LIGO: Portal to Spacetime

Reported on behalf of LIGO colleagues by

Fred Raab,

LIGO Hanford Observatory

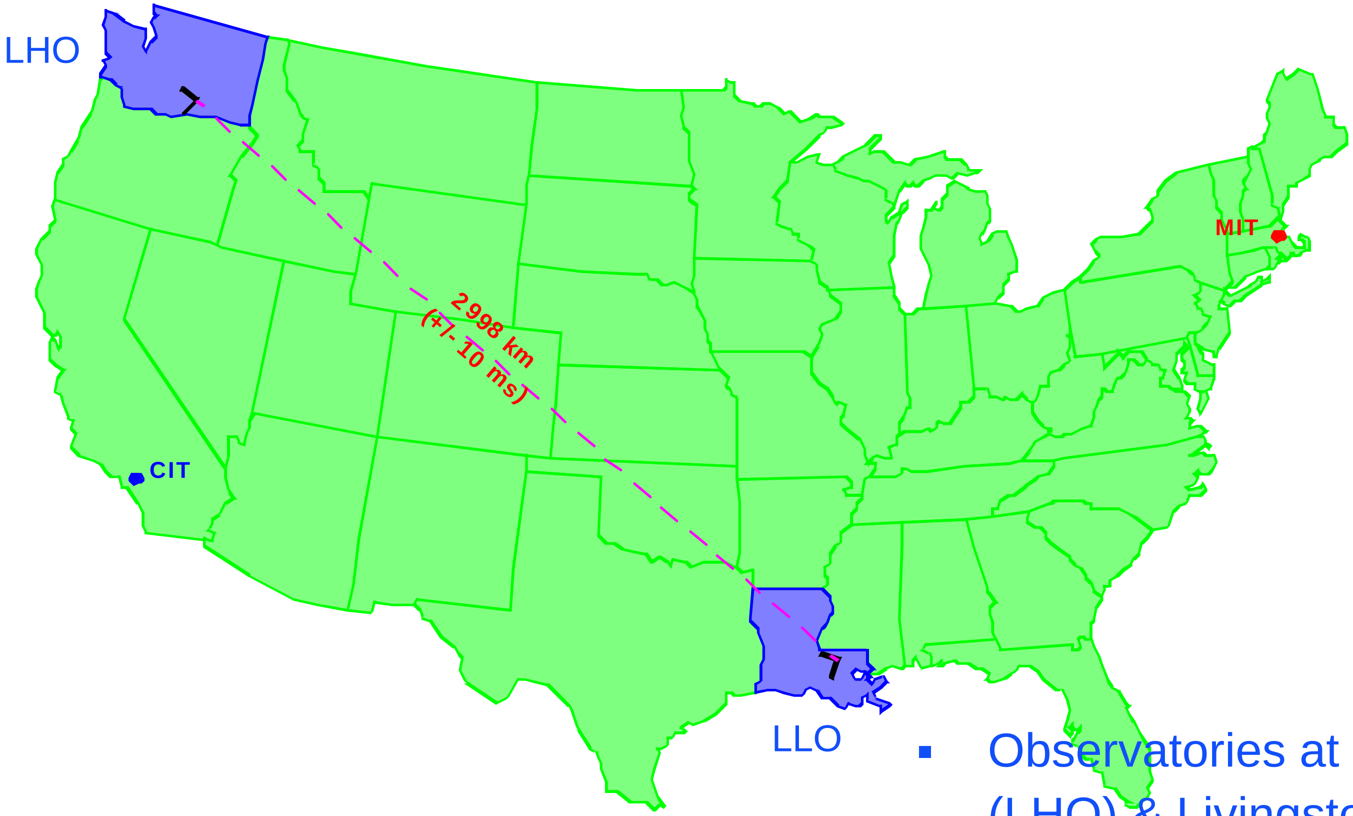
LIGO's Mission is to Open a New Portal on the Universe

- In 1609 Galileo viewed the sky through a 20X telescope and gave birth to modern astronomy
  - » The boost from "naked-eye" astronomy revolutionized humanity's view of the cosmos
  - » Ever since, astronomers have "looked" into space to uncover the natural history of our universe
- LIGO's quest is to create a radically new way to perceive the universe, by directly sensing the vibrations of space itself

LIGO Will Reveal the “Sound Track” for the Universe

- LIGO consists of large, earth-based, detectors that will act like huge microphones, listening for for cosmic cataclysms, like:
  - Supernovae
  - Inspiral and mergers of black holes & neutron stars
  - Starquakes and wobbles of neutron stars and black holes
  - The Big Bang
  - Unknown phenomena

The Four Corners of the LIGO Laboratory



- Observatories at Hanford, WA (LHO) & Livingston, LA (LLO)
- Support Facilities @ Caltech & MIT campuses

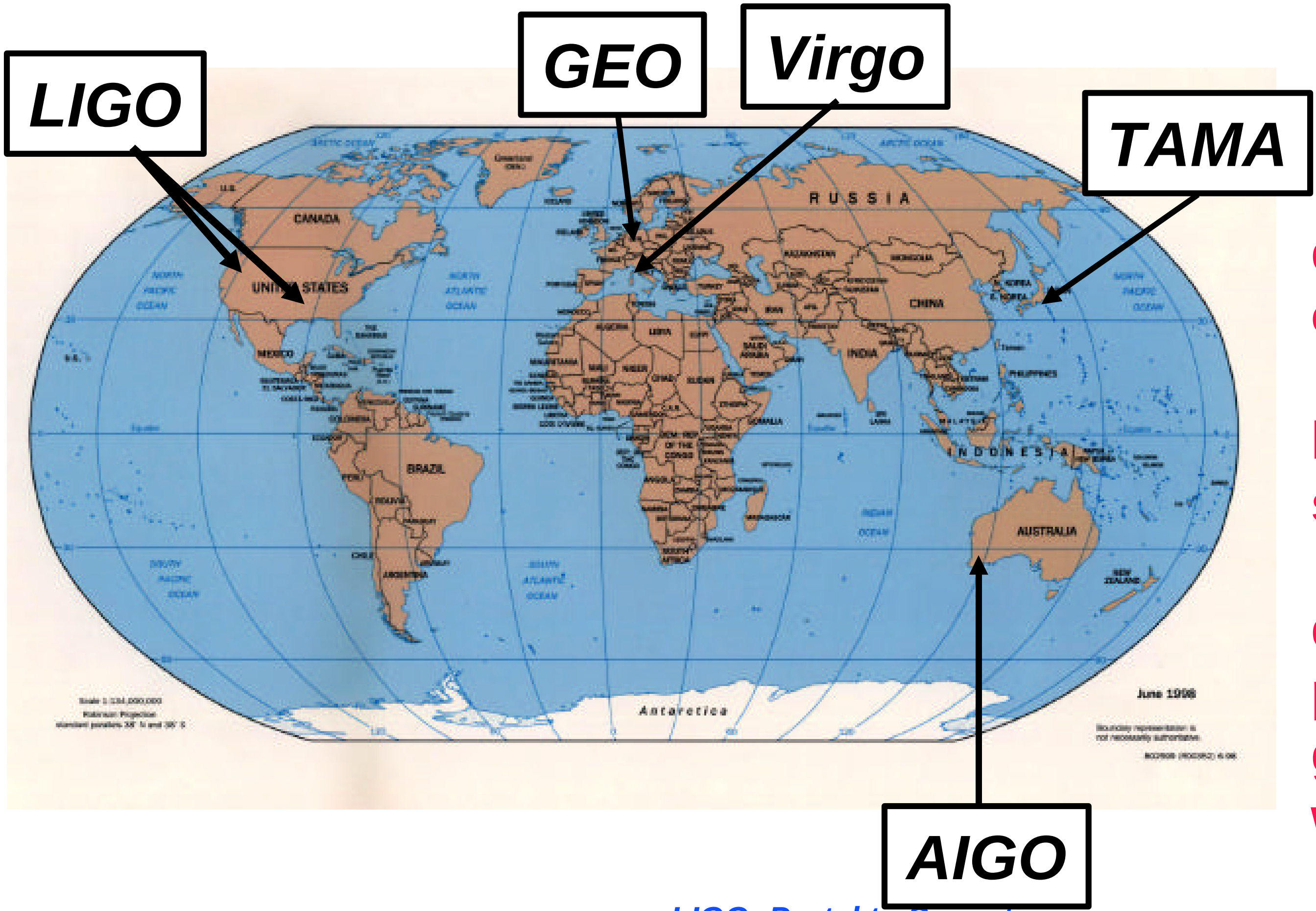
Aerial Views of LIGO Facilities

LIGO Hanford Observatory
(LHO)

LIGO Livingston Observatory
(LLO)

Part of Future International Detector Network

Simultaneously detect signal (within msec)



detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Laboratory & Science Collaboration

- LIGO Laboratory (Caltech/MIT) runs observatories and research/support facilities at Caltech/MIT
- LIGO Scientific Collaboration is the body that defines and pursues LIGO science goals
  - » >400 members at 44 institutions worldwide (including LIGO Lab)
  - » Includes GEO600 members & data sharing
  - » Working groups in detector technology advancement, detector characterization and astrophysical analyses
  - » Memoranda of understanding define duties and access to LIGO data

What Are Some Questions LIGO Will Try to Answer?

- What is the universe like now and what is its future?
- How do massive stars die and what happens to the stellar corpses?
- How do black holes and neutron stars evolve over time?
- What can colliding black holes and neutrons stars tell us about space, time and the nuclear equation of state
- What was the universe like in the earliest moments of the big bang?
- What surprises have we yet to discover about our universe?

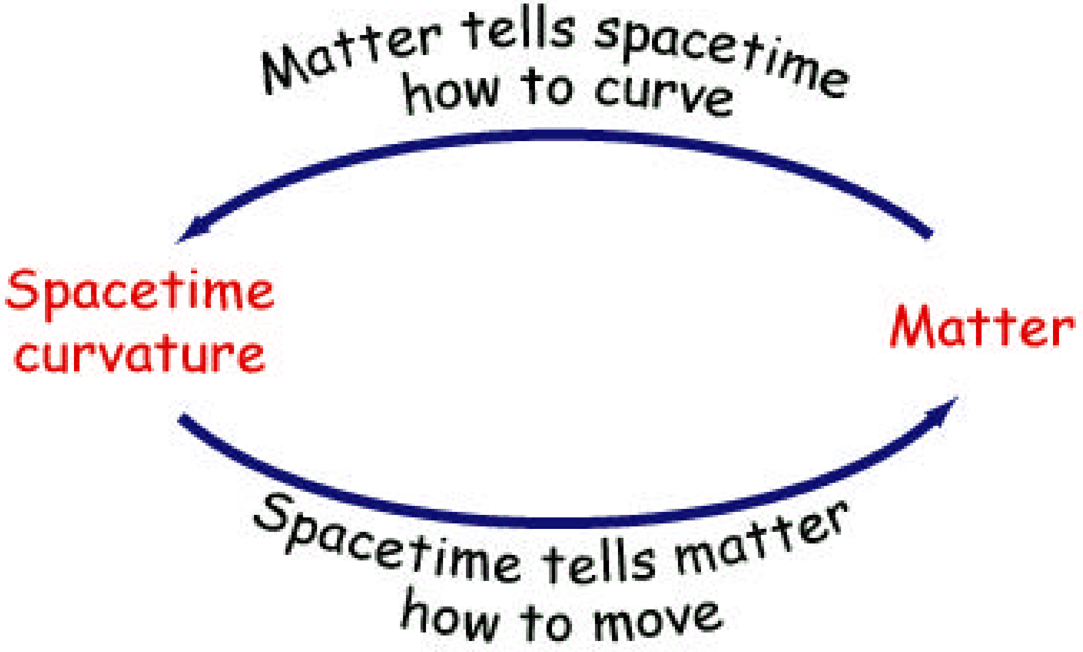
A Slight Problem

Regardless of what you see on Star Trek, the vacuum of interstellar space does not transmit conventional sound waves effectively.

Luckily General Relativity provides a work-around!

General relativity allows waves of rippling space that can substitute for sound if we know how to listen!

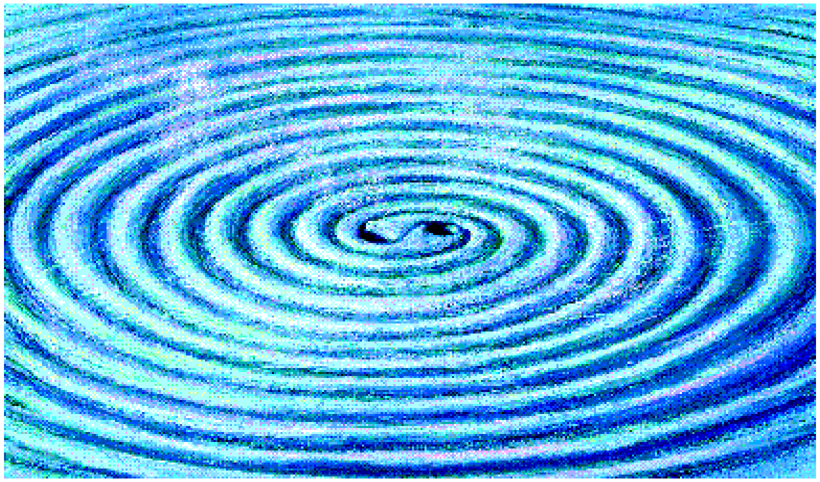
John Wheeler's Summary of General Relativity Theory



Gravitational Waves

Gravitational waves are ripples in space when it is stirred up by rapid motions of large concentrations of matter or energy

