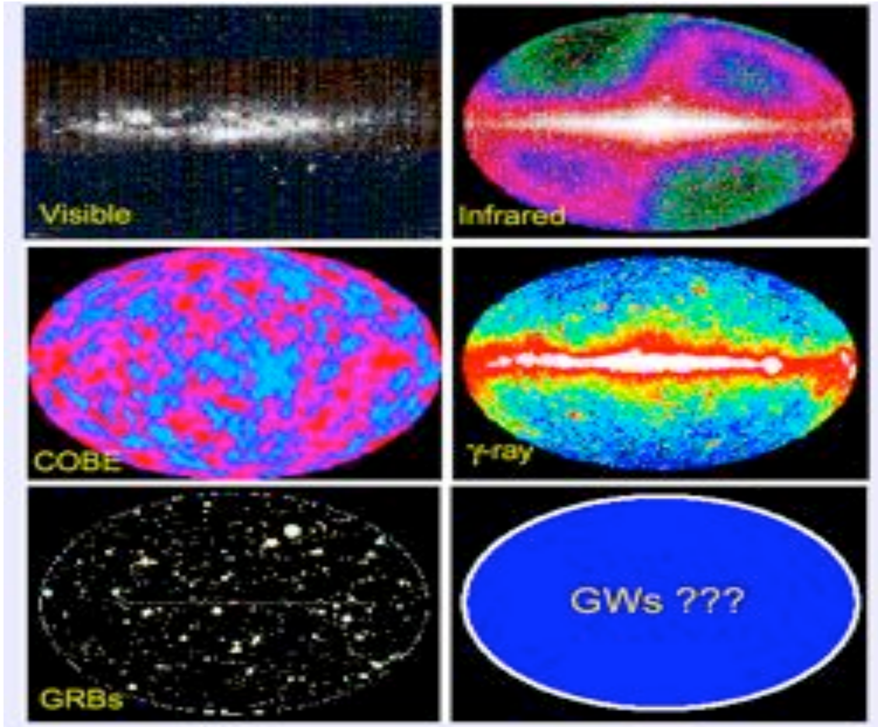
Status and perspectives of the Gravitational-Wave search in the US with LIGO

Fred Raab,

LIGO Hanford Observatory,

on behalf of the LIGO Scientific Collaboration

27 February 2007

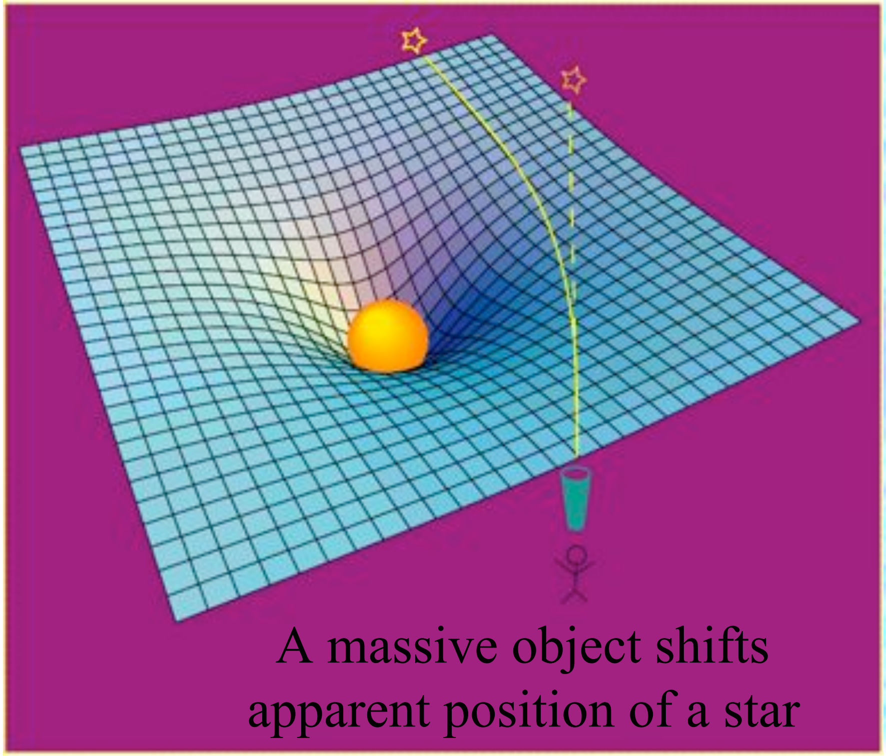


LIGO-G070024-01-W

Outline

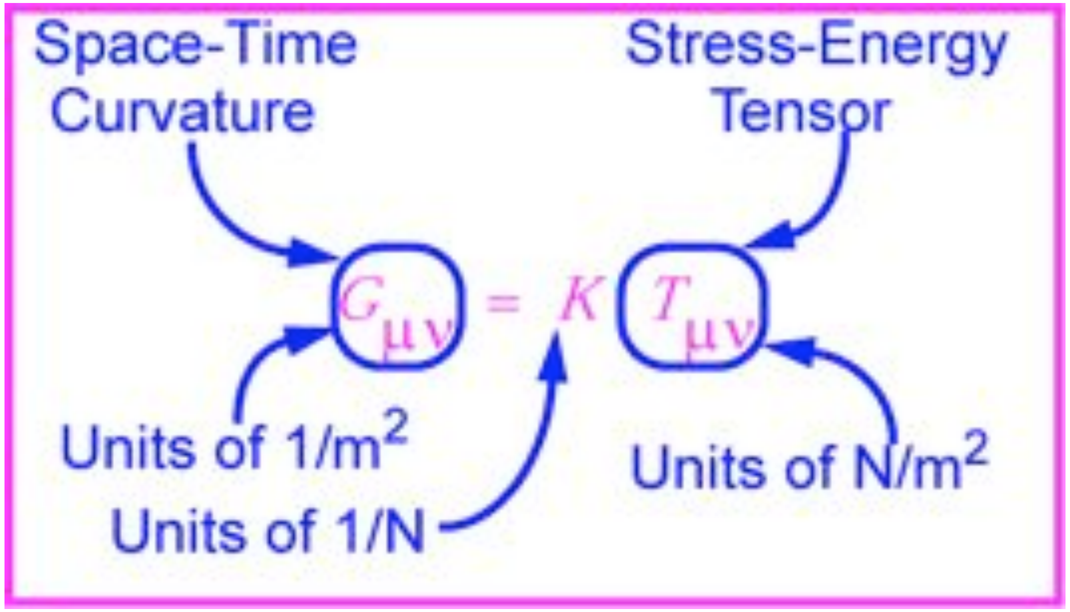
- Introduce topic with some tutorial material
- Show some pictures
- Discuss initial detector performance and propsects for current science run
- Advanced detector development
- Some closing thoughts about the long term (after 2015)

Principle of Equivalence + Special Relativity ⇒ Gravitational Waves



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!



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

⇒ Wave can carry huge energy with miniscule amplitude!

