Progress on radiation pressure induced squeezing

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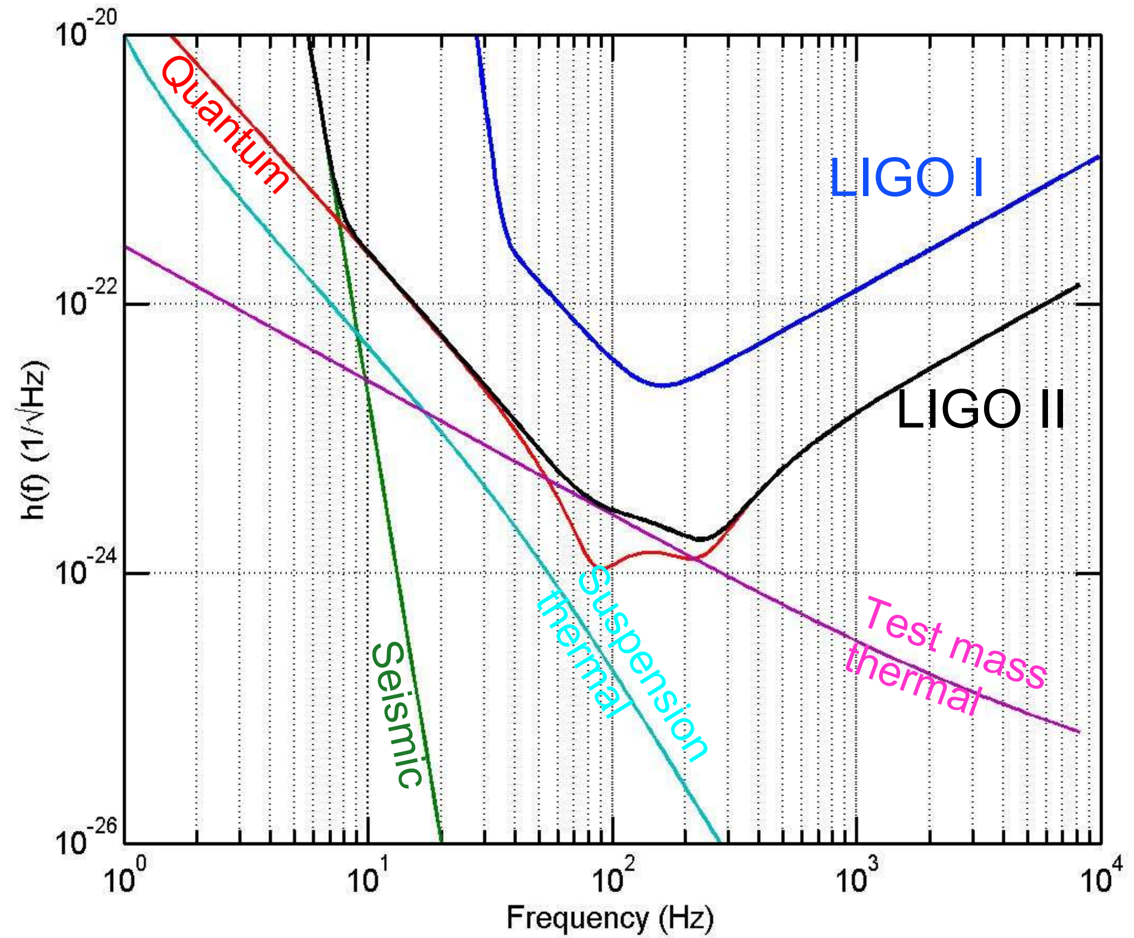
Quantum Measurement Group

LSC Meeting, March 2005

Outline

- Squeezing and radiation pressure in interferometers
- Experimental design
- Current status
- Future work

