Gravitational Wave Astronomy II

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on behalf of the LIGO Scientific Collaboration
http://www.ligo.org

CERN
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LIGO-G060514-00-Z

Overview

- Day 1 : Introduction. Sources. Detectors.
  - » An introduction to gravitational wave astronomy
  - » What are gravitational waves
  - » Sources
  - » Brief survey of detectors: bars, ground-based interferometers (each with one or two highlights), LISA
- Day 2 : Ground-based interferometery
  - » Interferometric detectors
    - – LIGO, GEO, Virgo
  - » Some topics in commissioning: the path to design sensitivity
  - » Science mode running with LIGO, GEO and TAMA
- Day 3 : Data analysis. Future detectors.
  - » Search methods
  - » Analyses from science runs for inspiral, burst, stochastic and continuous wave sources
  - » Advanced LIGO

LIGO machines

- Some installations and subsystems
  - » Vacuum chambers
  - » Seismic isolation
  - » Laser
  - » Core optics, suspensions and actuation systems
- Give an idea of some of the problems faced in bringing the machines to design sensitivity
  - » Control systems
  - » calibration
  - » Noise hunting

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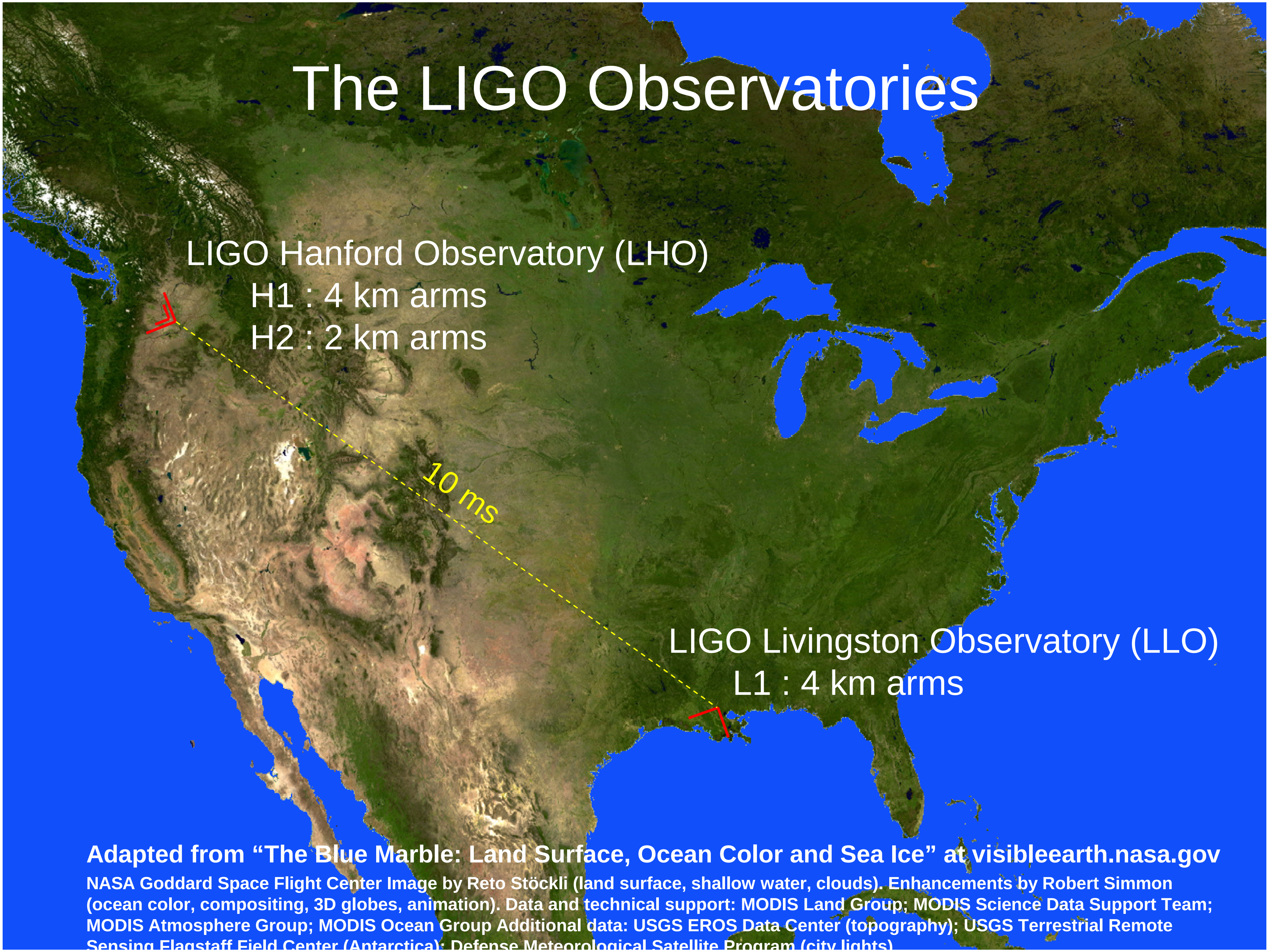
LIGO sites

LIGO (Washington)
(4km and 2km)

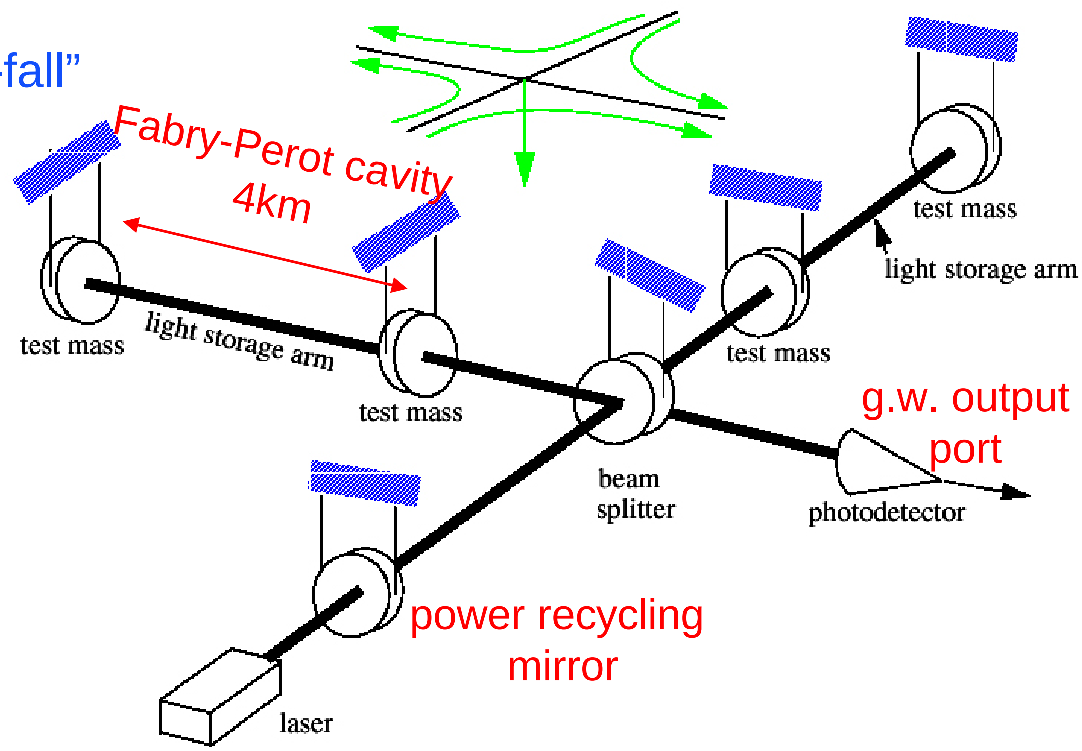
LIGO (Louisiana)
(4km)

Funded by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 500 LIGO Scientific Collaboration members worldwide.


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).

Gravitational wave detection

- Suspended Interferometers
  - » Suspended mirrors in "free-fall"
  - » Michelson IFO is "natural" GW detector
  - » Broad-band response (~50 Hz to few kHz)
  - » Waveform information (e.g., chirp reconstruction)



LIGO design length sensitivity: 10^{-18}m

Evacuated Beam Tubes Provide Clear Path for Light

Vacuum required:
$<10^{-9}$ Torr

Evacuated Beam Tubes Provide Clear Path for Light

Bakeout facts:

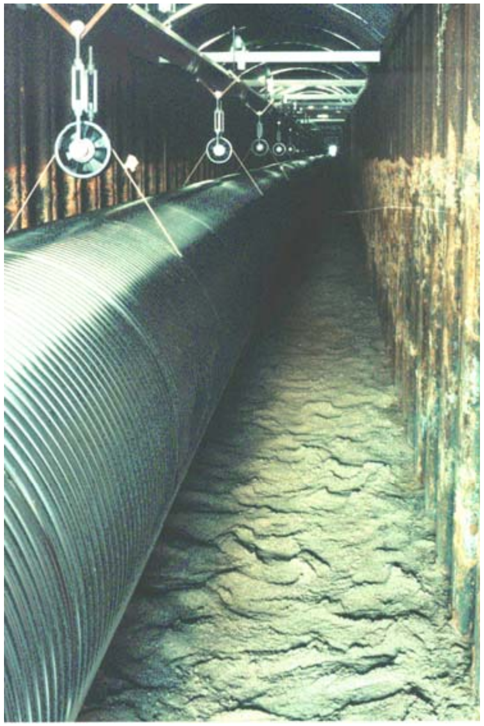
- **4 loops to return current, 1” gauge**
- **1700 amps to reach temperature**
- **bake temp 140 degrees C for 30 days**
- **400 thermocouples to ensure even heating**

- **each site has 4.8km of weld seams**
- **full vent of vacuum: ~ 1GJ of energy**

Vacuum required:
$<10^{-9}$ Torr

GEO, Virgo vacuum

Virgo



GEO

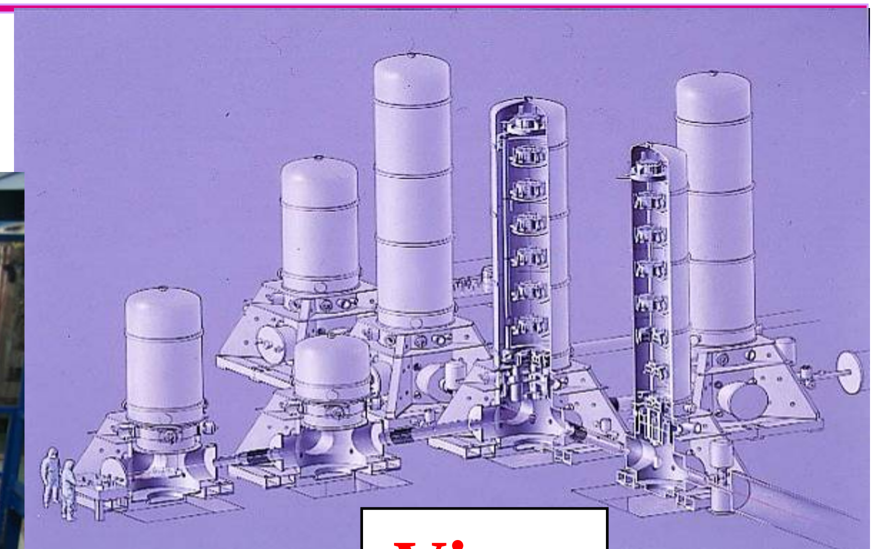
Vacuum chambers provide quiet homes for mirrors

