COSPAR 2000

Fundamental Physics in Space

LIGO: Progress and Prospects

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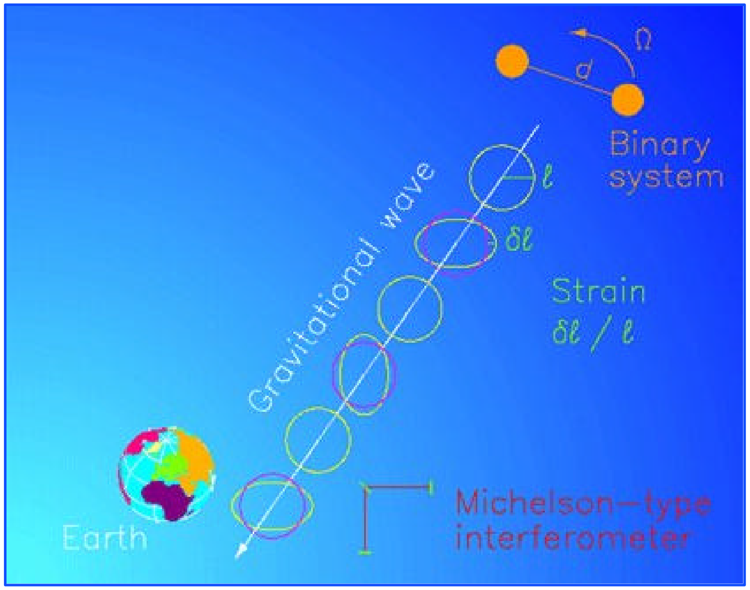
LIGO-G000176-00-M

Interferometers
terrestrial

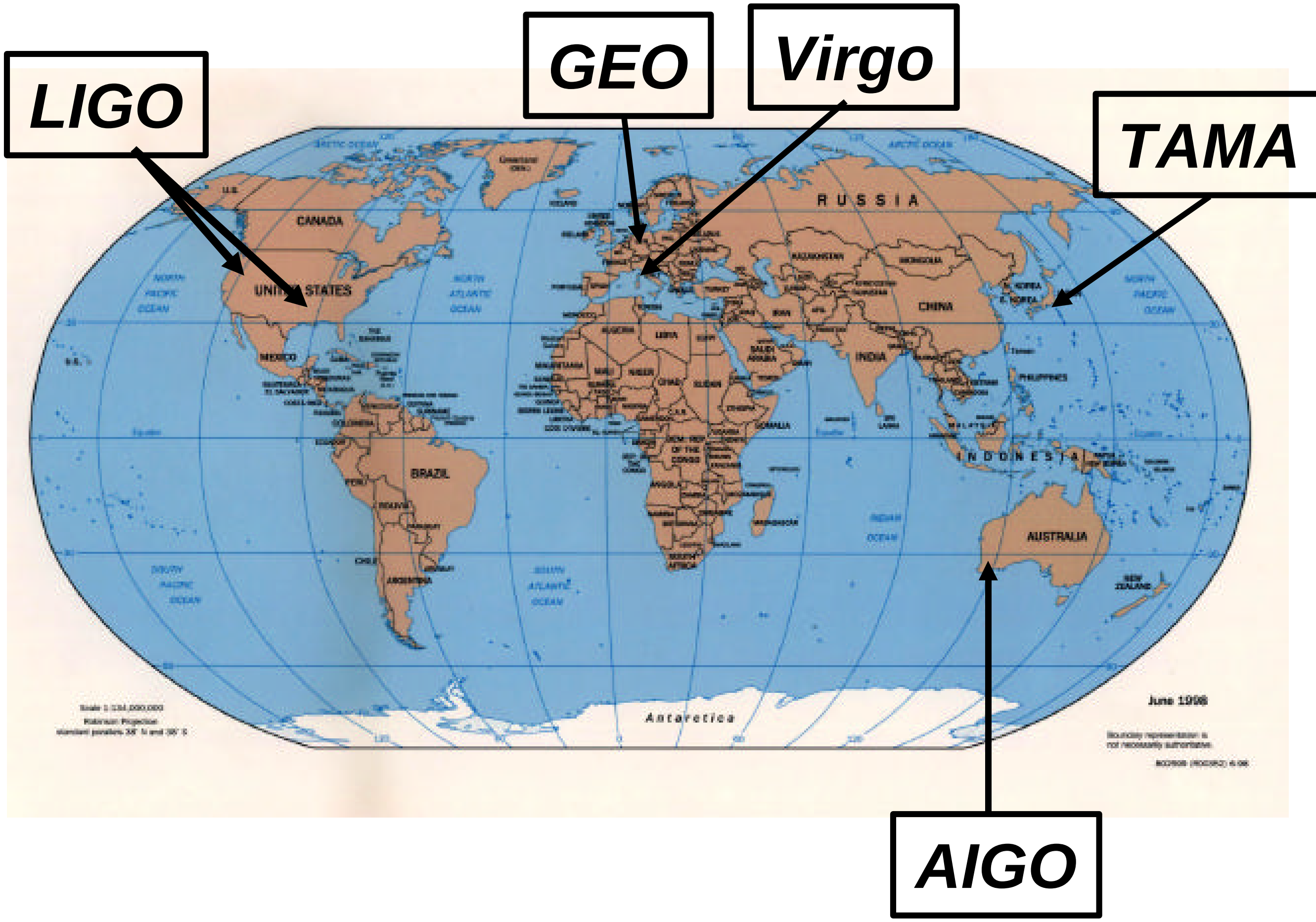
Suspended mass Michelson-type interferometers on earth's surface detect distant astrophysical sources

International network (LIGO, Virgo, GEO, TAMA) enable locating sources and decomposing polarization of gravitational waves.



Interferomers
international network

Simultaneously detect signal (within msec)



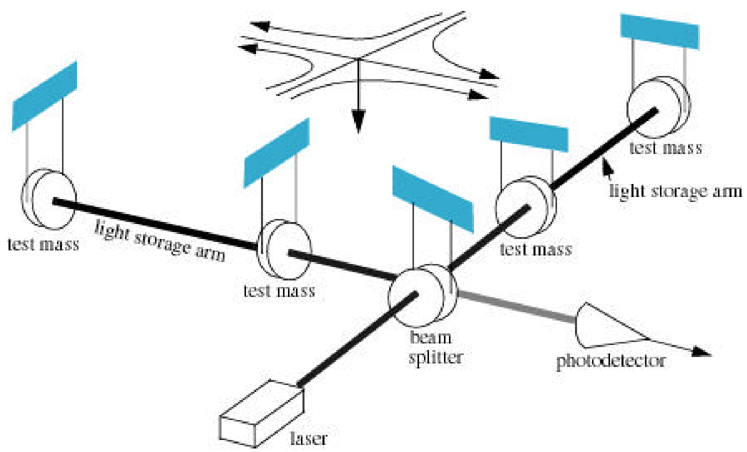
detection confidence

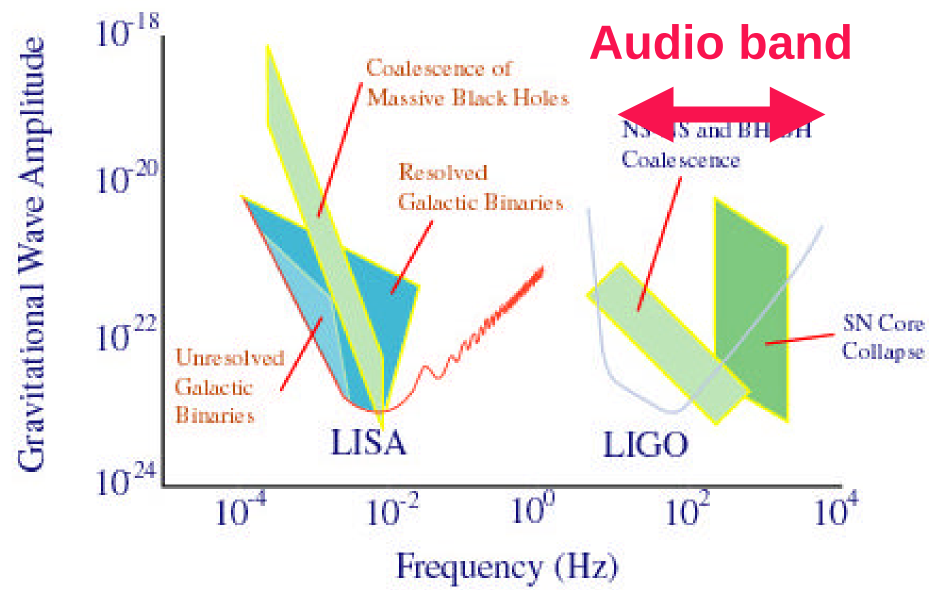
locate the sources

decompose the polarization of gravitational waves

Interferometers
space and terrestrial

- **EM waves are studied over ~20 orders of magnitude**
  - » **(ULF radio –> HE γ rays)**
- **Gravitational Waves over ~10 orders of magnitude**
  - » **(terrestrial + space)**

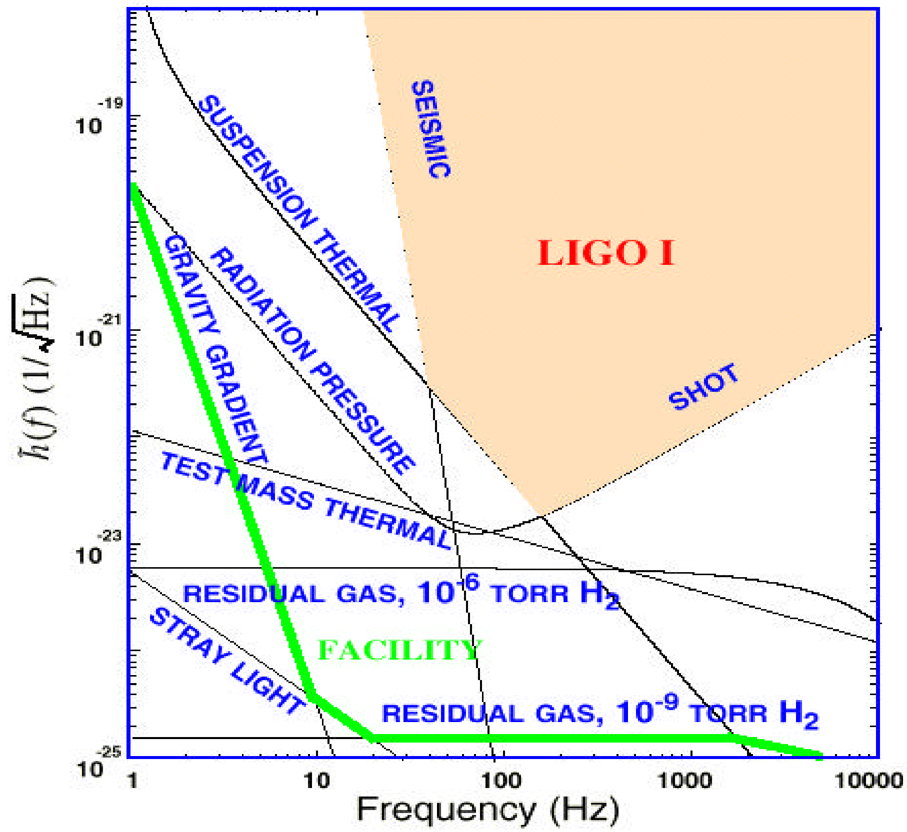




LIGO I
the noise floor

- **Interferometry is limited by three fundamental noise sources**
  - **seismic noise at the lowest frequencies**
  - **thermal noise at intermediate frequencies**
  - **shot noise at high frequencies**

- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**

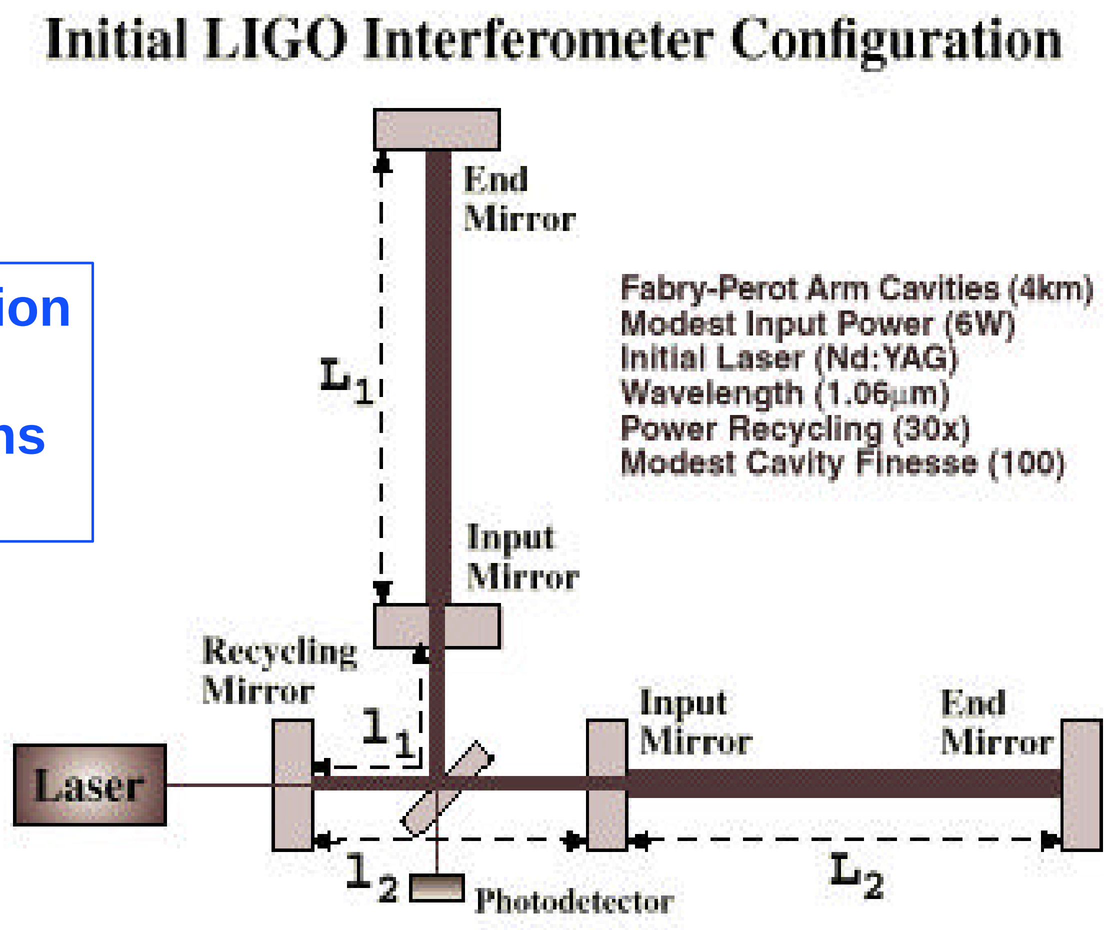


LIGO I

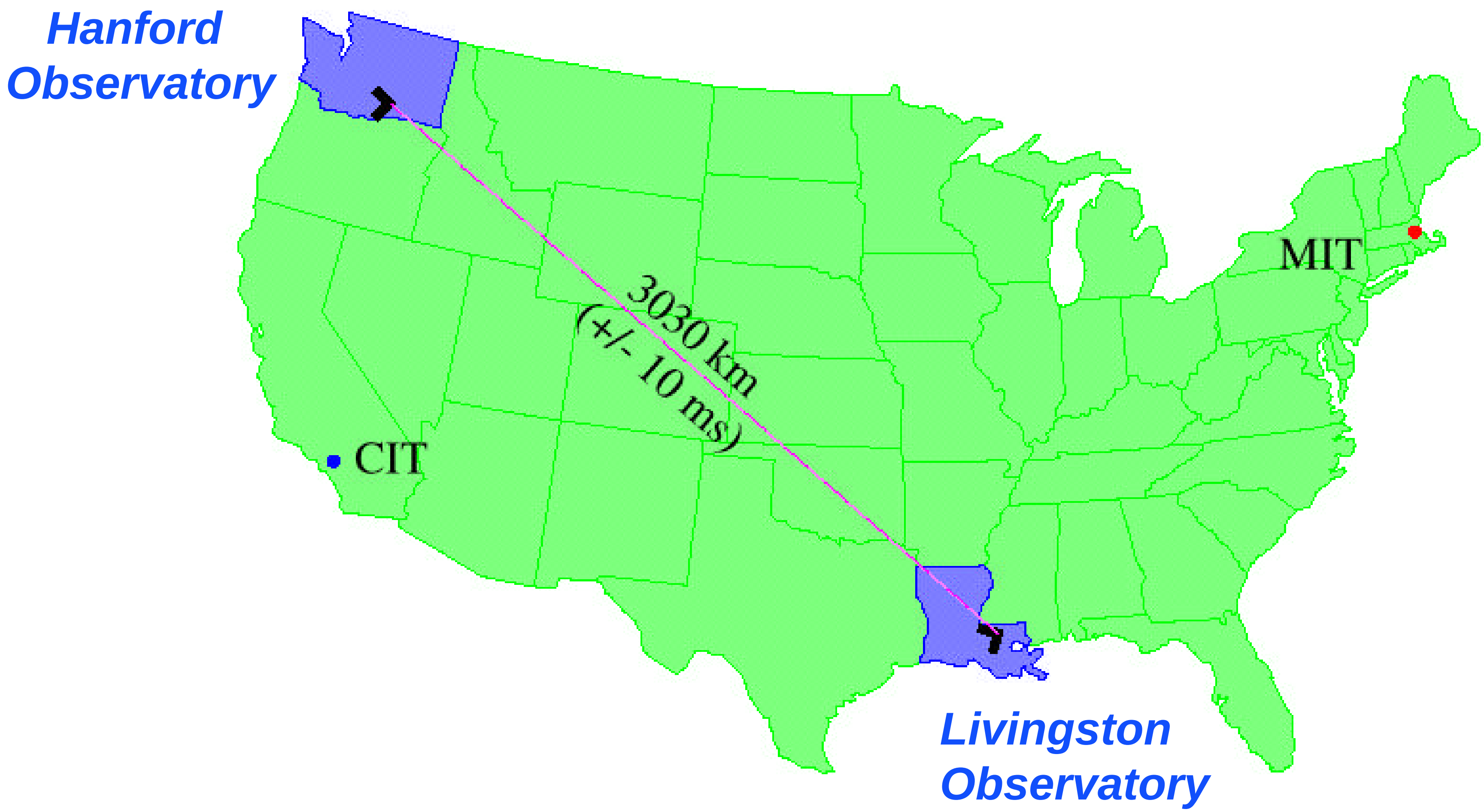
interferometer

- LIGO I configuration

- Science run begins in 2002



LIGO Sites


Hanford Observatory
3030 km
(+/- 10 ms)
CIT
MIT
Livingston Observatory

LIGO Plans

schedule

1996	**Construction Underway (mostly civil)**
1997	**Facility Construction (vacuum system)**
1998	**Interferometer Construction (complete facilities)**
1999	**Construction Complete (interferometers in vacuum)**
2000	**Detector Installation (commissioning subsystems)**
2001	**Commission Interferometers (first coincidences)**
2002	**Sensitivity studies (initiate LIGOI Science Run)**
2003+	**LIGO I data run (one year integrated data at $h \sim 10^{-21}$)**
2005	**Begin LIGO II installation**

LIGO

Livingston Observatory

LIGO

Hanford Observatory

LIGO Facilities

Beam Tube Enclosure

- minimal enclosure
- reinforced concrete
- no services

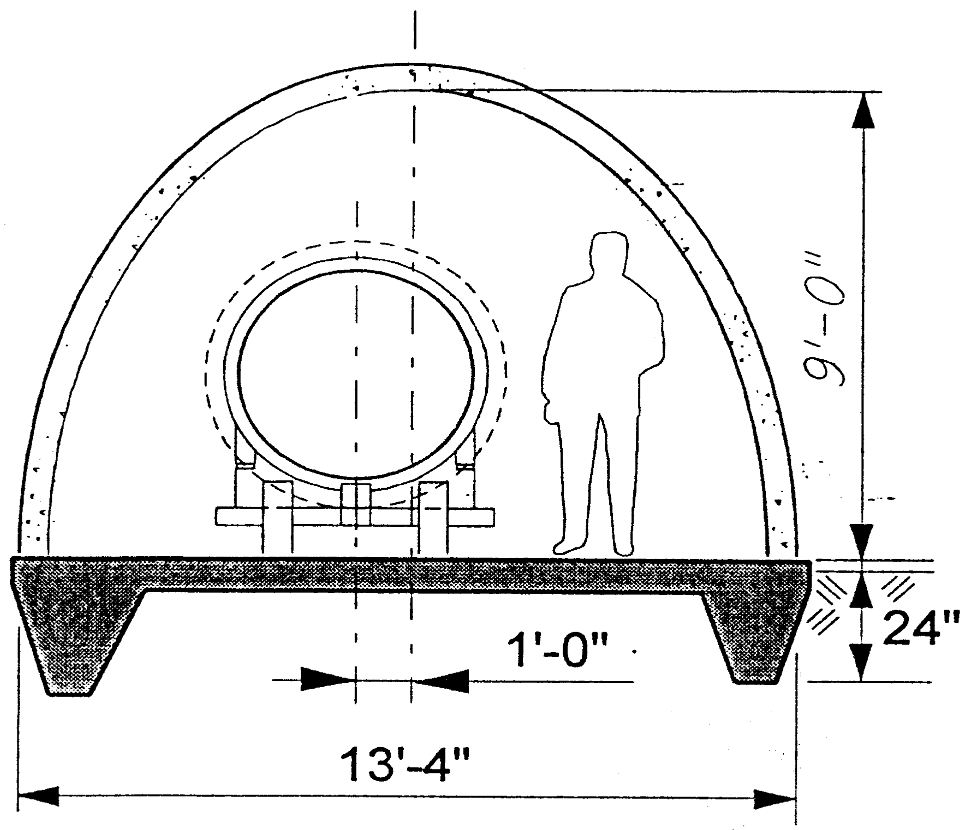


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

LIGO

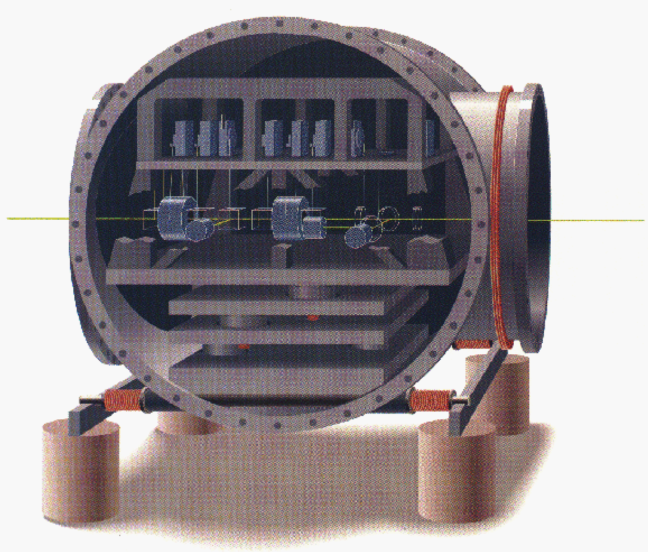
Beam Tube

- **LIGO beam tube under construction in January 1998**
- **65 ft spiral welded sections**
- **girth welded in portable clean room in the field**

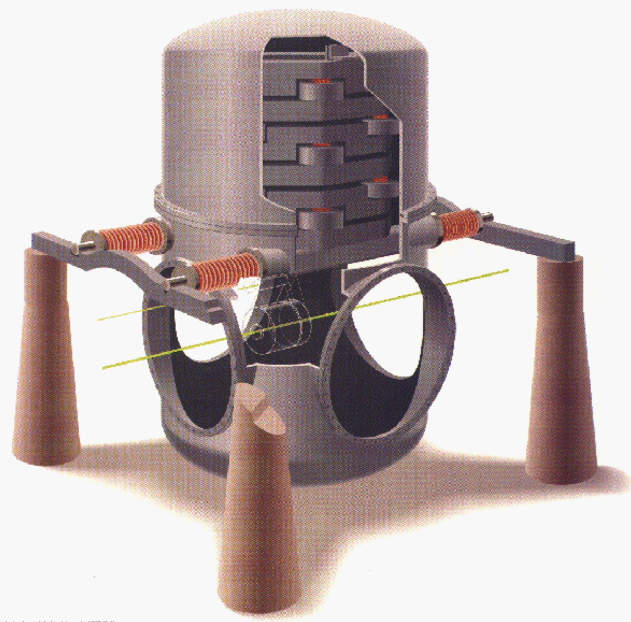
LIGO

vacuum equipment

Vacuum Chambers



HAM Chambers



BSC Chambers

Seismic Isolation

constrained layer damped springs

Seismic Isolation Systems

Progress

» production and delivery of components almost complete

» early quality problems have mostly disappeared

» the coarse actuation system for the BSC seismic isolation systems has been installed and tested successfully in the LVEA at both Observatories

