The Search for Gravitational Waves

Fred Raab,

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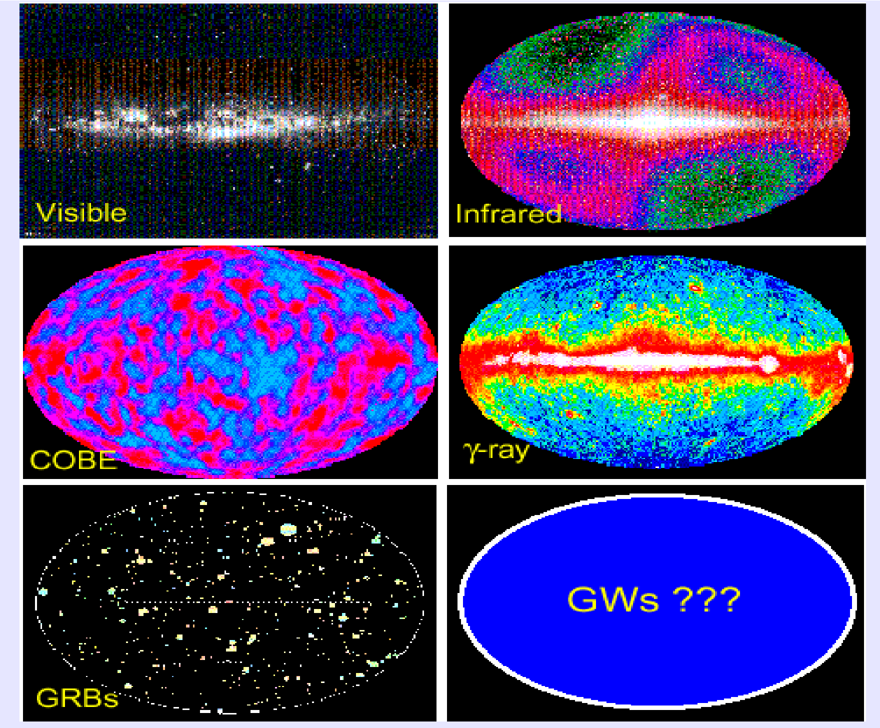
on behalf of the LIGO Scientific Collaboration

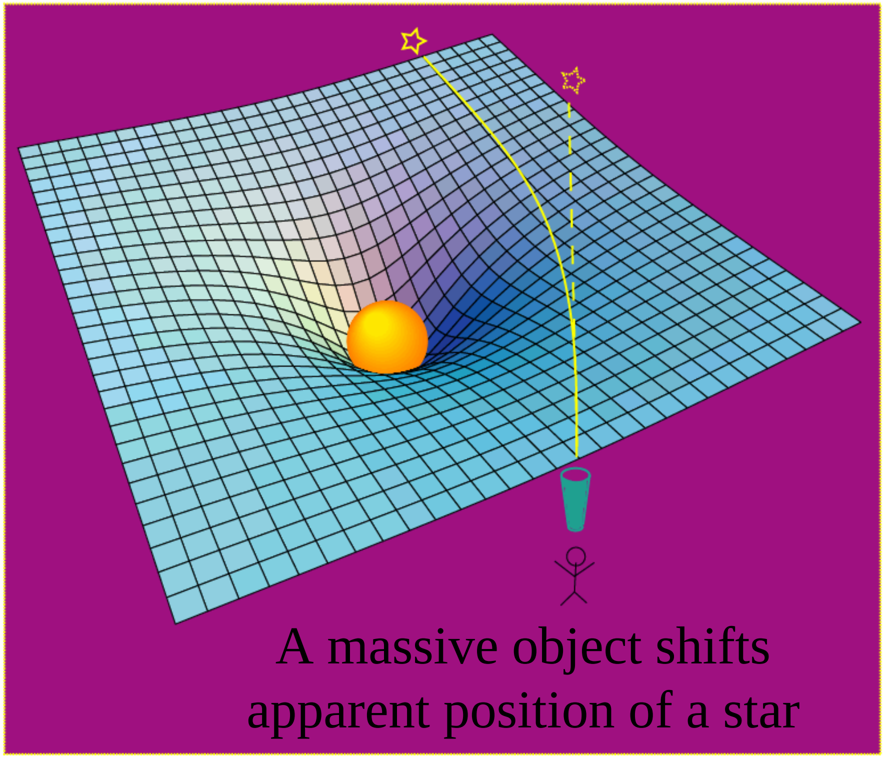
21 October 2008



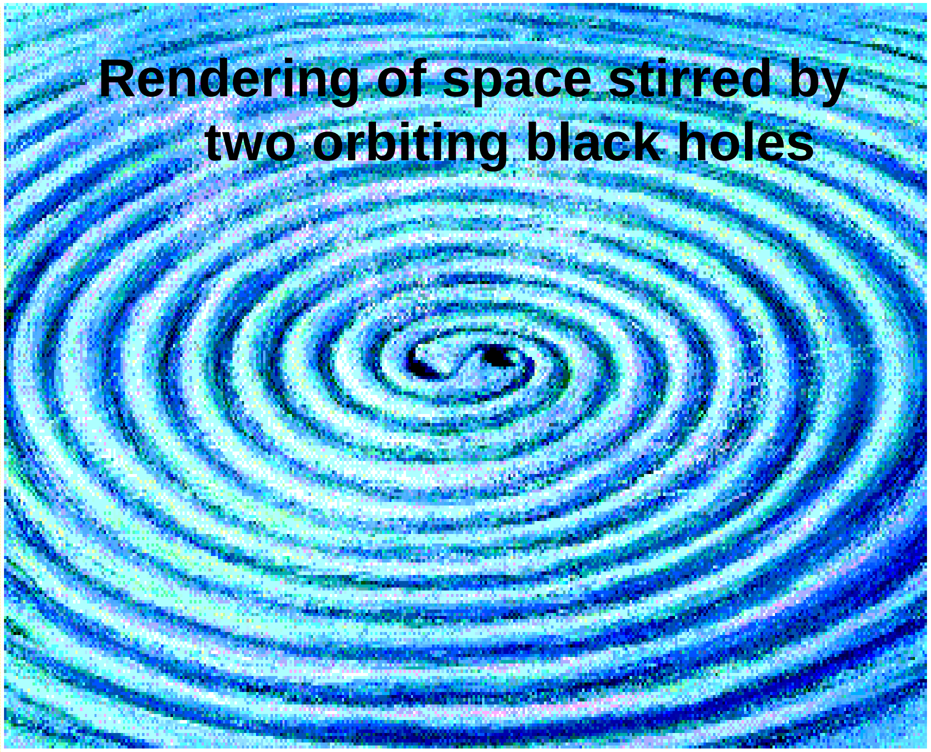
Outline

- What are gravitational waves?
- What do generic detectors look like and how do they work?
- Kilometer-scale detectors:
  - » First generation: Initial LIGO detectors and the worldwide network
  - » Second generation: Advanced LIGO
  - » Opening up the GW detector frequency band

Principle of Equivalence + Special Relativity ⇒ Gravitational Waves



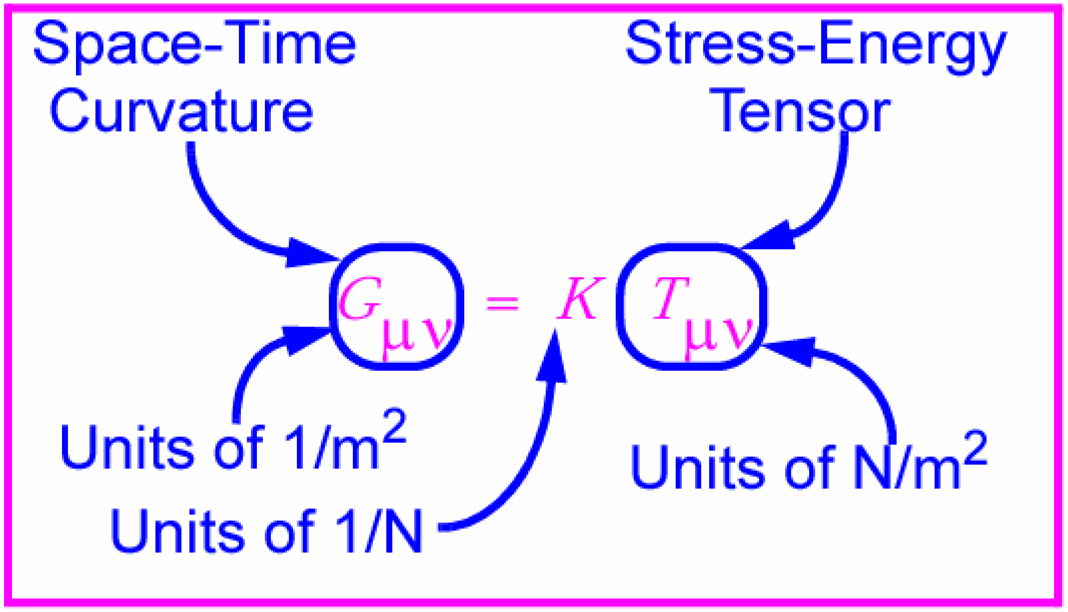
A massive object shifts apparent position of a star



Rendering of space stirred by two orbiting black holes

Changes in space warps produced by moving a mass are not felt instantaneously everywhere in space, but propagate as a wave.

Gravitational waves: hard to find because space-time is stiff!



Space-Time Curvature

Stress-Energy Tensor

$$\boxed{G_{\mu\nu}} = K \boxed{T_{\mu\nu}}$$

Units of $1/m^2$

Units of 1/N

Units of N/m^2

- $K \sim [G/c^4]$ is lowest order combination of G, c with units of 1/N

$$K \sim 10^{-44}\ N^{-1}$$

⇒ Wave can carry huge energy with miniscule amplitude!

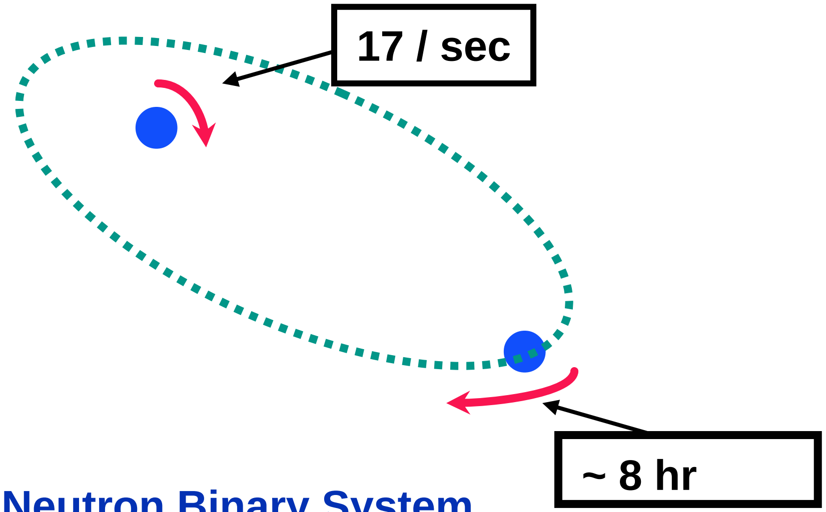
Gravitational Waves

known to exist, just hard to find

Emission of gravitational waves

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

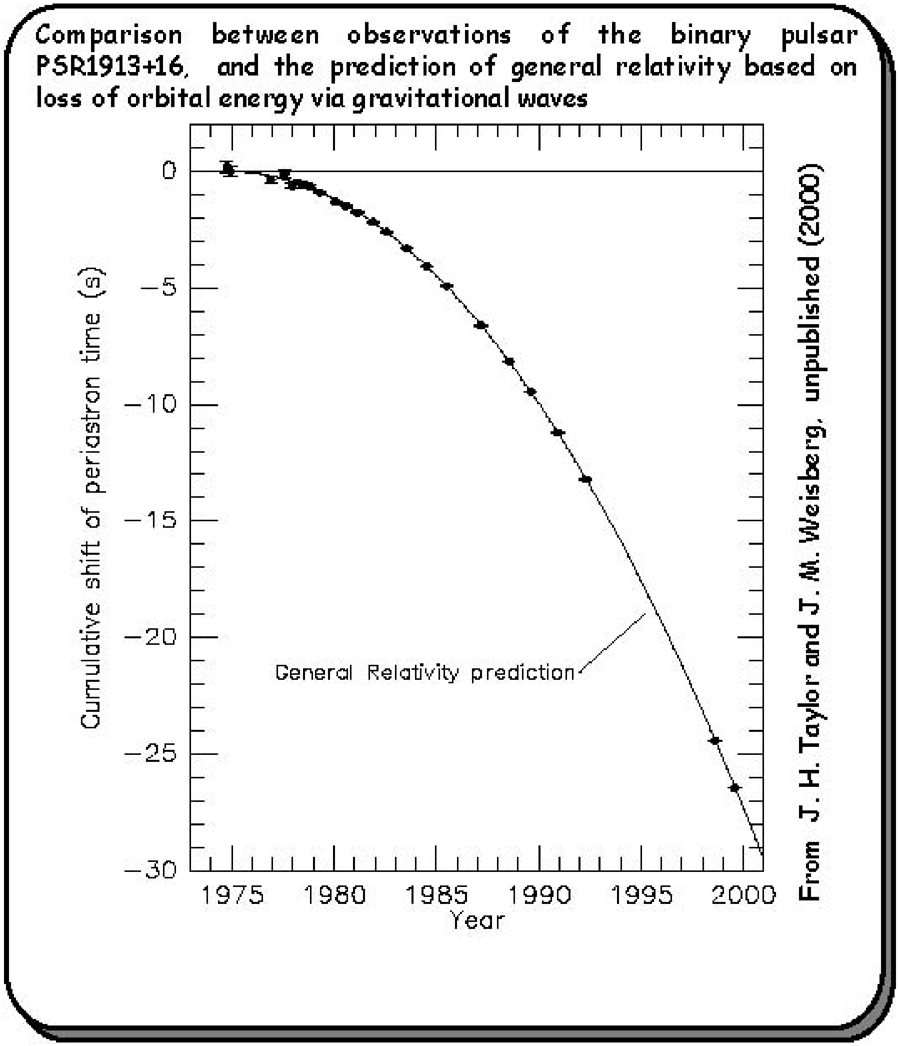


Neutron Binary System

- **separated by 10^6 miles**
- **$m_1 = 1.4m_\odot$; $m_2 = 1.36m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity

