Gravitational-Wave Astronomy

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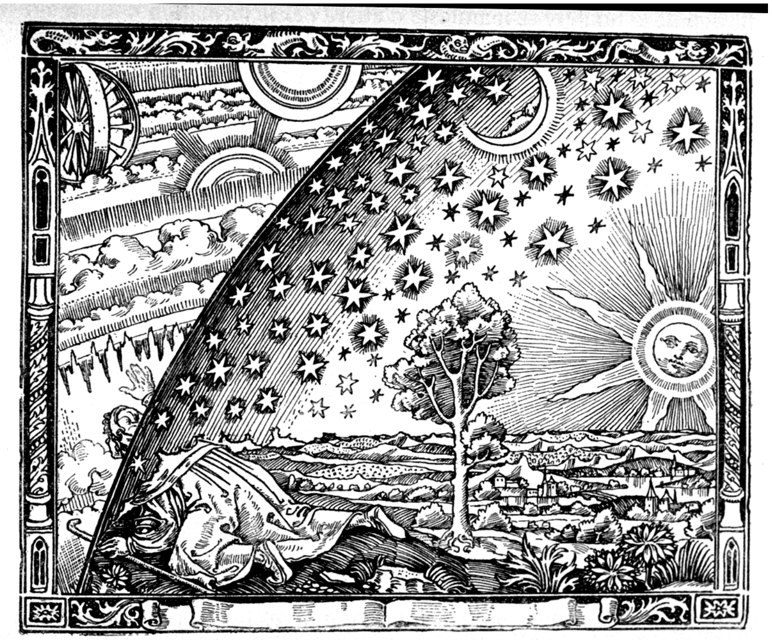
Caltech

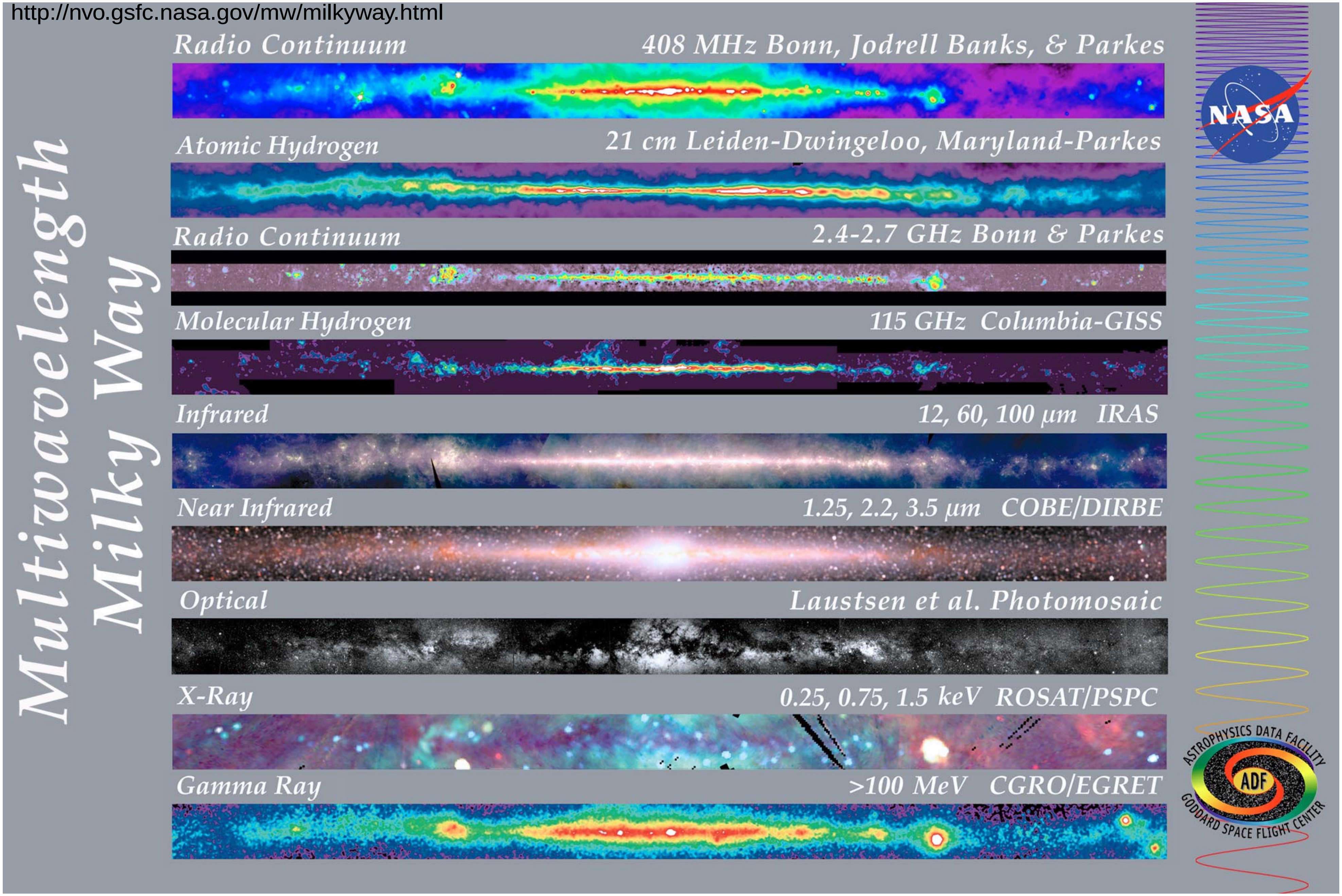


Un missionnaire du moyen âge raconte qu'il avait trouvé le point où le ciel et la Terre se touchent...

Courtesy University of Oklahoma
History of Science Collections

Summer Science Program
July 10, 2001

Most Astronomy Uses Electromagnetic Waves


http://nvo.gsfc.nasa.gov/mw/milkyway.html

How Else Can We Study the Universe?

Cosmic rays

High-energy charged particles (mostly protons)

Deflected by magnetic fields ⇒ do not form an image of the source

Energy distribution tells us about acceleration mechanisms

Highest-energy cosmic rays are an unsolved mystery

Neutrinos

Neutral particles, interacting only through the “weak” nuclear force

Need very massive detectors

19 neutrinos were detected from supernova 1987A

Gravitational waves

“Ripples in space-time” produced by massive, rapidly-moving objects

Penetrate all matter

Have not been detected — yet ...

