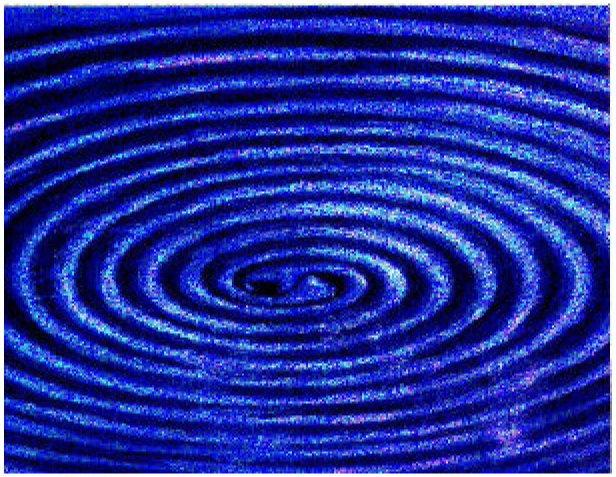
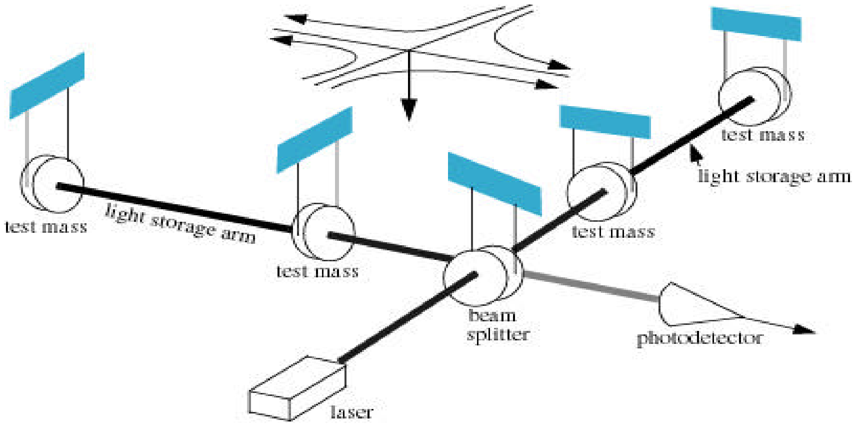
Gravitational Waves and LIGO

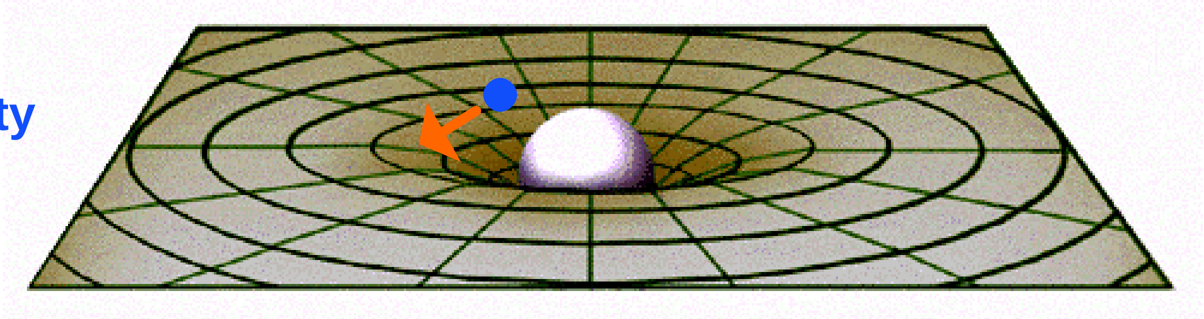
- What is a gravitational wave?
- Astrophysical sources
- Gravitational wave interferometers
- LIGO and its sister projects
- Progress report





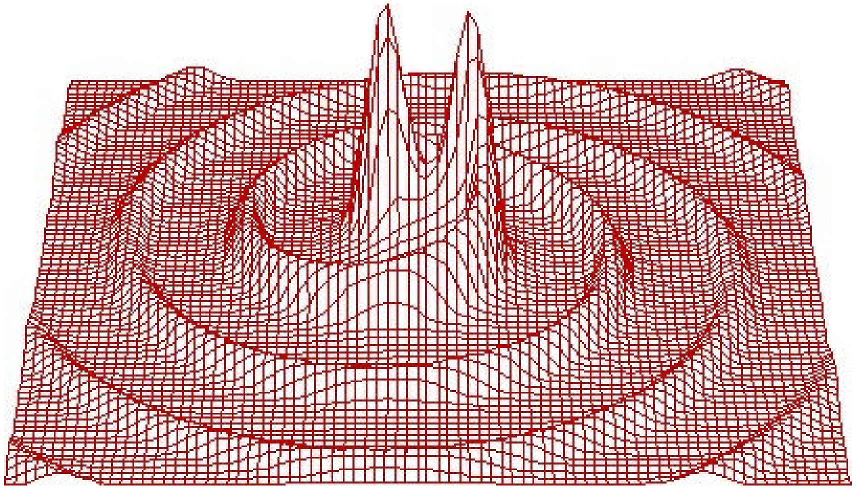
Alan Weinstein, Caltech

Gravitational Waves



Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.

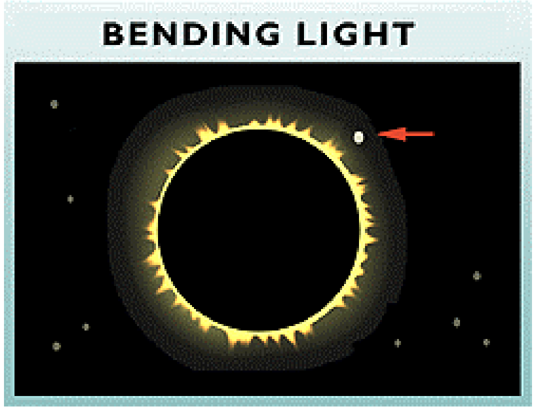
Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.



If the source is moving
(at speeds close to c),
eg, because it's orbiting a companion,
the "news" of the changing
gravitational field propagates outward
as gravitational radiation –
a wave of spacetime curvature

Einstein’s Theory of Gravitation

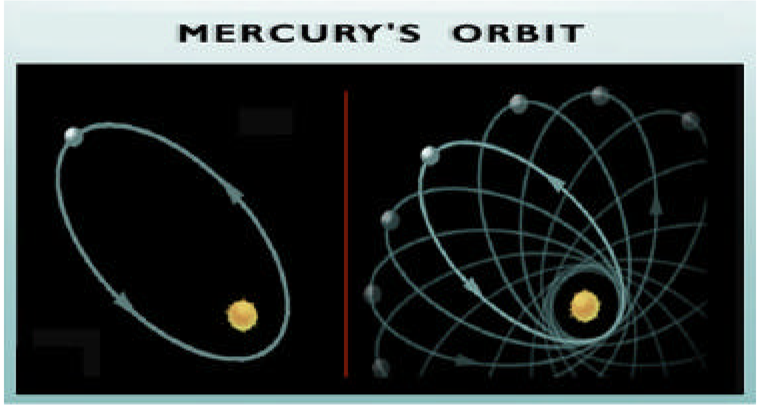
experimental tests



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”

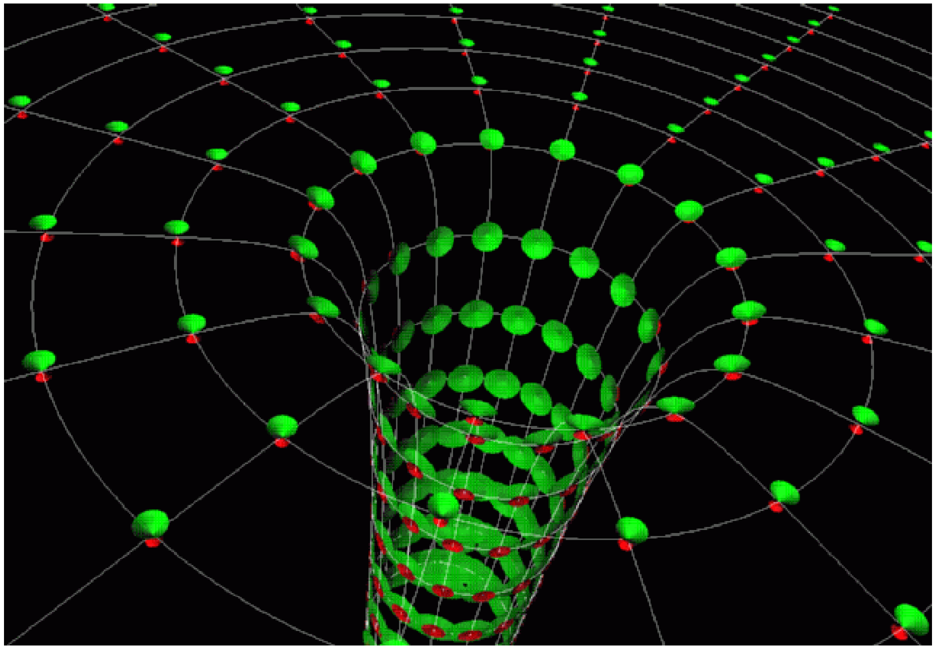
The bending of light rays

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

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

Nature of Gravitational Radiation

General Relativity predicts :

- transverse space-time distortions, freely propagating at speed of light

  mass of graviton = 0

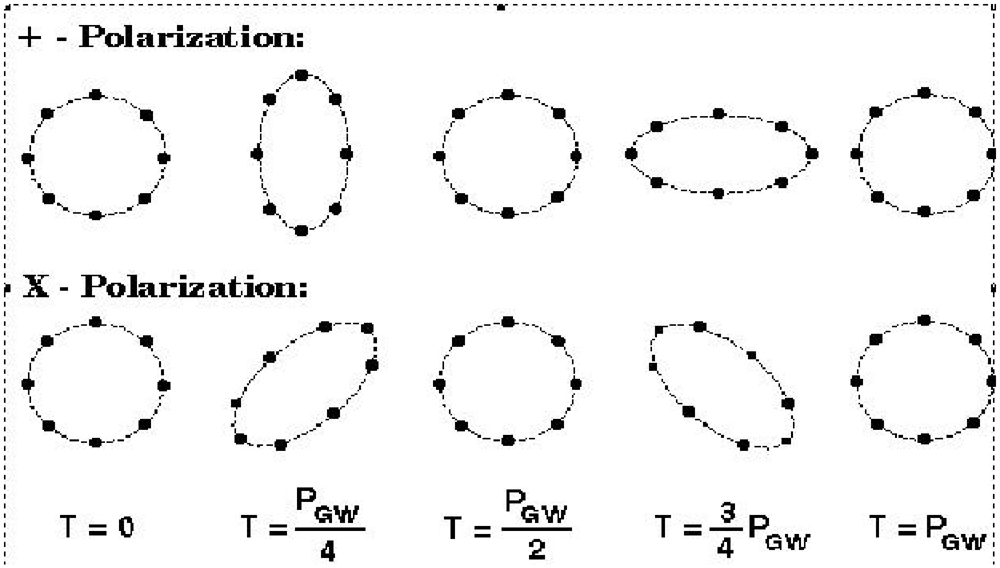
- Stretches and squashes space between “test masses” – strain

$$\boxed{h = \Delta L / L}$$

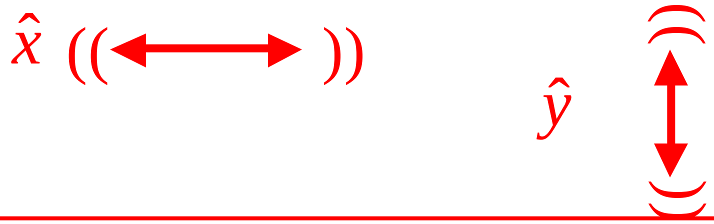
- Conservation laws:
  - cons of energy ⇒ no monopole radiation
  - cons of momentum ⇒ no dipole radiation
  - quadrupole wave (spin 2) ⇒ two polarizations

plus (⊕) and cross (⊗)

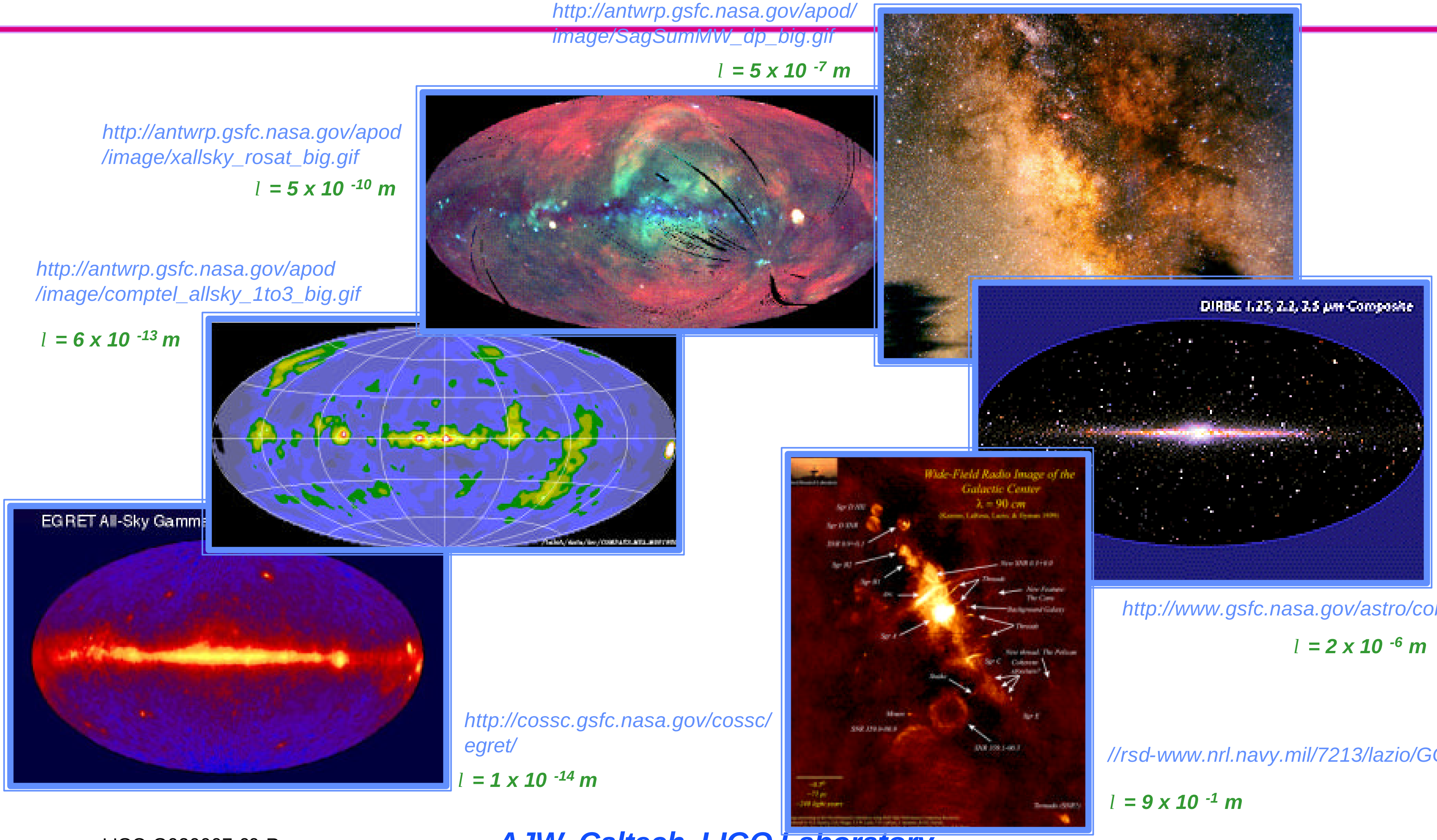
Spin of graviton = 2



Contrast with EM dipole radiation:



Observing the Galaxy with Different Electromagnetic Wavelengths



http://antwrp.gsfc.nasa.gov/apod/image/SagSumMW_dp_big.gif

$\lambda = 5 \times 10^{-7}$ m

http://antwrp.gsfc.nasa.gov/apod/image/xallsky_rosat_big.gif

$\lambda = 5 \times 10^{-10}$ m

http://antwrp.gsfc.nasa.gov/apod/image/comptel_allsky_1to3_big.gif

$\lambda = 6 \times 10^{-13}$ m

http://cossc.gsfc.nasa.gov/cossc/egret/

$\lambda = 1 \times 10^{-14}$ m

http://www.gsfc.nasa.gov/astro/cobe

$\lambda = 2 \times 10^{-6}$ m

//rsd-www.nrl.navy.mil/7213/lazio/GC/

$\lambda = 9 \times 10^{-1}$ m

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

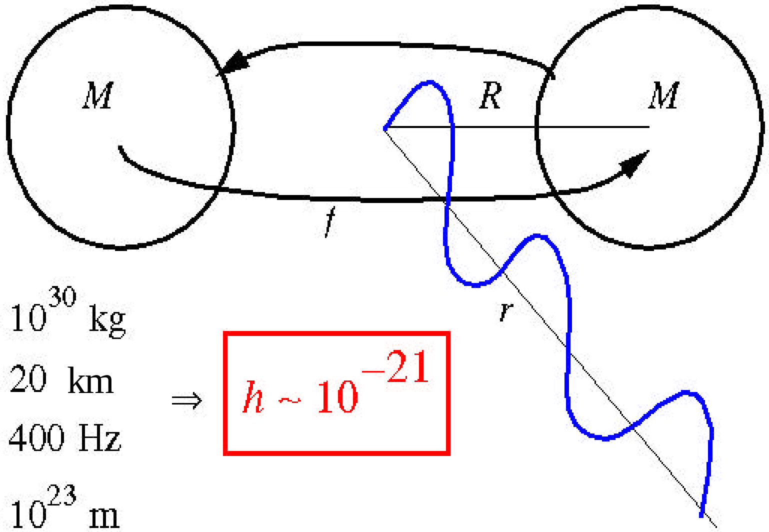
- Very different information, mostly mutually exclusive
- Difficult to predict GW sources based on E&M observations
- GW astronomy is a totally new and unique window on the universe

Sources of GWs

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

$$h_{mn} = \frac{2G}{c^4 r}\ddot{I}_{mn} \quad \Rightarrow \quad h \approx \frac{4p^2 GMR^2 f_{orb}^2}{c^4 r}$$

- $\ddot{I}_{mn}$ = 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:

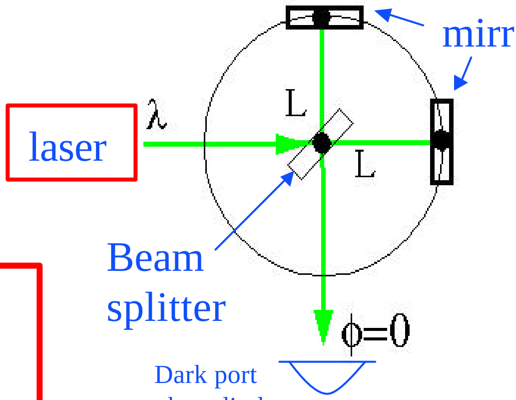


$$\begin{aligned} M &\sim 10^{30}\ \text{kg} \\ R &\sim 20\ \text{km} \\ f &\sim 400\ \text{Hz} \\ r &\sim 10^{23}\ \text{m} \end{aligned} \quad \Rightarrow \quad \boxed{h \sim 10^{-21}}$$

