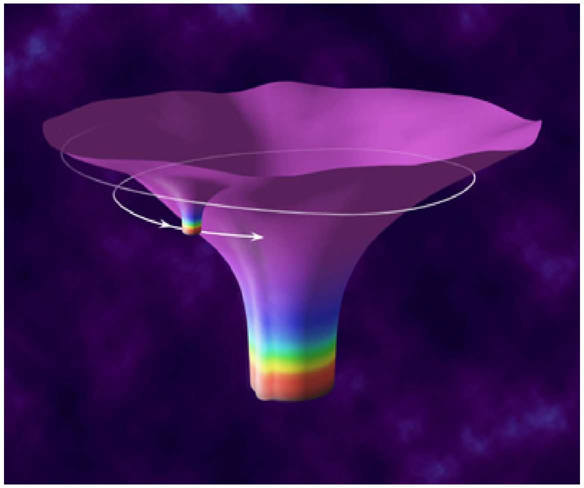
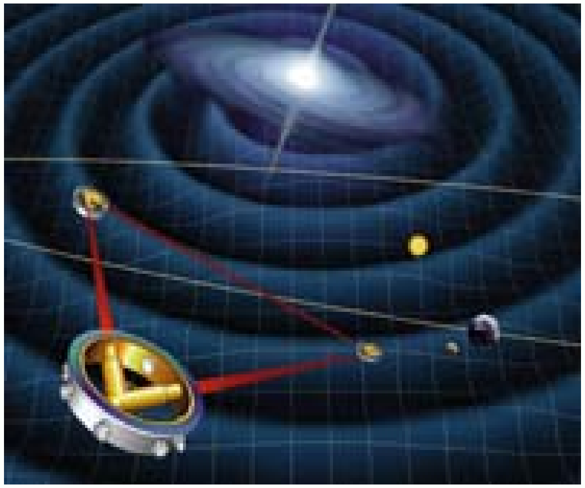
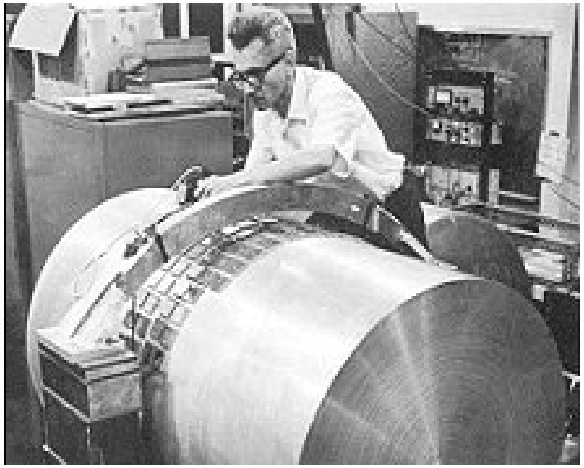
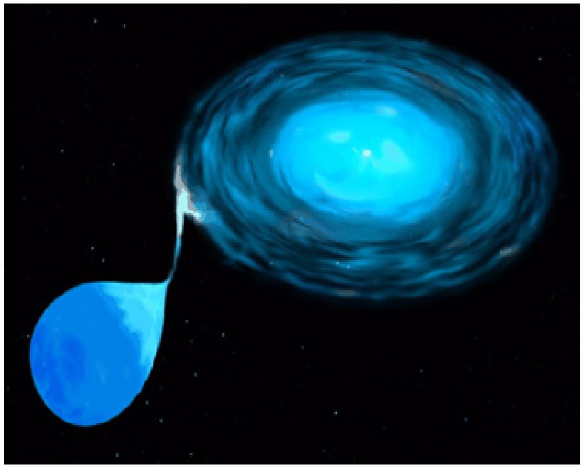
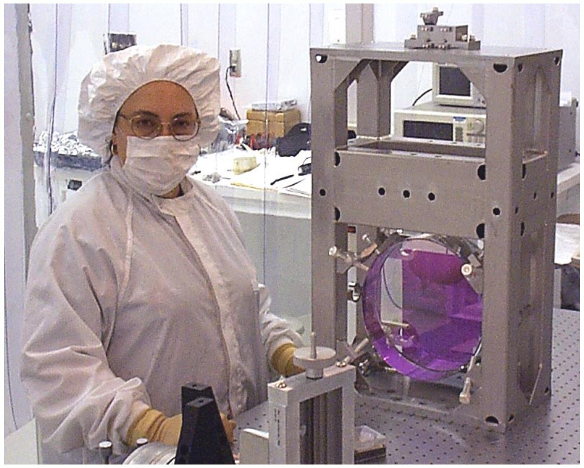
Gravitational Wave Astronomy

Lee Lindblom
California Institute of Technology





Los Angeles Valley College Astronomy Group – 20 May 2007

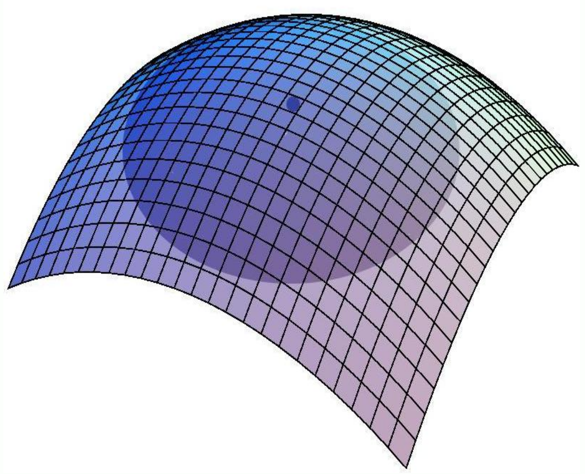
  

- What is Einstein's picture of gravity?
- What are gravitational waves?
- How are gravitational waves detected?
- How are gravitational waves emitted?
- What kinds of objects emit strong gravitational waves?
- Have gravitational waves been detected yet?

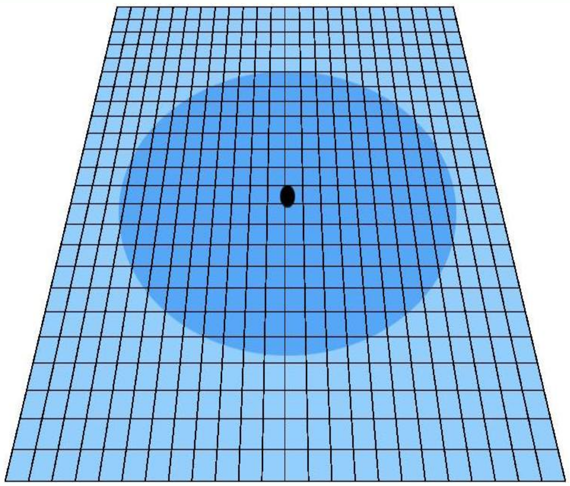
What is Gravity?

- Einstein's Great Idea: Gravity is Geometry. Matter curves the geometry of spacetime. Curved geometry influences the motion of matter.

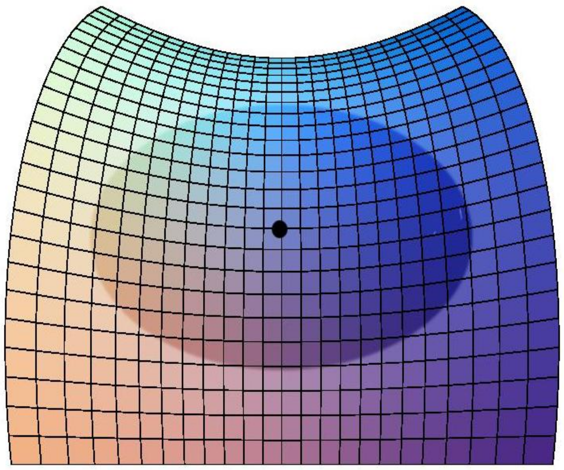
What is Curved Geometry?



