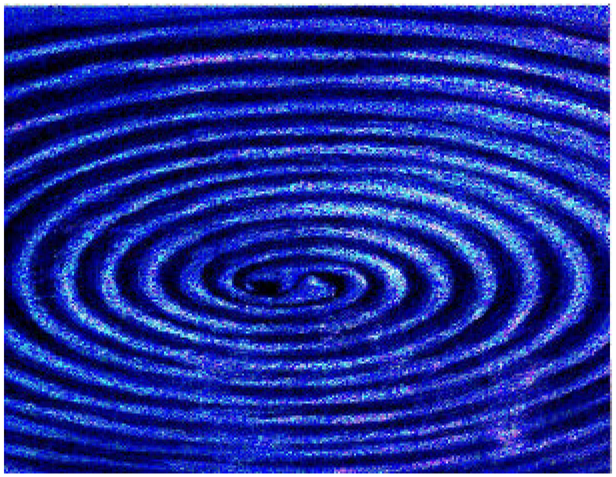
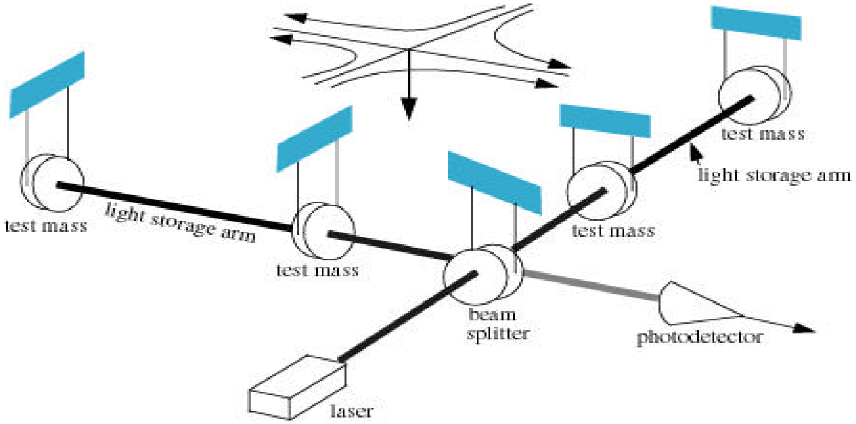
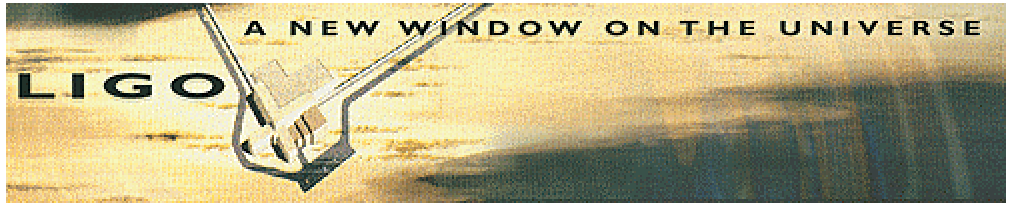
Gravitational waves and LIGO

- Brief introduction to LIGO
  - » What is a gravitational wave?
  - » Astrophysical sources
  - » Gravitational wave interferometers
  - » LIGO and its sister projects
- Progress report on Engineering runs
- Data analysis – finding signals in the noise





Alan Weinstein, Caltech



LIGO: Laser Interferometer Gravitational-Wave Observatory

- US project to build observatories for gravitational waves (GWs)
  - » ...and laboratory to run them
- to enable an initial detection, then an astronomy of GWs
- collaboration by MIT, Caltech; other institutions participating
  - » (LIGO Scientific Collaboration, LSC)
  - » Funded by the US National Science Foundation (NSF)

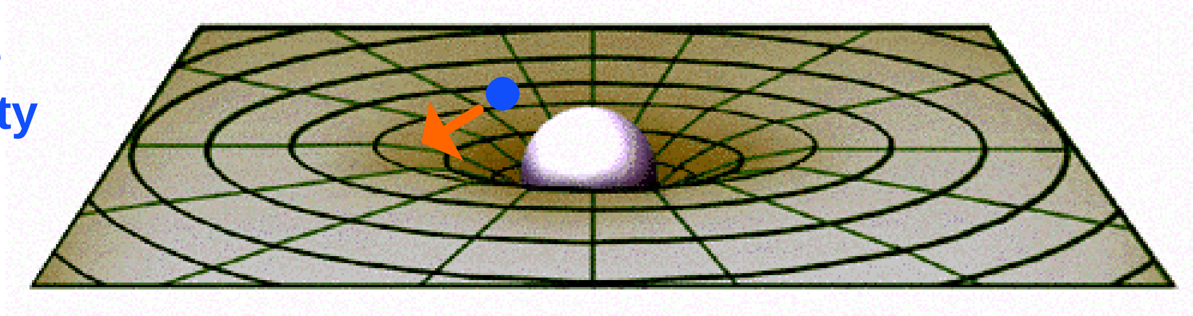
Observatory characteristics

- Two sites separated by 3000 km
- each site carries 4km vacuum system, infrastructure
- each site capable of multiple interferometers (IFOs)

Evolution of interferometers in LIGO

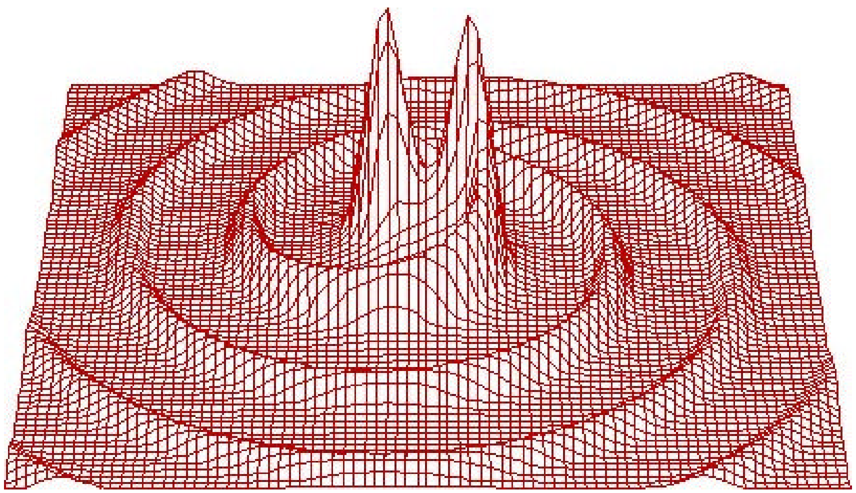
- establishment of a network with other interferometers
- A facility for a variety of GW searches
- lifetime of >20 years
- goal: best technology, to achieve fundamental noise limits for terrestrial IFOs

Gravitational Waves



Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.

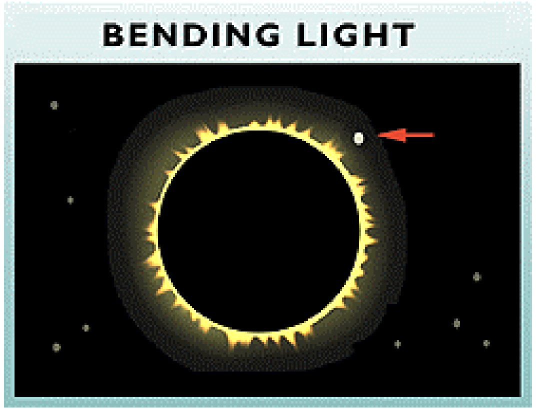
Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.

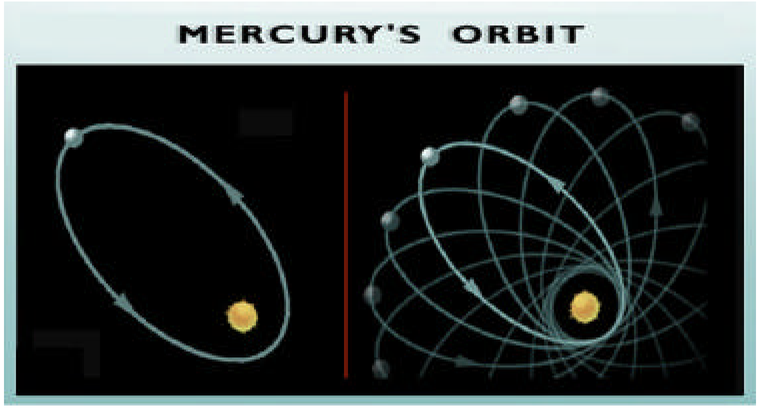


If the source is moving (at speeds close to c), *eg,* because it's orbiting a companion, the "news" of the changing gravitational field propagates outward as gravitational radiation – a wave of spacetime curvature

Einstein’s Theory of Gravitation

experimental tests





bending of light
As it passes in the vicinity of massive objects

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

Mercury’s orbit
perihelion shifts forward twice Post-Newton theory

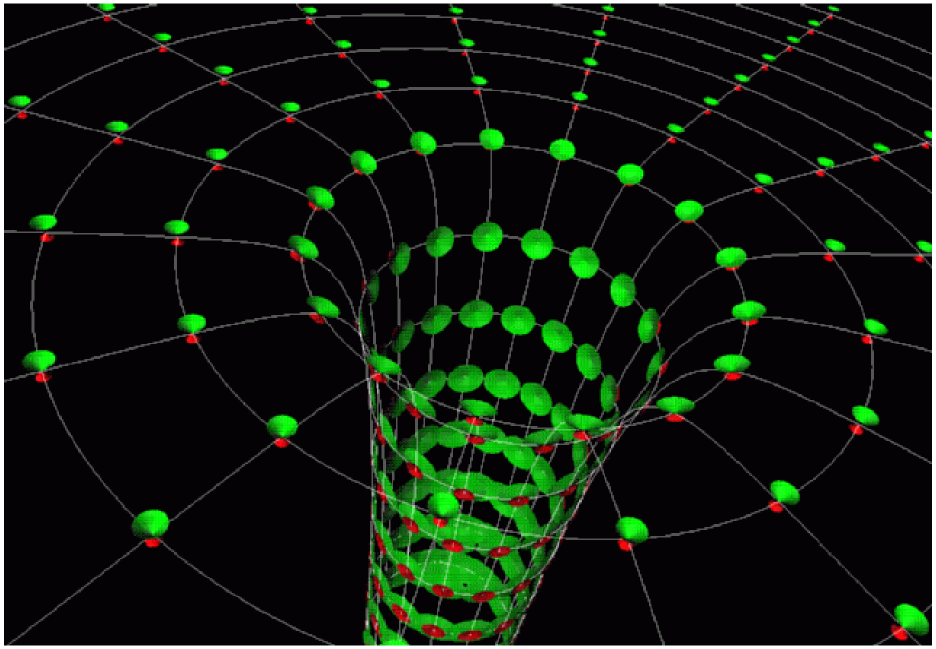
Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass.

“Einstein Cross”
The bending of light rays
gravitational lensing

Quasar image appears around the central glow formed by nearby galaxy. Such gravitational lensing images are used to detect a ‘dark matter’ body as the central object

Strong-field

- Most tests of GR focus on small deviations from Newtonian dynamics (post-Newtonian weak-field approximation)
- Space-time curvature is a *tiny* effect everywhere except:
  - The universe in the early moments of the big bang
  - Near/in the horizon of black holes
- This is where GR gets *non-linear* and interesting!
- We aren't very close to any black holes (fortunately!), and can't see them with light



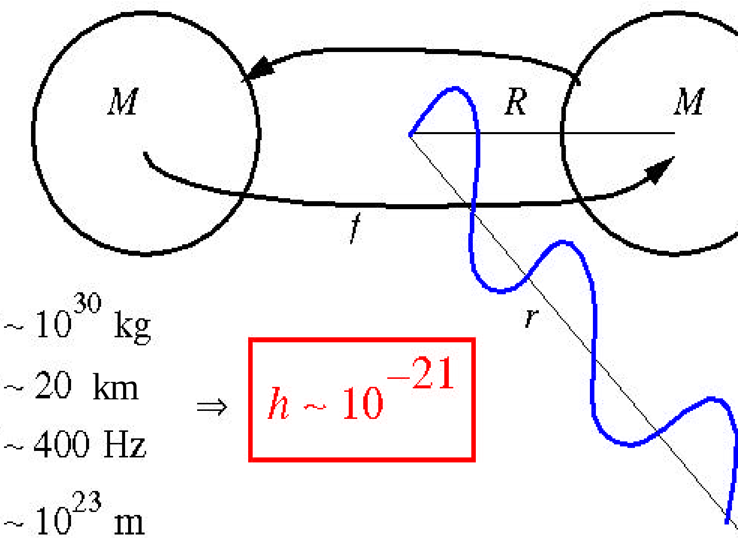
But we can search for (*weak-field*) gravitational waves as a signal of their presence and dynamics

Sources of GWs

- Accelerating charge $\Rightarrow$ electromagnetic radiation (dipole)
- Accelerating mass $\Rightarrow$ gravitational radiation (quadrupole)
- Amplitude of the gravitational wave (dimensional analysis):

$$h_{mn} = \frac{2G}{c^4 r}\ddot{I}_{mn} \quad \Rightarrow \quad h \approx \frac{4p^2 GMR^2 f_{orb}^2}{c^4 r}$$

- $\ddot{I}_{mn}$ = second derivative of mass quadrupole moment (non-spherical part of kinetic energy – tumbling dumb-bell)
- G is a small number!
- Need huge mass, relativistic velocities, nearby.
- For a binary neutron star pair, 10m light-years away, solar masses moving at 15% of speed of light:



$$\begin{array}{l} M \sim 10^{30}\ \text{kg} \\ R \sim 20\ \text{km} \\ f \sim 400\ \text{Hz} \\ r \sim 10^{23}\ \text{m} \end{array} \Rightarrow \boxed{h \sim 10^{-21}}$$

Terrestrial sources *TOO WEAK*!

Nature of Gravitational Radiation

General Relativity predicts :

- transverse space-time distortions, freely propagating at speed of light

  mass of graviton = 0

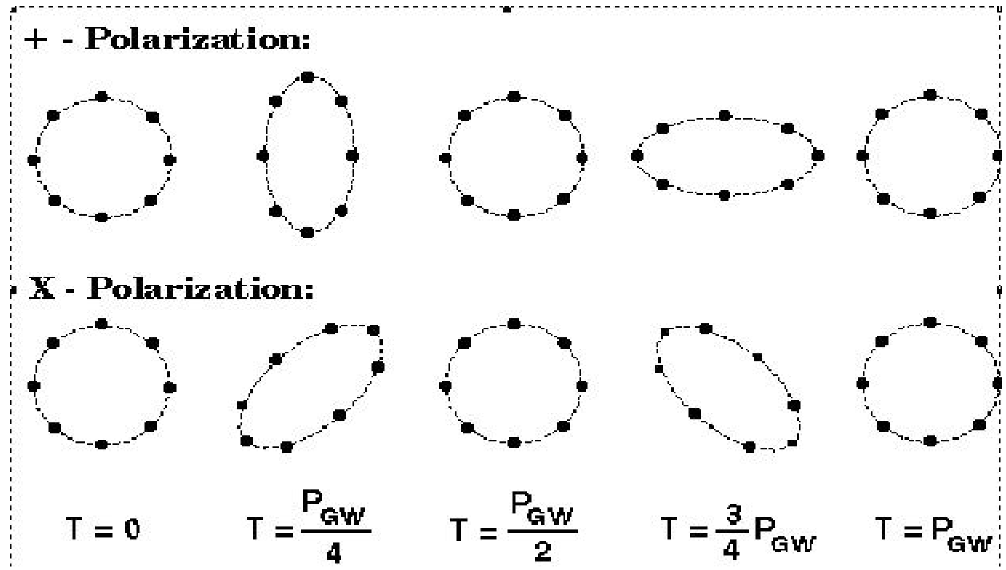
- Stretches and squashes space between "test masses" – strain

$$\boxed{h = \Delta L/L}$$

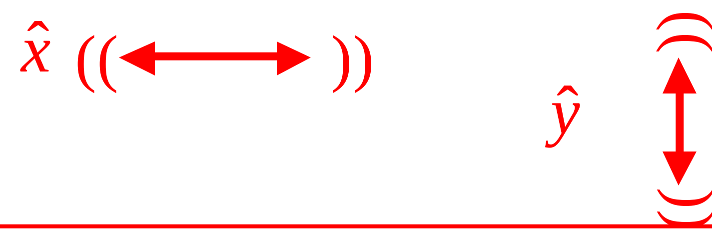
- Conservation laws:
  - cons of energy $\Rightarrow$ no monopole radiation
  - cons of momentum $\Rightarrow$ no dipole radiation
  - quadrupole wave (spin 2) $\Rightarrow$ two polarizations

plus (⊕) and cross (⊗)

Spin of graviton = 2



Contrast with EM dipole radiation:



Contrast EM and GW information

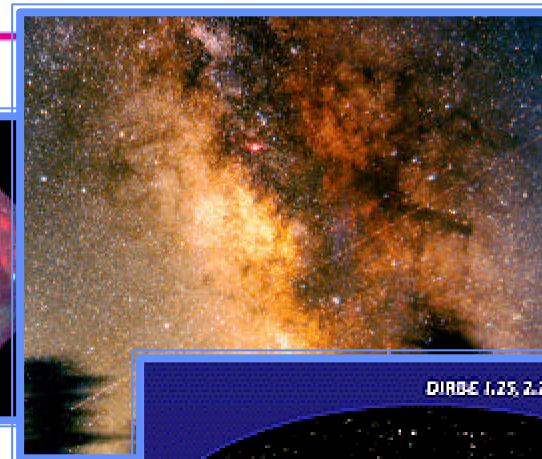
E&M	GW
space as medium for field	Space-time itself
incoherent superpositions of atoms, molecules	coherent motions of huge masses (or energy)
wavelength small compared to sources - images	wavelength ~large compared to sources - poor spatial resolution
absorbed, scattered, dispersed by matter	very small interaction; no shielding
10^6 Hz and up	10^3 Hz and down
measure amplitude (radio) or intensity (light)	measure amplitude
detectors have small solid angle acceptance	detectors have large solid angle acceptance

- Very different information, mostly mutually exclusive
- Difficult to predict GW sources based on E&M observations
- GW astronomy is a totally new and unique window on the universe

Observing the Galaxy with Different Electromagnetic Wavelengths

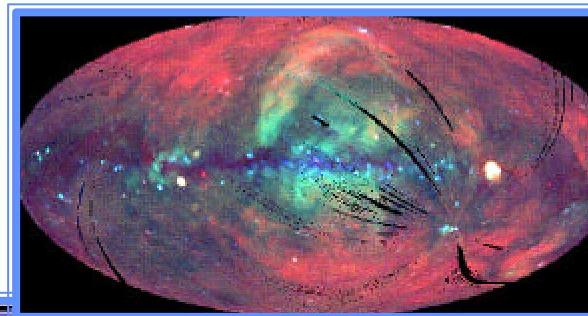
http://antwrp.gsfc.nasa.gov/apod/image/SagSumMW_dp_big.gif

$l = 5 \times 10^{-7}$ m



http://antwrp.gsfc.nasa.gov/apod/image/xallsky_rosat_big.gif

$l = 5 \times 10^{-10}$ m



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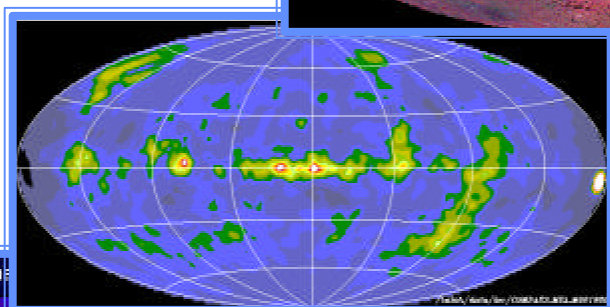
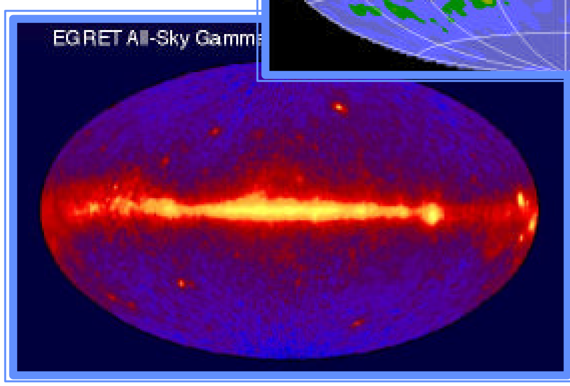
$l = 6 \times 10^{-13}$ m



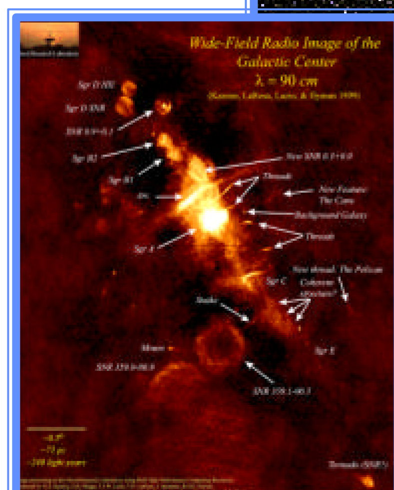


http://cossc.gsfc.nasa.gov/cossc/egret/

$l = 1 \times 10^{-14}$ m

http://www.gsfc.nasa.gov/astro/cobe

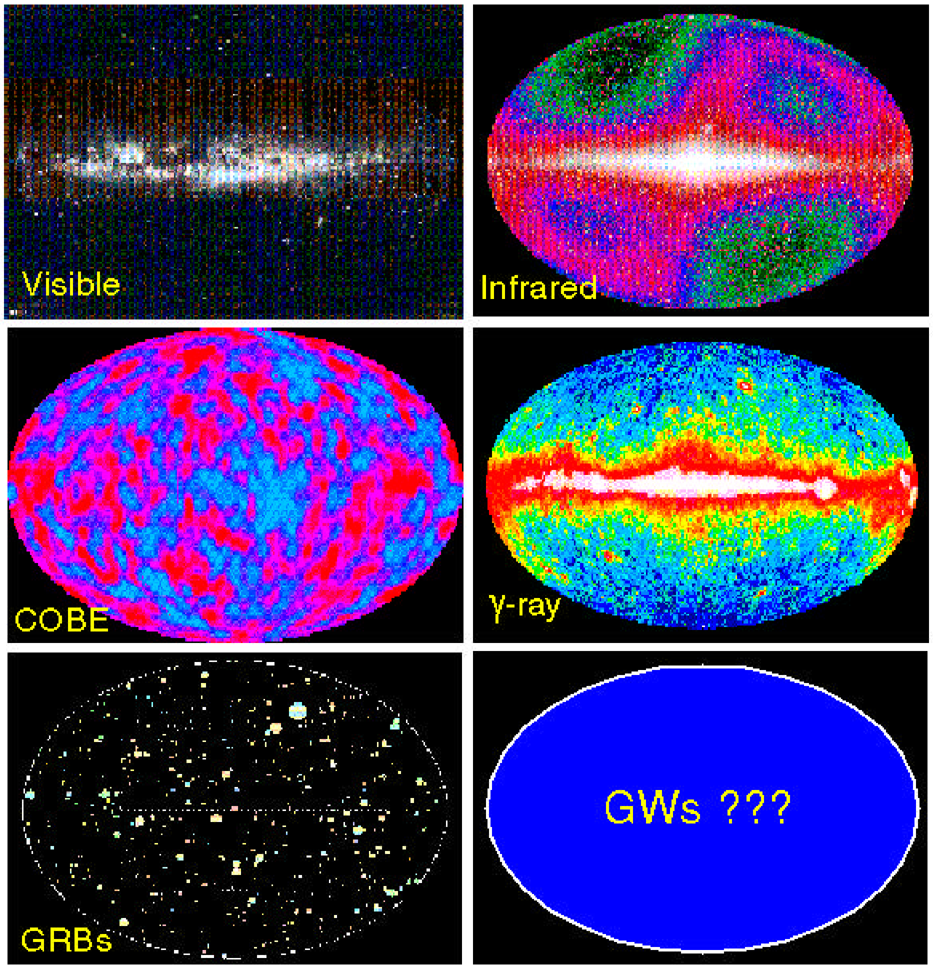
$l = 2 \times 10^{-6}$ m



//rsd-www.nrl.navy.mil/7213/lazio/GC/

$l = 9 \times 10^{-1}$ m

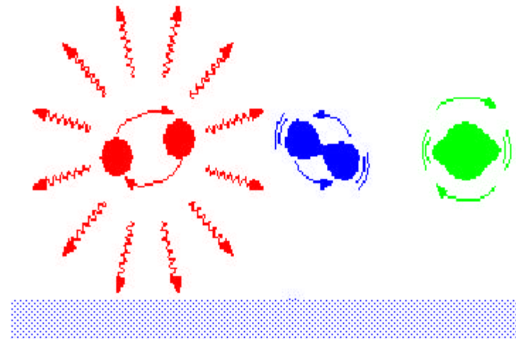
What will we see?



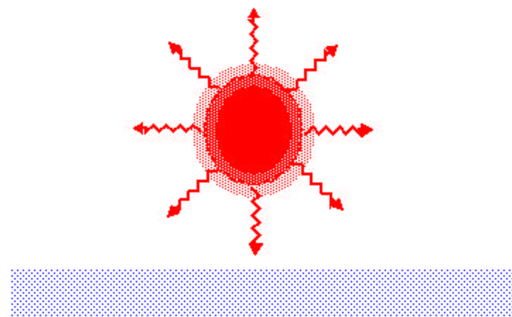
A NEW WINDOW
ON THE UNIVERSE
WILL OPEN UP
FOR EXPLORATION.
BE THERE!

