Intro to LIGO

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

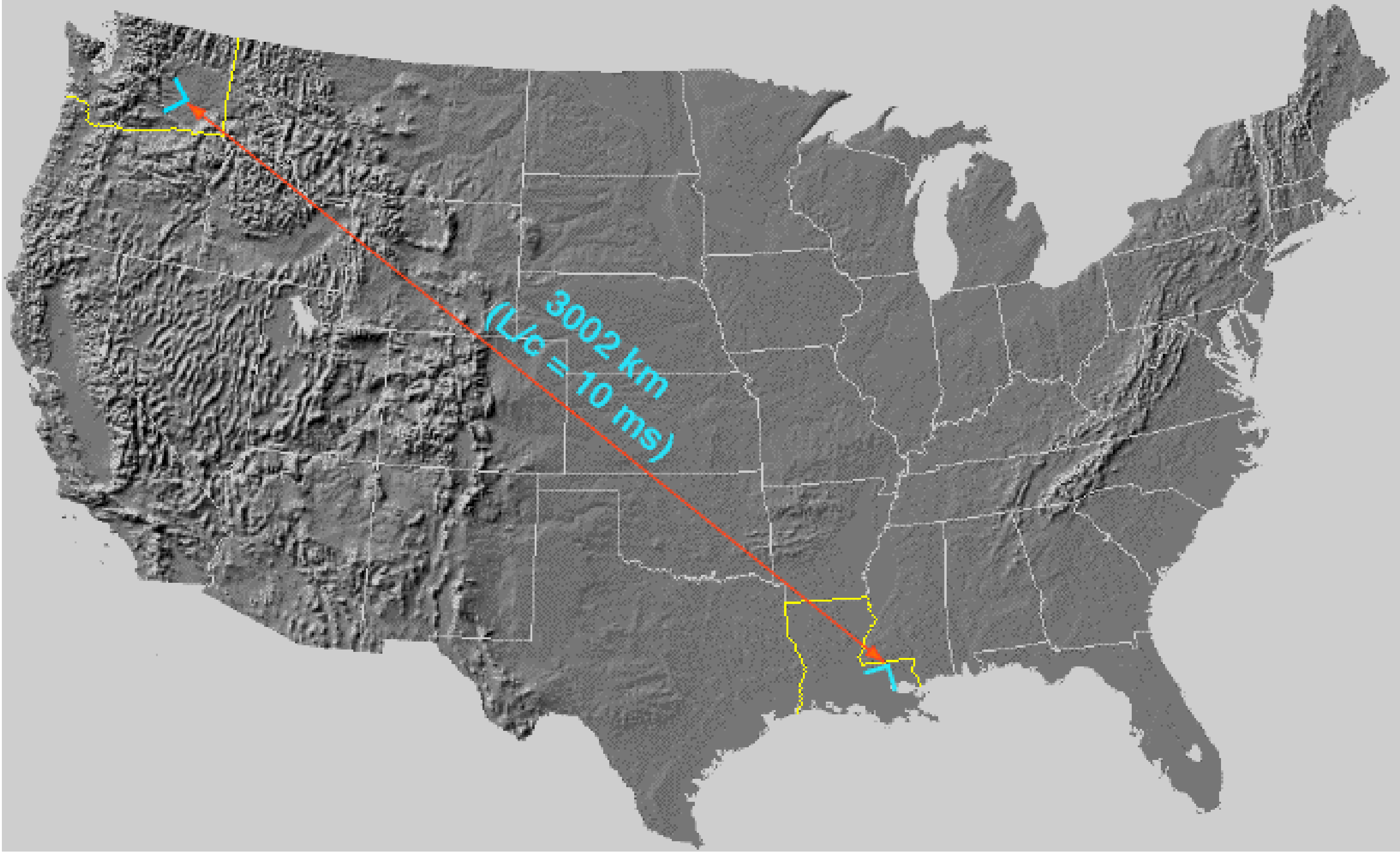
The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

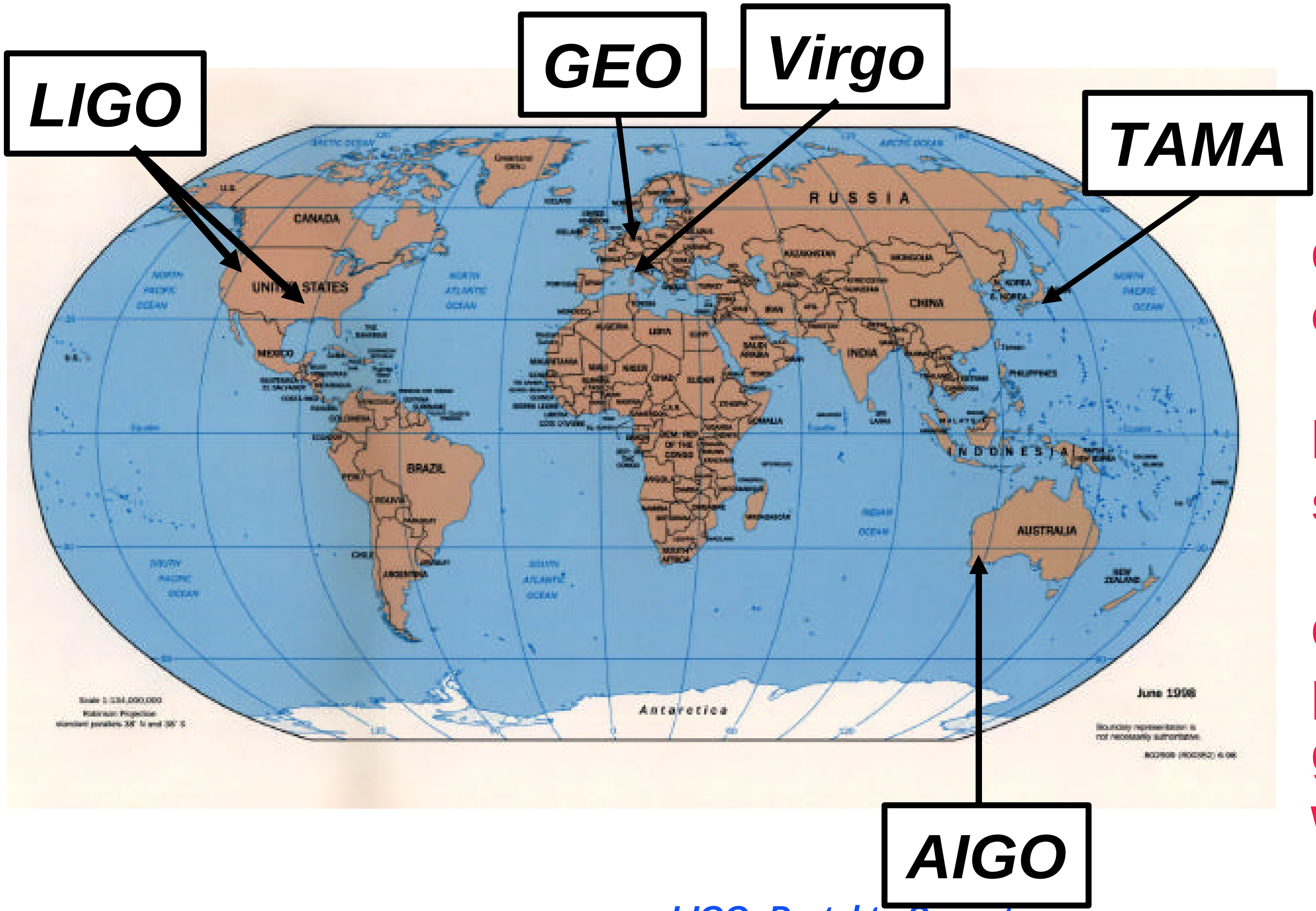
Brought to you by the National Science Foundation; operated by Caltech and MIT; the research focus for more than 400 LIGO Science Collaboration members worldwide.

LIGO Observatories



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?

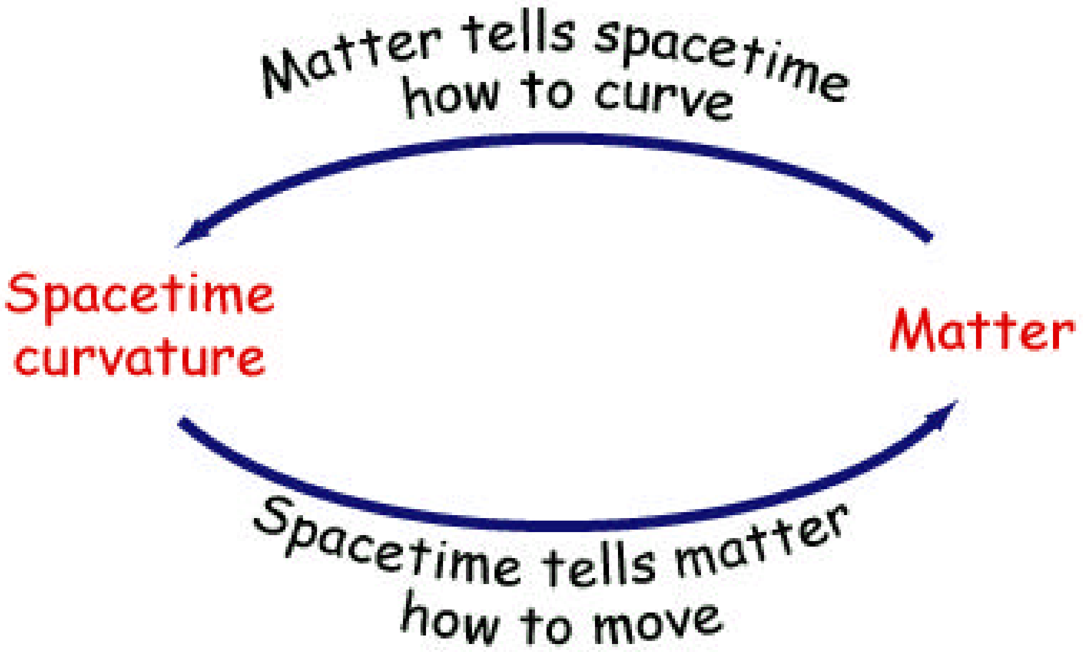
- What is the universe like now and what is its future?
- How do massive stars die and what happens to the stellar corpses?
- How do black holes and neutron stars evolve over time?
- What can colliding black holes and neutrons stars tell us about space, time and the nuclear equation of state
- What was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

A Slight Problem

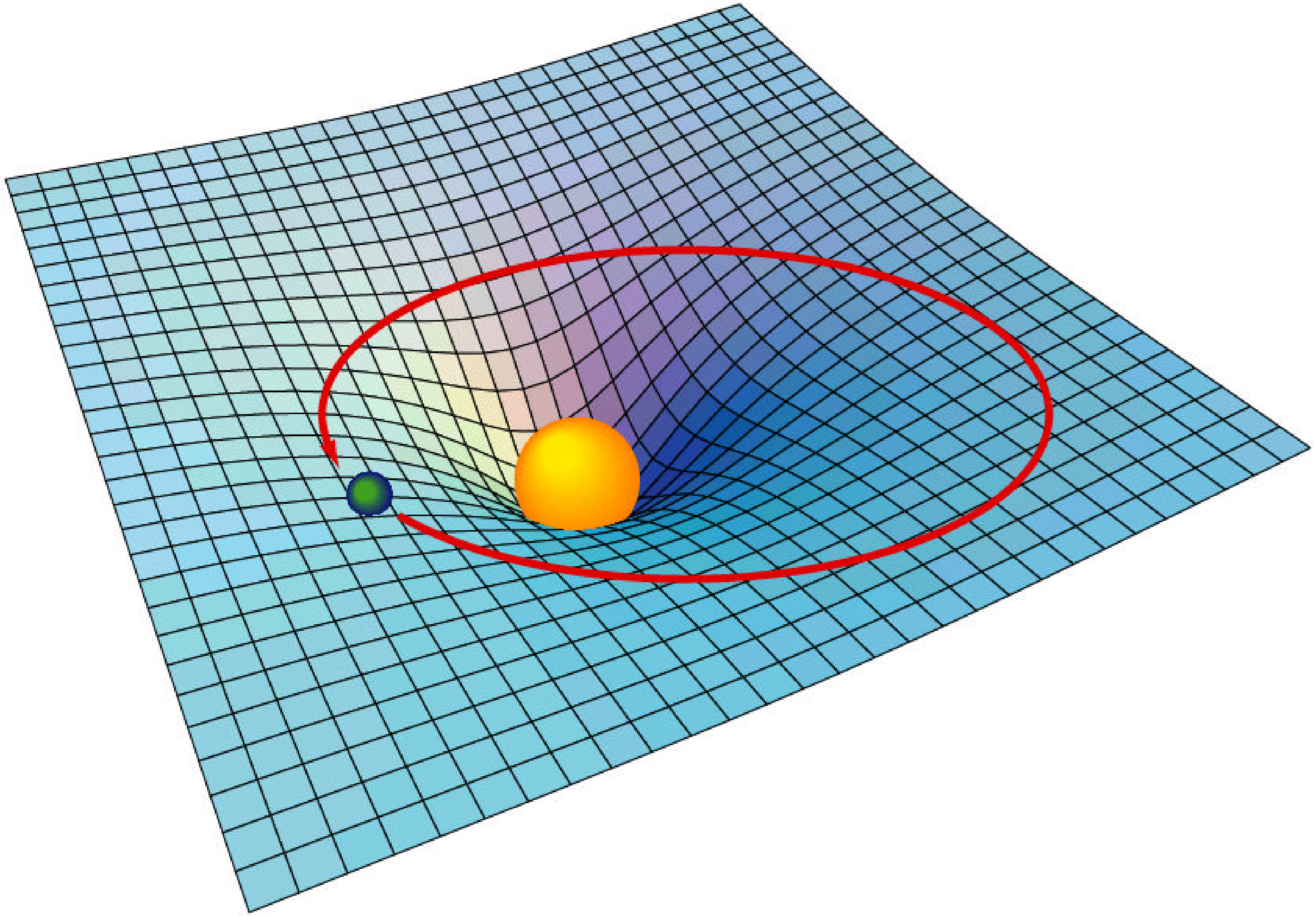
Regardless of what you see on Star Trek, the vacuum of interstellar space does not transmit conventional sound waves effectively.

