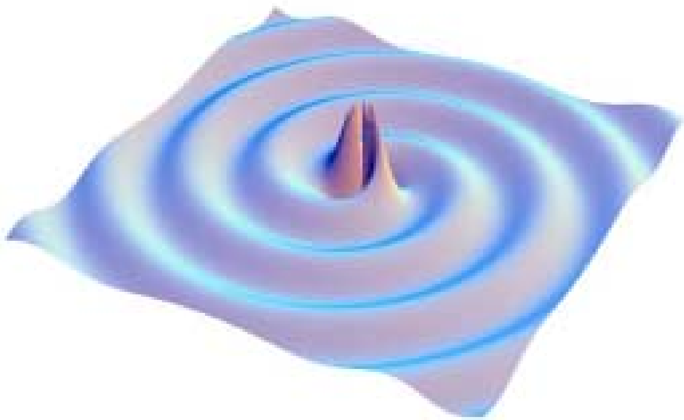
Status of the LIGO Experiment



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

Aspen Winter 2003 Conference on Particle Physics:
At the Frontiers of Particle Physics
Aspen Center for Physics – January 19-25, 2003

LIGO-G030164-00-Z

Outline

- Nature & Generation of Gravitational Waves
- Gravitational Wave Detection
- The Initial LIGO Detector (commissioning status & plans)
- Detector Studies, Data Runs (& Other Experiments)
- Preparing for Advanced LIGO

LIGO

Nature of Gravitational Waves

- Gravitational Waves = "Ripples in space-time"

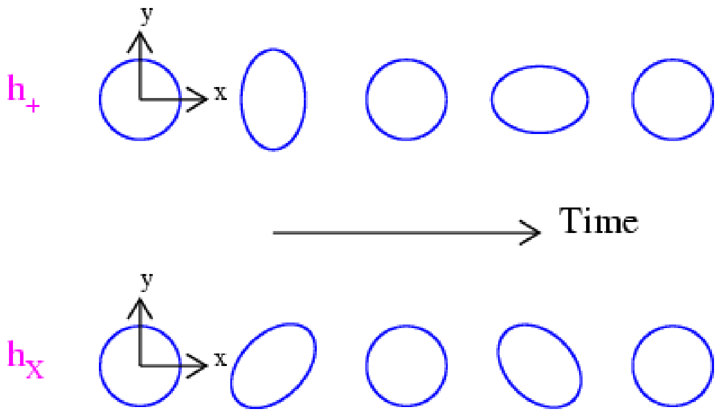
- Perturbation propagation similar to light
  - **Velocity = c**
  - **Two transverse polarizations - quadrupolar**: + and x

- 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



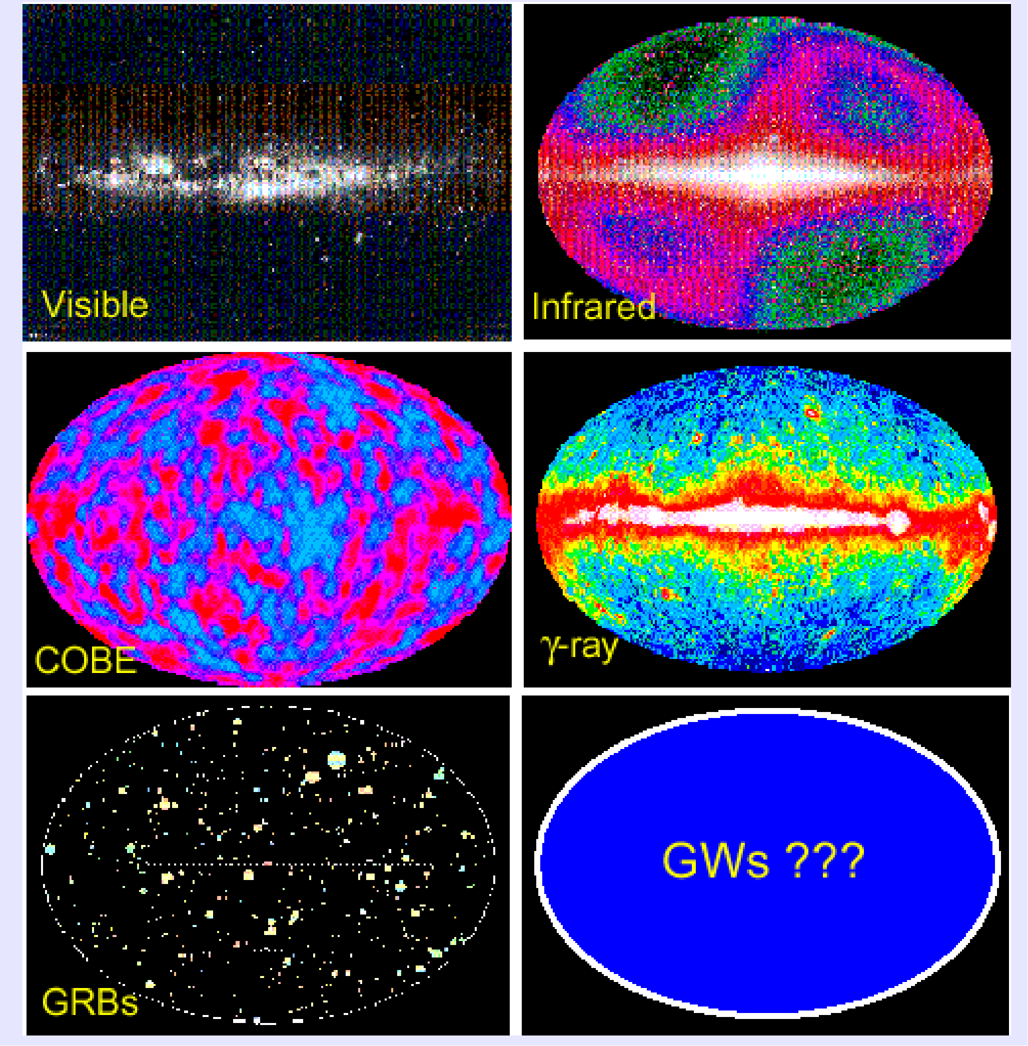
Why look for Gravitational Radiation?

- Because it's there! (presumably)

- Test General Relativity:
  - Quadrupolar radiation? Travels at speed of light?
  - Unique, quantitative 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?



Generation of Gravitational Waves

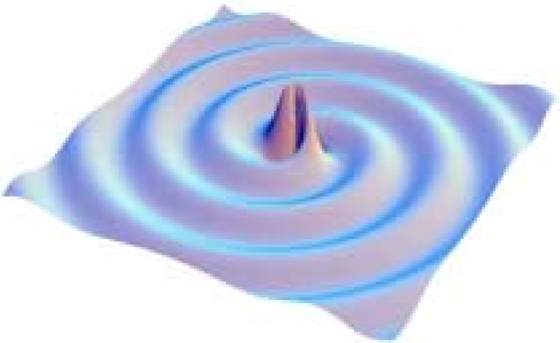
- Radiation generated by quadrupolar mass movements:

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

(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:

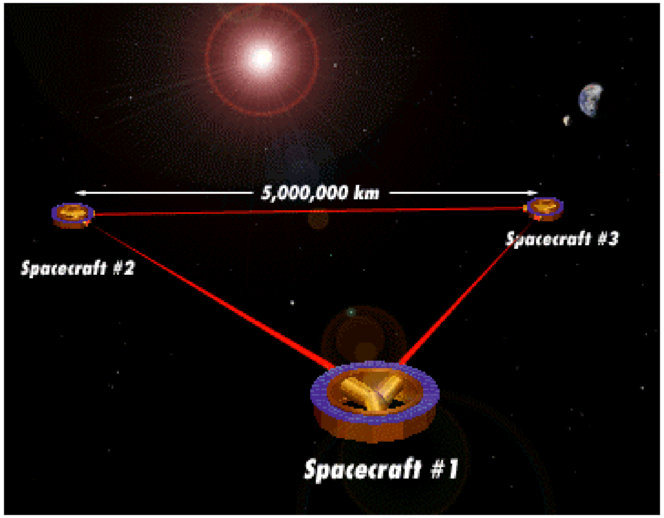
- Coalescences of binary compact star systems
  (NS-NS, NS-BH, BH-BH)
- Supernovae
  (requires asymmetry in explosion)
- Spinning neutron stars, e.g., pulsars
  (requires axial asymmetry or wobbling spin axis)

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?)