$$h \sim (G/c^4)\,(E_{NS}/r)$$

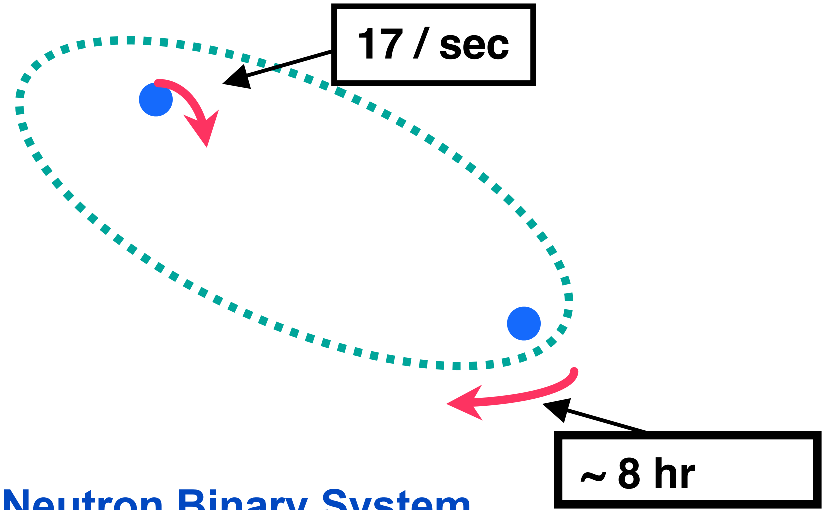
Gravitational Waves

known to exist, just hard to find

Emission of gravitational waves

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars

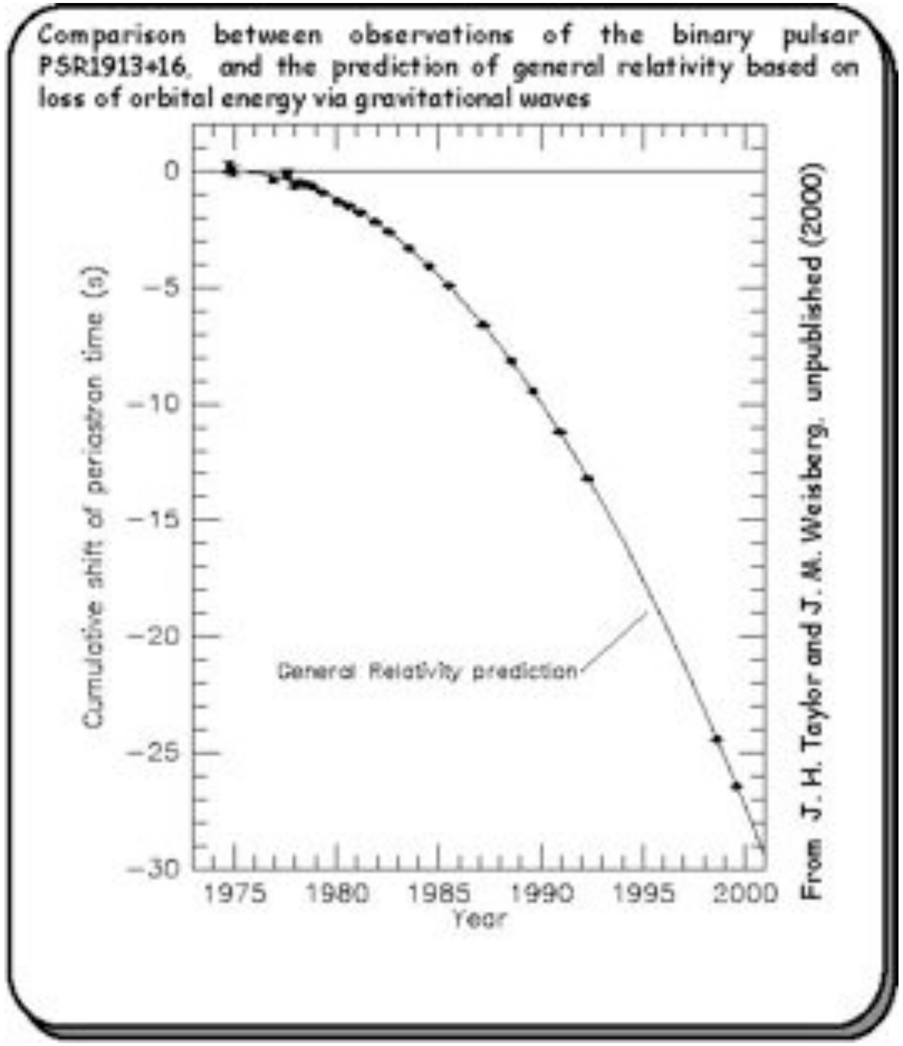


Neutron Binary System

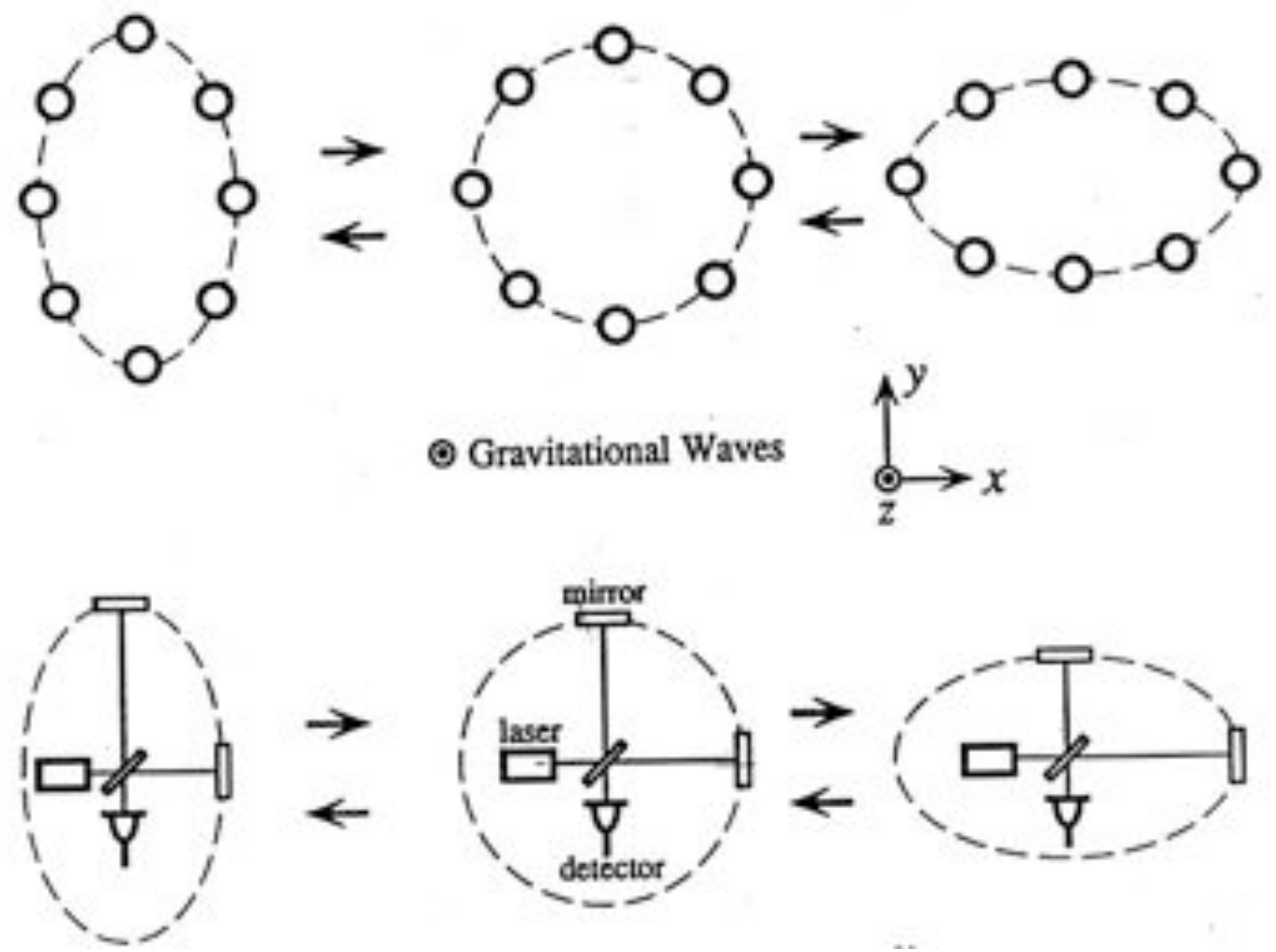
- **separated by 10^6 miles**
- **$m_1 = 1.4m_{\odot}$; $m_2 = 1.36m_{\odot}$; $\varepsilon = 0.617$**

Prediction from general relativity

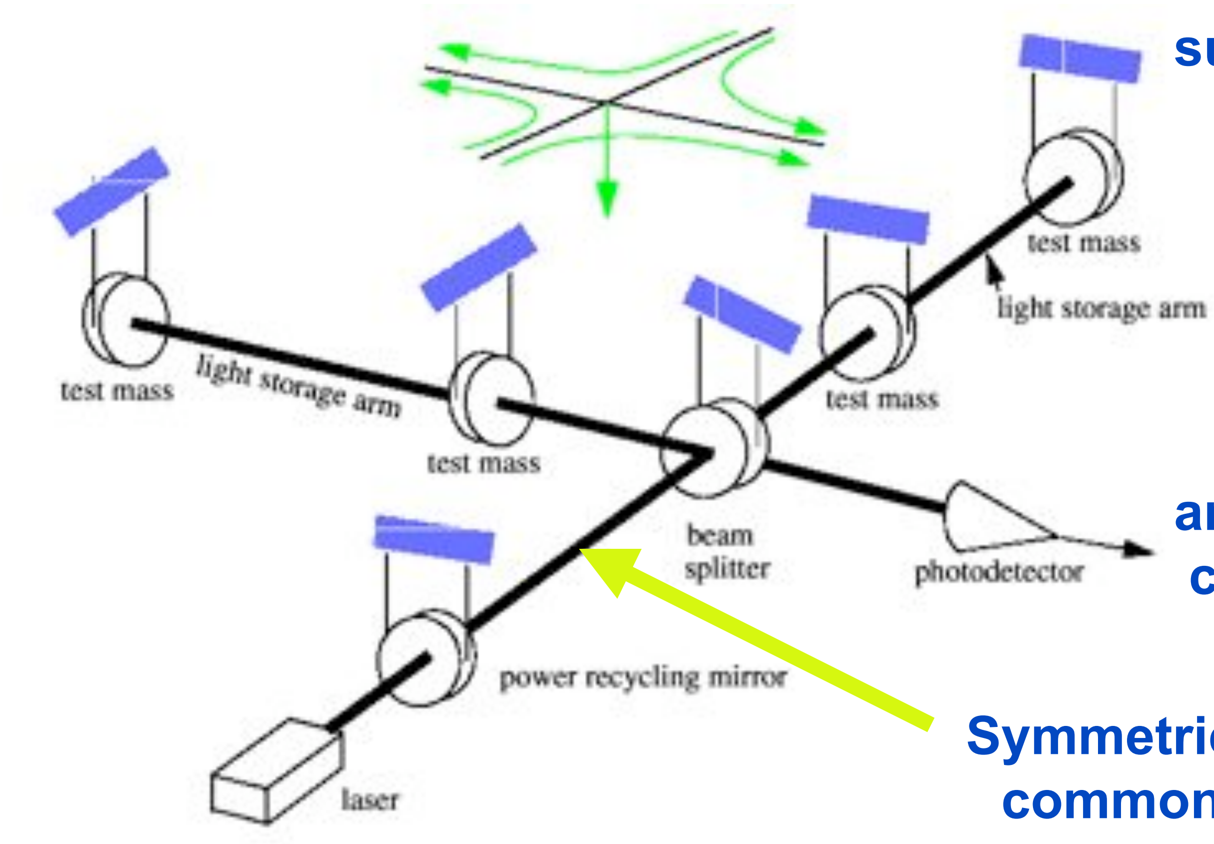
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**



