LIGO: The Portal to Spacetime

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LIGO Mission: To sense the distortions of spacetime, known as gravitational waves, created by cosmic cataclysms and to exploit this new sense for astrophysical studies

In other words: If the last 400 years of astronomy were about "seeing" a silent movie of the universe, then LIGO hopes to deliver the "sound track" using observatories that function like large terrestrial microphones.

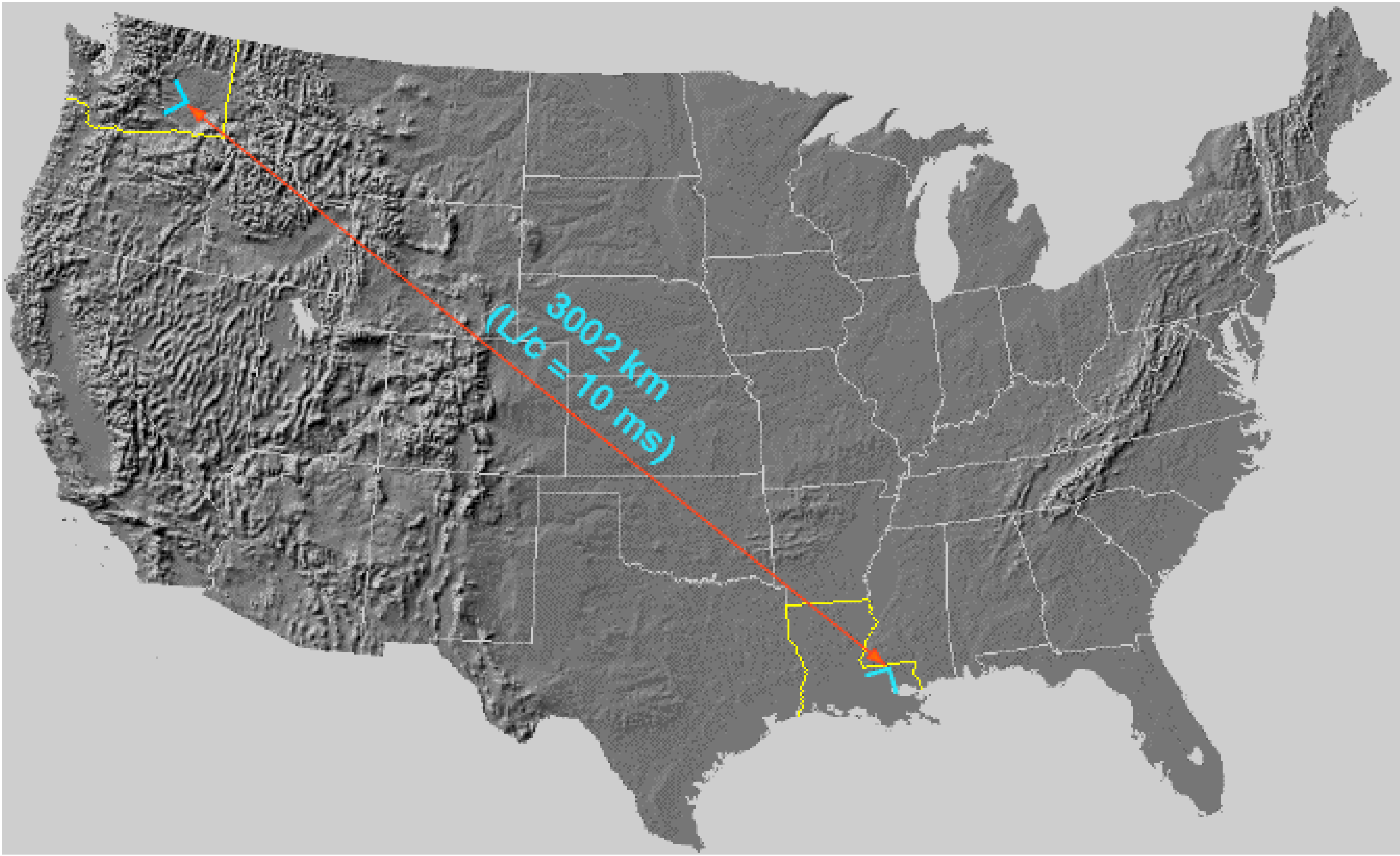
The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

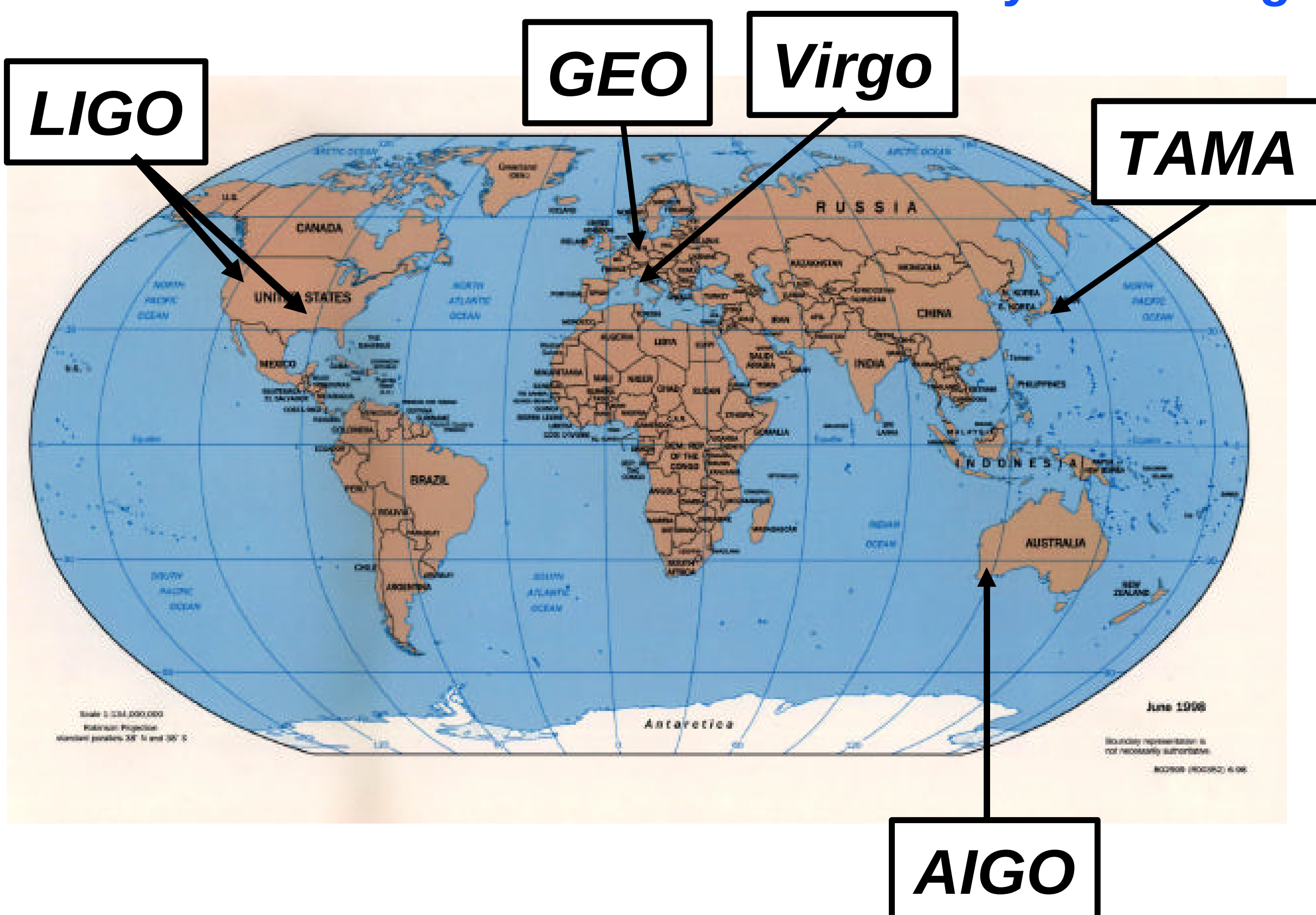
Brought to you by the National Science Foundation; operated by Caltech and MIT; the research focus for about 350 LIGO Science Collaboration members worldwide.

LIGO Observatories



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 early universe like?
- 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!

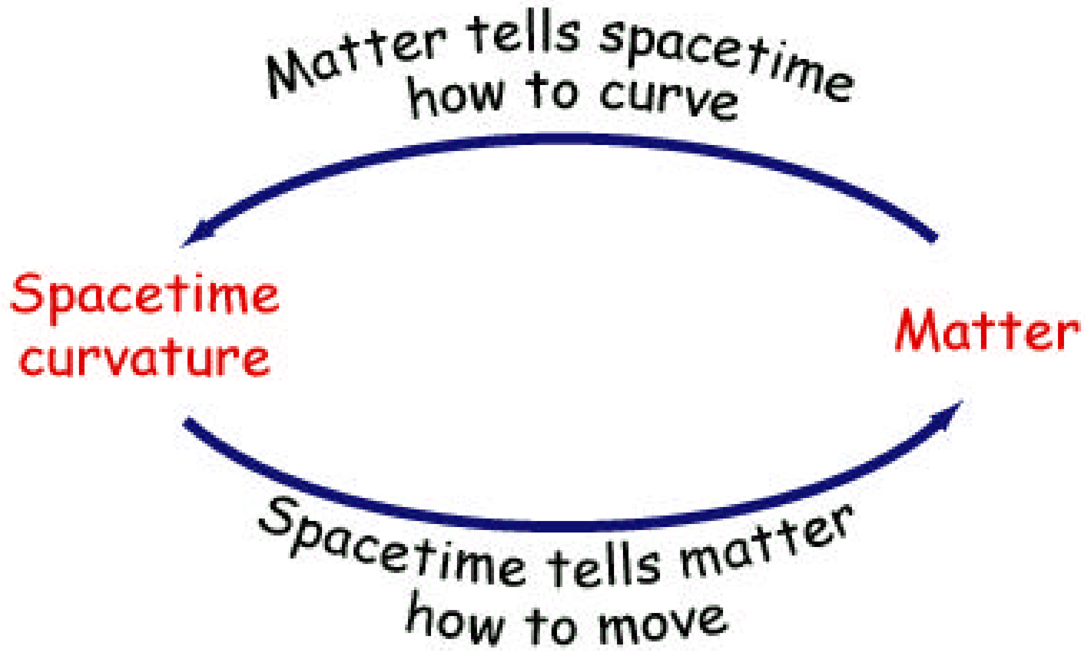
How Can We Listen to the "Sounds" of Space?

- A breakthrough in 20th century science was realizing that space and time are not just abstract concepts
- In 19th century, space devoid of matter was the "vacuum"; viewed as nothingness
- In 20th century, space devoid of matter was found to exhibit physical properties
  - » Quantum electrodynamics – space can be polarized like a dielectric
  - » General relativity – space can be deformed like the surface of a drum
- General relativity allows waves of rippling space that can substitute for sound if we know how to listen!