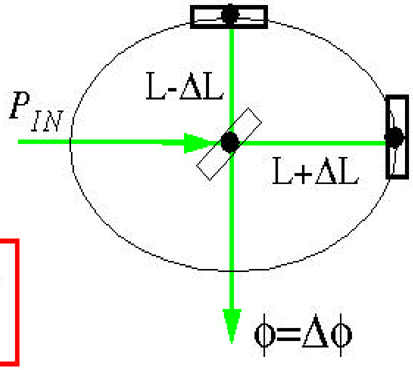
Terrestrial sources *TOO WEAK!*

Interferometric detection of GWs

GW acts on freely falling masses:



mirrors

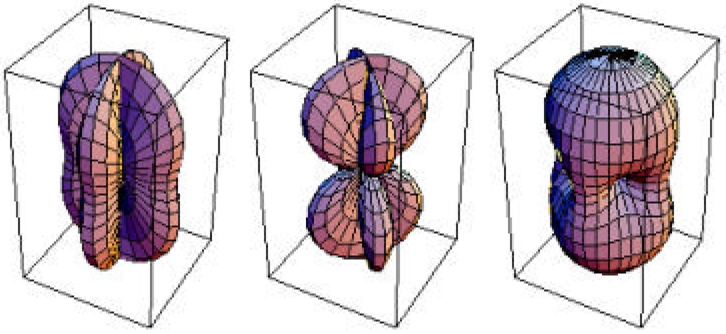


$$h = \frac{\Delta L}{L}$$

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

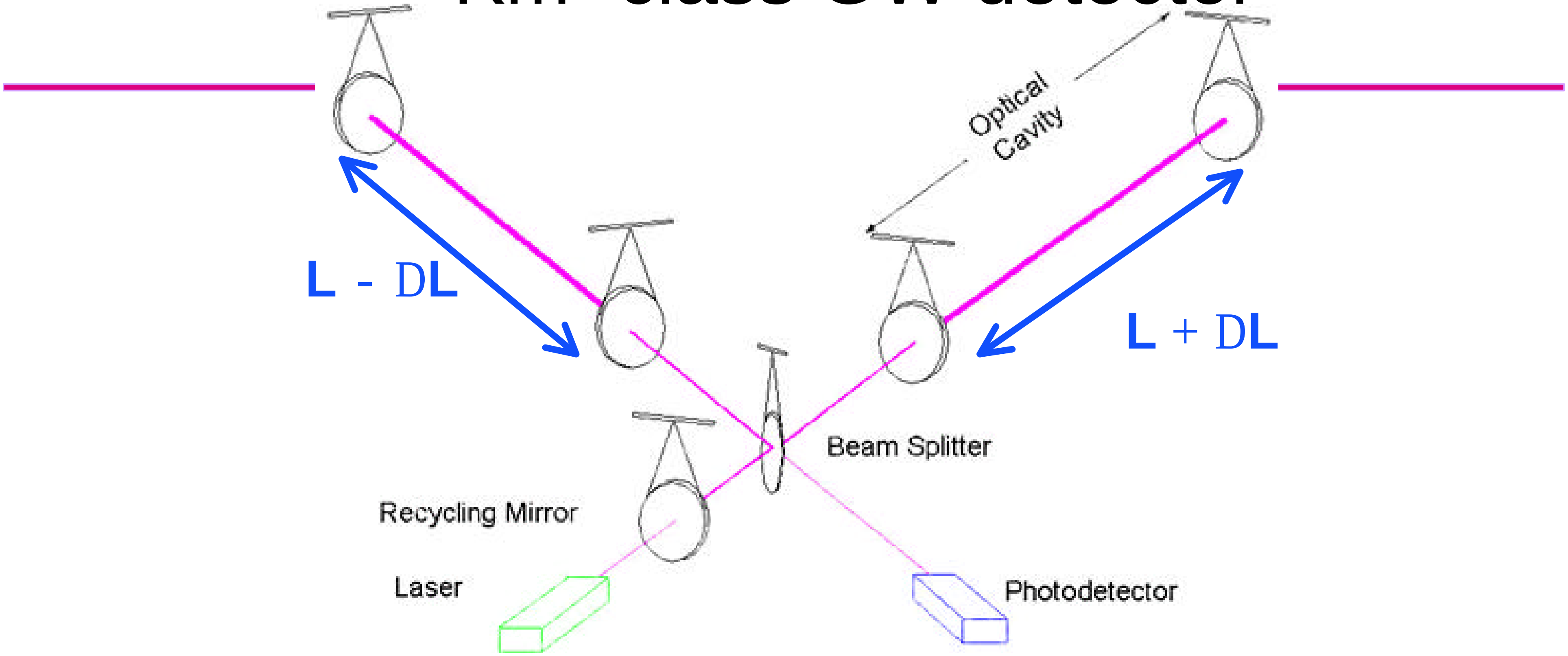
For fixed ability to measure *DL*, make *L* as big as possible!

Antenna pattern:
(not very directional!)

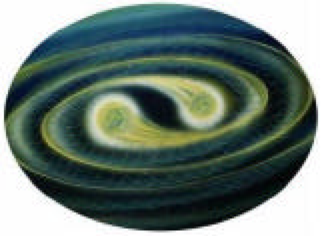


+ polarization × polarization unpolarized

LIGO – the first Km- class GW detector



$$\Delta L = \underset{\lesssim 10^{-21}}{h}\ \underset{4\ \text{km}}{L} \lesssim 4\times10^{-16}\ \text{cm}$$



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)

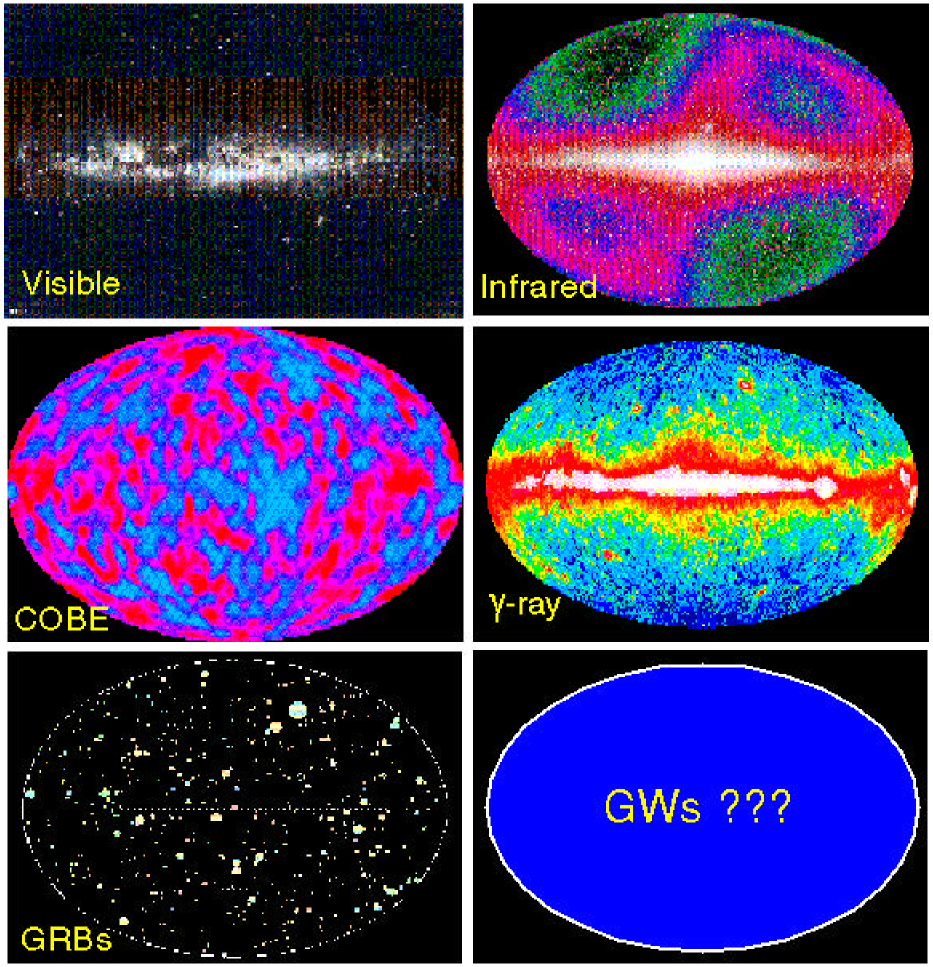
Observatory characteristics

- 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

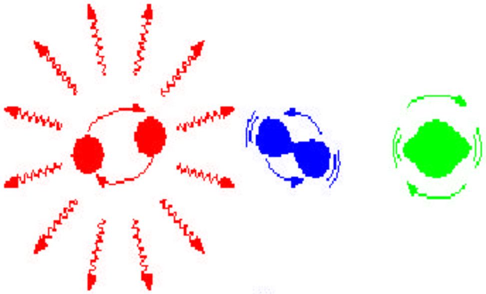
What will we see?



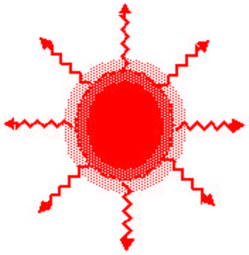
A NEW WINDOW
ON THE UNIVERSE
WILL OPEN UP
FOR EXPLORATION.
BE THERE!

Astrophysical Sources of Gravitational Waves

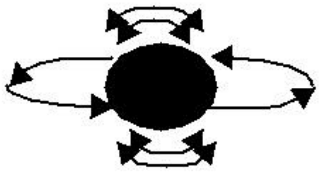
Coalescing compact binaries
(neutron stars, black holes)



Non-axi-symmetric
supernova collapse

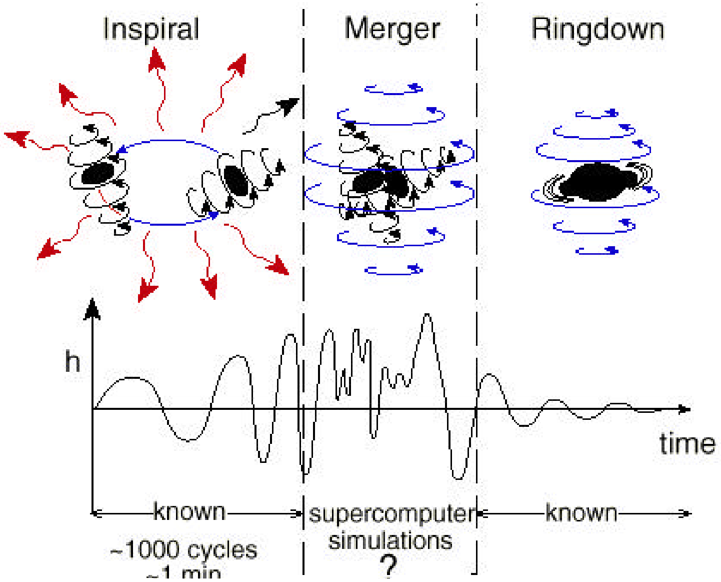


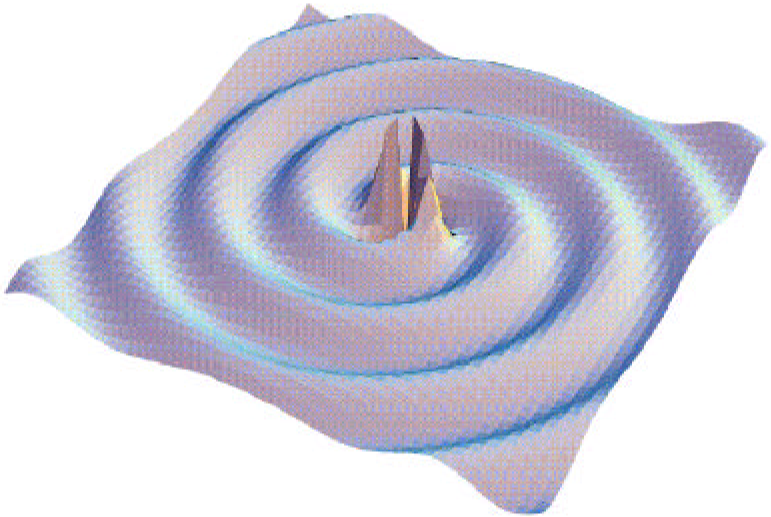
Non-axi-symmetric pulsar
(rotating, beaming
neutron star)



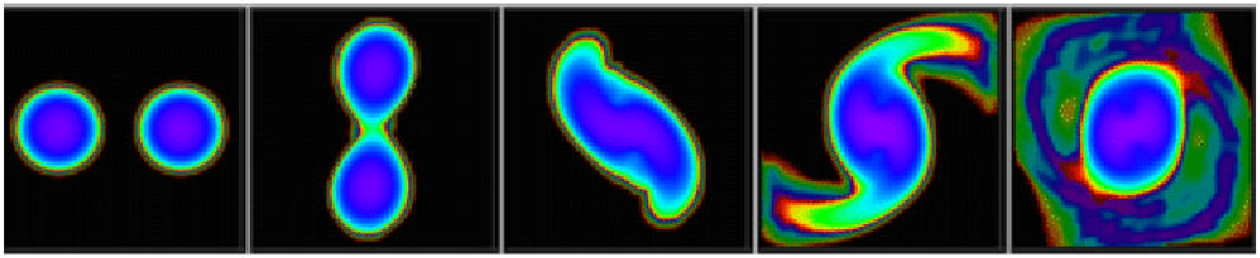
GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

Compact binary mergers

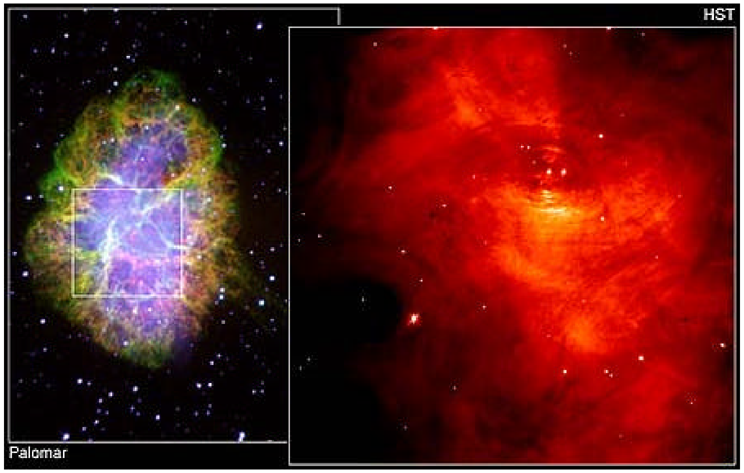




- Neutron star – neutron star (Centrella et al.)

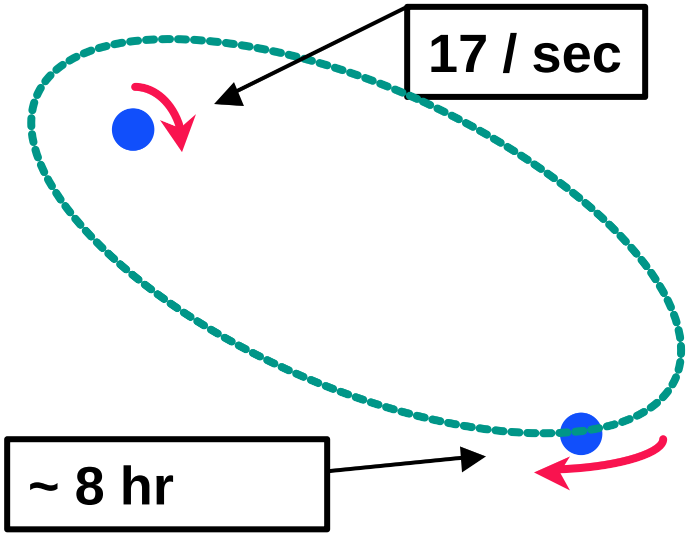


Hulse-Taylor binary pulsar



Neutron Binary System

PSR 1913 + 16 -- Timing of pulsars

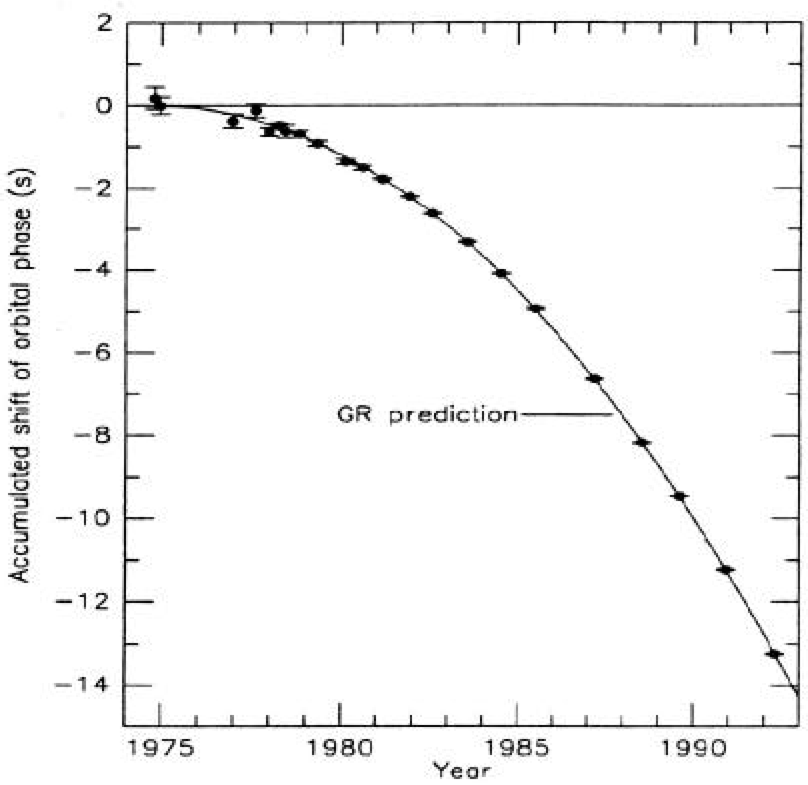


- A rapidly spinning pulsar (neutron star beaming EM radiation at us 17 x / sec)
- orbiting around an ordinary star with 8 hour period
- Only 7 kpc away
- discovered in 1975, orbital parameters measured
- continuously measured over 25 years!

