Suspended Mass Interferometry: Accomplishing the Impossible

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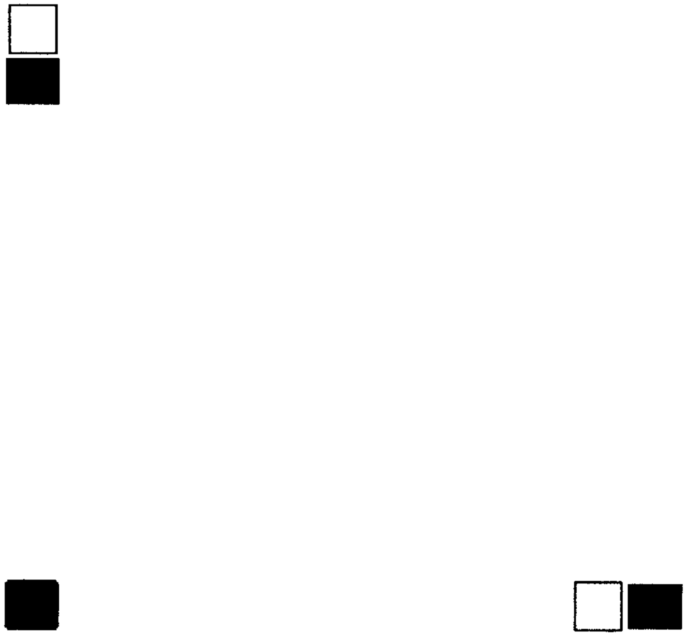
Outline

1. Is LIGO attempting the impossible?
2. What is hard about suspended mass interferometry at the 10^{-21} level?
3. How is the impossible being accomplished by LIGO?

The Challenge:



To measure motion of free masses with a strain amplitude of only 10^{-21} (or less.)

Einstein and tests of G.R.

- Classic tests:
  - Precession of Mercury's orbit: already seen
  - Deflection of starlight: ~1 arcsec, O.K.
  - Gravitational redshift in a star: ~10^{-6}, doable.
- Possible future test:
  - dragging of inertial frames, 42 marcsec/yr, Einstein considered possibly feasible in future
- Gravitational waves: no comment!

Why Einstein should have worried about g.w. detection

He knew about binary stars, but not about neutron stars or black holes.

His paradigm of measuring instruments:

- interferometer ($x_{rms} \sim \lambda/20$, $h_{rms} \sim 10^{-9}$)
- galvanometer ($\theta_{rms} \sim 10^{-6}$ rad.)

Gap between experimental sensitivity and any conceivable wave amplitude was huge!

