What If We Could Listen to the Stars?

Fred Raab

LIGO Hanford Observatory

LIGO-G030168-00-W

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 listening to the vibrations of space itself
- LIGO consists of large, earth-based, detectors that will act like huge microphones, listening for the most violent events in the universe

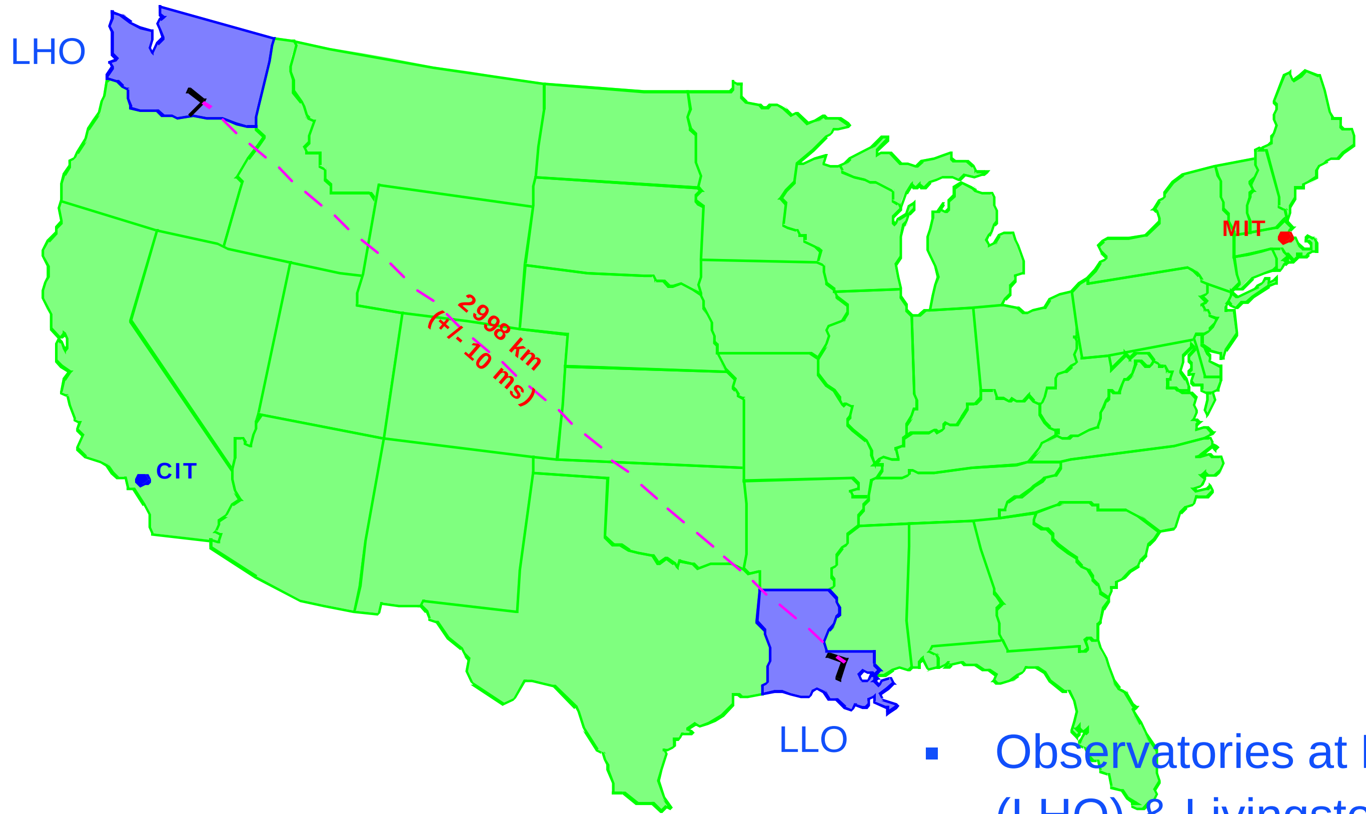
The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

Brought to you by the National Science Foundation; operated by Caltech and MIT; the research focus for about 350 LIGO Science Collaboration members worldwide.

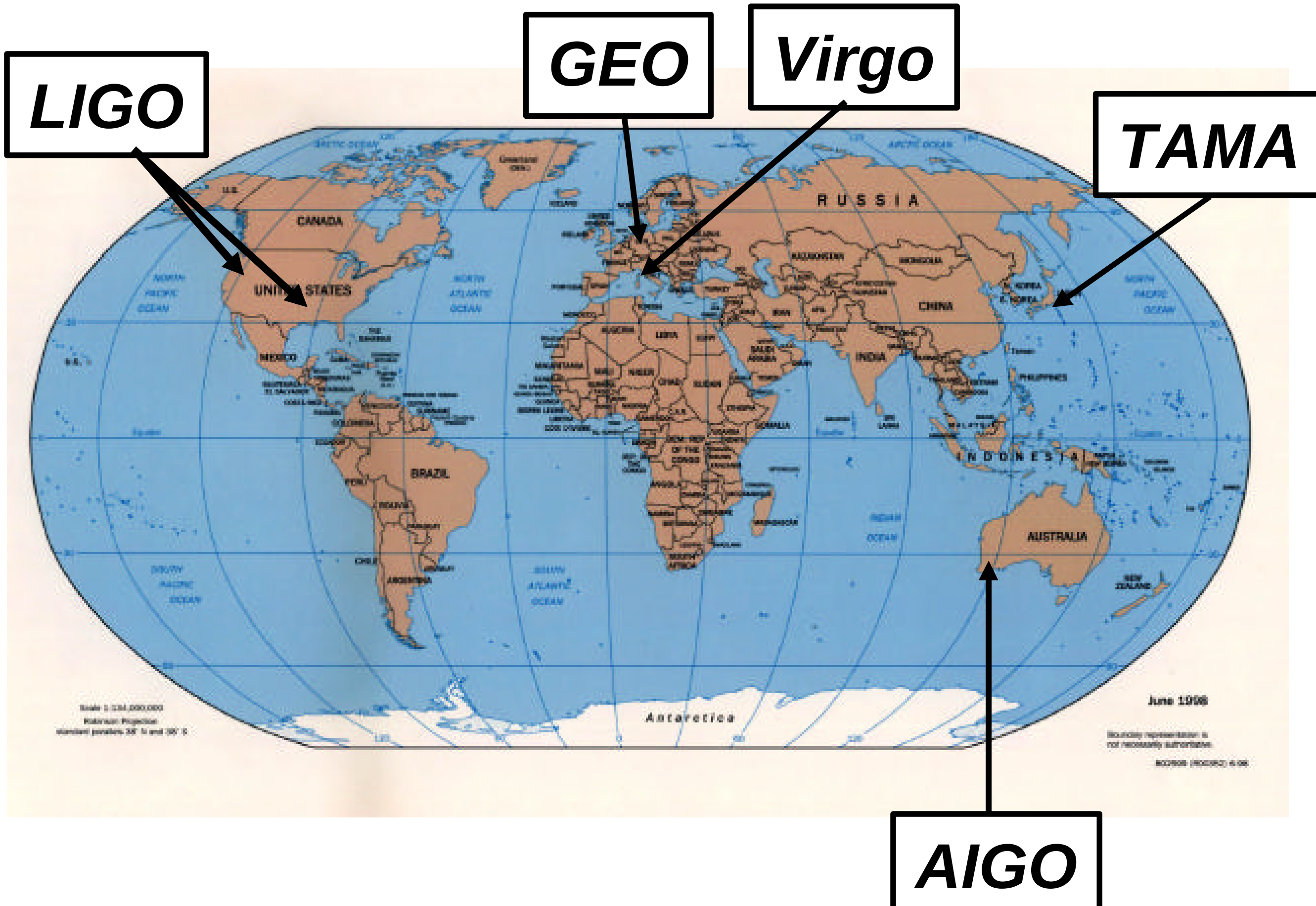
LIGO Laboratories Are Unique National Facilities



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

Part of Future International Detector Network

Simultaneously detect signal (within msec)



detection confidence

locate the sources

decompose the polarization of gravitational waves

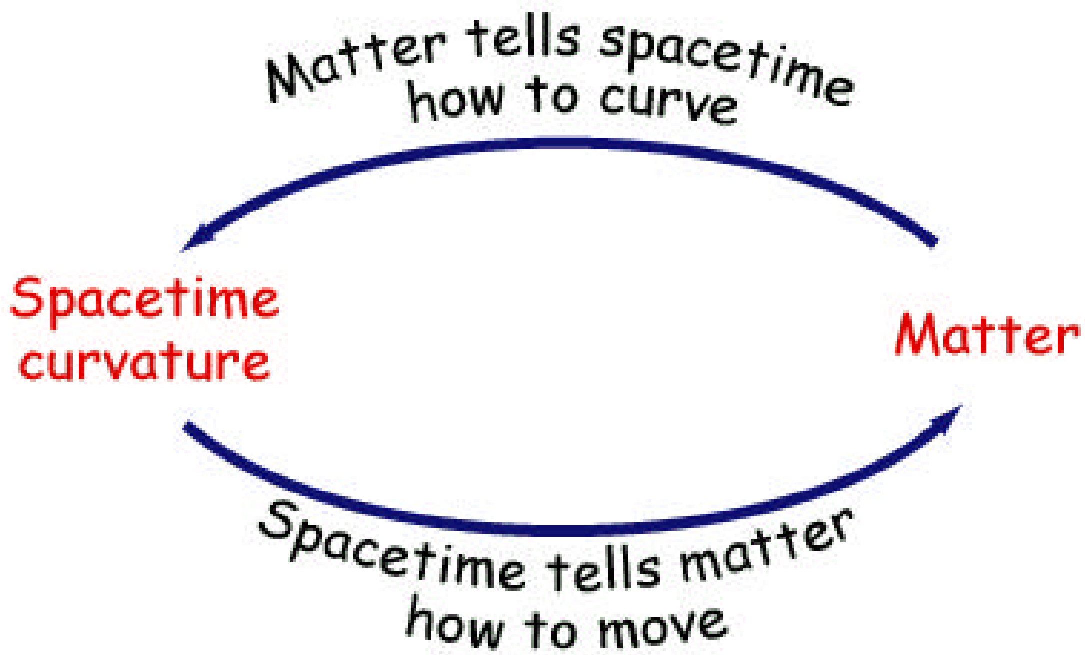
LIGO Laboratory & Science Collaboration

- 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?

