LIGO & the Search for Gravitational Waves

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Overview

- Background
  - Relativity and gravitational waves
  - Sources of gravitational wave

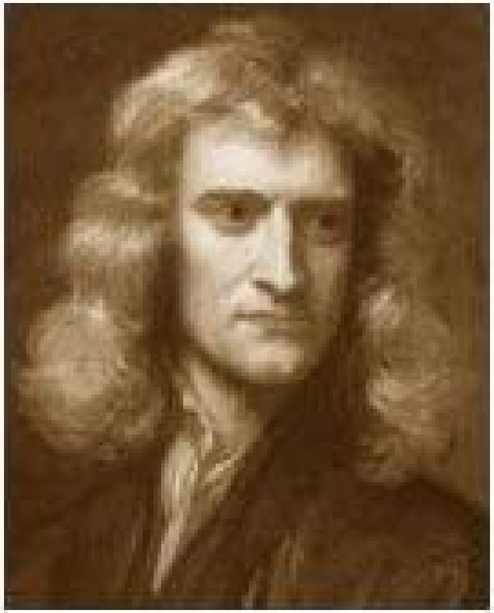
- Detectors
  - Principle of interferometic detectors
  - LIGO systems and operations

- Data Analysis
  - Search for Black Hole Ringdowns in LIGO S4 data

Theory of Gravity

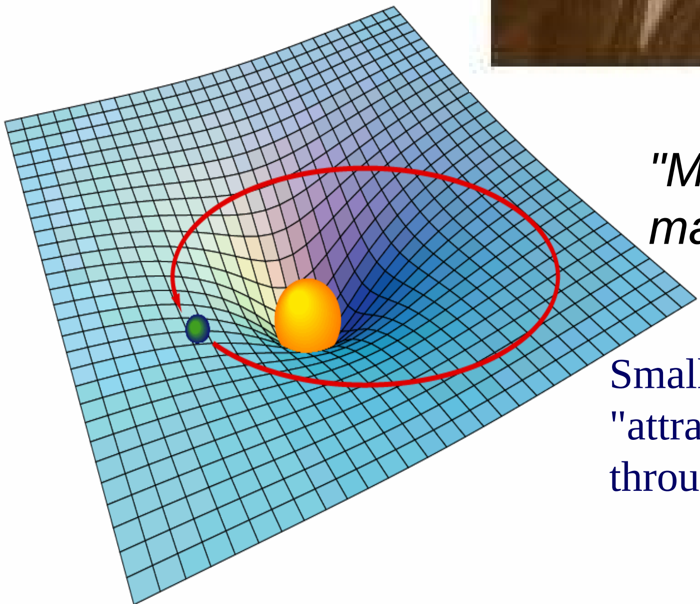
Newton

• instantaneous action at a distance



Einstein

• gravitational interaction mediated by a deformation of space-time

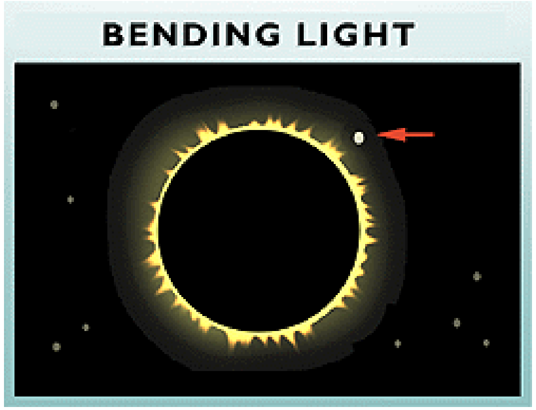


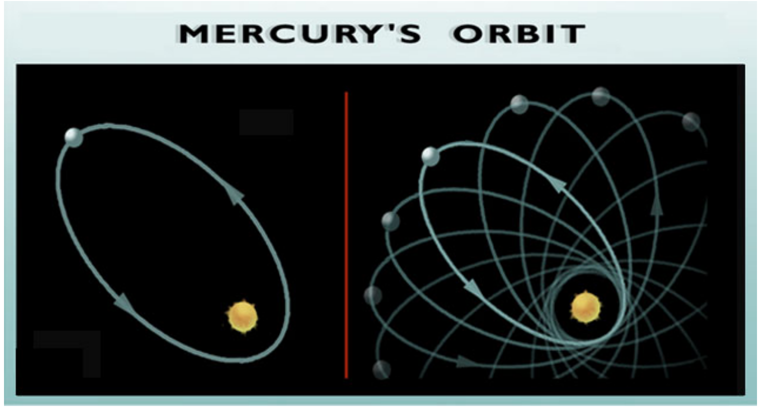
"Mass tells space-time how to curve, and space-time tells mass how to move." J. A. Wheeler

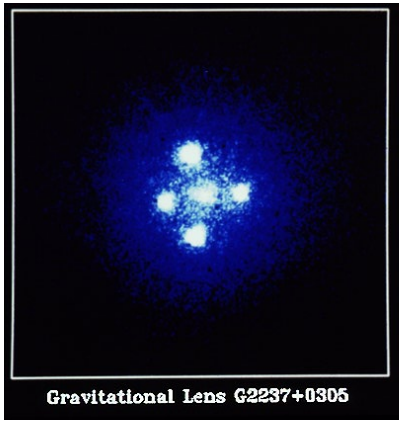
Smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object.

Einstein's Theory of Gravitation

experimental tests







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

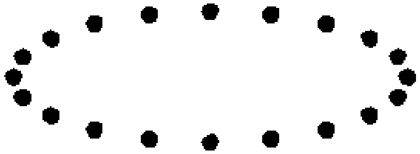
Quasar image appears around the central glow formed by nearby galaxy. Such gravitational lensing images are used to detect a 'dark matter' body as the central object

Gravitational Waves

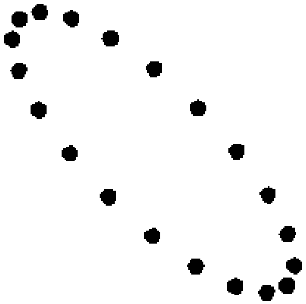
When matter moves, or changes its configuration, its gravitational field changes. This change propagates outward, at the speed of light, as a ripple in the curvature of space-time: a gravitational wave.

Waves deform space itself, stretching it first in one direction, then in the perpendicular direction.

Gravitational waves are a superposition of plus and cross polarizations



Plus polarization



Cross polarization

Indirect Evidence of GW's

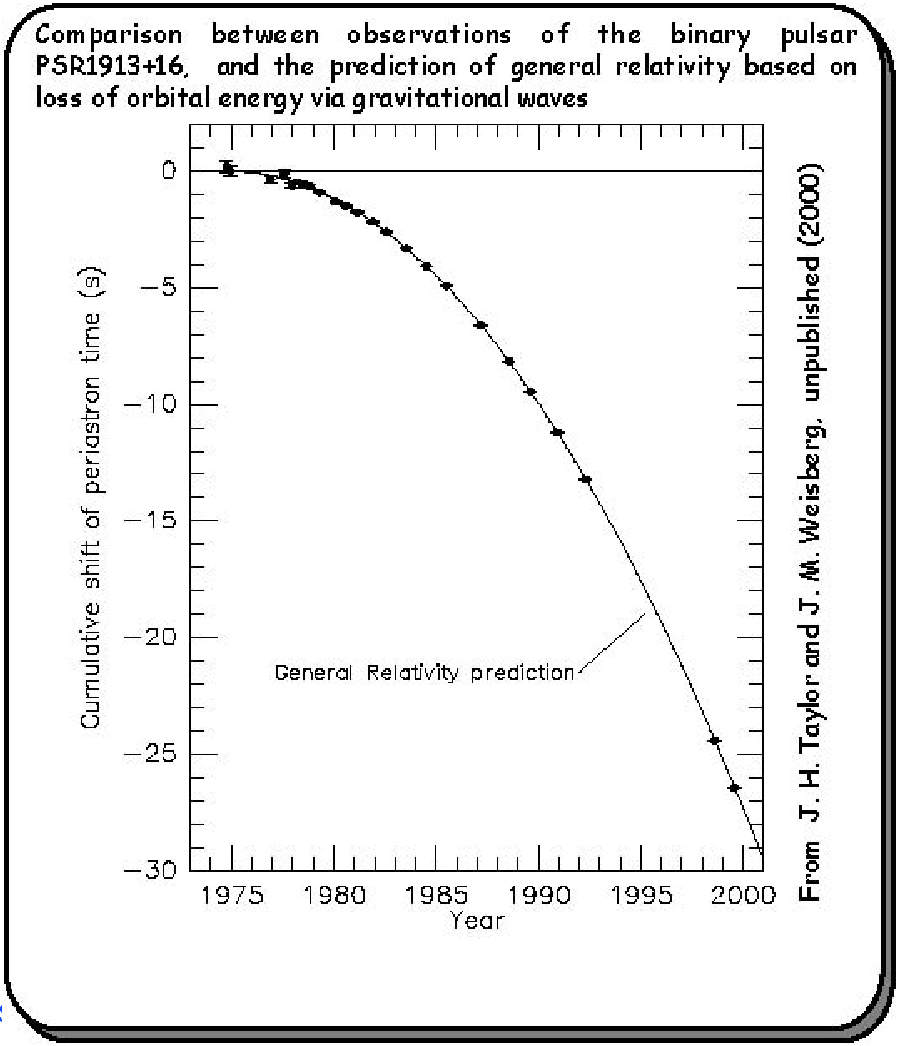
• Radio pulsar B1913+16, discovered in 1974 by Hulse and Taylor, is in a close orbit around an unseen companion

• Long-term radio observations have yielded neutron star masses (1.44 and 1.39 $M_{\odot}$) and orbital parameters

• System shows very gradual orbital decay – just as general relativity predicts!

⇒ Very strong indirect evidence for gravitational radiation

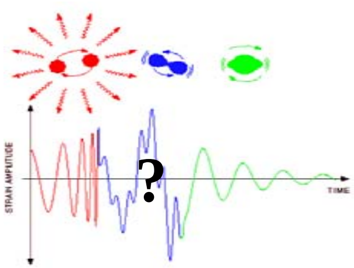
Emission of gravitational waves



Gravitational Wave Sources

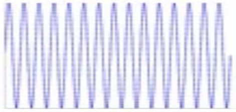
Compact binaries

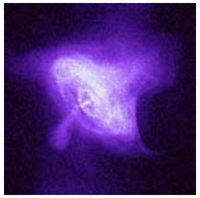
- Black holes & neutron stars
- Inspiral and merger
- Probe internal structure, populations, and spacetime geometry



Spinning neutron stars

- Isolated neutron stars with mountains or wobbles
- Low-mass x-ray binaries
- Probe internal structure and populations

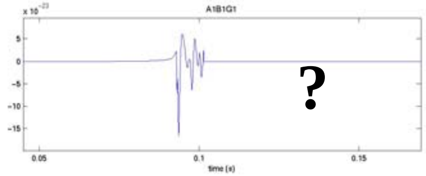




Crab pulsar (NASA, Chandra Observatory)

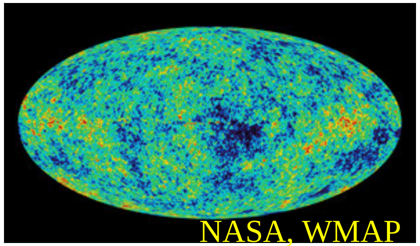
Bursts

- Neutron star birth, tumbling and/or convection
- Cosmic strings, black hole mergers, ...
- Correlations with electro-magnetic observations
- Surprises!



Stochastic background

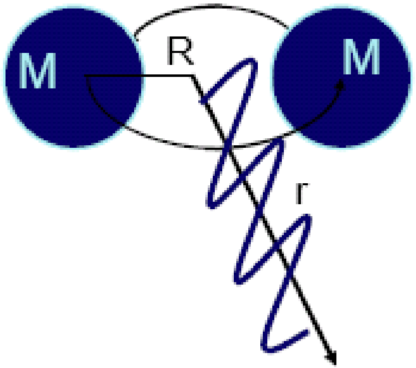
- Big bang & early universe
- Background of gravitational wave bursts



Gravitational Wave Strain

The stretching is described by a dimensionless strain. For a binary neutron star

$$|h| \approx \frac{4\pi^2 GMR^2 f_{orbit}^{\,2}}{c^4 r}$$



We can calculate the expected strain at Earth for a neutron star binary in the Virgo cluster;

$$M \approx 10^{30} kg$$

$$R \approx 20km$$

$$f_{orbit} \approx 400Hz$$

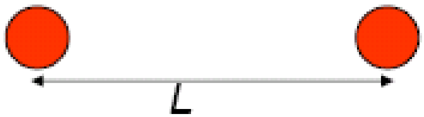
$$r \approx 10^{23} m$$

$$h \approx 10^{-21}$$

Detection Challenge

The stretching is described by a dimensionless strain, ***h*** = ΔL / L

Consider simplest detector –two free masses a distance *L* apart whose separation is monitored.



If *L* = 4km, then the change in length produced by a gravitational wave from binary neutron star in the Virgo cluster is

$$\Delta L = h \times L \approx 10^{-21} \times 4{,}000\, m \approx 10^{-18}\, m$$

1/1000th the size of a proton!!

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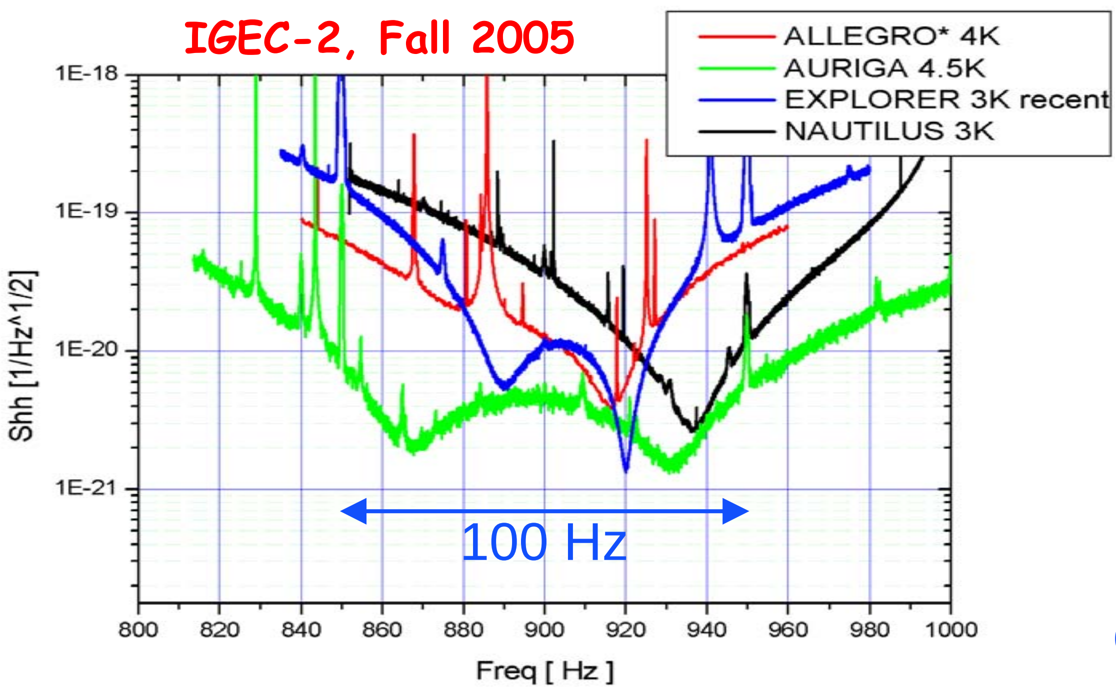
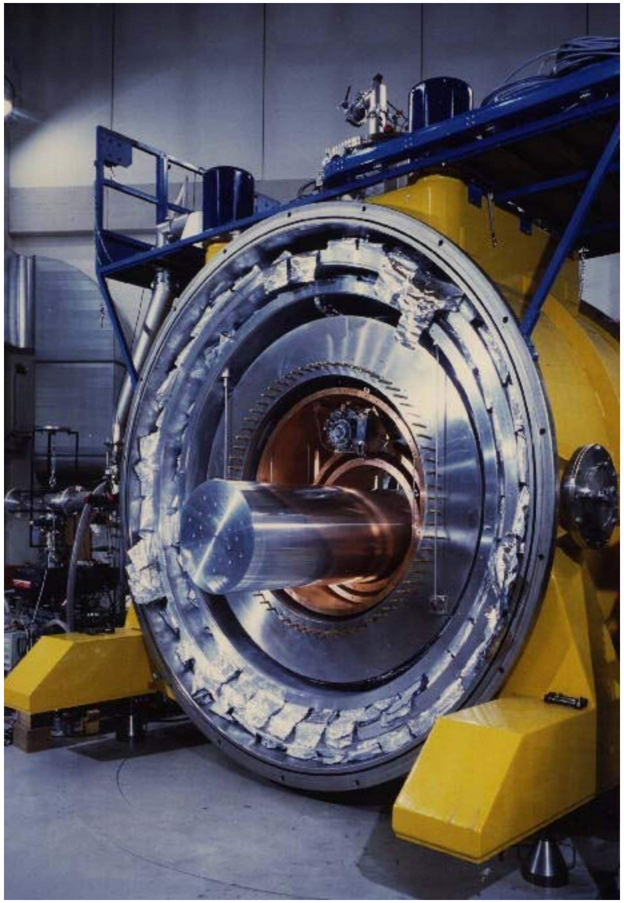
Resonant Bar Detectors

