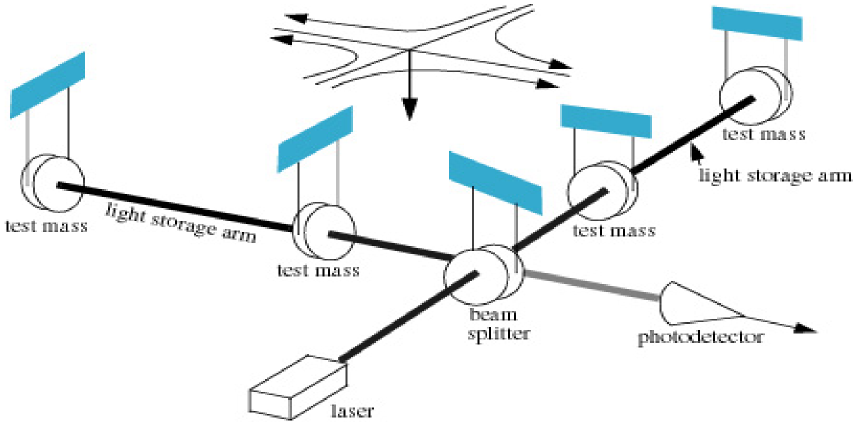
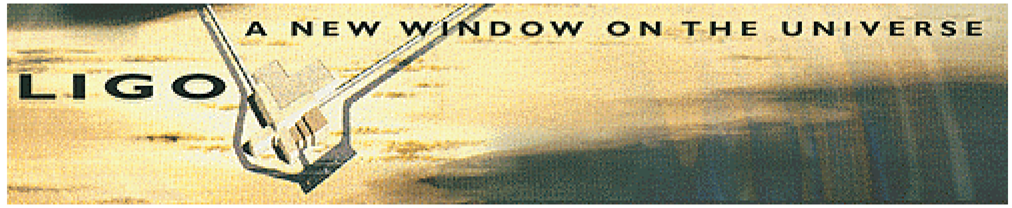
Gravitational Waves and LIGO

- What is a gravitational wave?
- Where do they come from?
- What can we learn from them?
- How can we detect them?
- LIGO and its sister projects



Alan Weinstein, Caltech



LIGO: Laser Interferometer Gravitational-Wave Observatory

- US project to build observatories for gravitational waves (GWs)
  - » ...and laboratory to run them
- to enable an initial detection, then an astronomy of GWs
- collaboration by MIT, Caltech; other institutions participating
  - » (LIGO Scientific Collaboration, LSC)
  - » Funded by the US National Science Foundation (NSF)

Observatory characteristics

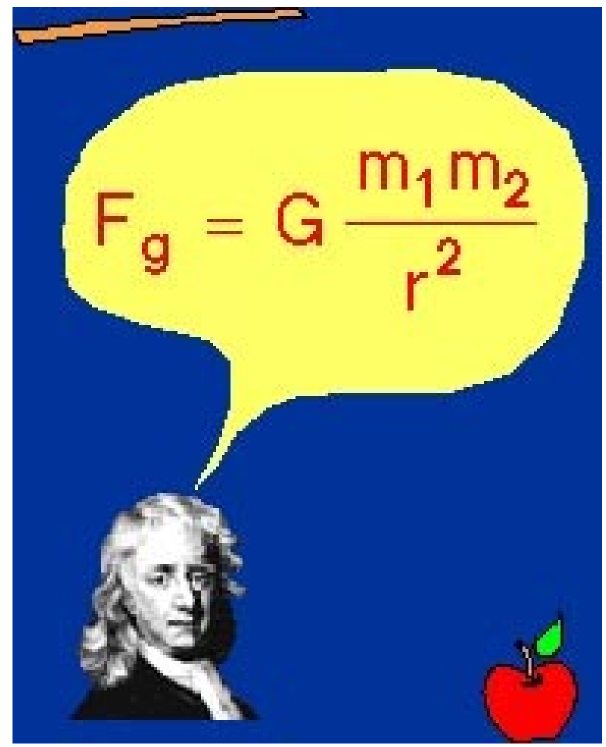
- Two sites separated by 3000 km
- each site carries 4km vacuum system, infrastructure
- each site capable of multiple interferometers (IFOs)

Evolution of interferometers in LIGO

- establishment of a network with other interferometers
- A facility for a variety of GW searches
- lifetime of >20 years
- goal: best technology, to achieve fundamental noise limits for terrestrial IFOs

Newtonian Gravity

- Three laws of motion (F=ma) and law of gravitation (centripetal force) disparate phenomena
  - » eccentric orbits of comets
  - » cause of tides and their variations
  - » the precession of the earth's axis
  - » the perturbation of the motion of the moon by gravity of the sun
- Solved most known problems of astronomy and terrestrial physics
  - » Work of Galileo, Copernicus and Kepler unified.
- Gravitational fields are static (or slowly changing), the force acts over large distances, "instantaneously"
- Space and time are the static, unchanging arena in which the dynamics of planetary motion (and all other motion) do their thing



Einstein and relativity

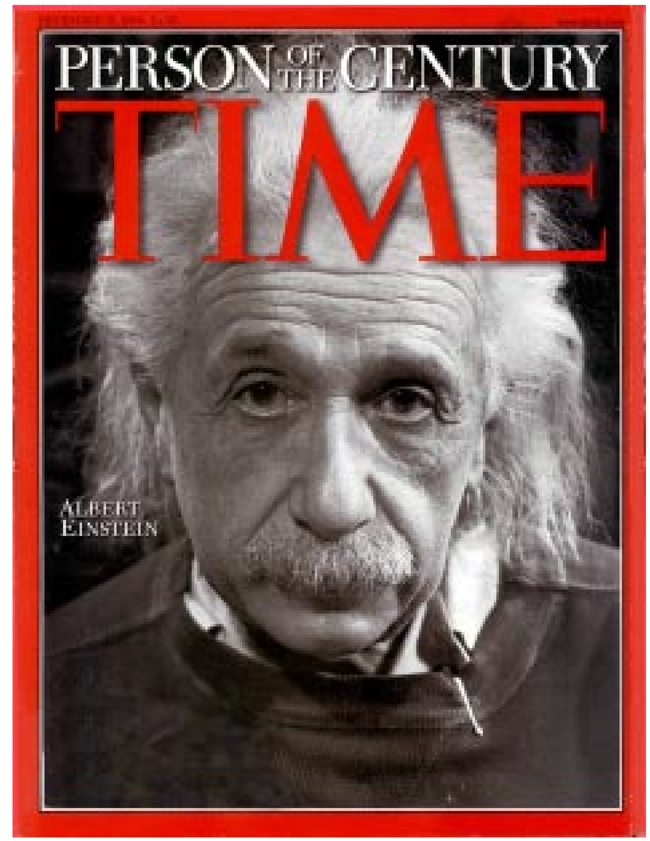
Enter Einstein!

- Special Relativity (1906):
  - Distances in space and time change between observers moving relative to one another, but the space-time interval remains invariant:

    $$ds^2 = dx^2+dy^2+dz^2 - c^2dt^2$$

  - space+time $\Rightarrow$ 4D space-time *geometry*
  - energy and momentum also change between observers moving relative to one another, but the invariant (rest) mass does not change

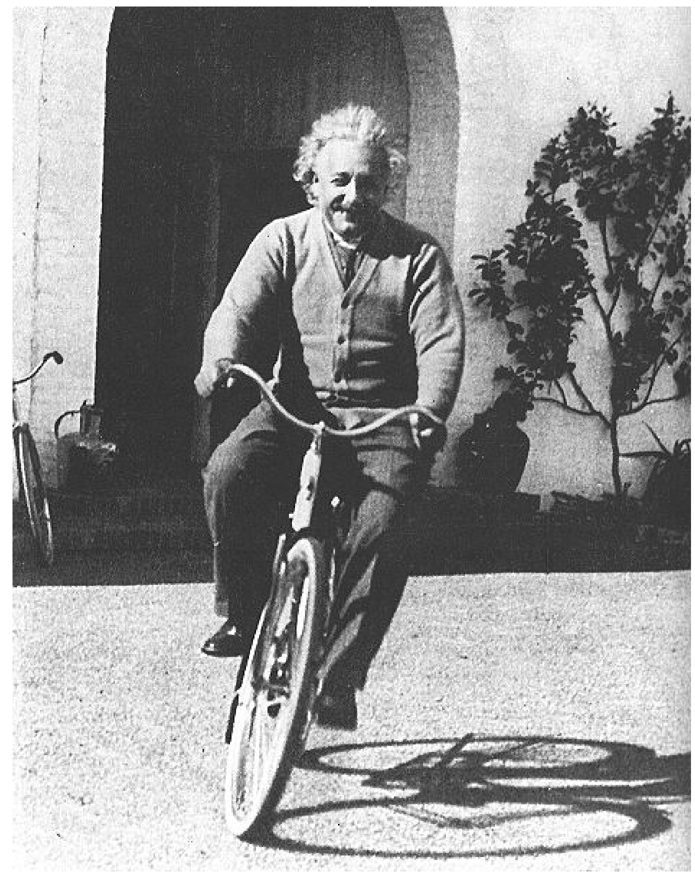
    $$(m_0c^2)^2 = E^2 - (pc)^2 \quad (\text{or } E = mc^2)$$



Space-time geometry

Relativity and space-time geometry:

- Discards concept of absolute motion; instead treats only relative motion between systems
- space and time no longer viewed as separate; rather as four dimensional space-time
- gravity described as a warpage (curving) of space-time, not a force acting at a distance



Warped space-time: Einstein's General Relativity (1916)

- **A *geometric* theory of gravity**

➢ gravitational acceleration depends only on the geometry of the space that the "test mass" occupies, not any properties of the test mass itself

➢ for gravity (as opposed to all other forces), motion (acceleration) depends only on location, not mass

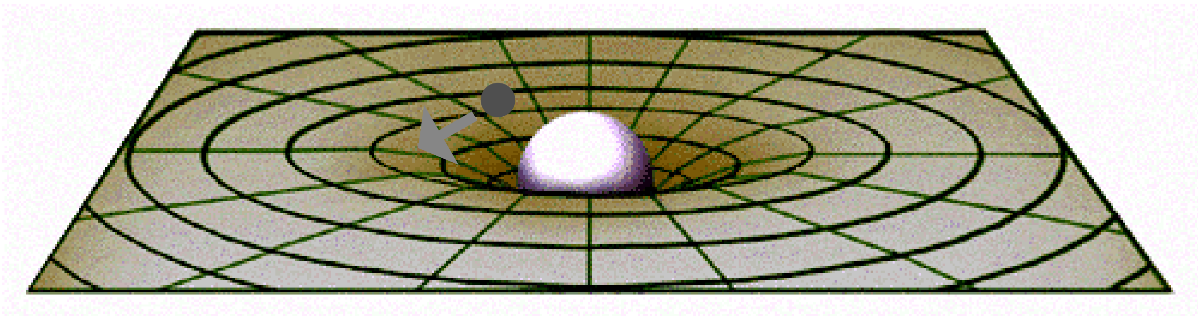
- **Imagine space as a stretched rubber sheet.**

$$F = \not{m}_1 a = G\not{m}_1 m_2 / r^2$$

- **A mass on the surface will cause a deformation.**

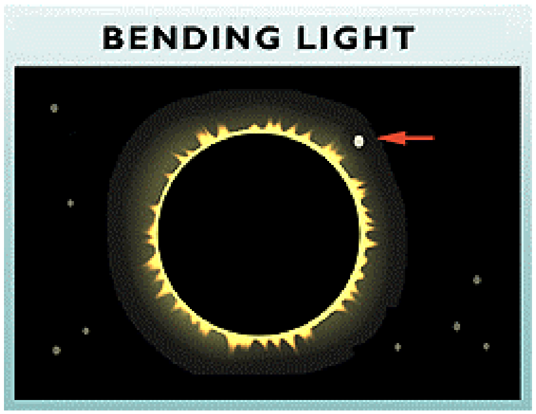
- **Another ("test") mass dropped onto the sheet will roll toward that mass.**

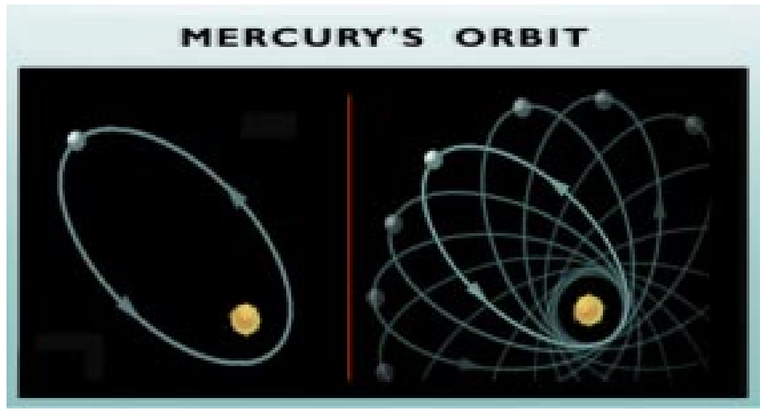
- **Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a force that acts across a distance, but because the smaller objects travel through space that is warped by the larger object.**



Einstein's Theory of Gravitation

experimental tests





bending of light
As it passes in the vicinity of massive objects

First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

Mercury's orbit
perihelion shifts forward twice Newton's theory

Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass.

"Einstein Cross"
The bending of light rays
gravitational lensing

Quasar image appears around the central glow formed by nearby galaxy. Such gravitational lensing images are used to detect a 'dark matter' body as the central object

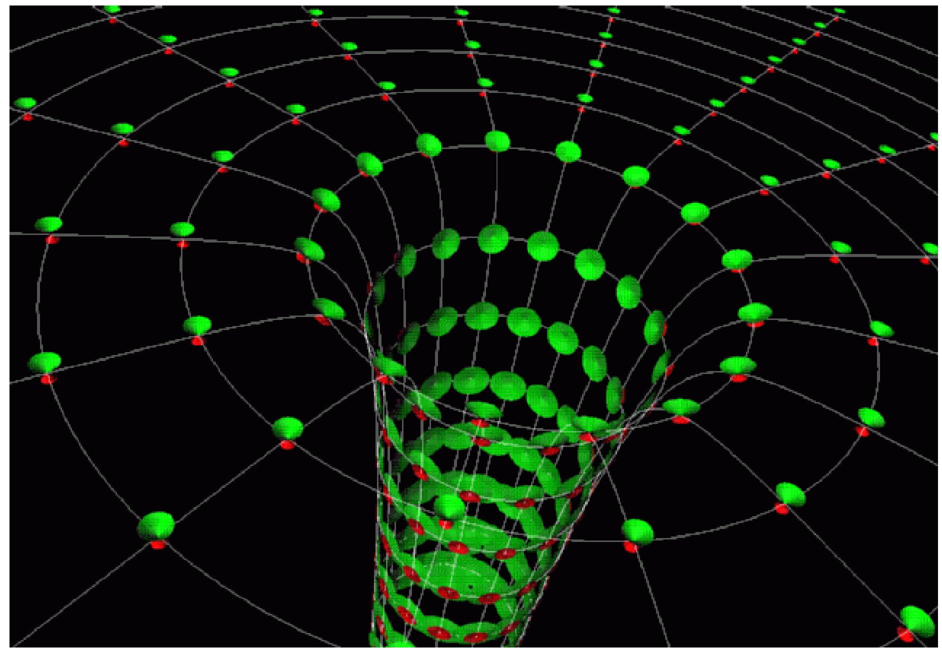
Strength of gravitational force

Interaction	Strength	Acts on	Charge	Carried by	theory
Strong nuclear	10	Quarks	Color	Gluons (*g*) (massless)	QCD
Electromagnetic	10^{-2}	Charged particles	Electric charge	Photon (γ) (massless)	QED
Weak nuclear	10^{-13}	Quarks, leptons	“flavor” charge	W^+, W^-, Z^0 (massive)	QFD
Gravitational	10^{-40}	All particles	Mass	Graviton(*G*) (massless)	GR…?