GWs from Hulse-Taylor binary

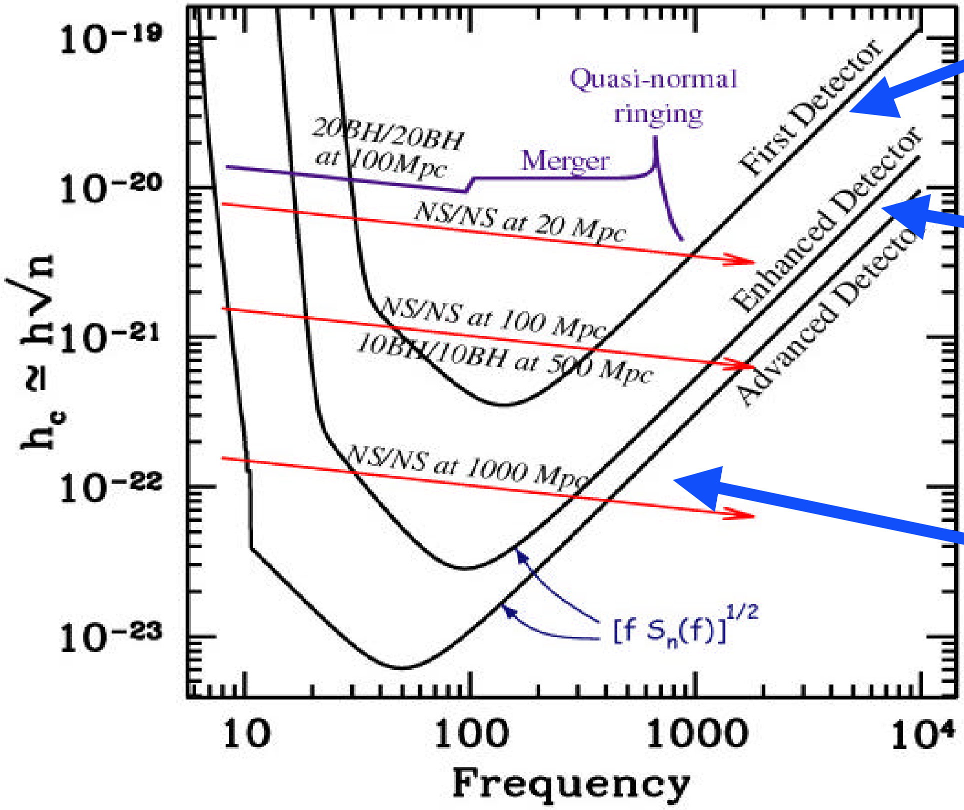
emission of gravitational waves by compact binary system

- 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 Ü 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



Astrophysical sources: Thorne diagrams

Sensitivity of LIGO to coalescing binaries



LIGO I (2002-2005)

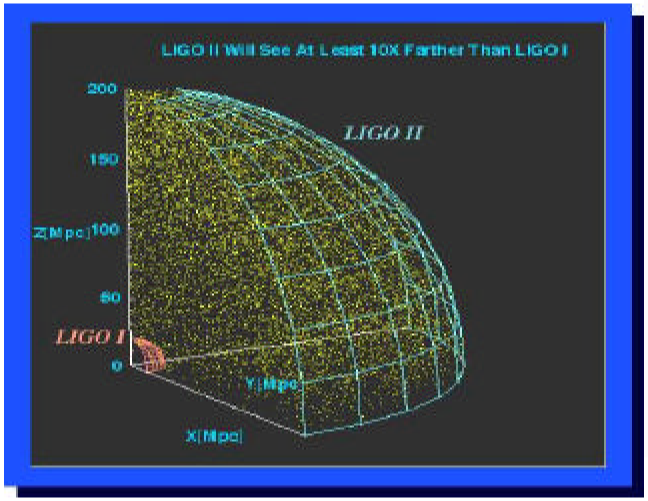
LIGO II (2007-)

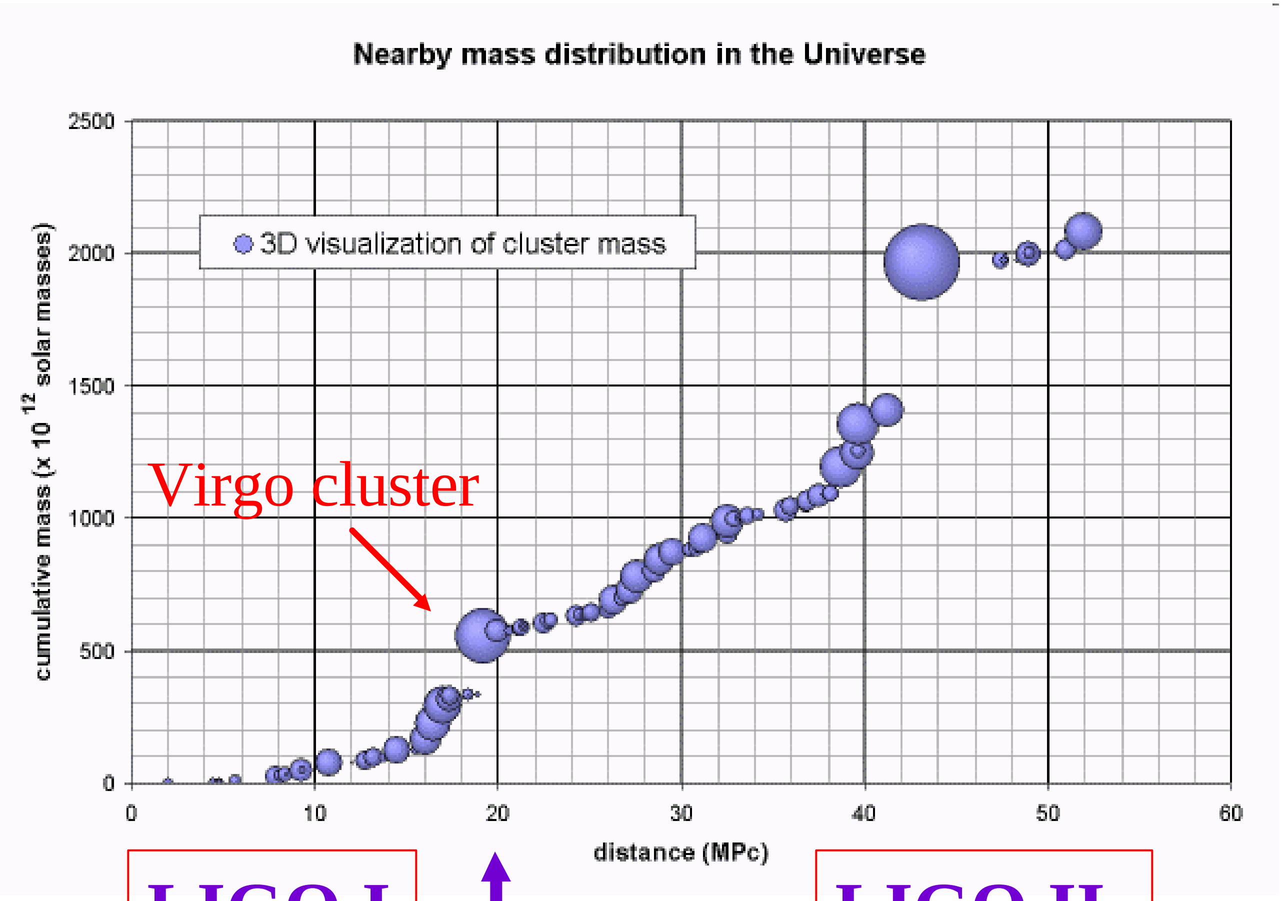
Advanced LIGO

How many sources can we see?

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

⇒ Number of sources goes up 1000x!



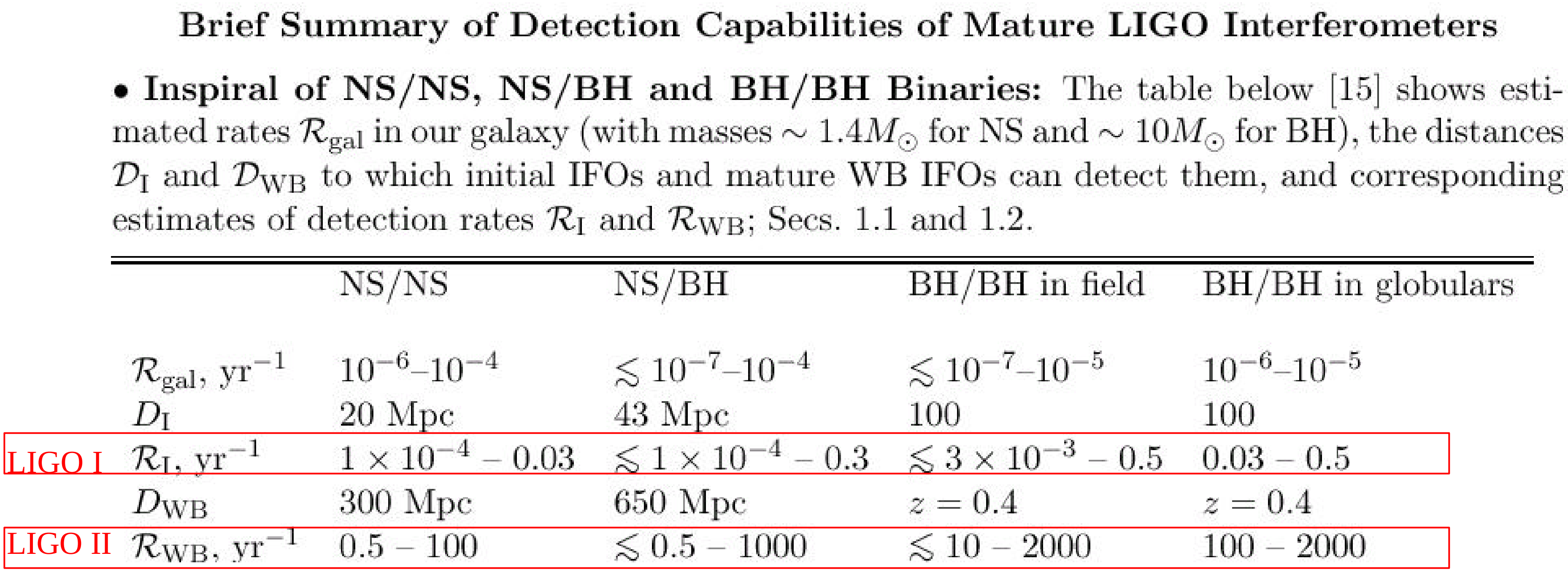


Virgo cluster

LIGO I ↑

LIGO II →

Estimated detection rates for compact binary inspiral events



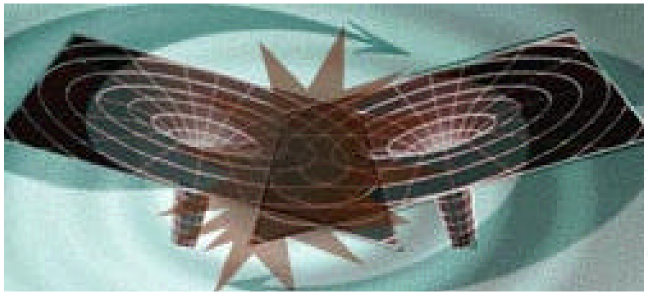
Brief Summary of Detection Capabilities of Mature LIGO Interferometers

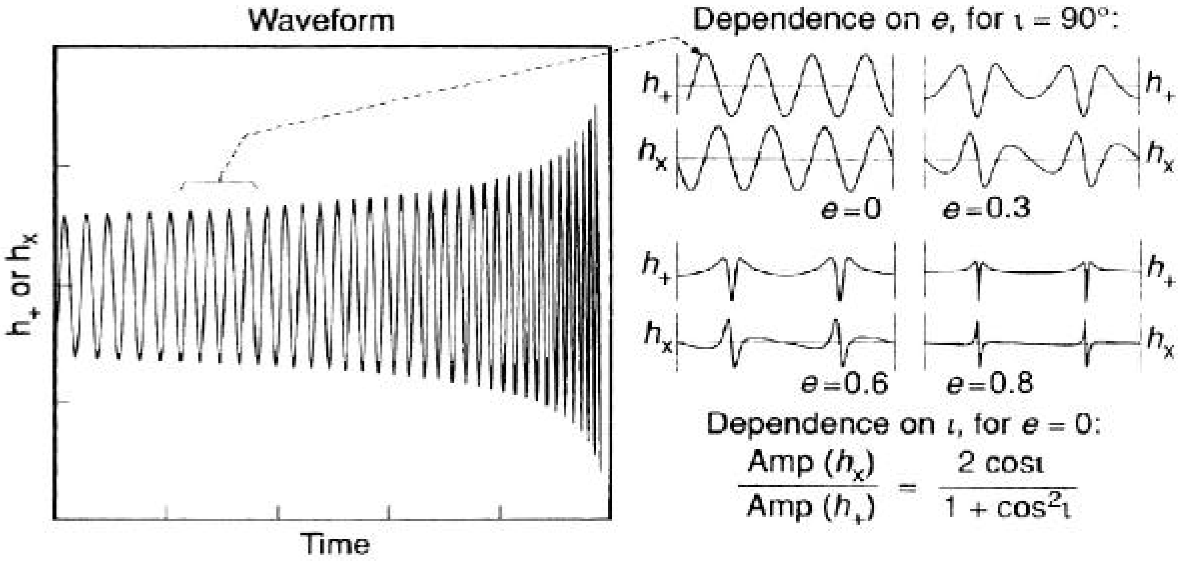
- **Inspiral of NS/NS, NS/BH and BH/BH Binaries:** The table below [15] shows estimated rates $\mathcal{R}_{\rm gal}$ in our galaxy (with masses $\sim 1.4M_\odot$ for NS and $\sim 10M_\odot$ for BH), the distances $\mathcal{D}_{\rm I}$ and $\mathcal{D}_{\rm WB}$ to which initial IFOs and mature WB IFOs can detect them, and corresponding estimates of detection rates $\mathcal{R}_{\rm I}$ and $\mathcal{R}_{\rm WB}$; Secs. 1.1 and 1.2.

		NS/NS	NS/BH	BH/BH in field	BH/BH in globulars
	$\mathcal{R}_{\rm gal}$, yr^{-1}	10^{-6}–10^{-4}	$\lesssim 10^{-7}$–10^{-4}	$\lesssim 10^{-7}$–10^{-5}	10^{-6}–10^{-5}
	$D_{\rm I}$	20 Mpc	43 Mpc	100	100
LIGO I	$\mathcal{R}_{\rm I}$, yr^{-1}	$1 \times 10^{-4} - 0.03$	$\lesssim 1 \times 10^{-4} - 0.3$	$\lesssim 3 \times 10^{-3} - 0.5$	$0.03 - 0.5$
	$D_{\rm WB}$	300 Mpc	650 Mpc	$z = 0.4$	$z = 0.4$
LIGO II	$\mathcal{R}_{\rm WB}$, yr^{-1}	$0.5 - 100$	$\lesssim 0.5 - 1000$	$\lesssim 10 - 2000$	$100 - 2000$

V. Kalogera (population synthesis)

Chirp signal from Binary Inspiral



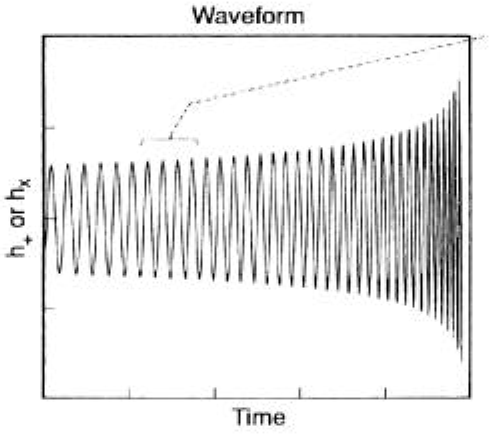


determine

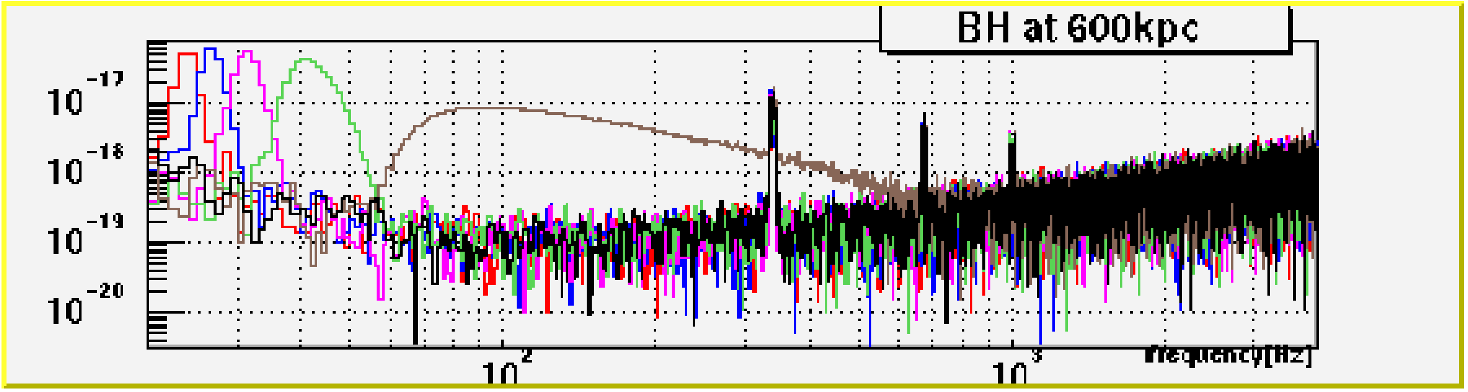
- distance from the earth r
- masses of the two bodies
- orbital eccentricity e and orbital inclination *i*

The sound of a chirp

BH-BH collision, no noise



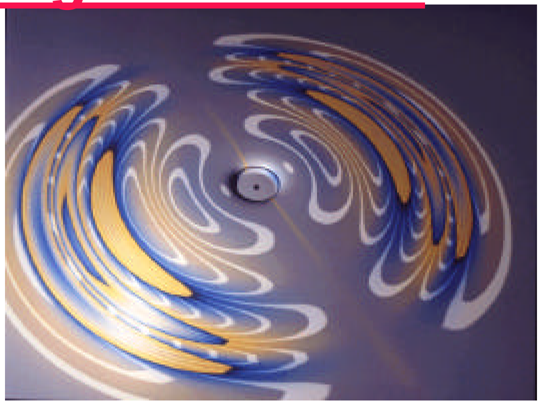
The sound of a BH-BH collision,
Fourier transformed over 5 one-second intervals
(red, blue, magenta, green, purple)
along with expected IFO noise (black)

