# Vibration isolation (passive)

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# Outline

1. Displacement noise goal
2. Seismic noise
3. Seismic isolators in theory and practice
4. Limits of performance

# Two classes of noise

We will talk about two kinds of noise that move an interferometer's mirrors:

- seismic noise
- thermal noise

This is in distinction to readout noise like shot noise, which only affects our ability to see where the mirrors are.

- Radiation pressure noise, shot noise's quantum-mechanical twin, was our first example of displacement noise.

# Large mechanical noise

How large?

Seismic: $x_{rms} \sim 1\ \mu$m.

Thermal

- mirror's CM: ~ 3 x $10^{-12}$ m.
- mirror's surface: ~ 3 x $10^{-16}$ m.

# LIGO's sensitivity goal

Earlier, I loosely gave Advanced LIGO's sensitivity as $h \sim 10^{-22}$. What did I mean?

We want the standard deviation of strain measurements averaged over the 10 msec duration of, say, a signal from a supernova or black hole ringdown to be $10^{-22}$.

Let's convert this spec to power spectrum language

$$\int_{50\,\mathrm{Hz}}^{150\,\mathrm{Hz}} h^2(f)\,df = \left(10^{-22}\right)^2.$$

This means we want a noise amplitude spectral density near 100 Hz of

$$h(f = 100\,\mathrm{Hz}) = 10^{-23}/\sqrt{\mathrm{Hz}}.$$

# Displacement noise goal

What spectrum of displacement noise is consistent with this goal?

We'll have four key mirrors (two in each arm to make the Fabry-Perot cavities, see later lecture.)

If their displacement noises are incoherent, they add in quadrature. The net result is

$$h_{disp}(f) = \frac{2}{L} x(f).$$

Thus, we need $x(f) = 2\ 10^{-20}$ m/Hz$^{1/2}$.

# How strong is seismic noise?

Amplitude spectrum of seismic noise above 10 Hz is typically
$10^{-9}$ m/Hz$^{1/2}$*(10 Hz/$f$)$^2$, quite diverse below 10 Hz.

Note basic pattern: Strong at low frequencies, weak at high frequencies.

At our target frequency of 100 Hz,
$x(f) = 10^{-11}$ m/Hz$^{1/2}$,

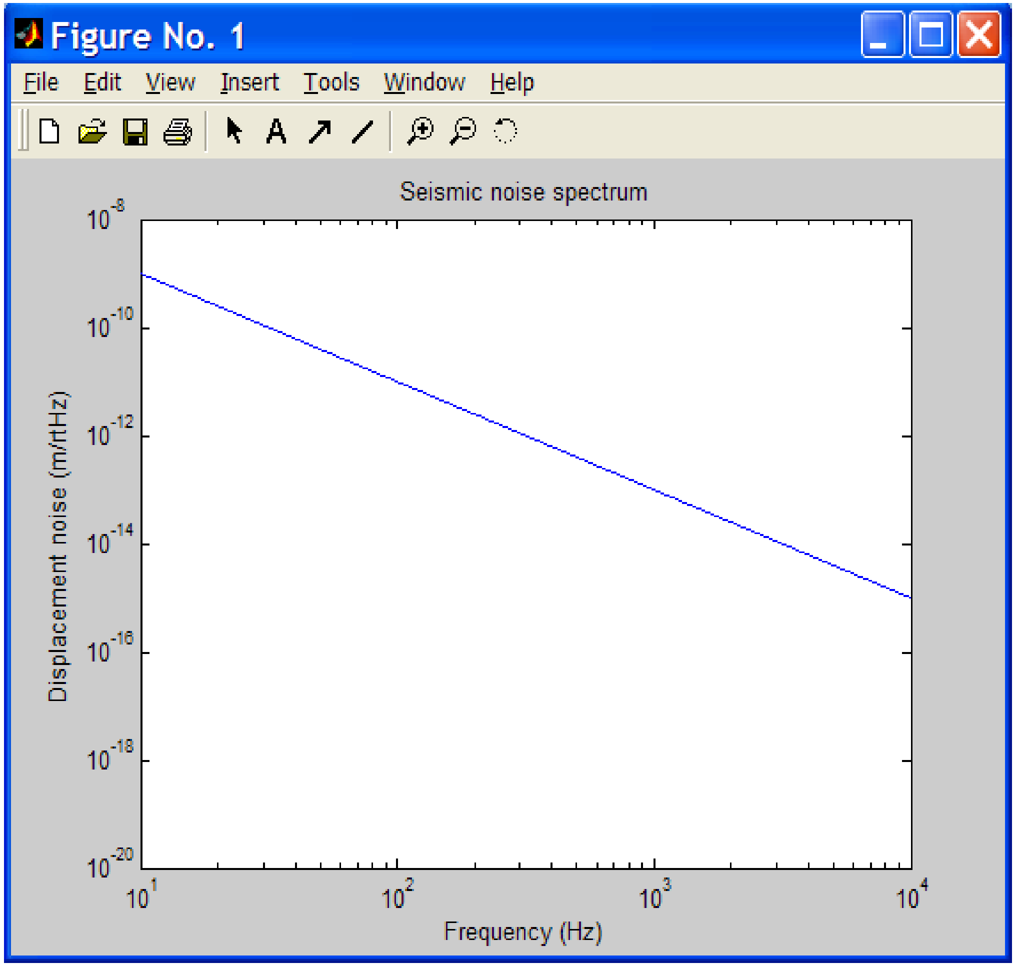
far from $x(f) = 2\ 10^{-20}$ m/Hz$^{1/2}$.

Seismic noise is serious!

We need 9 orders of magnitude of isolation at 100 Hz.

First, I'll describe the iLIGO system, aimed at 8 orders of magnitude at 100 Hz.

