The Quest to Detect Gravitational Waves

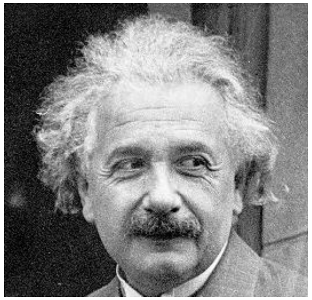
Peter Shawhan
California Institute of Technology / LIGO Laboratory

"What Physicists Do" lecture
Sonoma State University
March 8, 2004

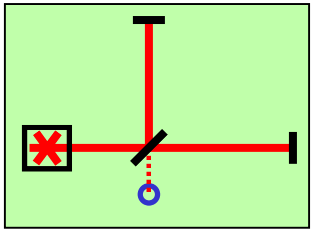
LIGO-G040055-00-E

Outline

Different Views of the Universe



Gravitational Waves



Laser Interferometry

LIGO

The New Era of Large Gravitational Wave Detectors

Different Views of the Universe

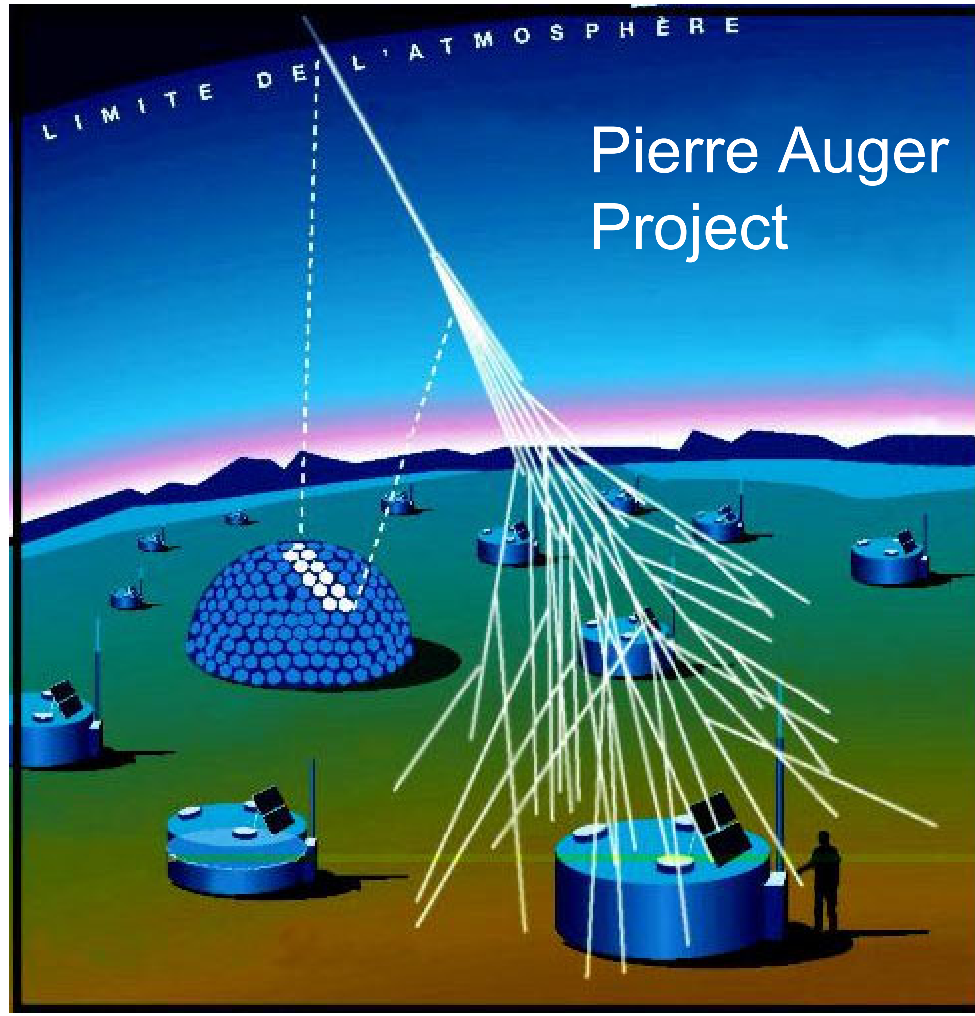
Image of the spiral galaxy M100
from "An Atlas of the Universe"
http://www.anzwers.org/free/universe

Electromagnetic Astronomy

Cosmic Ray Astronomy

A high-energy particle from outside our Galaxy interacts in atmosphere, producing a “shower” of lower-energy particles

Light emitted by the shower, and/or charged particles reaching the ground, allows trajectory and energy of original particle to be determined



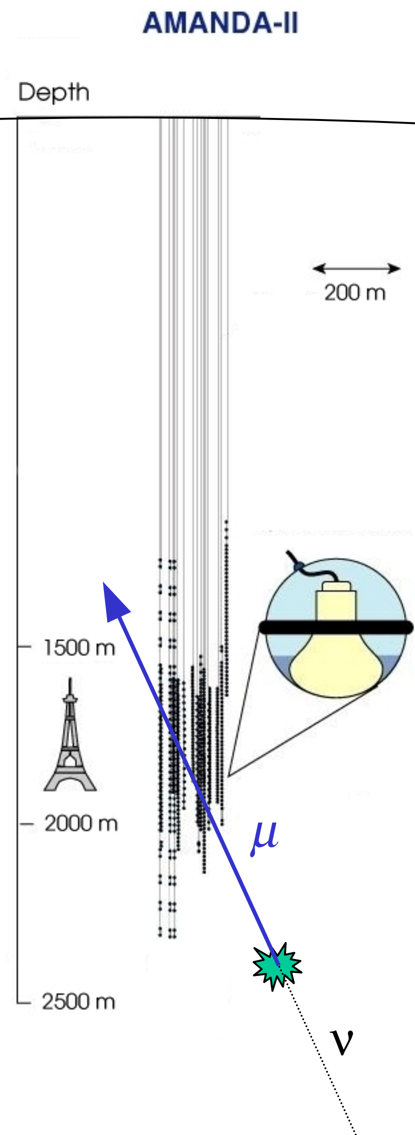
www.auger.org

Neutrino Astronomy

A neutral particle, interacting only through the "weak" nuclear force, travels a long distance before finally interacting inside the Earth

Muon or electron, detectable by Čerenkov light emission, follows trajectory of original neutrino

19 neutrinos were detected from supernova 1987A



Antarctic Muon and Neutrino Detector Array in South Pole ice

http://www.amanda.uci.edu/results.html

Gravitational Wave Astronomy ???

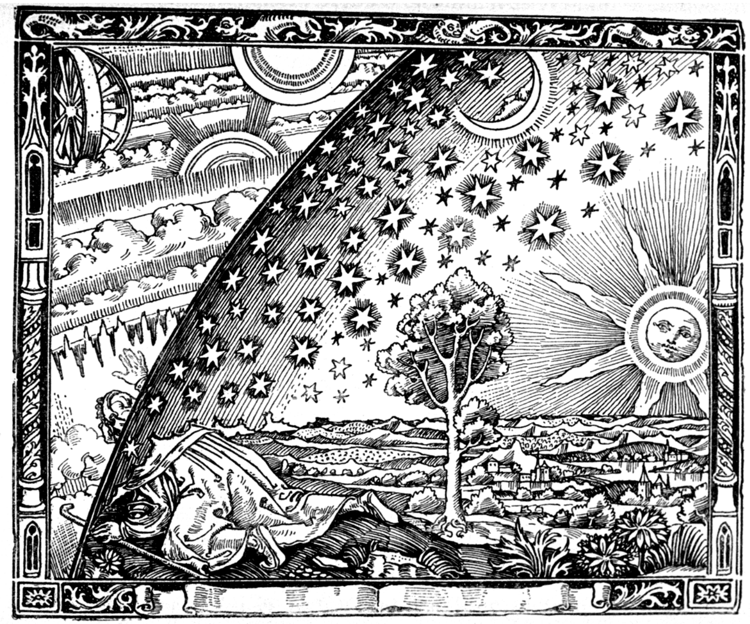
"Ripples in the geometry of space-time" produced by massive, rapidly-moving objects

Penetrate all matter

May carry unique information about black holes, neutron stars, supernovae, the early evolution of the universe, and gravity itself

But…

The waves are extremely weak when they reach Earth

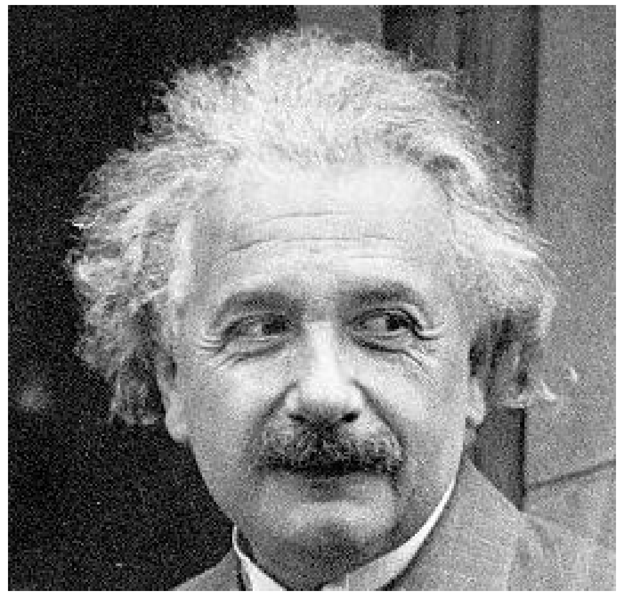


Un missionnaire du moyen âge raconte qu'il avait trouvé le point où le ciel et la Terre se touchent...