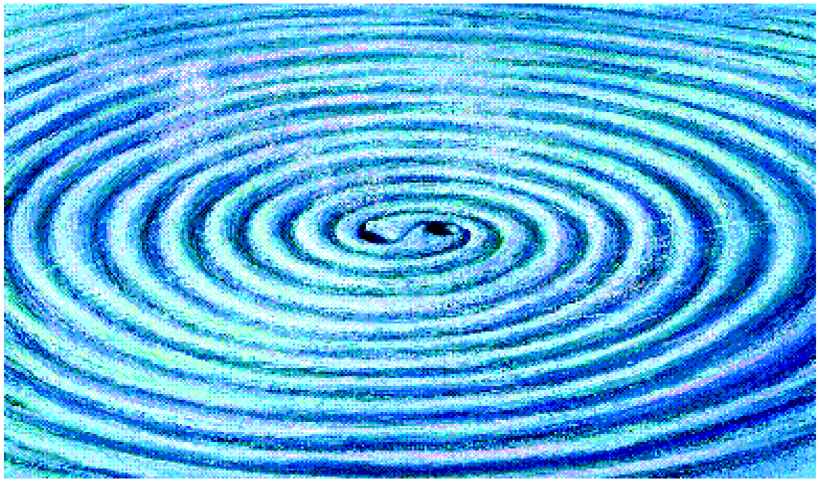
John Wheeler's Summary of General Relativity Theory



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:

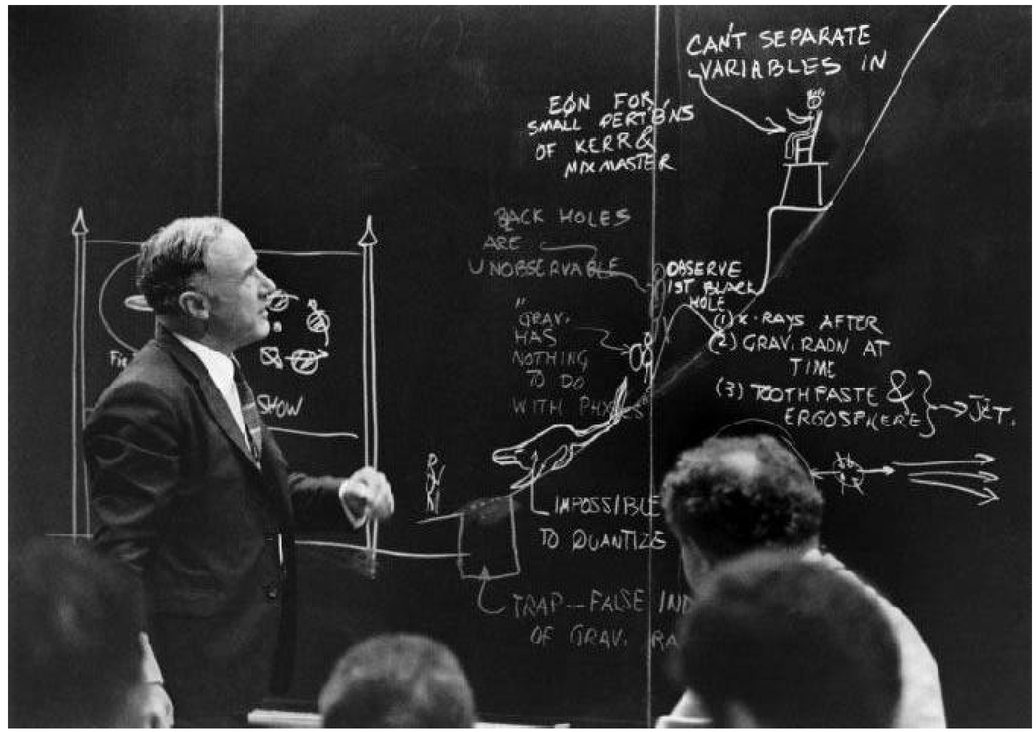


What Phenomena Do We Expect to Study With LIGO?

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."

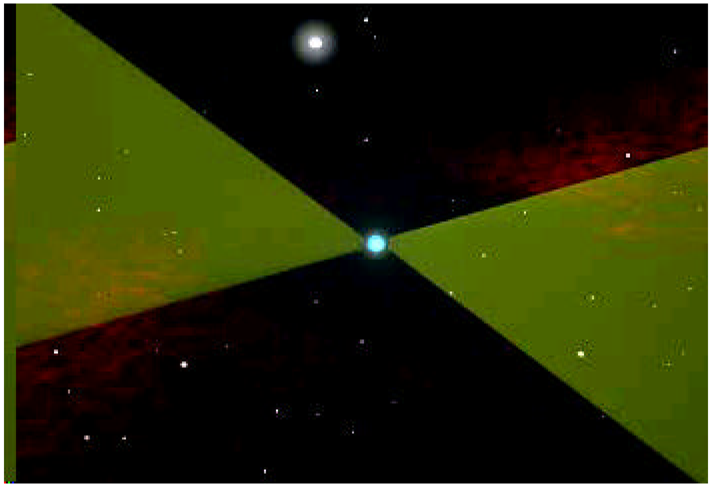
– John A. Wheeler in Geons, Black Holes and Quantum Foam



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

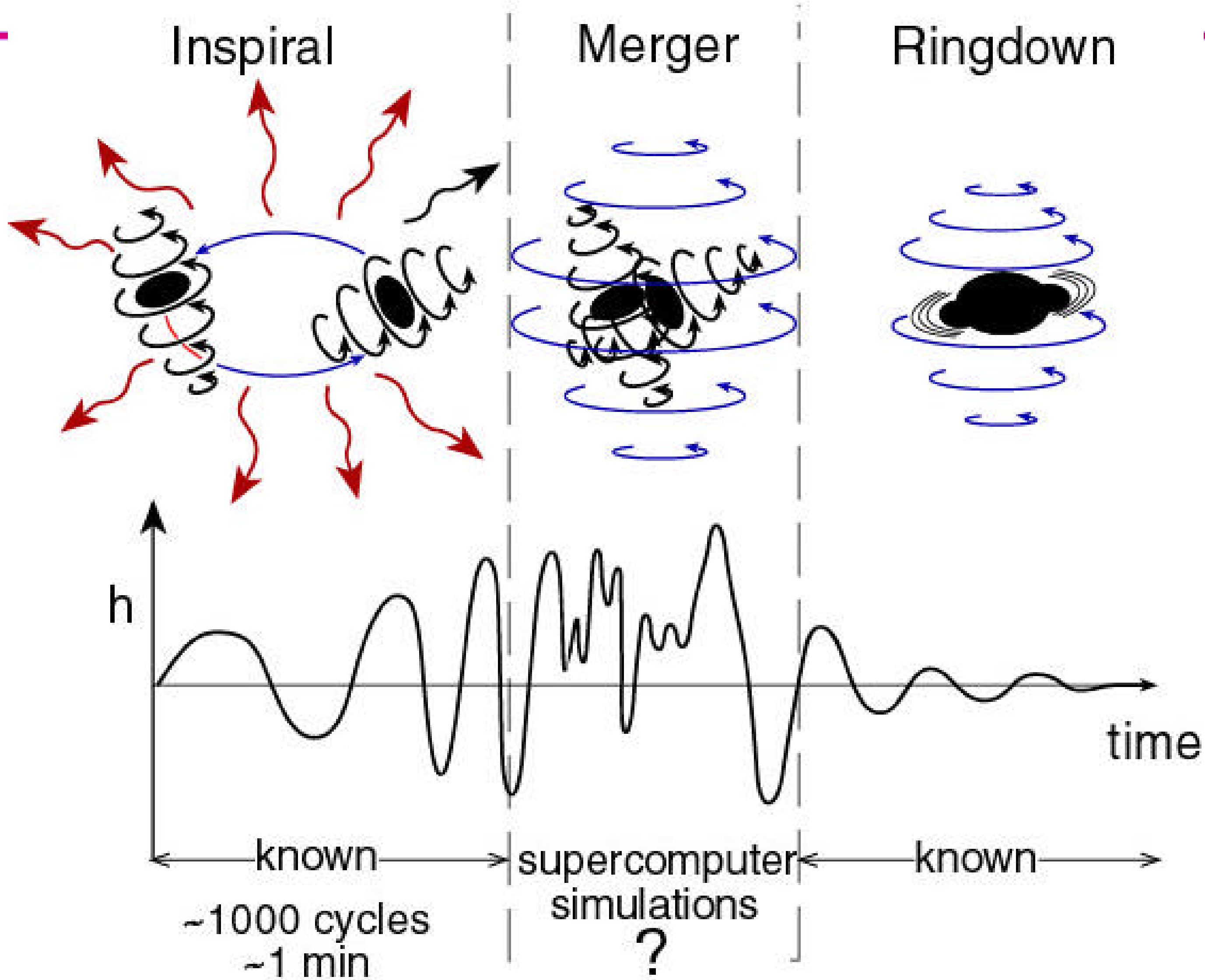
The "Undead" Corpses of Stars: Neutron Stars and Black Holes

- Neutron stars have a mass equivalent to 1.4 suns packed into a ball 10 miles in diameter, enormous magnetic fields and high spin rates
- Black holes are the extreme edges of the space-time fabric



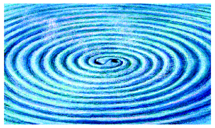
Artist: Walt Feimer, Space Telescope Science Institute

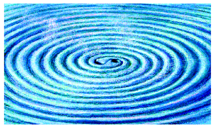
Catching Waves From Black Holes



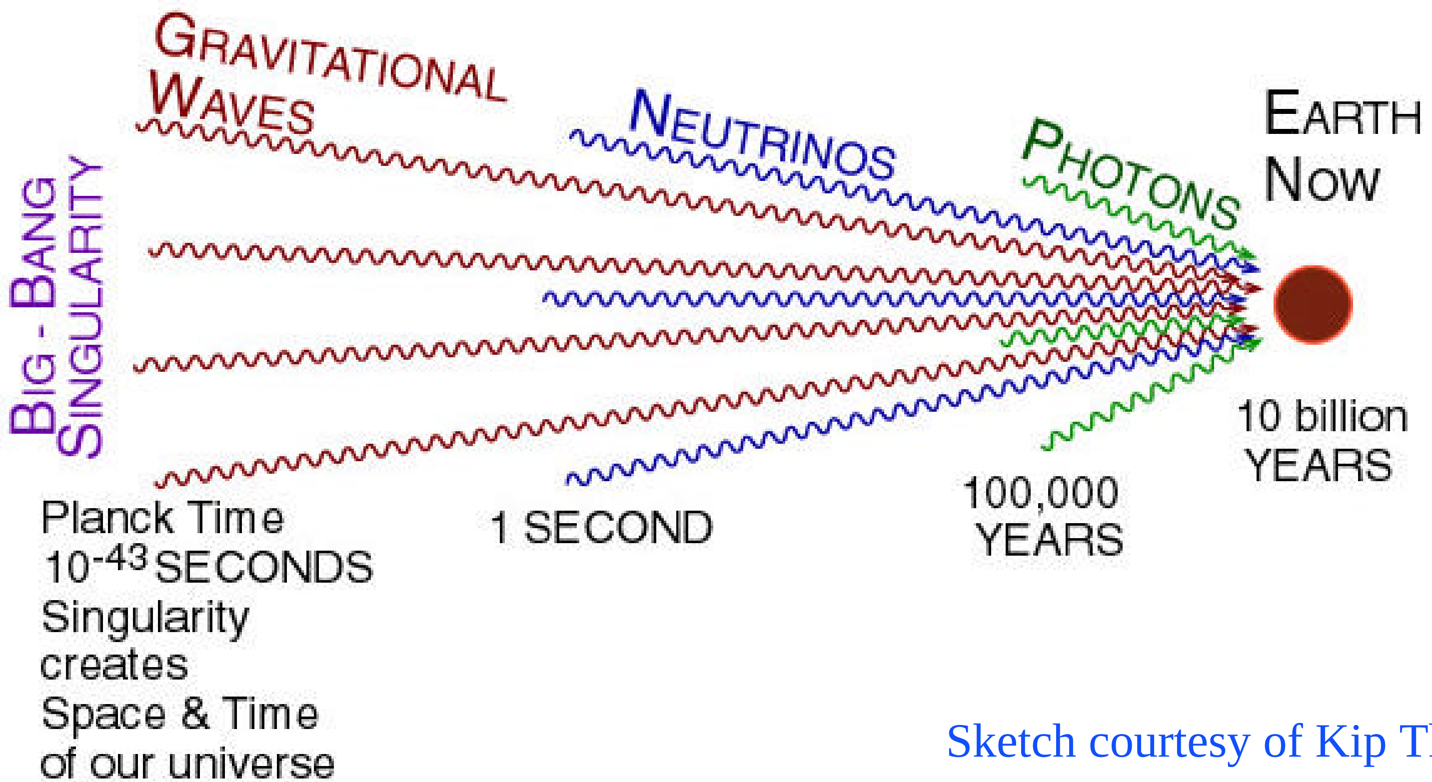
Sketches courtesy of Kip Thorne

Sounds of Compact Star Inspirals

Neutron-star binary inspiral: 