Gravitational force is very weak…
But at large scales (planets, stars, galaxies, universe) it dominates!

Strong-field

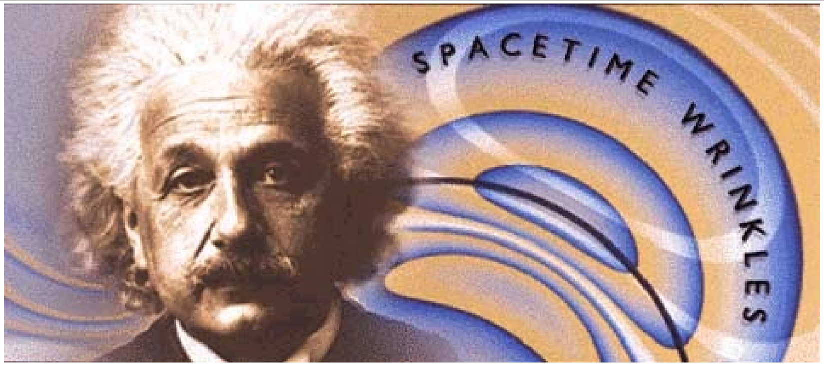
- Most tests of GR focus on small deviations from Newtonian dynamics (post-Newtonian weak-field approximation)
- Space-time curvature is a *tiny* effect everywhere except:
  - The universe in the early moments of the big bang
  - Near/in the horizon of black holes
- This is where GR gets *non-linear* and interesting!
- We aren't very close to any black holes (fortunately!), and can't see them with light

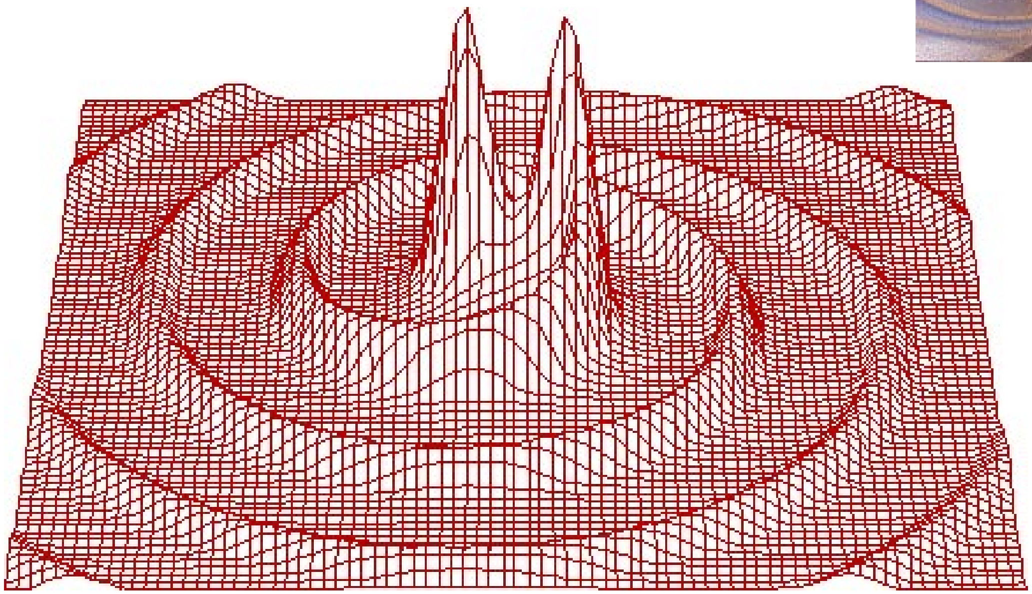


But we can search for (*weak-field*) gravitational waves as a signal of their presence and dynamics

Dynamics of changing Spacetime curvature

Newton's Theory
"instantaneous action at a distance"





Einstein's Theory
information carried by gravitational radiation at the speed of light

Nature of Gravitational Radiation

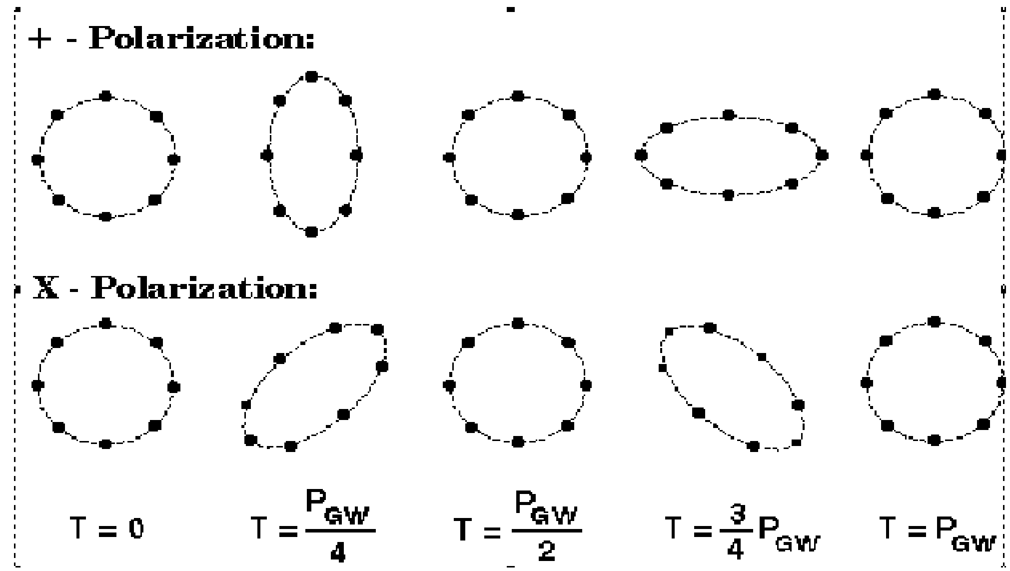
General Relativity predicts :

- transverse space-time distortions, freely propagating at speed of light
- Stretches and squashes space between "test masses" – strain

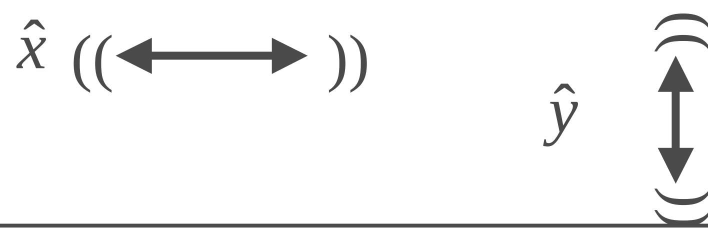
$$h = \Delta L/L$$

- Conservation laws:
  - conservation of energy ⇒ no monopole radiation
  - conservation of momentum ⇒ no dipole radiation
  - quadrupole wave (spin 2) ⇒ two polarizations

plus (⊕) and cross (⊗)



Contrast with EM dipole radiation:



Contrast EM and GW information

E&M	GW
space as medium for field	Space-time itself
incoherent superpositions of atoms, molecules	coherent motions of huge masses (or energy)
wavelength small compared to sources - images	wavelength ~large compared to sources - poor spatial resolution
absorbed, scattered, dispersed by matter	very small interaction; no shielding
10^6 Hz and up	10^3 Hz and down
measure amplitude (radio) or intensity (light)	measure amplitude
detectors have small solid angle acceptance	detectors have large solid angle acceptance

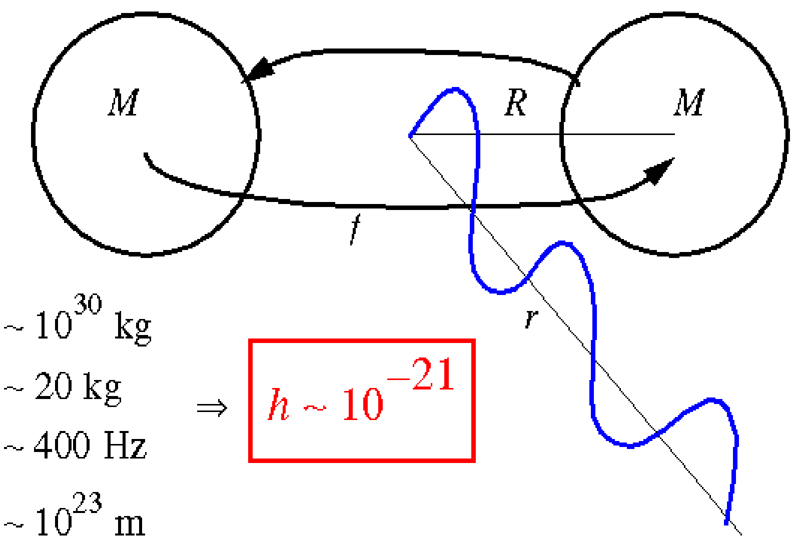
- Very different information, mostly mutually exclusive
- Difficult to predict GW sources based on E&M observations

Sources of GWs

- Accelerating charge ⇒ electromagnetic radiation (dipole)
- Accelerating mass ⇒ gravitational radiation (quadrupole)
- Amplitude of the gravitational wave (dimensional analysis):

$$h_{\mu\nu} = \frac{2G}{c^4 r} \ddot{I}_{\mu\nu} \quad \Rightarrow \quad h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r}$$

- $\ddot{I}_{\mu\nu}$ = second derivative of mass quadrupole moment (non-spherical part of kinetic energy – tumbling dumb-bell)
- G is a small number!
- Need huge mass, relativistic velocities, nearby.
- For a binary neutron star pair, 10m light-years away, solar masses moving at 15% of speed of light:



$M \sim 10^{30}$ kg

$R \sim 20$ kg

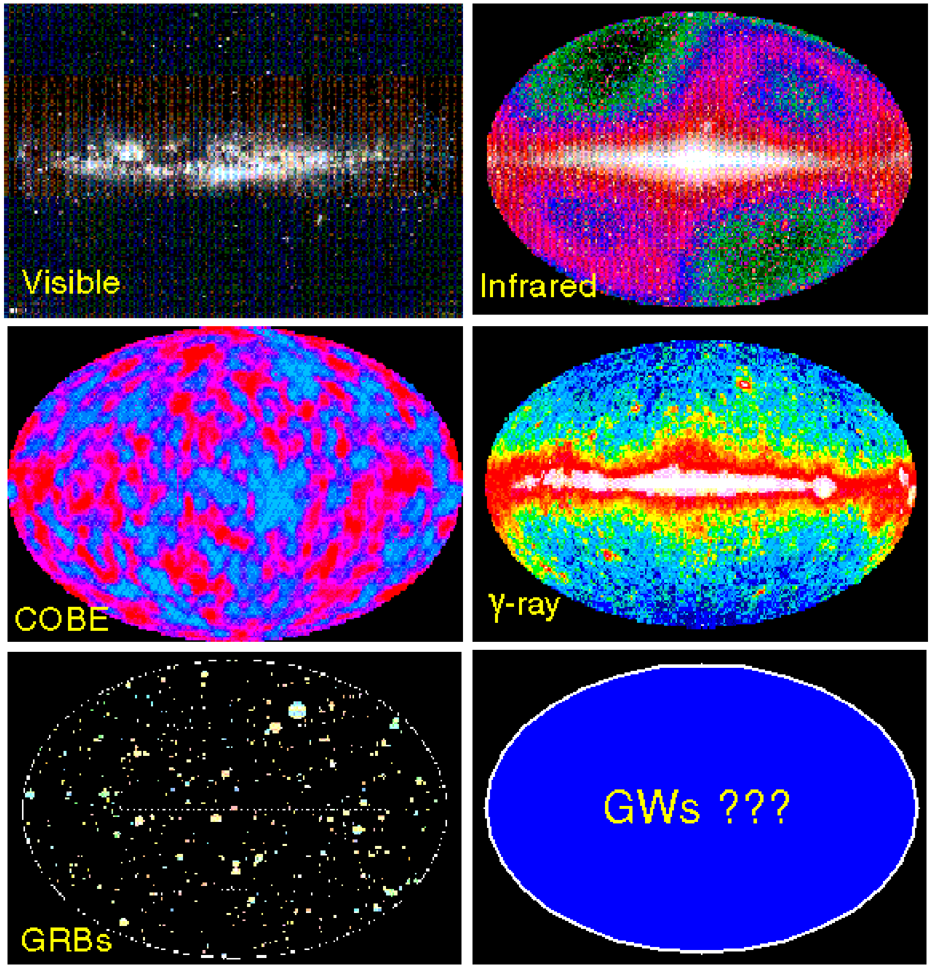
$f \sim 400$ Hz

$r \sim 10^{23}$ m

$\Rightarrow \; h \sim 10^{-21}$

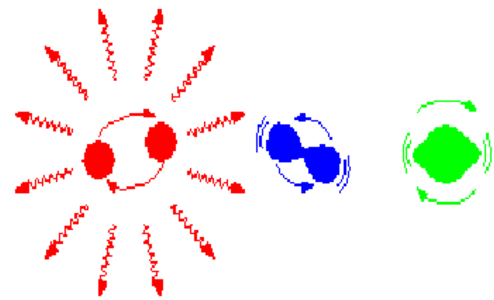
Terrestrial sources *TOO WEAK*!

What will we see?

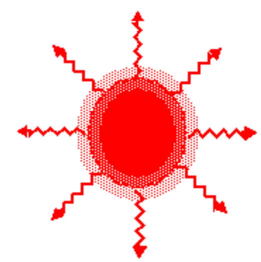


Astrophysical Sources of Gravitational Waves

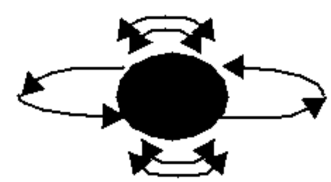
Coalescing compact binaries
(neutron stars, black holes)



Non-axi-symmetric
supernova collapse

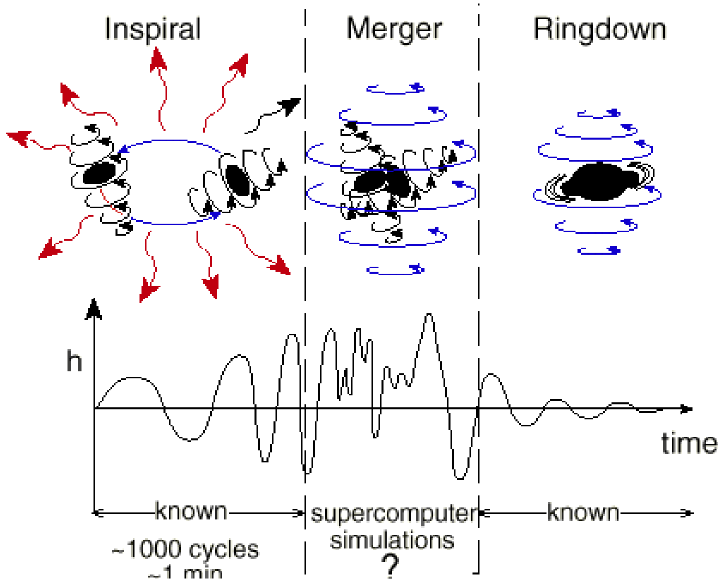


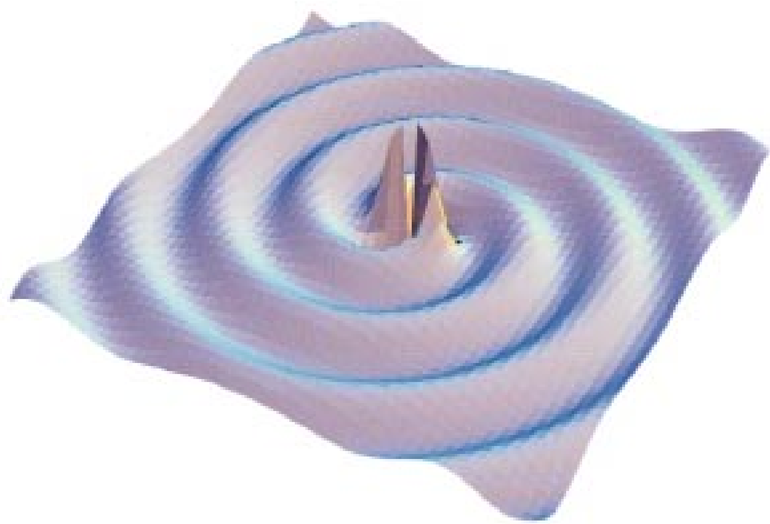
Non-axi-symmetric pulsar
(rotating, beaming
neutron star)



