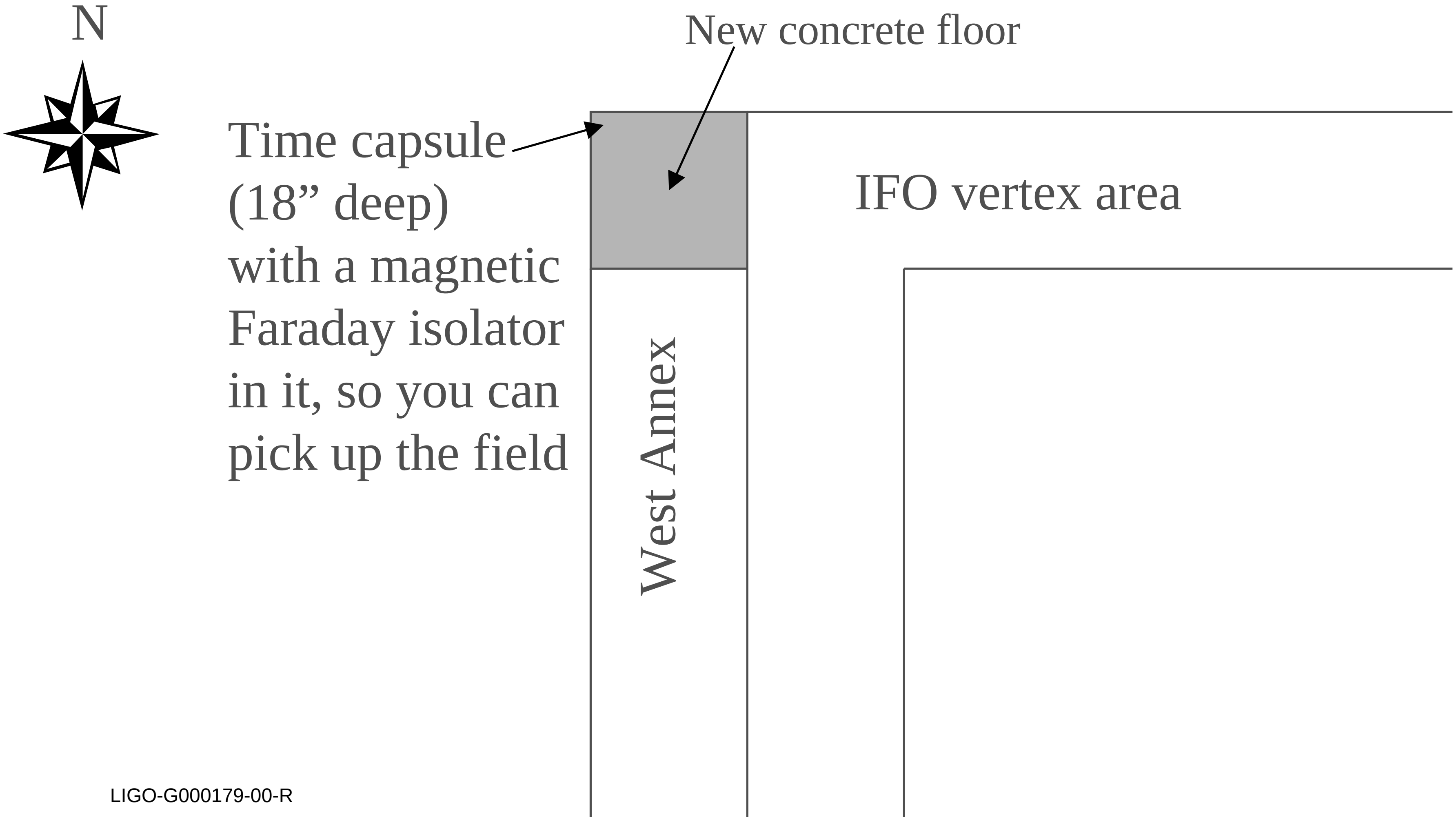
Time Capsule at 40m Laboratory

- On July 31, 2000, Steve Vass buried a time capsule under some concrete on the NW corner of the 40m lab (under the floor of what will be the operator station).
- It was a 6” diameter, 12” long PVC pipe, filled with:
  - » The 22 pages of LIGO slides in this document.
  - » Copies of the PDG 2000 review of astrophysics, obtained from
    - – http://pdg.lbl.gov/2000/contents_sports.html#astroetc
  - » The latest Boomerang paper on the CMB anisotropy, from
    - – http://www.physics.ucsb.edu/~boomerang/papers/lange00.pdf
  - » Some predictions and greetings from Kip Thorne (we’ll see GW’s by 12/31/2007 or before), Szabi Marka (we’ll see a SN before anyone else!), Ken Ganezer, AJW, 40m summer SURF students
  - » Old pockels cell, faraday isolator (magnetic!), filter board from Shanti Rao
  - » “Realizing LIGO” from E&S, 1998
  - » List of grad student stipends, 1996 and 2000

Location of Time Capsule



N

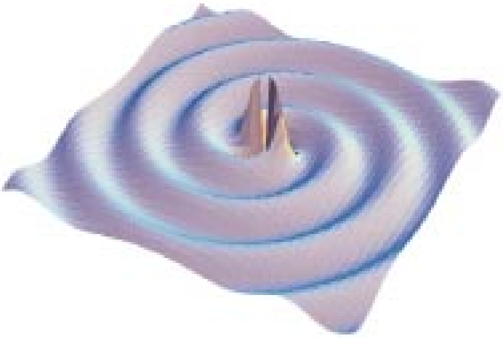
New concrete floor

Time capsule (18” deep) with a magnetic Faraday isolator in it, so you can pick up the field

IFO vertex area

West Annex

The LIGO Project



LIGO: Laser Interferometer Gravitational-Wave Observatory

- US project to build observatories for gravitational waves (GWs)
- 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