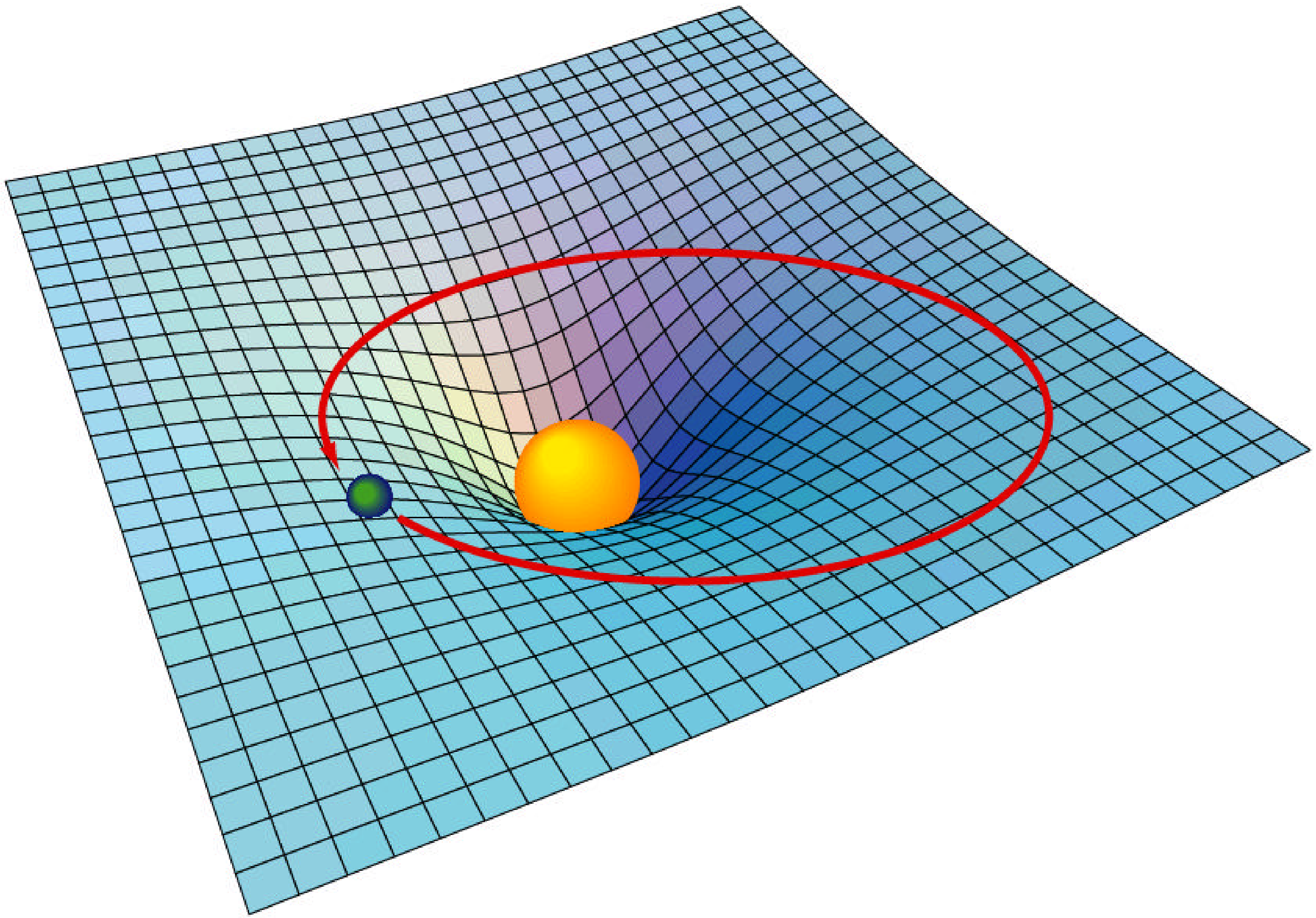
A Short Course in General Relativity

- Galileo and Newton discovered gravity was strikingly different from other known forces because all objects fall along the same paths under gravity
- Contrast that with Electricity or Magnetism, which have dramatically different effects on materials
- Einstein solved the puzzle: gravity is not a force, but a property of space & time
- Objects follow the shortest path through a warped spacetime; $\longrightarrow$ path is the same for all objects
- Concentrations of mass or energy distort (warp) spacetime $\longrightarrow$ origin of gravity

John Wheeler's Summary of General Relativity Theory

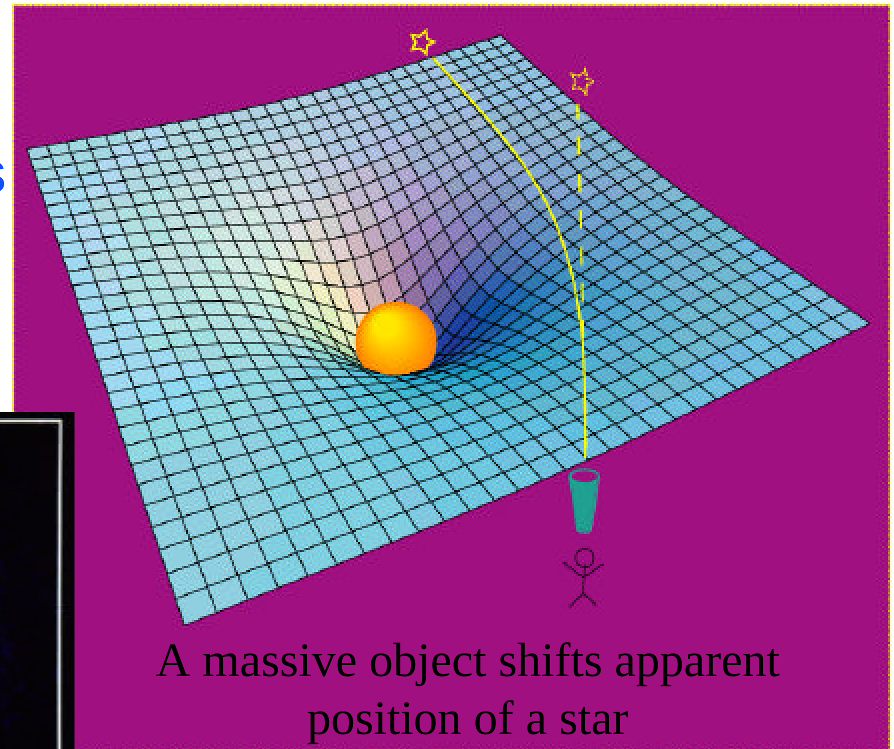


General Relativity: A Picture Worth a Thousand Words



The New Wrinkle on Equivalence

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



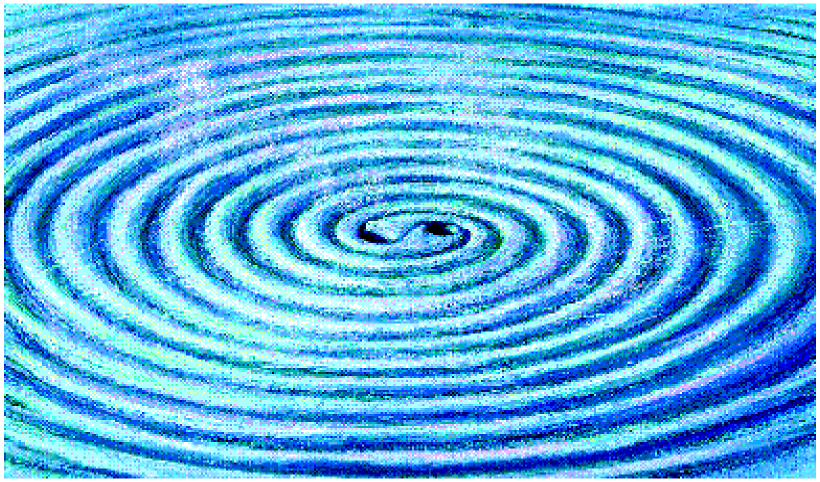
Einstein Cross

Photo credit: NASA and ESA

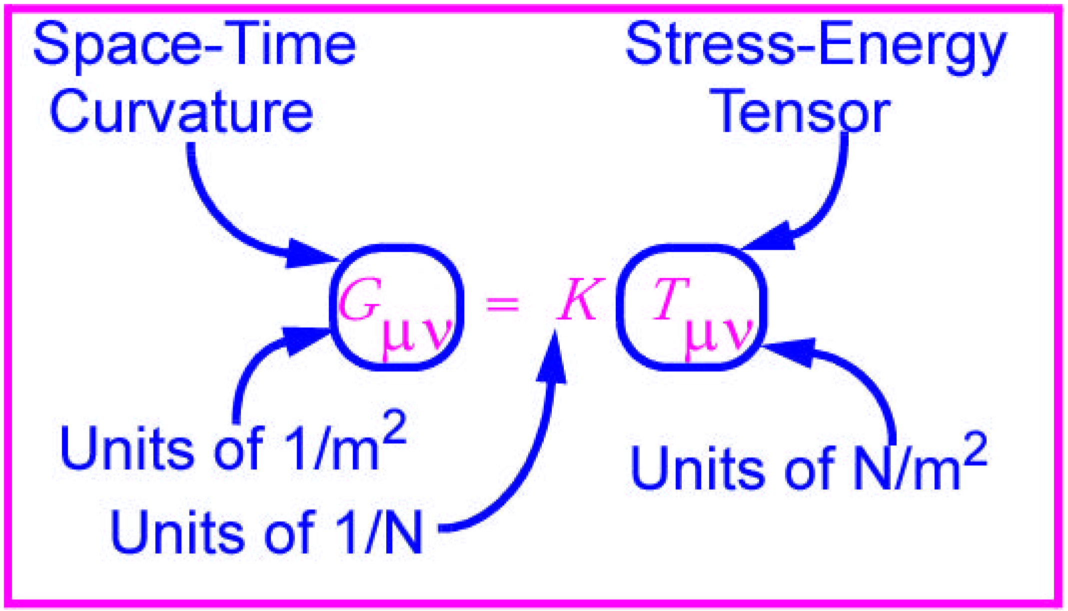
Gravitational Waves

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:



Spacetime is Stiff!



