1. Overview of gravitational waves and detectors (Waves and sources)

Peter Saulson

Syracuse University

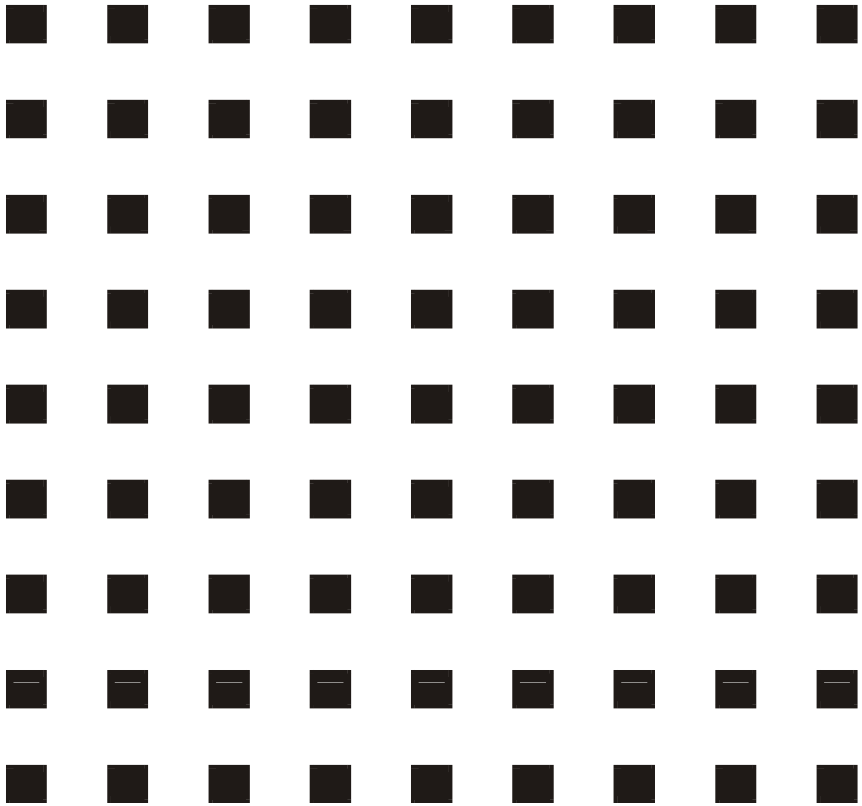
My lectures during this School

1. **Overview of gravitational waves and sources**
2. Interactions of waves and detectors
3. Shot noise and radiation pressure noise
4. Theory of linear systems
5. Vibration isolation (passive)
6. Thermal noise
7. Optics of Fabry-Perot cavities
8. Feedback control systems
9. Description of LIGO and other current detectors
10. Future detectors in space