The view inside the Corner Station

Standing at the 4k vertex: beam splitter

GEO, Virgo corner stations

GEO



Virgo

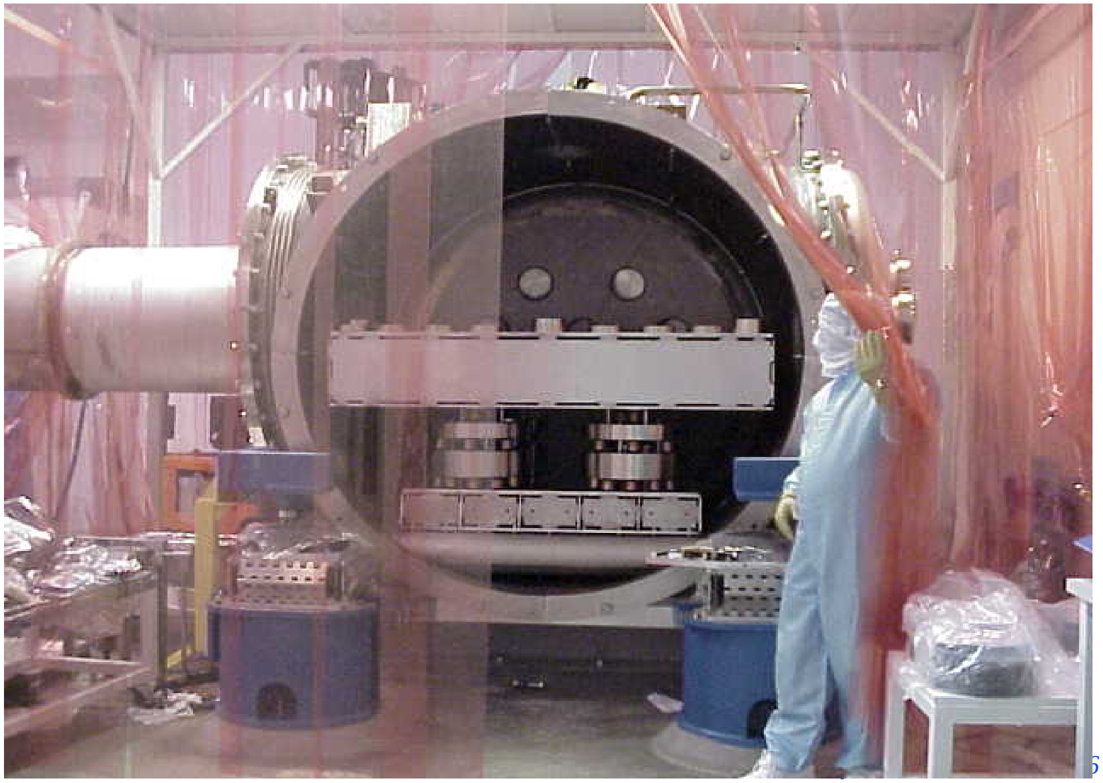
Seismic Isolation – Springs and Masses

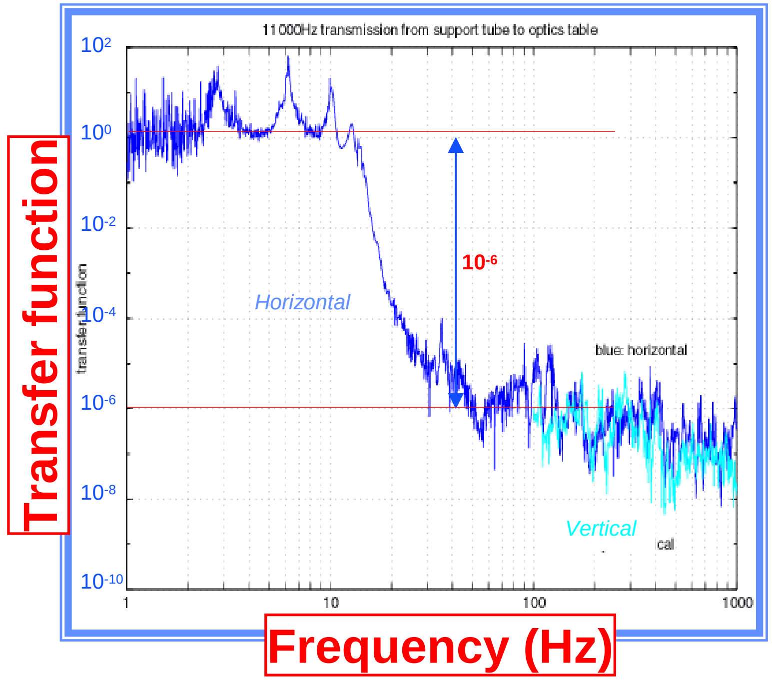
damped spring
cross section

LIGO detector facilities

Seismic Isolation

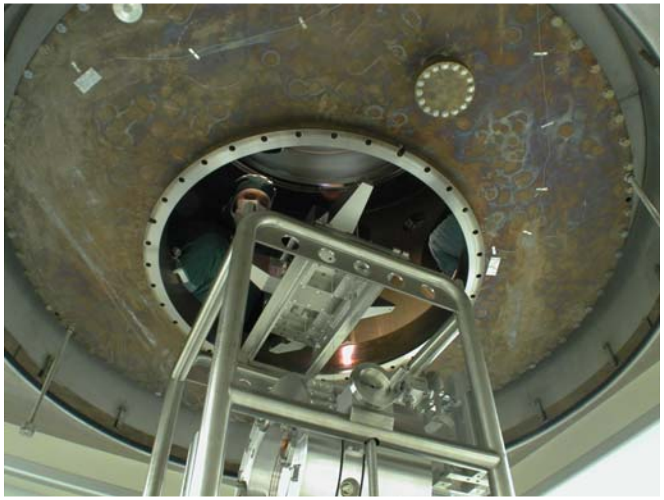
- Multi-stage (mass & springs) optical table support gives 10^6 suppression
- Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz

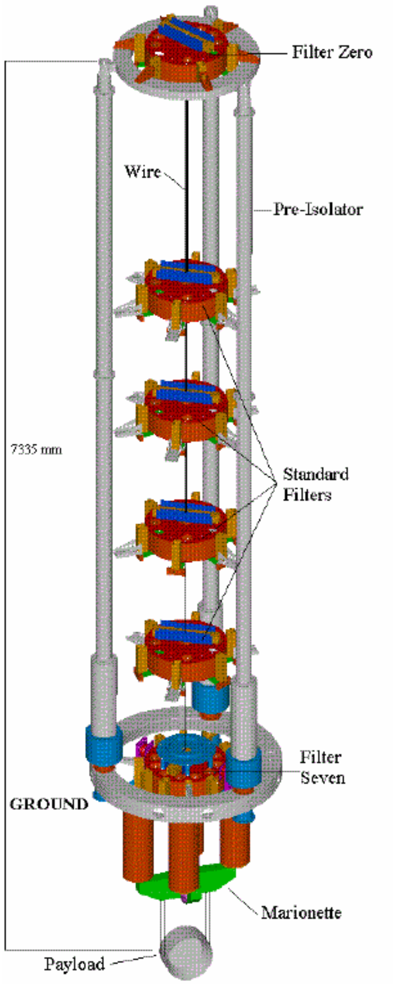


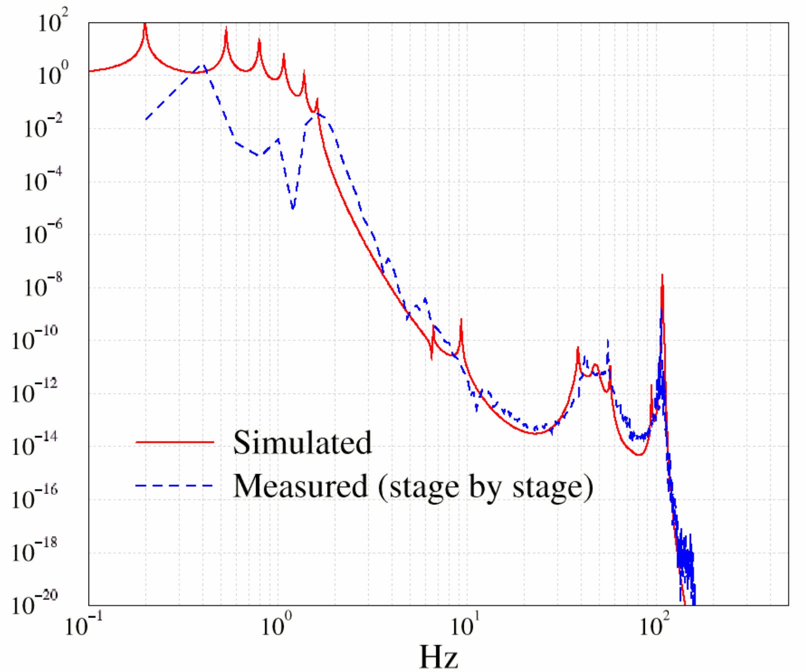


VIRGO Seismic Isolation and Suspensions

“Long Suspensions”
- **inverted pendulum**
- **five intermediate filters**

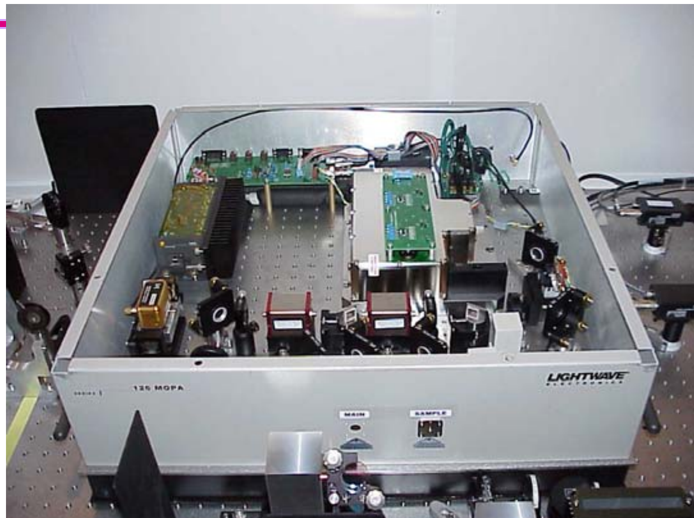




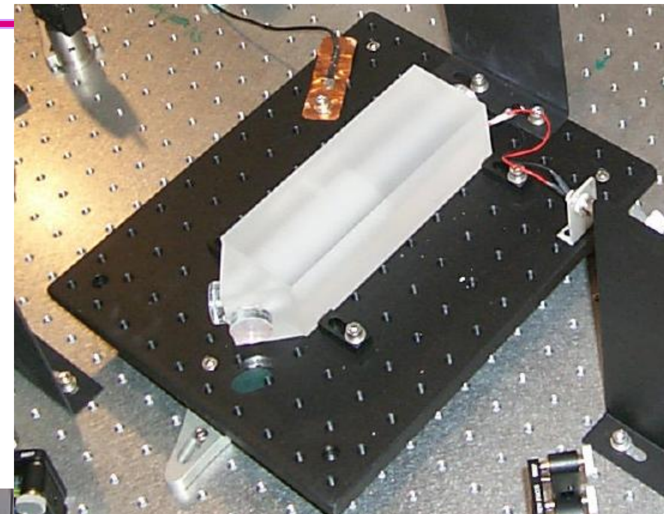


Suspension vertical transfer function measured and simulated (prototype)

All-Solid-State Nd:YAG Laser



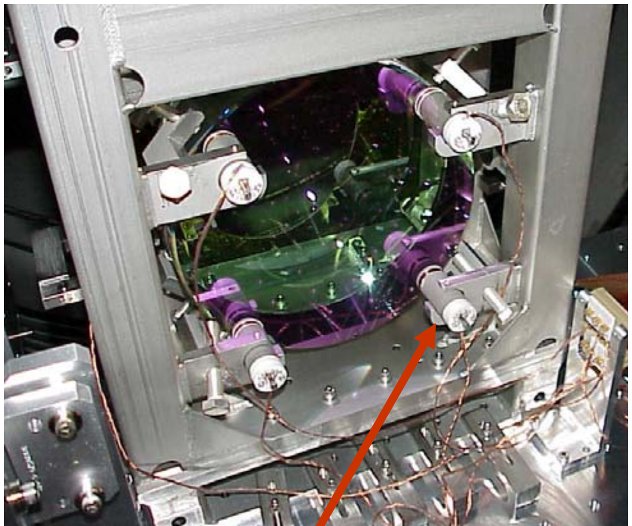
Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)

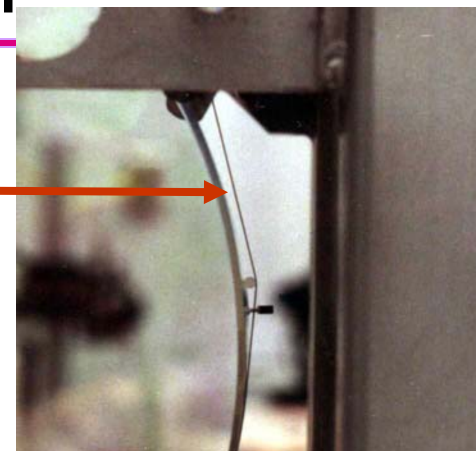


Cavity for
defining beam geometry,
joint development with
Stanford

Frequency reference
cavity (inside oven)

