LIGO Perks Up Its Ears

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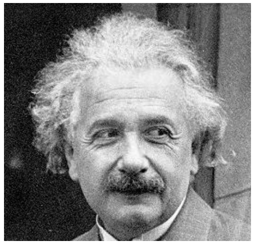
Outline

- **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

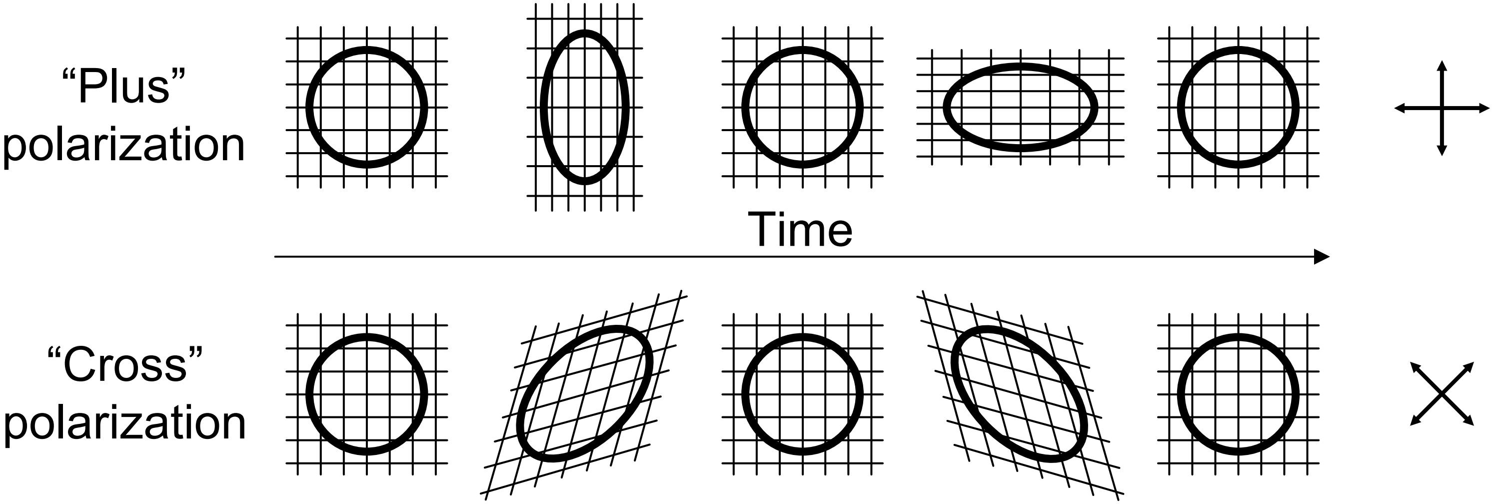


A consequence of Einstein's general theory of relativity

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

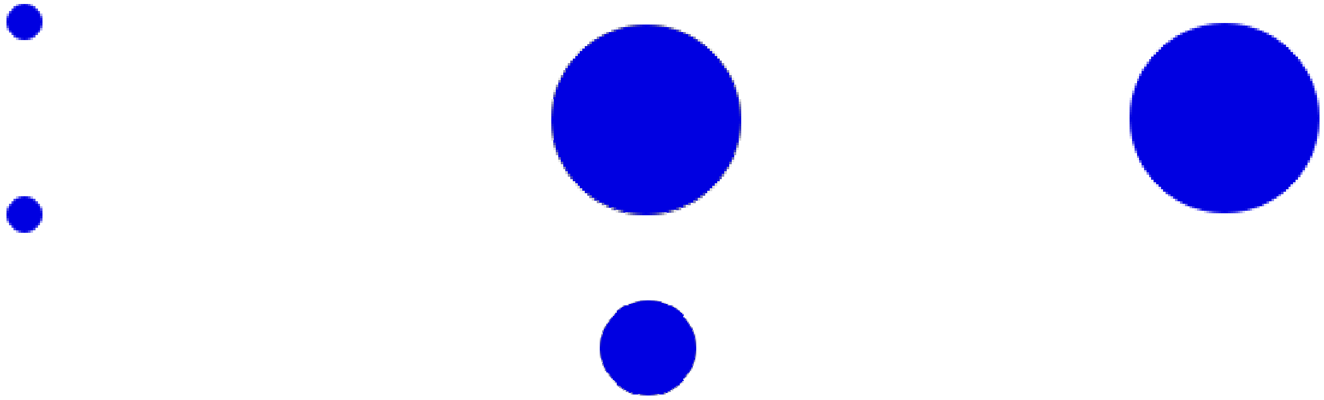
Waves deform space itself, stretching it first in one direction, then in the perpendicular direction



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*** = ΔL / L

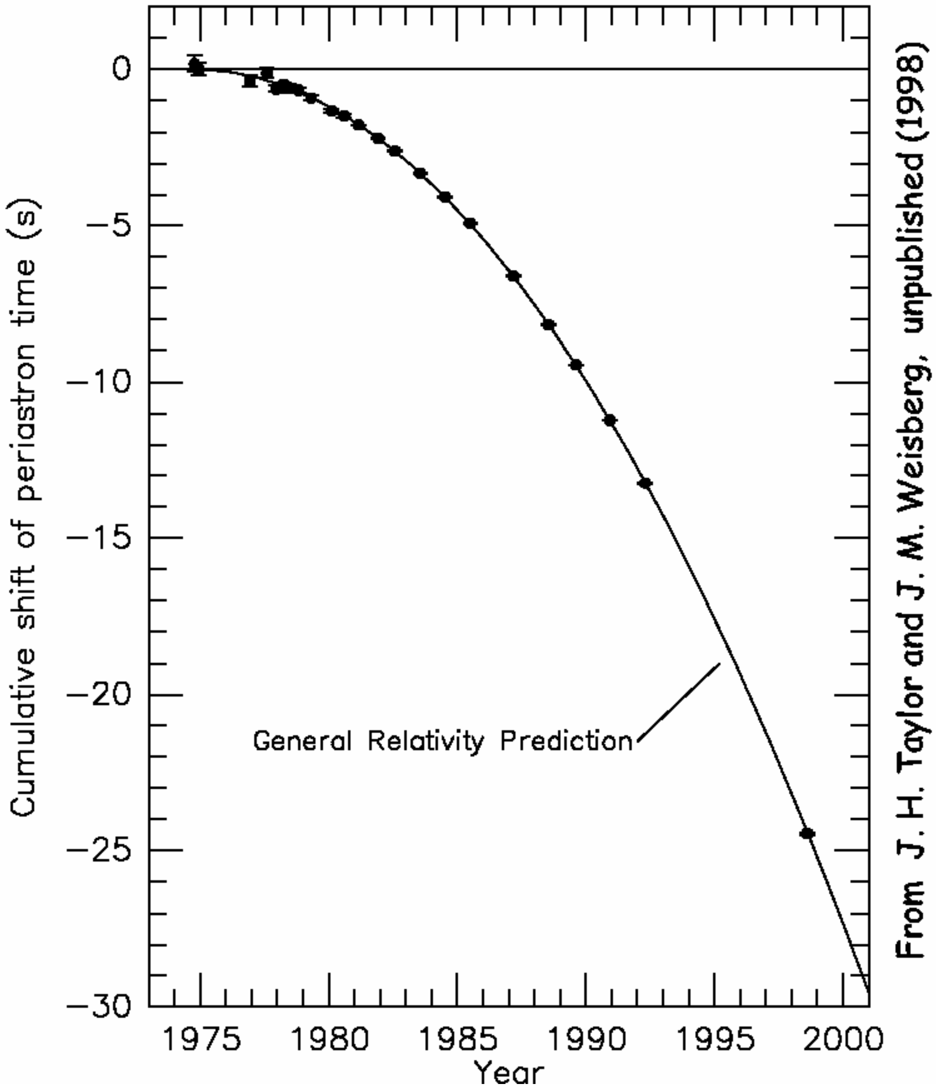
h is inversely proportional to the distance from the source

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

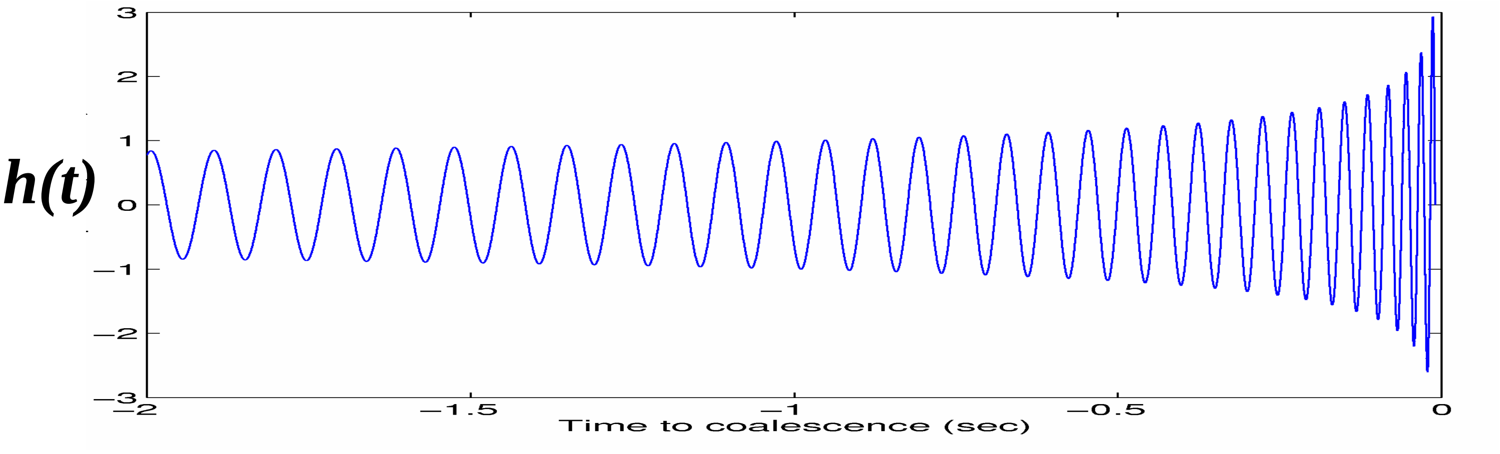


From J. H. Taylor and J. M. Weisberg, unpublished (1998)

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 ???

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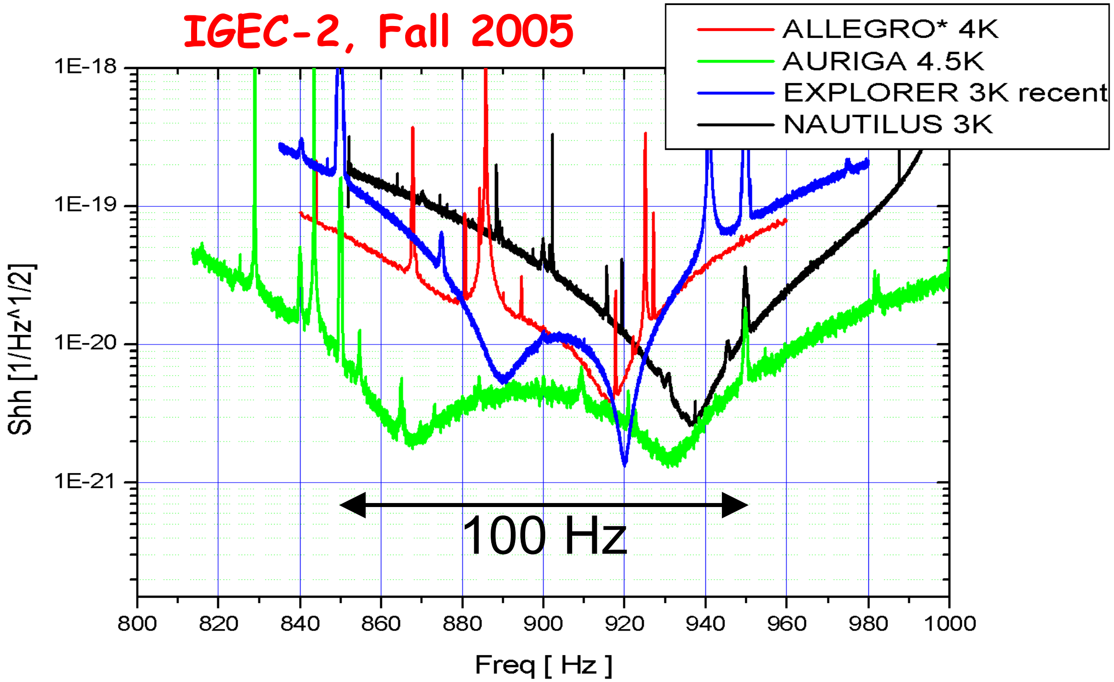
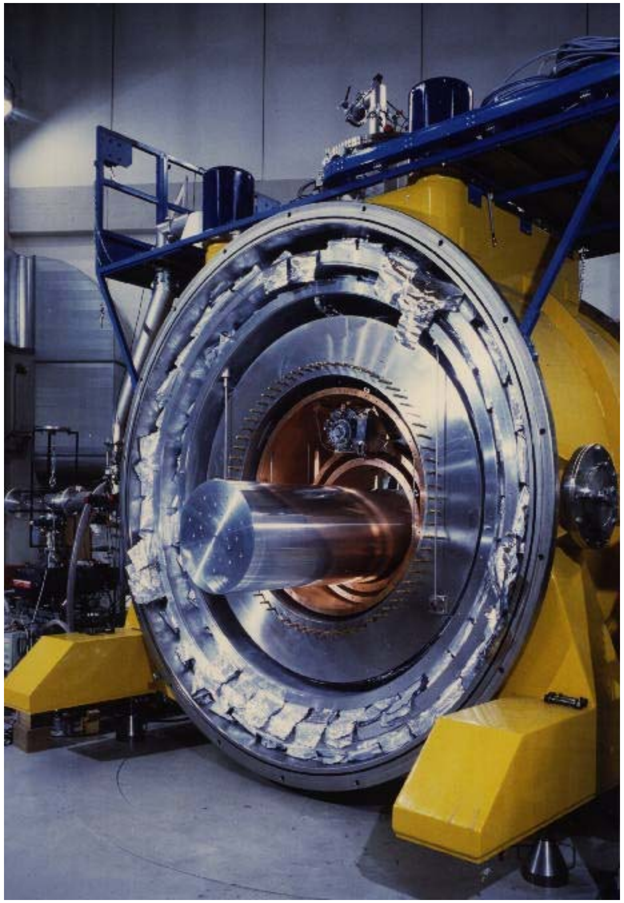
Resonant “Bar” Detectors

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



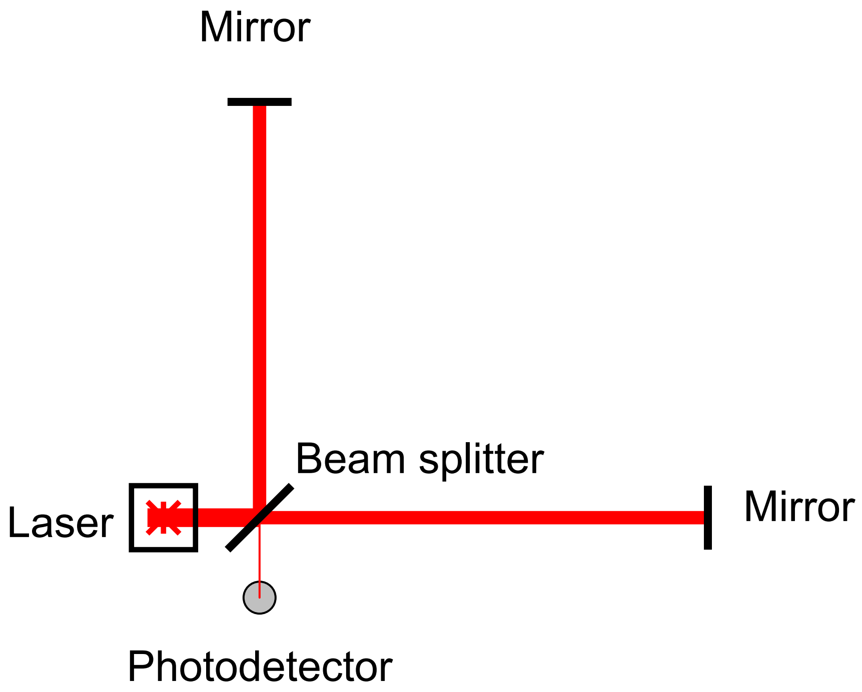


AURIGA detector (open)

Laser Interferometers

Variations on basic Michelson design, with two long arms

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

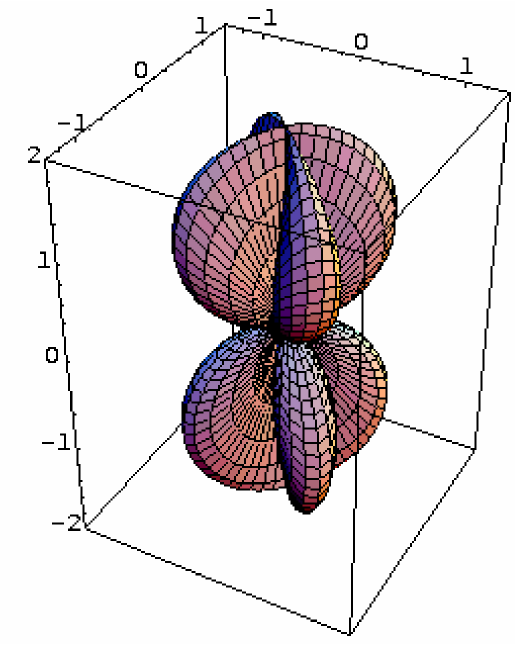


Effective lengths of interferometer arms are affected by a gravitational wave —
An ideal detector !

