LIGO Listens for Gravitational Waves

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LIGO-G070797-00-Z

Outline

- Gravitational waves
- Gravitational wave detectors
- LIGO
- LIGO data runs
- Recent and ongoing searches for gravitational waves
- The evolving worldwide network of gravitational wave detectors

LIGO

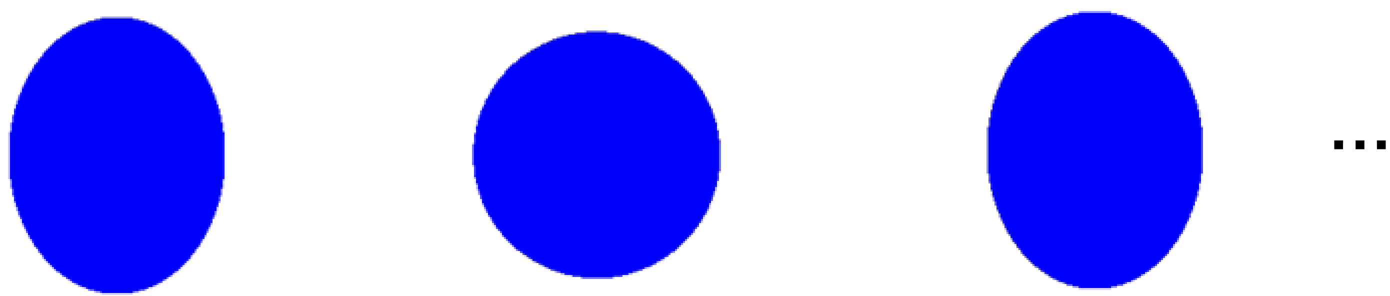
Gravitational Waves

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

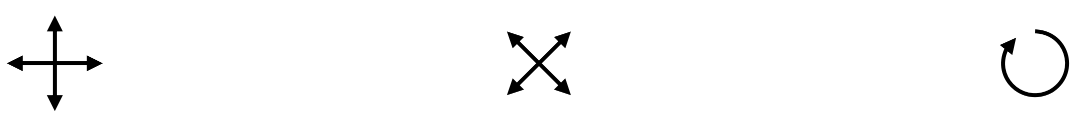
Perturbation of the spacetime metric

Strength and polarization depend on direction relative to source

Can be a linear combination of polarization components



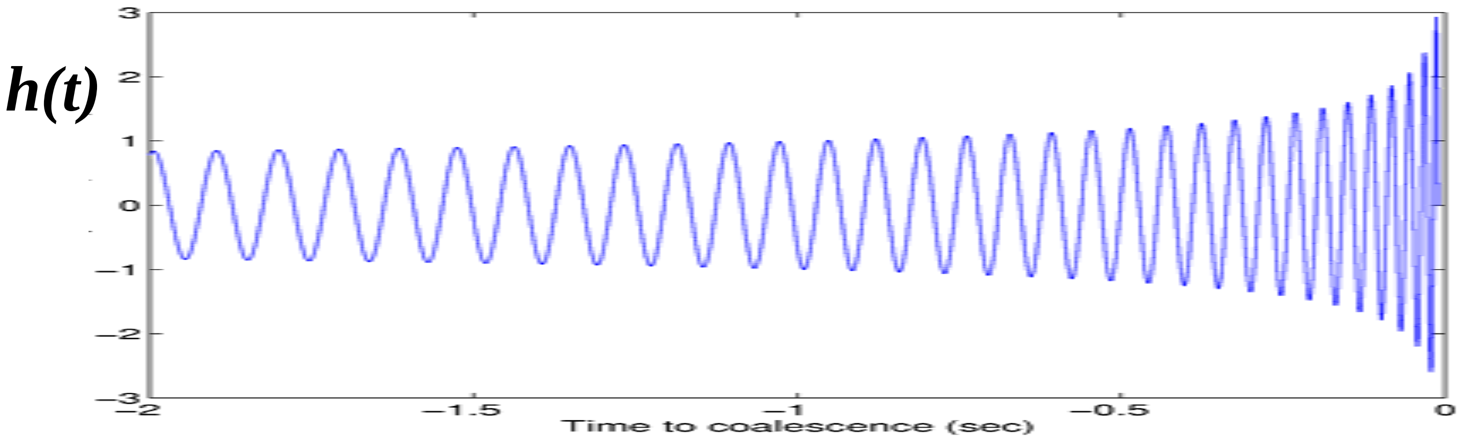
"Plus" polarization   "Cross" polarization   Circular polarization



Each component is described by a dimensionless strain, $h = \Delta L / L$, with amplitude inversely proportional to distance

Gravitational Waves from Compact Binary Systems

- For example, the original binary pulsar 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

⇒ Have to be able to search a large volume of space

⇒ 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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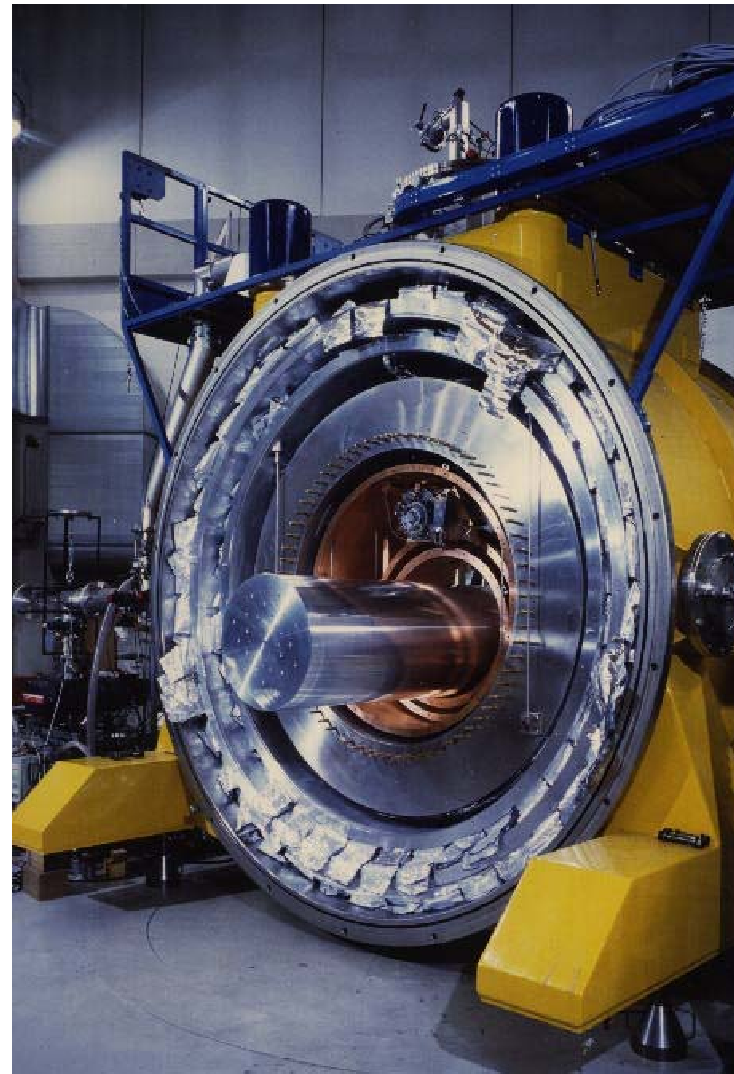
Resonant “Bar” Detectors

Joe Weber, circa 1969

AIP Emilio Segre Visual Archives

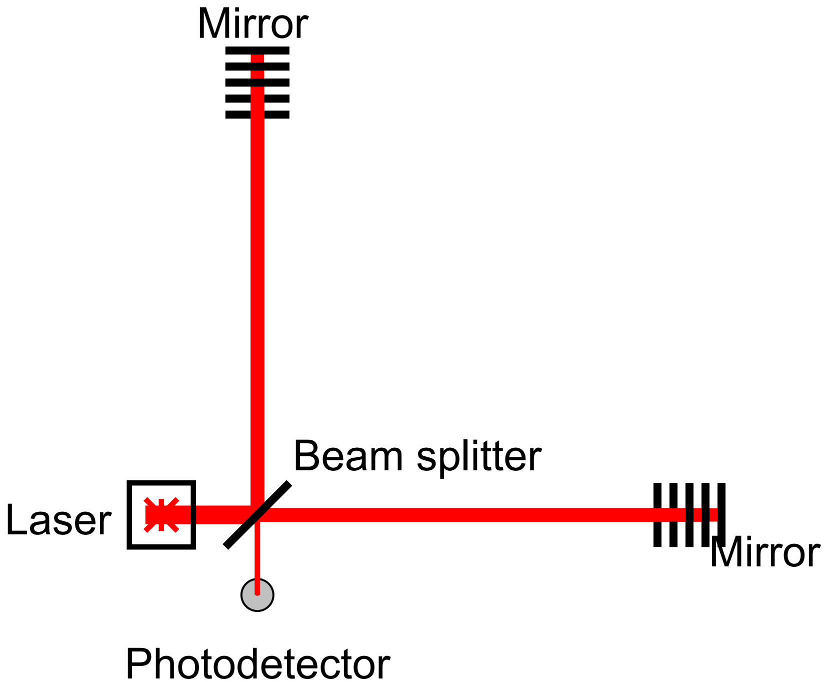
The AURIGA detector



Laser Interferometers

Variations on basic Michelson design, with two long arms

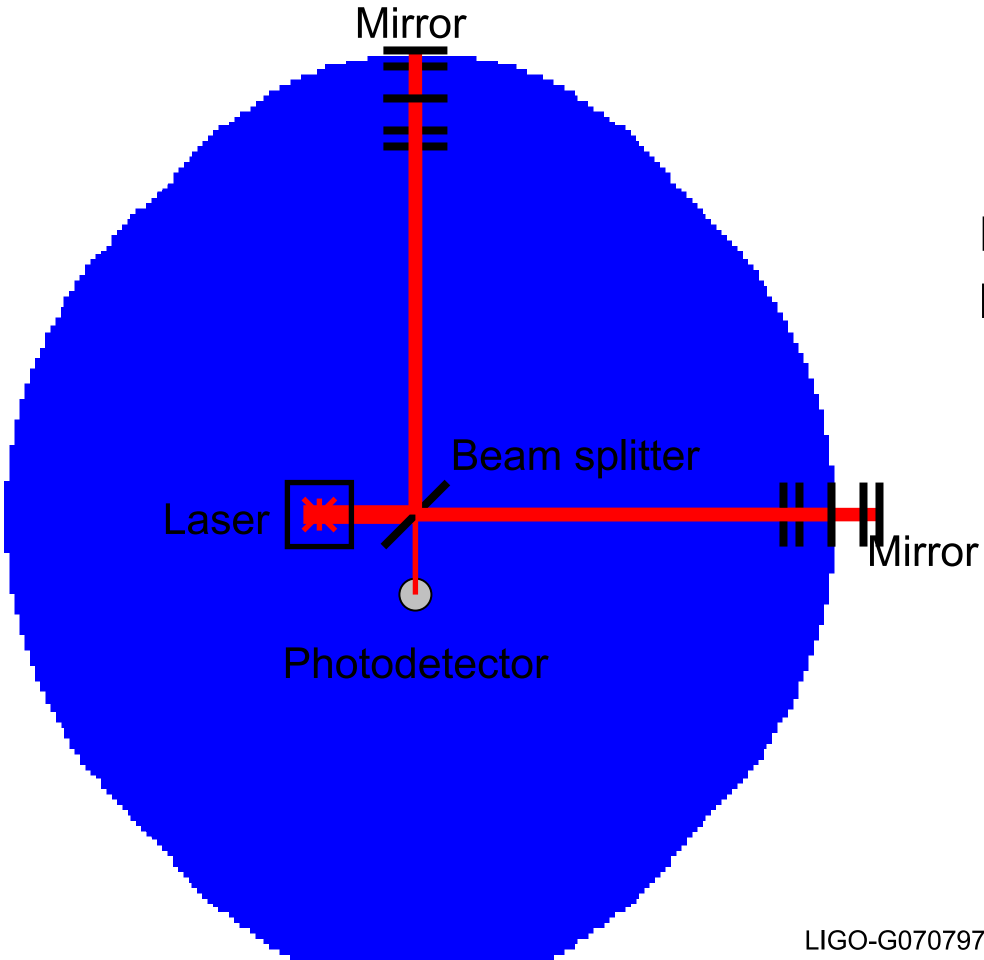
Measure *difference* in arm lengths to a fraction of a wavelength