Core optics suspension and control



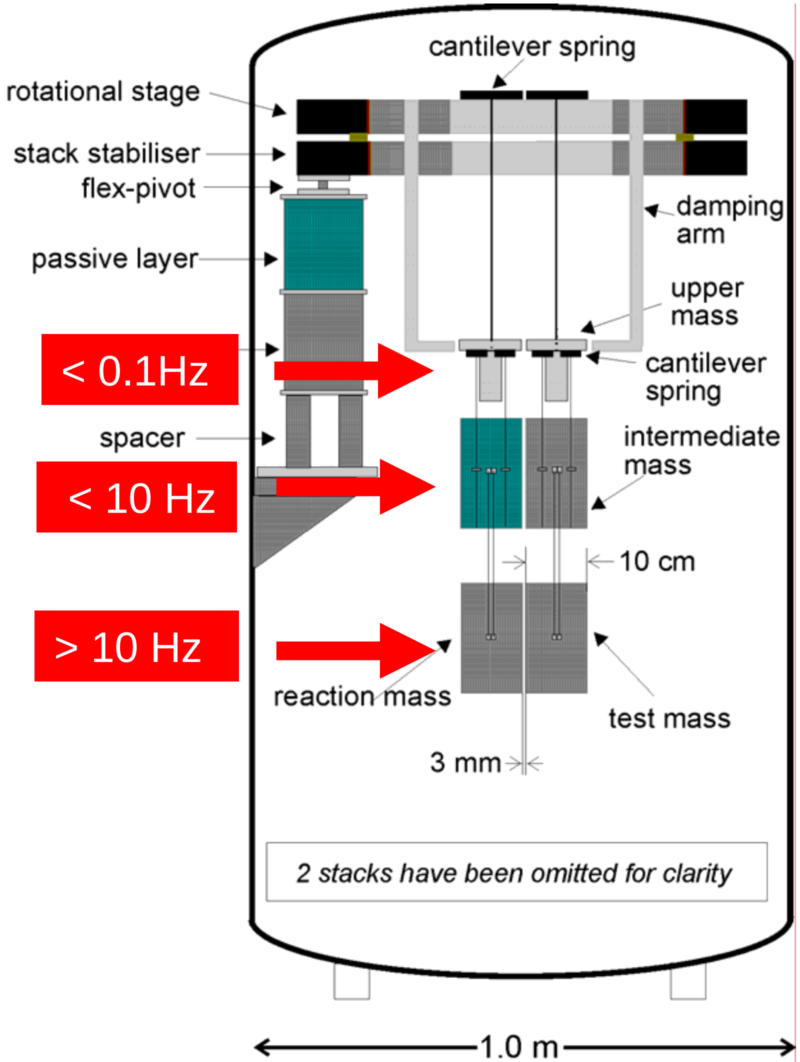


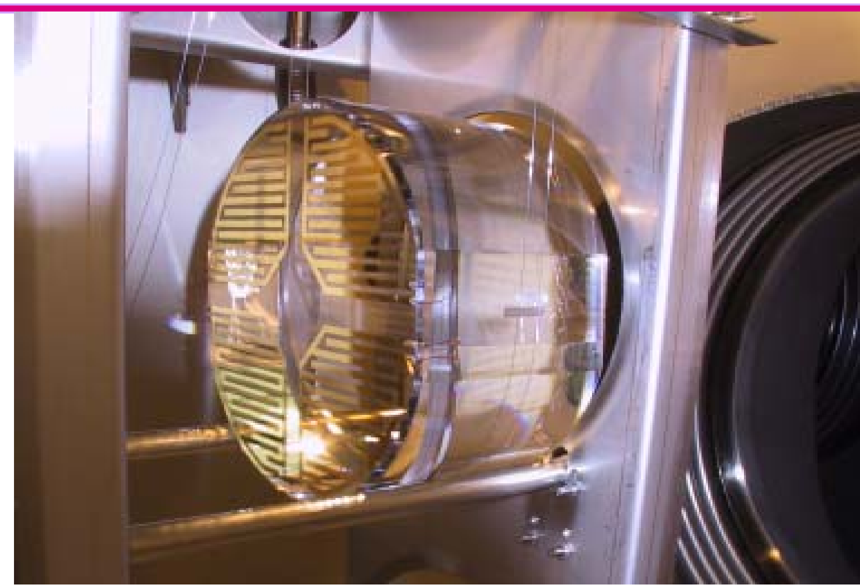
Optics suspended as simple pendulums

Shadow sensors & voice-coil actuators provide damping and control forces

Mirror is balanced on 30 micron diameter wire to 1/100th degree of arc

GEO Michelson length control

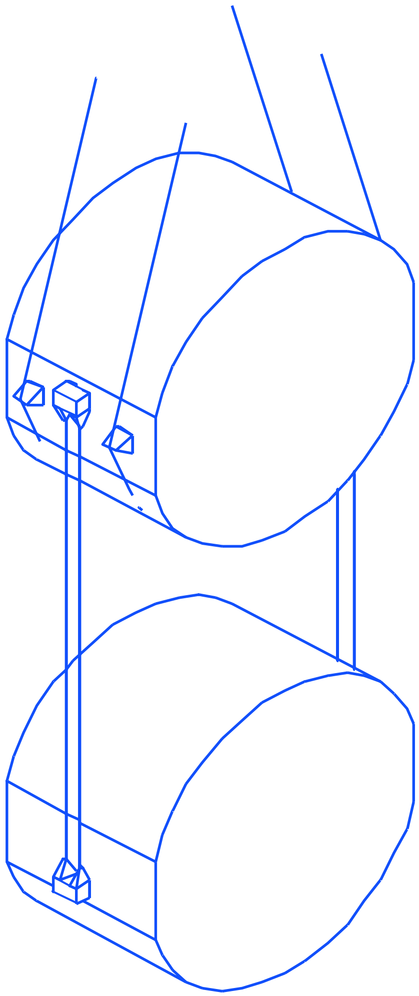


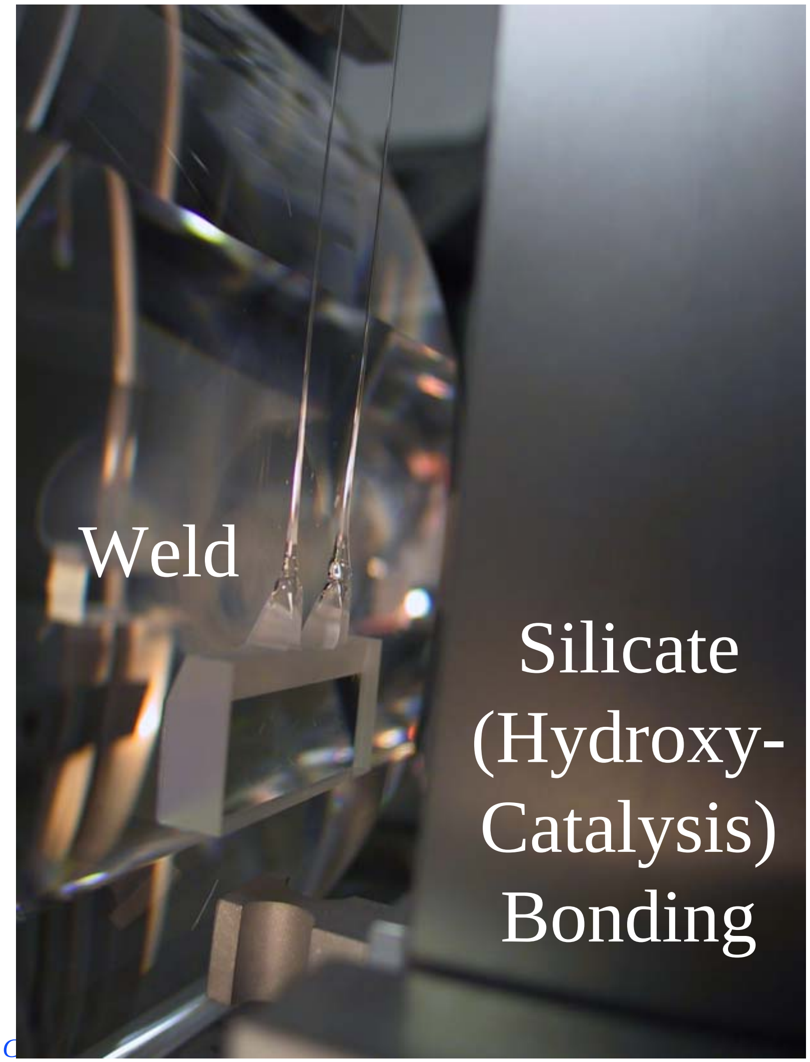


Reaction Pendulum:

- 3 coil-magnet actuators at intermediate mass, range ~ 100µm
- Electrostatic actuation on test mass bias 630V, range 0-900V= 3.5µm

GEO Thermal Noise / Monolithic Suspension





LIGO machines

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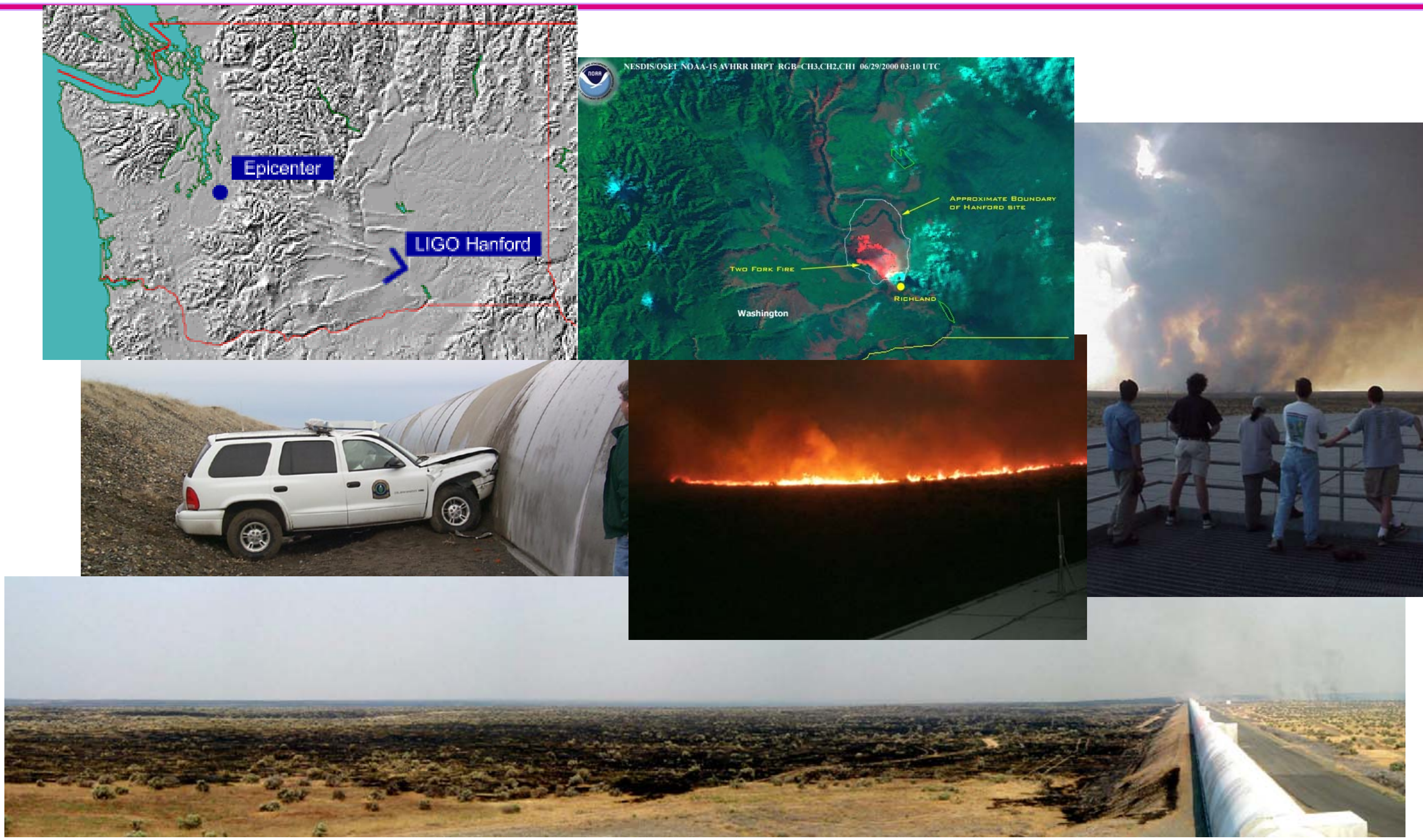
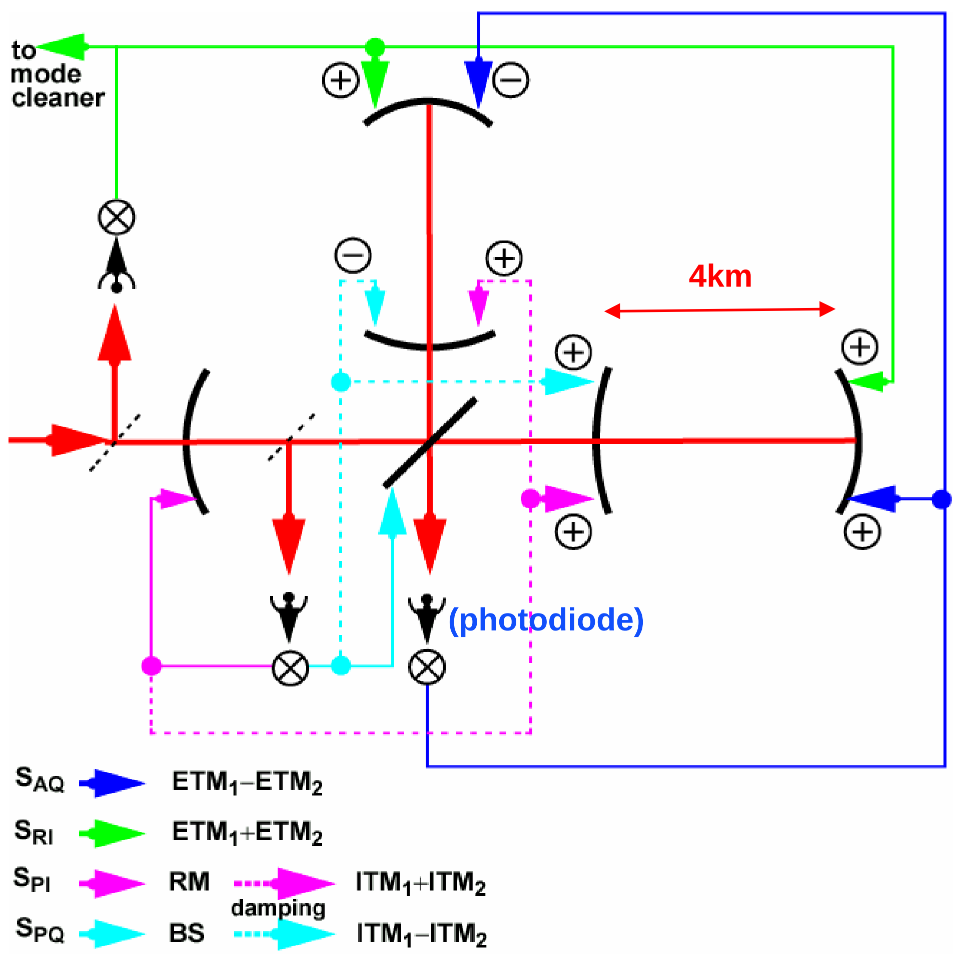
The road to design sensitivity…



