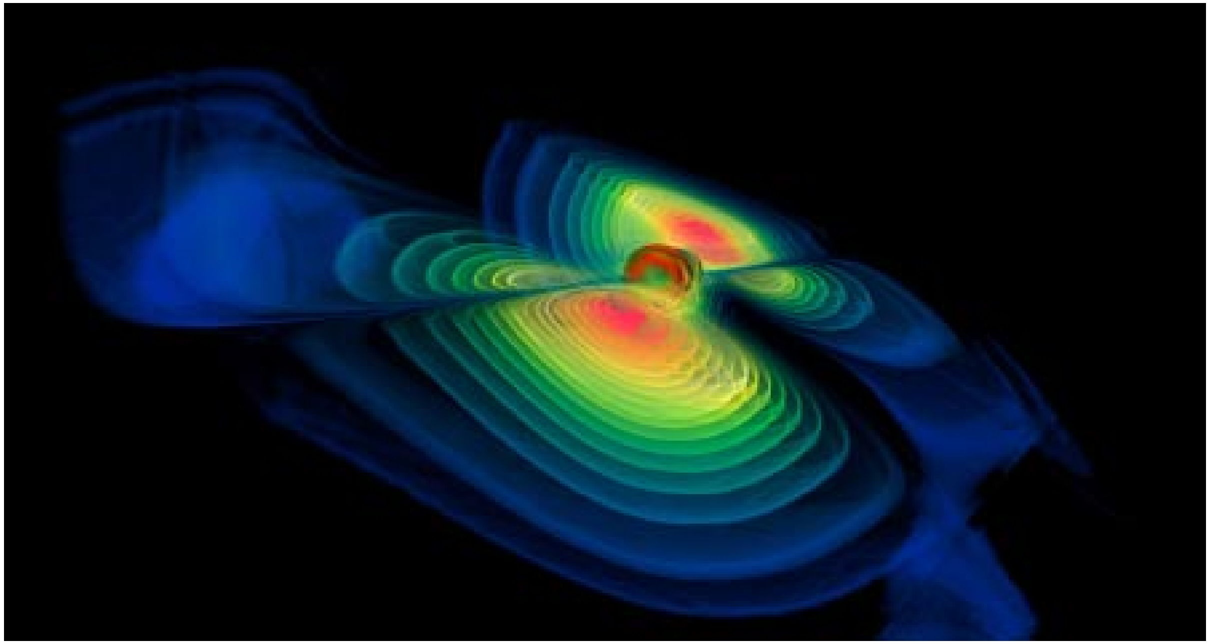
Gravity -- Studying the Fabric of the Universe



"Colliding Black Holes"

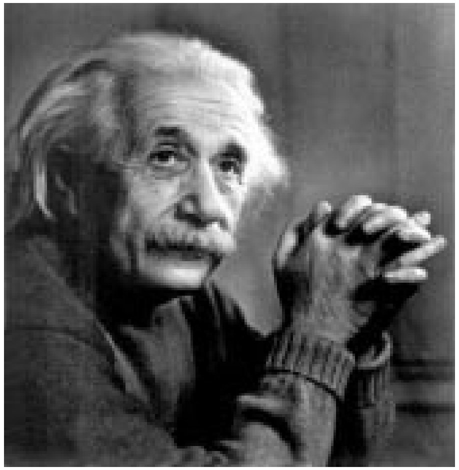
Credit:
National Center for Supercomputing Applications (NCSA)

Barry C. Barish
Caltech

AAAS Annual Meeting
Denver, Colorado
17-Feb-03

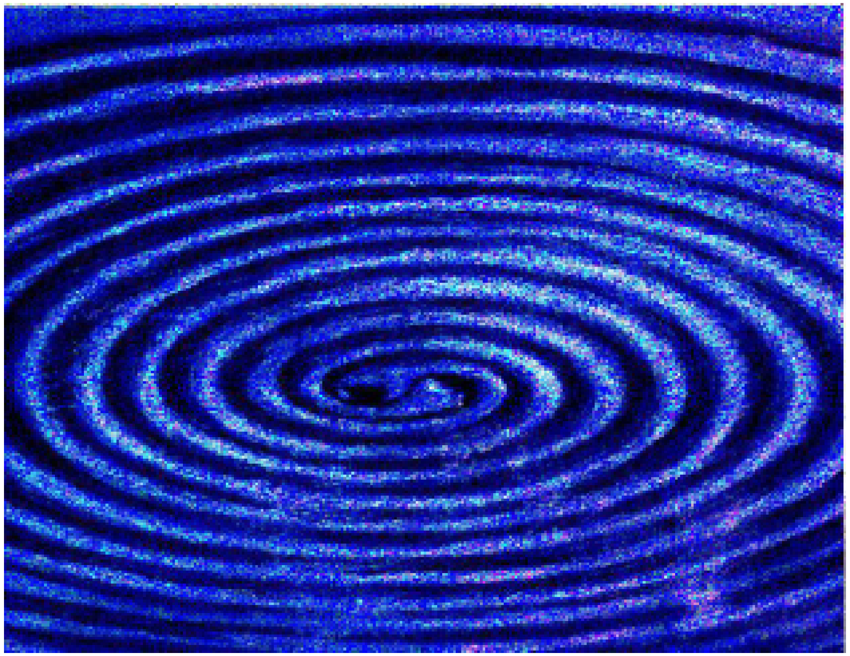
LIGO-G030020-00-M

Einstein's Theory of Gravitation



Newton's Theory

"instantaneous action at a distance"



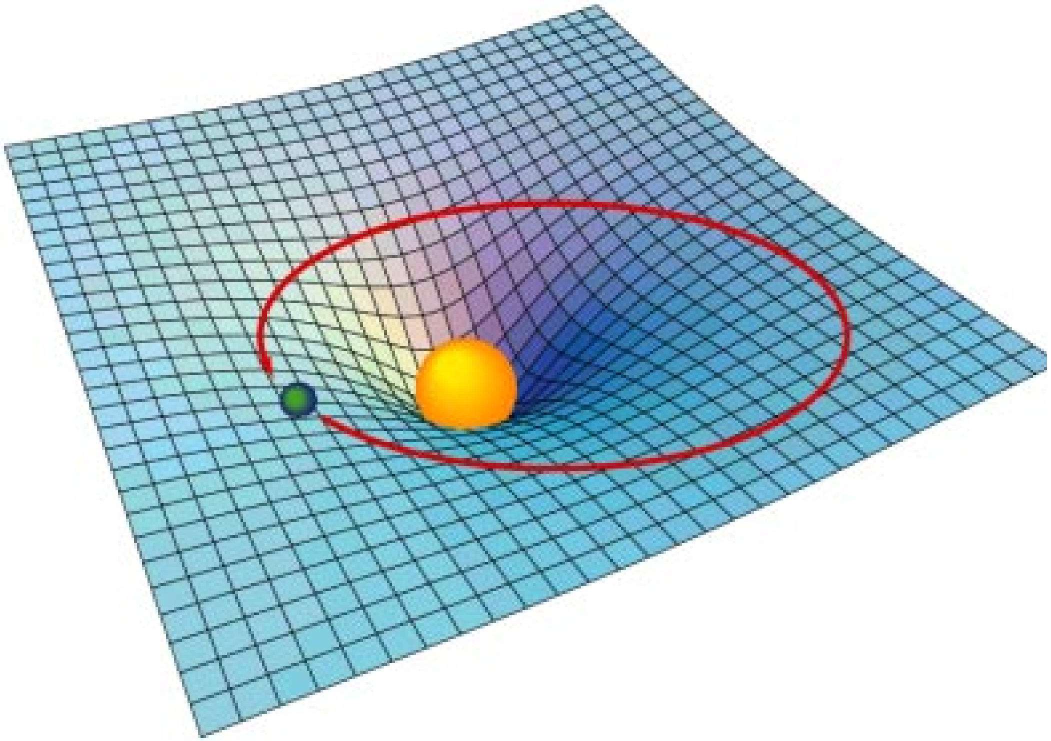
Einstein's Theory

information carried by gravitational radiation at the speed of light

LIGO

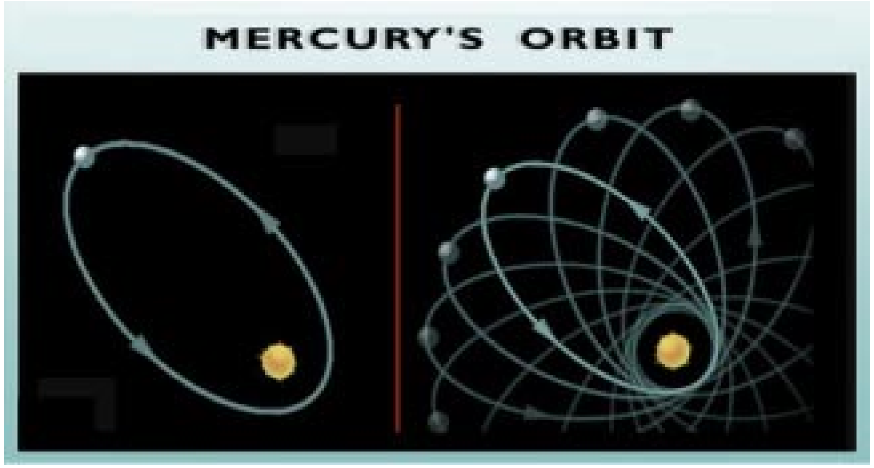
General Relativity

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



- **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.**

LIGO 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.

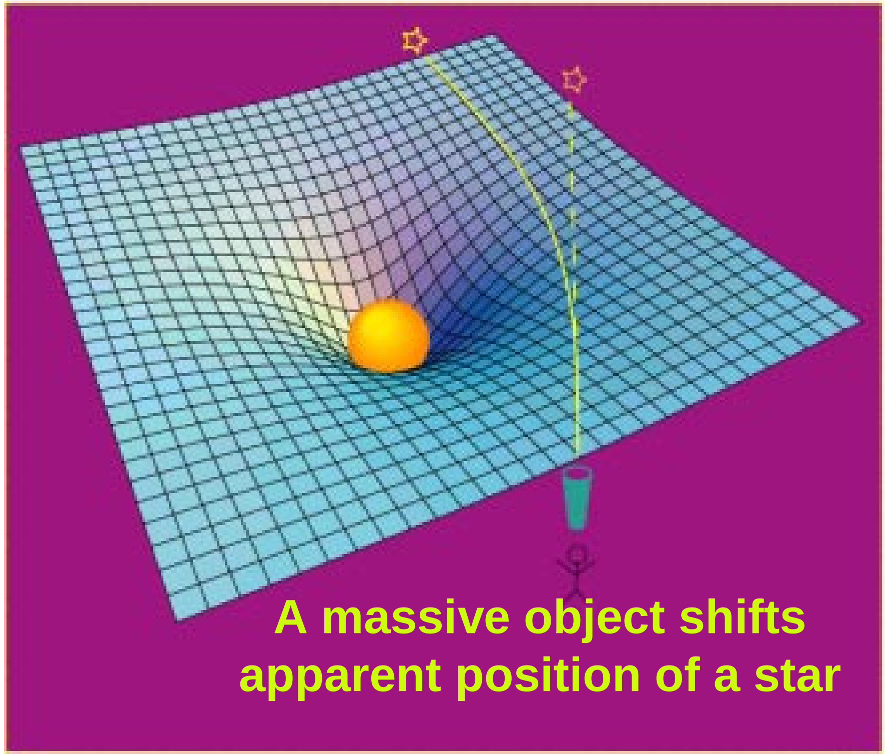
Einstein's predictions exactly matched the observation.