Basic Signature of Gravitational Waves for All Detectors



Initial LIGO: Power-recycled Fabry-Perot-Michelson



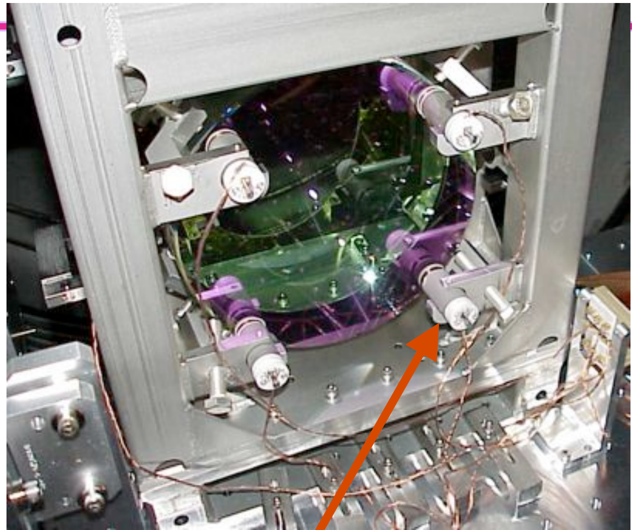
suspended mirrors mark inertial frames

antisymmetric port carries GW signal

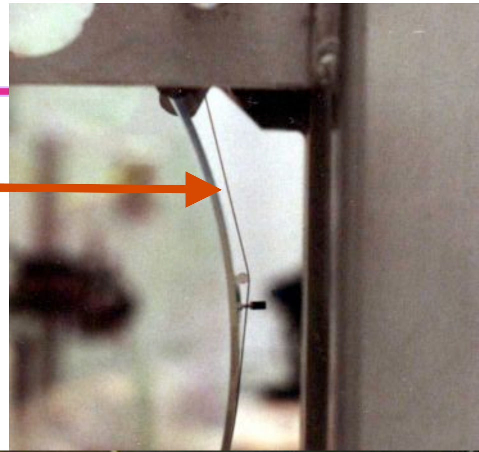
Symmetric port carries common-mode info

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

Core Optics Suspension and Control



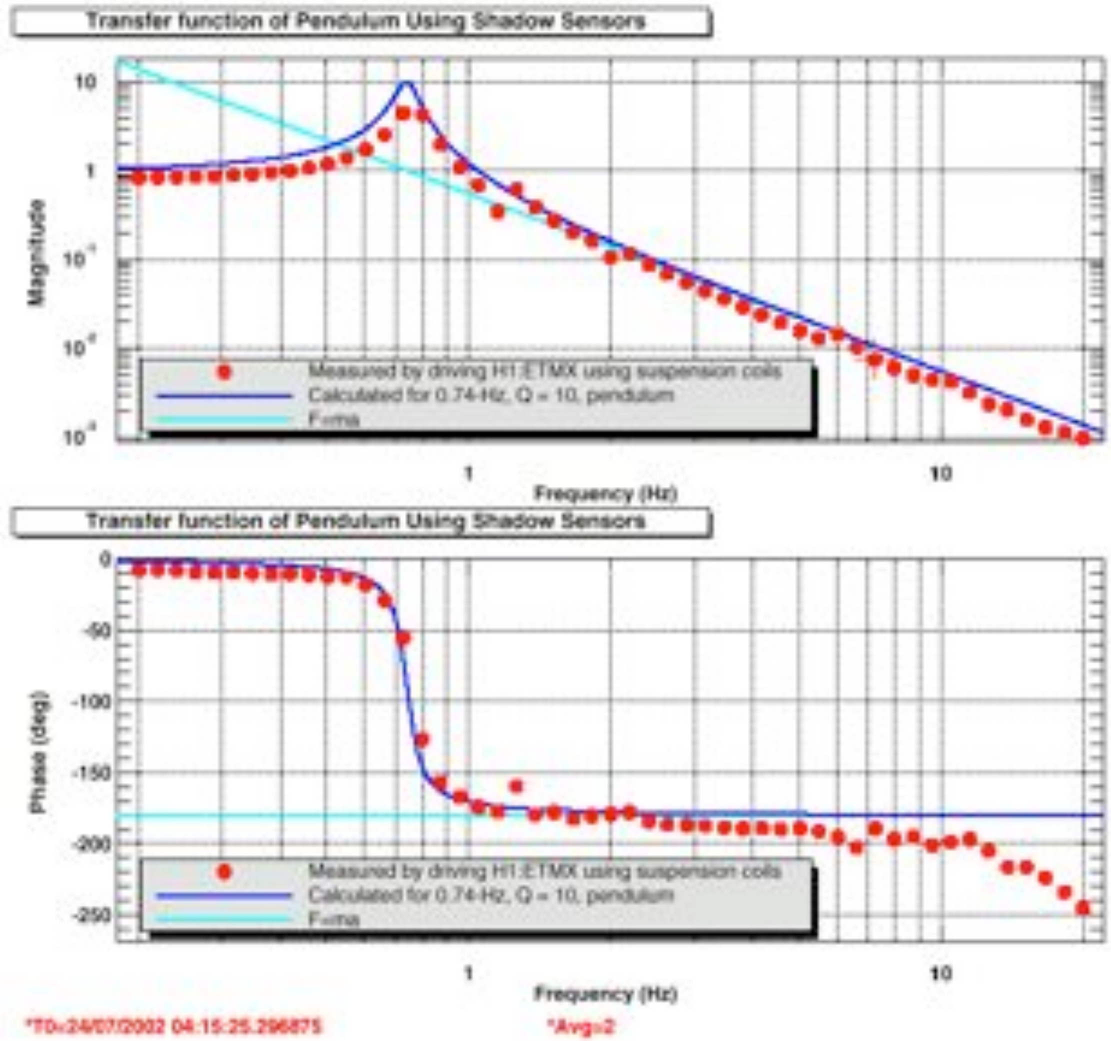
Optics suspended as simple pendulums



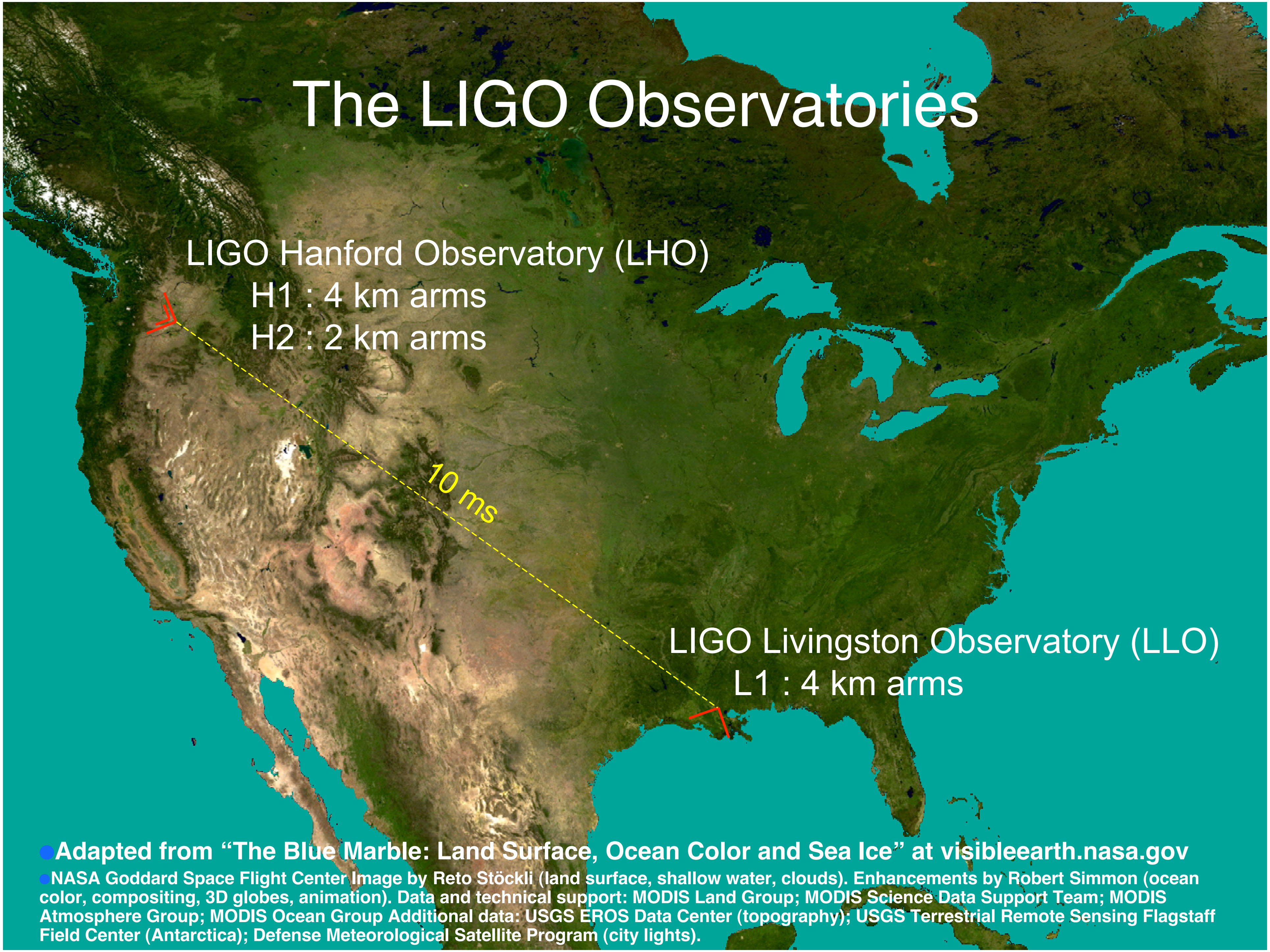
Local sensors/actuators provide damping and control forces

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



- **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).**

North America: Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)
(4-km and 2km)

LIGO (Louisiana)
(4-km)

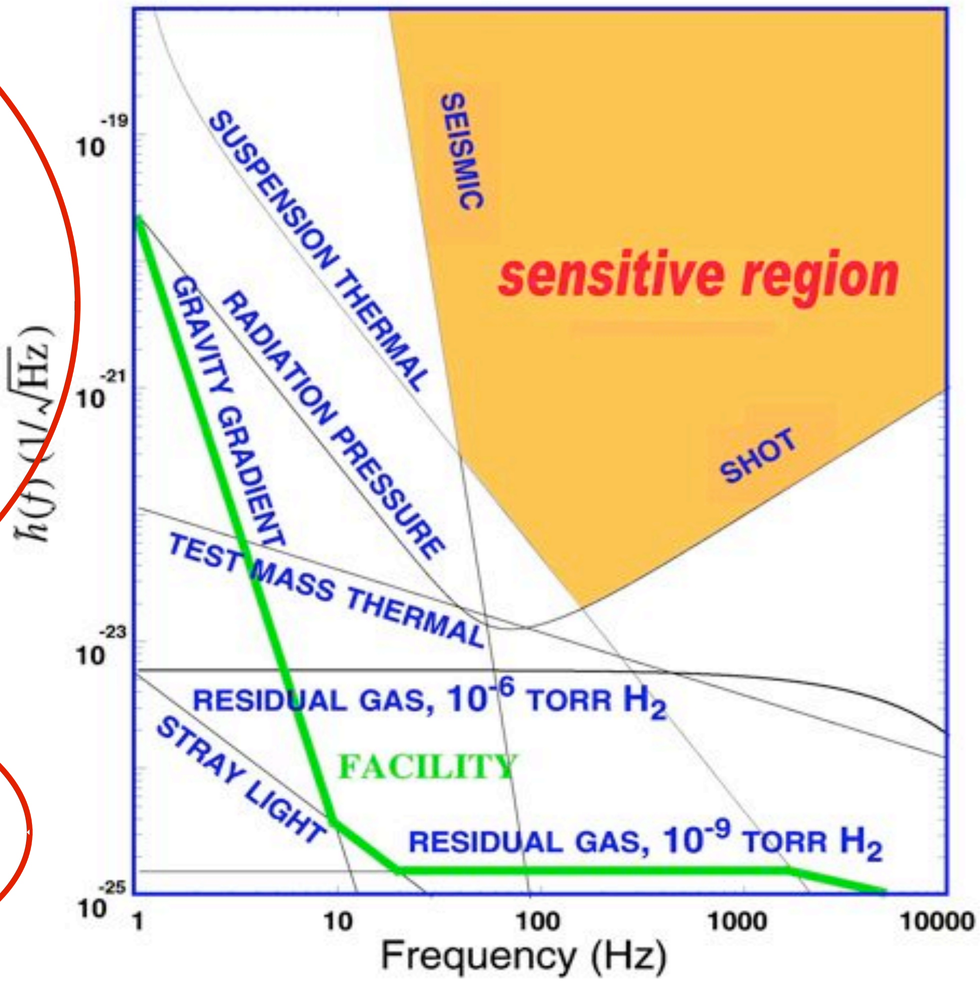
Funded by the National Science Foundation; operated by Caltech and MIT; the research focus for ~ 500 LIGO Scientific Collaboration members worldwide.

