LIGO Perks Up Its Ears

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Abstract

LIGO, the Laser Interferometer Gravitational-Wave Observatory, is designed to directly detect gravitational waves reaching Earth.

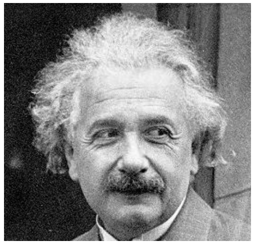
LIGO consists of three detectors at two sites, which are now operational.

Four short science runs have been undertaken, with increasing sensitivities, and the data is being analyzed in many ways.

LIGO is now beginning long-term observations.

The worldwide network of gravitational wave detectors is growing, and should see the dawn of gravitational-wave astronomy within the next decade.

Gravitational Wave Basics

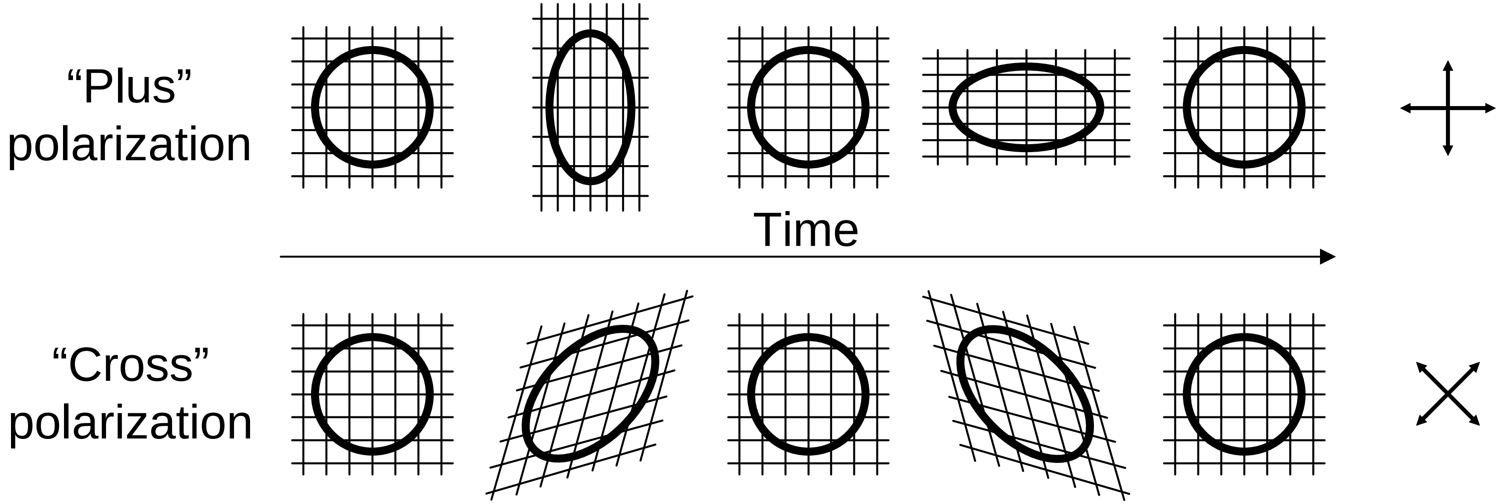


A consequence of Einstein's general theory of relativity

Emitted by a massive object, or group of objects, whose shape or orientation changes rapidly with time

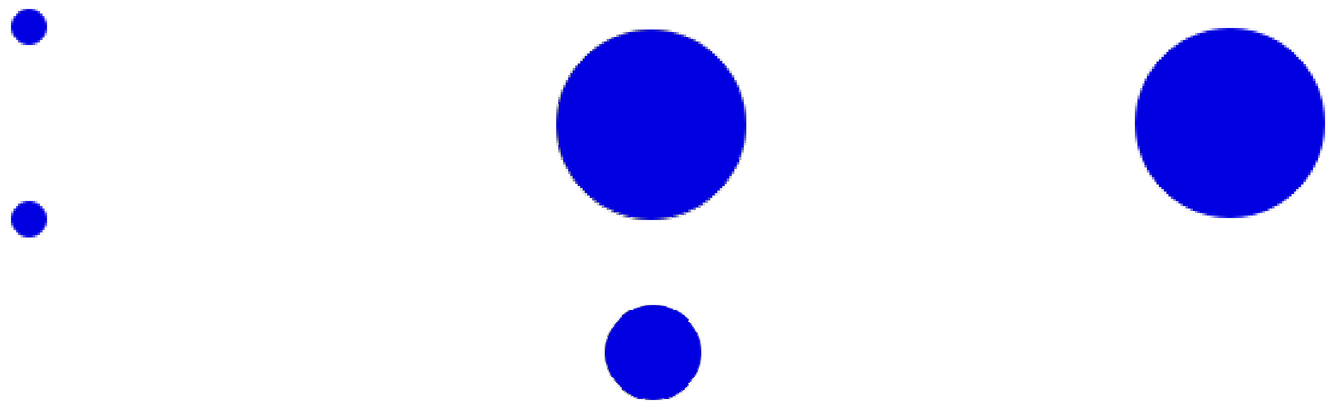
Waves travel away from the source at the speed of light

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



Gravitational Waves in Action

Two massive, compact objects in a tight orbit deform space (and any object in it) with a frequency which is twice the orbital frequency



The stretching is described by a dimensionless strain, $h = \Delta L / L$

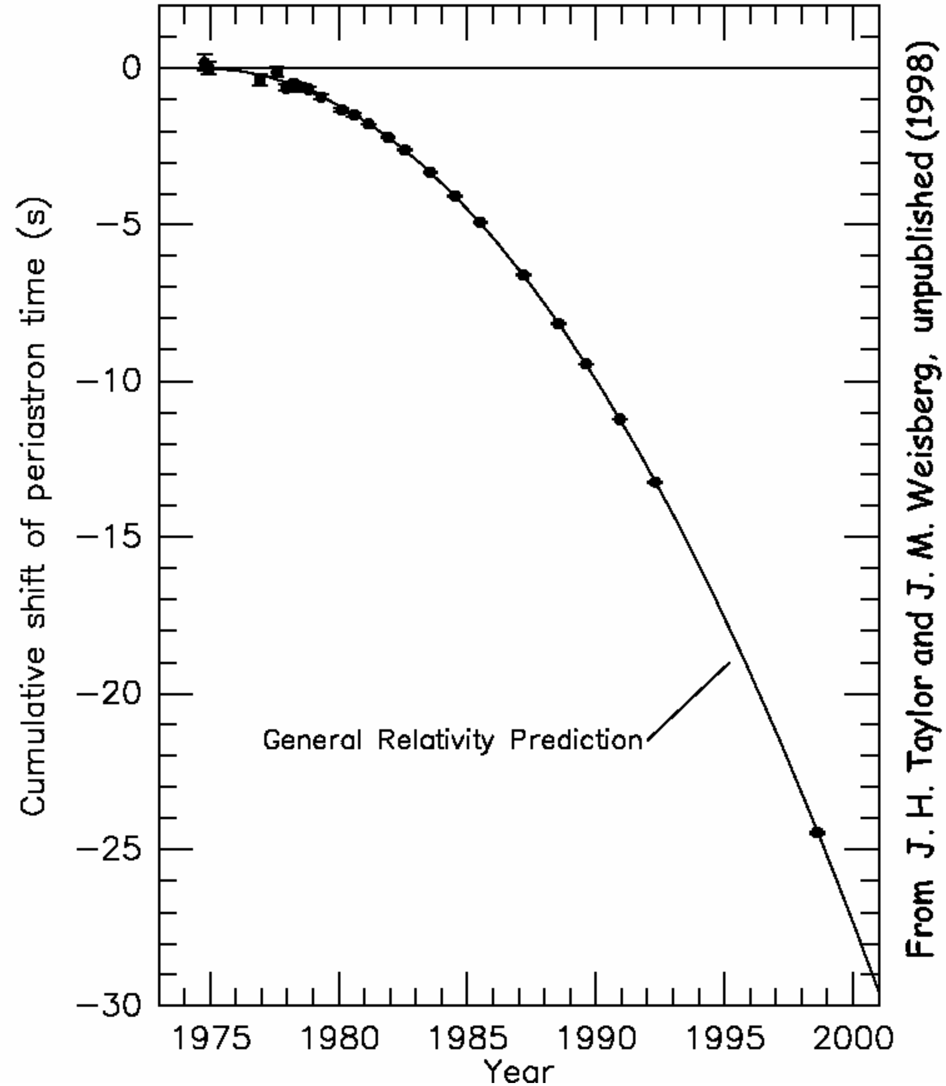
h is inversely proportional to the distance from the source

Do Gravitational Waves Exist?

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

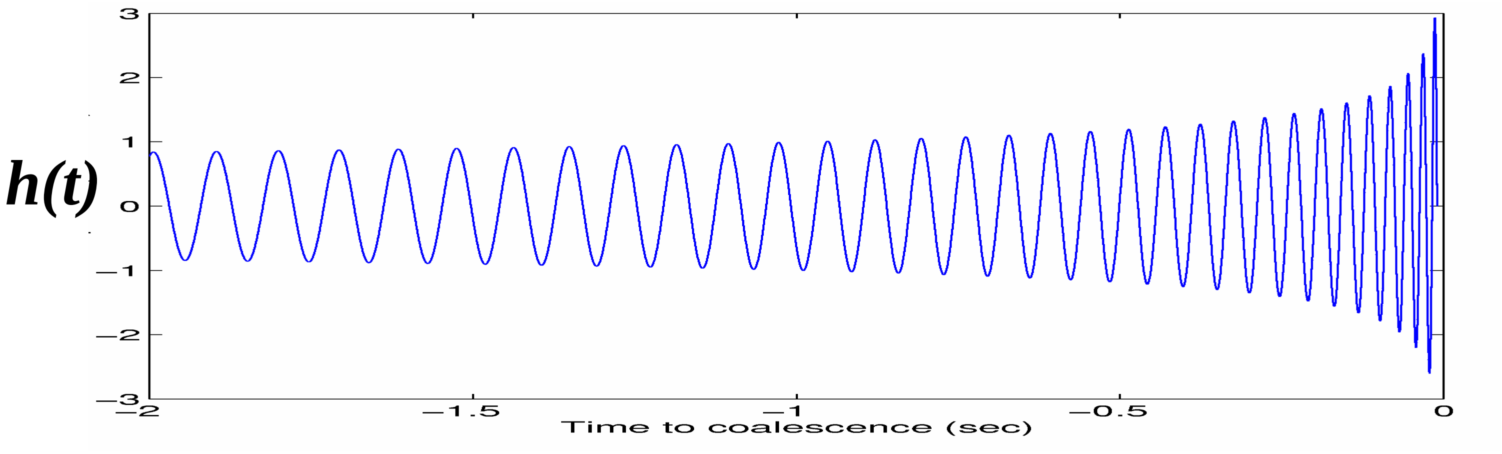
System shows very gradual orbital decay – just as general relativity predicts!
⇒ Very strong indirect evidence for gravitational radiation



The Fate of B1913+16

Gravitational waves carry away energy and angular momentum

Orbit will continue to decay over the next ~300 million years, until…



The “inspiral” will accelerate at the end, when the neutron stars coalesce

Gravitational wave emission will be strongest near the end

The Experimental Challenge

Binary neutron star inspirals and other sources are expected to be rare

$\Rightarrow$ Have to be able to search a large volume of space

$\Rightarrow$ Have to be able to detect very weak signals

Typical strain at Earth: $h \sim 10^{-21}$!

Stretches the diameter of the Earth by ~ 10^{-14} m
(about the size of an atomic nucleus)

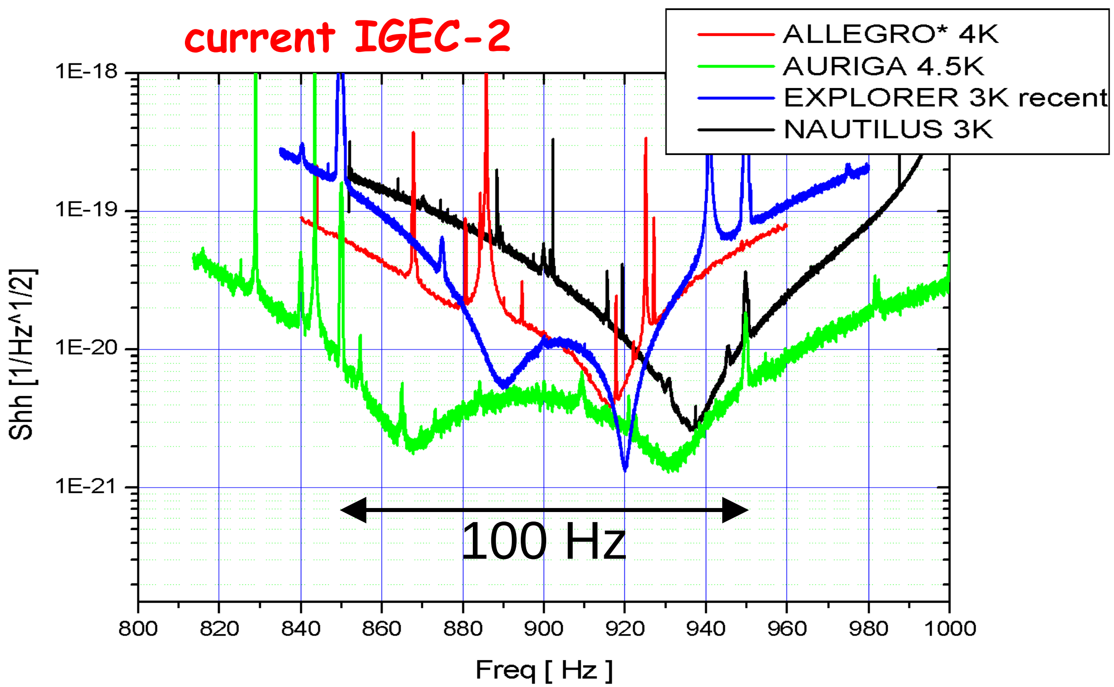
How can we possibly measure such small length changes ???

