The First LIGO Science Run

Peter Shawhan
Caltech / LIGO Laboratory

University of Chicago – HEP Seminar
February 3, 2003

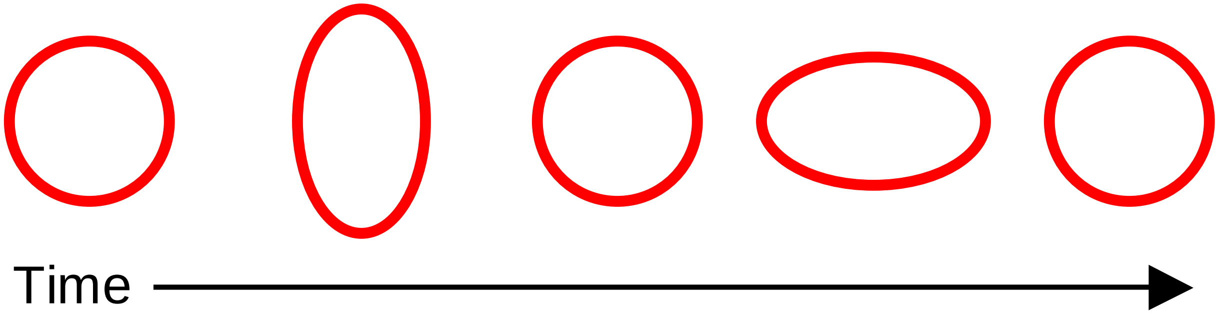
Outline

- Gravitational Waves
- LIGO Detectors
- Commissioning Progress
- The First Science Run
- Analyses in Progress
- The Future

Gravitational Waves

Massive objects, moving at velocities near the speed of light, distort the geometry of space-time

Far from source, appear as transverse quadrupolar waves



Dimensionless strain: $h = \Delta L / L$

Sources are expected to be rare, so we have to search a large volume of space

Typically think about waves reaching Earth with $h < 10^{-21}$ **!**

Gravitational-Wave Detectors

First detectors: resonant aluminum “bars”

First built by Joseph Weber in the 1960s

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

AURIGA detector

Several large *interferometric* detectors are now being beginning operations: LIGO, VIRGO, TAMA, GEO

Use a laser beam to measure distance

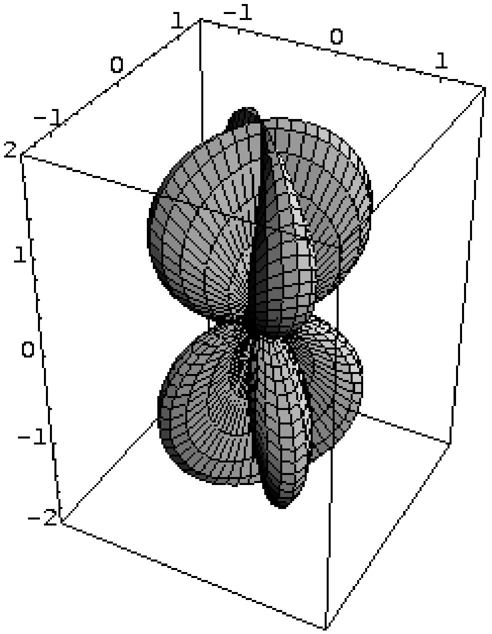
Sensitive over a wide frequency range

The search for gravitational waves is an international cooperative effort

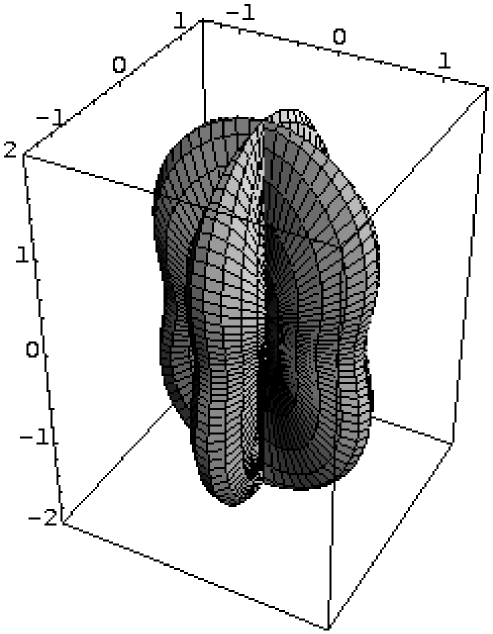
Antenna Patterns for Interferometric Detectors

Sensitivity depends on polarization of waves

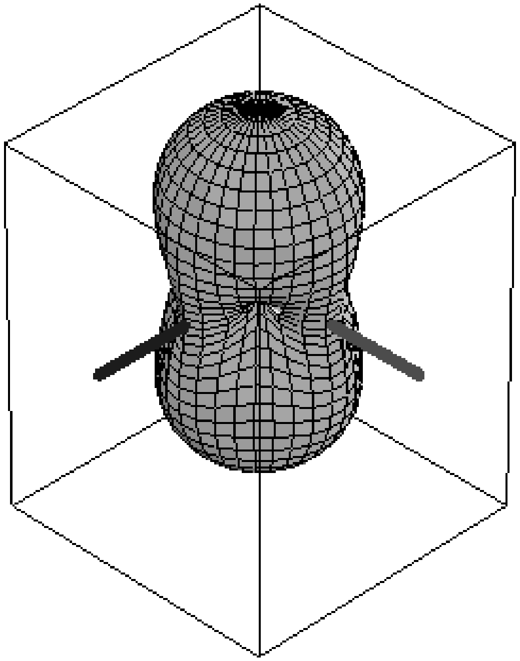
“×” polarization



“+” polarization



RMS sensitivity



A network of several detectors can extract information about the wave polarization

Outline

Gravitational Waves

LIGO Detectors

Commissioning Progress

The First Science Run

Analyses in Progress

The Future

The LIGO Project

LIGO = Laser Interferometer Gravitational-wave Observatory

Funded by the National Science Foundation

LIGO has built two "observatories"