# Seismic noise spectrum



# Our test masses need to be free …

- … free to move in response to gravitational wave
- … free from large disturbances from the environment

# Strategy to deal with seismic noise

Seismic noise is so large, we need multiple strategies for dealing with it.

1st, as much isolation as we can build.

- This will partly solve the problem, but will leave strong noise at low frequency.

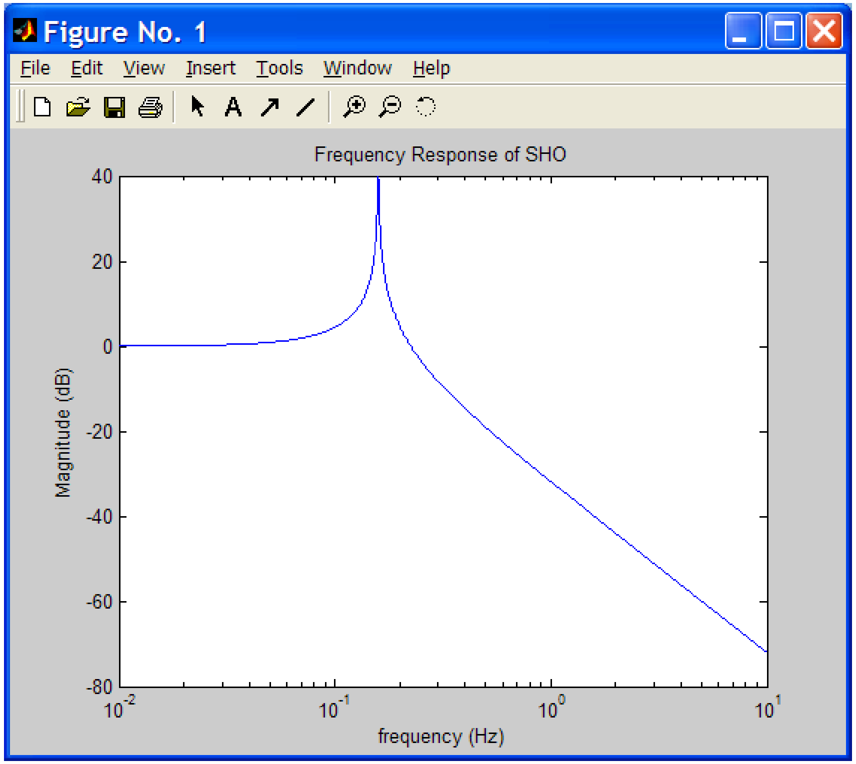
2nd, build an instrument that can be sensitive at high frequencies (where we can make seismic noise small), while tolerating the remaining strong noise at low frequencies.

- This means ensuring linearity, and making thoughtful use of servo control.

# SHO as filter

A mass on a spring makes a good isolator.

Frequency response goes like $1/f^2$ above resonance.



# Pendulum as isolator

One such SHO is built into our plans already – each test mass must be suspended as a pendulum, to allow it to respond freely to the gravitational wave.

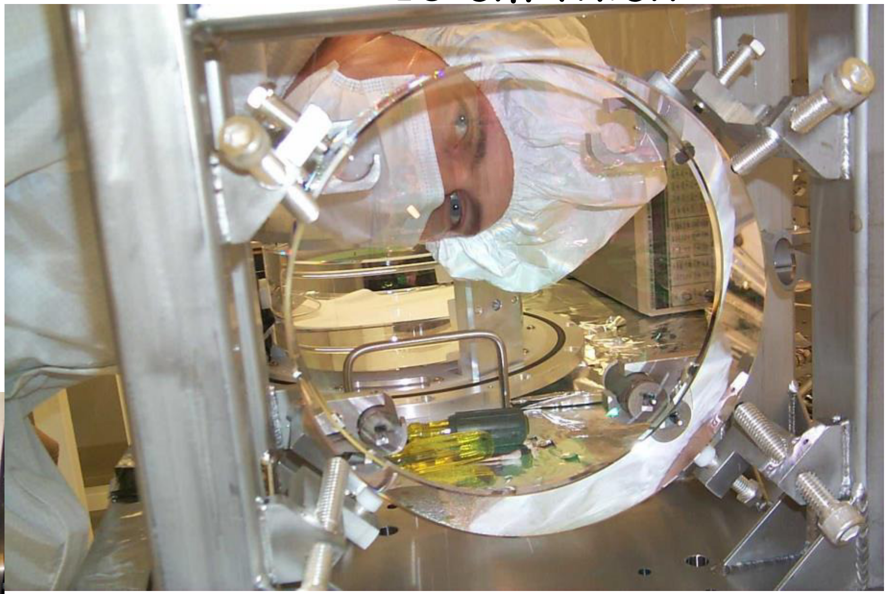
- It has a resonant frequency near 1 Hz.
- Thus, we should multiply the input spectrum by $(1\ \mathrm{Hz}/f)^2$ to find output spectrum (i.e., motion of mirror.)