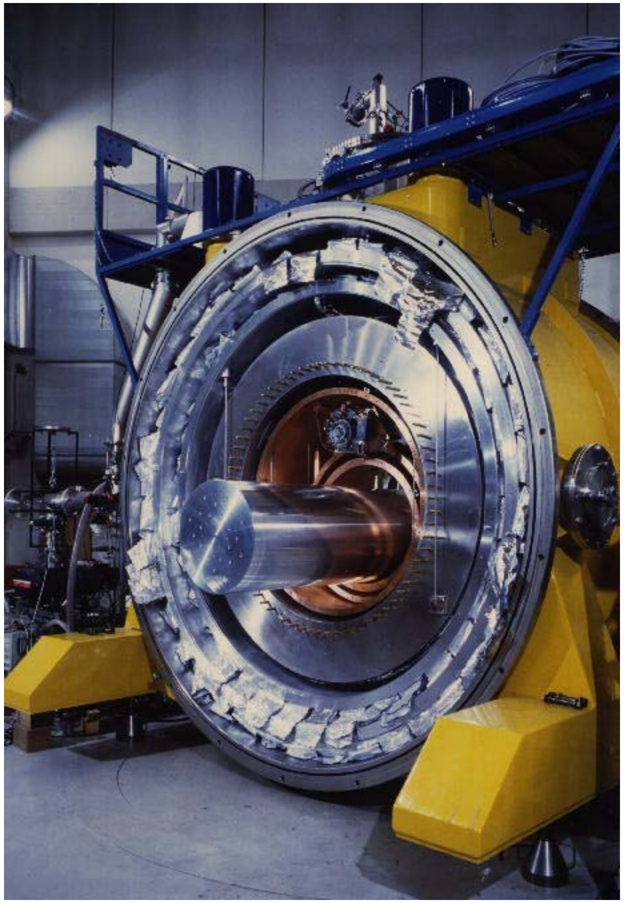
Resonant “Bar” Detectors

Aluminum cylinder, suspended in middle

GW causes it to ring at one or two resonant frequencies near 900 Hz

- Picked up by electromechanical transducer
- Sensitive in fairly narrow frequency band



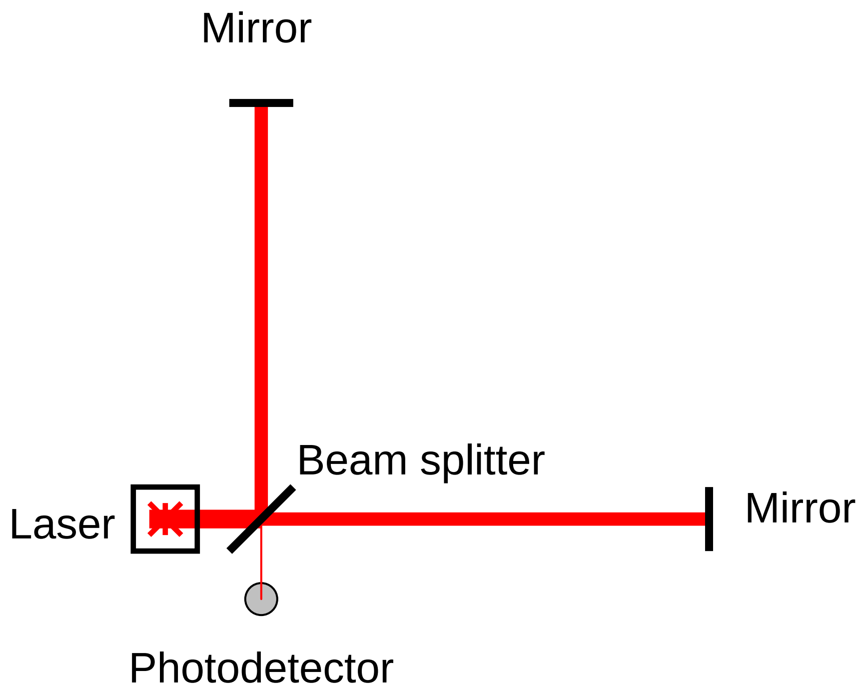


AURIGA detector (open)

Laser Interferometers

Variations on basic Michelson design, with two long arms

Measure *difference* in arm lengths to a fraction of a wavelength

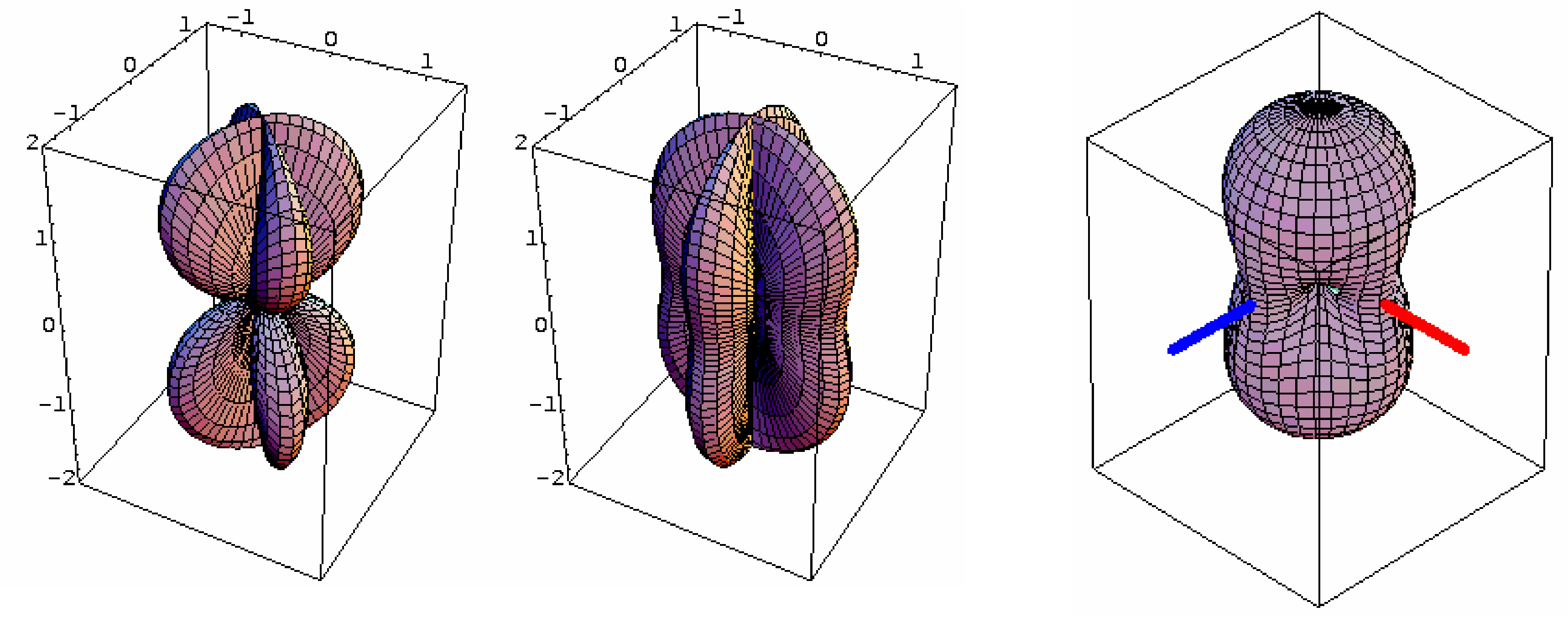


Effective lengths of interferometer arms are affected by a gravitational wave — An ideal detector !

Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

"×" polarization "+" polarization RMS sensitivity



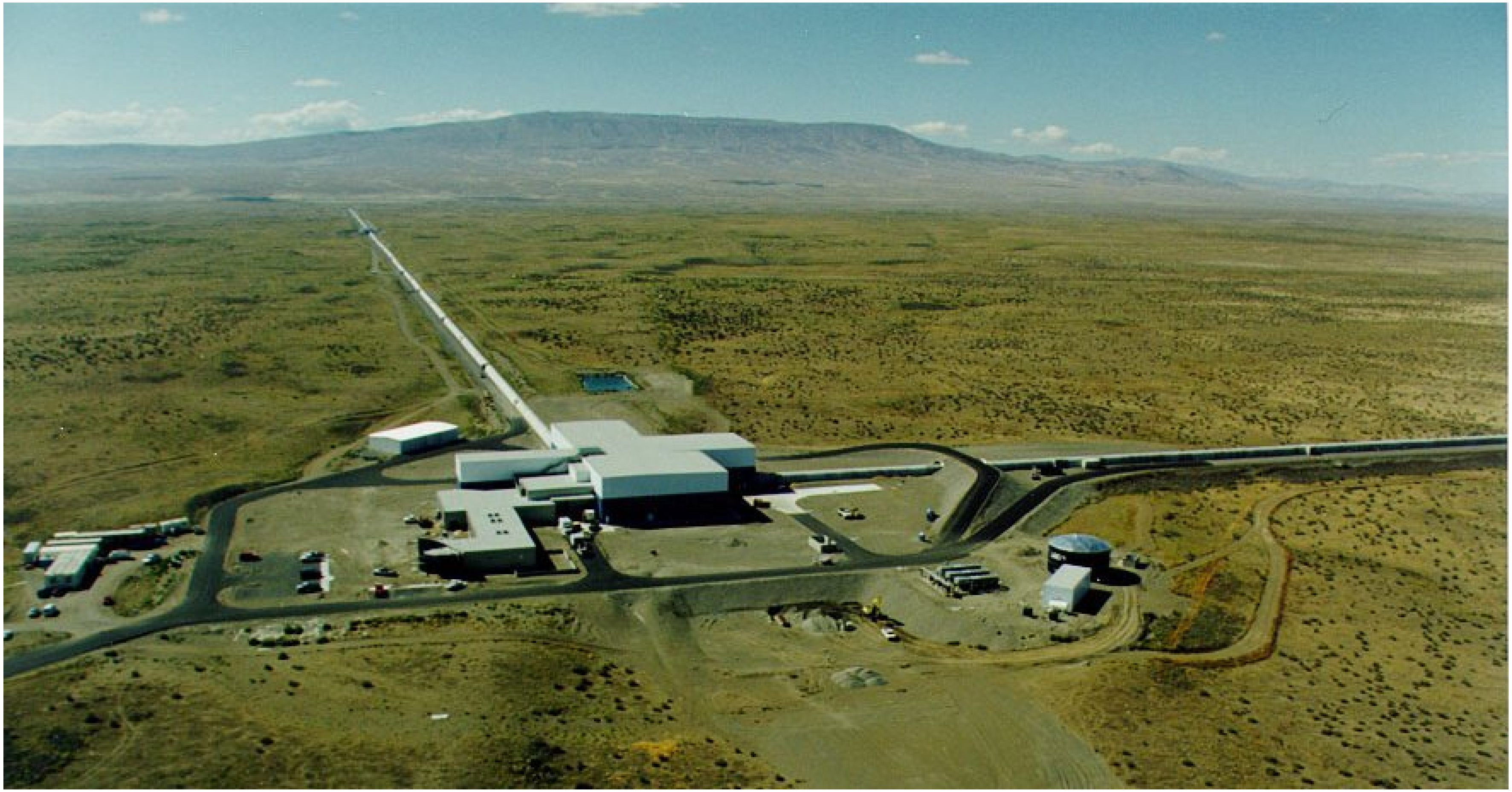
A broad antenna pattern

⇒ **More like a microphone than a telescope**


The LIGO Observatories
LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms
10 ms
LIGO Livingston Observatory (LLO)
L1 : 4 km arms
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).

