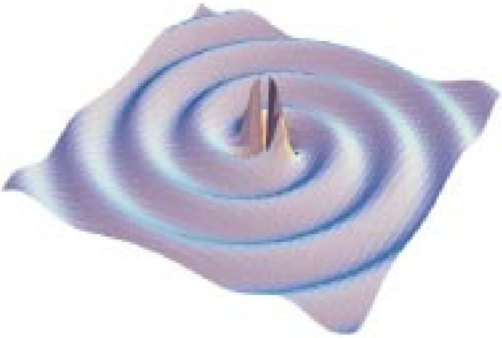
The LIGO Project

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

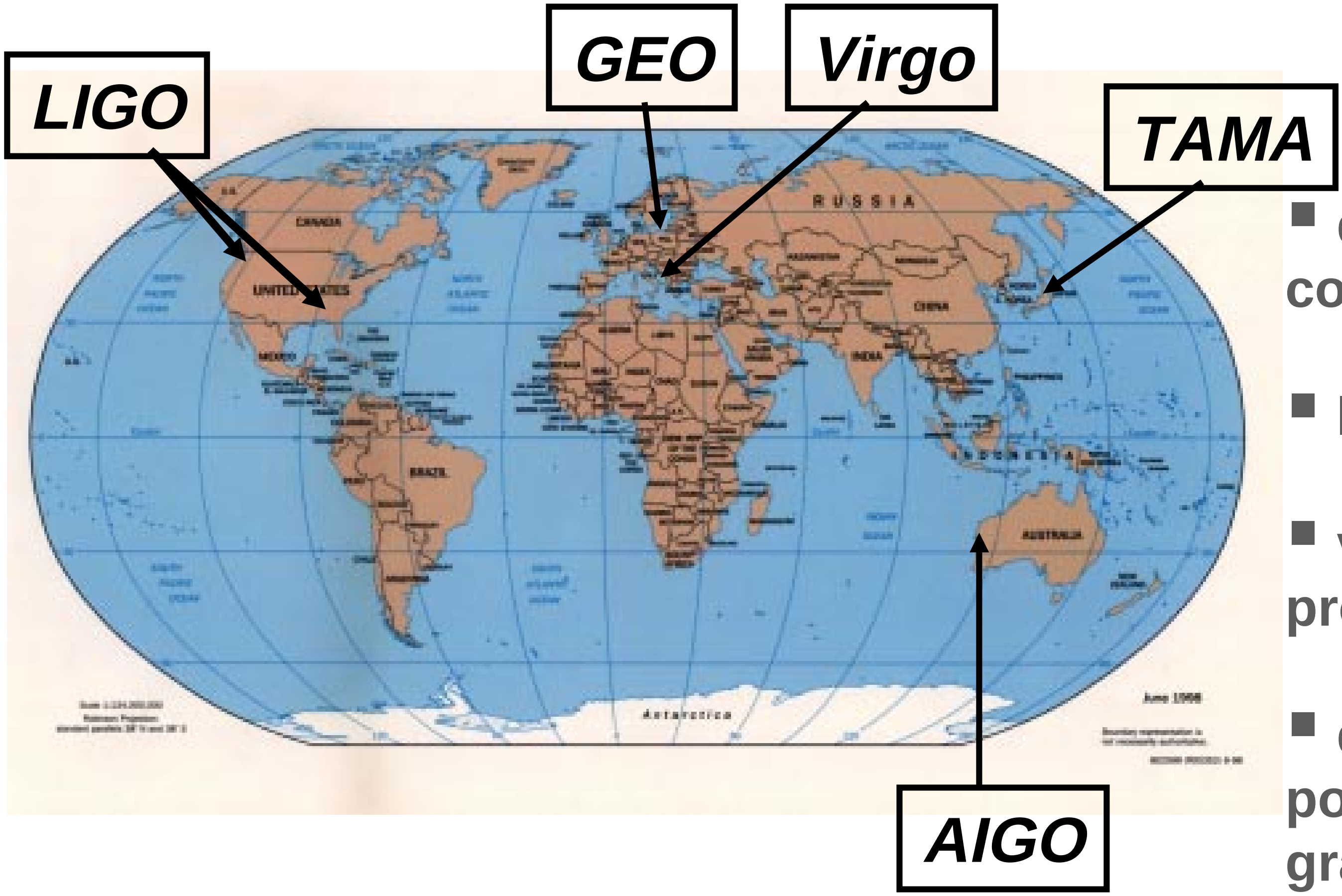
- Two sites separated by 3000 km
- each site carries 4km vacuum system, infrastructure
- each site capable of multiple interferometers (IFOs)