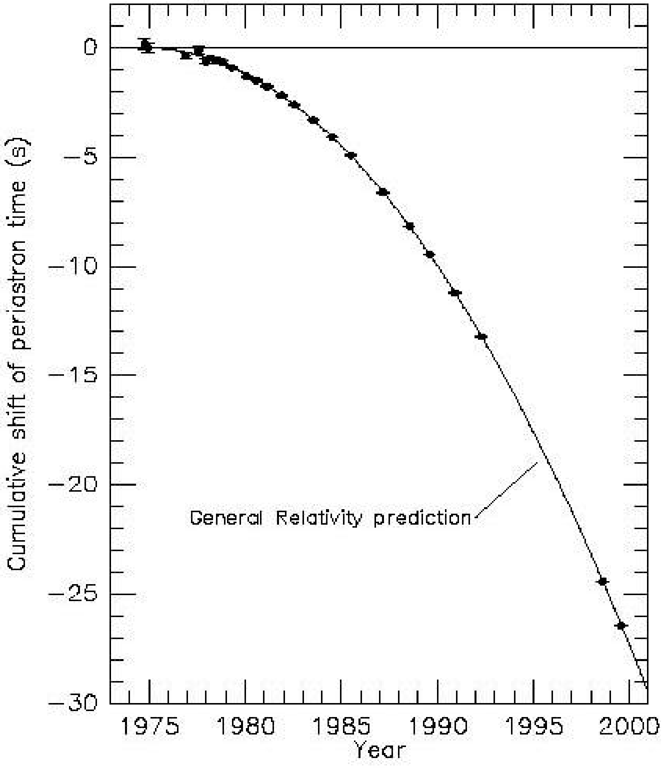
Rendering of space stirred by two orbiting black holes:



Energy Loss Caused By Gravitational Radiation Confirmed

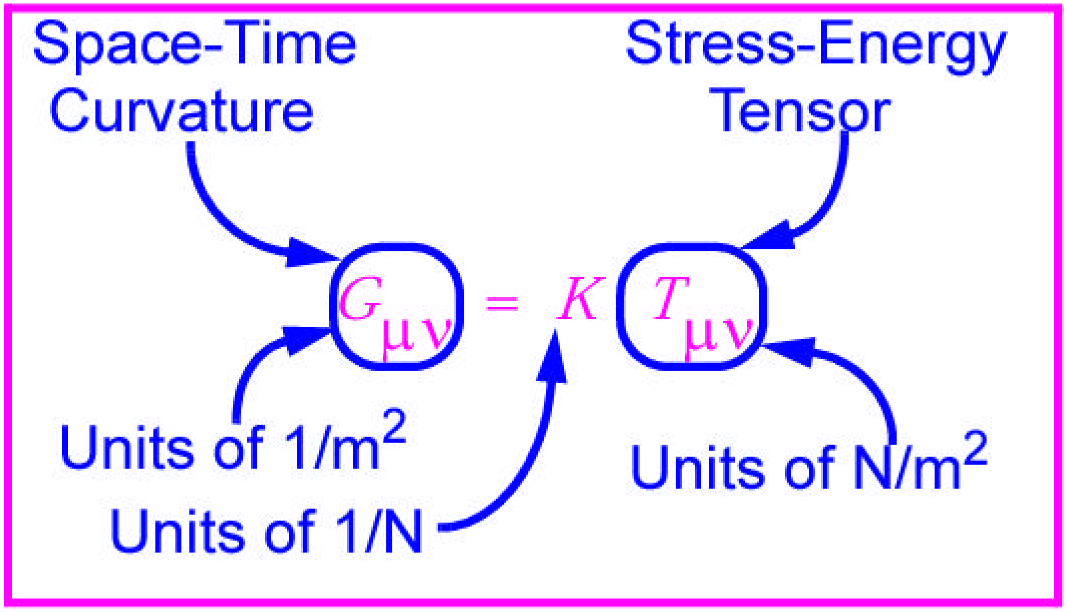
- In 1974, J. Taylor and R. Hulse discovered a pulsar orbiting a companion neutron star. This “binary pulsar” provides some of the best tests of General Relativity. Theory predicts the orbital period of 8 hours should change as energy is carried away by gravitational waves.
- Taylor and Hulse were awarded the 1993 Nobel Prize for Physics for this work.

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)

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

=> Wave can carry huge energy with miniscule amplitude!

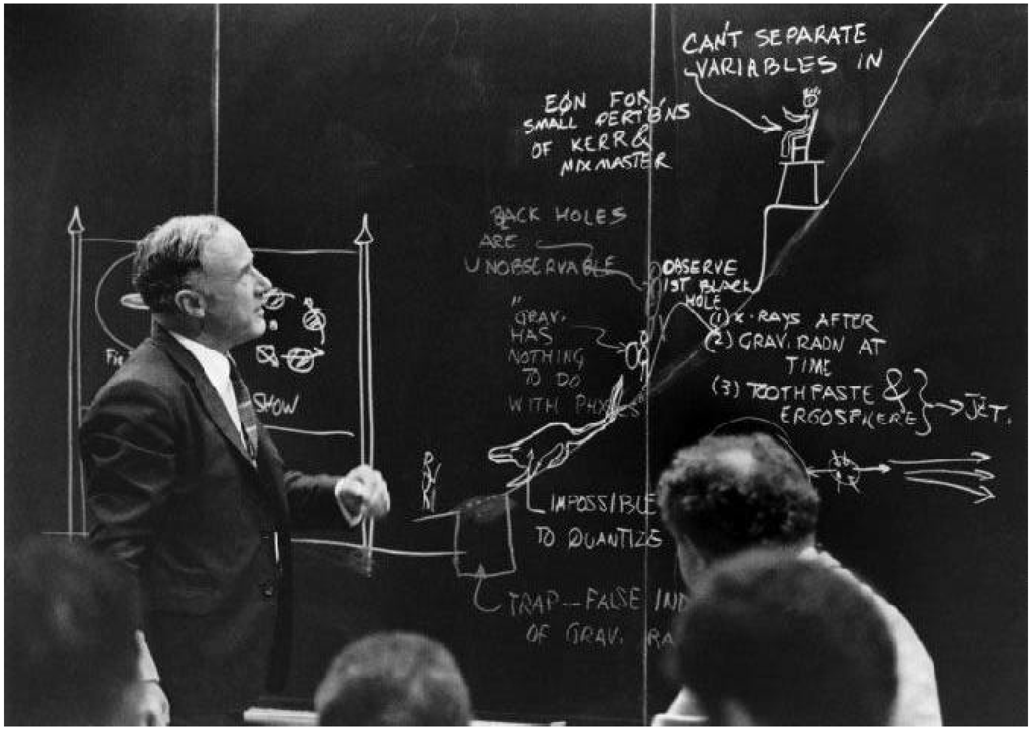
$$h \sim (G/c^4)\,(E_{NS}/r)$$

What Phenomena Do We Expect to Study With LIGO?

The Nature of Gravitational Collapse and Its Outcomes

"Since I first embarked on my study of general relativity, gravitational collapse has been for me the most compelling implication of the theory - indeed the most compelling idea in all of physics . . . It teaches us that space can be crumpled like a piece of paper into an infinitesimal dot, that time can be extinguished like a blown-out flame, and that the laws of physics that we regard as 'sacred,' as immutable, are anything but."

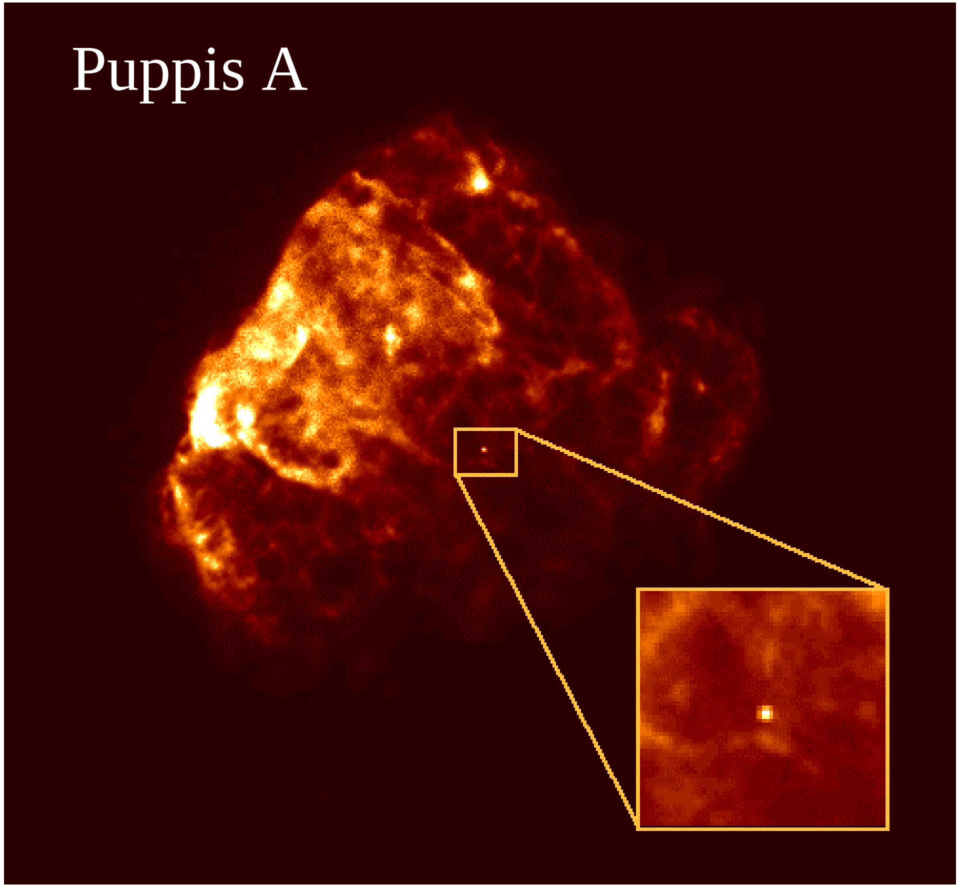
– John A. Wheeler in Geons, Black Holes and Quantum Foam



Photograph by Robert Matthews,
Courtesy of Princeton University (1971)

Do Supernovae Produce Gravitational Waves?

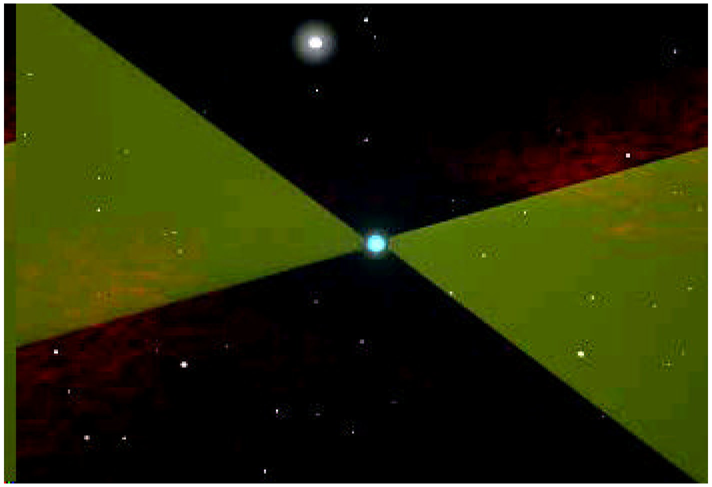
- Not if stellar core collapses symmetrically (like spiraling football)
- Strong waves if end-over-end rotation in collapse
- Increasing evidence for non-symmetry from speeding neutron stars
- Gravitational wave amplitudes uncertain by factors of 1,000's



Credits: Steve Snowden (supernova remnant); Christopher Becker, Robert Petre and Frank Winkler (Neutron Star Image).

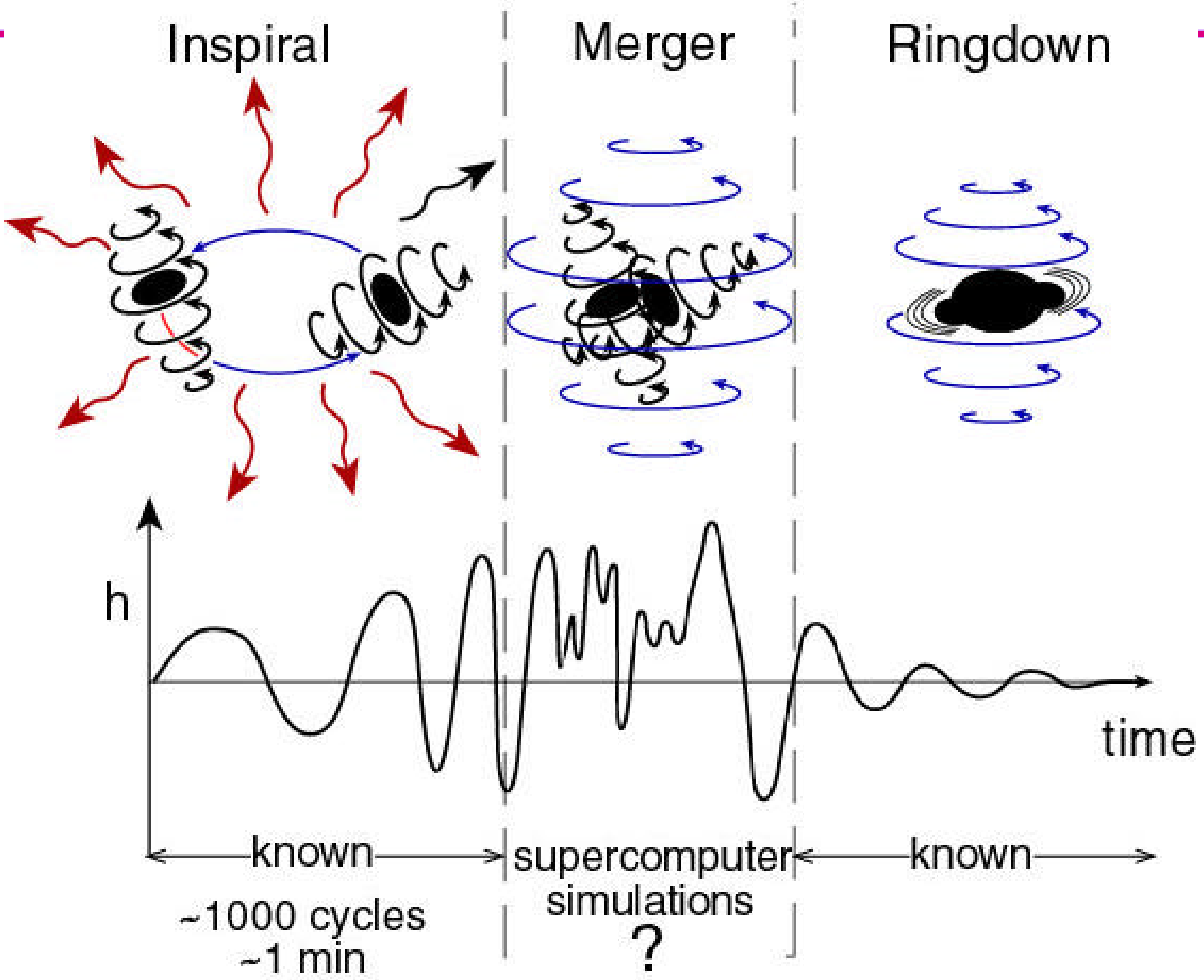
The “Undead” Corpses of Stars: Neutron Stars and Black Holes