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.**



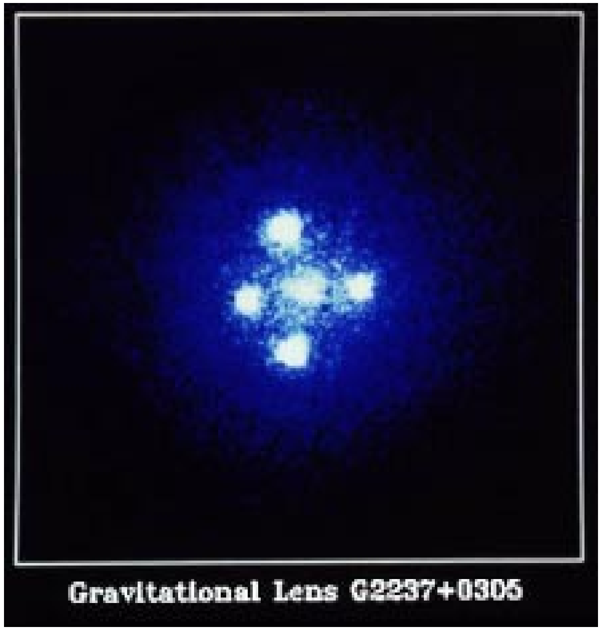
A massive object shifts apparent position of a star

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

LIGO Einstein's Theory of Gravitation

experimental tests

"Einstein Cross"
The bending of light rays
gravitational lensing



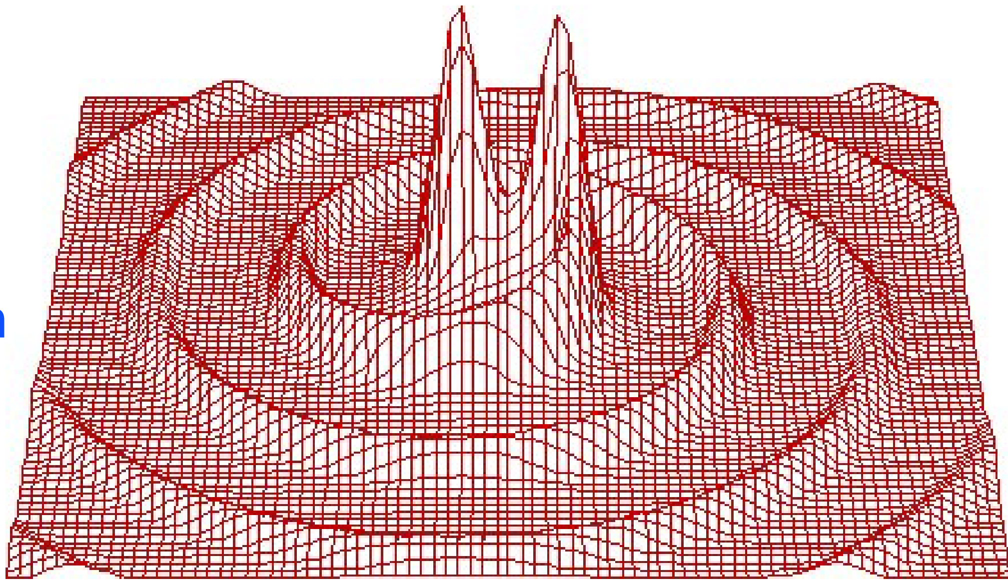
Quasar image appears around the central glow formed by nearby galaxy. The Einstein Cross is only visible in southern hemisphere.

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

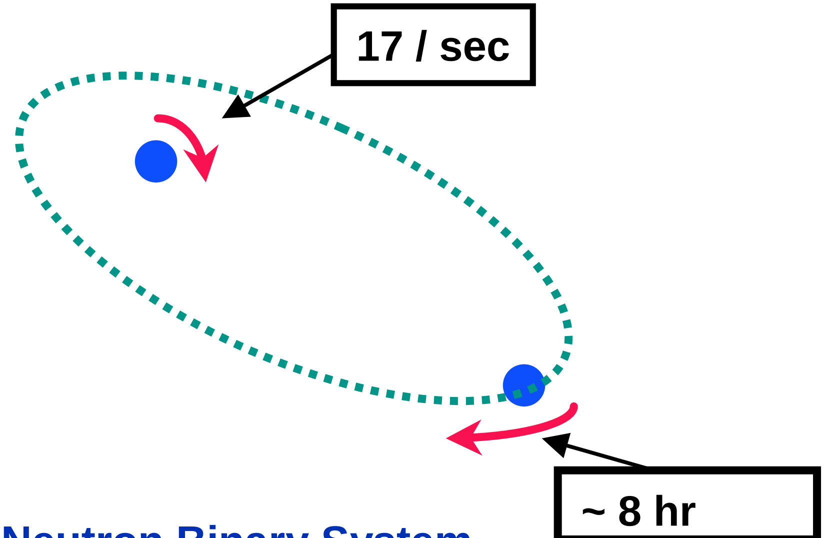


gravitational radiation
binary inspiral of compact objects

Gravitational Waves
the evidence

Neutron Binary System – Hulse & Taylor

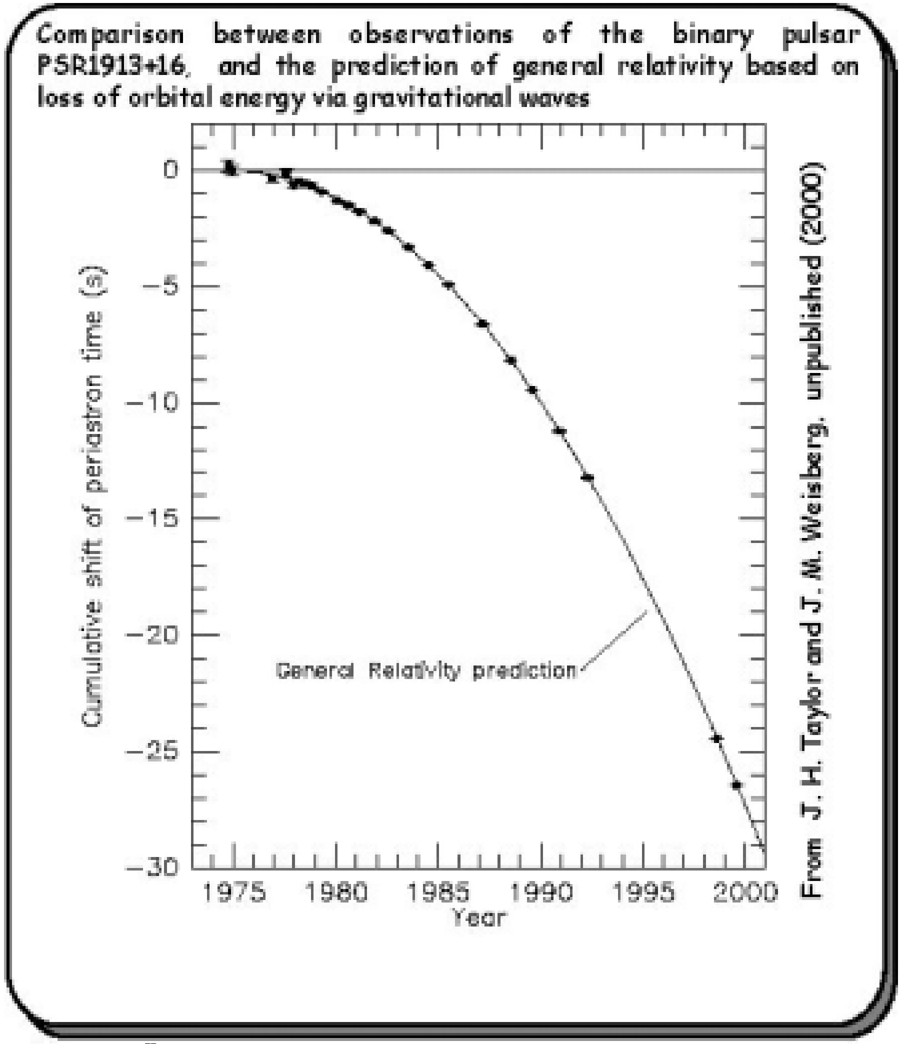
PSR 1913 + 16 -- Timing of pulsars



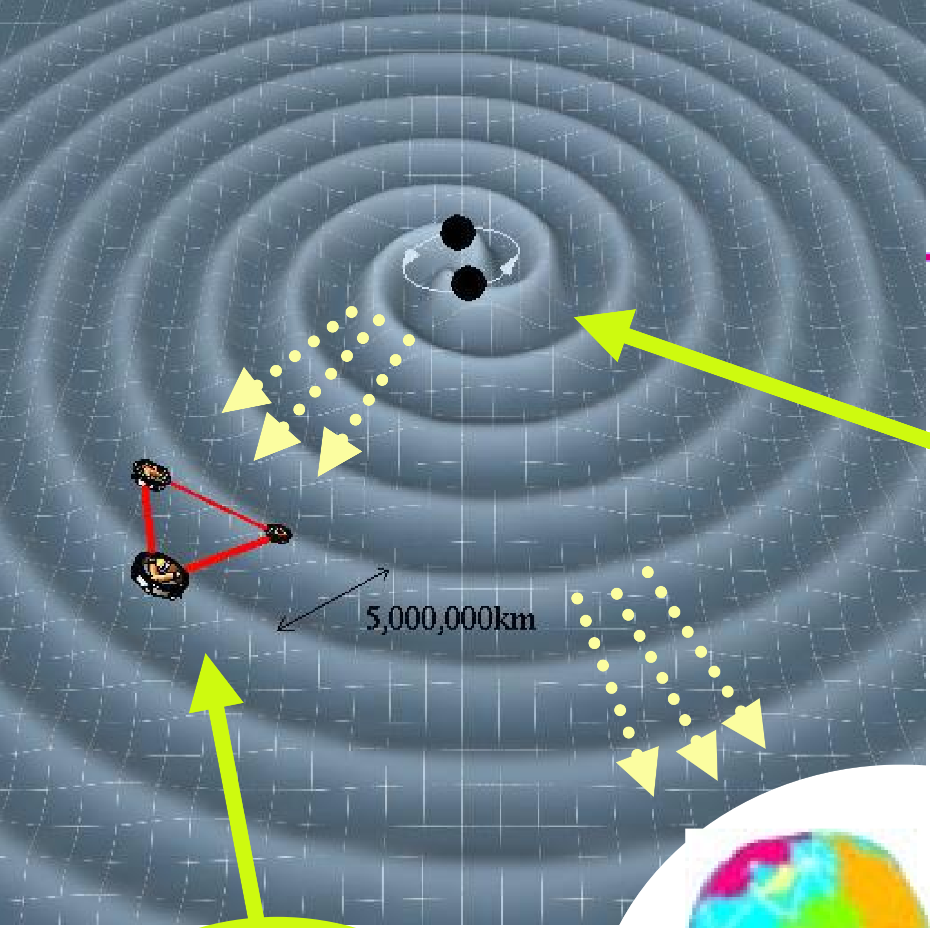
Neutron Binary System
- separated by 10^6 miles
- $m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$

