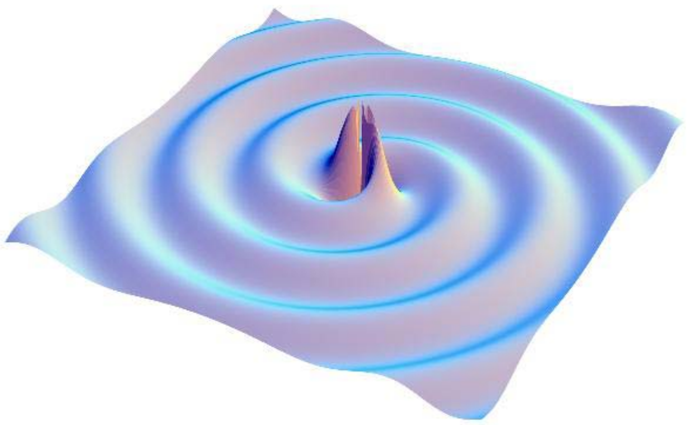
Status of the LIGO Experiment



Keith Riles
University of Michigan
(representing the LIGO Scientific Collaboration)

DPF Meeting – The College of William & Mary - May 26, 2002

LIGO-G020247-00-Z

Outline

- Nature & Generation of Gravitational Waves
- Gravitational Wave Detection
- The Initial LIGO Detector (commissioning status & plans)
- Detector Studies from January 2002 Engineering Run
- Preparing for Advanced LIGO

Nature of Gravitational Waves

- Gravitational Waves = “Ripples in space-time”

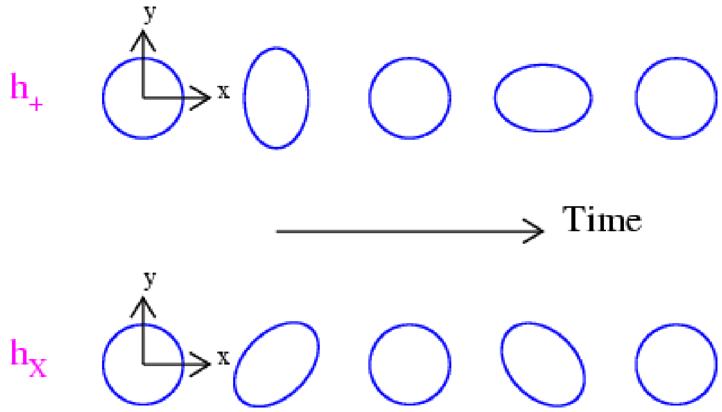
- Perturbation propagation similar to light
  - **Velocity = c**
  - **Two transverse polarizations - quadrupolar**: + and x

- Amplitude parameterized by (tiny) dimensionless strain h

$$\Delta L \sim h(t) \times L$$

Example:

Ring of test masses responding to wave propagating along z



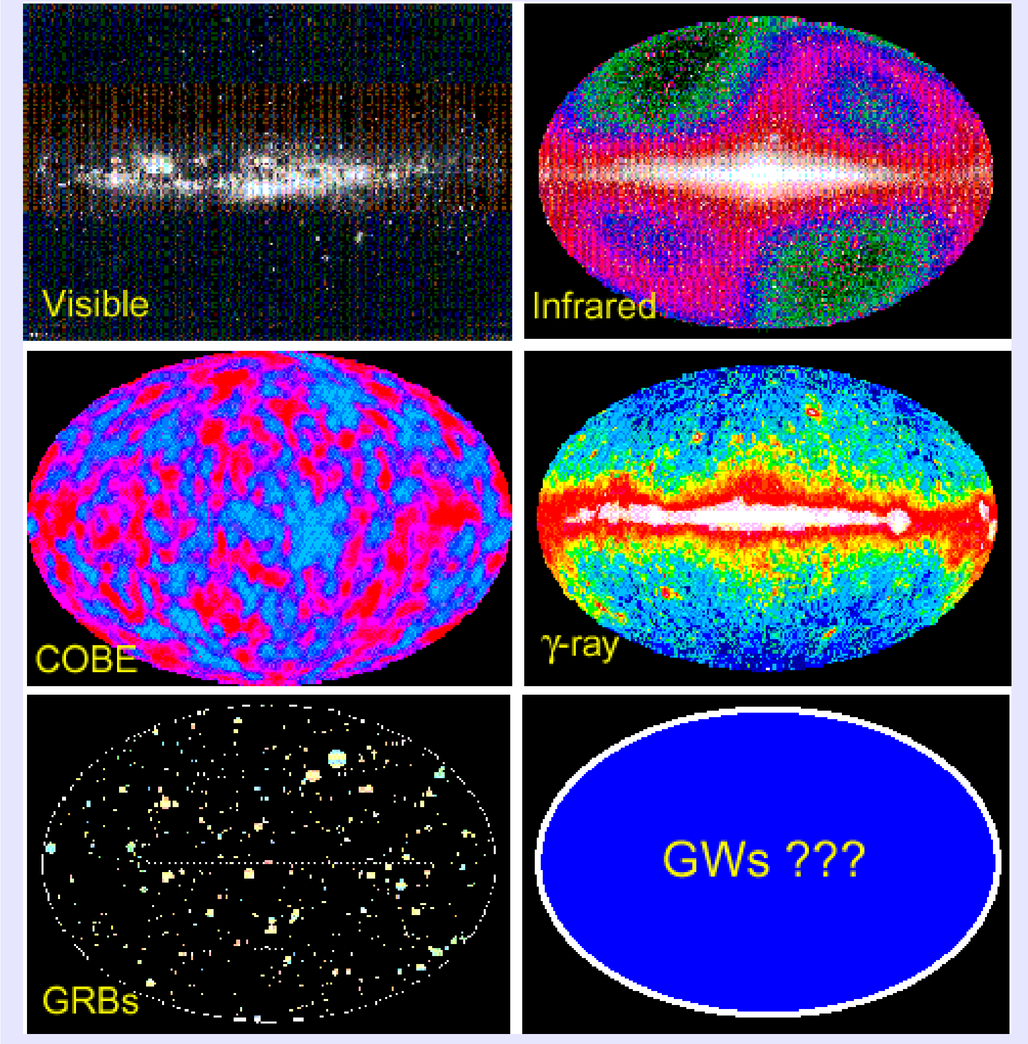
Why look for Gravitational Waves?

- Because it's there! (presumably)

- Test General Relativity:
  - Quadrupolar radiation? Travels at speed of light?
  - Unique probe of strong-field gravity

- Gain different view of Universe:
  - Sources cannot be obscured by dust
  - Detectable sources some of the most interesting, least understood in the Universe
  - **Opens up entirely new non-electromagnetic spectrum**

What will the sky look like?



(Thanks to N. Mavalvala for picture compilation)

Generation of Gravitational Waves

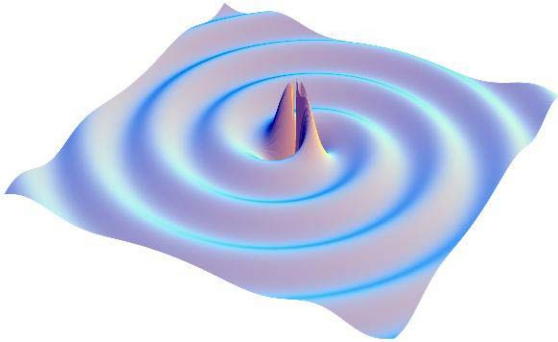
- Radiation generated by quadrupolar mass movements:

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}(I_{\mu\nu})$$

(with $I_{\mu\nu}$ = quadrupole tensor, r = source distance)

- Example: Pair of 1.4 M_{solar} neutron stars in circular orbit of radius 20 km (imminent coalescence) at orbital frequency 400 Hz gives 800 Hz radiation of amplitude:

$$h \approx \frac{10^{-21}}{(r/15\mathrm{Mpc})}$$



Generation of Gravitational Waves

Major expected sources in 10-1000 Hz band:

- Coalescences of binary compact star systems
  (NS-NS, NS-BH, BH-BH)

- Supernovae
  (requires asymmetry in explosion)

