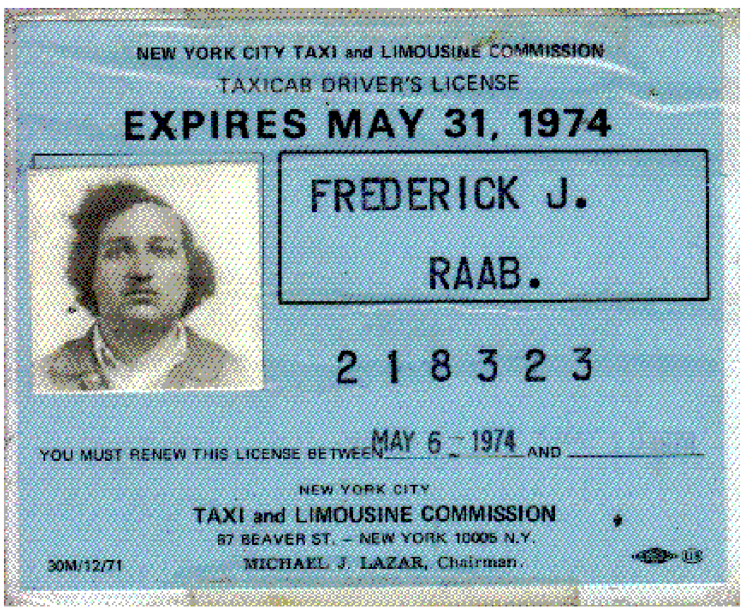
Gearing up for Gravitational Waves: the Status of Building LIGO



Frederick J. Raab, LIGO
Hanford Observatory

LIGO-G010189-00-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 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
  - » The unknown

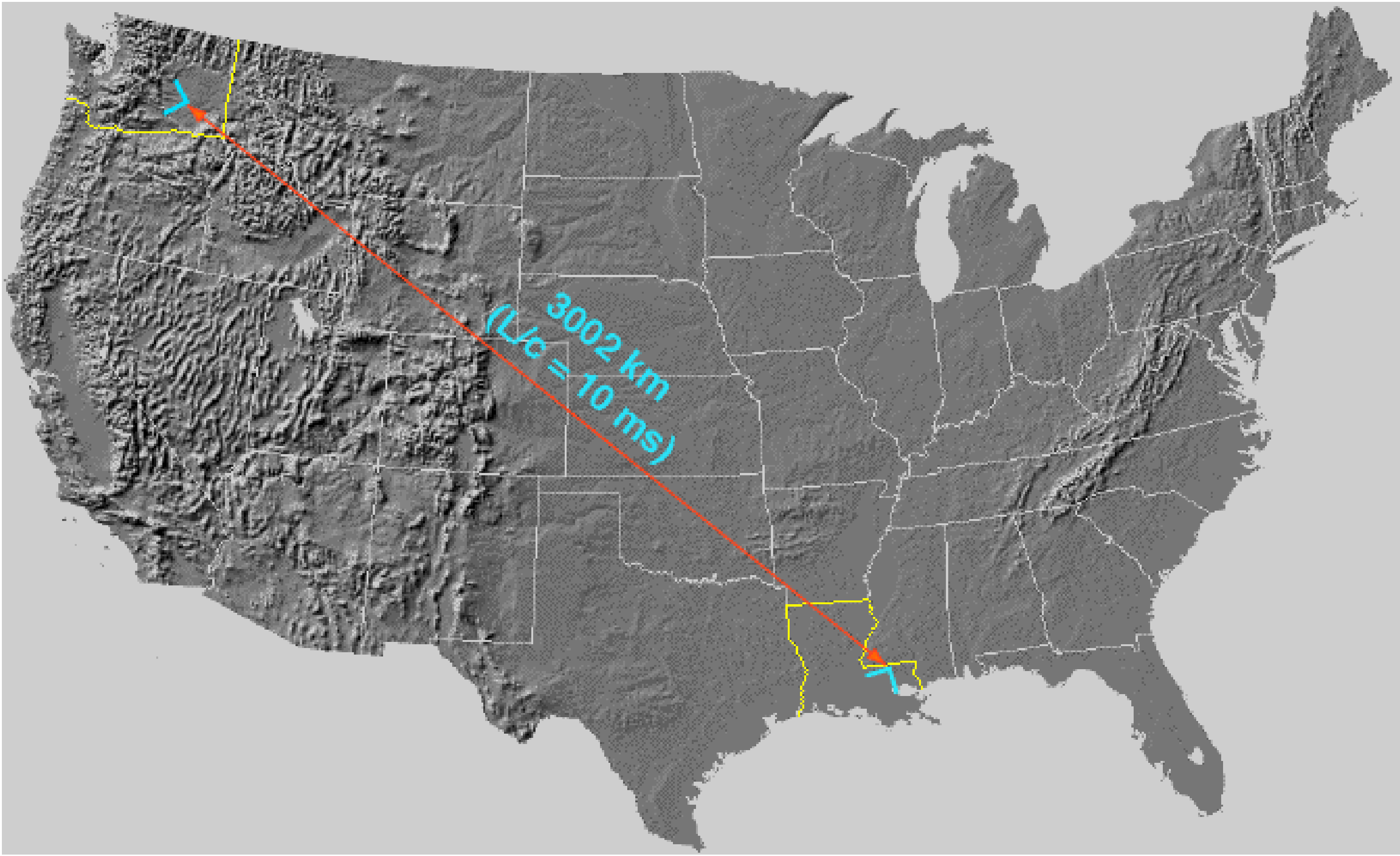
The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

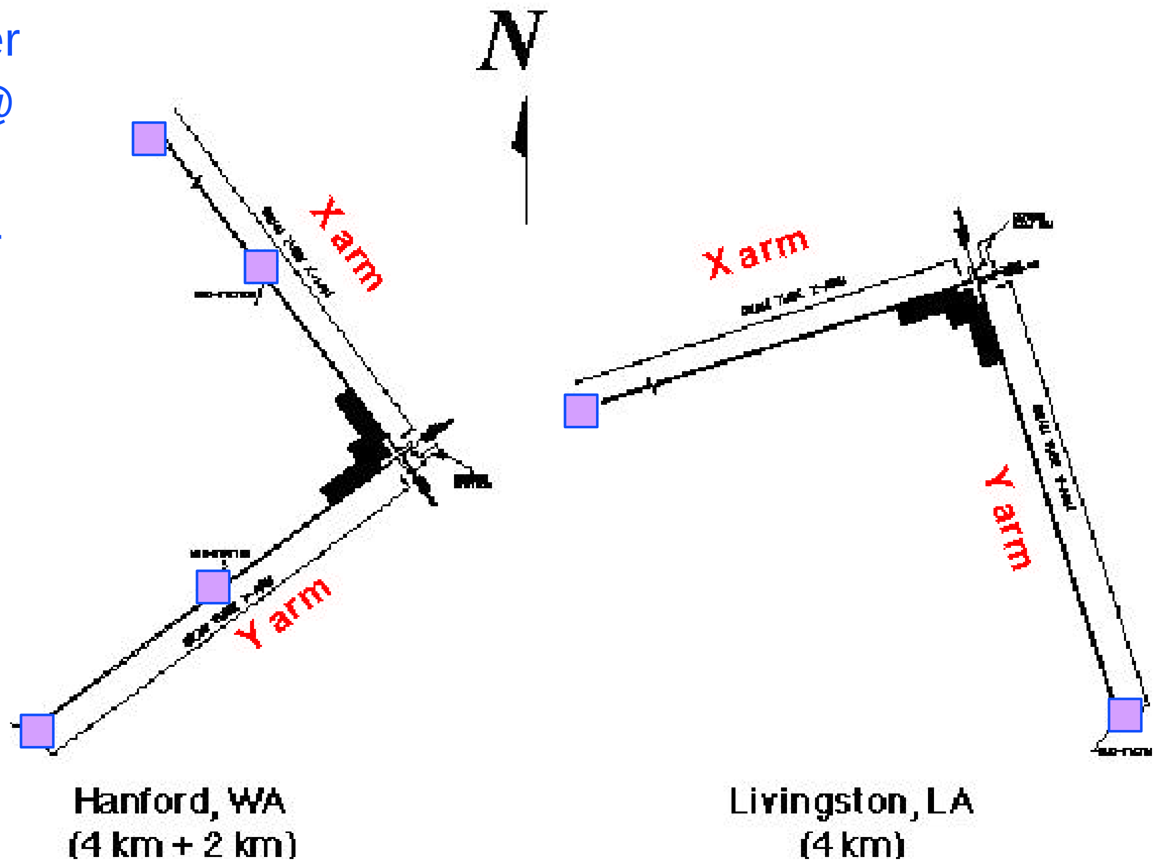
Sponsored by the National Science Foundation; operated by Caltech and MIT; the research focus for about 350 LIGO Science Collaboration members worldwide.

LIGO Observatories



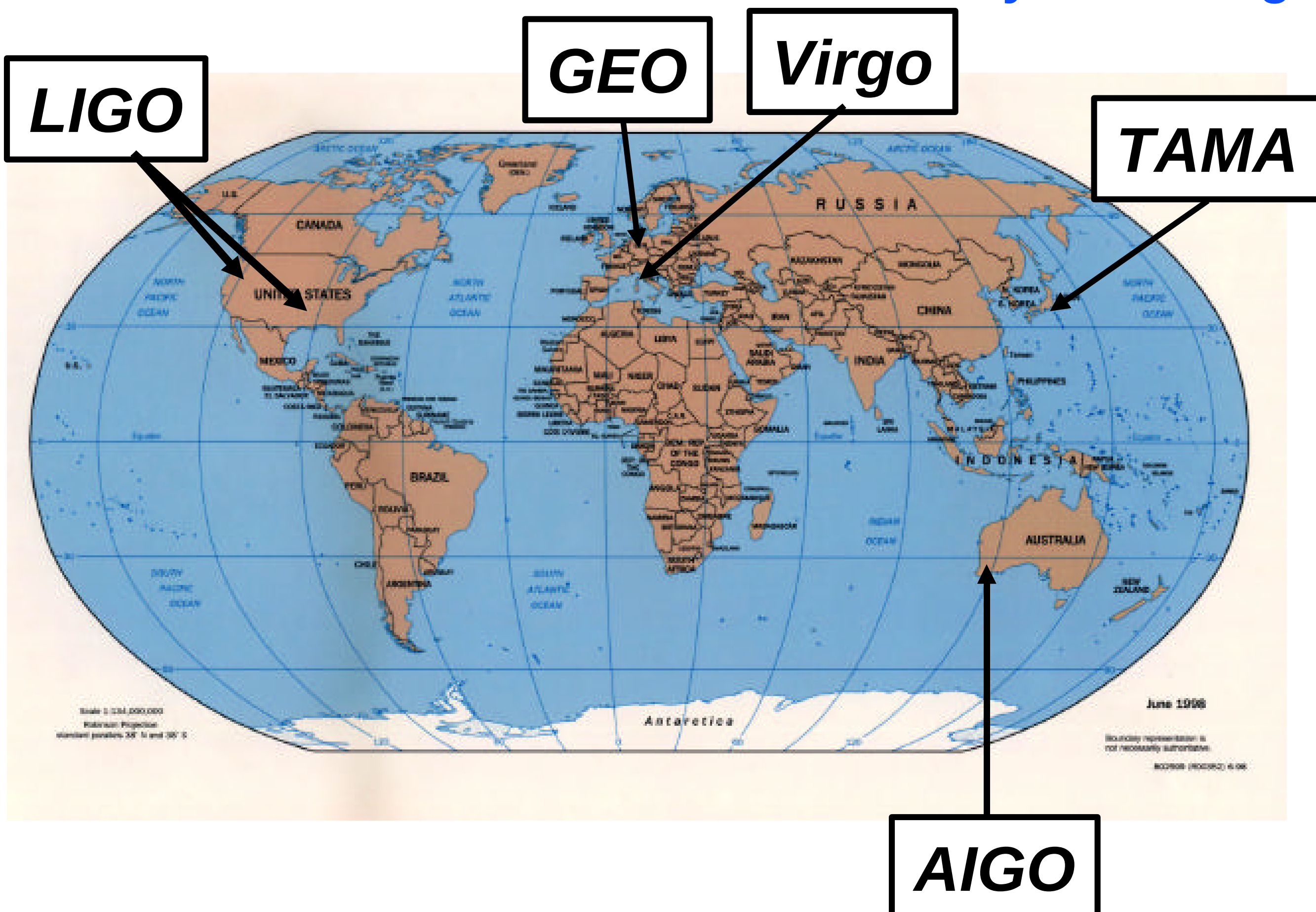
Configuration of LIGO Observatories

- 2-km & 4-km laser interferometers @ Hanford
- Single 4-km laser interferometer @ Livingston



Part of Future International Detector Network

Simultaneously detect signal (within msec)



detection confidence

locate the sources

decompose the polarization of gravitational waves

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?

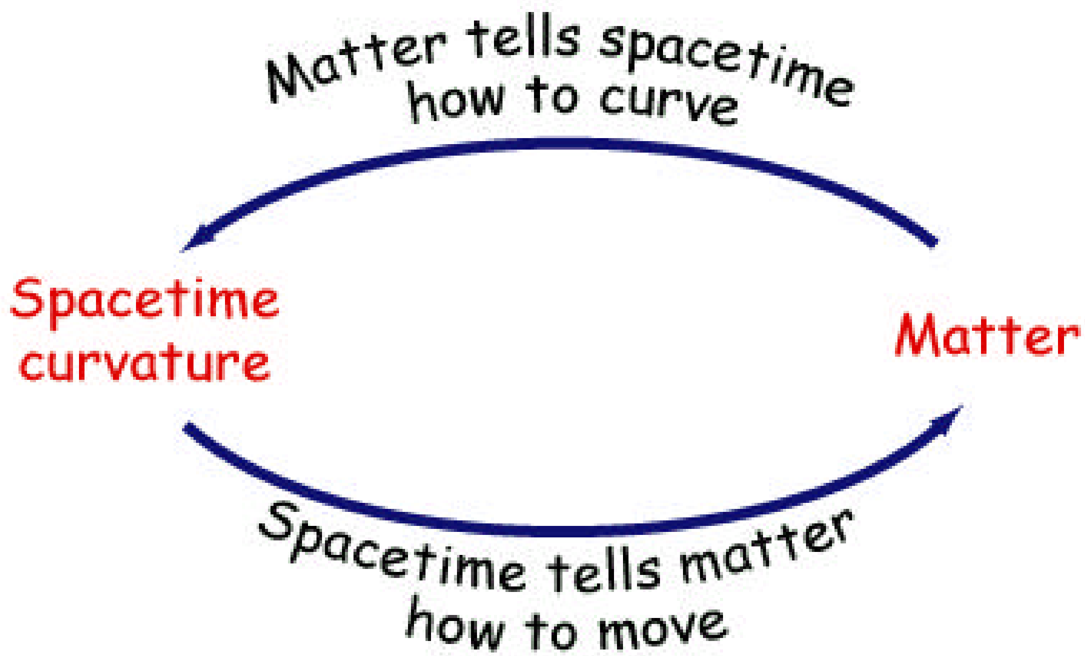
A Slight Problem

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!

