The Ninth Marcel Grossmann Meeting

University of Rome "La Sapienza"

Rome, July 2 - 8, 2000

Gravitational Waves
Laser Interferometric Detectors

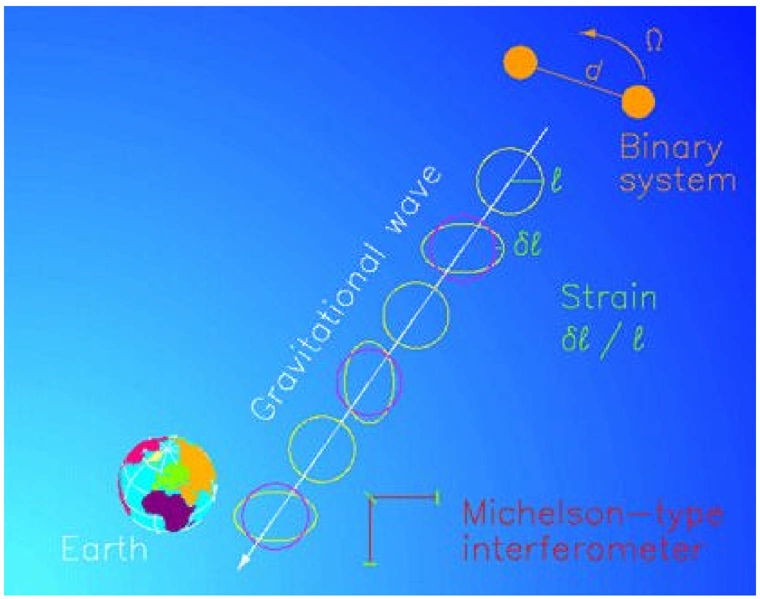
Barry Barish

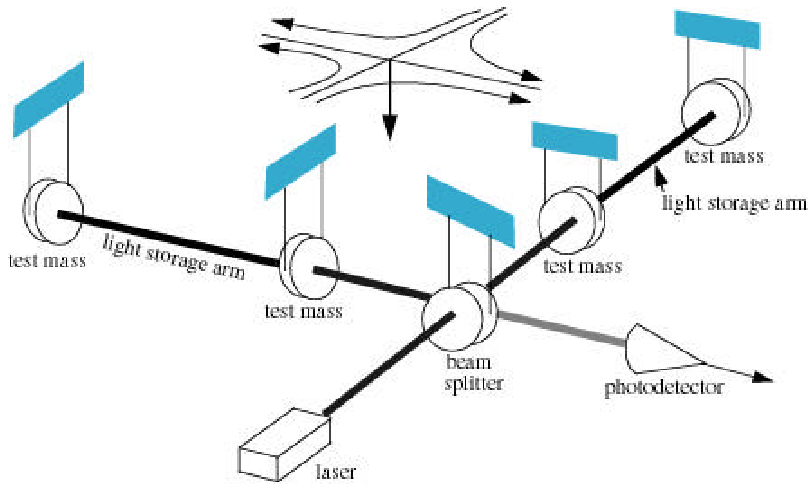
5 July 2000

Interferometers
terrestrial

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

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



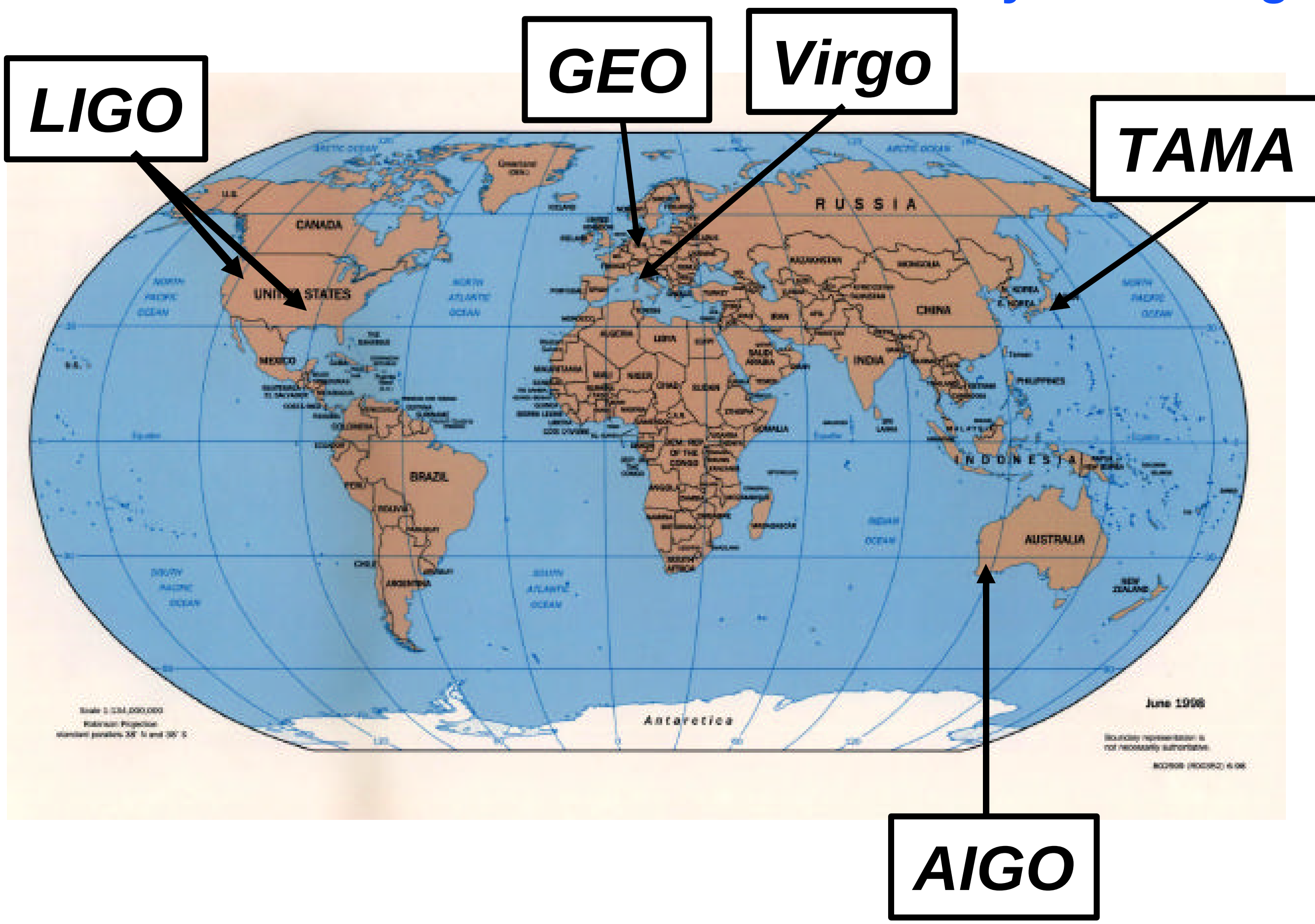


Suspended test masses

Interferomers

international network

Simultaneously detect signal (within msec)



detection confidence

locate the sources

decompose the polarization of gravitational waves

Interferometers
international network

LIGO (Washington)

LIGO (Louisiana)

Interferometers
international network

GEO 600 (Germany)

Virgo (Italy)

Interferometers

international network

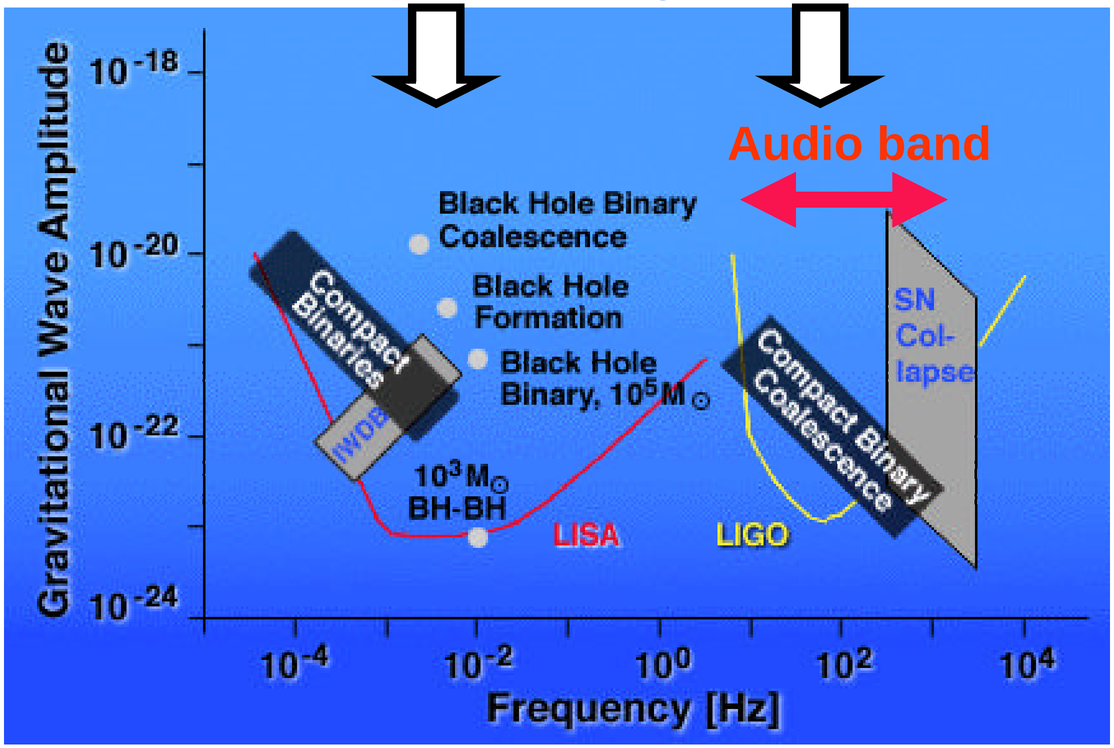
TAMA 300 (Japan)

AIGO (Australia)

Astrophysics Sources
frequency range

- **EM waves are studied over ~20 orders of magnitude**
  - » **(ULF radio –> HE γ rays)**
- **Gravitational Waves over ~8 orders of magnitude**
  - » **(terrestrial + space)**

space groundbased

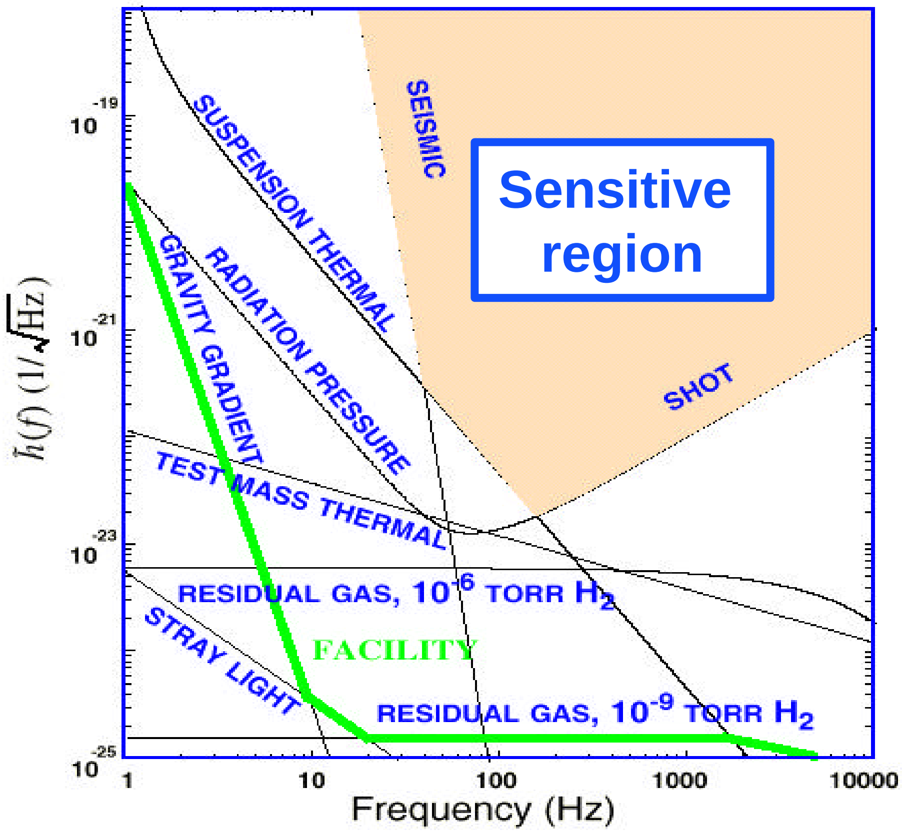


Interferometers

the noise floor

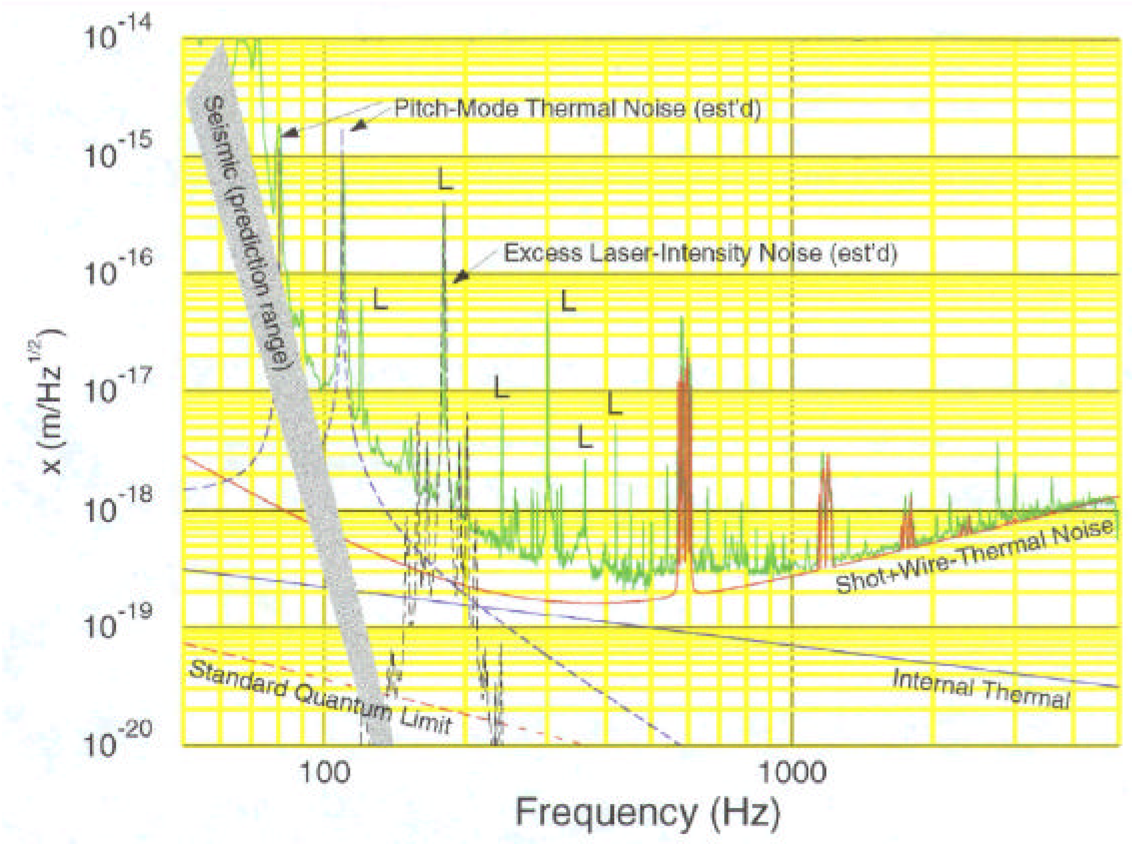
- Interferometry is limited by three fundamental noise sources
  - <u>seismic noise</u> at the lowest frequencies
  - <u>thermal noise</u> at intermediate frequencies
  - <u>shot noise</u> at high frequencies