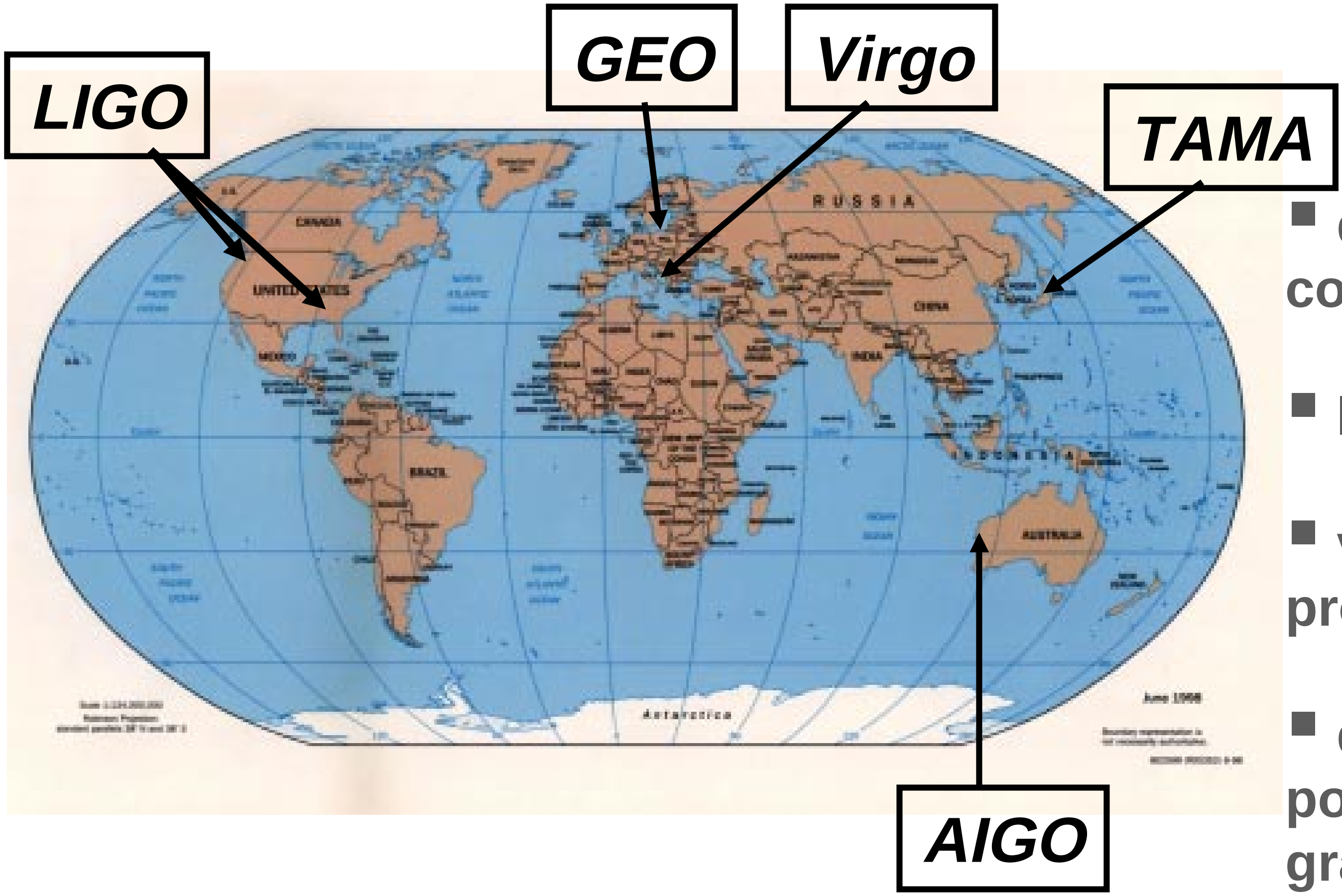
- Two sites separated by 3000 km
- each site carries 4km vacuum system, infrastructure
- each site capable of multiple interferometers (IFOs)

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

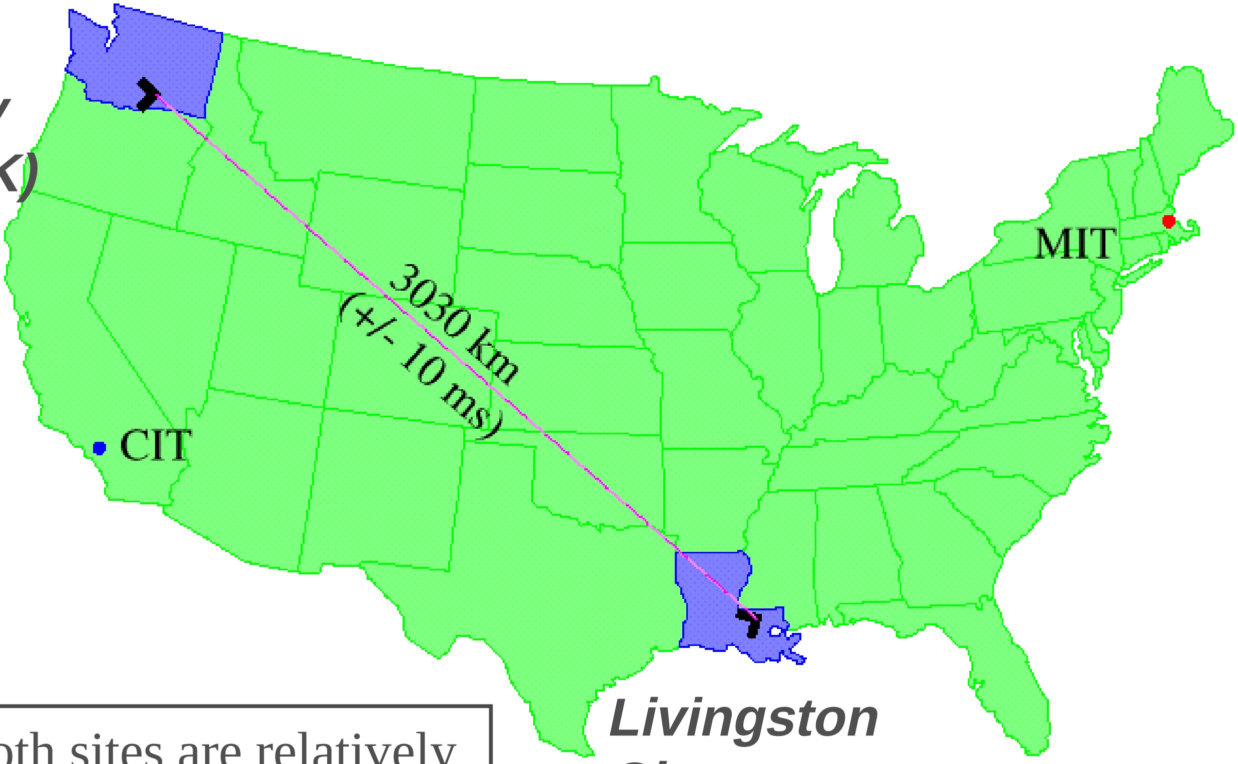
International network

Simultaneously detect signal (within msec)



- detection confidence
- locate the sources
- verify light speed propagation
- decompose the polarization of gravitational waves

LIGO sites



Hanford Observatory (H2K and H4K)

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

Livingston Observatory

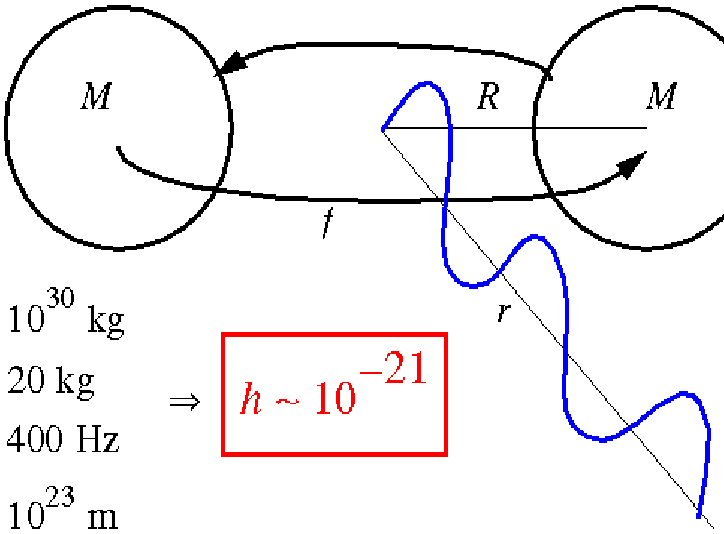
Both sites are relatively seismically quiet, low human noise

Sources of GWs

- Accelerating charge ⇒ electromagnetic radiation
- Accelerating mass ⇒ gravitational radiation
- Amplitude of the gravitational wave (dimensional analysis):

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

- $\ddot{I}_{\mu\nu}$ = second derivative of mass quadrupole moment (non-spherical part of kinetic energy)
- 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:



$M \sim 10^{30}$ kg
$R \sim 20$ kg
$f \sim 400$ Hz
$r \sim 10^{23}$ m

$$\Rightarrow \boxed{h \sim 10^{-21}}$$

Terrestrial sources *TOO WEAK!*

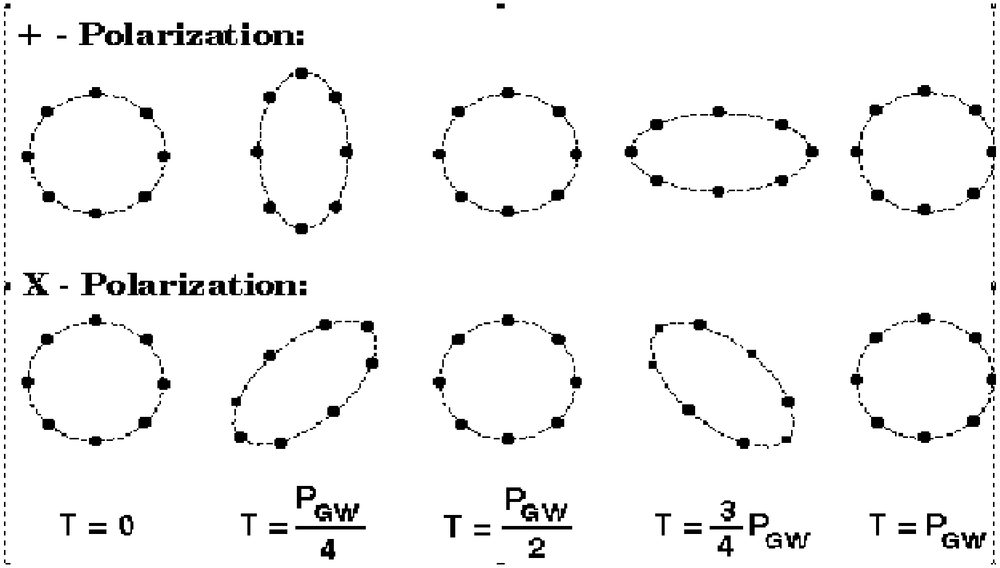
Nature of Gravitational Radiation

General Relativity predicts :

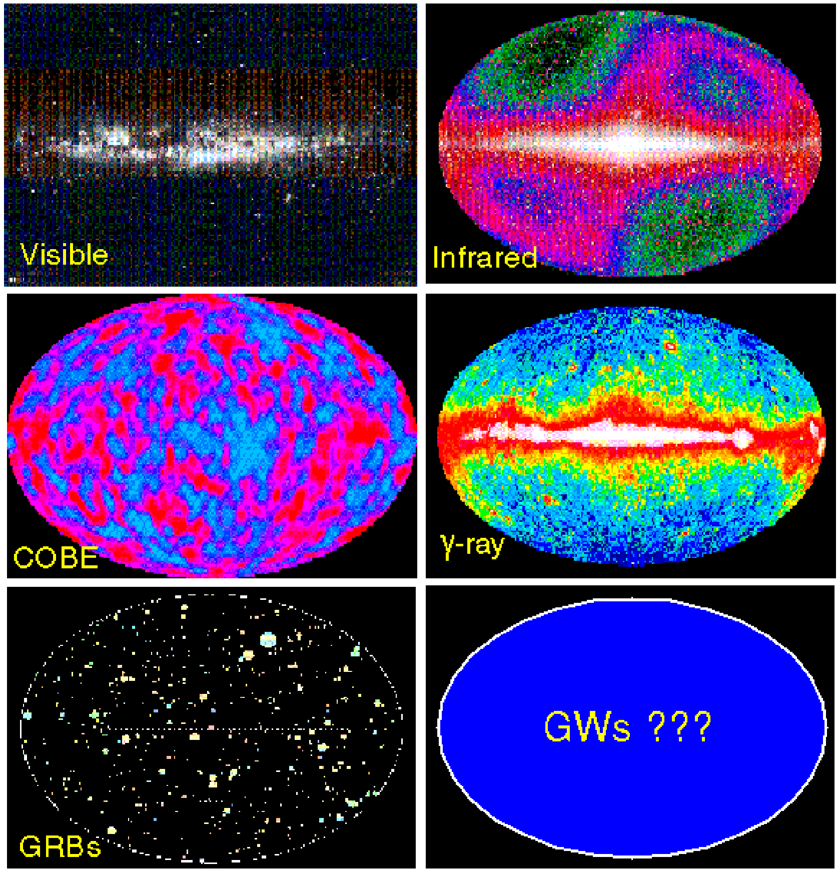
- transverse space-time distortions, freely propagating at speed of light ⇒ ⇒ mass of graviton = 0
- Conservation laws:
  - conservation of energy ⇒ no monopole radiation
  - conservation of momentum ⇒ no dipole radiation
  - quadrupole wave (spin 2) ⇒ two polarizations

plus (⊕) and cross (⊗)

⇒ spin of graviton is 2



What will LIGO see?
A new window on the universe!

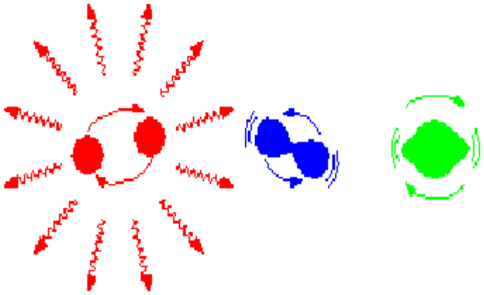


E&M	GW
space as medium for field	Space-time itself
incoherent superpositions of atoms, molecules	coherent motions of huge masses (or energy)
wavelength small compared to sources - images	wavelength ~large compared to sources - poor spatial resolution
absorbed, scattered, dispersed by matter	very small 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

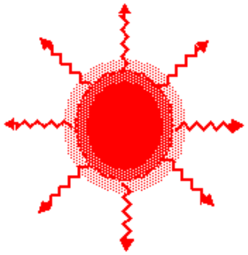
- **Very different information, mostly mutually exclusive**
- **Difficult to predict GW sources based on E&M observations**

Astrophysical
Sources of Gravitational Waves

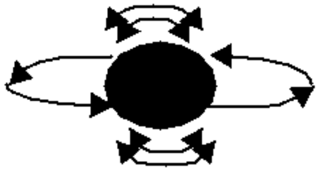
Coalescing compact binaries
(neutron stars, black holes)



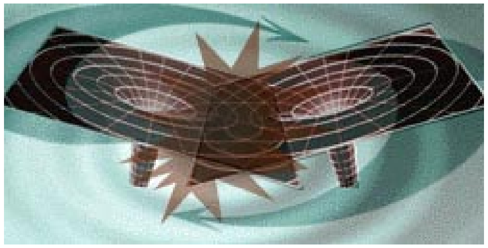
Non-axi-symmetric
supernova collapse



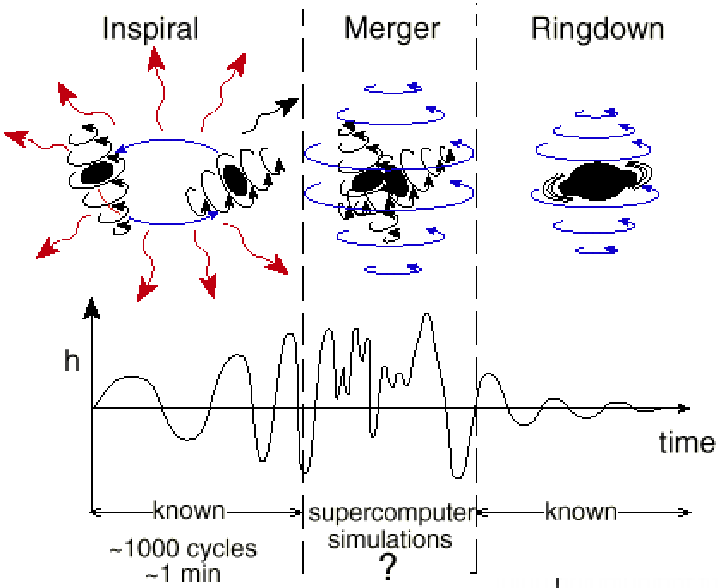
Non-axi-symmetric pulsar
(rotating, beaming
neutron star)

