LIGO Perks Up Its Ears

Peter Shawhan
The University of Maryland

for the LIGO Scientific Collaboration

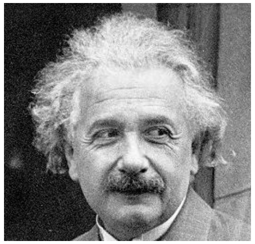
Kansas State University
August 27, 2007

LIGO-G070608-01-Z

Outline

- Gravitational waves
- Gravitational wave detectors
- LIGO
- LIGO data runs
- Plausible gravitational wave signals and data analysis methods
- LSC searches for gravitational waves
- The evolving worldwide network of gravitational wave detectors

Gravitational Wave Basics



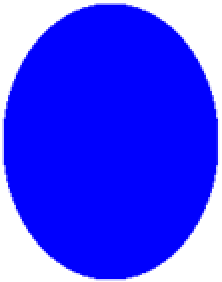
Wave solutions to the equations of general relativity

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

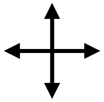
Travel away from the source at the speed of light

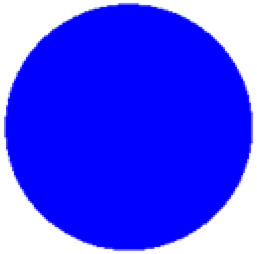
Waves deform space itself, stretching it first in one direction, then in the perpendicular direction

Can be a linear combination of polarization components

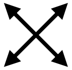


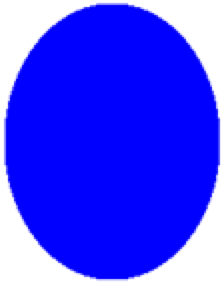
“Plus” polarization



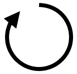


“Cross” polarization





Circular polarization

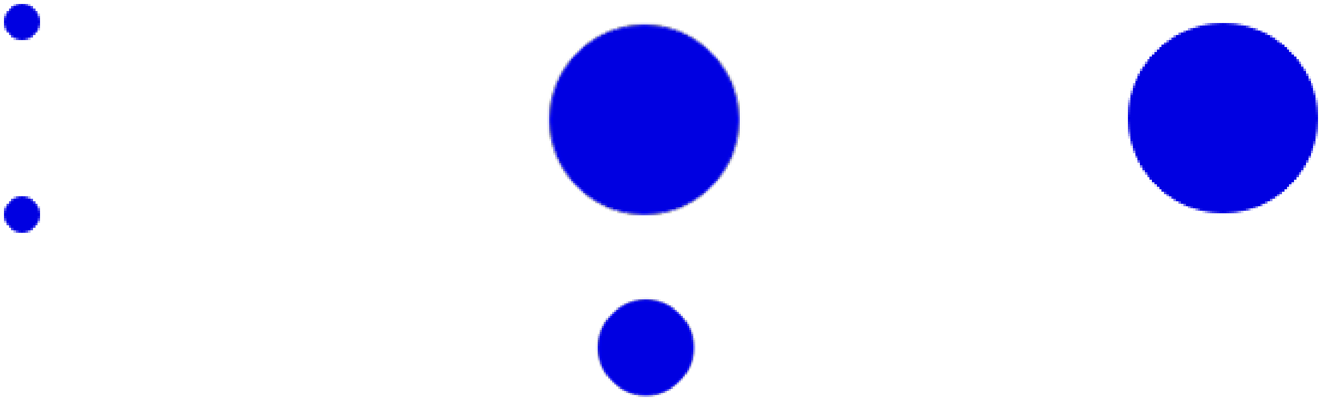


…

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*** = ΔL / L

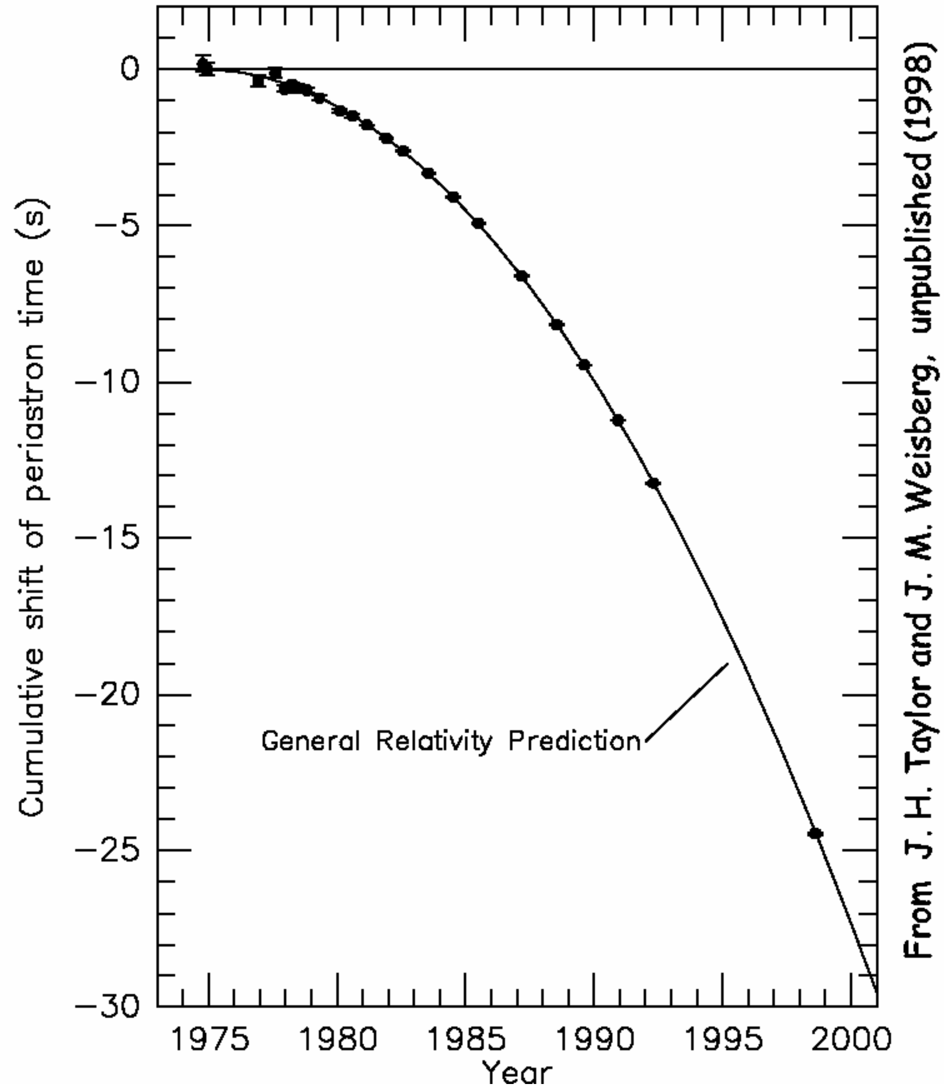
h is inversely proportional to the distance from the source

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

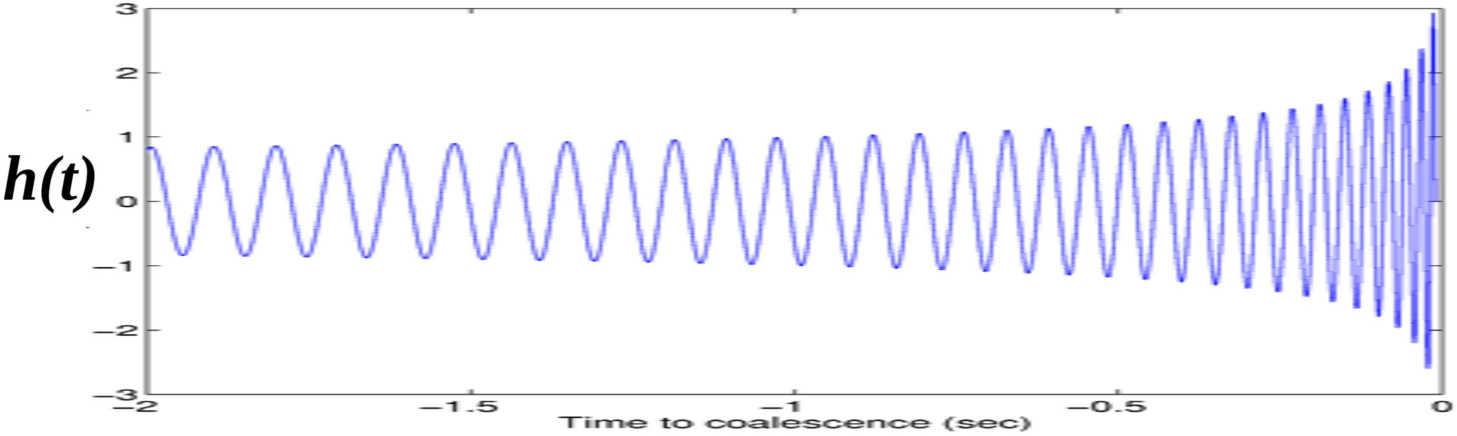


From J. H. Taylor and J. M. Weisberg, unpublished (1998)

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 ???

Outline

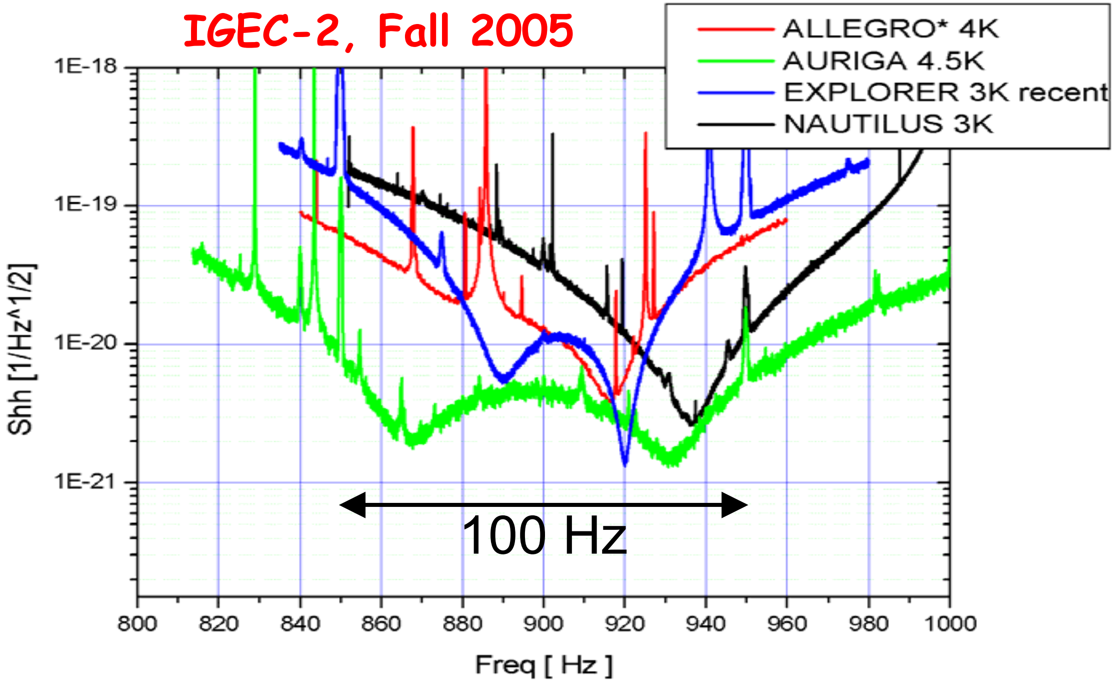
- Gravitational waves
- Gravitational wave detectors
- LIGO
- LIGO data runs
- Plausible gravitational wave signals and data analysis methods
- LSC searches for gravitational waves
- The evolving worldwide network of gravitational wave detectors

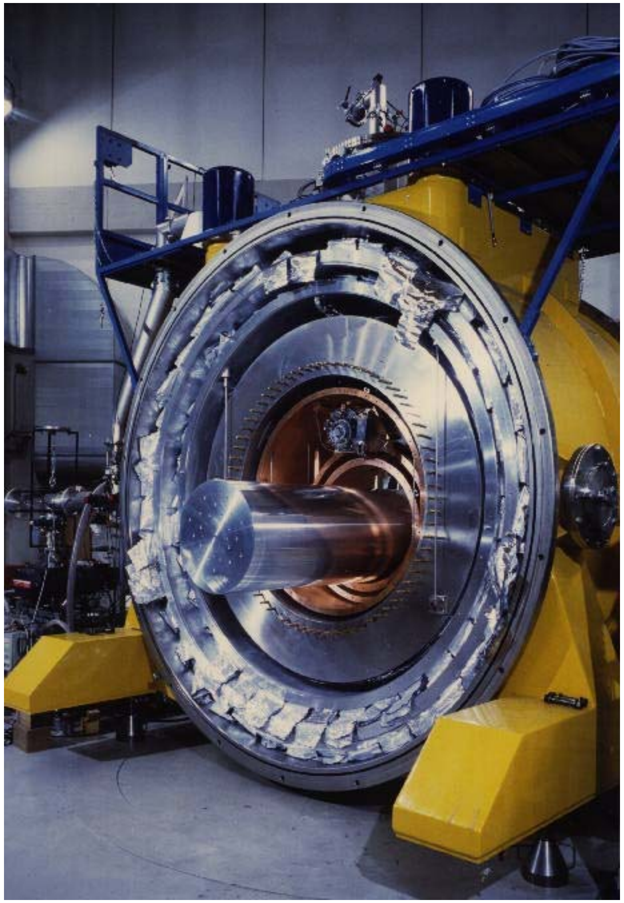
Resonant “Bar” Detectors

Aluminum cylinder, suspended in middle

Gravitational wave causes it to ring at resonant frequencies near 900 Hz

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



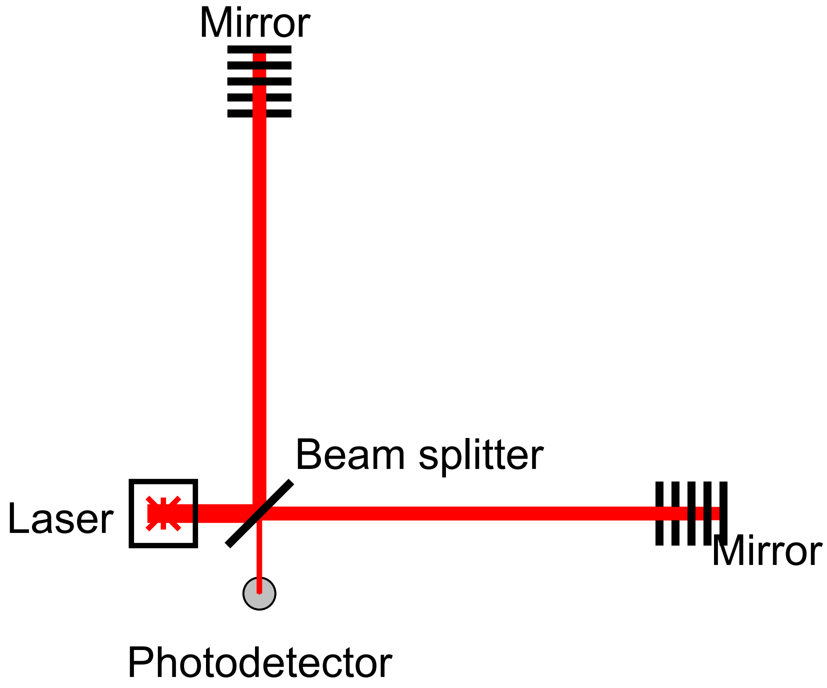


AURIGA detector (open)