$C < 2\pi R$

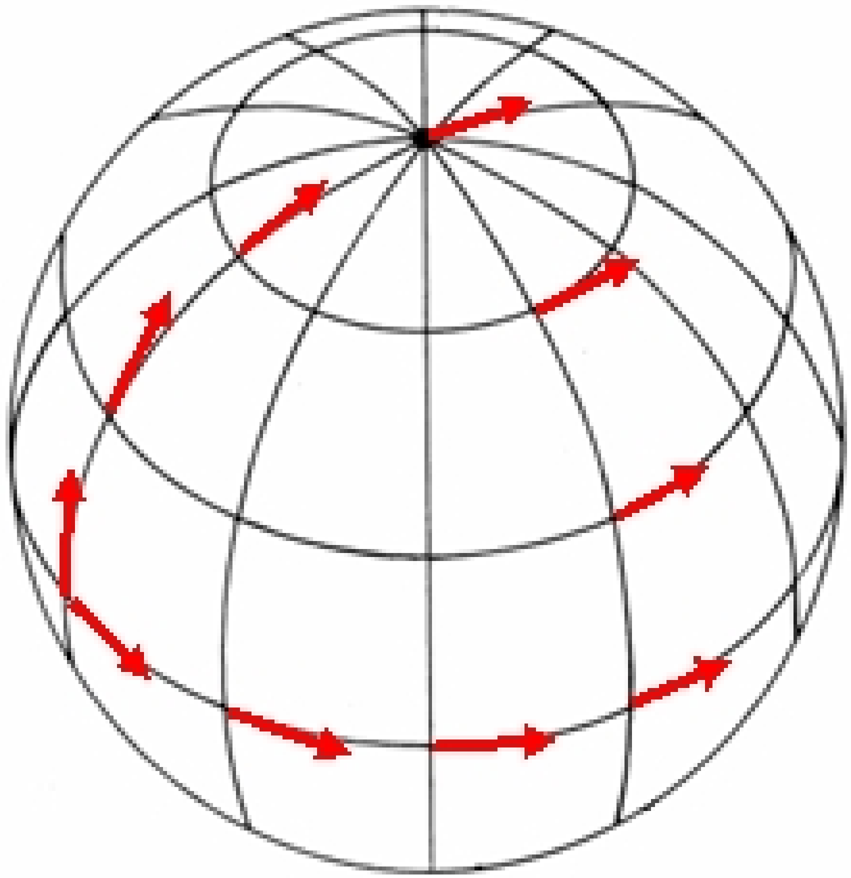


$C = 2\pi R$



$C > 2\pi R$

- The surface of a sphere (like the surface of the earth) is a familiar example of a curved 2-dimensional geometry.
- The sphere is obviously curved when we look at it from the outside.
- Many properties internal to the surface of a sphere also reveal curvature:
  - All parallel straight lines on a sphere intersect.
  - Sum of angles in triangles is always greater than 180 degrees.
  - Parallel transport of arrows causes rotation.



- Einstein’s great idea is that the geometry of space and time are curved and this curvature produces the effects we call gravitation. General Relativity Theory gives the precise mathematical relationship between the density of matter and spacetime curvature.

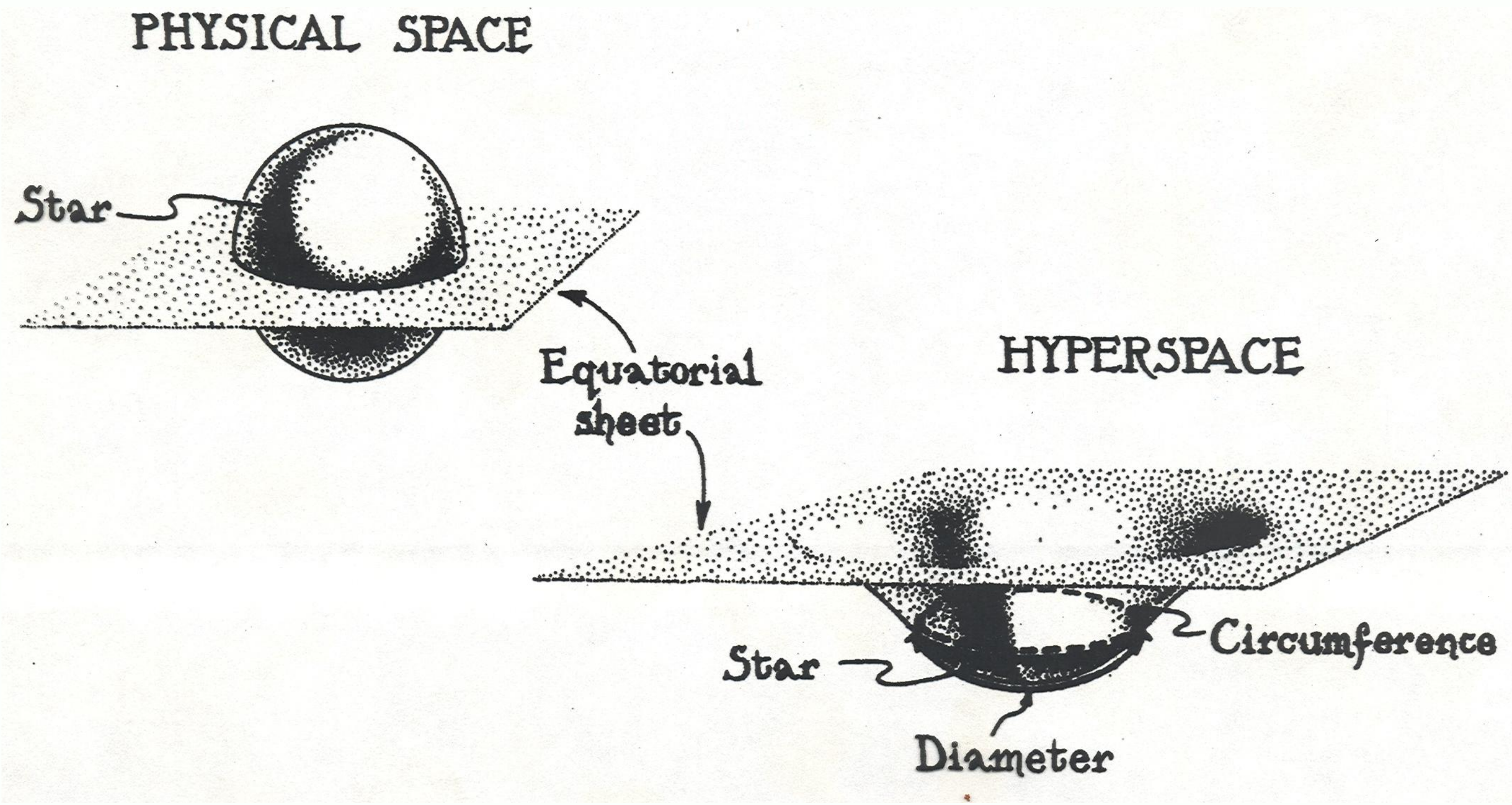


Figure from *Black Holes & Time Warps* by K. S. Thorne

- General Relativity Theory also determines how matter moves through curved spacetime: objects move on the straightest possible paths unless acted on by non-gravitational forces.
- These straightest possible paths, or geodesics, include the orbits of planets around the sun and the deflection of starlight as is passes close to the sun.

