LIGO: The Portal to Spacetime

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LIGO: The Portal to Spacetime

- Introduction to LIGO and its quest
- What questions will LIGO try to answer?
- Detour through General Relativity
- What phenomena do we expect to study?
- How does LIGO work?
- Has there been any progress on LIGO?
- When will it work?

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
  - » Clearly viewing the moons of Jupiter and the phases of Venus confirmed the Copernican view that Earth was not the center of the universe
  - » 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

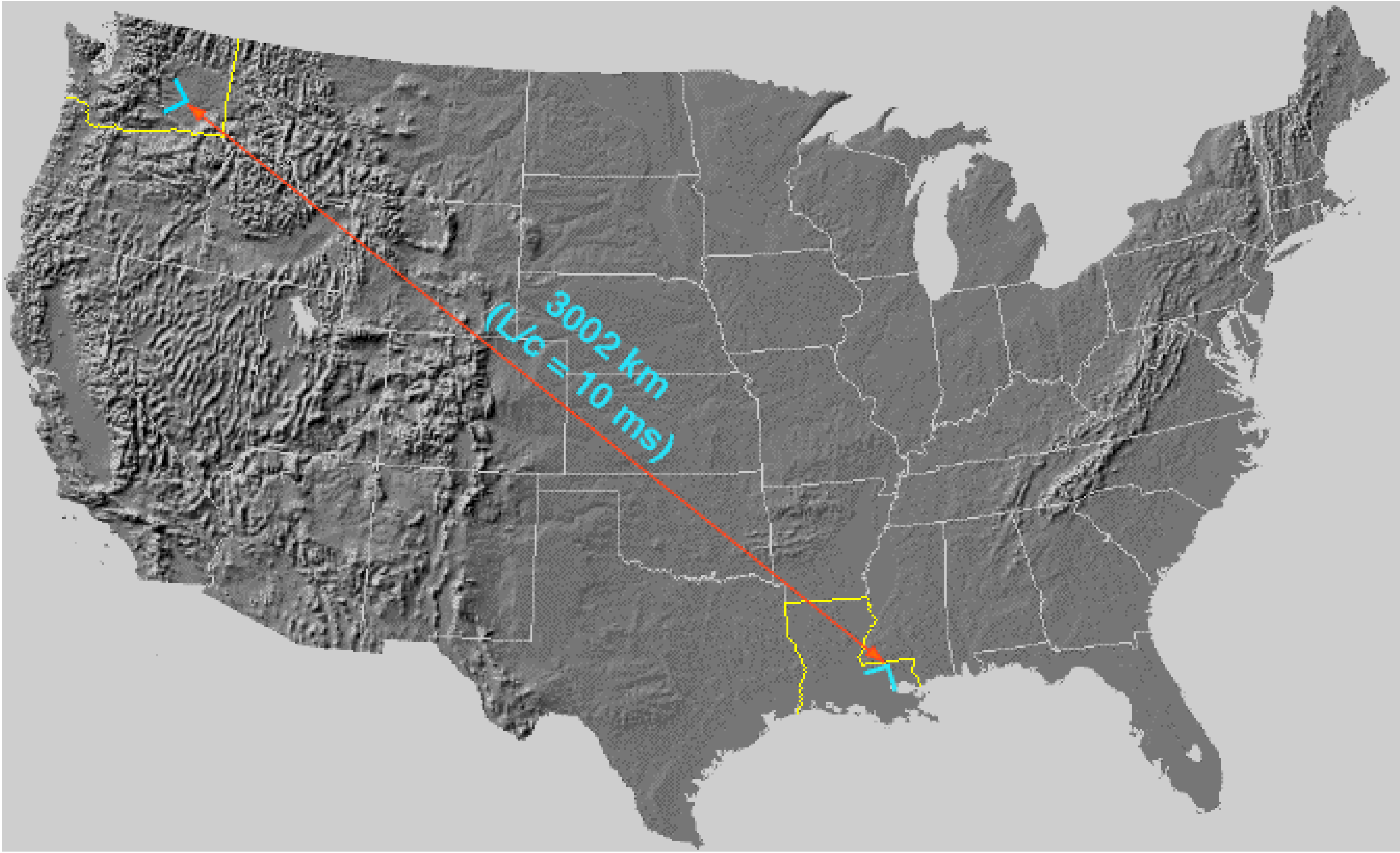
The Laser Interferometer Gravitational-Wave Observatory

LIGO (Washington)

LIGO (Louisiana)

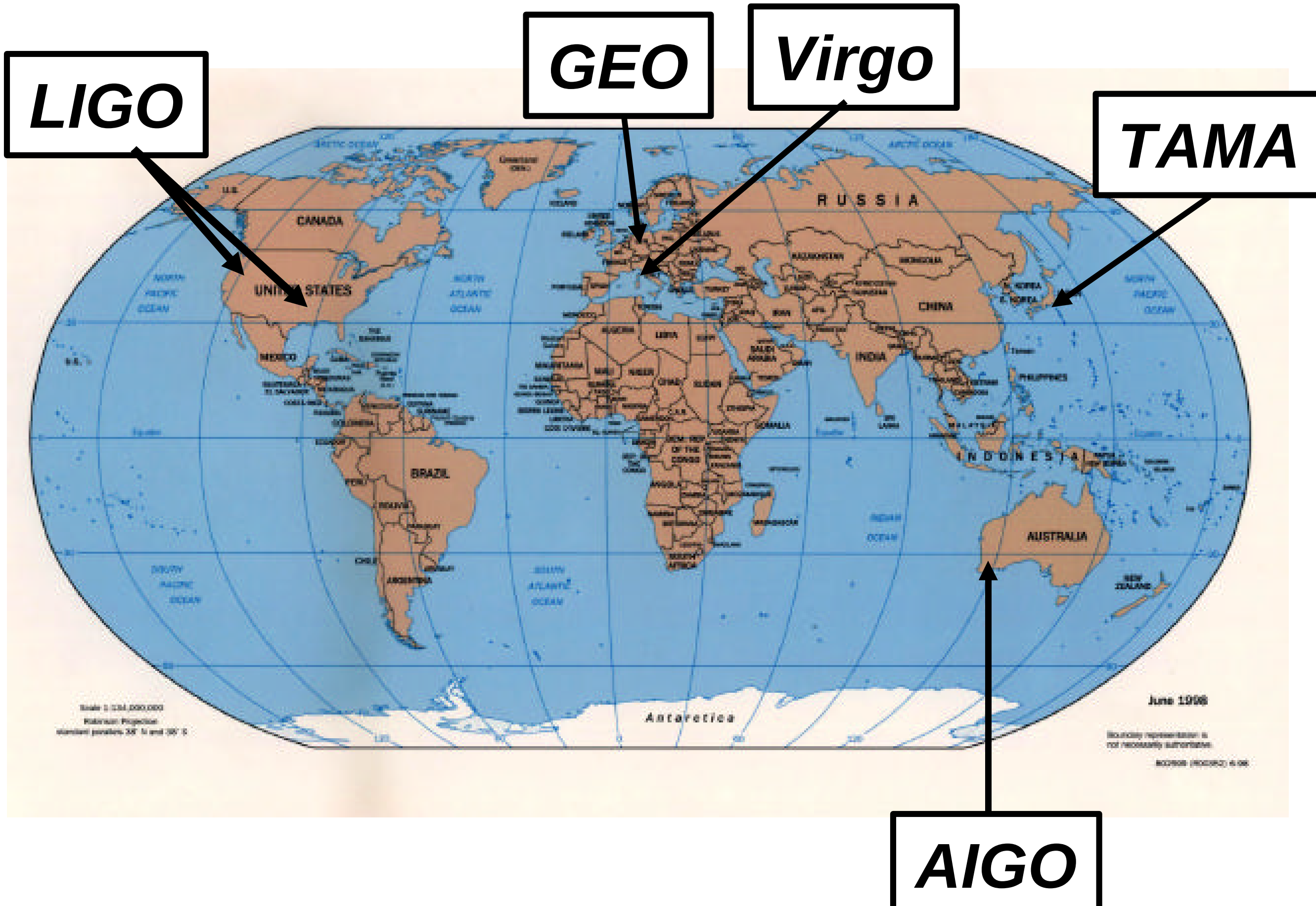
Brought to you by the National Science Foundation; operated by Caltech and MIT; the research focus for about 350 LIGO Science Collaboration members worldwide.

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 universe like in the earliest moments of the big bang?
- What surprises have we yet to discover about our universe?

A Slight Problem

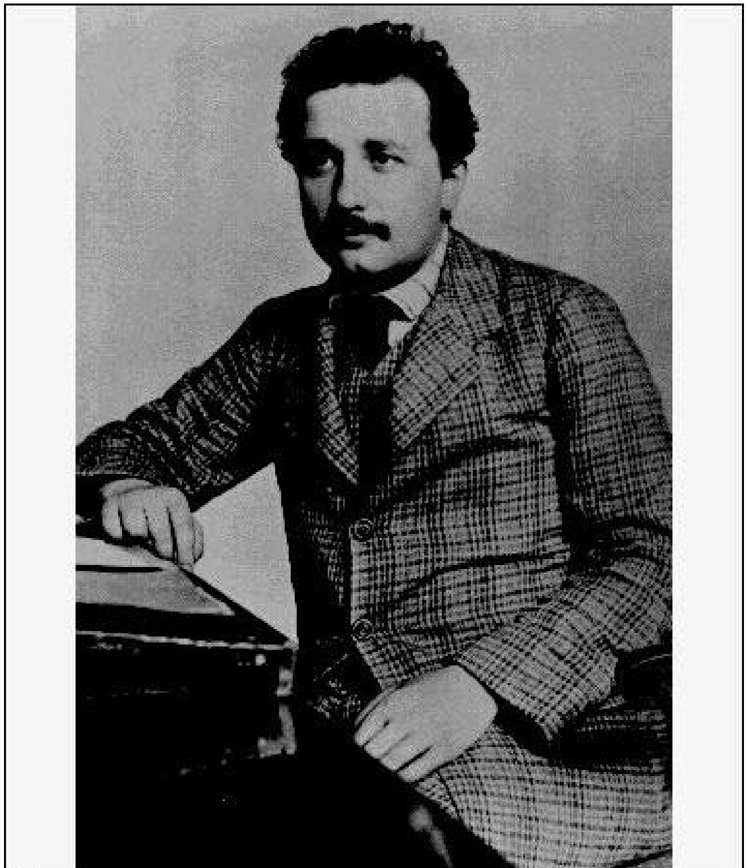
Regardless of what you see on Star Trek, the vacuum of interstellar space does not transmit conventional sound waves effectively.

Don’t worry, we’ll work around that!

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

- A breakthrough in 20^{th} century science was realizing that space and time are not just abstract concepts
- In 19^{th} century, space devoid of matter was the "vacuum"; viewed as nothingness
- In 20^{th} 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!