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



Noise Floor

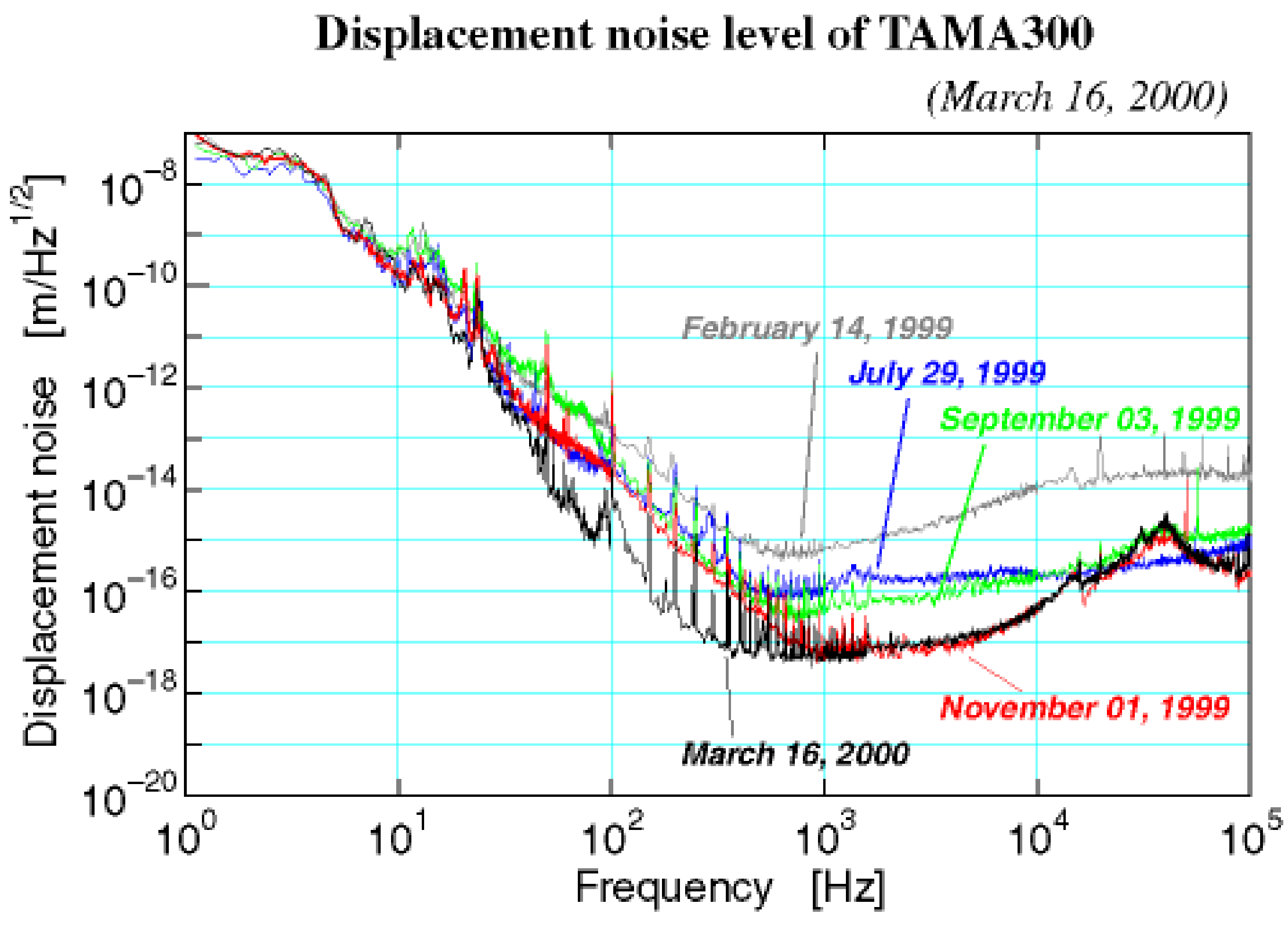
40 m prototype



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

Noise Floor

TAMA 300



Vacuum Systems

beam tube enclosures

Virgo
preparing arms

LIGO
minimal enclosures
no services

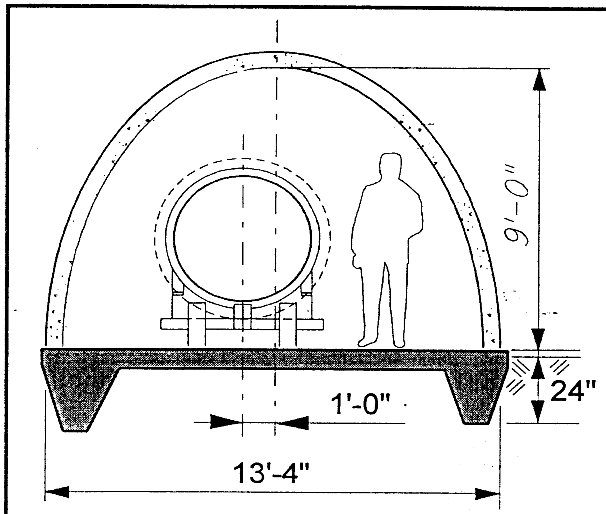


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

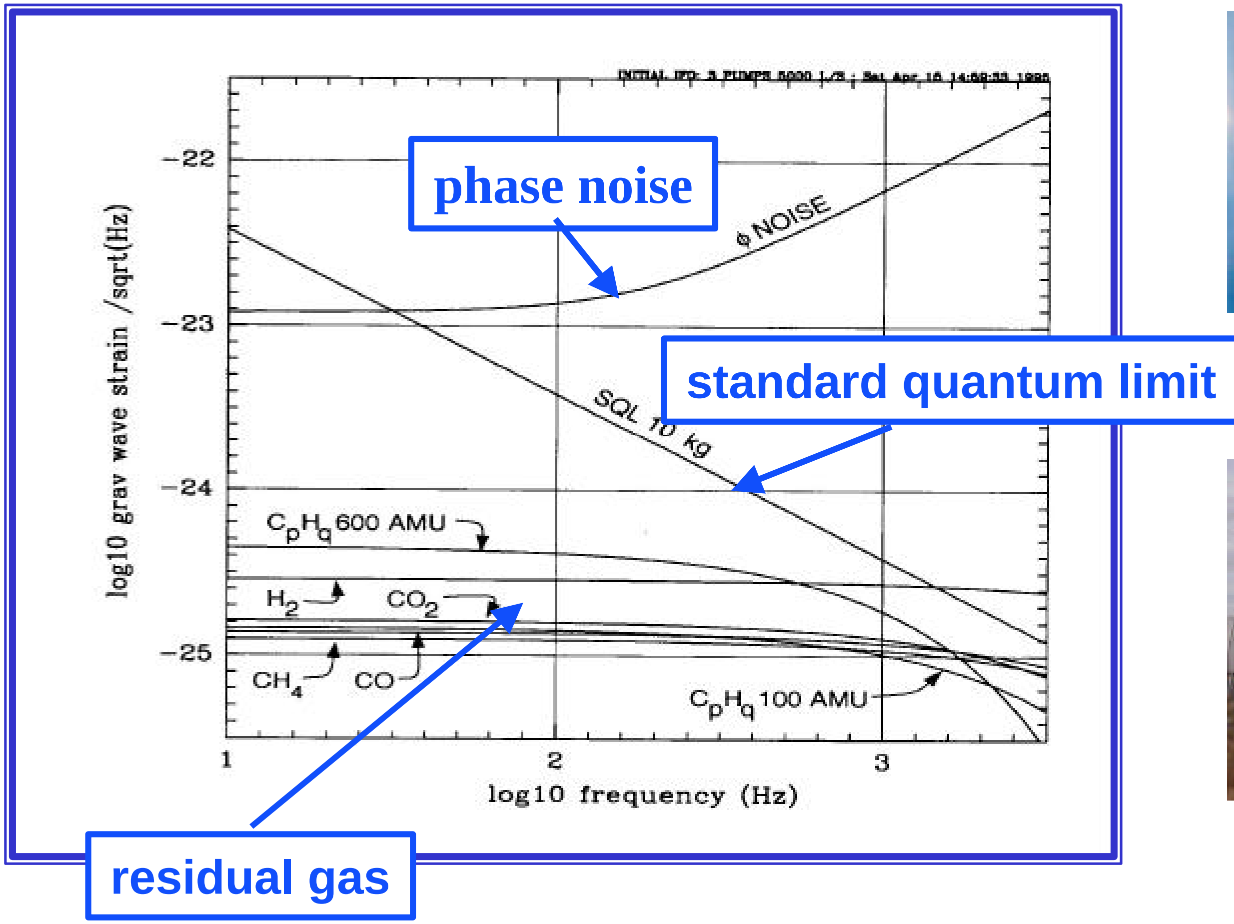
GEO
tube in the trench

Beam Tubes

TAMA 300 m beam pipe

LIGO 4 km beam tube (1998)

Beam Tube Bakeout

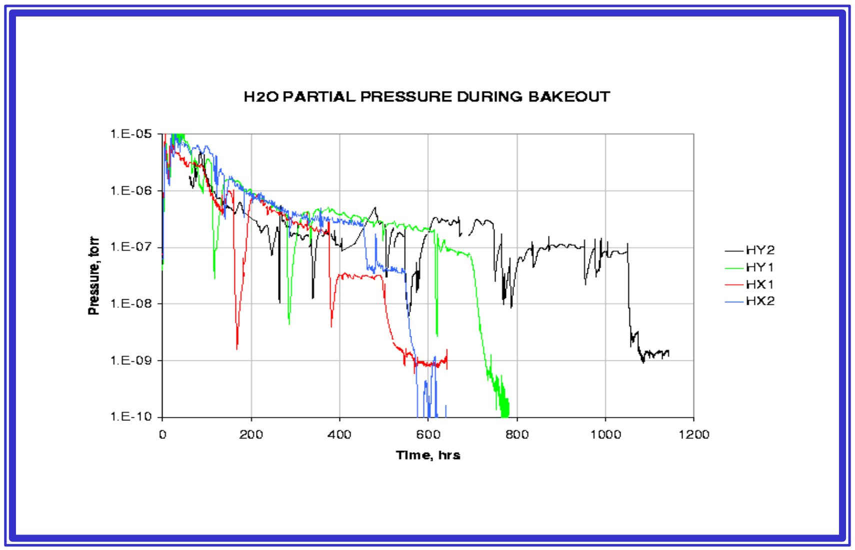


LIGO bakeout

Bakeout

LIGO performance

partial pressures during bakeout



Beam Tube Bakeout Results [a]

NOTE: All results except for H_2 are upper limits

		Hanford				Livingston	
Species	**Goal [b]**	**HY2**	**HY1**	**HX1**	**HX2**	**LX2**	
H_2	*4.7*	4.8	6.3	5.2	4.6	4.3	x 10^{-14} torr liters/sec/cm^2
CH_4	*48000*	< 900	< 220	< 8.8	< 95	< 40	x 10^{-20} torr liters/sec/cm^2
H_2O	*1500*	< 4	< 20	< 1.8	< 0.8	< 10	x 10^{-18} torr liters/sec/cm^2
CO	*650*	< 14	< 9	< 5.7	< 2	< 5	x 10^{-18} torr liters/sec/cm^2
CO_2	*2200*	< 40	< 18	< 2.9	< 8.5	< 8	x 10^{-19} torr liters/sec/cm^2
NO+C_2H_6	*7000*	< 2	< 14	< 6.6	< 1.0	< 1.1	x 10^{-19} torr liters/sec/cm^2
$H_nC_pO_q$	*50-2* [c]	< 15	< 8.5	< 5.3	< 0.4	< 4.3	x 10^{-19} torr liters/sec/cm^2
air leak	*1000*	< 20	< 10	< 3.5	< 16	< 7	x 10^{-11} torr liter/sec

[a] Outgassing results correct to 23 C

[b] Goal: maximum outgassing to achieve pressure equivalent to 10^{-9} torr H_2 using only pumps at stations

[c] Goal for hydrocarbons depends on weight of parent molecule; range given corresponds with 100-300 AMU

Achieved Design Requirements
(< 10^{-9} torr)

Vacuum Chambers

test masses, optics

LIGO chambers

TAMA chambers

Interferometers
the noise floor

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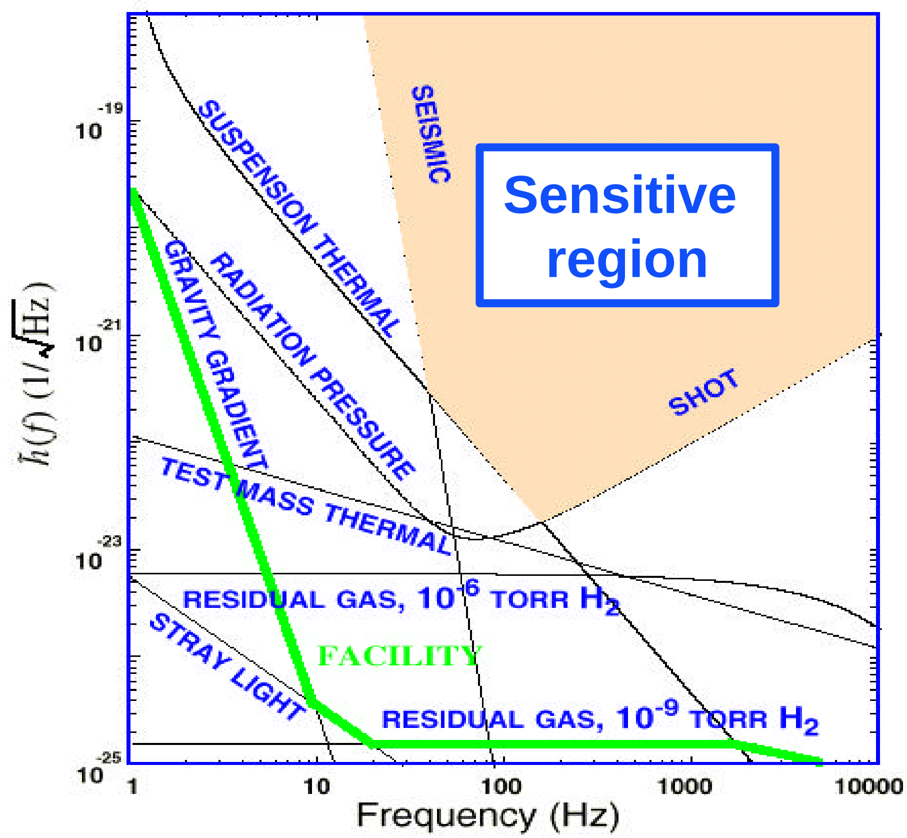
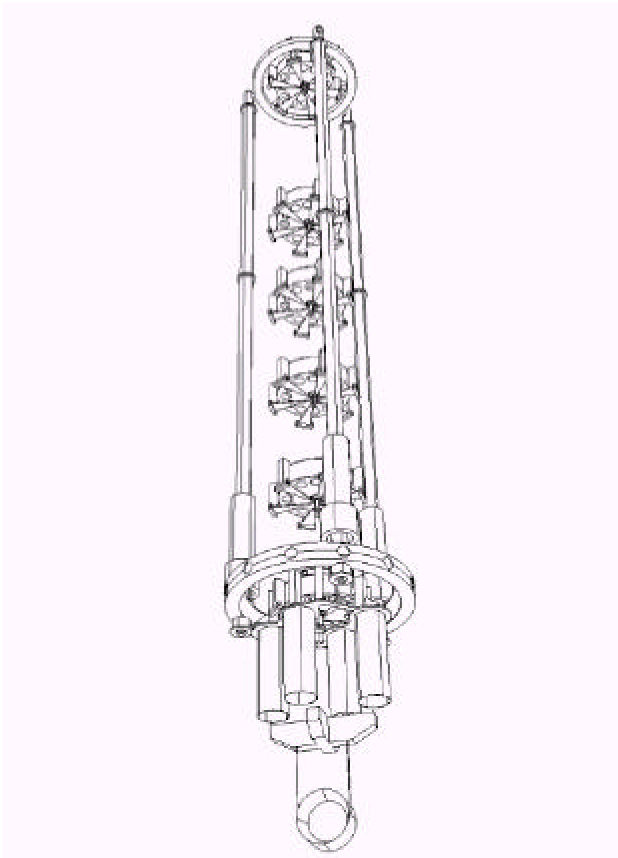
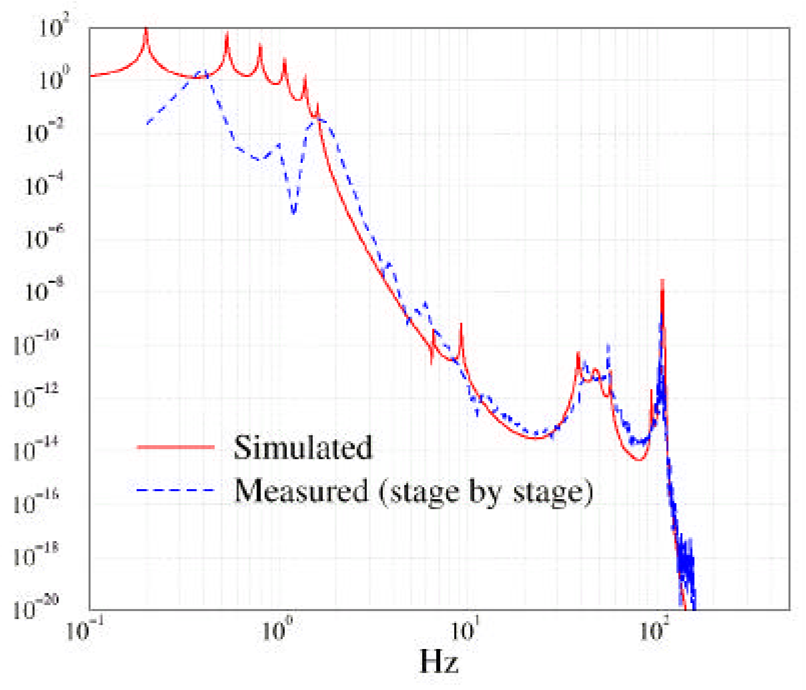