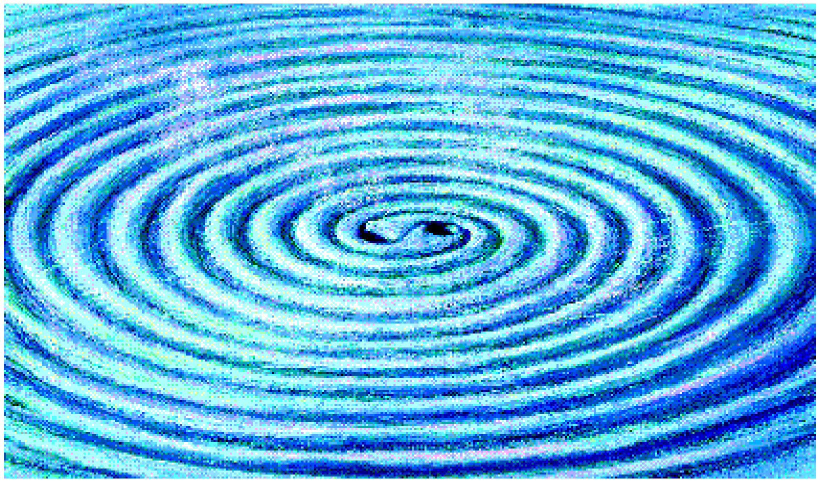
John Wheeler's Summary of General Relativity Theory



Gravitational Waves

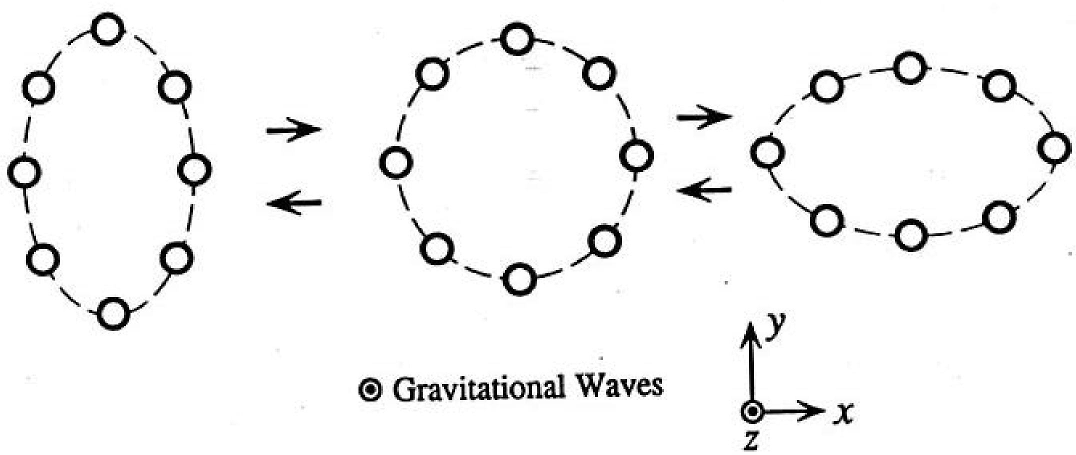
Gravitational waves are ripples in space when it is stirred up by rapid motions of large concentrations of matter or energy

Rendering of space stirred by two orbiting black holes:



Important Signature of Gravitational Waves

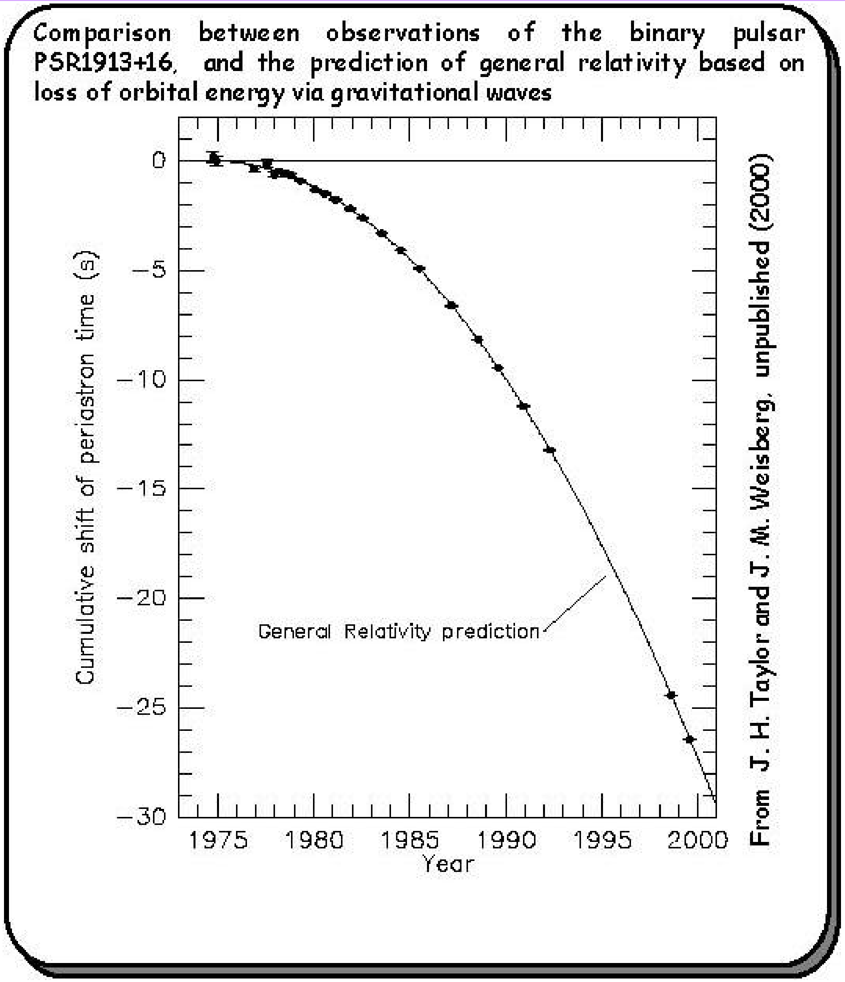
Gravitational waves shrink space along one axis perpendicular to the wave direction as they stretch space along another axis perpendicular both to the shrink axis and to the wave direction.



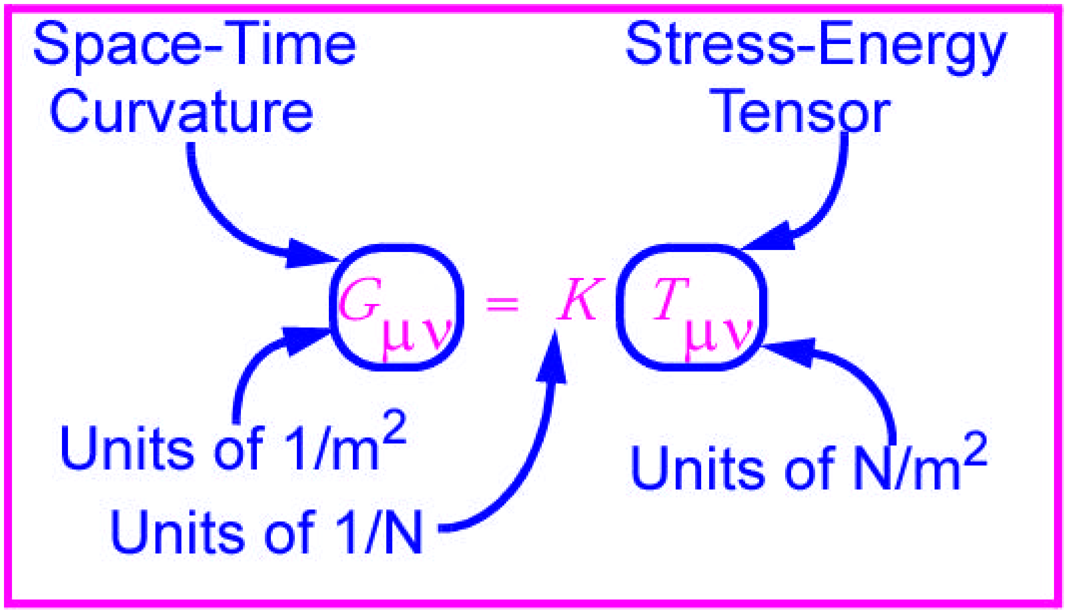
Energy Loss Caused By Gravitational Radiation Confirmed

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.



Spacetime is Stiff!



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

=> Wave can carry huge energy with miniscule amplitude!

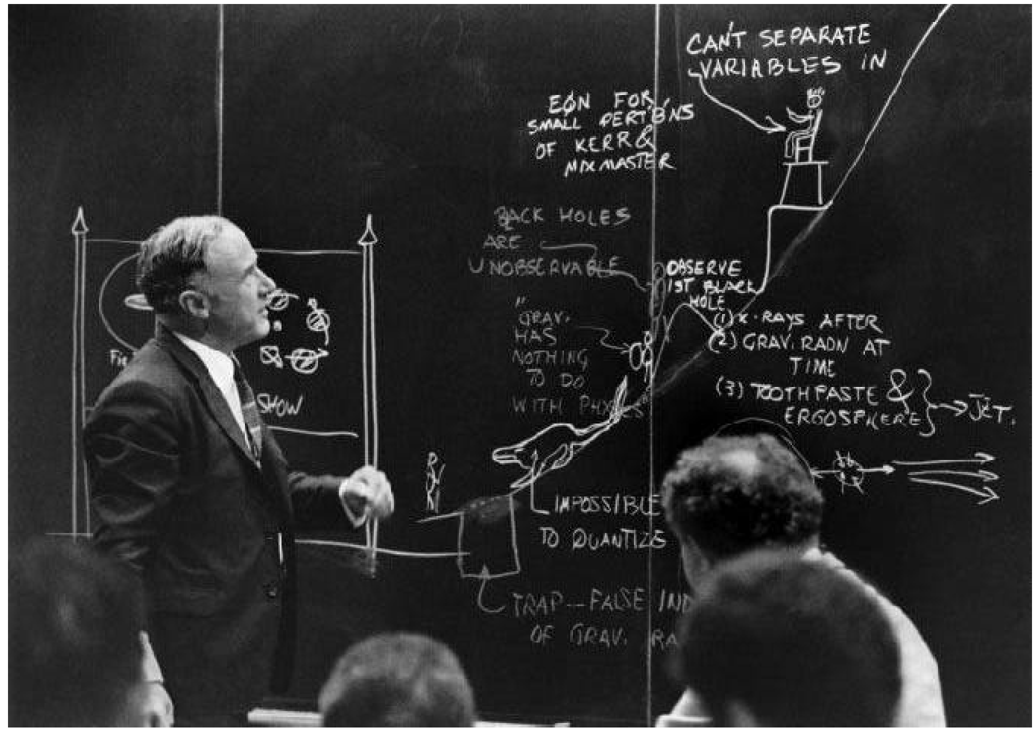
$$h \sim (G/c^4)\,(E_{NS}/r)$$

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."

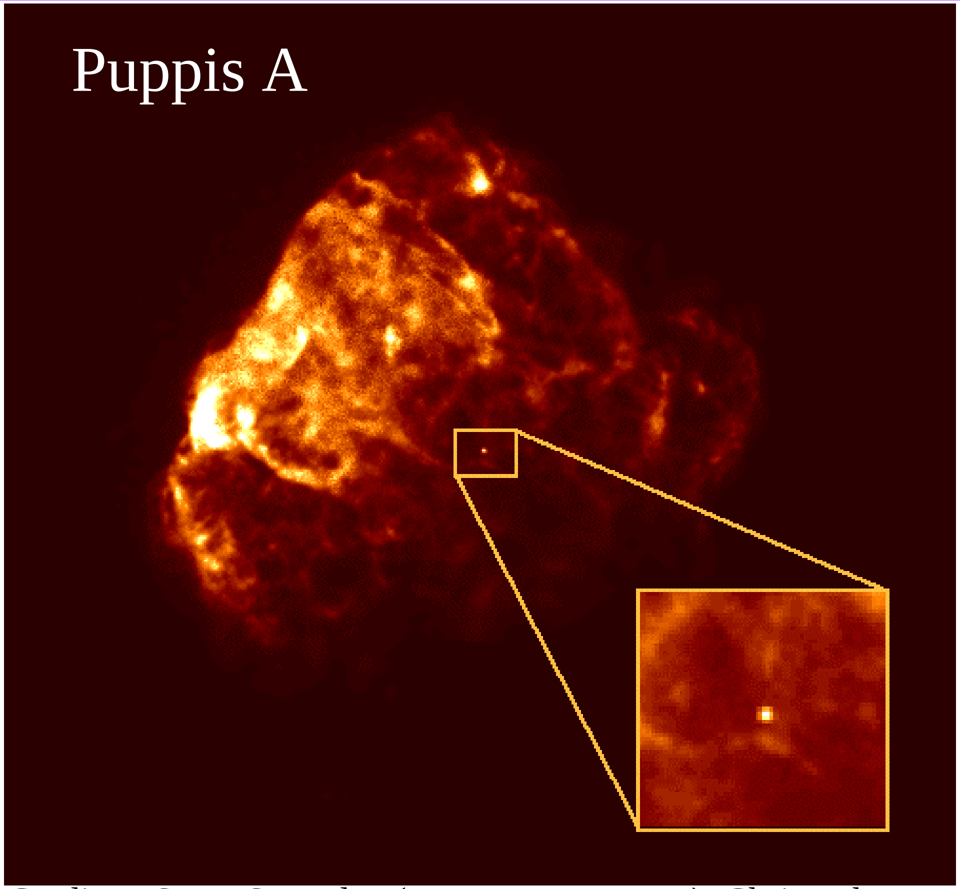
– John A. Wheeler in Geons, Black Holes and Quantum Foam