General Relativity: The Modern Theory of Gravity (for now)



"The most incomprehensible thing about the universe is that it is comprehensible"

- Albert Einstein

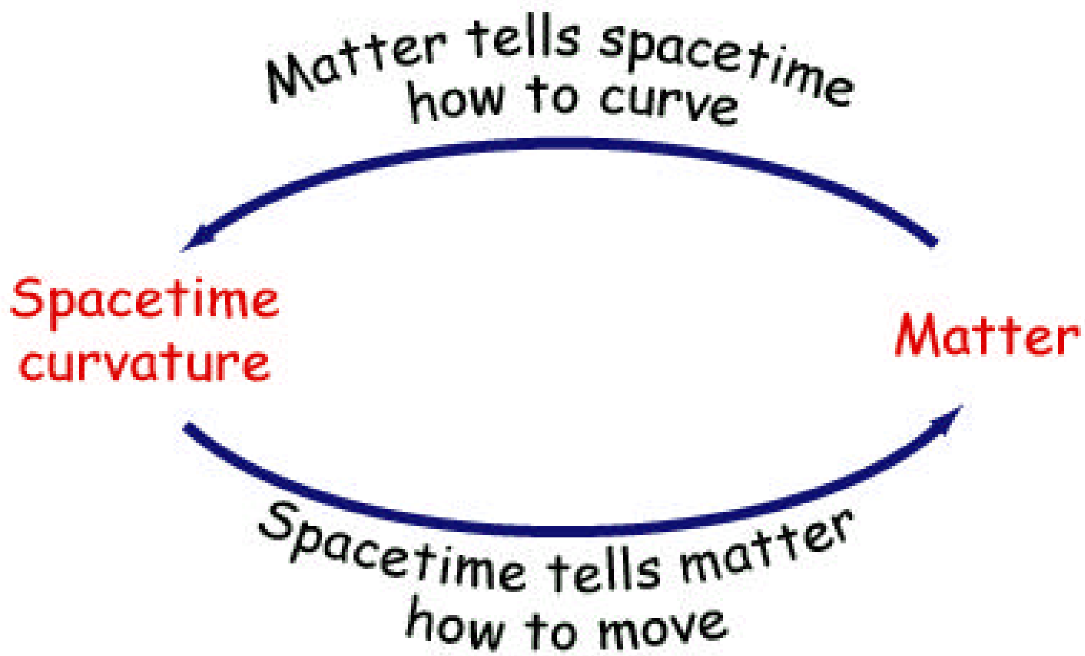
General Relativity: The Question Lurking in the Background

- Galileo and Newton uncovered a puzzling, but beautiful property of gravity, strikingly different from any of the other known forces
- In careful experiments they showed that all matter falls the same way under the influence of gravity
  - » once “spurious” effects, like air resistance, are taken into account
  - » Galileo rolled different materials down an inclined plane
  - » Newton used pendulums with various materials inside
  - » Later known as Newton’s Principle of Equivalence
- Contrast that with Electricity or Magnetism, which have dramatically different effects on materials

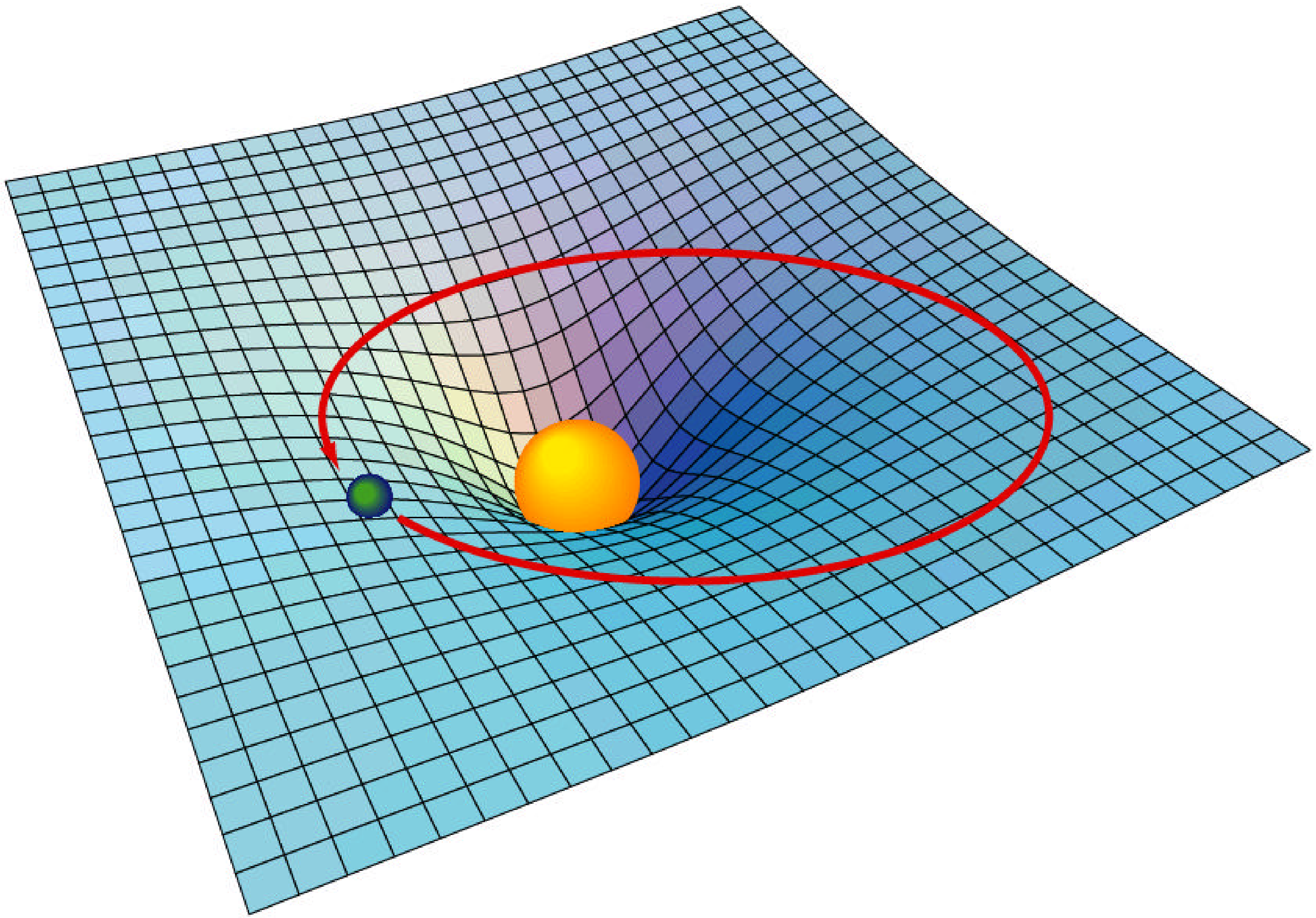
General Relativity: The Essential Idea Behind the Answer

- Einstein solved the puzzle: gravity is not a force, but a property of space & time
  - Spacetime = 3 spatial dimensions + time
  - Perception of space or time is relative
- Objects follow the shortest path through this warped spacetime; path is the same for all objects
- Concentrations of mass or energy distort (warp) spacetime
- The 19th-century concepts of absolute space and time were “hang-ups”; the physical reality of the universe is not constrained by our hang-ups