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

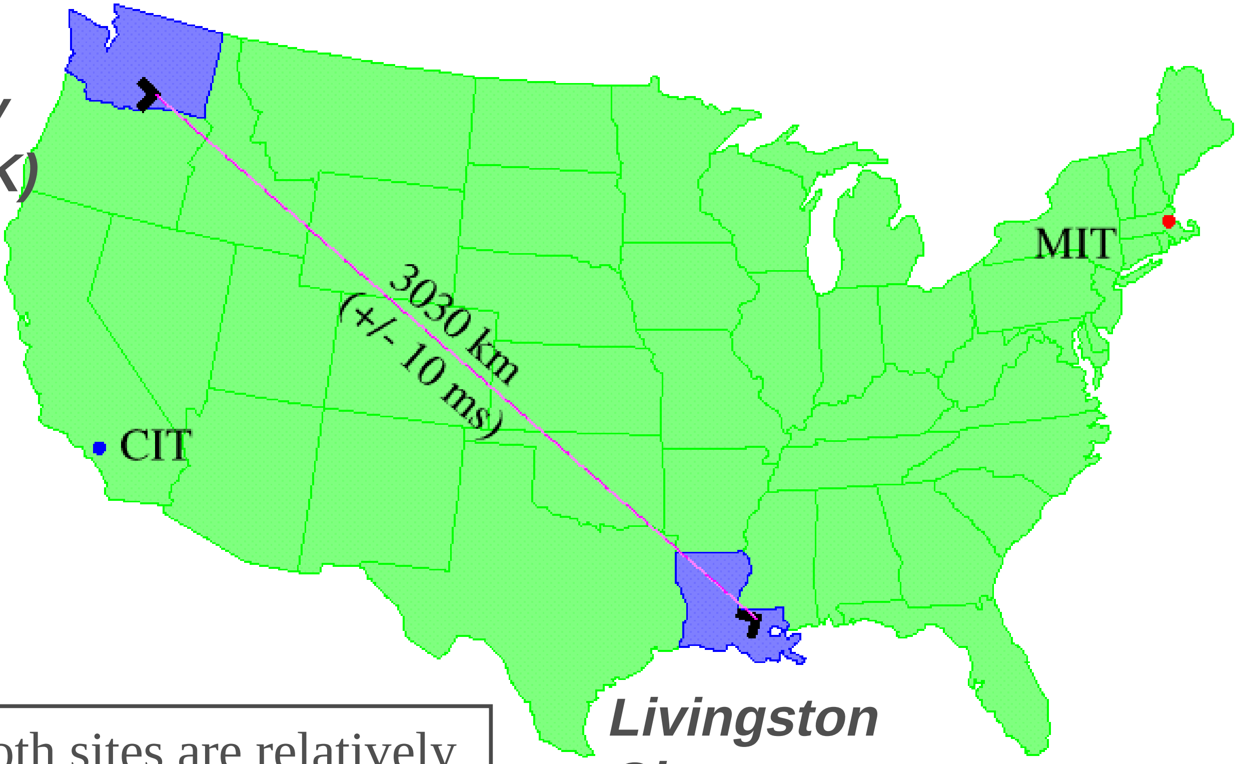
International network

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)

Livingston Observatory

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

Warped space-time: Einstein’s General Relativity (1916)

- **A *geometric* theory of gravity**

➢ gravitational acceleration depends only on the geometry of the space that the “test mass” occupies, not any properties of the test mass itself

➢ for gravity (as opposed to all other forces), motion (acceleration) depends only on location, not mass

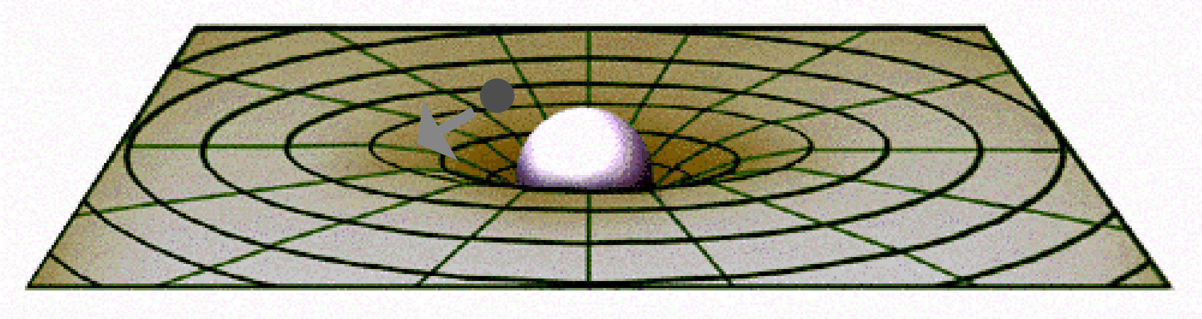
- **Imagine space as a stretched rubber sheet.**

$$F = \cancel{m}_1 a = G\cancel{m}_1 m_2 / r^2$$

- **A mass on the surface will cause a deformation.**

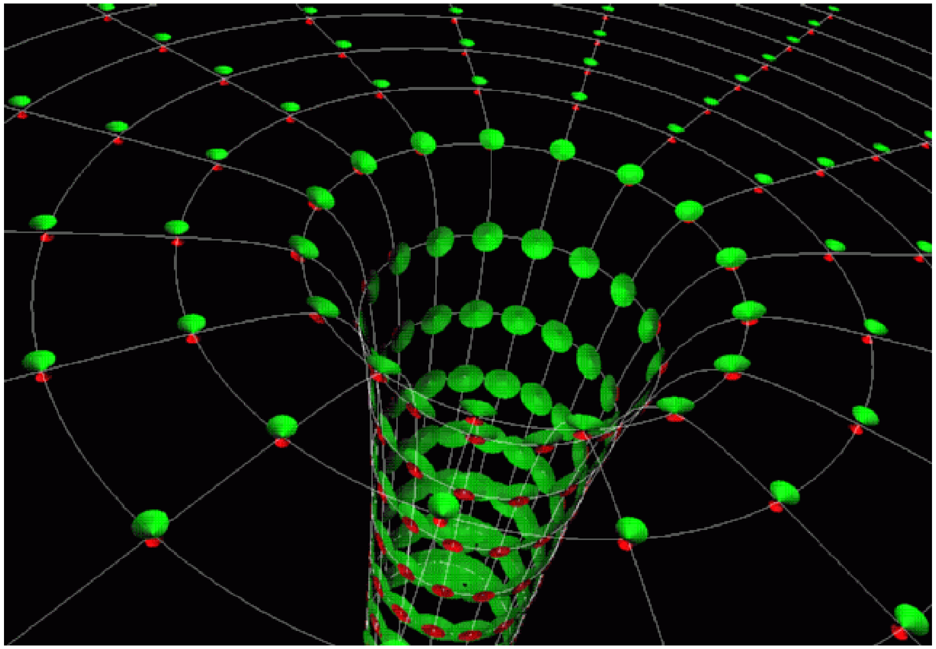
- **Another mass dropped onto the sheet will roll toward that mass.**

