How to Catch a Gravitational Wave

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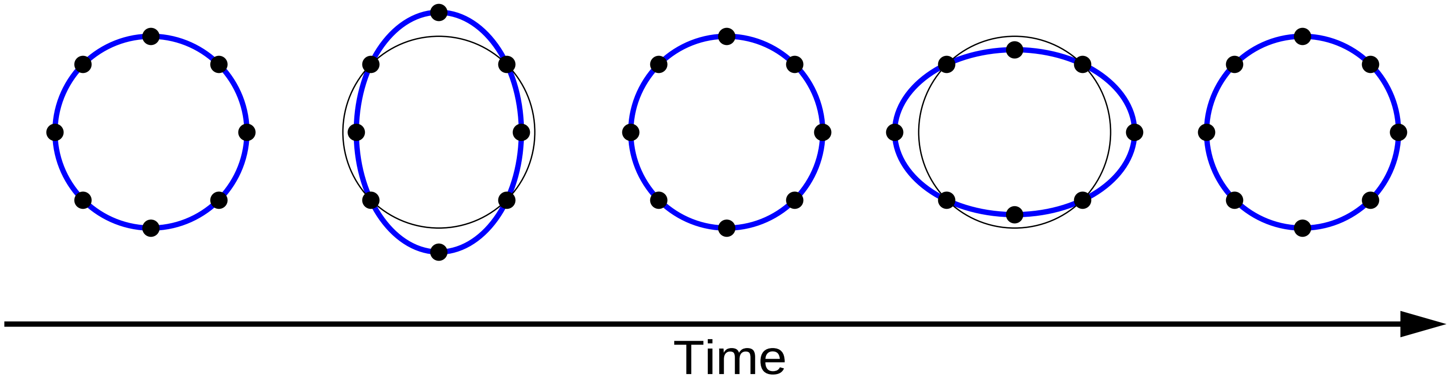
Gravitational Radiation

Gravitational radiation is a natural consequence of general relativity

Produced by a massive system with a time-varying quadrupole moment

Far from the source, get “ripples” in the space-time metric which may be viewed as quadrupole transverse waves



Gravitational waves have two polarization states: $+$ and $\times$

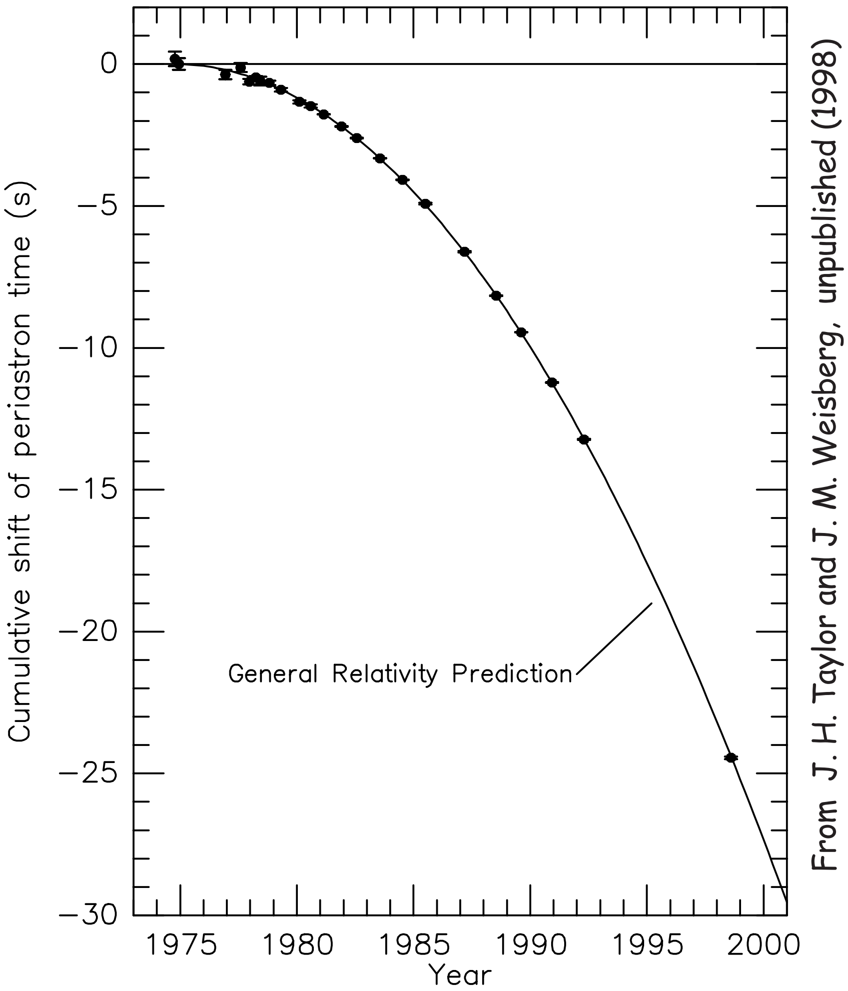
Dimensionless strain: $h = \Delta L / L$ (typical value at Earth: 10^{-21} !)

Evidence for Gravitational Radiation

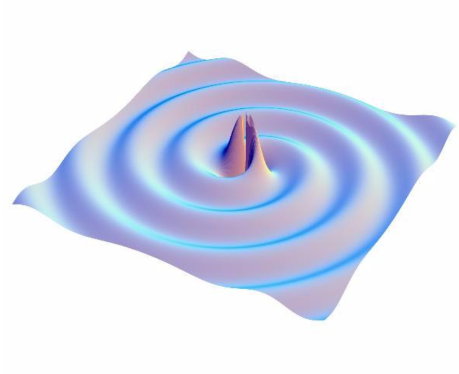
The observed gradual orbital decay of the Hulse-Taylor binary pulsar PSR 1913+16 perfectly matches the prediction from general relativity

⇒ very strong indirect evidence for gravitational radiation

A few other binary pulsars have also been studied



Potential Sources of Directly-Detectable Gravitational Waves

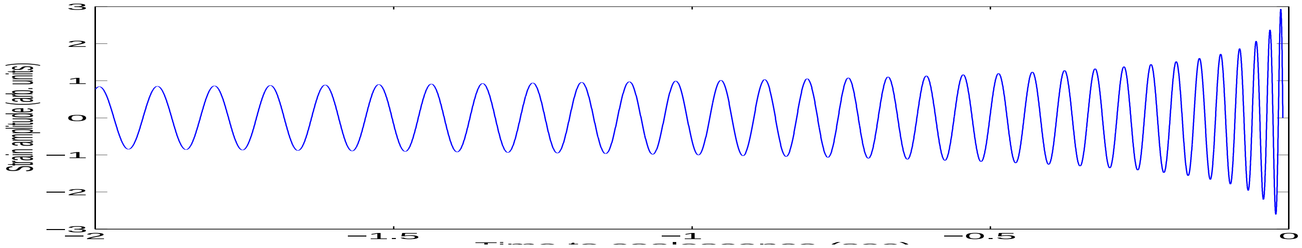


Final inspiral of compact binary system

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

One of the primary targets for LIGO, because:

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



Merger of compact objects

Gravity in the extreme strong-field limit

Waveforms unknown (a subject for numerical relativity calculations)

Ringdown of newly formed black hole

Sinusoid, damped by emission of gravitational radiation

Potential Sources of Directly-Detectable Gravitational Waves

Supernova

Requires an asymmetric explosion; waveform unknown

Stellar core collapse to form a neutron star

“*r* mode” currents in neutron star

Instability driven by gravitational radiation

Non-axisymmetric neutron star

Crust might be able to support inhomogeneities

Gives a persistent periodic signal — can integrate for a long time, correcting for Earth’s motion

Stochastic gravitational-wave background from early universe

Detectable in some non-standard models (strings, etc.)