John Wheeler's Summary of General Relativity Theory

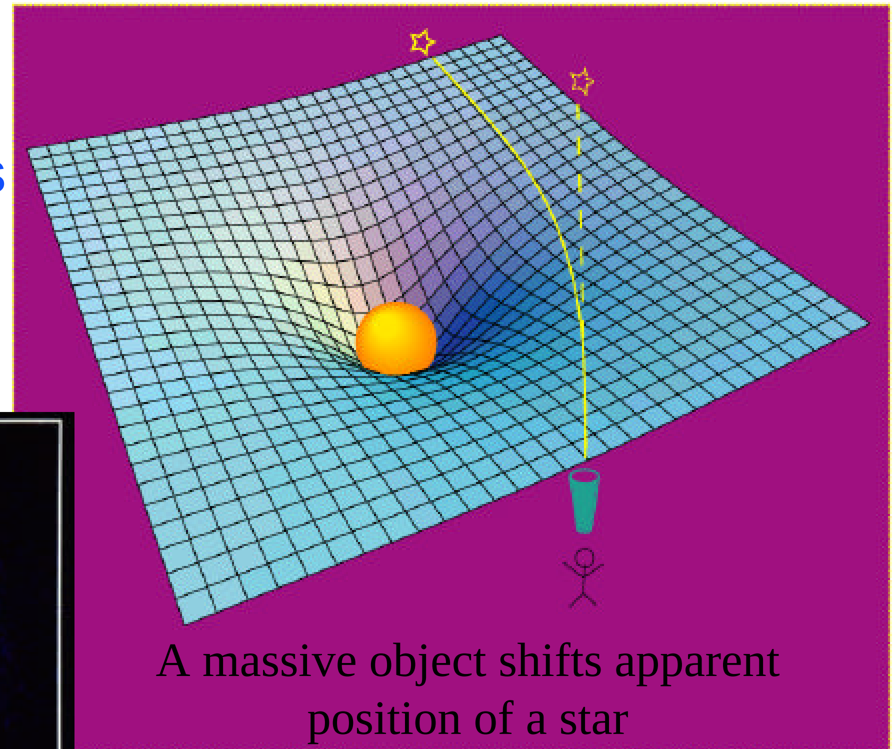


General Relativity: A Picture Worth a Thousand Words



The New Wrinkle on Equivalence

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



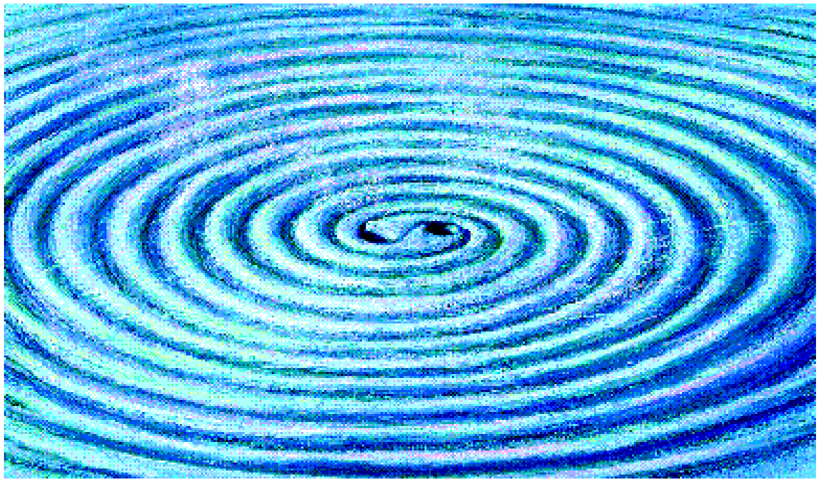
Einstein Cross

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

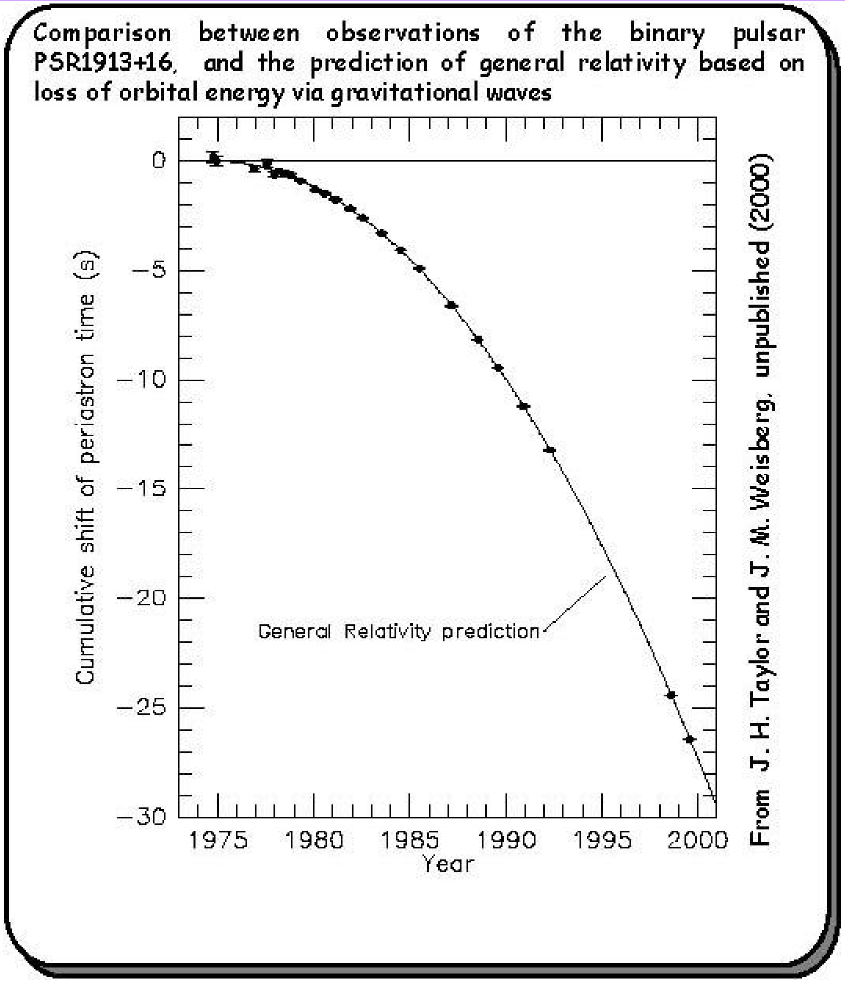
Rendering of space stirred by two orbiting black holes:



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.

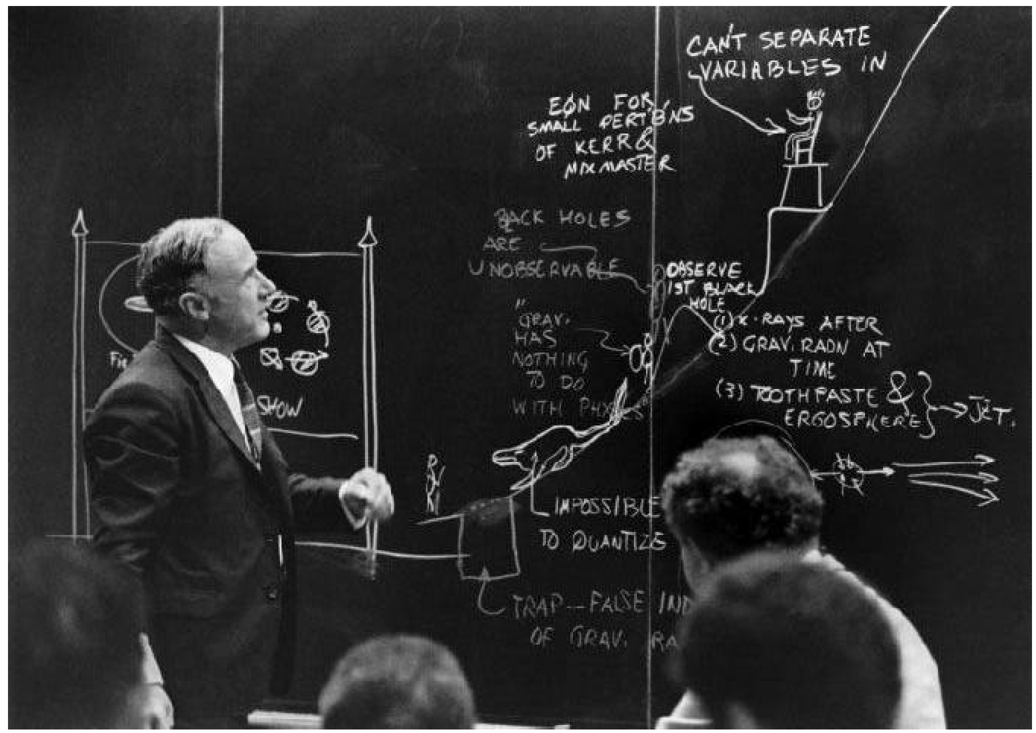


What Phenomena Do We Expect to Study With LIGO?

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)

Gravitational Collapse: Prelude

- Collapsing gas clouds heat up and ignite nuclear burning, fusing hydrogen, helium to heavier elements
- Star becomes “layered”, like an onion, with heavy elements fusing yet heavier elements at center
- Iron is the heaviest element that will fuse this way
- As the end of the fusion chain is reached, nuclear burning can no longer provide the pressure to hold the star up under gravity
- The star will now collapse unless/until some other force holds it up

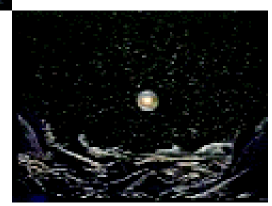
Gravitational Collapse: The Main Event

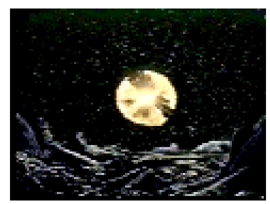
- The material in the star continues to crush together
- Eventually, the atoms in the star “melt” into a sea of electrons and nuclei. This sea resists compression and might stop collapse → “white dwarf”.
- In more massive stars, electrons and nuclei are crushed into pure nuclear matter → “neutron star”. This stiffer form of matter may halt collapse.
- No other form of matter exists to stop collapse in heavier stars → space and time warpage increase until an “event horizon” forms → “black hole”.

The Brilliant Deaths of Stars

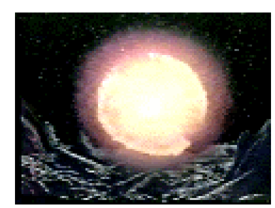
time evolution

Supernovae



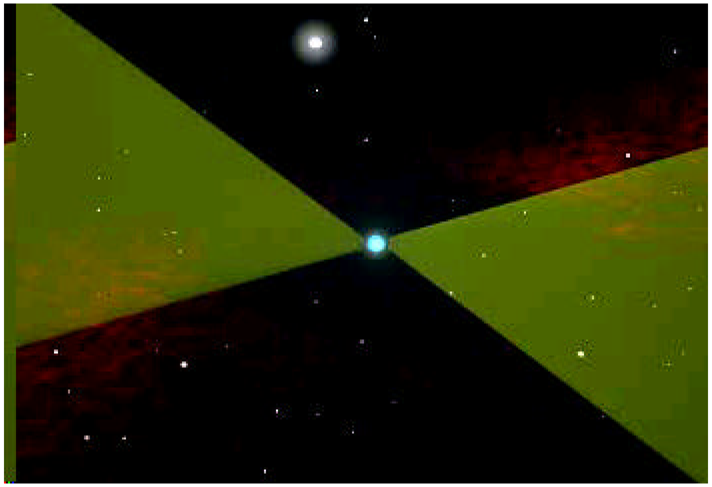


Images from NASA High Energy
Astrophysics Research Archive



The "Undead" Corpses of Stars: Neutron Stars

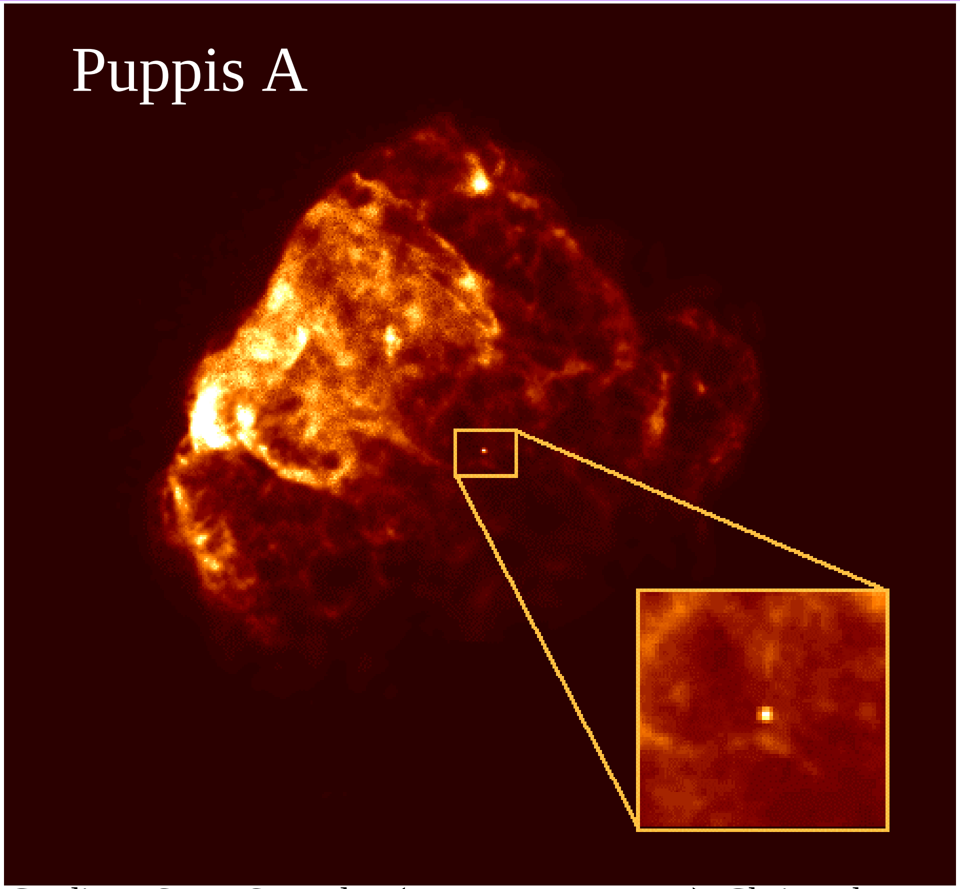
- Neutron stars have a mass equivalent to 1.4 suns packed into a ball 10 miles in diameter
- The large magnetic fields and high spin rates produces a beacon of radiation that appears to pulse if it sweeps past earth