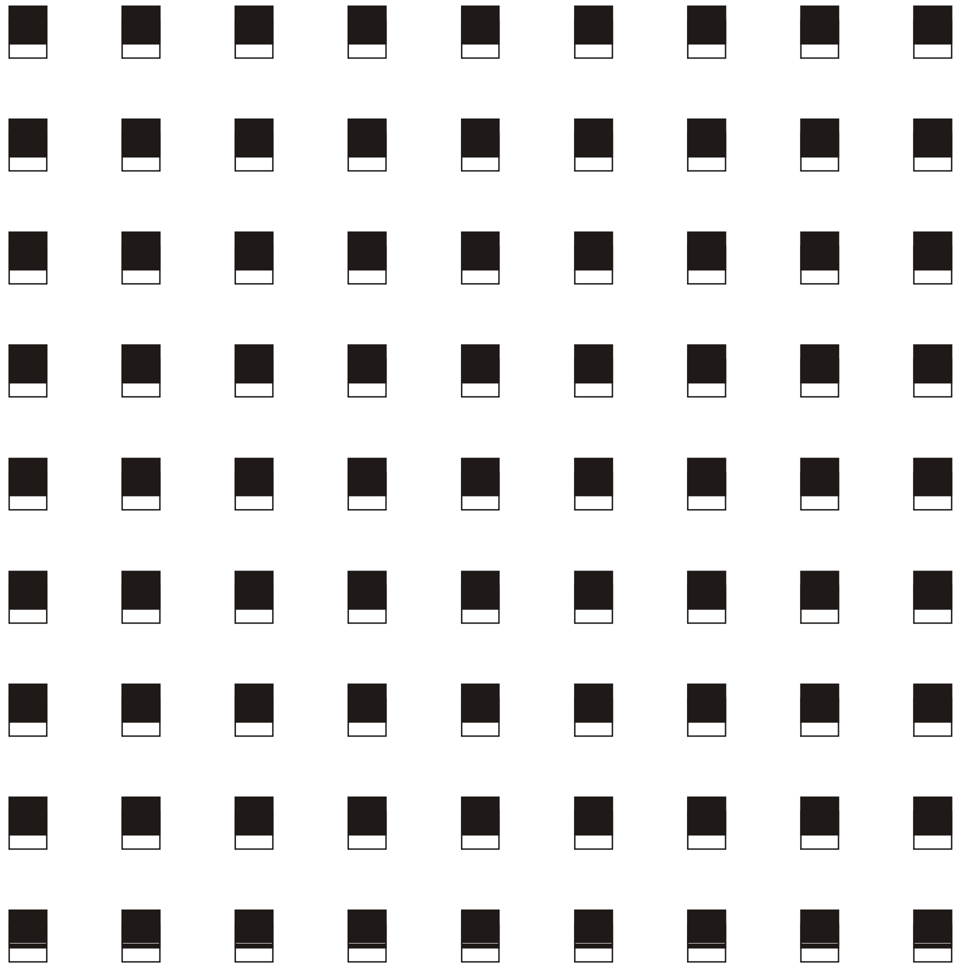
Outline of this lecture

- What is a gravitational wave?
- What sources make gravitational waves?
- What is a gravitational wave detector?
- Why is gravitational wave detection hard?