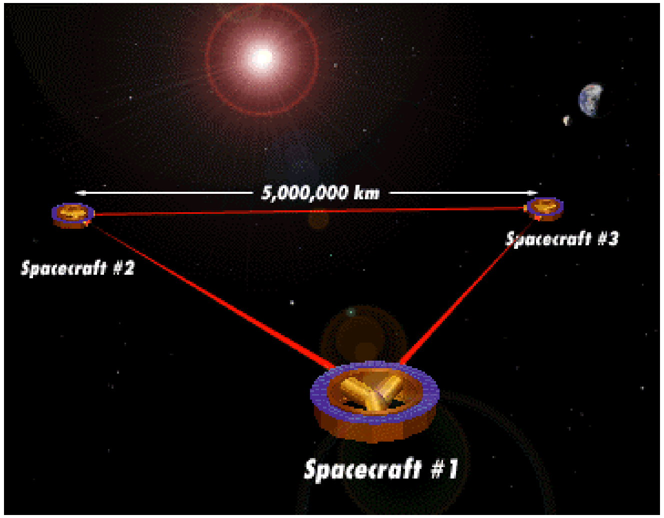
- Spinning neutron stars, e.g., pulsars
  (requires axial asymmetry or wobbling spin axis)

Generation of Gravitational Waves

- Sources well below LIGO bandwidth:
  - Binaries well before coalescence
  - Inspiral of stars into massive black holes
  - Coalescence of massive black holes
  - Stochastic background (e.g, big bang remnant, superposition of binaries)

- Irreducible seismic noise argues for space-based system at low frequencies - LISA

Three satellites forming interferometers with 5 x 10^6 km baselines (launch after 2010?)

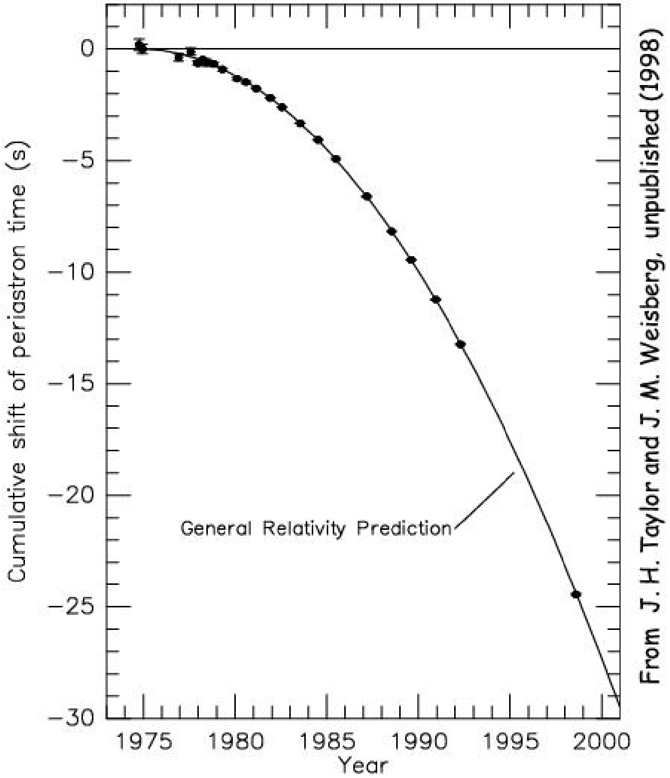


Generation of Gravitational Waves

- Strong indirect evidence for GW generation:

Taylor-Hulse Pulsar System (PSR1913+16)

- Two neutron stars (one=pulsar) in elliptical 8-hour orbit
- Measured perihelion advance quadratic in time in agreement with absolute GR prediction

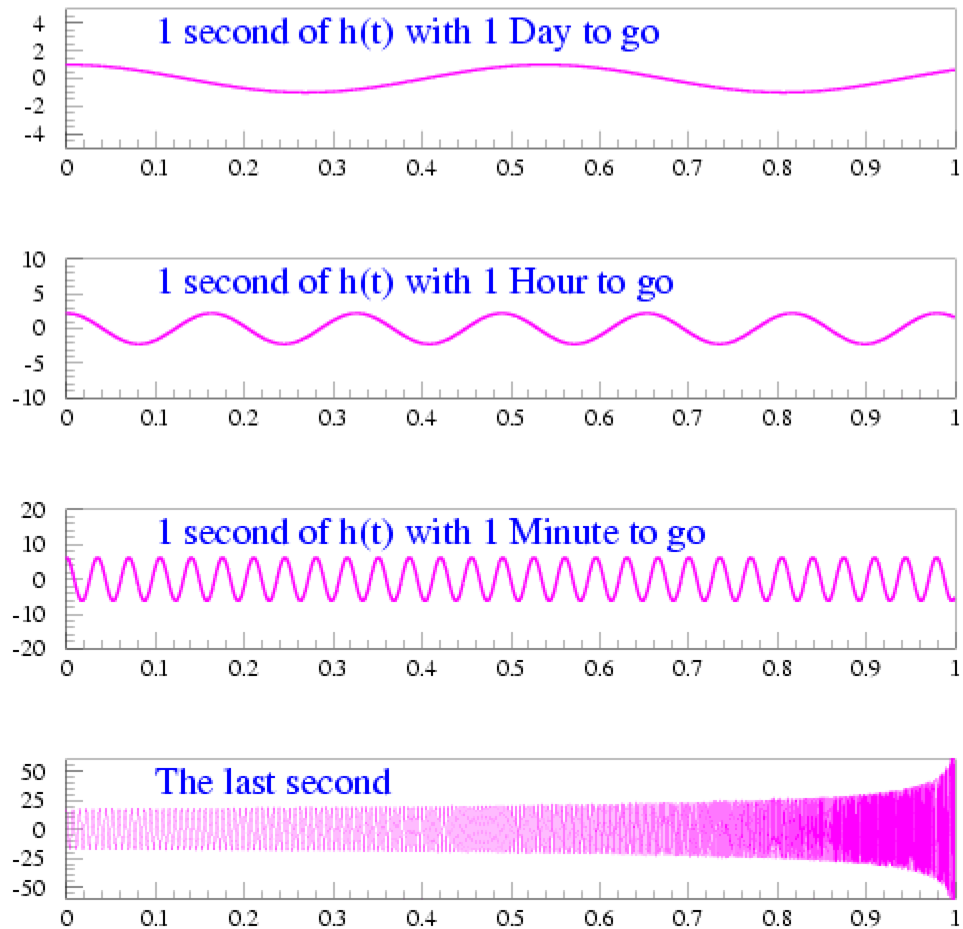


Generation of Gravitational Waves

Can we detect this radiation directly?

NO - freq too low

Must wait ~300 My for characteristic “chirp”:



Generation of Gravitational Waves

Coalescence rate estimates based on two methods:

- ❑ Use known NS/NS binaries in our galaxy (two!)
- ❑ *A priori* calculation from stellar and binary system evolution

→ Large uncertainties!

For initial LIGO design “seeing distance” (~20 Mpc):

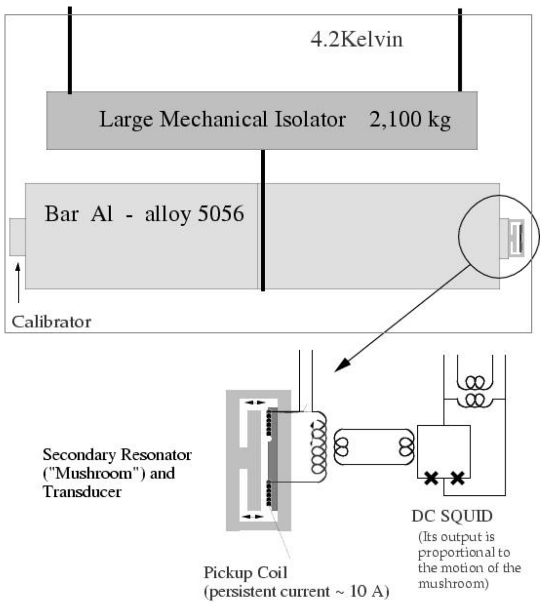
Expect 1/(3000 y) to 1/(4 y)