Don’t worry, we’ll work around that!

John Wheeler’s Summary of General Relativity Theory

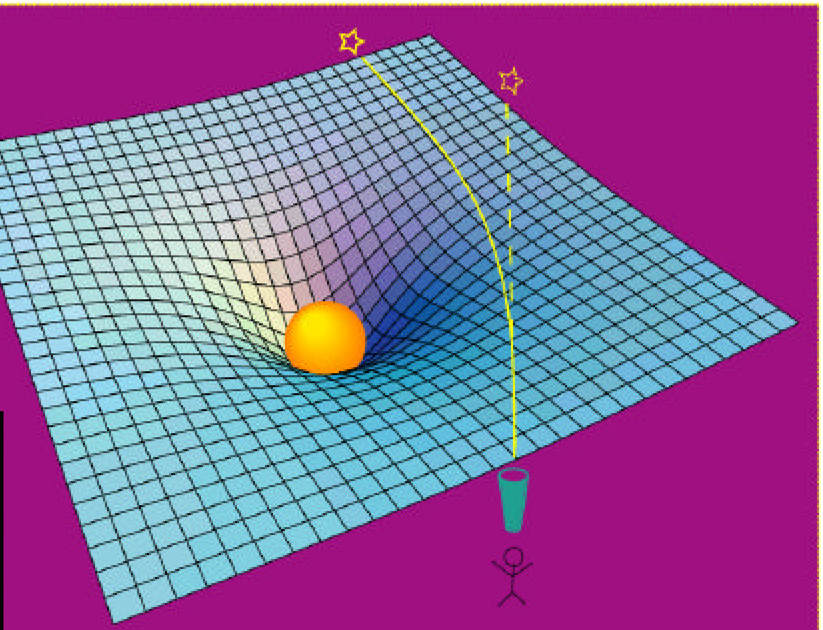


General Relativity: A Picture Worth a Thousand Words



The New Wrinkle on Equivalence

Not only the path of matter, but even the path of light is affected by gravity from massive objects



A massive object shifts apparent position of a star

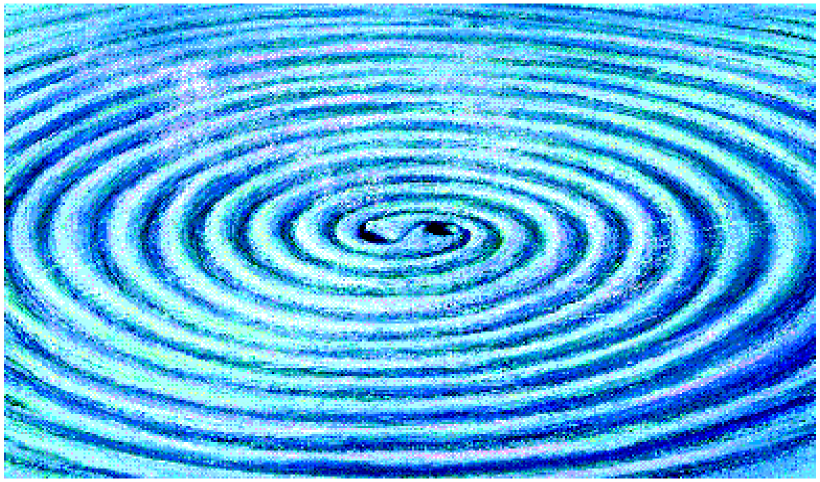
Einstein Cross

Photo credit: NASA and ESA

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:

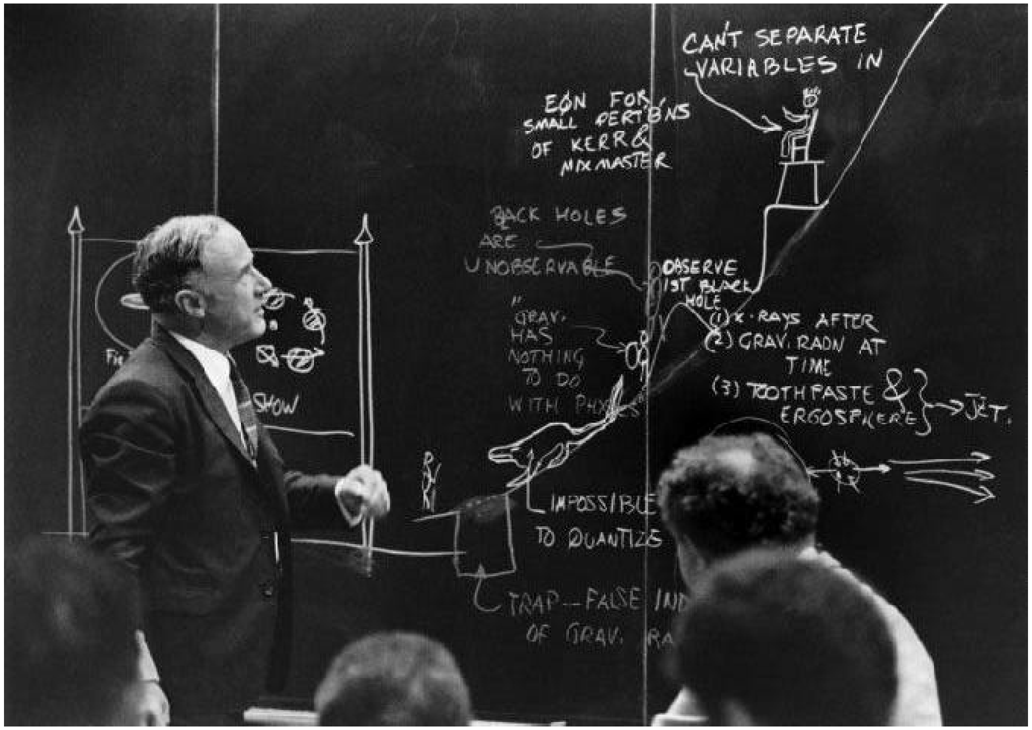


What Phenomena Do We Expect to Study With LIGO?

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."

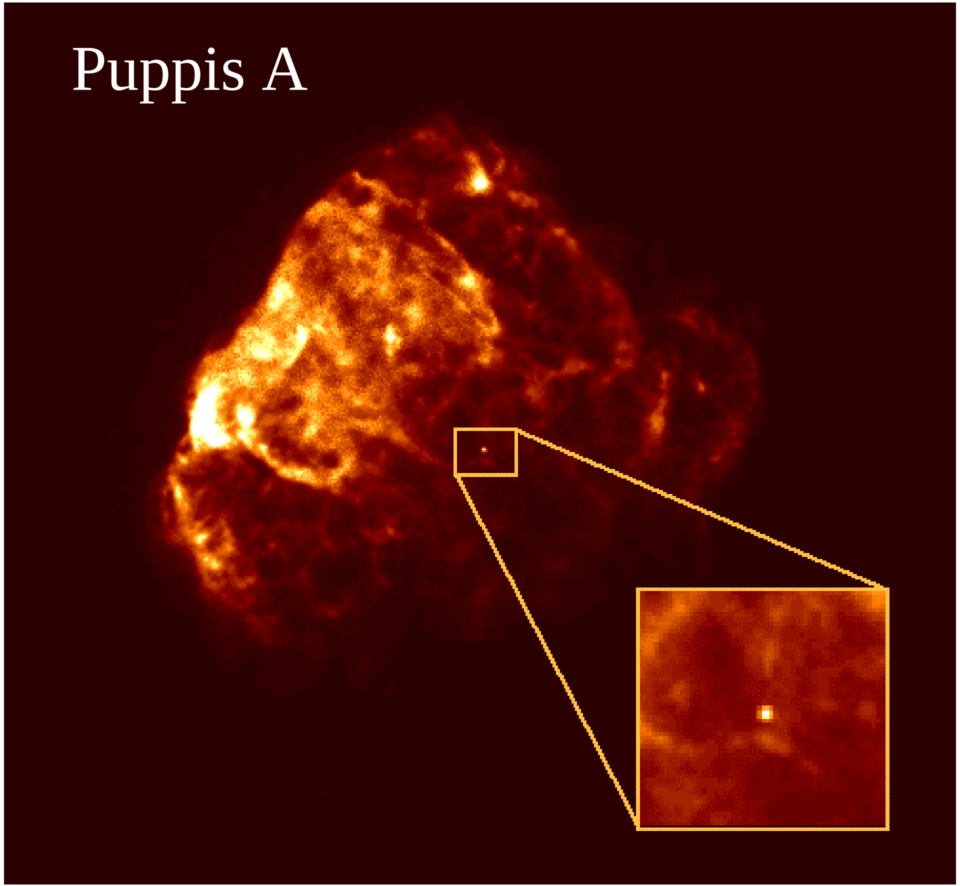
– John A. Wheeler in Geons, Black Holes and Quantum Foam



