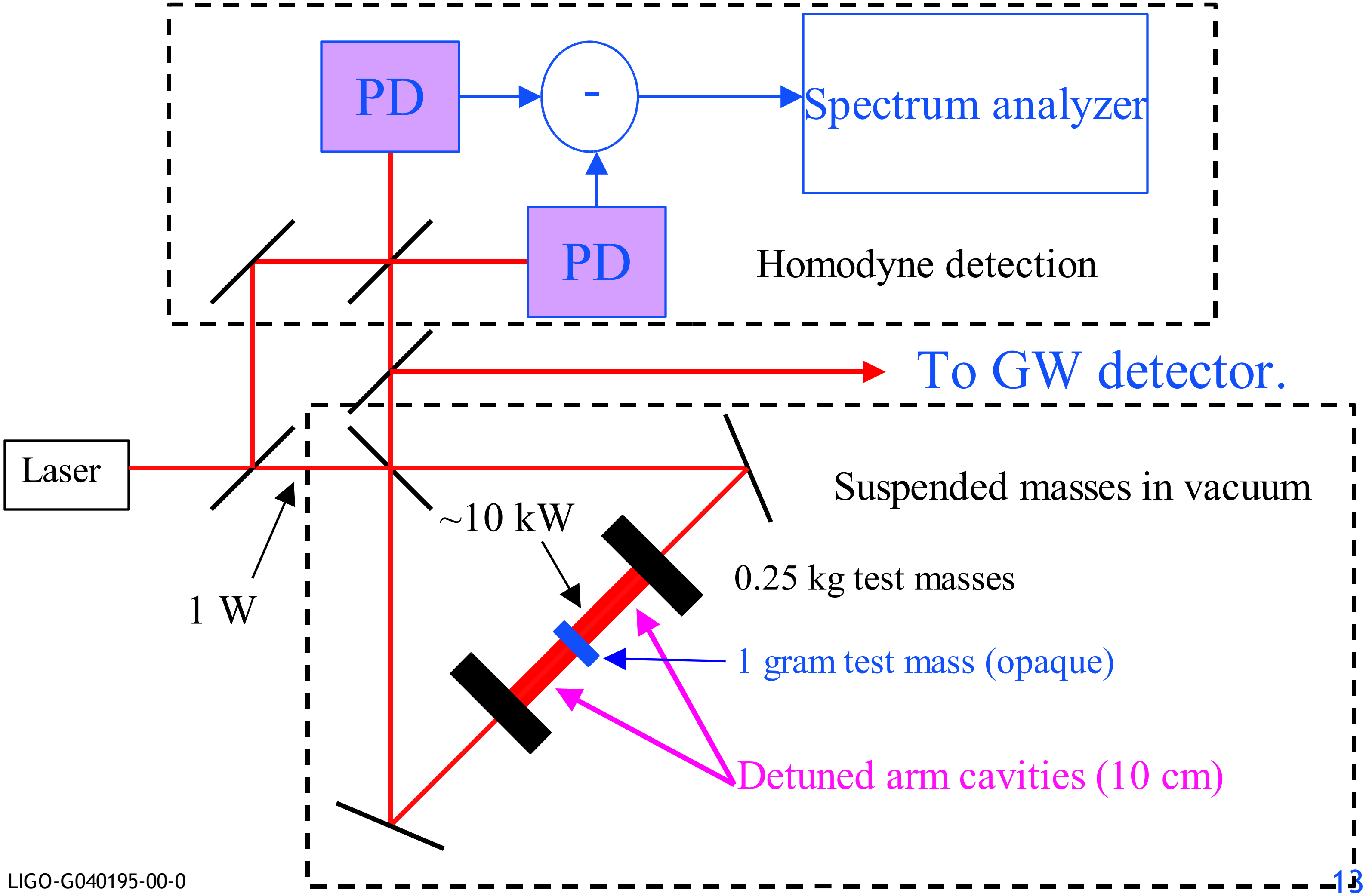
Optical Springs

When a Fabry-Perot cavity with movable mirrors is operated on the side of a fringe, the intra-cavity power changes linearly for small displacements around this point. The masses behave as though they were attached by a spring.