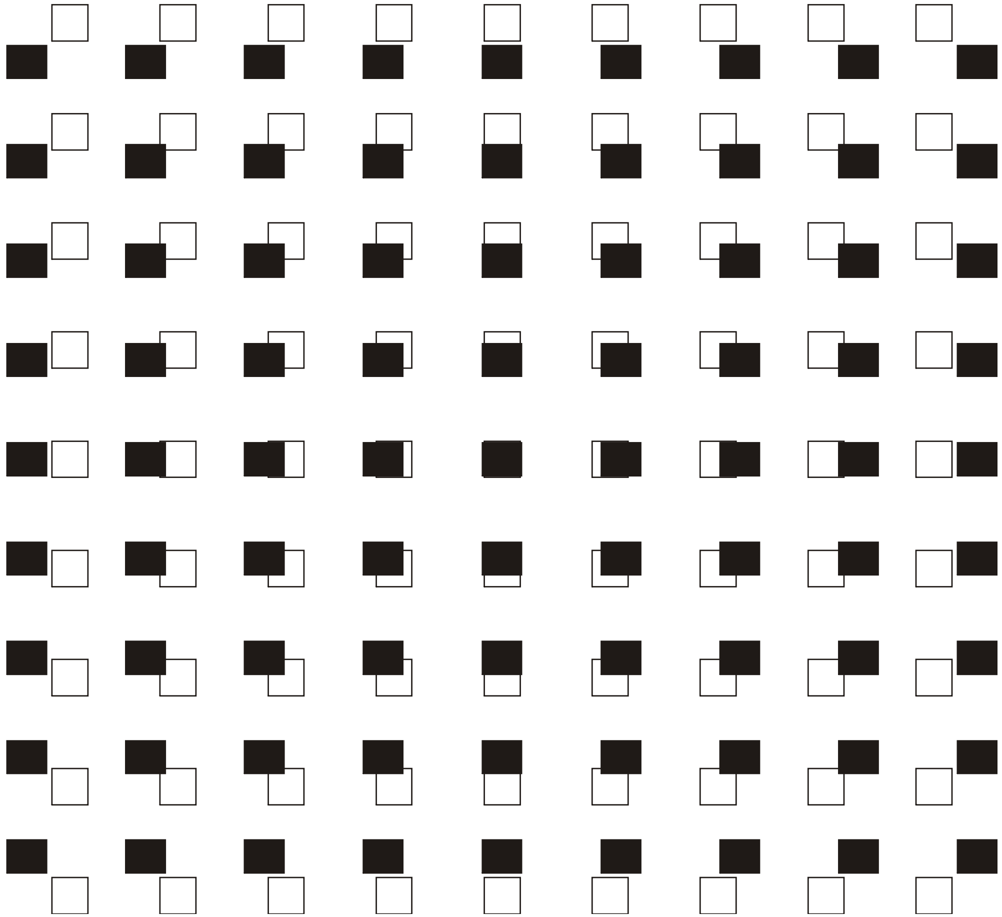
A set of freely-falling test particles



Electromagnetic wave moves charged test bodies

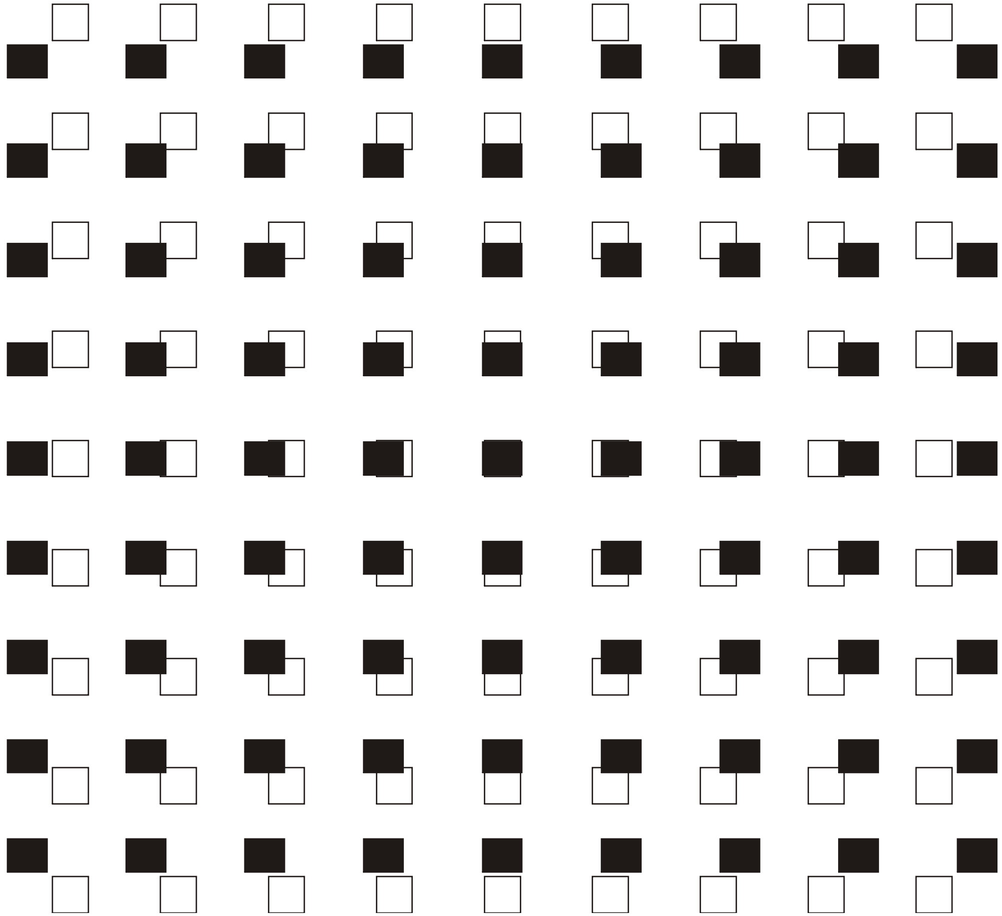


Gravity wave: distorts set of test masses in transverse directions



Gravitational wave:
a transverse quadrupolar strain

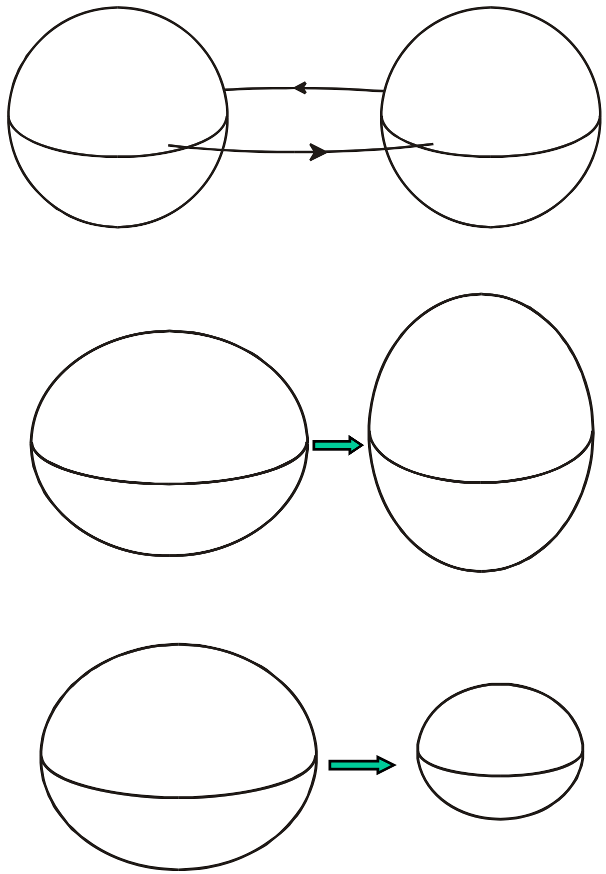
strain amplitude:
$h = 2\Delta L/L$



Comparison table, EM vs GW

charge	mass
E and B fields	h = shear strain
c	c
Maxwell 1867	Einstein 1916
Hertz 1886-91	?
pretty strong	very weak

Transmitters of gravitational waves: solar mass objects changing their quadrupole moments on msec time scales



Gravitational waveform lets you read out source dynamics