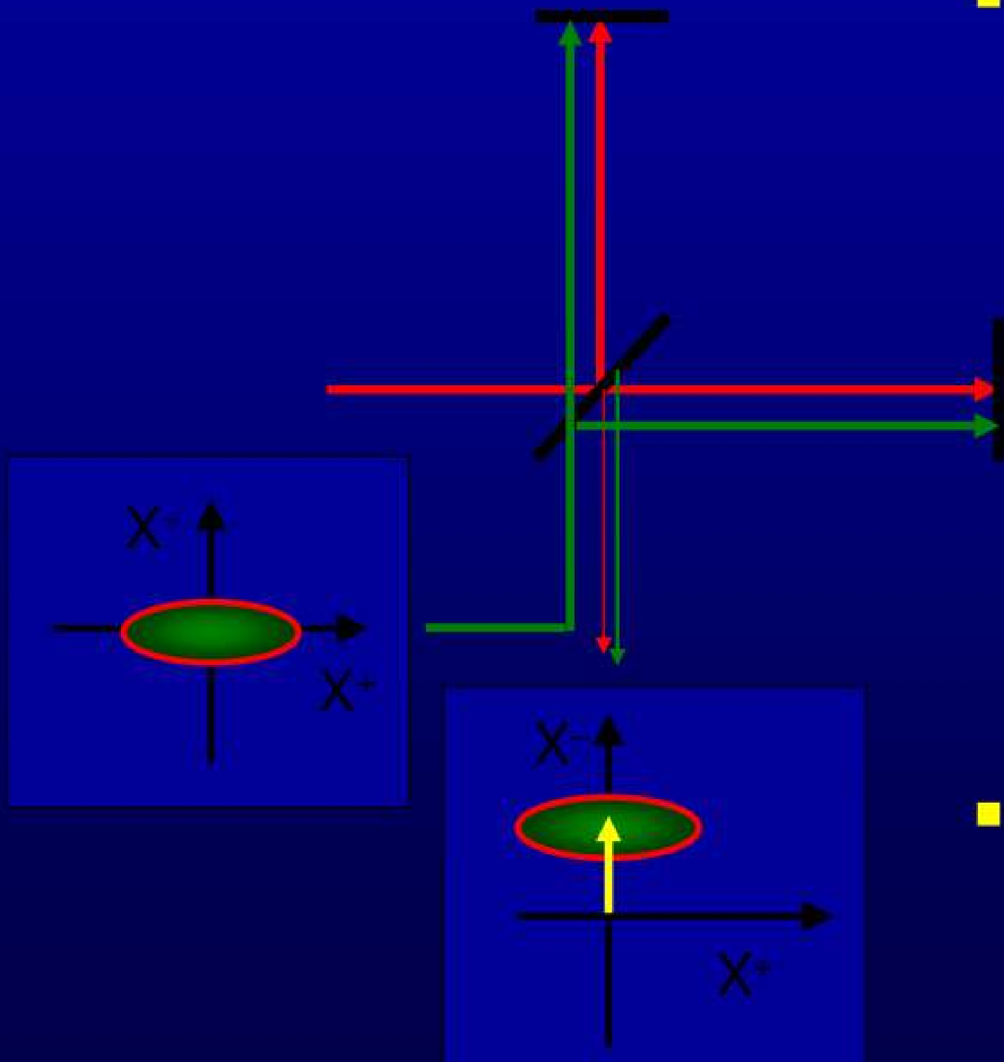
Quantum noise floor



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 – fluctuating force makes mirror move, and that motion creates phase nose of the reflected beam
    ➔ radiation pressure noise
  - Correlation of two noise sources creates quadrature dependent noise – squeezing.

Squeezed input vacuum state in Michelson Interferometer



- GW signal in the phase quadrature
  - Not true for all interferometer configurations
  - Detuned signal recycled interferometer → GW signal in both quadratures
- Orient squeezed state to reduce noise in phase quadrature