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

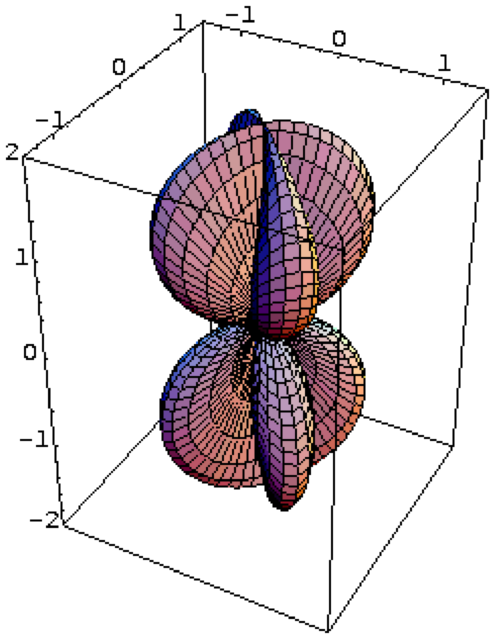


Responds to one polarization projection

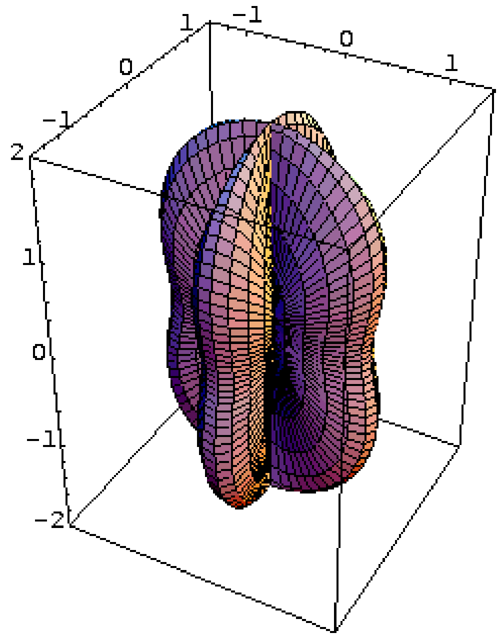
Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

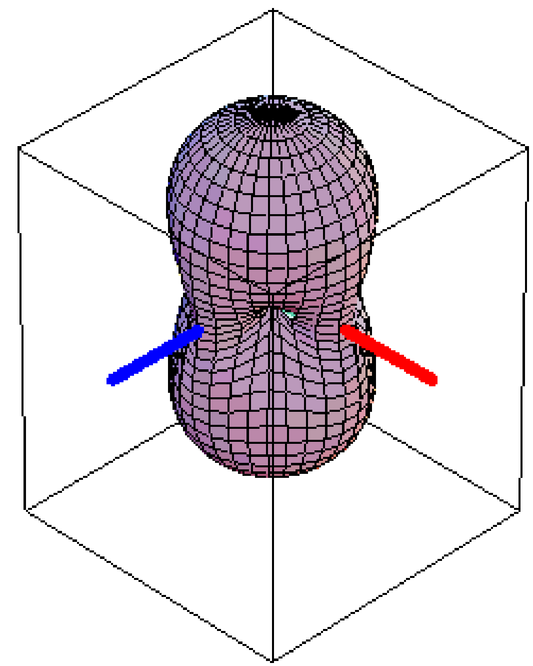
"×" polarization



"+" polarization



RMS sensitivity



A broad antenna pattern

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

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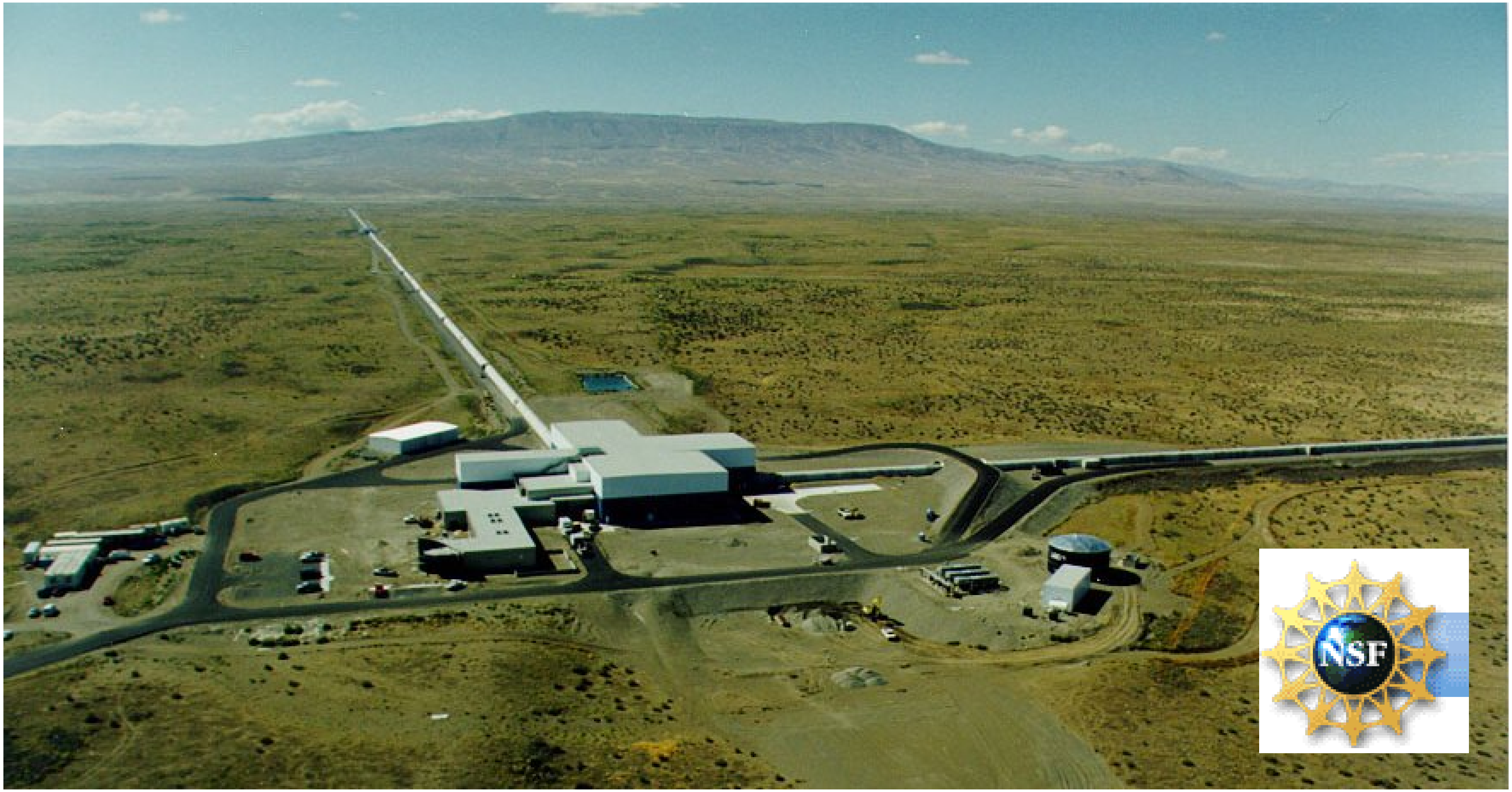
The LIGO Observatories

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 Hanford Observatory

LIGO Livingston Observatory

Located in a rural area of Livingston Parish east of Baton Rouge, Louisiana

One interferometer with 4 km arms

LIGO Science Education Center

Photo credit: Shawn Lani and Peter Richards, San Francisco explOratorium

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

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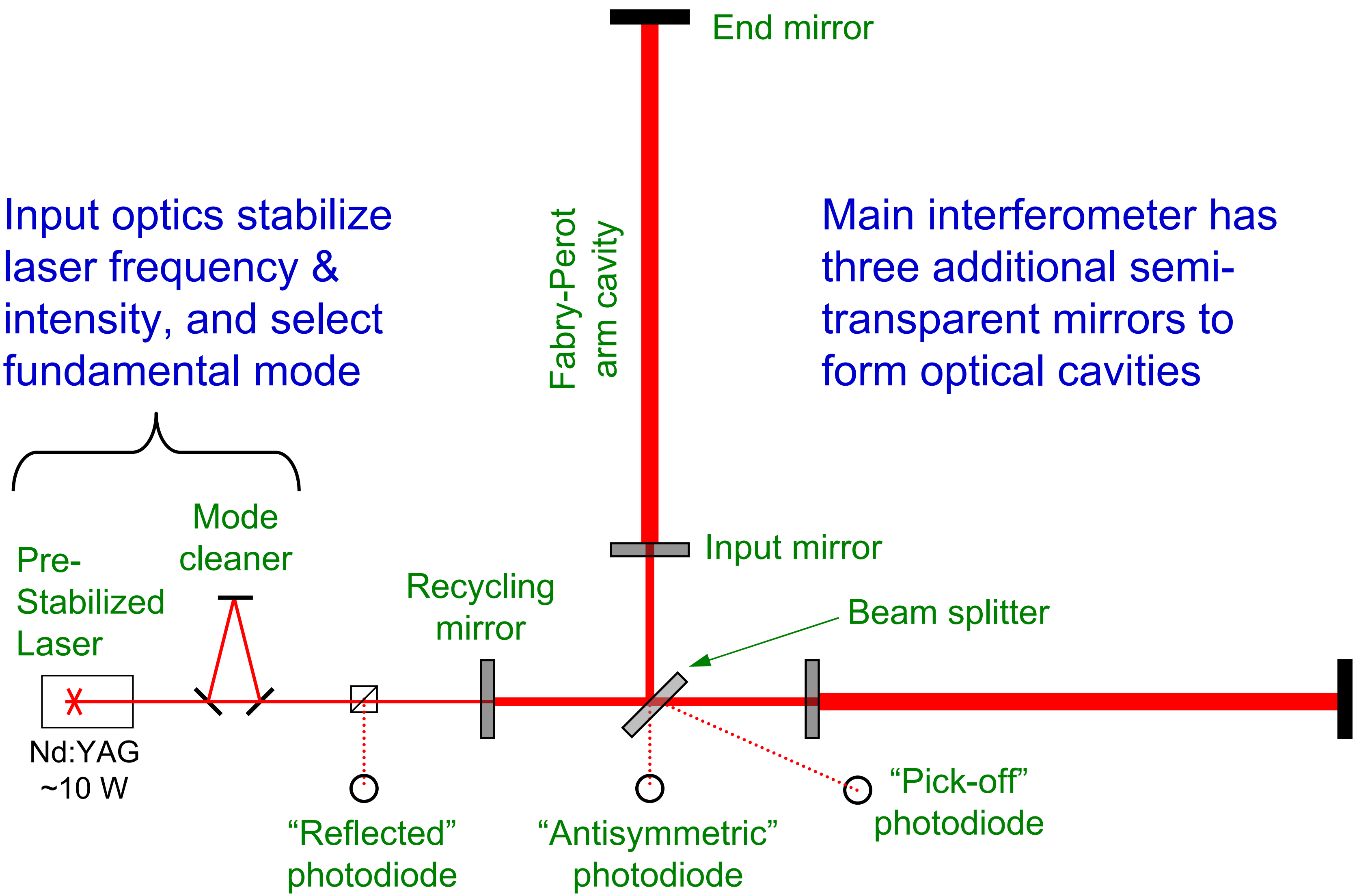
Optical Layout
(not to scale)