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

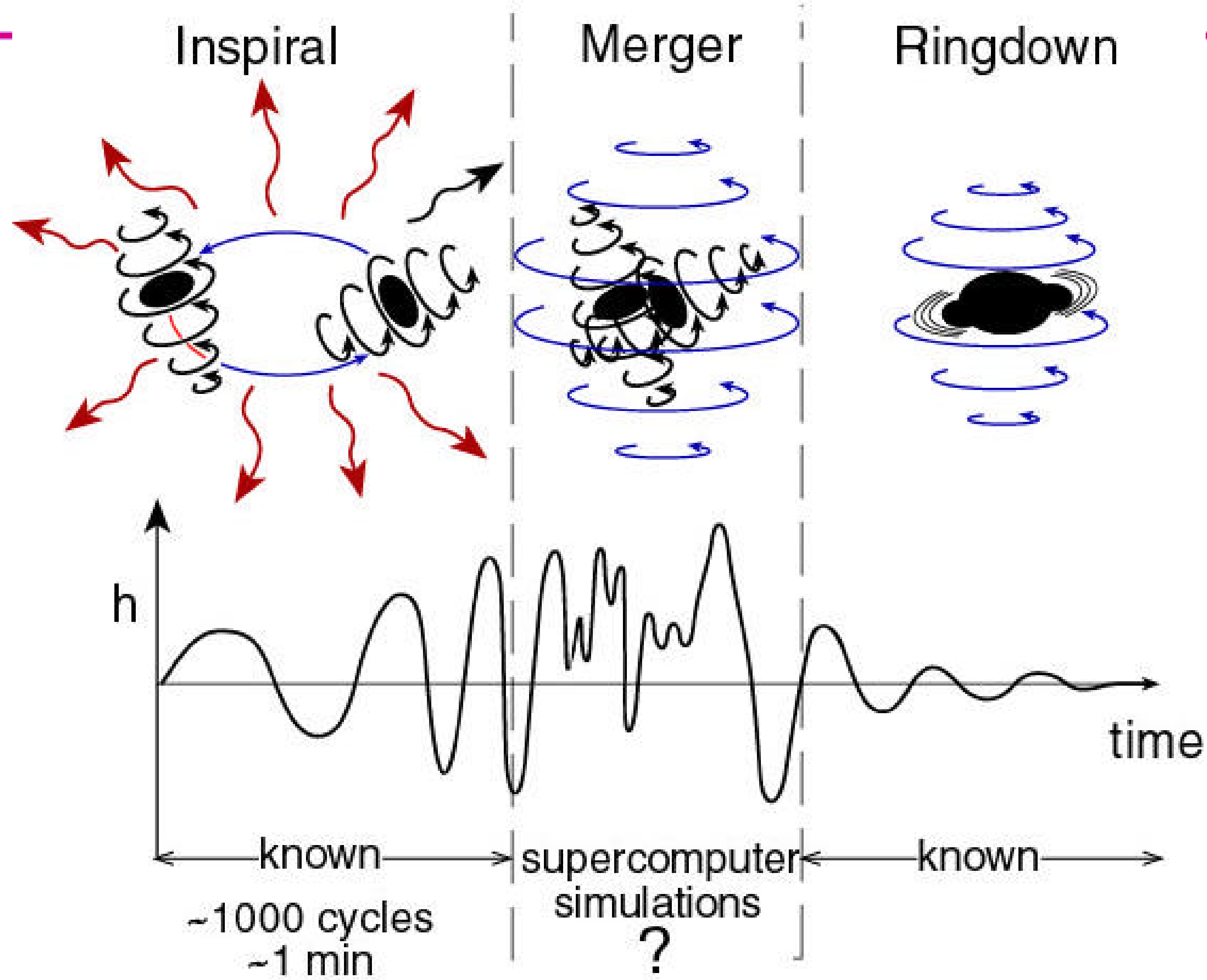
Do Supernovae Produce Gravitational Waves?

- 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).

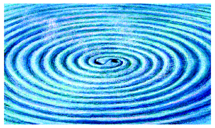
Catching Waves From Black Holes



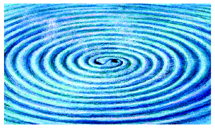
Sketches courtesy of Kip Thorne

Sounds of Compact Star Inspirals

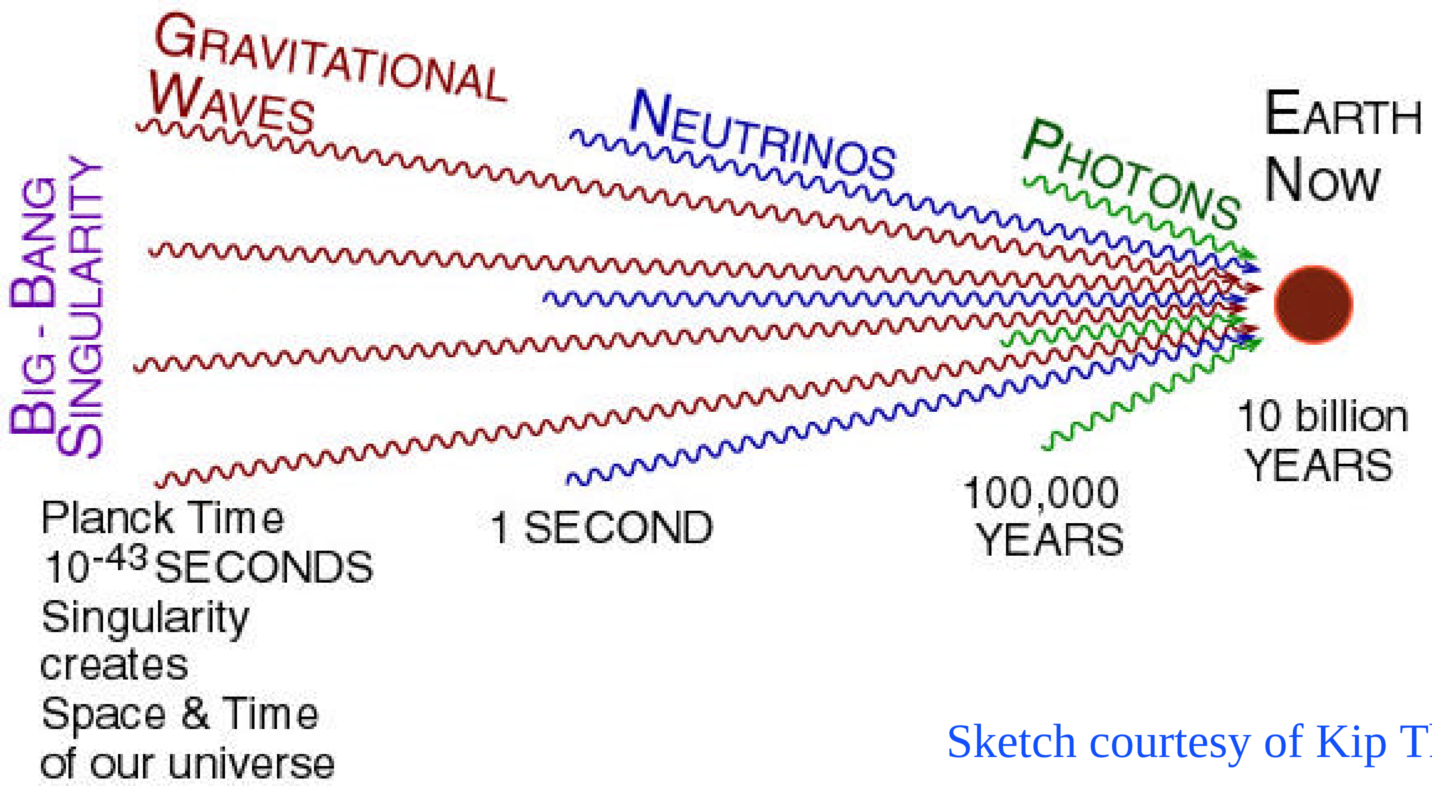
Neutron-star binary inspiral:



Black-hole binary inspiral:



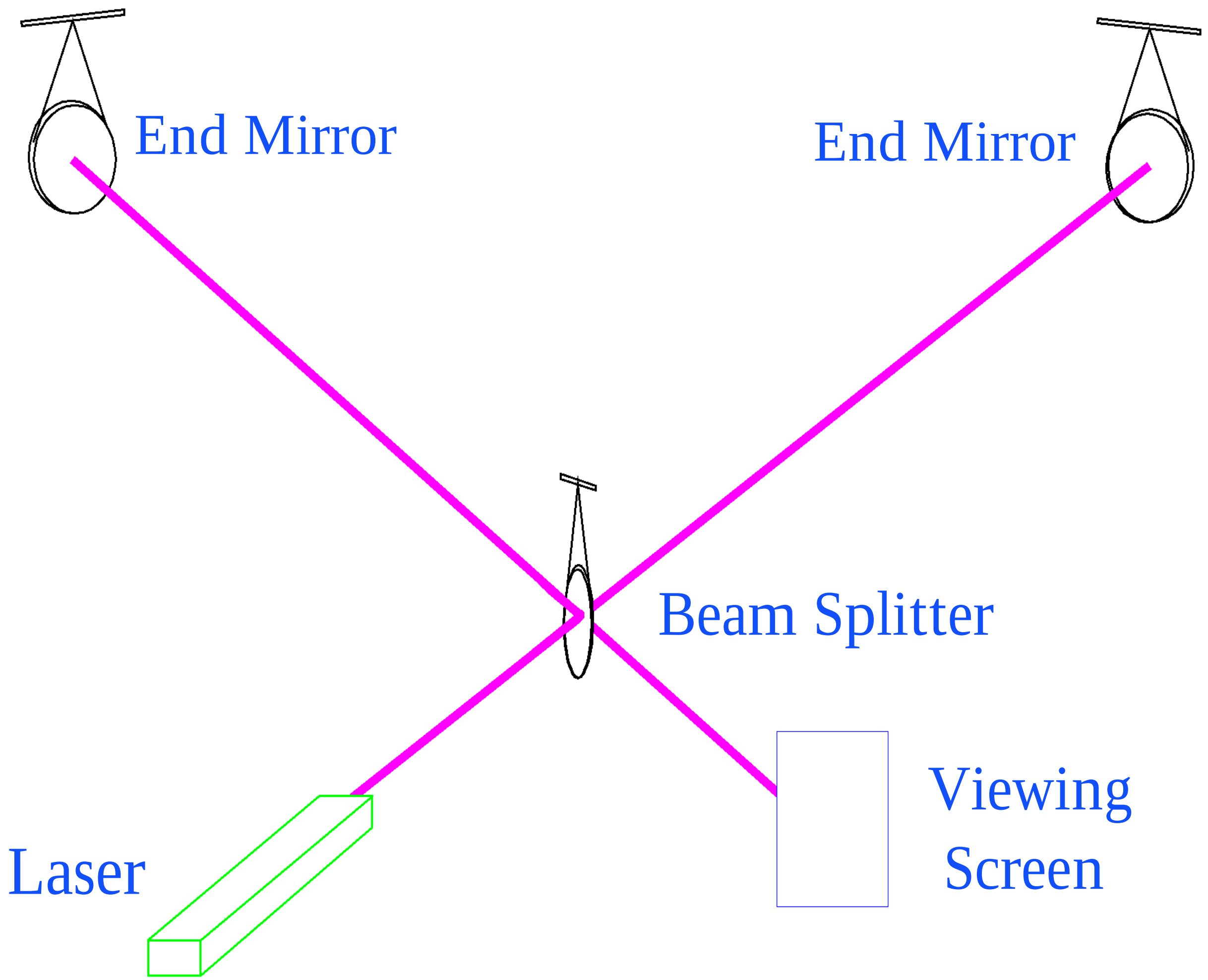
Searching for Echoes from Very Early Universe



Sketch courtesy of Kip Thorne

How does LIGO detect spacetime vibrations?

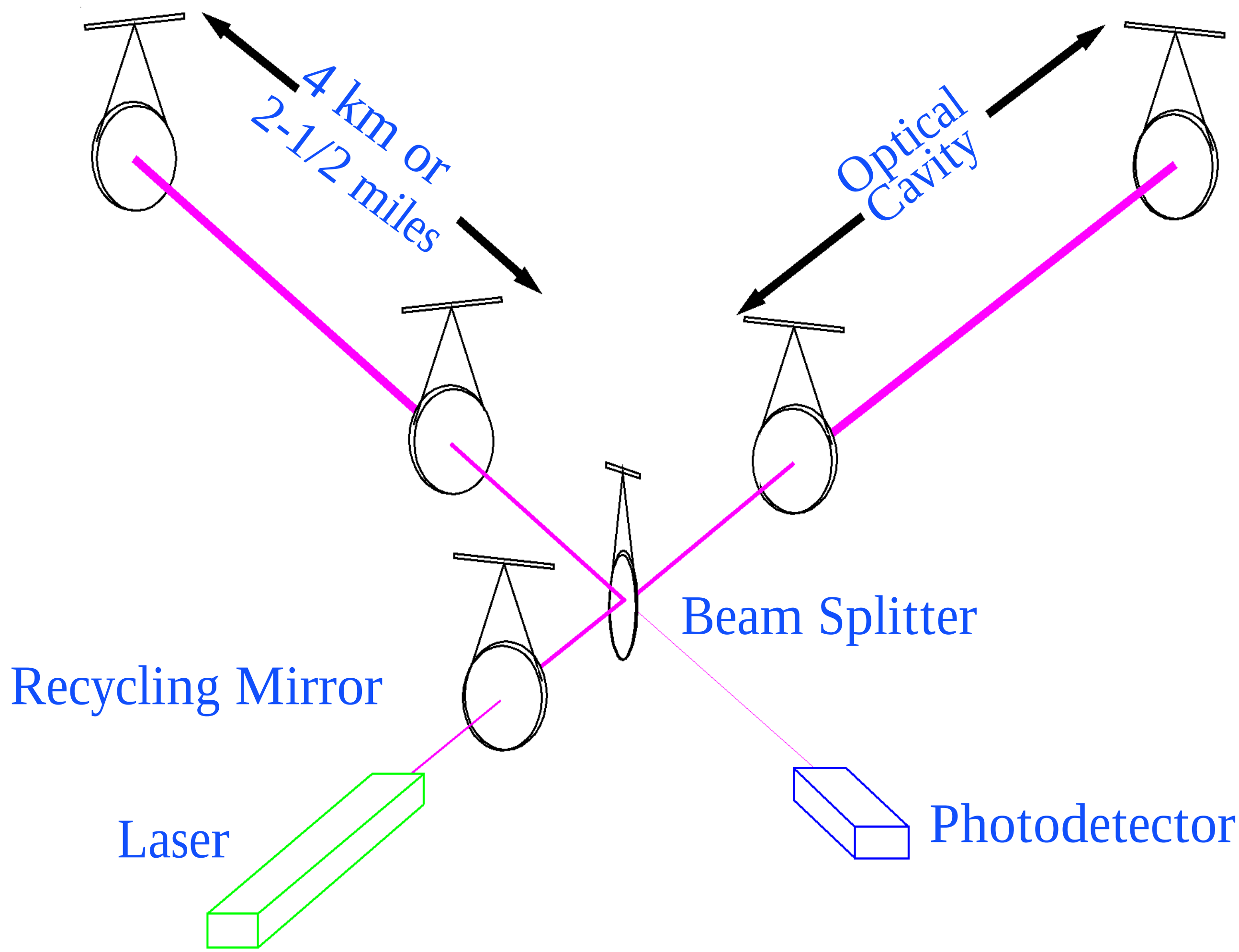
Sketch of a Michelson Interferometer



Some of the Technical Challenges

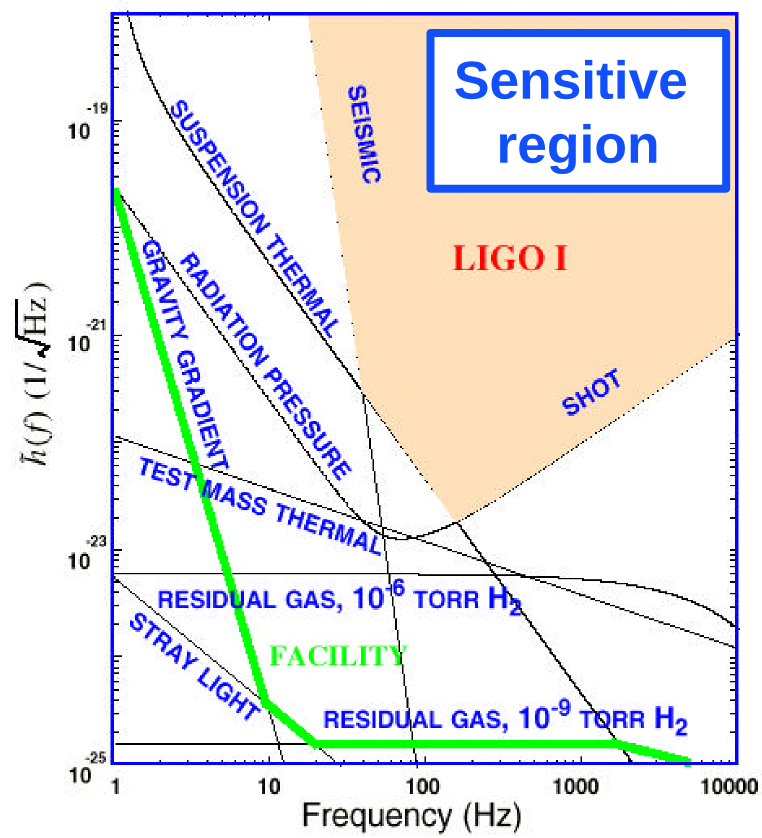
- Typical Strains ~ 10^{-21} at Earth ~ 1 hair's width at 4 light years
- Understand displacement fluctuations of 4-km arms at the millifermi level
- Control arm lengths to 10^{-13} meters, absolute
- Detect optical phase changes of ~ 10^{-10} radians
- Provide clear optical paths within 4-km UHV beam lines

Fabry-Perot-Michelson with Power Recycling



What Limits Sensitivity of Initial LIGO Interferometers?