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

Design Requirements

Even with 4-km arms, the length change due to a gravitational wave is *very* small, typically ~ 10^{-18} – 10^{-17} m

Wavelength of laser light = 10^{-6} m

Need a more sophisticated interferometer design to reach this sensitivity

- Add partially-transmitting mirrors to form resonant optical cavities
- Use feedback to lock mirror positions on resonance

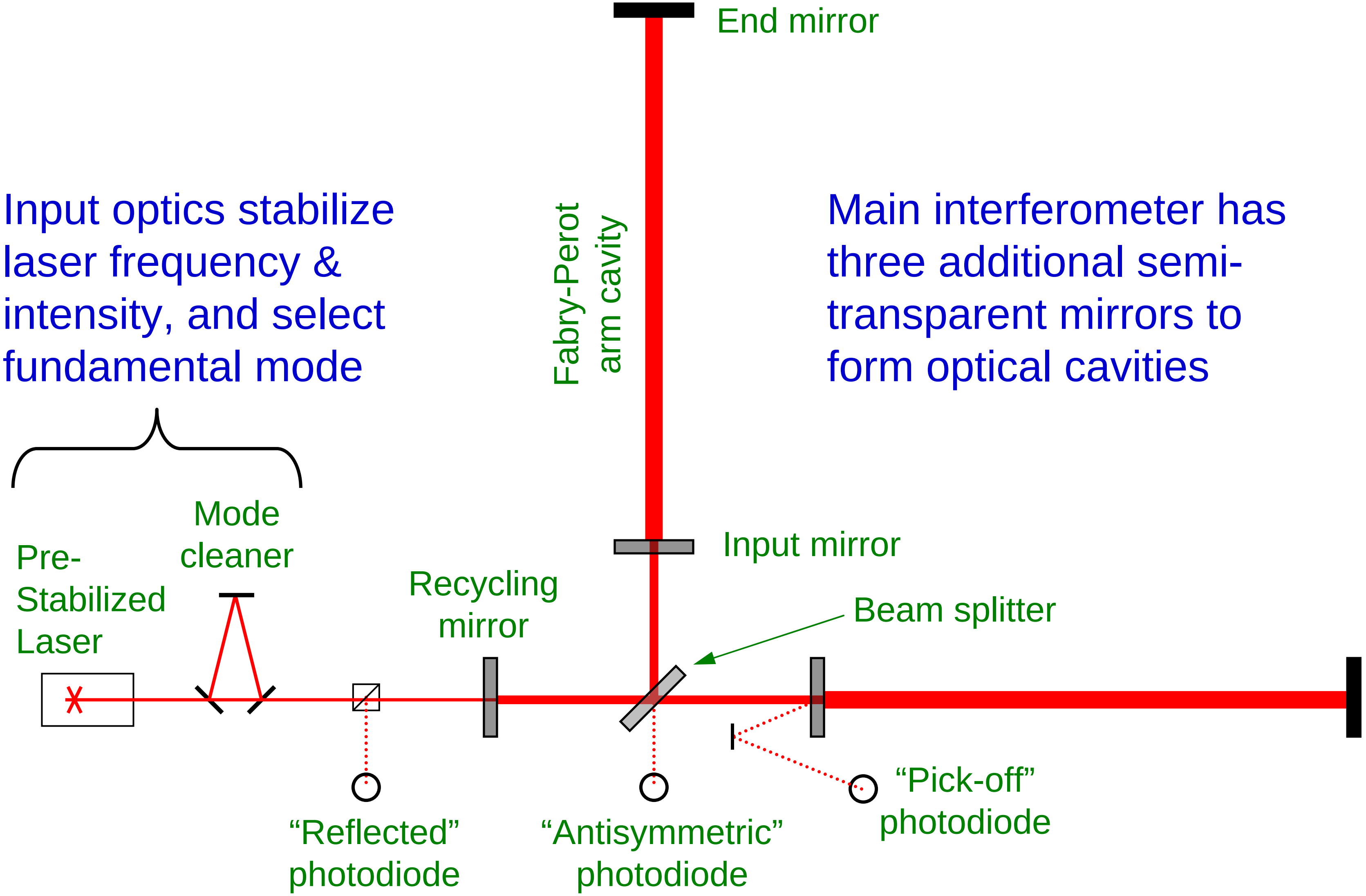
Need to control noise sources

- Stabilize laser frequency and intensity
- Use large mirrors to reduce quantum position uncertainty
- Isolate interferometer optics from environment
- Focus on a “sweet spot” in frequency range

Optical Layout
(not to scale)

Input optics stabilize laser frequency & intensity, and select fundamental mode

Main interferometer has three additional semi-transparent mirrors to form optical cavities



Servo Controls

Optical cavities must be kept in resonance

- Need to control lengths to within a small fraction of a wavelength – "lock"
- Nearly all of the disturbance is from low-frequency ground vibrations

Use a clever scheme to sense and control all four length degrees of freedom

- Modulate phase of laser light at very high frequency
- Demodulate signals from photodiodes
- Disentangle contributions from different lengths, apply digital filters
- Feed back to coil-and-magnet actuators on various mirrors

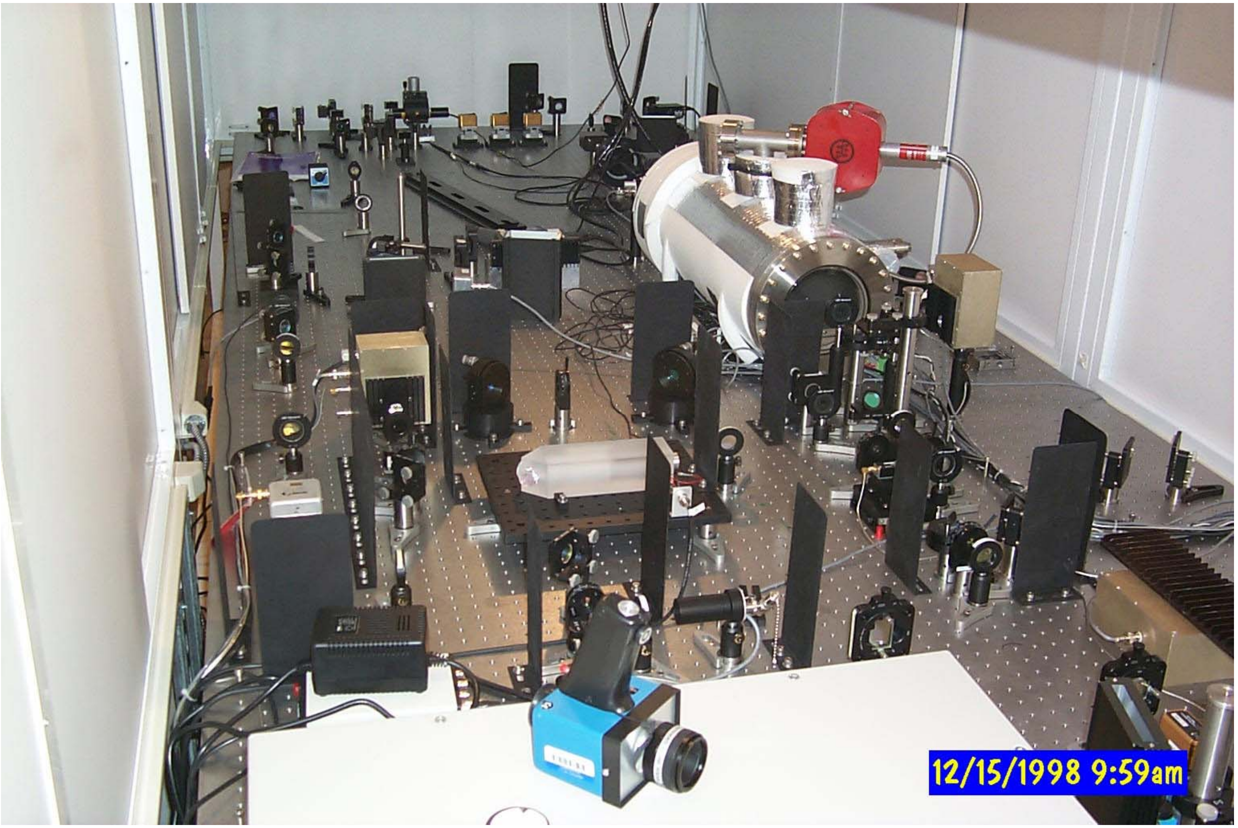
Arrange for destructive interference at "antisymmetric port"

There are many other servo loops besides length control !