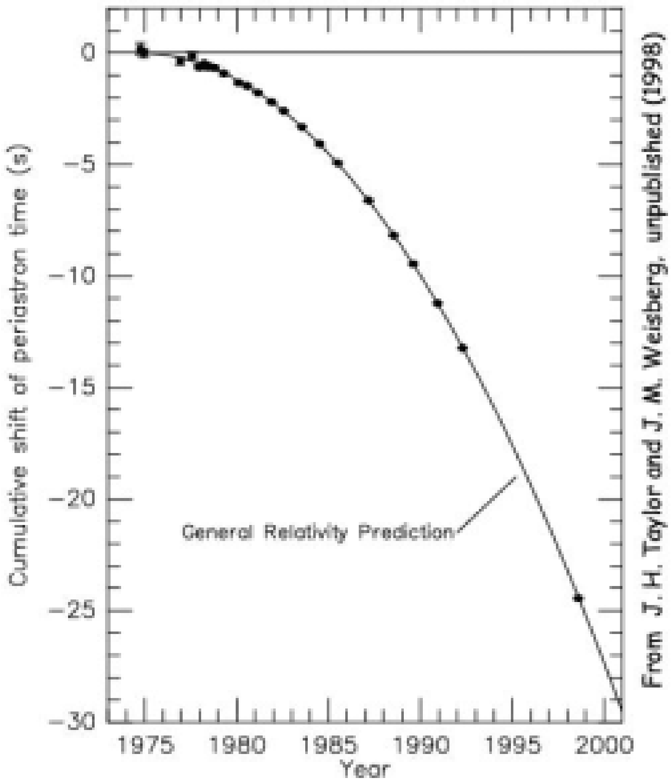


Generation of Gravitational Waves

- Strong <u>indirect</u> 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

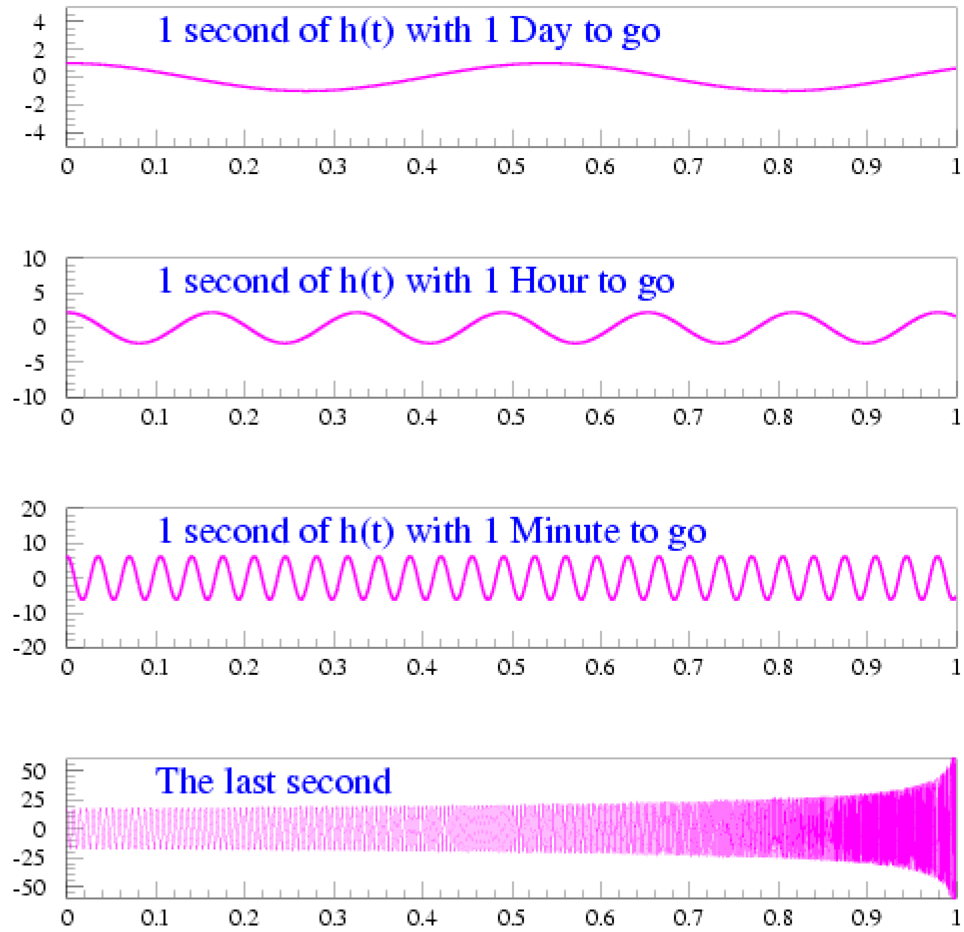


Generation of Gravitational Waves

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):

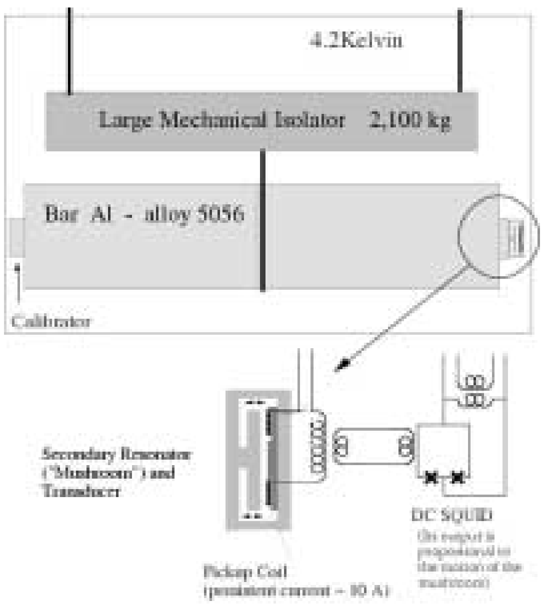
Expect 1/(3000 y) to 1/(4 y)

→ Will need Advanced LIGO to ensure detection

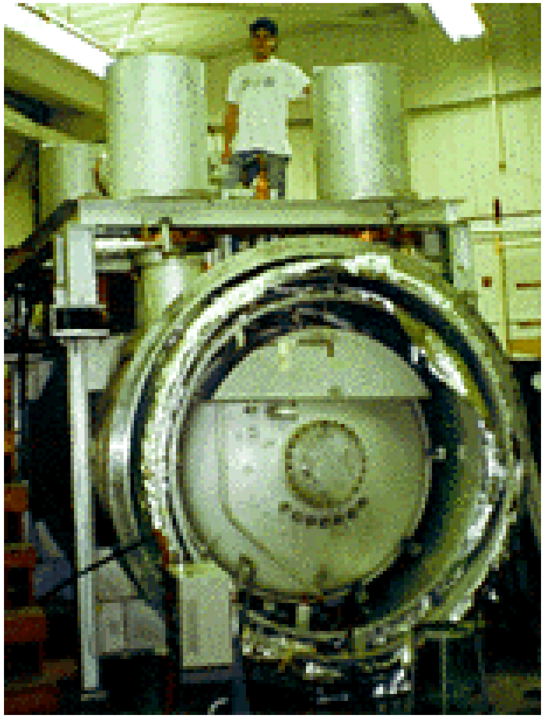
Gravitational Wave Detection

Two search methods used to date – Bars and interferometers

- Suspended Resonant Bars: (pioneered by J. Weber)
  - Narrow band (f_0 ~ 900 Hz, Δf ~ 1-10 Hz – present detectors)
  - Look for sudden change in amplitude of thermally driven resonance
  - No wave form information