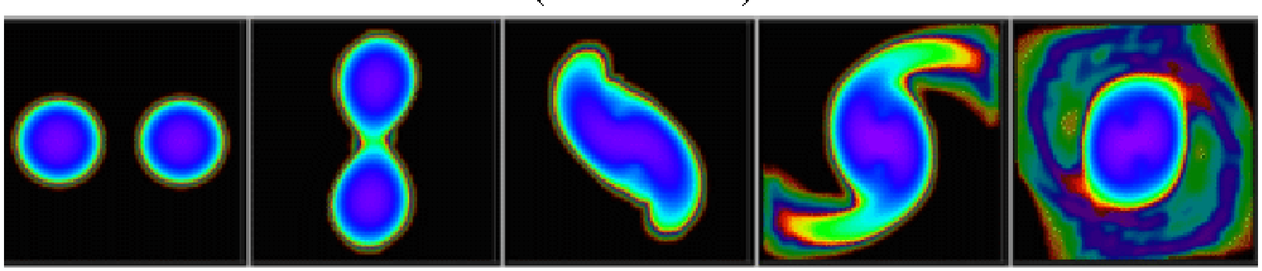
GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

Compact binary mergers



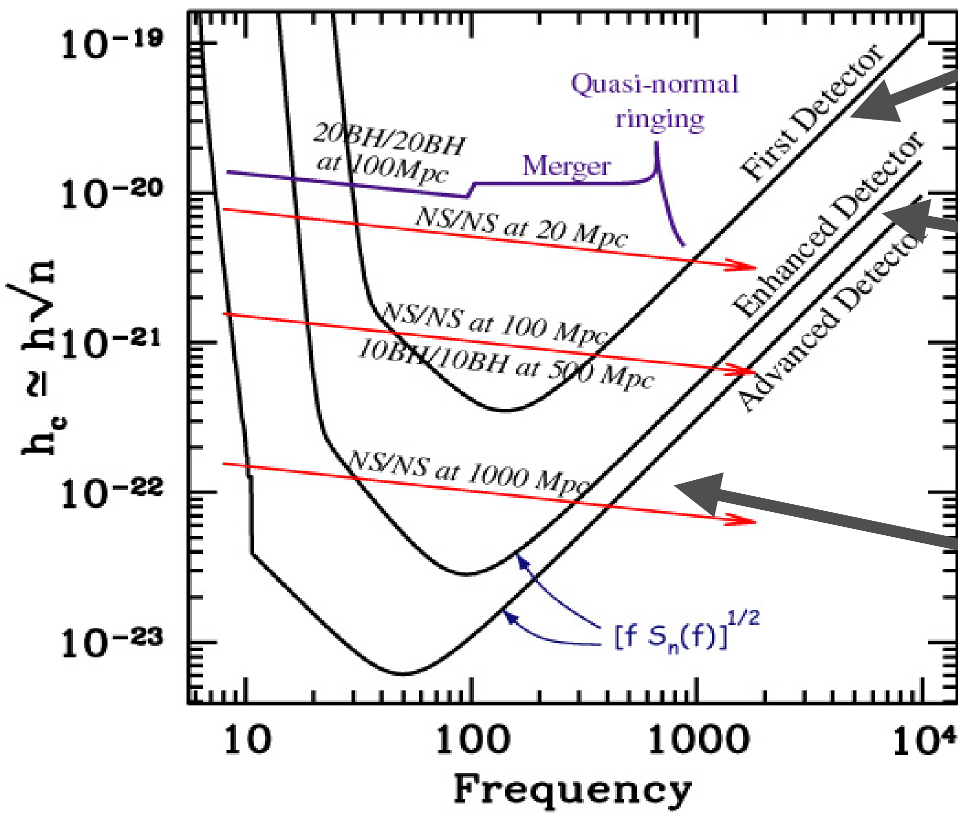


- Neutron star – neutron star (Centrella et al.)



Astrophysical sources: Thorne diagrams

Sensitivity of LIGO to coalescing binaries



LIGO I (2002-2005)

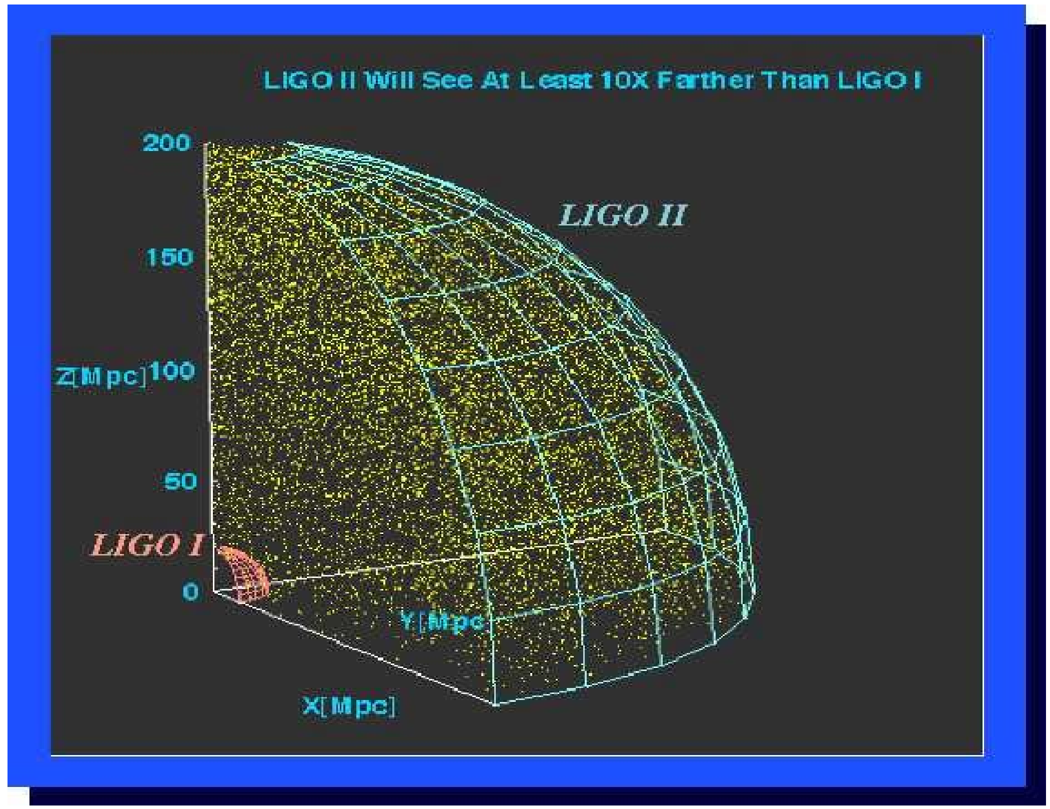
LIGO II (2007-)

Advanced LIGO

How far out can we see?

Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!



How many sources can we see?

Improve amplitude sensitivity by a factor of 10x, and…

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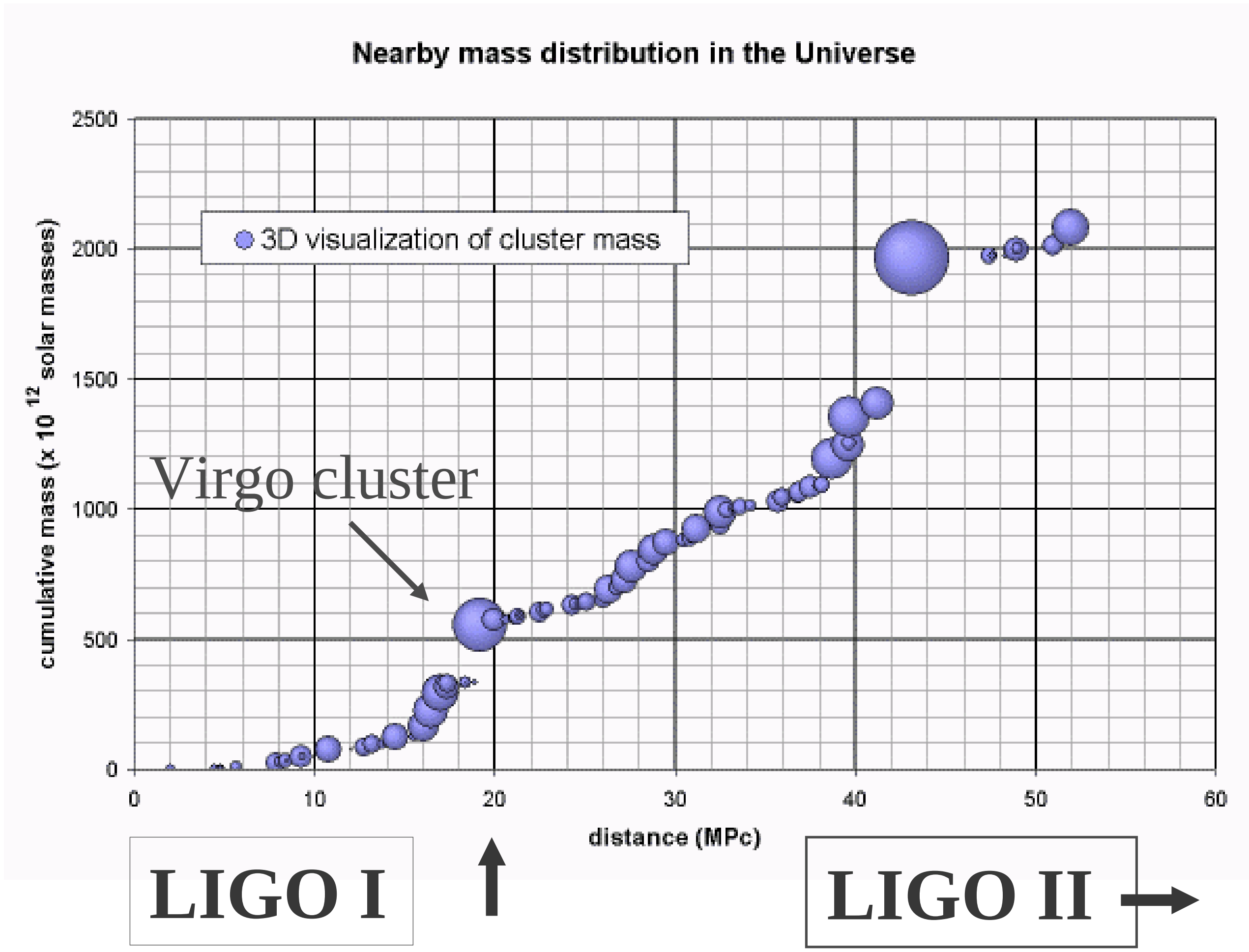
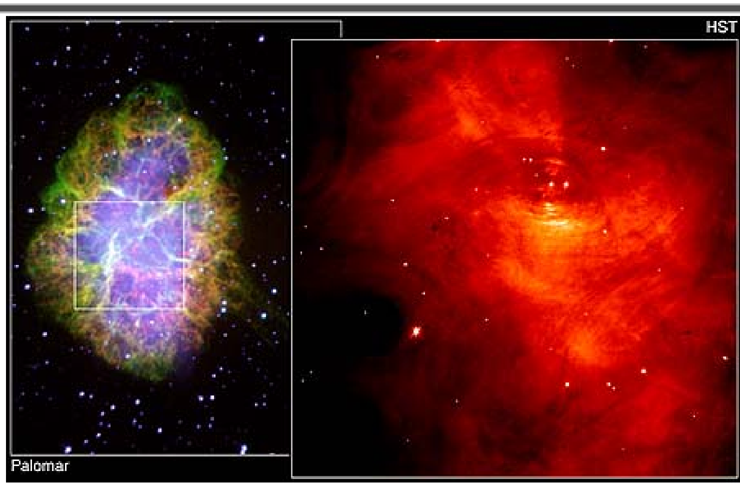
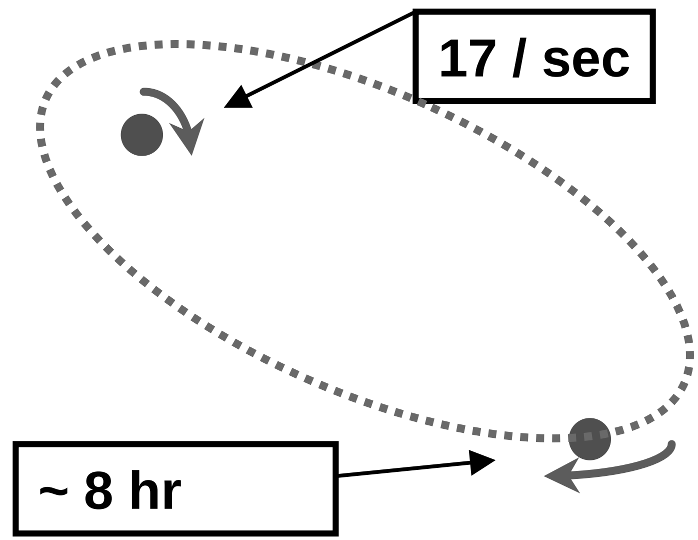


Hulse-Taylor binary pulsar



Neutron Binary System

PSR 1913 + 16 -- Timing of pulsars

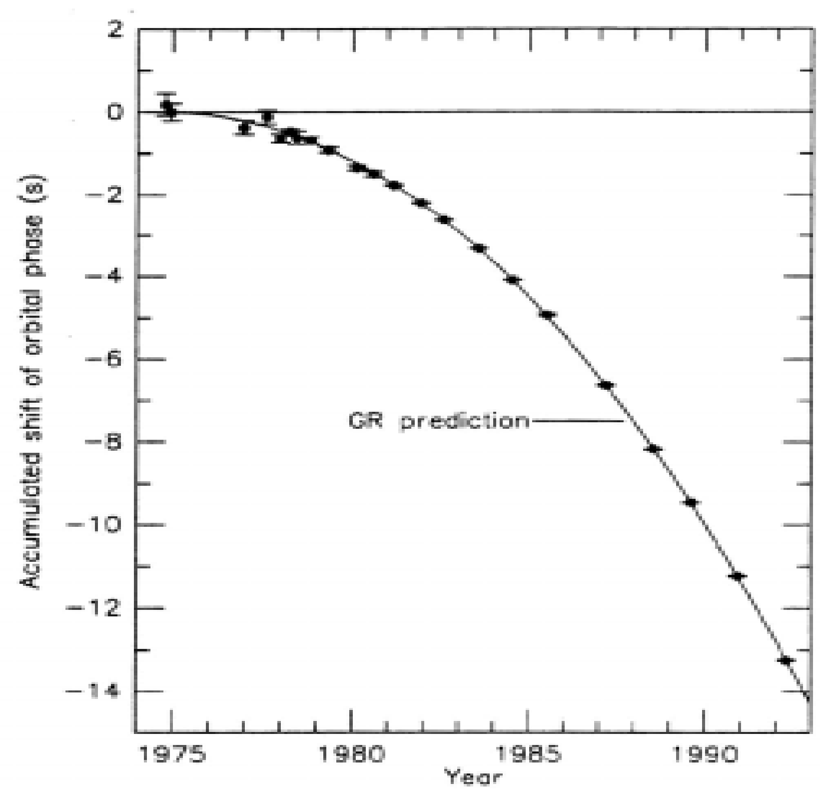


• A rapidly spinning pulsar (neutron star beaming EM radiation at us 17 x / sec)
• orbiting around an ordinary star with 8 hour period
• Only 7 kpc away
• discovered in 1975, orbital parameters measured
• continuously measured over 25 years!