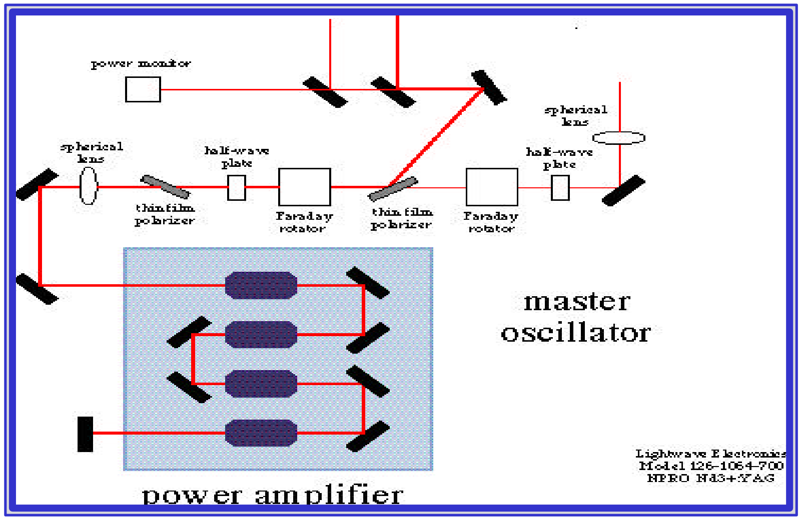
» Hanford 2km & Livingston seismic isolation system installation has been completed, with the exception of the tidal compensation (fine actuation) system

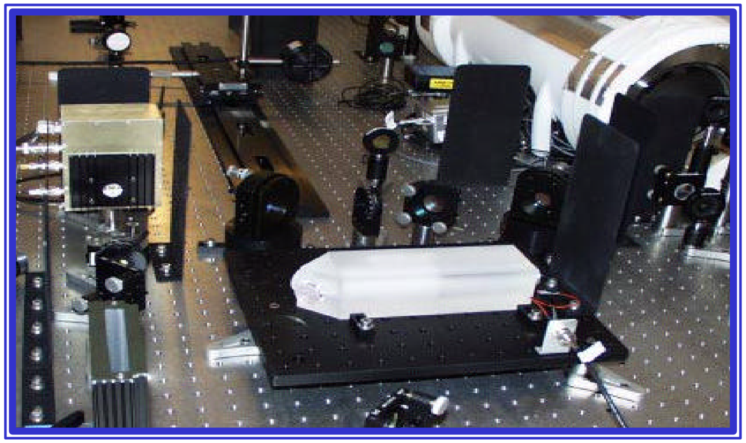
» Hanford 4km seismic isolation installation is complete

HAM Door Removal (Hanford 4km)

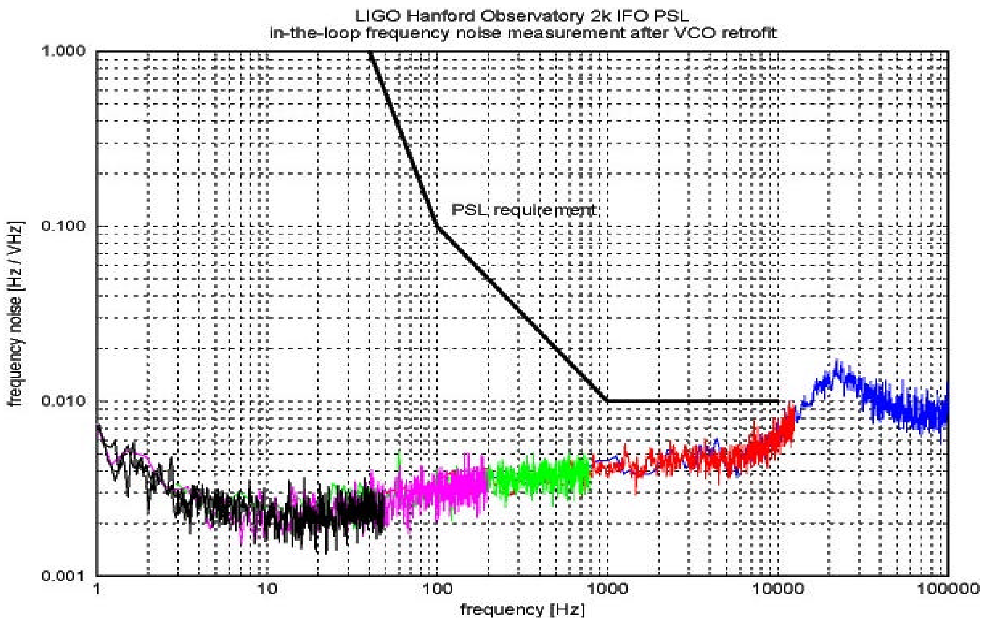
LIGO
Laser

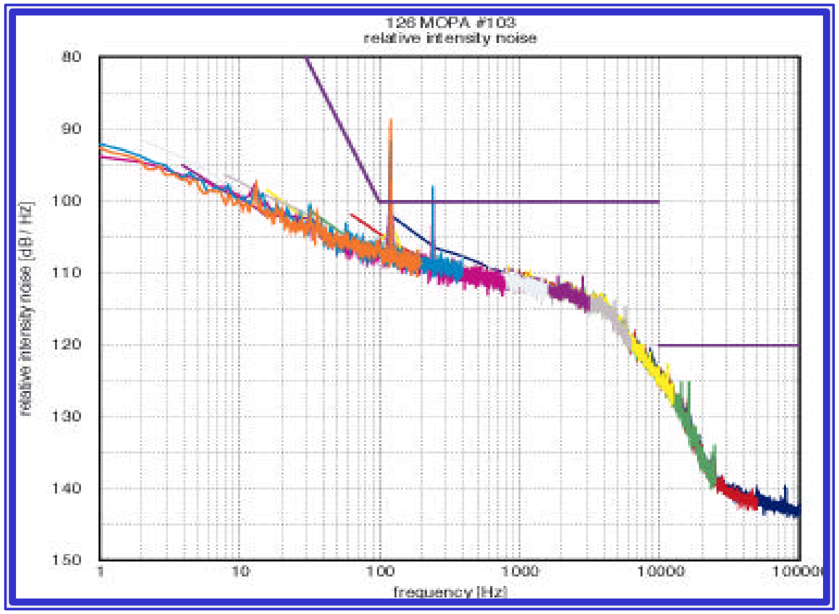
- Nd:YAG
- 1.064 μm
- Output power > 8W in TEM00 mode





Laser Prestabilization





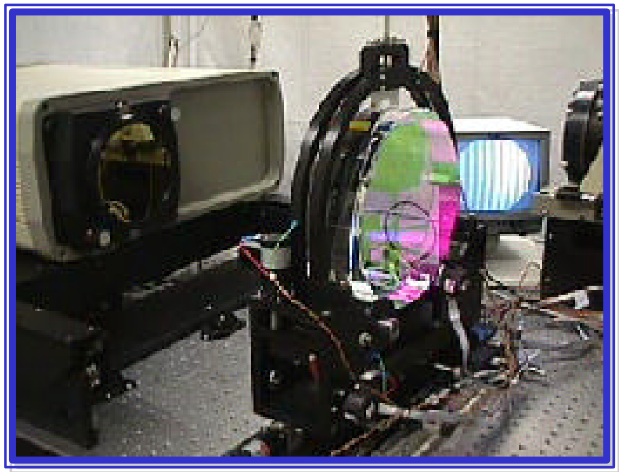
- **frequency noise:**
- **$\delta\nu(f) < 10^{-2} Hz/Hz^{1/2}$ 40Hz<f<10KHz**

- **intensity noise:**
- **$\delta I(f)/I < 10^{-6}/Hz^{1/2}$, 40 Hz<f<10 KHz**

Optics

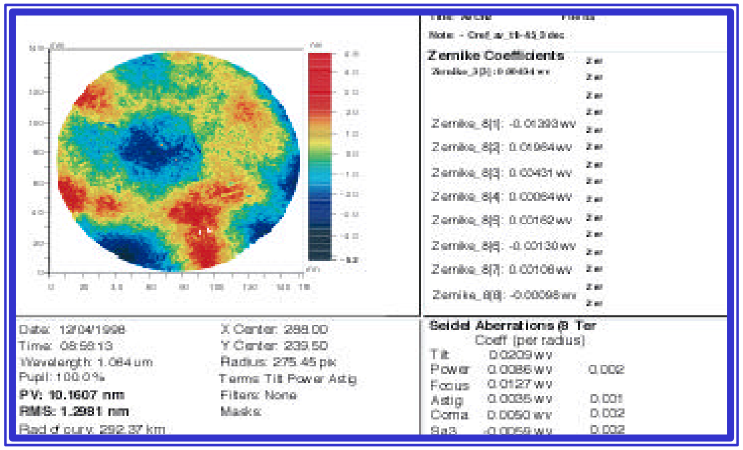
mirrors, coating and polishing

- All optics polished & coated
  - » Microroughness within spec. (<10 ppm scatter)
  - » Radius of curvature within spec. (δR/R < 5%)
  - » Coating defects within spec. (pt. defects < 2 ppm, 10 optics tested)
  - » Coating absorption within spec. (<1 ppm, 40 optics tested)

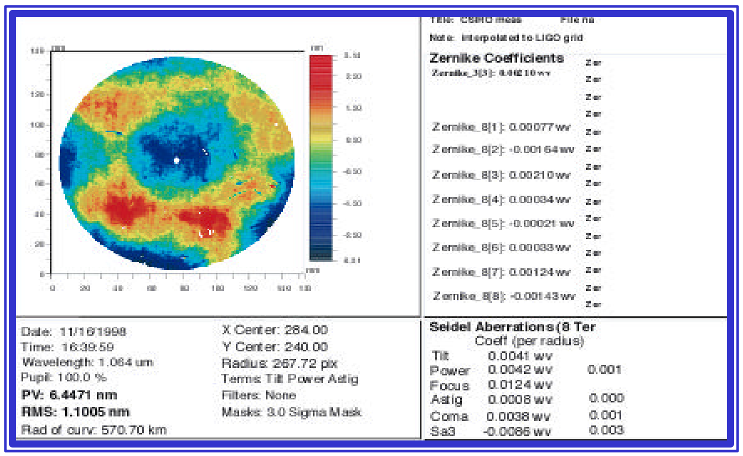


LIGO

metrology



- **Caltech**

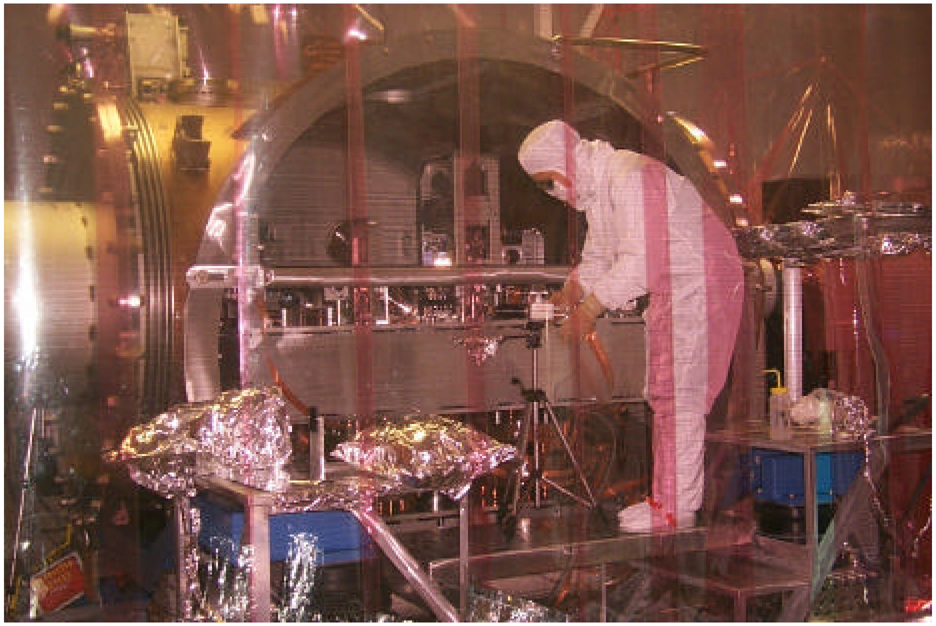


- **CSIRO**

Input Optics

installation & commissioning

- **The 2km Input Optics subsystem installation has been completed**
  - » **The Mode Cleaner routinely holds length servo-control lock for days**
  - » **Mode cleaner parameters are close to design specs, including the length, cavity linewidth and visibility**
  - » **Further characterization is underway**



