Laser Interferometer Gravitational-wave Observatory
LIGO

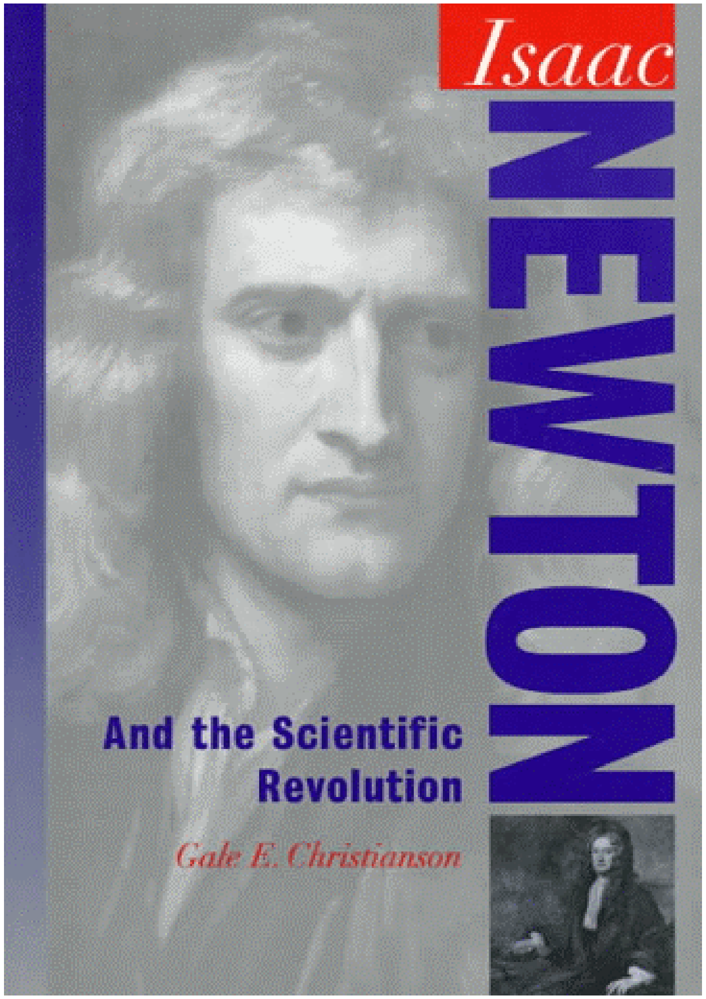
2000 Industrial Physics Forum

Barry Barish

7 November 2000

Sir Isaac Newton

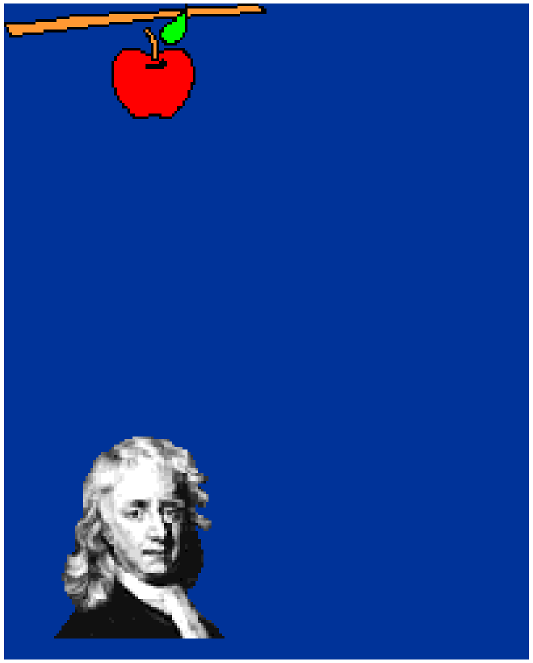
- **Perhaps the most important scientist of all time!**
- **Invented the scientific method in *Principia***
- **Greatest scientific achievement: *Universal Gravitation***



Newton

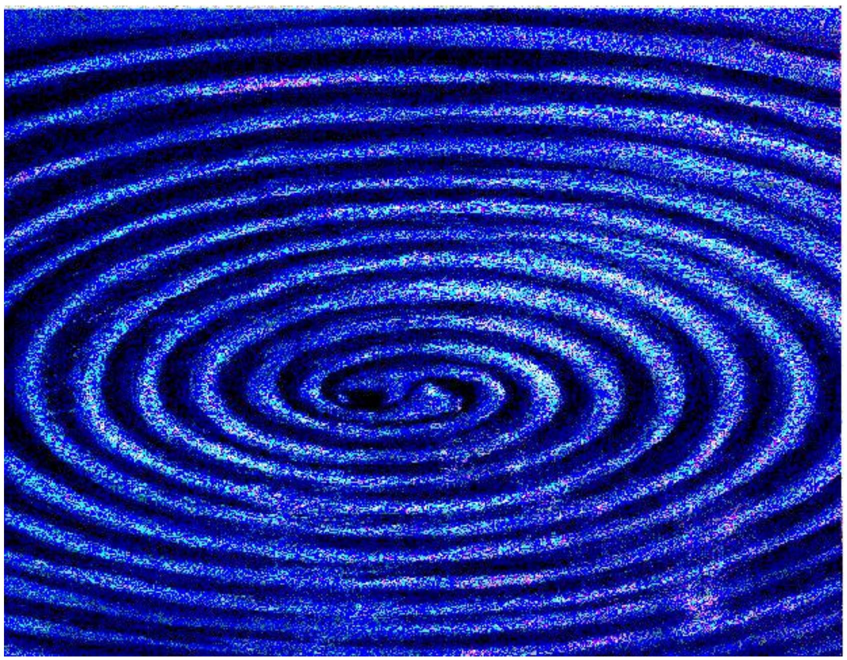
Universal Gravitation

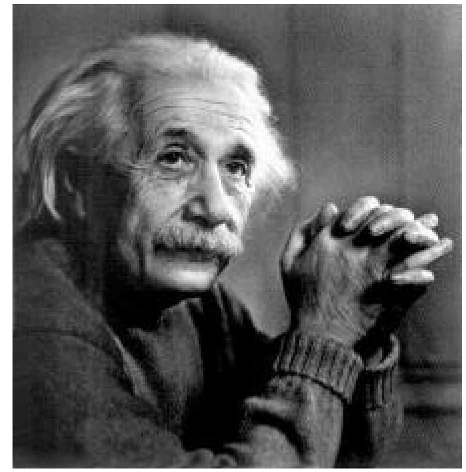
- **Three laws of motion and law of gravitation (centripetal force) disparate phenomena**
  - » **eccentric orbits of comets**
  - » **cause of tides and their variations**
  - » **the precession of the earth's axis**
  - » **the perturbation of the motion of the moon by gravity of the sun**
- **Solved most known problems of astronomy and terrestrial physics**
  - » **Work of Galileo, Copernicus and Kepler unified.**



Einstein's Theory of Gravitation

Newton's Theory
"instantaneous action at a distance"





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

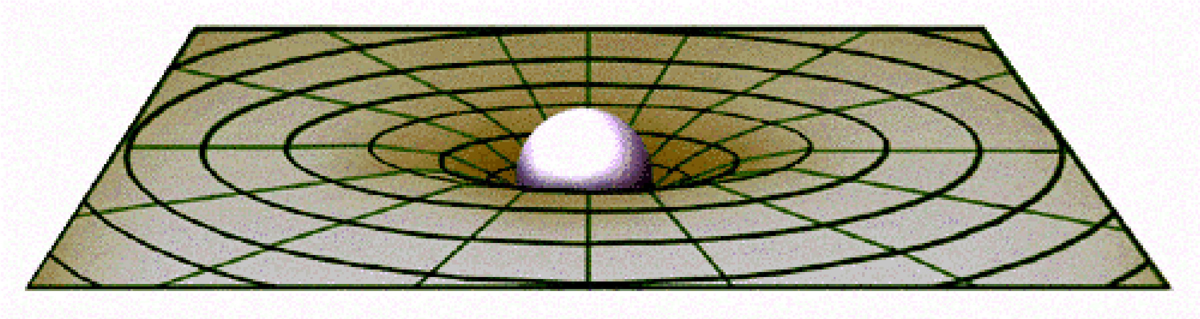
Einstein's
warpage of spacetime

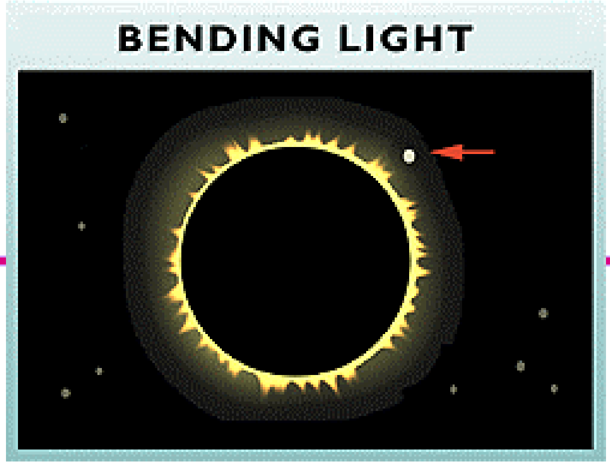
Imagine space as a stretched rubber sheet.

A mass on the surface will cause a deformation.

Another 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 mysterious force, but because the smaller objects travel through space that is warped by the larger object.





Predict the bending of light passing in the vicinity of the massive objects

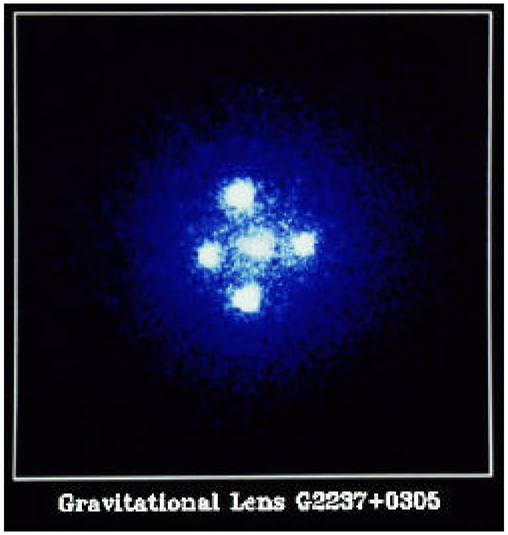
First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

Their measurements showed that the light from these stars was bent as it grazed the Sun, by the exact amount of Einstein's predictions.

The light never changes course, but merely follows the curvature of space. Astronomers now refer to this displacement of light as gravitational lensing.

Einstein's Theory of Gravitation
experimental tests

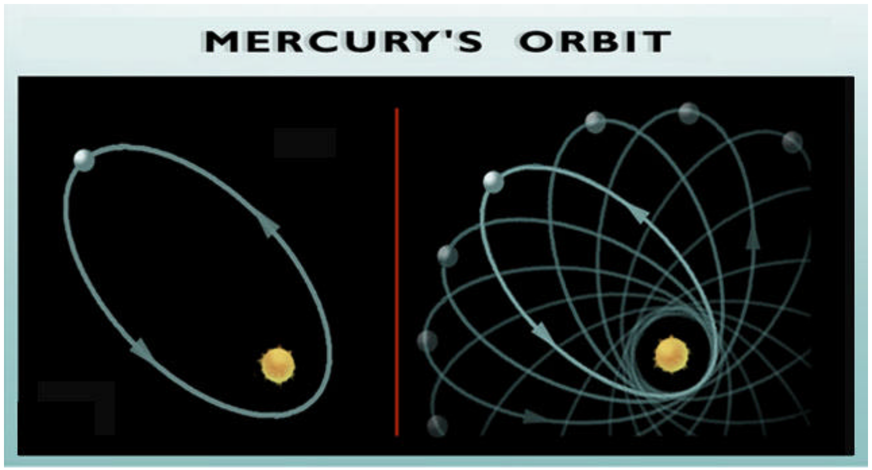
"Einstein Cross"
The bending of light rays
gravitational lensing



Quasar image appears around the central glow formed by nearby galaxy. The Einstein Cross is only visible in southern hemisphere.

In modern astronomy, such gravitational lensing images are used to detect a 'dark matter' body as the central object

Einstein’s Theory of Gravitation
experimental tests



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.

Astronomers had been aware for two centuries of a small flaw in the orbit, as predicted by Newton's laws.

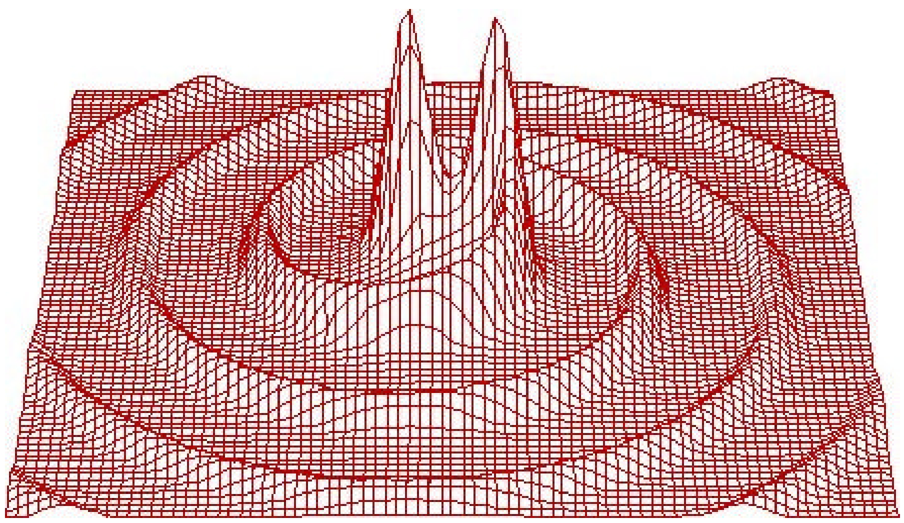
Einstein's predictions exactly matched the observation.