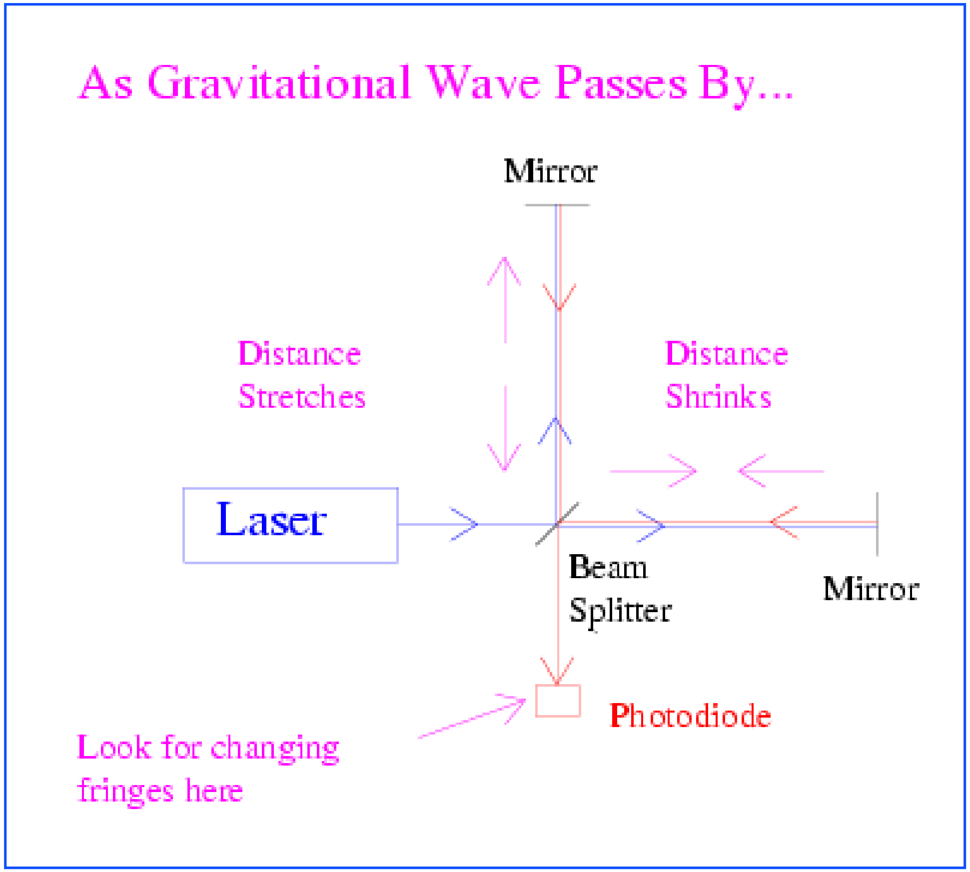


Allegro detector at LSU



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**



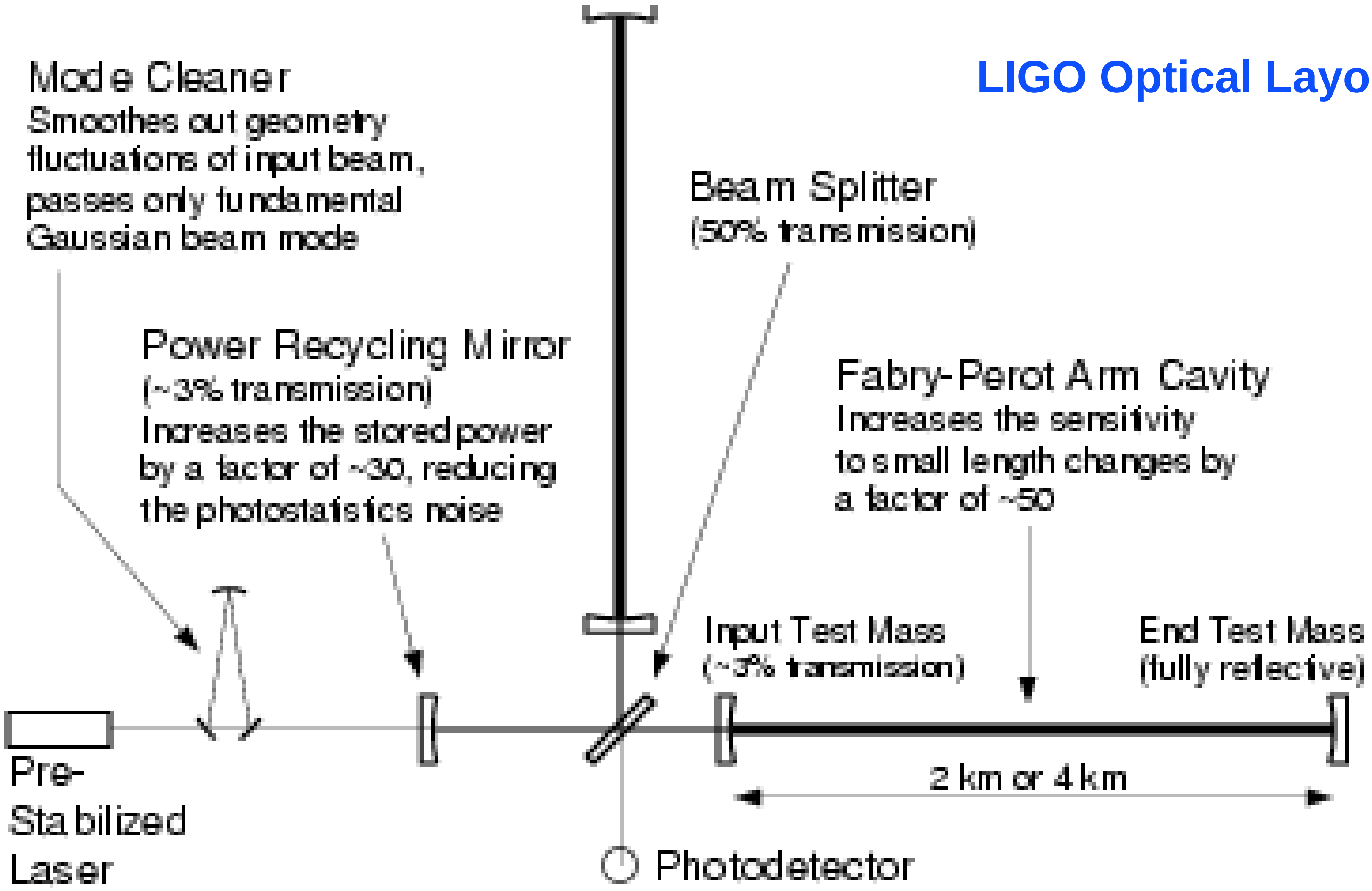
Gravitational Wave Detection

Major Interferometers coming on line world-wide

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

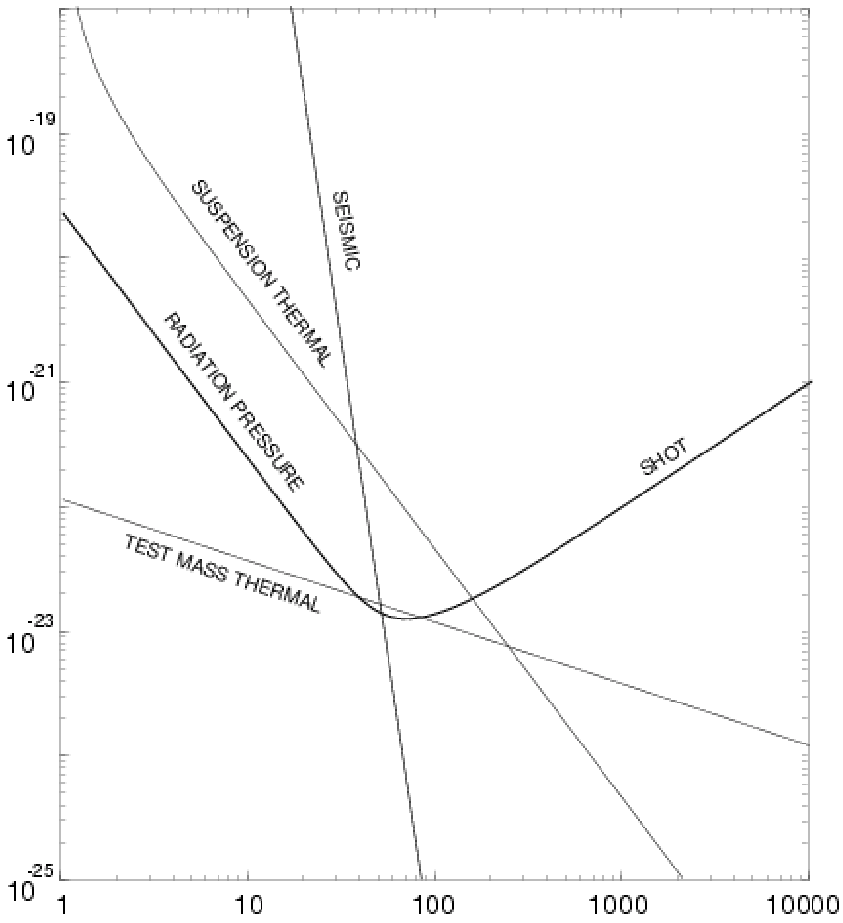
Gravitational Wave Detection

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 Scientific Collaboration (~400 scientists)

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

LIGO Hanford Observatory **LIGO Livingston Observatory**

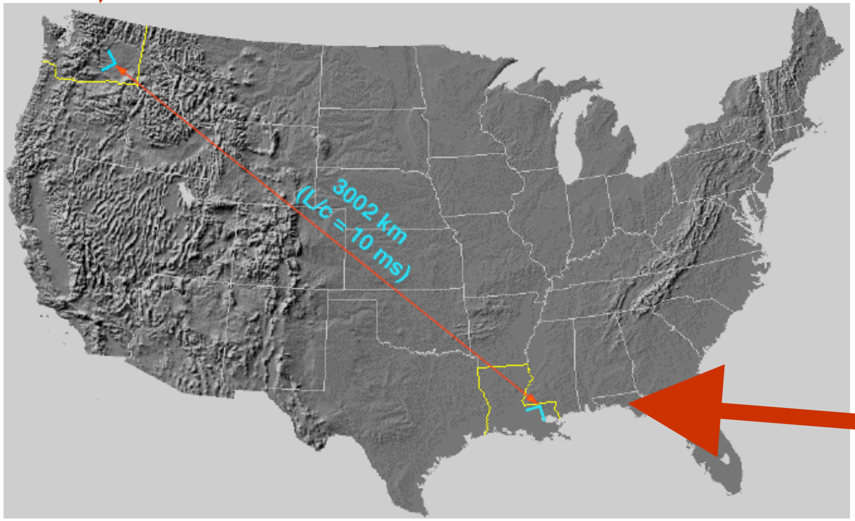
University of Adelaide ACIGA
Australian National University ACIGA
Balearic Islands University
California State Dominquez Hills
Caltech LIGO
Caltech Experimental Gravitation CEGG
Caltech Theory CART
University of Cardiff GEO
Carleton College
Cornell University
Fermi National Laboratory
University of Florida @ Gainesville
Glasgow University GEO
NASA-Goddard Spaceflight Center
University of Hannover GEO
Hobart – Williams University
India-IUCAA
IAP Nizhny Novgorod
IUCCA India
Iowa State University
Joint Institute of Laboratory Astrophysics
Salish Kootenai College

LIGO Livingston LIGOLA
LIGO Hanford LIGOWA
Loyola New Orleans
Louisiana State University
Louisiana Tech University
MIT LIGO
Max Planck (Garching) GEO
Max Planck (Potsdam) GEO
University of Michigan
Moscow State University
NAOJ - TAMA
Northwestern University
University of Oregon
Pennsylvania State University
Southeastern Louisiana University
Southern University
Stanford University
Syracuse University
University of Texas@Brownsville
Washington State University@ Pullman
University of Western Australia ACIGA
University of Wisconsin@Milwaukee

LIGO Observatories

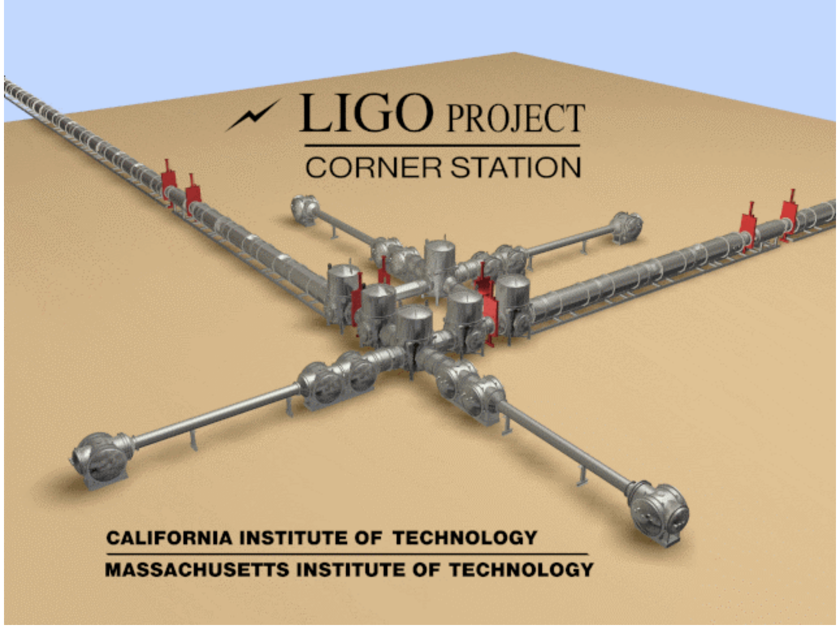
Hanford

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

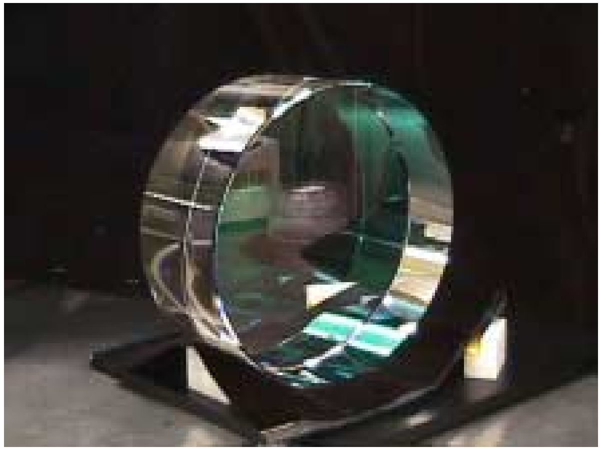
LIGO Detector Facilities

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

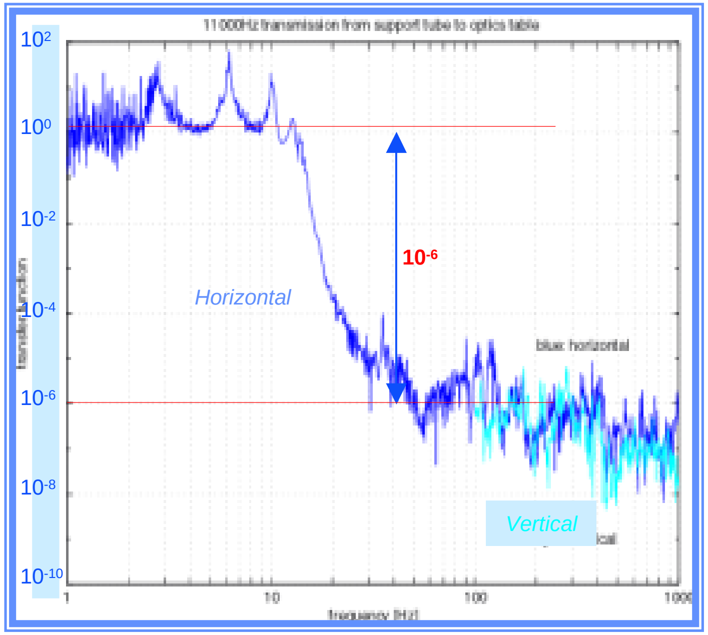
- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils



LIGO 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**



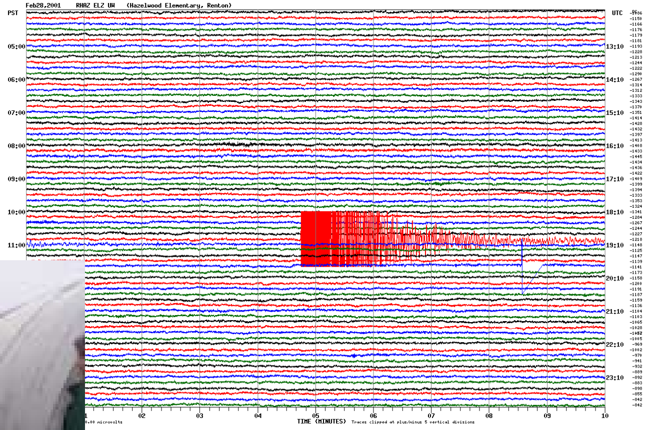
Some startup troubles at Hanford…

Brush fire sweeps over site – June 2000

Charred landscape, but no IFO damage!

Tacoma earthquake – Feb 2001

- Misaligned optics
- Actuation magnets dislodged
- Commissioning delay



Human error too!

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

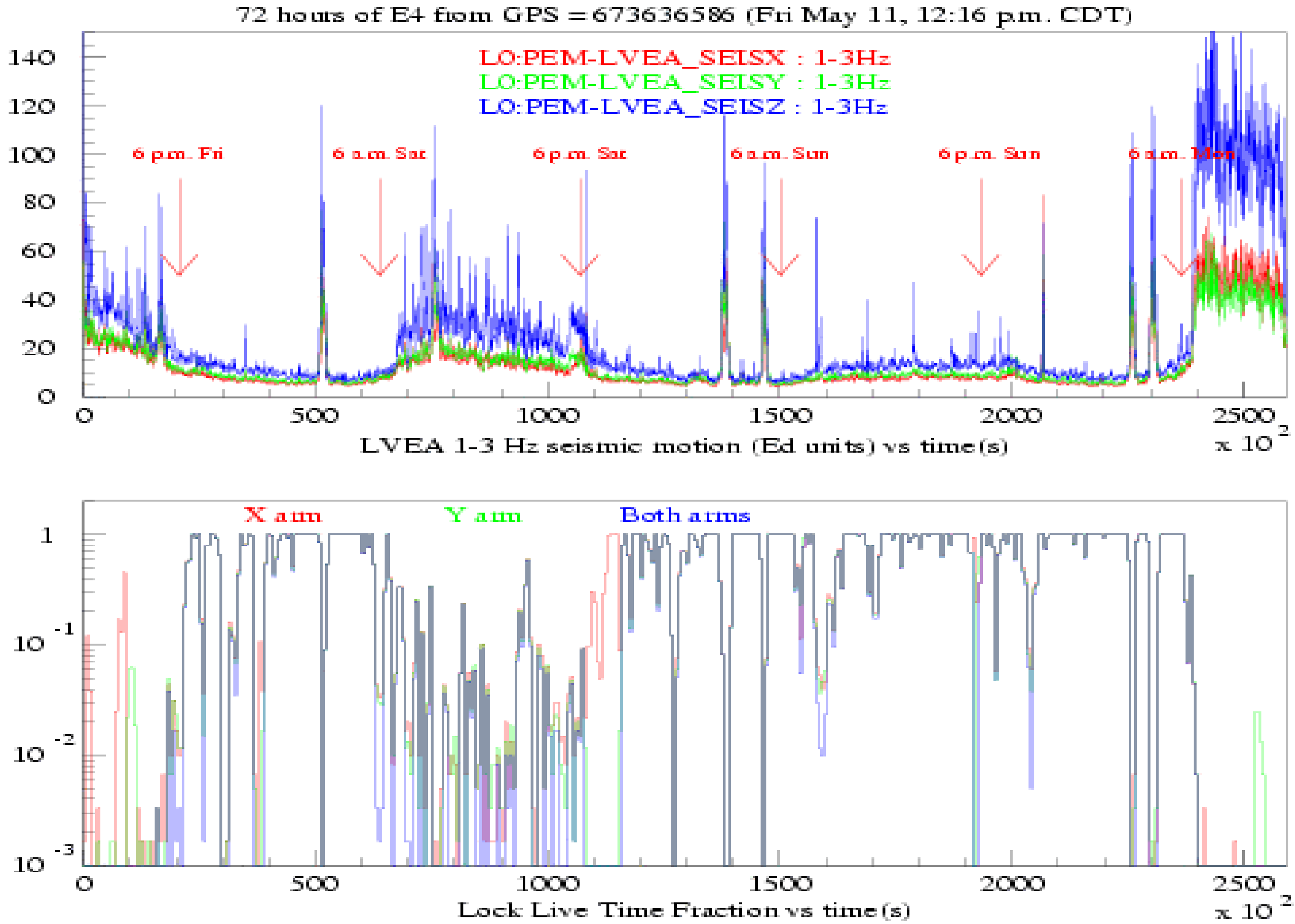
Temporary workaround:

> 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)

Engineering & Science Runs

A series of engineering runs ("E1" to "E8") have been completed in order to prepare for science runs: (E9 starts tomorrow!)

- Study detector sensitivity and calibration stability
- Shake down control room software and operational procedures
- Investigate artifacts, identify problems to be fixed
- Data have proven "rich" in artifacts (a good thing we looked!)

Science runs defined by priority given to maximizing performance & reliability (as opposed to "trying things"):

- "S1" science run in August/September 2002 (17 days)
- "S2" science run starts February 14, 2003 (59 days)
- "S3" science run starts late 2003 (~6 months)

Astrophysical Data Analysis

- Four "upper limits groups" organized for E7 run (as practice)

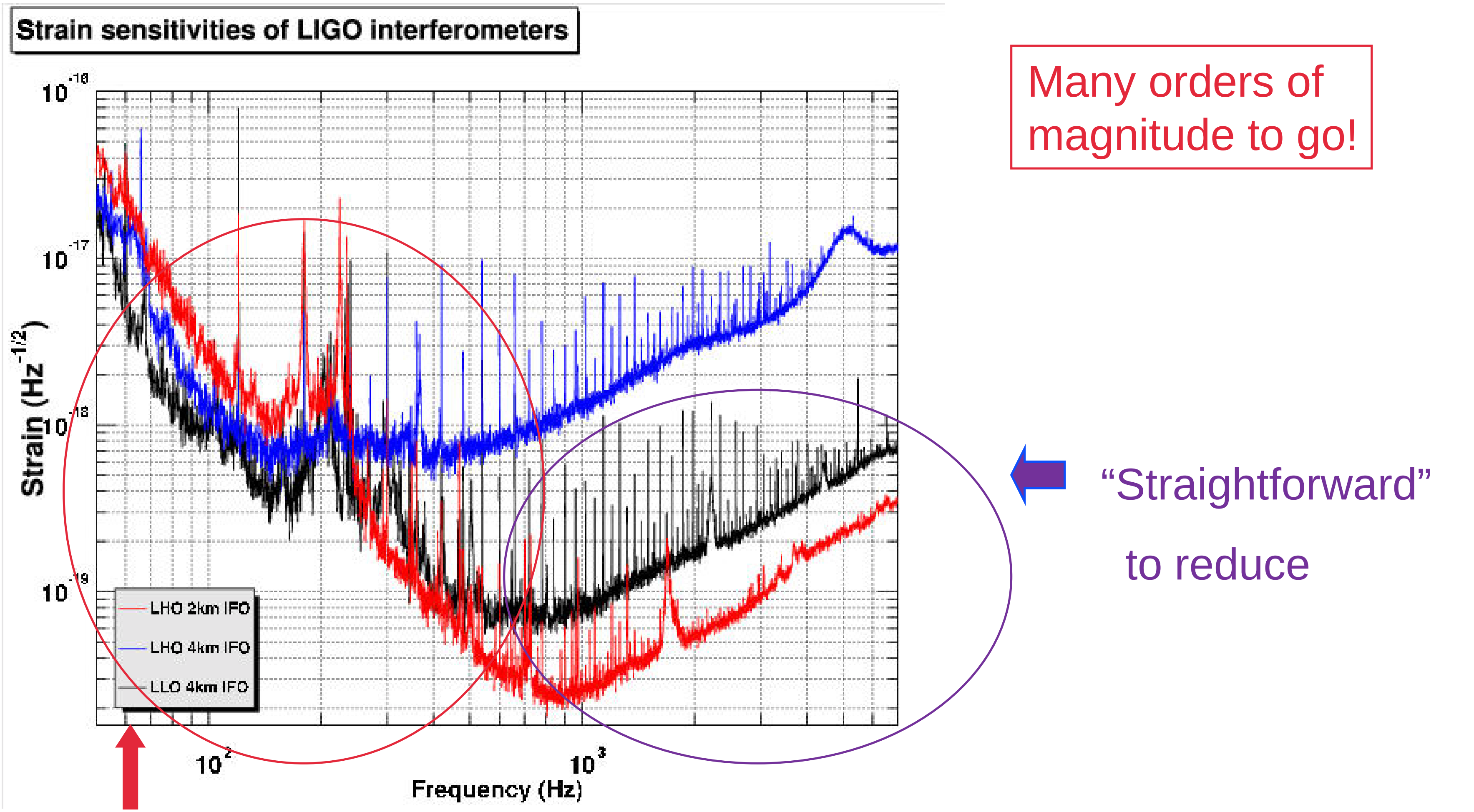
  (now working on S1 data, getting ready for S2)