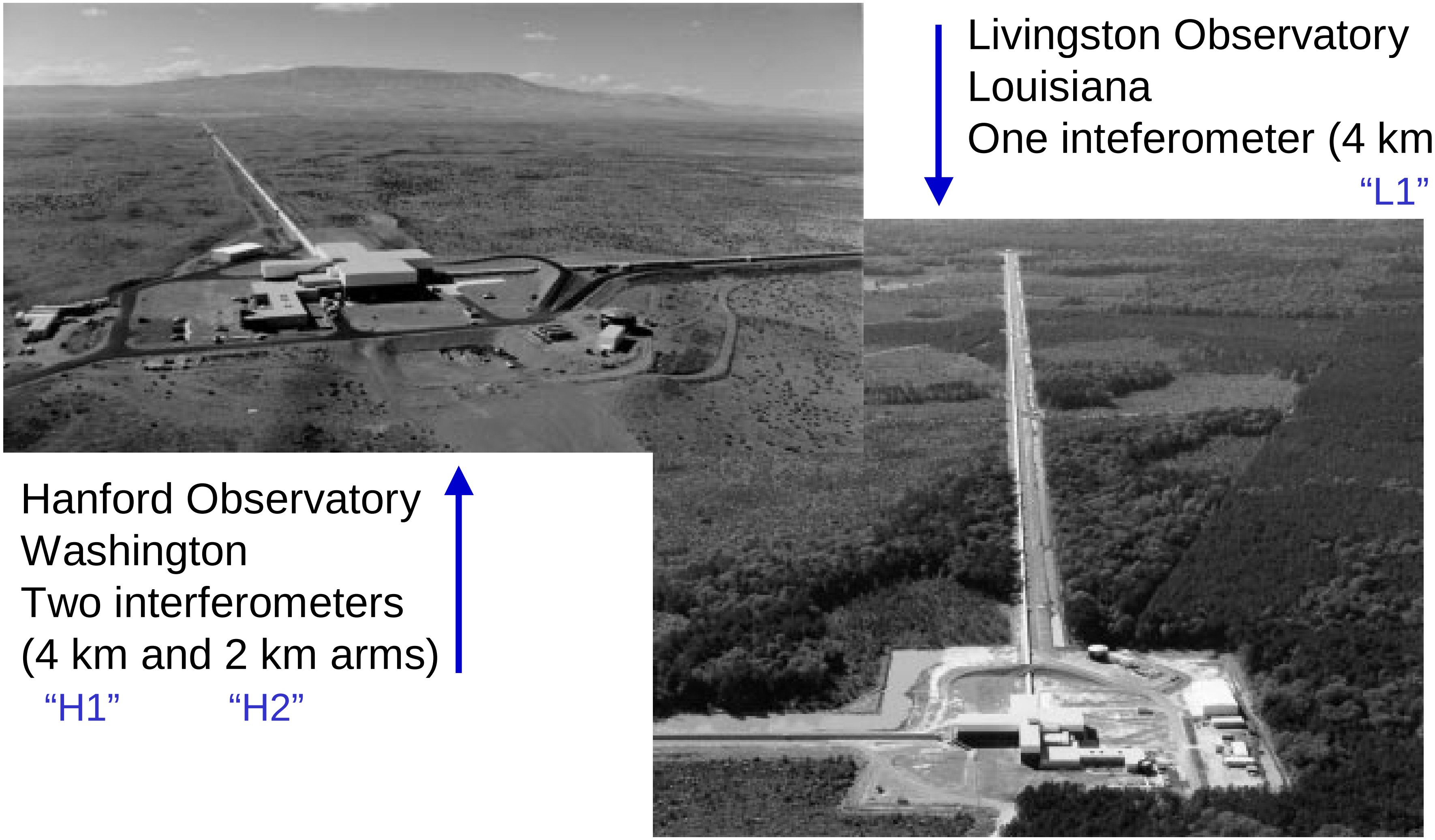
- Construction cost: $300 million

"LIGO Laboratory" is a joint project of Caltech and M.I.T.

The broader "LIGO Scientific Collaboration" (LSC) includes over 300 scientists from over 30 institutions worldwide

- Perhaps ~75 are actively involved in data analysis
- A little more than half are officially members of the "LIGO I" team
- The rest are involved in advanced detector R&D

LIGO Observatories



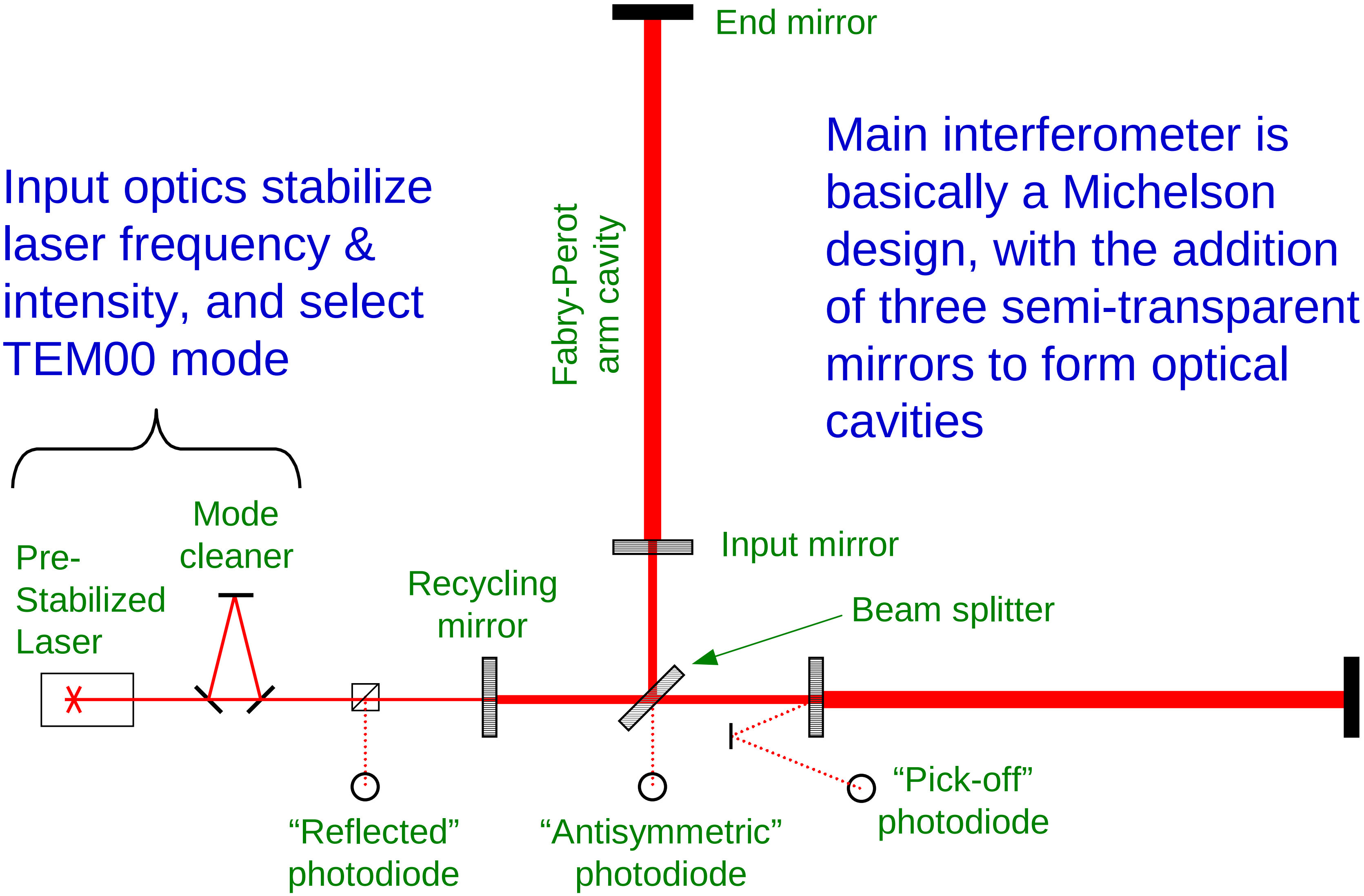
Livingston Observatory
Louisiana
One inteferometer (4 km)
“L1”