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

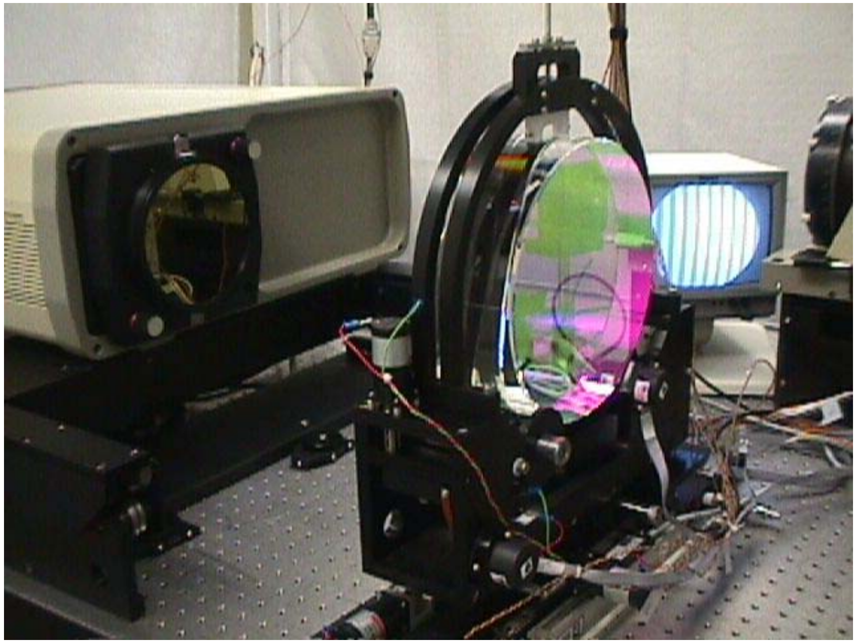
Mirrors

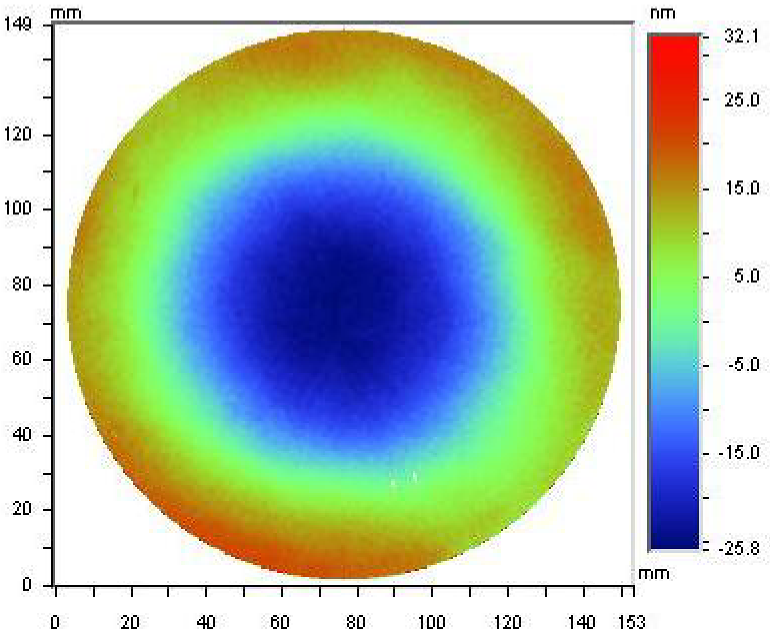
Made of high-purity fused silica

Largest mirrors are 25 cm diameter, 10 cm thick, 10.7 kg

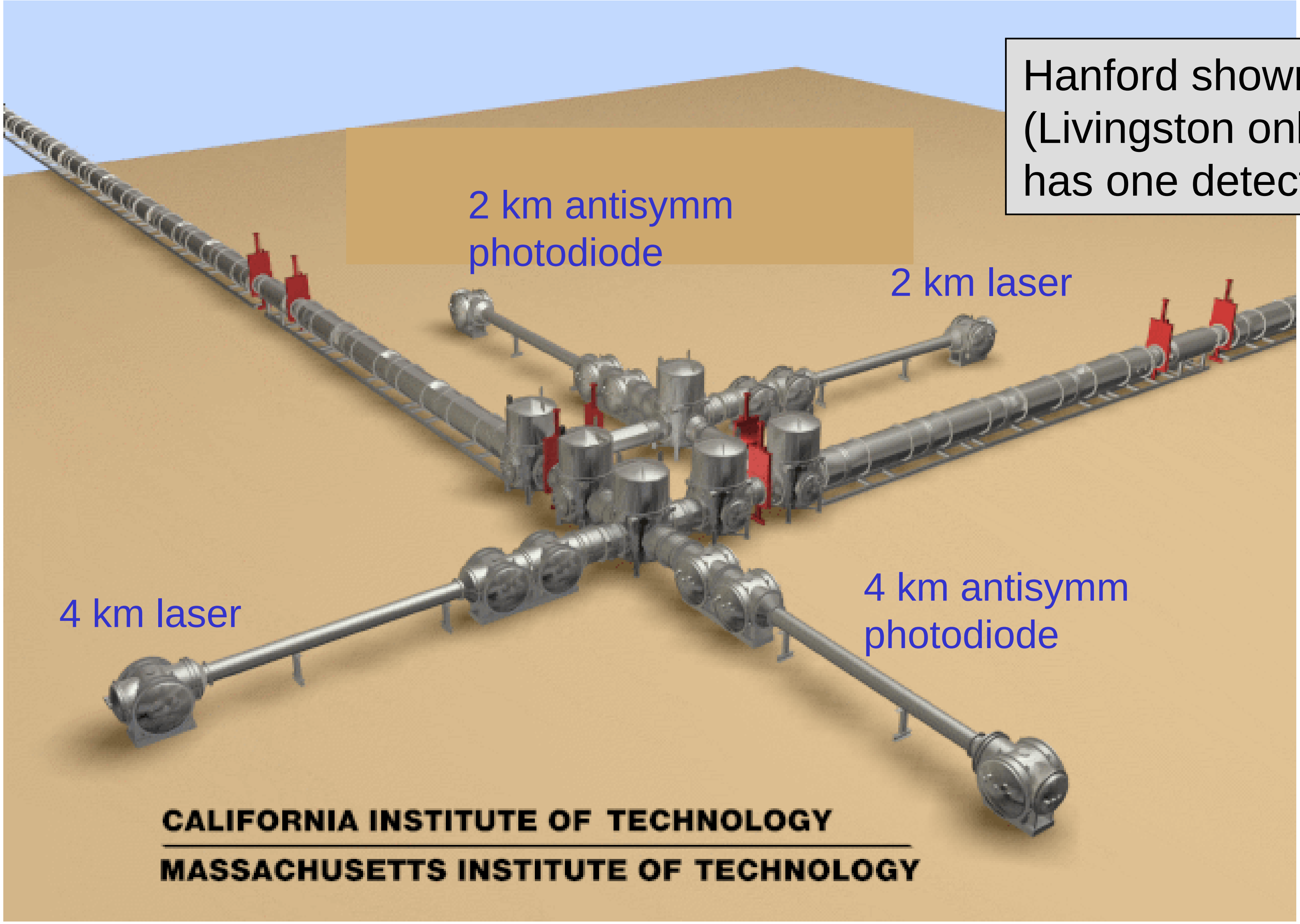
Surfaces polished to ~1 nm rms, some with slight curvature

Coated to reflect with extremely low scattering loss (<50 ppm)





Vacuum System

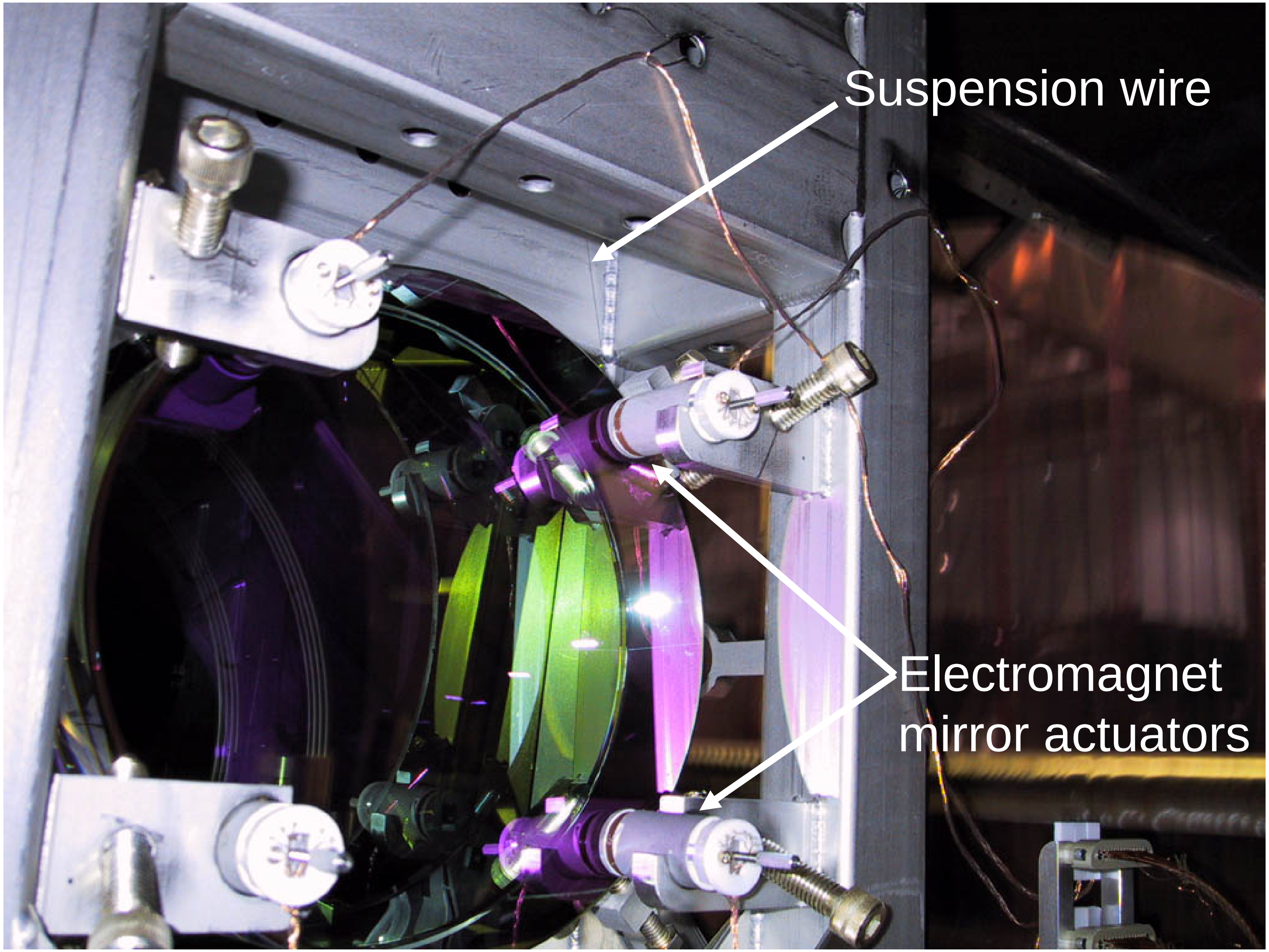


Hanford shown (Livingston only has one detector)