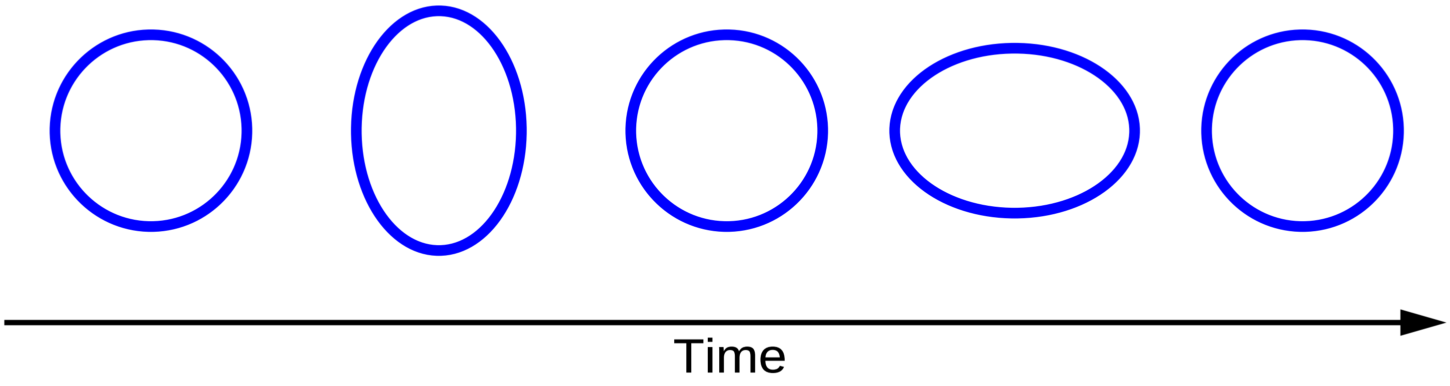
Gravitational Radiation

A natural consequence of Einstein's General Theory of Relativity, which describes gravity as curvature in the geometry of space-time

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



Amount of stretching is proportional to the size of the thing being stretched

Aside: Pulsars

Sources of repeating radio emissions with a regular period

First discovered in 1968 — several hundred known now

Period is extremely stable, but with a gradual slowdown in some cases
$\Longrightarrow$ must be a small, spinning object

$\Longrightarrow$ a neutron star!
(a supernova remnant, more massive than the Sun but with $r < 10$ km)

Some spot on the neutron star emits a beam of radio waves, sweeping around as the star spins. When the beam crosses the Earth, we detect a radio pulse

The Binary Pulsar PSR1913+16

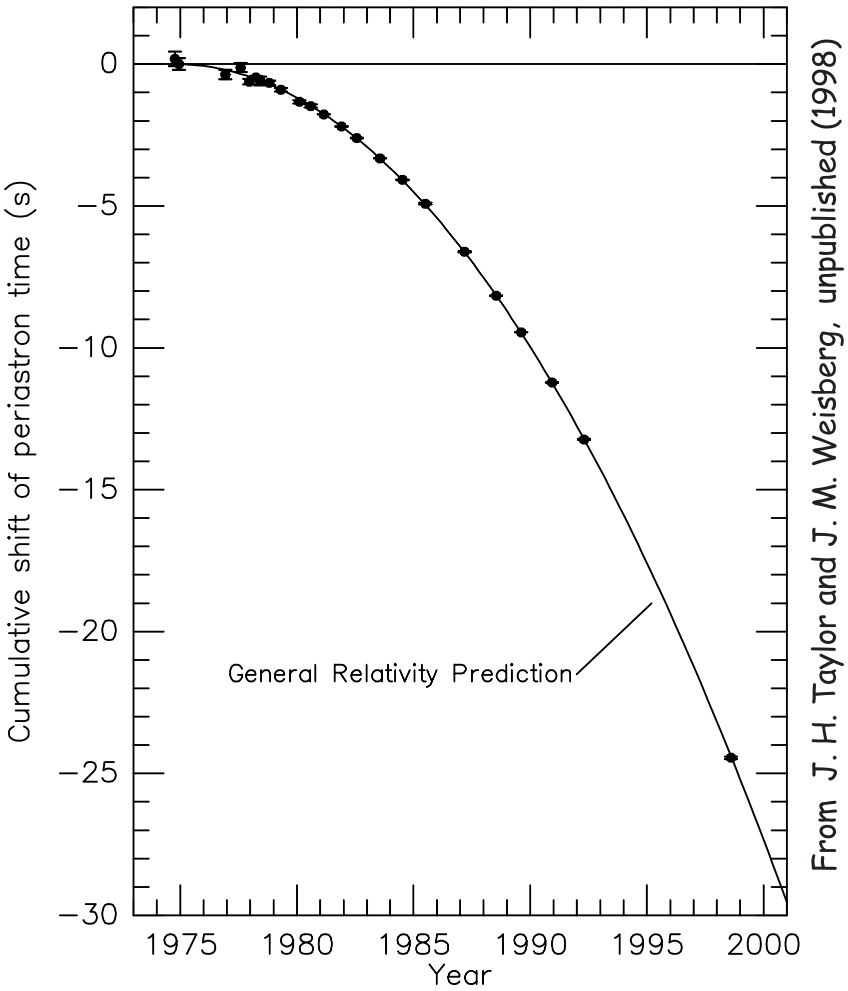
Discovered in 1974 by Russell Hulse and Joseph Taylor

The periodic radio signal from the pulsar was found to be modulated with an 8-hr period
⇒ orbiting a companion!

By tracking system over a long time, determined masses (1.44 & 1.39 M_{sun}) and orbital params

Over the years, the system has shown very gradual orbital decay — just as General Relativity predicts!

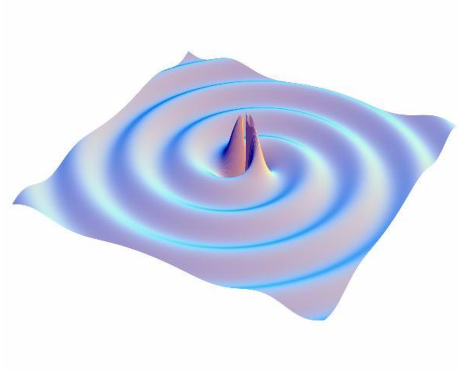
⇒ very strong indirect evidence for gravitational radiation



From J. H. Taylor and J. M. Weisberg, unpublished (1998)

Potential Sources of Directly-Detectable Gravitational Waves

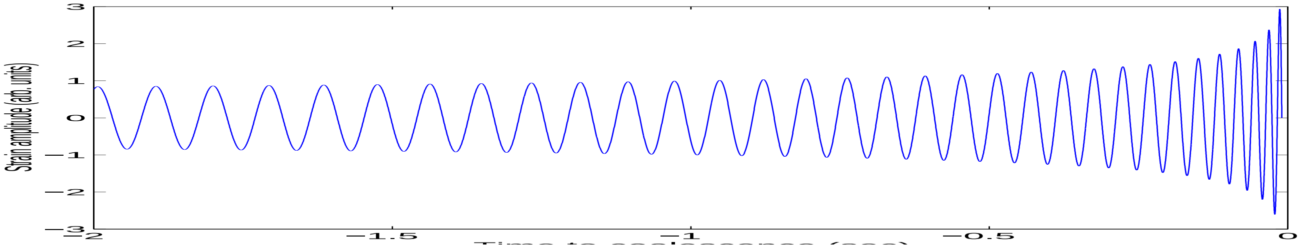
Final inspiral of two compact objects



"Compact object" = neutron star or black hole

One of the most promising sources, because:

- Binary neutron-star systems are known to exist
- The waveform and source strength are 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)

Ringdown of newly formed black hole

Oscillates, damped by emission of gravitational radiation

Potential Sources of Directly-Detectable Gravitational Waves

Supernova

- Gravitational waves are emitted if explosion is asymmetric
- Asymmetry and waveform are unknown

Stellar core collapse to form a neutron star

Asymmetric spinning neutron star

- Crust might allow a small deviation from a perfect sphere
- Gives a persistent periodic signal (like a radio pulsar) — can track for a long time to try to pick out a weak signal

Gravitational-wave background radiation from early universe

- Shows up as correlated noise in different detectors

Unexpected sources???