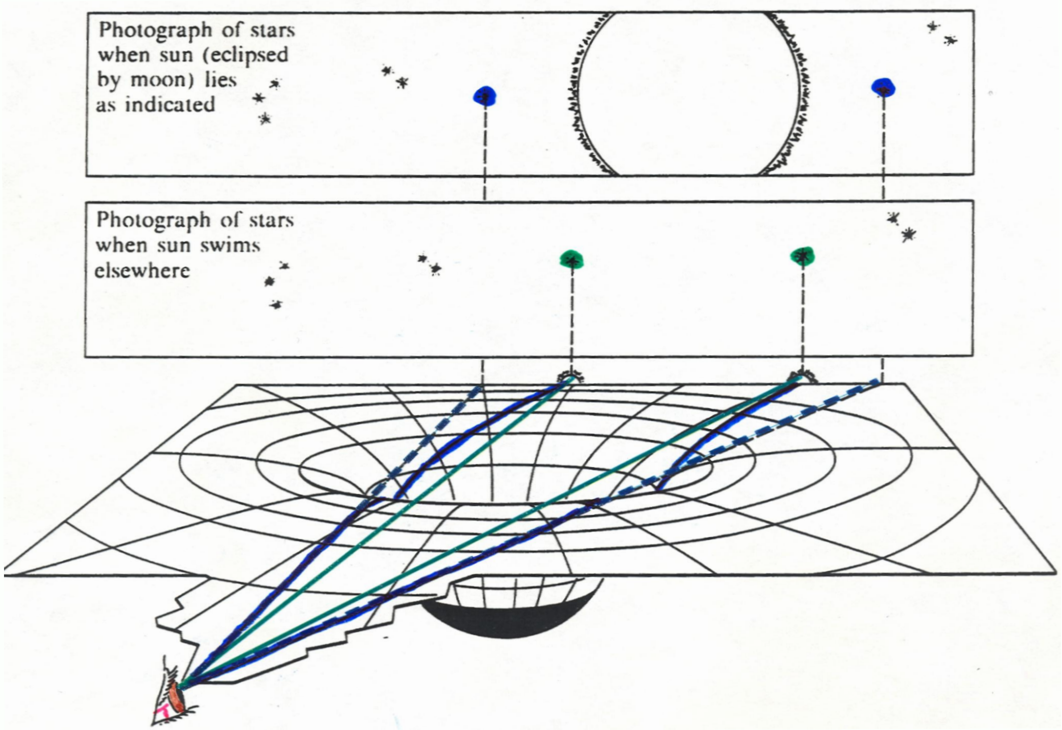
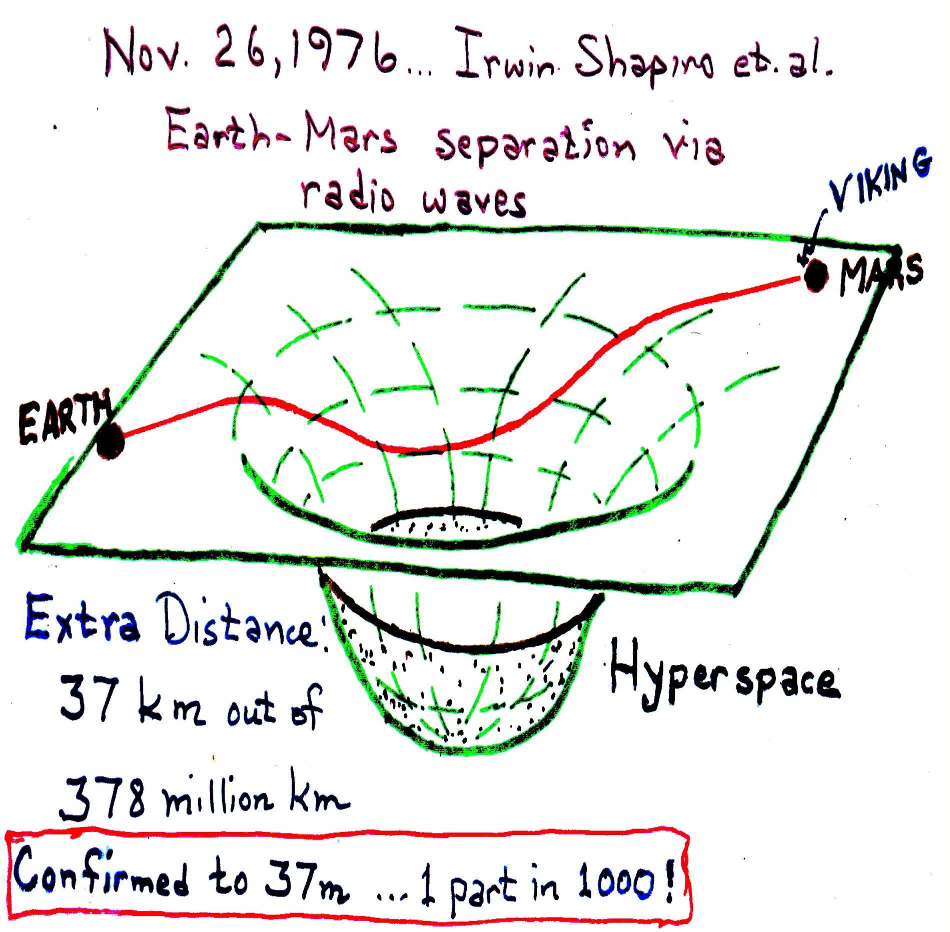
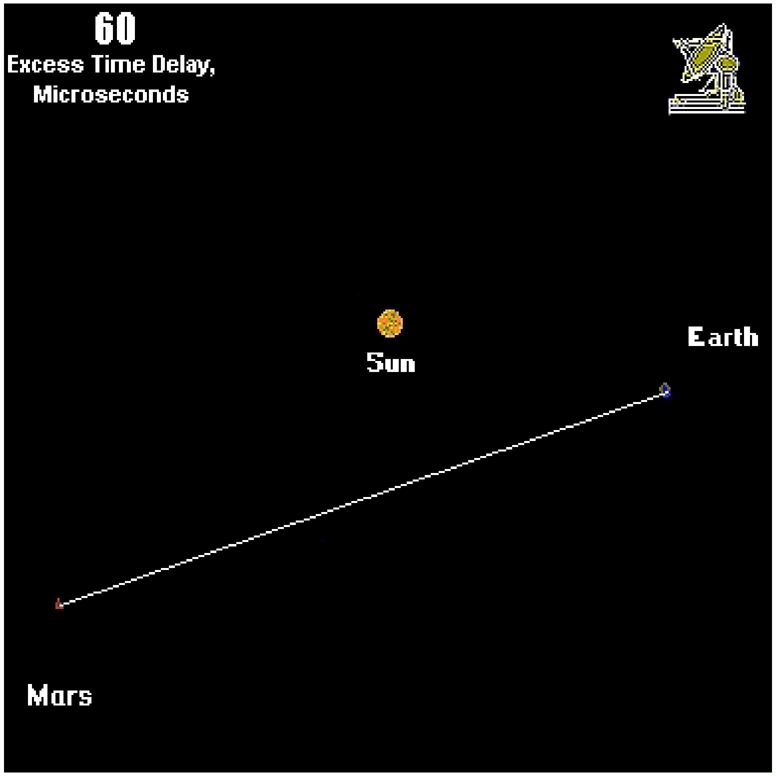


Figure from *Gravitation* by C. W. Misner, K. S Thorne, & J. A. Wheeler

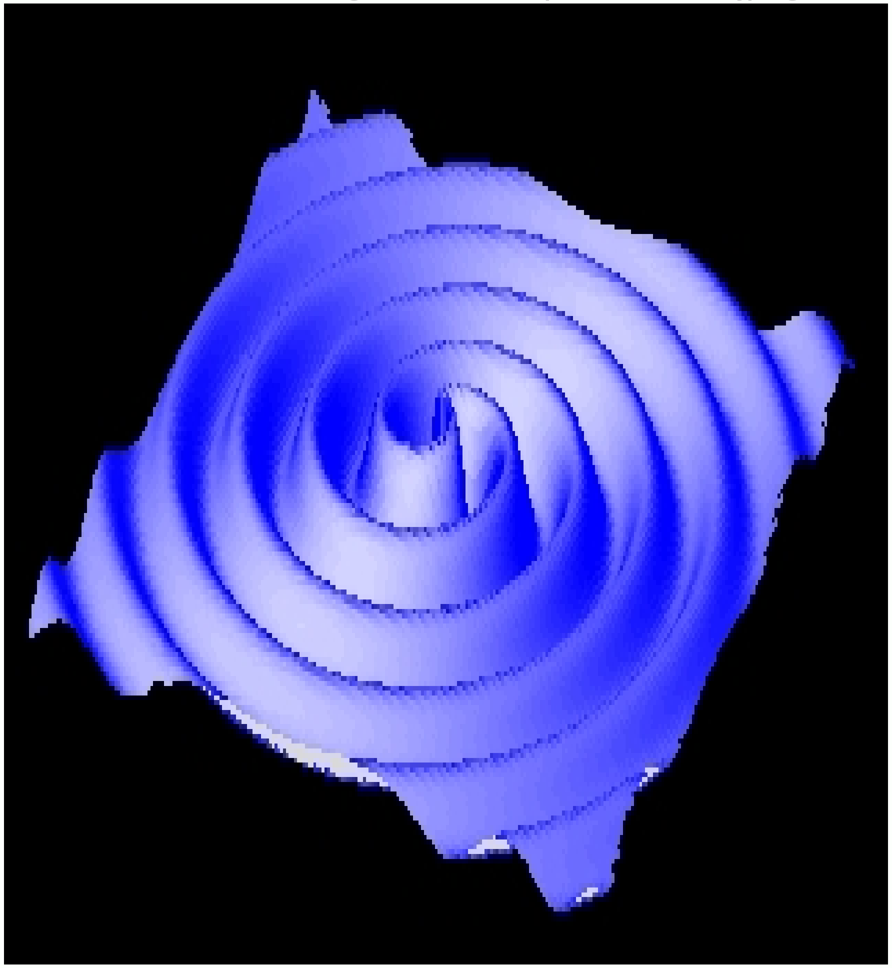
- The curvature of space within the solar system was demonstrated by accurately measuring the distance between the earth and Mars and finding this distance to be longer than it would have been in a flat space:



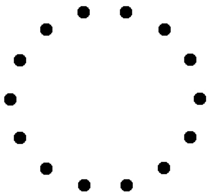


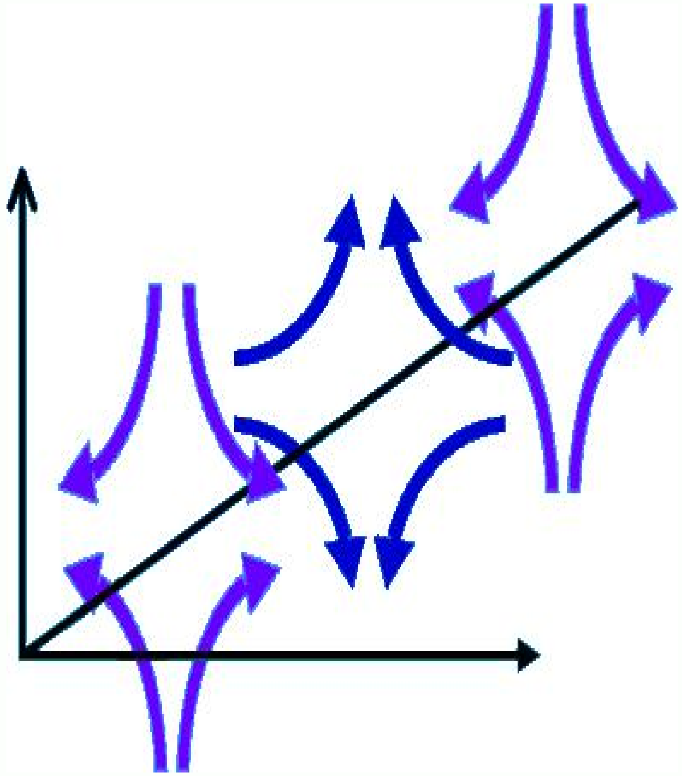
Gravitational waves are disturbances in the space-time geometry that travel at the speed of light.

Figure from http://www.lisa.jpl.gov/#



Gravitational waves interact with matter by alternately squeezing objects in one direction and stretching in the other.

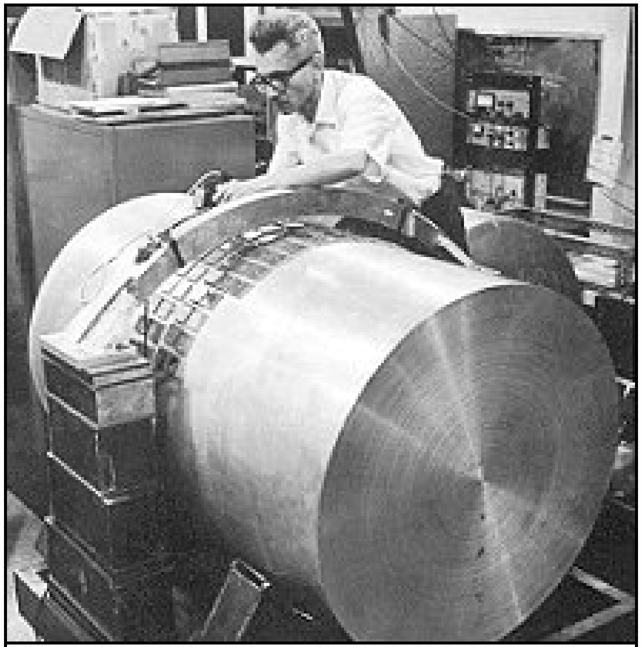




How are Gravitational Waves Detected?

- Gravitational waves alternately squeeze objects in one direction while pulling them apart in the other. The idea is to build detectors that can measure this squeezing and pulling.

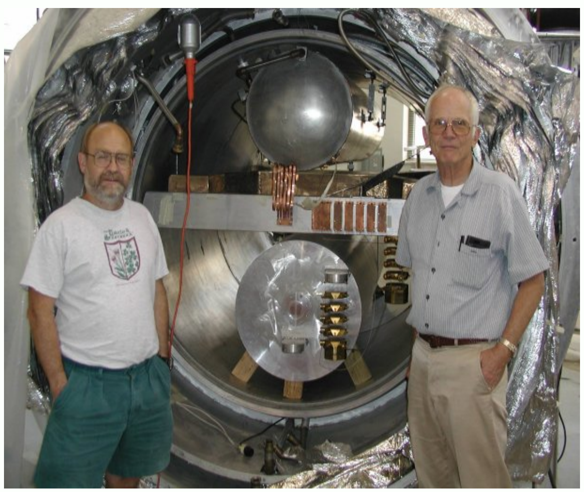
The first gravitational wave detectors (constructed by Joseph Weber in the 1970's) consisted of large aluminum cylinders instrumented with sensitive strain gauges that could measure the periodic squeezing and pulling of the bar caused by gravitational waves passing through them.

