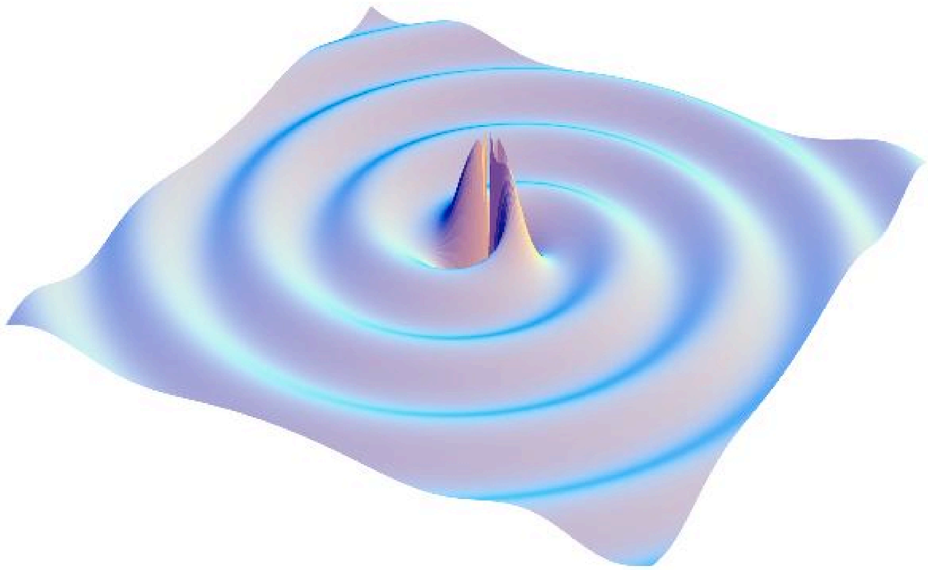
LIGO and the search for gravitational waves



Peter Beyersdorf
San José State University

Physics Seminar
October 12, 2005

The LIGO Scientific Collaboration

Washington State University

UTB TSC

University of Florida

GEO 600

Universitat de les Illes Balears

LSU

Southern University and Agricultural & Mechanical College

California Institute of Technology 1891

The University of Adelaide Australia

University of Wisconsin UW Milwaukee

Cardiff University

Southeastern Louisiana University

Cornell University

NAOJ 国立天文台

SKC

Hobart and William Smith College

Carleton

Loyola University New Orleans

Universität Hannover

Syracuse University Founded AD 1870

Michigan

Leland Stanford Junior University Organized 1891

Northwestern University

PAH

PennState 1855

The University of Western Australia

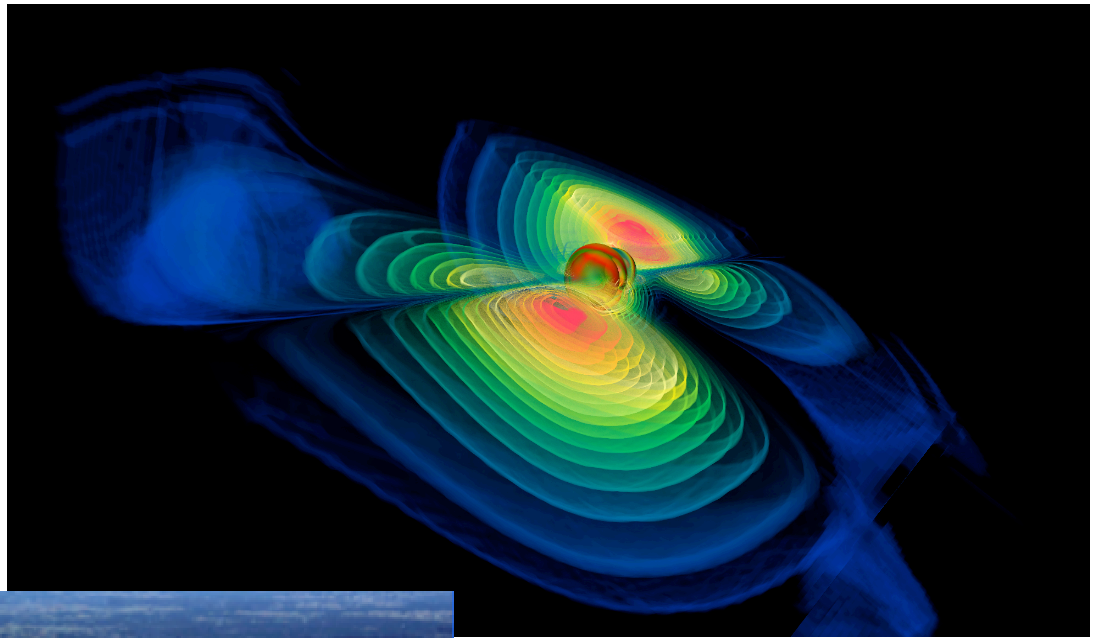
IGR

Massachusetts Institute of Technology

University of Glasgow

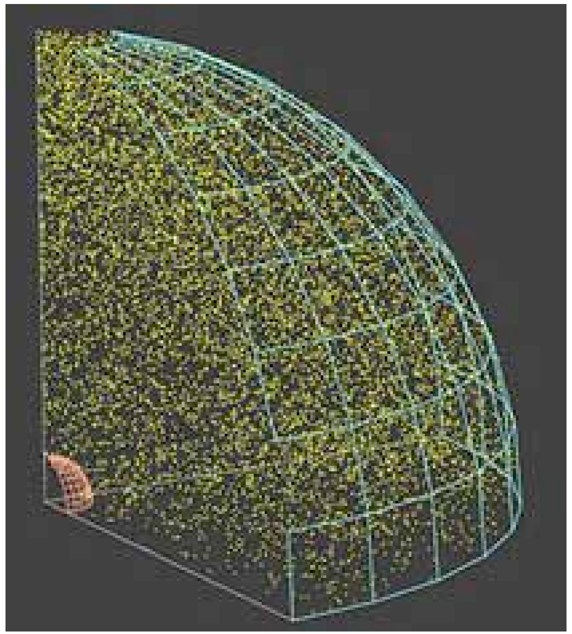
LIGO and the search for gravitational waves

- Gravity and gravitational waves in General Relativity
- LIGO, the Laser Interferometric Gravitational-Wave Observatory
  - Technical challenges
  - Scientific results
- Future direction of gravitational wave astronomy



"Colliding Black Holes"

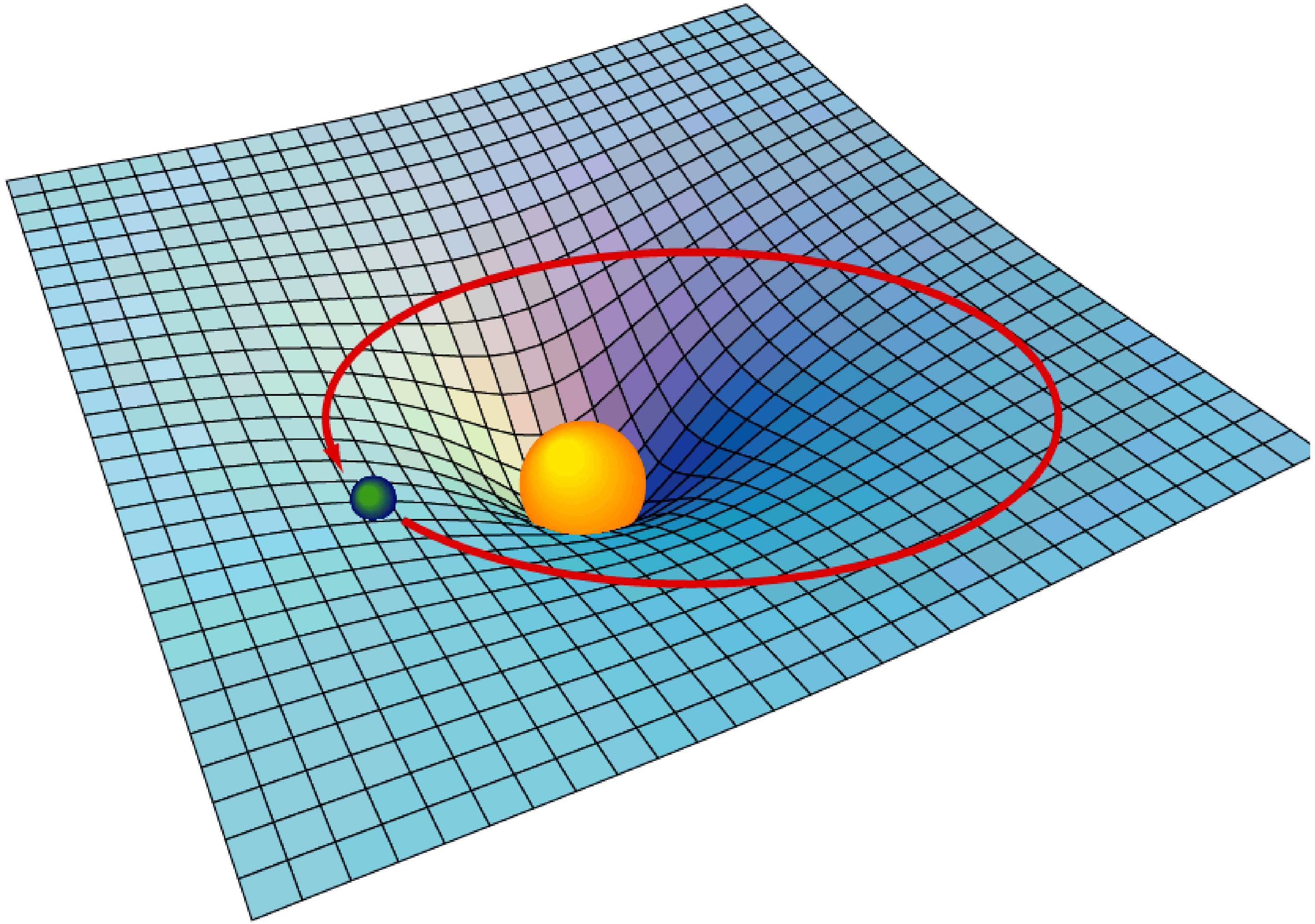
Credit:
National Center for Supercomputing Applications (NCSA)



Gravity and gravitational waves in General Relativity

General Relativity

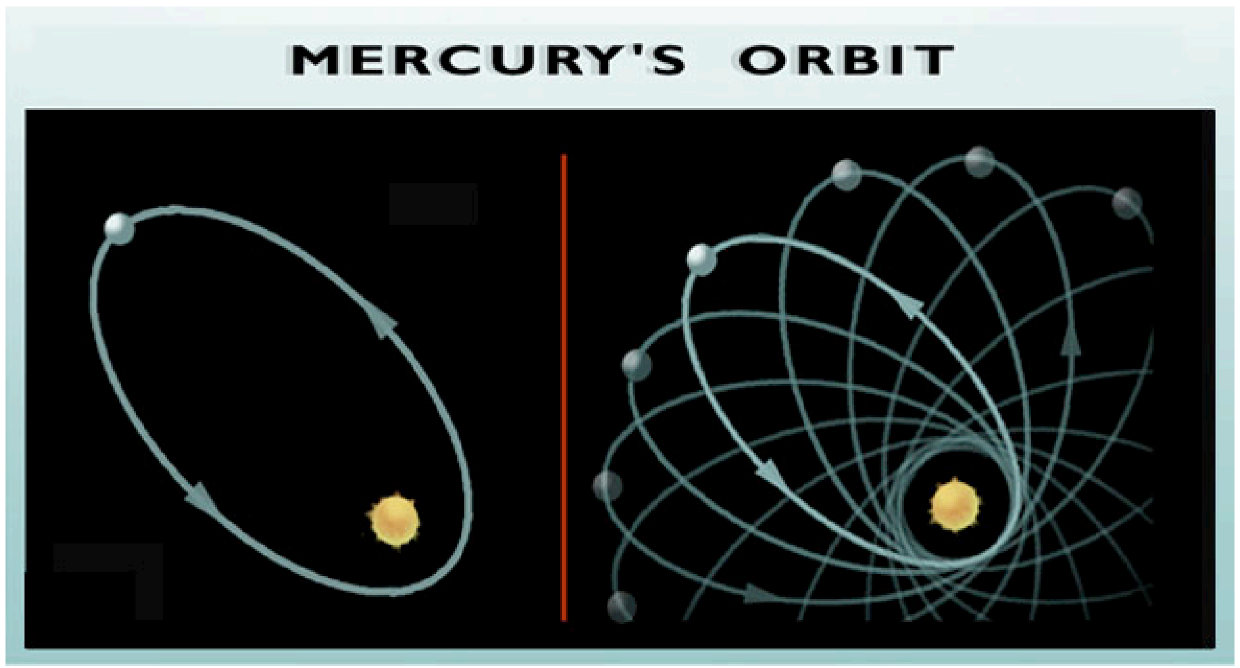
Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object



- 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.

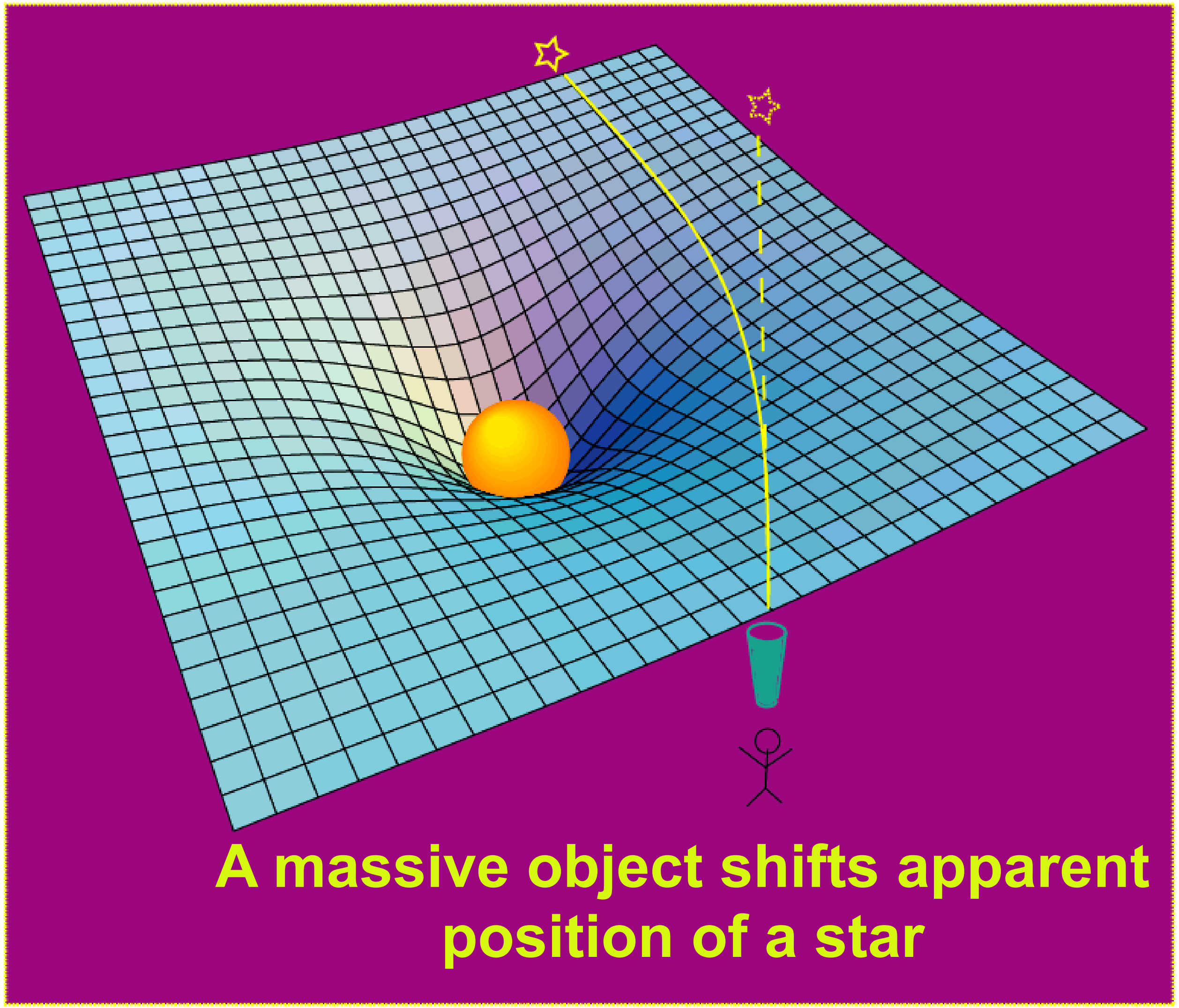
New Wrinkle on Equivalence

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

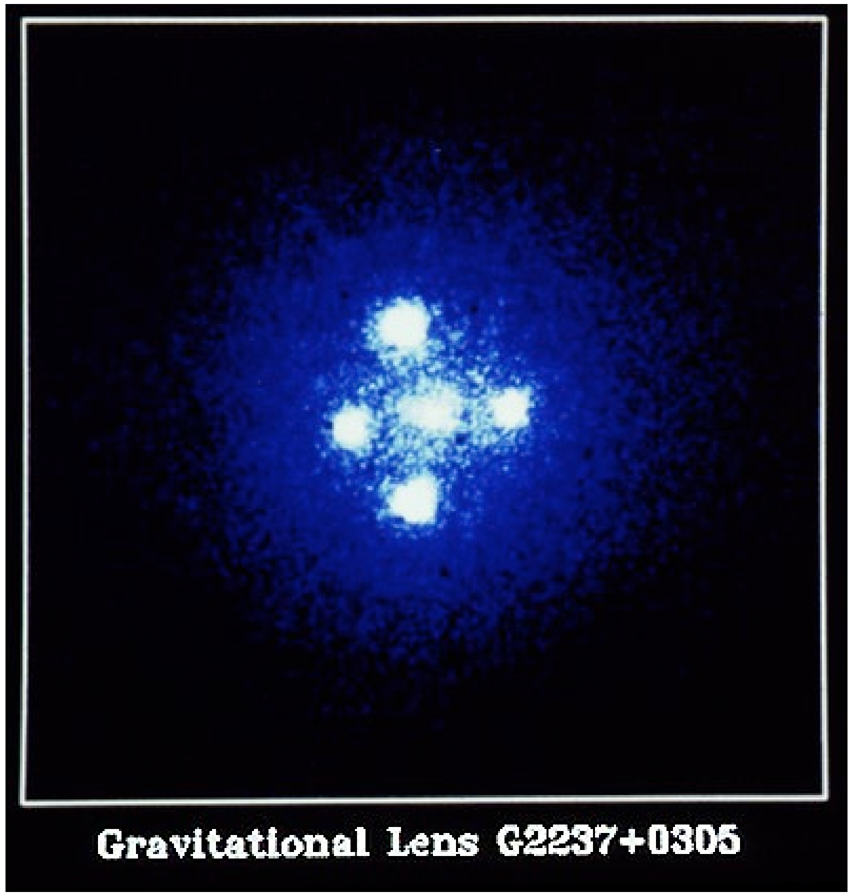
- Their measurements showed that the light from these stars was bent as it grazed the Sun, by the exact amount of Einstein's predictions.



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.