Artist: Walt Feimer, Space Telescope Science Institute

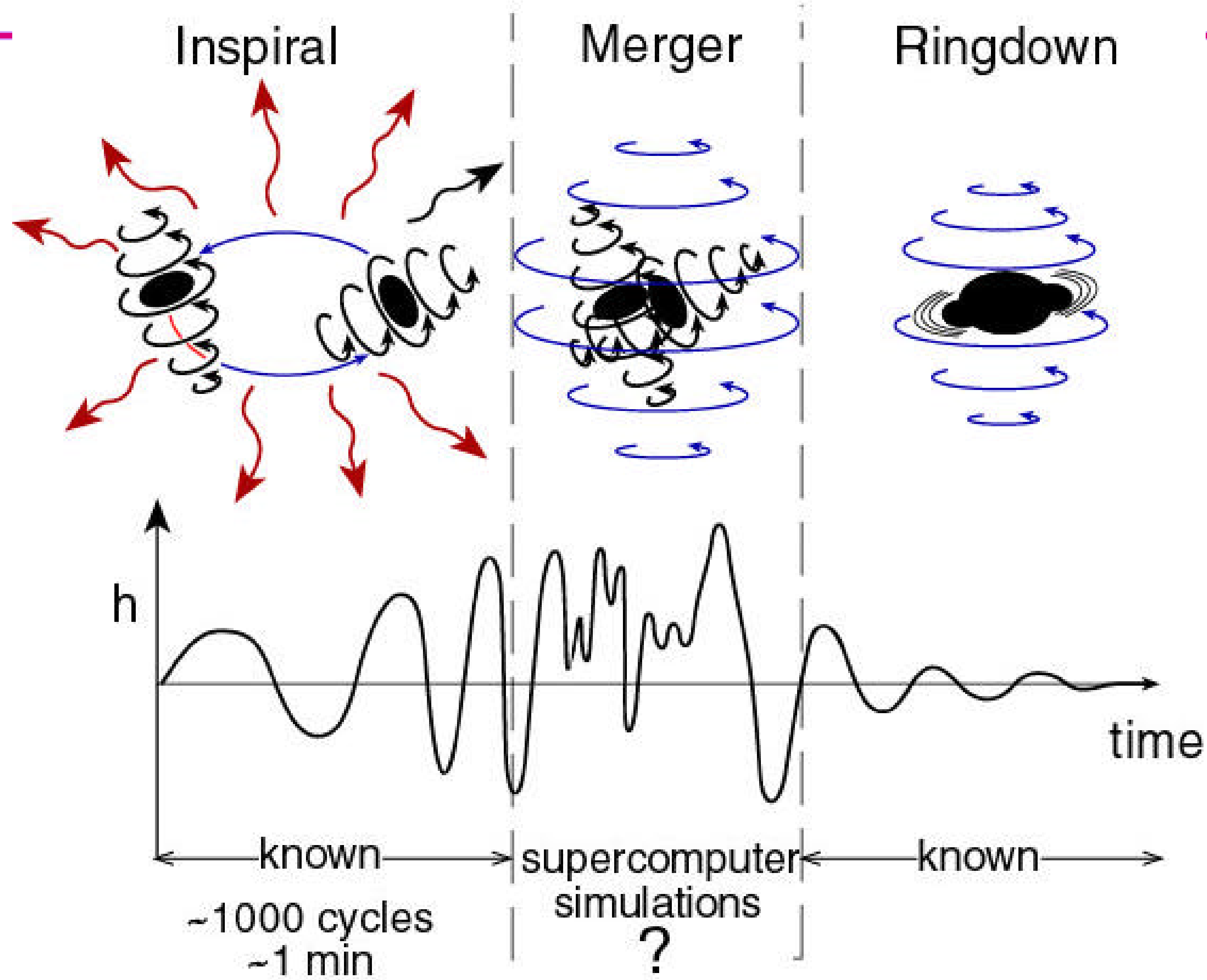
Do Supernovae Produce Gravitational Waves?

- 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



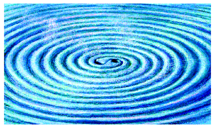
Credits: Steve Snowden (supernova remnant); Christopher Becker, Robert Petre and Frank Winkler (Neutron Star Image).

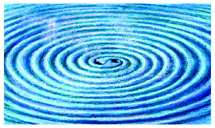
Catching Waves From Black Holes



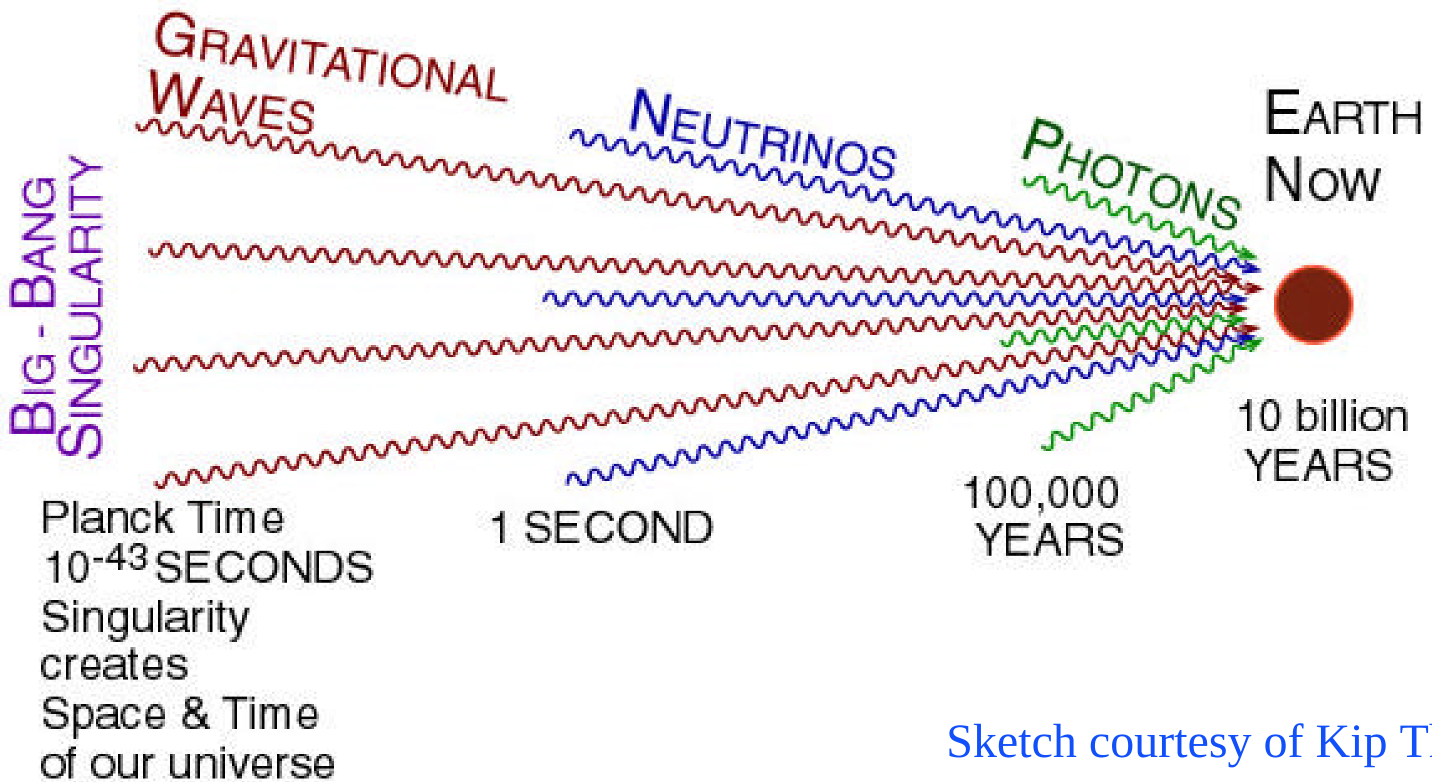
Sketches courtesy of Kip Thorne

Sounds of Compact Star Inspirals

Neutron-star binary inspiral: 

Black-hole binary inspiral: 

Echoes
from Very Early Universe



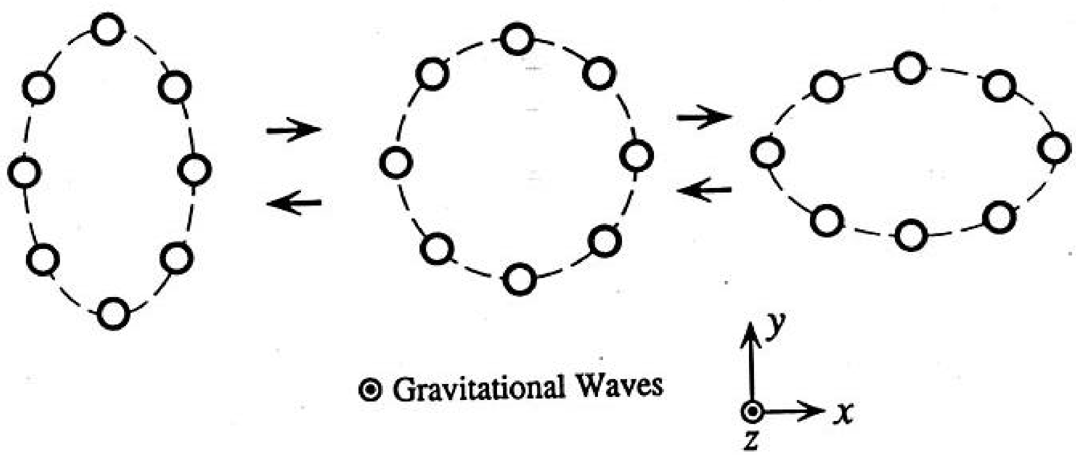
Sketch courtesy of Kip Thorne

How does LIGO detect spacetime vibrations?