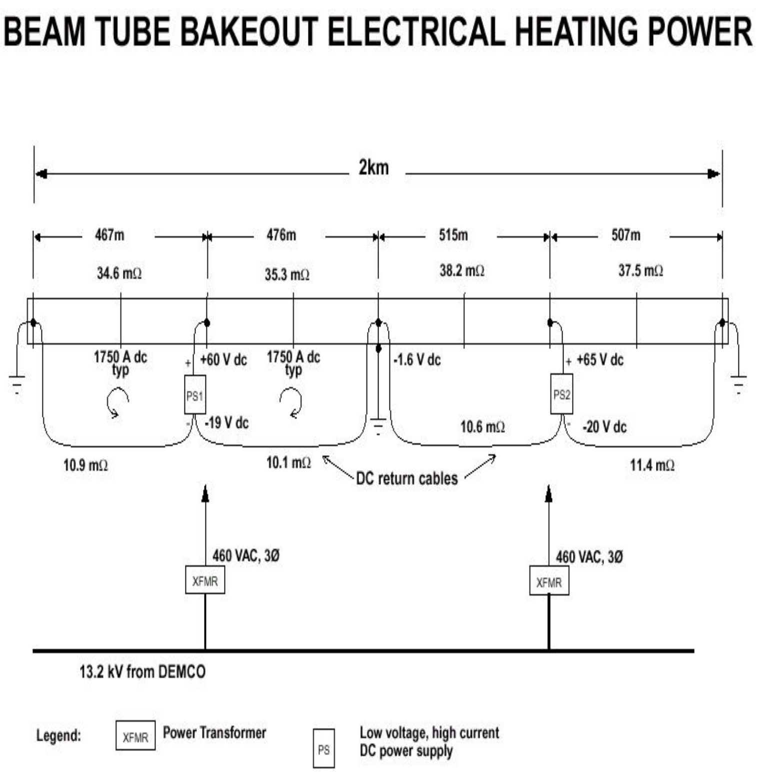
- Seismic noise & vibration limit at lowest frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels

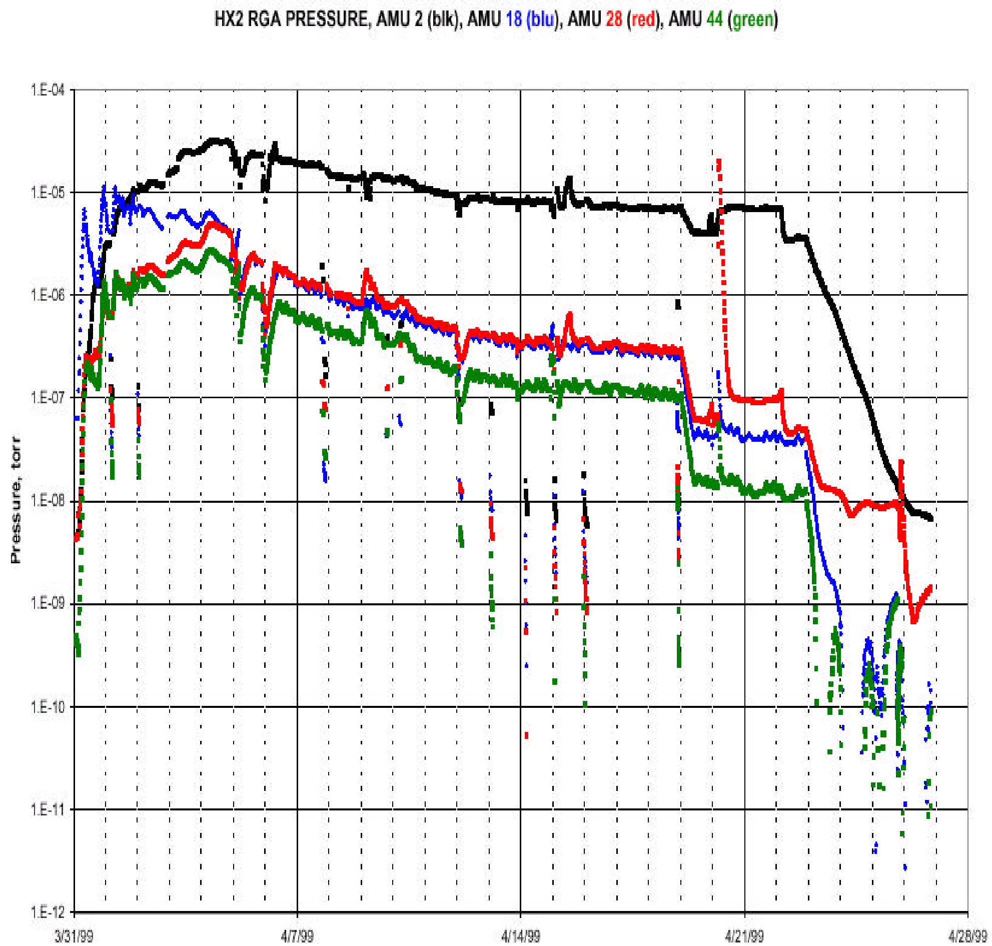


Beam Tube Bakeout Ensured Good Vacuum for Good "Seeing"

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

Beam Tube Bakeout





Beam Tube Bakeout Results

Postbake measurements of module X1 at Hanford

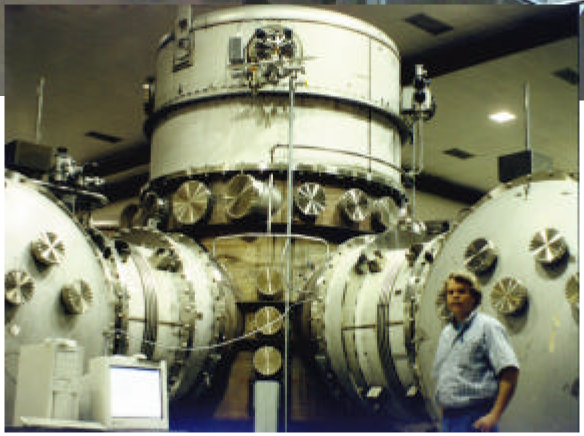
March 11-12, 1999

Table 1: Results from gas model solution of 16.9 hour postbake accumulation ending March 12, 1999 at 10:00AM .

molecule	Outgassing rate @ 10C	pressure@ 10C	outgassing rate @ 23C	pressure@ 23C
	torr liters/sec/cm^2	torr	torr liters/sec/cm^2	torr
H_2	1.6×10^{-14}	1.0×10^{-9}	5.2×10^{-14}	3.4×10^{-9}
CH_4	$< 2 \times 10^{-20}$	$< 3.4 \times 10^{-13}$	$< 8.8 \times 10^{-20}$	$< 1.5 \times 10^{-12}$
H_2O	$< 3 \times 10^{-19}$	$< 5.2 \times 10^{-13}$	$< 1.3 \times 10^{-18}$	$< 2.3 \times 10^{-12}$
N_2	$< 9 \times 10^{-19}$ **	$< 1.5 \times 10^{-13}$		
CO	$< 1.3 \times 10^{-18}$	$< 1.7 \times 10^{-13}$	$< 5.7 \times 10^{-18}$	$< 7 \times 10^{-13}$
O_2	$< 1.2 \times 10^{-20}$	$< 2.3 \times 10^{-14}$		
A	$< 2.5 \times 10^{-20}$	$< 3.6 \times 10^{-14}$		
CO_2	$< 6.5 \times 10^{-20}$	$< 1.2 \times 10^{-13}$	$< 2.9 \times 10^{-19}$	$< 5.2 \times 10^{-13}$

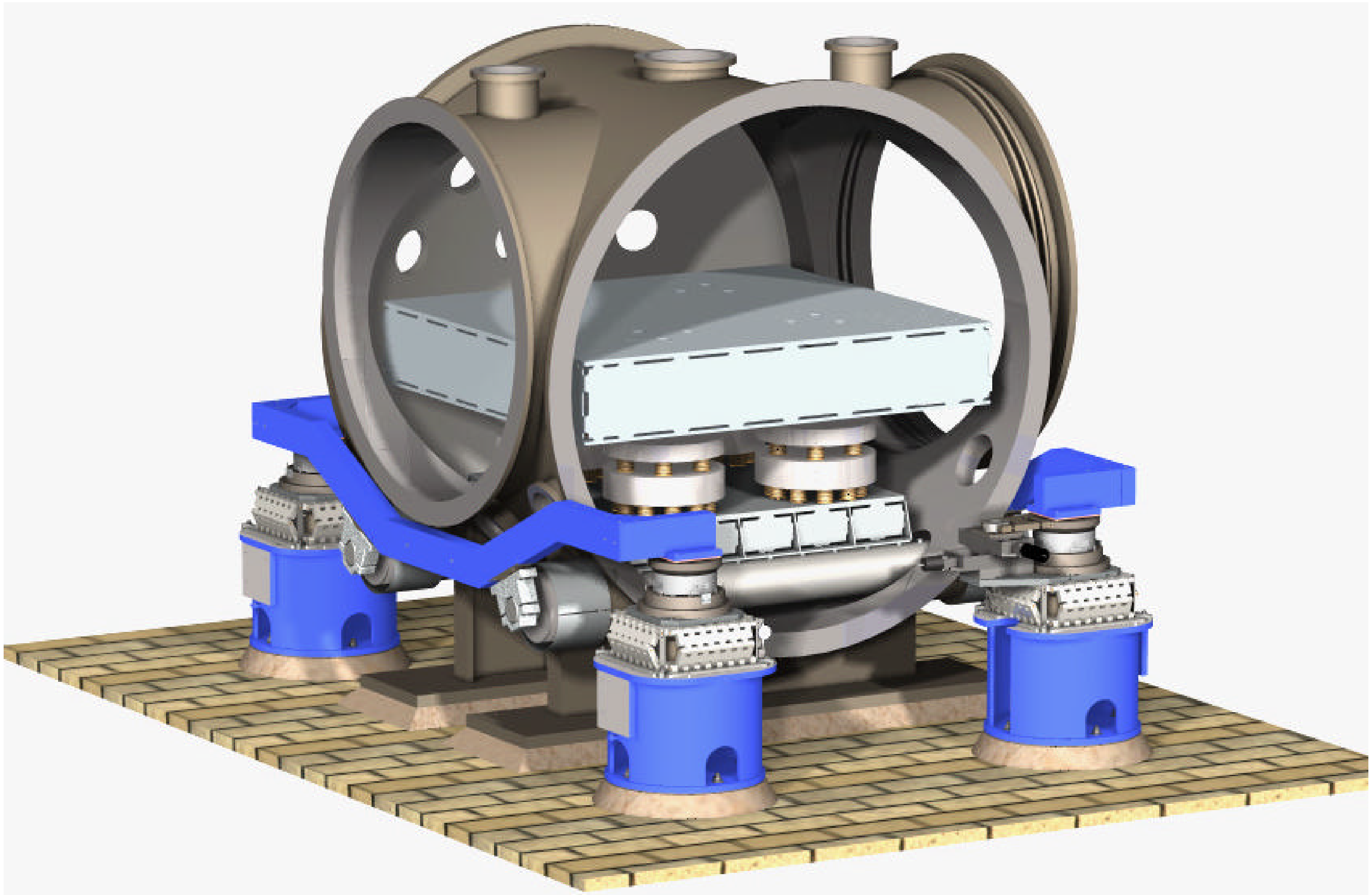
Vacuum Chambers Provide Quiet Homes for Mirrors

View inside Corner Station



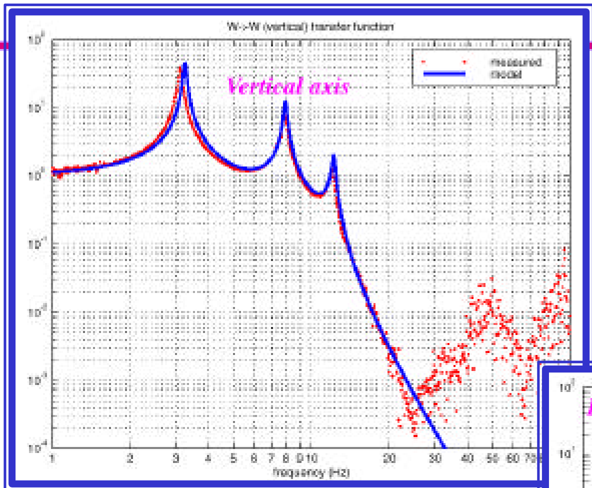
Standing at vertex beam splitter

HAM Chamber Seismic Isolation



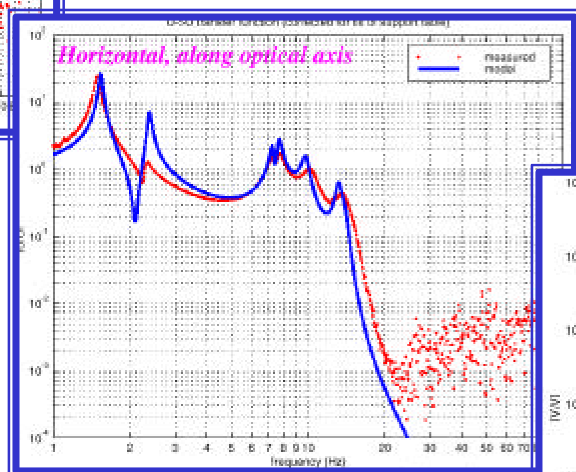
HAM Seismic Isolation Installation

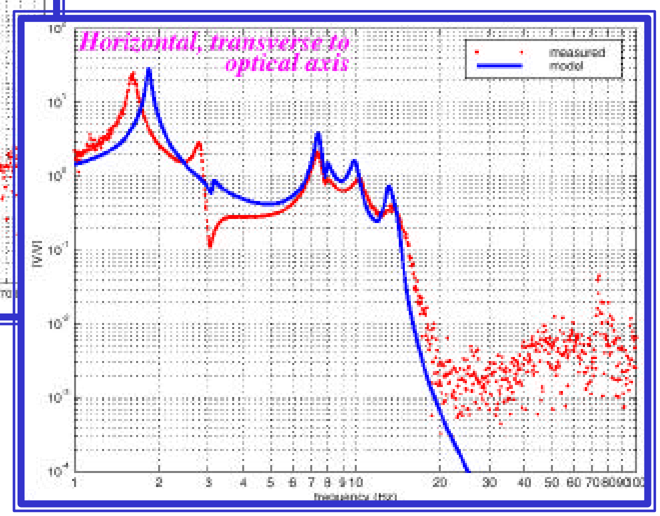
HAM Seismic Isolation Measured in Air at LHO