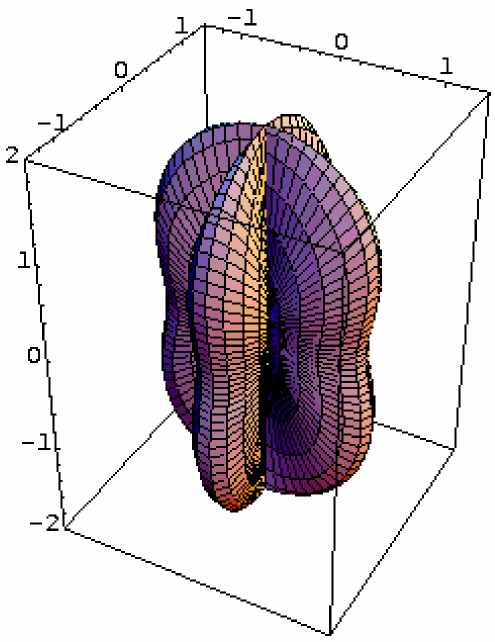
Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

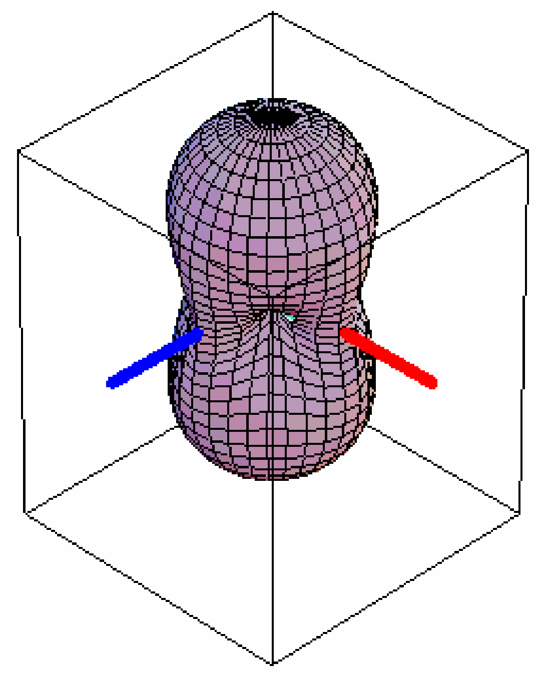
“×” polarization



“+” polarization



RMS sensitivity



A broad antenna pattern

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

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The LIGO Observatories

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

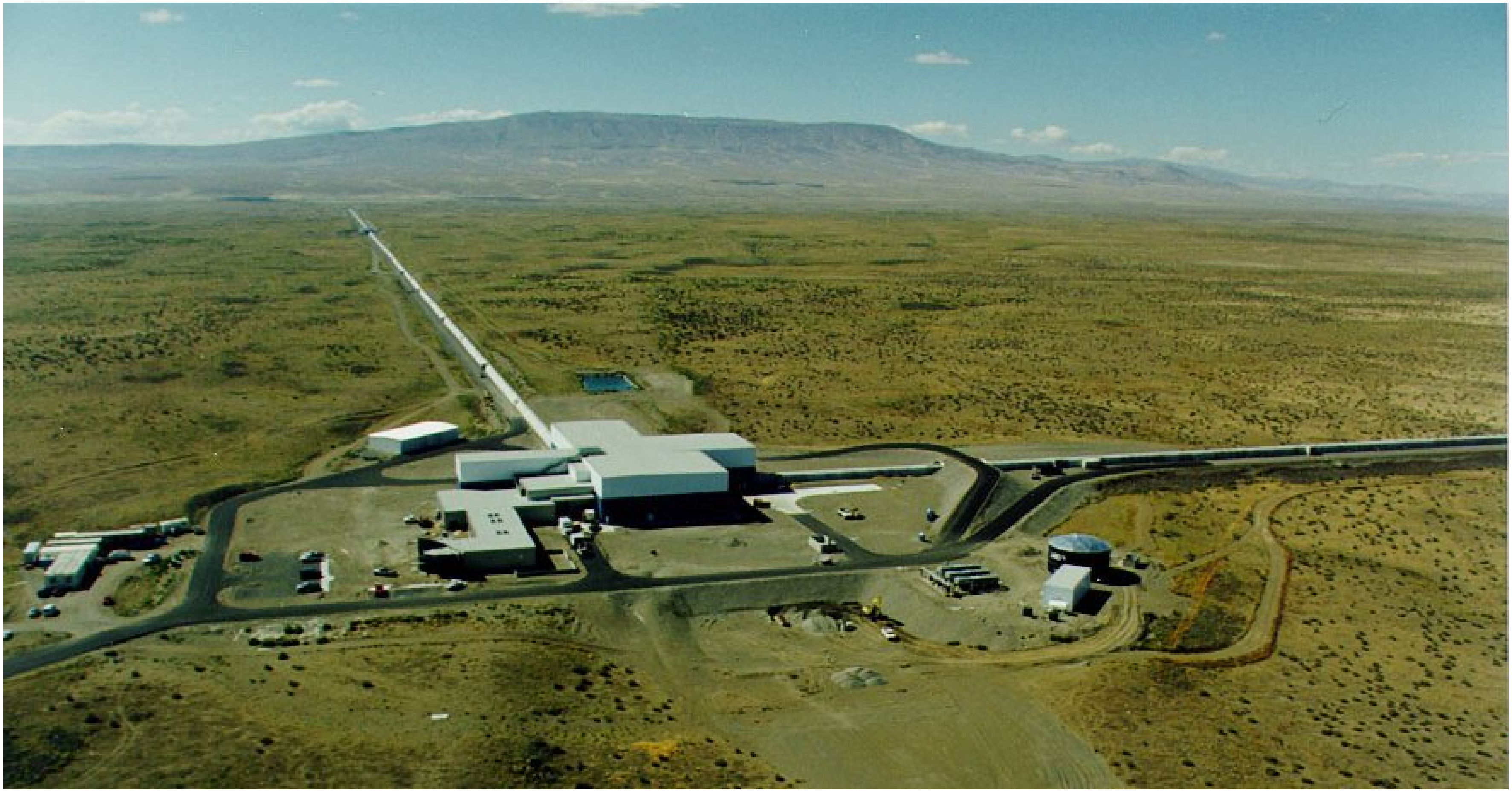
LIGO Livingston Observatory (LLO)
L1 : 4 km arms

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

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

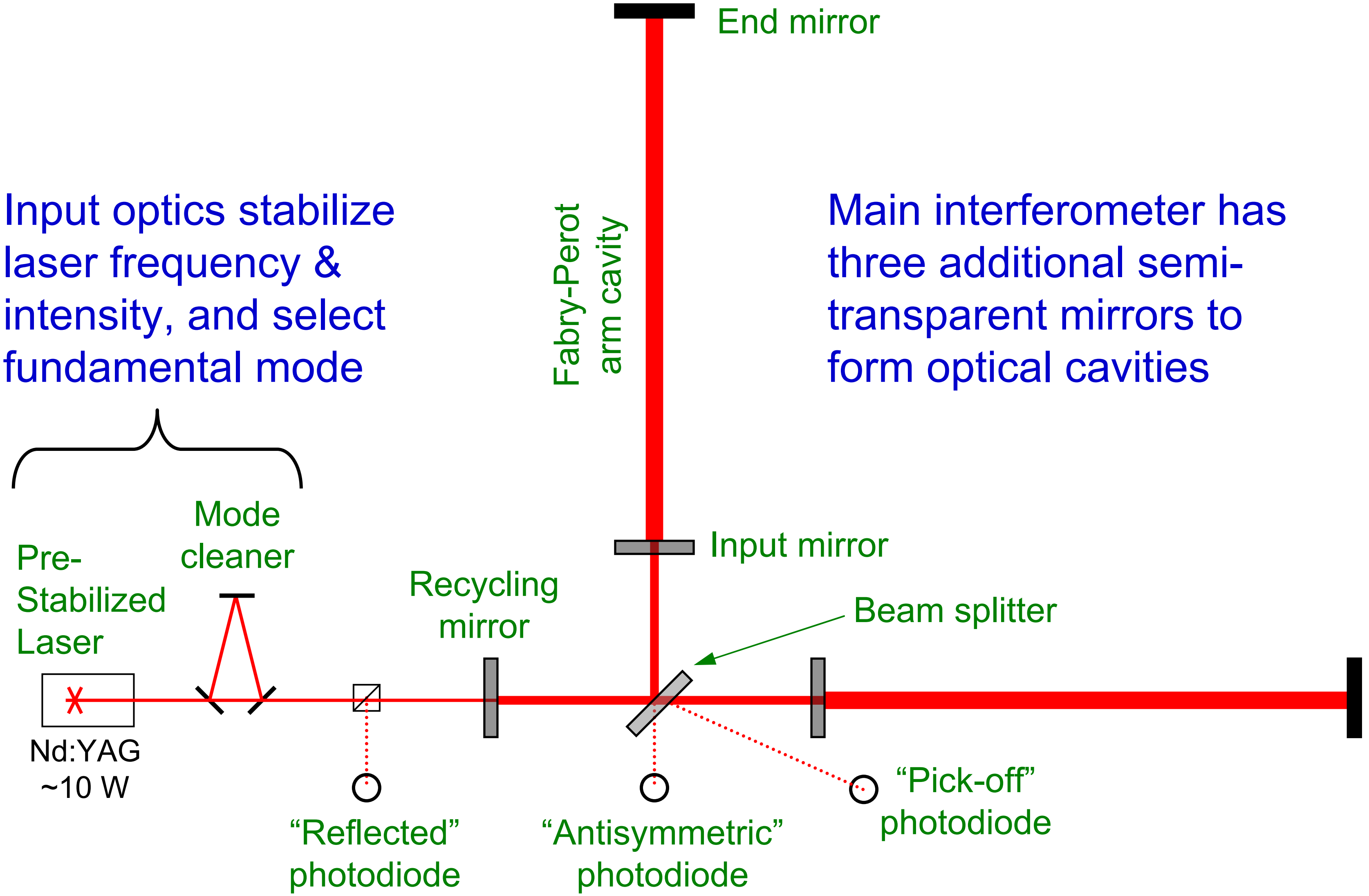
- Stabilize laser frequency and intensity
- Use large mirrors to reduce effect of quantum light noise
- Isolate interferometer optics from environment
- Focus on a “sweet spot” in frequency range

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”

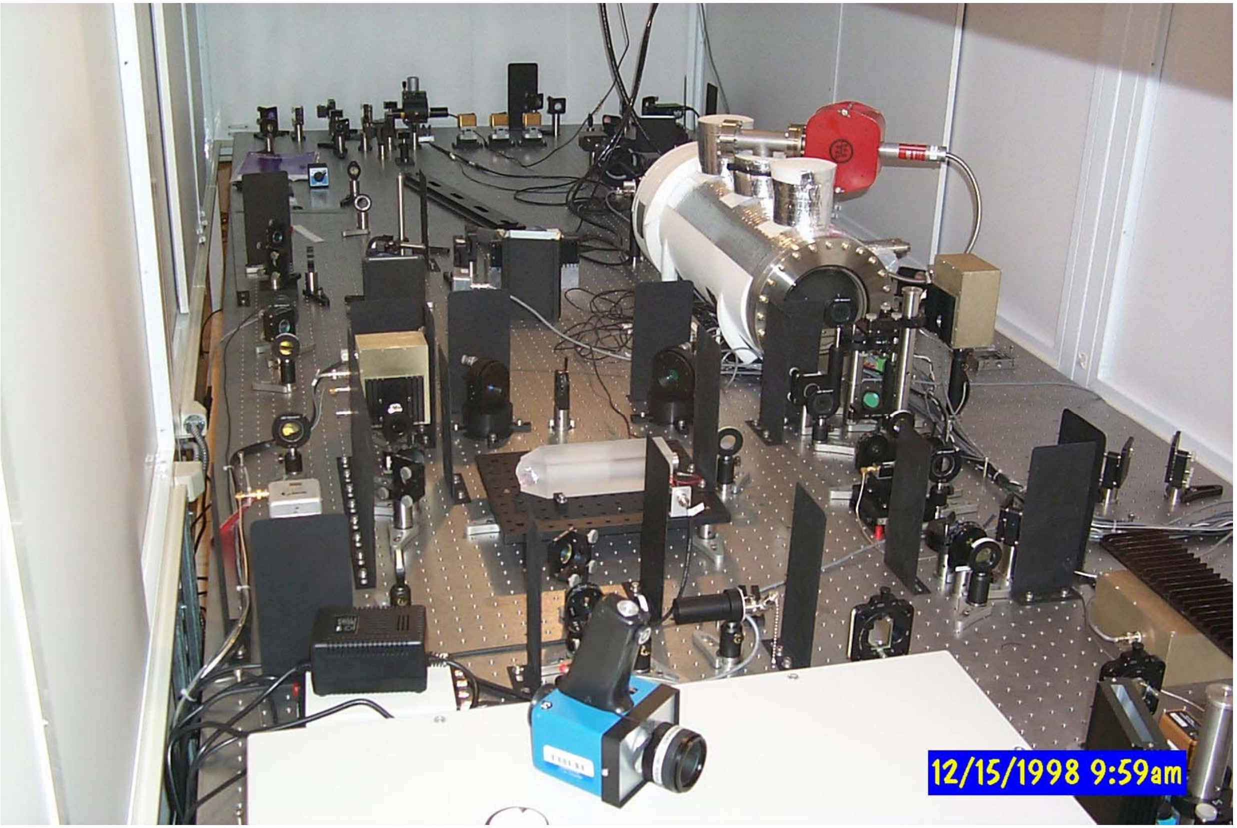
There are many other servo loops besides length control !