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

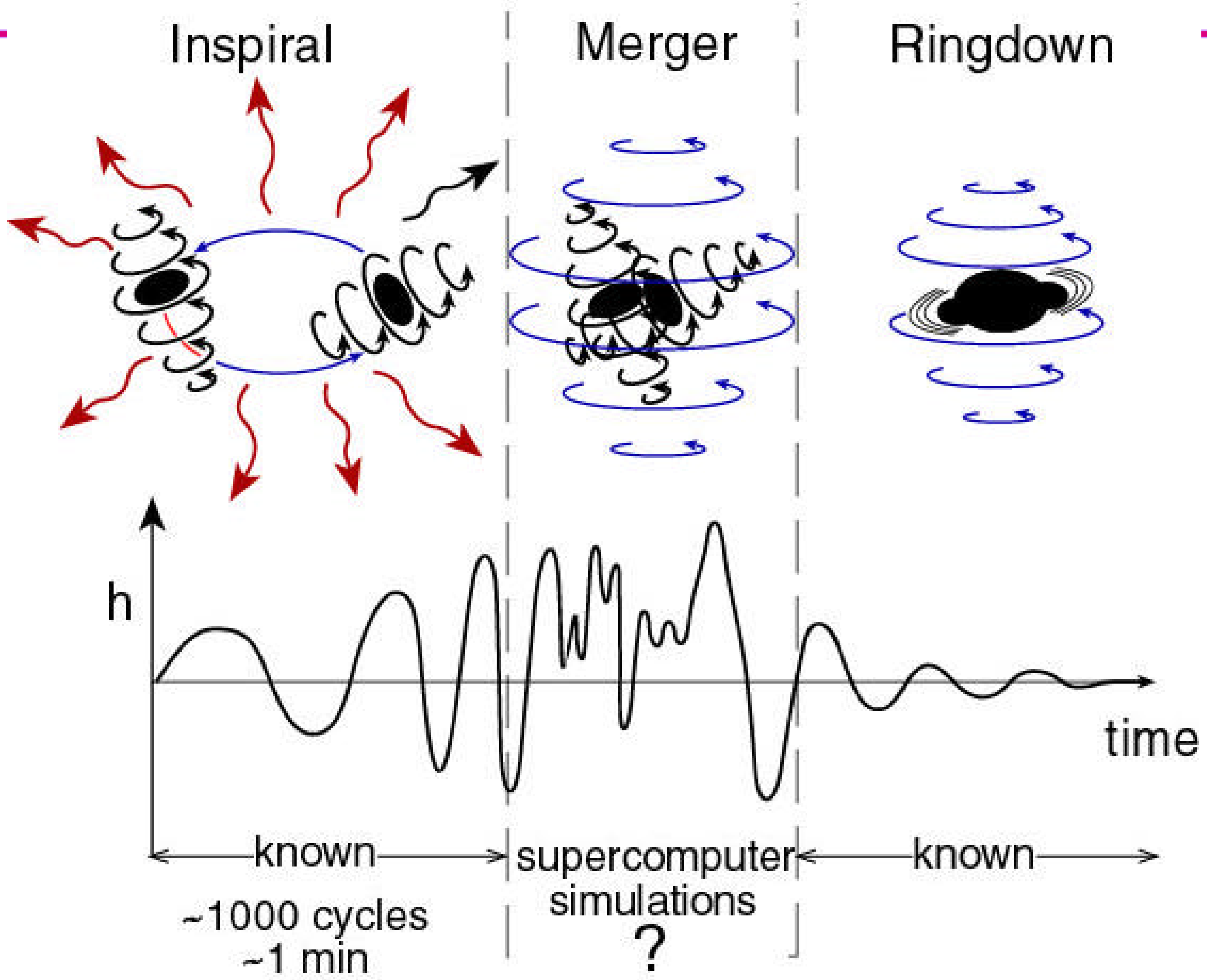
Do Supernovae Produce Gravitational Waves?

- 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).

Catching Waves From Black Holes

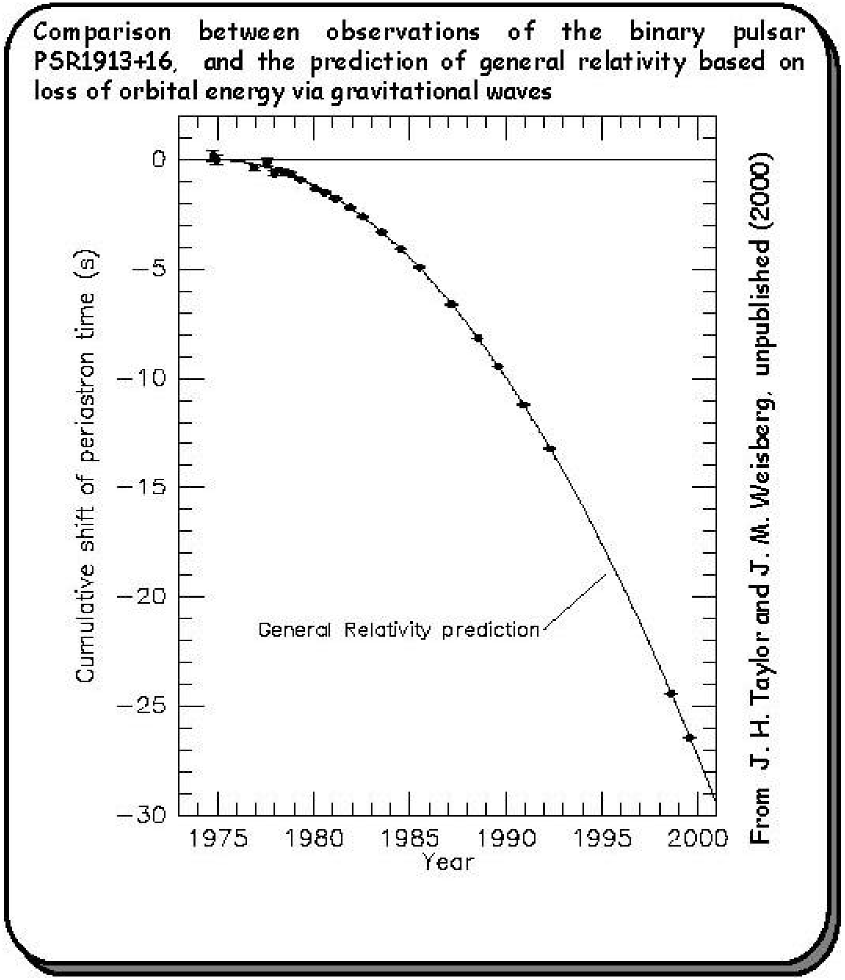


Sketches courtesy of Kip Thorne

Detection of Energy Loss Caused By Gravitational Radiation

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.

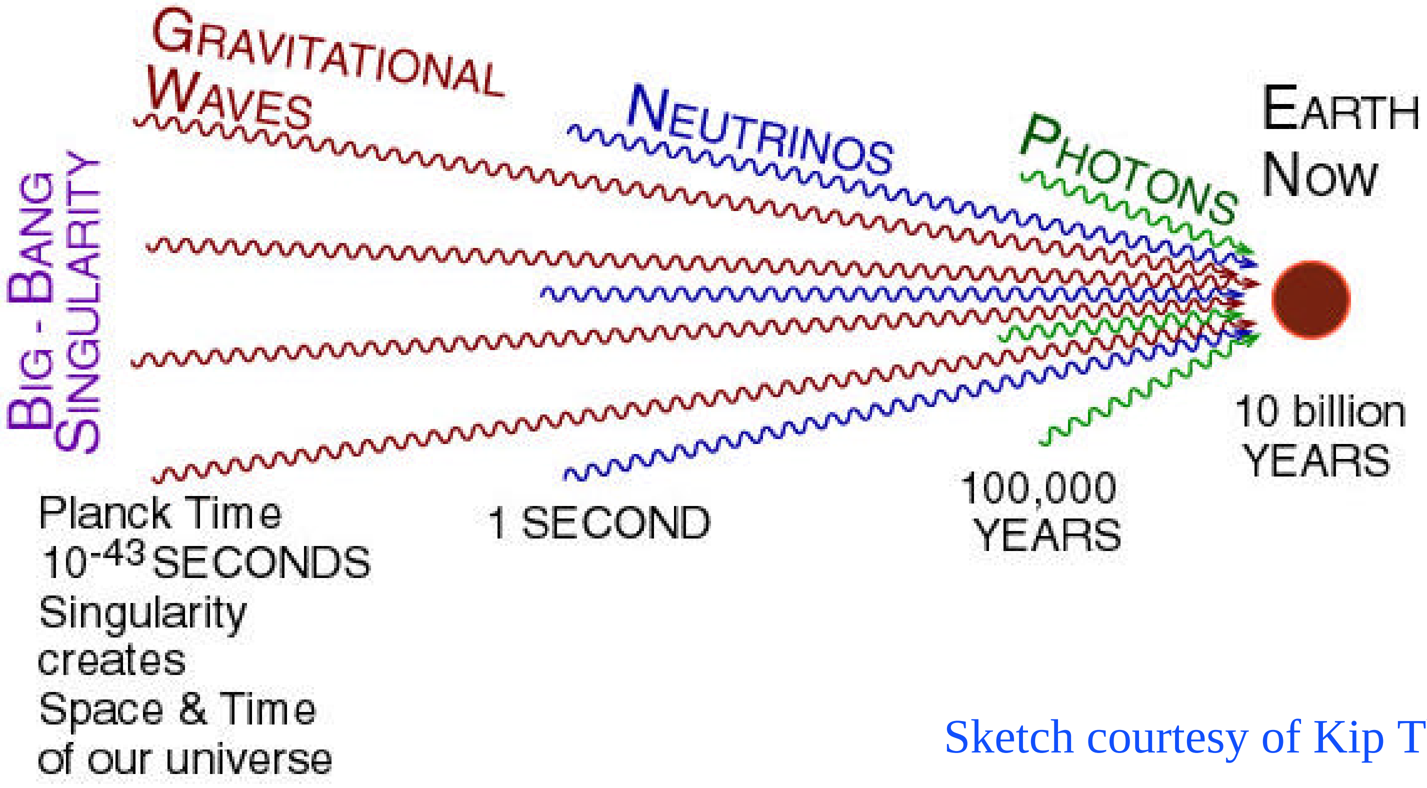
Taylor and Hulse were awarded the 1993 Nobel Prize for Physics for this work.



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)

Searching for Echoes from Very Early Universe

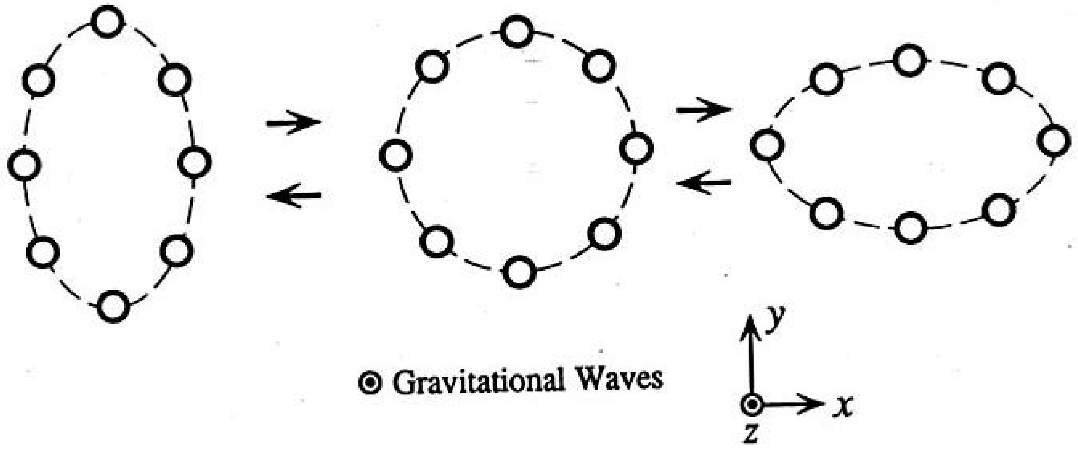


Sketch courtesy of Kip Thorne

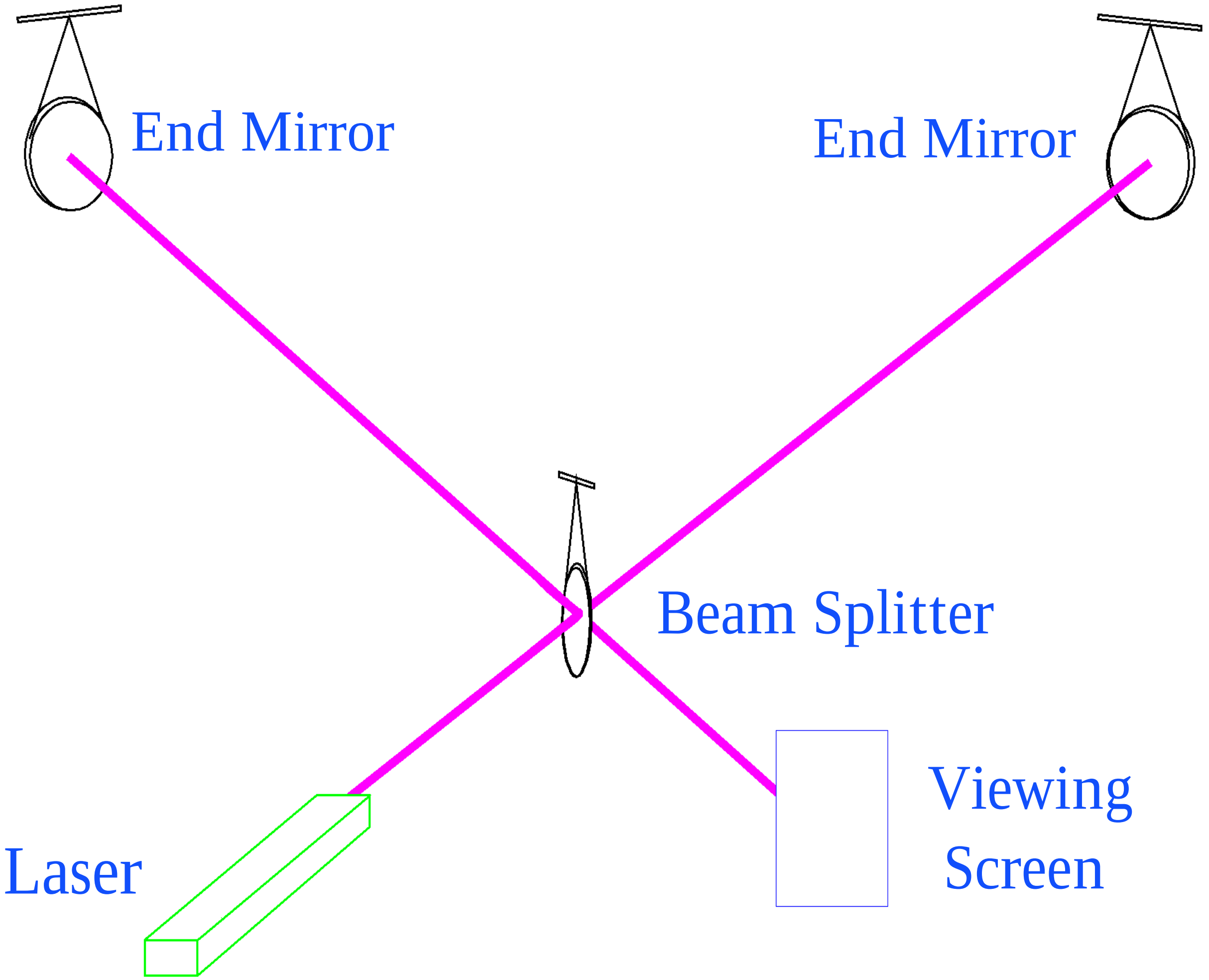
How does LIGO detect spacetime vibrations?