- **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.**



Strong-field GR

- 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

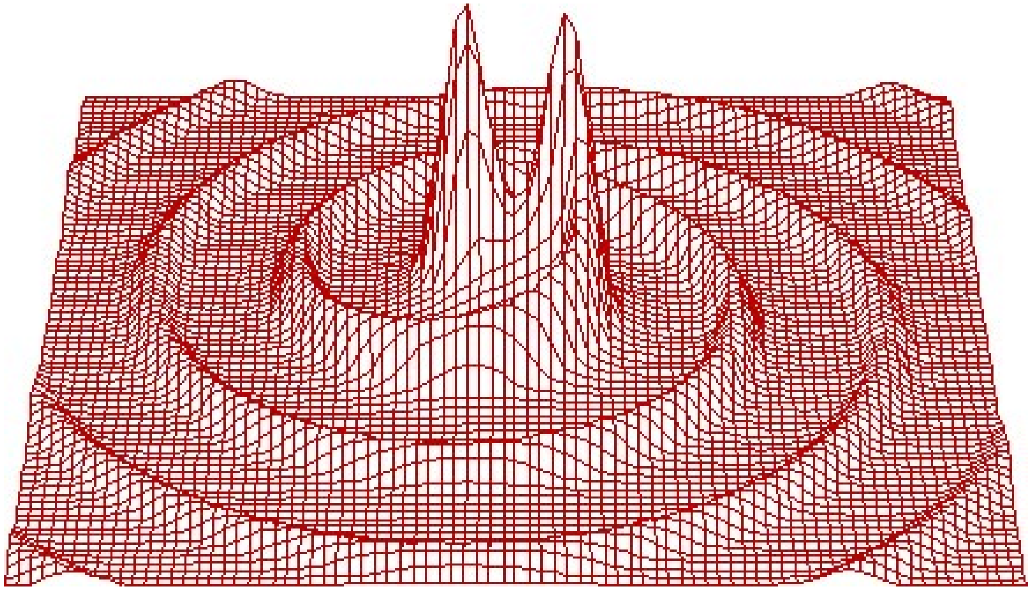


But we can search for (*weak-field*) gravitational waves as a signal of their presence and dynamics

Dynamics of changing Spacetime curvature

Newton's Theory

"instantaneous action at a distance"



Einstein's Theory

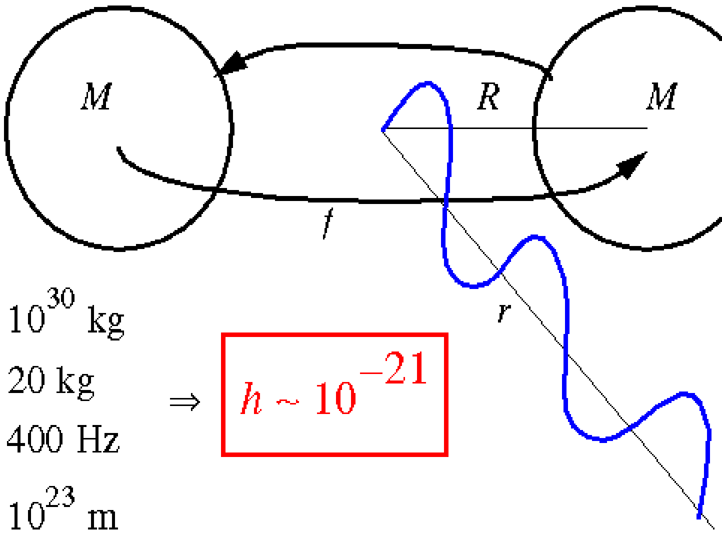
information carried by gravitational radiation at the speed of light

Sources of GWs

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

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

- $\ddot{I}_{\mu\nu}$ = 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!*

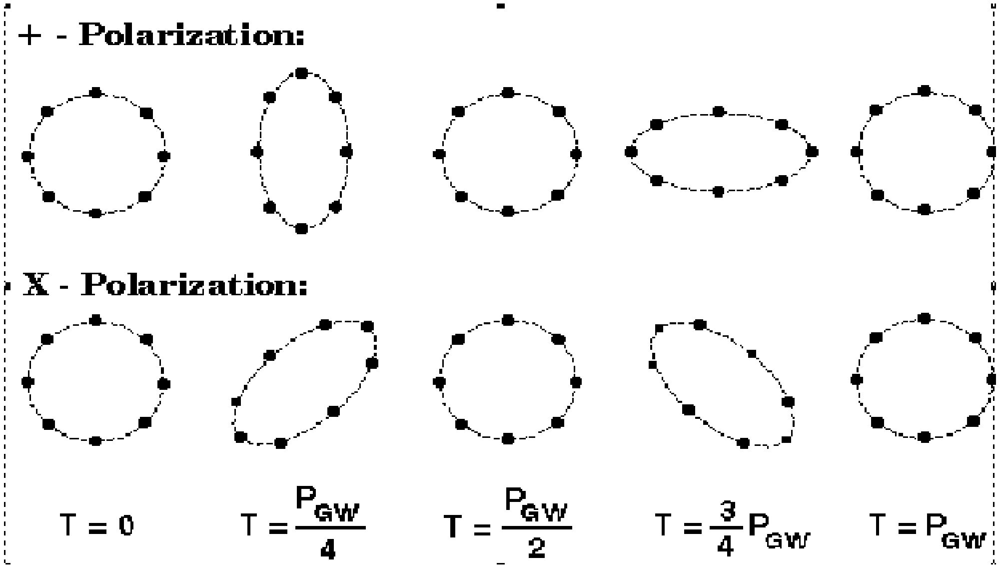
Nature of Gravitational Radiation

General Relativity predicts :