Hanford Observatory
Washington
Two interferometers
(4 km and 2 km arms)
“H1” “H2”

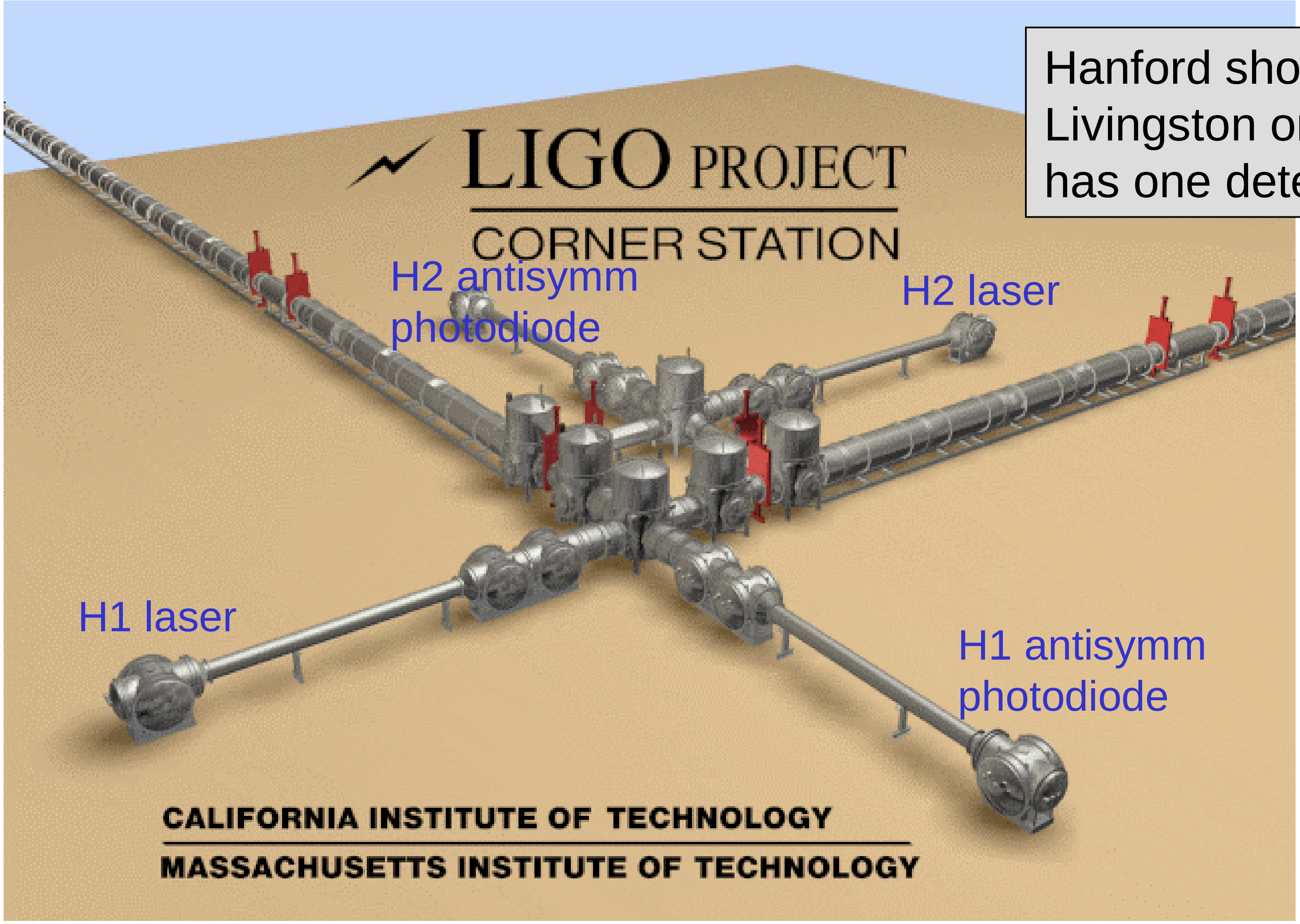
Optical Layout
(not to scale)