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

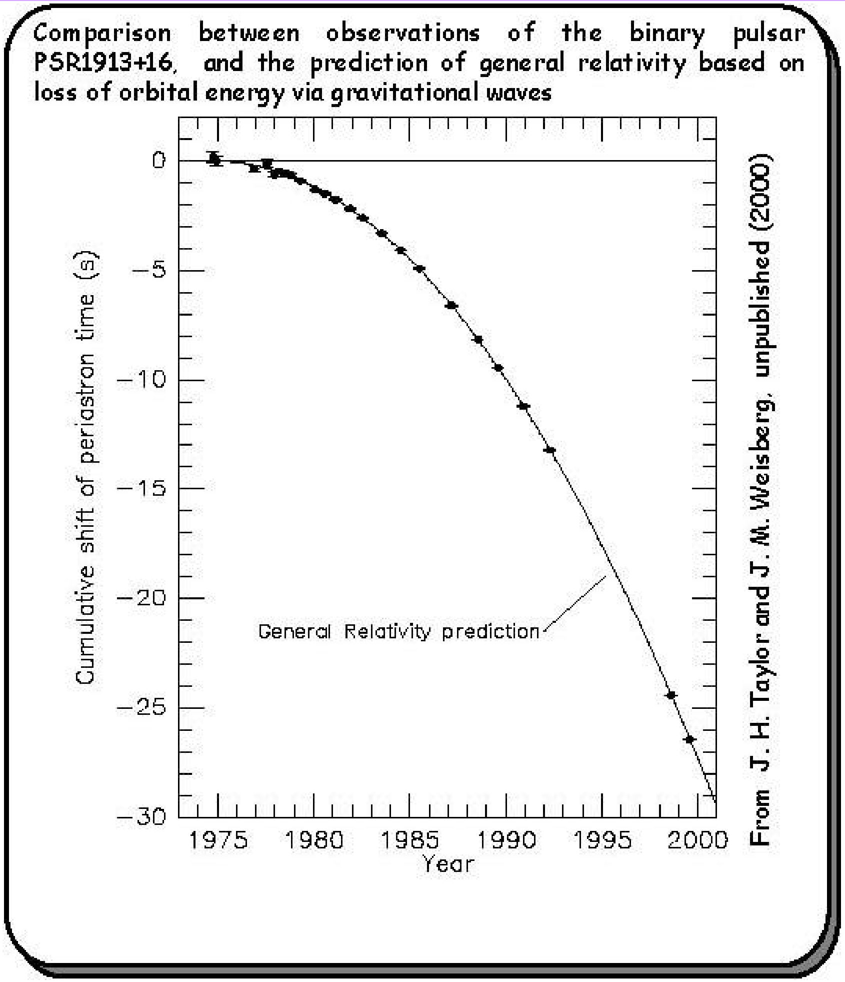
=> Wave can carry huge energy with miniscule amplitude!

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

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.

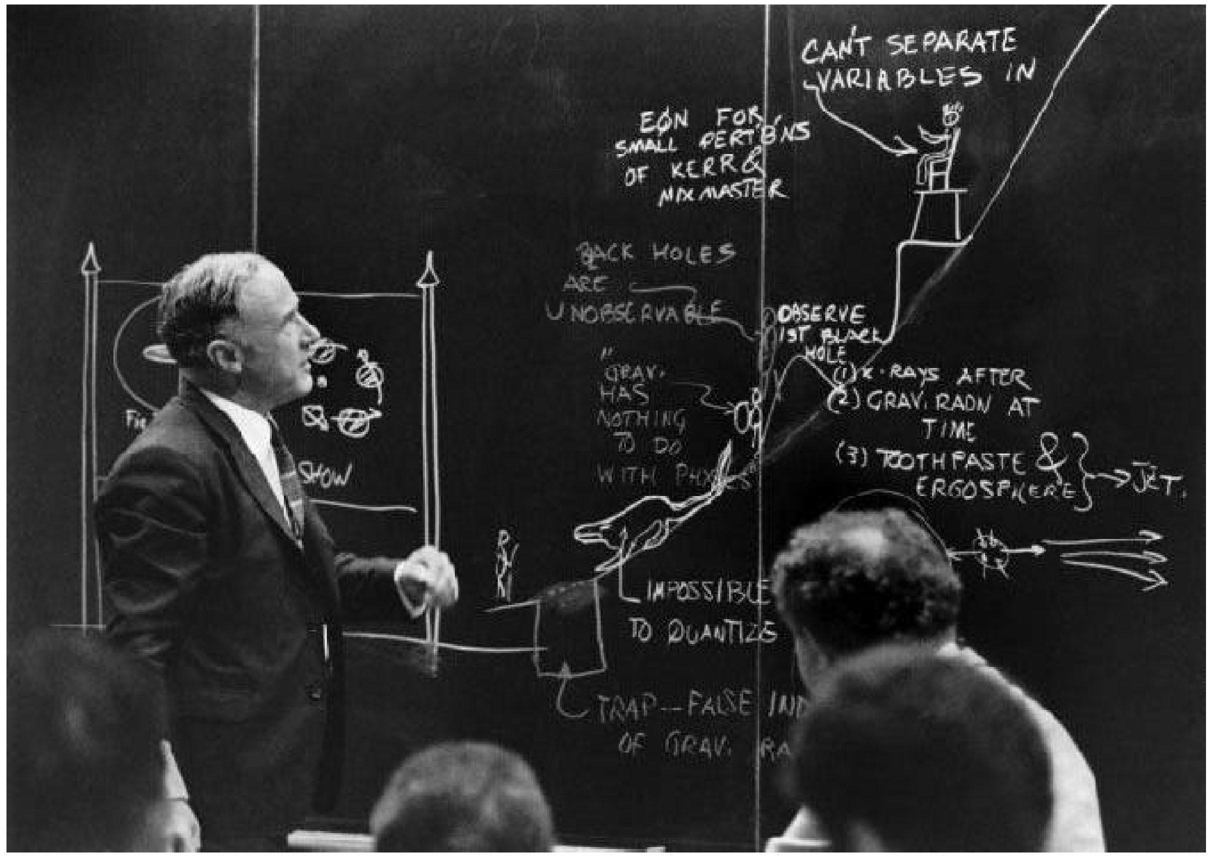


What Phenomena Do We Expect to Study With LIGO?

Gravitational Collapse and Its Outcomes Present Opportunities

f_{GW} > few Hz accessible from earth

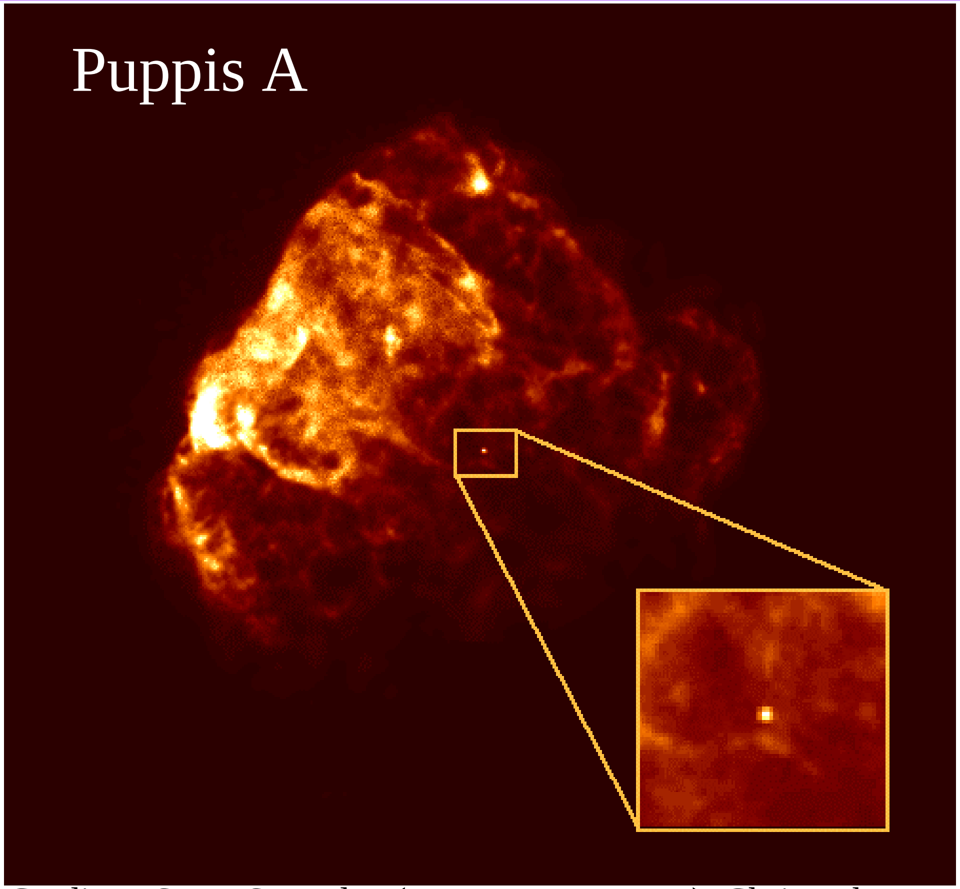
f_{GW} < several kHz interesting for compact objects



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

Do Supernovae Produce Gravitational Waves?

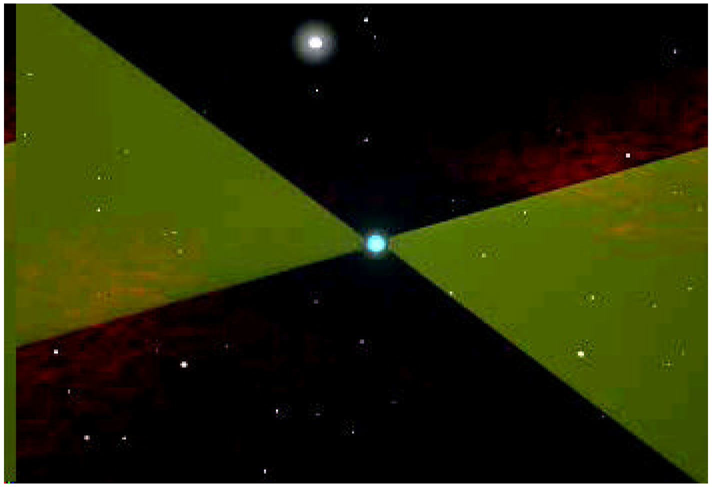
- Not much if stellar core collapses symmetrically (like spiraling football)
- Strong waves if end-over-end rotation in collapse
- Increasing evidence for non-symmetry from speeding neutron stars
- Gravitational wave amplitudes uncertain by factors of 1,000's