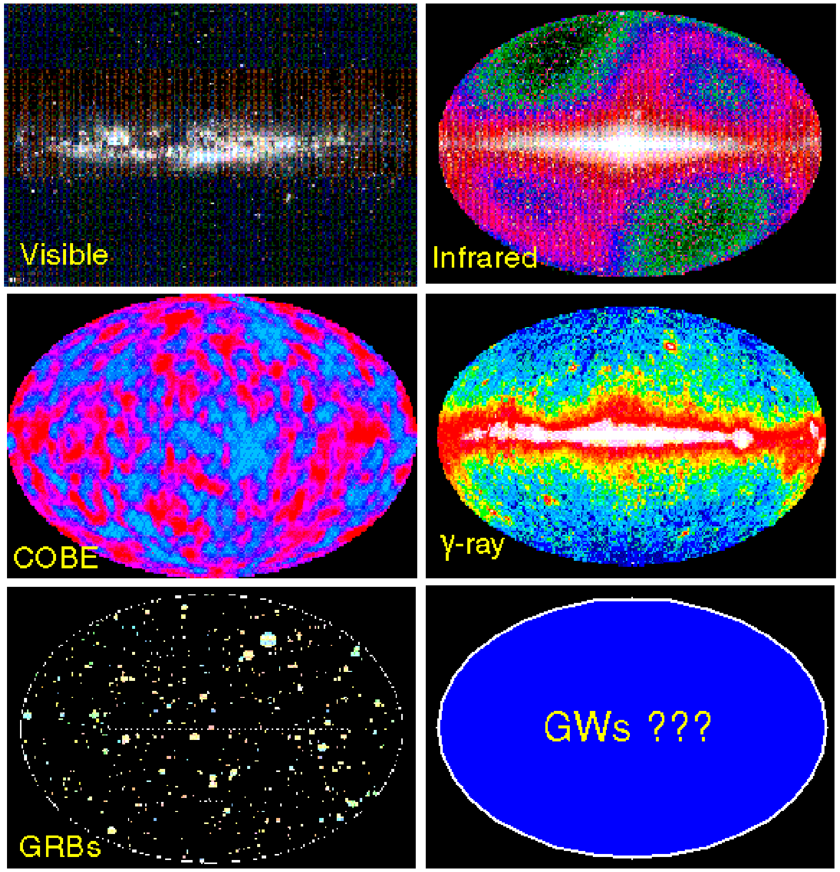
- transverse space-time distortions, freely propagating at speed of light ⇒ ⇒ mass of graviton = 0
- Conservation laws:
  - conservation of energy ⇒ no monopole radiation
  - conservation of momentum ⇒ no dipole radiation
  - quadrupole wave (spin 2) ⇒ two polarizations

plus (⊕) and cross (⊗)

⇒ spin of graviton is 2



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

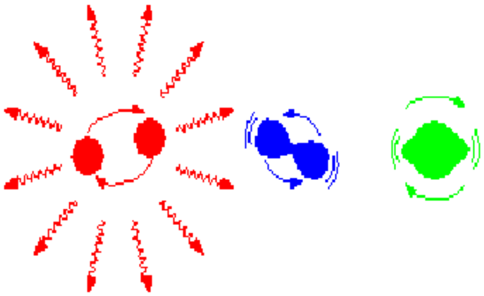


E&M	GW
space as medium for field	Space-time itself
incoherent superpositions of atoms, molecules	coherent motions of huge masses (or energy)
wavelength small compared to sources - images	wavelength ~large compared to sources - poor spatial resolution
absorbed, scattered, dispersed by matter	very small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

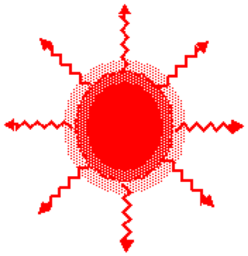
- **Very different information, mostly mutually exclusive**
- **Difficult to predict GW sources based on E&M observations**

Astrophysical
Sources of Gravitational Waves

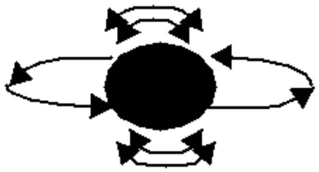
Coalescing compact binaries
(neutron stars, black holes)



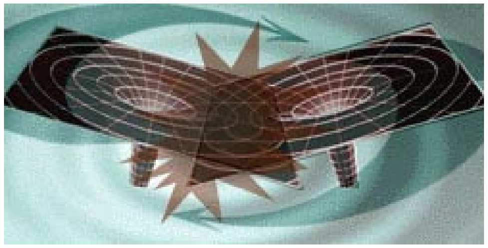
Non-axi-symmetric
supernova collapse



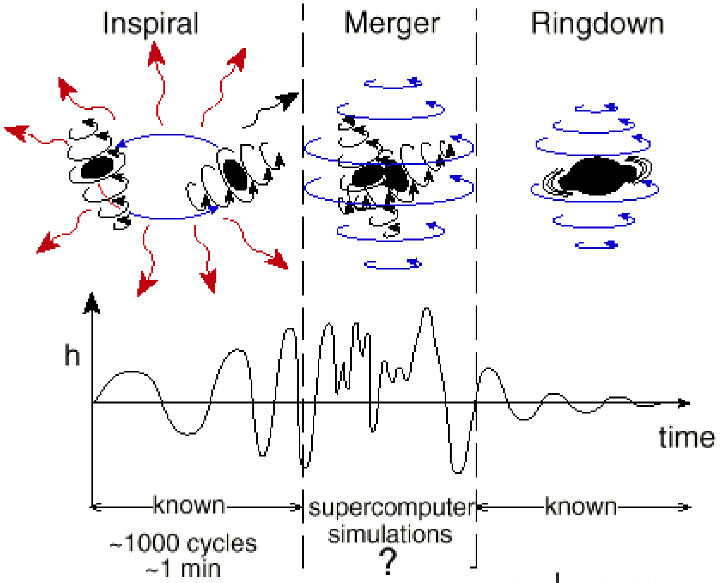
Non-axi-symmetric pulsar
(rotating, beaming
neutron star)