- Neutron stars have a mass equivalent to 1.4 suns packed into a ball 10 miles in diameter
- The large magnetic fields and high spin rates produces a beacon of radiation that appears to pulse if it sweeps past earth



Artist: Walt Feimer, Space Telescope Science Institute

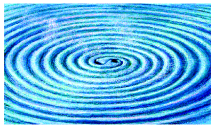
Catching Waves
From Black Holes



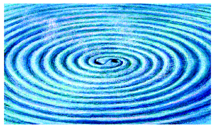
Sketches courtesy of Kip Thorne

Sounds of Compact Star Inspirals

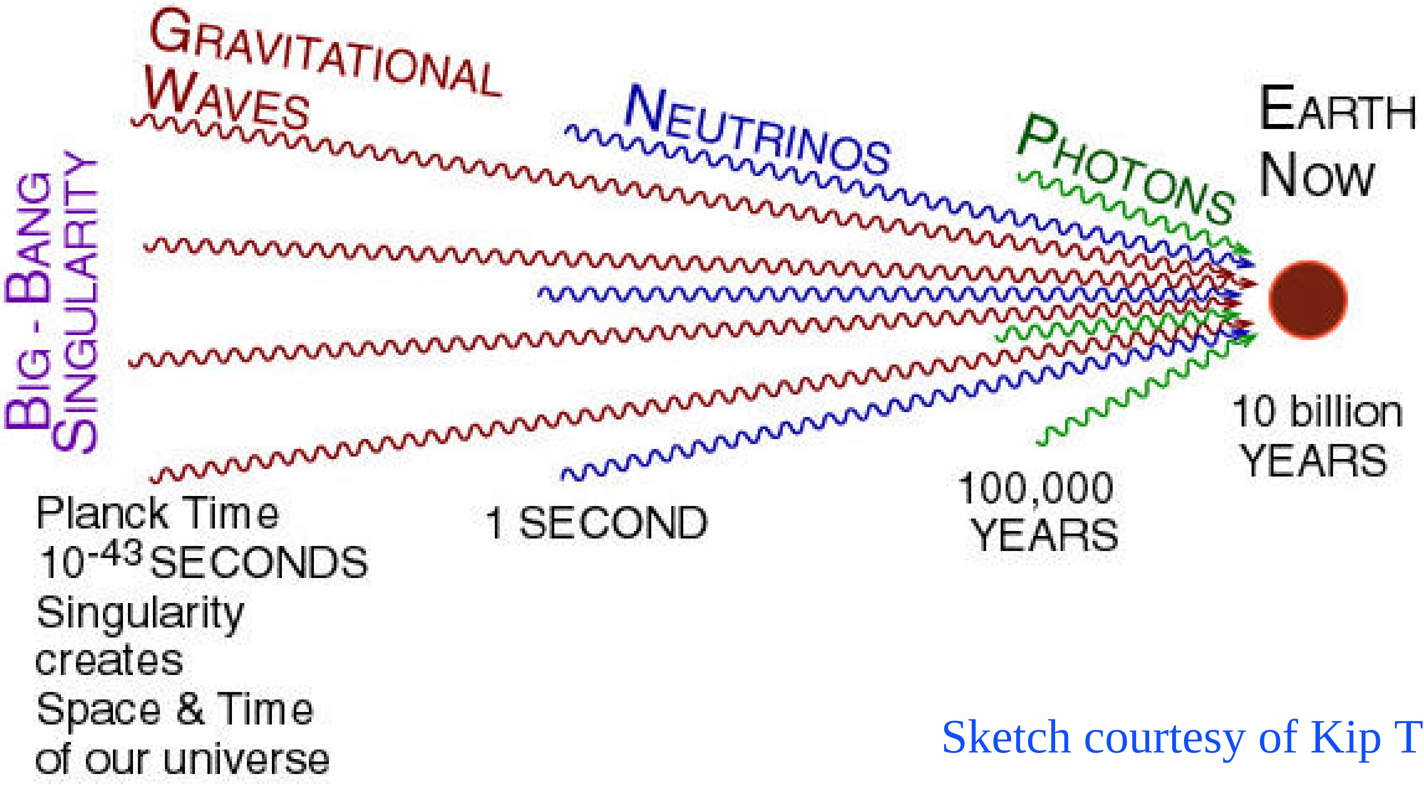
Neutron-star binary inspiral:



Black-hole binary inspiral:



Searching for Echoes from Very Early Universe

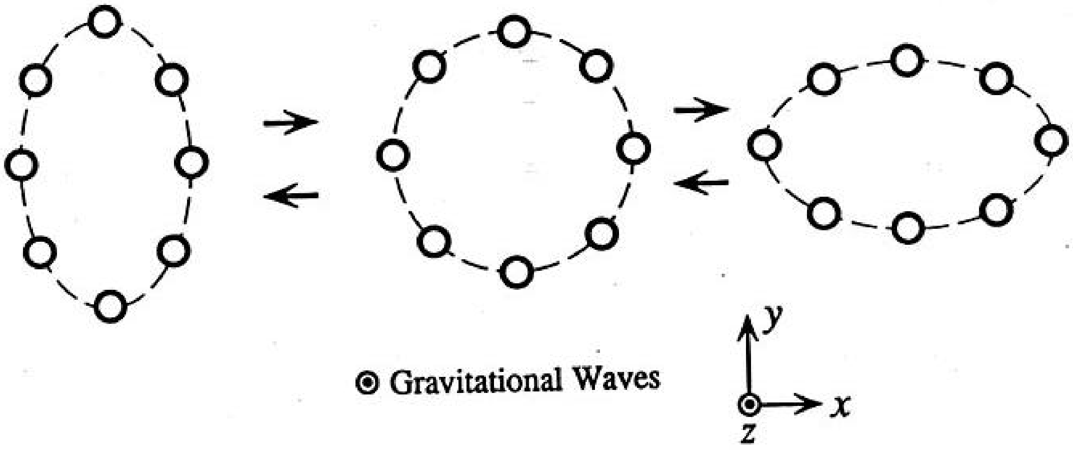


Sketch courtesy of Kip Thorne

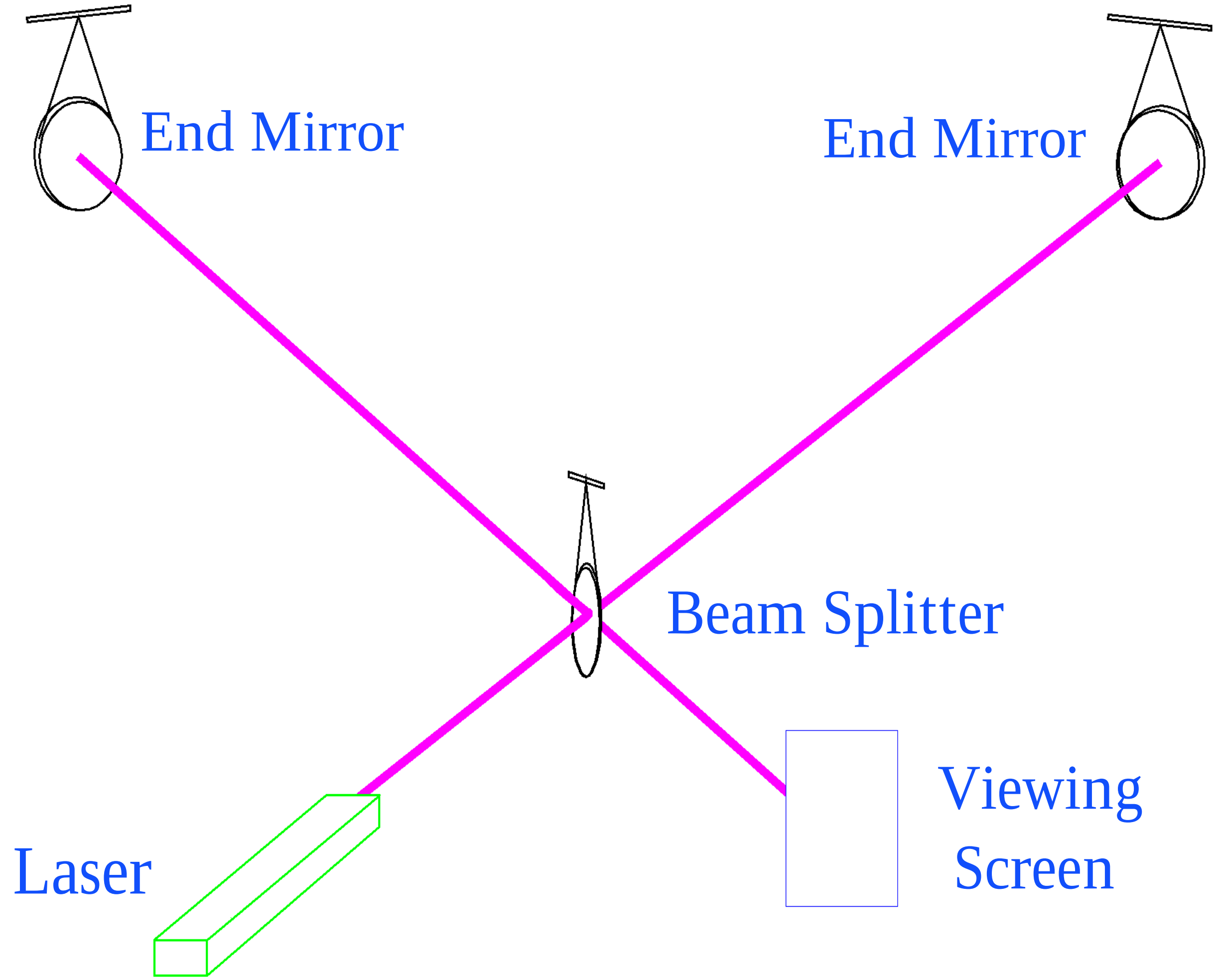
How does LIGO detect spacetime vibrations?

Important Signature of Gravitational Waves

Gravitational waves shrink space along one axis perpendicular to the wave direction as they stretch space along another axis perpendicular both to the shrink axis and to the wave direction.



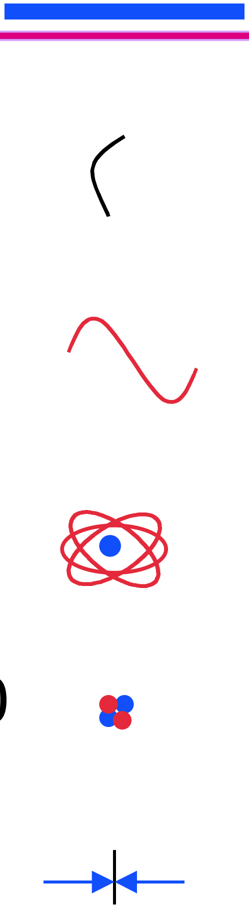
Sketch of a Michelson Interferometer



Some of the Technical Challenges

- 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, absolute
- Detect optical phase changes of ~ 10^{-10} radians
- Engineer structures to mitigate recoil from atomic vibrations in suspended mirrors
- Provide clear optical paths within 4-km UHV beam lines

How Small is 10^{-18} Meter?



	One meter, about 40 inches
÷10,000	*Human hair, about 100 microns*
÷100	*Wavelength of light, about 1 micron*
÷10,000	*Atomic diameter, 10^{-10} meter*
÷100,000	*Nuclear diameter, 10^{-15} meter*
÷1,000	*LIGO sensitivity, 10^{-18} meter*

Observatory Facilities

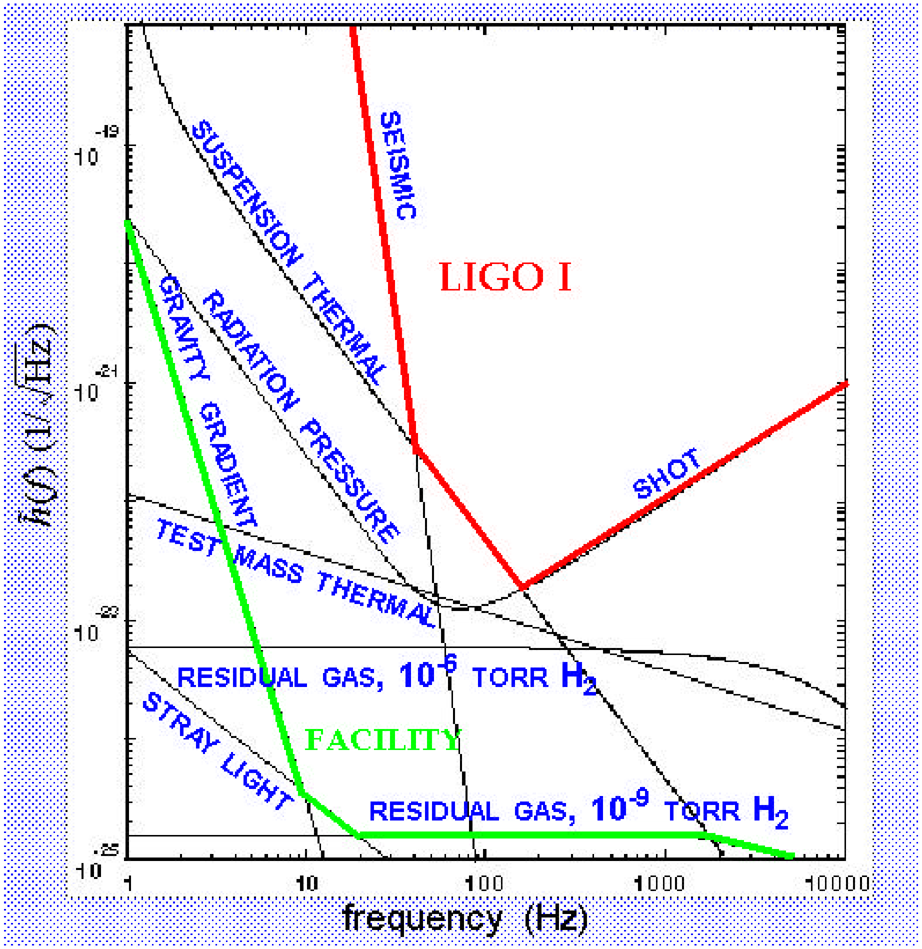
- Hanford and Livingston Lab facilities available starting 1997-8
- 16 km beam tube with 1.2-m diameter
- Beam-tube foundations in plane ~ 1 cm
- Turbo roughing with ion pumps for steady state
- Large experimental halls compatible with Class-3000 environment; portable enclosures around open chambers compatible with Class-100
- Some support buildings/laboratories still under construction