The Difficulty of Detecting Gravitational Waves

The detection of gravitational waves from any kind of source would be a further confirmation of General Relativity

But potential sources are rare ⇒ have to be able to search in a large volume of space to get any decent detection rate

Signal size is proportional to distance from the source

⇒ Have to be able to detect very weak signals

Typical fractional stretching: $\sim 10^{-21}$

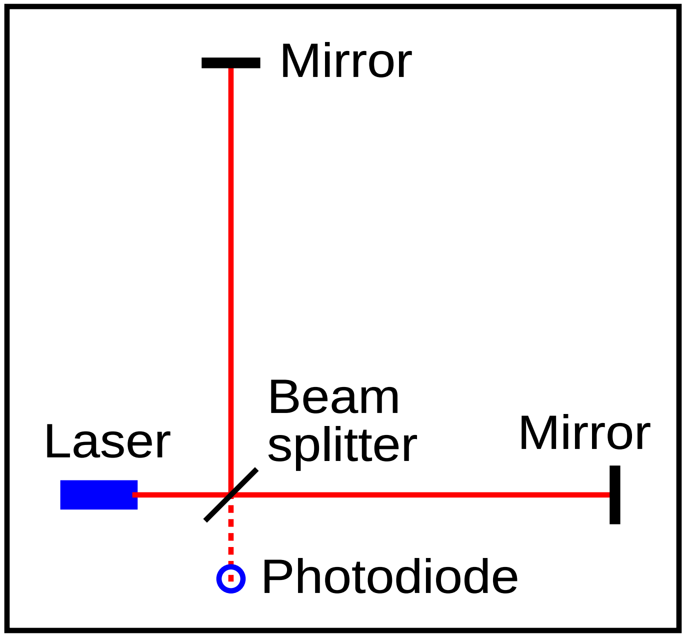
Stretches the diameter of the Earth by $\sim 10^{-14}$ meter, about the size of an atomic nucleus !

Michelson Interferometer

Basic interferometer design was first used by Albert A. Michelson in 1881

Output light intensity depends very sensitively on the *difference* in light travel times in the two perpendicular "arms", which determines the relative phase when the beams are recombined

Was the basis for the "Michelson–Morley experiment" in 1887, which failed to detect the "aether" in which light propagates

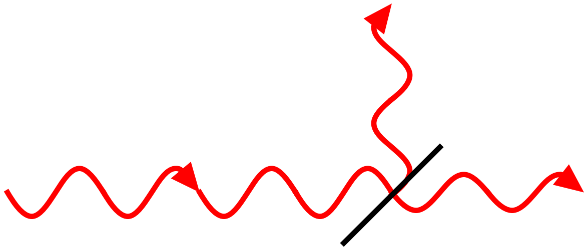


Modern interferometers use a laser as the light source and a photodiode to precisely measure the output light intensity

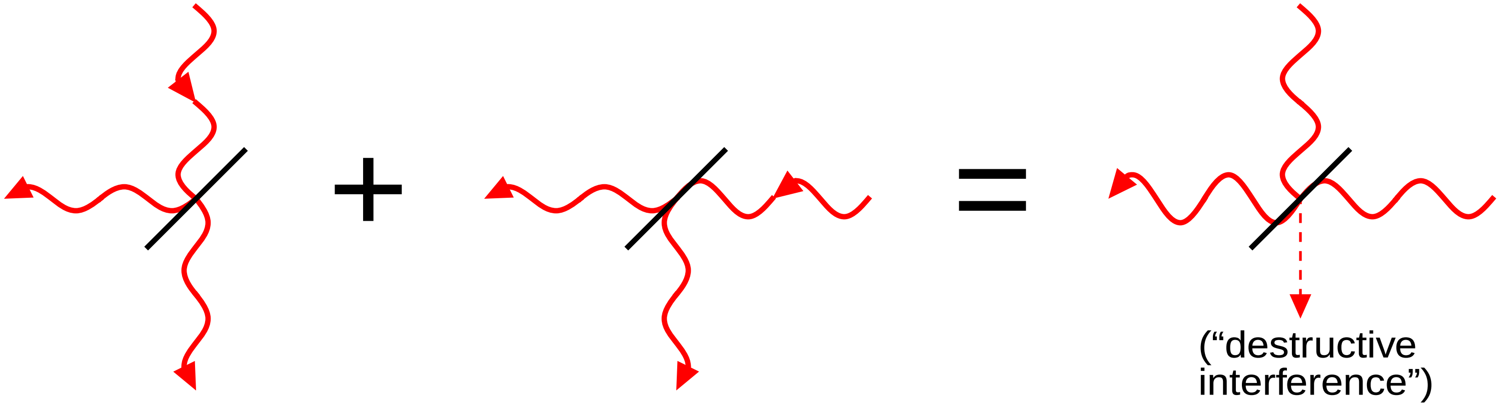
Interferometer Fundamentals

Laser light consists of oscillating electric & magnetic fields

Beam splitter reflects half of the incoming beam power [1/sqrt(2) of the EM field amplitude], and transmits the other half



The mirrors at the ends of the arms reflect the beams back to a spot on the beam splitter, where the fields are split again and added. The oscillating fields may be "in phase" or "out of phase" when they recombine, depending on the exact lengths of the arms



Note that energy is conserved at all times!

Interferometers as Gravitational Wave Detectors

The ability of an interferometer to detect tiny displacements of its mirrors makes it ideal as a gravitational wave detector

But, have to use very careful engineering and a number of “tricks” to make detection possible

Prototypes have been built and operated, *e.g.* Caltech 40-meter

In the last decade or so, technological improvements and accumulated experience have made it feasible to build large GW detectors

Several large interferometers currently being built / commissioned:

- TAMA (Japan, 300 m)
- GEO (Germany, 600 m)
- VIRGO (Italy, 3 km)
- LIGO (Washington state, 4 km & 2 km; Louisiana, 4 km)