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

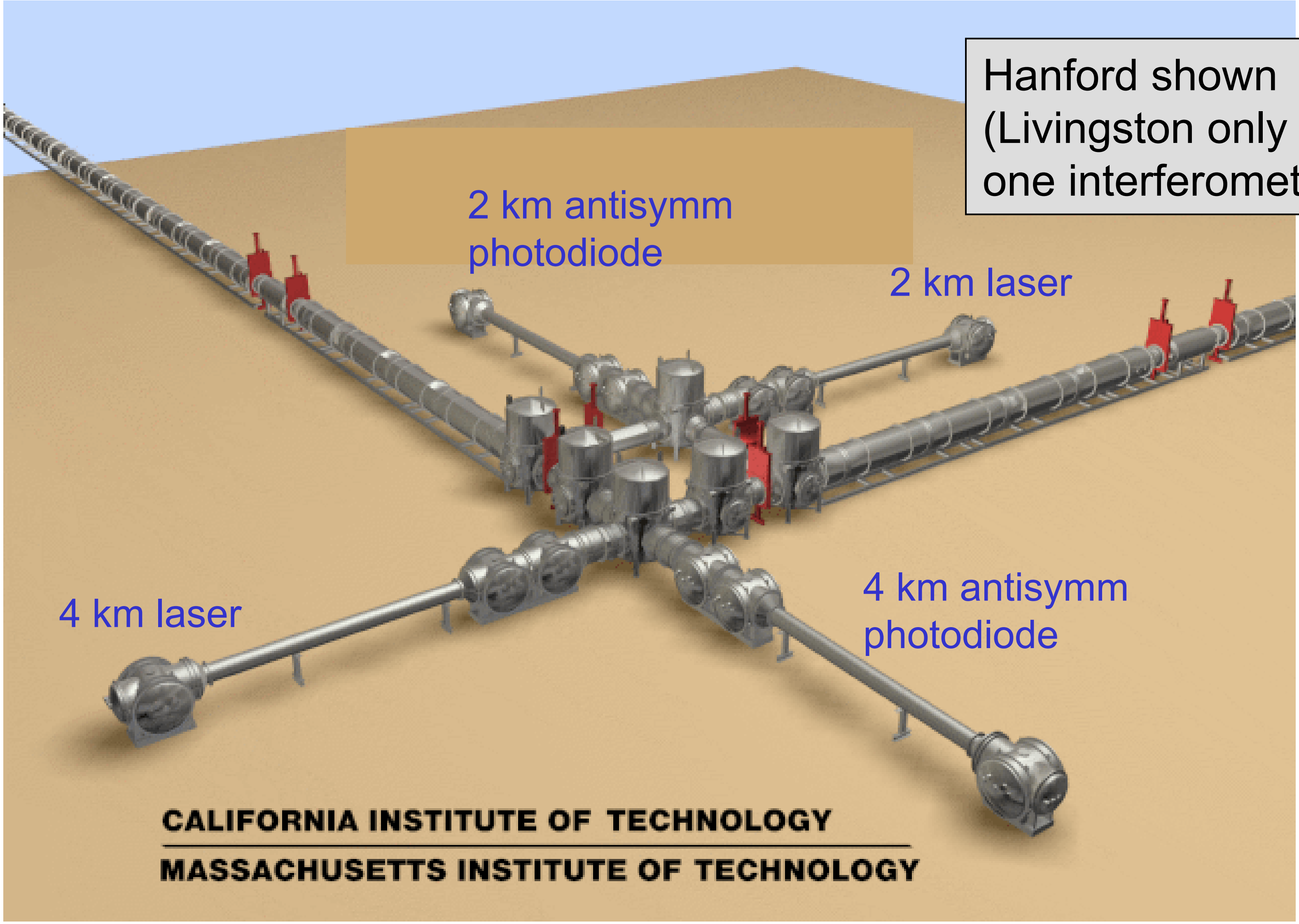
- Modulate phase of laser light at very high frequency
- Demodulate signals from photodiodes
- Disentangle contributions from different lengths, apply digital filters
- Feed back to coil-and-magnet actuators on various mirrors

Arrange for destructive interference at "antisymmetric port"

There are many other servo loops besides length control !

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

Vacuum System



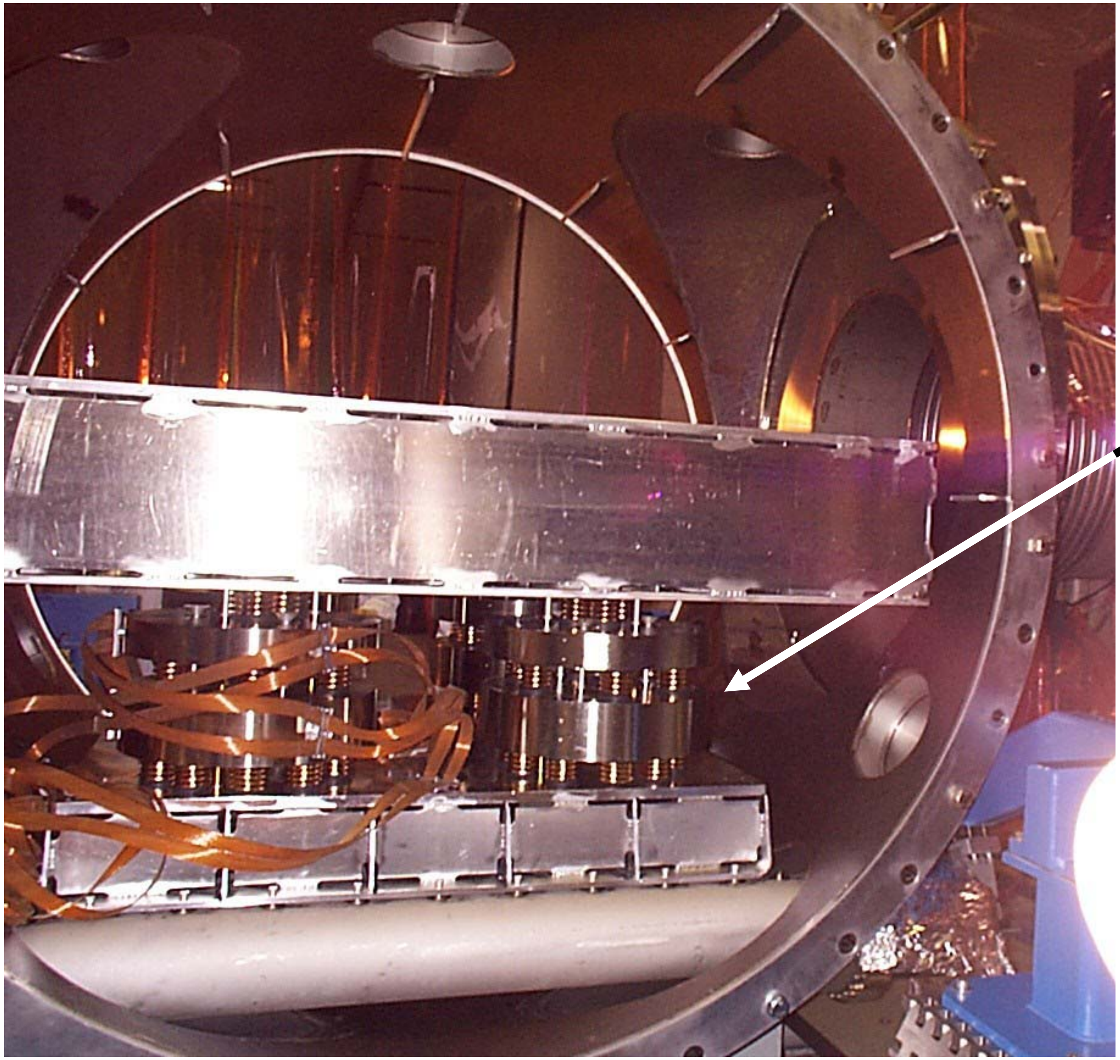
Hanford shown
(Livingston only has
one interferometer)