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

Emission of gravitational waves



Direct Detection
astrophysical sources



Gravitational Wave Astrophysical Source

Detectors in space LISA

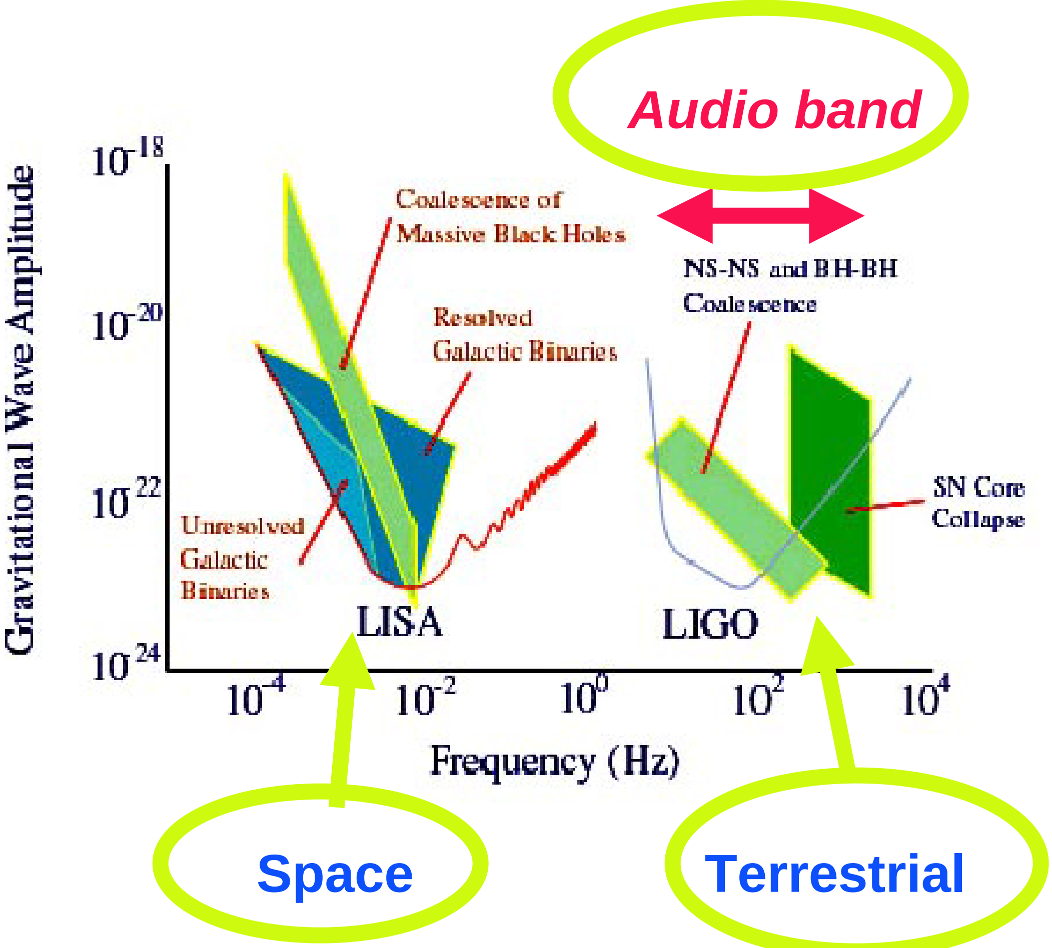
Terrestrial detectors
LIGO, TAMA, Virgo,AIGO

Astrophysics Sources

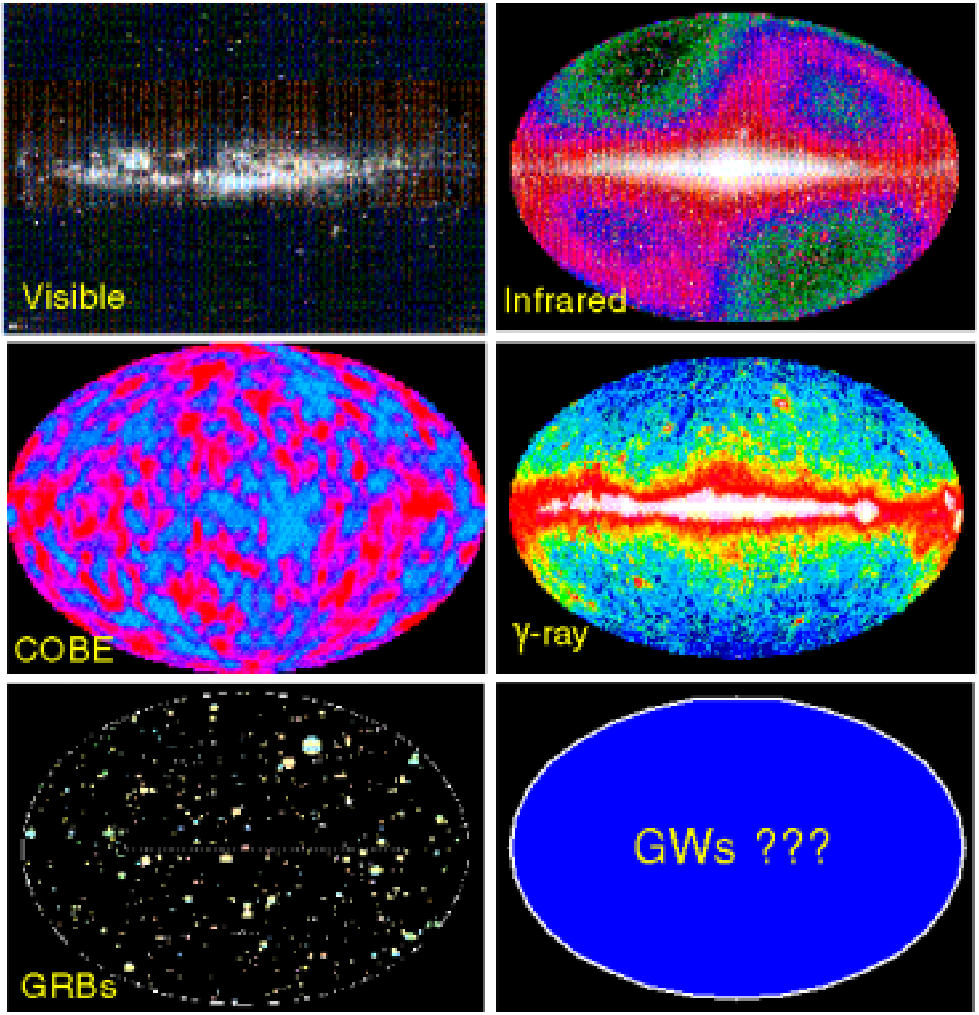
frequency range

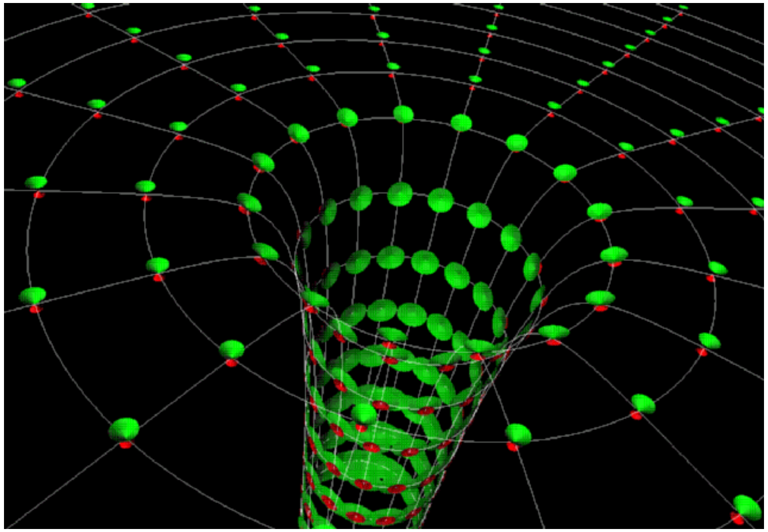
- **EM waves are studied over ~20 orders of magnitude**
  - » **(ULF radio –> HE γ-rays)**

- **Gravitational Waves over ~10 orders of magnitude**
  - » **(terrestrial + space)**



A New Window on the Universe

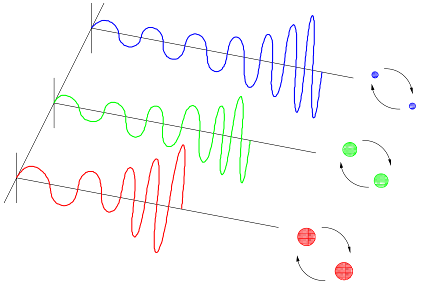




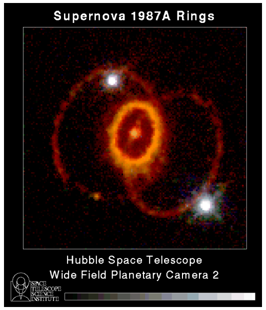
Gravitational Waves will provide a new way to view the dynamics of the Universe

Astrophysical Sources *signatures*

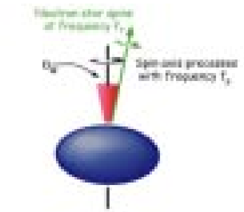
- **Compact binary inspiral:** *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
  - » search technique: matched templates



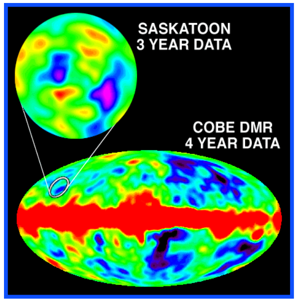
- **Supernovae / GRBs:** *"bursts"*
  - » burst signals in coincidence with signals in electromagnetic radiation
  - » prompt alarm (~ one hour) with neutrino detectors



- **Pulsars in our galaxy:** *"periodic"*
  - » search for observed neutron stars (frequency, doppler shift)
  - » all sky search (computing challenge)
  - » r-modes