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

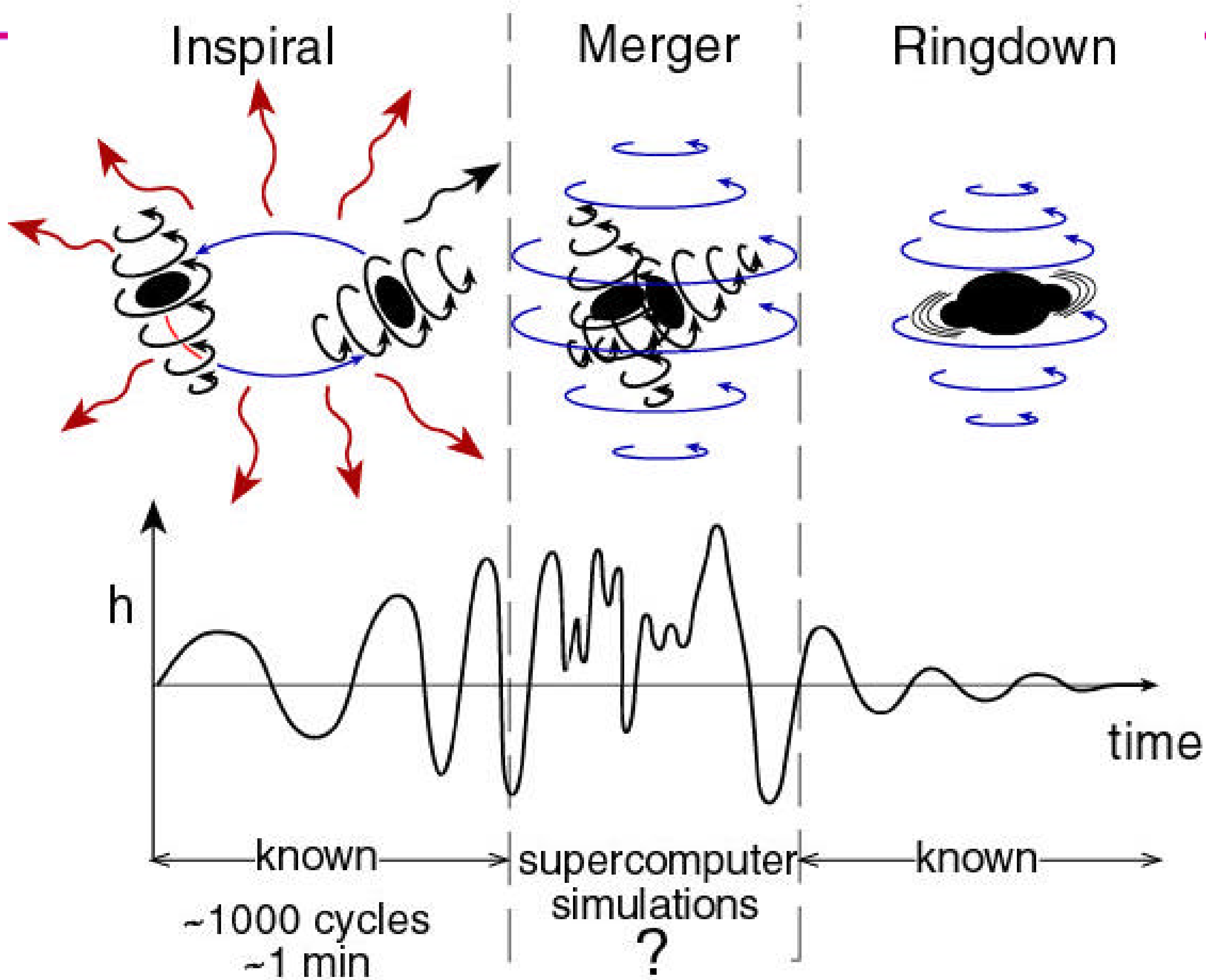
The "Undead" Corpses of Stars: Neutron Stars & Black Holes

- 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 produce a beacon of radiation that appears to pulse if it sweeps past earth
- Distortions or dynamics of neutron stars can give rise to gravitational waves



Artist: Walt Feimer, Space Telescope Science Institute

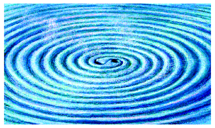
Catching Waves From Black Holes



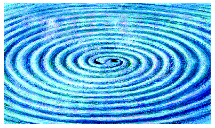
Sketches courtesy of Kip Thorne

Sounds of Compact Star Inspirals

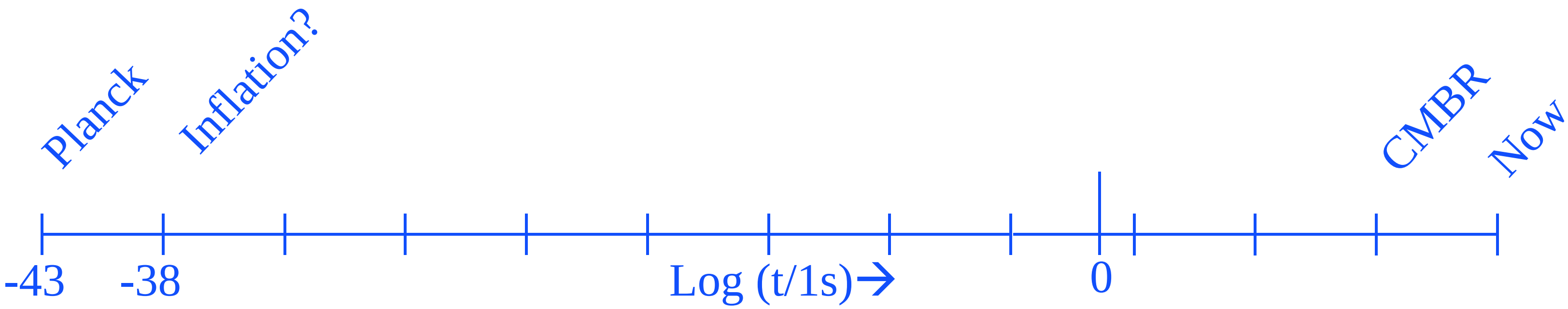
Neutron-star binary inspiral:



Black-hole binary inspiral:



Stochastic Gravitational Waves: Relics from the Early Universe



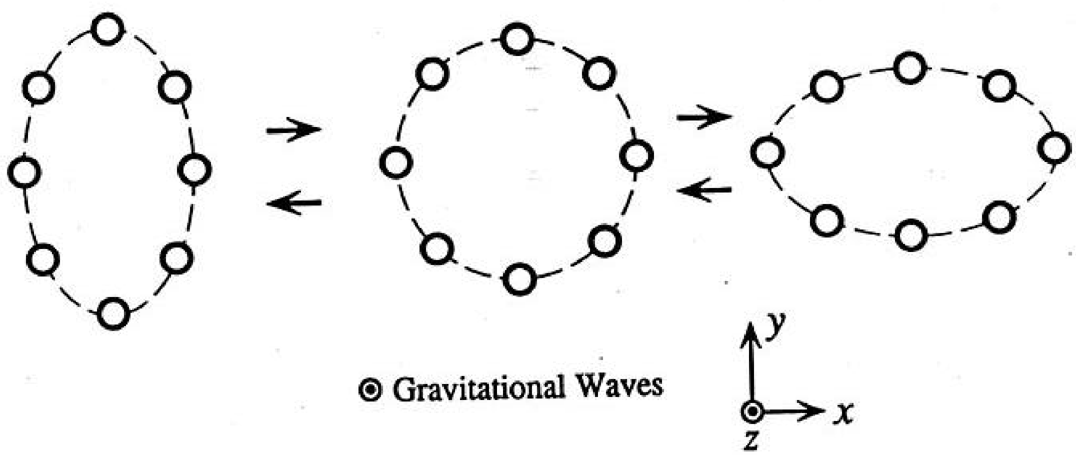
Initial LIGO: $\Omega_{GW} \sim 10^{-7}$ at $f_{GW} \sim 100$ Hz

How does LIGO detect spacetime vibrations?