- 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


12/15/1998 9:59am

Final stabilization uses feedback from average arm length

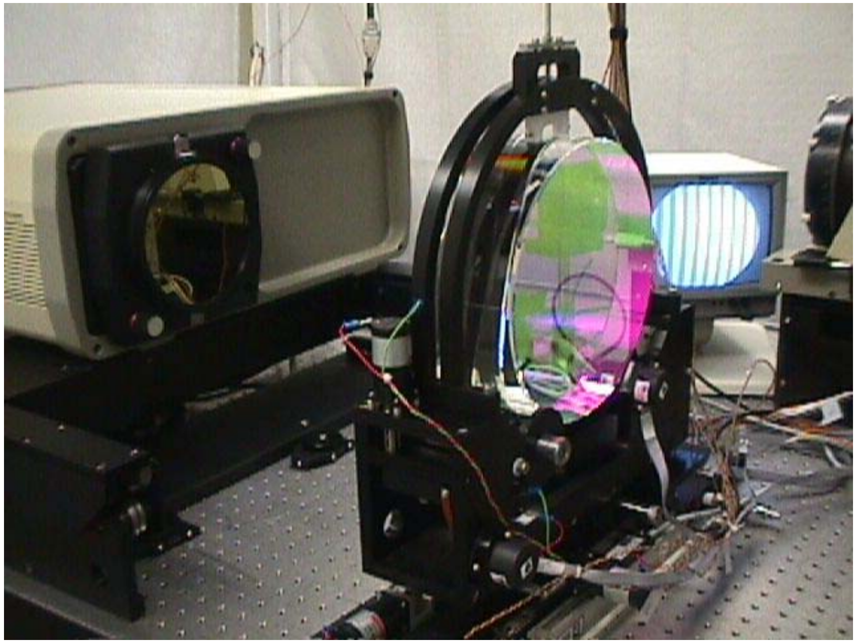
Mirrors

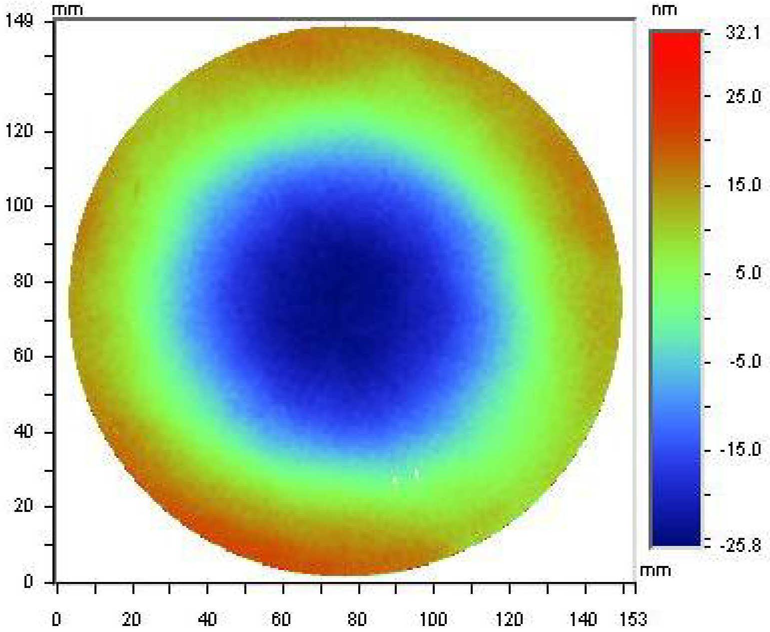
Made of high-purity fused silica

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

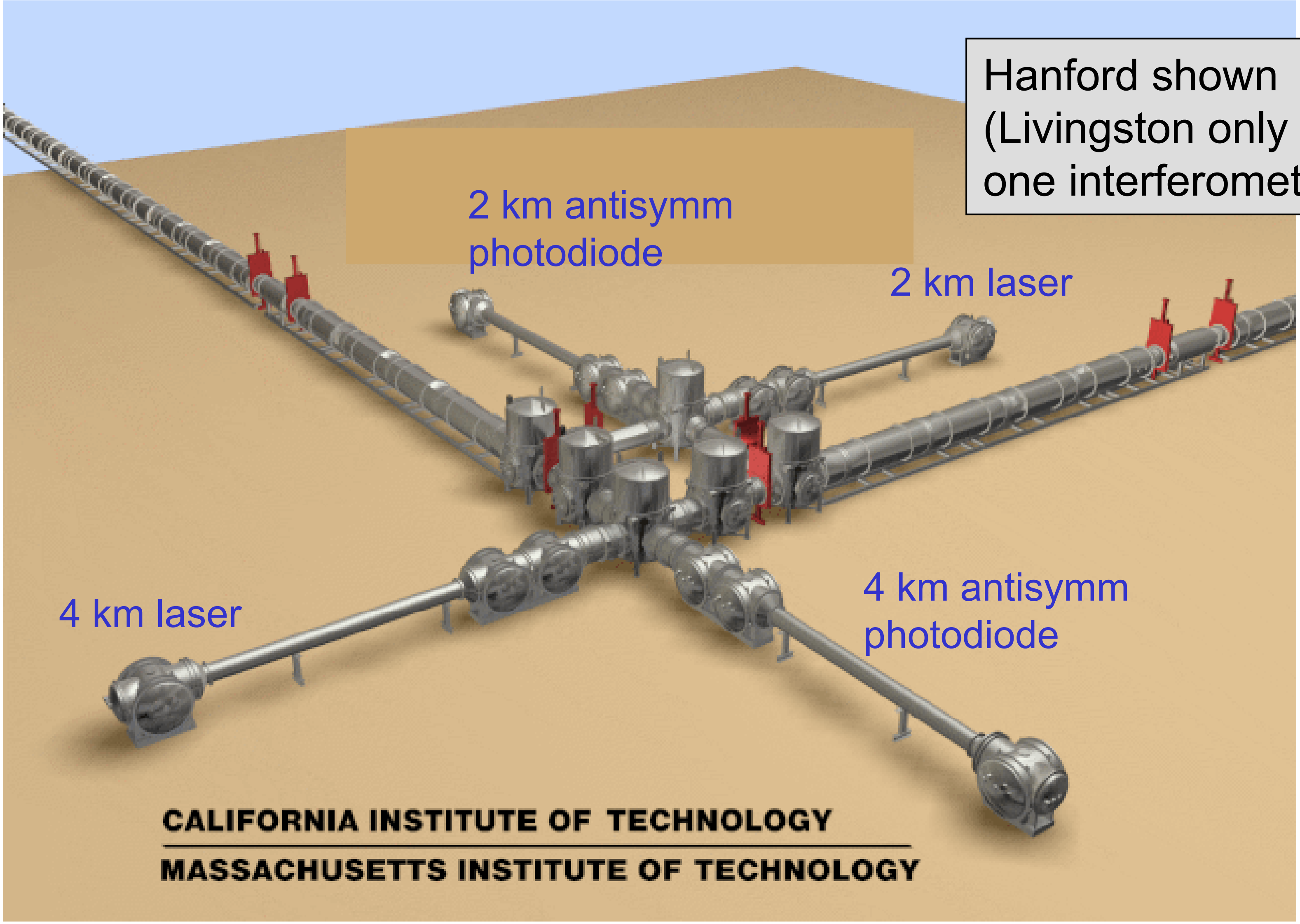
Surfaces polished to ~1 nm rms, some with slight curvature

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





Vacuum System

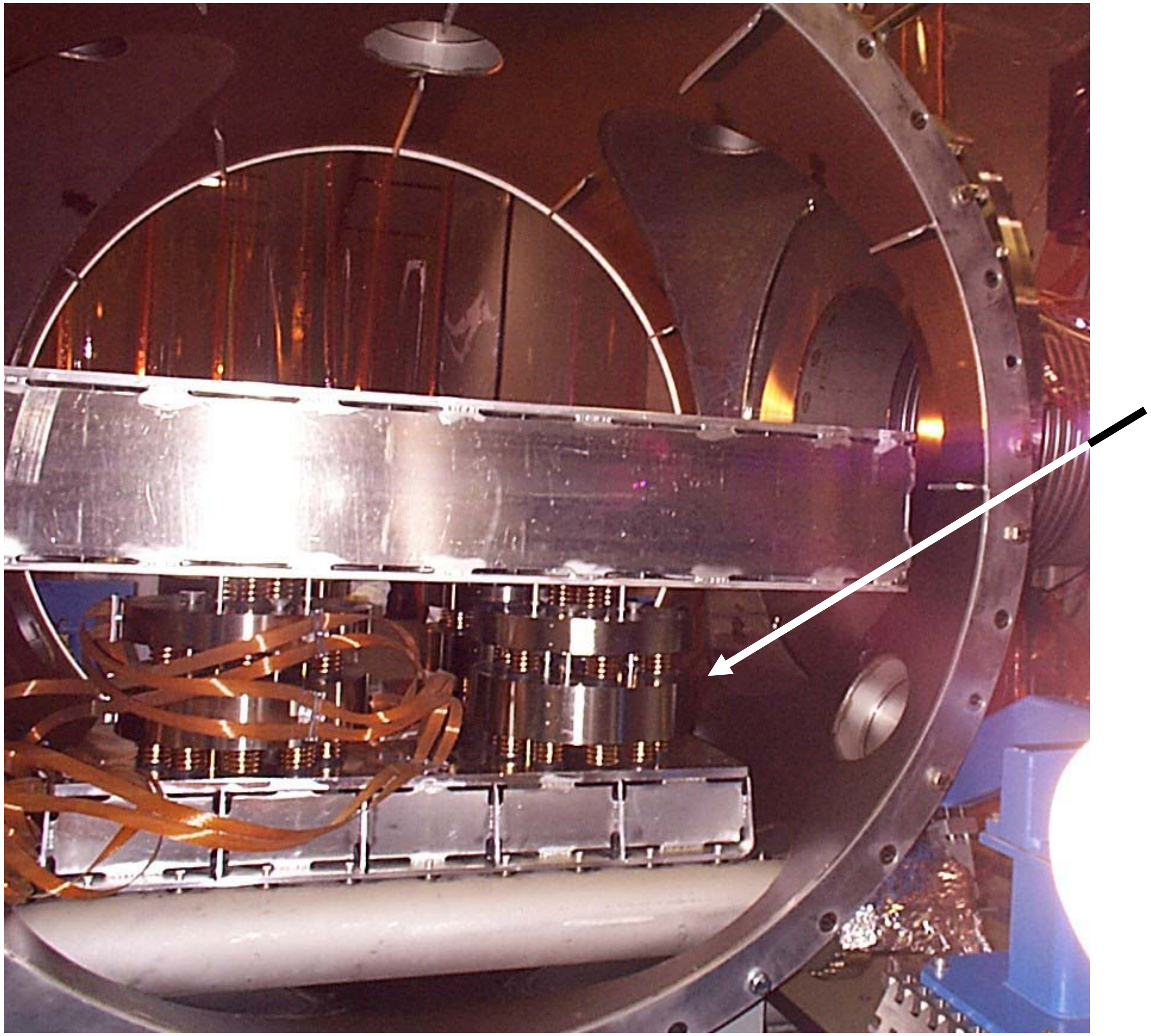


Hanford shown (Livingston only has one interferometer)