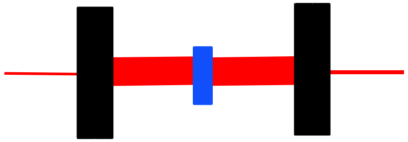
Design


PD
-
Spectrum analyzer
PD
Homodyne detection
To GW detector.
Laser
Suspended masses in vacuum
~10 kW
0.25 kg test masses
1 W
1 gram test mass (opaque)
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 for the suspension
    - Low suspension thermal noise
  - Coating thermal noise could be an issue
- Very high optical quality – losses ~ 5ppm per bounce

The Arm Cavities



- Cavity finesse ~ 20,000.
- Intra-cavity power ~10kW
- Beam waist ~ 1mm
- Power density hitting mirror face is on the order of 1 MW/cm^2. Have to be careful, or we'll destroy the coating.

The Arm Cavities

- Shared end mass
  - The static forces from the light on the each side of the end mass balance
  - Worse laser noise from common mode optical spring
  - Possibly easier to control
- Independent end masses
  - Less laser noise
  - The static forces from the light on the end mass displace it about 1mm from it’s equilibrium before it equilibrates with the gravitational force

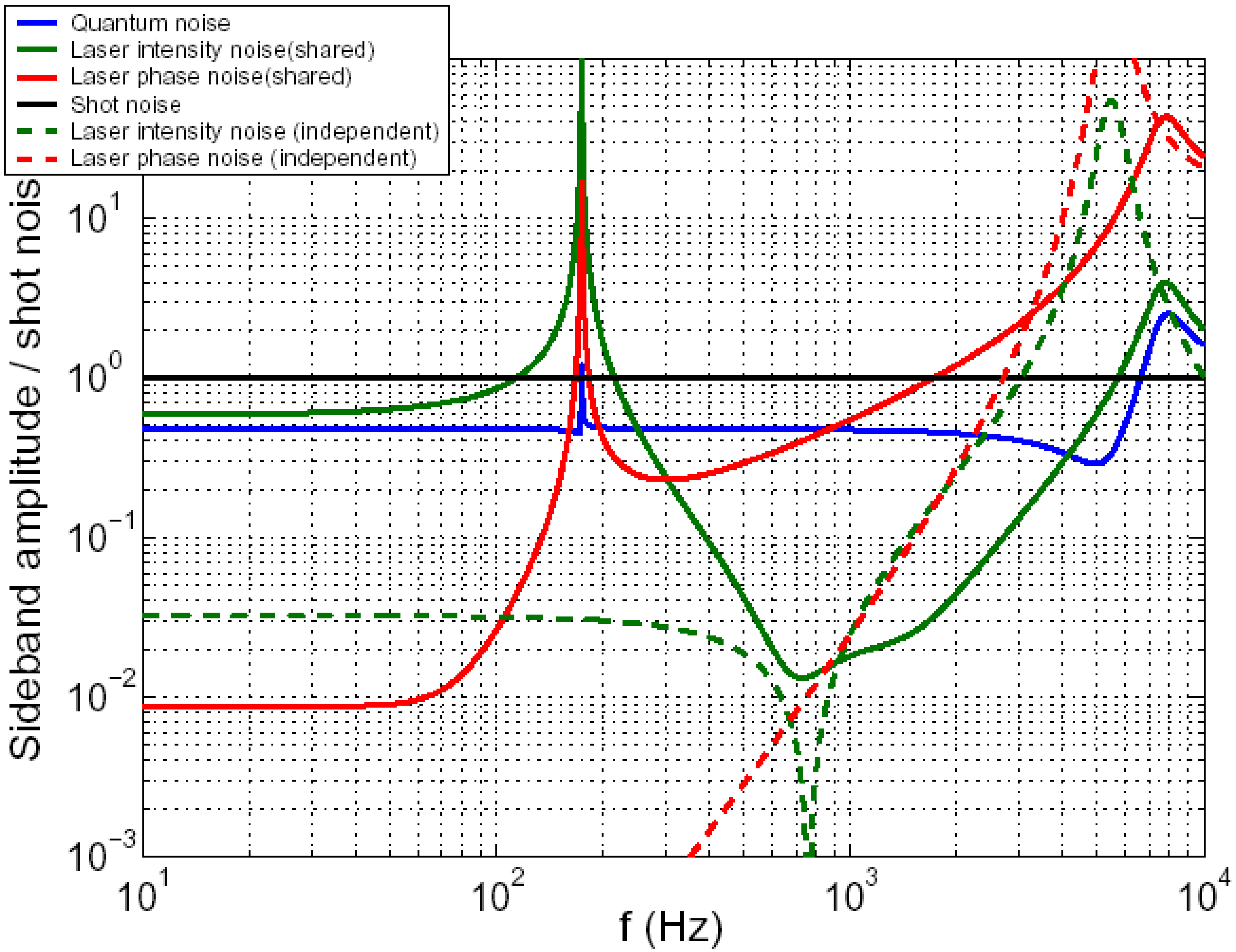
Laser Noise

- 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

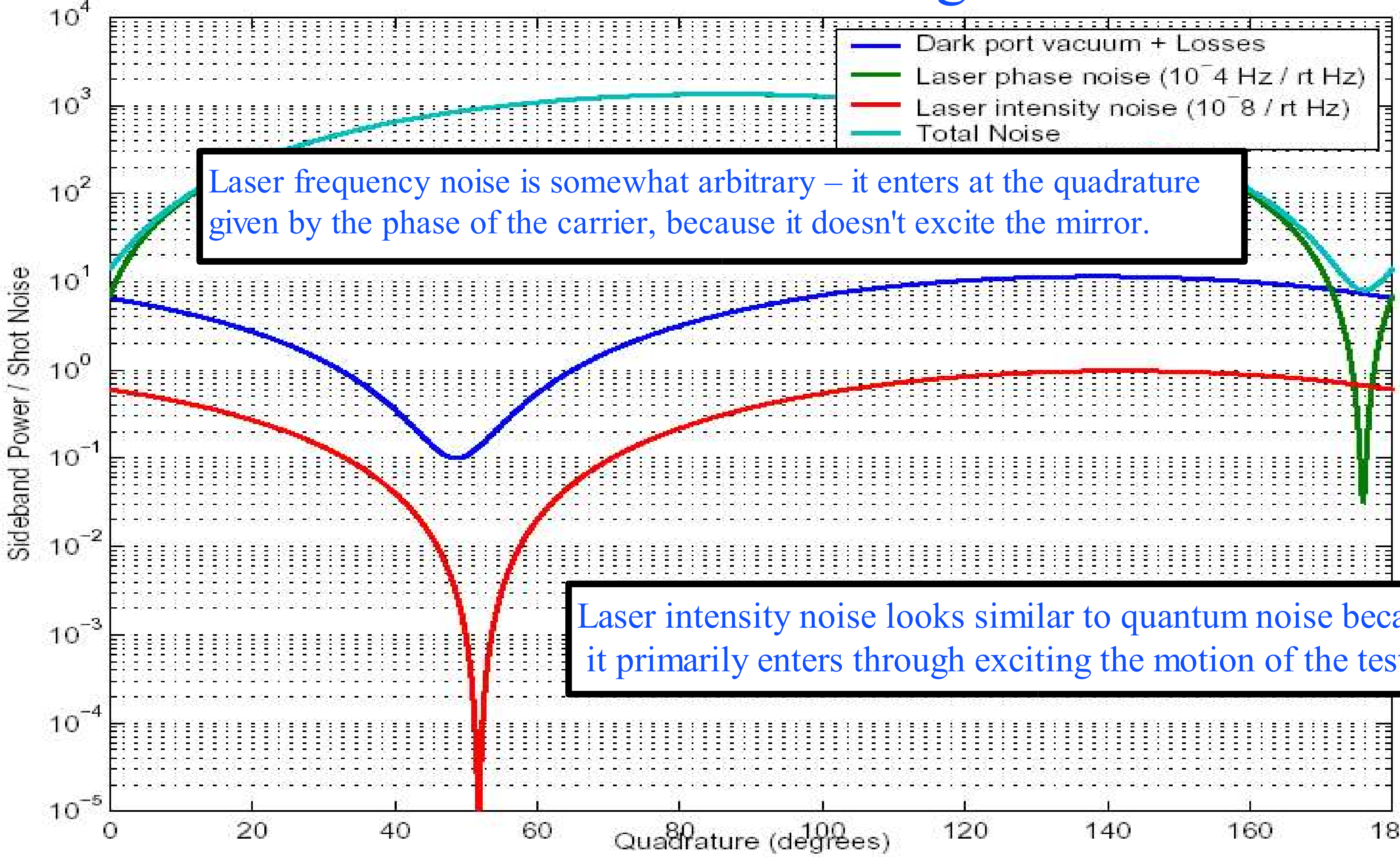
- Shared end mass
  - Differential mode
    - Primarily only moves the smaller end mass
  - Common mode
    - Insensitive to motions of the end mass
    - Primarily moves the more massive input masses, so the resonant frequency of the common mode optical spring is much lower than the resonant frequency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