Shows up as correlated noise in different detectors

Tests of General Relativity Using Gravitational Waves

Demonstrate conclusively that gravitational waves exist!

Measure propagation speed
- By comparing arrival times at different detectors
- By correlating with another prompt signal, *e.g.* gamma-ray burst

Check quadrupole nature, *i.e.* place bounds on scalar-tensor theories of gravity
- Deduce by comparing strain patterns in detectors with different orientations

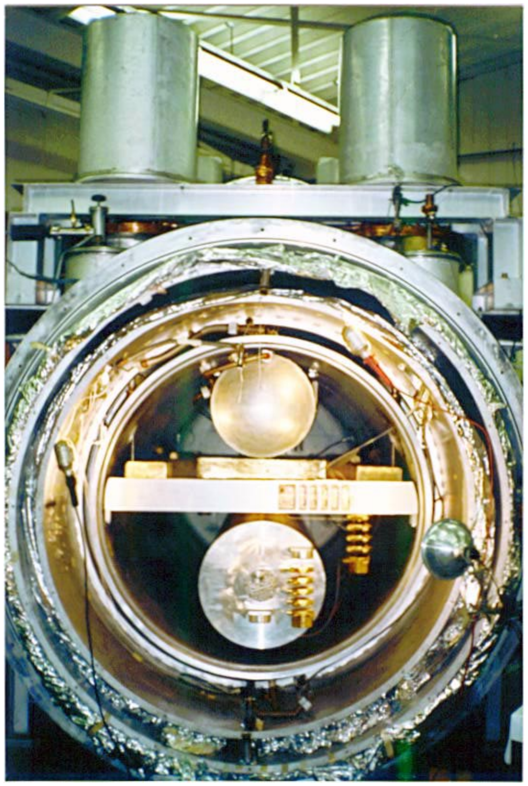
Study relativistic effects in late stages of binary inspirals

Study gravity in the strong-field limit, by analyzing waveforms from mergers

Gravitational Wave Detectors

Resonant “Bar” Detectors

- First built by Joseph Weber in the 1960s
- Watch for gravitational waves to excite a large metal bar at its resonant frequency
- Sensitive only to a narrow frequency band
- Several cryogenic detectors currently in operation in Italy, USA, and Australia
- Future plans: increase bandwidth, develop spherical detectors



ALLEGRO detector at LSU

Gravitational Wave Detectors

Laser Interferometers

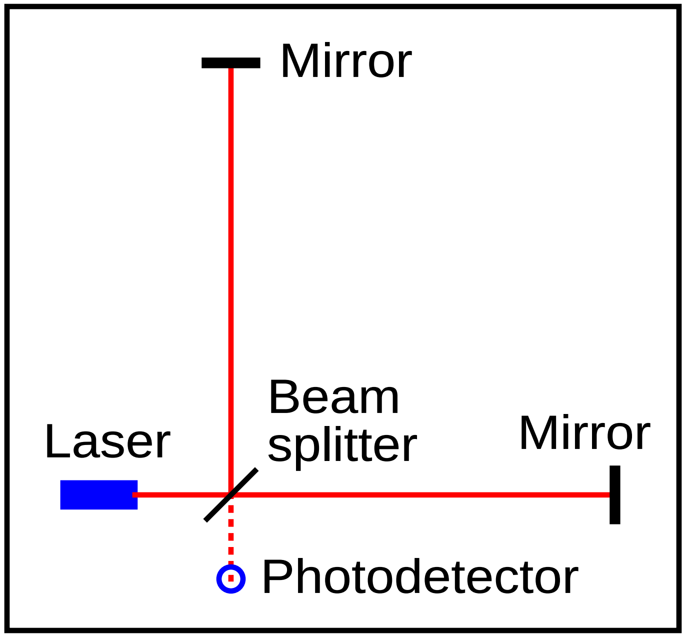
Watch for differential length oscillation in two perpendicular arms

Sensitive over a wide frequency range

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

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)



Interferometer in Space: LISA

Sensitive to much lower frequencies $\Longrightarrow$ different science goals

Currently in mission planning stage; launch in ~2010 ?

LIGO Organization

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)

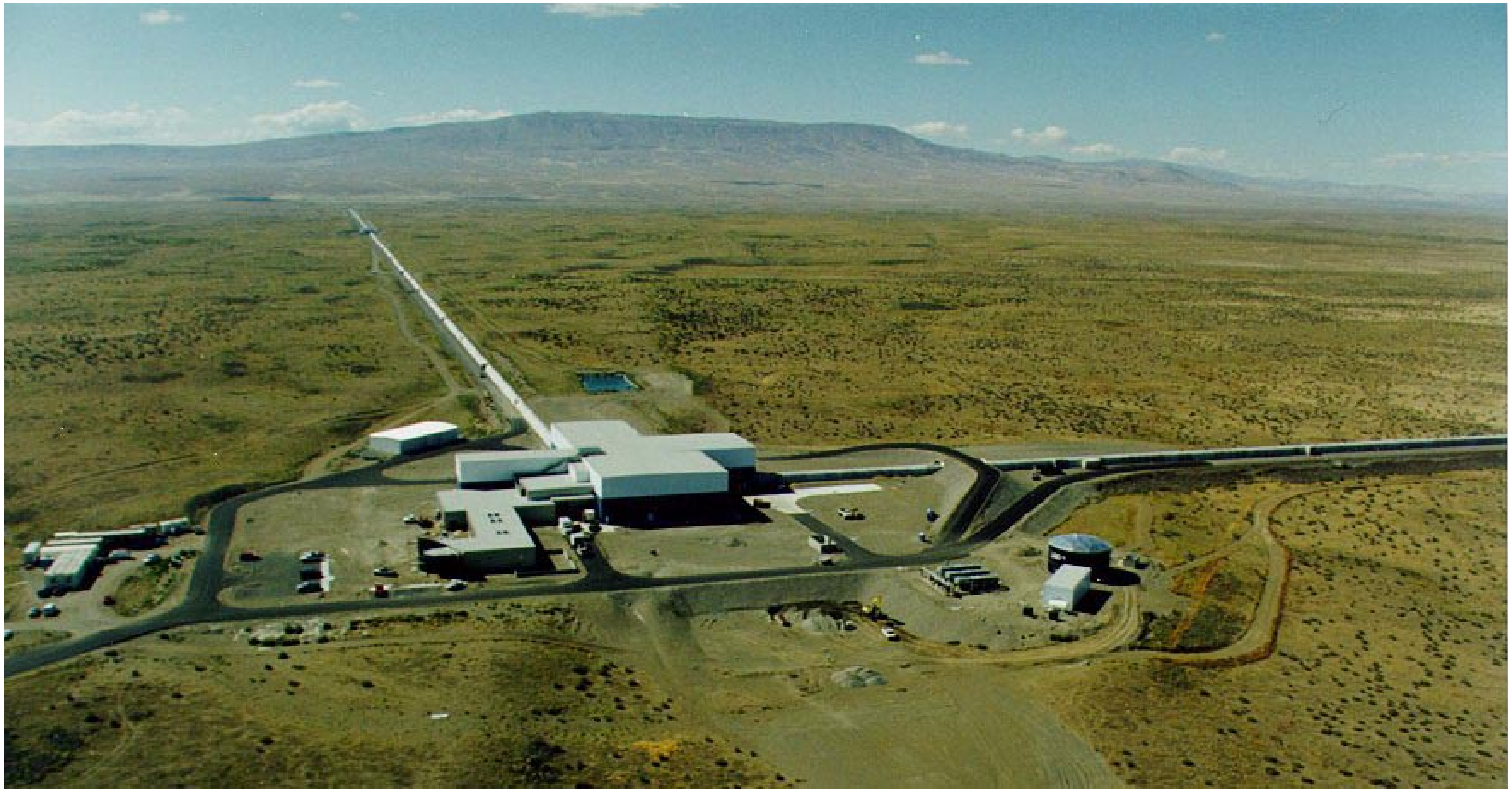
JILA – U. of Colorado
Louisiana State U.
Louisiana Tech U.
U. of Michigan
Moscow State U.
National Astronomical Observatory of Japan
U. of Oregon
Penn. State U.
Southern U.
Stanford U.
Syracuse U.
U. of Texas, Brownsville
U. of Wisconsin, Milwaukee

