The Curtain Rises on LIGO: Listening to Einstein's Gravitational Symphony

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Laser Interferometer Gravitational Wave Observatory

Caltech

SURF Seminar, July 31, 2002

LIGO-G020297-00-M

Catching the Waves with LIGO

Barry Barish

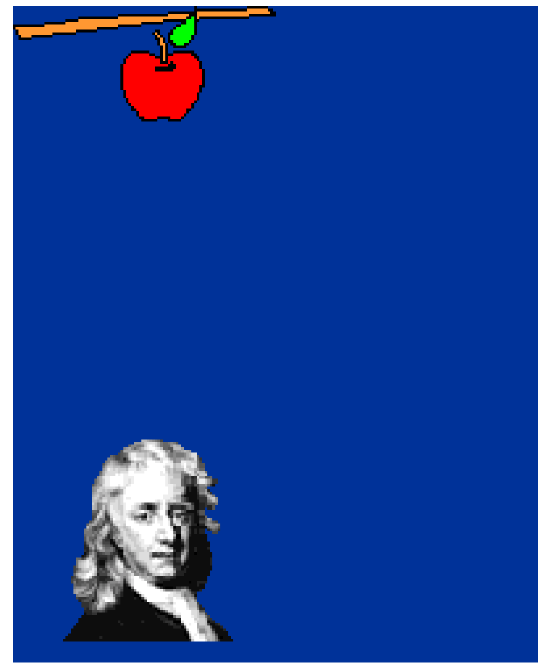
26 Sept 01

LIGO-G020297-00-M

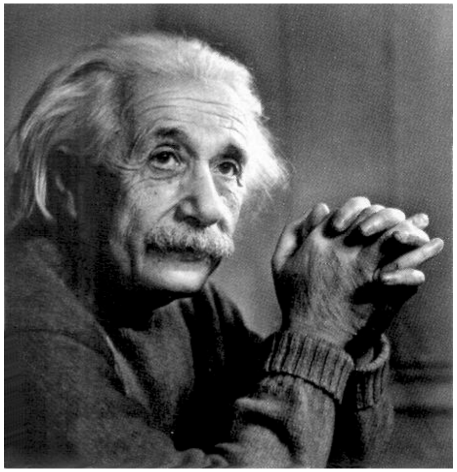
Newton

Universal Gravitation

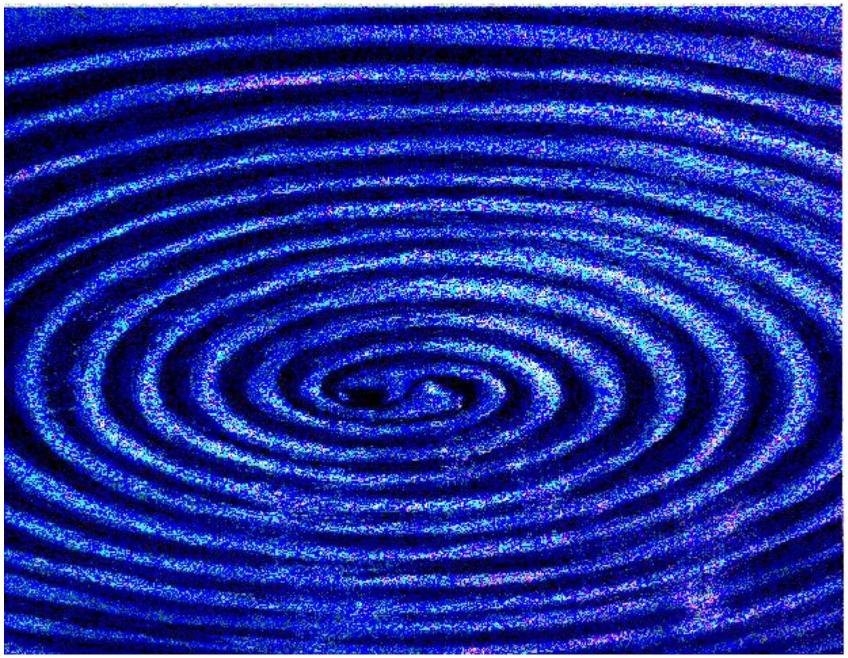
- **Three laws of motion and law of gravitation (centripetal force) disparate phenomena**
  - » **eccentric orbits of comets**
  - » **cause of tides and their variations**
  - » **the precession of the earth's axis**
  - » **the perturbation of the motion of the moon by gravity of the sun**
- **Solved 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"

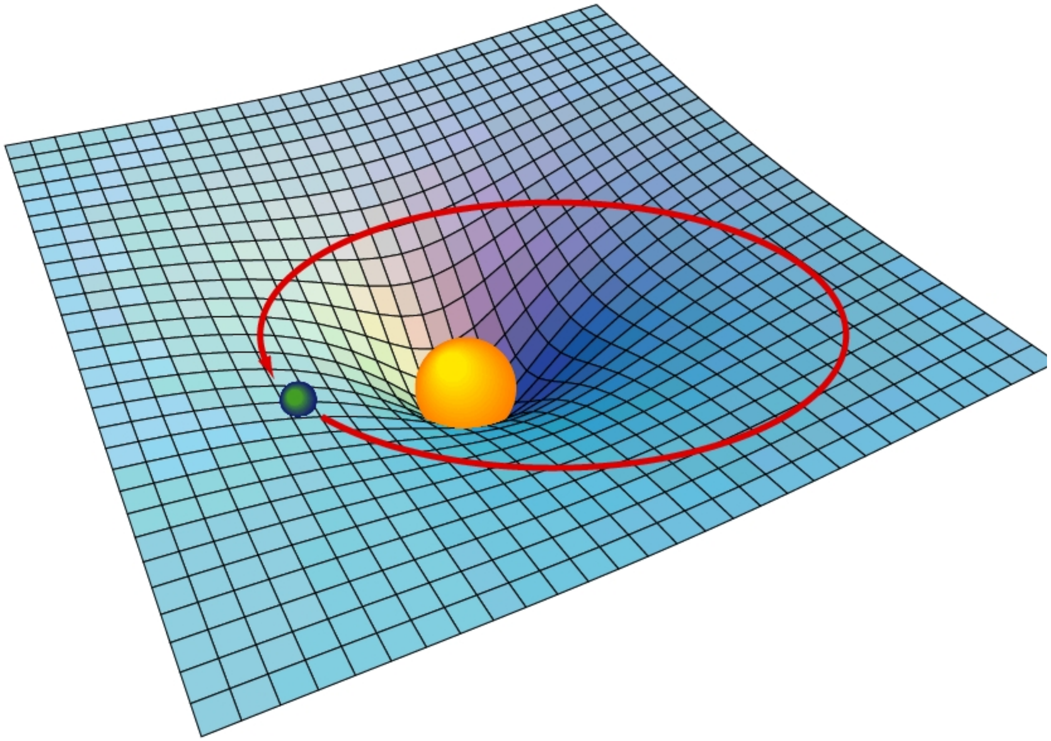


Einstein's Theory
information carried by gravitational radiation at the speed of light

General Relativity
the essential idea

- Overthrew the 19th-century concepts of absolute space and time
- Einstein: gravity is not a force, but a property of space & time
  - » Spacetime = 3 spatial dimensions + time
  - » Perception of space or time is relative
- Concentrations of mass or energy distort (warp) spacetime
- Objects follow the shortest path through this warped spacetime; path is the same for all objects

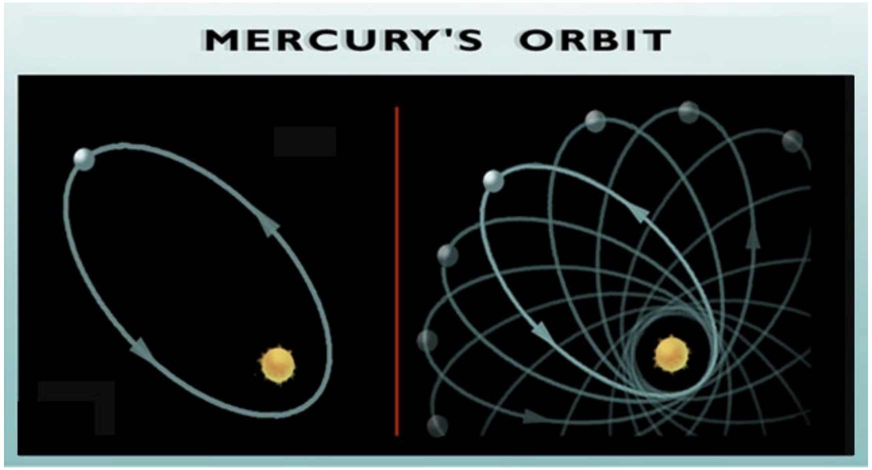
General Relativity



- 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

Einstein’s Theory of Gravitation
experimental tests



Mercury’s orbit
perihelion shifts forward an extra +43”/century compared to 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.

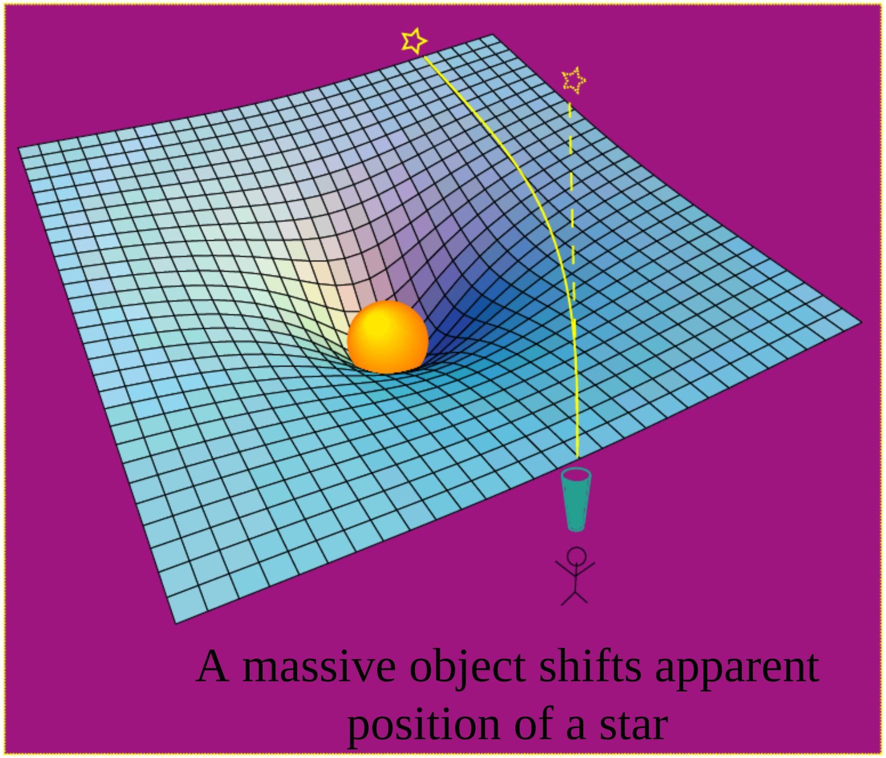
Einstein's predictions exactly matched the observation.

New Wrinkle on Equivalence
bending of light

- Not only the path of matter, but even the path of light is affected by gravity from 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.

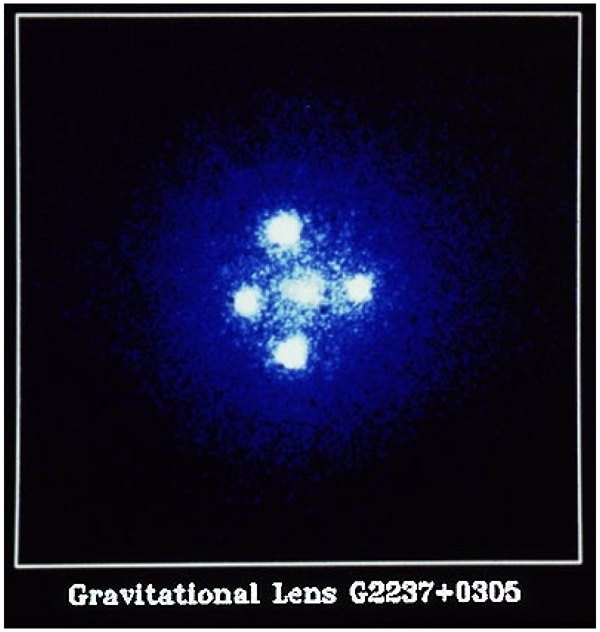


Einstein Cross
Photo credit: NASA and ESA

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



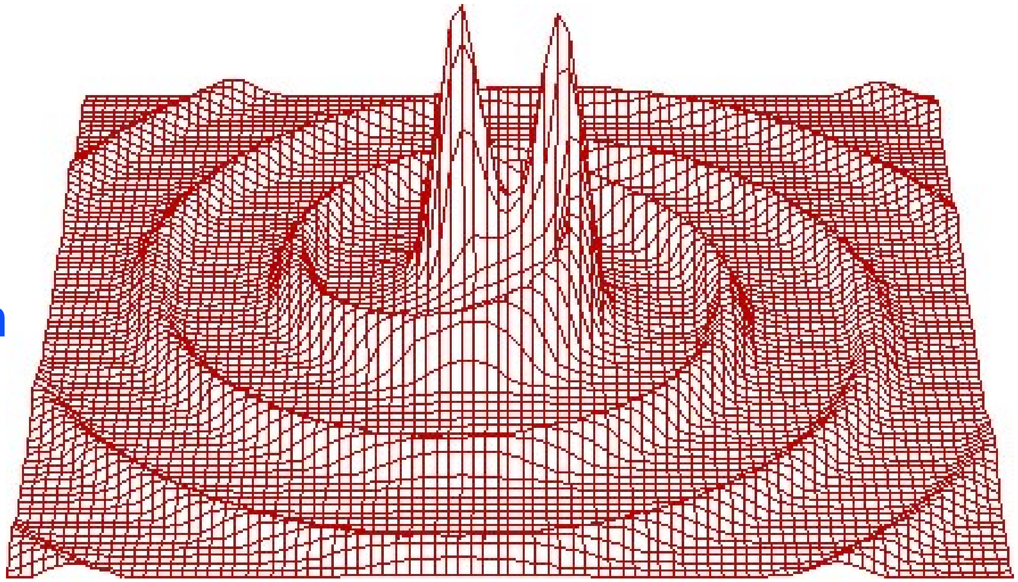
Quasar image appears around the central glow formed by nearby galaxy. The Einstein Cross is only visible in southern hemisphere.

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

Einstein's Theory of Gravitation
gravitational waves

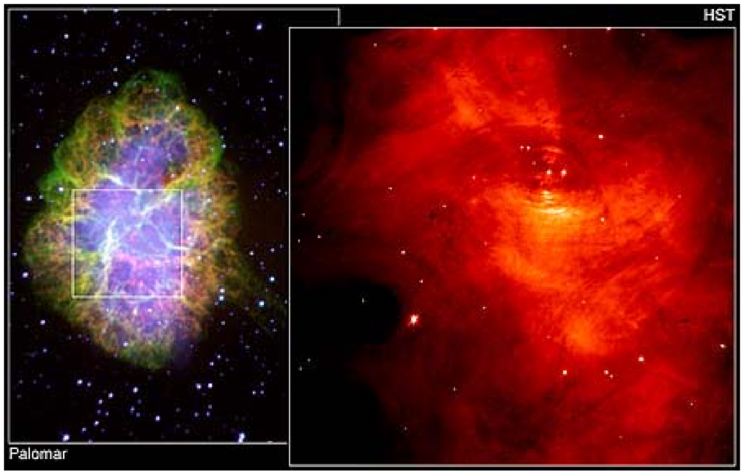
- **a necessary consequence of Special Relativity with its finite speed for information transfer**

- **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**



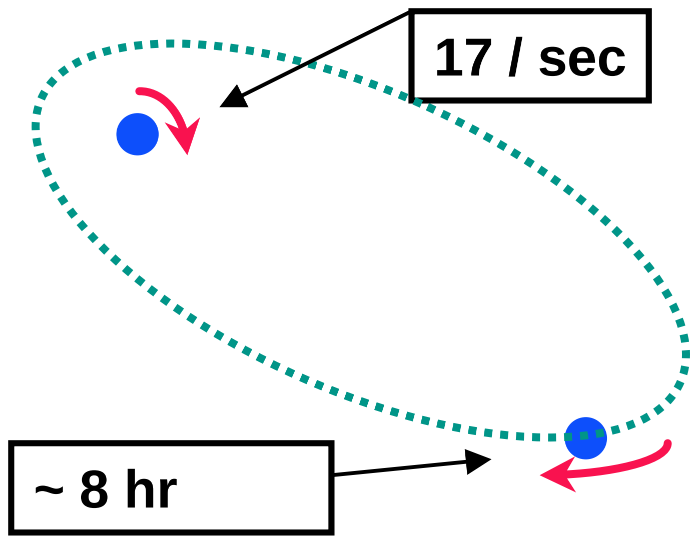
gravitational radiation
binary inspiral of compact objects

Gravitational Waves
the evidence



Neutron Binary System

PSR 1913 + 16 -- Timing of pulsars



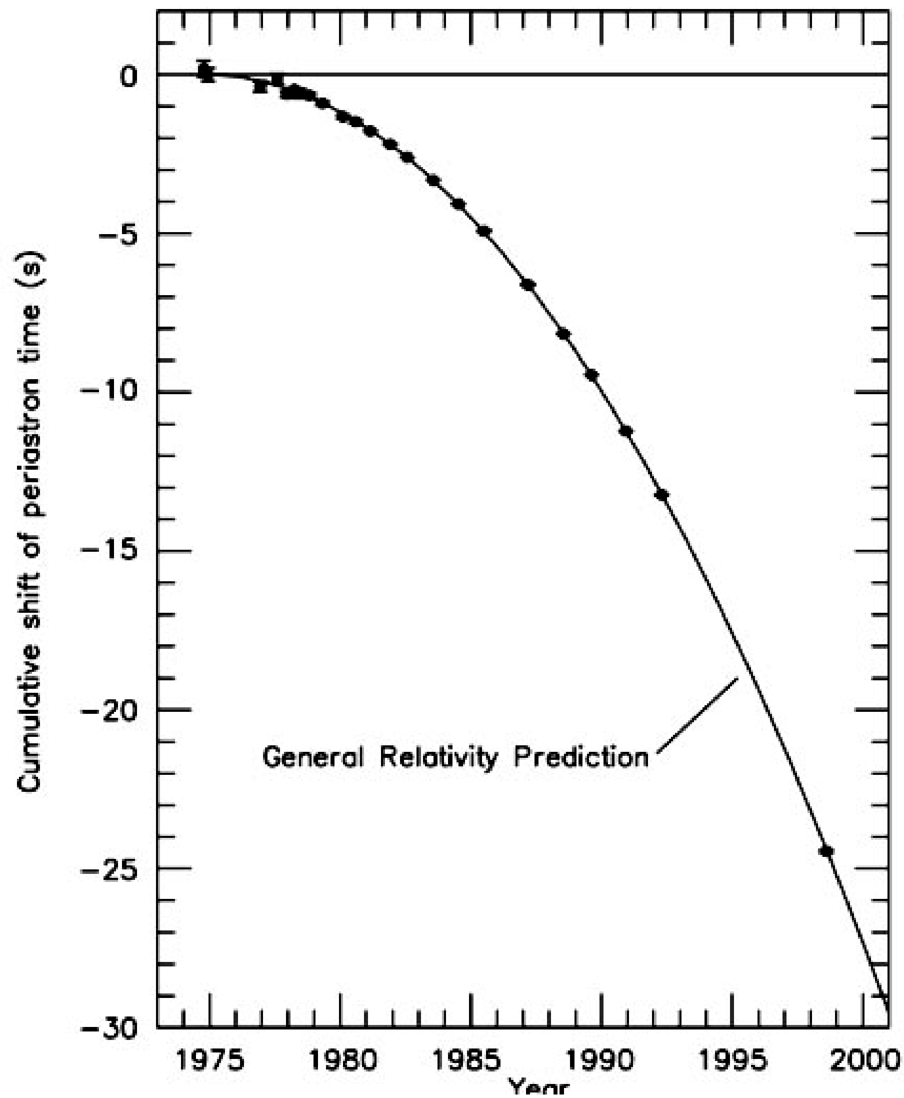
Neutron Binary System
- separated by 10^6 miles
- $m_1 = 1.4m_{\odot}$; $m_2 = 1.36m_{\odot}$; $\varepsilon = 0.617$