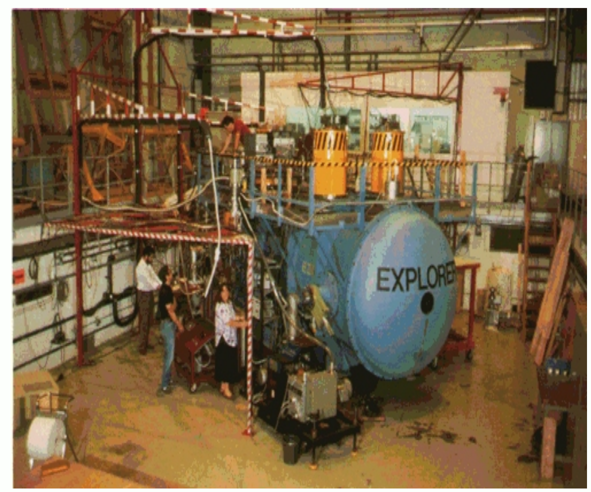


JOSEPH WEBER WITH GRAVITATIONAL WAVE DETECTOR

http://www.vectorsite.net/tagrav.html

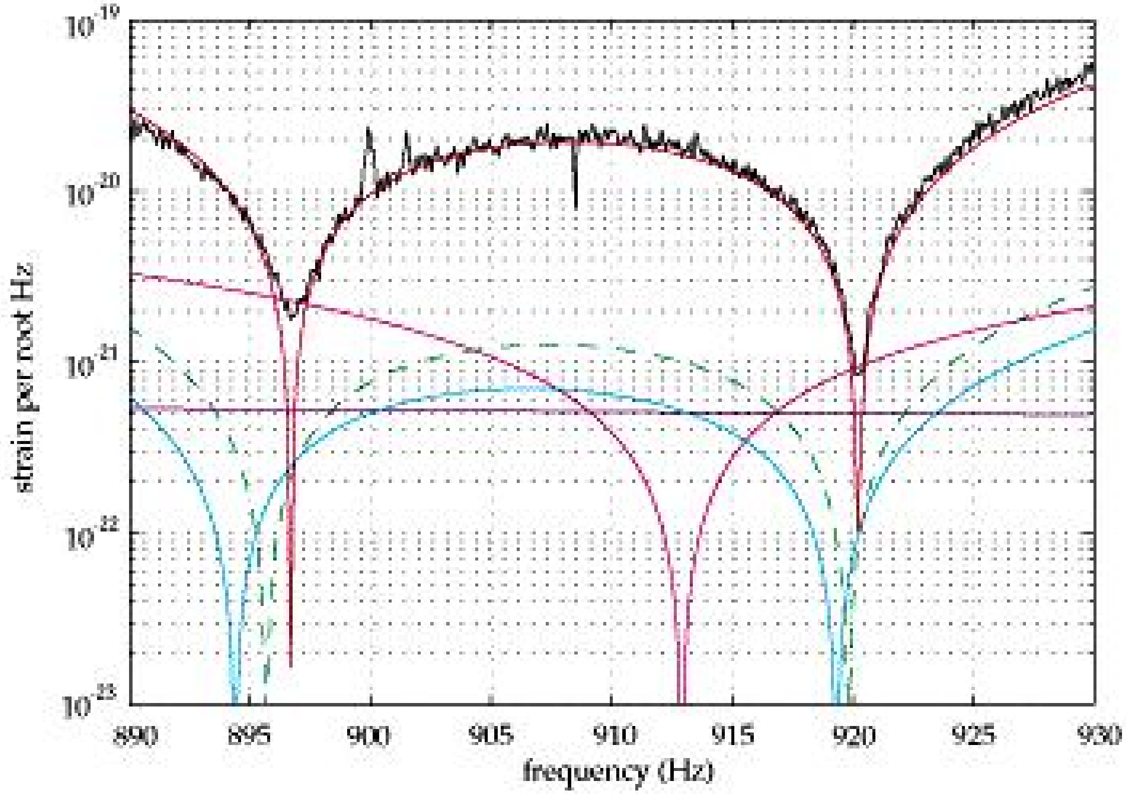
- Gravitational waves from astronomical sources are very very weak, so any detector must be carefully shielded to prevent noise sources from overwhelming the gravitational waves.
- Troublesome noise sources include: earthquakes, nearby passing trains, logging in nearby forests, vibrations caused by ocean waves breaking on a nearby shoreline, random thermal motions in the detectors, electronic noise in the circuits that amplify and record the signals, ...





Photos: http://gravity.phys.lsu.edu/ www.gravity.uwa.edu.au/bar/bar.html www.roma1.infn.it/rog/explorer/explorer.html

- Resonant mass detectors are very sensitive to gravitational waves with frequencies that match their own resonant "ringing" frequencies, but have poor sensitivity to other frequencies.
- Theoretical and measured noise in ALLEGRO, a modern resonant bar detector at LSU:



Graph from http://sam.phys.lsu.edu/Overview/sensitivity.html

- The frequencies of the strongest astronomical gravitational wave sources are still unknown, so detectors are now designed to be sensitive to a broad range of frequencies.
- Most current detectors use laser interferrometers to monitor the distance between test masses: $\mathbf{L+\Delta L(t) = L + h(t)L.}$

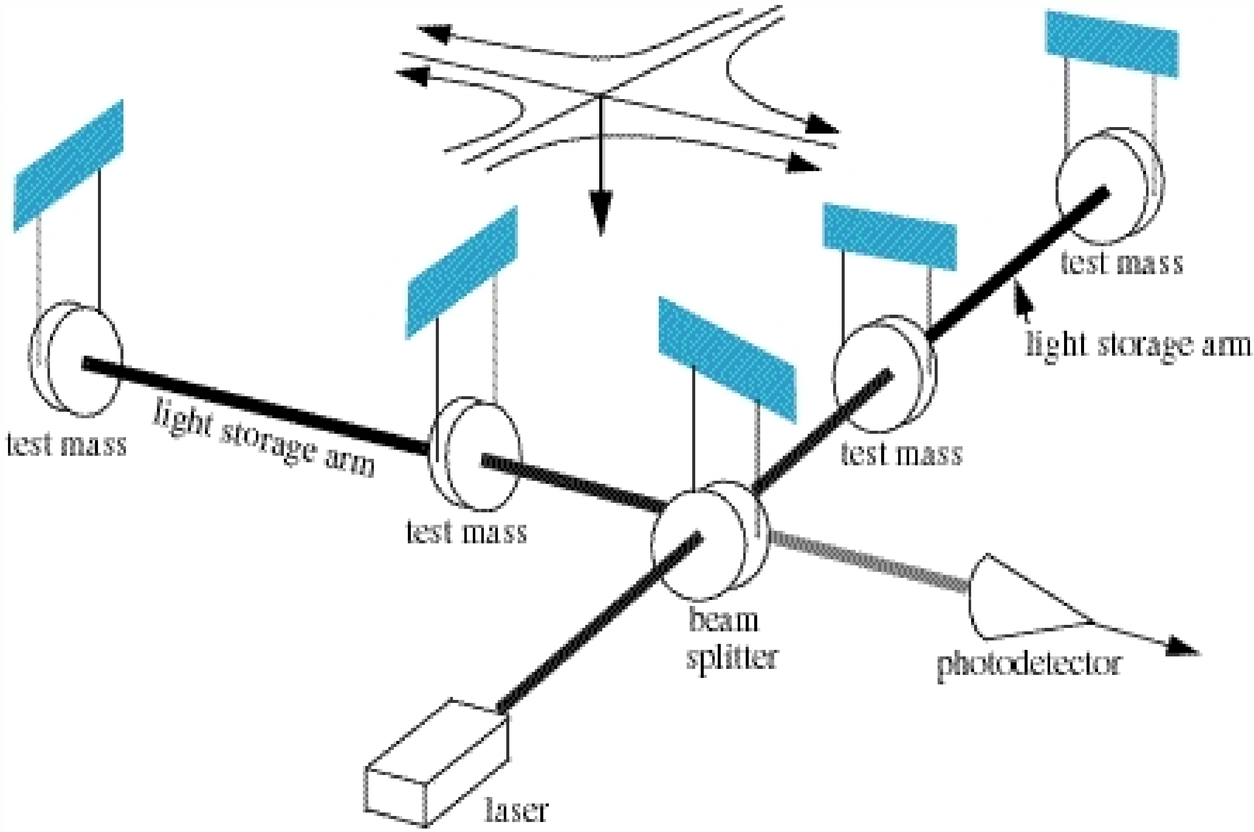
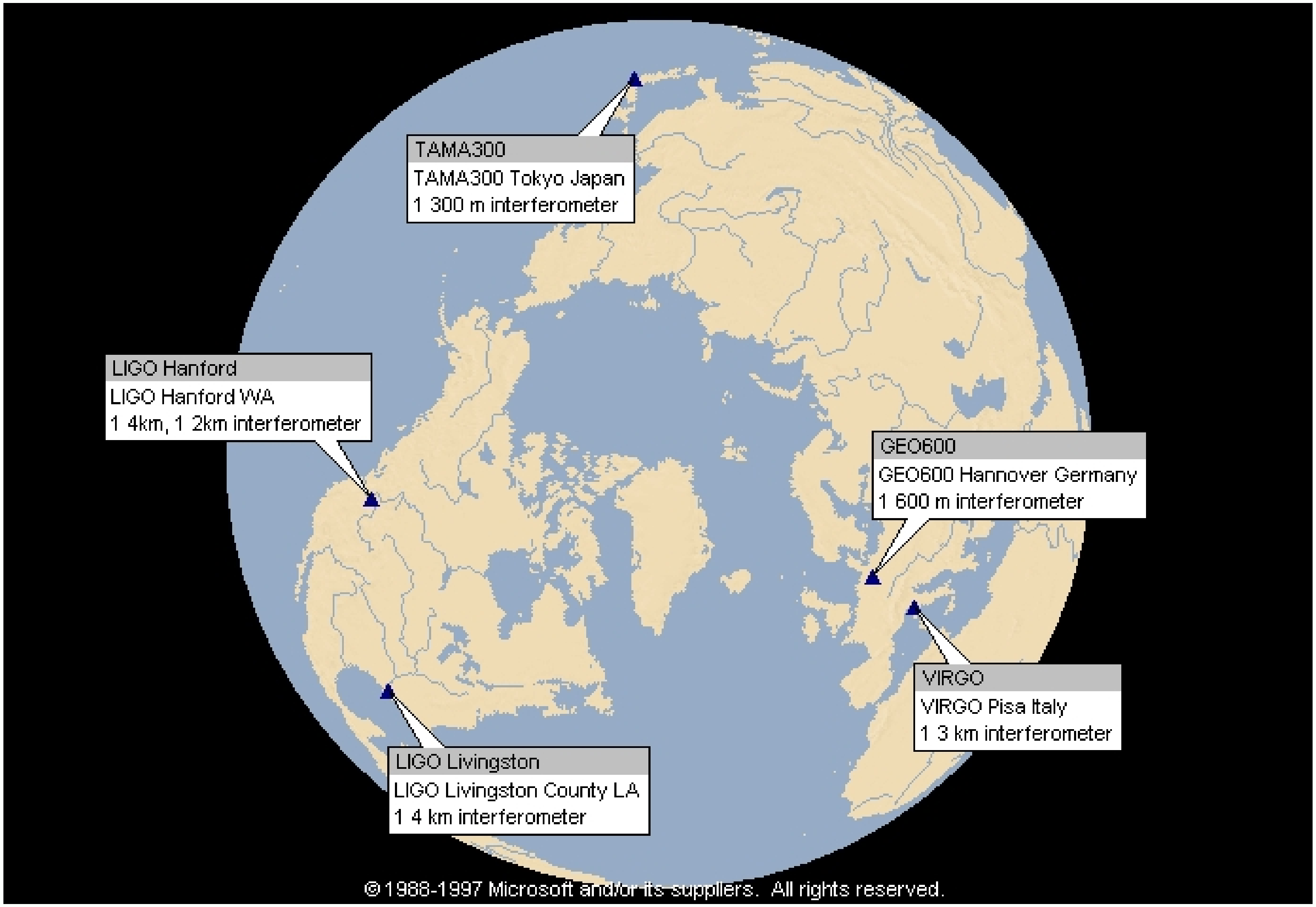