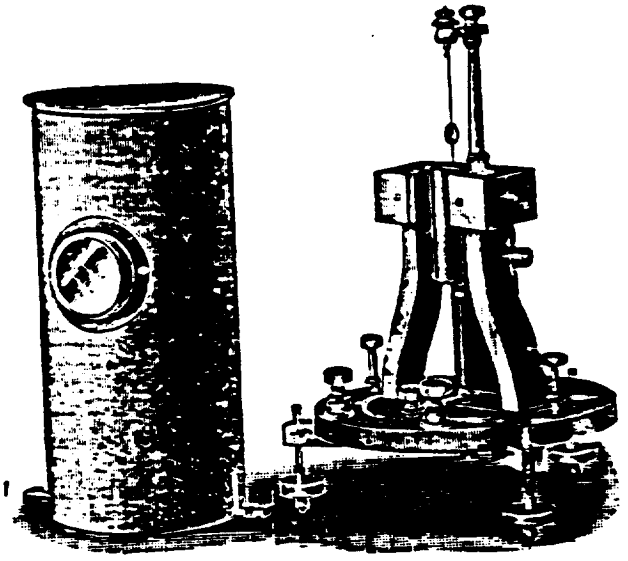
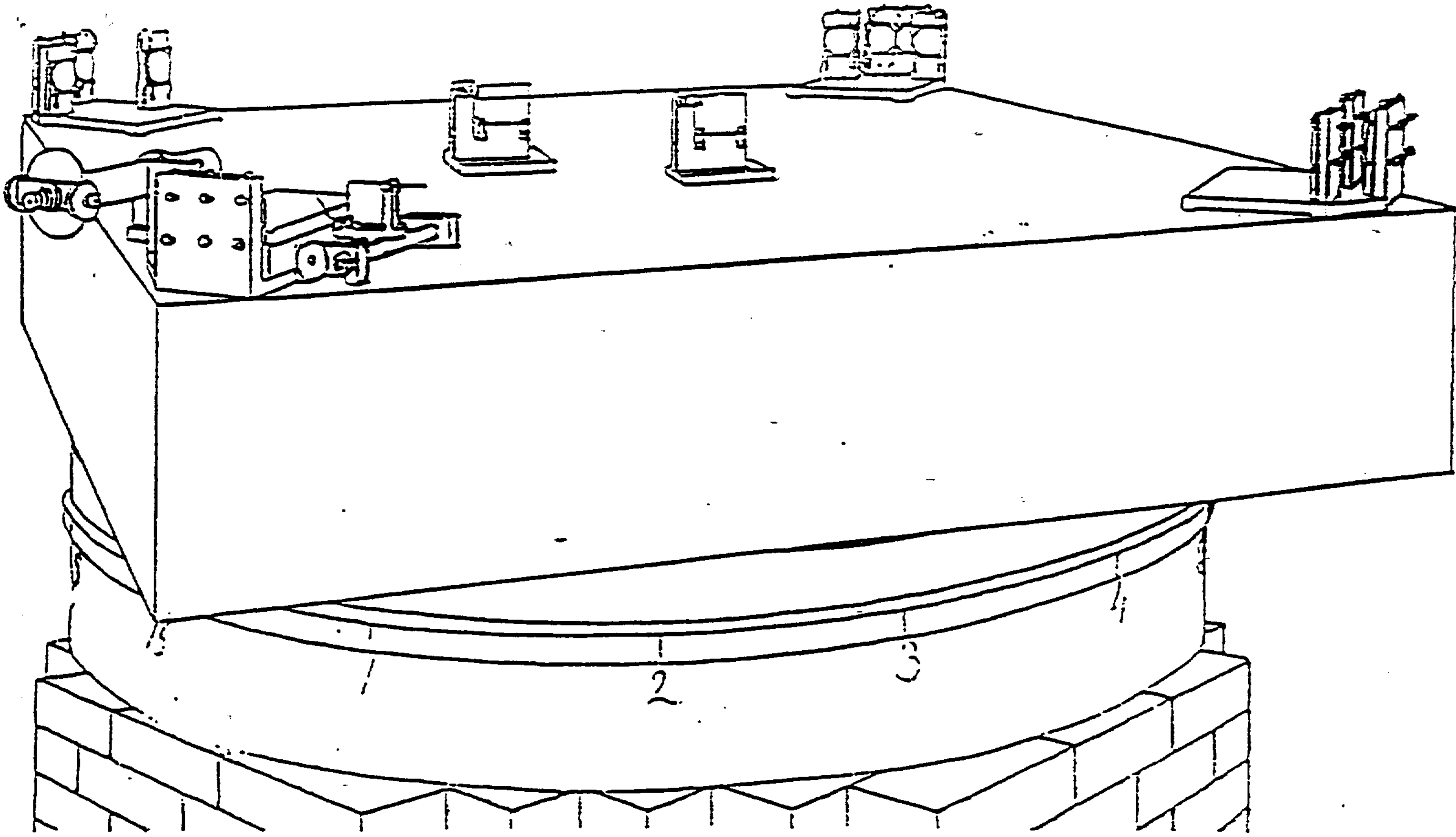