Prediction from general relativity
- spiral in by 3 mm/orbit
- rate of change orbital period

Hulse and Taylor *results*

emission of gravitational waves

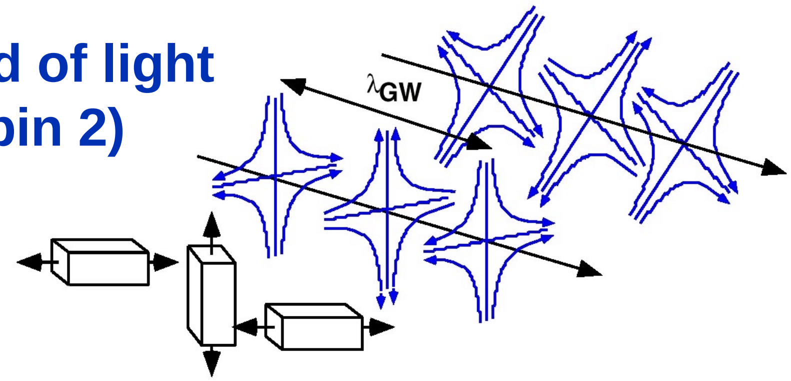
- due to loss of orbital energy
- period speeds up 25 sec from 1975-98
- measured to ~0.3% accuracy
- deviation grows quadratically with time
- CAN LIGO DETECT THESE WAVES?



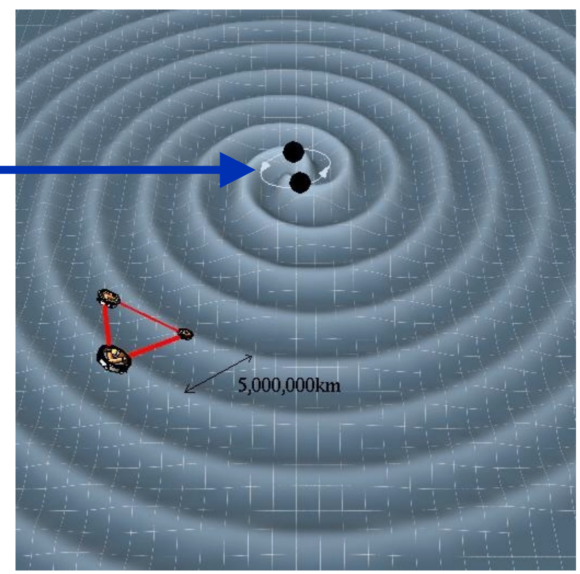
LIGO

Radiation of Gravitational Waves

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



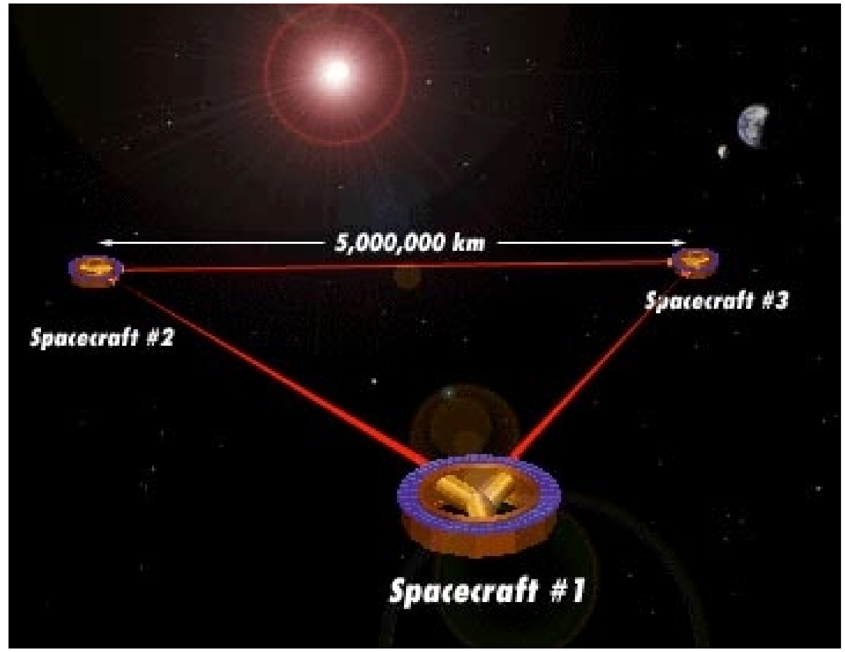
Radiation of Gravitational Waves from binary inspiral system



Interferometers

space

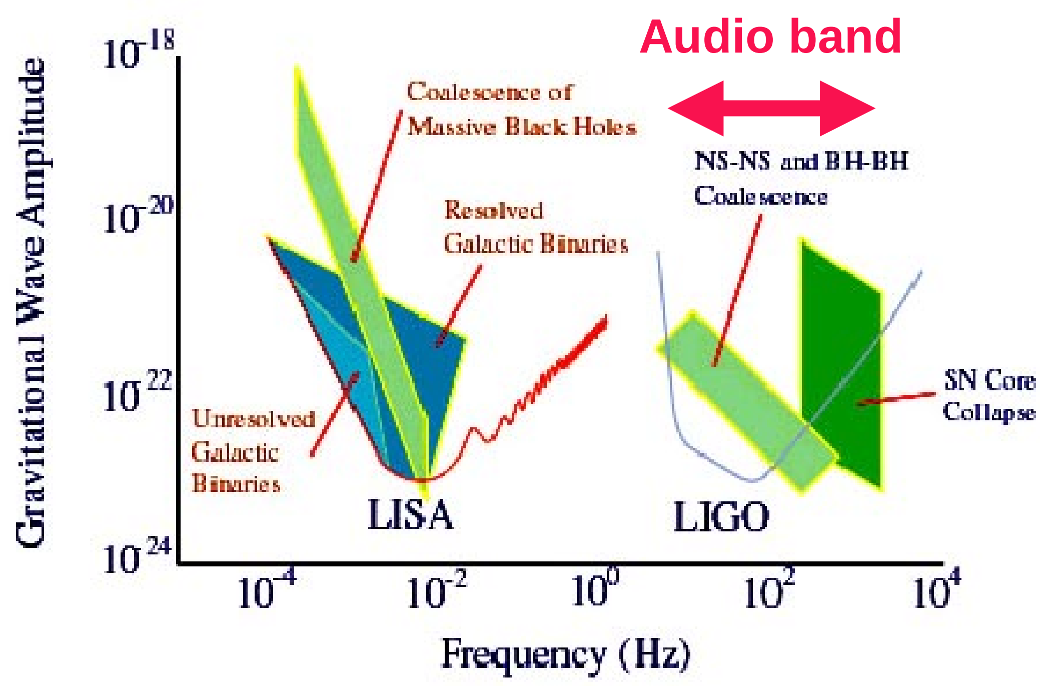
The Laser Interferometer Space Antenna (LISA)



- **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

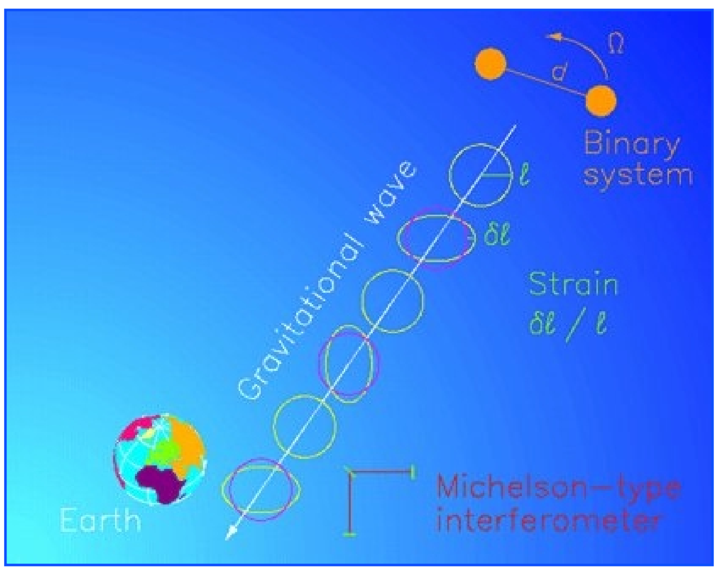
- **EM waves are studied over ~20 orders of magnitude**
  - » **(ULF radio –> HE γ-rays)**
- **Gravitational Waves over ~10 orders of magnitude**
  - » **(terrestrial + space)**

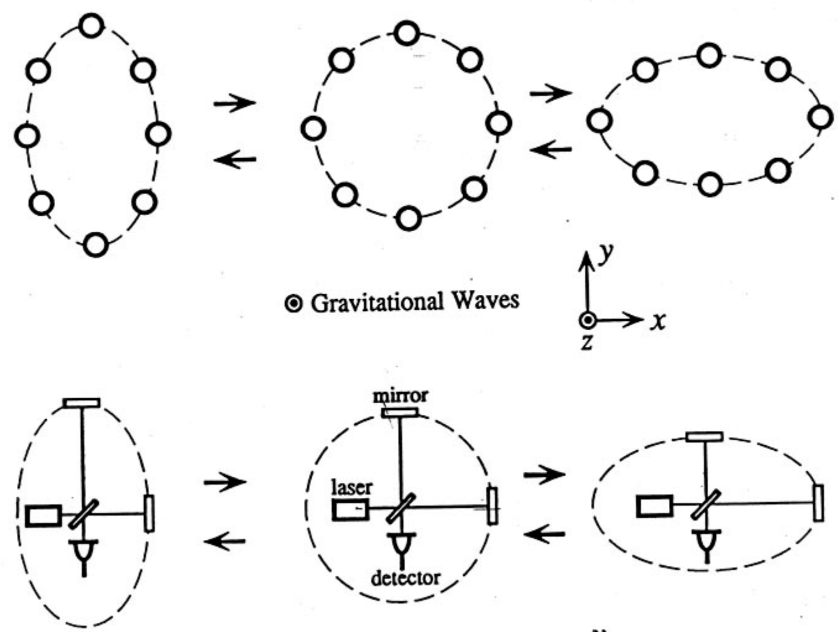


Interferometers
terrestrial

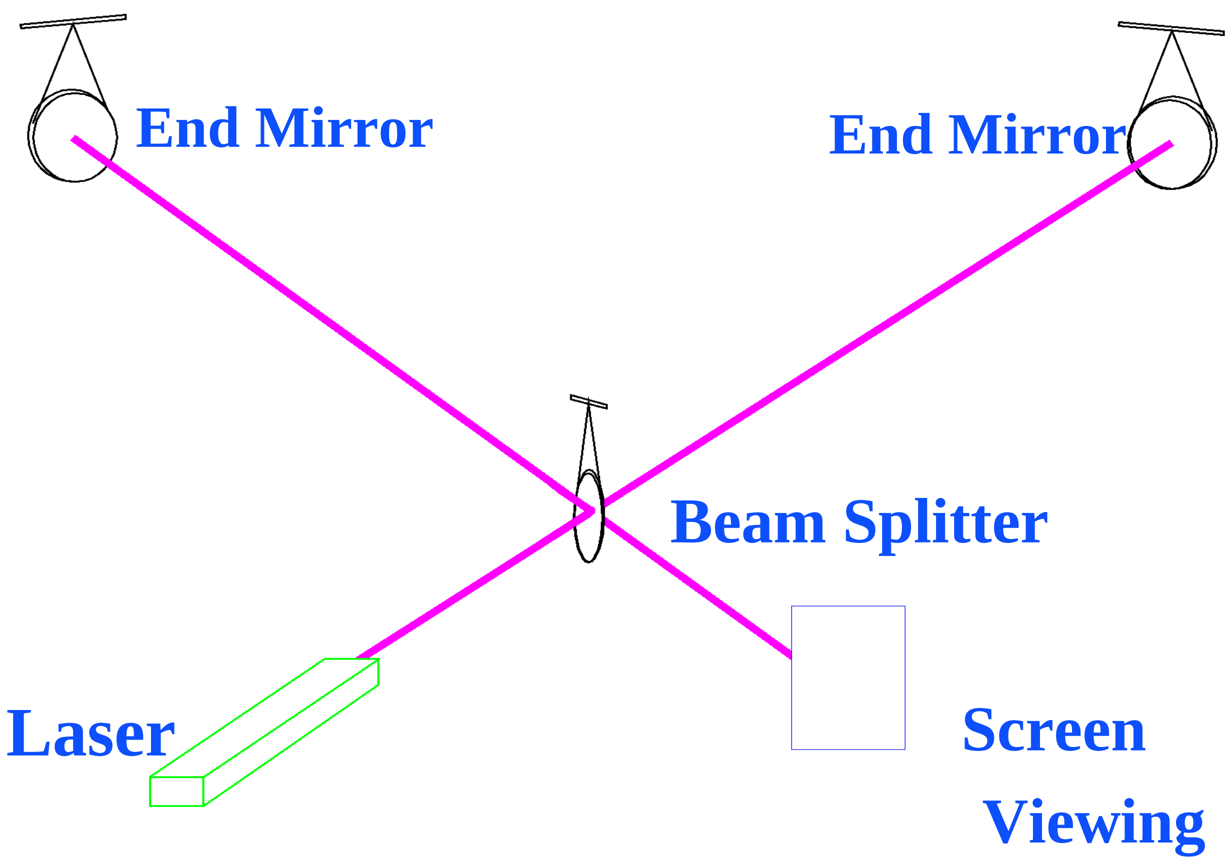
Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