Total of >300 participants

Funded by the National Science Foundation
– Construction cost ~ \$300 million

LIGO Hanford Observatory

Located on DOE Hanford Nuclear Reservation north of Richland, Washington



Brush fires swept across the LIGO site on June 28-29, but did no damage!

LIGO Livingston Observatory

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

LIGO Beam Tubes

Made from stainless steel, treated to minimize H_2 outgassing

Diameter = 1.24 m, thickness = 3 mm, sections welded together

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

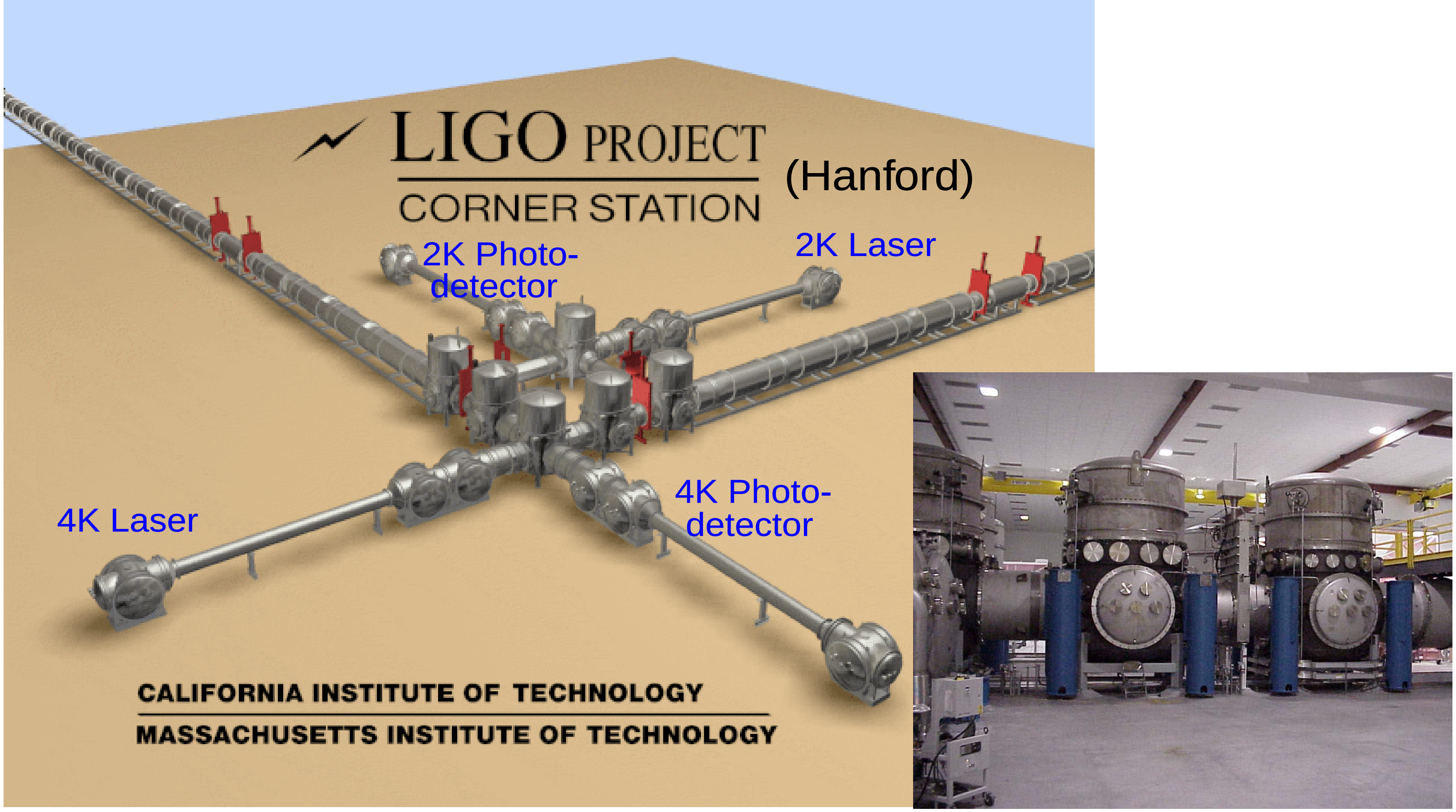
Liquid nitrogen cryopumps now maintain pressure at a few x 10^{-8} torr

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

Beam tubes are protected by a concrete enclosure

Vacuum System in Corner Station

At Hanford, the 4 km and 2 km interferometers have separate lasers and optical components, but share the arm beam tubes