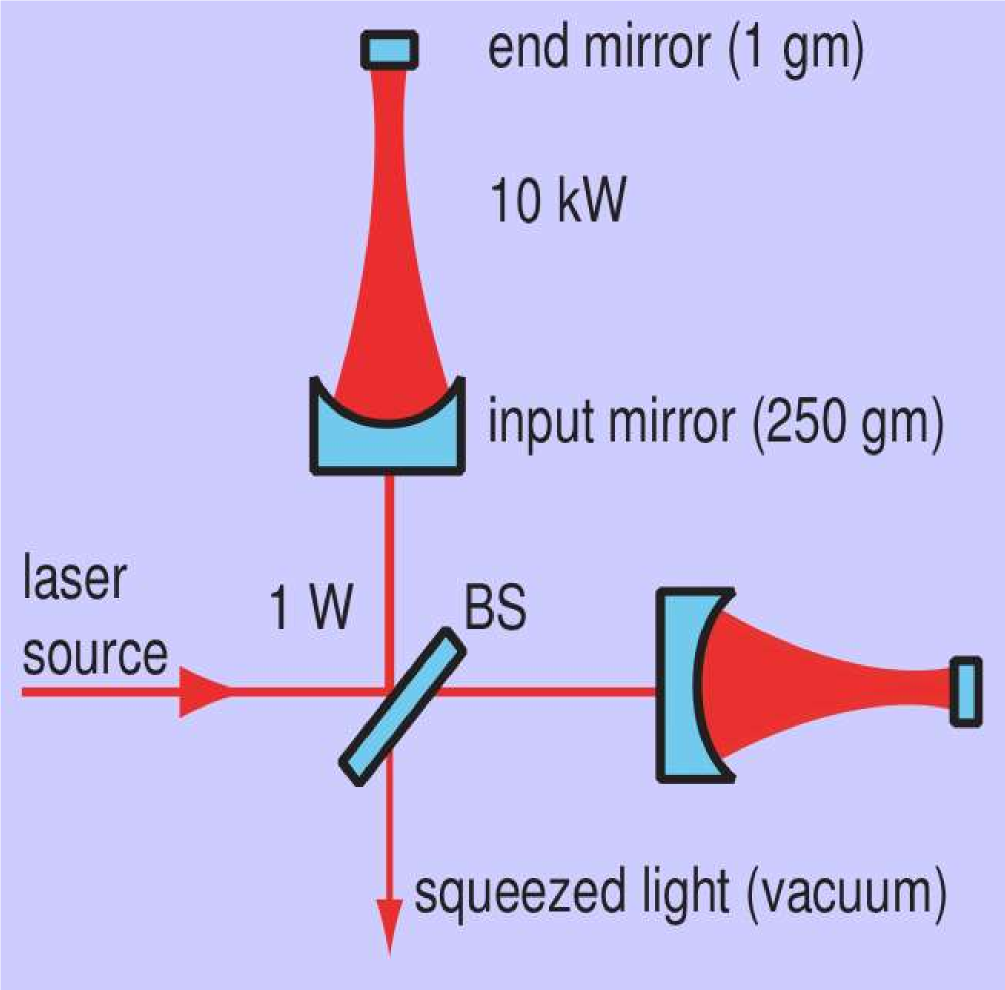
Squeezed input

- Requirements
  - » Squeezing at low frequencies in the GW band.
  - » Frequency (in)dependent squeeze angle.
  - » Increased levels of squeezing.
- Generation methods
  - » Non-linear optical media -- Crystal based squeezing
  - » Radiation pressure effects -- Ponderomotive squeezing
- Challenges
  - » Frequency dependence
    - – Squeeze angle rotation filter cavities
    - – Squeeze amplitude filter cavities
  - » Low optical loss

Experimental motivation

- Explore the idea of using an interferometer as a source for squeezed states.
- Test radiation pressure induced squeezing as a quantum non-demolition technique.
- Test our ability to control a QND interferometer.

Experimental design



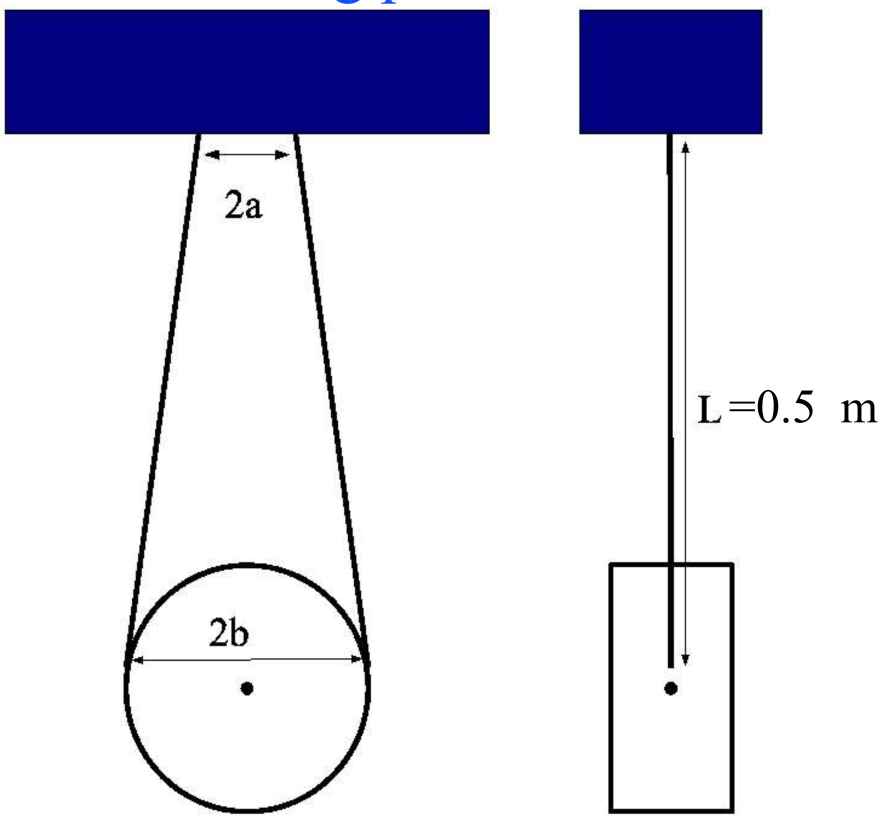
- ➔Low mass
- ➔High power
- ➔Detuned Cavities for optical spring

End mirrors

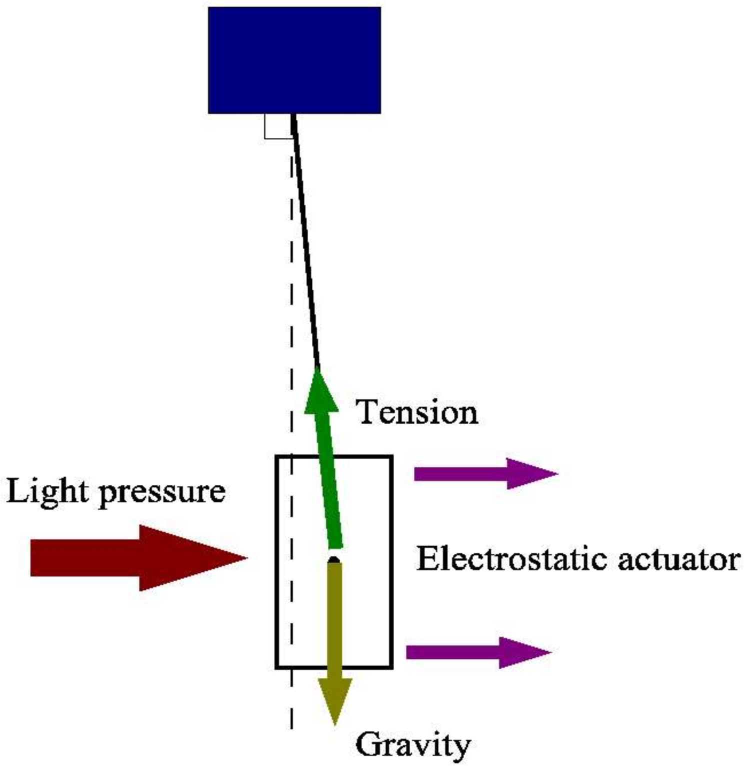
- Very small (12.6 mm diameter, 3 mm thick), light (1 gram) fused silica mirror.
- Low losses (about 10 ppm).
- Must have a high Q pendulum mode for low thermal noise
  - » Monolithic fused silica suspension.
- Electrostatic actuator used to control longitudinal, pitch and yaw degrees of freedom.