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



Vacuum System

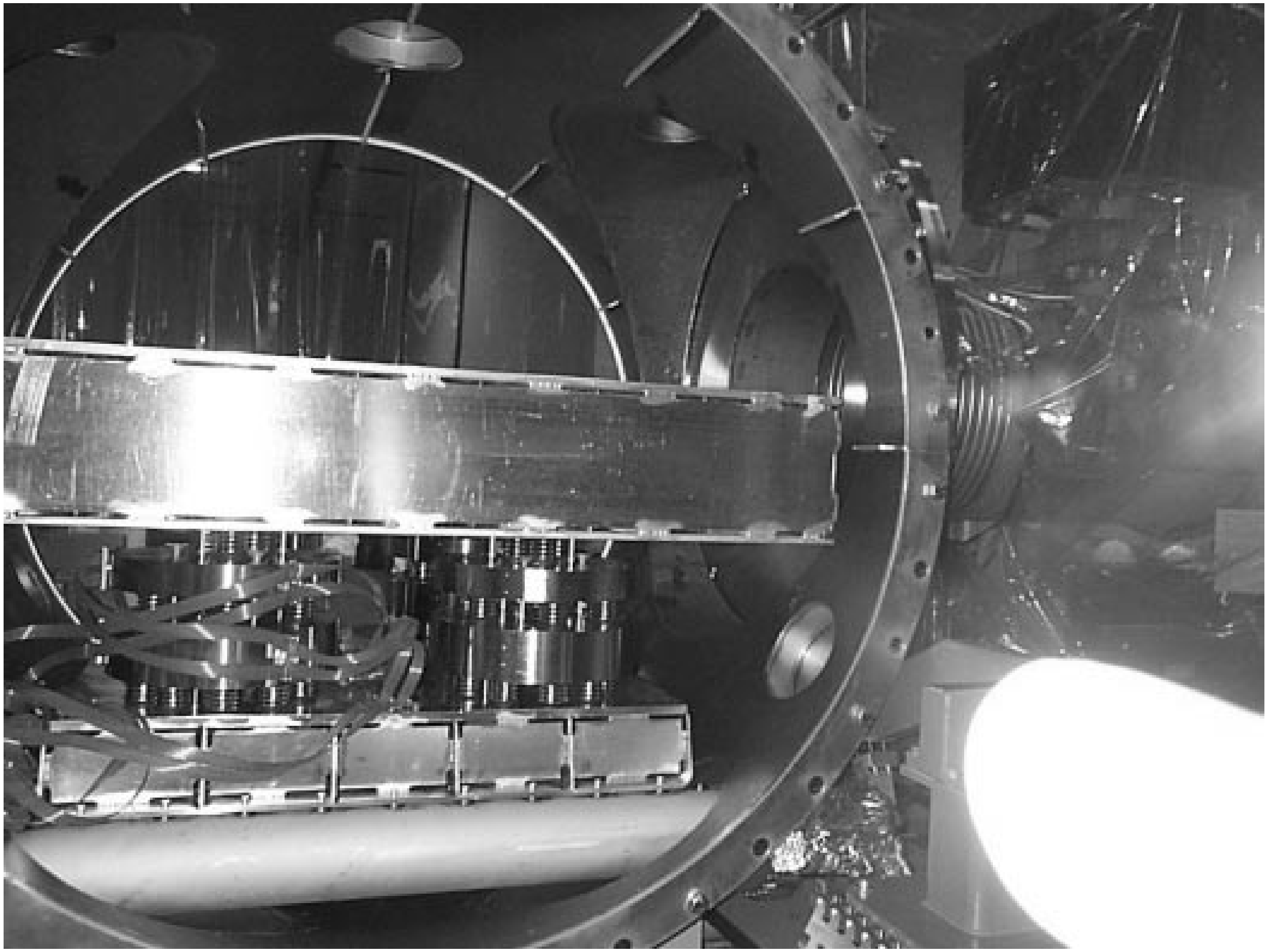


Hanford shown; Livingston only has one detector

Vacuum System

A Mirror *in situ*

Vibration Isolation

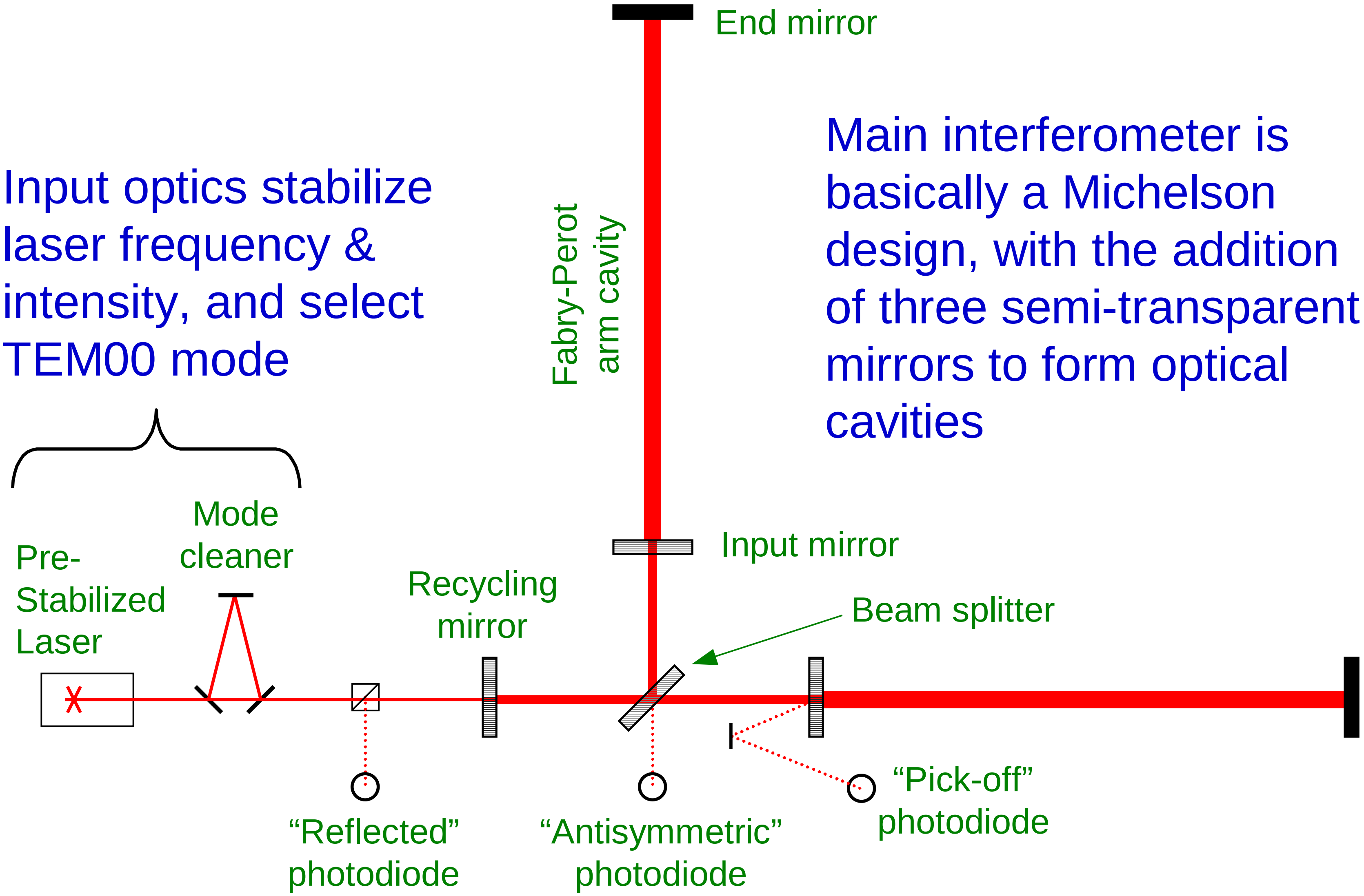


Optical Layout

(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

Also feed back to input optics to control frequency of laser

There are other servo loops to control alignment, etc.

Data Acquisition

Demodulated photodiode signals are sampled at 16384 Hz

- Synchronized to GPS time reference

Data stream also includes many auxiliary channels

- Readback channels from the various servo systems
- Environmental sensors (seismometers, magnetometers, etc.)