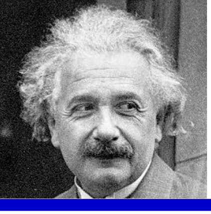
Courtesy University of Oklahoma History of Science Collections

Gravitational waves have not been directly detected – yet

Gravitational Waves



Albert Einstein, January 2, 1931
Courtesy of The Archives,
California Institute of Technology



Gravitational Waves

A consequence of Einstein's "general" theory of relativity

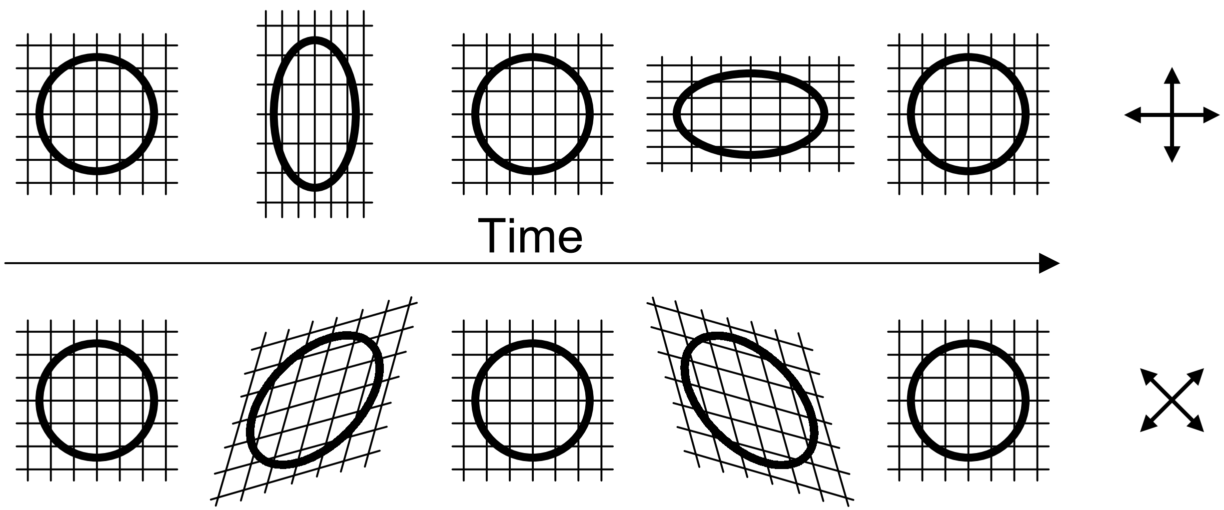
Emitted by a massive object, or group of objects, whose shape or orientation changes rapidly with time

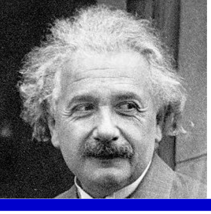
Waves travel away from the source at the speed of light

Waves deform space itself, stretching it first in one direction, then in the perpendicular direction

"Plus" polarization

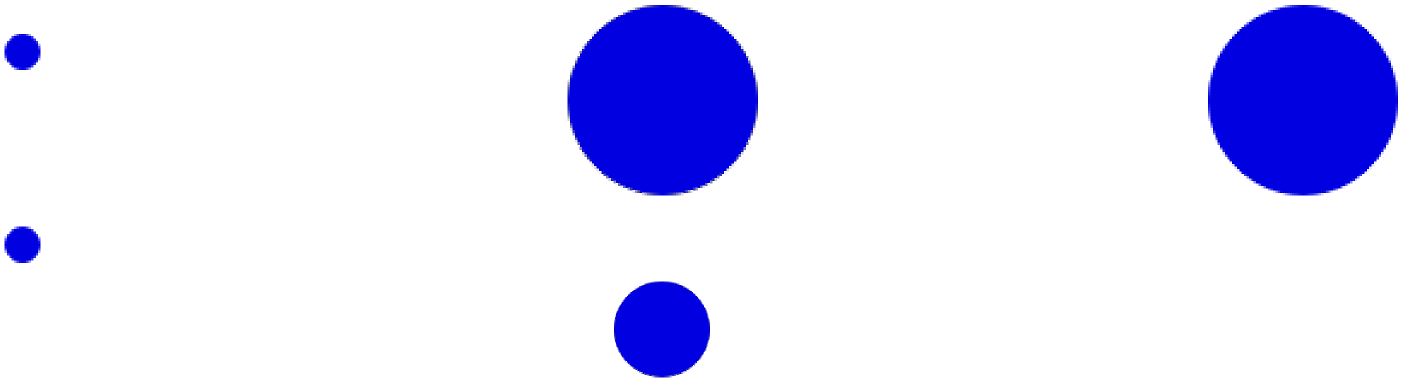
"Cross" polarization





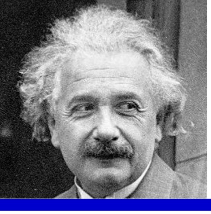
Gravitational Waves in Action

Two massive,
compact objects
in a tight orbit deform space (and any object
in it) with a frequency which
is twice the orbital frequency



The stretching is proportional to the size of the object, *i.e.* described by a dimensionless "strain", $h = \Delta L / L$

h is inversely proportional to the distance from the source



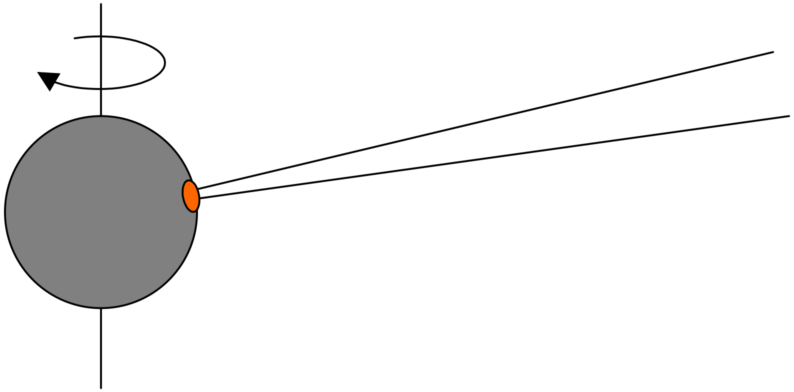
Aside: Pulsars

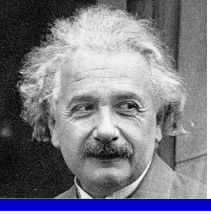
Sources of repeating radio and/or x-ray emissions with a regular period

First discovered in 1968 – a few thousand known now

Period is typically extremely stable, but with a gradual slowdown
⇒ must be a small, spinning object

⇒ a neutron star with a radio "hot spot" on its surface !
(a supernova remnant, more massive than the sun but with r < 10 km)



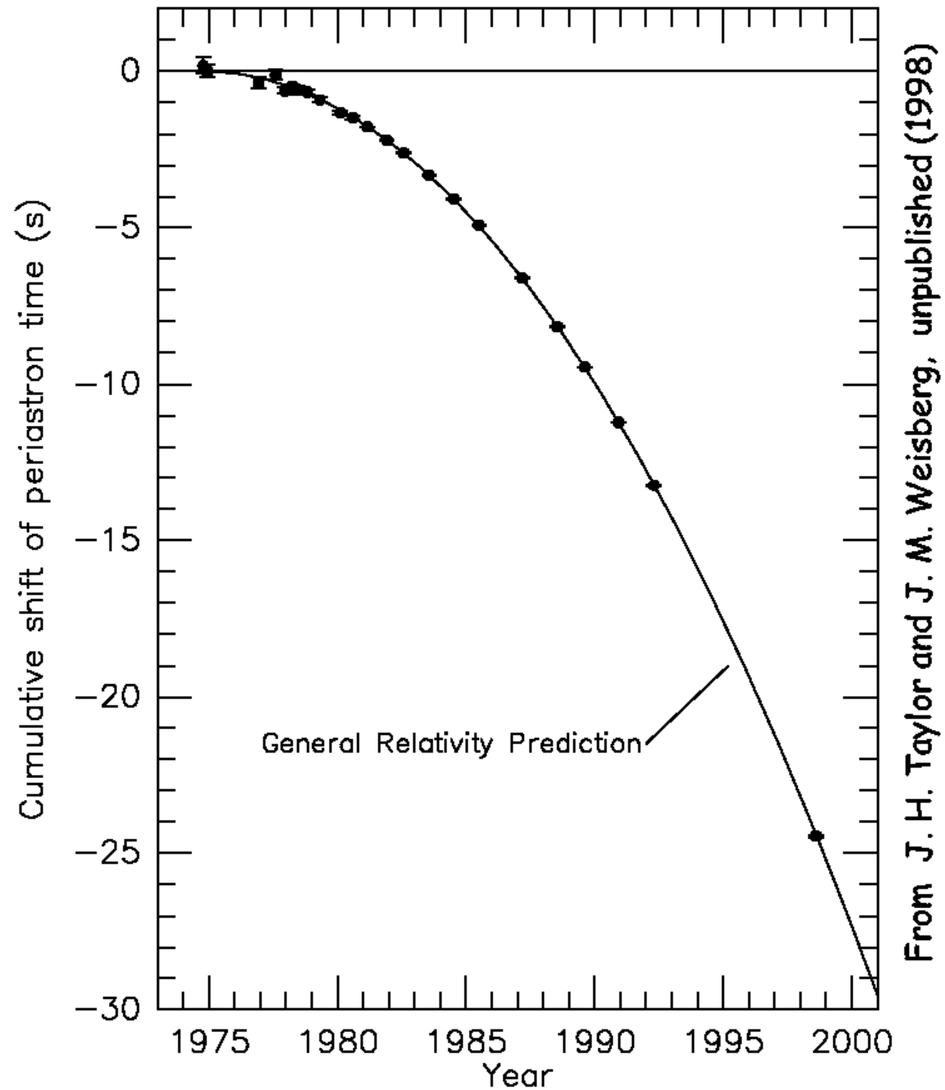


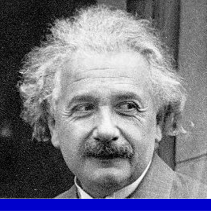
The Binary Pulsar PSR1913+16

Discovered in 1974 by Russell Hulse and Joseph Taylor

Long-term observations have yielded object masses (1.44 and 1.39 $M_{\odot}$) and orbital parameters

System shows very gradual orbital decay – just as general relativity predicts!
⇒ Very strong indirect evidence for gravitational radiation