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

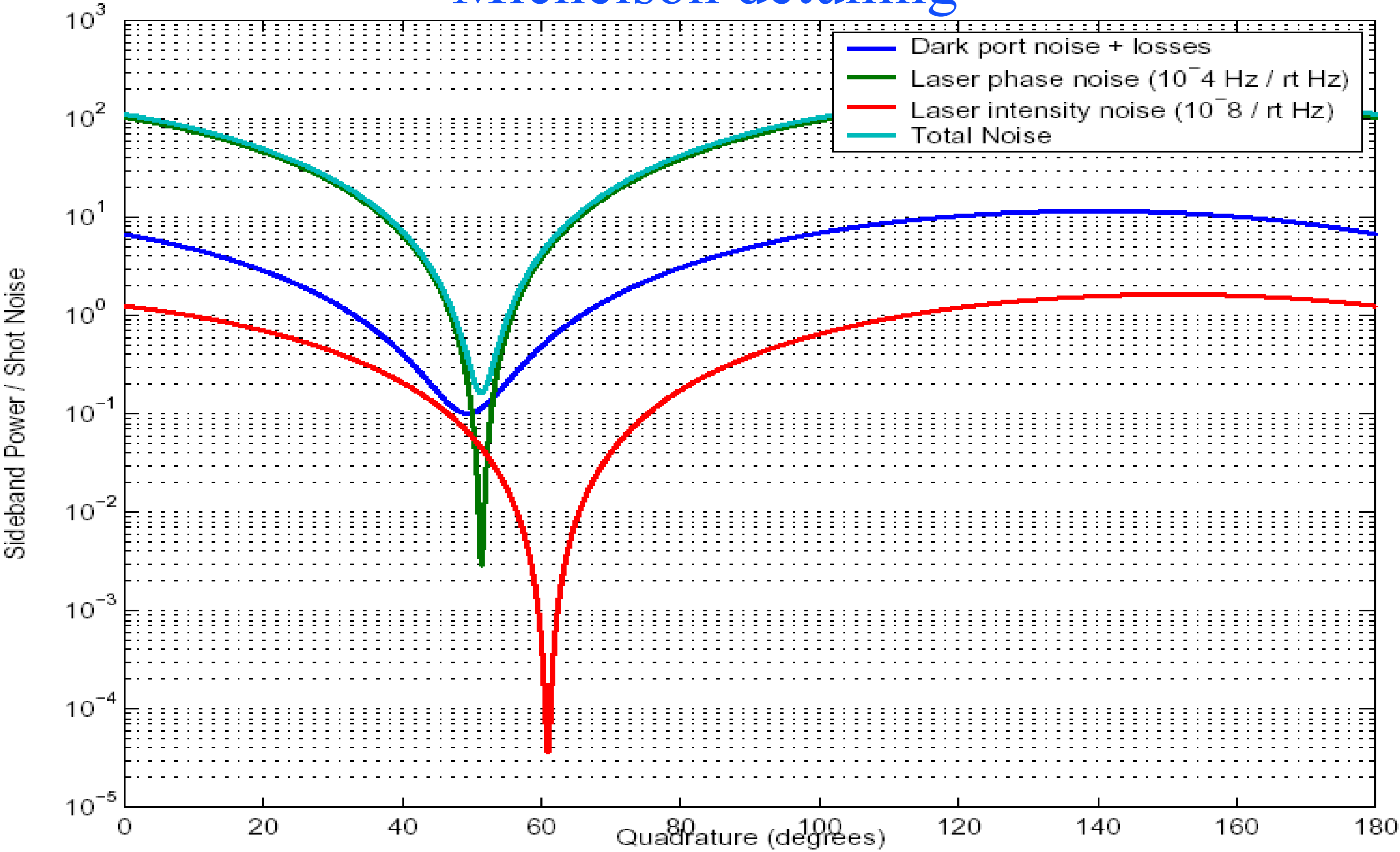


Laser frequency noise is somewhat arbitrary – it enters at the quadrature given by the phase of the carrier, because it doesn't excite the mirror.