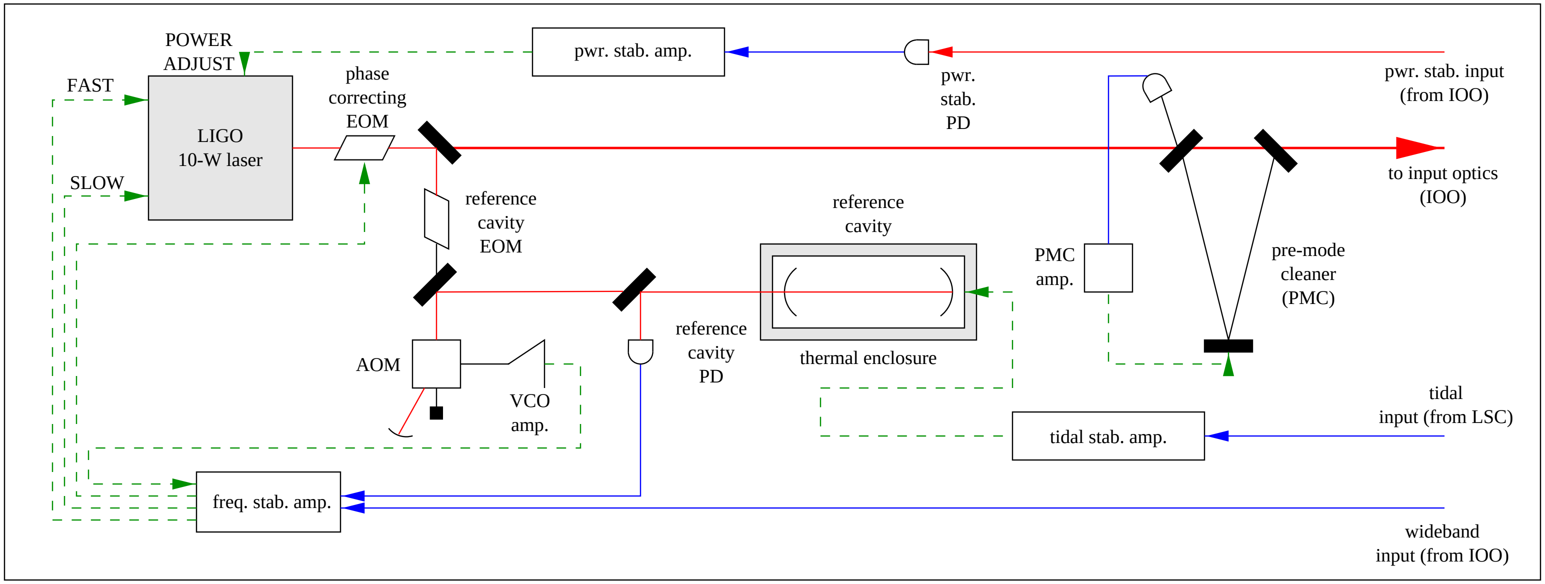
LIGO Pre-Stabilized Laser

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

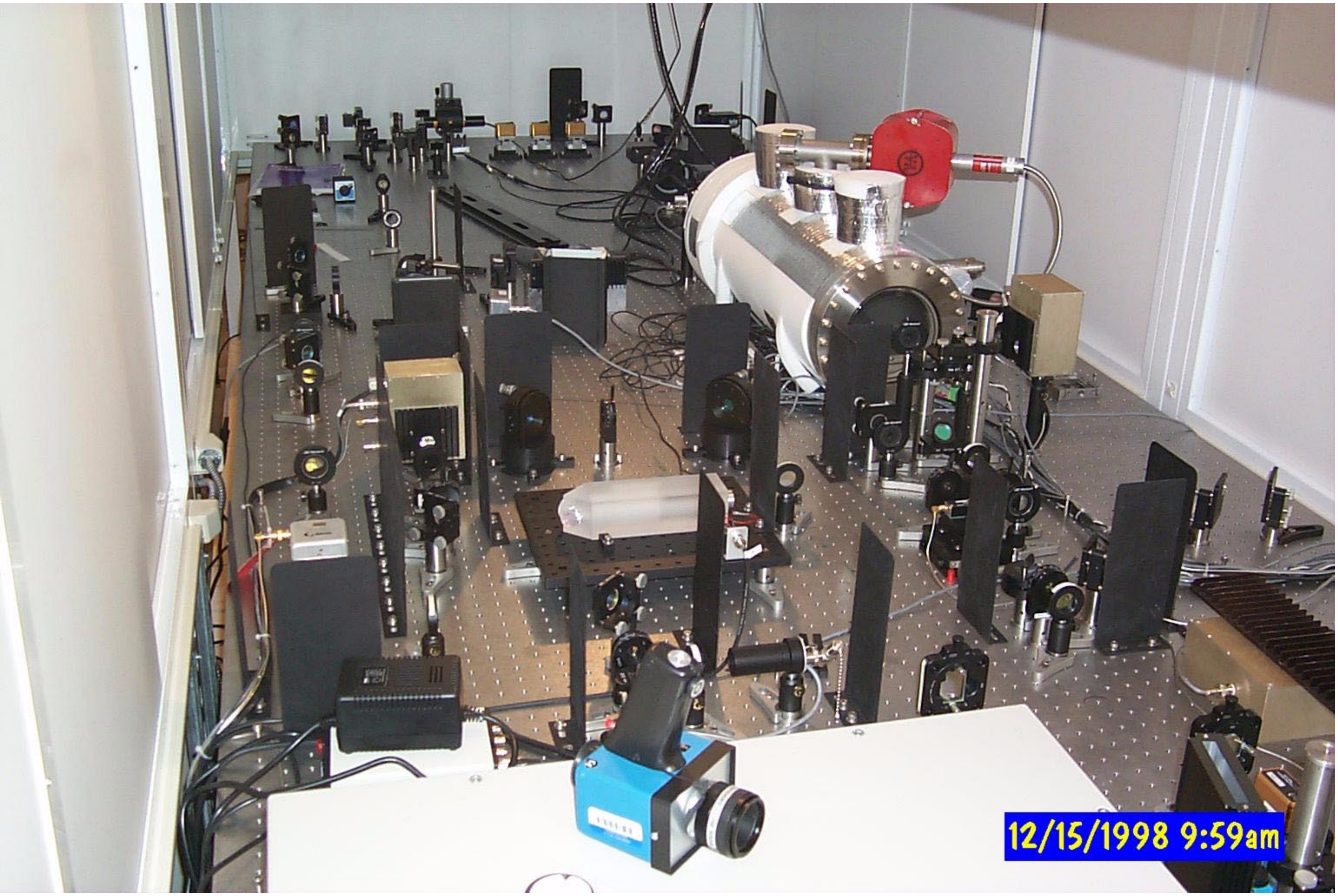
- Master oscillator plus 8 amplification stages
- Wavelength = 1064 nm (infrared), power ~10 W