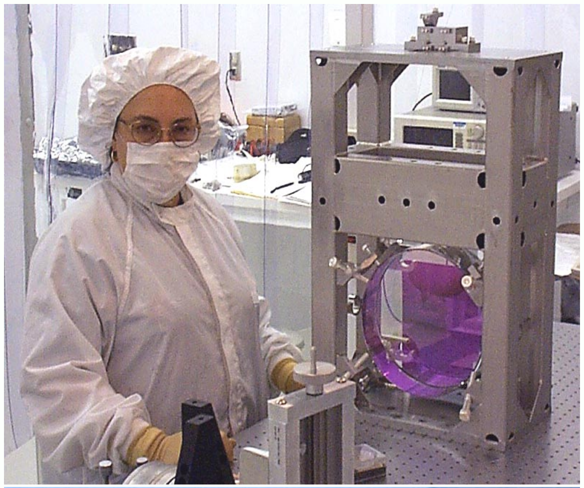
Diagram from http://www.ligo.caltech.edu

- To achieve the needed sensitivity $\mathbf{h = \Delta L / L \approx 10^{-21}}$ giant laser interferrometers have been constructed as gravitational wave detectors by a number of groups throughout the world:



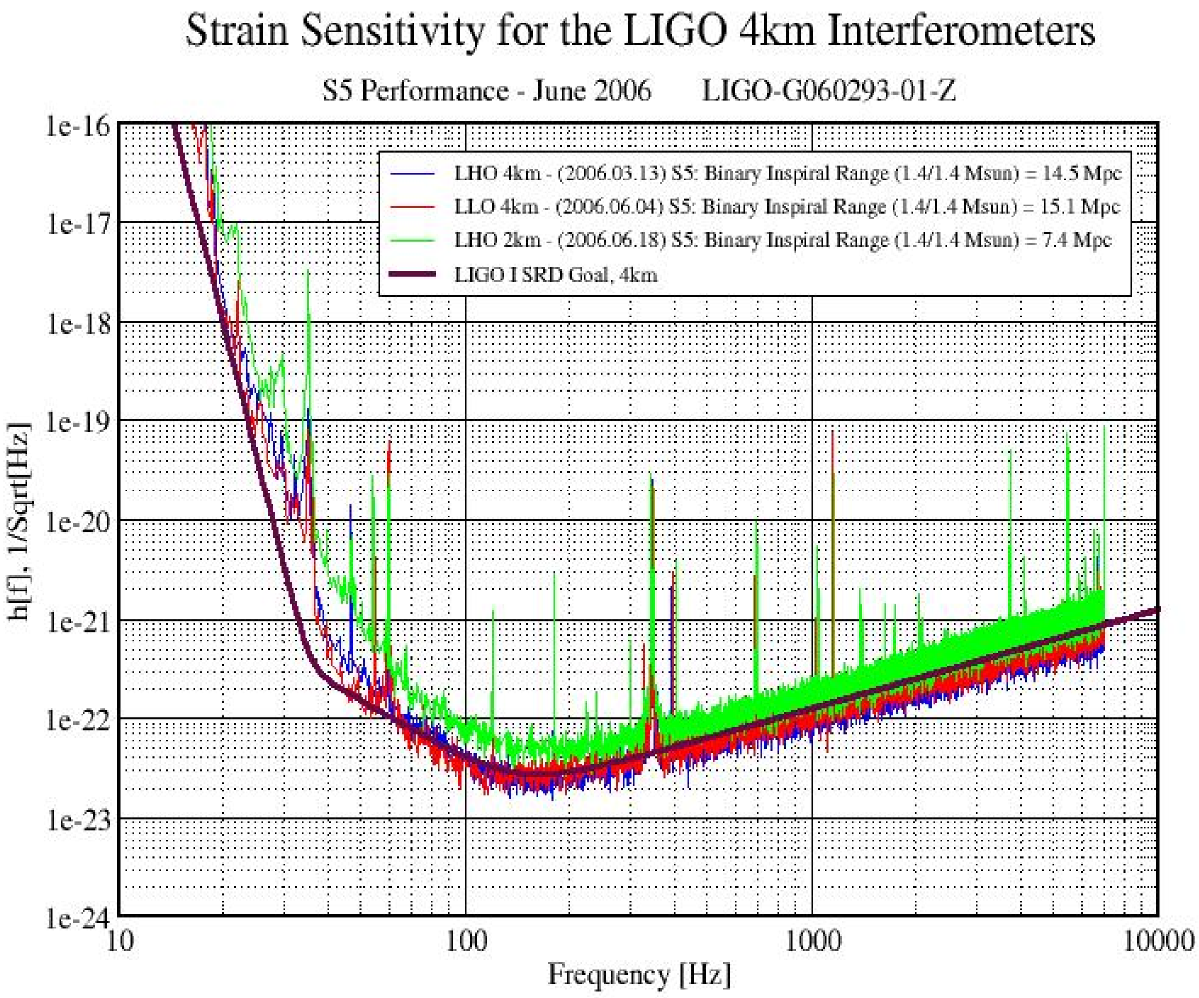
- In the US, the LIGO (Laser Interferrometer Gravitational Observatory) project (lead by Caltech and MIT) has constructed two detectors in Hanford, Washington and Livingston, Louisiana.

- The LIGO interferrometers use 25 cm diameter mirrors weighing 10 kg as test masses at each end of the 4 kilometer long arms. All the optics are protected by seismic isolation and are housed in 1.2 m diameter vacuum tubes.