Astrophysical Sources of Gravitational Waves

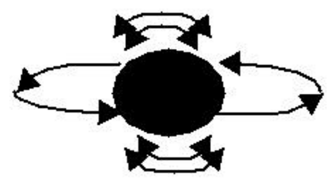
Coalescing compact binaries (neutron stars, black holes)



Non-axi-symmetric supernova collapse

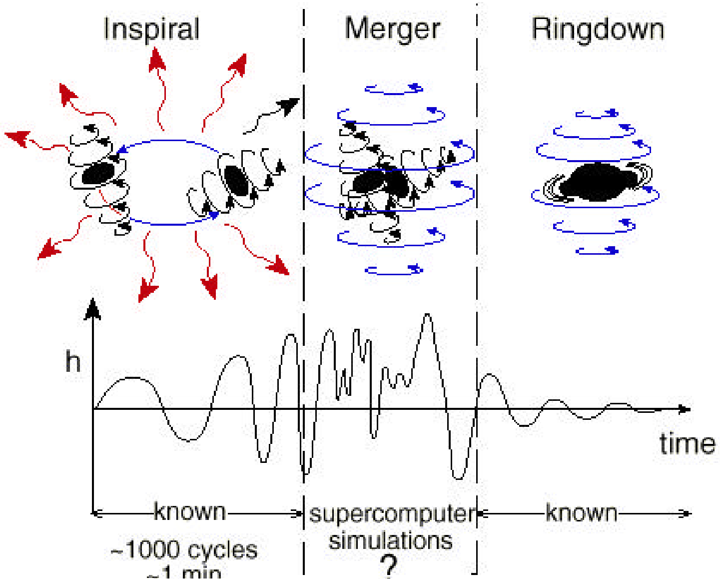


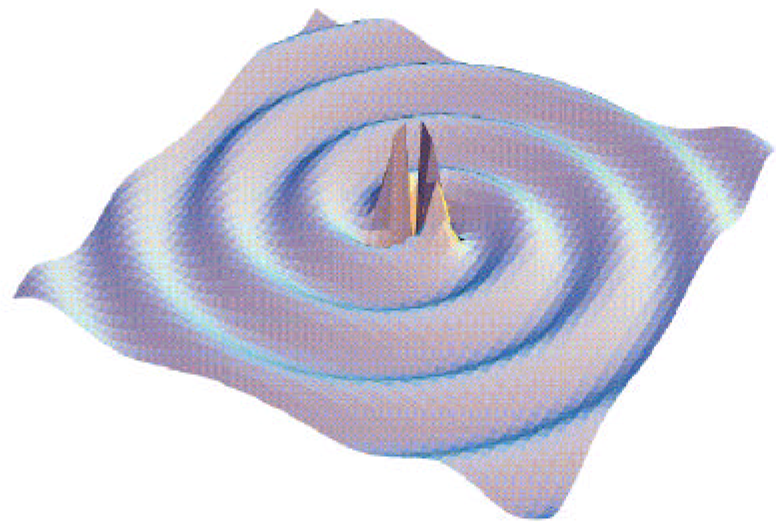
Non-axi-symmetric pulsar (rotating, beaming neutron star)



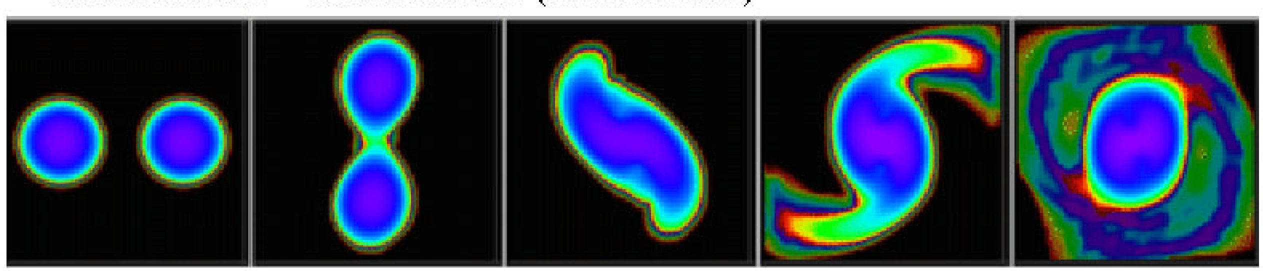
GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

Compact binary mergers

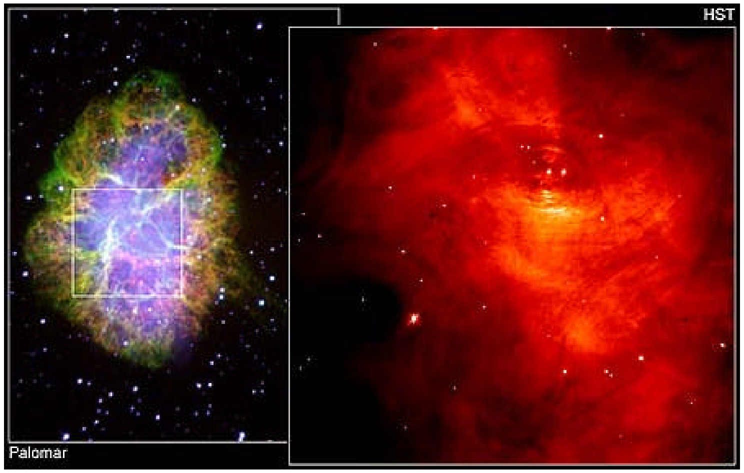




- Neutron star – neutron star (Centrella et al.)

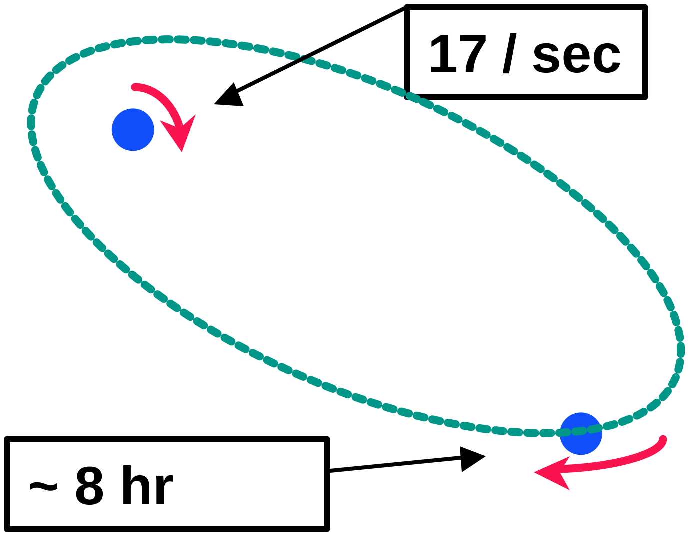


Hulse-Taylor binary pulsar



<u>Neutron Binary System</u>

PSR 1913 + 16 -- Timing of pulsars

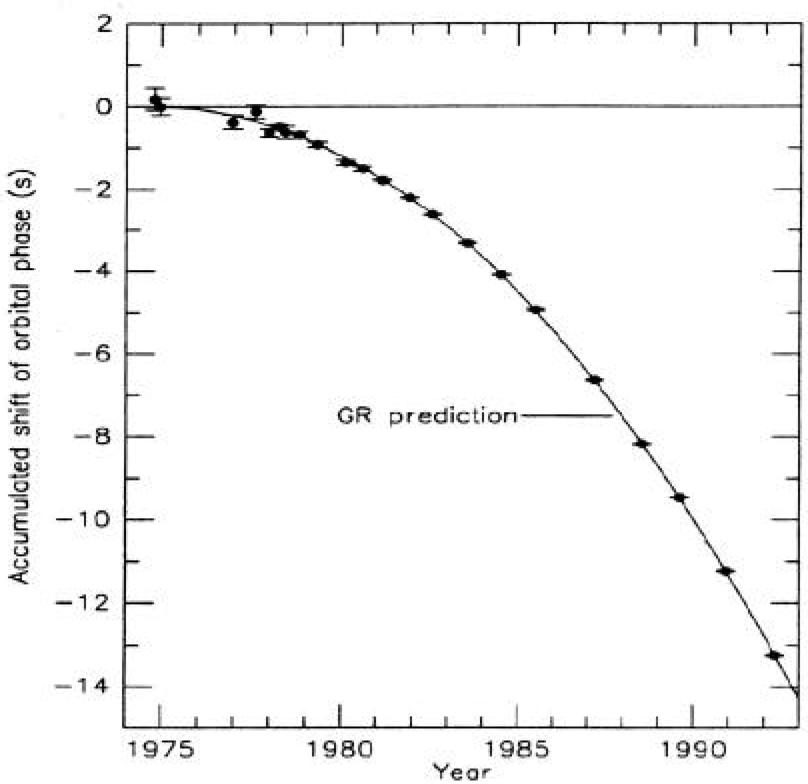


- **A rapidly spinning pulsar (neutron star beaming EM radiation at us 17 x / sec)**
- **orbiting around an ordinary star with 8 hour period**
- **Only 7 kpc away**
- **discovered in 1975, orbital parameters measured**
- **continuously measured over 25 years!**

GWs from Hulse-Taylor binary

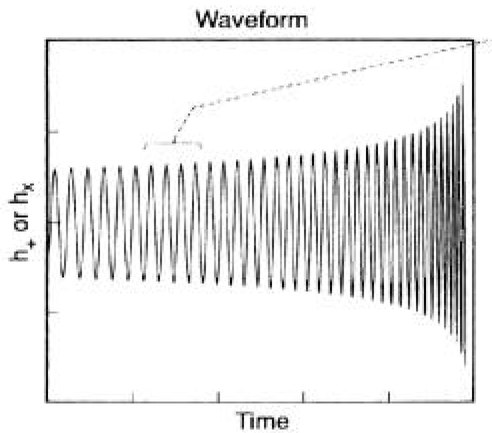
emission of gravitational waves by compact binary system

- **Only 7 kpc away**
- **period speeds up 14 sec from 1975-94**
- **measured to ~50 msec accuracy**
- **deviation grows quadratically with time**
- **Merger in about 300M years**
  - **(<< age of universe!)**
- **shortening of period Ü orbital energy loss**
- **Compact system:**
  - **negligible loss from friction, material flow**
- **beautiful agreement with GR prediction**
- **Apparently, loss is due to GWs!**
- **Nobel Prize, 1993**

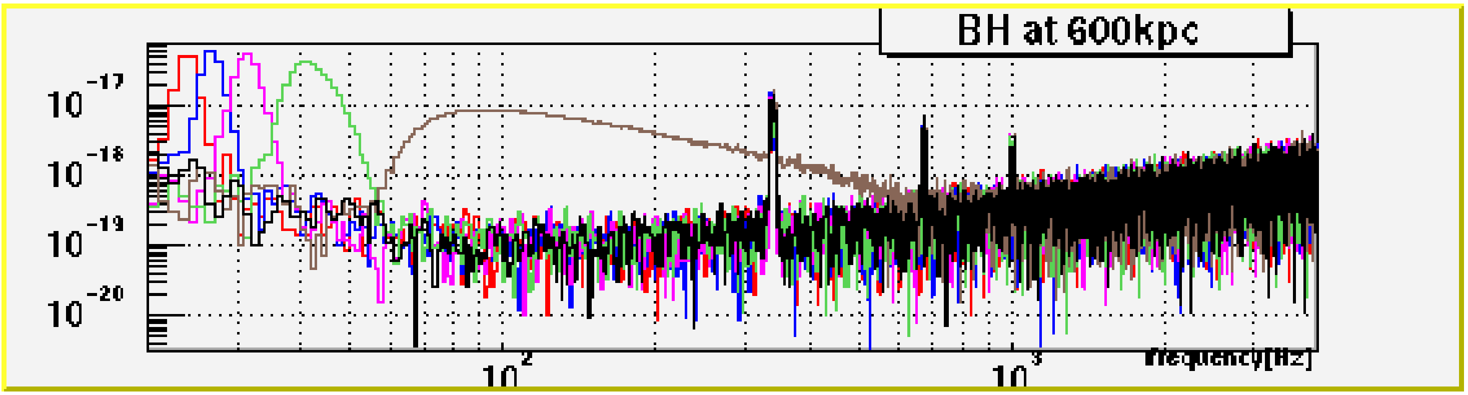


The sound of a chirp

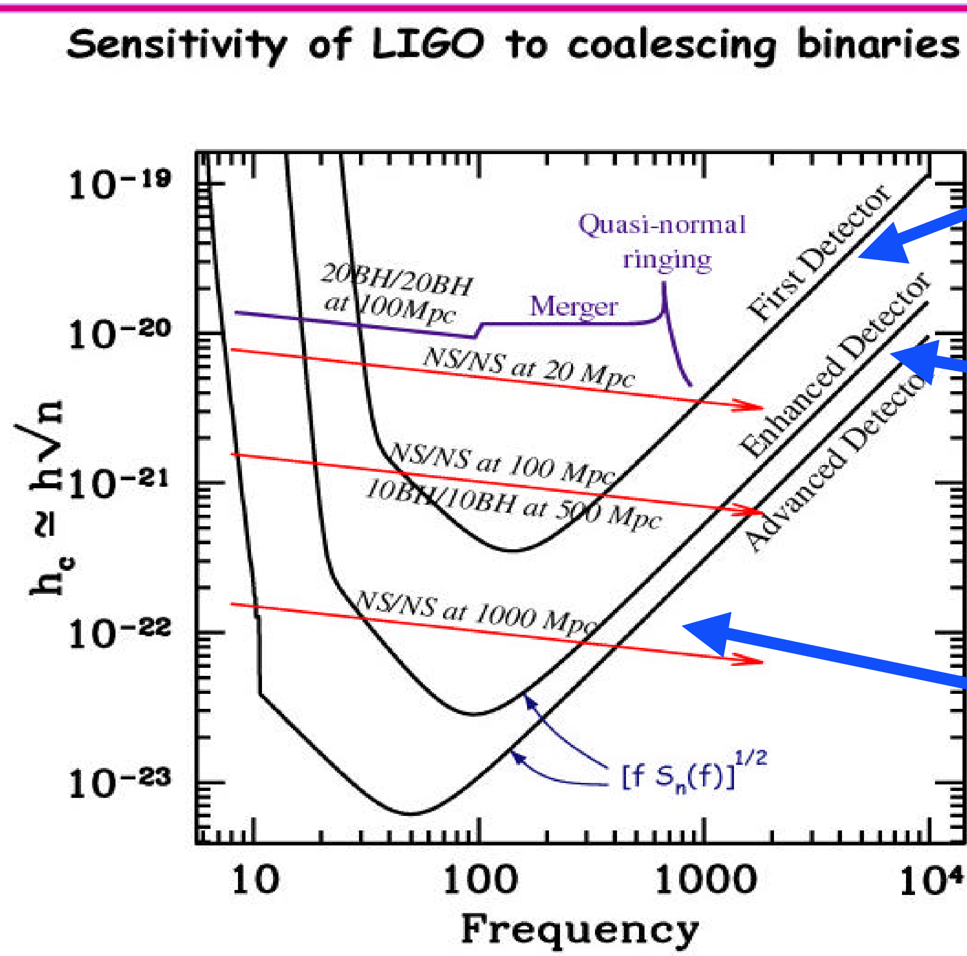
BH-BH collision, no noise



The sound of a BH-BH collision,
Fourier transformed over 5 one-second intervals
(red, blue, magenta, green, purple)
along with expected IFO noise (black)



Astrophysical sources: Thorne diagrams



LIGO I (2002-2005)

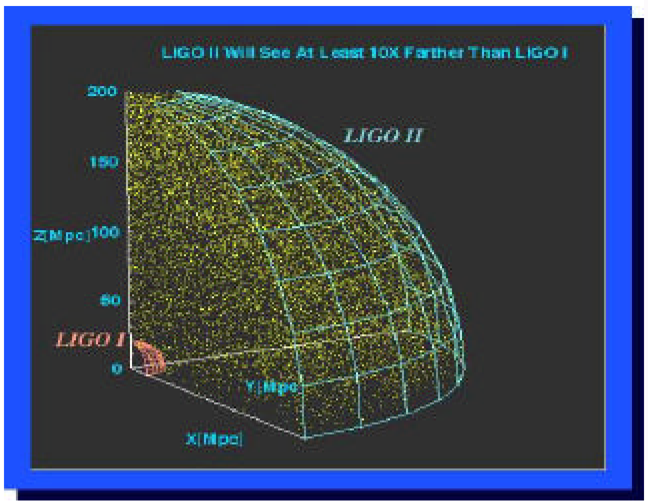
LIGO II (2007-)

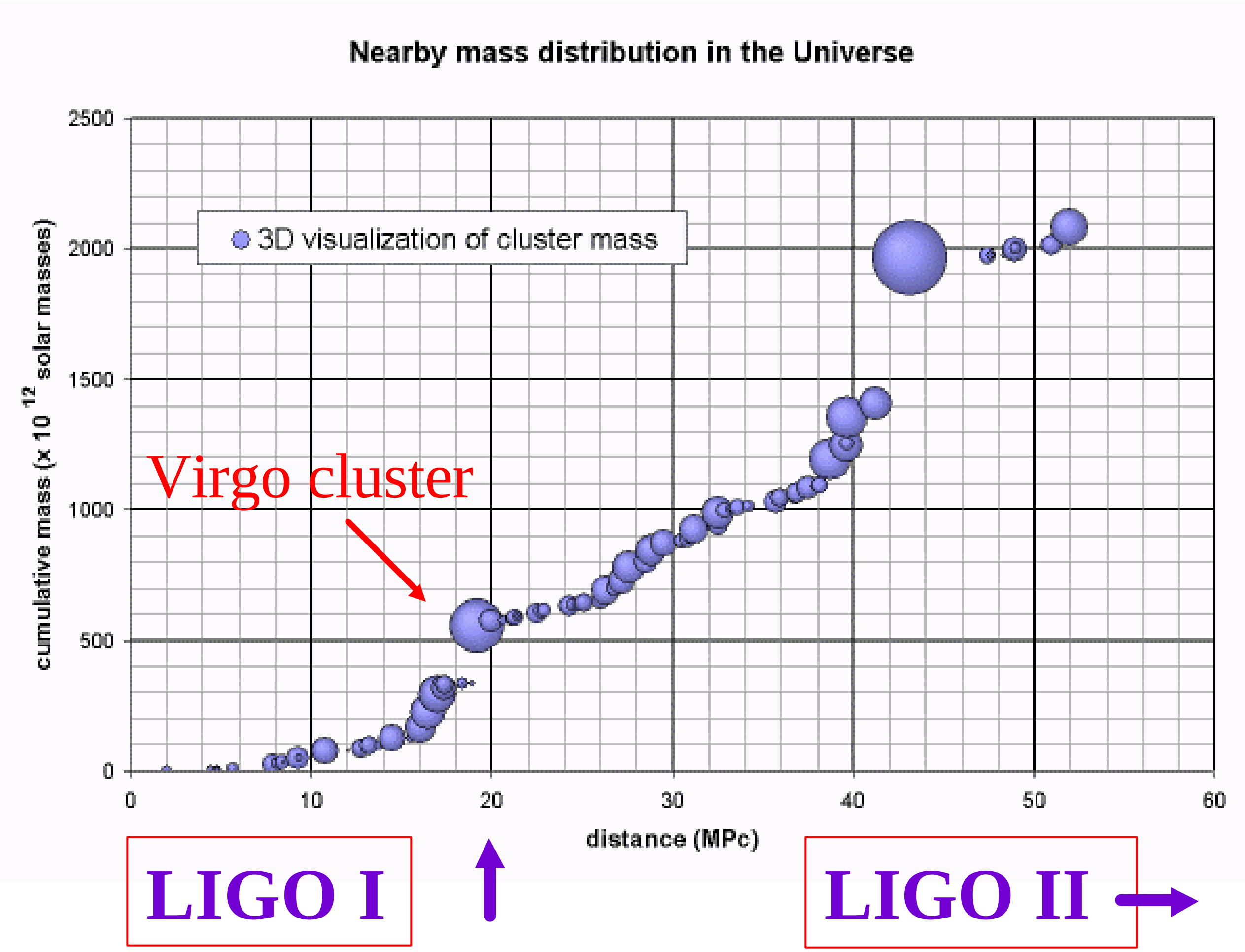
Advanced LIGO

How many sources can we see?

Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!





Estimated detection rates for compact binary inspiral events

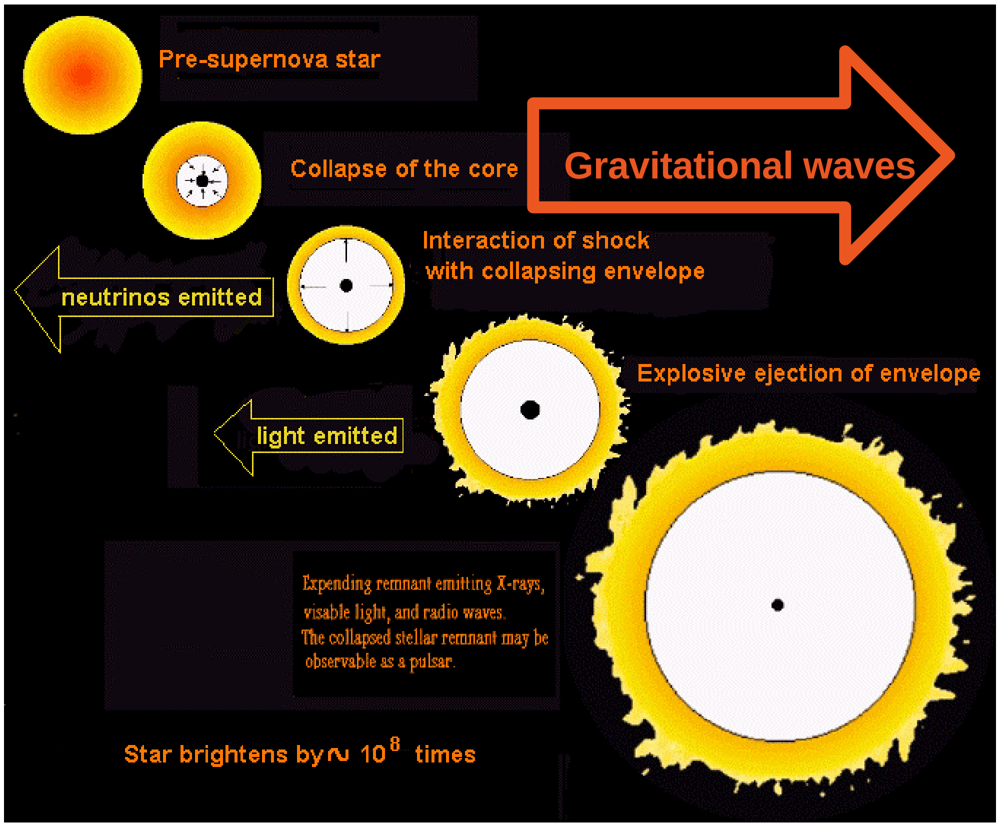
Brief Summary of Detection Capabilities of Mature LIGO Interferometers

• **Inspiral of NS/NS, NS/BH and BH/BH Binaries:** The table below [15] shows estimated rates $\mathcal{R}_{\rm gal}$ in our galaxy (with masses $\sim 1.4 M_\odot$ for NS and $\sim 10 M_\odot$ for BH), the distances $\mathcal{D}_{\rm I}$ and $\mathcal{D}_{\rm WB}$ to which initial IFOs and mature WB IFOs can detect them, and corresponding estimates of detection rates $\mathcal{R}_{\rm I}$ and $\mathcal{R}_{\rm WB}$; Secs. 1.1 and 1.2.

		NS/NS	NS/BH	BH/BH in field	BH/BH in globulars
	$\mathcal{R}_{\rm gal}$, yr^{-1}	10^{-6}–10^{-4}	$\lesssim 10^{-7}$–10^{-4}	$\lesssim 10^{-7}$–10^{-5}	10^{-6}–10^{-5}
	$D_{\rm I}$	20 Mpc	43 Mpc	100	100
LIGO I	$\mathcal{R}_{\rm I}$, yr^{-1}	$1 \times 10^{-4} - 0.03$	$\lesssim 1 \times 10^{-4} - 0.3$	$\lesssim 3 \times 10^{-3} - 0.5$	$0.03 - 0.5$
	$D_{\rm WB}$	300 Mpc	650 Mpc	$z = 0.4$	$z = 0.4$
LIGO II	$\mathcal{R}_{\rm WB}$, yr^{-1}	$0.5 - 100$	$\lesssim 0.5 - 1000$	$\lesssim 10 - 2000$	$100 - 2000$

V. Kalogera (population synthesis)

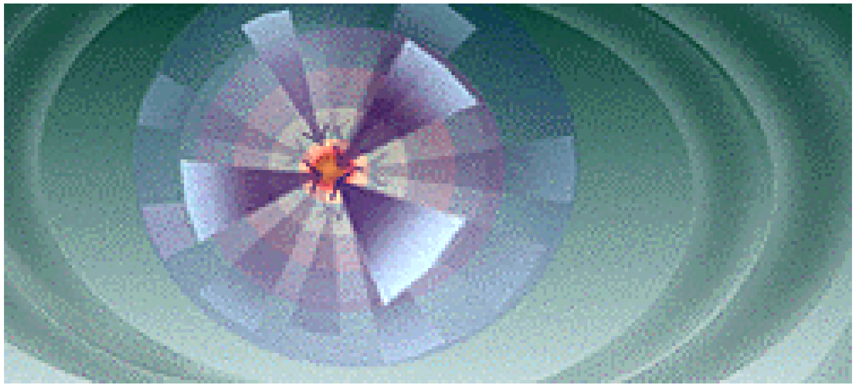
Supernova collapse sequence



- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- After about 0.5 second, the collapsing envelope interacts with the outward shock. Neutrinos are emitted.
- Within 2 hours, the envelope of the star is explosively ejected. When the photons reach the surface of the star, it brightens by a factor of 100 million.
- Over a period of months, the expanding remnant emits X-rays, visible light and radio waves in a decreasing fashion.