The LIGO Project

LIGO = Laser Interferometer Gravitational-Wave Observatory

LIGO Scientific Collaboration

LIGO Laboratory

Caltech
MIT

LIGO Hanford Observatory
LIGO Livingston Observatory

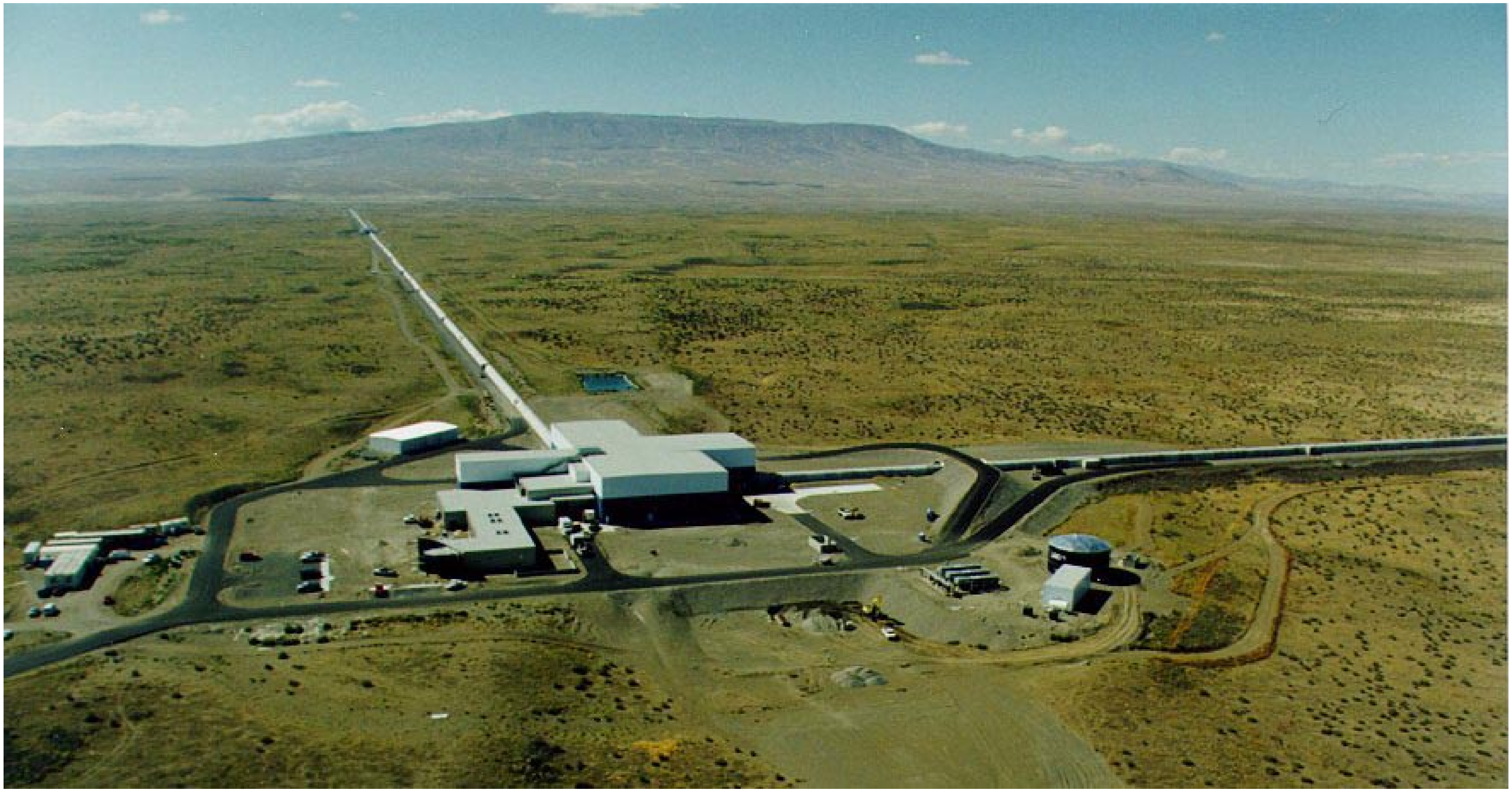
- ACIGA (Australian Consortium)
- Caltech Center for Adv. Computing Research
- Caltech Relativity Theory Group
- Caltech Experimental Gravity Group
- Calif. State U., Dominguez Hills
- Carleton College
- Cornell U.
- U. of Florida
- GEO 600 Collaboration (British/German)
- Harvard-Smithsonian Center for Astrophysics
- Institute of Applied Physics–Nizhny Novgorod
- Iowa State U.
- IUCAA (India)
- JILA – U. of Colorado
- Louisiana State U.
- Louisiana Tech U.
- U. of Michigan
- Moscow State U.
- National Astronomical Observatory of Japan
- U. of Oregon
- Penn. State U.
- Southern U.
- Stanford U.
- Syracuse U.
- U. of Texas, Brownsville
- U. of Wisconsin, Milwaukee

Total of ~350 participants

Funded by the National Science Foundation (approved in 1994)
– Construction cost ~ $300 million; operating cost ~ $30 million/yr