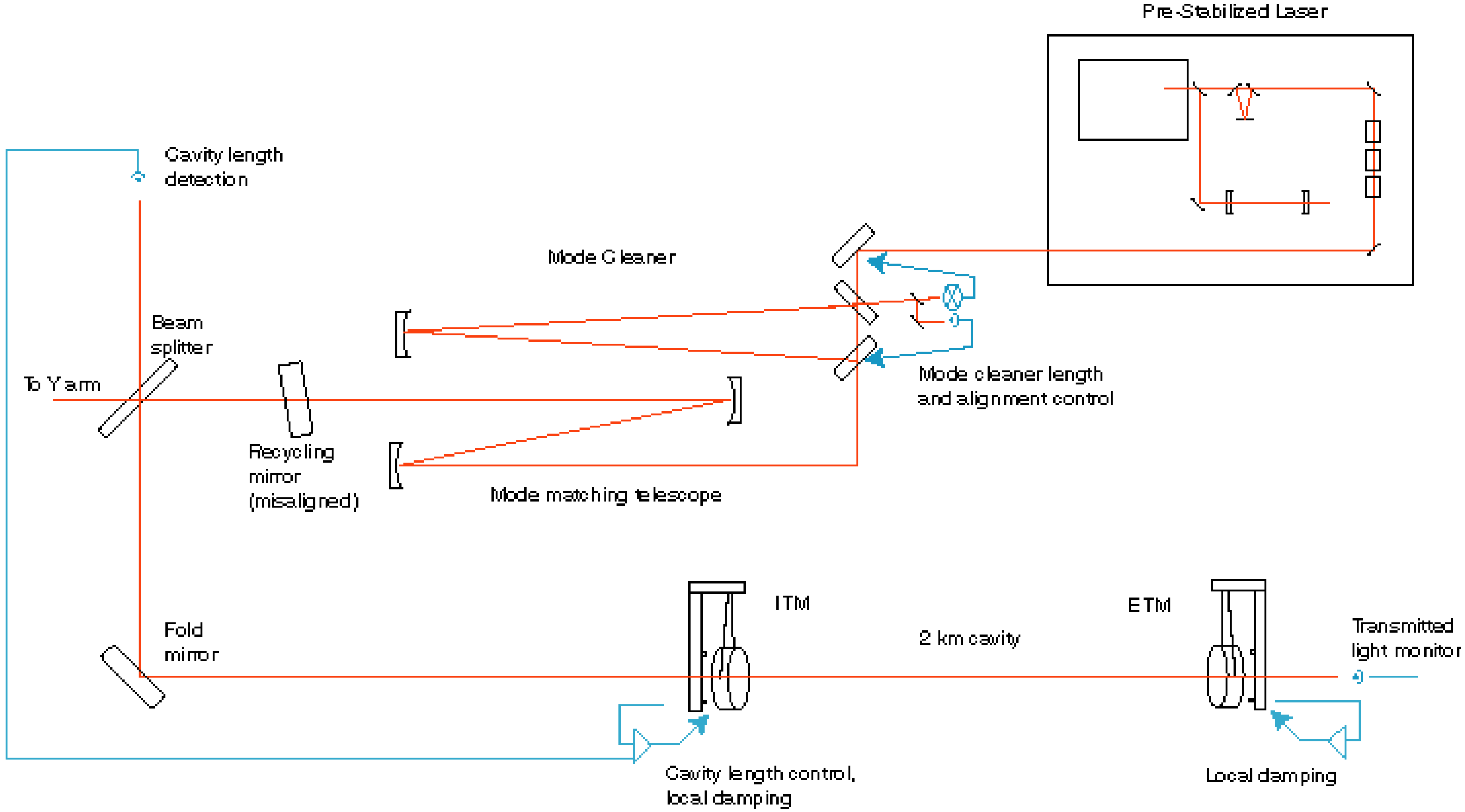
Commissioning

Configurations

- Mode cleaner and Pre-Stabilized Laser
- Michelson interferometer
- 2km one-arm cavity

- At present, activity focussed on Hanford Observatory
- Mode cleaner locking imminent at Livingston

Schematic of system



Commissioning

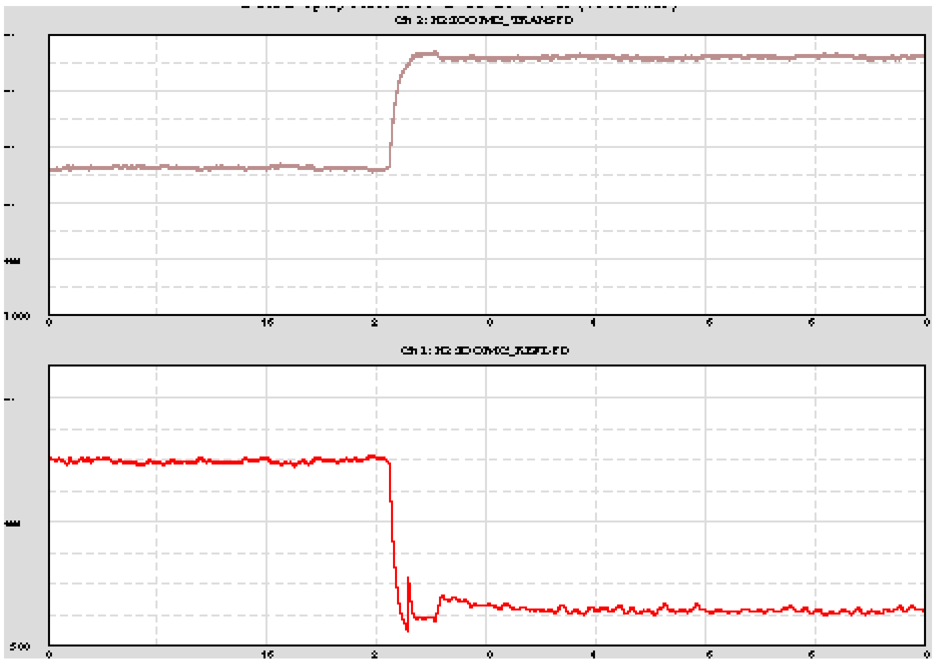
Pre-Stabilized Laser-Mode Cleaner

- **Suspension characterization**
  - » **actuation / diagonalization**
  - » **sensitivity of local controls to stray Nd:YAG light**
  - » **Qs of elements measured, 3 10^{-5} - 1 10^{-6}**
- **Laser - Mode Cleaner control system shakedown**
- **Laser frequency noise measurement**

Wavefront sensing

mode cleaner cavity

- **Alignment system function verified**



Michelson Interferometer

- **Interference quality of recombined beams (>0.99)**
- **Measurements of Qs of Test Masses**

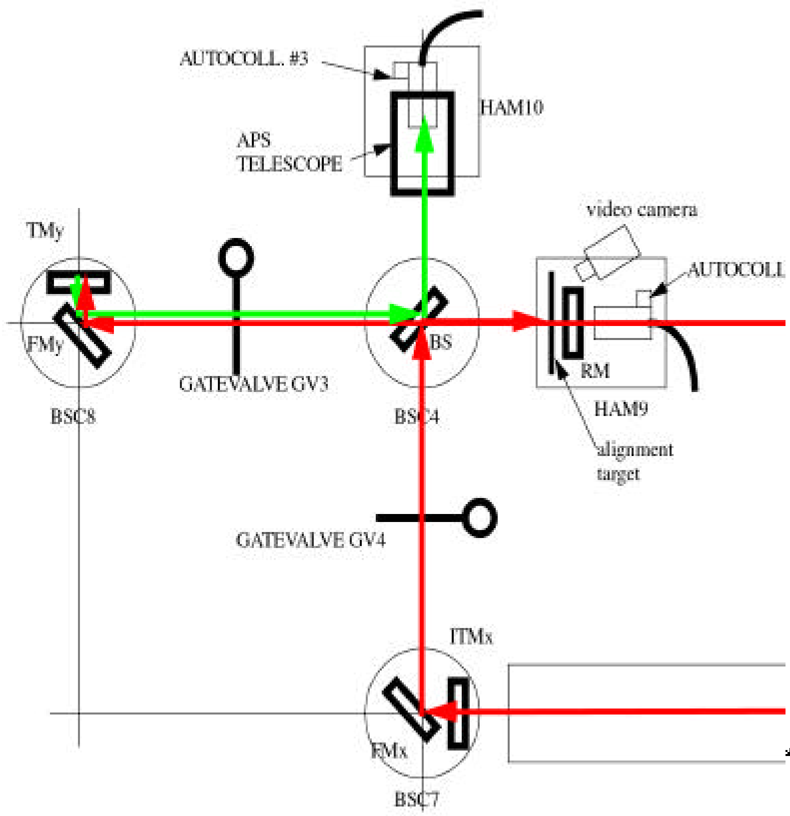


Table 1. Internal Resonance Measurement Data

Optic Name	*Resonant Frequency fo (kHZ)*	*Mode Name*	*Q Measured*	*Q Theoretical*
ITMx	6.7475	Butterfly	1.40×10^6	1.3×10^6
ITMx	9.395	Drum Head	*6.16×10^5	
ITMx	14.3737	Breathing	1.20×10^7	
BS	3.7337	Butterfly	1.85×10^6	
BS	5.4775	Drum Head	2.50×10^4	
BS	7.812	3-Fold Radial	2.65×10^5	2.6×10^6
BS	11.1387		3.60×10^5	
ITMy	9.3975	Drum Head	9.98×10^5	1.3×10^6

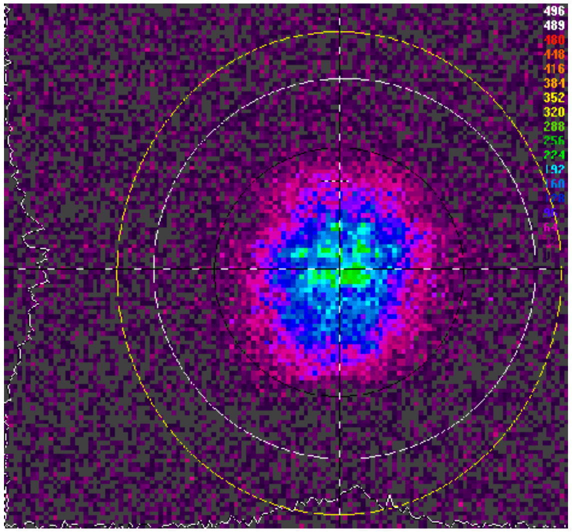
*A rough estimate compared to other values in table (data analysis method for this value was different). Betsy Weaver 1/19/00

2km Fabry-Perot cavity

- Includes all interferometer subsystems
  - » many in definitive form; analog servo on cavity length for test configuration
- confirmation of initial alignment
  - » ~100 microrad errors; beams easily found in both arms
- ability to lock cavity improves with understanding
  - » 0 sec 12/1 flashes of light
  - » 0.2 sec 12/9
  - » 2 min 1/14
  - » 60 sec 1/19
  - » 5 min 1/21 (and on a different arm)
  - » 18 min 2/12
  - » 1.5 hrs 3/4 (temperature stabilize pre modecleaner)