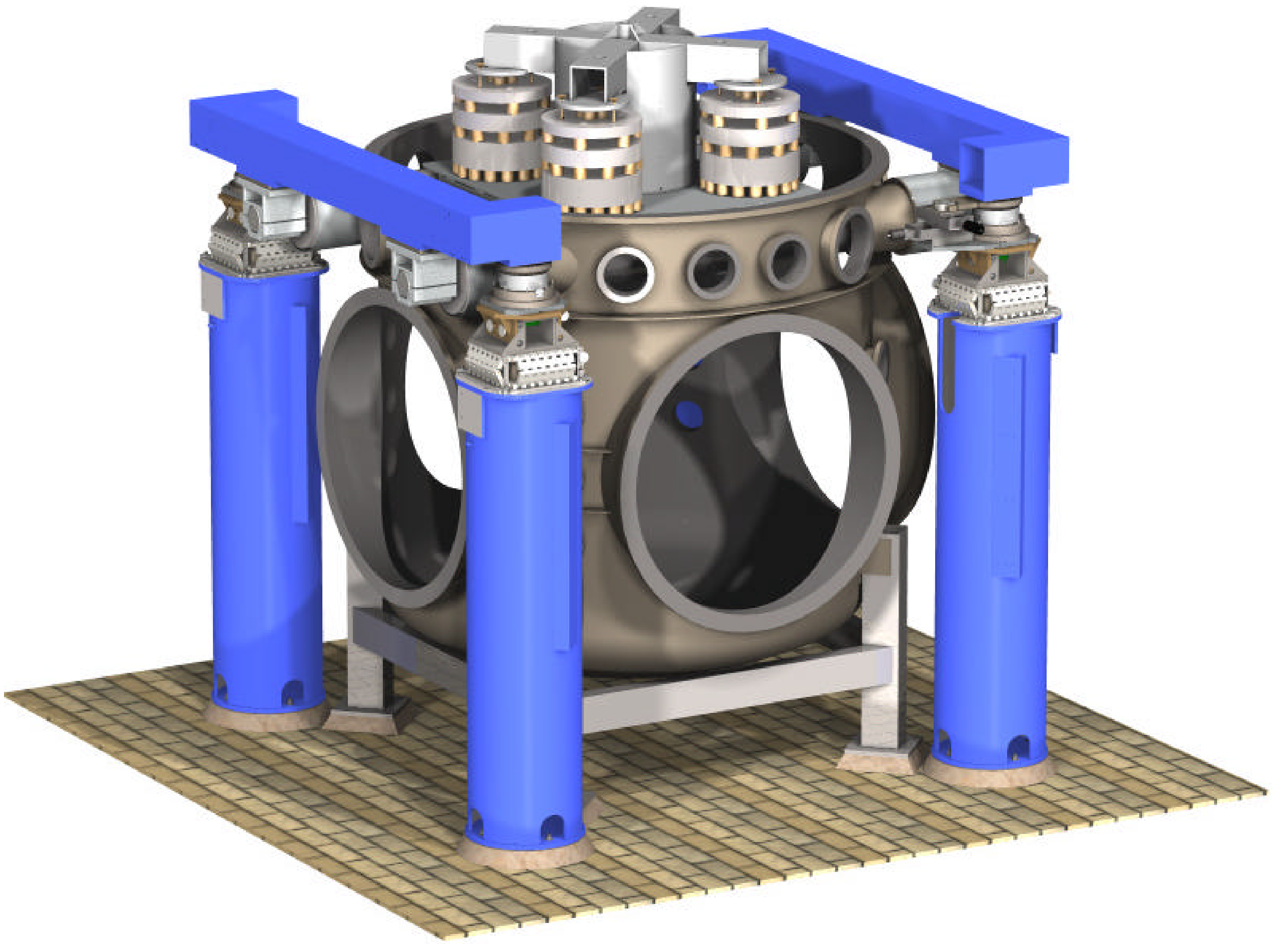
Seismic Design Model

Transfer Function Measurements

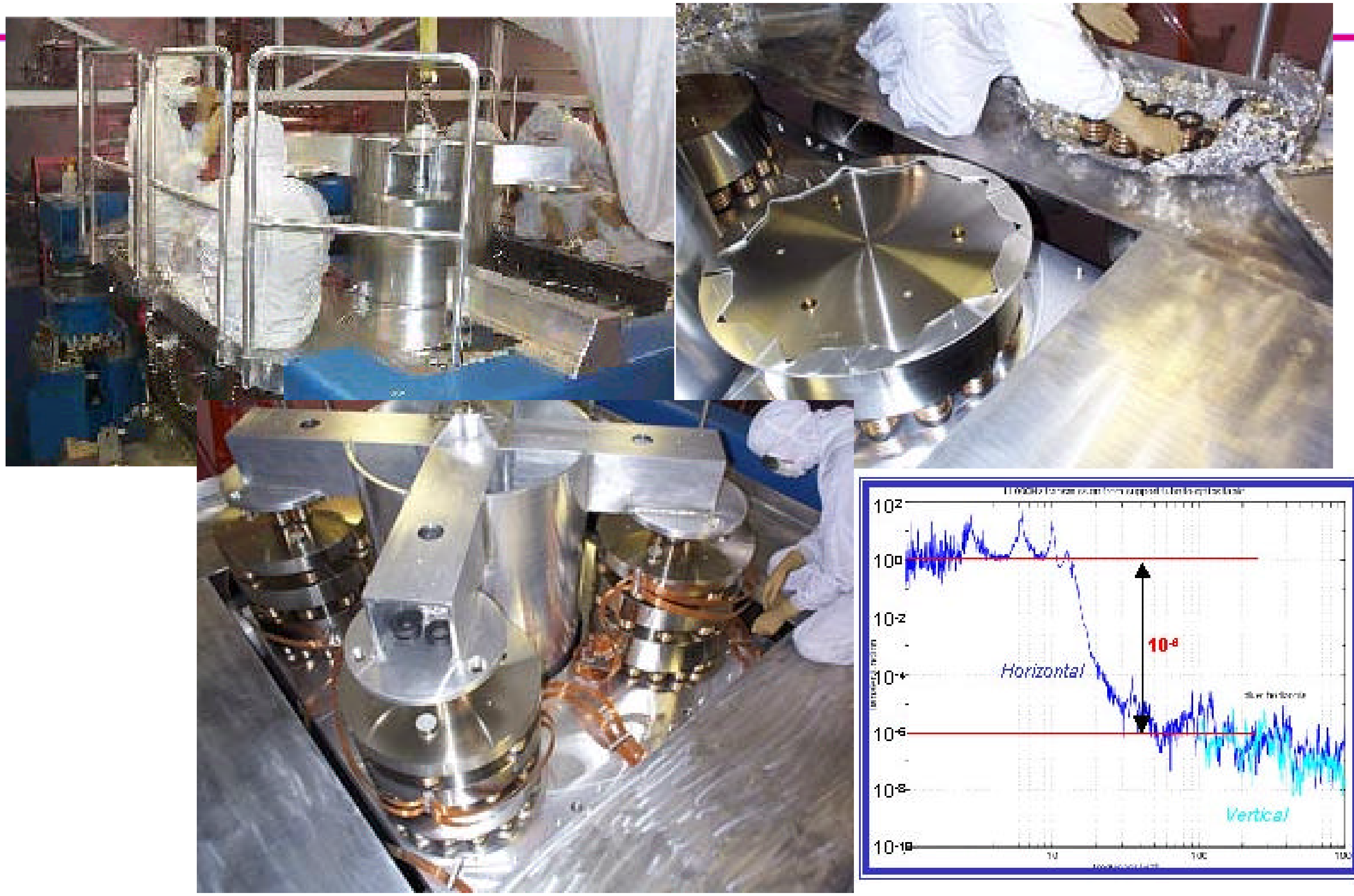




BSC Chamber Seismic Isolation

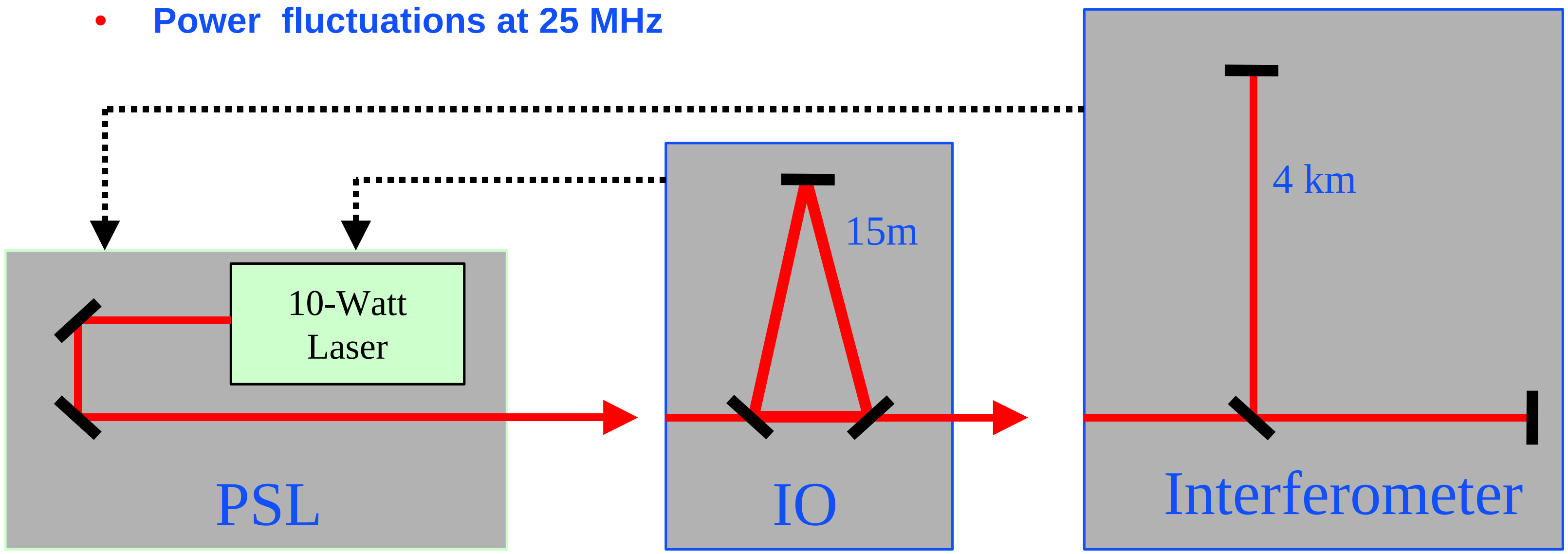


BSC Seismic Isolation Installation

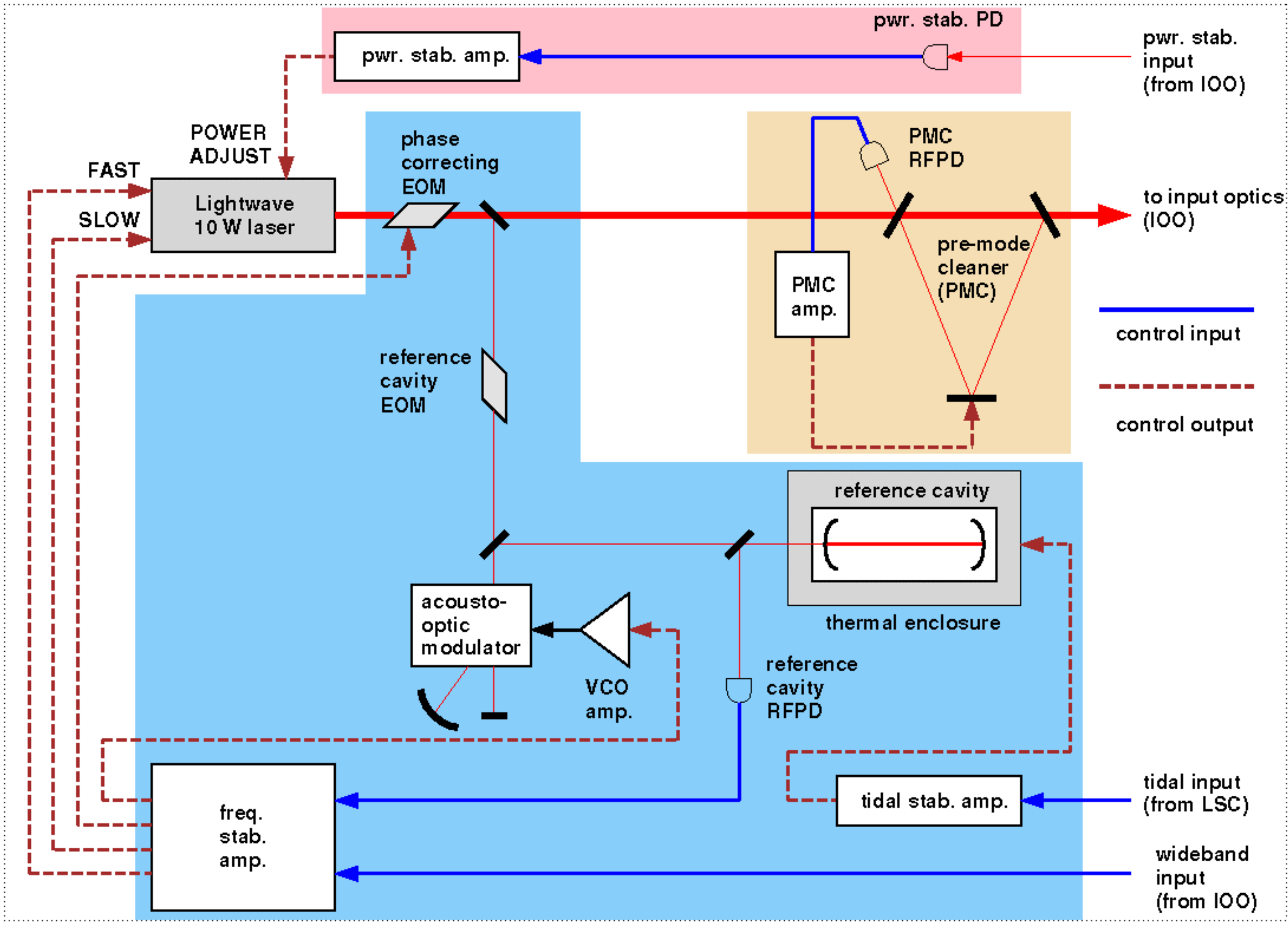


Frequency Stabilization of the Light

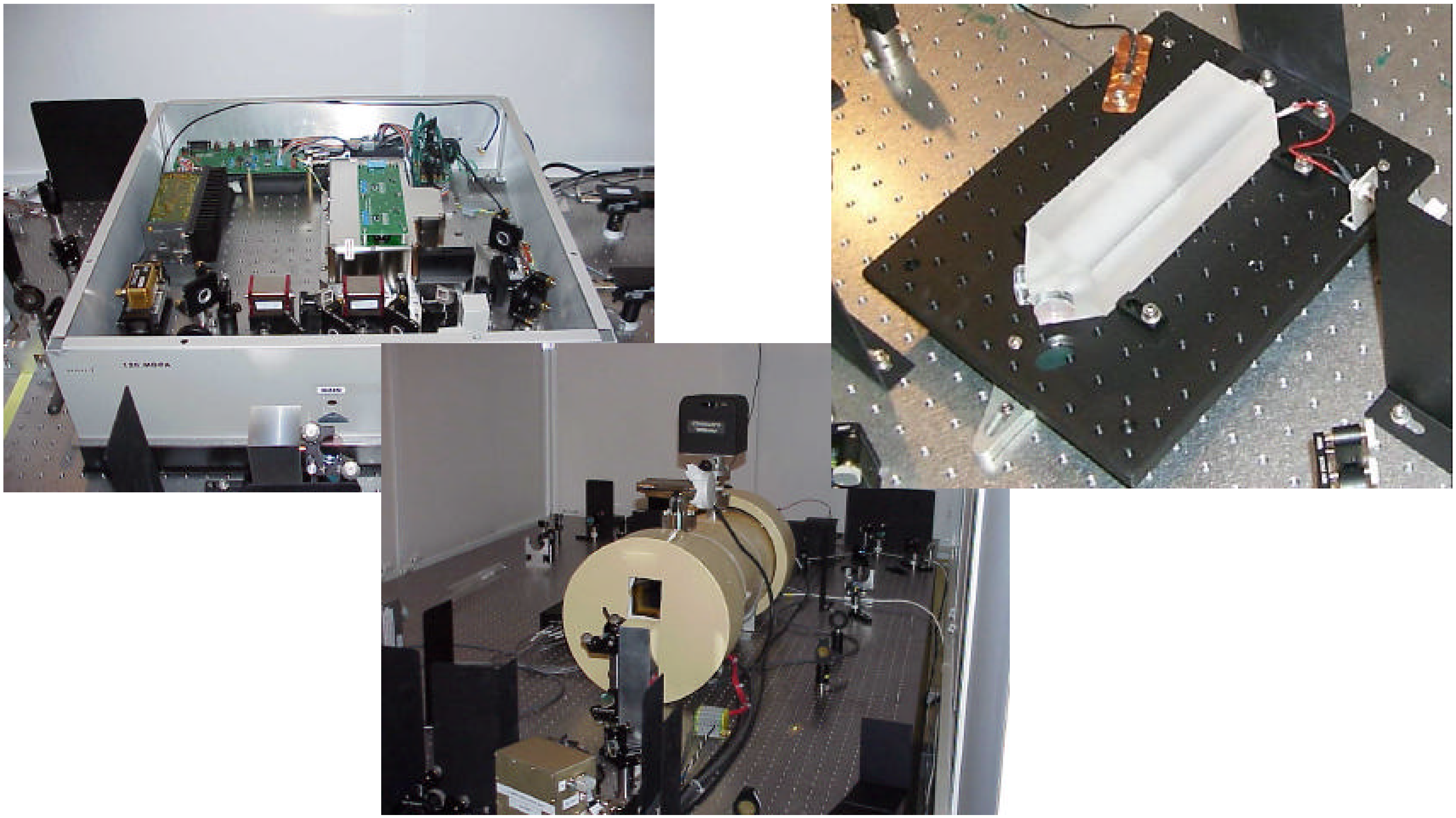
- Pre-stabilized laser delivers light to the long mode cleaner
  - **Frequency fluctuations**
  - **In-band power fluctuations**
  - **Power fluctuations at 25 MHz**
- Actuator inputs provide for further laser stabilization
  - **Wideband**
  - **Tidal**



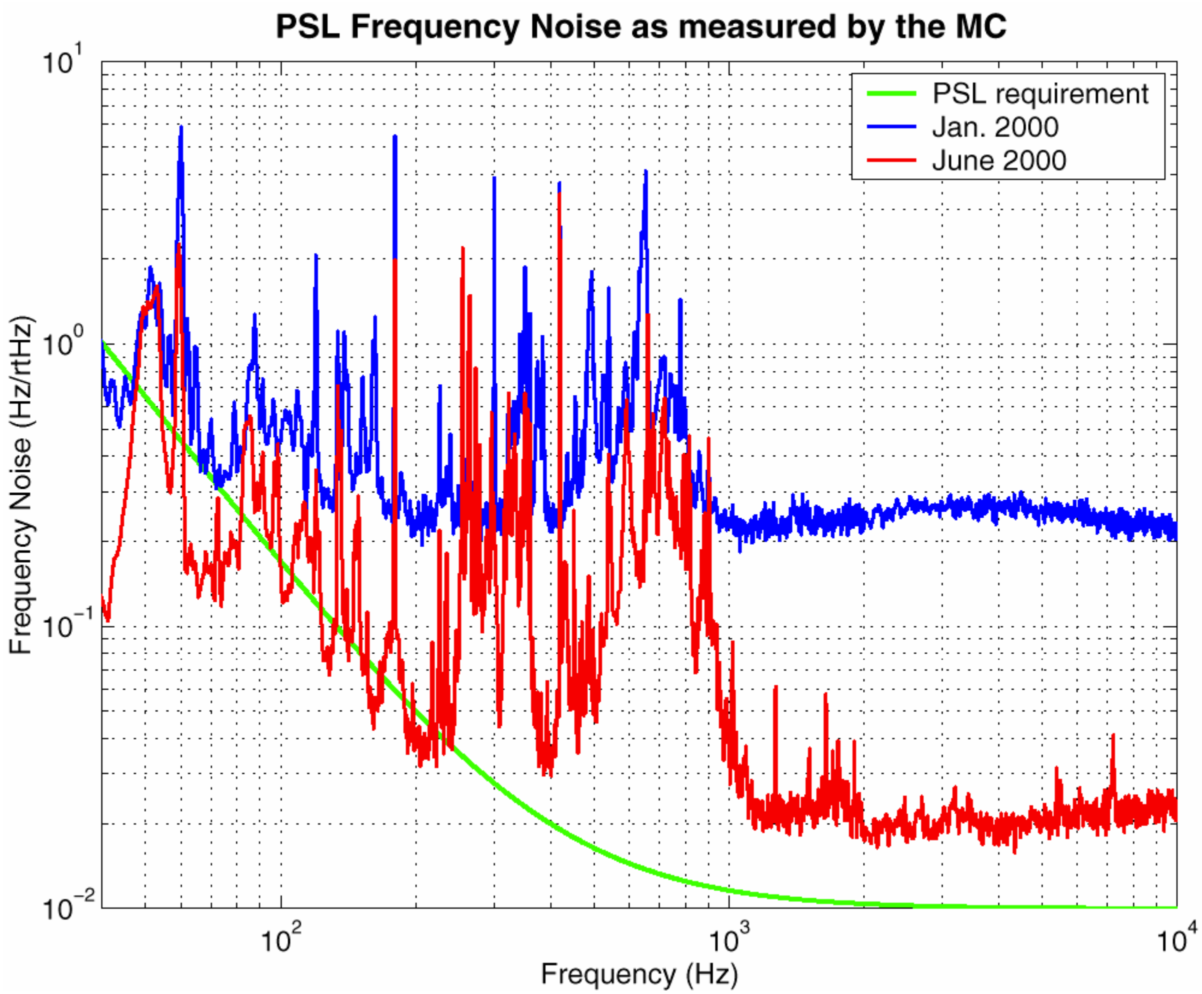
Prestabilized Laser Optical Layout



Washington 2k PSL