Vacuum System

A Mirror *in situ*

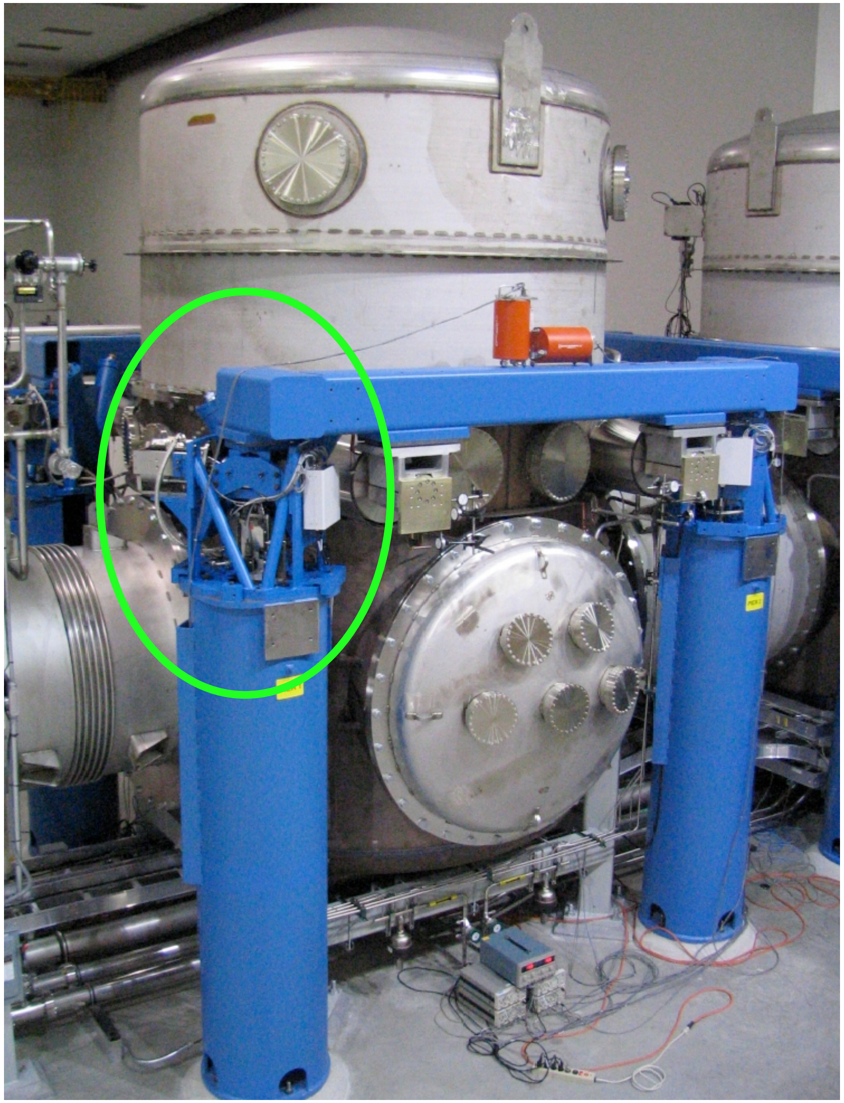
Vibration Isolation



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

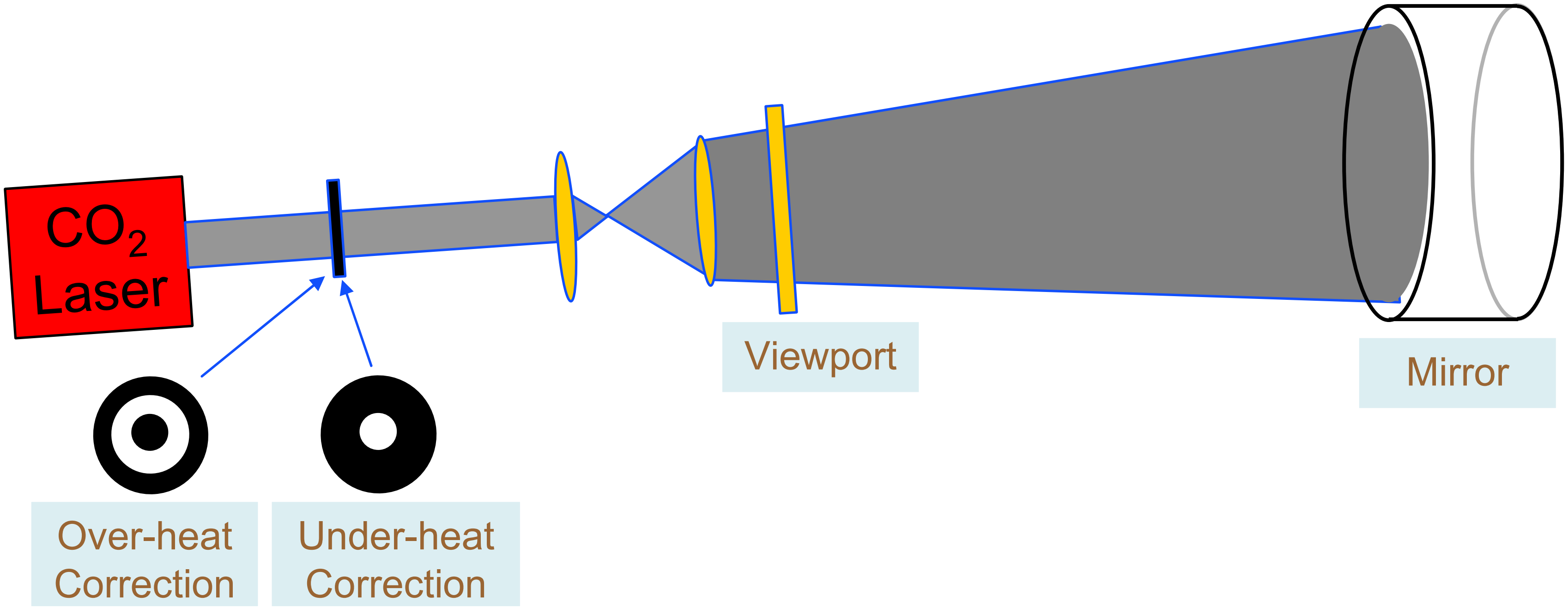
Handling High Laser Power

Use multiple photodiodes to handle increased light

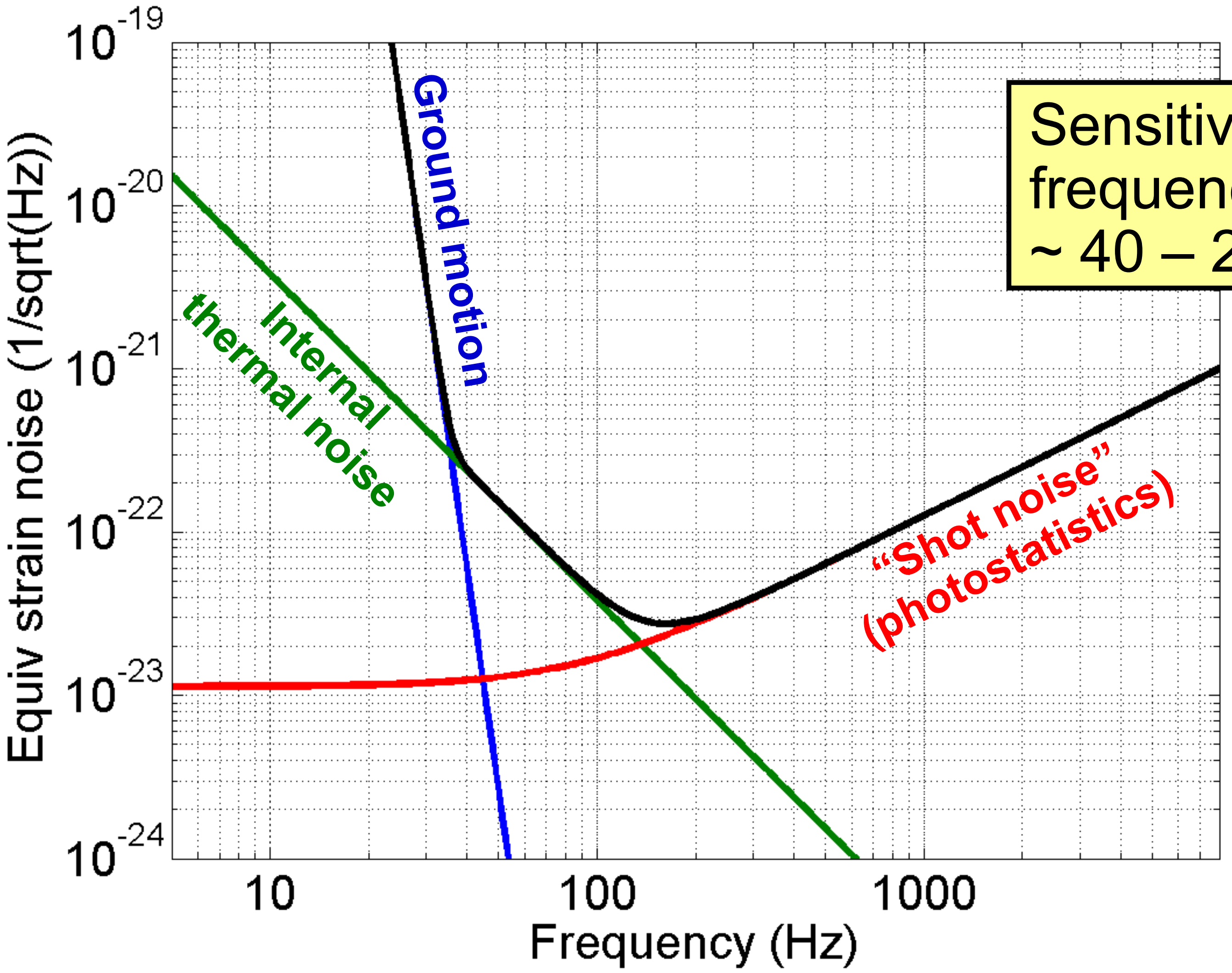
And fast shutters to protect photodiodes when lock is lost !

Compensate for radiation pressure in control software

Correct thermal lensing of mirrors by controlled heating



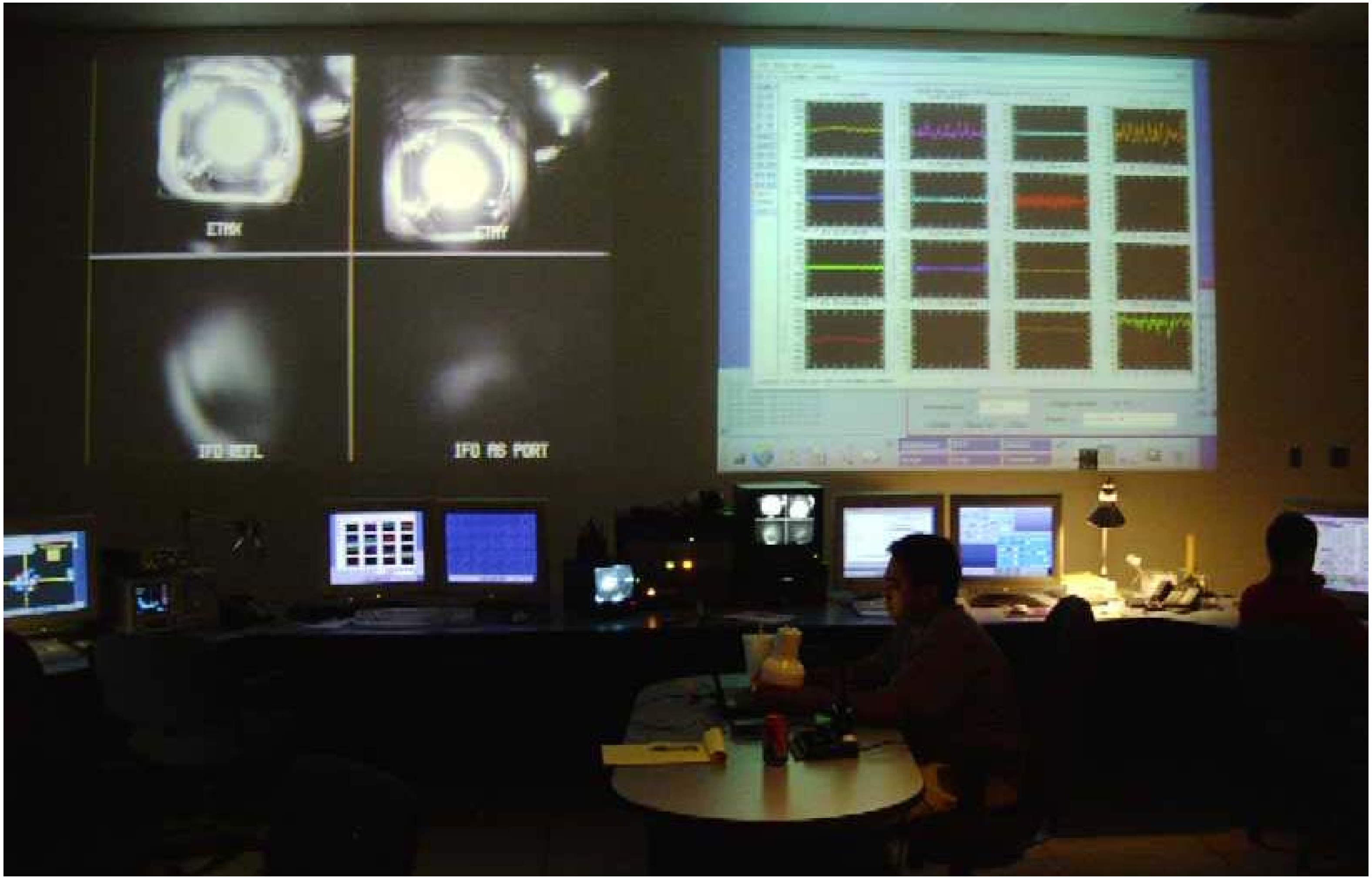
Limiting Fundamental Noise Sources



Sensitive frequency range: ~ 40 – 2000 Hz

Data Collection

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



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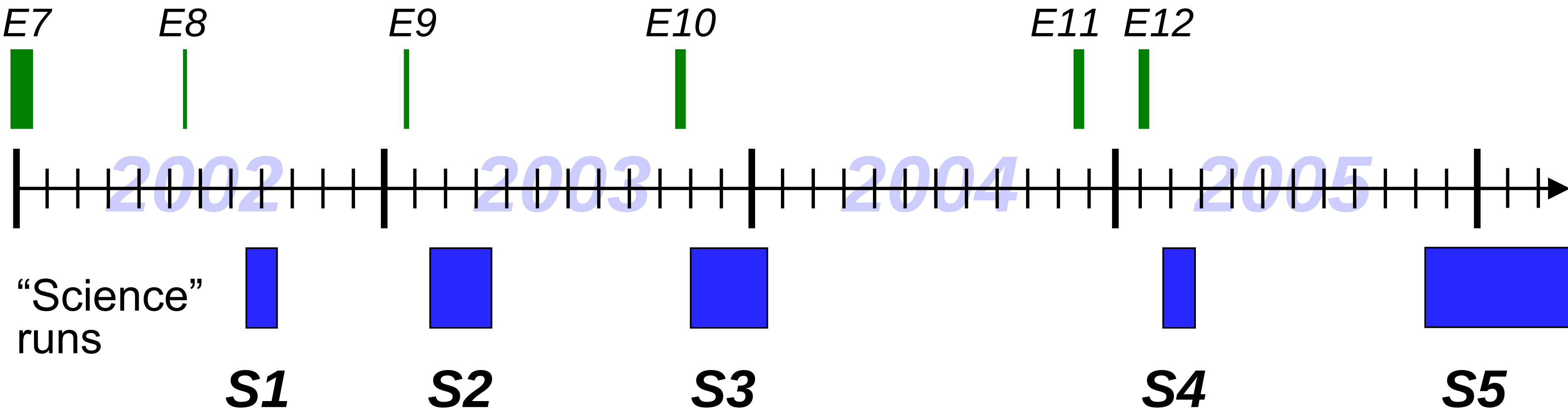
LIGO Data Runs

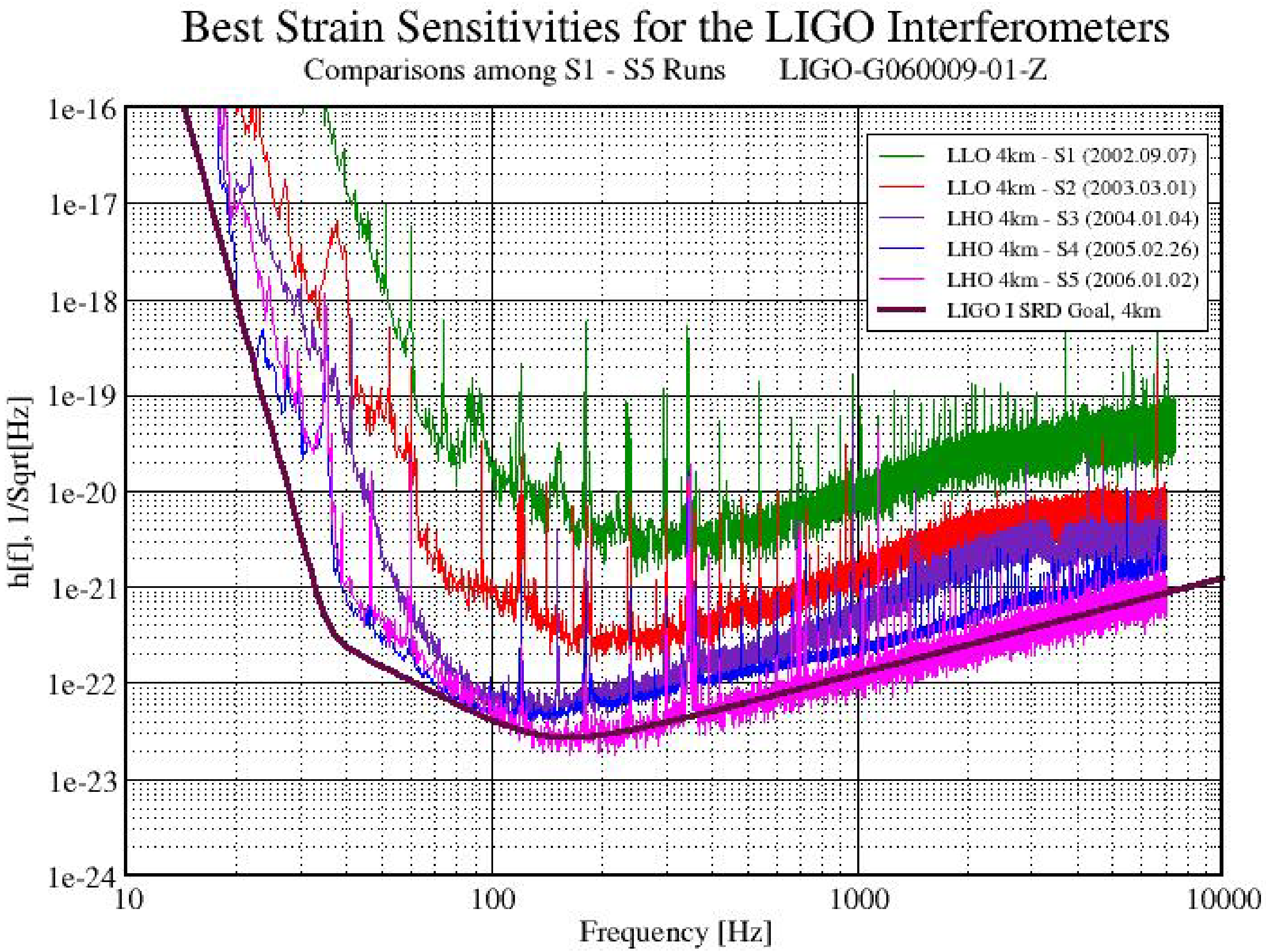
“Engineering” runs



“Science” 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:					(so far)
H1	59 %	74 %	69 %	80 %	68 %
H2	73 %	58 %	63 %	81 %	82 %
L1	43 %	37 %	22 %	74 %	56 %

Best Interferometer Sensitivity, Runs S1 through S5



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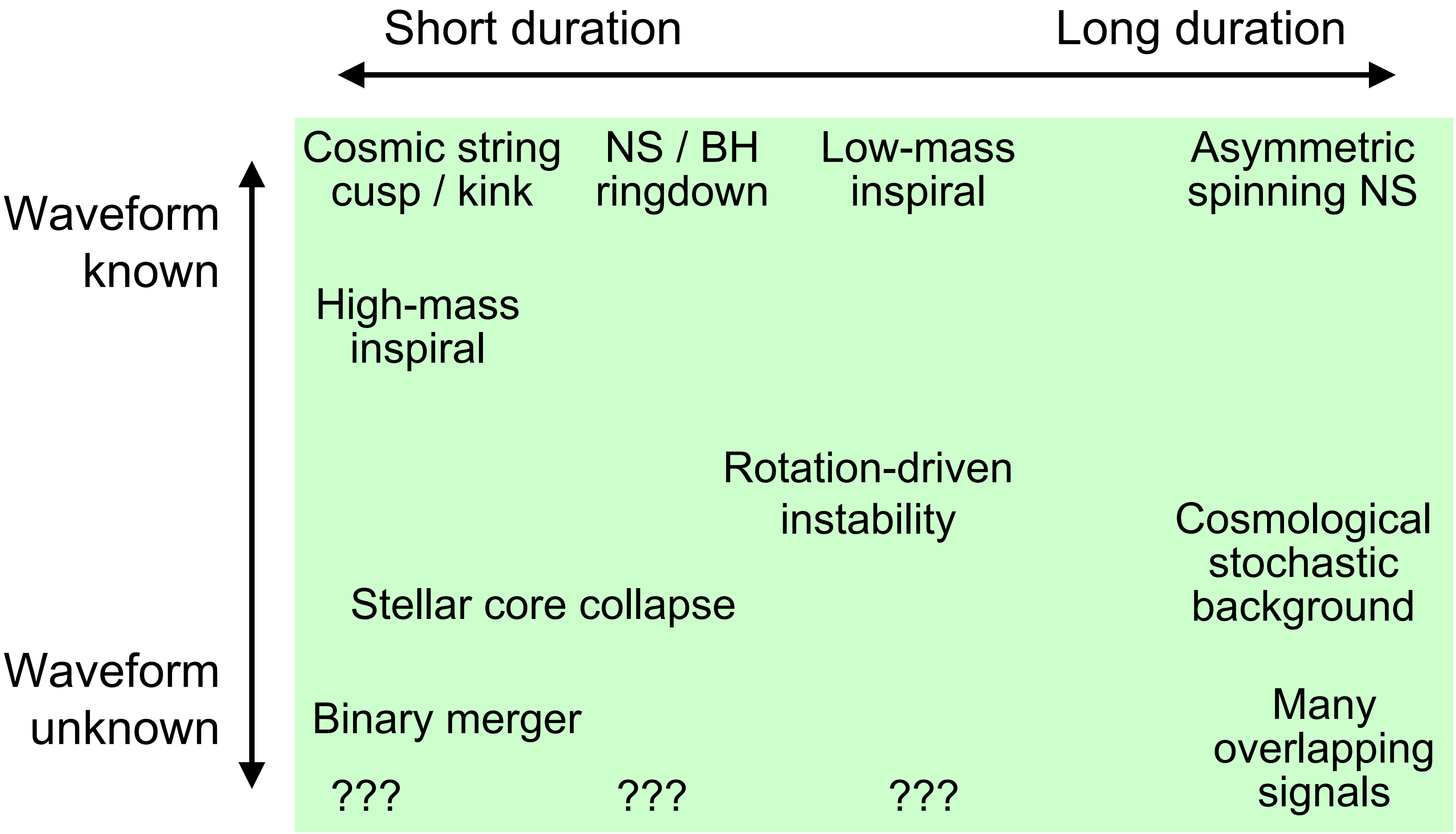
The Gravitational Wave Signal Tableau