Einstein's Theory of Gravitation
gravitational waves

• a necessary consequence of Special Relativity with its finite speed for information transfer

• Einstein in 1916 and 1918 put forward the formulation of gravitational waves in General Relativity

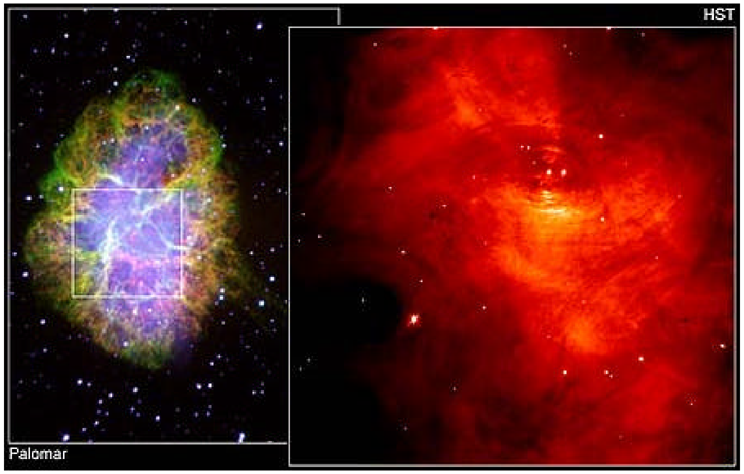
• time dependent gravitational fields come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light



gravitational radiation
binary inspiral of compact objects

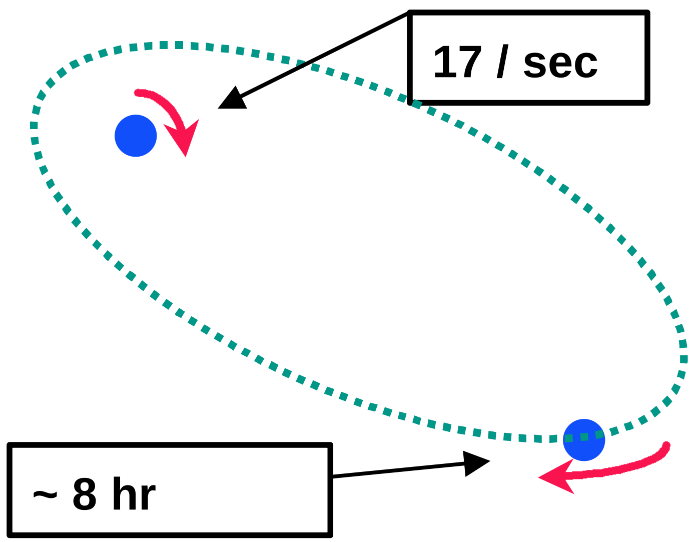
Gravitational Waves

the evidence



Neutron Binary System

PSR 1913 + 16 -- Timing of pulsars



Neutron Binary System

- separated by 106 miles
- $m_1 = 1.4 m_\odot$; $m_2 = 1.36 m_\odot$; $\varepsilon = 0.617$

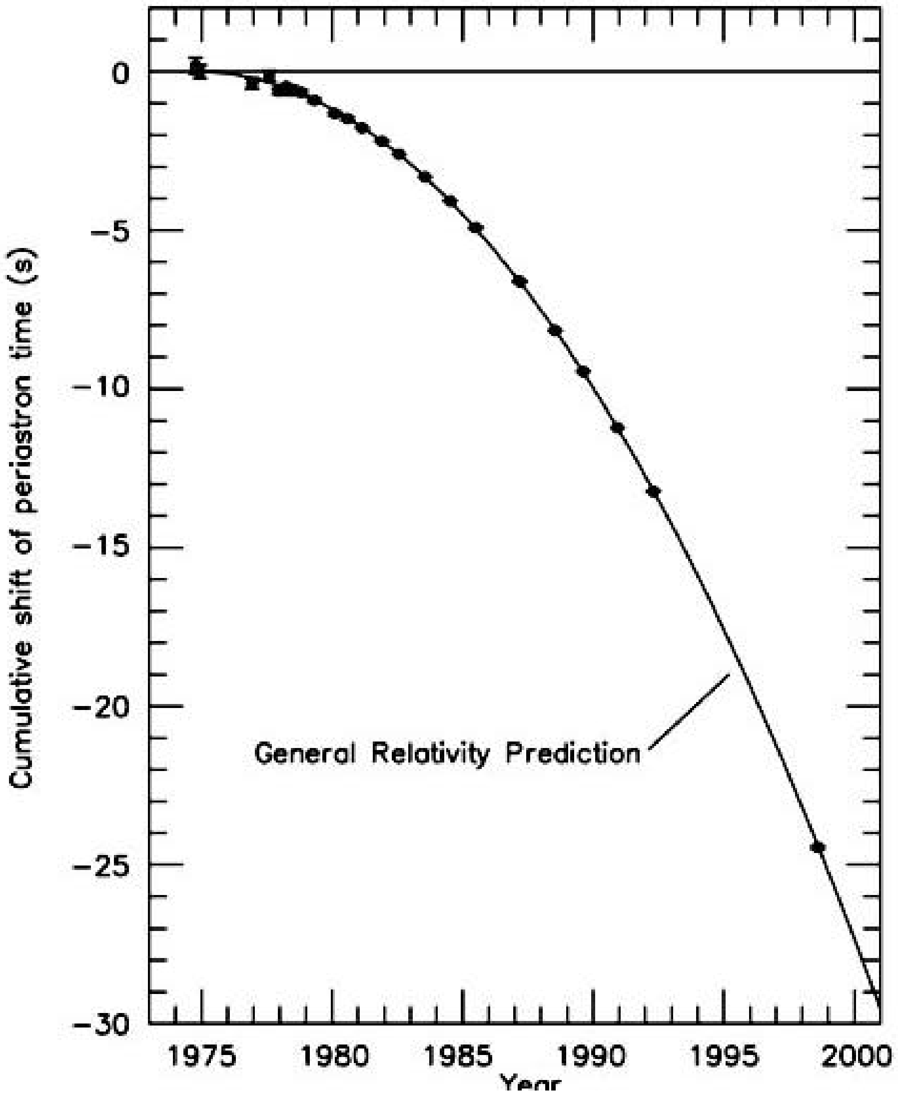
Prediction from general relativity

- spiral in by 3 mm/orbit
- rate of change orbital period

Hulse and Taylor
results

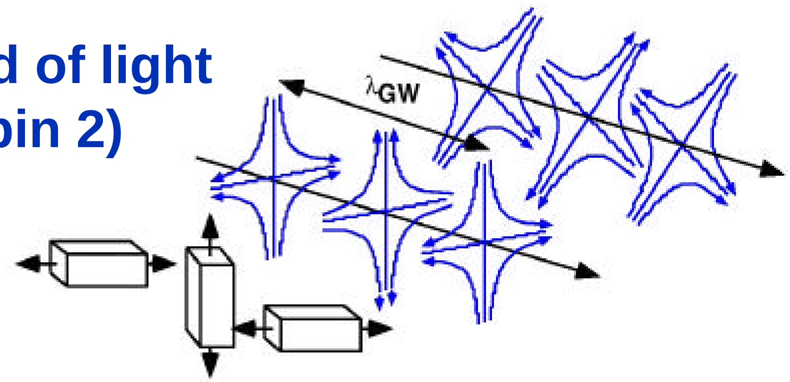
emission
of
gravitational waves

- due to loss of orbital energy
- period speeds up 25 sec from 1975-98
- measured to ~50 msec accuracy
- deviation grows quadratically with time

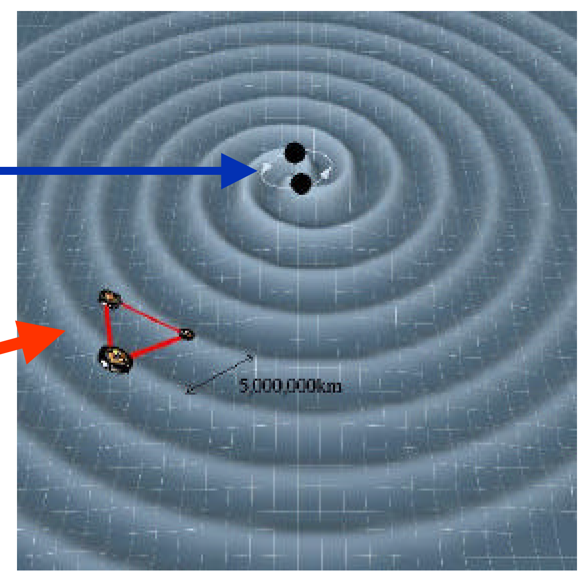


Radiation of Gravitational Waves

Waves propagates at the speed of light
Two polarizations at 45 deg (spin 2)



Radiation of Gravitational Waves from binary inspiral system

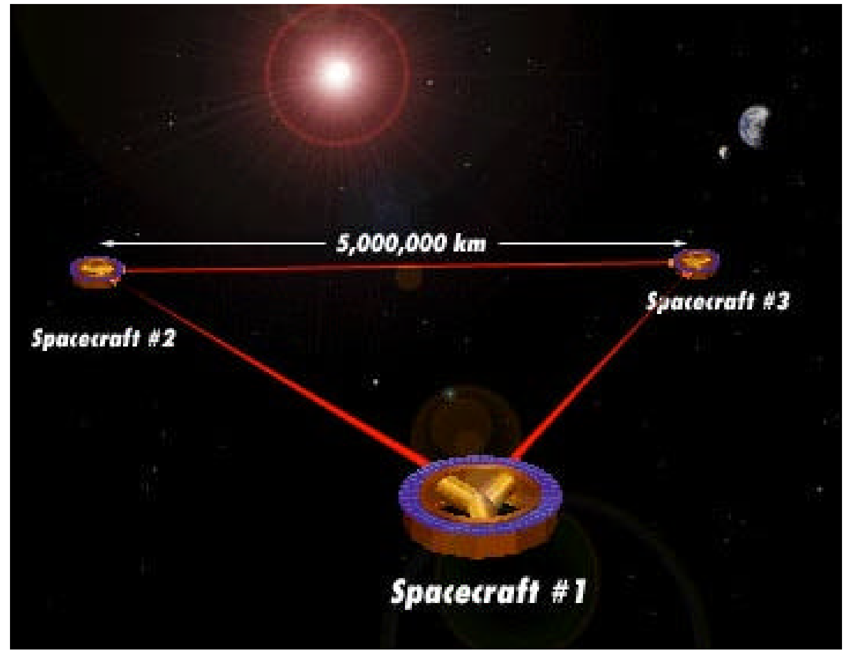


LISA

Interferometers

space

The Laser Interferometer Space Antenna (LISA)



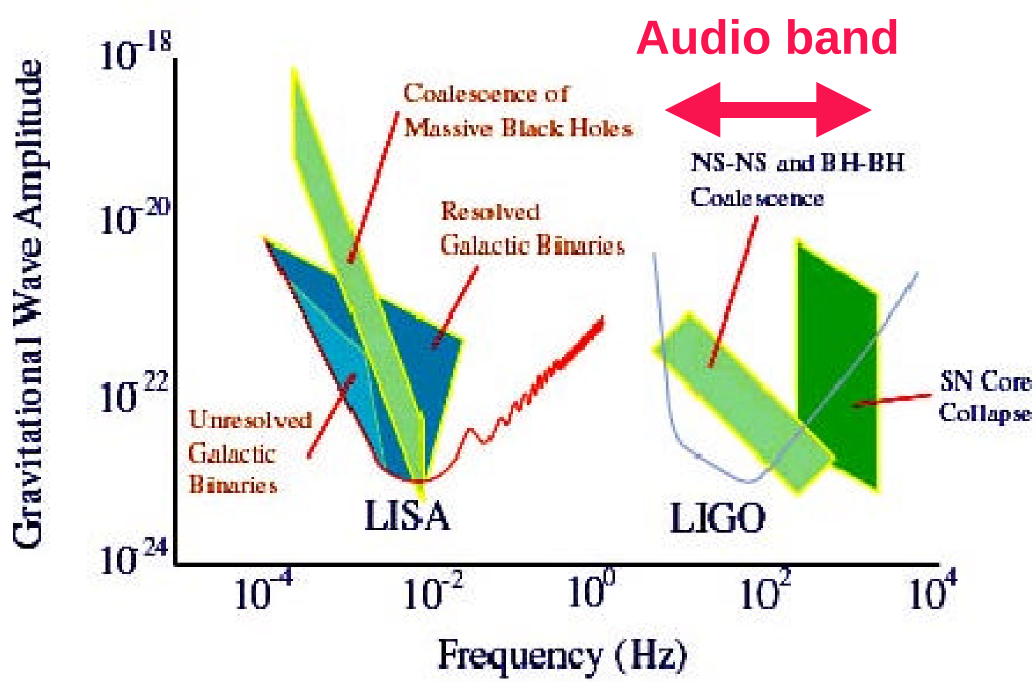
- The center of the triangle formation will be in the ecliptic plane

- 1 AU from the Sun and 20 degrees behind the Earth.

Astrophysics Sources

frequency range

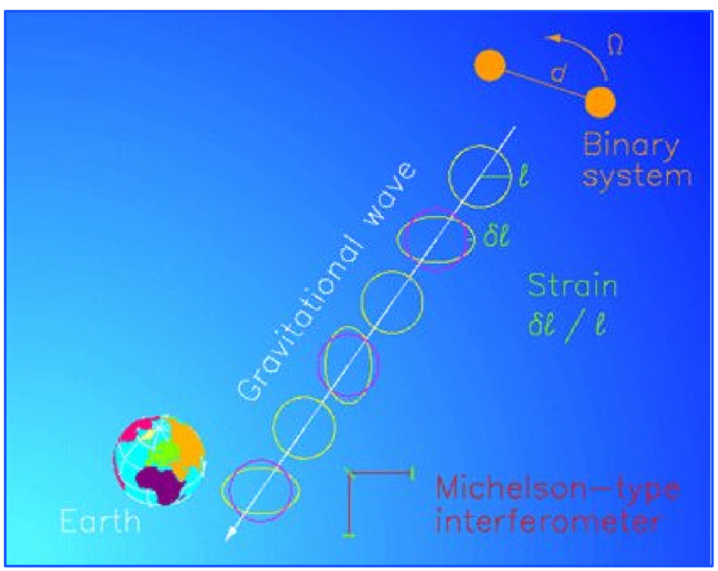
- **EM waves are studied over ~20 orders of magnitude**
  - » **(ULF radio –> HE γ-rays)**
- **Gravitational Waves over ~10 orders of magnitude**
  - » **(terrestrial + space)**