Beam Tube Bakeout

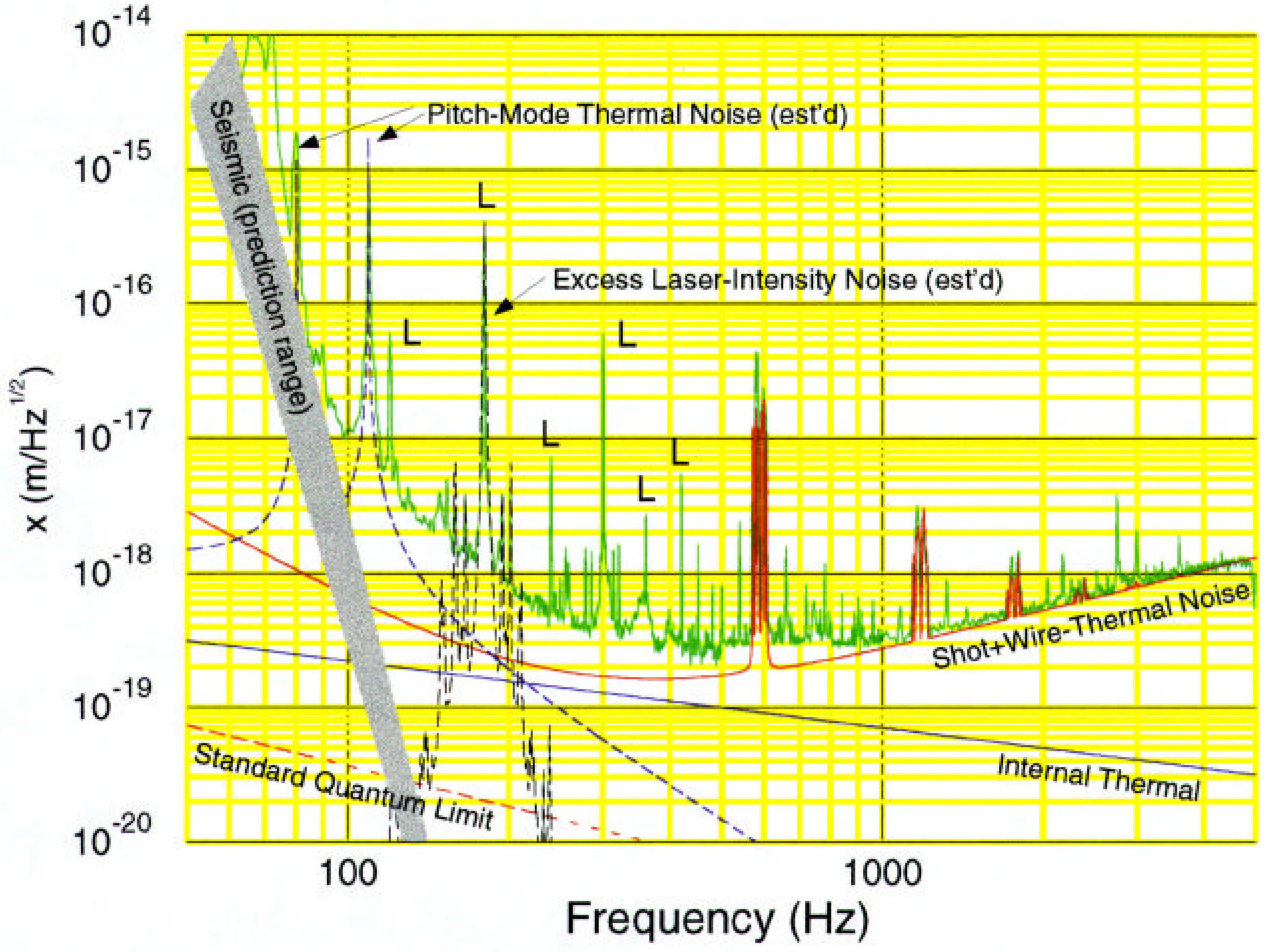
- Method: Insulate tube and drive ~2000 amps from end to end

LIGO I Detector Being Commissioned

- LIGO I has evolved from design principles successfully demonstrated in 40-m & phase noise interferometer test beds
- Design effort sought to optimize reliability (up time) and data accessibility
- Facilities and vacuum system designs provide an environment suitable for the most aggressive detector specifications imaginable in future.



Design for Low Background Spec'd From Prototype Operation

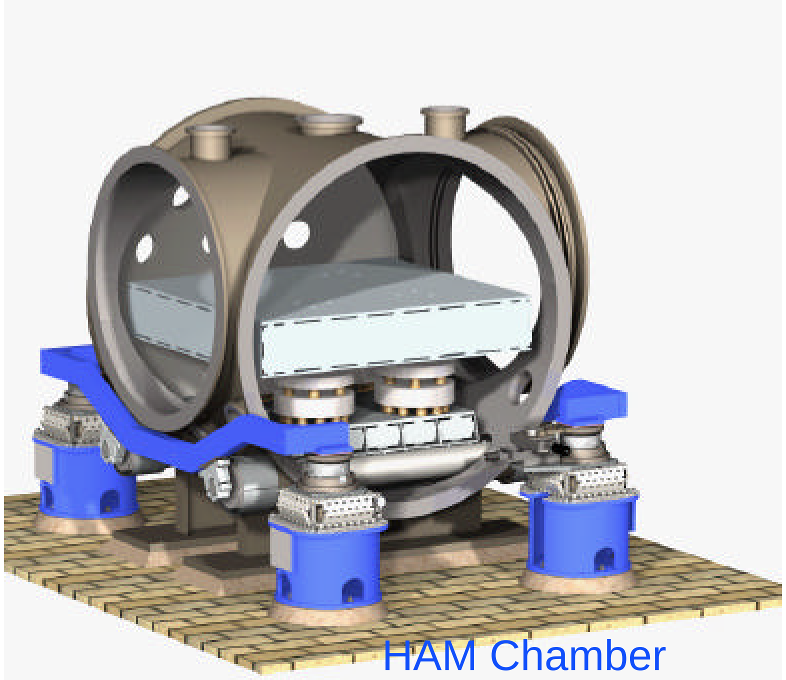


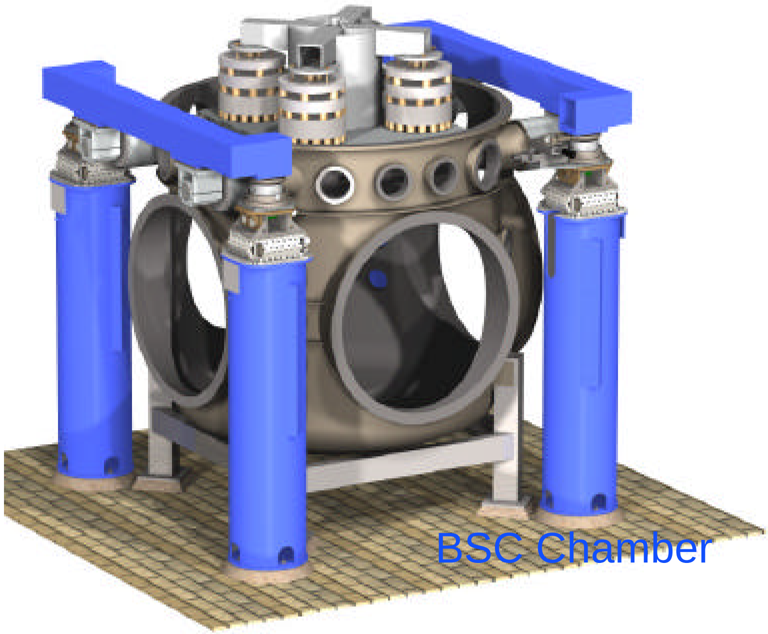
For Example:

Noise-Equivalent Displacement of 40-meter Interferometer (ca1994)