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



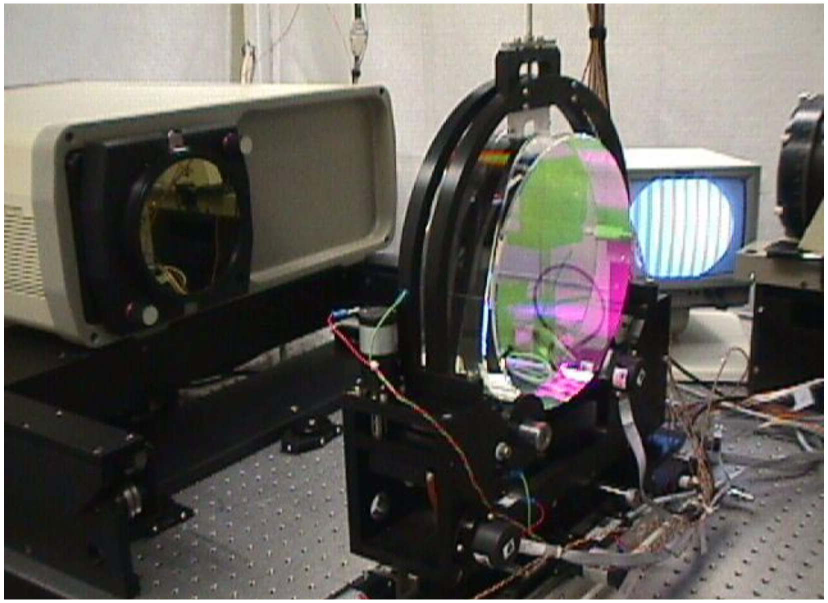
LIGO Mirrors

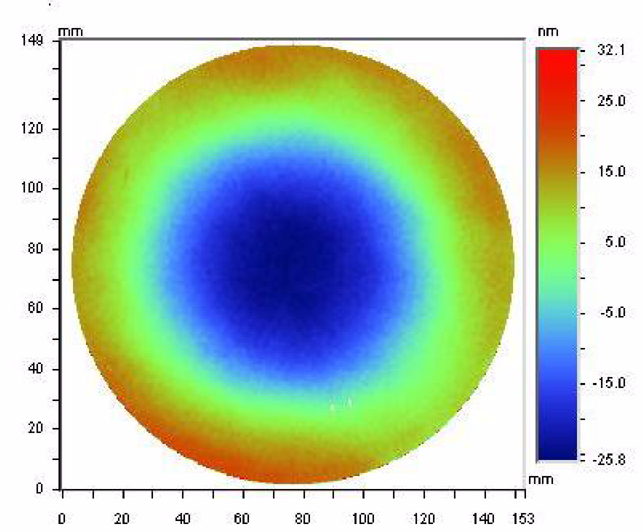
Fused silica with very low bulk absorption, high mechanical Q

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)





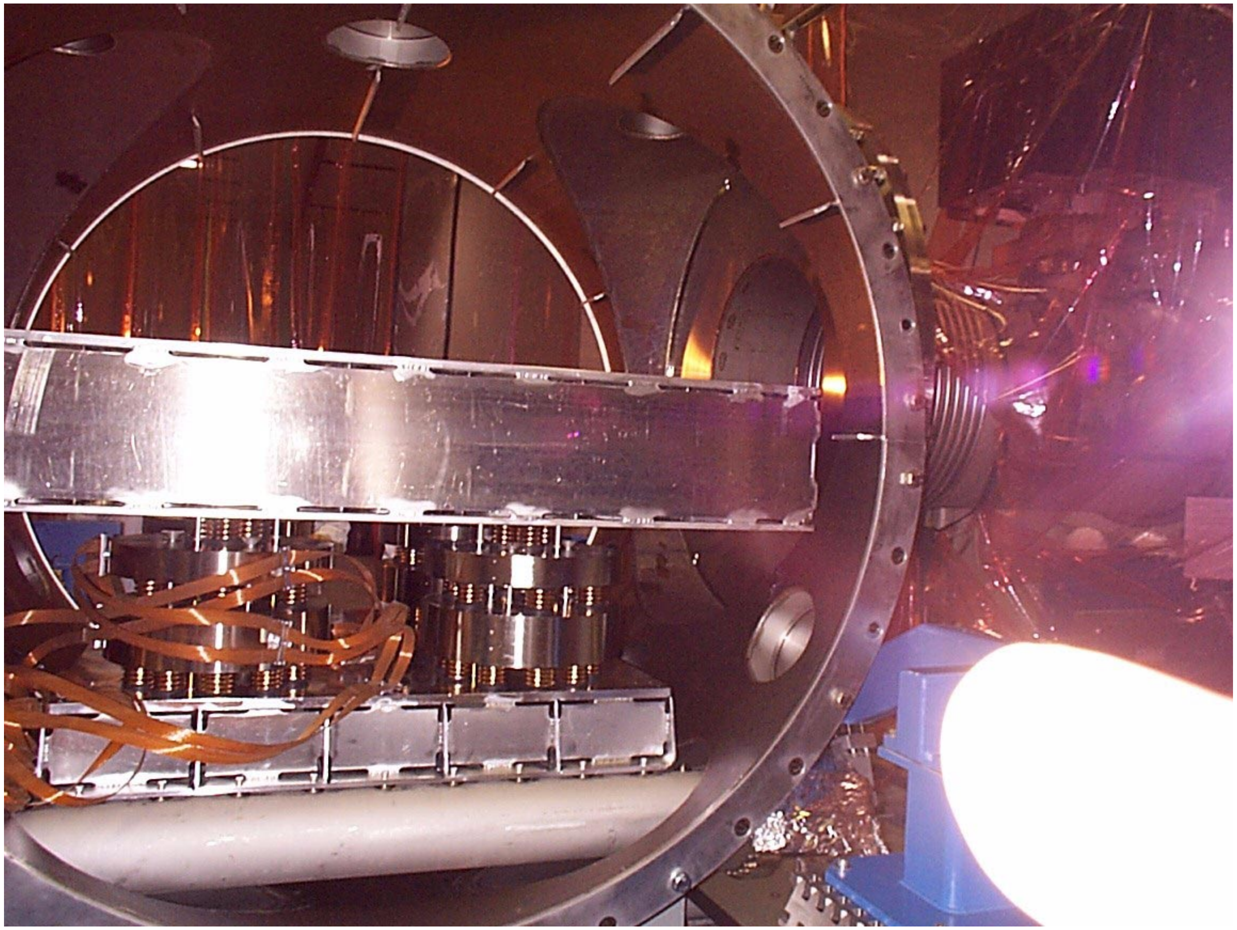
In interferometer, each mirror is suspended by a single steel wire