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

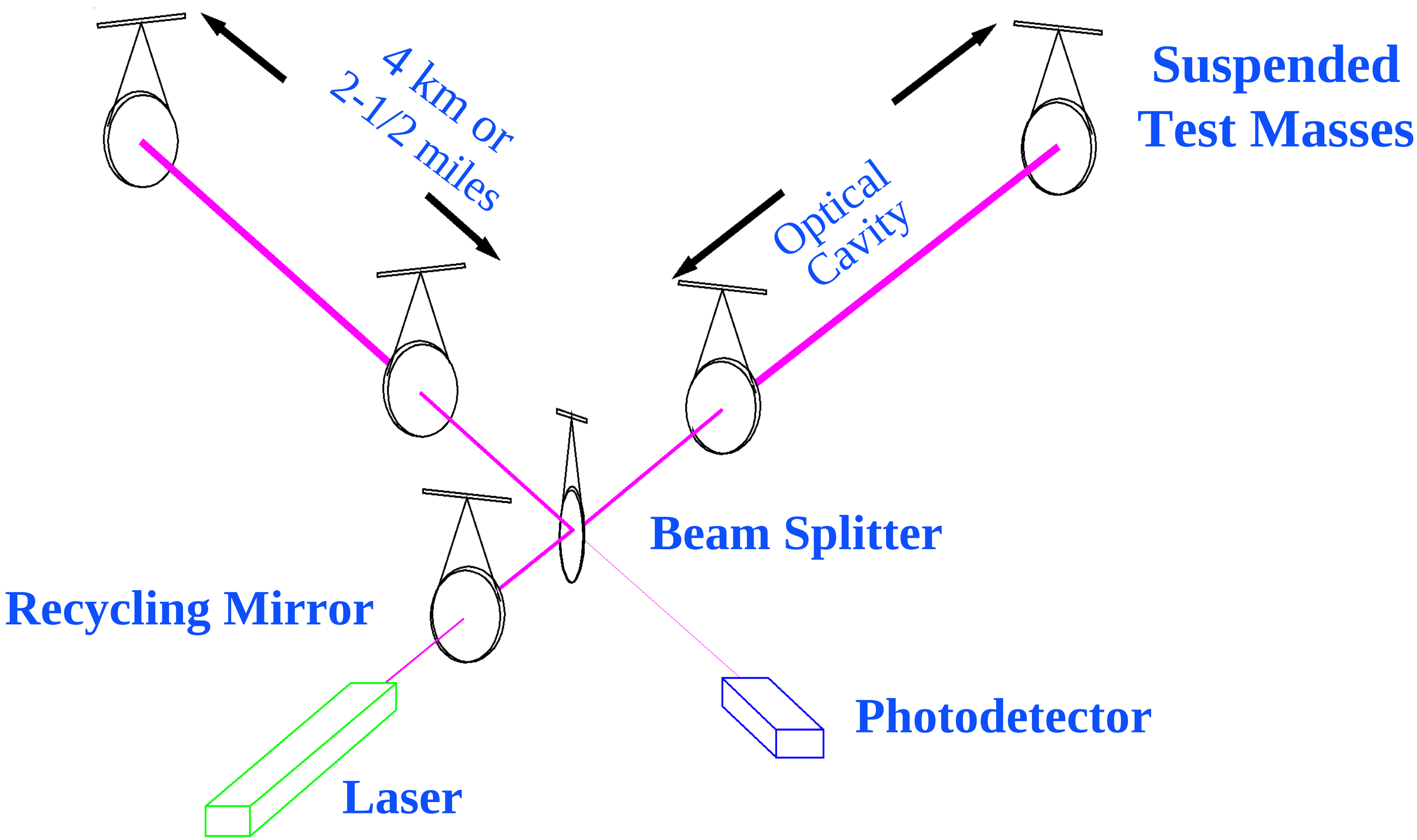




Michelson Interferometer

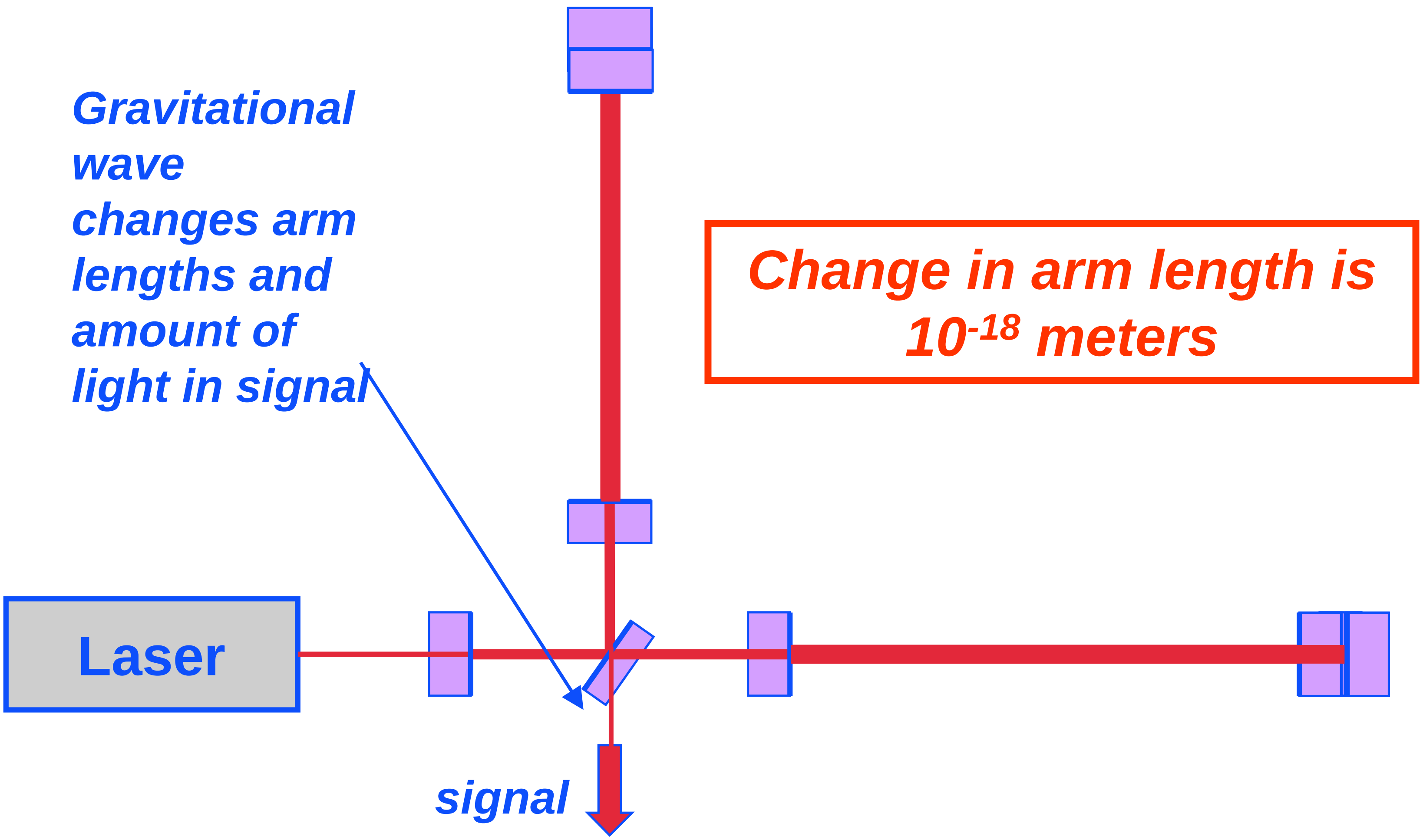


Fabry-Perot-Michelson with Power Recycling



LIGO-G020297-00-M

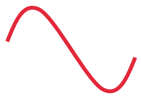
Sensing a Gravitational Wave

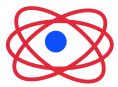


How Small is 10^{-18} Meter?

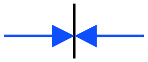
 *One meter, about 40 inches*

÷10,000  *Human hair, about 100 microns*

÷100  *Wavelength of light, about 1 micron*

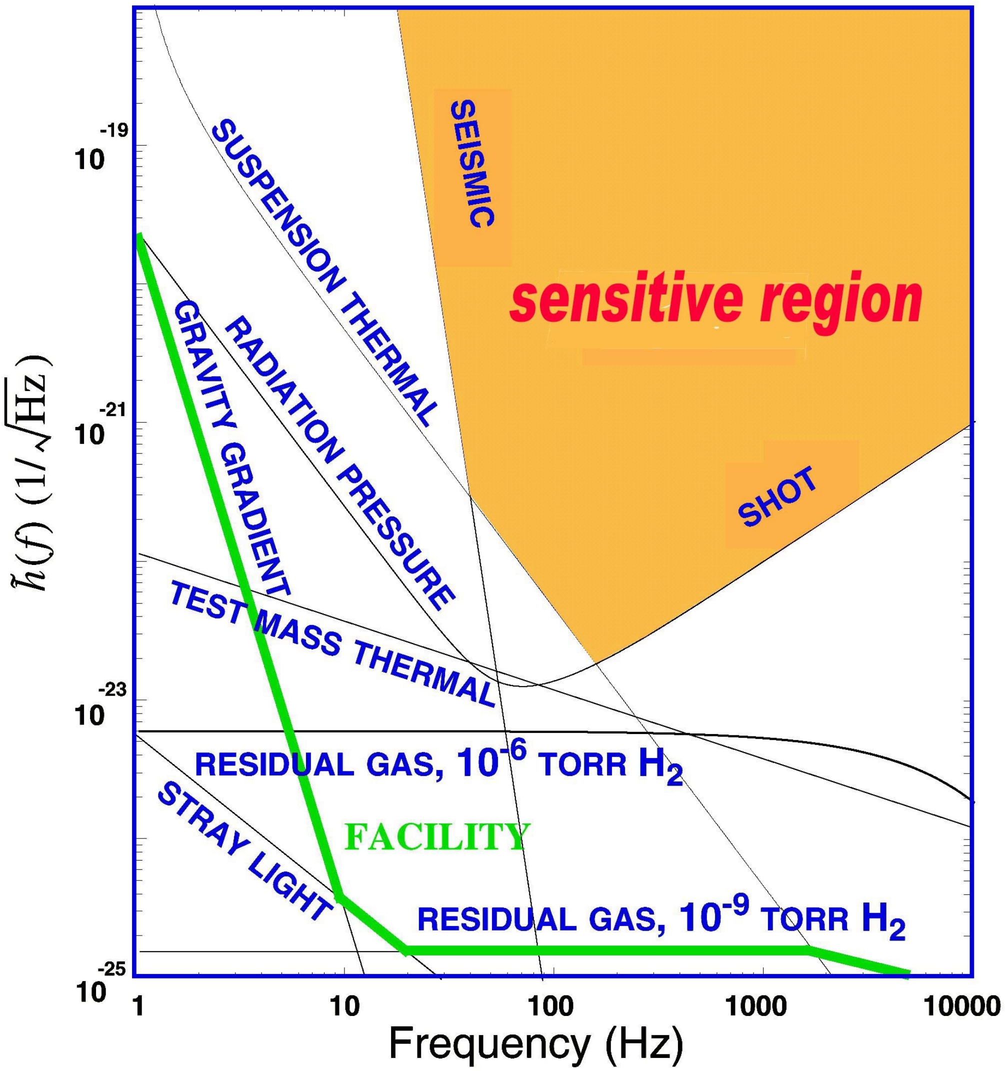
÷10,000  *Atomic diameter, 10^{-10} meter*

÷100,000  *Nuclear diameter, 10^{-15} meter*

÷1,000  *LIGO sensitivity, 10^{-18} meter*

What Limits Sensitivity of Interferometers?

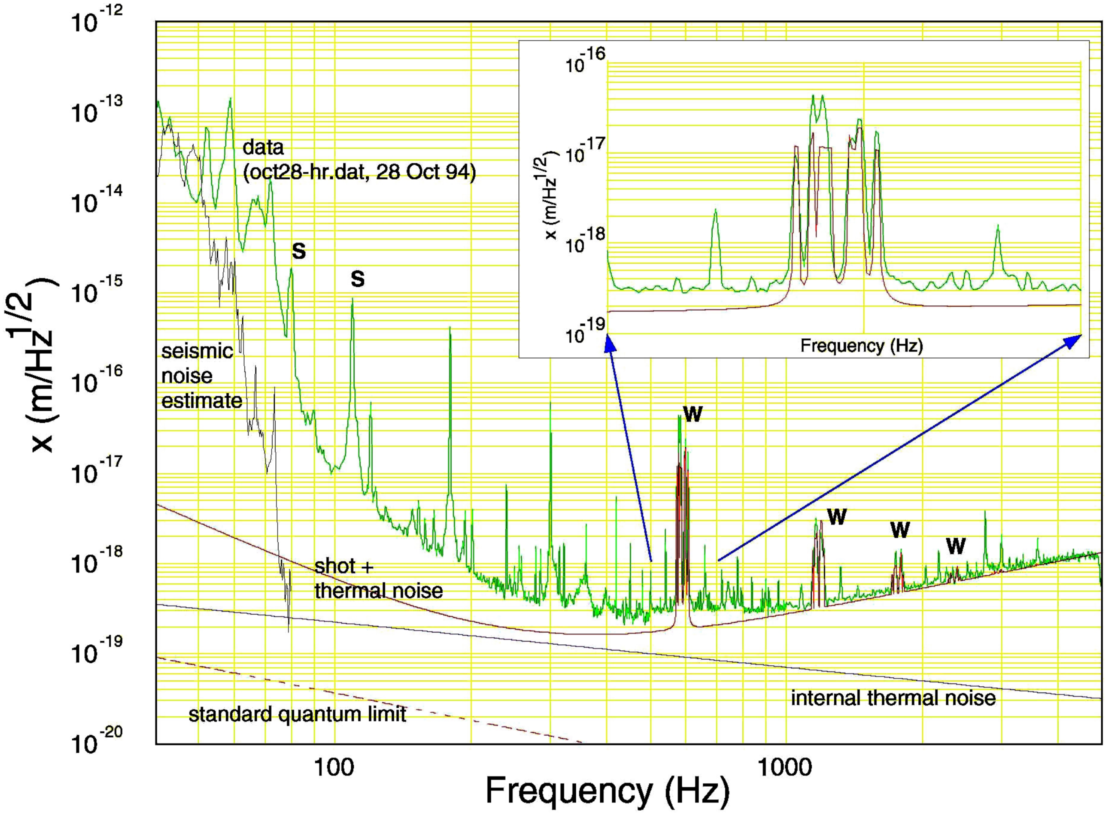
- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Sho Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



Noise Floor

40 m prototype

sensitivity demonstration



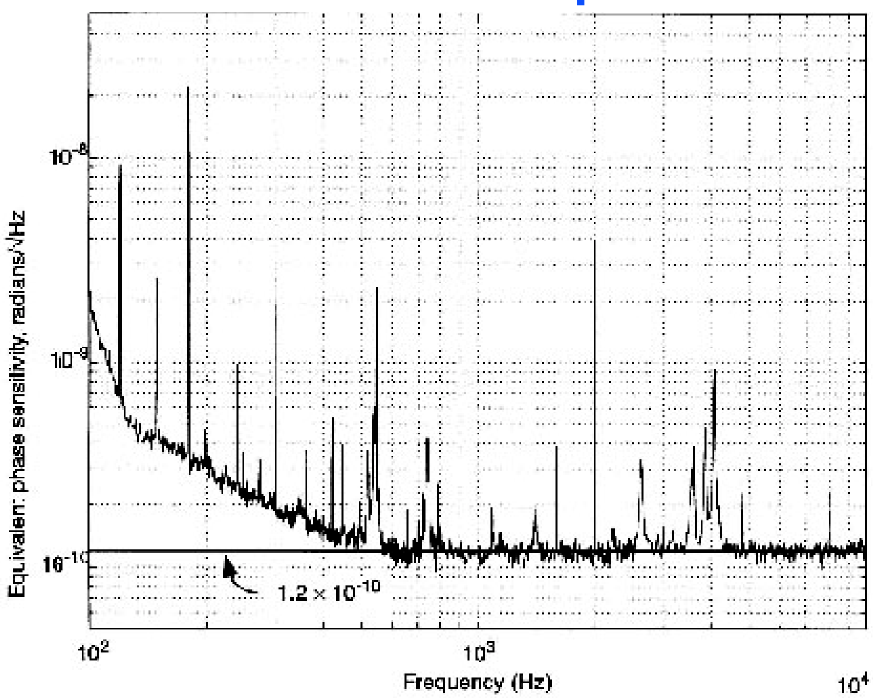
- **displacement sensitivity in 40 m prototype.**
- **comparison to predicted contributions from various noise sources**

Phase Noise

splitting the fringe

expected signal → 10^{-10} radians phase shift

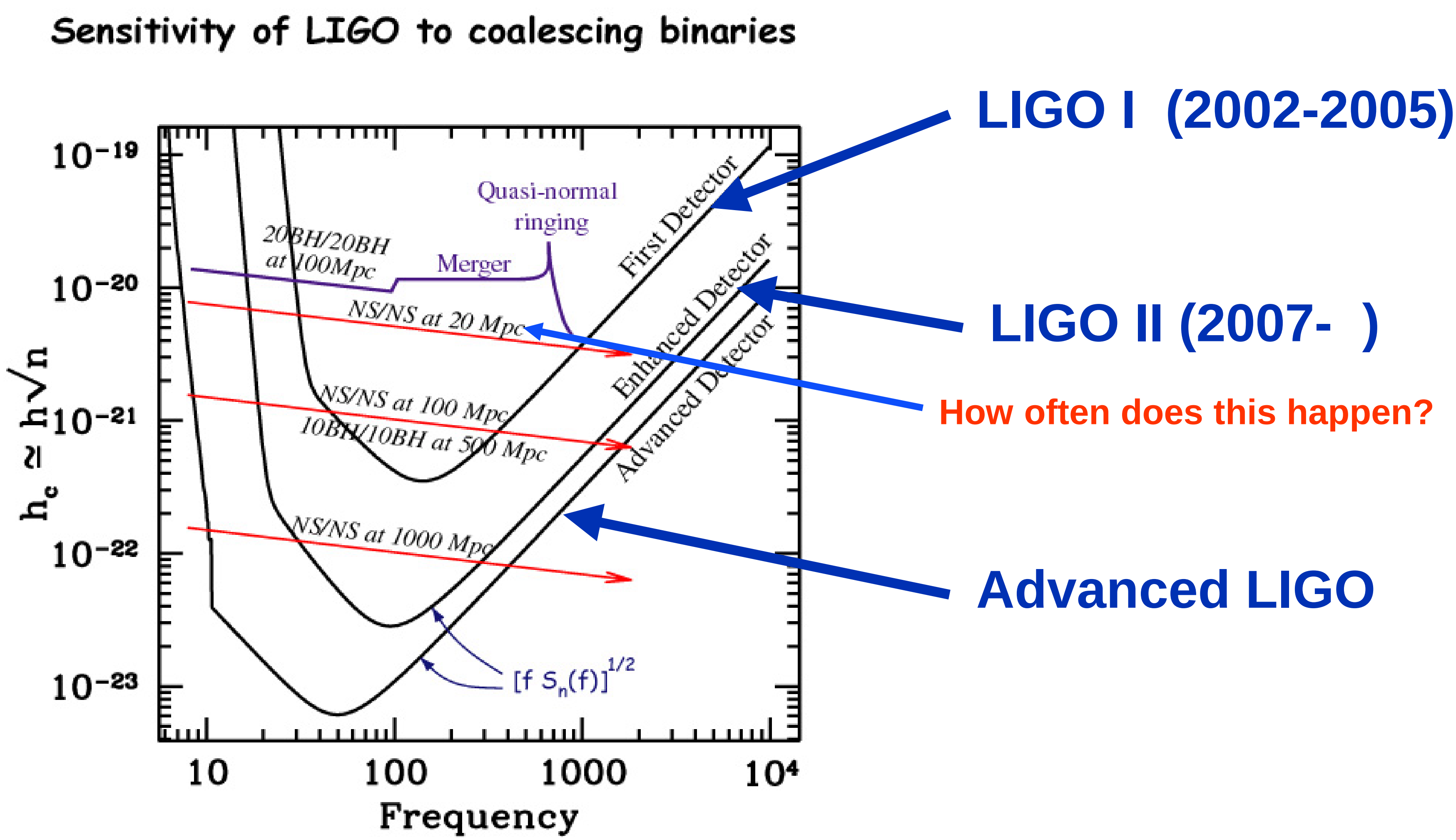
demonstration experiment



- **spectral sensitivity of MIT phase noise interferometer**
- **above 500 Hz shot noise limited near LIGO I goal**
- **additional features are from 60 Hz powerline harmonics, wire resonances (600 Hz), mount resonances, etc**