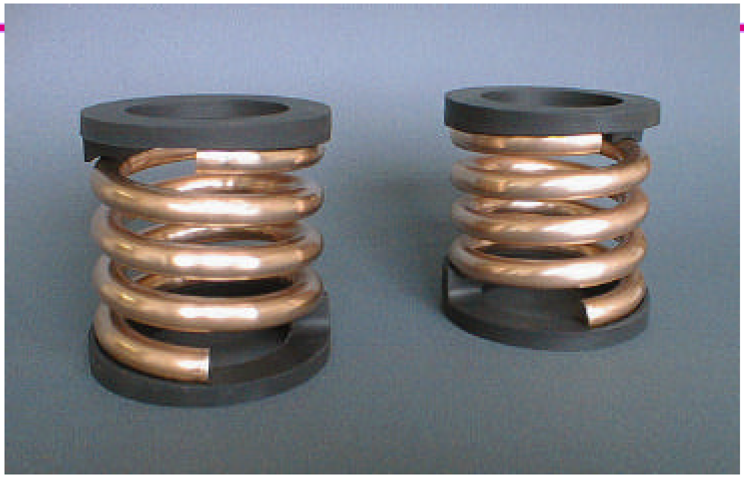
Vibration Isolation Systems

- 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

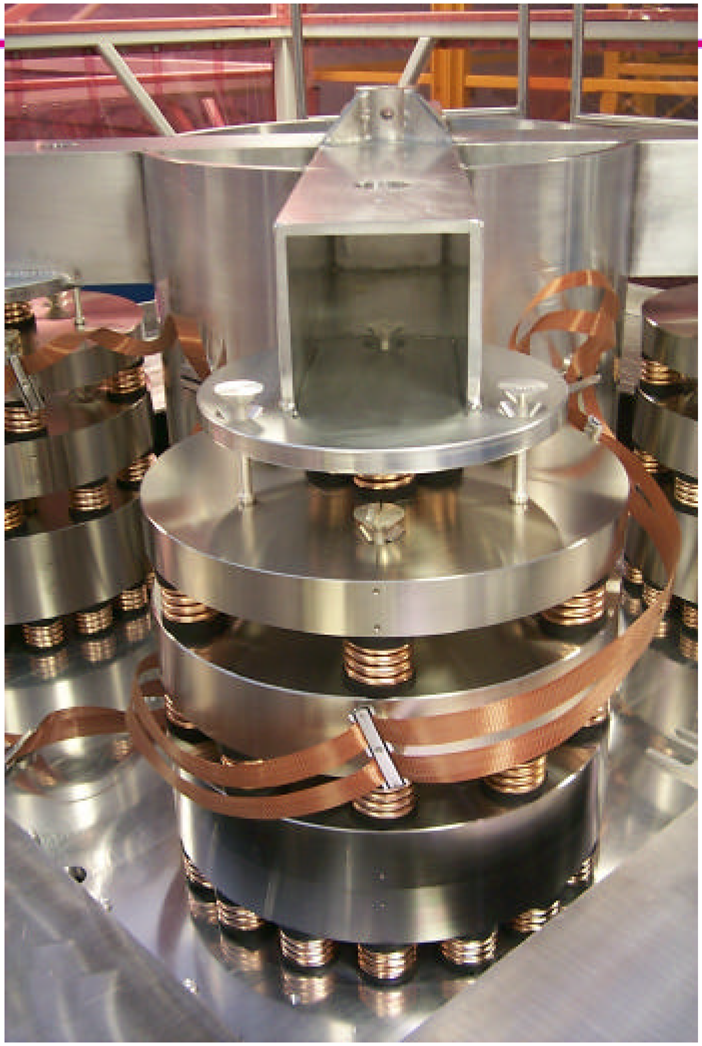

HAM Chamber


BSC Chamber

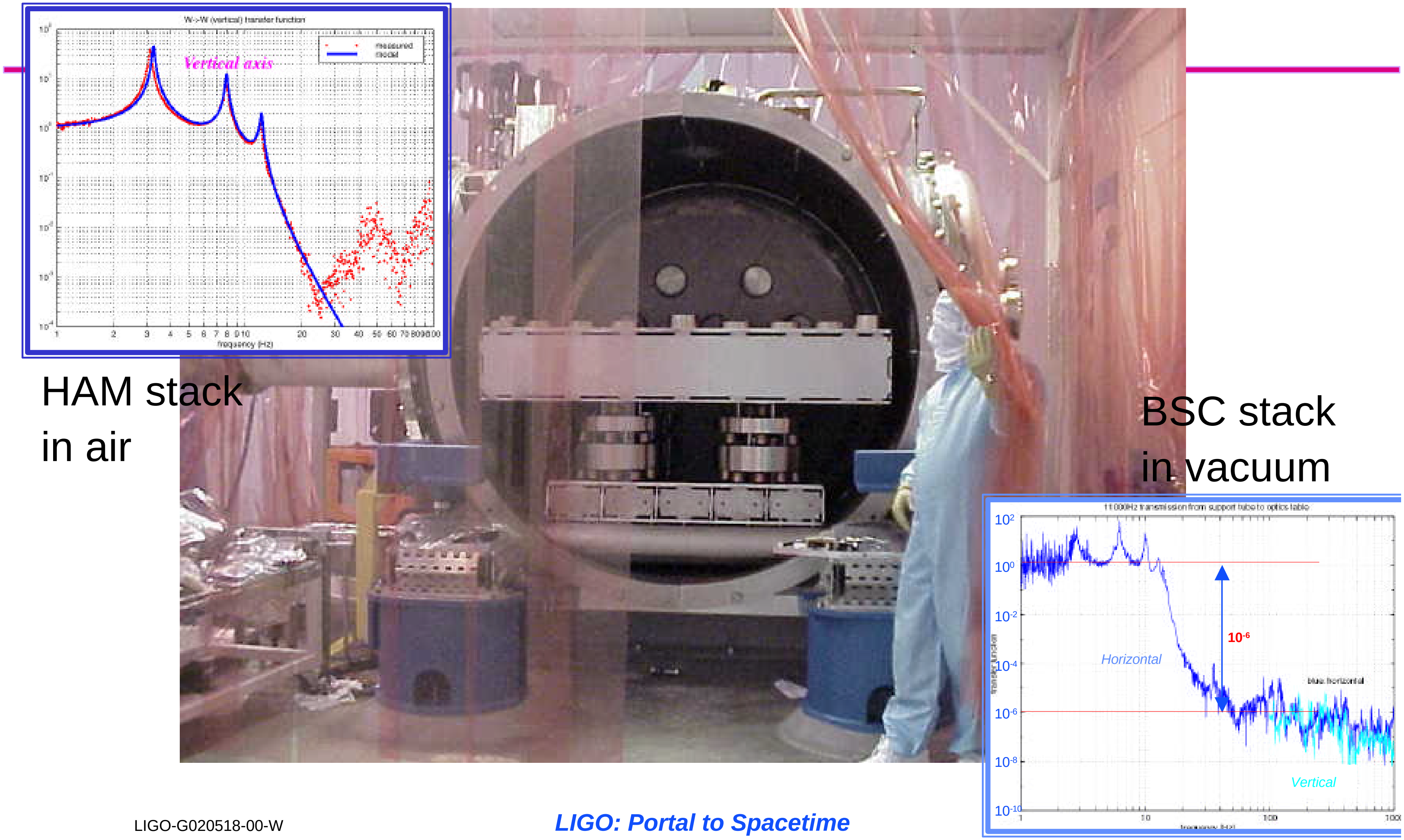
Seismic Isolation – Springs and Masses



damped spring
cross section



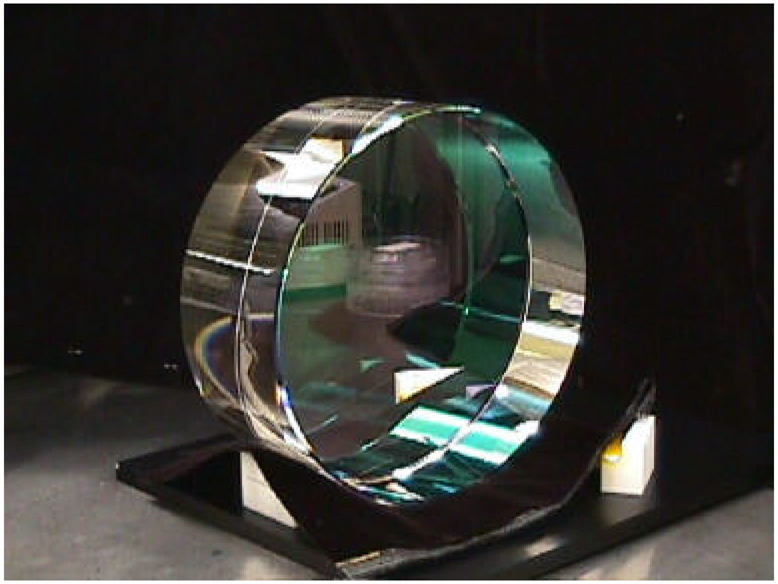
Seismic System Performance



HAM stack
in air

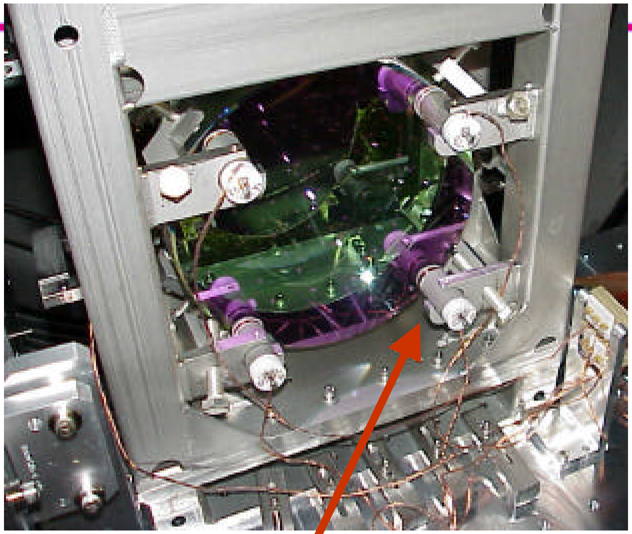
BSC stack
in vacuum

Core Optics



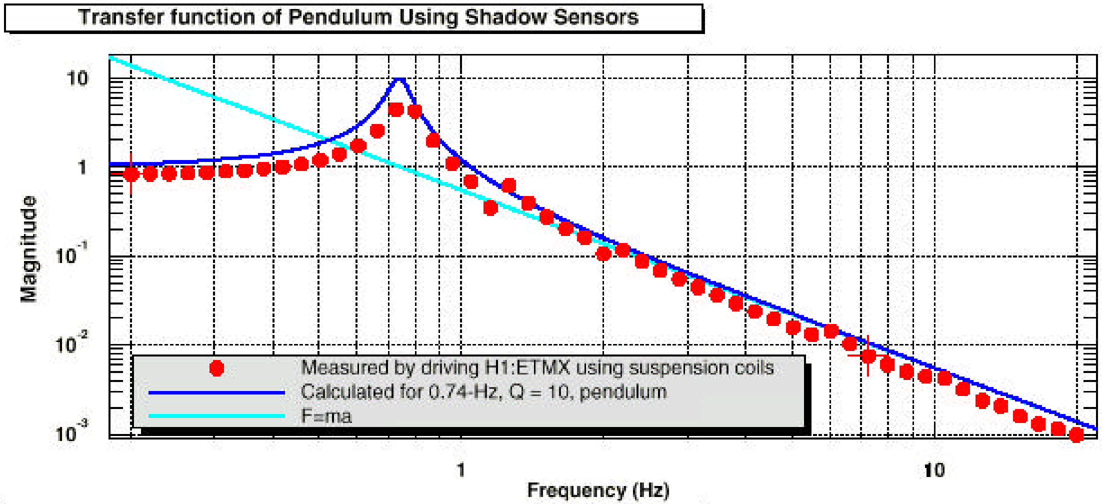
- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Homogeneity < 5×10^{-7}
  - » Internal mode Q's > 2×10^{6}
- Polishing
  - » Surface uniformity < 1 nm rms
  - » Radii of curvature matched < 3%
- Coating
  - » Scatter < 50 ppm
  - » Absorption < 2 ppm
  - » Uniformity $<10^{-3}$
- Production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

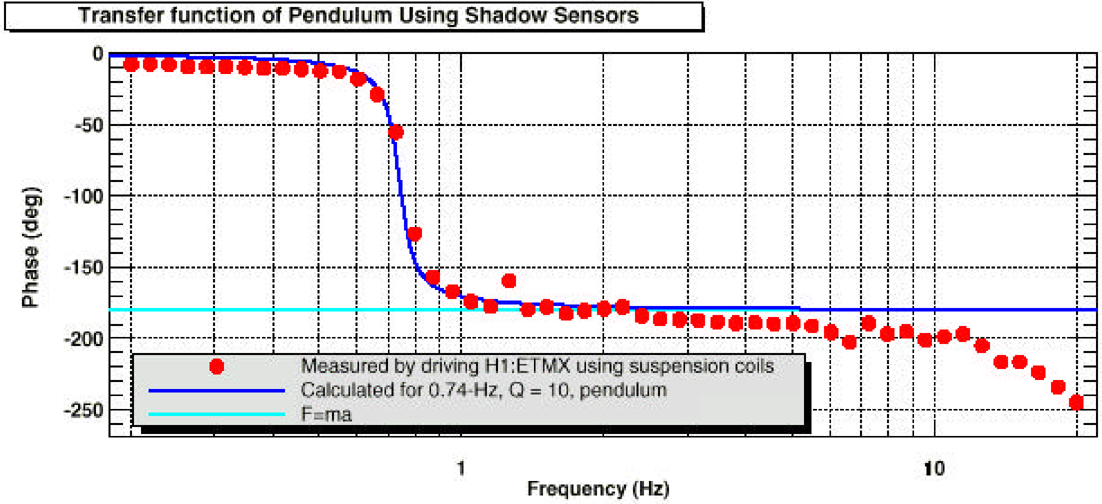
Core Optics Suspension and Control



- •Optics suspended as simple pendulums
- •Local sensors/actuators for damping and control

Suspended Mirror Approximates a Free Mass Above Resonance

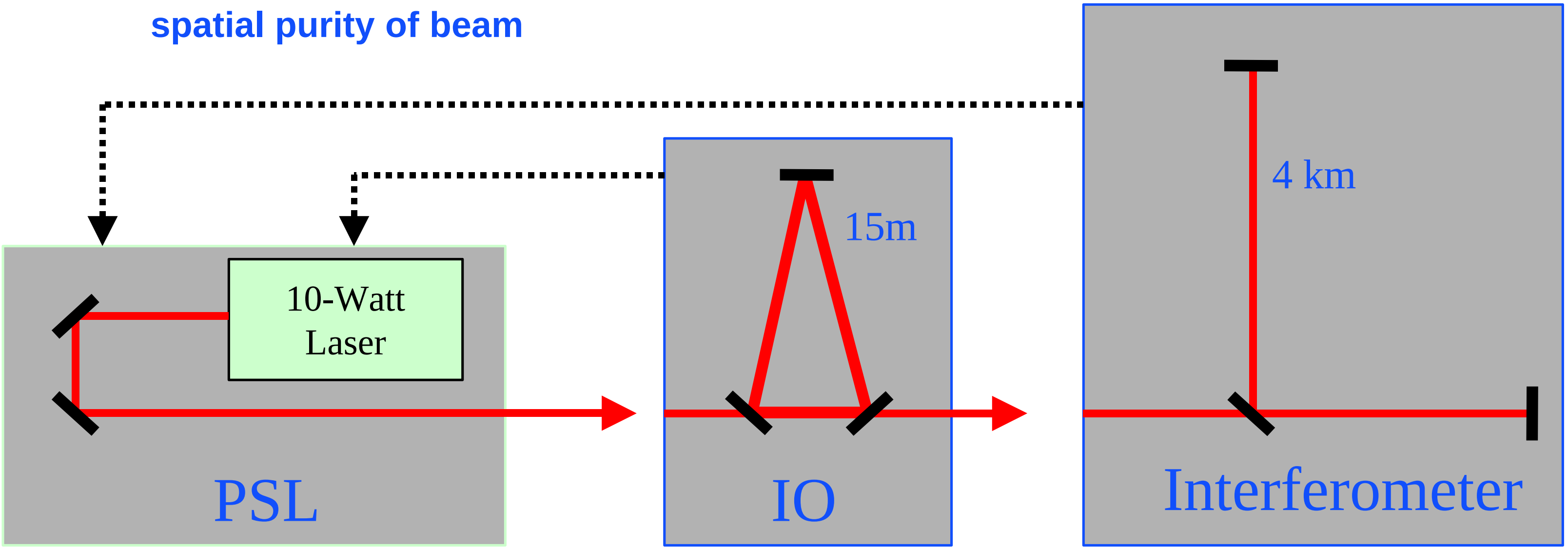




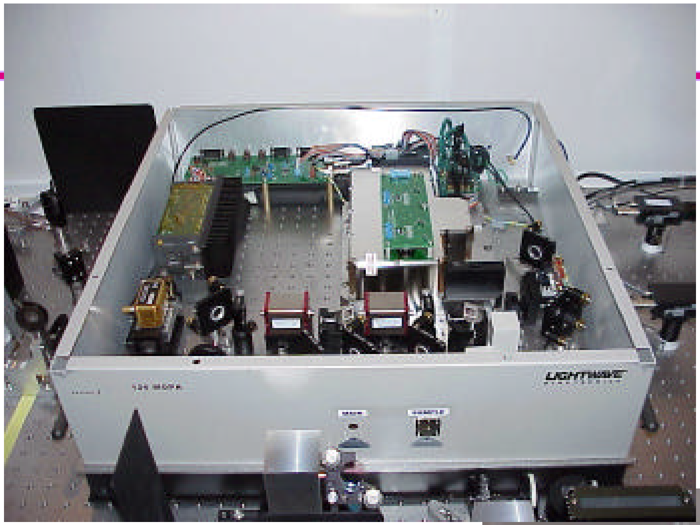
*T0=24/07/2002 04:15:25.296875 *Avg=2

Frequency Stabilization of the Light Employs Three Stages

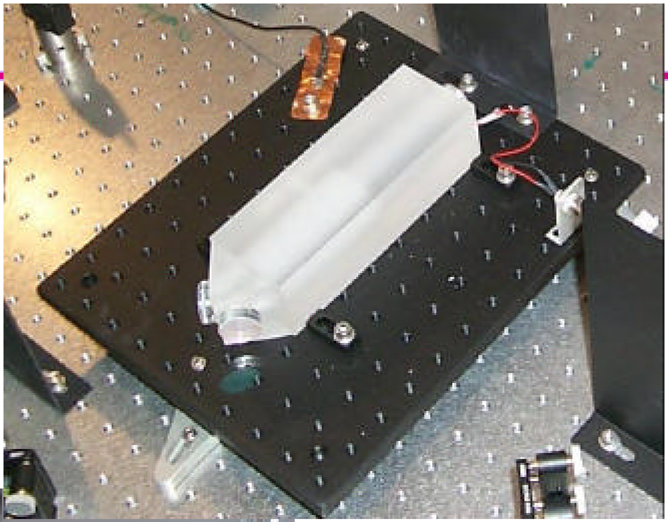
- Pre-stabilized laser delivers light to the long mode cleaner
  - **Start with high-quality, custom-built Nd:YAG laser**
  - **Improve frequency, amplitude and spatial purity of beam**
- Actuator inputs provide for further laser stabilization
  - **Wideband**
  - **Tidal**