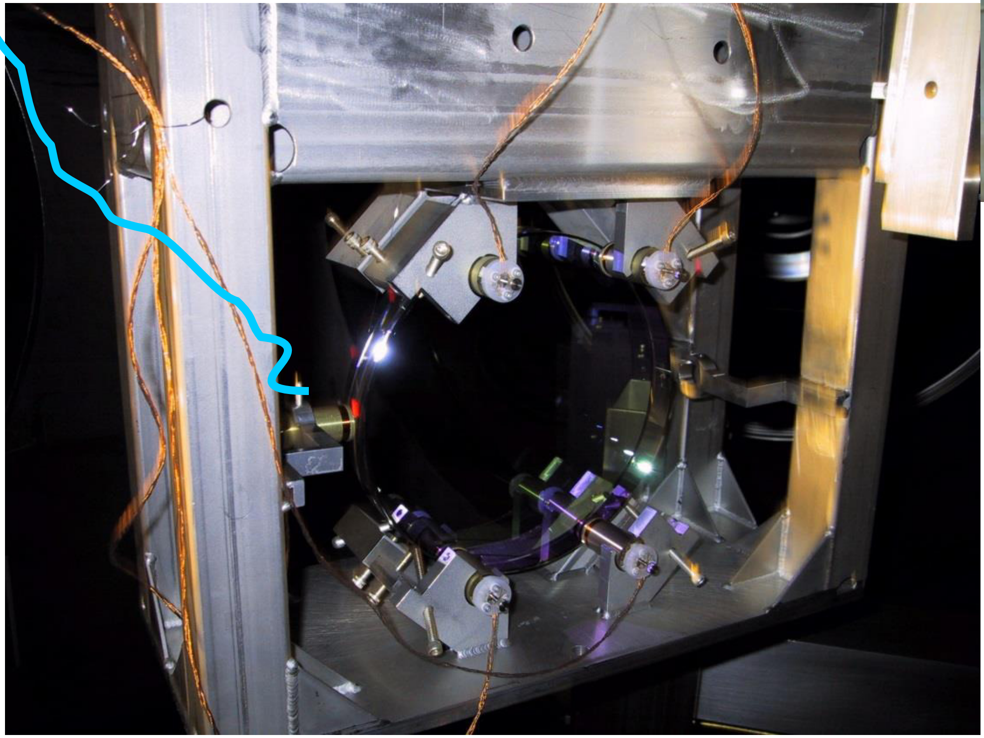
# Core Optics
## installation and alignment

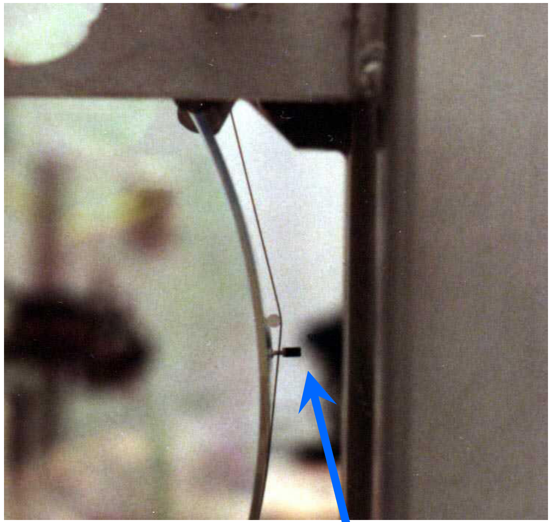
# Optic Suspension

10 kg Fused Silica
25 cm diameter
10 cm thick

- Magnet / coils control mirrors
- Suspending gives $1/f^2$ isolation above ~1 Hz.
- Low loss music wire minimizes thermal noise