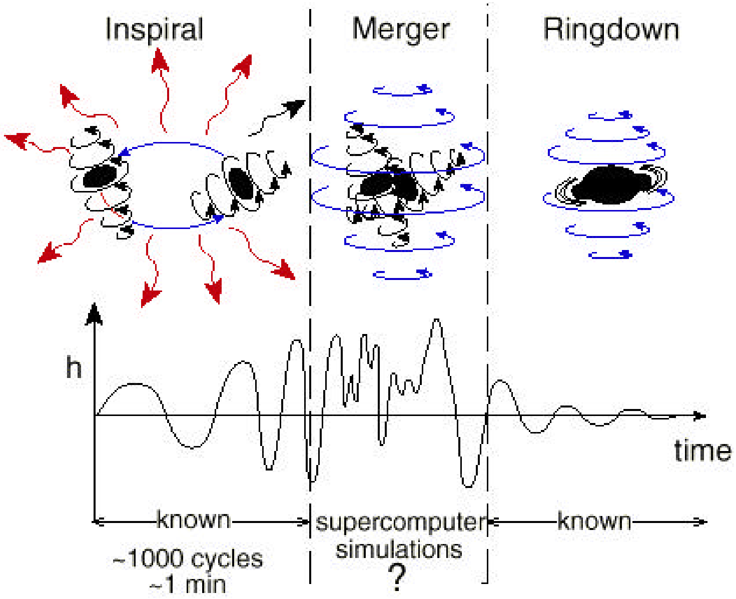


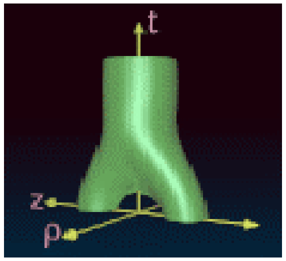
Black holes: computer simulations

Testing General Relativity in the Strong Field Limit

Distortion of space-time by a black hole



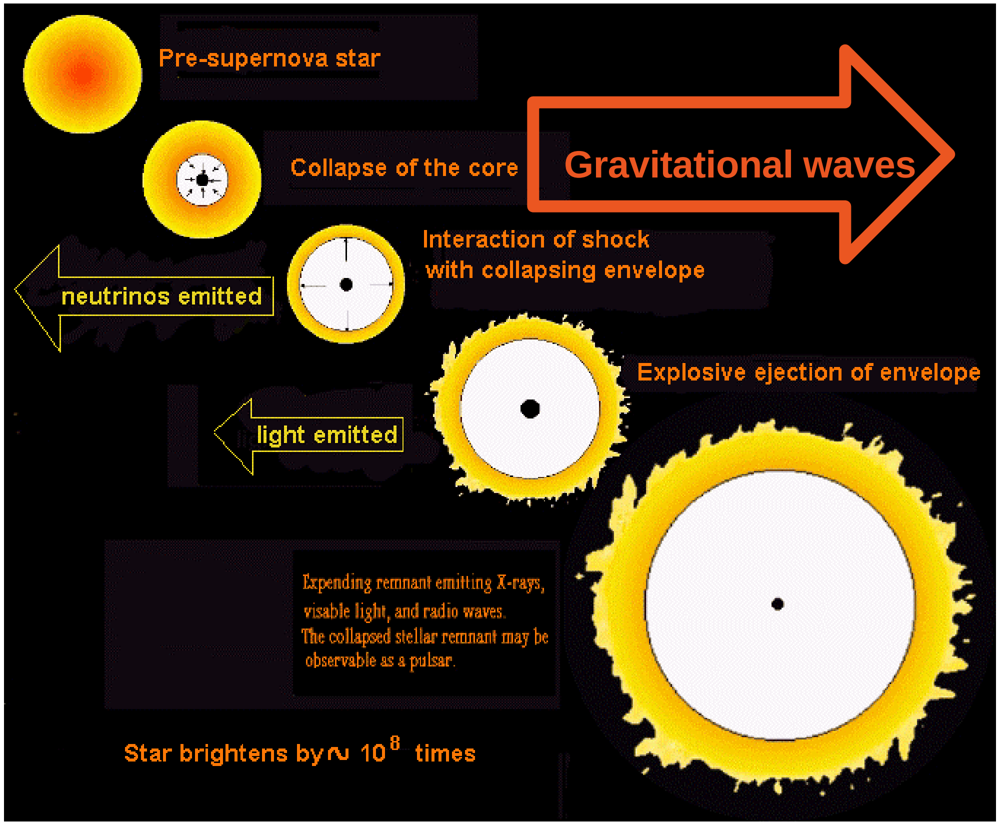




Collision of two black holes

“Grand Challenge” – Supercomputer Project

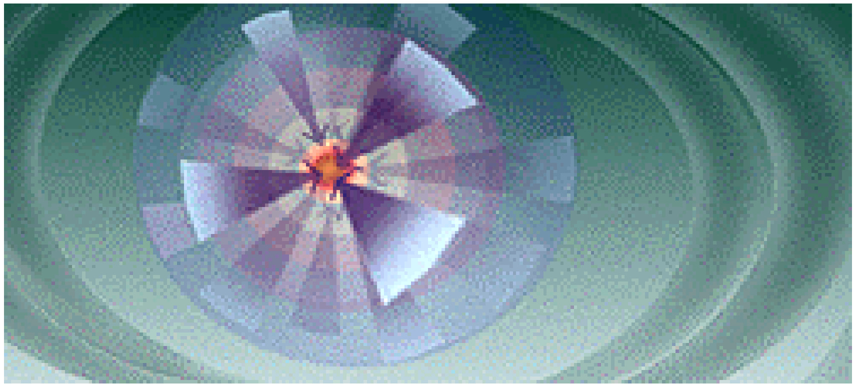
Supernova collapse sequence



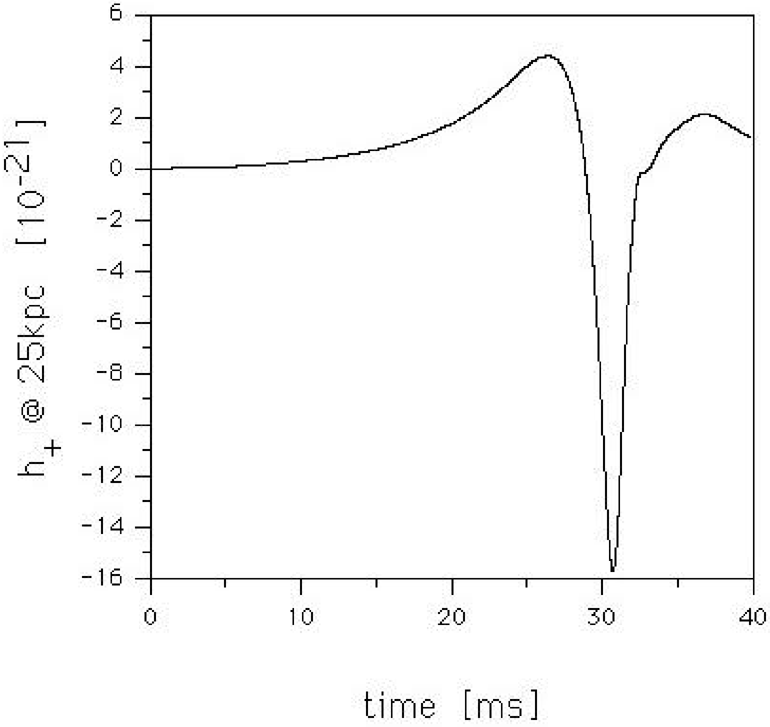
- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- After about 0.5 second, the collapsing envelope interacts with the outward shock. Neutrinos are emitted.
- Within 2 hours, the envelope of the star is explosively ejected. When the photons reach the surface of the star, 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.

Gravitational Waves from Supernova collapse

Non axisymmetric collapse



‘burst’ signal

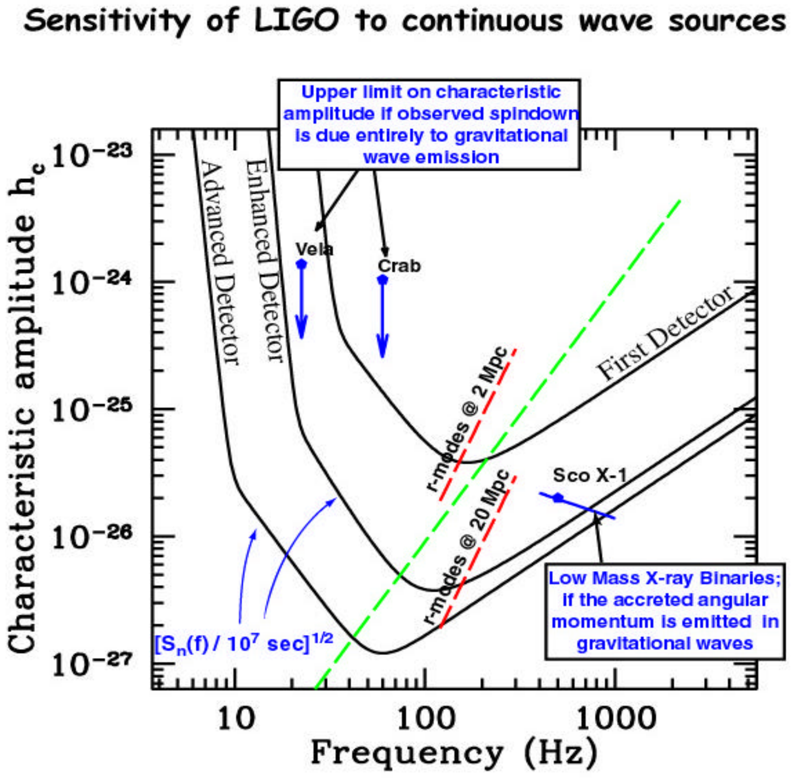


Rate

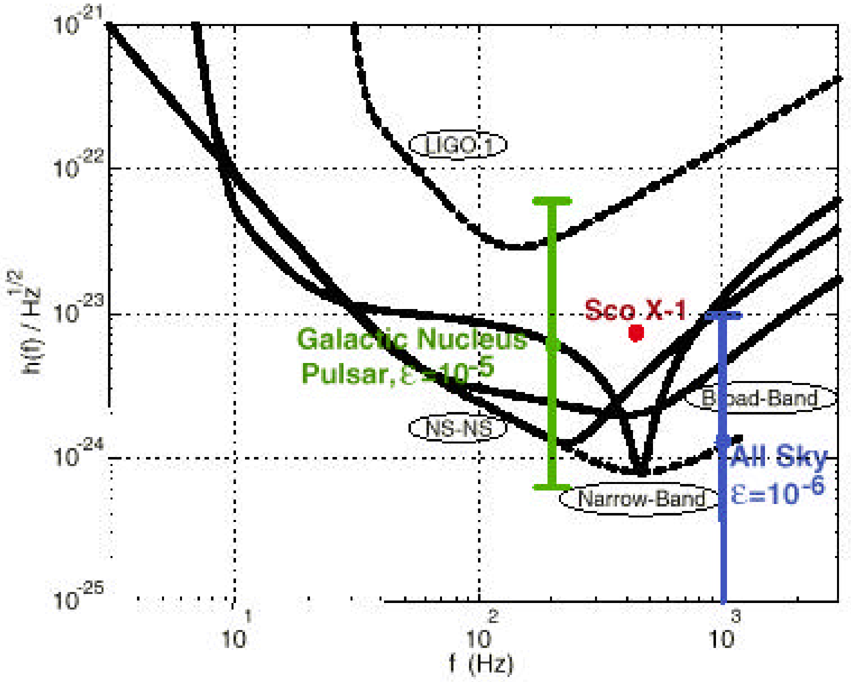
1/50 yr - our galaxy

3/yr - Virgo cluster

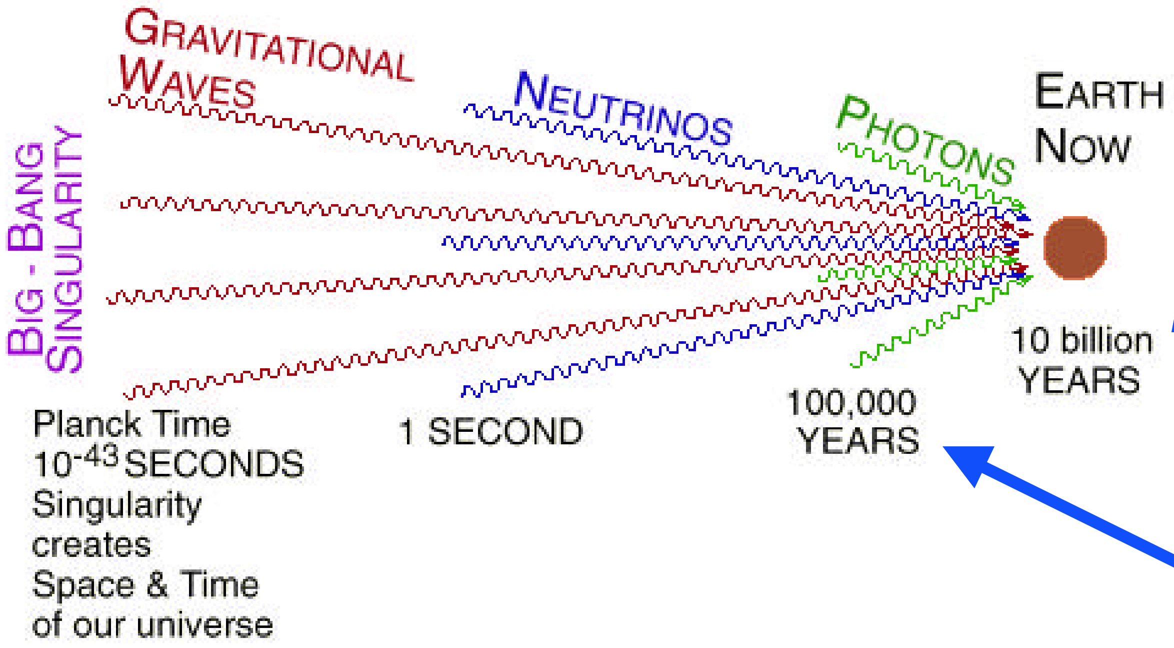
Pulsars and continuous wave sources



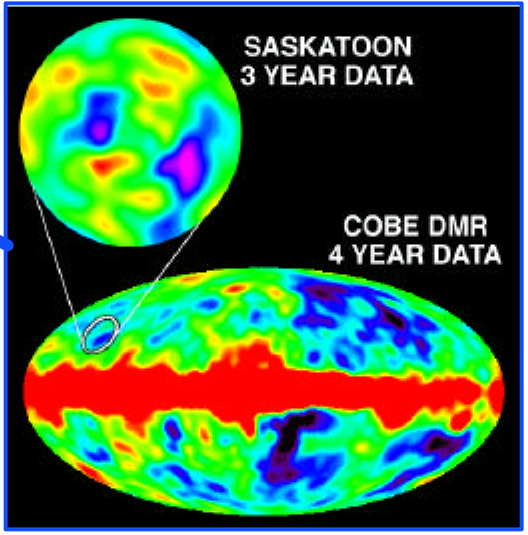
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: neutron star precession; interiors
  - »“R-mode” instabilities
  - »narrow band searches best



Gravitational waves from Big Bang



Cosmic microwave background

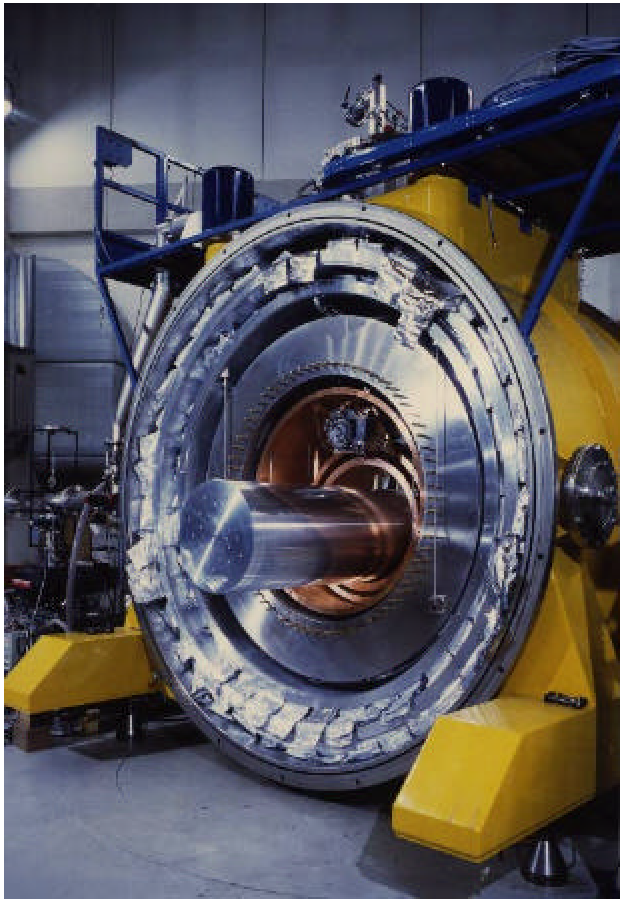


Gravitational wave detectors

- **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

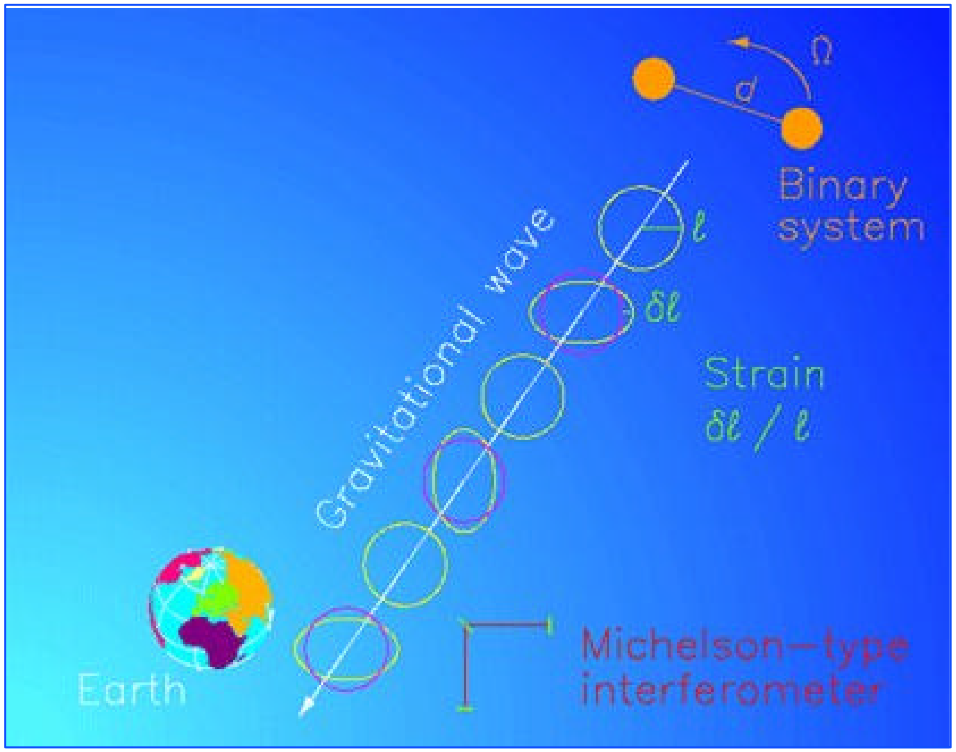
- AURIGA bar near Padova, Italy (typical of some ~6 around the world – Maryland, LSU, Rome, CERN, UWA)
- 2.3 tons of Aluminum, 3m long;
- Cooled to 0.1K with dilution fridge in LiHe cryostat
- $Q = 4\times10^6$ at < 1K
- Fundamental resonant mode at ~900 Hz; narrow bandwidth
- Ultra-low-noise capacitive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