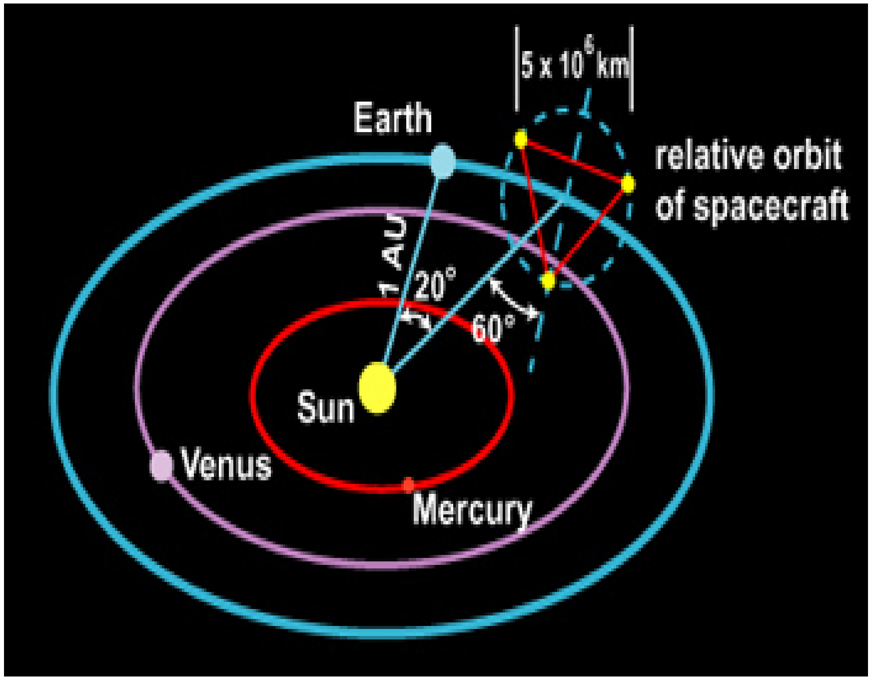


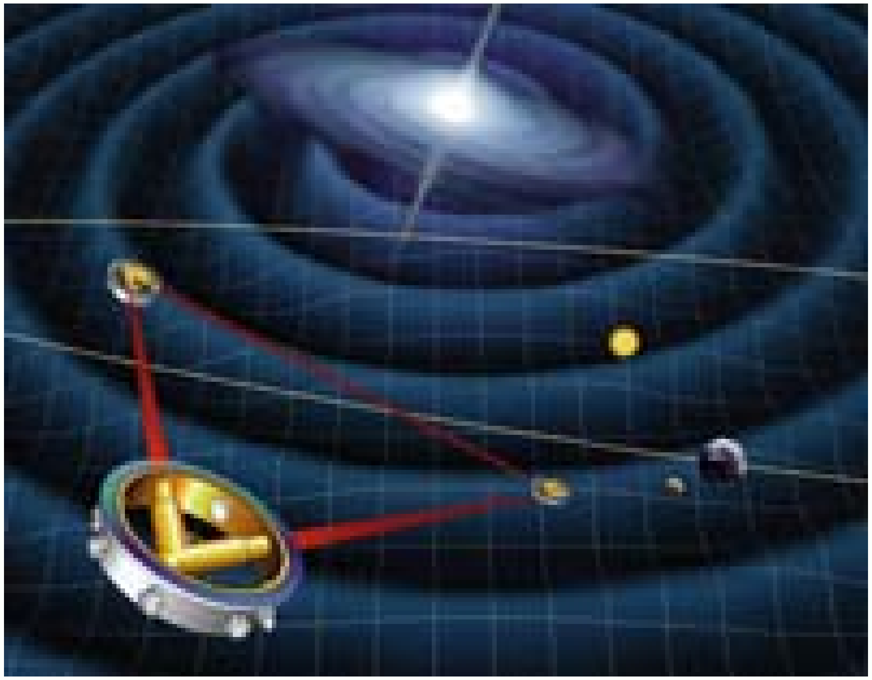

- The best laser interferrometer based gravitational wave detectors (LIGO) are now achieving good sensitivity for signals with frequencies in the range 70–1000 Hz.



Graph from Kip Thorne, Caltech

- The third type of gravitational wave detector, which is now in the planning stages as a joint NASA–ESA mission, is a very very large (5×10^6 km baseline) space based detector called LISA (Laser Interferrometer Space Antenna).
- LISA will use lasers to monitor the distances between three spacecraft. It will be sensitive to gravitational waves with frequencies in the range 10^{-4}–10^{-1} Hz.





How are gravitational waves emitted?

- Einstein's theory predicts that gravitational waves are emitted whenever matter is in motion. The situation is quite analogous to electromagnetism, where electromagnetic waves are emitted whenever charges are in motion.
- Einstein's theory predicts the amount of gravitational waves according to a formula, which in the simplest case is:

$$\mathbf{h_{ij}} = \frac{\mathbf{G}}{\mathbf{c^4}} \frac{\mathbf{2}}{\mathbf{D}} \frac{\mathbf{d^2}}{\mathbf{dt^2}} \int \rho \, \mathbf{x_i} \, \mathbf{x_j} \, \mathbf{dV}.$$

- The strongest gravitational waves are therefore produced by very massive objects that are undergoing very rapid changes in their structures.

What kinds of astronomical objects emit strong gravitational waves?

- Binary stars: When stars orbit one another they emit gravitational waves at a frequency that is twice the orbital frequency given by Kepler's third law:

$$\mathbf{f} = \frac{1}{P} = \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}}.$$

Einstein's theory predicts that the strength of the gravitational waves emitted by such systems is approximately

$$h_{ij} = \frac{G}{c^4}\frac{2}{D}\frac{d^2}{dt^2}\int \rho\, x_i x_j\, dV \sim \frac{G}{c^4}\frac{1}{D} f^2 M R^2 \sim \left(\frac{GM}{c^2 D}\right)\left(\frac{GM}{c^2 R}\right).$$

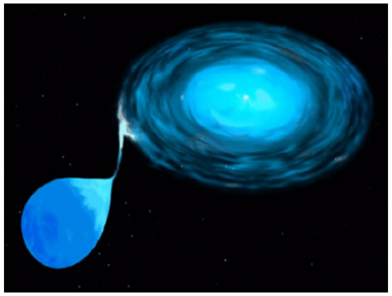
As a binary emits gravitational waves the size $\mathbf{R}$ of the orbit gets smaller, so the frequency of the waves $\mathbf{f}$ gets larger, and the strength of the gravitational waves $\mathbf{h_{ij}}$ also gets larger.

- Binary stars spiral into each other until they merge to form a larger star, or a black hole. The frequency of the gravitational waves $\mathbf{f}$ increases until the merger occurs, when

$$\mathbf{f} \leq \mathbf{f_{merge}} \approx \sqrt{\frac{\mathbf{GM}}{\mathbf{R^3_{star}}}}.$$

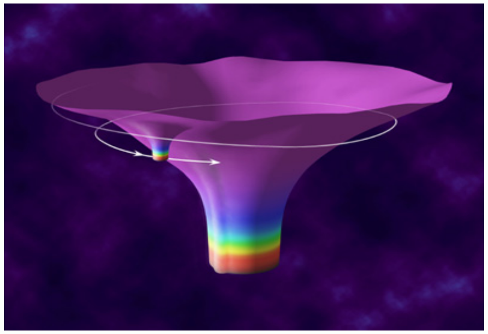
These merger frequencies for common types of stars are:

Main Sequence	$\mathbf{f_{merge}} \approx \mathbf{10^{-4}}$	Hz
White Dwarf	$\mathbf{f_{merge}} \approx \mathbf{10^{-2}}$	Hz
Neutron Star	$\mathbf{f_{merge}} \approx \mathbf{10^{3}}$	Hz



- Black holes can also orbit around each other in binary systems, emit gravitatinoal waves, and inspiral into each other until they merge into a single larger black hole. The merger frequency for black hole binaries is about $\mathbf{f_{merge}} \approx \mathbf{c^3/GM}$.