End mirrors

No circulating power



High circulating power



End mirror suspension

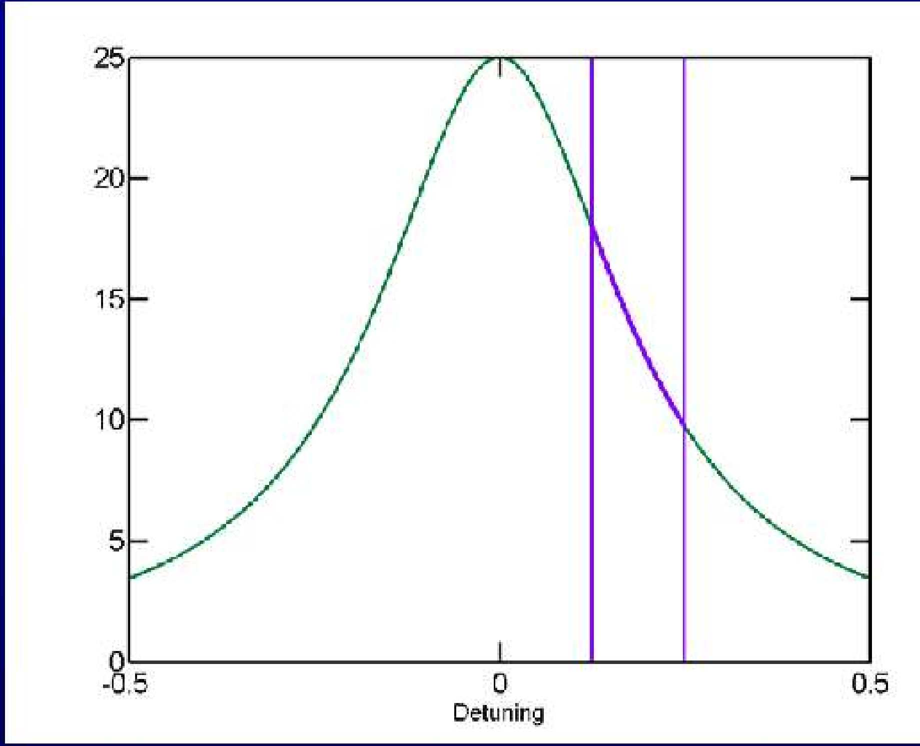
- Fused silica fibers with diameter ~ 10 microns and 0.5 meters long are the baseline.
  - » Small diameter is necessary to keep the pitch of the mirror easy to control and align.
- The fiber attachment points must be precisely located on the mirror substrate, with an accuracy ~ 20-100 microns.
  - » Laser welding
    - – Best in terms of precision and thermal noise.
    - – Very difficult to weld such small fibers to the relatively large substrate?
  - » Epoxy/glue
    - – Reasonably accurate, but what does it do to the internal mode Q's of the mirror?
  - » Silicate bonding?

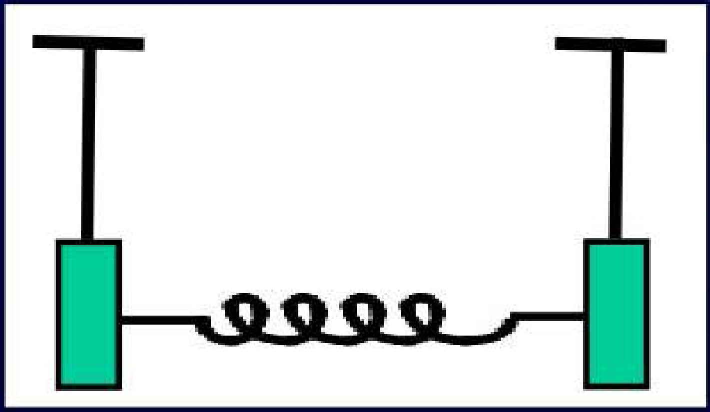
Arm cavities

- 1 meter in length
  - » Necessary for realistic values for the necessary radius of curvature and g ratios.
- Negative g ratio mirrors (R = 0.51cm) are chosen to reduce the instability of the mirrors to pitch and yaw motions.
- 4 kW circulating power with 1mm waist size, finesse of about 15,000.
- Detuned for optical spring effect (~8 kHz)
  - » Allows for measurements below the shot noise limit, while having a force sensitivity much worse than the standard quantum limit.
  - » Eliminates the frequency dependence of the induced squeezing.