FIG. 56.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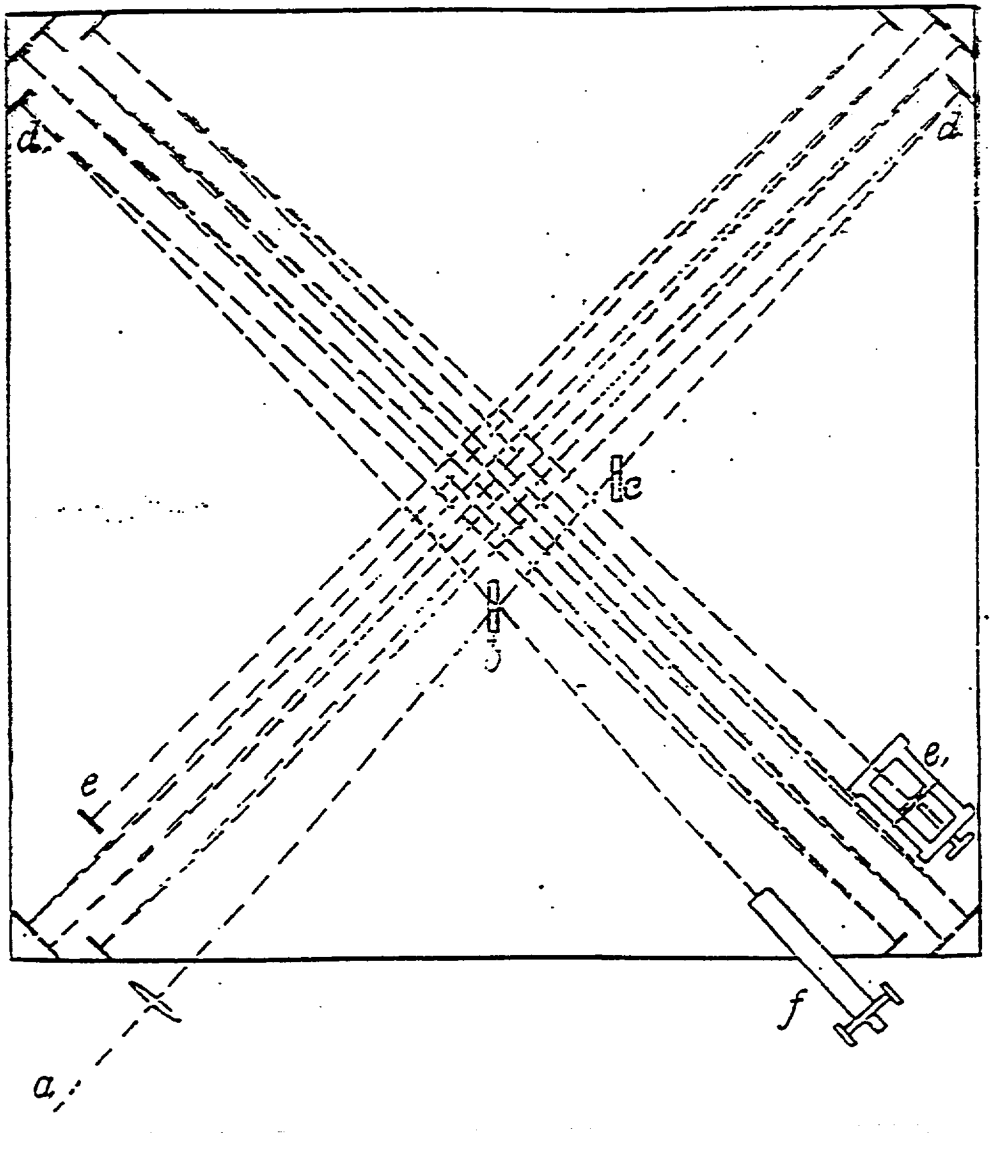
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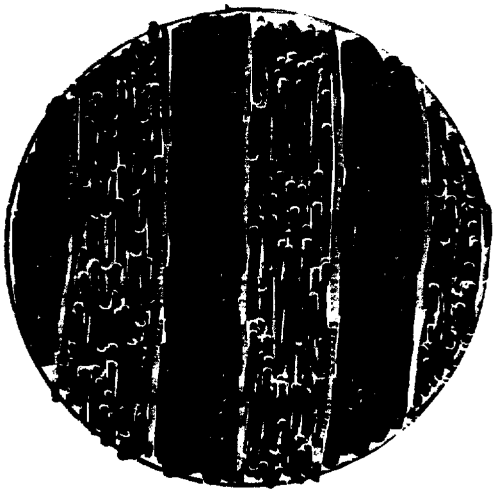
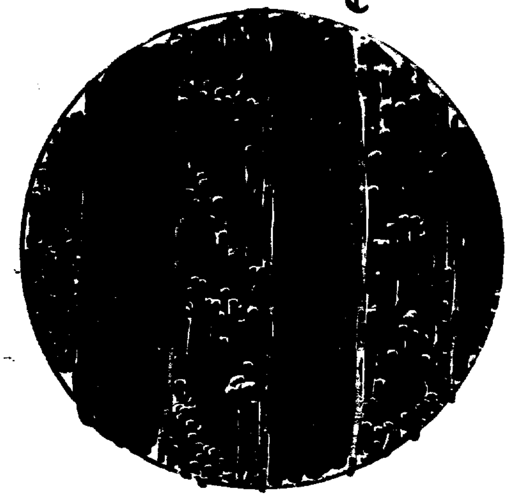
Misaligned Beams: "Fringes"