Inside the Enclosure for the Arms

Vacuum System

A Mirror *in situ*

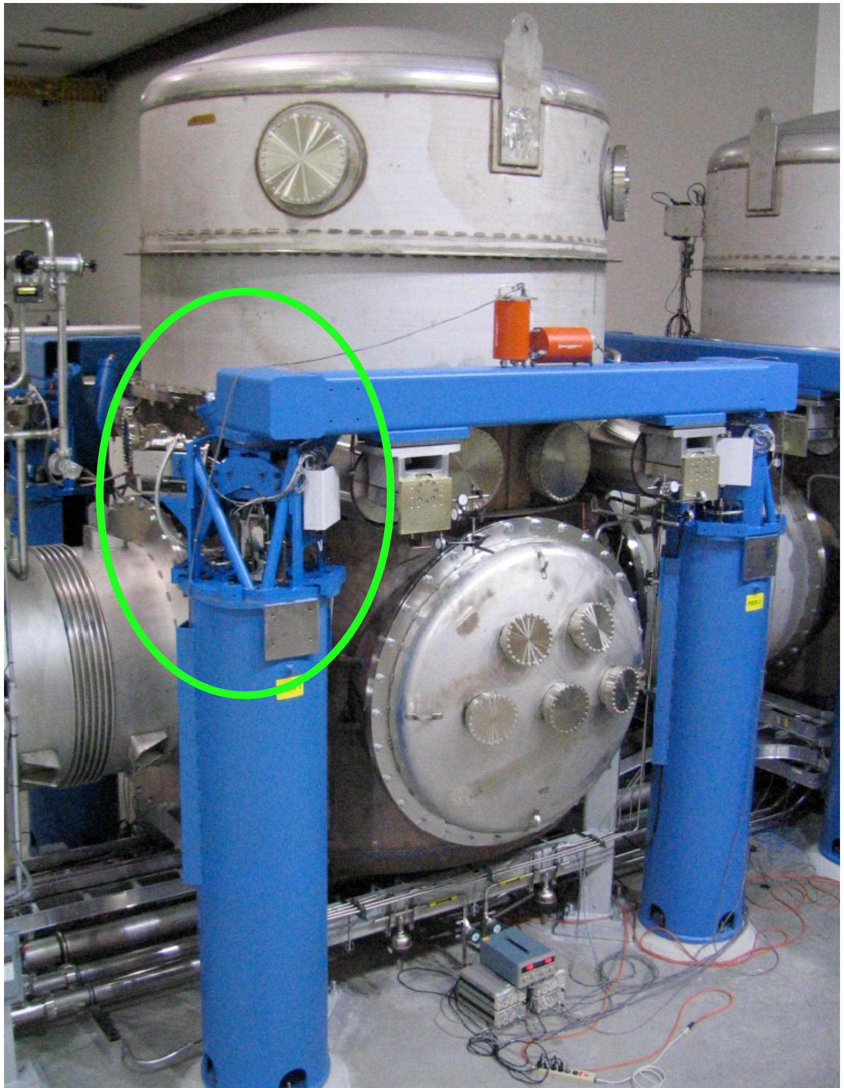
Vibration Isolation



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

Wire suspension used for mirrors provides additional isolation

Active Seismic Isolation at LLO

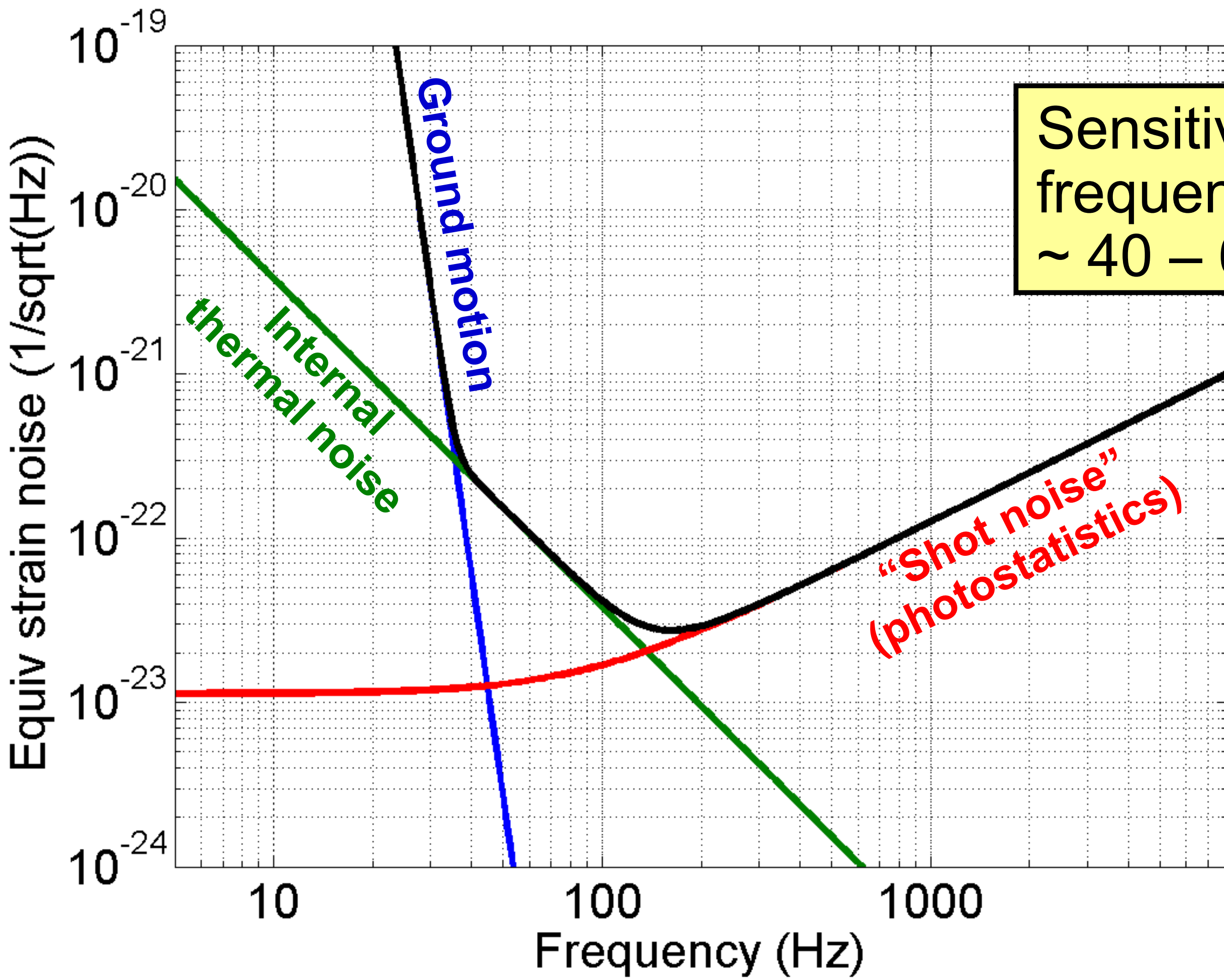


Hydraulic external pre-isolator (HEPI)

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

Limiting Fundamental Noise Sources



Sensitive frequency range: ~ 40 – 6000 Hz

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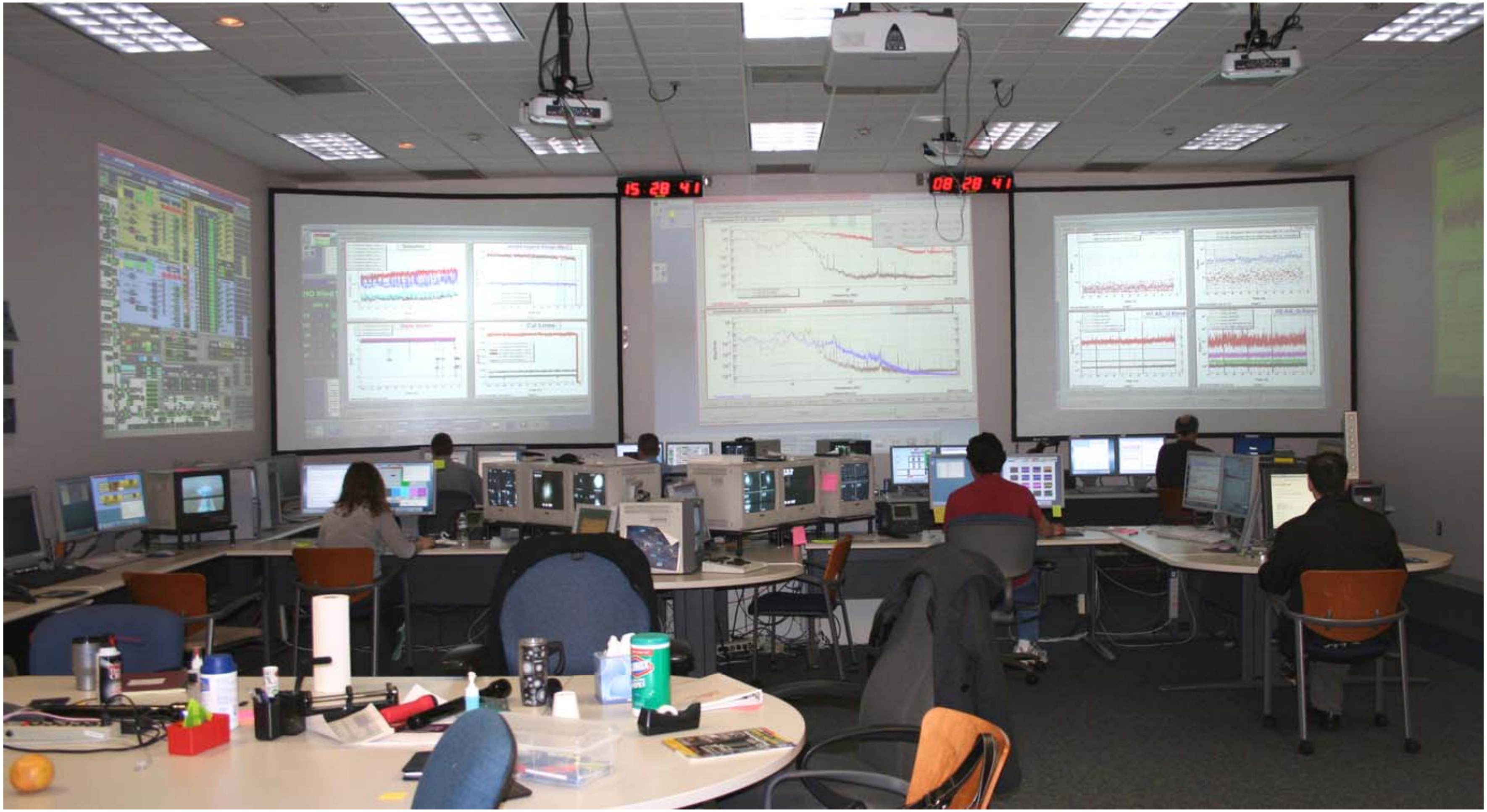
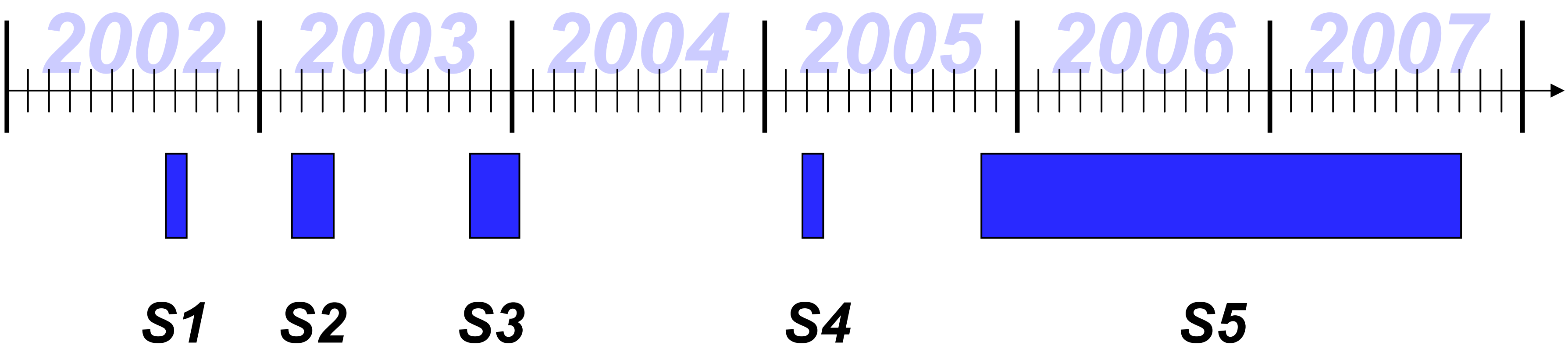
Data Collection

Shifts manned by resident "operators" and visiting "scientific monitors"