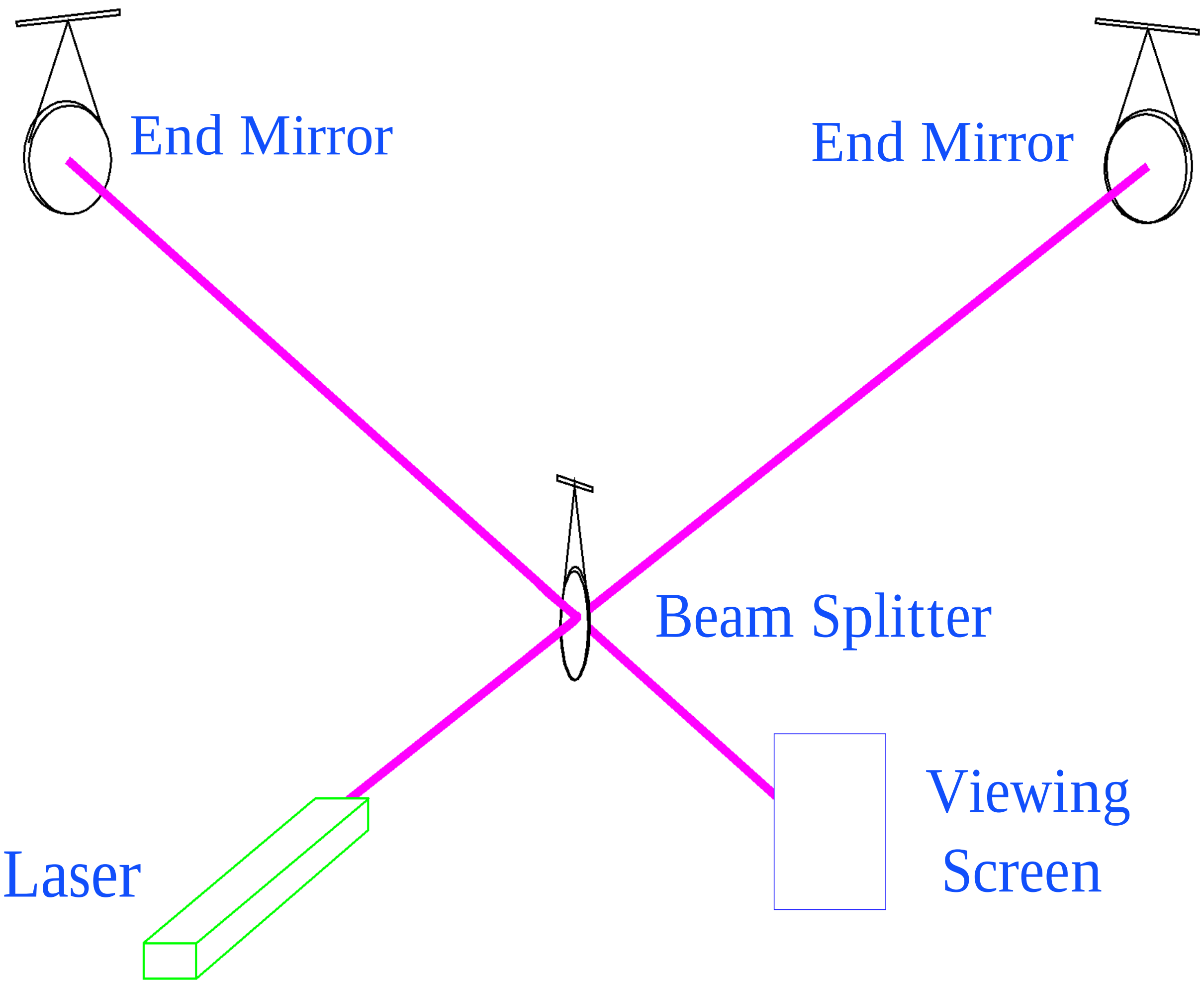
Answer: Very carefully

Important Signature of Gravitational Waves

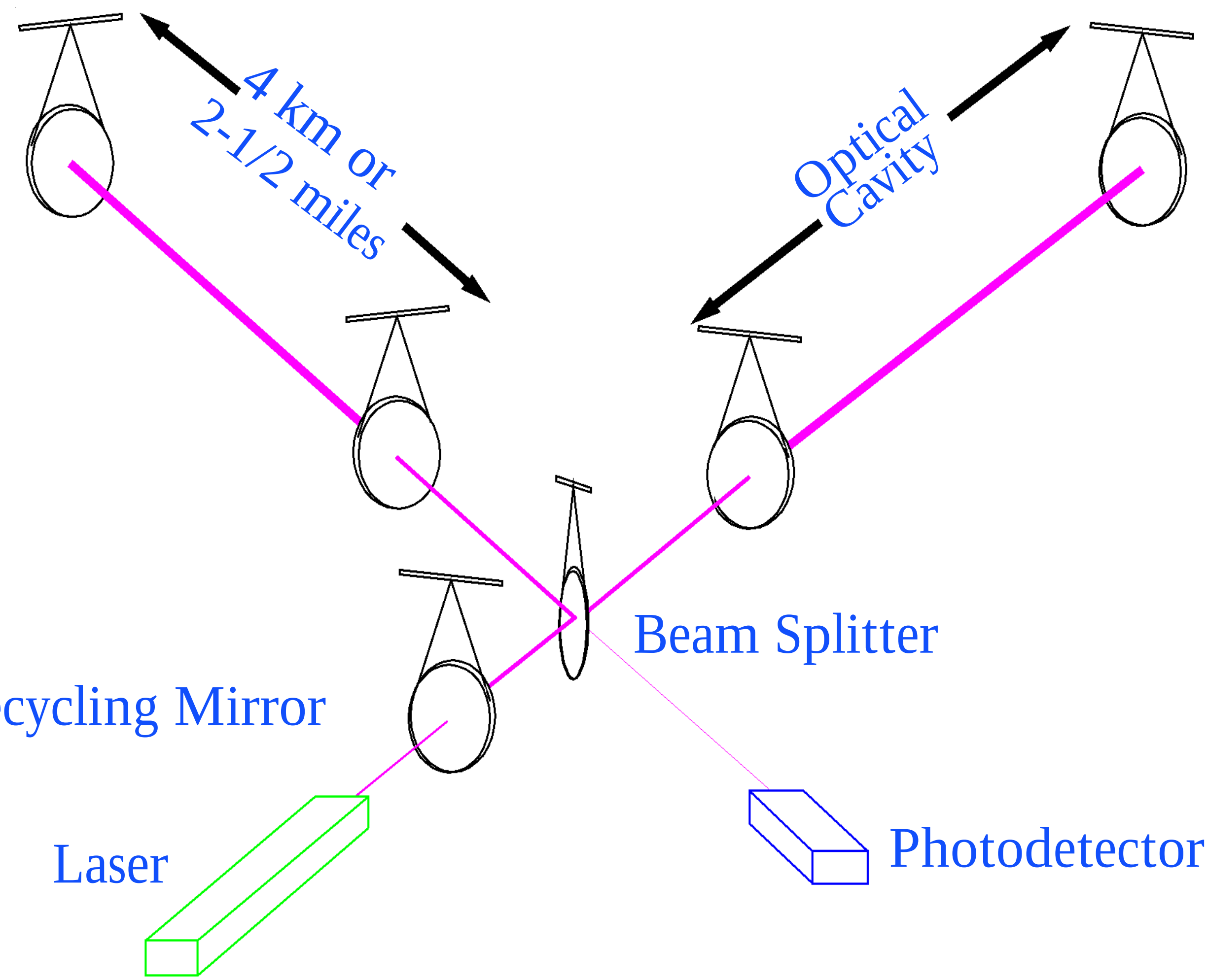
Gravitational waves shrink space along one axis perpendicular to the wave direction as they stretch space along another axis perpendicular both to the shrink axis and to the wave direction.



Sketch of a Michelson Interferometer



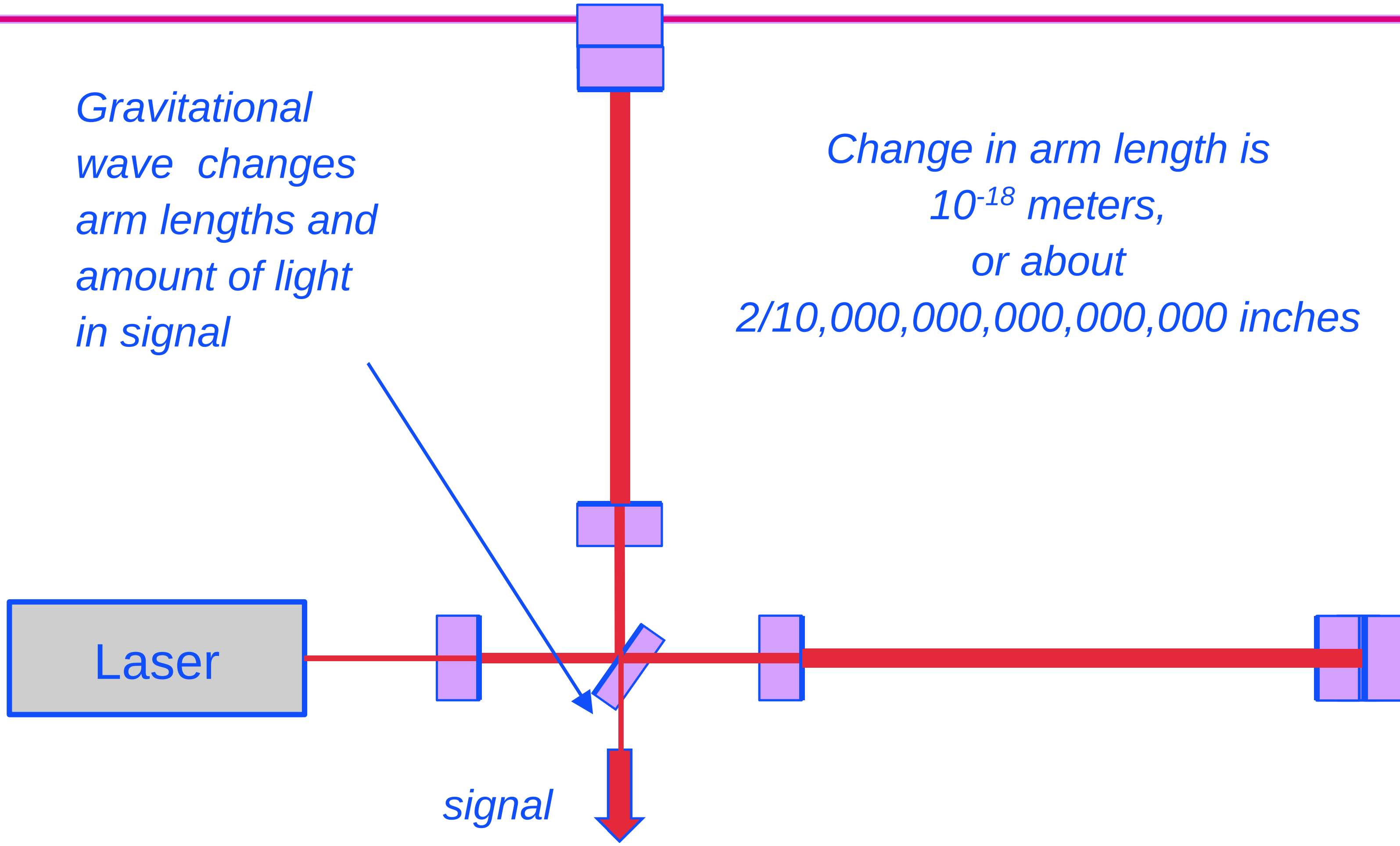
Fabry-Perot-Michelson with Power Recycling



Engineering Challenges

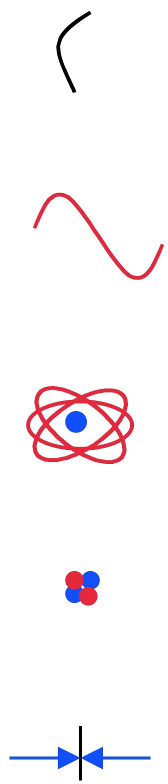
- Detect strains comparable to seeing distance from sun to nearest star changing by a hair's breadth
- Over 4000-meter baseline, mirrors will move 1/1000th the diameter of a proton
- Need to resolve optical phase shifts of 1 ppb with confidence
- Design mechanical structures so atomic vibrations dominate background motion of mirror surfaces, but do not obscure GW signals

Sensing the Effect of a Gravitational Wave



How Small is 10^{-18} Meter?

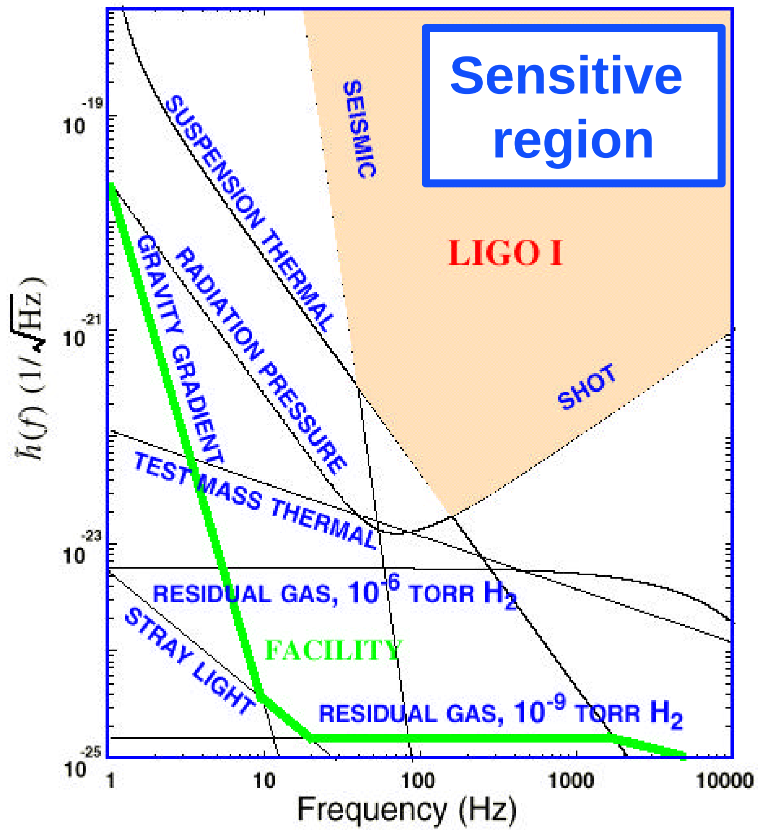
One meter, about 40 inches



÷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*

What Limits Sensitivity of Interferometers?