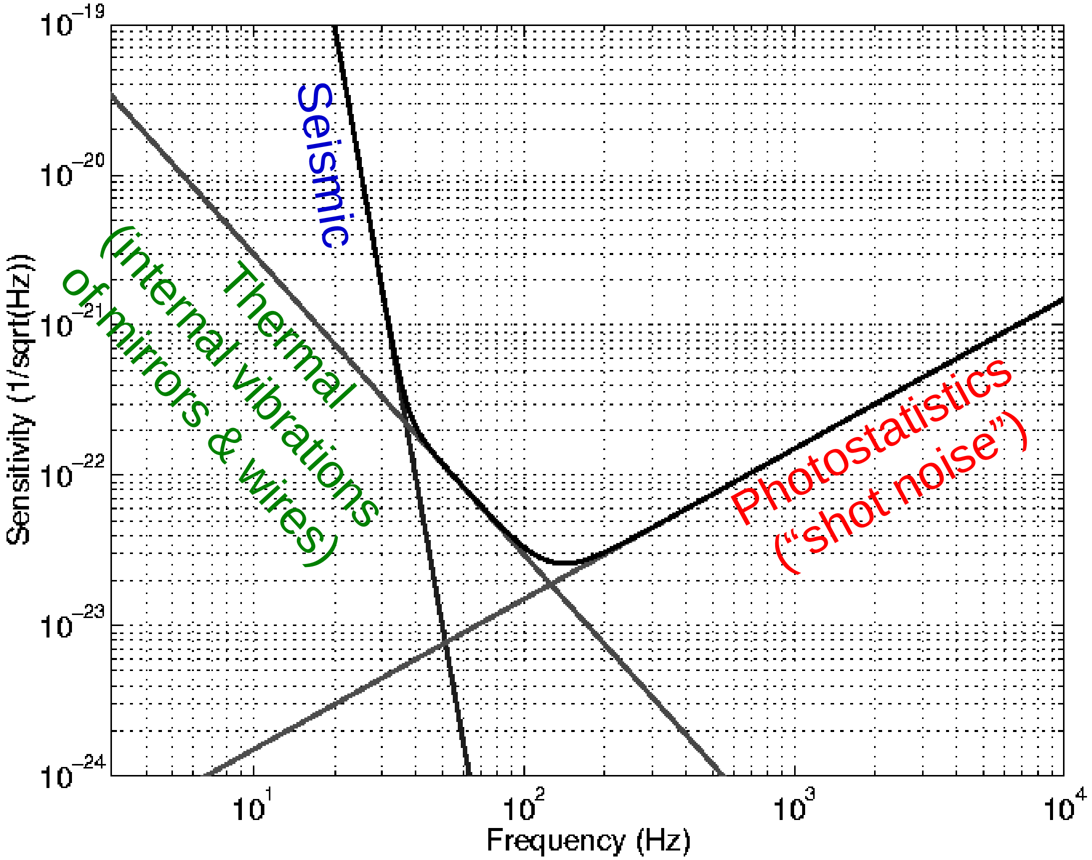
There is no trigger — channels are sampled continuously and written first to disk, later to tape

Total data rate from each interferometer: ~3 MB/sec

- Gravitational wave channel is only ~2% of the data stream

Data to be archived: ~100-200 TB per year

Fundamental Noise Sources



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

Outline

Gravitational Waves

LIGO Detectors

Commissioning Progress

The First Science Run

Analyses in Progress

The Future

Milestones

Construction of the observatory facilities completed in 1999

“First light” along a 2-km arm achieved in December 1999

- First (brief) locks of a single arm were achieved shortly thereafter

“First lock” of full recycled 2-km interferometer achieved in Oct 2000

Last in-vacuum mirror installed in July 2001

All interferometers operating in power-recycled configuration since January 2002

Commissioning Activities

- **Commissioning still takes up the majority of the time**
- **Adding and tuning servo loops to control degrees of freedom**
  - Common-mode servo
  - “Optical lever” damping
  - Alignment servo loops – using “wavefront sensors”
- **Revisions of control electronics**
- **Tracking down noise sources**
  - Electronic, acoustic, etc.
- **Working on improving robustness of locking**

Engineering Runs

Since April 2000, have occasionally interrupted commissioning to collect data in a stable configuration

- Optical configurations evolved over time
- Durations ranged from 1 day to 2 weeks

Practice around-the-clock running

- Operators
- Scientific monitoring shifts
- Test monitoring software

Get some data to analyze

- Try out data analysis software
- First attempts to do astrophysical analysis started with data from the “E7” engineering run, about a year ago

Last Year's Schedule Setback

The first science run was scheduled for 28 June – 15 July

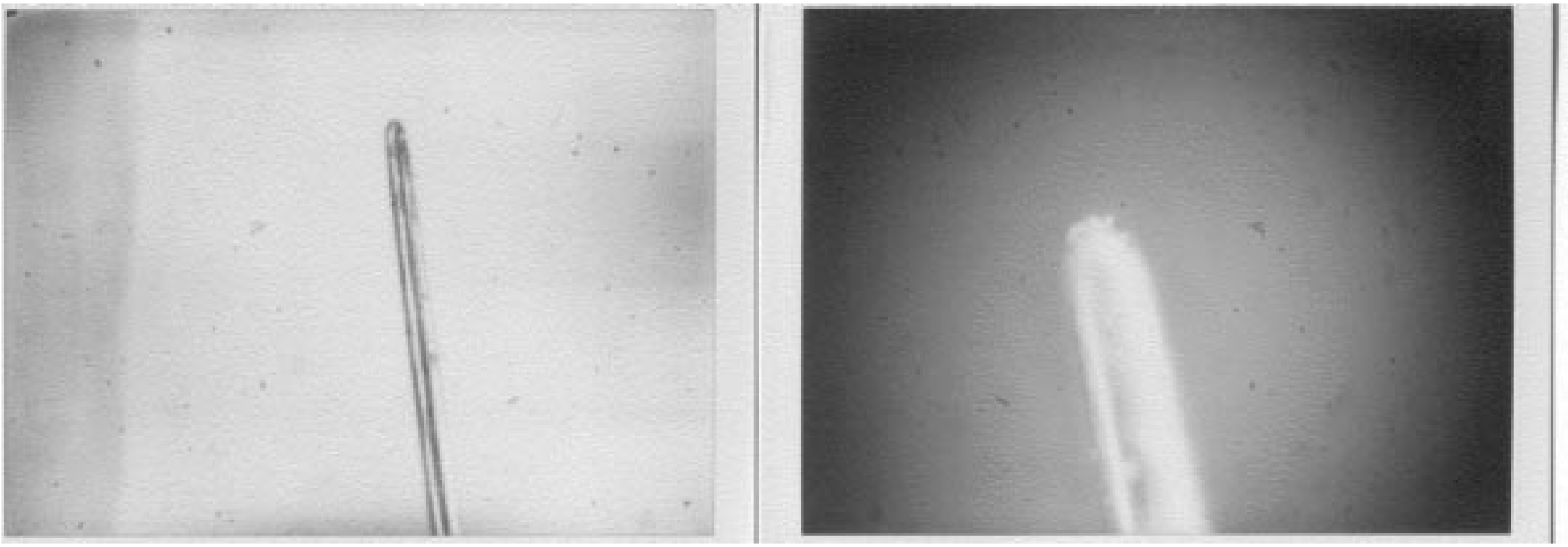
BUT: On 28 June, a magnitude 7.2 earthquake occurred in China