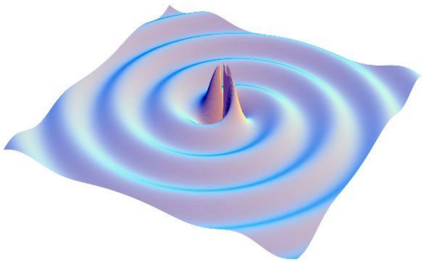




Potential Sources of Directly-Detectable Gravitational Waves

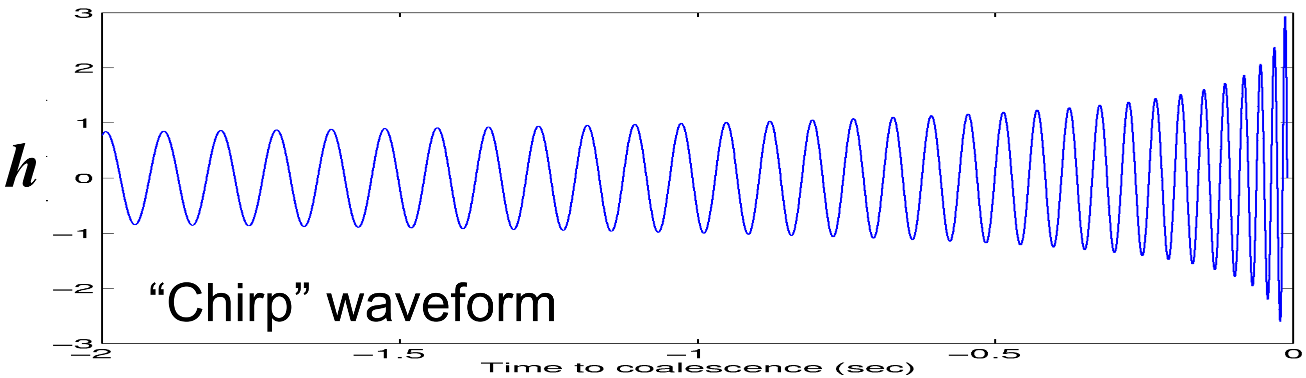
"Inspiral" (orbital decay) of a compact binary system

Two neutron stars, two black holes, or one of each



One of the most promising sources, since:

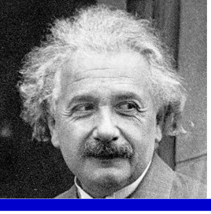
- Binary neutron-star systems are known to exist
- The waveform and source strength are fairly well known (until just before merging)



Merger of two compact objects

Gravity in the extreme strong-field limit

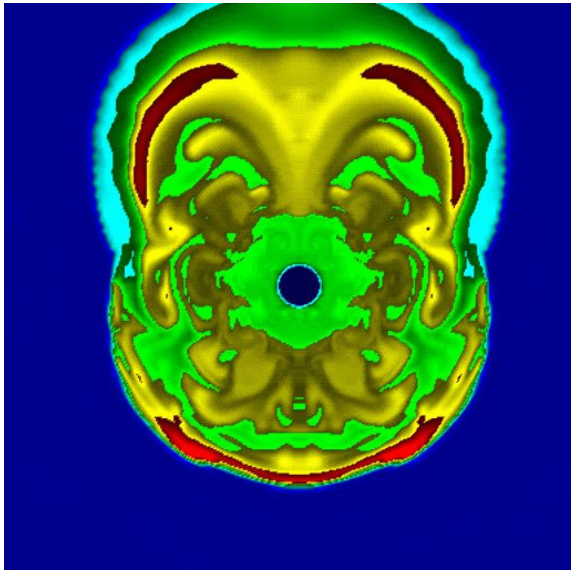
Waveforms unknown – a subject for numerical relativity calculations



Potential Sources of Directly-Detectable Gravitational Waves

Supernova explosion

- Wave emission depends on asymmetry of explosion
- Example numerical simulation →



Tony Mezzacappa
Oak Ridge National Laboratory

"Ringing" oscillations of a newly formed black hole

Rapidly-spinning neutron star

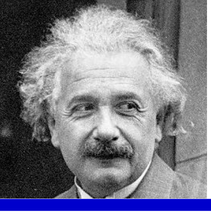
- Will radiate continuously if slightly asymmetric

Stochastic radiation from the early universe

- Shows up as correlated noise in different detectors

"Unexpected" sources ?

This is a new observational science !



The Experimental Challenge

Sources are expected to be rare

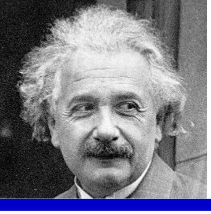
⇒ Have to be able to search a large volume of space

⇒ Have to be able to detect very weak signals

Typical strain at Earth: $h \sim 10^{-21}$!

Stretches the diameter of the Earth by ~ 10^{-14} m
(about the size of an atomic nucleus)

How can we possibly measure such small length changes ???



First Type of Gravitational Wave Detectors

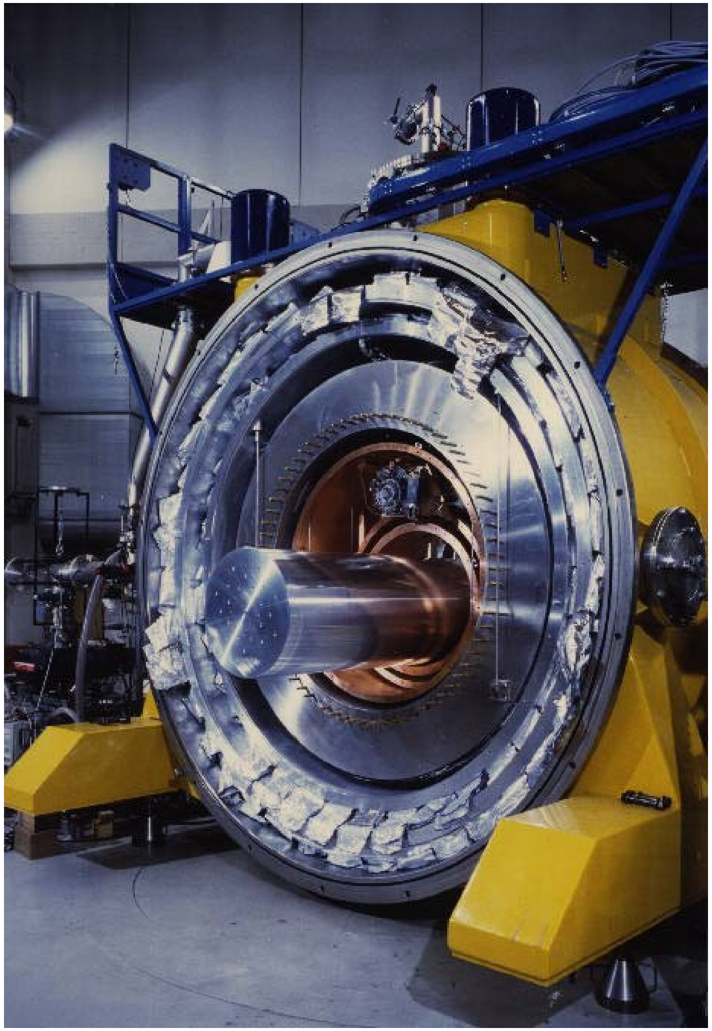
Resonant aluminum “bars”

- Suspended in the middle
- Ring if excited by a gravitational wave

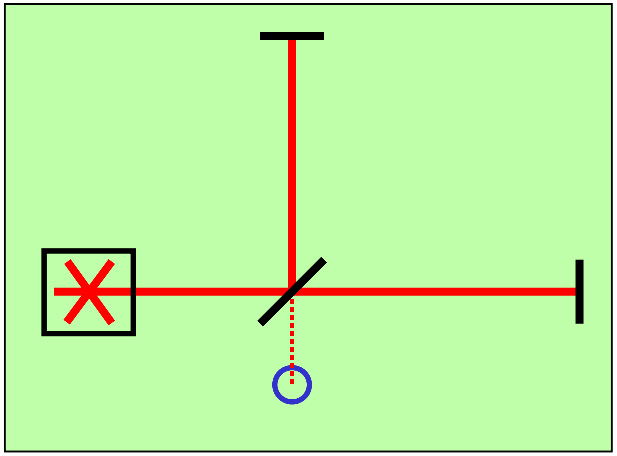
First built by Joseph Weber in the 1960s

A few cryogenic bars are currently in operation and achieve high sensitivity at their resonant frequencies

AURIGA detector →



Laser Interferometry

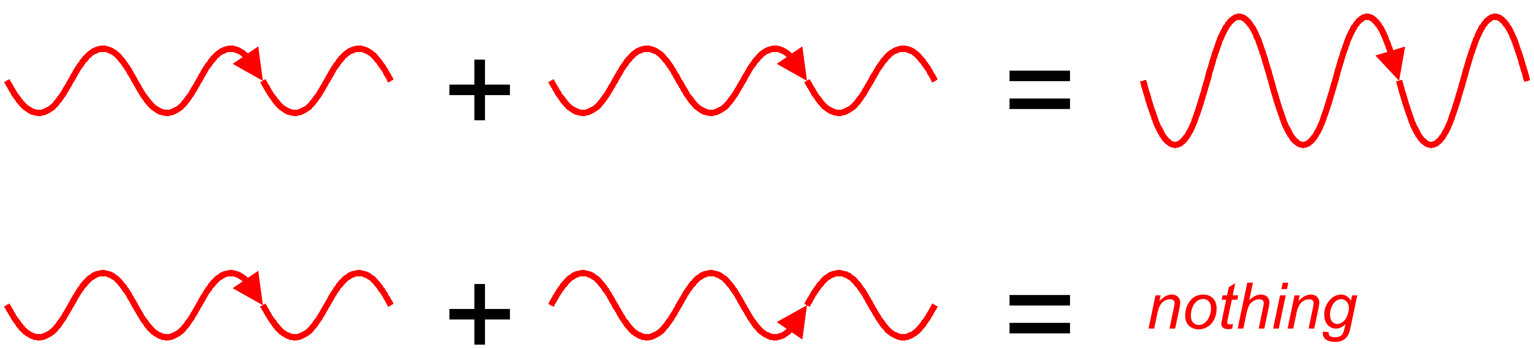


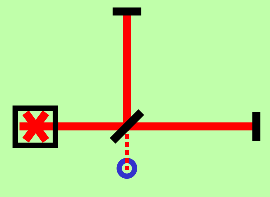
Interference of Light

Light consists of oscillating electric and magnetic fields

When two light beams meet, the electric & magnetic field amplitudes add

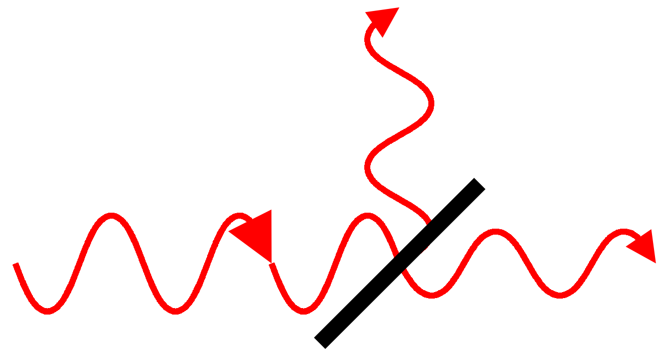
Depending on the relative phase, can get constructive or destructive interference