Gravitational Waves from Supernova collapse

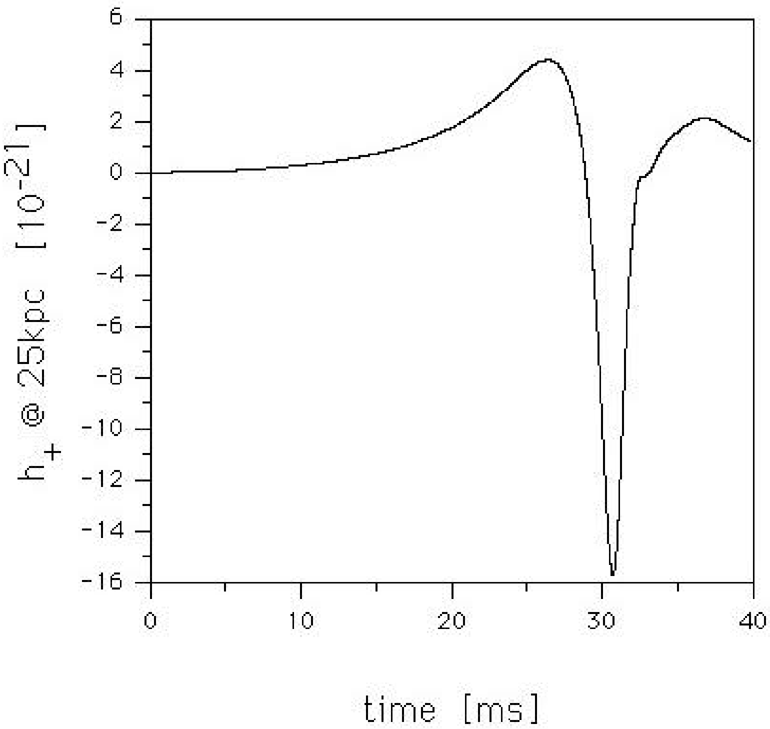
Non axisymmetric collapse



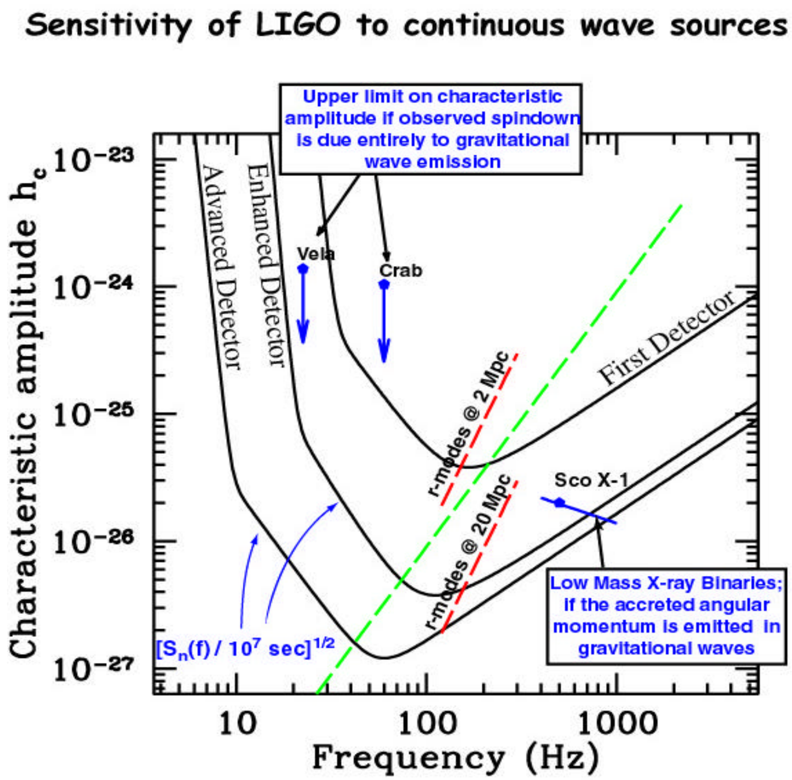
Rate

1/50 yr - our galaxy
3/yr - Virgo cluster

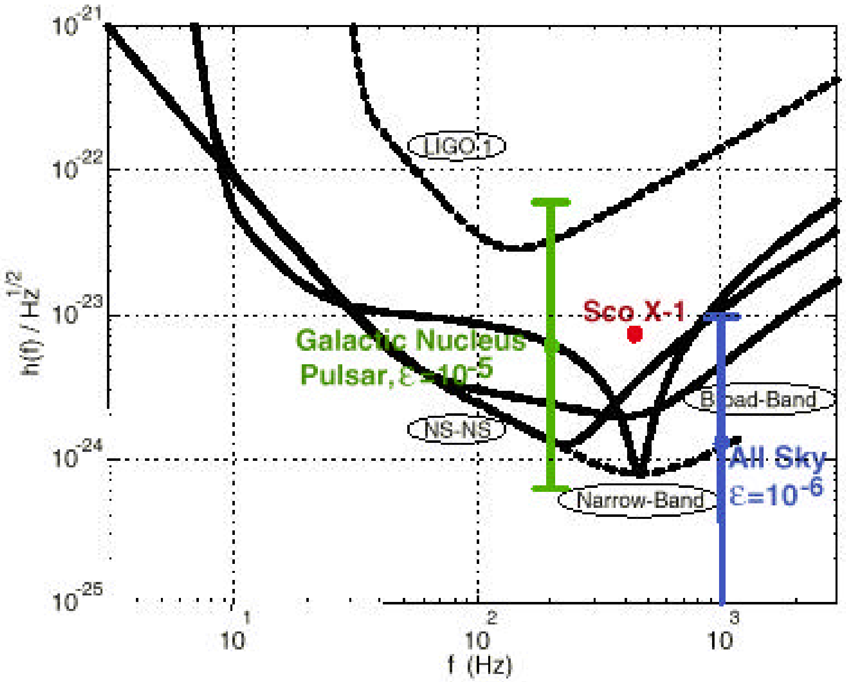
'burst' signal



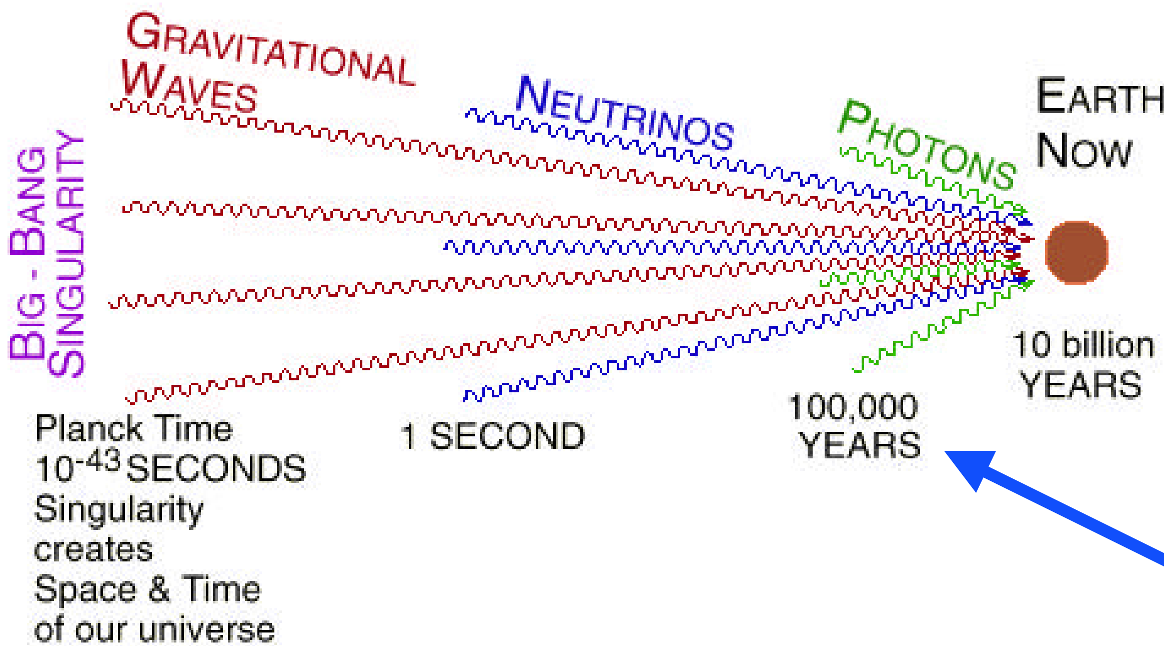
Pulsars and continuous wave sources



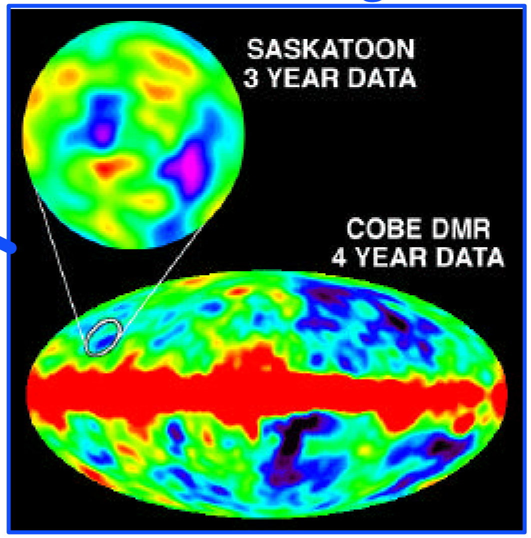
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: neutron star precession; interiors
  - »"R-mode" instabilities
  - »narrow band searches best



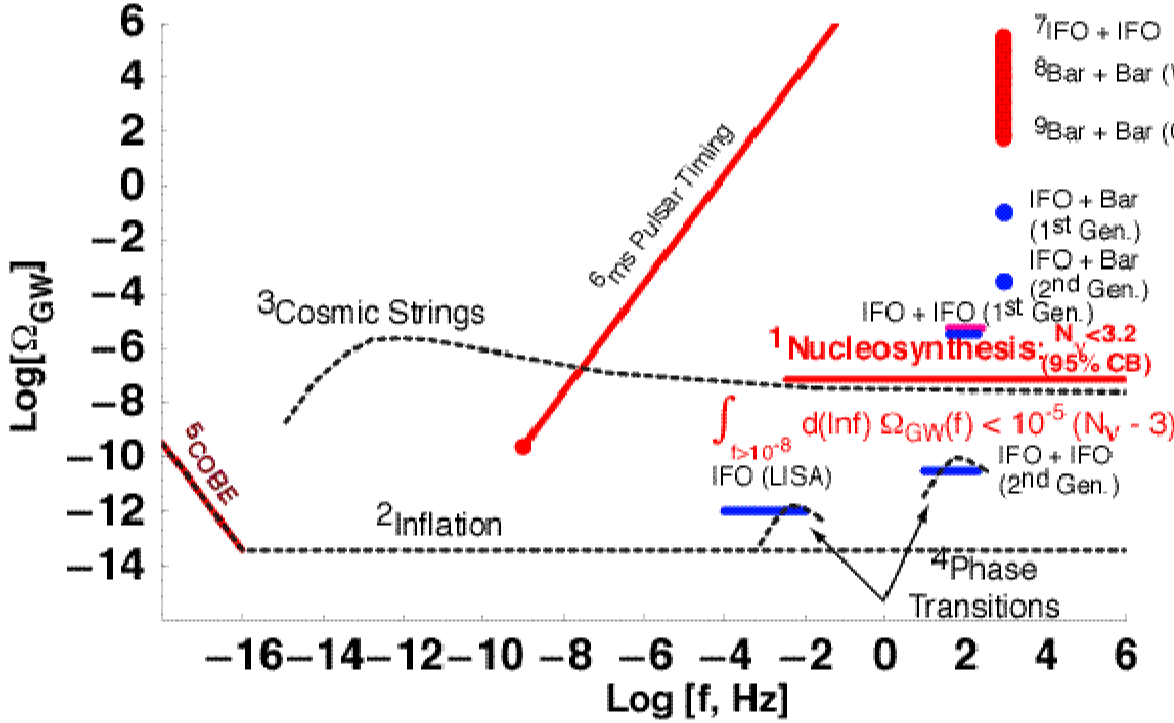
Gravitational waves from Big Bang



Cosmic microwave background



Predictions for BB-GW's



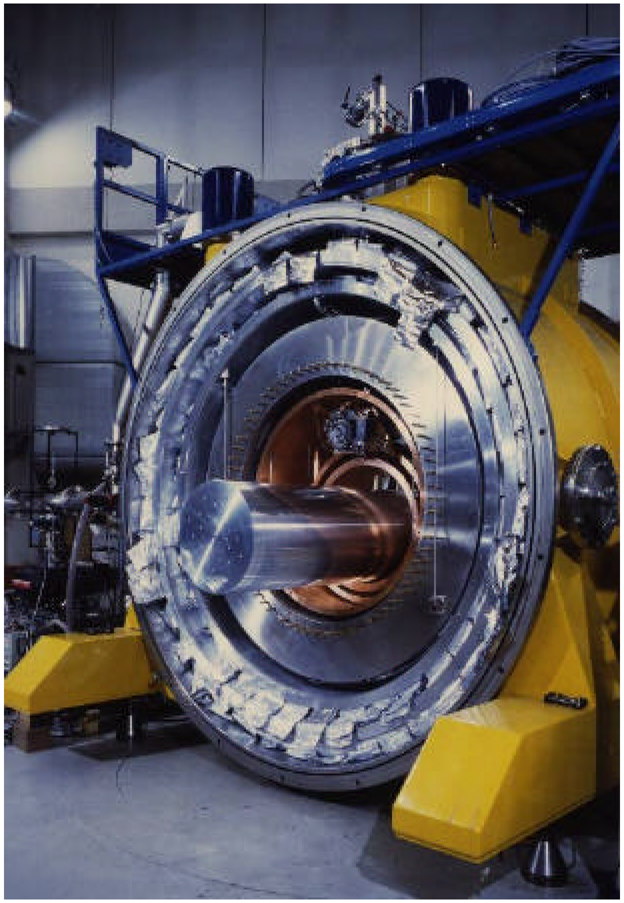
1 Kolb & Turner (The Early Universe, 1990)
Burles, Nollet, Trunan, Turner (PRL 82, 1999)
2 Grishchuk (SPJETP 40, 1975)
3 Allen & Brustein (gr-qc9609013)
Allen (gr-qc9604033)
4 Kamionkowski, Kosowoski & Turner (PRD 49, 1994)
5 Allen & Koranda (PRD 50, 1994)
6 Thorsett & Dewey (PRD 53, 1996)
Kaspi, Taylor, Ryba (ApJ 428, 1994)
7 Compton, Nicholson, Schutz, Proc. MG7 (1994)
8 Hough, Pugh, Bland, Drever, Nature 254 (1975)
9 Astone, et. al., Astr. Astroph. 351 (1999)

Gravitational wave detectors

- **Bar detectors**
  - Invented and pursued by Joe Weber in the 60's
  - Essentially, a large "bell", set ringing (at ~ 900 Hz) by GW
  - Won't discuss any further, here
- **Michelson interferometers (IFOs)**
  - At least 4 independent discovery of method:
  - Pirani `56, Gerstenshtein and Pustovoit, Weber, Weiss `72
  - Pioneering work by Weber and Robert Forward, in 60's
- LARGE Terrestrial and space-based IFOs now in construction and advanced planning stages!

Resonant bar detectors

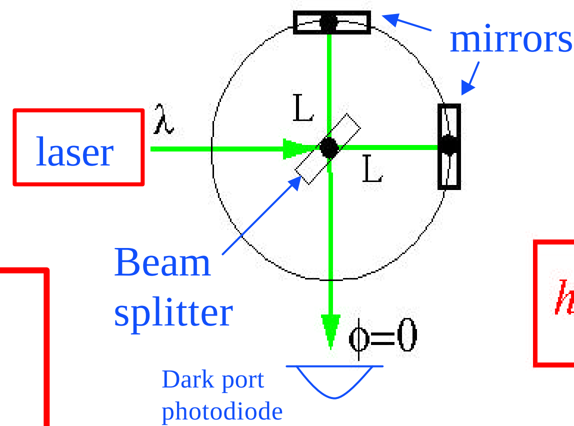
- AURIGA: Padova, Italy
- ALLEGRO: LSU, Baton Rouge, LA
- EXPLORER: CERN, Geneva
- NAUTILUS: CERN, Geneva
- NIOBE: UWA, Perth, Australia
- All nearly parallel to each other
- Typical (AURIGA):
  - » 2.3 tons of Al, 3m long;
  - » Cooled to 0.1K with dilution fridge in LiHe cryostat
  - » $Q = 4\times10^6$ at < 1K
  - » Fundamental resonant mode at ~900 Hz; narrow bandwidth
  - » Ultra-low-noise capacitive transducer and electronics (SQUID)

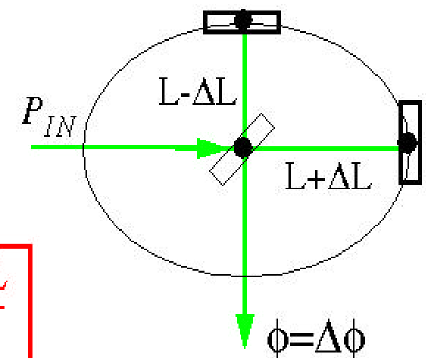


AURIGA

Interferometric detection of GWs

GW acts on freely falling masses:



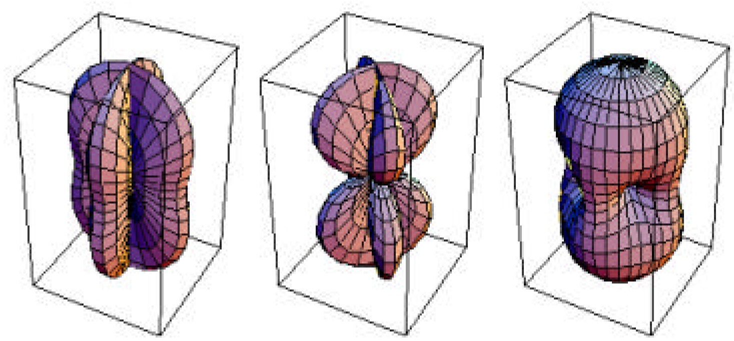


$$h = \frac{\Delta L}{L}$$

$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

For fixed ability to measure *DL*, make *L* as big as possible!

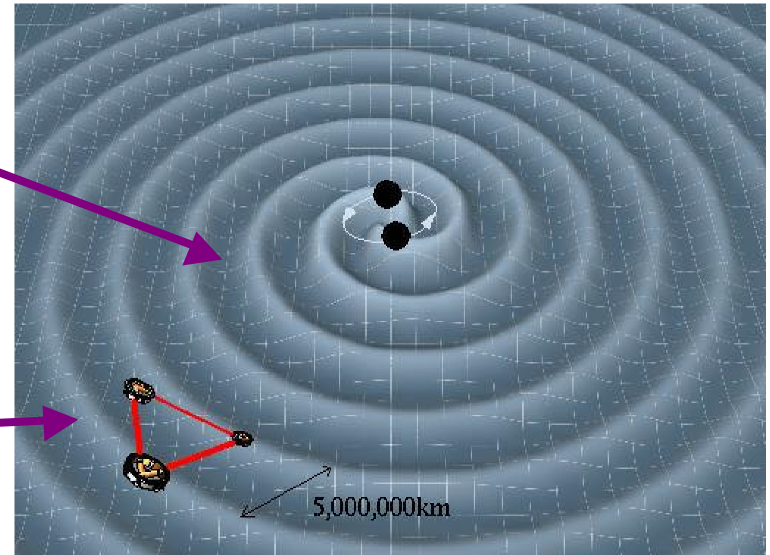
Antenna pattern:
(not very directional!)



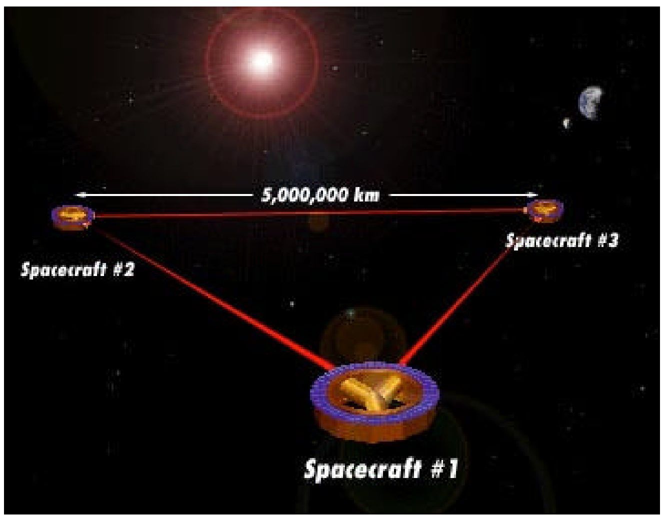
+ polarization × polarization unpolarized

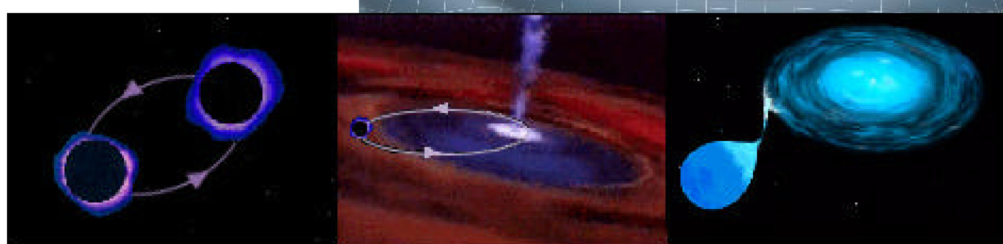
Laser Interferometer Space Antenna (LISA)

Radiation of Gravitational Waves from binary inspiral system



LISA

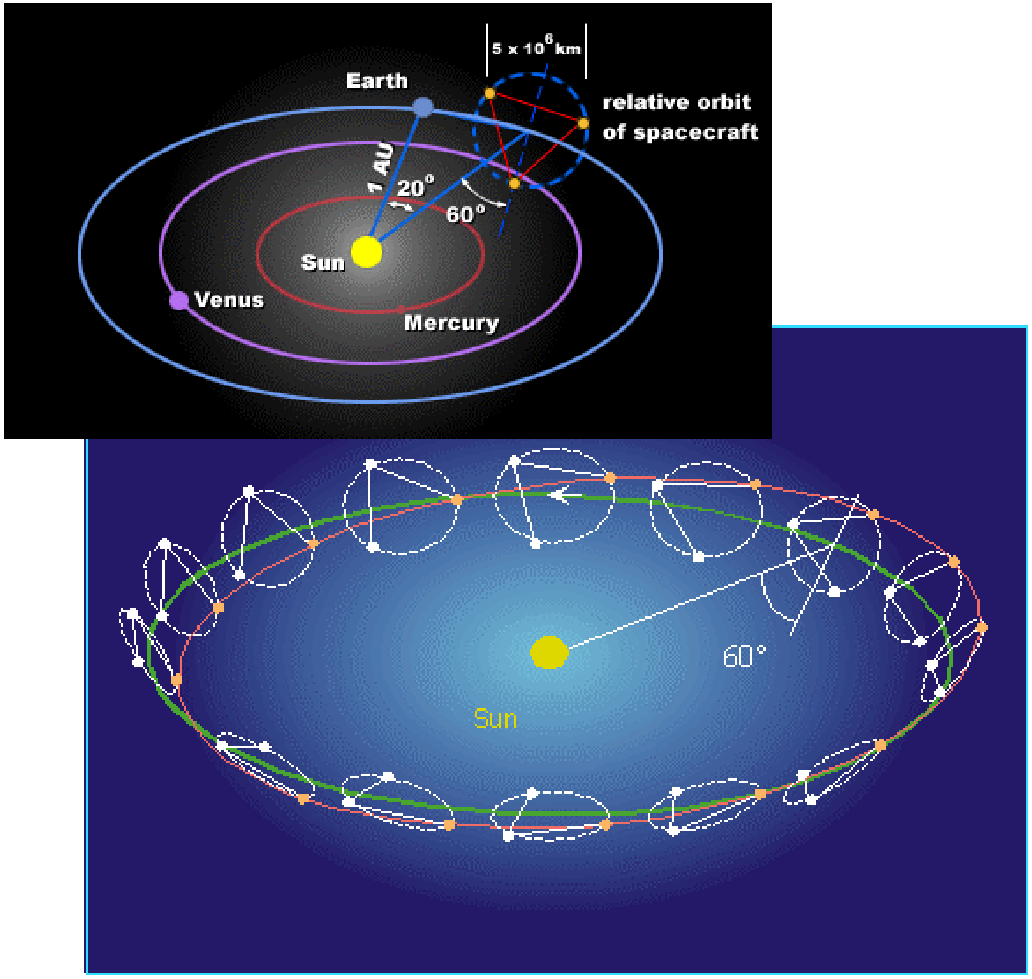




Coalescence of massive black holes during collisions between galaxies, perhaps in formation of massive black holes, probing the central engines powering quasars.	Black holes orbiting massive black holes, providing precision tests of gravitational theory in the high-field limit.	Hundreds of galactic binary star systems, many containing neutron stars or black holes, including several known binary systems.

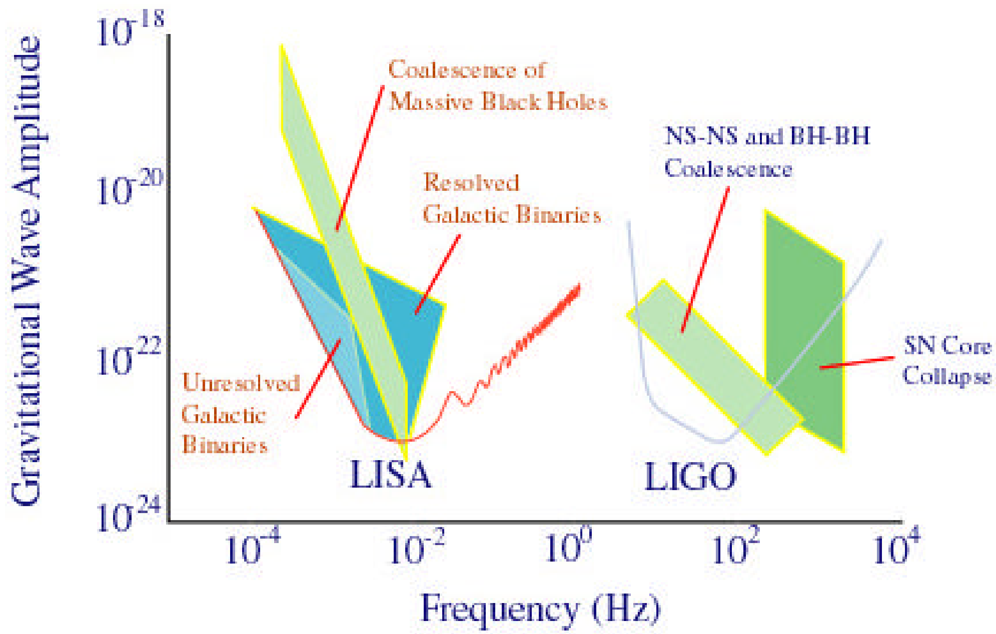
LISA orbit

The orbit of the "triangle" of spacecraft *tumbles* as it orbits the sun, to be sensitive to all directions in the sky, and to even out the thermal load (from the sun) on the three spacecraft.