… which shook the mirrors at Hanford

… which caused one of the mirror position controllers to start oscillating

… which caused the H2 input laser beam to swing wildly

… which melted the wire suspending one of the other mirrors



Outline

Gravitational Waves

LIGO Detectors

Commissioning Progress

The First Science Run

Analyses in Progress

The Future

The First Science Run (“S1”)

23 Aug – 9 Sept 2002 (17 days)

All 3 interferometers ran in power-recycled configuration

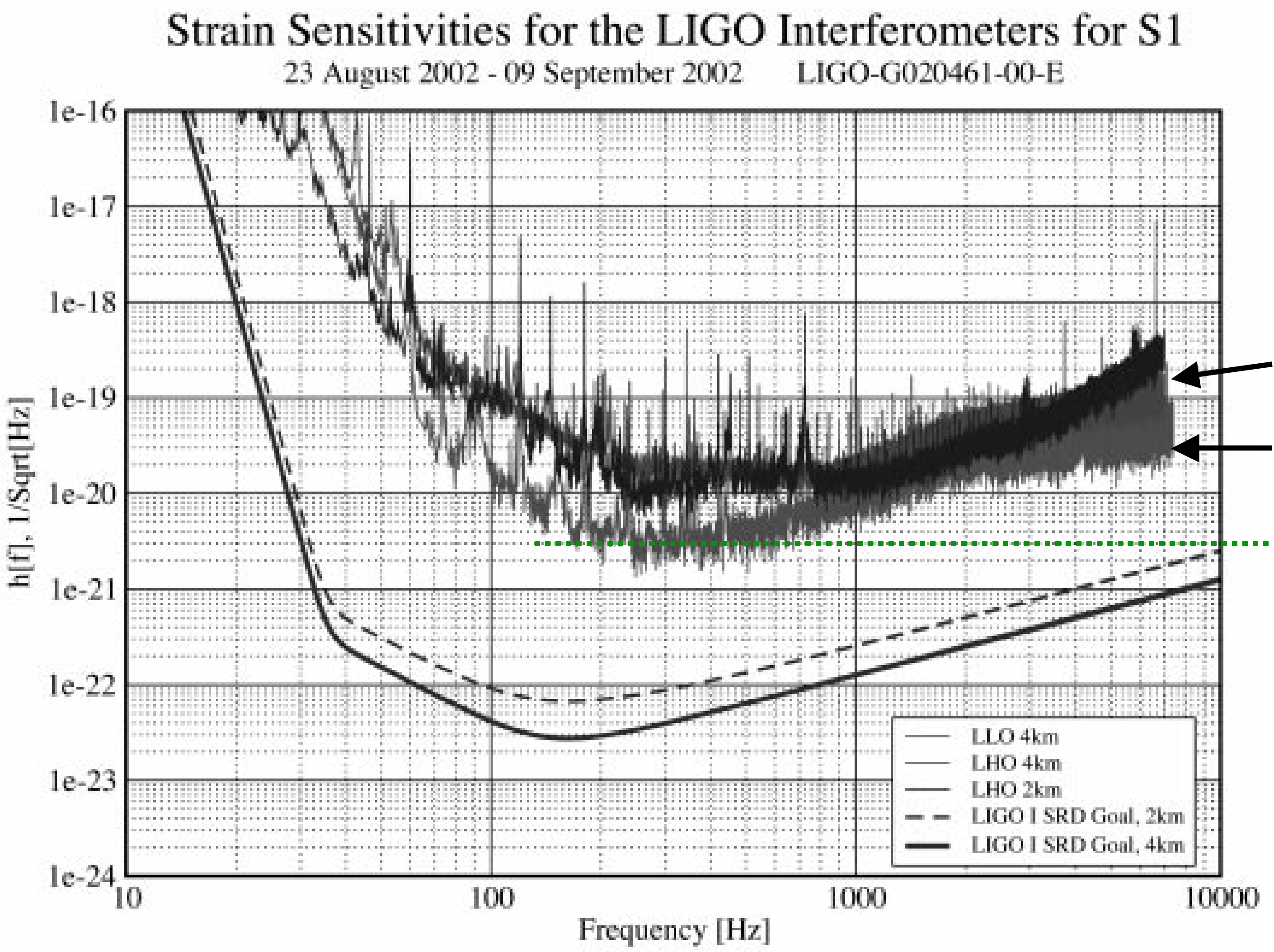
Observing time in “science mode”

L1	170 hours (42%)	Limited by daytime seismic noise
H1	235 hours (58%)	
H2	298 hours (73%)	
All 3	96 hours (23%)	

GEO detector ran at same time

- Still in a preliminary optical configuration
- Was much less sensitive than the LIGO interferometers

Strain Sensitivities During S1



3×10^{-21} at ~300 Hz

World's best sensitivity for binary neutron star inspirals

Data Selection and Algorithm Tuning

Operators marked "science mode" data as it was collected

Noise levels are pretty consistent for most of this data

Some intervals of elevated noise may be rejected

We define a "playground" consisting of ~10% of the 3-way simultaneous data, selected from throughout the S1 run

To avoid the possibility of human bias, only the playground data may be studied in detail and used to choose cuts, etc.

e.g. try to veto gravitational-wave event candidates by looking for simultaneous transients in auxiliary channels

Once analysis procedure is finalized, full data set (excluding playground) is processed to give final result

Hardware Signal Injection

There are no natural signals available to check the operation of the detector !

Drive mirror actuators to mimic gravitational-wave strain

For calibration purposes:

- Occasionally inject many sine waves of various frequencies, to measure complete frequency-dependent transfer function of detector
- Continuously inject a few sine waves, to track changes in response

As an end-to-end check on the analysis:

- Inject simulated astrophysical signals, see whether the search algorithm detects them with the correct parameters
- Inject **large** signals and look for coupling into auxiliary channels used for vetoes, to verify that it is safe to apply the veto

Outline

Gravitational Waves

LIGO Detectors

Commissioning Progress

The First Science Run

Analyses in Progress

The Future

Overview of LIGO Data Analysis

Mostly done within four working groups of the LIGO Scientific Collaboration, focused on different source types

Inspiral	– Orbital decay of compact binary system
Burst	– Short-duration signal of unknown waveform
Continuous-wave	– Emission at a constant (or slowly varying) frequency
Stochastic	– Persistent broadband “noise”

None of these groups has results ready yet for public presentation

A number of analyses are fairly near completion

Drafts exist for a few papers

Internal review committees have been formed, but have not done much yet

Data Analysis Tools

CPU-intensive data processing is done with the "LIGO Data Analysis System" (LDAS)

- A "computing center" concept, with a cluster of dedicated computers on a private network, and a software environment created specifically for LIGO
- Basically a batch system, with remote job submission and result retrieval via socket-based communication; no direct Unix login
- Provides a number of specific services, such as a relational database
- Includes a large cluster of PCs for parallel computing
- Scientists contribute and maintain the LIGO Algorithm Library (LAL)
- There are LDAS systems at Caltech, MIT, Hanford, Livingston, and a few LSC institutions

Other analysis tasks (*e.g.* statistical analysis, follow-up evaluation of candidate events) are done with other tools

- Common components are distributed as part of "LIGOtools" software suite

Challenges for LIGO Data Analysis

Communication

Collaborators are spread across many institutions

There's no natural "center of mass" to bring people physically together

Expertise

LIGO data analysis spans a wide range of techniques

Many collaborators have not done any analyses of these types before

There's a steep learning curve for writing analysis code to run on LDAS

Lack of standardization of high-level tools and methods

People use Matlab, ROOT, Mathematica, PAW, C or C++ programs, etc.