Seismic Isolation
Virgo

"Long Suspensions"
- **inverted pendulum**
- **five intermediate filters**





Suspension vertical transfer function measured and simulated (prototype)

Long Suspensions

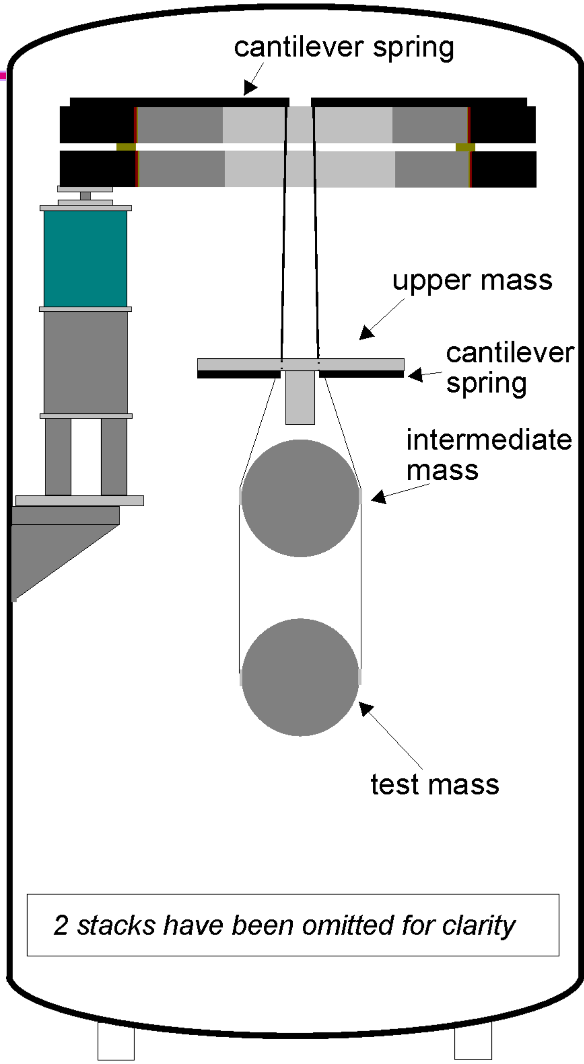
Virgo installation at the site

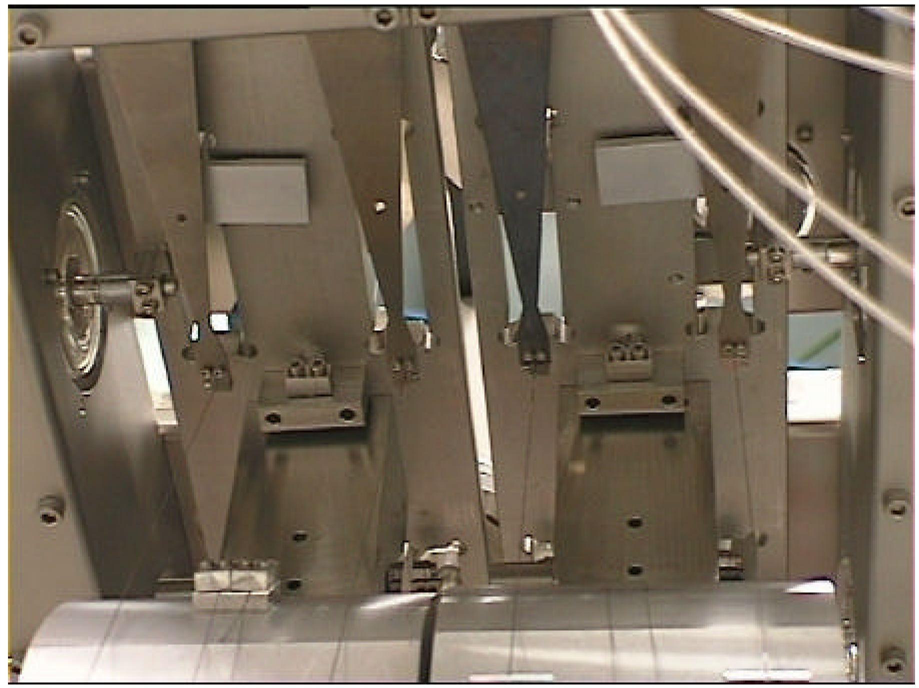
Beam Splitter and North Input mirror

All four long suspensions for the entire central interferometer will be complete by October 2000.

Suspensions

GEO triple suspension

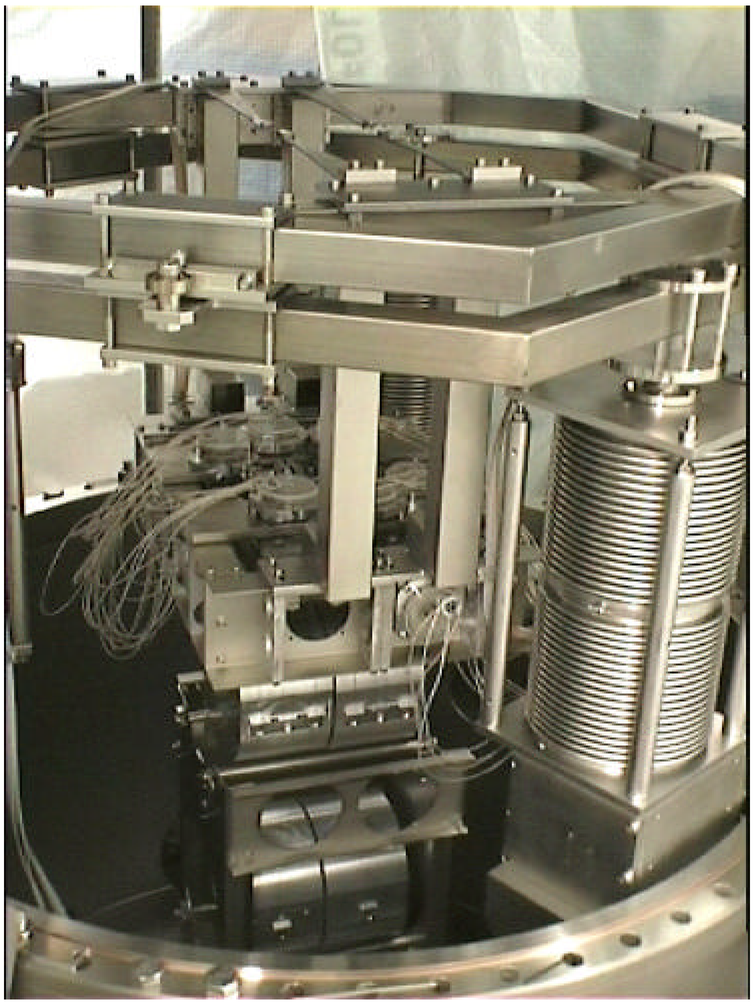


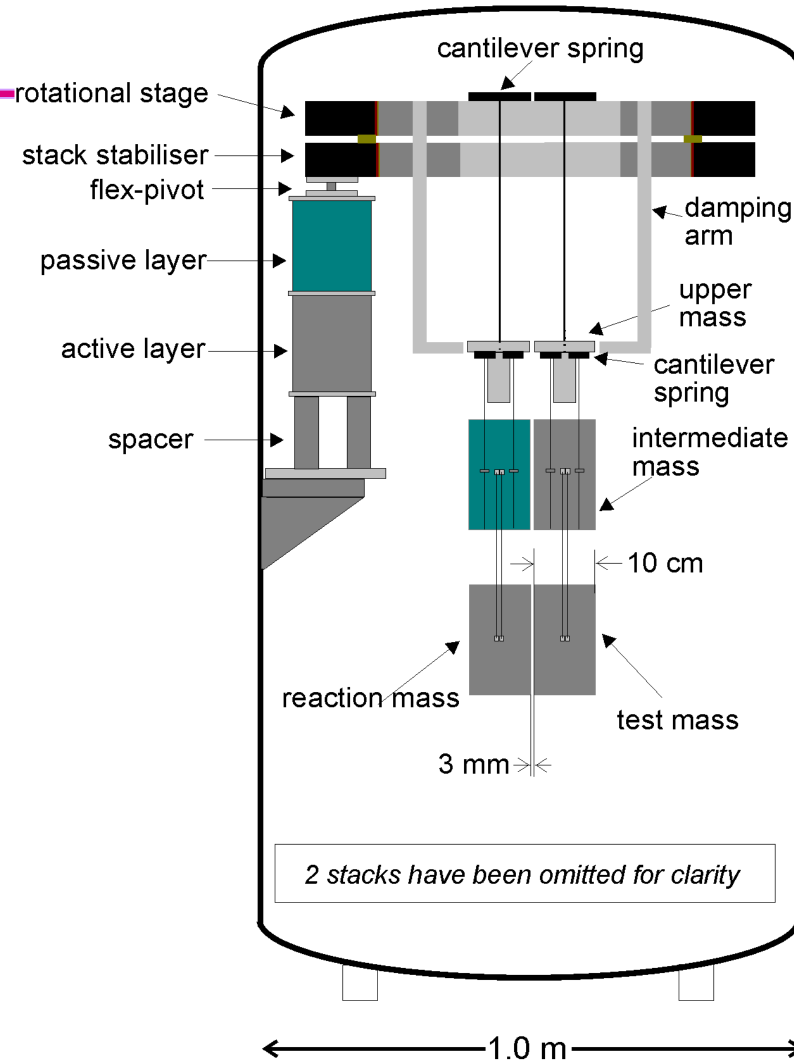


lower cantilever stage (view from below)