Frequency Servo Performance



N. Mavalvala

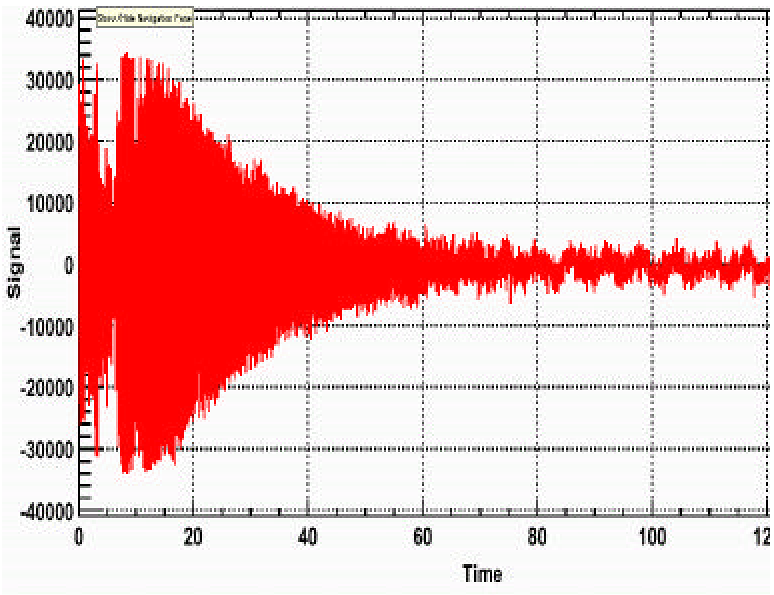
P. Fritschel

Suspended Mirrors

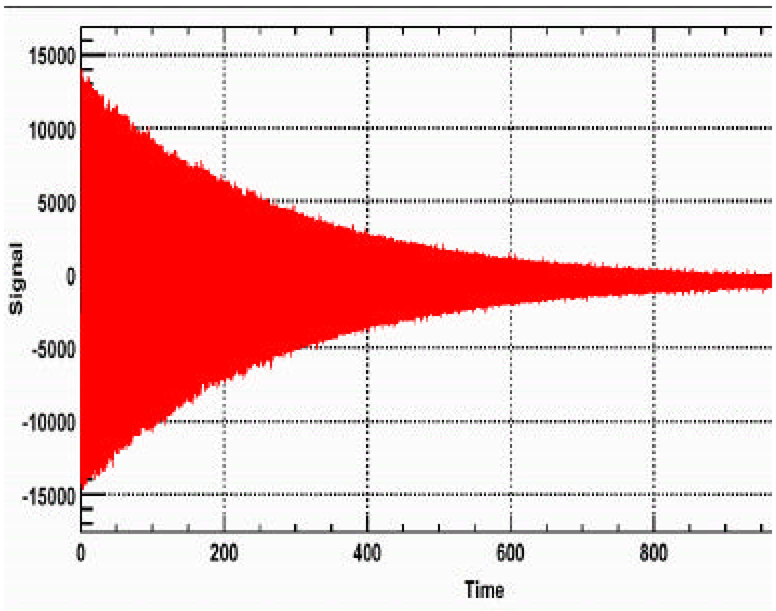
initial alignment

test mass is balanced on $1/100^{th}$ inch diameter wire to $1/100^{th}$ degree of arc

ITMx Internal Mode Ringdowns



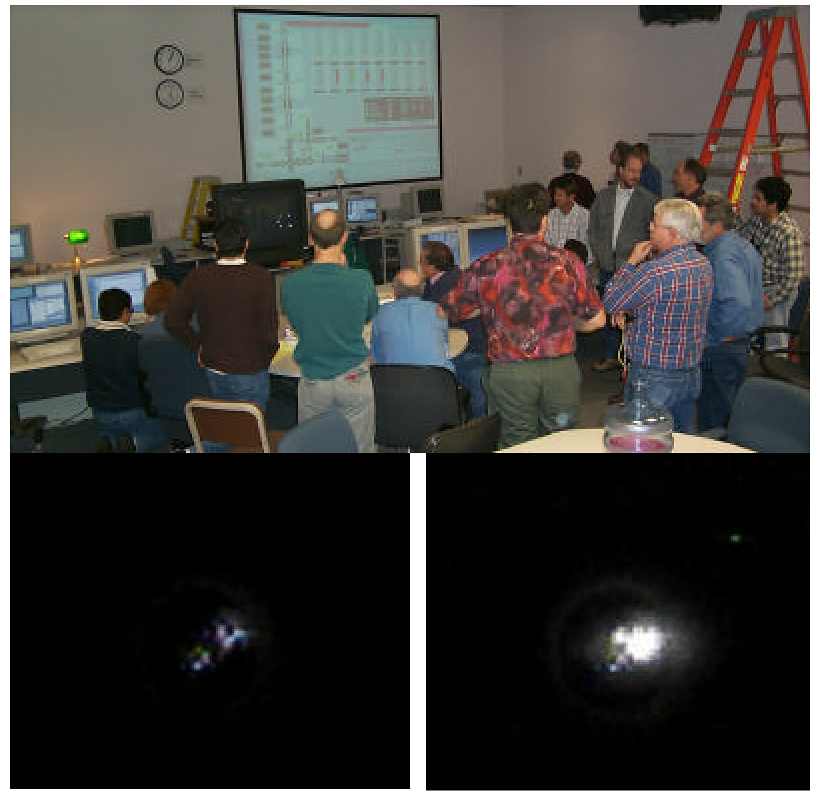
9.675 kHz; Q ~ 6e+5



14.3737 kHz; Q = 1.2e+7

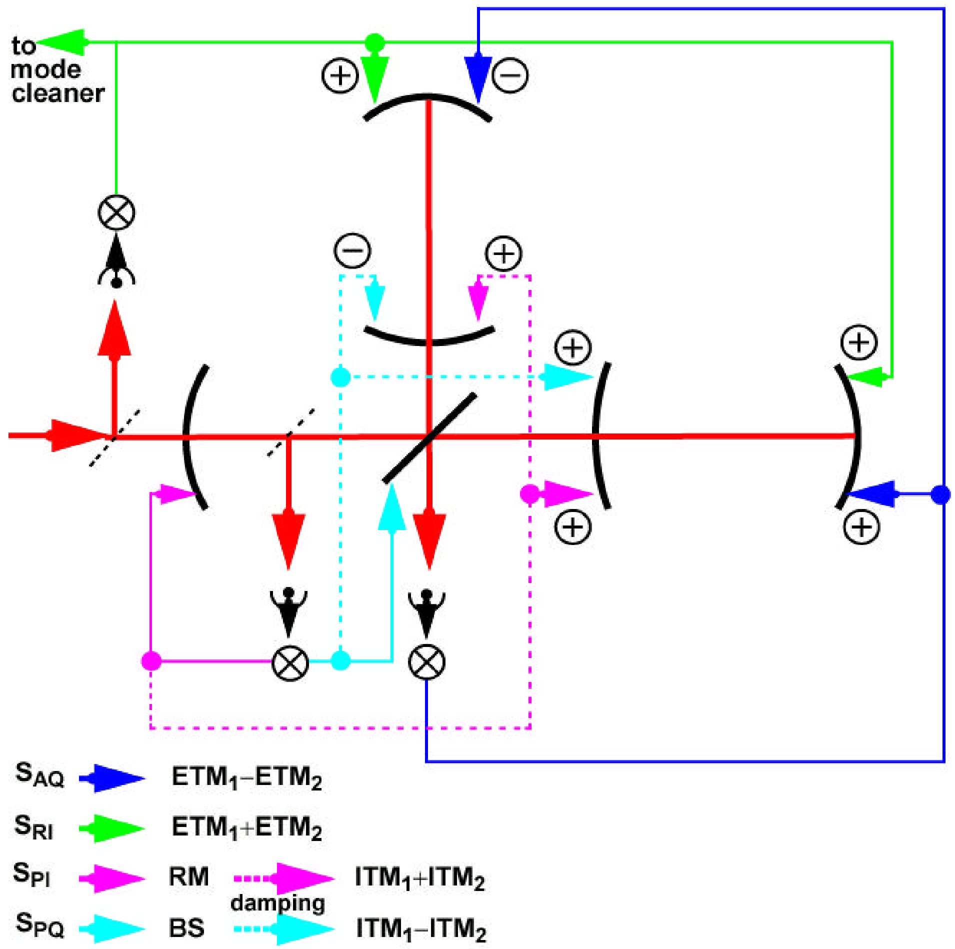
Single-Arm Tests

- Alignment of 2-km arms worked for both arms!
- The beam at 2-km was impressively quiet
- Stable locking was achieved for both arms by feeding back to arms
- Measured optical parameters of cavities
- Characterized suspensions
- Characterized Pre-Stabilized Laser & Input Optics