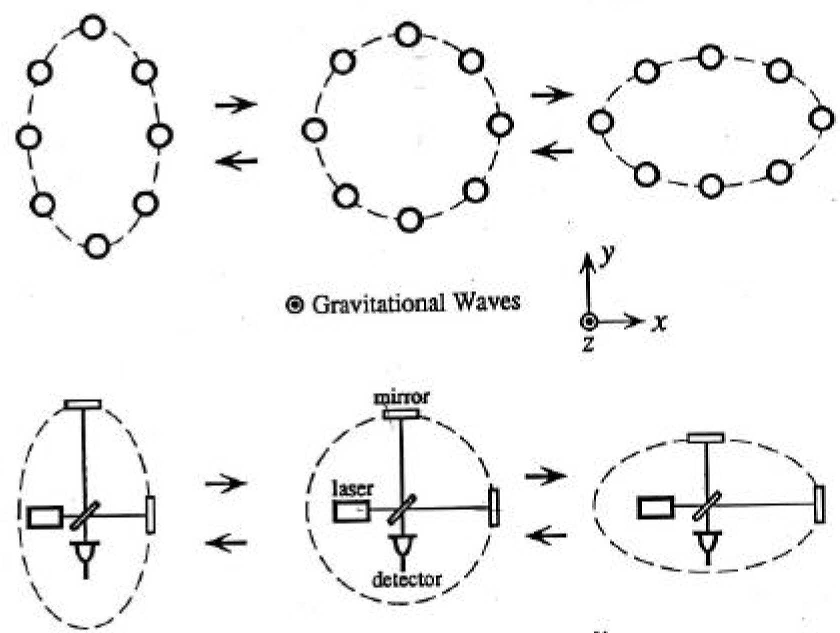


Interferometers
terrestrial

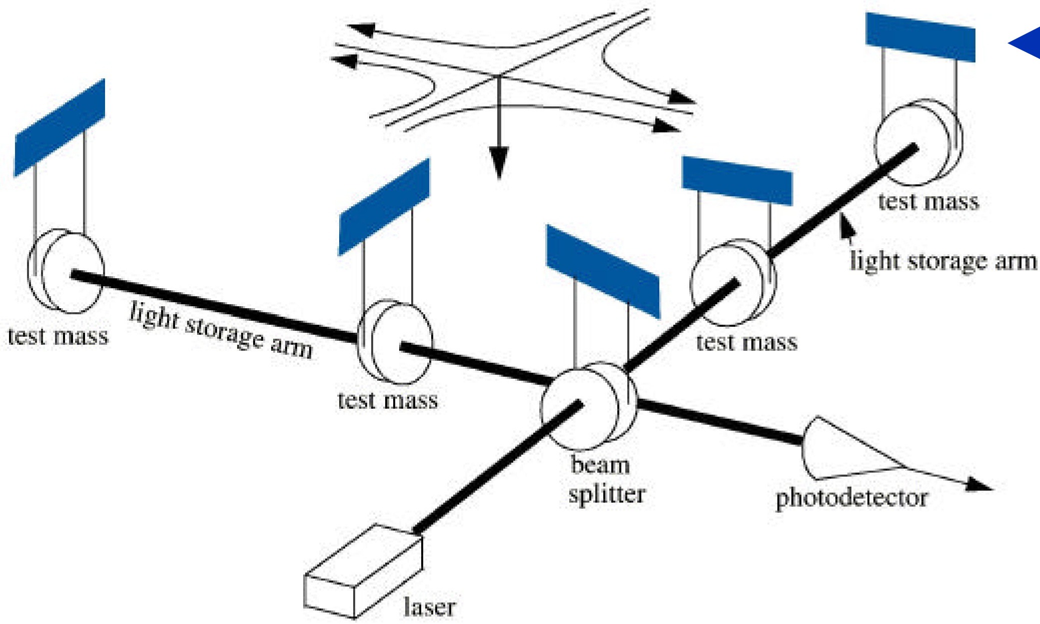
Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

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





Detection of Gravitational Waves
interferometry

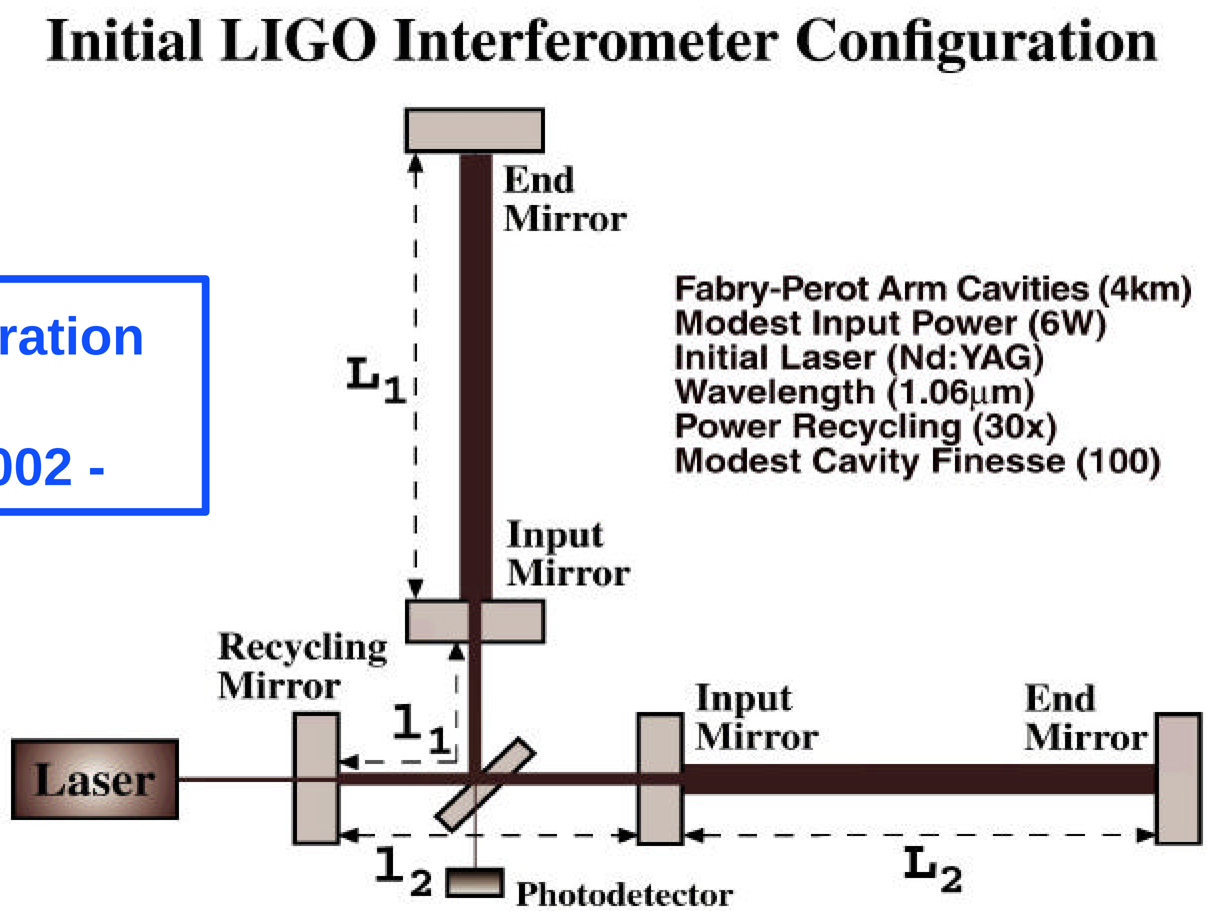


suspended test masses

LIGO (4 km), stretch (squash) = 10^{-18} m will be detected at frequencies of 10 Hz to 10^{4} Hz. It can detect waves from a distance of 600 10^{6} light years

LIGO I
interferometer

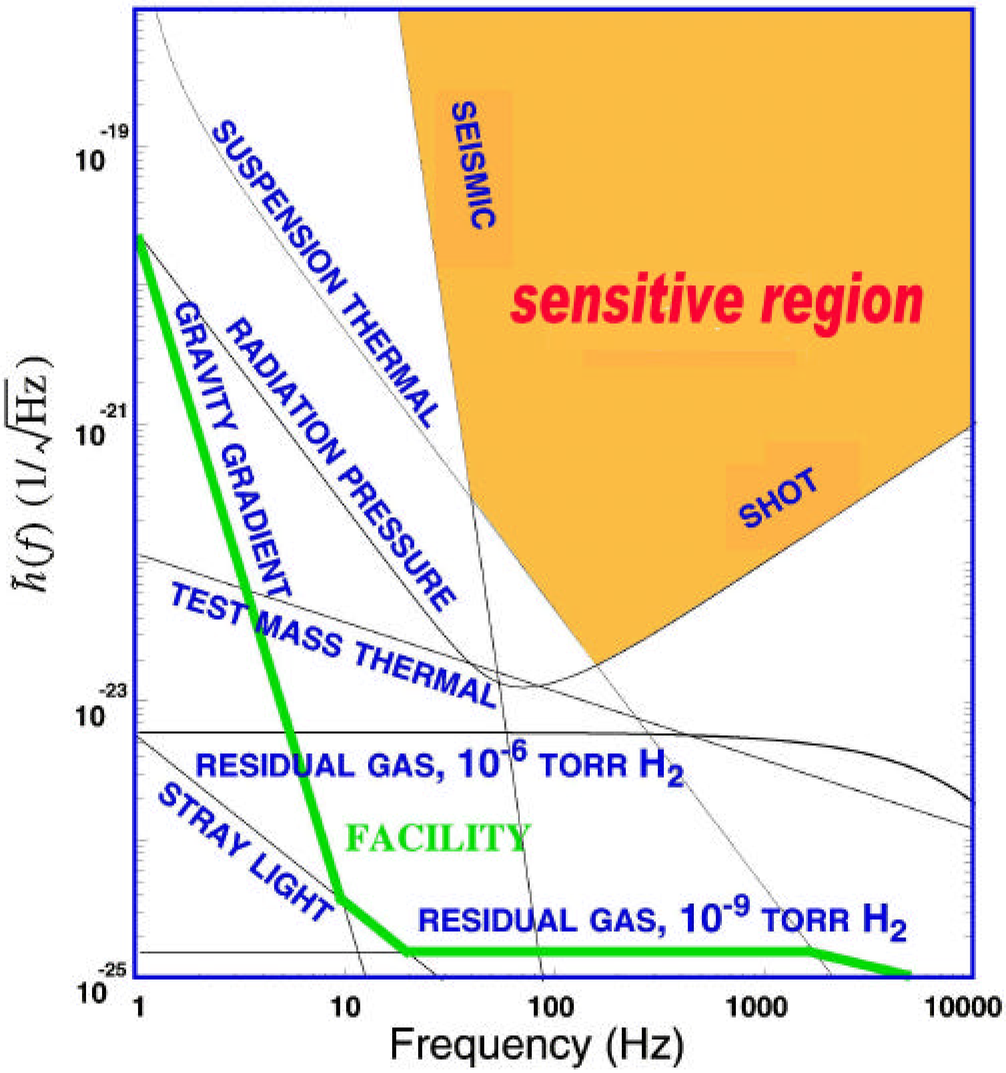
- LIGO I configuration
- Science Run 2002 -



LIGO I
the noise floor

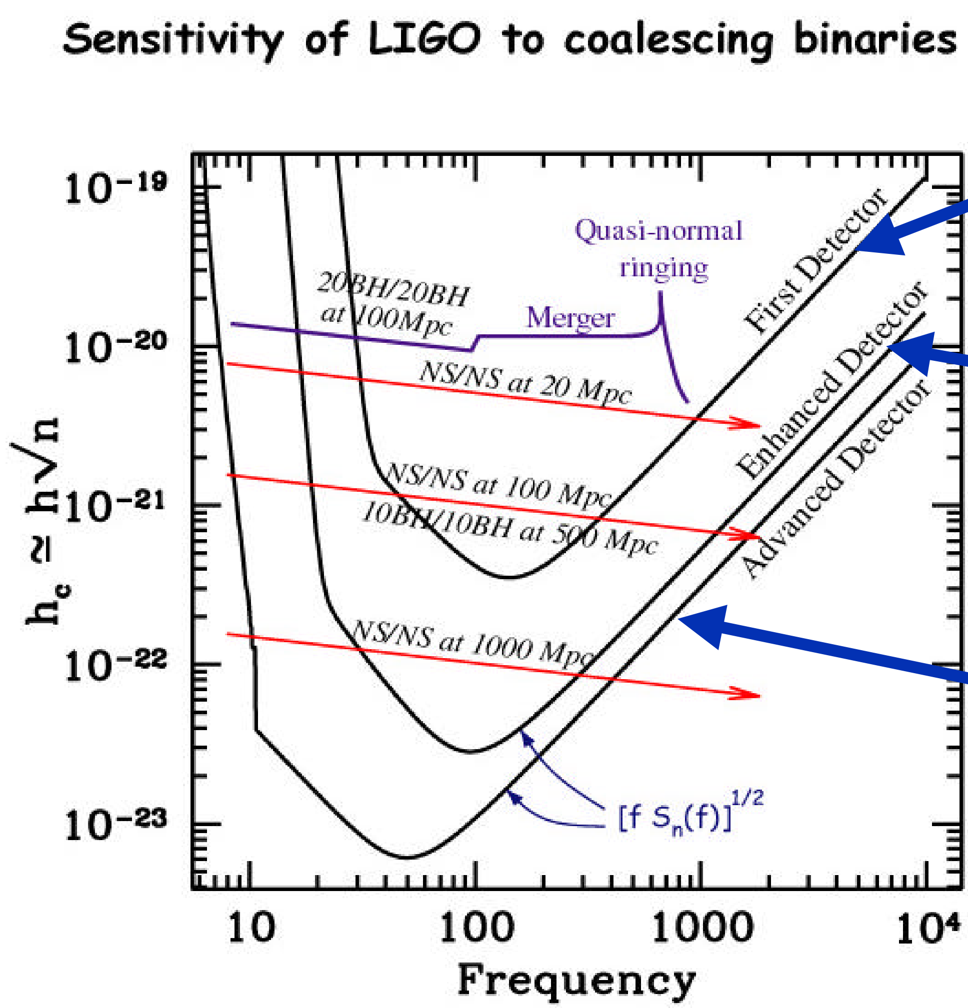
- **Interferometry is limited by three fundamental noise sources**
  - **<u>seismic noise</u> at the lowest frequencies**
  - **<u>thermal noise</u> at intermediate frequencies**
  - **<u>shot noise</u> at high frequencies**