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 core collapse

Binary merger

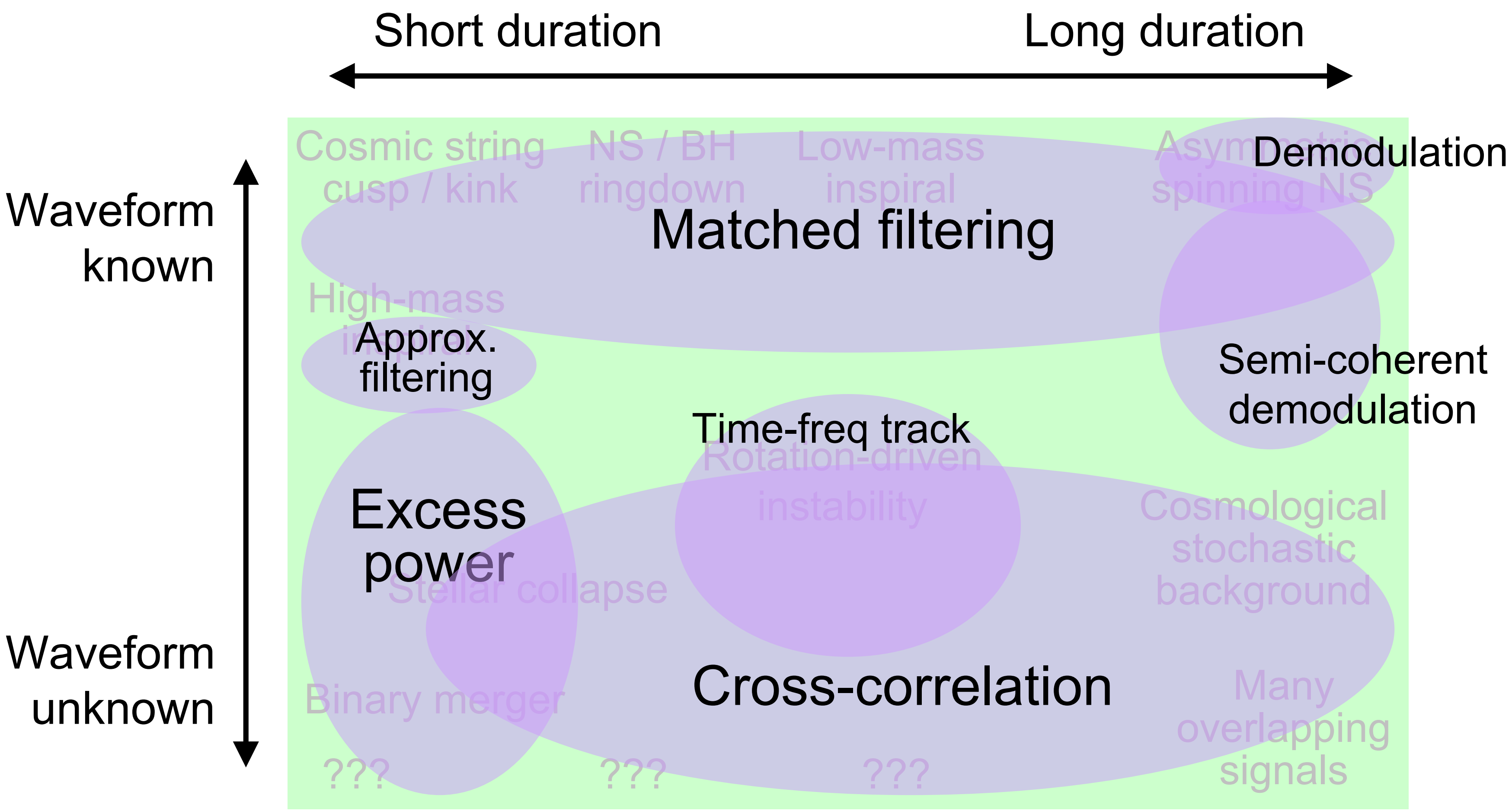
Many overlapping signals

???

???

???

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

Approx. filtering

Semi-coherent demodulation

Time-freq track

Rotation-driven instability

Excess power

Stellar collapse

Cosmological stochastic background

Binary merger

Cross-correlation

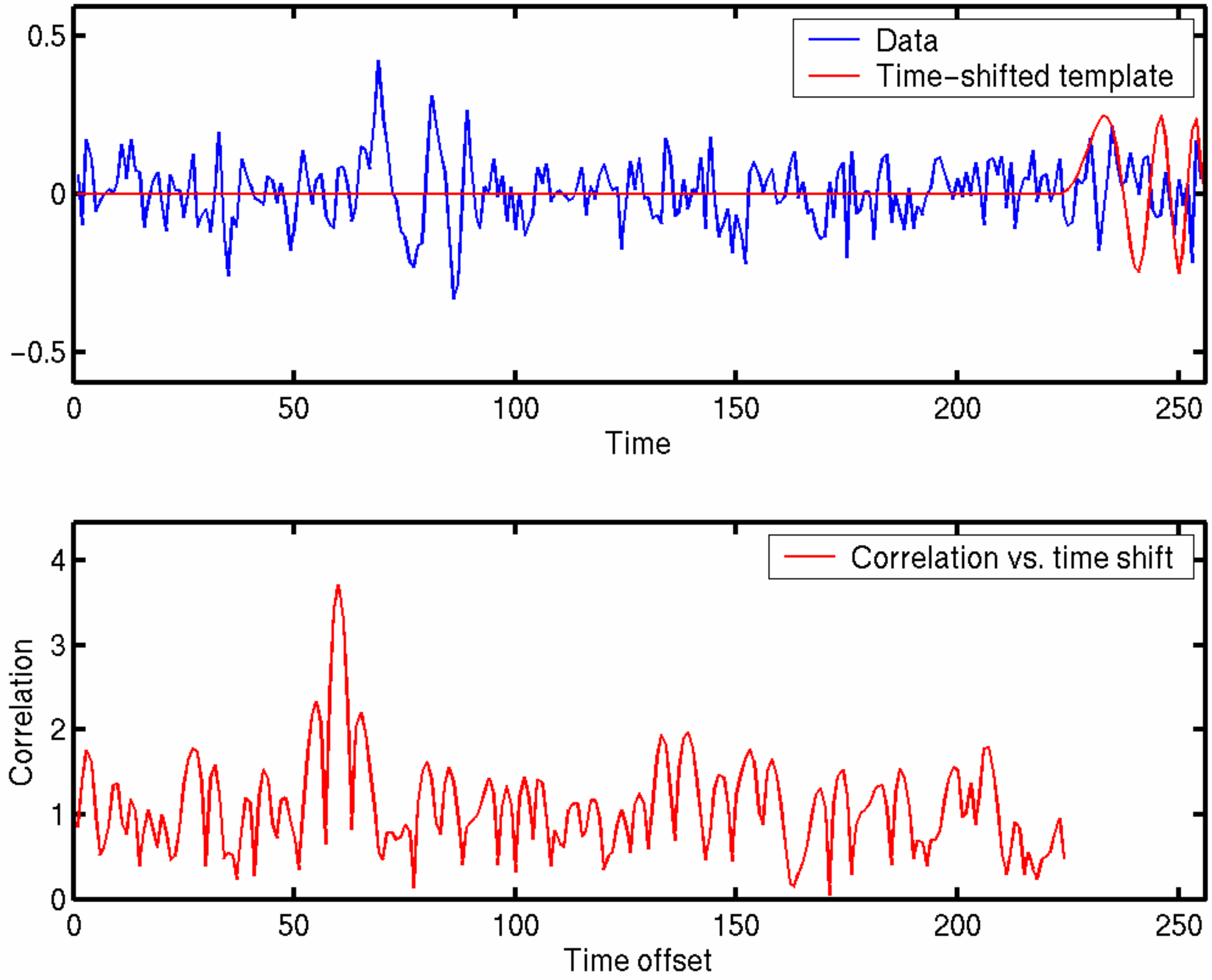
Many overlapping signals

???

???

???

Illustration of Matched Filtering



Optimal Matched Filtering in Frequency Domain

$$z(t) = 4 \int_0^\infty \frac{\overset{\text{Data}}{\tilde{s}(f)}\ \overset{\text{Template}}{\tilde{h}^*(f)}}{\underset{\text{Noise power spectral density}}{S_n(f)}}\, e^{2\pi i f t}\, df$$

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

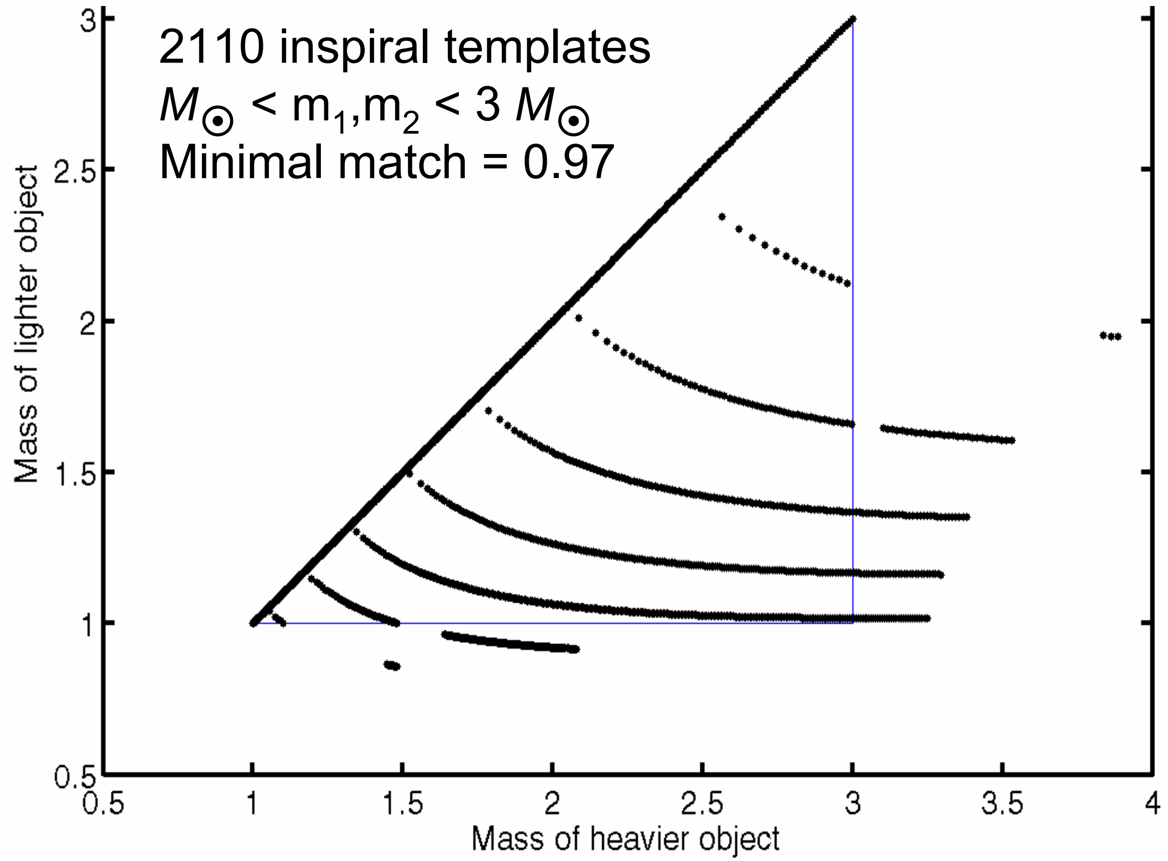
Require coincidence to make a detection

Triggers in multiple interferometers with consistent signal parameters

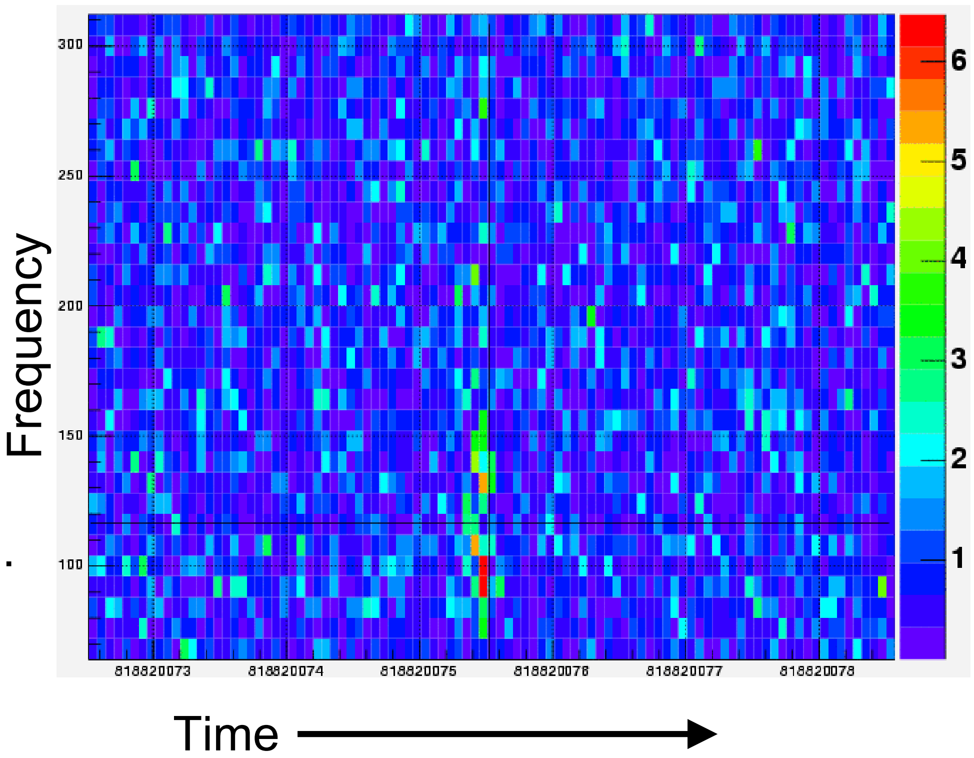
Matched Filtering for Inspirals

Use bank of templates to cover parameter space of target signals

Process data in parallel on many CPUs



Robust Burst Search Methods

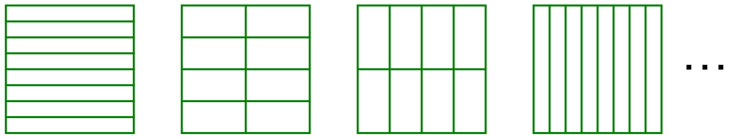


"Excess power" methods

Look at "hot" pixels or clusters in normalized time-frequency decomposition

"WaveBurst" compares wavelet decompositions for all detectors

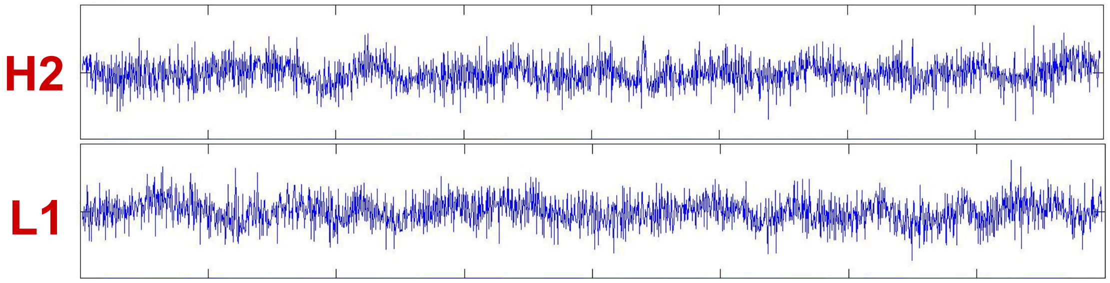
Use multiple ($\Delta t, \Delta f$) resolutions