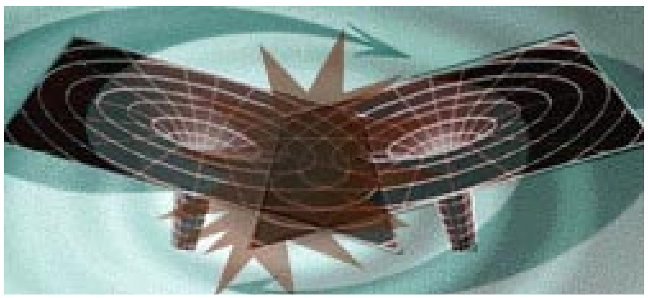
GWs from Hulse-Taylor binary

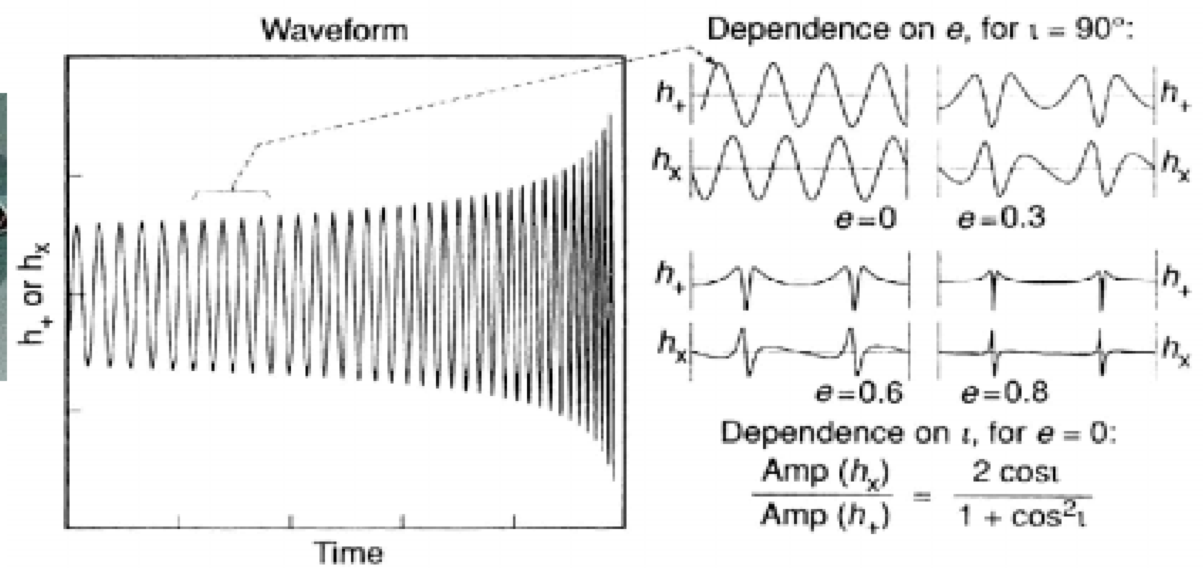
emission of gravitational waves by compact binary system

- **Only 7 kpc away**
- **period speeds up 14 sec from 1975-94**
- **measured to ~50 msec accuracy**
- **deviation grows quadratically with time**
- **Merger in about 300M years**
  - **(<< age of universe!)**
- **shortening of period ⇐ orbital energy loss**
- **Compact system:**
  - **negligible loss from friction, material flow**
- **beautiful agreement with GR prediction**
- **Apparently, loss is due to GWs!**
- **Nobel Prize, 1993**



Chirp signal from Binary Inspiral





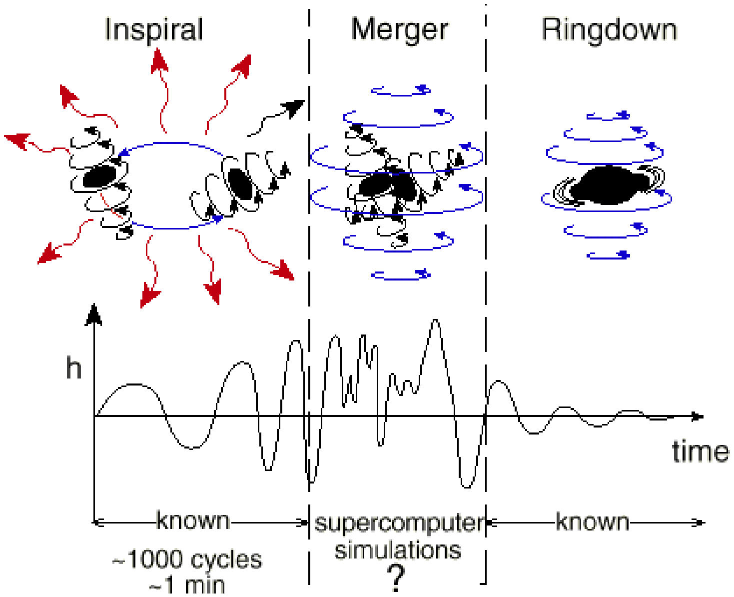
<u>determine</u>

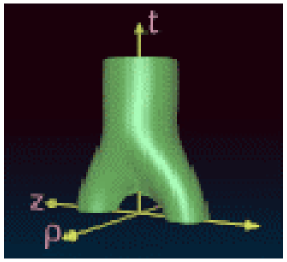
- **distance from the earth r**
- **masses of the two bodies**
- **orbital eccentricity e and orbital inclination *i***

Black holes: computer simulations

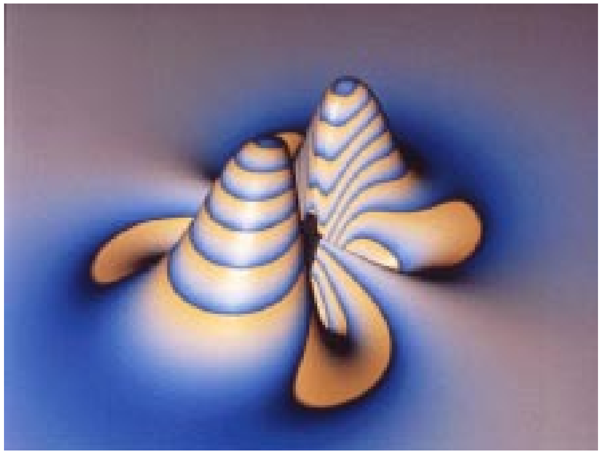
Testing General Relativity in the Strong Field Limit

Distortion of space-time by a black hole



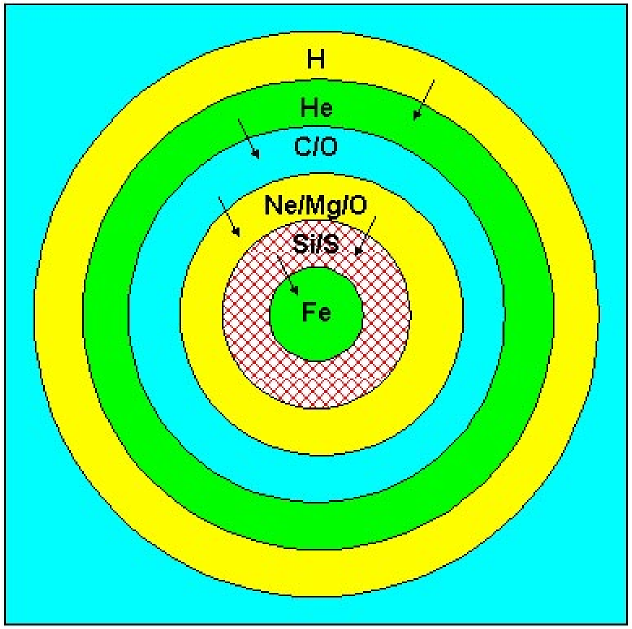


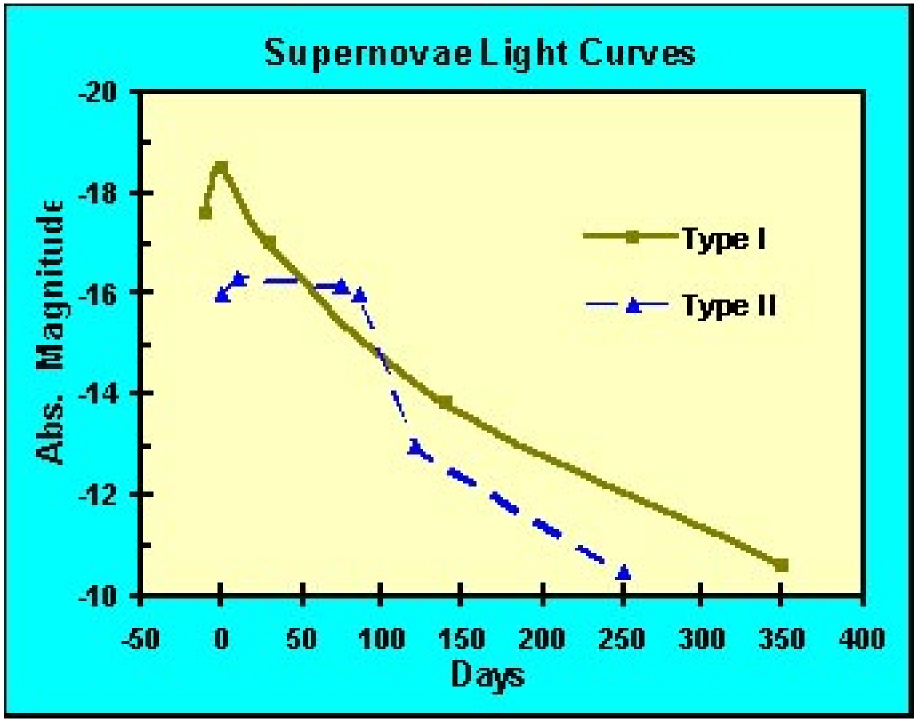
Collision of two black holes



"Grand Challenge" – Supercomputer Project

Supernova collapse

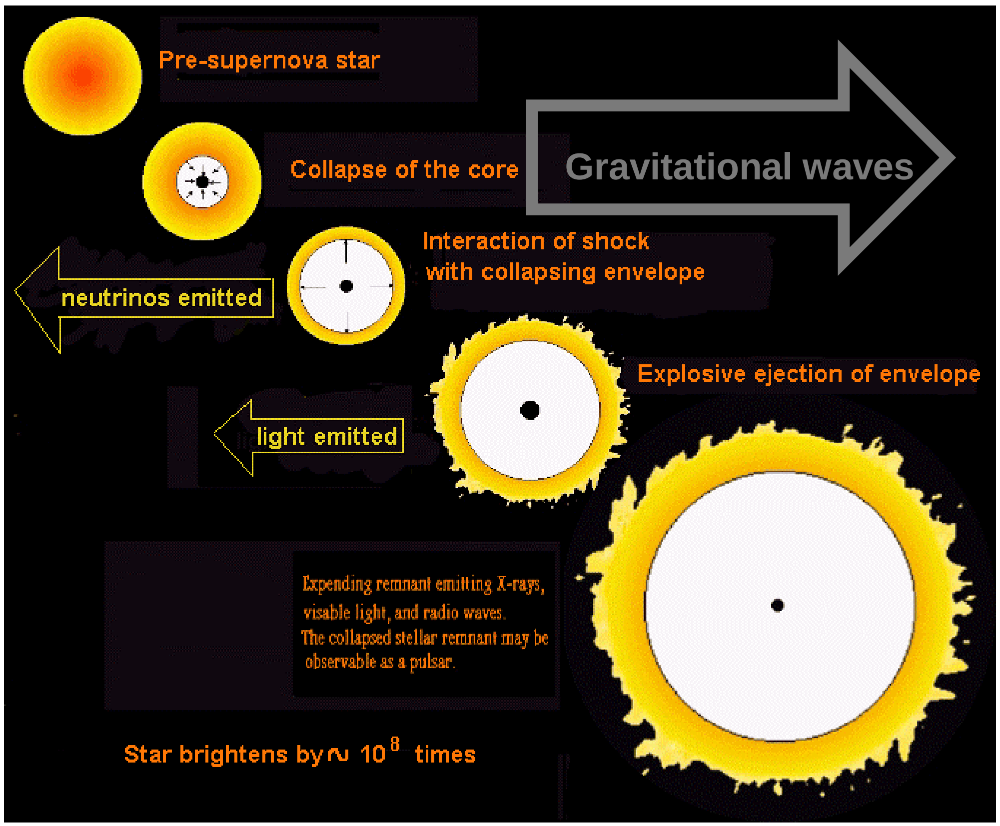




The Collapse

Optical Light Curve

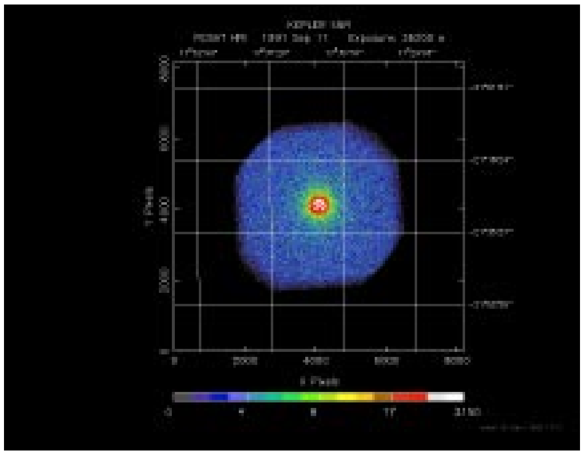
Supernova collapse sequence



- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- After about 0.5 second, the collapsing envelope interacts with the outward shock. Neutrinos are emitted.
- Within 2 hours, the envelope of the star is explosively ejected. When the photons reach the surface of the star, it brightens by a factor of 100 million.
- Over a period of months, the expanding remnant emits X-rays, visible light and radio waves in a decreasing fashion.