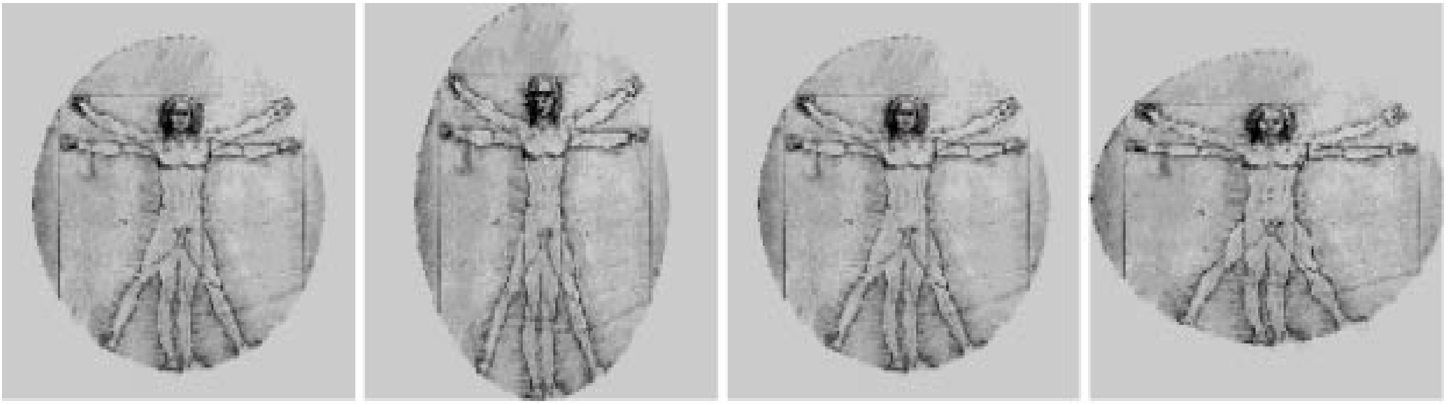


- **Cosmological Signals** *"stochastic background"*



Gravitational Waves
the effect

Leonardo da Vinci's Vitruvian man



stretch and squash in perpendicular directions at the frequency of the gravitational waves

The effect is greatly exaggerated!!

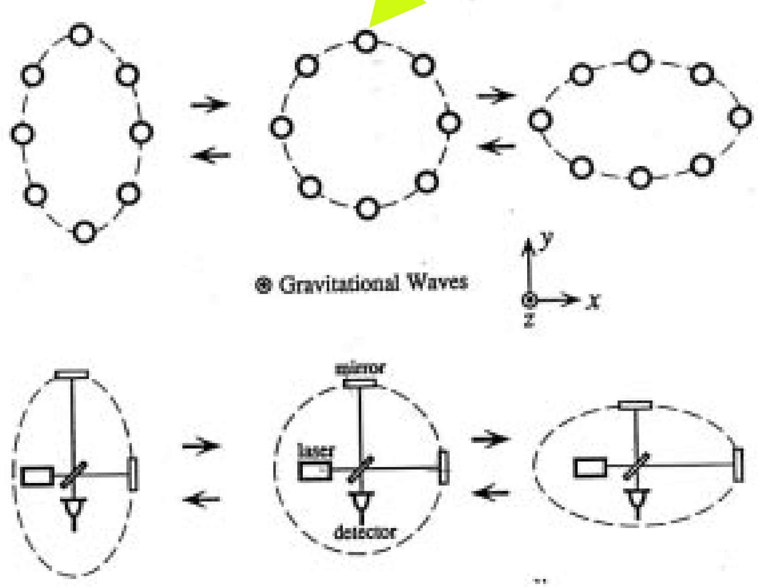
If the man was 4.5 light years high, he would grow by only a 'hairs width' LIGO (4 km), stretch (squash) = 10^{-18} m will be detected at frequencies of 10 Hz to 10^4 Hz. It can detect waves from a distance of 600 10^6 light years

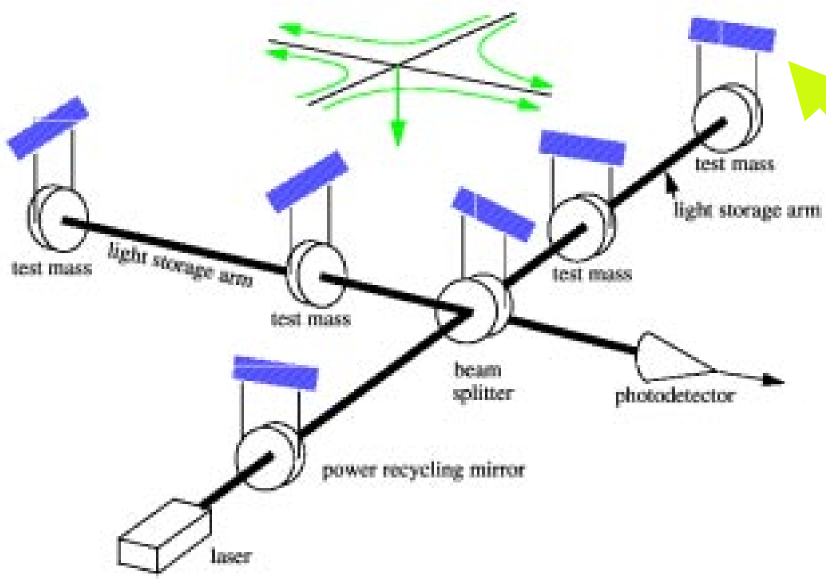
LIGO

Interferometers
terrestrial

free masses

International network (LIGO, Virgo, GEO, TAMA, AIGO) of suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

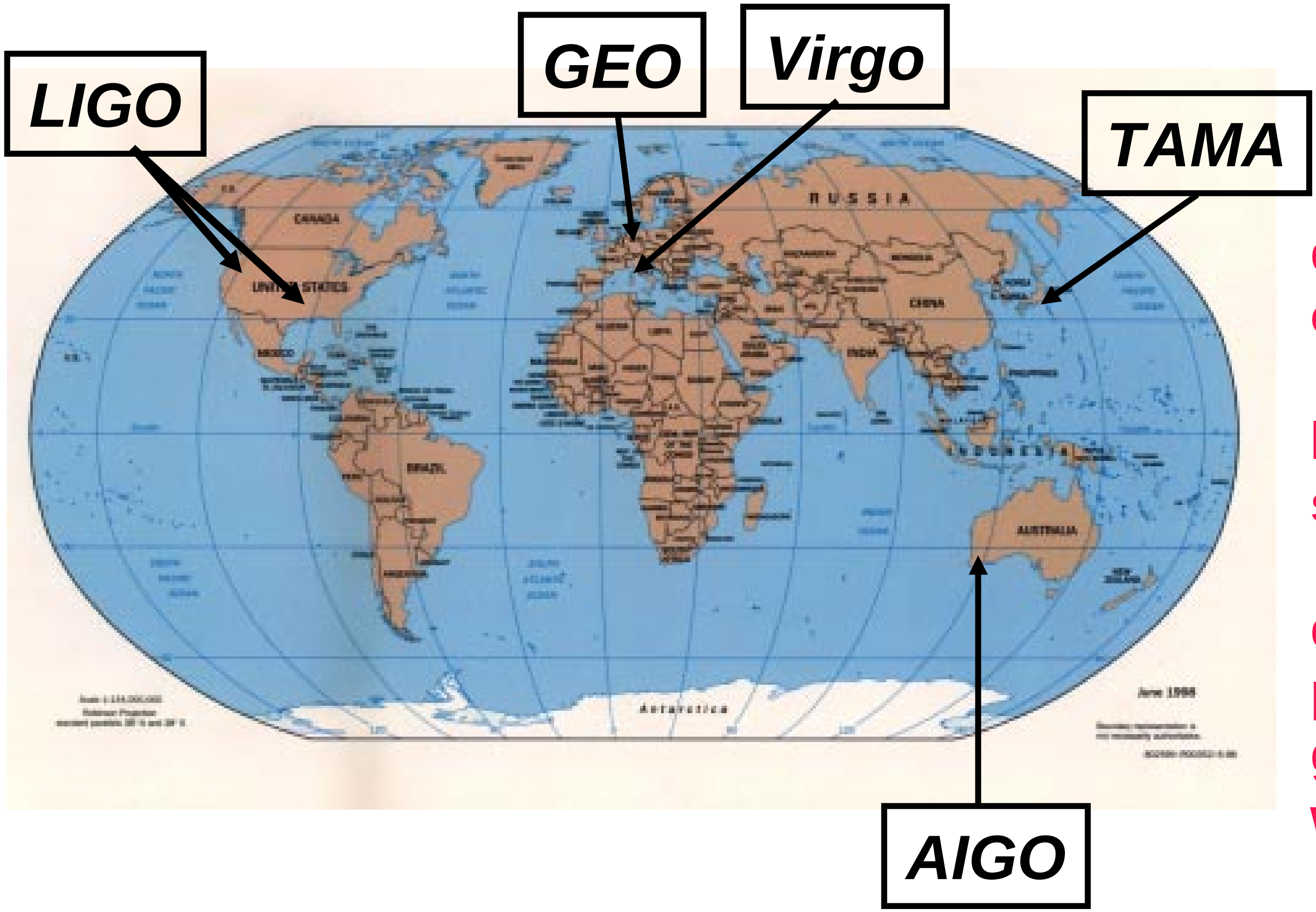




suspended test masses

Interferometers
international network

Simultaneously detect signal (within msec)