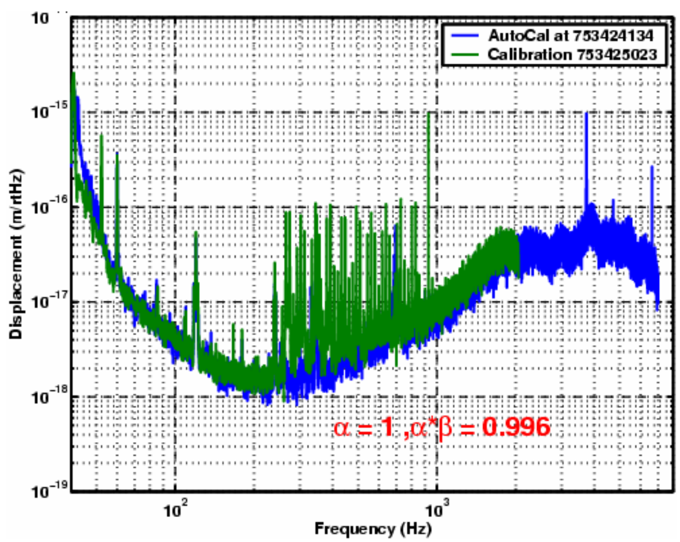
Interferometer length control system

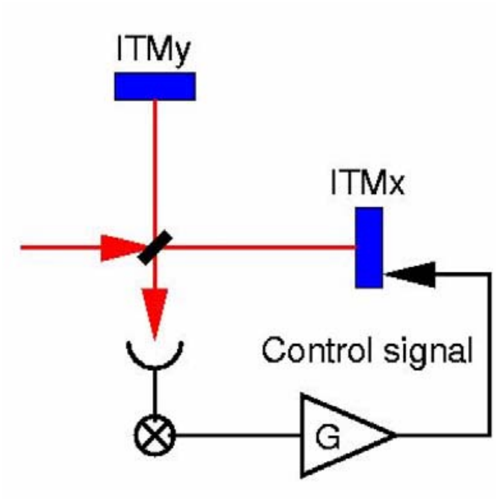


- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition

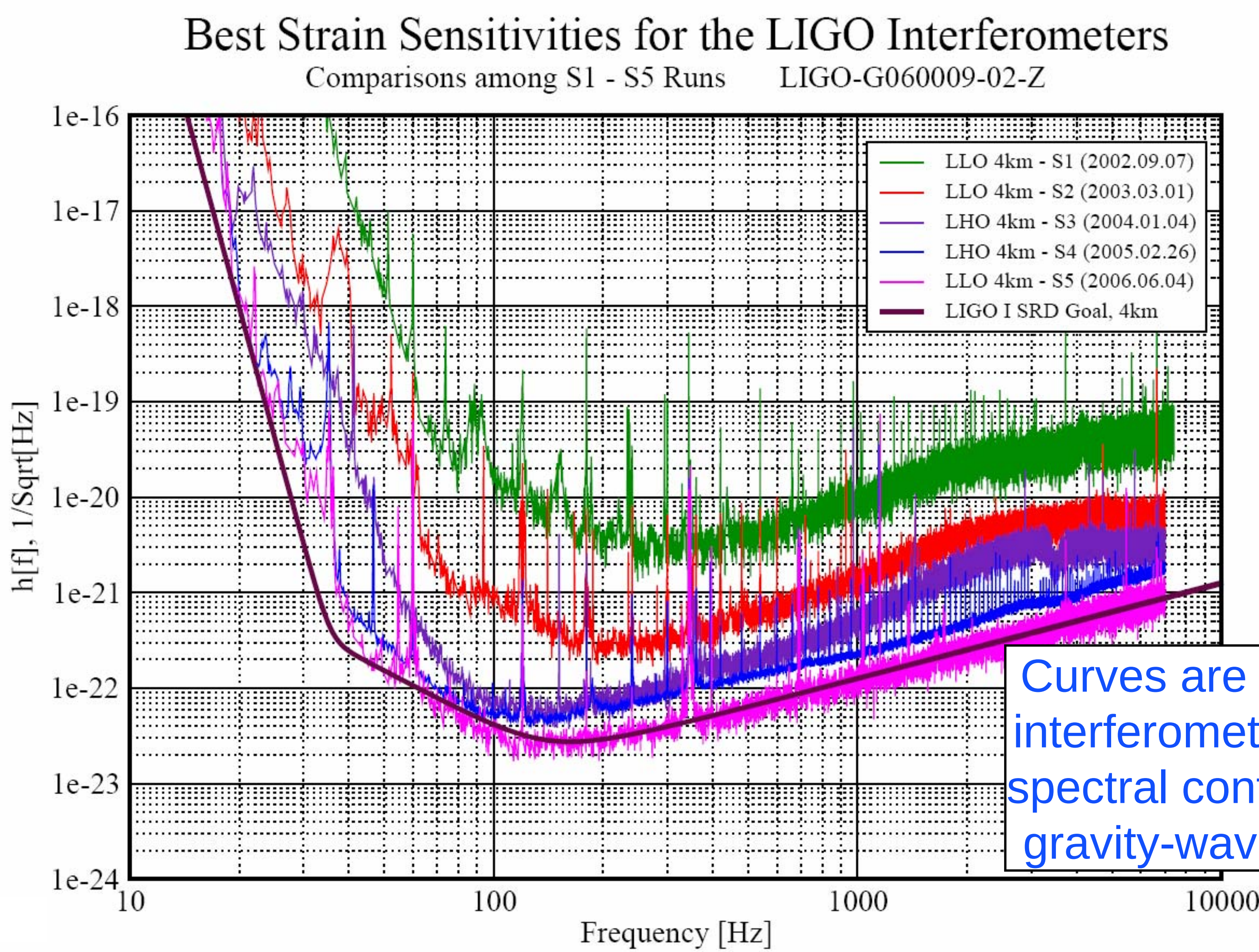
Calibration of interferometer output

- Combination of
  - » Swept-Sine methods (accounts for gain vs. frequency) calibrate meters of mirror motion per count at digital suspension controllers across the frequency spectrum
  - » DC measurements to set length scale (calibrates voice coil actuation of suspended mirror)
- Calibration lines injected during running to monitor optical gain changes due to drift



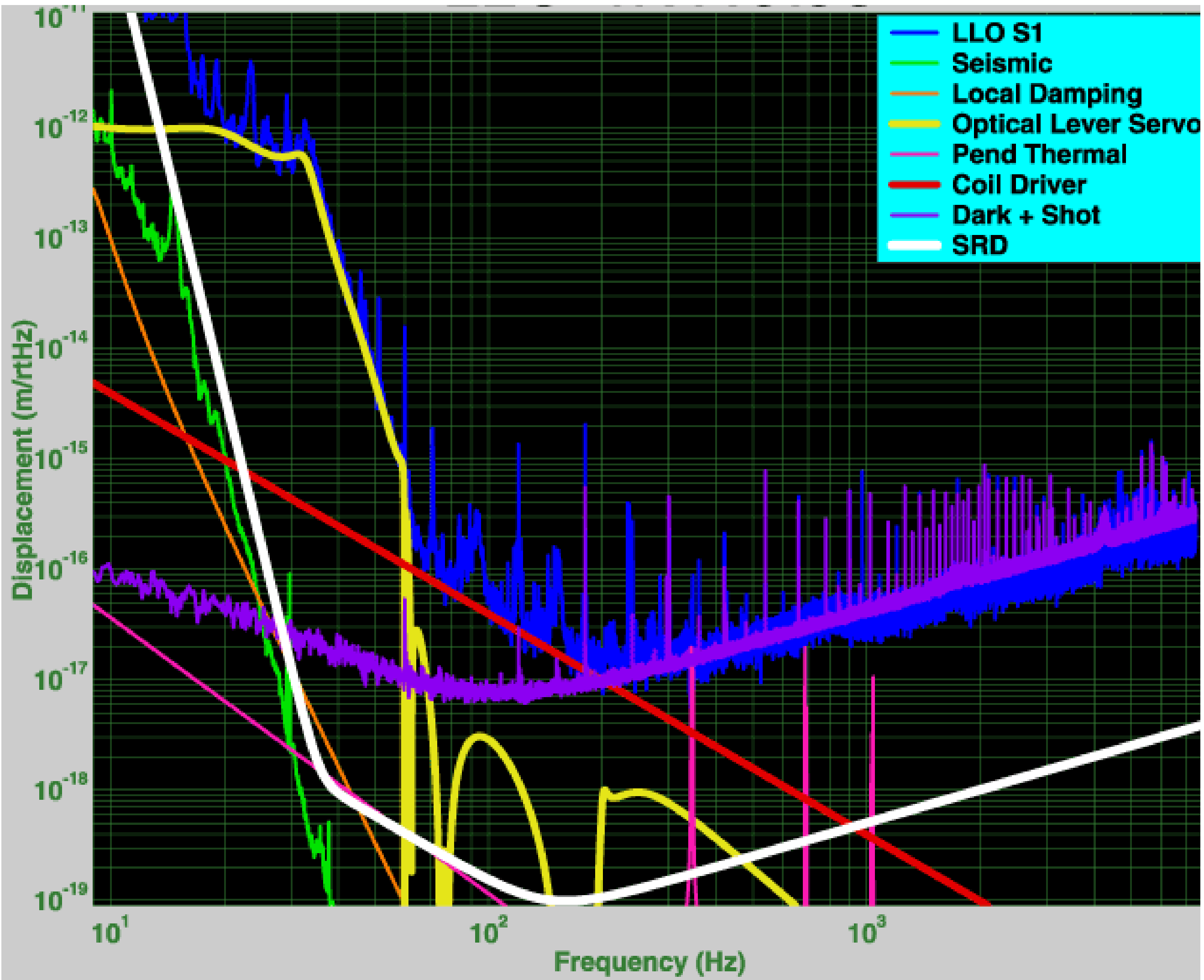


Calibrated output: LIGO noise history



Curves are calibrated interferometer output: spectral content of the gravity-wave channel

Noise component analysis from first science run (S1)



S1

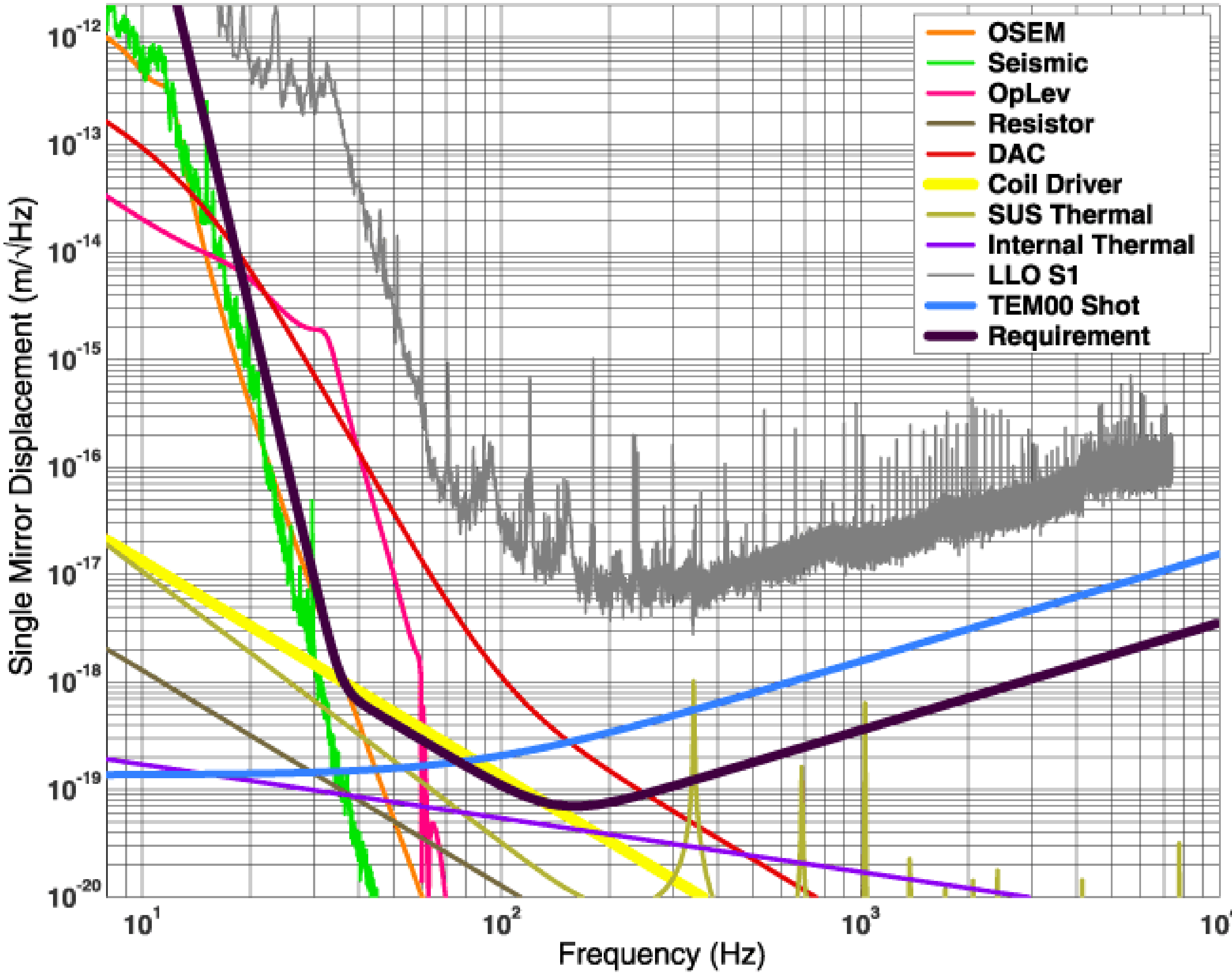
LLO 4k

Blue curve is calibrated interferometer output: spectral content of the gravity-wave channel

Measure and model noise contributions of various subsytems – understand your noise

5

Estimated noise limits for S2 (as planned in October 2002)