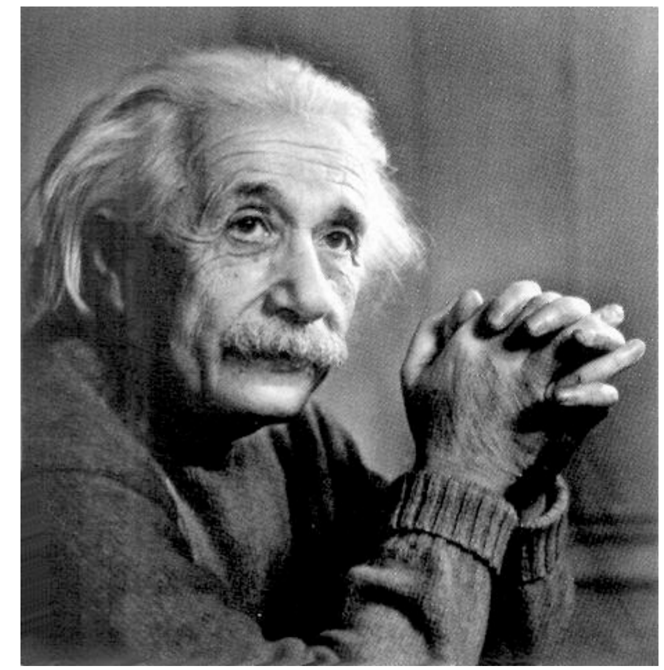
In modern astronomy, such gravitational lensing images are used to detect a 'dark matter' body as the central object

Einstein's Theory of Gravitation

Newton's Theory

"instantaneous action at a distance"

$$\vec{F}_{12} = -G\frac{m_1 m_2}{r_{12}^2}\hat{r}_{12}$$



Einstein's Theory

information carried by gravitational radiation at the speed of light

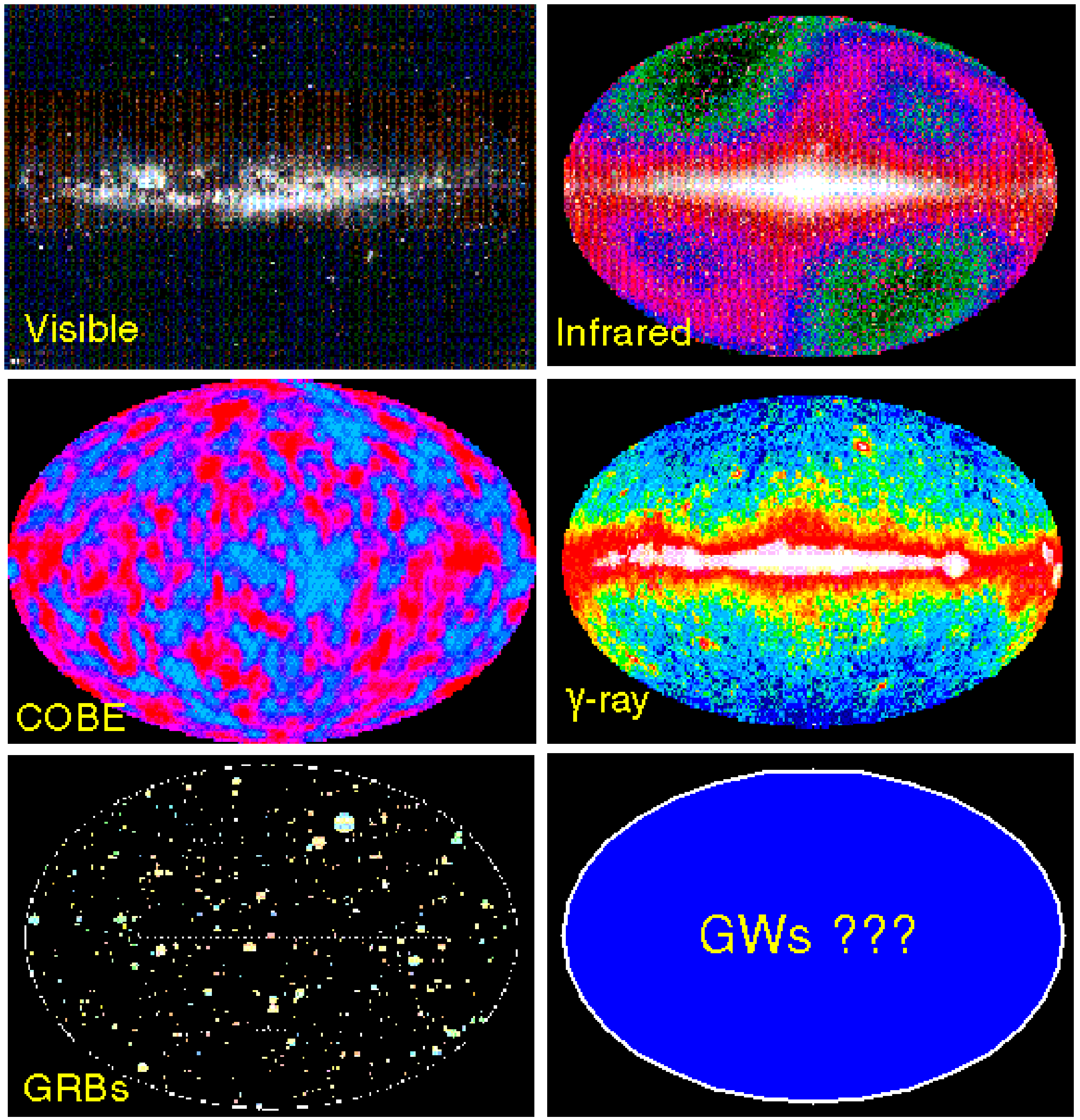
$$\overline{T} = \frac{c^4}{8\pi G}\overline{G}$$

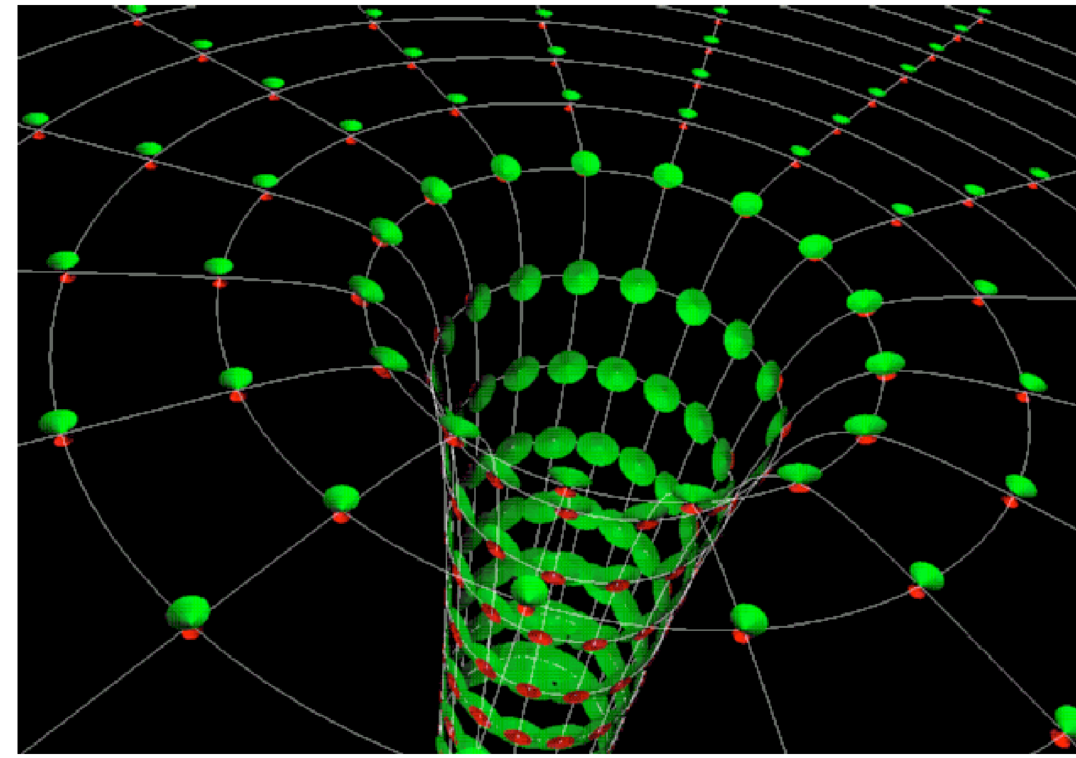
$F=-k\Delta x$ with $k=10^{43}$!

Why look for Gravitational Radiation?

- Because it's there! (presumably)
- Test General Relativity:
  - Travels at speed of light?
  - Unique probe of strong-field gravity
- Gain different view of Universe:
  - Sources cannot be obscured by dust / stellar envelopes
  - Detectable sources some of the most interesting, least understood in the Universe
  - **Opens up entirely new non-electromagnetic spectrum**

A New Window on the Universe





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

Looking at the universe

is like *looking* at a forest

Looking at the universe

is like *looking* at a forest - you miss a lot that can't be seen

Looking at the universe

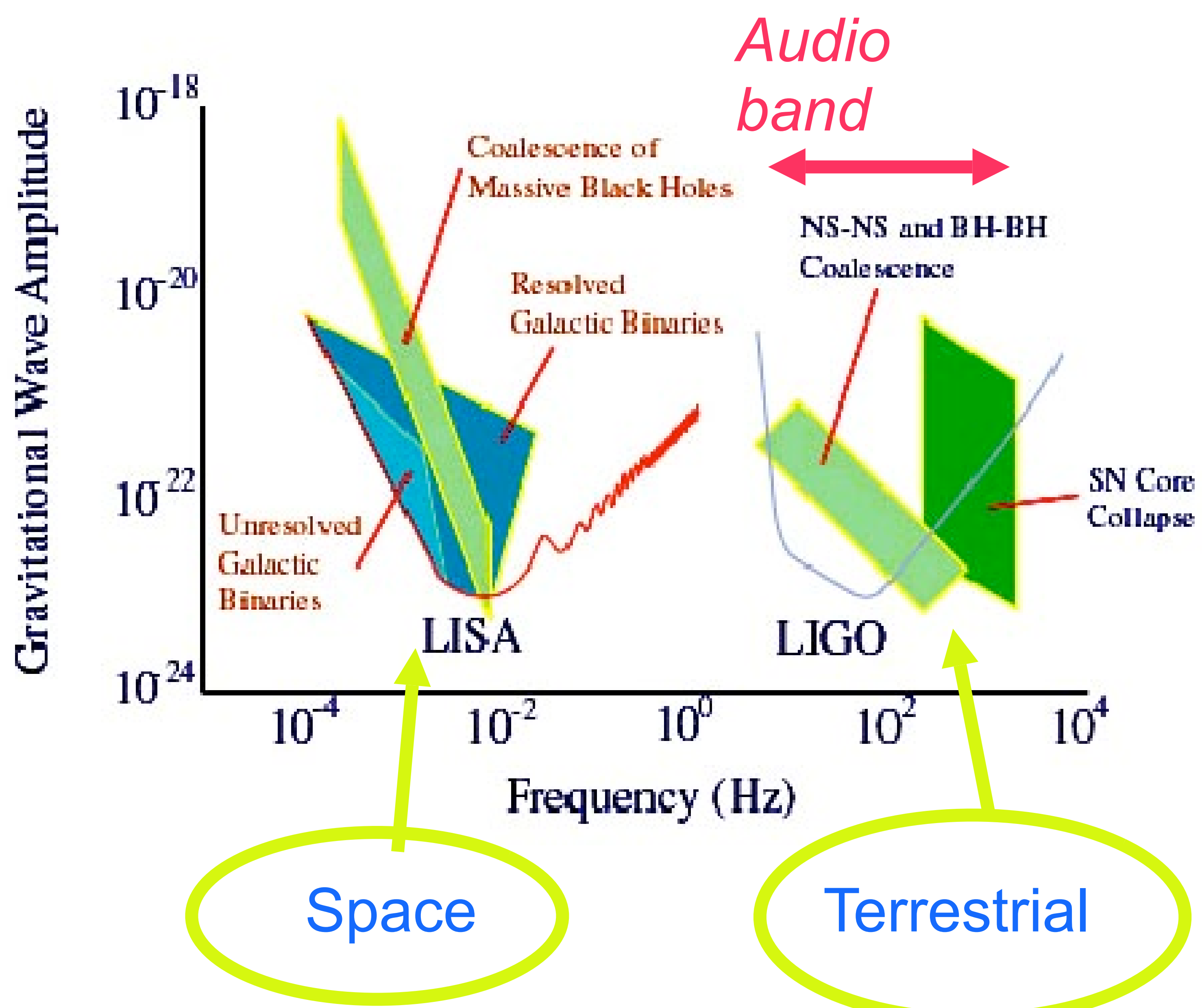
using only *electromagnetic* radiation

Looking *and listening* to the universe

using *gravitational* radiation

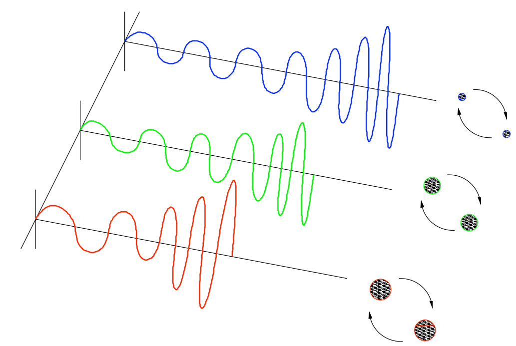
Astrophysics Sources by Frequency

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

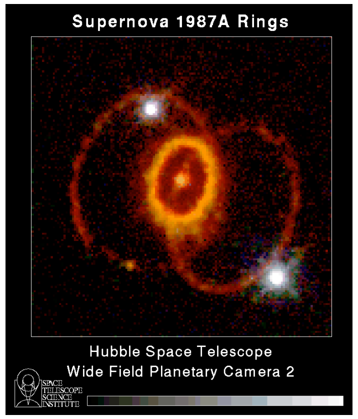


Astrophysical Sources of Gravitational Waves

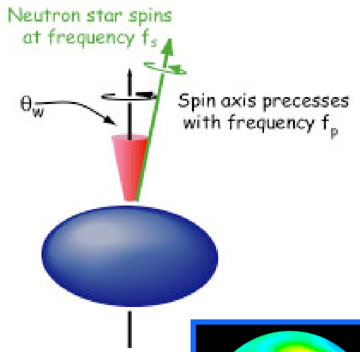
- Compact binary inspiral: *"chirps"*
  - » NS-NS waveforms are well described
  - » BH-BH need better waveforms
  - » search technique: matched templates



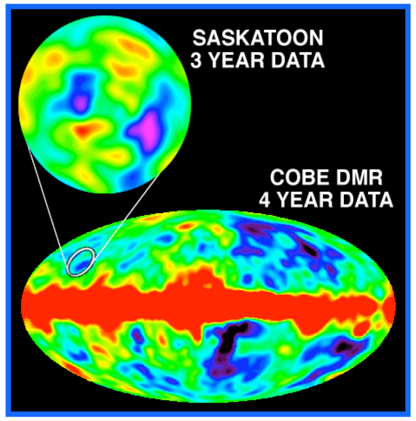
- Supernovae / γ-ray bursts: *"bursts"*
  - » burst signals in coincidence with signals in electromagnetic radiation
  - » Challenge to search for untriggered bursts



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



- Cosmological Signals *"stochastic background"*

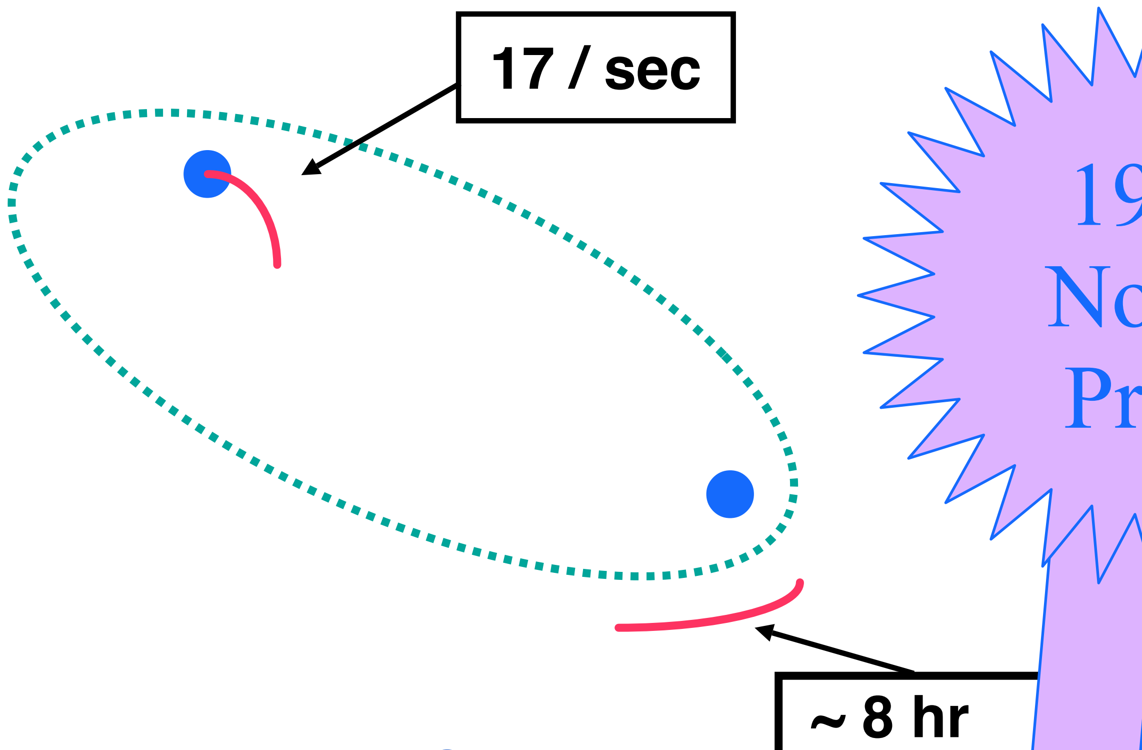


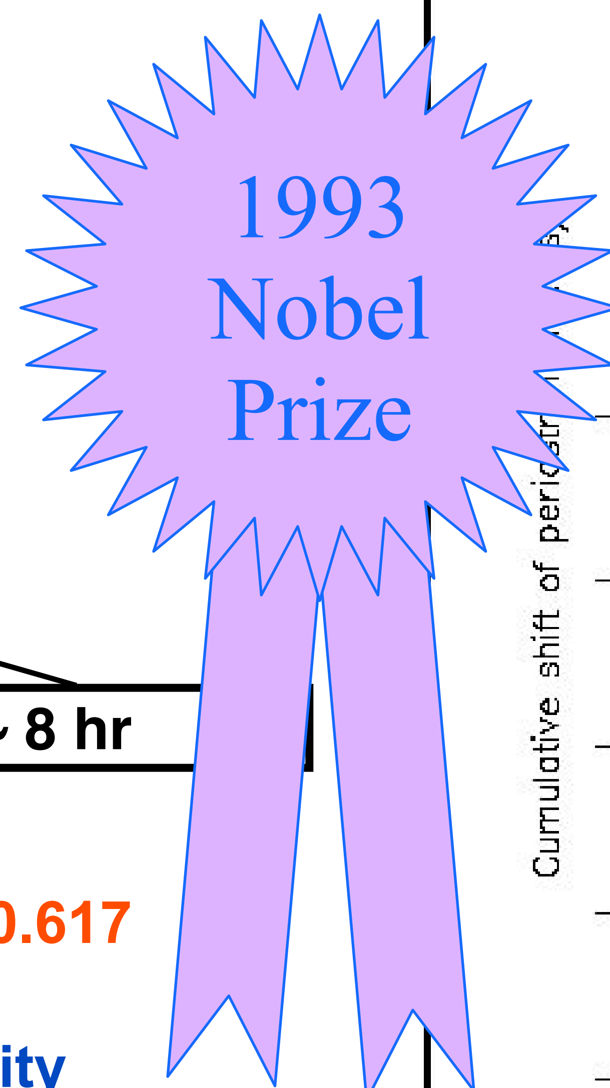
LIGO

Evidence for Gravitational Waves

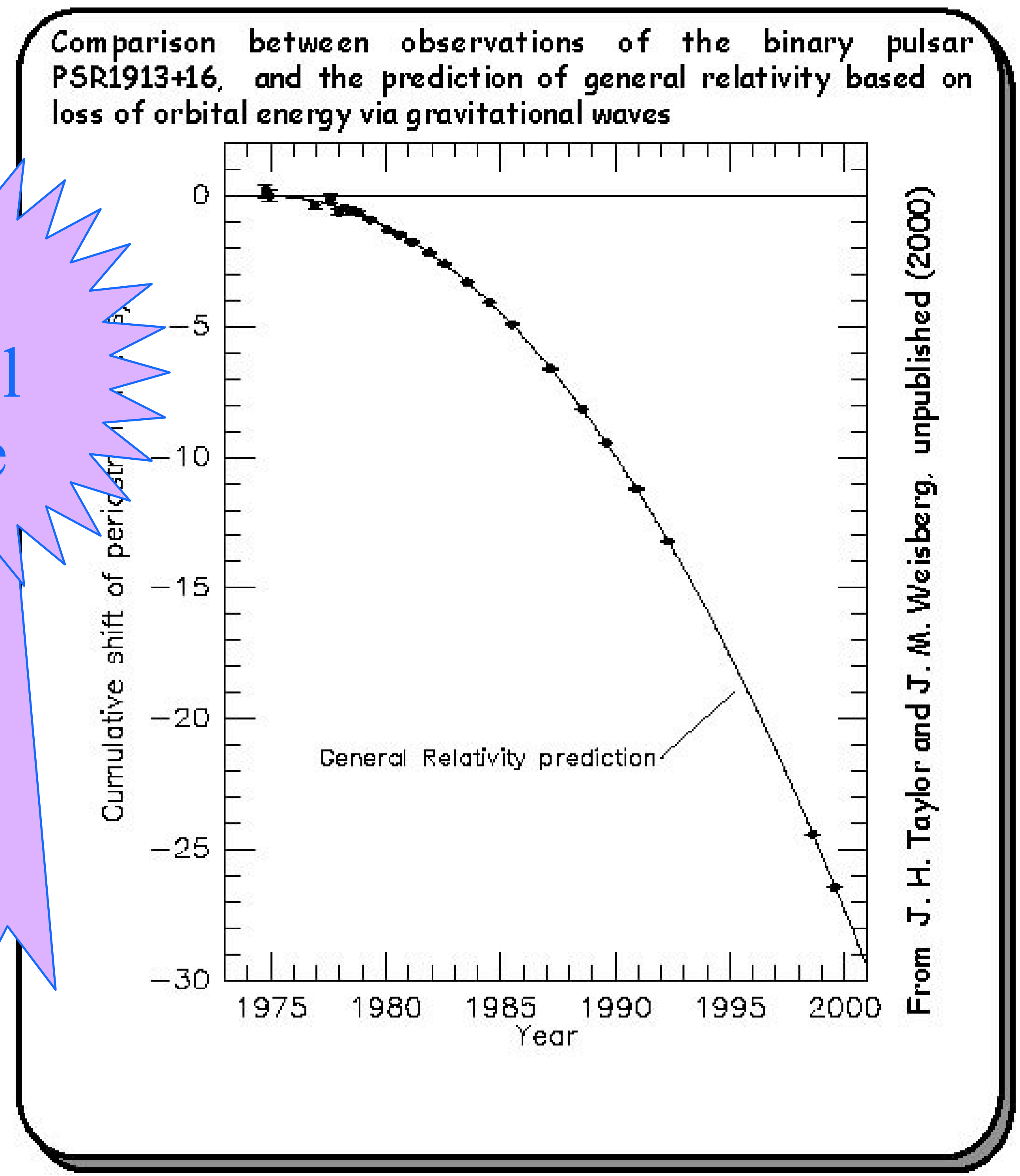
Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars