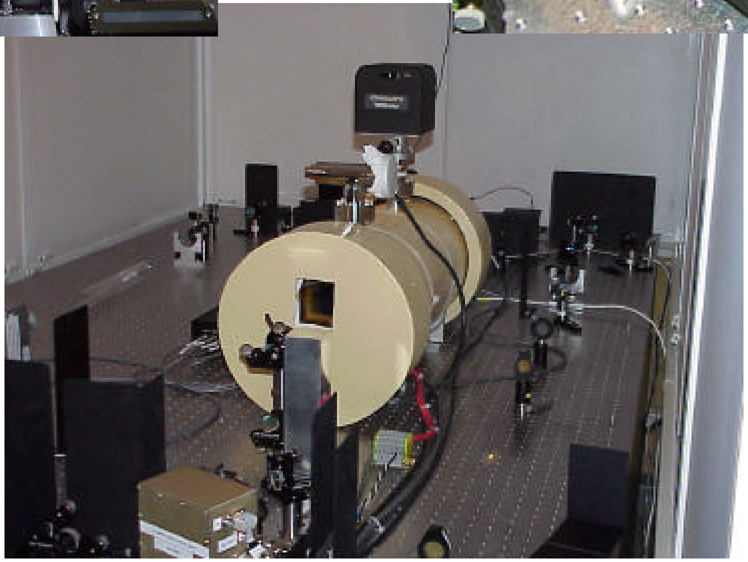
Pre-stabilized Laser (PSL)



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

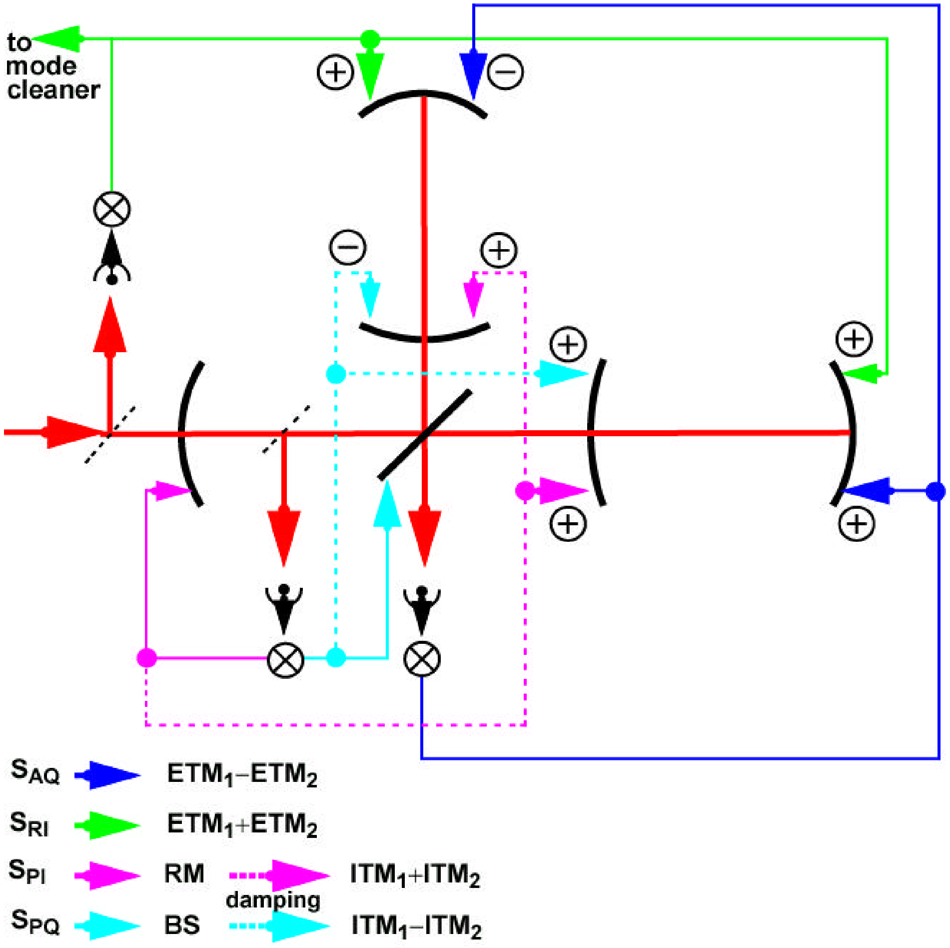


Cavity for
defining beam geometry,
joint development with
Stanford



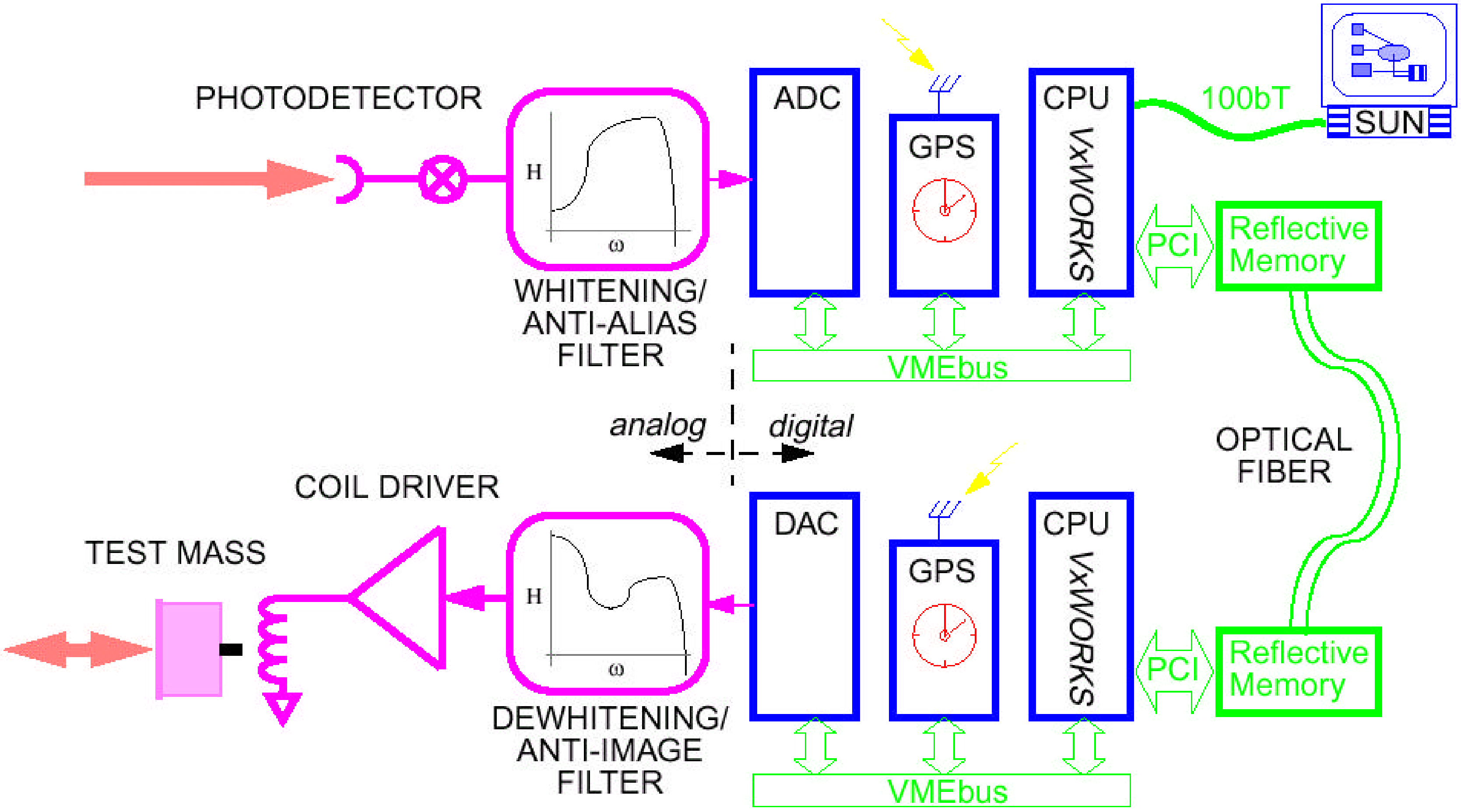
Frequency reference
cavity (inside oven)

Interferometer Control System

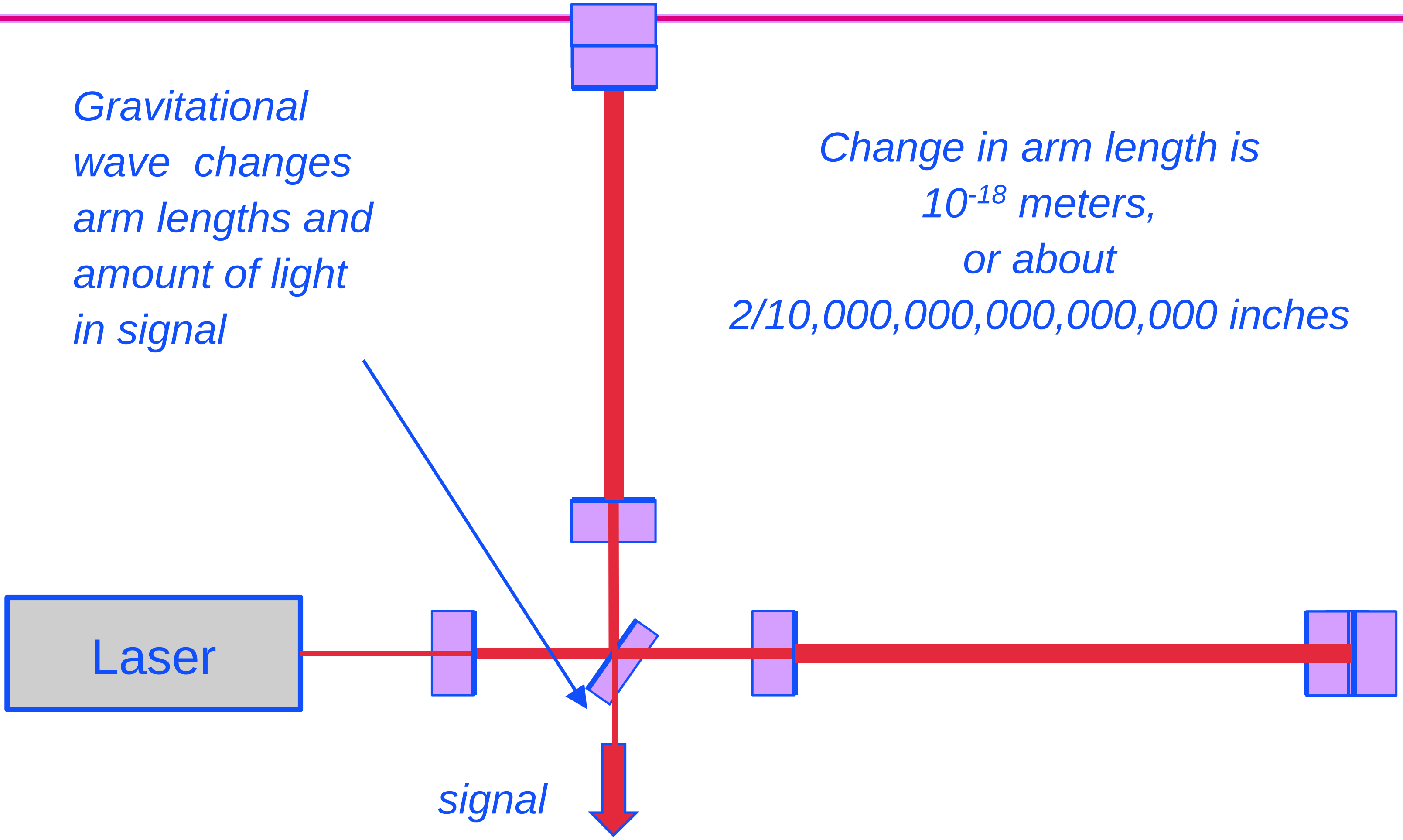


- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Ill-conditioned (off-diagonal) plant matrix
- Highly nonlinear response over most of phase space
- Transition to stable, linear regime takes plant through singularity
- Employs adaptive control system that evaluates plant evolution and reconfigures feedback paths and gains during lock acquisition
- But it works!

Digital Interferometer Sensing & Control System



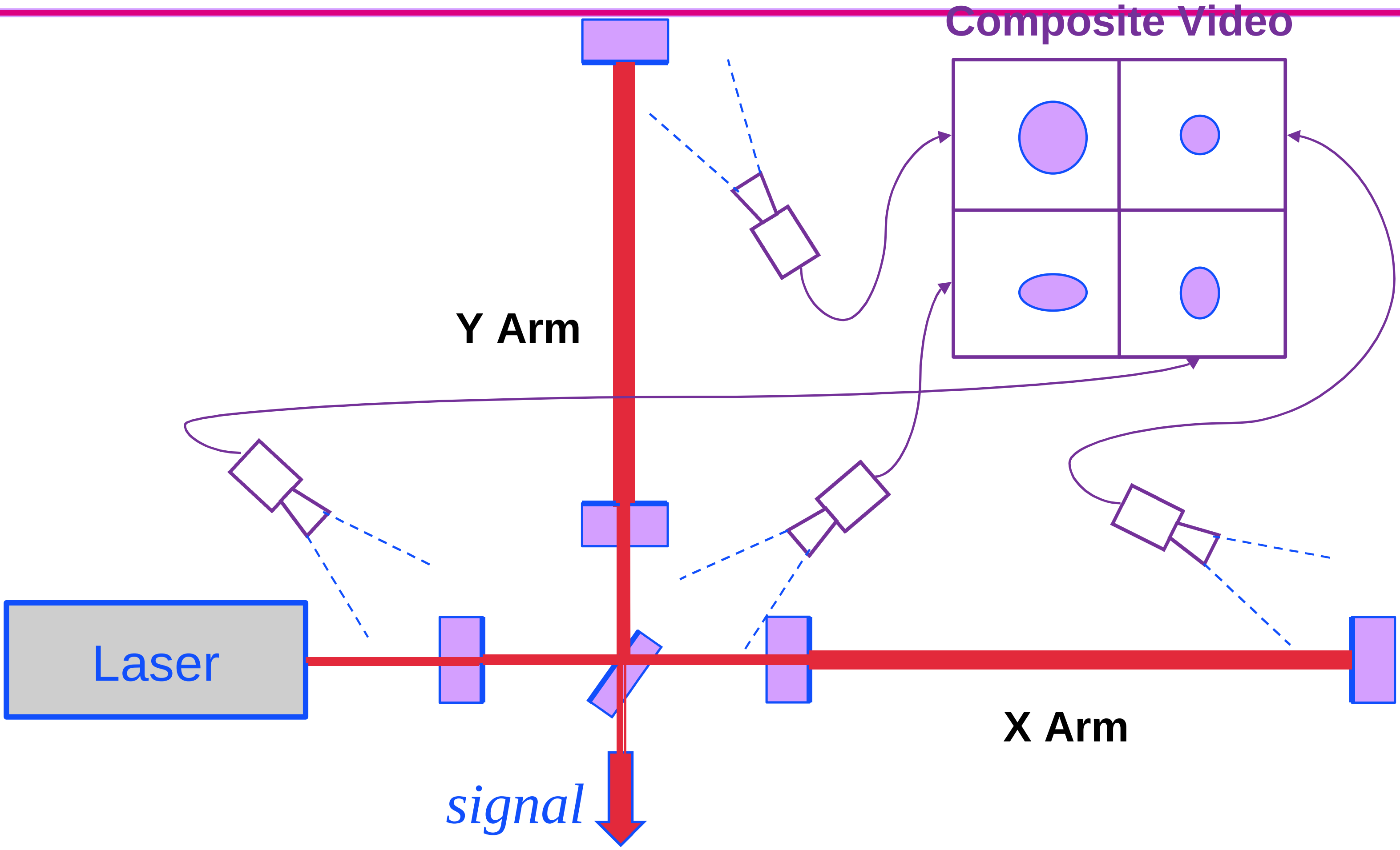
Sensing the Effect of a Gravitational Wave