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

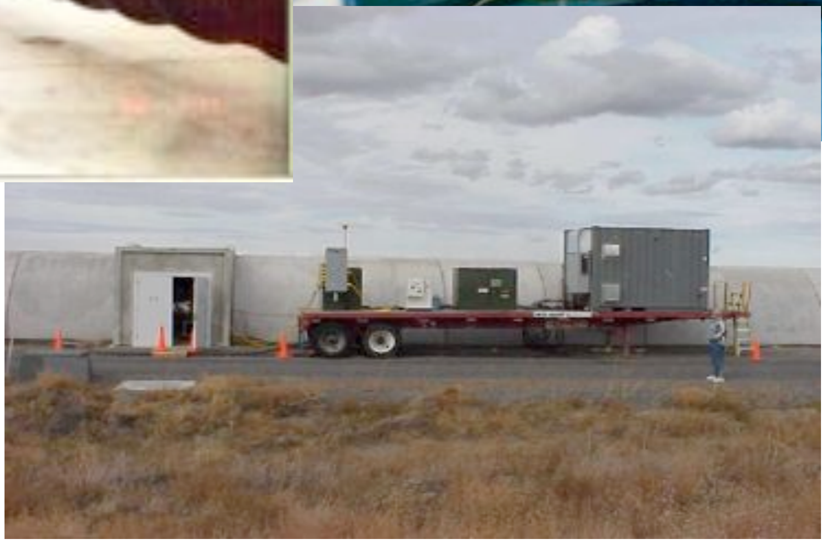


Some of the technical challenges for design and commissioning

- ✓ 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 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

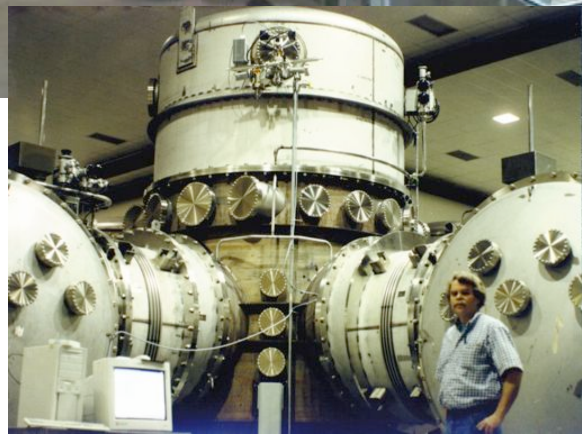
S5 science run started 14Nov2005…

Evacuated Beam Tubes Provide Clear Path for Light



Vacuum Chambers Provide Quiet Homes for Mirrors

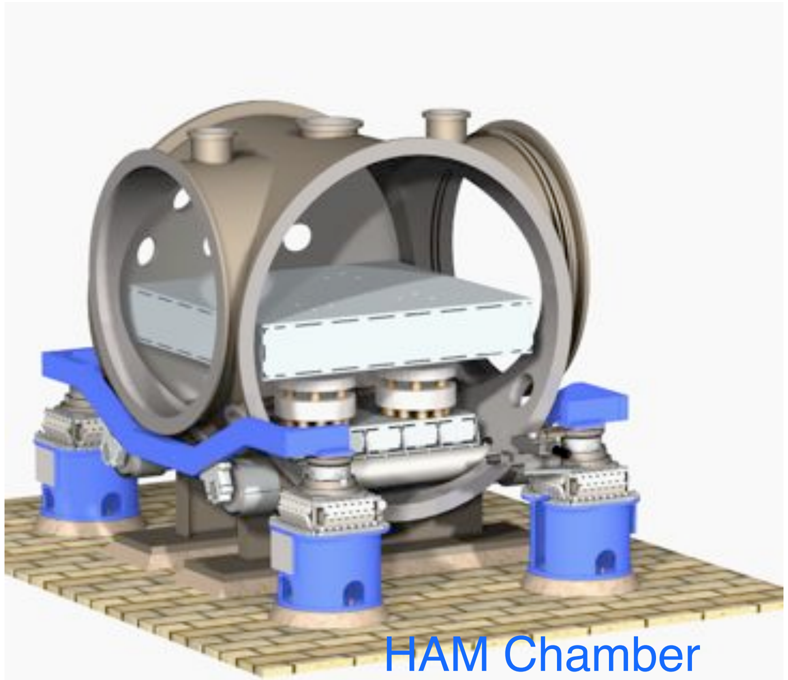
View inside Corner Station



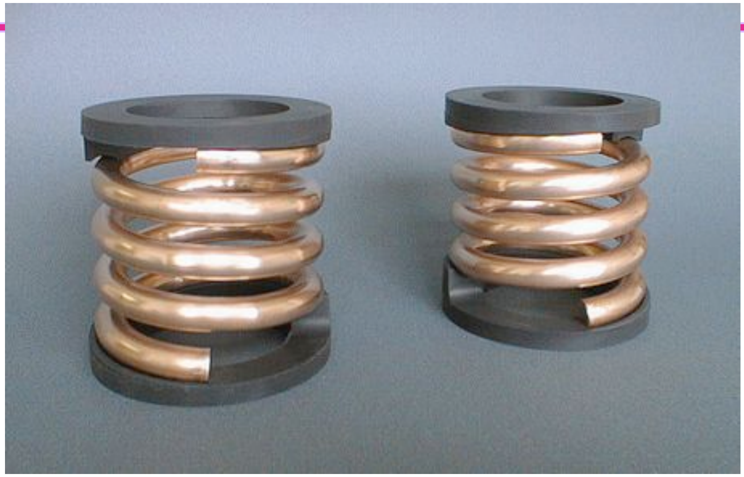
Standing at vertex beam splitter

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

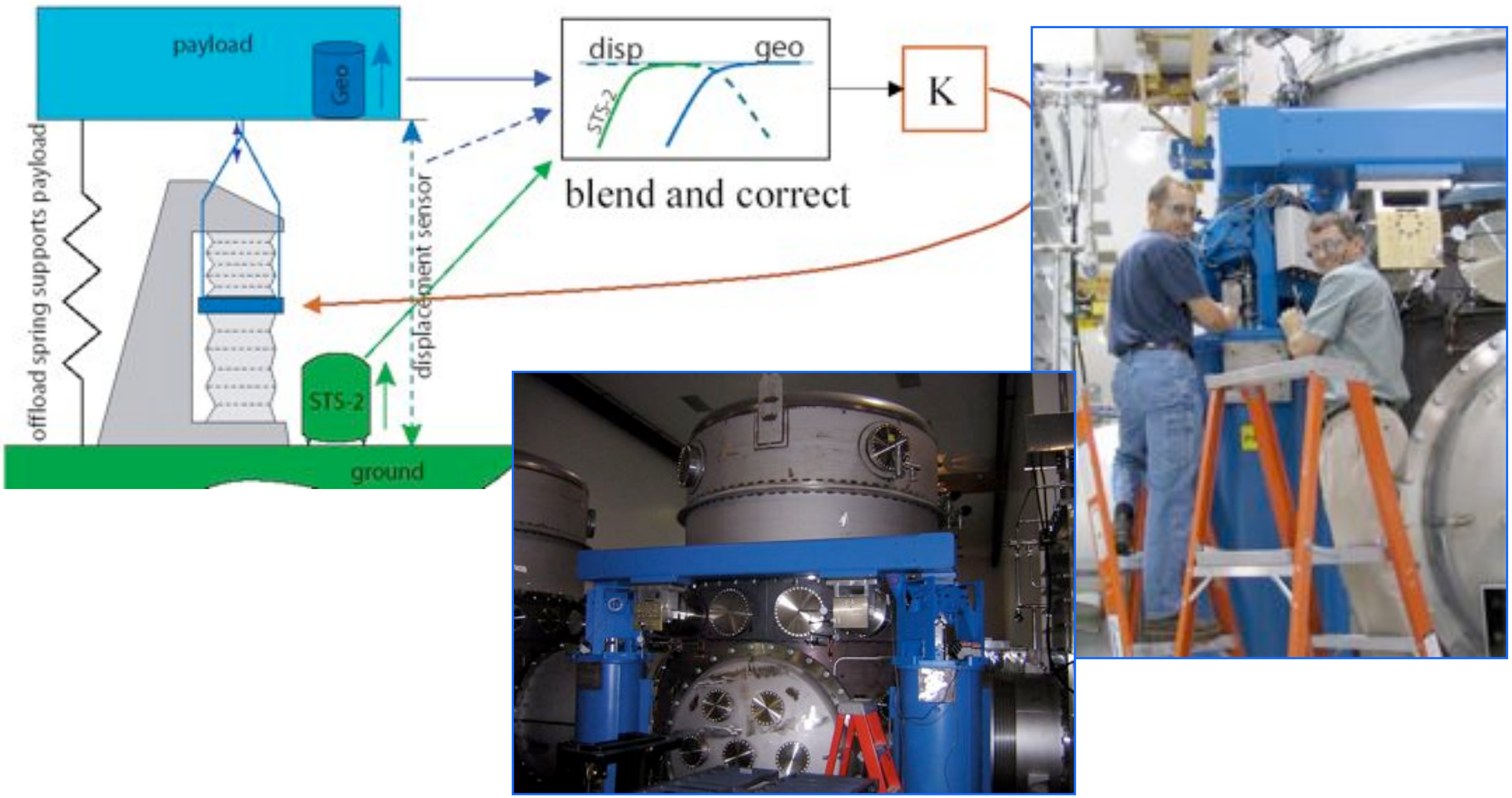


Seismic Isolation – Springs and Masses

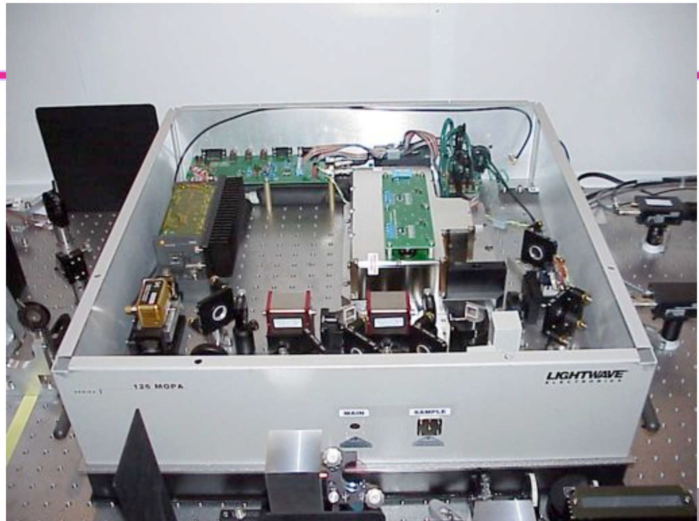


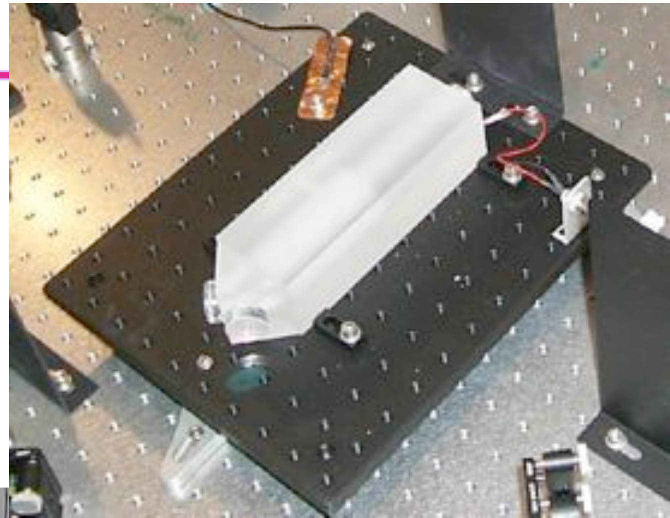
damped spring
cross section

Installation of HEPI at Livingston has improved the stability of L1



All-Solid-State Nd:YAG Laser





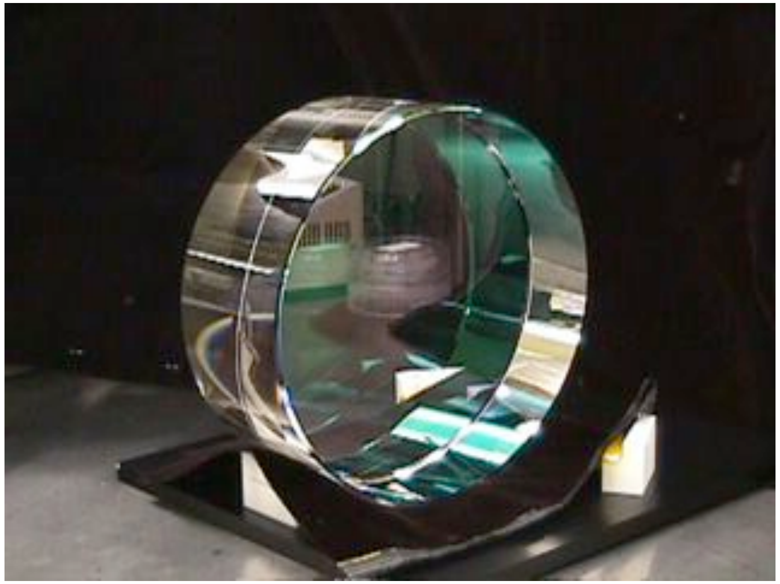
Custom-built
10 W Nd:YAG Laser,
joint development with
Lightwave Electronics
(now commercial product)