LIGO Science Runs



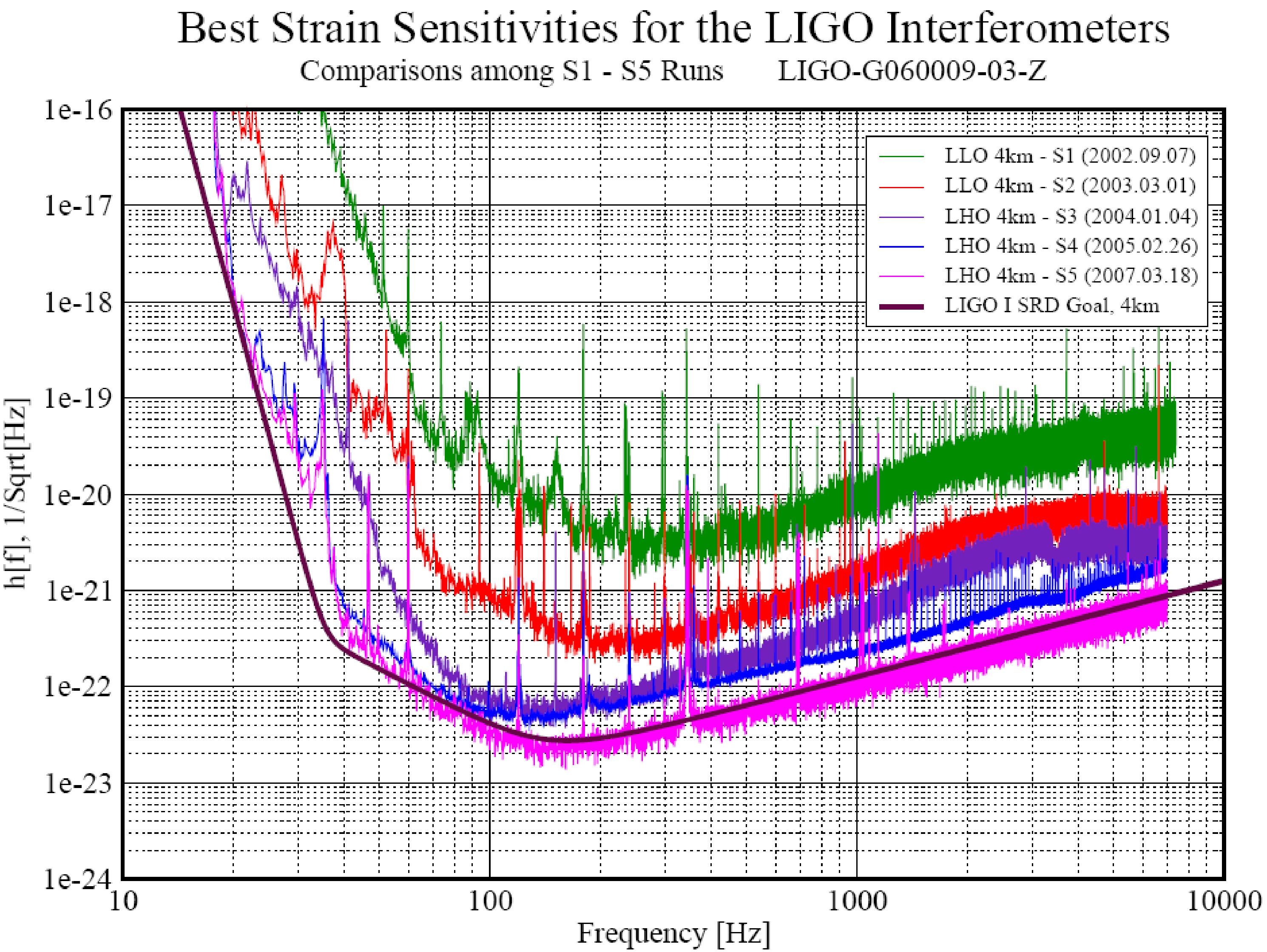
Duty factors:

	S1	S2	S3	S4	S5
H1	59 %	74 %	69 %	80 %	78 %
H2	73 %	58 %	63 %	81 %	79 %
L1	43 %	37 %	22 %	74 %	67 %

Active seismic isolation

368.8 live days
of triple-coincident observation time

Best Interferometer Sensitivity, Runs S1 through S5



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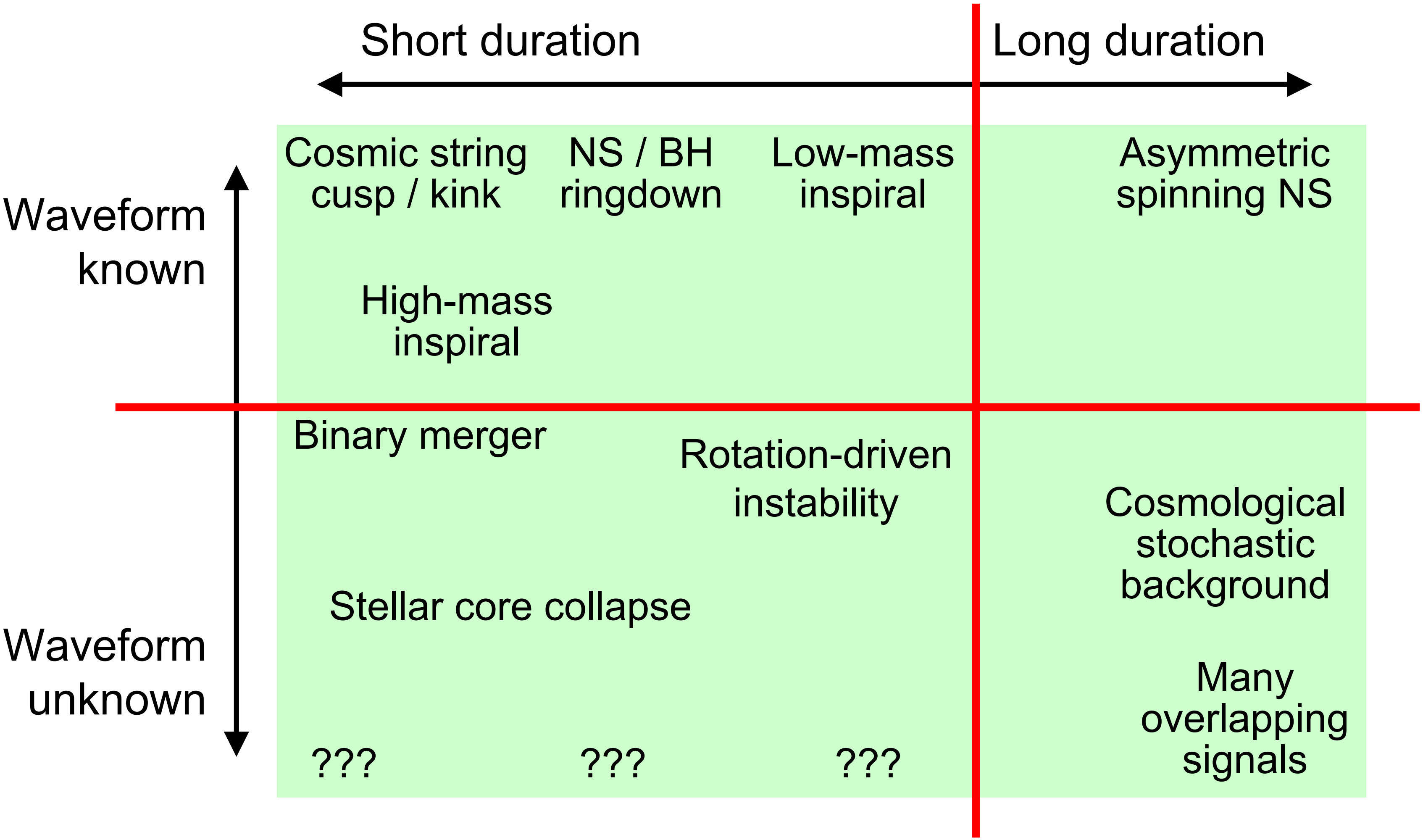
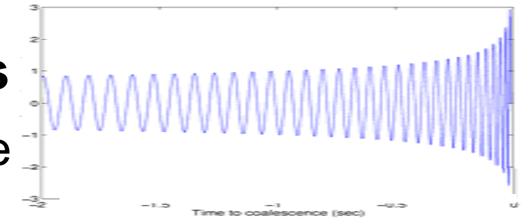
The Menu for Earthbound GW Detectors



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 *[Class Quant Grav **24**, 5343 (2007)]*

- 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 $\sim 0.25\ M_{\odot}$ at the distance of the Virgo Cluster

S5 prospects (analysis in progress)

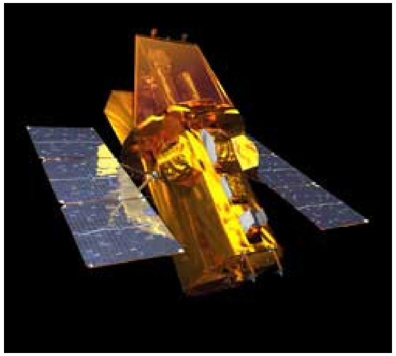
Factor of ~2 better amplitude sensitivity, and much longer observation time

Also doing coherent network analysis, and extending frequency band

Externally Triggered Searches

Search for gravitational wave inspirals or bursts 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



Swift

Analyzed 39 GRBs during runs S2+S3+S4 *[Preprint arXiv:0709.0766]*

Looked for quasiperiodic GW signals in tail of SGR 1806–20 hyperflare of Dec. 2004 *[PRD **76**, 062003 (2007)]*

During S5: over 200 GRBs, many SGR flares, etc.

- Doing or developing searches for GW signals associated with these

GRB 070201

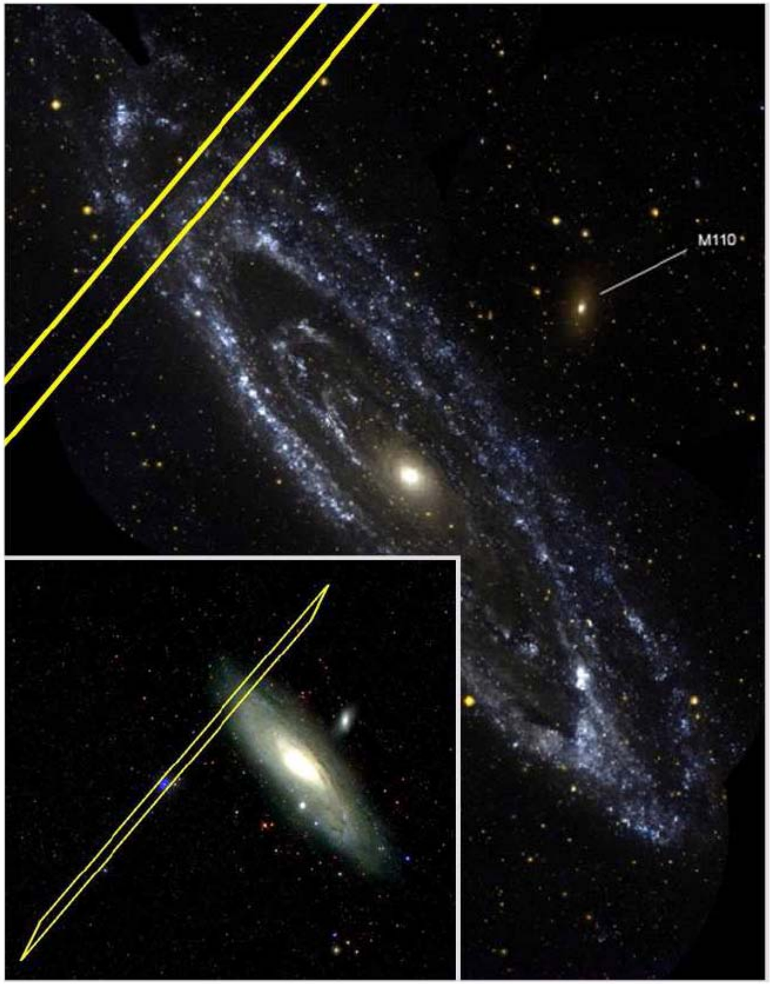


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

Short, hard gamma-ray burst

A leading model for short GRBs: binary merger involving a neutron star

Position (from IPN) is consistent with being in M31

LIGO H1 and H2 were operating

Result from LIGO data analysis:
No plausible GW signal found; therefore very unlikely to be from a binary merger in M31

[Preprint arXiv:0711.1163]