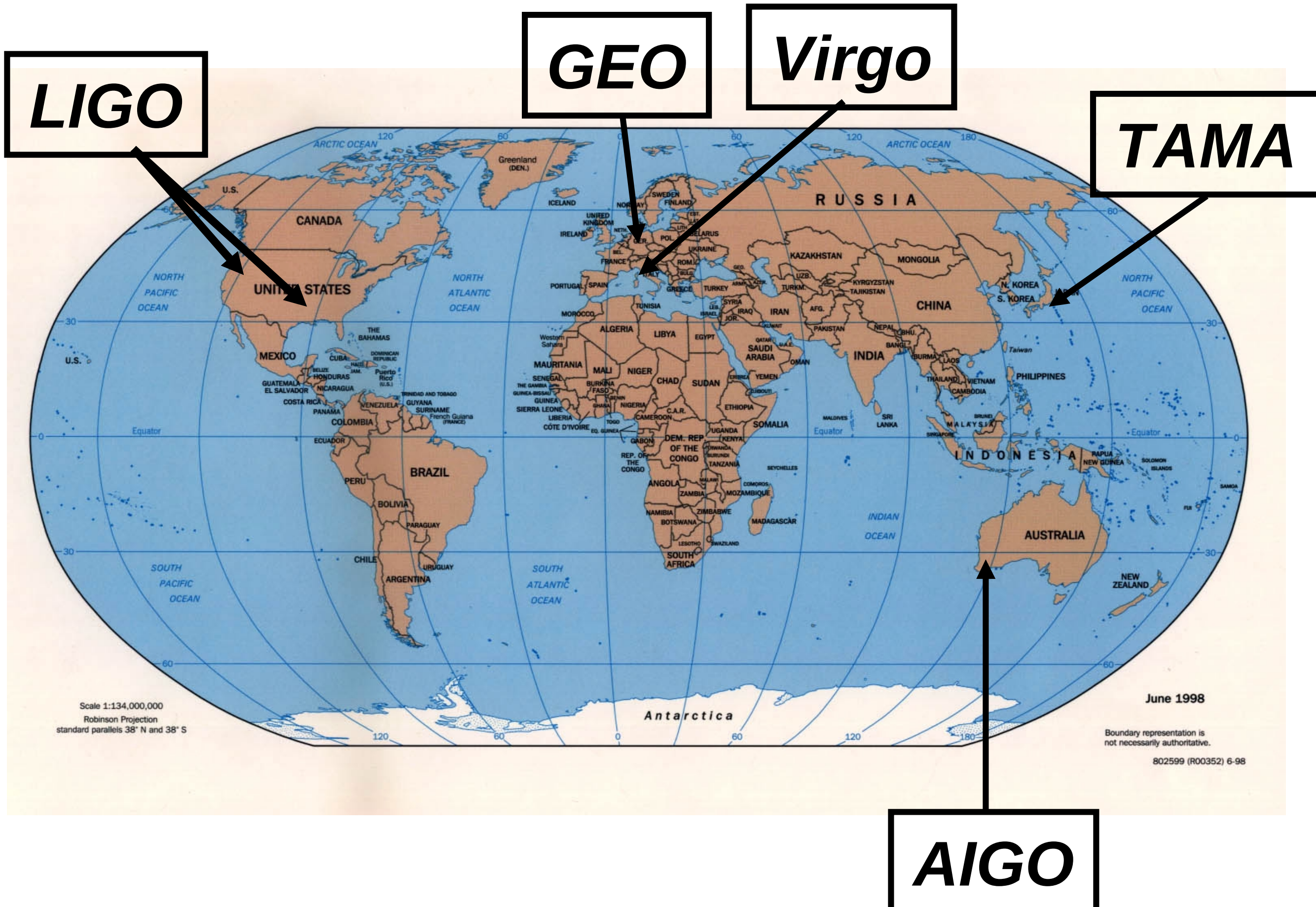
LIGO

astrophysical sources



Interferometers
international network

Simultaneously detect signal (within msec)



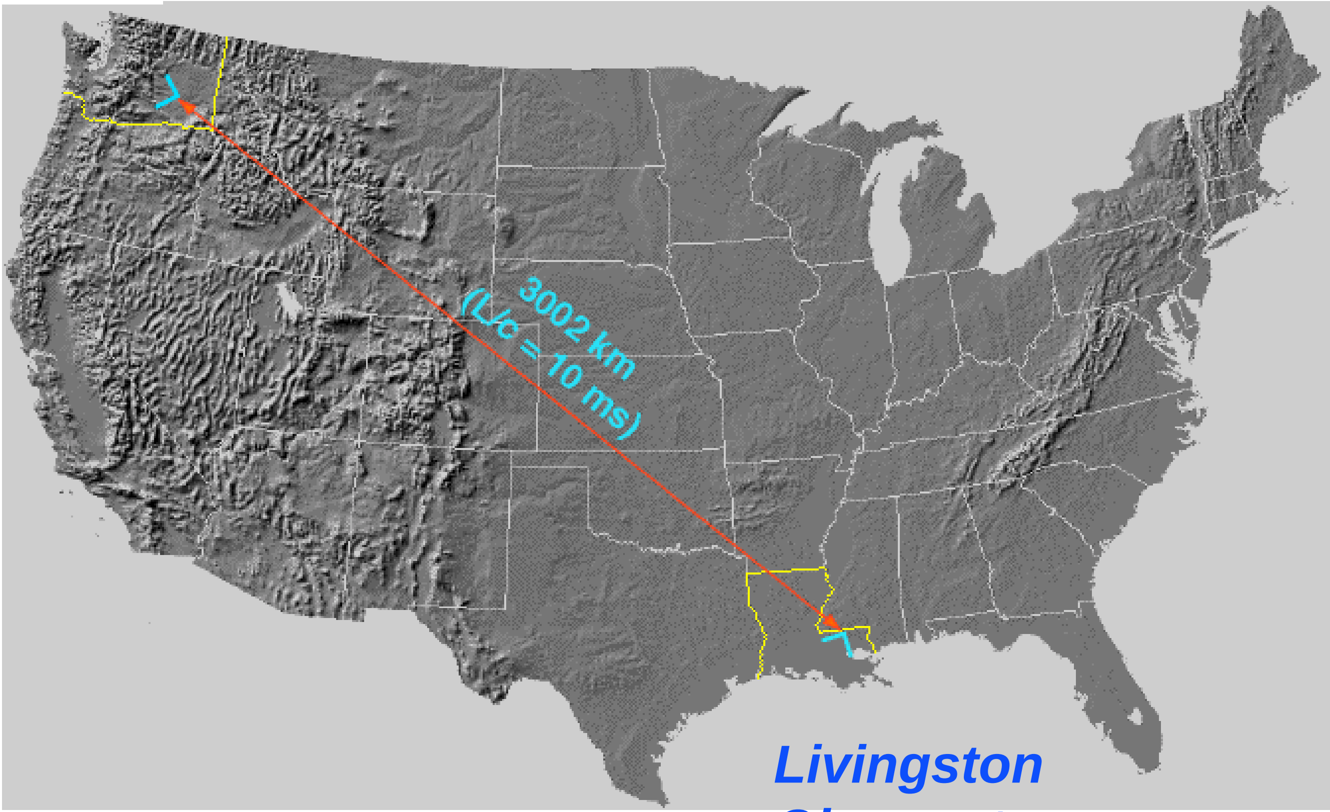
detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Sites

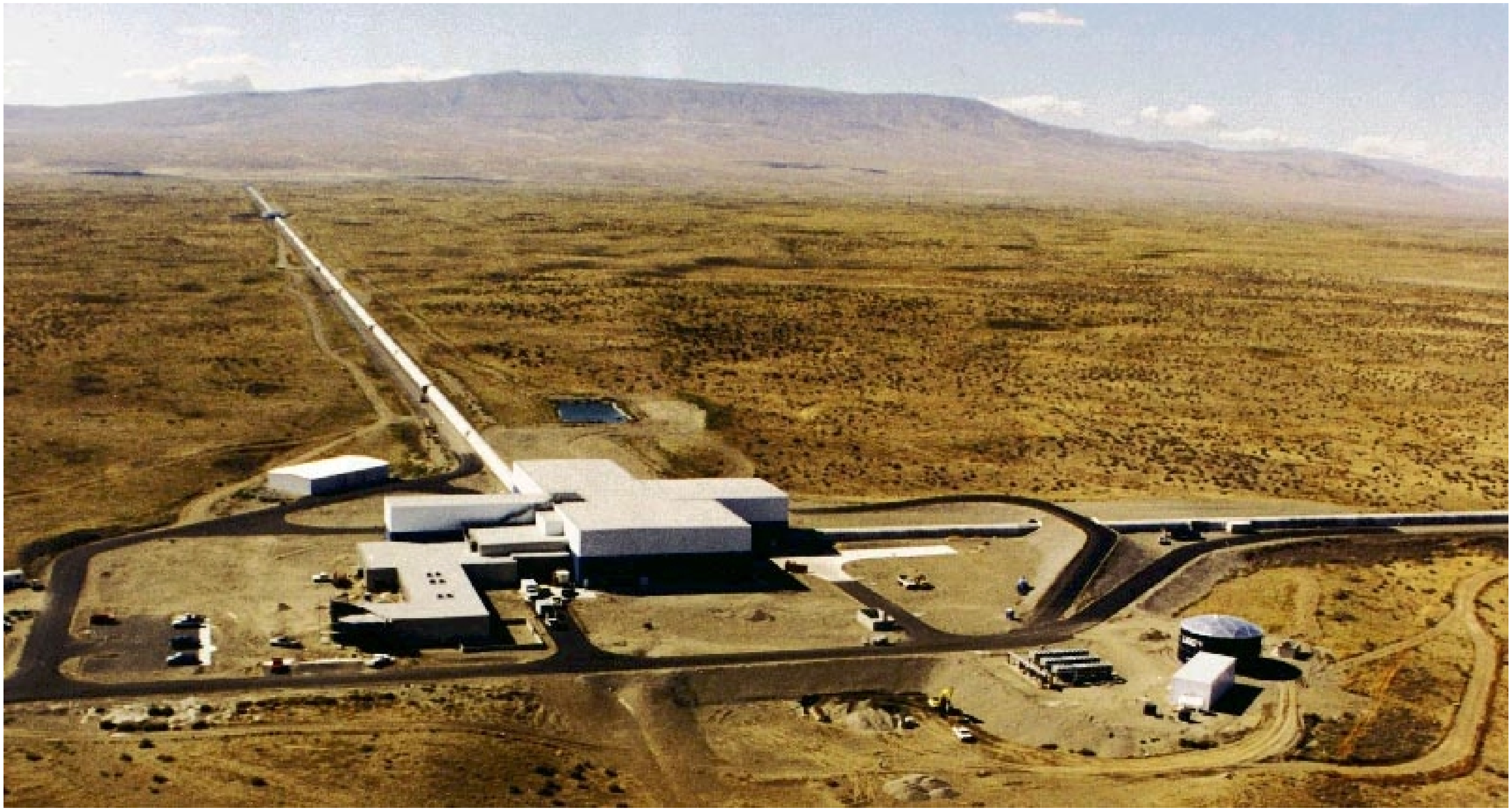
Hanford Observatory



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})
2006	Begin LIGO II installation	

LIGO Facilities
beam tube enclosure

- minimal enclosure
- reinforced concrete
- no services

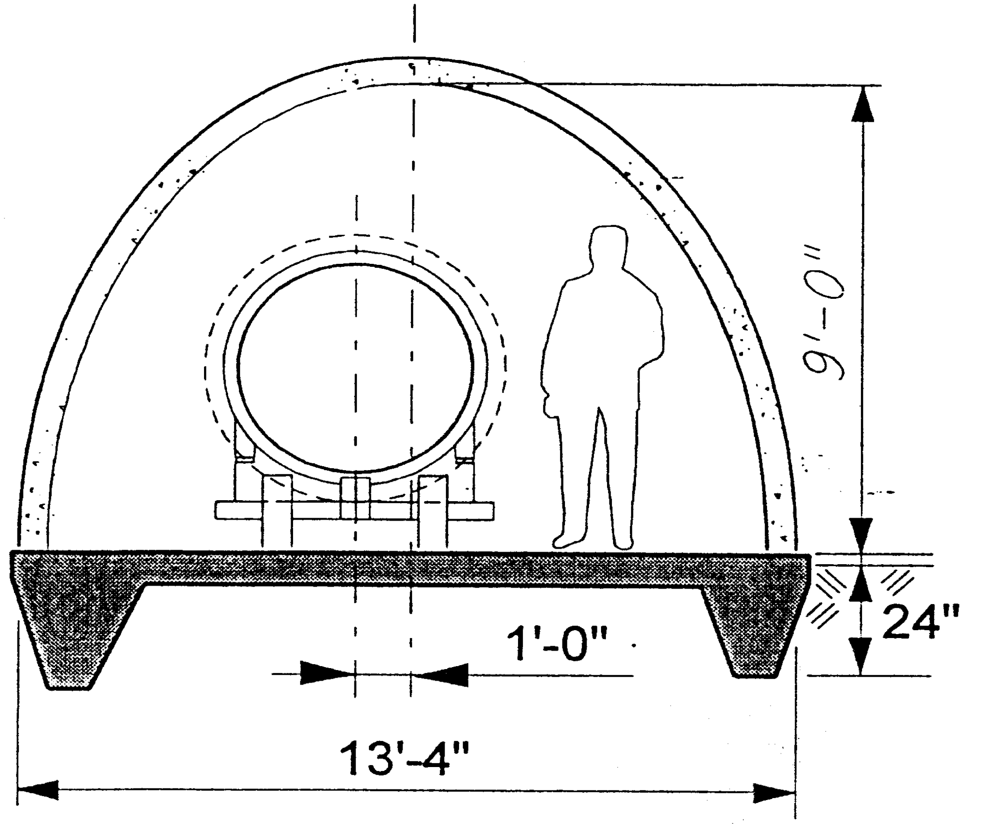


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

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

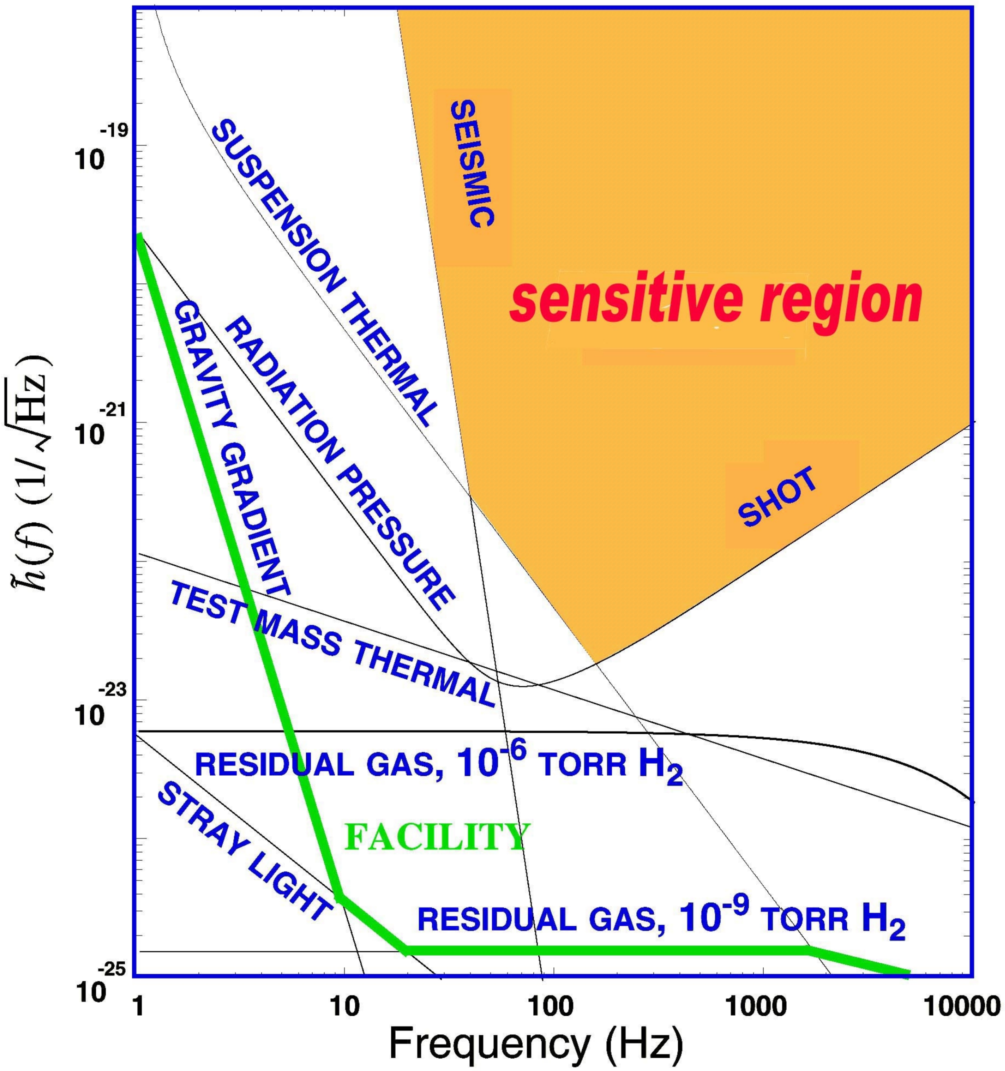
NO LEAKS !!

LIGO

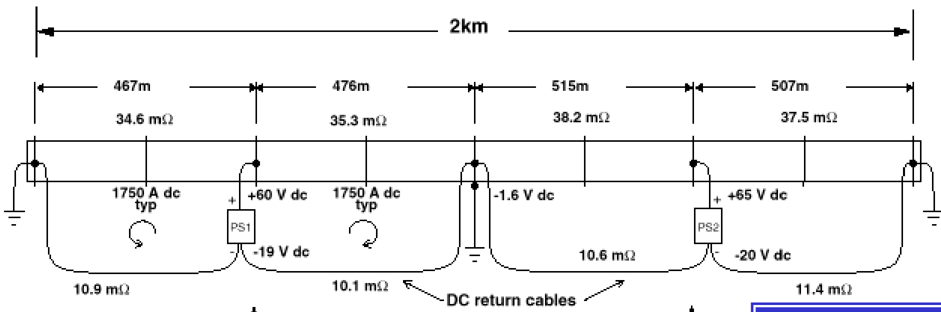
LIGO I
the noise floor

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

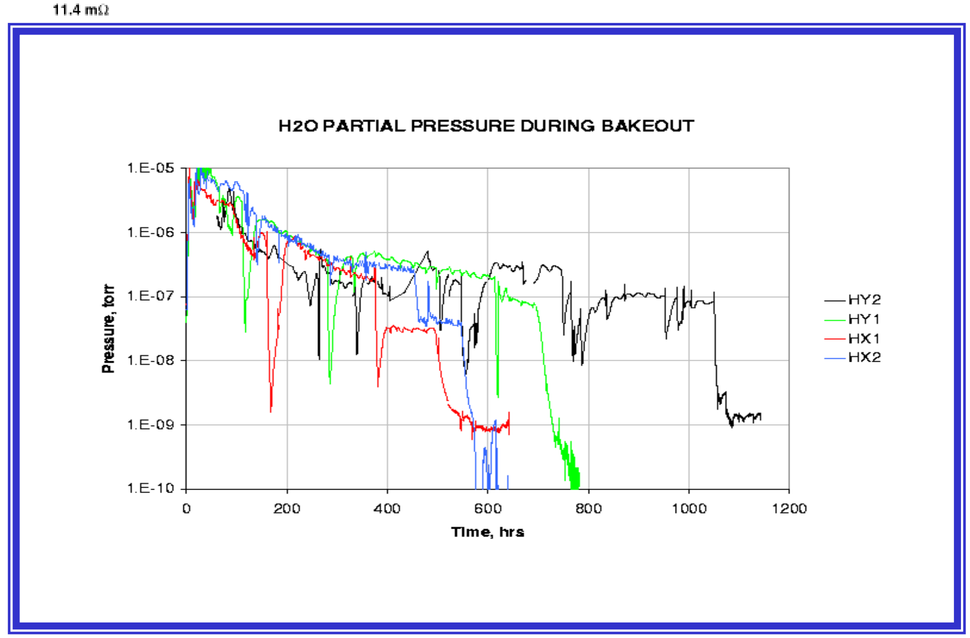
- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**