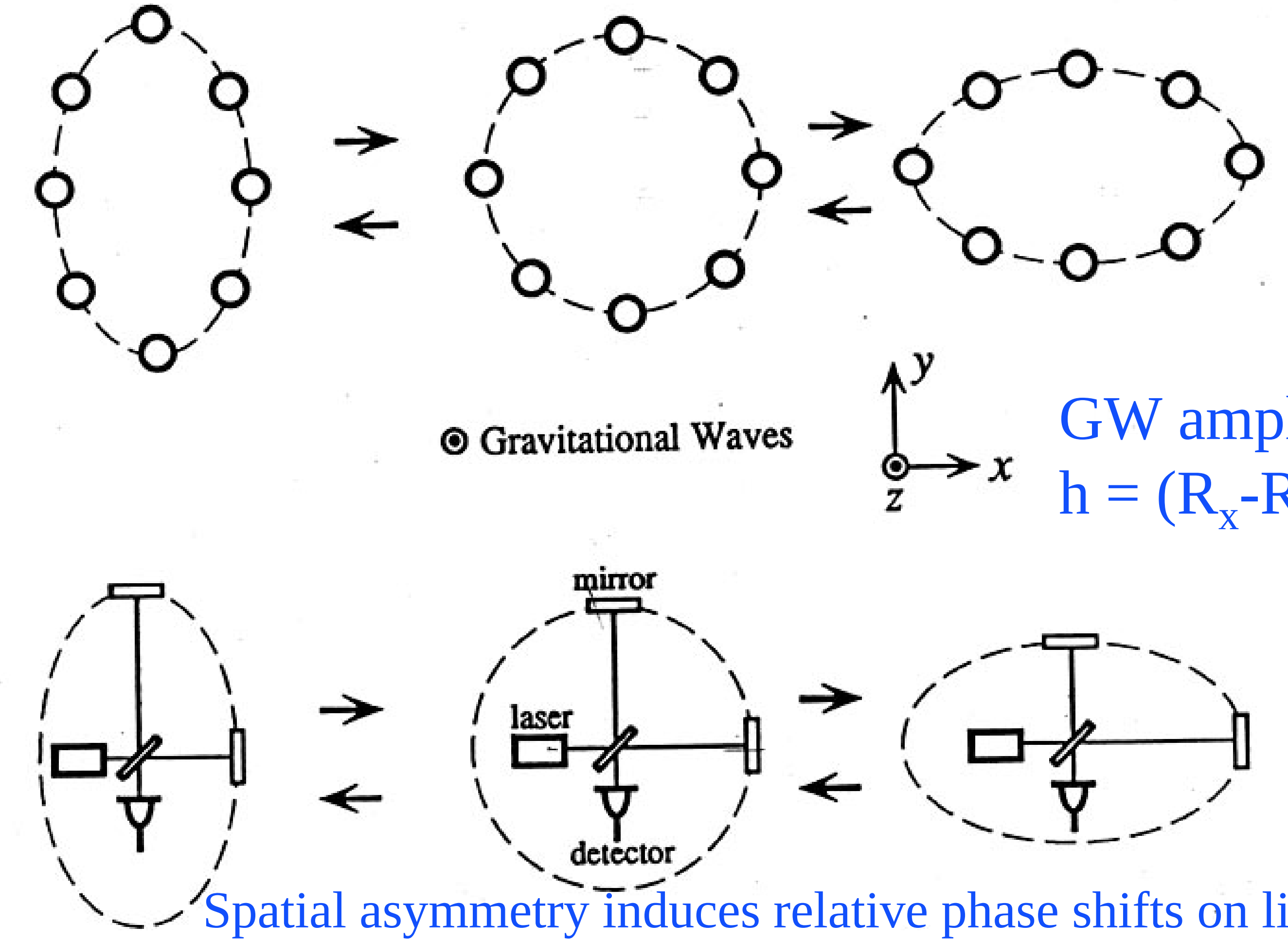
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**



Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

From J. H. Taylor and J. M. Weisberg, unpublished (2000)

Gravitational waves deform a circle of space into an ellipse



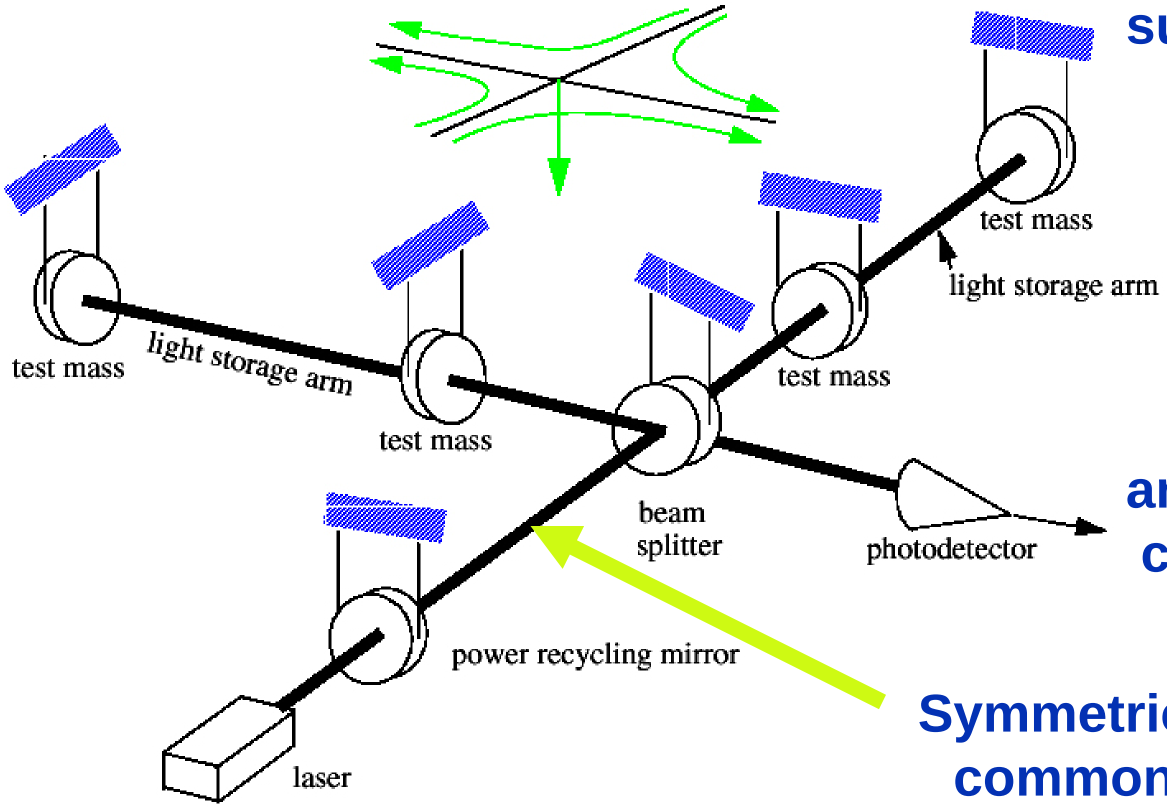
GW amplitude
$h = (R_x - R_y)/R$

Spatial asymmetry induces relative phase shifts on light in arms

Issues to address in 1989 proposal to build a gravitational wave detector

- Signal has never been detected directly
- Understanding of either source strengths or source populations ranges from “not well” to “poorly” known
- Simple arguments based on available information indicate the need to cover a space-time volume from billions to a trillion times larger than previous detector searches
- Need to scale up size 100-fold from largest existing device
- Need to push frontier of measurement science, but no law of physics prevents it
- Any feasible detector using current or close-to-hand technology may not be sufficiently sensitive to make detections
- Very expensive: failure is not a viable option
- Strategy: build initial km-scale detector (iLIGO) and conduct searches, while pushing R&D toward an advanced detector (aLIGO) capable of routine detections

Initial LIGO: Power-recycled Fabry-Perot-Michelson



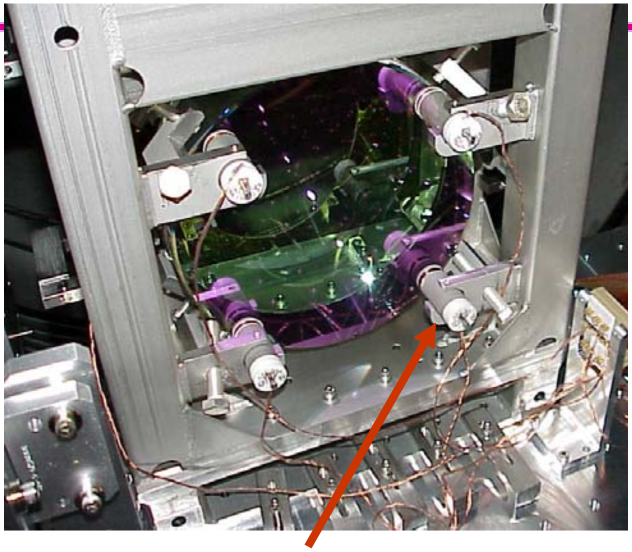
suspended mirrors mark inertial frames

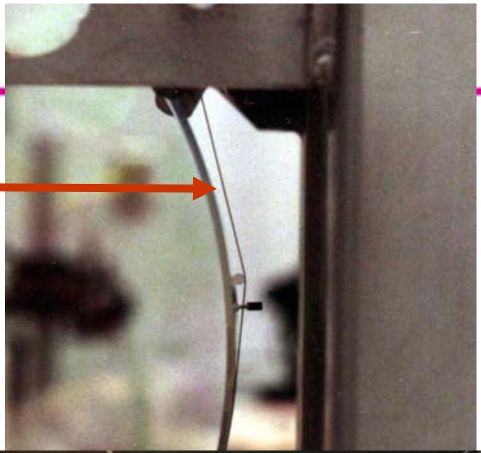
antisymmetric port carries GW signal

Symmetric port carries common-mode info

Intrinsically broad band and size-limited by speed of light.