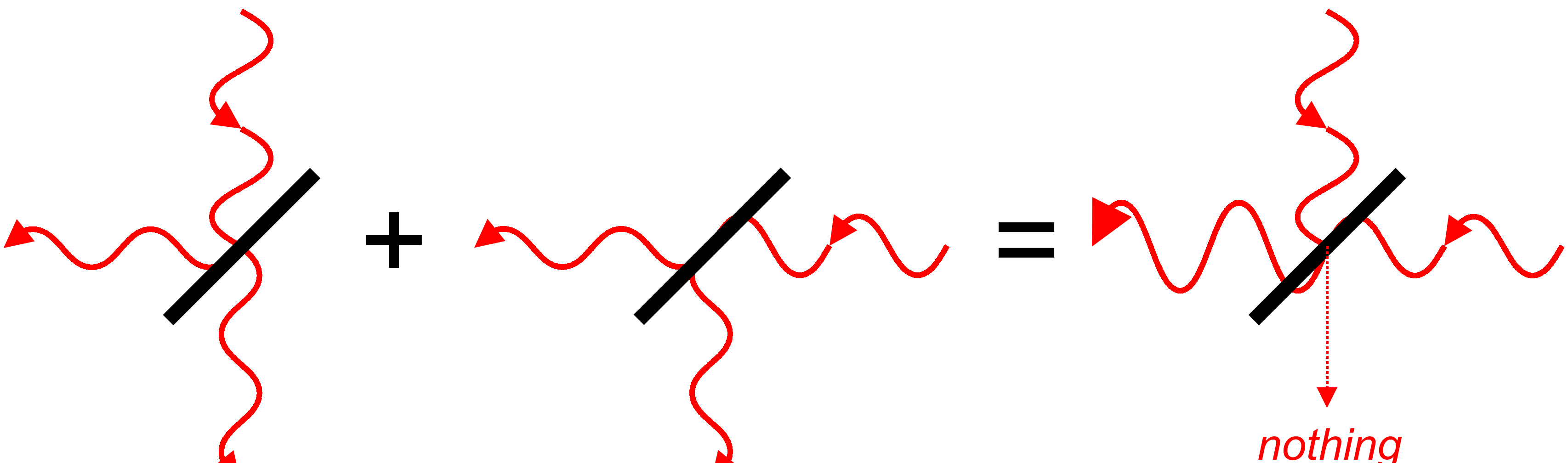


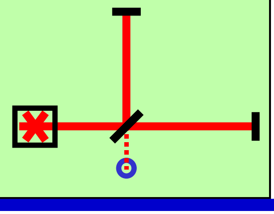
Interference at a Beam Splitter

A *beam splitter* reflects half of the incoming beam power ($1/\sqrt{2}$ of the EM field amplitude) and transmits other half



A beam splitter can also *combine* beams; the outputs depend on the relative phases of the input beams



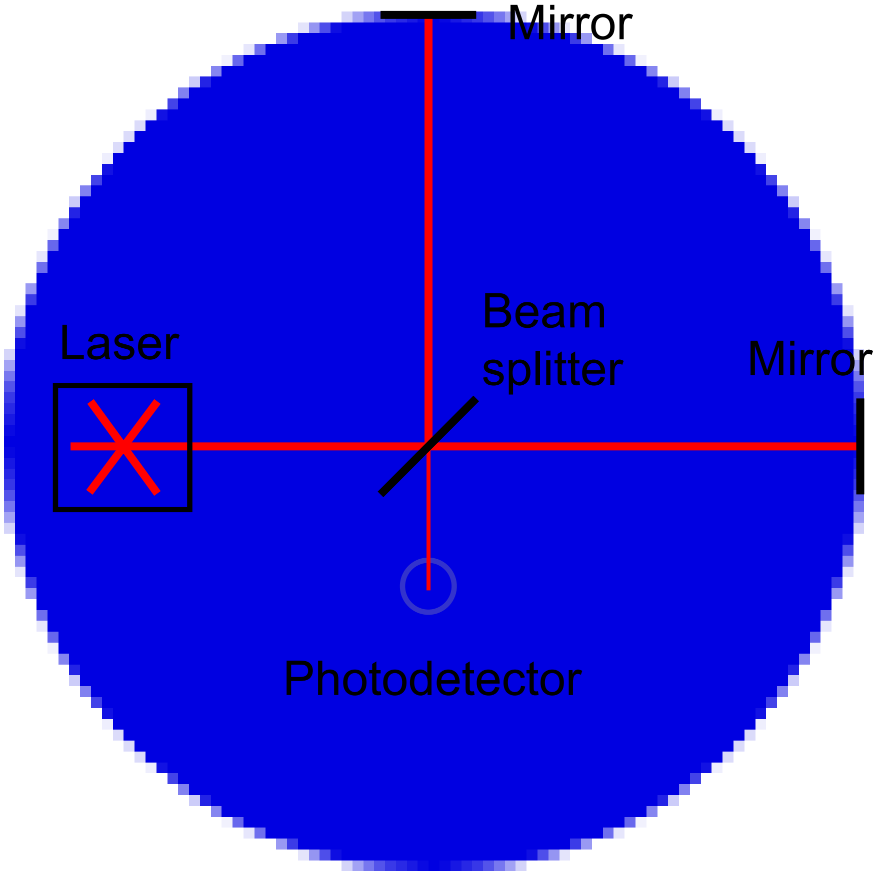


Basic Michelson Interferometer

Basic design first used by Albert A. Michelson in 1881

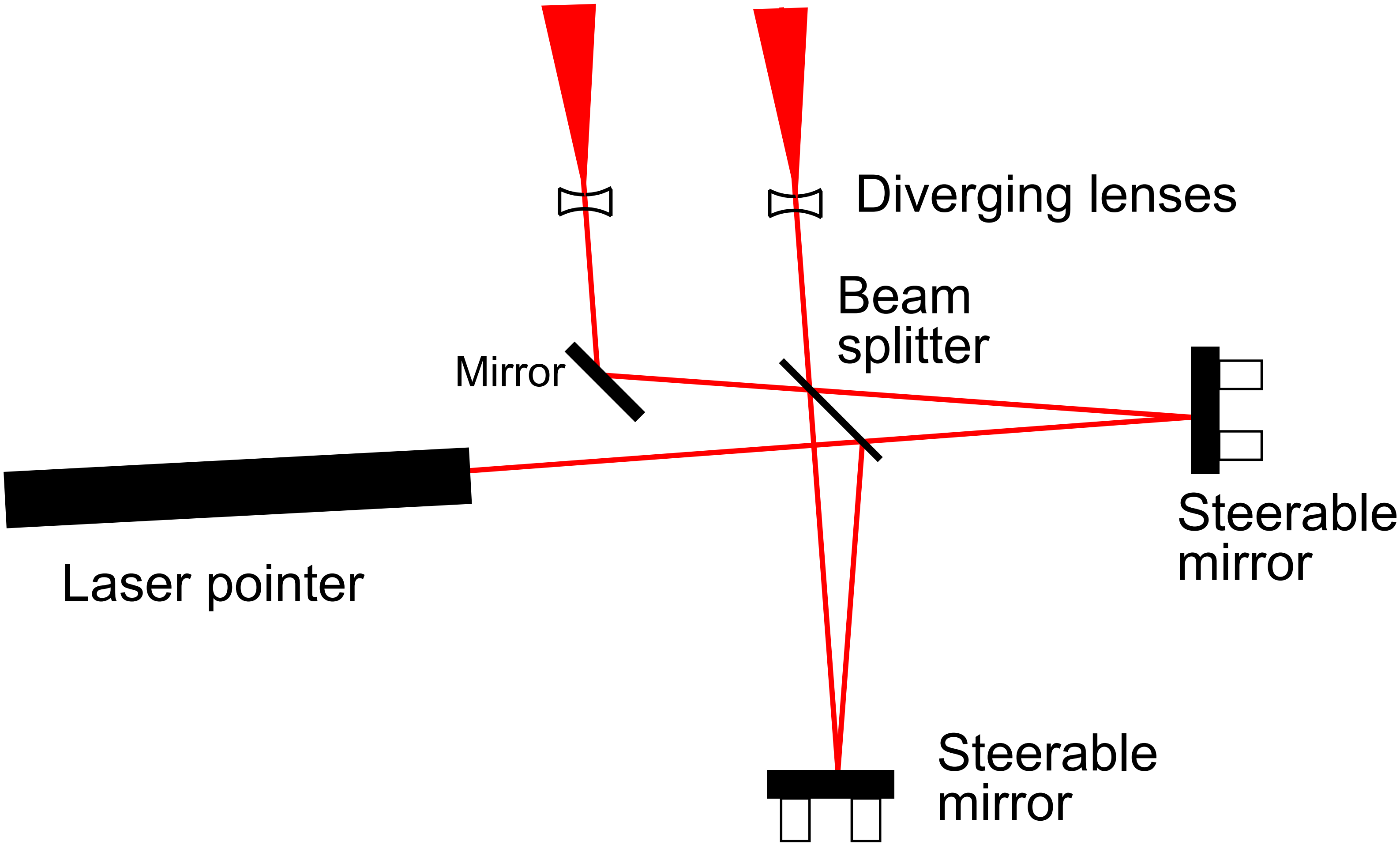
Light intensity on photodetector depends on *difference* in light travel times in the two perpendicular "arms"

Can measure length differences which are a small fraction of the wavelength of the light