→ Will need Advanced LIGO to ensure detection

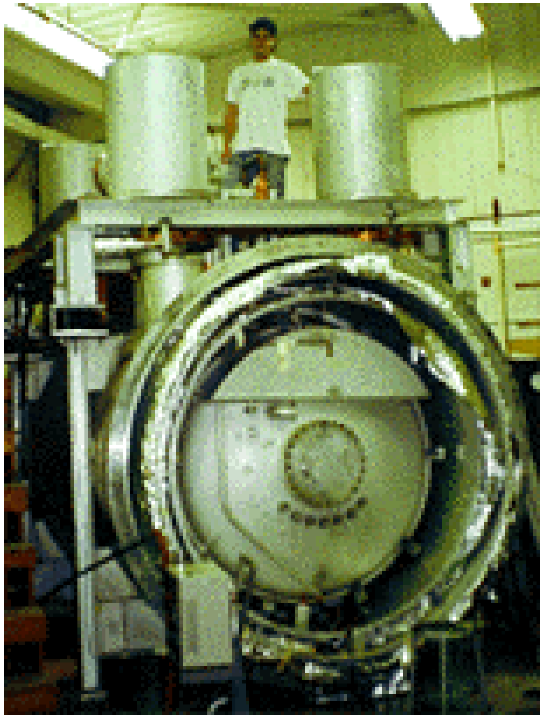
Gravitational Wave Detection

Two methods used to date – Bars and interferometers

- Suspended Resonant Bars: (pioneered by J. Weber)
  - Narrow band (f_0 ~ 900 Hz, Δf ~ 1 Hz – present detectors)
  - Look for sudden change in amplitude of thermally driven resonance
  - No wave form information

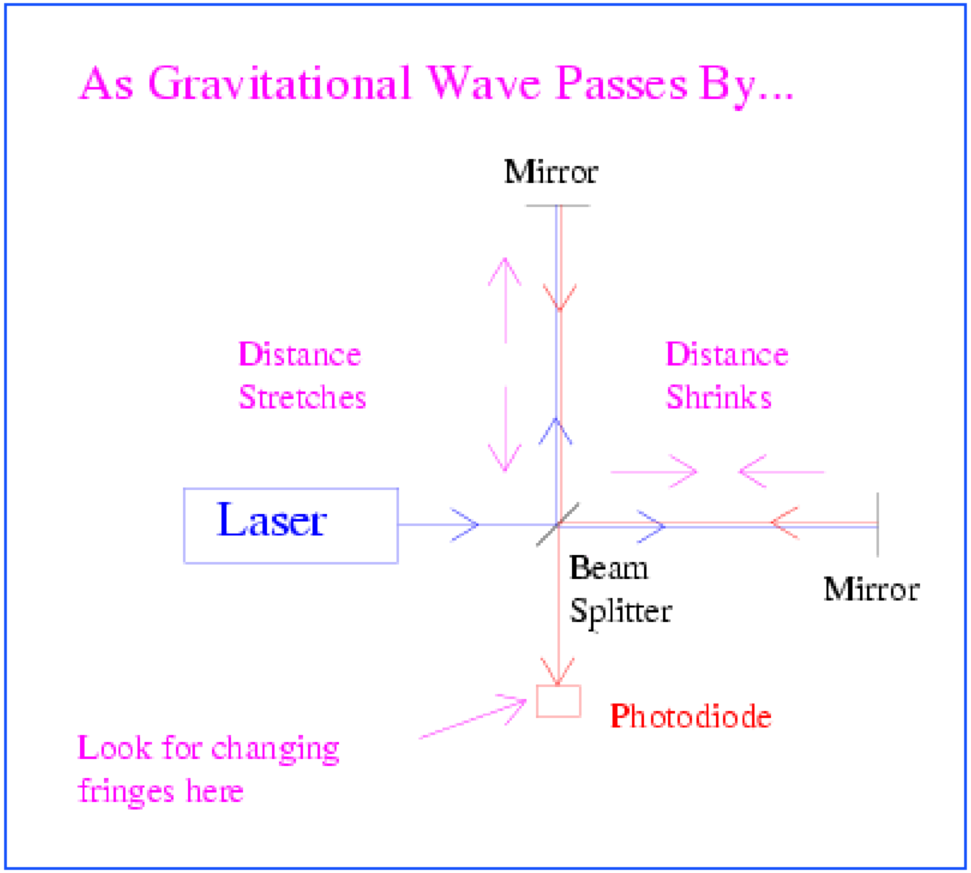


Allegro detector at LSU



Gravitational Wave Detection

- Suspended Interferometers (IFO's)
  - **Broad-band (~50 Hz to few kHz)**
  - **Waveform information (e.g., chirp reconstruction)**
  - **Michelson IFO is "natural" GW detector**



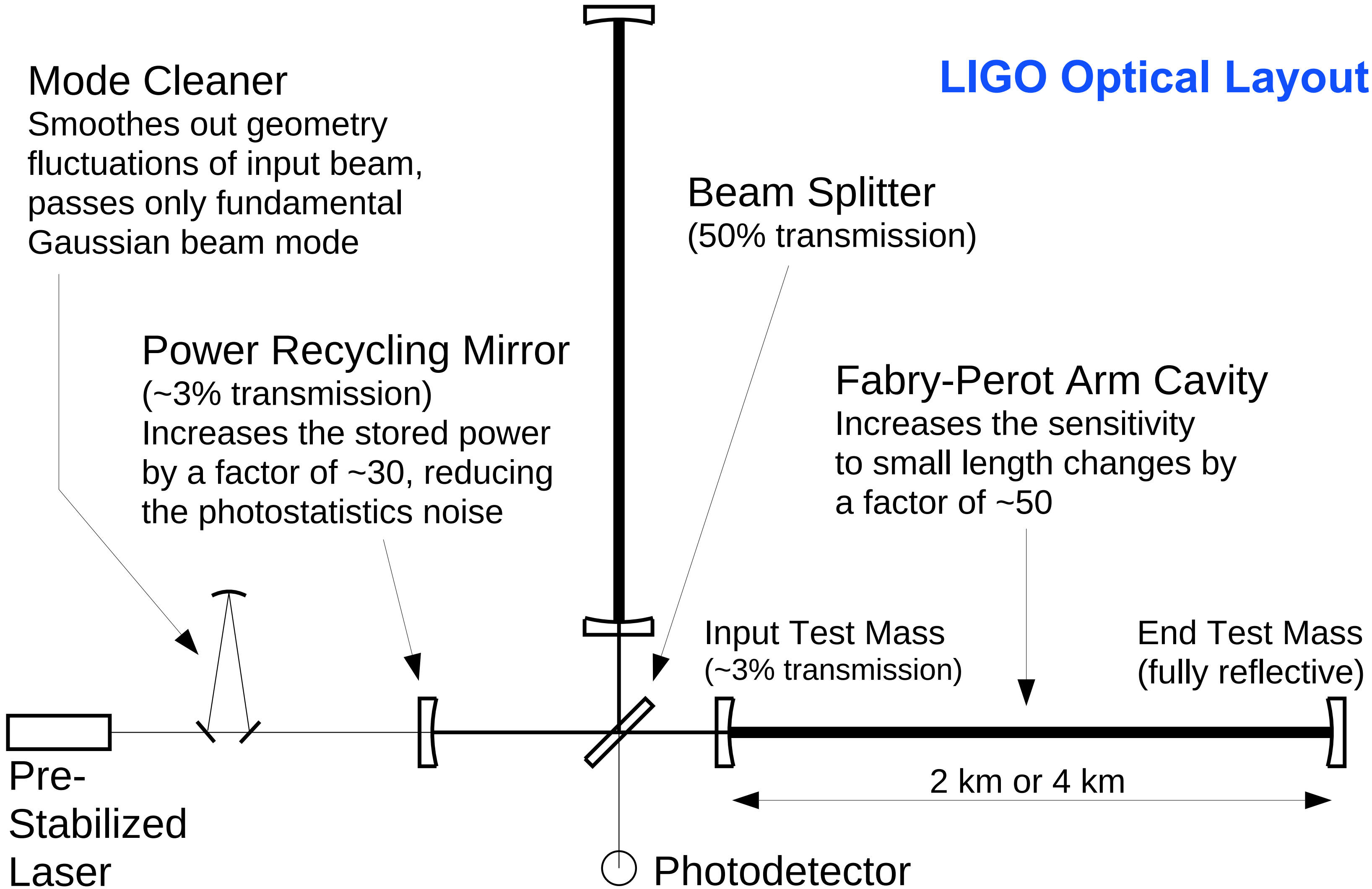
Gravitational Wave Detection

Major Interferometers coming on line world-wide

LIGO (NSF-$300M) Livingston, Louisiana & Hanford, Washington	2 x 4000-m 1 x 2000-m	Commissioning
VIRGO Near Pisa, Italy	1 x 3000-m	In construction
GEO Near Hannover, Germany	1 x 600-m	Commissioning
TAMA Tokyo, Japan	1 x 300-m	Commissioning