- Stars can be captured by supermassive black holes and emit gravitational waves as they inspiral into the hole.



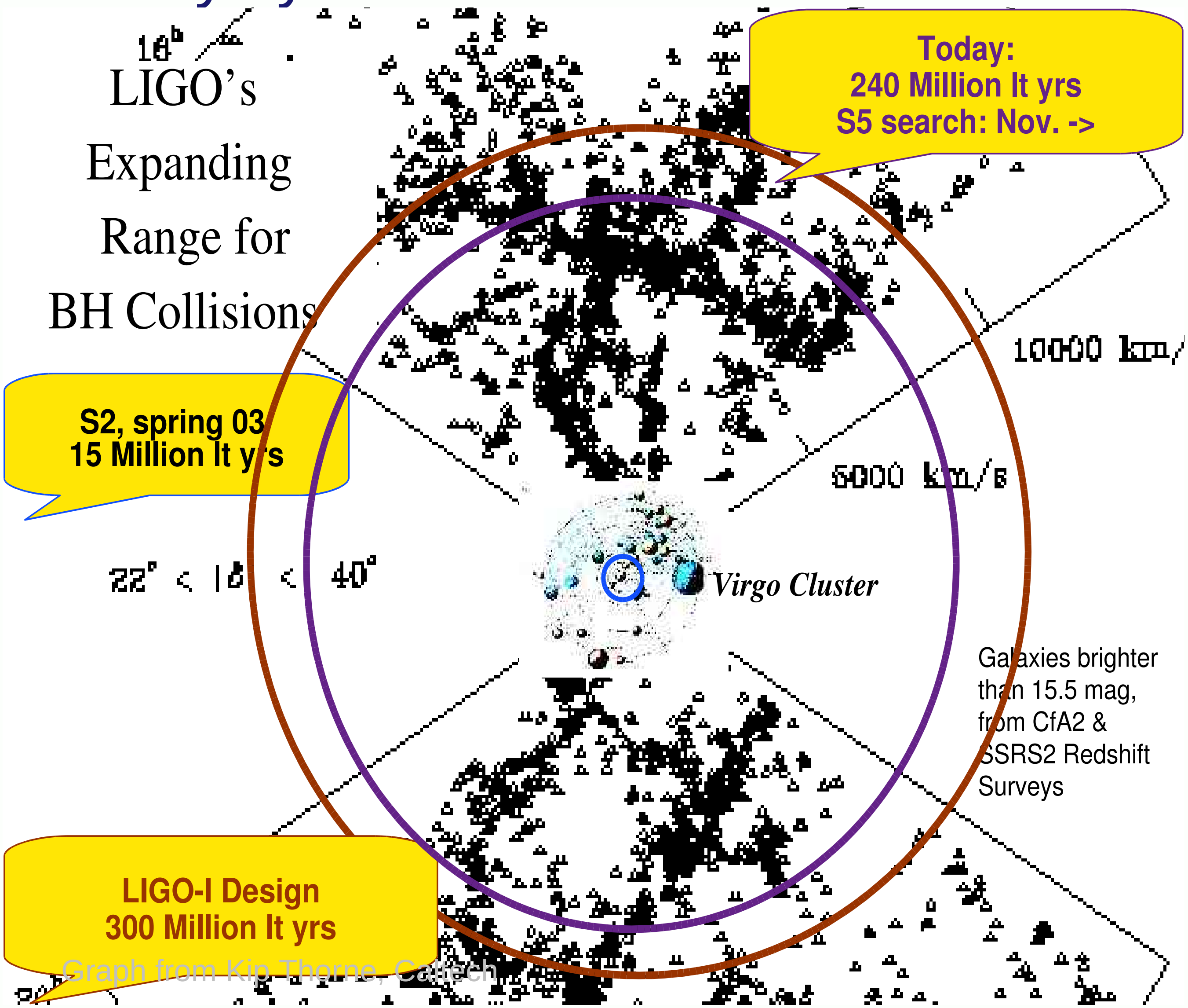
- Old neutron stars and white dwarfs cool down and solidify. These stars can emit gravitational waves if they are rotating and have distorted shapes (e.g. mountains).
- Gravitational waves can be emitted during supernova explosions as neutron stars and black holes are formed.
- Gravitational waves were undoubtedly emitted during the early universe as part of the big bang. These waves should now fill the universe and have very low frequencies, much like the electromagnetic cosmic microwave radiation.
- Gravitational waves may also be emitted by other more esoteric phenomena like the collision of cosmic strings.

How are gravitational wave data analyzed to determine what kind of source emitted the waves?

- Each type of astronomical source emits gravitational wave signals that are unique to that type of source.
- Just as different types of birds have unique calls (chirps, peeps, squaks, screeches) that can be used to identify them, the details of gravitational wave signals will be used to identify their sources.
- Each type of gravitational wave source must be modeled so that predicted waveforms can be compared to the gravitational wave data. Pretorius BBH Lapse Caltech/Cornell BBH Ψ_4
- Examples of gravitational wave models (transformed into sounds by Teviet Creighton):

Binary Inspiral EMRI1 EMRI2 EMRI3 Pulsar Supernova
Cosmic Background Cosmic String LIGO noise

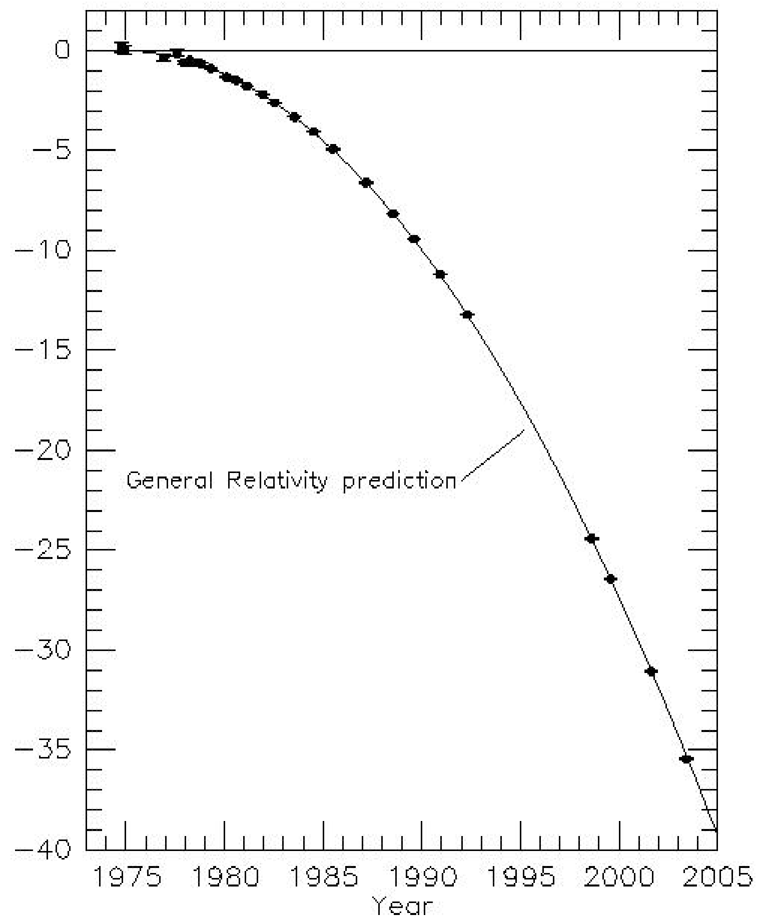
- How far can the current LIGO detectors see the gravitational waves from the inspiral and merger of a $10M_{sun} - 10M_{sun}$ black-hole binary system?



Have gravitational waves been detected yet?

- No, and yes.

- Gravitational waves cause all binaries to inspiral. As this occurs, the point of closest approach (pariastron) in the orbit occurs earlier and earlier. Precise measurements of these closest approaches in pulsar PSR 1913+16 agree exactly with Einstein's prediction of how the orbit should inspiral due to the emission of gravitational waves.



Weinberg & Taylor astro-ph/0407149 (2004).