Perfect for gravitational wave detection !
Has a broad antenna pattern

Demonstration Interferometer



The New Era of Large Gravitational Wave Detectors

LIGO

The LIGO Project

LIGO = Laser Interferometer Gravitational-Wave Observatory

Has constructed three large interferometers at two sites

Funded by the National Science Foundation

- Construction cost ~ $300 million
- Operating cost ~ $30 million per year

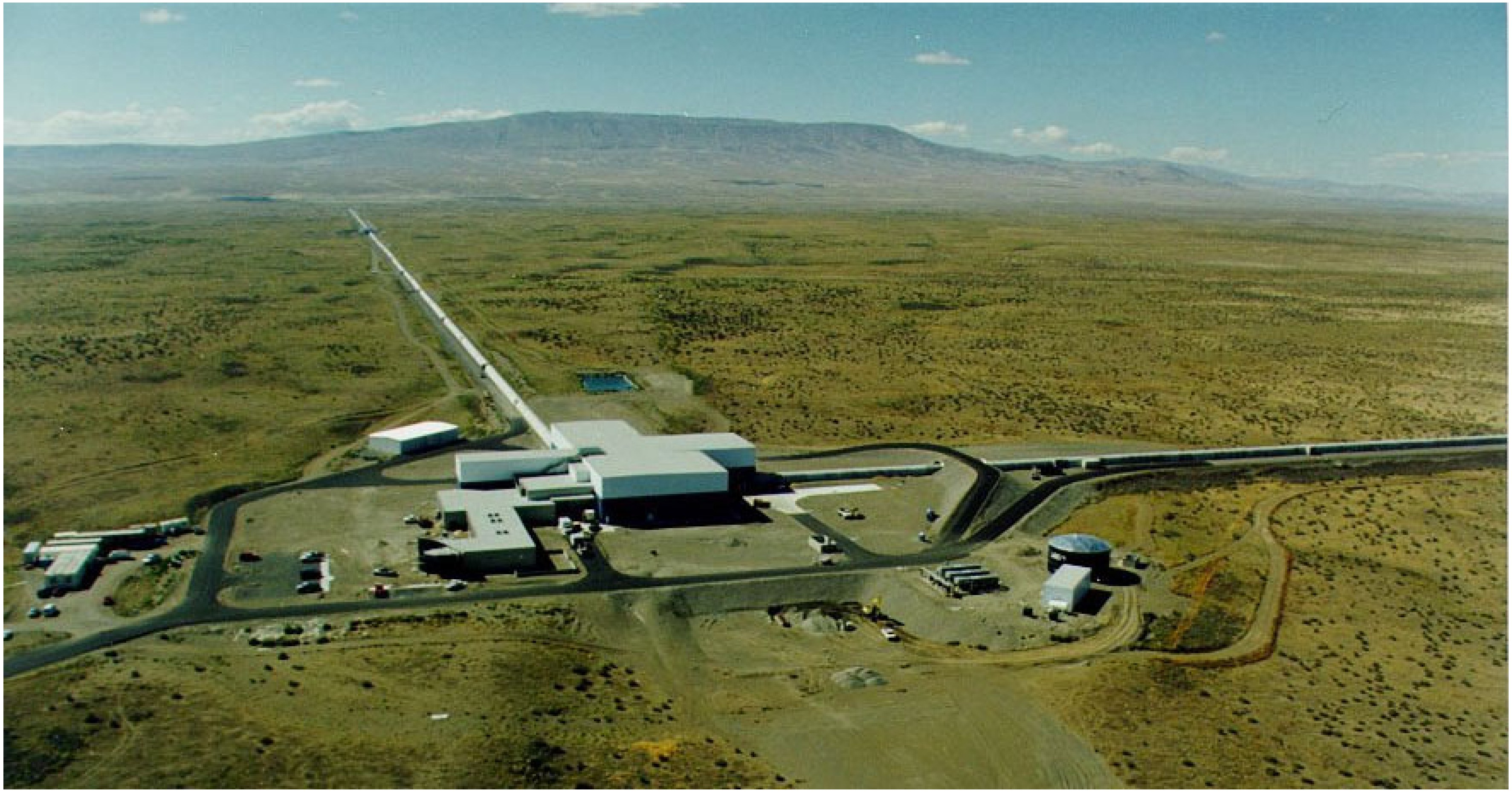
Led by the "LIGO Laboratory", based at Caltech and MIT

Scientific activities (data analysis, advanced detector R&D) are the responsibility of the "LIGO Scientific Collaboration" (LSC)

- Over 400 scientists at over 30 institutions around the world

LIGO Hanford Observatory

Located on DOE Hanford Nuclear Reservation north of Richland, Washington



Two separate interferometers (4 km and 2 km arms) coexist in the beam tubes

LIGO Livingston Observatory

Located in a rural area of Livingston Parish east of Baton Rouge, Louisiana

Has one interferometer with 4 km arms

Design Requirements

Even with 4-km arms, the length change due to a gravitational wave is *very* small, typically ~ 10^{-18} - 10^{-17} m

- Wavelength of laser light = 10^{-6} m

Need a more sophisticated interferometer design to reach this sensitivity

- Add partially-transmitting mirrors to form resonant optical cavities
- Use feedback to lock mirror positions on resonance

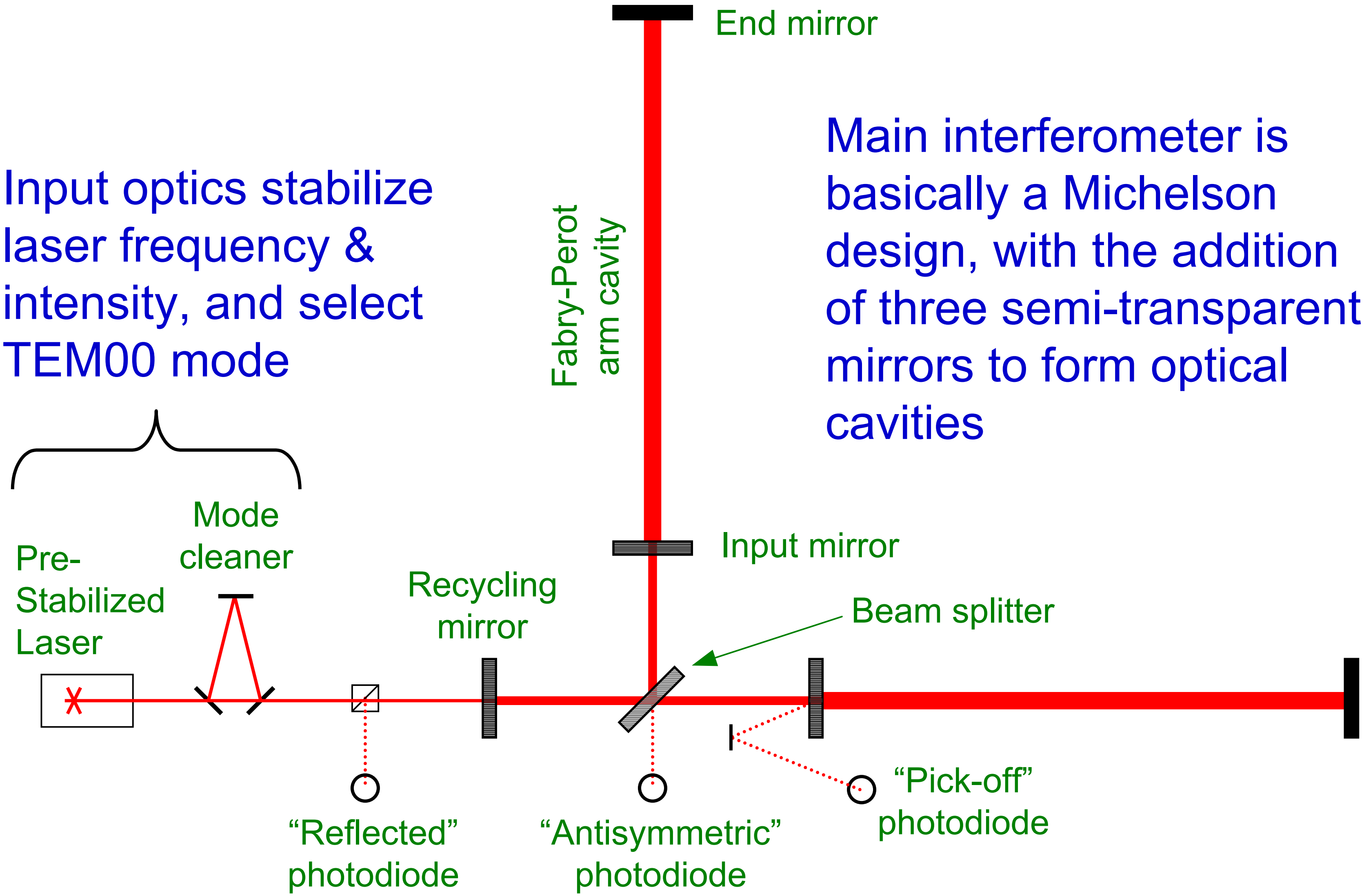
Need to control noise sources

- Stabilize laser frequency and intensity
- Use large mirrors to reduce quantum position uncertainty
- Isolate interferometer optics from environment
- Focus on a “sweet spot” in frequency range

Optical Layout
(not to scale)

Input optics stabilize laser frequency & intensity, and select TEM00 mode

Main interferometer is basically a Michelson design, with the addition of three semi-transparent mirrors to form optical cavities



Servo Controls

Optical cavities must be kept in resonance

- Need to control lengths to within a small fraction of a wavelength – “lock”
- Nearly all of the disturbance is from low-frequency ground vibrations

Use a clever scheme to sense and control all four length degrees of freedom

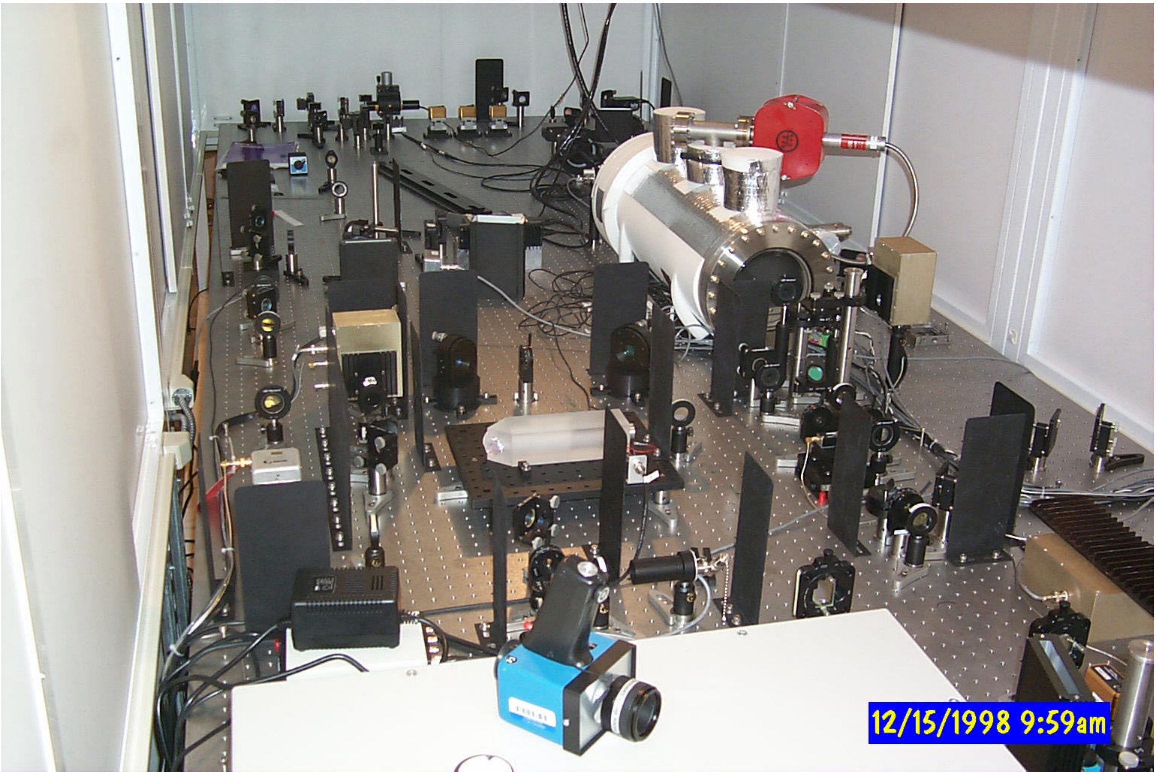
- Modulate phase of laser light at RF
- Demodulate signals at photodiodes
- Perform a basis transformation, apply digital filters
- Feed back to coil-and-magnet actuators on various mirrors

