LIGO

and

Detection of Gravitational Waves

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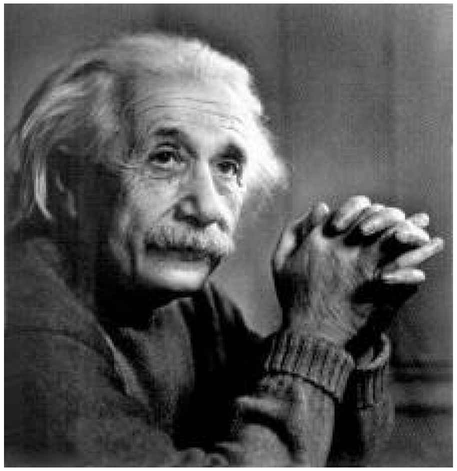
13 October 2000

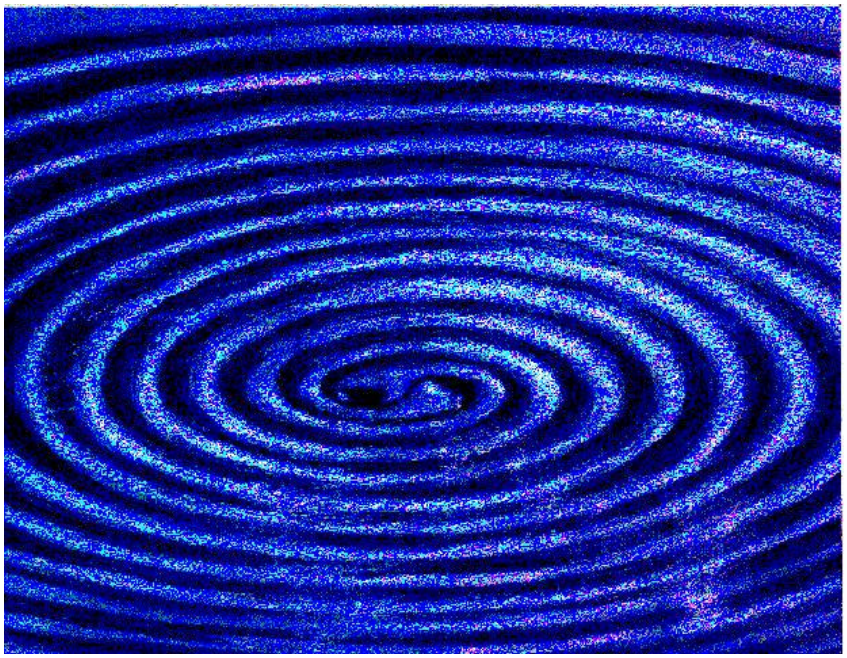
LIGO-G000306-00-M

Einstein’s Theory of Gravitation



Newton’s Theory

“instantaneous action at a distance”



Einstein’s Theory

information carried by gravitational radiation at the speed of light

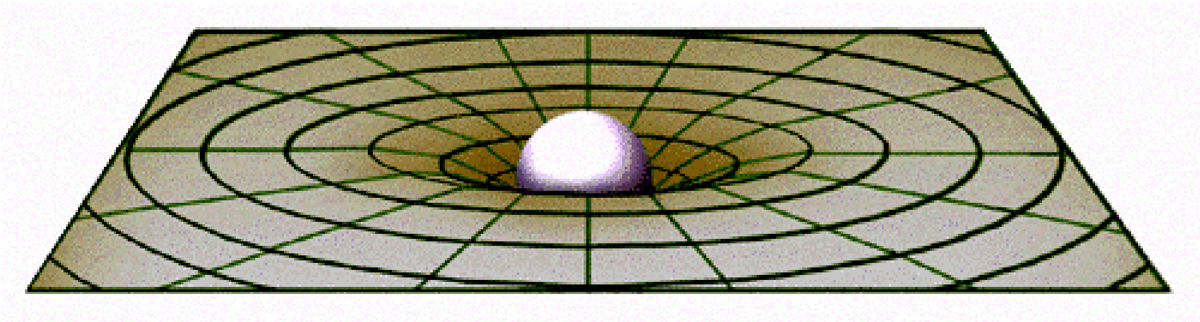
Einstein's
warpage of spacetime

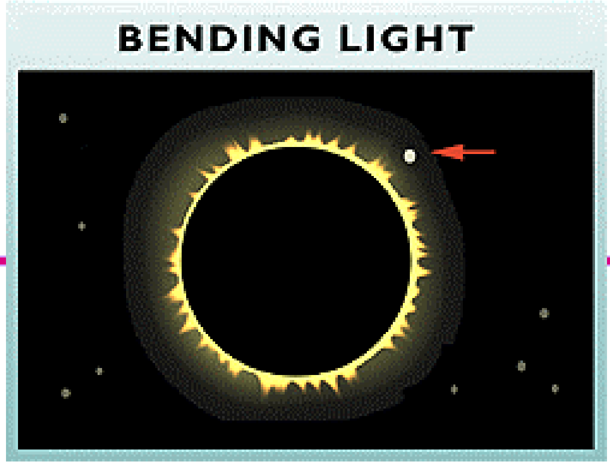
Imagine space as a stretched rubber sheet.

A mass on the surface will cause a deformation.

Another mass dropped onto the sheet will roll toward that mass.

**Einstein theorized that smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by
the larger object.**





Predict the bending of light passing in the vicinity of the massive objects

First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

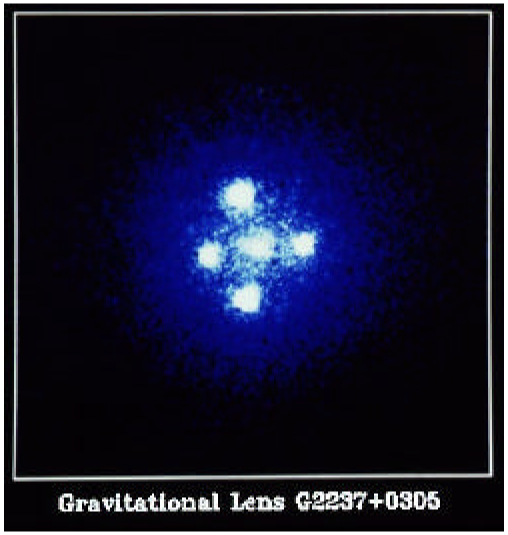
Their measurements showed that the light from these stars was bent as it grazed the Sun, by the exact amount of Einstein's predictions.

The light never changes course, but merely follows the curvature of space. Astronomers now refer to this displacement of light as gravitational lensing.

Einstein's Theory of Gravitation

experimental tests

"Einstein Cross"
The bending of light rays
gravitational lensing

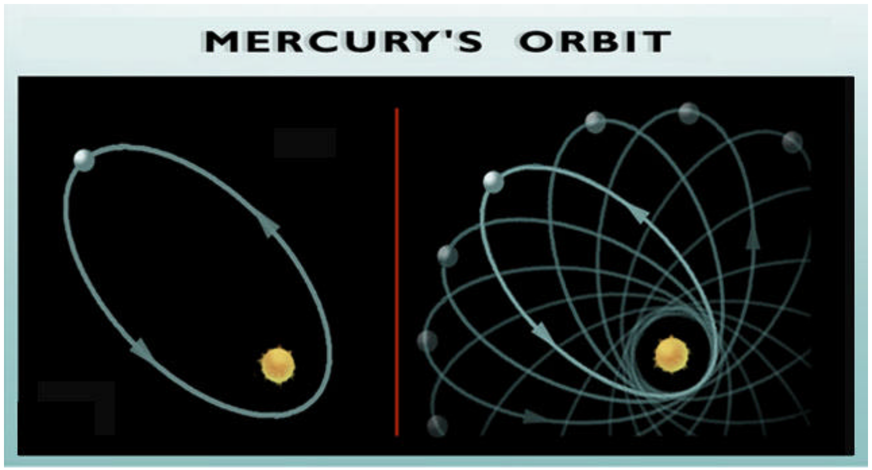


Quasar image appears around the central glow formed by nearby galaxy. The Einstein Cross is only visible in southern hemisphere.

In modern astronomy, such gravitational lensing images are used to detect a 'dark matter' body as the central object

Einstein's Theory of Gravitation

experimental tests



Mercury's orbit

perihelion shifts forward twice Newton's theory

Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass.

Astronomers had been aware for two centuries of a small flaw in the orbit, as predicted by Newton's laws.

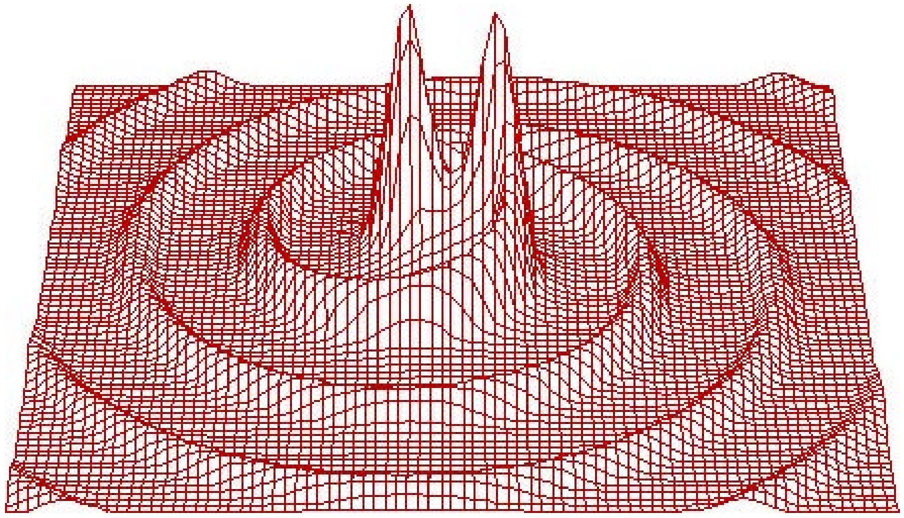
Einstein's predictions exactly matched the observation.

Einstein's Theory of Gravitation
gravitational waves

- a necessary consequence of Special Relativity with its finite speed for information transfer

- Einstein in 1916 and 1918 put forward the formulation of gravitational waves in General Relativity

- time dependent gravitational fields come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light



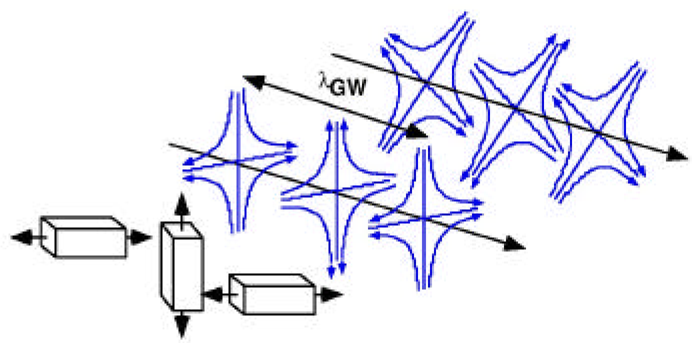
gravitational radiation
binary inspiral of compact objects

Einstein's Theory of Gravitation
gravitational waves

- Using Minkowski metric, the information about space-time curvature is contained in the metric as an added term, ***h**$_{mn}$*. In the weak field limit, the equation can be described with linear equations. If the choice of gauge is the *transverse traceless gauge* the formulation becomes a familiar wave equation

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{mn} = 0$$

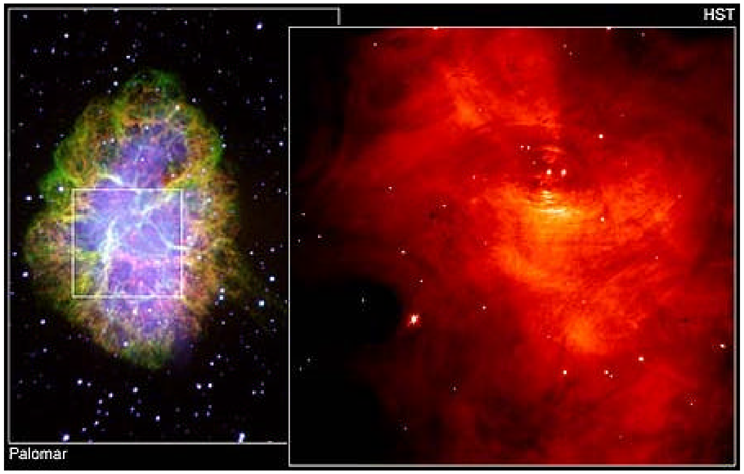
- The strain ***h**$_{mn}$* takes the form of a plane wave propagating with the speed of light (c).



- Since gravity is spin 2, the waves have two components, but rotated by 45^0 instead of 90^0 from each other.

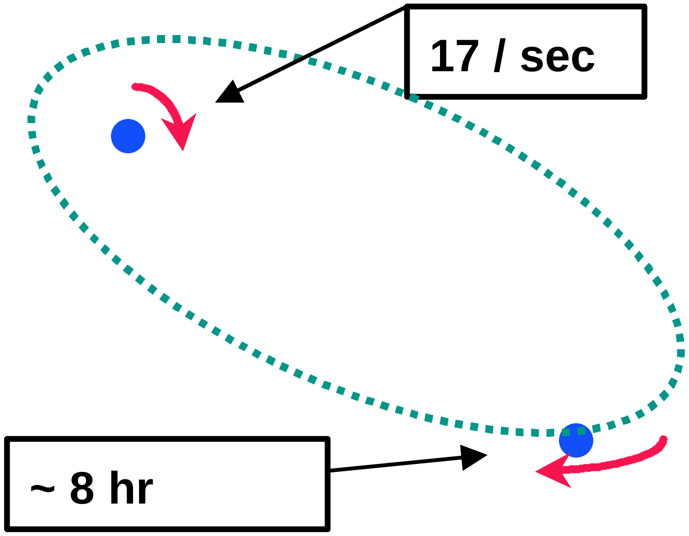
$$h_{mn} = h_+(t - z/c) + h_x(t - z/c)$$

Gravitational Waves
the evidence



Neutron Binary System

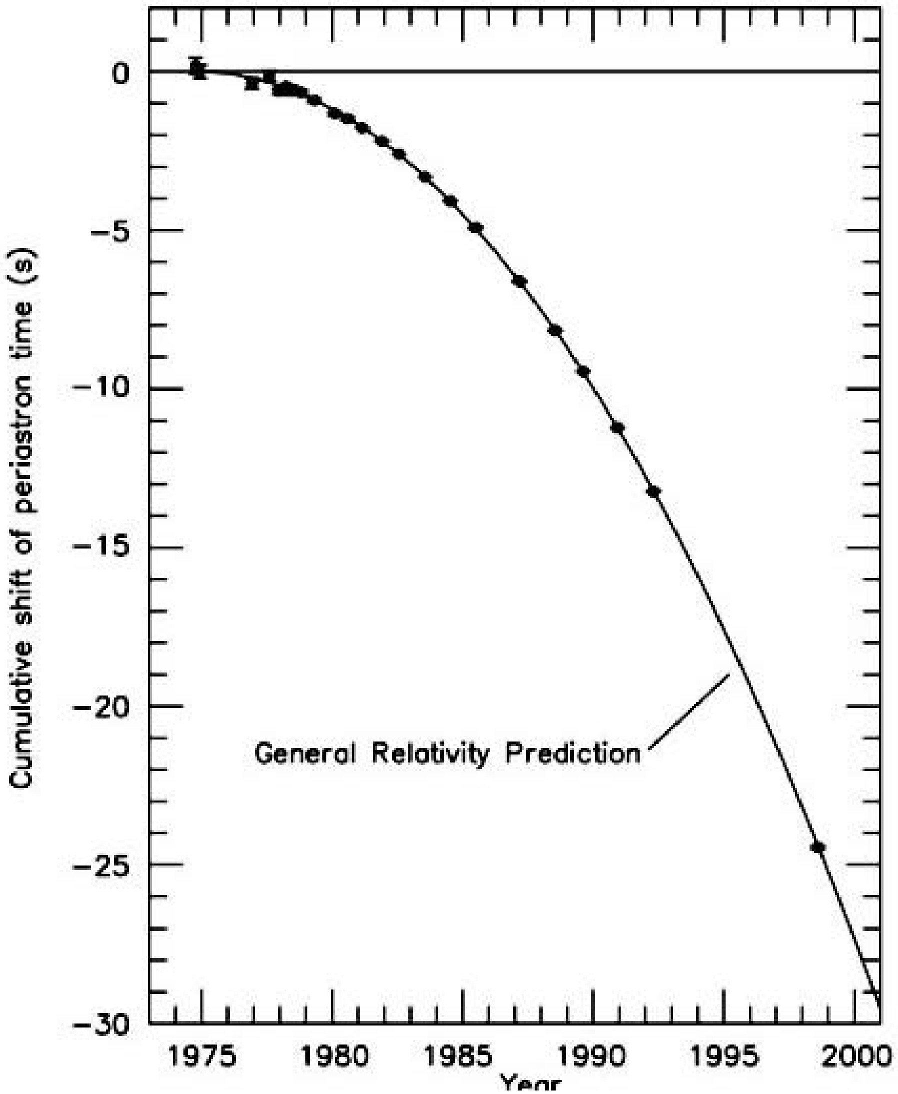
PSR 1913 + 16 -- Timing of pulsars



Hulse and Taylor
results

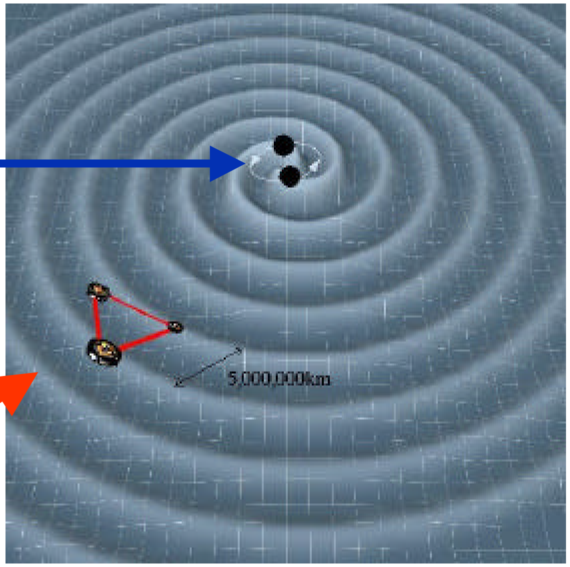
emission
of
gravitational waves

- due to loss of orbital energy
- period speeds up 25 sec from 1975-98
- measured to ~50 msec accuracy
- deviation grows quadratically with time

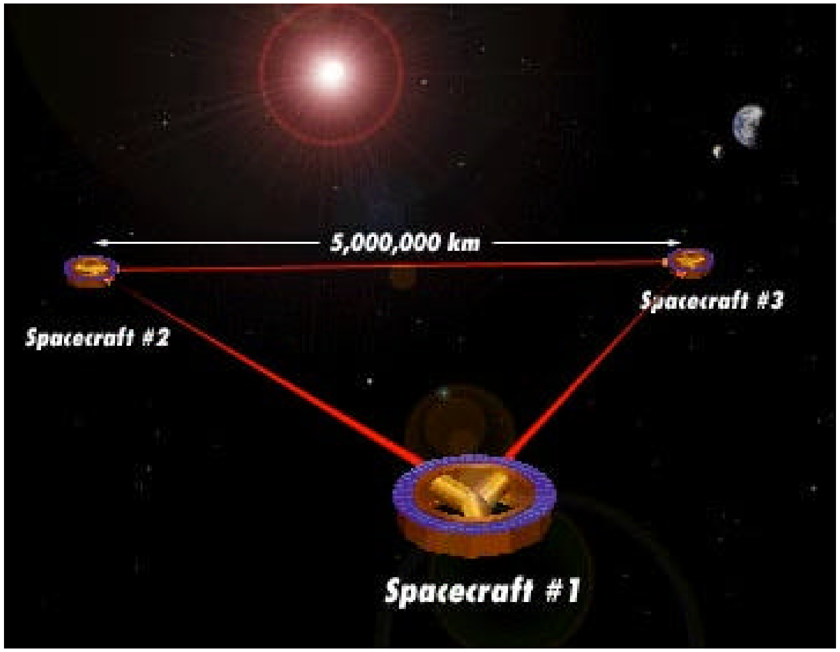


Radiation of Gravitational Waves

Radiation of gravitational waves from binary inspiral system



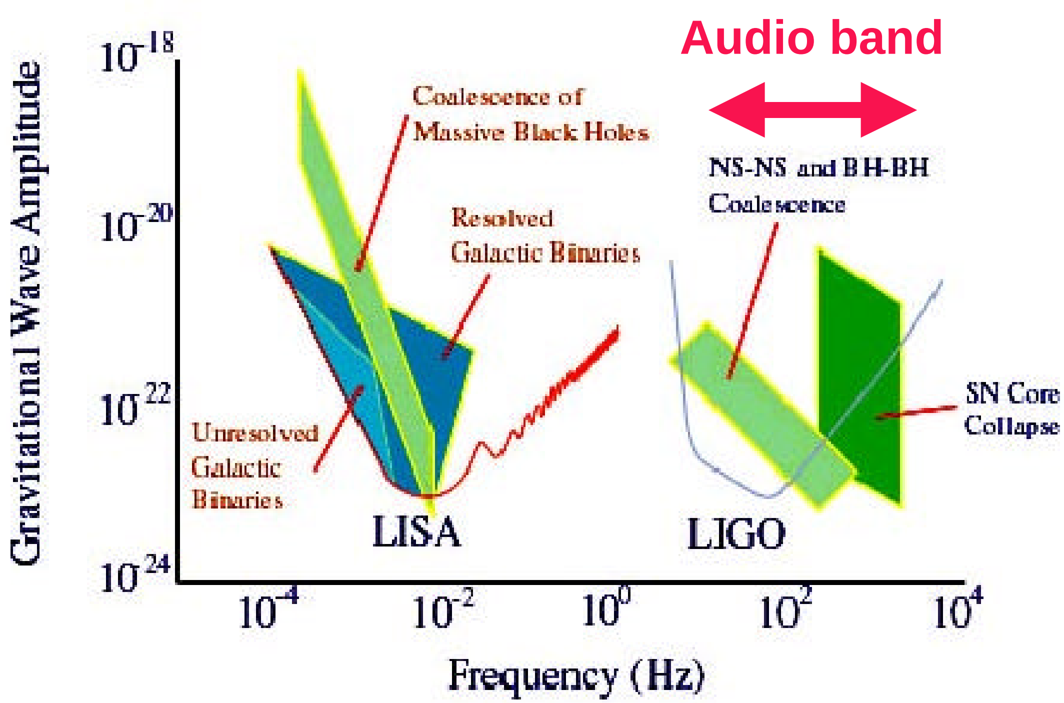
LISA



- **the center of the triangle formation will be in the ecliptic plane**
- **1 AU from the Sun and 20 degrees behind the Earth.**

Astrophysics Sources
frequency range

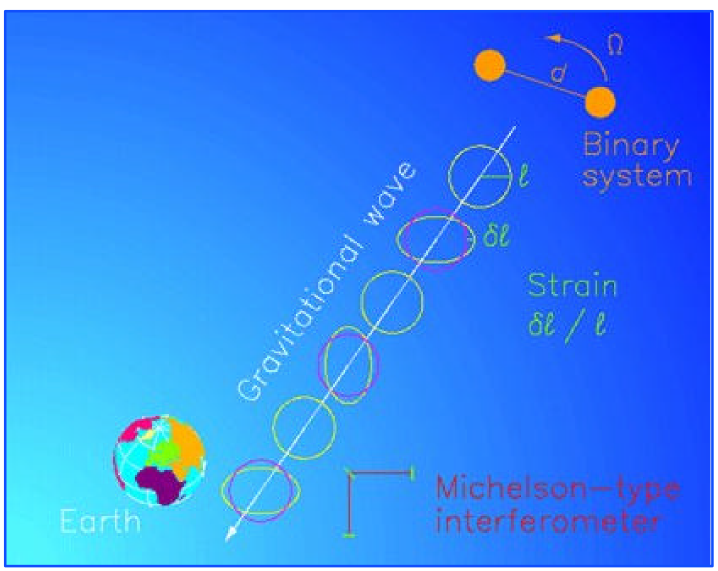
- **EM waves are studied over ~20 orders of magnitude**
  - » **(ULF radio –> HE γ rays)**
- **Gravitational Waves over ~10 orders of magnitude**
  - » **(terrestrial + space)**

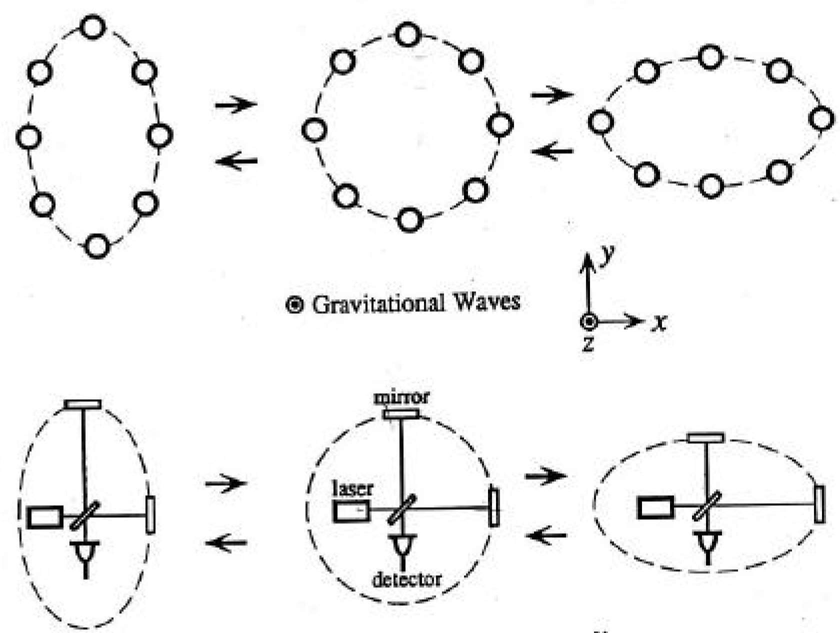


Interferometers
terrestrial

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

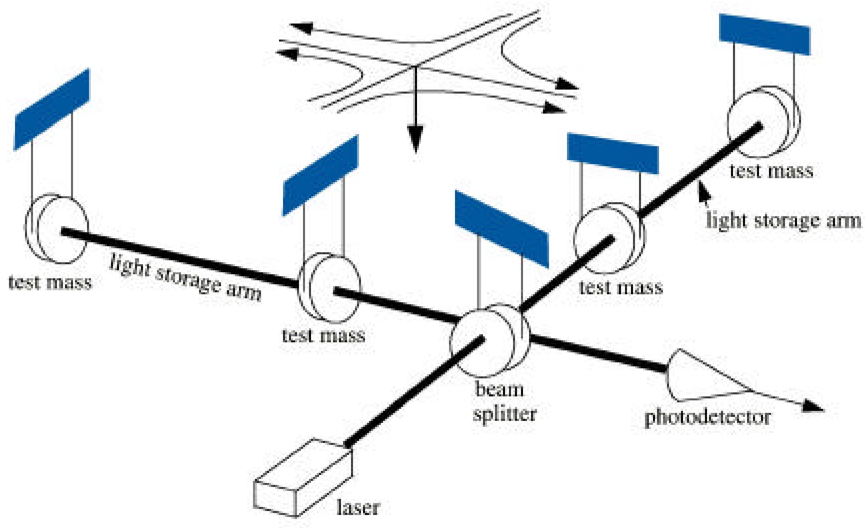
International network (LIGO, Virgo, GEO, TAMA) enable locating sources and decomposing polarization of gravitational waves.