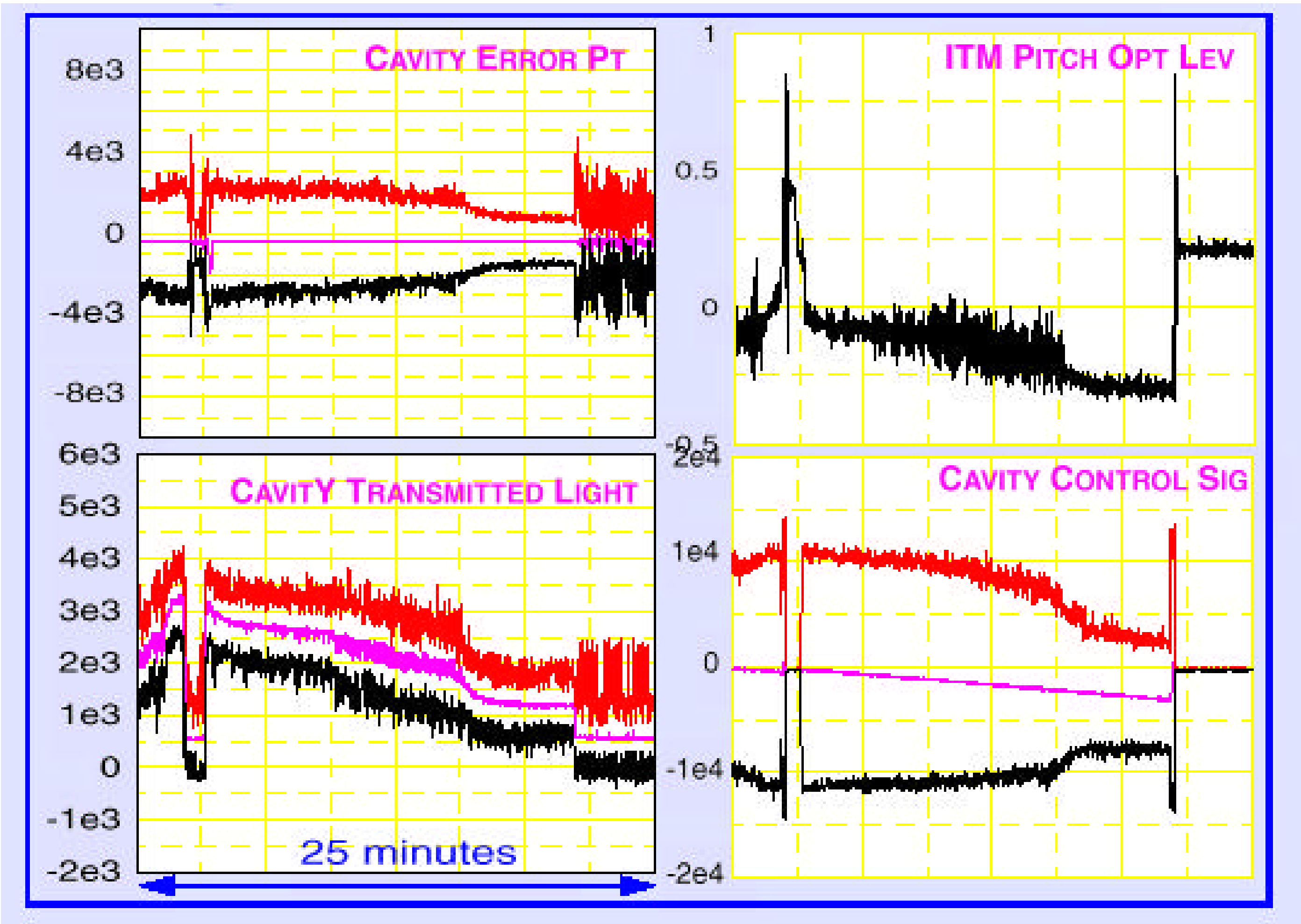
2km Fabry-Perot cavity

- models of environment
  - » temperature changes on laser frequency
  - » tidal forces changing baselines
  - » seismometer/tilt correlations with microseismic peak
- mirror characterization
  - » losses: ~6% dip, excess probably due to poor centering
  - » scatter: appears to be better than requirements
  - » figure 12/03 beam profile



2km Fabry-Perot cavity

15 minute locked stretch



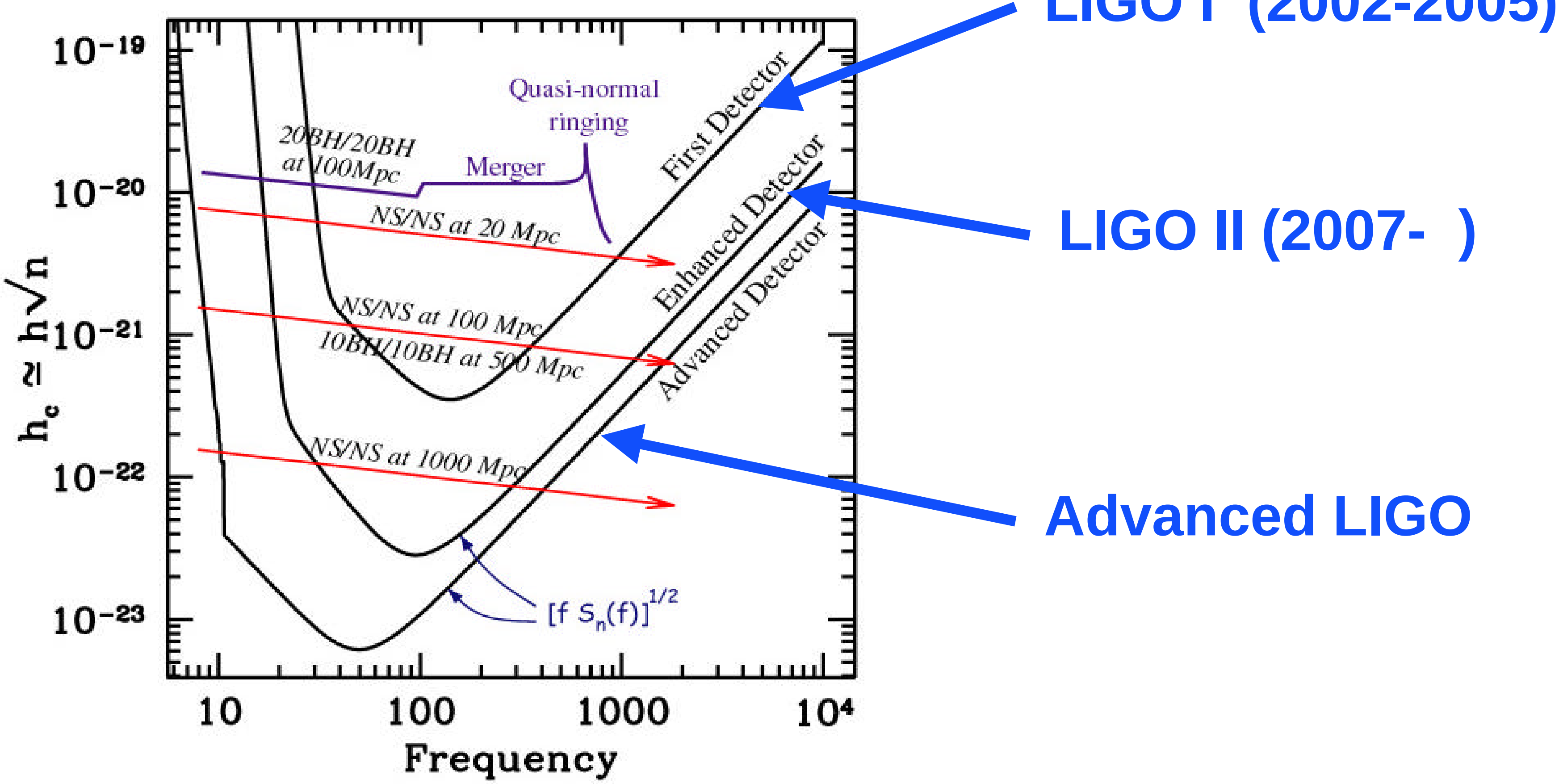
Significant Events

Hanford 2km interferometer	Single arm test complete installation complete interferometer locked	6/00 8/00 12/00
Livingston 4km interferometer	Input Optics completed interferometer installed interferometer locked	7/00 10/00 2/01
Coincidence Engineering Run (Hanford 2km & Livingston 4km)	Initiate Complete	7/01 7/02
Hanford 4km interferometer	All in-vacuum components installed interferometer installed interferometer locked	10/00 6/01 8/01
LIGO I Science Run (3 interferometers)	Initiate Complete (obtain 1 yr @ h ~ 10^{-21})	7/02 1/05

LIGO

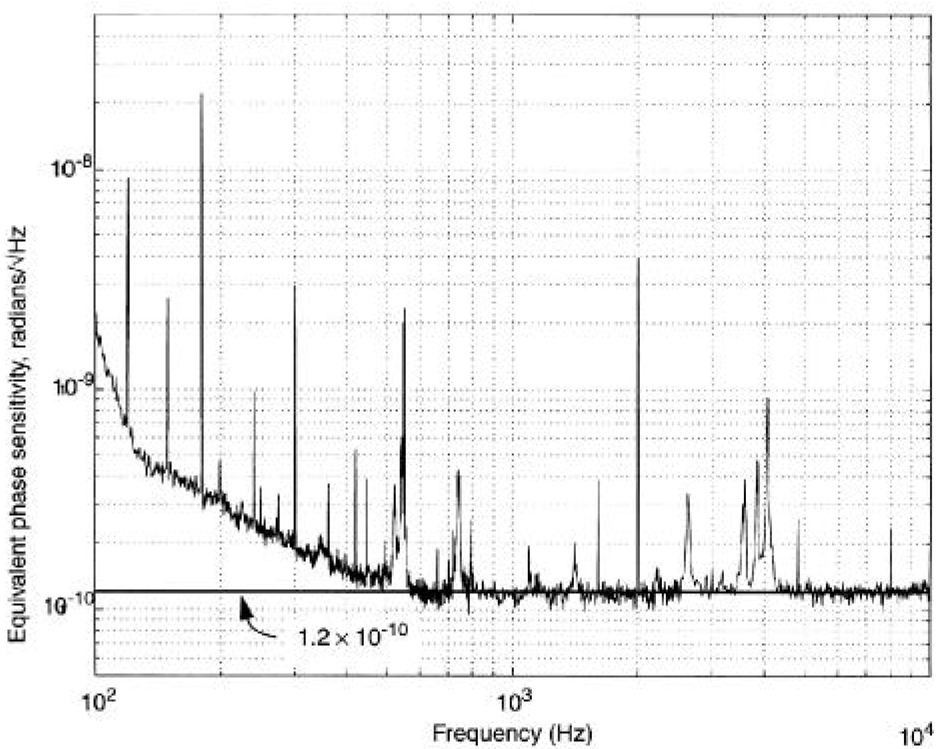
astrophysical sources

Sensitivity of LIGO to coalescing binaries



Phase Noise

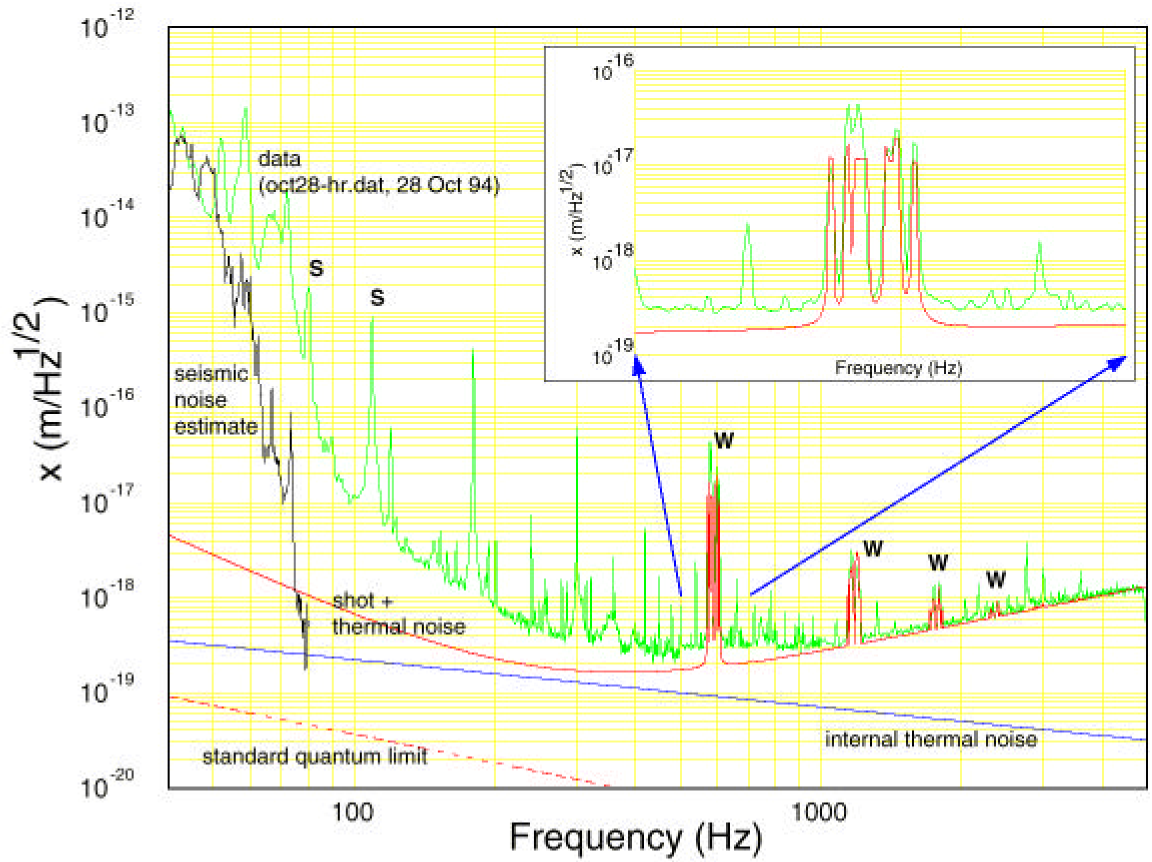
splitting the fringe



- spectral sensitivity of MIT phase noise interferometer
- above 500 Hz shot noise limited near LIGO I goal
- additional features are from 60 Hz powerline harmonics, wire resonances (600 Hz), mount resonances, etc