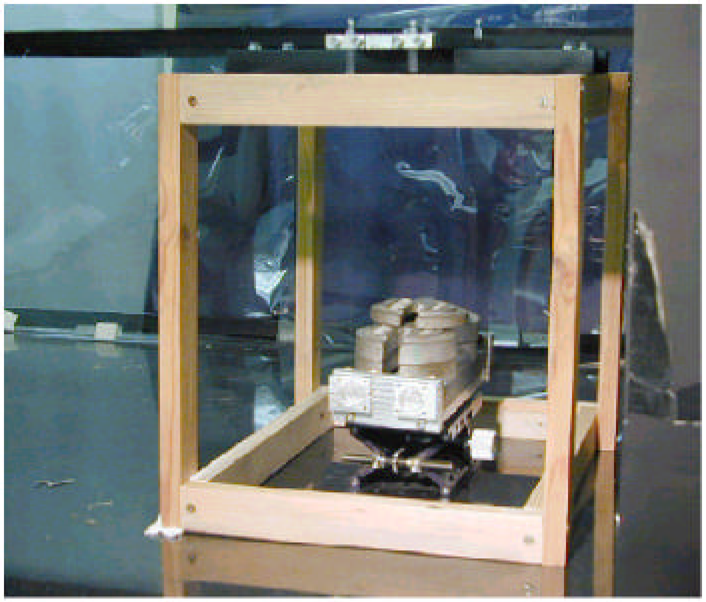
Suspensions

GEO triple pendulum

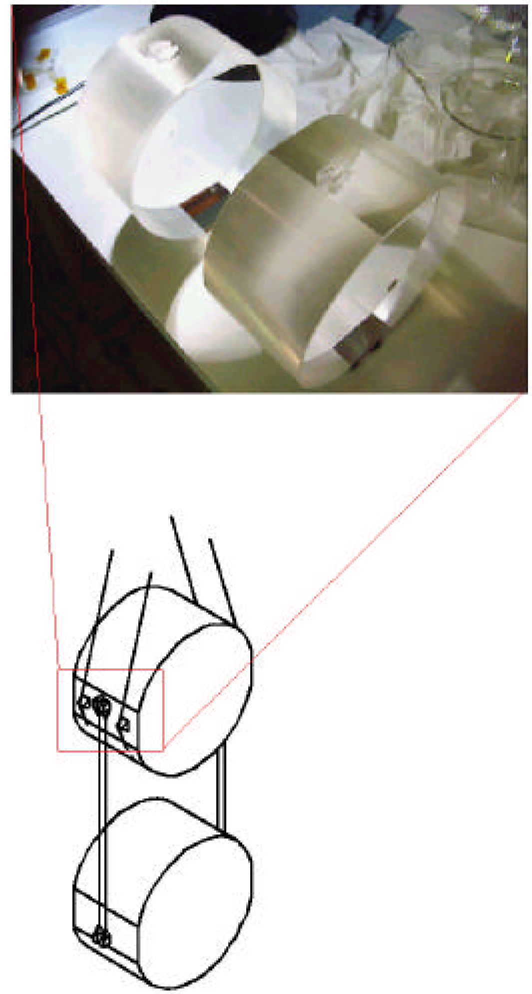




Test Masses
fibers and bonding - GEO

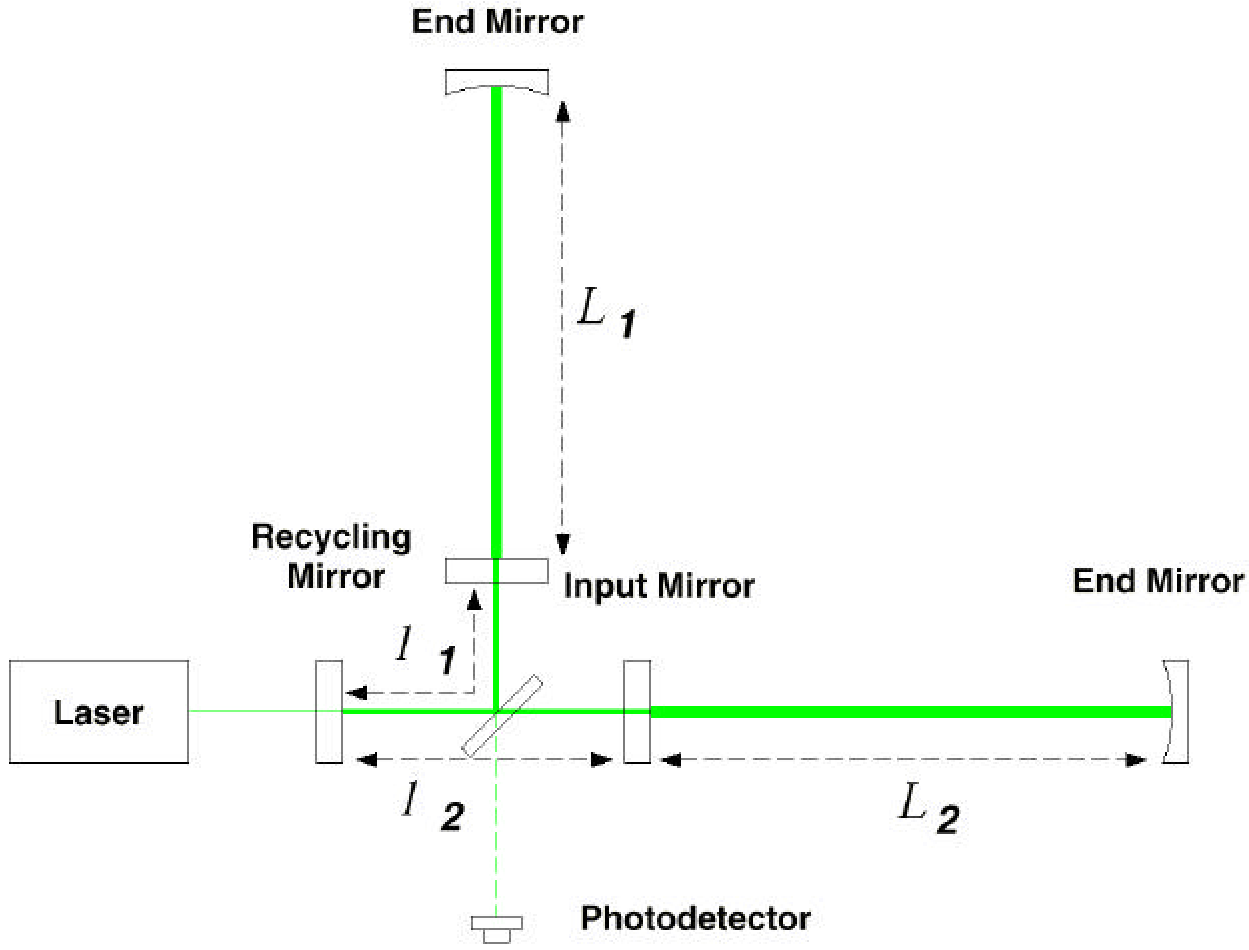


Since 2-11-99
10 kg are suspended
with 4 x 180 mm
welded fibres
in air



Interferometers

basic optical configuration

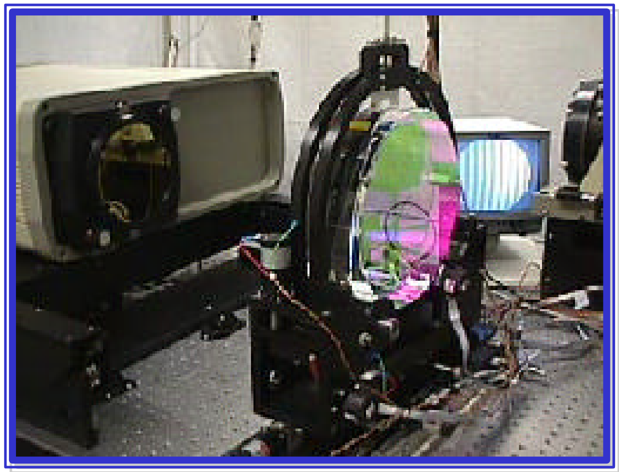


Optics

mirrors, coating and polishing

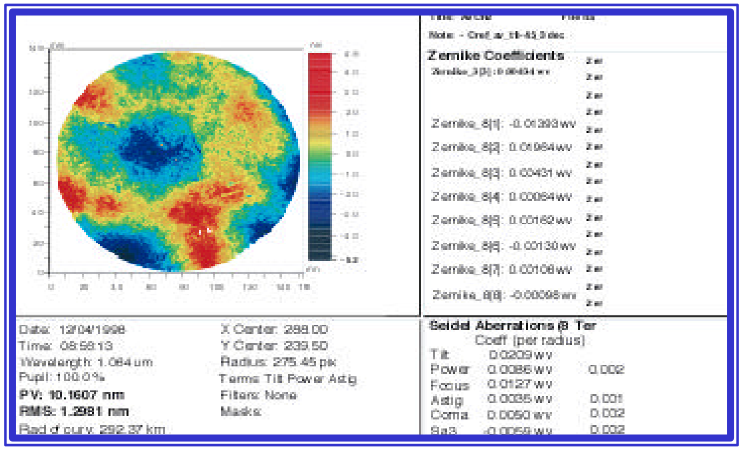
LIGO

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

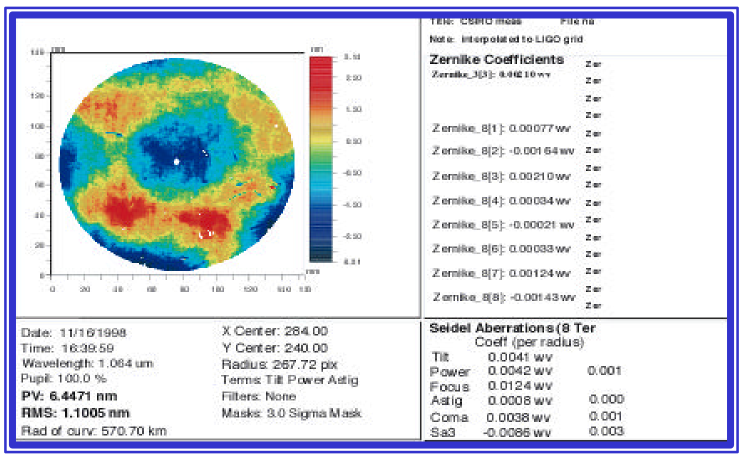


LIGO

metrology



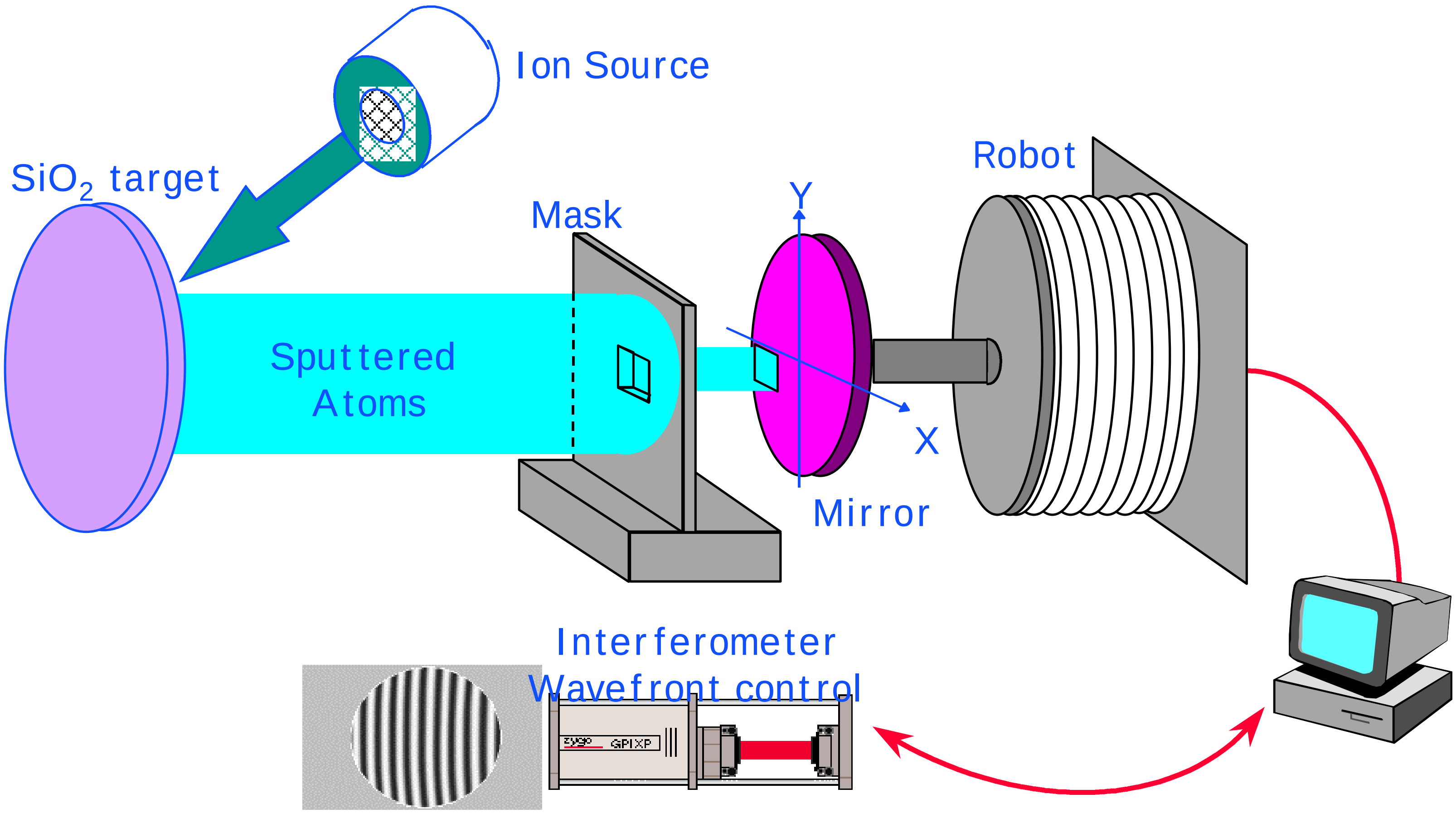
- **Caltech**



- **CSIRO**

Corrective Coating

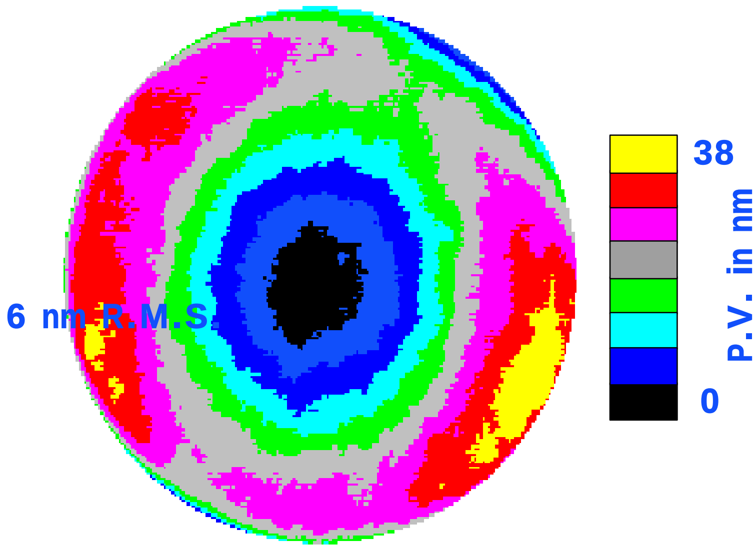
Virgo



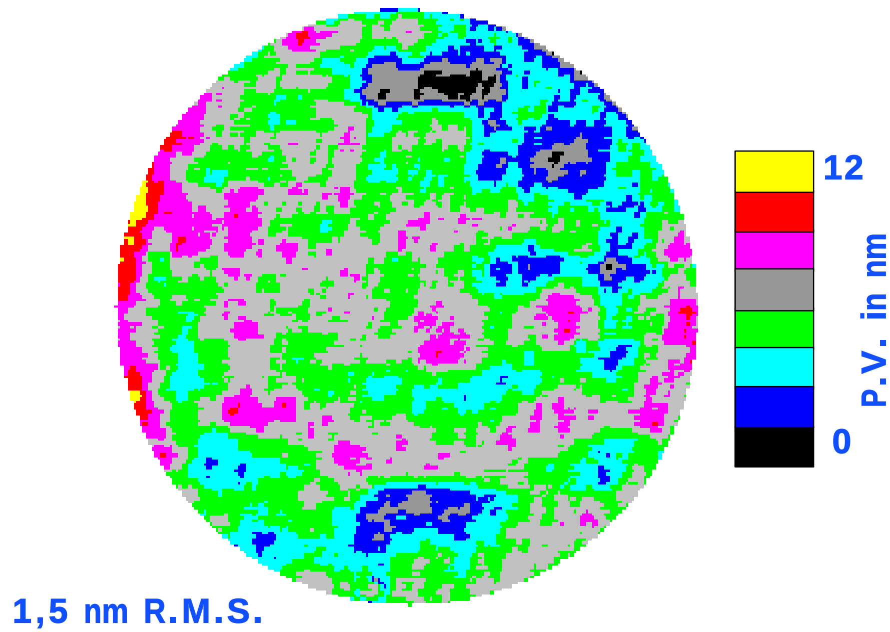
Corrective Coating
results

80 mm high reflectivity mirror @633 nm

Before



After



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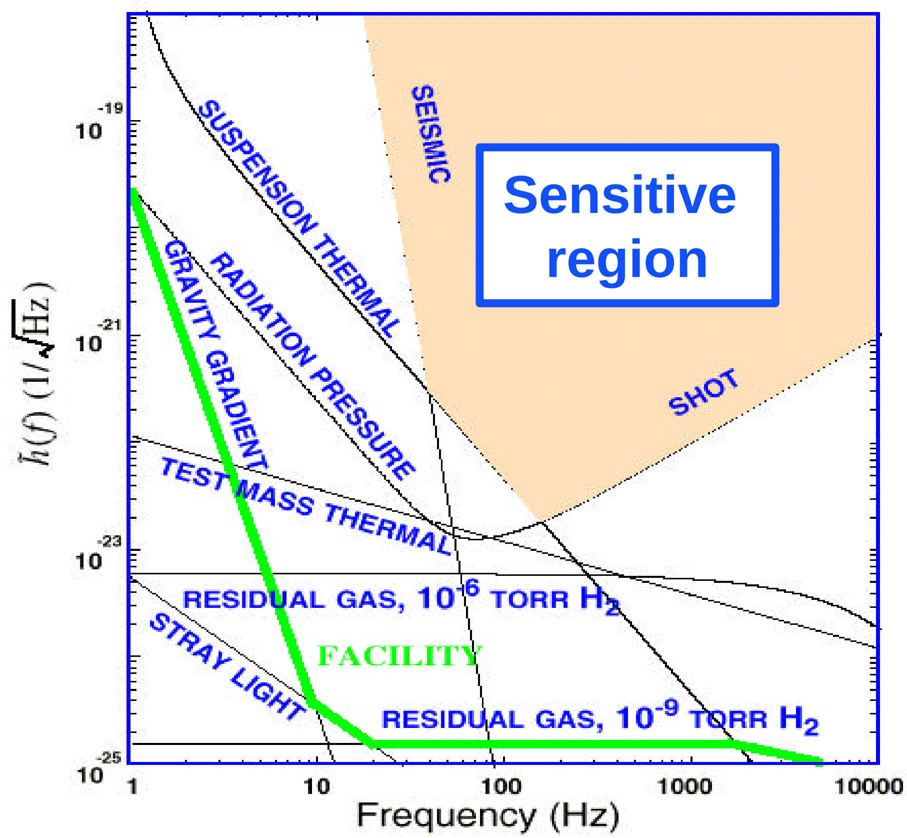
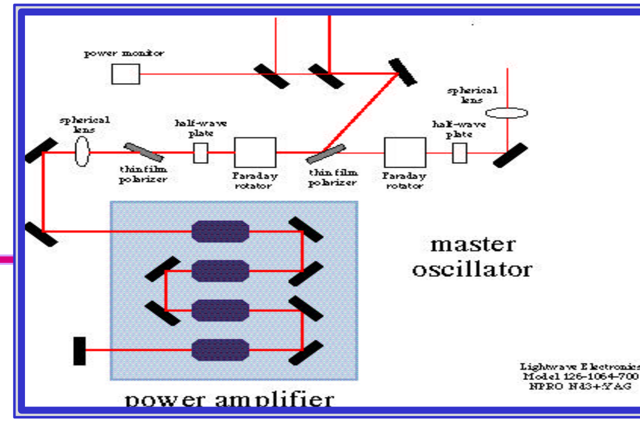