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



LIGO

astrophysical sources



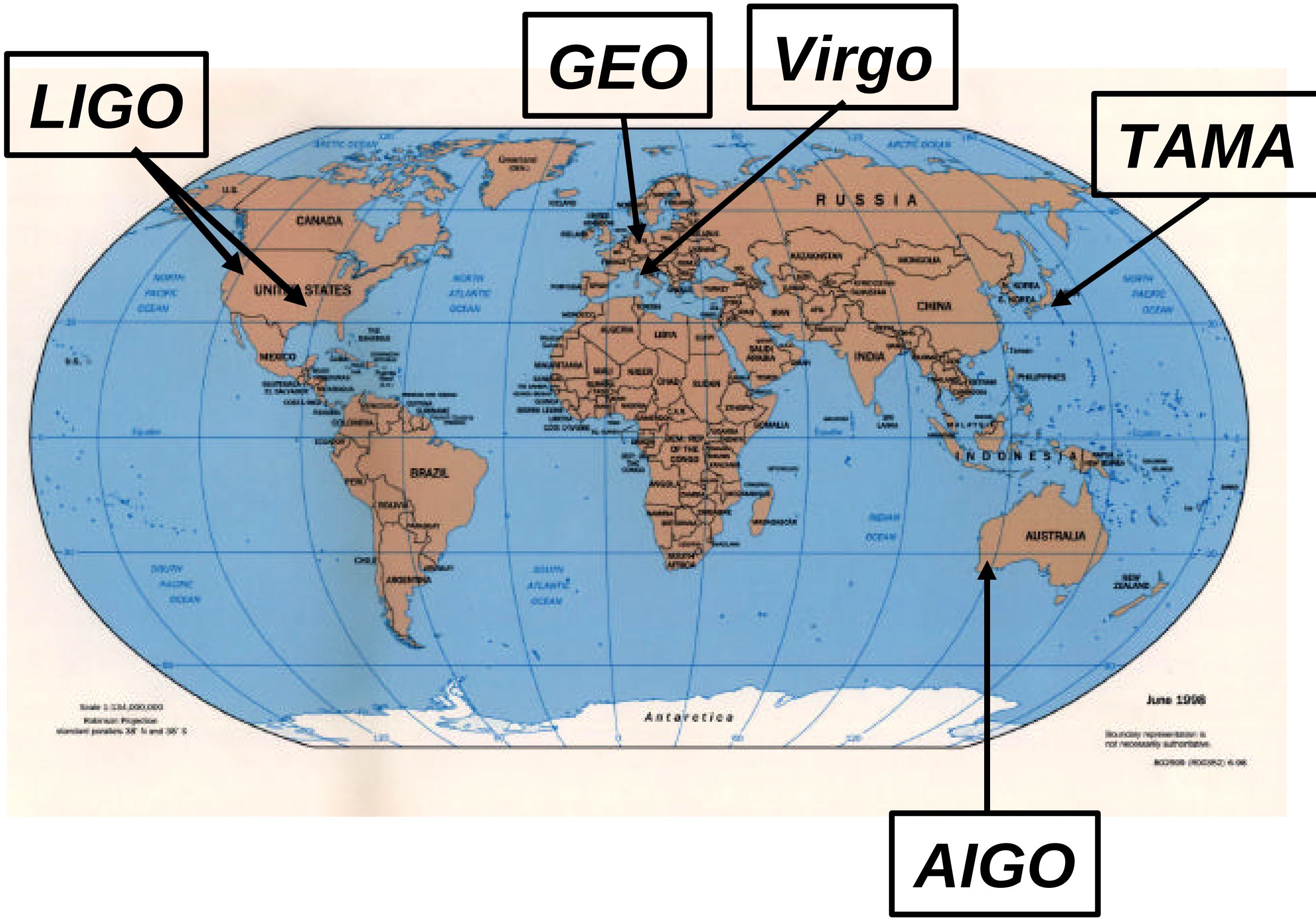
LIGO I (2002-2005)

LIGO II (2007-)

Advanced LIGO

Interferometers
international network

Simultaneously detect signal (within msec)



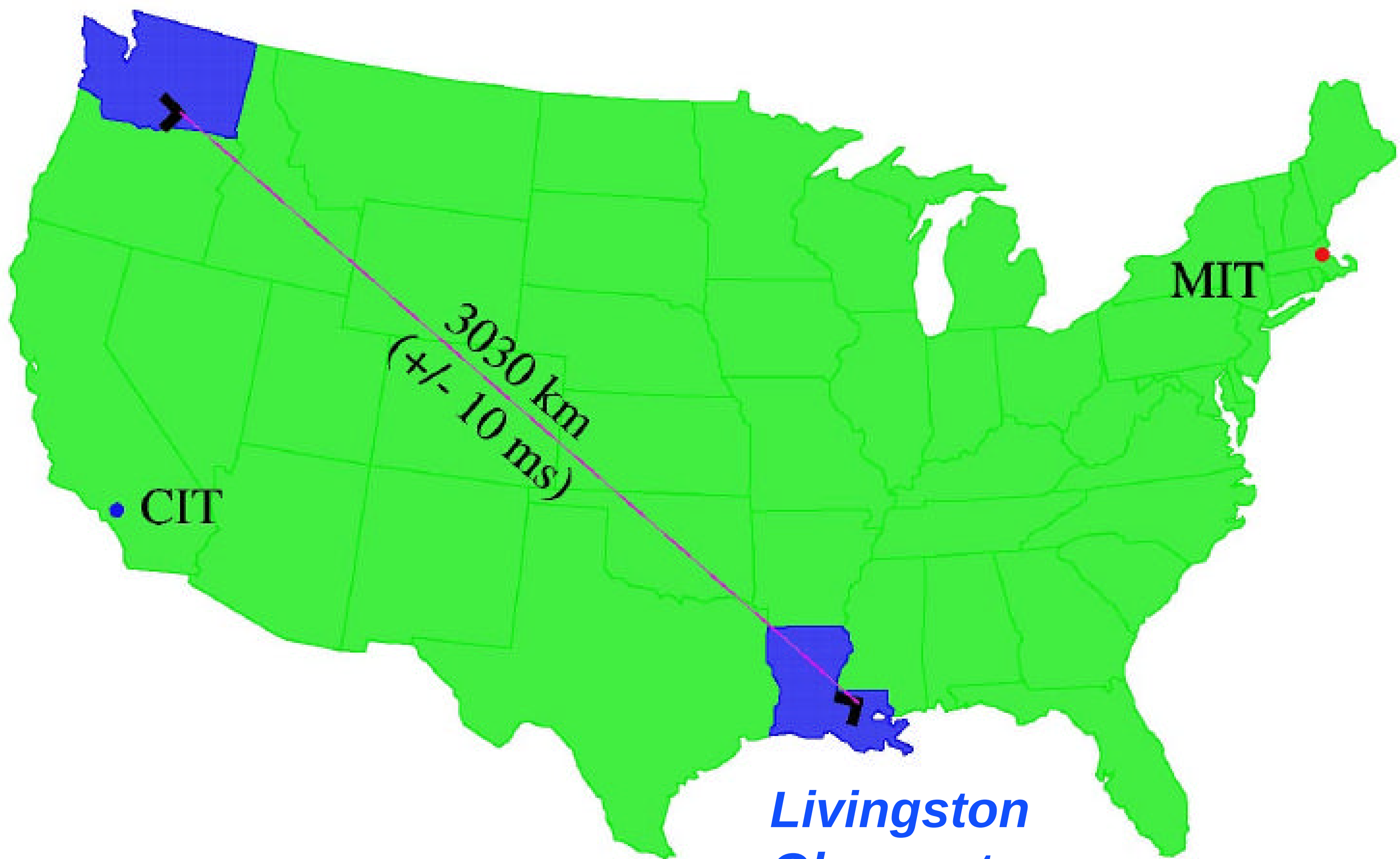
detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Sites

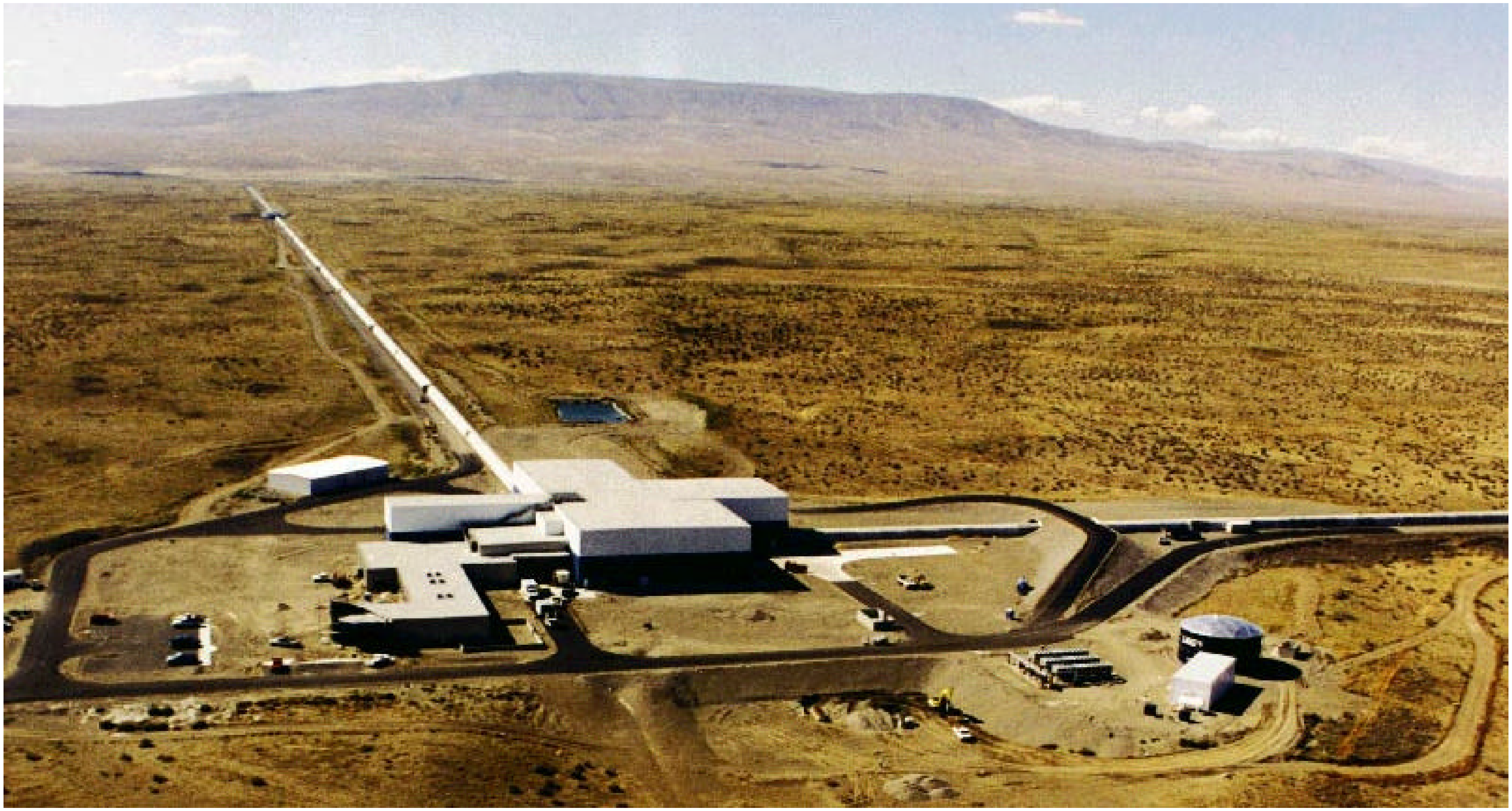
Hanford Observatory



Livingston Observatory

LIGO
Livingston Observatory

LIGO
Hanford Observatory



LIGO Plans

schedule

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 LIGOI Science Run)
2003+	**LIGO I data run**	(one year integrated data at h ~ 10^{-21})
2005	**Begin LIGO II installation**	

LIGO Facilities

beam tube enclosure

- minimal enclosure
- reinforced concrete
- no services

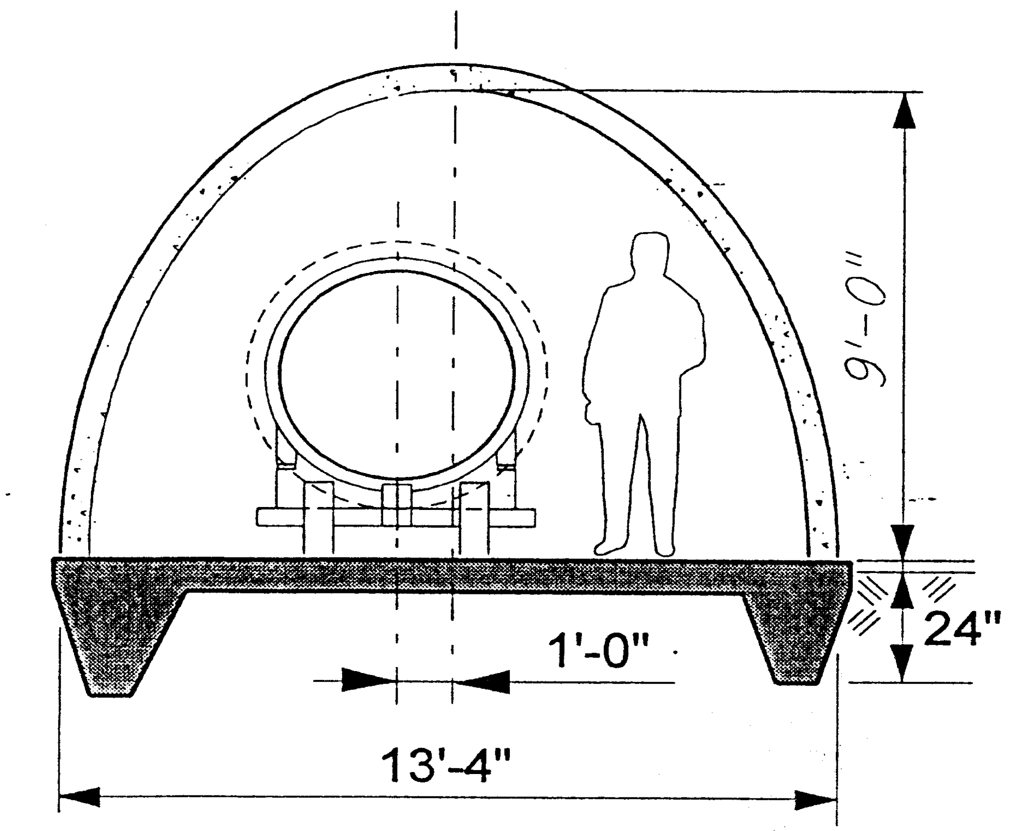


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

LIGO
beam tube

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

1.2 m diameter - 3mm stainless
50 km of weld

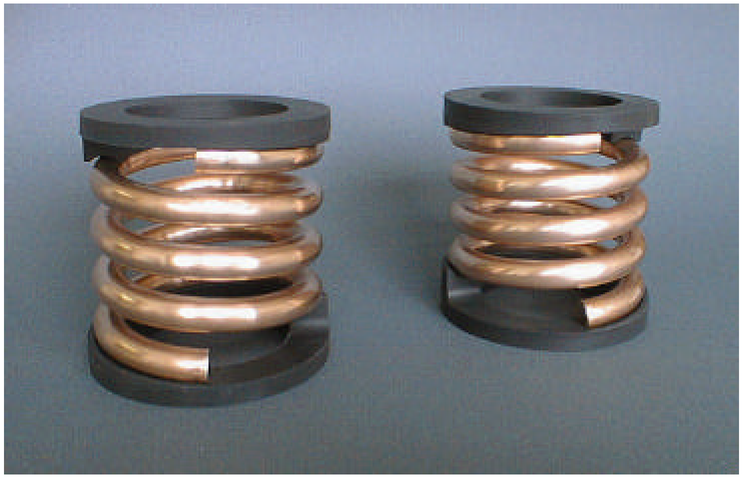
NO LEAKS !!