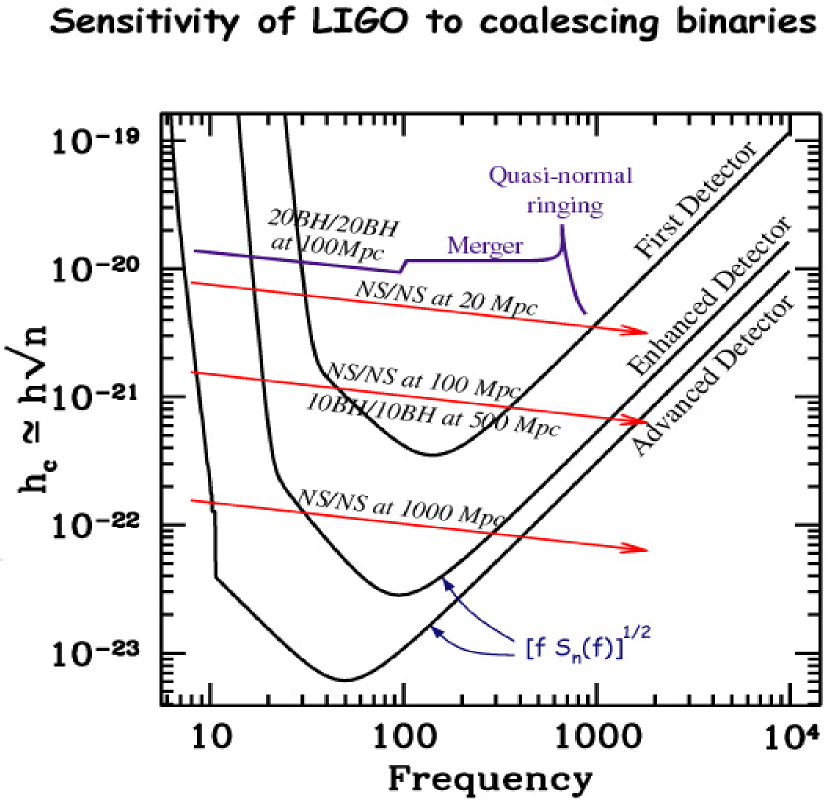


Gravitational Waves from coalescing binaries

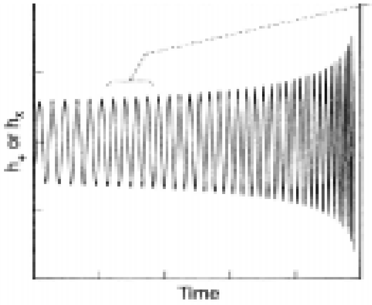


Compact binary mergers (NS/NS, NS/BH, BH/BH)