Cavity for
defining beam geometry,
joint development with
Stanford

Frequency reference
cavity (inside oven)

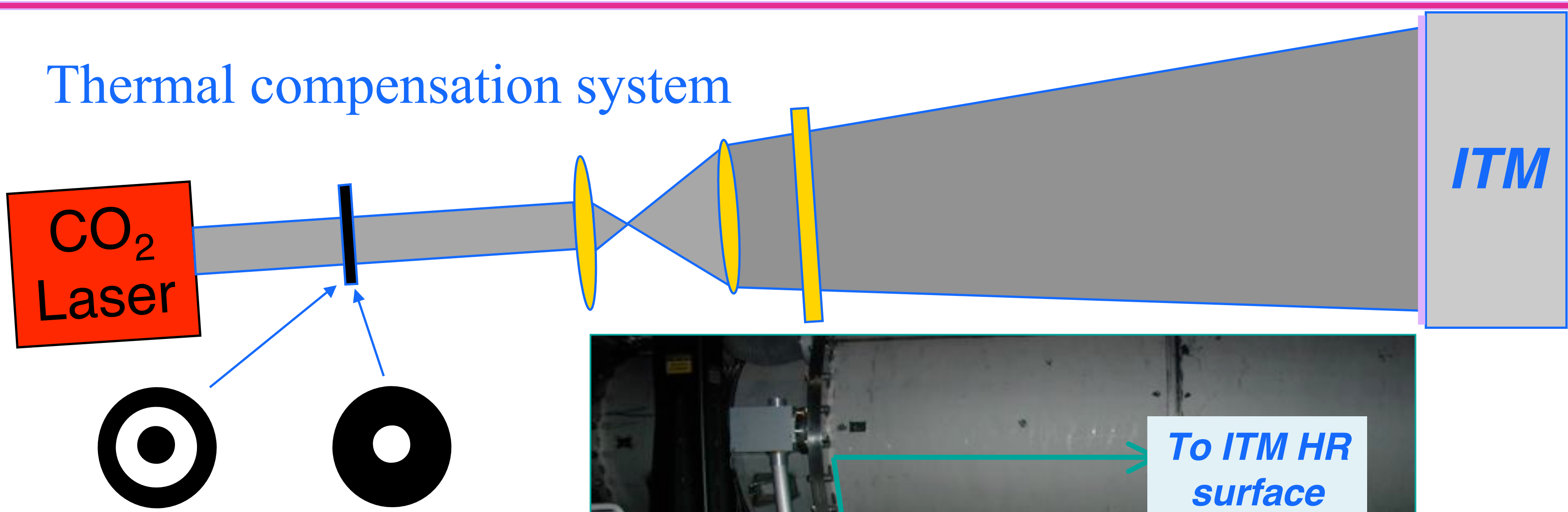
Core Optics

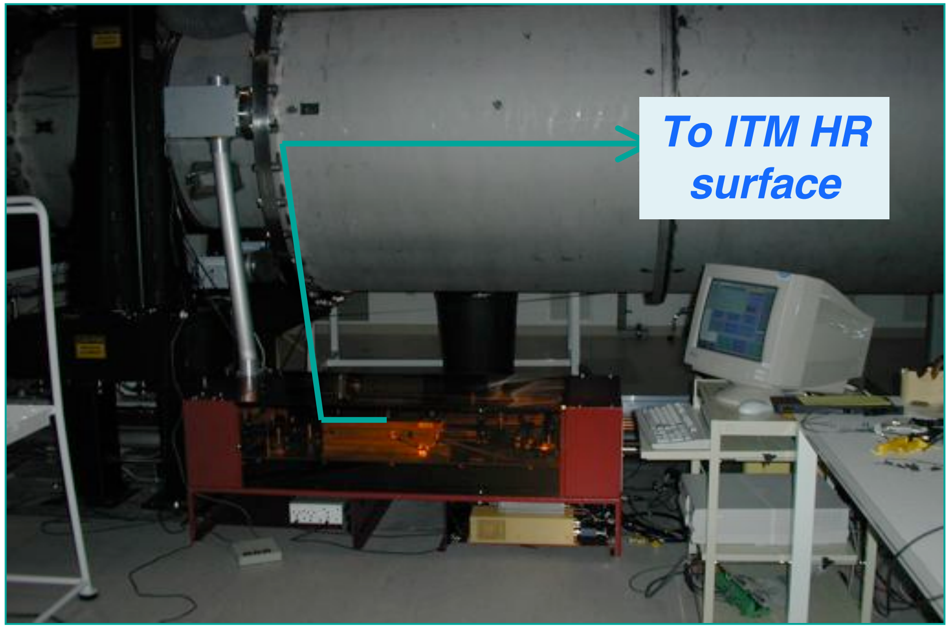
- Substrates: SiO_2
  - 25 cm Diameter, 10 cm thick
  - Homogeneity < 5 x 10^{-7}
  - Internal mode Q's > 2 x 10^{6}
- Polishing
  - Surface uniformity < 1 nm rms
  - Radii of curvature matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity <10^{-3}
- Production involved 6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



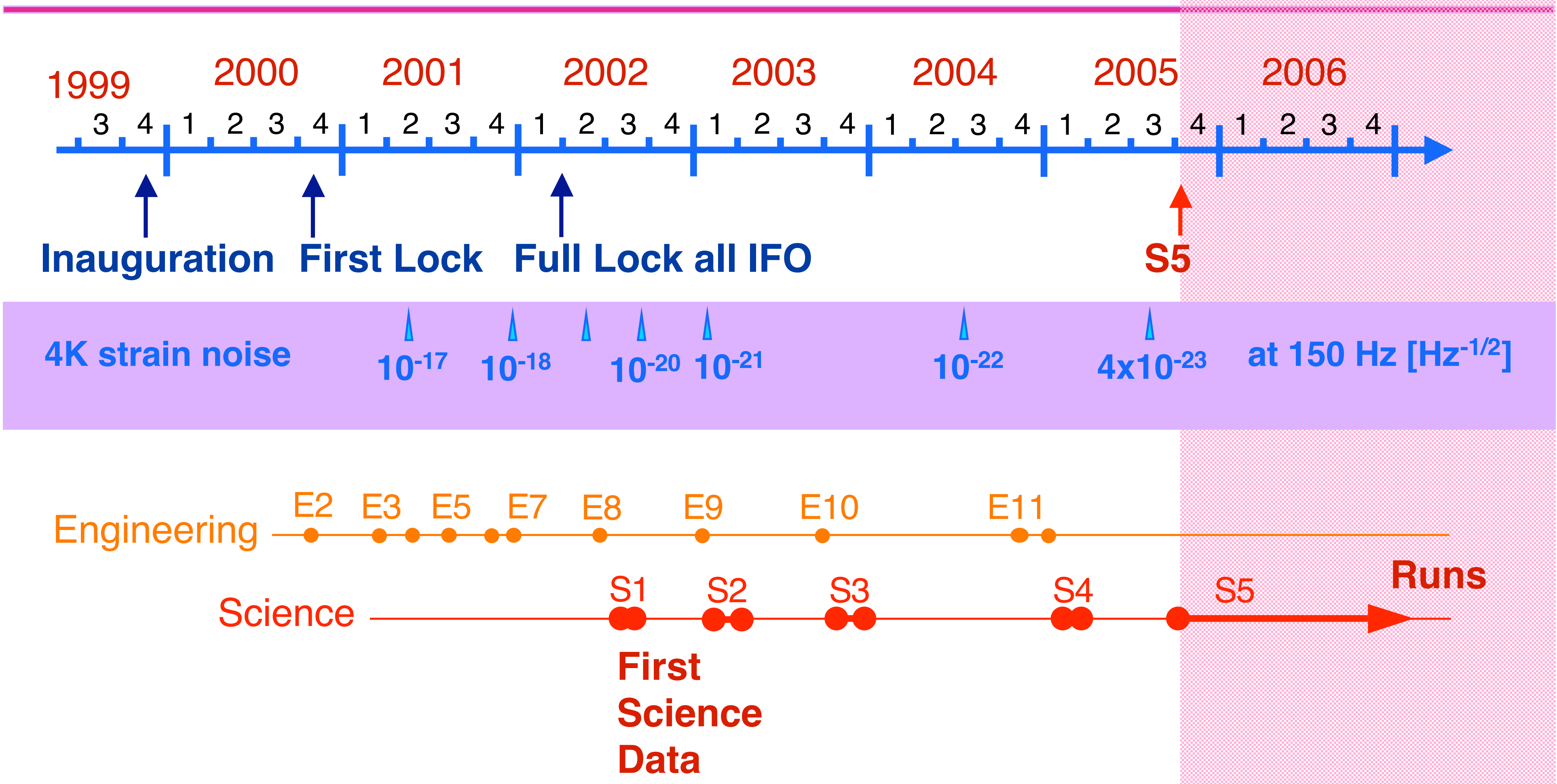
High laser power operation requires adaptive adjustments to optical figure