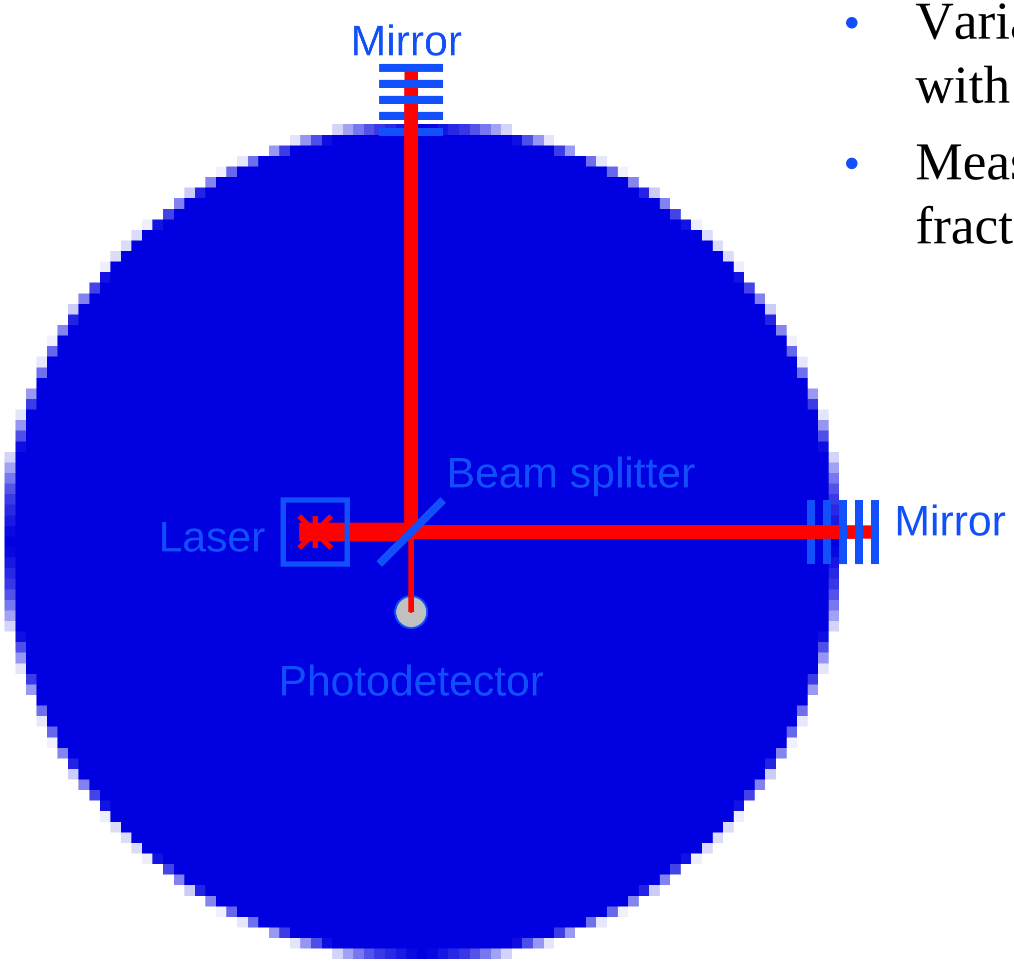
- 2.3 ton aluminum cylinder, 3m long
- Cooled to 0.1K with dilution fridge in LiHe cryostat
- Gravitational wave causes it to ring at resonant frequencies near 900 Hz
  - ➢Picked up by electromechanical transducer
  - ➢Sensitive in fairly narrow frequency band





AURIGA detector (open)

Laser Interferometers



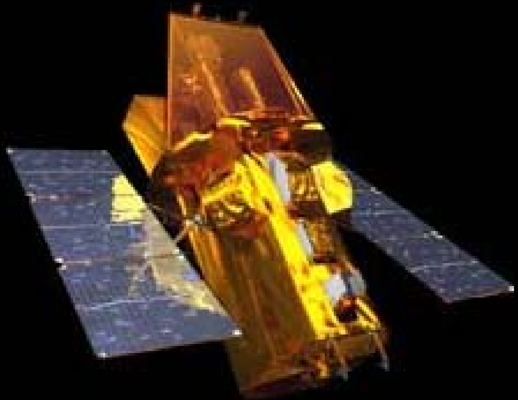
- Variations on basic Michelson design, with two long arms
- Measure *difference* in arm lengths to a fraction of a wavelength

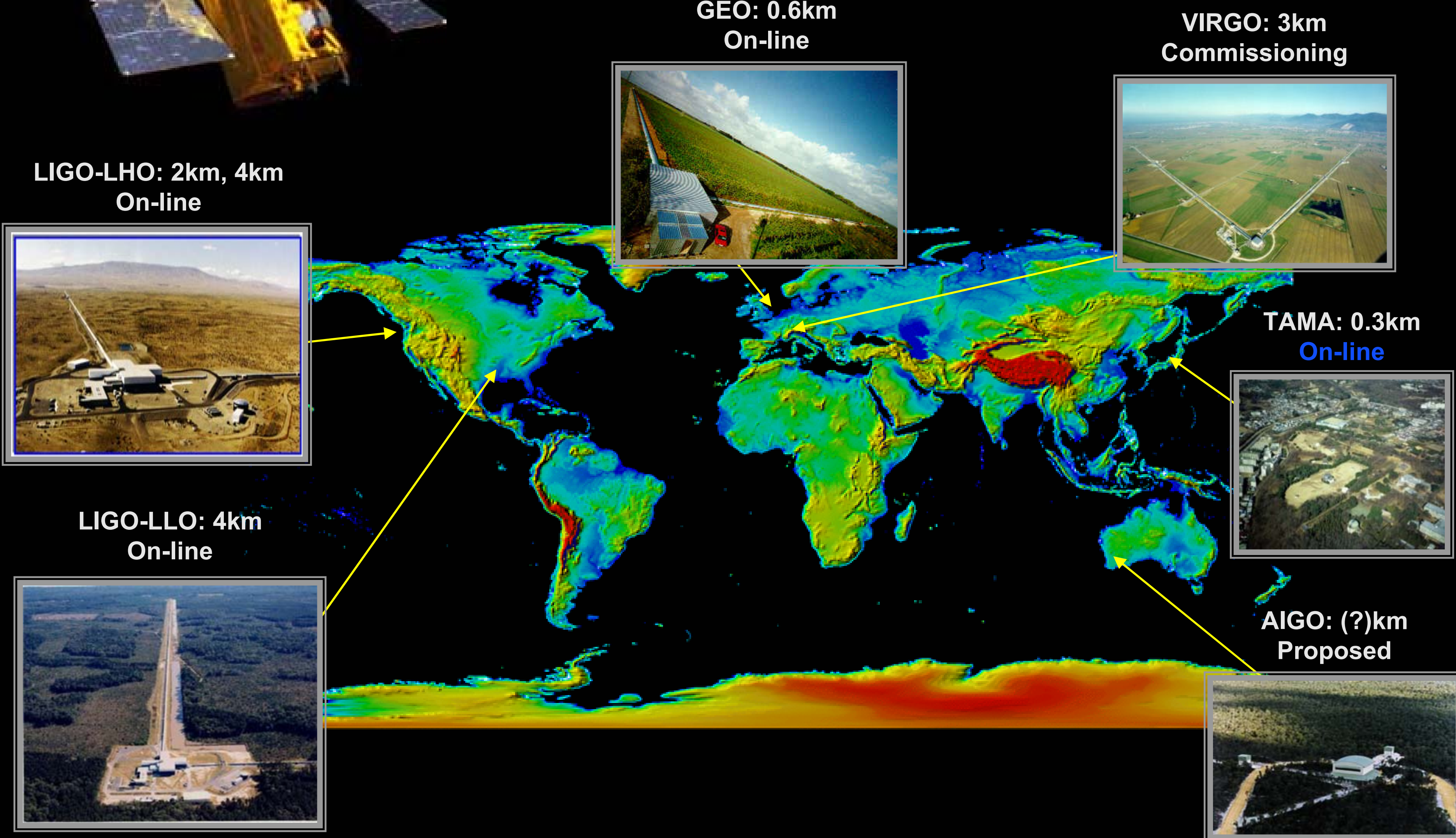
Effective lengths of interferometer arms are affected by a gravitational wave —
An ideal detector !

Growing International Network of GW Interferometers

Operated as a phased array:

- Enhance detection confidence
- Localize sources
- Decompose the polarization of gravitational waves
- Triggers from EM detectors





The LIGO Observatory Sites

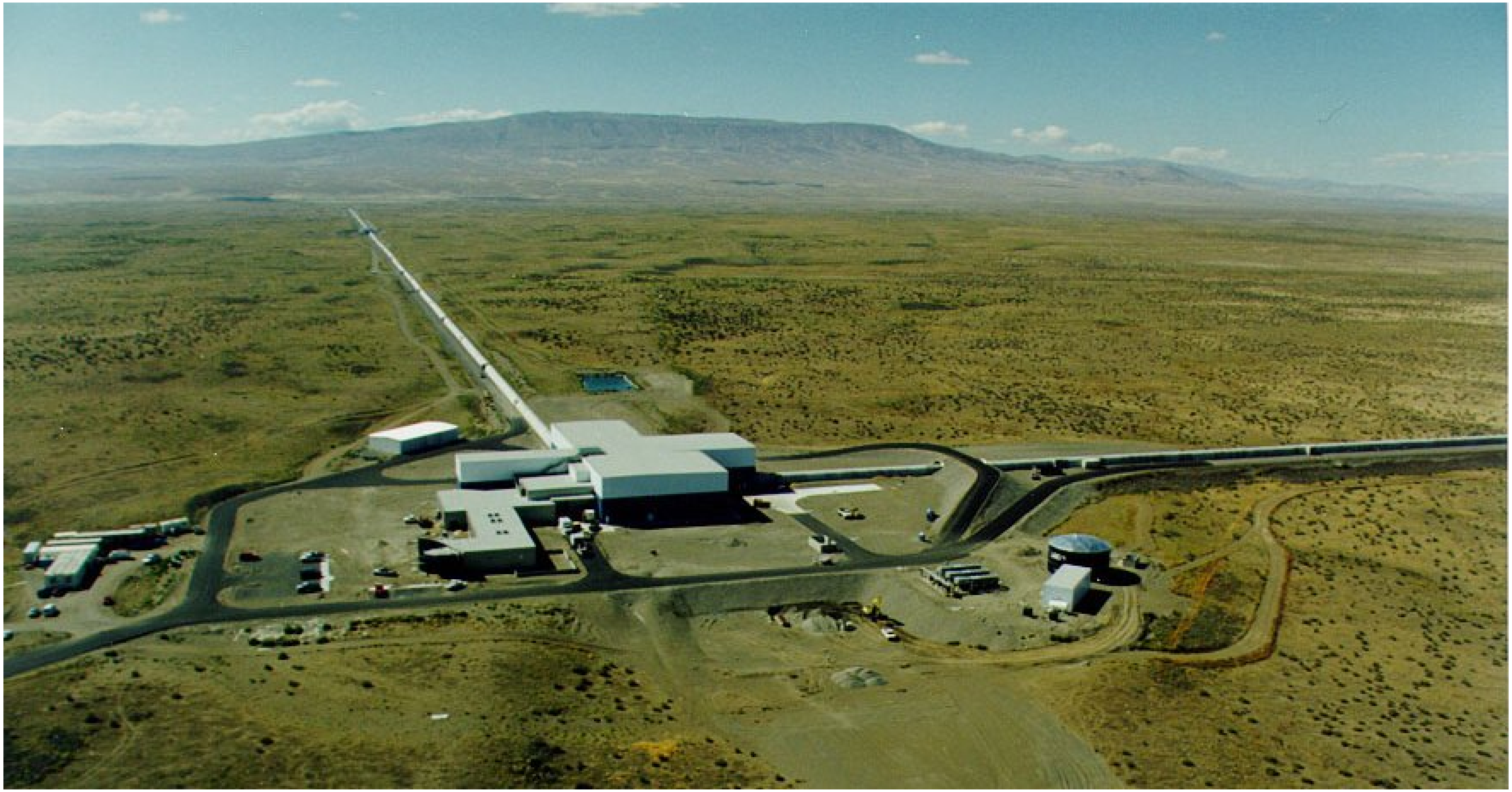
Interferometers are aligned along the great circle connecting the sites

- Adapted from "The Blue Marble: Land Surface, Ocean Color and Sea Ice" at visibleearth.nasa.gov
- NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

The LIGO Scientific Collaboration

LIGO Hanford Observatory

Located on DOE Hanford Nuclear Reservation north of Richland, Washington



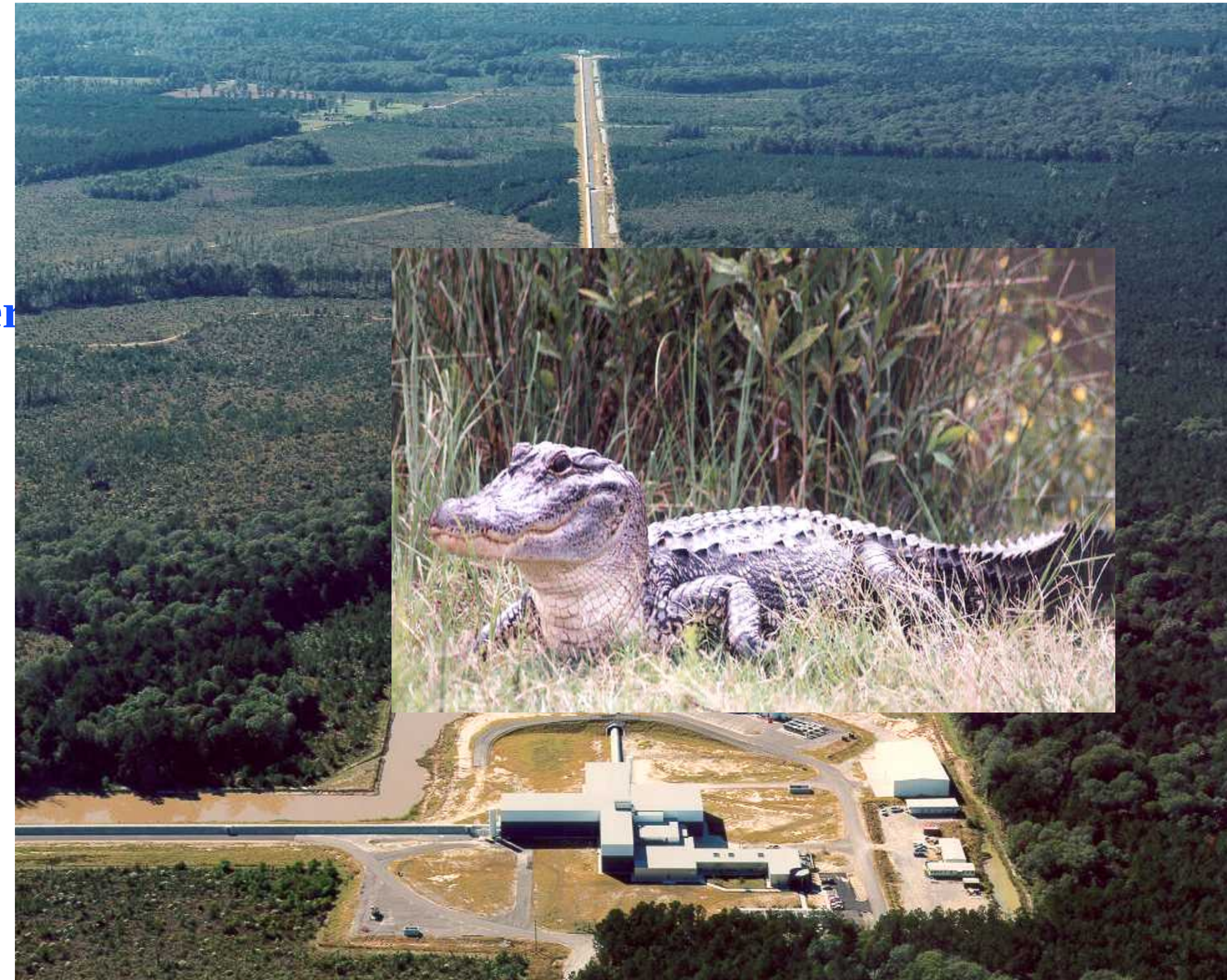
Two separate interferometers (4 km and 2 km arms) coexist in the beam tubes