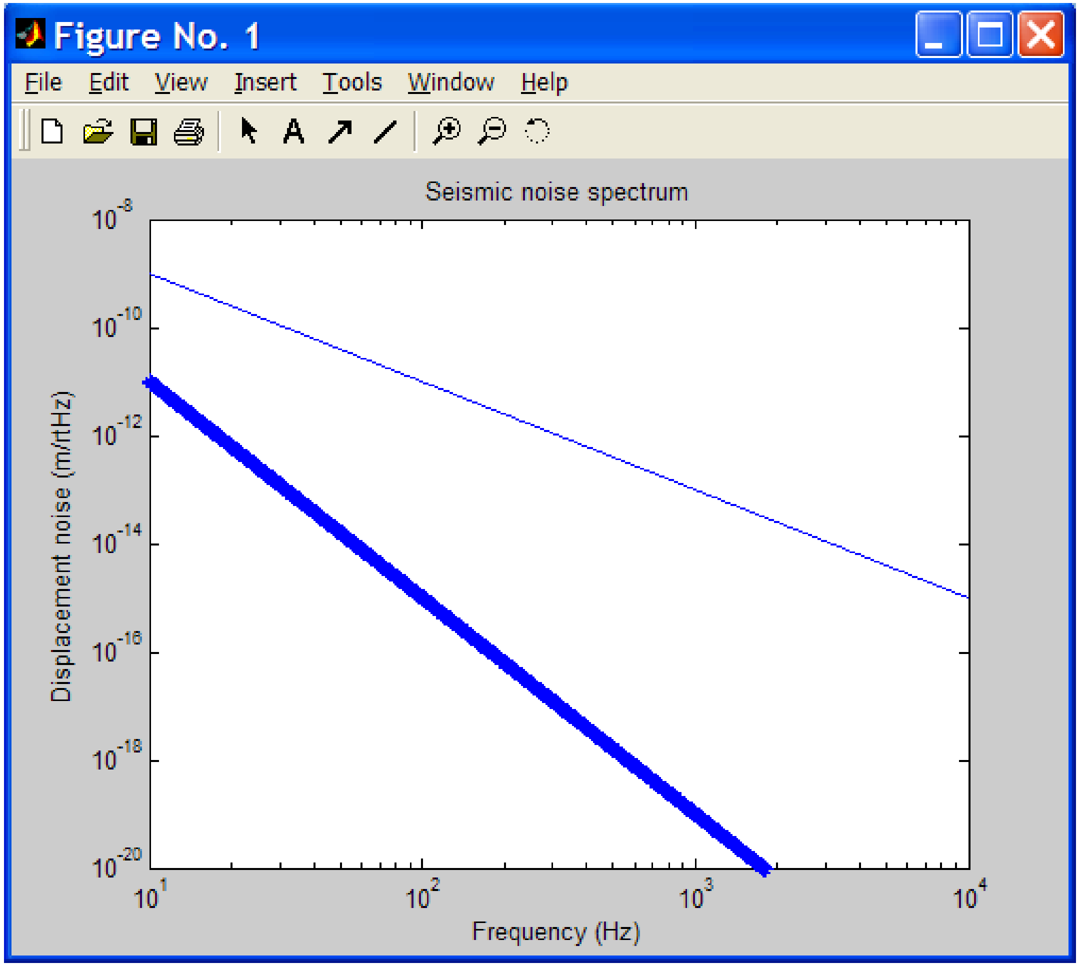






magnet

# Pendulum helps, but only makes seismic noise good enough at $f > 1$ kHz



# Multiple stages of isolation for better filtering

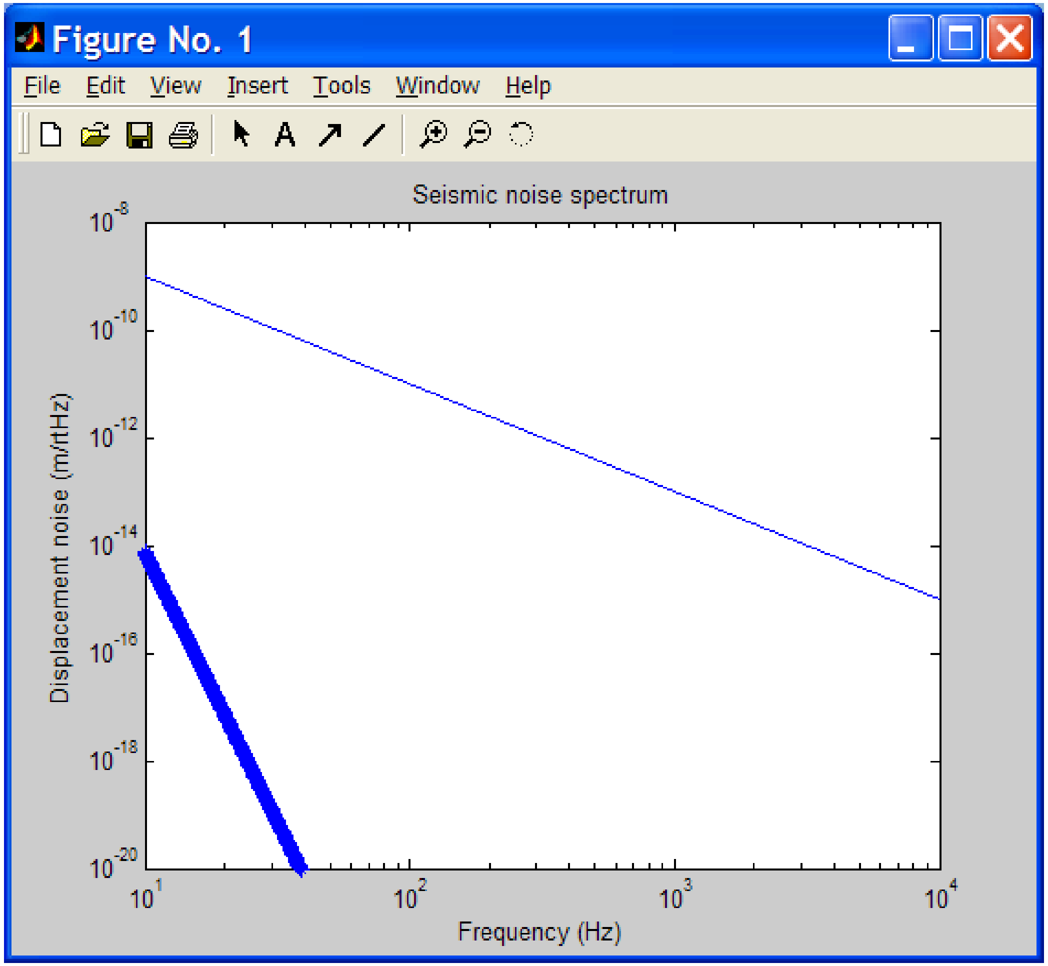
One SHO makes a good filter, but not good enough.

If we make a chain of *N* oscillators, we have a coupled system with *N* resonances, above which the frequency response is

$$G(f) = \left(\frac{f_0}{f}\right)^{2N}.$$

Just need to build enough stages of isolation.

# Add 3 stages of 3 Hz isolation, iLIGO could work down to 30 Hz



# Need for multi-dof isolation

We need good vertical (and transverse horizontal) isolation as well.

Why?

- If not, some of the large transverse motion would be converted into optic-axis motion by asymmetries in the pendulum.
- Interferometer has some sensitivity to vertical motion, because arms can't be level everywhere.
  - The earth is curved!

So, we need quasi-isotropic isolation. Such isolators are called mass-spring "stacks". They were invented by Joseph Weber.

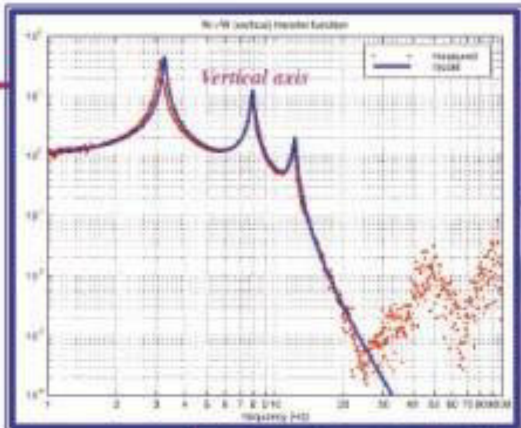
# Seismic Isolation – Springs and Masses

damped spring
cross section

# Vibration Isolation Systems

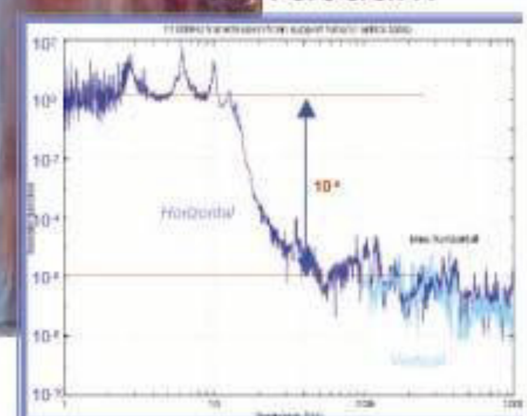
- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Little or no attenuation below 10Hz
- Large range actuation for initial alignment and drift compensation
- Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation


# Seismic System Performance




HAM stack
in air

BSC stack
in vacuum

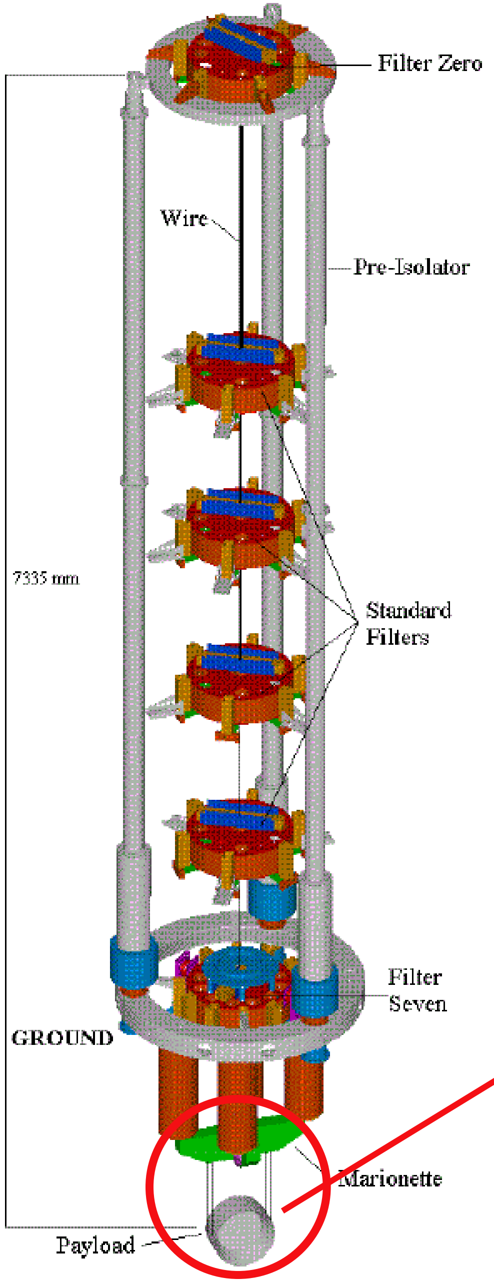


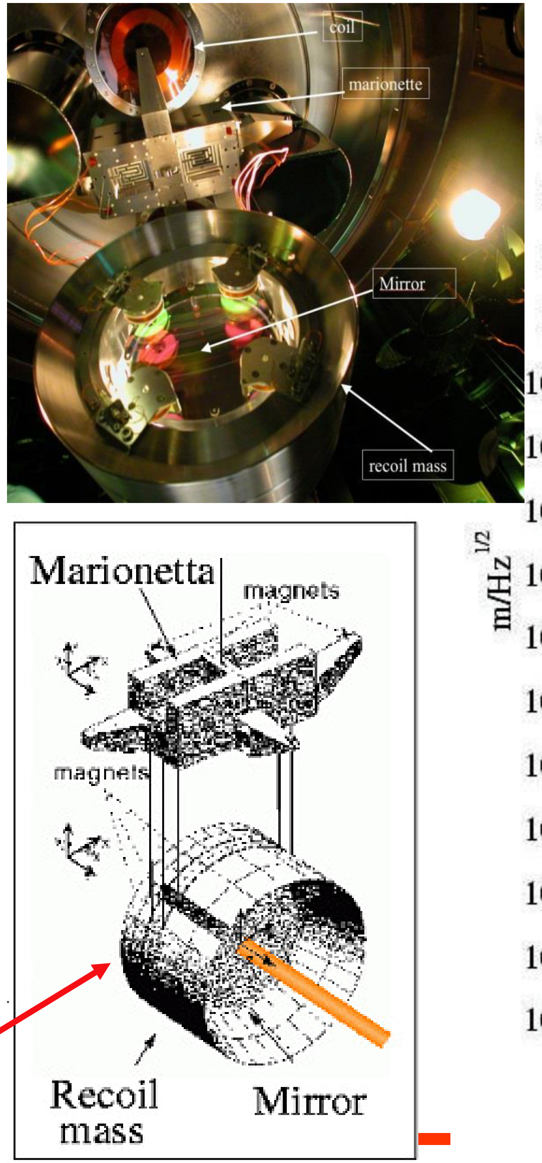
# Internal modes as limits to performance