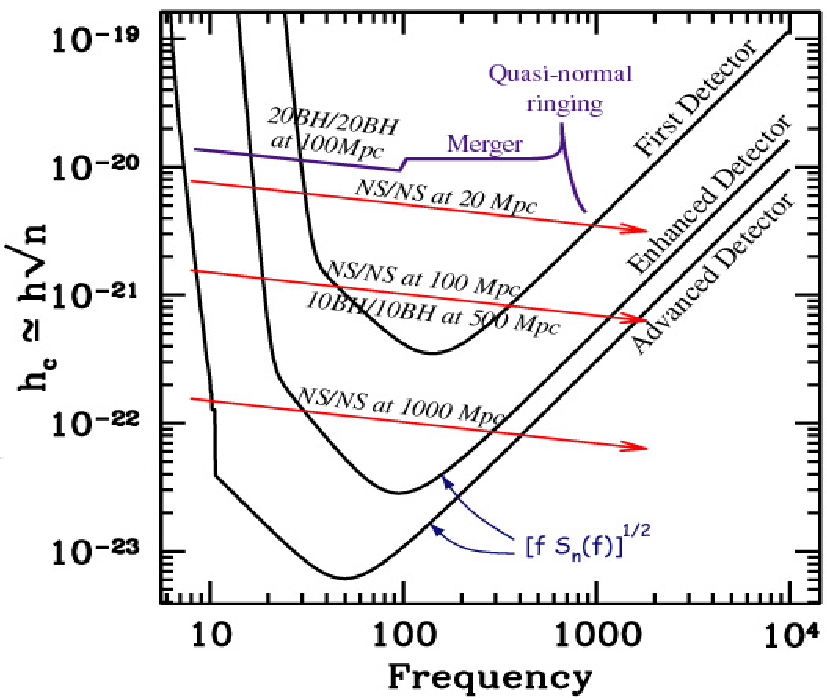


LIGO Gravitational Waves from coalescing binaries



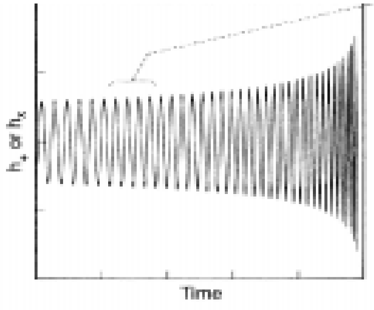
Compact binary mergers (NS/NS, NS/BH, BH/BH)



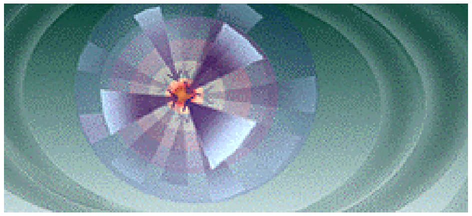


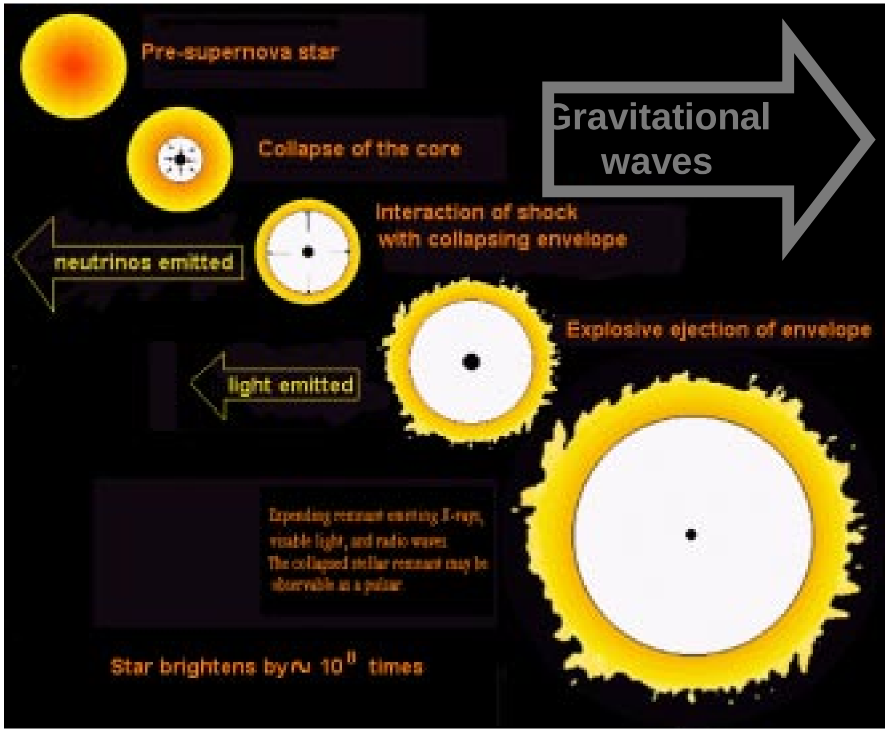
Sensitivity of LIGO to coalescing binaries