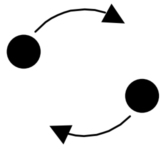
Manpower

Many of the key people are juggling multiple responsibilities

Basically, have to push analyses to completion before the next science run

Inspiral Sources

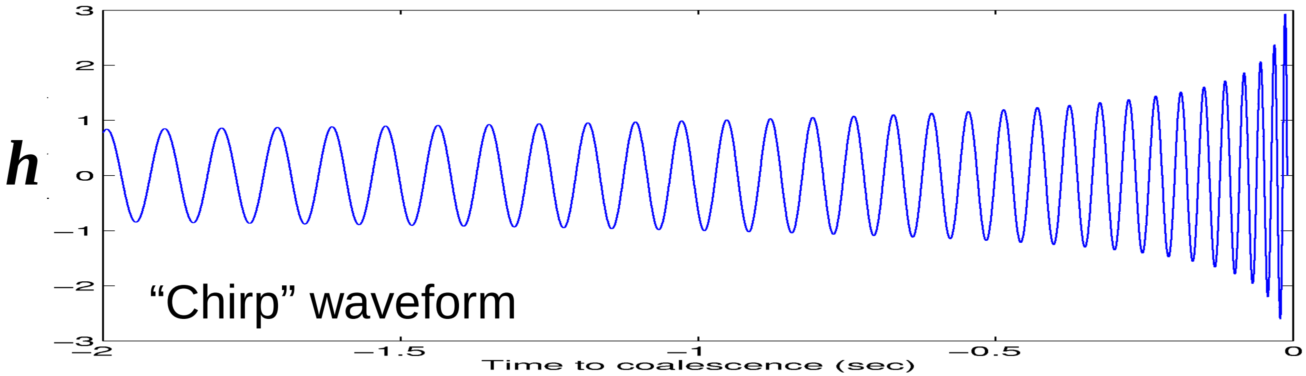
Orbital decay of a compact binary system



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 generally well known (until just before merging)



“Chirp” waveform

Note: the measured orbital decay rate of the binary pulsar PSR 1913+16 exactly matches the expected rate due to gravitational radiation !

Inspiral Search Algorithm

Since waveform is known, use “matched filtering”, *i.e.* calculate correlation of data stream with template waveform

Do this in Fourier domain for computational efficiency

Takes advantage of forward & inverse fast Fourier transforms

Make the filter “optimal” by weighting frequencies according to detector noise

Cut on a χ^2-like variable which checks power distribution

Template waveform depends on masses of objects

Also depends on spin, for high-mass objects

Need a “bank” of thousands of templates to cover interesting region of parameter space

This is computationally intensive, so use parallel computing

The S1 Inspiral Analysis

Restricted to low-mass objects (1–3 $M_\odot$ each) with no spin

Includes binary neutron star systems, nominally 1.4 + 1.4 $M_\odot$

Uses L1 and H1 interferometers, not H2

Both were sensitive enough to see essentially the whole Milky Way

SNR distributions are very clean, at least in playground data

Analysis optimized for placing the best upper limit on rate

Looks for coincidences during simultaneous observing time (for which background can be estimated by time-shifting)
plus single events when only one interferometer was locked (for which background is unknown, so we accept all events as signal candidates)

Use Monte Carlo to calculate analysis efficiency

Use a model of sources in the Milky Way and environs

Add simulated waveforms to real S1 data stream

Future Directions for Inspiral Searches

Lower-mass objects (search for MACHO binaries)

Higher-mass objects

- Waveforms can’t necessarily be calculated accurately
- Spin becomes relevant, and may greatly expand parameter space

Hierarchical search algorithms

- First search with a coarse template bank and a low threshold; for any threshold crossings found, follow up locally with a fine template bank
- There are several variations on this idea, none of them fully implemented in software yet
- Could gain up to a factor of ~100 in computational efficiency

Coherent analysis

- Apply matched filtering to combined data streams from multiple detectors

Burst Sources

By definition, “burst” sources have unknown waveform

If waveform were known, matched filtering would be the best algorithm

Supernova

Depends on asymmetry of explosion, which is not well known

Ringdown of a newly formed black hole

Expect a damped sinusoid

Coalescence of two compact objects

Waveform is unknown in this strong-gravity situation

Others ??

Burst Search Algorithms

A few different algorithms have been implemented

All designed to be fairly model-independent

“Excess power statistic”

A time-frequency algorithm which looks for a significant momentary increase in power in a particular frequency band

“TFCLUSTERS”

An algorithm which looks for excess power (crossing an adaptive threshold) in contiguous cells in a time-frequency spectrogram

“Slope”

Applies a filter to the data stream, then looks for trends in the time series over short time scales

S1 Burst Analyses

Coincidence search

Uses TFCLUSTERS and Slope algorithms

Records event candidates in each detector

Requires 3-way coincidence within a time window
(also, for TFCLUSTERS, requires consistency of frequency content)

Background rate is estimated by time-shifting

Efficiency of analysis calculated using a Monte Carlo, with a few types of "toy" waveforms with appropriate frequency content

Express result in terms of a hypothetical population of events with waveforms like these

Triggered search

Look for excess power, common to multiple interferometers, around the time of gamma-ray bursts

Future Directions for Burst Searches

Additional algorithms under development

“Block-normal”: Looks for changes in mean and/or RMS

“WaveBurst”: Does wavelet decomposition

Do analysis for specific astrophysical models

Source of Continuous Waves

Rotating neutron star

- Lots of these exist (*e.g.* pulsars)
- Emission of gravitational waves requires a deviation from axisymmetry
- It’s an open question whether the crust of a cool neutron star could support a significant non-axisymmetry
- Young, rapidly rotating neutron stars could possibly have bulk mass-flow instabilities which deform them and lead to radiation

Continuous-Wave Search Algorithms

Basic idea is to integrate coherently at some frequency over a long data stream

But frequency is not quite constant

- Have to correct for Doppler shift due to motion of Earth relative to the barycenter of the Solar System
- Also, intrinsic source frequency may change gradually

Searching among known radio pulsars is straightforward

A brute-force, all-sky, all-frequency search is computationally impossible

There are a few hierarchical techniques which can bring the computational cost down to a reasonable level