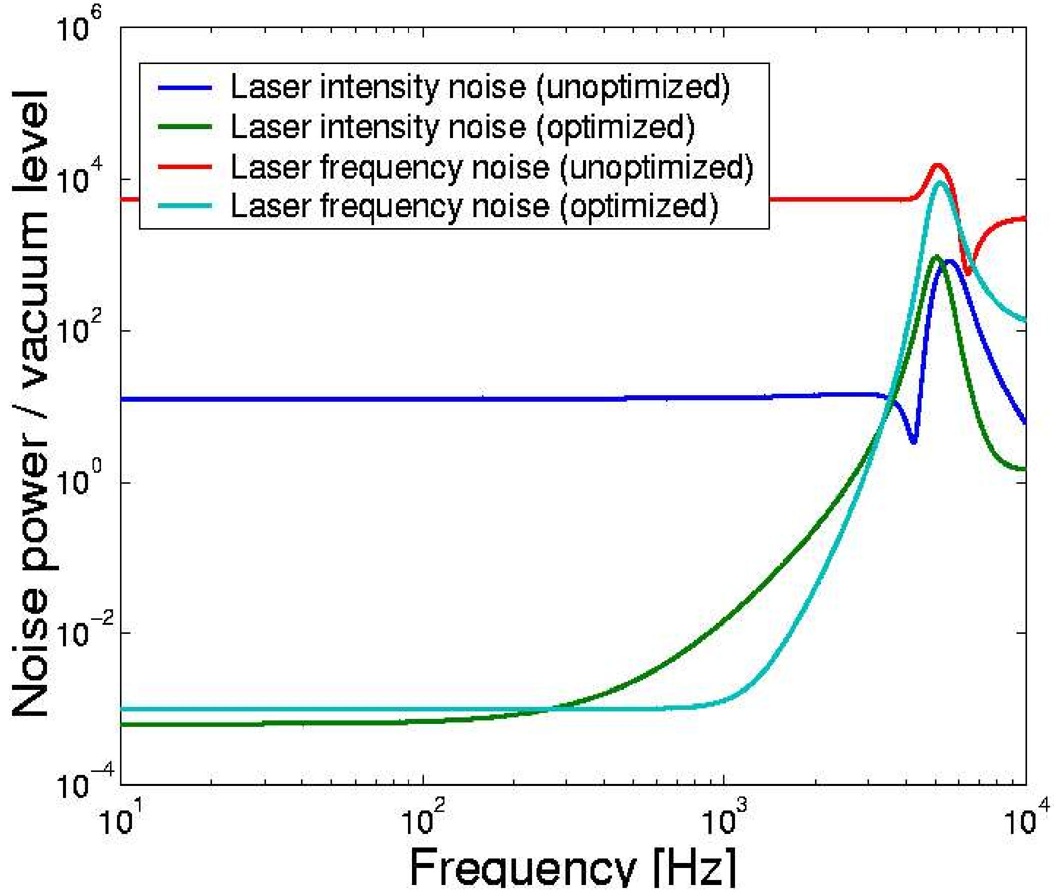
Detuned cavity for optical spring

- Positive detuning
  - Detuning increases
  - Cavity becomes longer
  - Power in cavity decreases
  - Radiation-pressure force decreases
  - Mirror ‘restored’ to original position
  - Cavity becomes shorter
  - Power in cavity increases
  - Mirror still ‘restored’ to original position