Thermal compensation system





Commissioning and Running Time Line

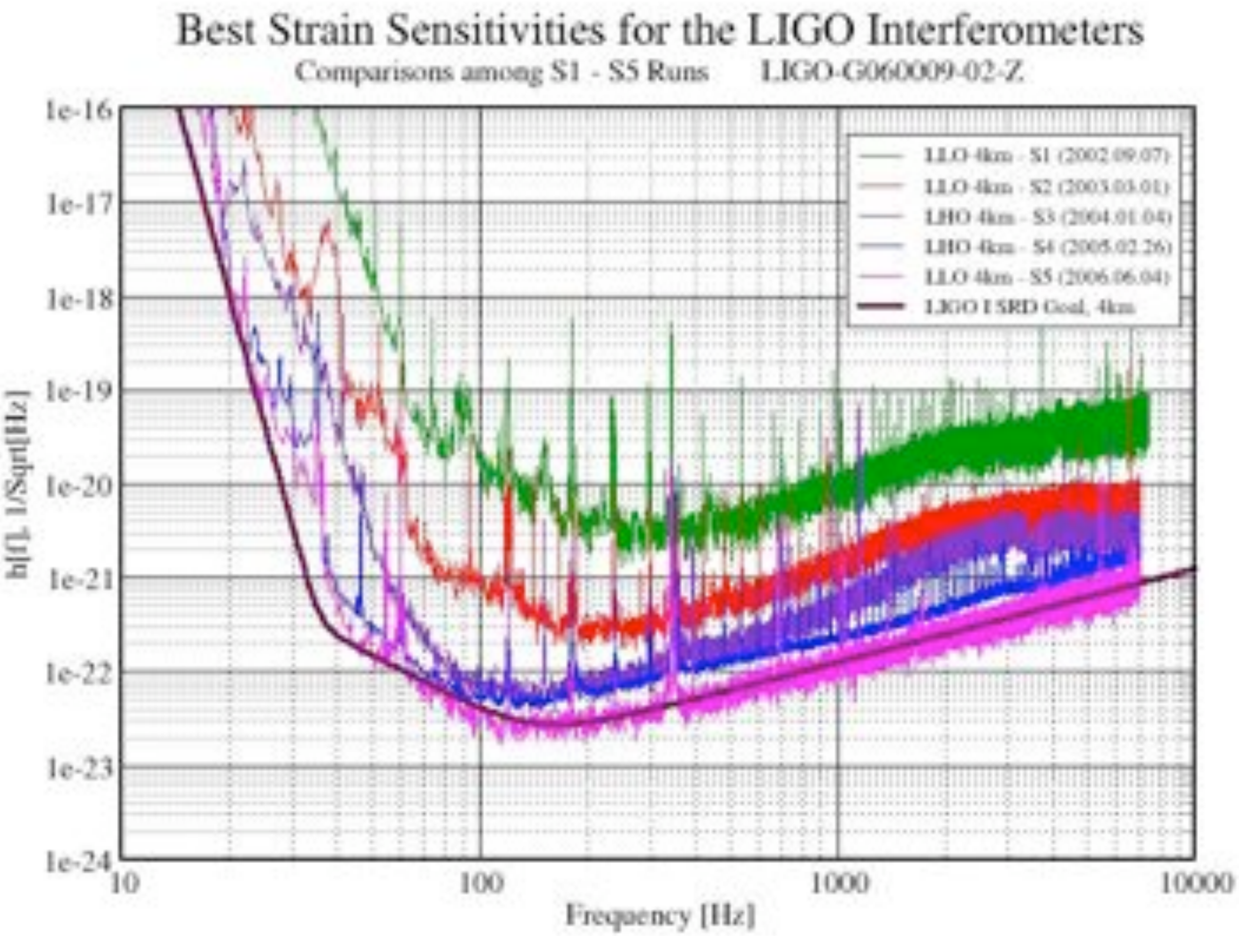


LIGO Science Runs …

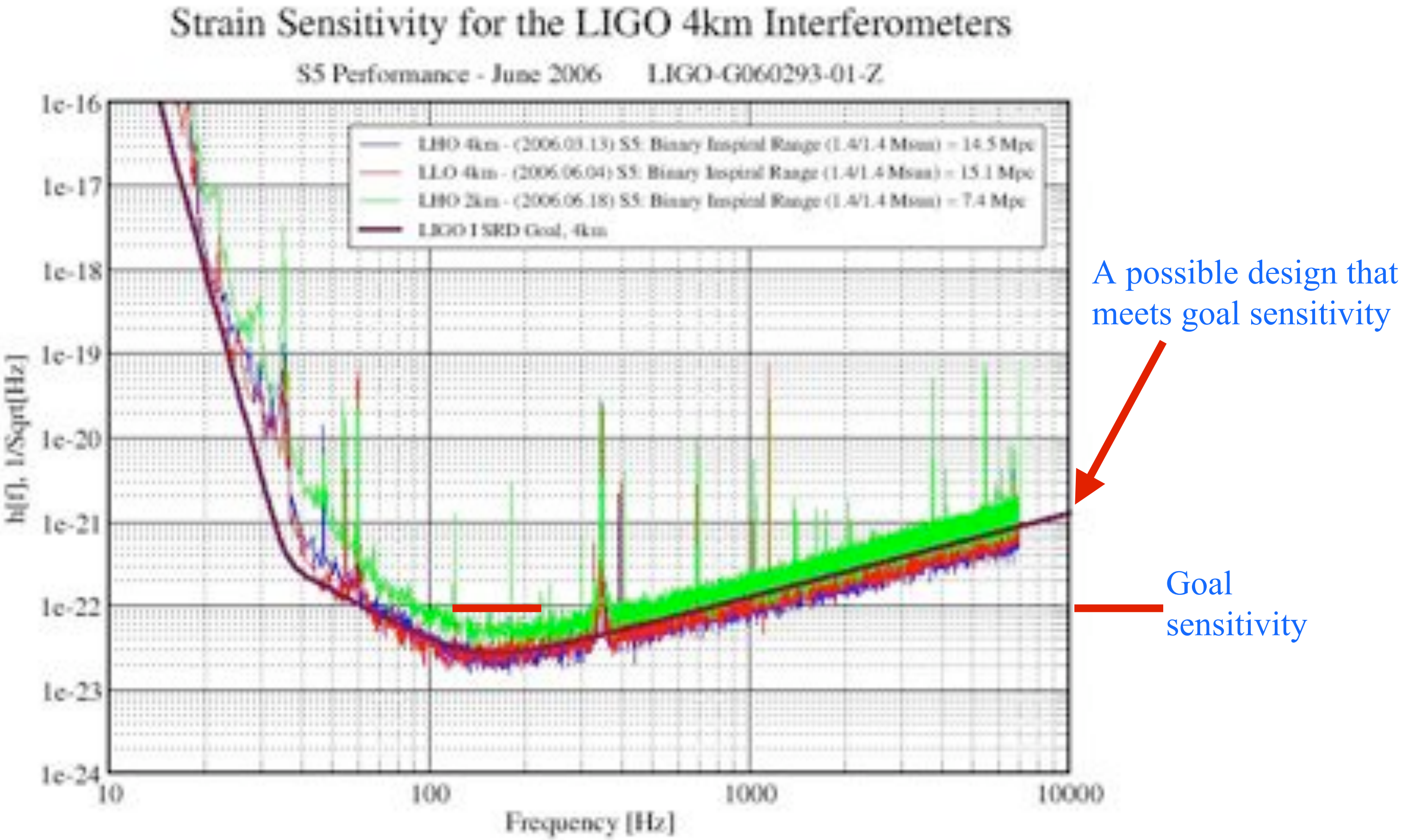
Papers at www.ligo.org

- S1: 17 days in Aug-Sep 2002
  - 3 LIGO interferometers in coincidence with GEO600 and ~2 days with TAMA300
- S2: Feb 14 – Apr 14, 2003
  - 3 LIGO interferometers in coincidence with TAMA300
- S3: Oct 31, 2003 – Jan 9, 2004
  - 3 LIGO interferometers in coincidence with periods of operation of TAMA300, GEO600 and Allegro
- S4: Feb 22 – Mar 23, 2005
  - 3 LIGO interferometers in coincidence with GEO600, Allegro, Auriga
- S5: Nov 14, 2005; goal is to accumulate one year of coincidence data

Commissioning Progress



Initial LIGO detectors are working to 1989 design goals



Binary Inspiral Search: LIGO Ranges

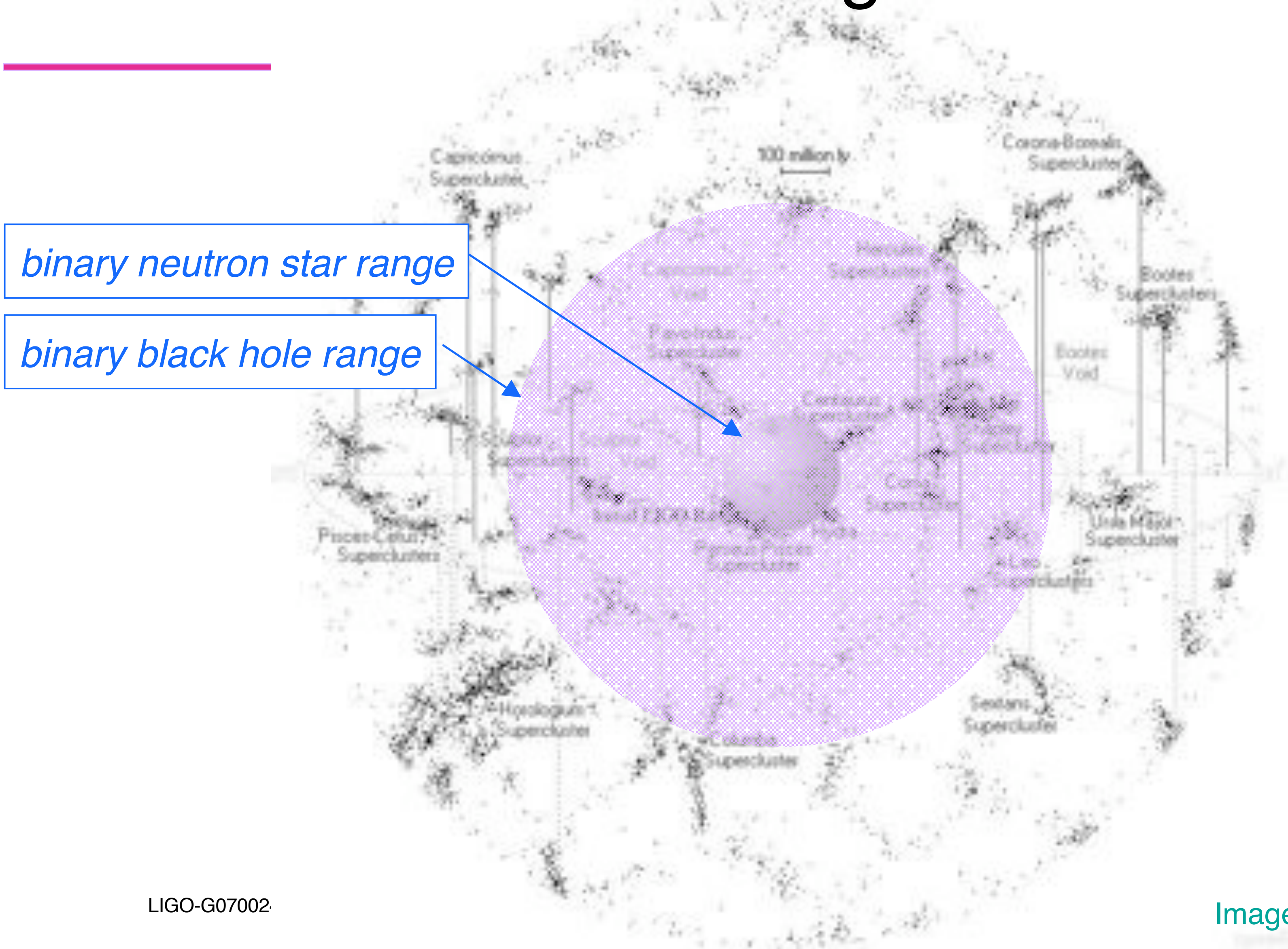
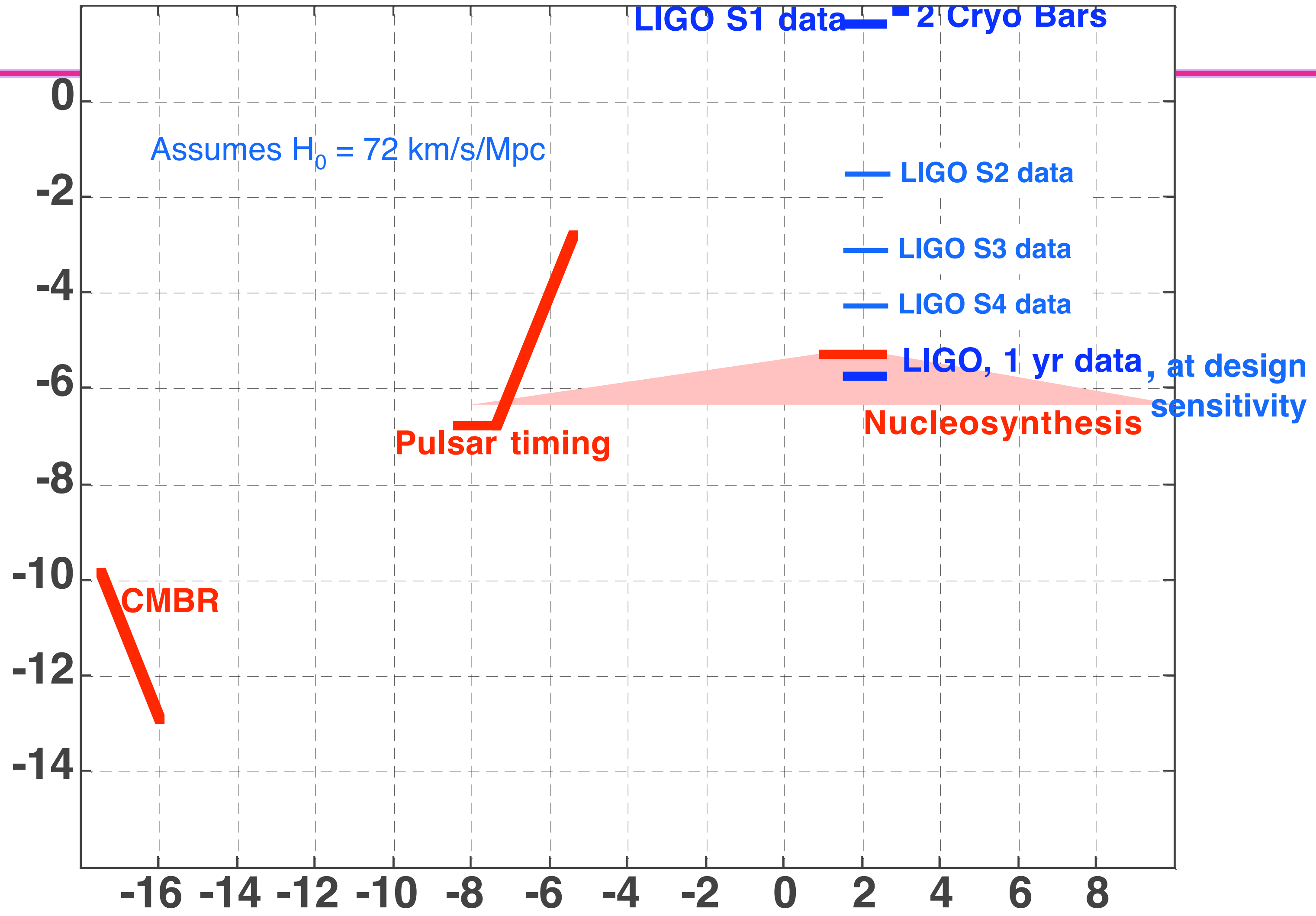