Core Optics Suspension and Control



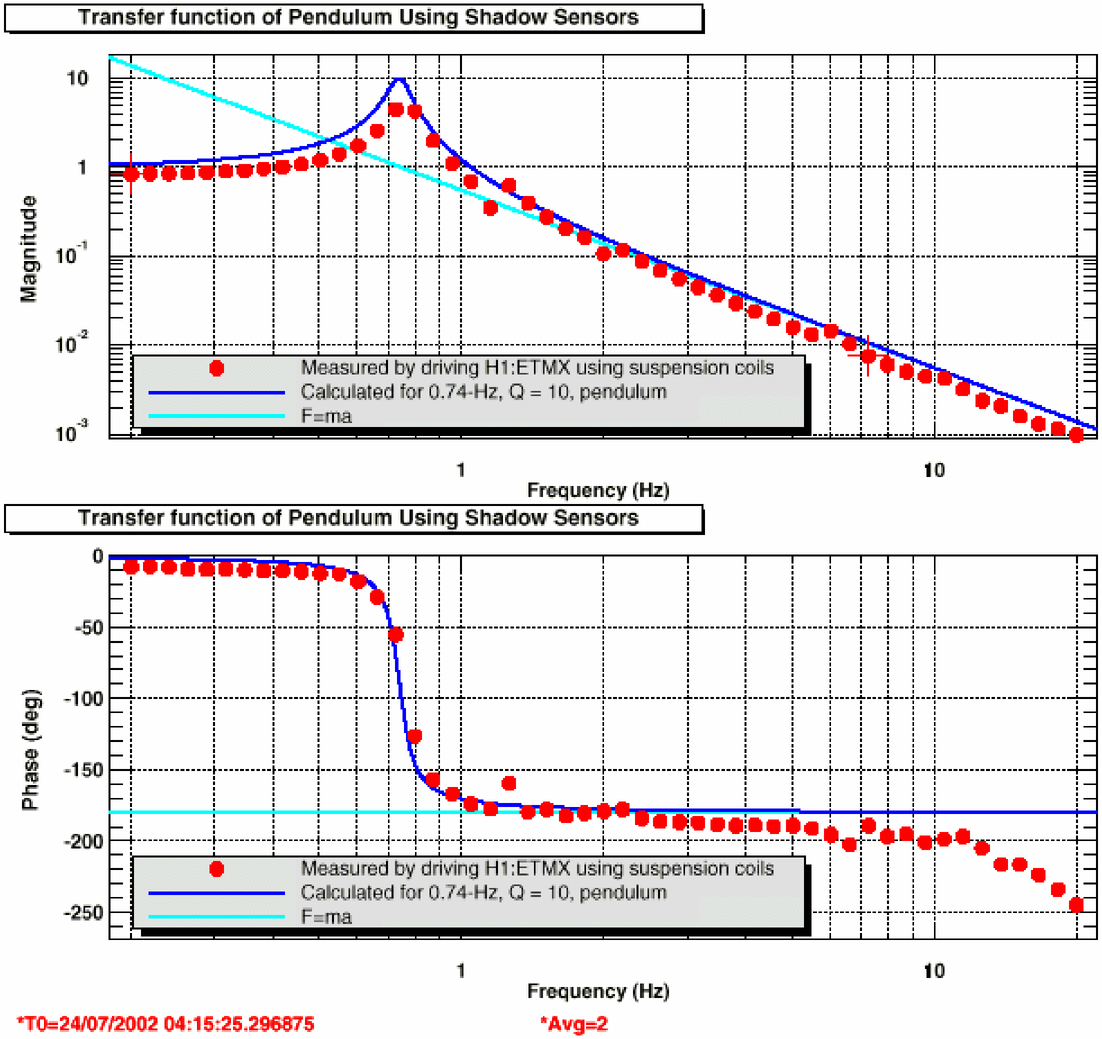


Optics suspended as simple pendulums

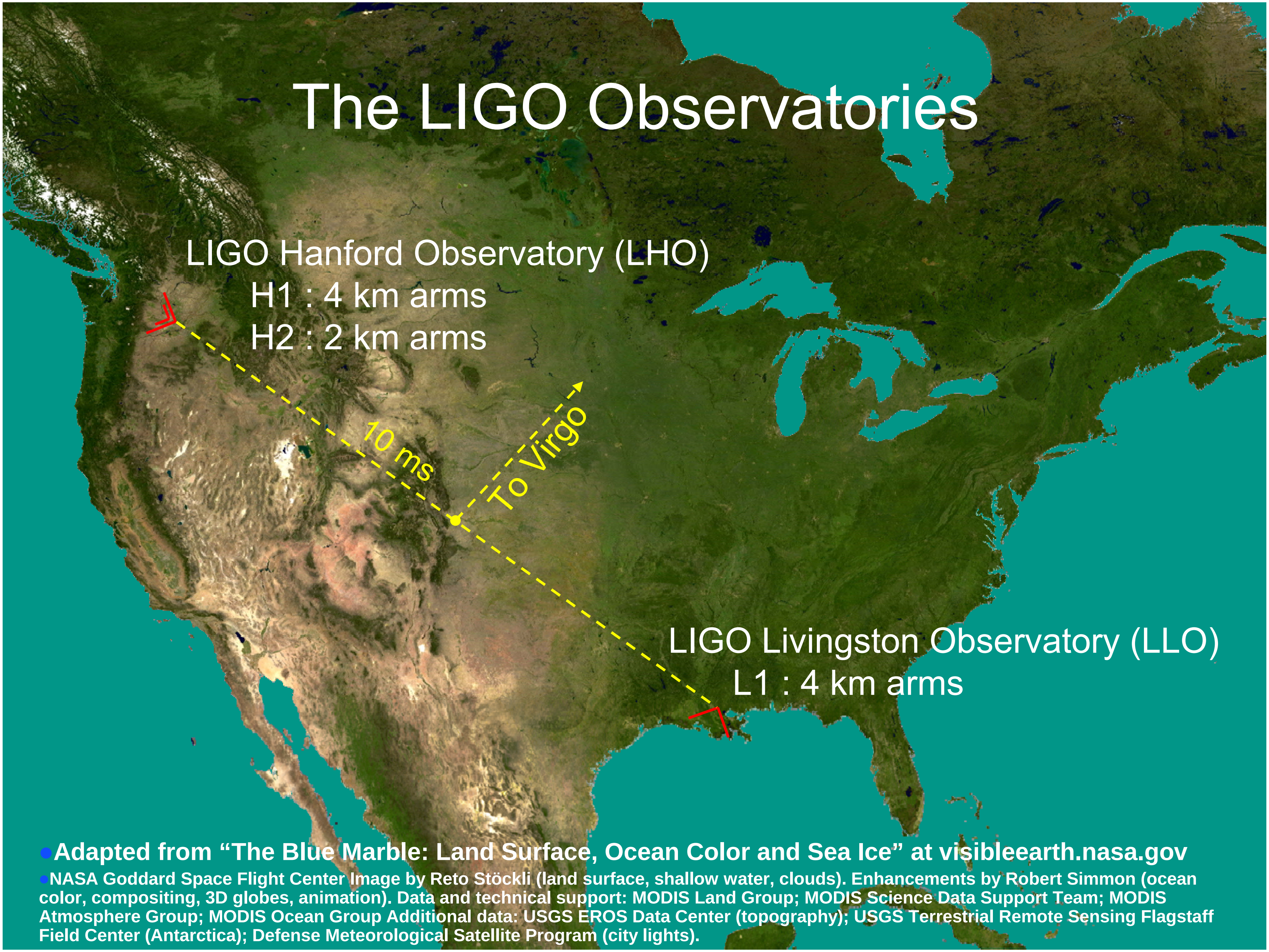
Local sensors/actuators provide damping and control forces

Mirror is balanced on 0.25-mm diameter wire to 1/100th degree of arc

Suspended Mirror Approximates a Free Mass Above Resonance



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).**

The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

Owned by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 600 LIGO Scientific Collaboration members worldwide. Now engaged in joint operations with Virgo.

Interferometers in Europe

**GEO 600 (Germany)
600-m**

**Virgo (Italy)
3-km**

Operated by GEO, member of LIGO Scientific Collaboration

CNRS/INFN collaboration; has joint operating agreement w/ LIGO

Interferometers in Asia, Australia

**TAMA 300 (Japan)
(300-m)**

Longest running detector: 9 data runs!

**AIGO (Australia)
(80-m, but 3-km site)**

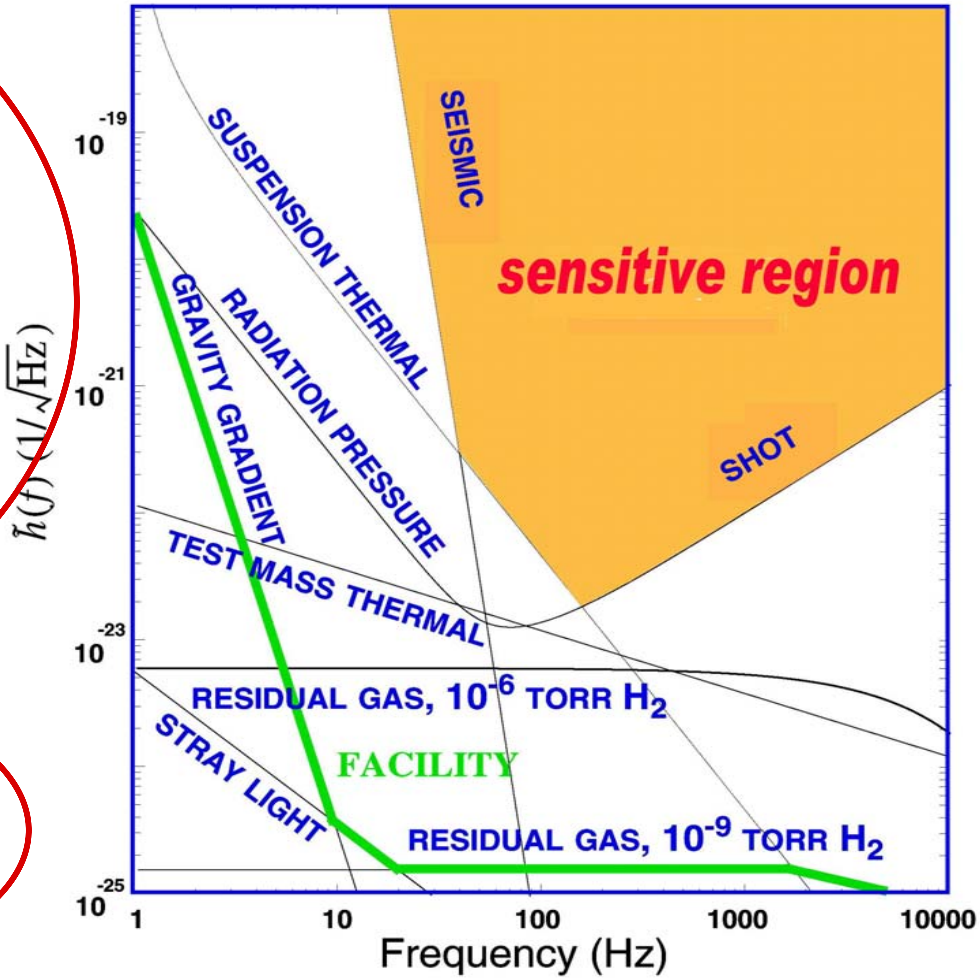
Operated by ACIGA; part of LIGO Scientific Collaboration.

What Limits Sensitivity of Interferometers?

DESIGN

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

COMMISSIONING



Some of the technical challenges for design and commissioning

- ✓ Typical Strains < 10^{-21} at Earth ~ 1 hair's width at 4 light years
- ✓ Understand displacement fluctuations of 4-km arms at the millifermi level (1/1000th of a proton diameter)
- ✓ Control km-scale arm lengths to 10^{-13} meters RMS
- ✓ Detect optical phase changes of ~ 10^{-10} radians
- ✓ Hold mirror alignments to 10^{-8} radians
- ✓ Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors
- Do all of the above 7x24x365

✓ S5 science run 14Nov05 to 30Sep07

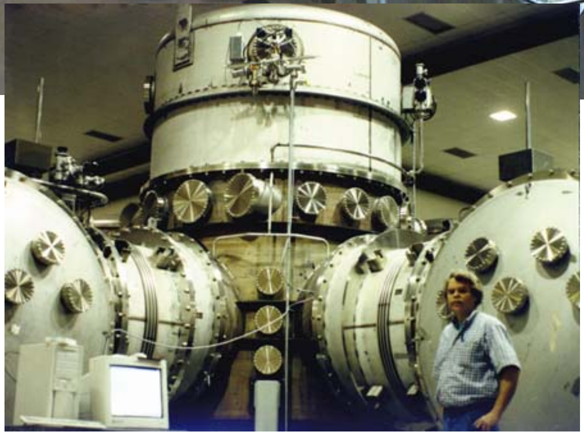
Evacuated Beam Tubes Provide Clear Path for Light

P< 10^{-9} Torr

Portable power supply for bakeout

Vacuum Chambers Provide Quiet Homes for Mirrors

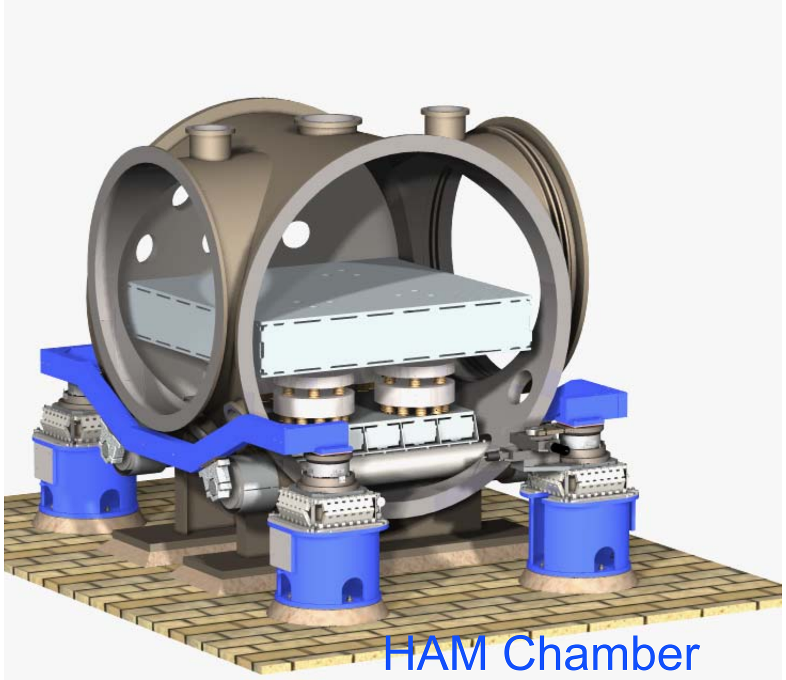
View inside Corner Station

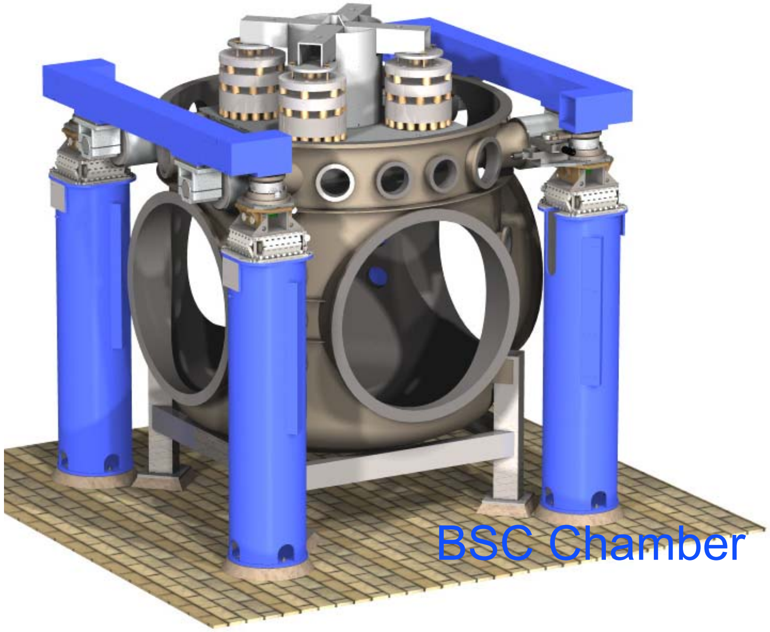


Standing at vertex beam splitter

Vibration Isolation Systems

- Reduce in-band seismic motion by 4 - 6 orders of magnitude
- Little or no attenuation below 10Hz
- Large range actuation for initial alignment and drift compensation
- Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