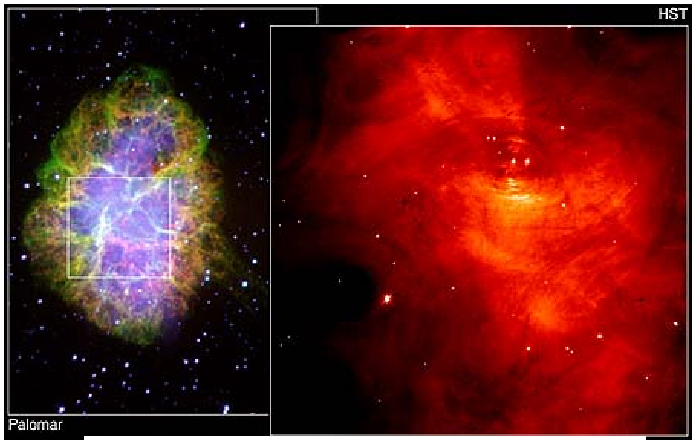


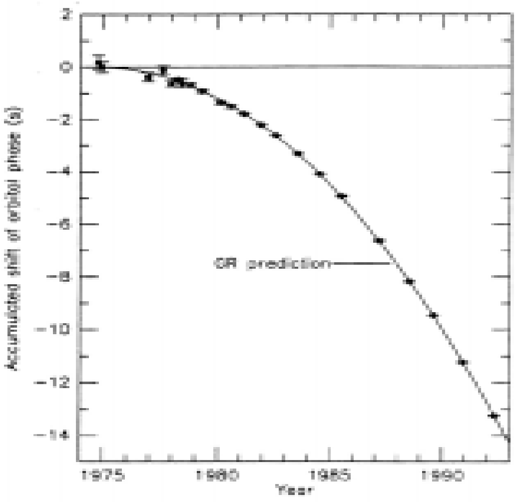

Sensitivity of LIGO to coalescing binaries

“chirp” waveform



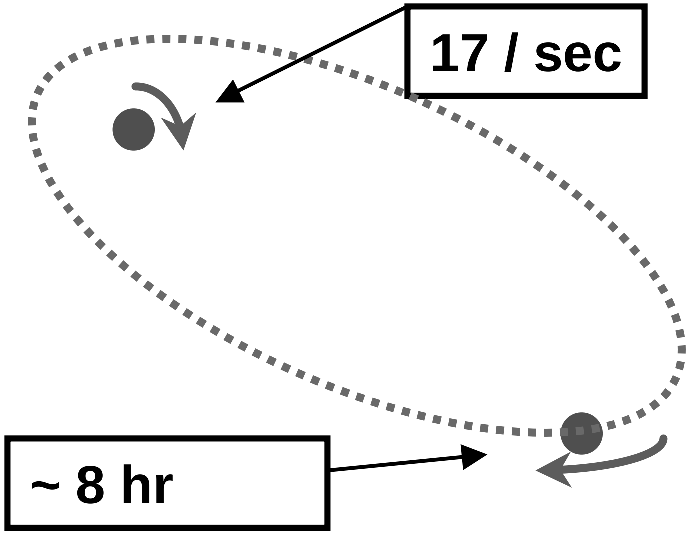
Hulse-Taylor binary pulsar





Neutron Binary System

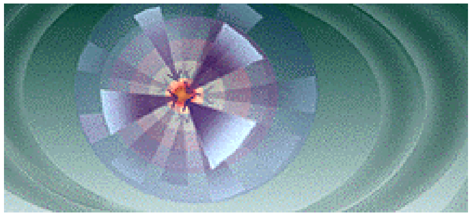
PSR 1913 + 16 -- Timing of pulsars

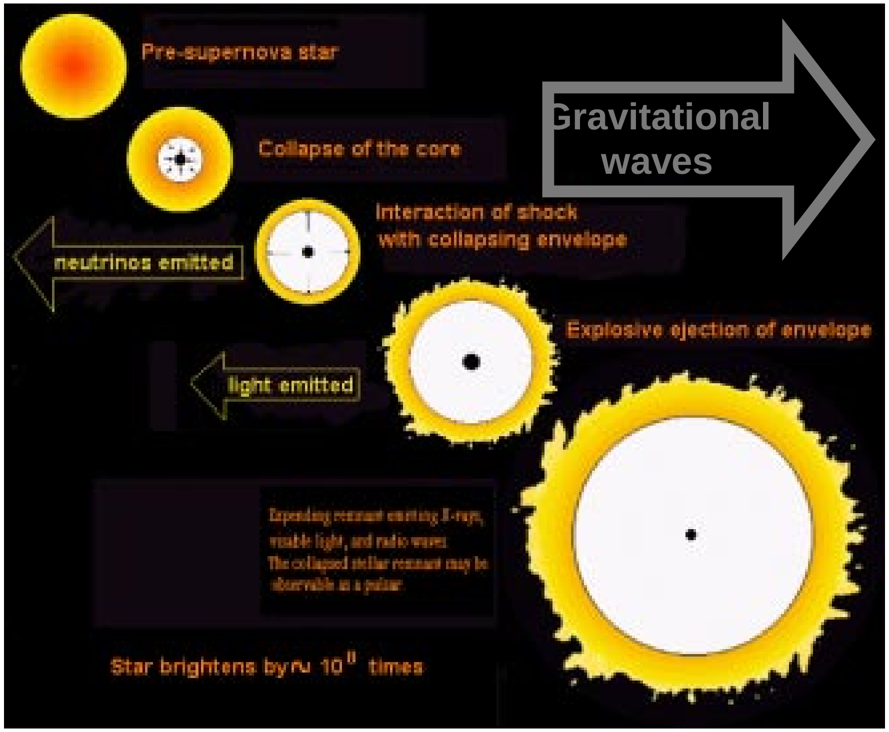