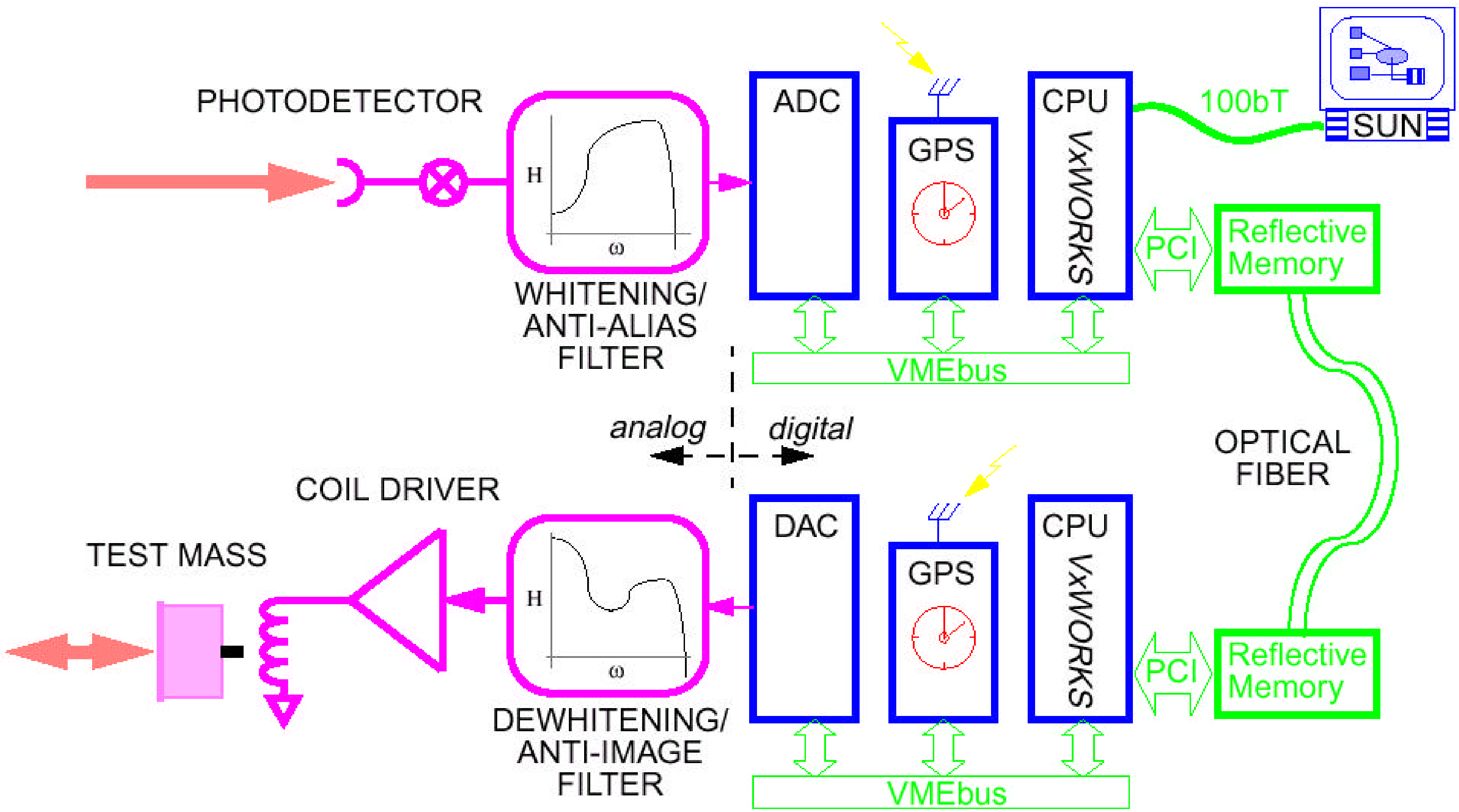
Swinging through 2-km arm fringes

Interferometer Control System

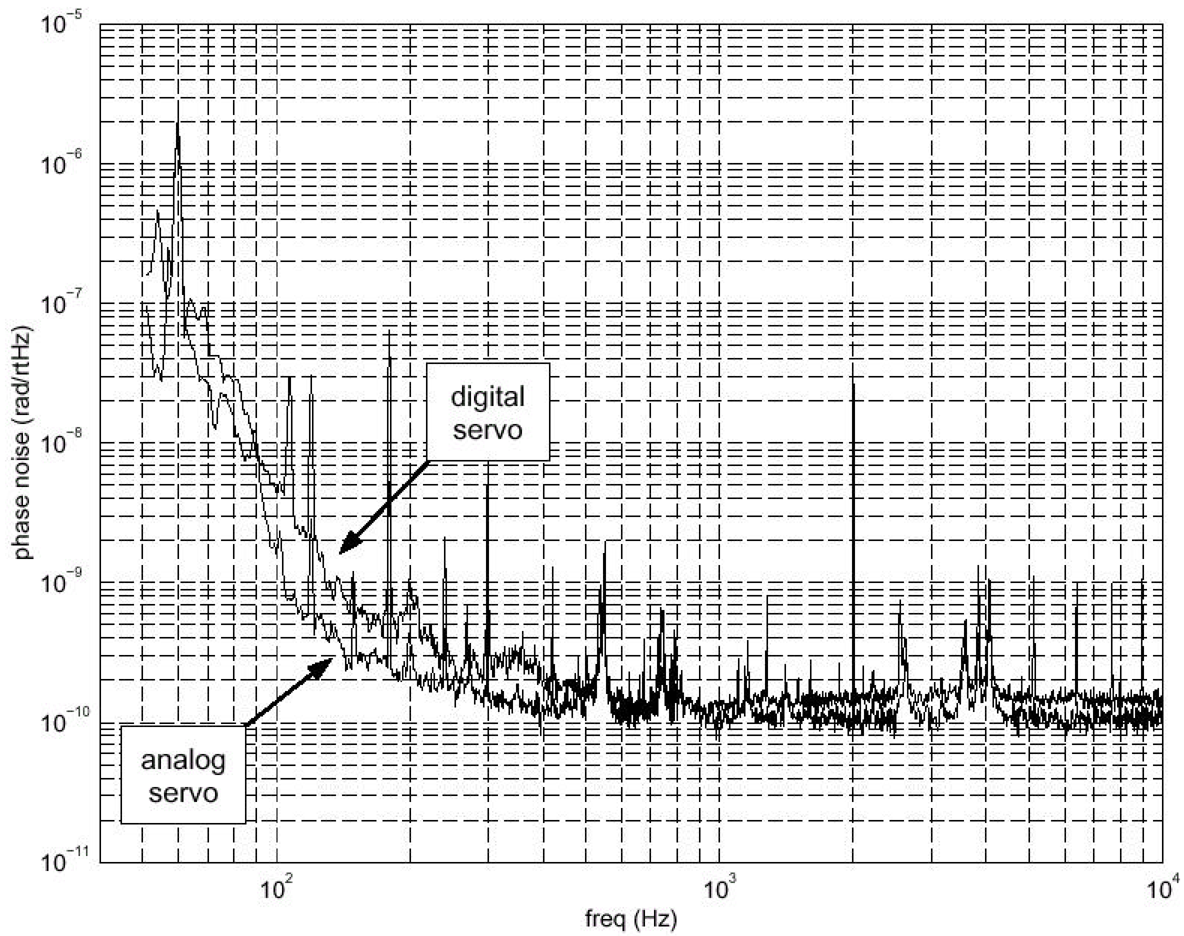


- Multiple Input / Multiple Output
- Three tightly coupled cavities
- Ill-conditioned (off-diagonal) plant matrix
- Highly nonlinear response over most of phase space
- Transition to stable, linear regime takes plant through singularity
- Requires adaptive control system that evaluates plant evolution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

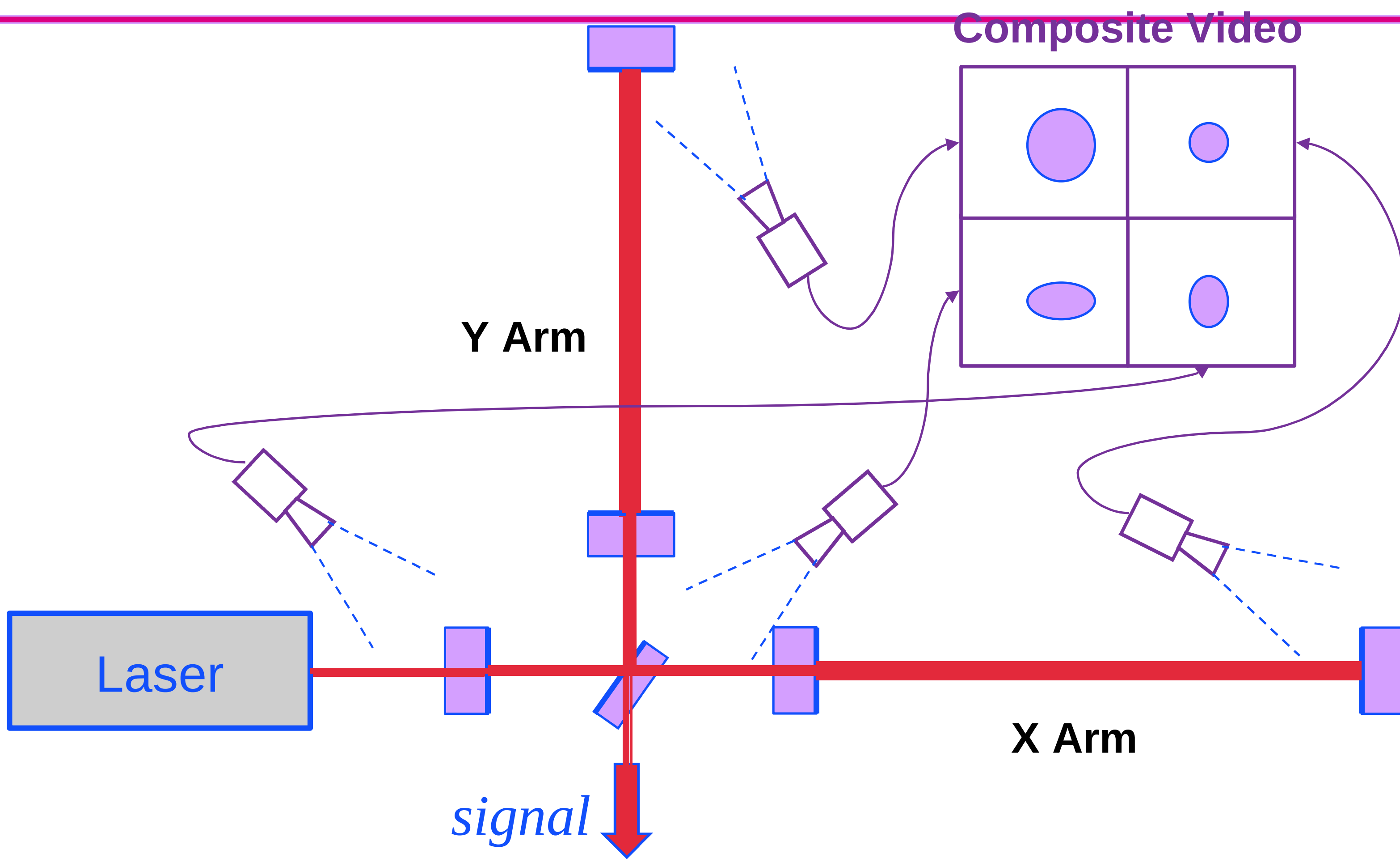
Digital Interferometer Sensing & Control System