Interferometers

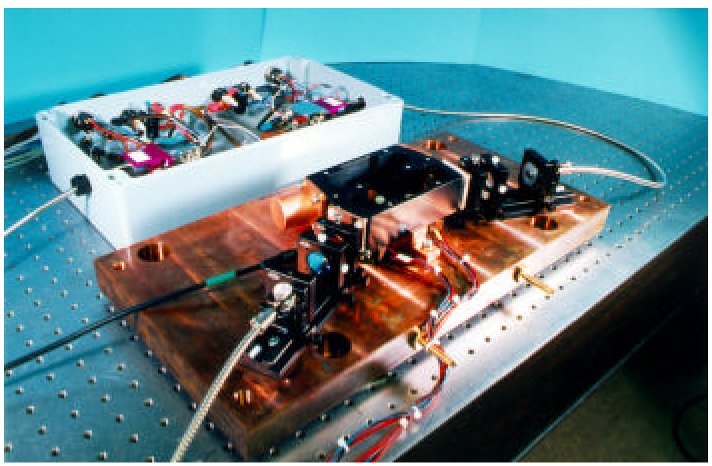
Lasers

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

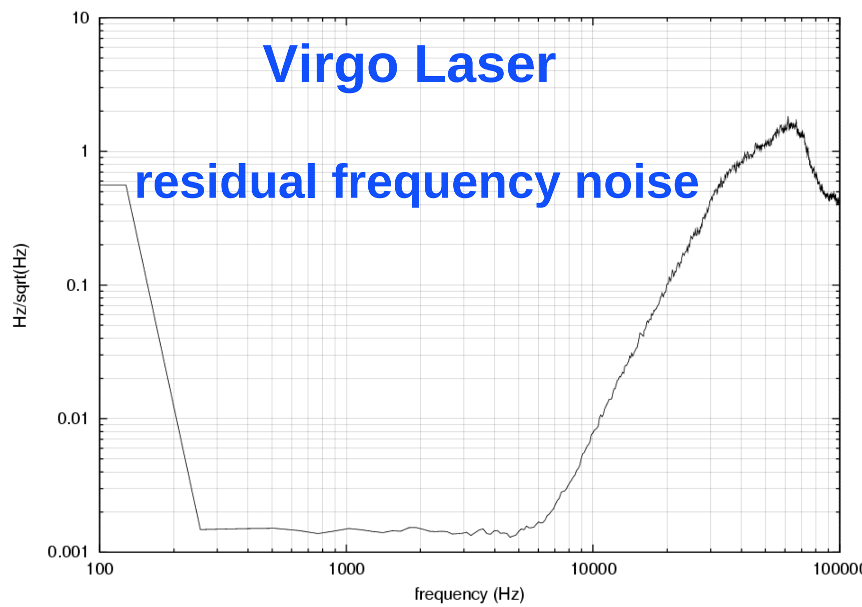


LIGO Laser
master oscillator power amplifier

GEO Laser

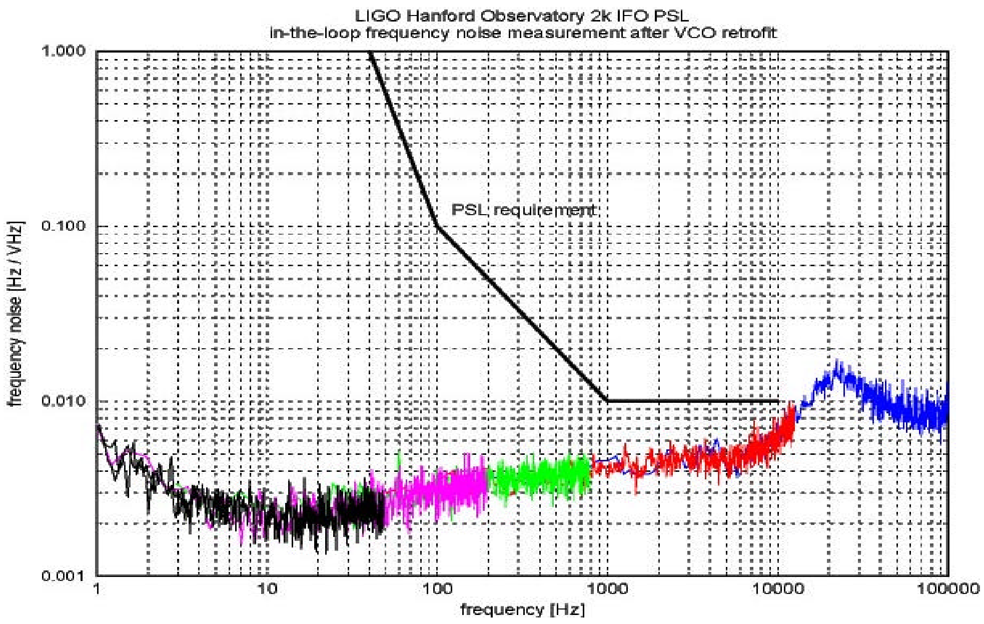


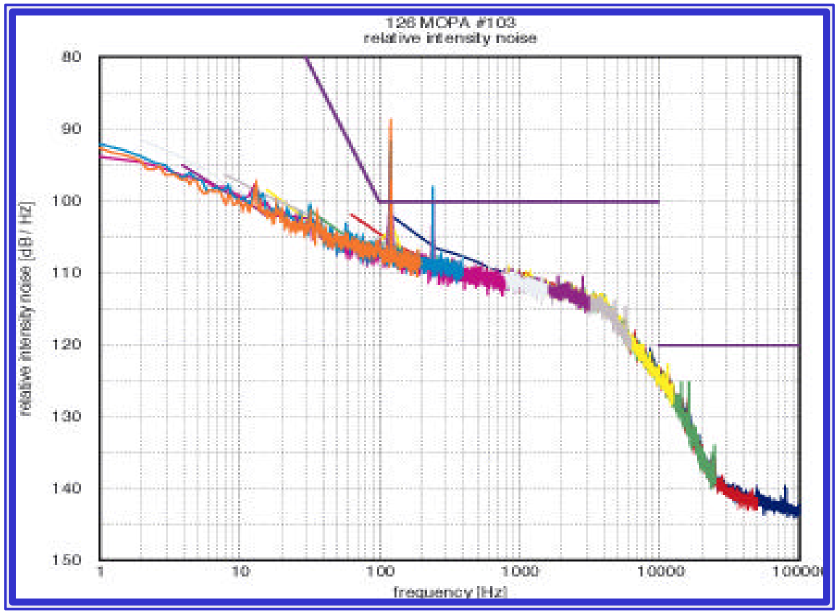
Master-Slave configuration with 12W output power



Laser

pre-stabilization



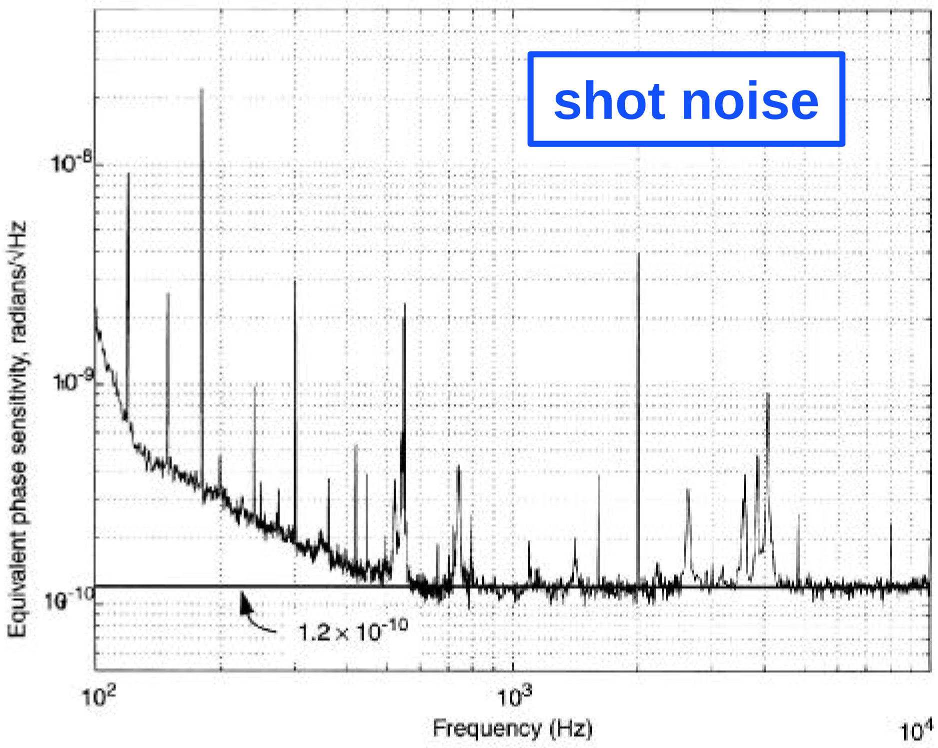


- **frequency noise:**
- **dn(f) < 10^{-2}Hz/$Hz^{1/2}$ 40Hz<f<10KHz**

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

Phase Noise

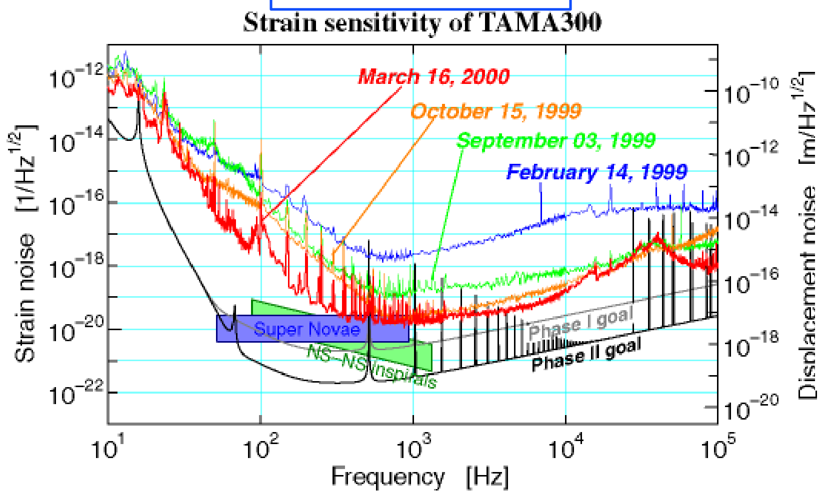
splitting the fringe

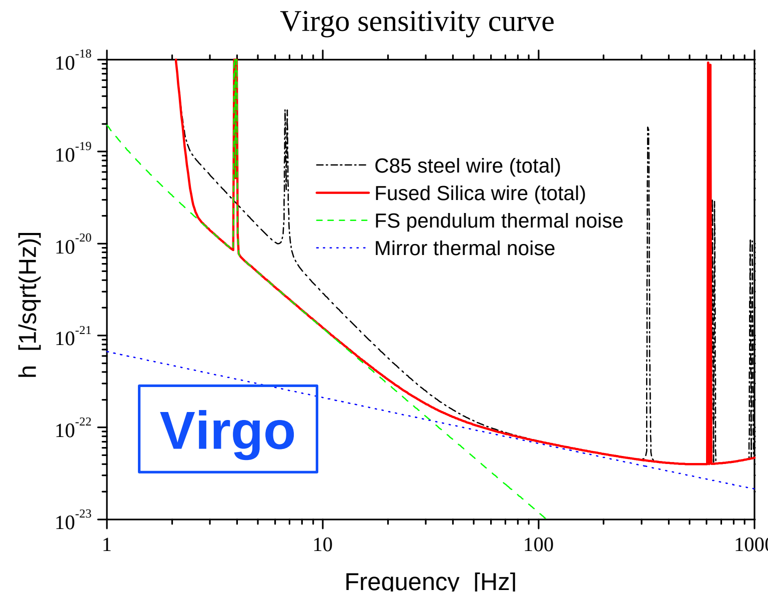


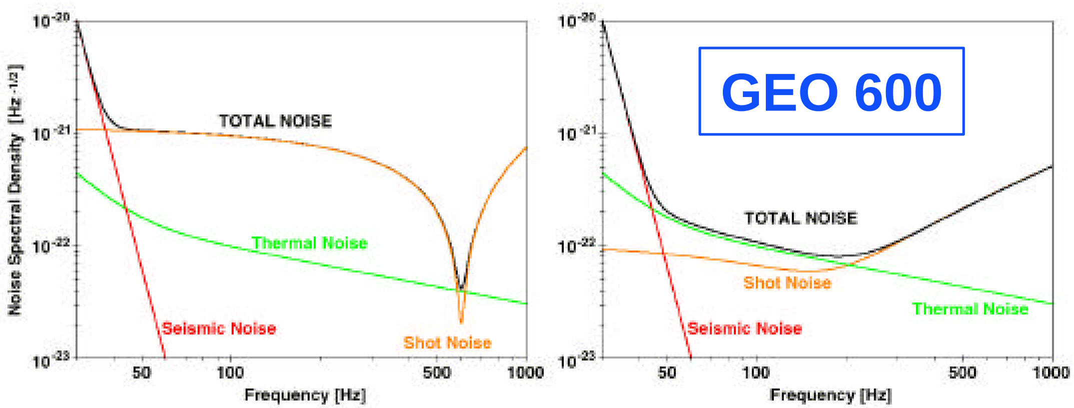
- spectral sensitivity of MIT phase noise interferometer
- above 500 Hz shot noise limited near LIGO I goal
- additional features are from 60 Hz powerline harmonics, wire resonances (600 Hz), mount resonances, etc

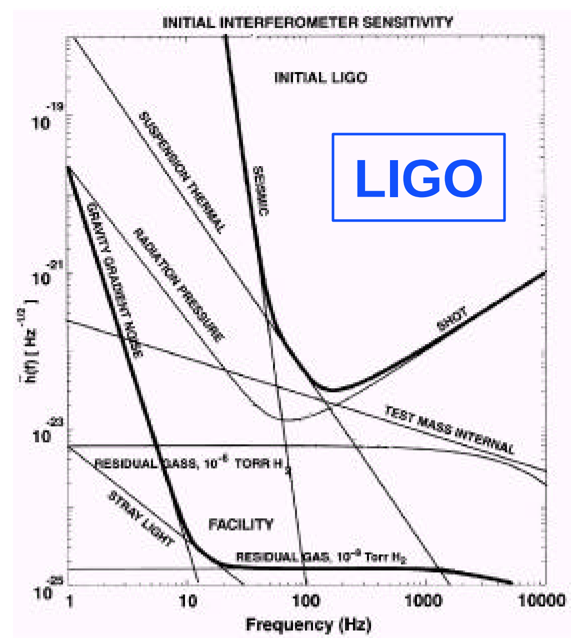
Interferometers
sensitivity curves

TAMA 300







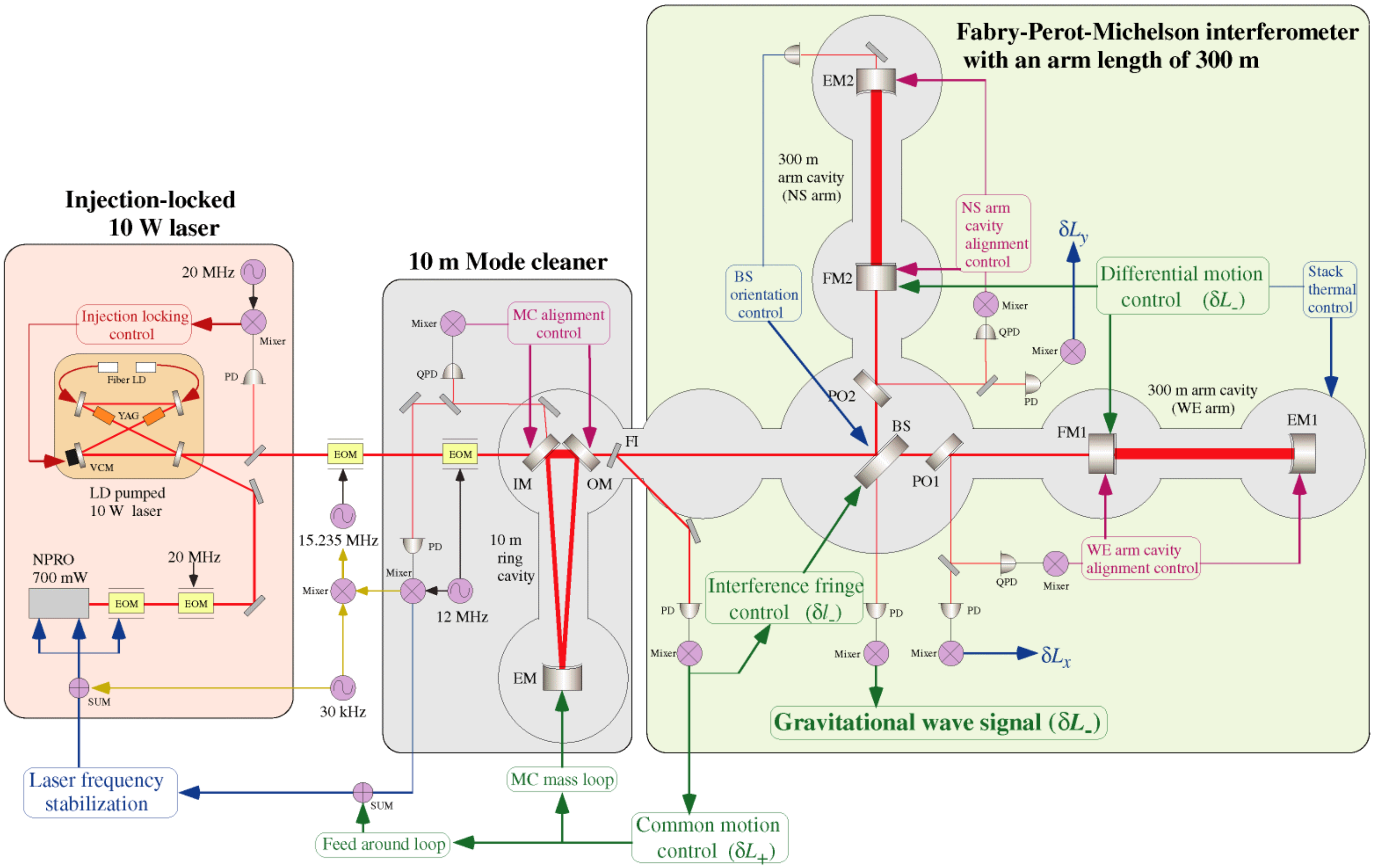


Interferometers

testing and commissioning

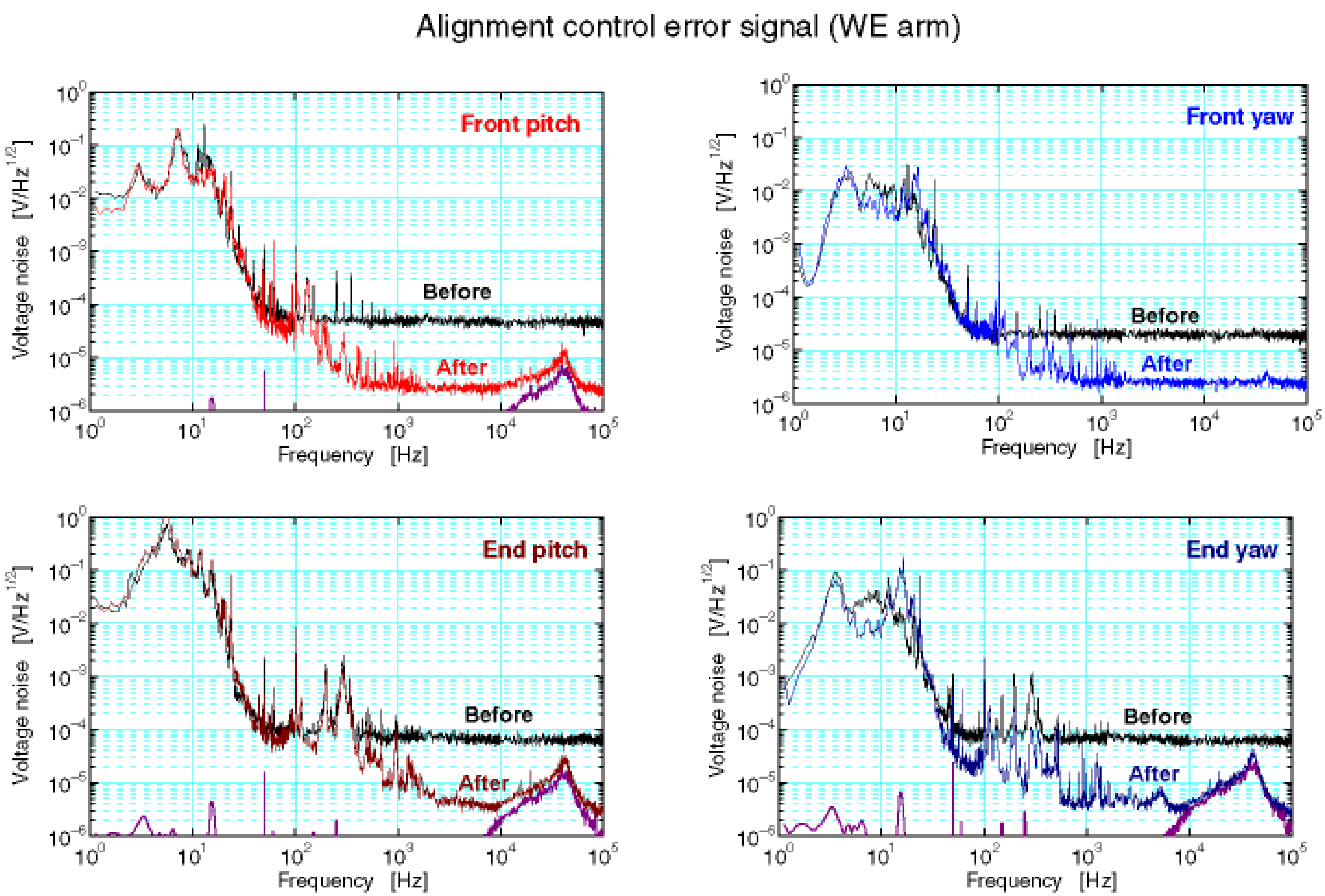
- TAMA 300
  - » interferometer locked; noise studies
- LIGO
  - » input optics commissioned;
  - » 2 km single arm locked/tested
- Geo 600
  - » commissioning tests
- Virgo
  - » testing isolation systems; input optics
- AIGO
  - » setting up central facility