Arrange for destructive interference at “antisymmetric port”

Pre-Stabilized Laser

Based on a 10-Watt Nd:YAG laser (infrared)

Uses additional sensors and optical components to locally stabilize the frequency and intensity



Final stabilization uses feedback from average arm length

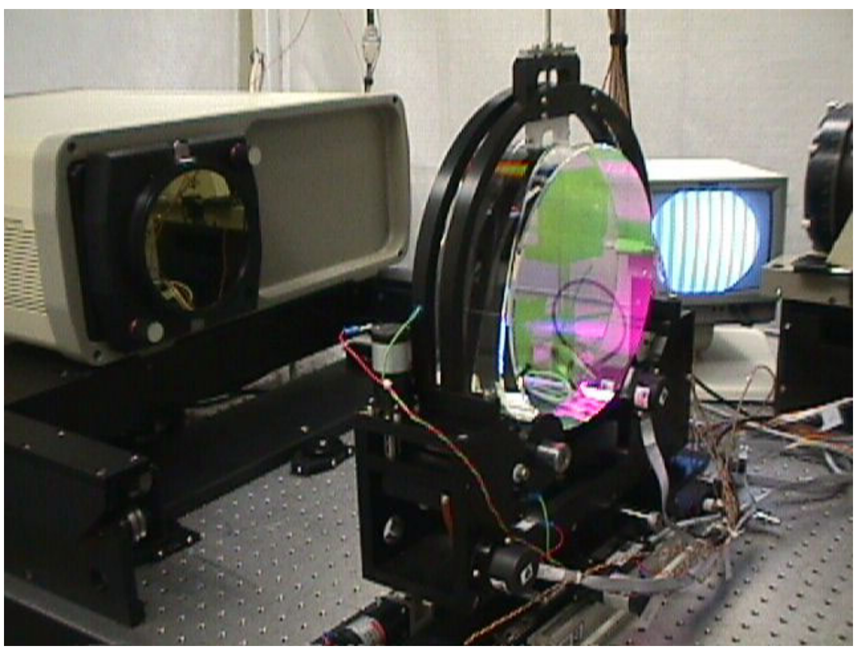
Mirrors

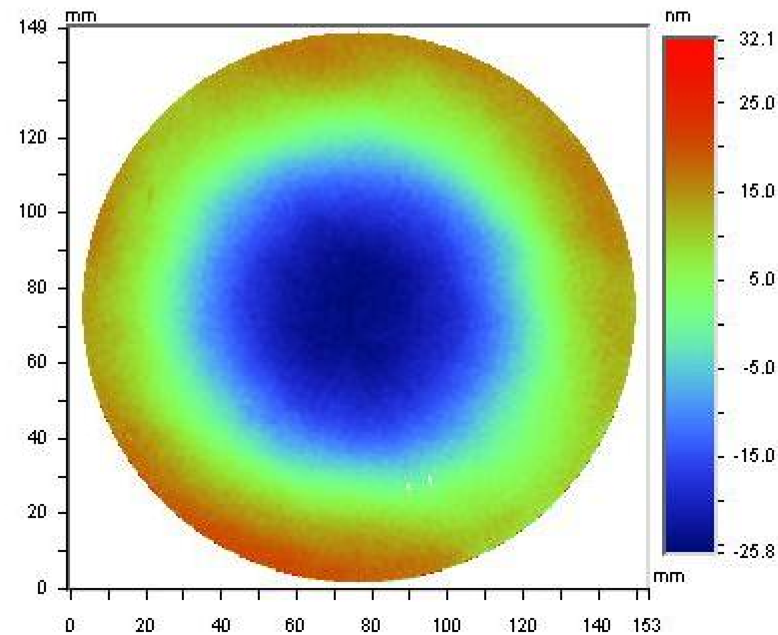
Made of high-purity fused silica

Largest mirrors are 25 cm diameter, 10 cm thick, 10.7 kg

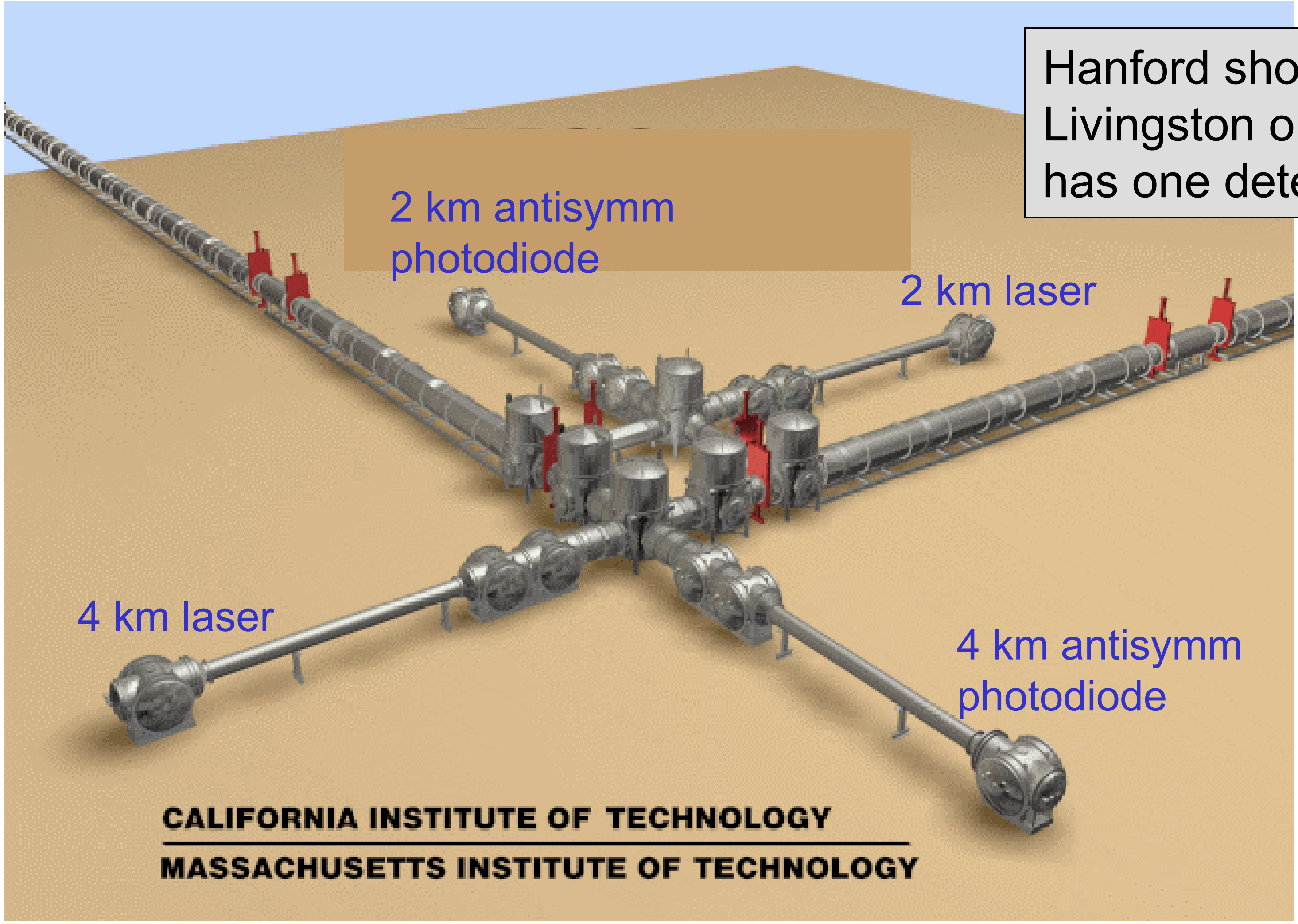
Surfaces polished to ~1 nm rms, some with slight curvature

Coated to reflect with extremely low scattering loss (<50 ppm)