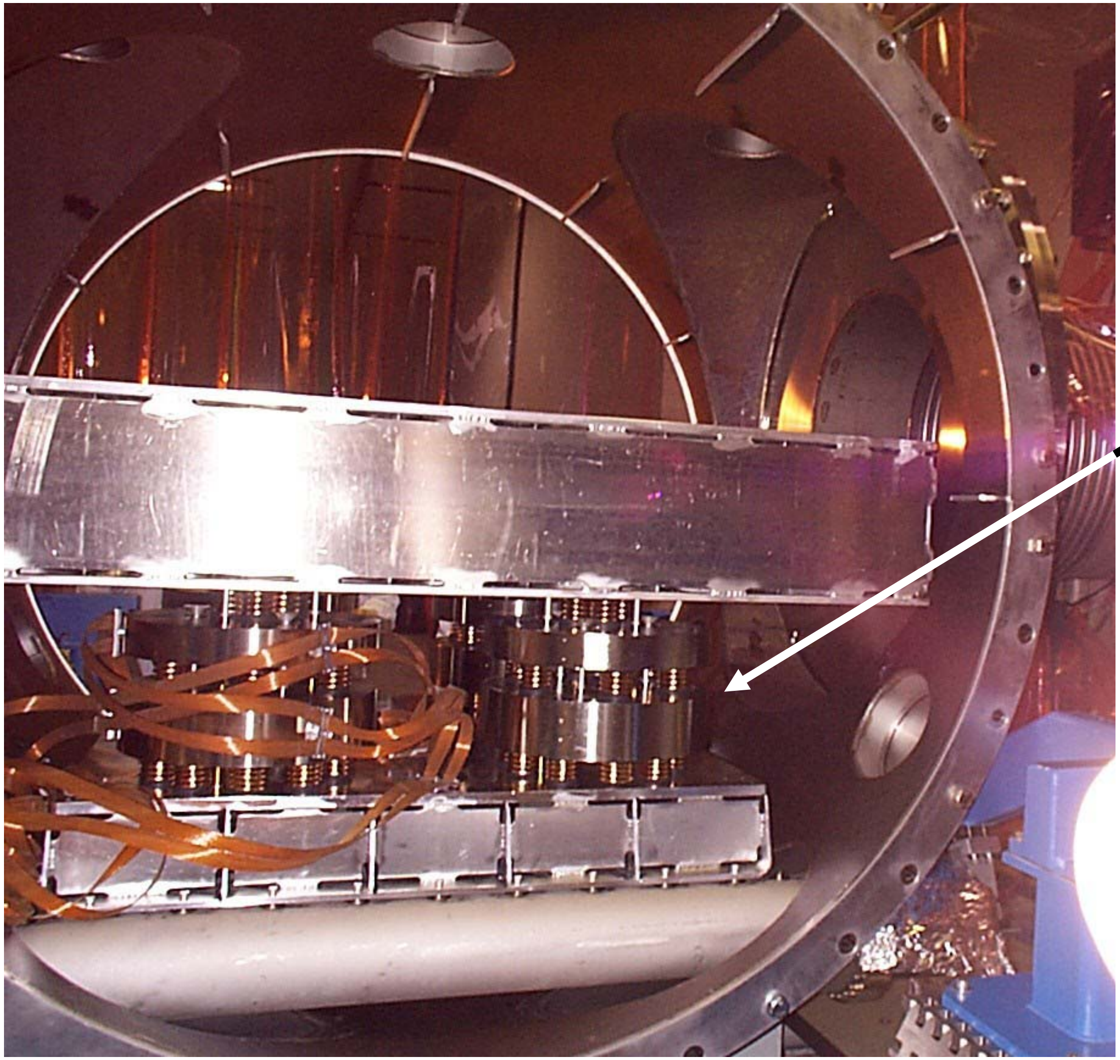
Vacuum System

A Mirror *in situ*

Mirror Close-Up



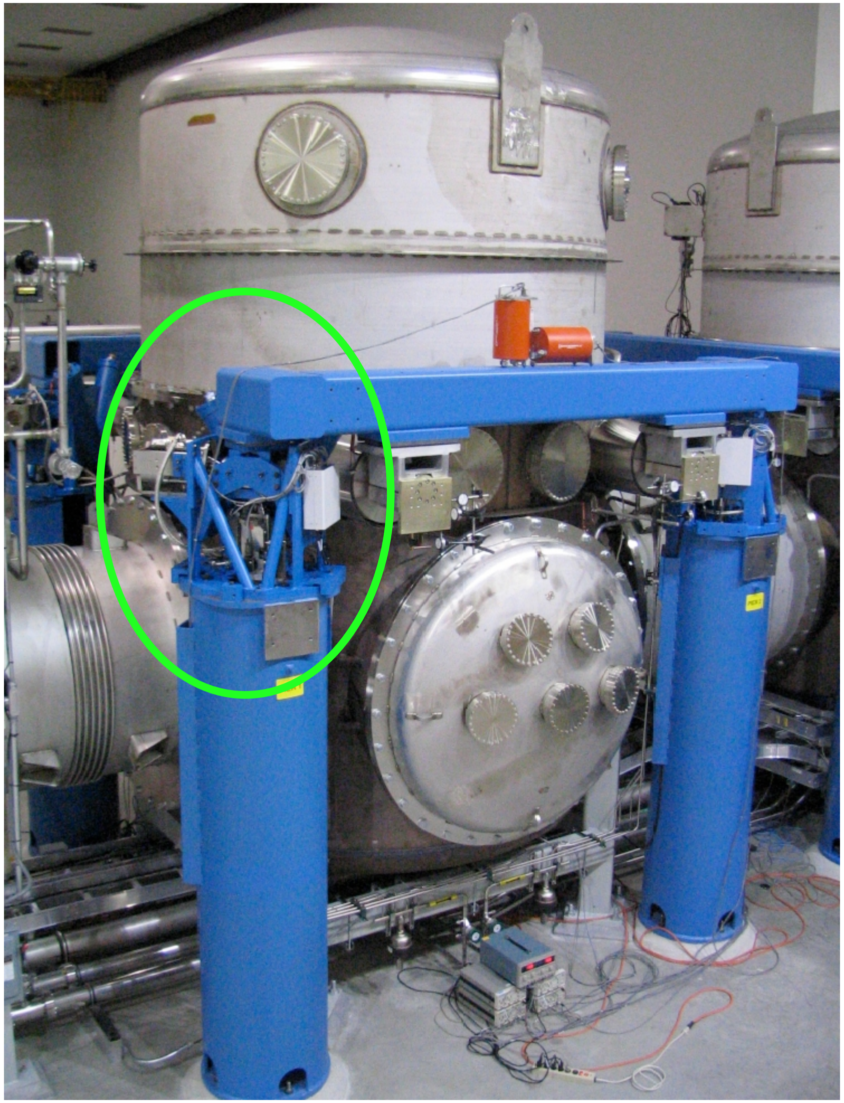
Vibration Isolation



Optical tables are supported on "stacks" of weights & damped springs

Wire suspension used for mirrors provides additional isolation

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

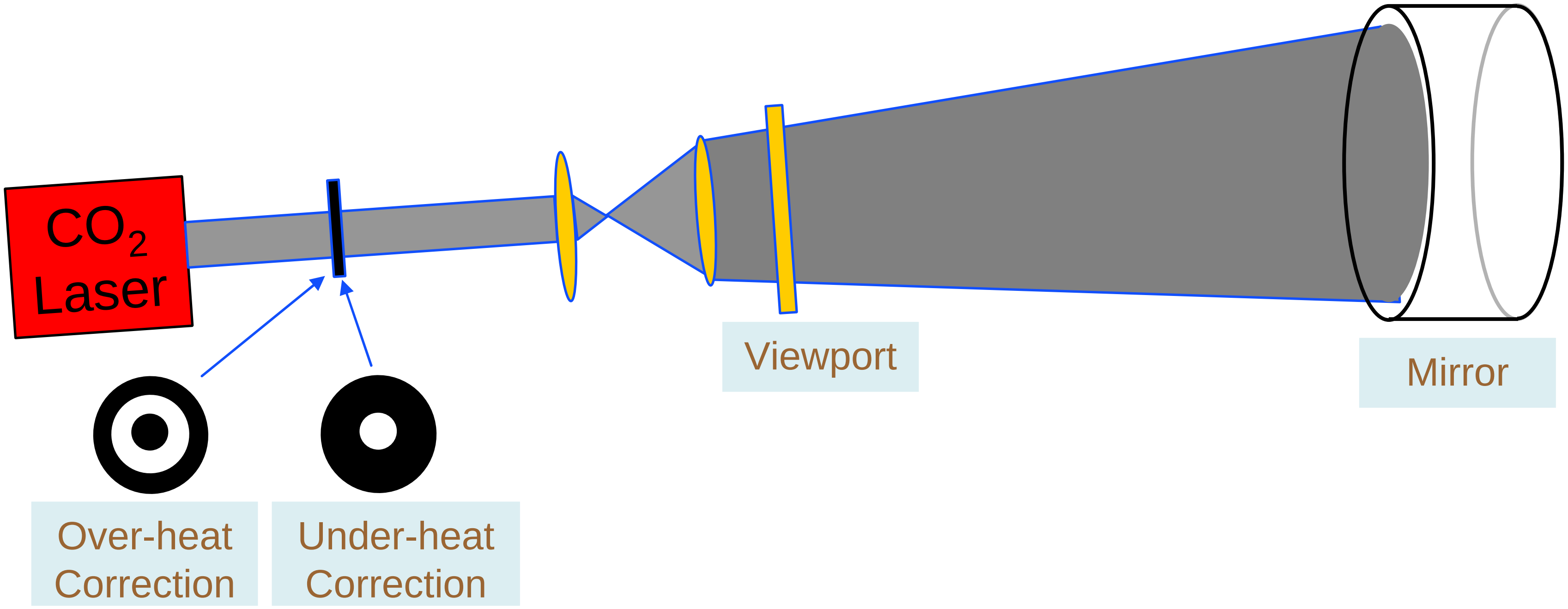
Handling High Laser Power

Use multiple photodiodes to handle increased light

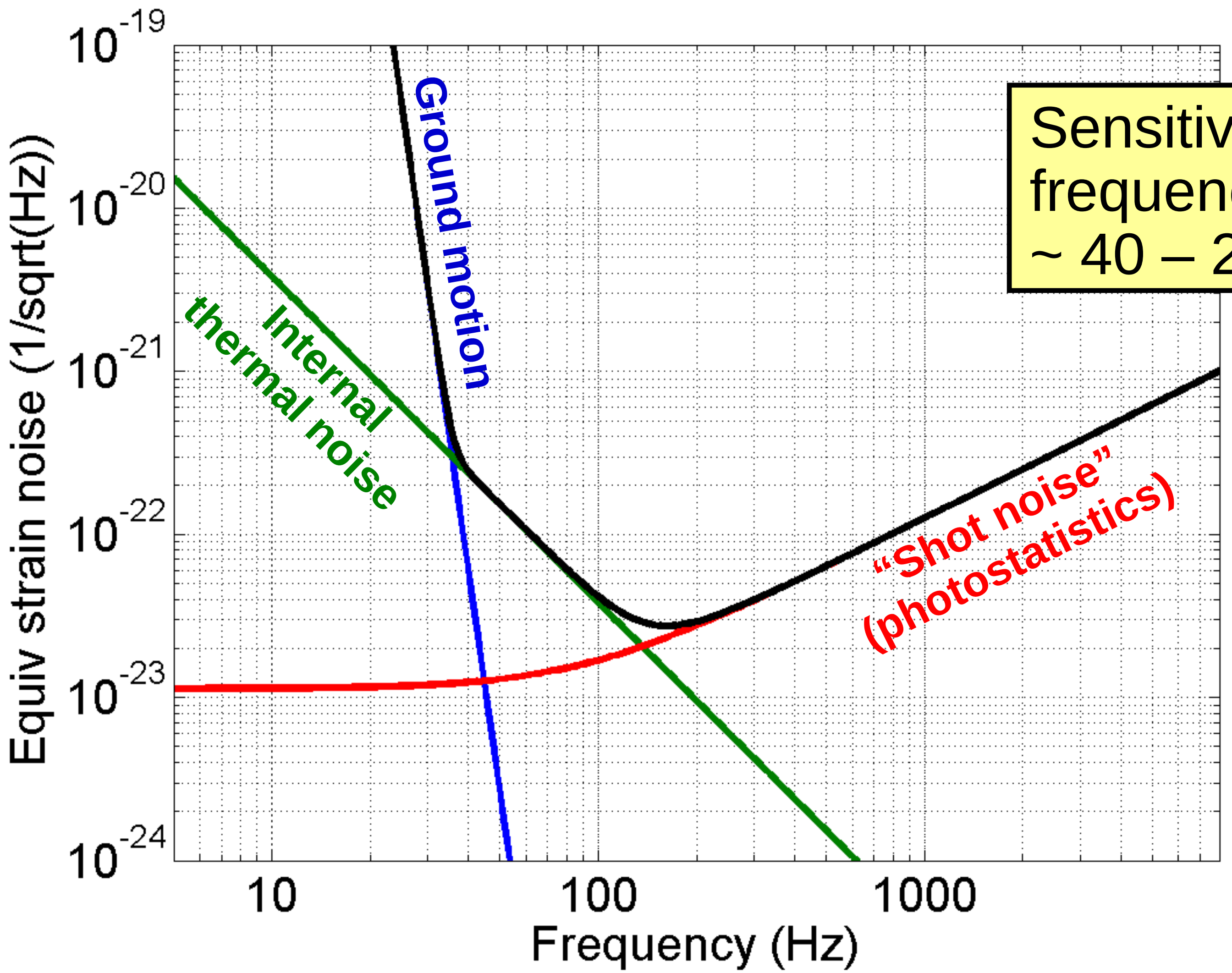
And fast shutters to protect photodiodes when lock is lost !

Compensate for radiation pressure in control software

Correct thermal lensing of mirrors by controlled heating



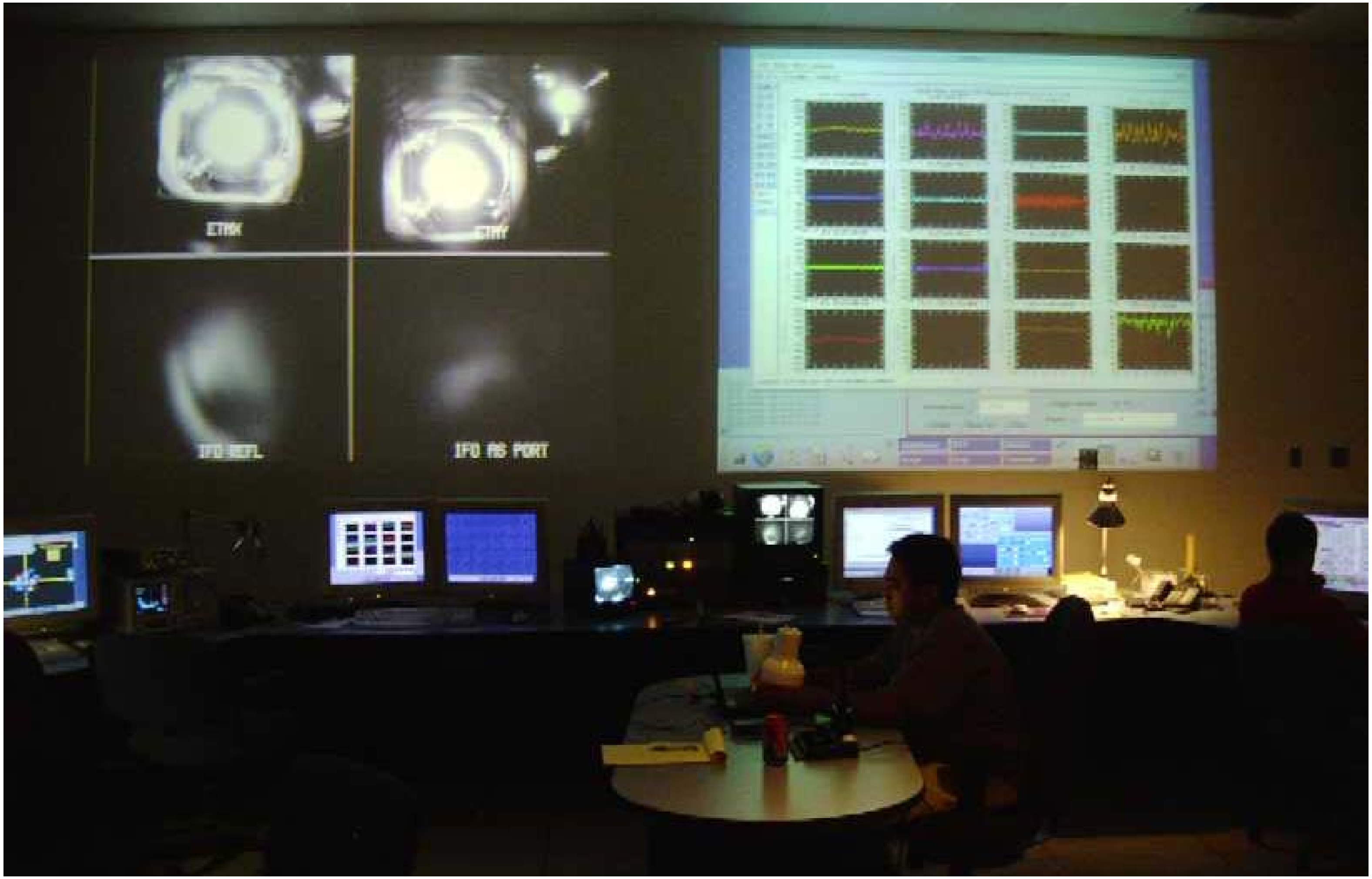
Limiting Fundamental Noise Sources



Sensitive frequency range:
~ 40 – 2000 Hz

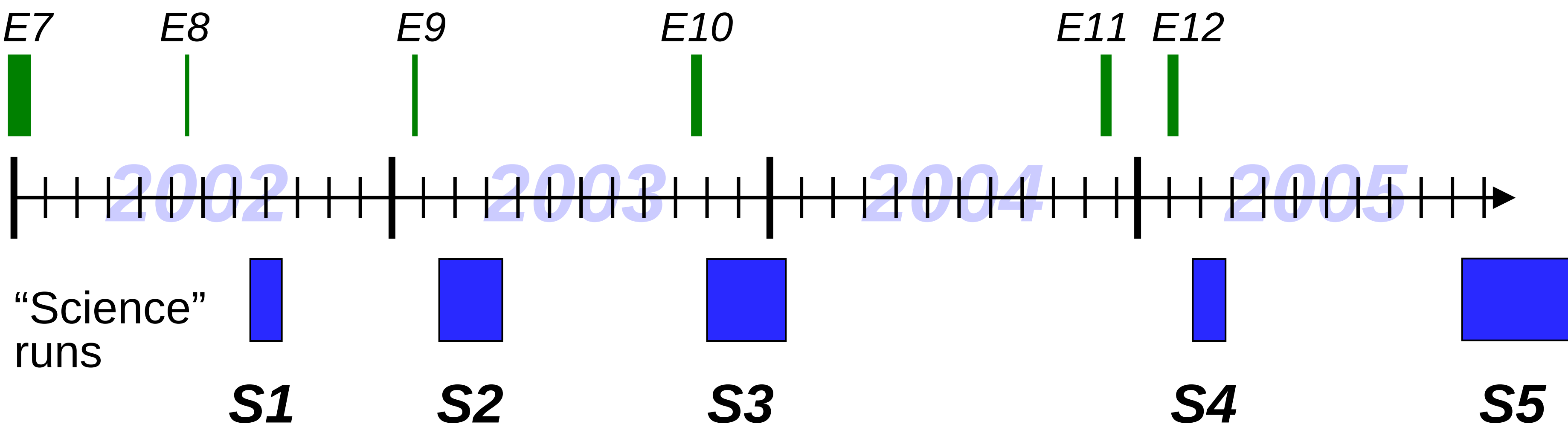
Data Collection

Shifts manned by resident “operators” and visiting “scientific monitors”