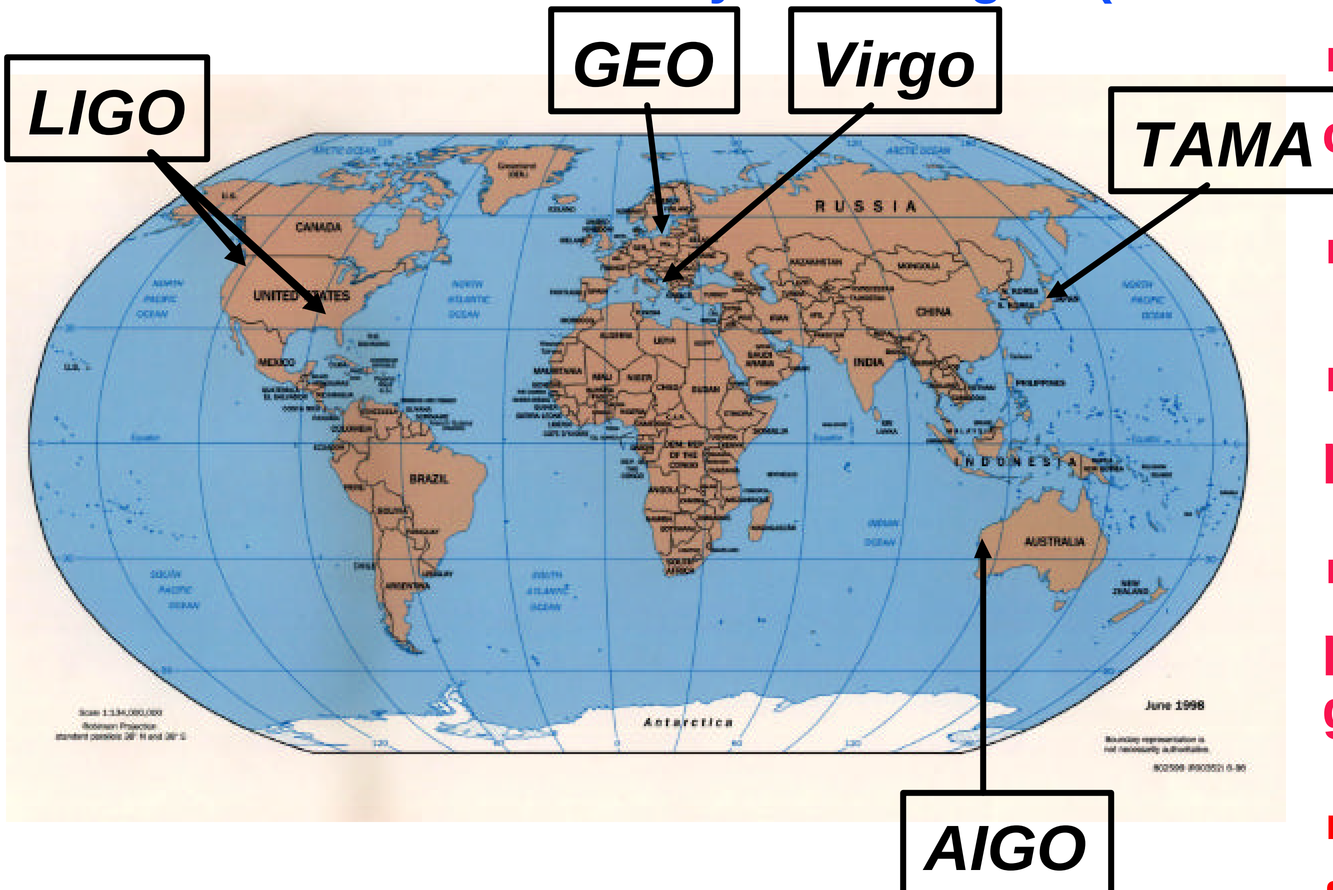
Sensitivity bandwidth

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



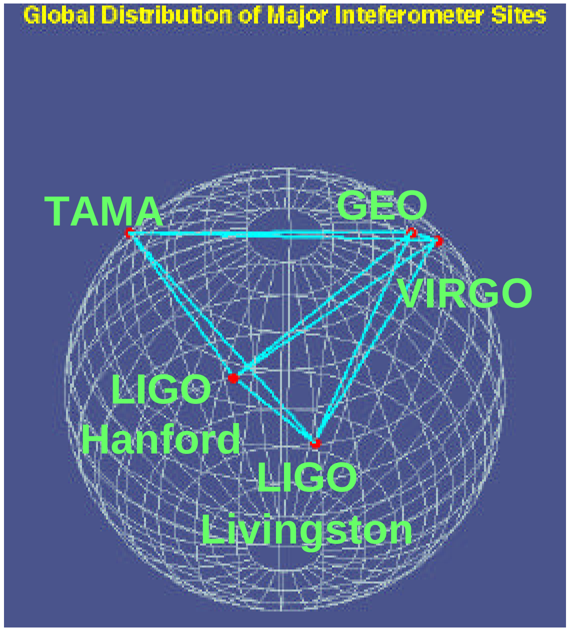
International network

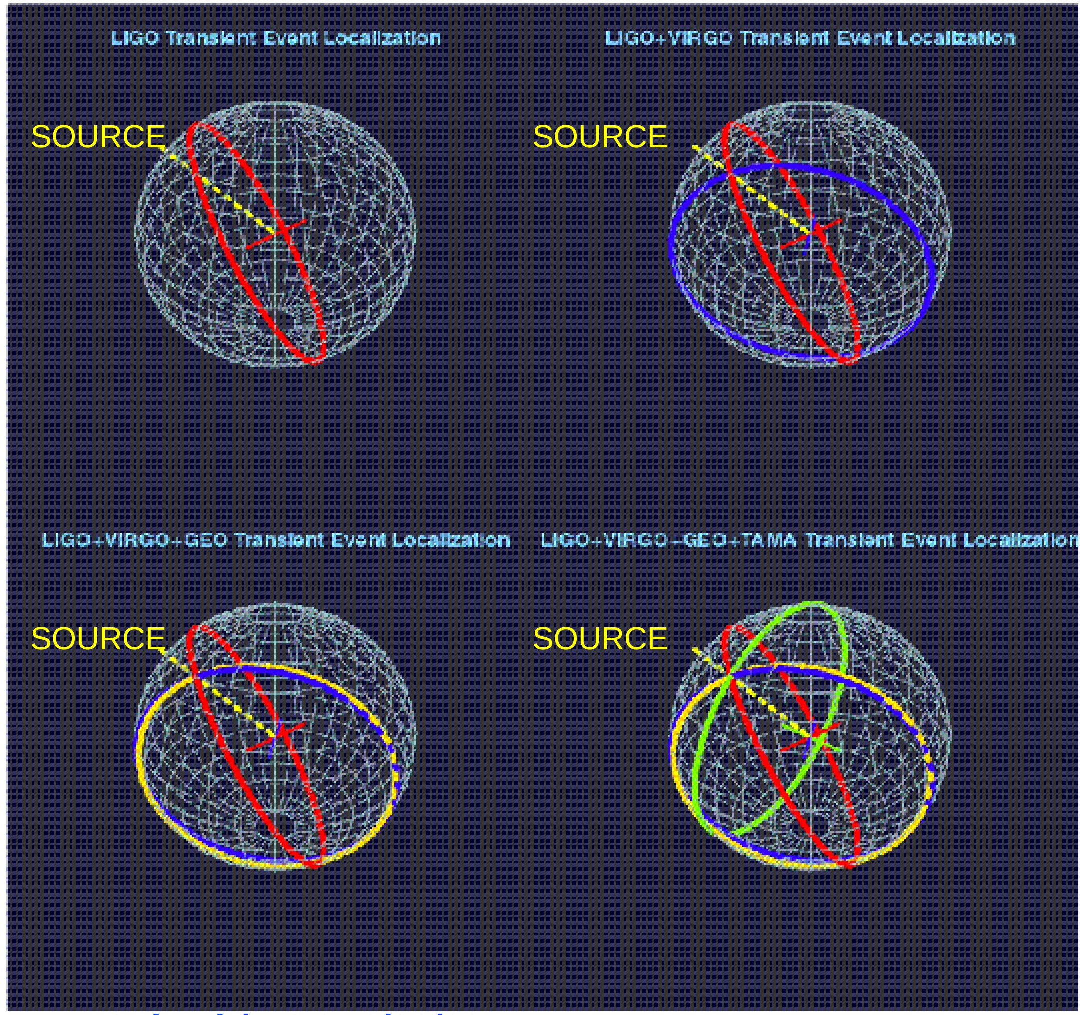
Simultaneously detect signal (within msec)



- **detection confidence**
- **locate the sources**
- **verify light speed propagation**
- **decompose the polarization of gravitational waves**
- **Open up a new field of astrophysics!**

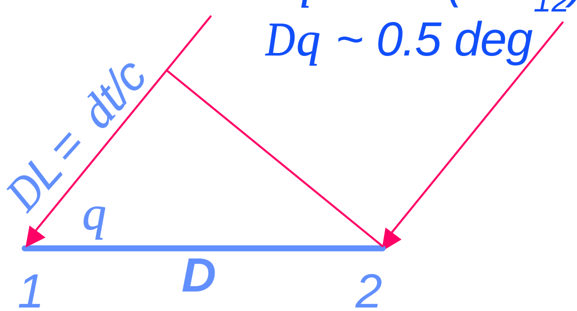
Event Localization With An Array of GW Interferometers



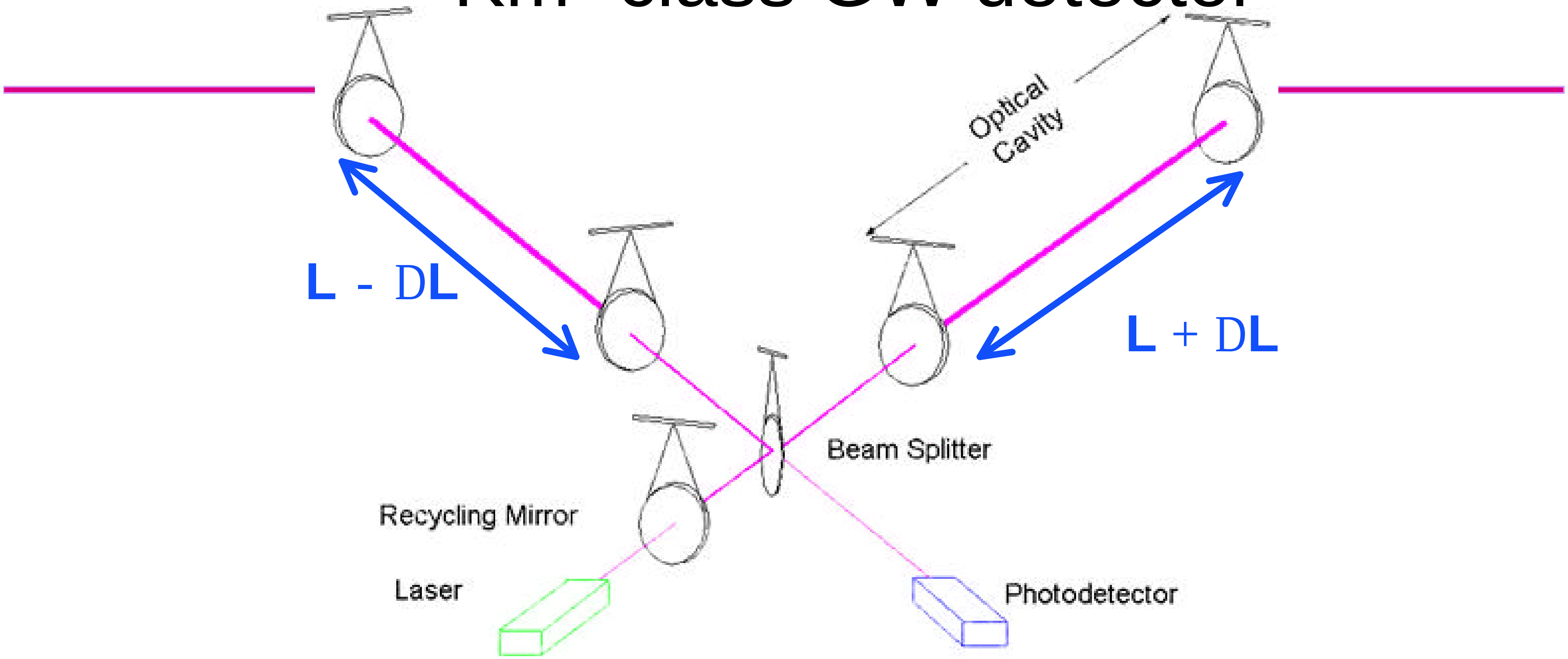


$cosq = dt / (c D_{12})$

$Dq \sim 0.5$ deg

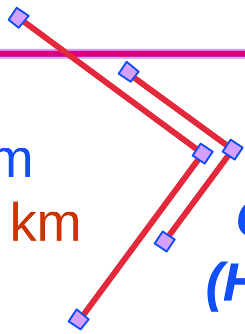


LIGO – the first Km- class GW detector



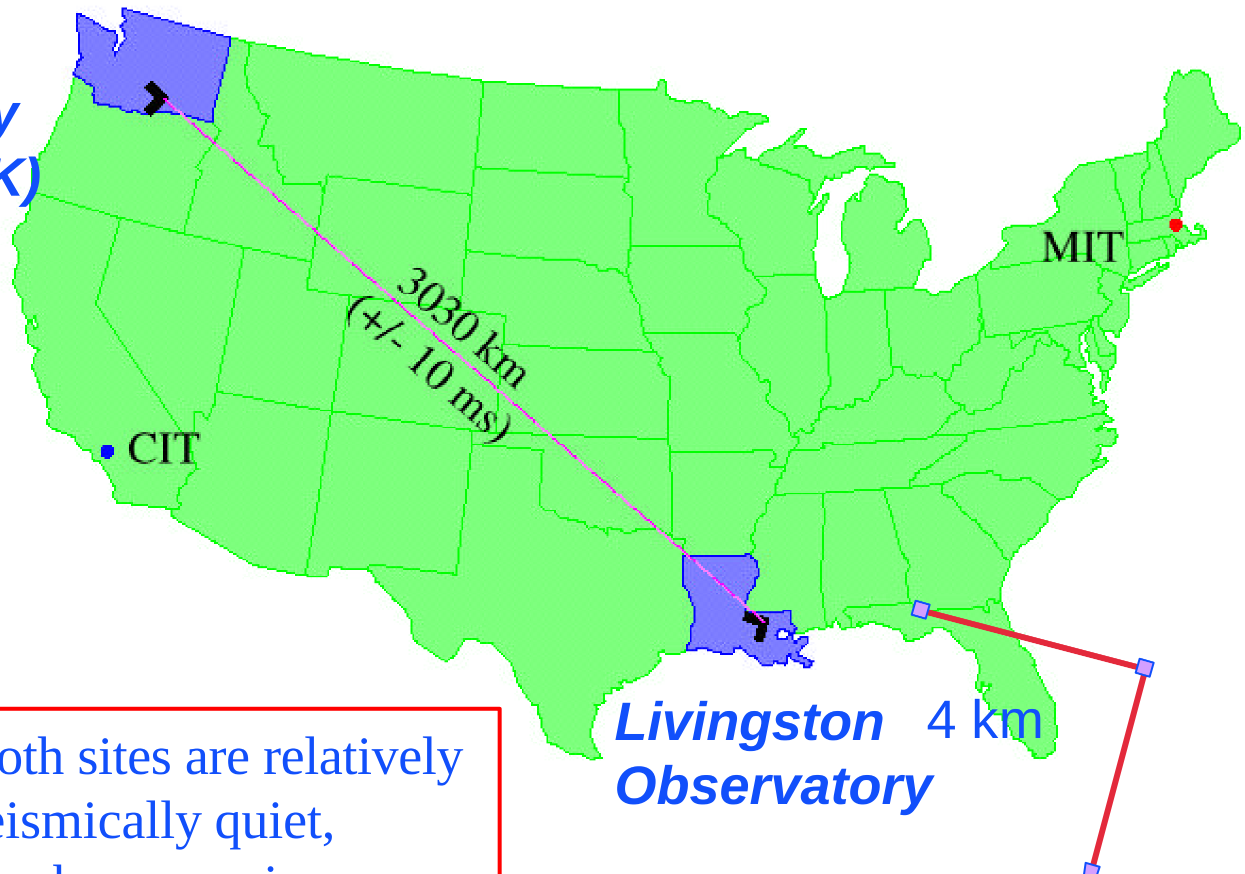
$$\Delta L = \underbrace{h}_{\lesssim 10^{-21}}\ \underbrace{L}_{4\text{ km}} \lesssim 4\times10^{-16}\ \text{cm}$$

LIGO sites



4 km
+ 2 km

Hanford Observatory (H2K and H4K)



Livingston Observatory 4 km

Hanford, WA (LHO)

- located on DOE reservation
- treeless, semi-arid high desert
- 25 km from Richland, WA
- Two IFOs: H2K and H4K

Livingston, LA (LLO)

- located in forested, rural area
- commercial logging, wet climate
- 50km from Baton Rouge, LA
- One L4K IFO

Both sites are relatively seismically quiet, low human noise

LIGO Livingston (LLO)

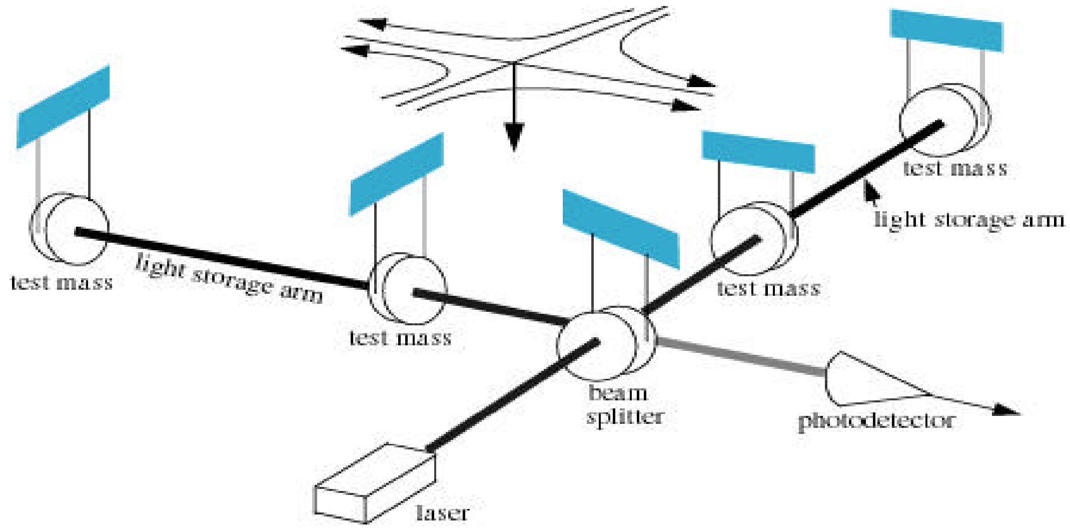
- 30 miles from Baton Rouge, LA (LSU)
- forested, rural area
- Commercial logging, wet climate
- need moats (with alligators)
- Seismically quiet, low human noise level

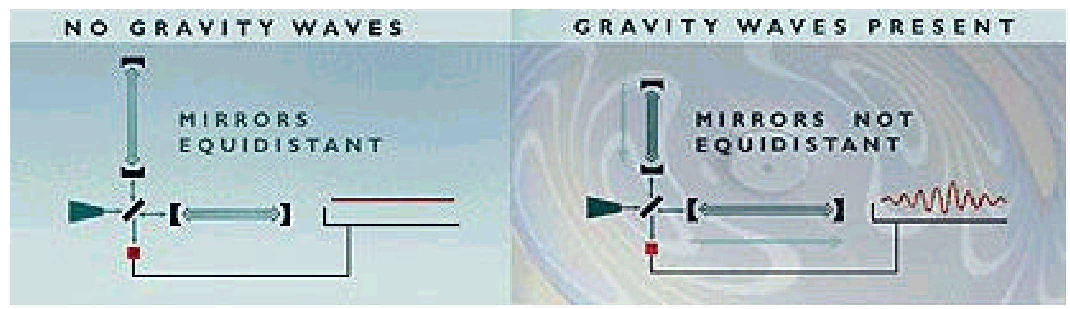
LIGO Hanford (LHO)

- DOE nuclear reservation
- treeless, semi-arid high desert
- 15 miles from Richmond, WA
- Seismically quiet, low human noise level

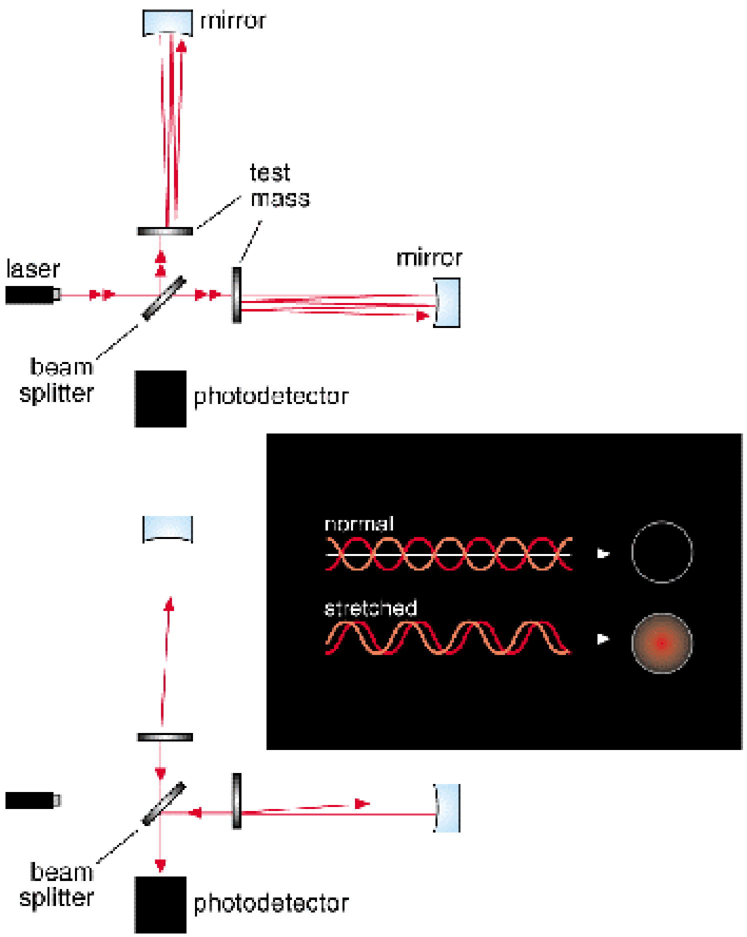
Interferometer for GWs

- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.
- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other.
- The interference pattern is measured (or the fringe is split) to one part in 10^{10}, in order to obtain the required sensitivity.





Interferometric phase difference



The effects of gravitational waves appear as a deviation in the phase differences between two orthogonal light paths of an interferometer.

For expected signal strengths, The effect is *tiny*:

Phase shift of ~10^{-10} radians

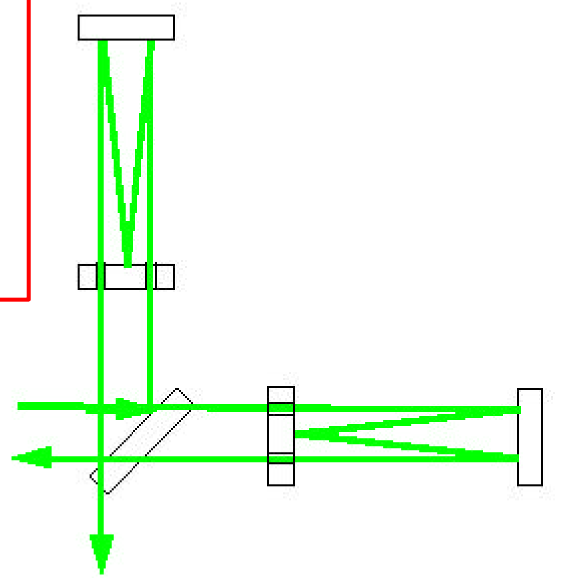
The longer the light path, the larger the phase shift…

Make the light path as long as possible!

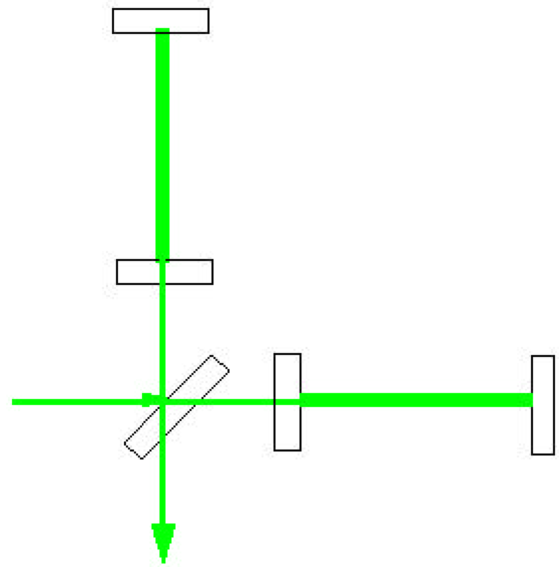
Light storage: folding the arms

How to get long light paths without making *huge* detectors:

Fold the light path!