Laser intensity noise looks similar to quantum noise because it primarily enters through exciting the motion of the test mass

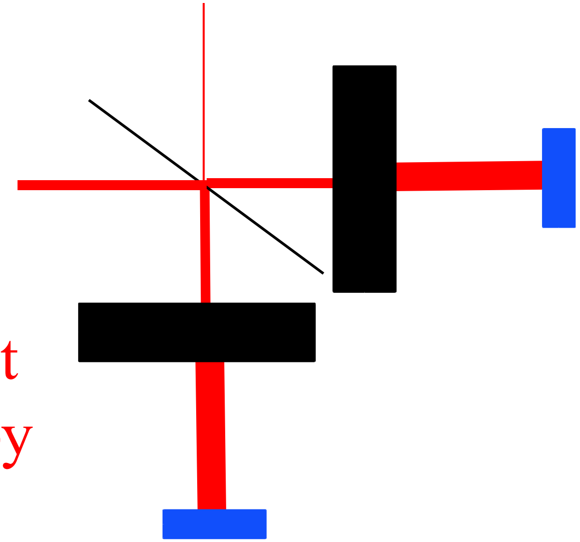
Laser Noise Optimization (squeezing)

Michelson detuning



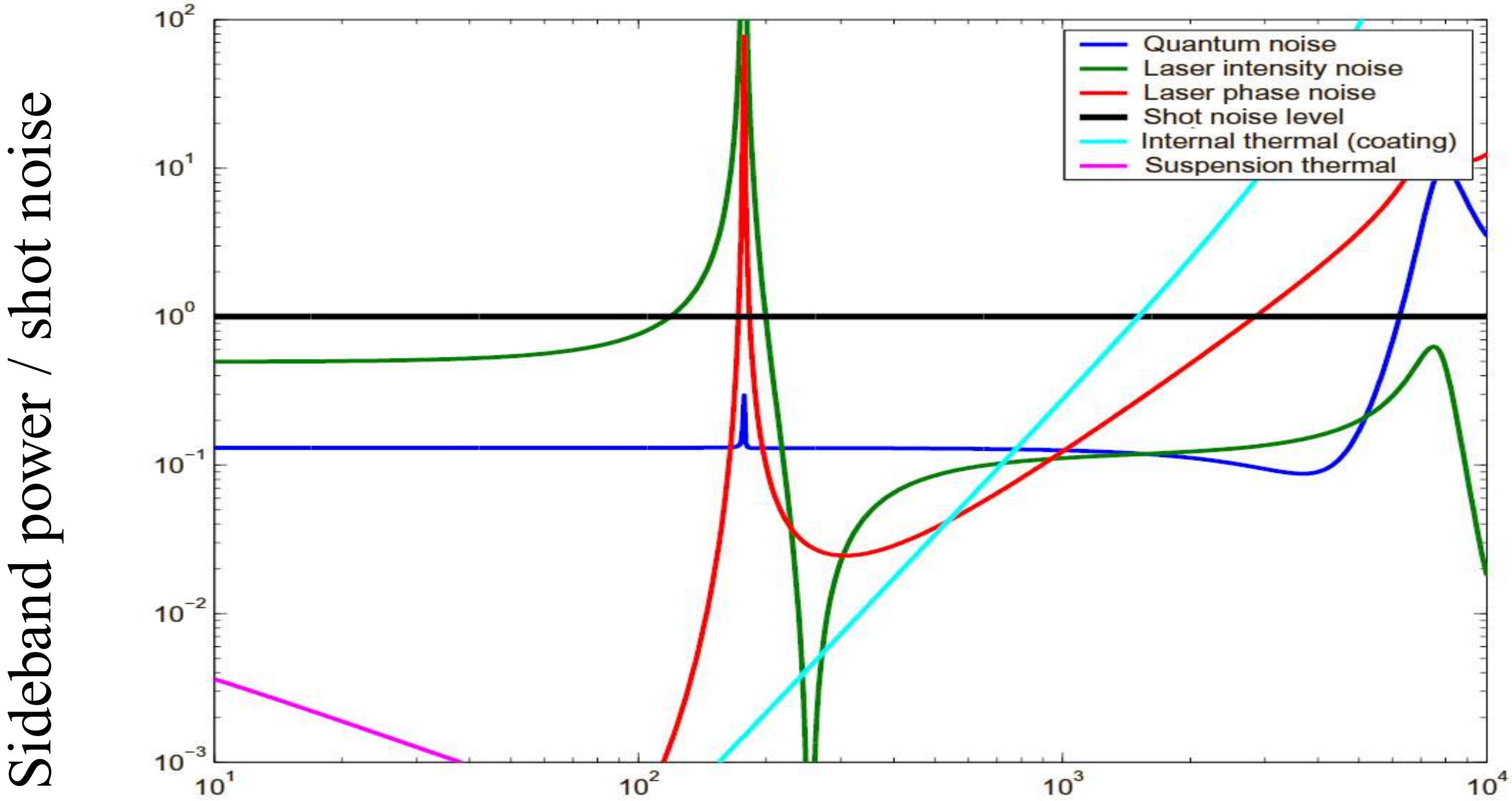
Michelson detuning

The phases of the beams returning from the two cavities are given a differential phase, so that the Michelson is no longer on a dark fringe, but is still close. The amount of light that leaks out is increased by this detuning, but the noise in the squeezed quadrature is minimized.