LIGO Livingston Observatory

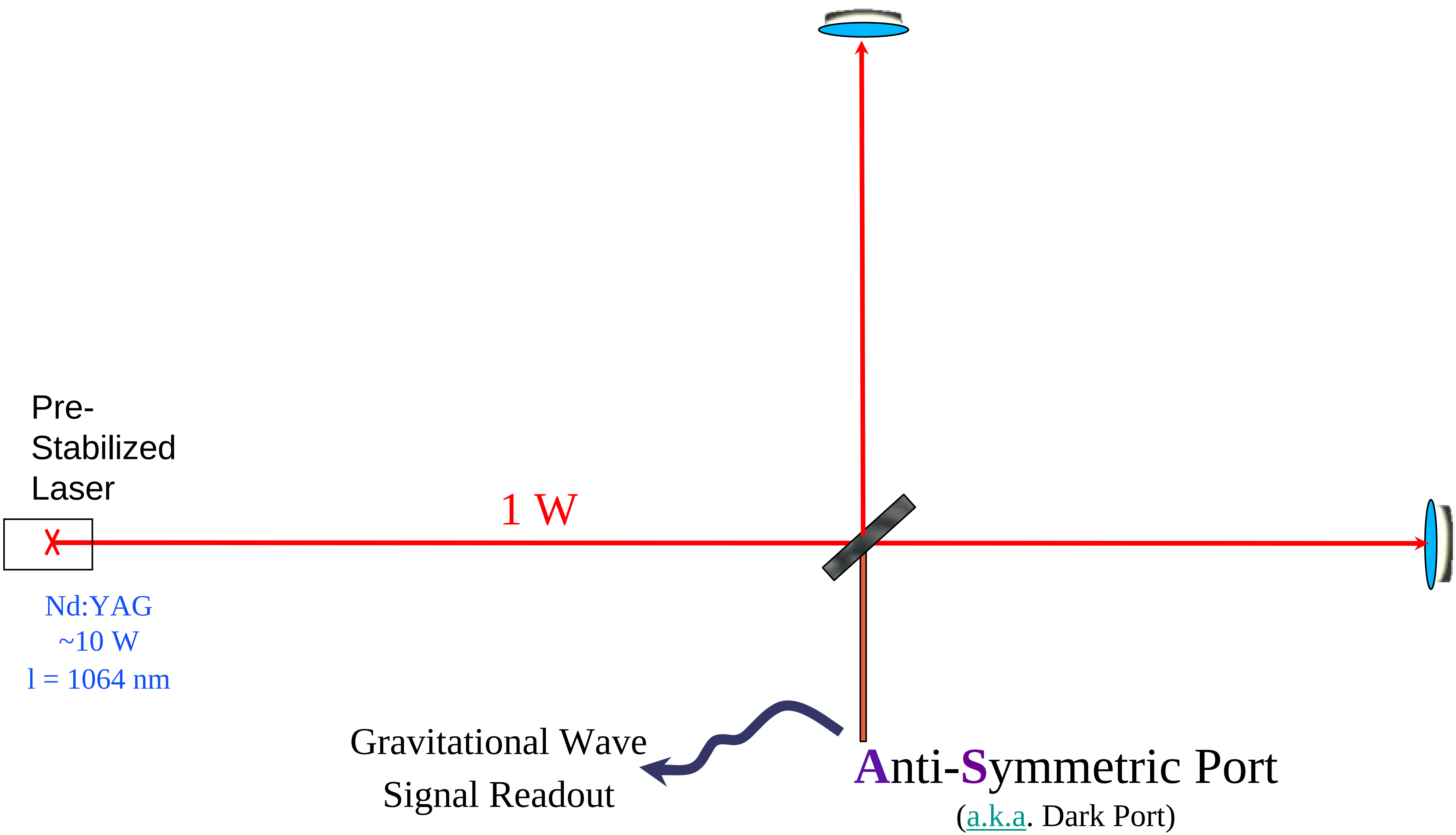
- Located in a rural area of Livingston Parish east of Baton Rouge, Louisiana
- One interferometer with 4 km arms

N.B.: Minimal damage from Katrina

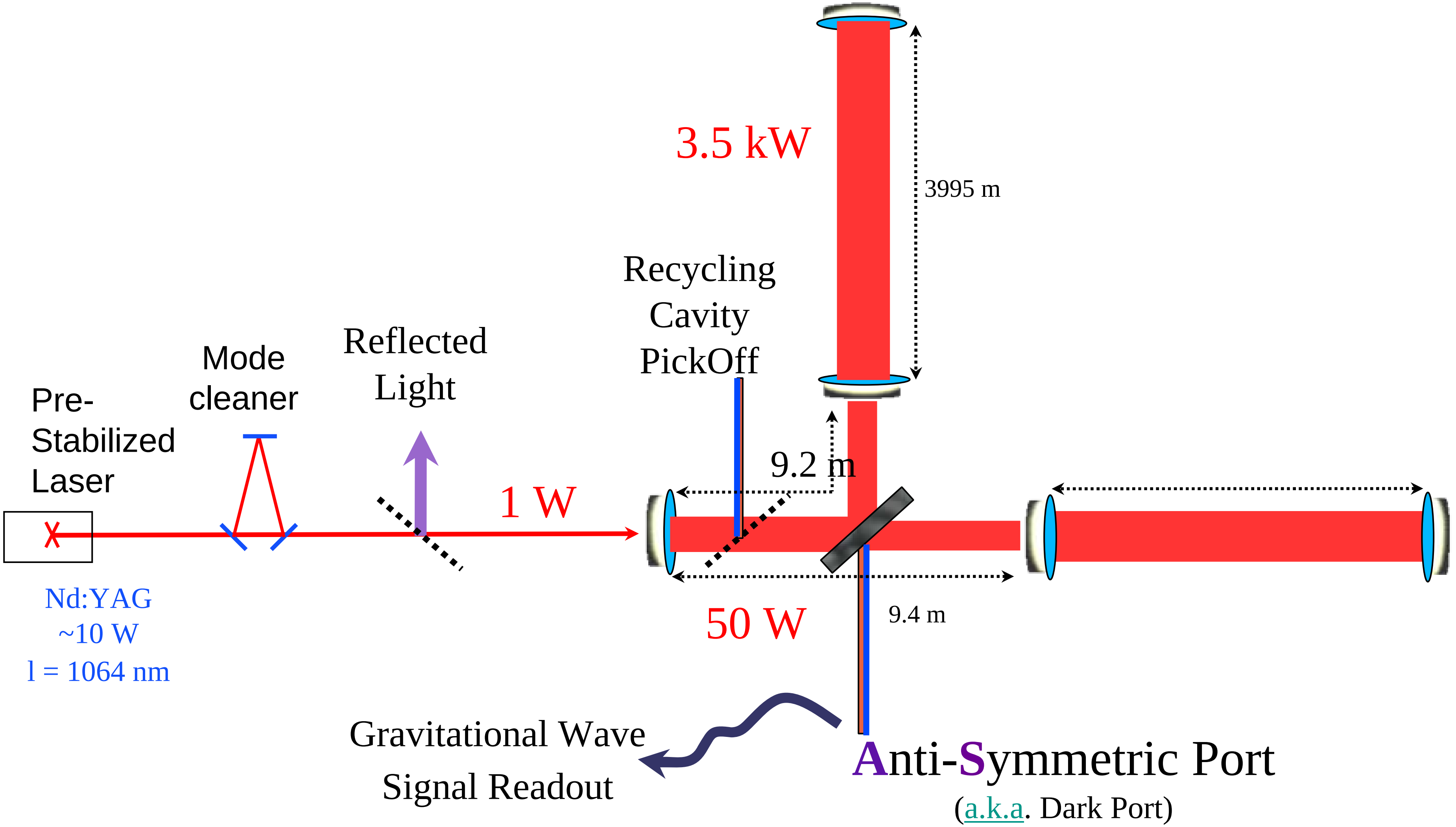
NASA/Jeff Schmaltz, MODIS Land Rapid Response Team



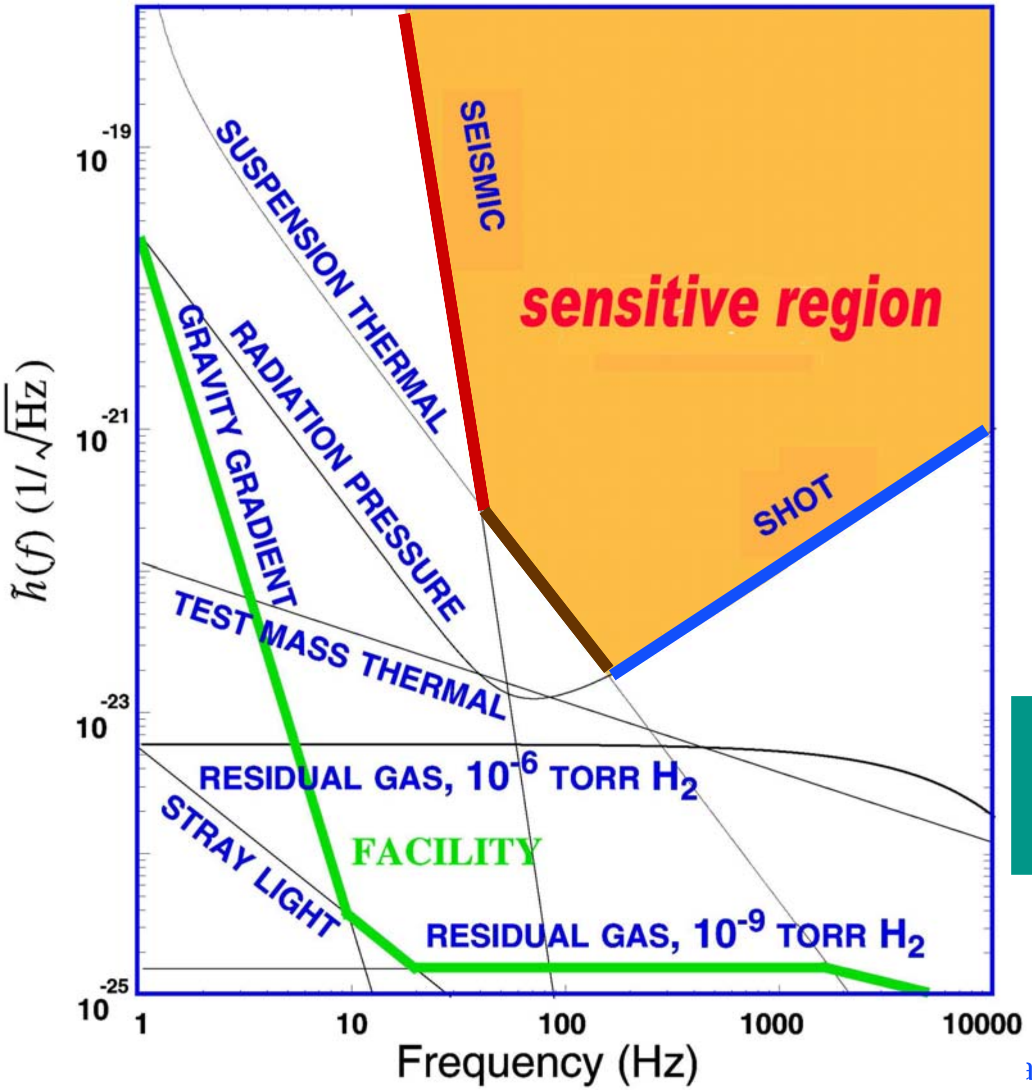
LIGO Interferometer

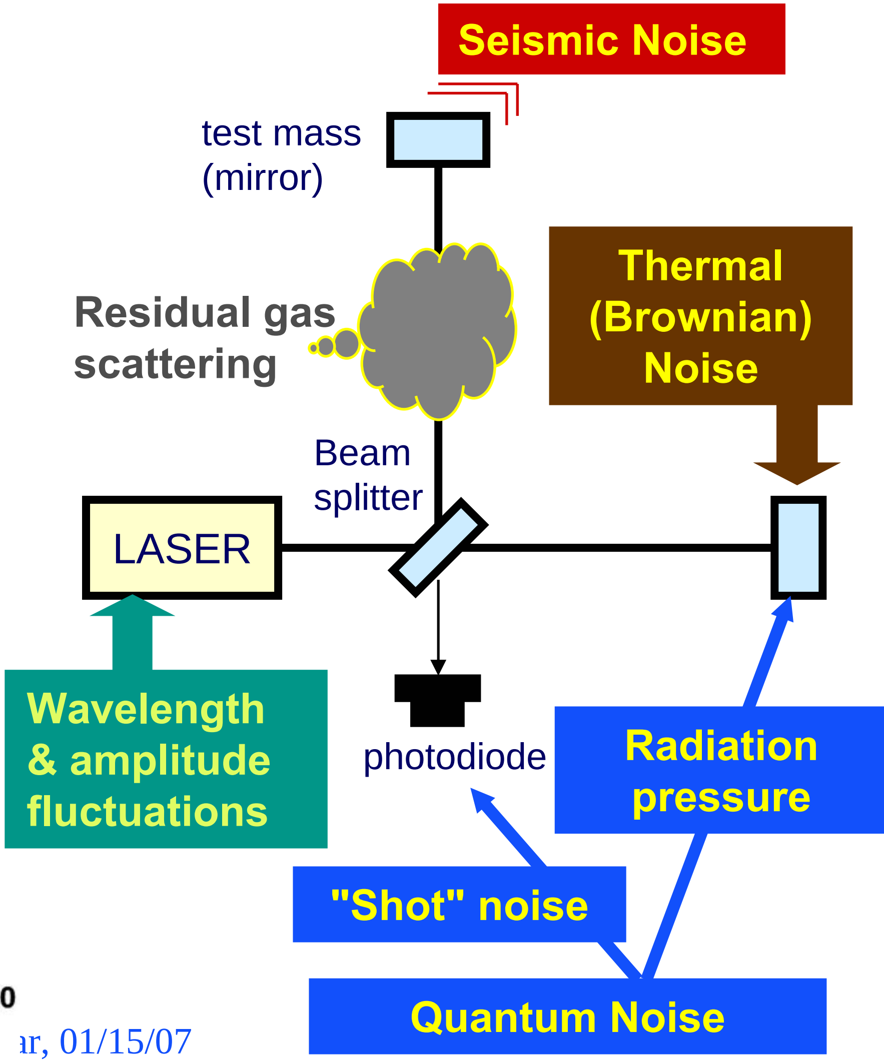


LIGO Interferometer



Initial LIGO Sensitivity Limits





Pre-Stabilized Laser

• Based on a 10-Watt Nd:YAG laser (infrared)