The evolution of the mass distribution can be read out from the gravitational waveform:

$$h_{\mu\nu}(t) = \frac{1}{R}\frac{2G}{c^4}\ddot{I}_{\mu\nu}(t - R/c)$$

Coherent relativistic motion of large masses can be directly observed from the waveform!

$$I_{\mu\nu} \equiv \int dV\left(x_\mu x_\nu - \delta_{\mu\nu} r^2/3\right)\rho(r).$$

Why not a Hertz experiment?

Hertz set up the first radio transmitter and receiver, on opposite sides of a room.

Two 1-ton masses, separated by 2 meters, spun at 1 kHz, has

$$\ddot{I} = 1.6 \times 10^{11} \text{ kg m}^2\text{s}^{-2}.$$

At distance of 1 $\lambda = 300$ km,

$$h = 9 \times 10^{-39}.$$

Not very strong.

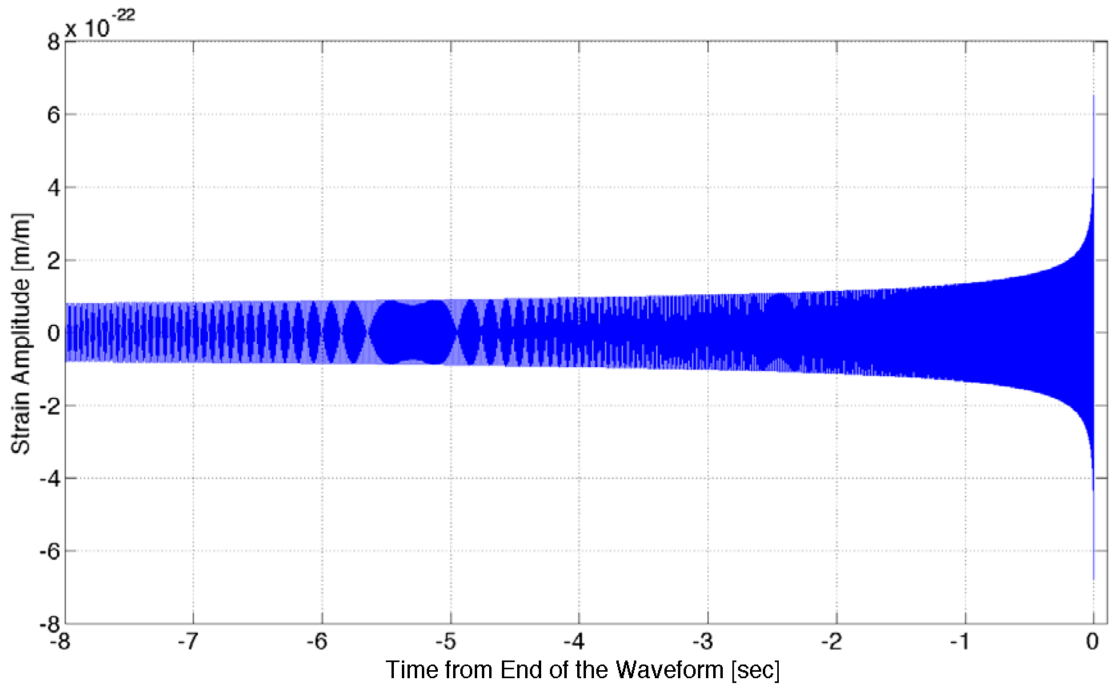
Binary stars made of neutron stars or black holes