Detection of Gravitational Waves

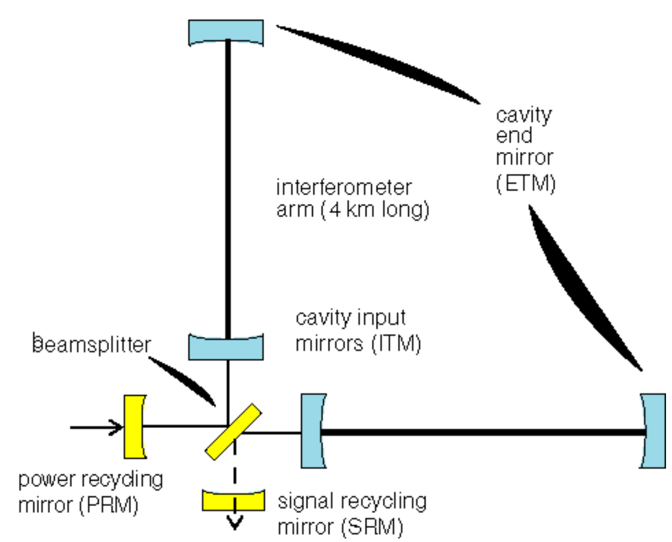
interferometry



suspended test masses

LIGO (4 km), stretch (squash) = 10^{-18} m will be detected at frequencies of 10 Hz to 10^4 Hz. It can detect waves from a distance of 600 10^6 light years

Michelson Interferometer
Fabry-Perot Arm Cavities

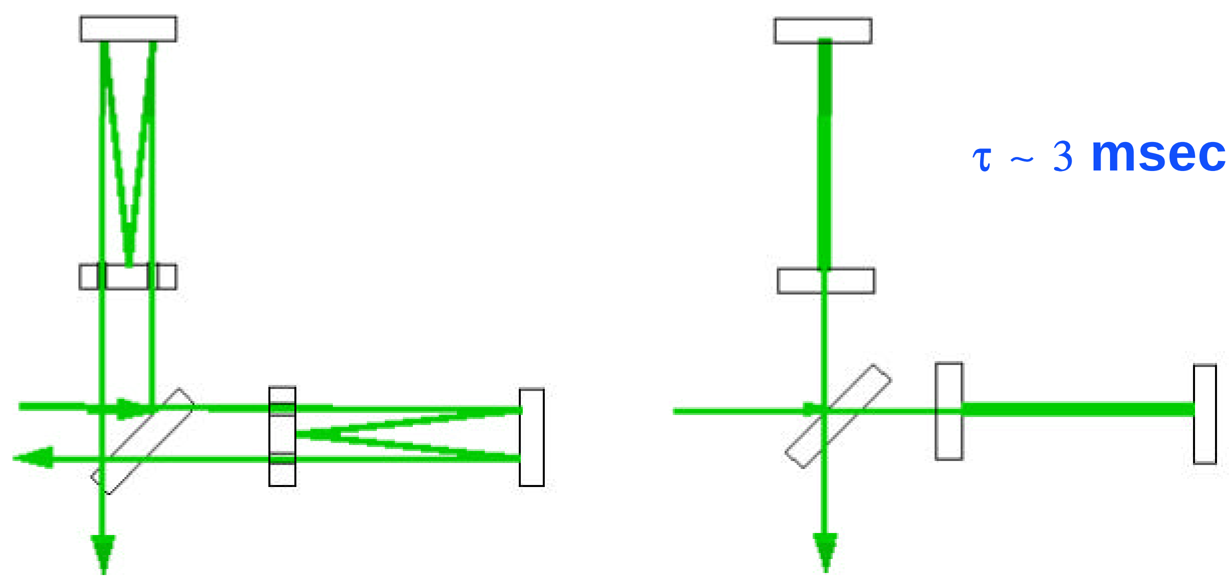


Detection of Gravitational Waves

Interferometry – folded arms

Folded arms – long light paths

Schemes - delay line is simple but requires large mirrors
- power recycling mirrors small, but harder controls problems



Delay line interferometer **Fabry Perot interferometer**

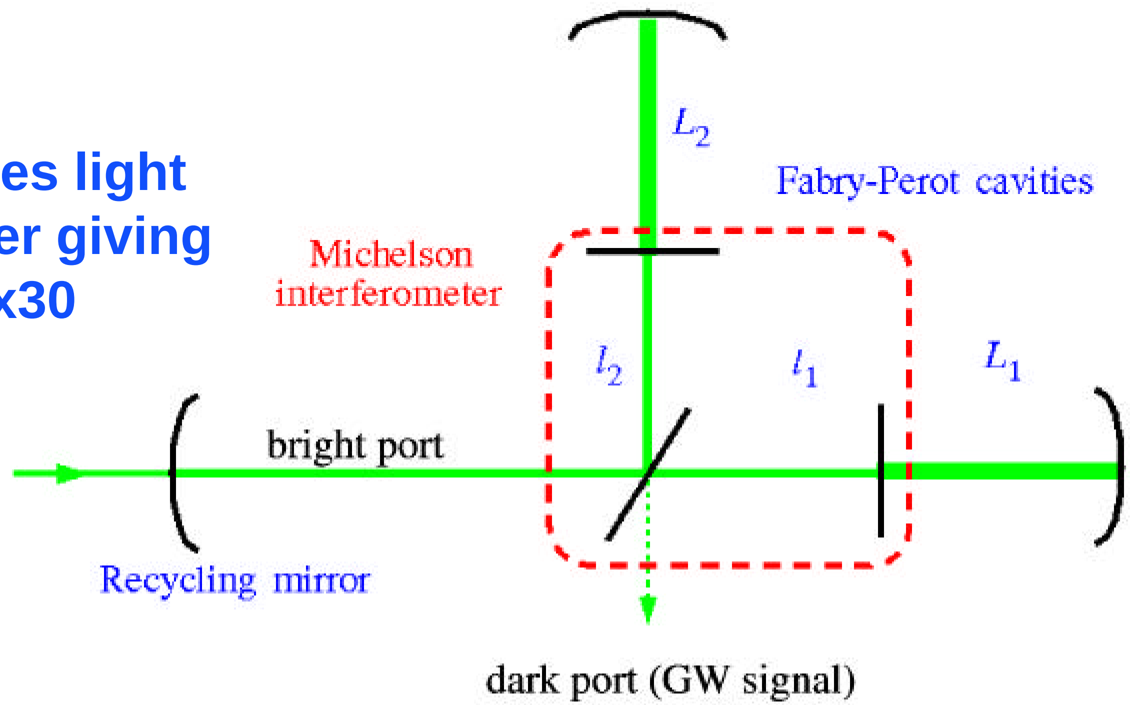
Detection of Gravitational Waves

Interferometry – folded arms

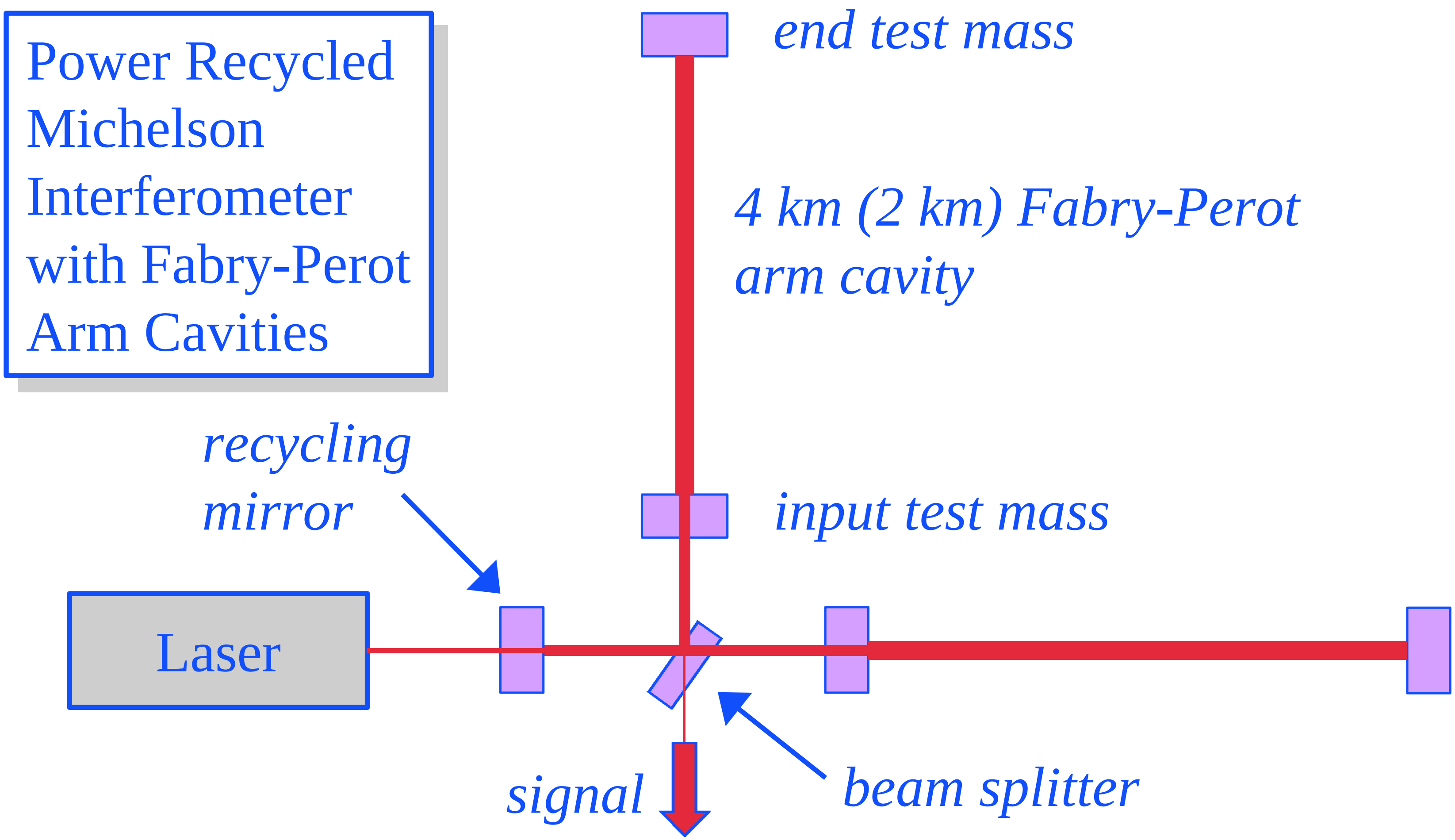
Power recycled Michelson Interferometer with Fabry-Perot arms

- **arm cavities store light for ~ 100 round trips or ~ 3 msec**

- **power recycling re-uses light heading back to the laser giving an additional factor of x30**



LIGO Interferometers

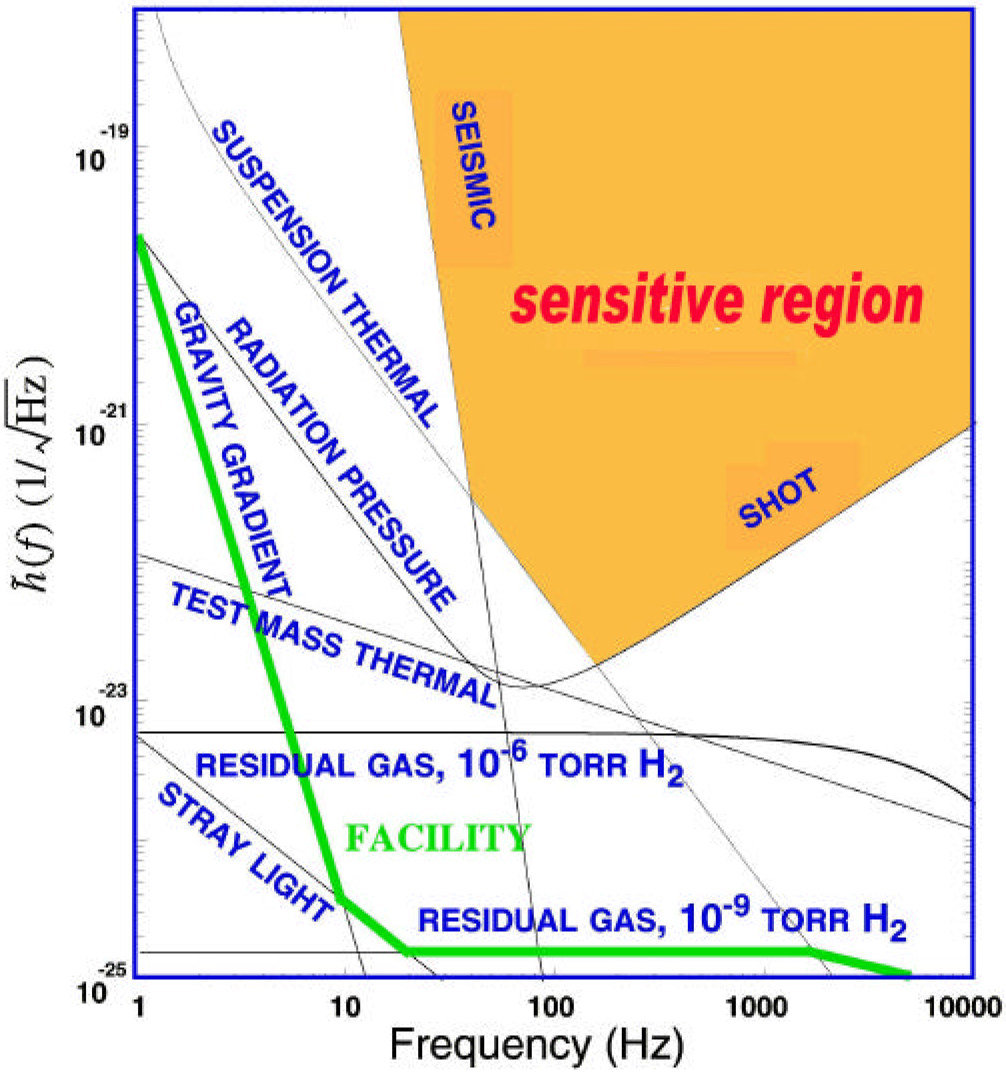


LIGO I

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**

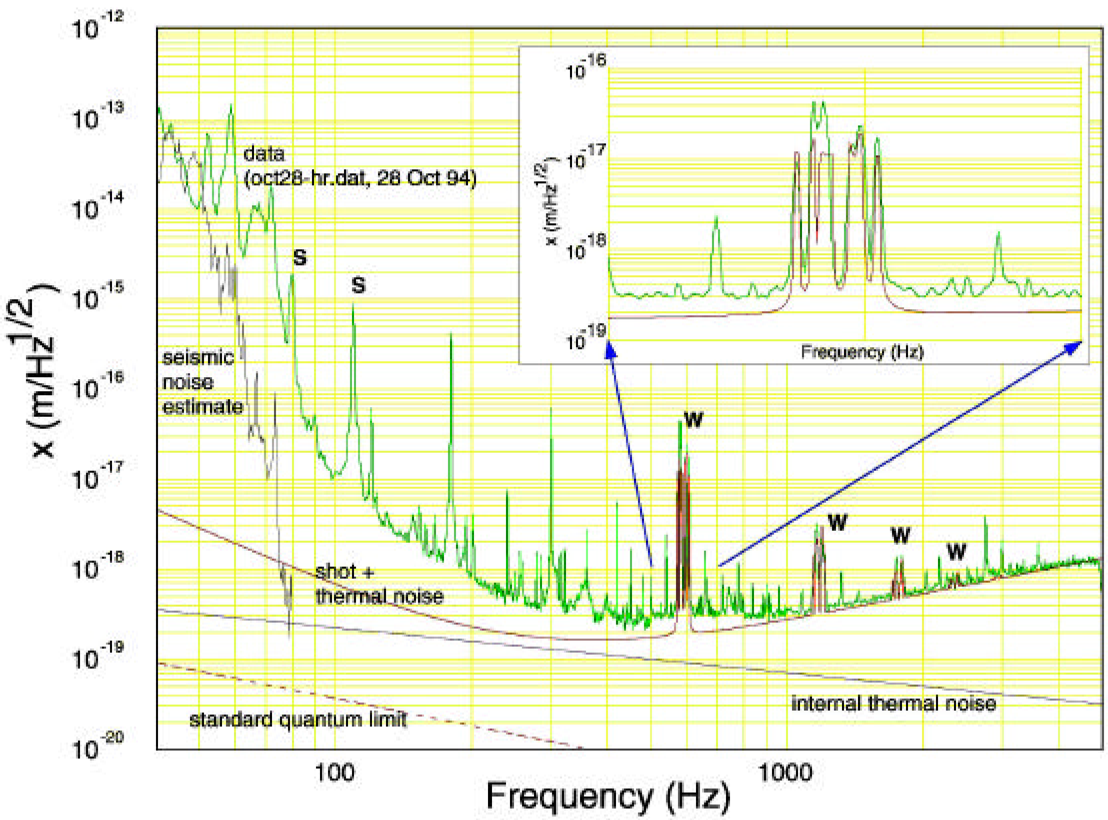
- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**



Noise Floor

40 m prototype

sensitivity demonstration



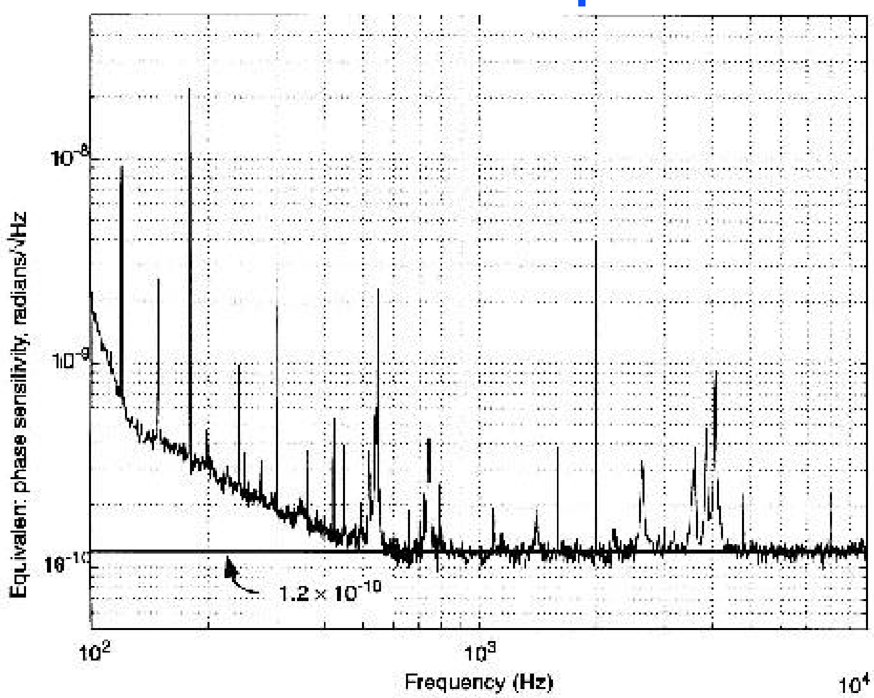
- **displacement sensitivity in 40 m prototype.**
- **comparison to predicted contributions from various noise sources**

Phase Noise

splitting the fringe

expected signal → 10^{-10} radians phase shift

demonstration experiment

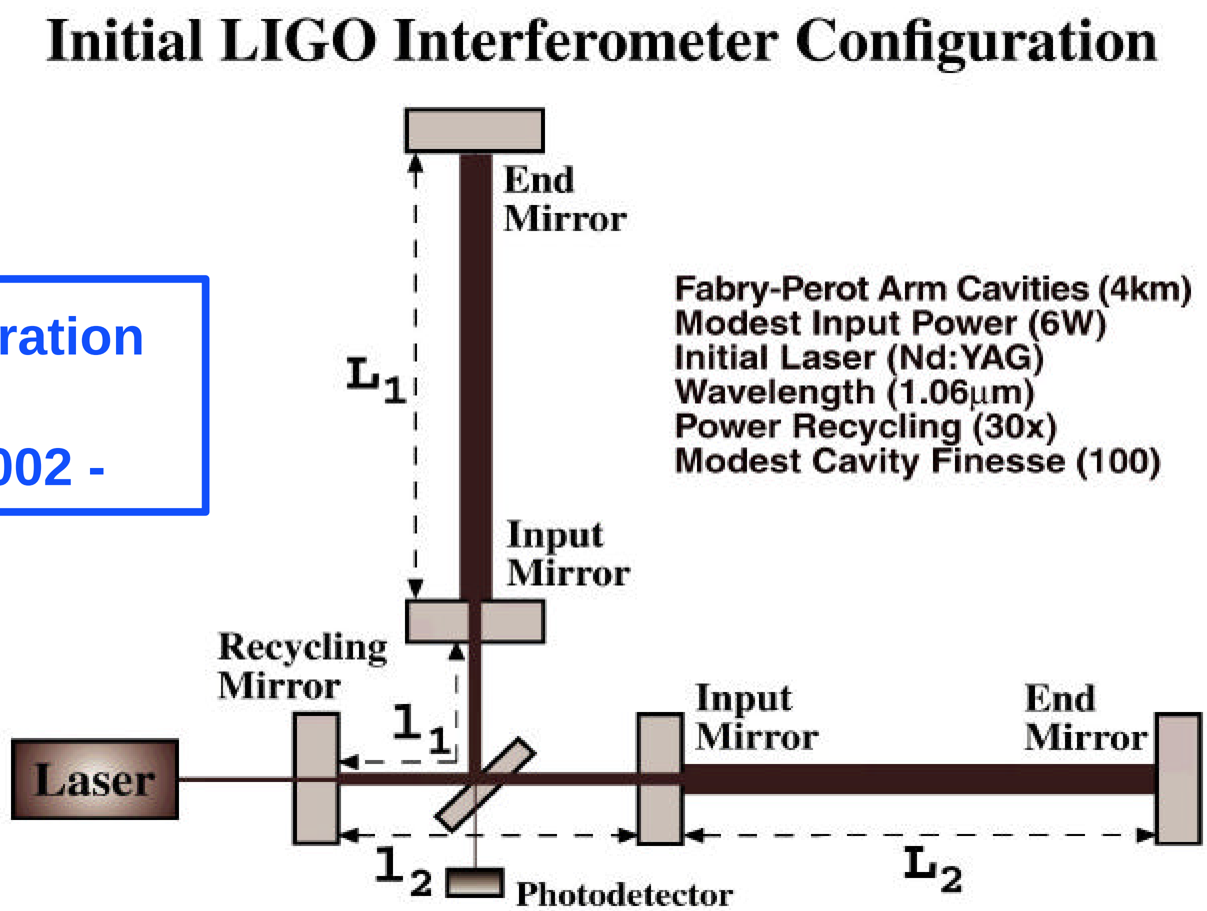


- **spectral sensitivity of MIT phase noise interferometer**
- **above 500 Hz shot noise limited near LIGO I goal**
- **additional features are from 60 Hz powerline harmonics, wire resonances (600 Hz), mount resonances, etc**