Mirrors are actively aligned & positioned with magnets & coils

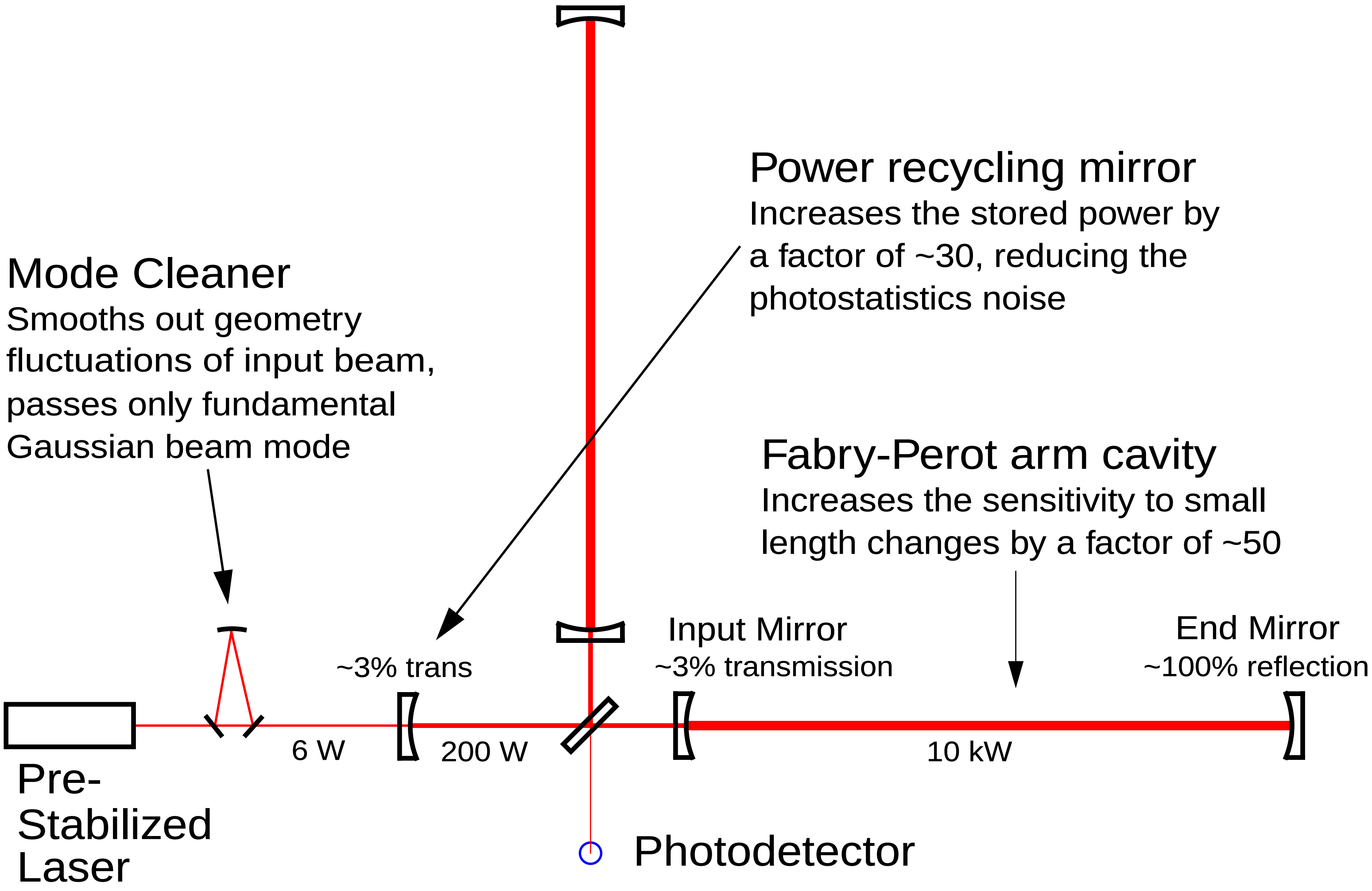
A Mirror In Its Vacuum Tank

Vibration Isolation

Optical table supports use a system 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, reducing the photostatistics noise

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

Pre-Stabilized Laser

Interferometer Controls

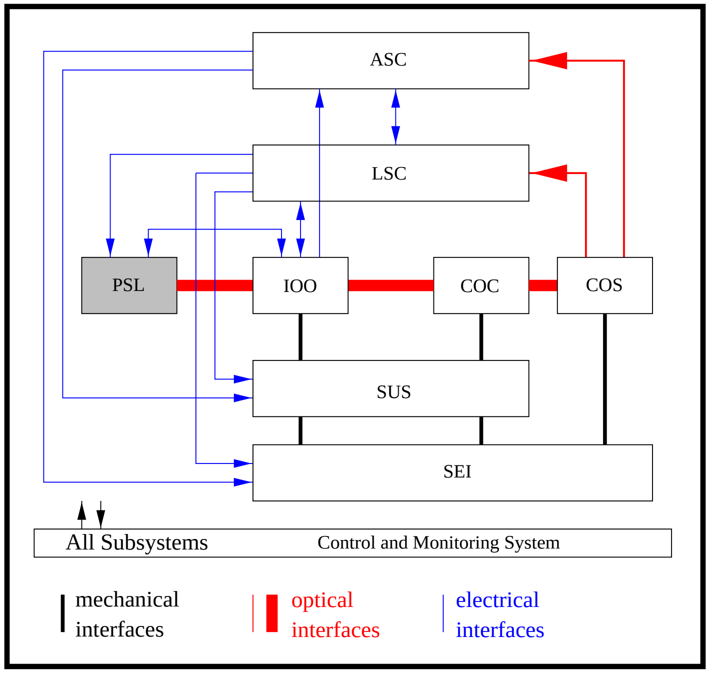
Servo control is the key to interferometer operation

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

Subsystems interact, forming complex network

- Laser (frequency & intensity)
- Mode cleaner length
- Input beam alignment
- Alignment of large mirrors (uses several “wavefront sensors”)
- Cavity lengths, recycling mirror position

Custom-built analog & digital servos, all computer-controlled



Optical Cavity Length Control

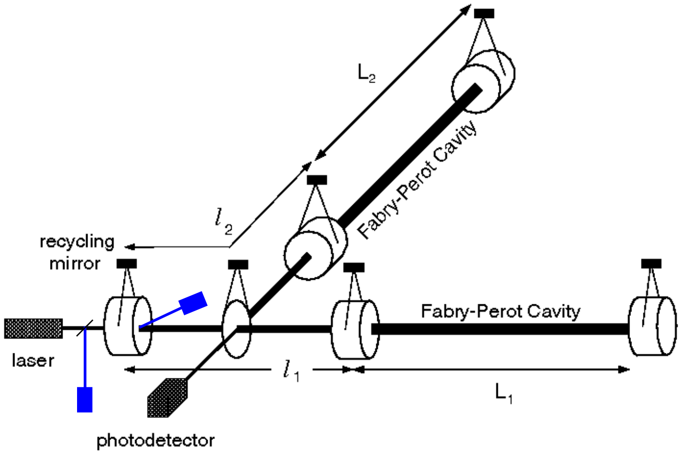
Basic method to lock an optical cavity on a dark fringe: use a Pockels cell to modulate phase of laser light going into cavity, then demodulate the output from the photodetector

- Produces an “error signal” proportional to mirror displacement

Full LIGO interferometer requires simultaneous control of four degrees of freedom