Important Signature of Gravitational Waves

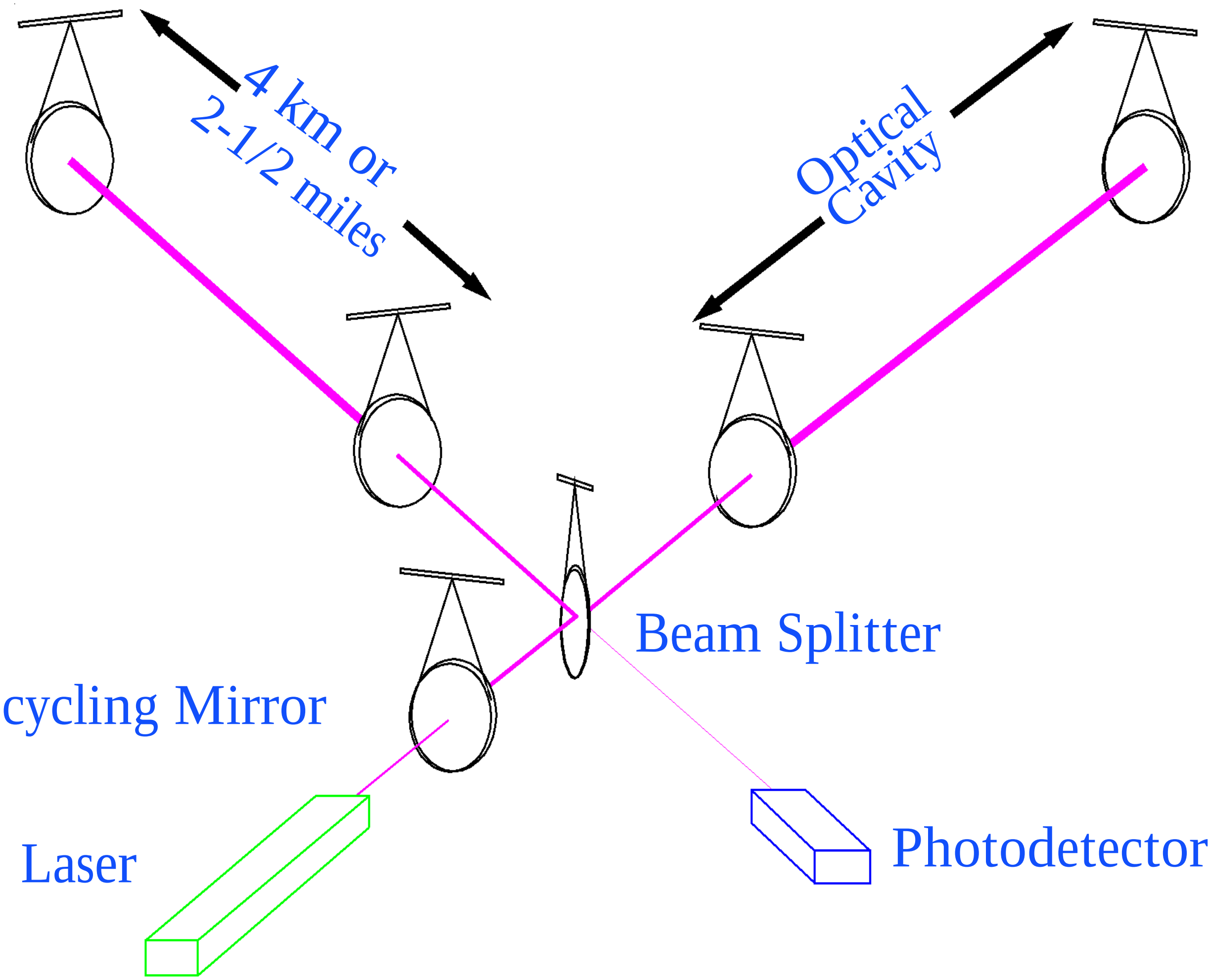
Gravitational waves shrink space along one axis perpendicular to the wave direction as they stretch space along another axis perpendicular both to the shrink axis and to the wave direction.