Laser Interferometers

Variations on basic Michelson design, with two long arms

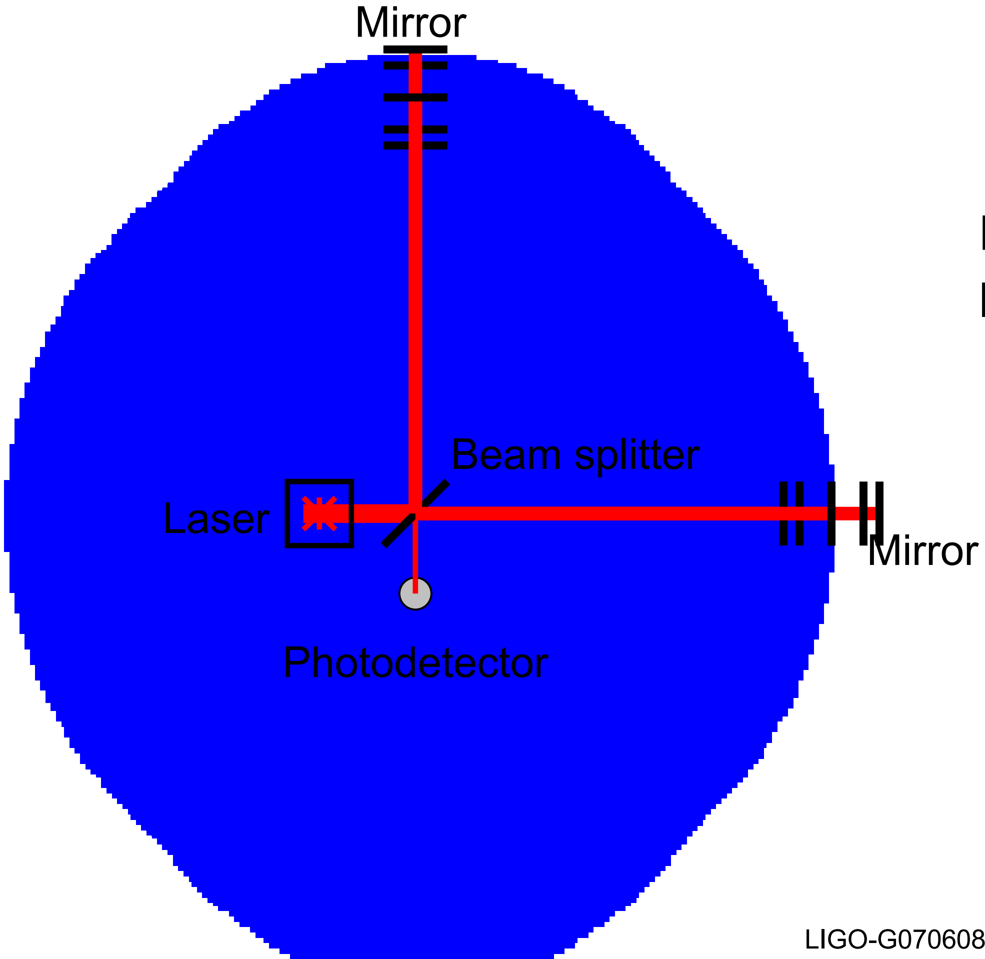
Measure *difference* in arm lengths to a fraction of a wavelength



Laser Interferometers as Gravitational-Wave Detectors

Variations on basic Michelson design, with two long arms

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

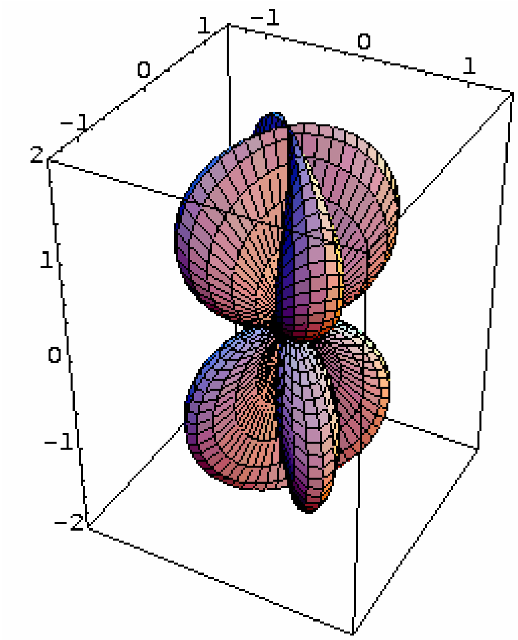


Responds to one polarization projection

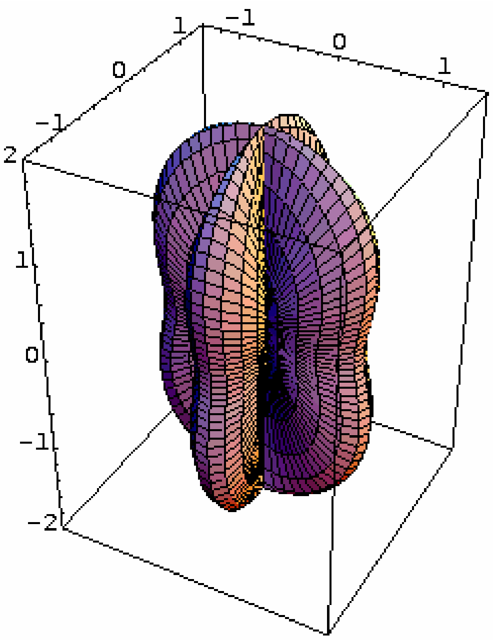
Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

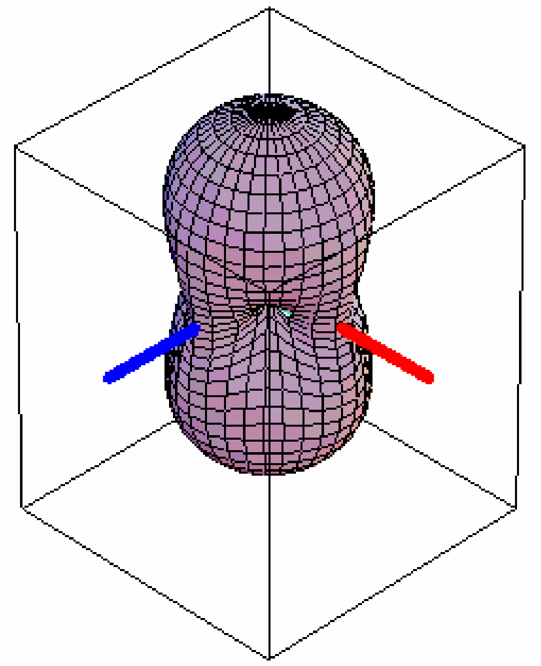
“×” polarization



“+” polarization



RMS sensitivity



A broad antenna pattern

⇒ More like a microphone than a telescope

Outline

- Gravitational waves
- Gravitational wave detectors
- **LIGO**
- LIGO data runs
- Plausible gravitational wave signals and data analysis methods
- LSC searches for gravitational waves
- The evolving worldwide network of gravitational wave detectors

The LIGO Observatories

LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms

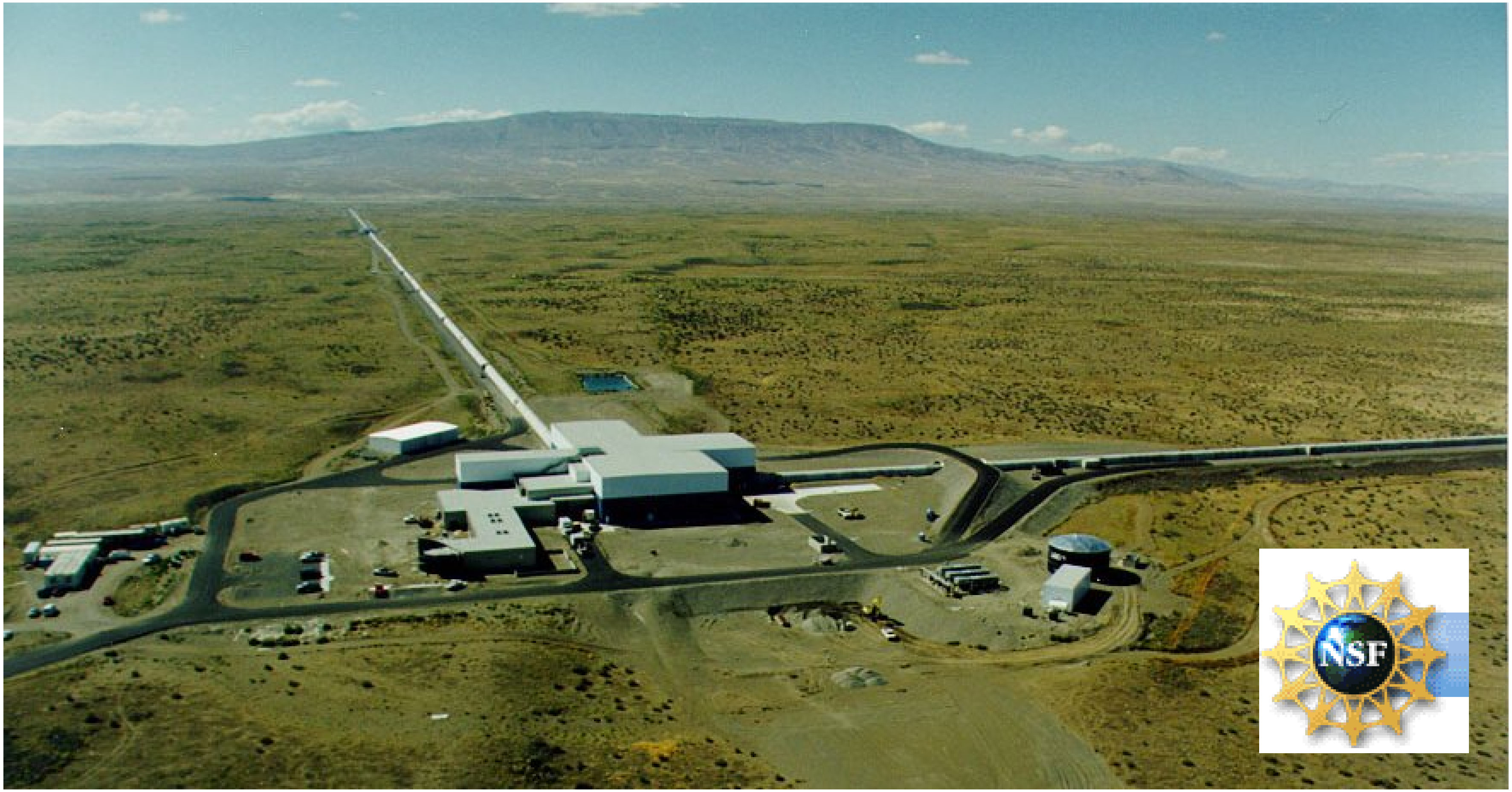
LIGO Livingston Observatory (LLO)
L1 : 4 km arms

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

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

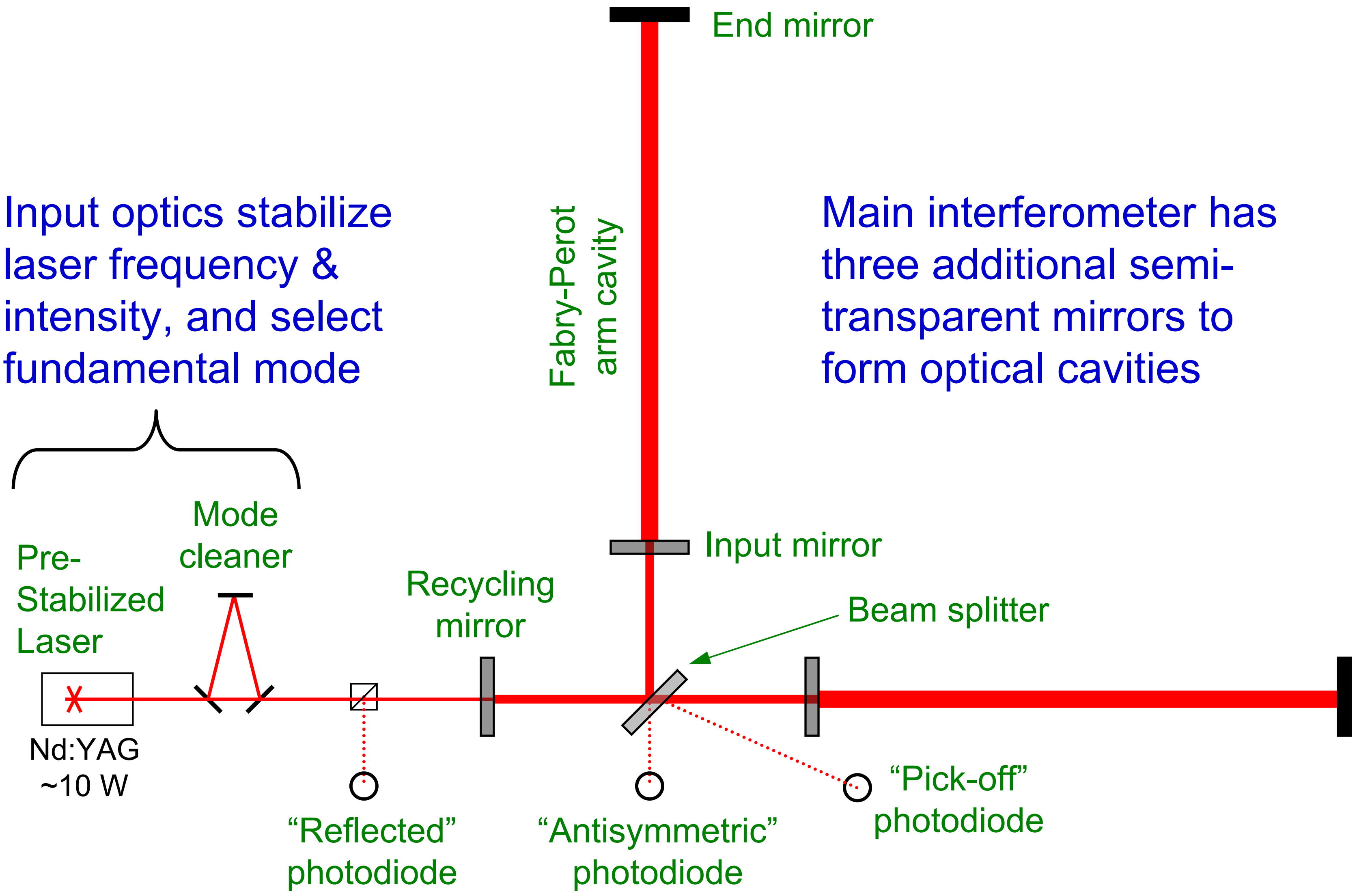
Need to control noise sources

- Stabilize laser frequency and intensity
- Use large mirrors to reduce effect of quantum light noise
- 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 !