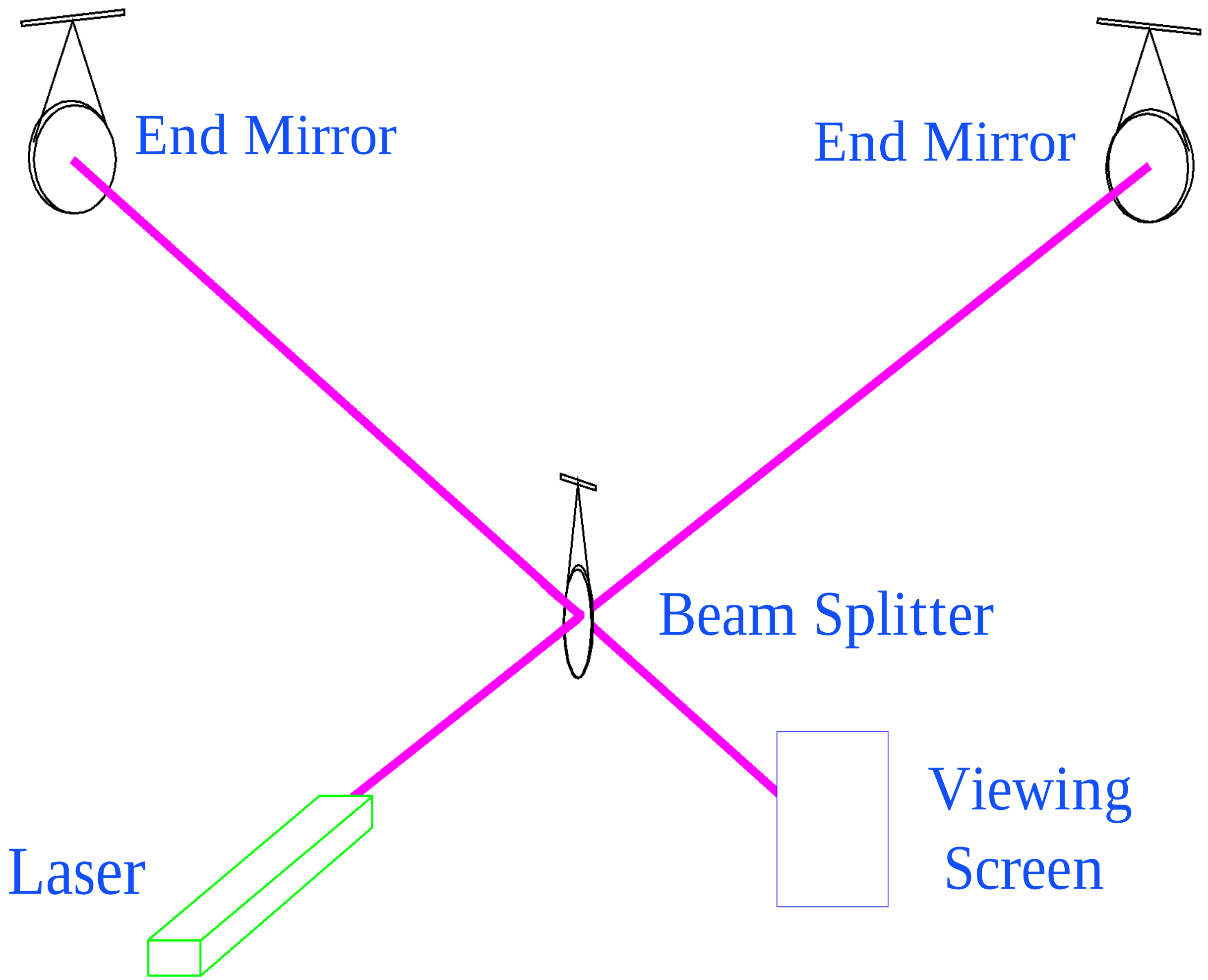
Answer: Very carefully

Important Signature of Gravitational Waves

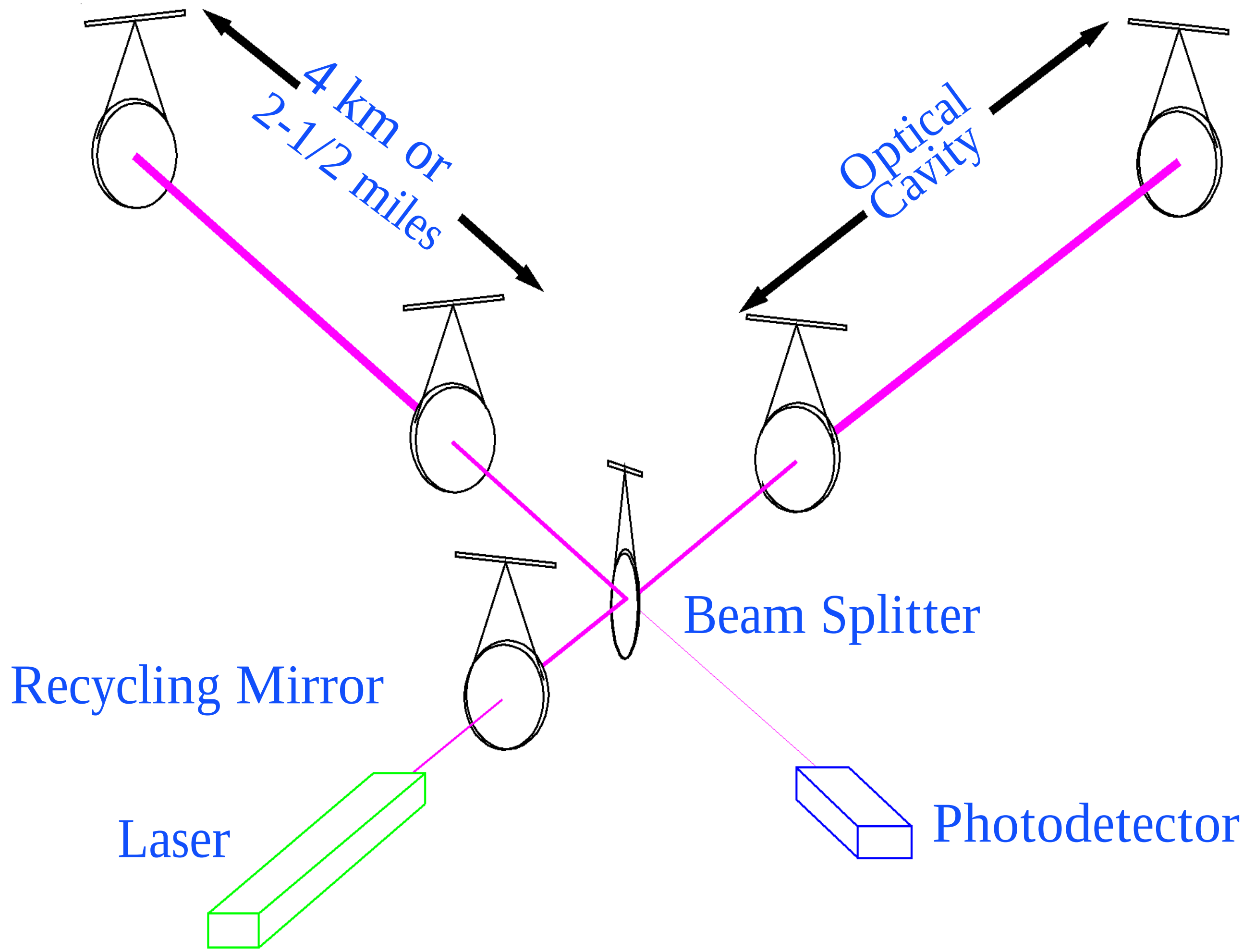
Gravitational waves shrink space along one axis perpendicular to the wave direction as they stretch space along another axis perpendicular both to the shrink axis and to the wave direction.



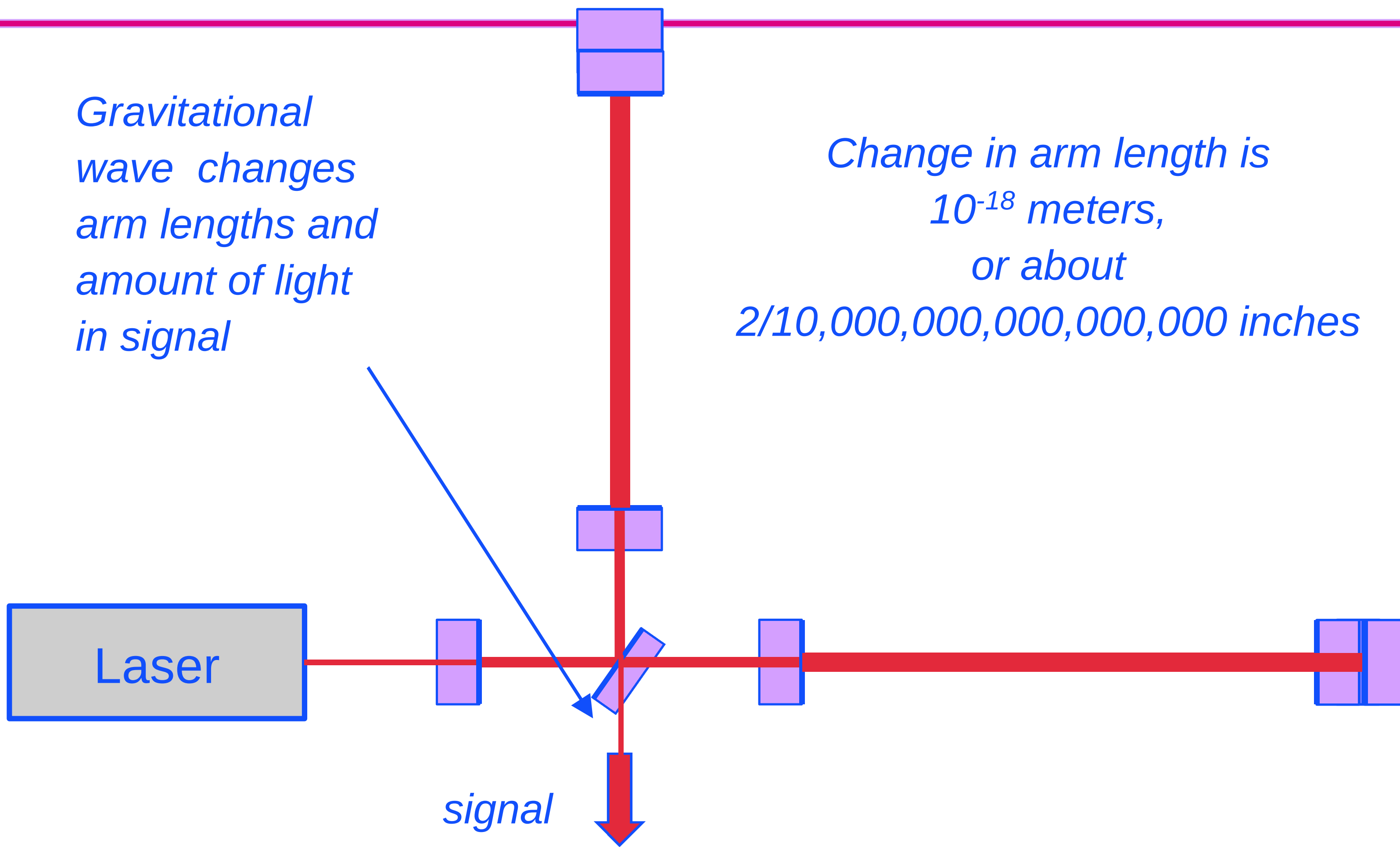
Sketch of a Michelson Interferometer



Fabry-Perot-Michelson with Power Recycling



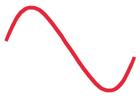
Sensing the Effect of a Gravitational Wave

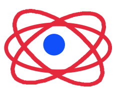


How Small is 10^{-18} Meter?