Sketch of a Michelson Interferometer

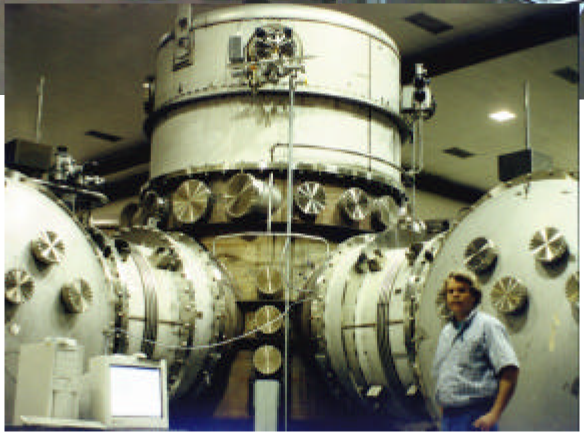


Fabry-Perot-Michelson with Power Recycling



Vacuum Chambers Provide Quiet Homes for Mirrors

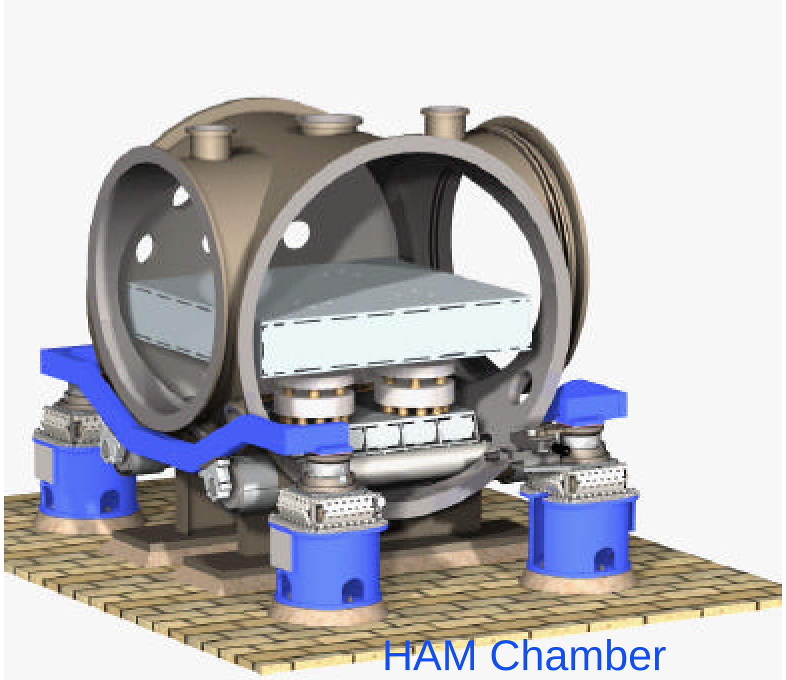
View inside Corner Station



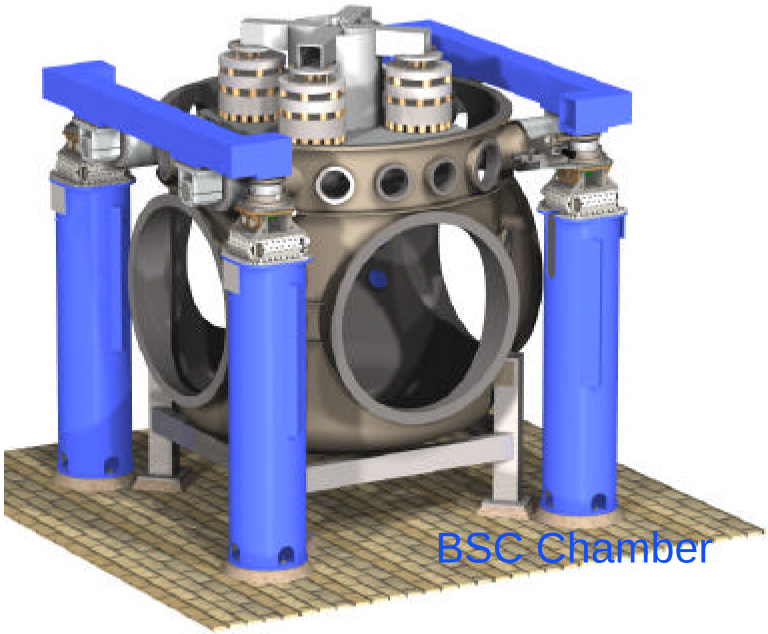
Standing at vertex beam splitter

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

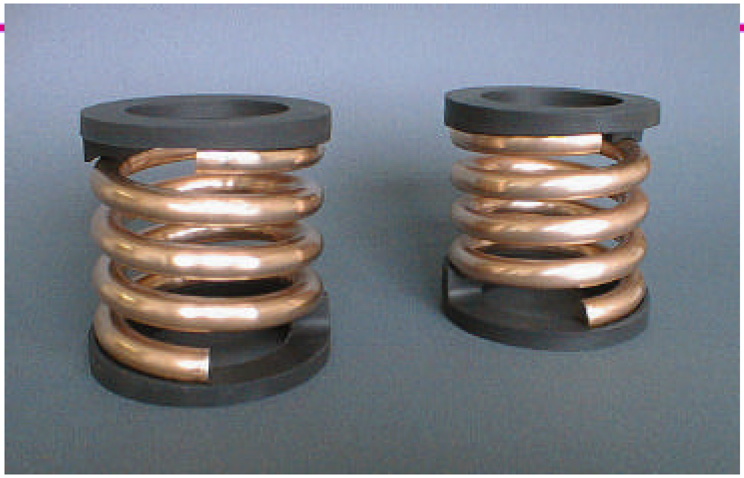


HAM Chamber

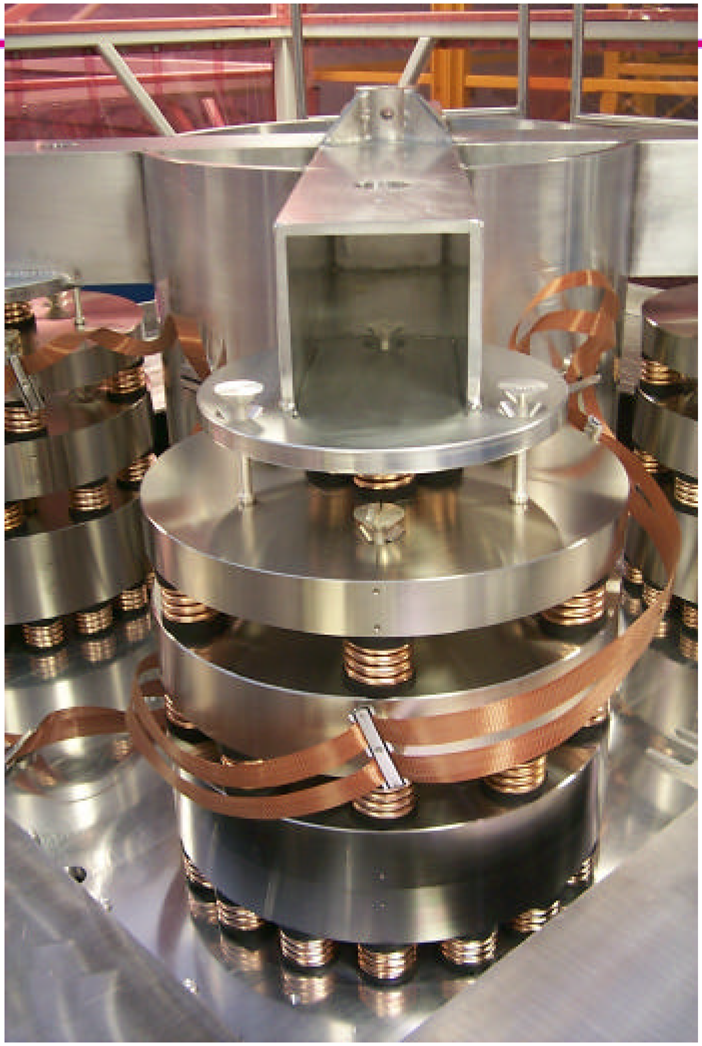


BSC Chamber

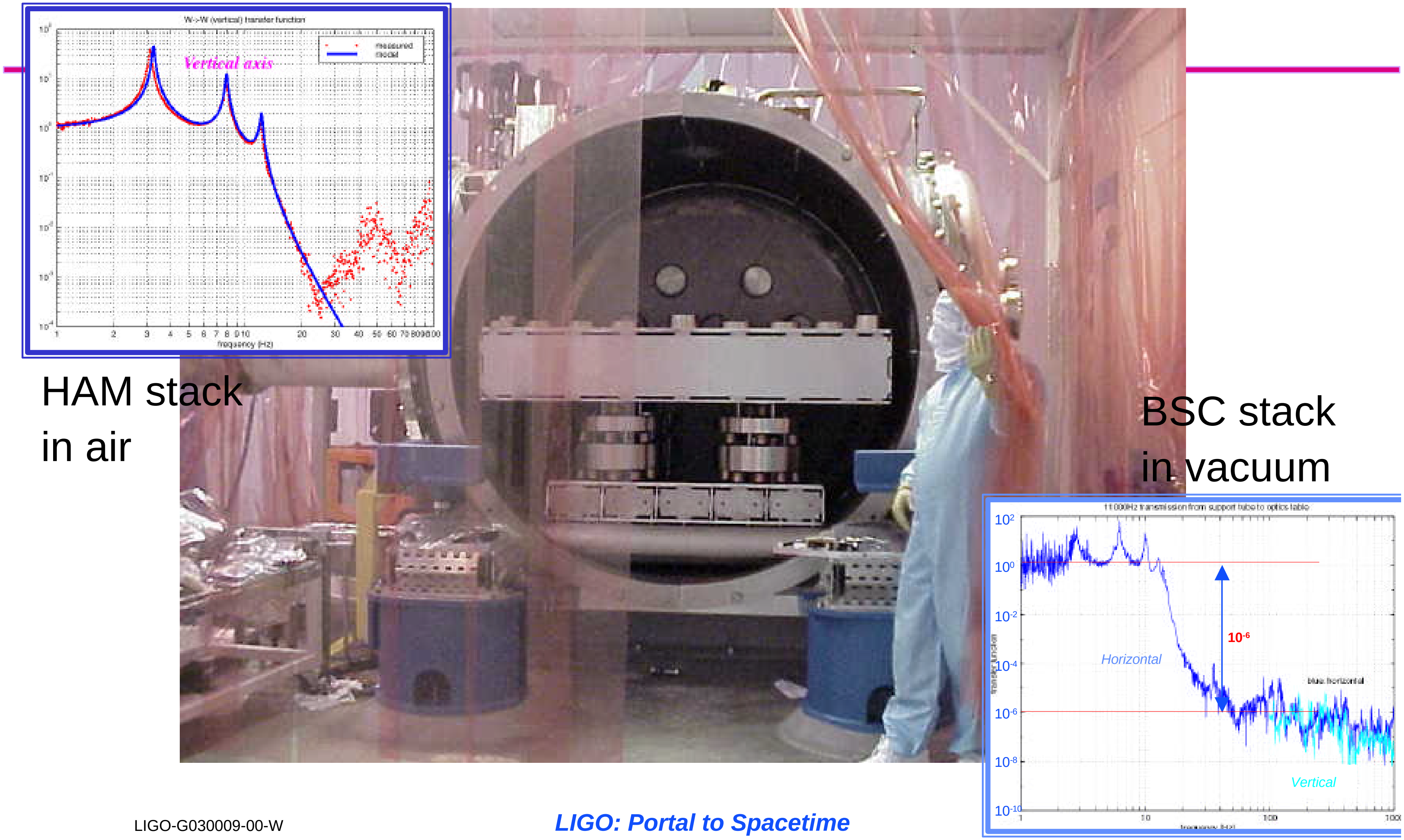
Seismic Isolation – Springs and Masses



damped spring
cross section



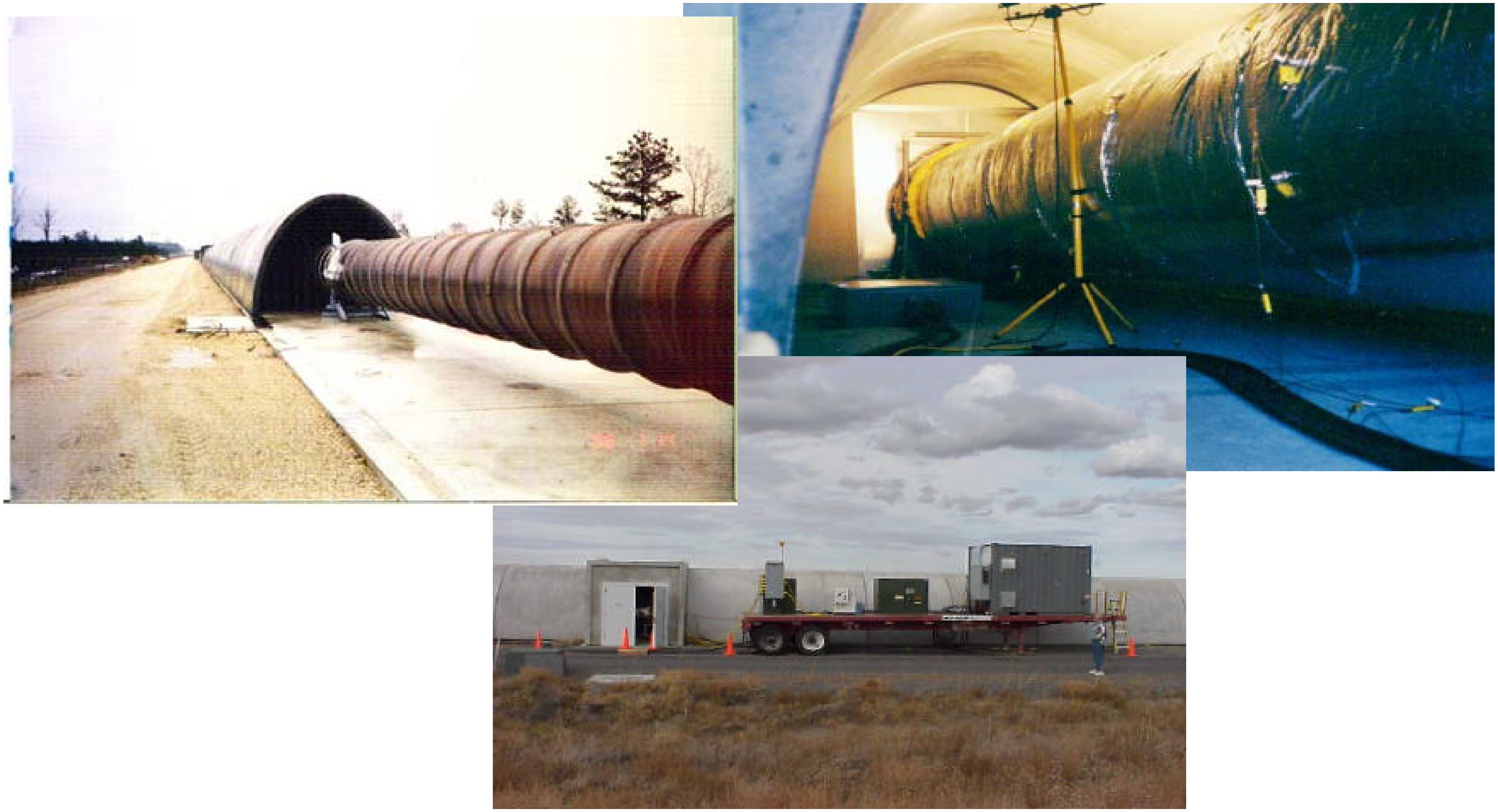
Seismic System Performance



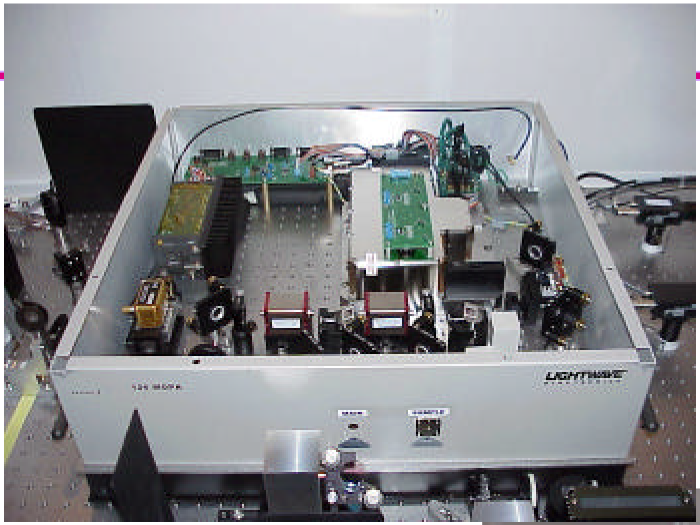
HAM stack
in air

BSC stack
in vacuum

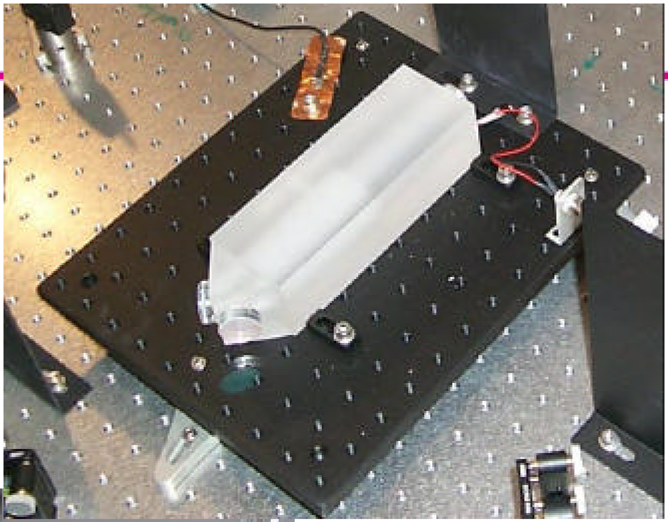
Evacuated Beam Tubes Provide Clear Path for Light