Beam Tube
bakeout



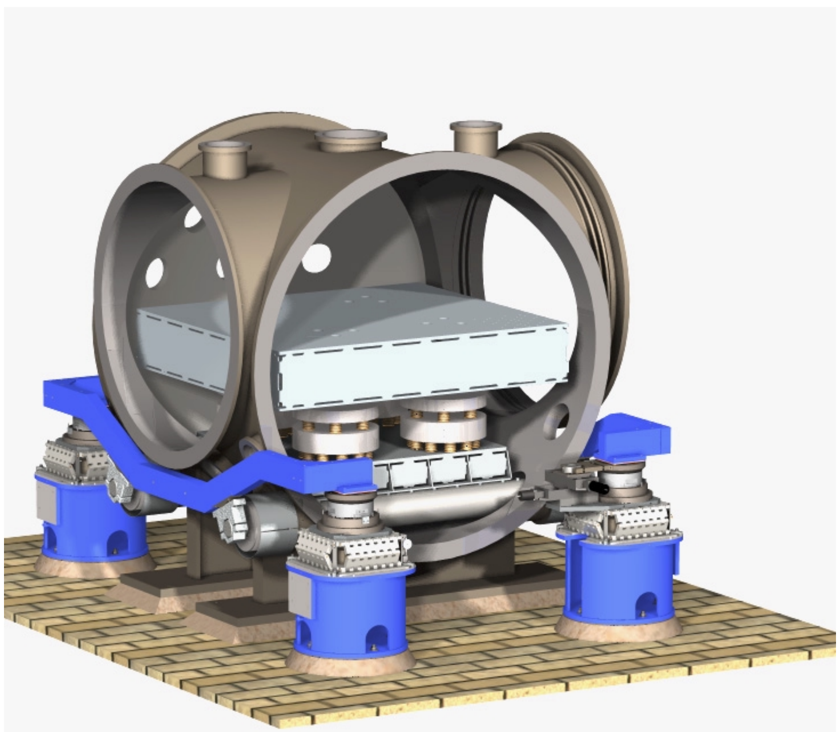
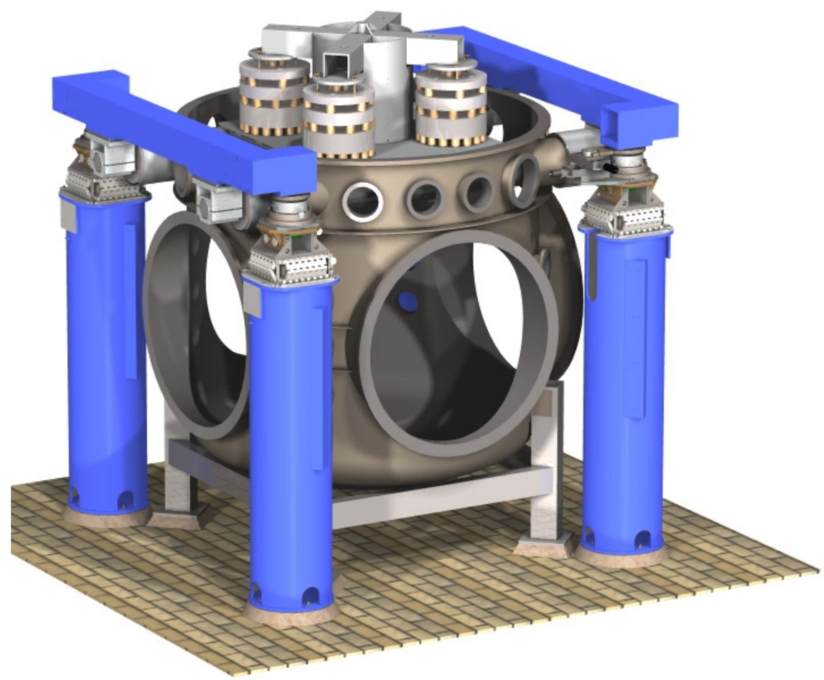
- **I = 2000 amps for ~ 1 week**
- **no leaks !!**
- **final vacuum at level where not limiting noise, even for future detectors**



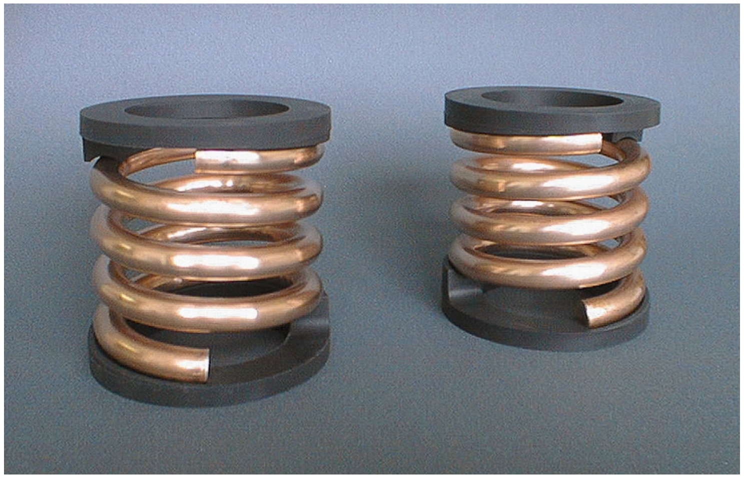
LIGO
vacuum equipment

Vacuum Chambers
vibration isolation systems

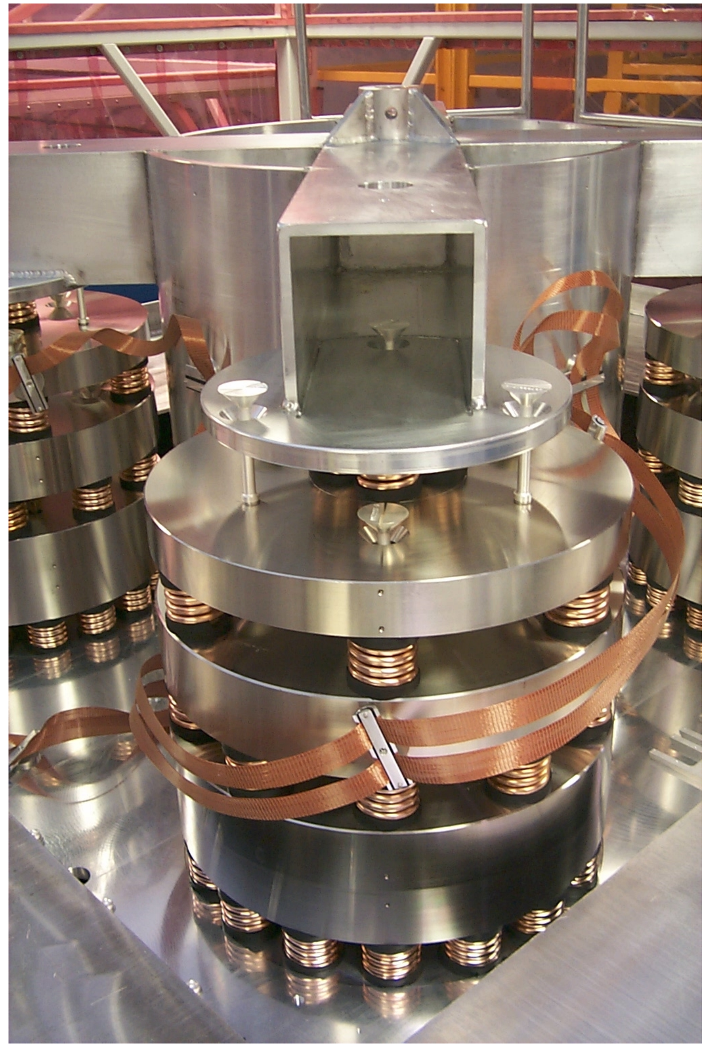
» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Compensate for microseism at 0.15 Hz by a factor of ten
» Compensate (partially) for Earth tides

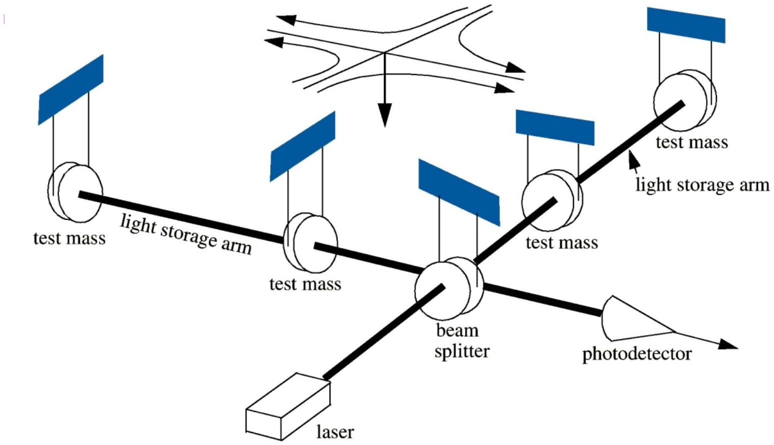
Seismic Isolation
springs and masses



damped spring cross section

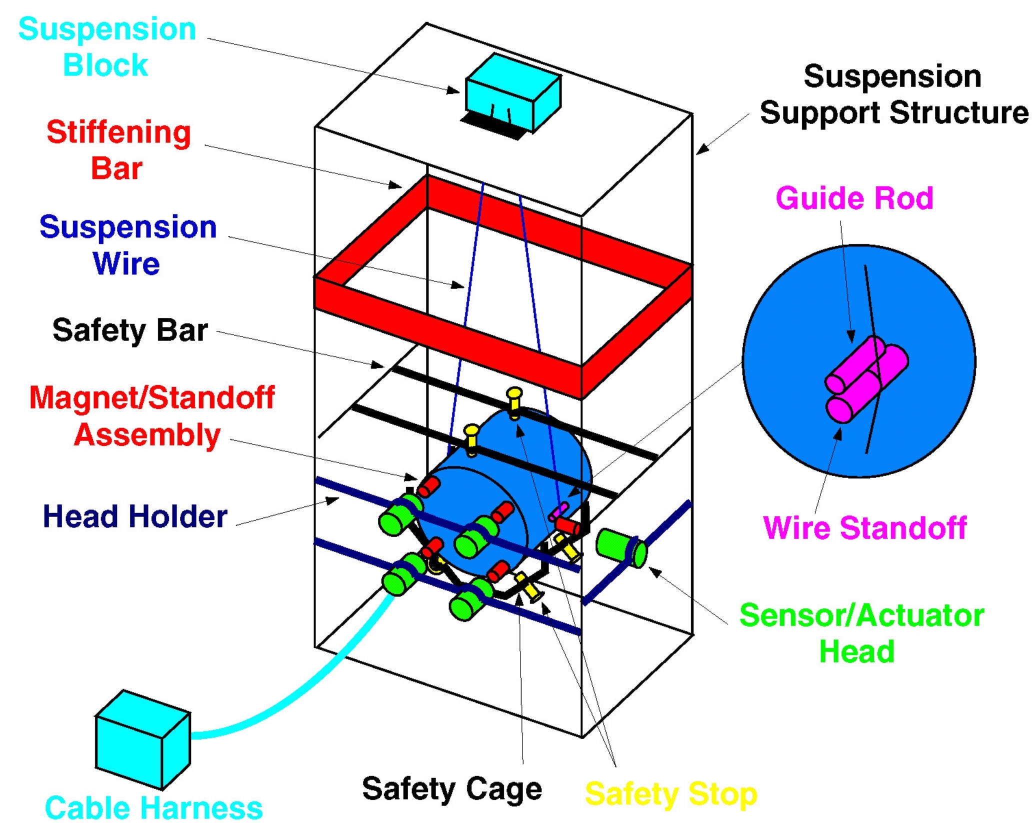


Seismic Isolation
suspension system



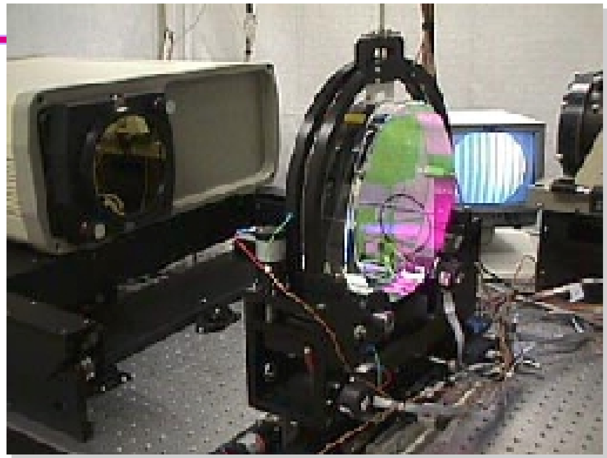
- support structure is welded tubular stainless steel
- suspension wire is 0.31 mm diameter steel music wire
- fundamental violin mode frequency of 340 Hz

suspension assembly for a core optic



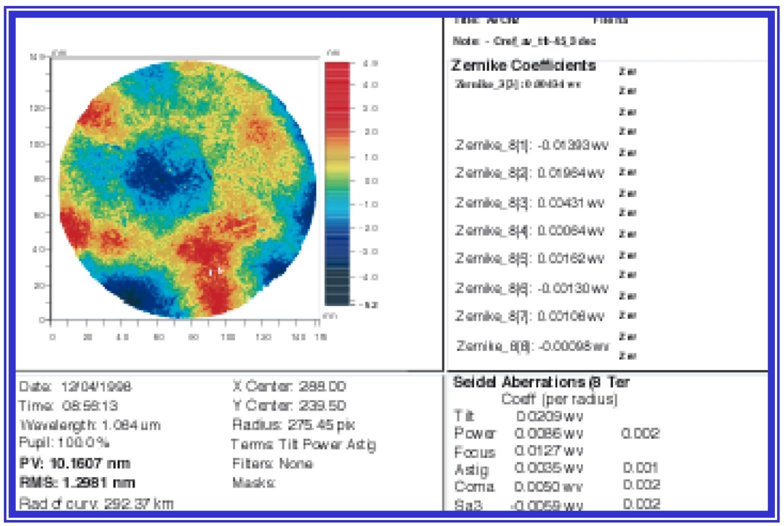
Core Optics

fused silica

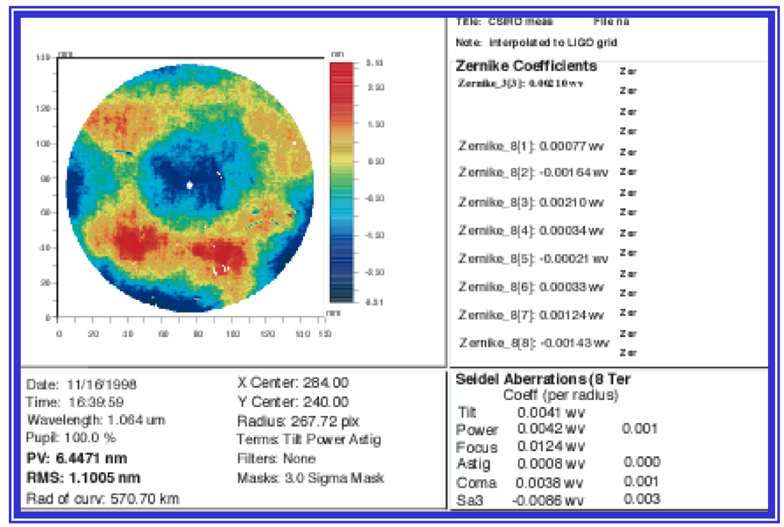


- Surface uniformity < 1 nm rms
- Scatter < 50 ppm
- Absorption < 2 ppm
- ROC matched < 3%
- Internal mode Q's > 2 x 10^6

<0.16 nm rms



Caltech data

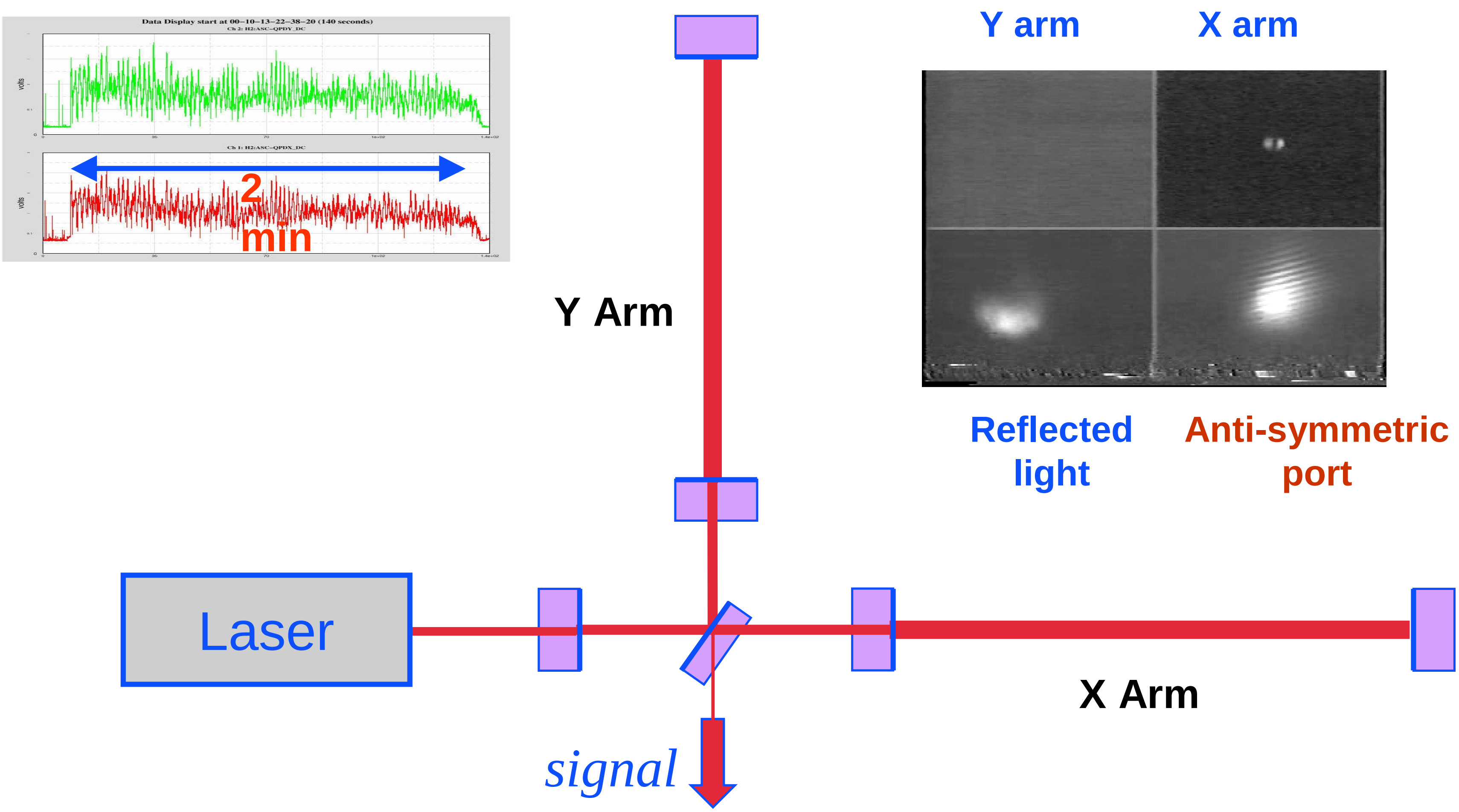


CSIRO data

Core Optics

installation and alignment

Watching the Interferometer Lock



Why is Locking Difficult?