Historical Supernova (our galaxy)

Kepler SNR



Crab Nebula 1054 AD

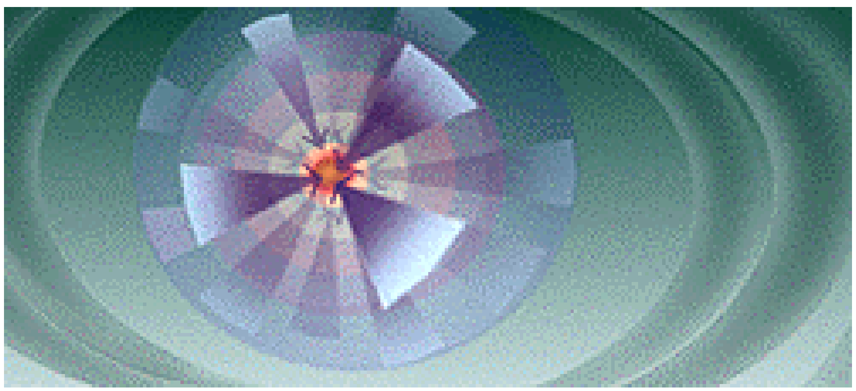
- **SN1006 in Centaurus in the southern sky**
- **SN1054 - The Crab Supernava in Taurus recorded by Chinese and Native American astronomers**
- **SN 1572 -Tycho's Supernova, studied in detail by Tycho Brahe**
- **SN 1604 Kepler's Supernava**
- **+other possible Milky Way supernovae**

Rate

our galaxy	**1/50 years**
within Virgo Cluster	**~ 3 / year**

Gravitational Waves from Supernova collapse

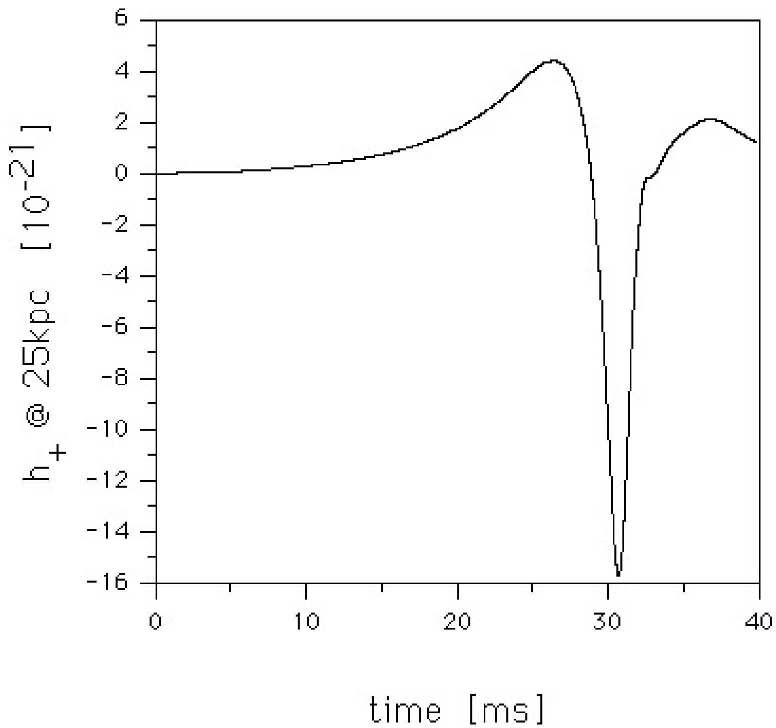
Non axisymmetric collapse



Rate

1/50 yr - our galaxy
3/yr - Virgo cluster

'burst' signal

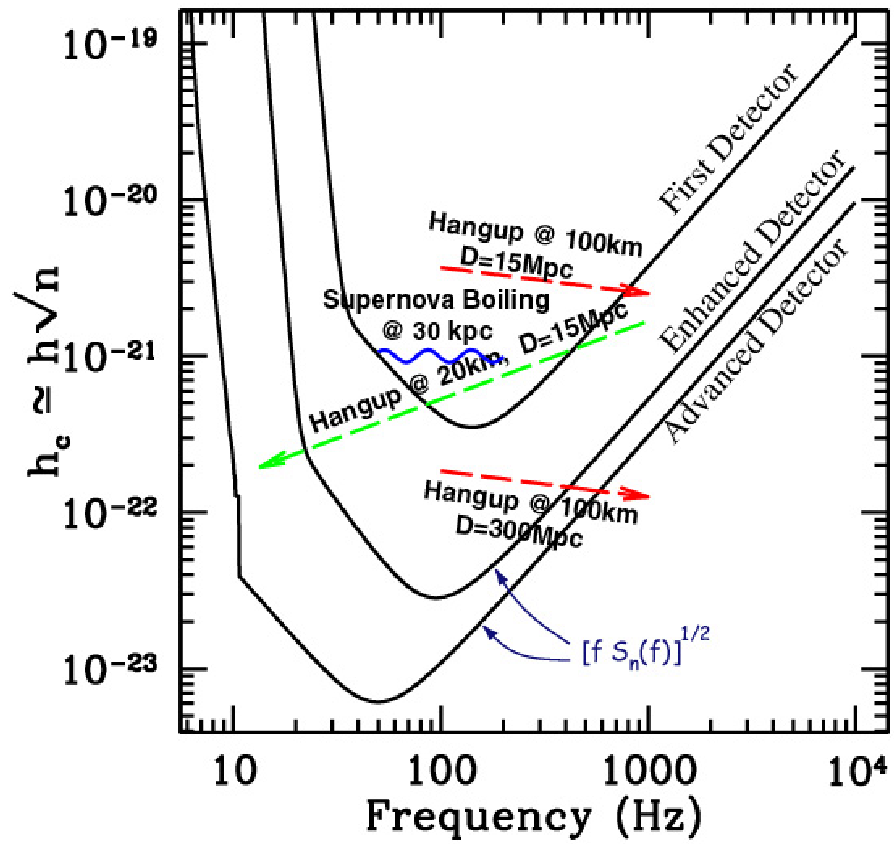


LIGO

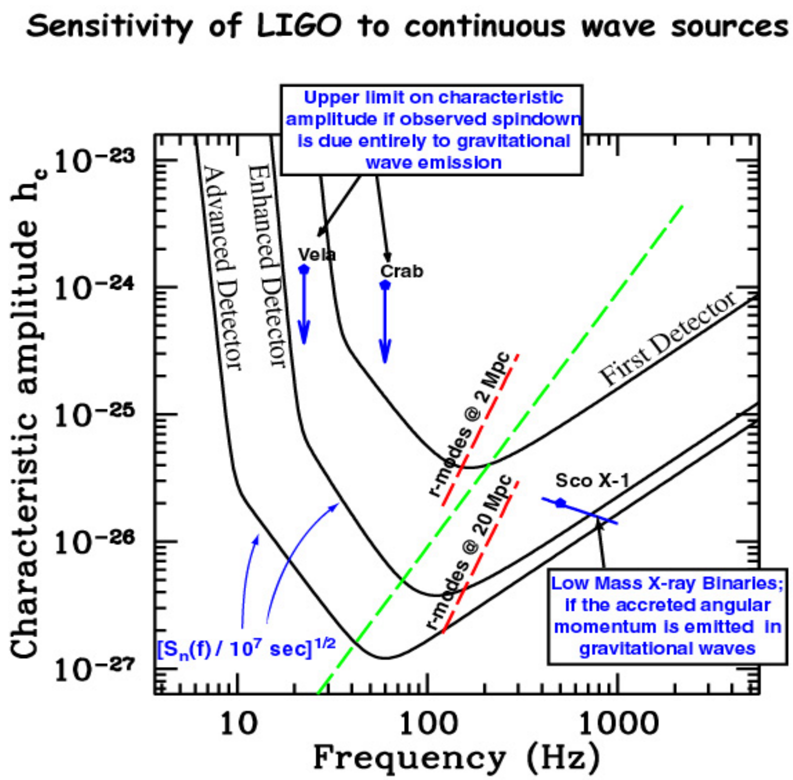
astrophysical sources

SN1987A

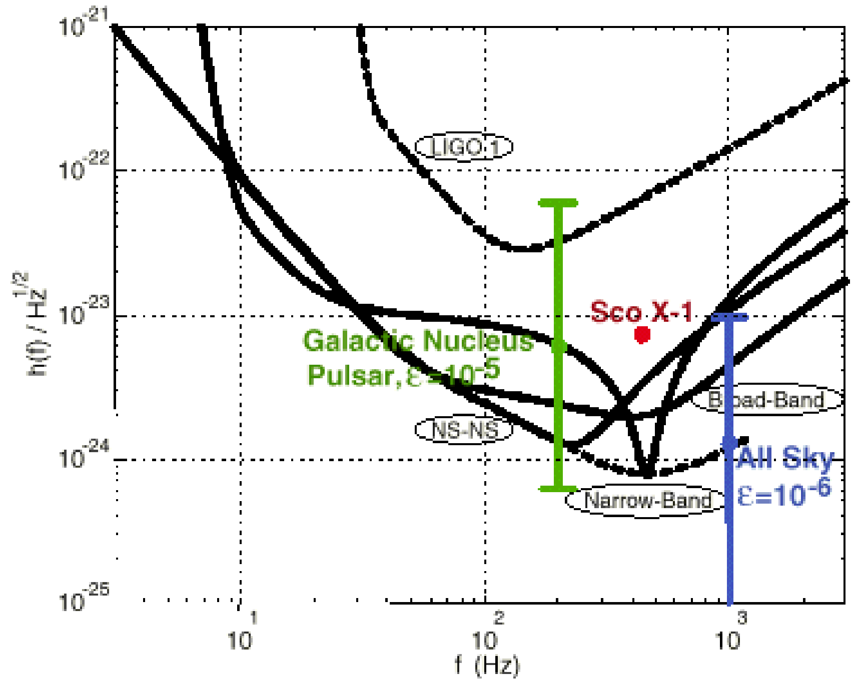
Sensitivity of LIGO to burst sources



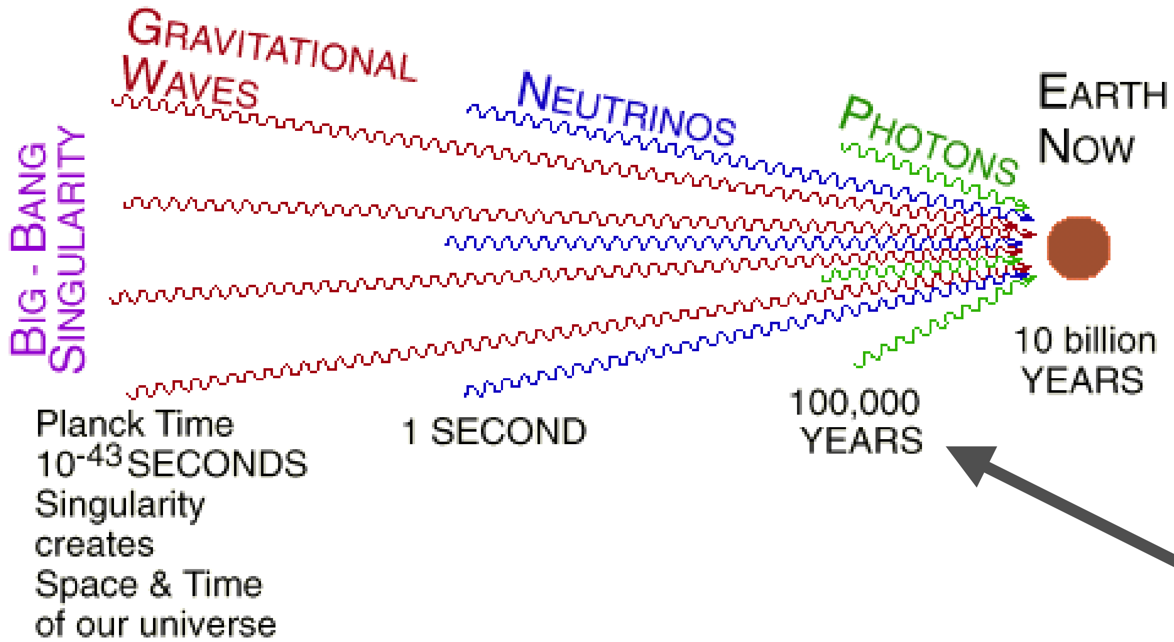
Pulsars and continuous wave sources



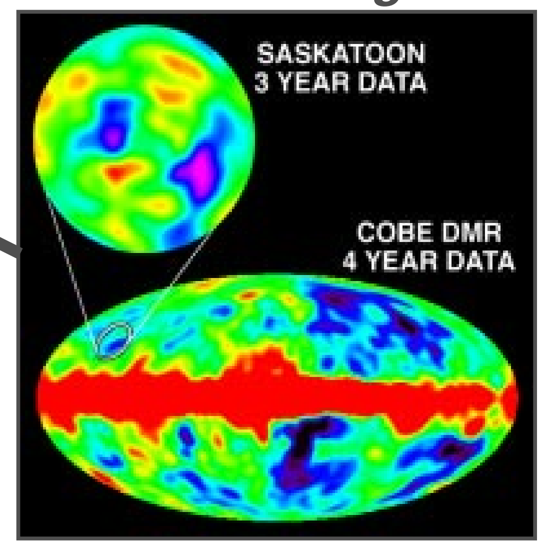
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: neutron star precession; interiors
  - »"R-mode" instabilities
  - »narrow band searches best



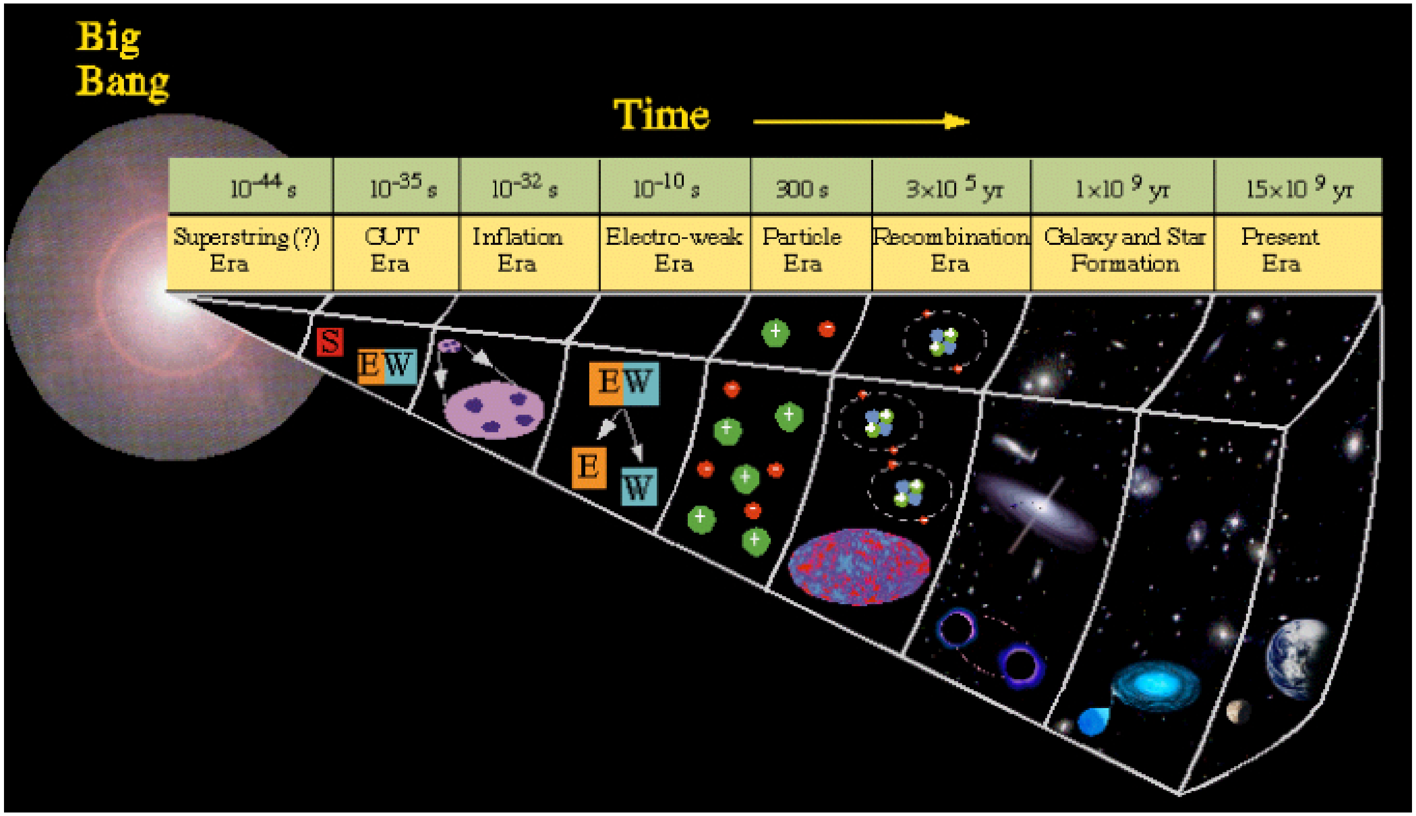
Gravitational waves from Big Bang



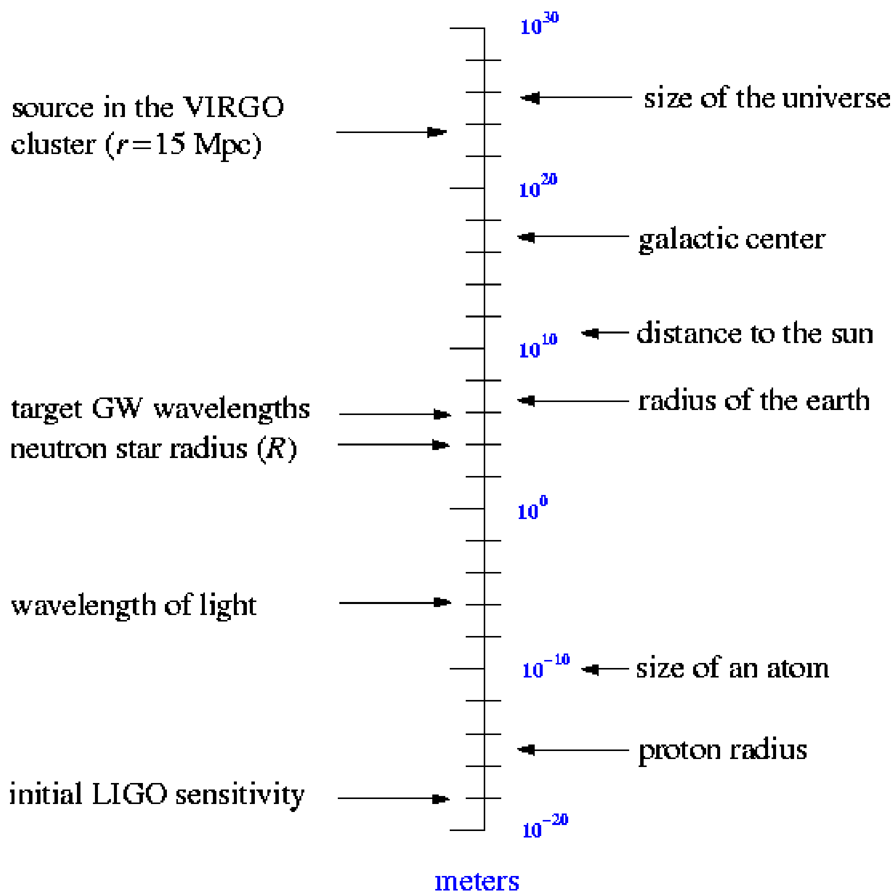
Cosmic microwave background



GWs probe the universe at earliest times after the Big Bang



Scales



10^{30}
size of the universe
source in the VIRGO cluster ($r = 15$ Mpc)
10^{20}
galactic center
distance to the sun
10^{10}
radius of the earth
target GW wavelengths
neutron star radius (R)
10^{0}
wavelength of light
10^{-10}
size of an atom
proton radius
initial LIGO sensitivity
10^{-20}
meters