• Uses additional sensors and optical components to locally stabilize the frequency and intensity

• Final stabilization uses feedback from average arm length

Beam Tubes and Enclosures

Precast concrete enclosure: *bulletproof*

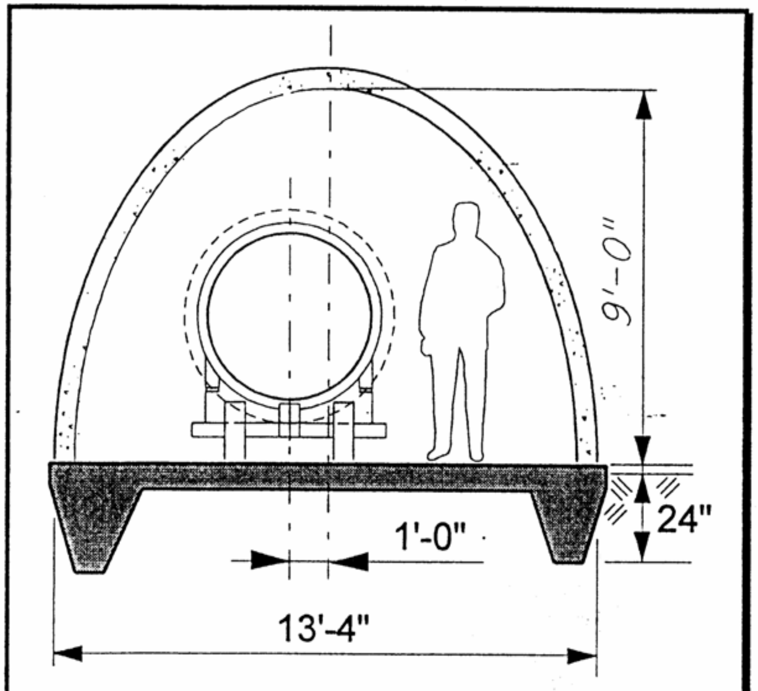


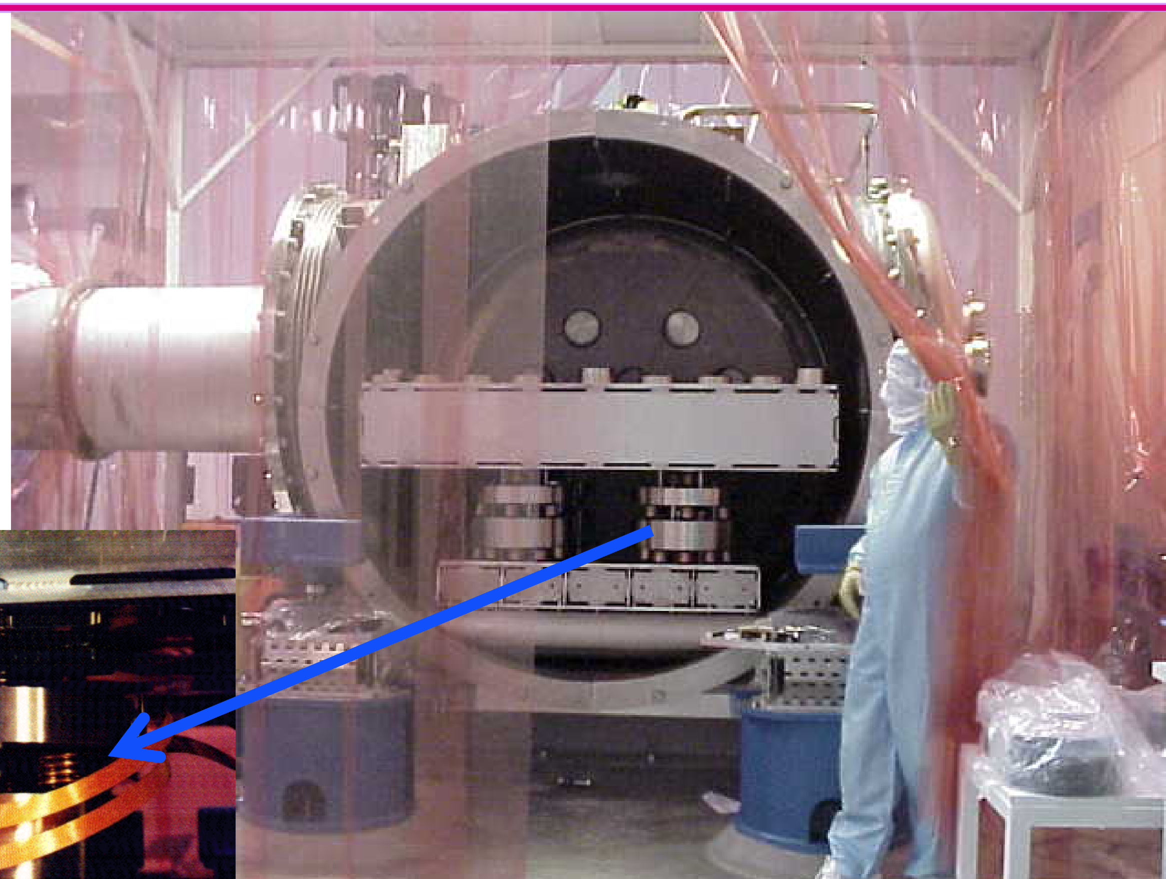
Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

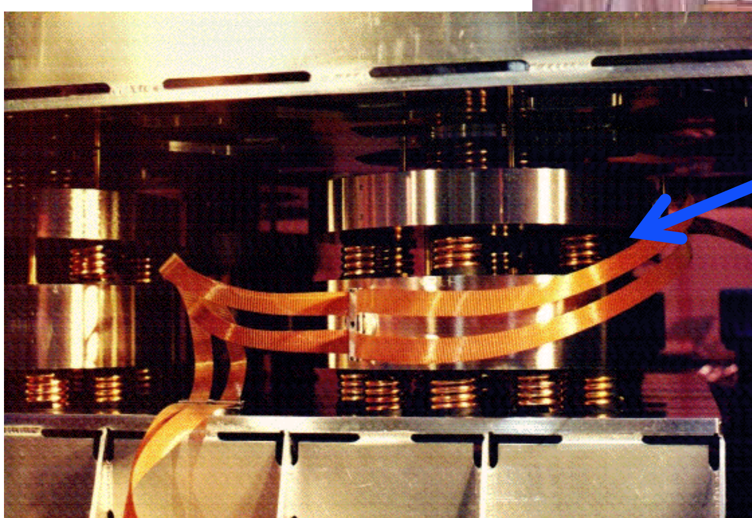
- **Beam Tube**
  - **1.2m diam; 3 mm stainless**
  - **special low-hydrogen steel process**
  - **65 ft spiral weld sections**
  - **50 km of weld (NO LEAKS!)**
  - **20,000 m³ @ 10^{-8} torr; earth's largest high vacuum system**

Vacuum Equipment

Seismic Isolation System

Tubular coil springs with internal constrained-layer damping, layered with reaction masses

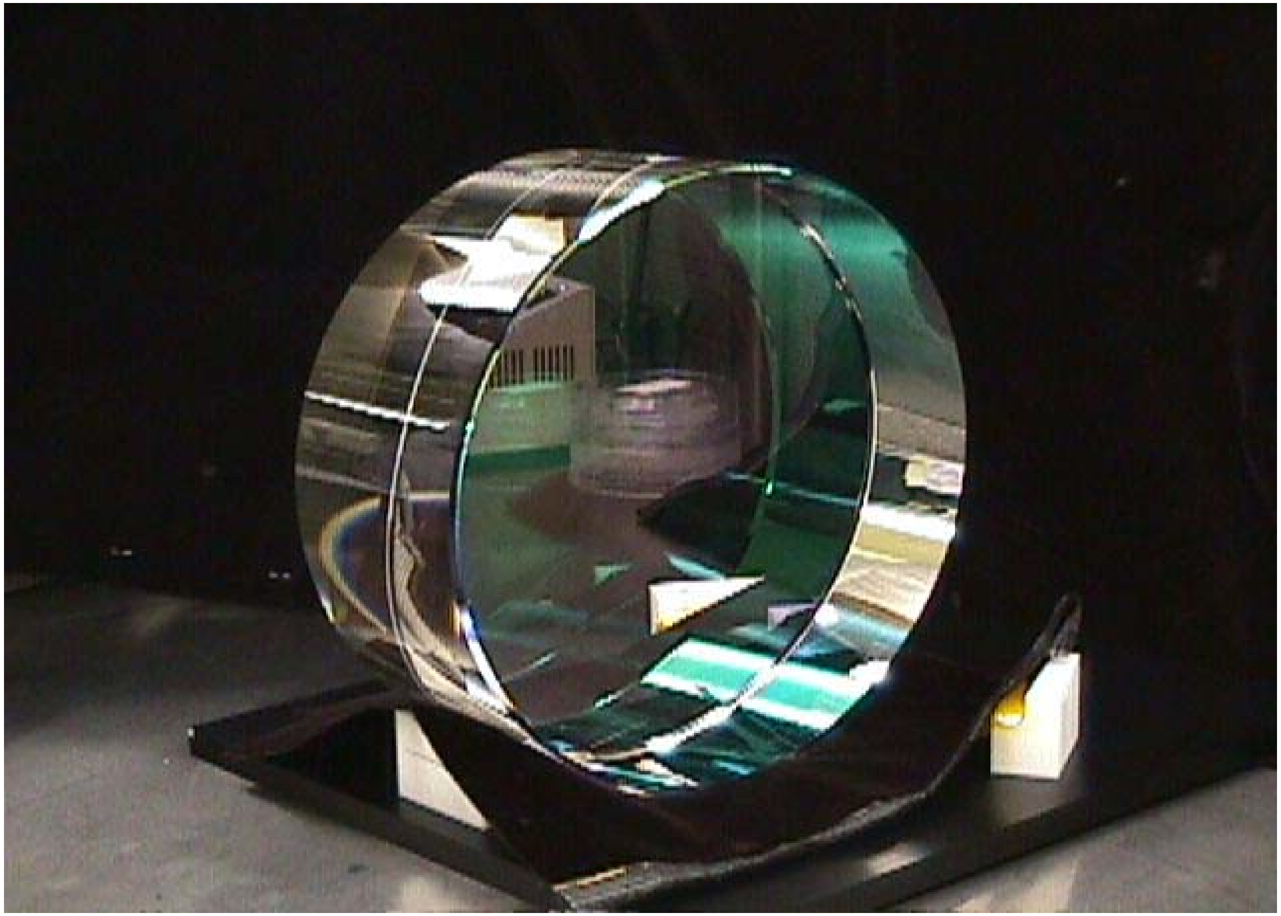




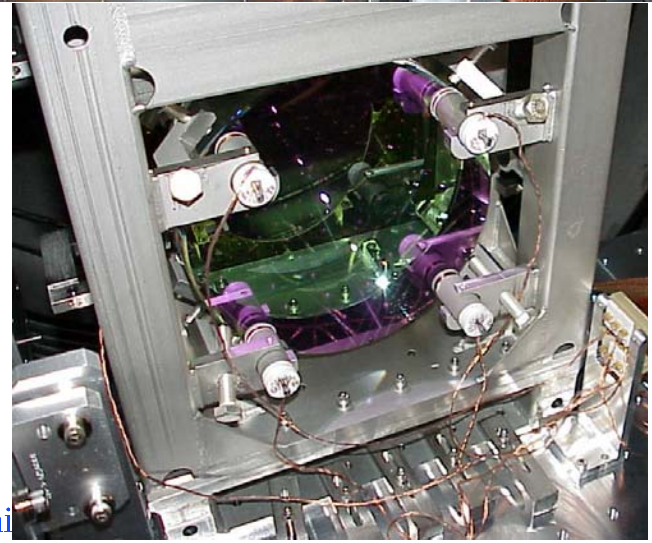
Isolation stack in chamber

Core Optics

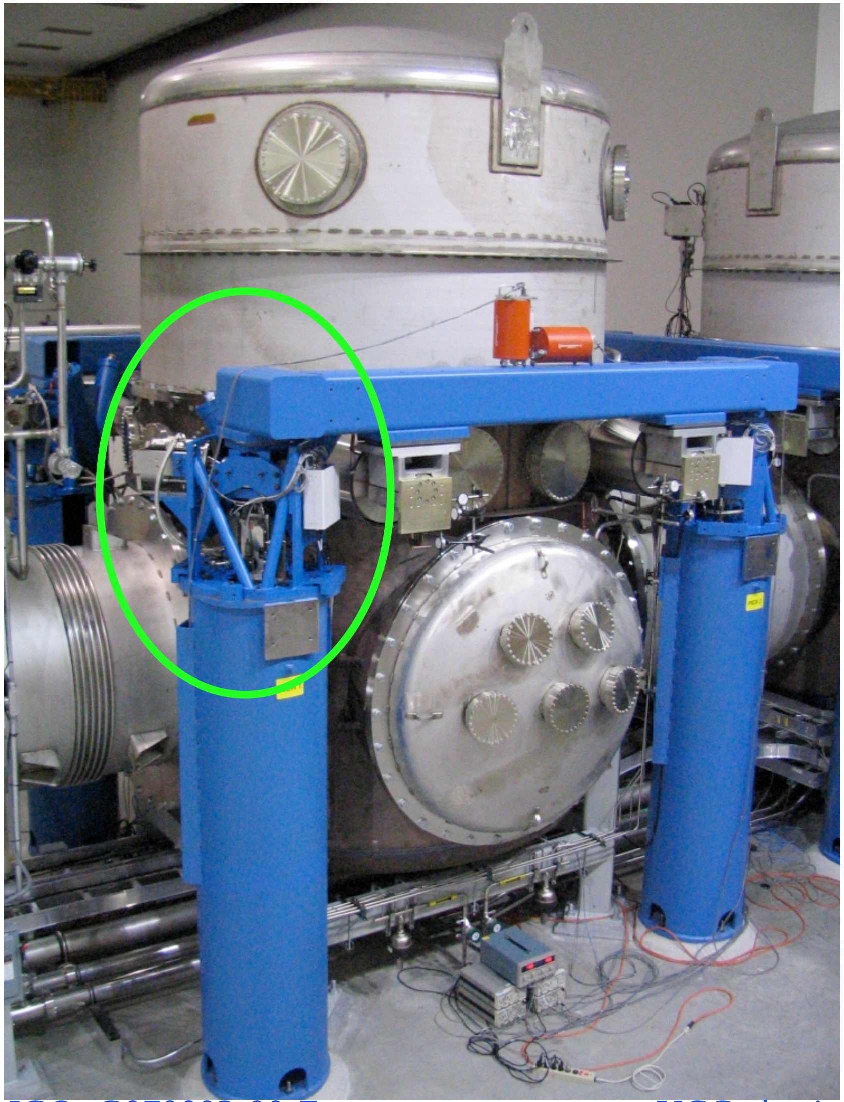
- Made of high-purity fused silica
- Largest mirrors are 25 cm diameter, 10 cm thick, 10.7 kg
- Surfaces polished to ~1 nm rms, some with slight curvature
- Coated to reflect with extremely low scattering loss (<50 ppm)