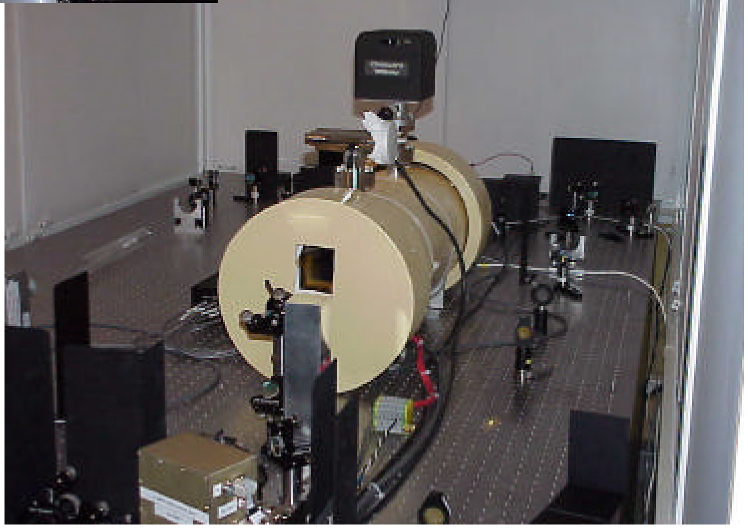
All-Solid-State Nd:YAG Laser



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



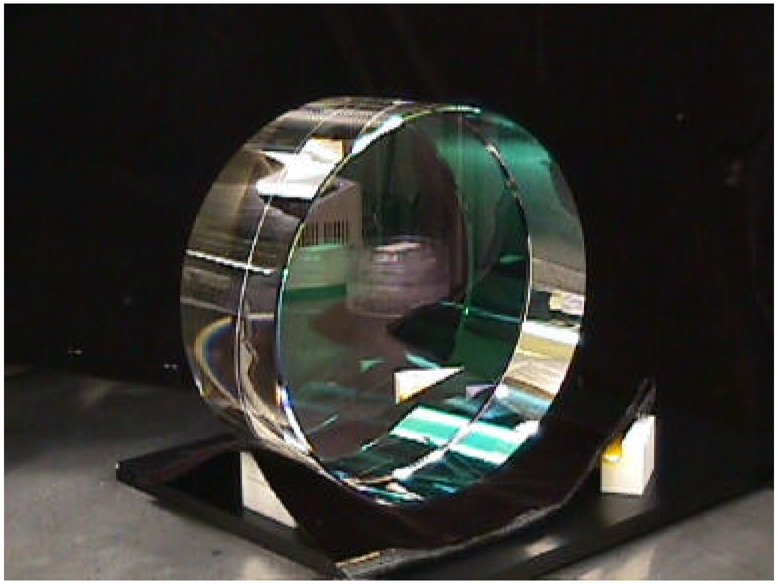
Cavity for
defining beam geometry,
joint development with
Stanford



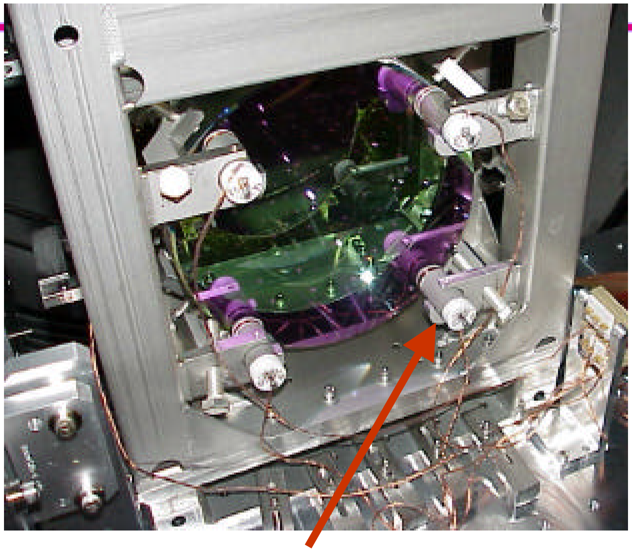
Frequency reference
cavity (inside oven)

Core Optics

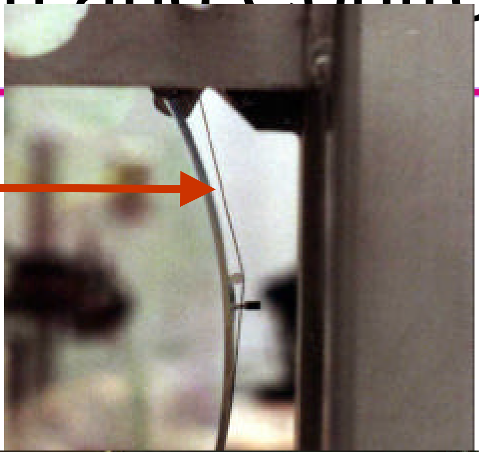
- Substrates: SiO_2
  - 25 cm Diameter, 10 cm thick
  - Homogeneity < 5×10^{-7}
  - Internal mode Q's > 2×10^{6}
- Polishing
  - Surface uniformity < 1 nm rms
  - Radii of curvature matched < 3%
- Coating
  - Scatter < 50 ppm
  - Absorption < 2 ppm
  - Uniformity $<10^{-3}$
- Production involved 6 companies,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



Core Optics Suspension and Control



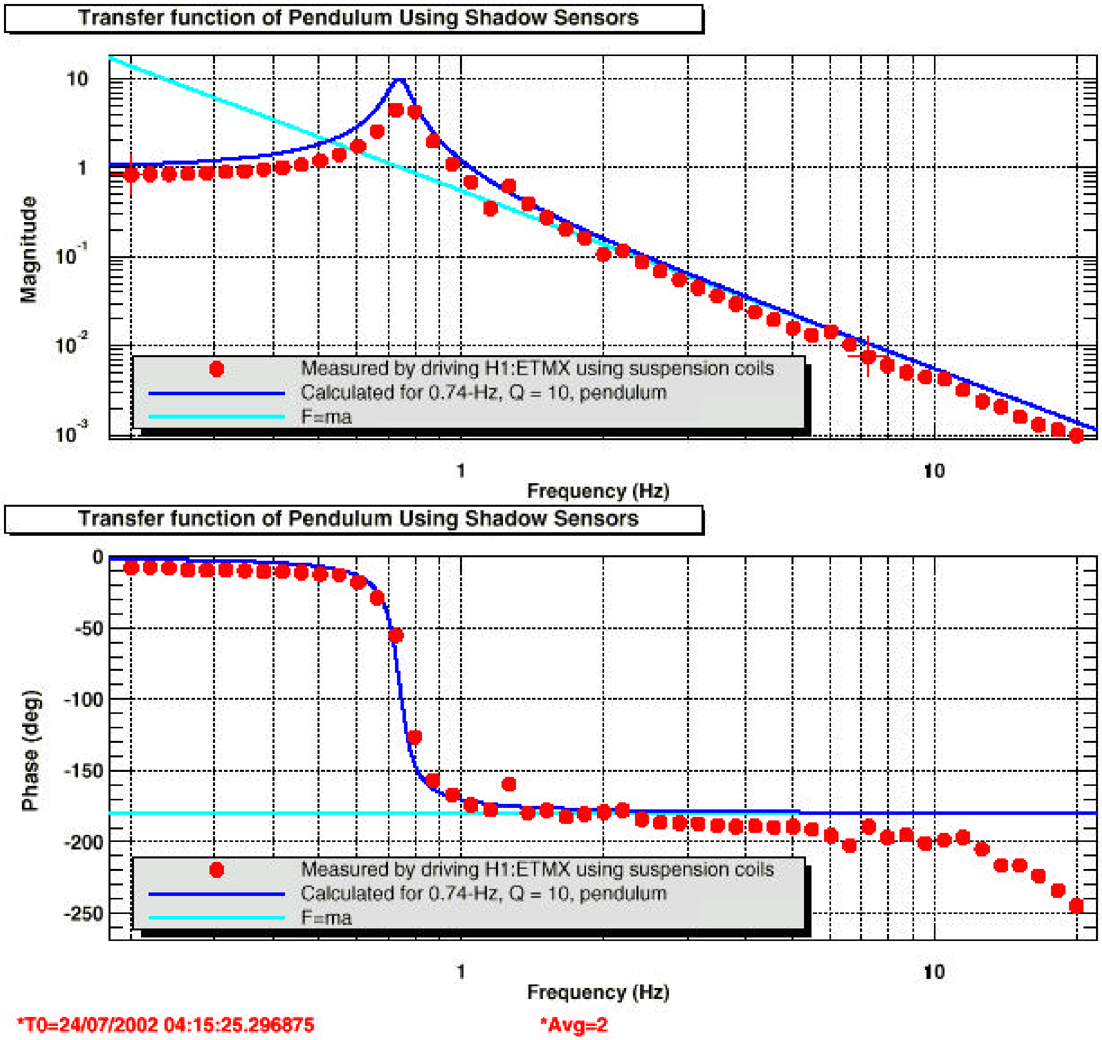
Local sensors/actuators provide damping and control forces



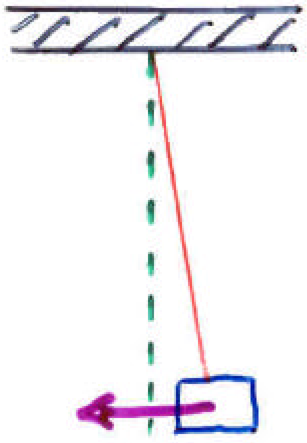
Optics suspended as simple pendulums

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

Suspended Mirror Approximates a Free Mass Above Resonance



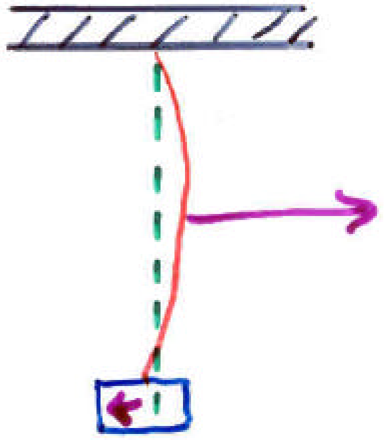
Background Forces in GW Band = Thermal Noise ~ $k_B T$/mode