TAMA 300
optical configuration

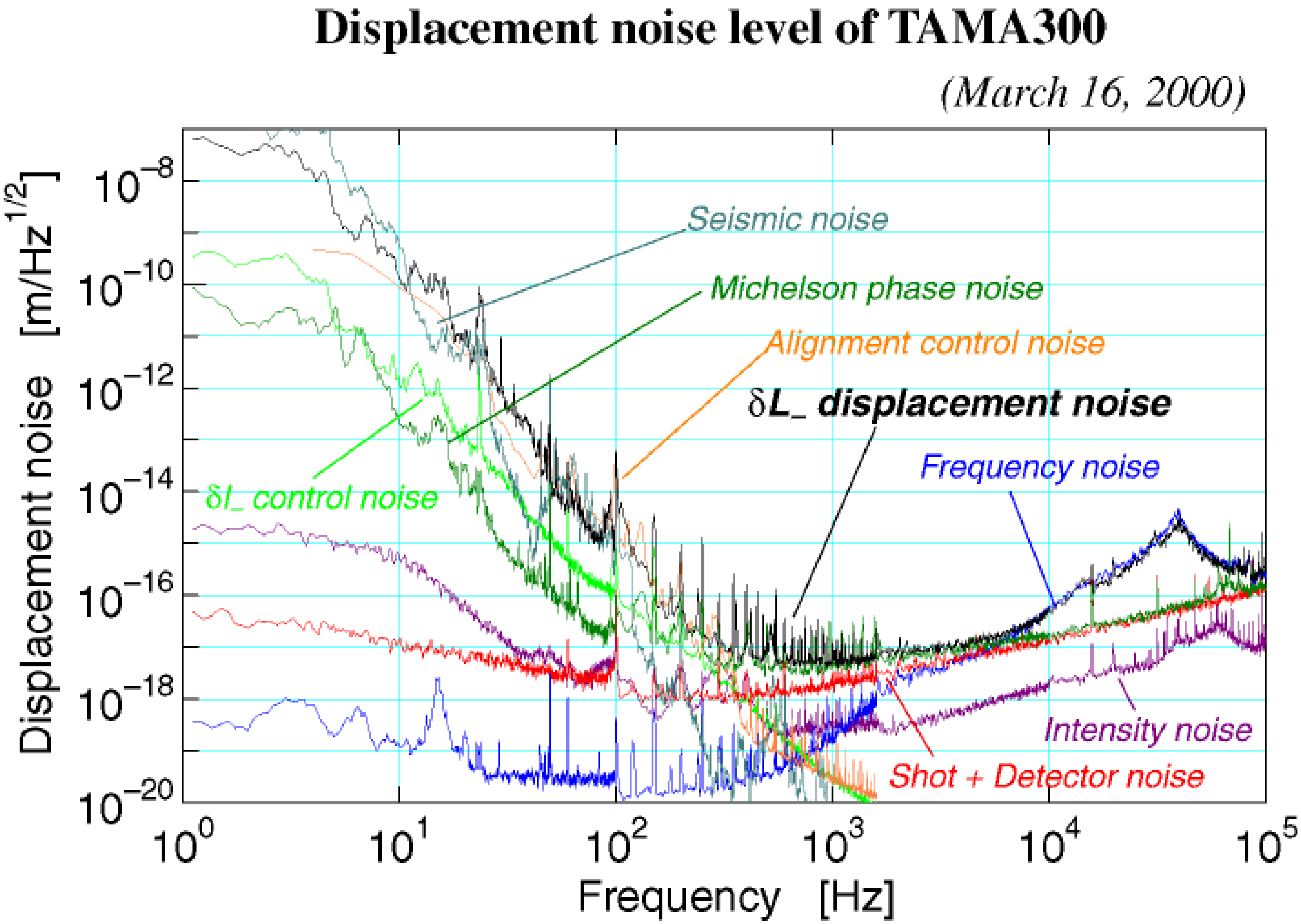


TAMA Commissioning

control error signals

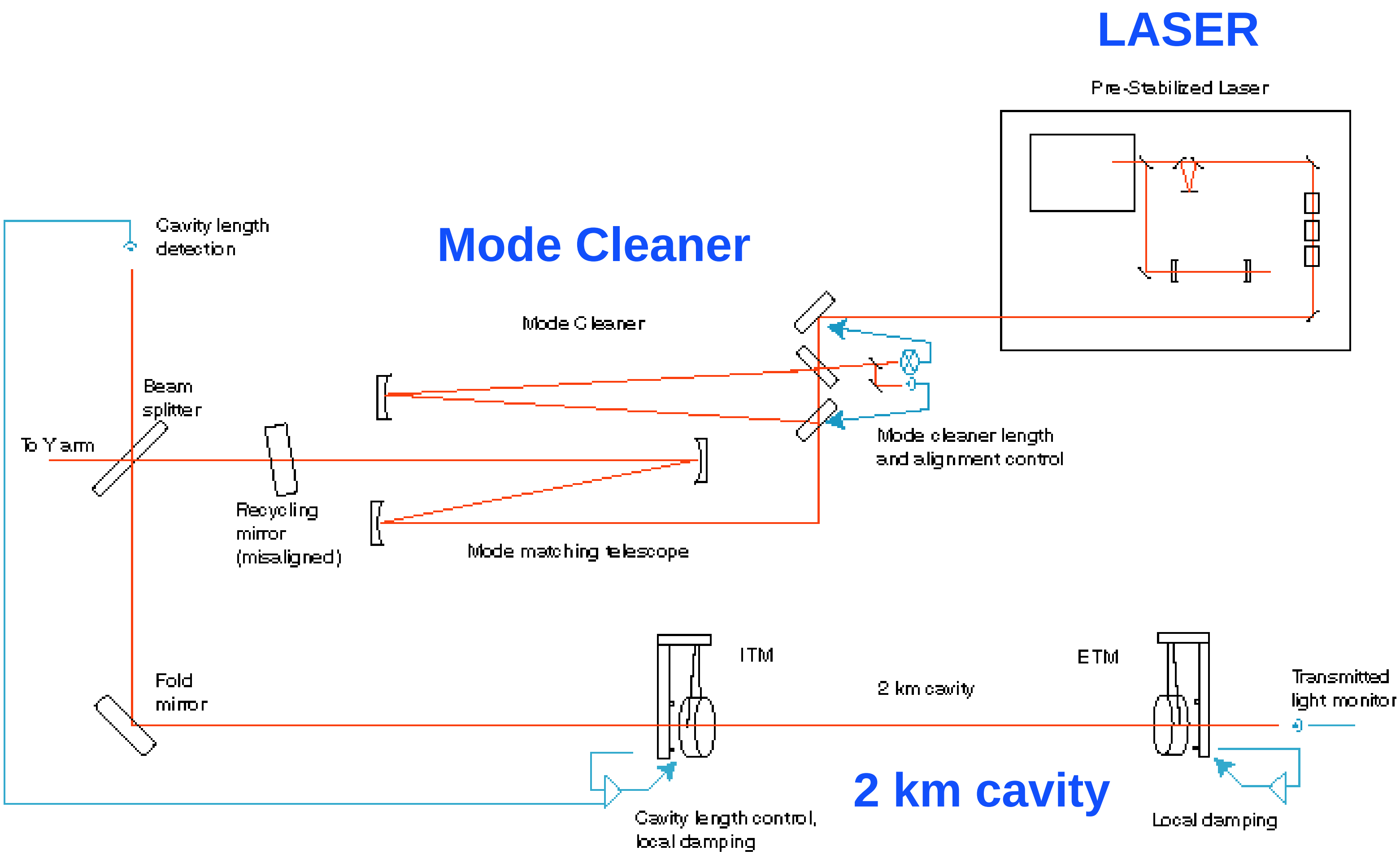


TAMA Performance
noise source analysis



LIGO

schematic of interferometer system

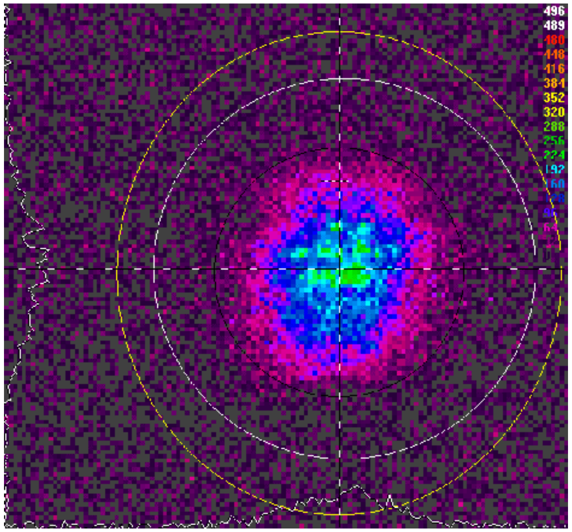


2km Fabry-Perot cavity

- 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)

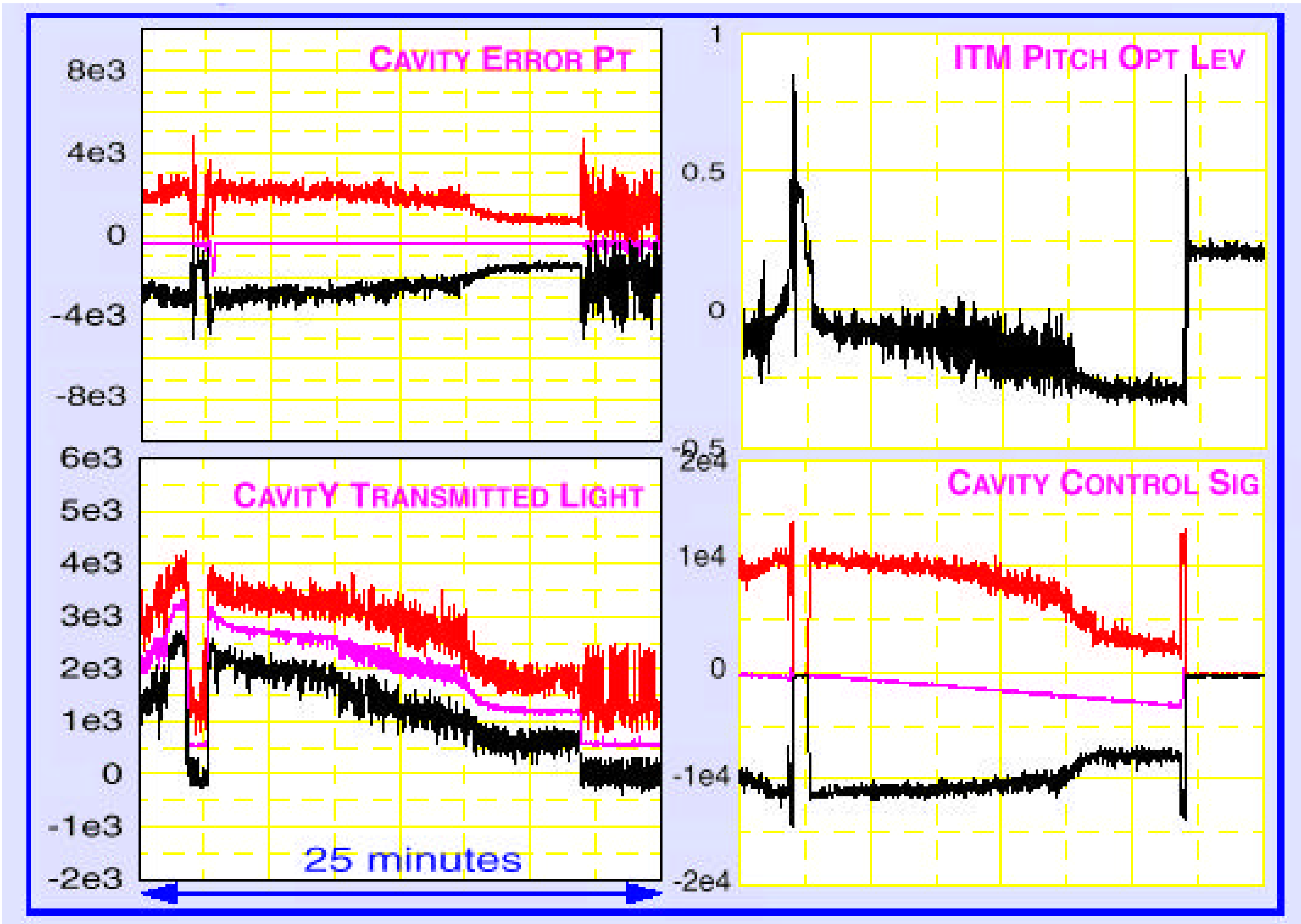
2km Fabry-Perot cavity

- 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

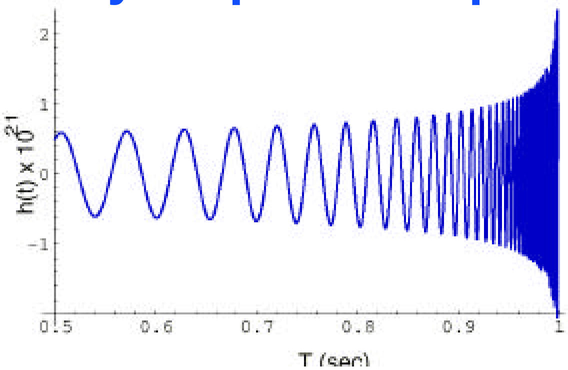
15 minute locked stretch



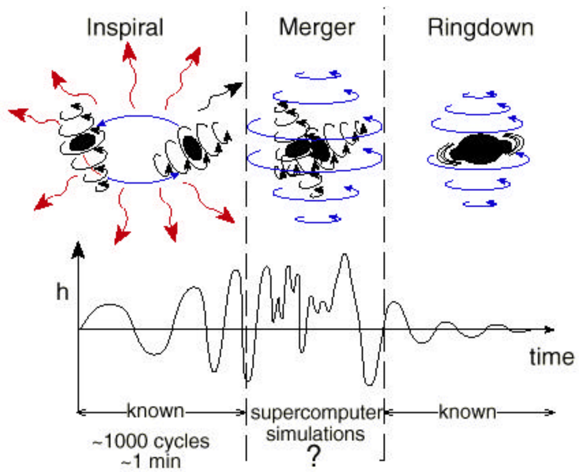
Interferometers

astrophysical sources

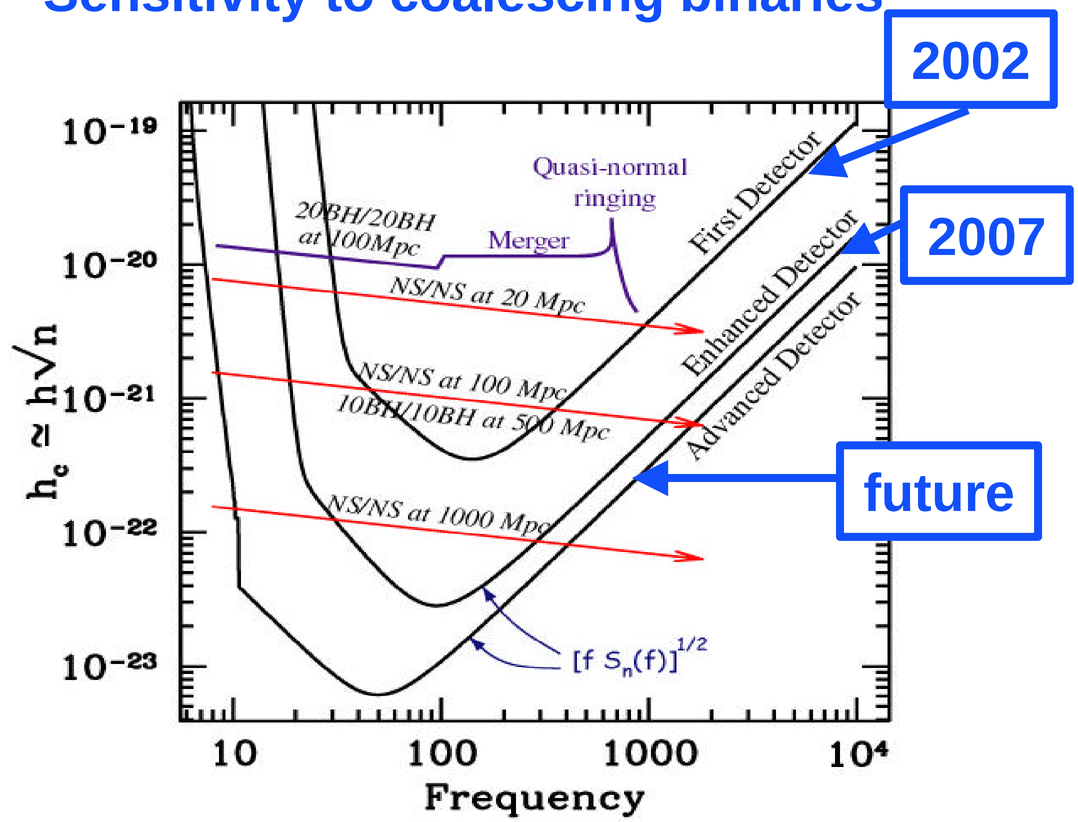
Binary inspiral ‘chirp’ signal



Compact binary mergers



Sensitivity to coalescing binaries



Interferometer
data analysis

- **Compact binary inspiral:** ***"chirps"***
  - **NS-NS waveforms are well described**
  - **BH-BH need better waveforms**
  - **search technique: matched templates**