17 / sec

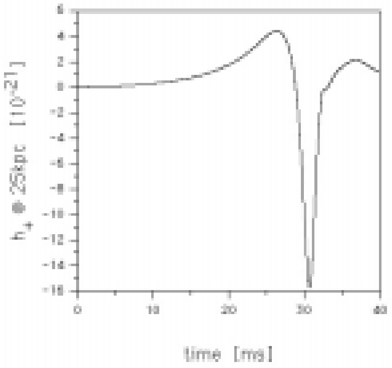
~ 8 hr

Gravitational Waves from Supernova collapse

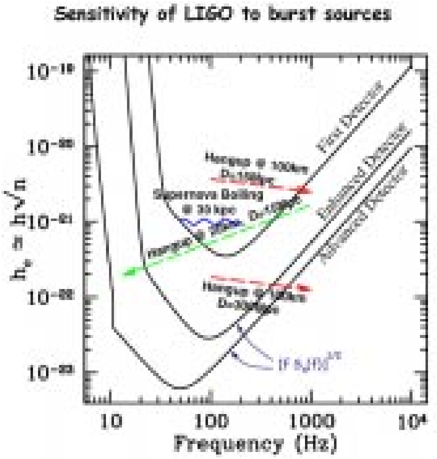




Non axisymmetric collapse ‘burst’ signal



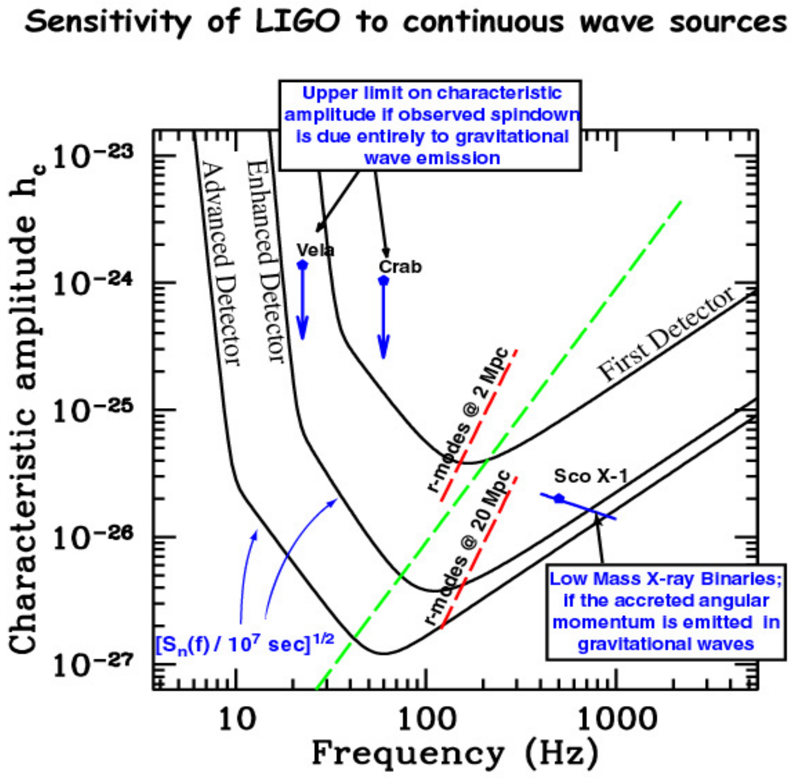
SN1987A



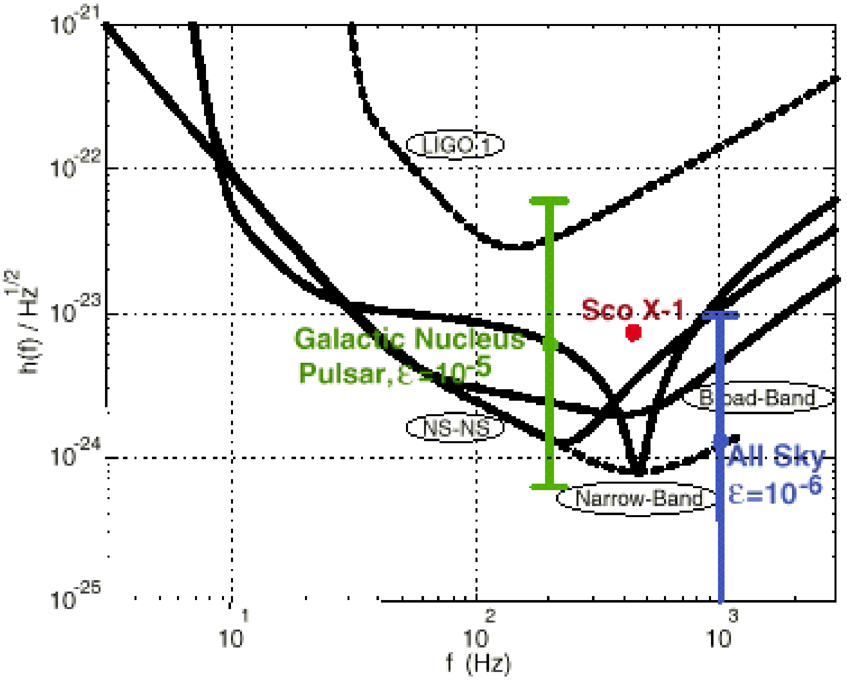
Rate: ***1/50 yr - our galaxy***
3/yr - Virgo cluster