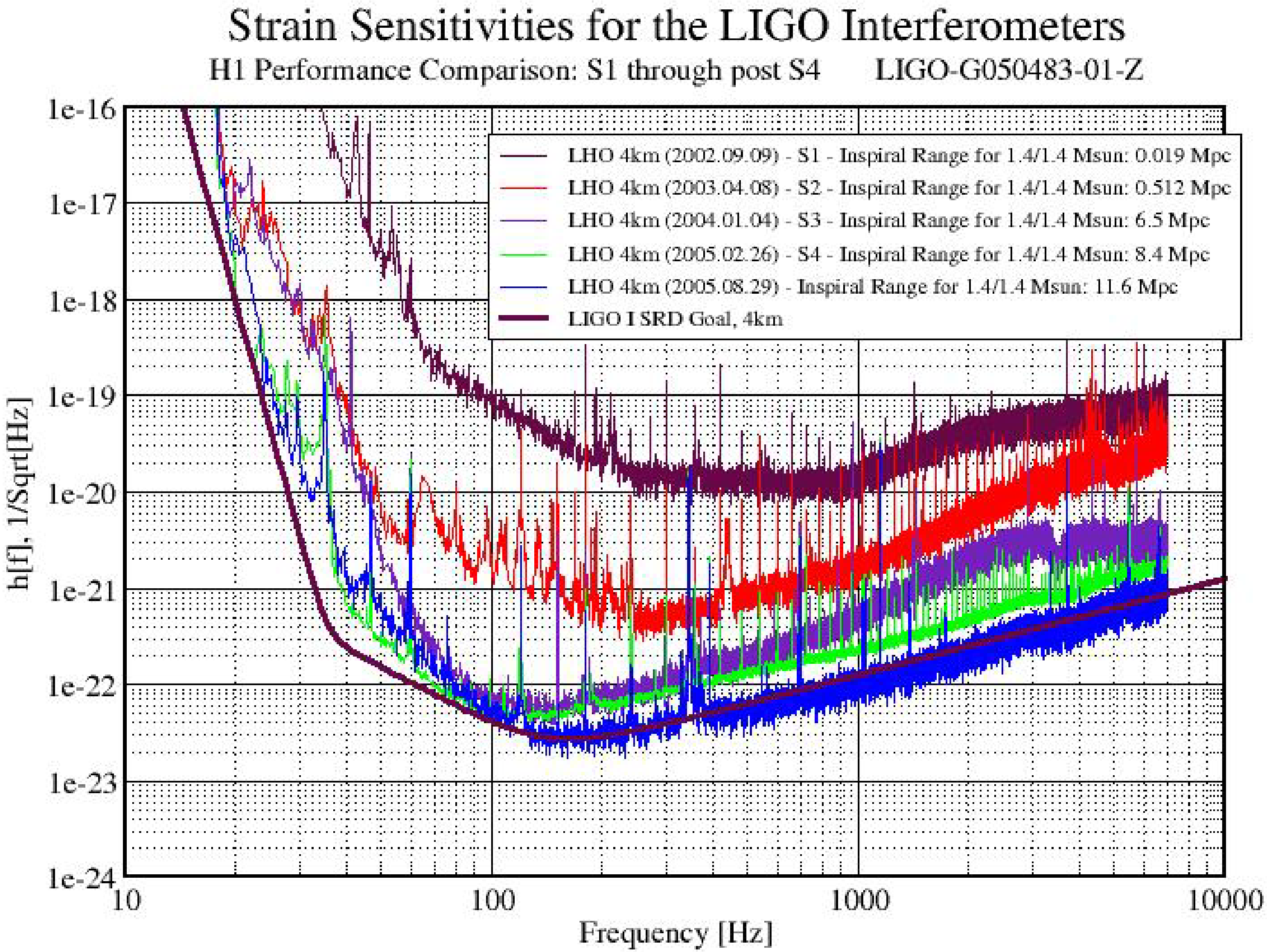
LIGO Data Runs

“Engineering” runs



	S1	S2	S3	S4	S5
	23 Aug – 9 Sep 2002	14 Feb – 14 Apr 2003	31 Oct 2003 – 9 Jan 2004	22 Feb – 23 Mar 2005	4/14 Nov – mid 2007?
Duty factors:					
H1	59 %	74 %	69 %	80 %	
H2	73 %	58 %	63 %	81 %	
L1	43 %	37 %	22 %	74 %	

LHO 4 km Sensitivity, Runs S1 through S5



The GW Signal Tableau
(for ground-based detectors)

Short duration ⟷ Long duration

Waveform known ↕ Waveform unknown

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

Asymmetric spinning NS

High-mass inspiral

Rotation-driven instability

Cosmological stochastic background

Stellar collapse

Binary merger

Many overlapping signals

???

???

???

General Data Analysis Methods

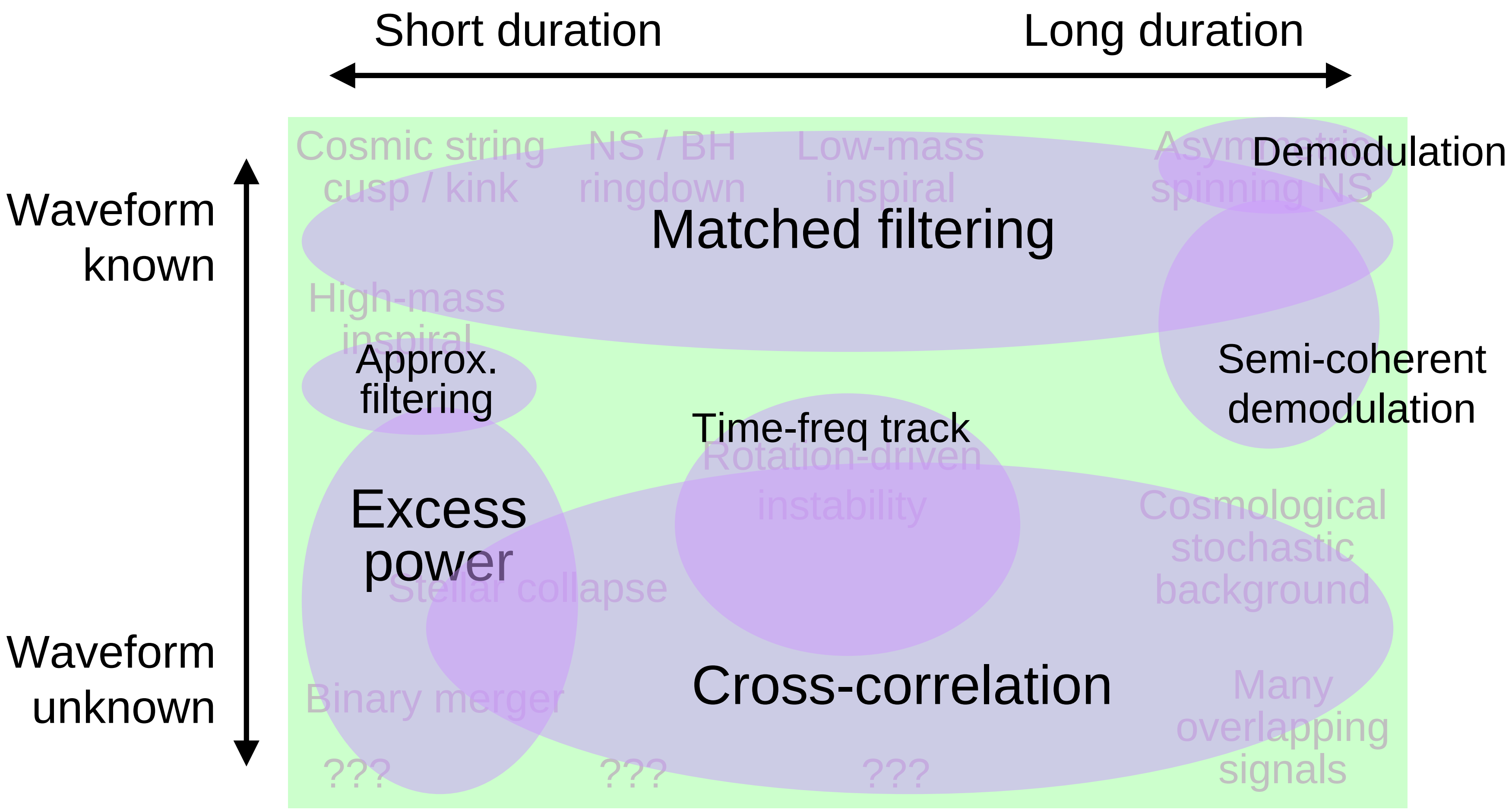
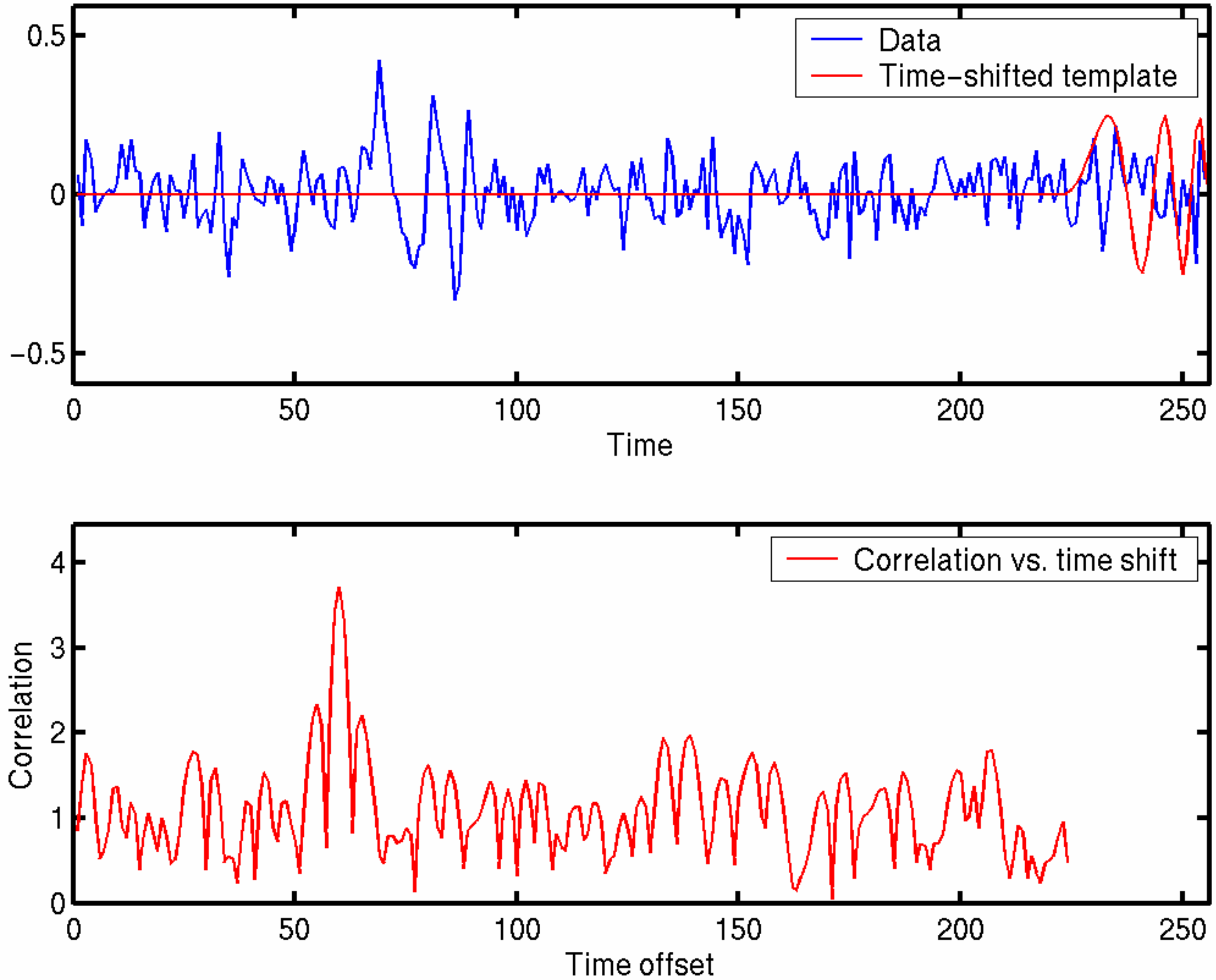