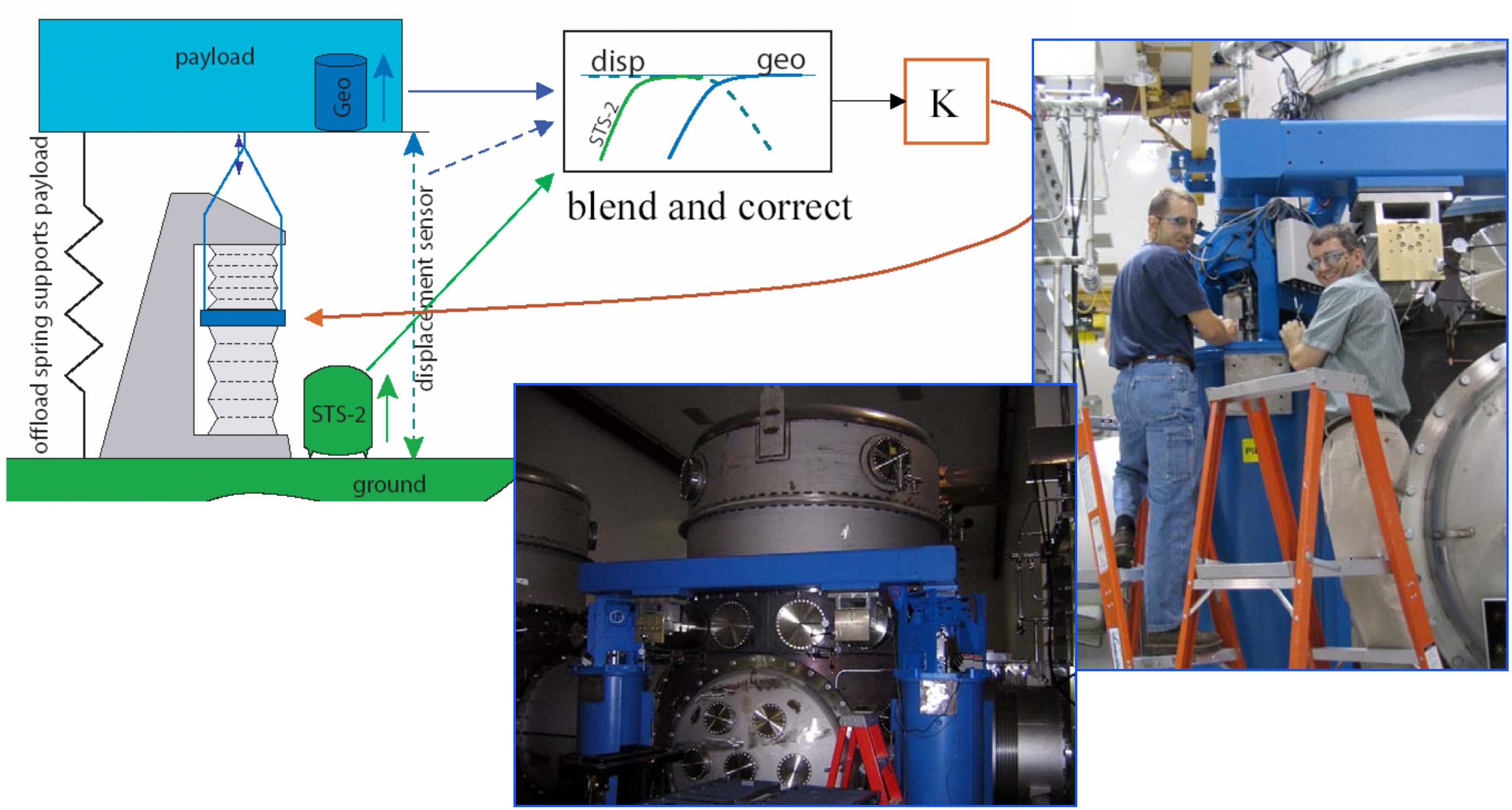

HAM Chamber


BSC Chamber

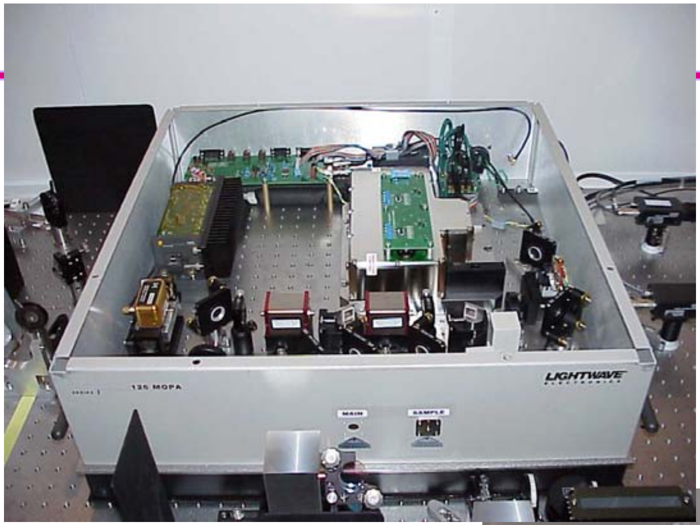
Seismic Isolation: Springs and Masses

damped spring
cross section

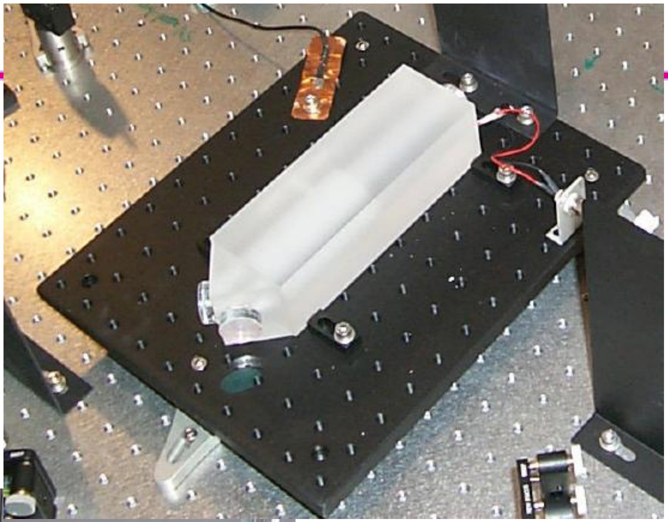
Installation of HEPI at Livingston has improved the stability of L1



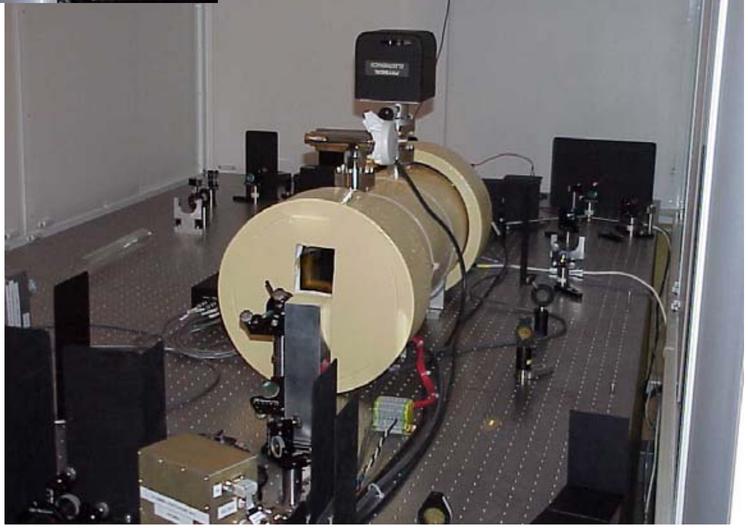
All-Solid-State Nd:YAG Laser



Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics



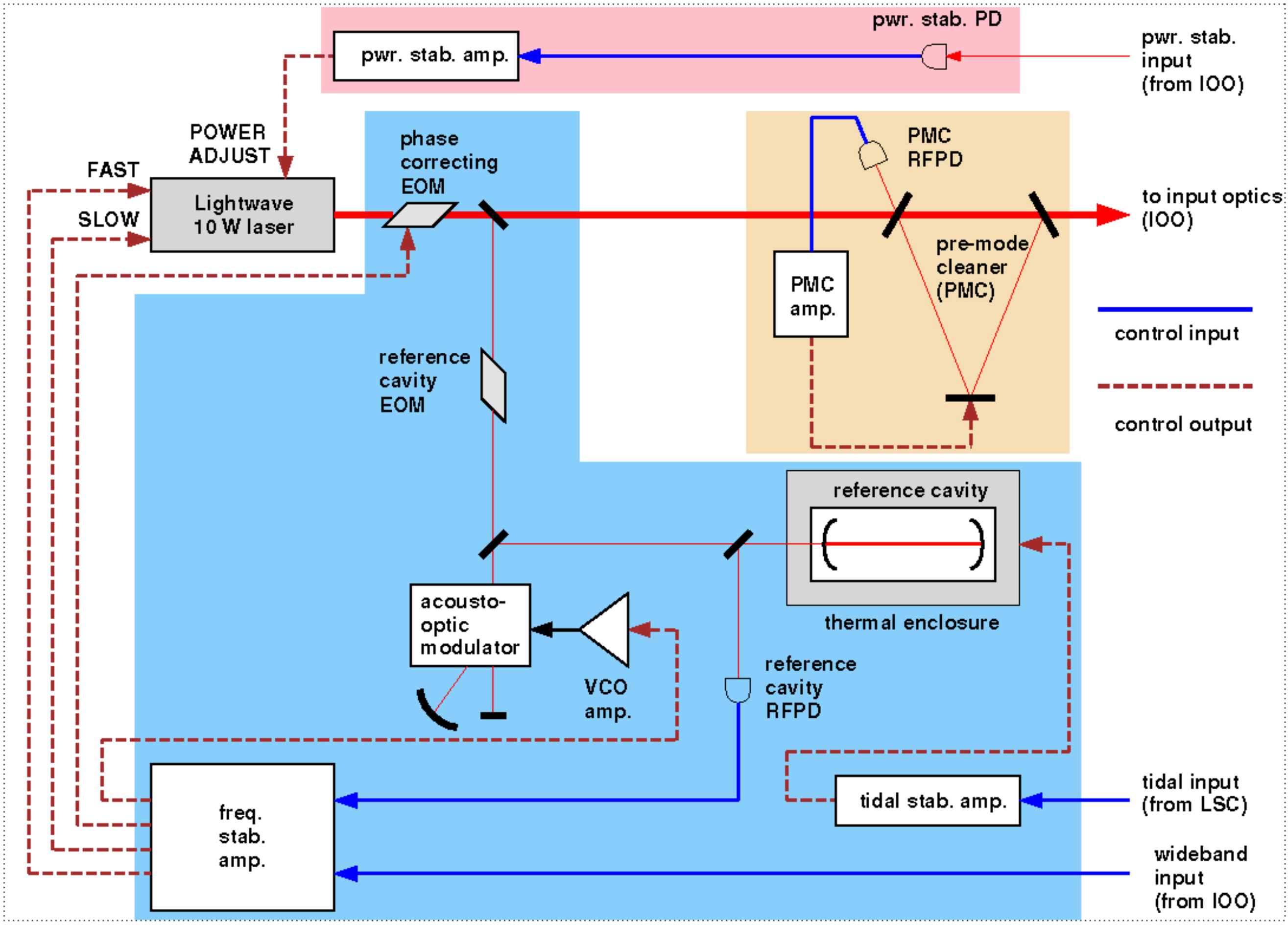
Cavity for
defining beam geometry,
joint development with
Stanford



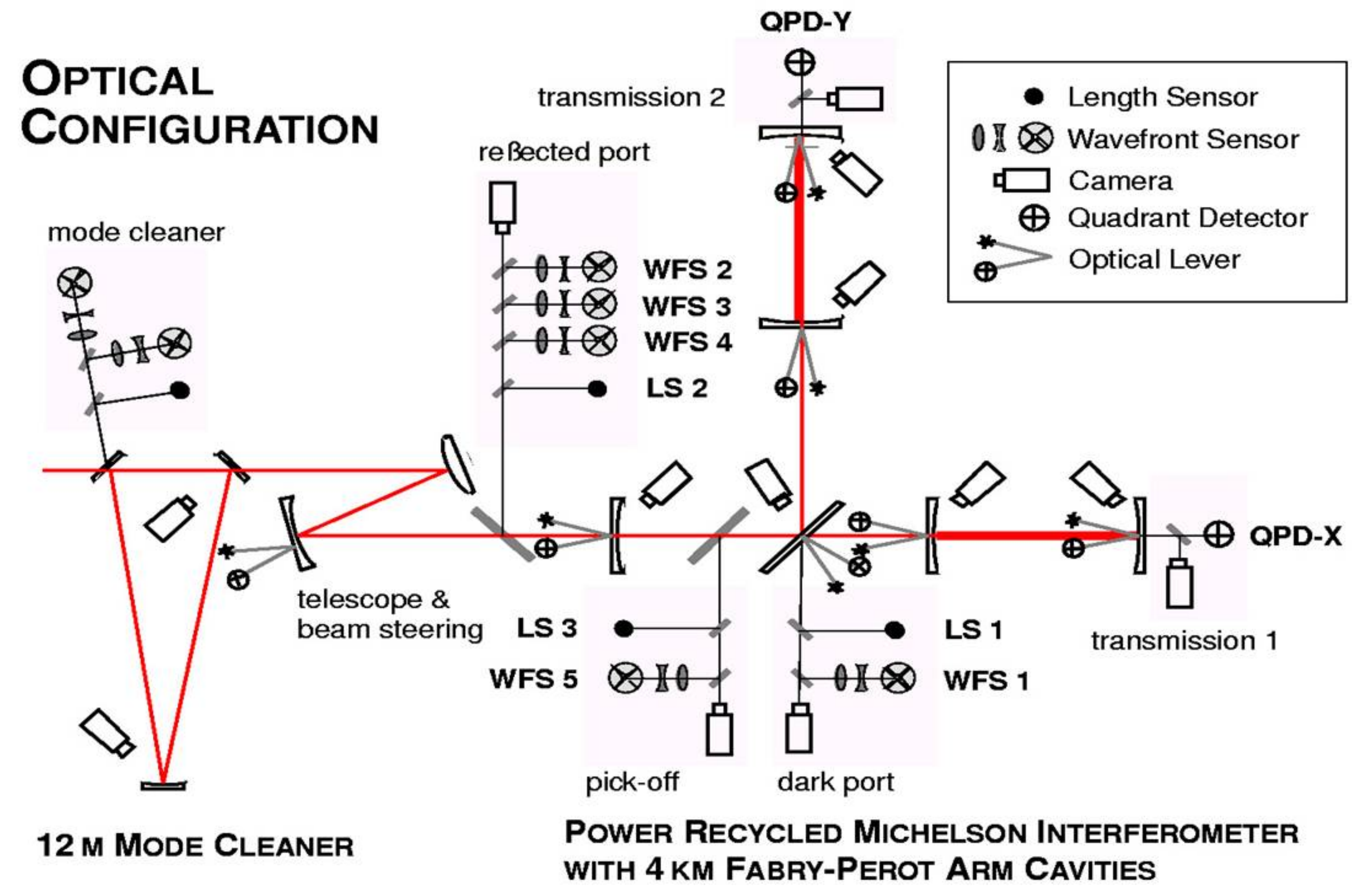
Frequency reference
cavity (inside oven)