LIGO

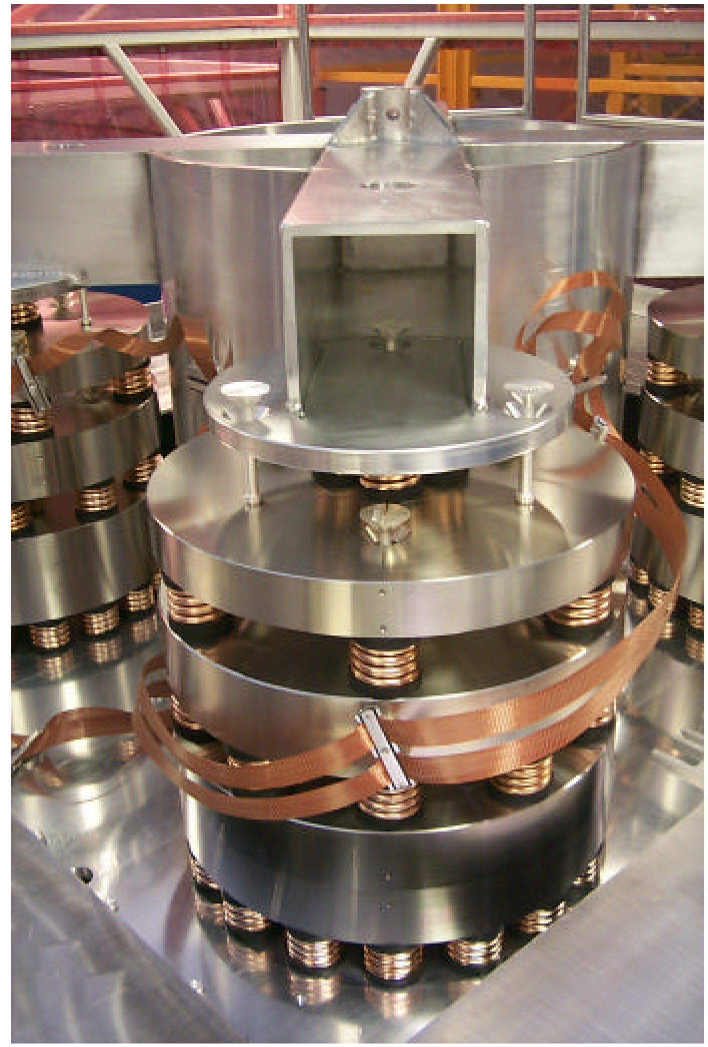
vacuum equipment

Seismic Isolation

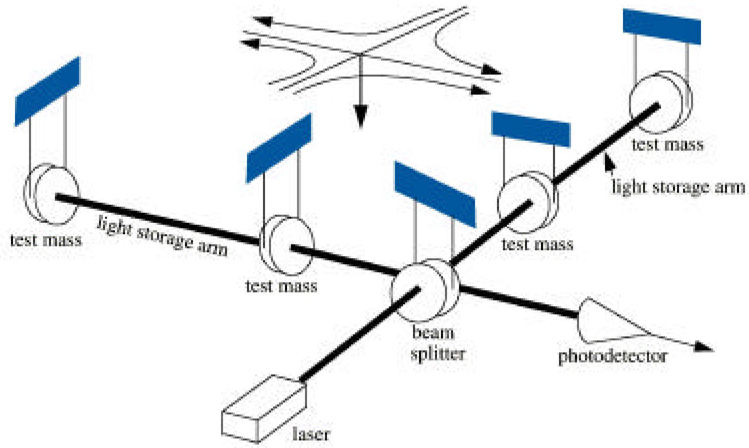
springs and masses



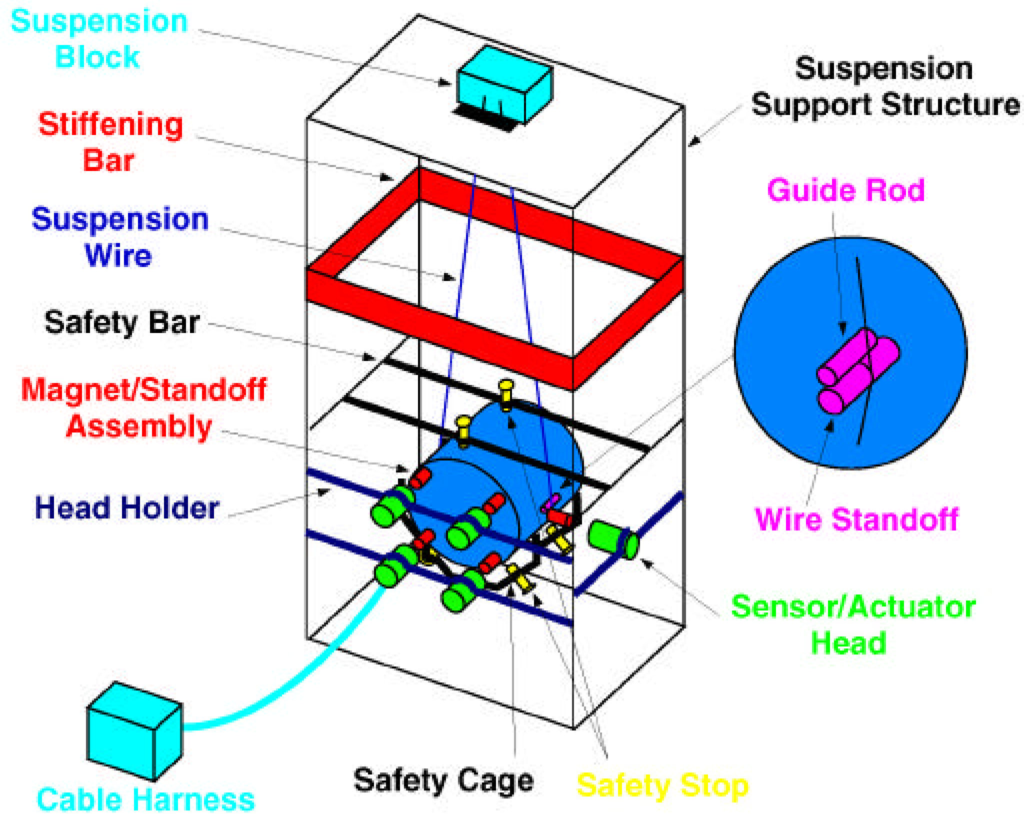
damped spring
cross section



Seismic Isolation
suspension system

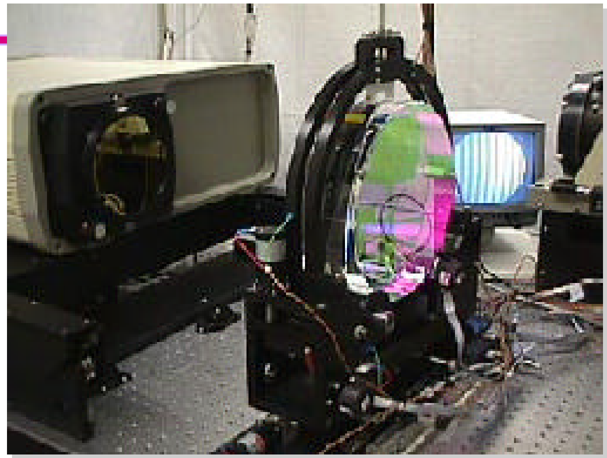


suspension assembly for a core optic

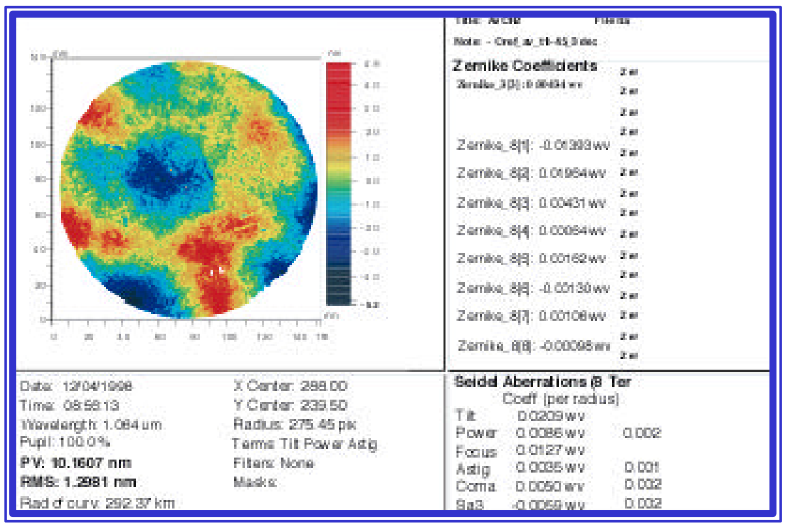


- support structure is welded tubular stainless steel
- suspension wire is 0.31 mm diameter steel music wire
- fundamental violin mode frequency of 340 Hz

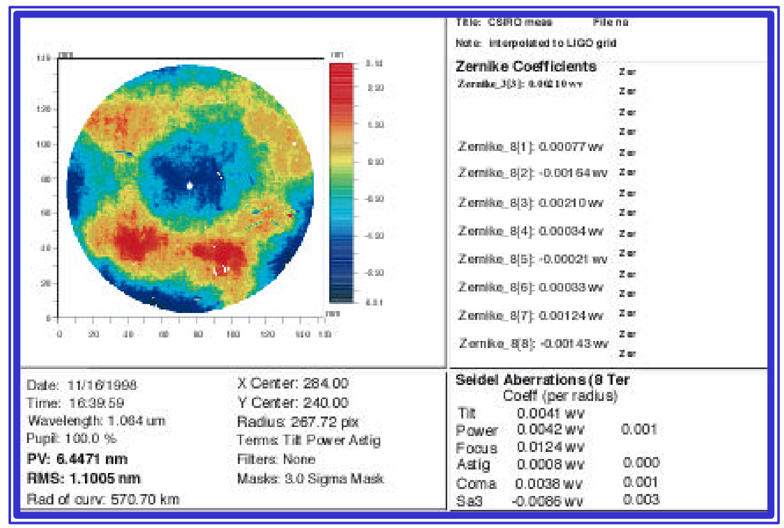
Core Optics
fused silica



- **Surface uniformity < 1 nm rms**
- **Scatter < 50 ppm**
- **Absorption < 2 ppm**
- **ROC matched < 3%**
- **Internal mode Q's > 2 x 10^6**