Black-hole binary inspiral: 

Searching for Echoes from Very Early Universe

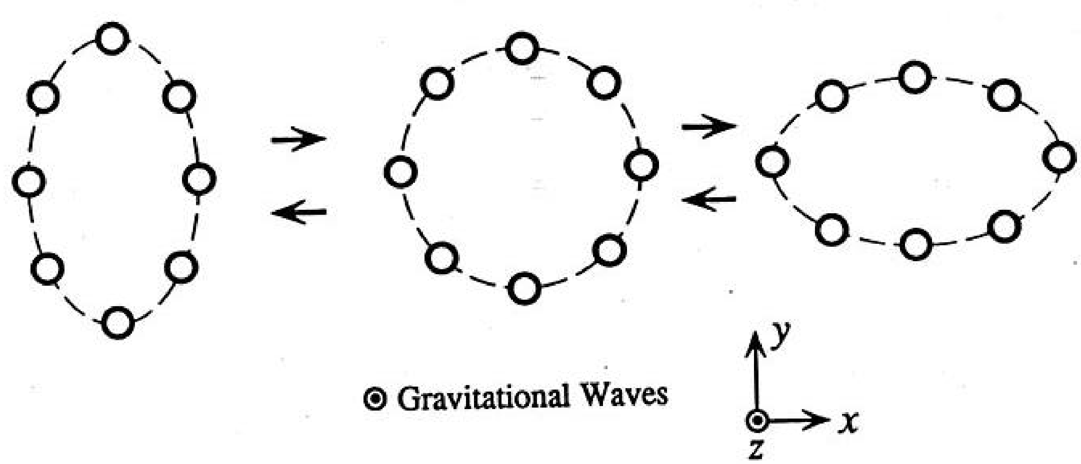


Sketch courtesy of Kip Thorne

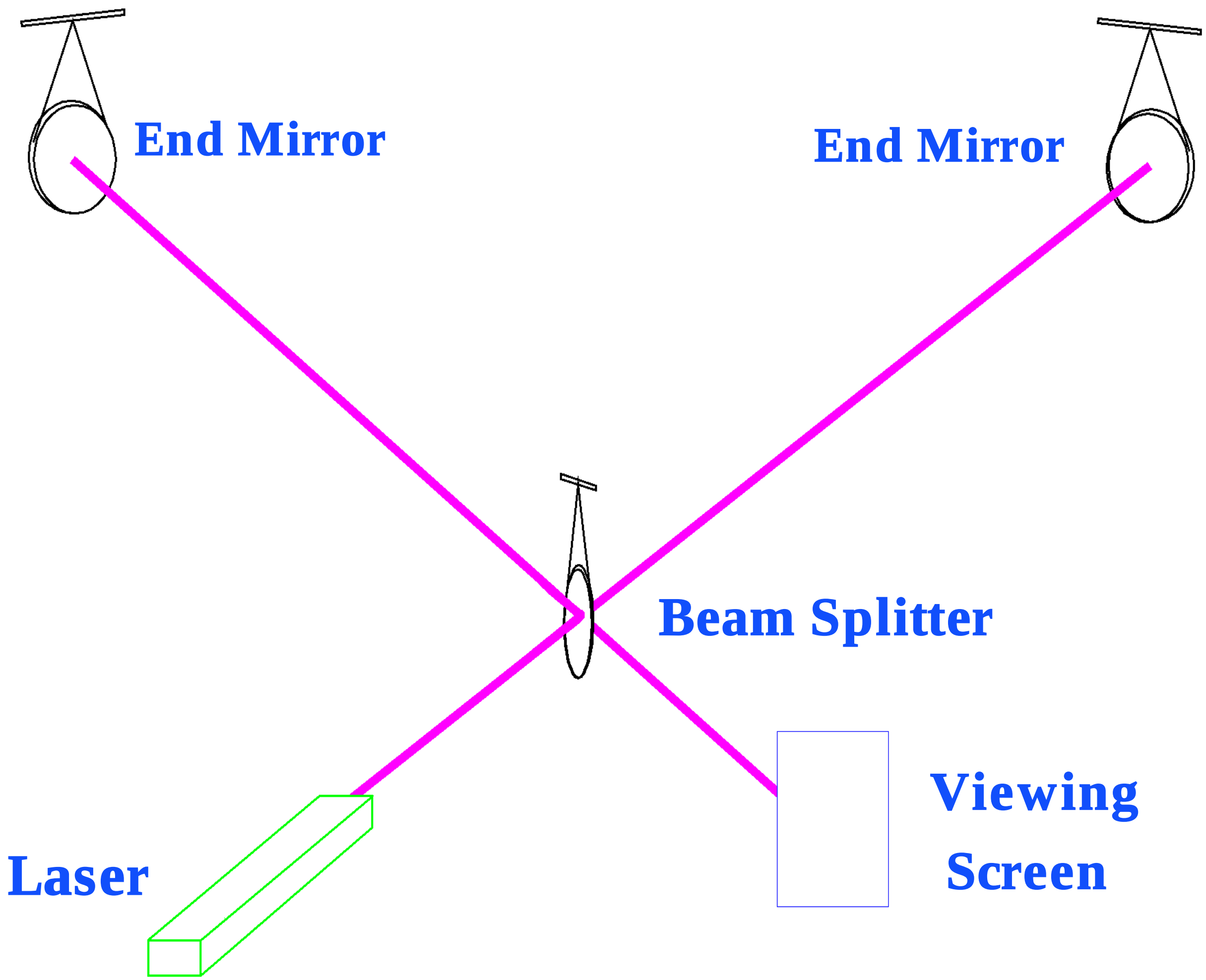
How does LIGO detect spacetime vibrations?

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.



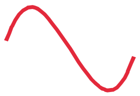
Sketch of a Michelson Interferometer

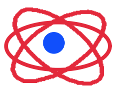


How Small is 10^{-18} Meter?

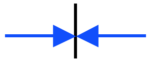
One meter, about 40 inches

÷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

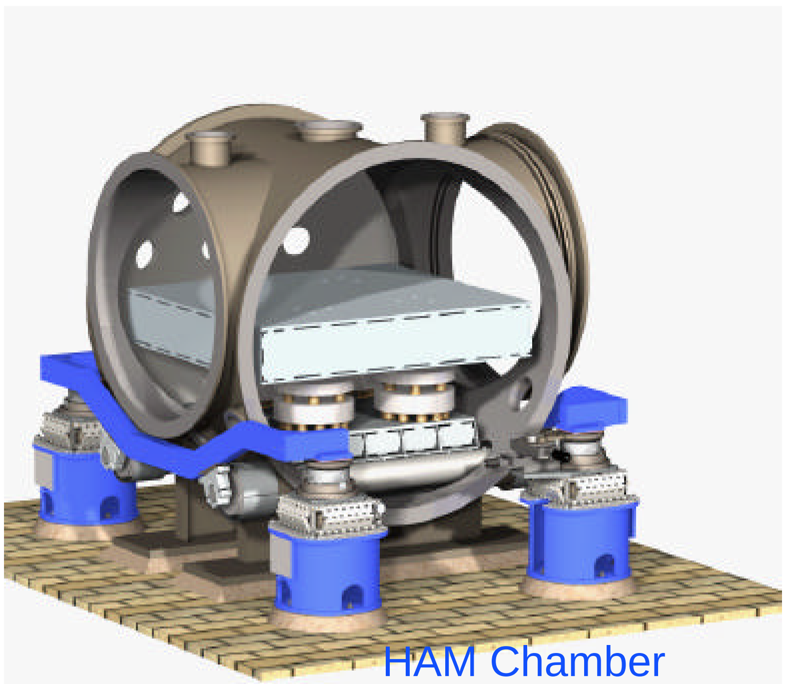
Vibration Isolation Systems

» Reduce in-band seismic motion by 4 - 6 orders of magnitude

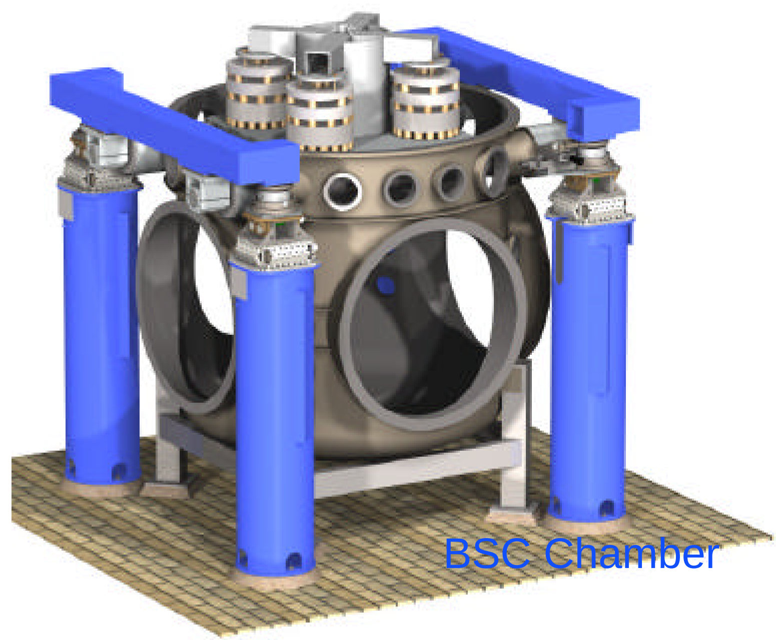
» Little or no attenuation below 10Hz

» Large range actuation for initial alignment and drift compensation

» Quiet actuation to correct for Earth tides and microseism at 0.15 Hz during observation