One meter, about 40 inches

÷10,000 — *Earthtides, about 100 microns*

÷100 — *Microseismic motion, about 1 micron*

÷10,000 — *Precision required to lock, about 10^{-10} meter*

÷100,000 — *Nuclear diameter, 10^{-15} meter*

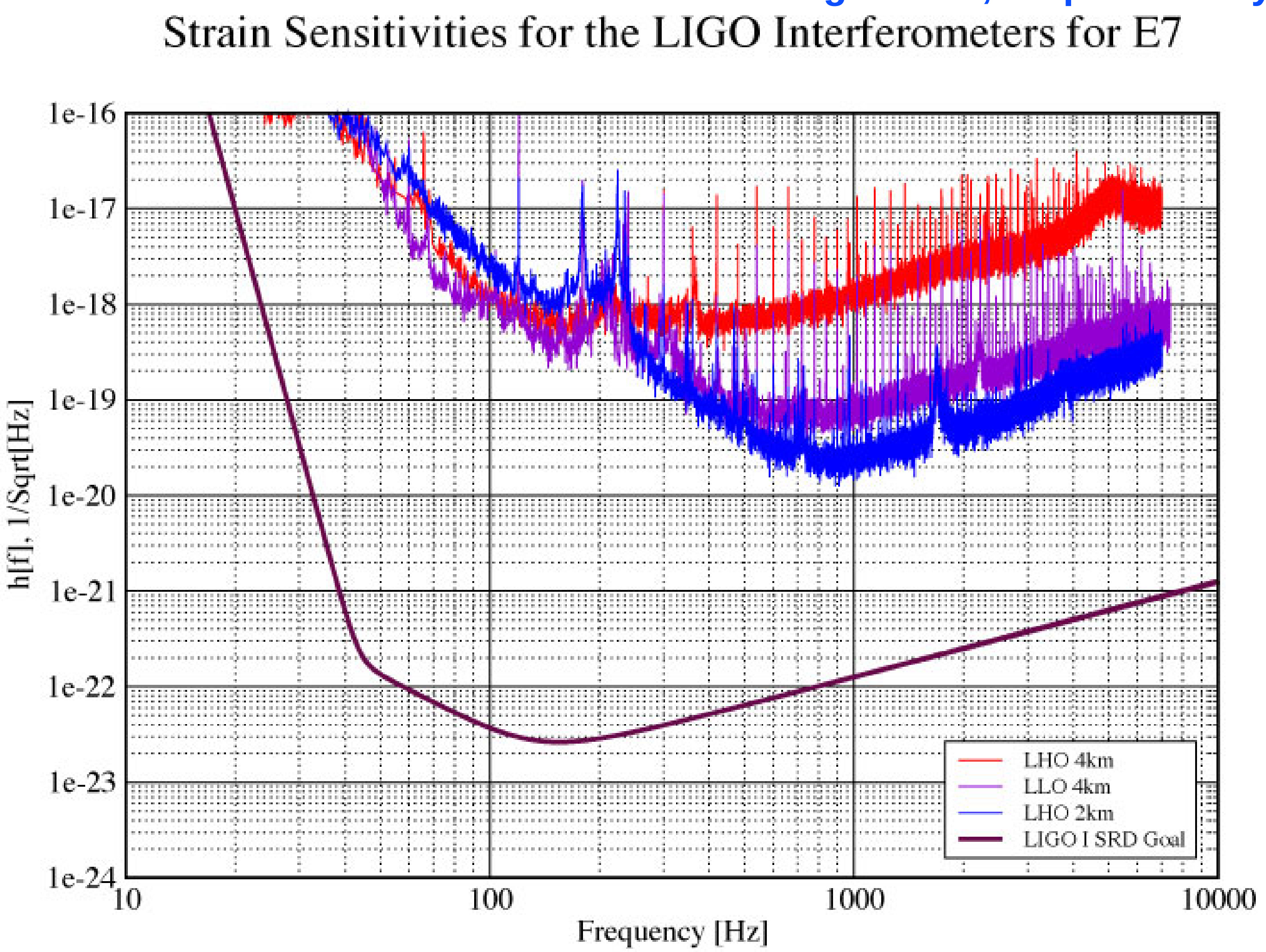
÷1,000 — *LIGO sensitivity, 10^{-18} meter*

E7 sensitivities for LIGO Interferometers

28 December 2001 - 14 January 2002

LHO2k: power recycled configuration;

LHO4k & LLO4k : recombined configuration, no power recycling



E7 Run Summary

LIGO + GEO Interferometers

Courtesy G. Gonzalez & M. Hewiston

28 Dec 2001 - 14 Jan 2002 (402 hr)

Singles data

	All segments	Segments >15min
L1 locked	284hrs (71%)	249hrs (62%)
L1 clean	265hrs (61%)	231hrs (53%)

L1 longest clean segment: 3:58

	All segments	Segments >15min
H1 locked	294hrs (72%)	231hrs (57%)
H1 clean	267hrs (62%)	206hrs (48%)

H1 longest clean segment: 4:04

	All segments	Segments >15min
H2 locked	214hrs (53%)	157hrs (39%)
H2 clean	162hrs (38%)	125hrs (28%)

H2 longest clean segment: 7:24

Coincidence Data

2X: H2, L1

	All segments	Segments >15min
locked	160hrs (39%)	99hrs (24%)
clean	113hrs (26%)	70hrs (16%)

H2,L1 longest clean segment: 1:50

3X : L1+H1+ H2

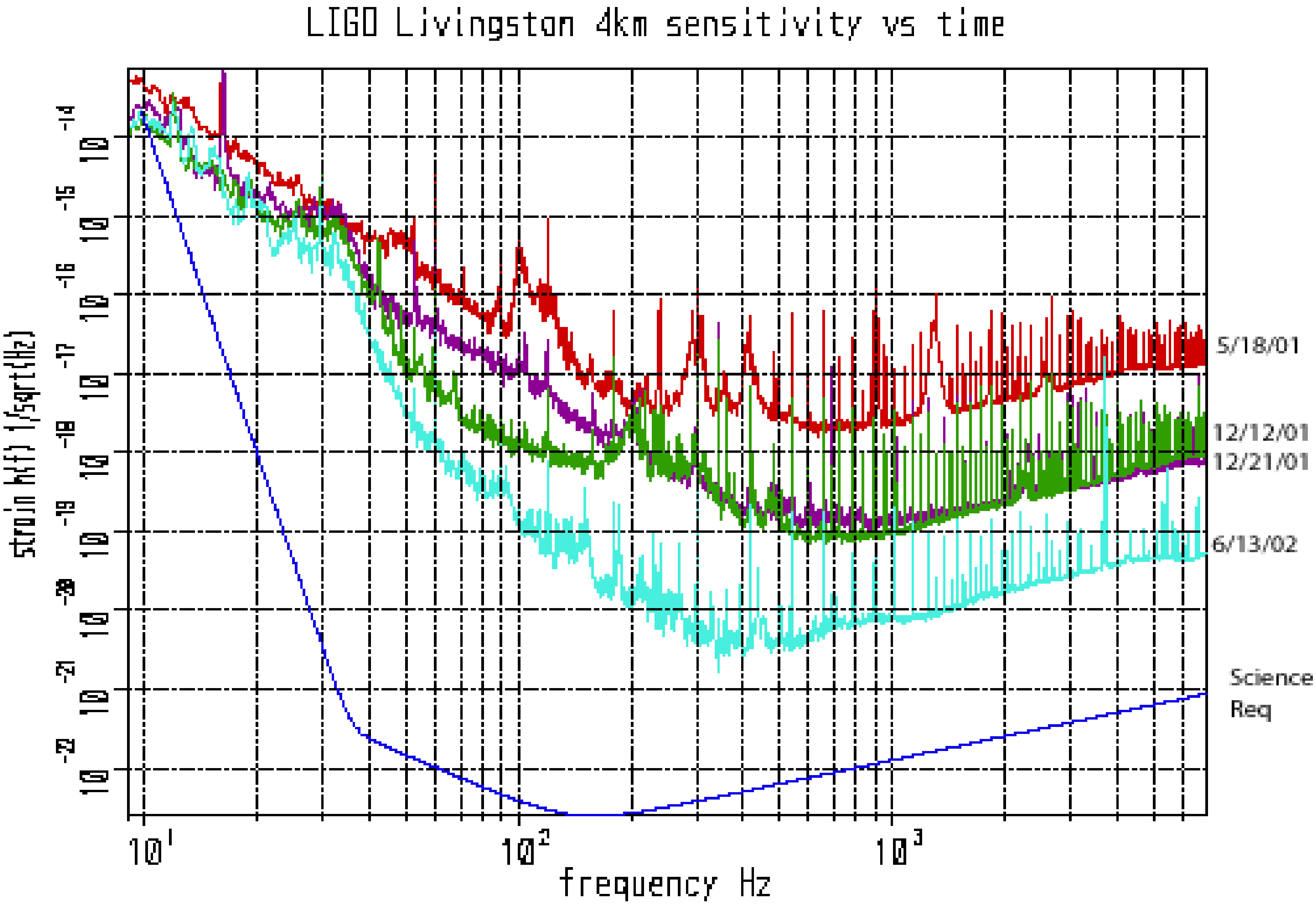
	All segments	Segments >15min
locked	140hrs (35%)	72hrs (18%)
clean	93hrs (21%)	46hrs (11%)

L1+H1+ H2 : longest clean segment: 1:18

4X: L1+H1+ H2 +GEO:

	All segments	Segments >15min
	77 hrs (23 %)	26.1 hrs (7.81 %)

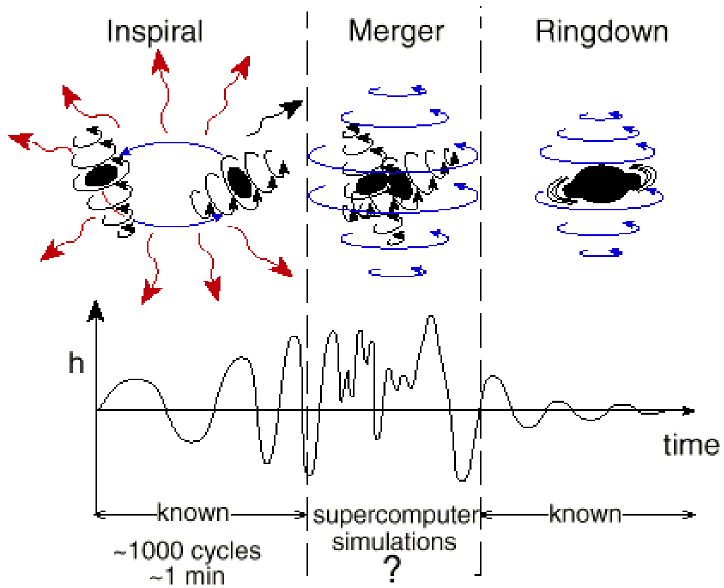
5X: ALLEGRO + …


LIGO Livingston 4km sensitivity vs time
strain h(f) 1/sqrt(Hz)
frequency Hz
5/18/01
12/12/01
12/21/01
6/13/02
Science
Req

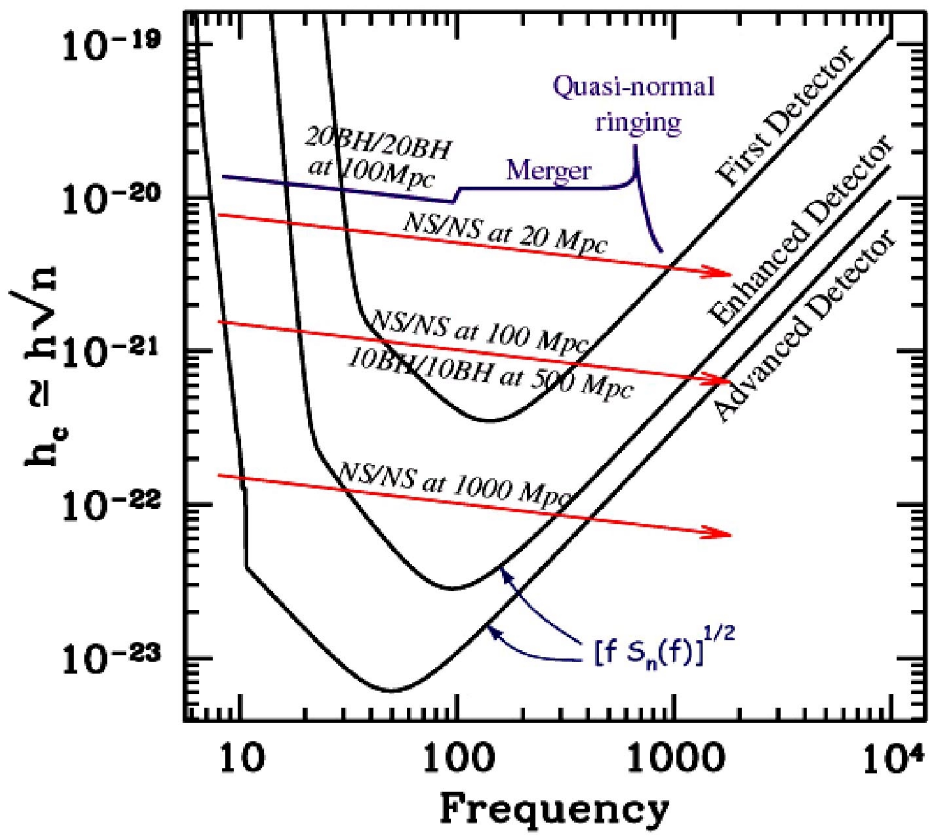
Binary Inspirals

signatures and sensitivity

Compact binary mergers

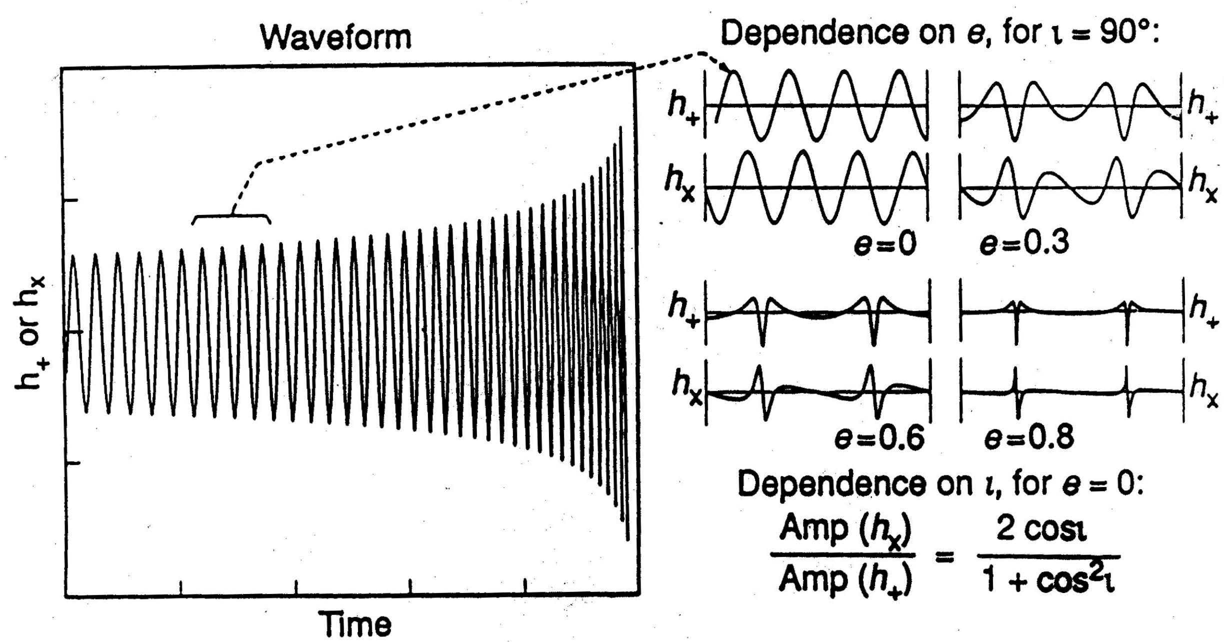


LIGO sensitivity to coalescing binaries



“Chirp Signal”