Caltech data



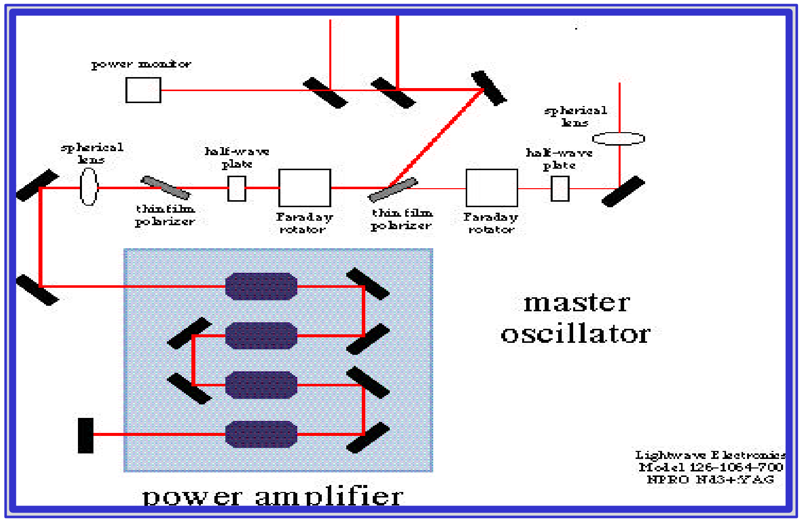
CSIRO data

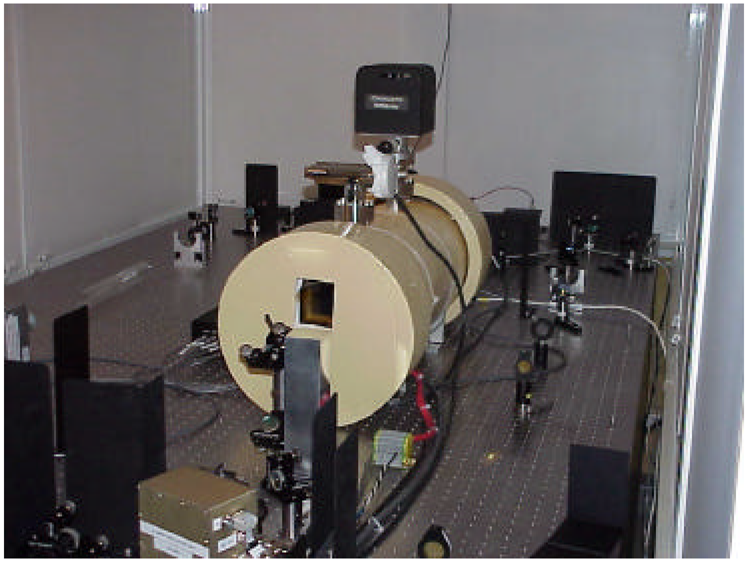
Core Optics

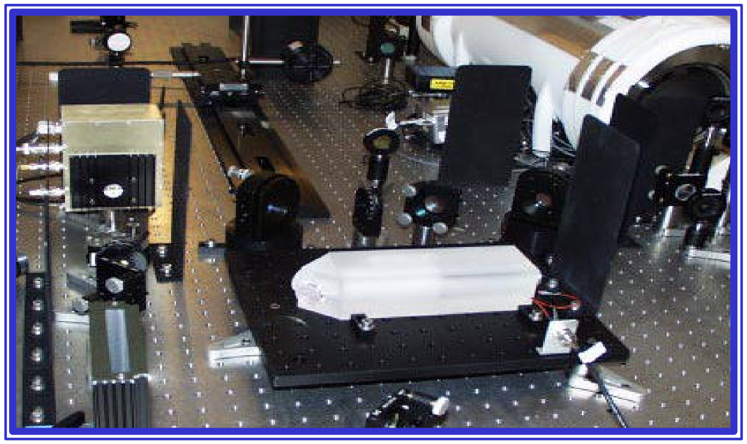
installation and alignment

LIGO
laser

- **Nd:YAG**
- **1.064 μm**
- **Output power > 8W in TEM00 mode**







Commissioning *configurations*

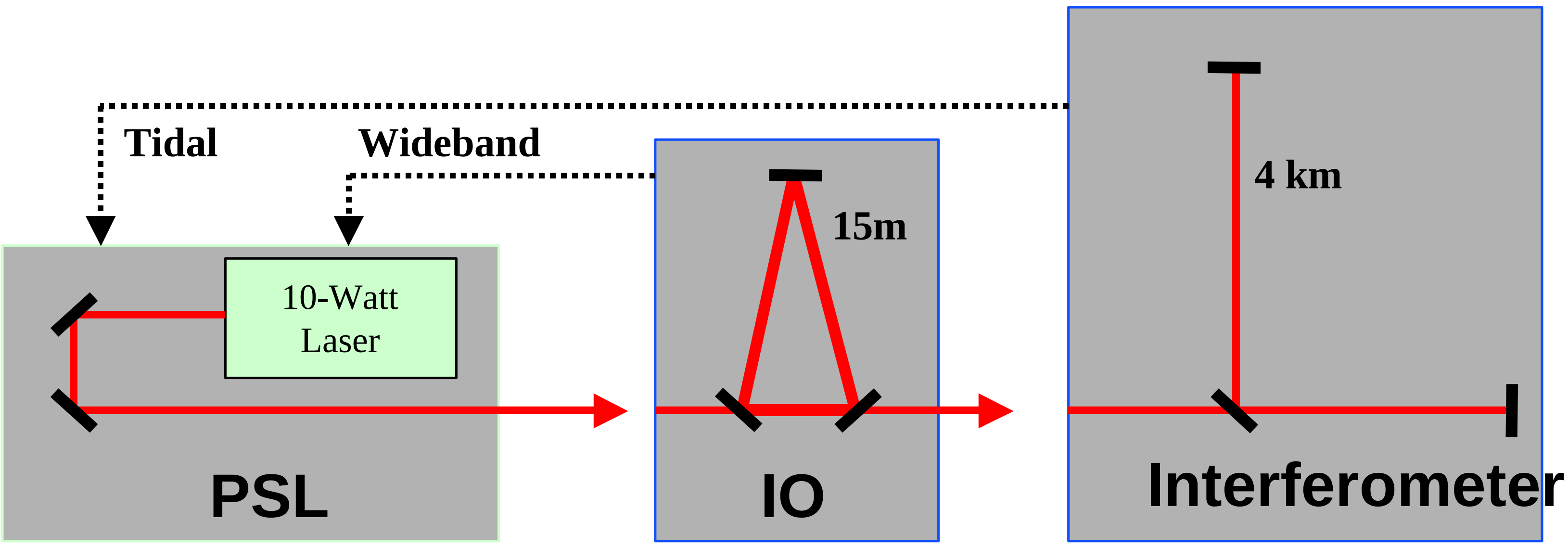
- Mode cleaner and Pre-Stabilized Laser
- 2km one-arm cavity
- short Michelson interferometer studies

- Lock entire Michelson Fabry-Perot interferometer

"First Lock"

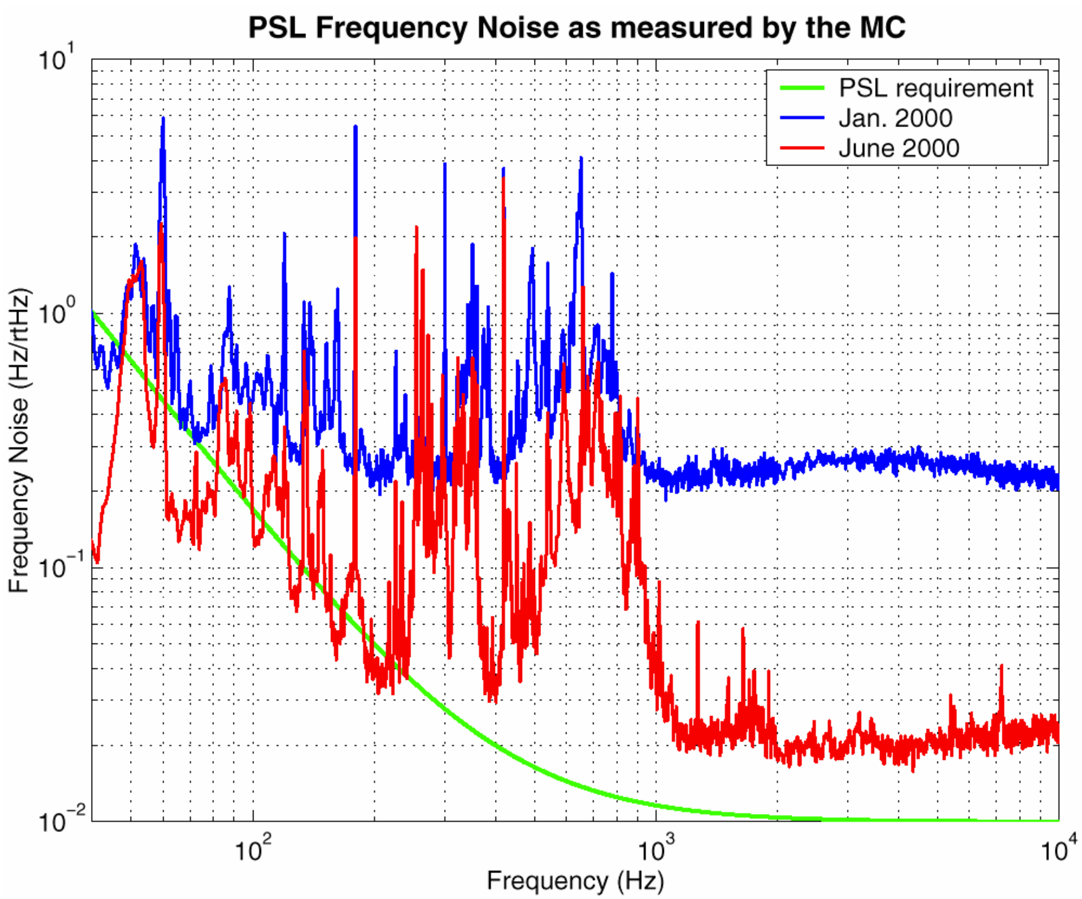
Laser *stabilization*

- **Deliver pre-stabilized laser light to the 15-m mode cleaner**
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- **Provide actuator inputs for further stabilization**
  - **Wideband**
  - **Tidal**



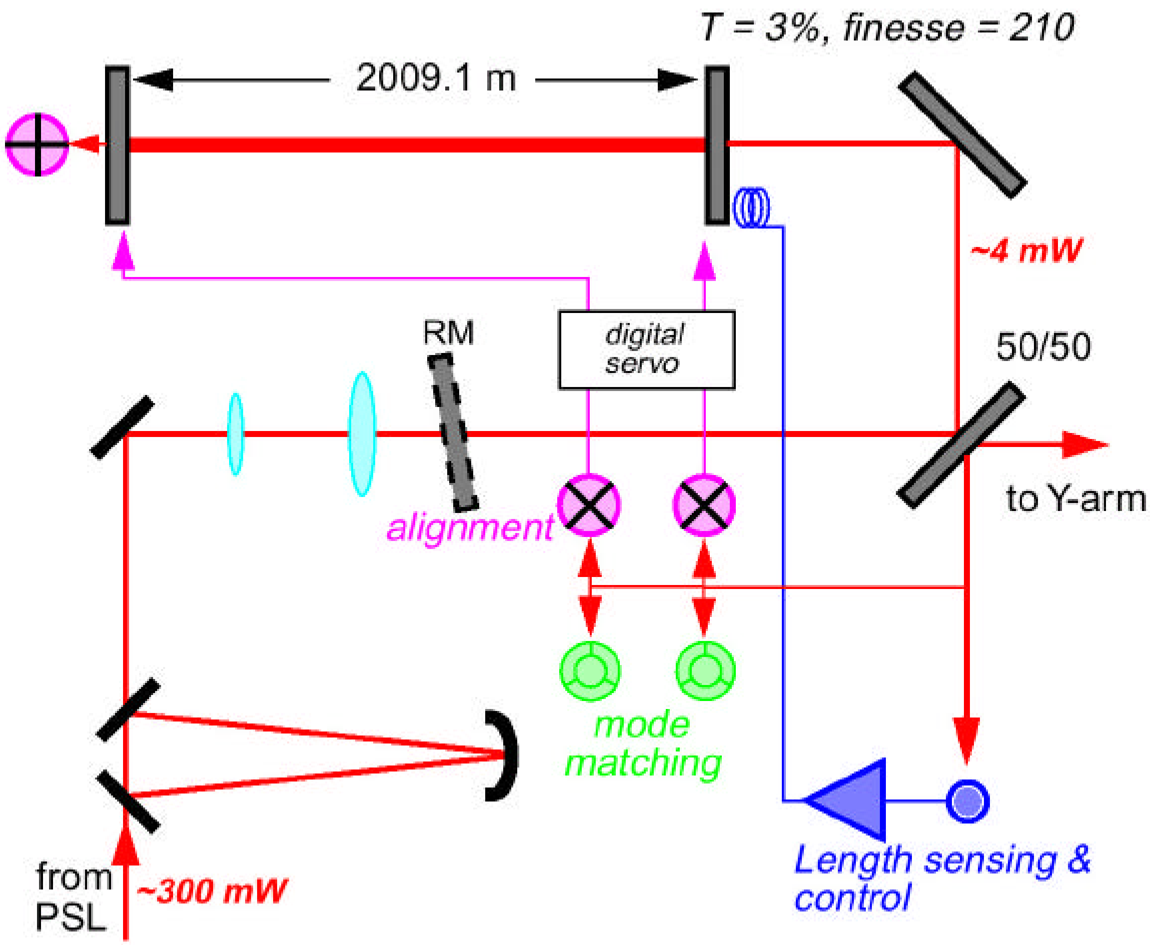
10^{-1} Hz/Hz$^{1/2}$ 10^{-4} Hz/ Hz$^{1/2}$ 10^{-7} Hz/ Hz$^{1/2}$

Prestabalized Laser
performance



- **> 18,000 hours continuous operation**
- **Frequency and lock very robust**
- **TEM_{00} power > 8 watts**
- **Non-TEM_{00} power < 10%**

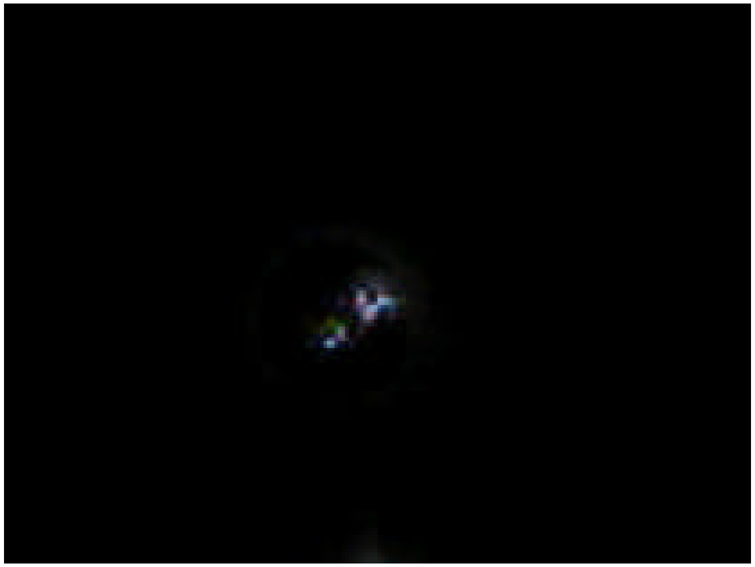
Detector Commissioning:
2-km arm test



- 12/99 – 3/00
- Alignment "dead reckoning" worked
- Digital controls, networks, and software all worked
- Exercised fast analog laser frequency control
- Verified that core optics meet specs
- Long-term drifts consistent with earth tides

Locking the Long Arm

- 12/1/99 Flashes of light
- 12/9/99 0.2 seconds lock
- 1/14/00 2 seconds lock
- 1/19/00 60 seconds lock
- 1/21/00 5 minutes lock
  (on other arm)
- 2/12/00 18 minutes lock
- 3/4/00 90 minutes lock
  (temperature stabilized laser
  reference cavity)
- 3/26/00 10 hours lock

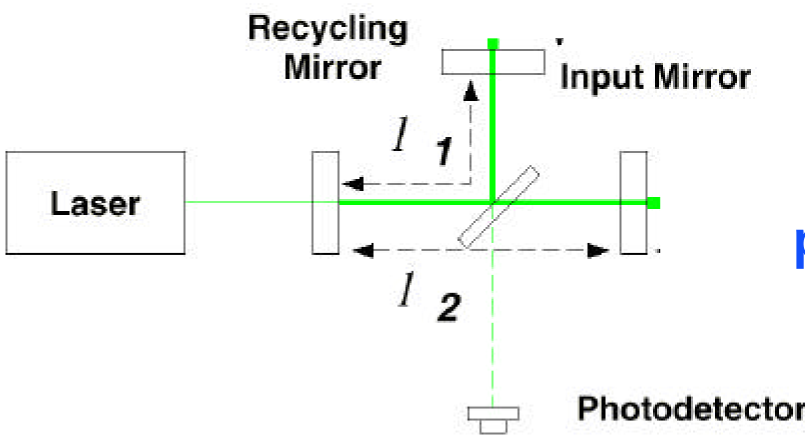


First interference fringes
from the 2-km arm

Near-Michelson interferometer

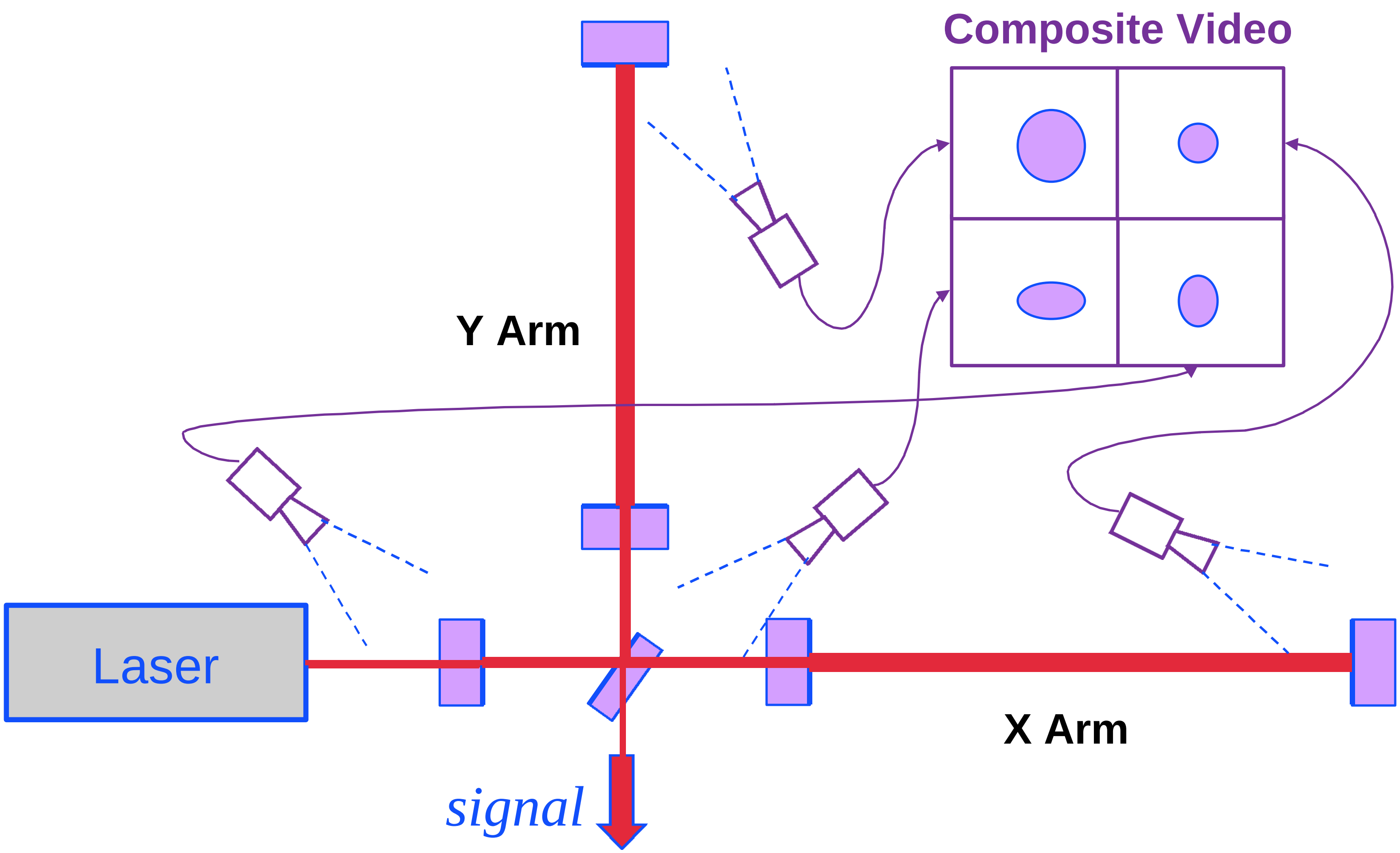
- power recycled (short) Michelson Interferometer