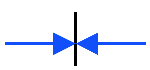
One meter, about 40 inches

÷10,000  *Human hair, about 100 microns*

÷100  *Wavelength of light, about 1 micron*

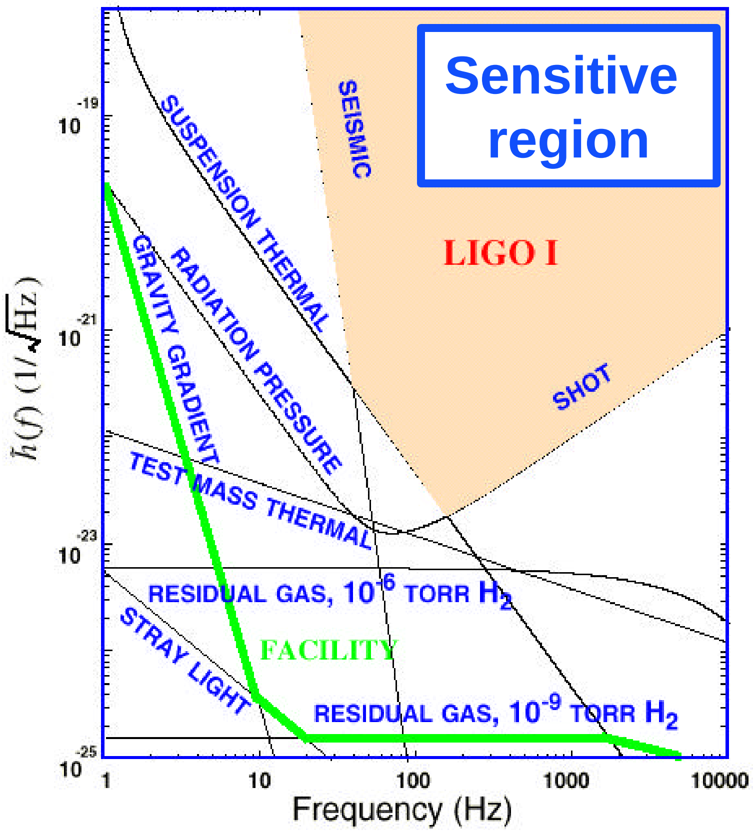
÷10,000  *Atomic diameter, 10^{-10} meter*

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

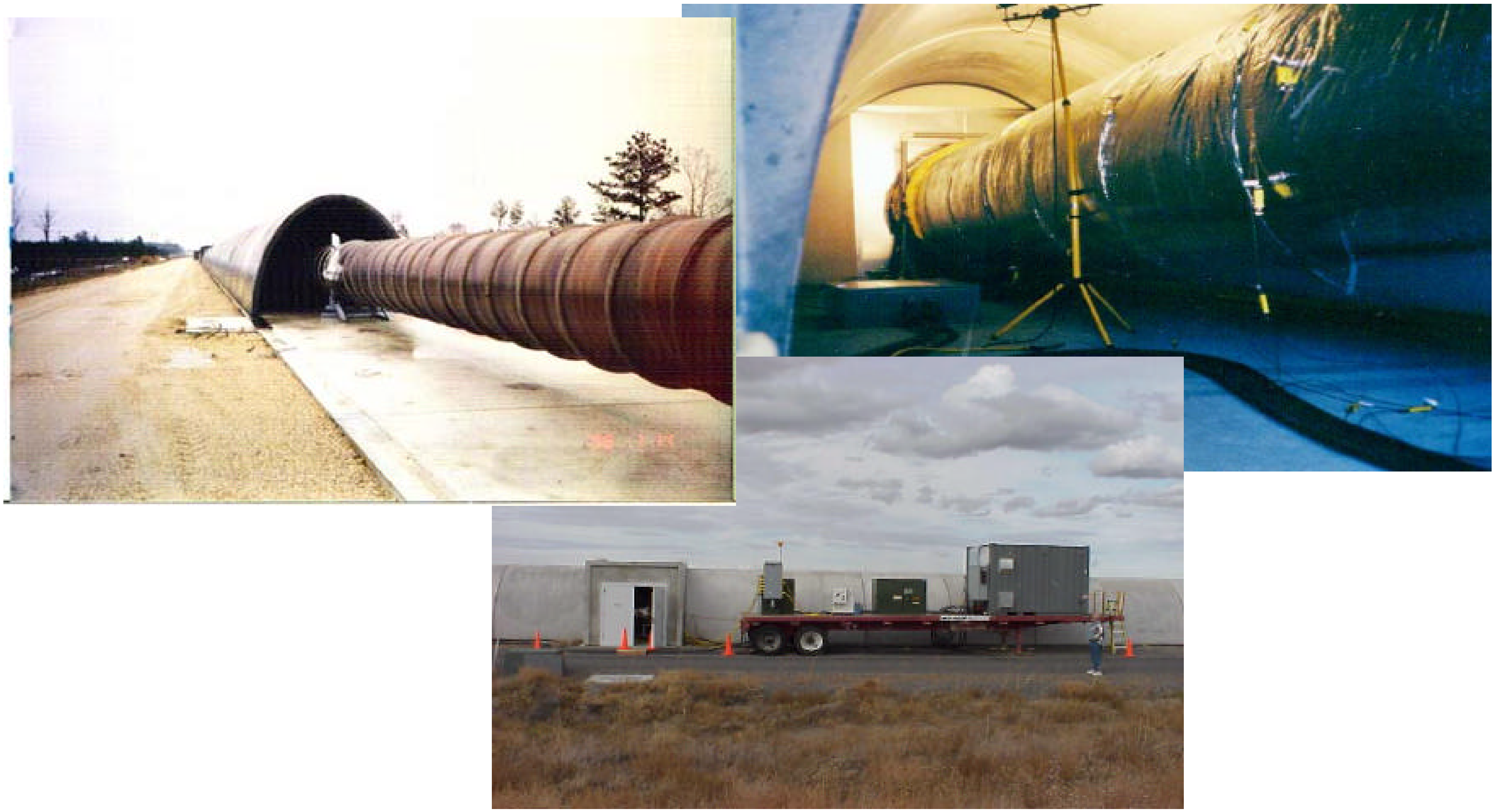
÷1,000  *LIGO sensitivity, 10^{-18} meter*