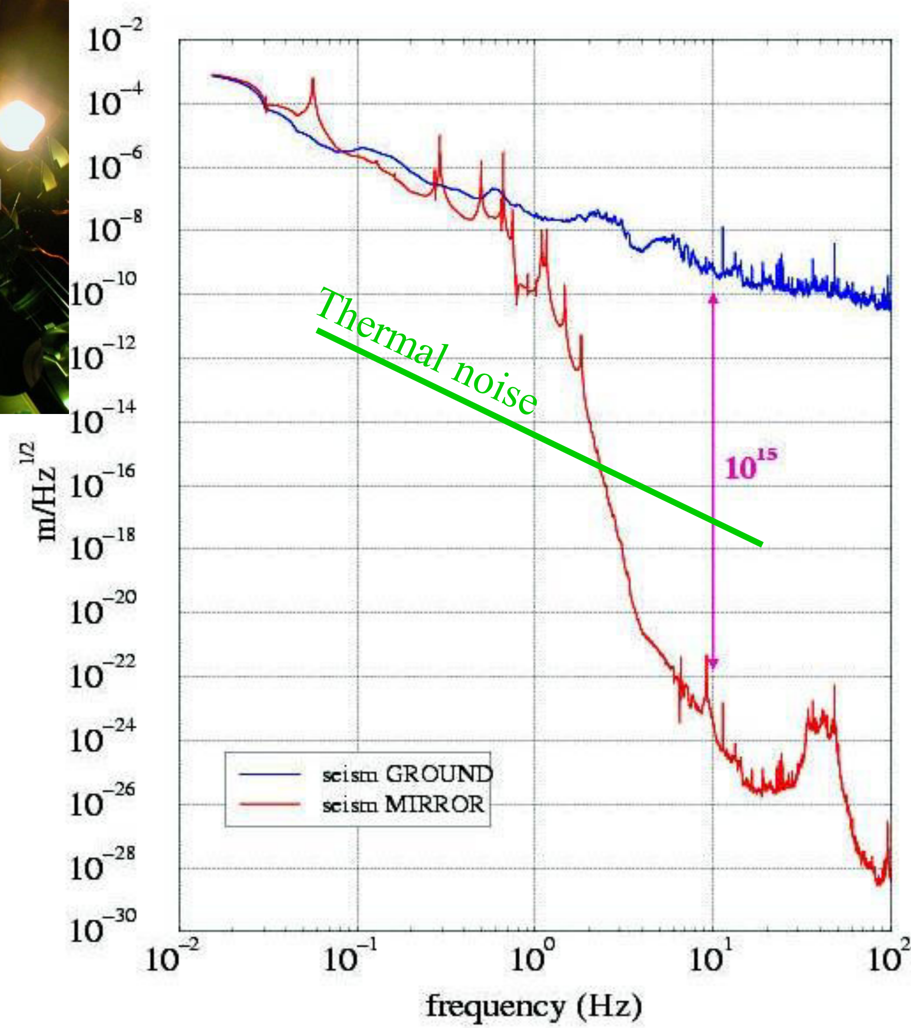
Note that iLIGO stack's frequency response levels off above ~ 30 Hz, at a level of about $10^{-6}$ (about –120 dB.)

Internal degrees of freedom in springs and masses have resonant frequencies there. E.o.m. isn't well approximated by the point-mass model in that regime.