Emission of gravitational waves



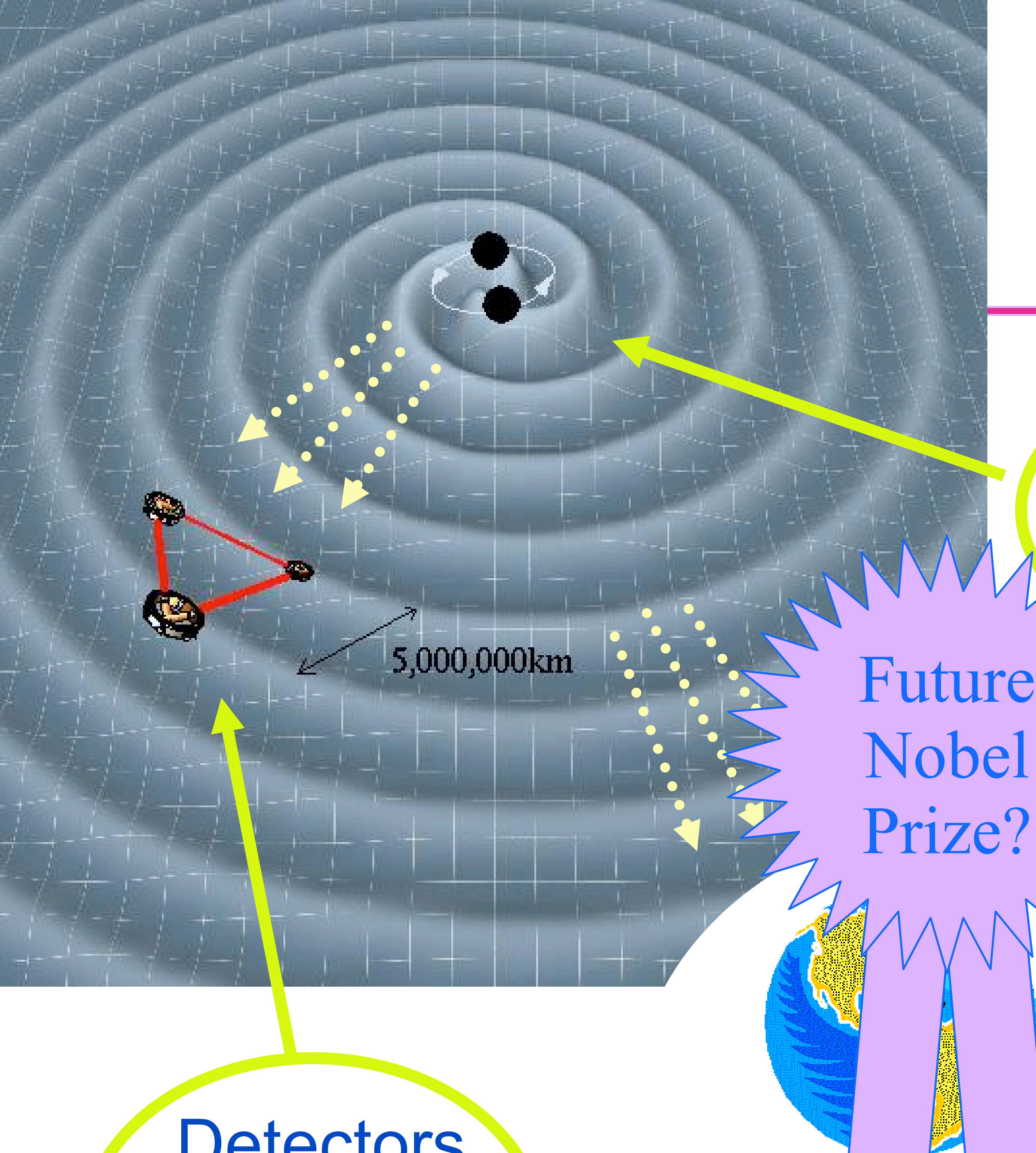
Neutron Binary System

- 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

Direct detection



Gravitational Wave Astrophysical Source

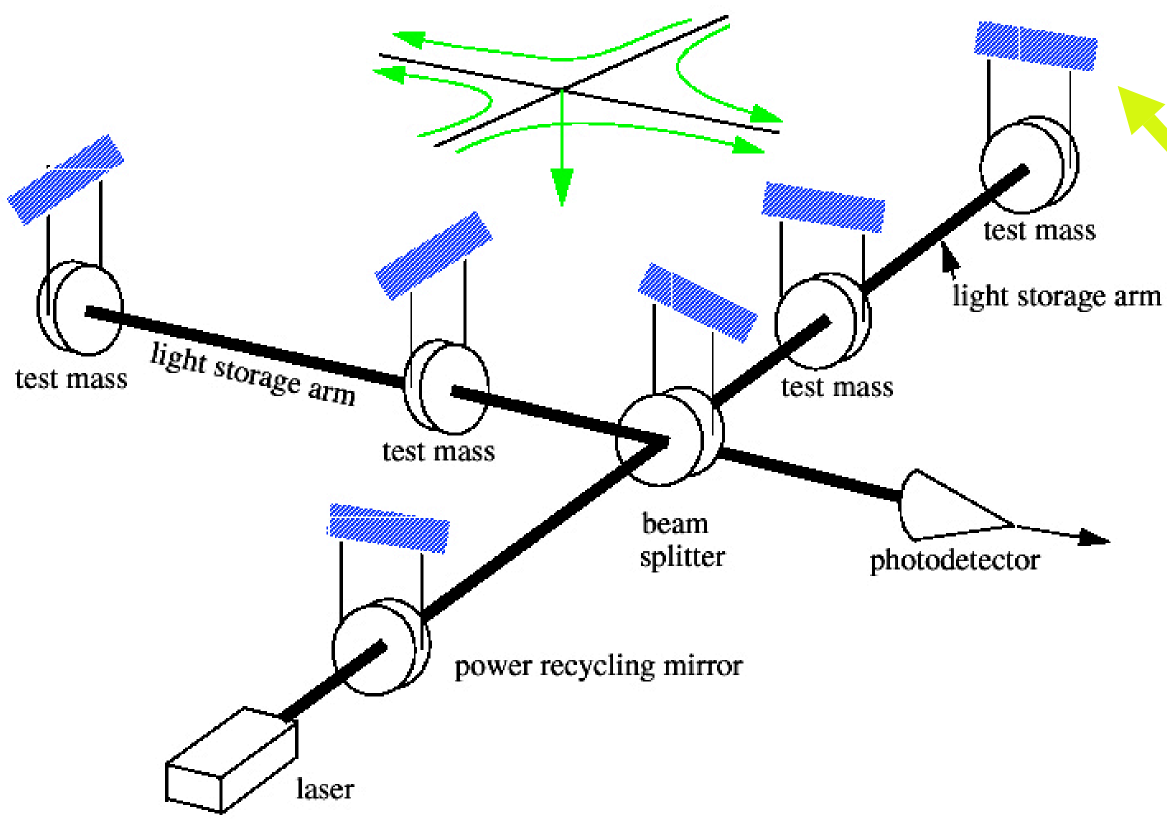
Detectors in space
LISA

Future Nobel Prize?

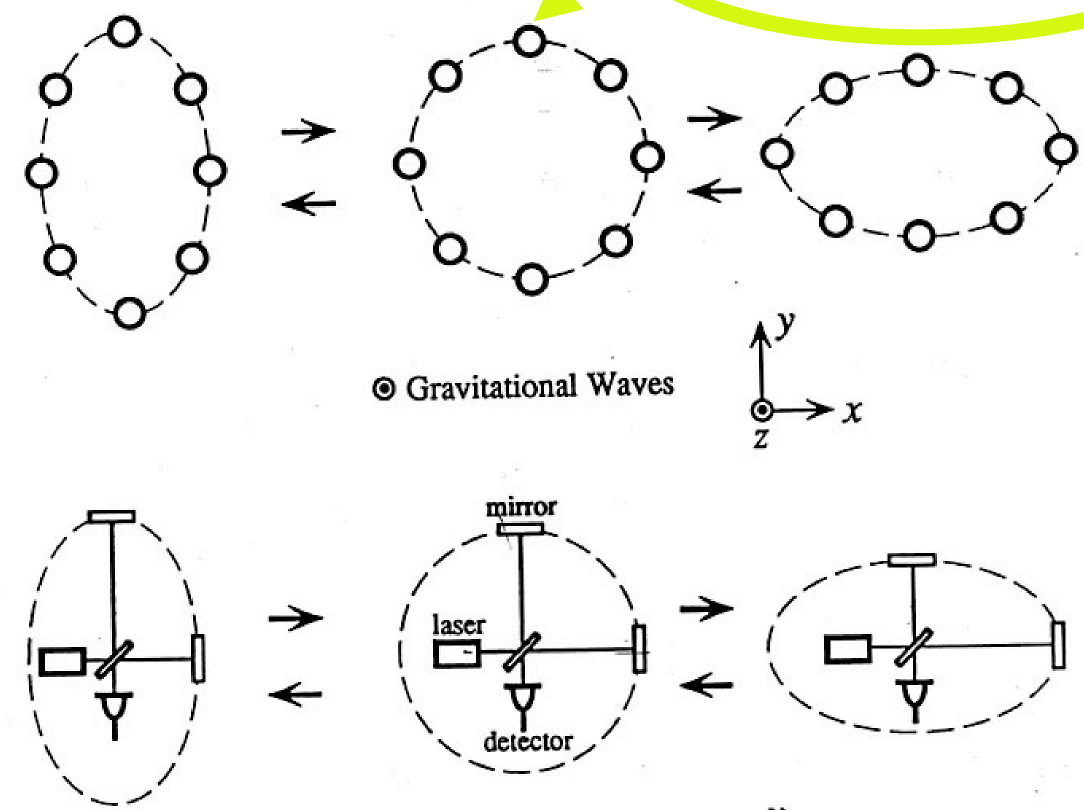
Terrestrial detectors
LIGO, GEO, TAMA, Virgo

Terrestrial Interferometers

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

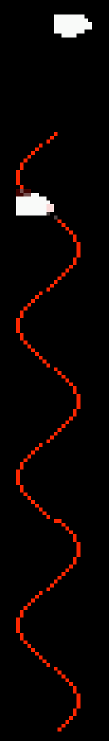


free masses



suspended test masses

LIGO technical challenges

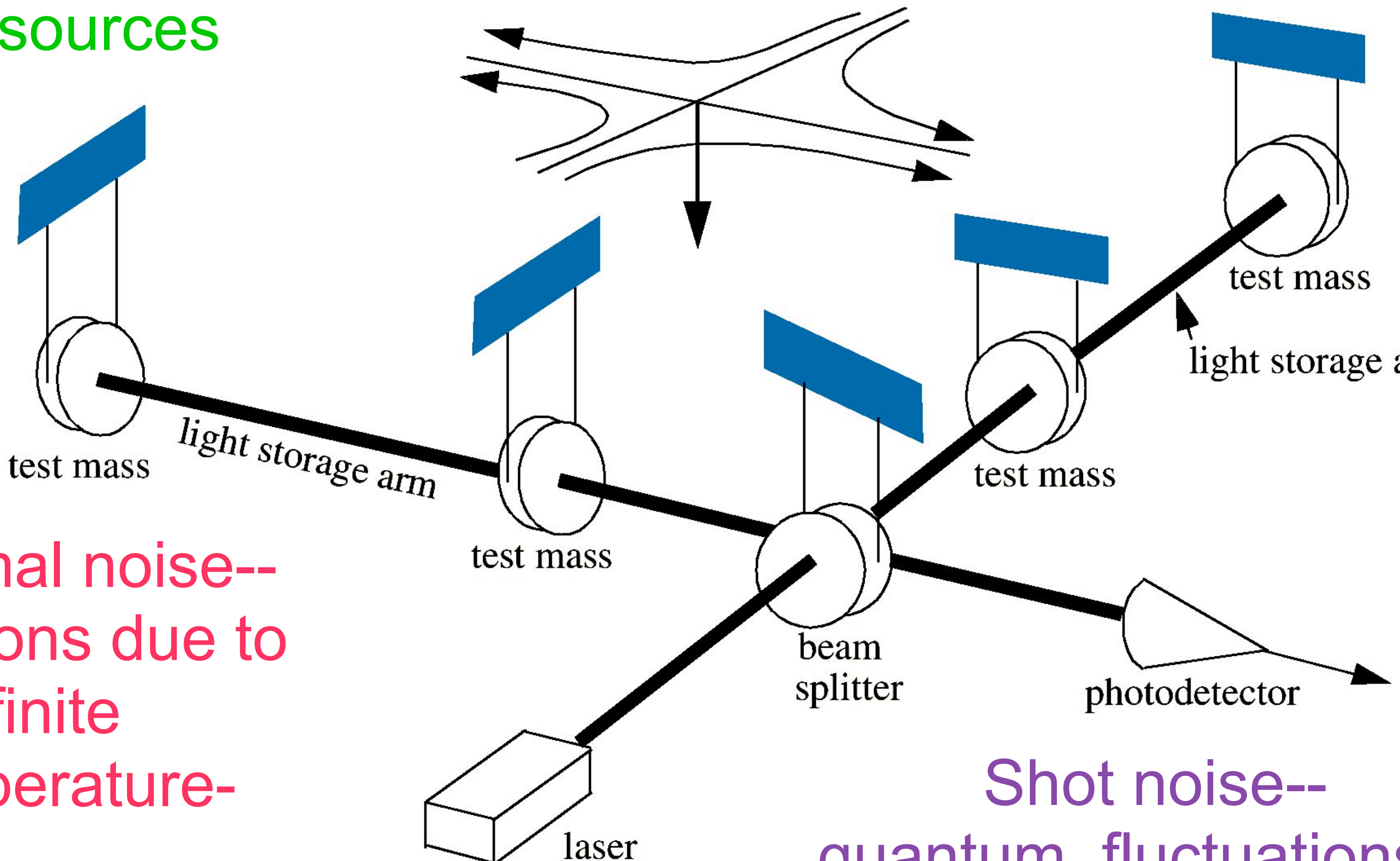


The Detection Challenge

Seismic motion-- ground motion due to natural and anthropogenic sources

$$h = \Delta L / L$$

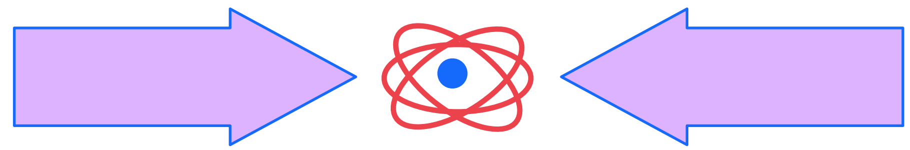
$L \sim 4$ km
For $h \sim 10^{-21}$
$\Delta L \sim 10^{-18}$ m



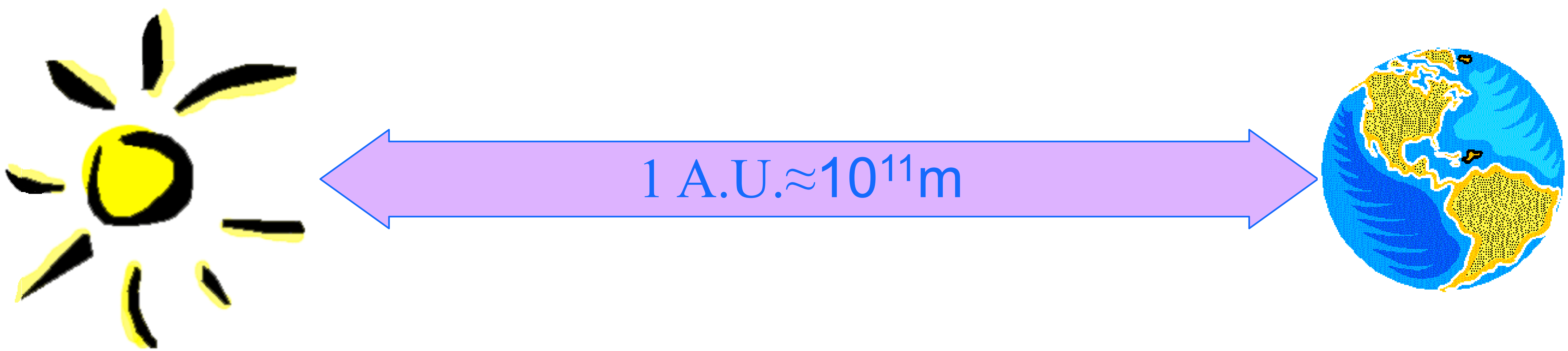
Thermal noise-- vibrations due to finite temperature-

Shot noise-- quantum fluctuations in the number of photons detected

How small is a strain of $\Delta L/L=10^{-21}$?



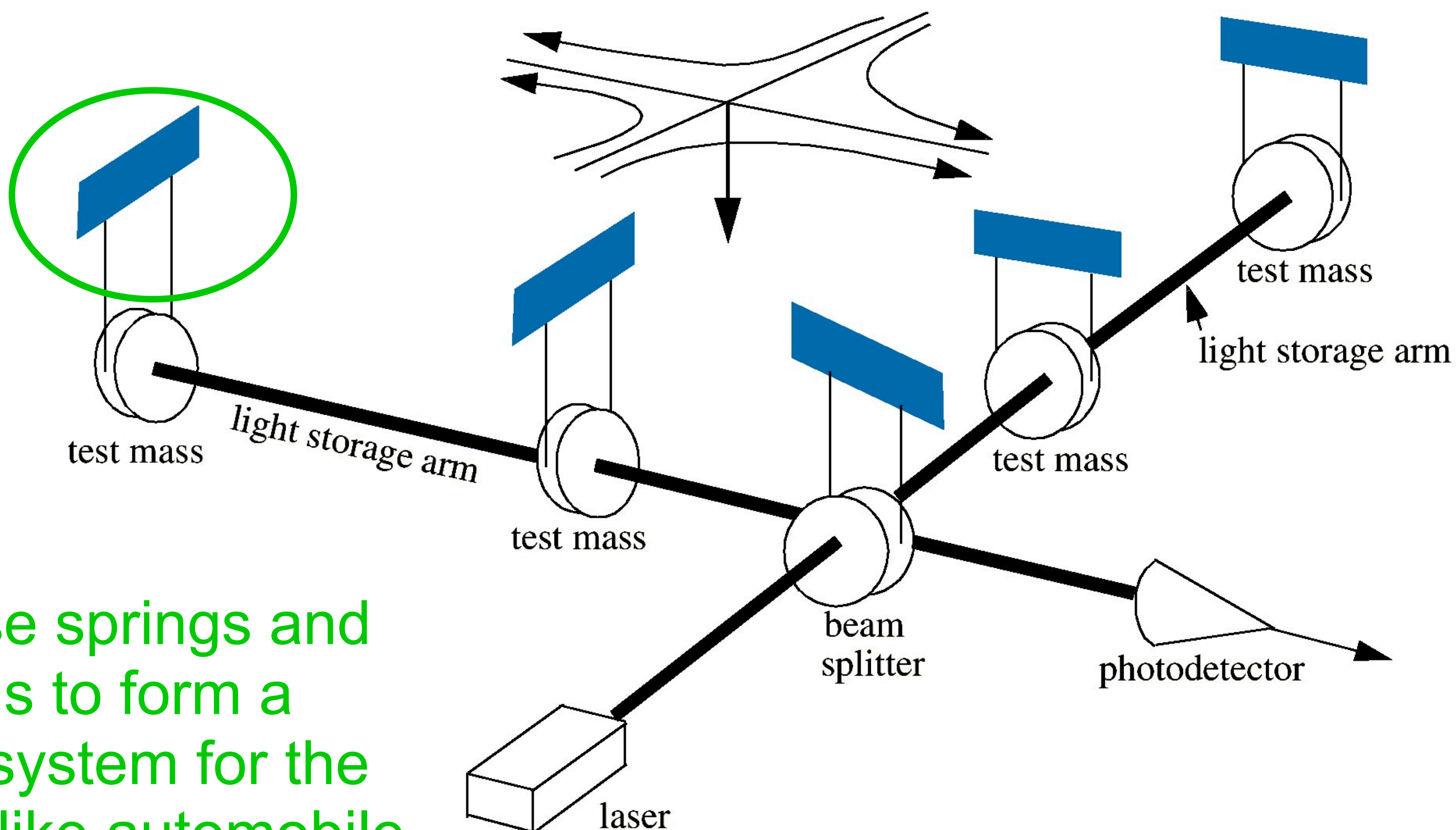
$1\ \text{Å}=10^{-10}\text{m}$



The Detection Challenge

seismic noise

Problem: Seismic motion causes the ground to move thereby moving the mirrors

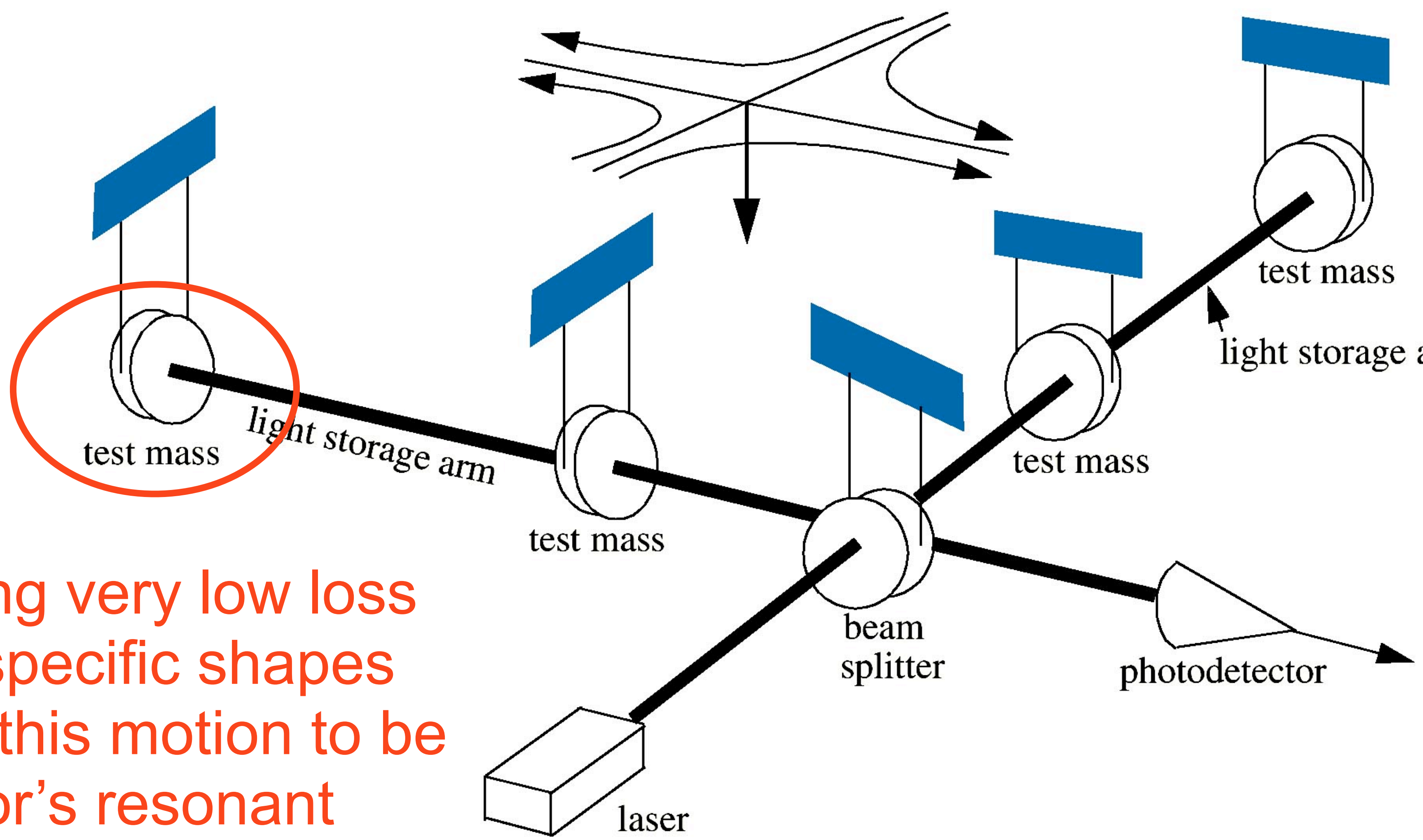


Solution: Use springs and pendulums to form a suspension system for the mirrors much like automobile shock abosrobers