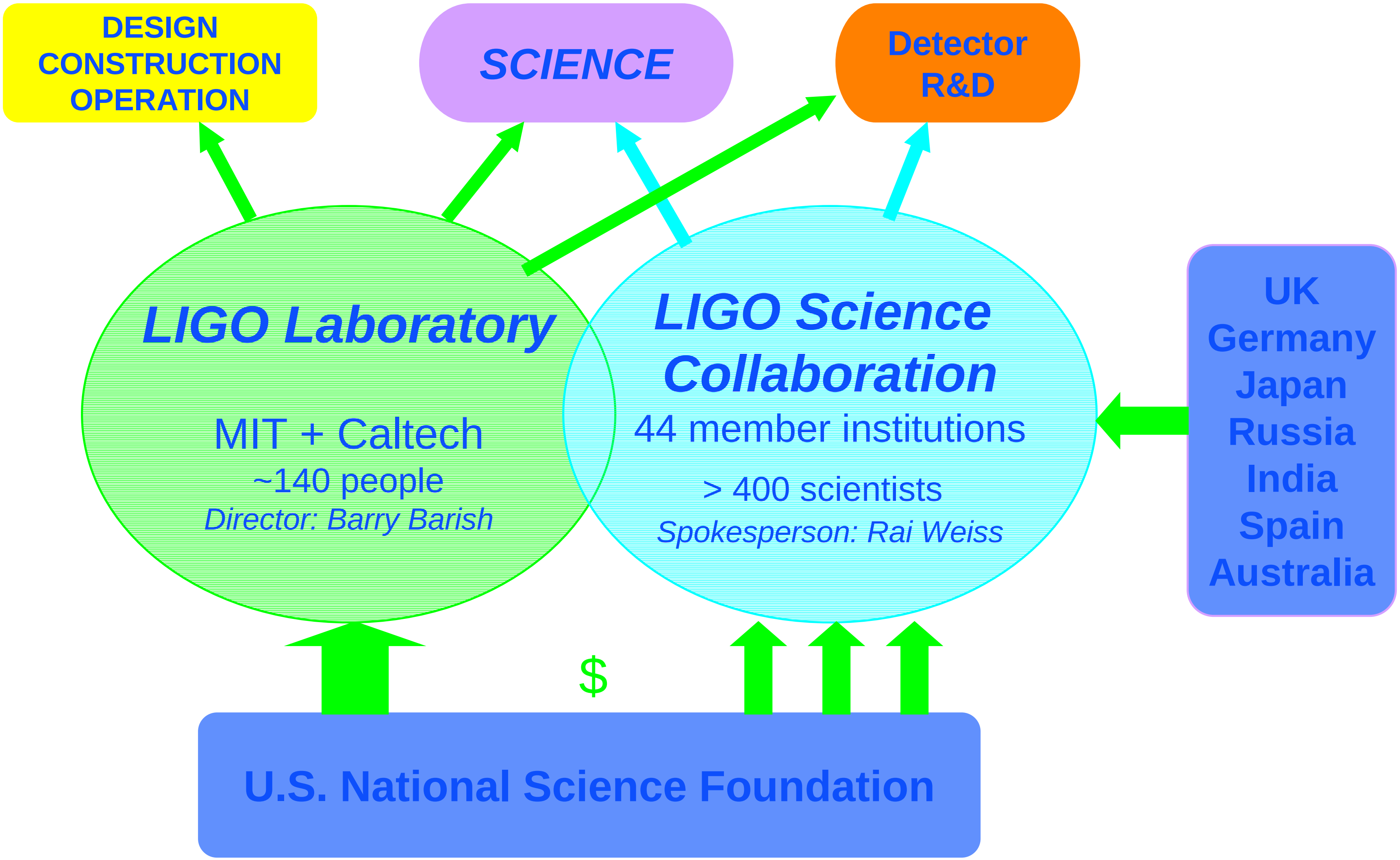


detection confidence

locate the sources

decompose the polarization of gravitational waves

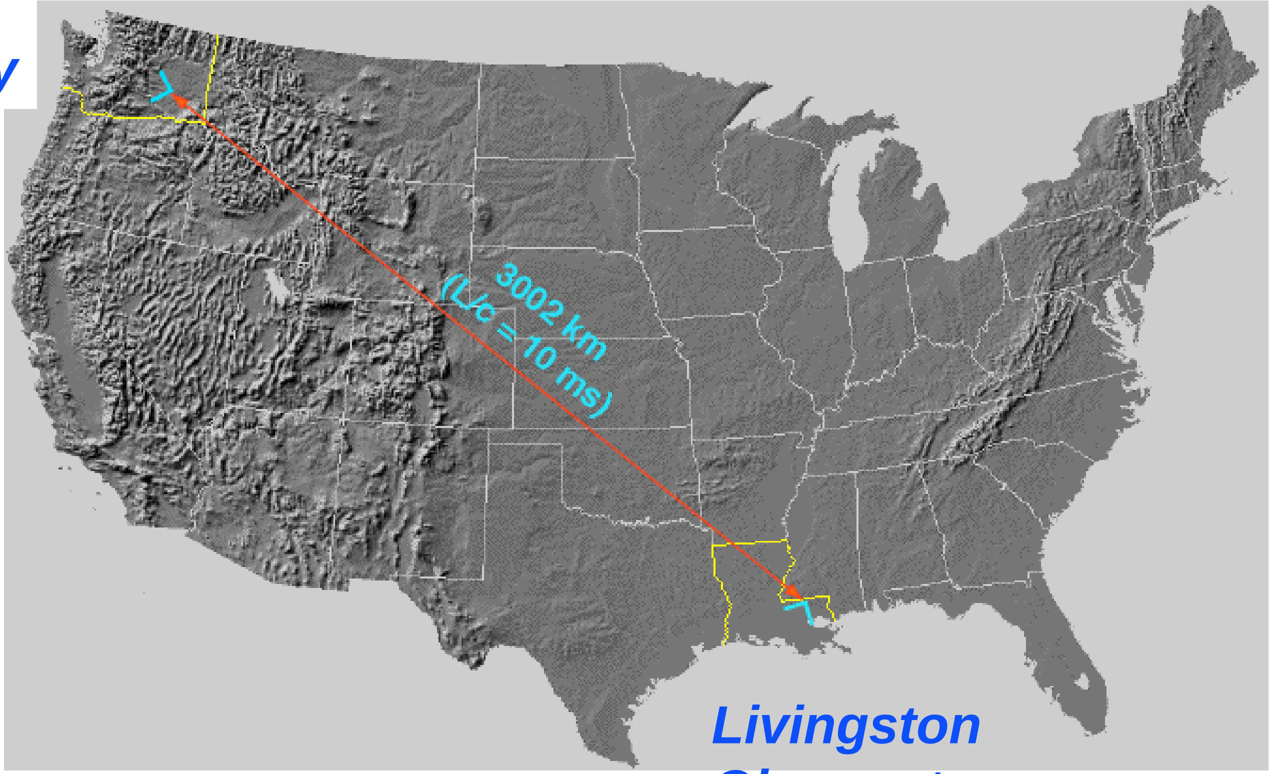
LIGO Organization & Support



The Laboratory Sites

<u>*Laser Interferometer Gravitational-wave Observatory*</u> *(LIGO)*

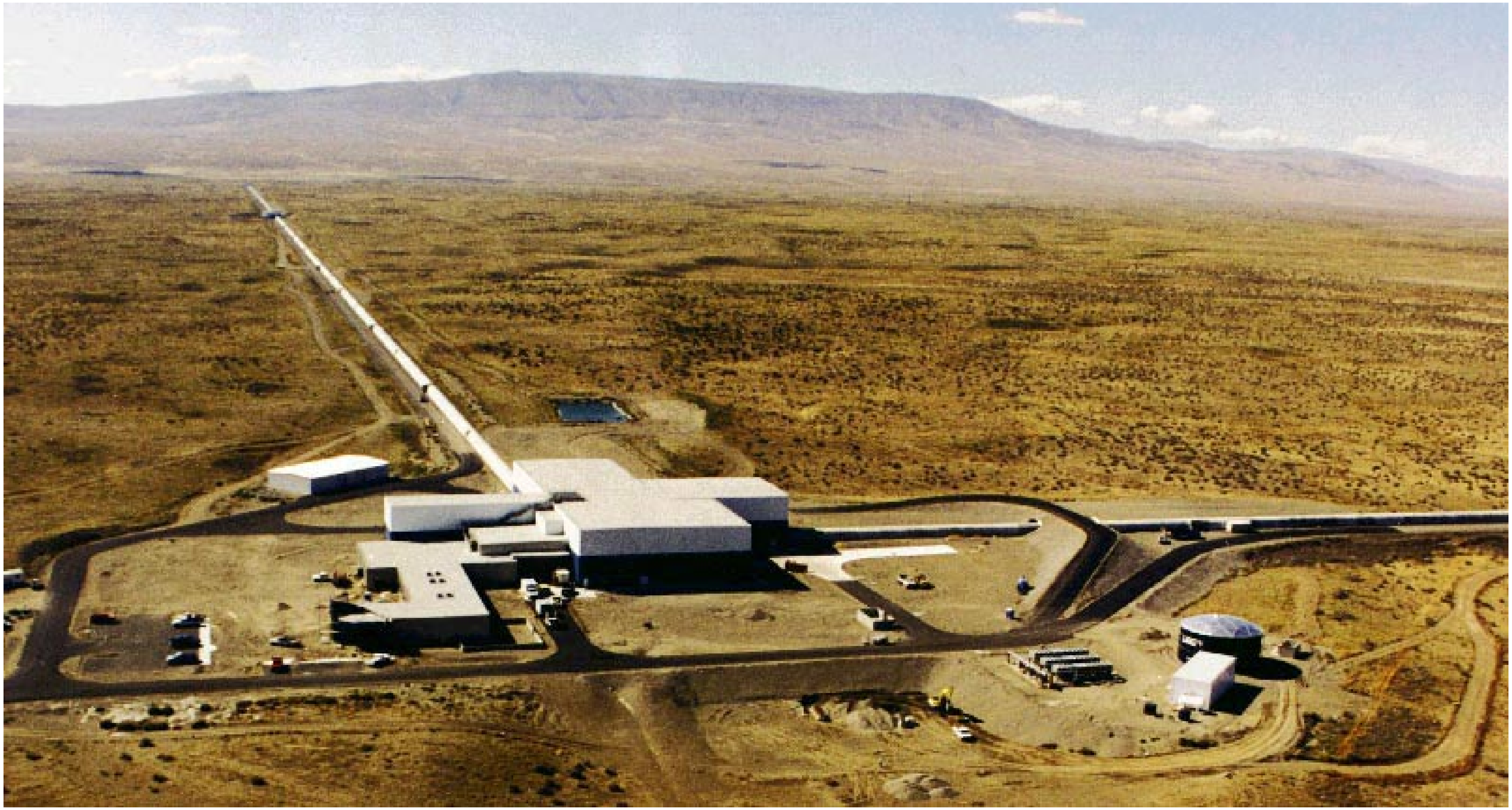
Hanford Observatory



Livingston Observatory

LIGO
Livingston Observatory

LIGO
Hanford Observatory



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

LIGO Optic

Substrates: SiO_2

25 cm Diameter, 10 cm thick

Homogeneity < 5 x 10^{-7}

Internal mode Q's > 2 x 10^{6}

Polishing

Surface uniformity < 1 nm rms

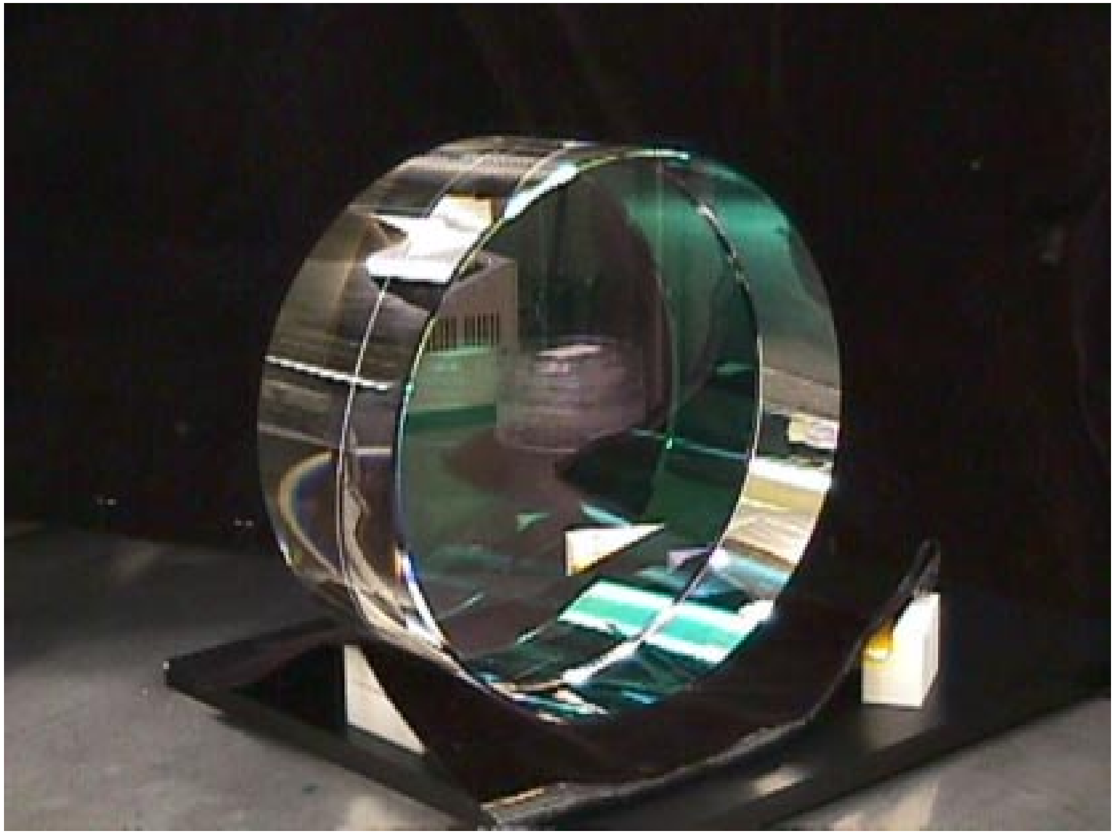