Delay line interferometer



Fabry Perot interferometer

Simple, but requires large mirrors; limited t_{stor}

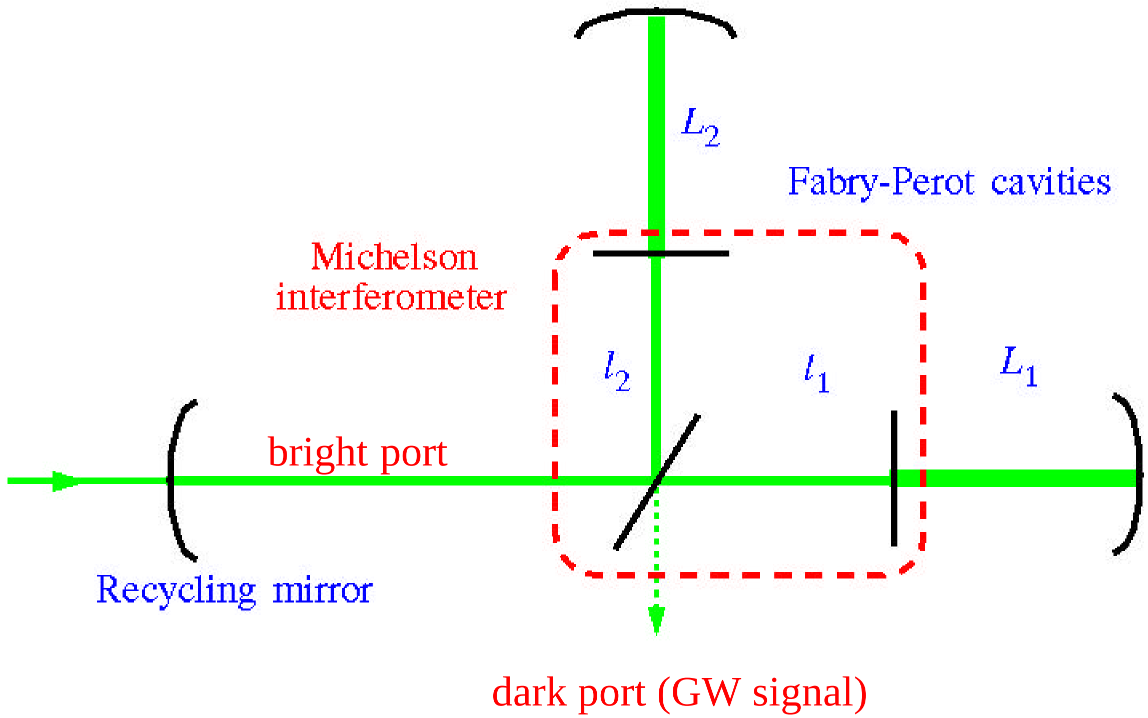
(LIGO design) $t_{stor} \sim 3$ *msec*

More compact, but harder to control

LIGO I configuration

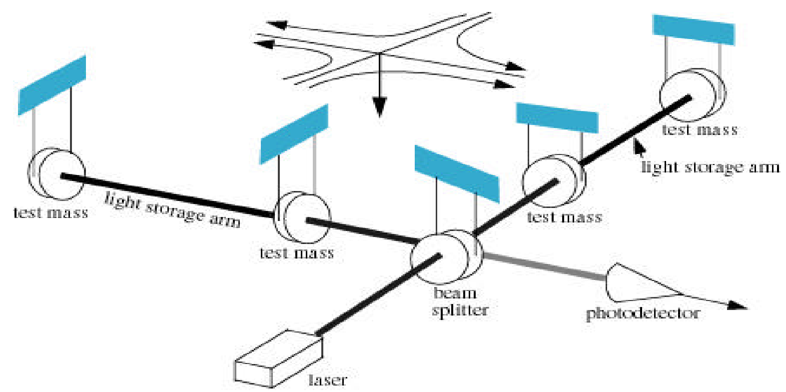
Power-recycled Michelson with Fabry-Perot arms:

- Fabry-Perot optical cavities in the two arms store the light for many (~200) round trips
- Michelson interferometer: change in arm lengths destroy destructive interference, light emerges from dark port
- Normally, light returns to laser at bright port
- Power recycling mirror sends the light back in (coherently!) to be reused

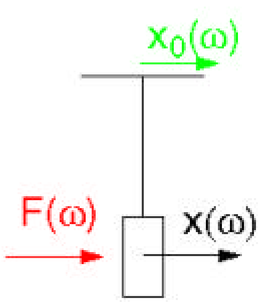


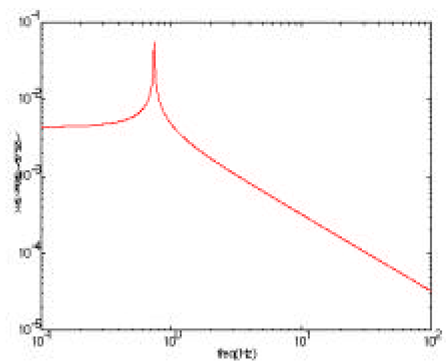
Suspended test masses

- To respond to the GW, test masses must be "free falling"
- On Earth, test masses must be supported against DC gravity field
- The Earth, and the lab, is vibrating like mad at low frequencies (seismic, thermal, acoustic, electrical);
    - can't simply bolt the masses to the table (as in typical ifo's in physics labs)
- So, IFO is insensitive to low frequency GW's
- Test masses are suspended on a pendulum resting on a seismic isolation stack
    - "fixed" against gravity at low frequencies, but
    - "free" to move at frequencies above ~ 100 Hz



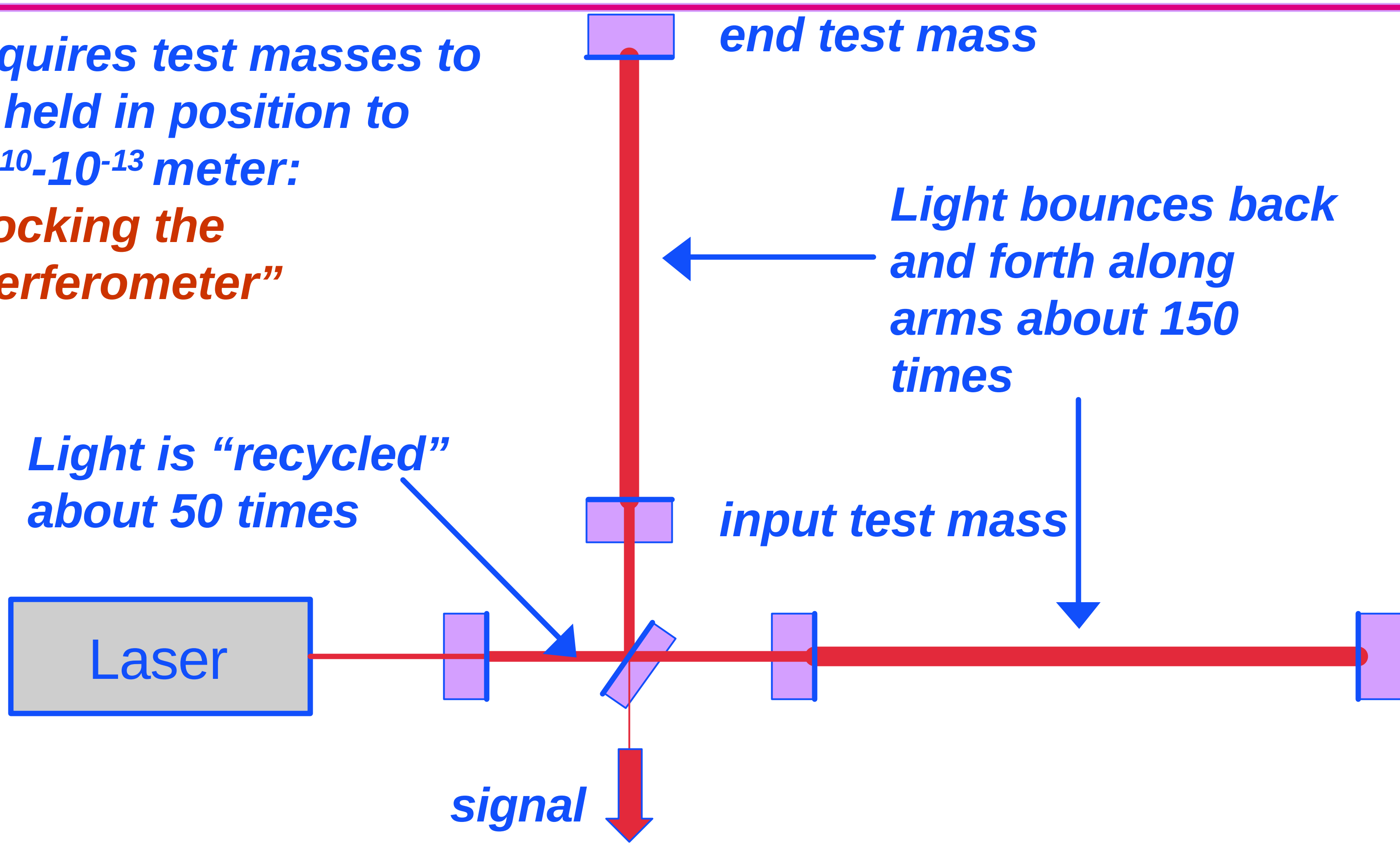
"Free" mass: pendulum at $f \gg f_0$





Interferometer *locking*

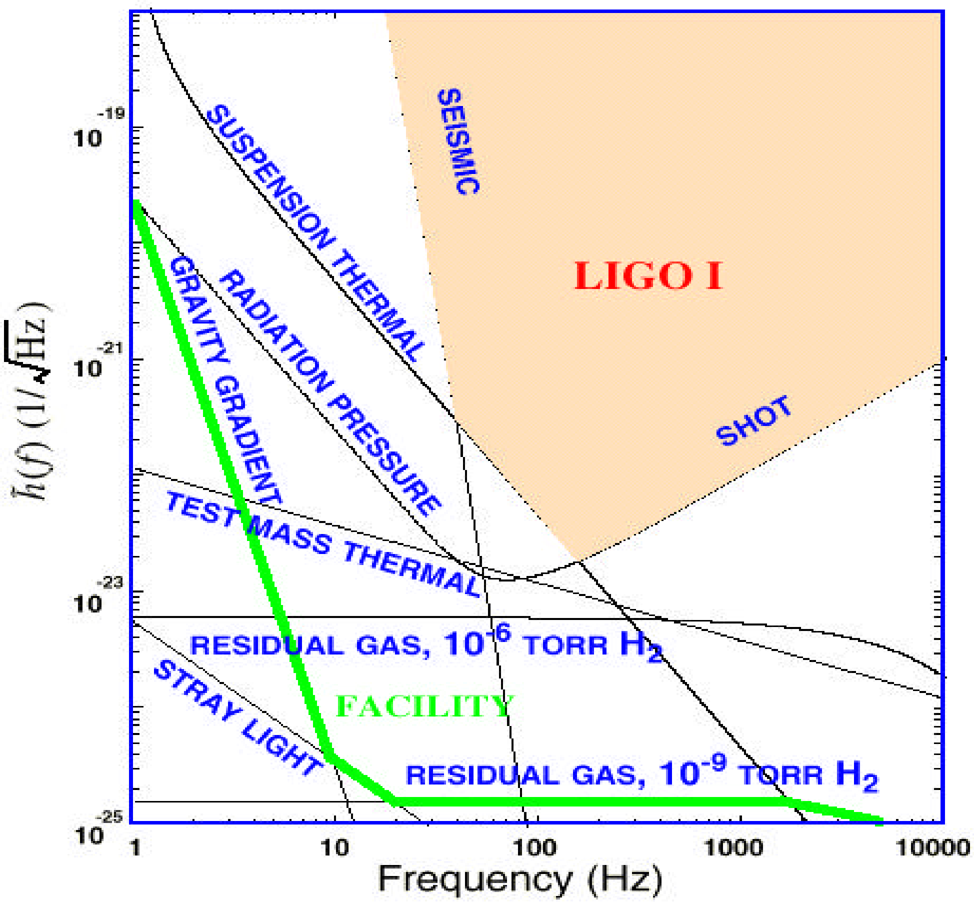
Requires test masses to be held in position to 10^{-10}-10^{-13} meter:
"Locking the interferometer"



LIGO I 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**

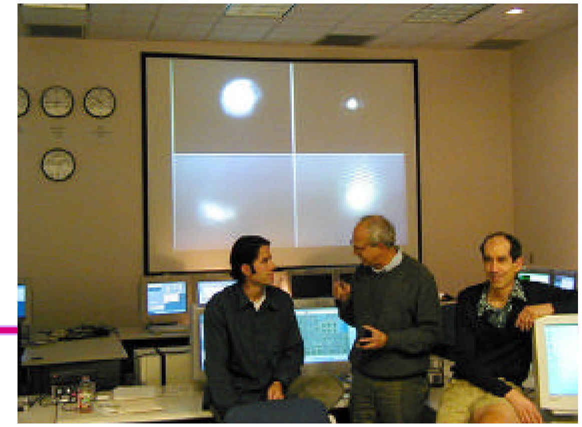
- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**



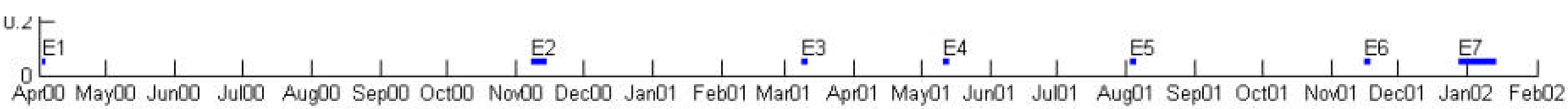
LIGO I schedule

1995	NSF funding secured ($360M)
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 LIGO I Science Run)
2003+	LIGO I data run (one year integrated data at $h \sim 10^{-21}$)
2007	Begin Advanced LIGO upgrade

LIGO Engineering runs

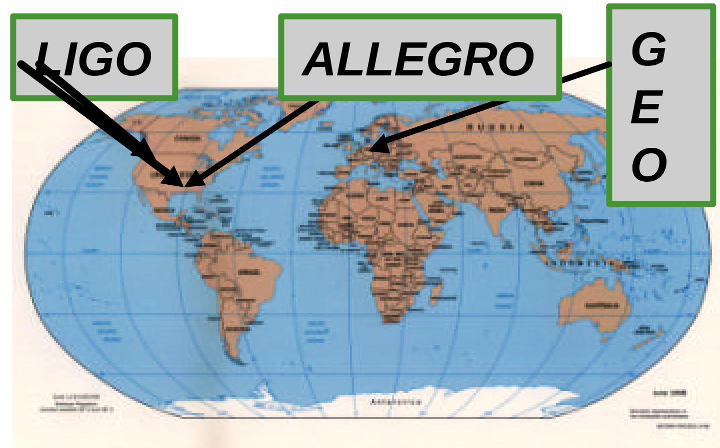


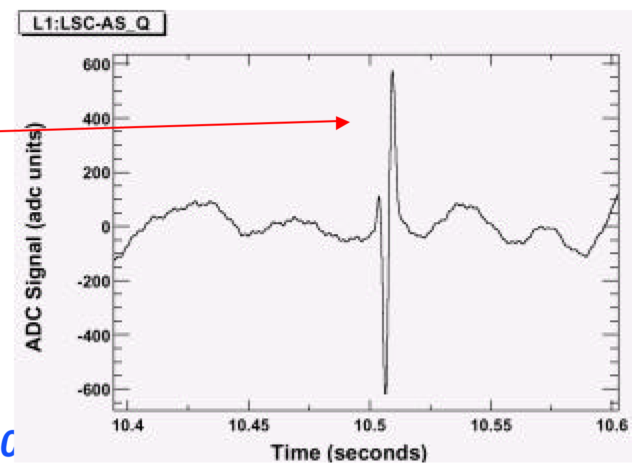
- Commissioning GW IFO's is a very tricky business!
  - » They are complex, non-linear, non-reductionistic systems
  - » There's precious little experience…
- First task is to get the IFO's to operate in the correct configuration, with all optical cavities resonating – "In Lock"
- Next task is to reduce the noise (reduce all non-fundamental noise sources to insignificance), improve sensitivity
- LIGO has had 6 engineering runs in 2000-2001, focusing on keeping IFO's In Lock for long periods of time (duty cycle)
- "First Lock" achieved at H2K on October 2000
- Rarely had more than one IFO (of 3) operating at a time – till E7!
- Engineering Run 7 (Dec 28, 2001 – Jan 14, 2002) is by far the most successful we've had!
- E8 completed last wee; and first Science run by END OF JUNE!



LIGO Engineering run 7 (E7)

- **Focus on duty-cycle, not noise or noise reduction**
- **ALL 3 IFO's were running and achieving lock for significant fraction of the time**
- **GEO IFO was also up, and participating; also ALLEGRO and GRBs**
- **Some ongoing investigations:**
  - » **Compile statistics on lock acquisition and lock loss, study sources of lock loss**
  - » **Quantify correlations between GW and other (IFO and environmental) channels**
  - » **Correlations between noise, transients in GW channel between IFOs**
  - » **Test simulated astrophysical signal injection**
  - » **Identify environmental disturbances**
  - » **Gaussianity, stationarity of noise in GW channel**
- **"physics searches" ran online in LIGO Data Analysis System (LDAS)**





A variety of learning experiences

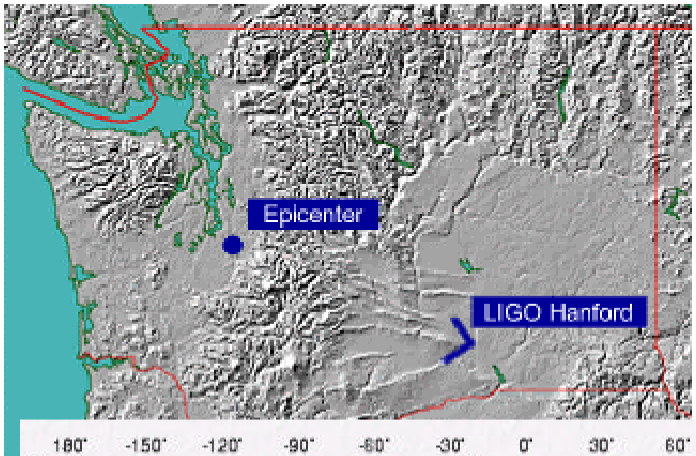
- Computer crashes
- Earthquakes
- No fire or floods yet…
- Logging at Livingston
- Cars driving over cattle guards
- Wind at Hanford
- Snow in Louisiana

AJW, Caltech/LIGO, 6/20/02

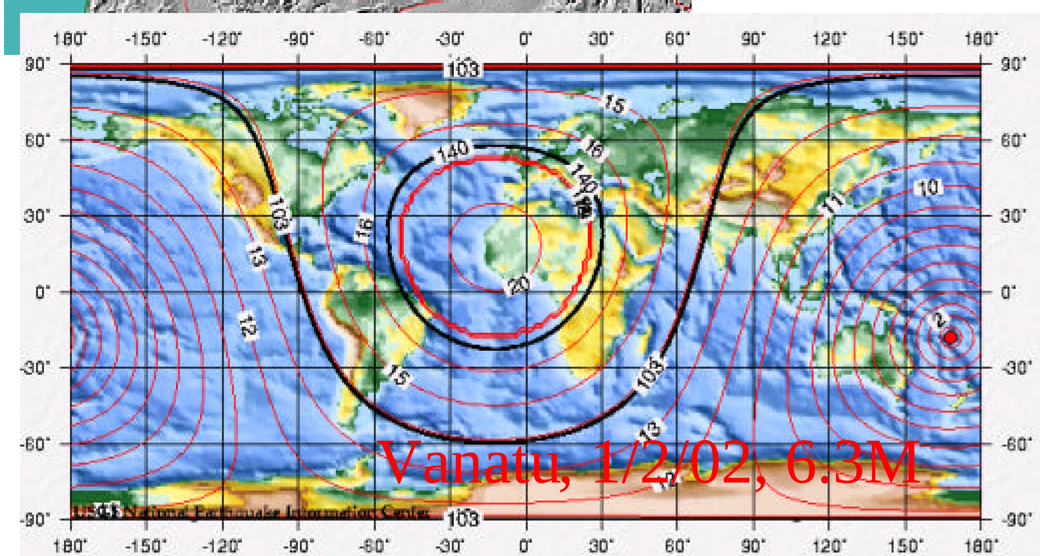
Logging at Livingston

Less than 3 km away…
Dragging big logs …
Remedial measures at LIGO are in progress; this will not be a problem in the future.

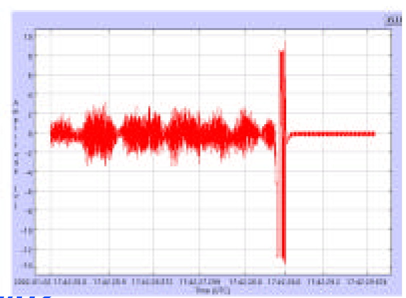
Earthquakes…



This one, on
February 28, 2000
knocked out the H2K
For months…

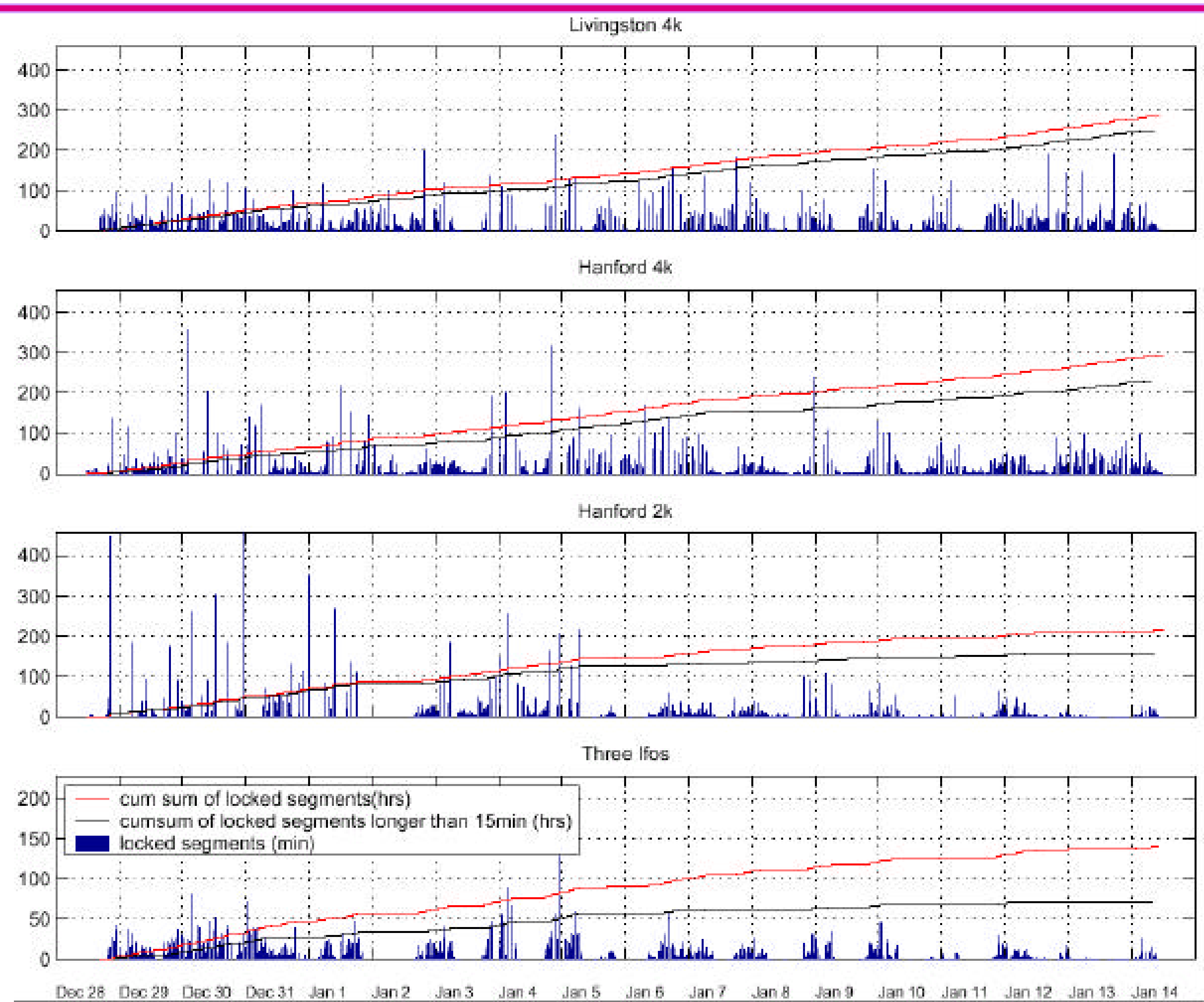


Earthquakes have not been a problem for E7, but we can "hear" them with the IFO



From GEO

LIGO IFO duty cycle, E7



380 hrs

Livingston 4k:
Total locked time: 265 hrs
Duty cycle: 69.8 %
Total time locked with locks longer than 15min: 232 hrs
Duty cycle for long locks: 61.3 %

Hanford 4k:
Total locked time: 274 hrs
Duty cycle: 71.3 %
Total time locked with locks longer than 15min: 216 hrs
Duty cycle for long locks: 56.3 %

Hanford 2k:
Total locked time: 210 hrs
Duty cycle: 54.9 %
Total time locked with locks longer than 15min: 156 hrs
Duty cycle for long locks: 40.6 %

Hanford and Livingston 4k:
Total locked time: 209 hrs
Duty cycle: 54.5 %
Total time locked with locks longer than 15min: 143 hrs
Duty cycle for long locks: 54 %

Three LIGO Interferometers:
Total locked time: **138 hrs**
Duty cycle: 35.9 %
Total time locked with locks longer than 15min: 70.8 hrs
Duty cycle for long locks: 18.5 %

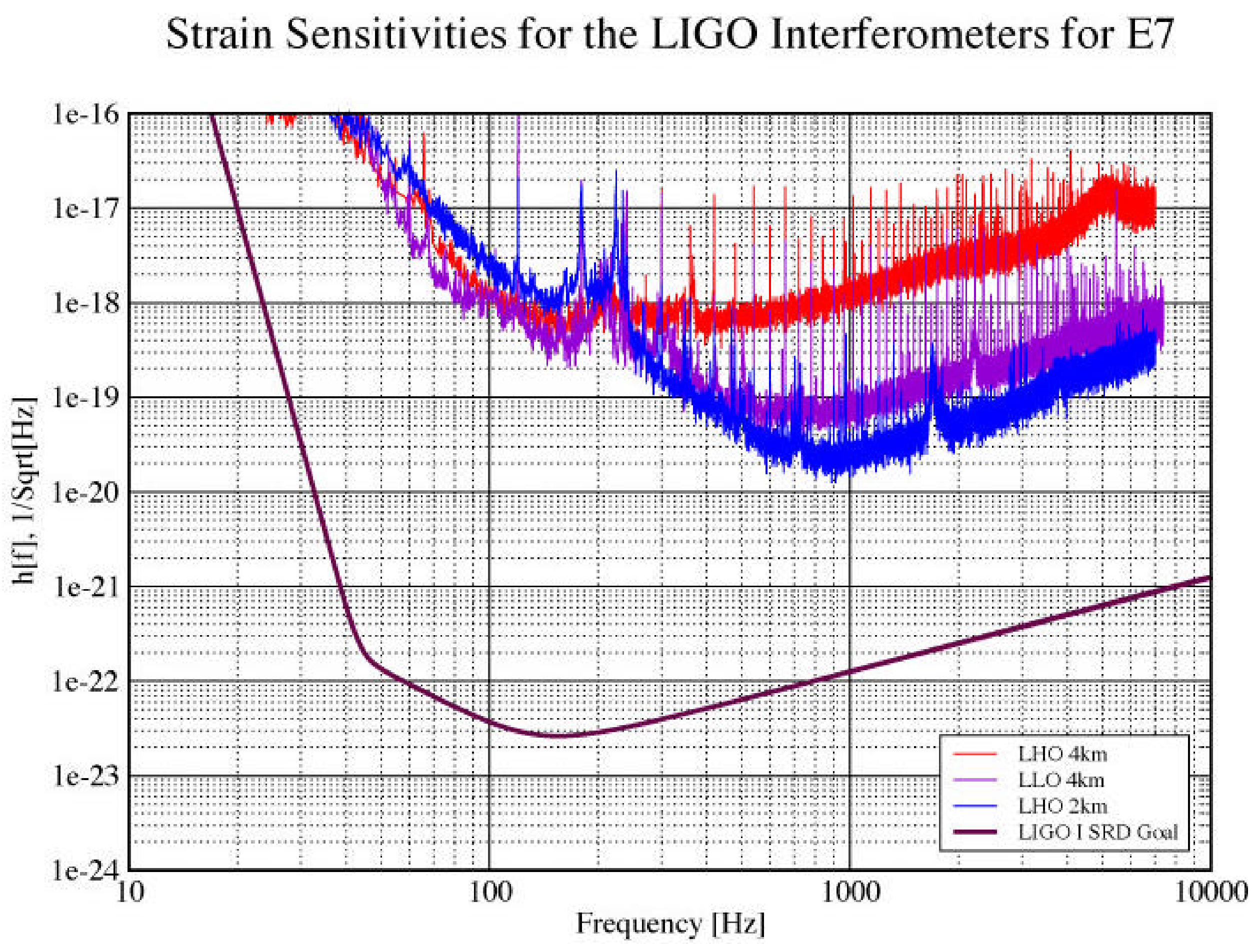
We are thrilled!!