  - Inspiraling binary systems
  - Unmodelled bursts
  - Periodic sources (e.g. pulsars)
  - Stochastic background (e.g., big-bang remnant)

- Present status:
  - Preliminary limits on sources under review by collaboration;
  - Results to be presented soon and submitted for publication
  - No surprises (astrophysical ones, anyway…)

E7 Data Analysis

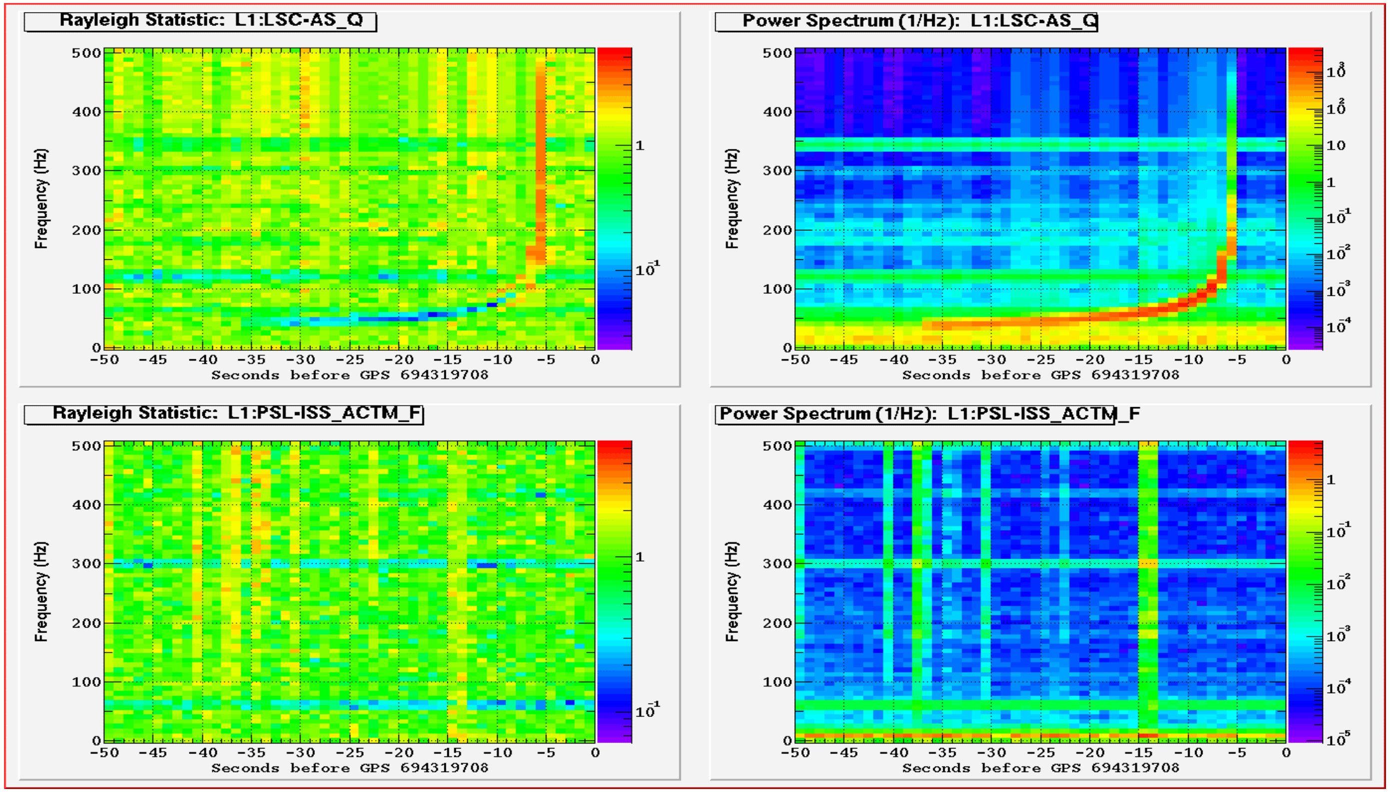
Sensitivity curves for the three interferometers: (Jan 2002)



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

E7 Data Analysis

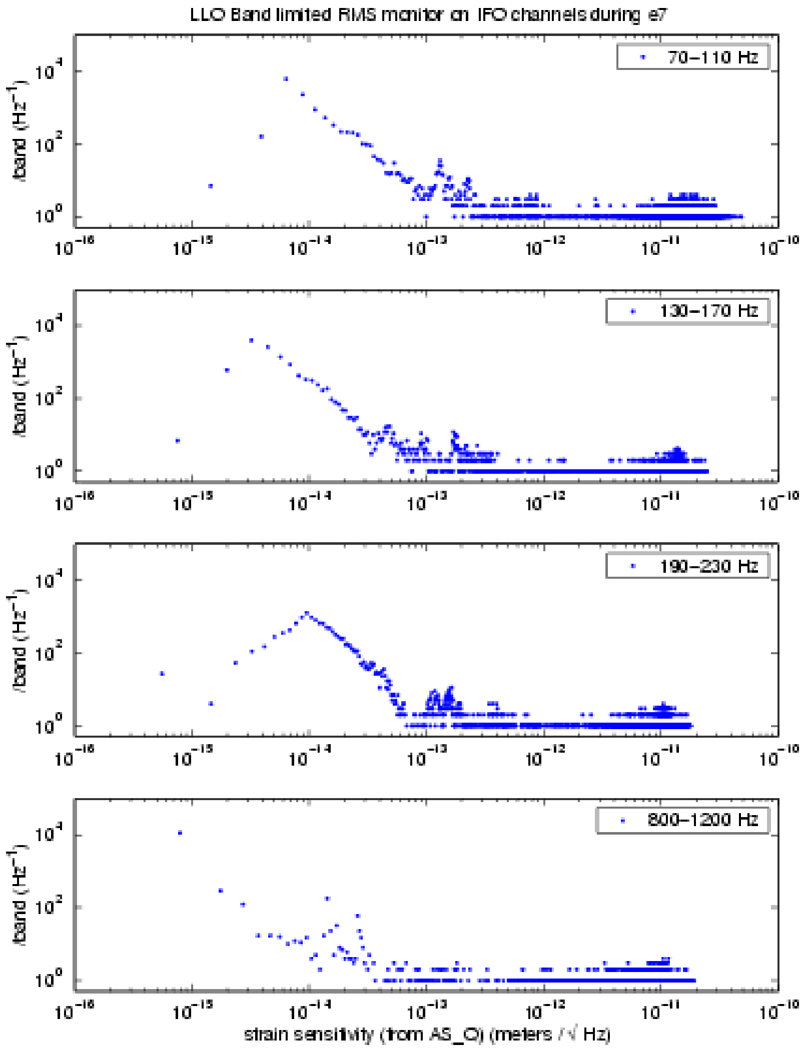
Viewing injected inspiral "chirp" via spectogram and "Rayleigh monitor"
(top plots for GW channel, bottom for an auxiliary laser channel)



Chirp easy to see (good)

Instrumental artifacts easy to see too! (bad)

E7 Data Analysis



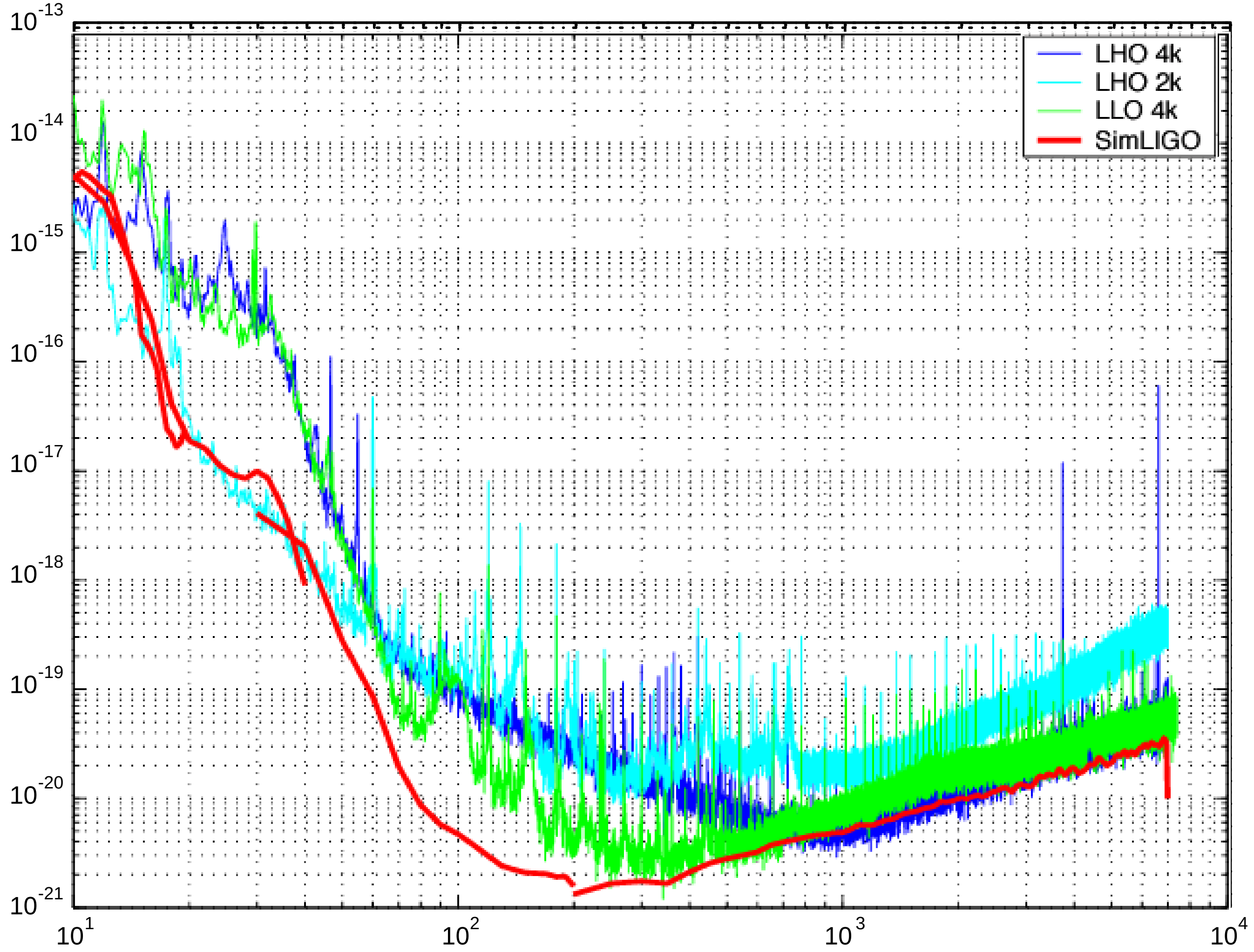
Histograms of band-limited RMS in several bands of interest