- **Supernovae / GRBs:** ***"bursts"***
  - **burst signals in coincidence with signals in electromagnetic radiation**
  - **prompt alarm (~ one hour) with neutrino detectors**

- **Pulsars in our galaxy:** ***"periodic"***
  - **search for observed neutron stars (frequency, doppler shift)**
  - **all sky search (computing challenge)**
  - **r-modes**

Interferometer Data

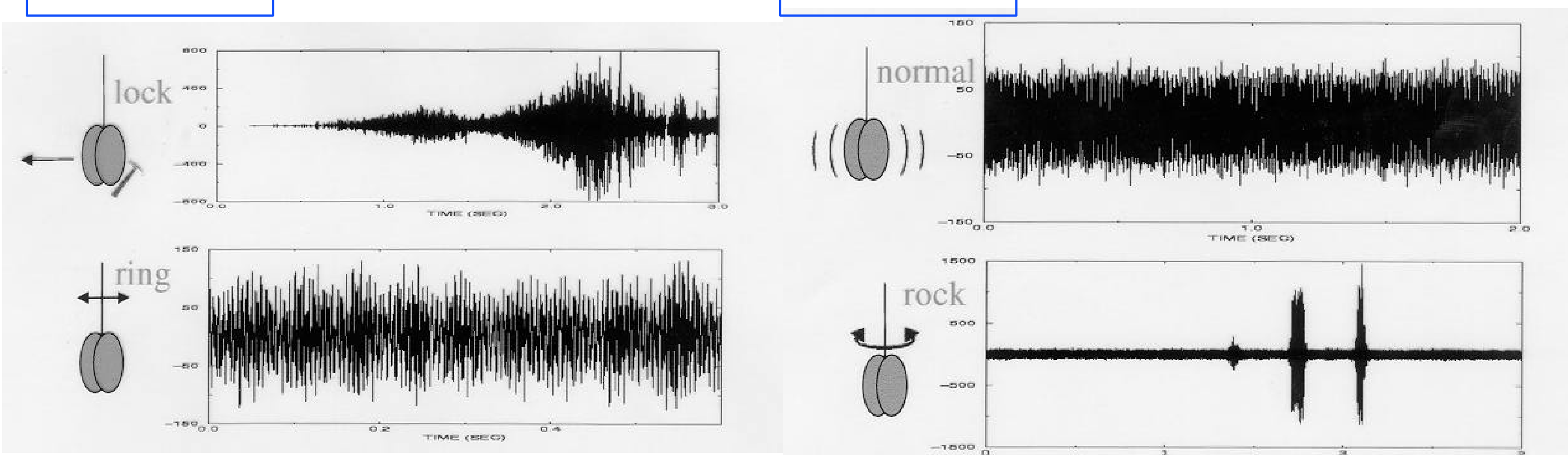
40 m

Real interferometer data is UGLY!!!

(Gliches - known and unknown)

LOCKING

NORMAL

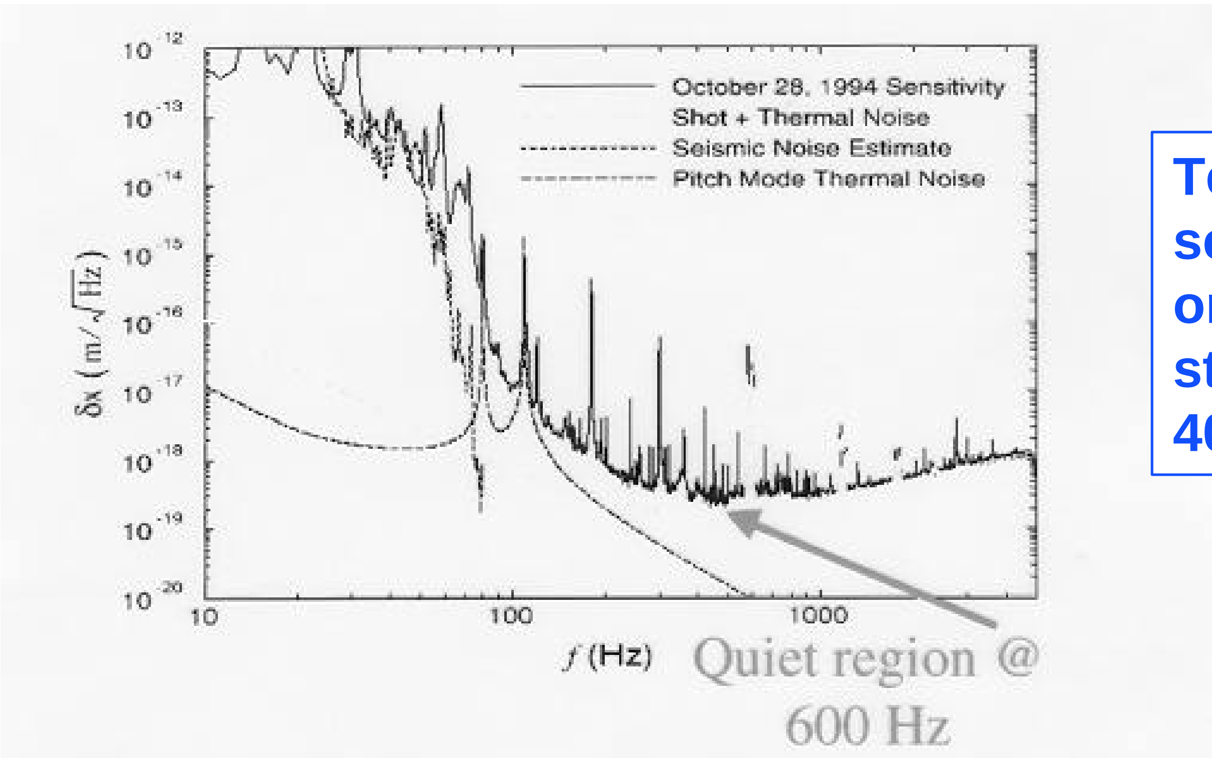


RINGING

ROCKING

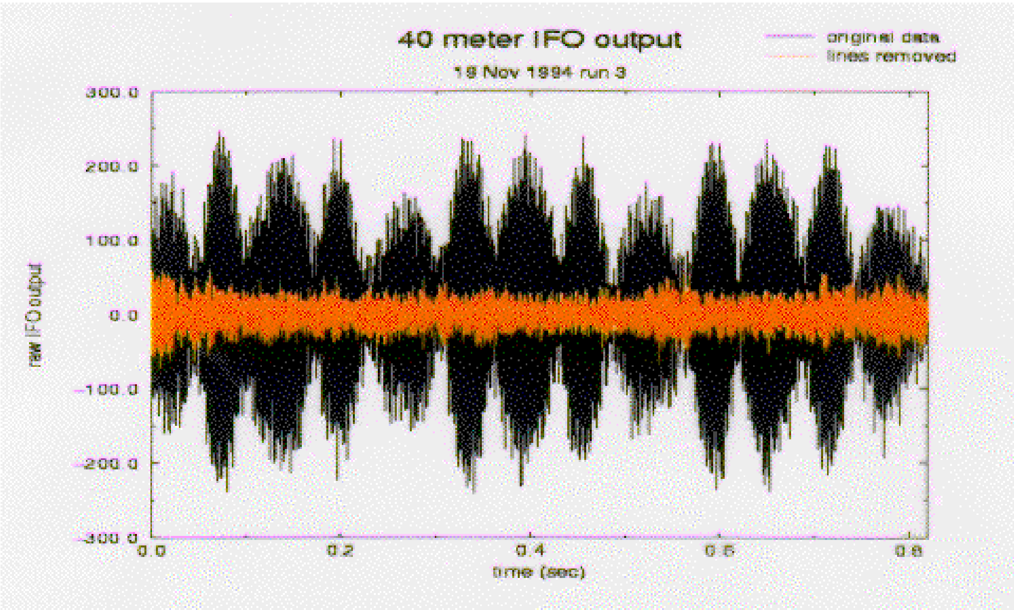
The Problem

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

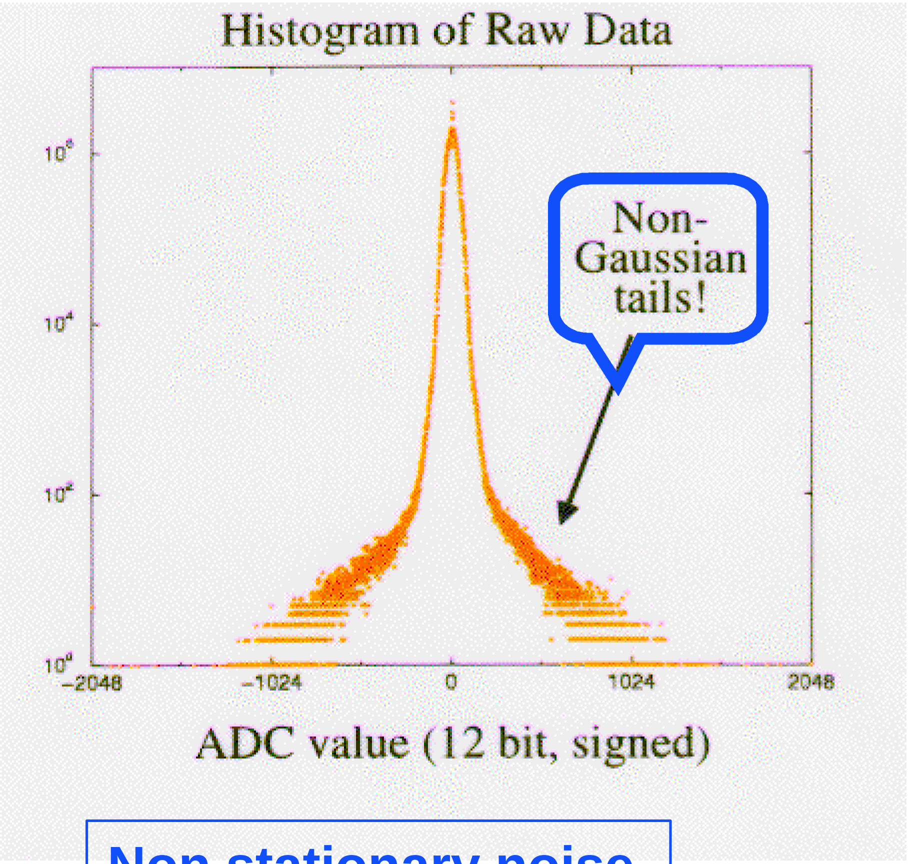


Test with real data by setting an upper limit on galactic neutron star inspiral rate using 40 m data

“Clean up” data stream



Effect of removing sinusoidal artifacts using multi-taper methods



Non stationary noise
Non gaussian tails

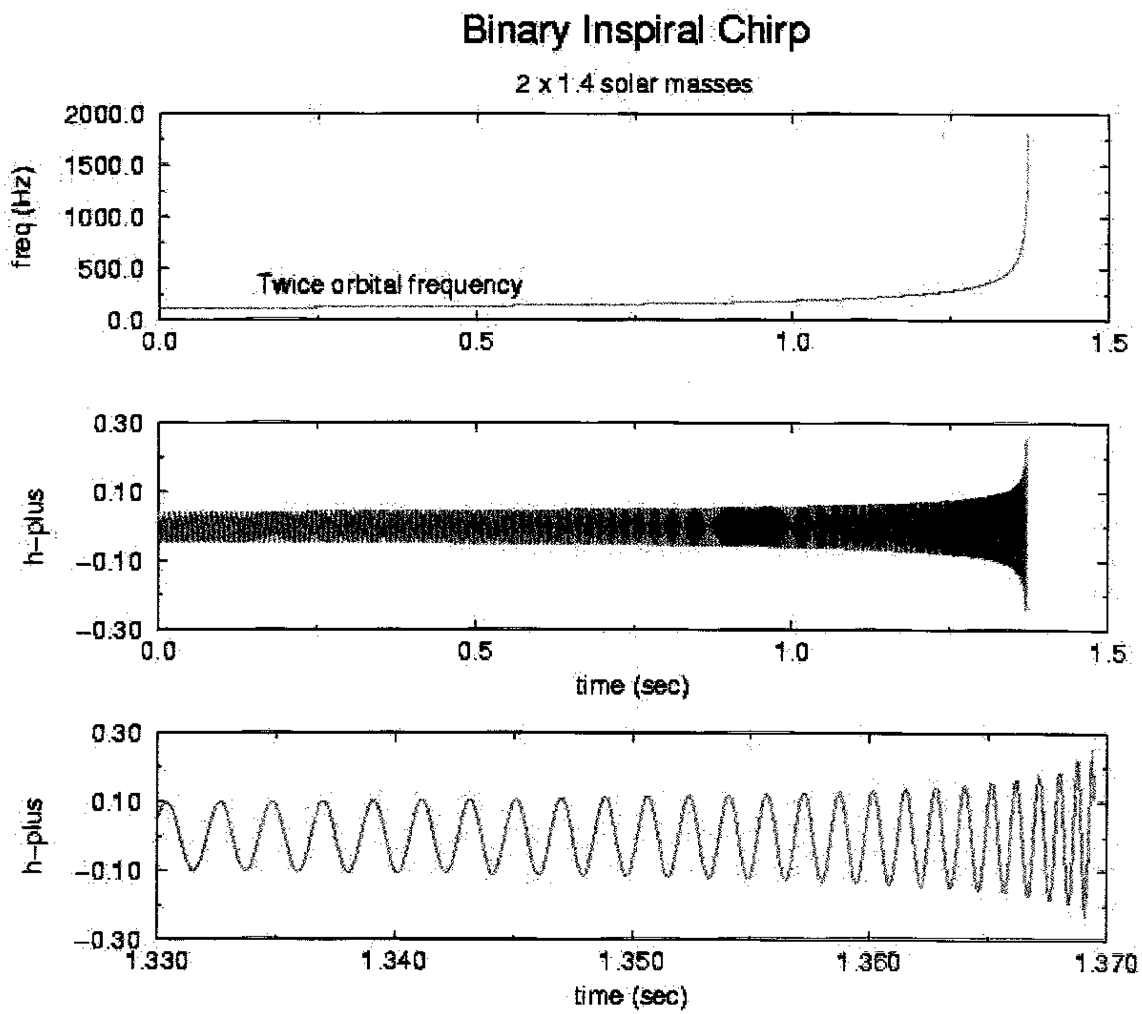
Inspiral 'Chirp' Signal

Template Waveforms

"matched filtering"
687 filters

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

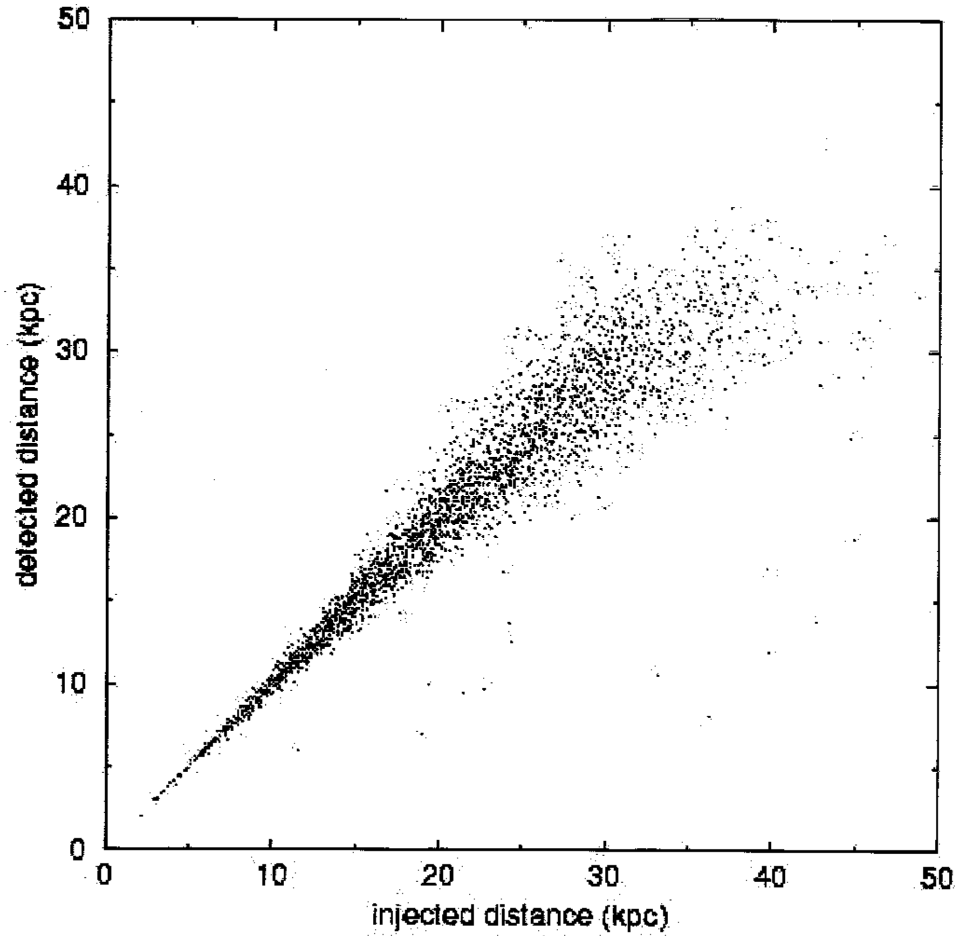
sensitivity to our galaxy
***h* ~ 3.5 10^{-19} m$Hz^{-1/2}$**
expected rate ~10^{-6}/yr