LIGO Hanford Observatory

Located on DOE Hanford Nuclear Reservation north of Richland, Washington



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

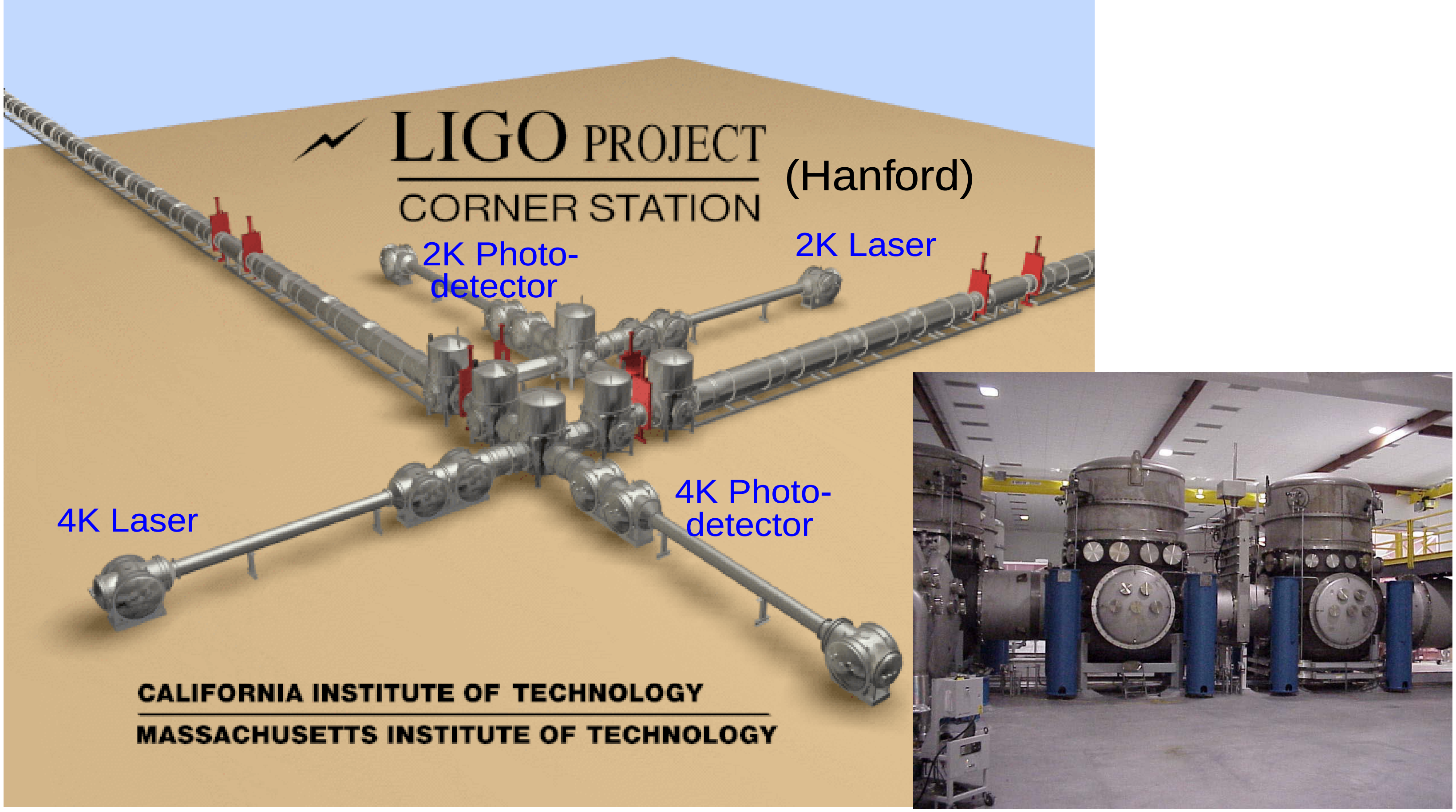
LIGO Livingston Observatory

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

Vacuum System in Corner Station

The entire interferometers are contained within a vacuum system

At Hanford, the 4 km and 2 km interferometers share the arm beam tubes



LIGO Beam Tubes

Beam tubes are made of stainless steel

- 3 mm thick, diameter=1.24 m, sections welded together

Baked at ~170 C by flowing ~2000 amps through tubes for a few weeks

Liquid nitrogen cryopumps now maintain pressure at a few x 10^{-8} torr

Large gate valves allow interferometer optics to be installed / serviced without venting beam tubes