Core Optic Suspensions

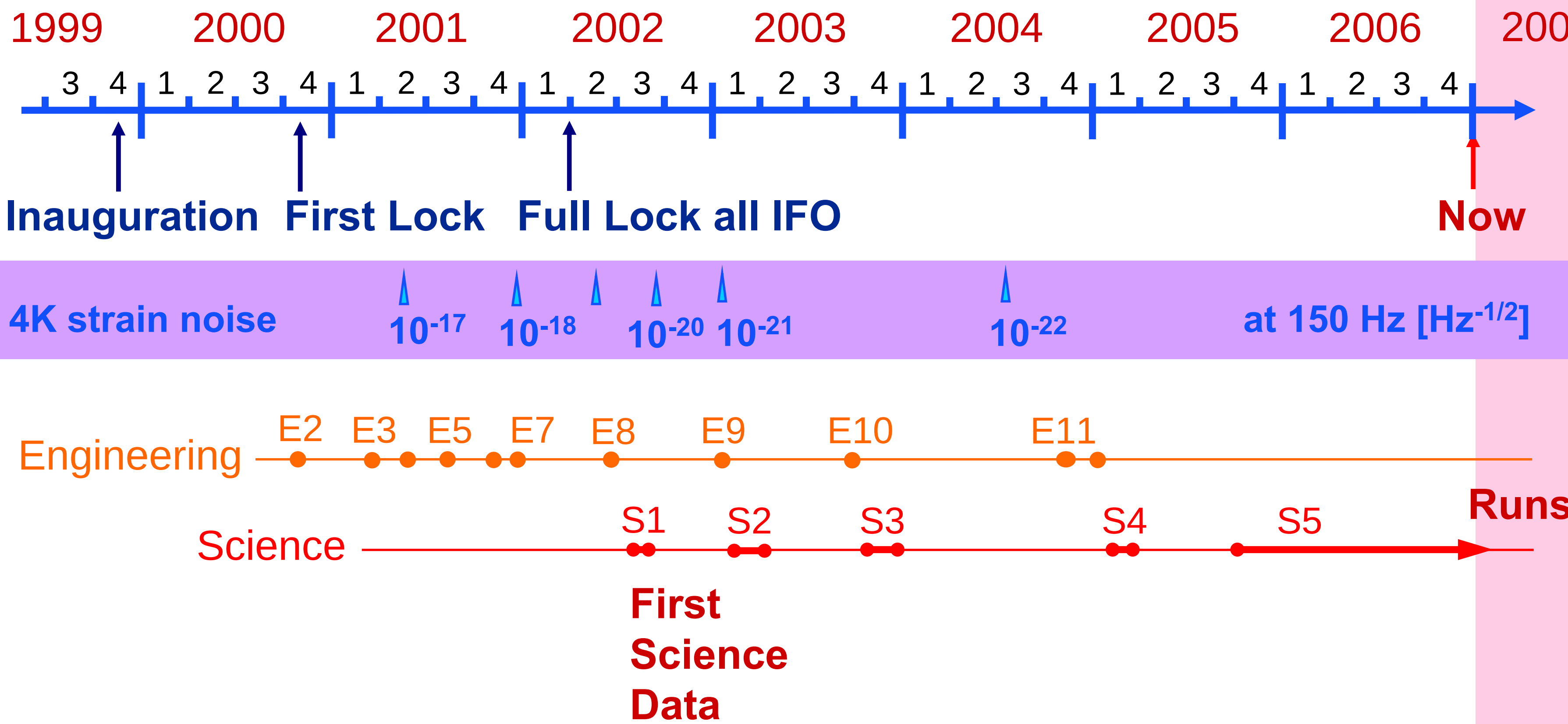


Active Seismic Isolation at LLO



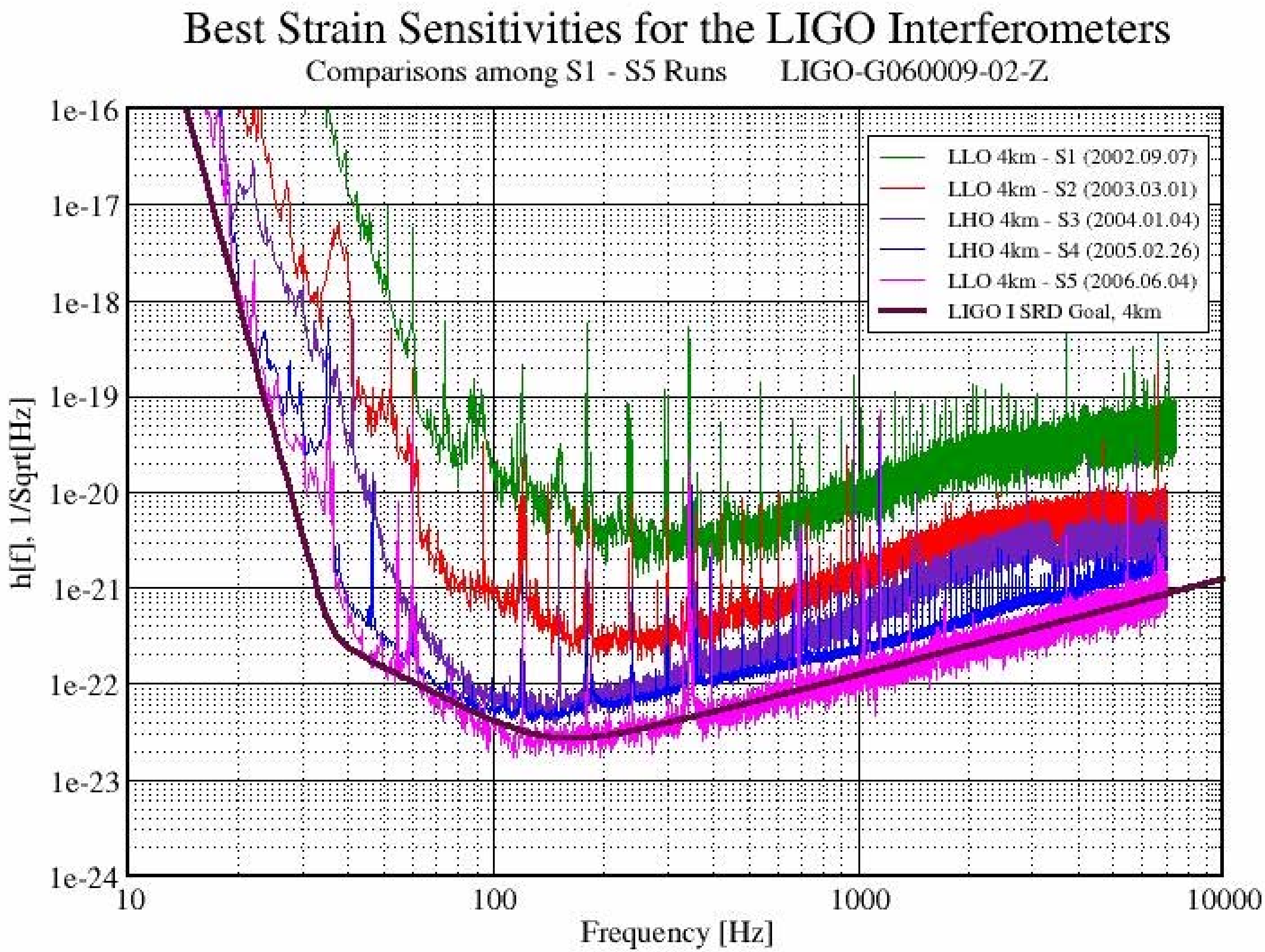
- Hydraulic external pre-isolator (HEPI)
- Signals from sensors on ground and cross-beam are blended and fed into hydraulic actuators
- Provides much-needed immunity against normal daytime ground motion at LLO

LIGO Time Line

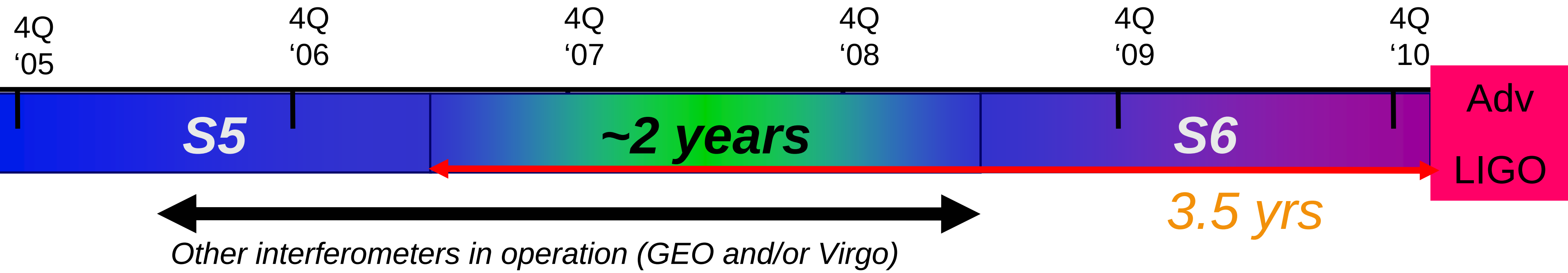


Best Interferometer Sensitivity, Runs S1 through S5

Run	*#of days*
S1	17
S2	59
S3	70
S4	30
S5	435+



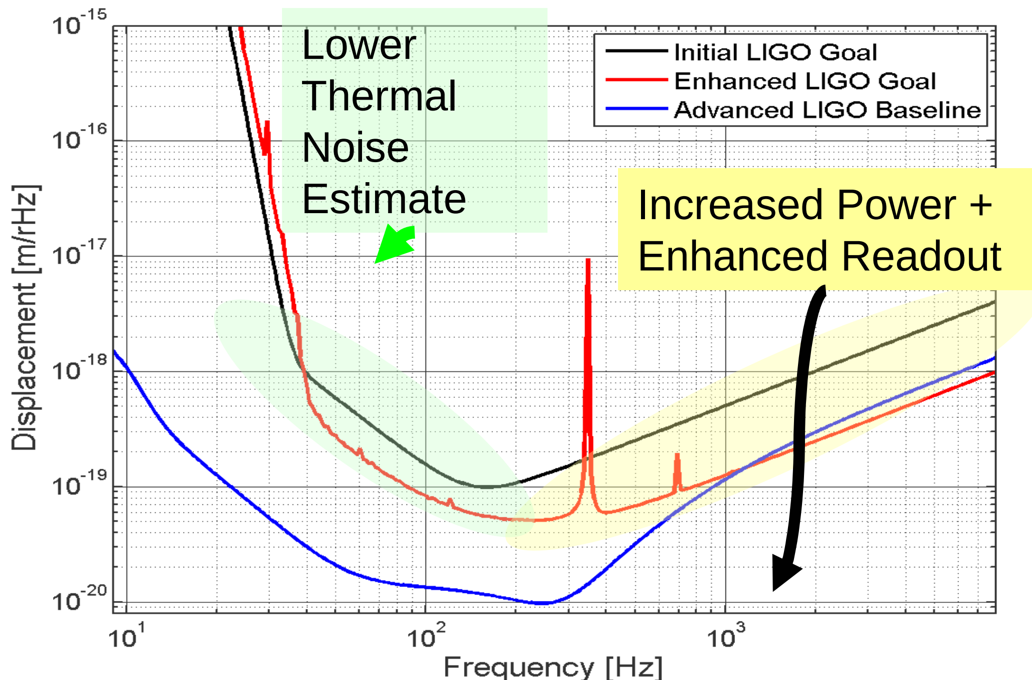
Enhanced LIGO for S6



Motivation:

Factor of ~2 in noise improvement above 100 Hz
Factor ~6.5 in inspiral binary neutron star event rate

Debug new Advanced LIGO technology in actual low noise interferometers
Reduce the Advanced LIGO commissioning time



Advanced LIGO

Goal: quantum-noise-limited interferometer

x10 better amplitude sensitivity

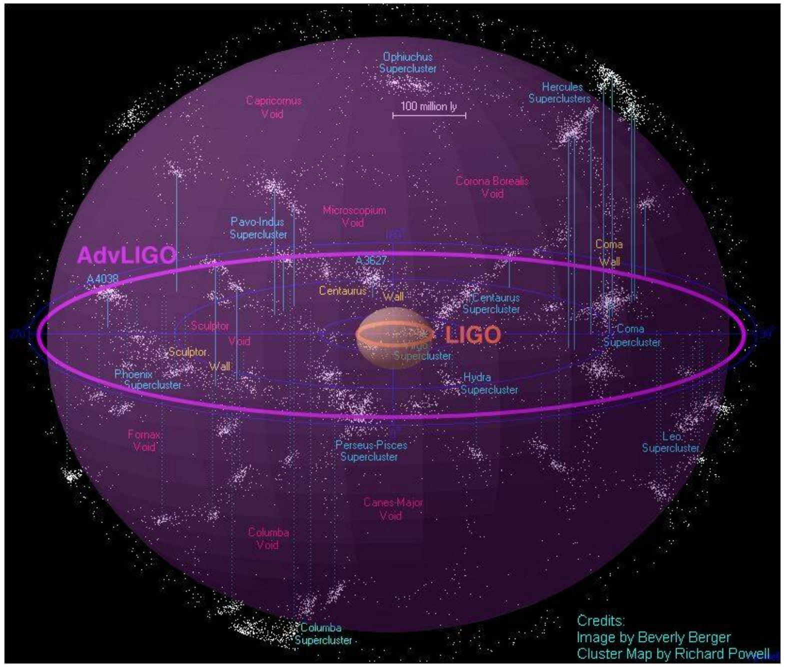
x1000 rate=(reach)^3

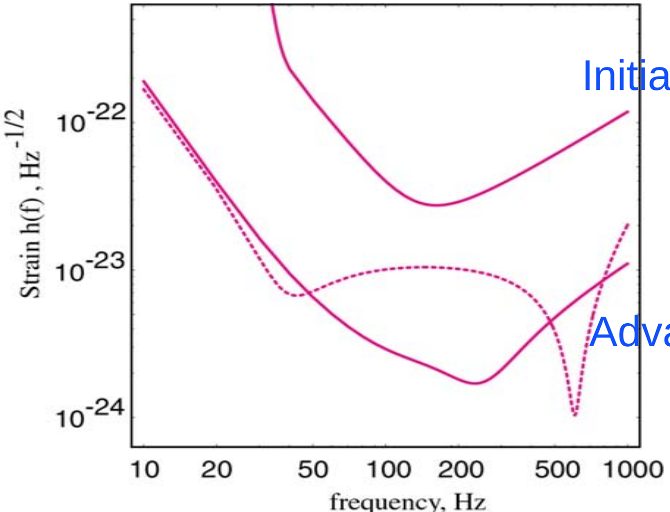
x4 lower frequency bound

40Hz $\rightarrow$ 10Hz

x100 better narrow-band at high frequencies

The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO





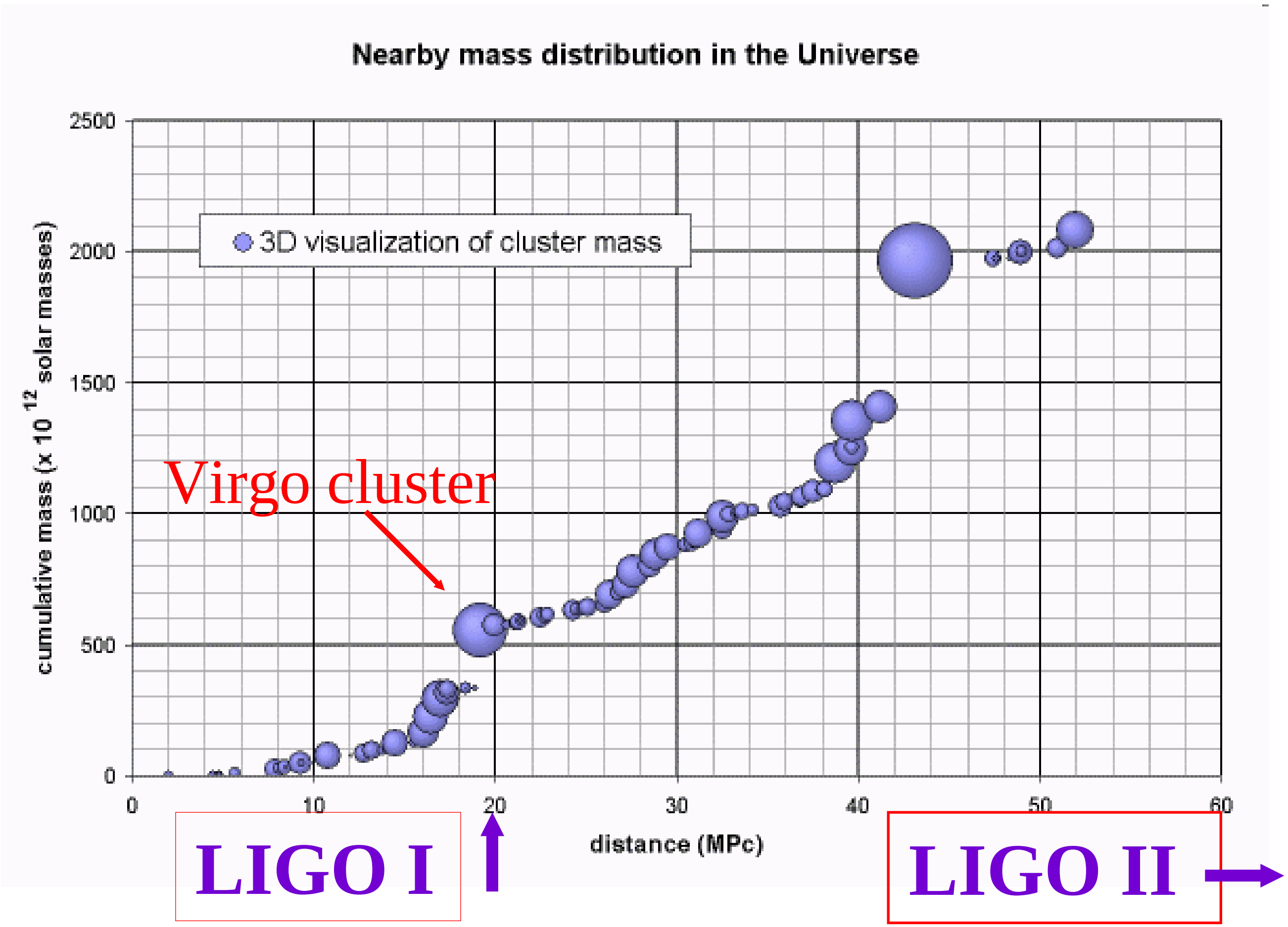
- Approved by NSF – to be proposed for Congress approval in FY2008
- Begin installation: 2011
- Begin observing: 2014

How many sources can we see?