The Detection Challenge

thermal noise

Problem: Thermal noise causes the mirrors to vibrate

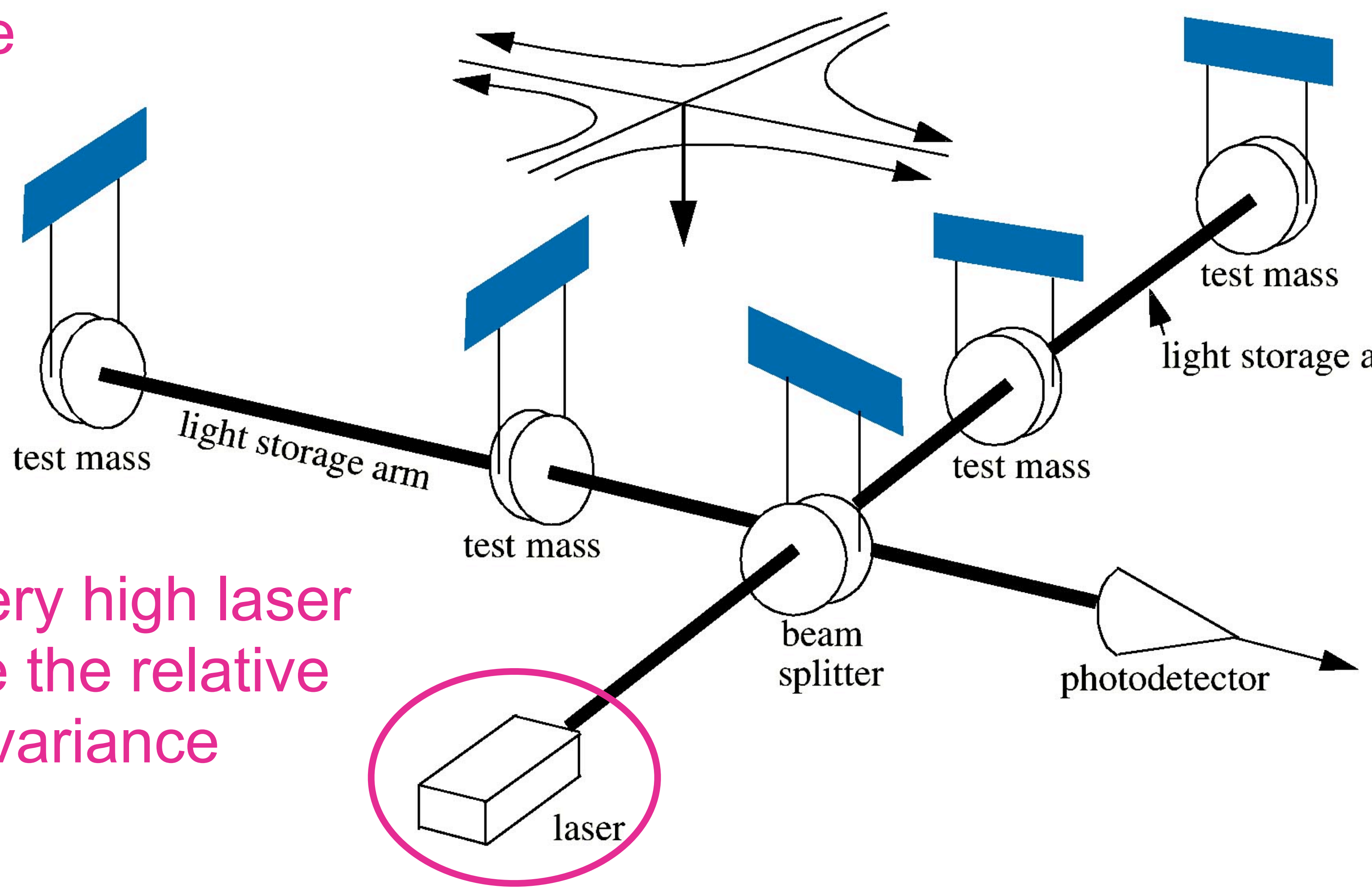


Solution: Using very low loss materials of specific shapes allows most of this motion to be at the mirror's resonant frequency outside of the signal band.

The Detection Challenge

shot noise

Problem: There is a natural variance in the number of photons detected per unit of time



Solution: Use very high laser power to reduce the relative size of this variance

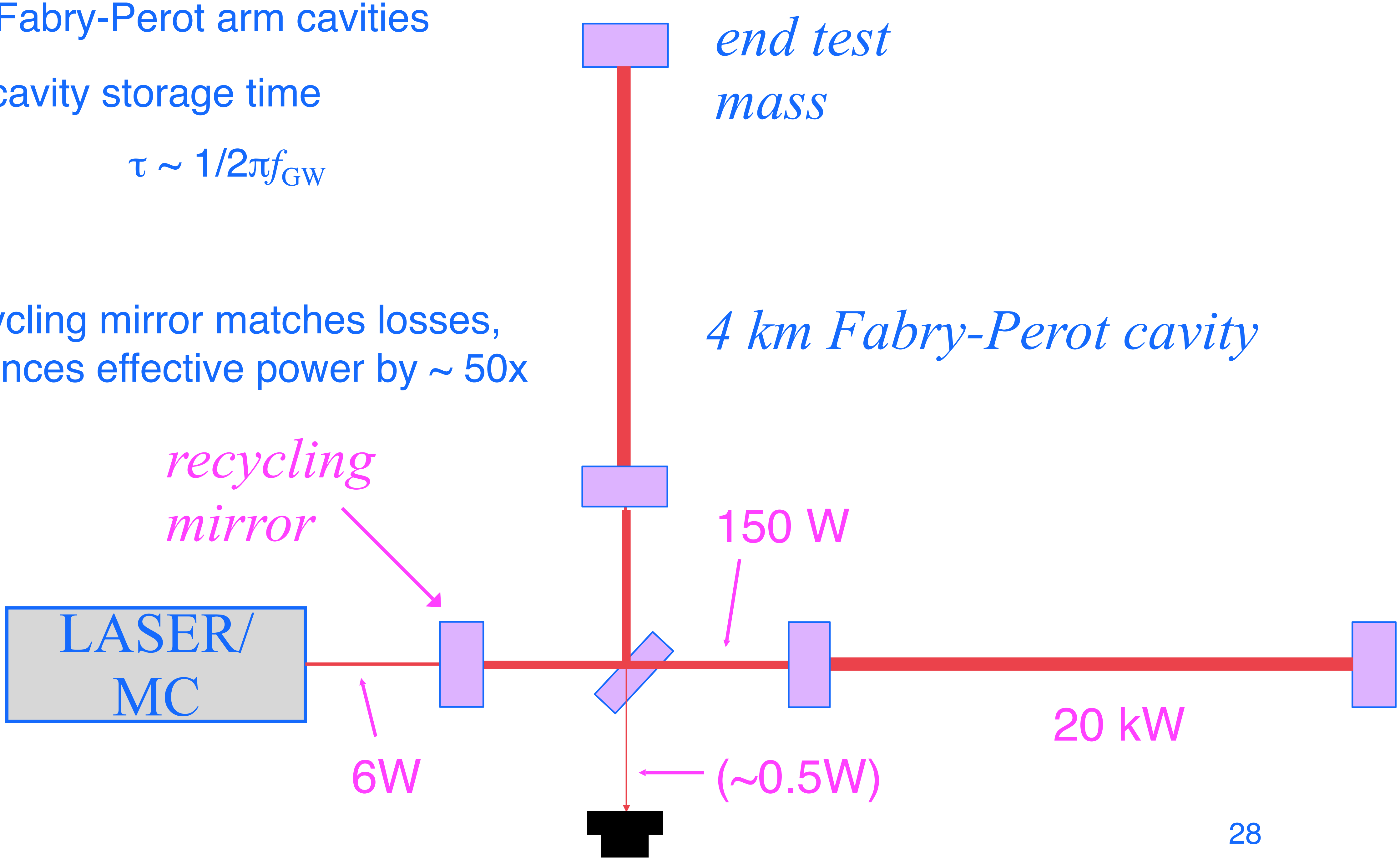
LIGO Interferometer Optical Scheme

- Michelson interferometer with Fabry-Perot arm cavities

- Arm cavity storage time

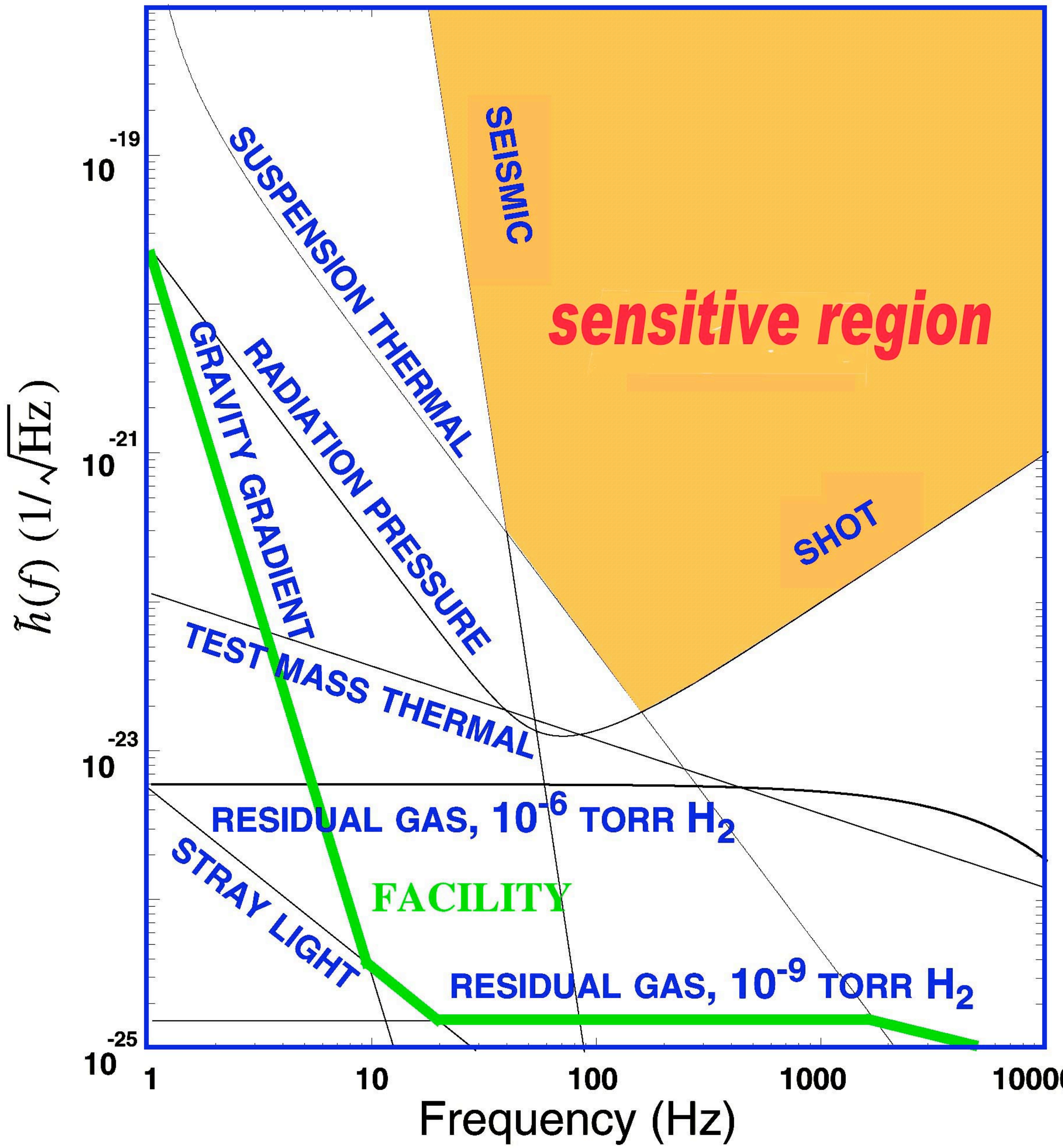
  $\tau \sim 1/2\pi f_{GW}$

- Recycling mirror matches losses, enhances effective power by ~ 50x



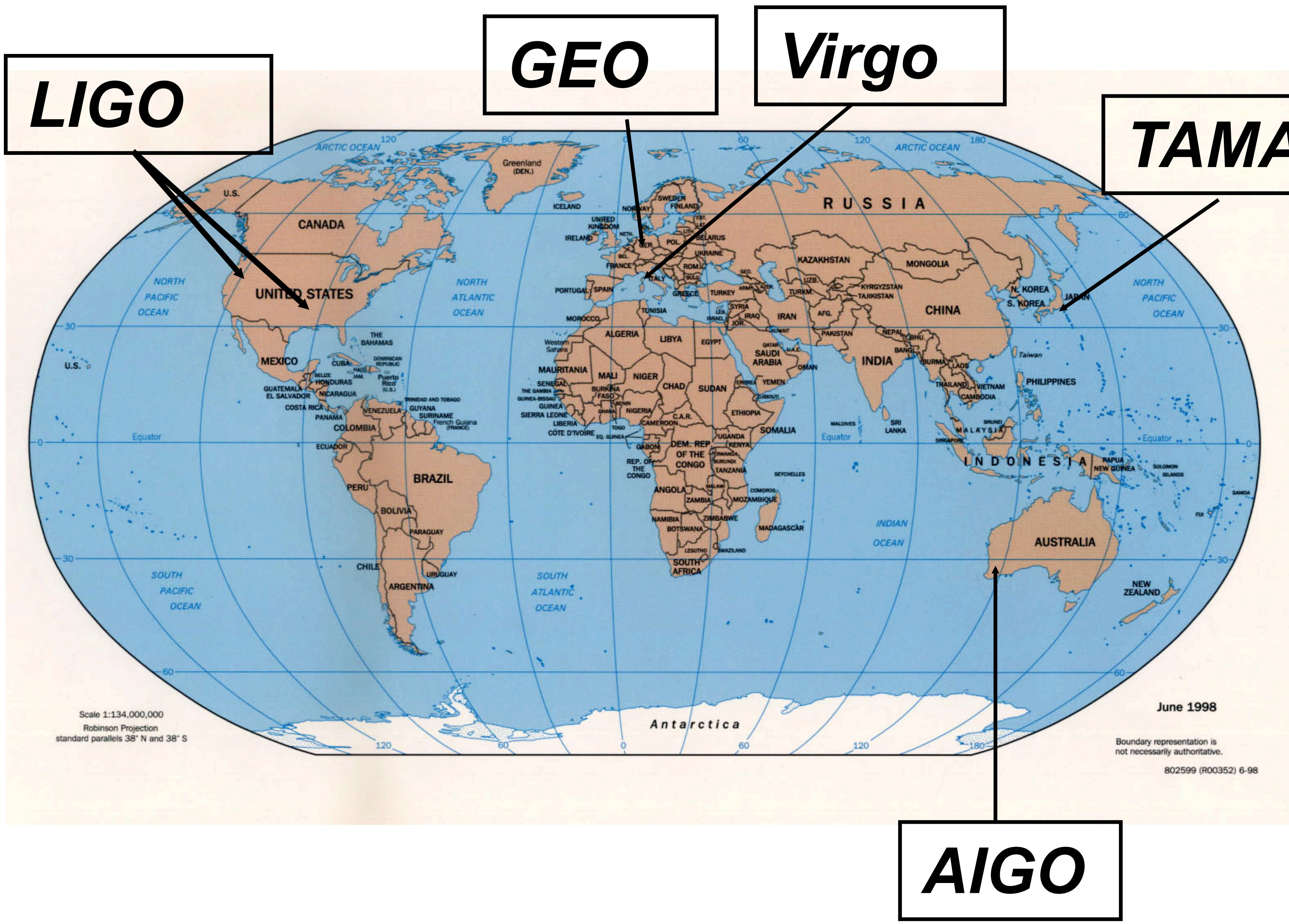
What Limits Sensitivity of Interferometers?

- 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
- A myriad of details of the lasers, electronics, etc., can make problems above these levels



An International Network of Interferometers

Simultaneously detect signal (within msec)



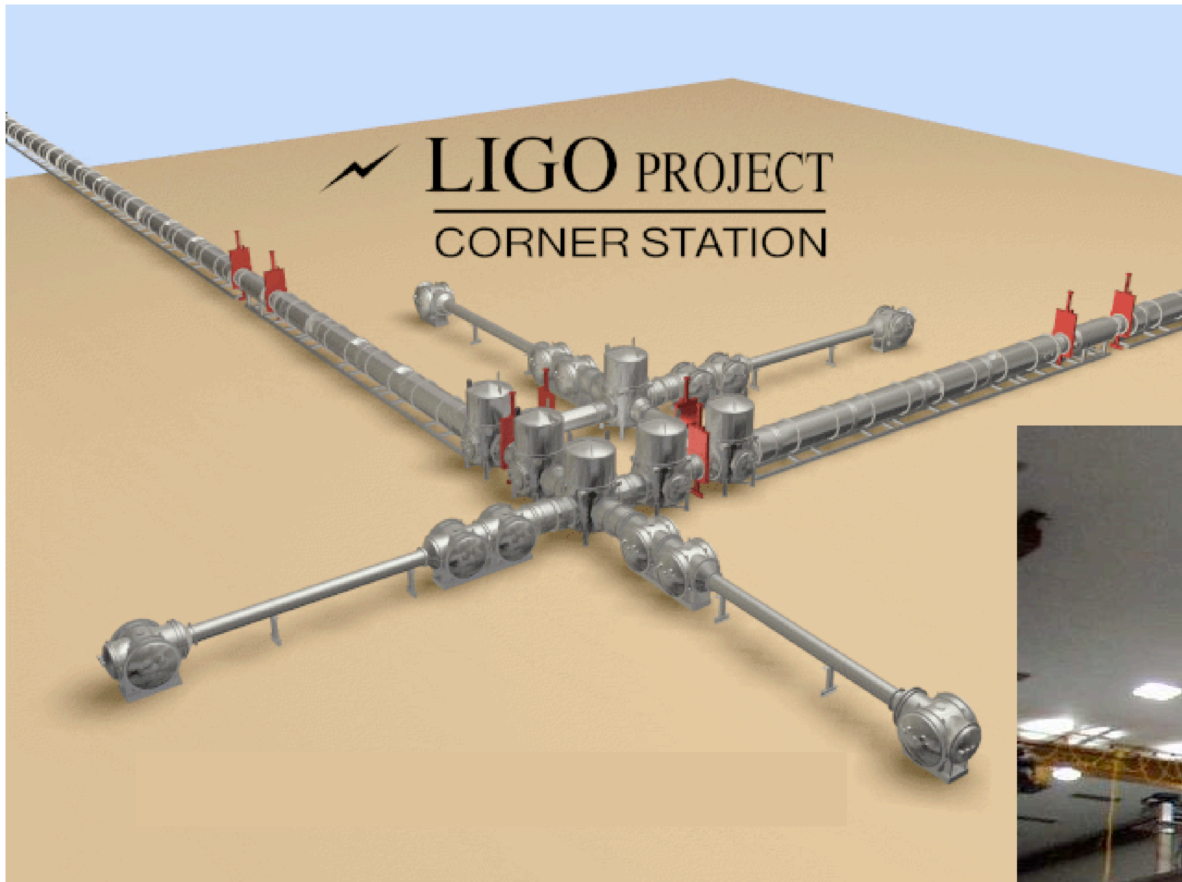
Increase detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Observatories