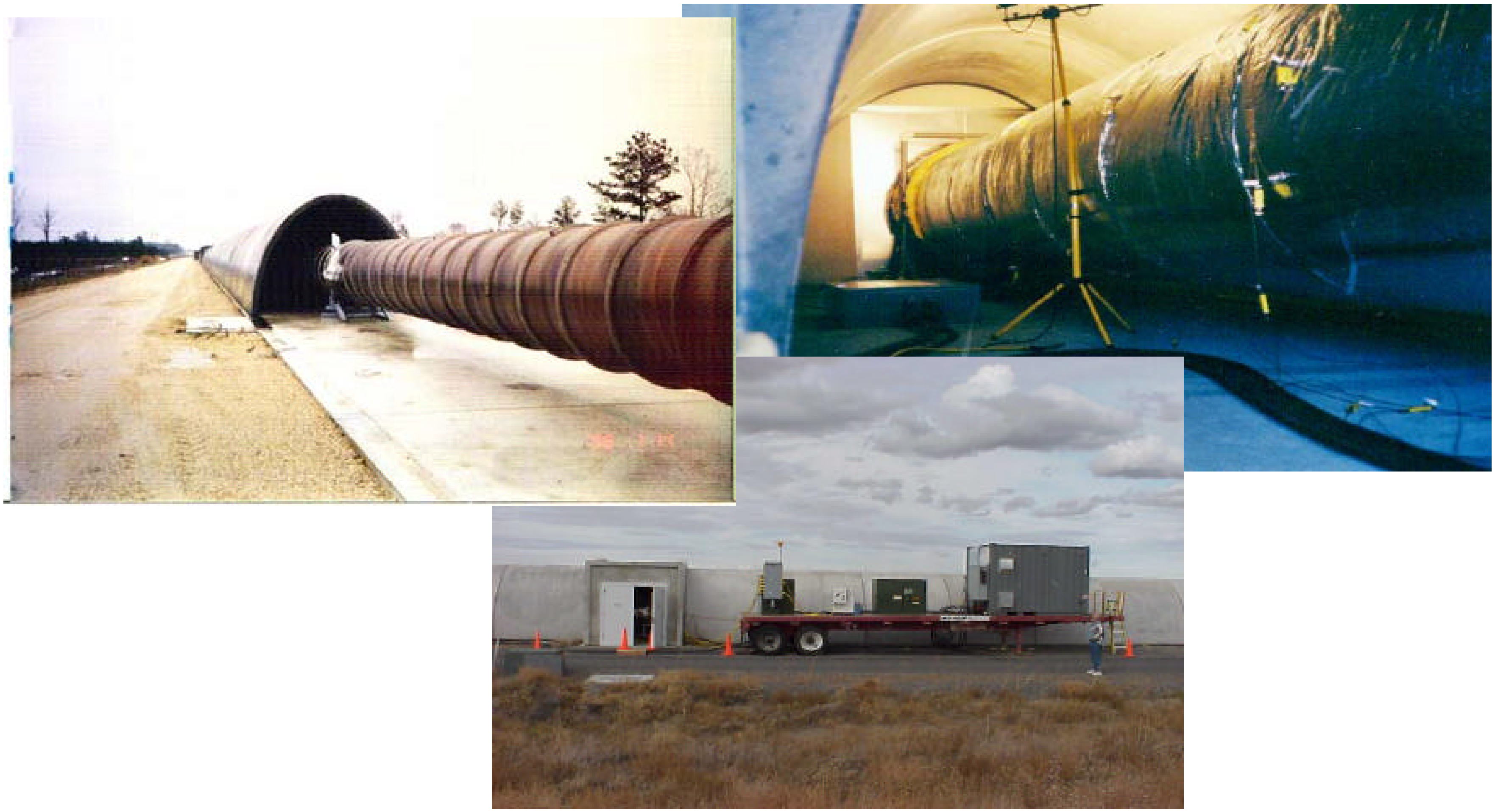
- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



The LIGO Plan

- Construct flexible facilities that can accommodate the most sensitive detectors imaginable
- Evolve the detector design through upgrades that make follow advancing technology
- Maintain aggressive engineering and R&D program to break down technology barriers
- LIGO-I run (2002-2004): search spacetime volume 10,000,000,000 times large than previous runs

Evacuated Beam Tubes Provide Clear Path for Light

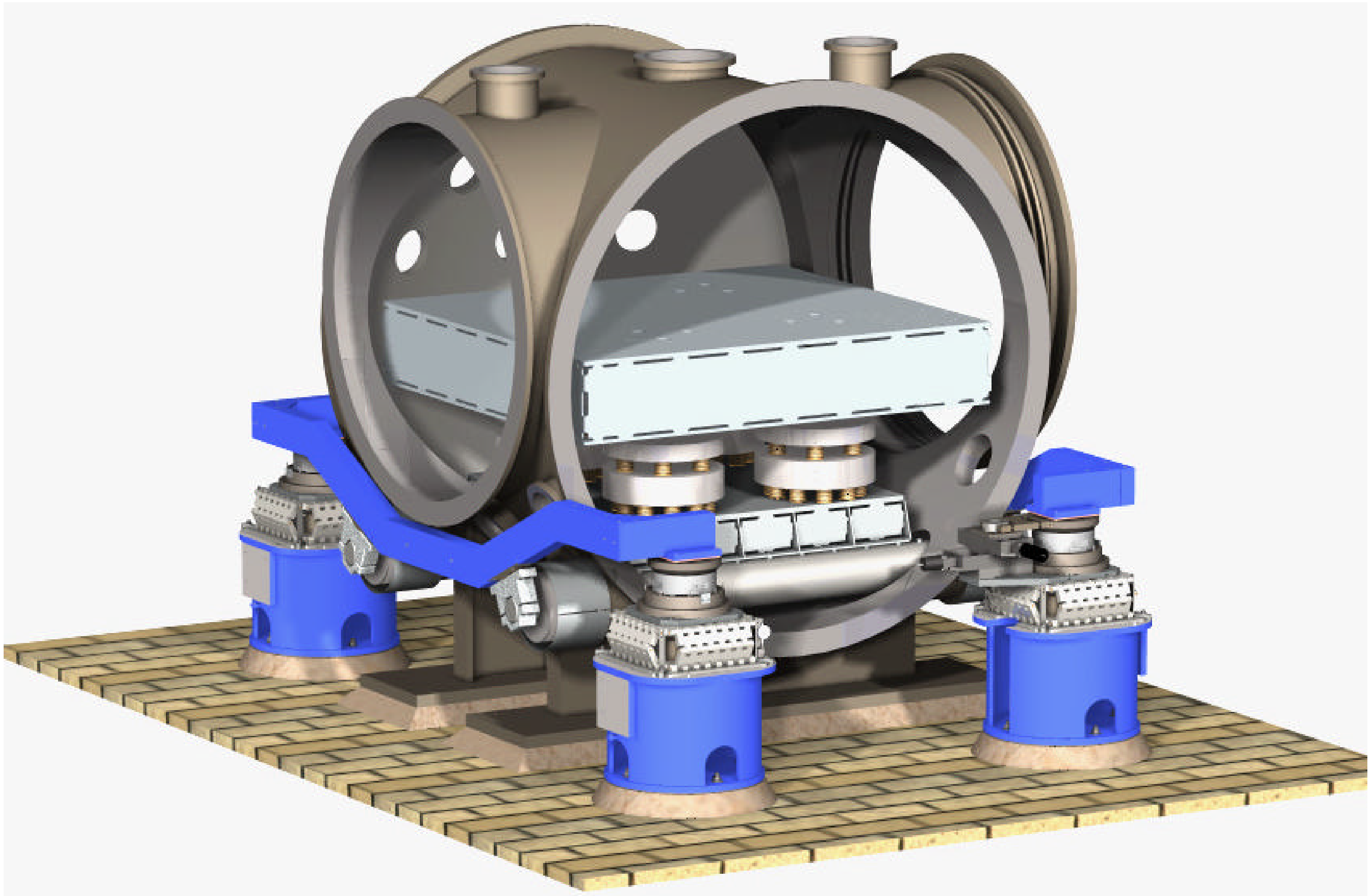


Vacuum Chambers Provide Quiet Homes for Mirrors

View inside Corner Station

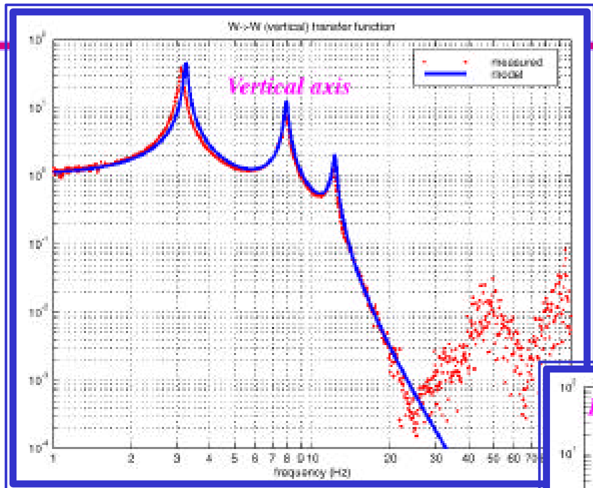
Standing at vertex beam splitter

HAM Chamber Seismic Isolation



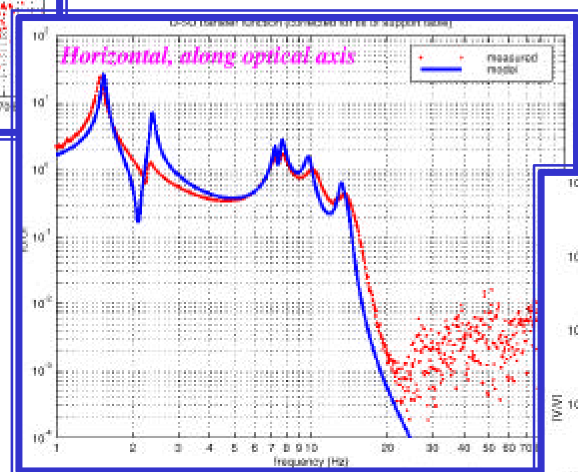
HAM Seismic Isolation Installation

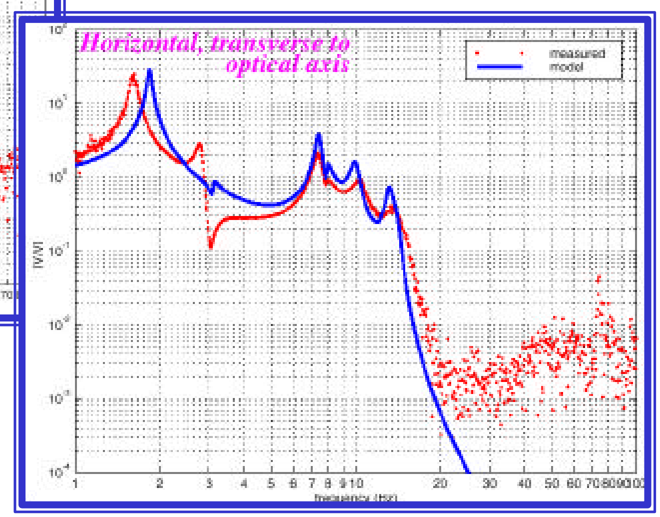
HAM Seismic Isolation Measured in Air at LHO