Cross-correlation

Look for same signal buried in two (or more) data streams

Integrate over a short time interval



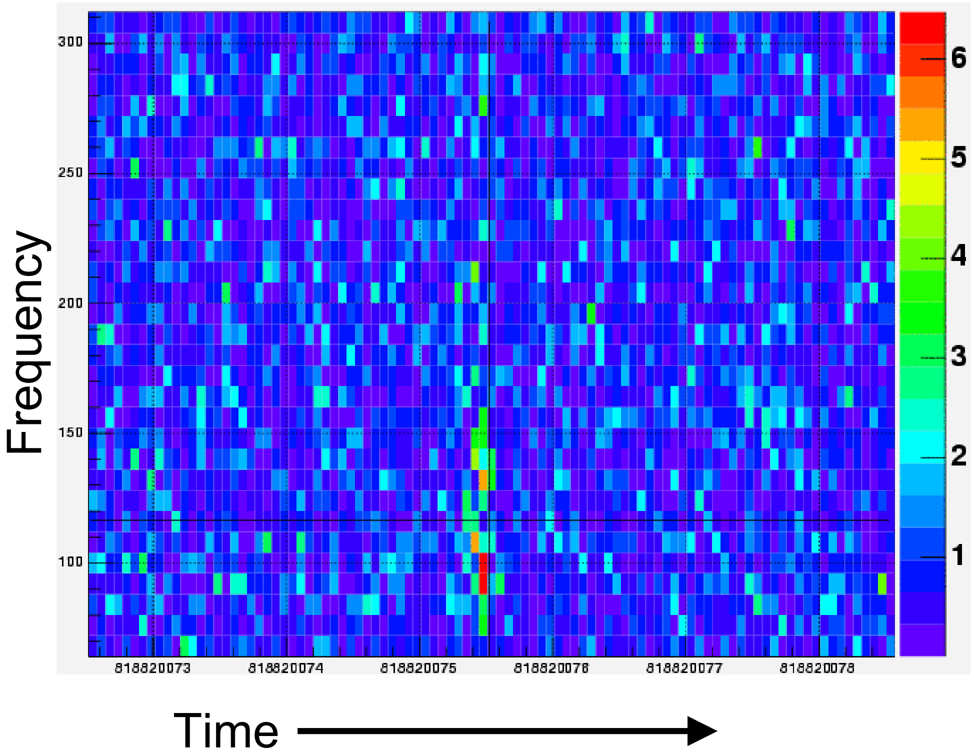
“Excess Power” Search Methods

Decompose data stream into time-frequency pixels

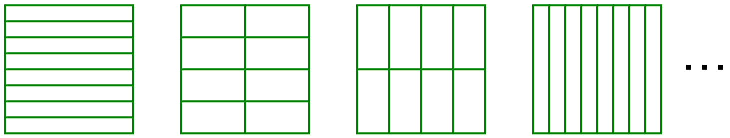
Fourier components, wavelets, “Q transform”, etc.

Normalize relative to noise as a function of frequency

Look for “hot” pixels or clusters of pixels

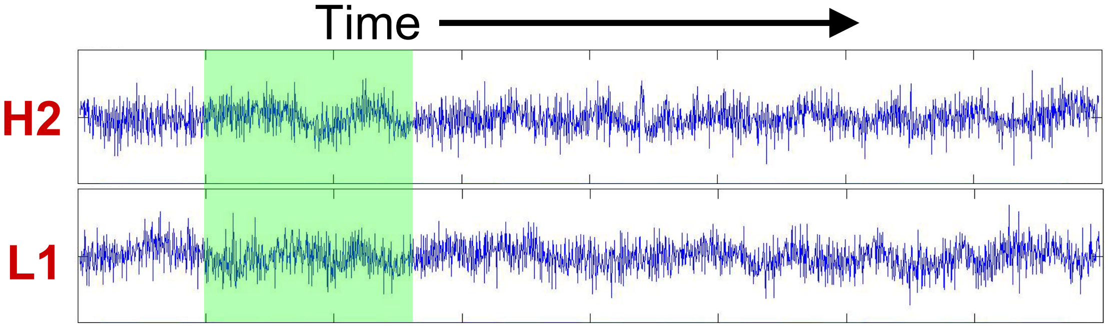


Can use multiple ($\Delta t, \Delta f$) pixel resolutions



Cross-Correlation Methods

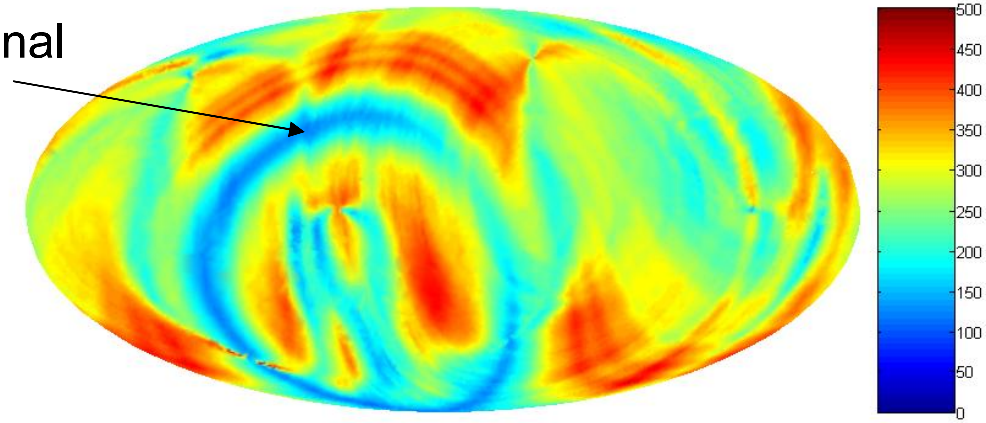
Look for same signal buried in two data streams



Integrate over a short time interval

Extensions to three or more detector sites being worked on

Simulated signal injected here



Inconsistent

Consistent

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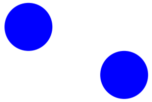
Inspiral Searches



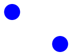
Neutron star binaries (1-3 $M_\odot$)

S2 result: *[LSC, Phys. Rev. D **72,** 082001 (2005)]*

No inspirals detected — range ~1.5 Mpc if optimally oriented

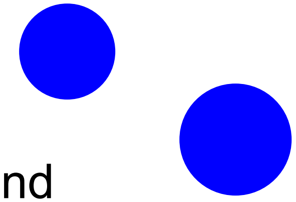
Set upper limit (90% C.L.) of 47 per year per Milky Way equiv. galaxy for a plausible population model

S3 / S4 / S5 ranges: ~3, ~15, ~24 Mpc; analysis in progress



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

S2 upper limit: 63/year/MWEG *[LSC, Phys. Rev. D **72,** 082002 (2005)]*



Binaries containing a black hole (>3 $M_\odot$)

Generally visible farther away than neutron star binaries

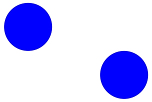
Post-Newtonian expansion breaks down within sensitive band

If spins are significant, physical parameter space is very large

⇒ Use a parametrized detection template family for efficient filtering

S2 search: none observed out to a few Mpc *[LSC, to appear in Phys. Rev. D; gr-qc/0509129]*

Low-Mass Inspiral Searches



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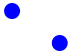
Set upper limit (90% C.L.) of 47 per year per Milky Way equiv. galaxy for a plausible population model

S3 / S4 / S5 ranges: ~3, ~15, ~24 Mpc; analysis in progress



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

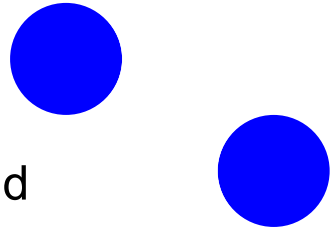
S2 result: *[LSC, Phys. Rev. D **72,** 082002 (2005)]*

No inspirals detected — range a few hundred kpc

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 $M_\odot$)

Generally visible farther away than neutron star binaries

Post-Newtonian expansion breaks down within sensitive band

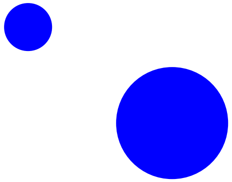
If spins are significant, physical parameter space is very large

⇒ Use a parametrized detection template family for efficient filtering

S2 result: *[LSC, to appear in Phys. Rev. D; gr-qc/0509129]*

Searched for systems with negligible spins with BCV template family
No inspirals detected — range ~few Mpc, depending on mass

Searches in progress using S3 / S4 data—
spinning and non-spinning template families



Black hole – neutron star binaries

Similar issues

All-Sky Burst Searches

Example: S4 general all-sky burst search

- 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 WaveBurst triggers with cross-correlation tests based on the *r* statistic (pair-wise linear correlation coefficient)
- No event candidates observed
- Upper limit on rate of *detectable* events:

$$R_{90\%} = \frac{2.303}{15.53 \text{ days}} = 0.148 \text{ per day}$$

Preliminary

S4 All-Sky Burst Search: Overview

- **Searched triple-coincidence (H1+H2+L1) LIGO data for short (<1 sec) signals with frequency content in range 64–1600 Hz**

- **Used WaveBurst time-wavelet decomposition to generate triggers**

  Compares wavelet decomposition pixels from all three data streams

  [S. Klimenko et al., Class. Quantum Grav. ***21****, S1685 (2004)]*

- **Followed up WaveBurst triggers with cross-correlation tests based on the *r* statistic** *[L. Cadonati, Class. Quantum Grav.* ***21****, S1695 (2004)]*

- **Data quality cuts, significance cuts and veto conditions chosen largely based on time-shifted coincidences**

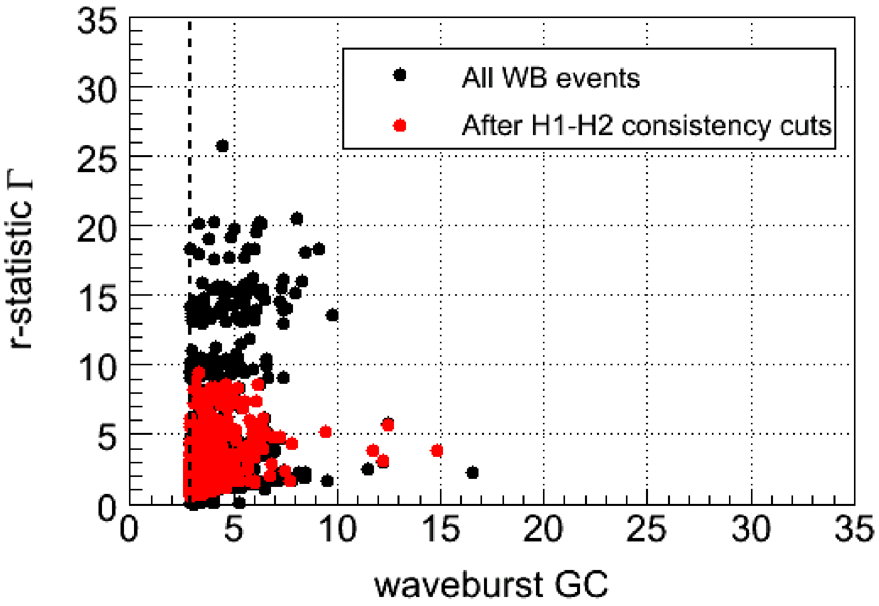
- **Preliminary results being presented today**

S4 All-Sky Burst Search:
Data Quality Cuts

Various environmental and instrumental conditions catalogued; studied relevance using *time-shifted* coincident triggers

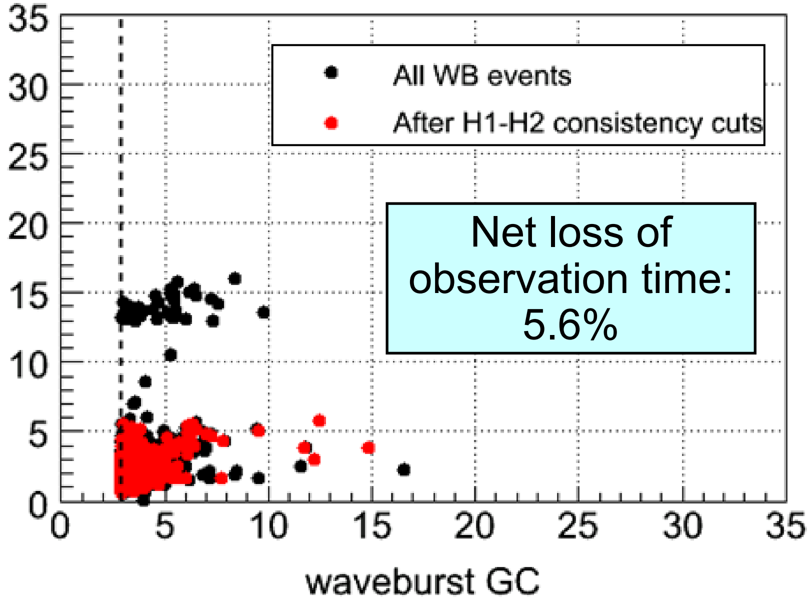
Minimal data quality cuts

Require locked interferometers
Omit hardware injections
Avoid times of ADC overflows



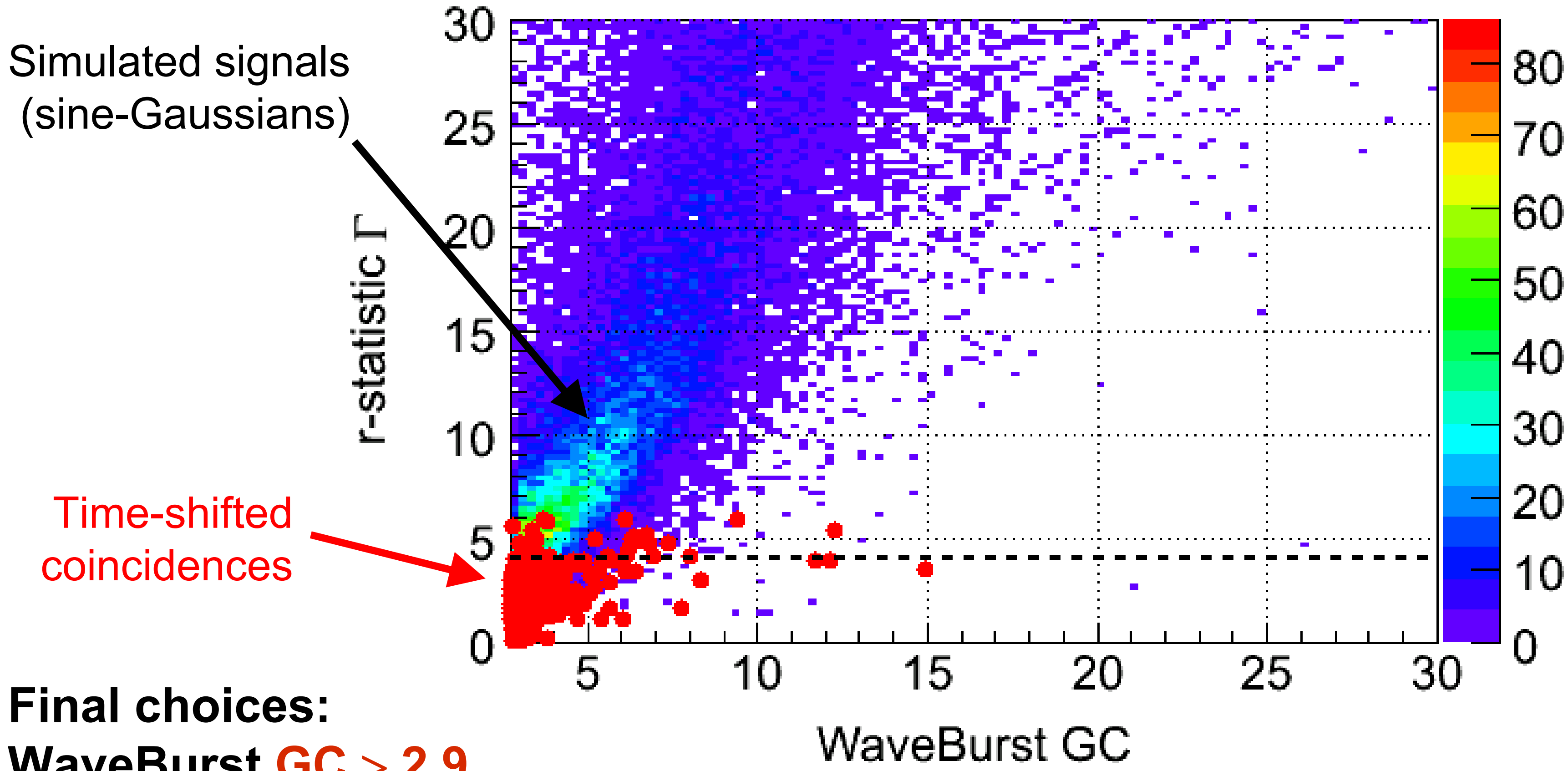
Additional data quality cuts

Avoid high seismic noise, wind, jet
Avoid calibration line drop-outs
Avoid times of “dips” in stored light
Omit last 30 sec of each lock