LIGO Vacuum Equipment



A LIGO Mirror

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

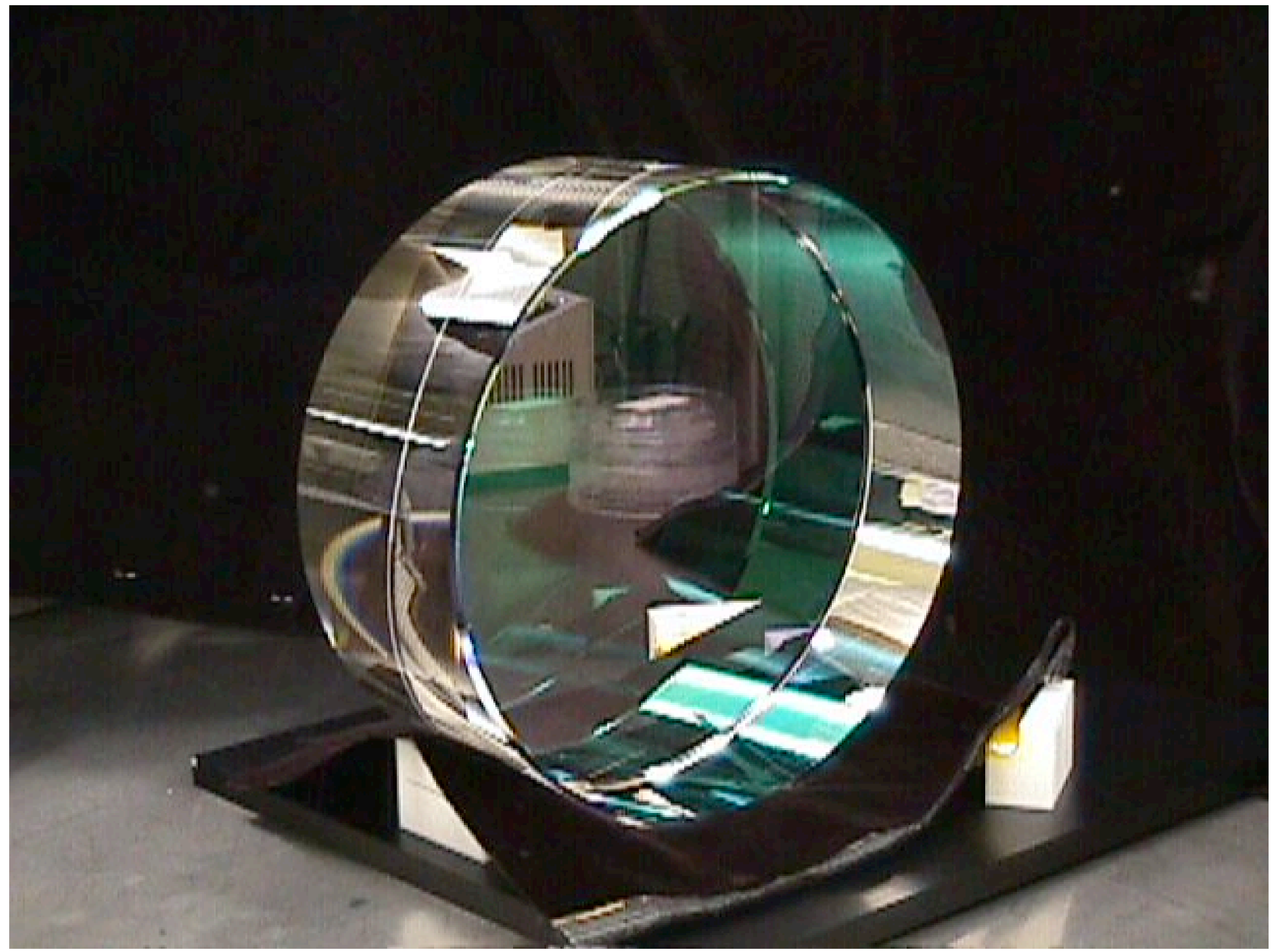
Radii of curvature matched < 3%

Coating

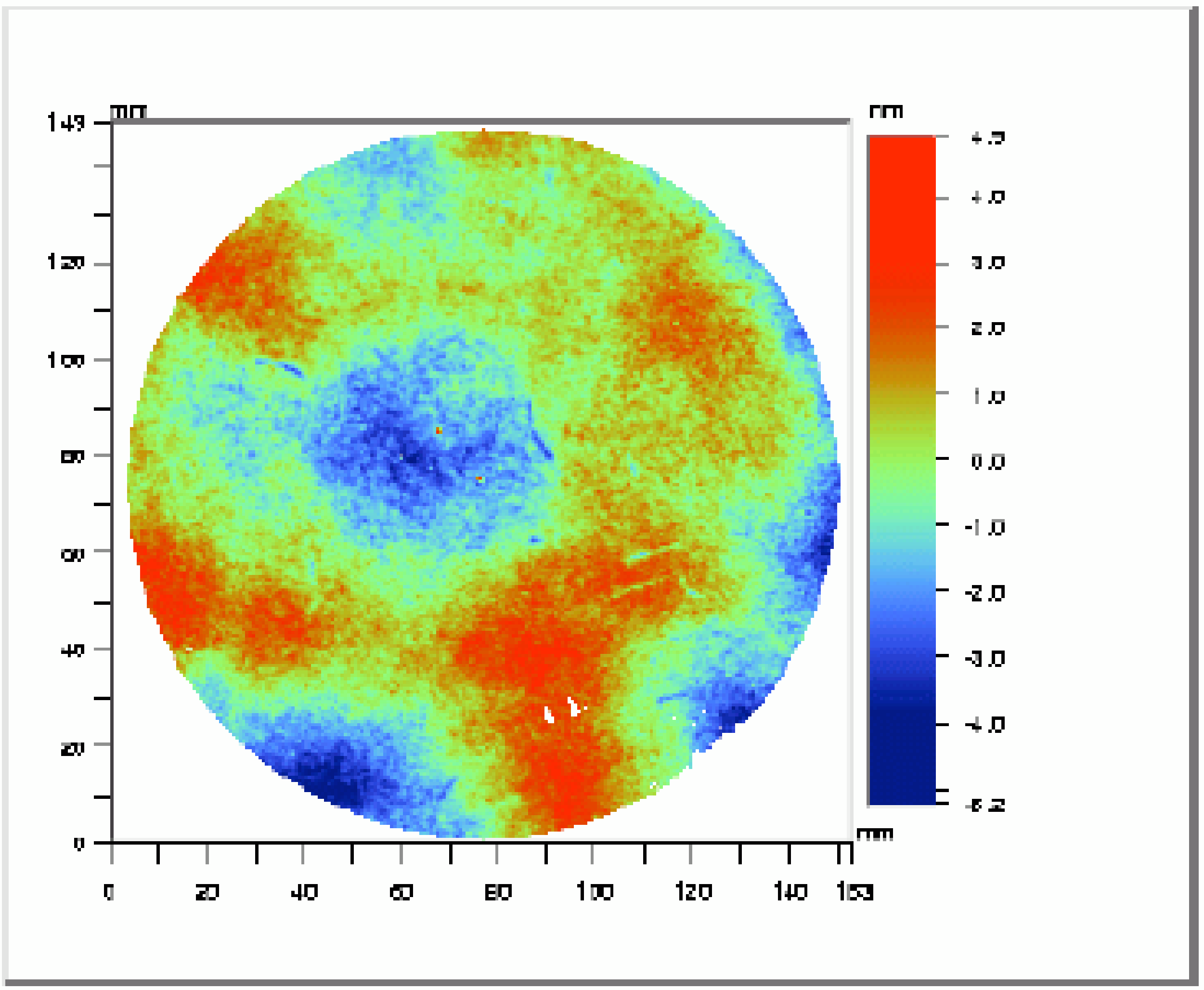
Scatter < 50 ppm

Absorption < 2 ppm

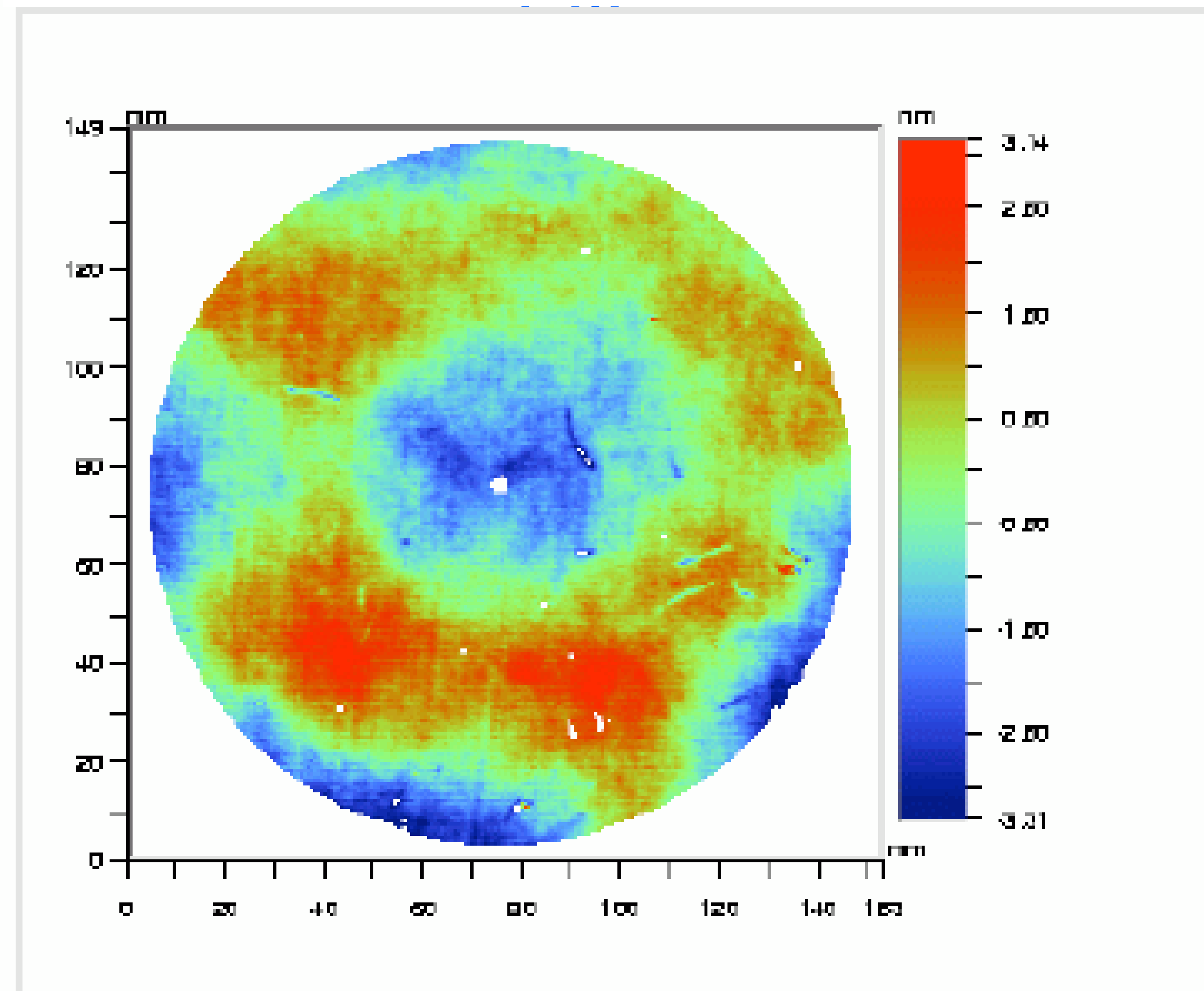
Uniformity <10^{-3}



Core Optics Metrology



LIGO data (1.2 nm rms)



CSIRO data (1.1 nm rms)

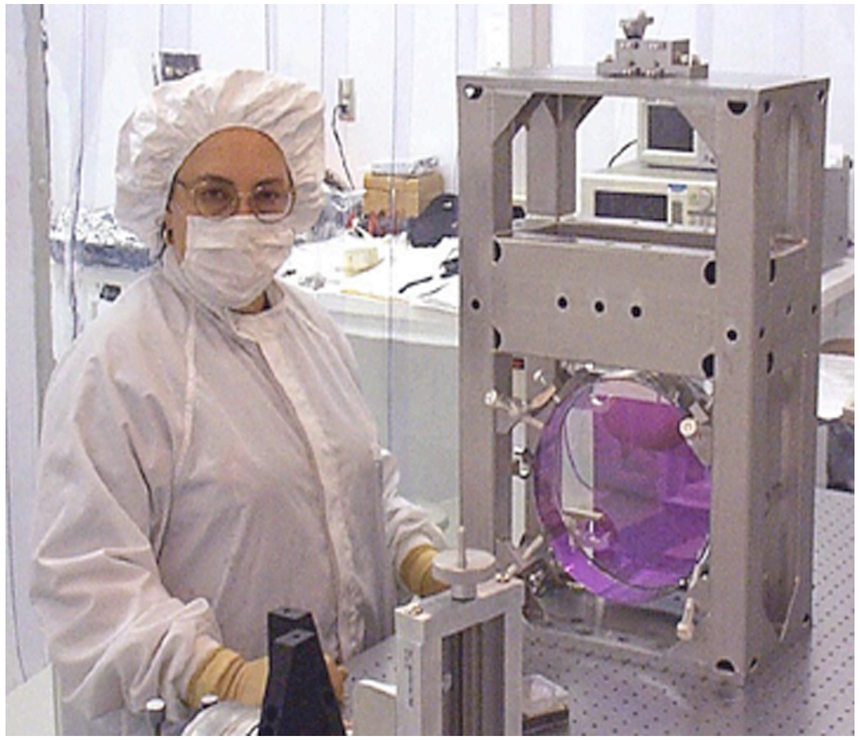
➢ *Best mirrors are λ/6000 over the central 8 cm diameter*

LIGO

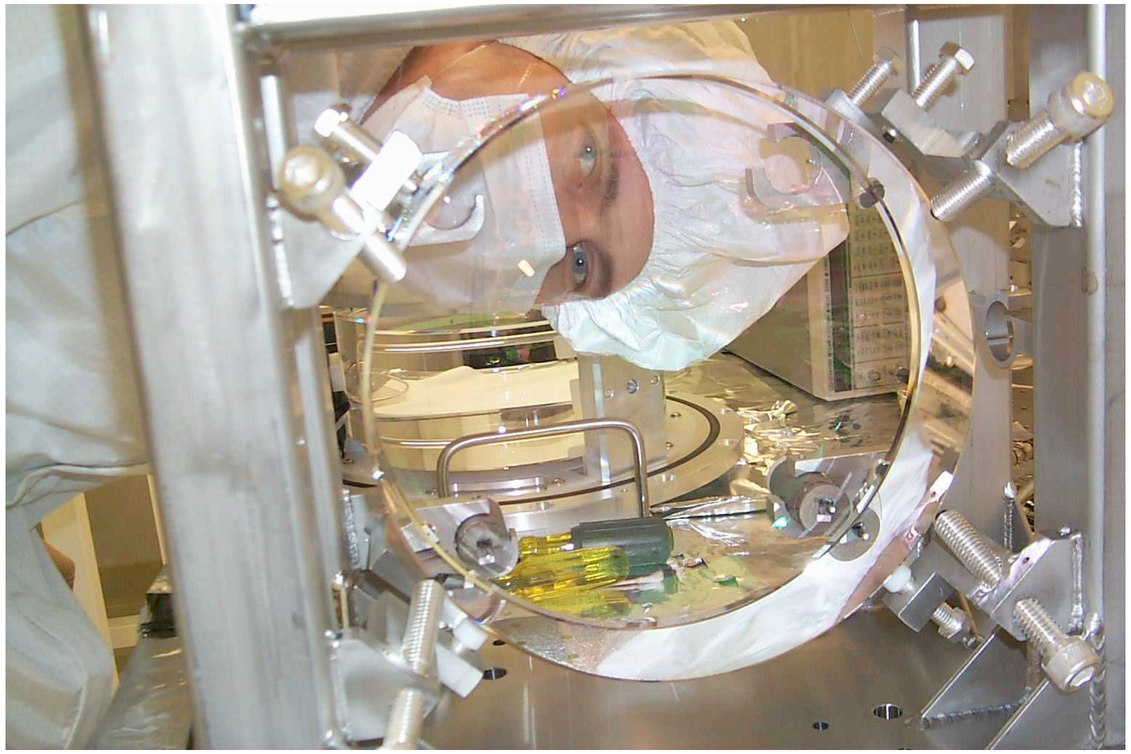
Core Optics

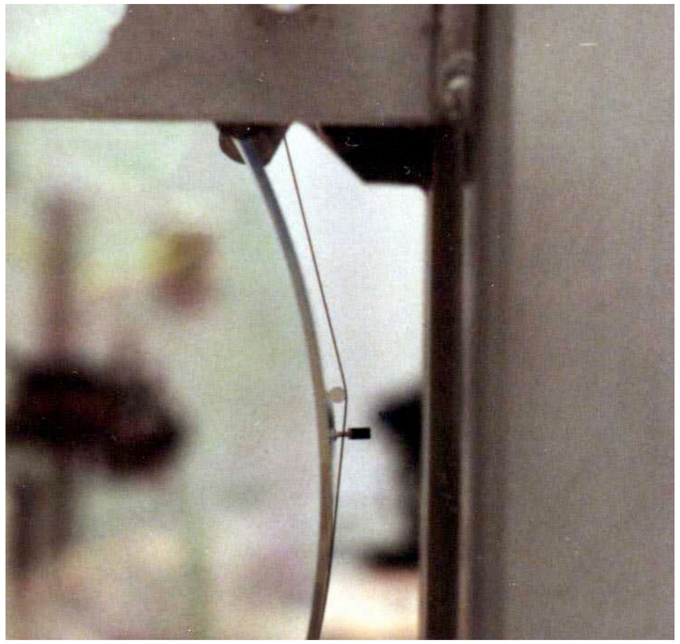
installation and alignment

Optics Suspension and Control



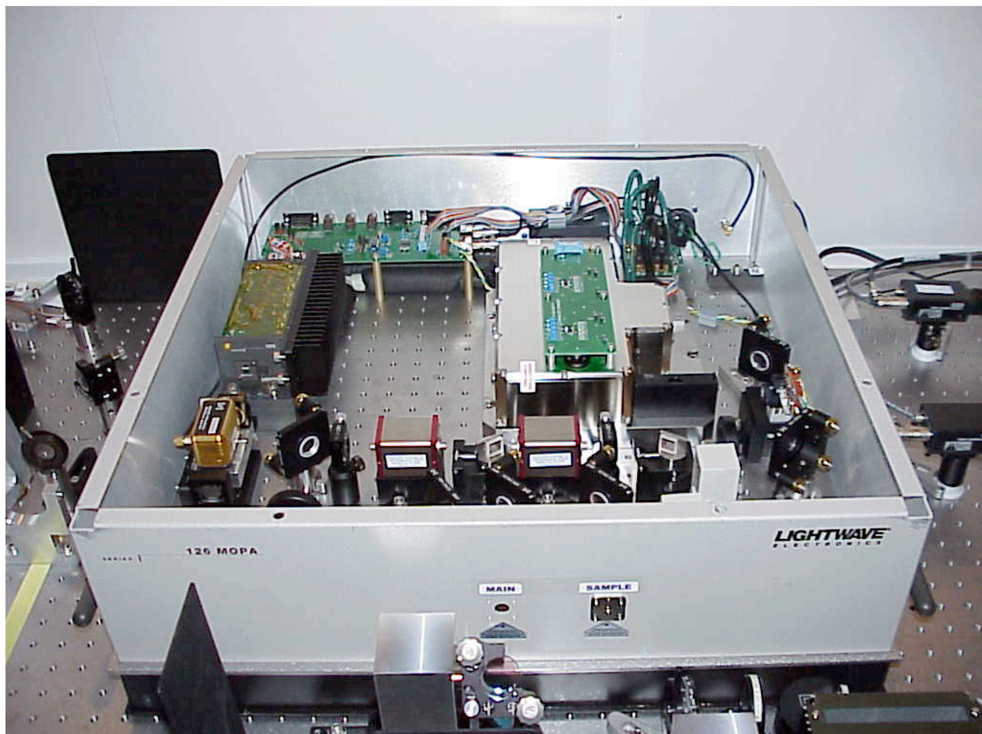
- Suspension is the key to controlling thermal noise
- Magnets and coils to control position and angle of mirrors