Improve sensitivity by a factor of 2x

⇒ Improve sensitivity to distance by 2x (h ~ 1/r)

⇒ Number of sources goes up 8x ($1/r^3$) !



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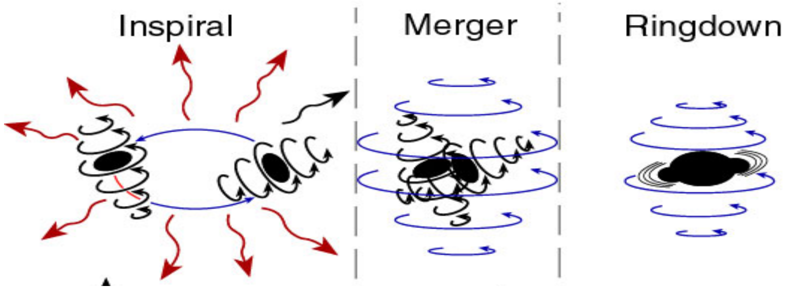
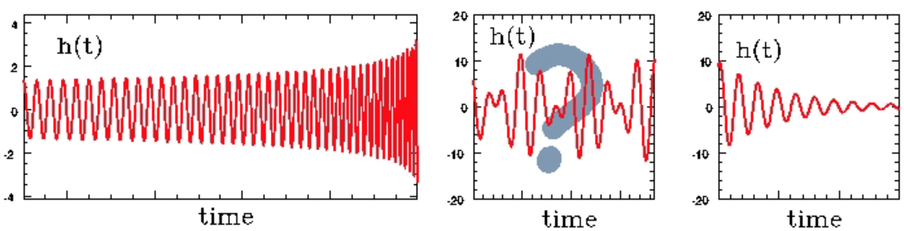
Coalescing Binaries

LIGO is sensitive to gravitational waves from neutron star (BNS) and black hole (BBH) binaries

Thorne diagram





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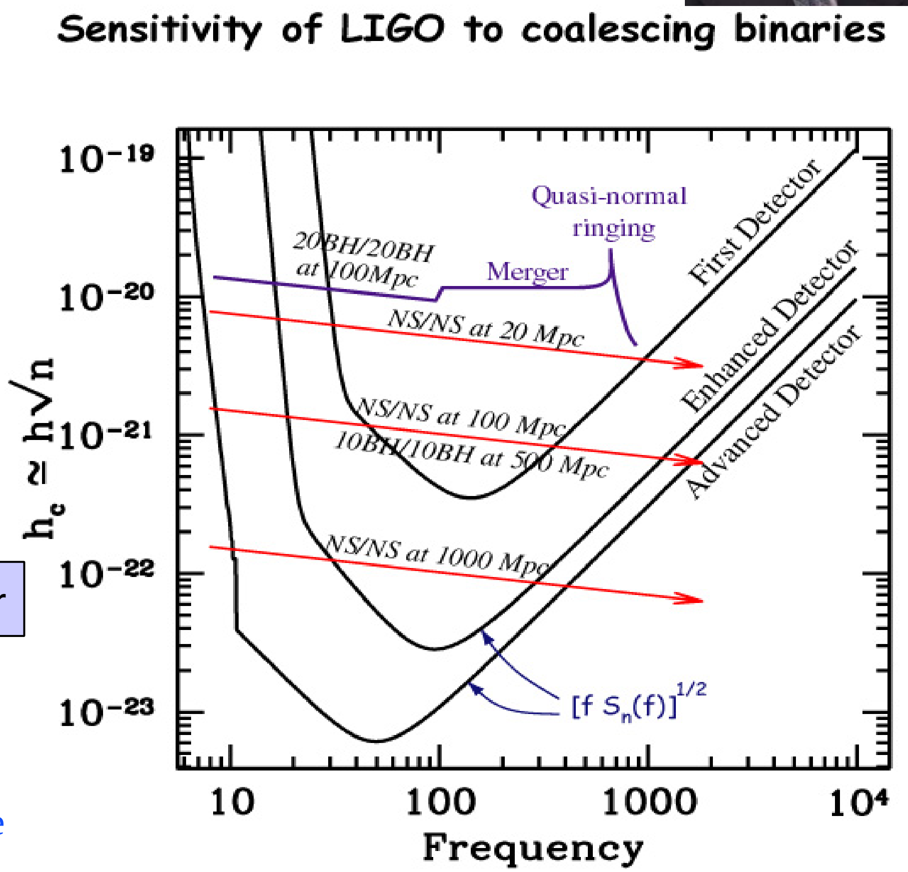
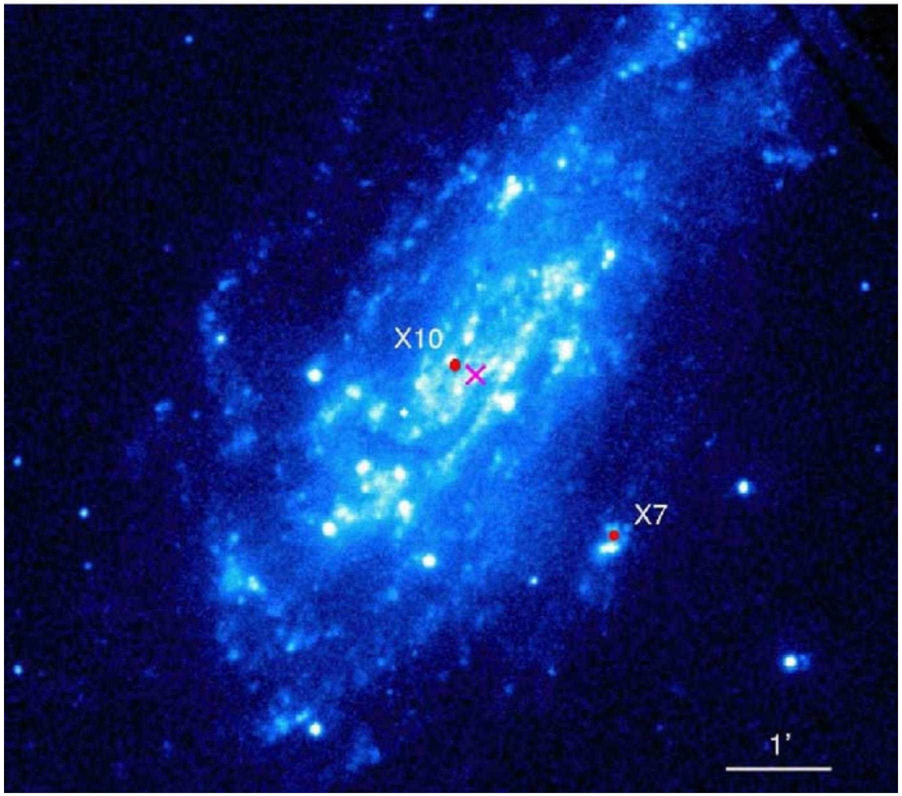


Intermediate Mass Black Holes (IMBH)

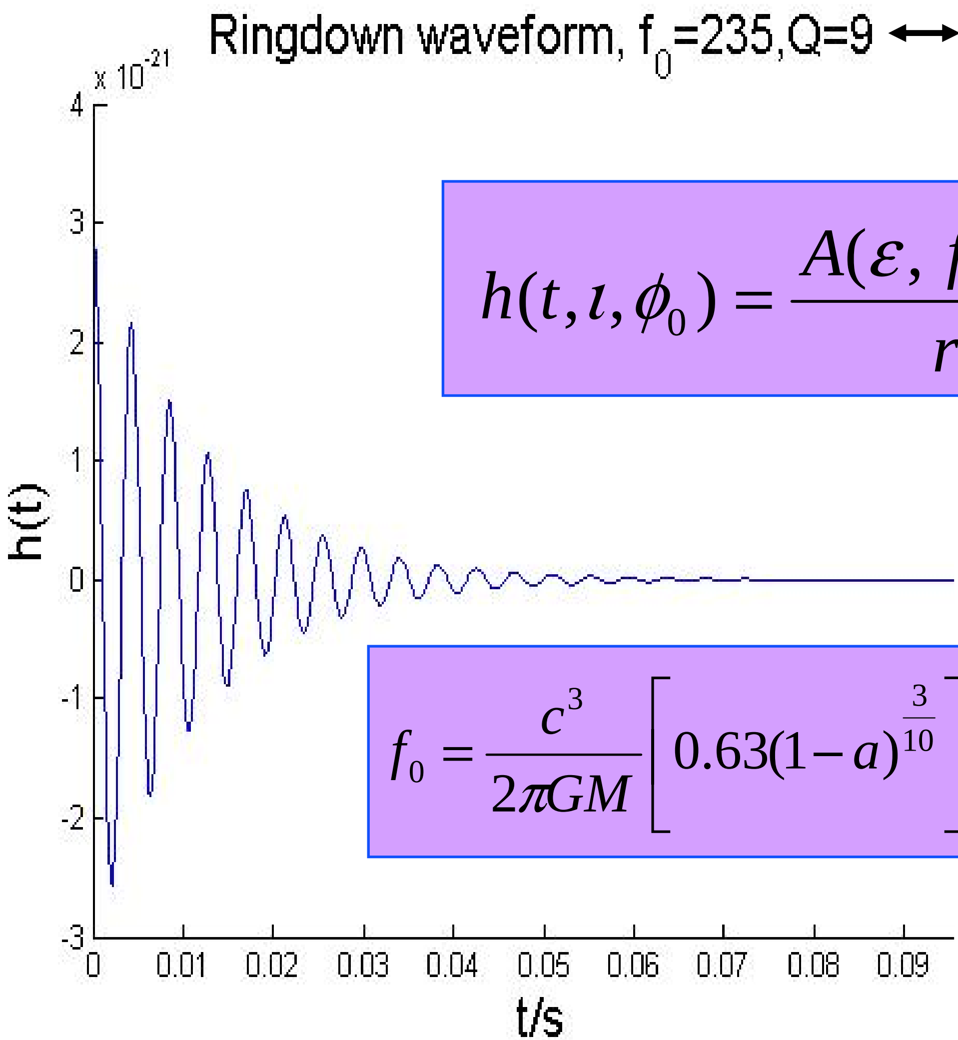
- $10^2 M_{sun} < M < 10^5 M_{sun}$
- Little evidence for their existence
- Observational hints from studies of
  - ultra-luminous X-ray sources
  - kinematics of central regions of nearby galaxies and globular clusters
- Formation scenarios include
  - Runaway growth of a supermassive star, collapsing to a black hole
  - core collapse of massive young star cluster



NGC 4559, XMM-Newton image, Cropper et al 2004

Detection of gravitational waves from black holes in this mass range would provide key evidence for the existence of IMBHs.

Ringdown Waveform



↔ **M=100M$_{sun}$, a=0.96**

$$h(t,\iota,\phi_0) = \frac{A(\varepsilon, f_0, Q)}{r} e^{-\frac{\pi f_0}{Q}t} \cos(2\pi f_0 t - \phi_0)$$

Amount of mass emitted as gw's,

ε = 1%

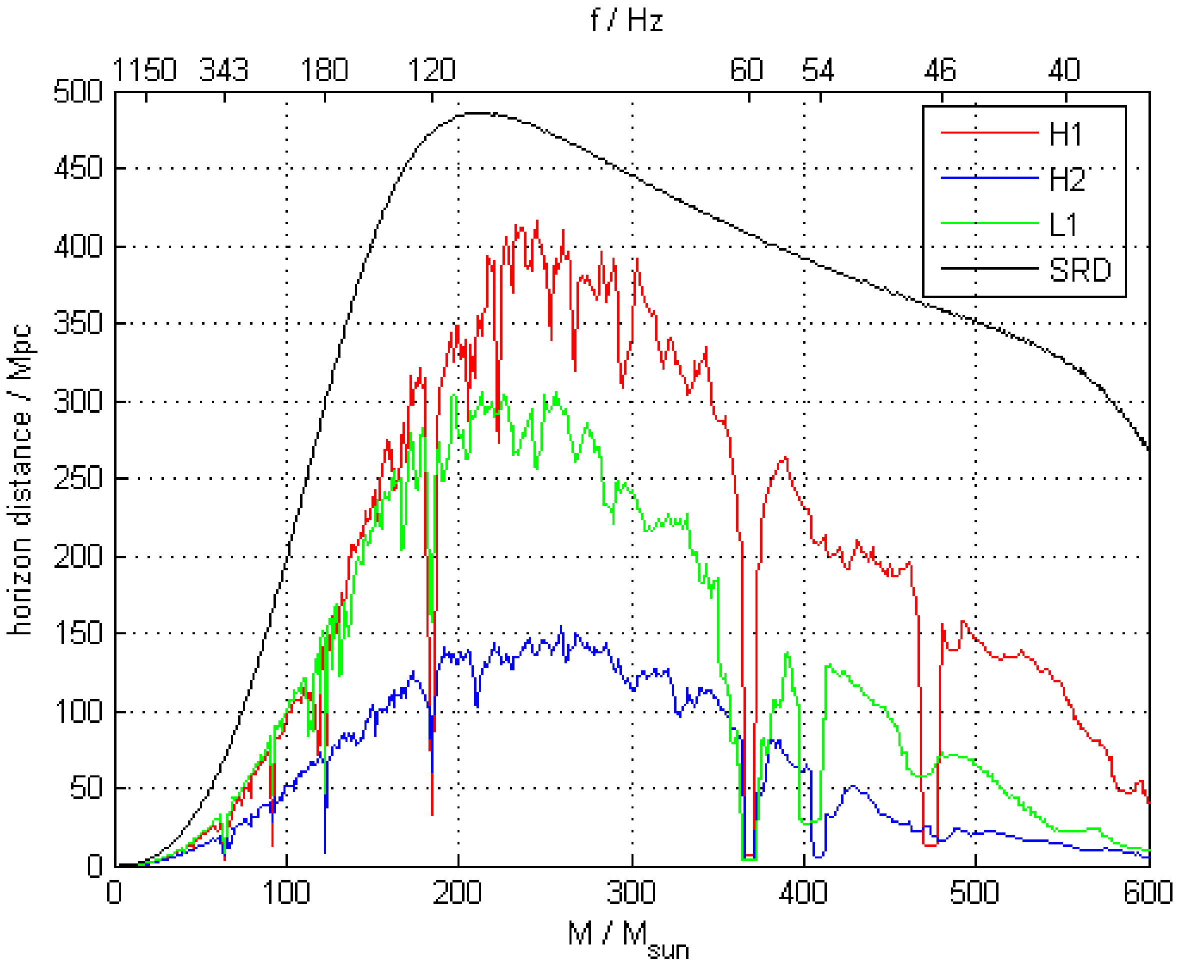
$$f_0 = \frac{c^3}{2\pi GM}\left[0.63(1-a)^{\frac{3}{10}}\right]$$

$$Q \approx 2(1-a)^{-\frac{9}{20}}$$

$$a = S\frac{c}{GM^2} \qquad 0 \leq a \leq 1$$

(Echeverria, 1989)