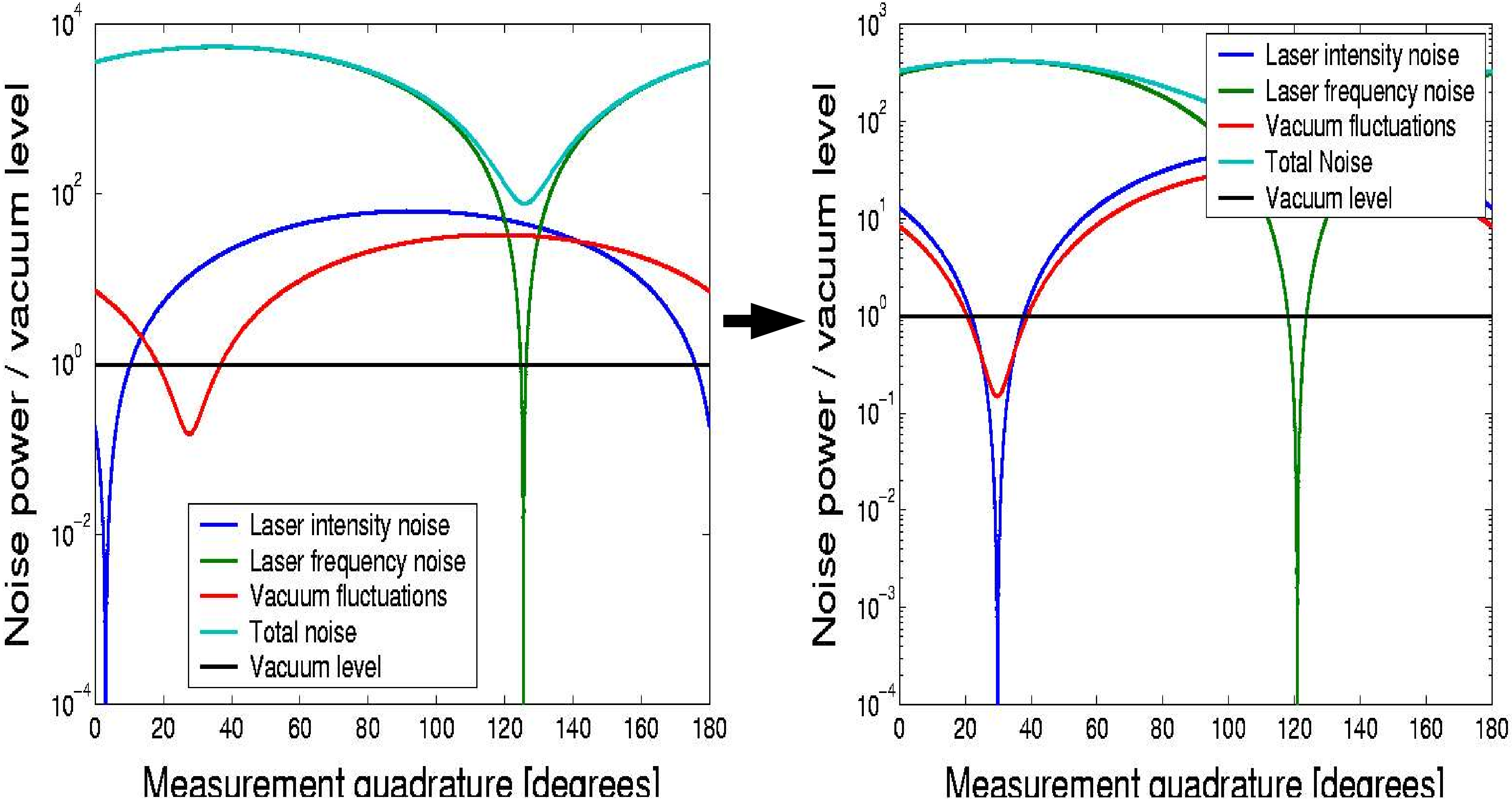


Laser noise reduction

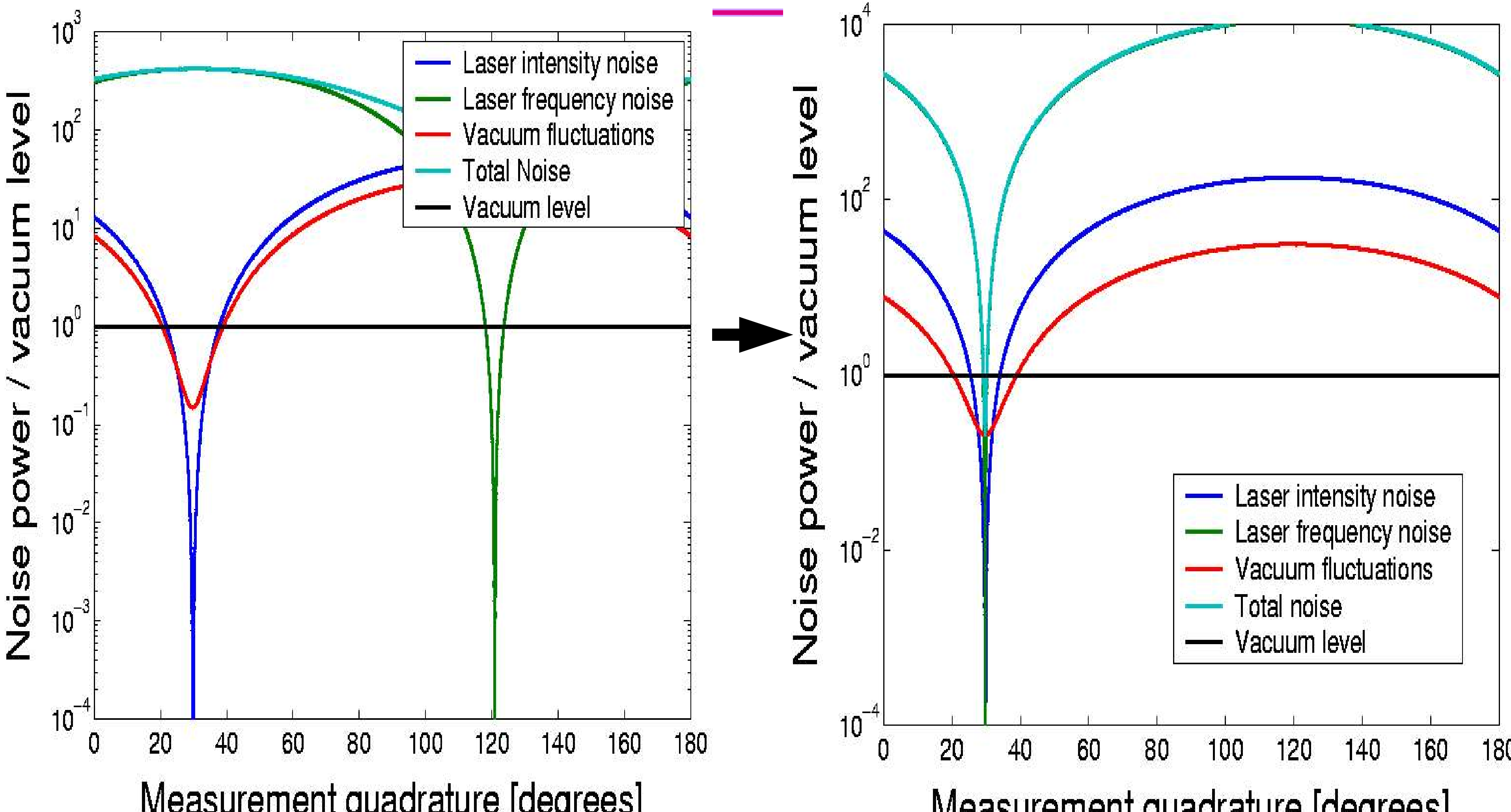


- Relative intensity noise at the level of 10^{-8} / rt Hz, and frequency noise of 10^{-4} Hz/rt Hz are assumed near 100 Hz.
- Must develop techniques to reduce laser noise dependence.