Gravitational wave detectors

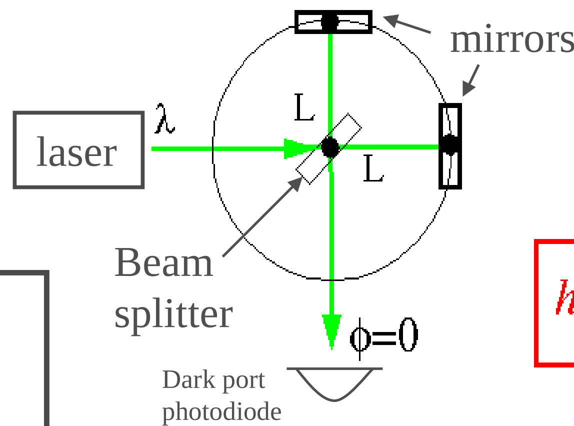
- **Bar detectors**
  - Invented and pursued by Joe Weber in the 60's
  - Essentially, a large "bell", set ringing (at ~ 900 Hz) by GW
  - Won't discuss any further, here
- **Michelson interferometers**
  - At least 4 independent discovery of method:
  - Pirani `56, Gerstenshtein and Pustovoit, Weber, Weiss `72
  - Pioneering work by Weber and Robert Forward, in 60's

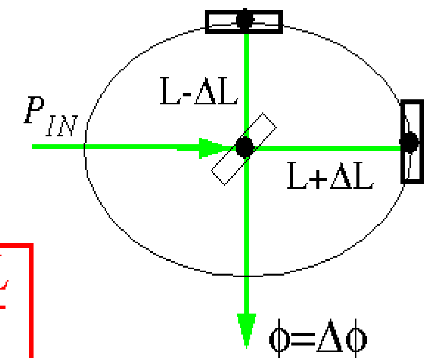
Resonant bar detectors

- AURIGA bar near Padova, Italy
  (typical of some ~6 around the world – Maryland, LSU, Rome, CERN, UWA)
- 2.3 tons of Aluminum, 3m long;
- Cooled to 0.1K with dilution fridge in LiHe cryostat
- $Q = 4\times10^6$ at < 1K
- Fundamental resonant mode at ~900 Hz; narrow bandwidth
- Ultra-low-noise capacitive transducer and electronics (SQUID)

Interferometric detection of GWs

GW acts on freely falling masses:



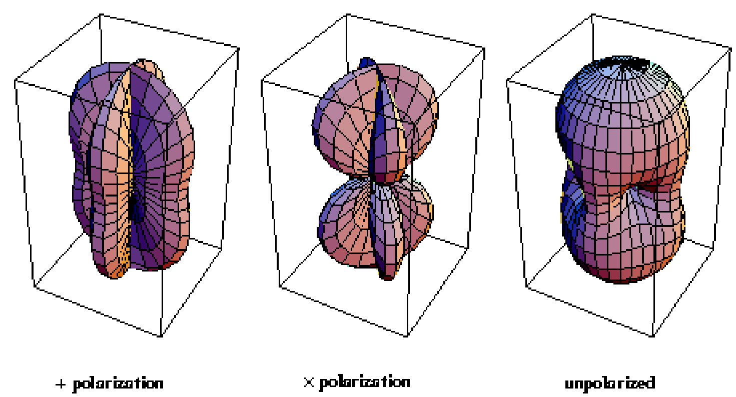


$$h = \frac{\Delta L}{L}$$

$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

For fixed ability to measure ΔL, make L as big as possible!

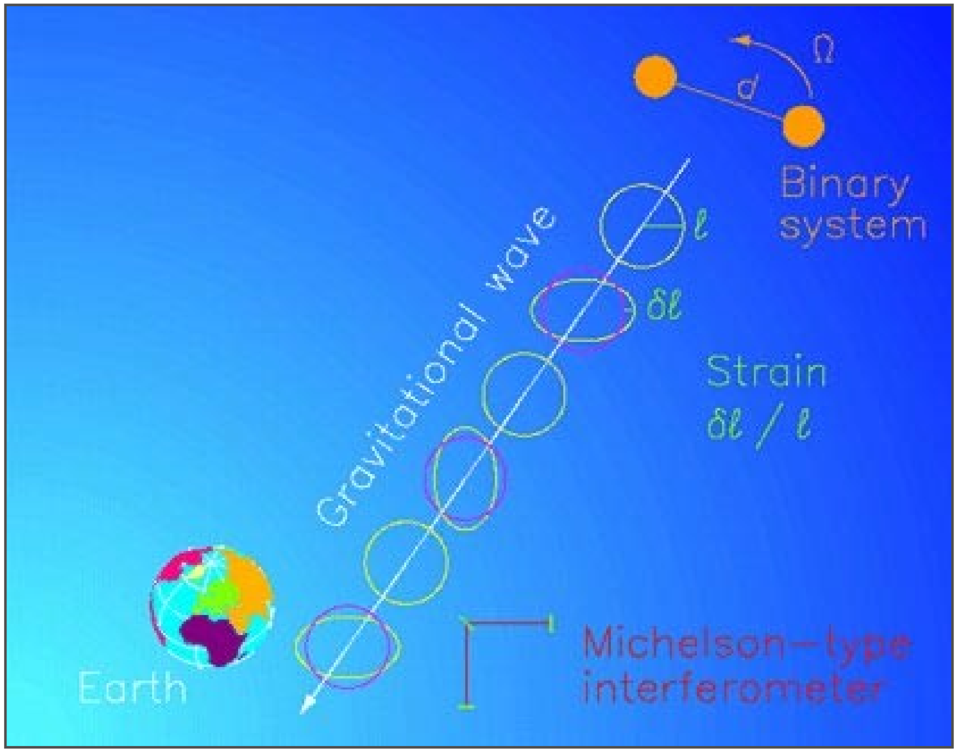
Antenna pattern:
(not very directional!)



Terrestrial Interferometers

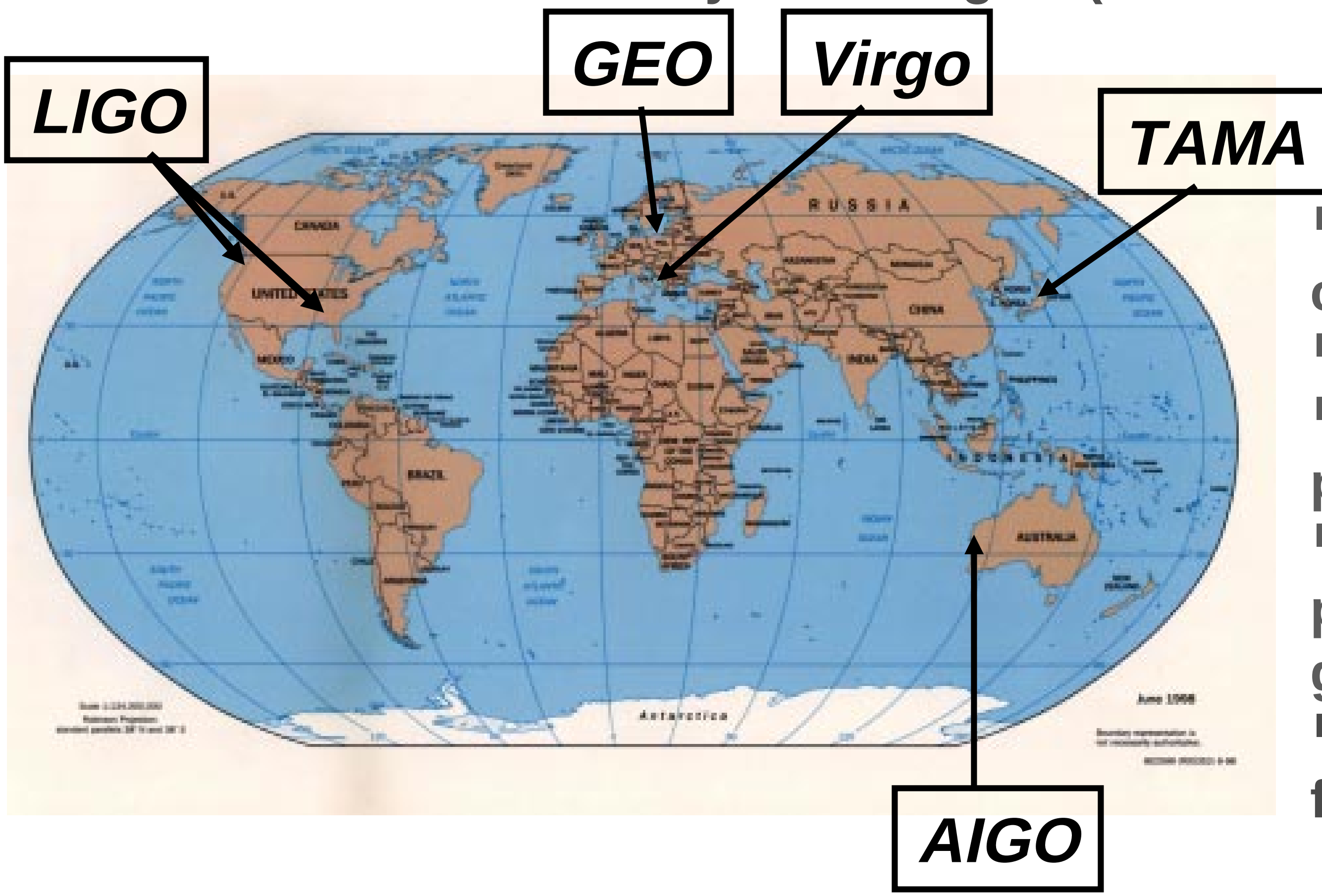
Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

International network (LIGO, Virgo, GEO, TAMA) enable locating sources and decomposing polarization of gravitational waves.



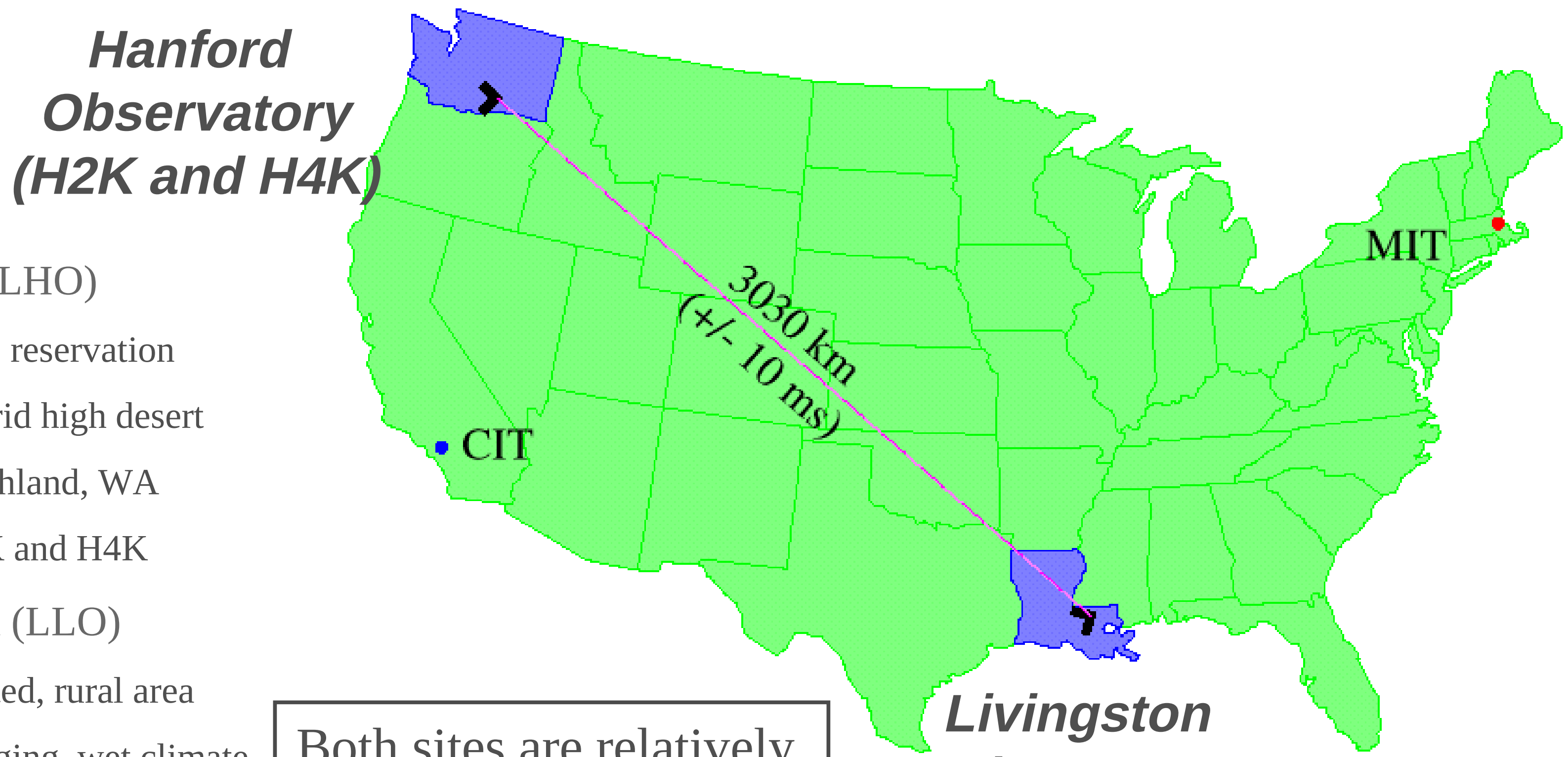
International network

Simultaneously detect signal (within msec)



- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves
- Open up a new field of astrophysics!