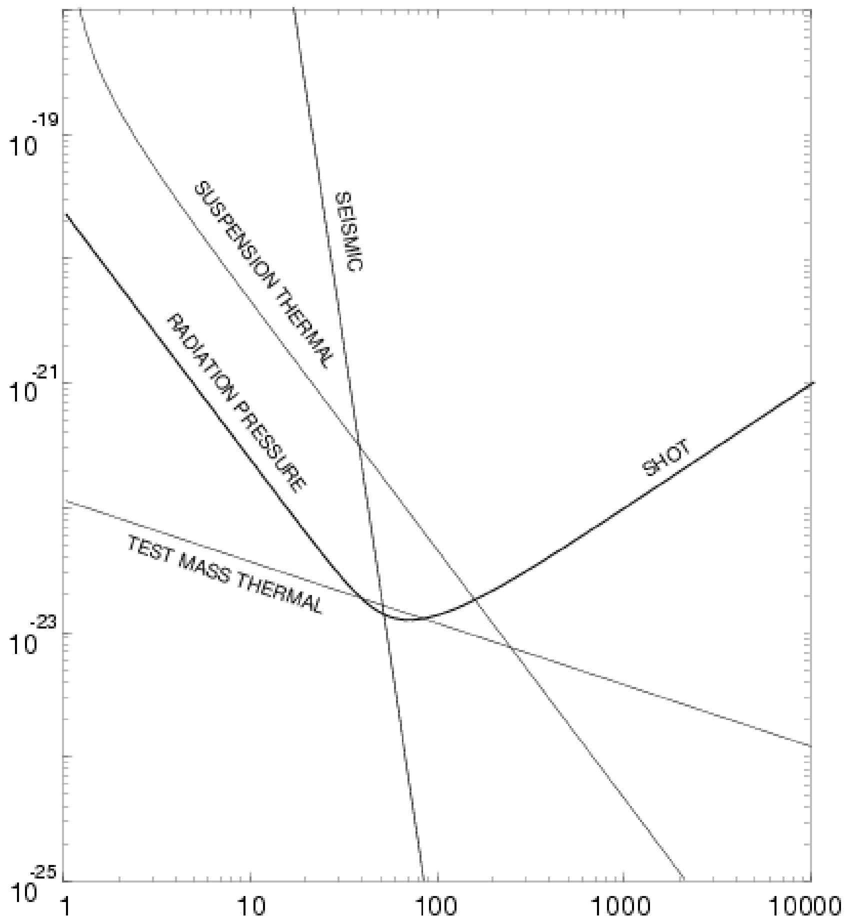
Gravitational Wave Detection

LIGO Optical Layout



Gravitational Wave Detection

Initial LIGO Design Sensitivity



Dominant noise sources:

- Seismic below 50 Hz
- Suspensions in 50-150 Hz
- Shot noise above 150 Hz

Best design sensitivity:

~3 x 10^{-23} $Hz^{-1/2}$ @ 150 Hz

LIGO Organization

LIGO Scientific Collaboration (>300 scientists)

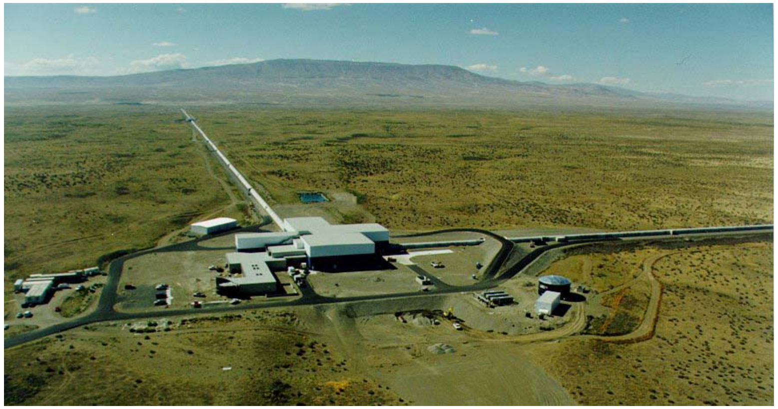
Caltech | **LIGO Laboratory** | **MIT**

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.
- Fermilab
- U. of Florida
- GEO 600 Collaboration (British/German)
- Goddard Space Flight Center
- Harvard-Smithsonian Center for Astrophysics
- Institute of Applied Physics – Nizhny Novgorod
- Iowa State U.
- IUCAA
- JILA – U. of Colorado
- Louisiana State U.
- Louisiana Tech U.
- Loyola 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

LIGO Observatories

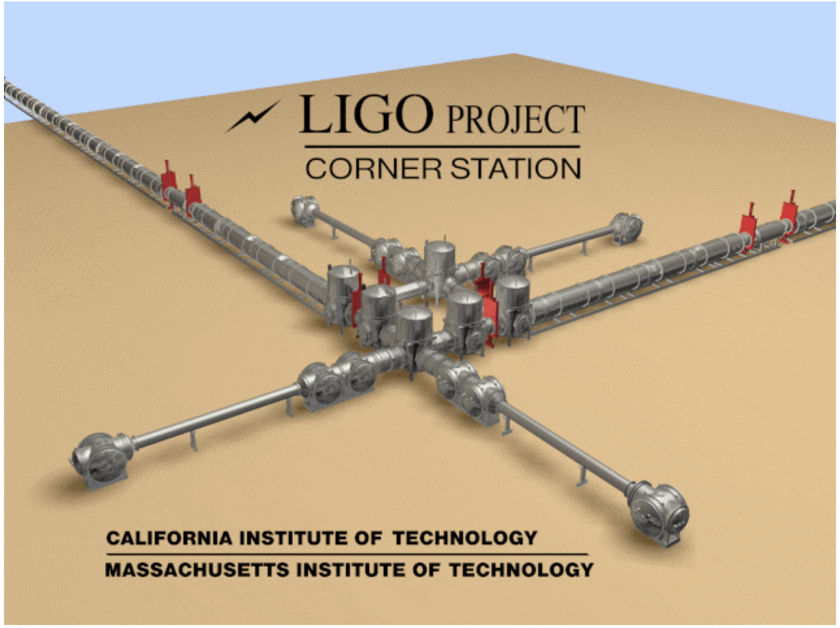
Hanford



Observation of nearly simultaneous signals 3000 km apart rules out terrestrial artifacts

Livingston

LIGO Detector Facilities



- Stainless-steel tubes

  (1.24 m diameter, ~10^{-8} torr)
- Gate valves for optics isolation
- Protected by concrete enclosure

Vacuum System

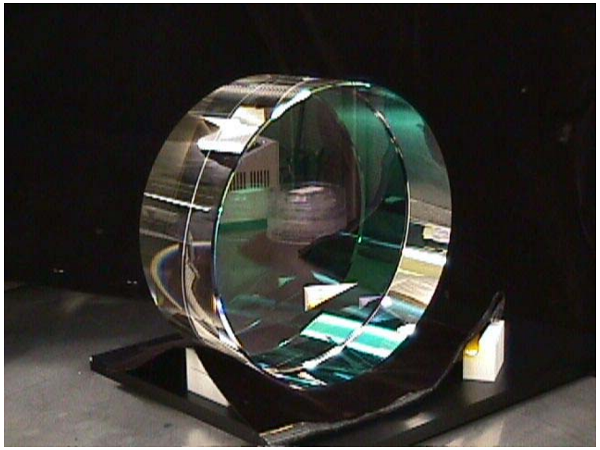
LIGO Detector Facilities

LASER

- Infrared (1064 nm, 10-W) Nd-YAG laser from Lightwave (now commercial product!)
- Elaborate intensity & frequency stabilization system, including feedback from main inteferometer