Net loss of observation time: 5.6%

S4 All-Sky Burst Search: Final “Significance” Cuts



Final choices:
WaveBurst GC > 2.9
***r*-statistic Gamma > 4**

Chosen to make expected background low, but not zero

S4 All-Sky Burst Search: Auxiliary-Channel Vetoes

Checked for glitches in dozens of auxiliary channels

- Accelerometers, microphones, magnetometers, radio interference monitor
- Interferometer error & control signals for other length degrees of freedom
- Automatic alignment system channels

Looked for correlation with glitches in gravitational wave channel

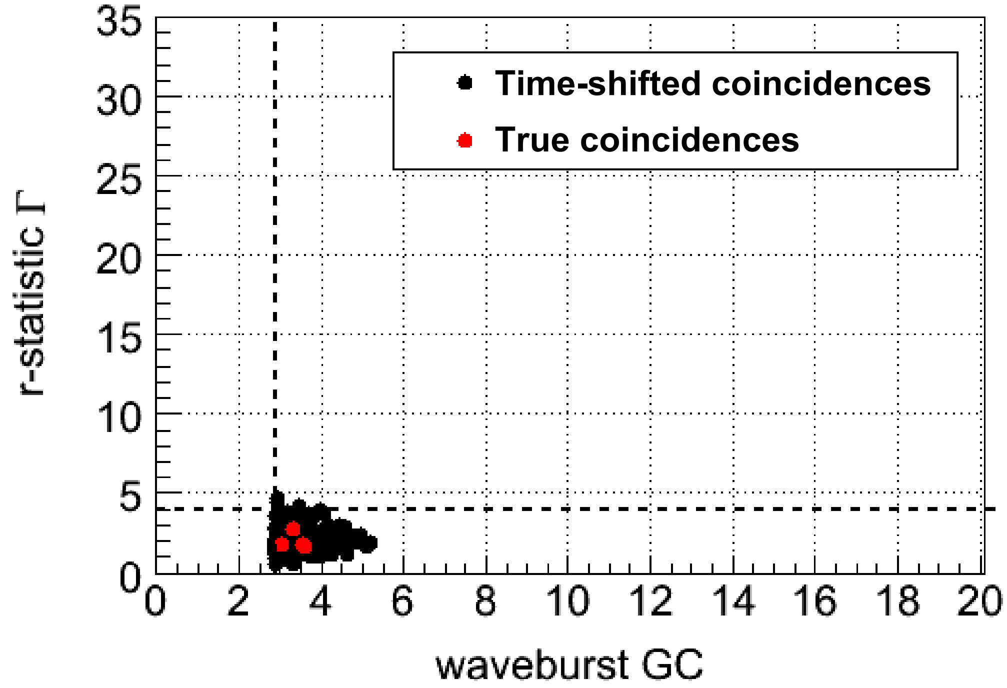
Final choice of 7 veto conditions based largely on examining time-shifted WaveBurst / *r*-stat triggers with largest Gamma values

- Vetoed 6 of the top 10, including:
  - ► 2 with strong signals in accelerometers on H1 and H2 antisymmetric port optical tables
  - ► 3 with glitches in H1 beam-splitter pick-off channels
  - ► 1 with big excursions in H2 alignment system

Dead-time from vetoes: less than 2%

S4 All-Sky Burst Search Result

After “opening the box” …



No event candidates pass all cuts

Upper limit on rate of *detectable* events:

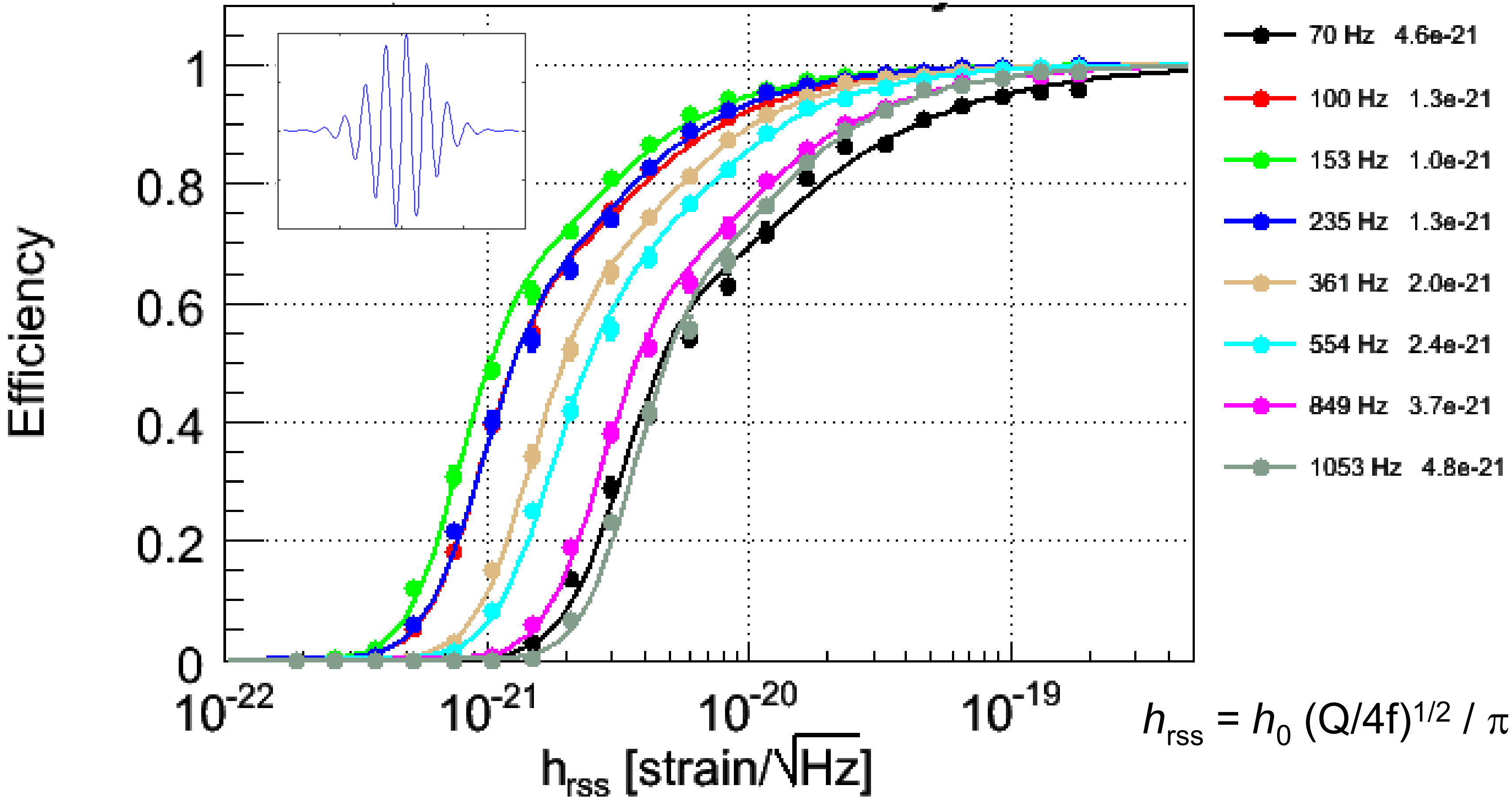
$$R_{90\%} = \frac{2.303}{15.53 \text{ days}} = \mathbf{0.148 \text{ per day}}$$

S4 All-Sky Burst Search Efficiency for Q=8.9 Sine-Gaussians (preliminary)

Caveats: preliminary calibration; auxiliary-channel vetoes *not* applied

$h(t) = h_0 \sin(2\pi f t) \exp(-2(\pi f t/Q)^2)$

Linearly polarized; random sky position & polarization angle



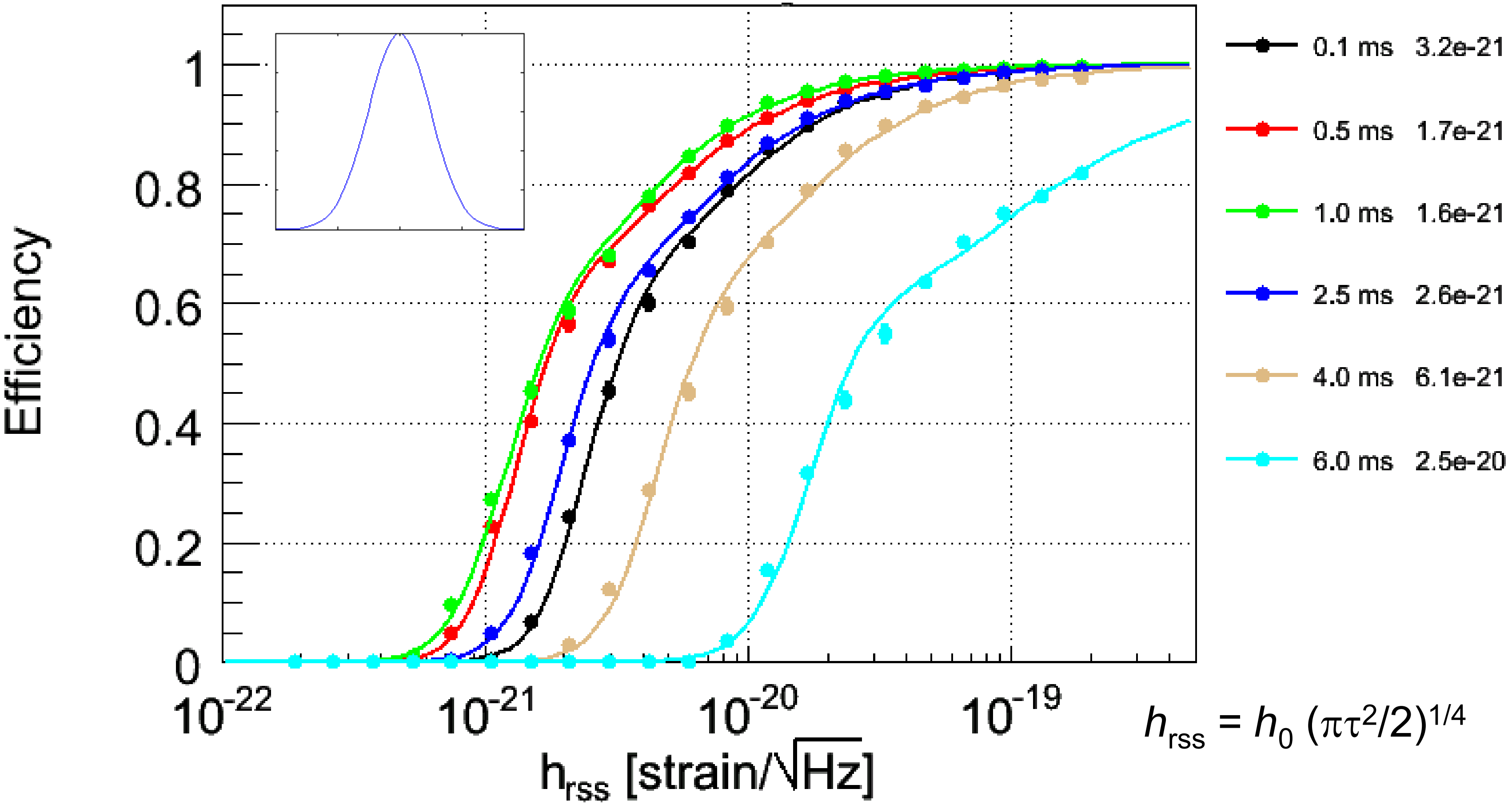
$h_{rss} = h_0 (Q/4f)^{1/2} / \pi^{1/4}$

S4 All-Sky Burst Search Efficiency for Gaussians (preliminary)

Caveats: preliminary calibration; auxiliary-channel vetoes *not* applied

$h(t) = h_0 \exp(-t^2/\tau^2)$

Linearly polarized; random sky position & polarization angle



$h_{rss} = h_0\,(\pi\tau^2/2)^{1/4}$

Summary of Sensitivities
(preliminary)

h_{rss} at 50% detection efficiency, in units of 10^{-21}

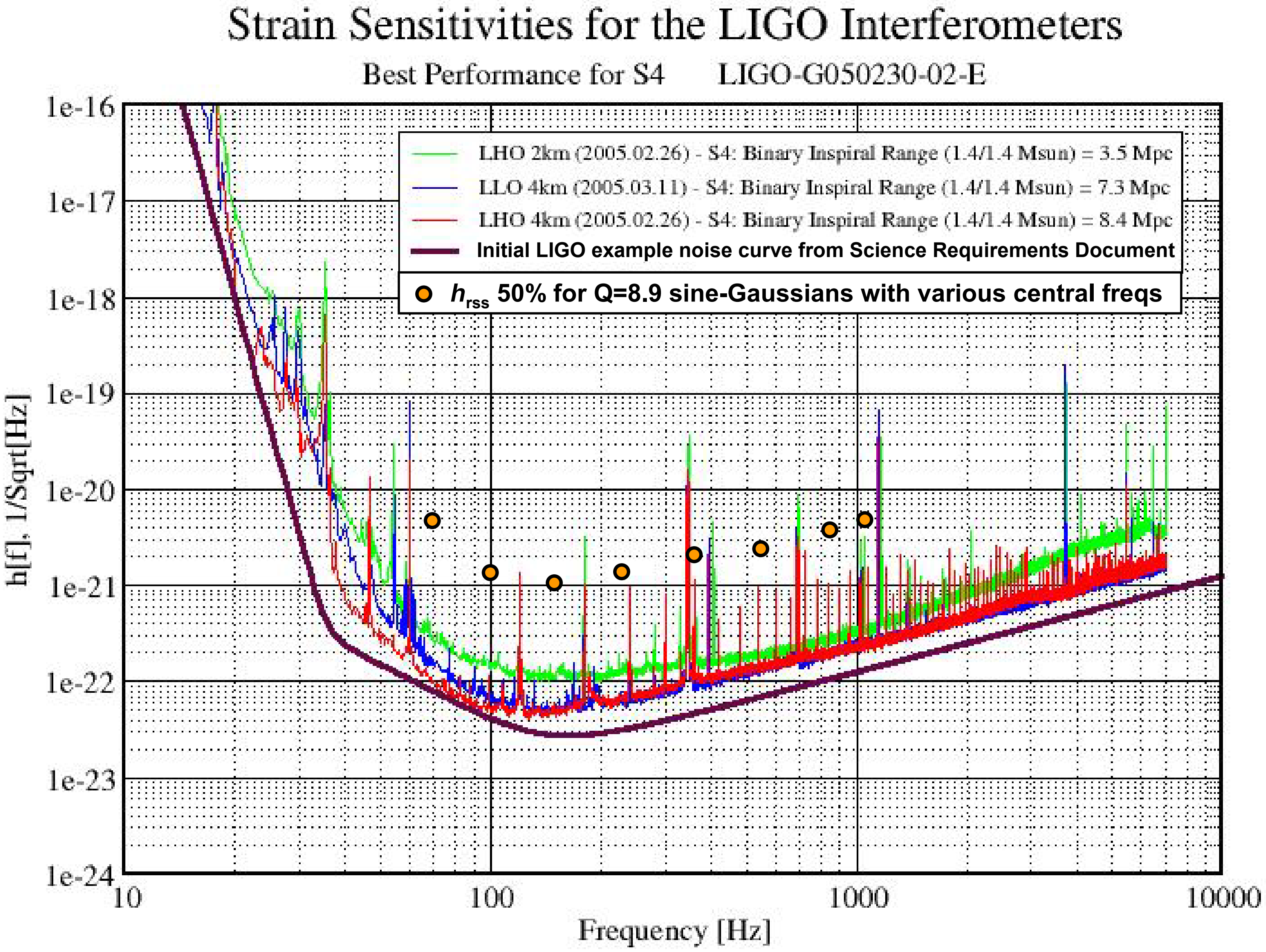
Caveat: prelim calibration, no vetoes

	Freq (Hz)		S3:	S2:
Sine-Gaussians with Q=8.9	70	**4.6**	–	–
	100	**1.3**	–	82
	153	**1.0**	–	55
	235	**1.3**	9	15
	361	**2.0**	–	17
	554	**2.4**	13	23
	849	**3.7**	23	39
	1053	**4.8**	–	–
	Tau (ms)			
Gaussians	0.1	**3.2**	18	43
	0.5	**1.7**	–	26
	1.0	**1.6**	–	33
	2.5	**2.6**	–	140
	4.0	**6.1**	–	340

S3 values from Amaldi6 presentation and proceedings: gr-qc/0511146

S2 values from Phys. Rev. **D** 72, 062001 (2005).