Image: R. Powell

Sensitivity to Isotropic Stochastic Background

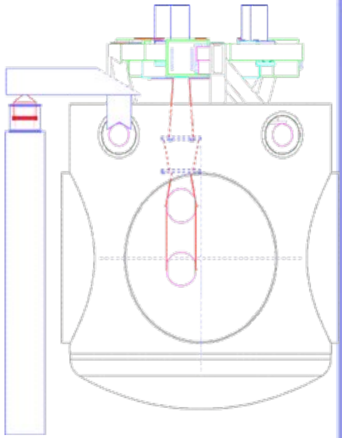


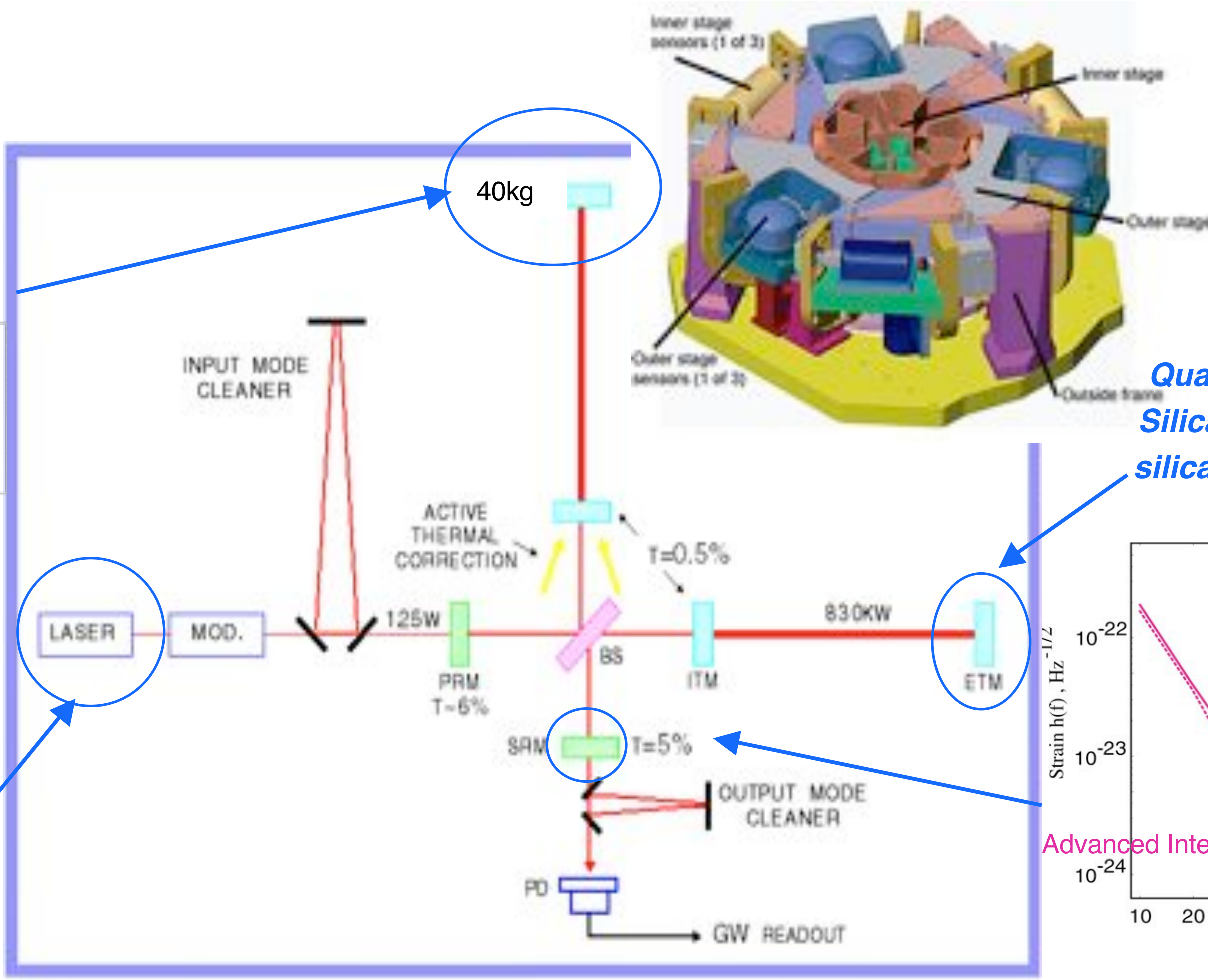
What to expect from S5 analyses

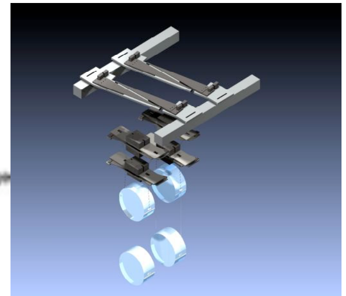
- Sensitivity to bursts ~ few times 0.1 Msolar @ 20 Mpc
- Sensitivity to neutron-star inspirals at Virgo cluster
- Pulsars
  - » expect best limits on known neutron star ellipticities at few x10^{-7}
  - ✓» expect to beat spindown limit on Crab pulsar
  - » Hierarchical all-sky/all-frequency search
-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

Advanced LIGO: President requests FY2008 construction start

Major technological differences between LIGO and Advanced LIGO



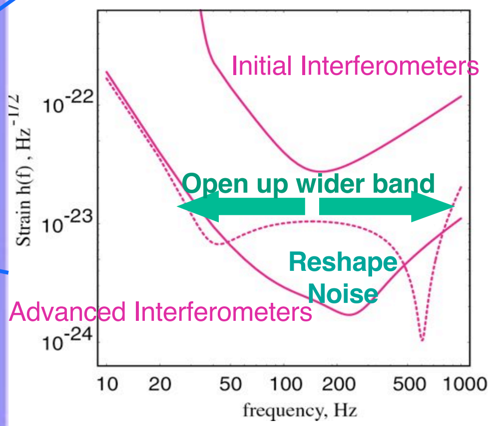




Quadruple pendulum: Silica optics, welded to silica suspension fibers

Active vibration isolation systems

High power laser (180W)



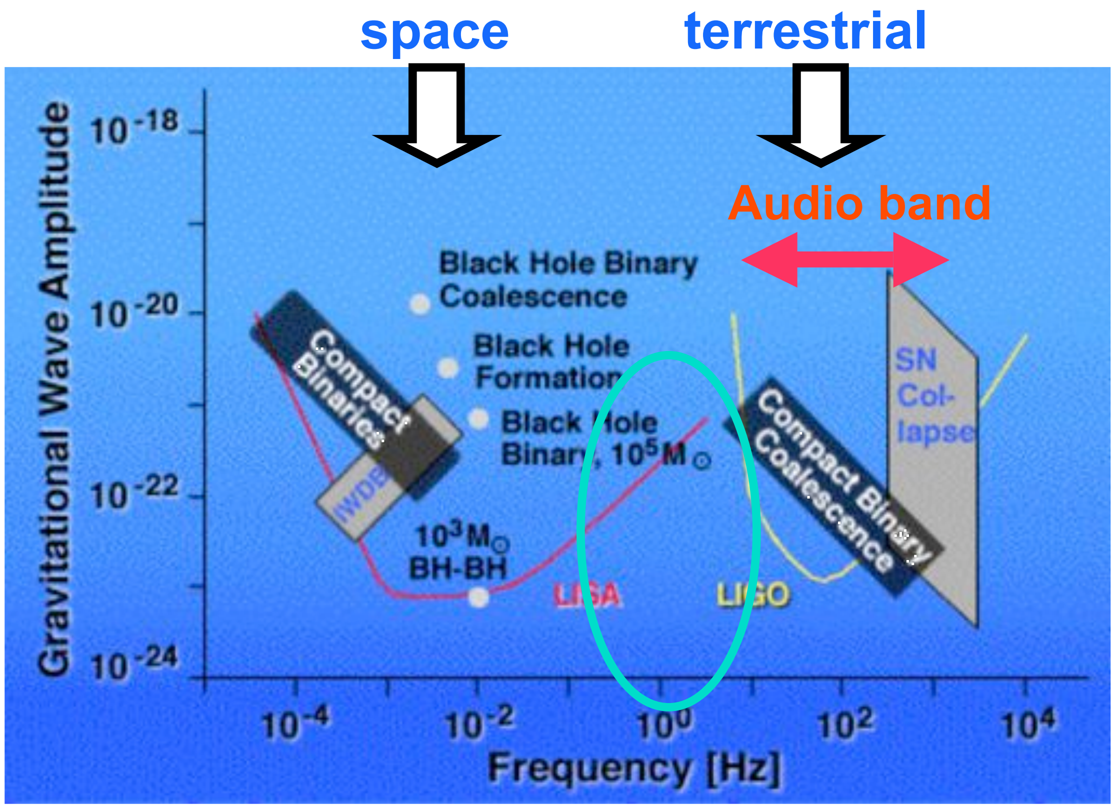
Advanced interferometry Signal recycling