Gamma Ray Bursts during E7 and LIGO coverage

- 16 triggers for the duration of E7 !
- Various degrees of confidence
- Various degrees of directional information
- Very promising, the analysis is ongoing !

	Detector	DATE
1.	ULYSSES	01/12/28
2.	BEPPOSAX GRBM, ULYSSES, KONUS WIND	01/12/28
3.	BEPPOSAX GRBM	01/12/30
4.	BEPPOSAX GRBM	01/12/31
5.	KONUS WIND	02/01/02
6.	BEPPOSAX GRBM	02/01/02
7.	GCN/HETE	02/01/05
8.	BEPPOSAX GRBM	02/01/06
9.	ULYSSES, KONUS WIND	02/01/06
10.	GCN/HETE	02/01/08
11.	GCN/HETE	02/01/08
12.	GCN/HETE	02/01/10
13.	BEPPOSAX GRBM	02/01/12
14.	KONUS WIND, BEPPOSAX, HETE	02/01/13
15.	KONUS WIND, BEPPOSAX	02/01/13
16.	ULYSSES, HETE	02/01/14

Strain Sensitivity of LIGO IFO's during E7 (preliminary…)

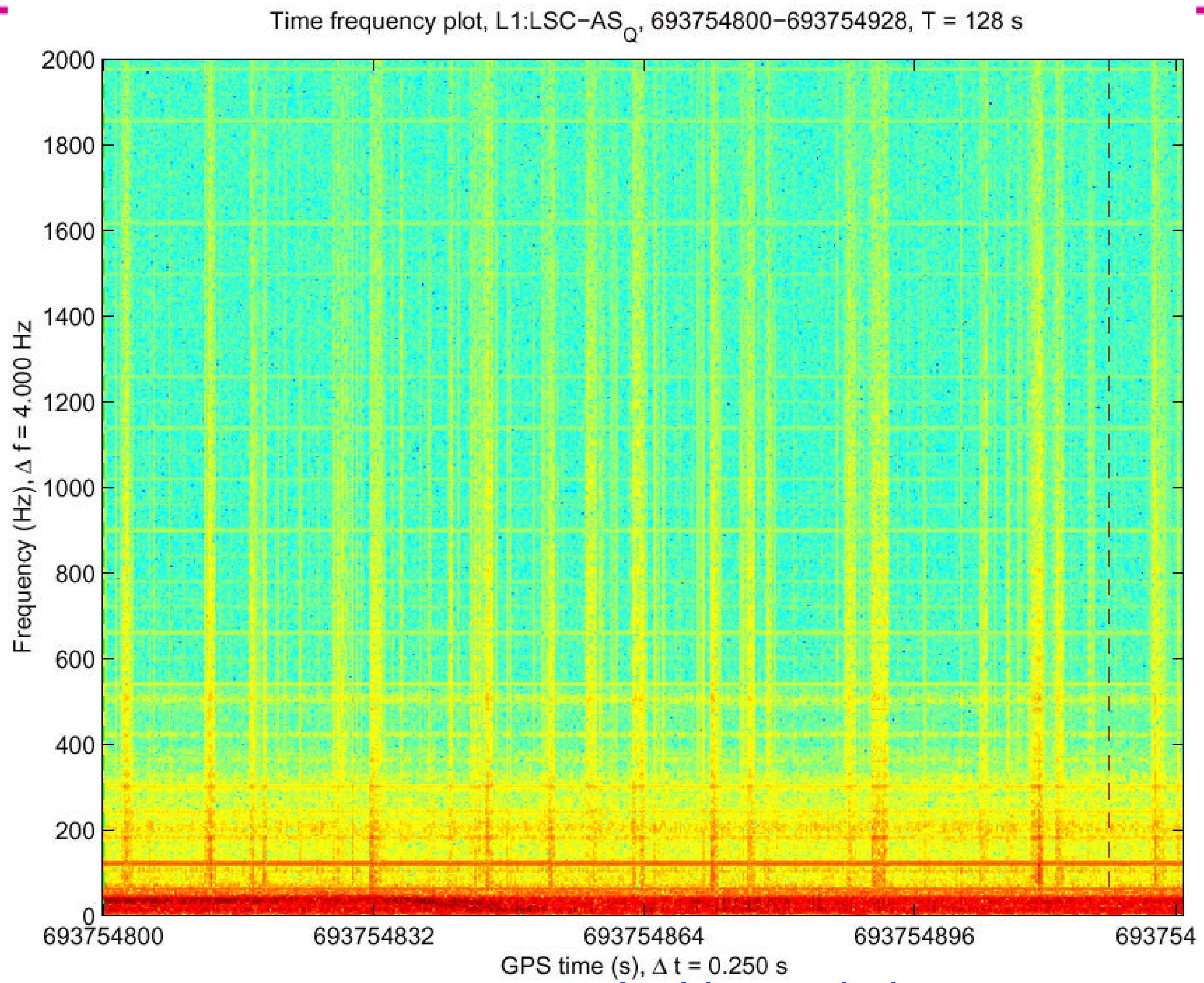


Contributions:

- PSL frequency noise (need common mode servo on all IFOs)
- Misalignments (reduce noise in oplevs; tuning of alignments servos needed)
- Laser glitches & bursts (reduce acoustic coupling into PSL)
- Periscope vibrations on PSL table (~200 Hz)
- Photodetector preamp Johnson noise (high-f)
- Excess noise in Pentek ADCs
- Excess coil driver/DAC noise
- Unidentified electronics noise
- Low laser power (operating at 1 watt, not 6 watts)
- …

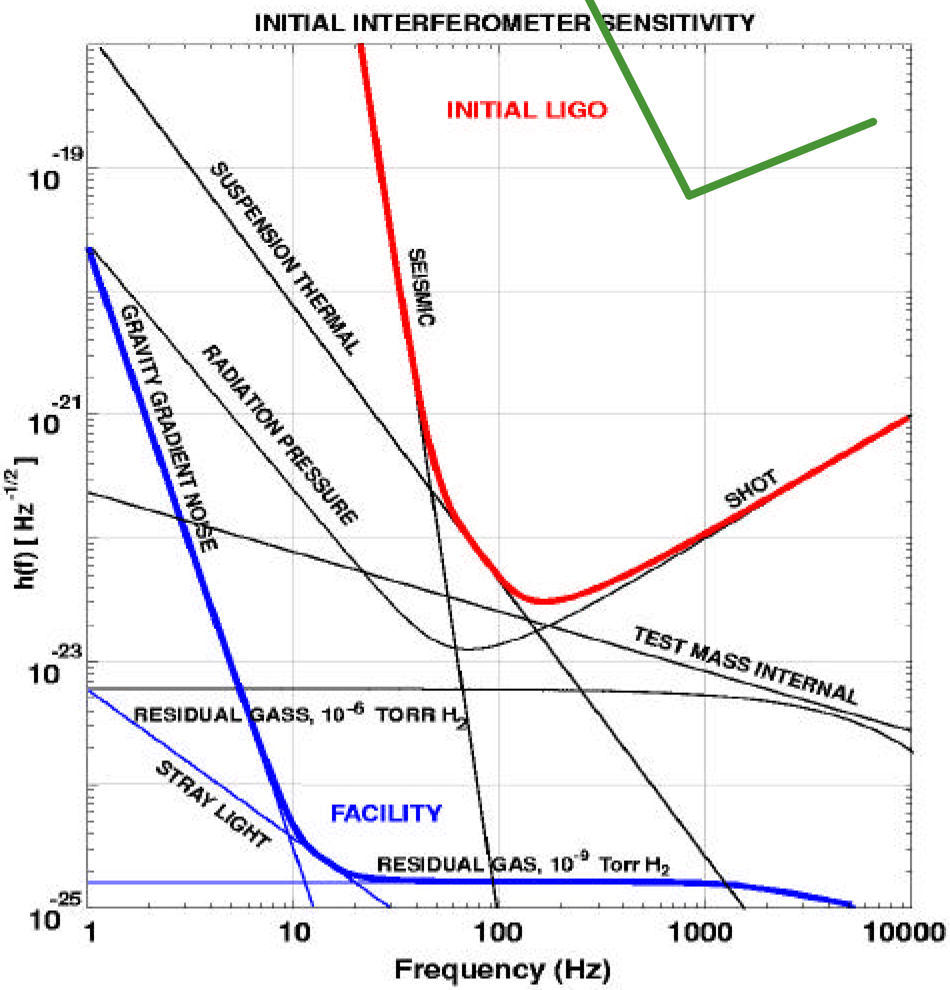
ALL technical noise; No fundamental noise exposed yet.

Time-frequency spectrogram of GW signal – stationary?



AJW, Caltech/LIGO, 6/20/02

Initial LIGO Sensitivity Goal



- Strain sensitivity goal:
  $<3\times10^{-23}$ 1/Hz$^{1/2}$
  at 200 Hz
- So far, getting
  $\sim(5\text{-}10)\times10^{-20}$ 1/Hz$^{1/2}$
  at ~1000 Hz

- Better than we expected!
- During E7, sensitivity is a bit better than for H2K during previous runs; but…
- We're getting similar sensitivity out of all 3 IFO's, simultaneously!

LIGO E7 summary

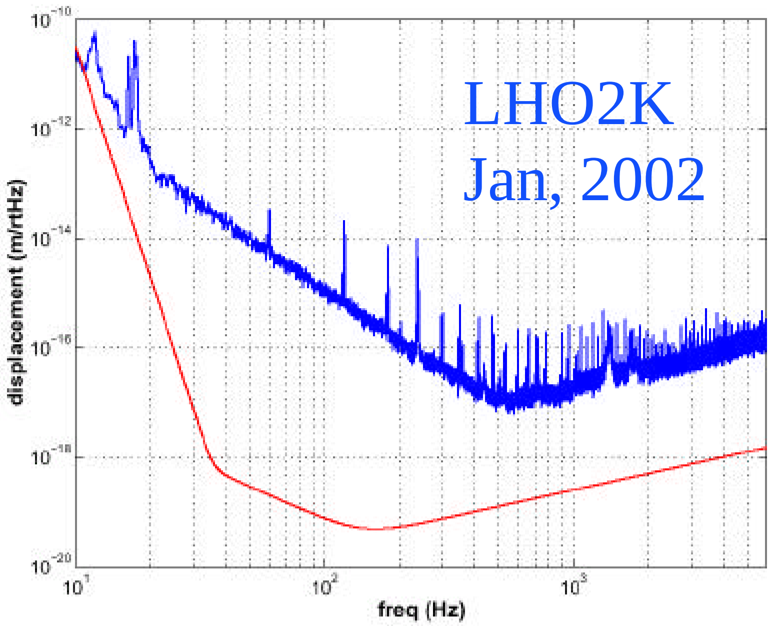
- Coincident operation of 3 LIGO detectors, GEO, ALLEGRO is unprecedented.
- Duty cycle has greatly exceeded our expectations.
- We are operating in a new regime of sensitivity and bandwidth; will be able to set new experimental limits.
- Coincidence with ALLEGRO will permit a limit for a stochastic background limited by the sensitivity of the bar.

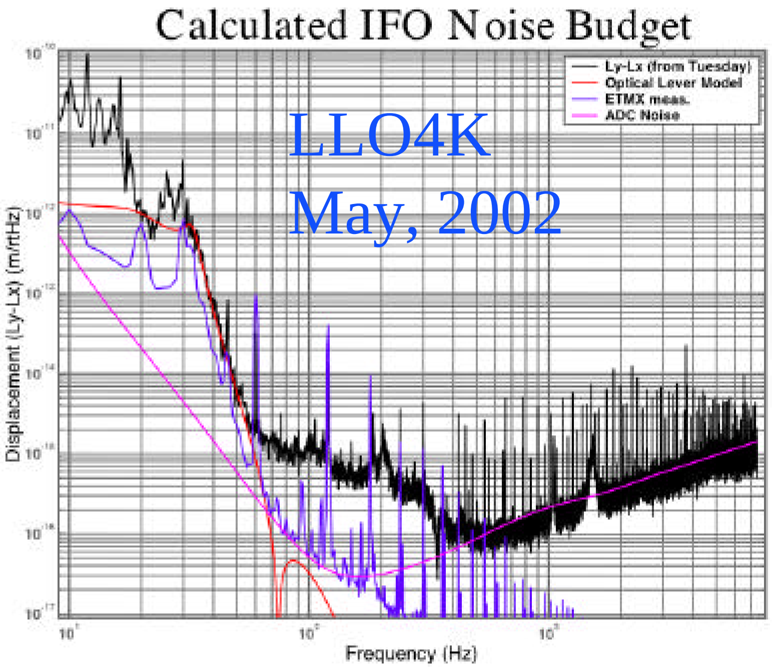
- MANY lessons learned and needs being addressed.
- Work on improving sensitivity has now recommenced.
- Already major improvements have been made!
  - » new and/or tuned servos; better laser isolation; higher laser power; better alignment and mis-alignment sensing; seismic pre-isolation upgrade; …
- First science run (S1) planned for June 28 – July 14.

Significant, Planned Detector Modifications

- Seismic Isolation:
  - » Fine actuation system stack mode suppression
    - – LLO End test mass chambers for S1
    - – LLO Input test mass chambers also for S2
    - – Possibly added to the Hanford observatory for S3
  - » Seismic retrofit with a 6-dof active pre-isolation system
    - – Planned at the Livingston observatory right after S2
    - – active pre-isolation system is placed under the existing passive stack, external to the chamber
- Digital Suspension Controls
  - » Currently implemented on the LHO 4km interferometer
  - » Plan is to install on the other two interferometers before S2
- Laser intensity stabilization servo improvements
- Auto-alignment:
  - » Automate Fabry-Perot cavity angular alignment for S1
  - » Centering of recycling cavity, dark port and end test mass transmission beams for S2

Post-E7 *displacement* sensitivity





New and important servos commissioned.
Still operating at low power.
Improvements being made continuously…

Upcoming data taking

- Engineering run 8
  - » June 8 – 10
  - » ~72 hours only LHO
  - » Tool and procedure practice before S1
- Science 1 run: 13 TB data
  - » 29 June - 15 July
  - » 2.5 weeks - comparable to E7
- Science 2 run: 44 TB data
  - » 22 November - 6 January 2003
  - » 8 weeks -- 15% of 1 yr
- Science 3 run: 142 TB data
  - » 1 July 2003 -- 1January 2004
  - » 26 weeks -- 50% of 1 yr

LIGO Data analysis

- LIGO is a broad-band amplitude detector, measures **waveforms.**
- The experimentalist thinks not in terms of astrophysical sources, but in terms of **waveform morphologies.**
- Specific astrophysical sources suggest specific waveforms, but **we don't want to miss the unexpected!**
- Waveform morphologies being considered:
  - » Bursts (of limited duration), for which we have models (chirps, ringdowns)
  - » Bursts, for which we have no reliable models (supernovas, …)
  - » Continuous waves, narrow bandwidth - periodic (pulsars)
  - » Continuous waves, broad bandwidth - stochastic (BB background)
- Each requires radically different data analysis techniques.
- Algorithms, implementation development is in its infancy.

Waveforms of Gravitational Waves

- “Chirps” (reasonably known waveforms)
  - » Neutron star (NS/NS) binary pairs
  - » Black hole (BH/BH) binaries; NS/BH binaries
- Periodic (well defined waveforms)
  - » Pulsars with ellipticity, in our galaxy
  - » R-modes (neutron stars spinning up, with instabilities)
- Impulsive (unknown waveforms)
  - » Supernova bursts, BH mergers
- Stochastic (random, indistinguishable from noise)
  - » Background from primordial cosmological event (Big Bang)
- Unknown???
  - » Rates, signal sizes, waveforms for all the above are *very* uncertain
  - » Surprises are *certain*!

If we don't have a well-modeled waveform: Detection Confidence

With all the noise faking GW signals,

How can we be sure we've seen the real thing (*for first time*!)?

Multiple interferometers – coincidence!

- three interferometers within LIGO
  - 4 km at Hanford, 4 km at Livingston
  - also 2 km at Hanford
- absolute timing accuracy of 10 microsec
  - 10 msec light travel time between sites
- AND: other detectors (interferometers, bars)

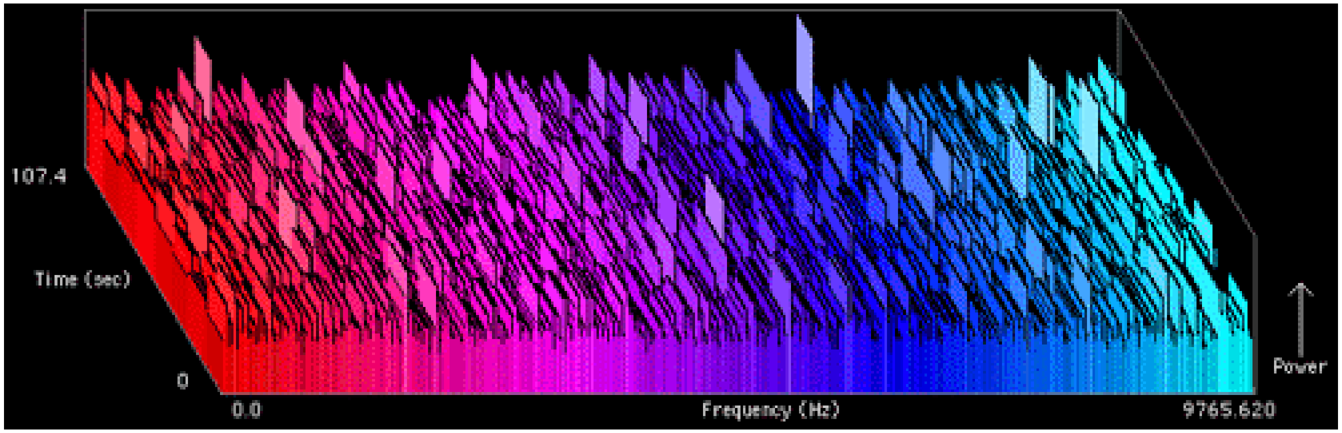
VETO Environmental noise

- Try to eliminate locally all possible false signals
- Detectors for many possible sources
  - seismic, acoustic, electromagnetic, muon
- Also trend (slowly-varying) information
  - tilts, temperature, weather

Detection computation

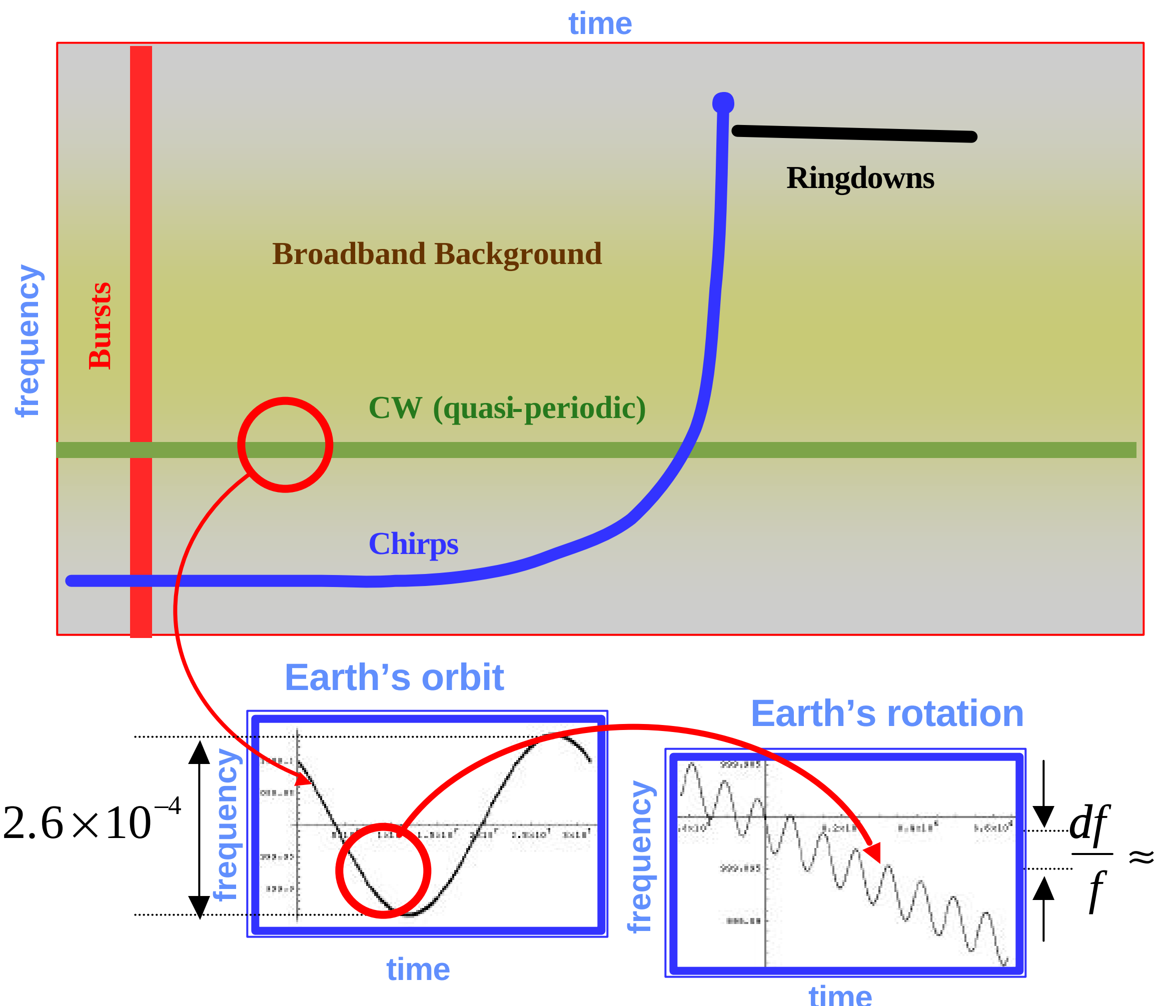
- coincidences (lack of inconsistency) among detectors
  - also non-GW: e.g., optical, X-ray, GRB, neutrino
- matched filter techniques for `known' signals
- correlations for broad-band suspects
- deviations from explicable instrumental behavior

Frequency-Time Maps ("Images") - your PC may already be doing them!