pendulum mode

$x_{rms} \approx 10^{-11}$ m

f < 1 Hz



violin mode

$x_{rms} \approx 2\times10^{-17}$ m

f ~ 350 Hz

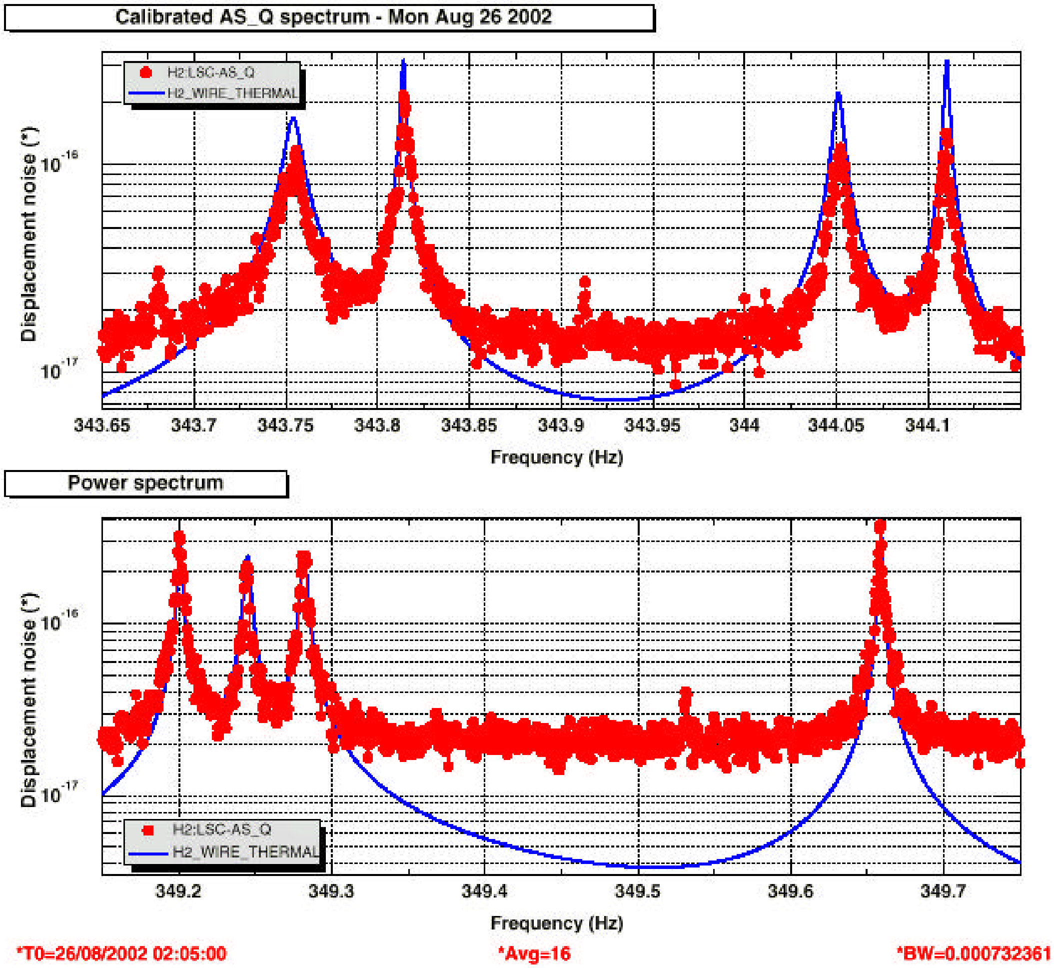
test mass vibrational mode

$x_{rms} \approx 5\times10^{-16}$ m

f ≥ 10 kHz

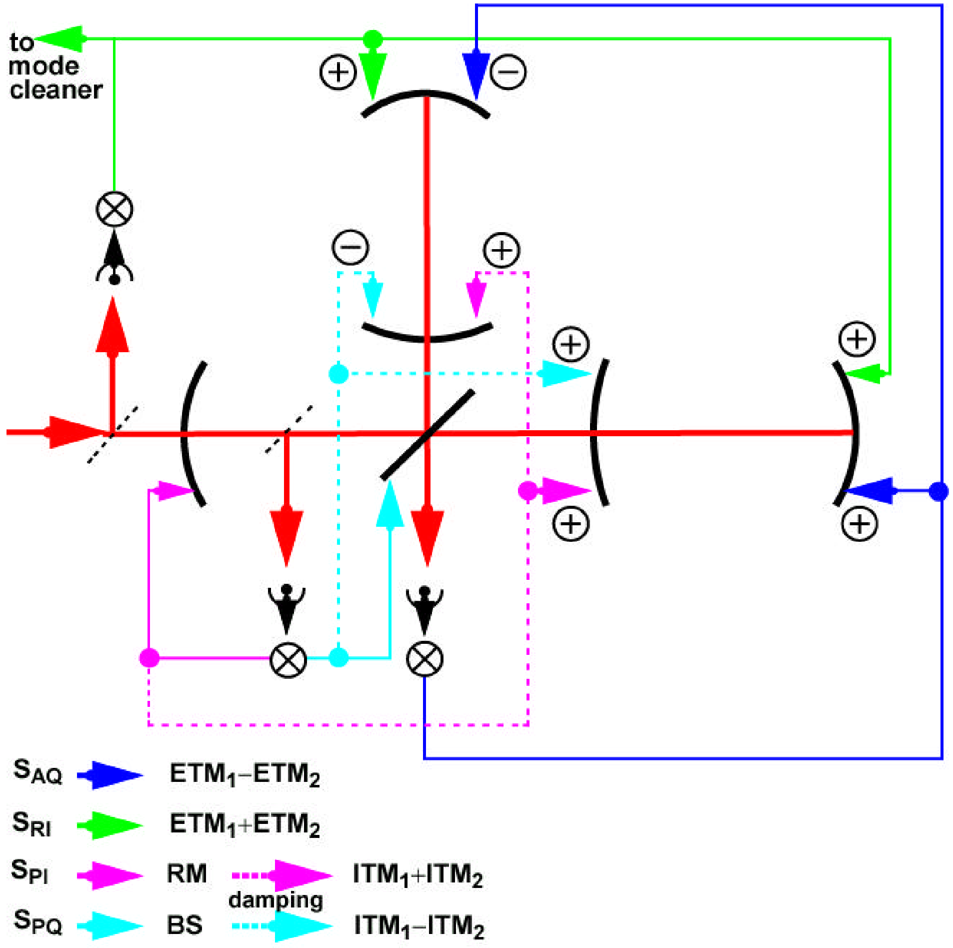
Strategy: Compress energy into narrow resonance outside band of interest ⇒ require high mechanical Q, low friction

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



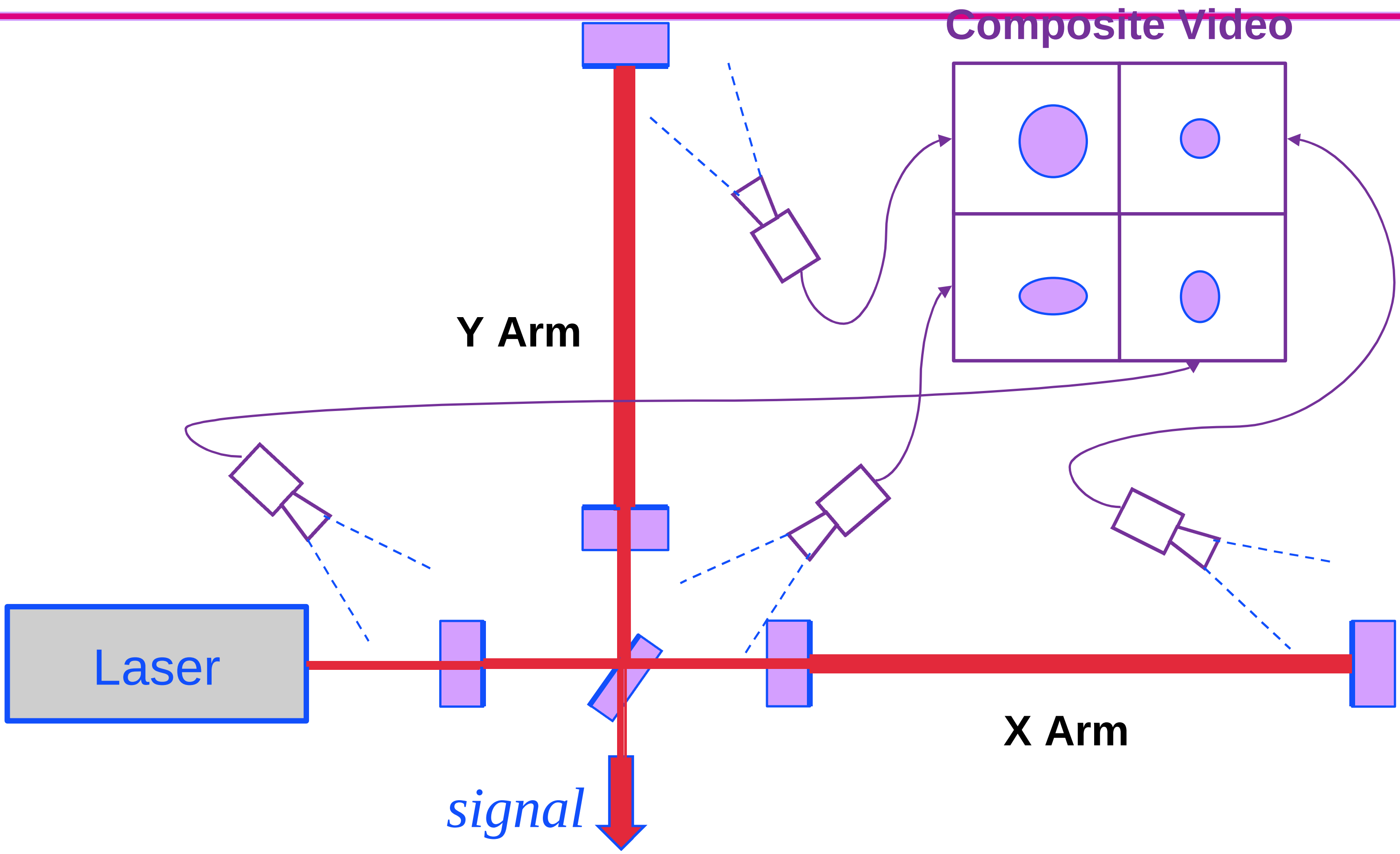
Almost good enough for tracking calibration.

Interferometer Control System

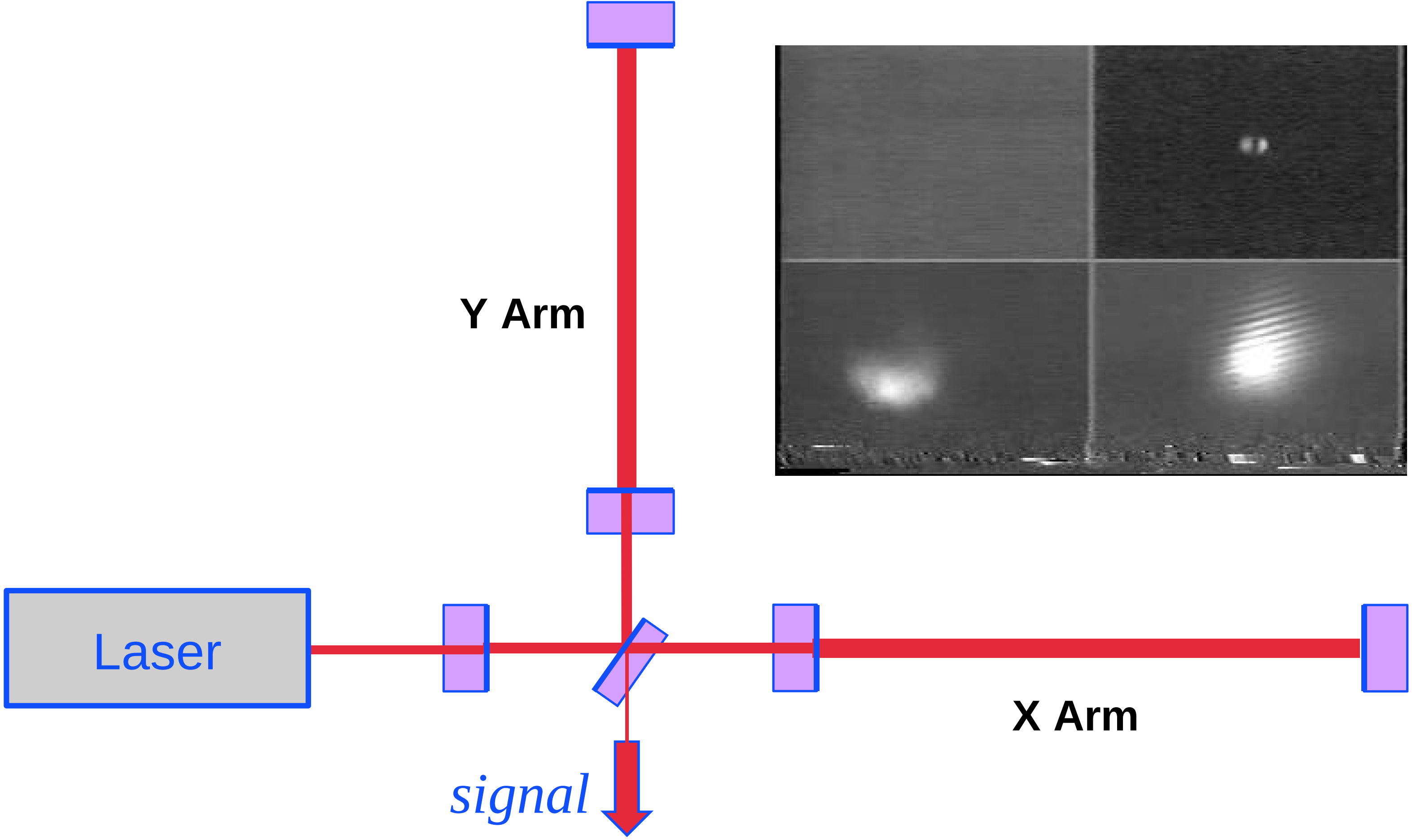


- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Ill-conditioned (off-diagonal) plant matrix
- Highly nonlinear response over most of phase space
- Transition to stable, linear regime takes plant through singularity
- Employs adaptive control system that evaluates plant evolution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

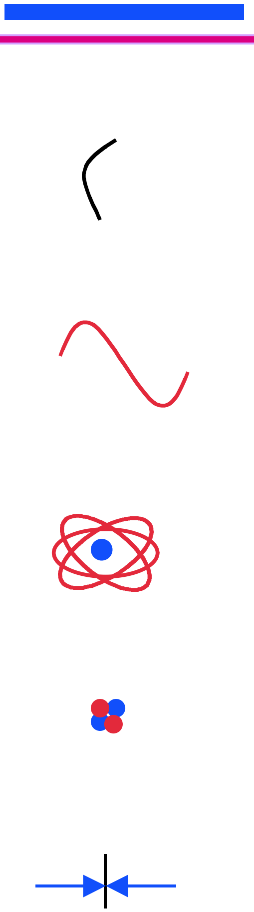
Steps to Locking an Interferometer



Watching the Interferometer Lock for the First Time in October 2000



Why is Locking Difficult?