Today's status and then a question…

- Progressive detector improvements have achieved design goals for Initial LIGO detector
- Early implementation of Advanced LIGO techniques helped achieve goals
  - HEPI for duty-cycle boost
  - Thermal compensation of mirrors for high-power operation
- Believe still room for post-S5 improvements before 2010 shutdown for Advanced LIGO upgrade
- Detection is possible, but not assured for initial LIGO detector; Advanced LIGO will usher in the age of gravitational-wave astronomy
- Advanced LIGO will reach the low-frequency limit of detectors on Earth's surface given by fluctuations in gravity at surface

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



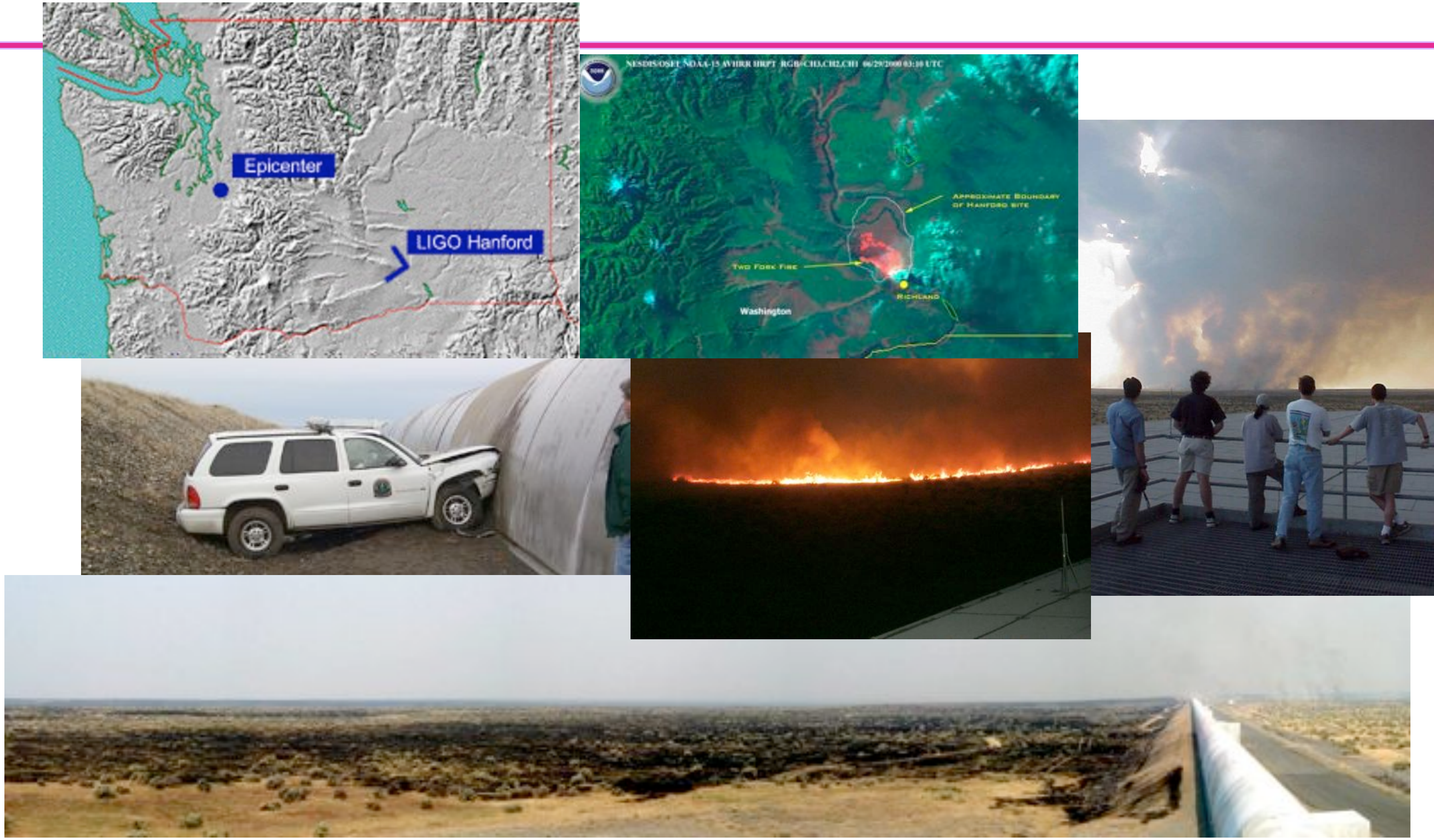
Gravity gradients: low-f limit for terrestrial detectors

- First estimated by Saulson (1984) prior to LIGO construction
  - Revisited by Hughes and Thorne (1998) after LIGO sites were selected and seismic backgrounds characterized
  - Limits detection band of surface terrestrial detectors to f > 10-20 Hz
  - Advanced LIGO will reach that limit
- Lower-f operation a rationale for space-based detectors
  - LISA is optimized for a much lower band (10^{-4} – 10^{-2}) Hz
  - Seto, Kawamura and Nakamura (2001) introduce idea of DECIGO to target band around 0.1 Hz
- Can operation at 1 Hz be achieved most cost-effectively far above or far below Earth's surface?

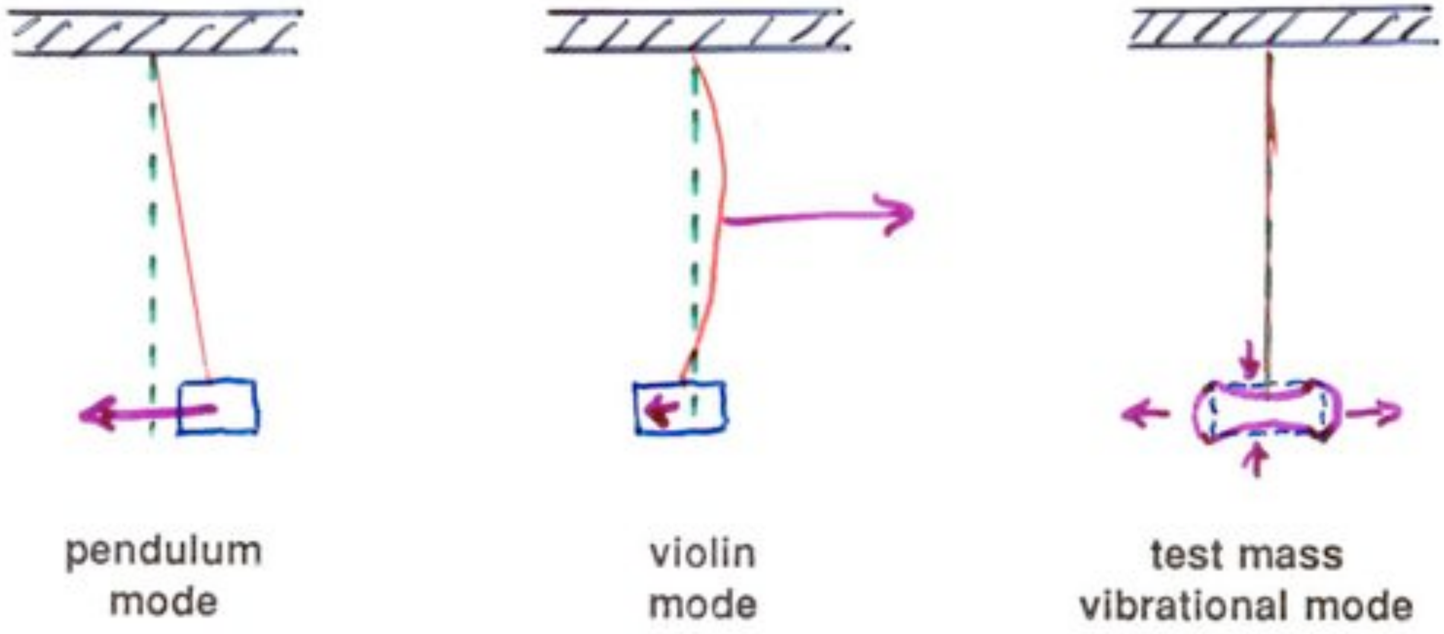
Scientific rationale to push for lower frequency operation

- Binary neutron star inspirals have longer dwell times at lower frequencies; more opportunity to integrate up signals
- Black hole binaries merge at lower frequencies as the mass rises
- Known radio pulsars exist in larger numbers at lower frequencies

It’s never as easy as it looks…



Background Forces in GW Band = Thermal Noise ~ $k_B T$/mode



pendulum mode	violin mode	test mass vibrational mode
$x_{rms} \approx 10^{-11}$ m	$x_{rms} \approx 2\times10^{-17}$ m	$x_{rms} \approx 5\times10^{-16}$ m
$f < 1$ Hz	$f \sim 350$ Hz	$f \geq 10$ kHz

Strategy: Compress energy into narrow resonance outside band of interest ⇒ require high mechanical Q, low friction

Science-mode statistics for S5 run

Up to Feb 12 2007 21:26:04 UTC; Elapsed run time = 11165.4 hours

Sample	Hours	Percent (of calendar time incl. maintenance periods)
H1	8194.9	73.4 since Nov 4, 2005 8:00 PST
H2	8549.6	76.6 since Nov 4, 2005 8:00 PST
L1	6747.0	61.8 since Nov 14, 2005 12:00 CST
G1 since Jan	6421.2	69.0 since Jan 21, 2006 0:00 UTC
H1+H2	7522.8	67.4 since Nov 4, 2005 8:00 PST
H1+L1	5630.5	51.5 since Nov 14, 2005 12:00 CST
H2+L1	5672.3	51.9 since Nov 14, 2005 12:00 CST
H1+H2+L1	5214.3	47.7 since Nov 14, 2005 12:00 CST
(H1orH2)+L1	6089.3	54.5 since Nov 4, 2005 8:00 PST
H1+H2+L1+G1	2719.7	40.6 since May 10, 2006 0:00 UTC
One or more LSC	10591.6	94.9 since Nov 4, 2005 8:00 PST