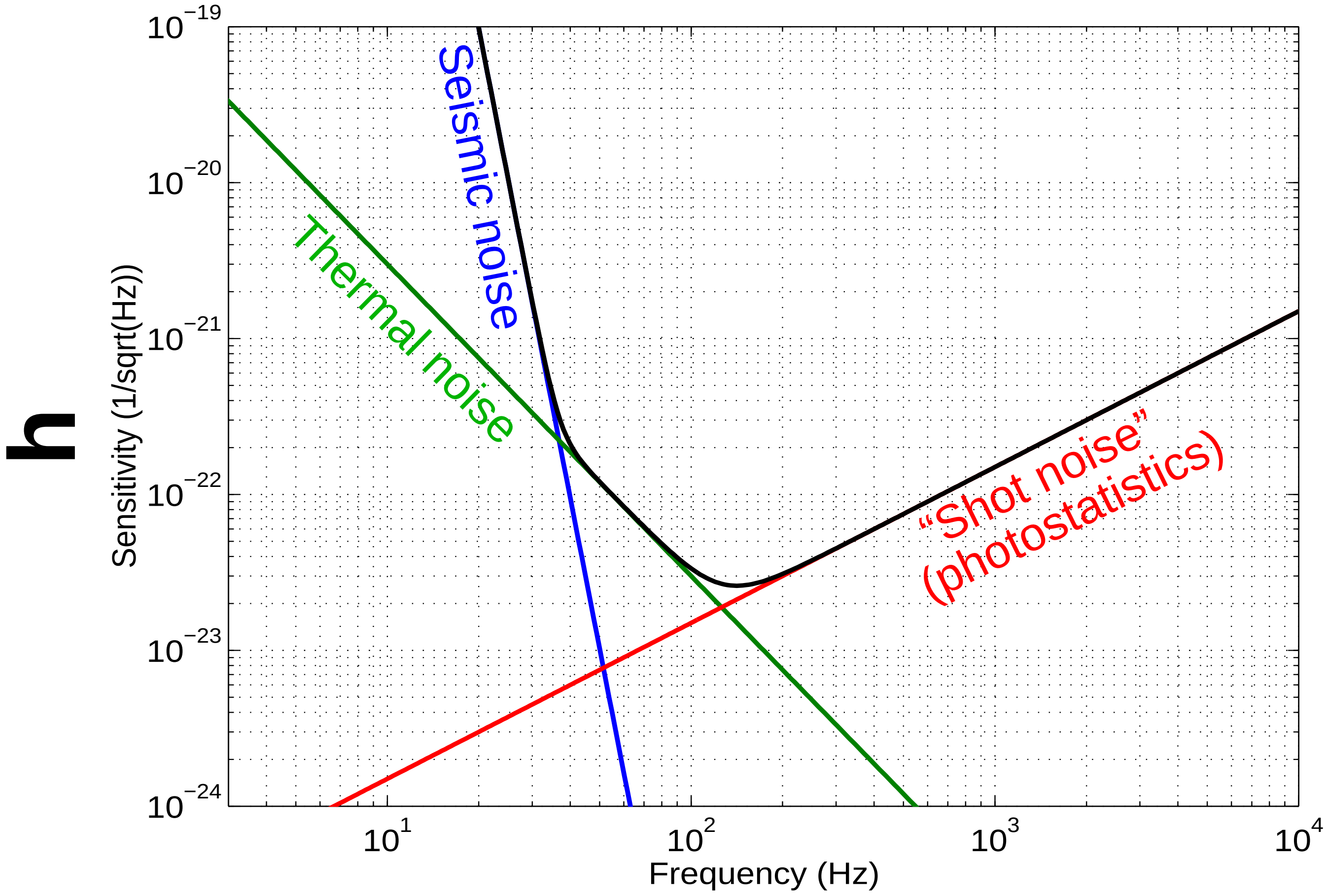
This requires photodetectors at two additional places, and careful selection of modulation frequency & nominal cavity lengths

Linear combinations of these signals are fed back to actuators driving the positions of the various mirrors



A gravitational-wave signal shows up in the L_1-L_2 degree of freedom

Noise vs. Frequency



Not shown: narrow resonances from suspension wire vibrational modes; resonances outside of useful frequency range

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

Overview of Data Analysis Techniques

Transient signals with known waveform

Use “matched filtering” — essentially, correlate detector output with signal template, with weighting to favor quietest frequencies

Need to use many templates spanning possible parameter values

Can make a list of event candidates from each detector, then compare lists; *or*

Can do a coherent analysis with data from multiple interferometers (Hanford 4K + Hanford 2K + Livingston + VIRGO + ...)

Multiple detectors allow determination of source direction, and can check for dipole component of wave

Transient signals with unknown waveform

Look for impulse or excess power — “something which is not noise”

Coincidence among multiple detectors is crucial

Can look for coincidences with gamma-ray bursts, supernovae, neutrinos

Overview of Data Analysis Techniques

Periodic signals

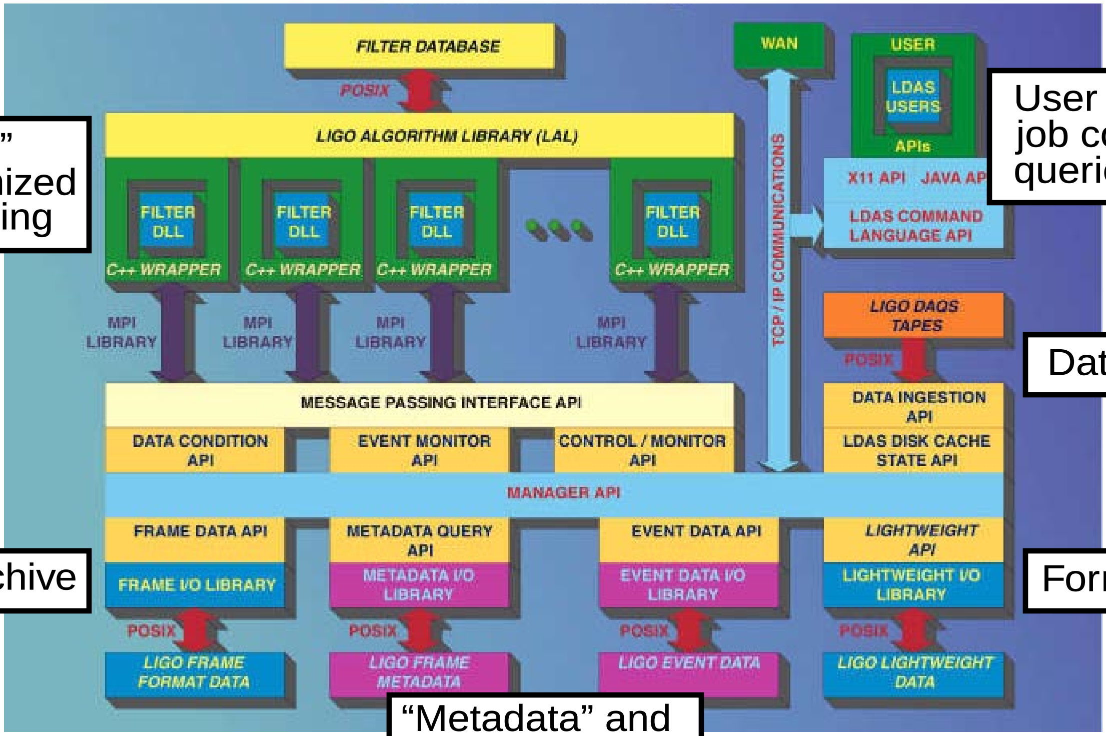
- Integrate over a long time, correcting for Earth's motion and antenna pattern of detector(s) with respect to a direction in the sky
- Easy to look at known pulsars
- A general full-sky search requires a lot of CPU!

Stochastic signals

- Cross-correlate outputs from pairs of detectors
- Can correlate an interferometer with a "bar" detector

LIGO Data Analysis System

Unified system consisting of various software components running on many computers connected to a high-bandwidth network



"Beowulf cluster" (PC farm) optimized for parallel filtering

User interface for job control, database queries, data export

Data ingestion

Raw data archive

Format translation

"Metadata" and event database

Installations at Hanford & Livingston (for online event searches) plus one or more offline analysis centers; main raw data archive at Caltech

Prospects for Signal Detection

Inspiral of two neutron stars

- A few systems known to exist
- LIGO reach: ~20 Mpc (65 million light-years)
- Expected rate: ~(10^{-3} – 1) event/year; best guess ~10^{-2}

Inspiral of black hole and neutron star *or* two black holes

- Larger signal amplitude ⇒ farther reach
- No examples known ⇒ rates uncertain, but likely to be significantly higher than NS-NS

Supernova

- Asymmetry of explosion is unknown, but probably small ⇒ <1 event/year ?