- employs full mixed digital/analog servos

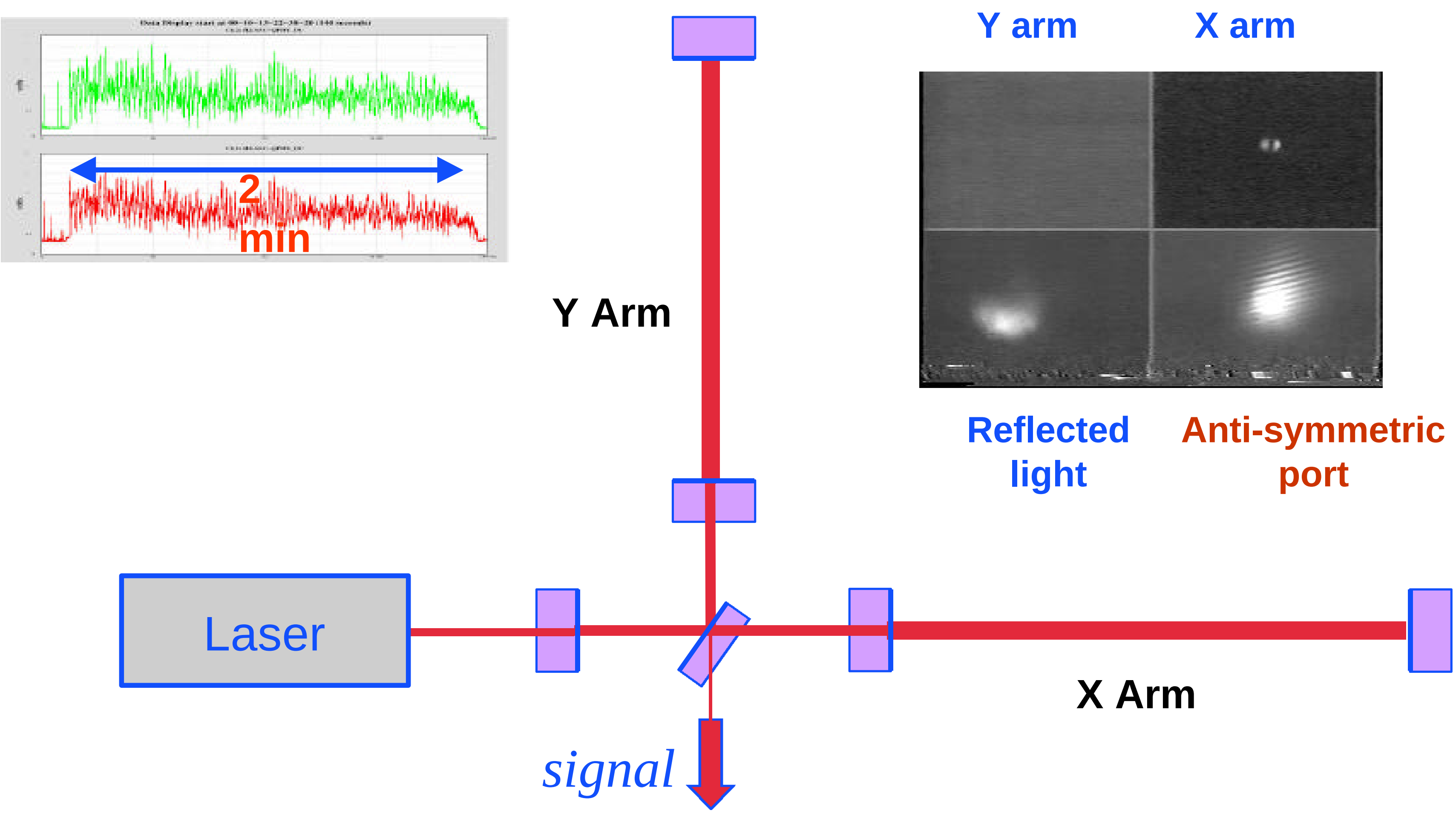


Interference fringes from the power recycled near Michelson interferometer

LIGO
“first lock”



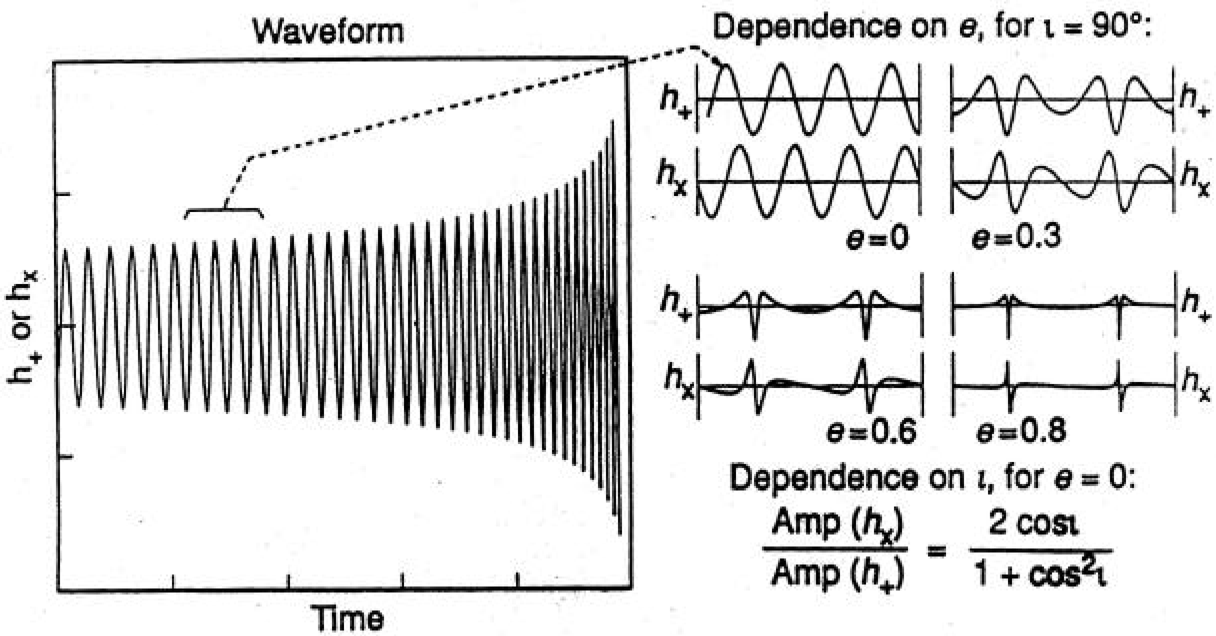
Watching the Interferometer Lock



Astrophysical Signatures
data analysis

- **Compact binary inspiral:** ***"chirps"***
  - » **NS-NS waveforms are well described**
  - » **BH-BH need better waveforms**
  - » **search technique: matched templates**
- **Supernovae / GRBs:** ***"bursts"***
  - » **burst signals in coincidence with signals in electromagnetic radiation**
  - » **prompt alarm (~ one hour) with neutrino detectors**
- **Pulsars in our galaxy:** ***"periodic"***
  - » **search for observed neutron stars (frequency, doppler shift)**
  - » **all sky search (computing challenge)**
  - » **r-modes**
- **Cosmological Signals** ***"stochastic background"***