Beam tubes are protected by a concrete enclosure

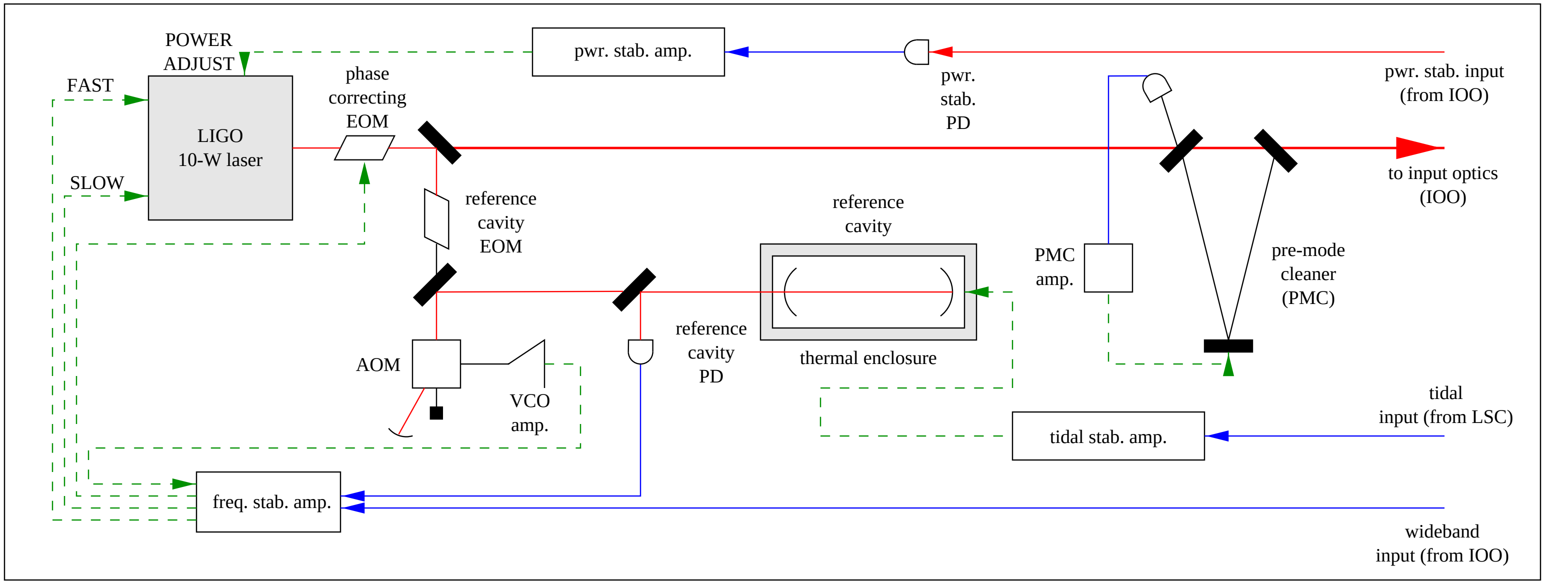
LIGO Pre-Stabilized Laser

Based on a “commercial” Nd:YAG laser from Lightwave Electronics

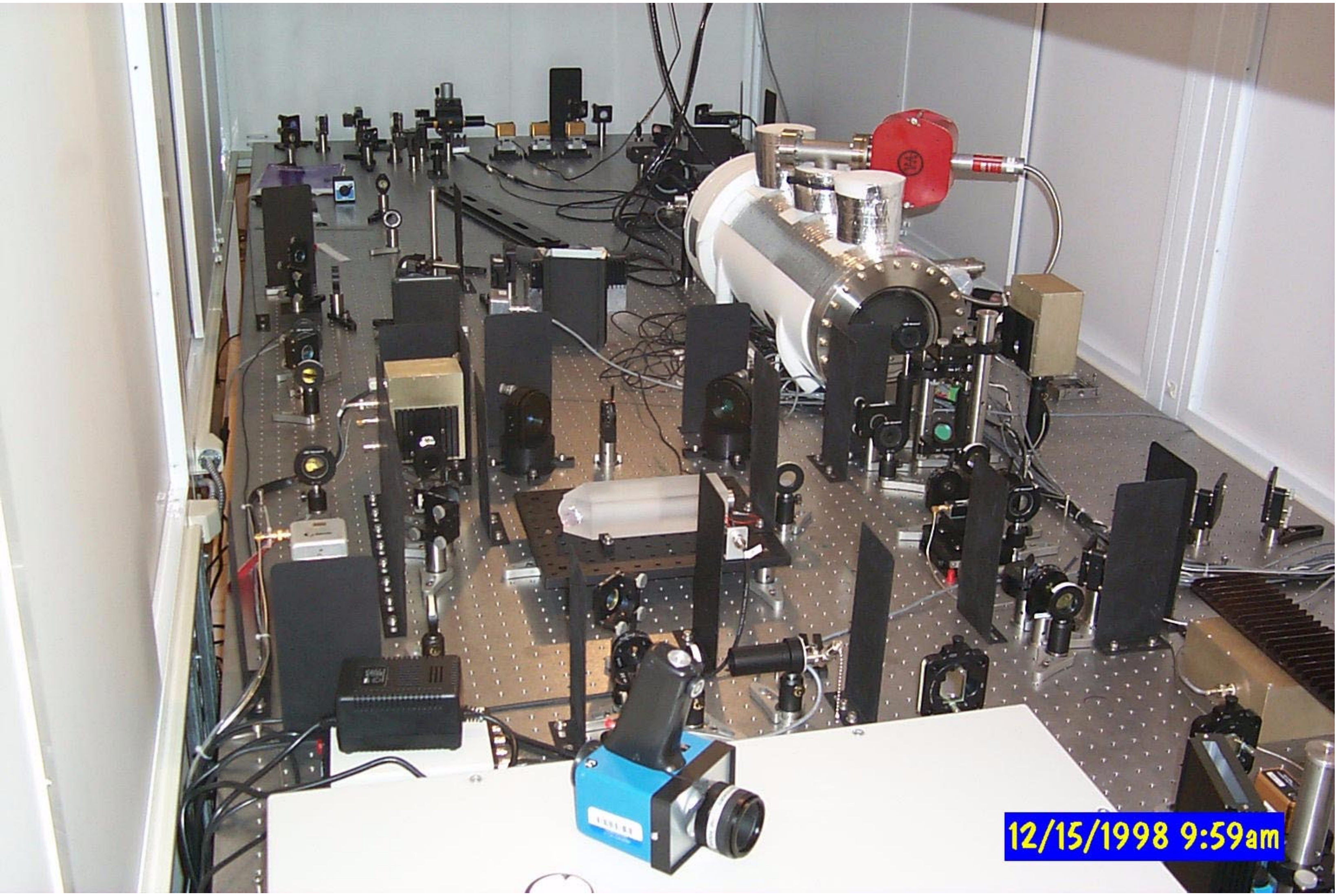
- Wavelength = 1064 nm (infrared)
- Power ~10 Watts

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

Final stabilization uses feedback from rest of interferometer



LIGO Pre-Stabilized Laser



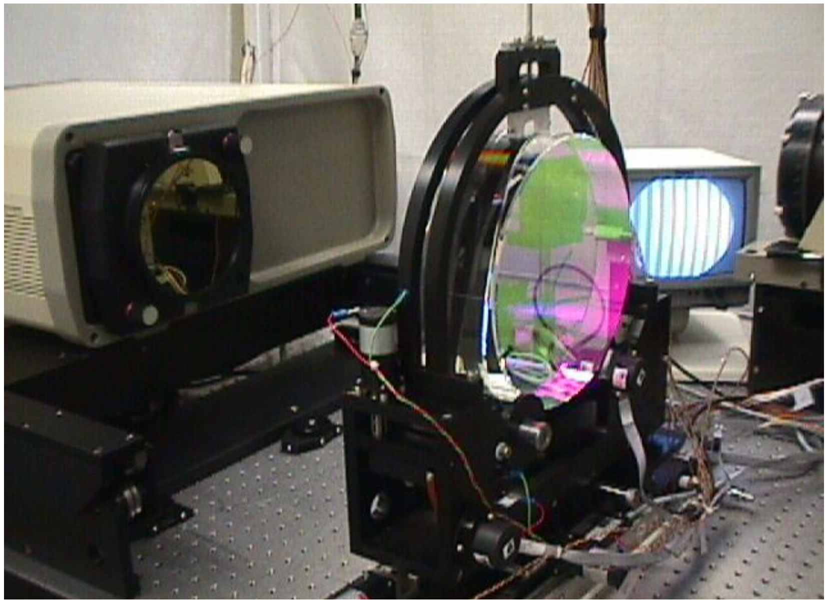
LIGO Mirrors

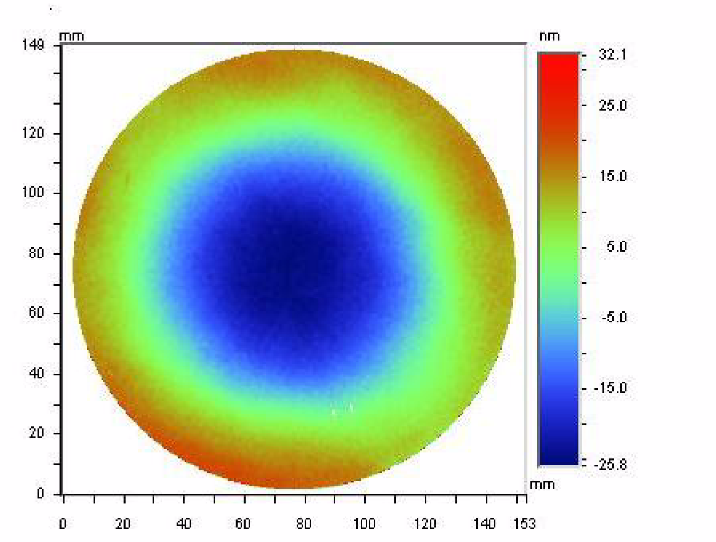
Fused silica with very low bulk absorption, high mechanical Q

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)