binary inspiral

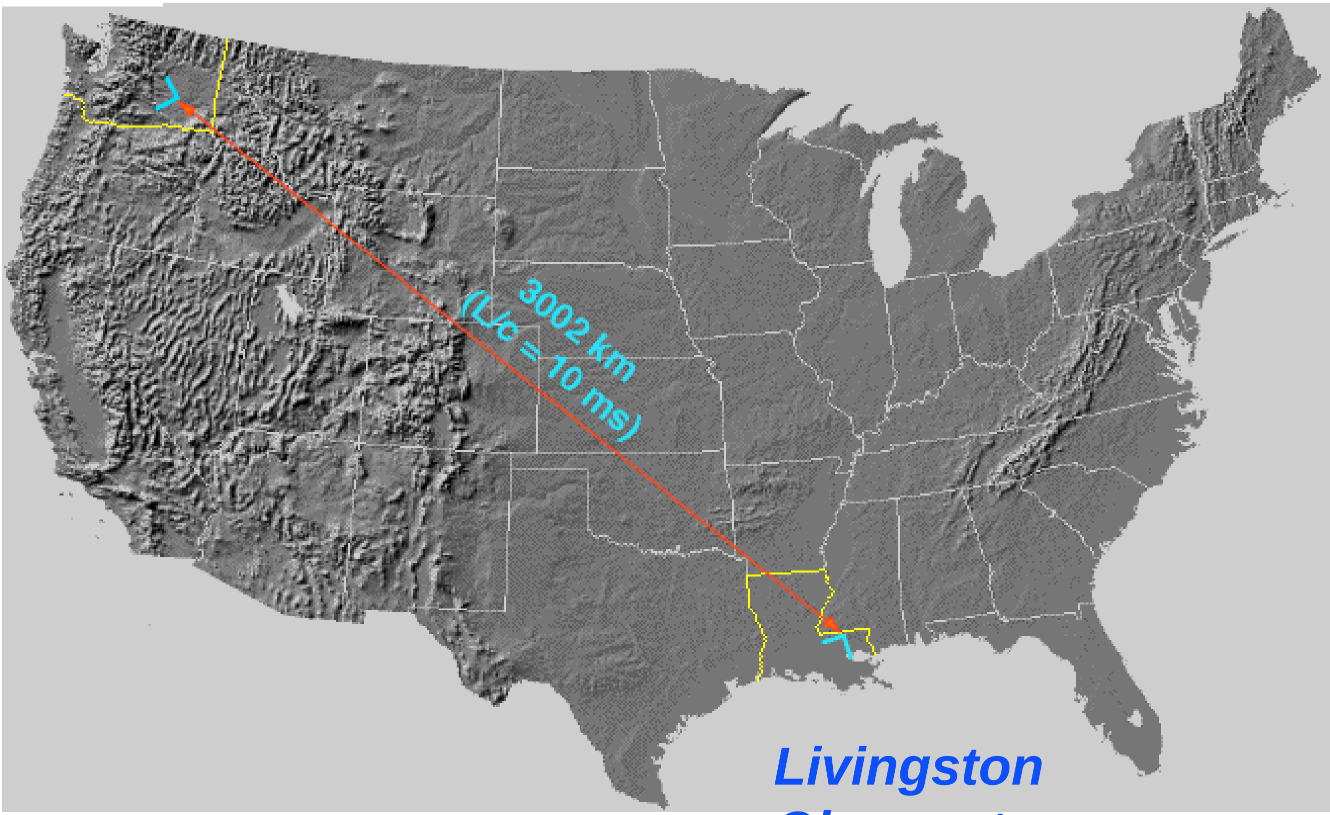


determine

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

Signals in Coincidence

Hanford Observatory



Livingston Observatory

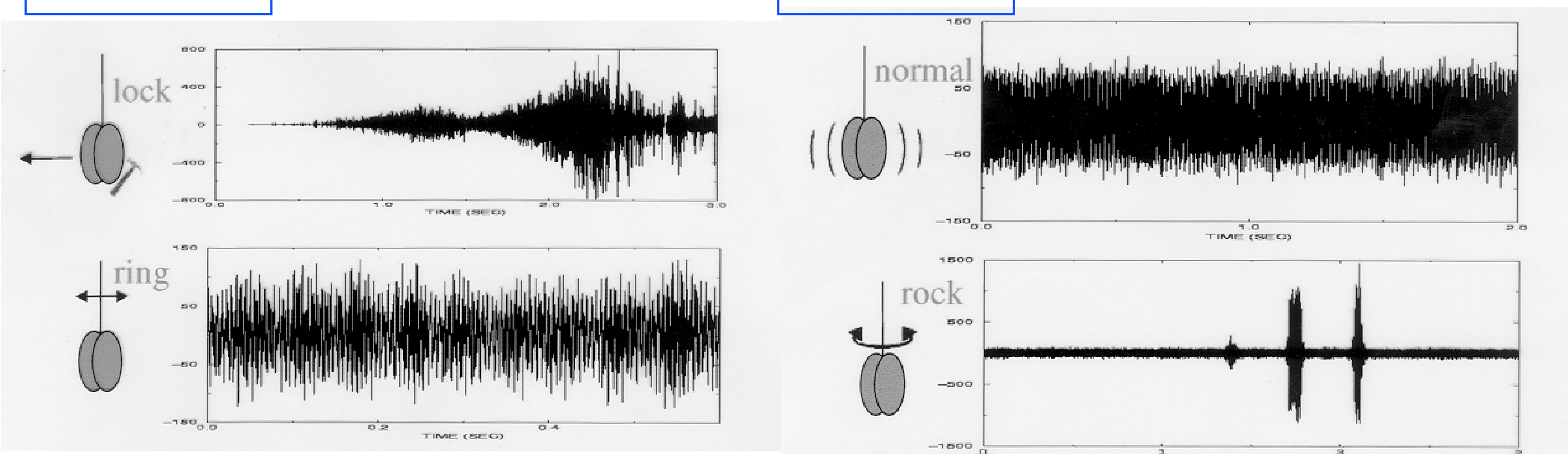
Interferometer Data

40 m prototype

Real interferometer data is UGLY!!!

(Gliches - known and unknown)

LOCKING **NORMAL**



RINGING **ROCKING**

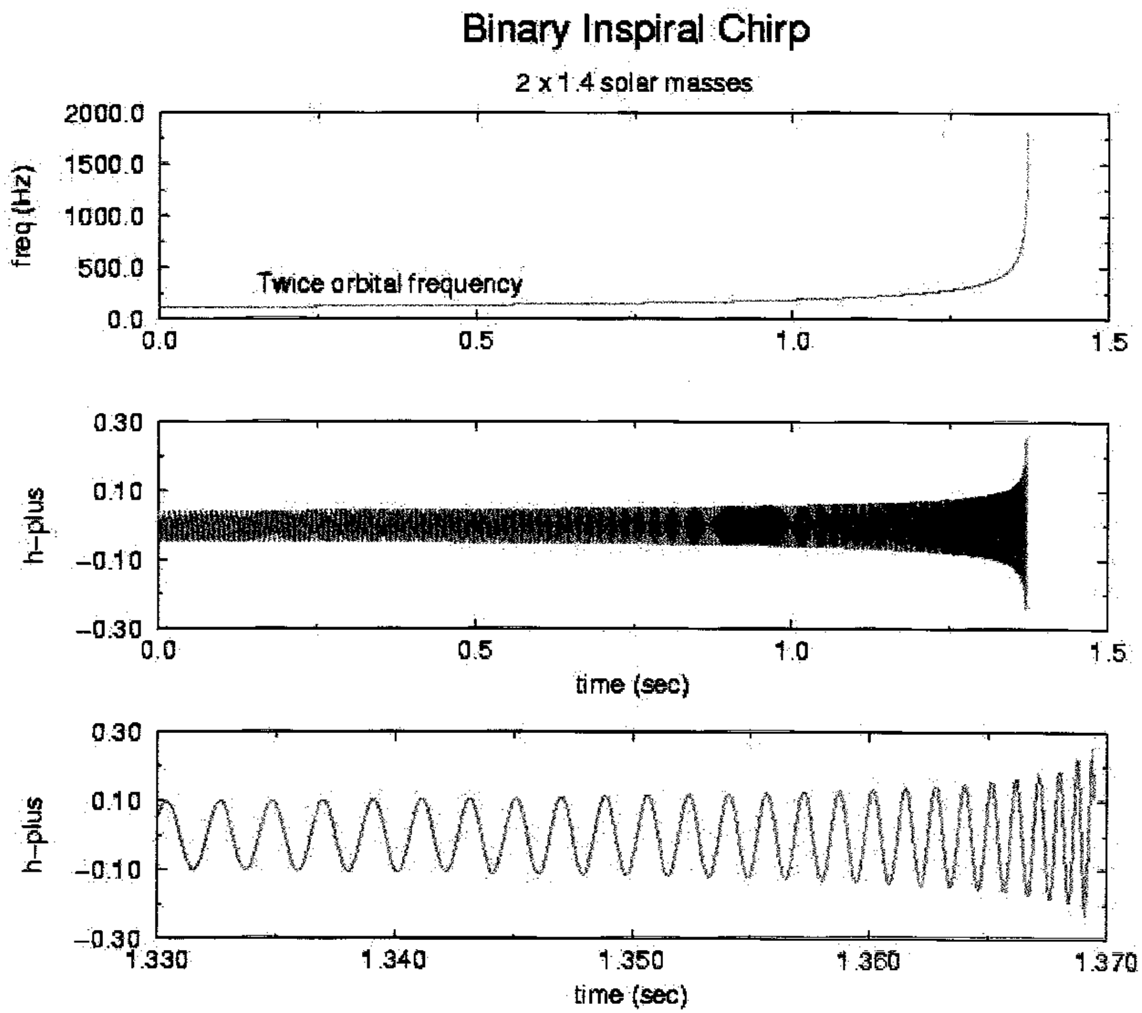
Inspiral 'Chirp' Signal

Template Waveforms

"matched filtering"
687 filters

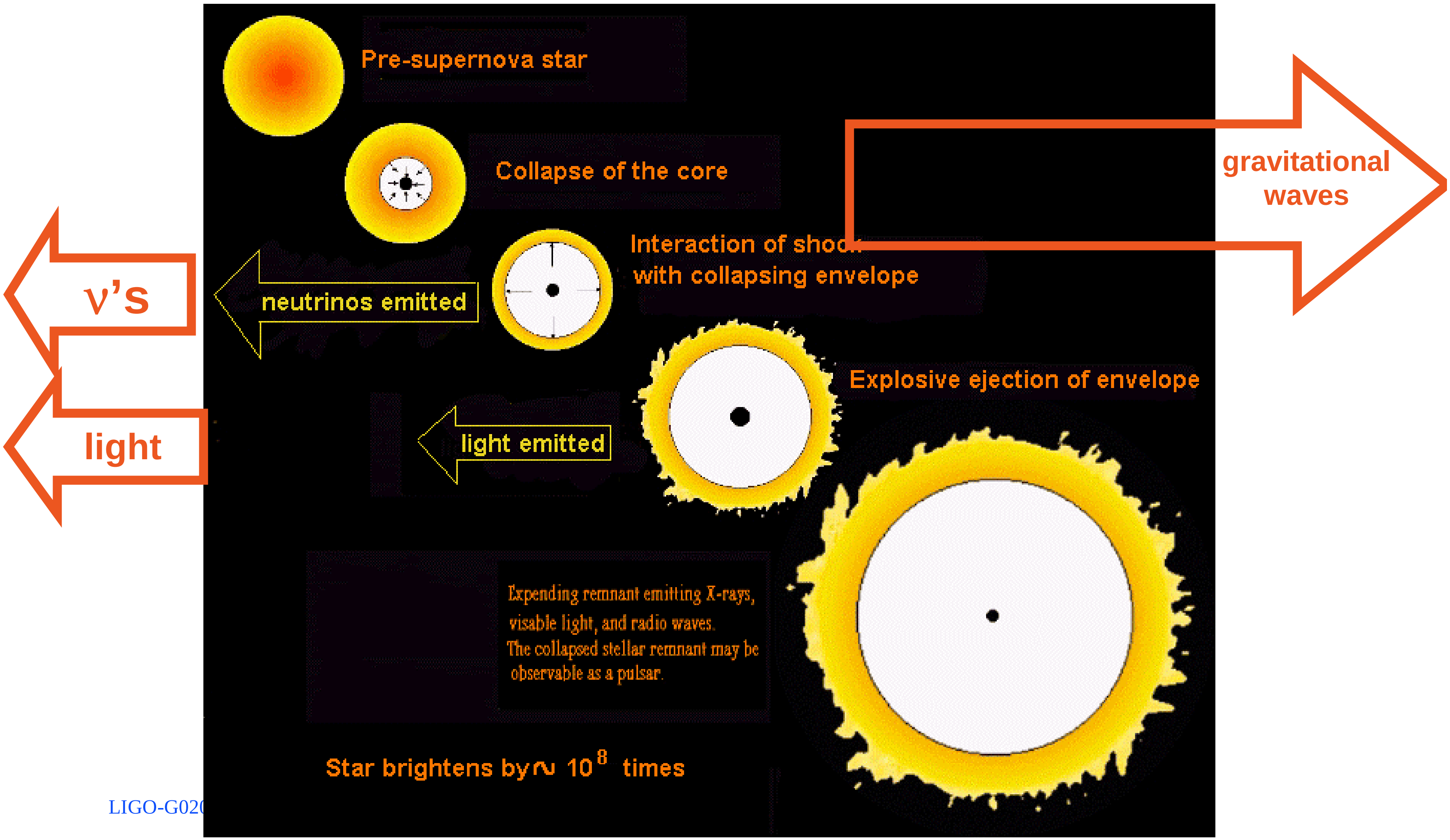
44.8 hrs of data
39.9 hrs arms locked
25.0 hrs good data

sensitivity to our galaxy
h ~ 3.5 10^{-19} $mHz^{-1/2}$
expected rate ~10^{-6}/yr



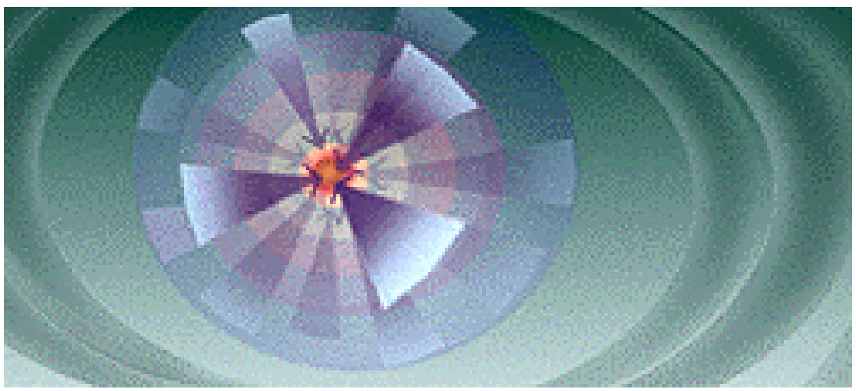
“Burst Signal”