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



Evacuated Beam Tubes Provide Clear Path for Light

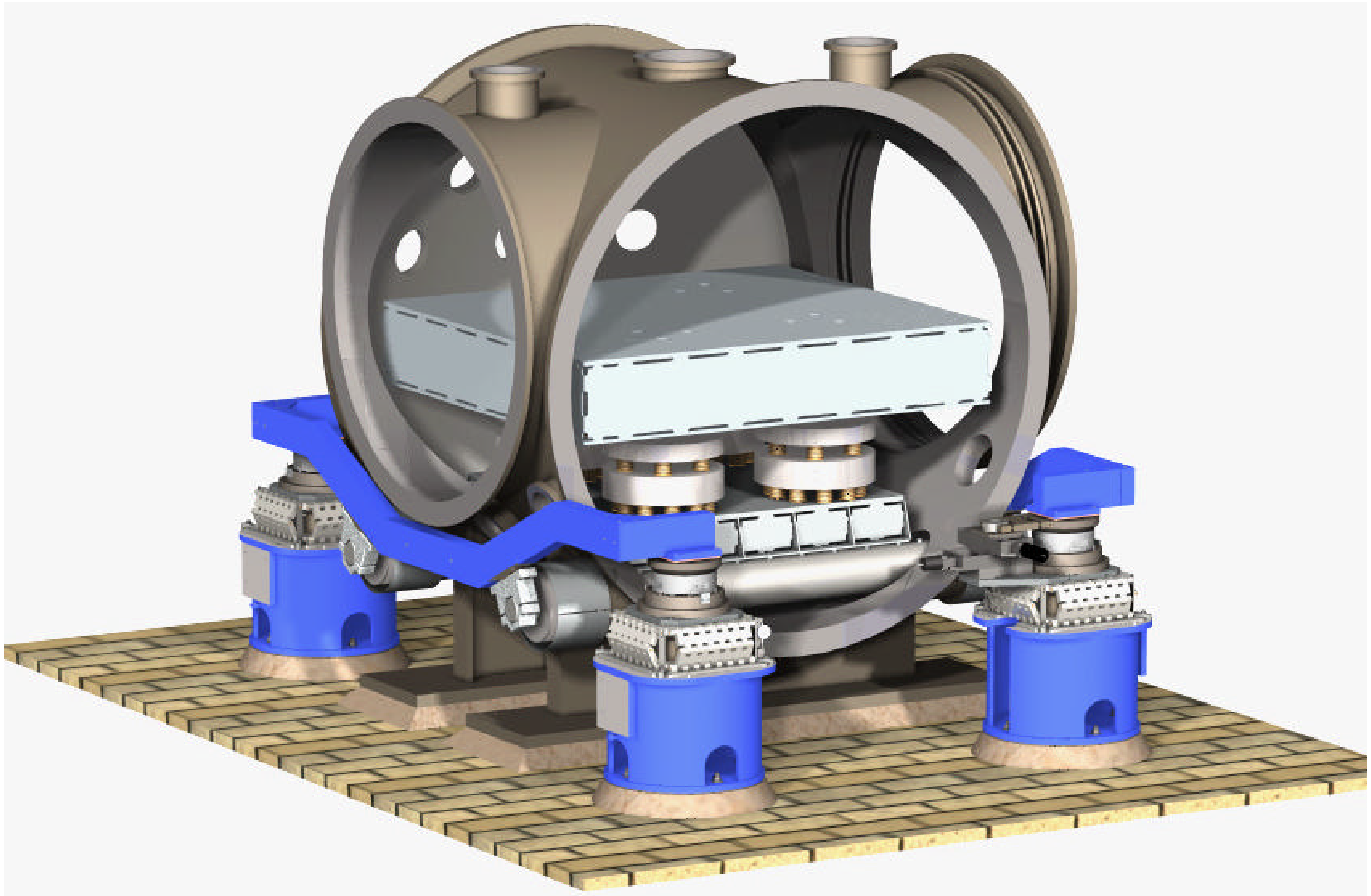


Vacuum Chambers Provide Quiet Homes for Mirrors

View inside Corner Station

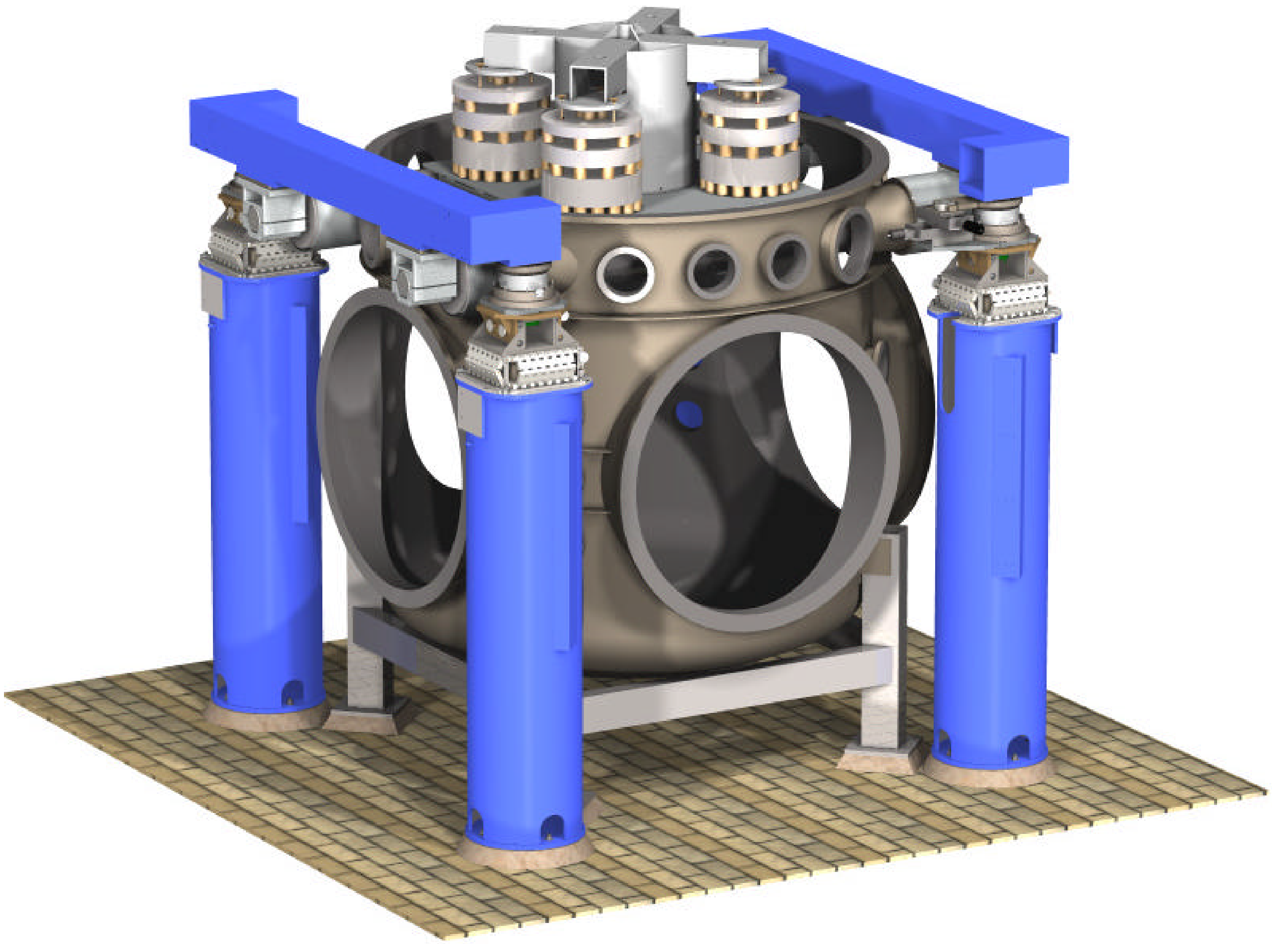
Standing at vertex beam splitter

HAM Chamber Seismic Isolation

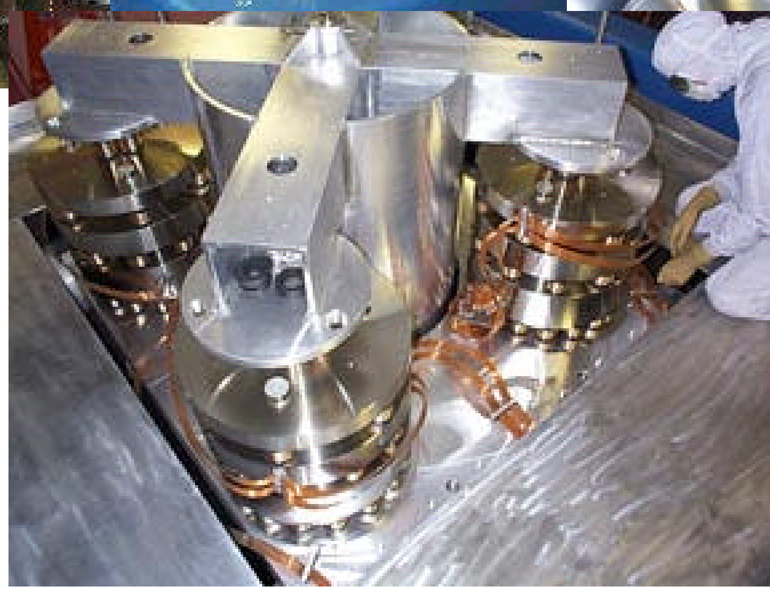


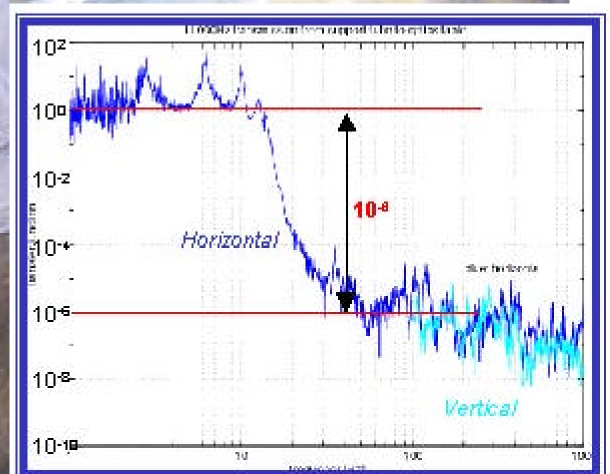
HAM Seismic Isolation Installation

BSC Chamber Seismic Isolation



BSC Seismic Isolation Installation



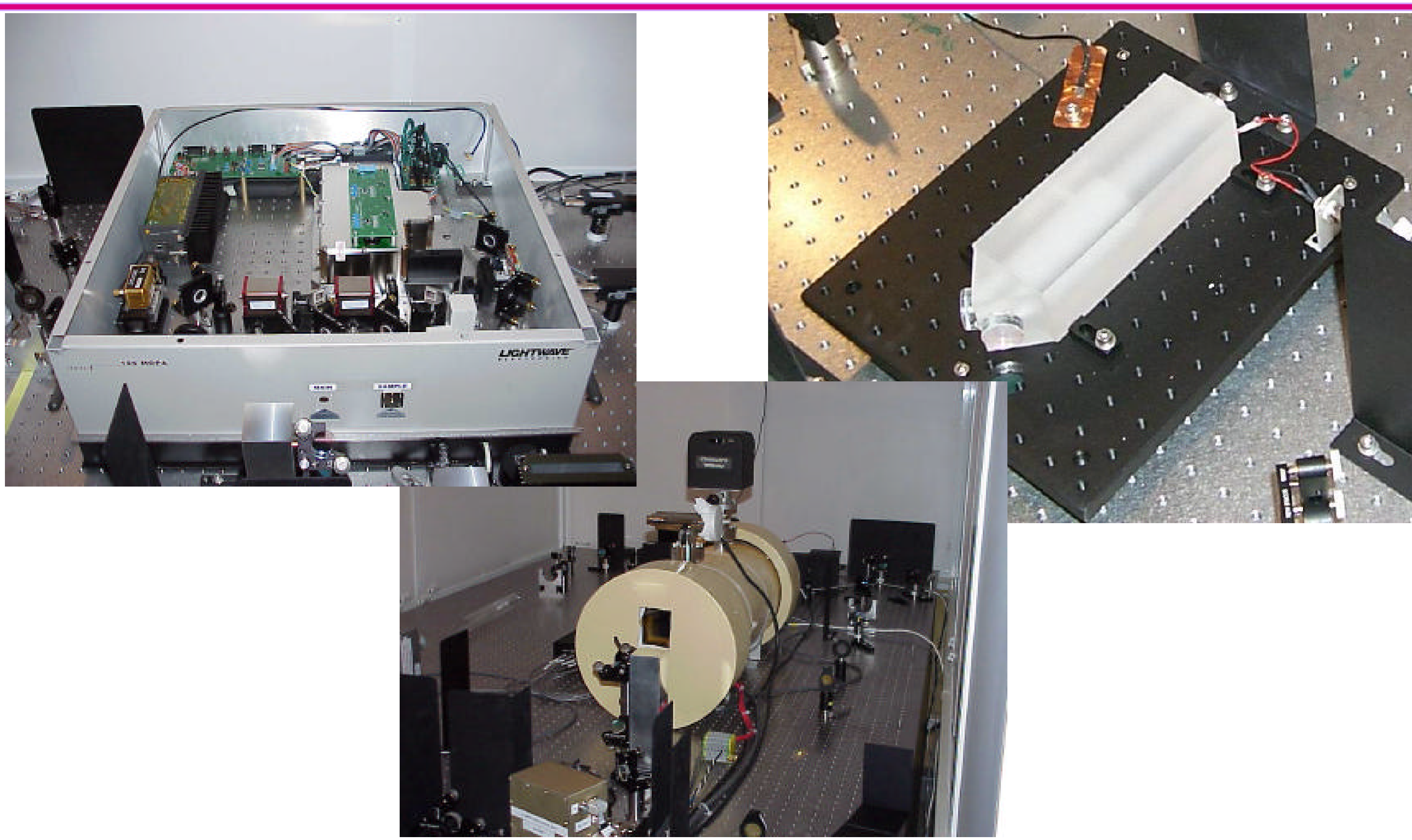


Suspended Mirrors

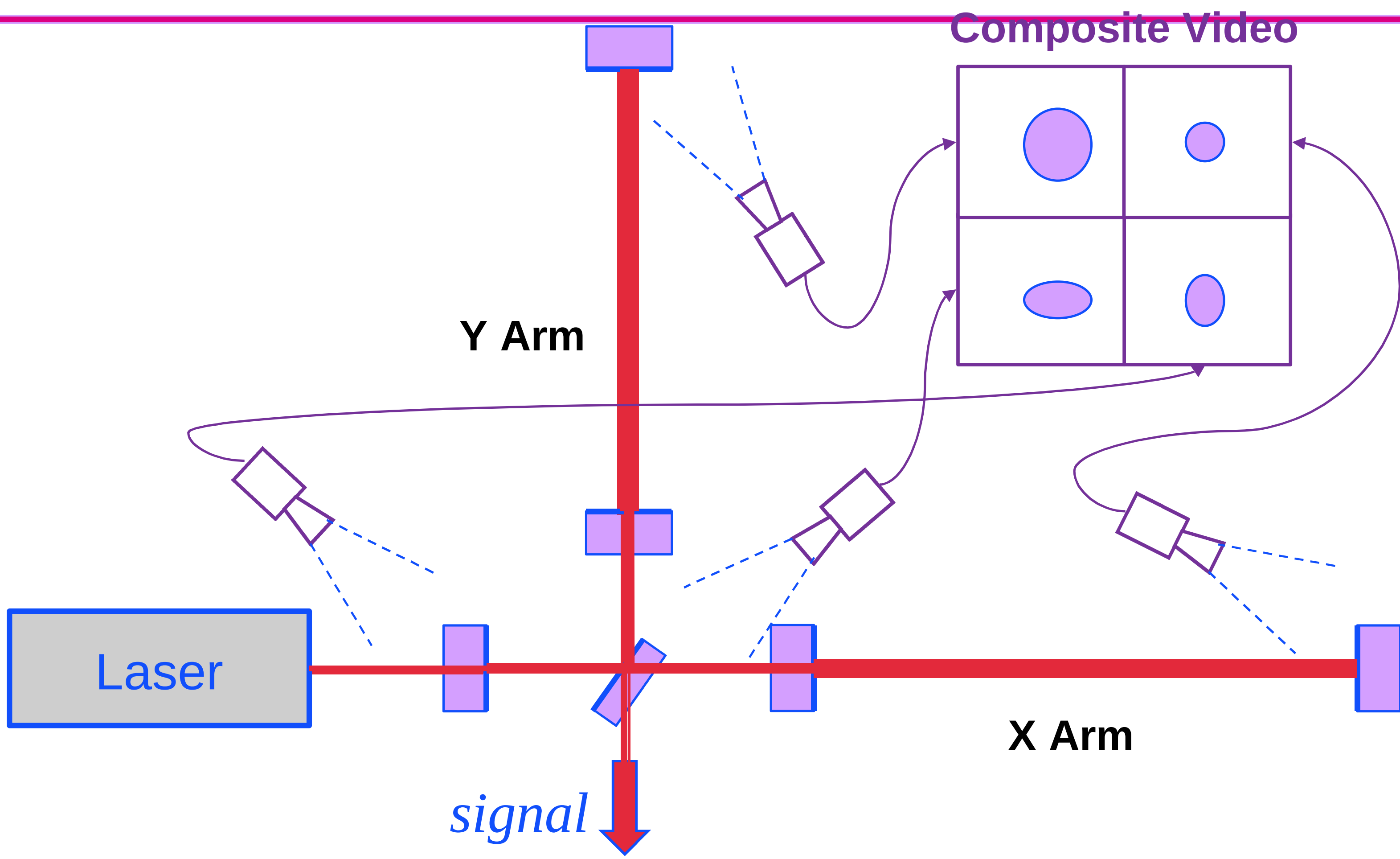
initial alignment

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

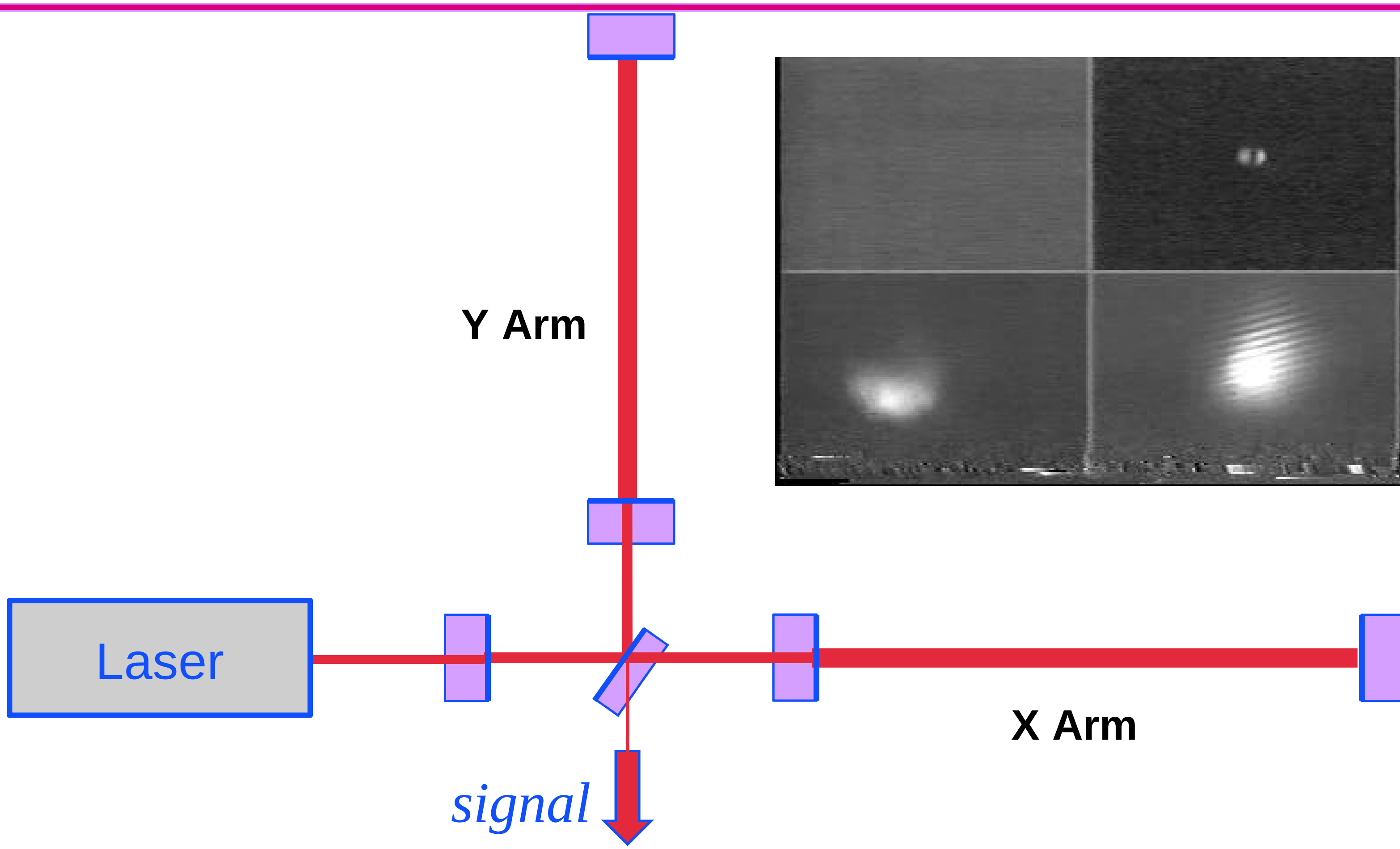
All-Solid-State Nd:YAG Laser System



Steps to Locking an Interferometer



Watching the Interferometer Lock



Why is Locking Difficult?

One meter, about 40 inches