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

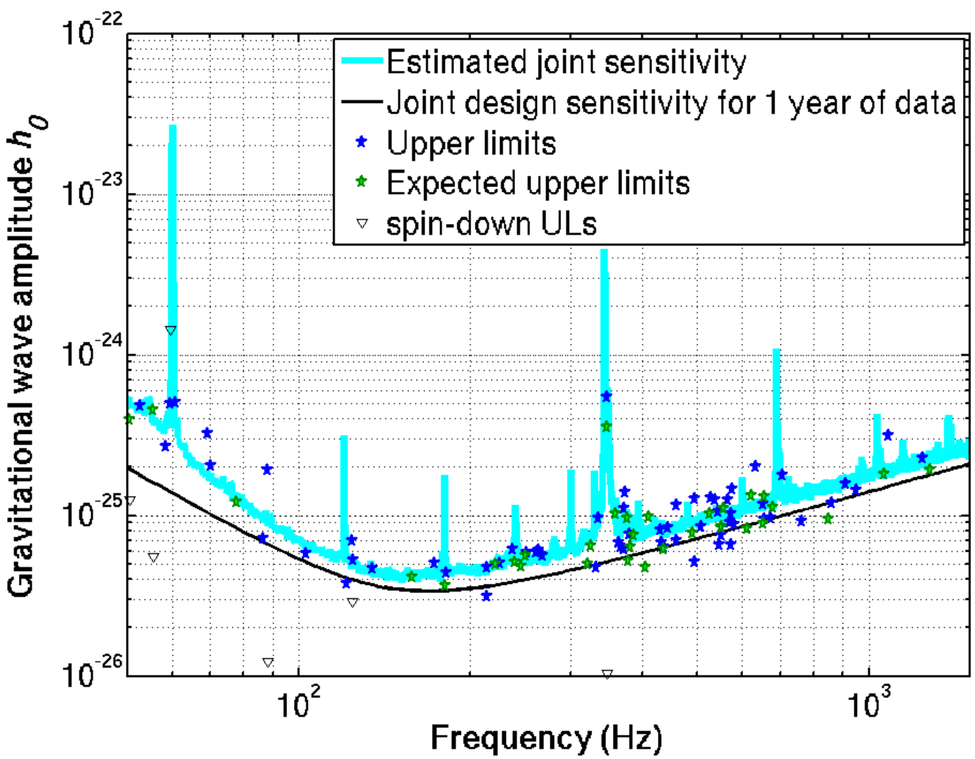
Demodulate data at twice the spin frequency

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.

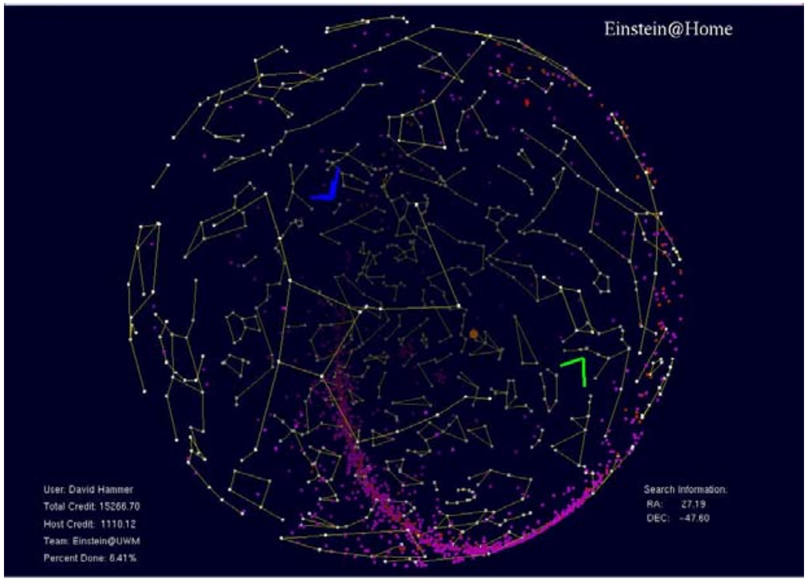
All-sky coherent search for *unknown* isolated periodic signals

- Computationally very expensive!
- S4 search using semi-coherent methods: *[PRD in press, preprint arXiv:0708.3818]* placed upper limits on strain amplitude as low as 4×10^{-24}

Doing S5 search with a "hierarchical" approach

- Semi-coherent and coherent stages
- Main processing power provided by *Einstein@Home*

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

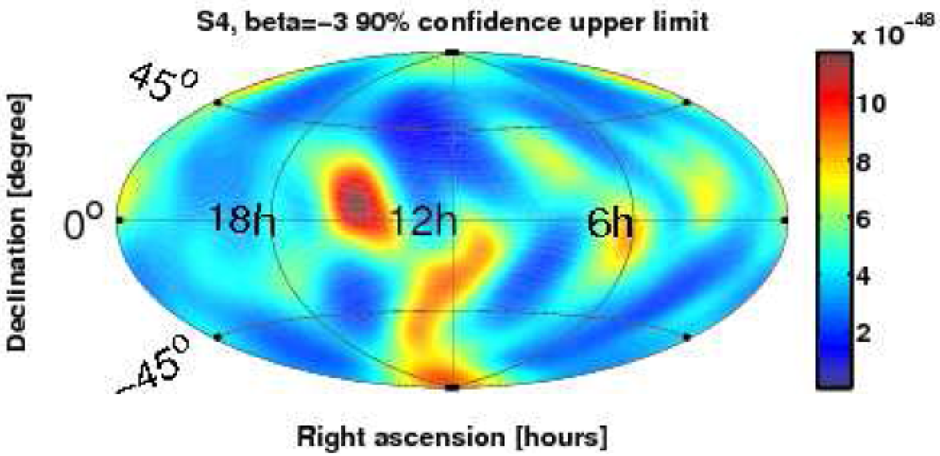
For flat spectrum, set upper limit on energy density in gravitational waves:

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

Or look for anisotropic signal:

*[PRD **76**, 082003 (2007)]*

S5 analysis in progress



Current Directions in Data Analysis

Preparing to be able to make a first detection

- Trying to find just the right level of conservatism
- "Blind injection" detection challenge

Strengthening ties with "mainstream" astrophysics

gwdaw12@mit

Connecting Gravitational Waves with Observational Astrophysics

December 13-16, 2007, Royal Sonesta Hotel, Cambridge, MA, USA

- Exploring prospects for more coordinated observations

Making optimal use of all of the available data

- Different combinations of detectors, coherent analysis…

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- ► LIGO
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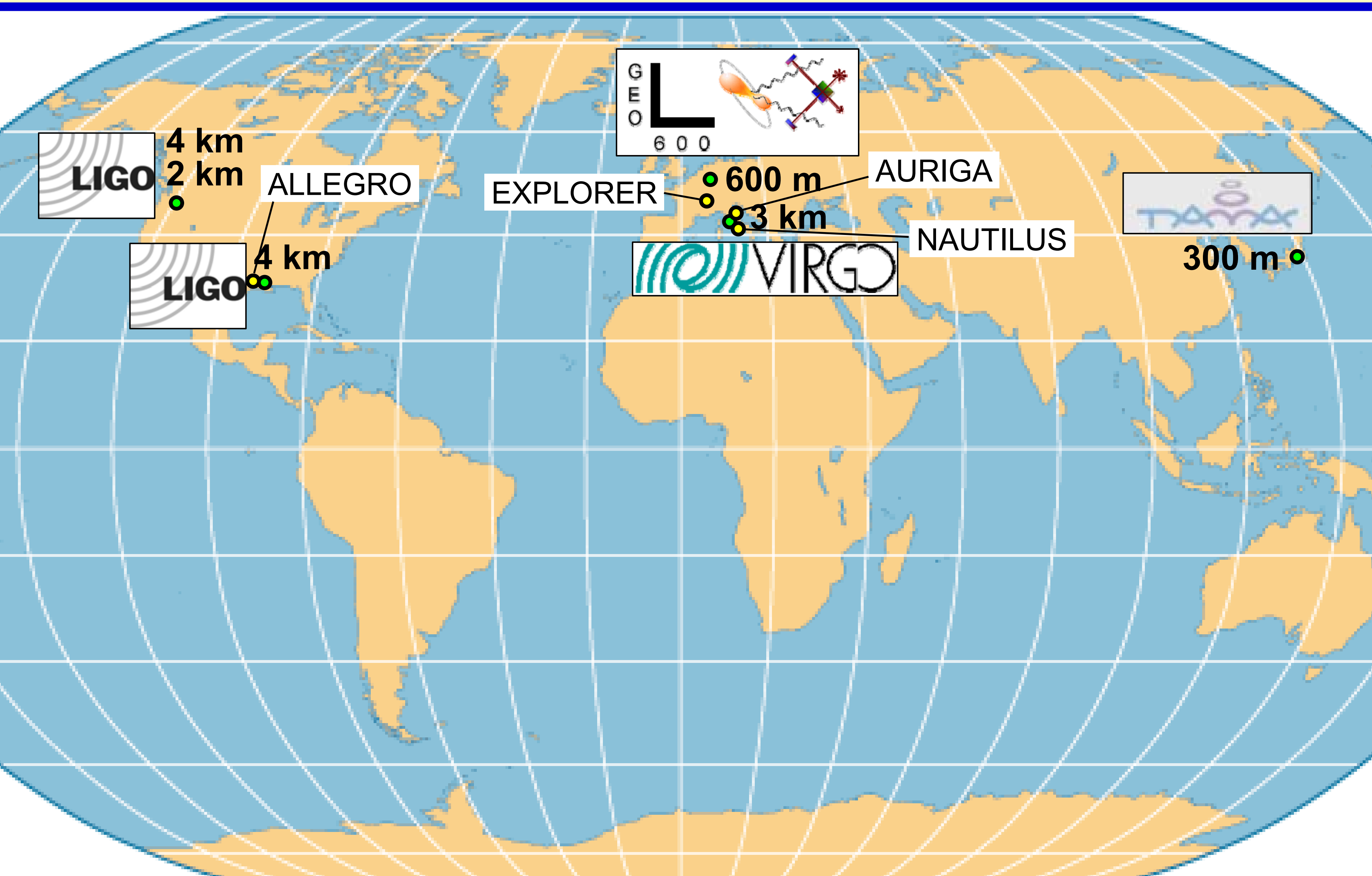
The Worldwide Network