LIGO sites



Hanford, WA (LHO)

- located on DOE reservation
- treeless, semi-arid high desert
- 25 km from Richland, WA
- Two IFOs: H2K and H4K

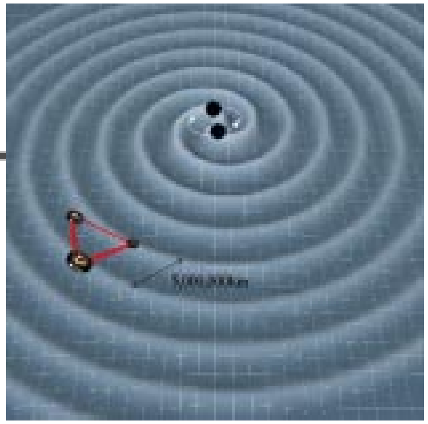
Livingston, LA (LLO)

- located in forested, rural area
- commercial logging, wet climate
- 50km from Baton Rouge, LA
- One L4K IFO

Both sites are relatively seismically quiet, low human noise

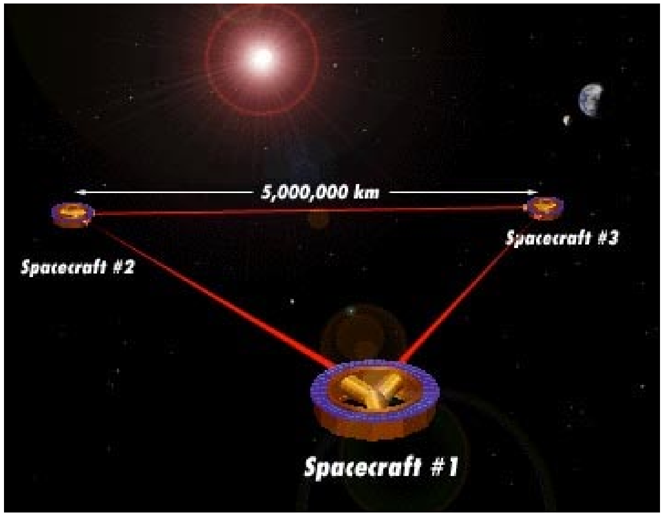
The Laser Interferometer Space Antenna

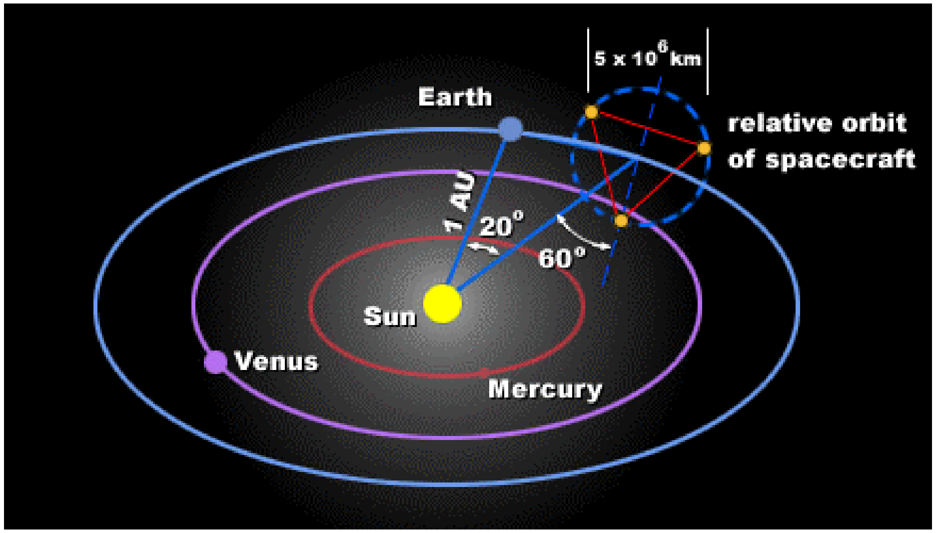
LISA



Three spacecraft in orbit about the sun,
with 5 million km baseline

The center of the triangle formation will be in the ecliptic plane
1 AU from the Sun and 20 degrees behind the Earth.

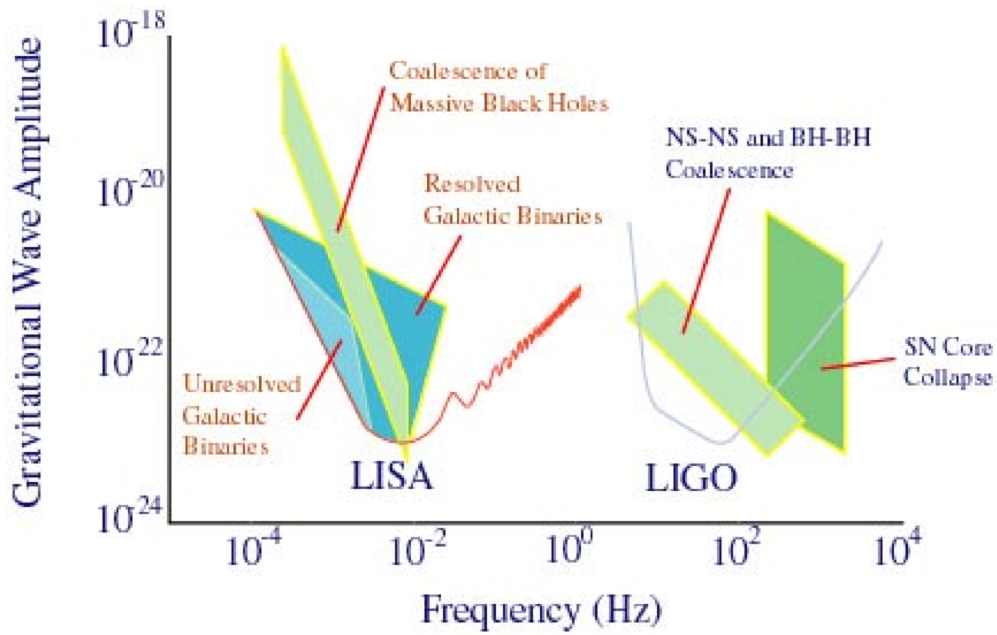




LISA (NASA/JPL, ESA) may fly in the next 10 years!

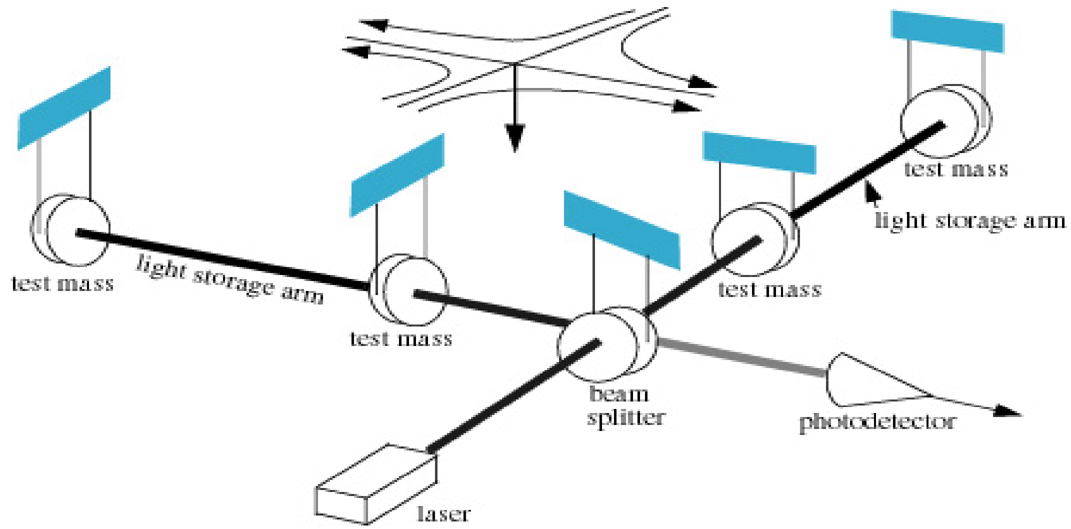
Sensitivity bandwidth

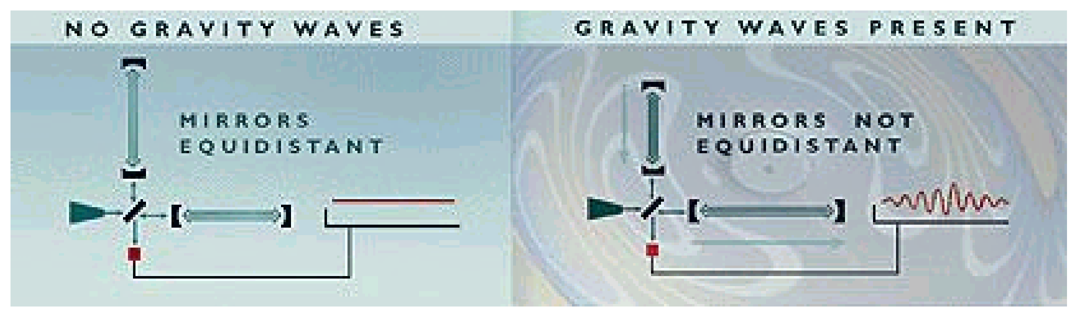
- EM waves are studied over ~20 orders of magnitude
  - » (ULF radio –> HE γ rays)
- Gravitational Waves over ~10 orders of magnitude
  - » (terrestrial + space)



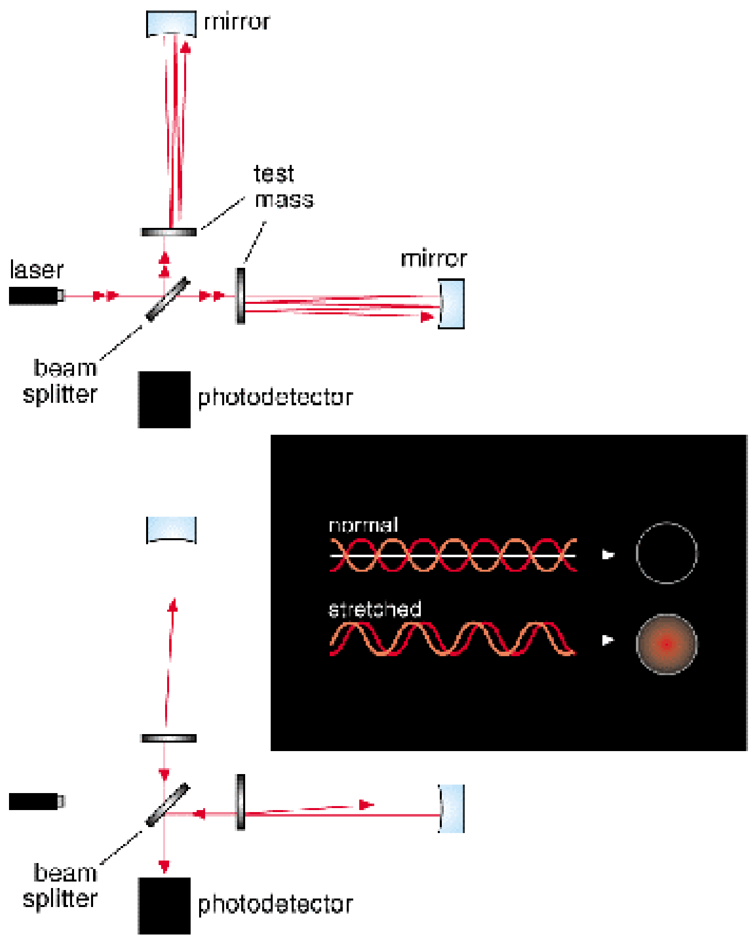
Interferometer for GWs

- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- The interference pattern is measured (or the fringe is split) to one part in 10^{10}, in order to obtain the required sensitivity.





Interferometric phase difference



The effects of gravitational waves appear as a deviation in the phase differences between two orthogonal light paths of an interferometer.

For expected signal strengths, The effect is *tiny*:

Phase shift of ~10^{-10} radians

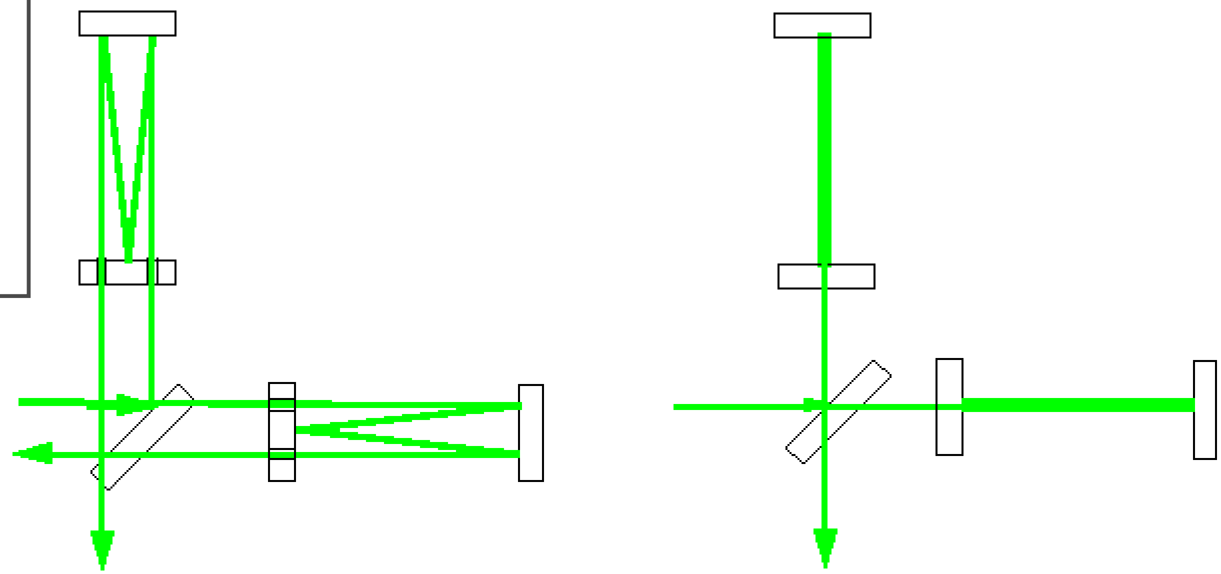
The longer the light path, the larger the phase shift…

Make the light path as long as possible!

Light storage: folding the arms

How to get long light paths without making *huge* detectors:

Fold the light path!