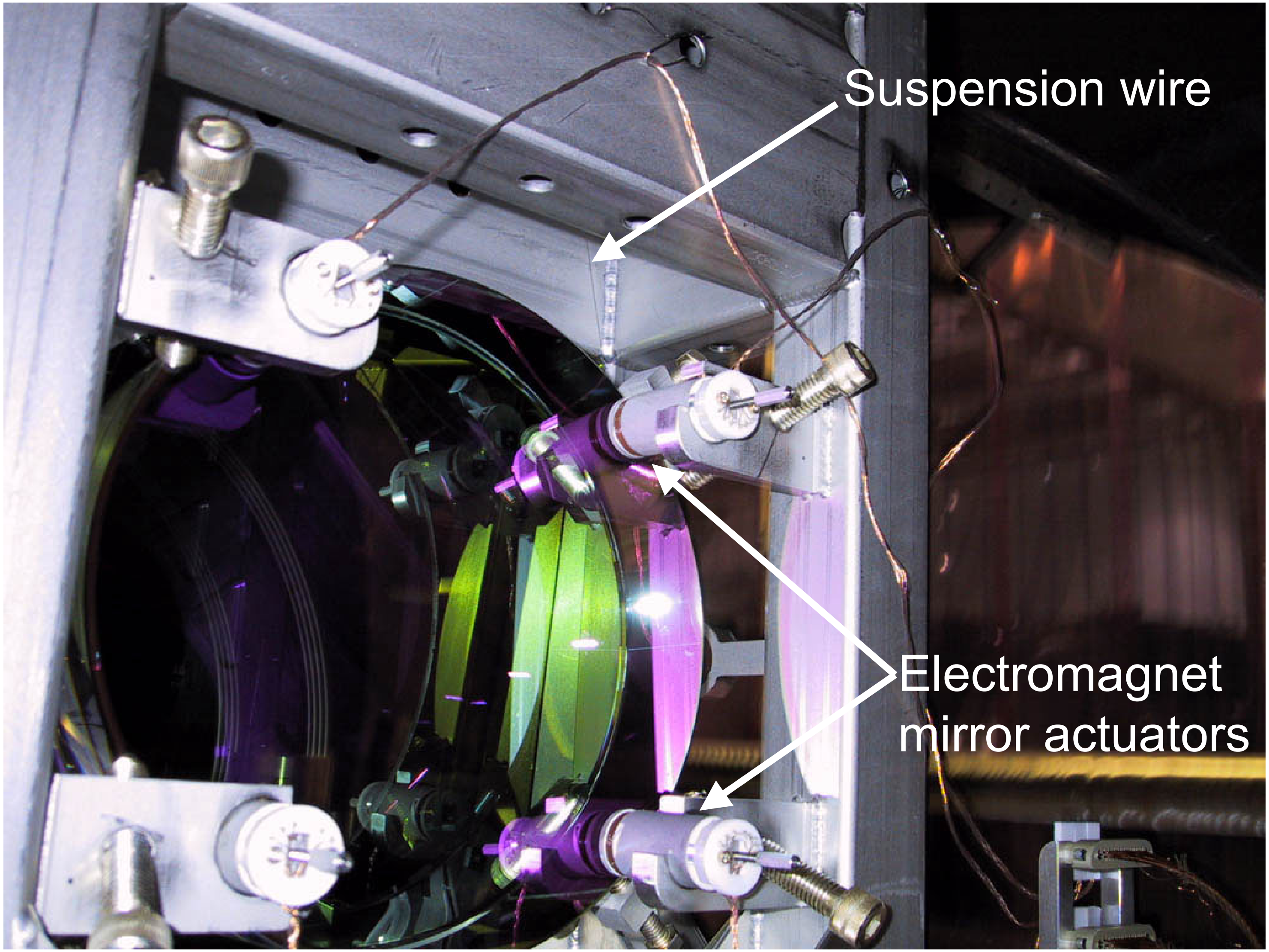
Vacuum System



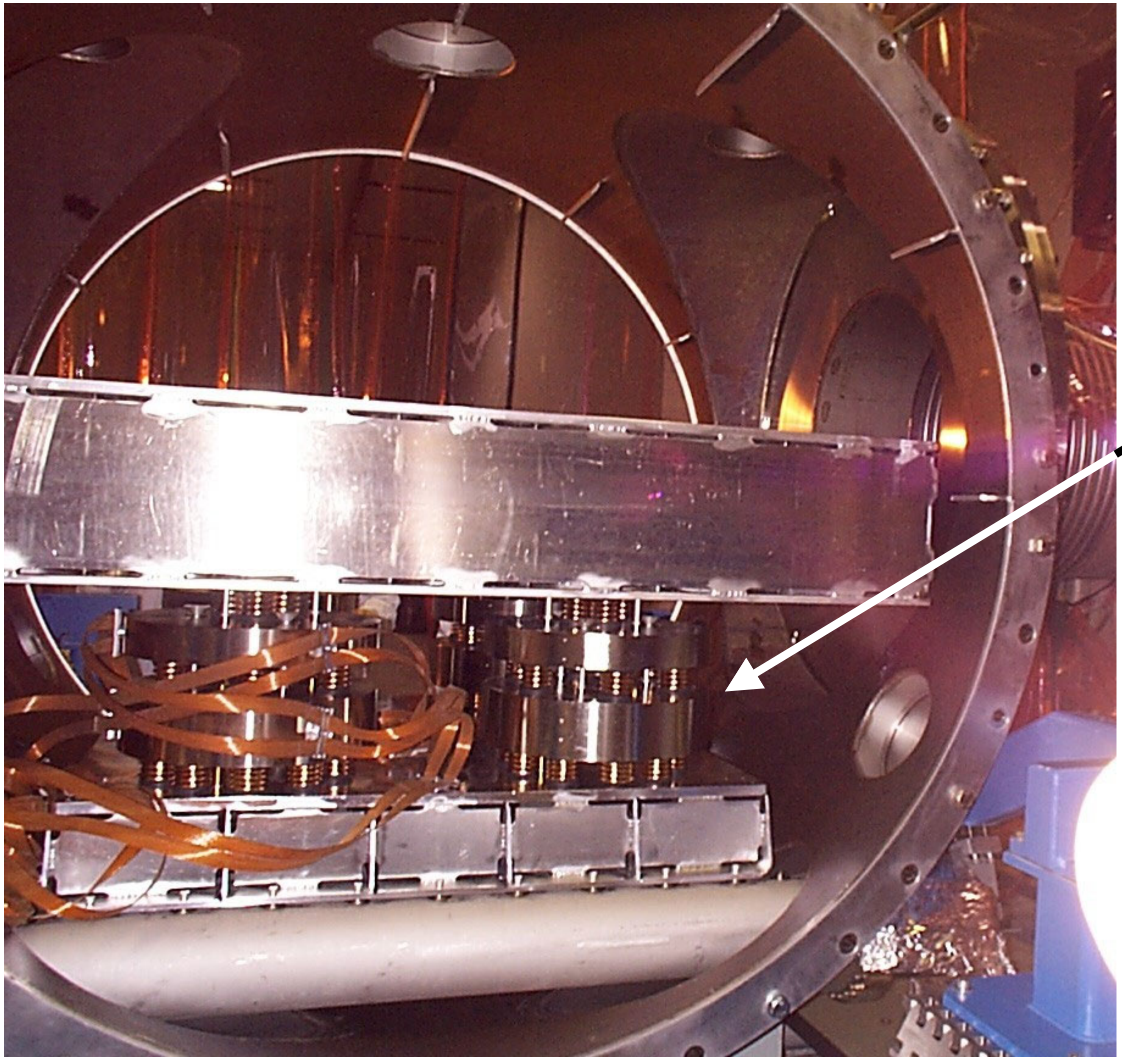
Vacuum System

A Mirror *in situ*

Mirror Close-Up



Vibration Isolation

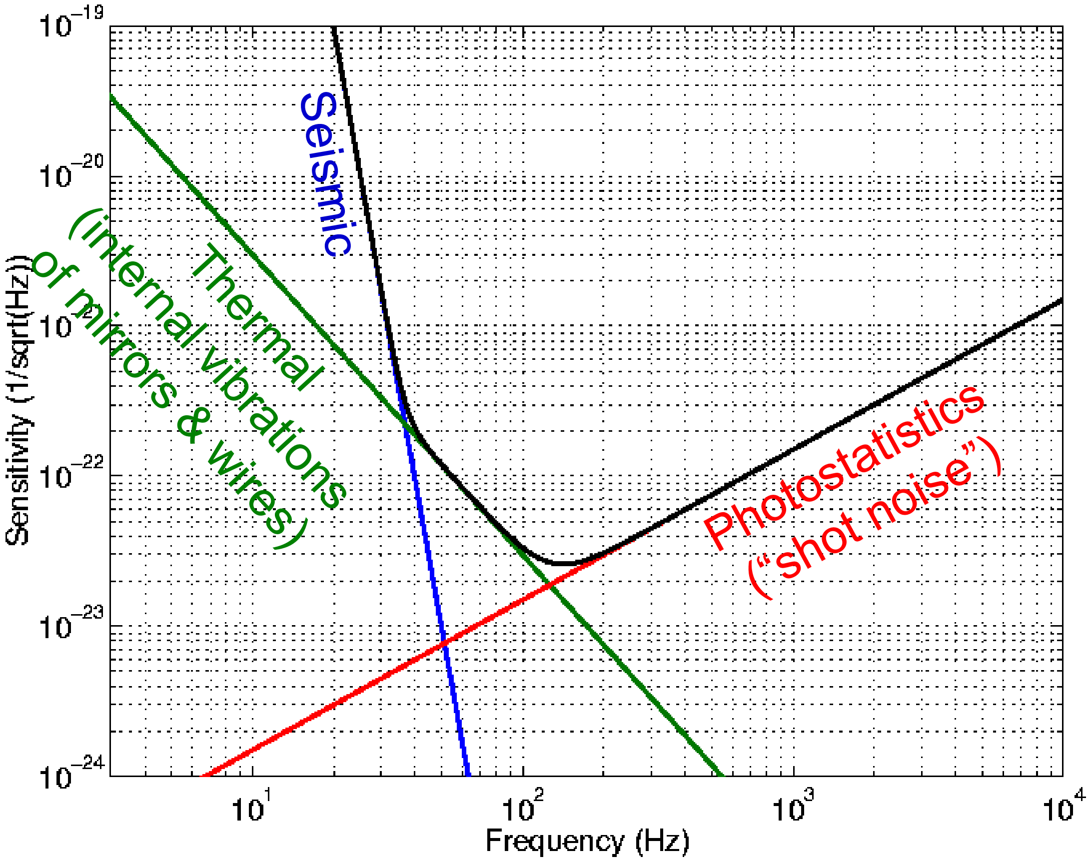


Optical tables are supported on "stacks" of weights & damped springs

Wire suspension used for mirrors provides additional isolation

Active isolation now being added at Livingston

Fundamental Noise Sources
(conceptual)