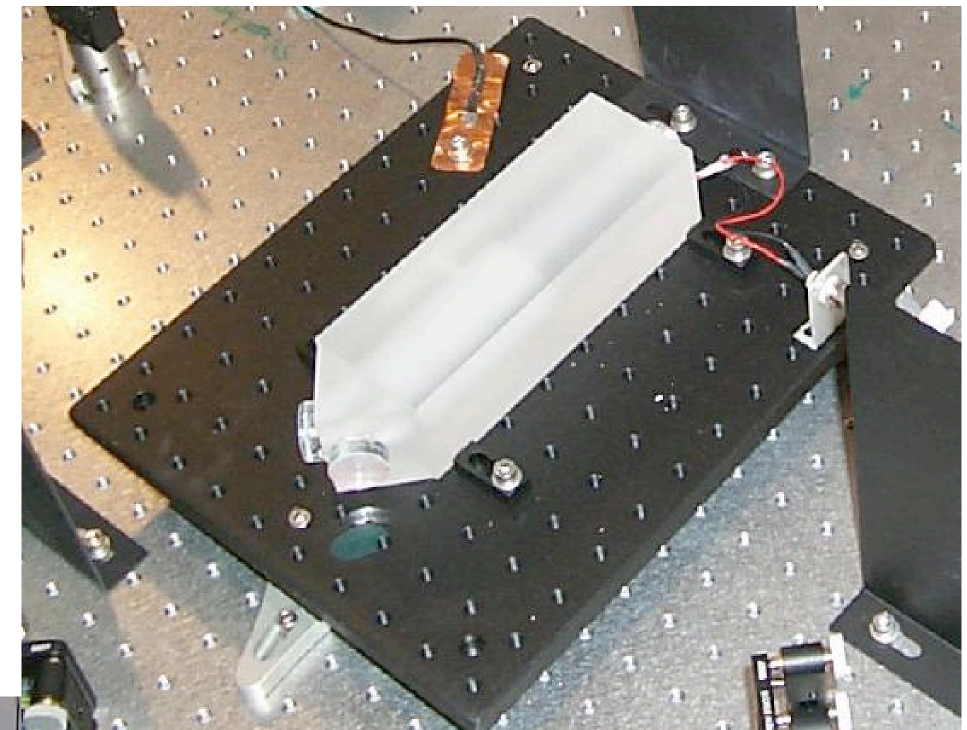


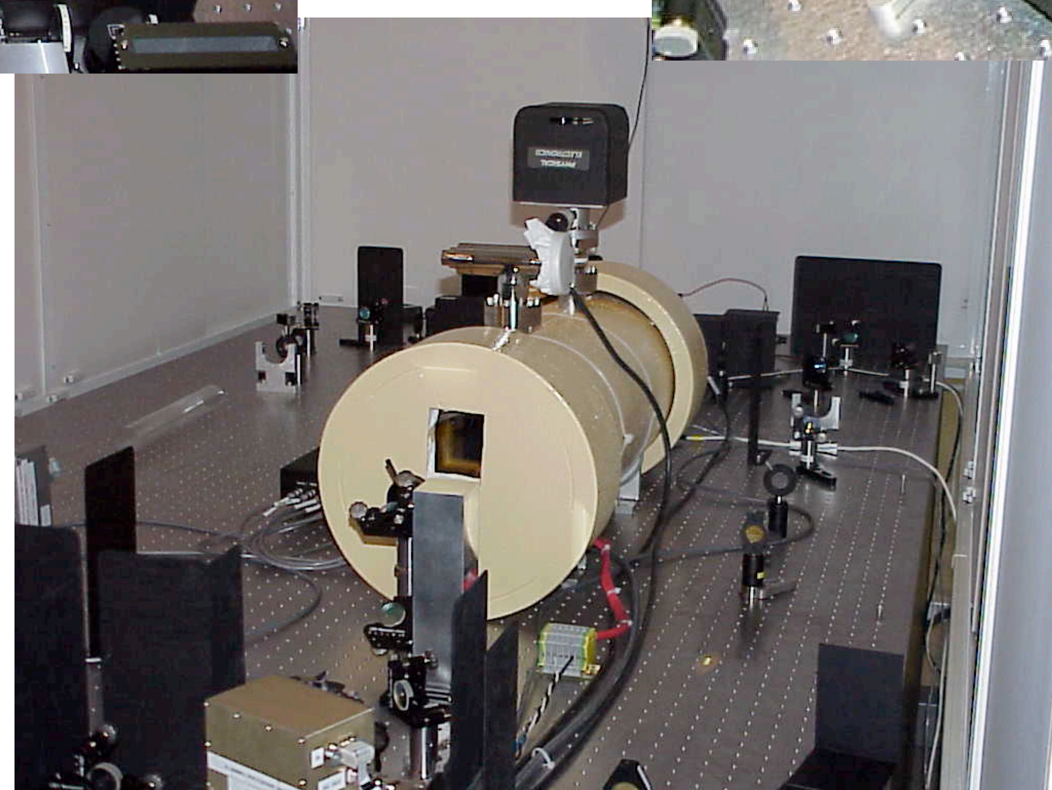
LIGO

Stabilized Laser



Custom-built
10 W Nd:YAG
laser





Stabilization cavities
for laser beam—
Widely used for
precision optical
applications

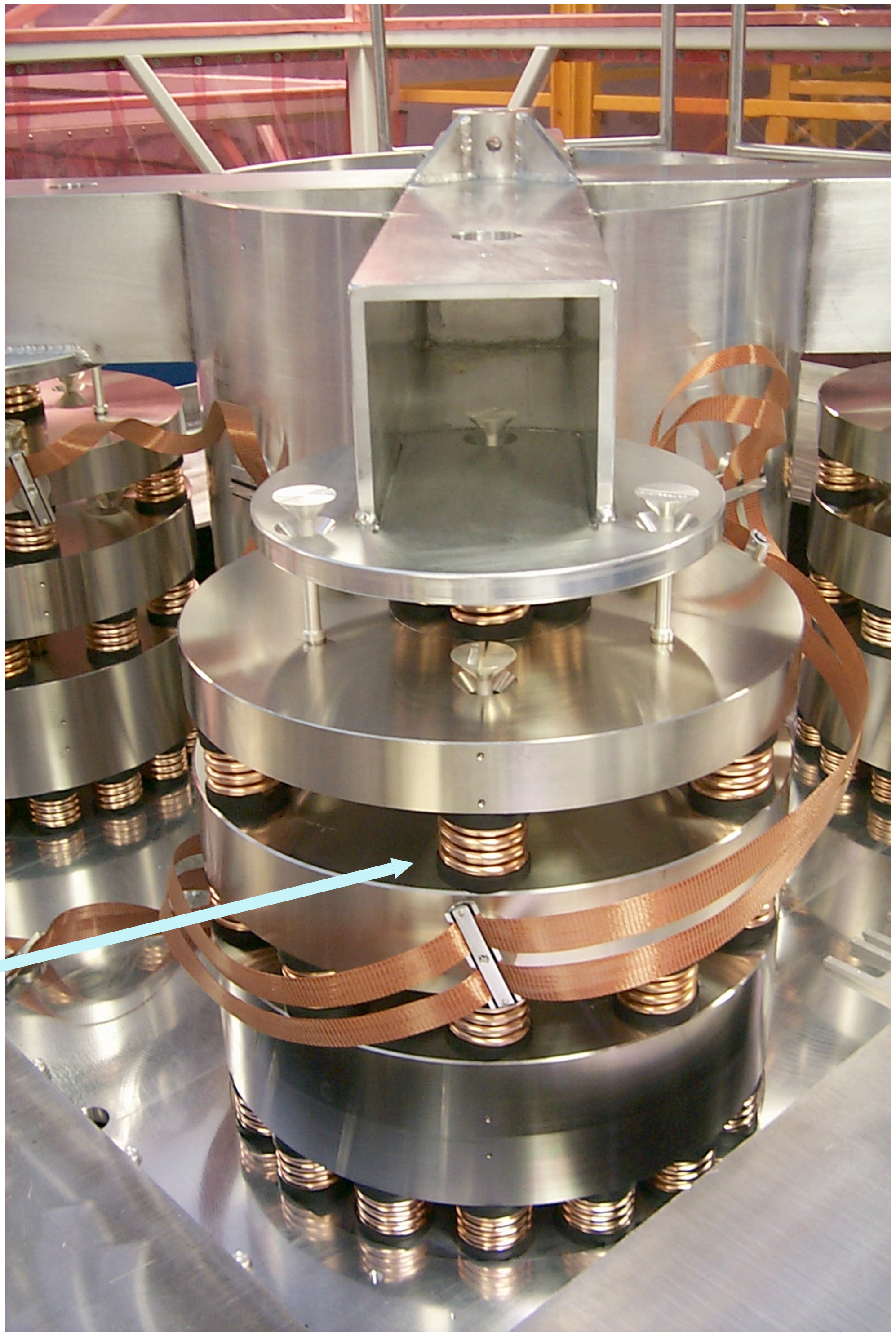
$$\frac{\delta f}{f} \approx 10^{-21}$$

LIGO

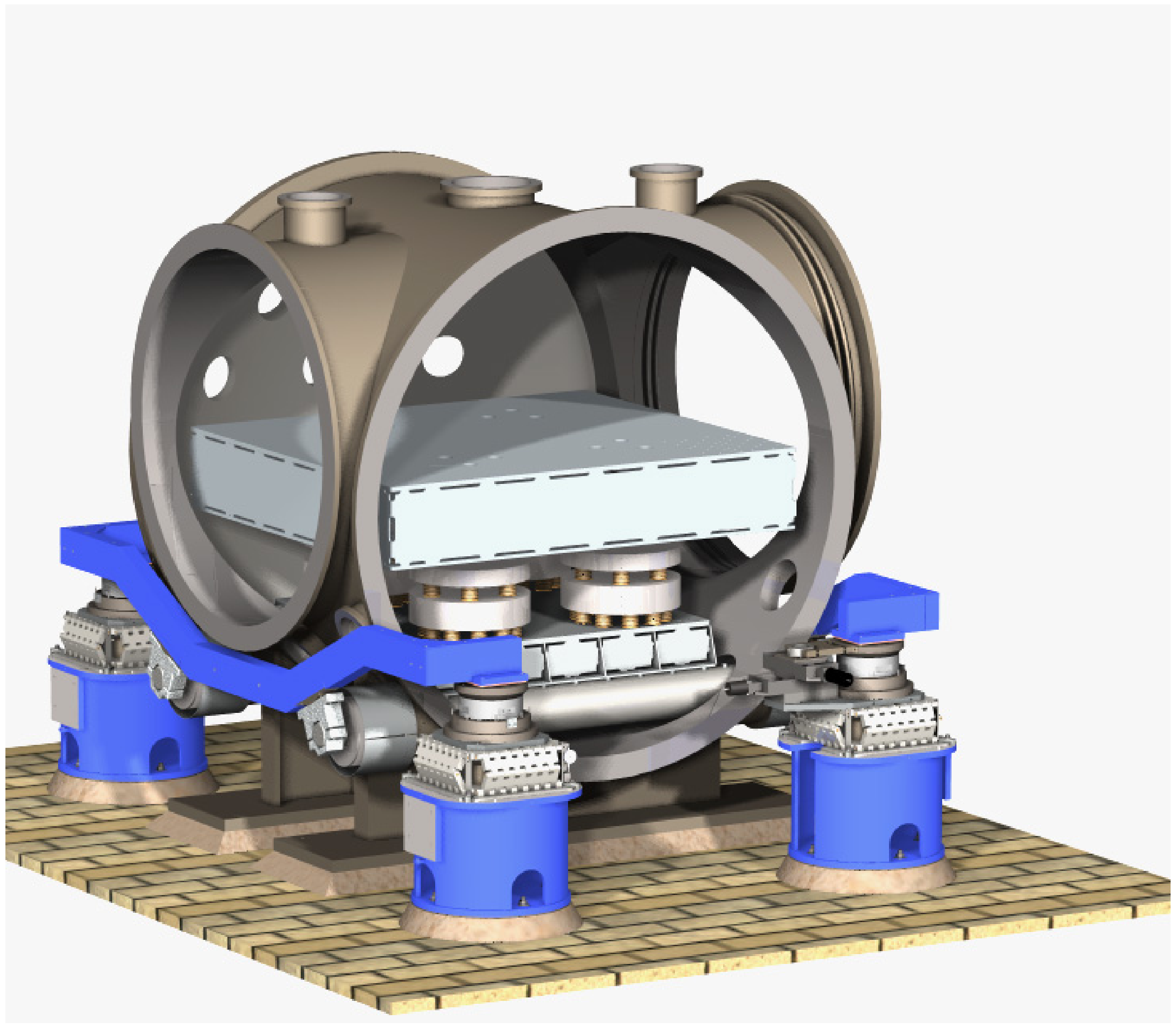
Seismic Isolation

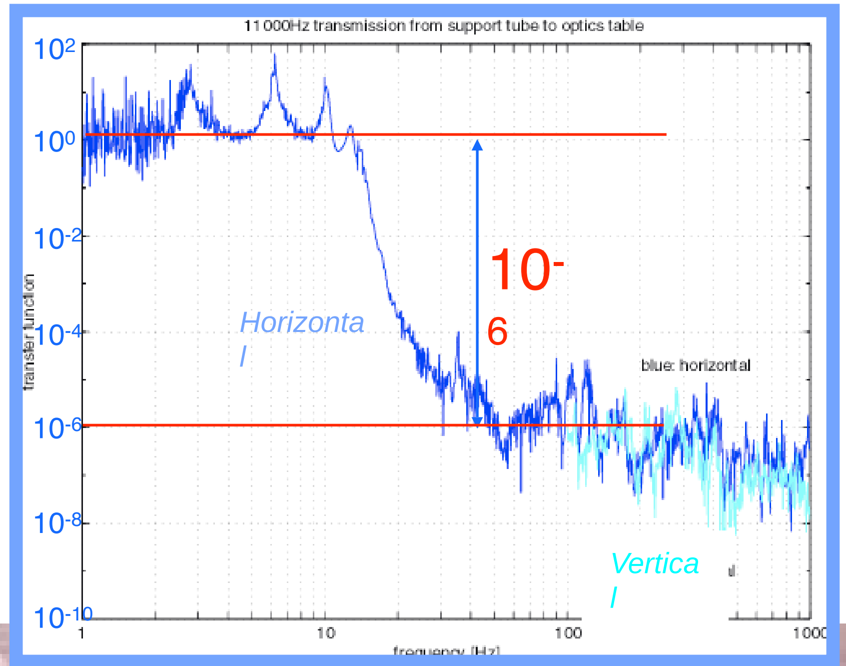
- Cascaded stages of masses on springs (same principle as car suspension)

damped spring
cross section

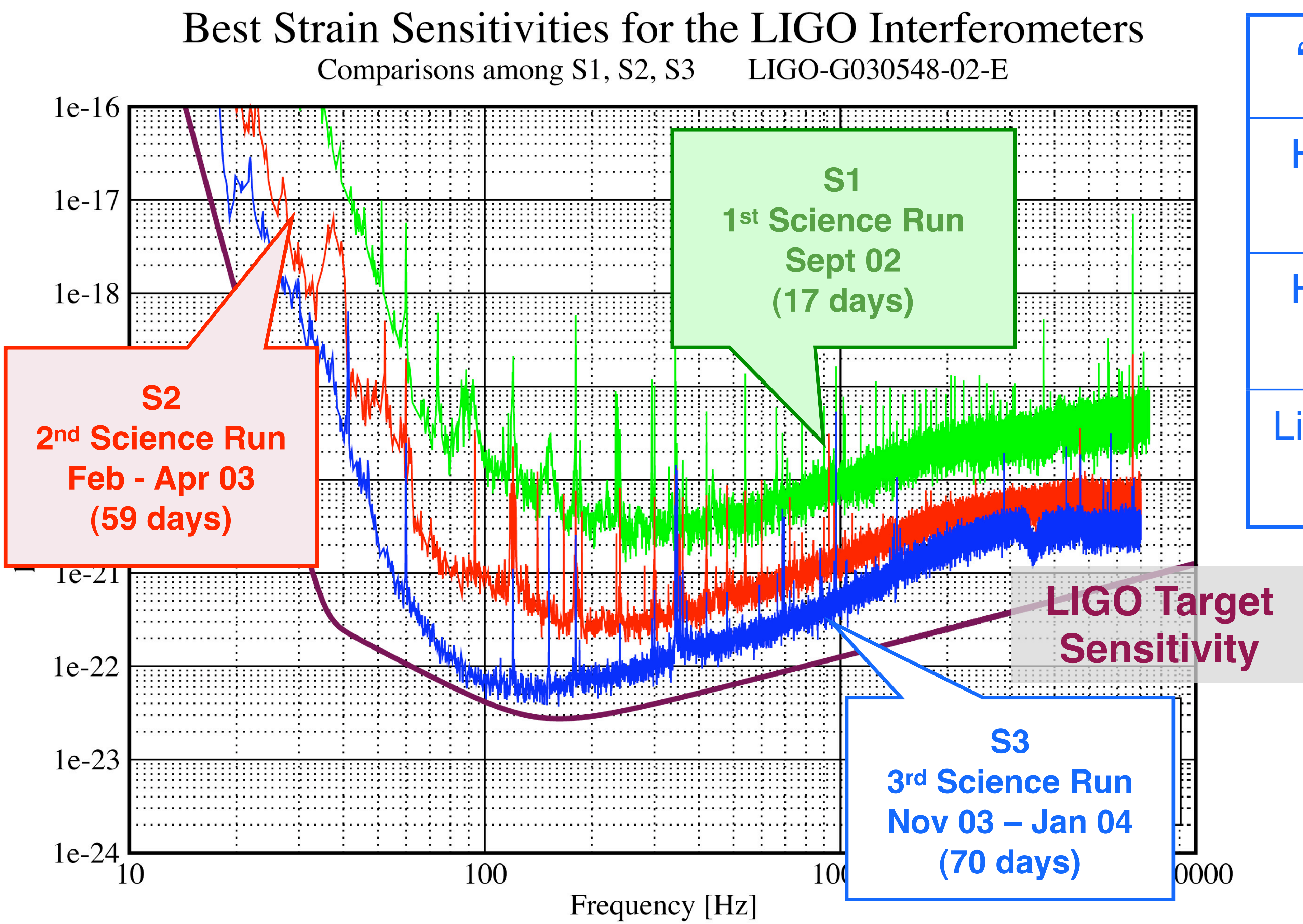


Seismic Isolation





LIGO Science Runs



"S3" Duty Cycle	
Hanford 4km	69%
Hanford 2km	63%
Livingston 4 km	22%

LIGO scientific results

LIGO Scientific results

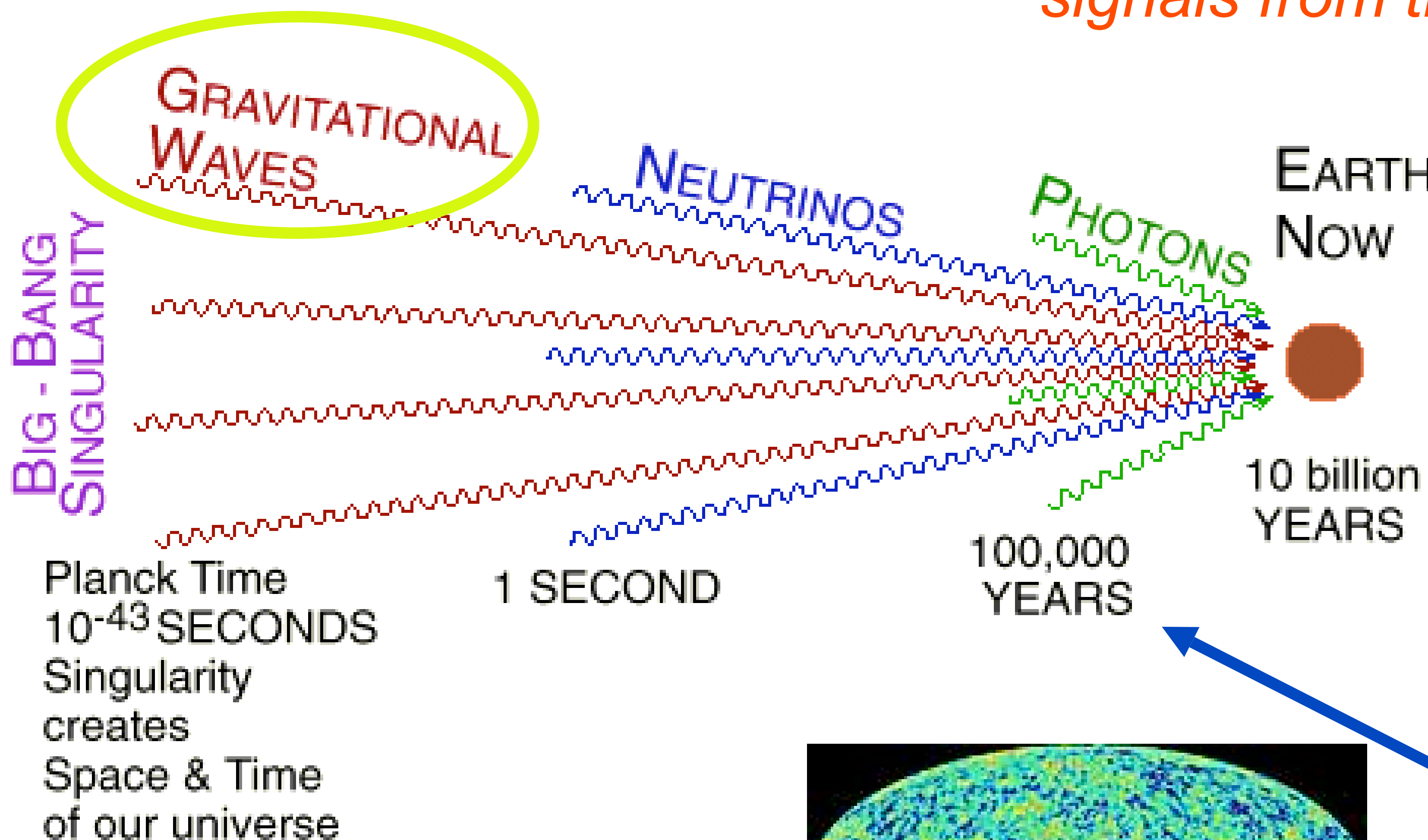
- A limit on the strength of the gravitational wave stochastic background has been published
- A search for gravitational waves from a gamma ray burst source has been performed and published
- "all-sky" searches for periodic signals are in progress
- No gravitational waves have been seen (yet)

“Stochastic Background”