Noise Floor

40 m prototype



- displacement sensitivity in 40 m prototype.
- comparison to predicted contributions from various noise sources

Detection Strategy

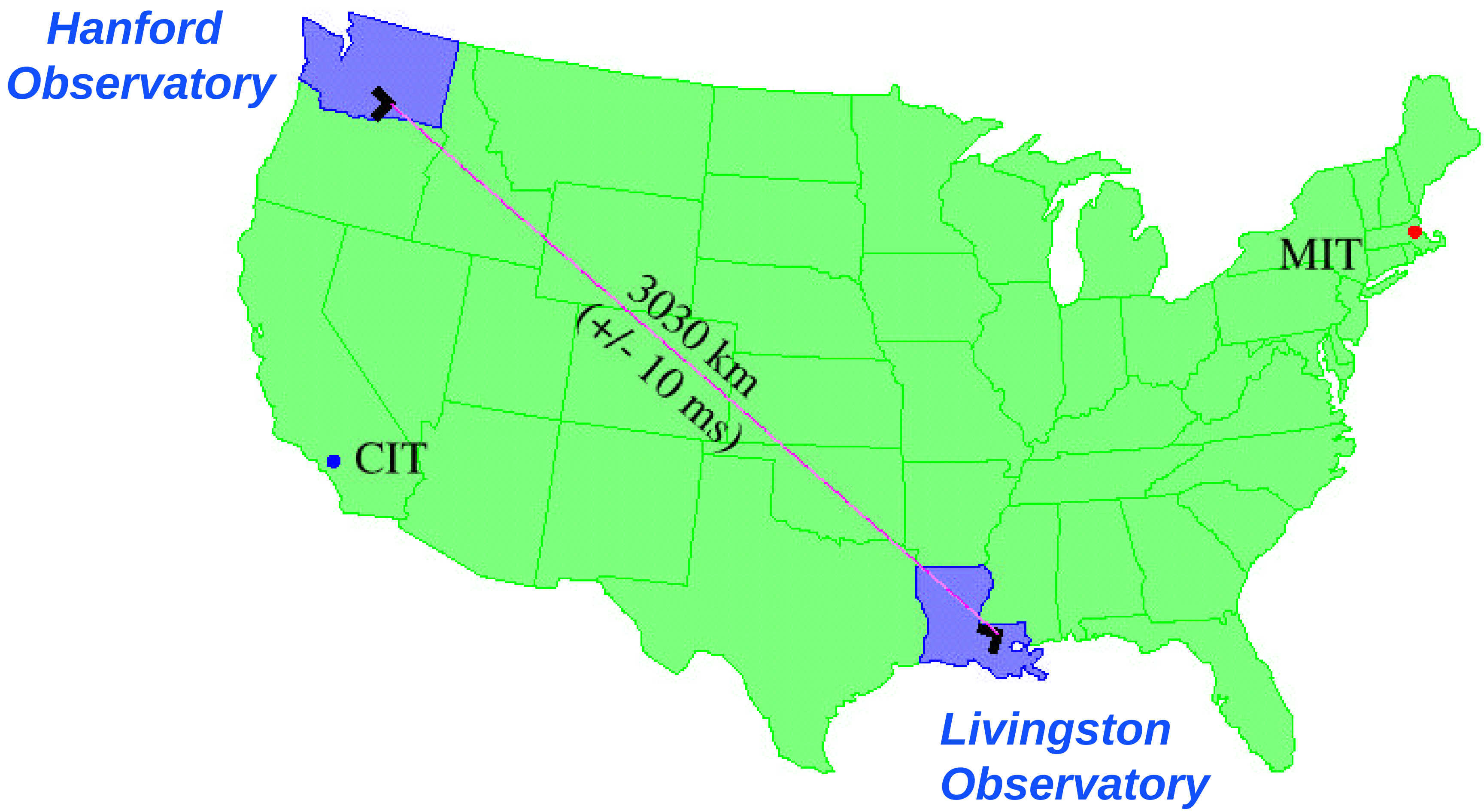
Coincidences

Two Sites - Three Interferometers

» Single Interferometer	non-gaussian level ~50/hr	
» Hanford (Doubles)	correlated rate (x1000)	~1/day
» Hanford + Livingston	uncorrelated (x5000)	<0.1/yr

- **Data Recording (time series)**
  - » gravitational wave signal (0.2 MB/sec)
  - » total data (16 MB/s)
  - » on-line filters, diagnostics, data compression
  - » off line data analysis, archive etc
- **Signal Extraction**
  - » signal from noise (vetoes, noise analysis)
  - » templates, wavelets, etc

LIGO Sites



Hanford Observatory
3030 km
(+/- 10 ms)
CIT
MIT
Livingston Observatory

Interferometer Data

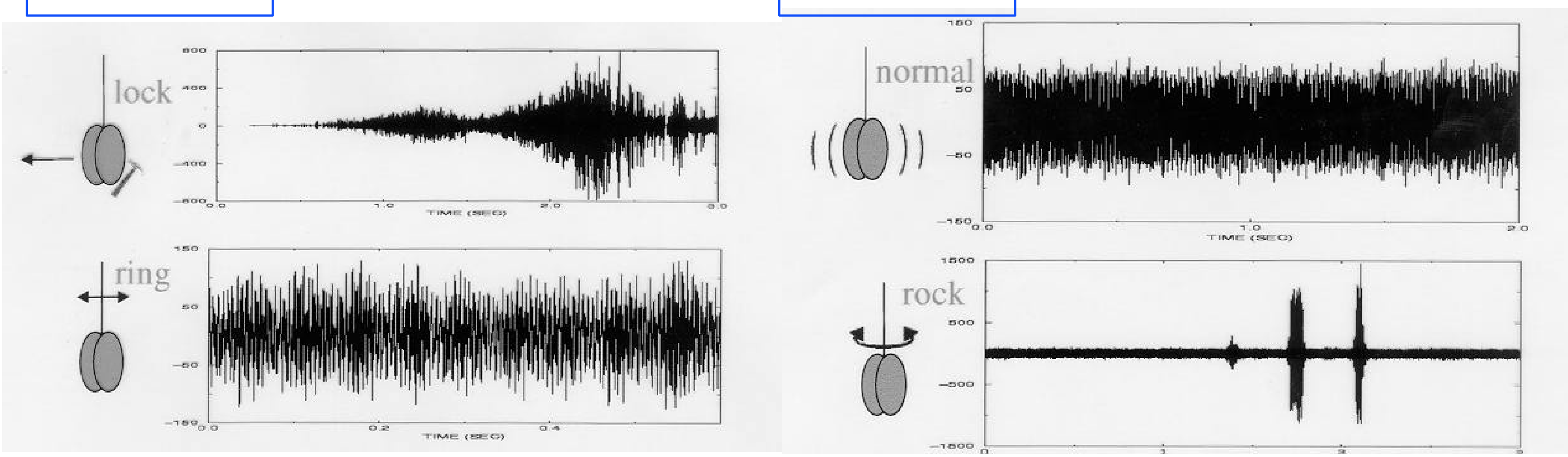
40 m

Real interferometer data is UGLY!!!

(Gliches - known and unknown)

LOCKING

NORMAL

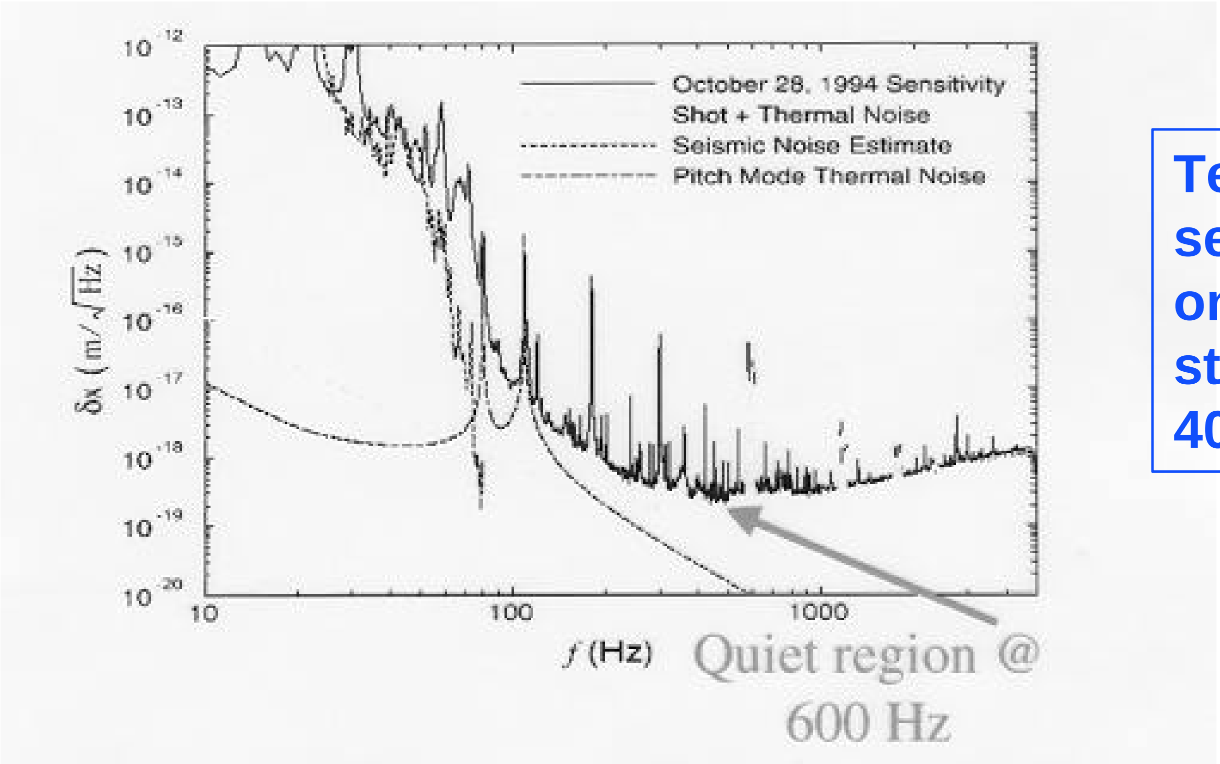


RINGING

ROCKING

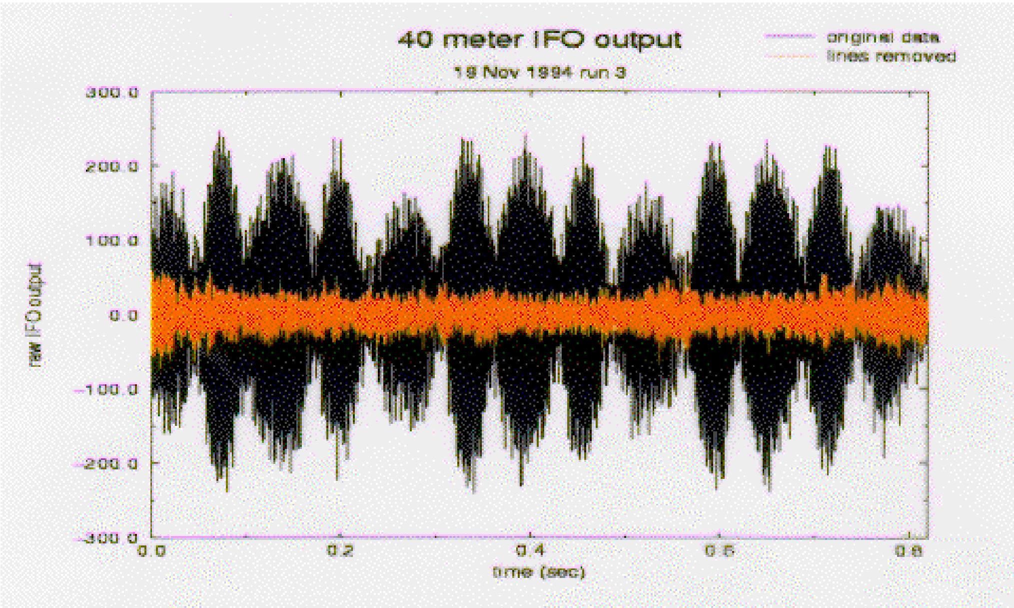
The Problem

How much does real data degrade complicate the data analysis and degrade the sensitivity ??