SETI@home* uses frequency-time analysis methods to detect *unexpected* or *novel* features in otherwise *featureless "hiss"

Frequency-Time Characteristics of GW Sources



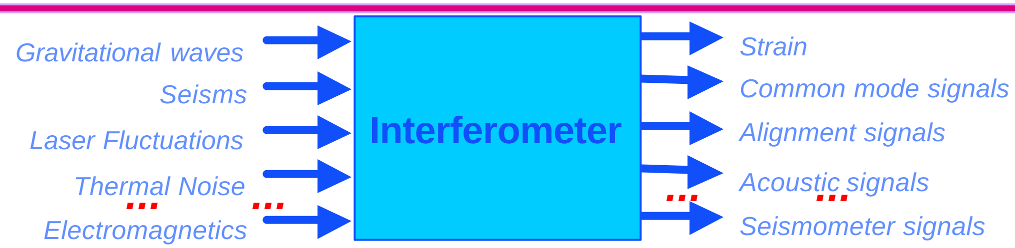
$$\frac{df}{f} \approx 2.6\times10^{-4}$$

$$\frac{df}{f} \approx 4\times10^{-6}$$

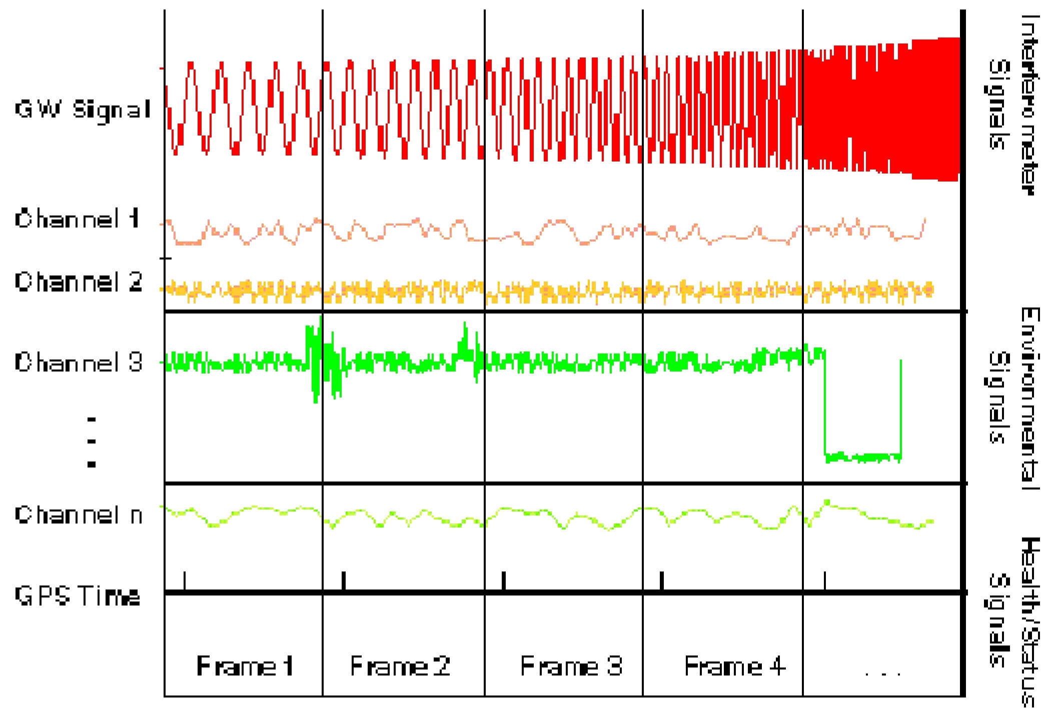
- Bursts are short duration, broadband events
- Chirps explore the greatest time-frequency area
- BH Ringdowns expected to be associated with chirps
- CW sources have FM characteristics which depend on position on the sky (*and source parameters*)
- Stochastic background is stationary and broadband

- For each source, the optimal signal to noise ratio is obtained by integrating signal ***along*** the trajectory
  - •If SNR >> 1, kernel µ |signal|^2
  - •If SNR $\leq$ 1, kernel µ |template* signal| or |signal_j* signal_k|
  - •Optimal filter: kernel µ 1/(noise power)

Interferometer Data Channels



- **All interferometric detector projects have agreed on a standard data format**
- **Anticipates joint data analysis**
- **LIGO Frames for 1 interferometer are ~3MB/s**
    - **32 kB/s strain**
    - **~2 MB/s other interferometer signals**
    - **~1MB/s environmental sensors**
    - ***Strain is ~1% of all data***

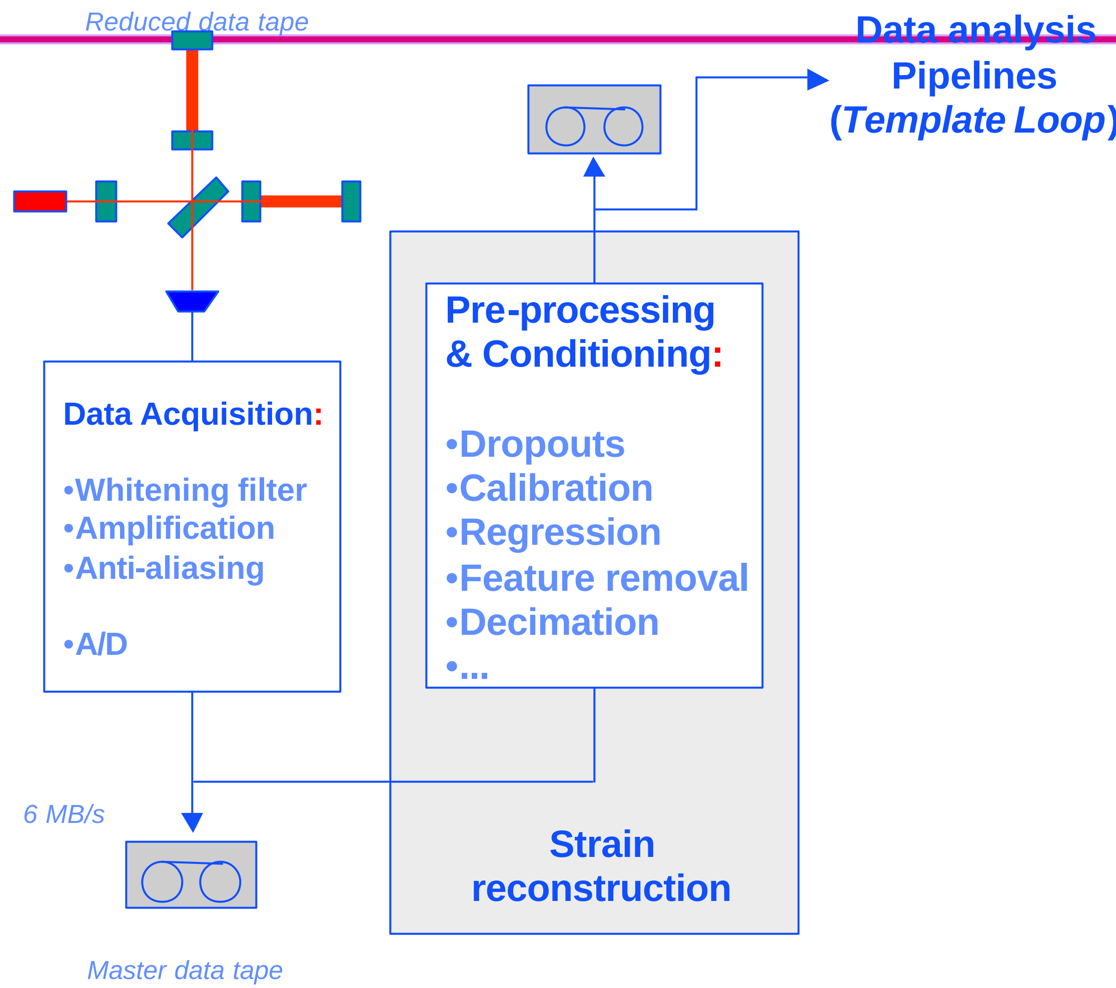


DAQS data channels and rates

- Each IFO has dozens of fast (16 kHz) and hundreds of slow (< 1 kHz) channels; equivalent of ~ 150 fast channels/IFO.
- (16 kHz) × (2 bytes) × (3 IFOs) × (150 ch/IFO) × (3×10^7 sec/year) × (2 years) × (50% duty cycle) = 500 Tbytes!
- Store full data stream on disk for ~ 1 day.
- Archive 10% of data to tape: 50 Tbytes!
- GW stream alone, decimated to 1 kHz: 200 GB
- Data stored in Frames and in Meta-Database

System	*DAQS Network*		*Data Storage*	
	Channels	*Rate (MByte/sec)*	*Channels*	*Rate (MByte/sec)*
LHO-4K	510	4.22	300	1.88
LHO-2K	548	4.37	332	1.99
LHO-PEM	204	0.89	204	0.89
LHO-VAC	500	0.01	500	0.01
LHO-GDS	133	2.45		
LLO-4K	515	4.22	305	1.89
LLO-PEM	95	0.46	95	0.46
LLO-VAC	300	0.01	300	0.01
LLO-GDS	76	0.89		

Data Flow: Pre-processing

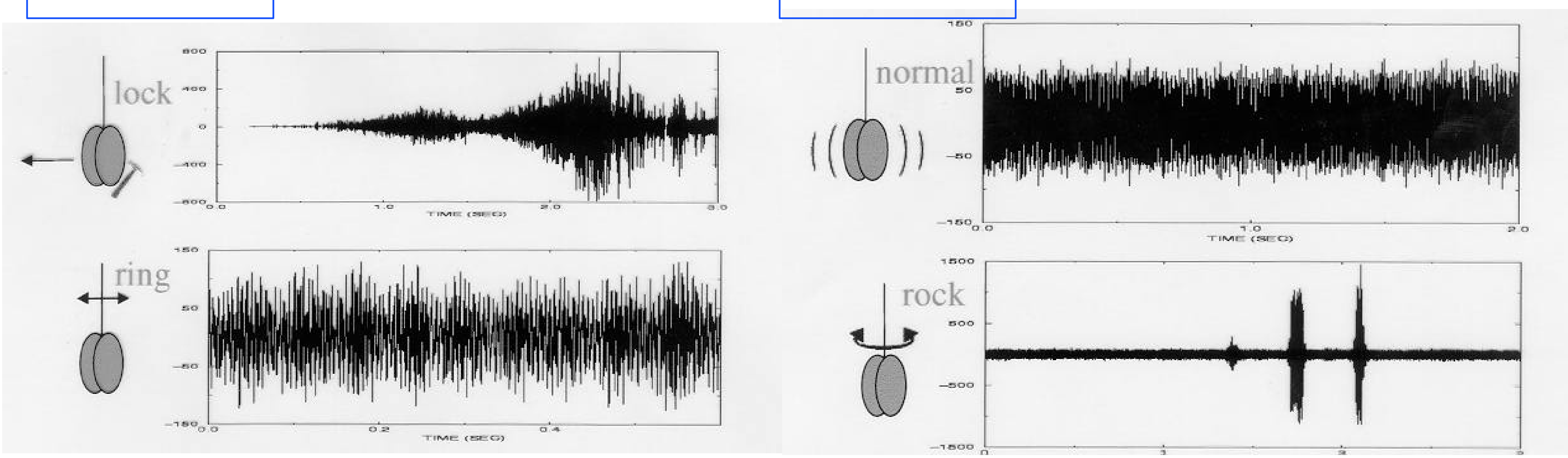


Interferometer Transients -- Examples from 40m Data

Real interferometer data is UGLY!!!

(Glitches - known and unknown)

LOCKING **NORMAL**

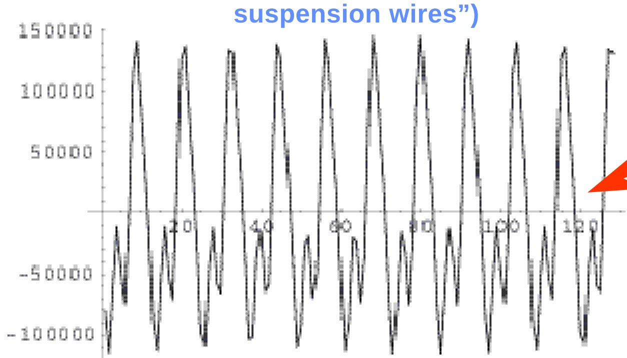


RINGING **ROCKING**

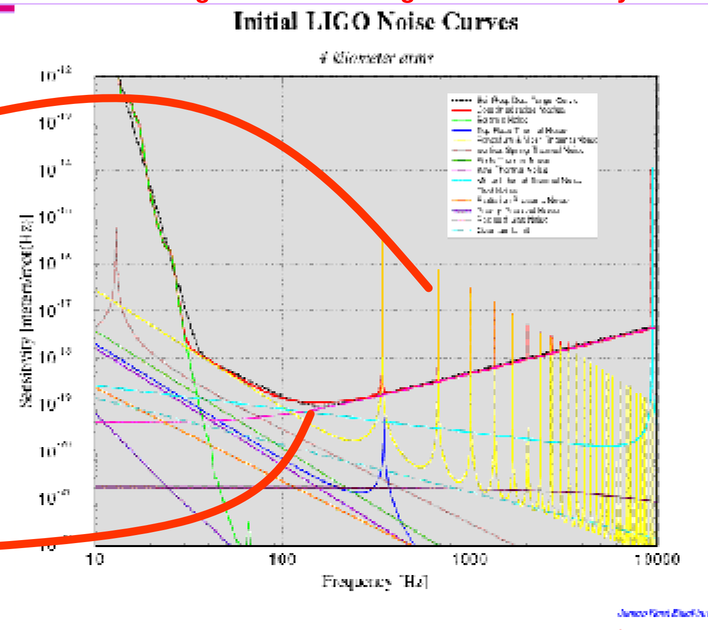
LIGO

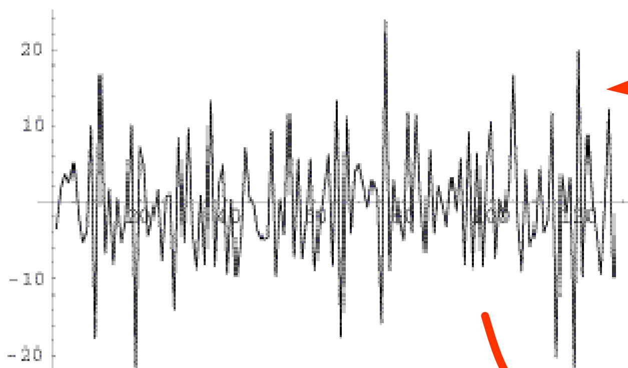
Interferometer Strain Signal (Simulated)

Dominated by narrowband features in spectrum ("violin resonances" of suspension wires")

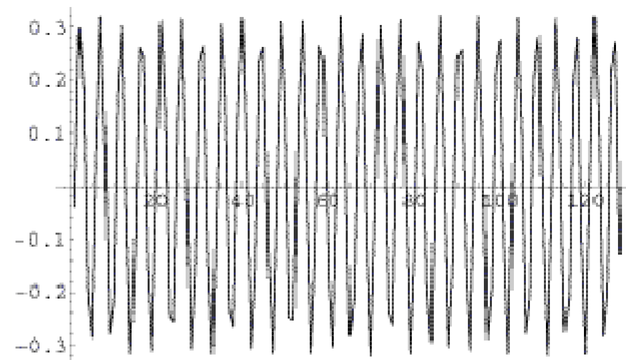


Design LIGO I limiting strain sensitivity



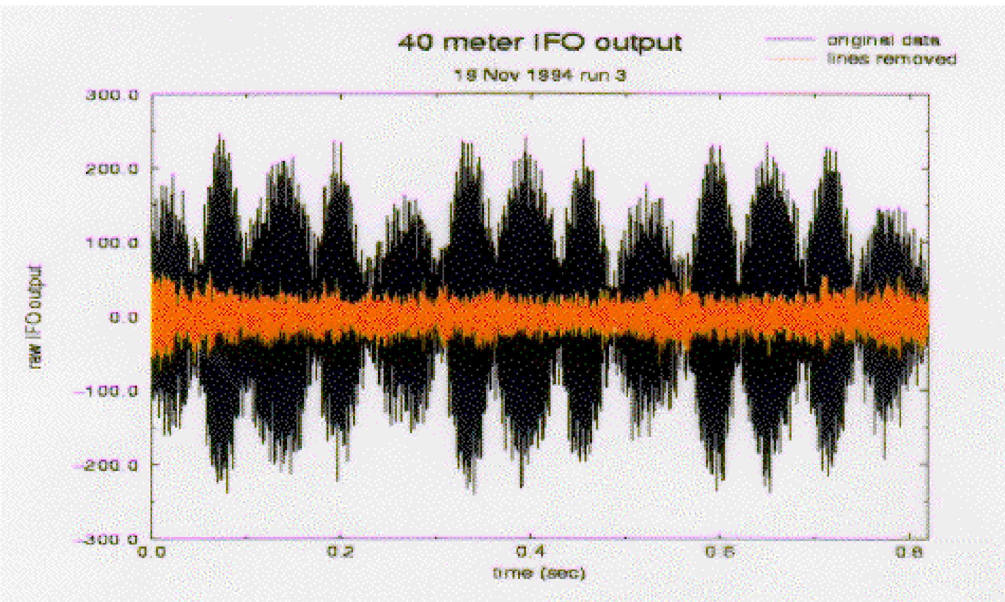


Broadband noise spectrum

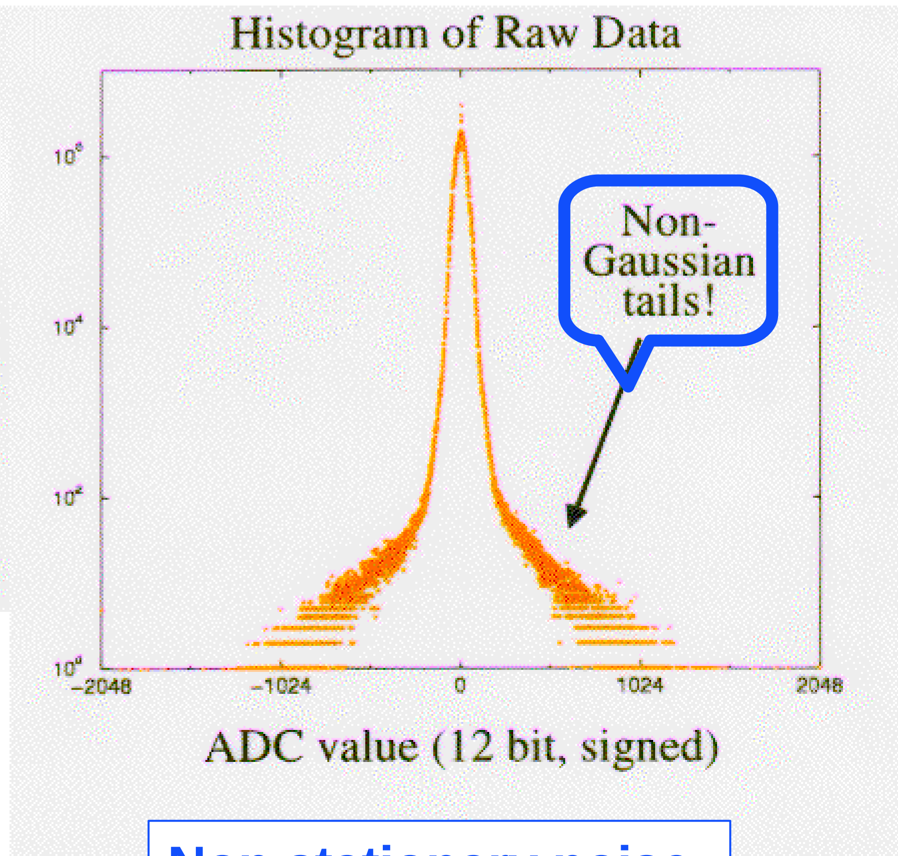


Chirped waveform

“Clean up” data stream

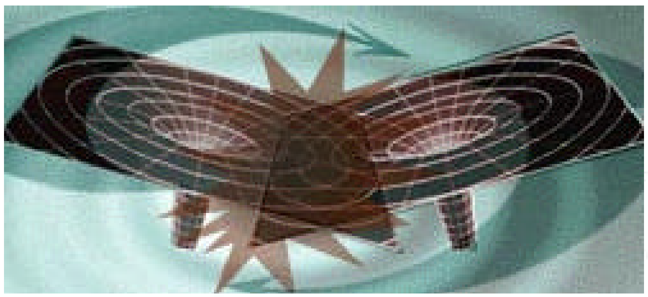


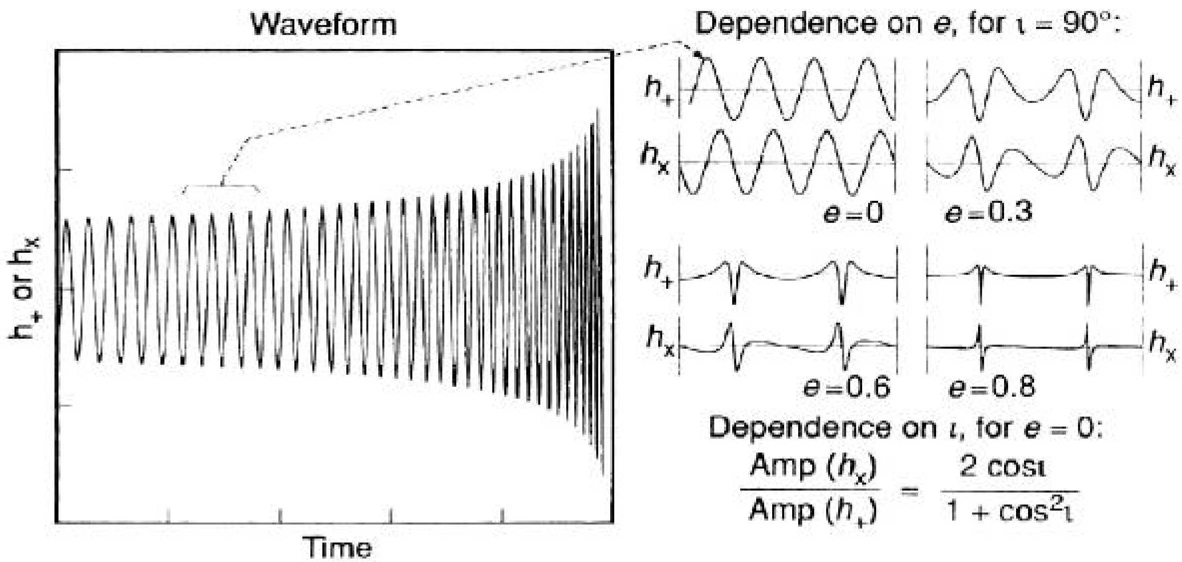
Effect of removing sinusoidal artifacts using multi-taper methods



Non stationary noise
Non gaussian tails

Chirp signal from Binary Inspiral





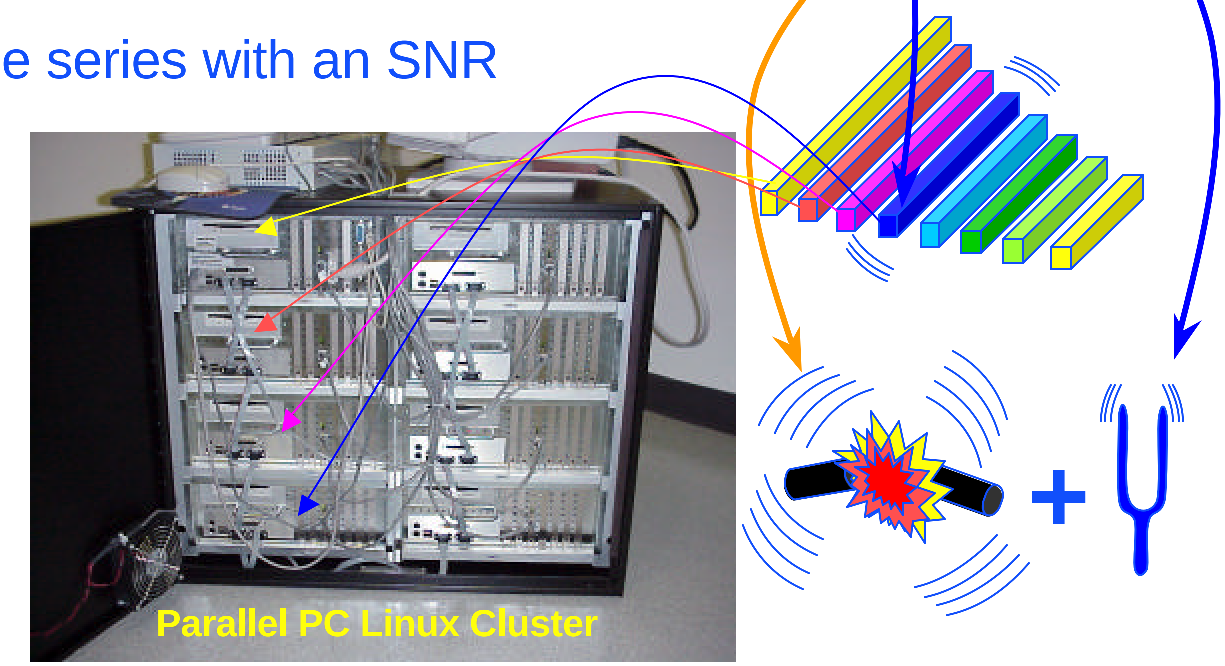
determine

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

Optimal Wiener Filtering

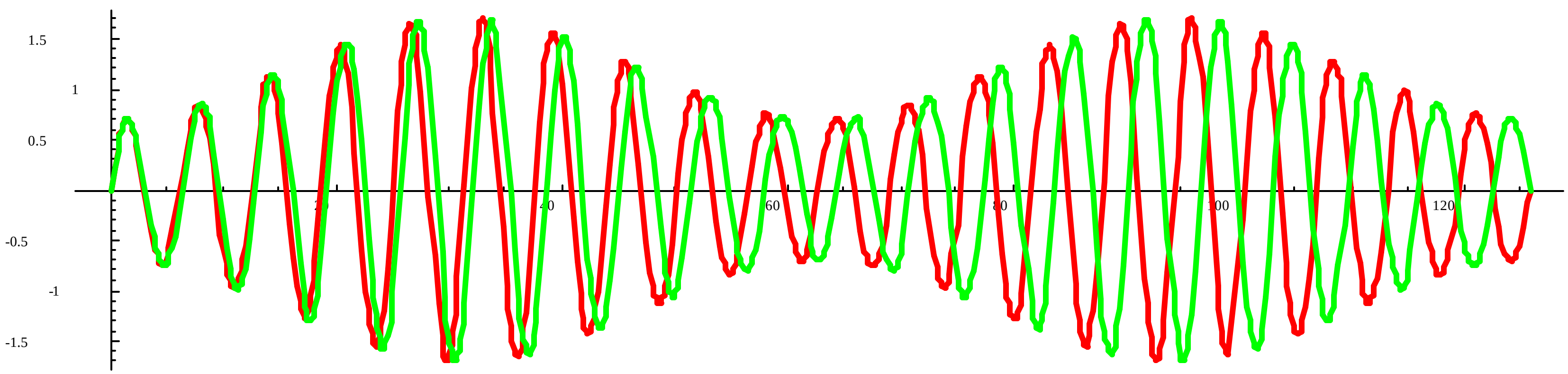
- Matched filtering (optimal) looks for best overlap between a signal and a set of expected (template) signals in the presence of the instrument noise -- correlation filter
- Replace the data time series with an SNR time
  series
- Look for excess SNR to flag possible detection

$$x_p[t_c] = \int \frac{\hat{T}_p^*(f)\ \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2pift_c} df$$