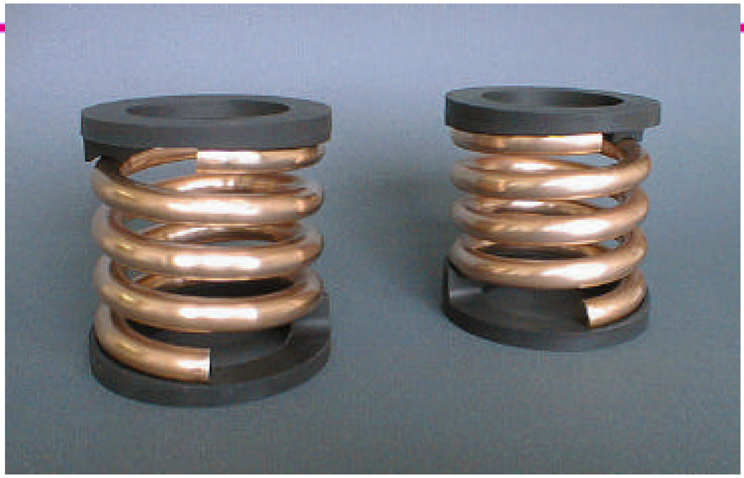


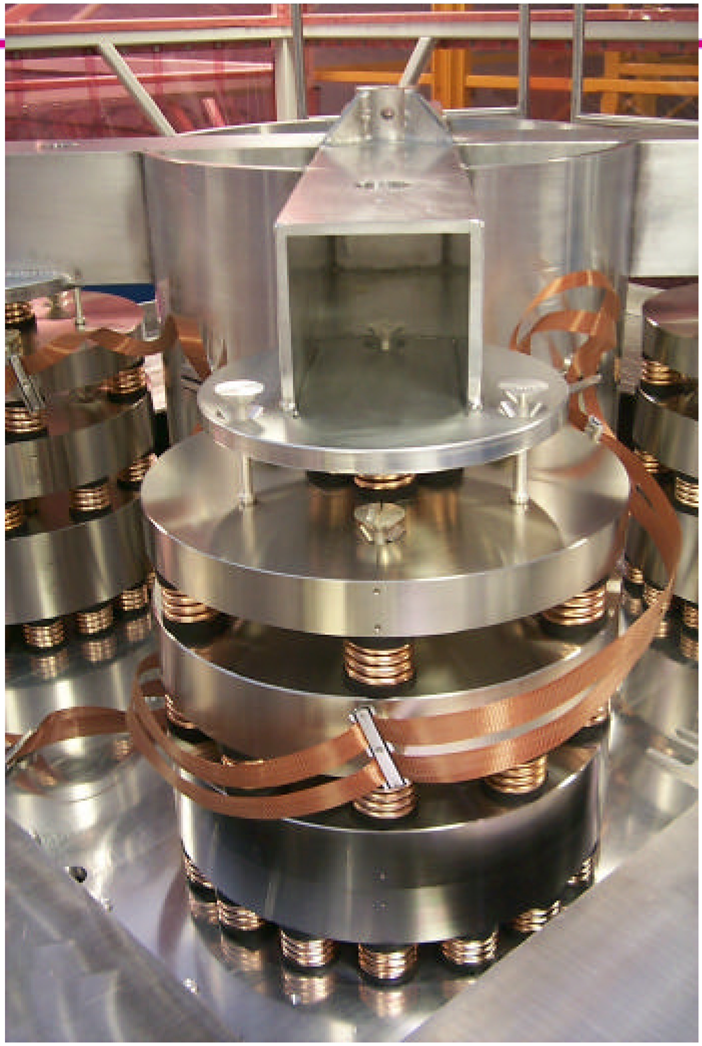
HAM Chamber



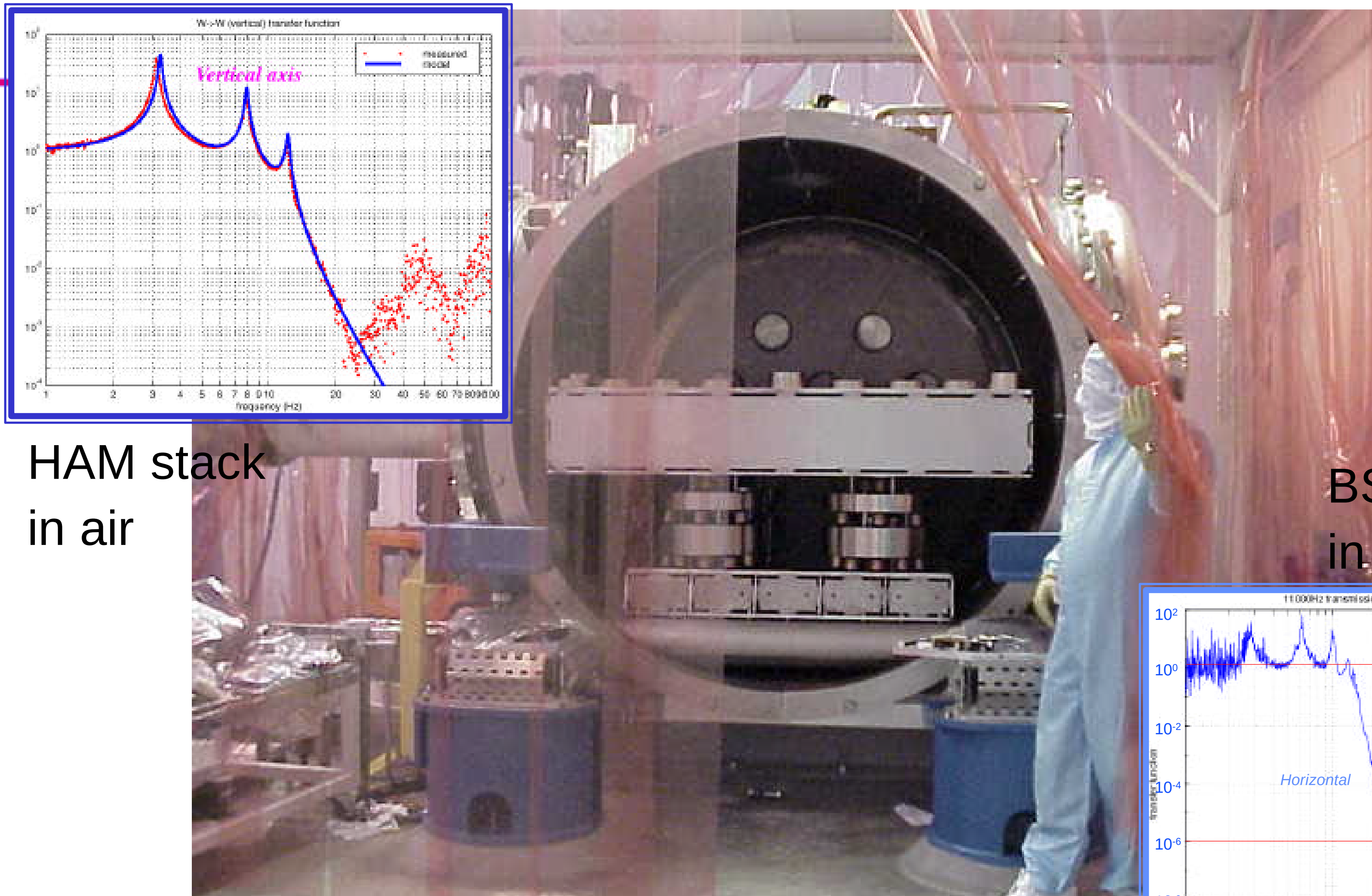
BSC Chamber

Seismic Isolation – Springs and Masses



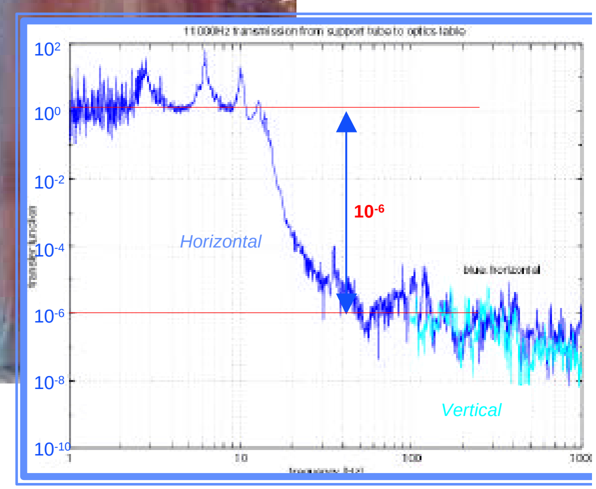


Seismic System Performance



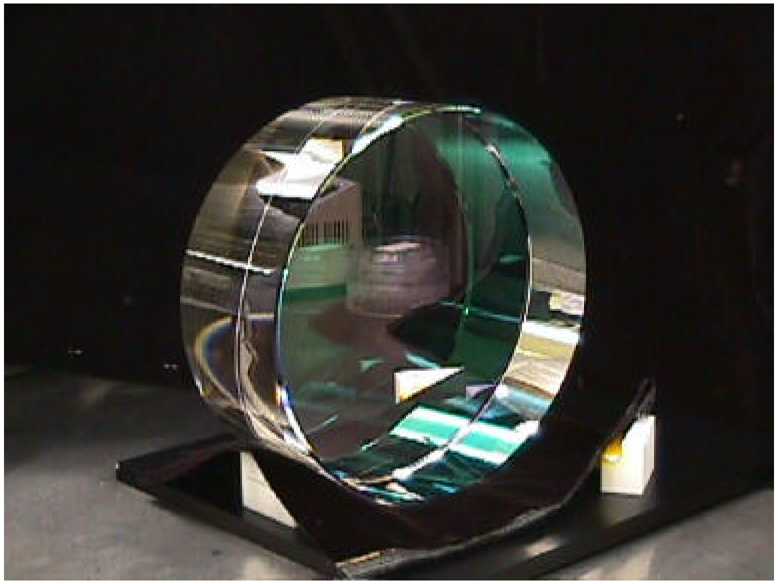
HAM stack
in air

BSC stack
in vacuum

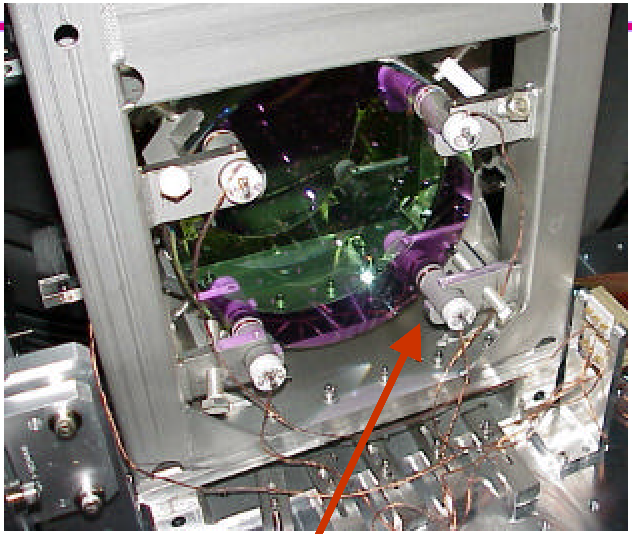


Core Optics

- 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

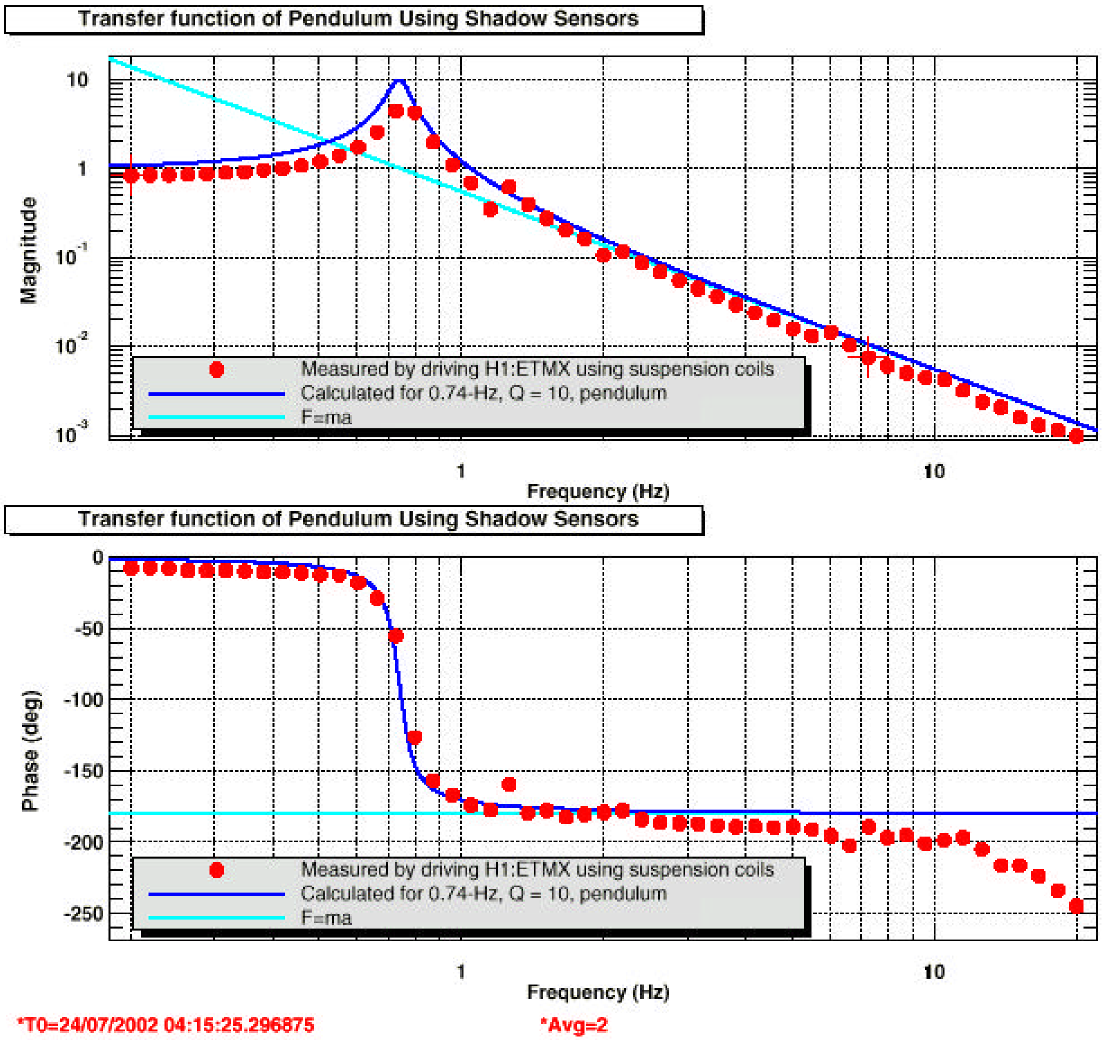


Core Optics Suspension and Control

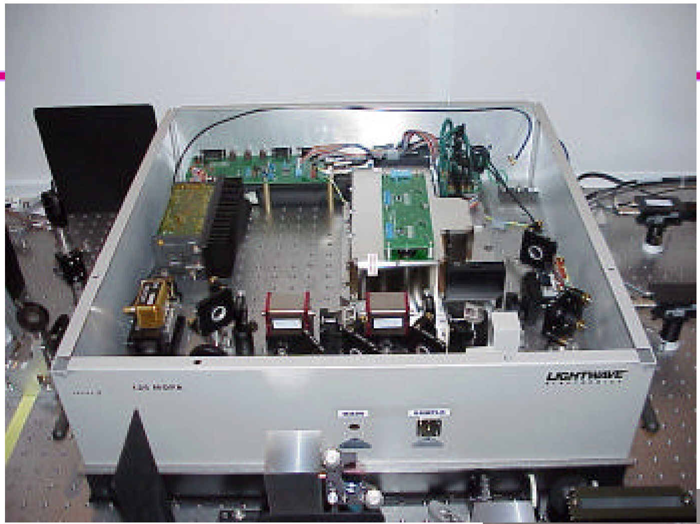