↑
Relative shift of 0.5 λ
↓



Expected shift: 0.4 λ
Michelson's sensitivity: 0.025–0.05 λ

Noted modern experts thought it was impossible

1. The Relative Motions of Two Freely Falling Bodies

As a gravitational wave passes two freely falling bodies, their proper separation oscillates (Figure 37.3). This produces corresponding oscillations in the redshift and round-trip travel times for electromagnetic signals propagating back and forth between the two bodies. Either effect, oscillating redshift or oscillating travel time, could be used in principle to detect the passage of the waves. Examples of such detectors are the Earth-Moon separation, as monitored by laser ranging [Fig. 37.2(a)]; Earth-spacecraft separations as monitored by radio ranging; and the separation between two test masses in an Earth-orbiting laboratory, as monitored by redshift measurements or by laser interferometry. Several features of such detectors are explored in exercises 37.6 and 37.7. As shown in exercise 37.7, such detectors have so low a sensitivity that they are of little experimental interest.

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Gravitational wave detection is almost impossible

What is required for LIGO to succeed:

- interferometry with free masses,
- with strain sensitivity of 10^{-21} (or better!),
- equivalent to ultra-subnuclear position sensitivity,
- in the presence of much larger noise.

How has the impossible been made possible?

OEK-STD Series

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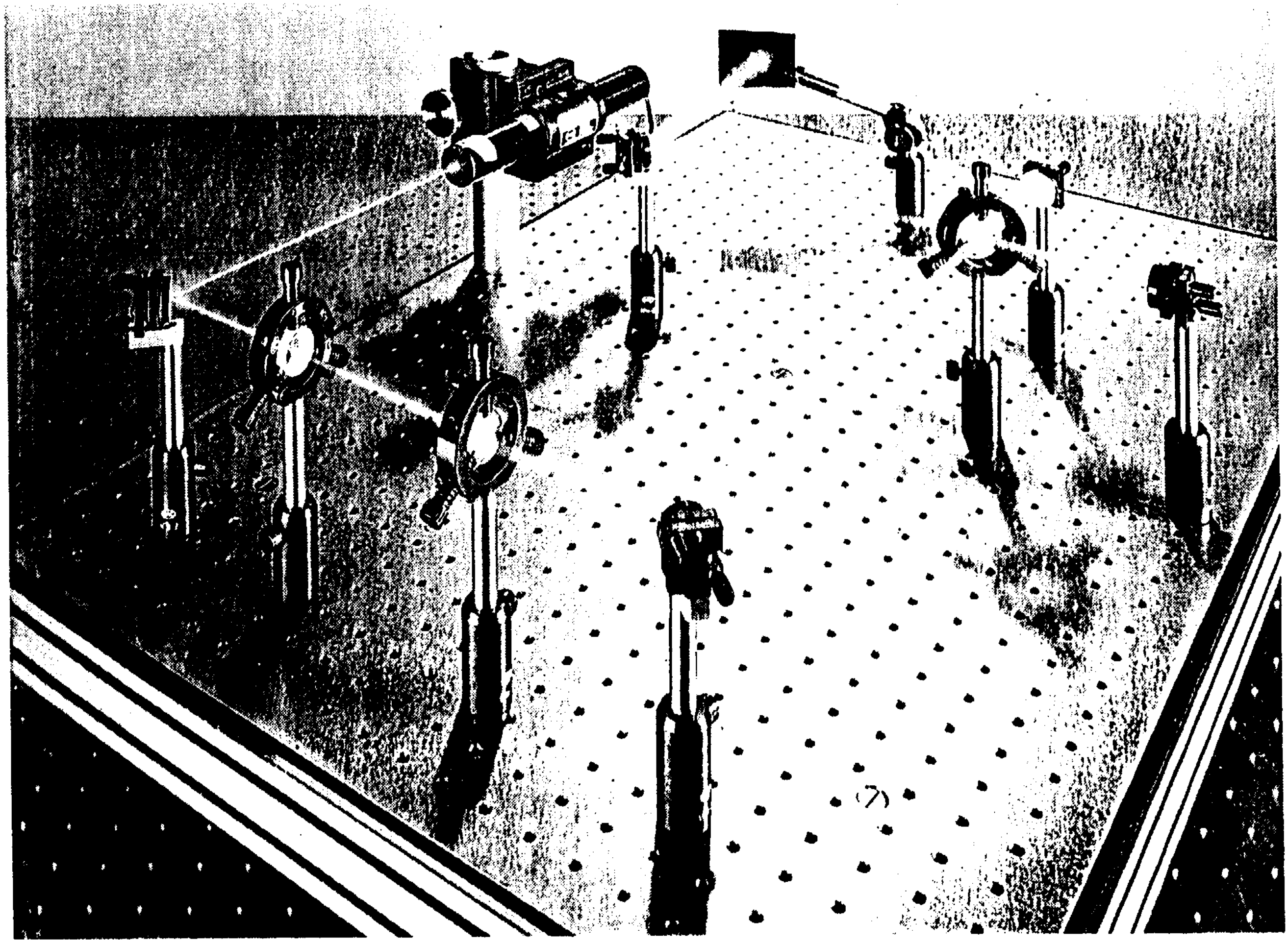

Project #6: Building a Michelson interferometer.

Projects in Optics is a self-paced

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Interferometry with free masses

What's impossible: everything!

Mirrors need to be very accurately aligned (so that beams overlap and interfere) and held very close to an operating point (so that output is a linear function of input.)

Otherwise, interferometer is dead or swinging thru fringes.

Michelson bolted everything down.