Illustration of Matched Filtering



Optimal Matched Filtering in Frequency Domain

Data → $\tilde{s}(f)$

Template → $\tilde{h}^*(f)$

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

Noise power spectral density → $S_n(f)$

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

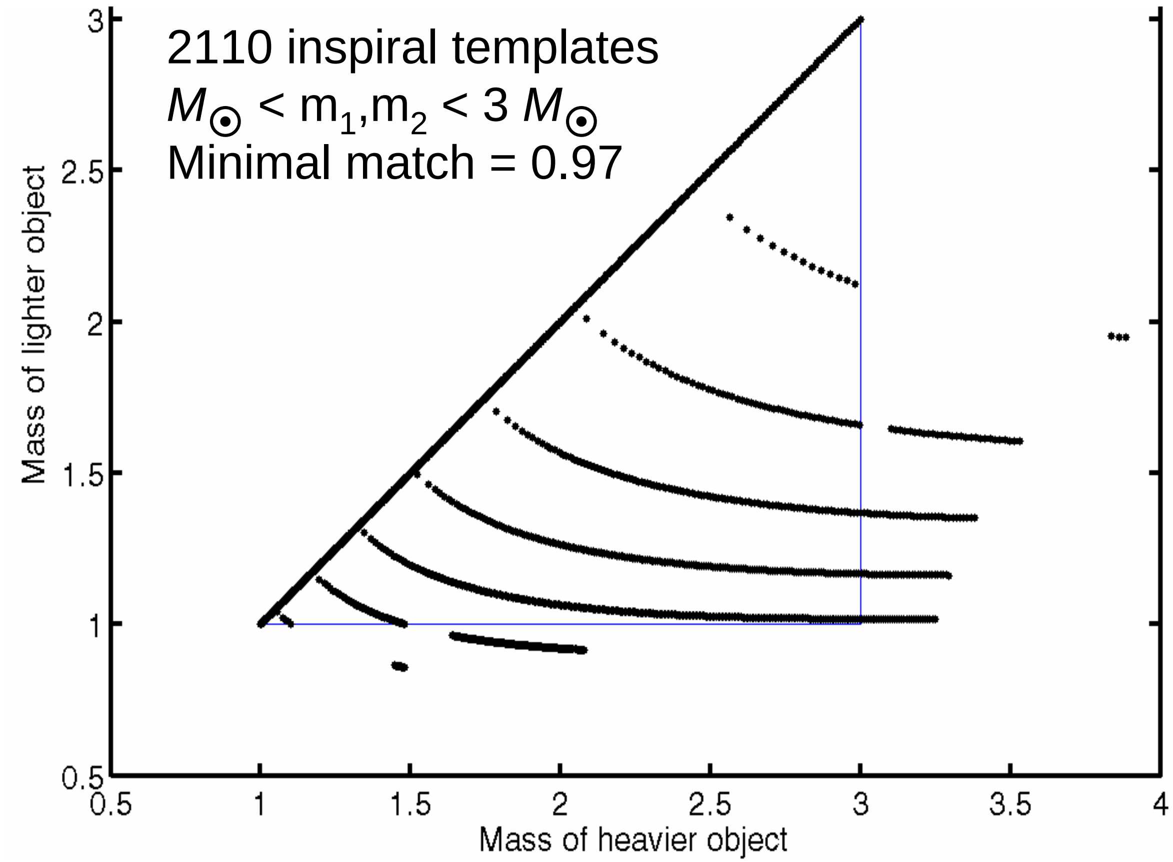
Require coincidence to make a detection

Triggers in multiple interferometers with consistent times and signal parameters

Matched Filtering in Practice

Use bank of templates to cover parameter space of target signals

Process data in parallel on many CPUs



Low-Mass Inspiral Searches

Neutron star binaries (1-3 $M_\odot$)

S2 range (if optimally oriented): ~1.5 Mpc

S2 result: *[PRD **72,** 082001 (2005)]*

No inspirals detected

Set upper limit (90% C.L.) of 47 per year per Milky Way equiv. galaxy for a plausible population model

S3 / S4 / S5 range: ~3, ~15, ~22 Mpc; analysis in progress

Primordial black hole binaries (0.2-1.0 $M_\odot$) in galactic halo

S2 range: a few hundred kpc

S2 result: *[PRD **72,** 082002 (2005)]*

No inspirals detected

Set upper limit (90% C.L.) of 63 per year in the Milky Way halo for a guess at a population model

S5 range: several Mpc

High-Mass Inspiral Searches

Black hole binaries (>3 $M_\odot$)

- Range: several times farther than range for neutron star binaries
- Waveforms are not known very reliably
- If spins are significant, parameter space is very large
- $\Rightarrow$ Use a parametrized detection template family for efficient filtering
- Searches in progress using S3 / S4 data—
  spinning and non-spinning template families

Black hole – neutron star binaries

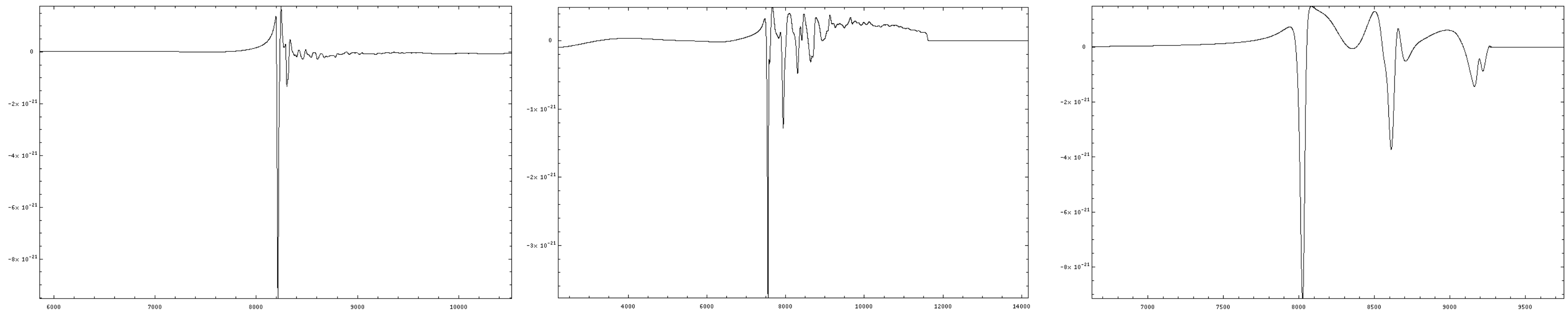
- Extreme mass ratio makes waveforms uncertain

Potential “Burst” Sources

Stellar core collapse (leading to a supernova)

Gravitational wave emission depends on asymmetry of collapse / recoil

Simulations exist, but do not give reliable waveforms
(Zwerger & Müller; Dimmelmeier, Font & Müller; Ott, Burrows, Livne & Walder; etc.)



Black hole formation

Black hole binary merger

Unanticipated sources

How can we search for unknown signals?

"Excess Power" Search Methods

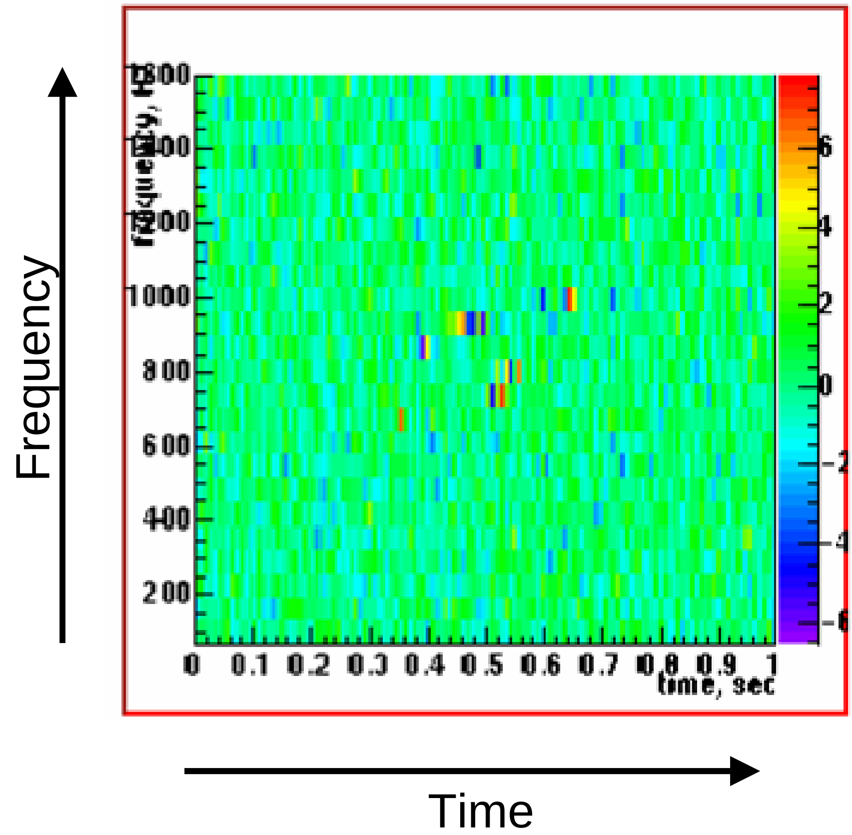
Look for an increase in signal power in a time interval, compared to baseline noise

- Evaluate significance of the excess

Typically start by decomposing data into a time-frequency map

- Each row (frequency) normalized
- Could be wavelets instead of Fourier components
- Might use multiple resolutions

Look for "hot" pixels, alone or in clusters



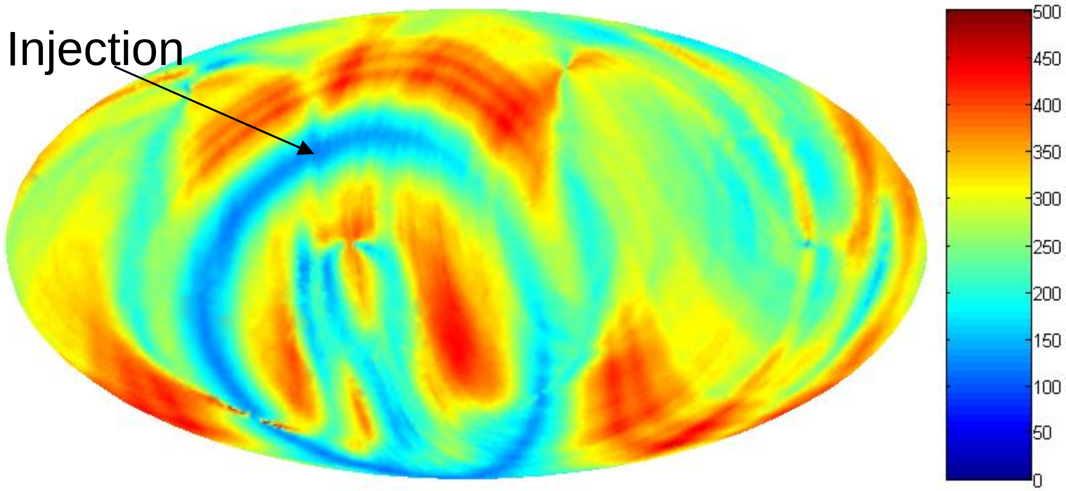
Cross-Correlation

Look for correlation between data streams over short time interval

May be used as a follow-up check around times of coincident excess power triggers

Can be extended to three or more sites, incorporating antenna patterns as a function of sky position