LIGO I

interferometer

- LIGO I configuration
- Science Run 2002 -



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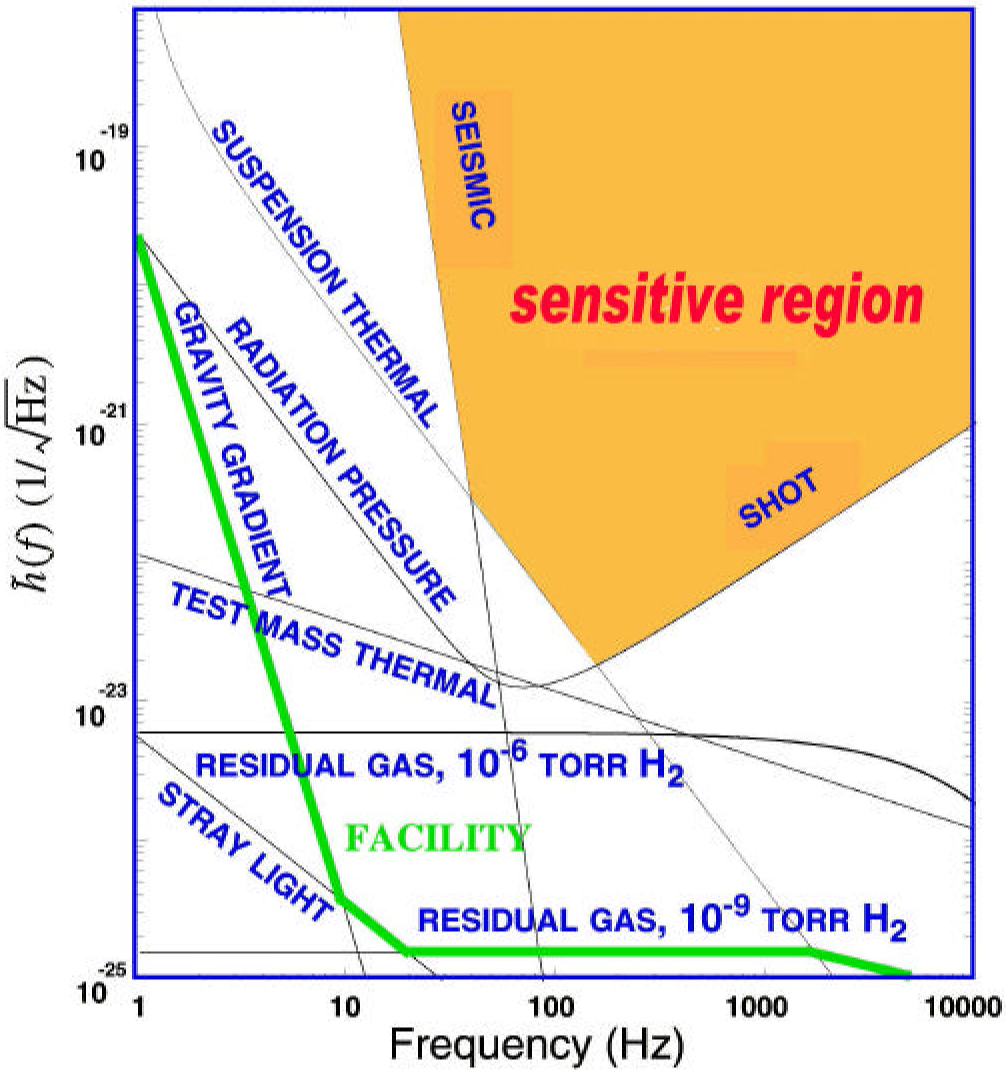
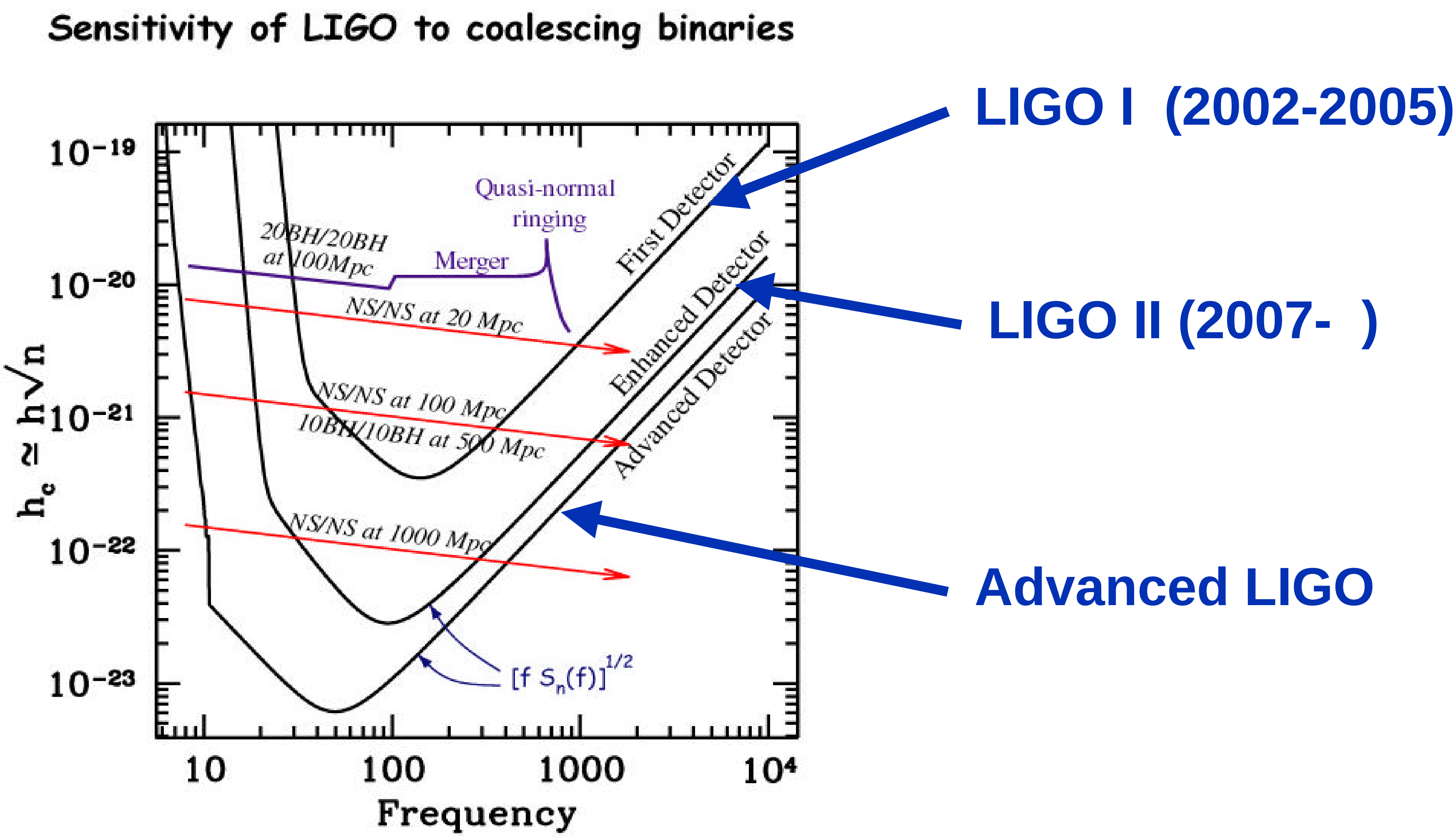


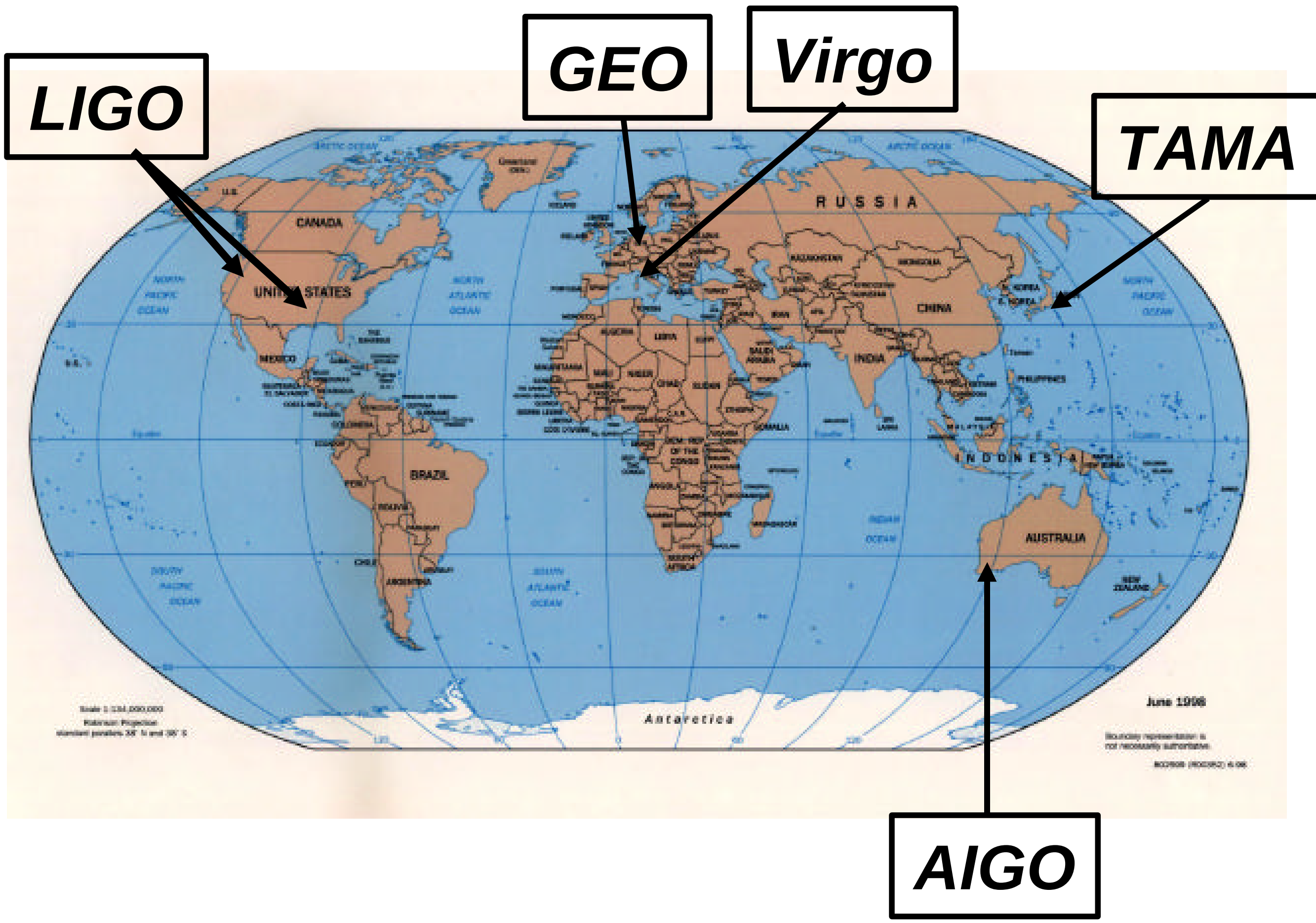
LIGO

astrophysical sources



Interferometers
international network

Simultaneously detect signal (within msec)



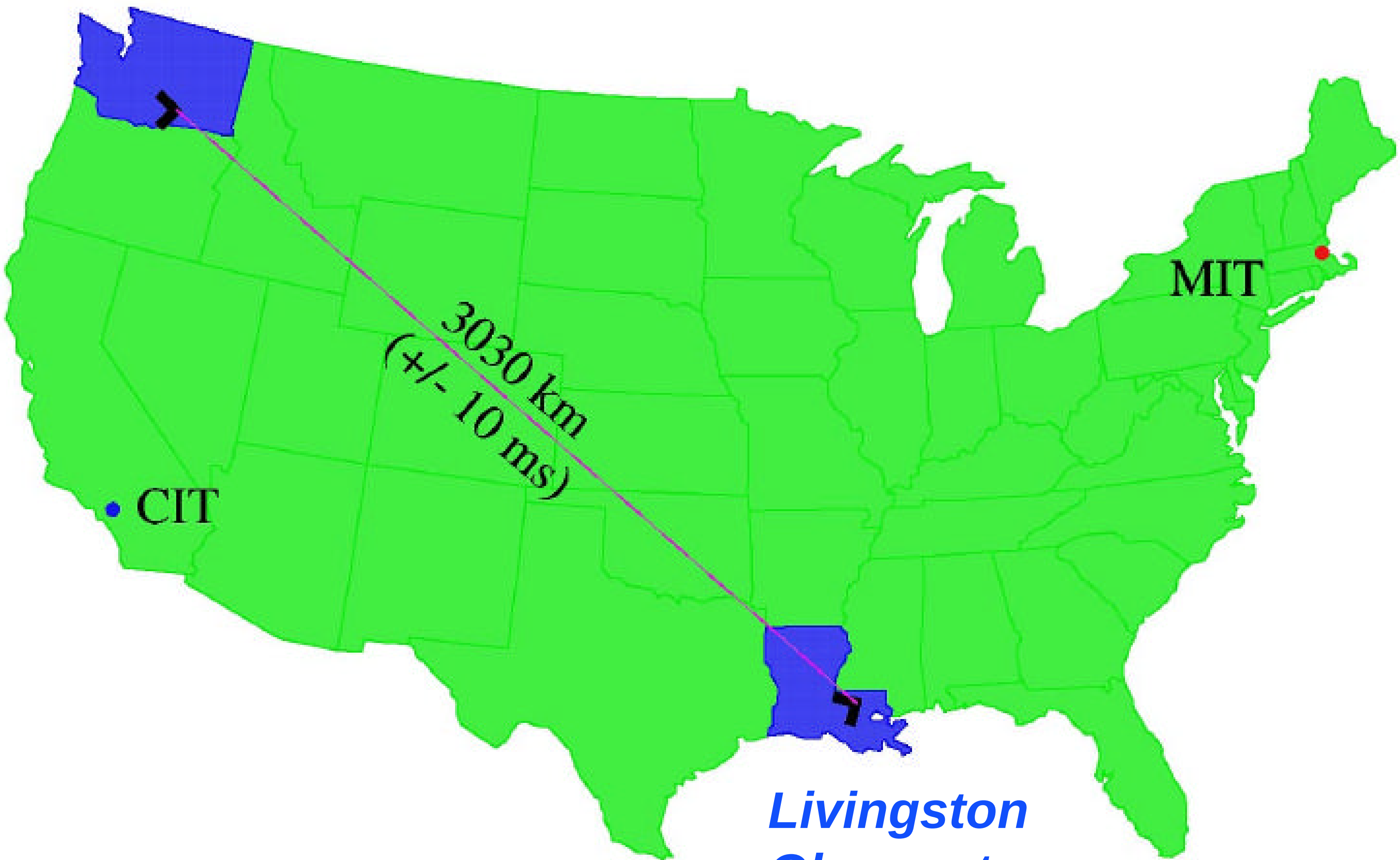
detection confidence

locate the sources

decompose the polarization of gravitational waves

LIGO Sites

Hanford Observatory

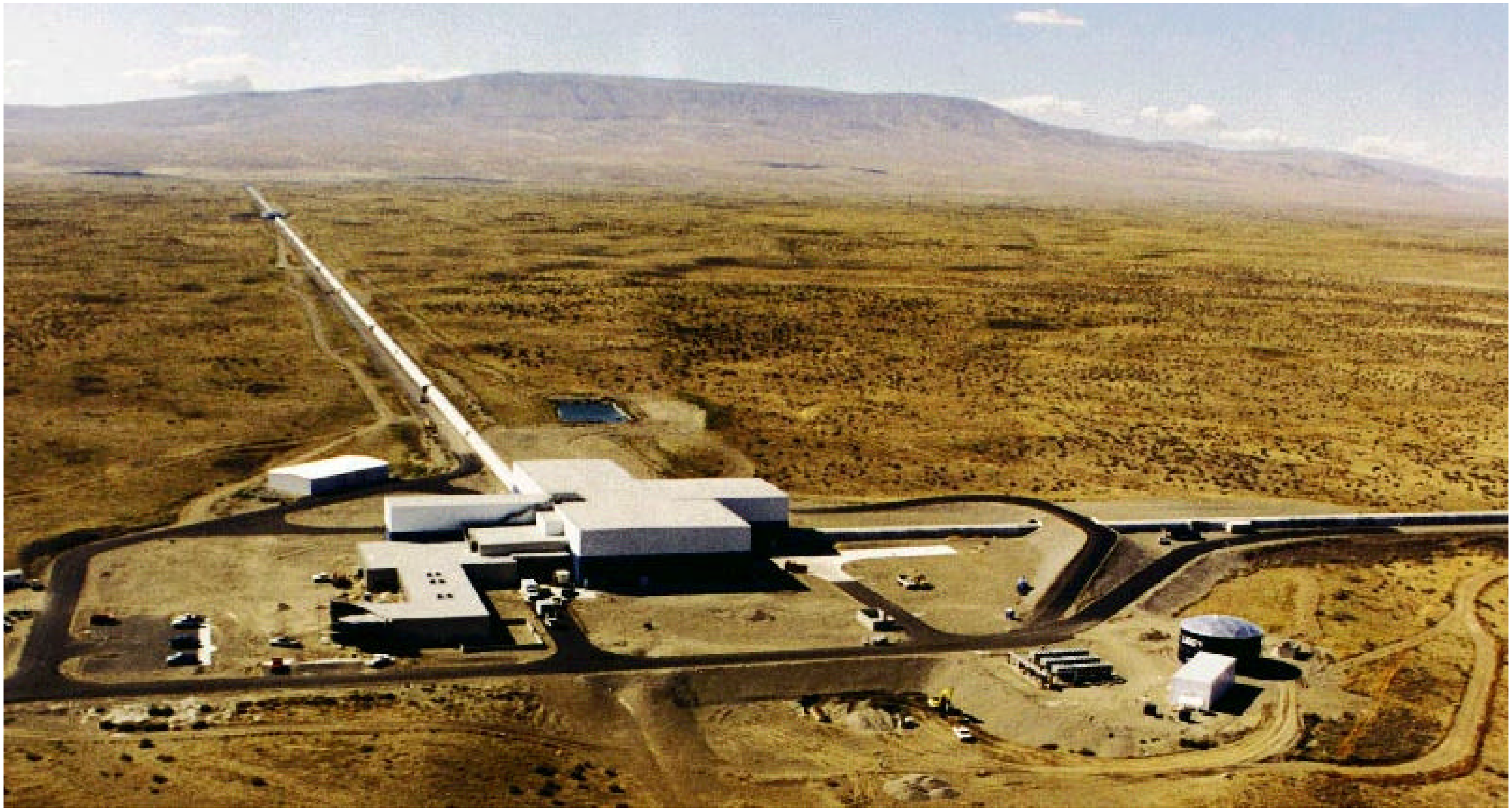


Livingston Observatory

LIGO
Livingston Observatory

LIGO

Hanford 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 Facilities

Beam Tube Enclosure

- minimal enclosure
- reinforced concrete
- no services

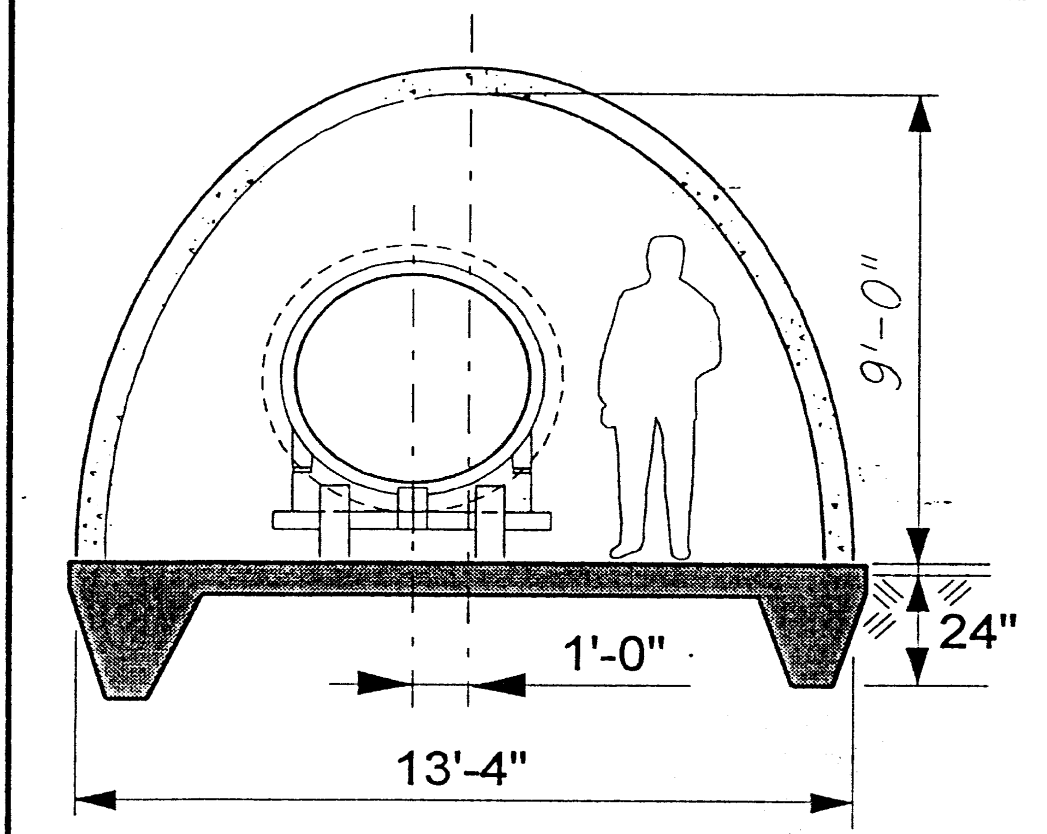


Figure 2.1-1 -- Cross Section of Design Baseline at Hanford

LIGO
Beam Tube

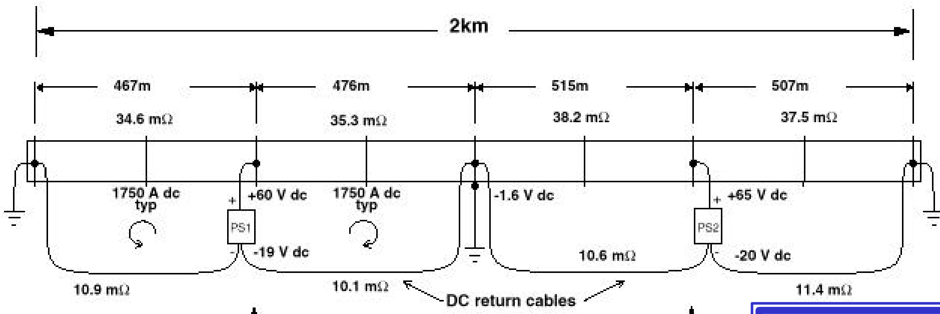
- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

1.2 m diameter - 3mm stainless
50 km of weld

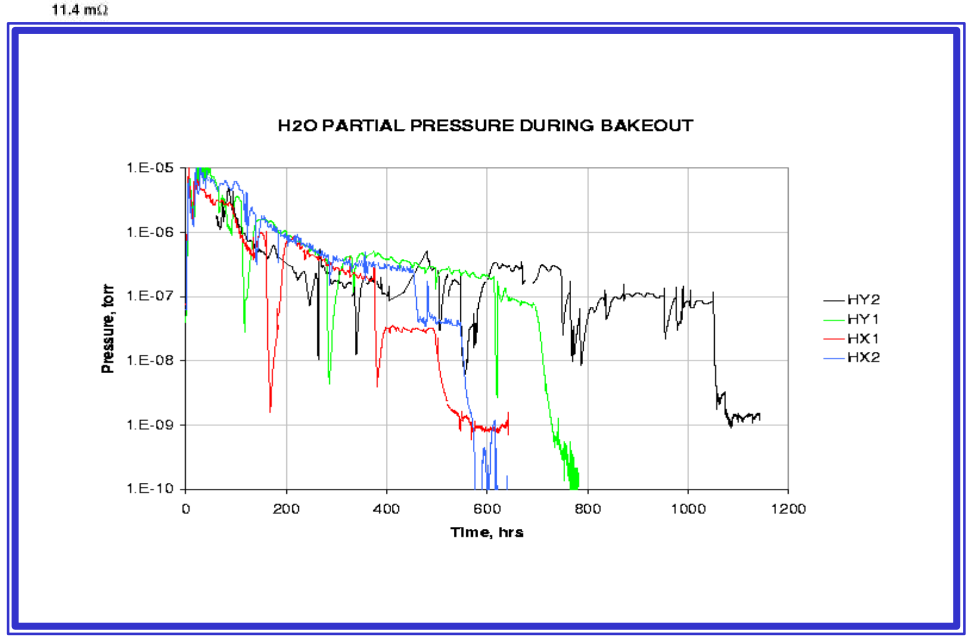
NO LEAKS !!