Laser noise reduction – Michelson offset

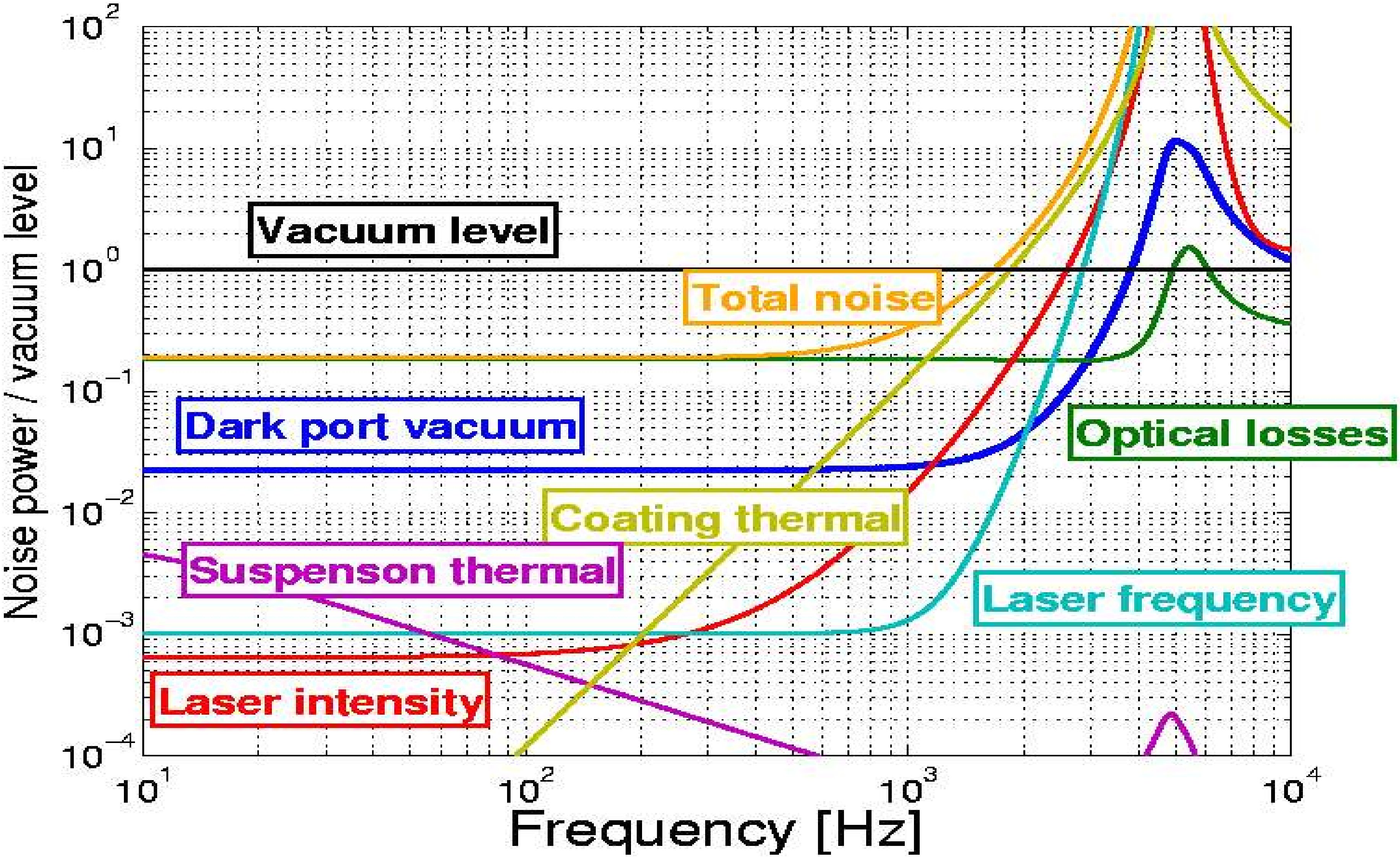


Laser noise reduction – introduce a loss

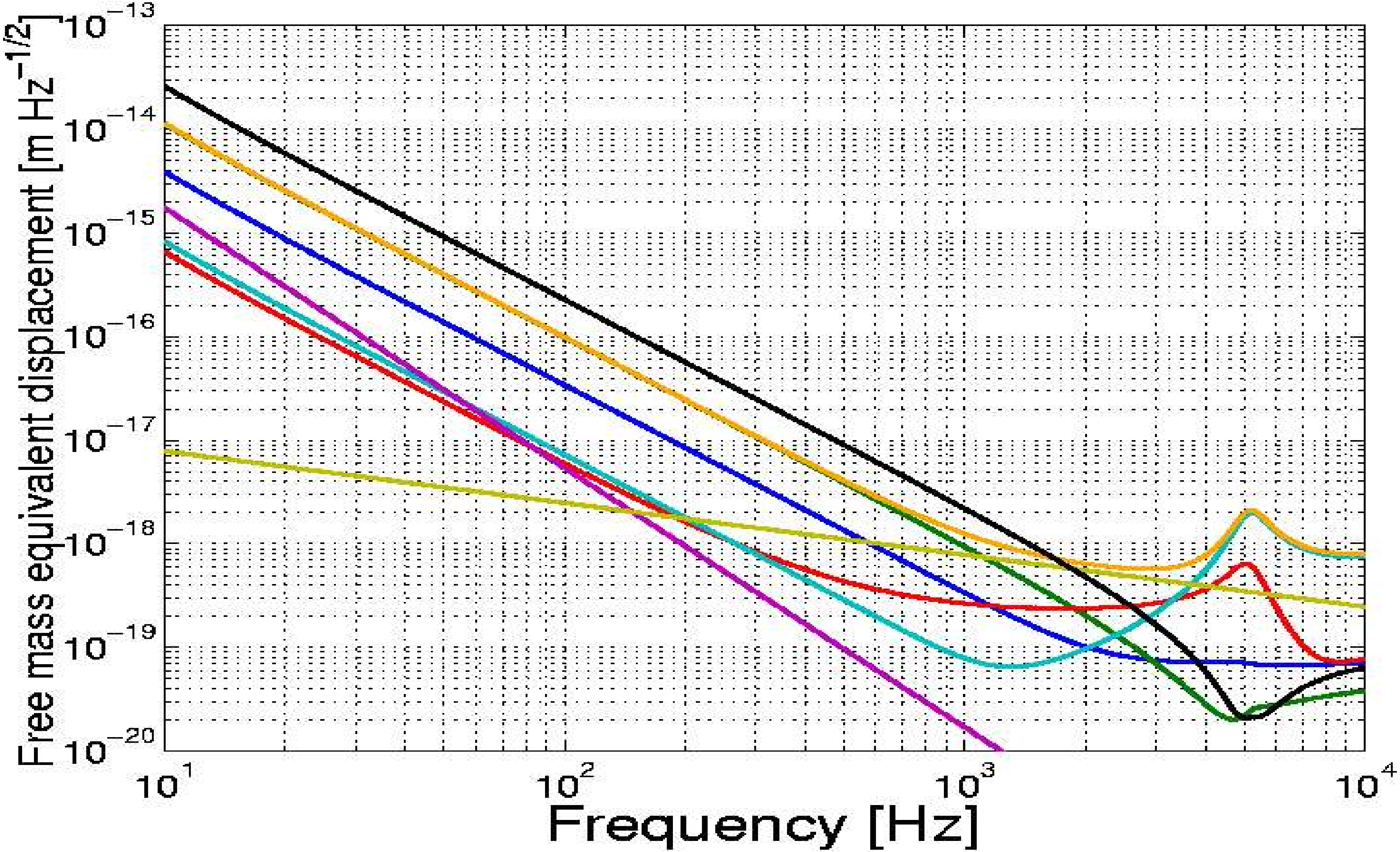


LIGO

Noise budget



Noise budget 2



Current status

- Detailed noise models
  - » Simulation tool that propagates the quantum fields and include losses, mismatches and radiation pressure effects has been developed. Useful for analyzing any interferometer which exhibits quantum effects.
- Location and infrastructure. LASTI laser, seismic isolation and vacuum system.
- Mirrors are spec'd, quotes have been received, and order will go out shortly.
- Suspension tower for end mirrors is designed and built, and dummy mirrors are being suspended.
  - » We can routinely make make fibers with diameters ~20 microns at MIT, but they lack uniformity and consistency between fibers. Good enough for testing, but we plan to enlist the help of Glasgow for making uniform and consistent 10 micron fibers.
  - » Initial test of laser welding with a 20 micron fiber was unsuccessful. The problem seems to be with any tension in the fiber, it snaps immediately when the laser is applied. Techniques to resolve this problem are currently being explored.
  - » A suspended mirror has been made using epoxy to attach the fibers to the substrate. This is being used to characterize the pendulum's mechanical modes, and as a testbed for the electrostatic actuator.

Future work

- Resolve laser welding problems (or use alternative method)
- Control system.
- High finesse cavity tests in vacuum
  - Suspended ITM and fixed ETM.
  - **Suspended ITM and suspended ETM.**
- Full interferometer.
- Noise hunting.