Radii of curvature matched < 3%

Coating

Scatter < 50 ppm

Absorption < 2 ppm

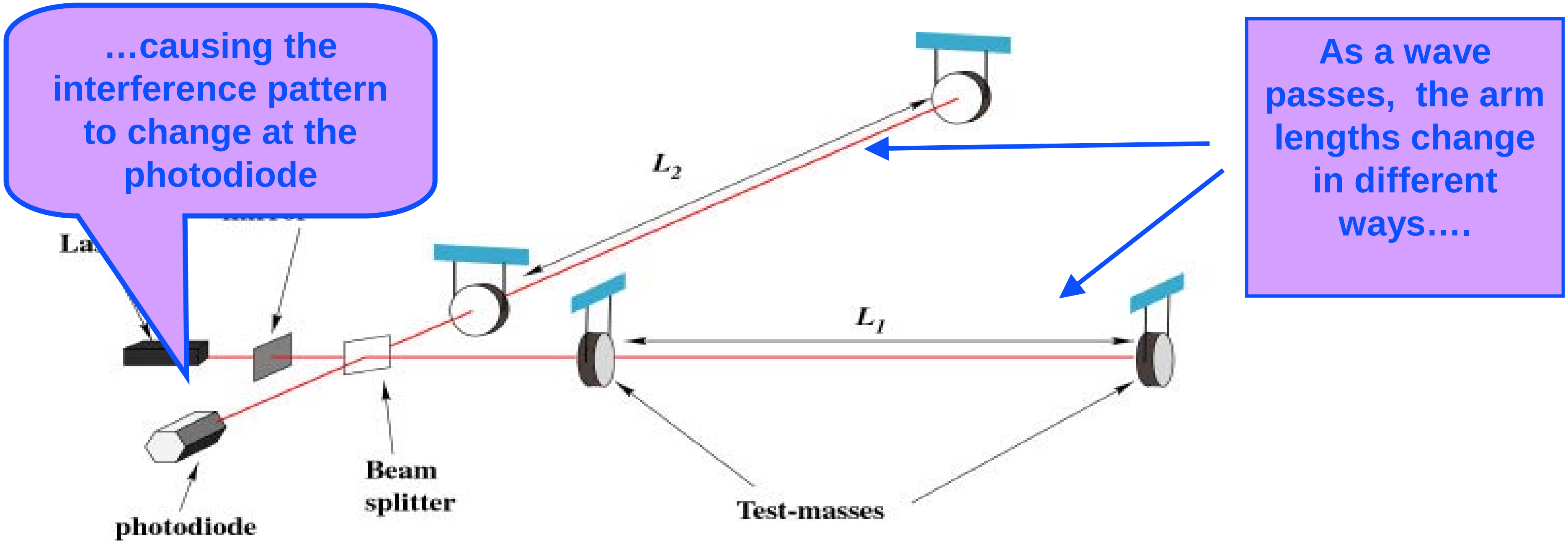
Uniformity <10^{-3}



Core Optics
installation and alignment

Suspended Mass Interferometer
the concept

- **An interferometric gravitational wave detector**
  - » **A laser is used to measure the relative lengths of two orthogonal cavities (or arms)**
- **Arms in LIGO are 4km**
  - » **Current technology then allows one to measure $h = \delta L/L \sim 10^{-21}$ which turns out to be an interesting target**



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*

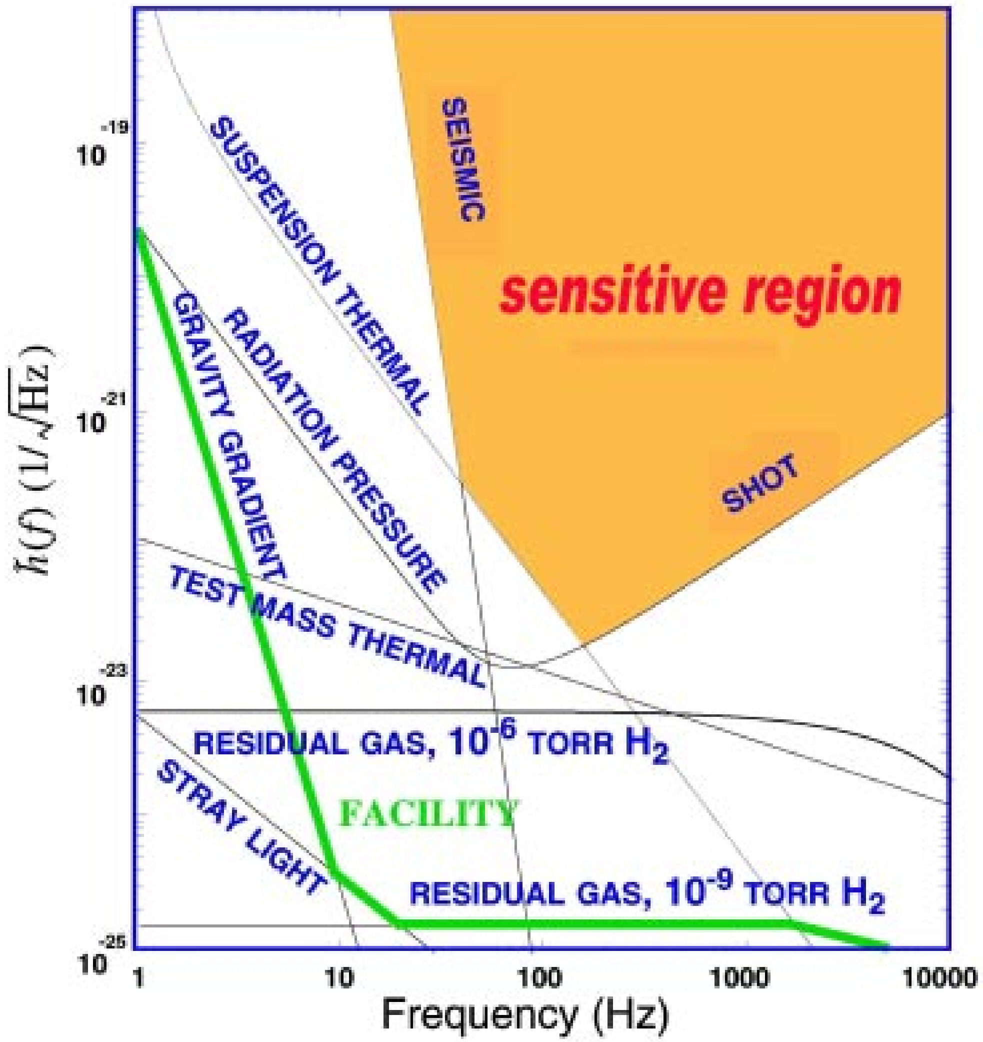
÷10,000 — *Atomic diameter, 10^{-10} meter*