Binary systems have a quadrupole moment that is easy to calculate.

Neutron star binaries are known to exist, and to be abundant enough for Advanced LIGO to detect.

Black holes: less is known, but many think that they should be visible, too. And, it would be way cool to see them!

A binary inspiral "chirp": amplitude and frequency grow as stars spiral together due to loss of energy



(A lot of deep physics is encoded in this waveform. Bala is one of the main people who has worked this out.)

Binary signal strength estimate

For a binary star,

$$h = r/R,$$

where

R = distance to source, and

$r = r_{S1} r_{S2}/a$, with

$r_{S1,2}$ Schwarzschild radii of the stars,

and a is their separation.

Often, r ~ 1 km (black hole binary).

At Virgo Cluster, $R \sim 10^{21}$ km.

Hence, expect $h \sim 10^{-21}$

(on msec time scales!)

Other sources

- Stellar core collapse (supernova)
  - forms a dense proto-neutron star. Physics poorly known, but signal is expected to be weak.
- Rotating neutron stars:
  - Must be out of round, but by how much?
- Space-time fluctuations in the early universe:
  - Will form a stochastic background from the Planck era. Not sure of the physics, but could be the most interesting discovery of all!

Gravity wave detectors

Need:

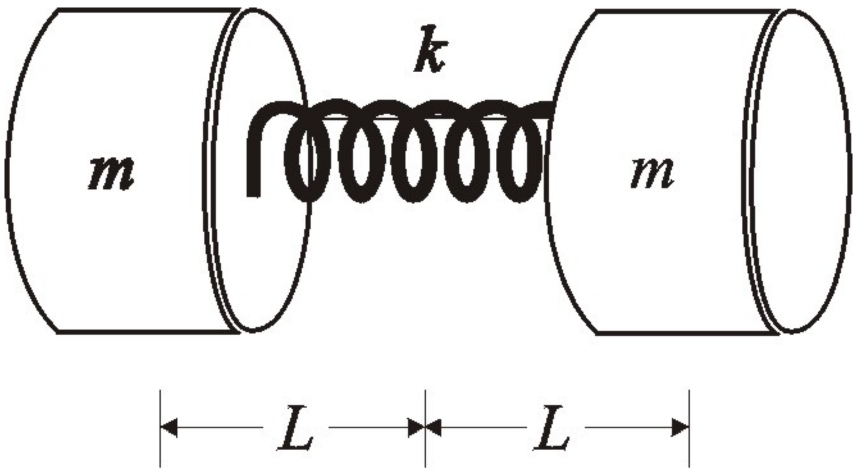
- A set of test masses,
- Instrumentation sufficient to see tiny motions,
- Isolation from other causes of motions.

Challenge:

Best astrophysical estimates predict fractional separation changes of only 1 part in 10^{21}, or less.