- Optics suspended as simple pendulums
- Local sensors/actuators for damping and control

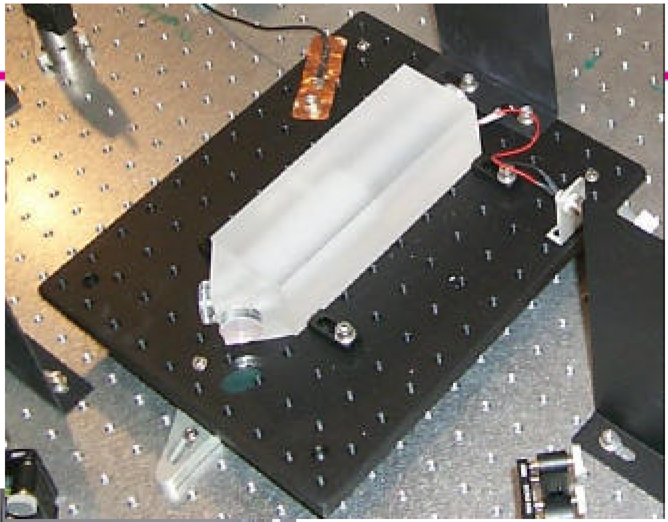
Suspended Mirror Approximates a Free Mass Above Resonance



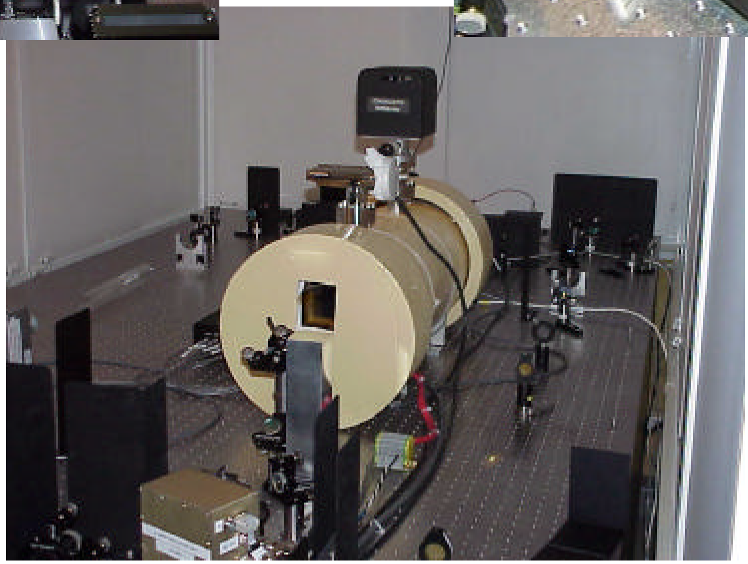
Pre-stabilized Laser (PSL)



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



Cavity for
defining beam geometry,
joint development with
Stanford

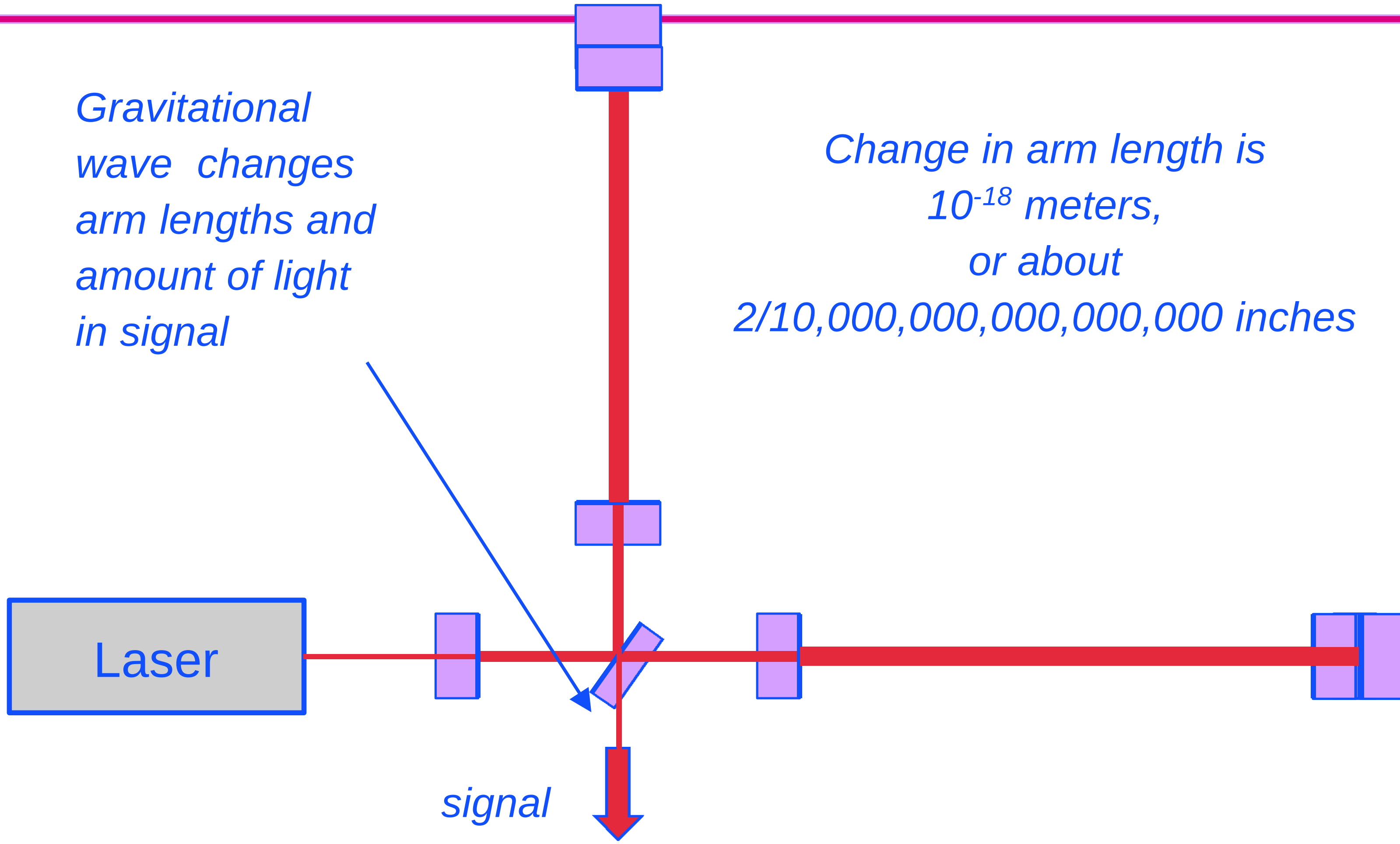


Frequency reference
cavity (inside oven)

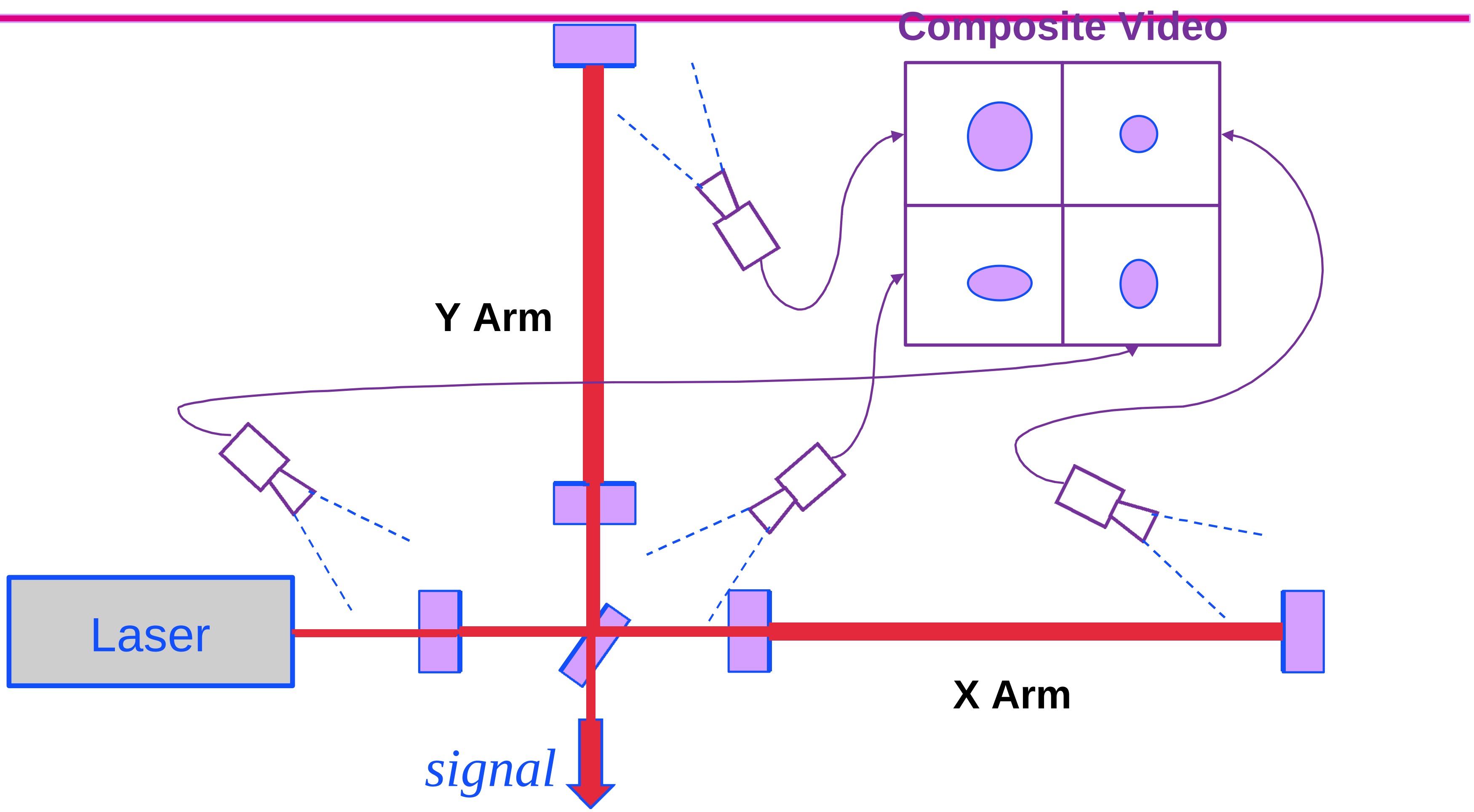
Sensing the Effect of a Gravitational Wave