Including •Bars

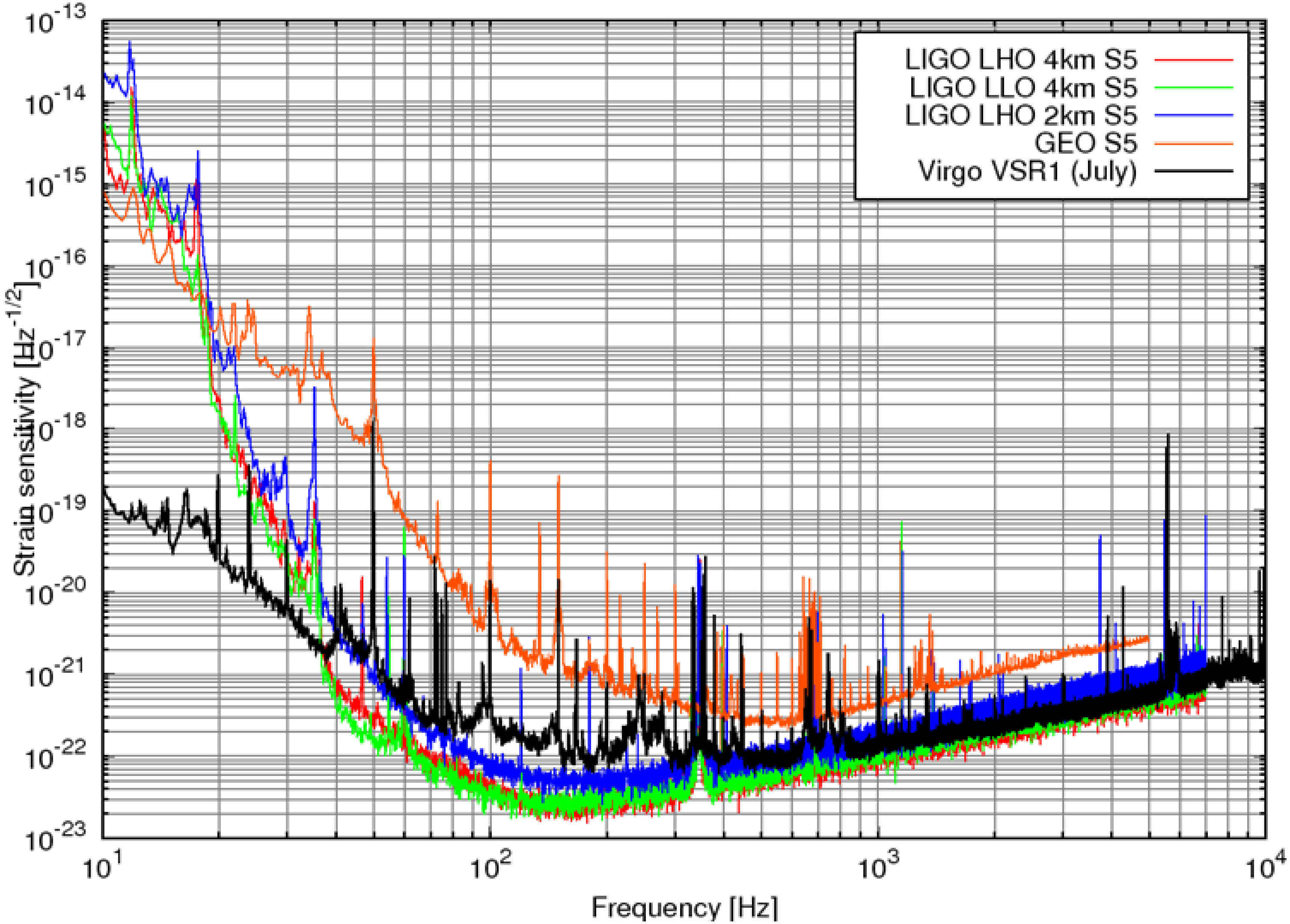


Virgo

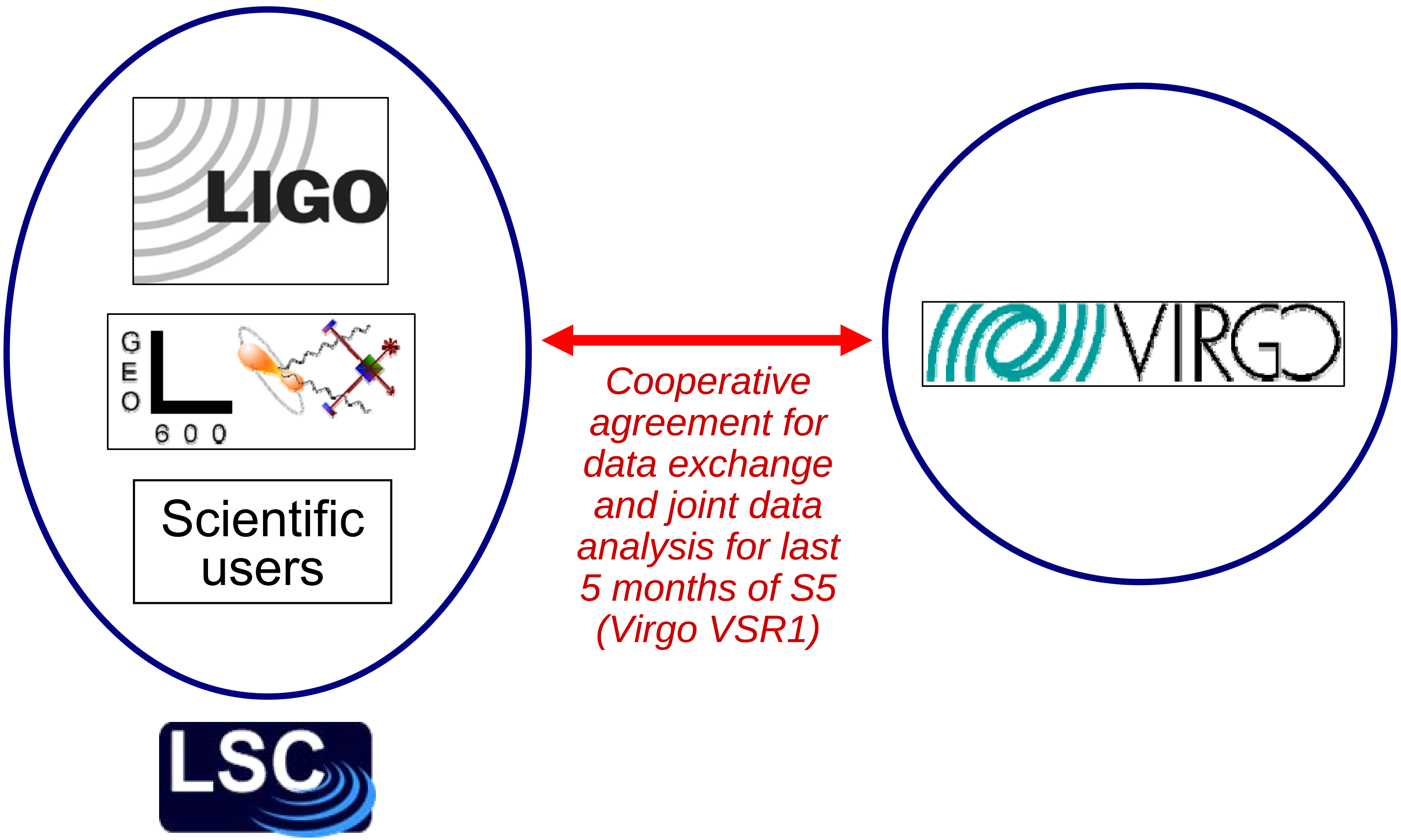
Generally similar to LIGO

GEO 600

Summer 2007 Performance of the Large Interferometers



Organization of the Projects



Life After S5: Detector Enhancements

Increase laser power to 35 W

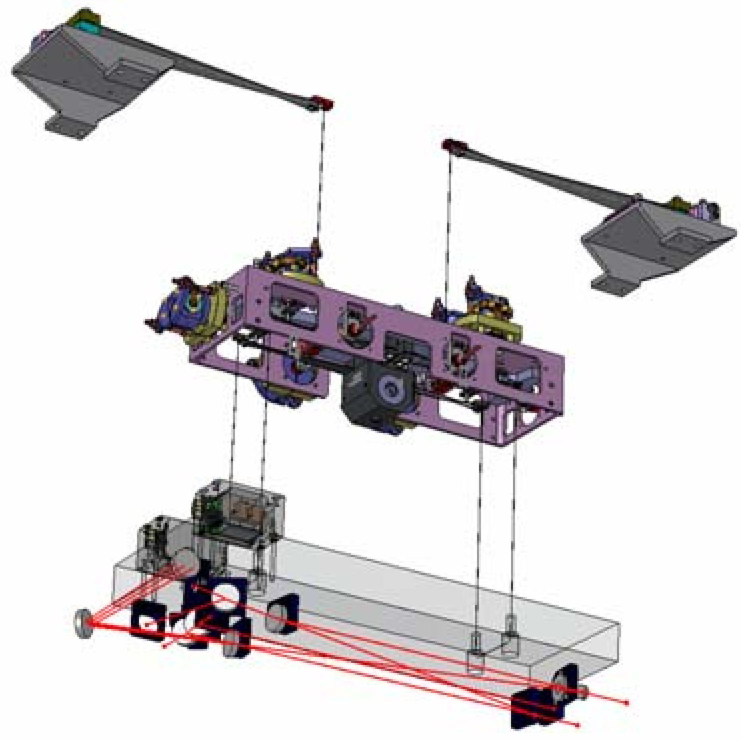
Requires new thermal compensation system