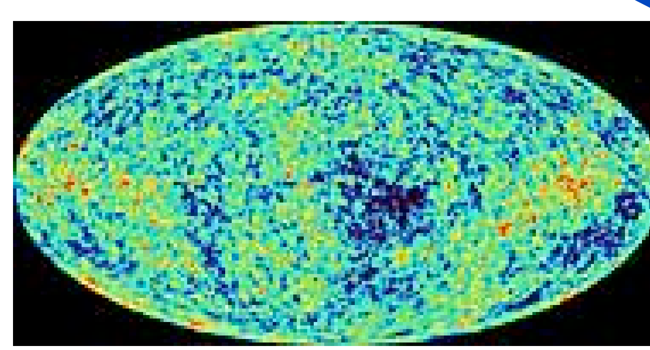
cosmological signals

‘Murmurs’ from the Big Bang

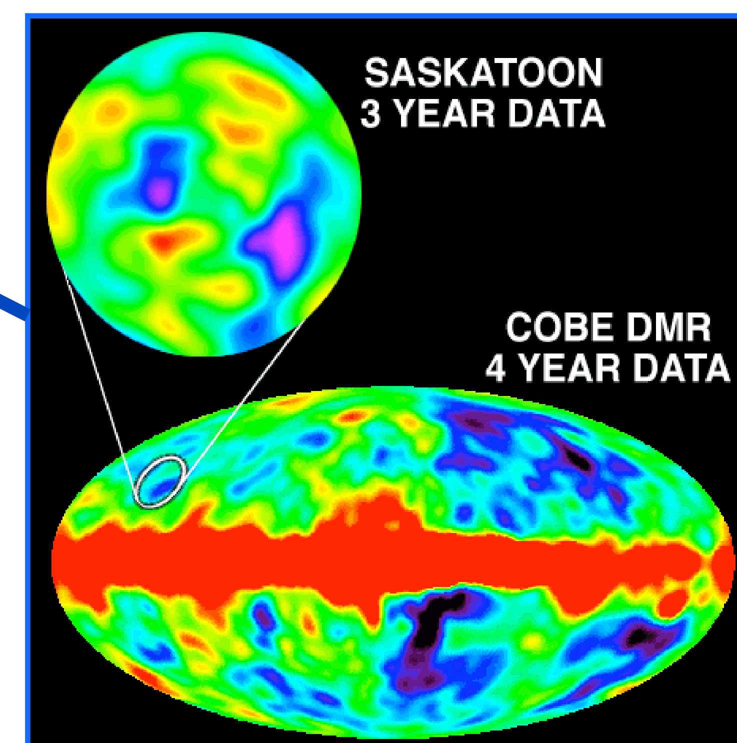
signals from the early universe



Cosmic microwave background



WMAP 2003



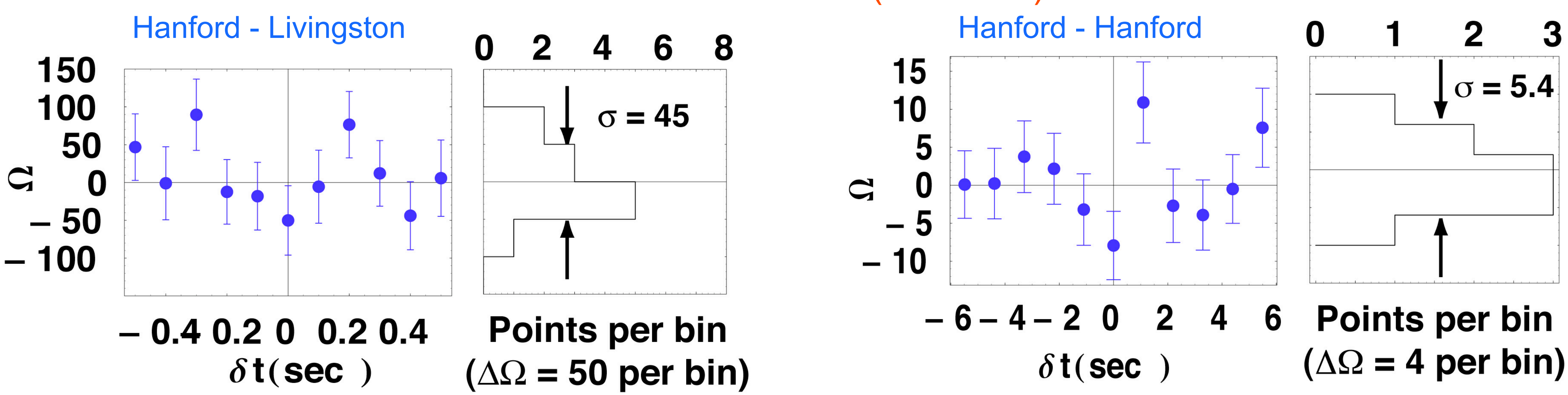
Stochastic Background
no observed correlations

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

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

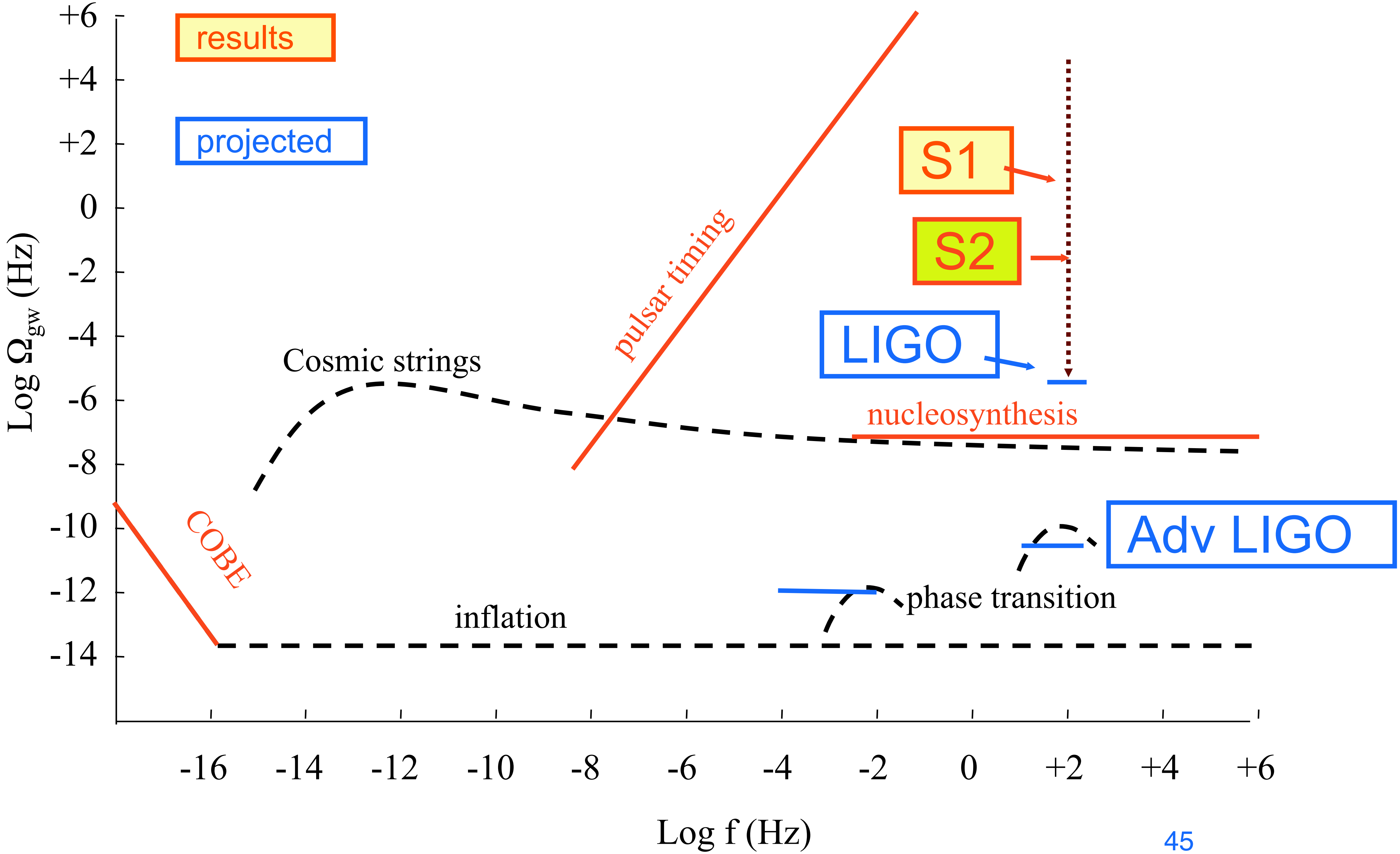
- Detect by *cross-correlating* output of two GW detectors:

First LIGO Science Data (Lazzarini)

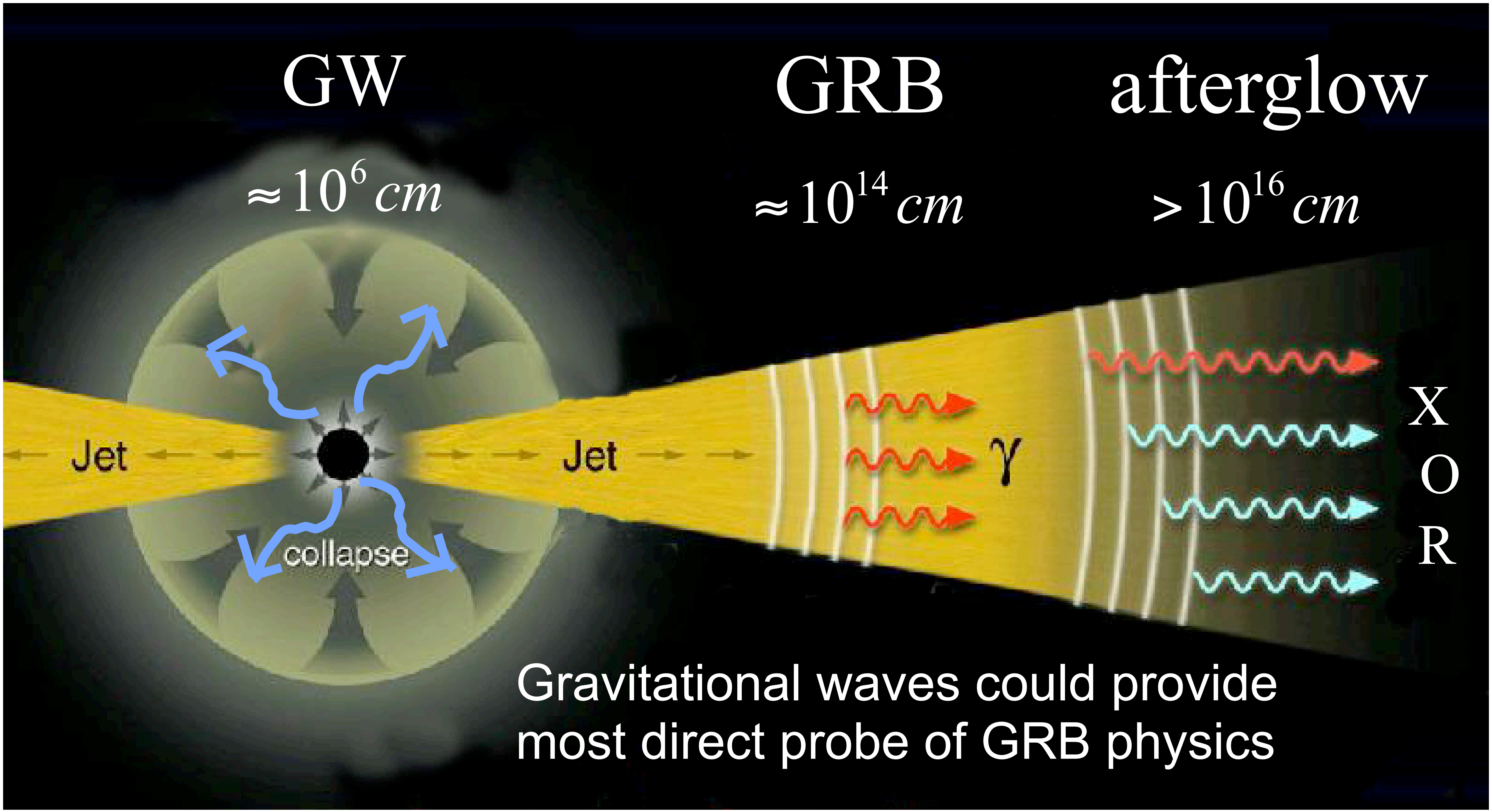


Preliminary limits from 7.5 hr of data

Stochastic Background
sensitivities and theory

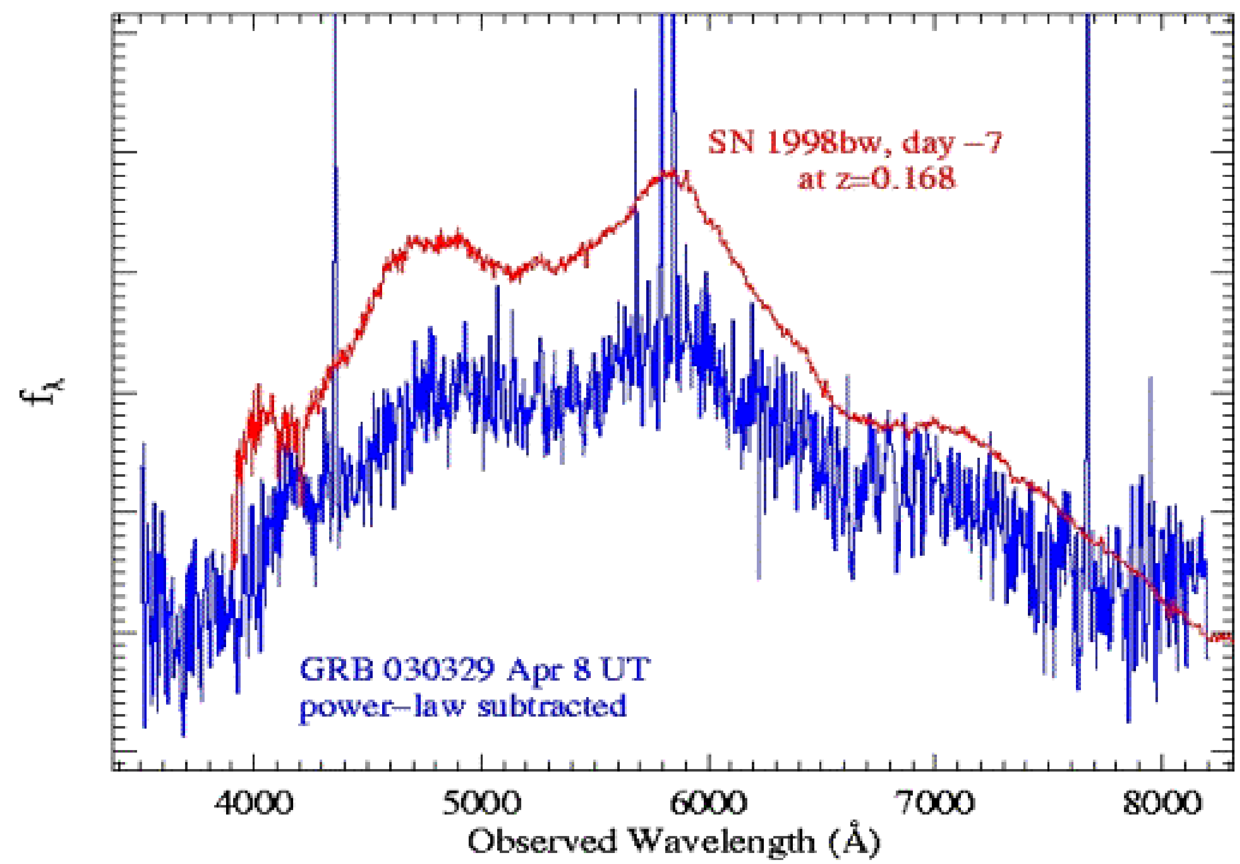


Gamma ray bursts
from sources of gravitational waves?



GRB030329: “Monster Gamma Ray Burst”

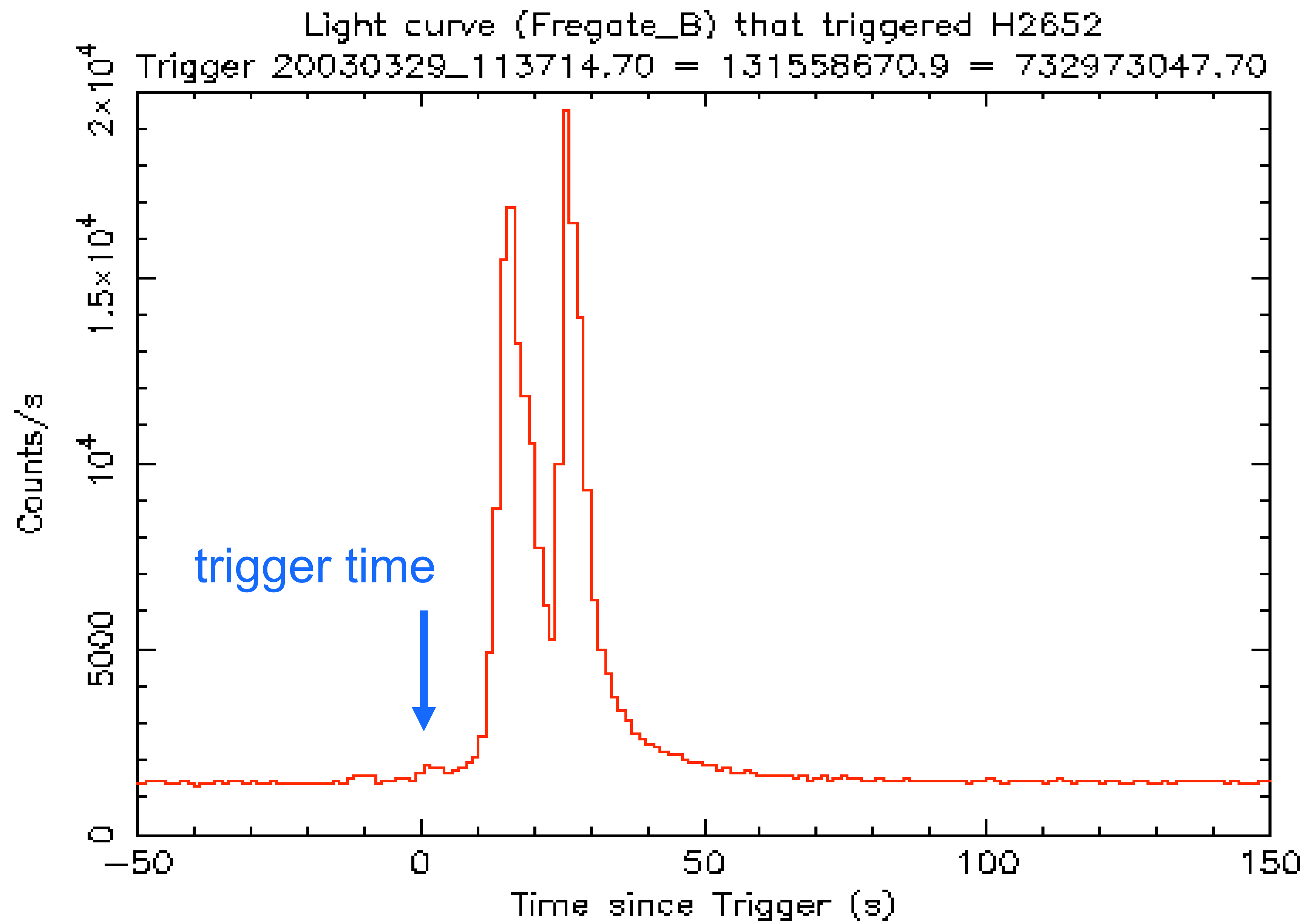
- Detected March 29 2003 by HETE-2 & Wind satellites
- One of closest ever seen with known distance
  - z=0.1685
  - d=800Mpc
- Provides strong evidence for supernova origin of long GRBs.
- LIGO was operating!
  - Hanford 2km & 4km
  - look for GWB!



http://cfa-www.harvard.edu/~tmatheson/compgrb.jpg

Signal Region for GRB030329

Gamma-ray flux measured by HETE satellite (5-120 keV band)



http://space.mit.edu/HETE/Bursts/GRB030329/

Analysis Methodology

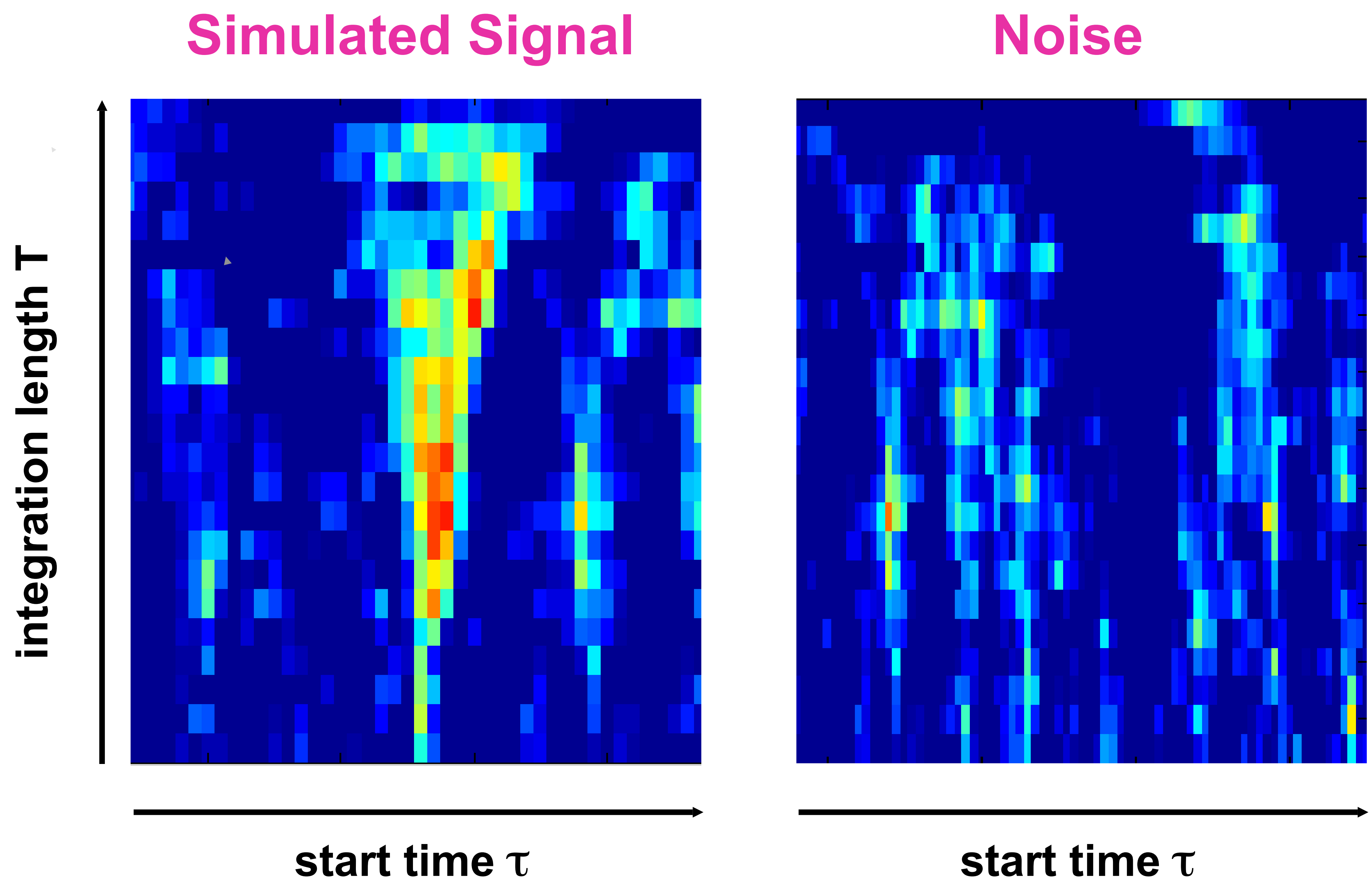
- Use data from a narrow time window centered on the gamma ray burst arrival time
- Look for cross correlations in the data from both detectors
- Compare to the correlation level of detector noise from two uncorrelated observation times

L. Finn, S. Mohanty, J. Romano, Phys. Rev. D *60* 121101 (1999)

P. Astone et al, Phys. Rev. D 66 102002 (2002): NAUTILUS & EXPLORER + 47 GRBs from BeppoSAX: $h_{rms} < 6.5 \times 10^{-19}$ at 95% confidence.