Interferometry with free masses

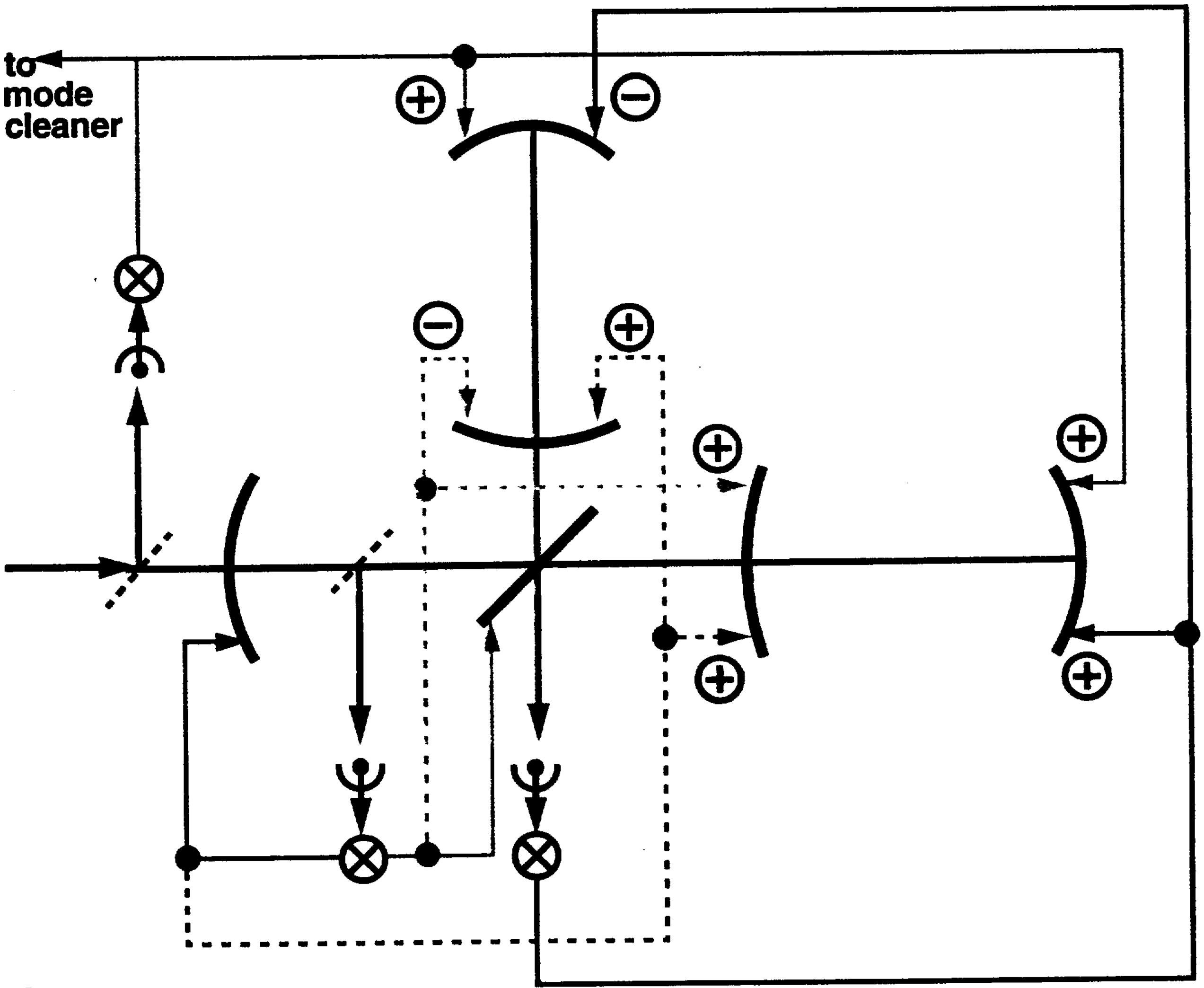
How it became possible:

Servos

- let mirrors swing freely on pendulum suspensions (at high frequencies),
- while keeping them aimed properly and at the right interferometric operating point (at low frequencies.)

LIGO has dozens of servo loops.

CONTROL TOPOLOGY



$S_{AQ} \longrightarrow$ ETM$_1$−ETM$_2$

$S_{RI} \longrightarrow$ ETM$_1$+ETM$_2$

$S_{PI} \longrightarrow$ RM $\dashrightarrow$ ITM$_1$+ITM$_2$
damping
$S_{PQ} \longrightarrow$ BS $\dashrightarrow$ ITM$_1$−ITM$_2$

Strain sensitivity of 10^{-21}

Why it is impossible: $h_{rms} \sim \dfrac{\Delta\lambda}{L_{opt}}$.

Natural “tick mark” on interferometric ruler is one wavelength.

Michelson achieved $\lambda/20$, or h_{rms} of a few times 10^{-9}.

Strain sensitivity of 10^{-21}

How it became possible: Make L_{opt} long.

LIGO has 4 km long arms.

L_{opt} is even longer, since light is stored for multiple round trips through the arms, which have the form of Fabry-Perot cavities.