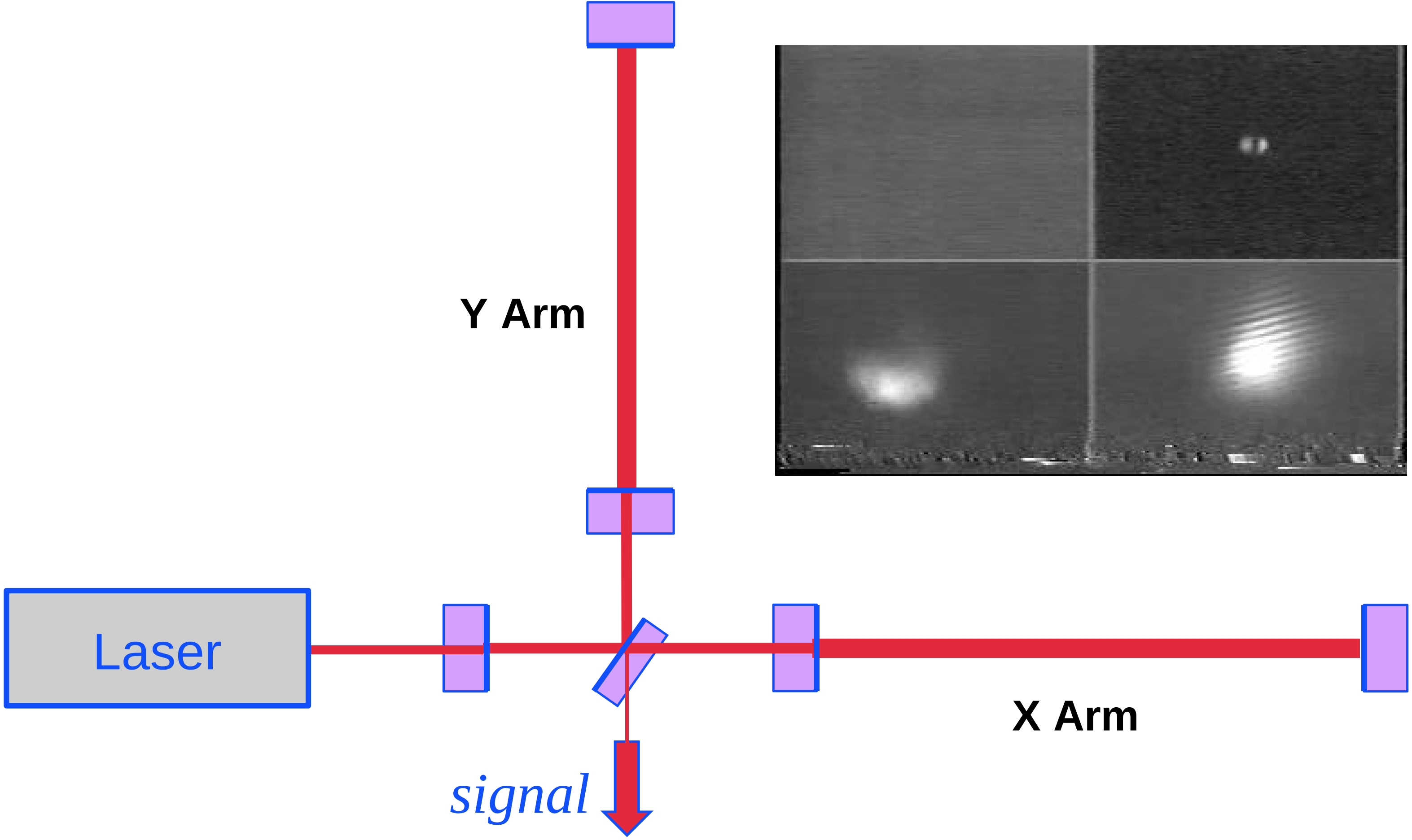
Gravitational wave changes arm lengths and amount of light in signal

Change in arm length is
10^{-18} meters,
or about
2/10,000,000,000,000,000 inches

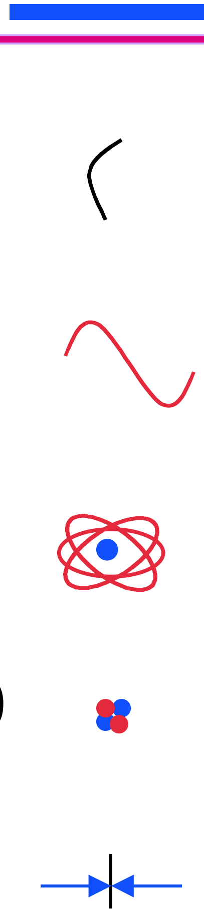
Steps to Locking an Interferometer



Watching the Interferometer Lock



Why is Locking Difficult?



One meter, about 40 inches

÷10,000

Earthtides, about 100 microns

÷100

Microseismic motion, about 1 micron

÷10,000

Precision required to lock, about 10^{-10} meter

÷100,000

Nuclear diameter, 10^{-15} meter

÷1,000

LIGO sensitivity, 10^{-18} meter

Tidal Compensation Data

Tidal evaluation on 21-hour locked section of S1 data

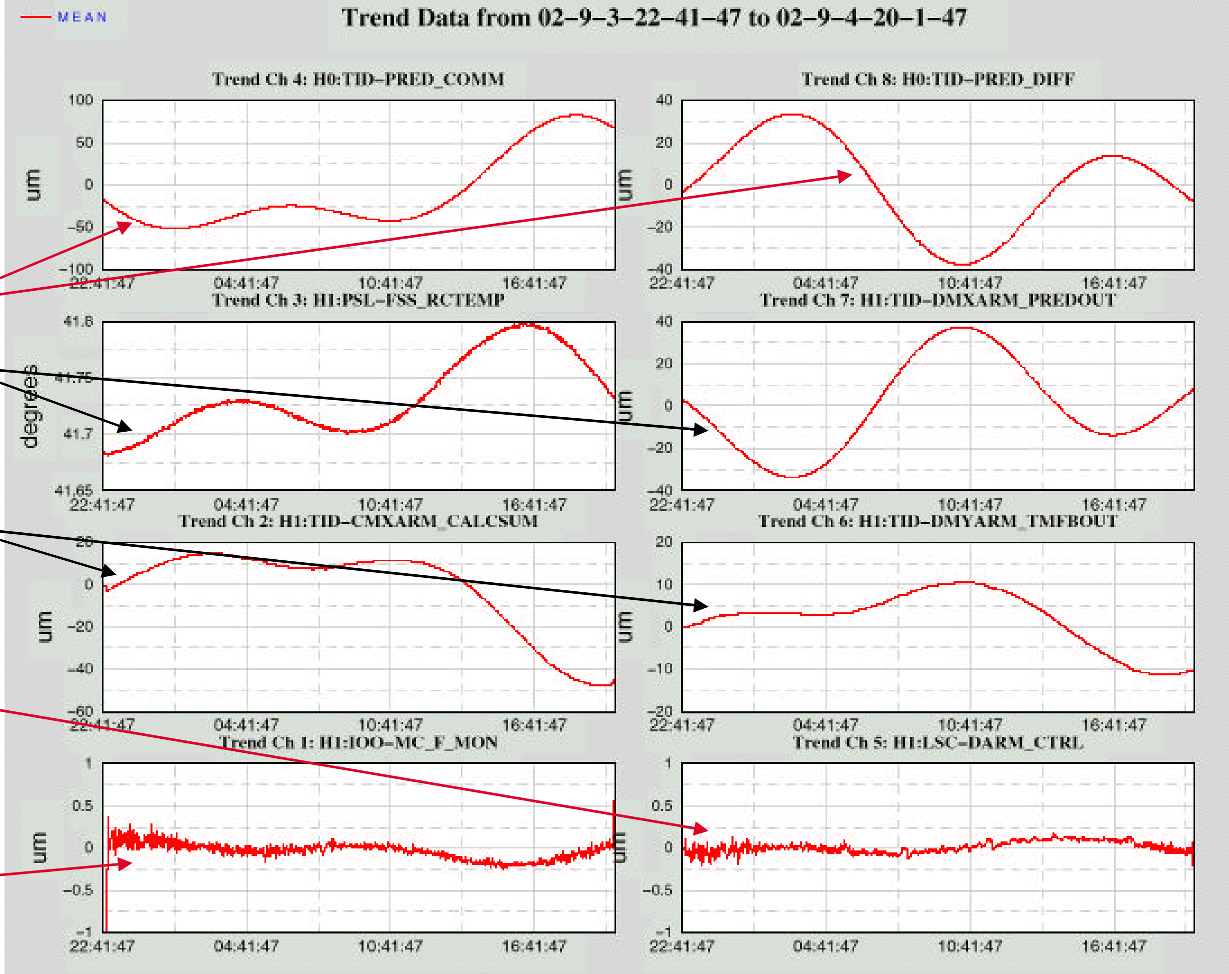
Predicted tides

Feedforward

Feedback

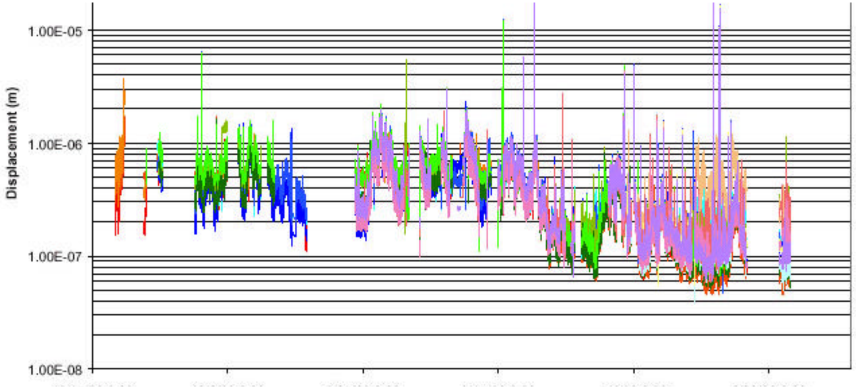
Residual signal on voice coils

Residual signal on laser



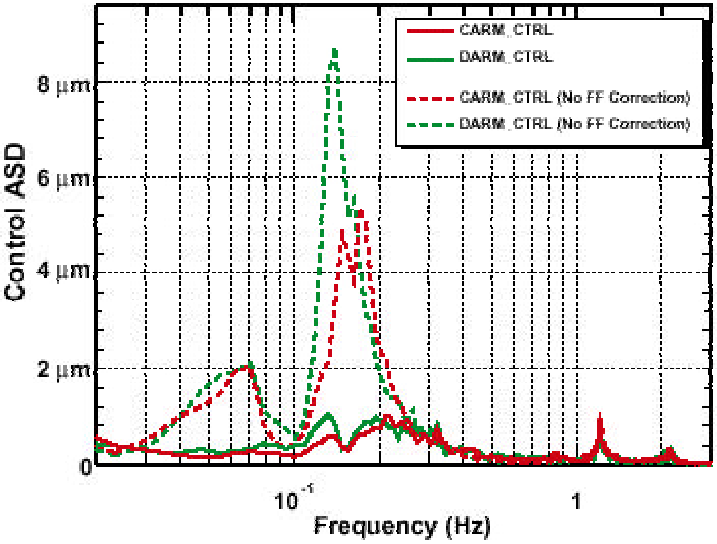
Microseism

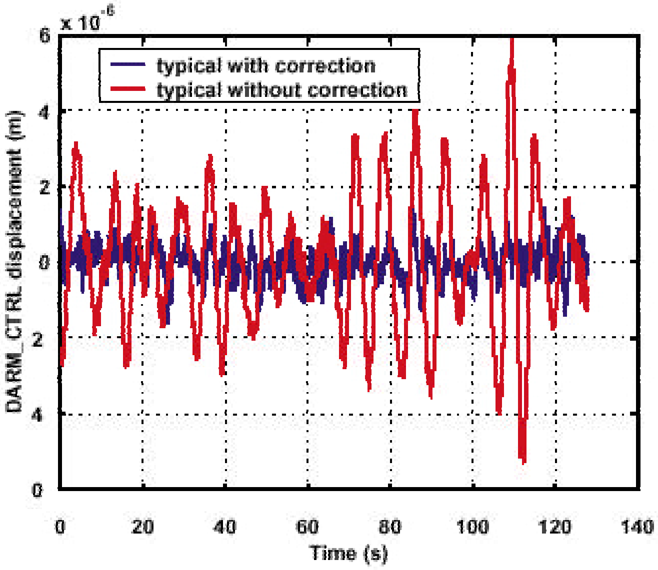
Microseism at 0.12 Hz dominates ground velocity