Beam Tube

bakeout



- I = 2000 amps for ~ 1 week
- no leaks !!
- final vacuum at level where not limiting noise, even for future detectors



LIGO I

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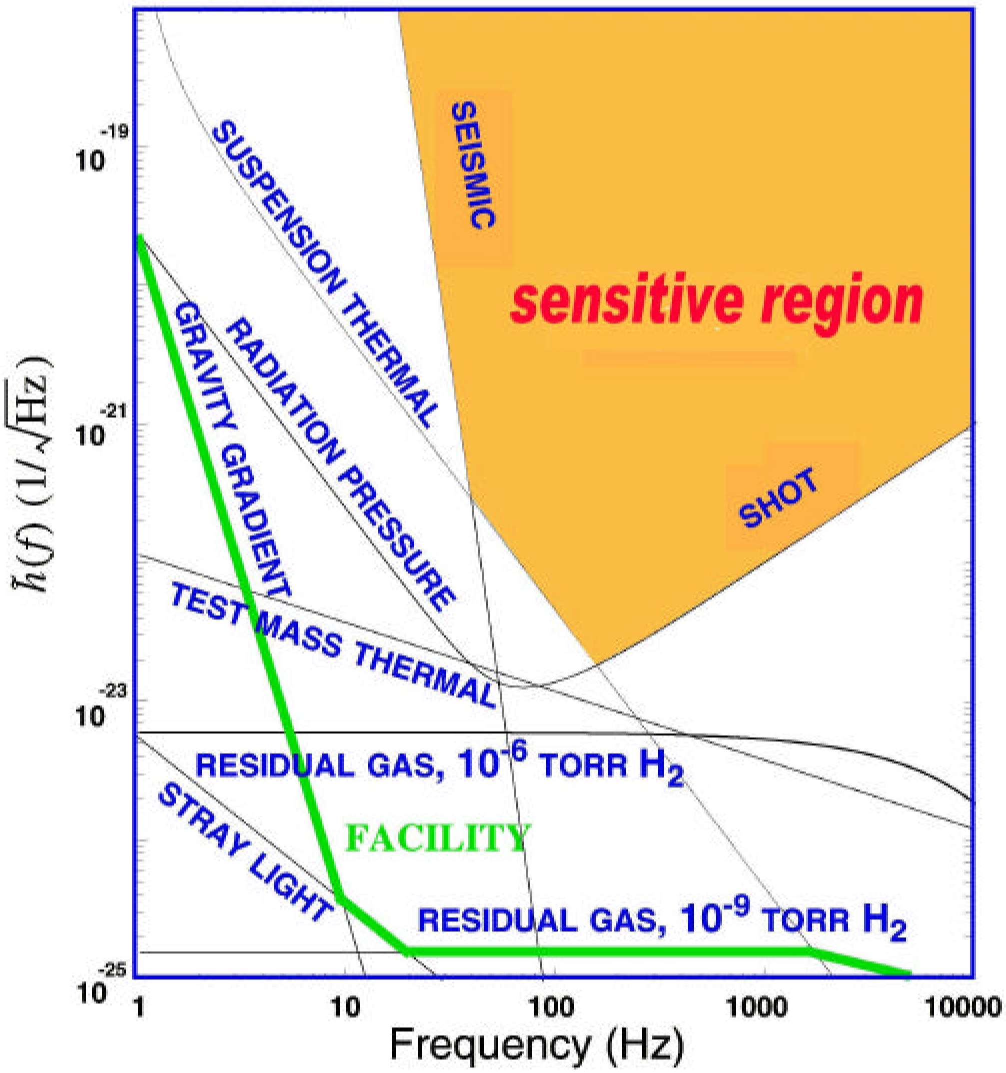


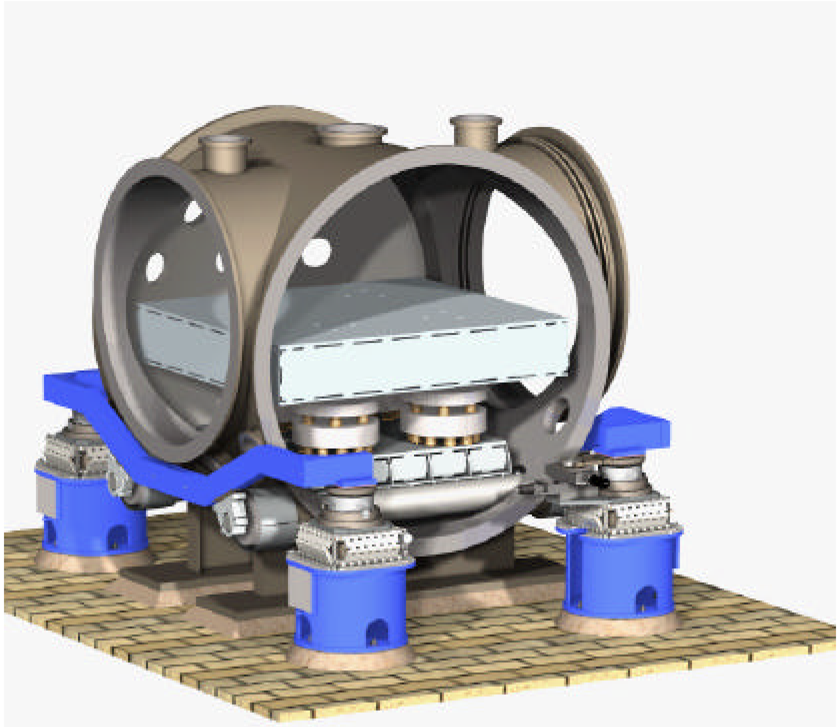
LIGO

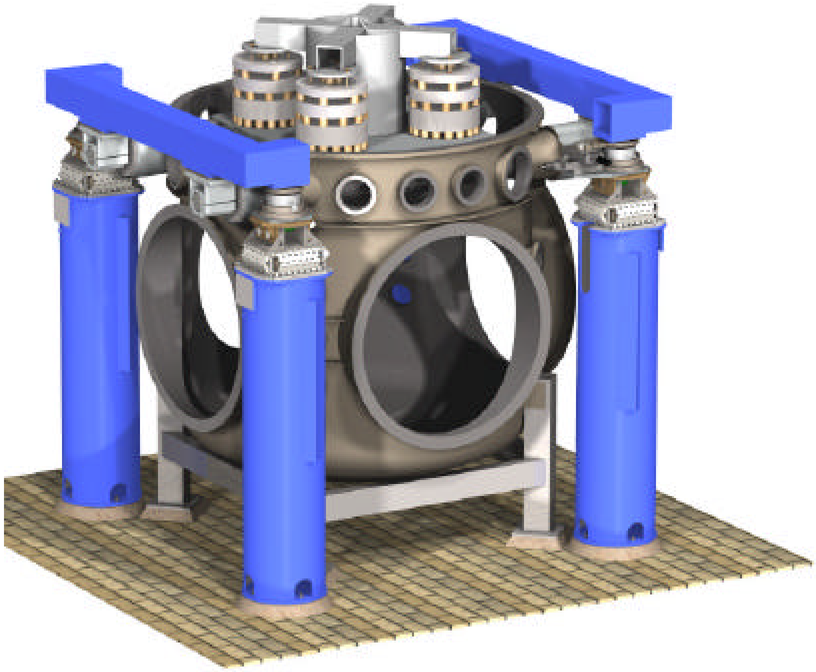
vacuum equipment

Vacuum Chambers

Vibration Isolation Systems

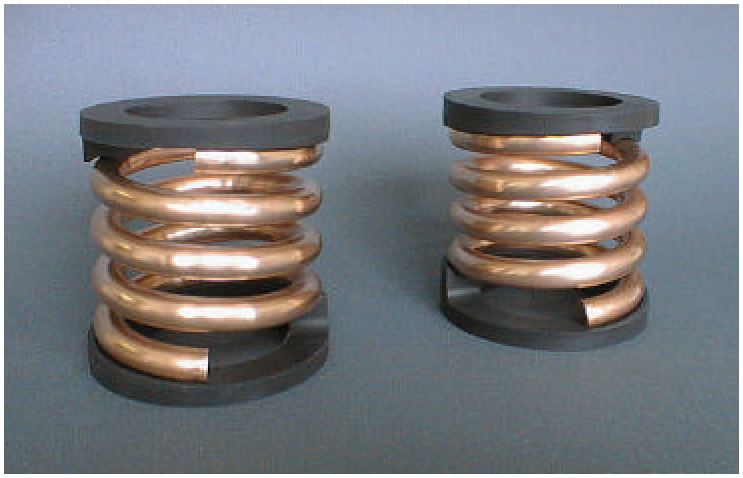
» Reduce in-band seismic motion by 4 - 6 orders of magnitude
» Compensate for microseism at 0.15 Hz by a factor of ten
» Compensate (partially) for Earth tides



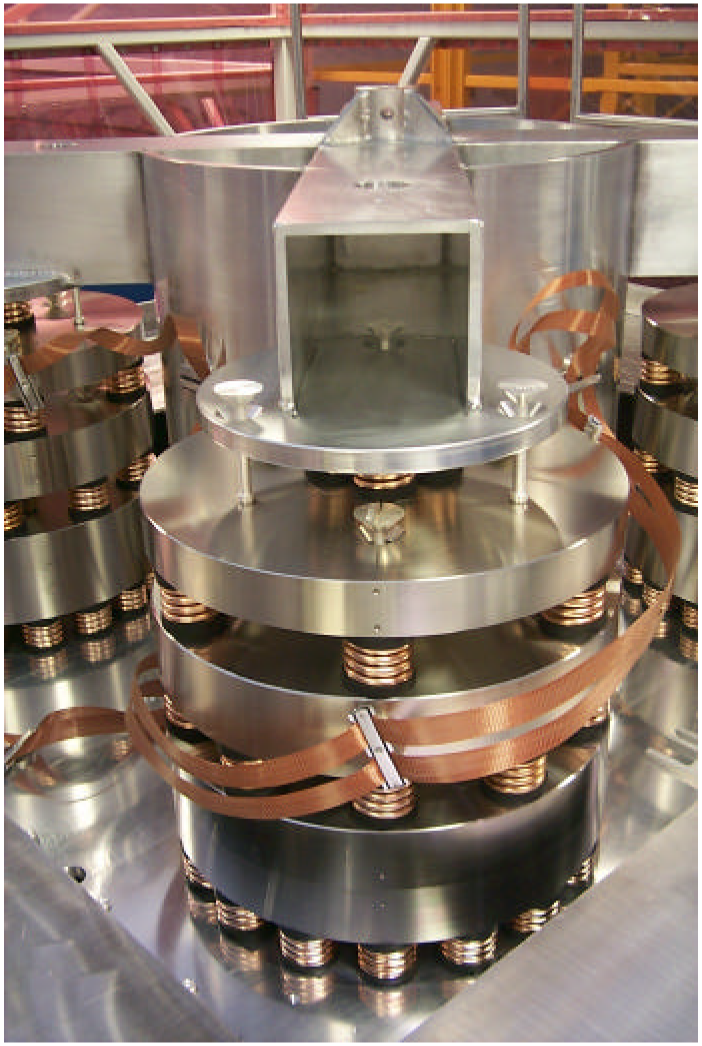


Seismic Isolation

Springs and Masses

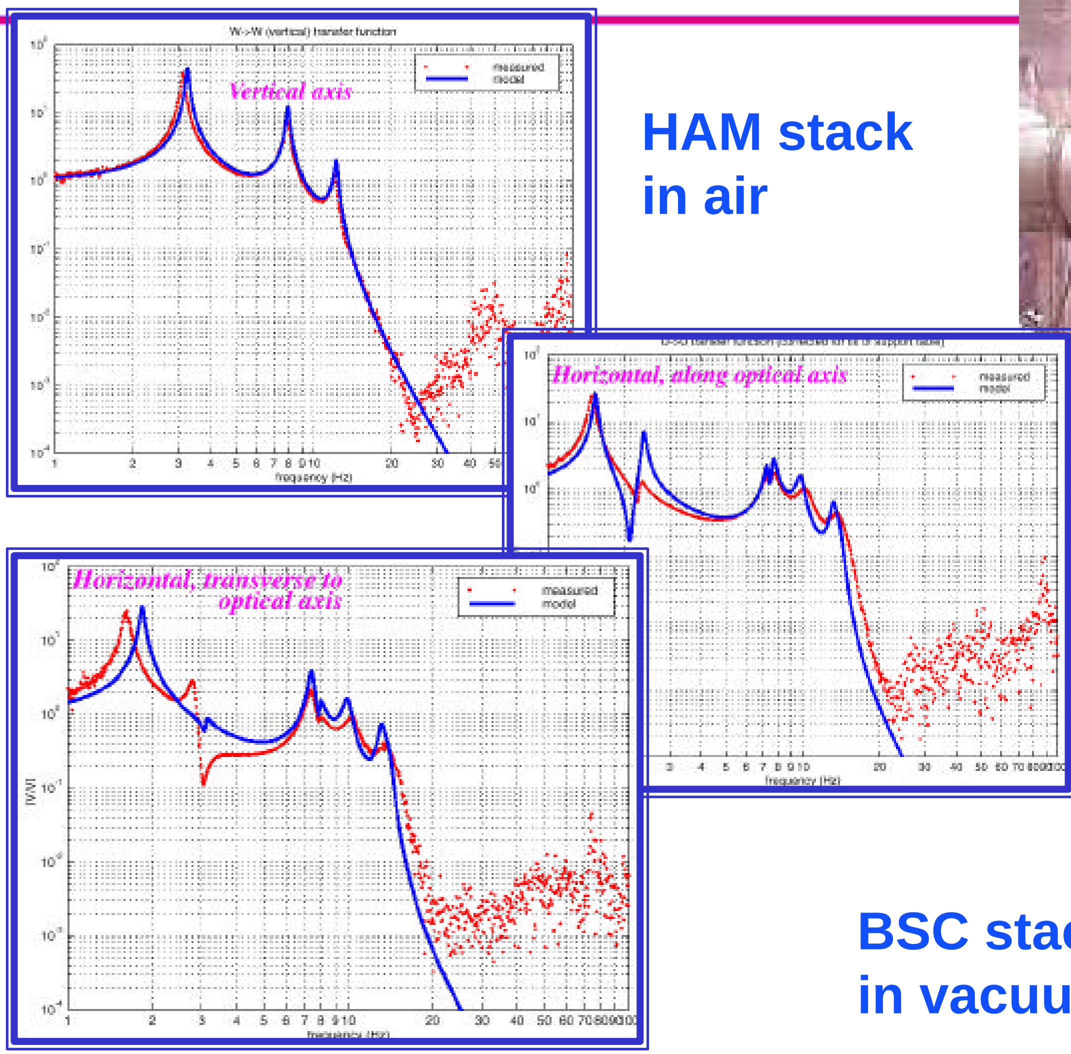


damped spring cross section



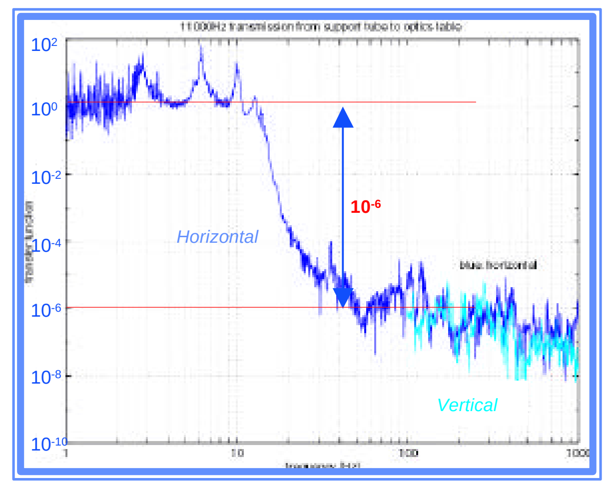
Seismic Isolation

performance



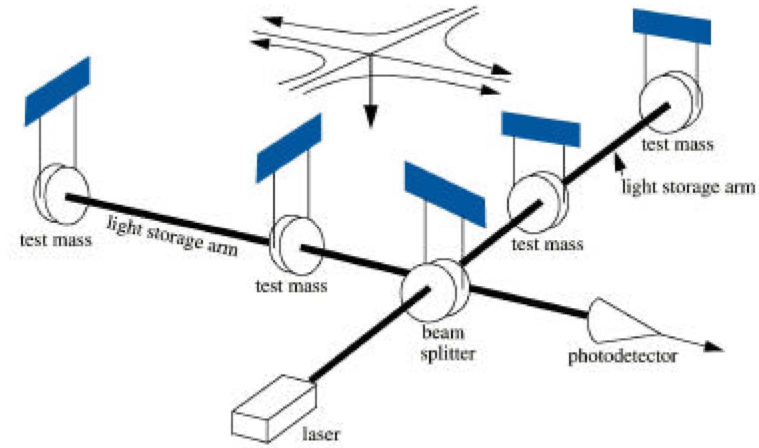
HAM stack
in air

BSC stack
in vacuum



Seismic Isolation

suspension system

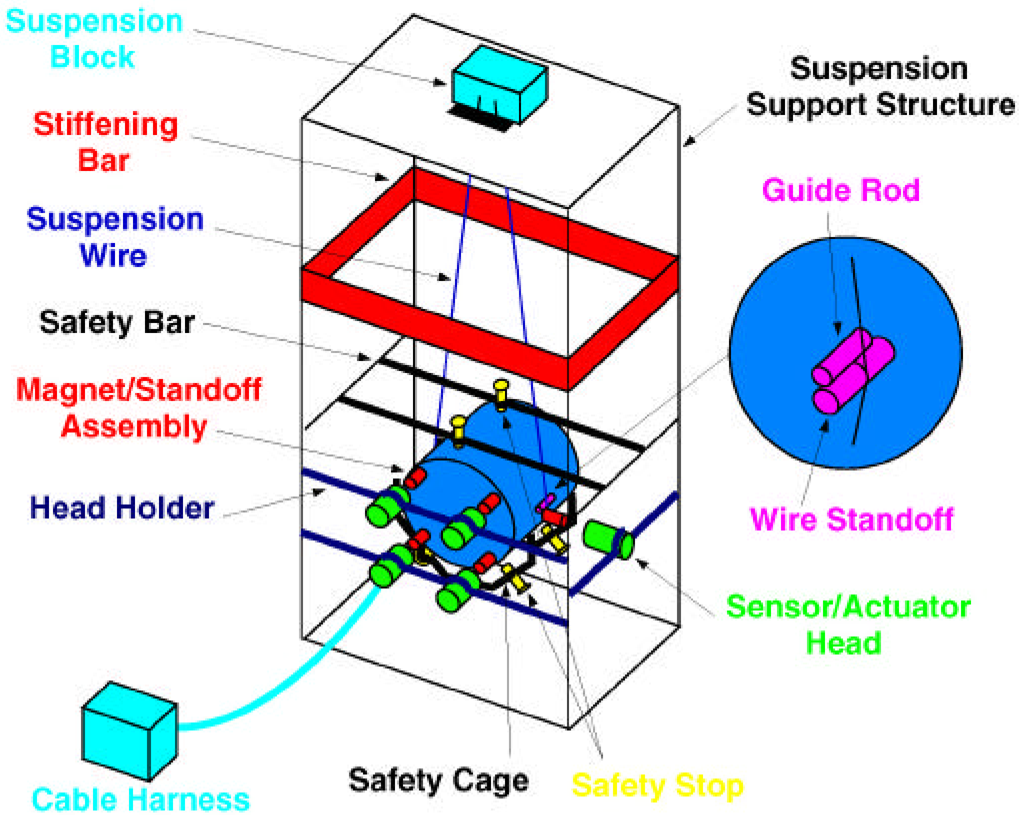


• support structure is welded tubular stainless steel

• suspension wire is 0.31 mm diameter steel music wire

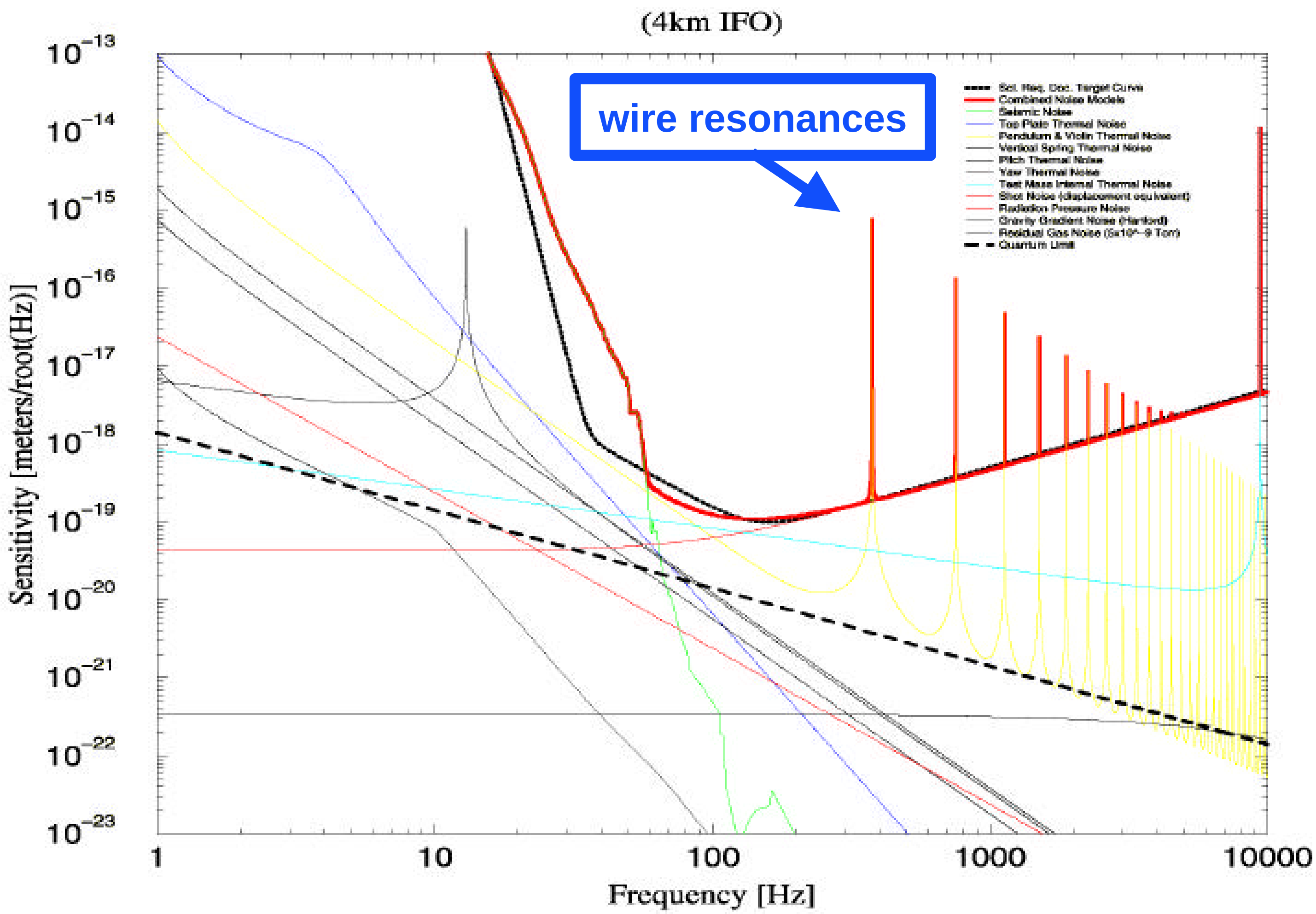
• fundamental violin mode frequency of 340 Hz