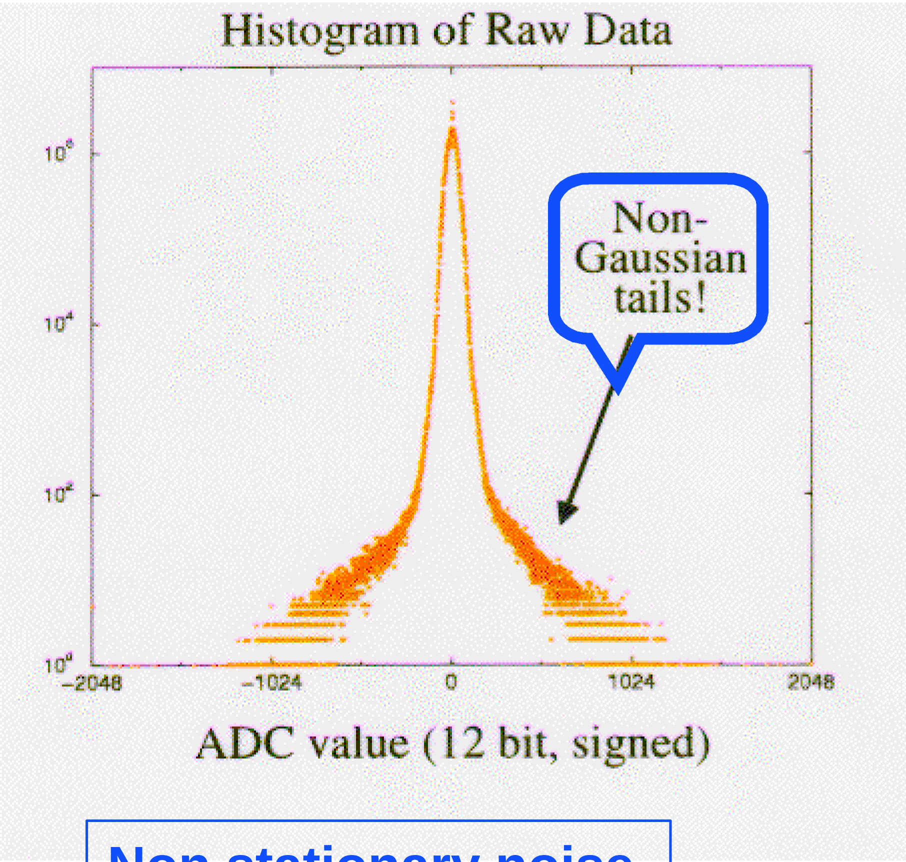


Test with real data by setting an upper limit on galactic neutron star inspiral rate using 40 m data

"Clean up" data stream



Effect of removing sinusoidal artifacts using multi-taper methods



Non stationary noise
Non gaussian tails

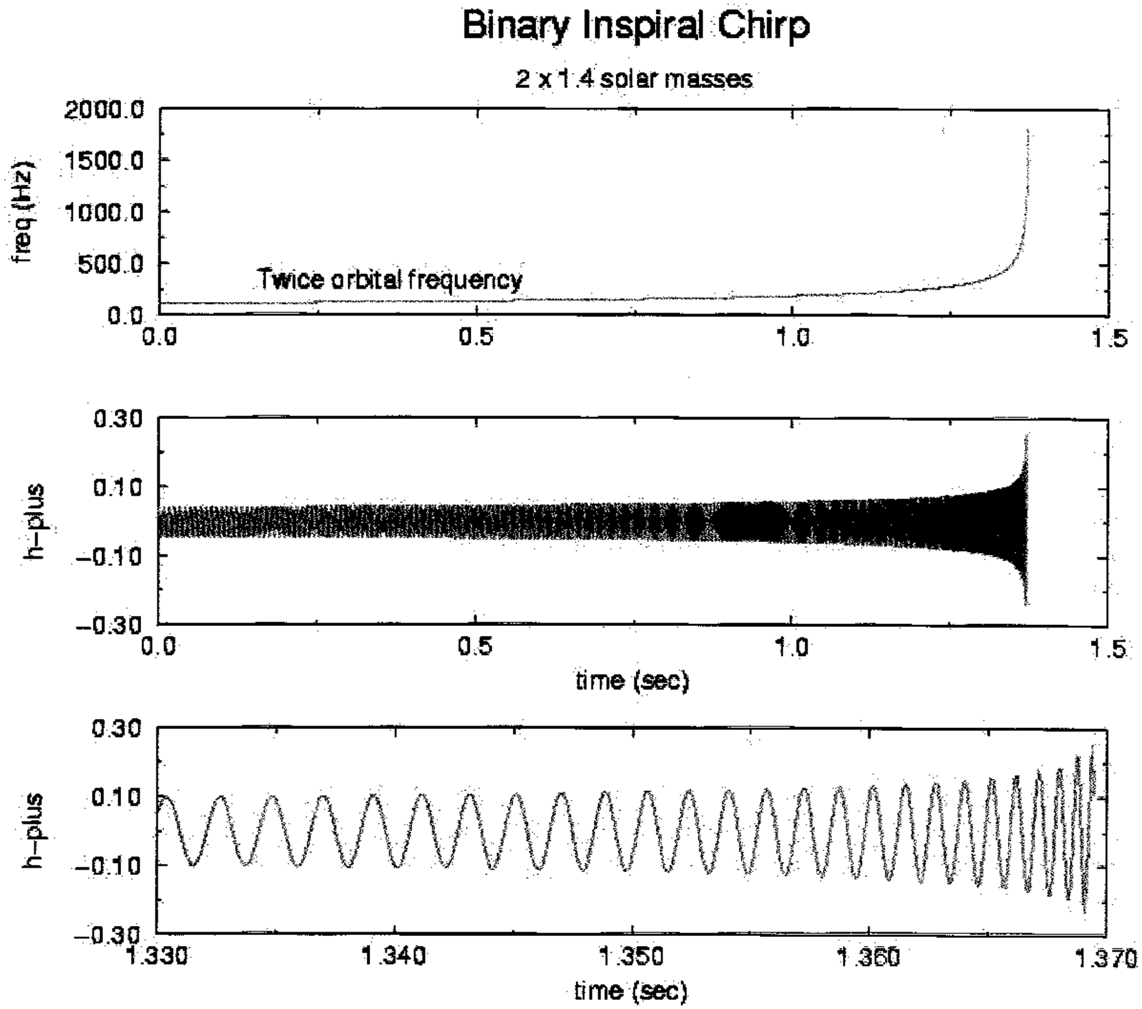
Inspiral 'Chirp' Signal

Template Waveforms

"matched filtering"
687 filters

44.8 hrs of data
39.9 hrs arms locked
25.0 hrs good data

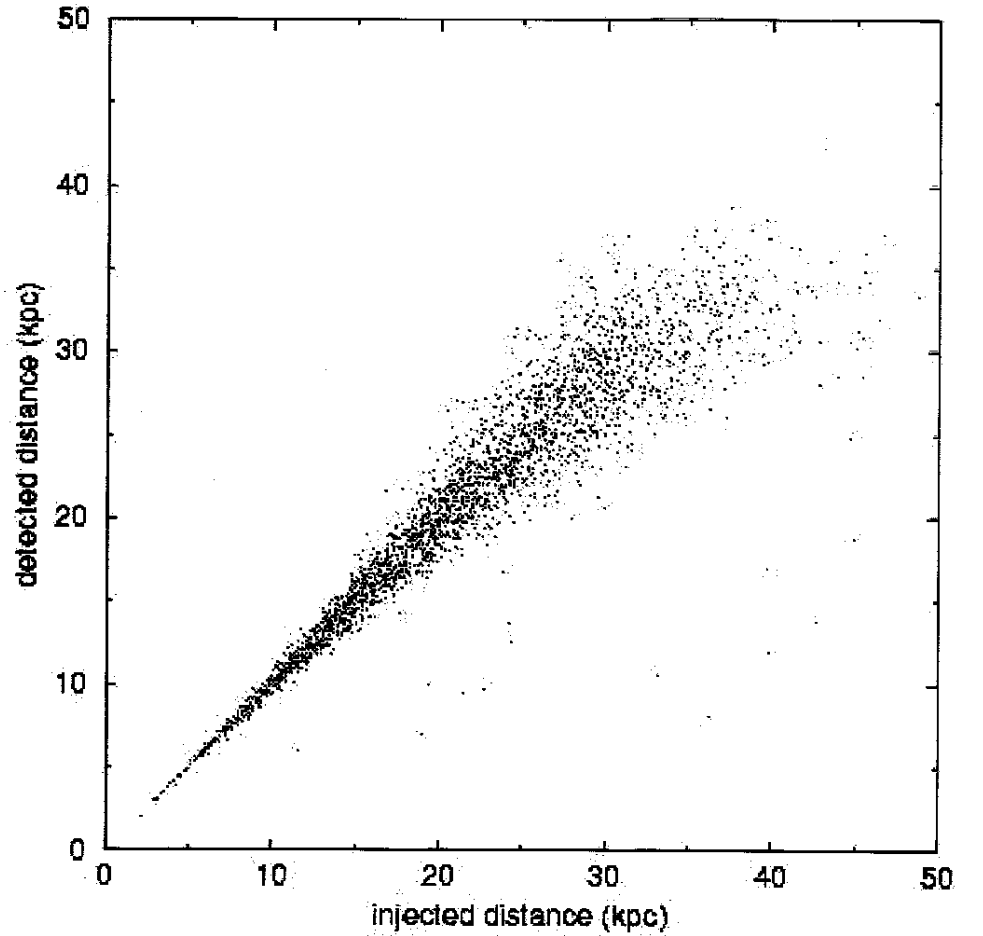
sensitivity to our galaxy
h **~ 3.5 10^{-19} $mHz^{-1/2}$**
expected rate ~10^{-6}/yr



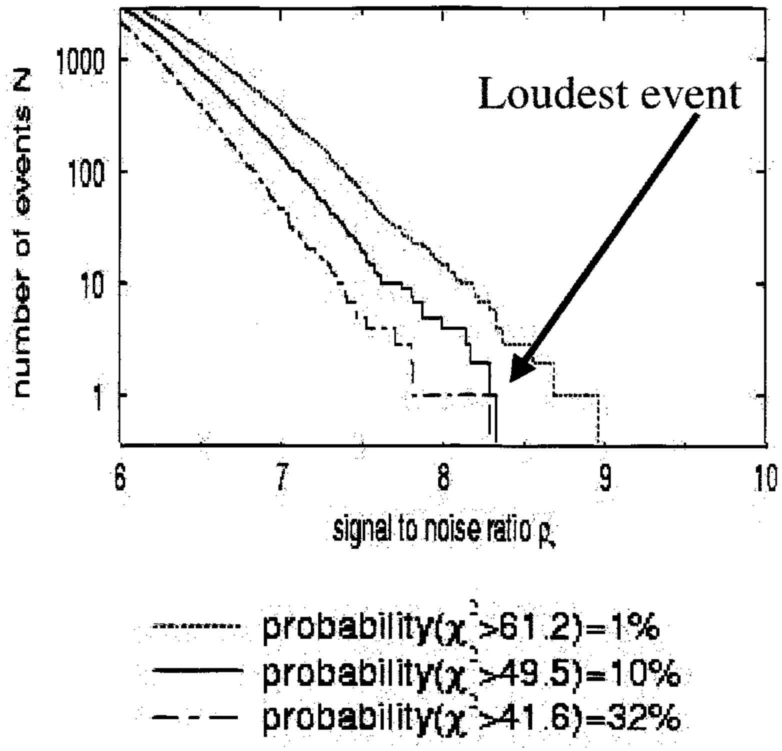
Detection Efficiency

- Simulated inspiral events provide end to end test of analysis and simulation code for reconstruction efficiency