Gravitational wave changes arm lengths and amount of light in signal

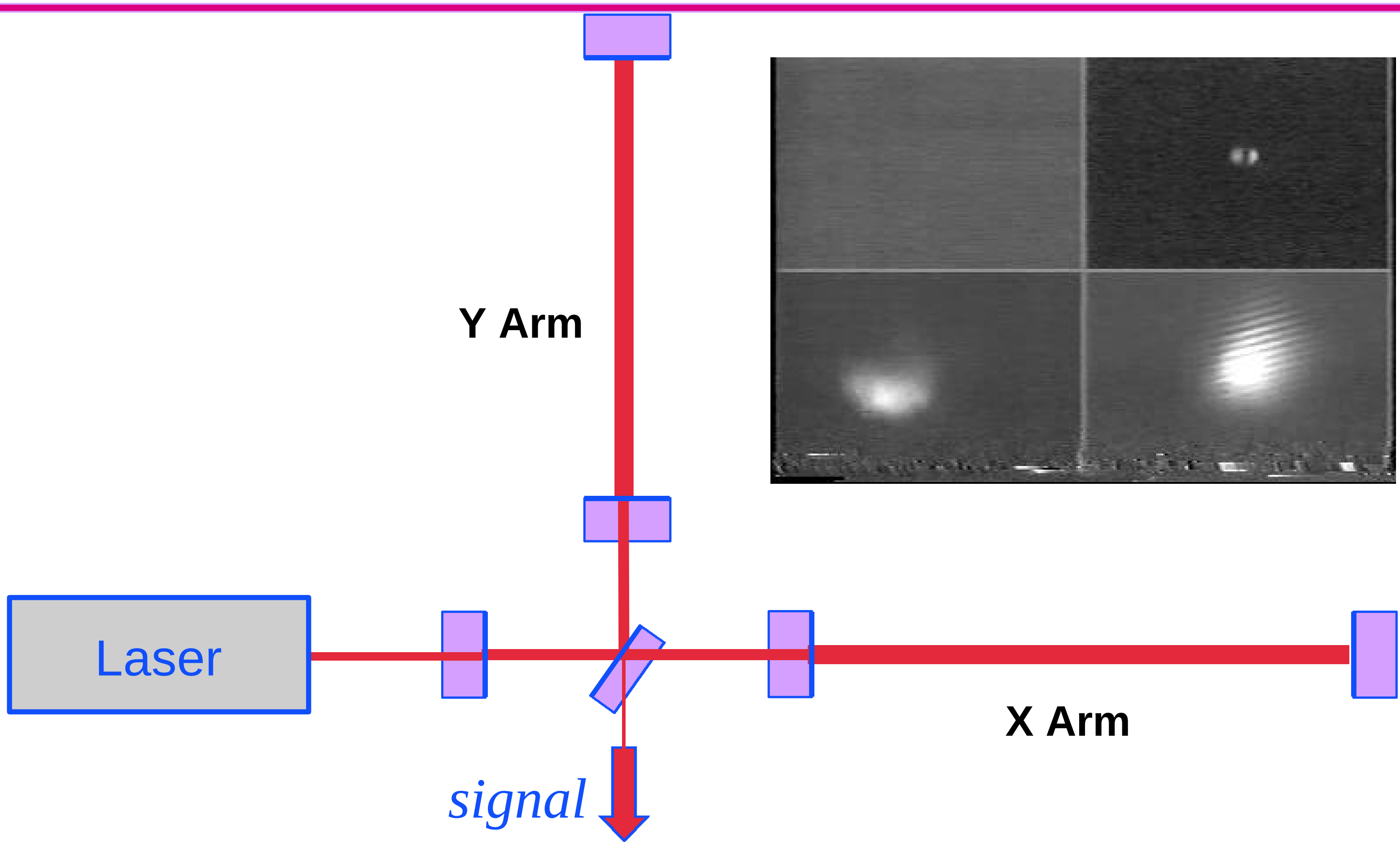
Change in arm length is 10^{-18} meters, or about 2/10,000,000,000,000,000 inches