Strain sensitivity of 10^{-21}

How it became possible: Make $\Delta\lambda$ small.

Don't rely on eye to judge sideways motion of interference fringes.

Align beams, so that entire spot varies in brightness together.

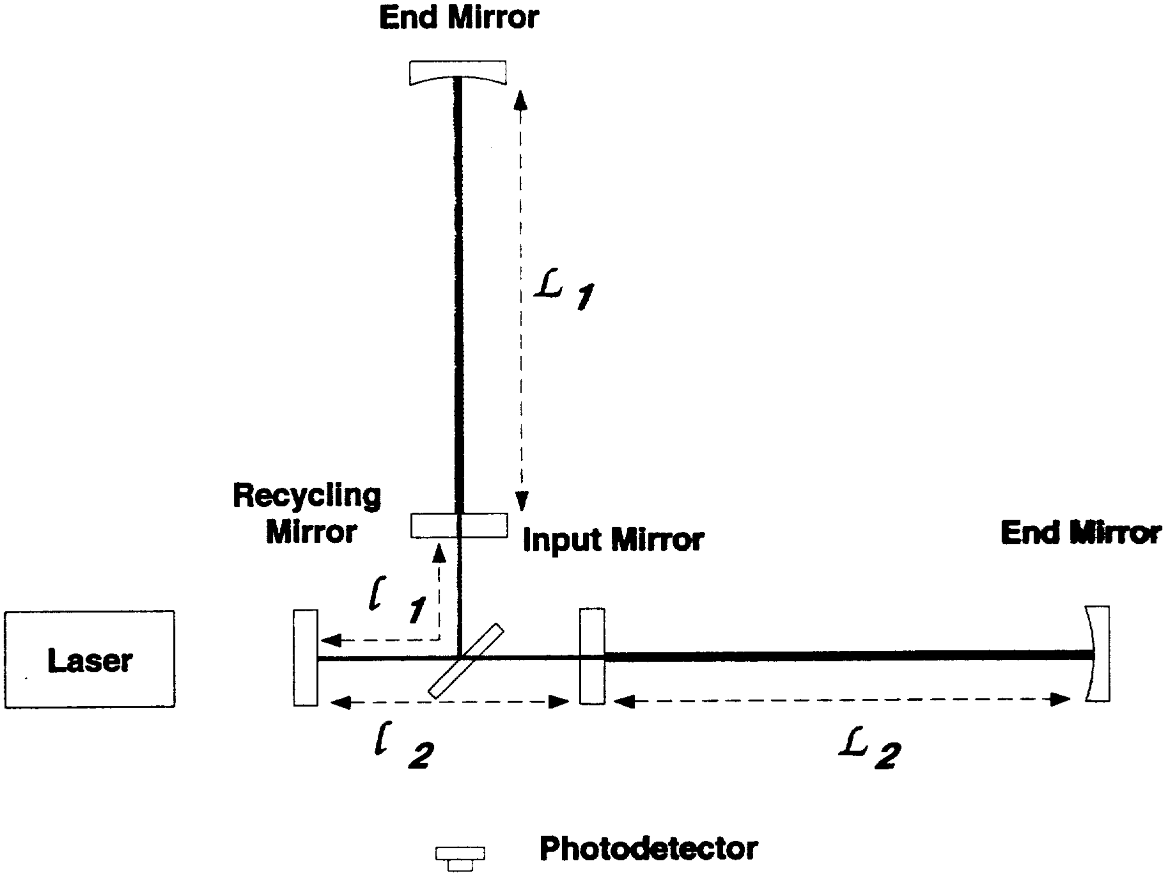
Then, interference is judged by a power measurement, and can be shot noise limited.

Strain sensitivity of 10^{-21}

How it became possible: Make $\Delta\lambda$ small.

Minimize shot noise by using lots of light. LIGO uses a 10 W Nd:YAG laser.

Low-loss optics, dark-fringe operating point, let most light survive passage through the interferometer. Recycle that power, for even lower shot noise.