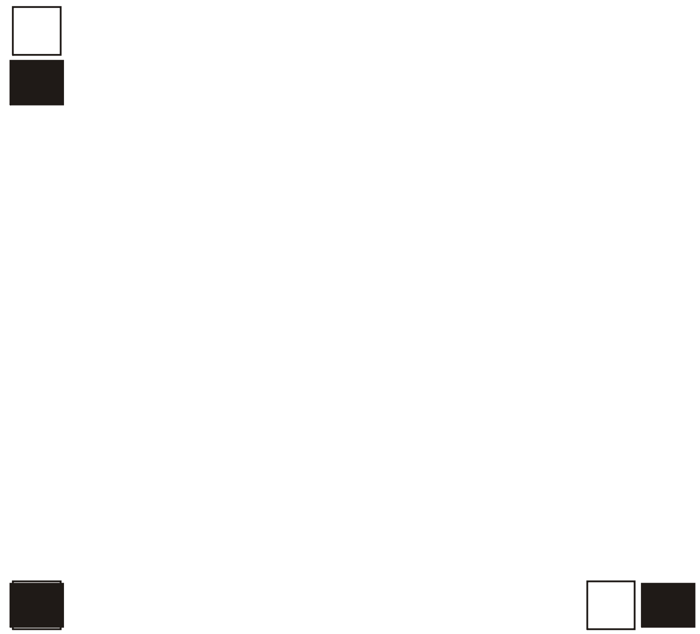
Resonant detector (or “Weber bar”)

A massive (aluminum) cylinder. Vibrating in its gravest longitudinal mode, its two ends are like two test masses connected by a spring.



Cooled by liquid He, rms sensitivity at/below 10^{-18}.

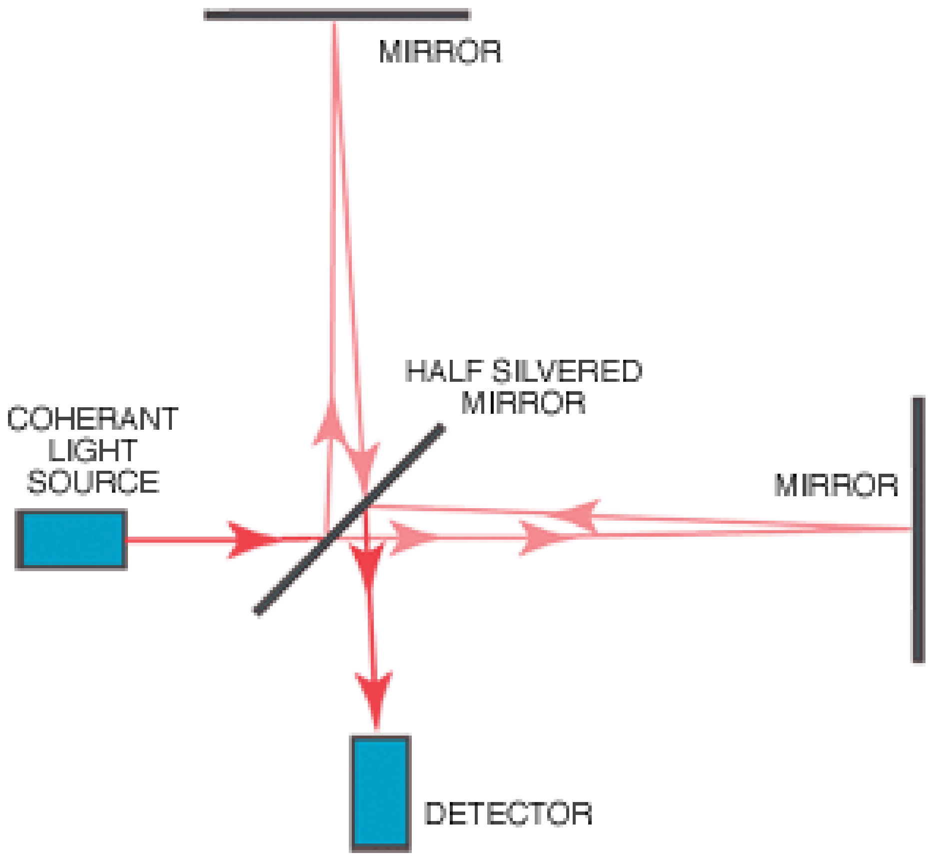
A more modern detection strategy



Tidal character of wave argues for test masses as far apart as practicable. Perhaps masses hung as pendulums, kilometers apart.