Pre-Stabilized Laser System

- Laser source
- Frequency pre-stabilization and actuator for further stab.
- Compensation for Earth tides
- Power stab. in GW band
- Power stab. at modulation freq. (~ 25 MHz)

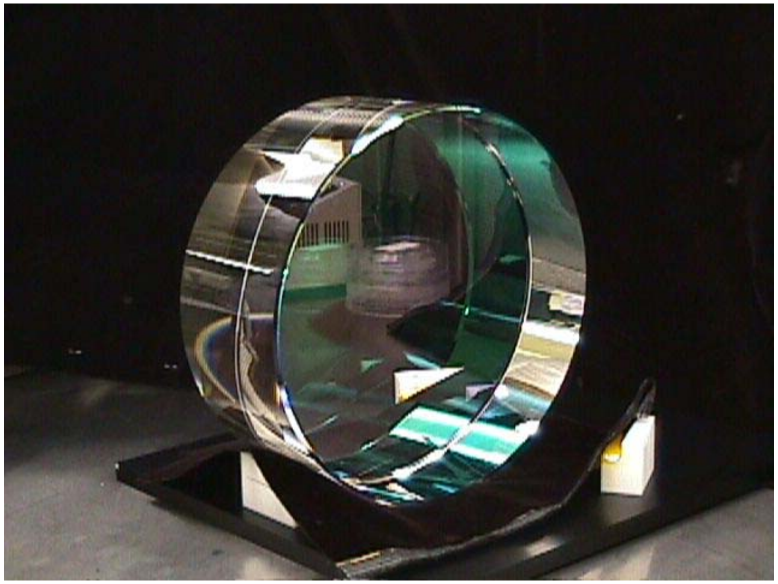


Closer look - more lasers and optics



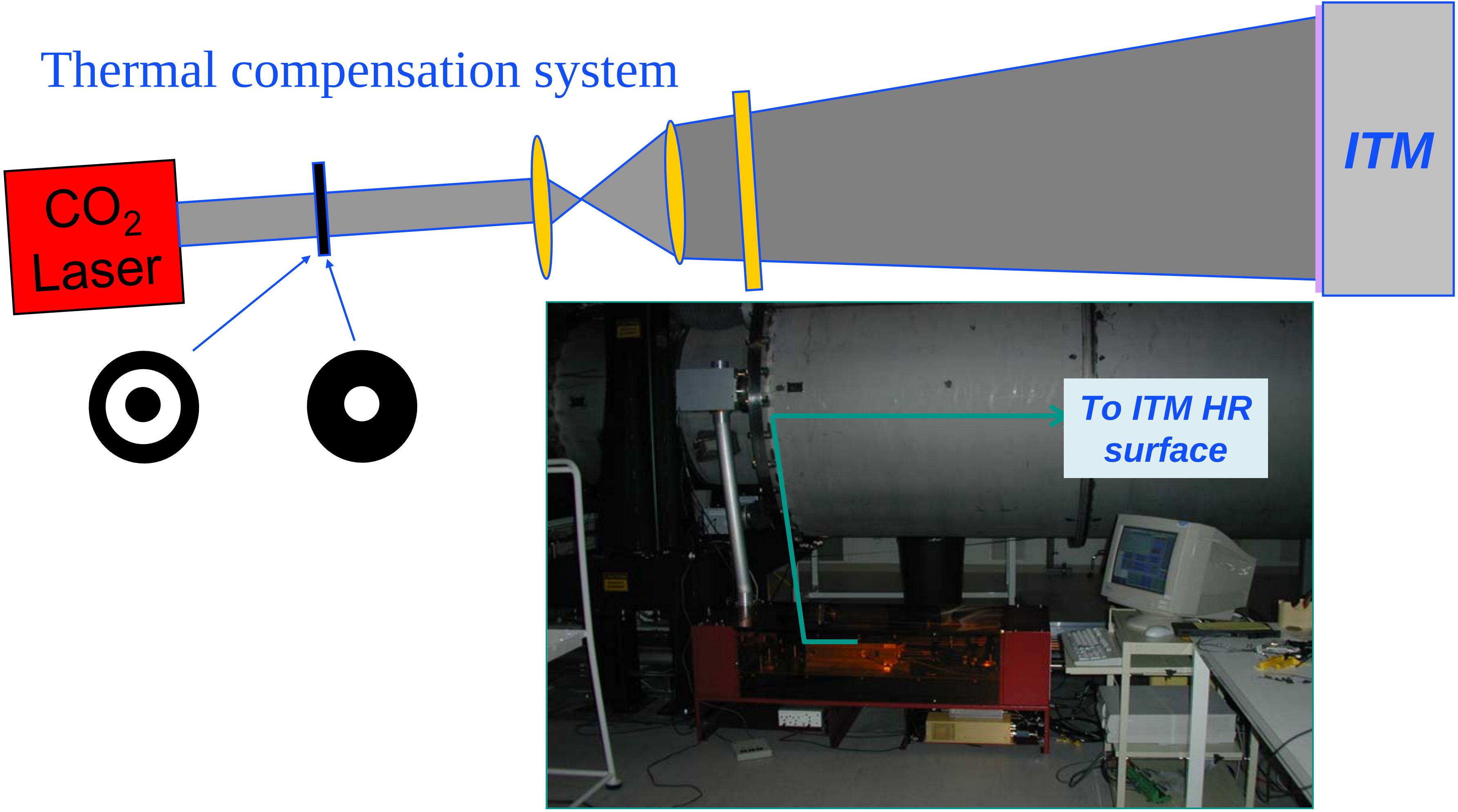
Core Optics

- Substrates: SiO_2
    - » 25 cm Diameter, 10 cm thick
    - » Homogeneity $< 5 \times 10^{-7}$
    - » Internal mode Q's $> 2 \times 10^{6}$
- Polishing
    - » Surface uniformity < 1 nm rms
    - » Radii of curvature matched < 3%
- Coating
    - » Scatter < 50 ppm
    - » Absorption < 2 ppm
    - » Uniformity $<10^{-3}$
- Production involved 6 companies, NIST, and LIGO

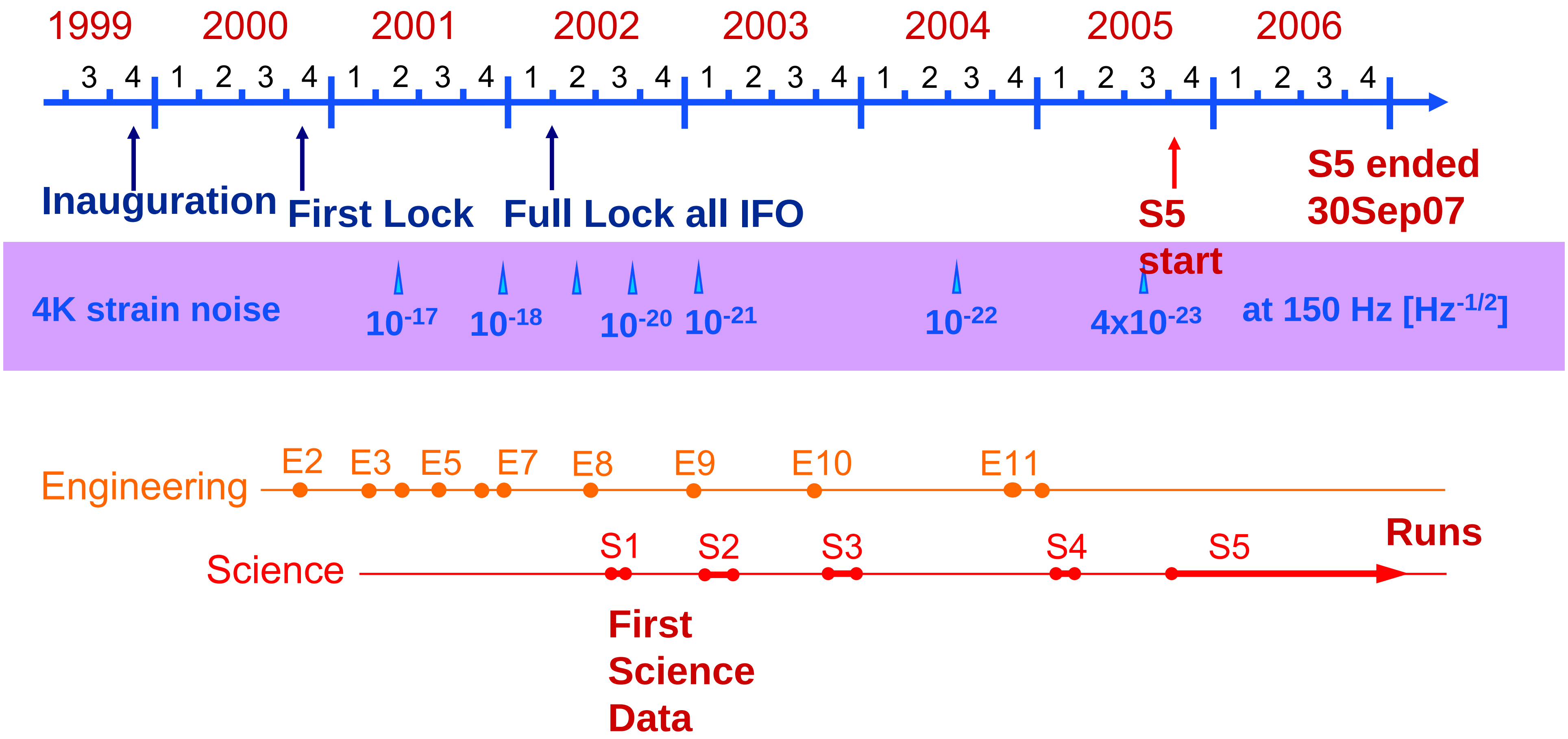


High laser power operation requires adaptive tuning of optical figure

Thermal compensation system



Commissioning and Running 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

S5 start

S5 ended 30Sep07

4K strain noise **10^{-17}** **10^{-18}** **10^{-20}** **10^{-21}** **10^{-22}** **4×10^{-23}** **at 150 Hz [$Hz^{-1/2}$]**