suspension assembly for a core optic



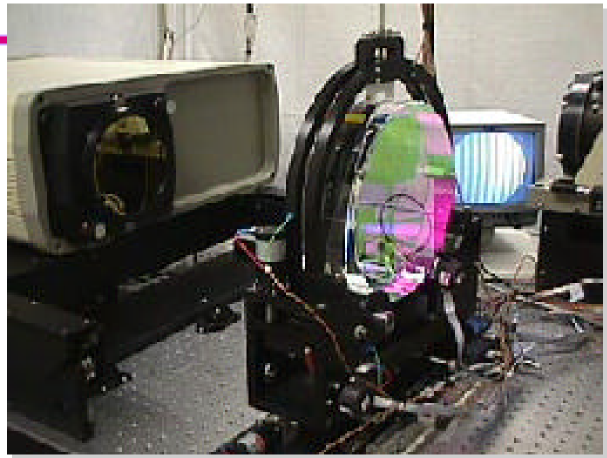
LIGO Noise Curves

modeled

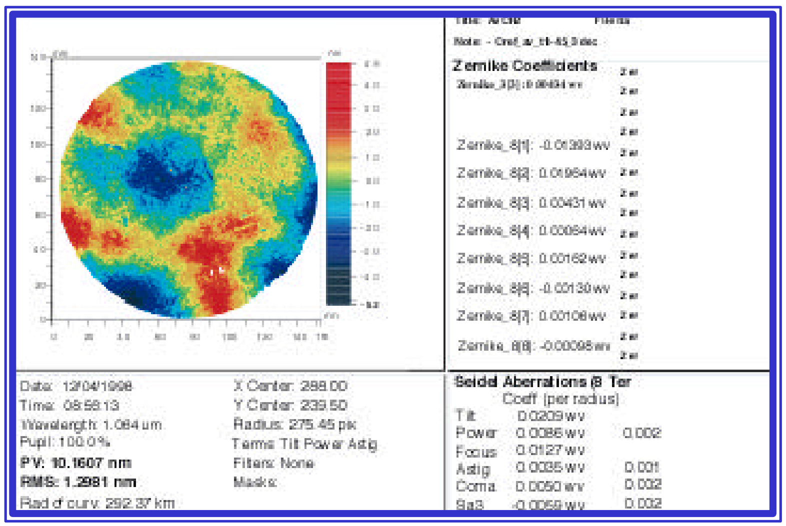


Core Optics

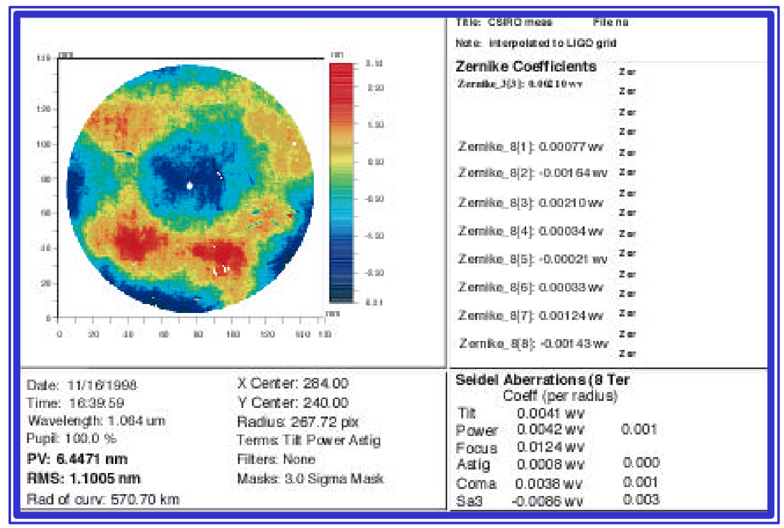
fused silica



- **Surface uniformity < 1 nm rms**
- **Scatter < 50 ppm**
- **Absorption < 2 ppm**
- **ROC matched < 3%**
- **Internal mode Q's > 2 x 10^6**



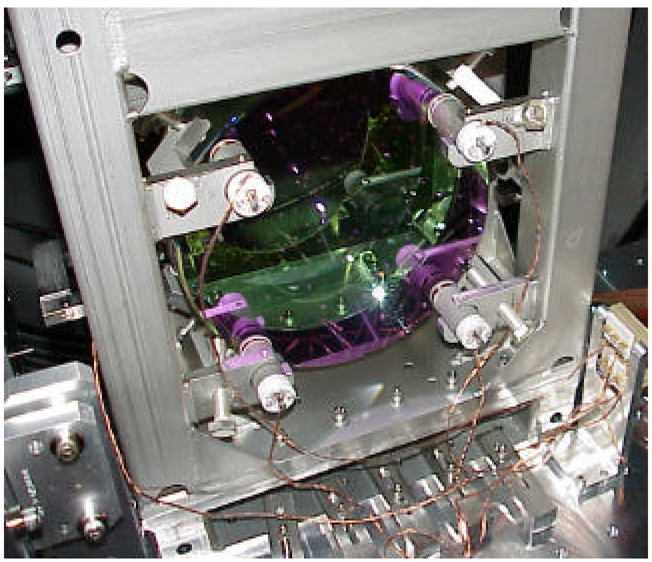
Caltech data

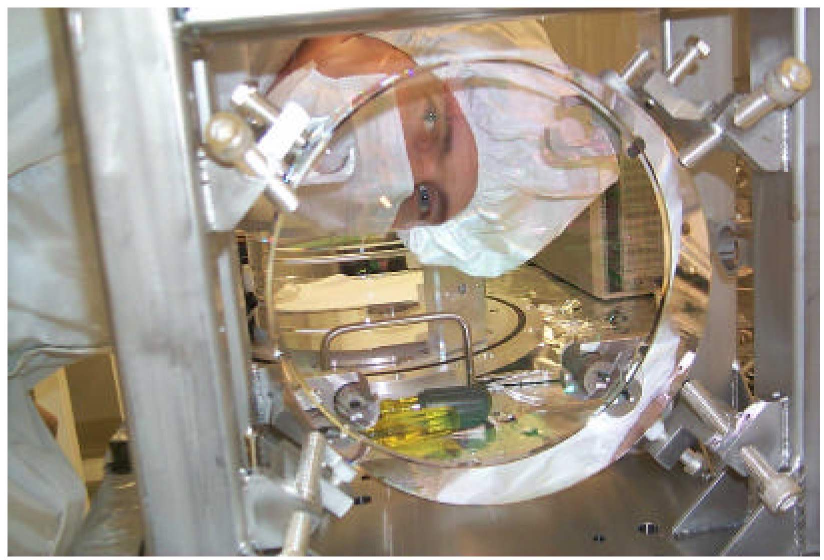


CSIRO data

Core Optics

Suspension



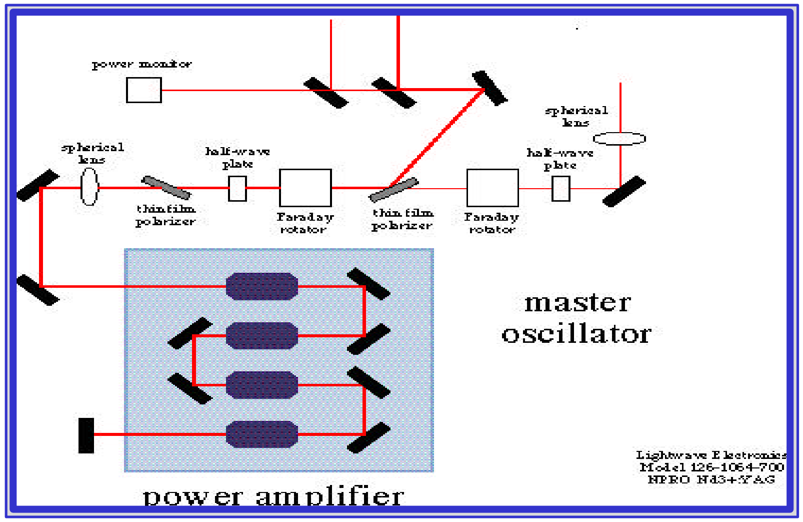


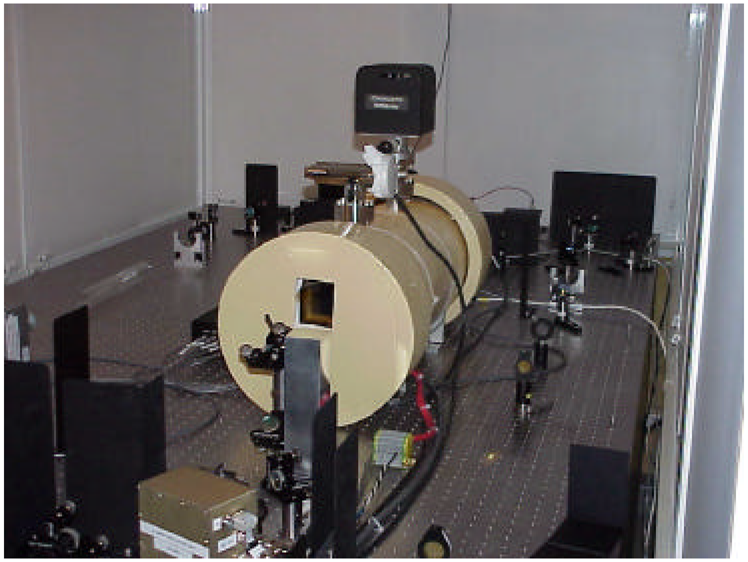
Core Optics
Installation and Alignment

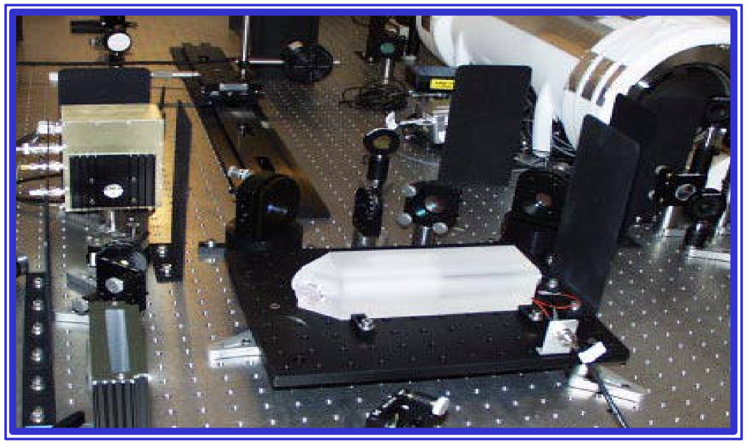
LIGO

Laser

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



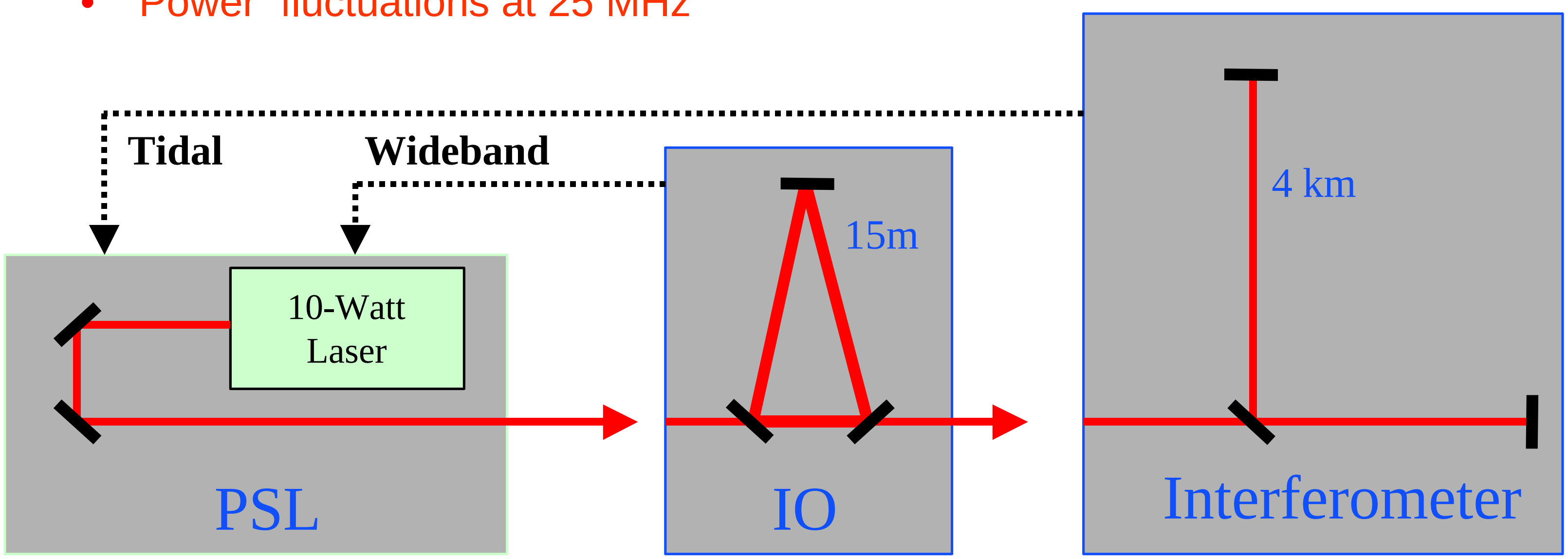




Laser

stabilization

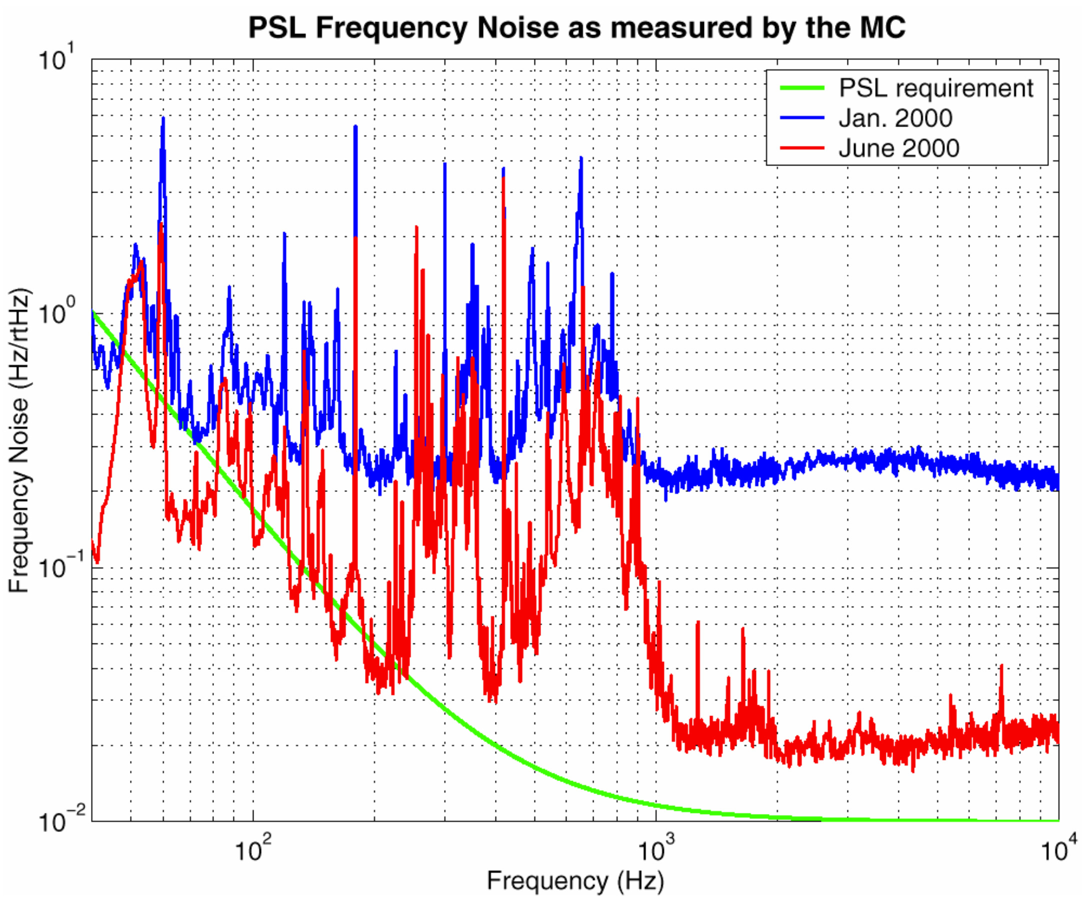
- **Deliver pre-stabilized laser light to the 15-m mode cleaner**
  - Frequency fluctuations
  - In-band power fluctuations
  - Power fluctuations at 25 MHz
- Provide actuator inputs for further stabilization
  - **Wideband**
  - **Tidal**



10^{-1} Hz/Hz$^{1/2}$ 10^{-4} Hz/ Hz$^{1/2}$ 10^{-7} Hz/ Hz$^{1/2}$

Prestabalized Laser

performance



- > 18,000 hours continuous operation
- Frequency and lock very robust
- TEM_{00} power > 8 watts
- Non-TEM_{00} power < 10%

Commissioning

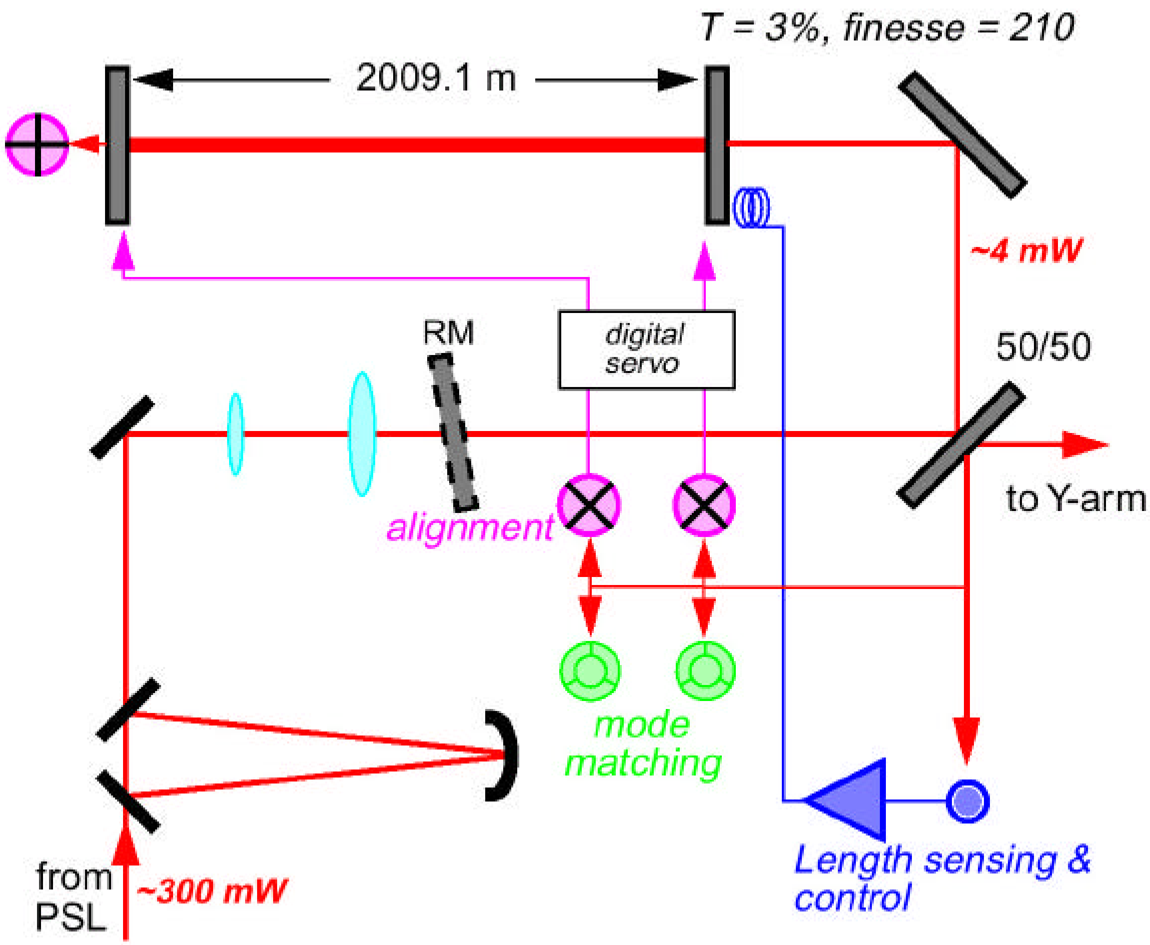
Configurations

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

- **Lock entire Michelson Fabry-Perot interferometer**

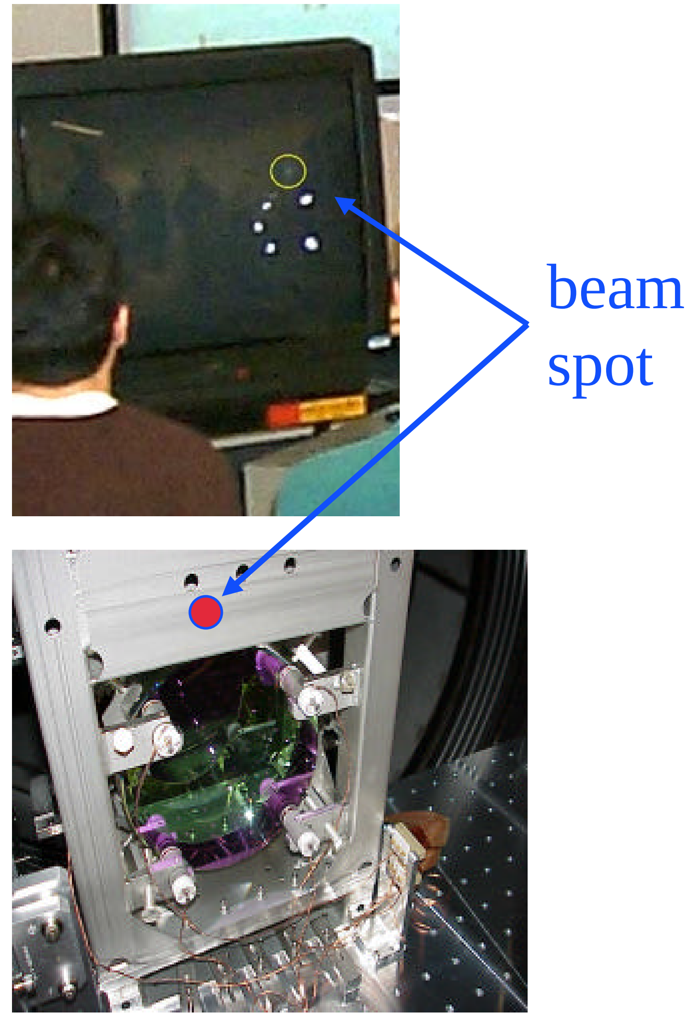
"FIRST LOCK"

Detector Commissioning:
2-km Arm Test



- **12/99 – 3/00**
- **Alignment "dead reckoning" worked**
- **Digital controls, networks, and software all worked**
- **Exercised fast analog laser frequency control**
- **Verified that core optics meet specs**
- **Long-term drifts consistent with earth tides**

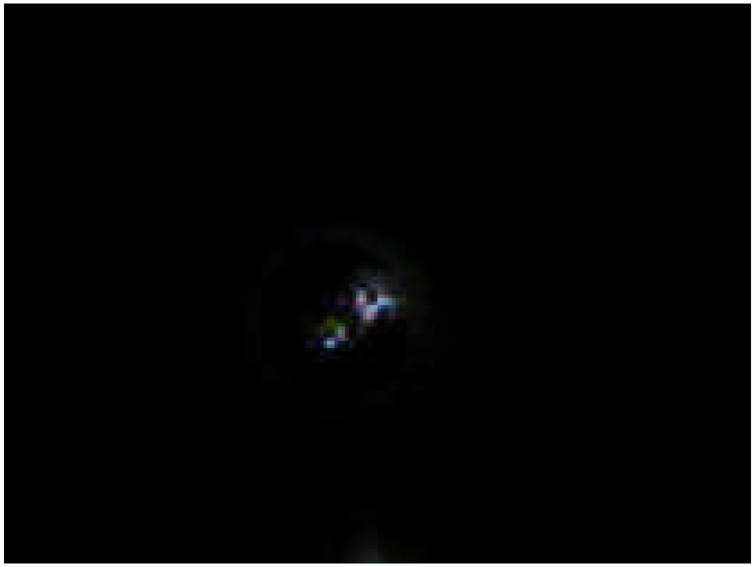
Confirmation of Initial Alignment



- **Opening gate valves revealed alignment “dead reckoned” from corner station was within 100 micro radians**