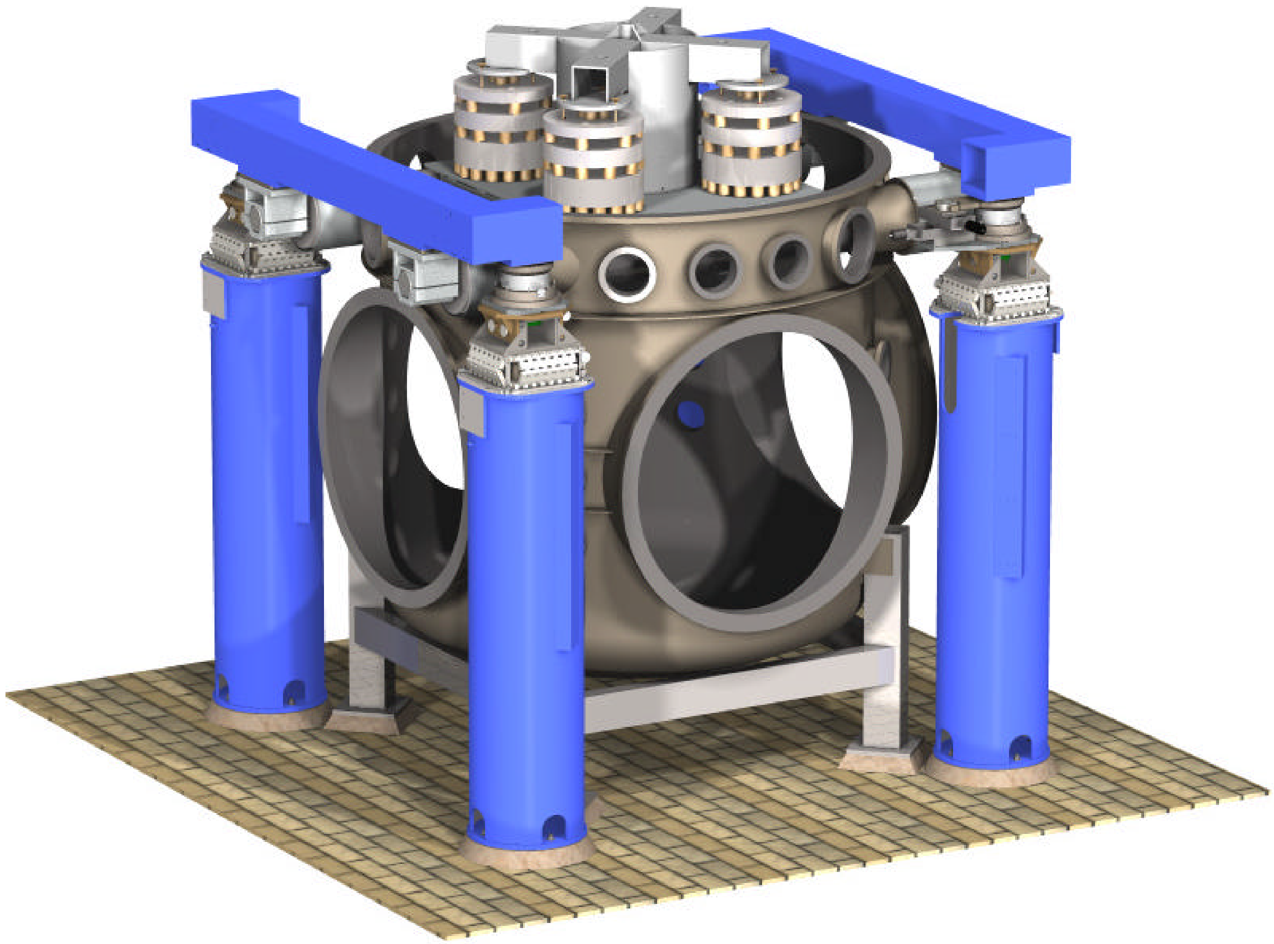
Seismic Design Model

Transfer Function Measurements

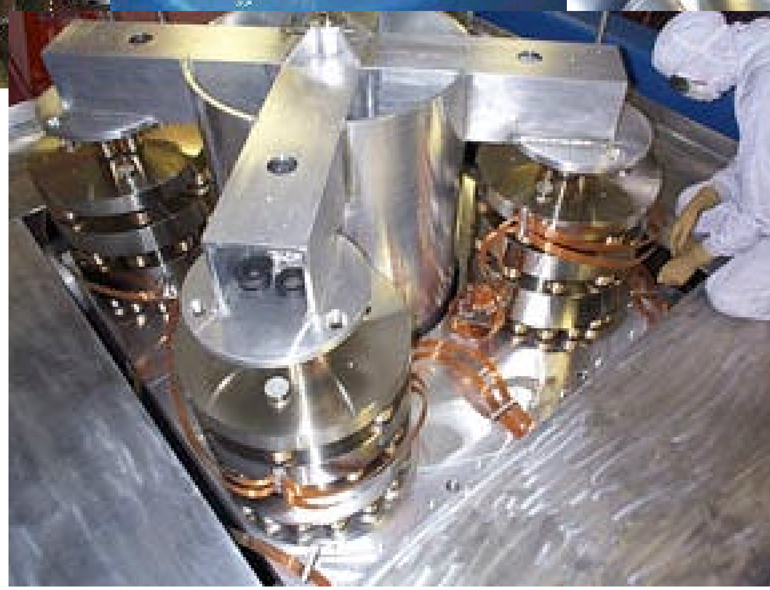


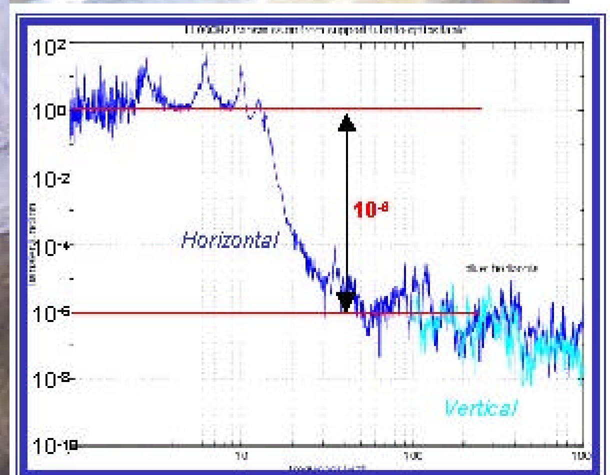


BSC Chamber Seismic Isolation



BSC Seismic Isolation Installation



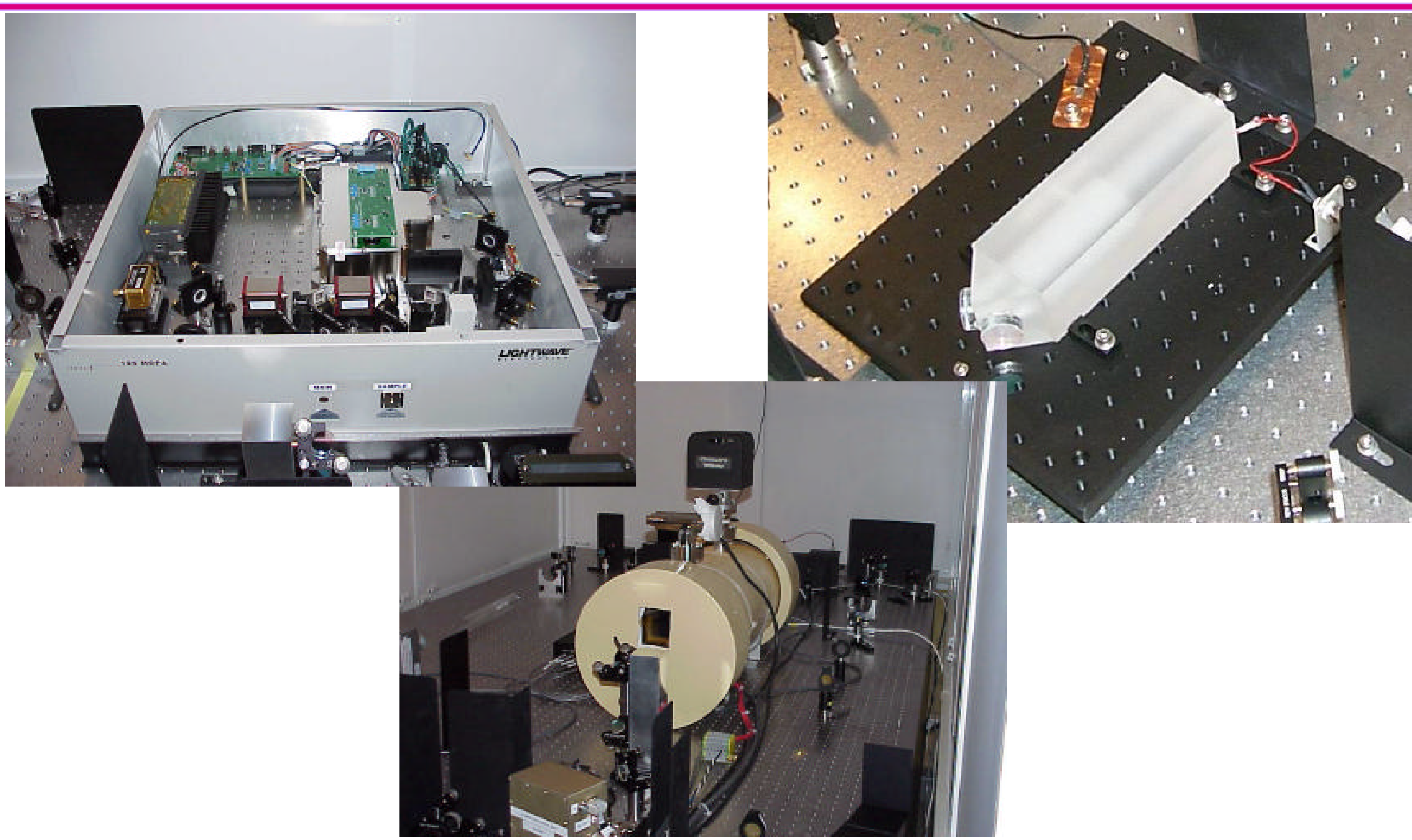


Suspended Mirrors

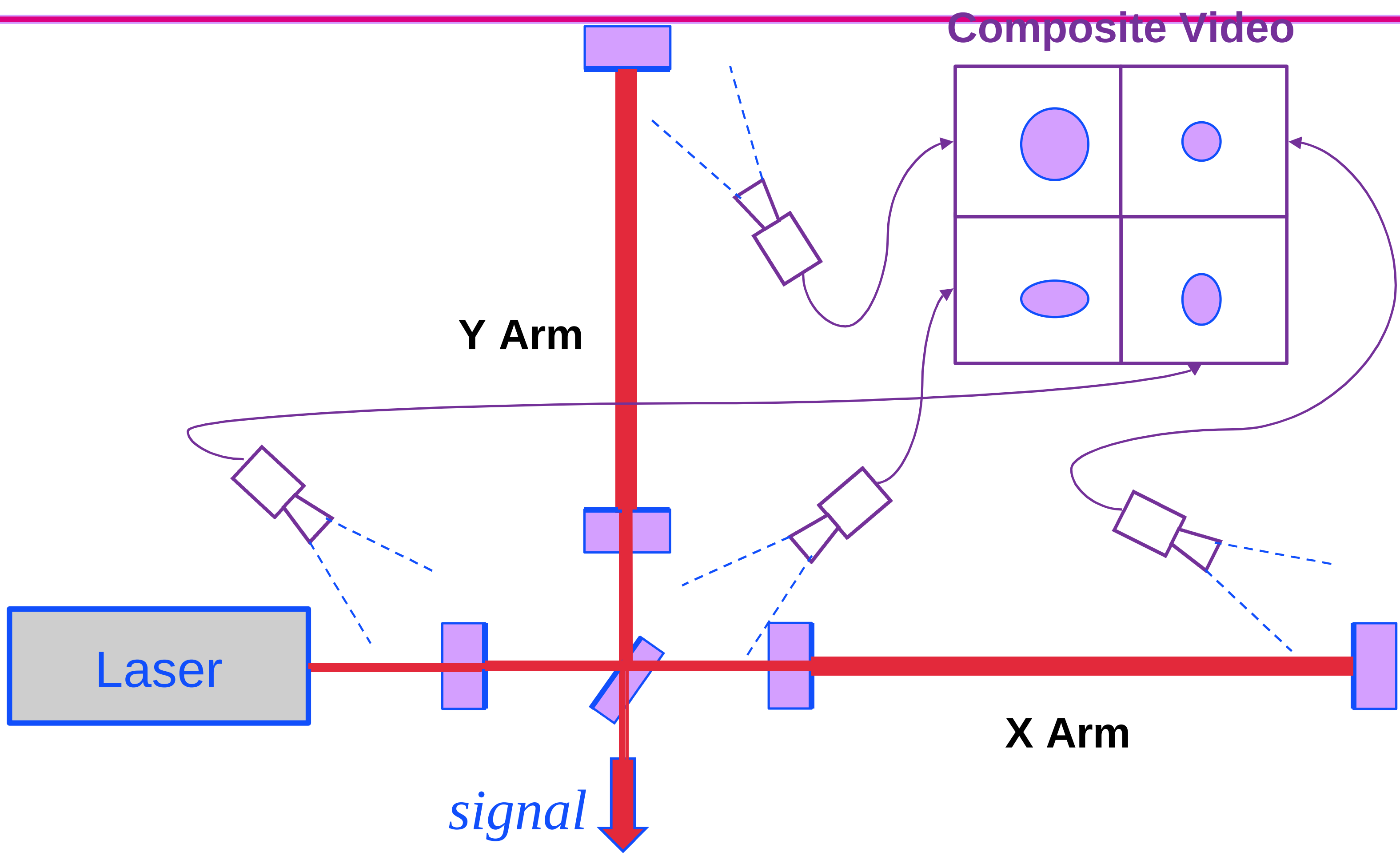
initial alignment

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

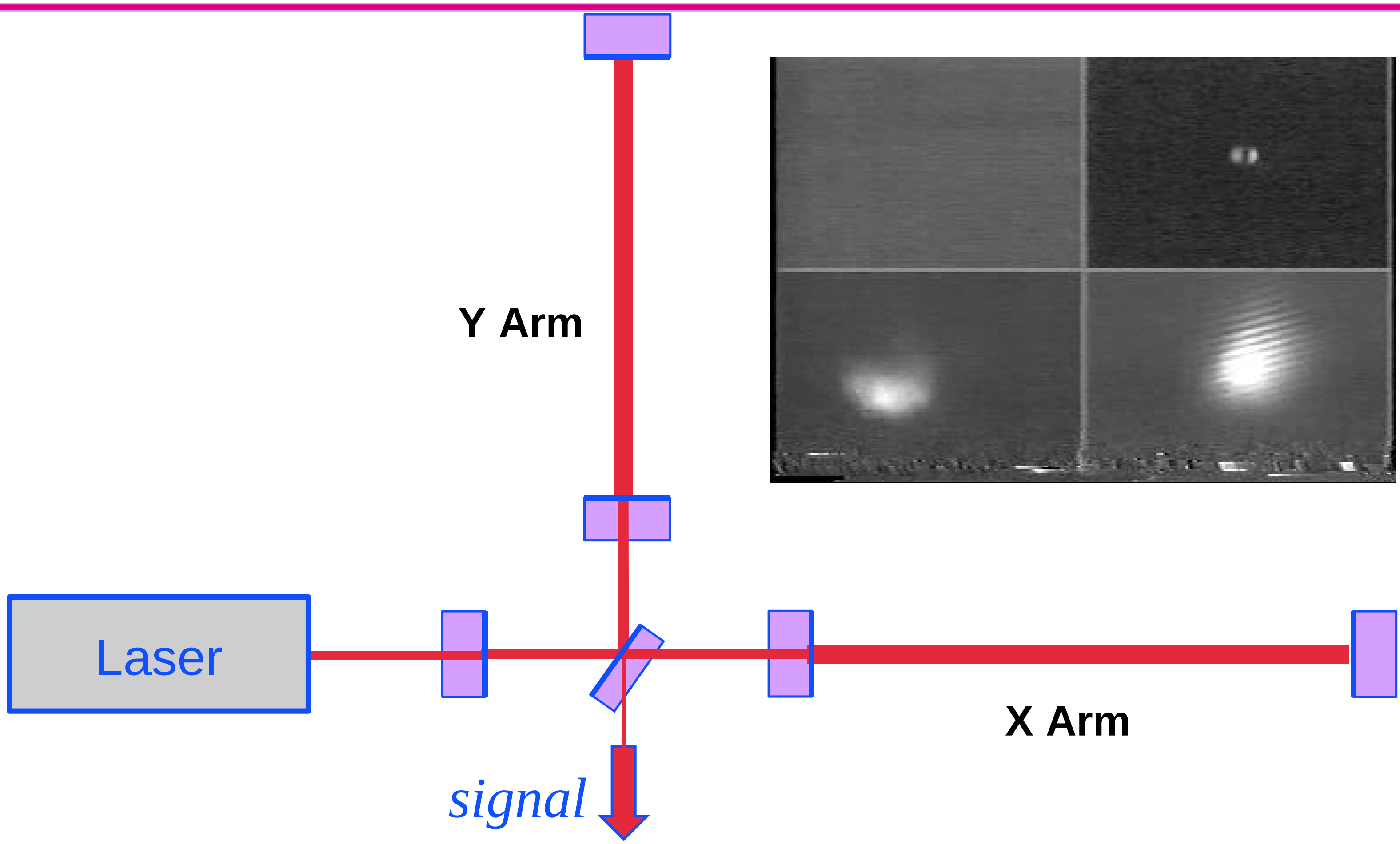
All-Solid-State Nd:YAG Laser System



Steps to Locking an Interferometer

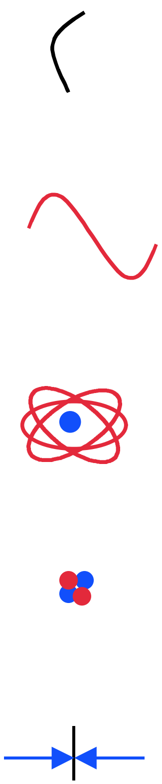