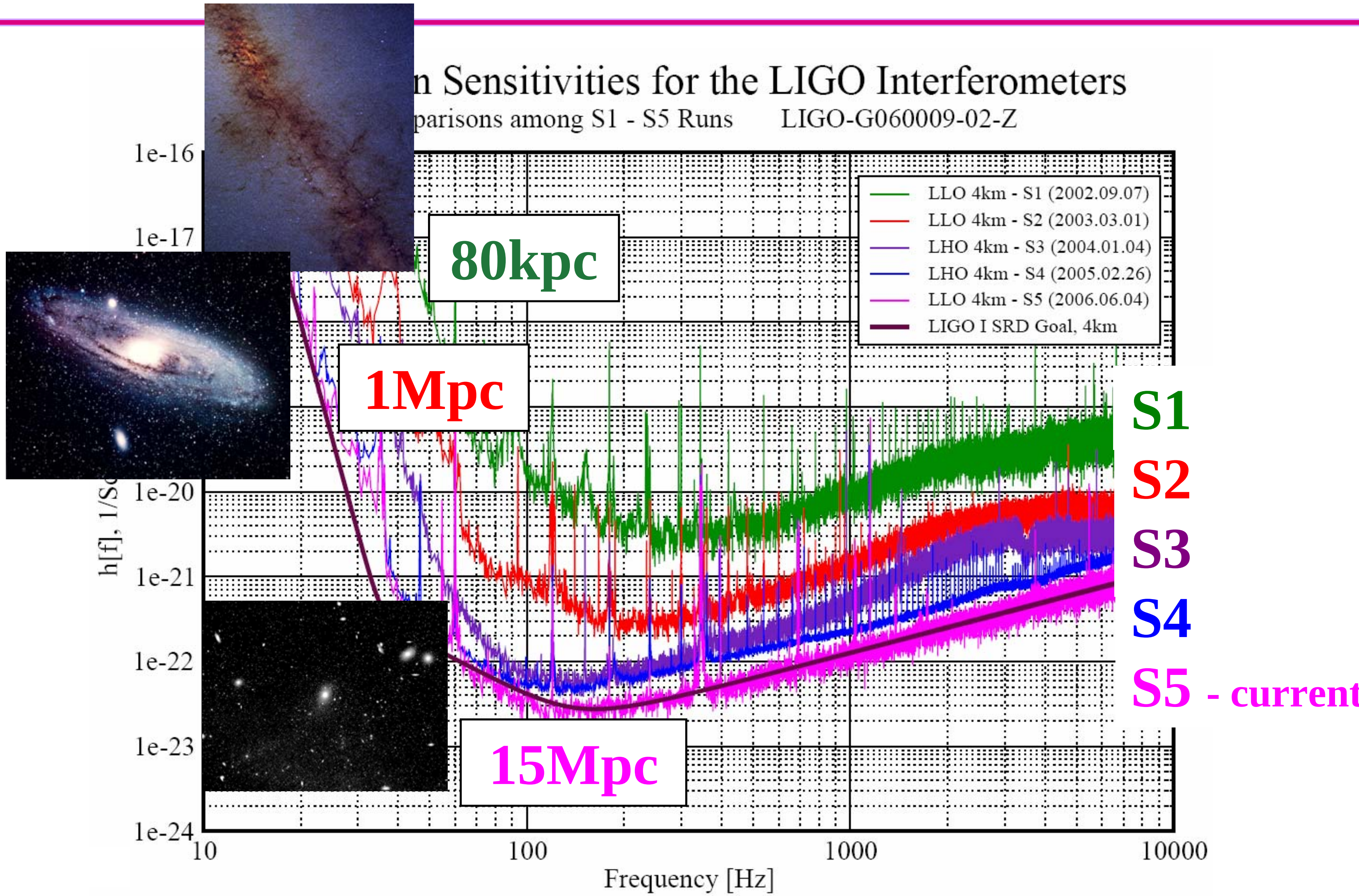


S1

S2

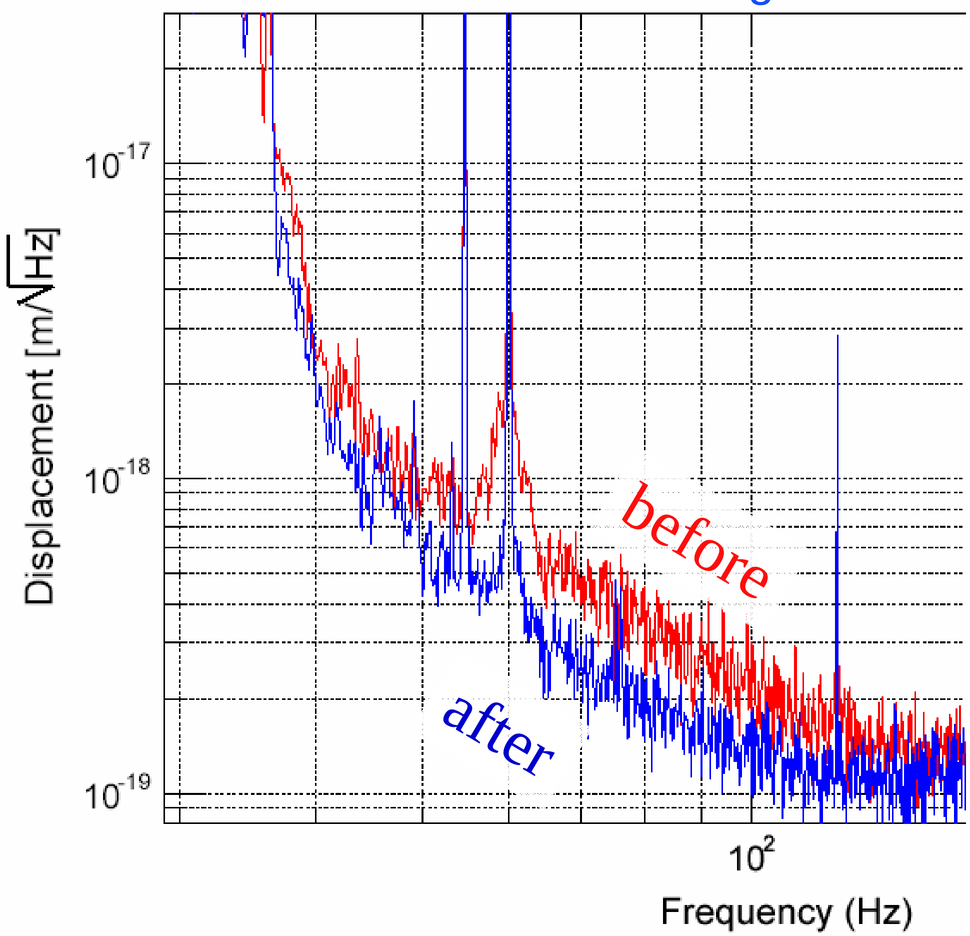
(expected from targeted improvements)

Calibrated output: LIGO noise history

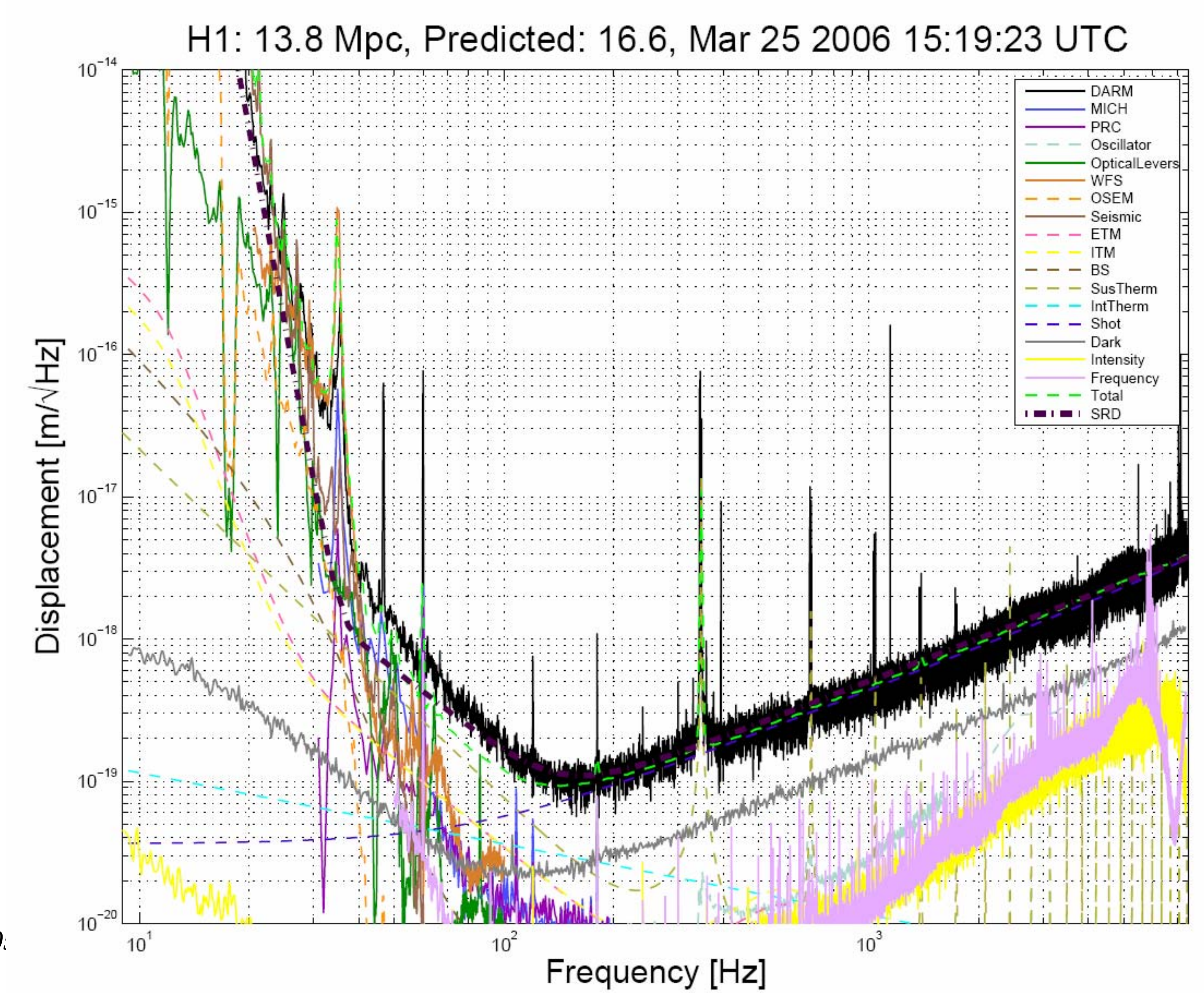


Now and then you get lucky

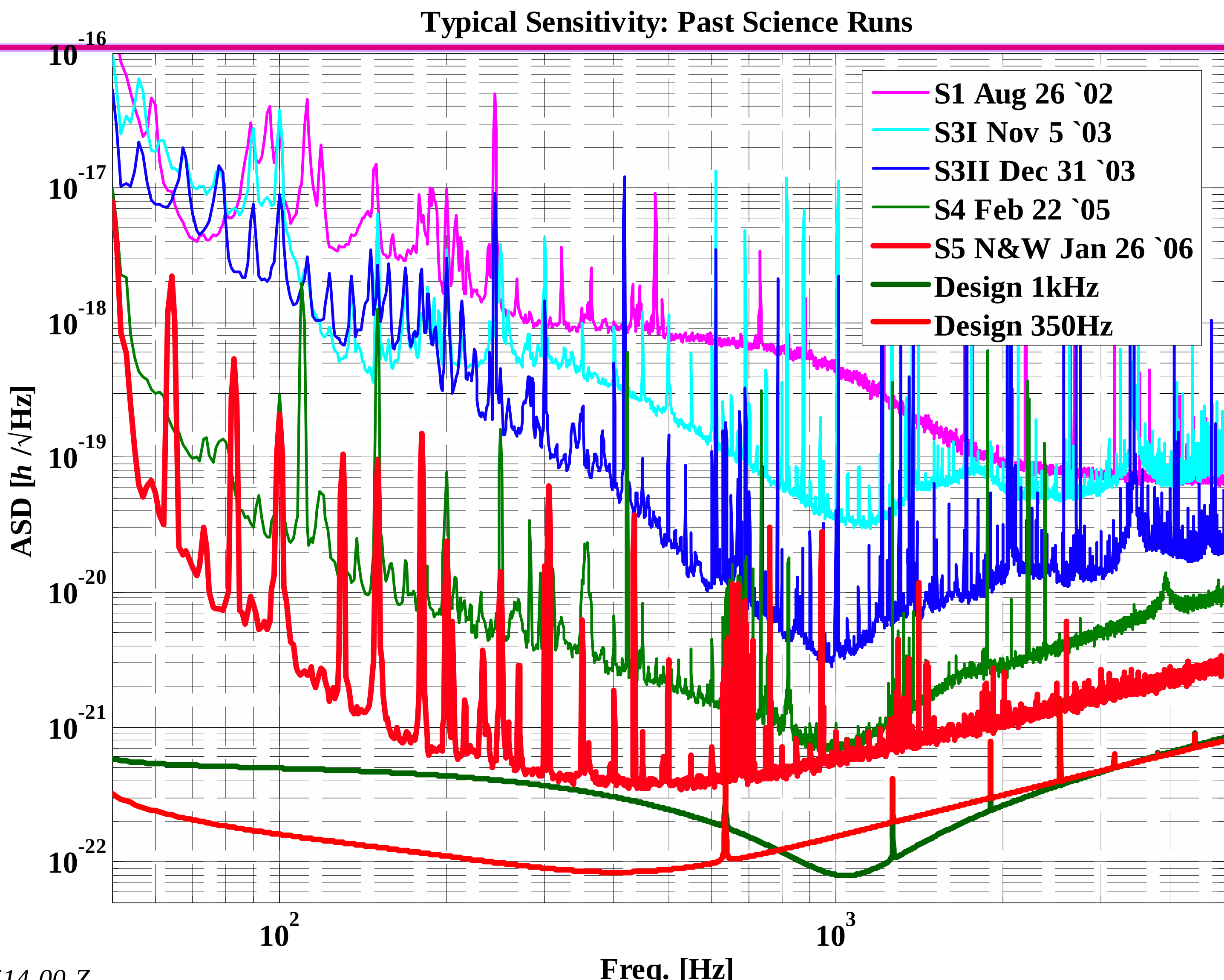
- Near disaster: L1 ITMy got stuck-
- Vented and fixed it: Noise got better!!!