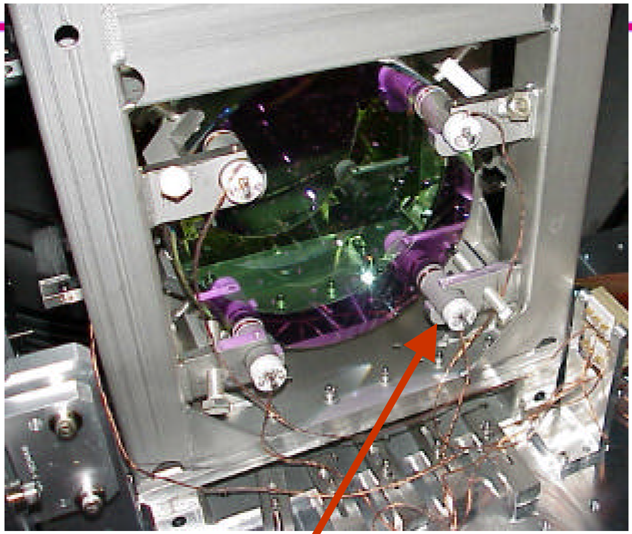
Steps to Locking an Interferometer

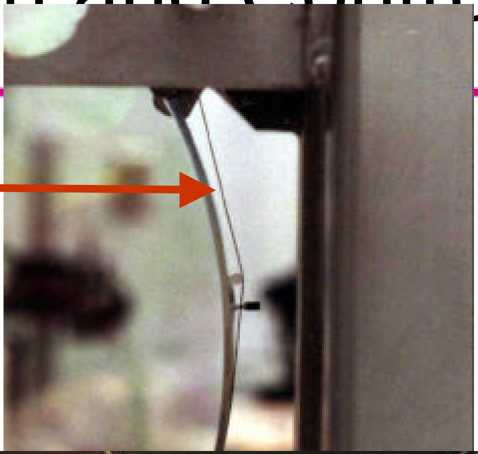


Watching the Interferometer Lock



Core Optics Suspension and Control



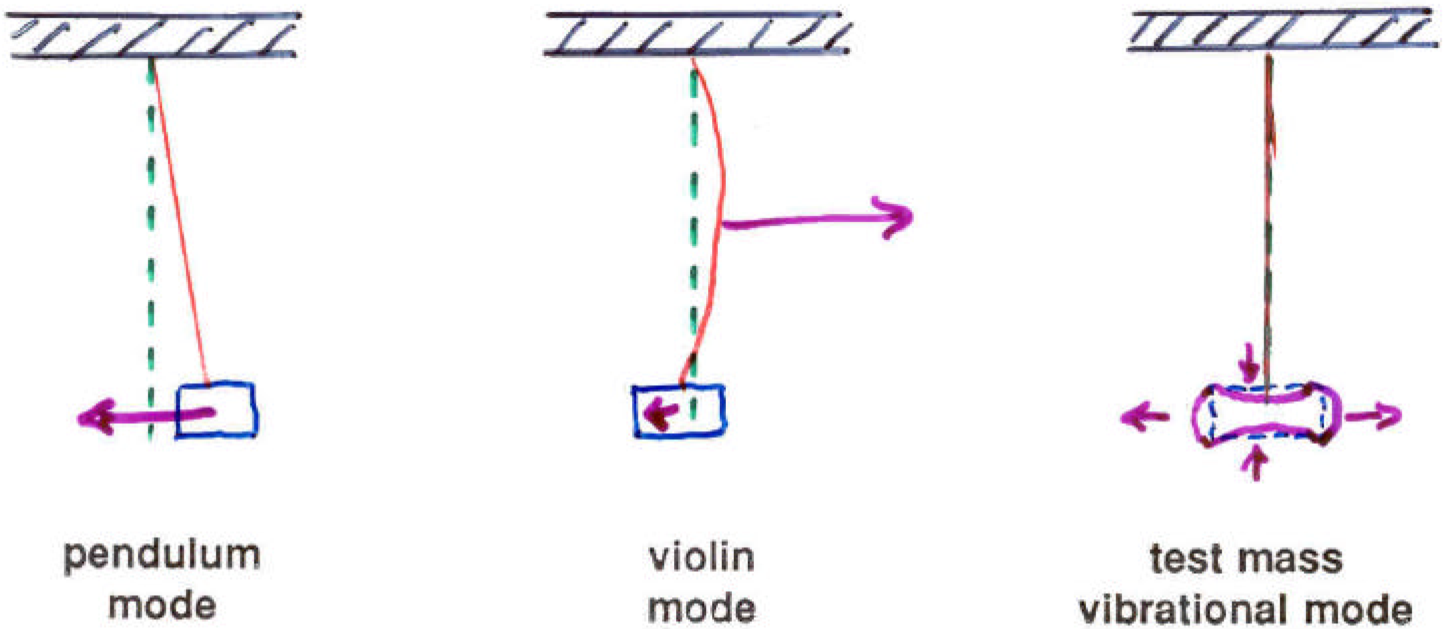


Optics suspended as simple pendulums

Local sensors/actuators provide damping and control forces

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

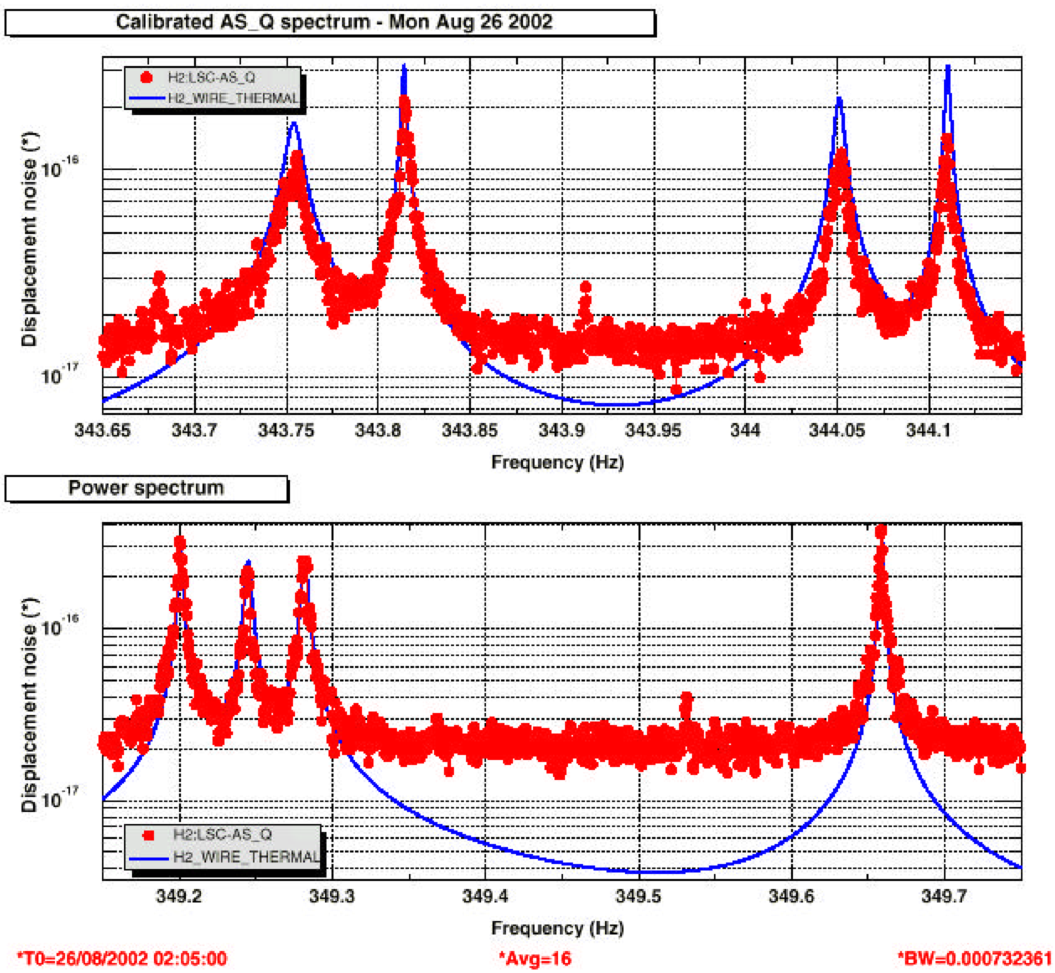
Background Forces in GW Band = Thermal Noise ~ $k_B T$/mode



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

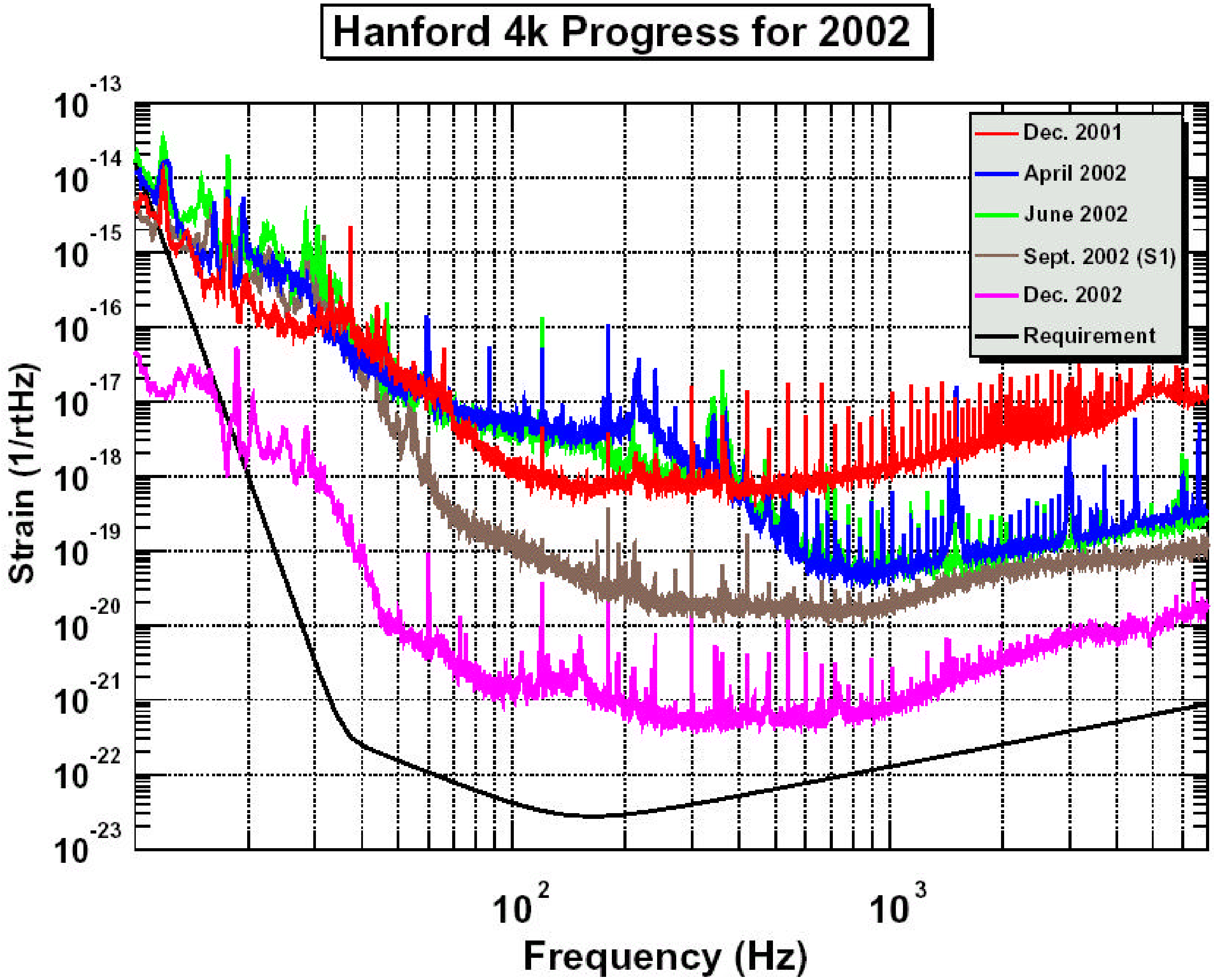
Strategy: Compress energy into narrow resonance outside band of interest $\Rightarrow$ require high mechanical Q, low friction

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

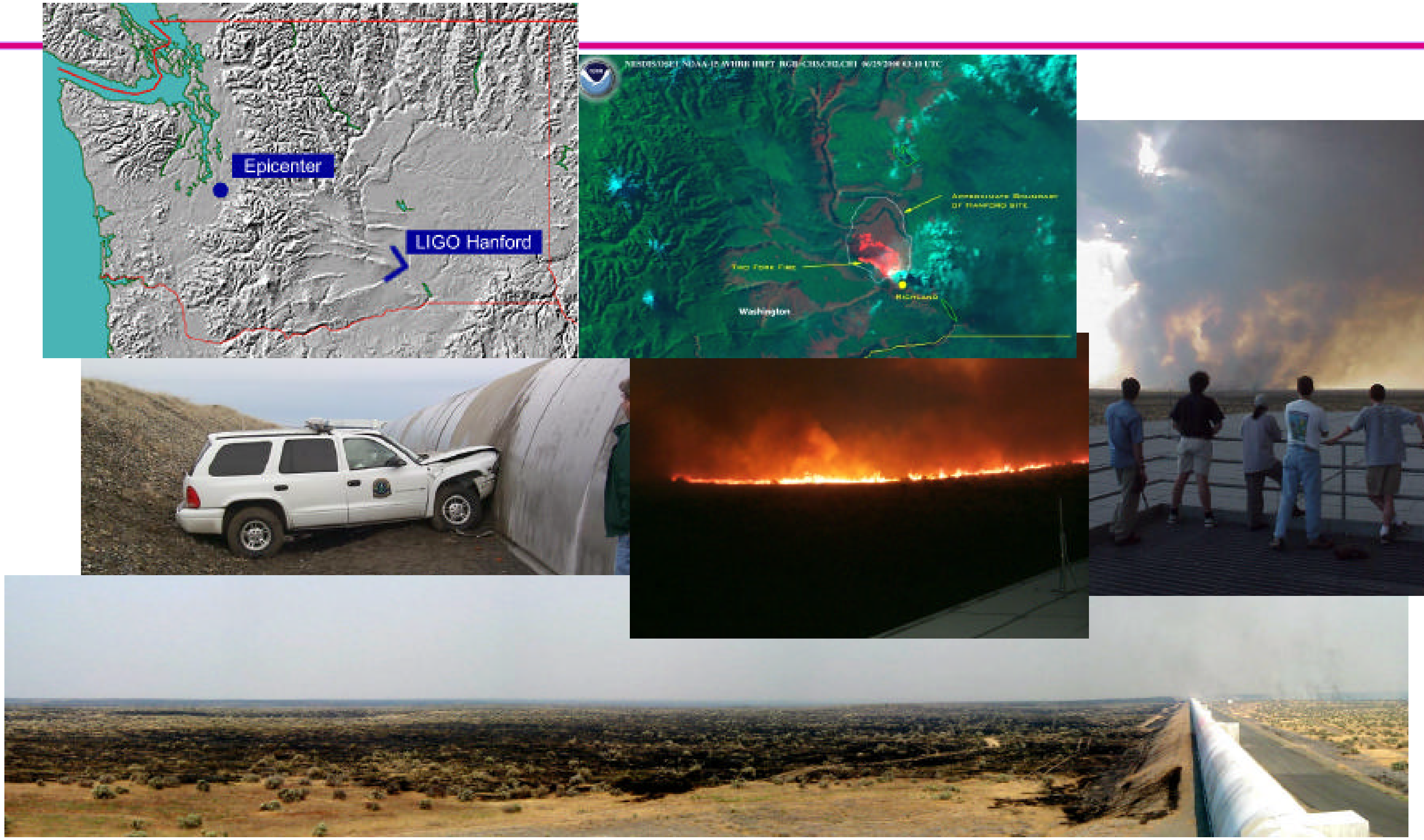


Almost good enough for tracking calibration.

We Have Continued to Progress…



And despite a few difficulties, science runs started in 2002…



We Cannot Miss the Opportunity to Make this Science Accessible!