Locking the Long Arm

- 12/1/99 Flashes of light
- 12/9/99 0.2 seconds lock
- 1/14/00 2 seconds lock
- 1/19/00 60 seconds lock
- 1/21/00 5 minutes lock (on other arm)
- 2/12/00 18 minutes lock
- 3/4/00 90 minutes lock (temperature stabilized laser reference cavity)
- 3/26/00 10 hours lock

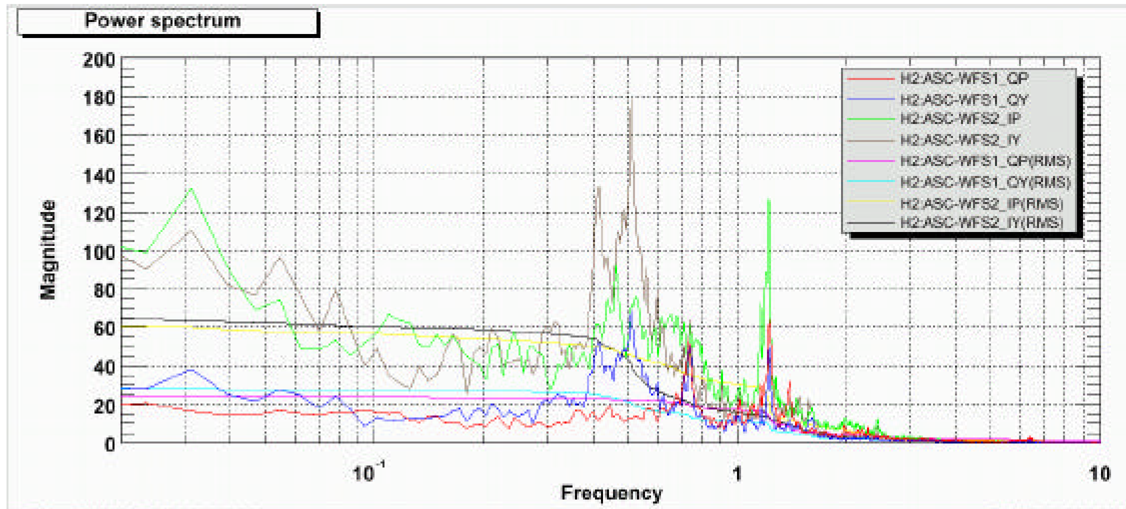


First interference fringes from the 2-km arm

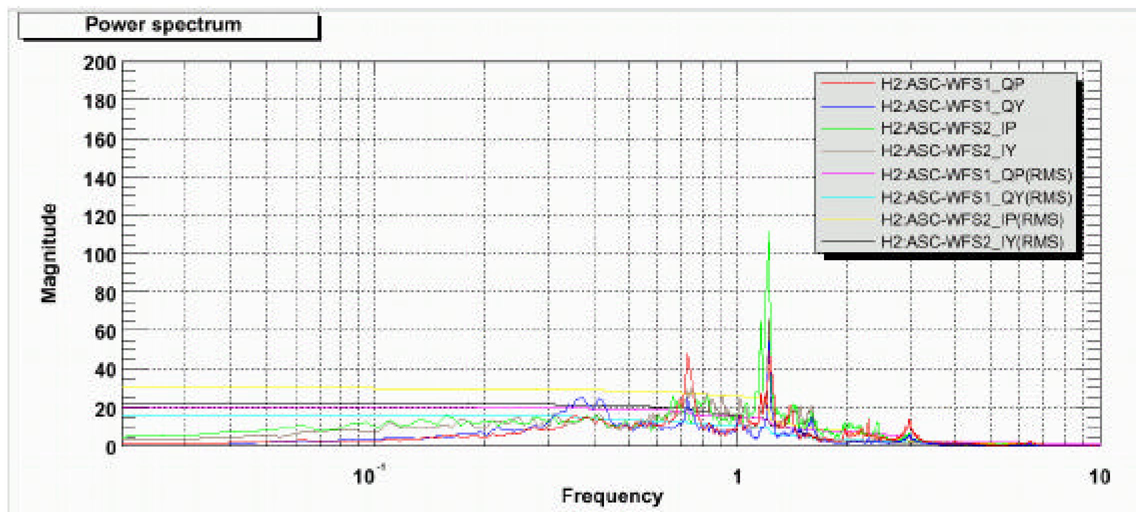
locked long arm

alignment - wavefront sensors

Alignment fluctuations before engaging wavefront sensors

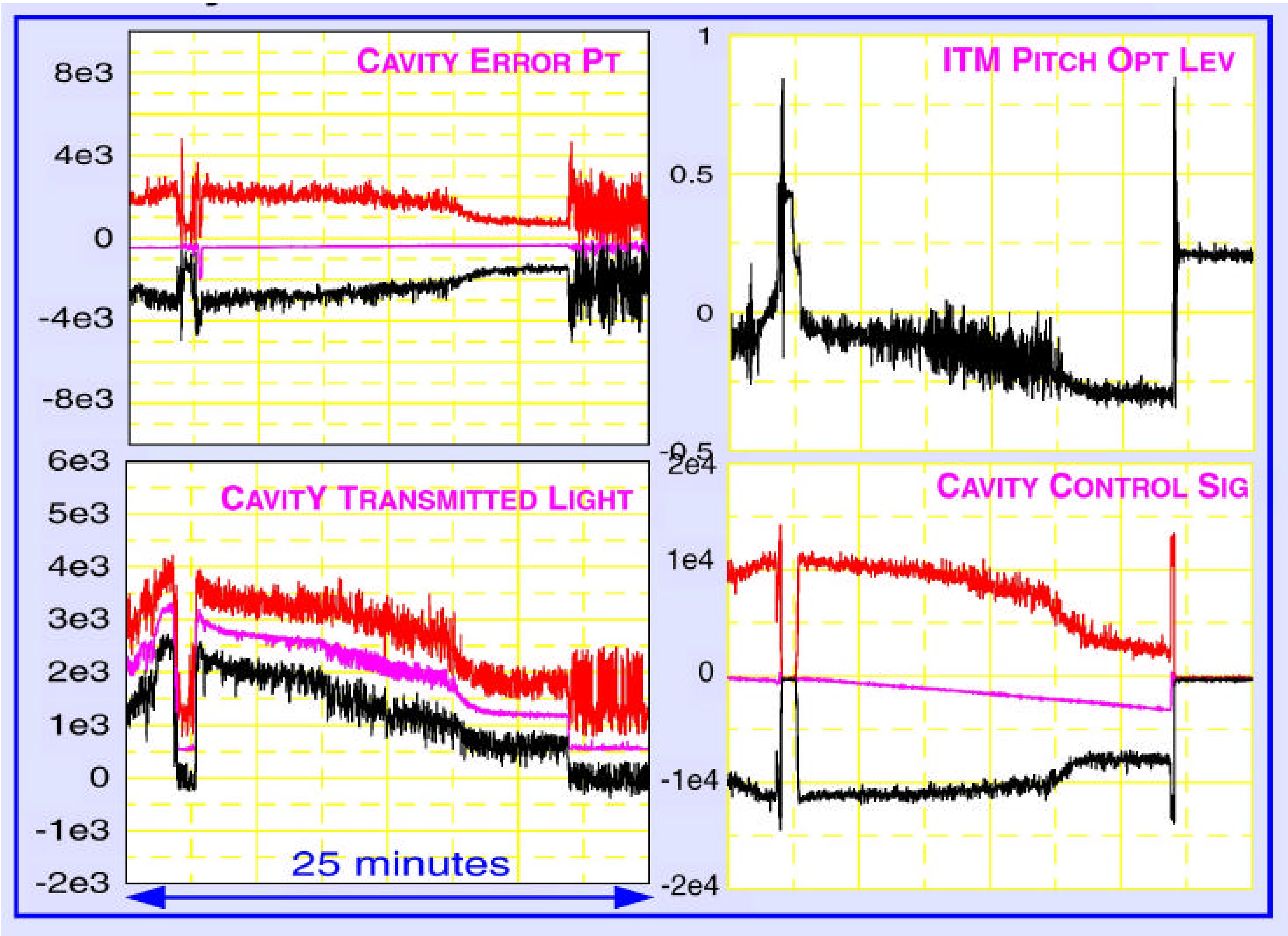


After engaging wavefront sensors



2km Fabry-Perot cavity

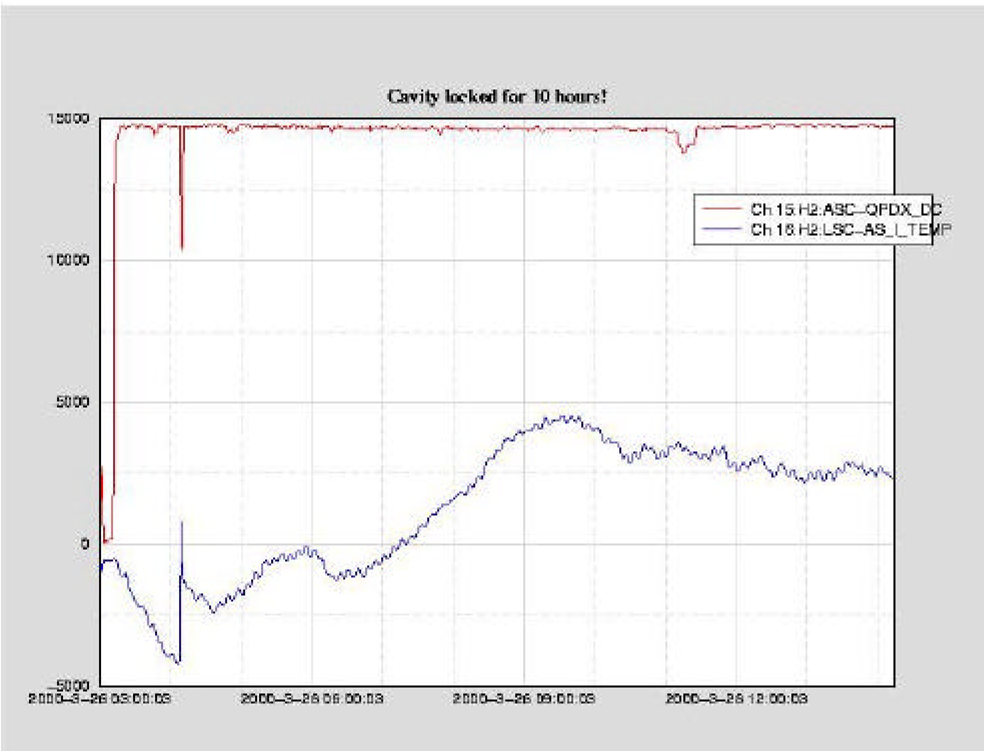
15 minute locked stretch



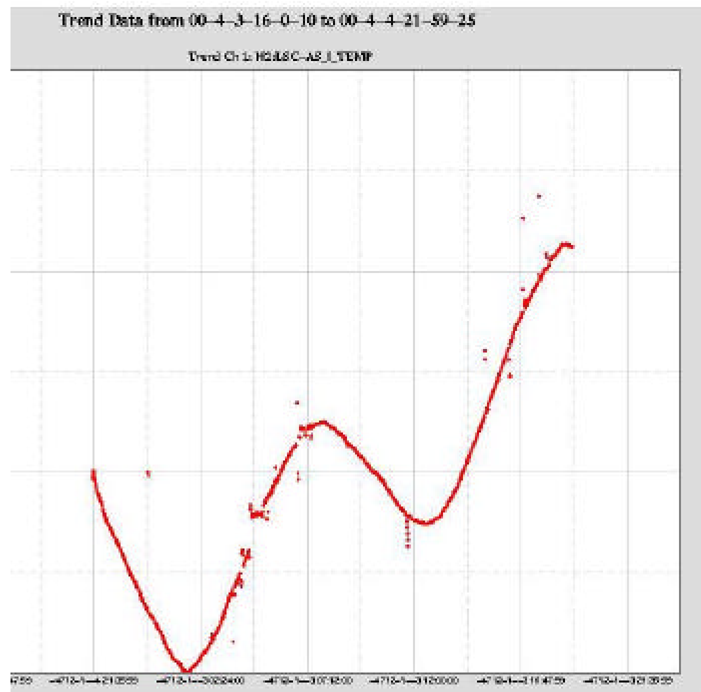
Locked long arm

long term effects

10 hour locked section



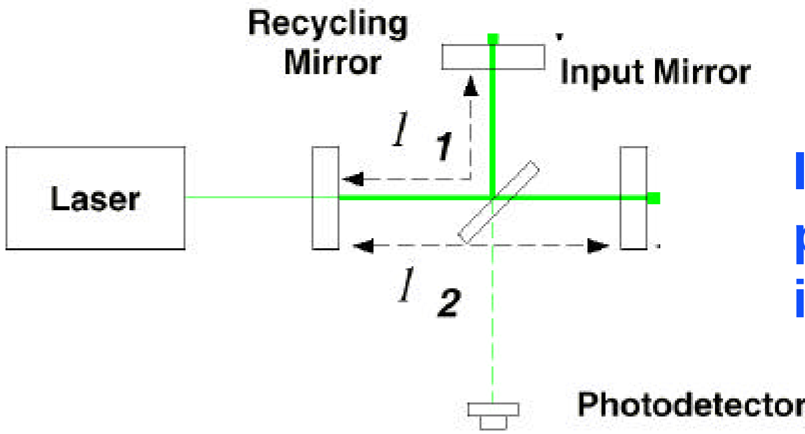
Stretching consistent with earth tides



Near-Michelson interferometer

- power recycled (short) Michelson Interferometer

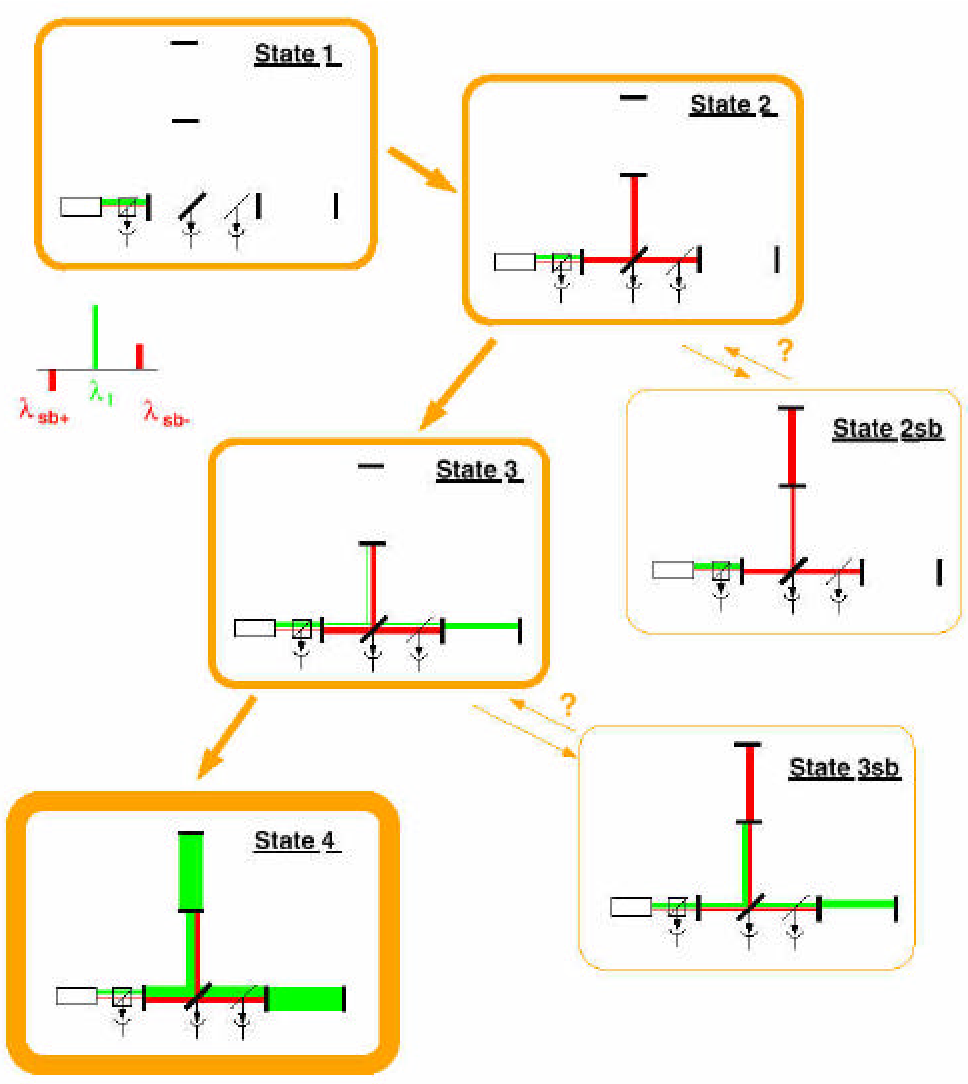
- employs full mixed digital/analog servos



Interference fringes from the power recycled near Michelson interferometer

Complete Interferometer
locking

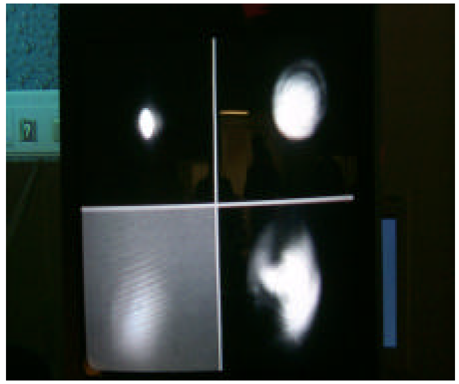
Interferometer lock states



Brief Locked Stretch

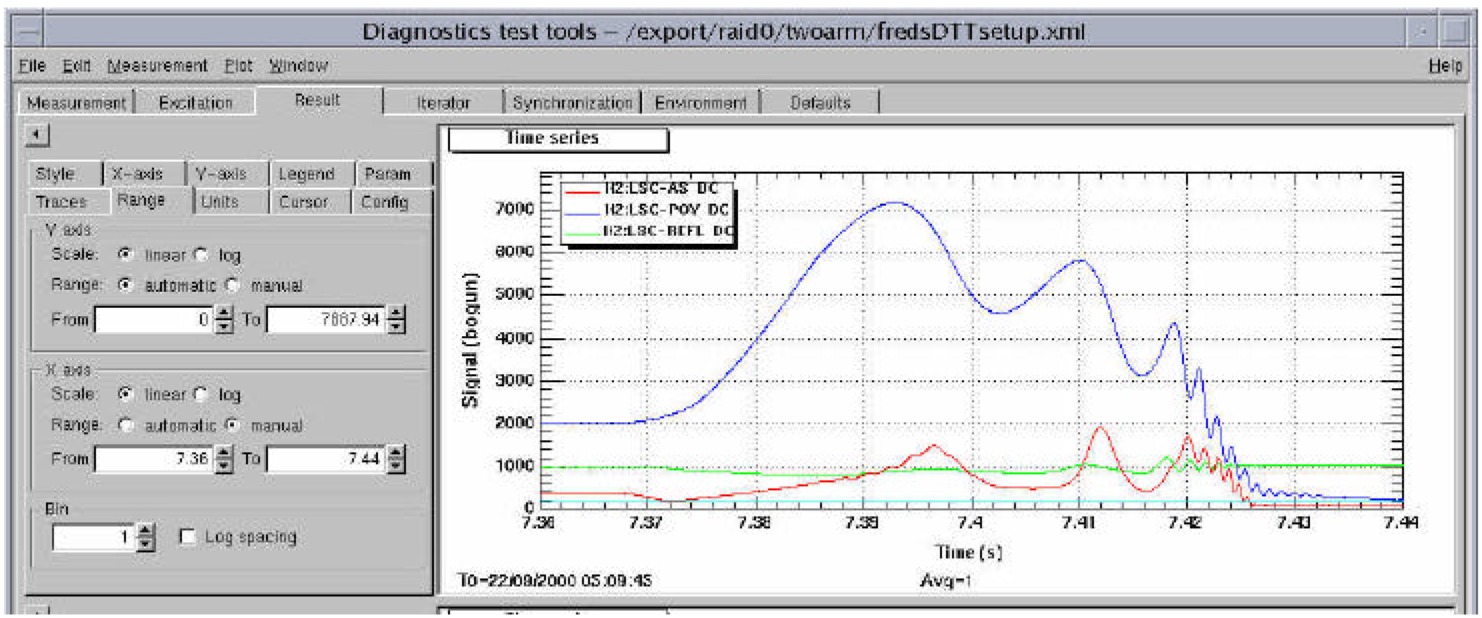
Y arm

Reflected light



X arm

Anti-symmetric port

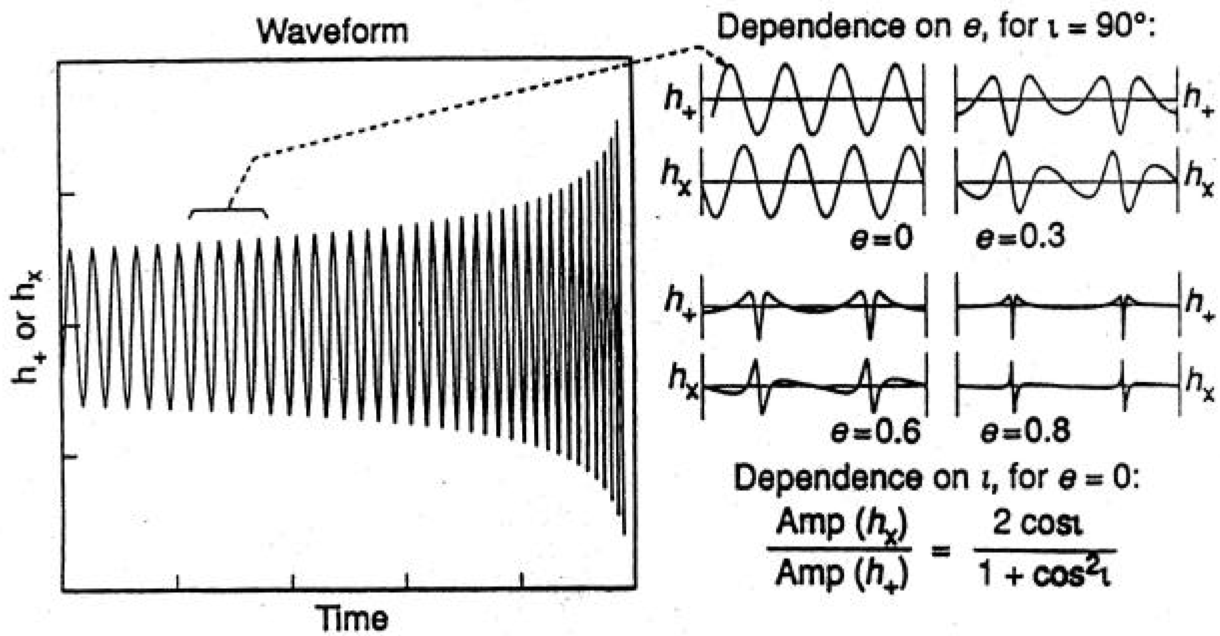


Significant Events

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

Chirp Signal

binary inspiral



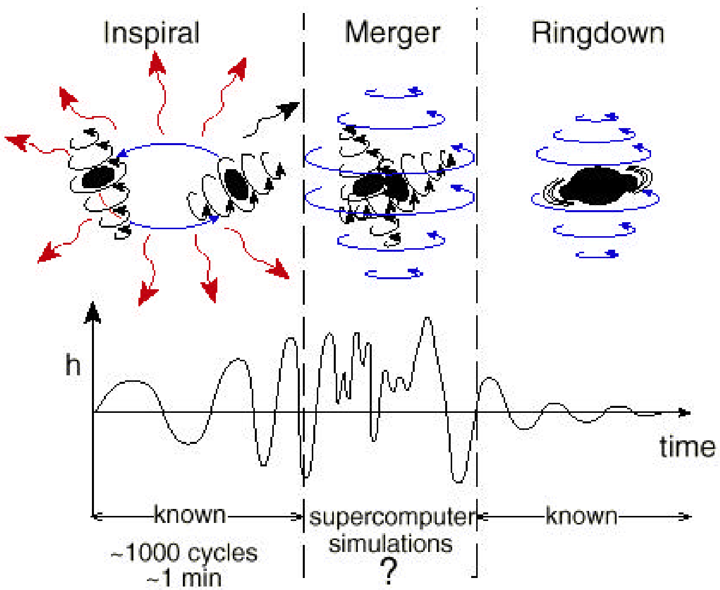
<u>determine</u>

- **distance from the earth r**
- **masses of the two bodies**
- **orbital eccentricity e and orbital inclination *i***