Terrestrial Interferometers

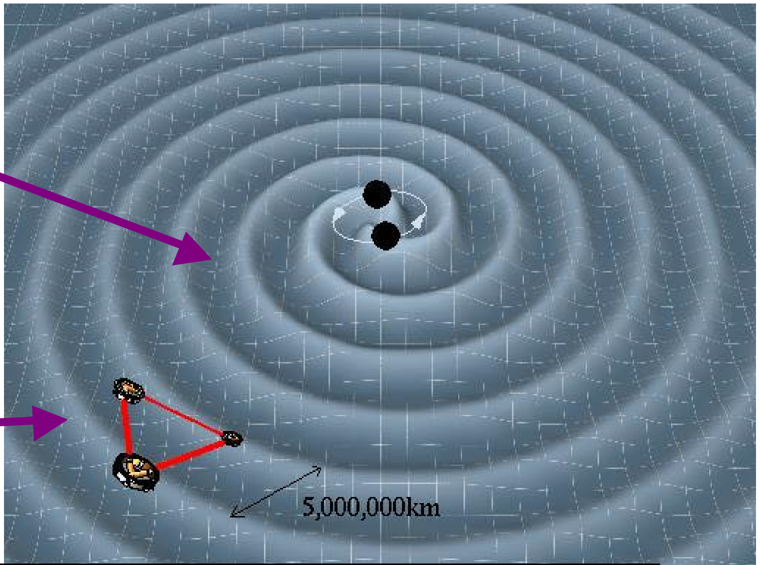
Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

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

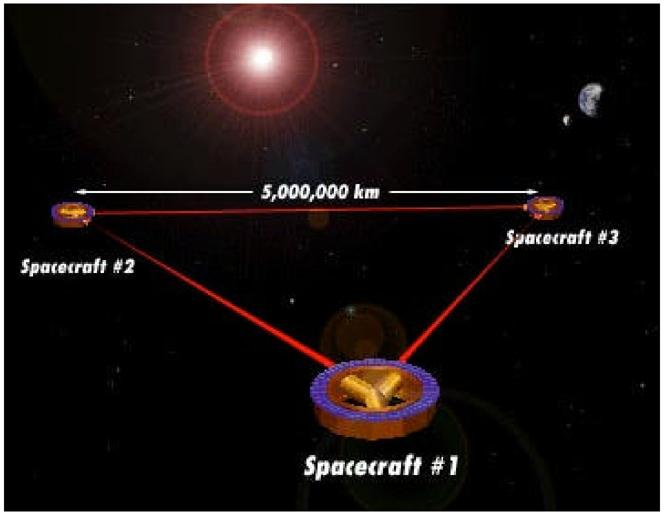


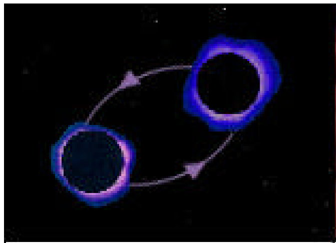
Laser Interferometer Space Antenna (LISA)

Radiation of Gravitational Waves from binary inspiral system

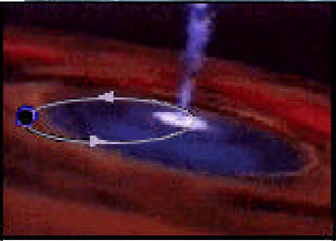


LISA

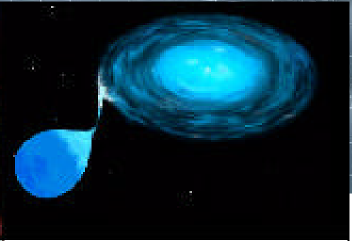




Coalescence of massive black holes during collisions between galaxies, perhaps in formation of massive black holes, probing the central engines powering quasars.



Black holes orbiting massive black holes, providing precision tests of gravitational theory in the high-field limit.

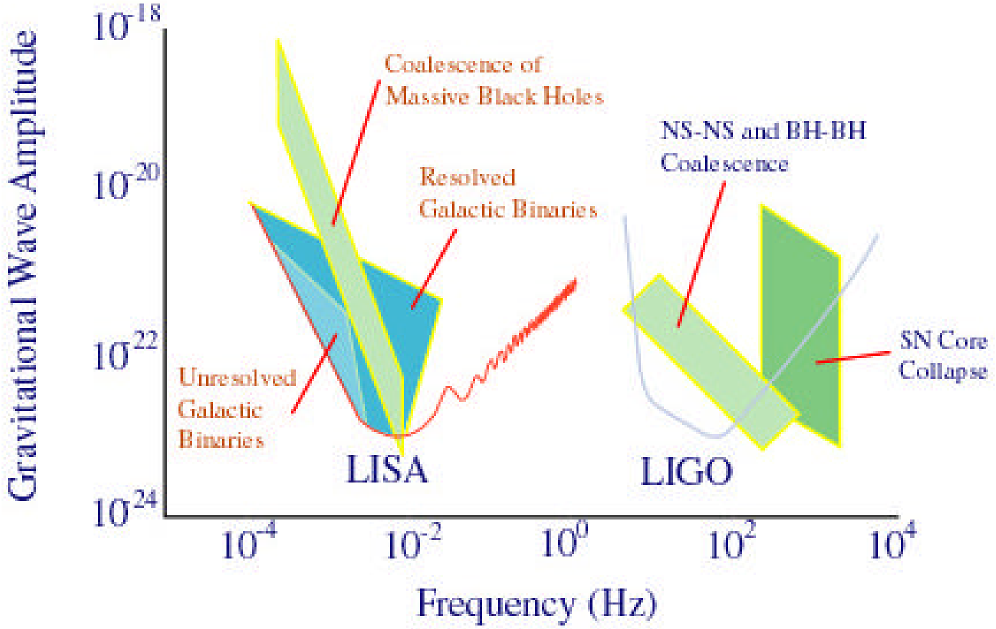


Hundreds of galactic binary star systems, many containing neutron stars or black holes, including several known binary systems.

AJW, Caltech, LIGO Laboratory

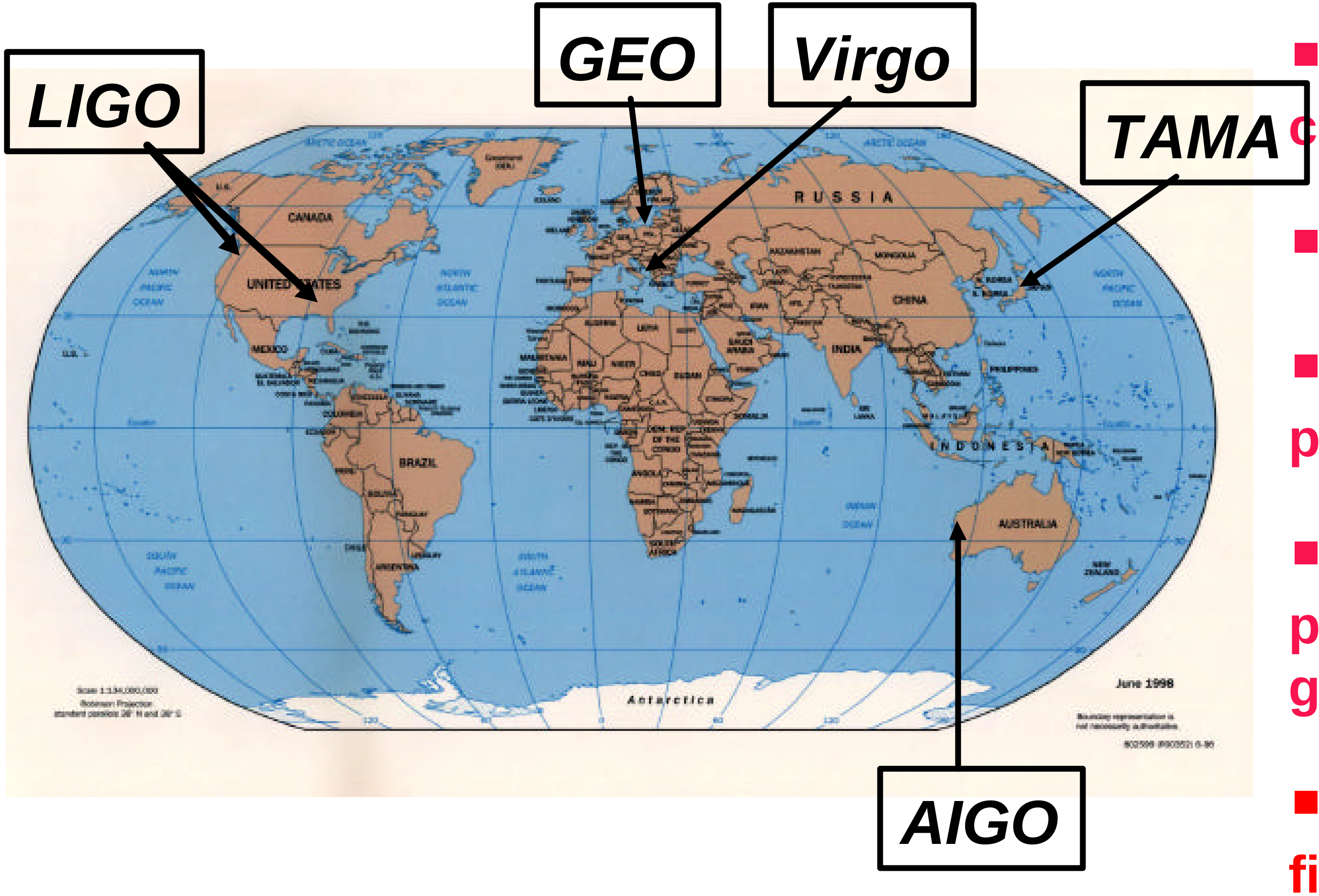
Sensitivity bandwidth

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



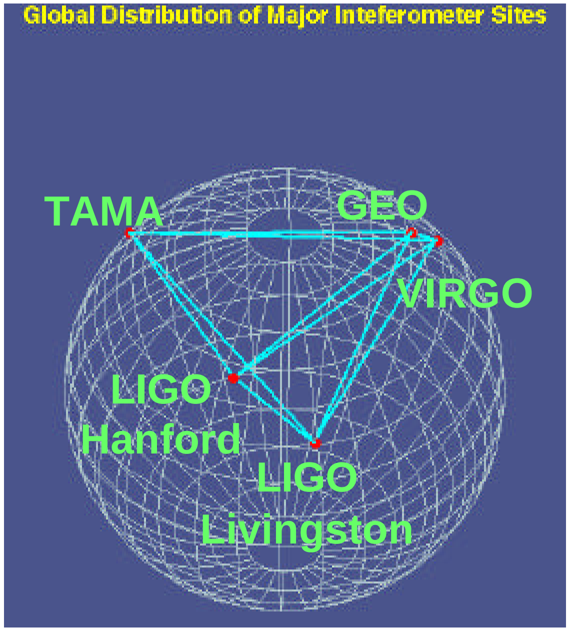
International network

Simultaneously detect signal (within msec)



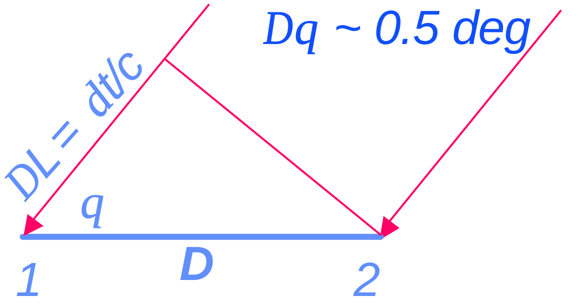
- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves
- Open up a new field of astrophysics!

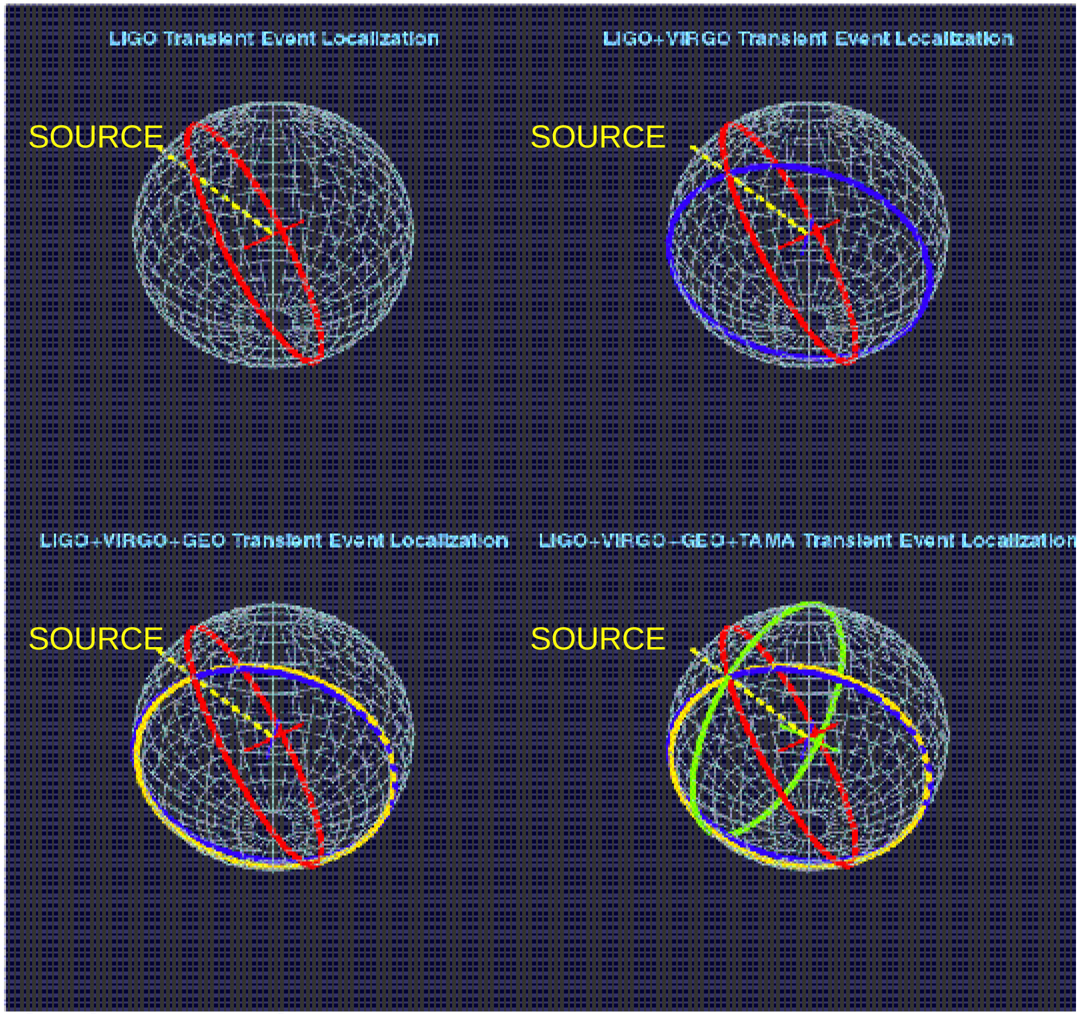
Event Localization With An Array of GW Interferometers



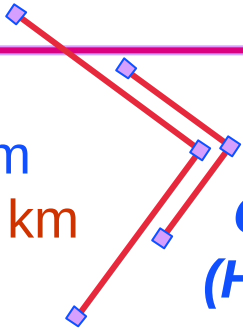
$\cos q = dt / (c\, D_{12})$

$Dq \sim 0.5$ deg





LIGO sites



4 km
+ 2 km

Hanford Observatory (H2K and H4K)

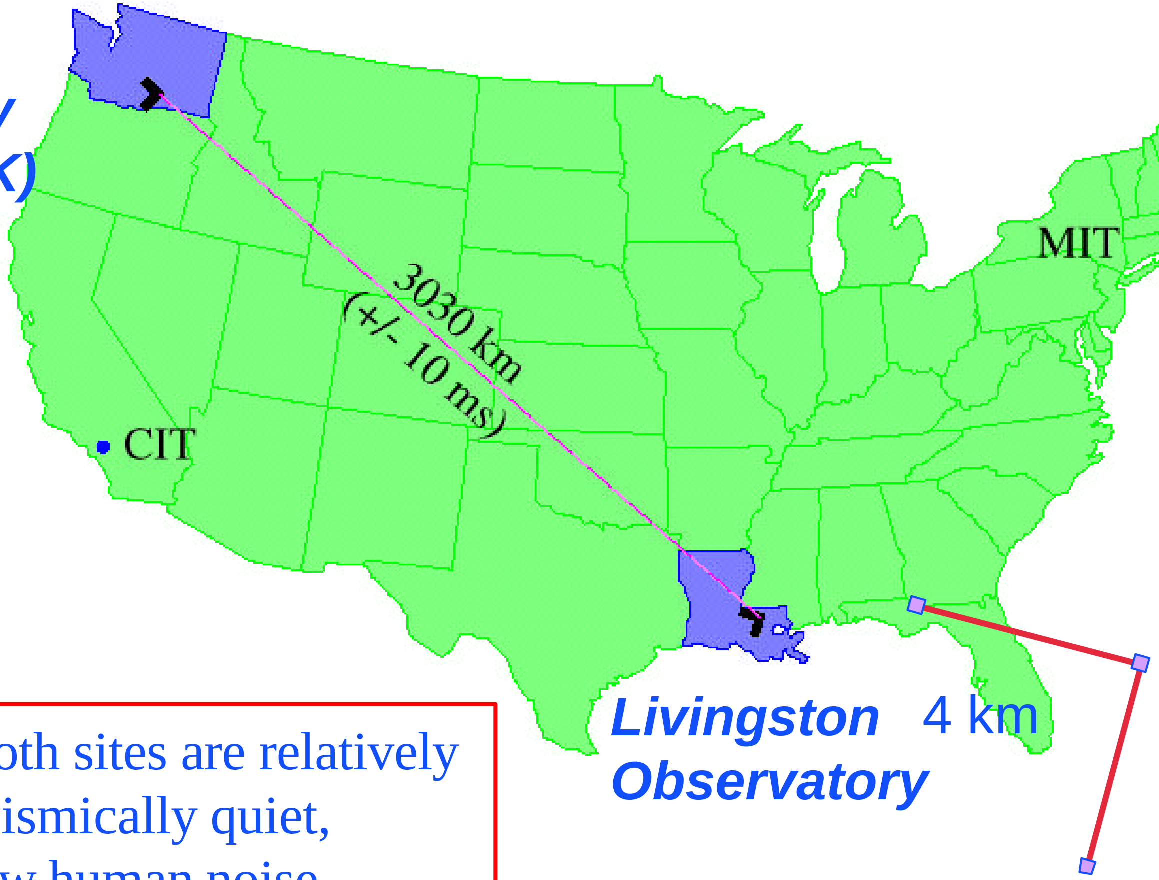
Hanford, WA (LHO)