End Mirror
$\mathcal{L}_1$
Recycling Mirror
Input Mirror
End Mirror
l_1
Laser
l_2
$\mathcal{L}_2$
Photodetector

Ultra-subnuclear position sensitivity

Why people thought it was impossible:

- Mirrors made of atoms, 10^{-10} m.
- Mirror surfaces rough on atomic scale.
- Atoms jitter by large amounts.

Ultra-subnuclear position sensitivity

Why it is possible nevertheless:

We don't look at atoms; laser beam samples many cm^2 of mirror surface, ~ 10^{17} atoms.

We don't see atomic jitter either, but coherent motion of mirror surfaces (which is bad enough but not as bad as atom-scale motion.)

Precision better than 10^{-18} m is possible.

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.

Large mechanical noise

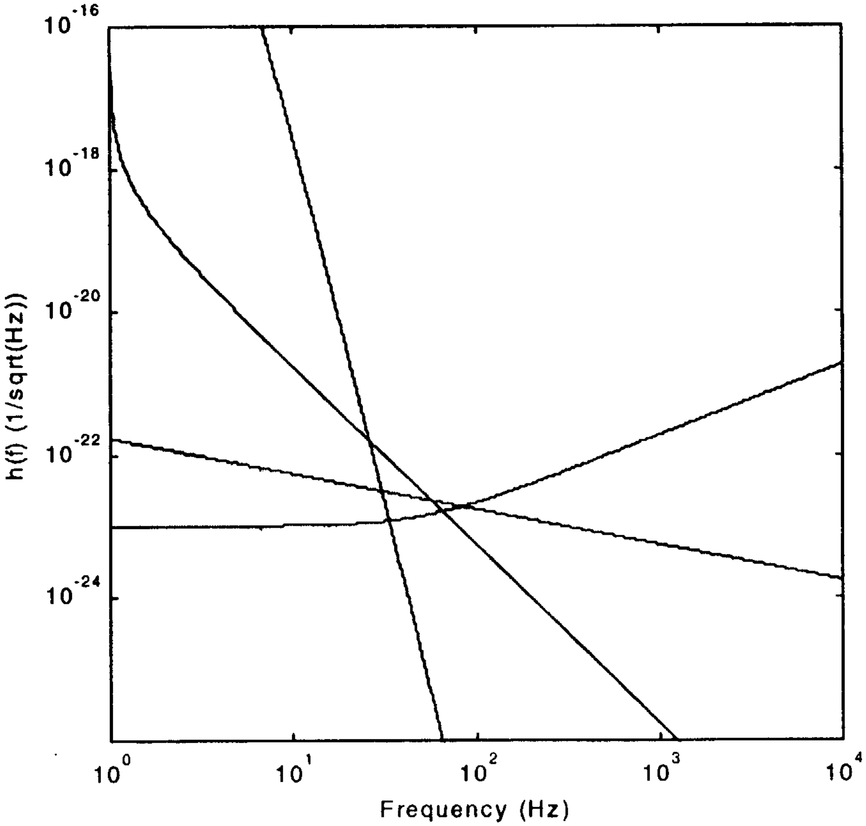
How measurement will succeed nevertheless:

Noise is strongly frequency dependent:

- seismic noise falls with frequency, especially after passing through isolators, and
- thermal noise is peaked at resonances, especially when Q's are high.

Fringe lock servo holds interferometer at operating point, ensuring the linearity necessary for filtering.

Noise spectrum



Finding small signals in large noise

Why it is impossible:

Everyone knows you need a signal-to-noise ratio much larger than unity to detect a signal.

Finding small signals in large noise

Why it is possible nevertheless:

As long as the signal has different spectral character than the noise, then matched filtering can preferentially reject noise.

We use this

- in a crude way to reject low freq seismic noise,
- in a refined way to hunt for precisely known waveforms of, e.g., coalescing binaries.

LIGO is a *tour de force*

Collectively, our wizardry is in the process of producing a marvel of measurement technique.

Today, we should take pride in what we have accomplished so far.

In the coming years, we should be proud to struggle with the challenges yet to come.