Delay line interferometer

Fabry Perot interferometer

Simple, but requires large mirrors; limited τ_{stor}

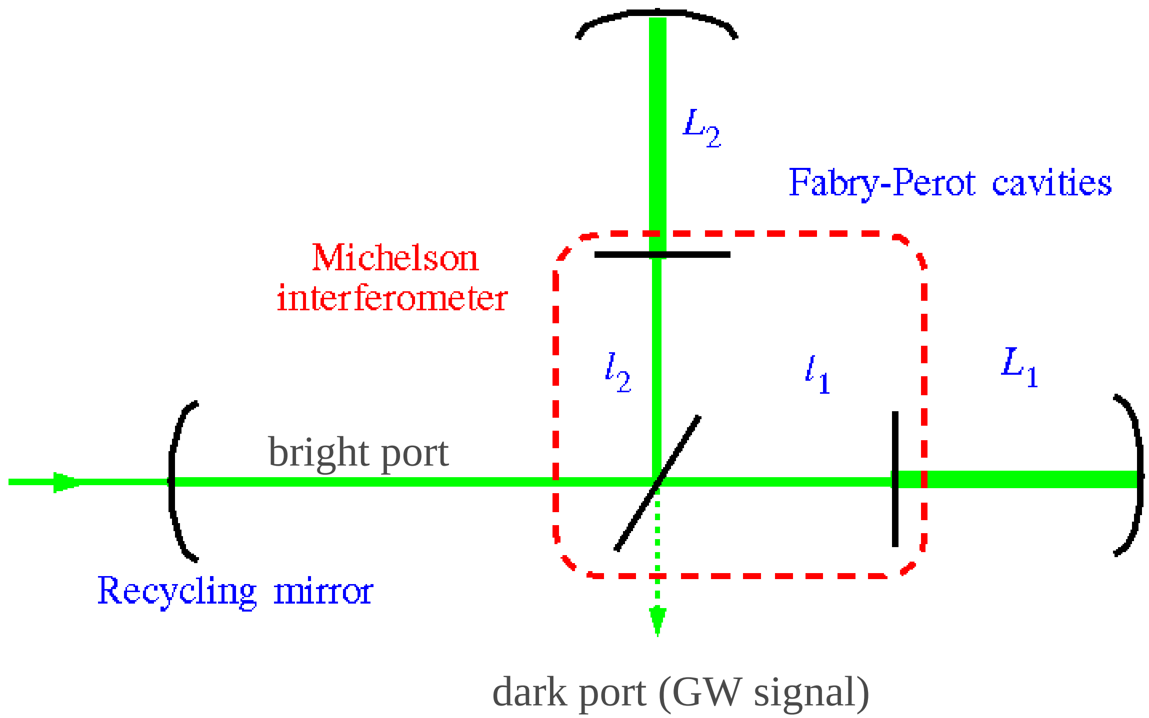
(LIGO design) $\tau_{stor} \sim 3$ *msec*

More compact, but harder to control

LIGO I configuration

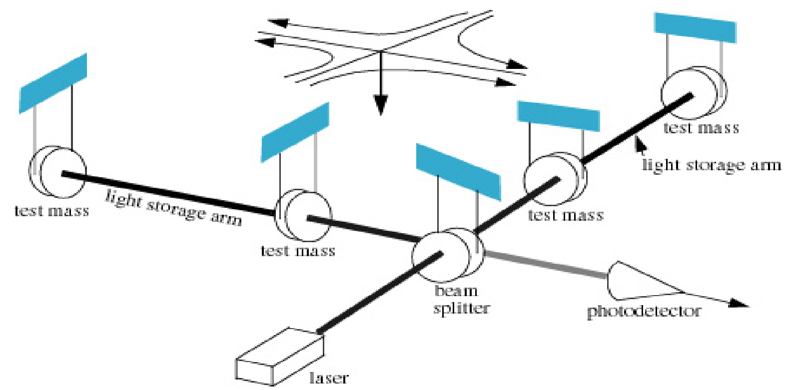
Power-recycled Michelson with Fabry-Perot arms:

- Fabry-Perot optical cavities in the two arms store the light for many (~200) round trips
- Michelson interferometer: change in arm lengths destroy destructive interference, light emerges from dark port
- Normally, light returns to laser at bright port
- Power recycling mirror sends the light back in (coherently!) to be reused

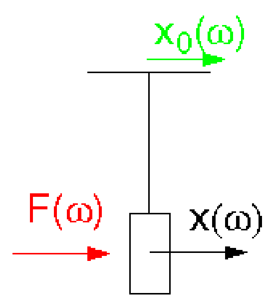


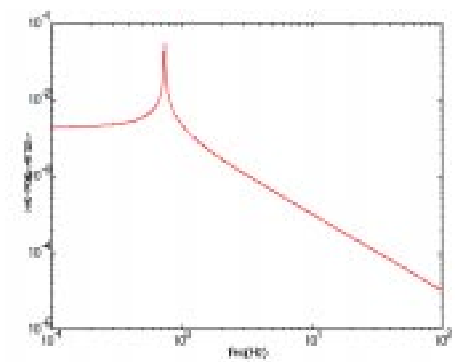
Suspended test masses

- To respond to the GW, test masses must be "free falling"
- On Earth, test masses must be supported against DC gravity field
- The Earth, and the lab, is vibrating like mad at low frequencies (seismic, thermal, acoustic, electrical);
  - can't simply bolt the masses to the table (as in typical ifo's in physics labs)
- So, IFO is insensitive to low frequency GW's
- Test masses are suspended on a pendulum resting on a seismic isolation stack
  - "fixed" against gravity at low frequencies, but
  - "free" to move at frequencies above ~ 100 Hz



"Free" mass:
pendulum at $f \gg f_0$





LIGO Livingston (LLO)

• 30 miles from Baton Rouge, LA (LSU)

• forested, rural area

•Commercial logging, wet climate

• need moats (with alligators)

•Seismically quiet, low human noise level

LIGO Hanford (LHO)

- DOE nuclear reservation
- treeless, semi-arid high desert
- 15 miles from Richmond, WA
- Seismically quiet, low human noise level

LIGO *Beam Tube*

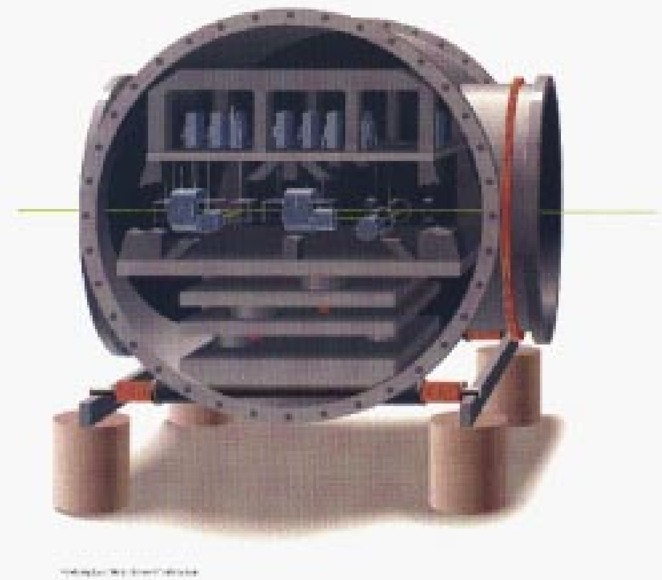
Beam light path must be high vacuum, to minimize “phase noise”

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

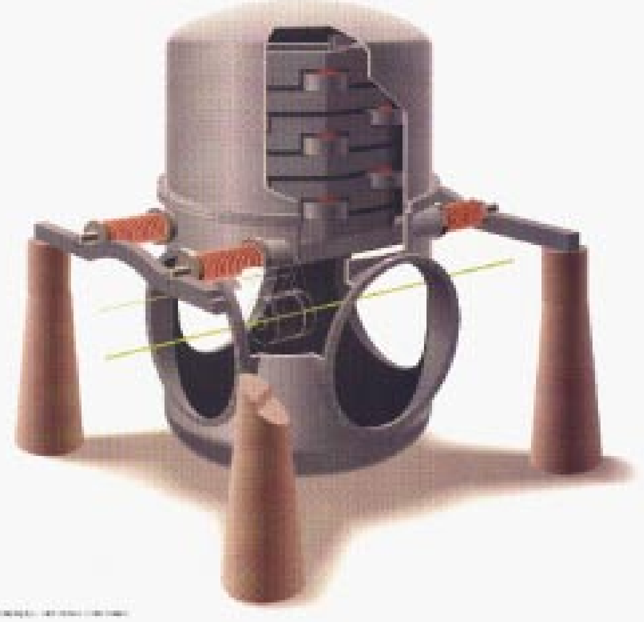
LIGO vacuum equipment

All optical components must be in high vacuum, so mirrors are not "knocked around" by gas pressure

LIGO Vacuum Chambers

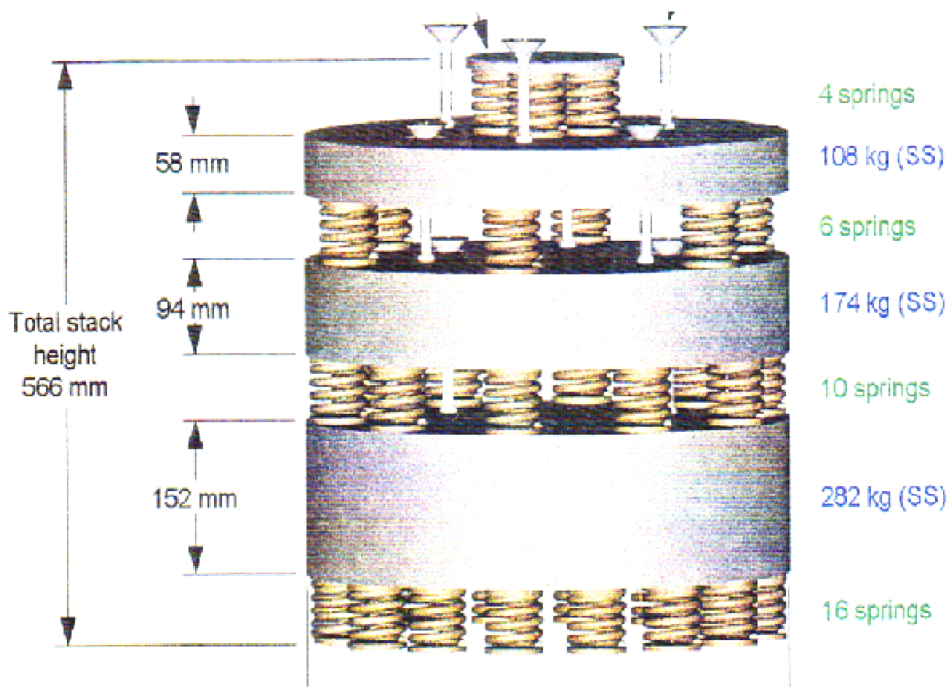


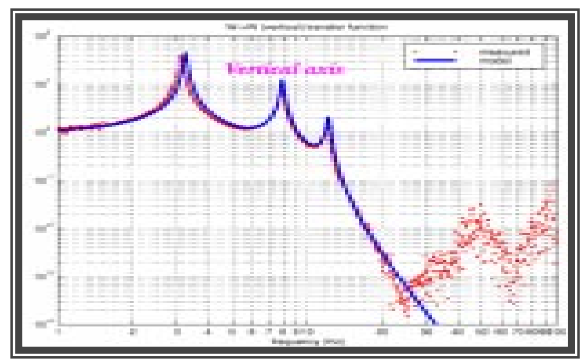
HAM Chambers



BSC Chambers

Seismic isolation stacks

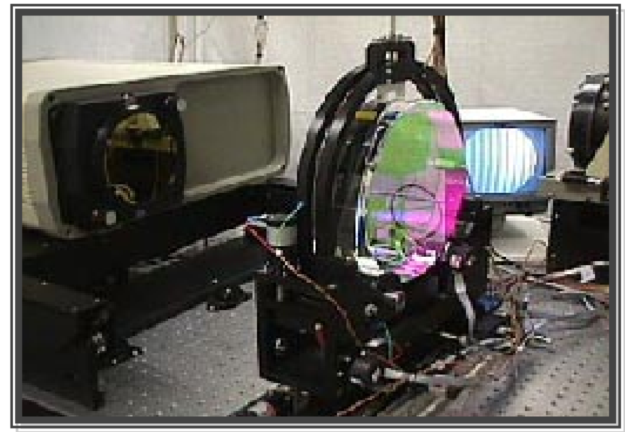




LIGO Optics

mirrors, coating and polishing

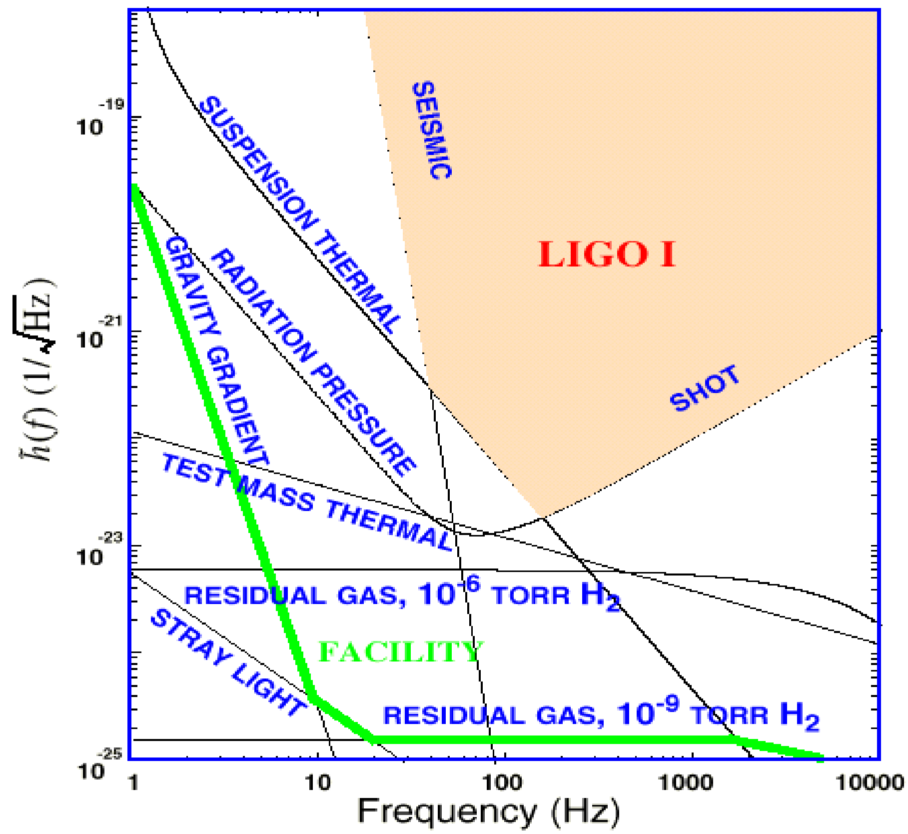
- SUPERmirrors:
  - » High uniformity fused silica quartz
  - » reflectivity as high as 99.999%
  - » losses < 1 ppm in coating, 10 ppm in substrate
  - » polished with mircoroughness < $\lambda/1800 \approx 0.5$ nm
  - » and ROC within spec.
  - ≈ ($\delta R/R < 5\%$, except for BS)
- Suspensions: hang 10kg optic by a single loop of wire, and hold it steady at low *f*, with feedback system
- Mirrors are at room temperature, so they vibrate, producing phase noise



LIGO I noise floor

- **Interferometry is limited by three fundamental noise sources**
  - **<u>seismic noise</u> at the lowest frequencies**
  - **<u>thermal noise</u> at intermediate frequencies**
  - **<u>shot noise</u> at high frequencies**

- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**



Detection Confidence

With all the noise faking GW signals,

How can we be sure we've seen the real thing (*for first time*!)?

Multiple interferometers – coincidence!

- three interferometers within LIGO
  - 4 km at Hanford, 4 km at Livingston
  - also 2 km at Hanford
- absolute timing accuracy of 10 microsec
  - 10 msec light travel time between sites
- AND: other detectors (interferometers, bars)

Environmental Monitoring

- Try to eliminate locally all possible false signals
- Detectors for many possible sources
  - seismic, acoustic, electromagnetic, muon
- Also trend (slowly-varying) information
  - tilts, temperature, weather

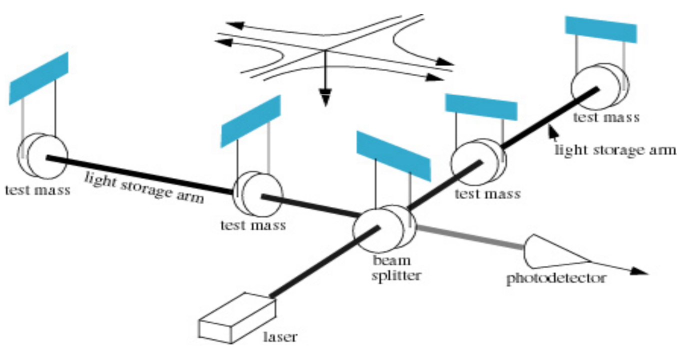
Detection computation

- coincidences (lack of inconsistency) among detectors
  - also non-GW: e.g., optical, γ-ray , X-ray, neutrino
- matched filter techniques for `known' signals
- correlations for broad-band suspects
- deviations from explicable instrumental behavior

LIGO I schedule

1995	NSF funding secured ($360M)
1996	Construction Underway (mostly civil)
1997	Facility Construction (vacuum system)
1998	Interferometer Construction (complete facilities)
1999	Construction Complete (interferometers in vacuum)
2000	Detector Installation (commissioning subsystems)
2001	Commission Interferometers (first coincidences)
2002	Sensitivity studies (initiate LIGO I Science Run)
2003+	LIGO I data run (one year integrated data at $h \sim 10^{-21}$)
2005	Begin LIGO II upgrade installation

Einstein's Symphony



- Space-time of the universe is (presumably!) filled with vibrations: Einstein's Symphony
- LIGO will soon 'listen' for Einstein's Symphony with gravitational waves, permitting
  - » Basic tests of General Relativity
  - » A new field of astronomy and astrophysics
- A new window on the universe!