- Organizations as diverse as the American Physical Society and the Congressional Budget Office have identified LIGO as the vanguard of 21st century science
- Our role today is to identify how we best share the excitement and possibilities of this science and utilize it to meets critical needs in our communities
- Let me introduce some ideas and activities we have developed to provide a backdrop for today's discussions

K-12 Students and Teachers

- K-12 programs in collaboration with Pacific Northwest National Laboratory (PNNL) and Educational Service District (ESD) 123 in southeast Washington, Gladstone School District in Oregon, Columbia River Exhibition of History, Science & Technology.
- Scientist-Student-Teacher program started in 1999, involved ~70 students on projects related to LIGO research in AY2002
- LHO featured in “The Scientific Method on the Job” video for Middle/High School science resource
- Distance learning initiative with ESD 123 developed interactive science program for WA K-20 teleconferencing network
- Teacher interns developed exhibit guide, lesson plans, K20 scripts and internet resources during summers of 2001, 2002
- District-level workshops for science teachers

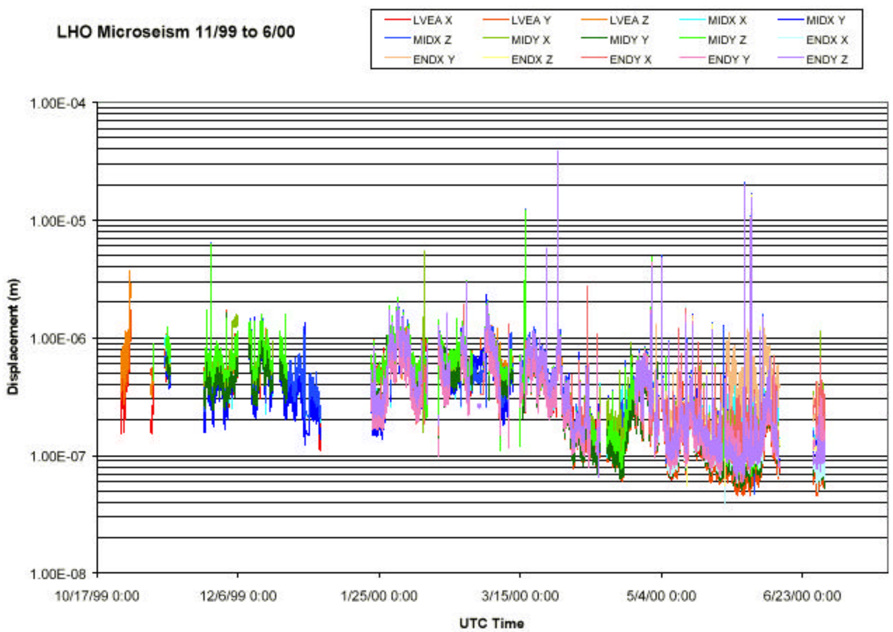
Scientist-Student-Teacher Program with Gladstone High

- Objective: address the Essential Academic Learning Requirement (EALR) on "the nature and methods of scientific inquiry" by involving classes in real scientific research
- Problem: analyze seismic data taken at LIGO Hanford Observatory (LHO) and produce long-term study of microseism
- Why? The microseism produces the fastest changes of the LIGO baseline, but there are no historical records of microseism near the Hanford site
- Instrumentation: LIGO has 5 triple-axis seismometers on site connected to a data acquisition system and significant high-speed computing capacity
- Gladstone High School supplies commitment to long-term monitoring & data trending

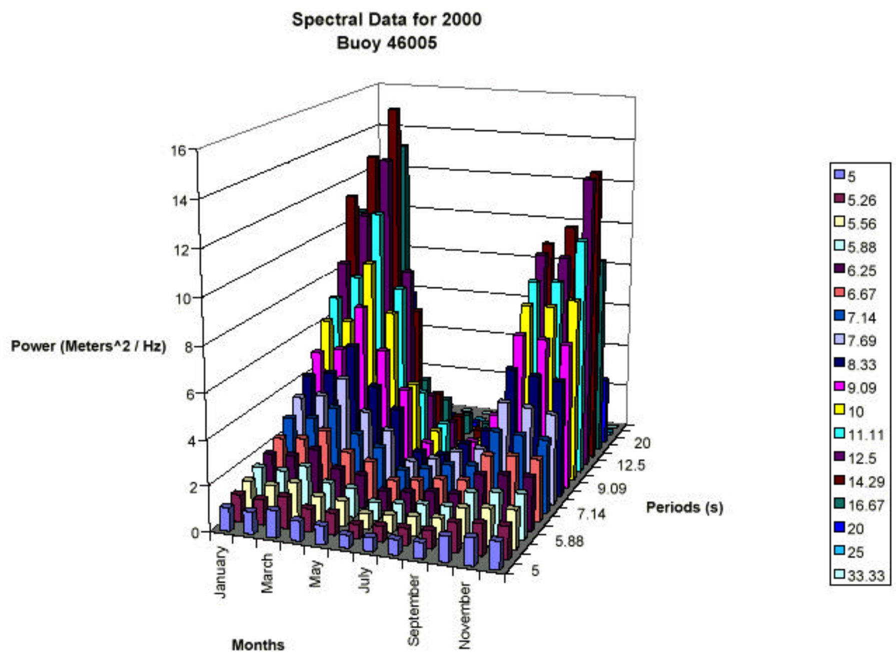
Gladstone High School Contributions to LIGO Research

- Now have multiple-year record of microseism
- Seasonal variability on high end traced to ocean wave activity using specific NOAA buoys
  - » students also measured the wave propagation velocity between buoys by using a cross-correlation technique
- During quiet season, searched for potential correlation with local weather patterns
- Demonstrated general insensitivity of microseism band to human-generated noise by studying day/night statistics
- Reports on Gladstone High School physics web page at http://www.gladstone.k12.or.us/ghs/users/ingramd/Physics
- Annual community science night draws about 100 parents, 50-70 student presenters

Long-term microseism connection to ocean-wave activity



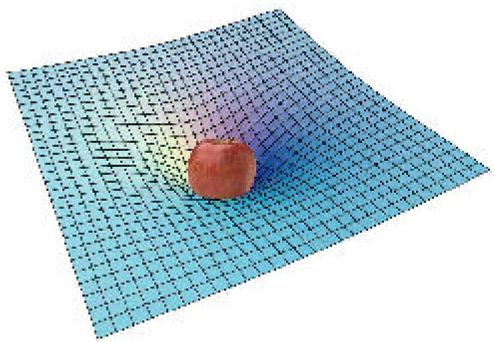
Seasonal trend in microseism identified in early analysis (left) found to agree qualitatively with ocean-buoy wave-height data (below)



Internet-Accessible Resources for Teachers, by Teachers

Hanford Observatory

Teachers Corner

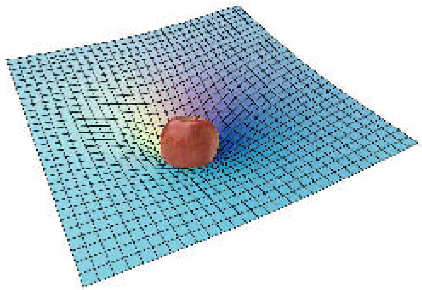


Have a look at the resources and programs for teachers available through the LIGO Hanford Observatory.

- Research Opportunities for Schools
- Internships in Public Science Education
- Classroom Resources
    - An Overview of LIGO (.pdf format)
    - Observatory Tours for Classes
    - Classroom Activities, Lessons, and Projects Related to LIGO Science

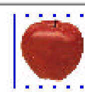
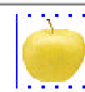
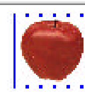
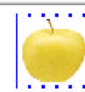
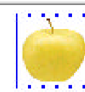
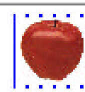
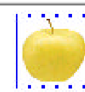
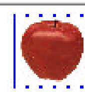
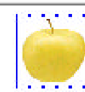
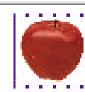
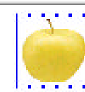
Last modified July 8, 2002
For comments or suggestions about Web material, contact webmaster@ligo-wa.caltech.edu
For information about LIGO, contact info@ligo.caltech.edu

Web Lesson Plans Tied to State Standards in WA & OR



Classroom Activities, Lessons and Projects Related to LIGO Science

The links in the table below will take you to packages of lessons whose outcomes are referenced to science standards in both Washington and Oregon. The grade range for each package can be determined from the table. Some have versions for both middle and high school levels. The packages are linked to a set of additional activities that students would do at the LIGO Hanford site as part of a field trip. The on-site LIGO activities will hopefully provide an avenue for students to apply what they have learned in the classroom lessons to the 'real world' of science research. The classroom packages are also written to be meaningful as stand-alones in the event that a field trip to LIGO does not occur.

Package	Grades 5-8	Grades 9-12
Helpful Hints for Using these Packages		
The Scientific Method with a Pendulum		
Build and Use Your Own Michelson Interferometer		
Build and Use a Simple Spectroscope		
Powers of Two		
Scaling the Earth's Atmosphere		

Integrated In-Class and Field Trip Activities

Swing Into the Scientific Method

SUBJECT AREA: Scientific processes, physical science and mathematics

Grade Level: 5-8

Learning objectives for the lessons
State science standards addressed by the lessons
The procedures for the lessons
Student handouts and worksheets (two items)
A set of LIGO field trip activities
A downloadable MS Word version of the package

OVERVIEW

This short unit was designed to help teachers guide students on how to conduct and evaluate a scientific investigation using a pendulum as the experiment apparatus. The unit is presented in a way that allows for inquiry-based learning. Students learn to identify variables, then to simplify the experimental process by controlling those variables in the tests. These concepts are explored while addressing several Washington and Oregon State Standards in science and mathematics.

OBJECTIVES

- To develop an understanding of variables
- To understand the need to change only one variable at a time
- To collect and analyze data

College Students and Faculty

- REU/SURF program involves ~4 undergrad research interns/yr at LHO + hosting SURF field trip from CIT
  - » Betsy Weaver developed/commissioned vac-prep facility
  - » Eric Morganson wrote earth-tides prediction software
  - » Tom Corbitt developed automated laser sideband analyzer
  - » Brian Cameron simulated periodic source analysis
- Typically 2-4 grad students doing research
  - » U.Rochester, U. Oregon, U. Michigan, Caltech, MIT, Penn.St.
- Visitors program
  - » U. Michigan, U. Oregon collaborators on long-term appointments
  - » Oregon Institute of Technology visiting professor developed ideas for Laser Institute courses

Informal Education

- Observatory tours draw approx. 800-1000 visitors/yr
  - » Einstein, interferometers and the work that we do.
  - » Audience comes from professional groups, boy scouts, families, bicycle club, etc.
  - » Hosted WA State Science Teachers in Nov 01
- Public talks and LIGO Public Lectures
  - » Wheeler/Thorne lecture (00) drew > 350 people
  - » Kamionkowski lecture on cosmology (01)
  - » Adelberger lecture on extra dimensions (02)
  - » Rotary/Kiwanis clubs & professional societies
  - » Adler Planetarium lecture as part of "Cosmic Happenings" series
- Cooperative "happenings" w/ other outreach groups
  - » Wheeler book signing at CREHST
  - » B-Reactor reunion

Targeting Underserved Populations

- Hispanics and Native Americans are largest groups near LHO that are typically underserved by science education and underrepresented in technical fields
- LHO's location is encircled by a constellation of tribal colleges and reservations
- Salish-Kootenai College (SKC) - near Flathead Lake, Montana - has now joined LIGO Science Collaboration
- SKC will provide software for detector characterization, operate a Tier-3 GRID center for data analysis
- LHO and SKC have entered discussions on a program to widen the doorway for Indian students to enter the physical sciences
- Heritage College (on Yakama Rez) also interested in working with LIGO

LIGO Partnership to Create Doorway into Science for Native- & African-Americans

Enlisted Warren Buck, Chancellor UW Bothell, to help coordinate

LIGO

- WA
  - Salish-Kootenai
  - U. of Washington
  - School District(s)
  - Community Colleges
- LA
  - Southern U.
  - S.E. Louisiana U.
  - Louisiana State U.
  - School Districts
  - Community Colleges

Future Possibilities?

- Formalize educator inputs through advisory and user groups
- Expand SST participation to more schools and more sites throughout nation via LIGO Scientific Collaboration.
- Expand “distance learning” initiative through K20/Internet
  - » More interactive programming
  - » More teacher involvement through summer internships
- Use unique facilities for in-service / pre-service training
- University-level programs
  - » Continue current scope through REU program
  - » Goal to increase “breadth” of graduate-level students from other fields
- Improve informal educational program within current envelope
  - » More exhibits with “hands-on/minds-on” content
  - » Teacher-developed “use” plans and classroom materials

Work toward a regional science center for the inland Northwest

- Partners/Resources
  - » Columbia River Exhibition of History, Science & Technology
    - – Access to non-classified Hanford DOE artifacts
    - – Active K-6, summer & other programs in science & environment
    - – Museum at ‘gateway’ to Hanford Works & Nat’l Monument
  - » Alliance for Science Teaching Through Astronomy
    - – Robot 0.8-m observatory atop Rattlesnake Mountain for internet use in classrooms
  - » B-Reactor Museum Society
    - – World’s 1st production nuclear reactor
  - » Economic, Community and Tourism Development Agencies
    - – Hungry to develop economic independence from D.O.E.
- Develop alliance, proposal over next few years