- 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

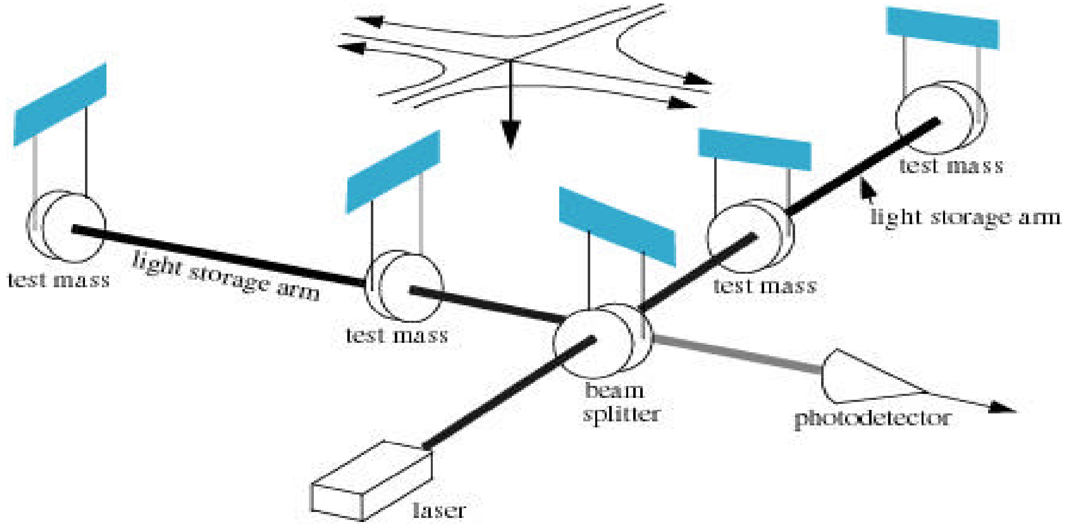
Both sites are relatively seismically quiet, low human noise

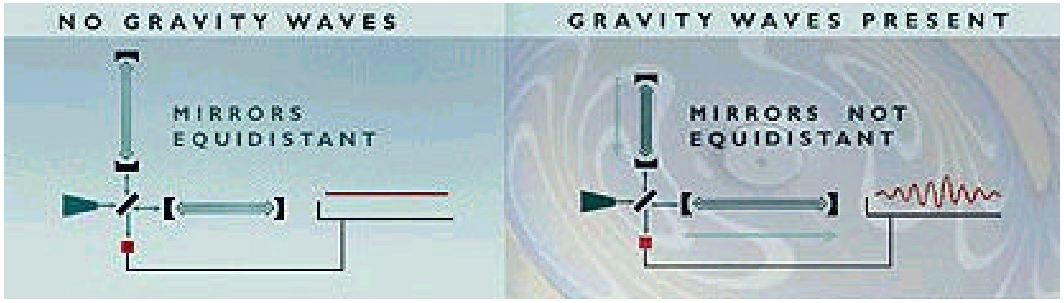


Livingston Observatory 4 km

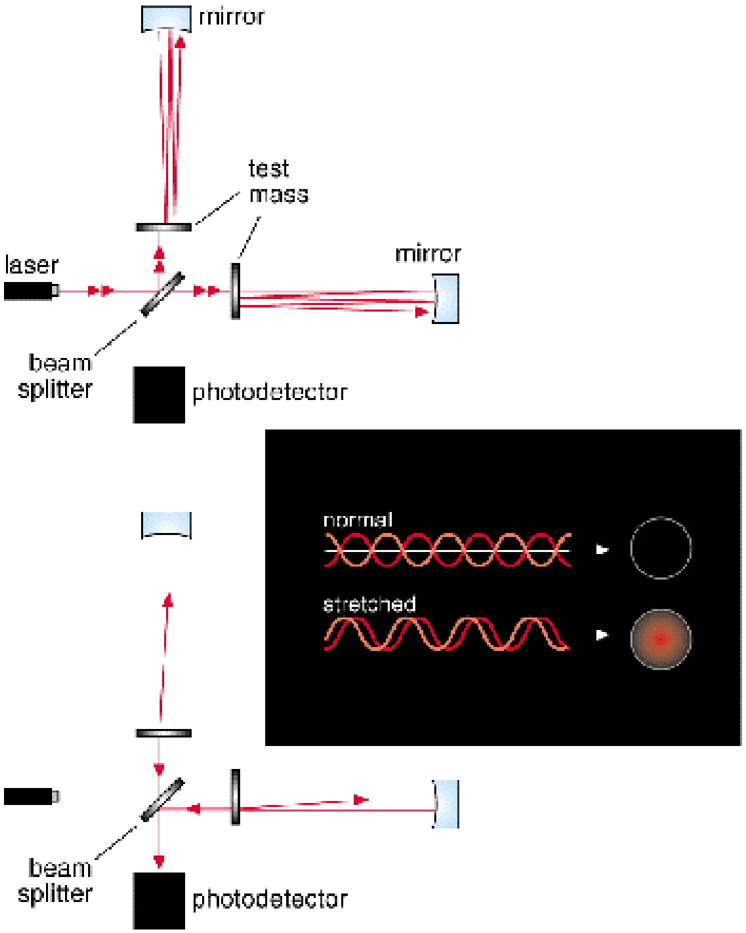
Interferometer for GWs

- 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

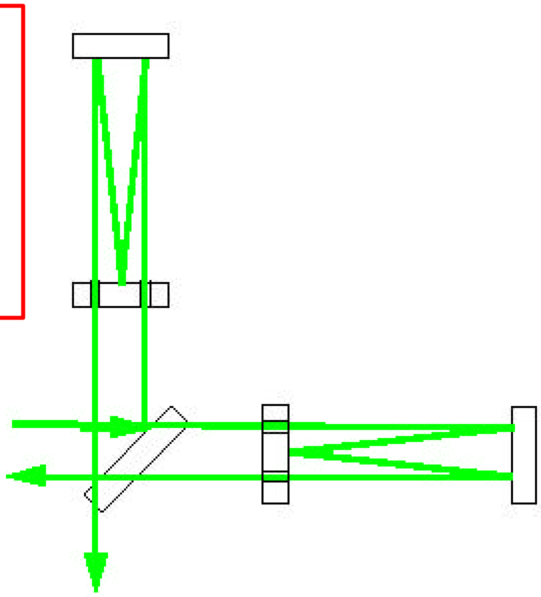
The longer the light path, the larger the phase shift…

Make the light path as long as possible!

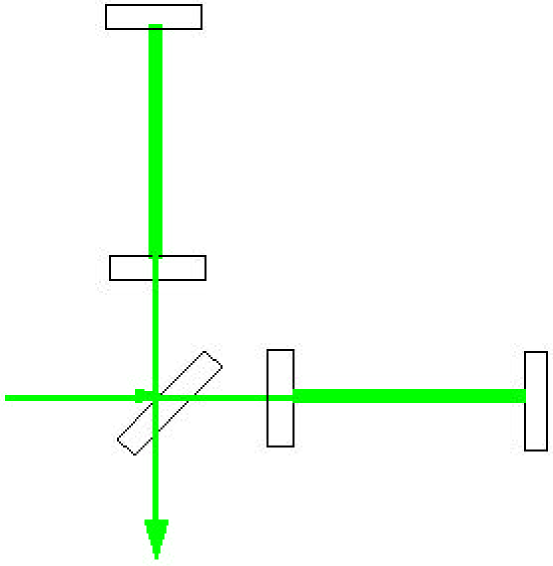
Light storage: folding the arms

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 t_{stor}

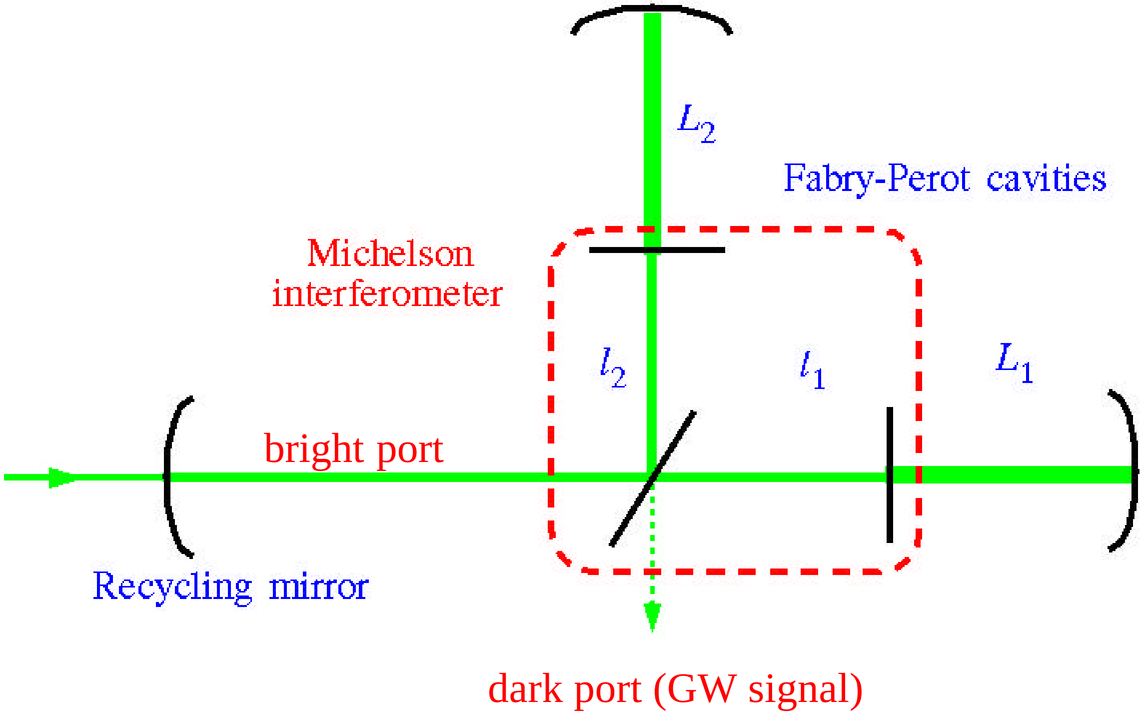
(LIGO design) $t_{stor} \sim 3\ msec$

More compact, but harder to control

LIGO I configuration

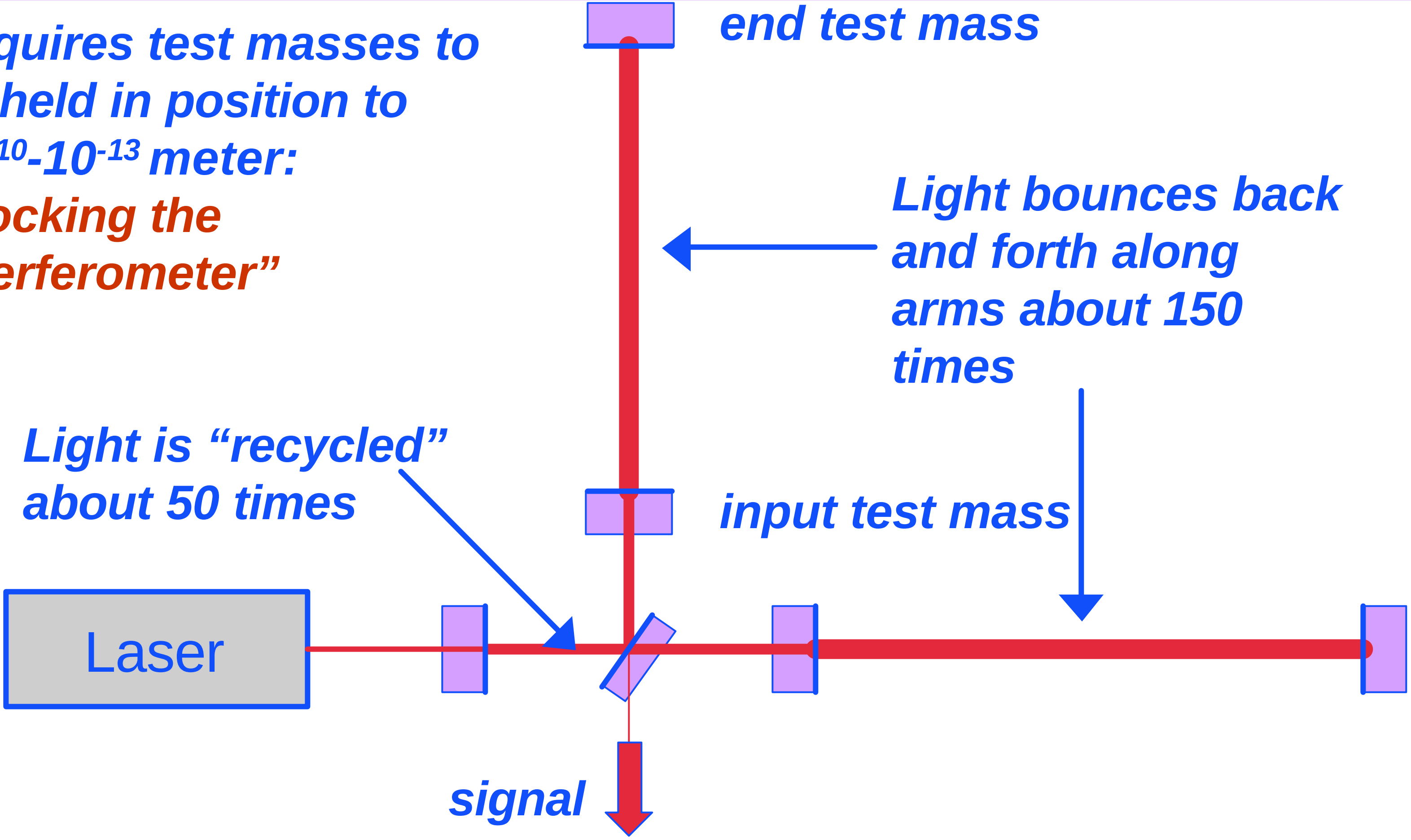
Power-recycled Michelson with Fabry-Perot arms:

- 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



Interferometer
locking

Requires test masses to be held in position to 10^{-10}-10^{-13} meter:
"Locking the interferometer"



end test mass

Light bounces back and forth along arms about 150 times

Light is "recycled" about 50 times

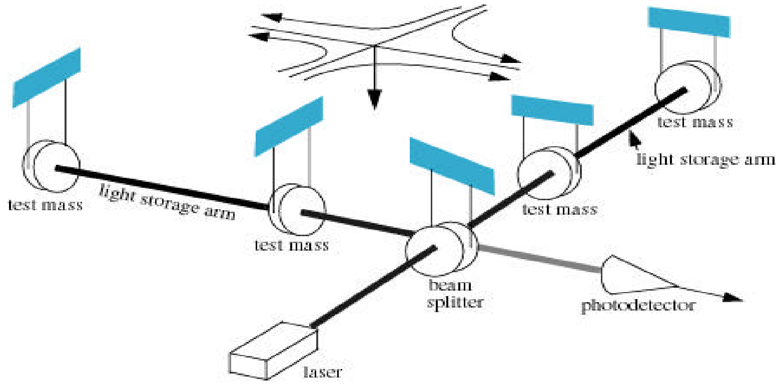
input test mass

Laser

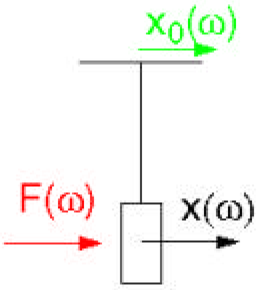
signal

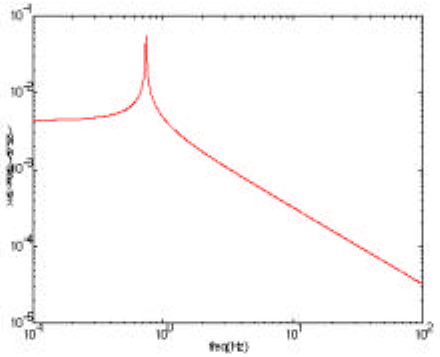
Suspended test masses

- 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*

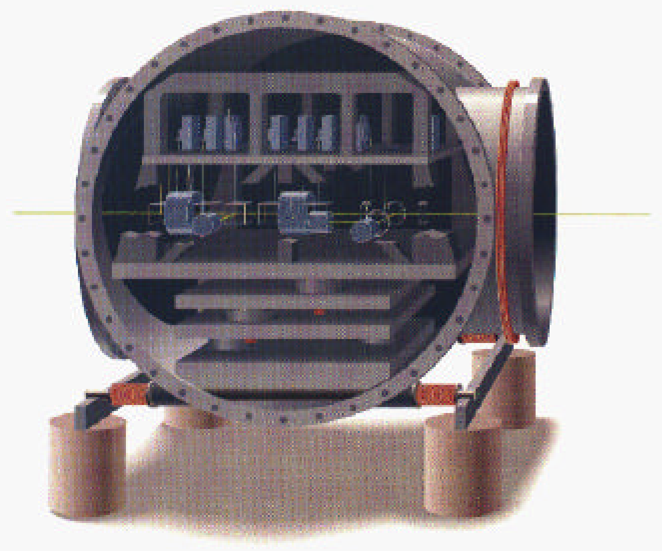
Beam light path must be high vacuum, to minimize “phase noise”