Outliers indicate non-Gaussianity, primarily broad-band transients

→ "Glitches"

Lots of work to reduce these…

S1 Strain Sensitivities (red = simulation)

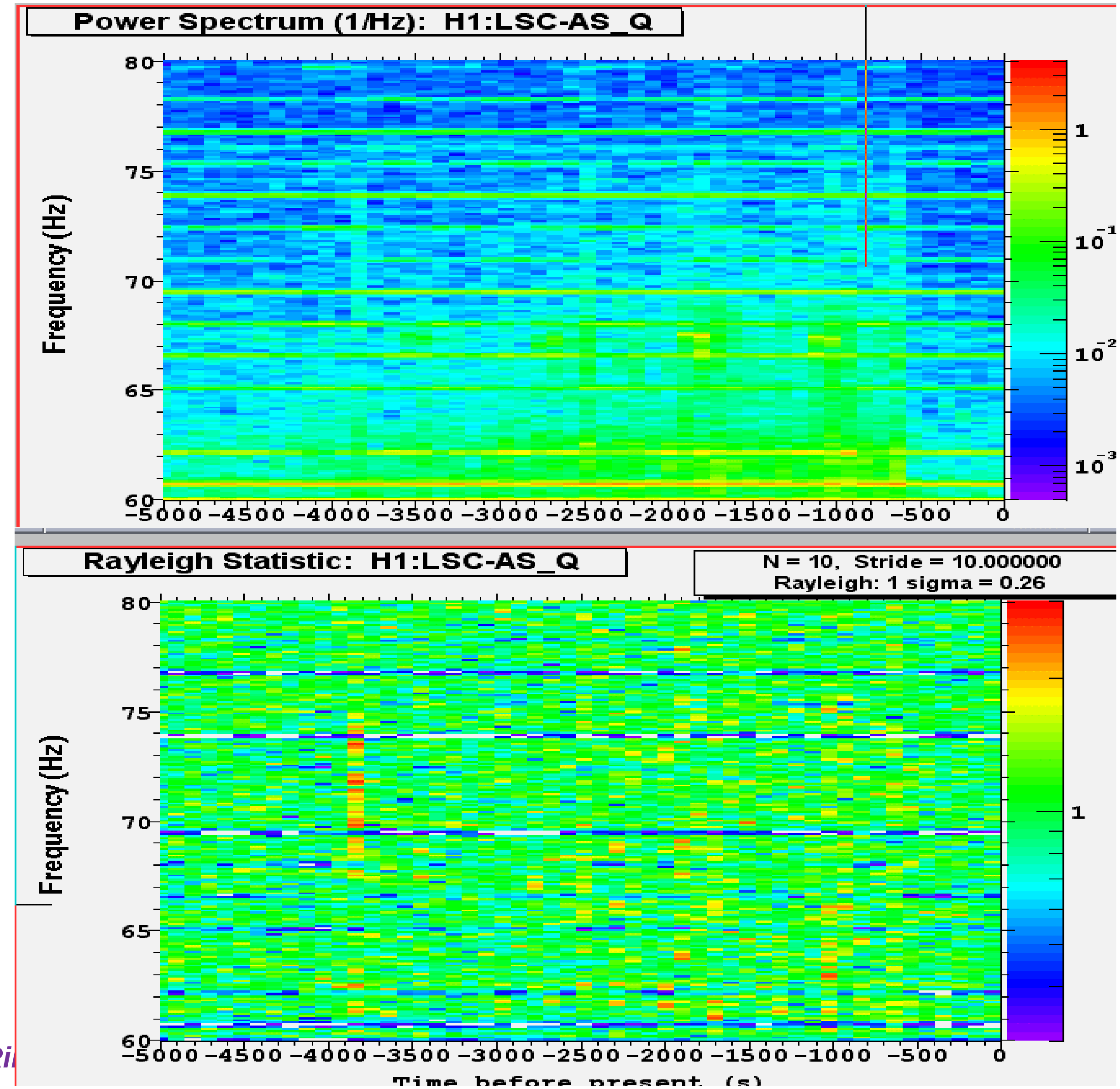


S1 Data Analysis

Despite these improvements, occasional artifacts appeared:

Hanford 4-km "heartbeat"

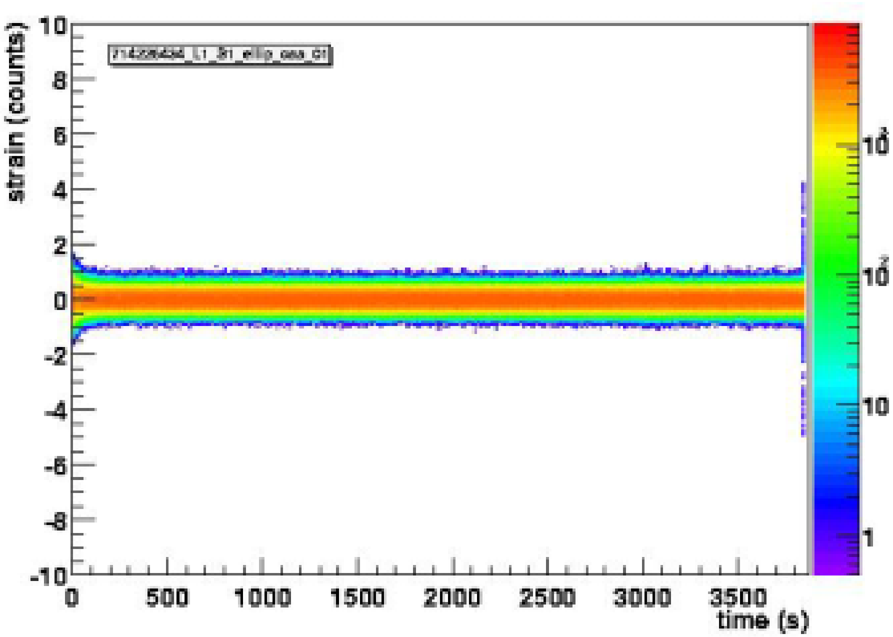
Tracked down to undamped "side motion" of one end mirror kicked up by Oregon earthquake



S1 Data Analysis

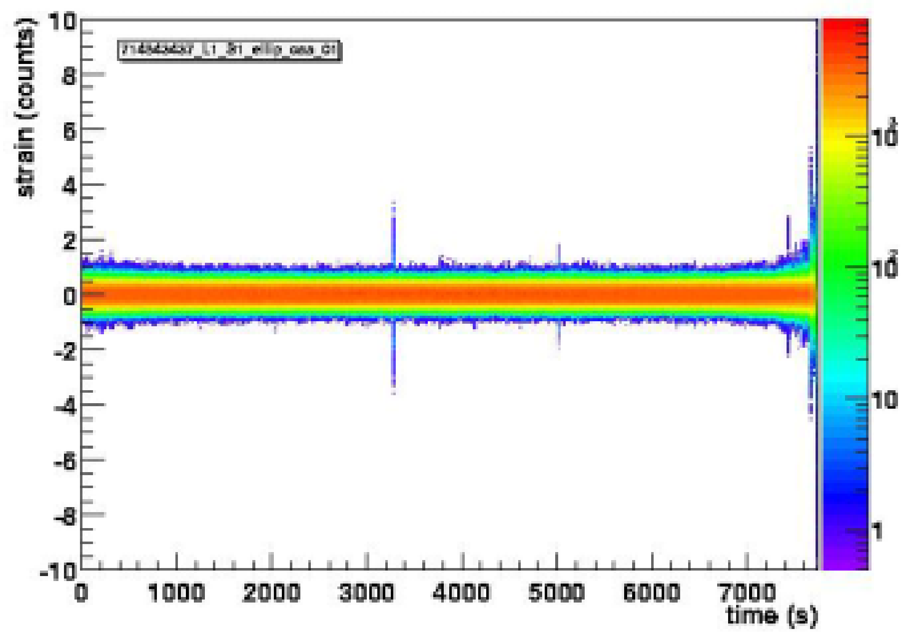
(three hours of Livingston 4-km)