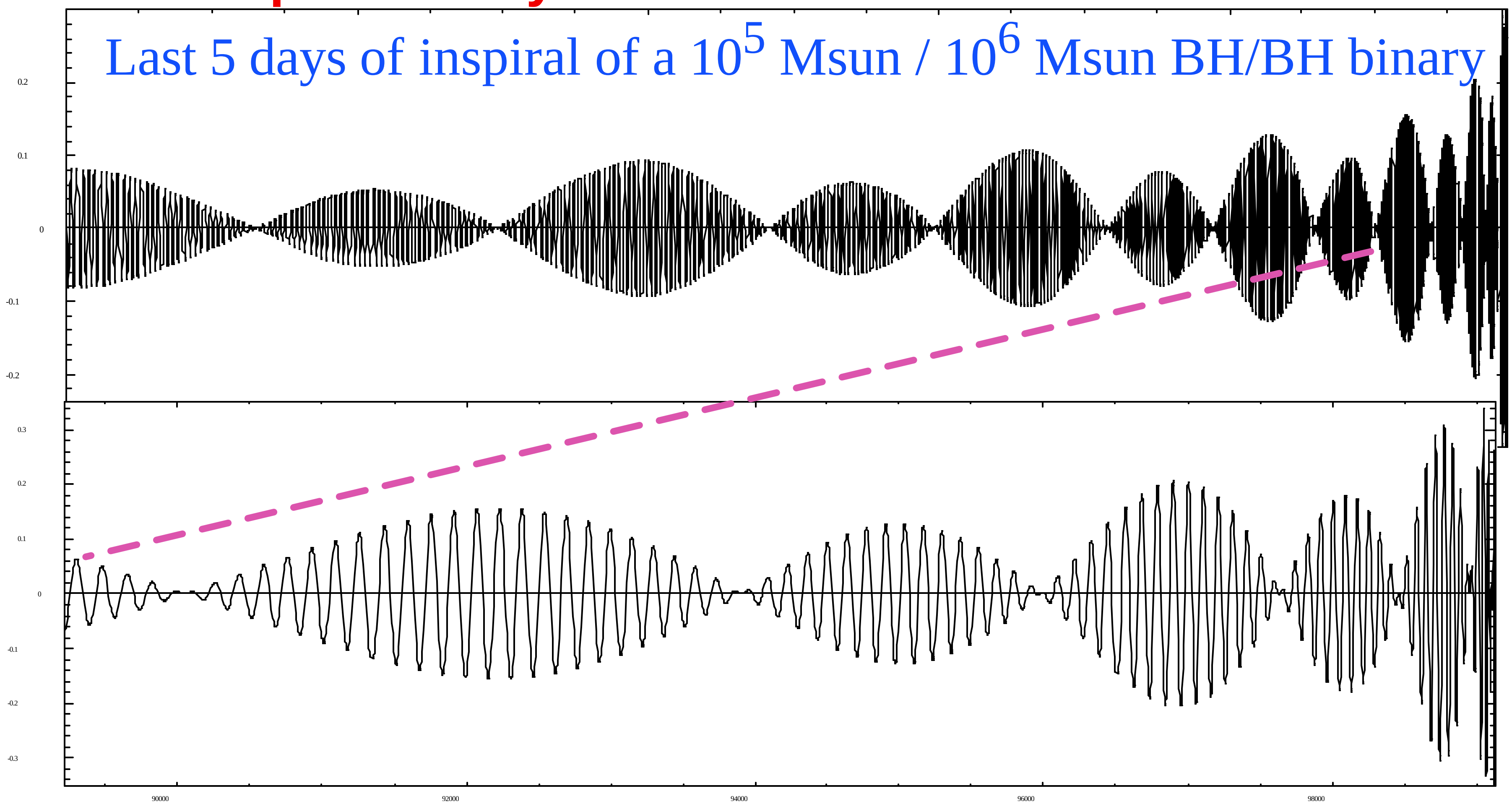
Got to get the templates RIGHT

- **Compute the dynamics of sources and their emitted waveforms**
  - » **Why we need waveforms:**
    - – **As templates to use in searches for waves via matched filtering**

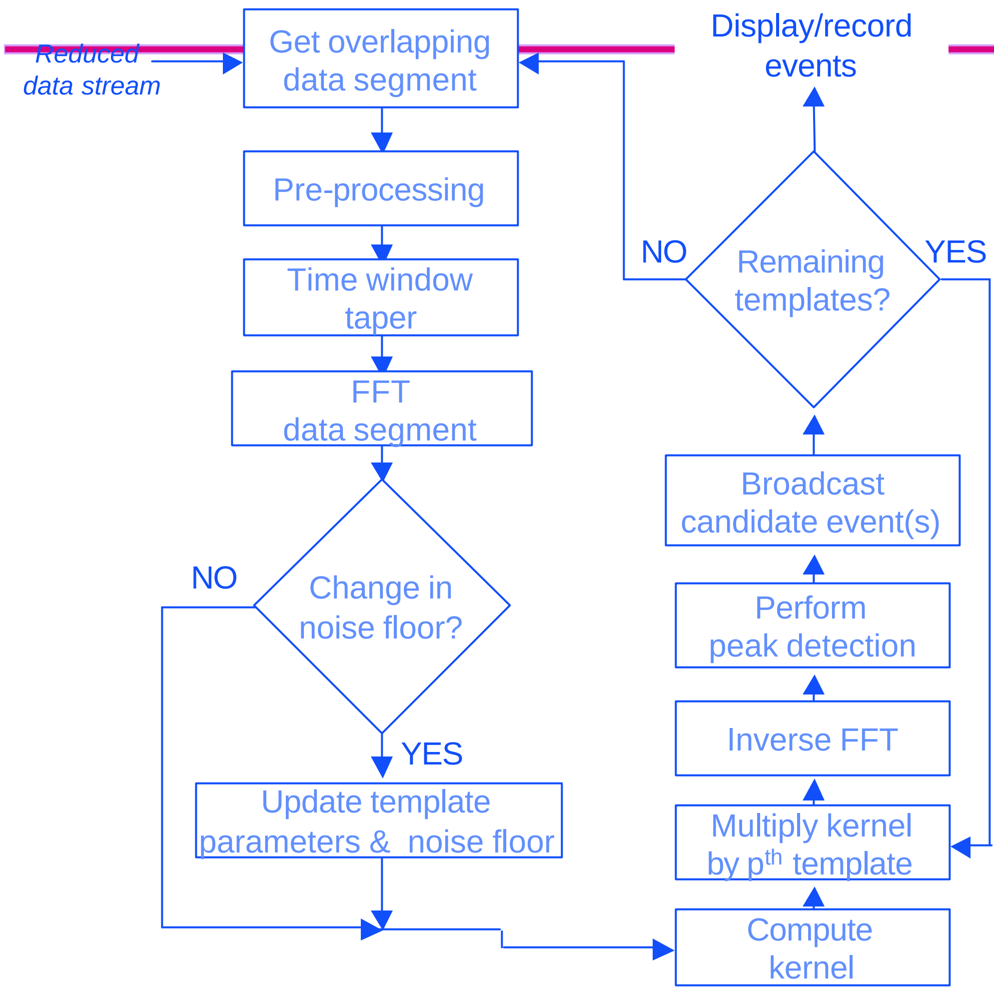


Lots to learn from the waveforms!

- **Compute the dynamics of sources and their**

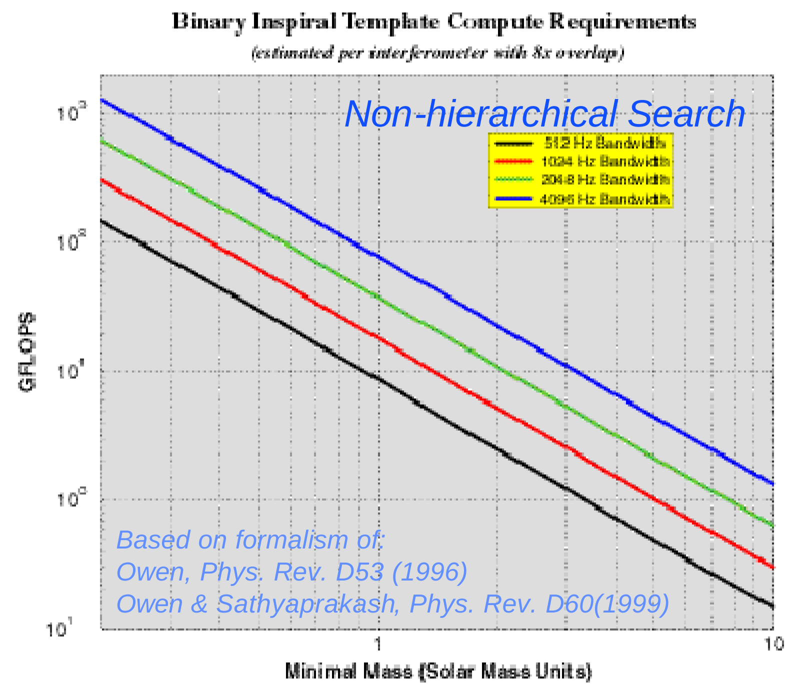


Compact Binary Inspirals Data Analysis Flow



Data Loop **Template Loop**

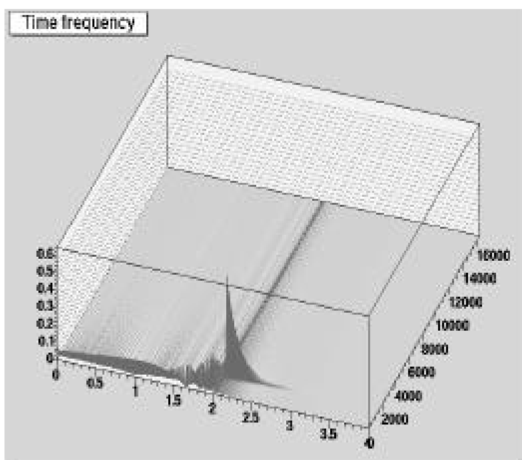
$$x_p[t_c] = 2\int \frac{\hat{T}_p^*(f)\ \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2\pi i f t_c} df$$

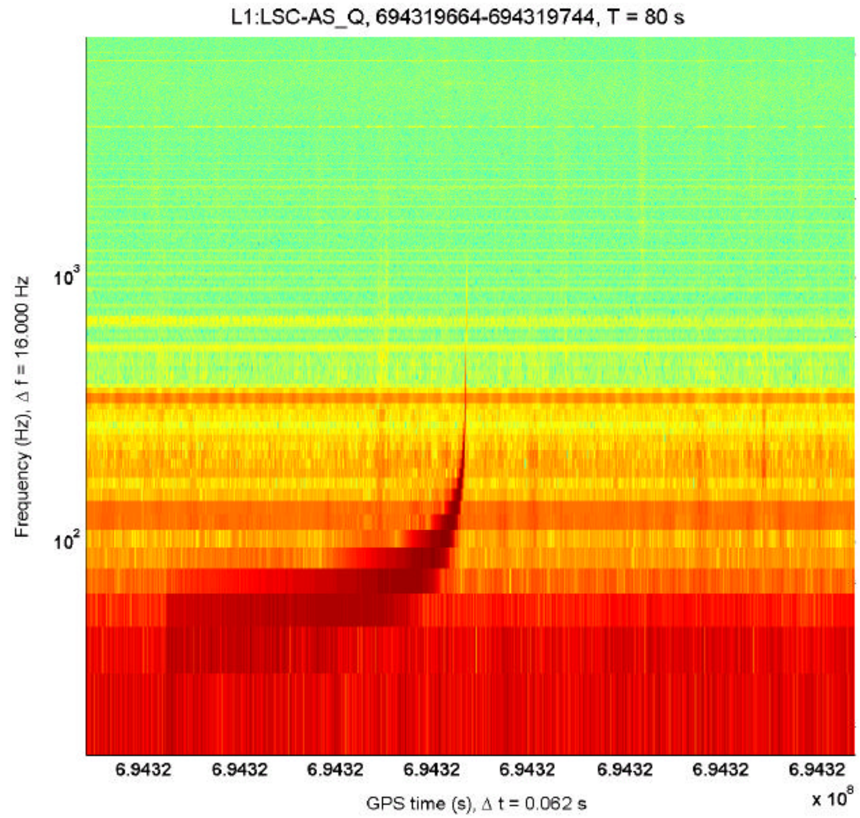


- **Process data at real time rate**
- **Improvements:**
  - » **Hierarchical searches developed**
  - » **Phase coherent analysis of multiple detectors (Finn, in progress)**

Simulations

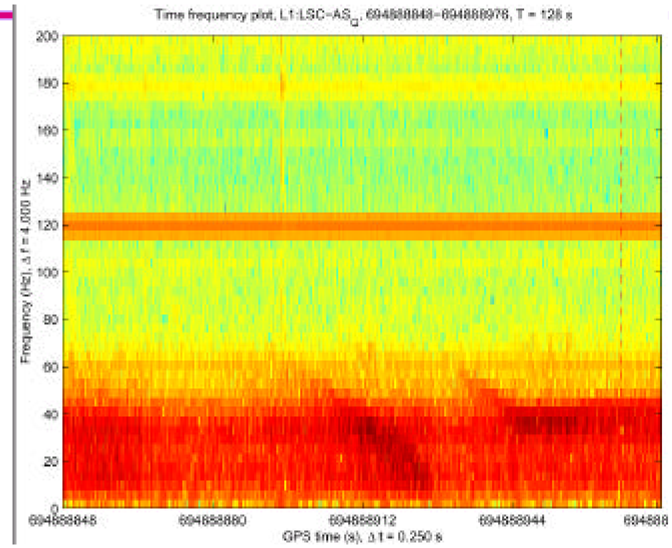
- Test search codes with simulated inspirals and bursts added to the noisy data stream.
- Can also inject arbitrary waveform signals directly into the IFO, by moving the end mirrors.
- This also tests the interferometer response function, as measured through calibration procedure.
- It also tests the detailed E2E simulations of IFO performance.

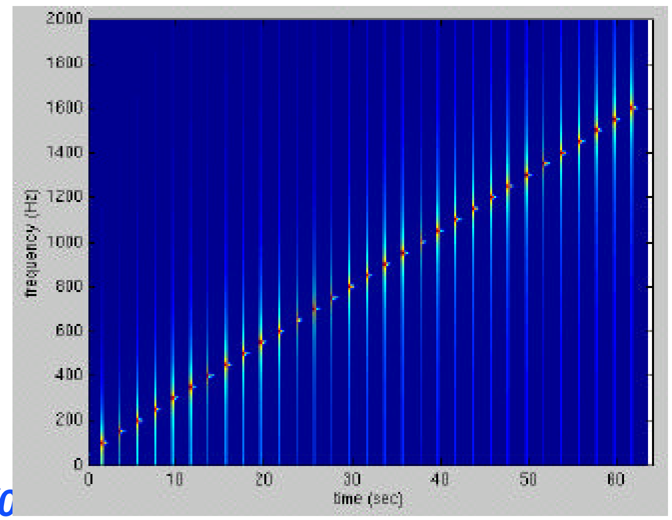




Unmodeled bursts

- Look for excess power in time-frequency plane.
- Unfortunately, there are MANY noise bursts.
- Set excess power thresholds carefully; noise is NOT (yet) Gaussian and stationary!
- Veto on ones that correlate with environmental or non-GW-related IFO signals.
- Try not to veto away all the live time!
- Trade-off between efficiency and live-time.
- Must rely on in-time coincidences between sites
- Study correlations between sites very carefully!
- Can also look for coincidences with other IFOs, bars, GRBs, etc.

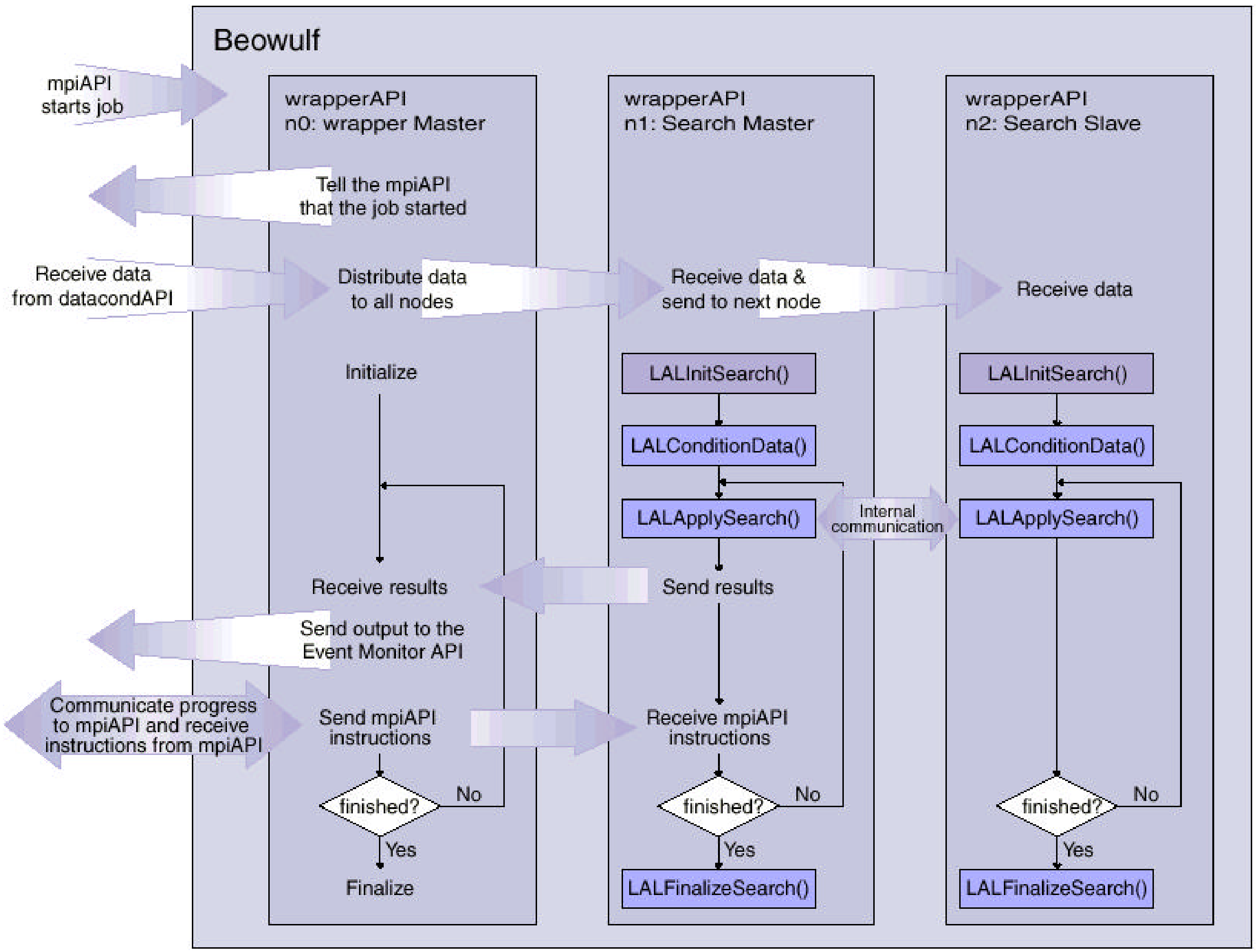




Perform CPU-intensive searches near real-time on parallel compute farms

LIGO labs and LSC institutions maintain 6 (and growing) LDAS installations with Beowulf PC/linux/MPI-based search engines.

Also involved in GRID computing initiatives (CACR, Harvey's group).



Software Block Diagram

LIGO-T990101-E
LAL Specification

LIGO-T990097-E
wrapperAPI Requirements

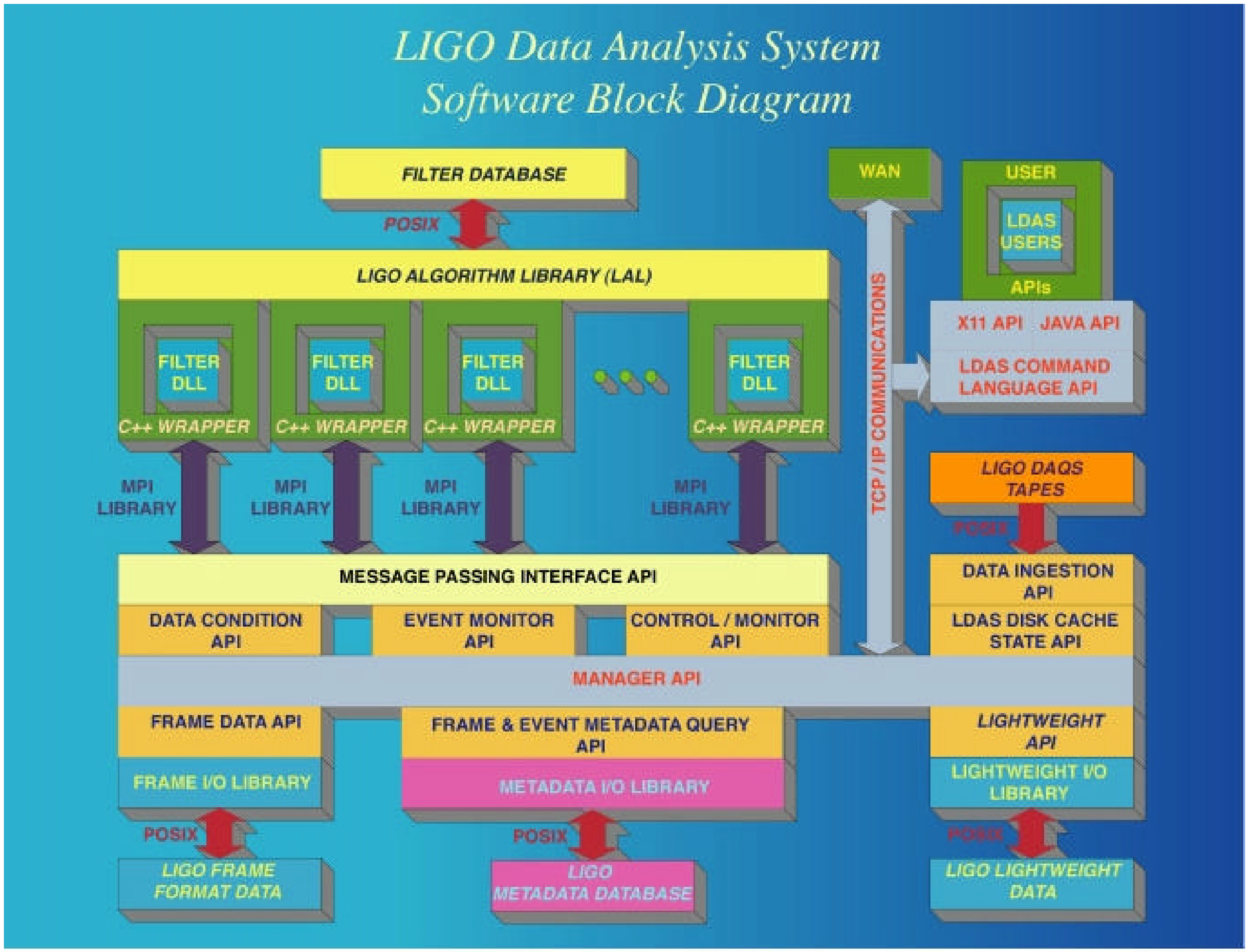
www.lam.org
LAM version 5.6.1

LIGO-T990086-E
mpiAPI Requirements

LIGO-T990002-E
dataConditionAPI Requirements
FFTW version 2.3.1
CLAPACK version

LIGO-T980115-E
managerAPI Requirements

LIGO-T980117-E
frameAPI Requirements



GUILD
TCL/TK GUI

UNIX Sockets (TELNET)
User Commands (TCL)

LIGO-T010052-E
dataIngestionAPI Requirements
"In Development"

LIGO-T010051-E
diskCacheAPI Requirements
"In Development"

LIGO-T000026-E
controlMonitorAPI Requirements

LIGO-T990037-E
lightWeightAPI Requirements

www.apache.org
C++ XML Parser Library

LIGO-T970130-E
LIGO-VIRGO Frame Specification
FrameCPP Version 4

LIGO-T980119-E
metaDataAPI Requirements

dbEasy Library
ODBC Level 3

LIGO-T990101-E
LDAS Database Tables

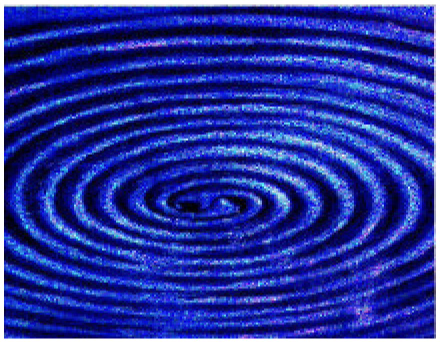
LIGO-T990023-E
LIGO-Lightweight Format

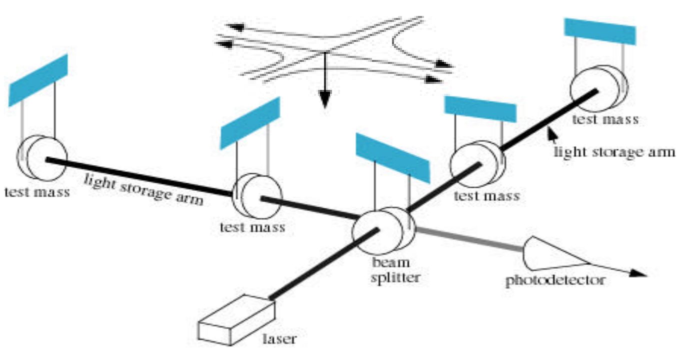
When will physics results be available?

- We have hundreds of hours of E7 data in the can
  - » LLO4K, LHO2K, LHO4K, GEO600, ALLEGRO, GRB alerts
- Work on improving detectors is ongoing.
- Plan on first science run (S1) in summer 2002.
- Currently working towards a pile of papers (Various inspiral, burst, periodic, stochastic searches) based on E7 data.
- *It is not yet clear whether this will bear fruit before the first science run!*
- If so, first papers might appear this summer.
- Else, papers based on S1 should be available by the end of 2002.

In parallel with science running,
Intense R&D on AdvLIGO – aim to install in 2007-9

Einstein's Symphony





- Space-time of the universe is (presumably!) filled with vibrations: Einstein's Symphony
- LIGO will soon 'listen' for Einstein's Symphony with gravitational waves, permitting
  - Basic tests of General Relativity
  - A new field of astronomy and astrophysics
- A new window on the universe!