Continuous-Wave Searches for S1 and Beyond

Using the S1 data

Have completed a time-domain analysis for one known pulsar, J1939+2134

Getting ready to repeat analysis for other known pulsars

Future plans

Working to refine a few varieties of frequency-domain searches, which can be used as pieces of all-sky hierarchical searches

Stochastic Sources

Gravitational-wave background radiation

Isotropic, stationary, broadband

Bulk motion of matter in the early universe

Amplitude and frequency content depends on physics of early universe (slow-roll inflation, or some alternative)

Many overlapping short-duration sources

Stochastic Search Algorithms

Calculate cross-correlation between two interferometers

Separation between detectors determines what frequency components will be correlated

- At Hanford, H1 and H2 would have perfect correlation
- Hanford–Livingston correlation is significant only below 100 Hz

Apply a filter to give greatest weight to frequencies where expected correlation is high and detector noise is low

- Strongly suppresses the effect of 60 Hz and harmonics

Calculate cross-correlation between L1 and ALLEGRO

- Sensitive to a narrow band around 1 kHz
- ALLEGRO can be rotated to null out the correlation, as a check

Stochastic Searches for S1 and Beyond

Using the S1 Data

Place a limit on Ω_{GW}, assuming flat as a function of frequency

Future plans

S2 data should yield limits on Ω_{GW} well below unity

Repeat analysis with different models for $\Omega_{GW}(f)$

L1–ALLEGRO analysis

Outline

Gravitational Waves

LIGO Detectors

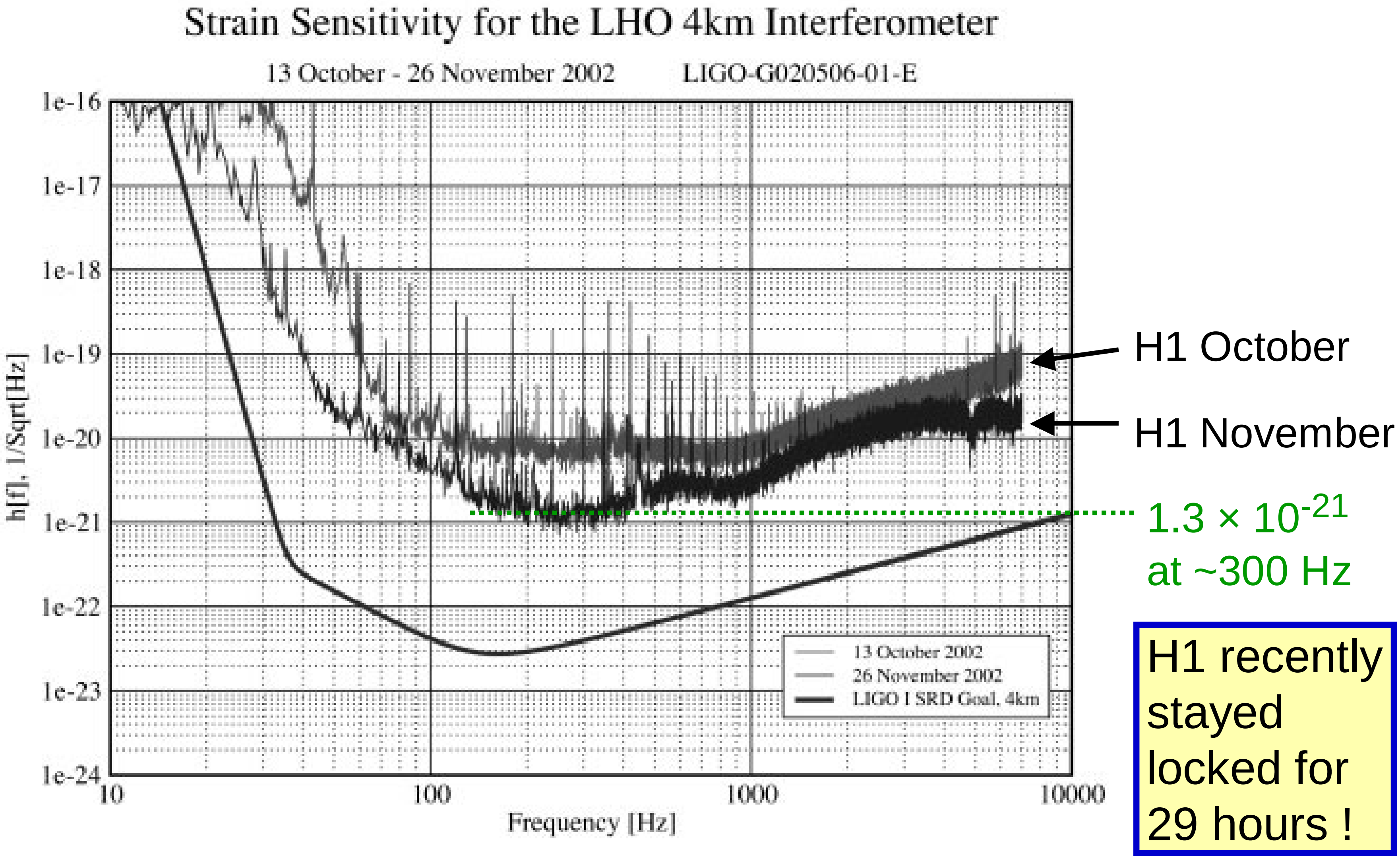
Commissioning Progress

The First Science Run

Analyses in Progress

The Future

Sensitivity Improvements Continue



1.3 × 10^{-21} at ~300 Hz

H1 recently stayed locked for 29 hours !

Future Science Runs

S2 run: February 14 to April 14, 2003

- Expect to have better monitoring and calibration
- Just completed E9 “dress rehearsal” (January 24-27)
- Still a lot of work to do to get ready!

S3 run: A several-month run to start in late 2003

- Livingston will have active seismic isolation

LIGO goal for the next ~4 years: at least one year (integrated) of simultaneous observing by all three interferometers at or near the design sensitivity

Advanced LIGO

Motivation

Take advantage of advances in detector technology and engineering

Install completely new detectors at existing observatories

Expect to reach at least 10 times as far as current LIGO detectors

Progress continues on detailed design and R&D

Technical issues include choice of mirror material (sapphire vs. silica), compensation for thermal distortion, losses in coatings, readout scheme

Schedule

Submit MRE proposal to NSF in early 2003

Finalize design in 2005

Begin installation in 2007

Begin science observations in 2009

Summary

Detectors

Construction and installation was a big success

Commissioning is coming along well

There is still work to be done on the detectors

Data analysis

We finally have some interesting data to work with !

First scientific results and papers will come out this year

There is still work to be done on the analyses

The future

We'll have better data soon

Advanced LIGO promises a significant improvement in science reach

This is a busy but rewarding time to be working on LIGO