- Laser frequency stabilization, mirror alignment, Earth-tide correction, …

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

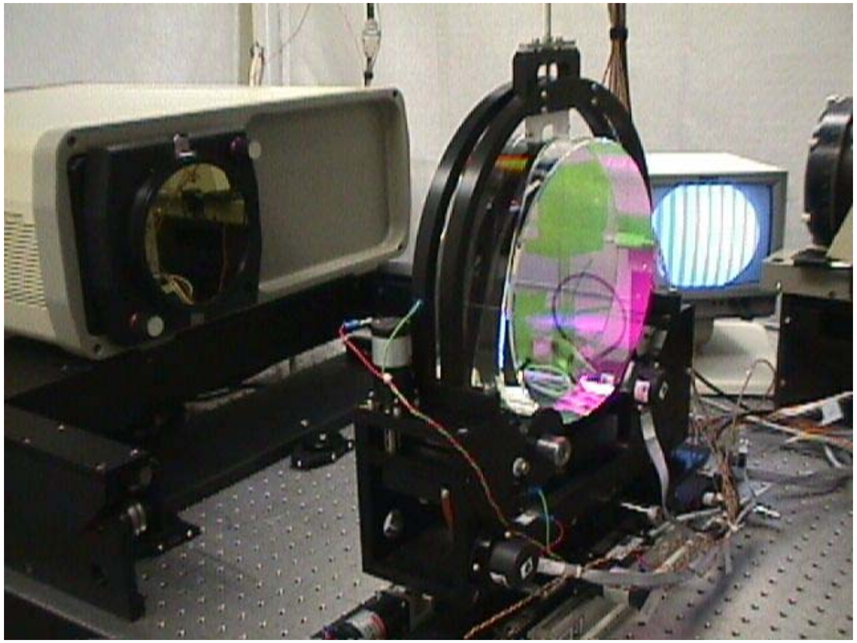
Mirrors

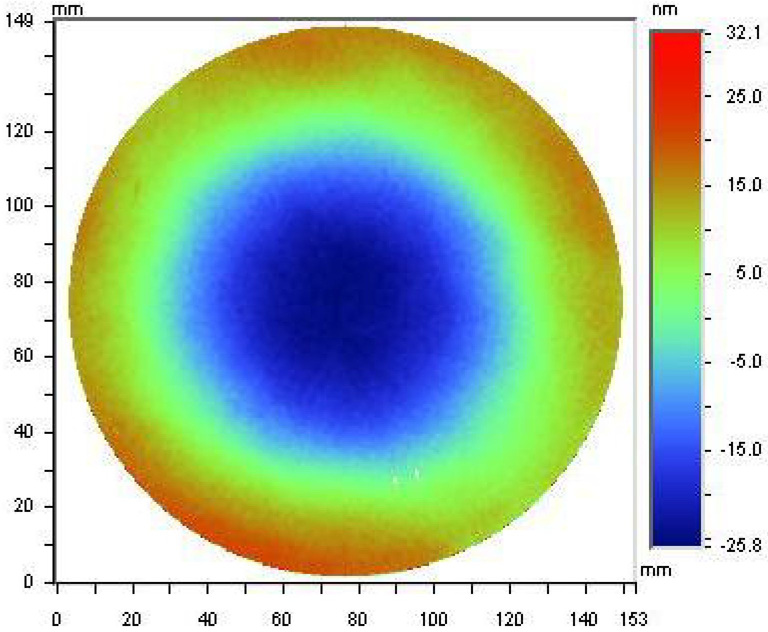
Made of high-purity fused silica

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

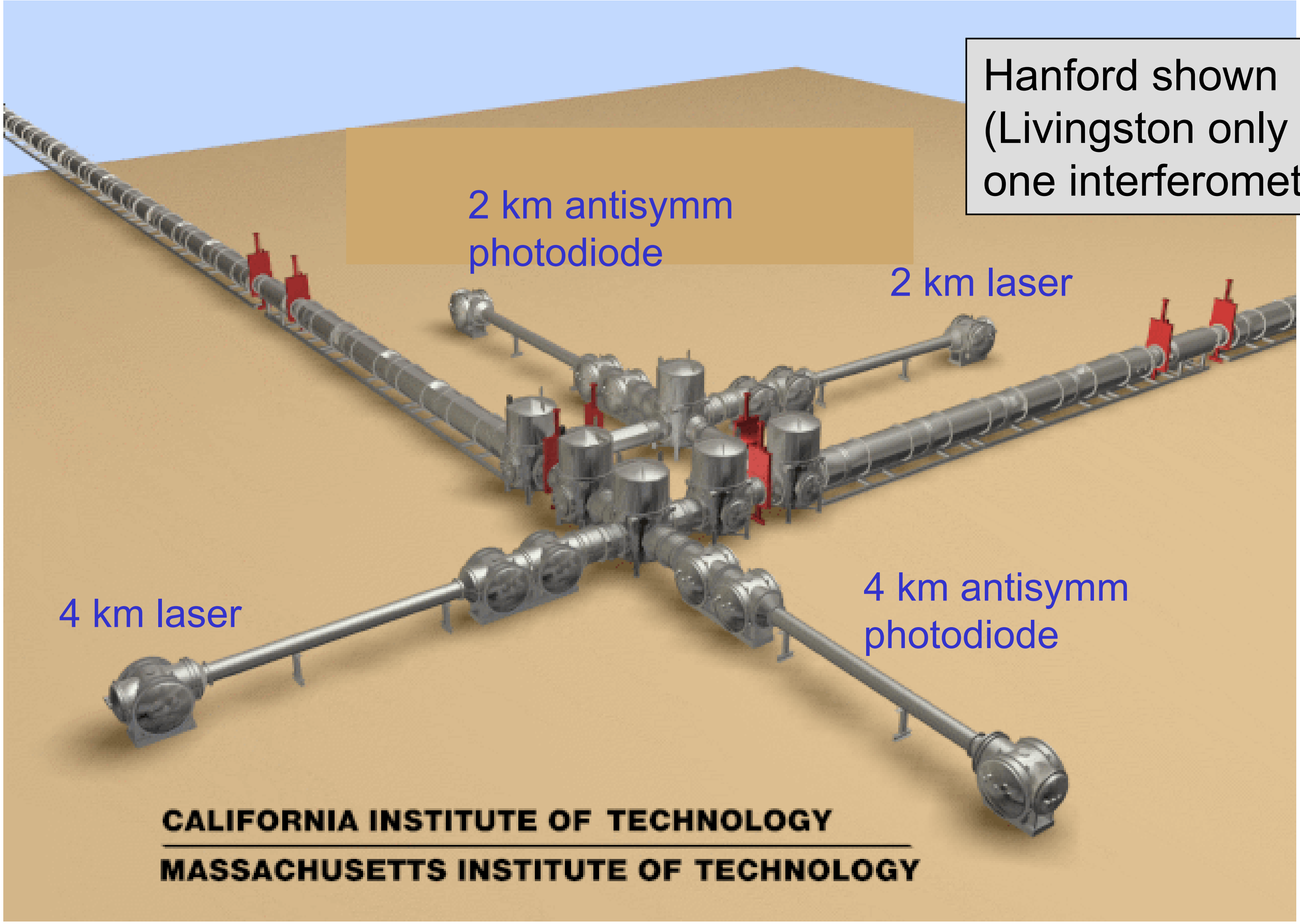
Surfaces polished to ~1 nm rms, some with slight curvature

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





Vacuum System

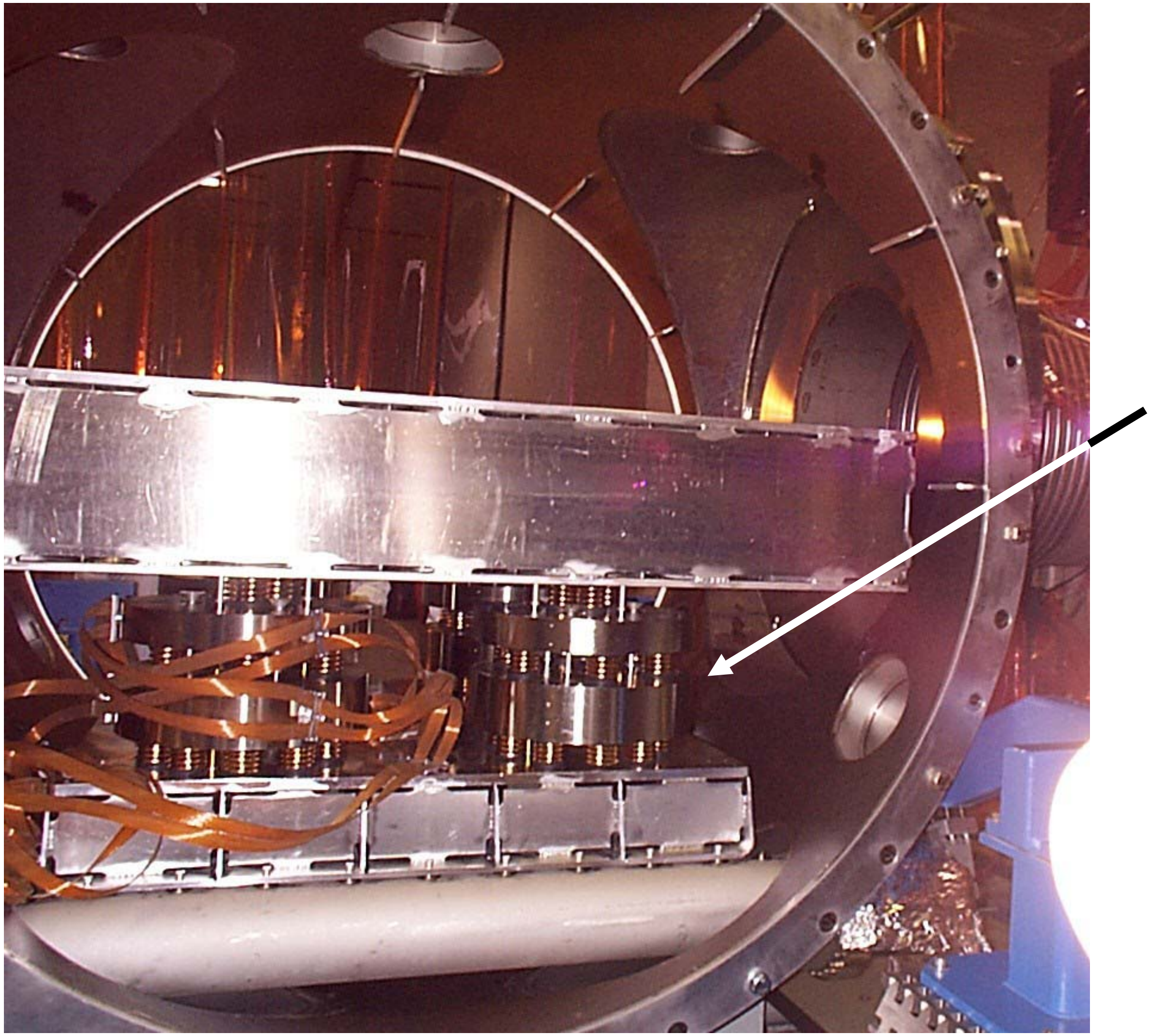


Hanford shown (Livingston only has one interferometer)