Rapidly-spinning neutron star

- Non-axisymmetry probably too small? *r*-mode might be damped?

Stochastic gravitational-wave background from early universe

- May be detectable in certain non-standard models

Black hole formation, stellar core collapse, etc. — ????

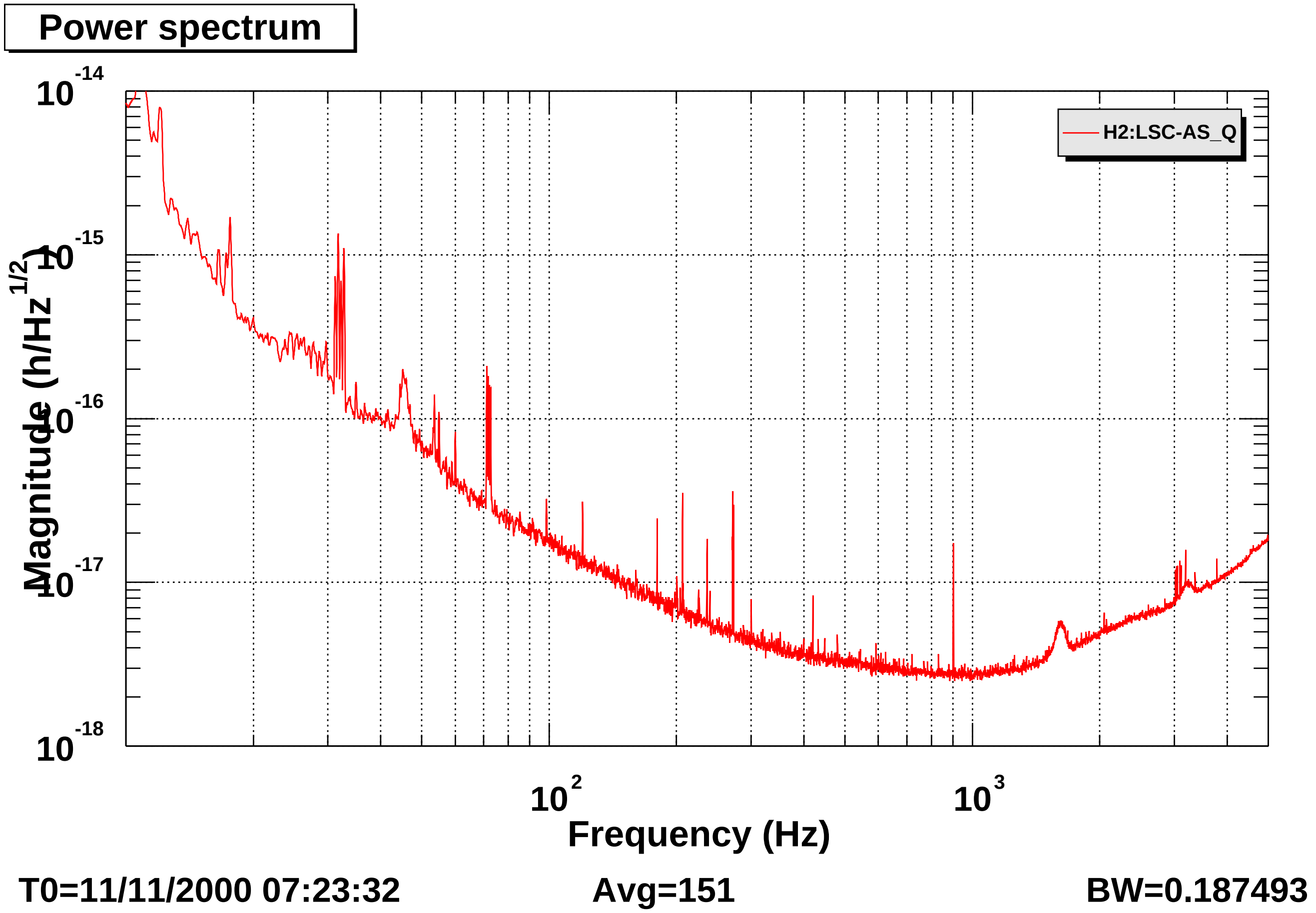
Some Recent Milestones

Dec 1999	Hanford	First light along a 2 km arm cavity
Dec 1999	Hanford	Single arm locked (briefly at first, then longer)
Apr 2000	Hanford	“Engineering data run” with single arm locked
May 2000	Livingston	Beam tube bakeout complete
July 2000	Hanford	“Vertex Michelson interferometer” locked
Aug 2000	Hanford	2 km interferometer installation complete
Aug 2000	Livingston	Mode cleaner commissioning complete
Oct 2000	Livingston	Interferometer installation complete
Oct 2000	Hanford	“First lock” of full 2 km interferometer
Nov 2000	Hanford	Engineering test run with 2 km interferometer

Engineering Run — Going On Now!

2-km interferometer with both arms, but with recycling mirror misaligned

Several servo loops not yet enabled



Current Activities and Schedule

Some current activities:

- Studies of environmental transients (earthquakes, airplanes, ...)
- Suspension debugging and tuning
- Servo evaluation and modification
- Comparing detector behavior against end-to-end simulation
- Studies of lock acquisition

Projected Schedule:

Nov 2000	Hanford 4K	All in-vacuum installation complete
Dec 2000	Hanford 2K	Full interferometer locked
Feb 2001	Livingston	Full interferometer locked
Apr 2001	Hanford 4K	Interferometer installation complete
Apr 2001	H2 + L	Coincidence engineering runs begin
Aug 2001	Hanford 4K	Full interferometer locked
Early 2002	H2 + H4 + L	Begin science run

Planning for a LIGO Detector Upgrade

A reference design, resulting from ongoing R&D, has been formulated:

- Increase laser power to 180 W
- Increase mirror mass to 30 kg; probably switch to sapphire
- Add active compensation for thermal lensing in input mirrors
- Improve vibration isolation with new active & passive stages
- Redesign mirror suspension (multiple pendulum stages, silica fibers)
- Electrostatic actuation for mirror alignment & positioning
- Add a "signal recycling mirror" to enhance signal extraction; also provides some frequency tunability
- Add a mode cleaner at the output port

Expect to achieve a factor of 10 better sensitivity than initial LIGO
$\Longrightarrow$ a factor of 1000 in event rate!

Could be ready to install as early as 2005-6

Summary

Construction of the LIGO observatories was a great success

Installation is complete for two of the three interferometers

Commissioning is progressing, with no serious setbacks

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

The initial LIGO detectors may need a little luck to observe gravitational waves, *if* the current predictions are to be believed and there is no “new astrophysics”

There is a mature plan for upgrading the detectors which promises a dramatic increase in sensitivity

There are ideas for even more advanced interferometer designs...

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