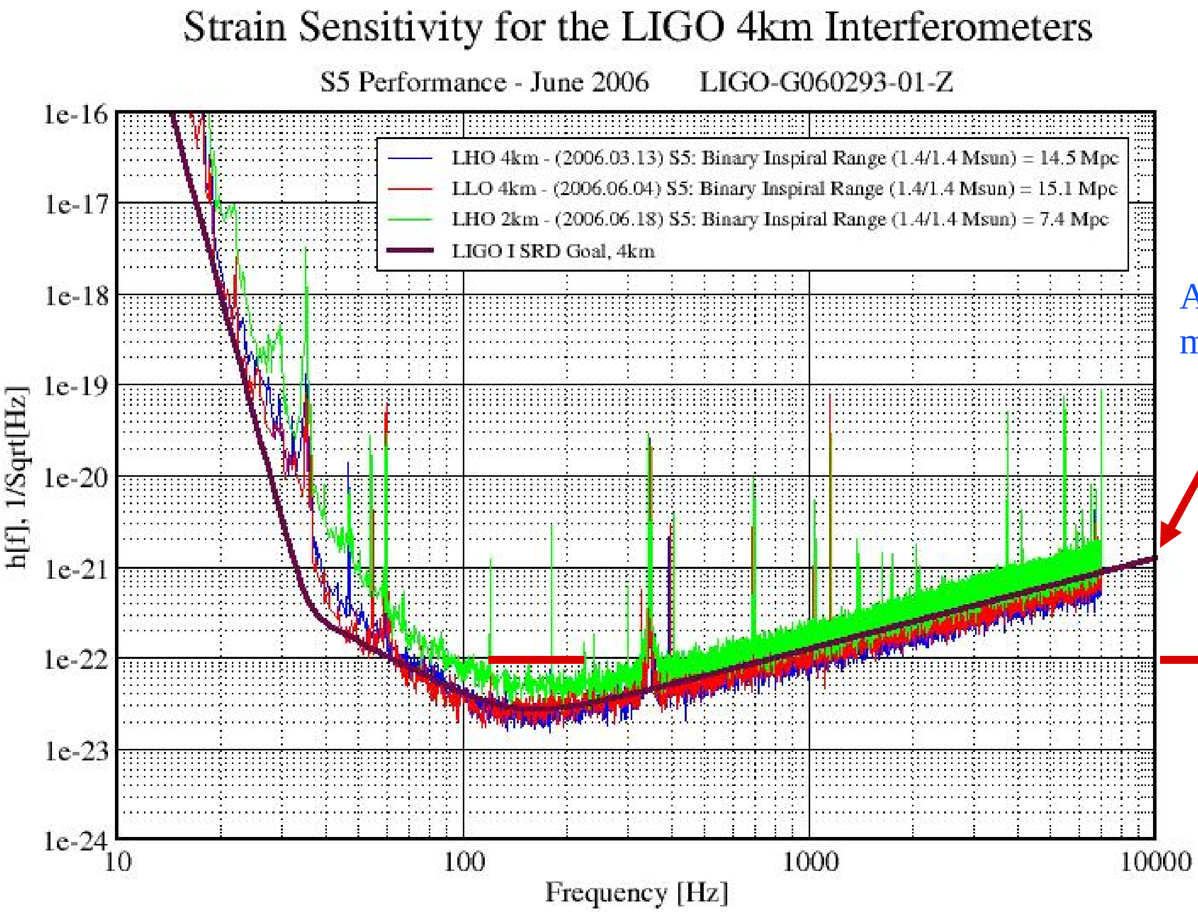
Engineering E2 E3 E5 E7 E8 E9 E10 E11

Science S1 S2 S3 S4 S5

Runs

First Science Data

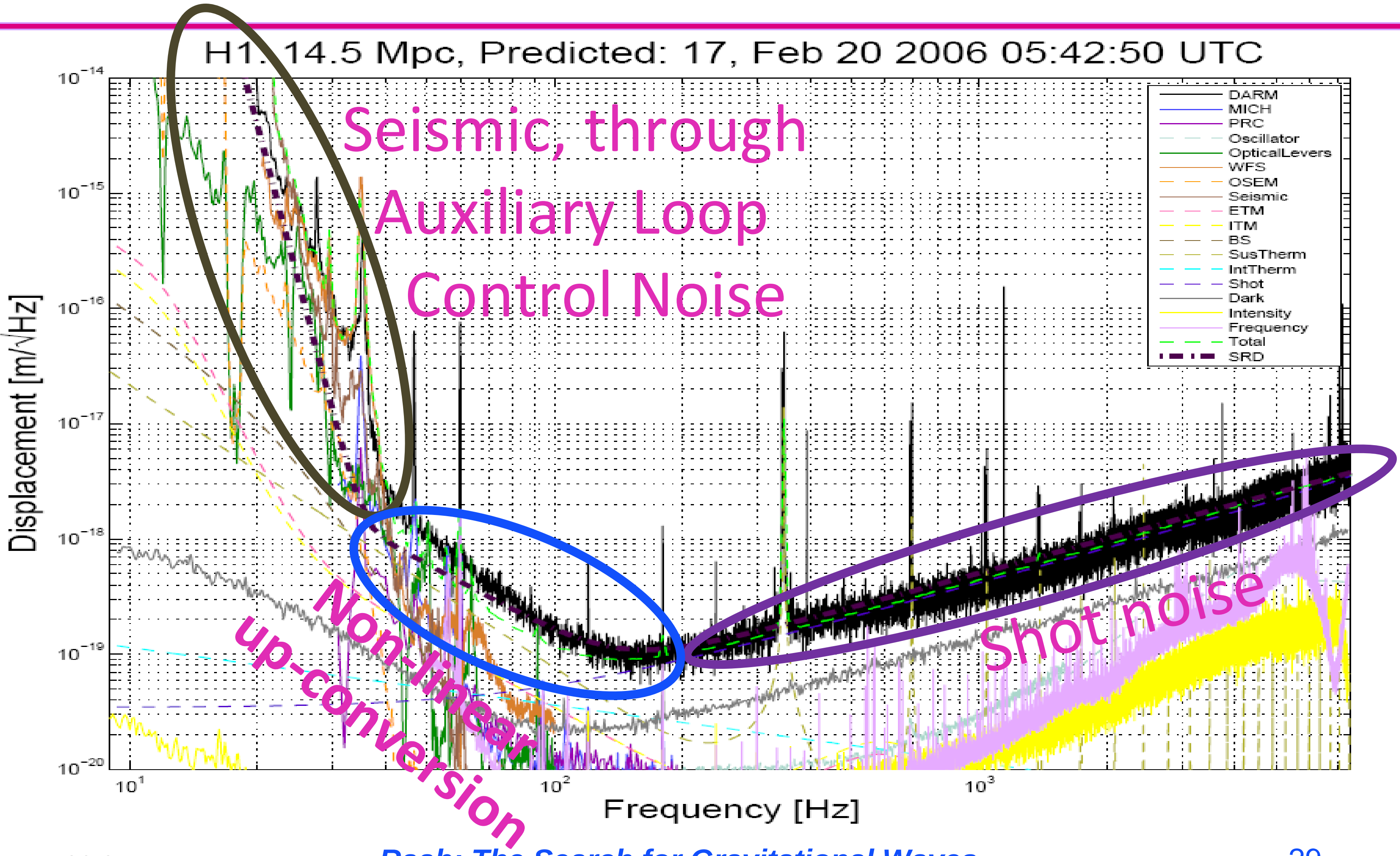
Initial LIGO (iLIGO) detectors are working to 1989 design goals



A possible design that meets goal sensitivity

Goal sensitivity

S5 Noise Analysis



Seismic, through Auxiliary Loop Control Noise

Non-linear up-conversion

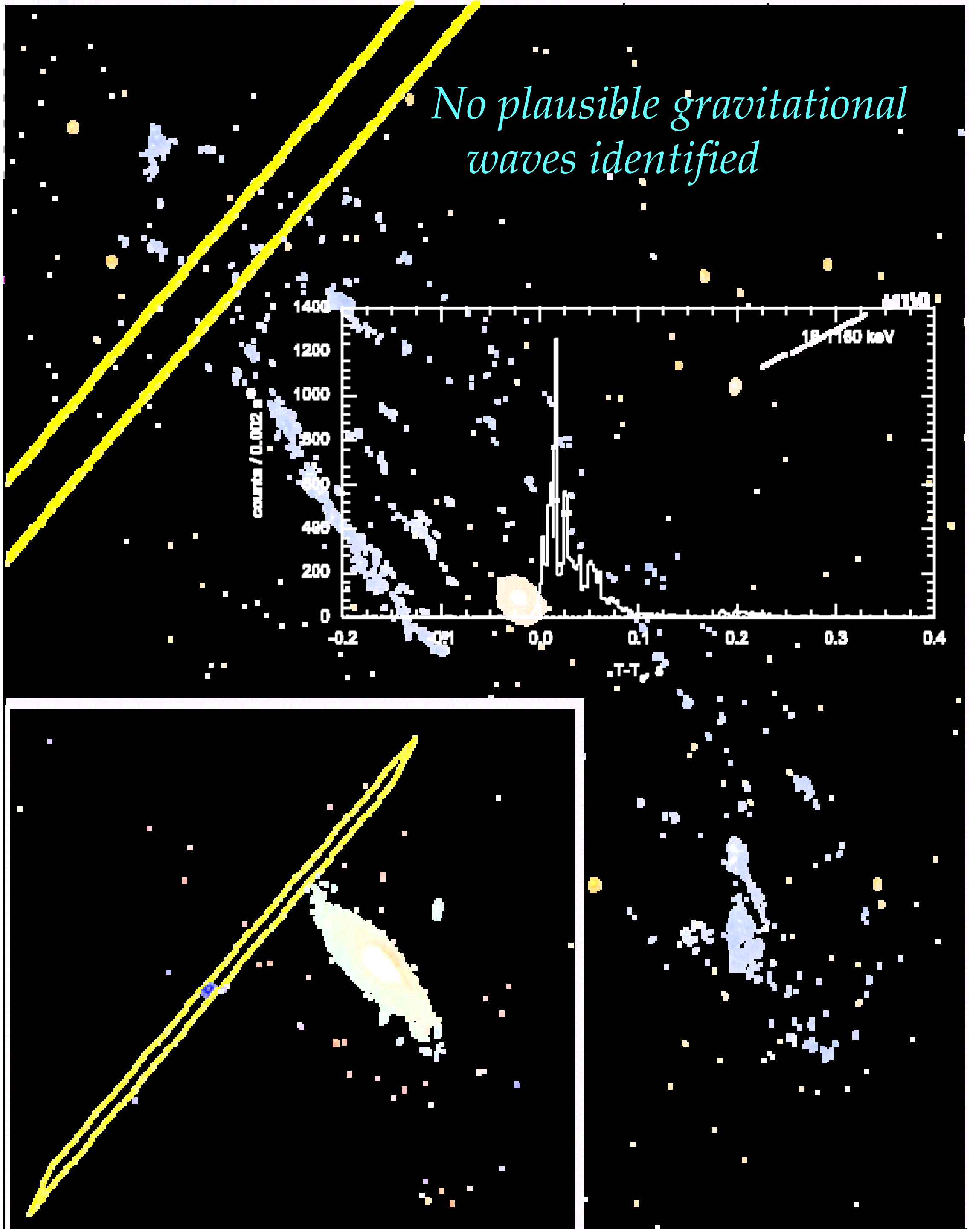
Shot noise

Science to date

- No published detection yet, but ~35 papers based on search data interpretation, such as
  - Limit on %-age of energy emitted by Crab Pulsar going into GWs
  - Limits on the ellipticities of known pulsars
  - Limit on GW background from early universe
  - Limits on GW waves emitted by GRBs and SGRs
  - Limits on rates of mergers of black holes and neutron stars
  - Determined that the short GRB 070201, possibly in M31, was either a compact binary merger at much greater distance or a different source in M31, such as an SGR

What to expect from S5 analyses

- Sensitivity to bursts ~ few times 0.1 Msolar @ 20 Mpc
- Sensitivity to neutron-star inspirals at Virgo cluster
- Pulsars
  - » expect best limits on known neutron star ellipticities at few x10^{-7}
  - ✓» beat spindown limit on Crab pulsar
  - » Hierarchical all-sky/all-frequency search
- Cosmic GW background limits expected to be near $\Omega_{GW} \sim 10^{-5}$
- Perhaps a discovery?


No plausible gravitational waves identified

GRB 070201

- Short gamma-ray burst
- IPN error box included M31!
- **Exclude** any compact binary progenitor in our simulation space at the distance of M31 at > 99% confidence level
- **Exclude** compact binary progenitor with masses

  $1\ M_{\odot} < m_1 < 3\ M_{\odot}$ and
  $1\ M_{\odot} < m_2 < 40\ M_{\odot}$ with $D <$ 3.5 Mpc away at 90% CL

From Discovery to Astronomy

2nd generation:

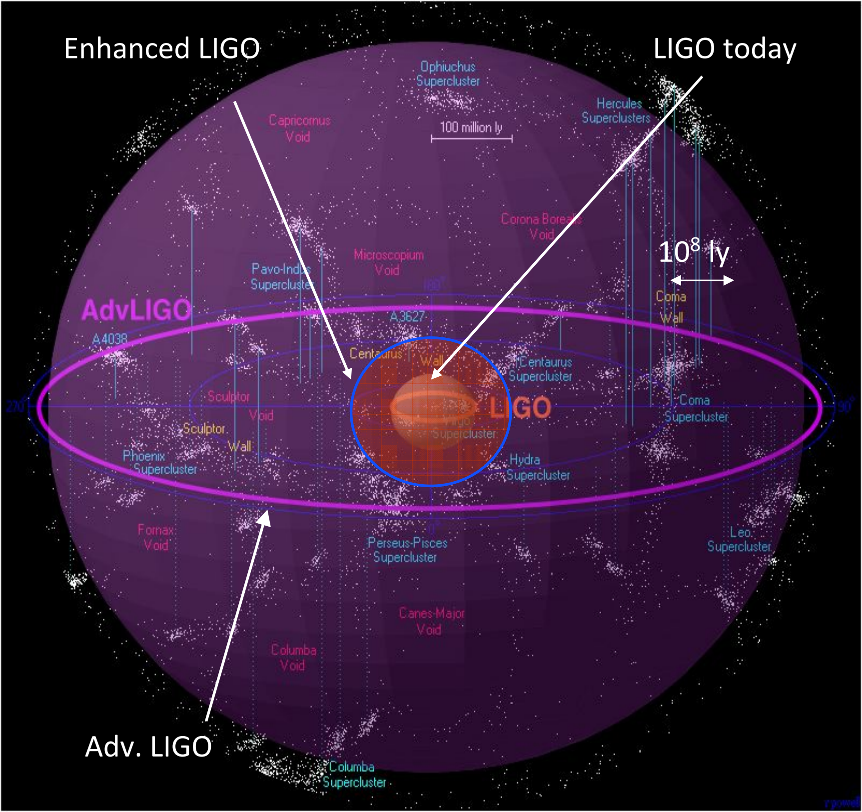
Advanced LIGO

GOAL:

sensitivity 10x better →

look 10x further →

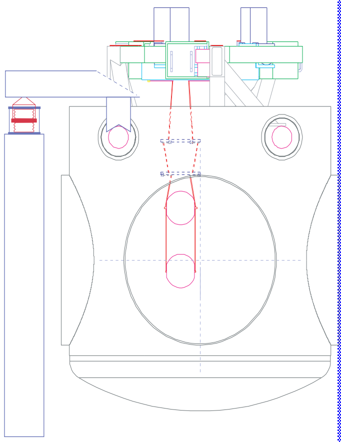
Detection rate 1000x larger



Credit: R.Powell, B.Berger

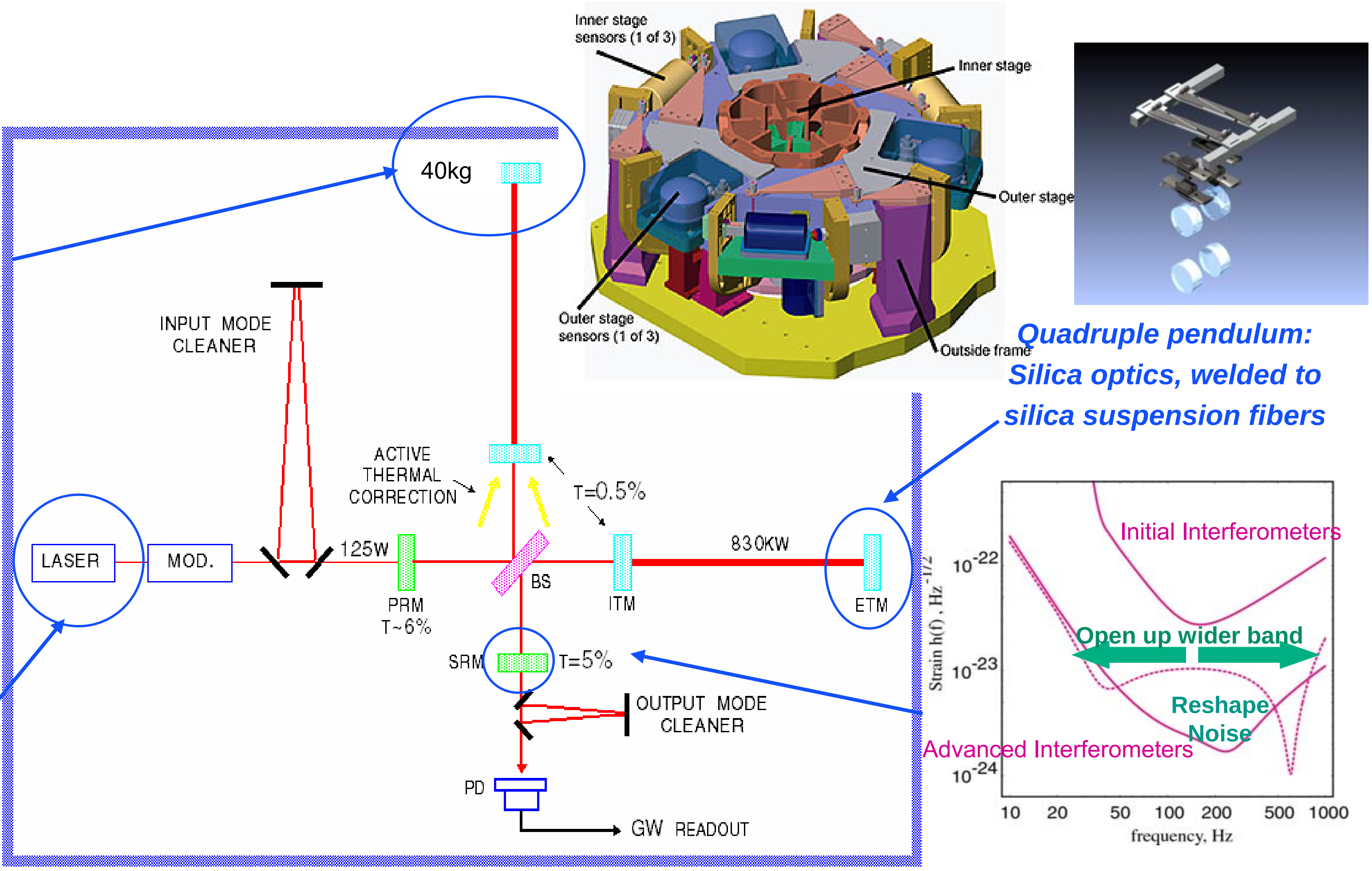
Advanced LIGO construction (aLIGO) started 1Apr2008

Major technological differences between LIGO and Advanced LIGO



Active vibration isolation systems

High power laser (180W)



Quadruple pendulum: Silica optics, welded to silica suspension fibers

Advanced interferometry Signal recycling

LIGO-G080572-00-W

Raab: The Search for Gravitational Waves

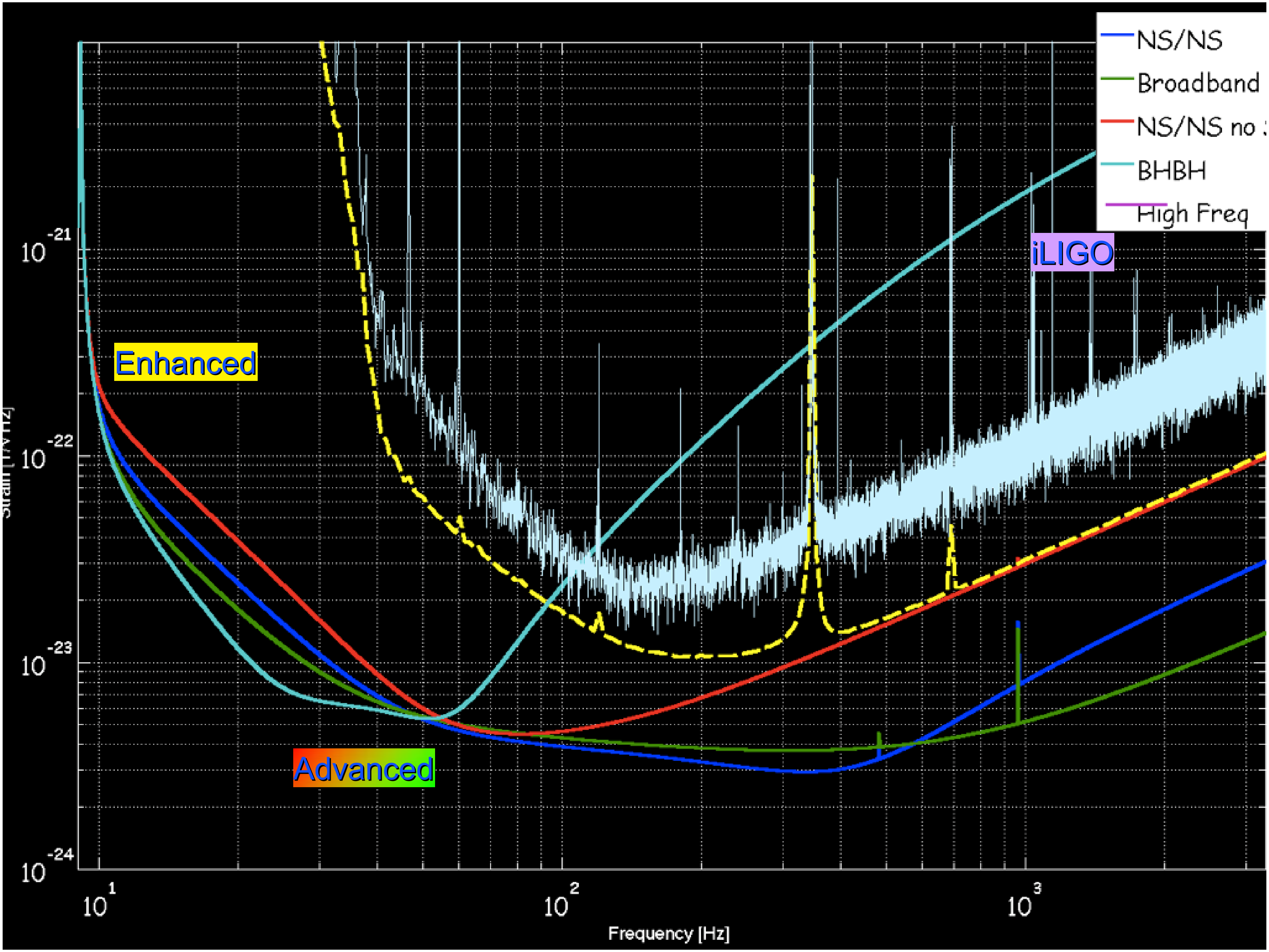
Enhancing 1st generation LIGO interferometers

- Construction of AdLIGO instrumentation has begun
- But installation doesn’t start till ~2011

- In the meantime, exploit opportunity to
  - » Implement selected upgrades & run for ~ 1 year
  - » Gain experience with some Advanced LIGO technologies
  - » Goal: strain sensitivity improvement of 2 - 2.5
    - – Increases event rate by x10

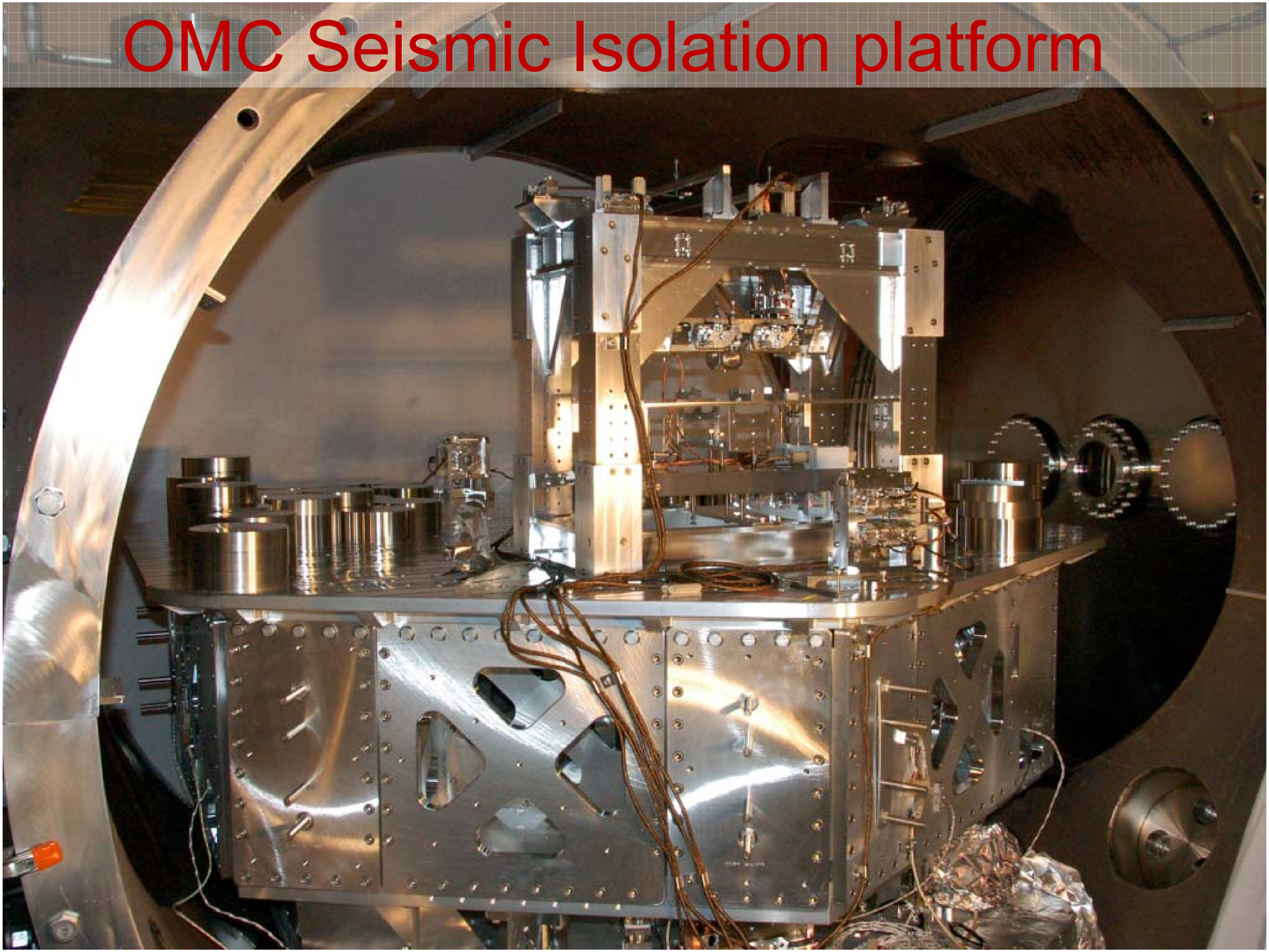
Enhanced LIGO Upgrades (eLIGO)

- Major upgrades
  - ✓ » 35 Watt Laser (lower shot noise)
  - ✓ » Switch to DC readout
  - ✓ » Output Mode cleaner (reduce junk light)
    - – Including new internal seismic isolation & suspension
  - » Other misc.:
    - ✓ – Replace mirrror actuation magnets (eliminate Domain-flipping)
    - ✓ – Replaced Earthquake stops (mitigate charging of optics)
    - In progress… – Upgrade Thermal compensation system (handle power)
    - ✓ – New Faraday isolator (handle power)