Vacuum System

A Mirror *in situ*

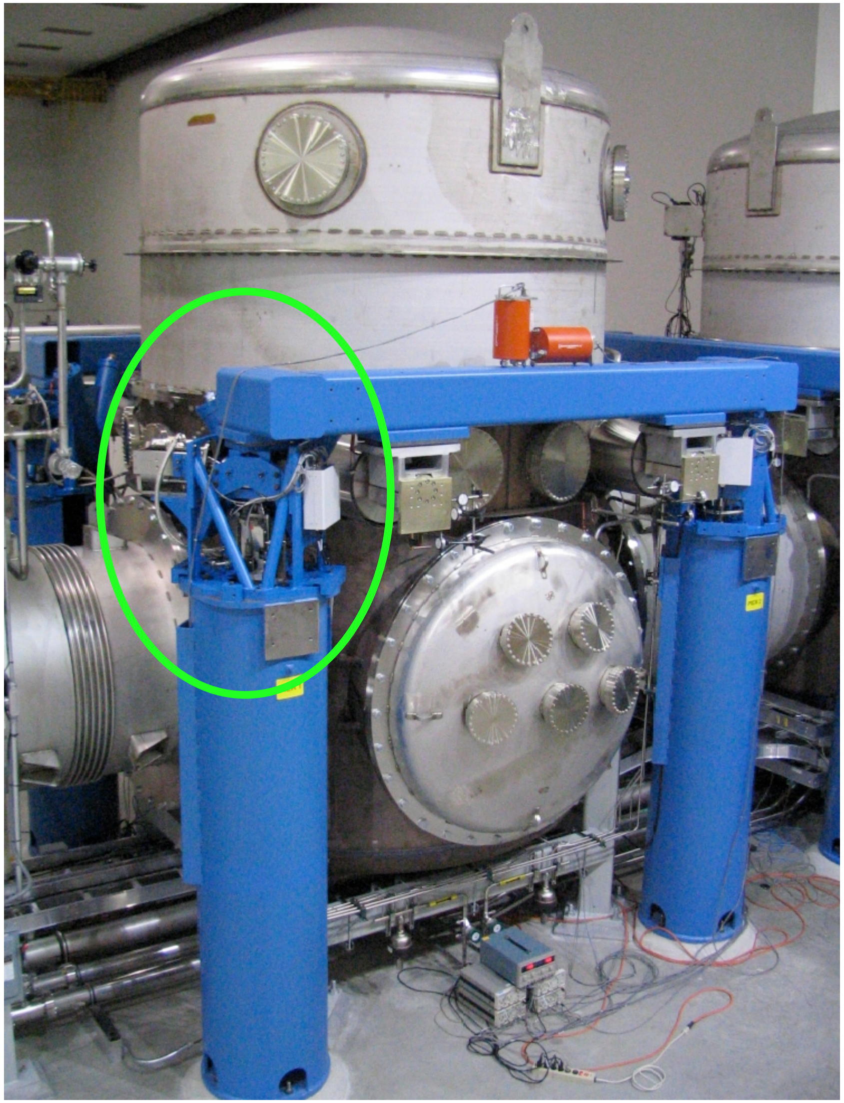
Vibration Isolation



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

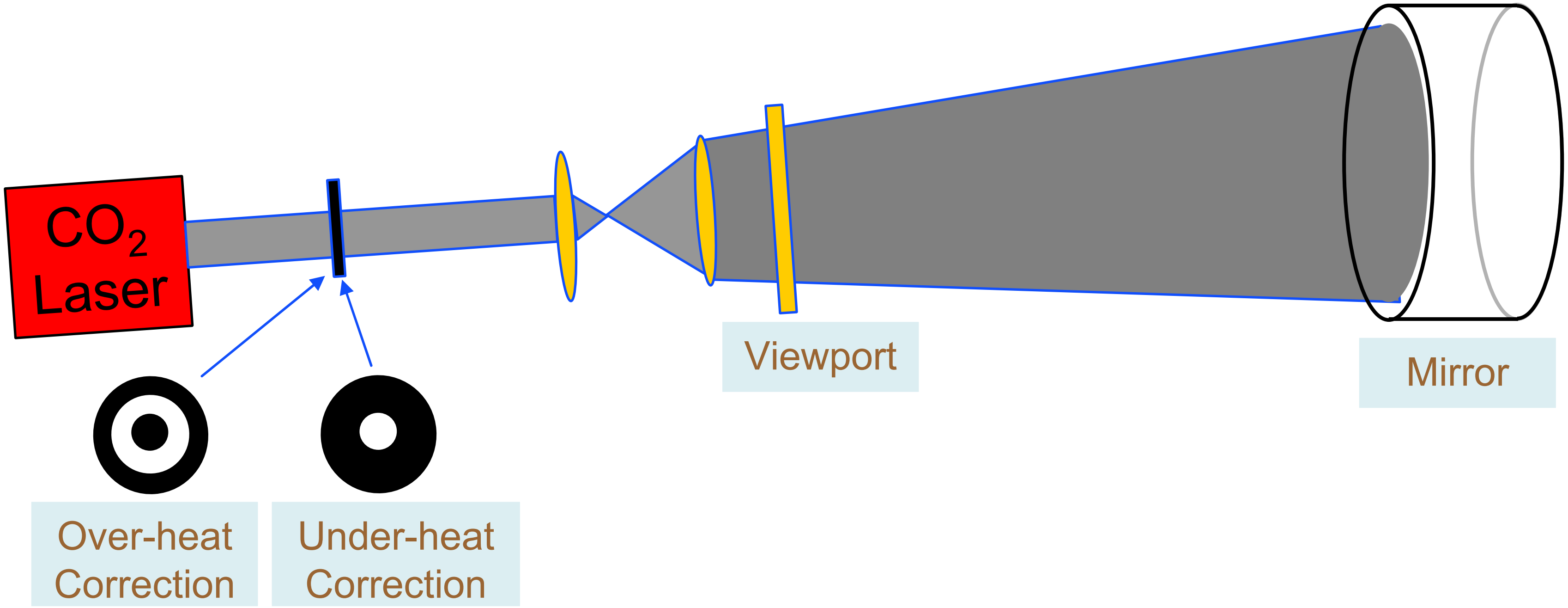
Handling High Laser Power

Use multiple photodiodes to handle increased light

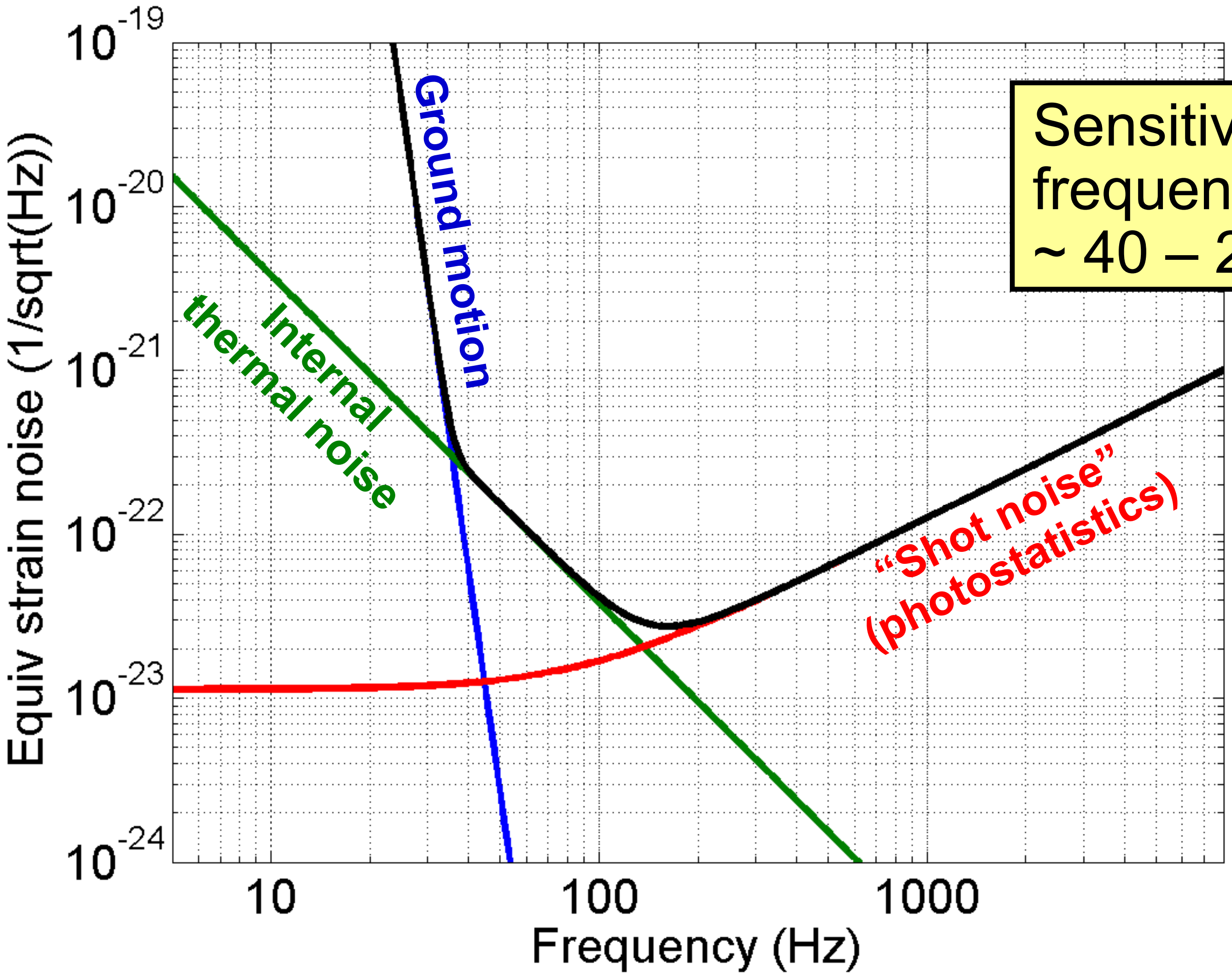
And fast shutters to protect photodiodes when lock is lost !

Compensate for radiation pressure in control software

Correct thermal lensing of mirrors by controlled heating



Limiting Fundamental Noise Sources



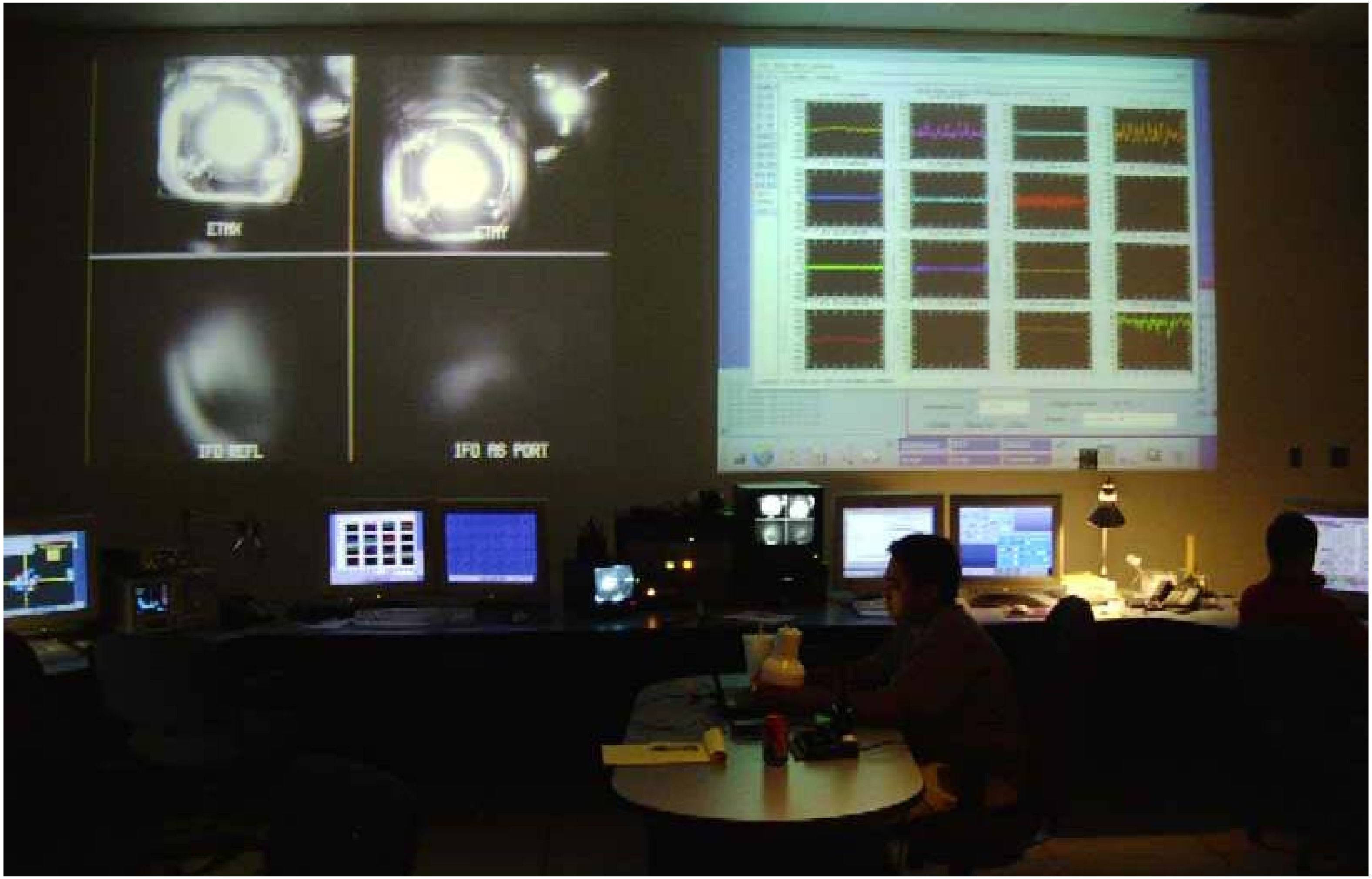
Sensitive frequency range:
~ 40 – 2000 Hz

Outline

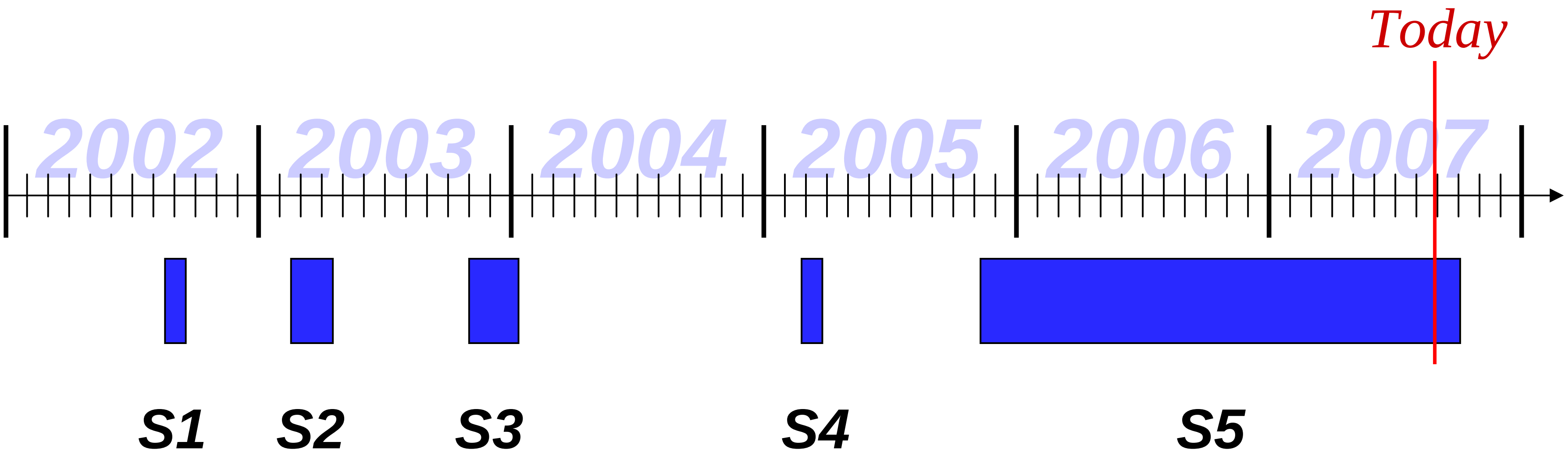
- Gravitational waves
- Gravitational wave detectors
- LIGO
- LIGO data runs
- Plausible gravitational wave signals and data analysis methods
- LSC searches for gravitational waves
- The evolving worldwide network of gravitational wave detectors