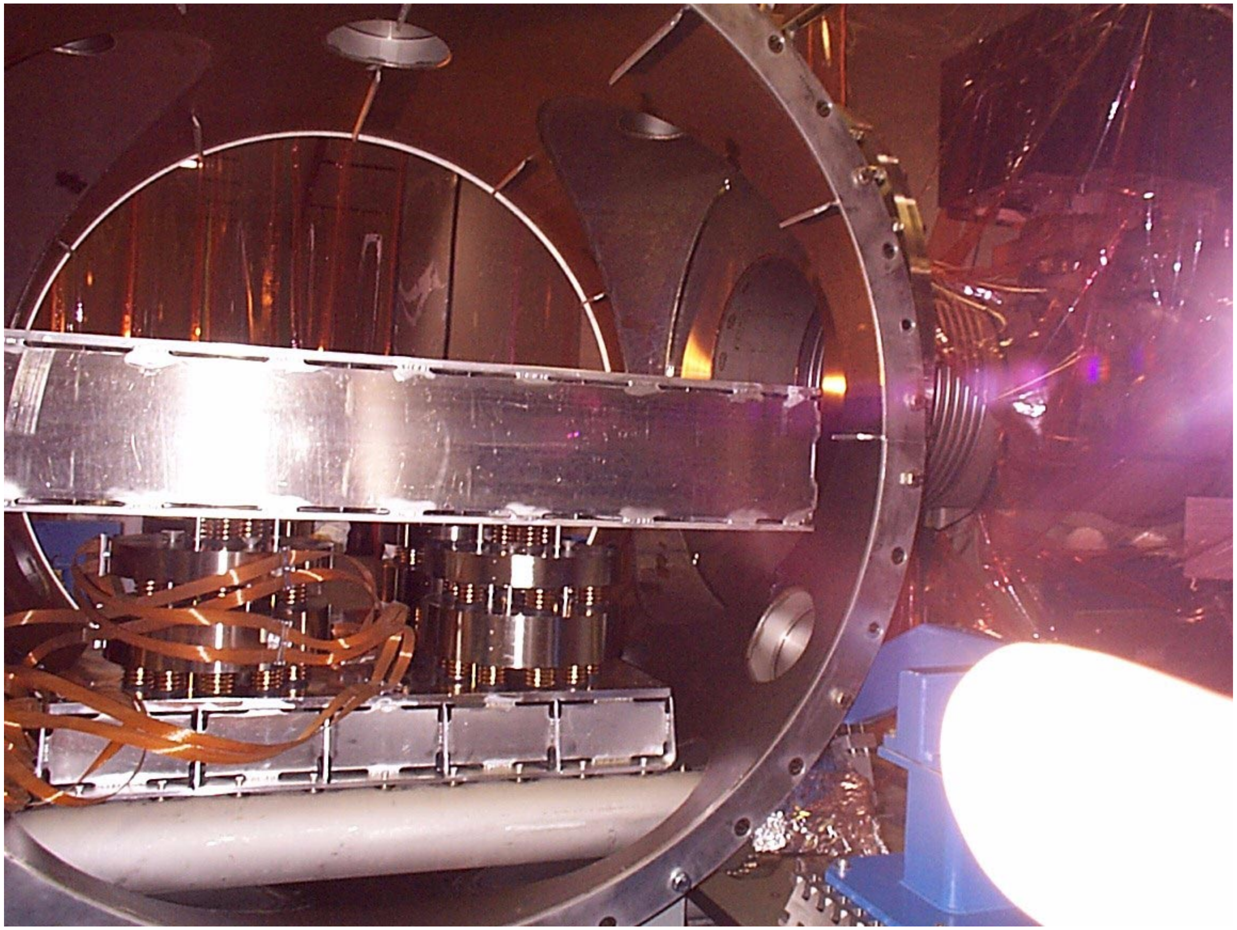
In interferometer, each mirror is suspended by a single steel wire

Mirrors are actively aligned & positioned with magnets & coils

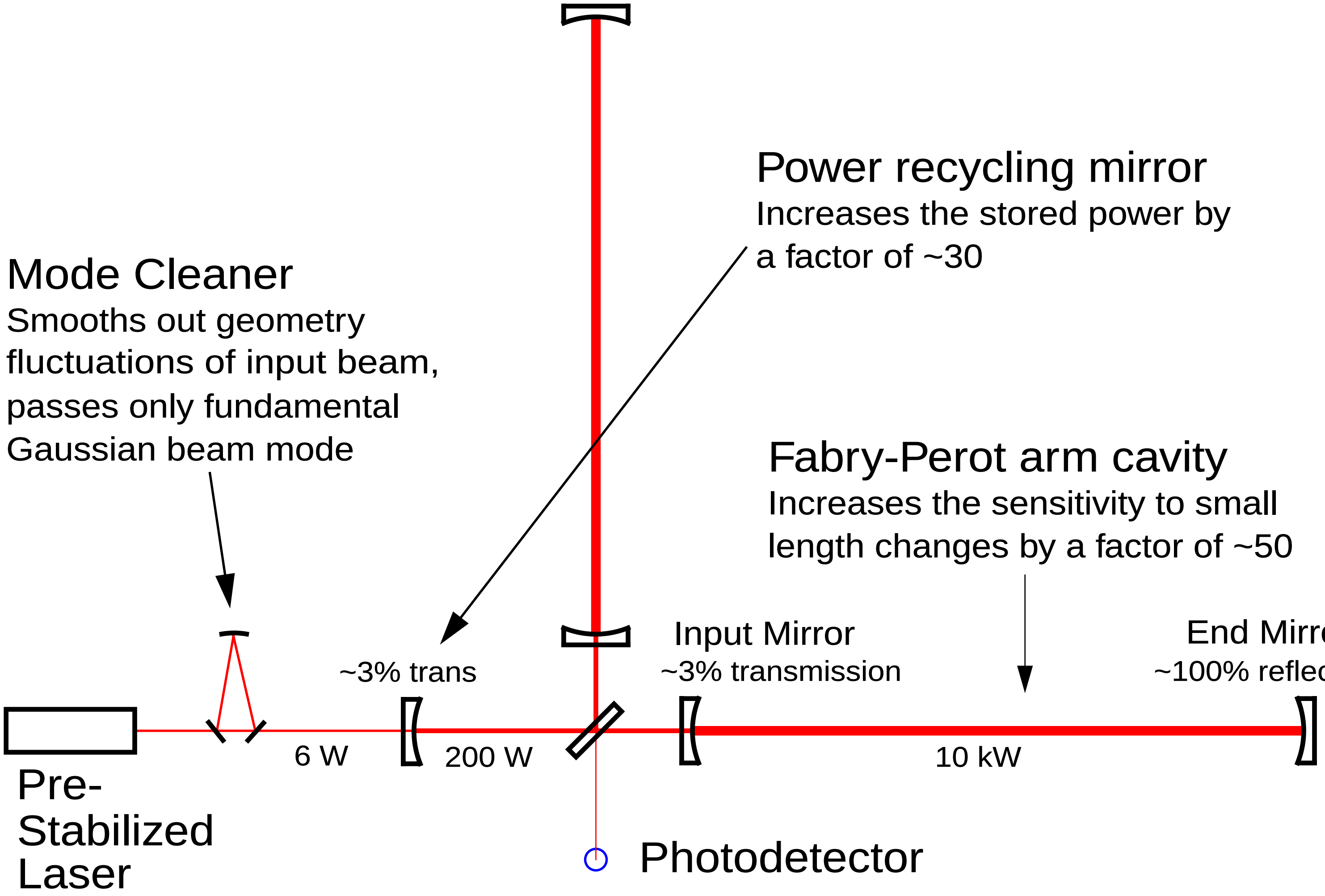
A Mirror In Its Vacuum Tank

Vibration Isolation System

Optical tables are supported by columns of masses and damped springs



Optical Layout of LIGO Interferometers



Mode Cleaner
Smooths out geometry fluctuations of input beam, passes only fundamental Gaussian beam mode

Power recycling mirror
Increases the stored power by a factor of ~30

Fabry-Perot arm cavity
Increases the sensitivity to small length changes by a factor of ~50

Interferometer Controls

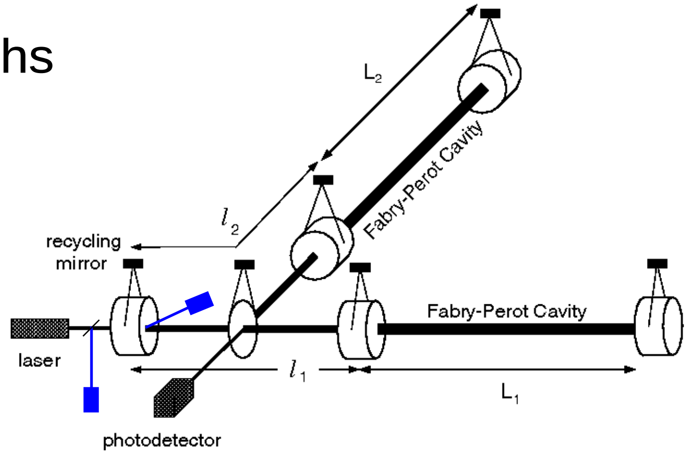
Servo control (linear feedback) is the key to interferometer operation !