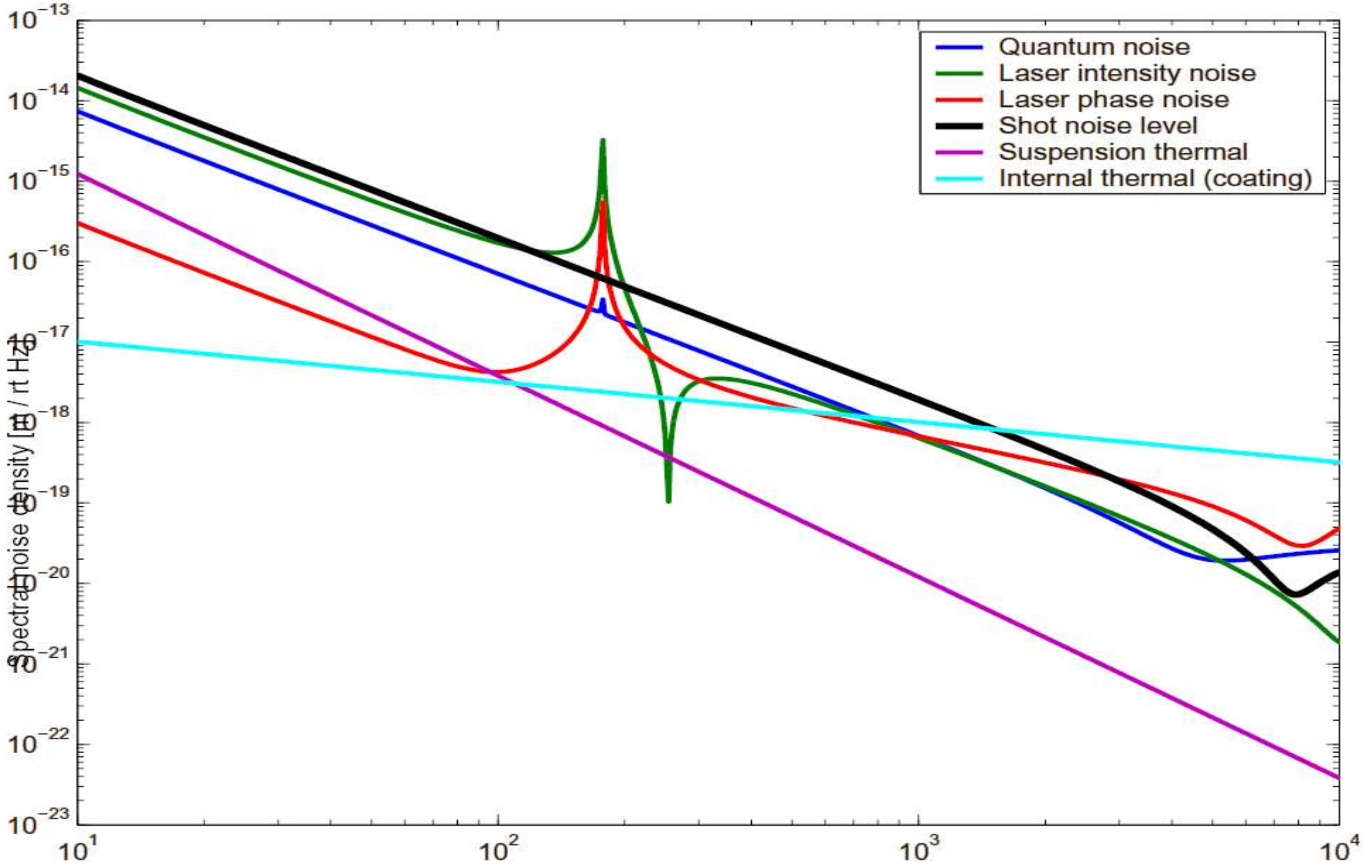
Noise Sources

The case of shared end masses is shown. The bandwidth and margin for error with independent masses is larger.



Noise Sources

Free mass equivalent displacement noise



Frequency(Hz)

Why is this interesting?

- Alternative to crystal squeezing at low frequencies
- Test quantum limited radiation pressure effects – gain confidence that the modeling and understanding 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