Histograms vs time of filtered GW channel



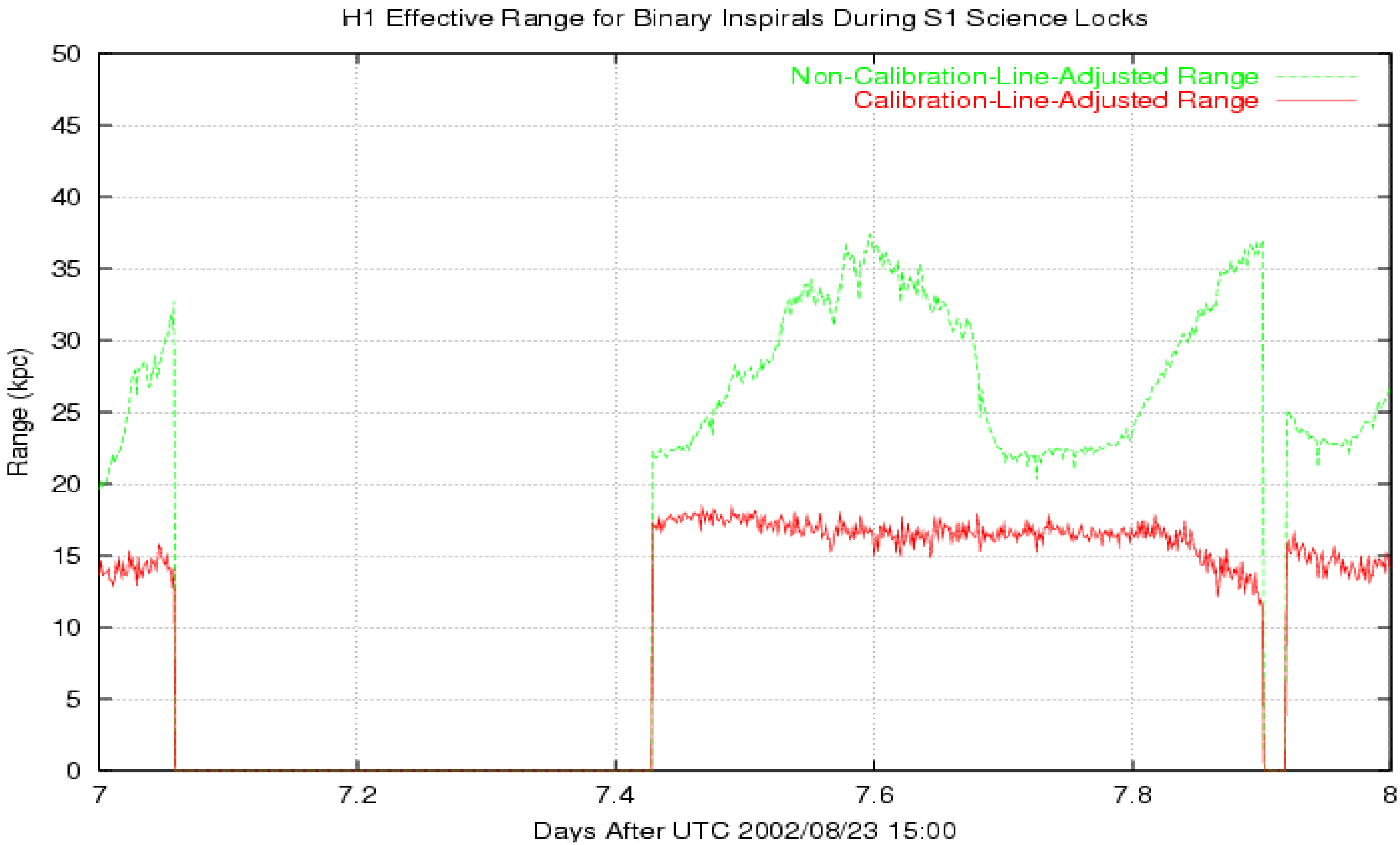
CLEAN DATA

SLIGHTLY RAGGED DATA



S1 Data Analysis – "Inspiral Range" (kpc)

Calibration not as stable as we want: (one day of S1 Hanford 4-km running)



S1 Data Analysis

Non-stationarity, glitches, etc., make analysis delicate

But one can estimate very rough expected upper limit sensitivities from preliminary work:

- **Stochastic backgrounds**
  - **Upper limit Ω_0 < ~30 (energy density!)**
- **Neutron binary inspiral**
  - **Upper limit distance < ~200 kpc**
- **Known pulsar**
  - **Upper limit $h < \sim 10^{-21}$**

Results for presentation / publication in early 2003

S2 should give substantial improvement in h

Looking Ahead

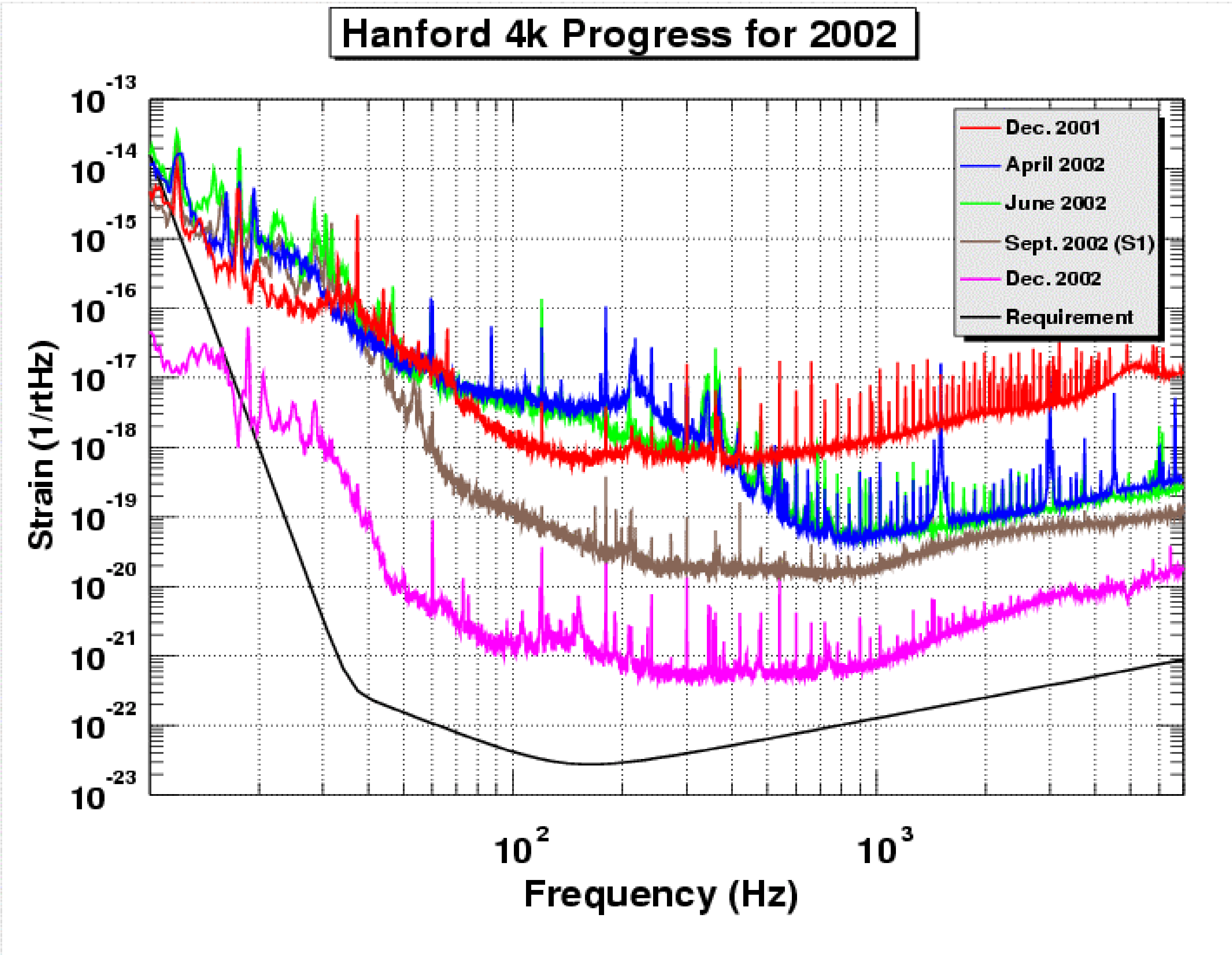
E7 and S1 have been eye-openingly useful

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

Future milestones

Feb-April 2003	S2 Science Run (8 weeks)
Spring 2003	Livingston seismic retrofit
Summer 2003	More commissioning
Late 2003	S3 Science Run (~6 months)
	(first of series of extended runs)