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

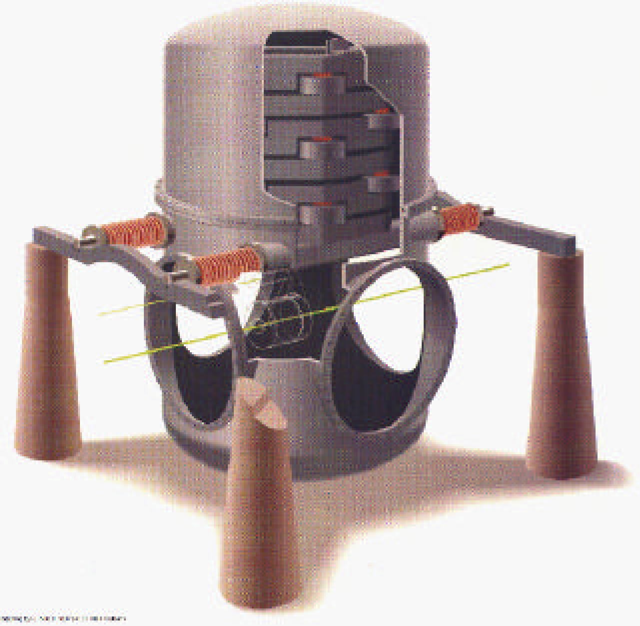
LIGO vacuum equipment

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

LIGO Vacuum Chambers

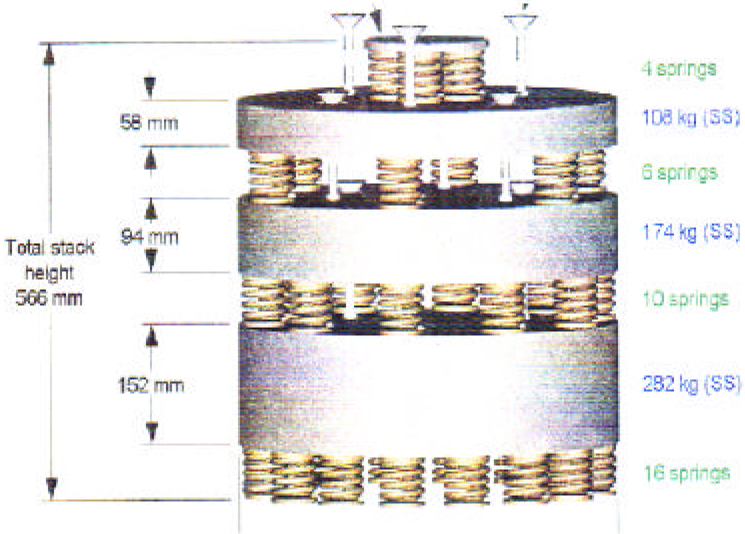


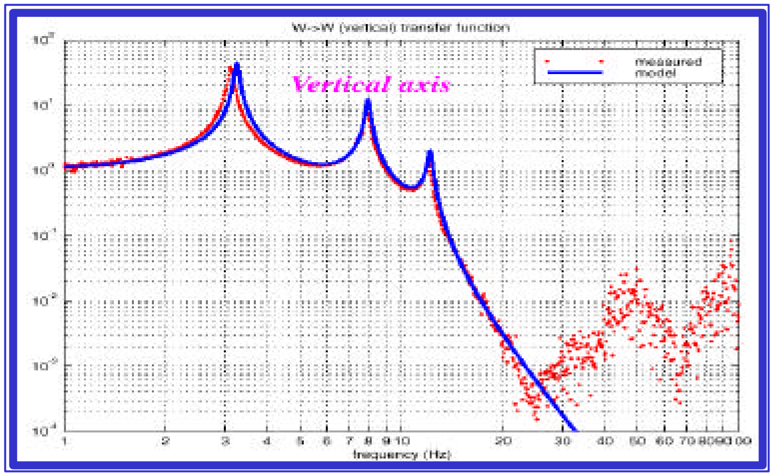
HAM Chambers

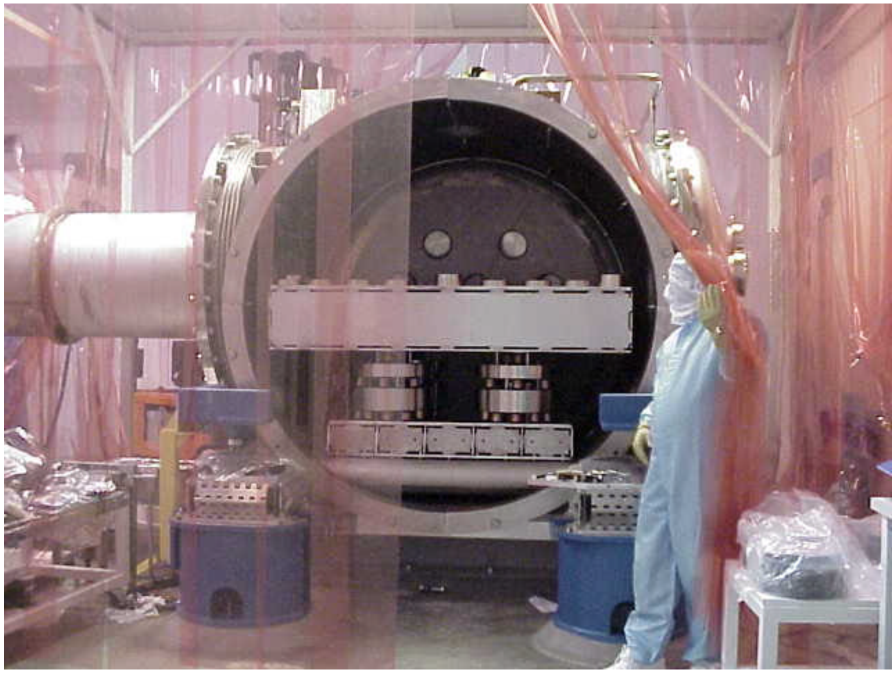


BSC Chambers

Seismic isolation stacks



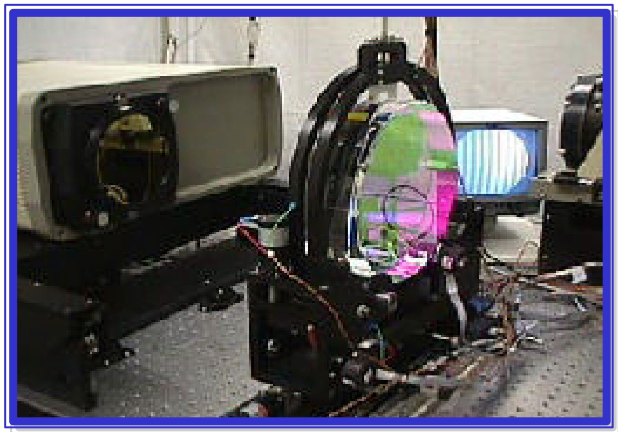


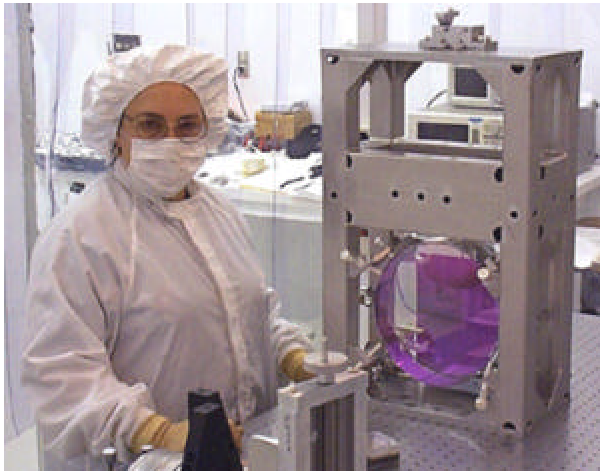


LIGO Optics

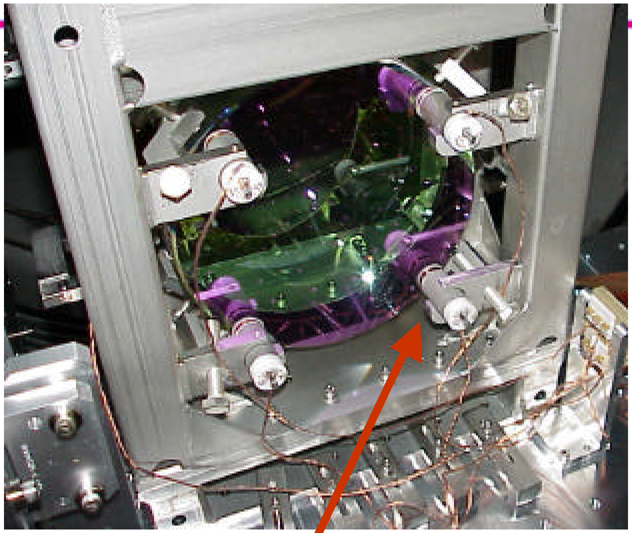
mirrors, coating and polishing

- 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





Suspended Core Optics

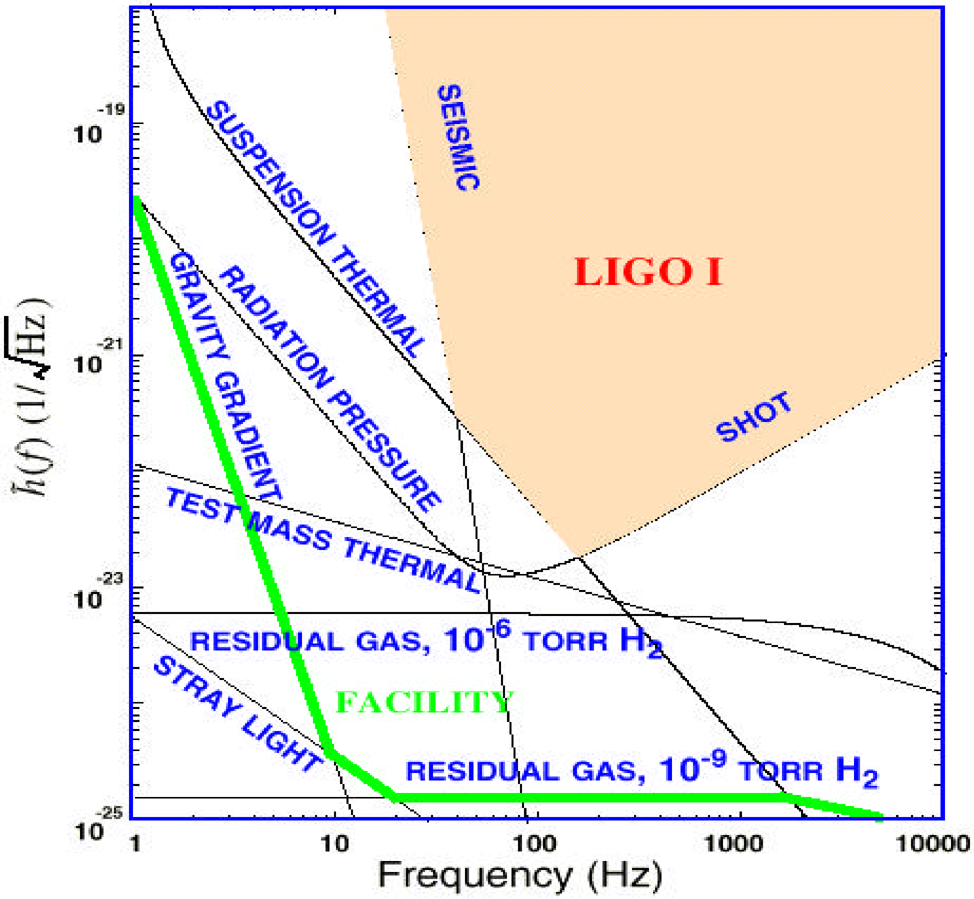


- Optics suspended as simple pendulums
- Local sensors/actuators for damping and control
- Coils push/pull on tiny magnets glued to optics
- Earthquake stops to prevent break-off of tiny magnets

LIGO I noise floor

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

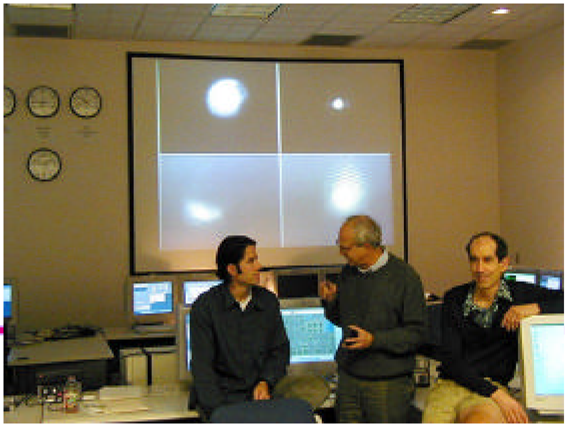
- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**



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 $h \sim 10^{-21}$)
2006	Begin Advanced LIGO upgrade

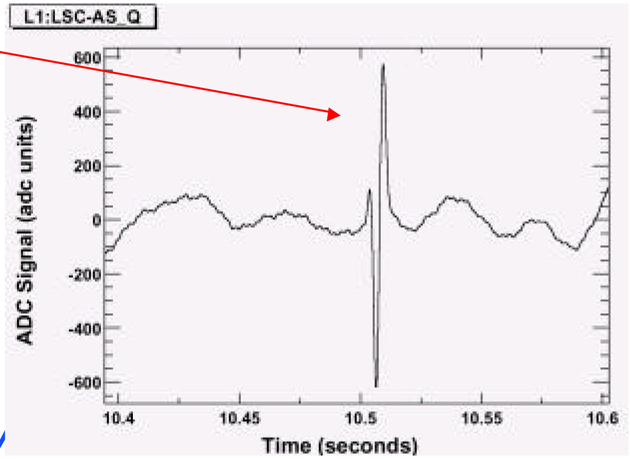
LIGO Engineering runs



- Commissioning GW IFO's is a very tricky business!
  - They are complex, non-linear, non-reductionistic systems
  - There's precious little experience…
- First task is to get the IFO's to operate in the correct configuration, with all optical cavities resonating – "In Lock"
- Next task is to reduce the noise (reduce all non-fundamental noise sources to insignificance), improve sensitivity
- LIGO has had 6 engineering runs in 2000-2001, focusing on keeping IFO's In Lock for long periods of time (duty cycle)
- "First Lock" achieved at H2K on October 2000
- Rarely had more than one IFO (of 3) operating at a time – till E7!
- Engineering Run 7 (Dec 28, 2001 – Jan 14, 2002) is in progress; it's by far the most successful we've had!
- Plan first Science run for later in 2002.

LIGO Engineering run 7 (E7)

- Focus on duty-cycle, not noise or noise reduction
- ALL 3 IFO's are running and achieving lock for significant fraction of the time
- GEO IFO is also up, and is participating
  (maybe also ALLEGRO and GRBs)
- Some ongoing investigations:
  - Compile statistics on lock acquisition and lock loss, study sources of lock loss
  - Quantify correlations between GW and other (IFO and environmental) channels
  - Correlations between noise, transients in GW channel between IFOs
  - Test simulated astrophysical signal injection
  - Identify environmental disturbances
  - Gaussianity, stationarity of noise in GW channel
- "physics searches" are running online
  in LIGO Data Analysis System (LDAS)



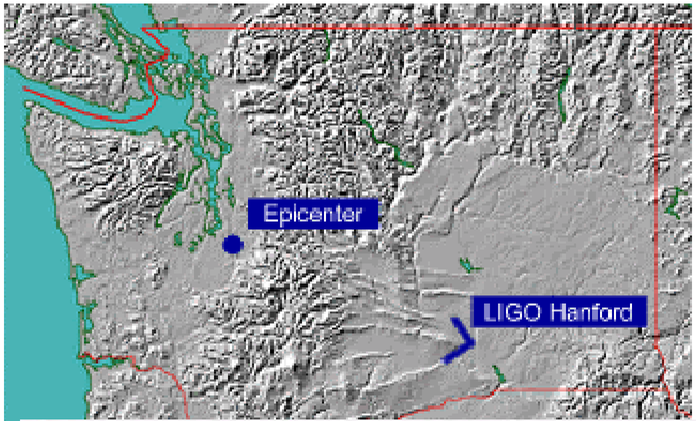
A variety of learning experiences

- Computer crashes
- Earthquakes
- No fire or floods yet…
- Logging at Livingston
- Wind at Hanford
- Snow in Louisiana

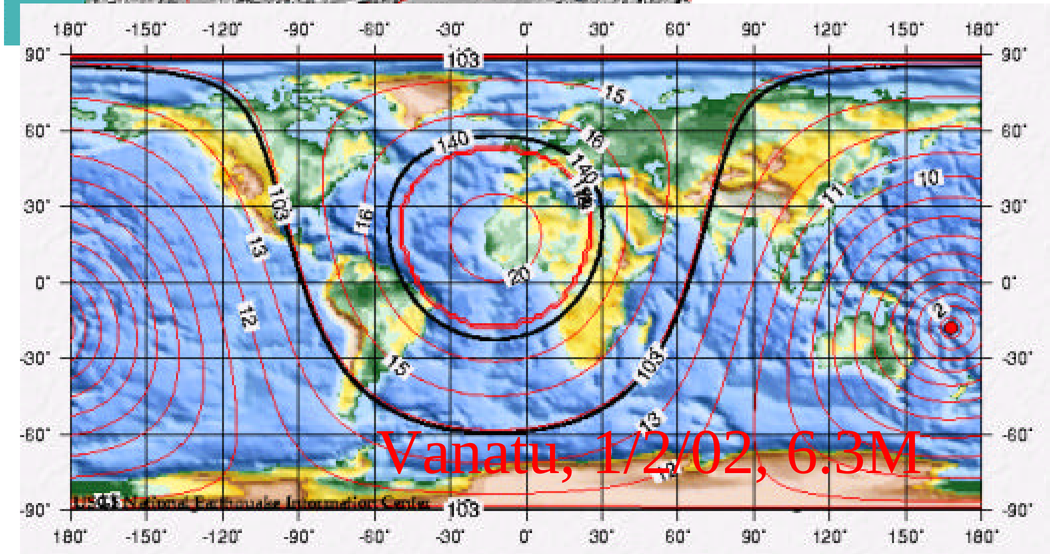
Logging at Livingston

Less than 3 km away…
Dragging big logs …
Remedial measures at LIGO are in progress; this will not be a problem in the future.

Earthquakes…

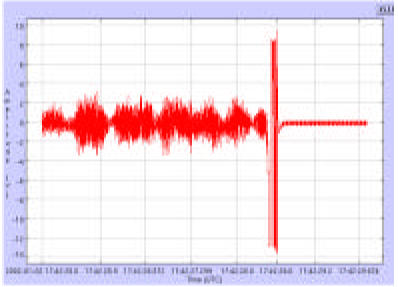


This one, on
February 28, 2000
knocked out the H2K
For months…



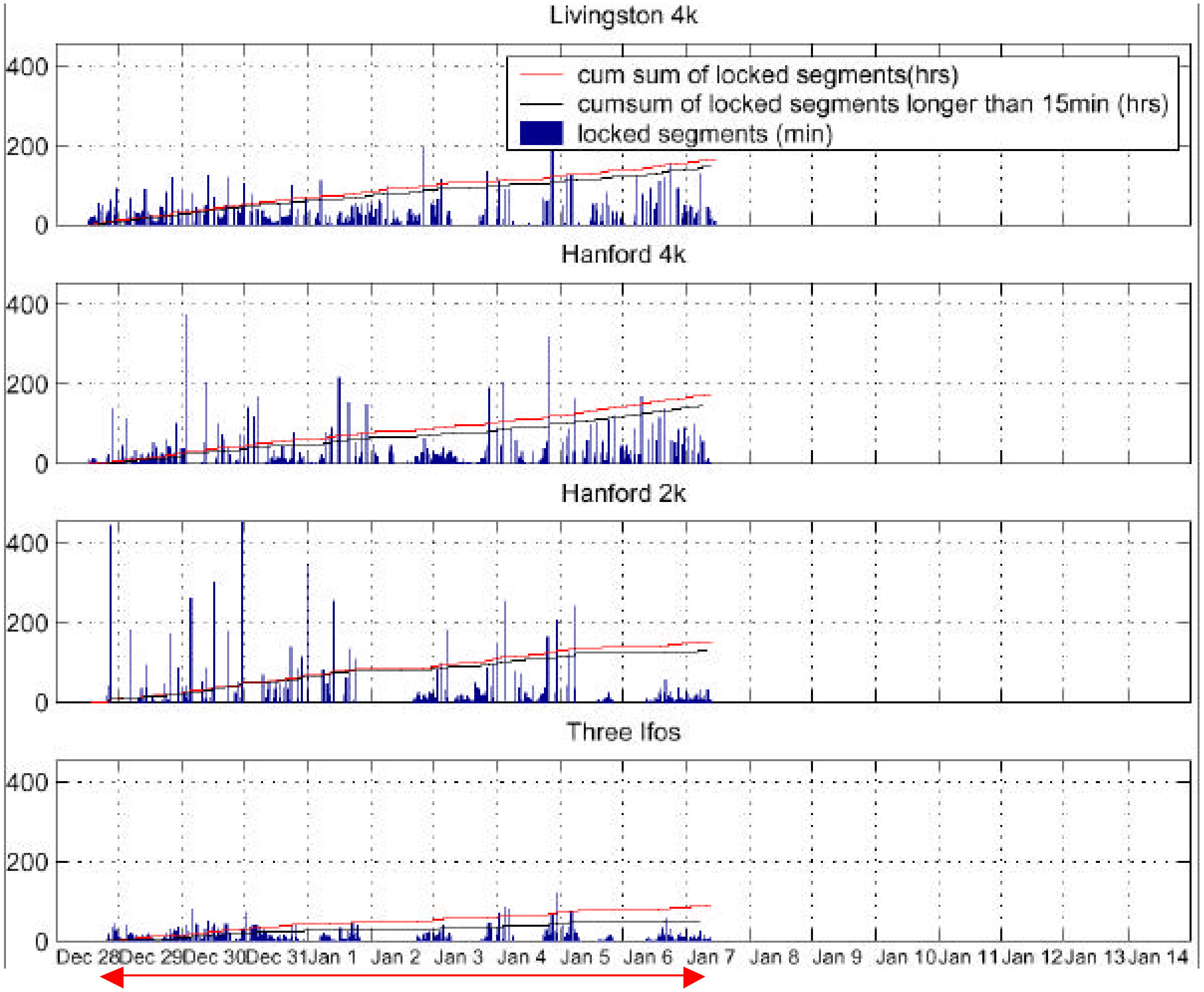
Vanatu, 1/2/02, 6.3M

Earthquakes have not been a problem for E7, but we can "hear" them with the IFO



From
GEO

LIGO IFO duty cycle, E7
(in progress!)