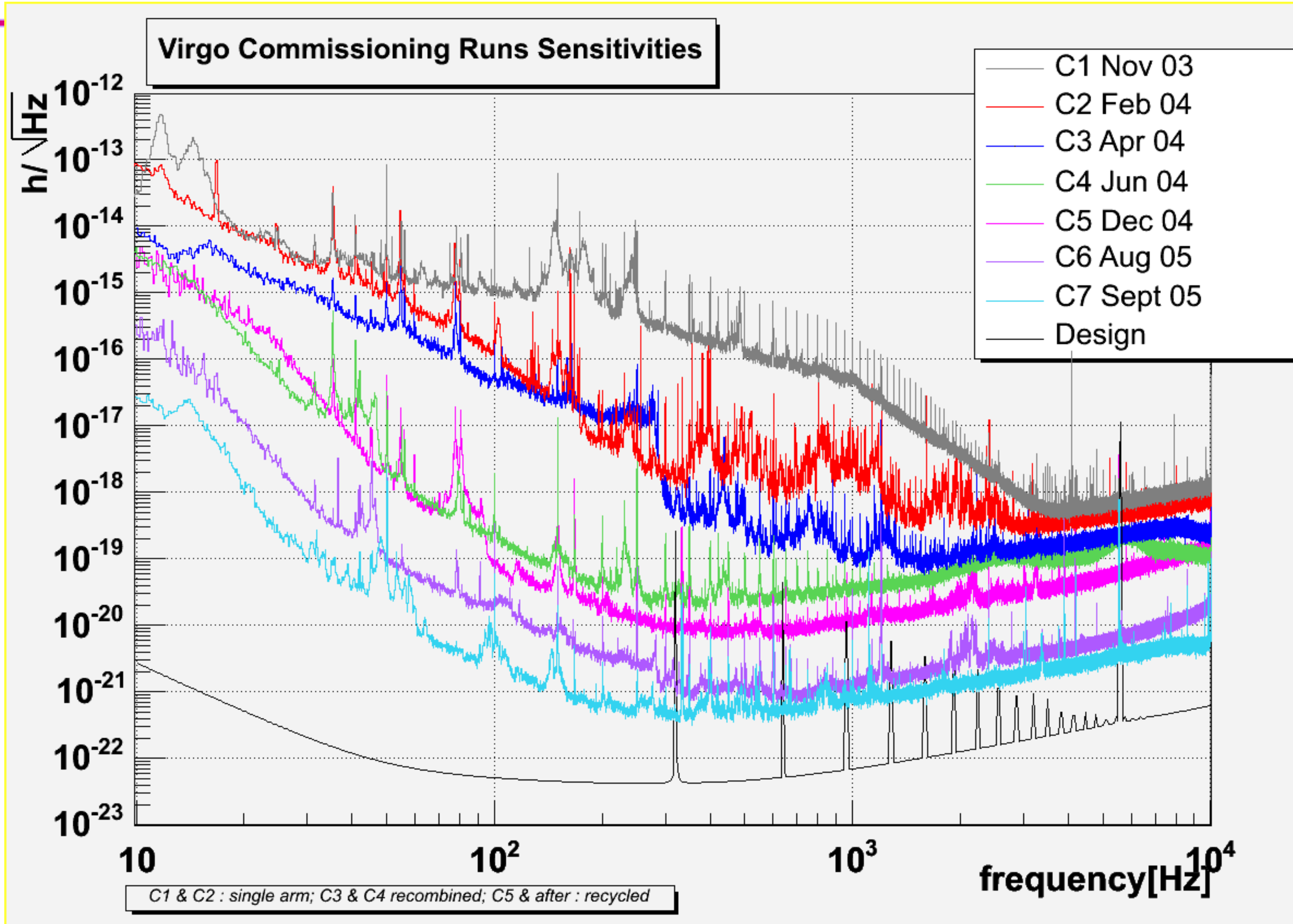
Recent noise budgets more complicated



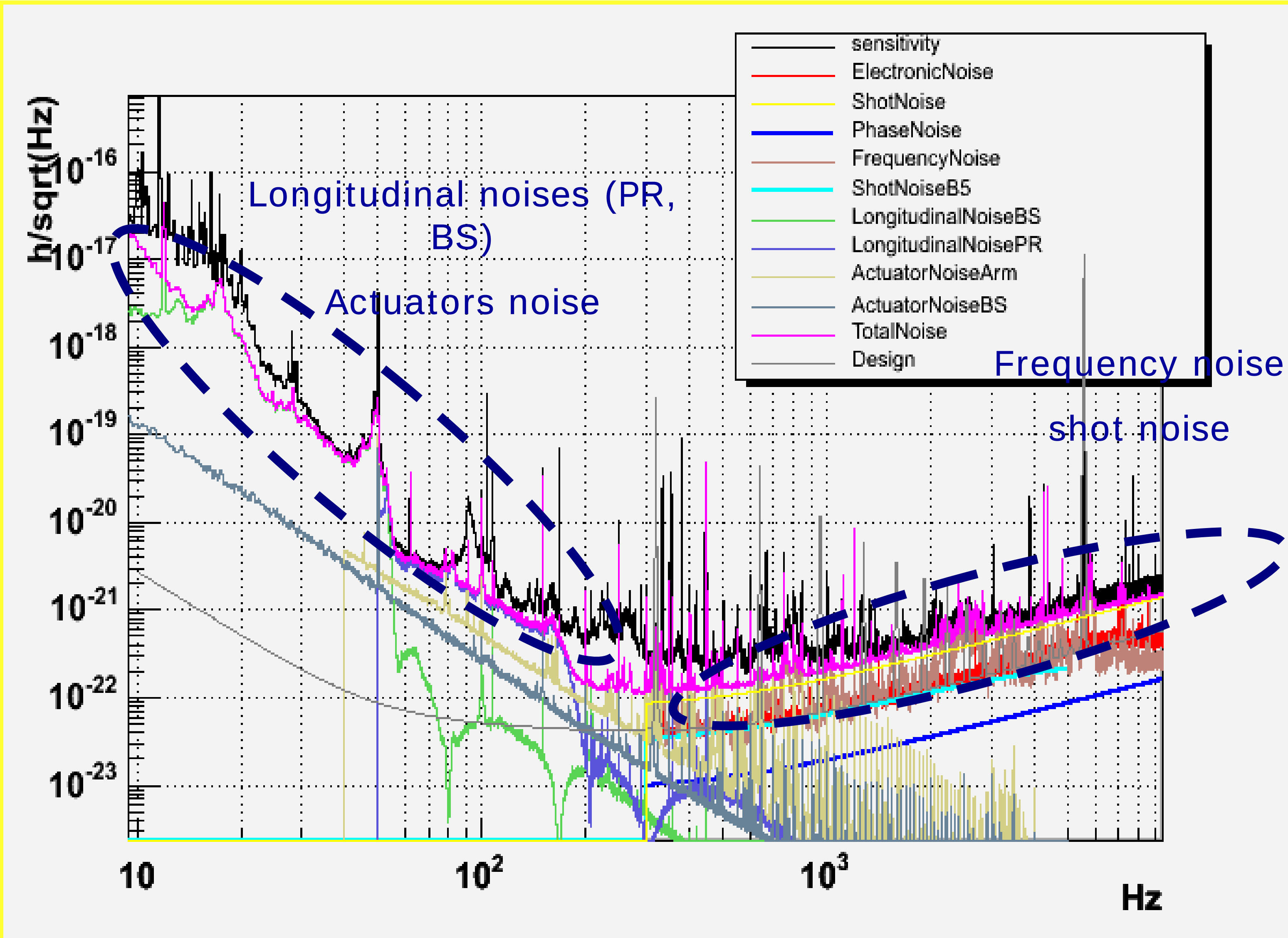
GEO sensitivity improvements



Virgo sensitivity improvements



Recent Virgo noise budget



Tidal compensation data

common mode   differential mode

Tidal evaluation on 21-hour locked section of S1 data

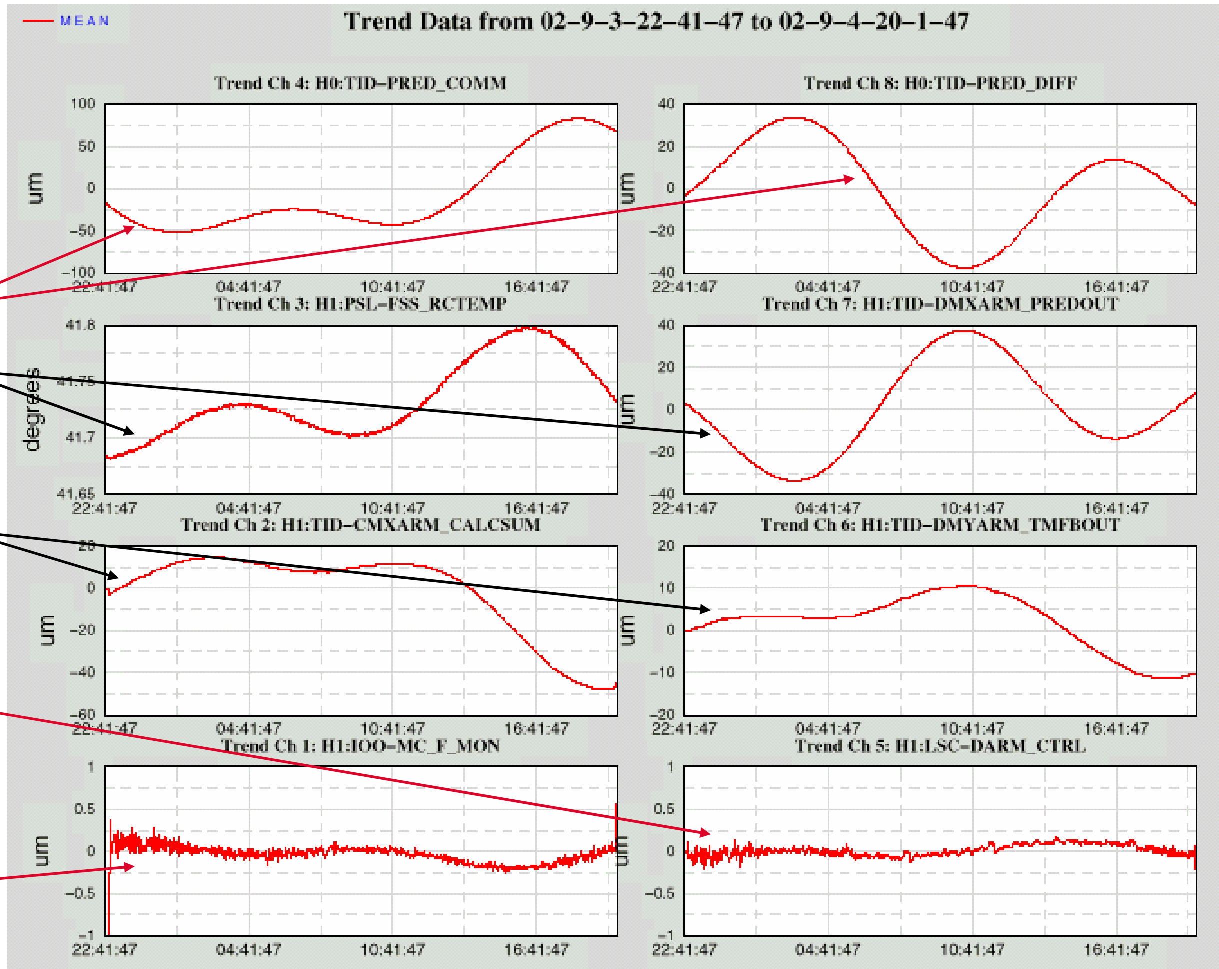
Predicted tides

Feedforward

Feedback

Residual signal on coils

Residual signal on laser



Special Livingston problem -- logging

Livingston Observatory located in pine forest popular with pulp wood cutters

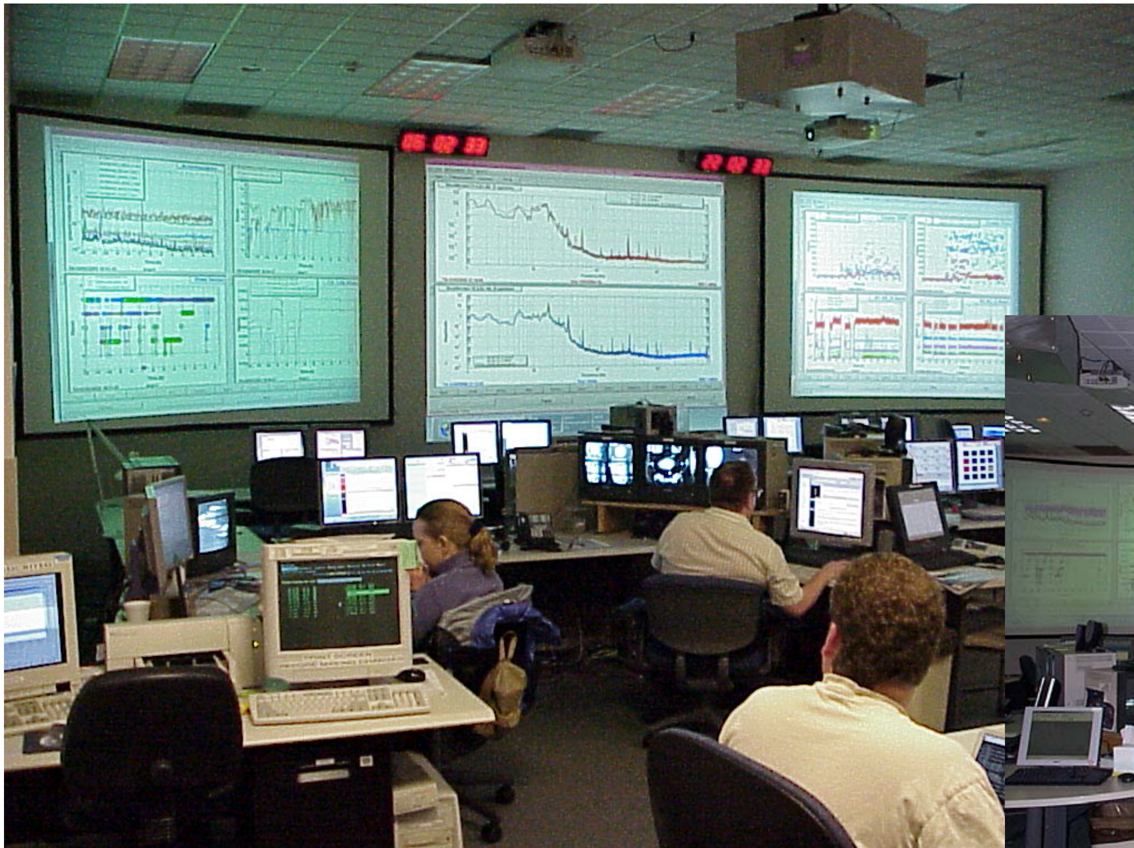
Spiky noise (e.g. falling trees) in 1-3 Hz band creates dynamic range problem for arm cavity control

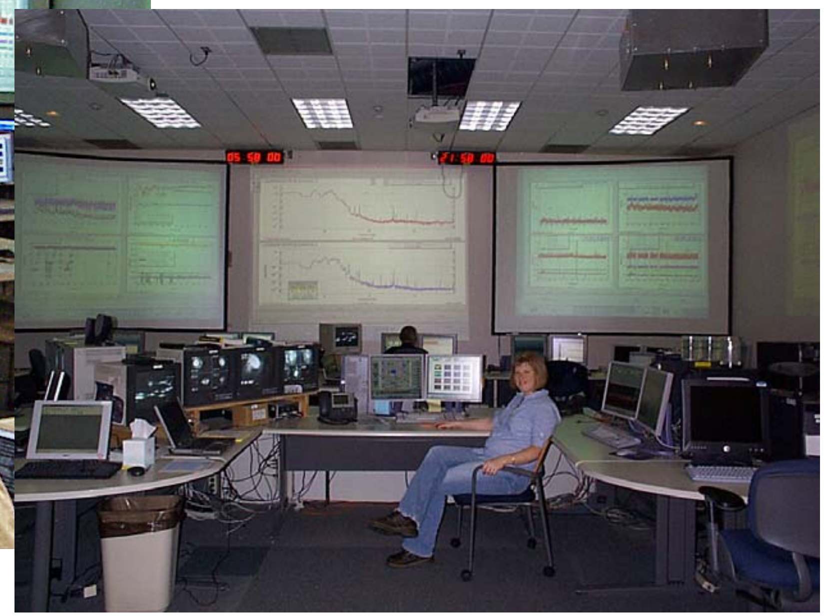
→ ~ 40% livetime at best

Solution: Retrofit with active feed-forward isolation system **(using Advanced LIGO technology)**