Optics

- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils

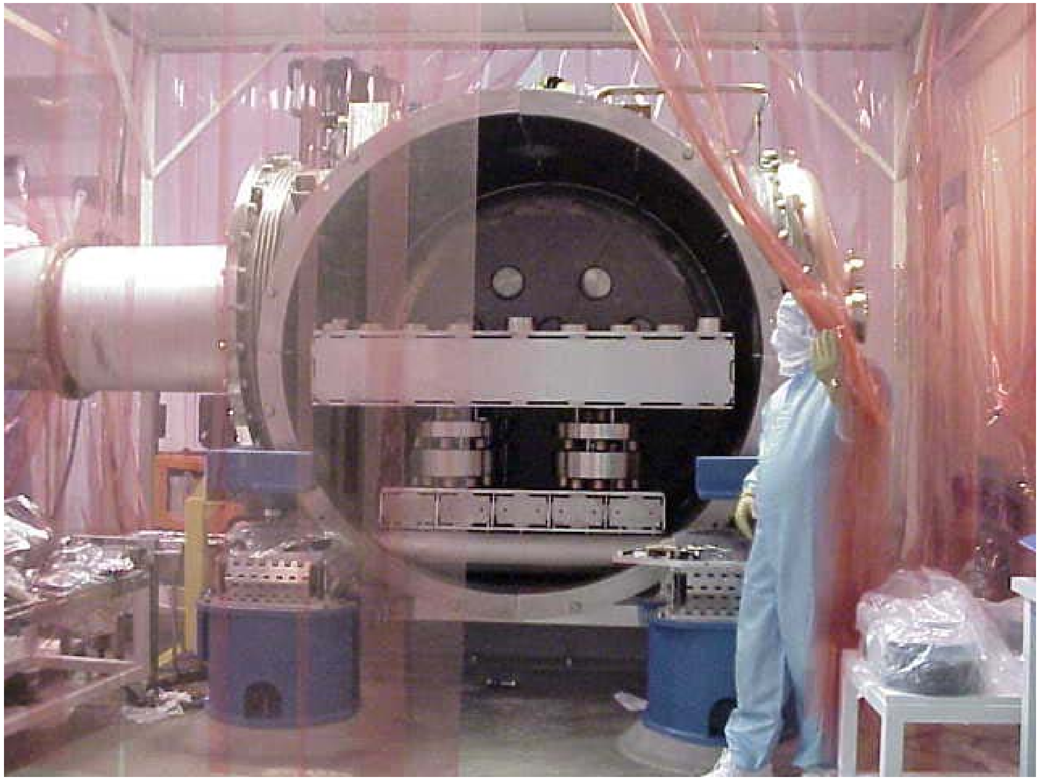


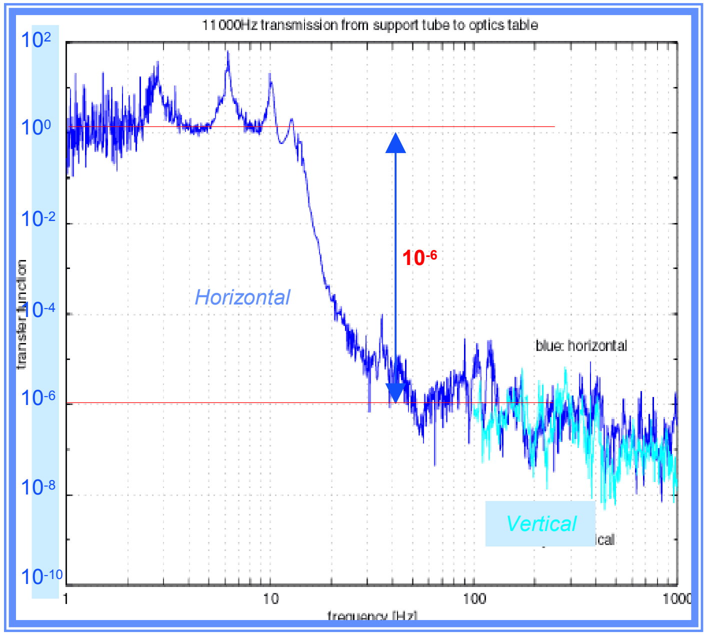
LIGO

LIGO Detector Facilities

Seismic Isolation

- Multi-stage (mass & springs) optical table support gives 10^6 suppression
- Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz





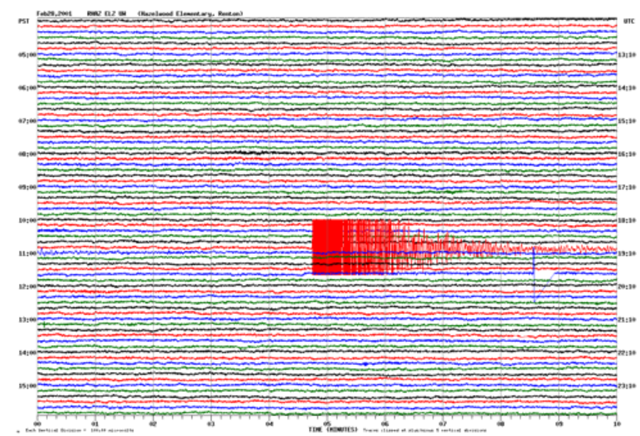
Some startup troubles at Hanford…

Brush fire sweeps over site – June 2000

Charred landscape, but no IFO damage!

Tacoma earthquake – Feb 2001

- **Misaligned optics**
- **Actuation magnets dislodged**
- **Commissioning delay**



And at Livingston…

First access road a bit damp – now paved and higher

Gators & schoolchildren tours don't mix...

And at Livingston…

A Truly Serious Problem - LOGGING

Livingston Observatory located in pine forest popular with pulp wood cutters

Spiky noise (e.g. falling trees) in 1-3 Hz band creates dynamic range problem for arm cavity control

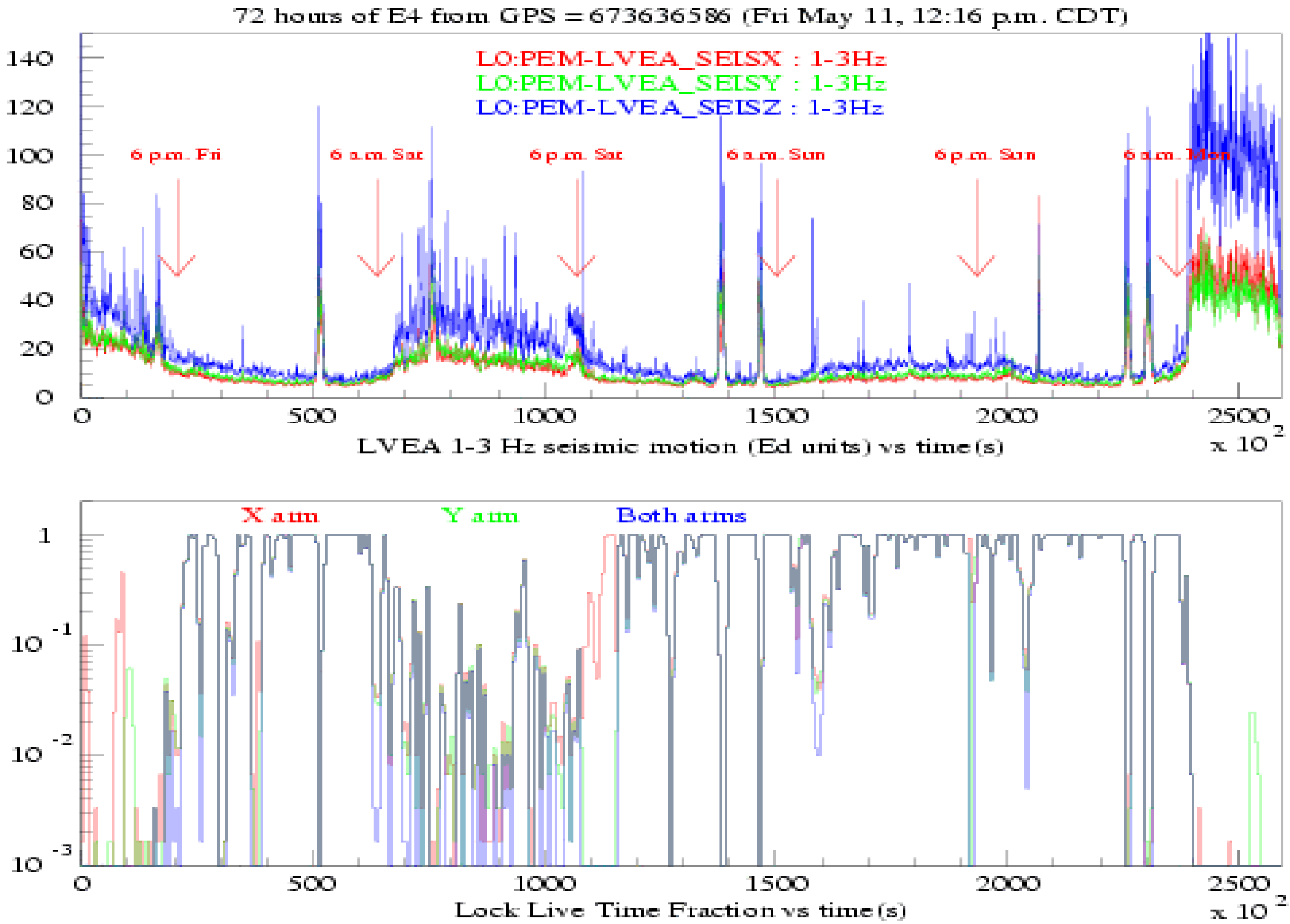
Temporary workaround:

Boost actuation gain at cost in attainable sensitivity

Long-term Solution: Retrofit with active feed-forward isolation system (using technology developed for Advanced LIGO)

And at Livingston…

Until actuation boosted, was nearly impossible to lock IFO on weekdays



Correlation between seismic noise and lock livetime

(4-day weekend)

LIGO

Sampling of Milestones

May 1999	Hanford beam tube bakeout
Dec 1999	First light in 2-km cavity & brief arm lock
Apr 2000	Engineering run “E1” (1 day, one 2-km arm)
Aug 2000	Hanford 2-km installation complete
Oct 2000	Hanford 2-km “First-Lock” (whole kit & caboodle)
Oct 2000	Livingston 4-km installation complete
Nov 2000	Engineering run “E2” (1 week, full 2-km lock)
Feb 2001	Tacoma earthquake damages 2-km arms
Mar 2001	Engineering run “E3” (3 days, one Livingston arm)
Jul 2001	Hanford 4-km installation complete
Jan 2002	Eng. run “E7” (17 days, all IFO’s + GEO + ALLEGRO)

E7 Data Analysis

- Warm-up exercise for the "real thing"

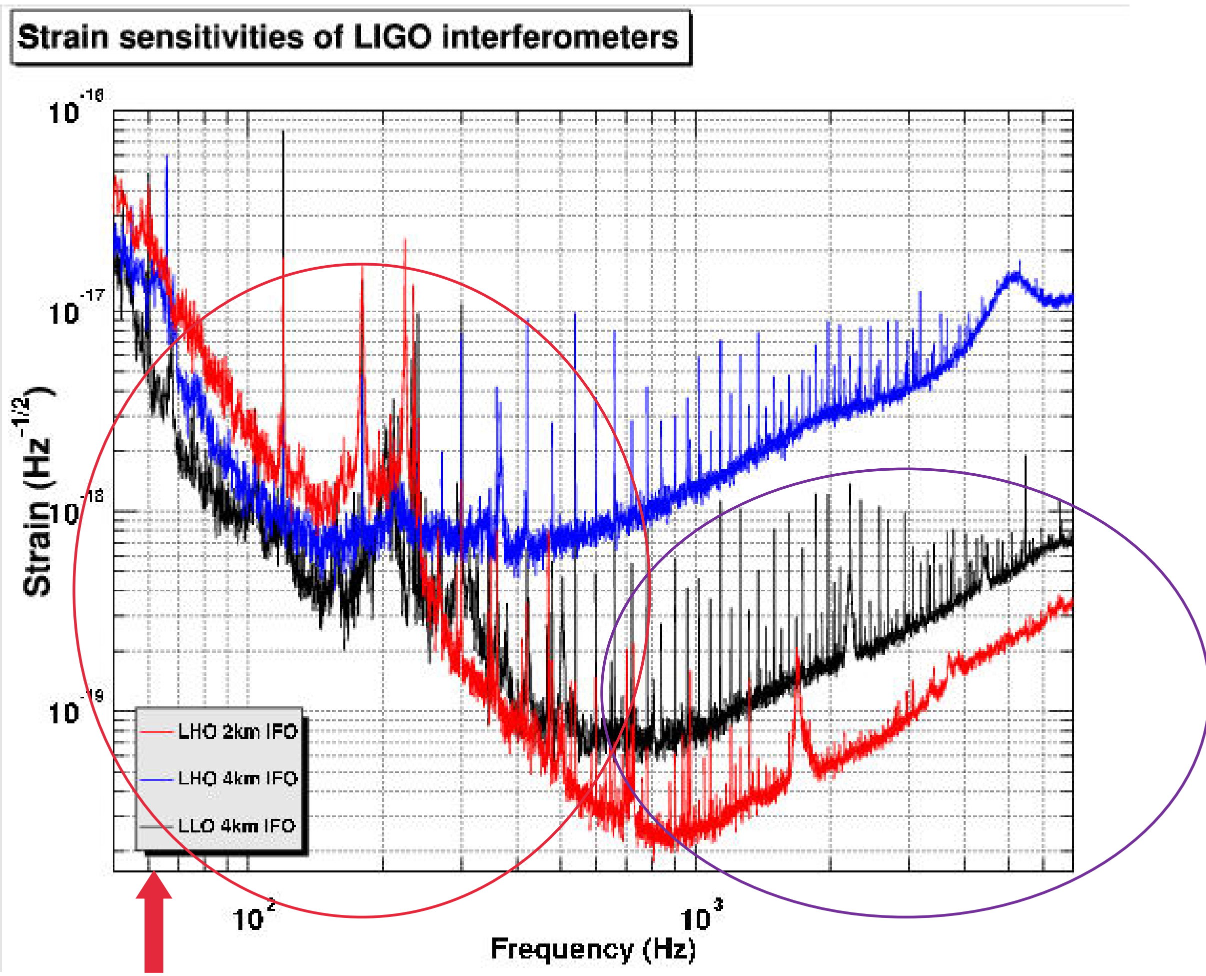
  Expect to set upper limits on astrophysical source strengths

- Four "upper limits groups" organized:
  - Inspiraling binary systems
  - Unmodelled bursts
  - Periodic sources (e.g. pulsars)
  - Stochastic background (e.g., big-bang remnant)

- Present status:
  - Evaluating instrumental sensitivity (~galaxy center for inspirals)
  - Defining instrumental vetoes using "playground" data subset
  - Defining strategy (e.g., acceptable single-IFO signal rate prior to coincidence searching)