Data Collection

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



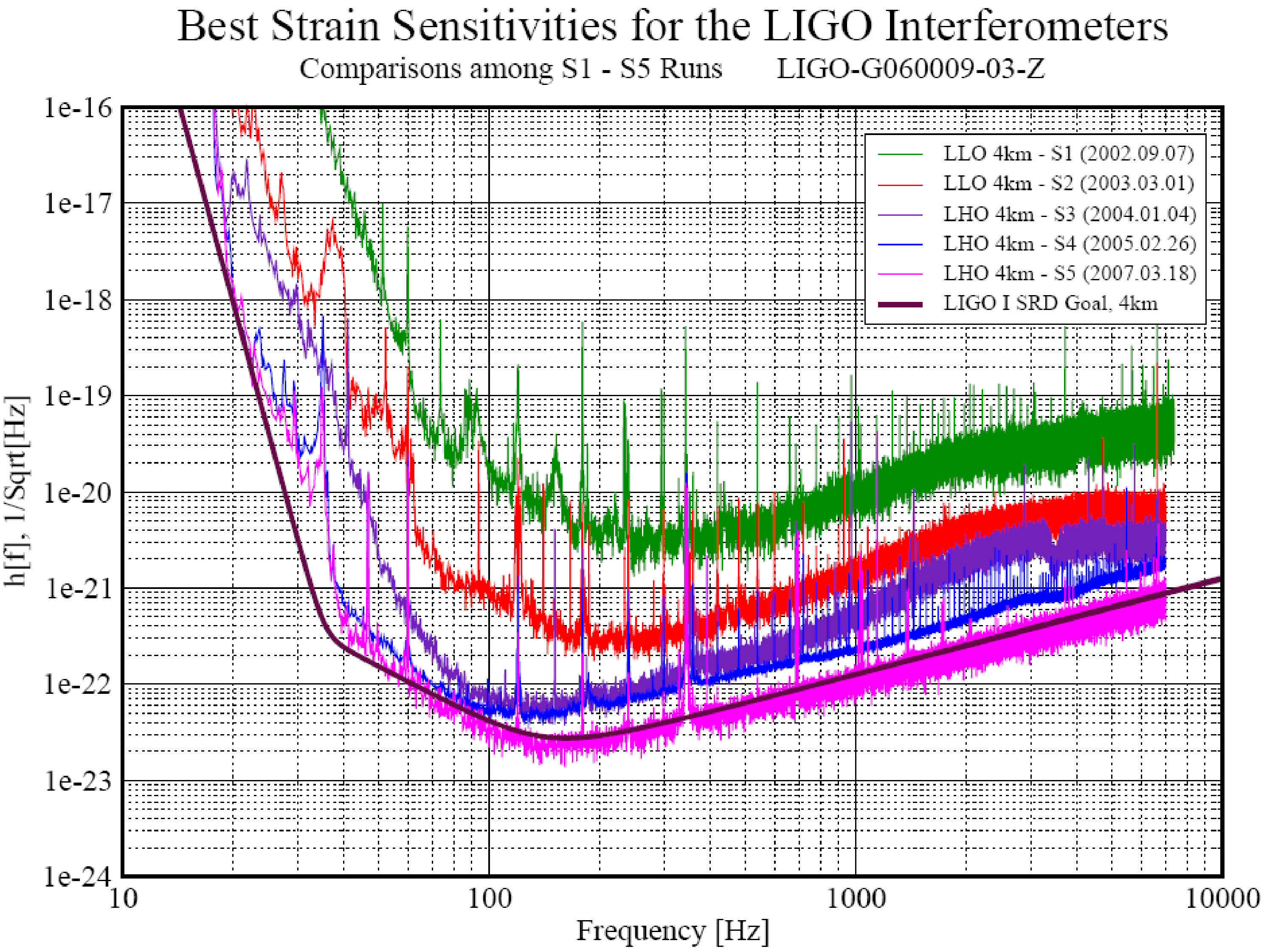
LIGO Science Runs



Duty factors:

					(so far)
H1	59 %	74 %	69 %	80 %	77 %
H2	73 %	58 %	63 %	81 %	78 %
L1	43 %	37 %	22 %	74 %	66 %

Best Interferometer Sensitivity, Runs S1 through S5



Outline

- Gravitational waves
- Gravitational wave detectors
- LIGO
- LIGO data runs
- Plausible gravitational wave signals and data analysis methods
- LSC searches for gravitational waves
- The evolving worldwide network of gravitational wave detectors

The Gravitational Wave Signal Tableau

Short duration ⟷ Long duration

Waveform known

Waveform unknown

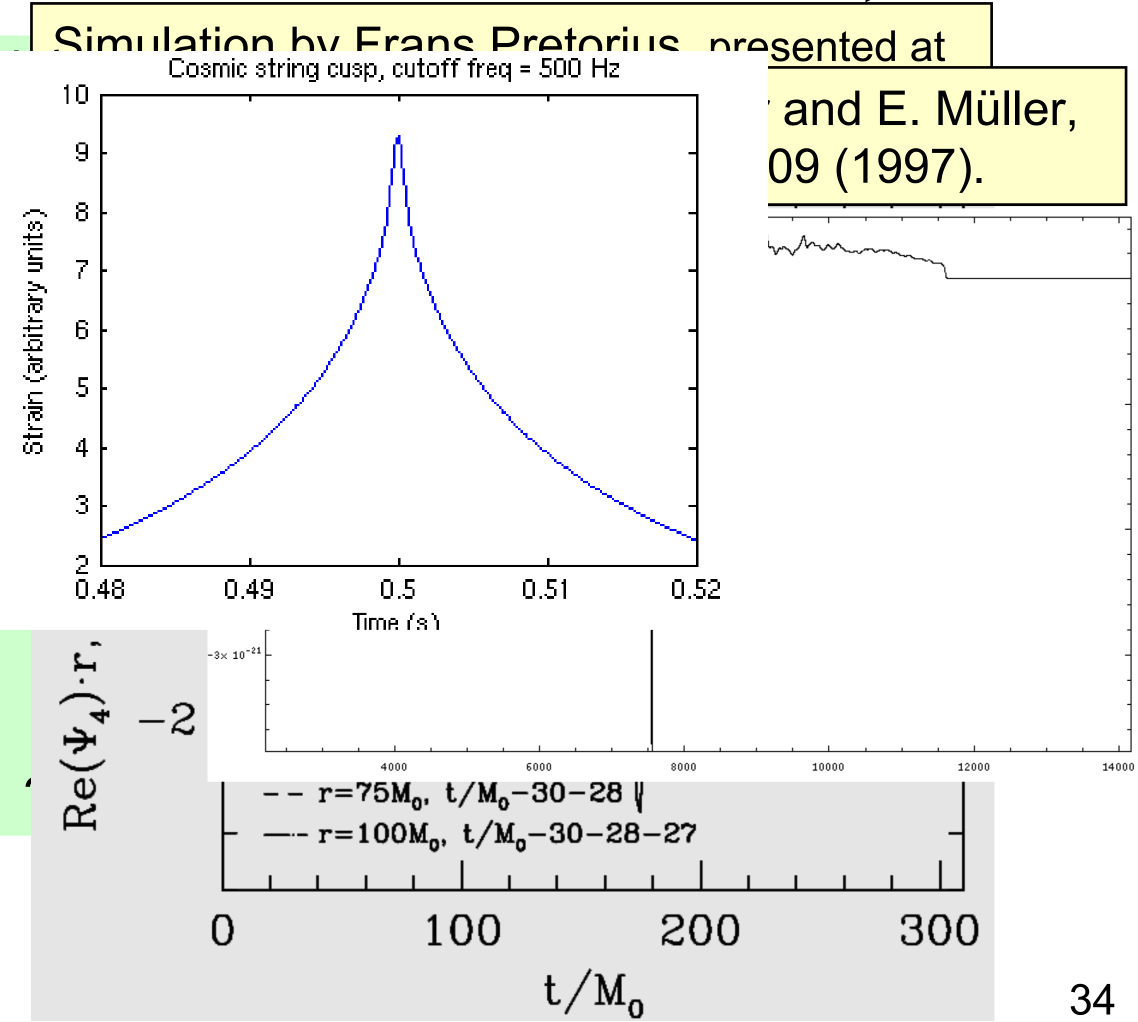
Cosmic string cusp / kink

High-mass inspiral

Stellar core c

Binary merger

???

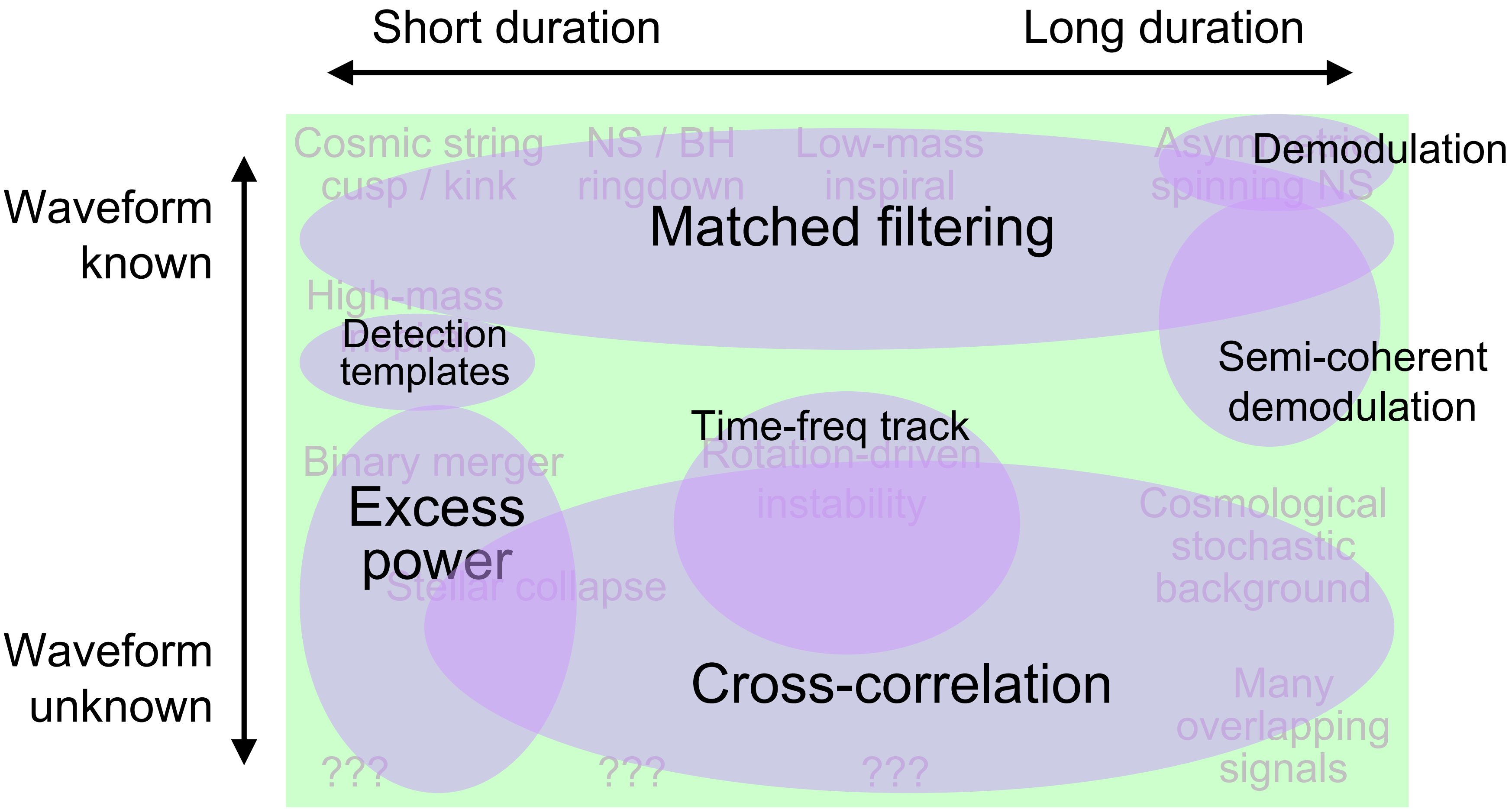


Simulation by Frans Pretorius, presented at

and E. Müller,

09 (1997).