“chirp” waveform

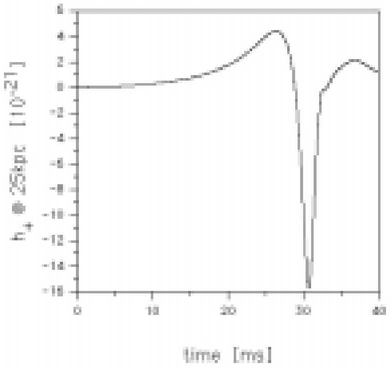


Gravitational Waves from Supernova collapse

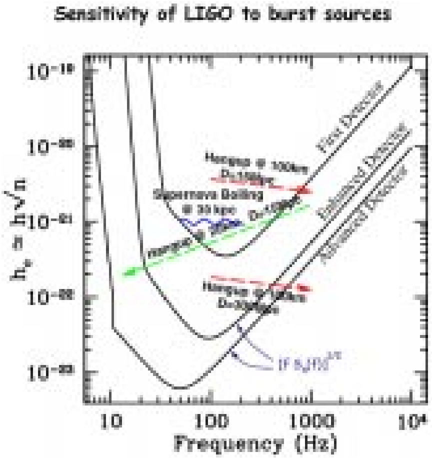




Non axisymmetric collapse ‘burst’ signal



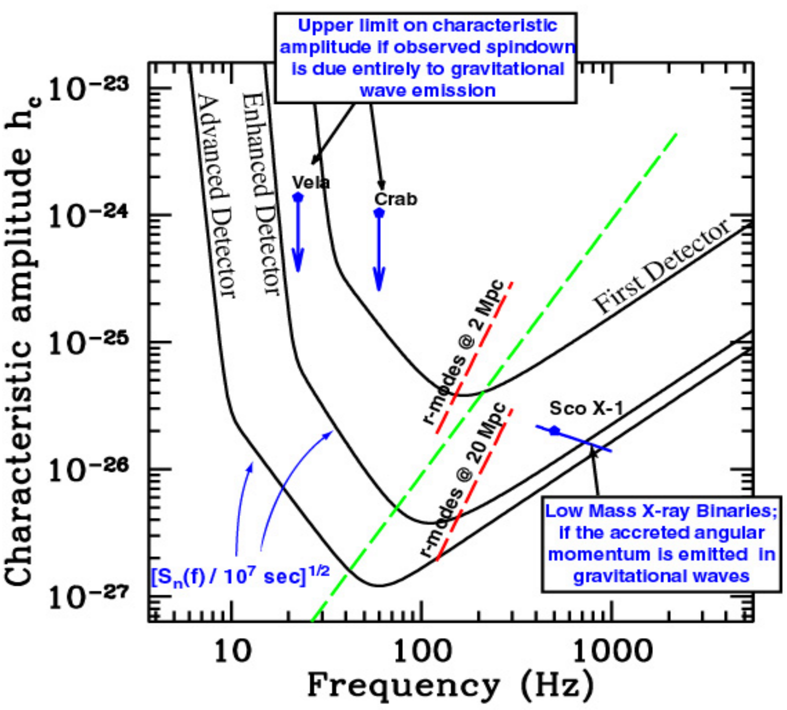
SN1987A



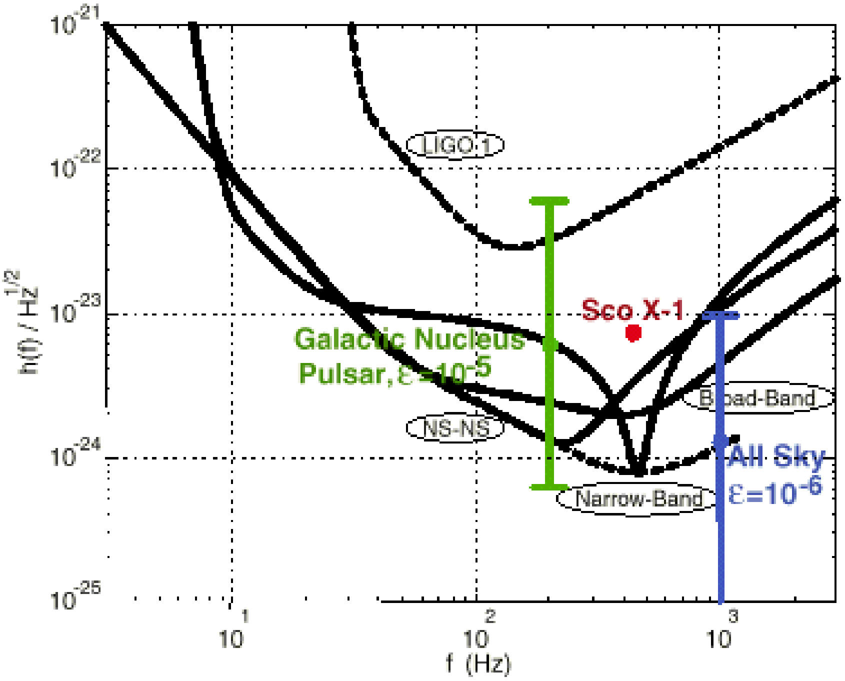
Rate: ***1/50 yr - our galaxy***
3/yr - Virgo cluster

LIGO will be part of worldwide ***supernova watch*** (optical, ν, GW)

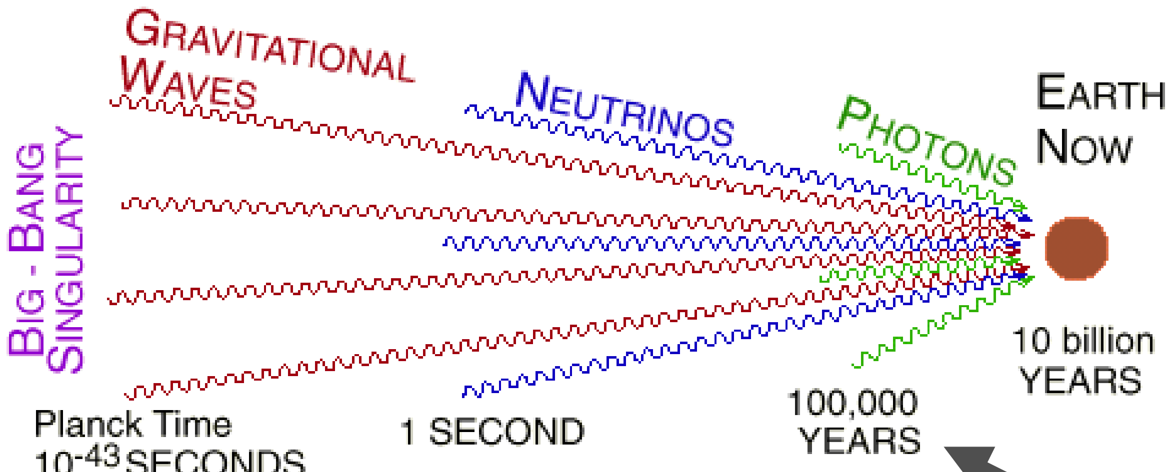
Pulsars and continuous wave sources


Sensitivity of LIGO to continuous wave sources

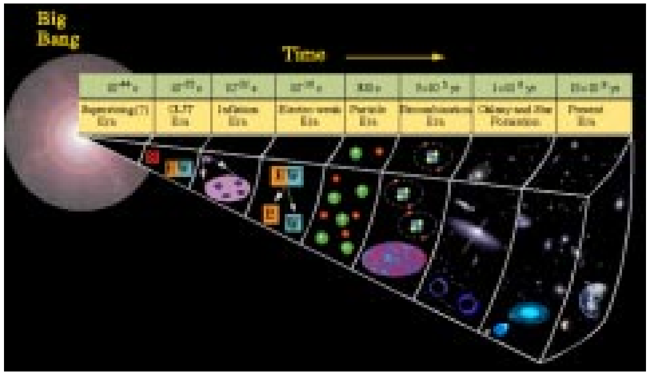
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: neutron star precession; interiors
  - »“R-mode” instabilities
  - »narrow band searches best