Watching the Interferometer Lock



Why is Locking Difficult?

One meter, about 40 inches



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

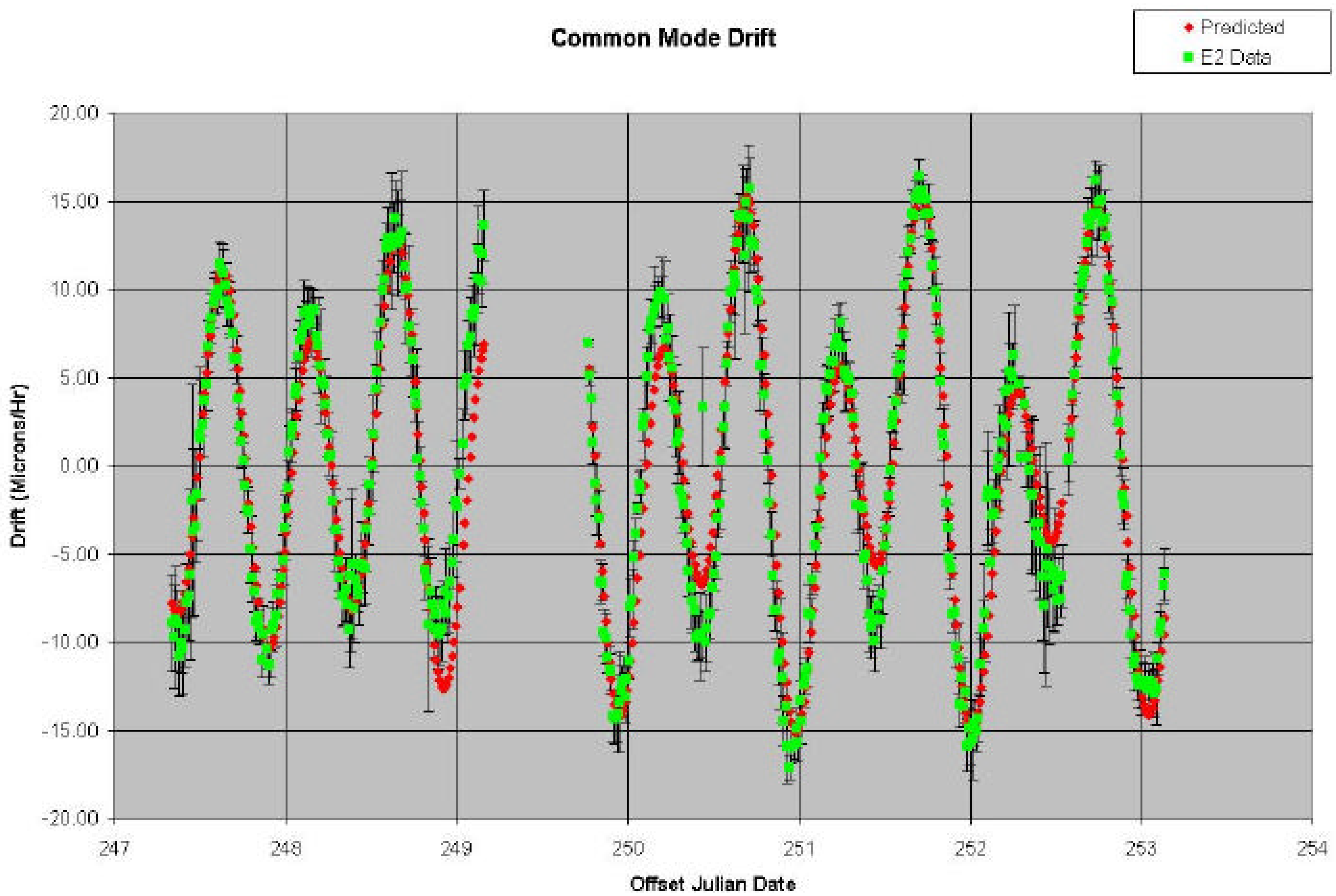
÷ 100 — *Microseismic motion, about 1 micron*

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

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

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

Detecting the Earth Tide from the Sun and Moon



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?)

Despite a Few Glitches, Science Starts in 2002