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

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

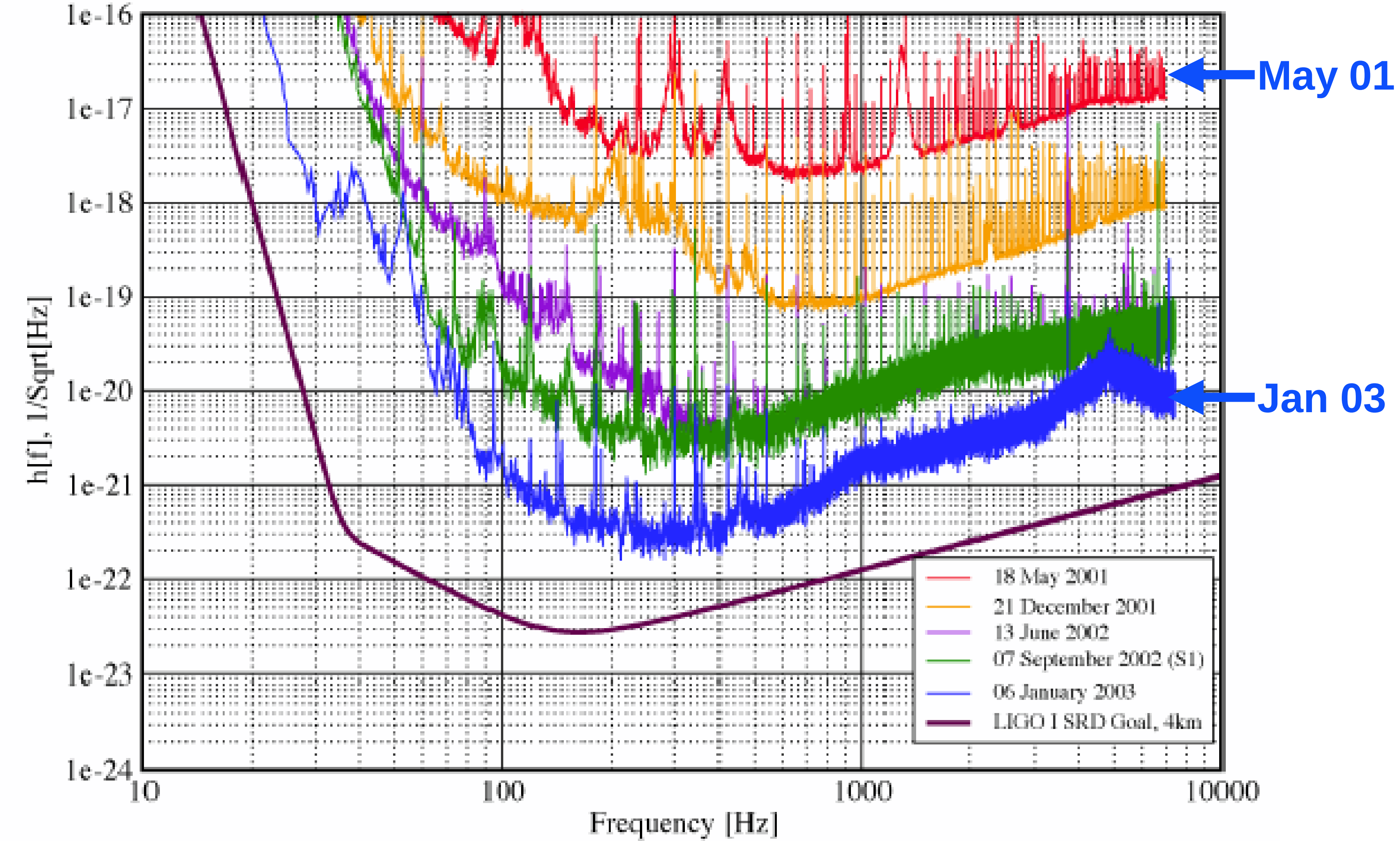
What Limits Sensitivity of Interferometers?

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



LIGO Sensitivity

Livingston 4km Interferometer



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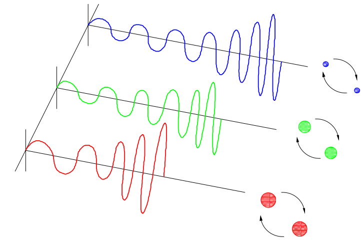

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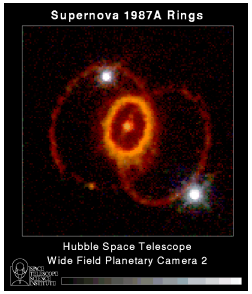

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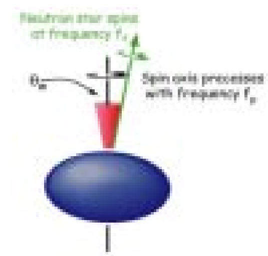

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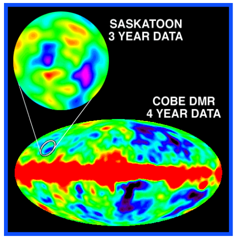
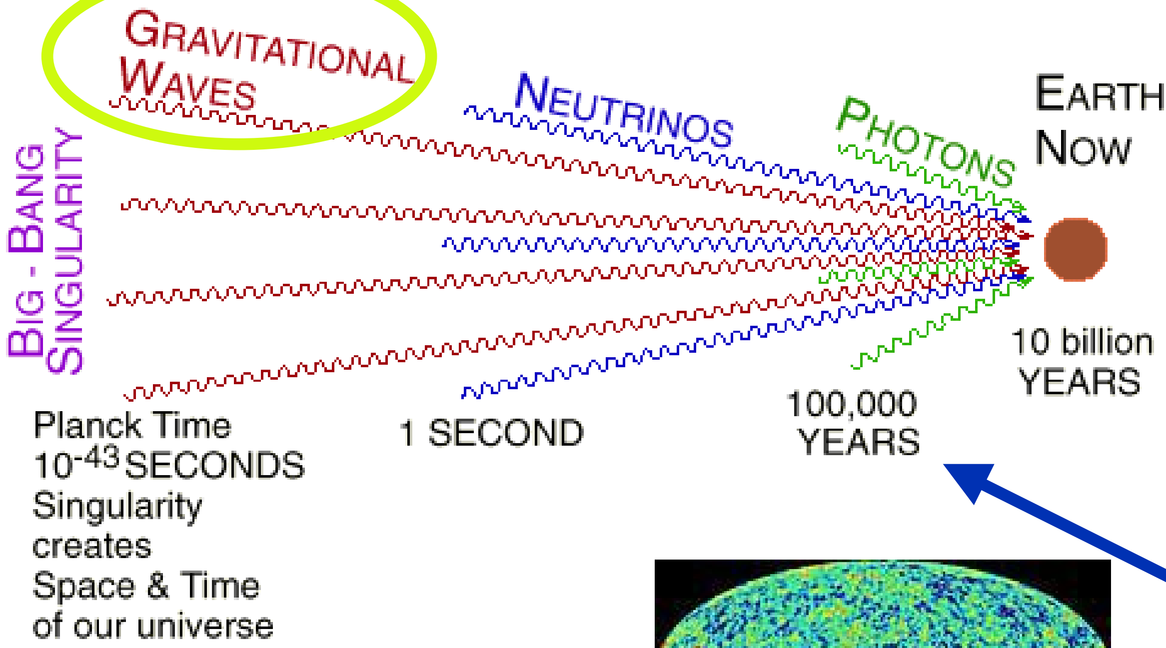


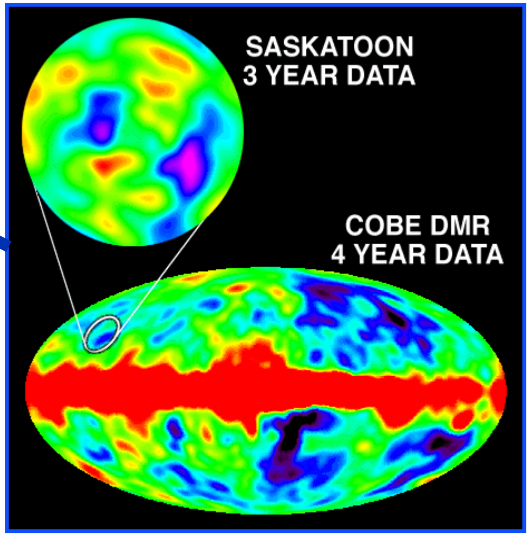
“Stochastic Background”
cosmological signals

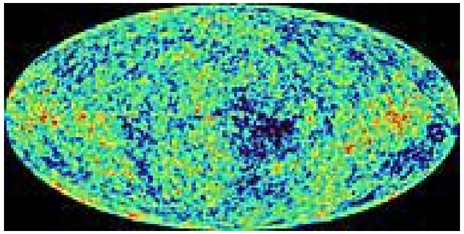
'Murmurs' from the Big Bang

signals from the early universe



Cosmic microwave background





WMAP 2003

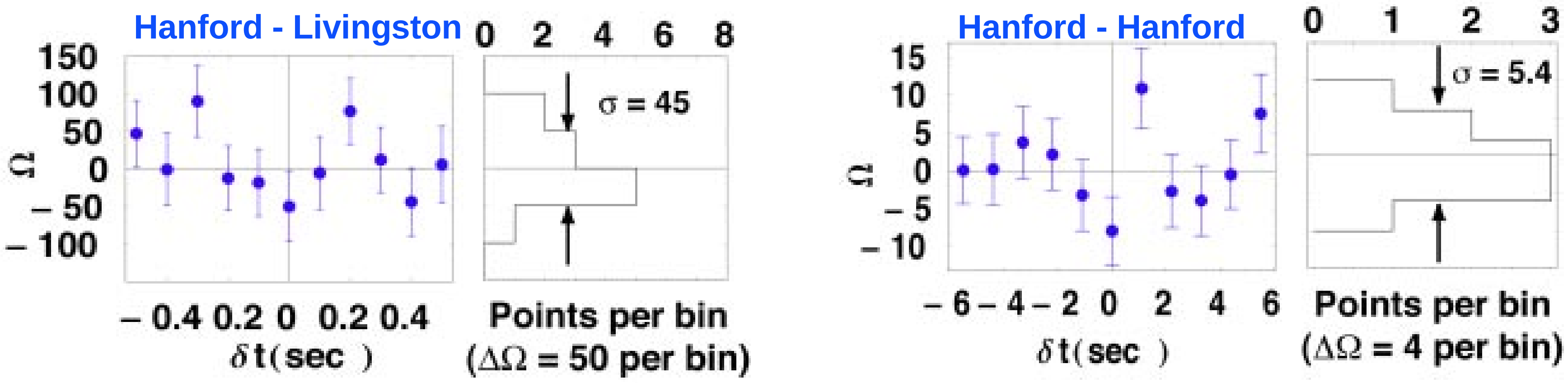
Stochastic Background
no observed correlations

- **Strength specified by *ratio of energy density in GWs to total energy density* needed to close the universe:**

$$\Omega_{GW}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{GW}}{d(\ln f)}$$

- **Detect by *cross-correlating* output of two GW detectors:**

First LIGO Science Data (Lazzarini)