Sensitive frequency range: ~ 40 – 2000 Hz

If detector is not perfectly tuned, other noise sources can easily dominate

LIGO Status

Commissioning and engineering runs started in 2000

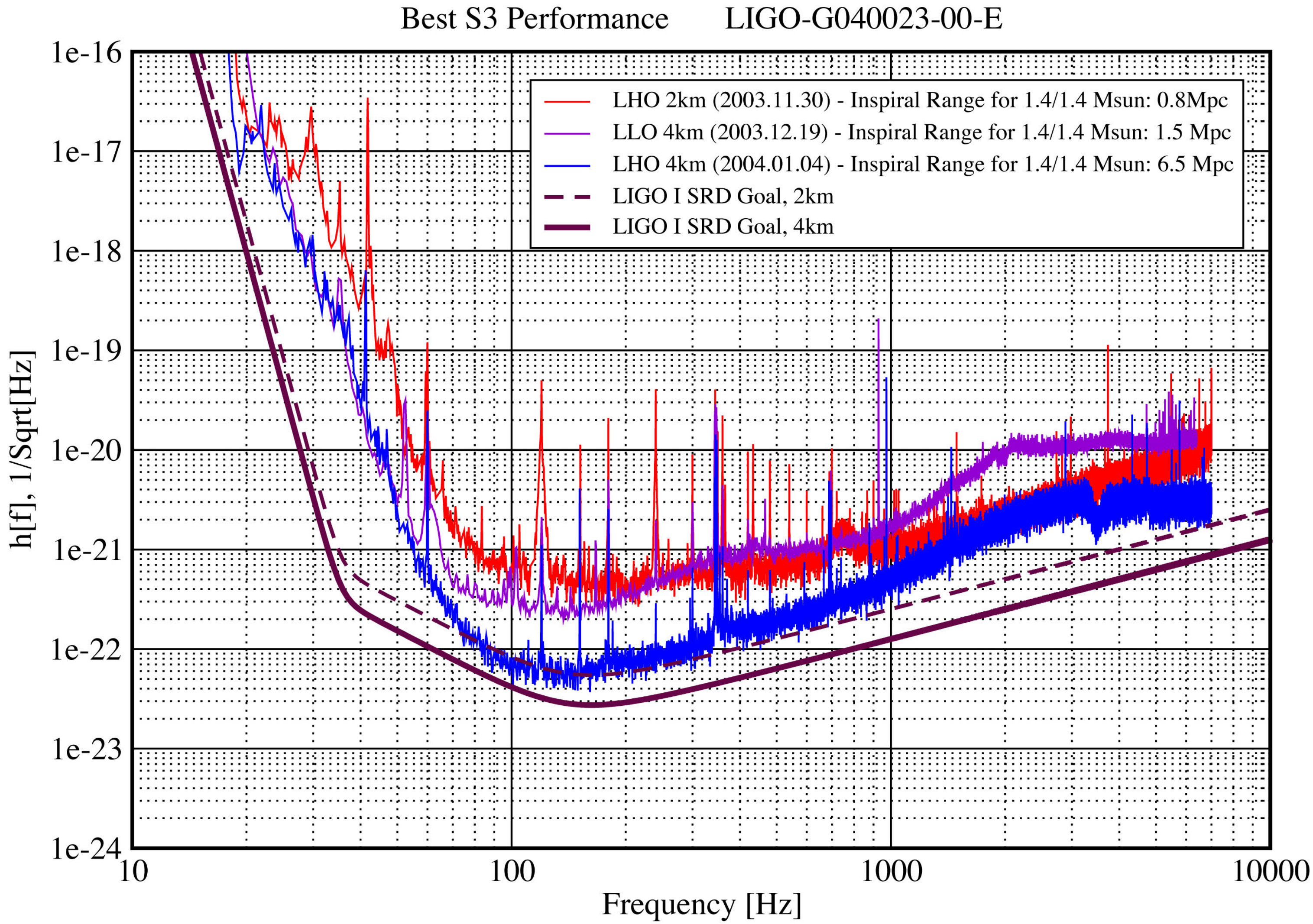
Science runs

- S1 : August 23 – September 9, 2002 (17 days)
- S2 : February 14 – April 14, 2003 (59 days)
- S3 : October 31, 2003 – January 9, 2004 (70 days)
- S4 : Planned to begin in late 2004

Commissioning in between

- Working to reduce noise and improve robustness

Best Performance to Date
(during S3 science run)



Data Analysis

Goal is to detect weak signals buried in noisy data

- Antisymmetric photodiode is continuously sampled at 16384 Hz

Use matched filtering if waveform is known;

- Need a lot of CPU time, *e.g.* using *"Einstein@home"* for periodic sources

Use more general techniques (*e.g.* "excess power") to look for unknown waveforms

"Veto" events which can be identified as environmental or instrumental glitches

Powerful check: require coincidence (consistent signals at consistent times) between the different interferometers

Analysis effort in LSC organized into four working groups according to source type: inspiral, periodic, burst, stochastic

Publications

Papers have been published using S1 data

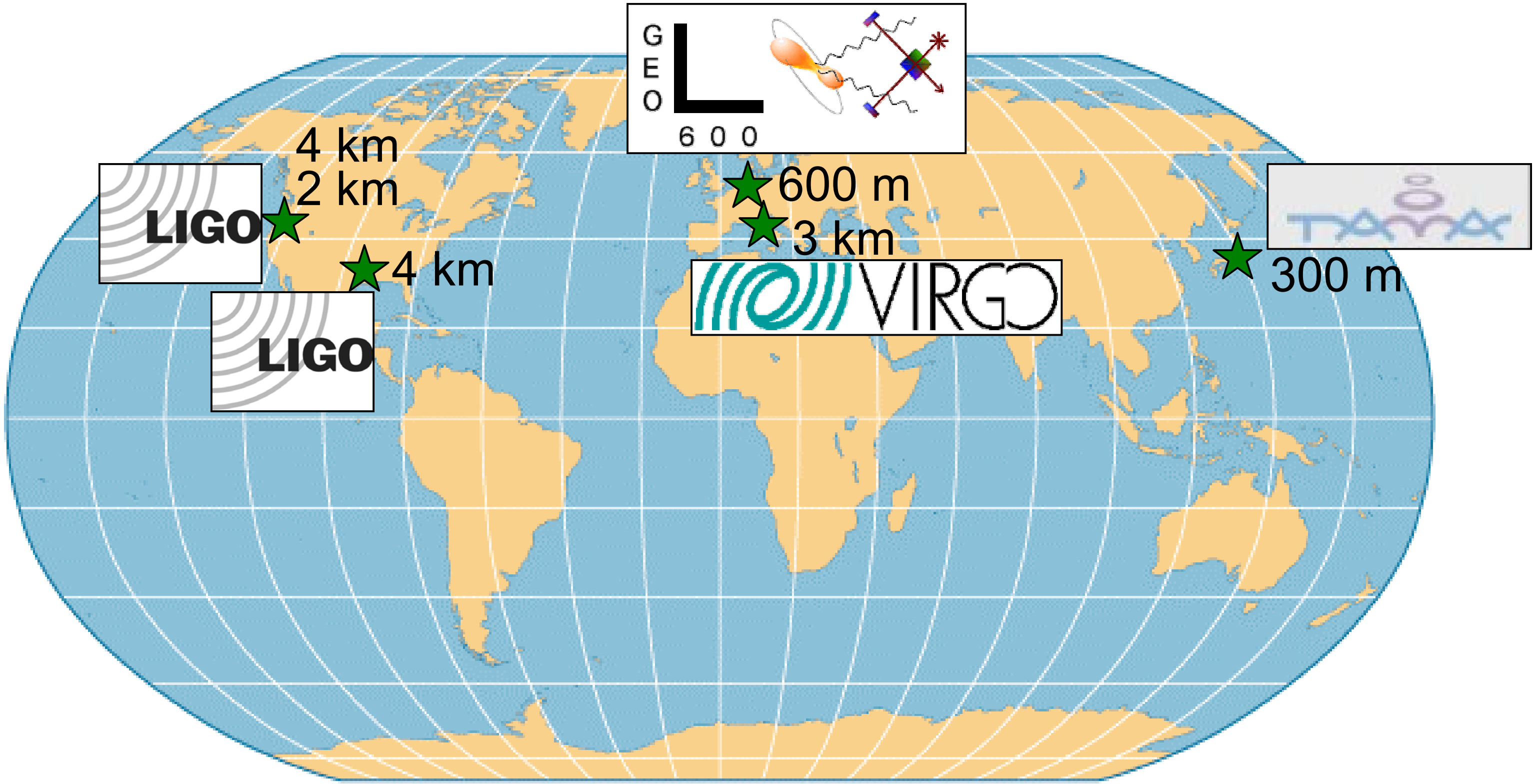
Papers are currently being written using S2 data

Analyses are getting underway using S3 data

Process of writing and internally reviewing papers has taken an effort to get going for this new field

LIGO

The Worldwide Network of Gravitational Wave Detectors



Simultaneous detection from multiple sites would give sky location and polarization information, and can check properties of the waves themselves

There is a strong spirit of cooperation among the projects

Future Detectors

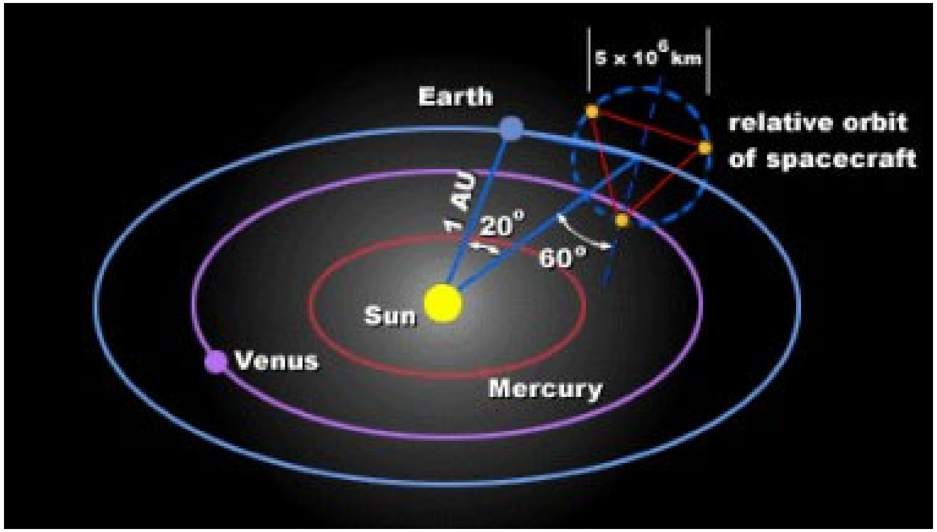
Advanced LIGO

- Complete upgrade of LIGO interferometers toward end of this decade

Large interferometers being considered in Japan, China, Australia?

LISA – Laser Interferometer Space Antenna

- Three spacecraft in solar orbit, to be launched in 2012 (?) by ESA / NASA
- Free of earthly environmental disturbances
- 5×10^6 km arms $\Rightarrow$ sensitive to much lower frequencies (different science)



LIGO

Summary

There is a bold effort underway to get a new view of the universe

Detecting weak signals is extremely challenging, but solvable!

LIGO is now operating, getting close to design sensitivity

TAMA operating too; GEO and VIRGO being commissioned

When will we first see gravitational waves? We don't know

- Rates generally expected to be low
- It's possible that initial LIGO will not see anything
- This is an exploratory science !
- Advanced LIGO, LISA are certain to see sources – may have to wait until then to begin doing real gravitational wave astronomy