- Errors in distance measurements from presence of noise are consistent with SNR fluctuations



Setting a limit



Upper limit on event rate can be determined from SNR of 'loudest' event

Limit on rate:

R < 0.5/hour with 90% CL

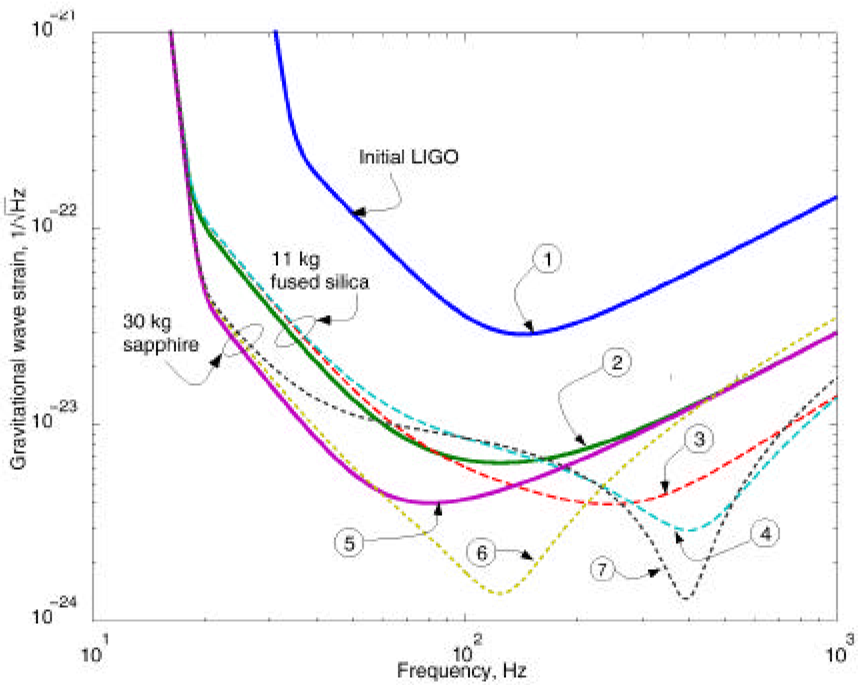
ε = 0.33 = detection efficiency

An ideal detector would set a limit:

R < 0.16/hour

LIGO II

incremental improvements

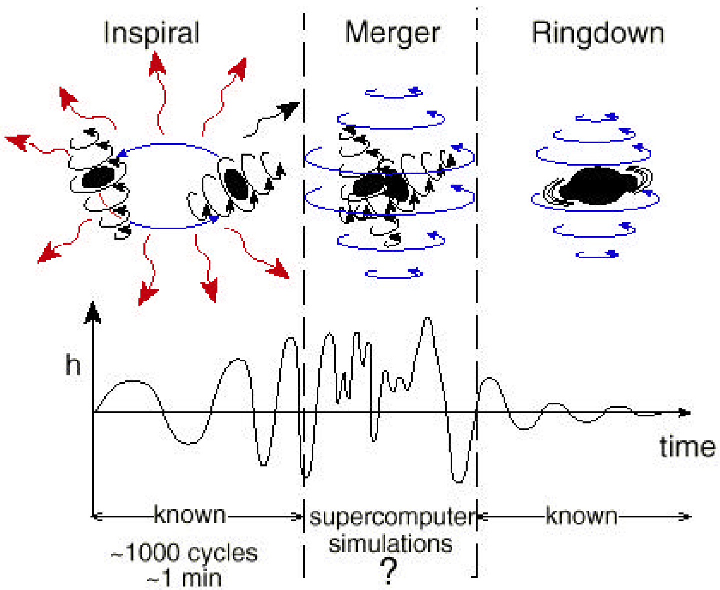


Parameter	Curve 1	Curve 2	Curve 3, 4	Curve 5, 6, 7
Parameter	Initial LIGO I value	Double suspension, 100 W laser, thermal de-lensing	Signal tuned configuration	Alternative test mass material
Input power to recycling mirror	6w	62w	140w	
Mirror loss (transmission+scatter)	50 ppm	20 ppm		
Effective power recycling	30	93		
Substrate absorption	5ppm/cm	0.4 ppm/cm		17 ppm/ cm
Thermal lensing correction	(none)	factor 10		
Suspension fiber	steel wire, $Q = 1.6\times10^5$	fused silica $Q = 3 \times 10^7$		
Test mass	fused silica, 10.8 kg, $Q = 1\times10^6$	fused silica, 10.8 kg, $Q = 3\times10^7$		sapphire, 30 kg, $Q = 2\times10^8$
Signal recycling mirror transmission	(none)		T=0.6 (curve 3) T=0.15 (curve 4)	Curve 5: none T=0.3 (curve 6) T=0.09 (curve 7)
Tuning phase			0.7 rad (curve 3) 0.45 rad (curve 4)	1.3 rad (curve 6) 0.45 rad (curve 7)

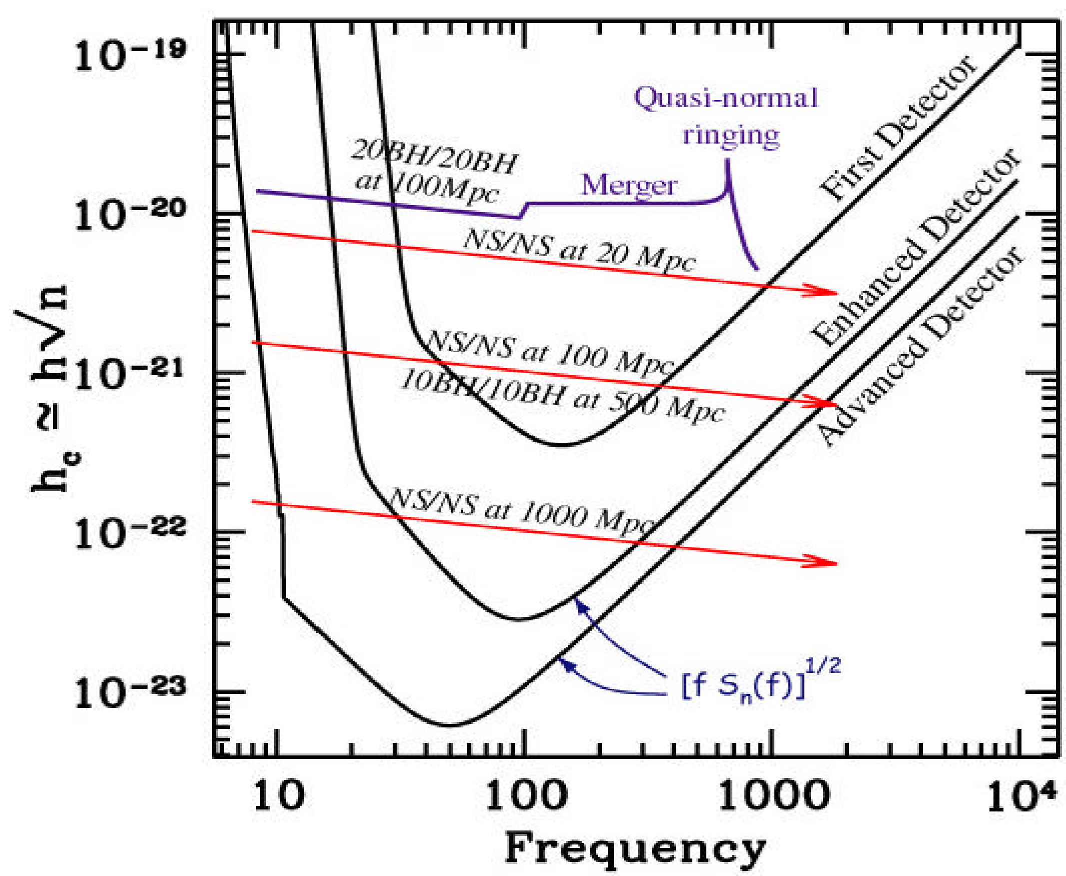
LIGO

astrophysical sources

Compact binary mergers

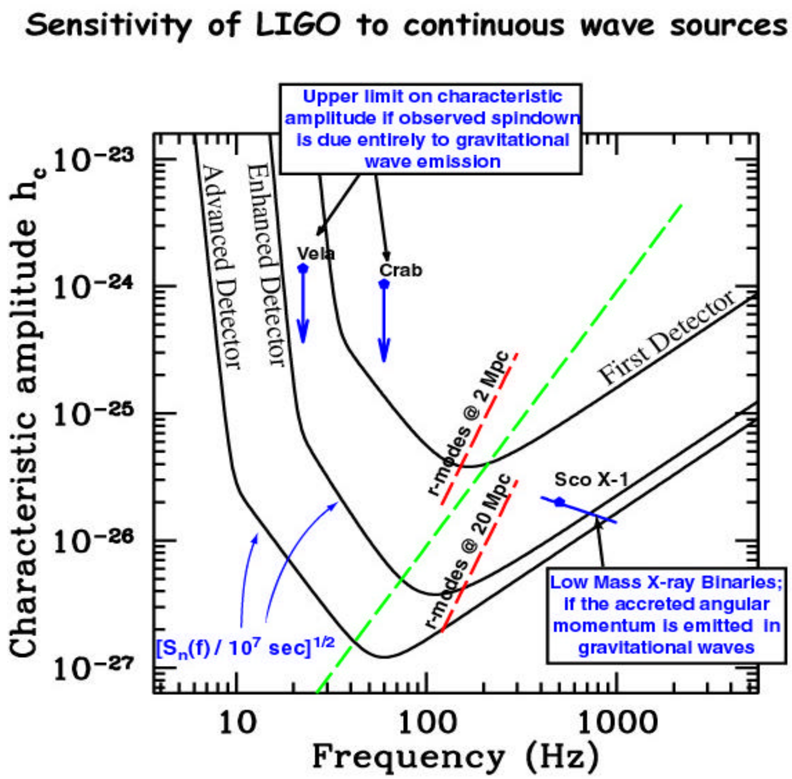


Sensitivity of LIGO to coalescing binaries

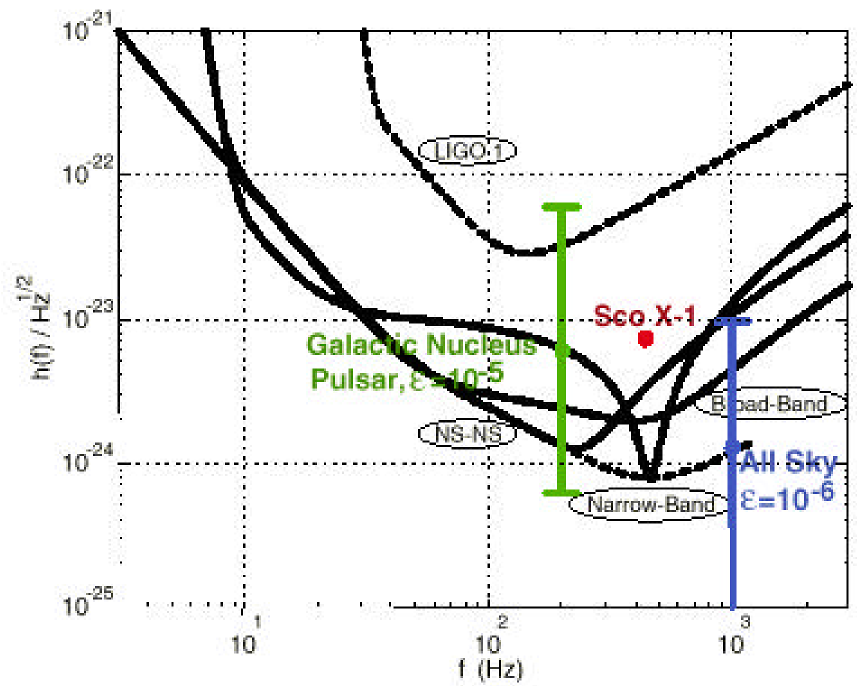


LIGO

astrophysical sources



- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: neutron star precession; interiors
  - »narrow band searches best



Conclusions

- LIGO I construction complete
- LIGO I commissioning and testing ‘on track’
- Interferometer characterization underway
- Data analysis schemes are being developed, including tests with 40 m data
- First Science Run will begin in 2002
- Significant improvements in sensitivity anticipated to begin about 2006