Preliminary limits from 7.5 hr of data

Stochastic Background
results and projections

Best Previously Published Limits

» Garching-Glasgow interferometers (1994): $\Omega_{GW}(f) \leq 3\times10^{5}$

» EXPLORER-NAUTILUS resonant bars (1999): $\Omega_{GW}(f) \leq 60$

LIGO Initial Results

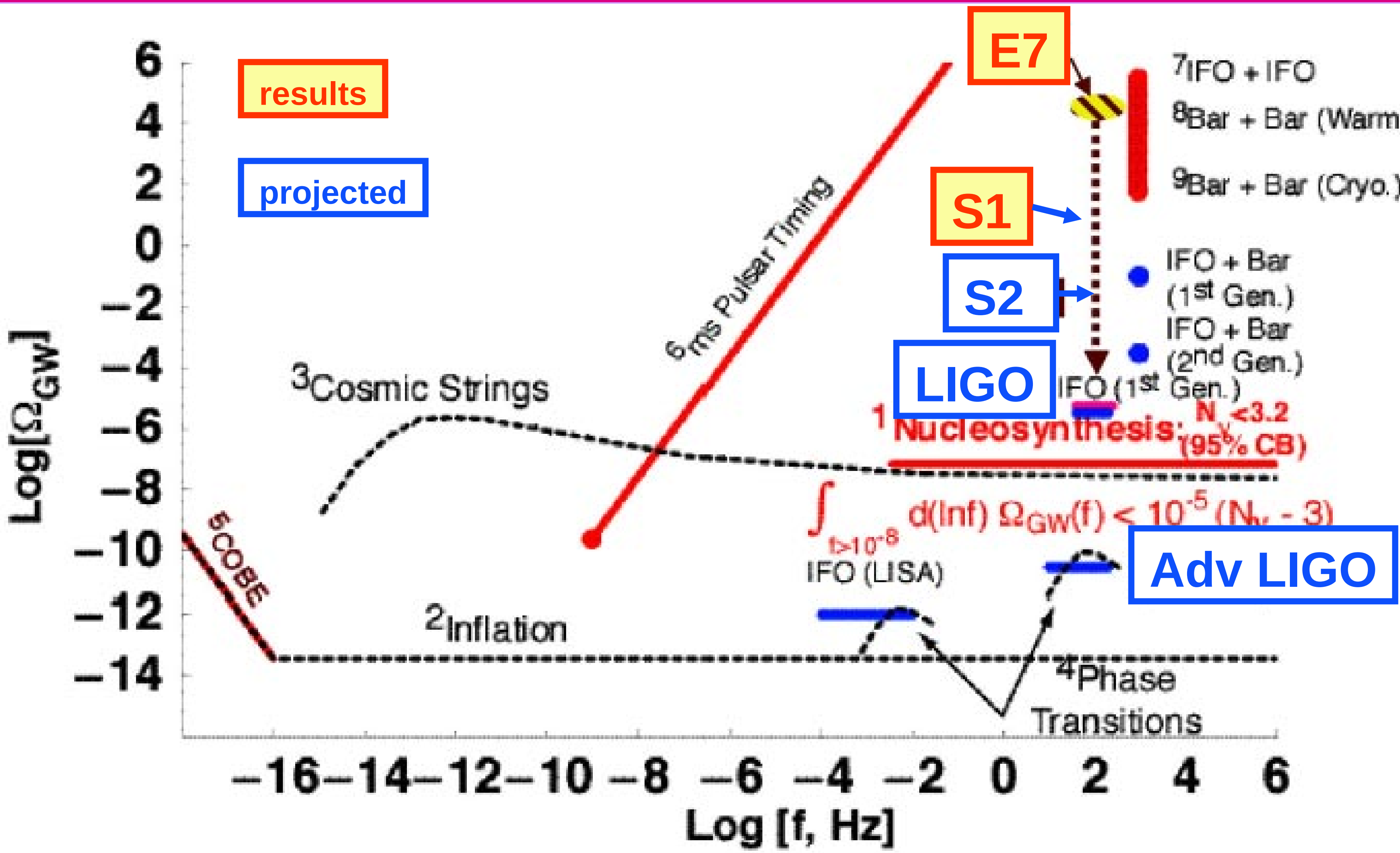
- Test data (Dec 01) $\Omega_{GW}(f) \leq 50$
- First data (Sept 02) NEW RESULT – Lazzarini $\Omega_{GW}(f) \leq 5$

LIGO Projections

- Second data run (underway) - Projected $\Omega_{GW}(f) \leq 3\times10^{-3}$
- Initial LIGO sensitivity - Projected $\Omega_{GW}(f) \leq 10^{-5}$
- Advanced LIGO sensitivity - Projected $\Omega_{GW}(f) \leq 5\times10^{-9}$

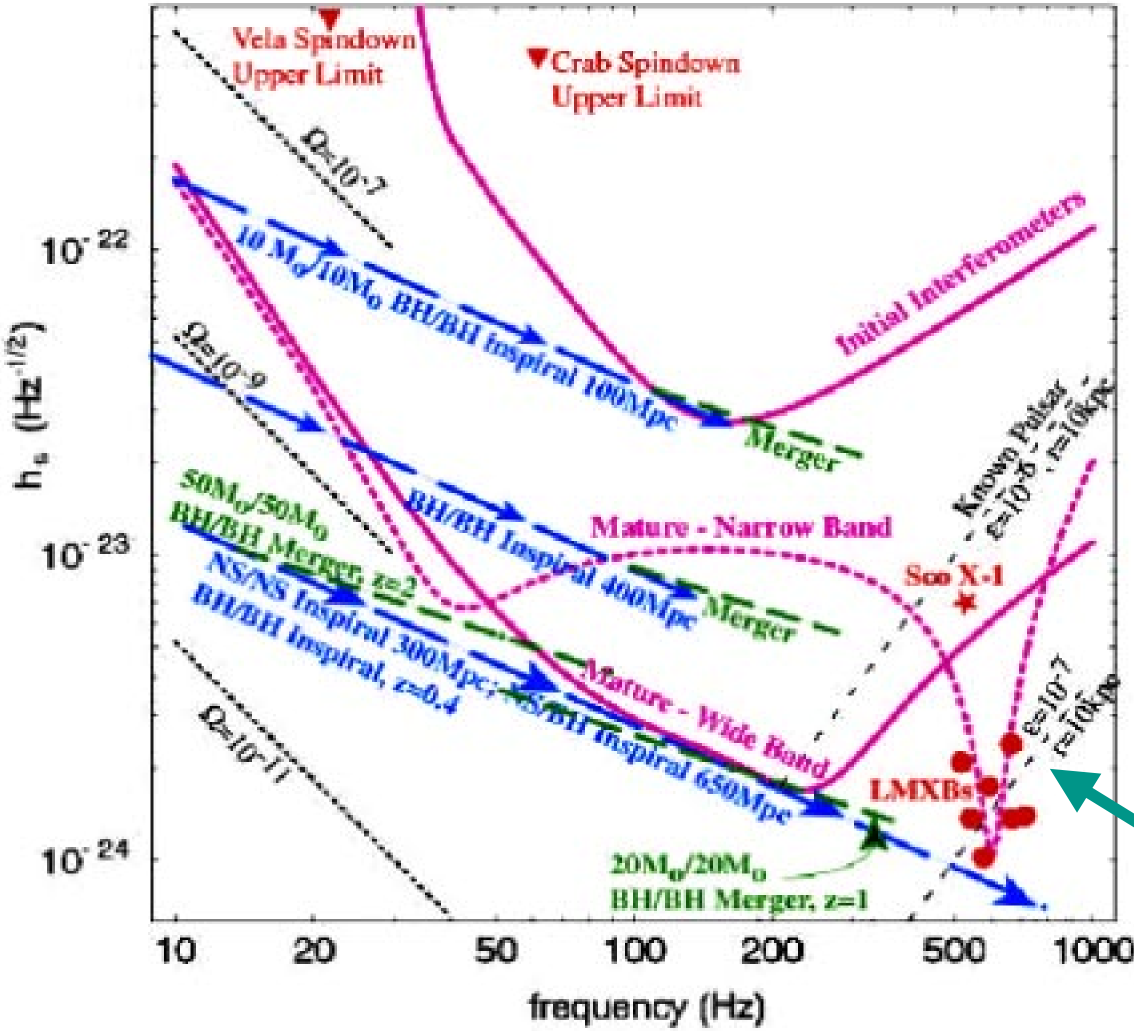
Stochastic Background

sensitivities and theory



Advanced LIGO

2007 +



Enhanced Systems

- **laser**
- **suspension**
- **seismic isolation**
- **test mass**

Improvement factor in rate
~ 10^4

+

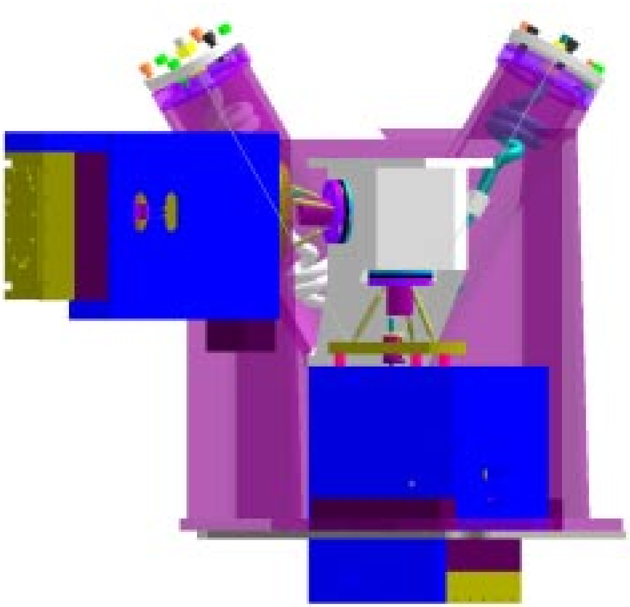
narrow band optical configuration

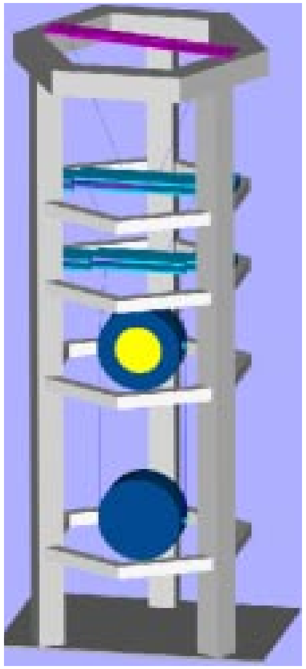
Advanced LIGO

improved subsystems

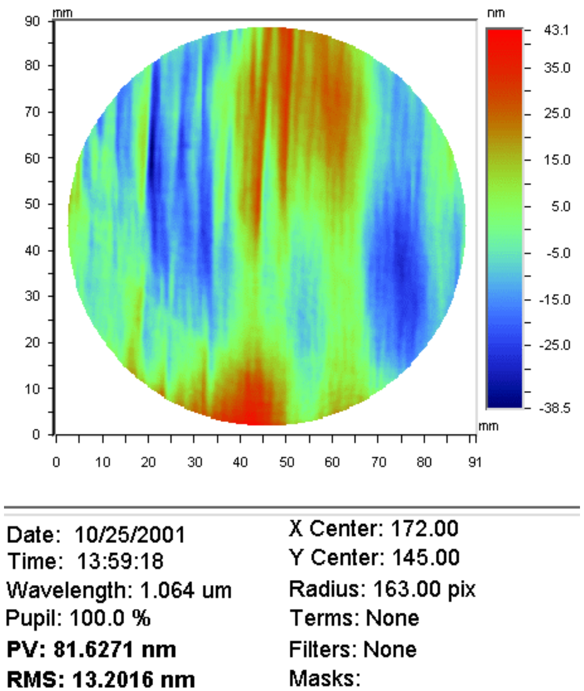
Multiple Suspensions

Active Seismic





Sapphire Optics



Higher Power Laser

Conclusions

- LIGO commissioning is well underway
  - » Good progress toward design sensitivity (Weiss)
- Science Running is beginning
  - » Initial results from our first LIGO data run (Lazzarini)
- Our Plan
  - » Improved data run is underway
  - » Our goal is to obtain one year of integrated data at design sensitivity before the end of 2006
  - » Advanced interferometer with dramatically improved sensitivity – 2007+ (Shoemaker)
- LIGO should be detecting gravitational waves within the next decade !