E7 Data Analysis

•**Preliminary sensitivity curves for the three interferometers: (Jan 2002)**



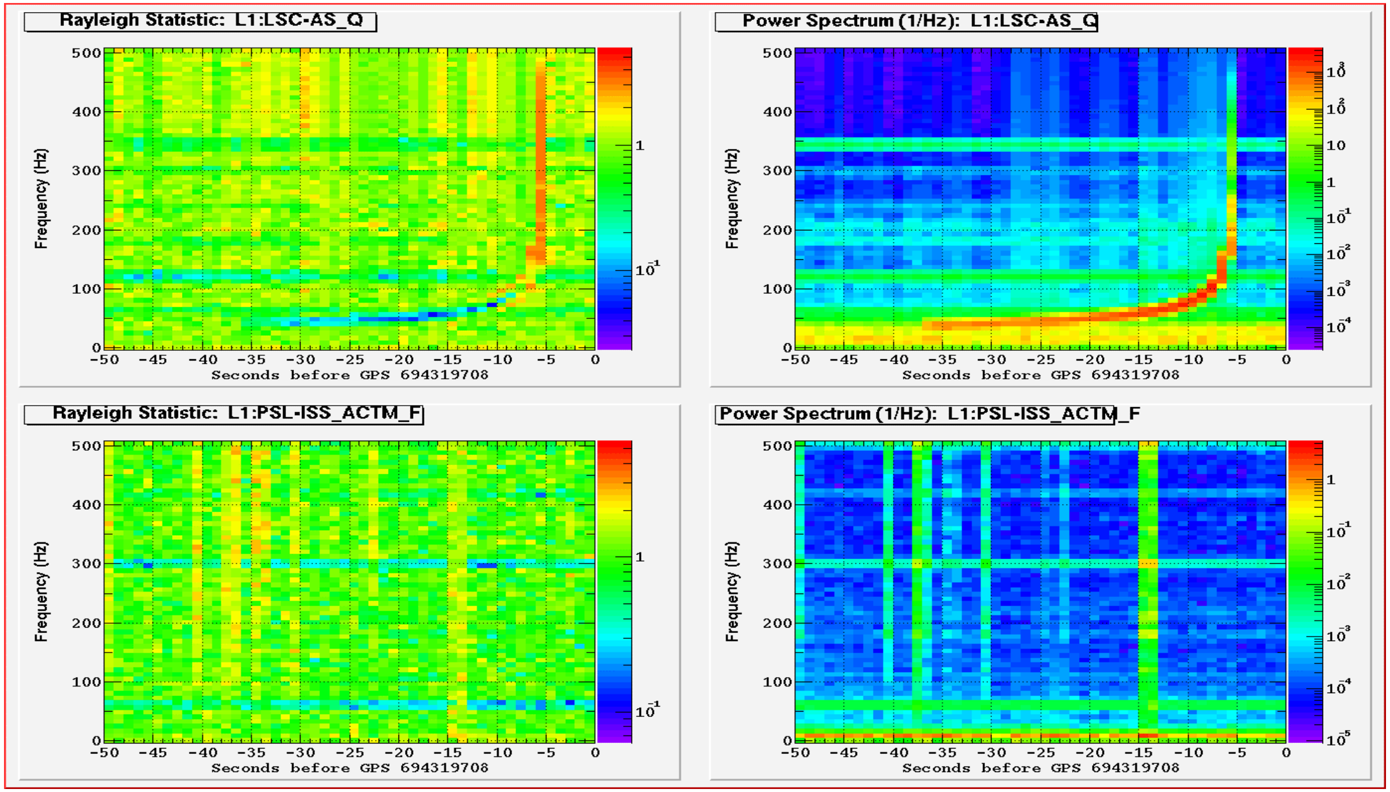
Many orders of magnitude to go!

"Straightforward" to reduce

Much harder! (instrumental artifacts, many potential noise sources)

E7 Data Analysis

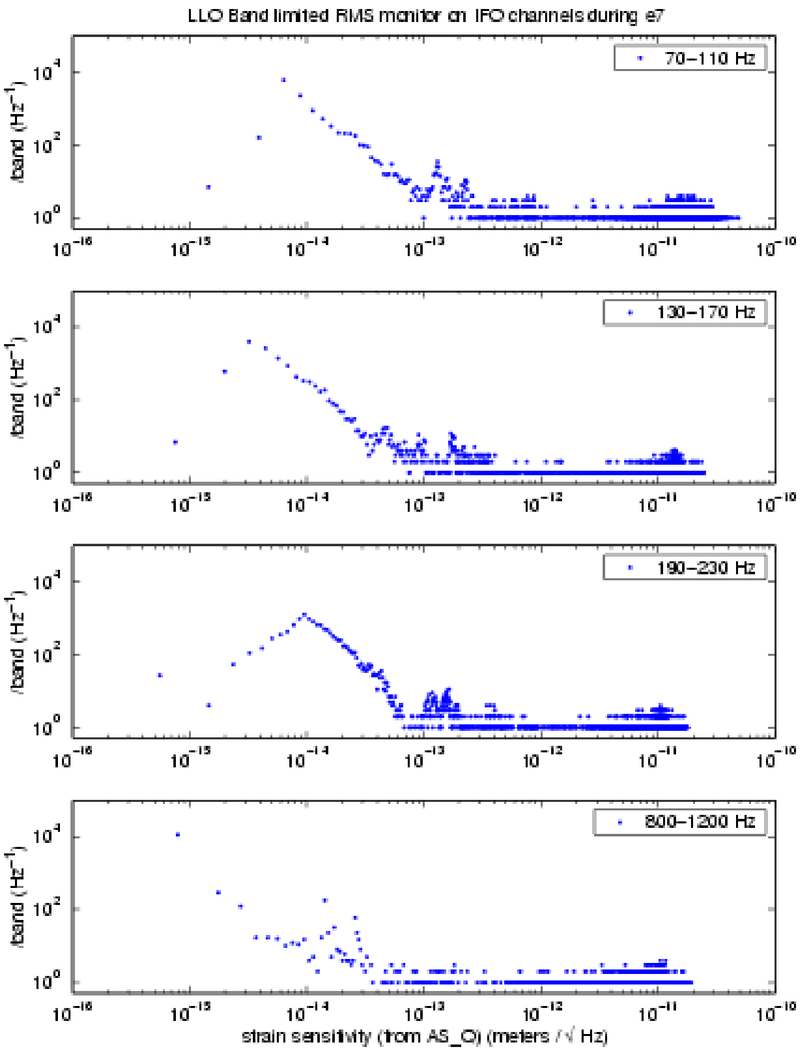
Viewing injected inspiral "chirp" via spectogram and "Rayleigh monitor"
(top plots for GW channel, bottom for an auxiliary laser channel)



Chirp easy to see (good)

Instrumental artifacts easy to see too! (bad)

E7 Data Analysis



Histograms of band-limited RMS in several bands of interest

Outliers indicate non-Gaussianity, primarily broad-band transients

→ "Glitches"

Lots of work to do to reduce these…

Looking Ahead

E7 has been eye-openingly useful

- Forcing us to confront instrumental artifacts in astrophysical searches (no more Gaussian noise modelling!)
- Excellent preparation for upcoming "Science Runs"
- Meanwhile, IFO sensitivities improving with further commissioning …

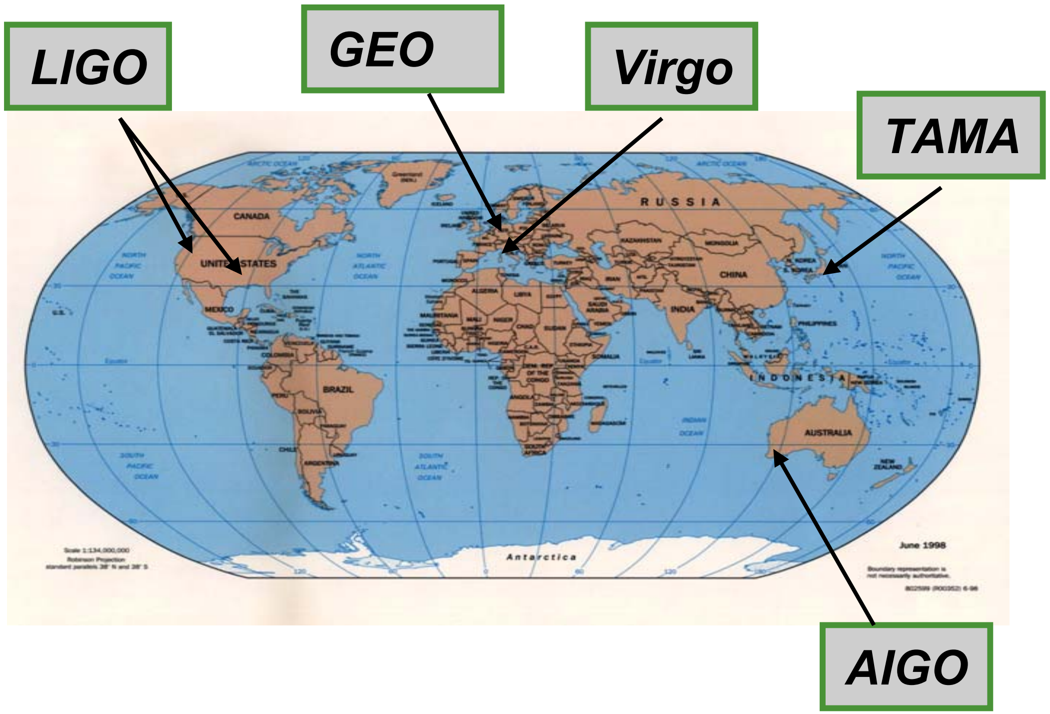
Future milestones

June/July 2002	S1 Science Run (16 days, all IFO's)
Nov/Dec 2002	S2 Science Run (46 days, all IFO's)
Winter 2003	Livingston seismic retrofit
~June 2003	S3 Science Run
	(first of series of multi-month runs)

Looking Ahead

The three LIGO interferometers will be part of a global network.