S4 Horizon Distance



(based on average noise spectra)

- Optimally oriented source
- Single detector signal-to-noise ratio = 8
- Spin a = 0.9

For M=230M_{sun}, sensitive to black hole ringdowns at a distance of

H1: 400 Mpc

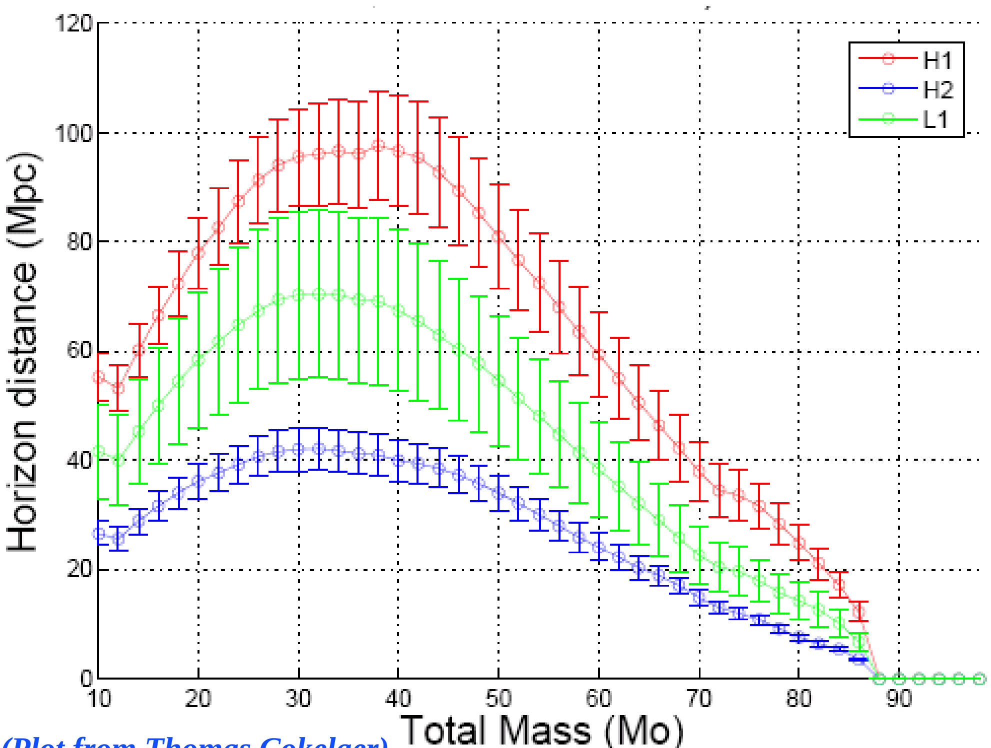
H2: 150 Mpc

L1: 300 Mpc

Binary Coalescence

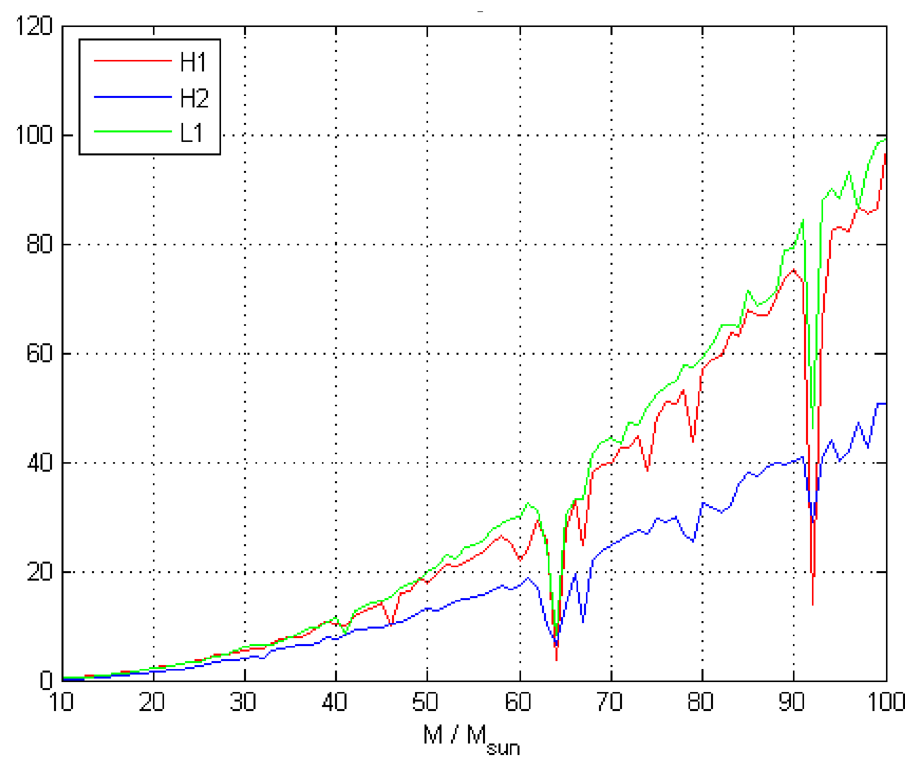
- Ringdowns are produced during the final stage of binary coalescence
- There is an overlap between the mass range of the binary black hole (BBH) inspiral search and the ringdown search

Inspiral phase (S4 BBH search)

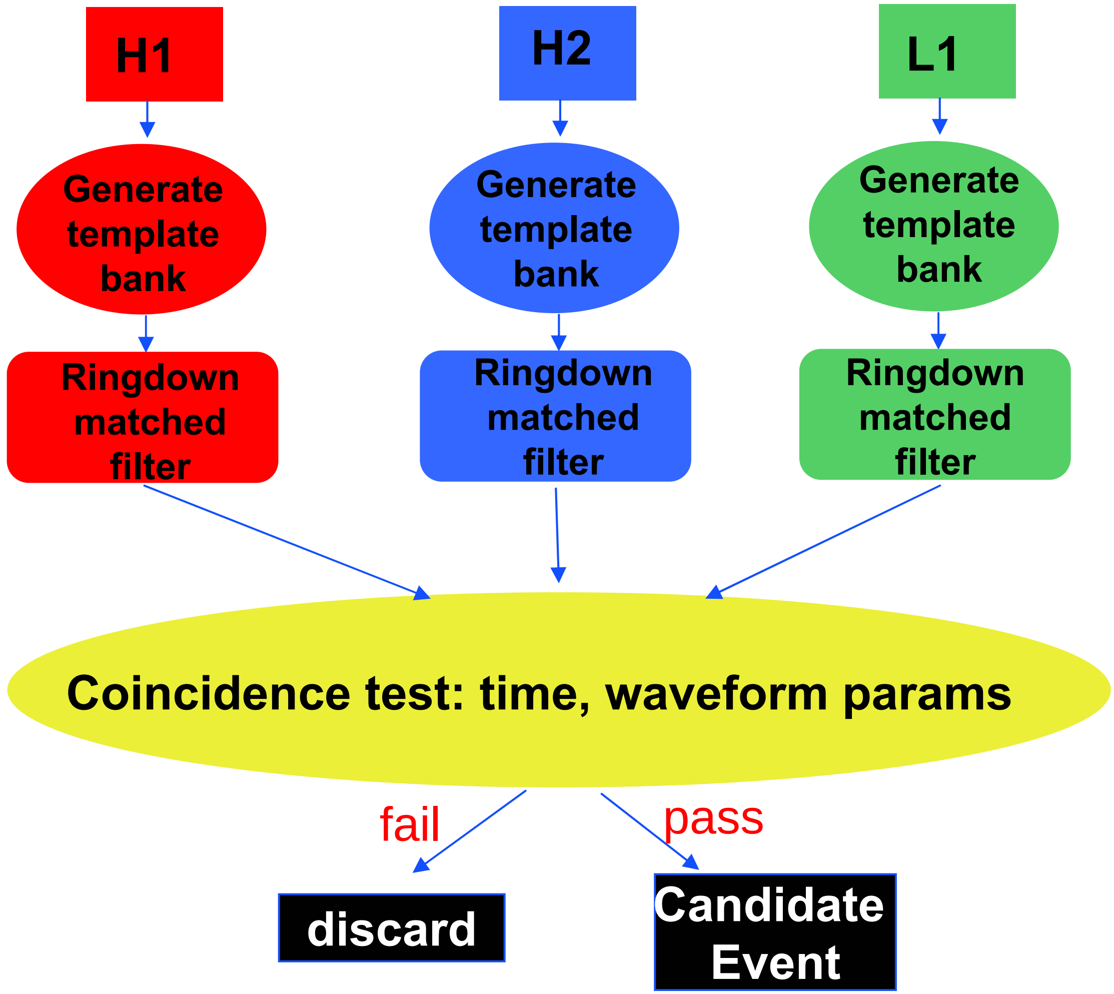


(Plot from Thomas Cokelaer)

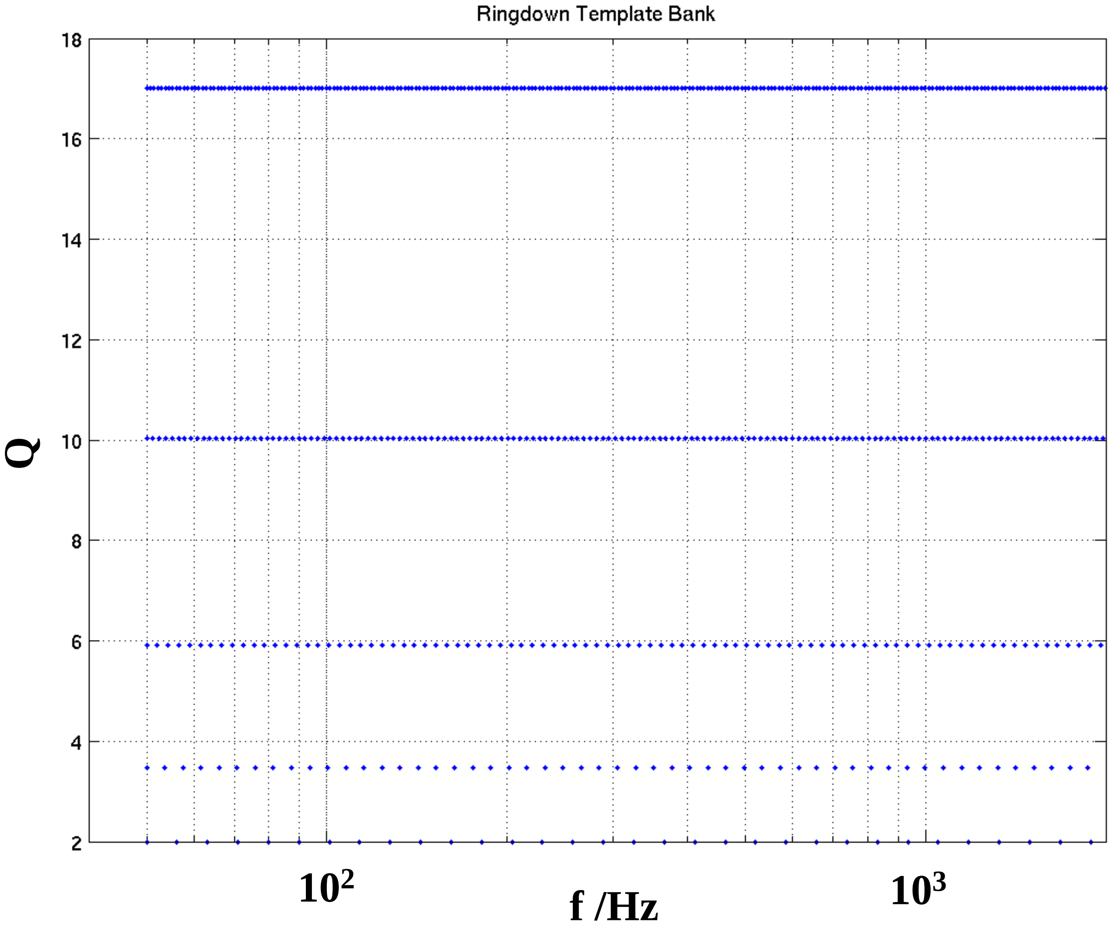
Ringdown phase (S4)



Overview of Ringdown Analysis Pipeline



Template Bank



$$ds^2 \approx \frac{1}{8}\frac{dQ^2}{Q^2} - \frac{1}{4}\frac{dQ}{Q}\frac{df}{f} + Q^2\frac{df^2}{f^2}$$