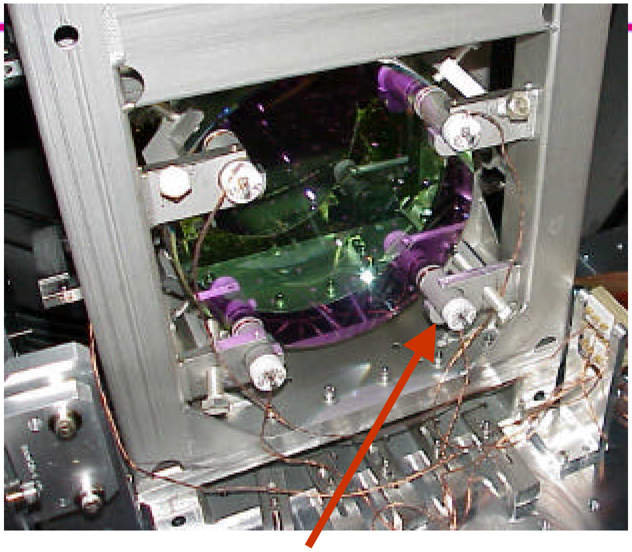
Trended data (courtesy of Gladstone High School) shows large variability of microseism, on several-day- and annual- cycles

Reduction by feed-forward derived from seismometers

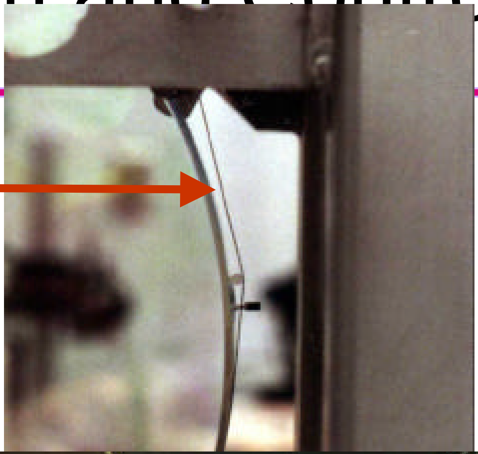




Core Optics Suspension and Control



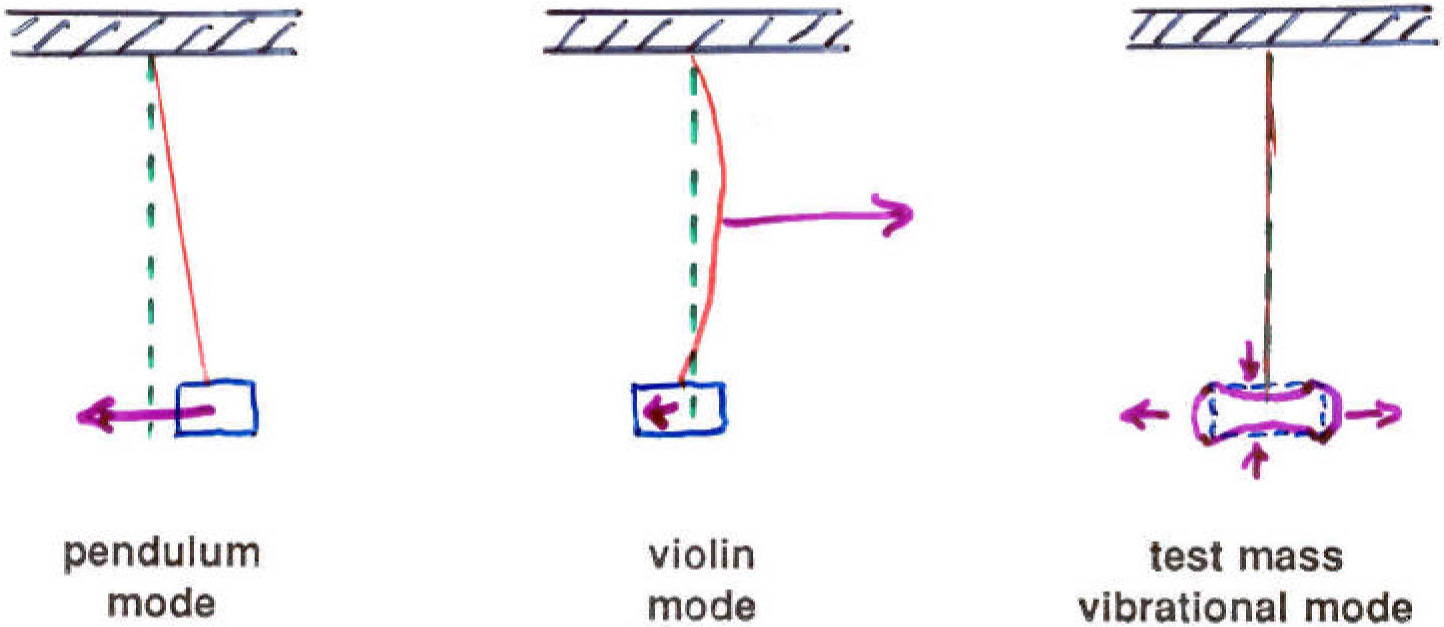
Optics suspended as simple pendulums



Local sensors/actuators provide damping and control forces

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

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



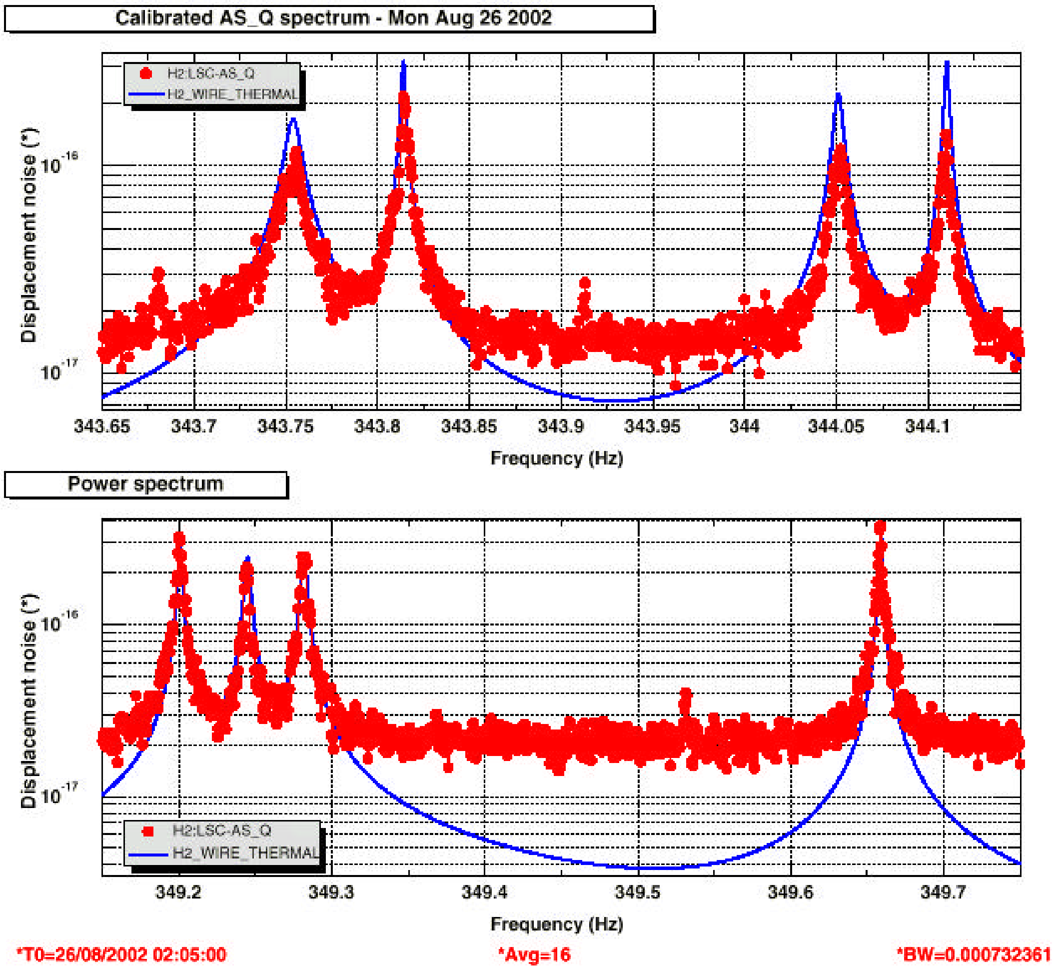
$x_{rms} \approx 10^{-11}$ m
f < 1 Hz

$x_{rms} \approx 2\times10^{-17}$ m
f ~ 350 Hz

$x_{rms} \approx 5\times10^{-16}$ m
f ≥ 10 kHz

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

Thermal Noise Observed in 1st Violins on H2, L1 During S1

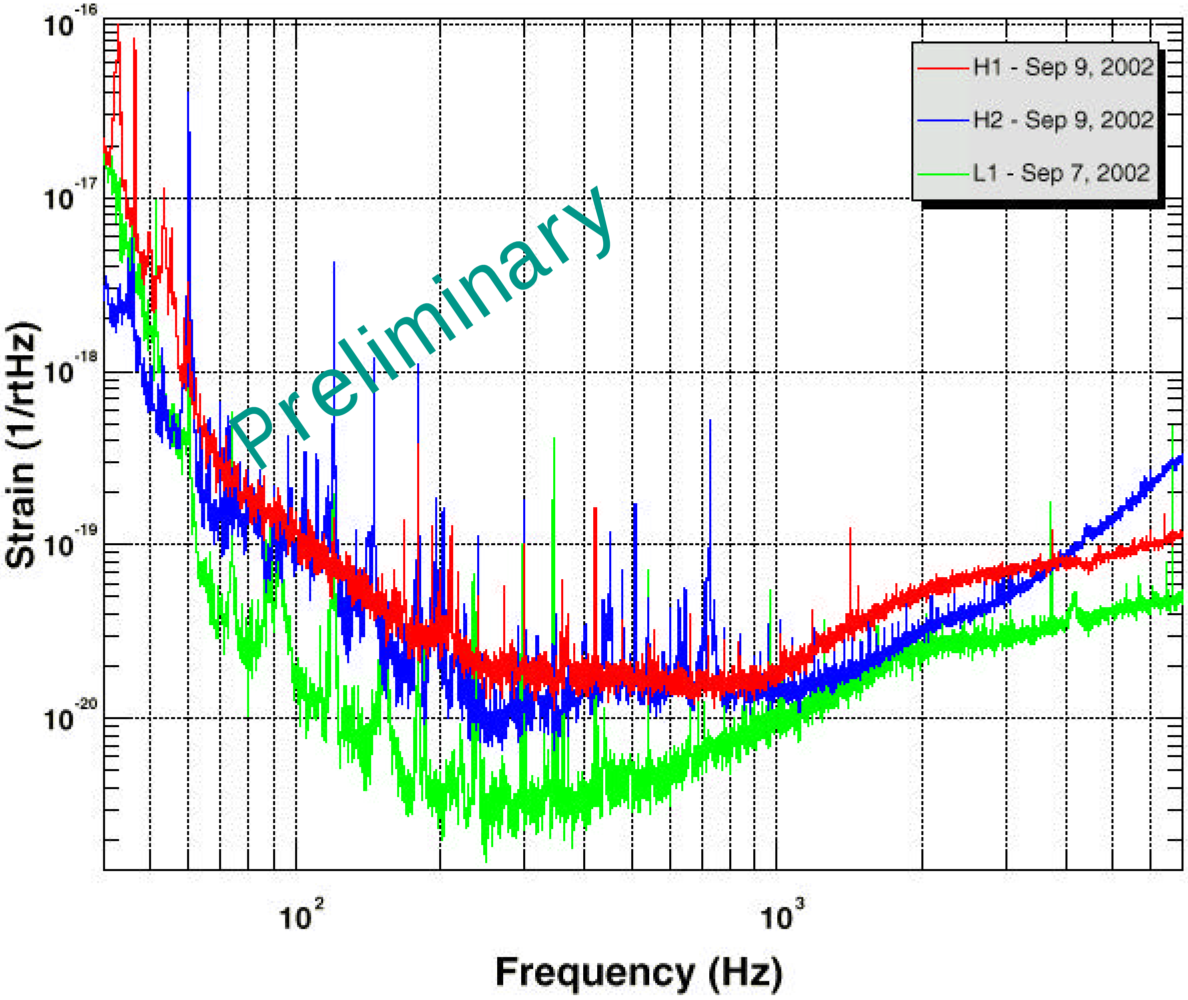


Almost good enough for tracking calibration.

Chronology of Detector Installation & Commissioning

- 7/98 Begin detector installation
- 6/99 Lock first mode cleaner
- 11/99 Laser spot on first end mirror
- 12/99 First lock of a 2-km Fabry-Perot arm
- 4/00 Engineering Run 1 (E1)
- 6/00 Brush Fire burns 500 km^2 of land surrounding LHO
- 10/00 Recombined LHO-2km interferometer in E2 run
- 10/00 First lock of LHO-2km power-recycled interferometer
- 2/01 Nisqually earthquake damages LHO interferometers
- 4/01 Recombined 4-km interferometer at LLO
- 5/01 Earthquake repairs completed at LHO
- 6/01 Last LIGO-1 mirror installed
- 12/01 Power recycling achieved for LLO-4km
- 1/2002 E7: First triple coincidence run; first on-site data analysis
- 1/2002 Power recycling achieved for LHO-4km
- 9/2002 First Science Run (S1) completed

Preliminary Noise Equivalent Strain Spectra for S1



S1 Analysis Working Groups

- Data from S1 is being analyzed by LSC working groups for:
  - Detector Characterization
  - Binary Inspirals
  - Bursts
  - Periodic Sources
  - Stochastic Background

Summary

- First triple coincidence run completed (17 days with ~23% triple coincidence duty factor)
- On-line data analysis systems (Beowulf parallel supercomputer) functional at LHO and LLO
- S1 coincidence analyses with GEO & TAMA are first science with international laser-GW network
- First science data analysis ongoing
- Interferometer control system still being commissioned and tuned
- Working to increase immunity to high seismic noise periods (especially important at LLO)
- S2 scheduled to run 2 months in early 2003

Despite a few difficulties, science runs started in 2002.