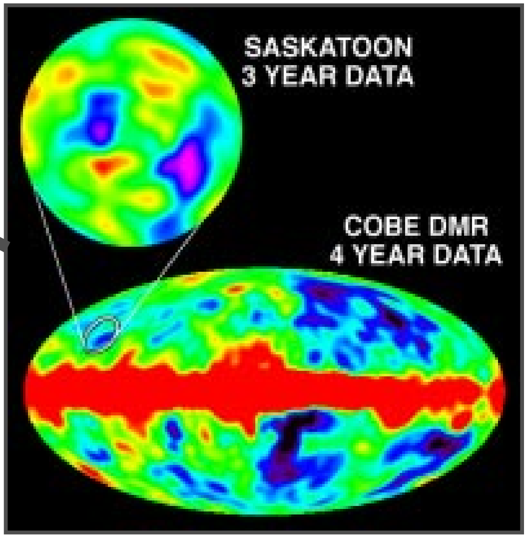
Gravitational waves from Big Bang



Planck Time
10^{-43} SECONDS
Singularity
creates
Space & Time
of our universe



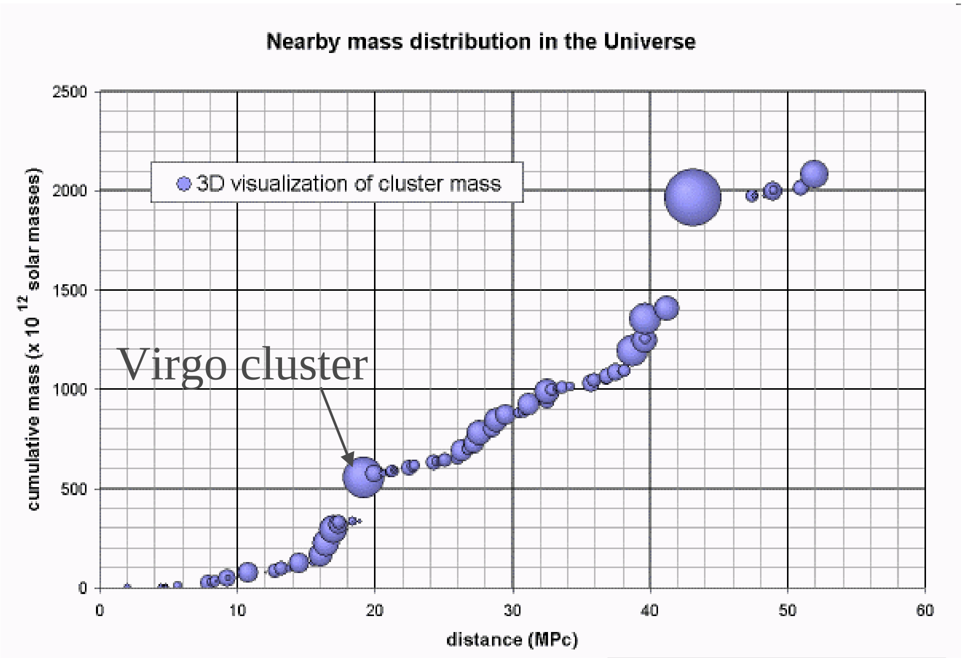
Cosmic microwave background

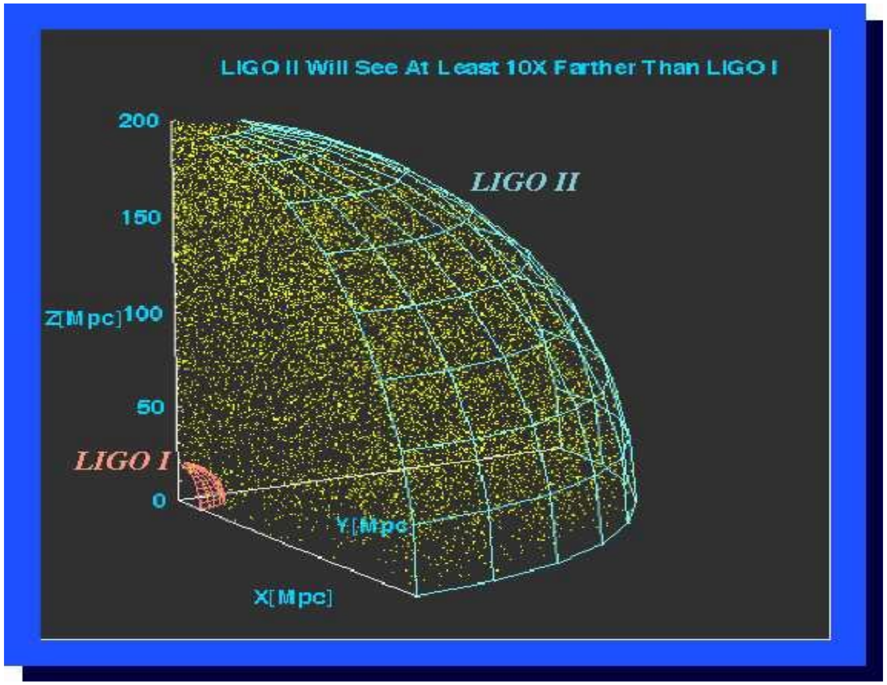


How far out can we see?

⇒ Improve sensitivity to distance by 10x (h ~ 1/r)

⇒ Number of sources goes up 1000x ($1/r^3$) !



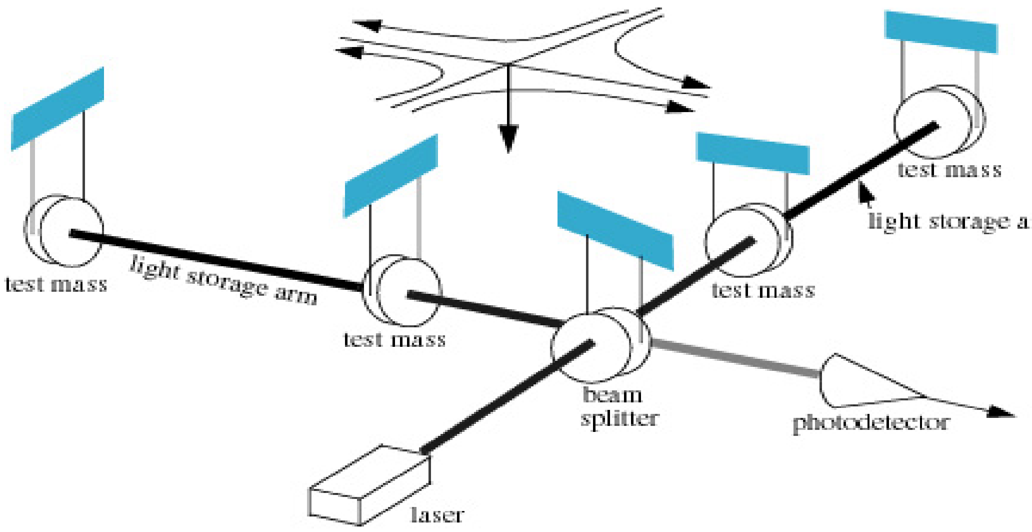


LIGO I ↑

LIGO II →

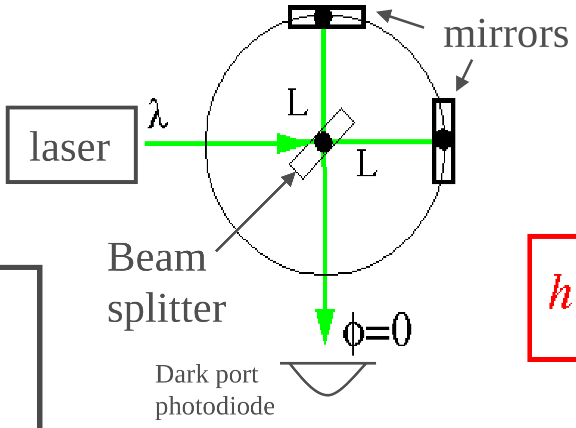
Interferometer for GWs

- 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.