General Data Analysis Methods



Short duration

Long duration

Waveform known

Waveform unknown

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

Asymmetric spinning NS

Demodulation

Matched filtering

High-mass inspiral

Detection templates

Semi-coherent demodulation

Time-freq track

Rotation-driven instability

Binary merger

Excess power

Stellar collapse

Cosmological stochastic background

Cross-correlation

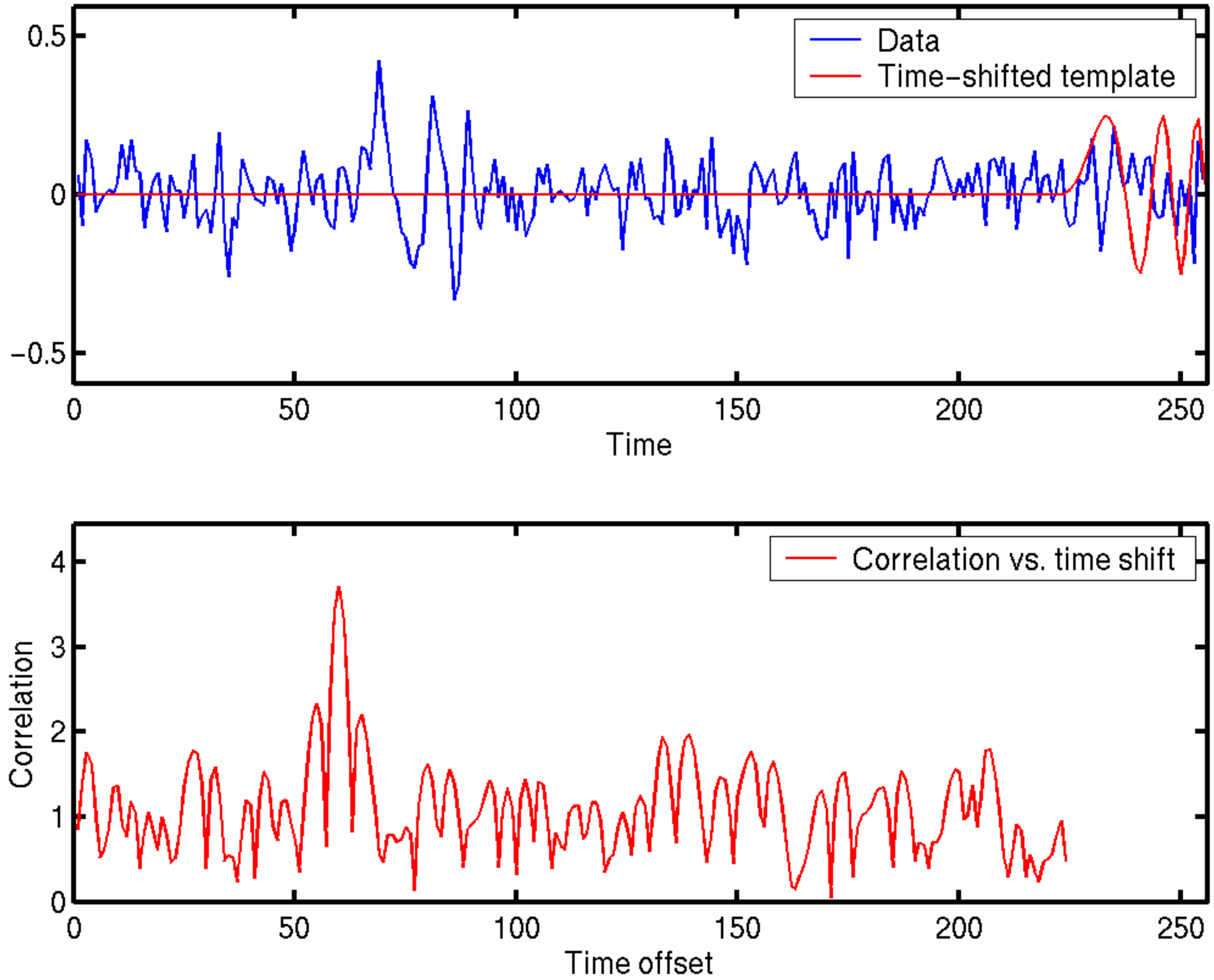
Many overlapping signals

???

???

???

Illustration of Matched Filtering



Optimal Matched Filtering in Frequency Domain

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 ➔ triggers

Require coincidence to make a detection

- Triggers in multiple interferometers with consistent signal parameters
- Essential to suppress false signals from localized disturbances

Use a template bank to cover parameter space of target signals

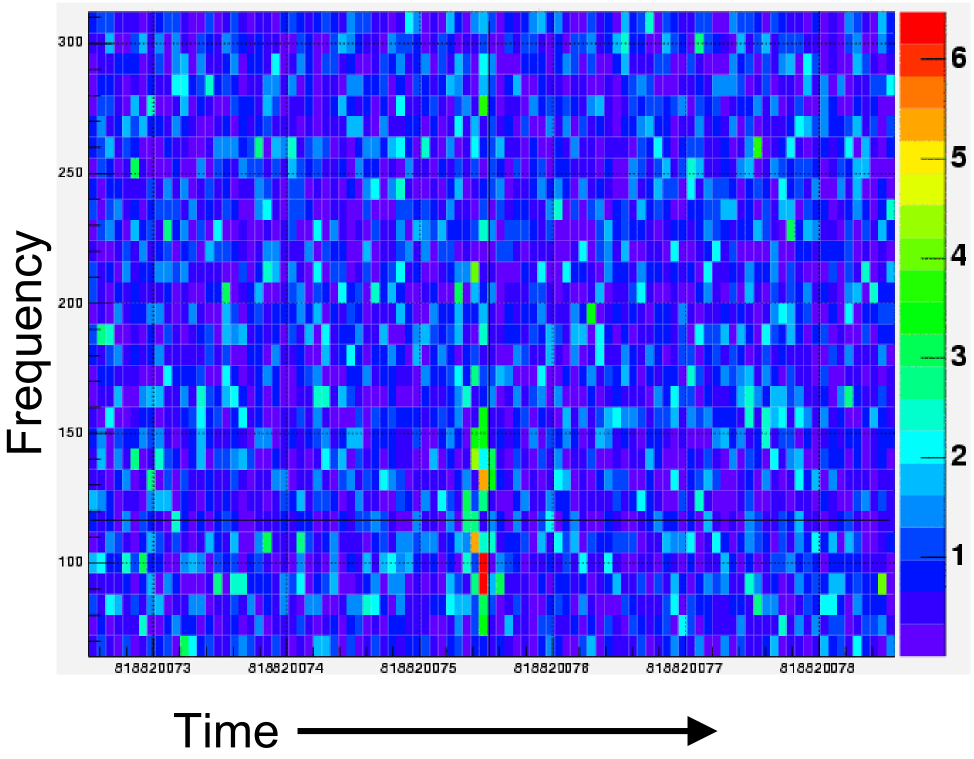
“Excess Power” Search Methods

Decompose data stream into time-frequency pixels

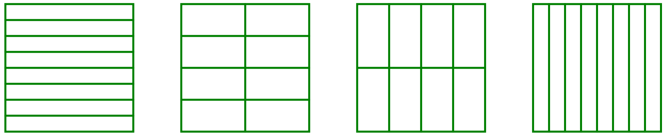
Fourier components, wavelets, “Q transform”, etc.

Normalize relative to noise as a function of frequency

Look for “hot” pixels or clusters of pixels



Can use multiple (Δt,Δf) pixel resolutions

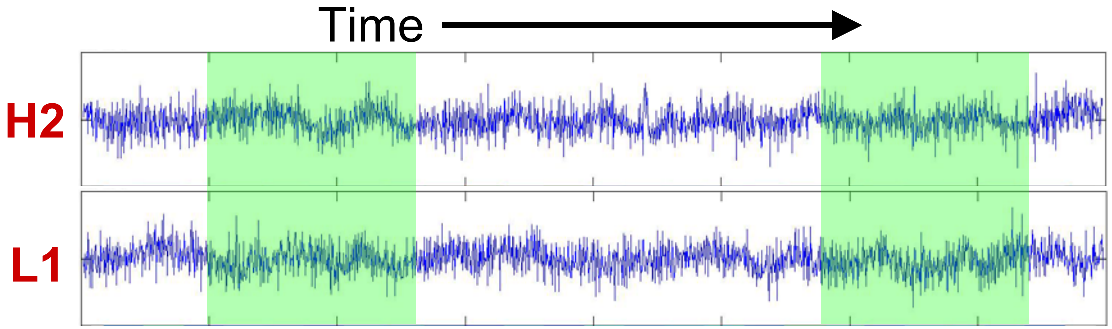


…

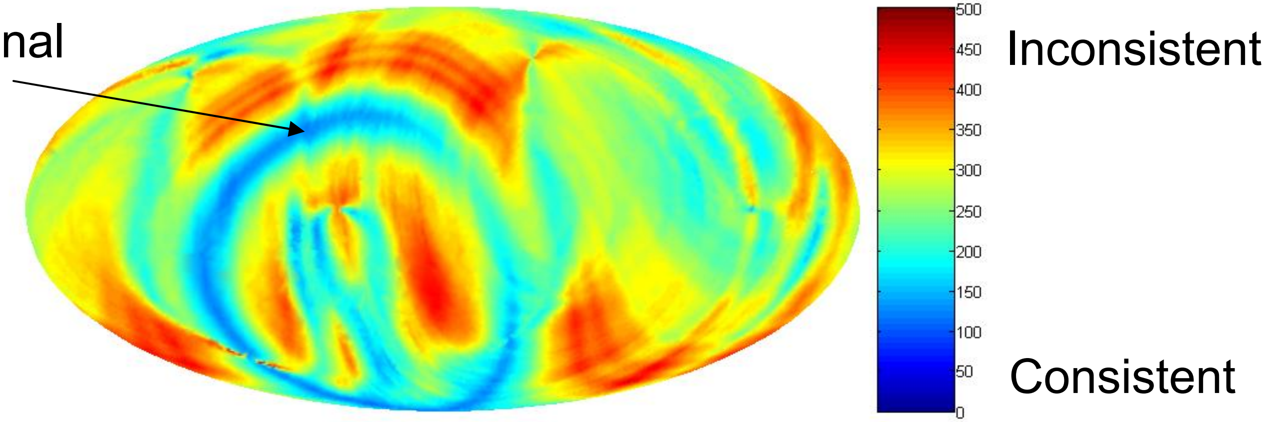
Cross-Correlation Methods

Look for same signal buried in two data streams

Calculate cross-correlation over a short time interval



Extensions to three or more detector sites being implemented

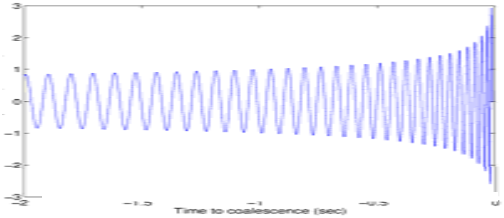


Simulated signal injected here

Outline

- Gravitational waves
- Gravitational wave detectors
- LIGO
- LIGO data runs
- Plausible gravitational wave signals and data analysis methods
- LSC searches for gravitational waves
- The evolving worldwide network of gravitational wave detectors

Binary Inspiral Searches



Use **matched filtering** **with thousands of templates**

- Good match with a signal anywhere in the param space

Template accuracy becomes an issue for higher masses

- Post-Newtonian expansion breaks down within sensitive band
- If spins are significant, physical parameter space is very large
- ⇒ Can use a parametrized detection template family for efficient filtering

Results from the S3+S4 science runs ***[Preprint arXiv:0704.3368]***

- No GW signals identified
- Binary neutron star signal could be detected out to ~17 Mpc (optimal case)
- Binary black hole signals out to tens of Mpc
- Place limits on binary coalescence rate for certain population models

S5 prospects (analysis in progress)

- A factor of ~2 more sensitive, and much longer observation time

All-Sky Burst Searches

Use excess power and/or cross-correlation

Multiple methods in use

Example: S4 general all-sky burst search ***[Preprint arXiv:0704.0943]***

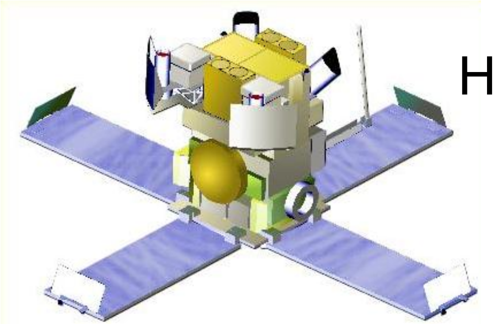
- ► Searched 15.53 days of triple-coincidence data (H1+H2+L1) for short (<1 sec) signals with frequency content in range 64-1600 Hz
- ► Used "WaveBurst" excess power method to generate triggers
- ► Followed up with cross-correlation consistency tests
- ► No event candidates observed
- ► Upper limit on rate of *detectable* events: 0.15 per day (at 90% C.L.)
- ► Sensitive to GW energy emission as small as $\sim 10^{-7}$ $M_\odot$ at 10 kpc, or ~ 0.2 $M_\odot$ at the distance of the Virgo Cluster

S5 prospects (analysis in progress)

Factor of ~2 better amplitude sensitivity, and much longer observation time

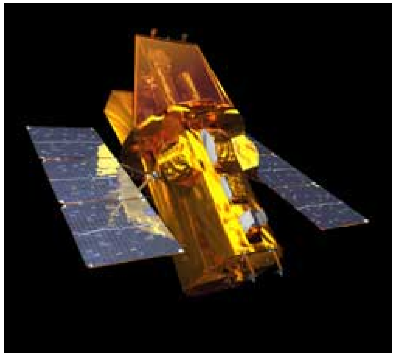
Also doing coherent network analysis using data from multiple detectors

Externally Triggered Searches



HETE-2

Swift



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

Analyzed 39 GRBs during runs S2+S3+S4, over 200 so far in S5

- Including GRB 070201—short hard burst with position consistent with M31
- Preliminary result: No plausible GW signal found from GRB 070201; therefore unlikely to be from a binary coalescence in M31

Searches for Periodic Signals from Known Radio/X-ray Pulsars

Use demodulation, correcting for motion of detector

Doppler frequency shift, amplitude modulation from antenna pattern

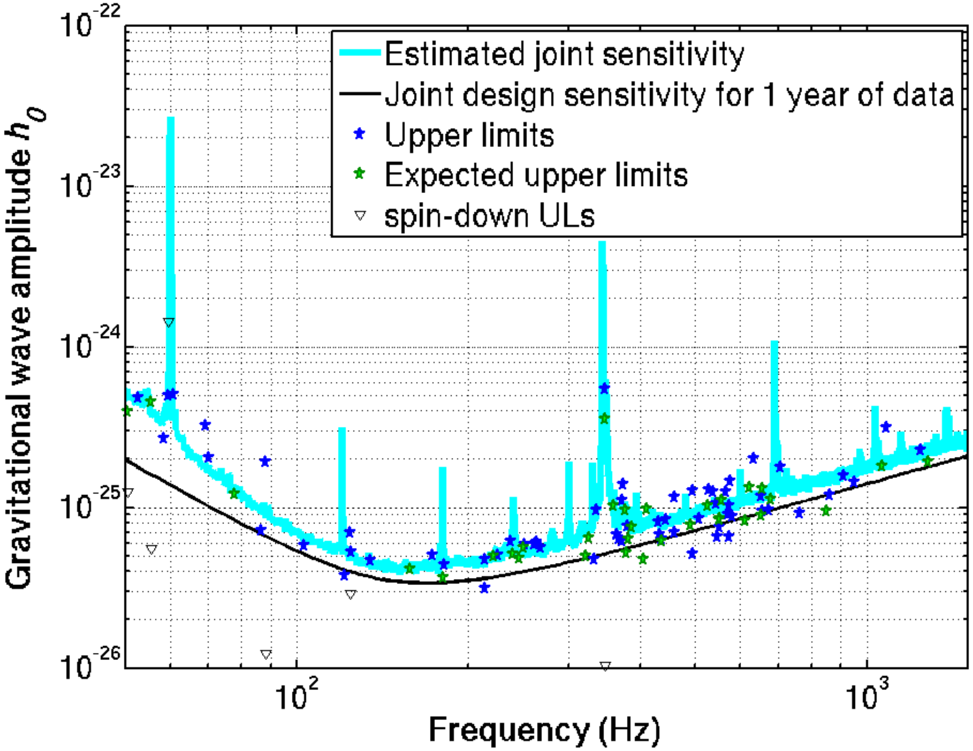
Demodulate data at twice the spin frequency