J. D. E. Creighton '99

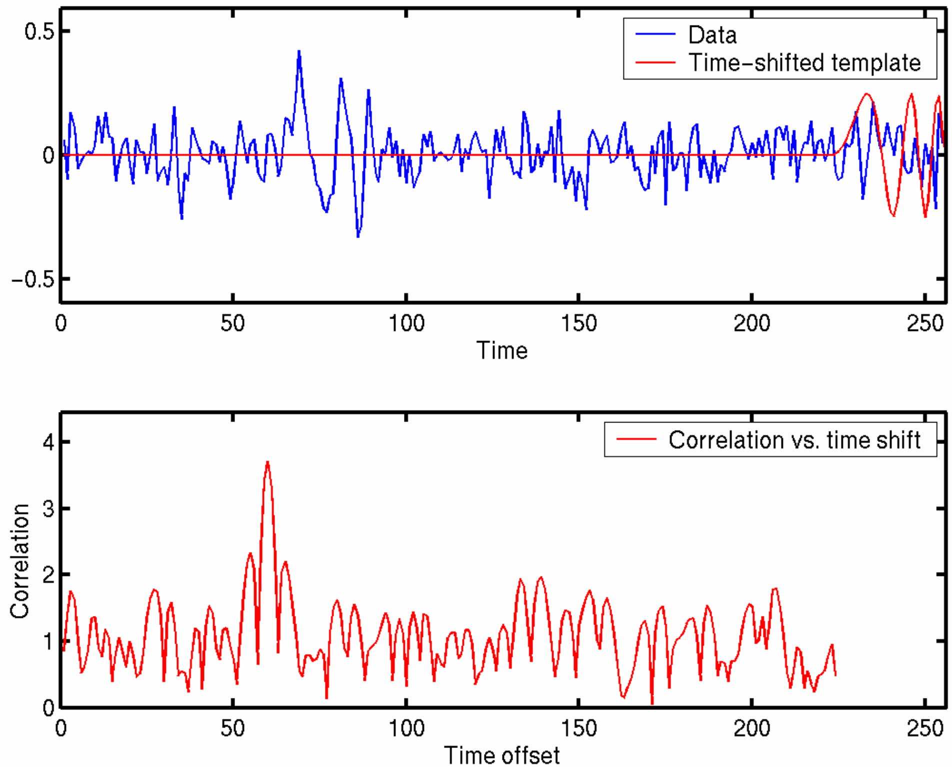
$$40 \leq f \leq 4000 Hz$$

$$2 \leq Q \leq 20$$

- **N~700**
- **mismatch = 0.03**

$$h(t - t_0) = e^{-\frac{\pi f_0}{Q}t}\cos(2\pi f_0 t)$$

Matched Filtering



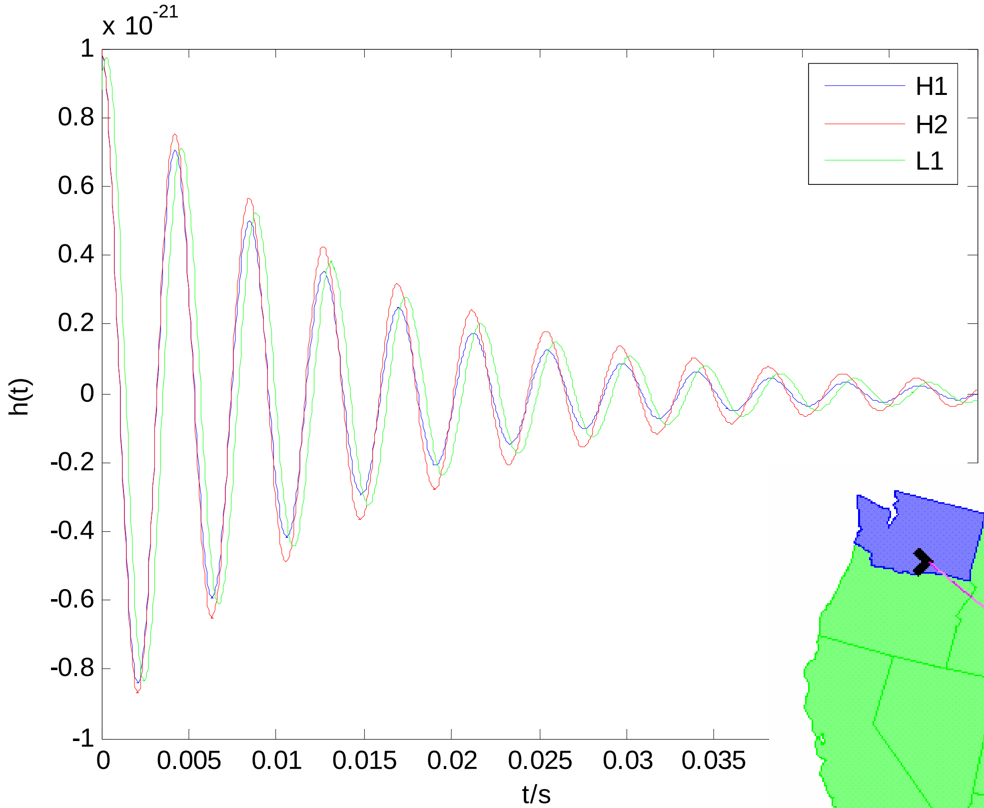
Data → Template →

$$z(t) = 4 \int_0^\infty \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_n(f)}\ e^{2\pi i f t}\ df$$

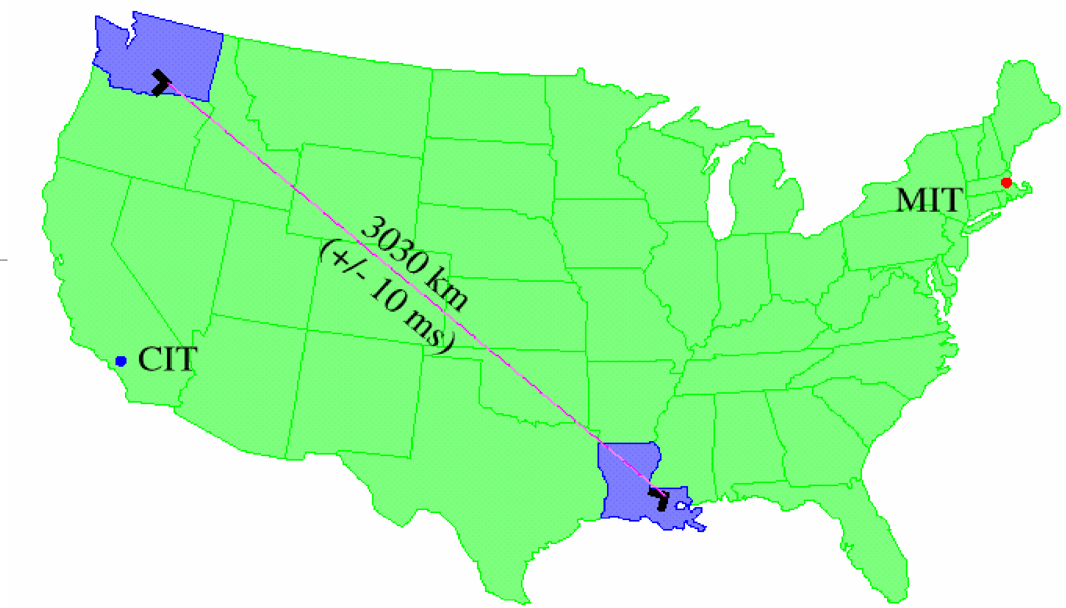
Noise power spectral density

Look for maxima of $|z(t)|$ above some threshold

Coincidence Test



- Demand coincidence between interferometers in time and waveform parameters



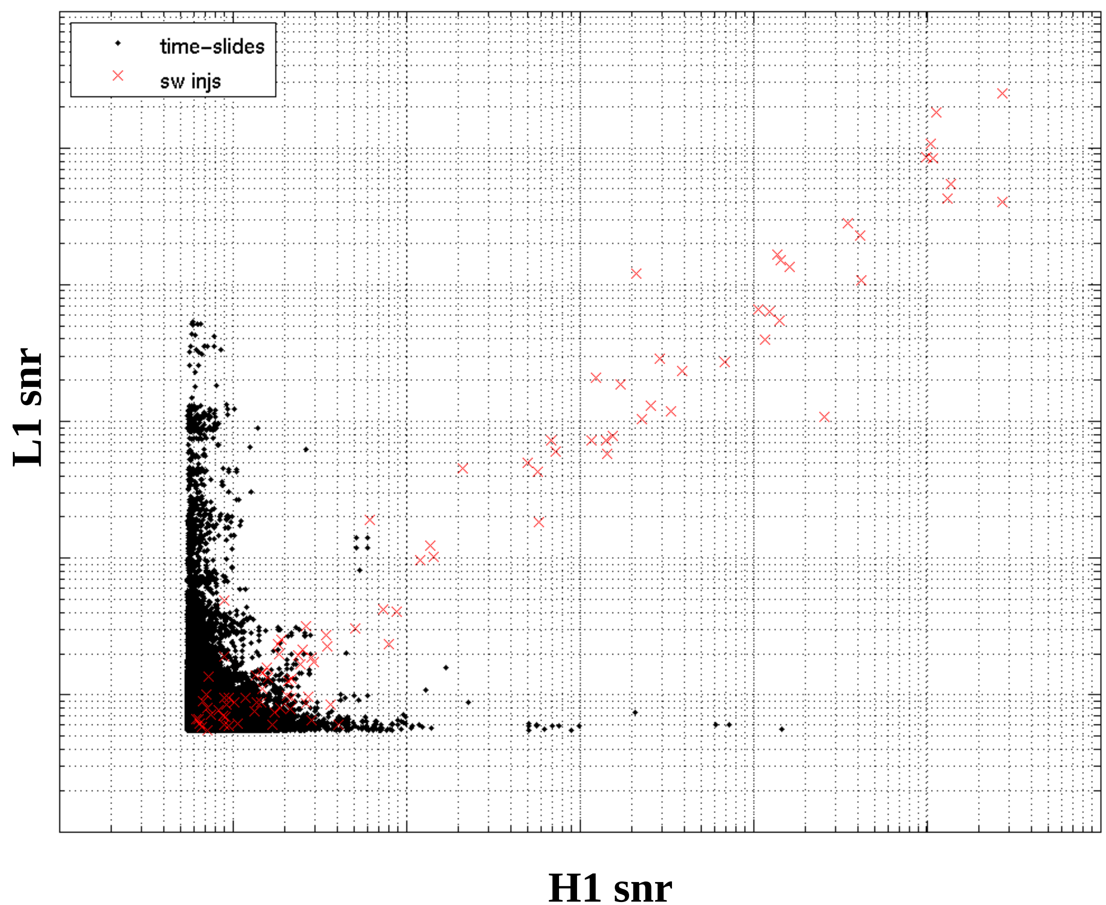
Tuning of Search

- Estimate background by sliding one data set with respect to the other

- Triggers passing coincidence test are false coincidences

- Inject a population of ringdowns into the data stream

H1L1 coincident triggers: injections, timeslides



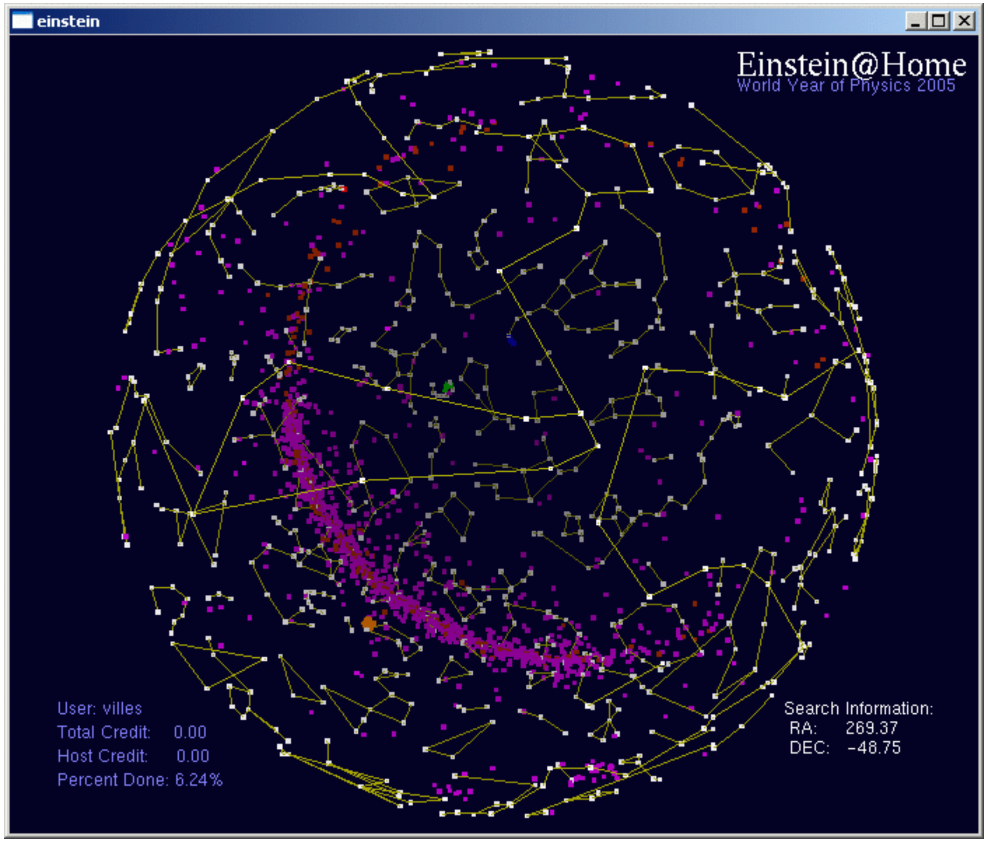
(Example of coincidences found with a particular choice of tuning parameters, - these are not final)

Future Direction of the Ringdown Search

- S4 ringdown analysis is almost complete, paper coming soon
- In absence of detection will present an upper limit on the rate of black hole ringdowns

- S5 ringdown search (high mass)
- S5 Inspiral-Merger-Ringdown search (lower mass)

The Einstein@home Project



Einstein@Home uses computer time donated by computer owners all over the world to process LIGO and GEO data.

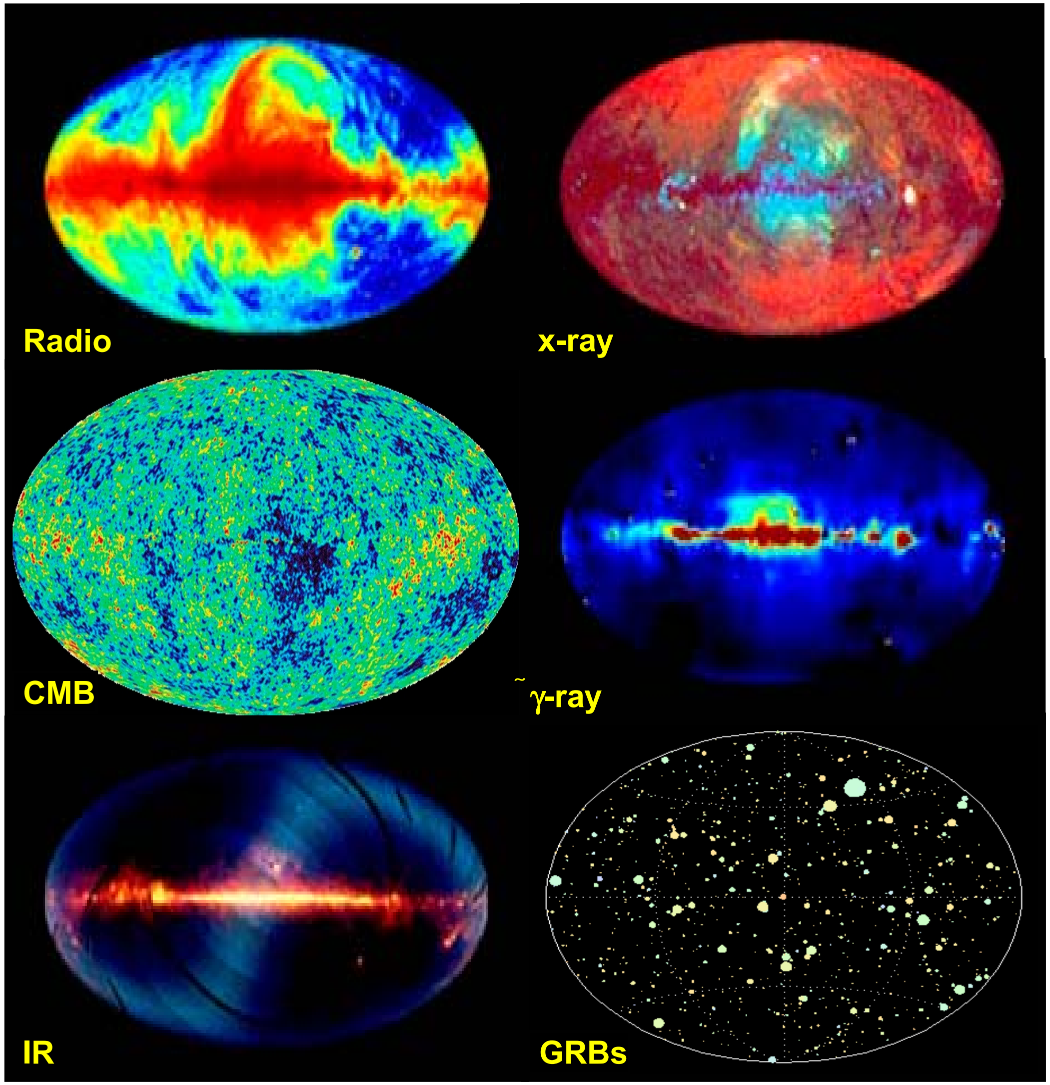
Participants in Einstein@Home download software to their computers, which process gravitational wave data when not being used for other computer applications.

To sign up:
http://www.physics2005.org

Summary

- The LIGO gravitational wave detectors have now reached their target sensitivities and have begun long-term observing.
- Analysis groups are using many different methods to identify gravitational waves from many types of sources.
- Searches are being run both online and offline, targeted and all-sky,.
- Planning and testing of Enhanced and Advanced LIGO interferometers are well underway.
- Increased collaboration between international groups.
- The coming decade should be very exciting with the dawn of gravitational wave astronomy.

A New 'Sense'- A New Universe



Gravitational Waves will provide complementary information, as different from what we know as sound is from sight.

The End