÷ 10,000 — Earthtides, about 100 microns

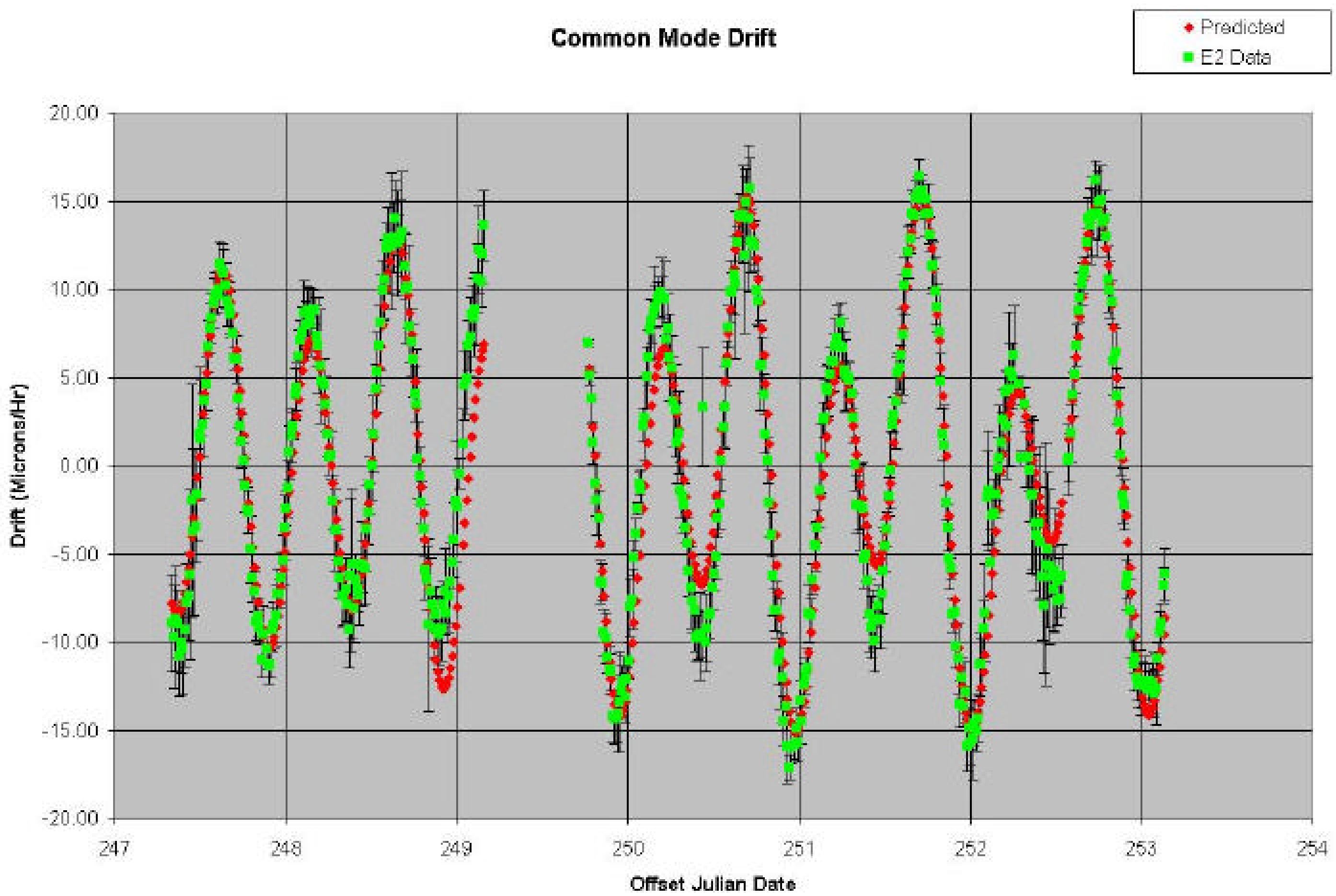
÷ 100 — Microseismic motion, about 1 micron

÷ 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

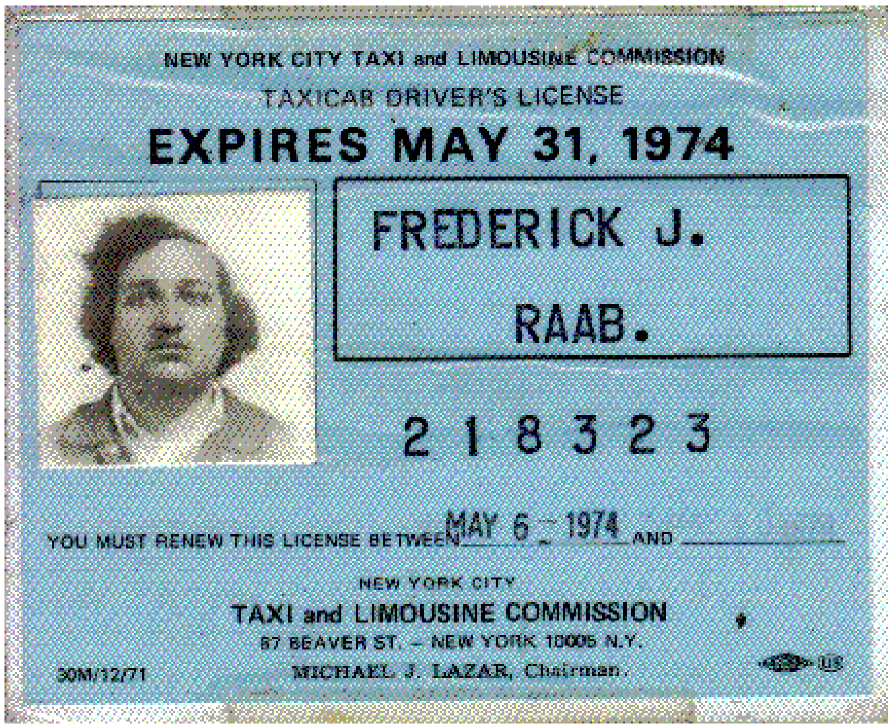


When Will It Work?
Status of LIGO in Spring 2001

- 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?)

The Universe Is Full of Surprises!

Stay tuned for the vibrations of spacetime! You never know what we will find.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TAXICAB DRIVER'S LICENSE
EXPIRES MAY 31, 1974
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RAAB.
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YOU MUST RENEW THIS LICENSE BETWEEN MAY 6 - 1974 AND
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TAXI and LIMOUSINE COMMISSION
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MICHAEL J. LAZAR, Chairman.
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