→Complete! – S4 science run duty cycle (lock time/run time): 75%

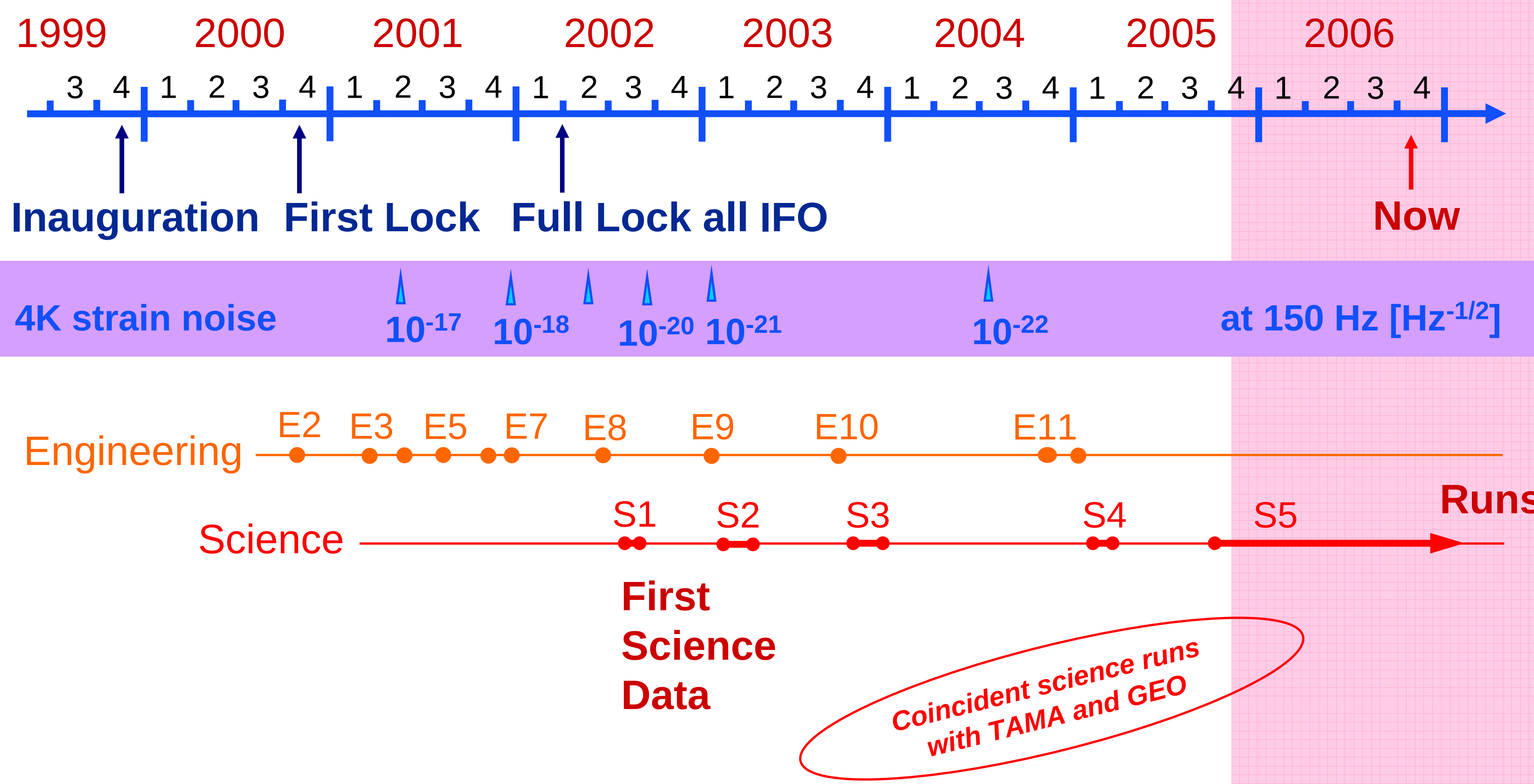
LIGO/GEO/TAMA Science runs





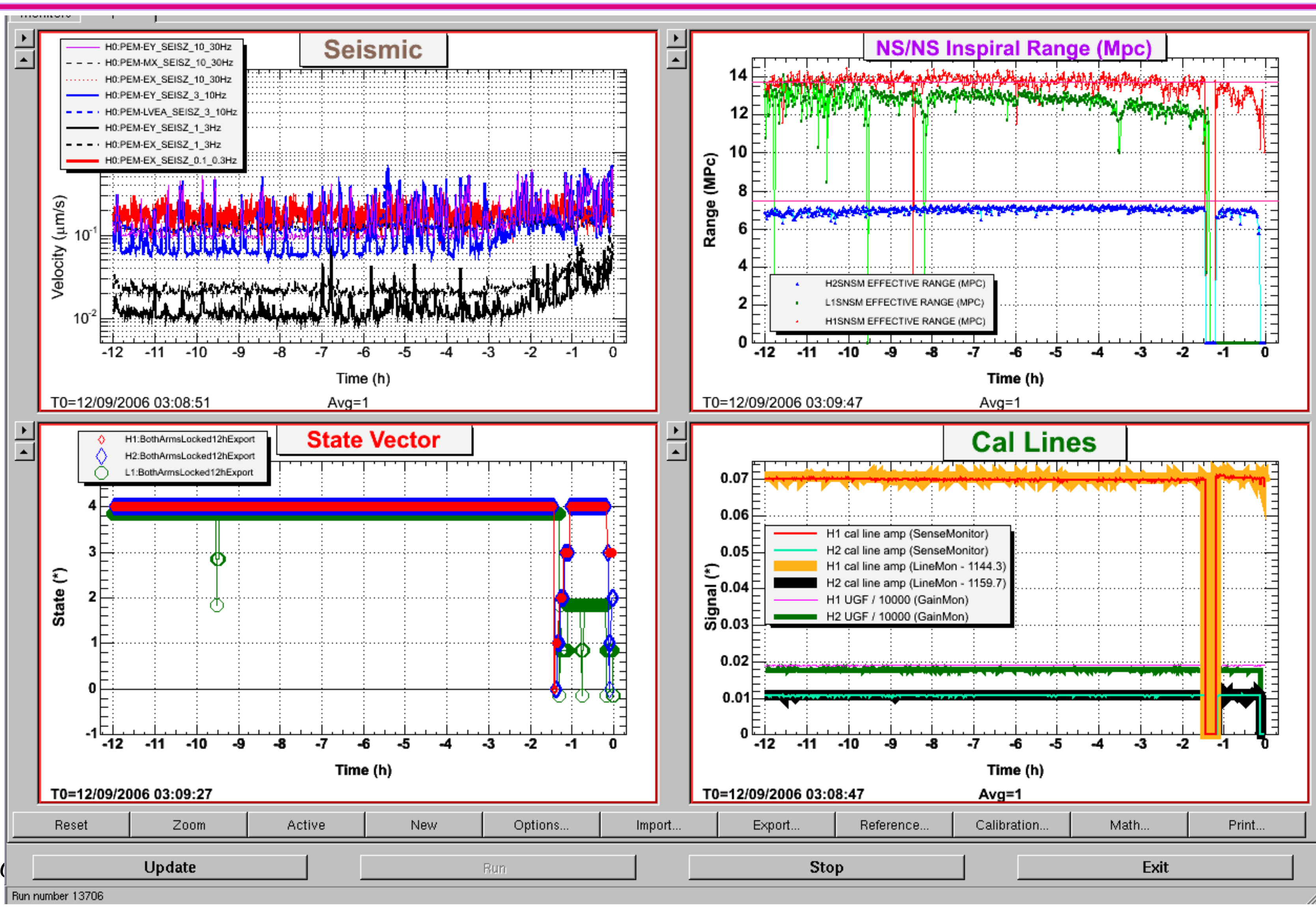
LIGO Hanford control room
31 Mar 2006 – S5

Time line



1999 2000 2001 2002 2003 2004 2005 2006
3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Inauguration
First Lock
Full Lock all IFO
Now
4K strain noise
10^{-17} 10^{-18} 10^{-20} 10^{-21} 10^{-22}
at 150 Hz [$Hz^{-1/2}$]
Engineering
E2 E3 E5 E7 E8 E9 E10 E11
Science
S1 S2 S3 S4 S5
Runs
First Science Data
Coincident science runs with TAMA and GEO

Recent S5 running



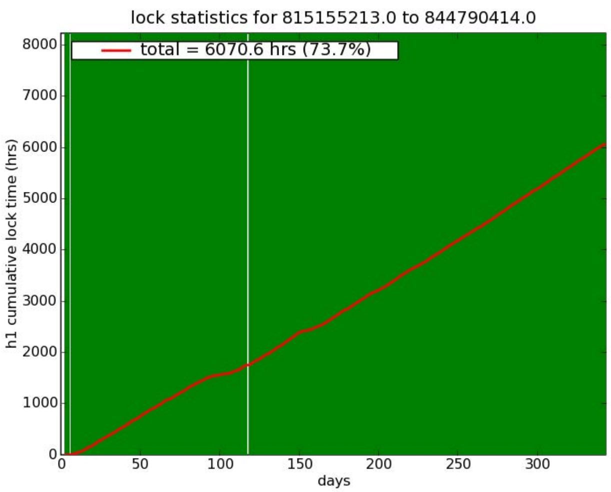
LIGO, GEO S5 duty cycle

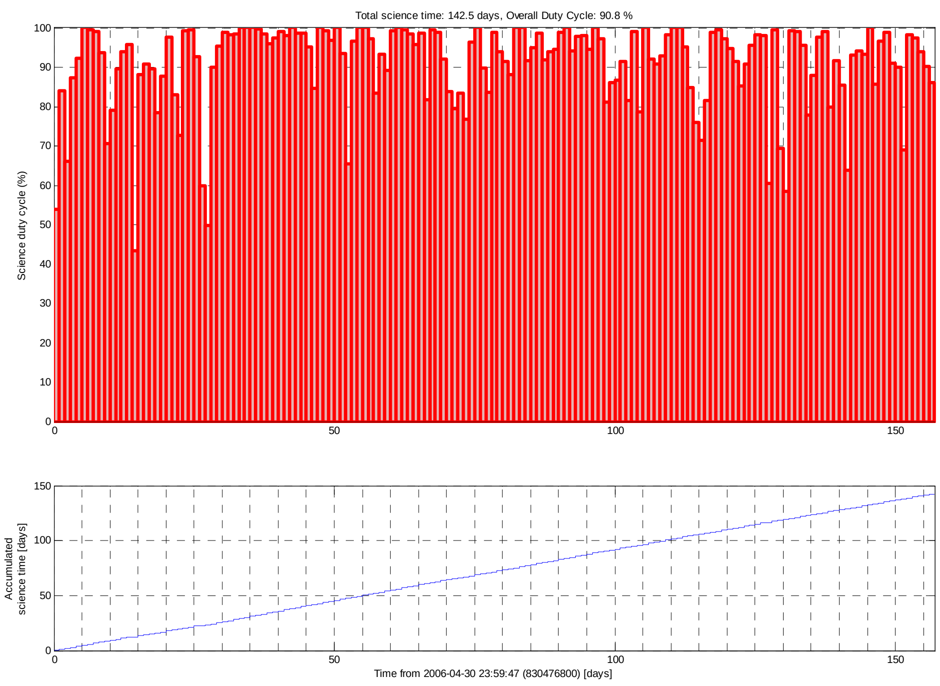
S5 overall duty cycles:

H1: 74%
H2: 79%
L1: 59%

Percentage of 1-year LHO-LLO coincidence:
54% Halfway through S5!