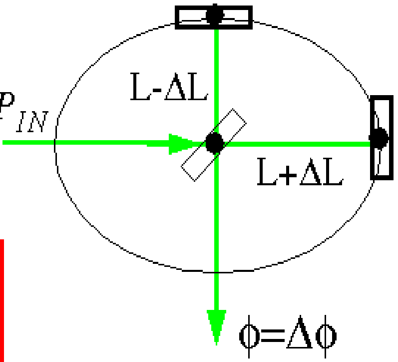


Interferometric detection of GWs

GW acts on freely falling masses:



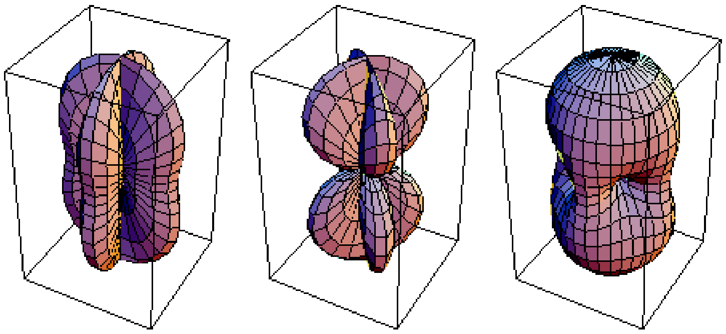
$$h = \frac{\Delta L}{L}$$



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

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

Antenna pattern:
(not very directional!)



+ polarization × polarization unpolarized

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

LIGO I schedule

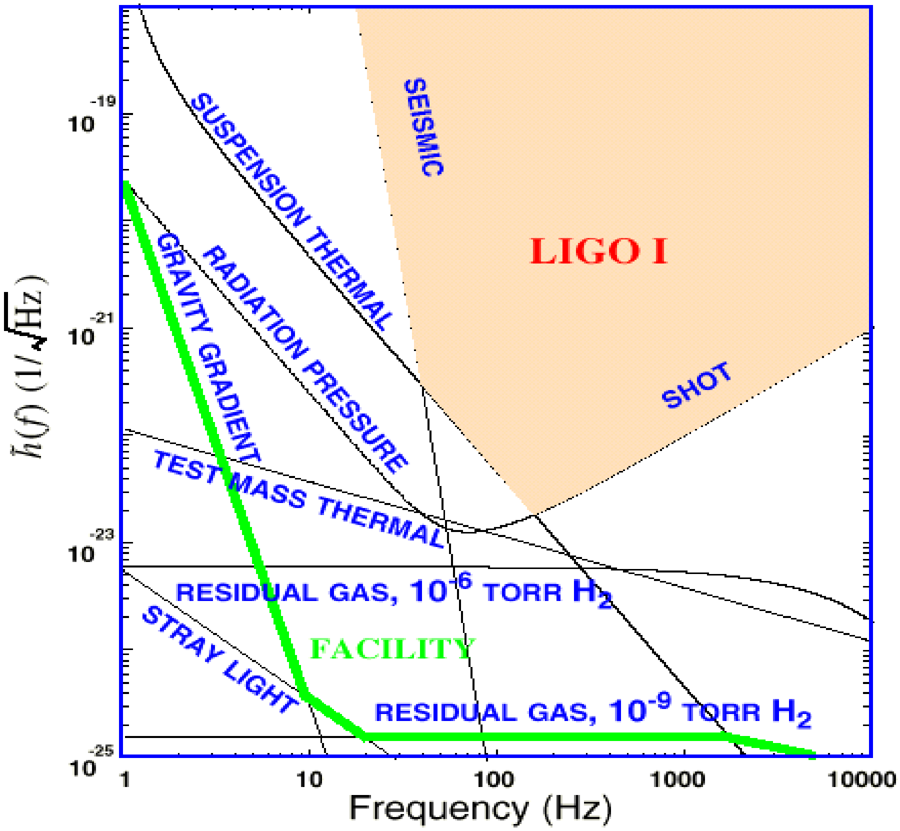
1995	NSF Funding secured ($360M)
1996	Construction Underway (mostly civil)
1997	Facility Construction (vacuum system)
1998	Interferometer Construction (complete facilities)
1999	Construction Complete (interferometers in vacuum)
2000	Detector Installation (commissioning subsystems)
2001	Commission Interferometers (first coincidences)
2002	Sensitivity studies (initiate LIGO I Science Run)
2003+	LIGO I data run (one year integrated data at h ~ 10^{-21})
2005	Begin LIGO II installation

Prototype IFOs

- **40 meter (Caltech)** :
  full engineering prototype for optical and control plant for LIGO II
- **Thermal Noise Interferometer (TNI, Caltech)** :
  measure thermal noise in LIGO II test masses
- **LIGO Advanced Systems Testbed IFO (LASTI, MIT)** :
  full-scale prototyping of LIGO II seismic isolation & suspensions
- **Engineering Test Facility (ETF, Stanford) :**
  advanced IFO configs (Sagnac)
- **10 meter IFO at Glasgow** : prototype optics and control of RSE
- **TAMA 30 meter (Tokyo) :** Advanced technologies
  (SAS, RSE, control schemes, sapphire, cryogenic mirrors)
- Several table-top (non-suspended) IFOs for development of RSE/DR – Caltech (Jim Mason), UFla, ANU

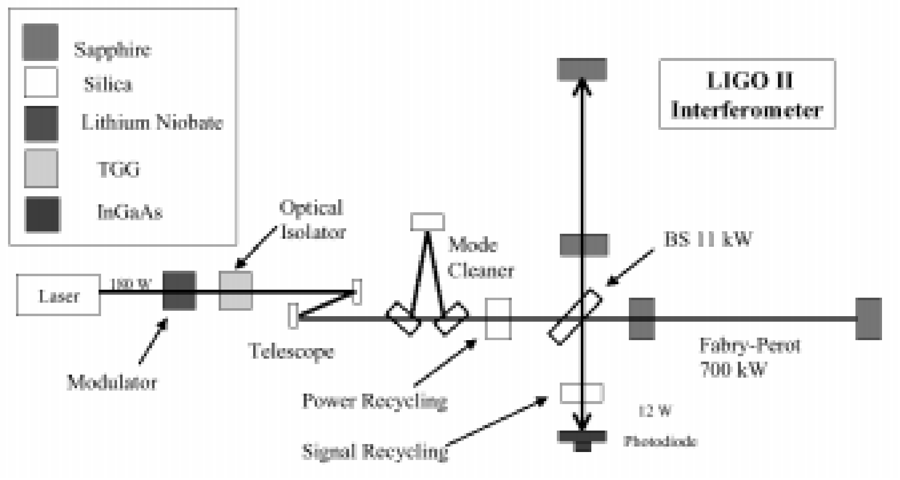
LIGO I noise floor

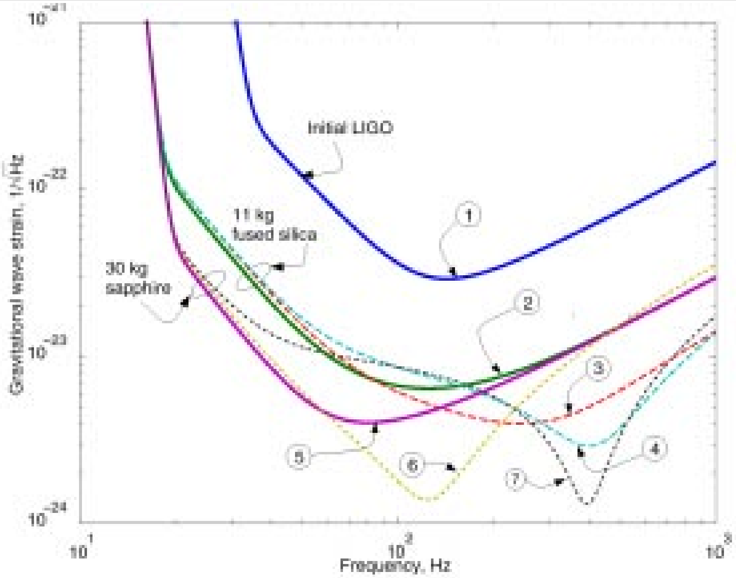
- **Interferometry is limited by three fundamental noise sources**
  - **seismic noise at the lowest frequencies**
  - **thermal noise at intermediate frequencies**
  - **shot noise at high frequencies**
- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**