S4 All-Sky Burst Search Efficiency for Q=8.9 Sine-Gaussians (preliminary)



Other All-Sky Burst Searches

Joint searches with GEO and with other detectors

Searches for cosmic string cusps/kinks and for ringdowns

- Use matched filtering for these known waveforms

Other searches under development …

Externally Triggered Searches

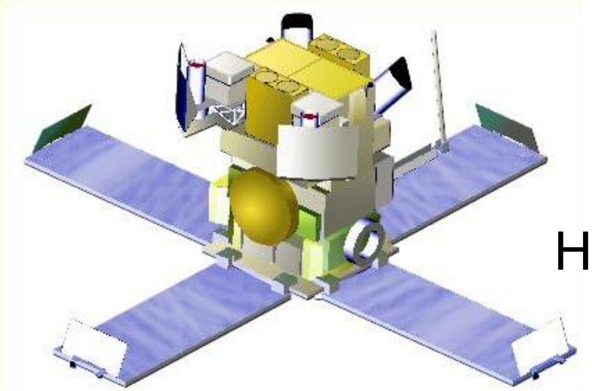
Search for gravitational wave bursts or inspirals associated with GRBs or other observed astrophysical events

- Known time allows use of lower detection threshold
- Known sky position fixes relative time of arrival at detectors

First cross-correlation analysis published for GRB030329

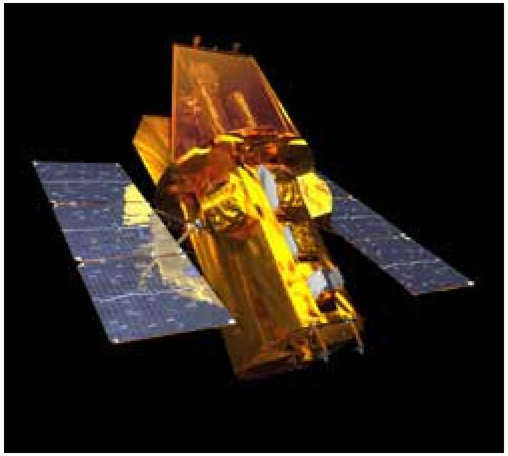
- Limit on gravitational wave amplitude *[LSC, Phys. Rev. D **72**, 042002 (2005)]*

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 grav. waves from *known* radio/X-ray pulsars

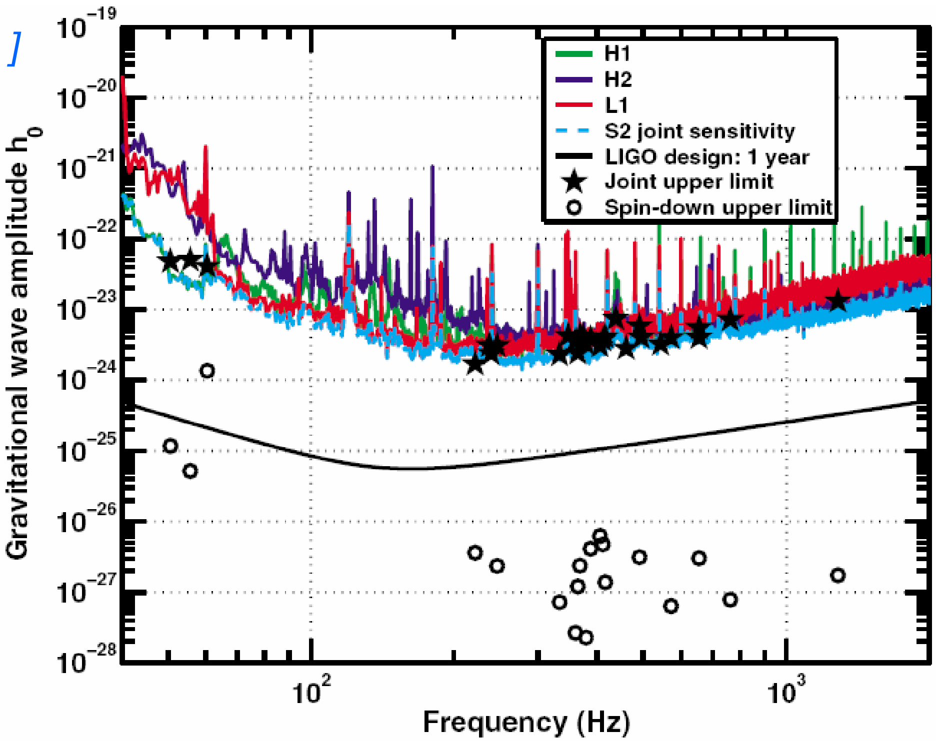
Demodulate data at twice the spin frequency

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

Placed limits on strain h_0 and equatorial ellipticity ε 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 reach the spin-down limit of the Crab pulsar



Searches for Periodic Signals from Spinning Neutron Stars

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

Computationally very expensive!

First search, using S2 data, will be published soon

Also 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 *[LSC, Phys. Rev. D **72,** 102004 (2005)]*

Additional methods being applied now

Ultimately plan hierarchical searches combining semi-coherent and coherent methods

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

Assumes that data streams have no instrumental correlations

S3 result *[LSC, Phys. Rev. Lett.* ***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

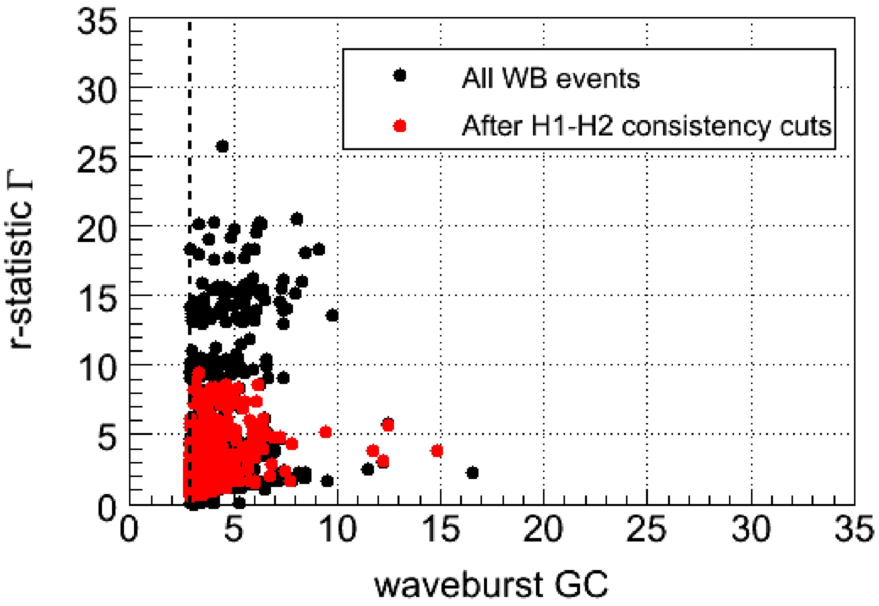
Data Analysis Challenge: Variable Data Quality

Various environmental and instrumental conditions catalogued; can study relevance using *time-shifted* coincident triggers

Example from S4 all-sky burst search:

Minimal data quality cuts

Require locked interferometers
Omit hardware injections
Avoid times of ADC overflows



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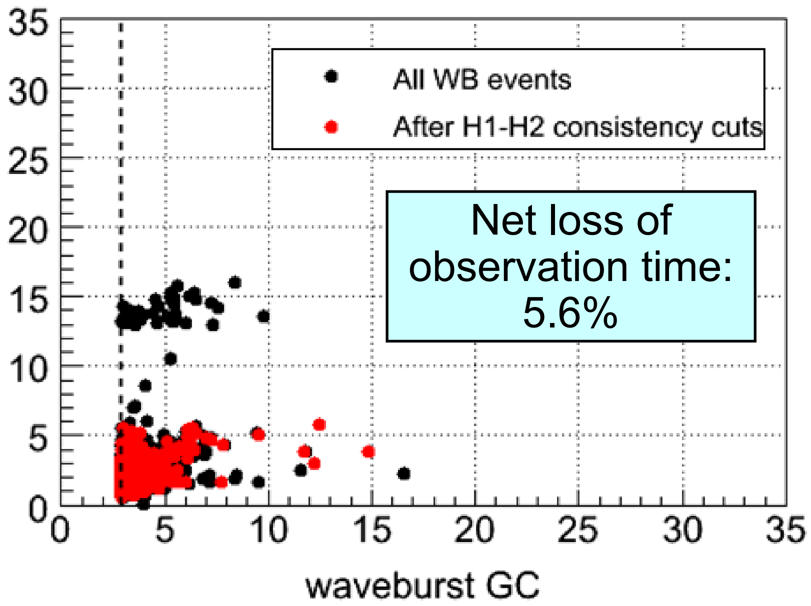
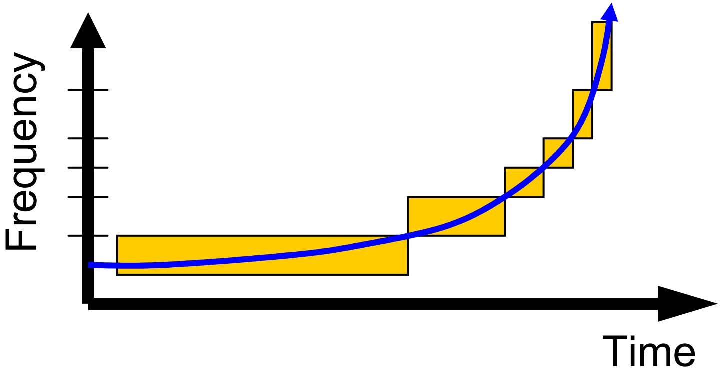


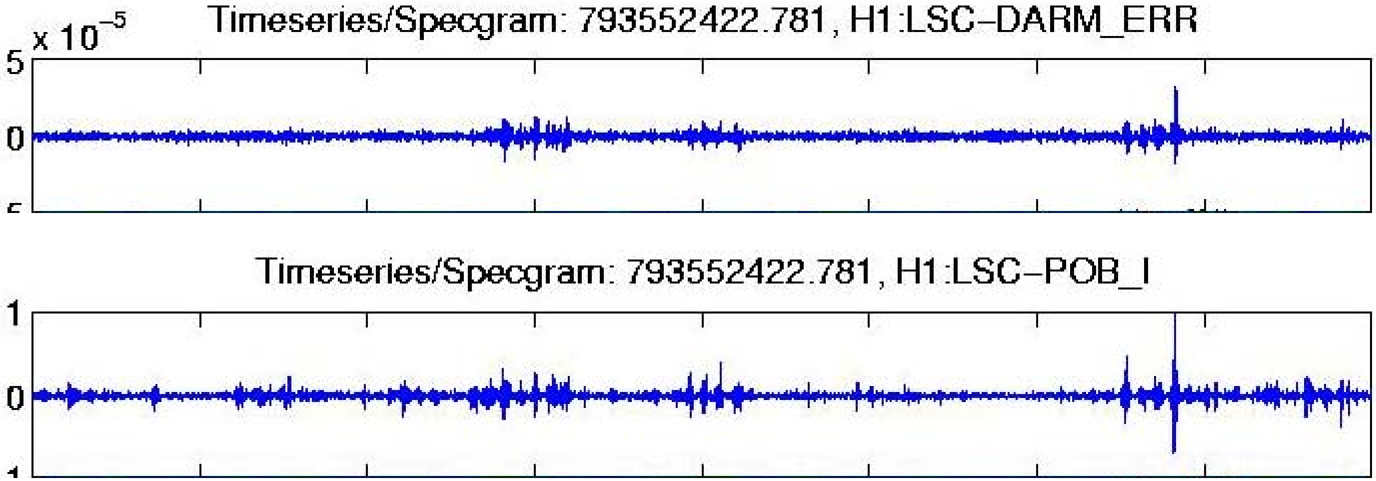
Net loss of observation time: 5.6%

Data Analysis Challenge: Non-Stationary Noise / Glitches

For inspirals: chi-squared test and other consistency tests



Auxiliary-channel vetoes



GW channel

Beam splitter pick-off

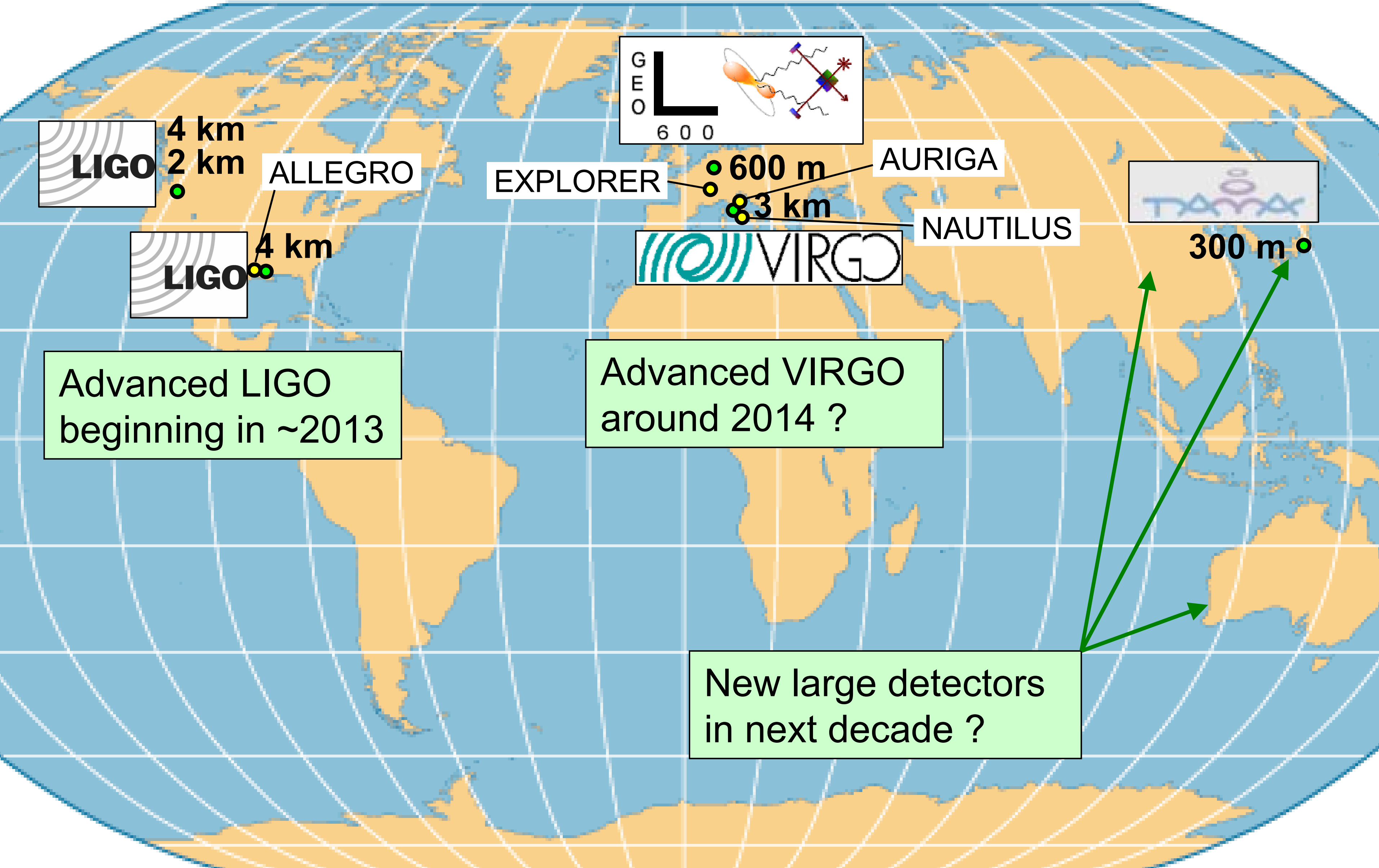
Most important: require consistent signals in multiple detectors!

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



Advanced LIGO beginning in ~2013

Advanced VIRGO around 2014 ?

New large detectors in next decade ?

Summary

After much hard work, the LIGO gravitational wave detectors have now reached their target sensitivities and have begun long-term observing

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

Many searches have been completed or are underway

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