Cross-Correlation Power

Cross correlation for each start time τ, integration length T:



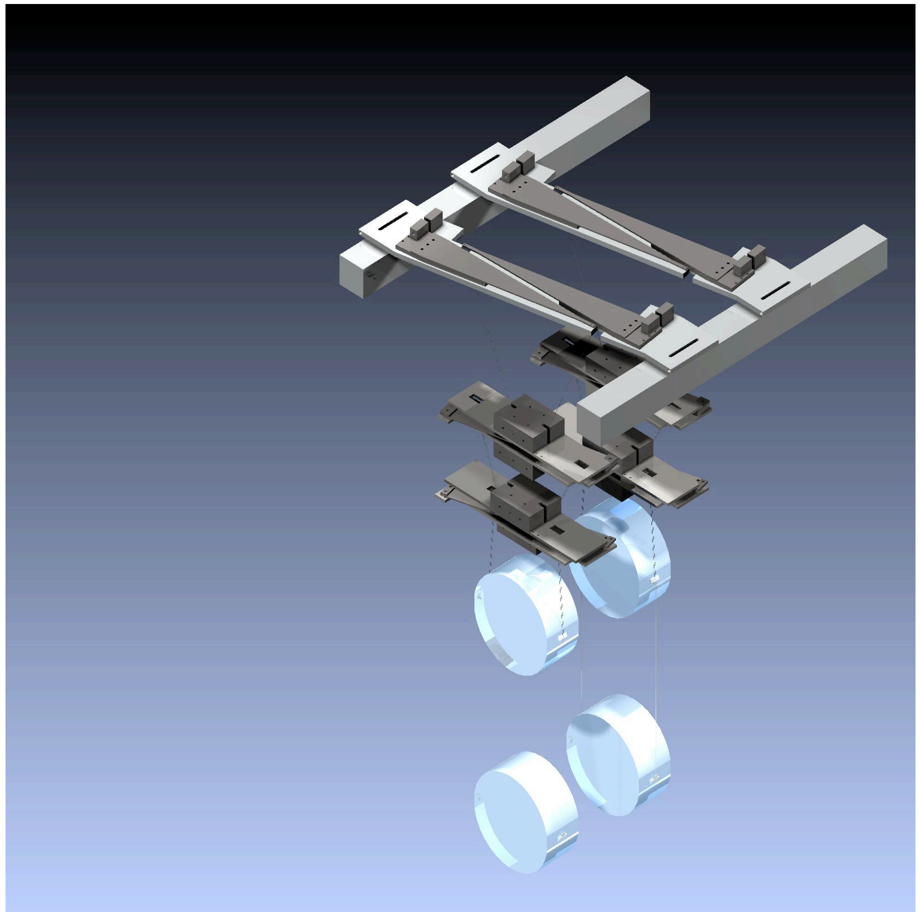
Results of search for Burst Sources

- Maximum of correlation of detector data at arrival time of gamma-ray bursts was only 1.2x the average level of uncorrelated background - statistically insignificant.
- Gravitational waves from sources of gamma ray bursts have still not been detected.

Future direction of gravitational wave astronomy

Advanced LIGO

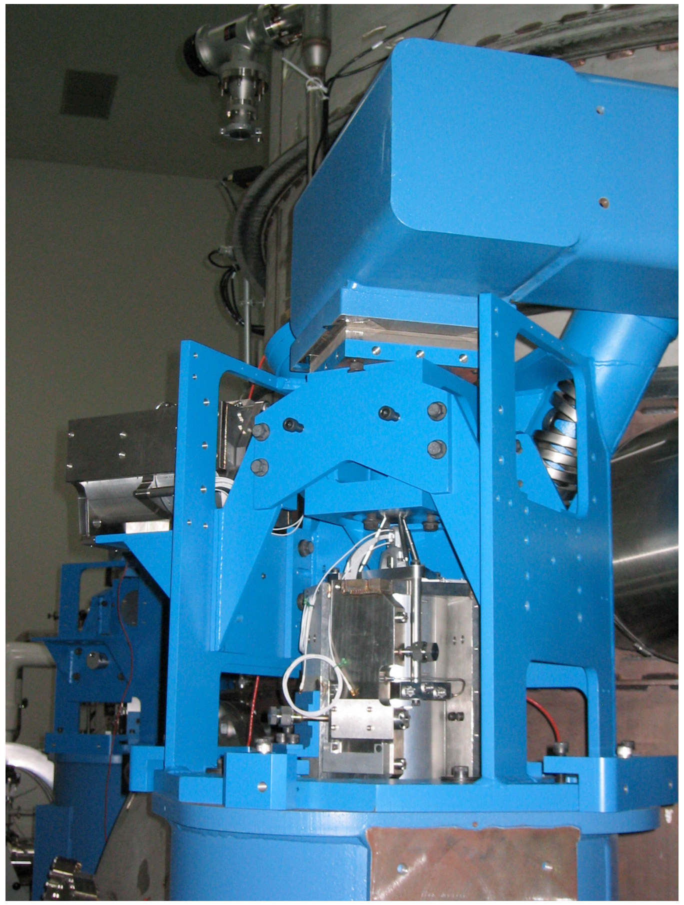
Detector Improvements:



New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in bandwidth



Improved seismic isolation:

Passive → Active

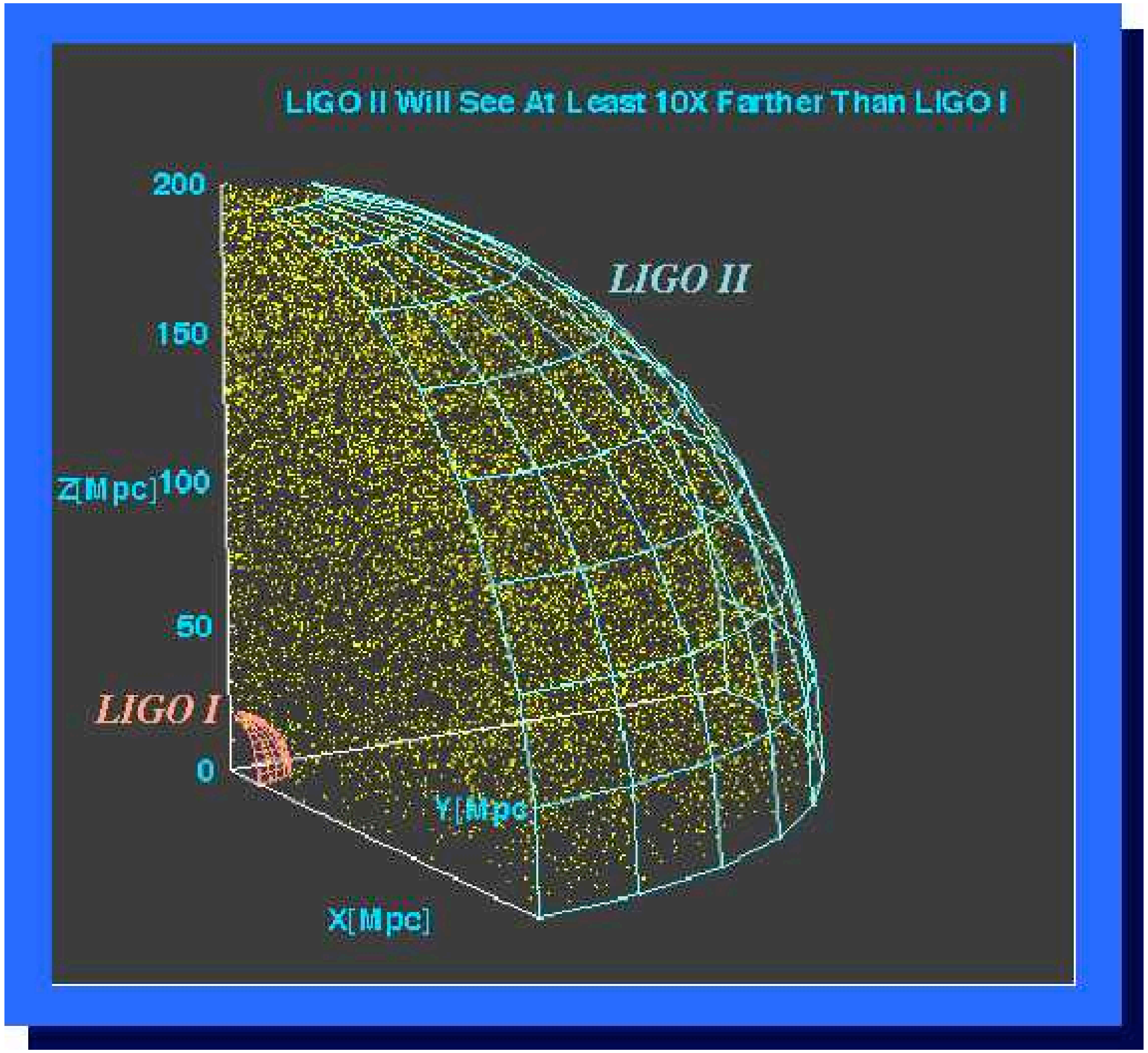
Lowers seismic “wall” to ~10 Hz

Higher power lasers:

10W → 200W

Lower shot noise floor

Advanced LIGO Reach



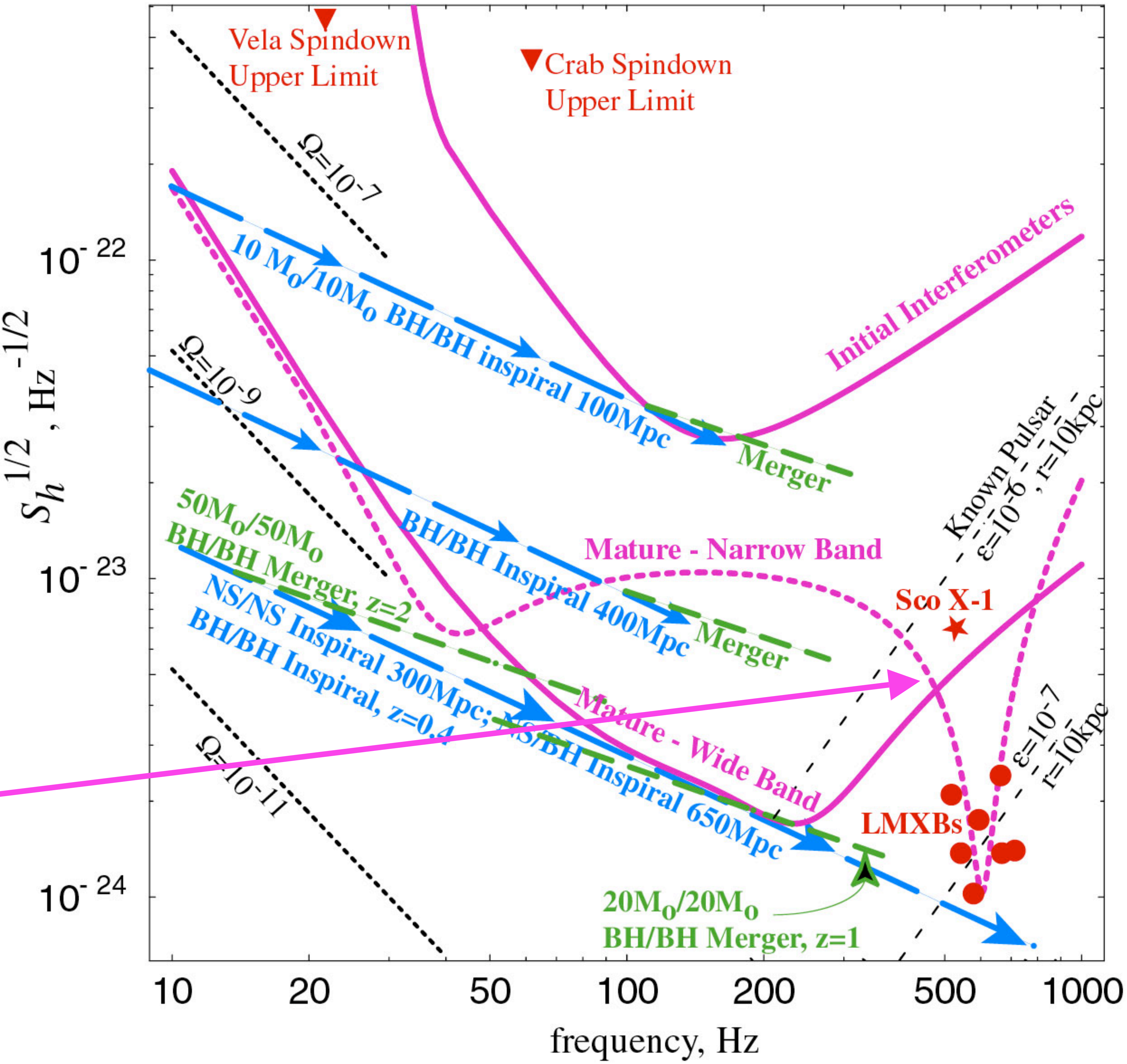
Science from the first few hours of Advanced LIGO observing should be comparable to 1 year of initial LIGO!

Advanced LIGO

Sampling of source strengths relevant to Initial LIGO and Advanced LIGO

Better peak sensitivity and wider bandwidth are both important

"Signal recycling" offers potential for tuning shape of noise curve to improve sensitivity in target band (e.g., known pulsar cluster)



LIGO

Summary

- Einstein's prediction that gravity is a warping of space-time that can support traveling waves is being tested by a worldwide network of gravitation wave observatories
- The challenge of detection is immense, due to the minute scale of the curvature being measured
- Initial observations place an "upper limit" on the event rate of various sources of gravitational waves
- As detector sensitivity improves the exciting prospects of initial detection and the birth of a new field of gravitational astronomy are becoming quite high. Stay tuned…

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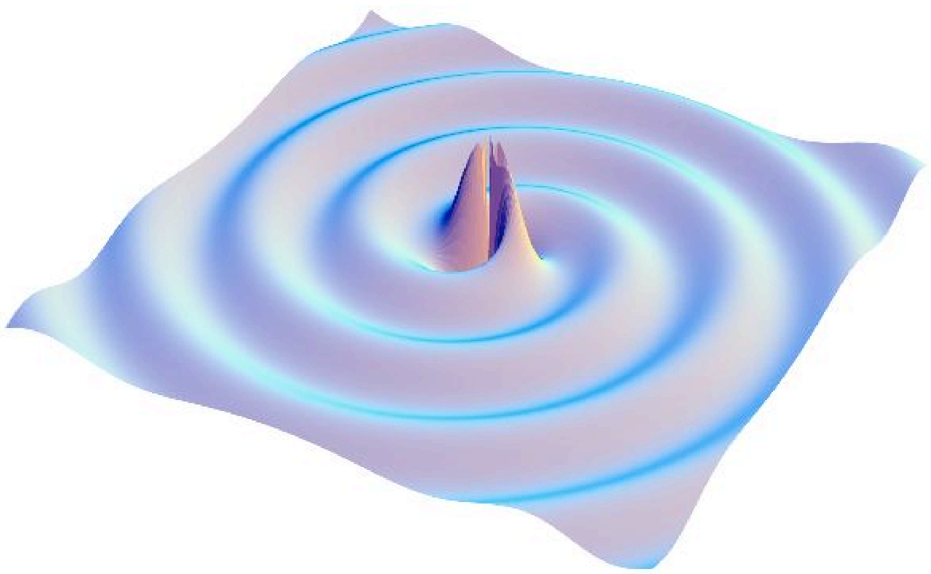

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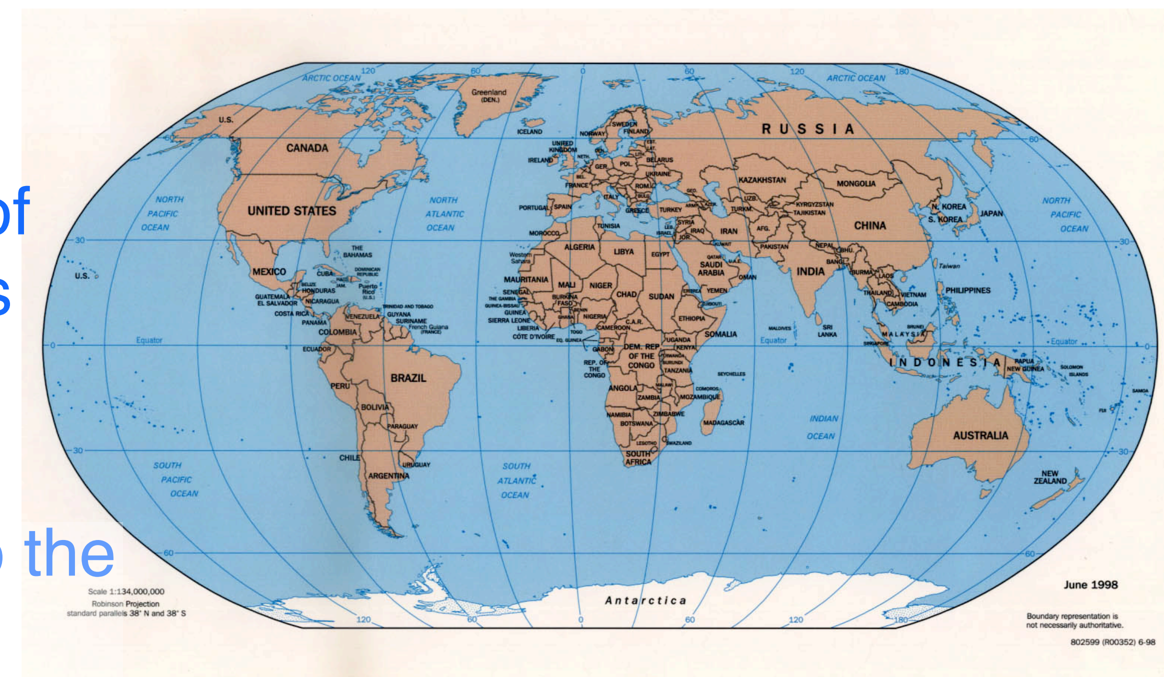

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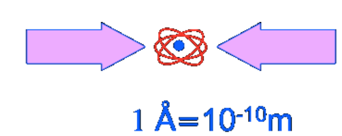

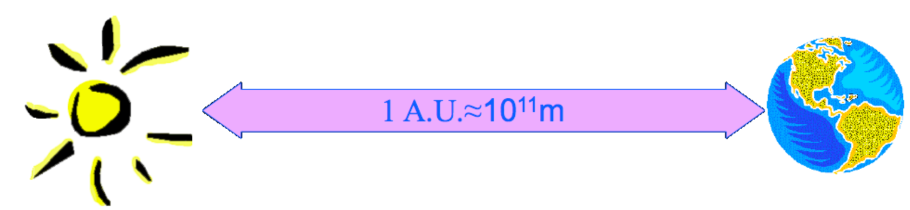

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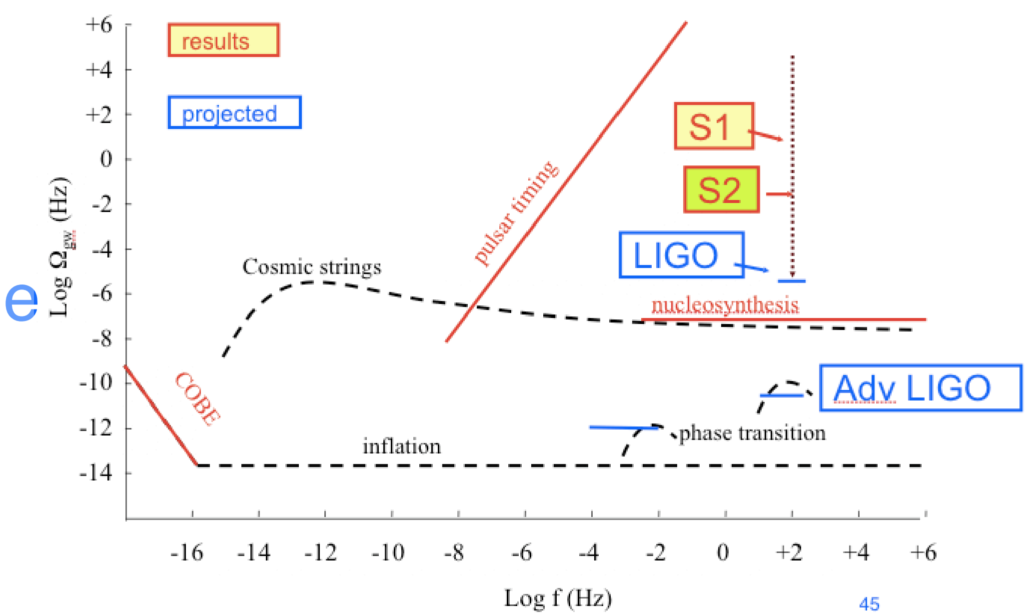

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