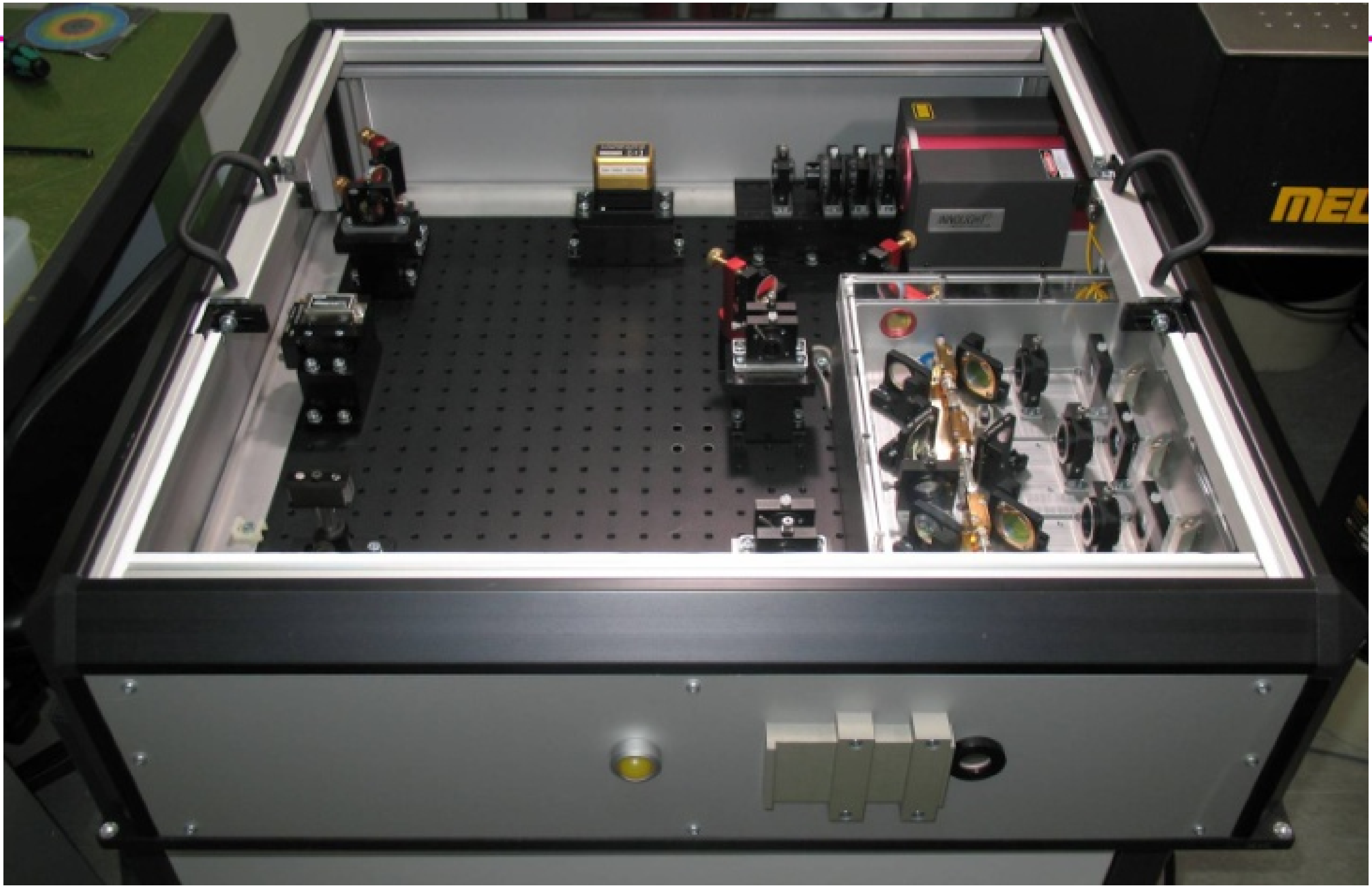


NS/NS
Broadband
NS/NS no
BHBH
High Freq
iLIGO
Enhanced
Advanced
Strain
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Frequency [Hz]

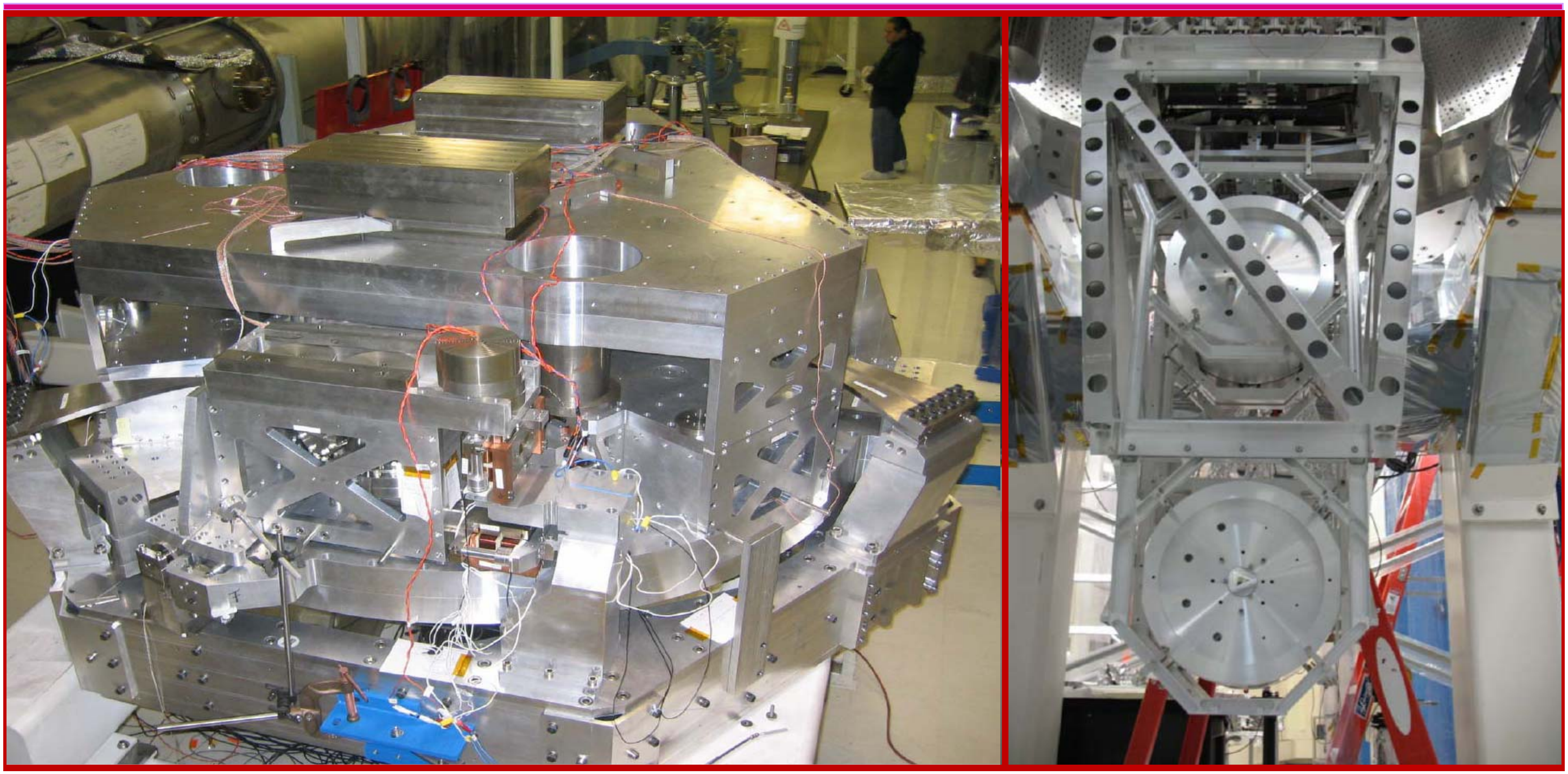
OMC Seismic Isolation platform



35W Laser from LZH



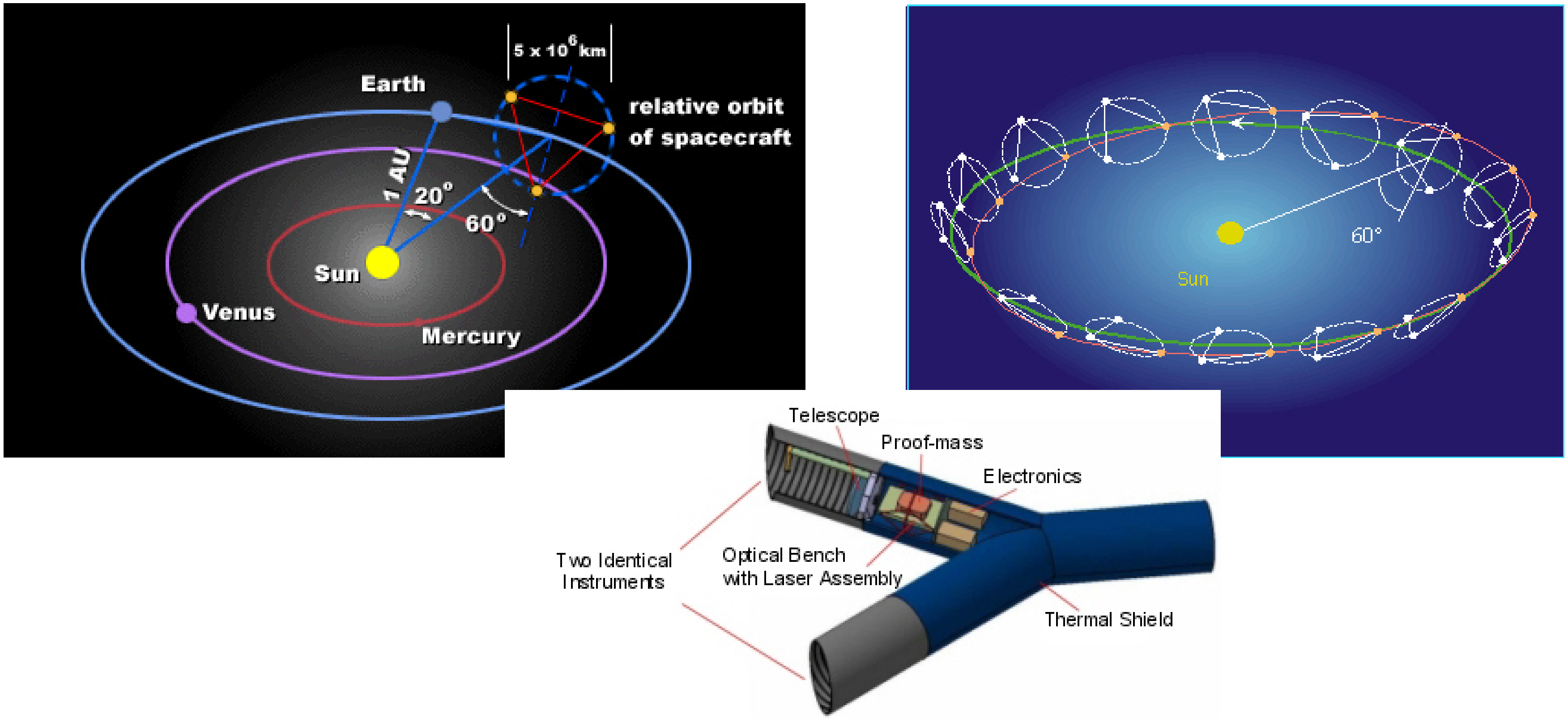
Seismic Isolation & Suspension undergoing testing at MIT



What’s next?

- Detection is possible, but not assured in iLIGO (S5) or eLIGO (S6) data.
- Advanced LIGO will usher in the age of gravitational-wave astronomy with routine detection of sources.
- Advanced LIGO will also reach the low-frequency limit of detectors on Earth’s surface due to surface gravity fluctuations.
- What’s next?

Very low frequency detection from space

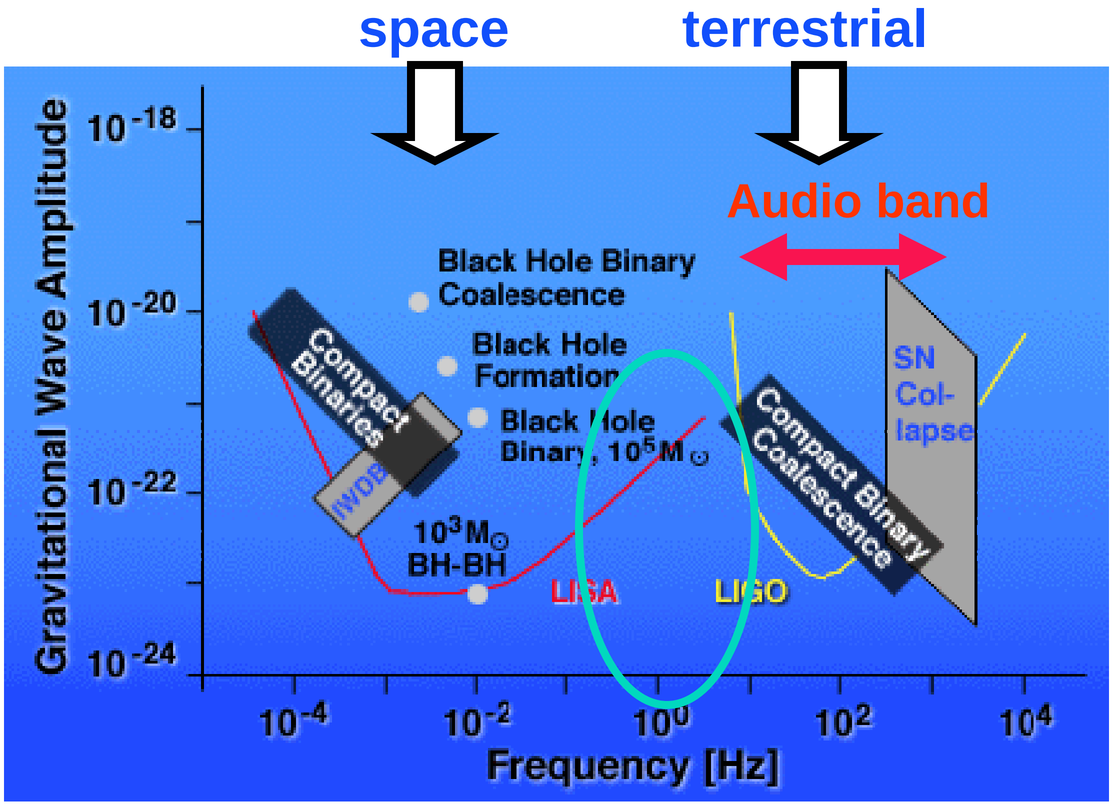


Planning underway for space-based detector, LISA, hoping to fly in next decade to open up a lower frequency band

Different Frequency Bands of Laser-Based Detectors and Sources

There exists a hole in the coverage afforded by currently planned terrestrial surface and space-based gravitational-wave detectors

Might be filled by future space mission or by detectors beneath Earth’s surface



Summary

- Km-scale interferometers are now operating reliably at sensitivities where detections are possible.
- Astrophysically interesting observational constraints are being set by latest search run.
- In less than a decade, GW astronomy should be in place with routine detections shedding light on the endpoints of stellar evolution.
- Within the next 10-15 years, LISA should be providing data on much more massive objects like super-massive black holes.

It’s never as easy as it looks…