Multiple signal detections will increase detection confidence and provide better precision on source locations and wave polarizations

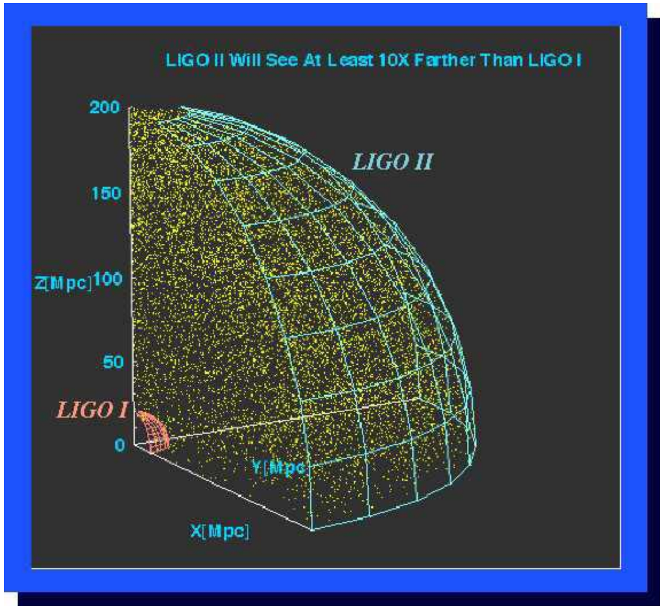


Looking Way Ahead

Despite their immense technical challenges, the initial LIGO IFO's were designed conservatively, based on "tabletop" prototypes, but with expected sensitivity gain of ~1000.

Given the expected low rate of detectable GW events, it was always planned that in engineering, building and commissioning initial LIGO, one would learn how reliably to build Advanced LIGO with another factor of ~10 improved sensitivity.

Because LIGO measures GW amplitude, an increase in sensitivity by 10 gives an increase in sampling volume, i.e, rate by ~1000



Advanced LIGO

Detector Improvements

Increased laser power: 10 W → 180 W

→Improved shot noise (high freq)

Increased test mass: 10 kg → 30 kg

→Compensates increased radiation pressure noise

New test mass material: Fused silica → Sapphire

→Lower internal thermal noise in bandwidth

New suspensions: Single → Quadruple pendulum

→Lower suspensions thermal noise in bandwidth

Improved seismic isolation: Passive → Active

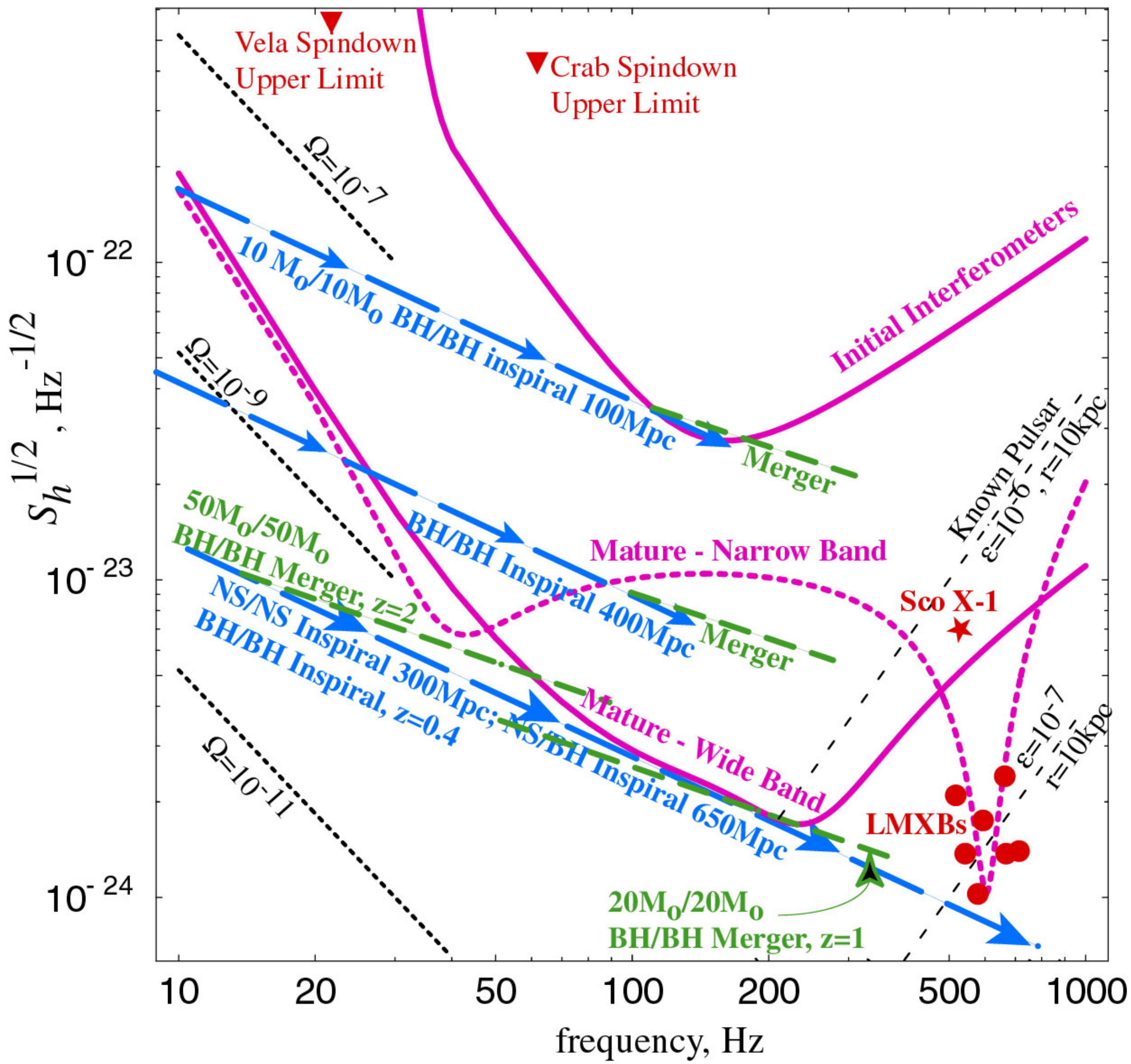
→Lowers seismic “wall” to ~10 Hz

Advanced LIGO

Sampling of source strengths vis a vis Initial LIGO and Advanced LIGO

Lower h_{rms} and wider bandwidth both important

"Signal recycling" offers potential for tuning shape of noise curve to improve sensitivity in target band (e.g., known pulsar range)



Advanced LIGO

Ambitious upgrade program:

•MRE proposal for NSF now in preparation

•Hope to begin detector upgrades in 2006

→ Begin observing in 2007

First 2-3 hours of Advanced LIGO is equivalent

to a Snowmass year of Initial LIGO

Summary

Initial LIGO commissioning well underway

Much instrumental noise to beat down, but no show-stoppers have appeared

Confronting realities of dirty-data analysis

Engineering runs giving way to sporadic science runs (with astrophysical measurements as primary purpose) interspersed with ongoing commissioning

Looking ahead to several years of high-duty-cycle data taking

Looking farther ahead to major detector upgrade with more than 1000-fold increase in event rate

Direct GW detection only a matter of time

Exciting years to come!