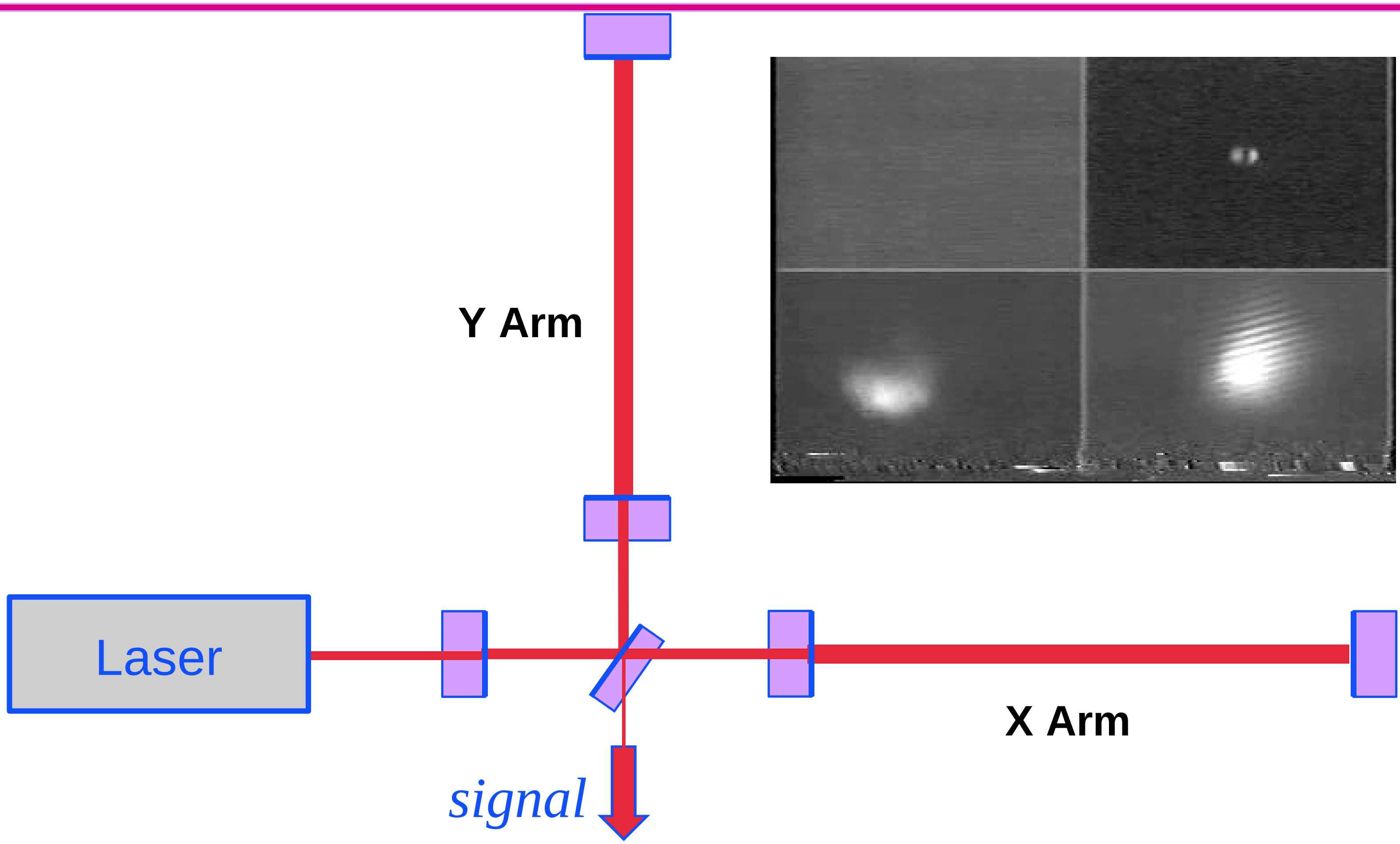
Digital Phase Control Test on Phase Noise Interferometer



Steps to Locking an Interferometer



Watching the Interferometer Lock



Why is Locking Difficult?

One meter, about 40 inches

÷10,000 — *Earthtides, about 100 microns*

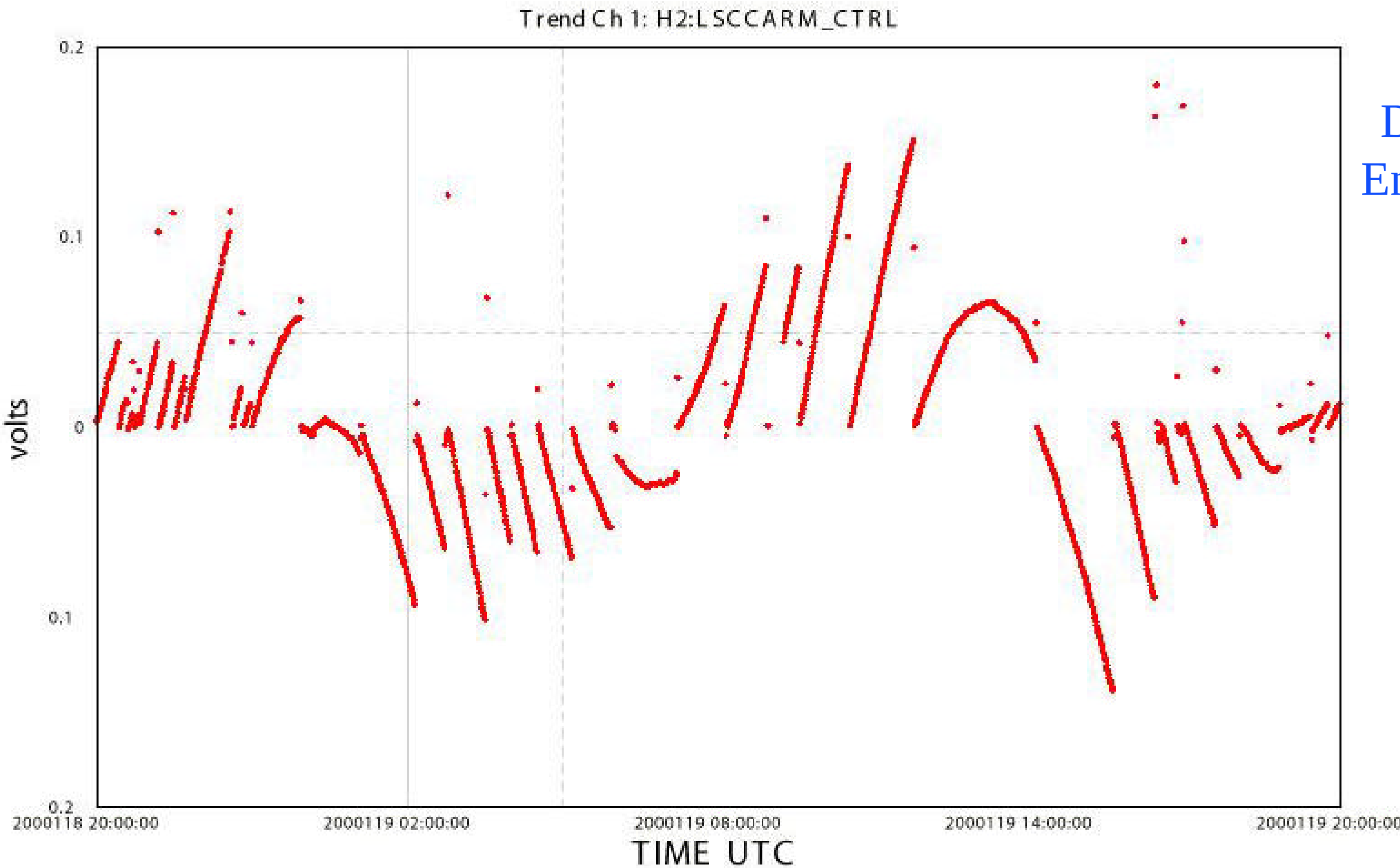
÷100 — *Microseismic motion, about 1 micron*

÷10,000 — *Precision required to lock, about 10^{-10} meter*

÷100,000 — *Nuclear diameter, 10^{-15} meter*

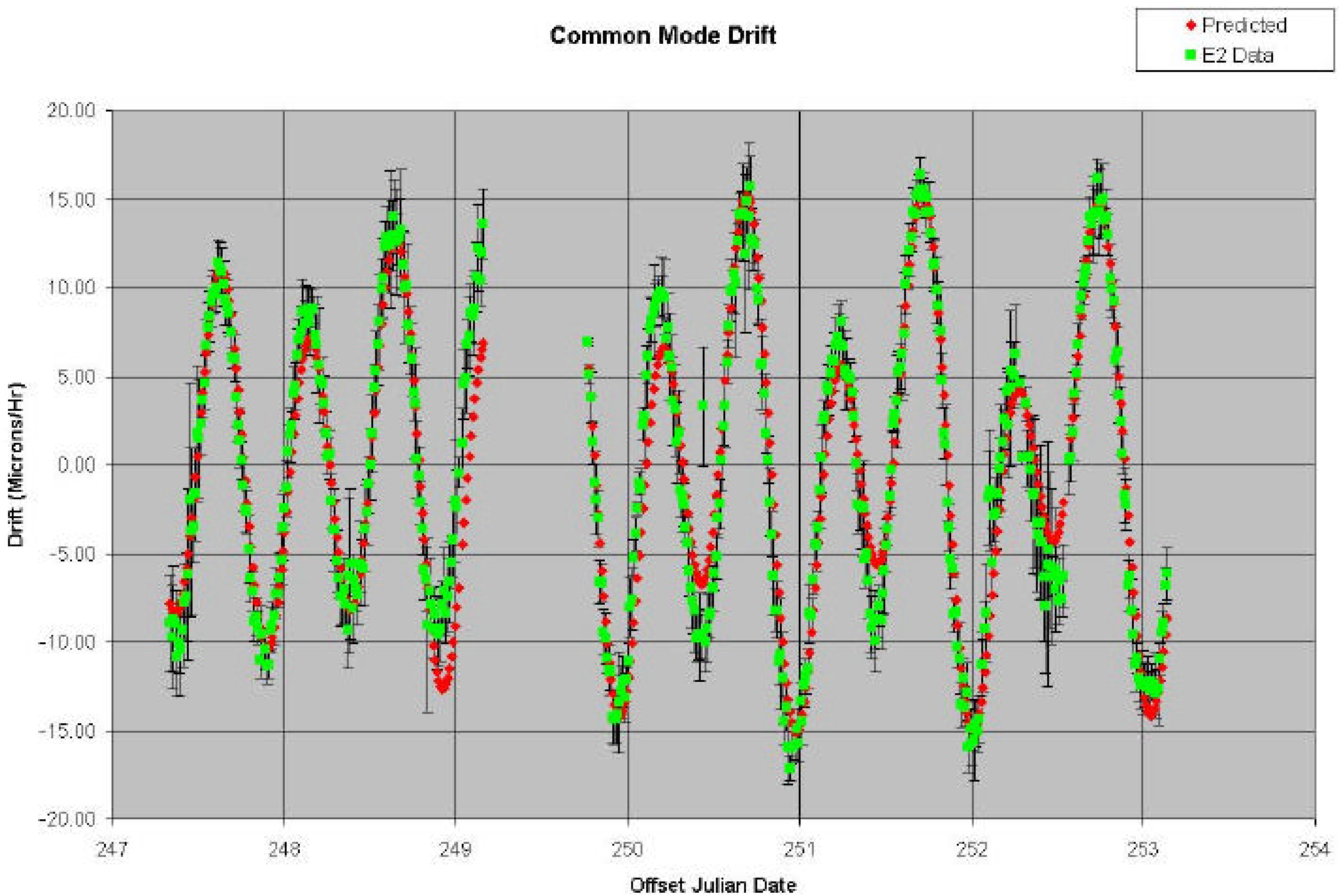
÷1,000 — *LIGO sensitivity, 10^{-18} meter*

Earth Tide is Largest Source of Interferometer Drift

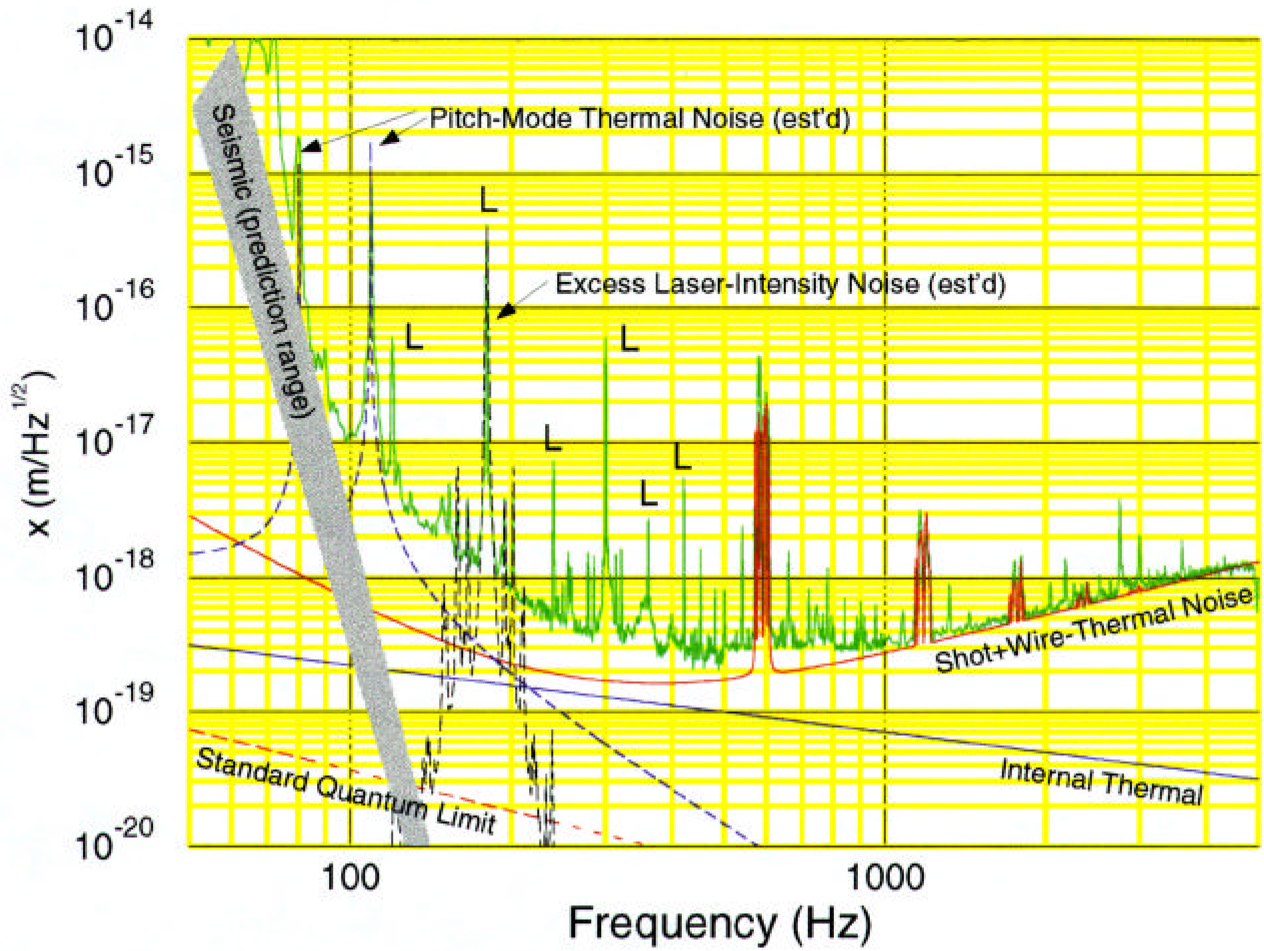


Data from Engineering Run E3

Earth Tides: Freshman Physics to the Rescue



Commissioning of Full Interferometer Underway



For Example:
Noise-Equivalent Displacement of 40-meter Interferometer (ca1994)

When Will It Work?
Status of LIGO in Spring 2001

- Initial detectors are being commissioned, with first Science Runs commencing in 2002.
- Advanced detector R&D underway, planning for upgrade near end of 2006
  - Active seismic isolation systems
  - Single-crystal sapphire mirrors
  - 1 megawatt of laser power circulating in arms
  - Tunable frequency response at the quantum limit
- Quantum Non Demolition / Cryogenic detectors in future?
- Laser Interferometer Space Antenna (LISA) in planning and design stage (2015 launch?)

LIGO, Built to Last