Sensing relative motions of distant free masses

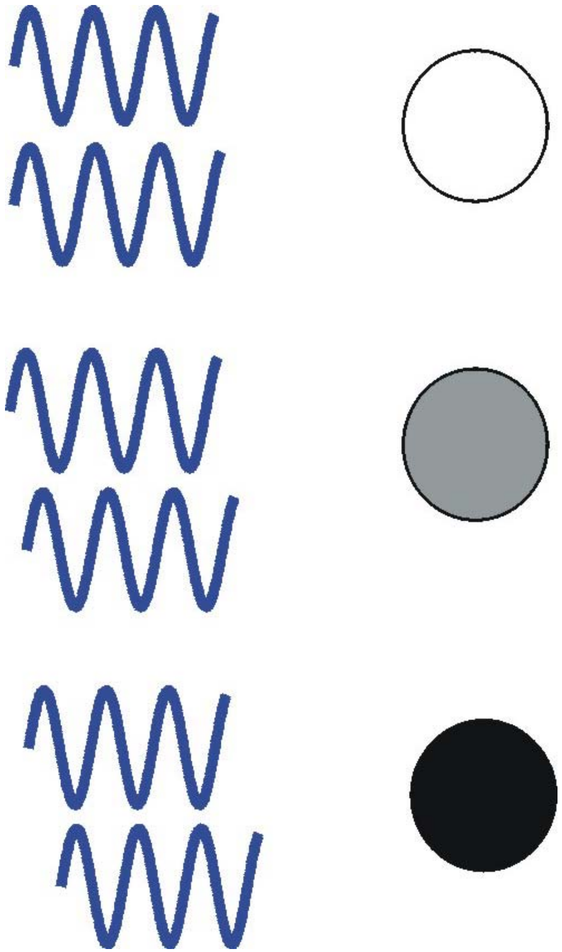
Michelson interferometer



A length-difference-to-brightness transducer

Wave from x arm.

Wave from y arm.



Light exiting from beam splitter.

As relative arm lengths change, interference causes change in brightness at output.

Laser Interferometer Gravitational Wave Observatory

4-km Michelson interferometers, with mirrors on pendulum suspensions, at Livingston LA and Hanford WA.

Initial LIGO had $h_{rms} \sim 10^{-21}$.

Advanced LIGO will be 10x more sensitive.

Other large interferometers

- Virgo (Italy, France, etc.) 3 km

  Advanced Virgo upgrade now under way; will be almost as sensitive as Advanced LIGO, almost as soon.

- GEO (Germany, Britain), 600 m

  Now studying squeezing and doing some "astrowatch" observing. Will continue upgrades through the advanced detector era.

- KAGRA (Japan), 3 km

  Underground cryogenic detector, now under construction.

- and, LIGO-India, 4 km !

Gravity wave detection: challenge and promise

Challenges of gravity wave detection appear so great as to make success seem almost impossible.

The challenges are real, but are being overcome.

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!),
- (which is equivalent to ultra-subnuclear position sensitivity),
- in the presence of much larger noise.

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 through fringes.

Michelson bolted everything down.

Strain sensitivity of 10^{-21}

Why it is "impossible":

Sensitivity h_{rms} can be expressed as

$$h_{rms} \sim \frac{\text{precision to which we can compare arm lengths}}{\text{length of arms}}.$$

Natural "tick mark" on interferometric ruler is one wavelength.

Michelson could read a fringe to $\lambda/20$, yielding h_{rms} of a few times 10^{-9}.

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.

Large mechanical noise

How large?

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

Can you filter it enough?

Thermal:

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

No filtering is possible. Can lower the temperature, but by enough?

Gravitational wave detection will succeed very soon

All of these challenges sound impossible.

And yet, all of them can be met.

Detectors of 10^{-21} have been built and run.

Detectors 10 or more times better will start operating in a few years, including in India.

With them, we are just about certain to detect gravitational waves.

This week's goal is to know why we should be confident that this is true.