"Chirp Signal"
binary inspiral



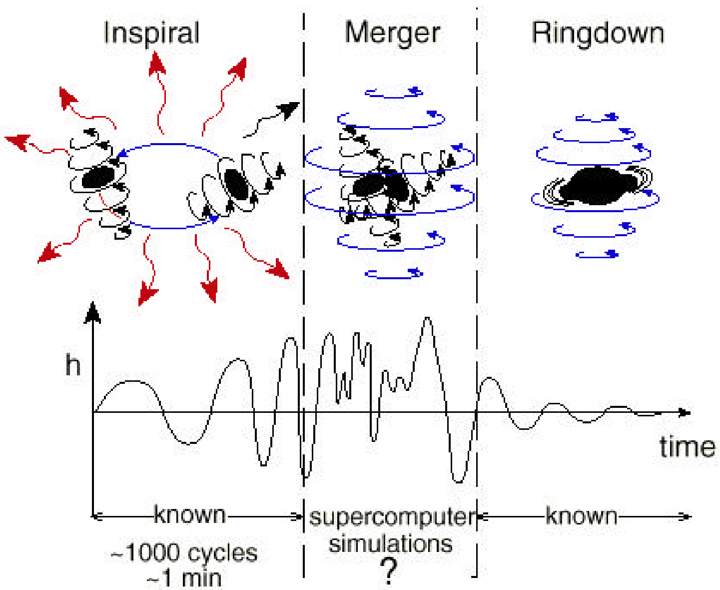
determine

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

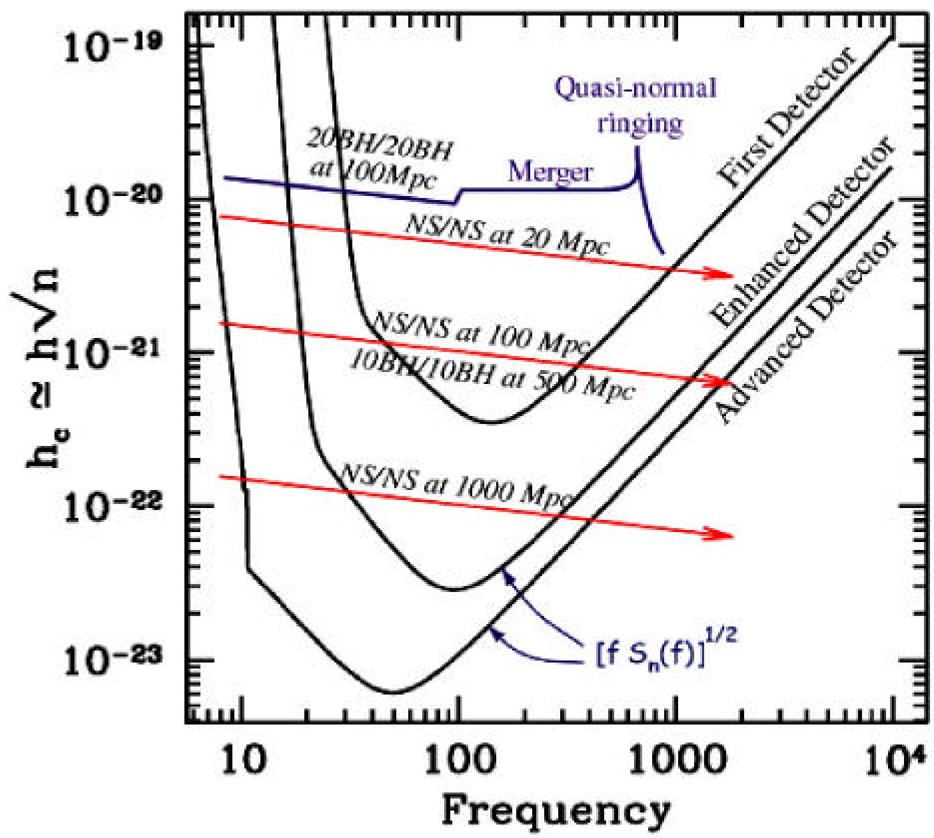
Binary Inspirals

signatures and sensitivity

Compact binary mergers

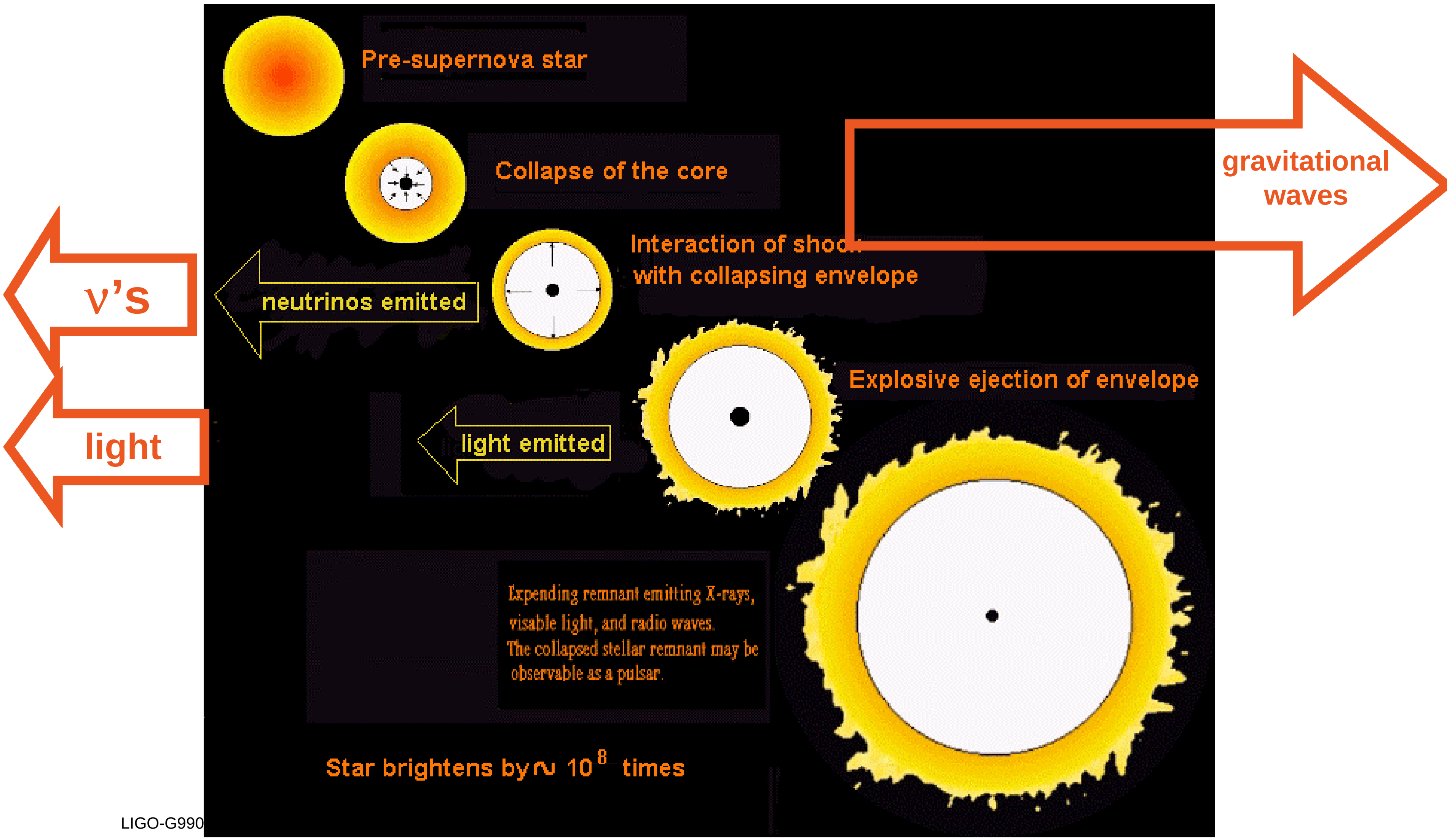


LIGO sensitivity to coalescing binaries

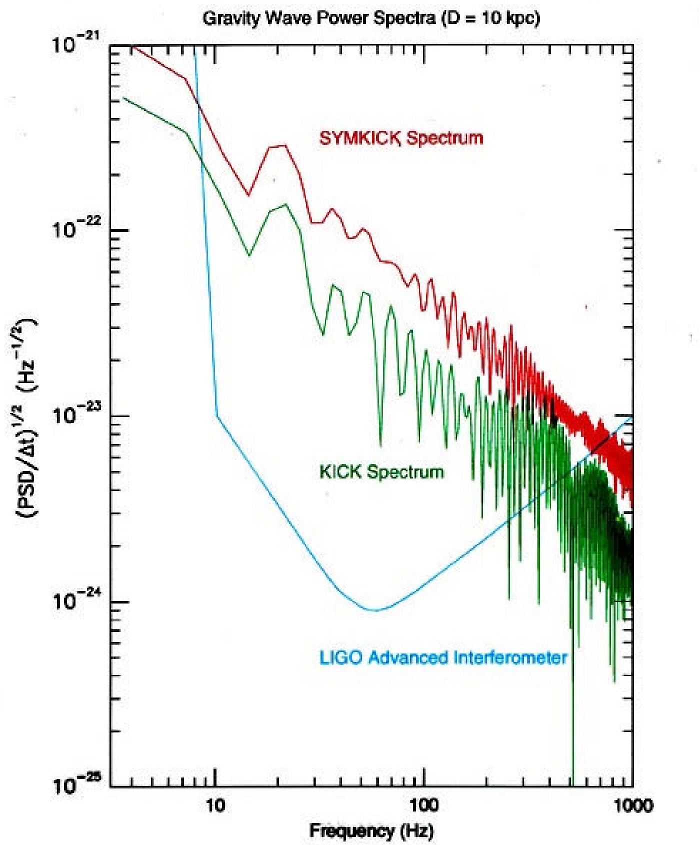


“Burst Signal”

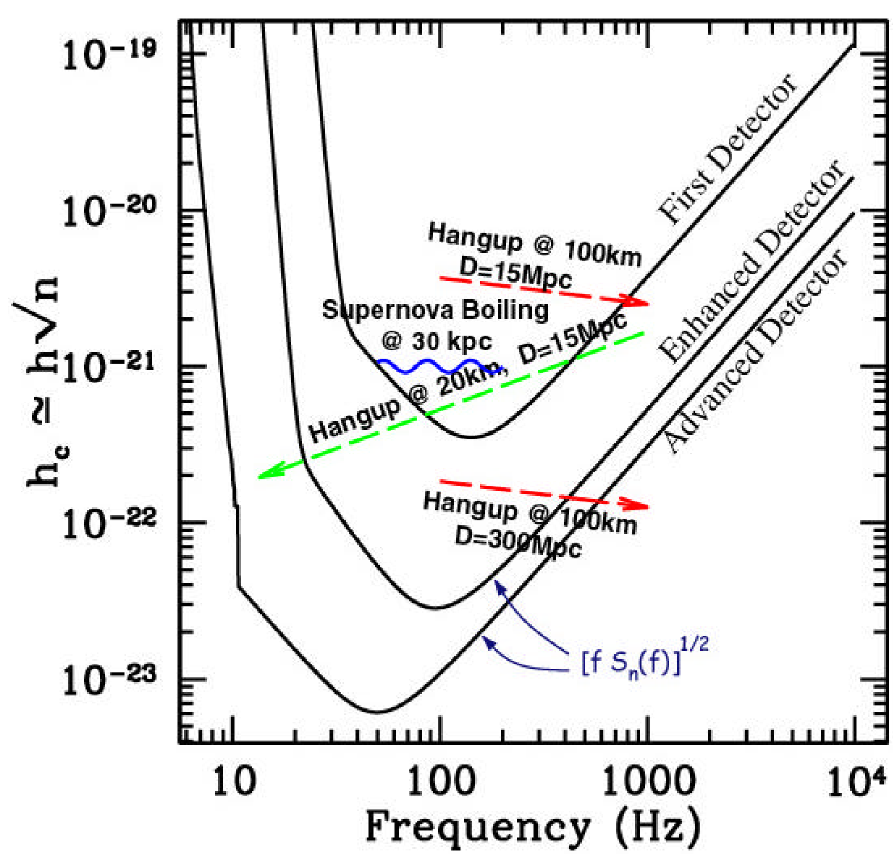
supernova



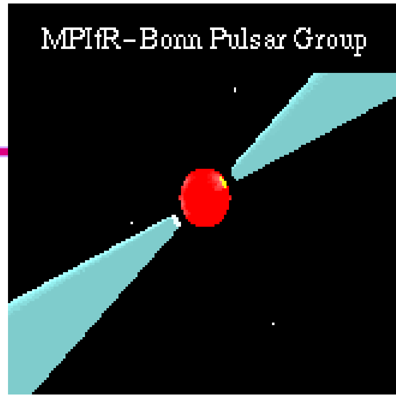
Supernovae
signatures and sensitivity



Sensitivity of LIGO to burst sources

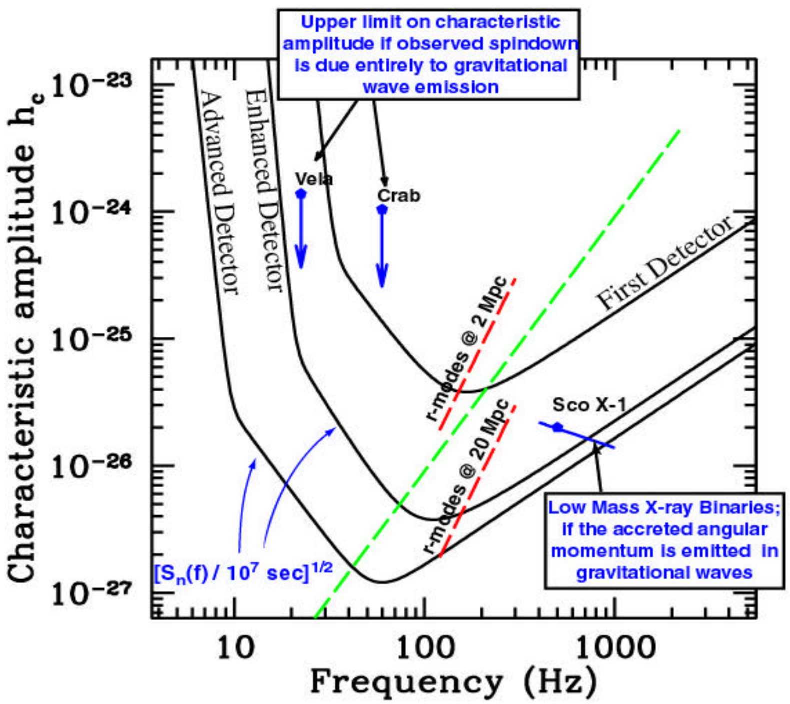


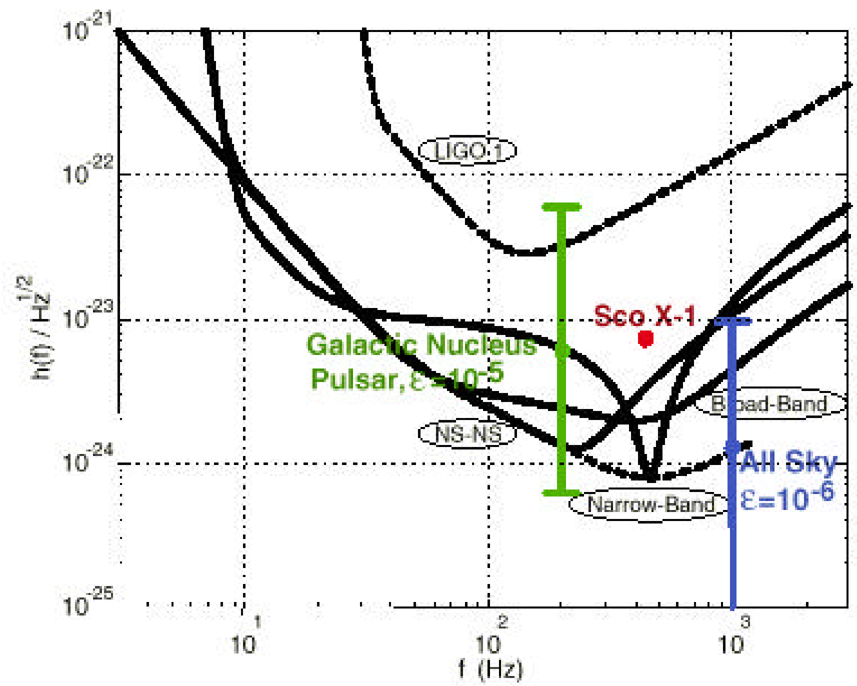
"Periodic Signals"
pulsars sensitivity



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

Sensitivity of LIGO to continuous wave sources

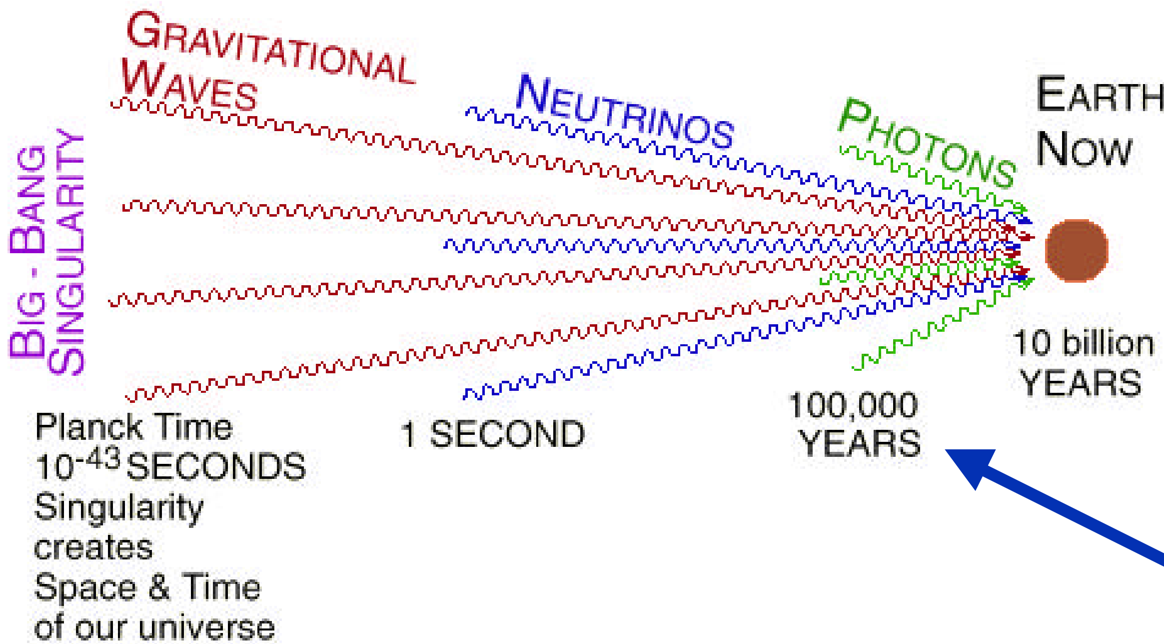




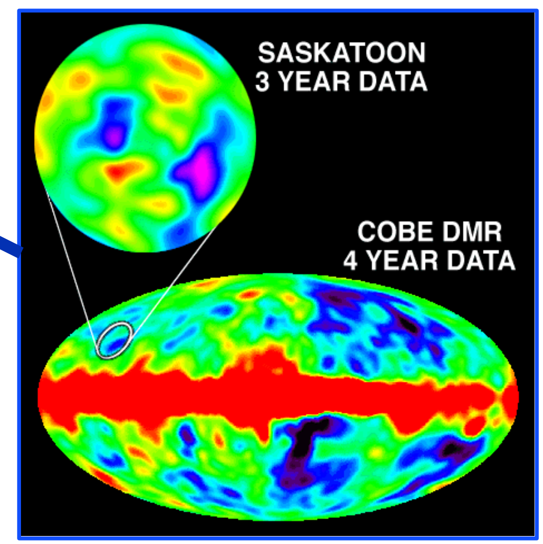
“Stochastic Background”
cosmological signals

‘Murmurs’ from the Big Bang

signals from the early universe



Cosmic microwave background



LIGO
conclusions

- LIGO construction complete
- LIGO commissioning and testing ‘on track’
- “First Lock” officially established 20 Oct 00
- Engineering test runs begin now, during period when emphasis is on commissioning, detector sensitivity and reliability
- First Science Run will begin during 2002
- Significant improvements in sensitivity anticipated to begin about 2006