S5 *preliminary* results (using first 13 months of data):

Placed limits on strain h_0 and equatorial ellipticity ε

► ε limits as low as ~10^{-7}

Crab pulsar: LIGO limit on GW emission is now below upper limit inferred from spindown rate

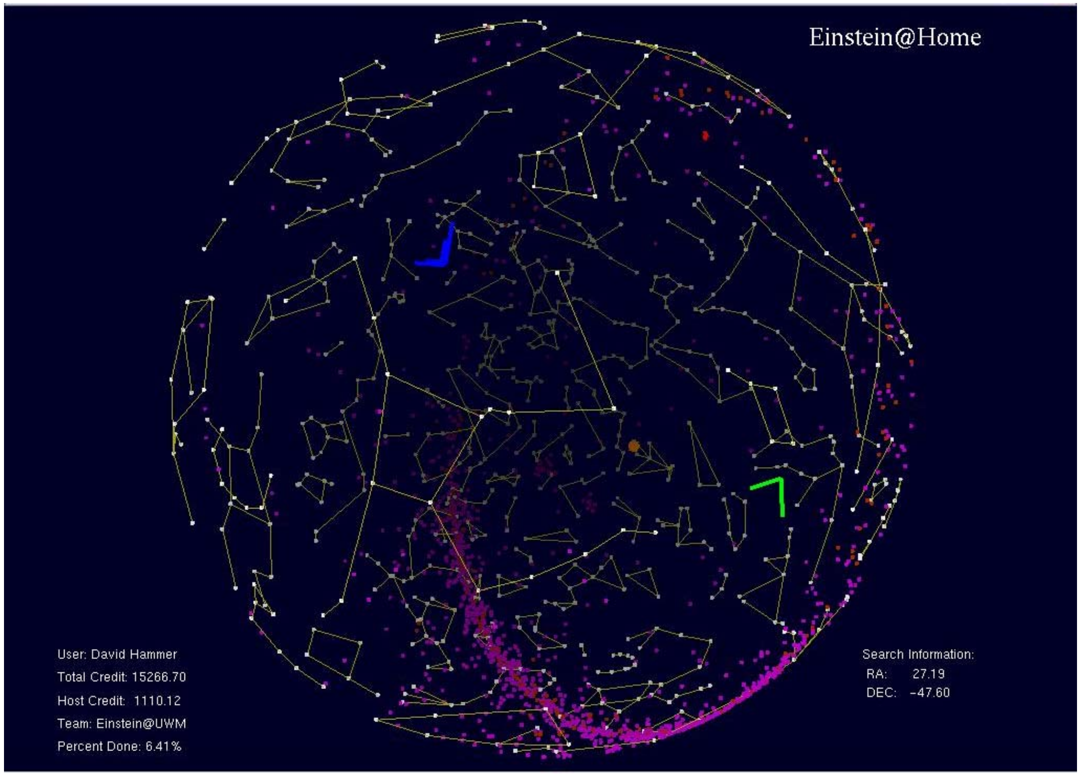


Wide Parameter Space Searches for Periodic Signals

Search for signals from LMXBs, supernova remnants, etc.

All-sky coherent search for *unknown* isolated periodic signals

- Computationally very expensive!
- Now doing a hierarchical search with semi-coherent and coherent stages



User: David Hammer
Total Credit: 15266.70
Host Credit: 1110.12
Team: Einstein@UWM
Percent Done: 6.41%

Search Information:
RA: 27.19
DEC: -47.60

Einstein@Home

~175,000 users

~75 Tflops on average

Searches for a Stochastic Signal

Weak, random gravitational waves could be bathing the Earth

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

S4 result *[Astrophys. J.* ***659****, 918 (2007)]*

Searched for isotropic stochastic signal with power-law spectrum

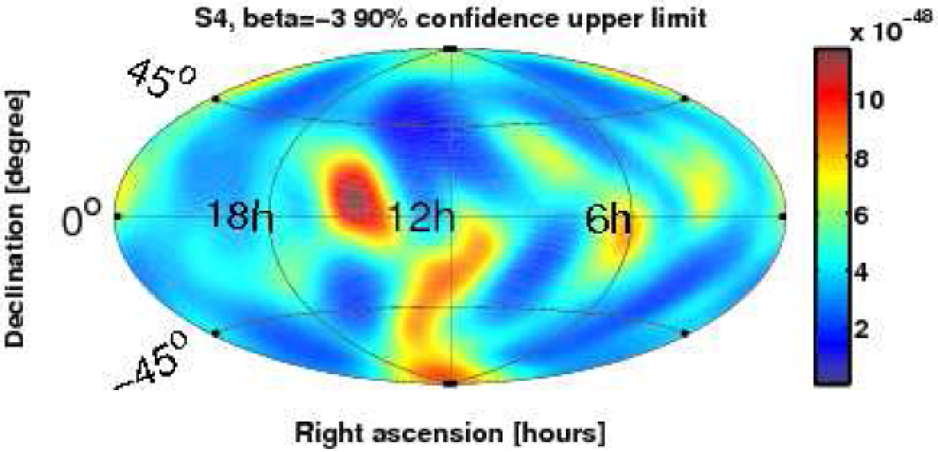
For flat spectrum, set upper limit on energy density in gravitational waves:

$\Omega_0 < 6.5 \times 10^{-5}$

Or look for anisotropic signal:

[Phys. Rev. D in press]

S5 analysis in progress

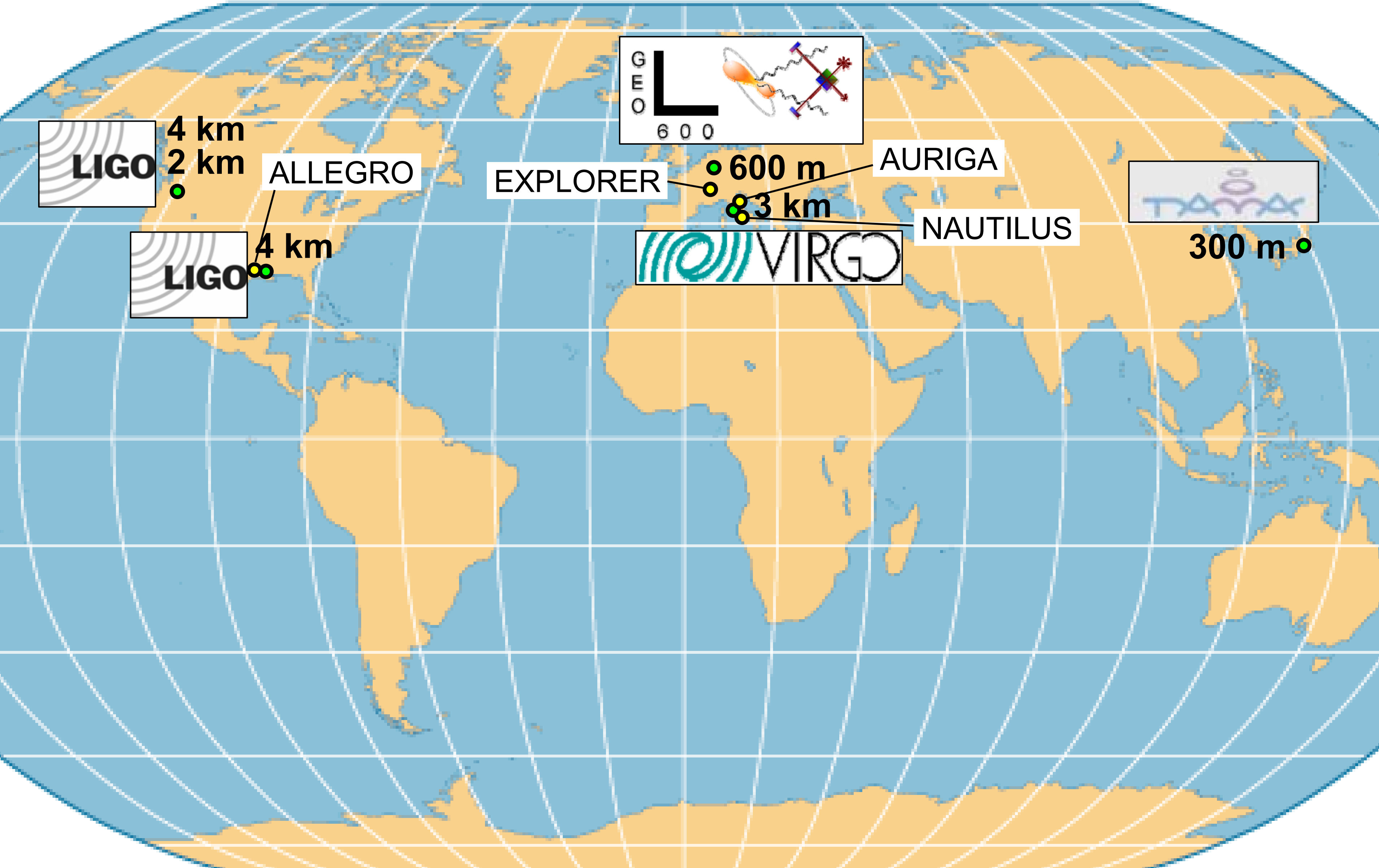


Outline

- Gravitational waves
- Gravitational wave detectors
- LIGO
- LIGO data runs
- Plausible gravitational wave signals and data analysis methods
- LSC searches for gravitational waves
- The evolving worldwide network of gravitational wave detectors