GEO: since May06 full attendance of S5: 91% duty cycle (143 days of total science time)

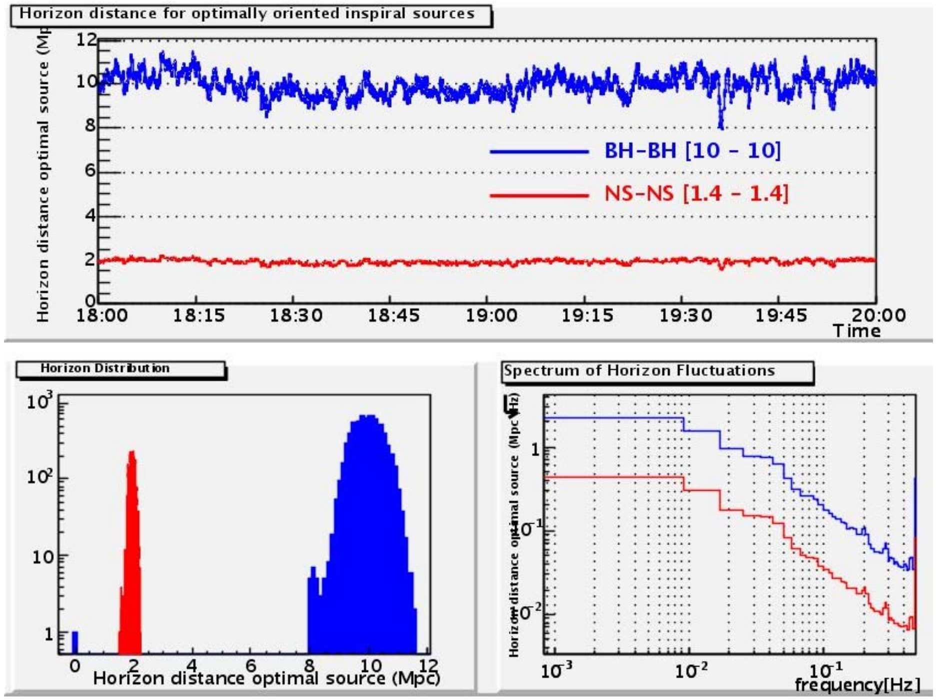


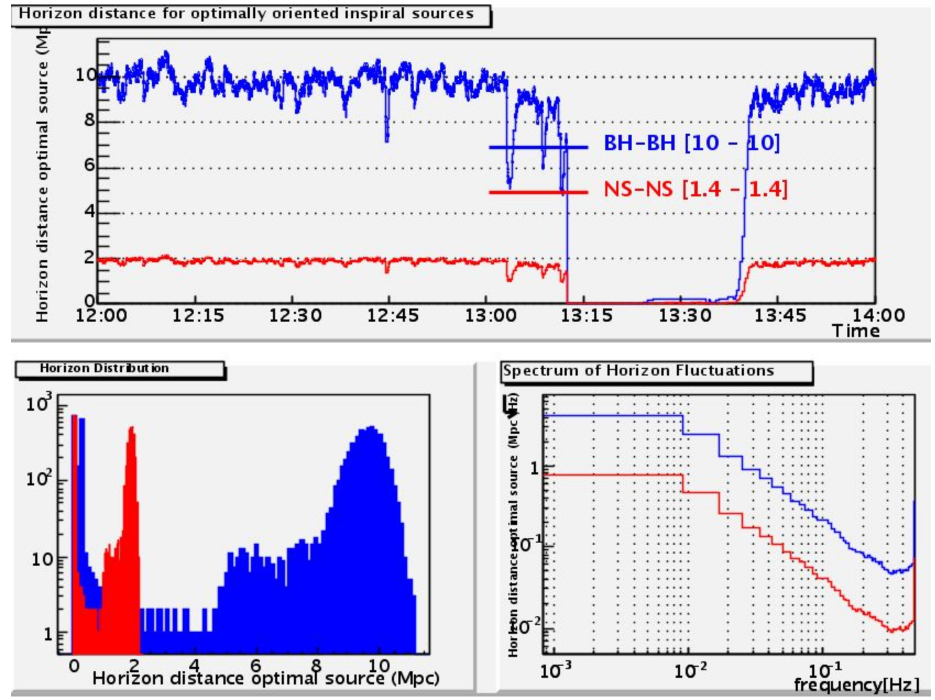


Virgo Weekly Science Runs (WSR)

- Bi-weekly long week ends of data taking
  - » Start moving towards a science run operation
  - » Light organization: 1 run coordinator, 3 shifts/day with 1 scientist + 1 operator
  - » 7 shifts of 8 hours (from 11pm Friday to 7am Monday)
  - » Scientist duties defined by the physics groups
    - – Mainly noise characterization with focus on the different searches.
- Expected benefits
  - » Take snapshots of the commissioning progress
  - » Get organized for a long run.
  - » Acquire data of controlled quality, do noise studies, run DA pipelines.
- Started in September: how is it going?
  - » Very good start at WSR1: 88% duty cycle (science mode)
  - » WSR2 more difficult: air conditioning failure a few hours before the start!
    - – 68% science mode; but 98% after stable operation
  - » WSR3 canceled, because of a series of last minute hardware problems

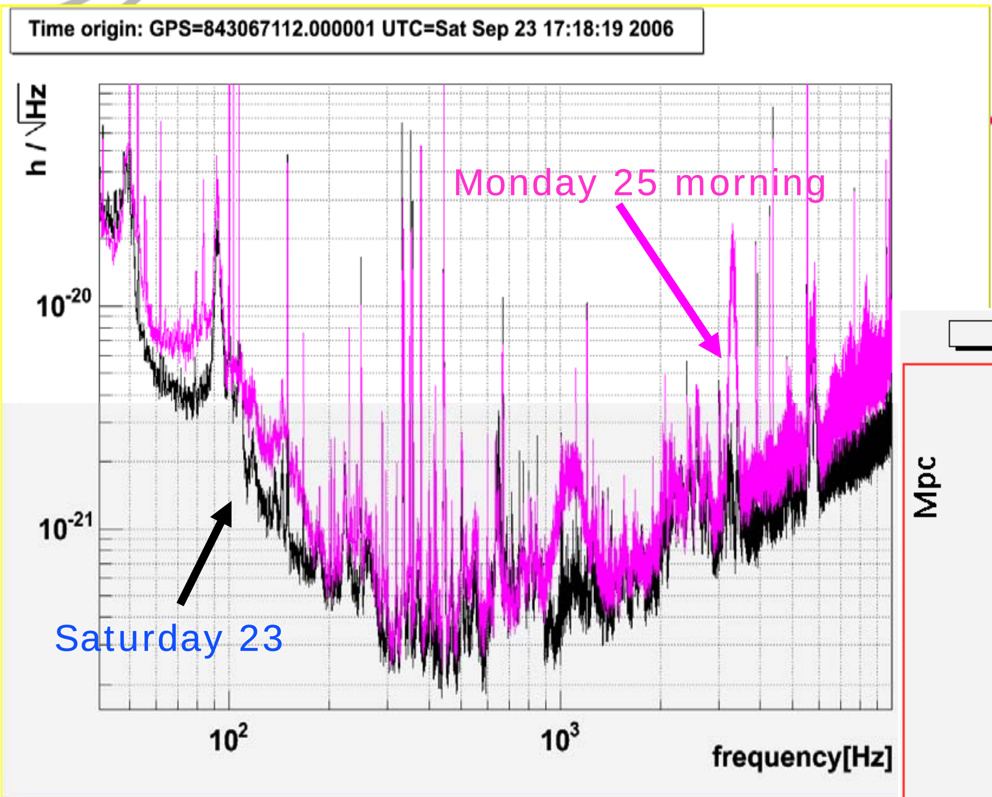
Virgo BNS, BBH horizon stability



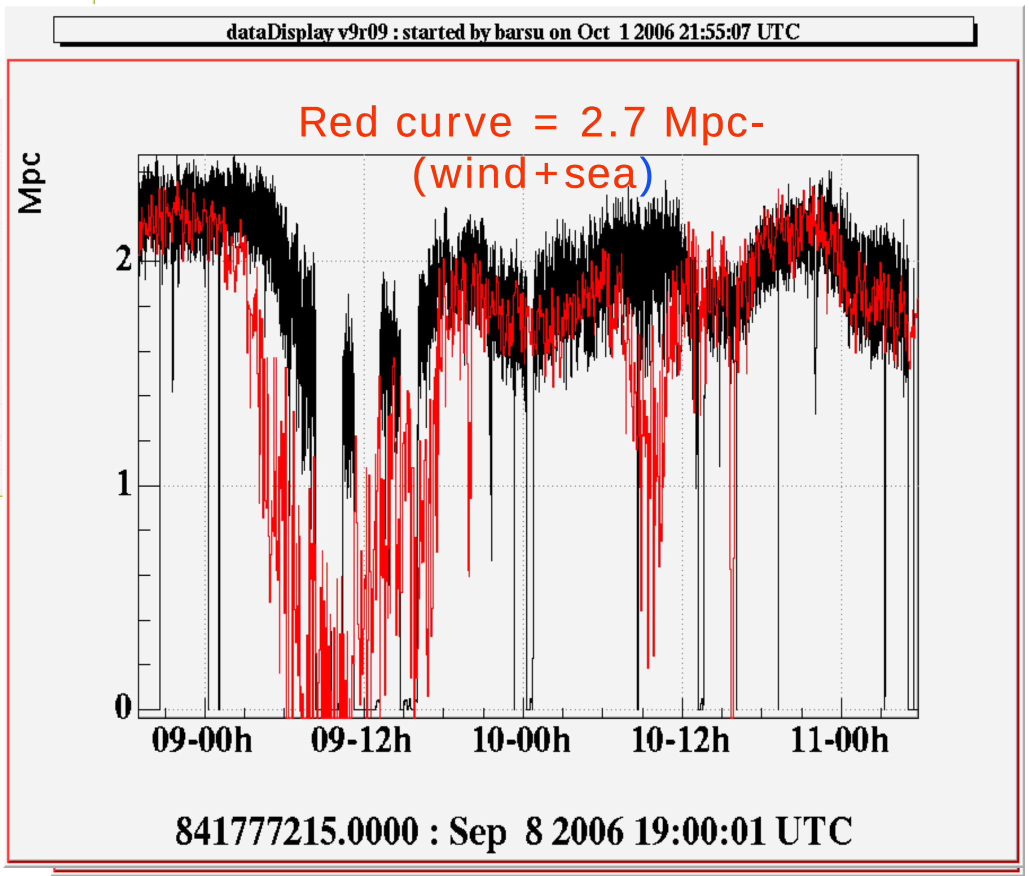


- Left: a typical evolution covering a long locked period
- Right: an example of a period including an unlock

Virgo WSR2 horizon and sensitivity



- » Sensitivity displays large variations
- » Variations appear correlated with RMS noise in bands associated with bad weather and sea activity



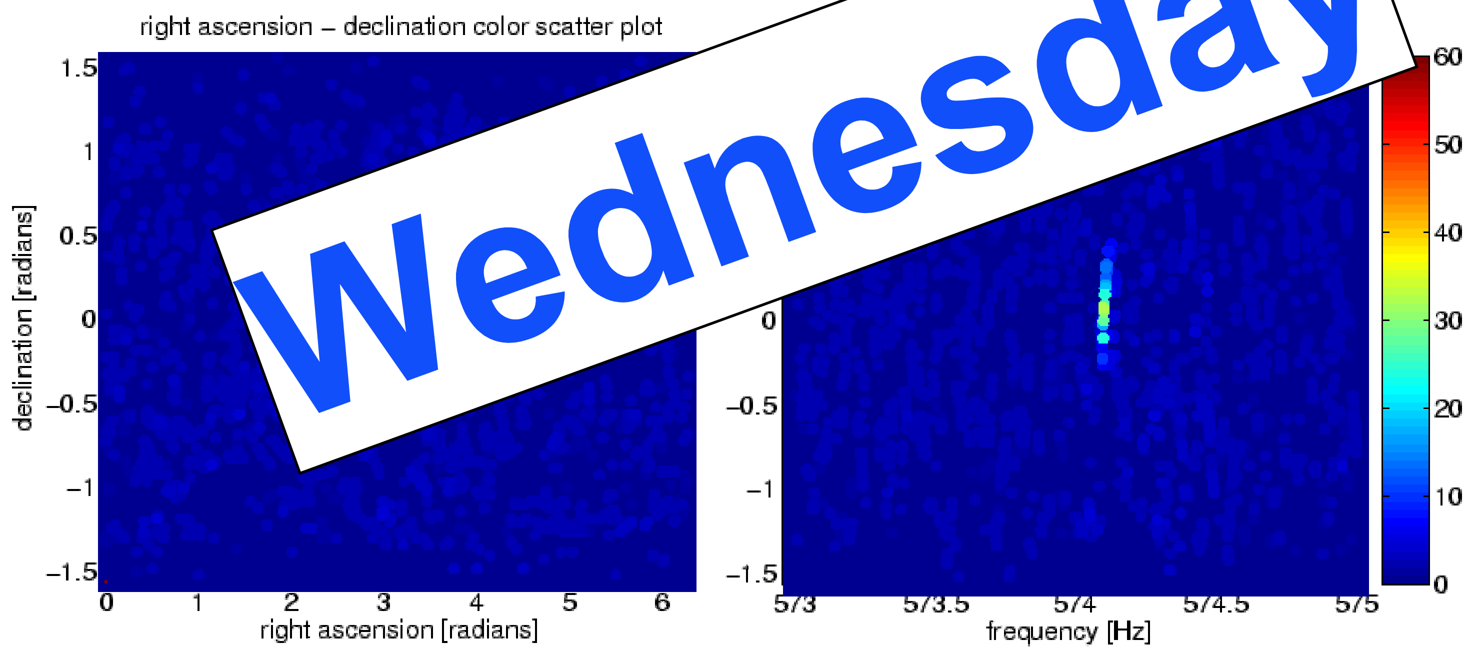
- » Data explained with a simple linear dependence on these noises
- » Same model works at other epochs, even predicting horizon < 0
- » **Problem probably pinned down. Work is underway to mitigate it.**

Summary remarks

- LIGO achieved design sensitivity in Nov 05, a major milestone
- LIGO/GEO launched coincident S5 science run, which is to run until ~fall 07
- Virgo/GEO making progress on sensitivity, close to design at high frequency. Virgo rapid progress
- Virgo currently making weekend science runs to exercise machine and pipelines

What would a pulsar look like?

- Post-processing step: find points on the sky and in frequency that exceeded threshold in many of the sixty ten-hour segments
- Software-injected fake pulsar signal is recovered



Simulated (software) pulsar signal in S3 data

Advanced LIGO

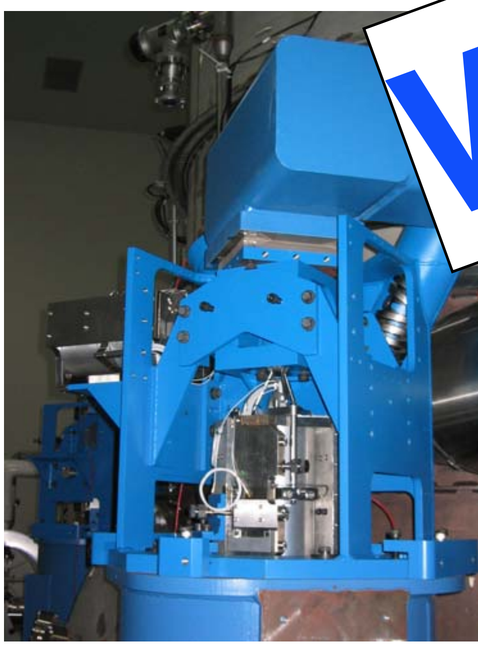
Detector Improvements:

New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal
in bandwidth

Wednesday



Improved seismic isolation:

Passive → Active

Lowers seismic “wall” to ~10 Hz