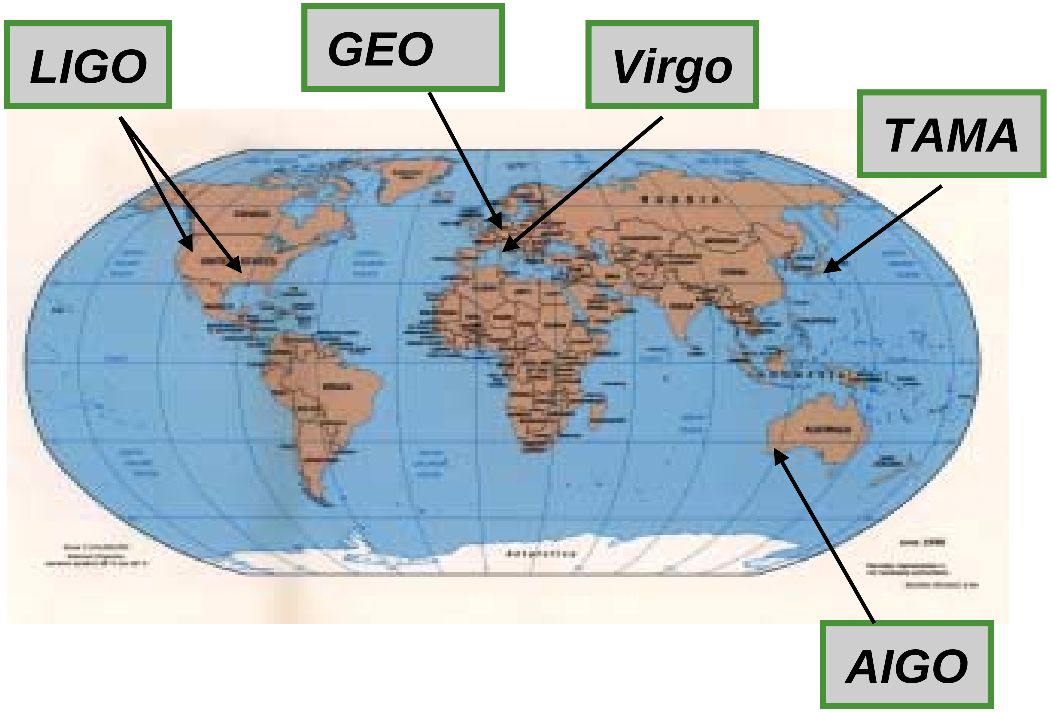
Looking back one year



Looking Ahead

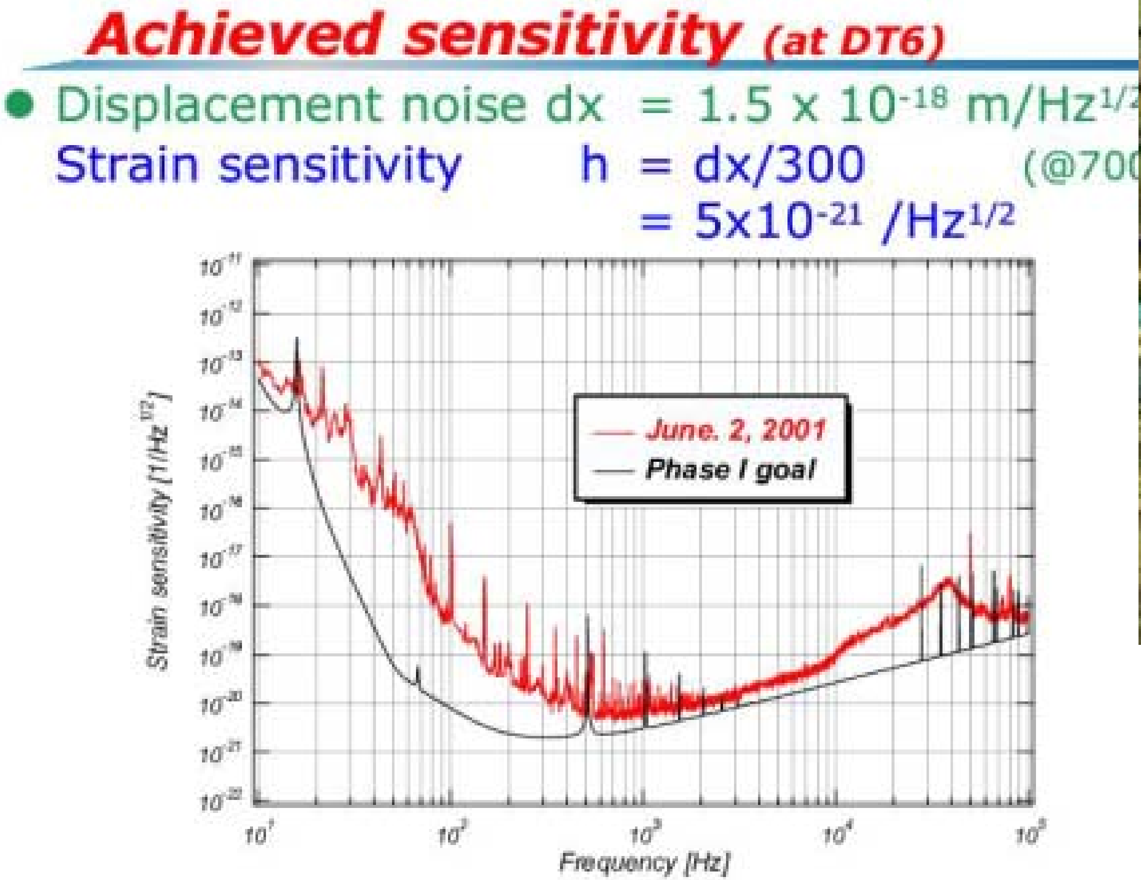
The three LIGO interferometers will be part of a global network.

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



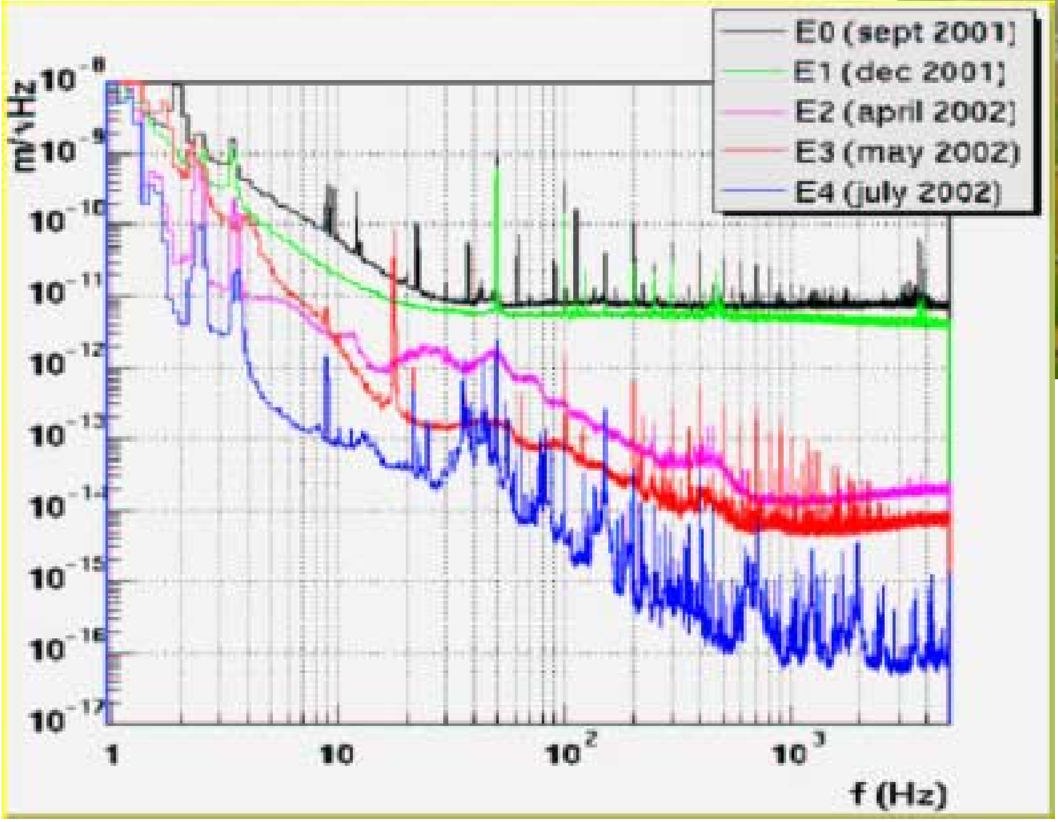
Looking Ahead

TAMA (300-meter – Japan):



Looking Ahead

Virgo (3000-meter – Italy/France):

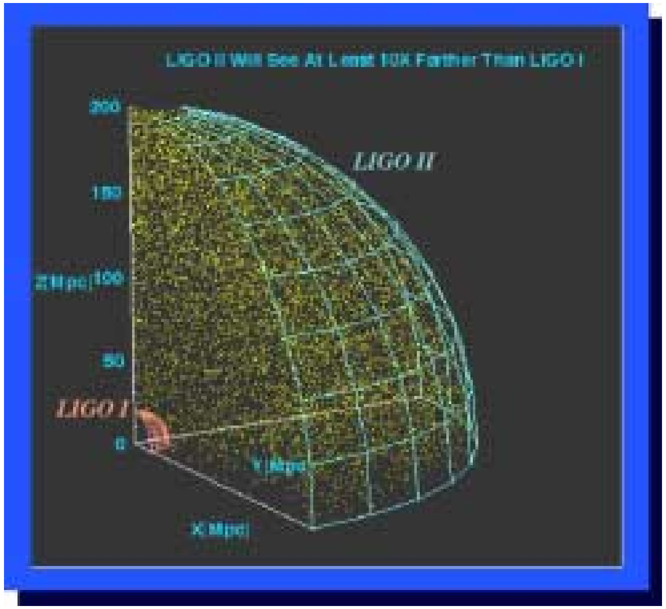


Looking Way Ahead

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

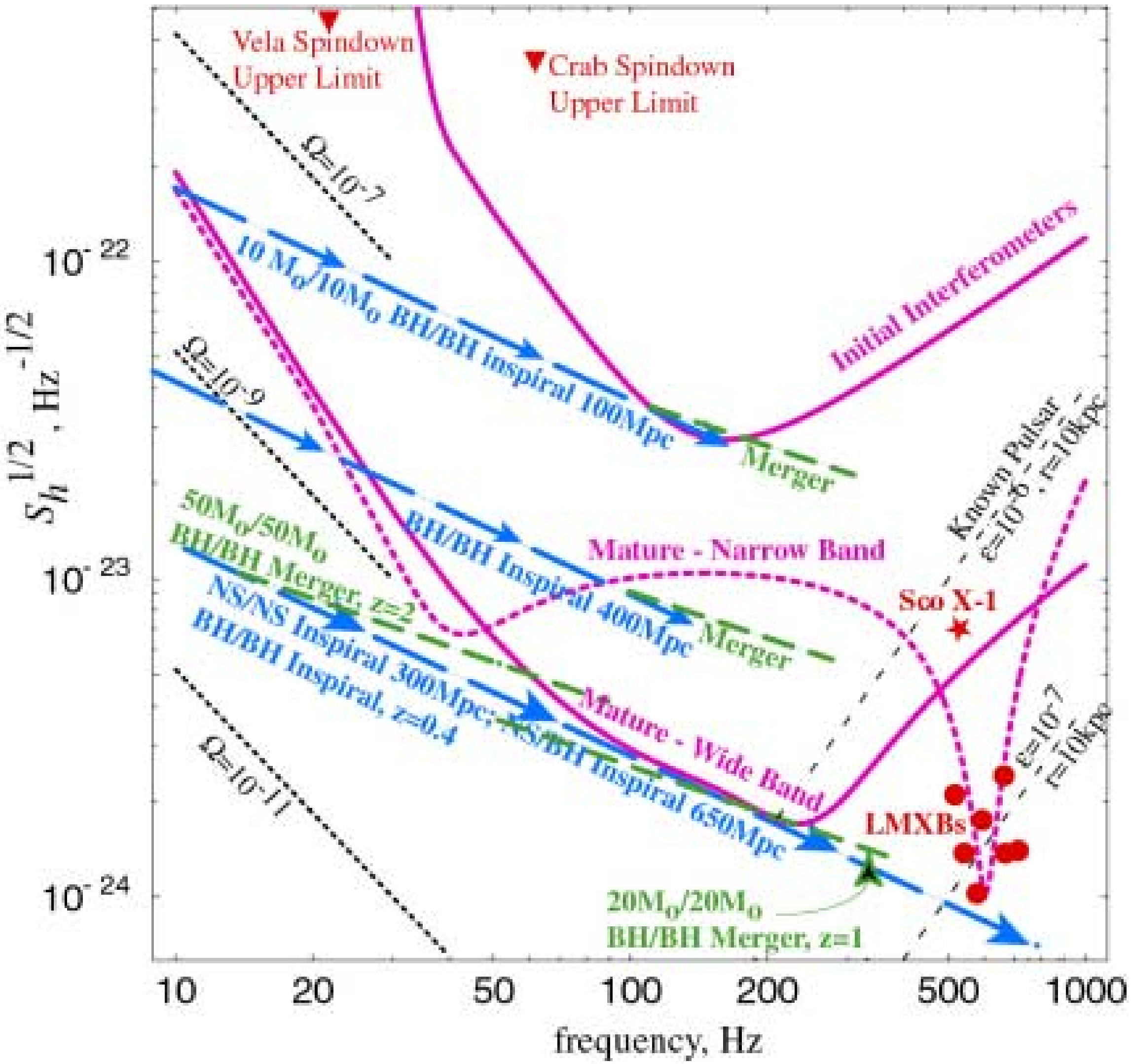
→Lowers seismic “wall” to ~10 Hz

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!