The Worldwide Network

Including ● Bars

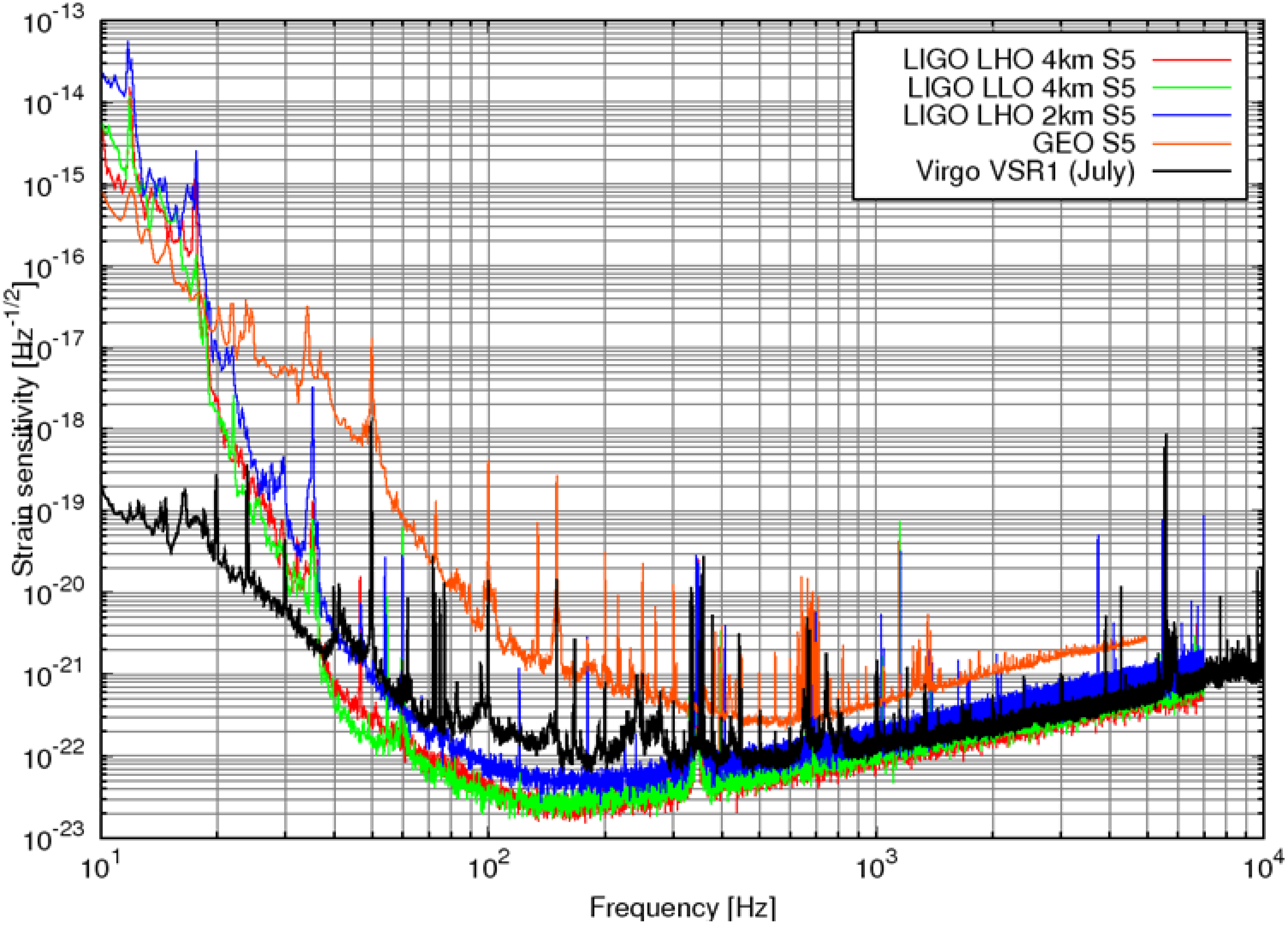


Virgo

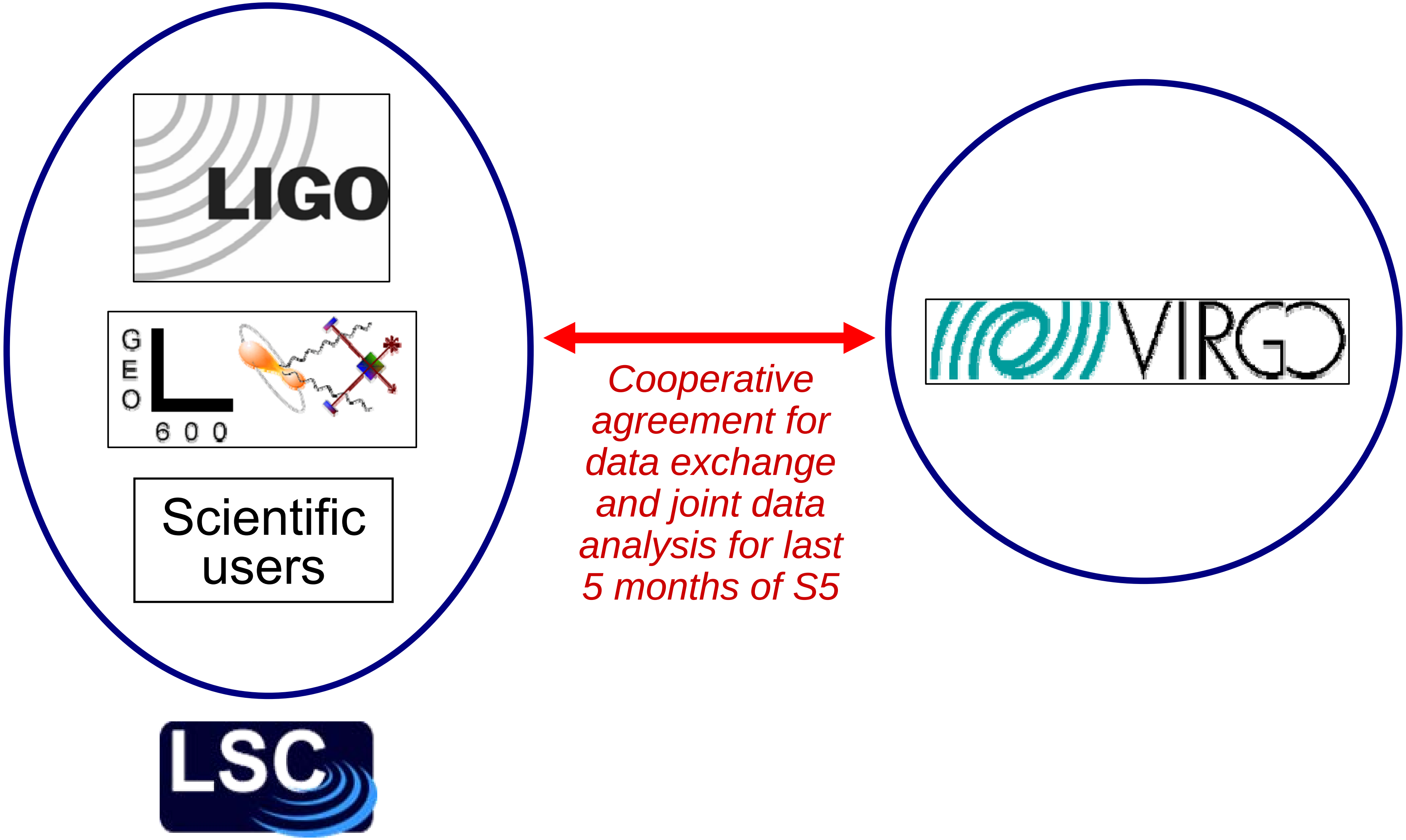
Generally similar to LIGO

GEO 600

Current Performance of the Large Interferometers



Organization of the Projects



Scientific users

Cooperative agreement for data exchange and joint data analysis for last 5 months of S5

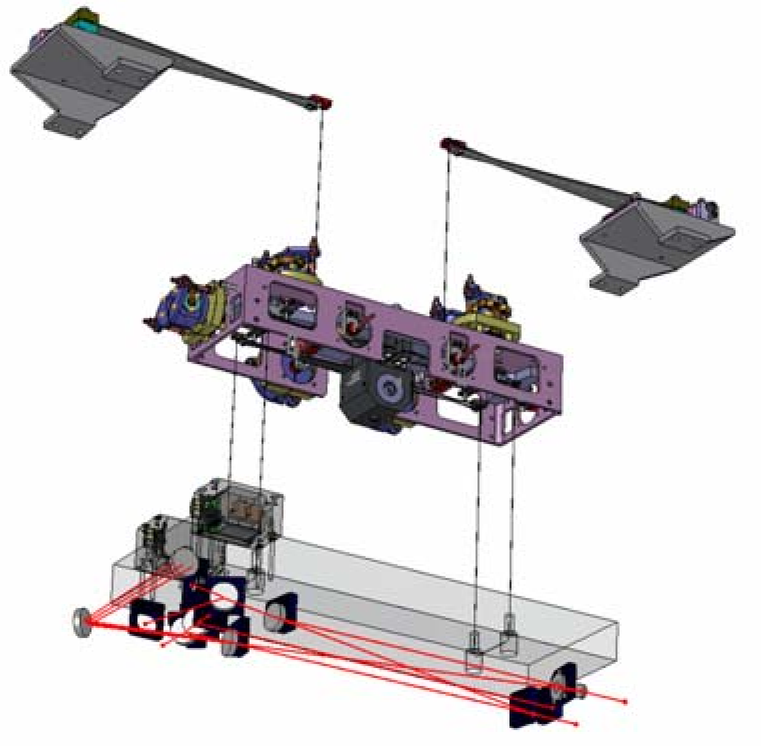
Life After S5: Detector Enhancements

Increase laser power to 35 W

- Requires new thermal compensation system

DC readout scheme

- Photodetector in vacuum, suspended
- Output mode cleaner
- Active beam stabilization

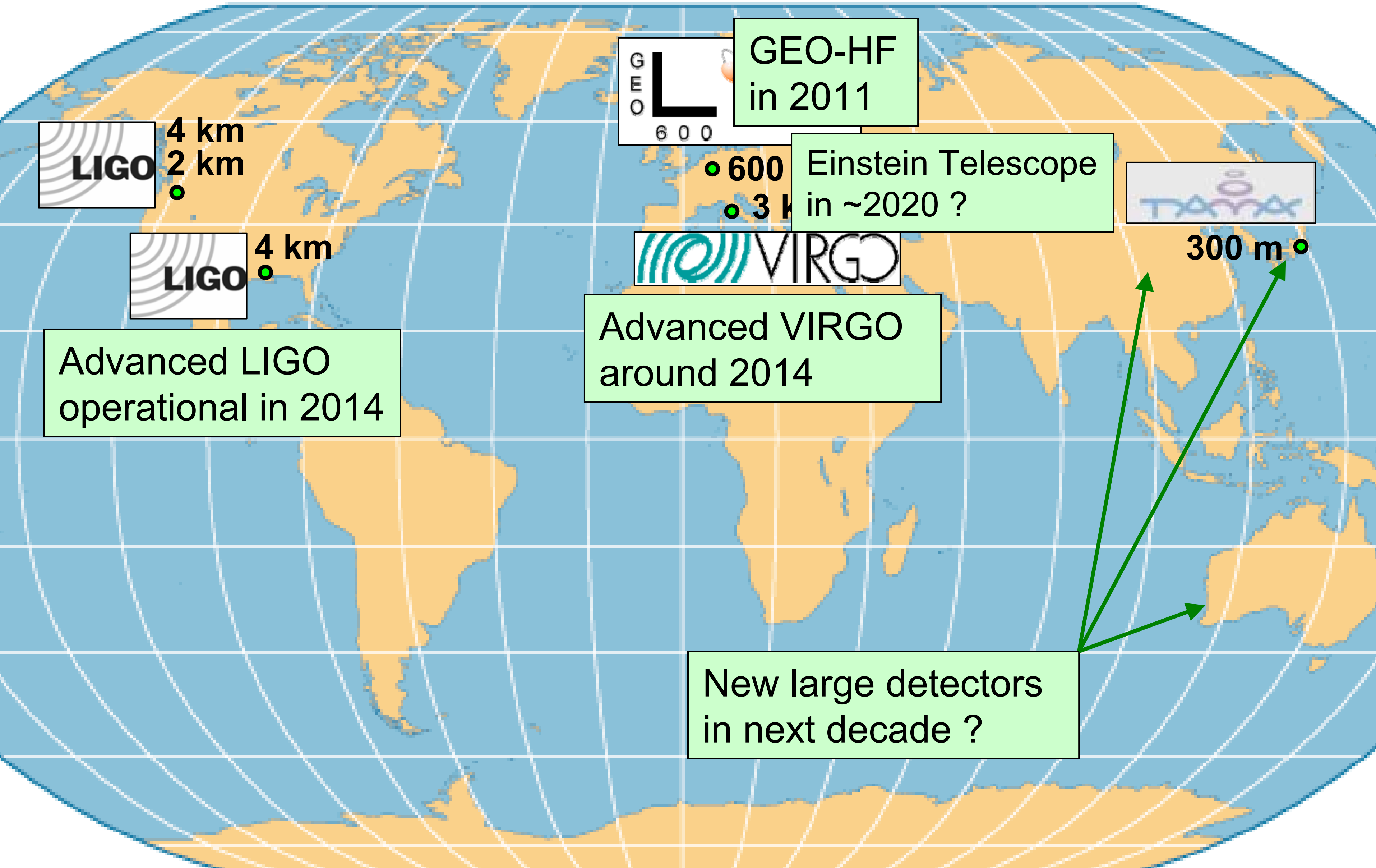


Aiming for a factor of ~2 sensitivity improvement

S6 run planned to begin in 2009, duration ~1.5 years

- Virgo improvements and joint running planned on same time scale

The Future Worldwide Network



Advanced LIGO operational in 2014

GEO-HF in 2011

Einstein Telescope in ~2020 ?

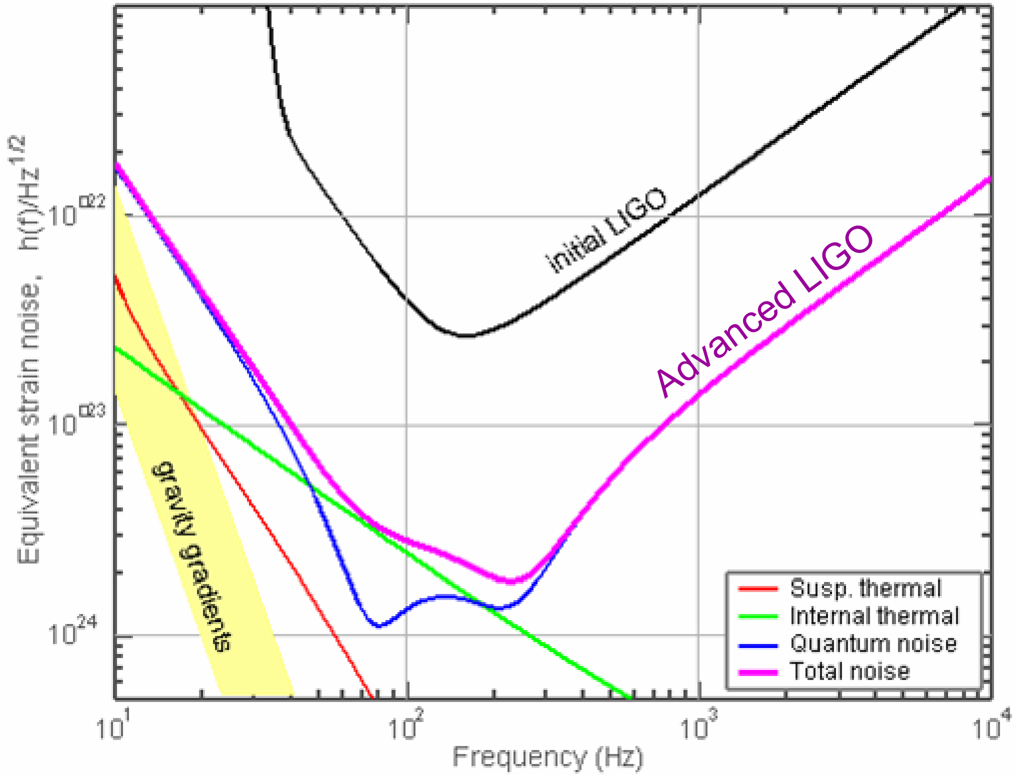
Advanced VIRGO around 2014

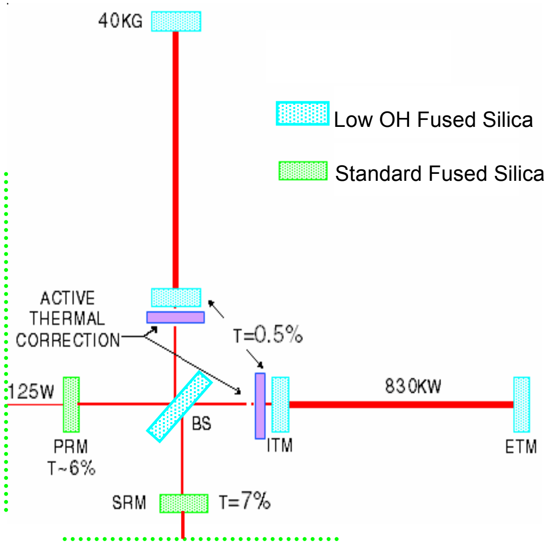
New large detectors in next decade ?

Advanced LIGO

Same observatory sites, new interferometers

New mirrors, suspensions, seismic isolation, laser, etc.





New "signal recycling" mirror allows tuning of sensitivity curve

Factor of ~10 better than current LIGO ⇒ factor of ~1000 in volume

In Federal budget plans for FY2008 start

Summary

The LIGO detectors have reached their target sensitivities

Long-duration observing runs have begun

There are many types of plausible signals, requiring different data analysis methods

Many searches have been completed and more are underway

The worldwide network of gravitational wave detectors is growing

Detector upgrades will allow us to do real gravitational-wave astronomy within the next decade