supernova



Supernovae
gravitational waves

Non axisymmetric collapse

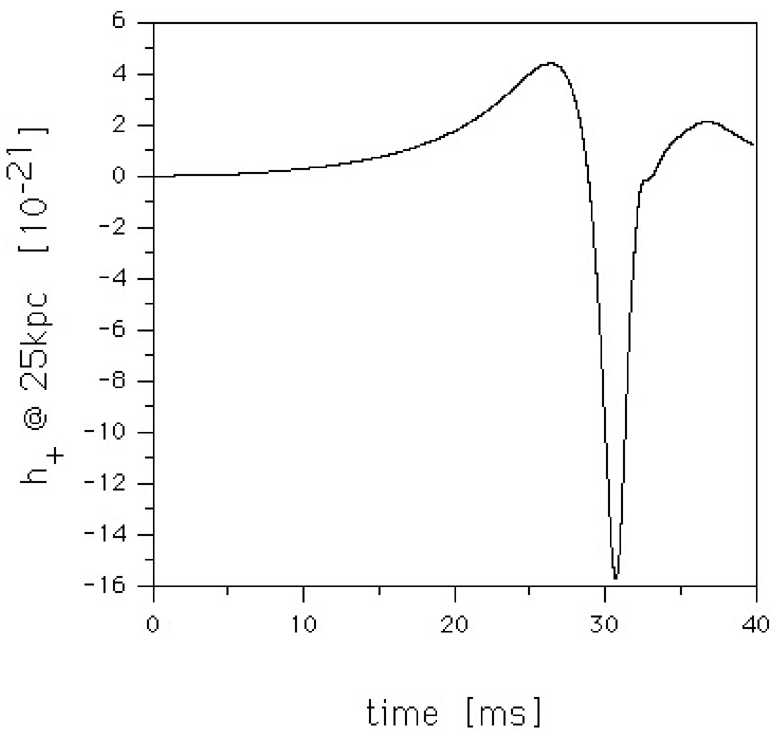


Rate

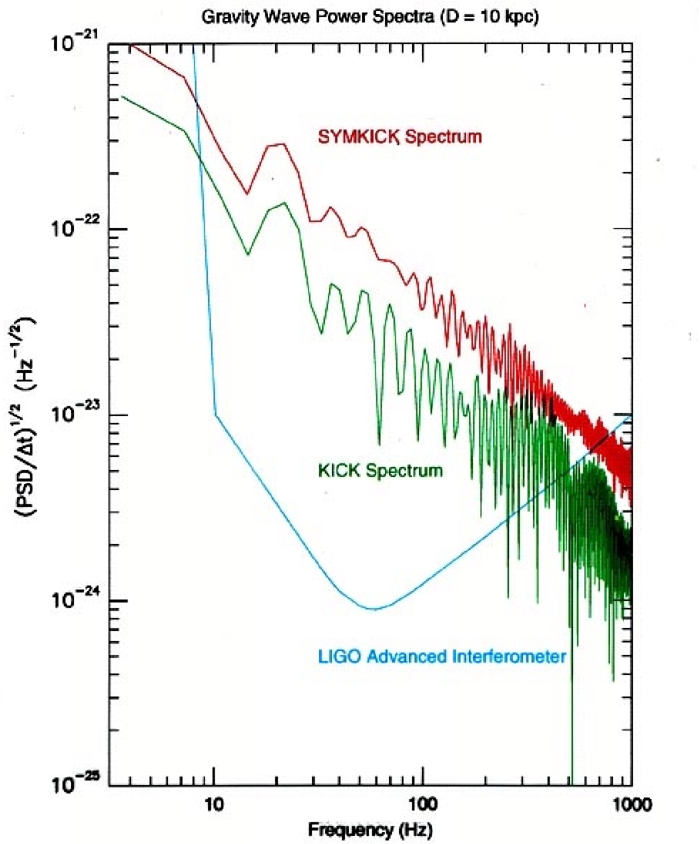
1/50 yr - our galaxy

3/yr - Virgo cluster

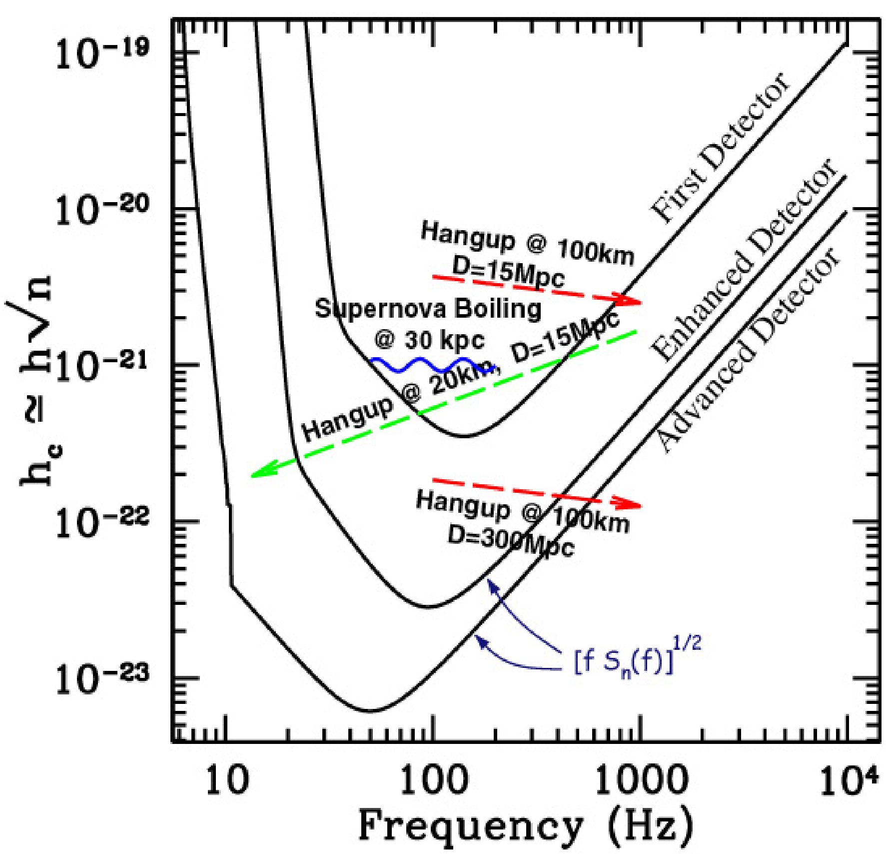
'burst' signal



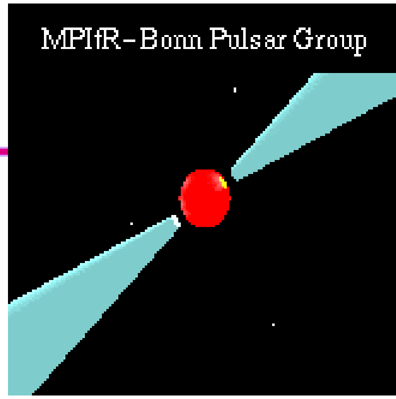
Supernovae
signatures and sensitivity



Sensitivity of LIGO to burst sources

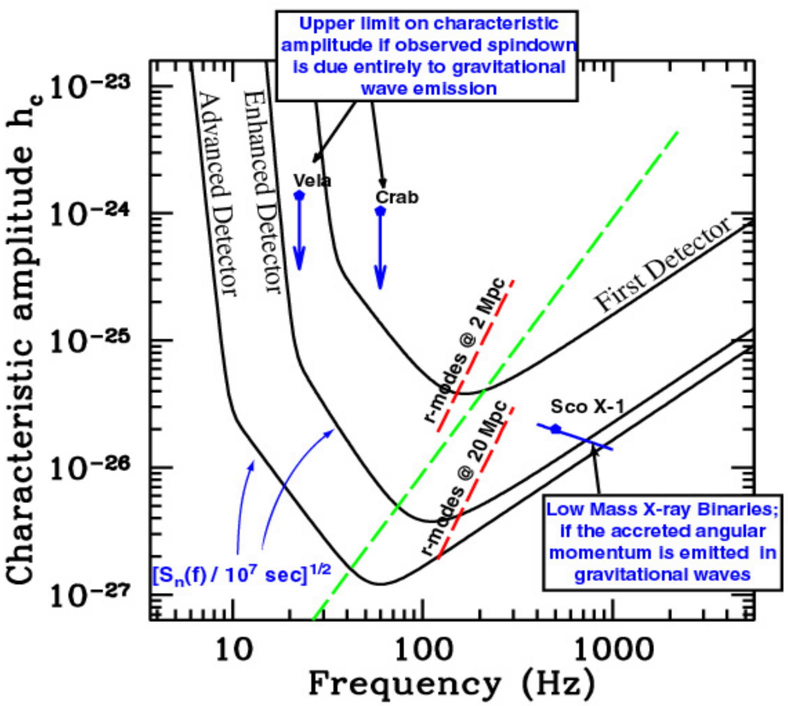


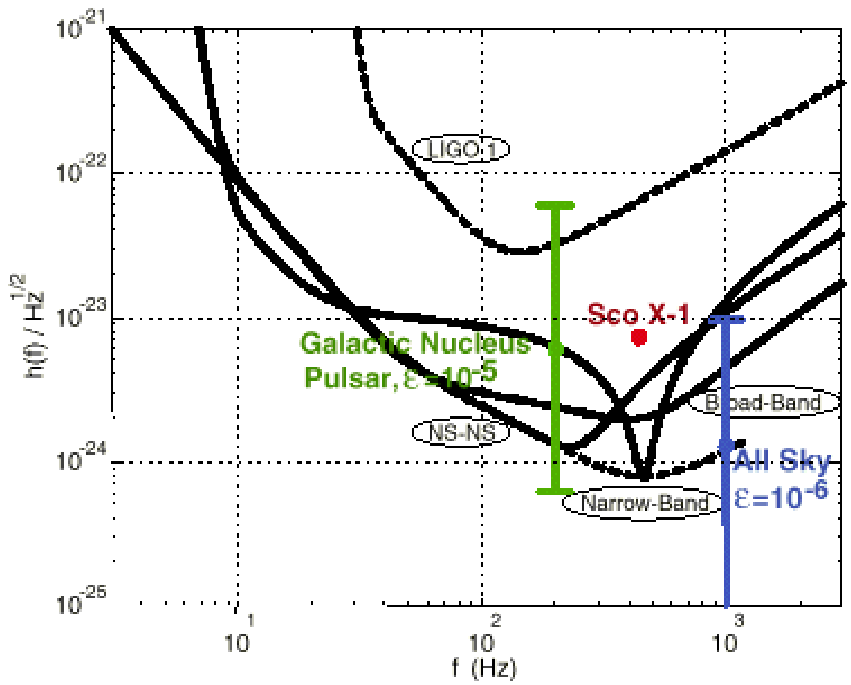
“Periodic Signals”
pulsars sensitivity



- **Pulsars in our galaxy**
  - »non axisymmetric: $10^{-4} < \varepsilon < 10^{-6}$
  - »science: neutron star precession; interiors
  - »narrow band searches best

Sensitivity of LIGO to continuous wave sources



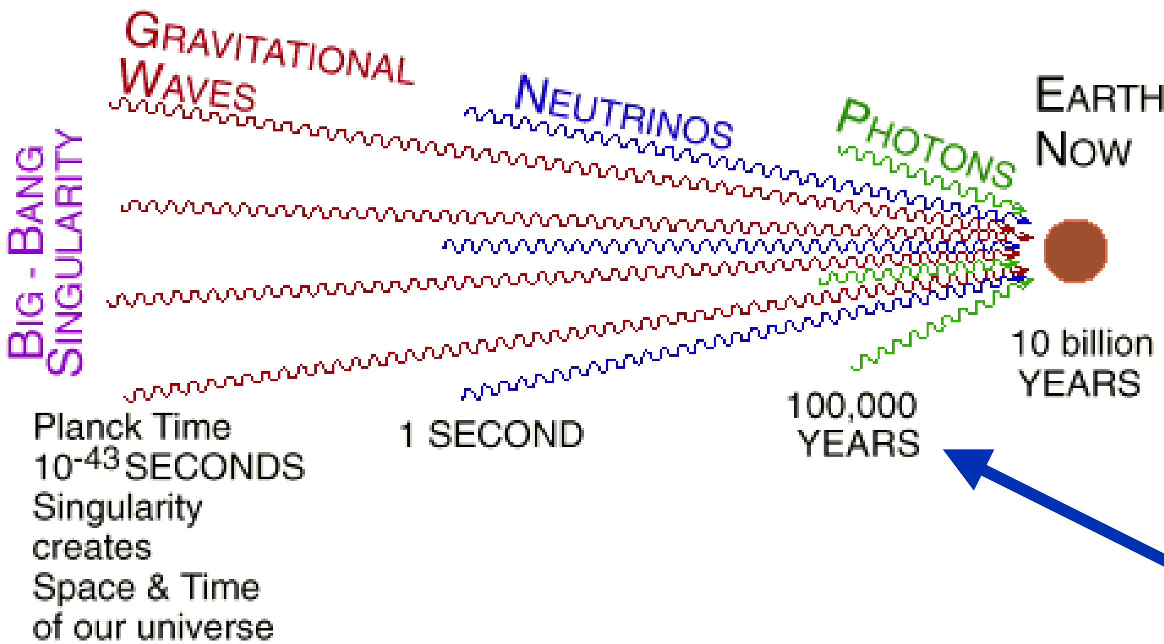


“Stochastic Background”

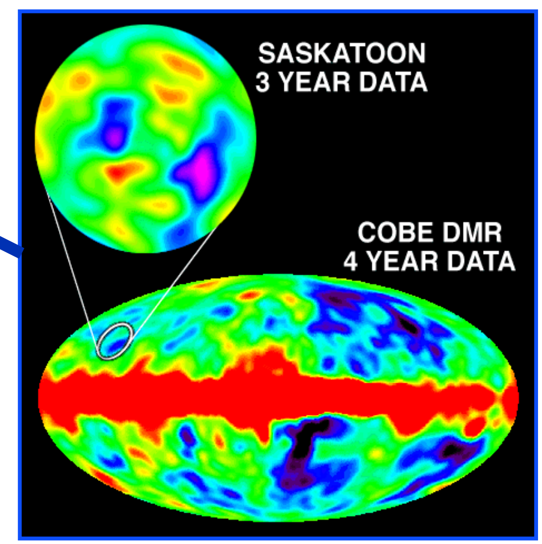
cosmological signals

‘Murmurs’ from the Big Bang

signals from the early universe

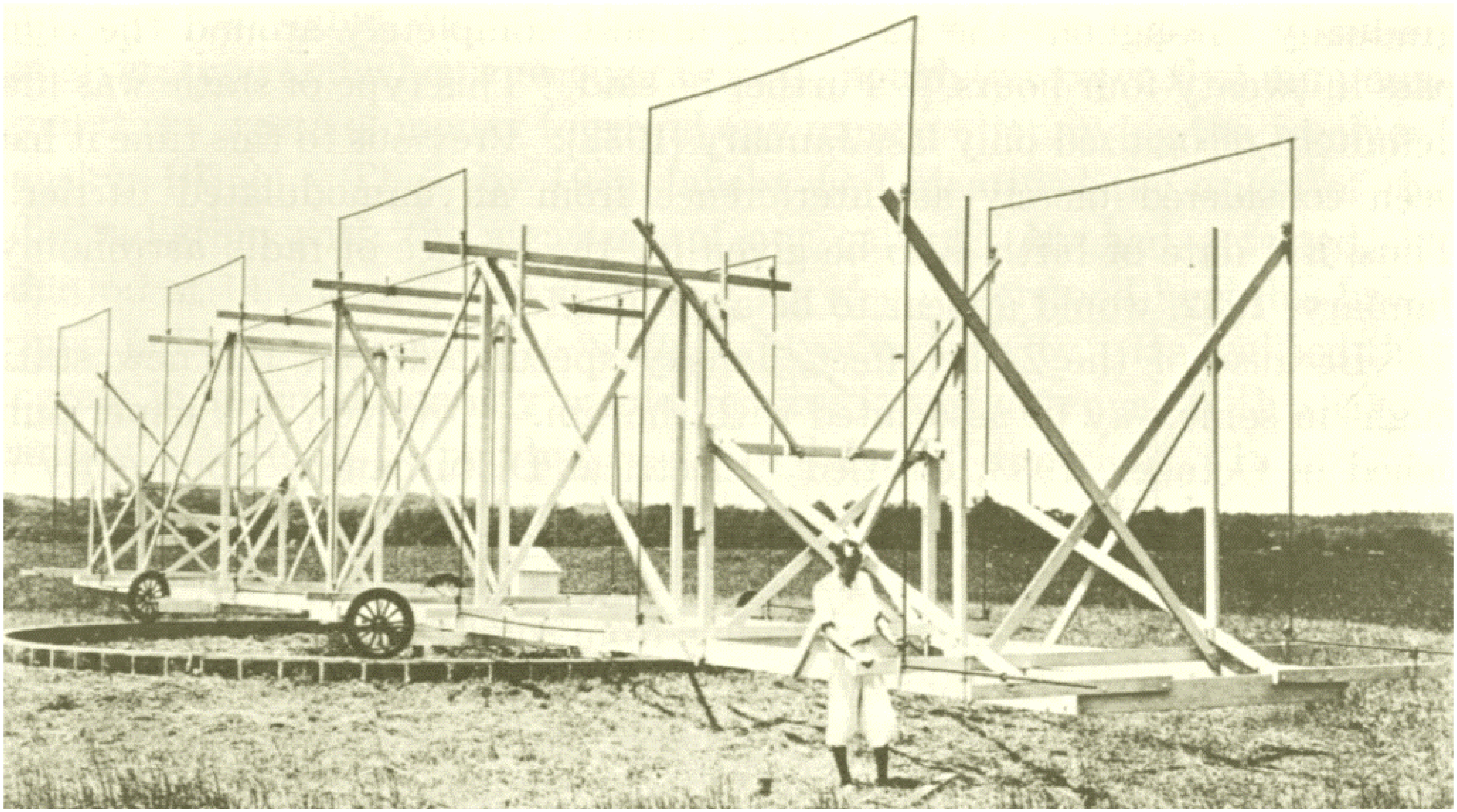


Cosmic microwave background

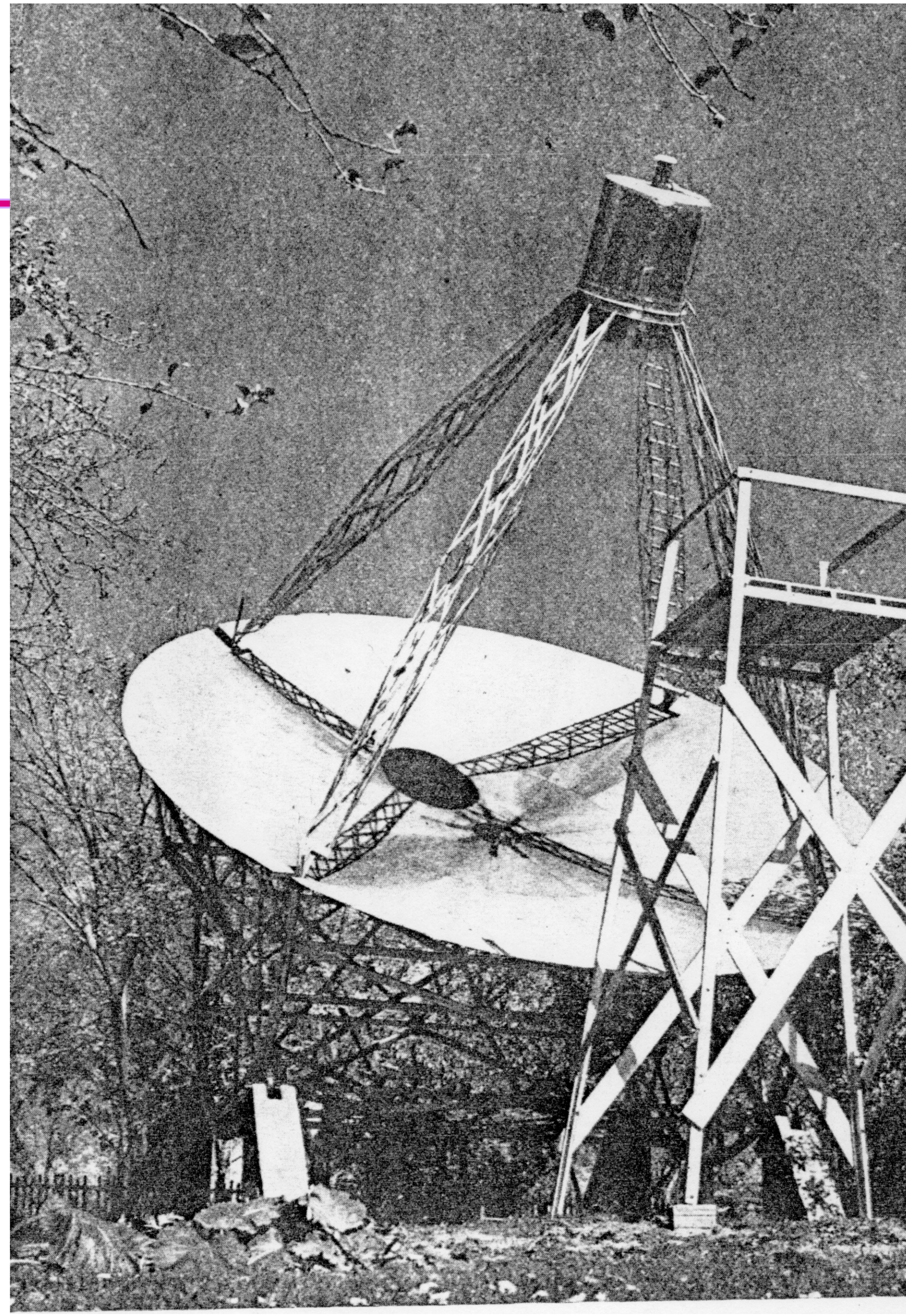


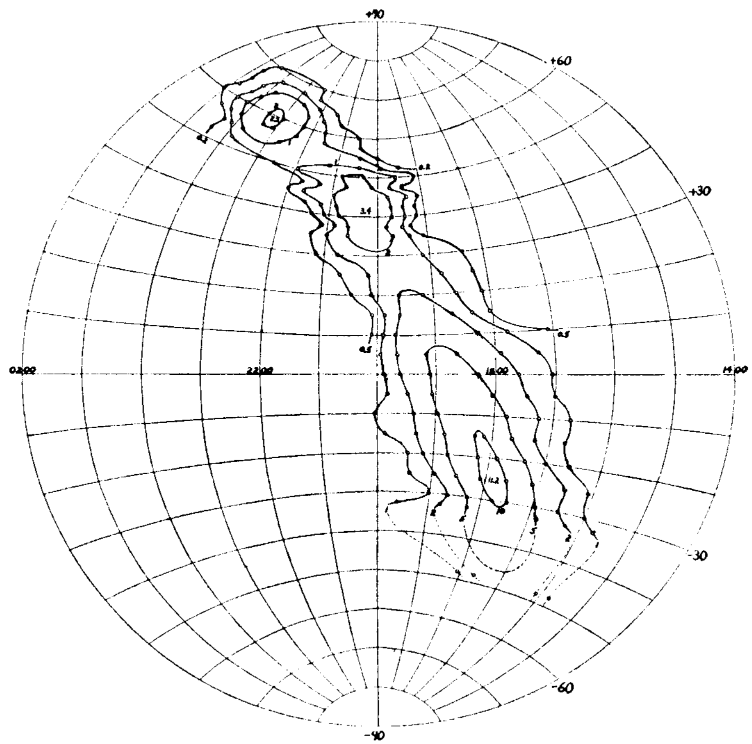
LIGO
conclusions

- LIGO construction complete
- LIGO commissioning and testing 'on track'
- "First Lock" officially established 20 Oct 00
- First Science Run will begin next month
- Significant improvements in sensitivity anticipated to begin about 2006
- Measure General Relativity directly
- Open a new form of astronomy



LIGO





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