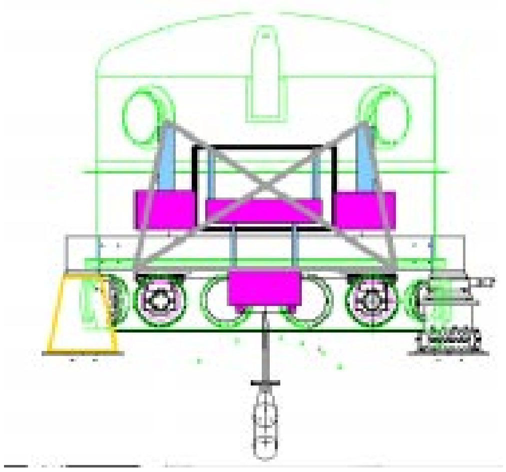


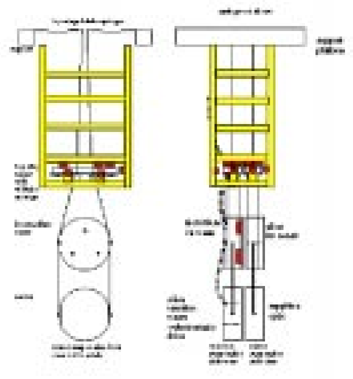
LIGO II

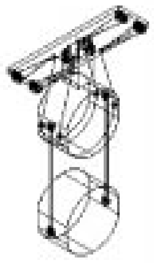
predicted noise curves

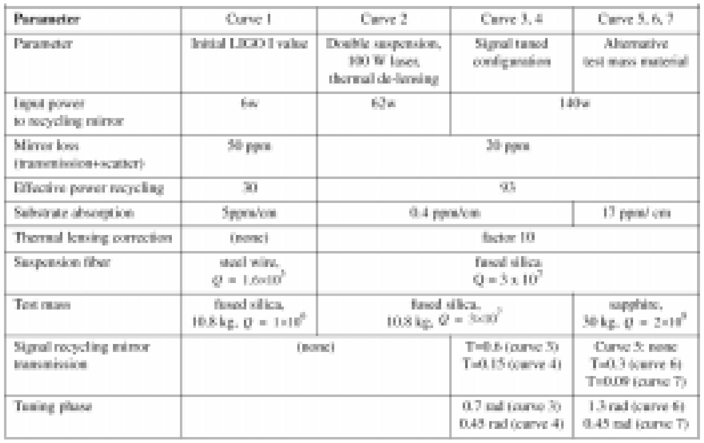






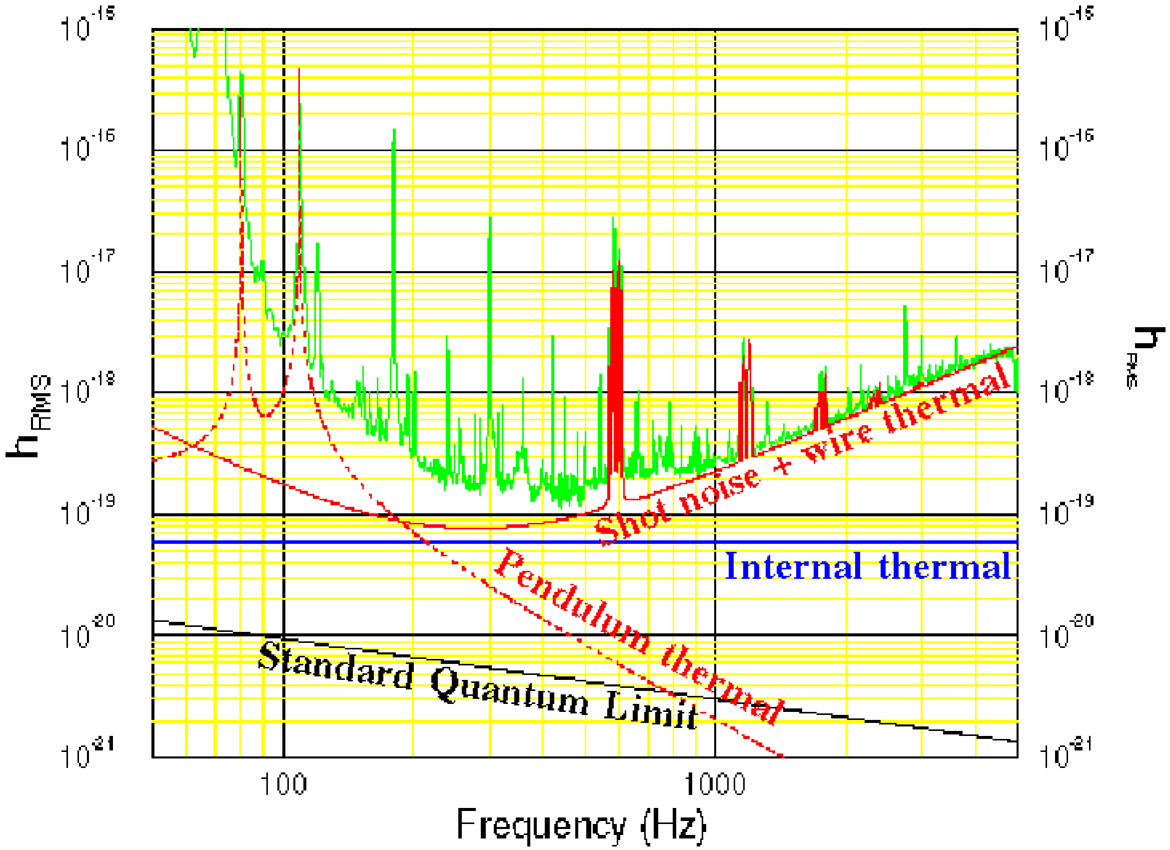






Parameter	Curve 1	Curve 2	Curve 3, 4	Curve 5, 6, 7
Parameter	Initial LIGO I value	Double suspension, 100 W laser, thermal de-lensing	Signal tuned configuration	Alternative test mass material
Input power to recycling mirror	6w	62w	140w	
Mirror loss (transmission+scatter)	50 ppm	20 ppm		
Effective power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

40 meter noise spectrum, 1994



LIGO Subsystems

- PSL – Pre-Stabilized Laser
- IOO – Input Optics
- SUS – Suspension (mechanical and electronic)
- ISC – Interferometer sensing and control
- LSC – Length sensing and control
- ASC – Alignment sensing and control
- Oplev – Optical levers
- WFS – Wavefront sensors
- GDS – Global Diagnostic System
- PEM – Physical environment monitoring
- VAC – Vacuum system control
- DAQS – Data acquisition System
- CDS – Control and Data Systems
- LDAS – LIGO Data Analysis System