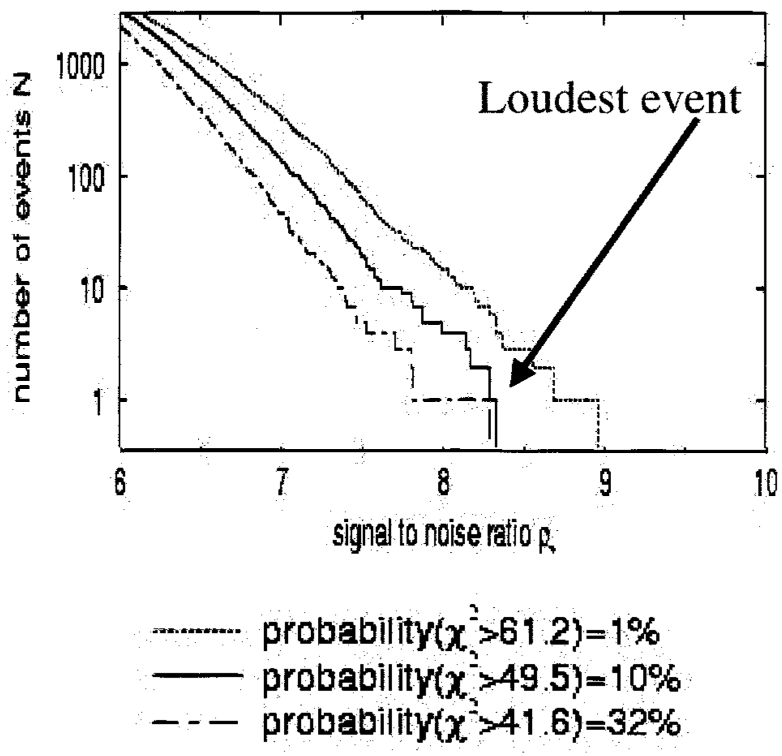
Detection Efficiency

• 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:

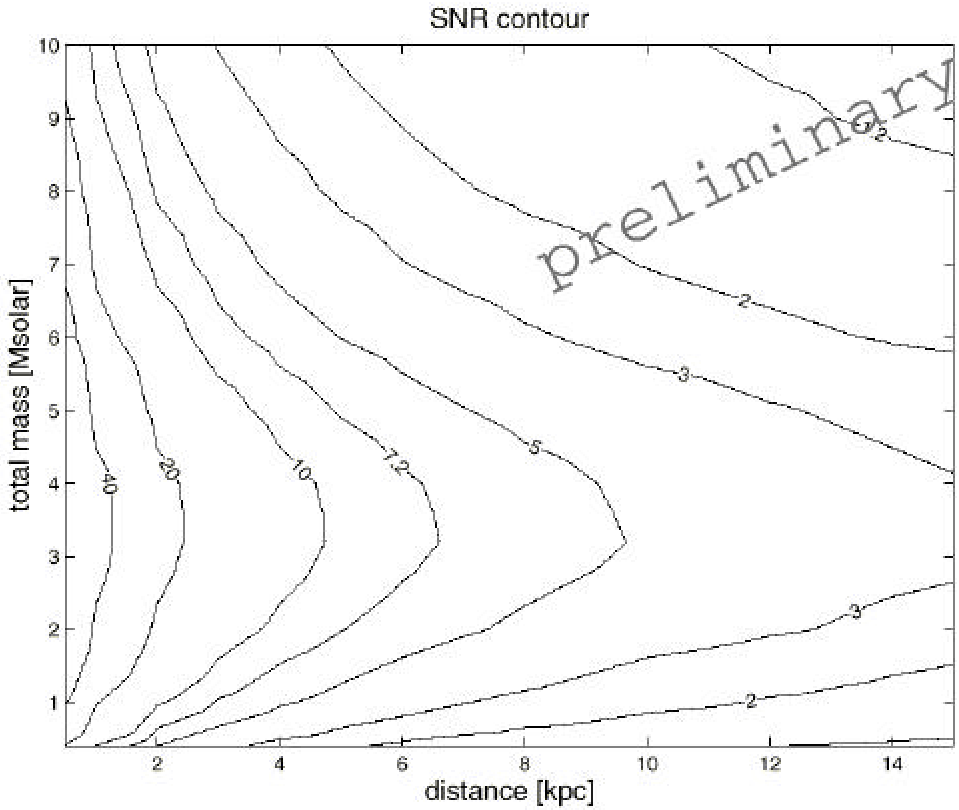
R < 0.16/hour

TAMA 300

search for binary coalescence

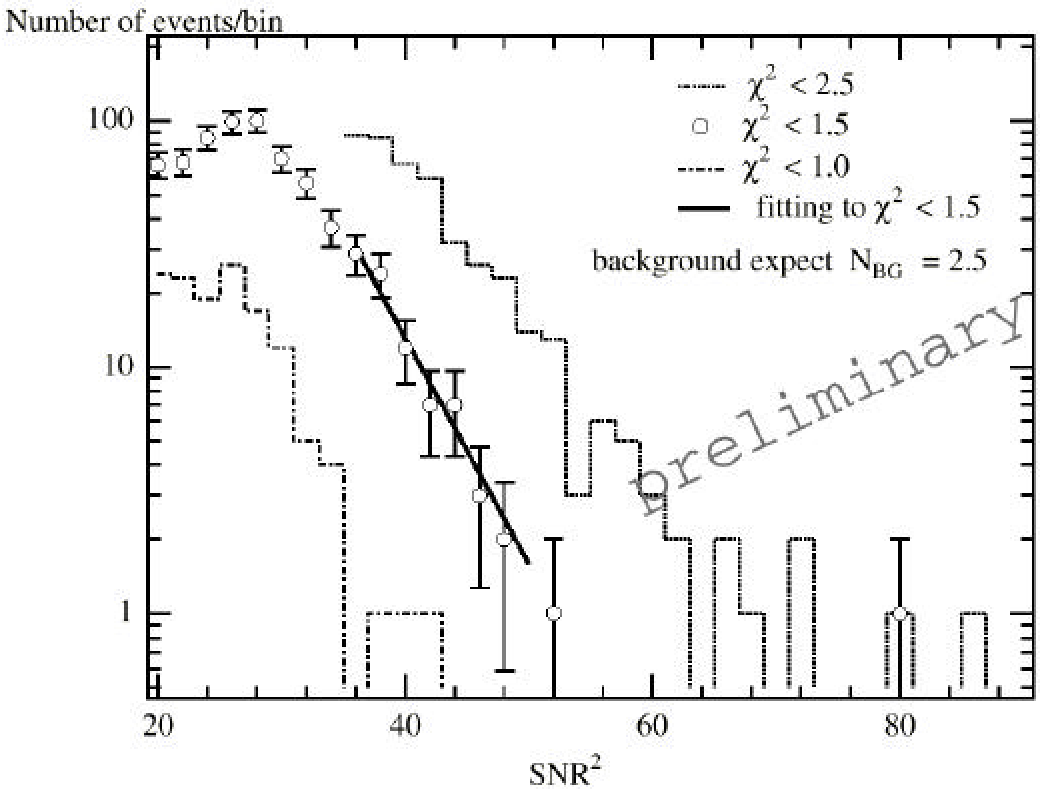
Matched templates

- **2-step hierarchical method**
- **chirp masses (0.3-10)M_0**
- **strain calibrated *dh/h ~ 1 %***



TAMA 300

preliminary result



For signal/noise = 7.2

Expect: 2.5 events
Observe: 2 events

Rate < 0.59 ev/hr 90% C.L.

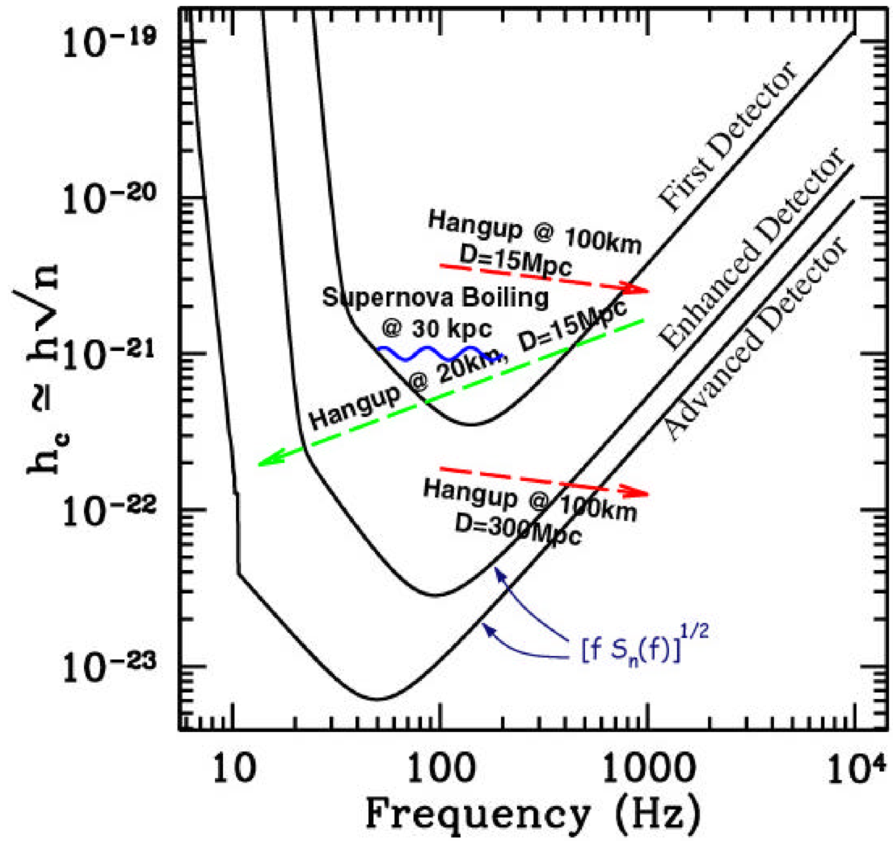
Note: for a 1.4 M_0 NS-NS inspiral this limit corresponds to a max distance = 6.2 kpc

Interferometers

astrophysical sources

SN1987A

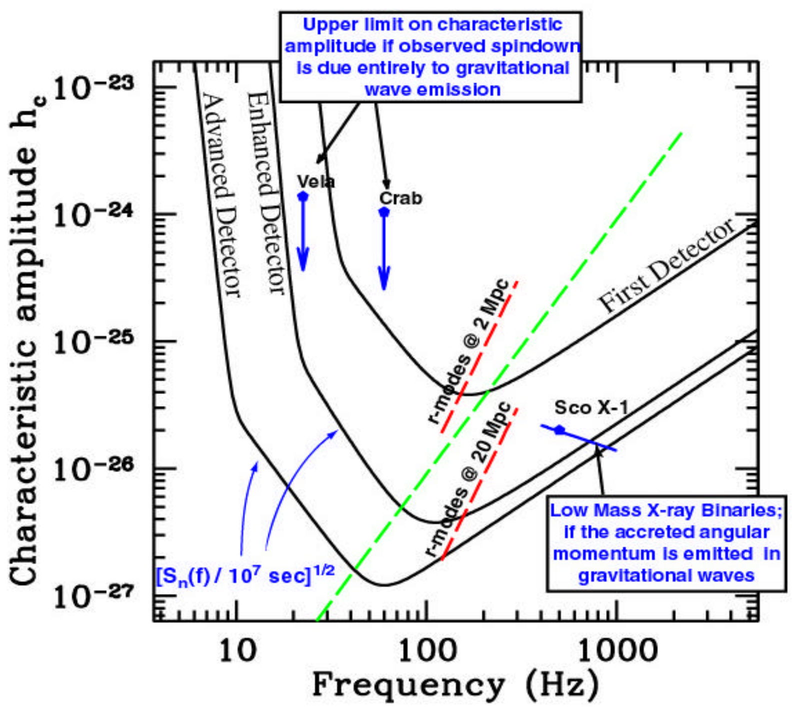
sensitivity to burst sources



LIGO

astrophysical sources

Continuous wave sources

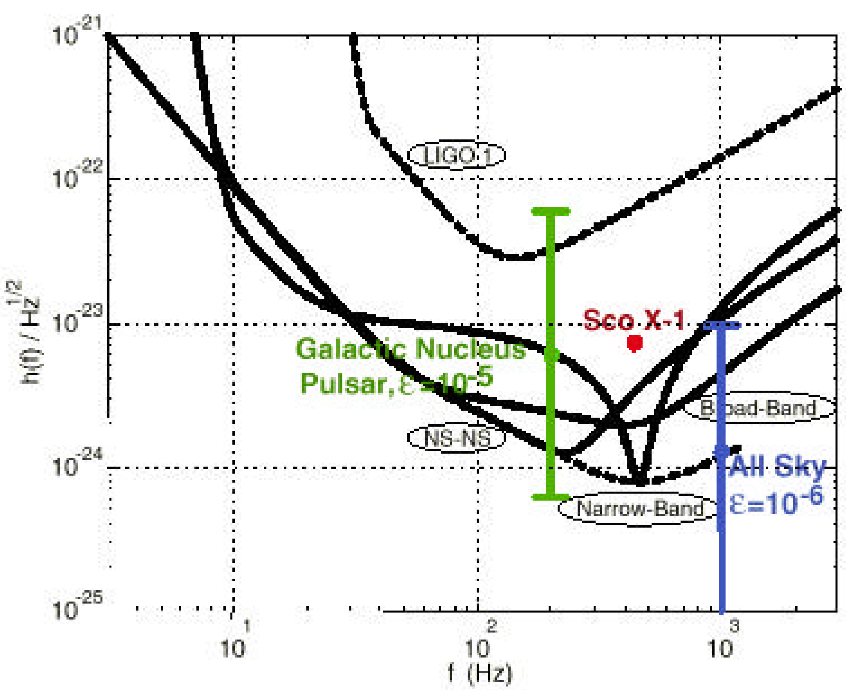


Pulsars in our galaxy

»non axisymmetric: 10-4 < e < 10-6

»science: neutron star precession; interiors

»narrow band searches best



Conclusions

- **a new generation of long baseline suspended mass interferometers are being completed with $h \sim 10^{-21}$**
- **commissioning, testing and characterization of the interferometers is underway**
- **data analysis schemes are being developed, including tests with real data from the 40 m prototype and TAMA *(see Tsubono)***
- **science data taking to begin within two years**
- **plans and agreements being made for exchange of data for coincidences between detectors (GWIC)**
- **significant improvements in sensitivity ($h \sim 10^{-22}$) are anticipated about 2007+ *(see Danzmann)***