e.g. form a “null stream” to find sky position most consistent with a signal

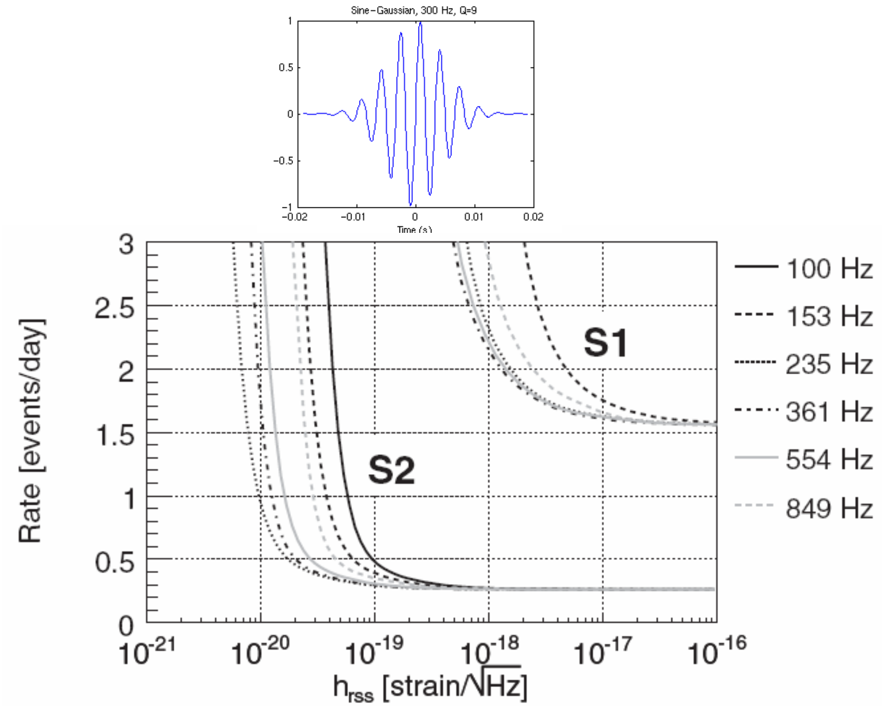


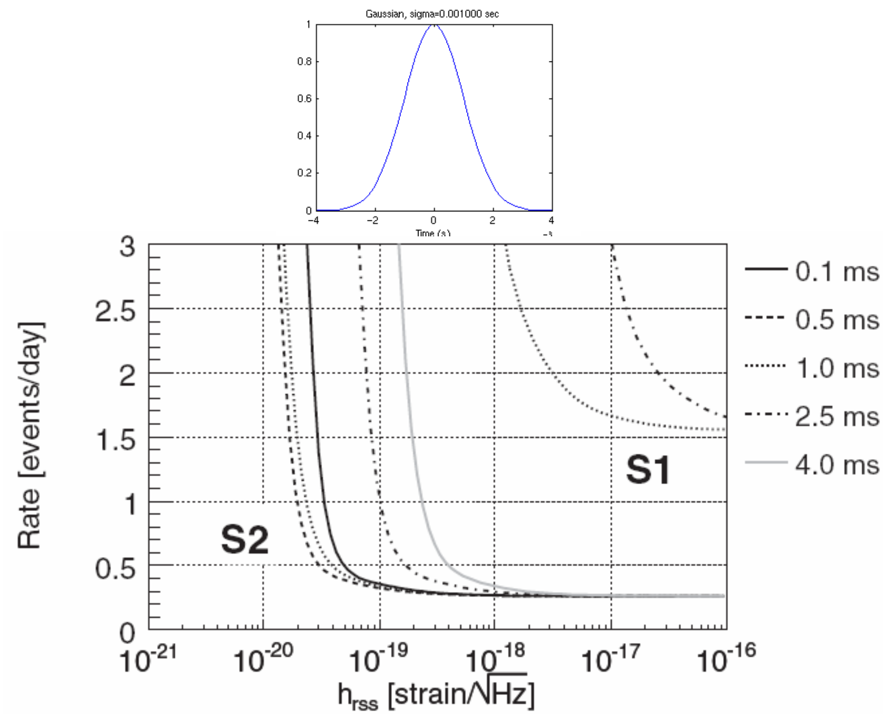
Burst Searches

All-sky searches

S2 result: *[PRD **72,** 062001 (2005)]*

- Wavelet-based excess power triggers followed by cross-correlation
- No gravitational wave bursts detected
- Upper limit on rate of *detectable* bursts: 0.26 per day
- Sensitivity evaluated for various ad-hoc and modeled waveforms





Burst Searches

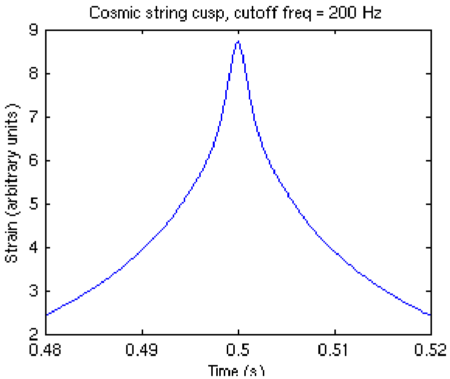
All-sky searches (continued)

S3: Somewhat better sensitivity

S4: Several times better sensitivity; somewhat longer observation time

Cosmic string cusps / kinks

Use matched filtering; search in progress



Ringdowns (damped sinusoids)

Use matched filtering; search in progress

Externally Triggered Searches

Search for gravitational wave bursts or inspirals associated with GRBs or other observed astrophysical events

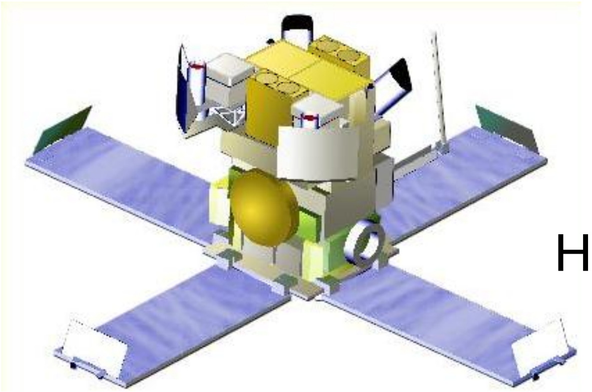
Known time allows use of lower detection threshold

Known sky position fixes relative time of arrival at detectors

Analysis published for GRB030329 *[PRD 72, 042002 (2005)]*

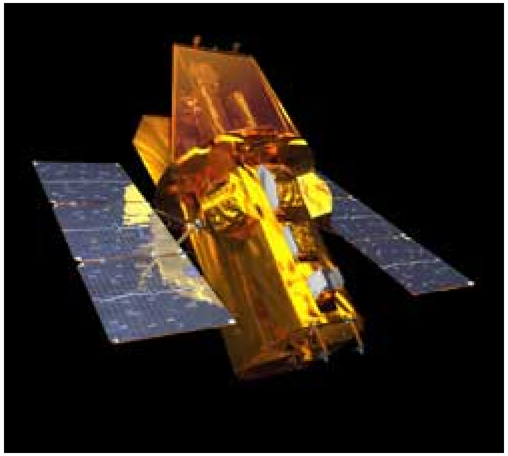
Placed limit on gravitational wave amplitude

Analyses in progress for many GRBs reported during science runs



HETE-2

Swift



Searches for Periodic Signals from Spinning Neutron Stars

Basically matched filtering, after correcting for motion of detector

Doppler frequency shift, amplitude modulation from antenna pattern

Search for periodic gravitational waves from known radio pulsars

Demodulate data at twice the spin frequency

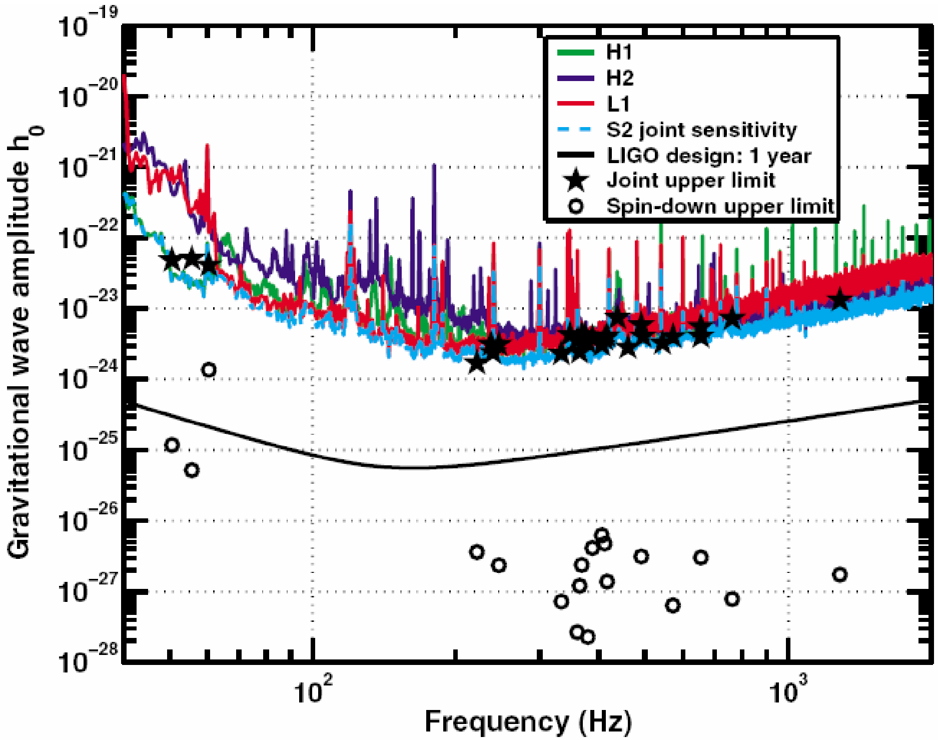
S2 result: *[PRL **94,** 181103 (2005)]*

Placed limits on strain and equatorial ellipticity for 28 known pulsars

Lowest h_0 limit: 1.7×10^{-24}

Lowest ε limit: 4.5×10^{-6}

S5 sensitivity: should be able to pass the spin-down limit of the Crab pulsar



Searches for Periodic Signals from Spinning Neutron Stars

All-sky coherent search for isolated periodic signals

Computationally very expensive!

First search, using S2 data, will be published soon

Search over orbital parameter space for source in binary system

Search for gravitational waves from companion to Sco X-1
will be published soon

Semi-coherent methods

S2 upper limits using Hough transform *[PRD **72,** 102004 (2005)]*

Other methods being implemented

Ultimately plan hierarchical searches combining semi-coherent and coherent methods

Searches for a Stochastic Signal

Weak, random gravitational waves could be bathing us

Left over from the early universe, analogous to CMBR ; or

From many overlapping signals from astrophysical objects

Assume spectrum is constant in time

Search by cross-correlating data streams

Assumes that data streams have no instrumental correlations

S3 result *[**PRL** 95, **221101 (2005)**]*

Searched for isotropic stochastic signal with power-law spectrum

For flat spectrum (expected from inflation or cosmic string models), set upper limit on energy density in gravitational waves:

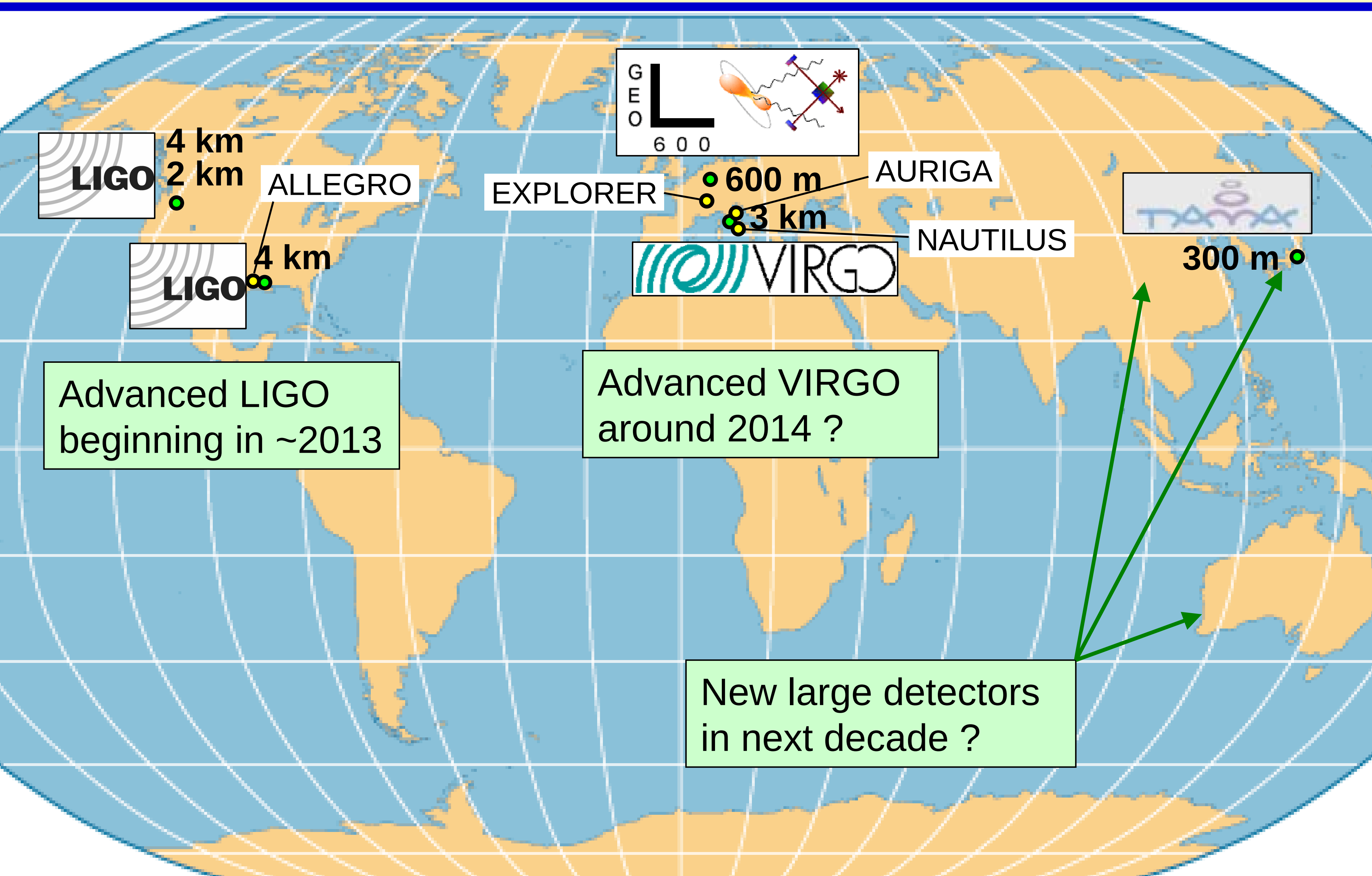
$\Omega_0 < 8.4 \times 10^{-4}$

S4 analysis

In progress; more than an order of magnitude more sensitive

The Worldwide Network

Including • Bars



Summary

The LIGO observatories are now operational.

Four short science runs have been undertaken, with increasing sensitivities, and the data is being analyzed in many ways.

After much hard work, the LIGO interferometers are now essentially at their target sensitivities.

LIGO is now beginning long-term observations.

The worldwide network of gravitational wave detectors is growing, and should see the dawn of gravitational-wave astronomy within the next decade.