240 hrs

Livingston 4k:
Total locked time: 164 hrs
Duty cycle: 68.5 %
Total time locked with locks longer than 15min: 146 hrs
Duty cycle for long locks: 60.9 %

Hanford 4k:
Total locked time: 172 hrs
Duty cycle: 71.7 %
Total time locked with locks longer than 15min: 146 hrs
Duty cycle for long locks: 60.7 %

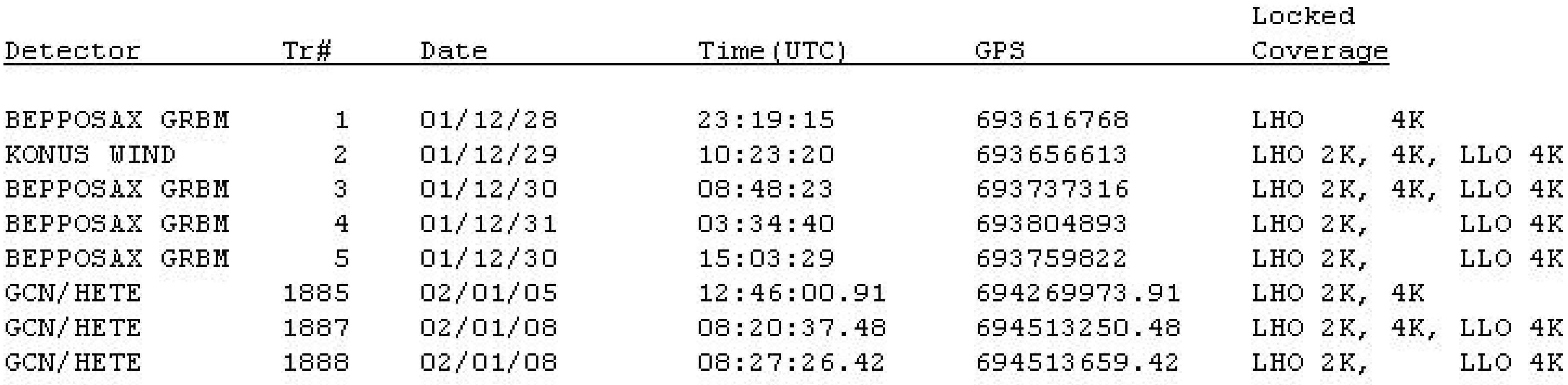
Hanford 2k:
Total locked time: 152 hrs
Duty cycle: 63.3 %
Total time locked with locks longer than 15min: 129 hrs
Duty cycle for long locks: 53.7 %

Hanford and Livingston 4k:
Total locked time: 125 hrs
Duty cycle: 52.1 %
Total time locked with locks longer than 15min: 91 hrs
Duty cycle for long locks: 38 %

Three LIGO Interferometers:
Total locked time: 88.2 hrs
Duty cycle: 36.8 %
Total time locked with locks longer than 15min: 51.3 hrs
Duty cycle for long locks: 21.4 %

We are thrilled!!

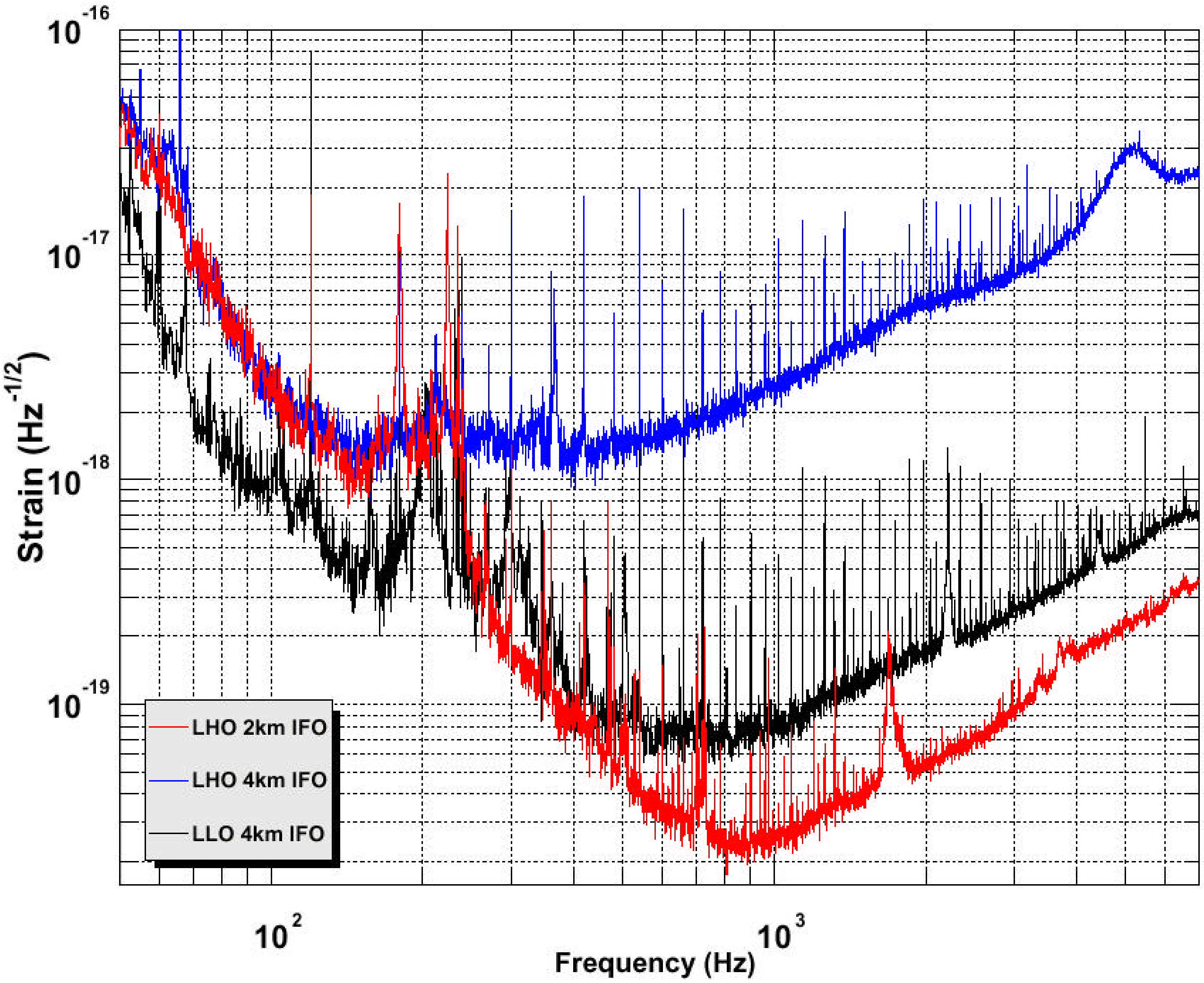
Gamma Ray Bursts during E7 and LIGO coverage



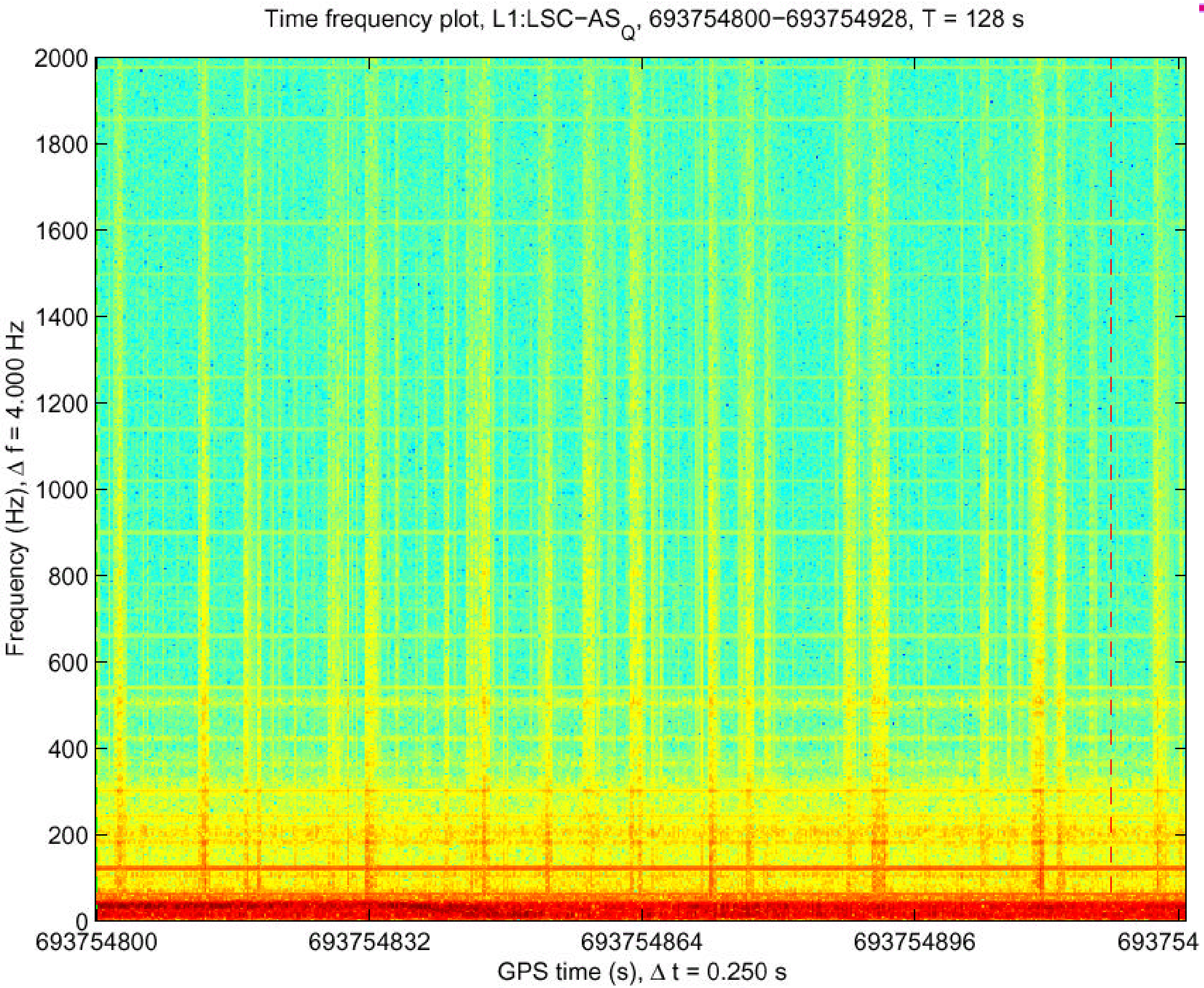
Detector	Tr#	Date	Time (UTC)	GPS	Locked Coverage
BEPPOSAX GRBM	1	01/12/28	23:19:15	693616768	LHO 4K
KONUS WIND	2	01/12/29	10:23:20	693656613	LHO 2K, 4K, LLO 4K
BEPPOSAX GRBM	3	01/12/30	08:48:23	693737316	LHO 2K, 4K, LLO 4K
BEPPOSAX GRBM	4	01/12/31	03:34:40	693804893	LHO 2K, LLO 4K
BEPPOSAX GRBM	5	01/12/30	15:03:29	693759822	LHO 2K, LLO 4K
GCN/HETE	1885	02/01/05	12:46:00.91	694269973.91	LHO 2K, 4K
GCN/HETE	1887	02/01/08	08:20:37.48	694513250.48	LHO 2K, 4K, LLO 4K
GCN/HETE	1888	02/01/08	08:27:26.42	694513659.42	LHO 2K, LLO 4K

We are also running simultaneously with ALLEGRO bar at LSU.

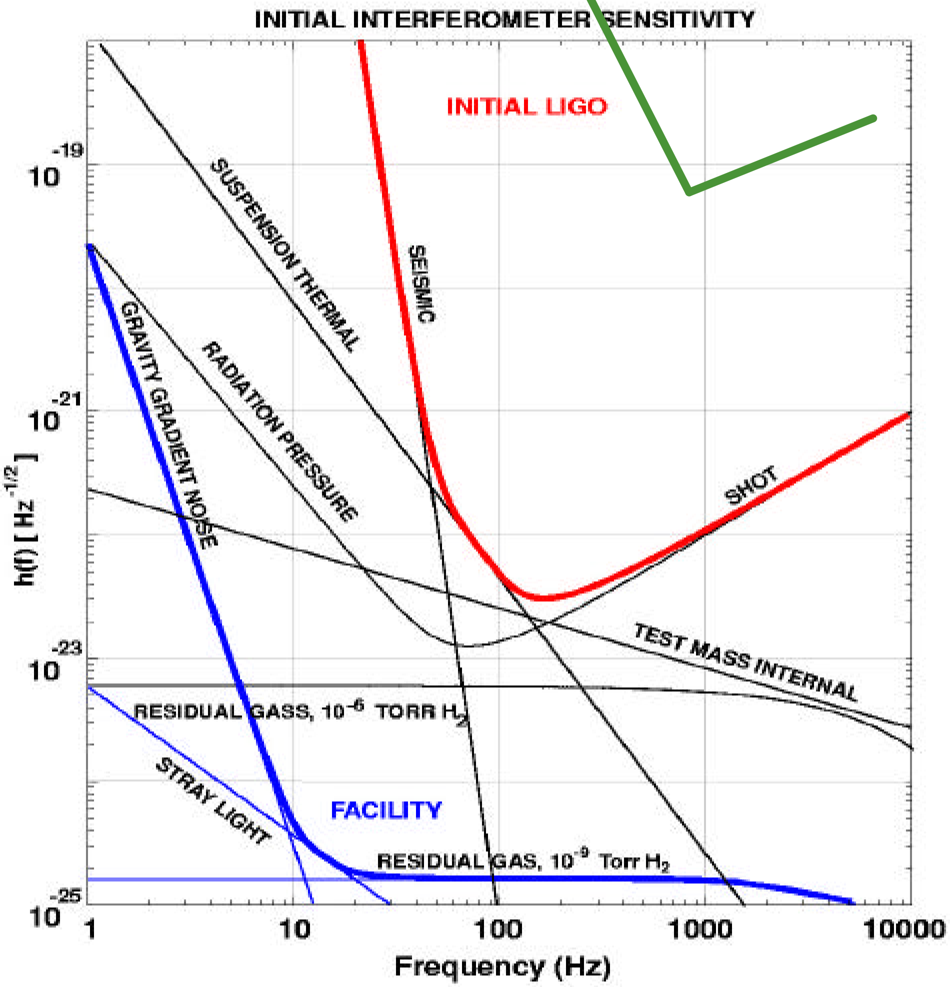
Strain Sensitivity of LIGO IFO's during E7 (very preliminary!!)



Time-frequency spectrogram of GW signal – stationary?



Initial LIGO Sensitivity Goal



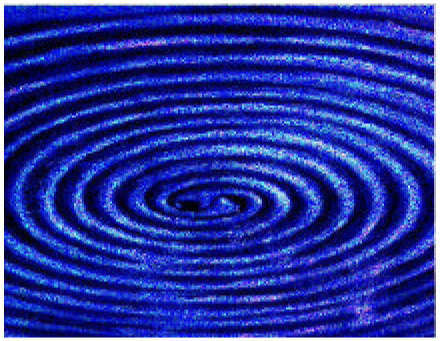
- Strain sensitivity goal:
  <3x10^{-23} 1/Hz$^{1/2}$
  at 200 Hz
- So far, getting
  ~(5-10)x10^{-20} 1/Hz$^{1/2}$
  at ~1000 Hz

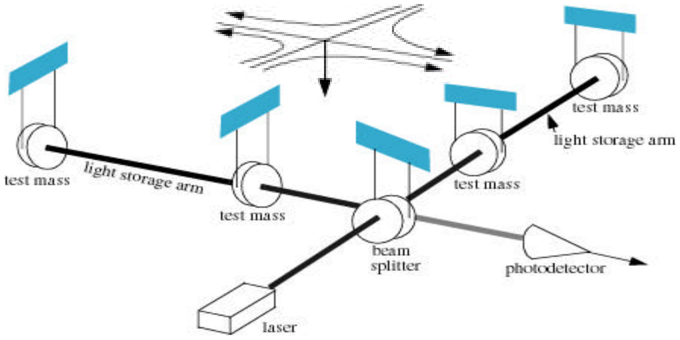
- Better than we expected!
- During E7, sensitivity is a bit better than for H2K during previous runs; but…
- We're getting similar sensitivity out of all 3 IFO's, simultaneously!

LIGO E7 so far

- Coincident operation of 3 LIGO detectors, GEO, ALLEGRO is unprecedented.
- Duty cycle has greatly exceeded our expectations.
- We are operating in a new regime of sensitivity and bandwidth; will be able to set new experimental limits.
- Coincidence with ALLEGRO will permit a limit for a stochastic background limited by the sensitivity of the bar.
- Work on improving sensitivity will recommence next week.

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!