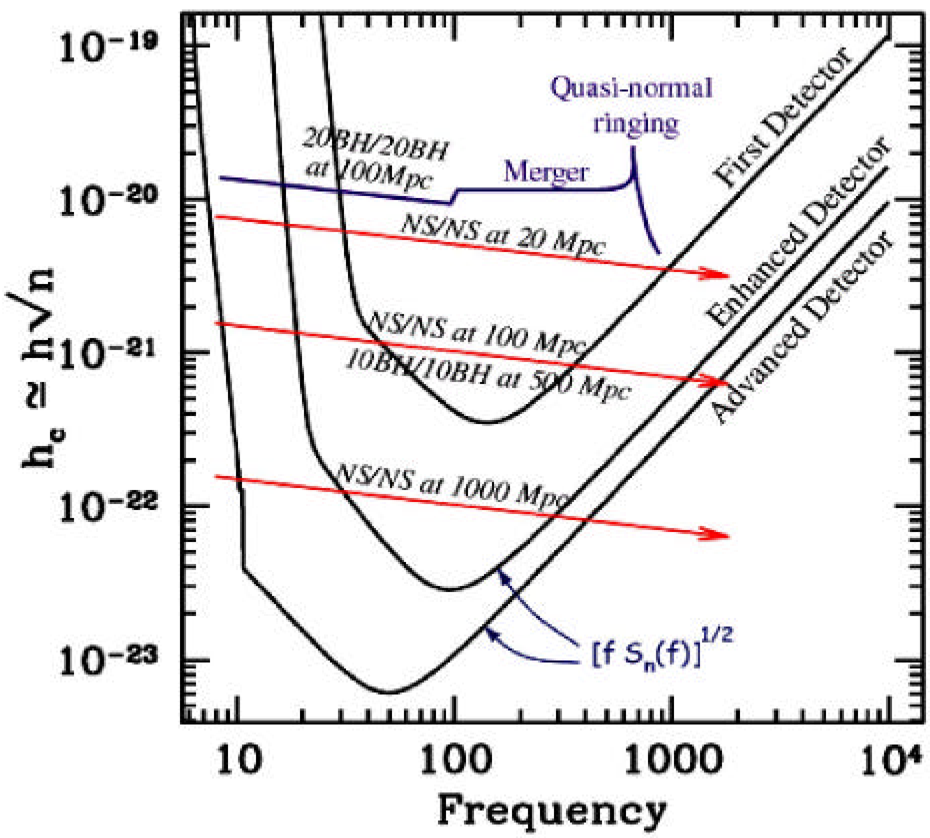
LIGO

astrophysical sources

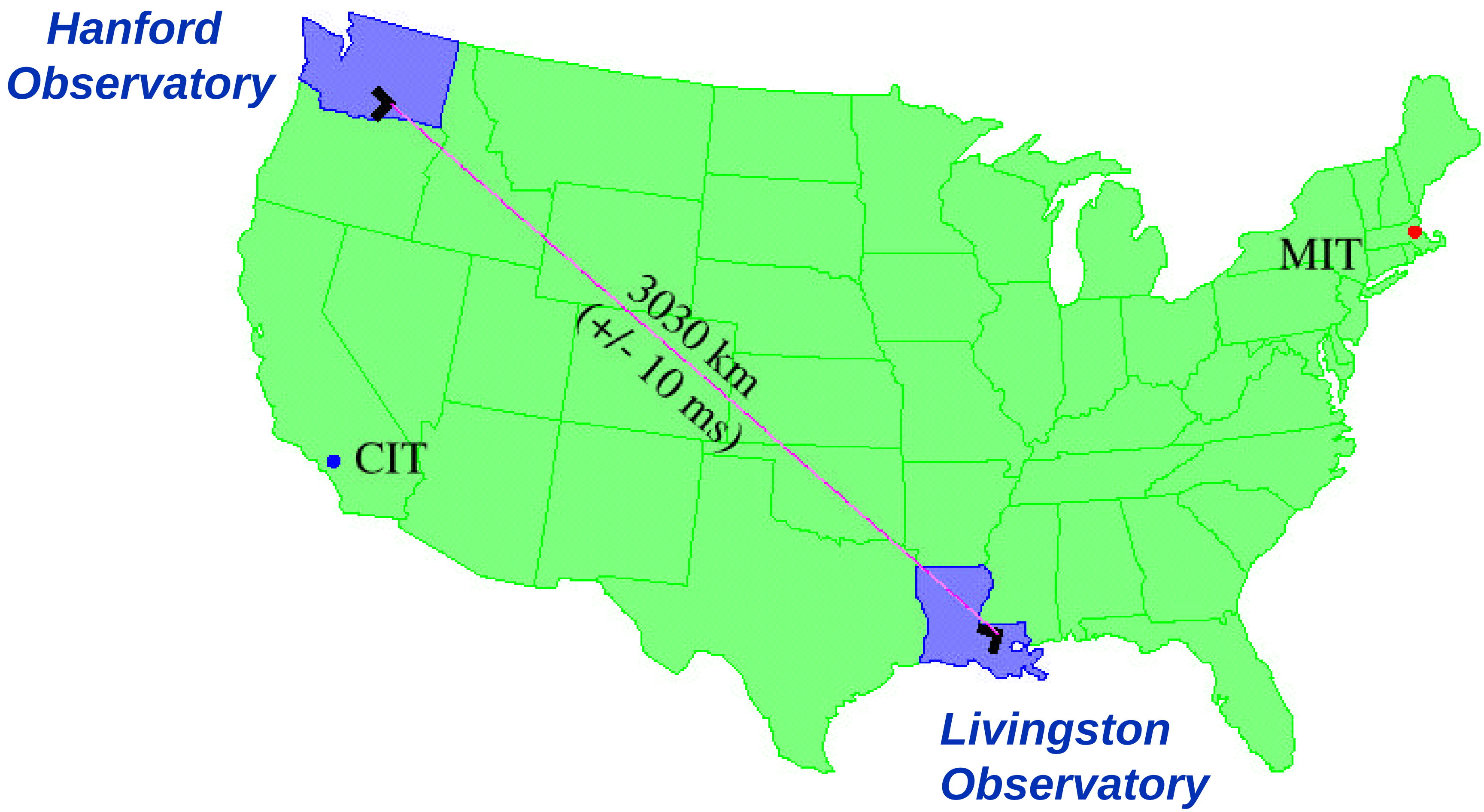
Compact binary mergers



LIGO sensitivity to coalescing binaries



LIGO Sites



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

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**

Interferometer Data

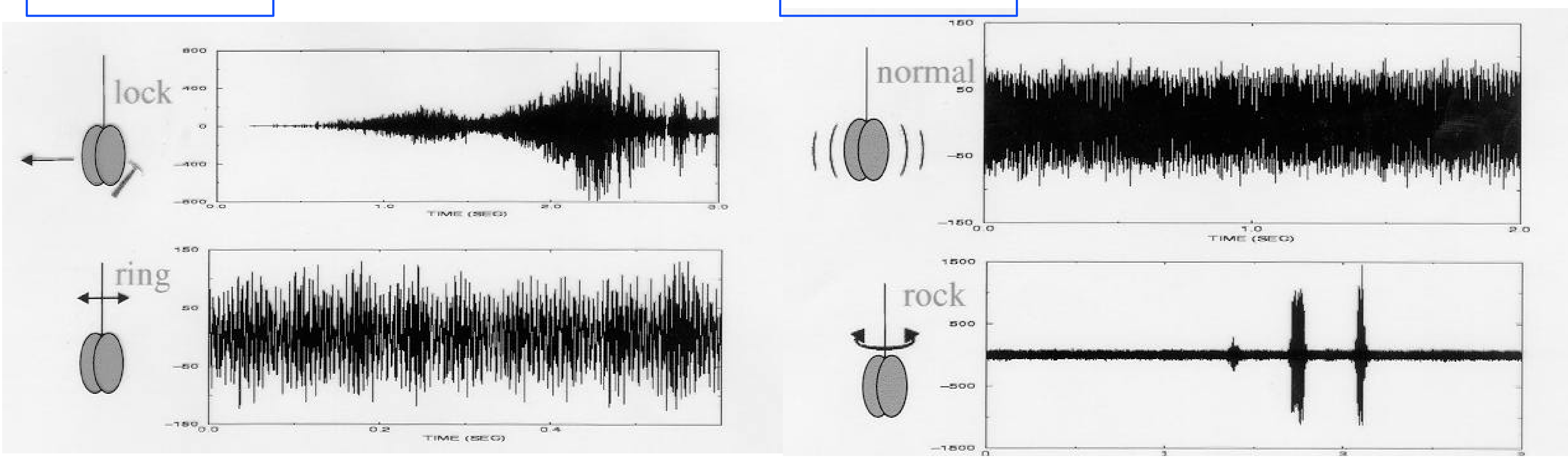
40 m

Real interferometer data is UGLY!!!

(Gliches - known and unknown)

LOCKING

NORMAL

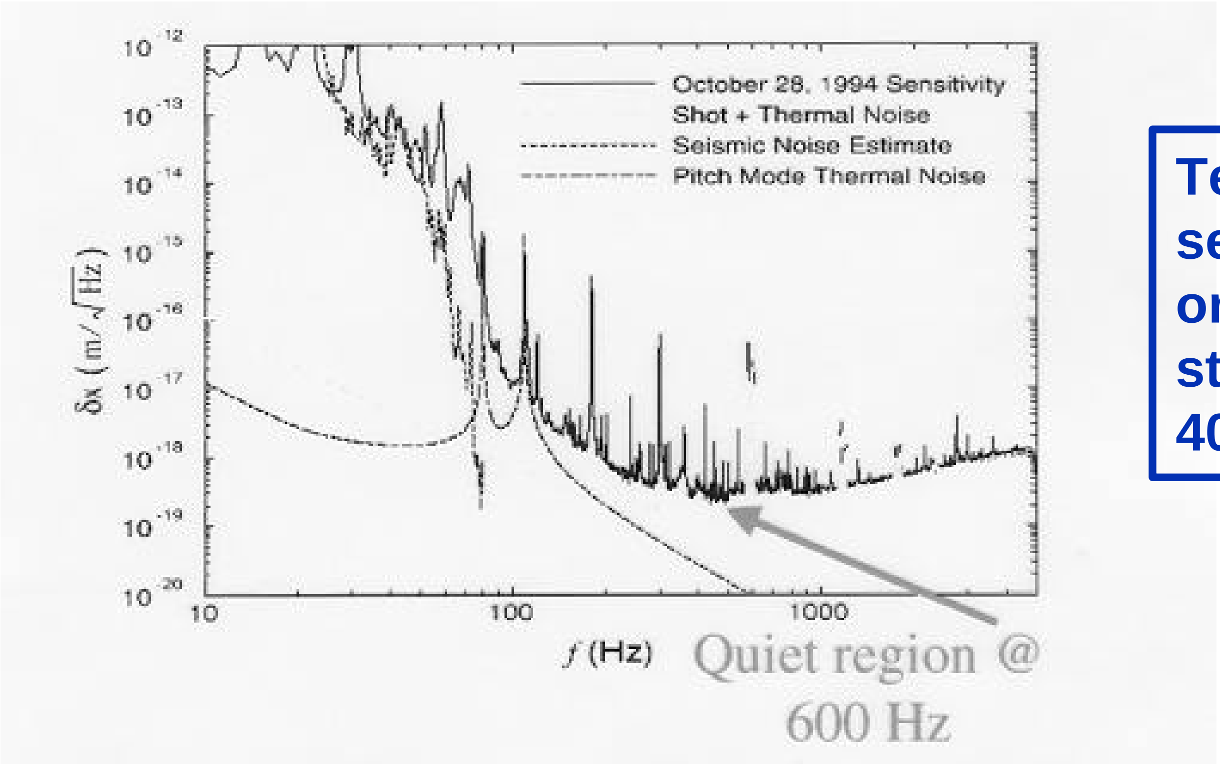


RINGING

ROCKING

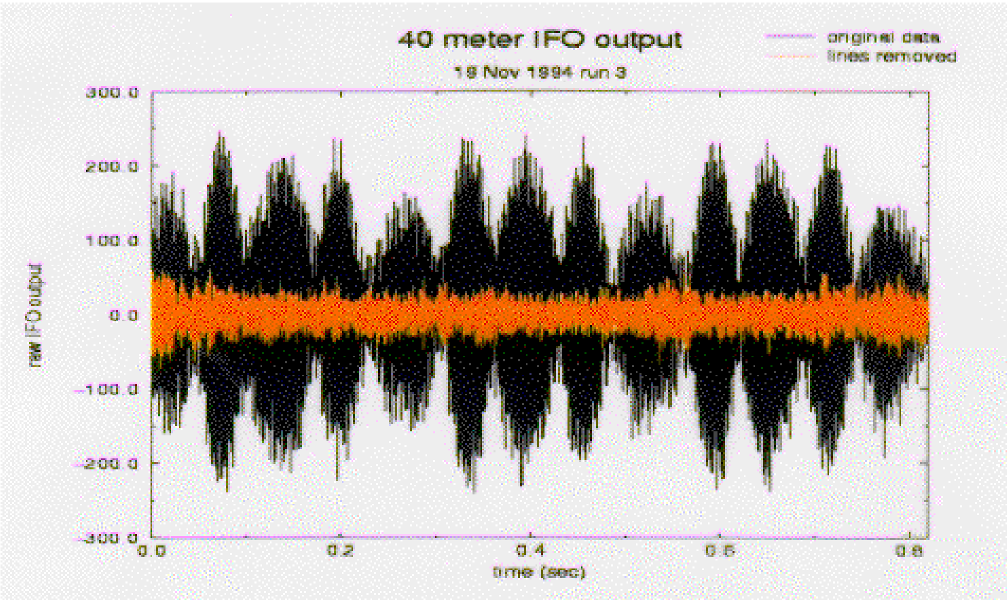
The Problem

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

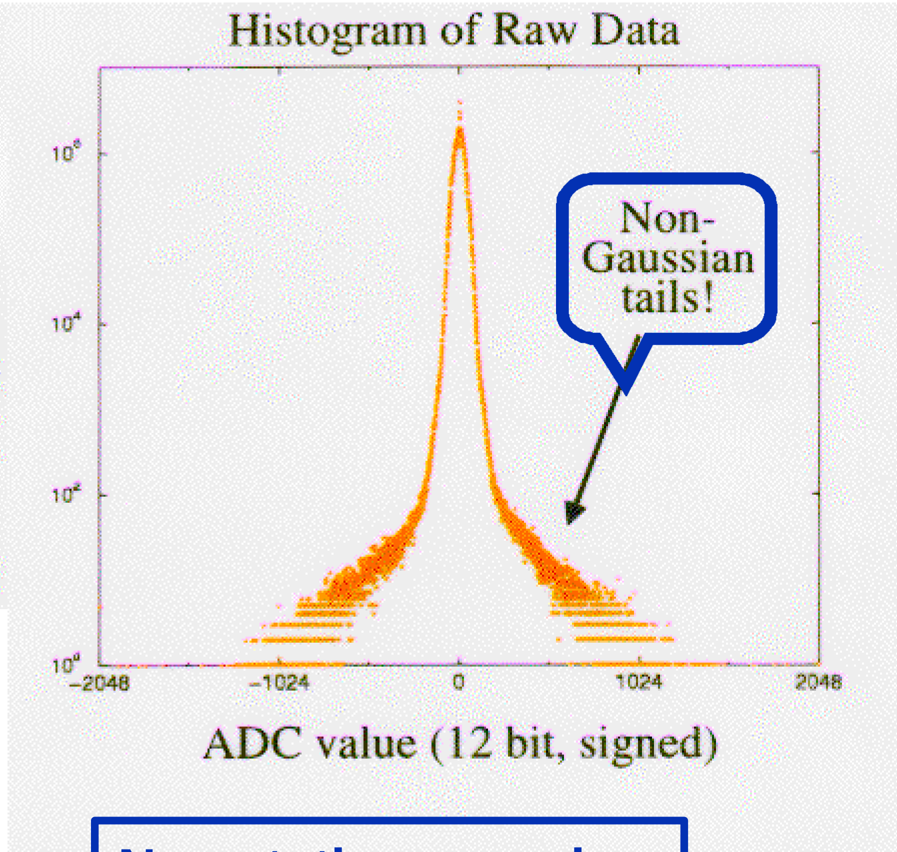


Test with real data by setting an upper limit on galactic neutron star inspiral rate using 40 m data

“Clean up” data stream



Effect of removing sinusoidal artifacts using multi-taper methods



Non stationary noise
Non gaussian tails

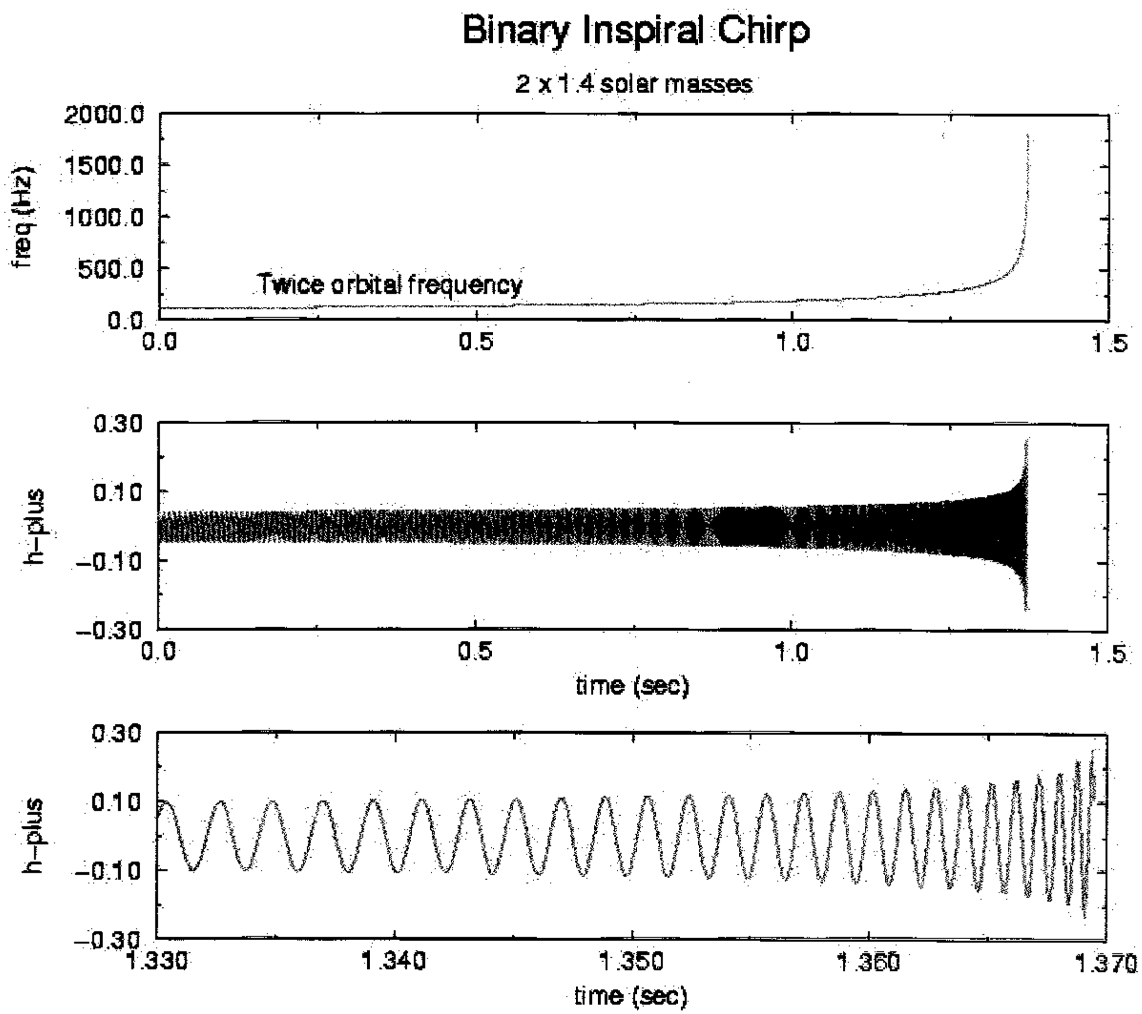
Inspiral ‘Chirp’ Signal

Template Waveforms

“matched filtering”
687 filters

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

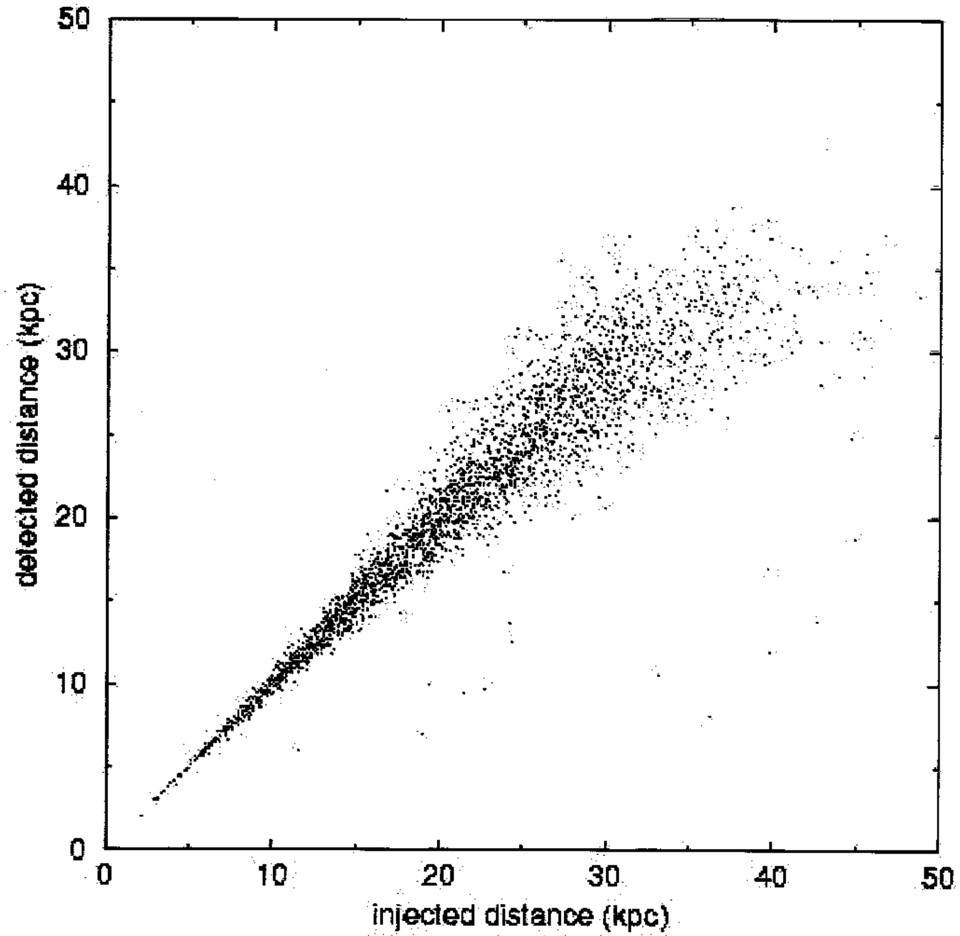
sensitivity to our galaxy
$h \sim 3.5\ 10^{-19}\ \mathrm{mHz}^{-1/2}$
expected rate $\sim 10^{-6}$/yr



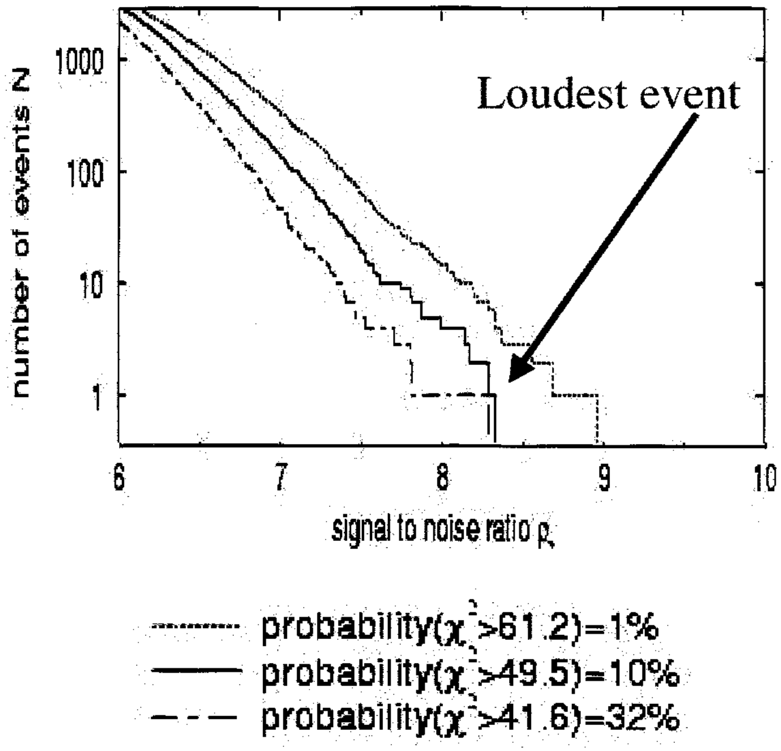
Detection Efficiency

- 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:

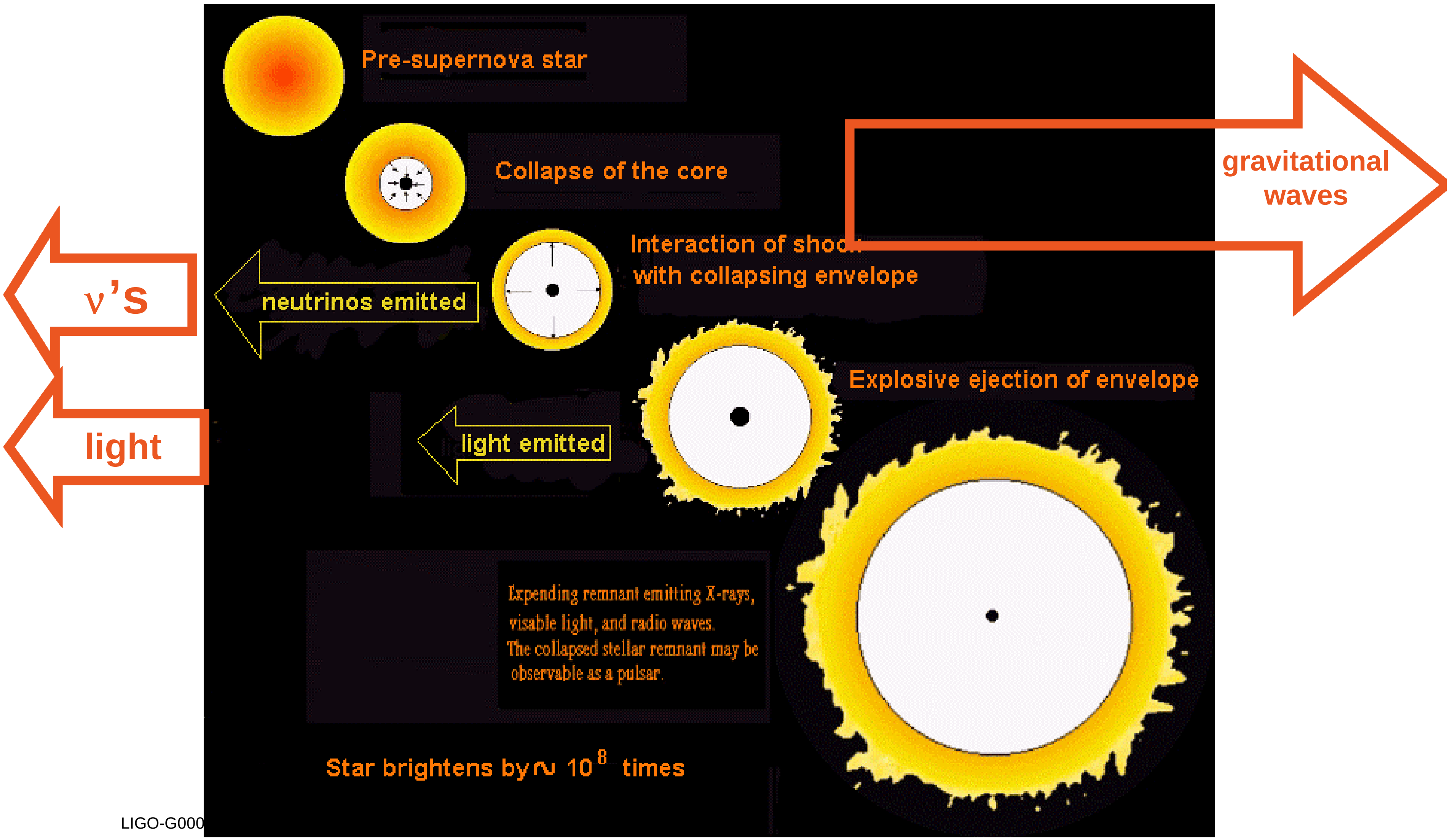
R < 0.5/hour with 90% CL

ε = 0.33 = detection efficiency

An ideal detector would set a limit:

R < 0.16/hour

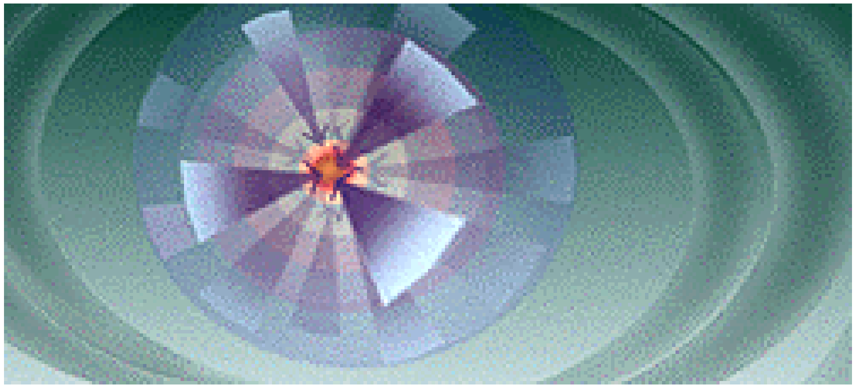
Supernova


Pre-supernova star
Collapse of the core
Interaction of shoc
with collapsing envelope
neutrinos emitted
Explosive ejection of envelope
light emitted
Expending remnant emitting X-rays, visable light, and radio waves.
The collapsed stellar remnant may be observable as a pulsar.
Star brightens by ~ 10^8 times
gravitational waves
ν's
light

Supernovae

Gravitational Waves

Non axisymmetric collapse

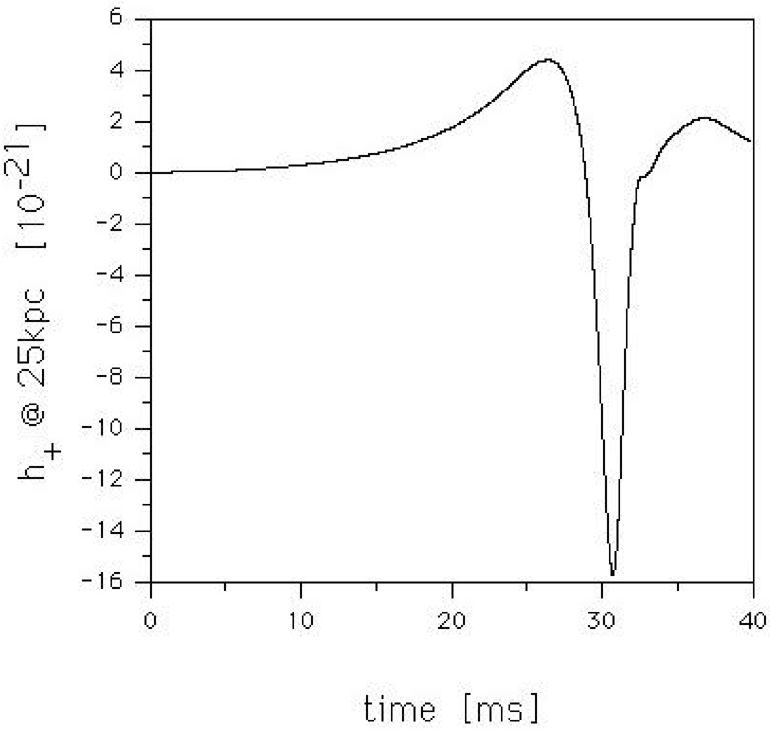


Rate

1/50 yr - our galaxy

3/yr - Virgo cluster

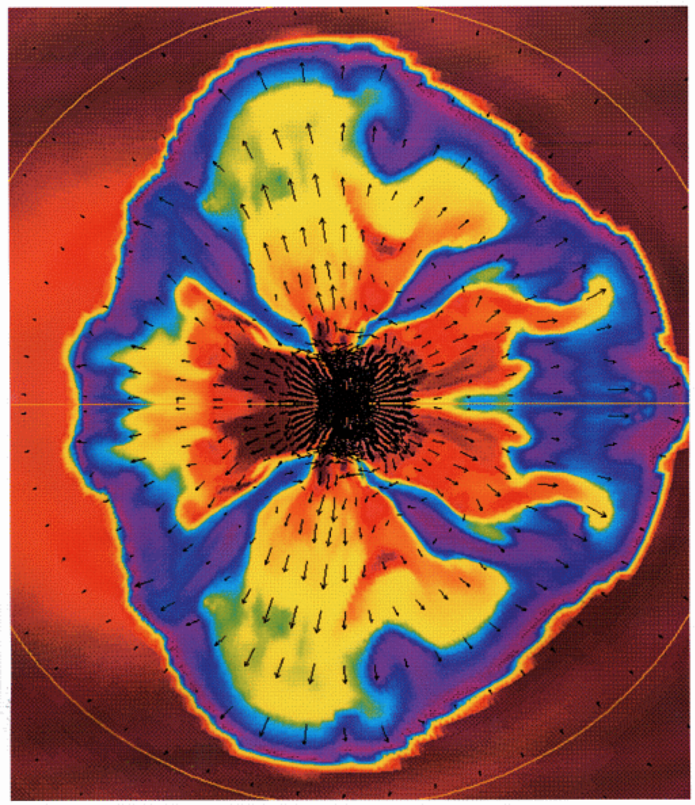
'burst' signal



Model of Core Collapse

A. Burrows et al

kick sequence



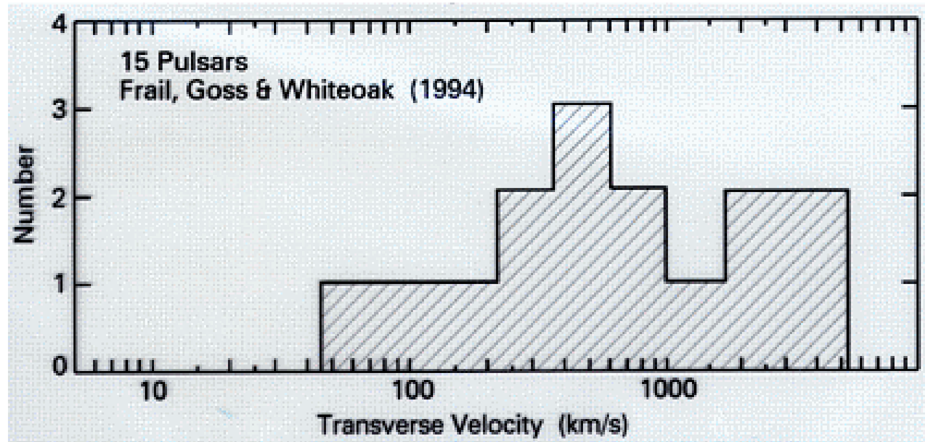
gravitational core collapse

Asymmetric Collapse?

pulsar proper motions

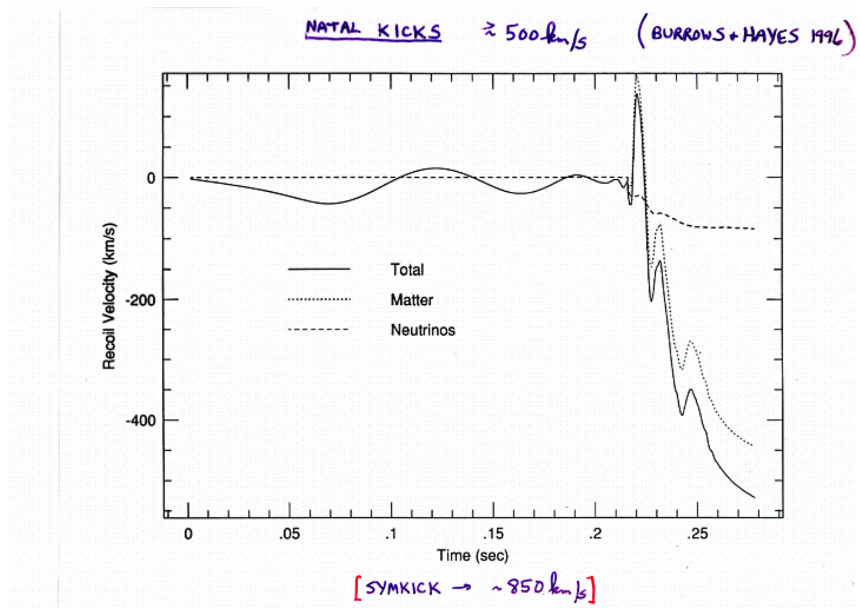
Velocities -

- **young SNR(pulsars?)**
- **> 500 km/sec**



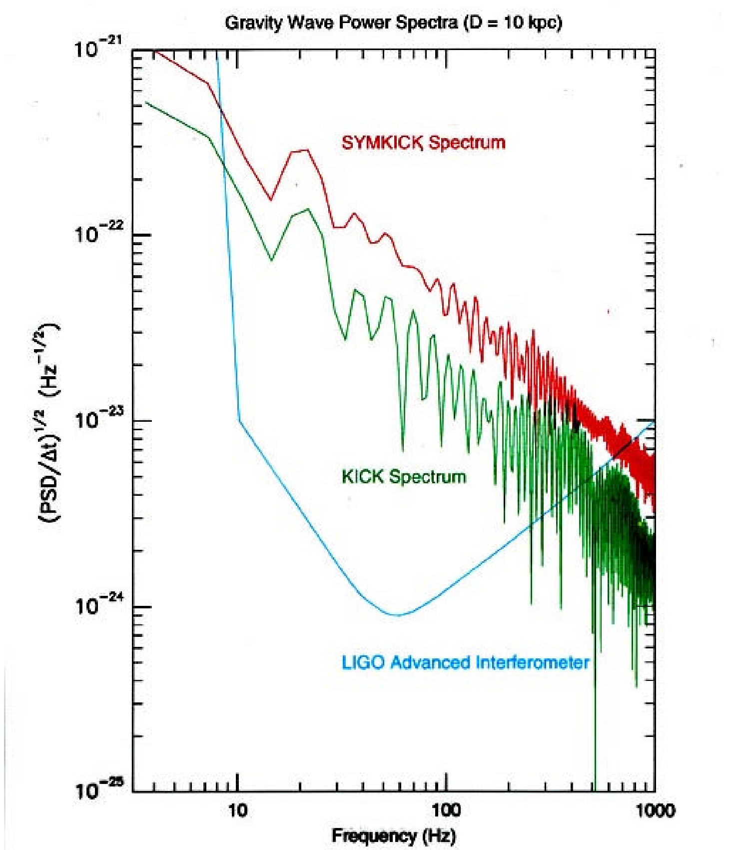
Burrows et al

- **recoil velocity of matter and neutrinos**

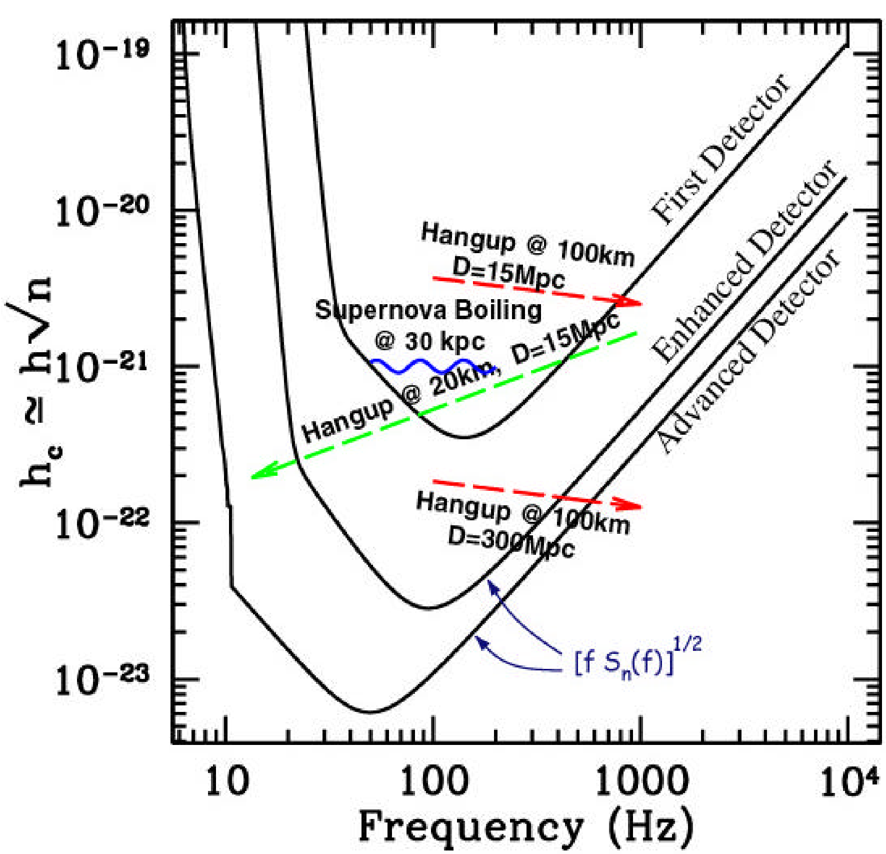


LIGO

astrophysical sources



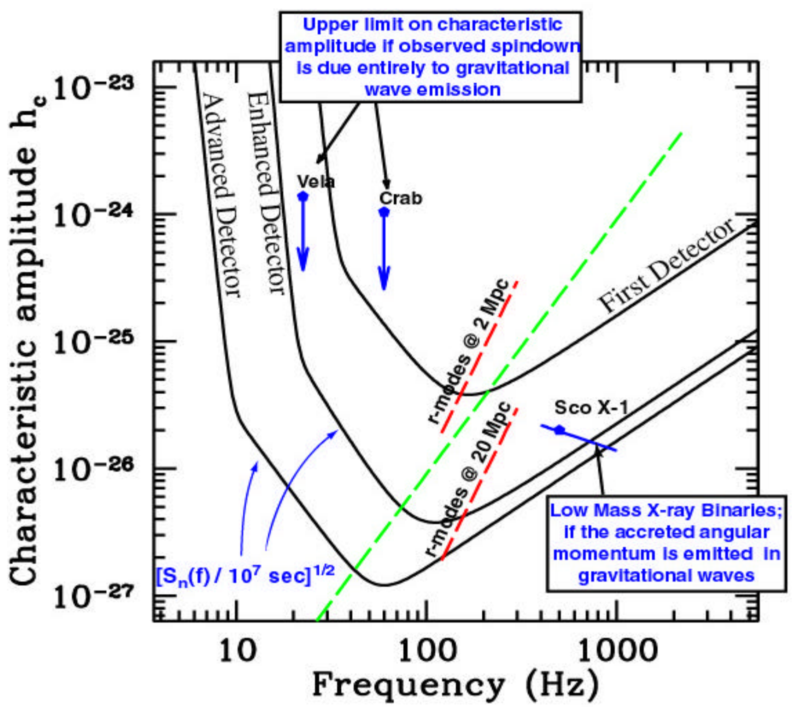
Sensitivity of LIGO to burst sources



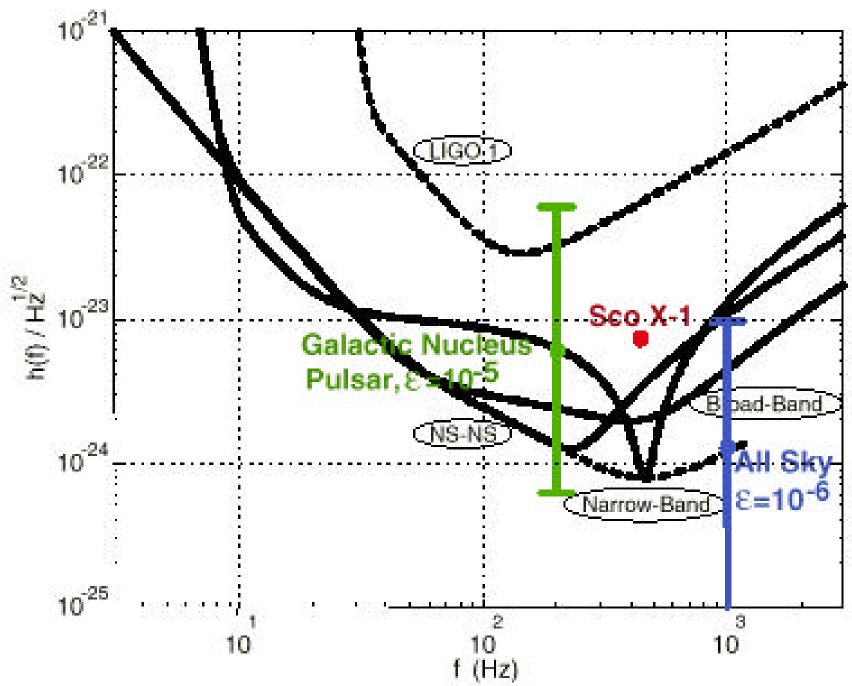
LIGO

astrophysical sources

Sensitivity of LIGO to continuous wave sources



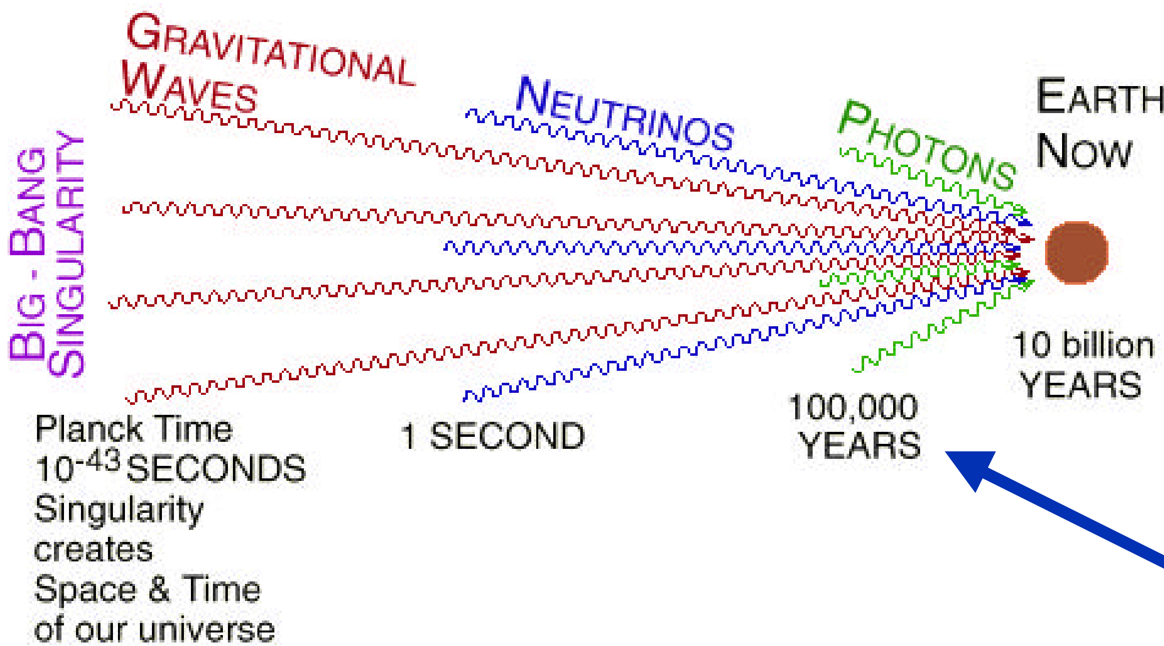
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: neutron star precession; interiors
  - »narrow band searches best



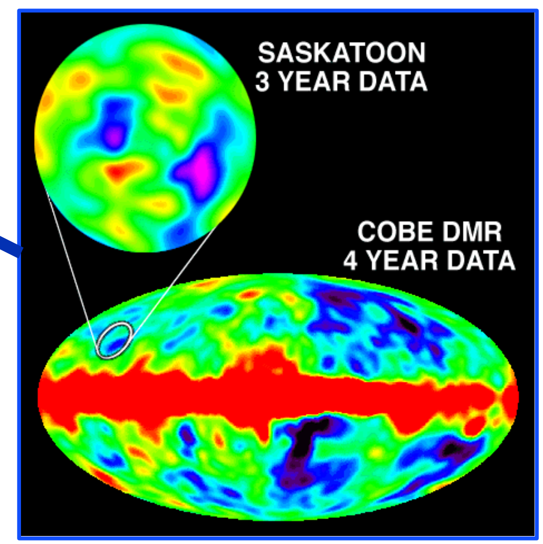
Sources of Gravitational Waves

‘Murmurs’ from the Big Bang

signals from the early universe



Cosmic microwave background



Conclusions

- LIGO I construction complete
- LIGO I commissioning and testing 'on track'
- "First Lock" will be officially established 20 Oct 00
- Data analysis schemes are being developed, including tests with 40 m data
- First Science Run will begin during 2002
- Significant improvements in sensitivity anticipated to begin about 2006