One meter, about 40 inches

÷10,000 *Earthtides, about 100 microns*

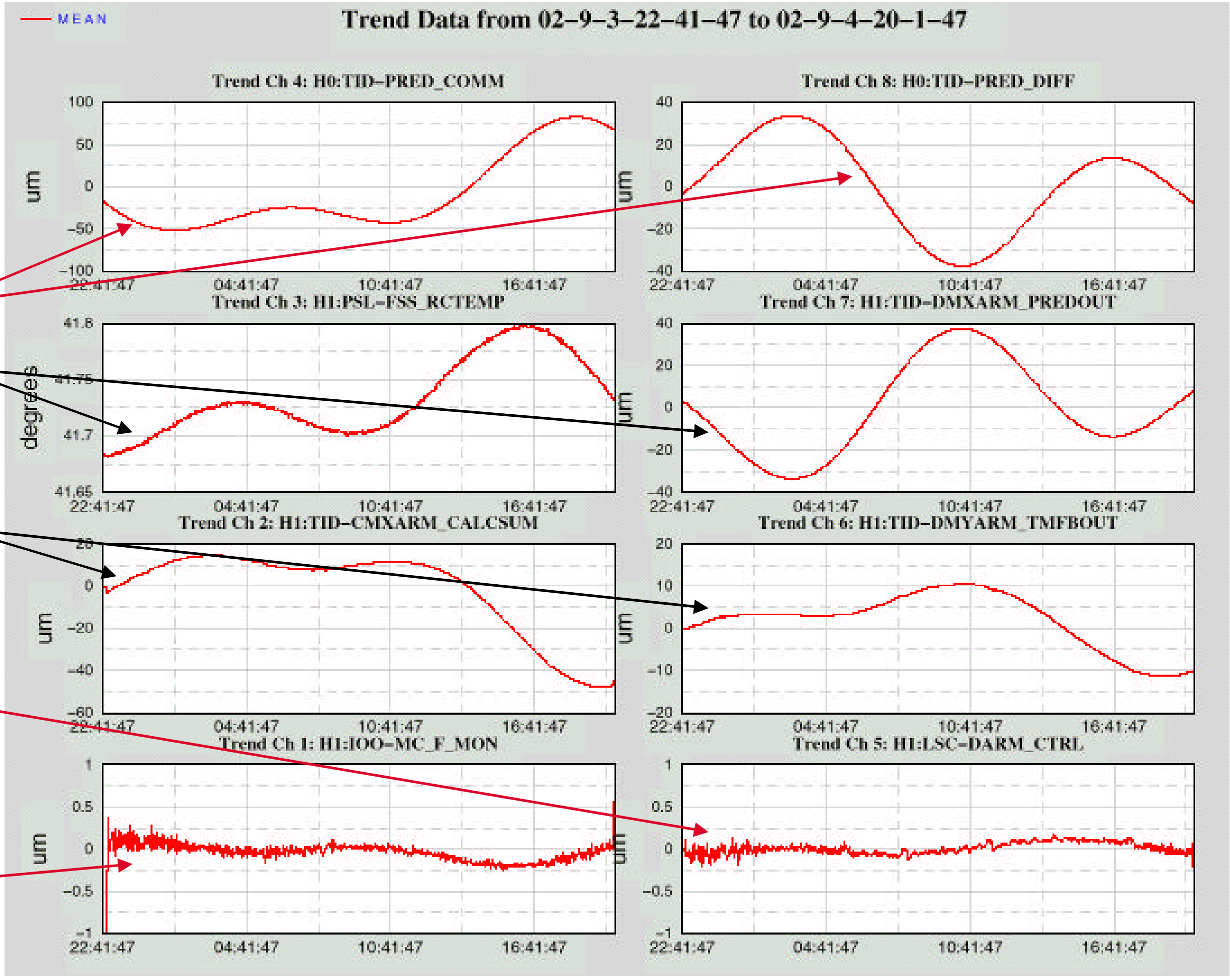
÷100 *Microseismic motion, about 1 micron*

÷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

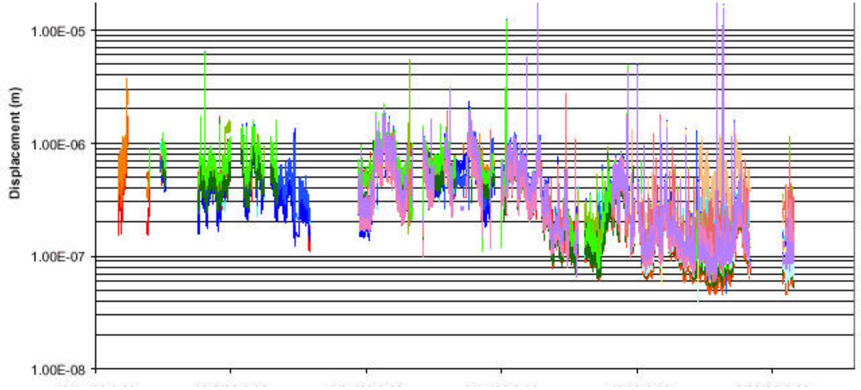
Feedback

Residual signal on voice coils

Residual signal on laser

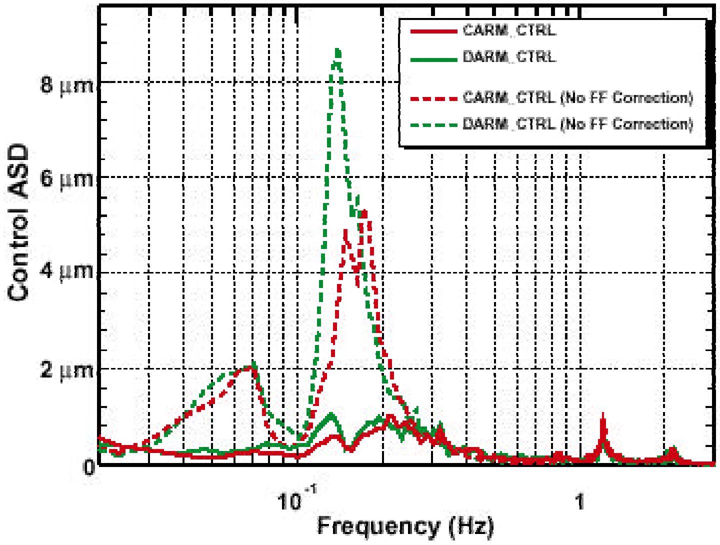
Microseism

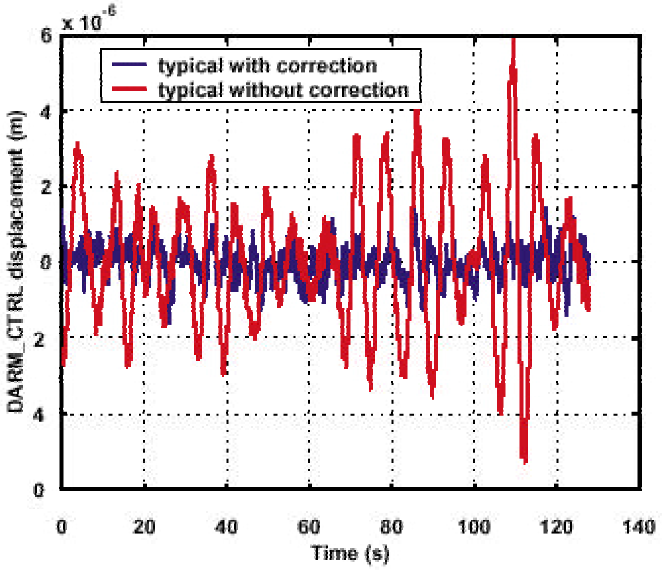
Microseism at 0.12 Hz dominates ground velocity



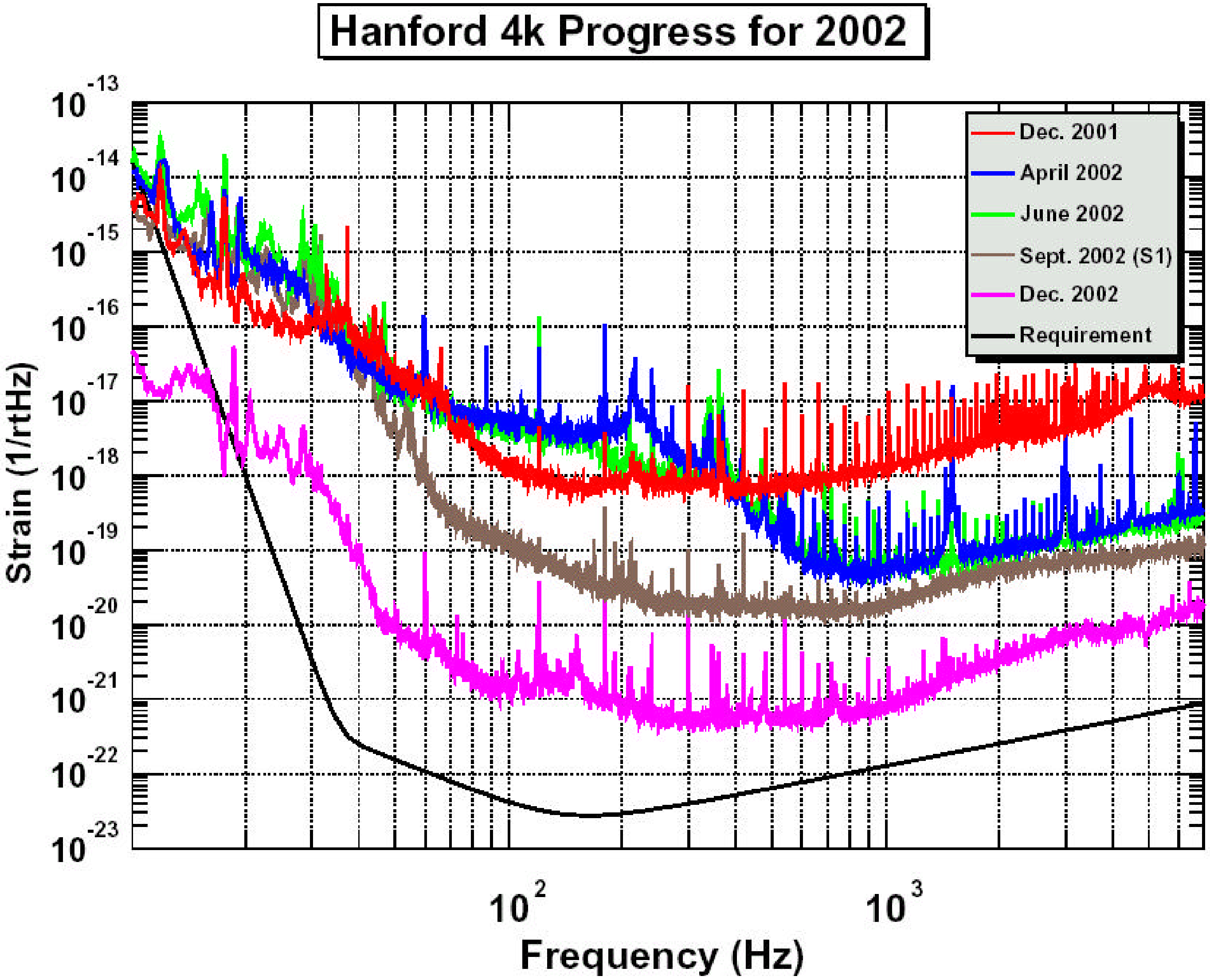
Trended data (courtesy of Gladstone High School) shows large variability of microseism, on several-day- and annual- cycles

Reduction by feed-forward derived from seismometers





We Have Continued to Progress…



LIGO: Portal to Spacetime

A Sampling of PhD Theses on LIGO

- Giaime – Signal Analysis & Control of Power-Recycled Fabry-Perot-Michelson Interferometer
- Regehr – Signal Analysis & Control of Power-Recycled Fabry-Perot-Michelson Interferometer
- Gillespie – Thermal Noise in Suspended Mirrors
- Bochner – Optical Modeling of LIGO
- Malvalvala – Angular Control by Wave-Front Sensing
- Lyons – Noise Processes in a Recombined Suspended Mirror Interferometer
- Evans – Automated Lock Acquisition for LIGO
- Adhikari – Noise & Sensitivity for Initial LIGO
- Sylvestre – Detection of GW Bursts by Cluster Analysis

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