DC readout scheme

Photodetector in vacuum, suspended

Output mode cleaner

Active beam stabilization

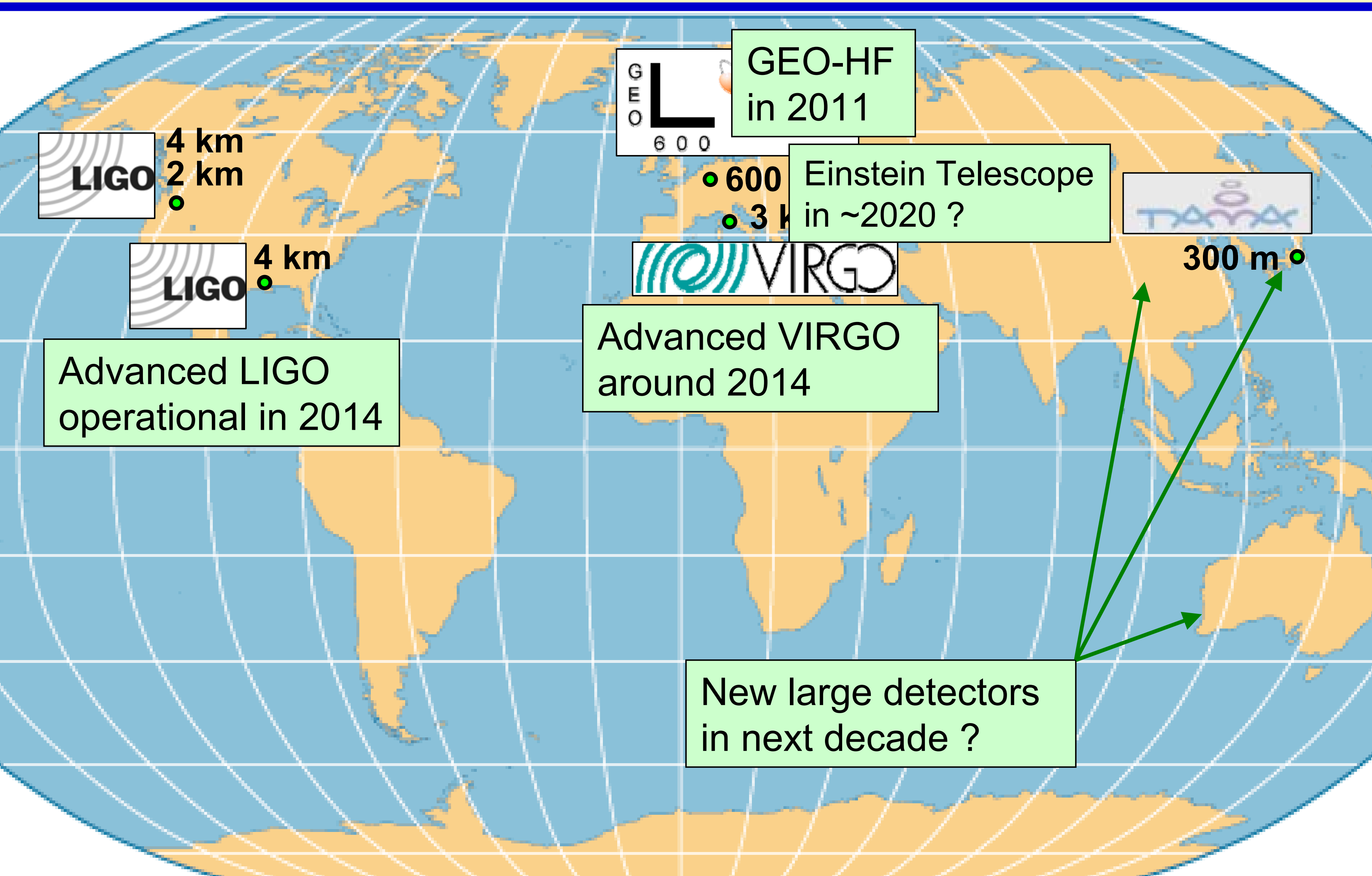


Aiming for a factor of ~2 sensitivity improvement

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

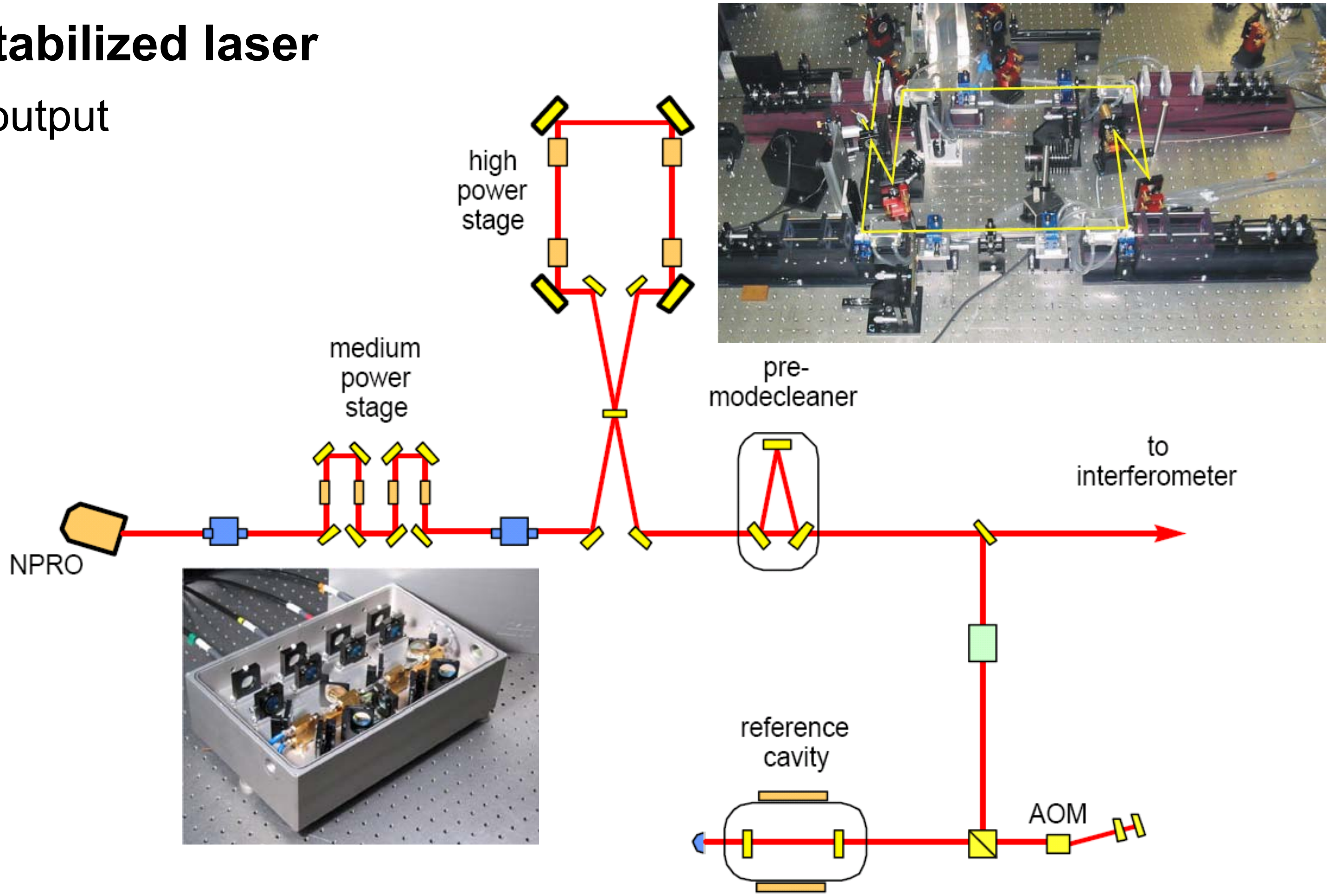


Advanced LIGO

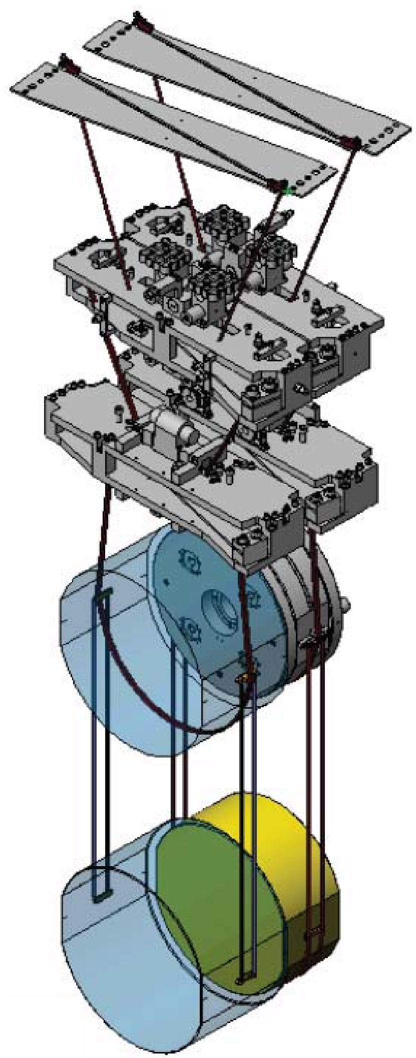
Completely new interferometers at same observatory sites

New pre-stabilized laser

180 W output



Advanced LIGO Mirrors



Fused silica, 40 kg

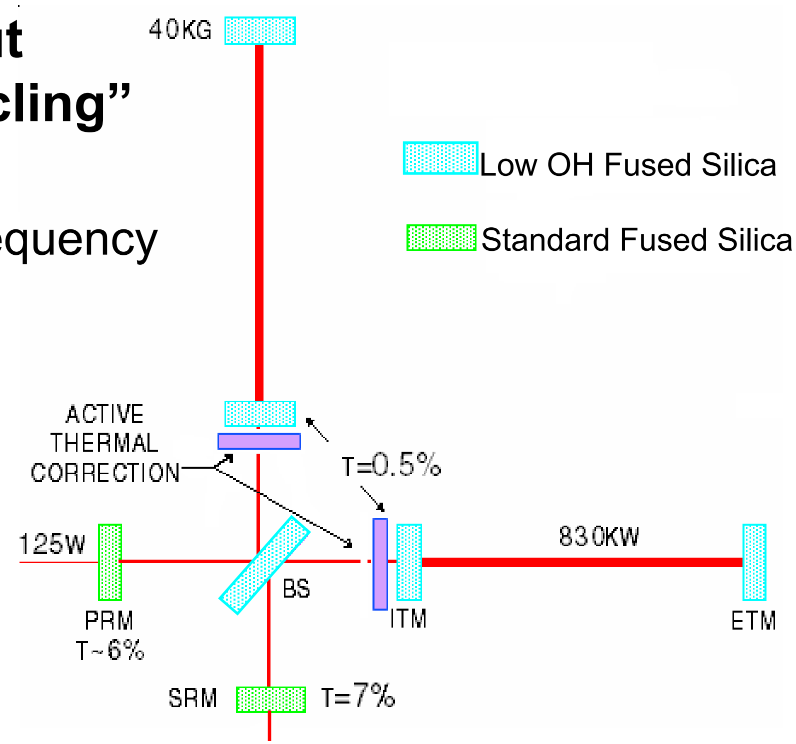
Hung by fused silica ribbons

Quadruple pendulum suspension

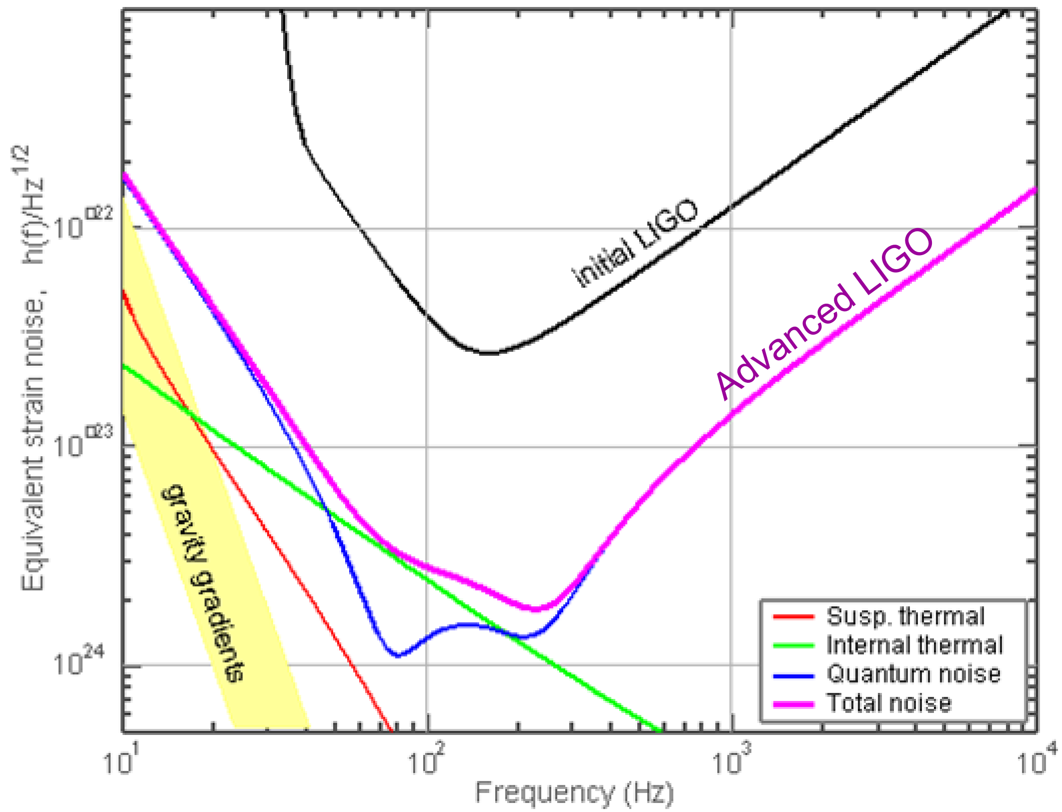
With reaction masses for quiet actuation

New optical layout with “signal recycling”

Allows tuning of sensitivity vs. frequency



Advanced LIGO Sensitivity



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

Also extends sensitive band to lower frequencies

In the pending appropriations bill for FY2008 start

Summary

The S5 run achieved the goal of collecting one year of triple-coincident data at the design sensitivity level for the LIGO detectors

Many searches for GW signals have been completed and more are underway

The worldwide network of detectors is being used in a unified way

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

End