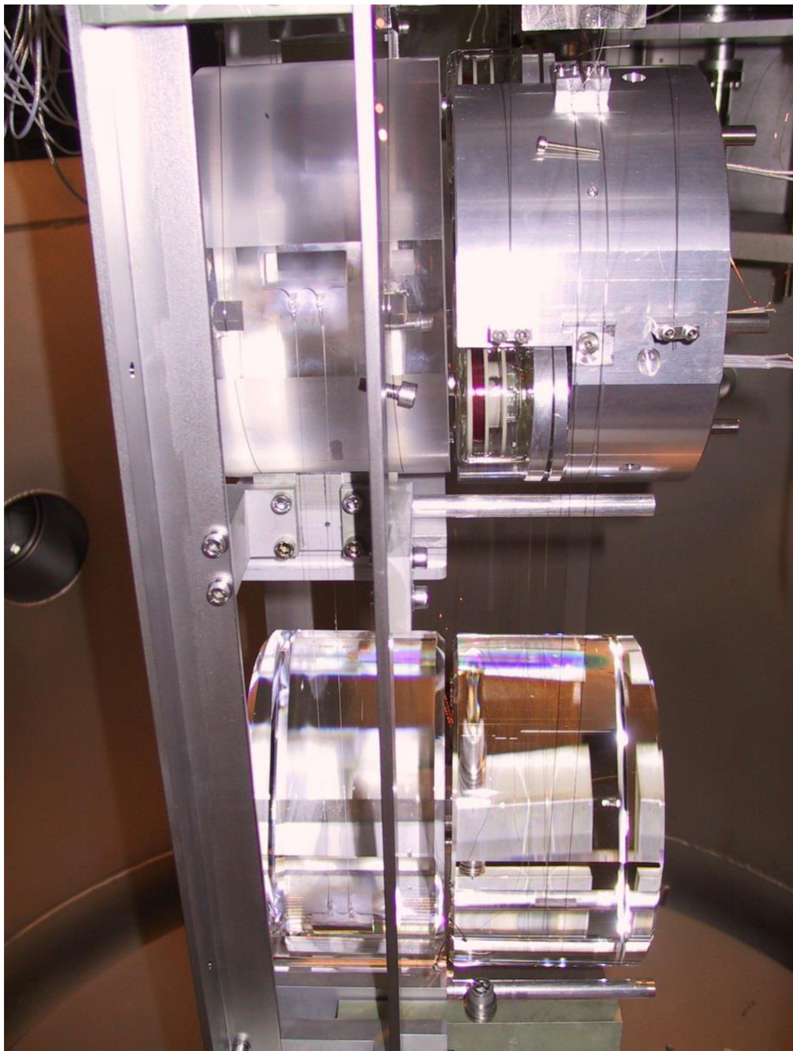
# Virgo’s Free falling test masses

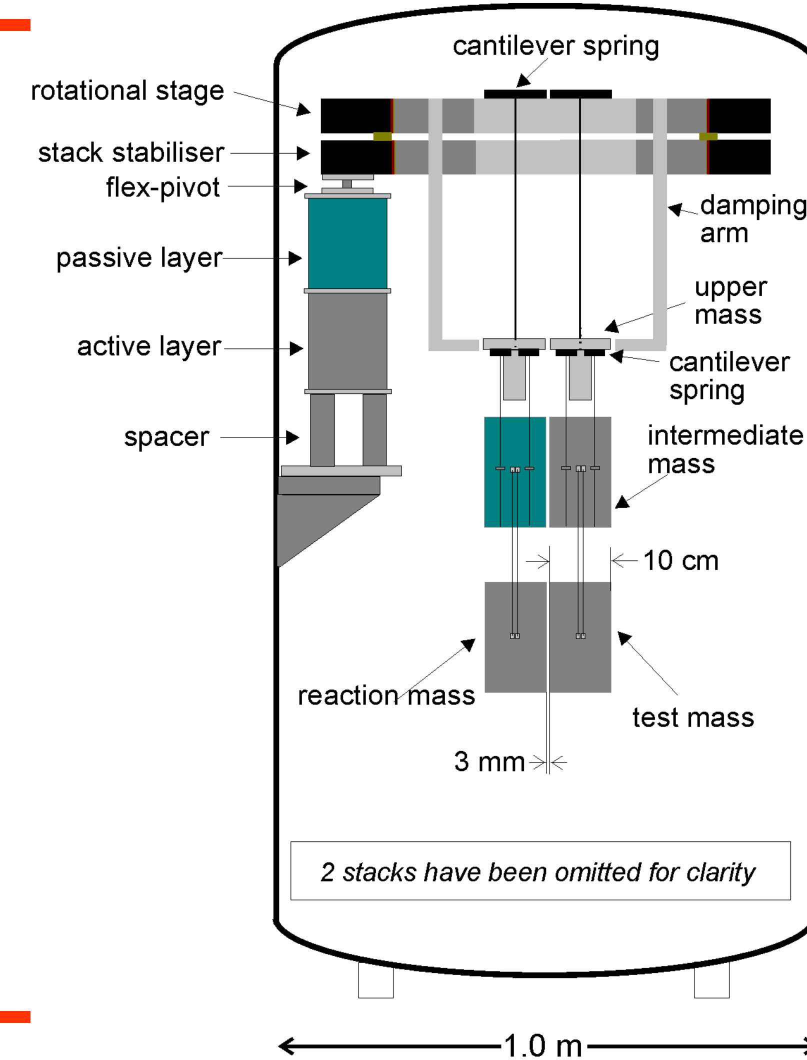


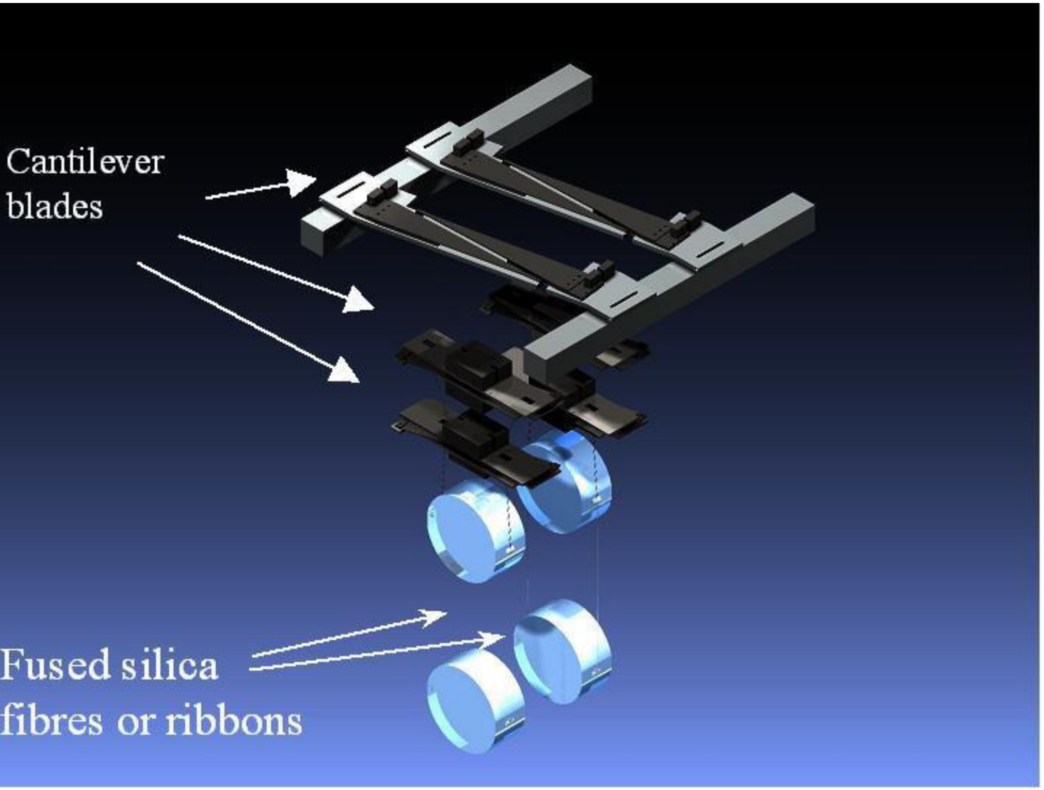



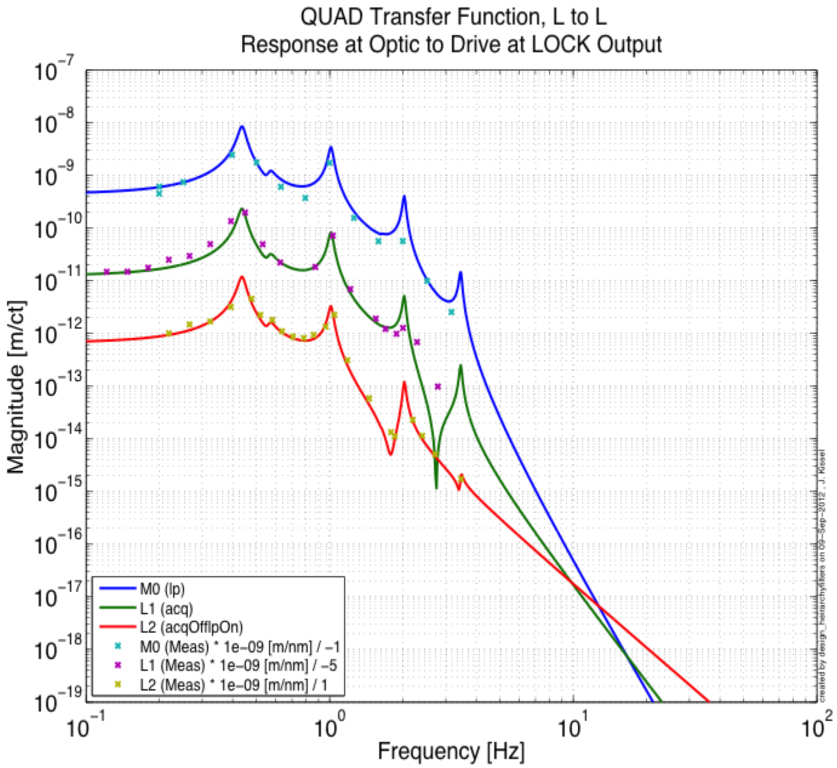
# GEO600 Reaction Pendulum





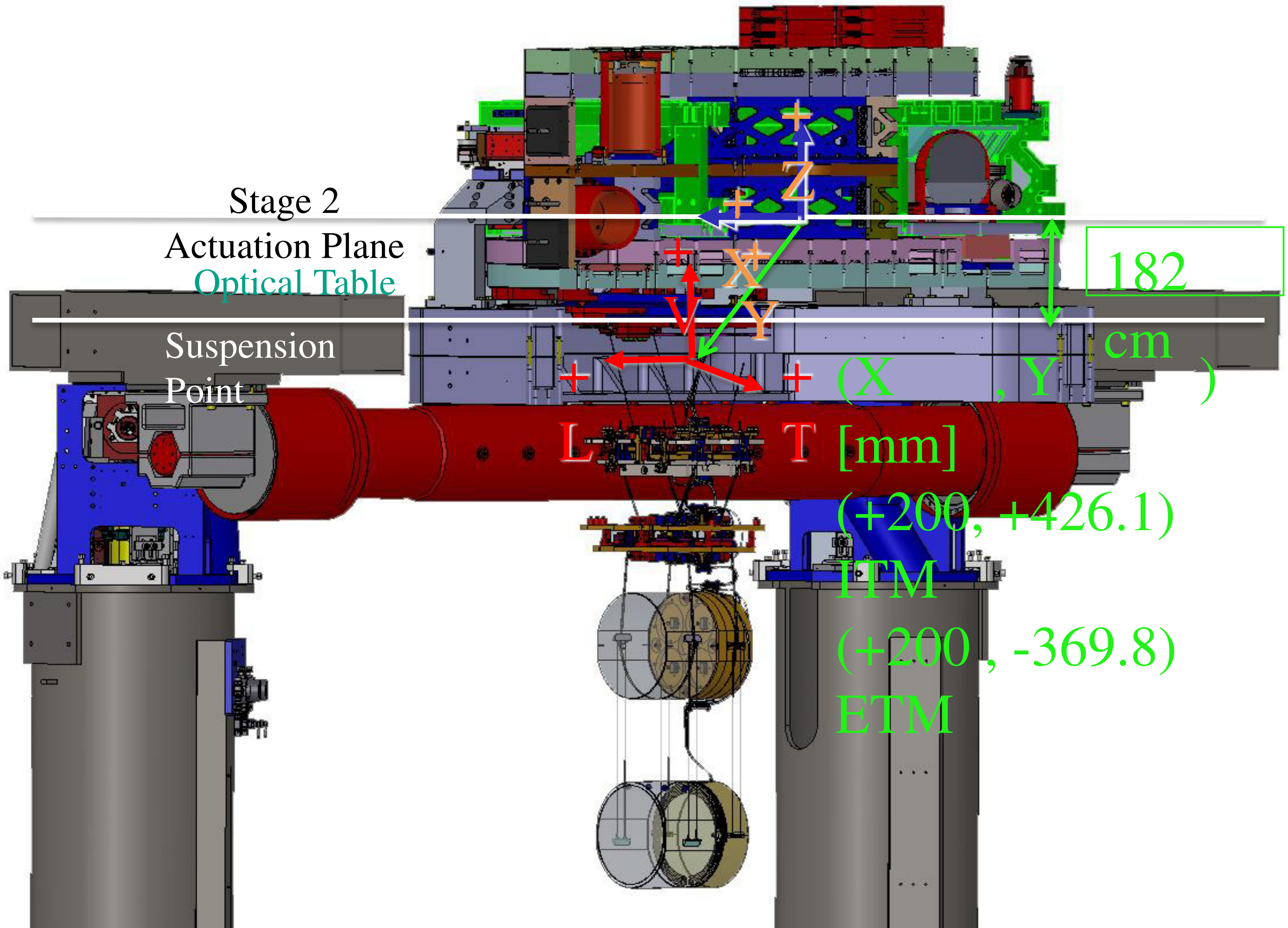
# aLIGO suspension




aLIGO req't: seismic noise is negligible above 10 Hz.

# aLIGO also has active isolation (more on this later this week)



# Newtonian gravitational noise

Fluctuating density of the ground near the test masses causes gravitational force noise.

It is like coupling the test masses to the ground through a spring of resonant frequency

$$f_{grav} = \frac{1}{2\pi}\sqrt{G\rho_{earth}}.$$

This is a low frequency (below $10^{-4}$ Hz), but is only like one isolation stage.

Net effect is un-isolatable noise that is stronger than seismic noise below about 3 Hz.

(Perhaps can measure seismic field, model this noise, and subtract …)

# The case for space

The best seismic isolators are still low-pass filters, admitting all seismic noise below a few Hz.

Even if you work hard on direct isolation, there will always be the Newtonian noise.

- N.B. There are some ideas for measuring the seismic noise at many places around each mass, computing the Newtonian noise, and subtracting it.

Why not get away from it all, in space?

A good idea. A little more about proposed space missions on Friday afternoon.