Fundamental concept: “lock” interferometer by using feedback to keep it on a “dark fringe” (destructive interference at the output photodetector), to within a small fraction of a wavelength

Need to get an electrical signal which is proportional to the difference in the lengths of the two long arms

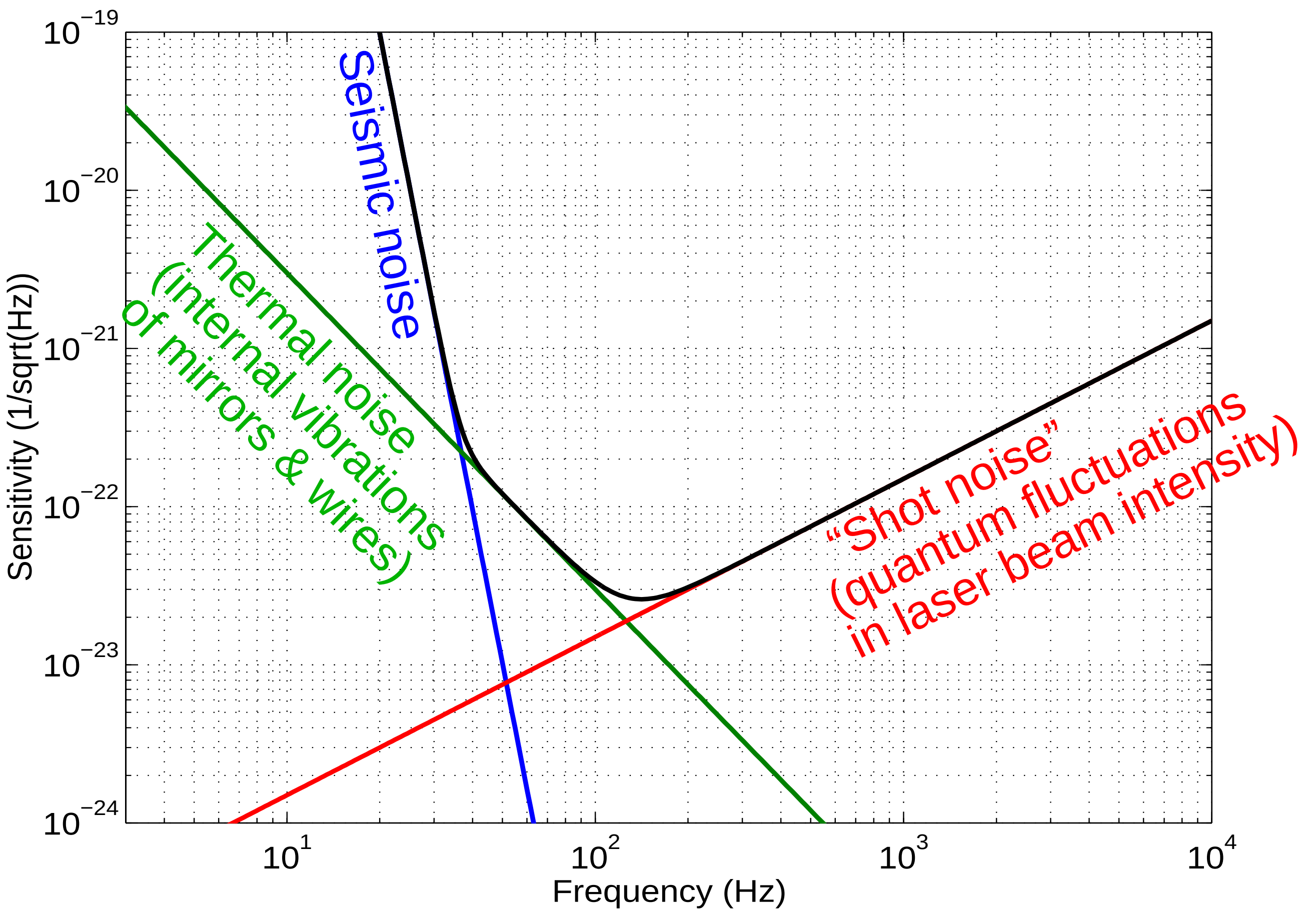
Do this using a “trick”: modulate the phase of the laser light, then demodulate the photodector output

Feed this signal back to actuators which control the mirror positions



Actually need several additional photodetectors to control the positions and alignment of all of the hanging mirrors

Noise vs. Frequency (Conceptual)



⟹ LIGO is sensitive to roughly the same frequency range as human hearing

Data Acquisition

Each interferometer produces one gravitational-wave channel, continuously sampled at 16384 Hz, plus hundreds of auxiliary and environmental channels:

- Laser monitoring channels
- Servo inputs and outputs
- Suspension controller coil currents
- Alignment system raw signals
- Seismometers, accelerometers, microphones
- Magnetometers, temperatures, wind speed & direction

These “extra” channels are used to study the performance of the interferometer and to reject events caused by environment or instrument

Total data rate for 3 interferometers ~10 MB/sec (100 kB/sec GW data)

Data to be archived: ~100 TB/year

Data Analysis

Goal is to detect weak signals buried in a noisy data stream

Techniques for doing this are mathematically well defined, but require a lot of computer processing — e.g. ~50 Pentium-4 PCs working in parallel

Also need to make sure that apparent signals are not due to environmental disturbances (earthquakes, lightning strikes, etc.)
$\Longrightarrow$ study the auxiliary channels

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

Ultimately, LIGO will analyze data jointly with the other experimental groups (GEO, VIRGO, ...) to get the best possible sensitivity

Current Status and Schedule

Some major milestones:

- Construction of the observatory facilities was completed in 1999
- "First light" along a 2-km arm was achieved in December 1999
- "First lock" of full 2-km interferometer was achieved in October 2000

The Livingston interferometer has also been operated successfully

The last mirror was recently installed for the Hanford 4-km interferometer

Now "commissioning" the interferometers

- Studying lock acquisition and stability
- Tuning up servo controls
- Enabling additional servo loops

Have conducted 4 "engineering runs" so far, more to come

Plan to have a "science test run" late this year

Long-term science running will start next year

Outlook

Construction of the LIGO observatories was a great success

Installation is complete for all three interferometers

Commissioning is well underway

⟹ After many years of preparation, LIGO is poised to begin operation!

When will LIGO first detect gravitational waves? We don’t know! Depends on nature, and on how soon the detectors reach maximum sensitivity

There is a mature plan for upgrading the LIGO interferometers which promises a dramatic increase in sensitivity. It could be installed later this decade, depending on the availability of funding

There is a strong spirit of cooperation with our international colleagues

⟹ Gravitational-wave astronomy should tell us much in the years ahead