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

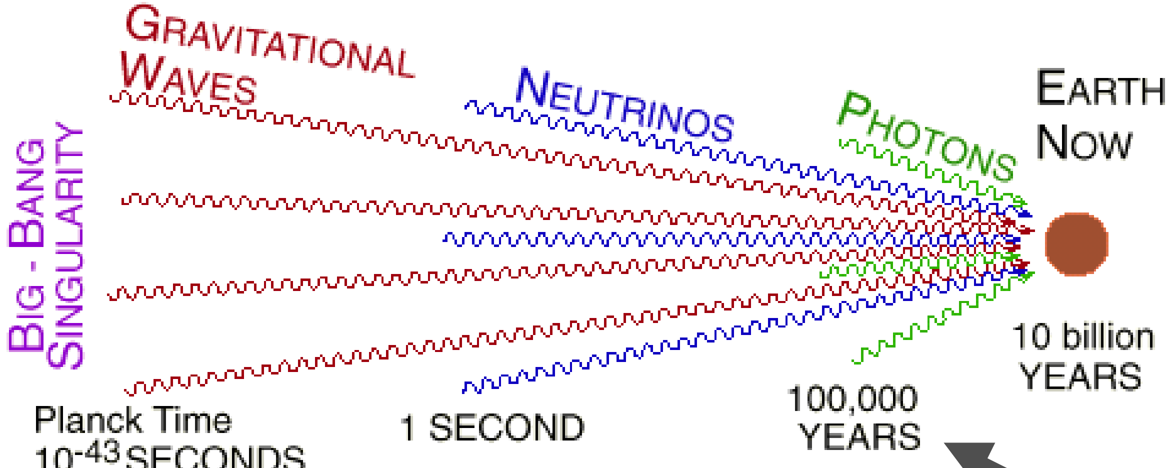
Pulsars and continuous wave sources



- **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



GRAVITATIONAL WAVES

NEUTRINOS

PHOTONS

EARTH NOW

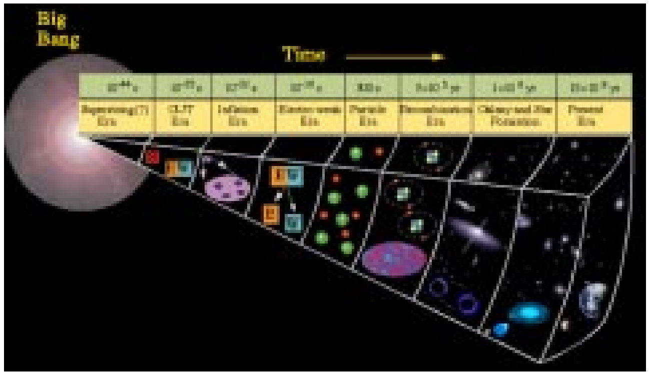
BIG - BANG SINGULARITY

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

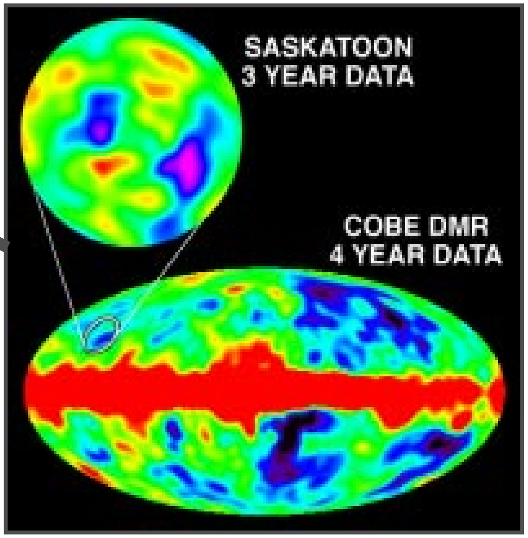
1 SECOND

100,000
YEARS

10 billion
YEARS



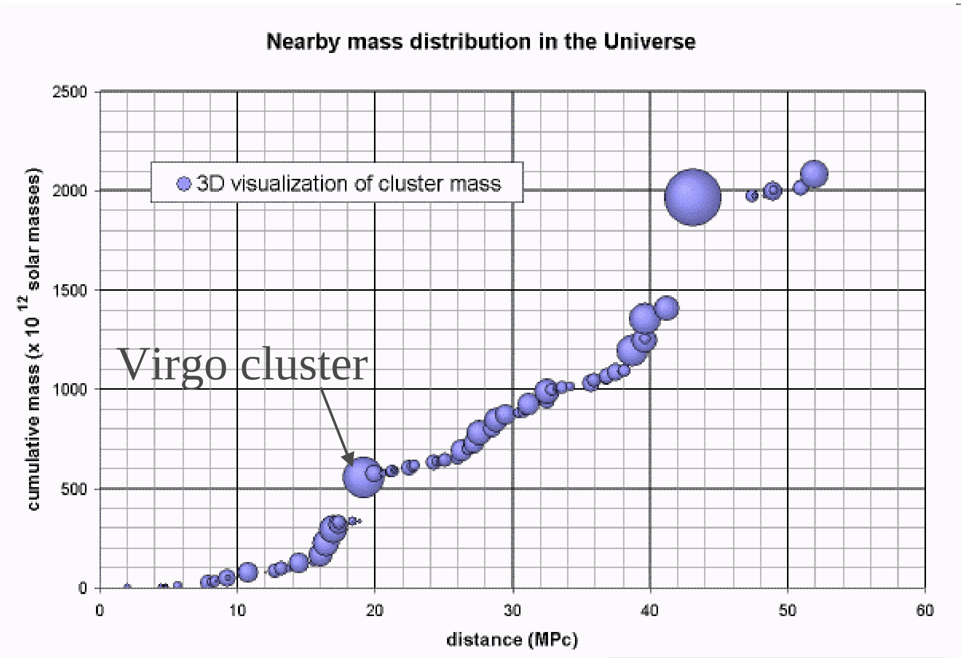
Cosmic microwave background

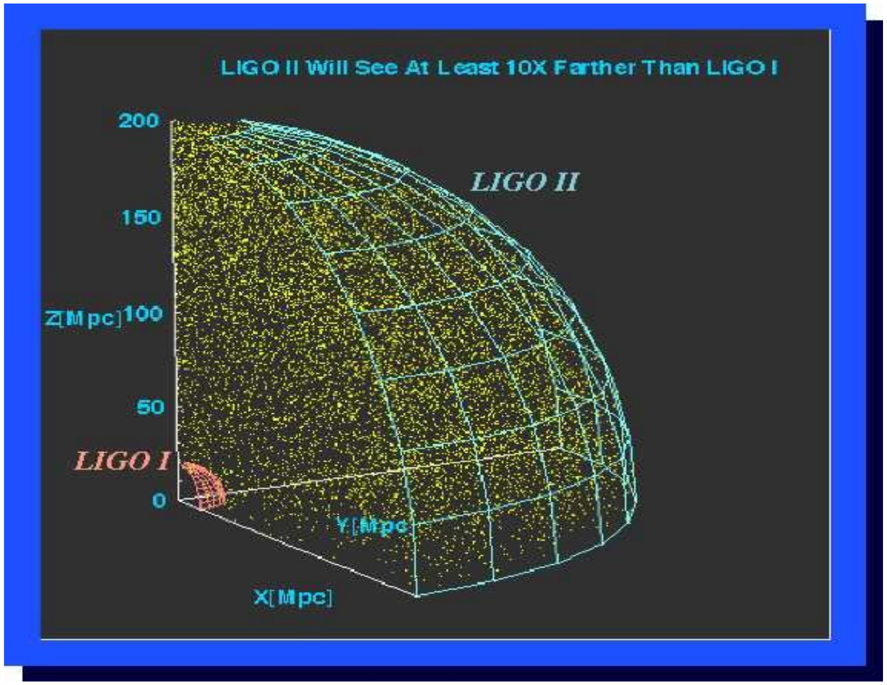


How far out can we see?

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

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



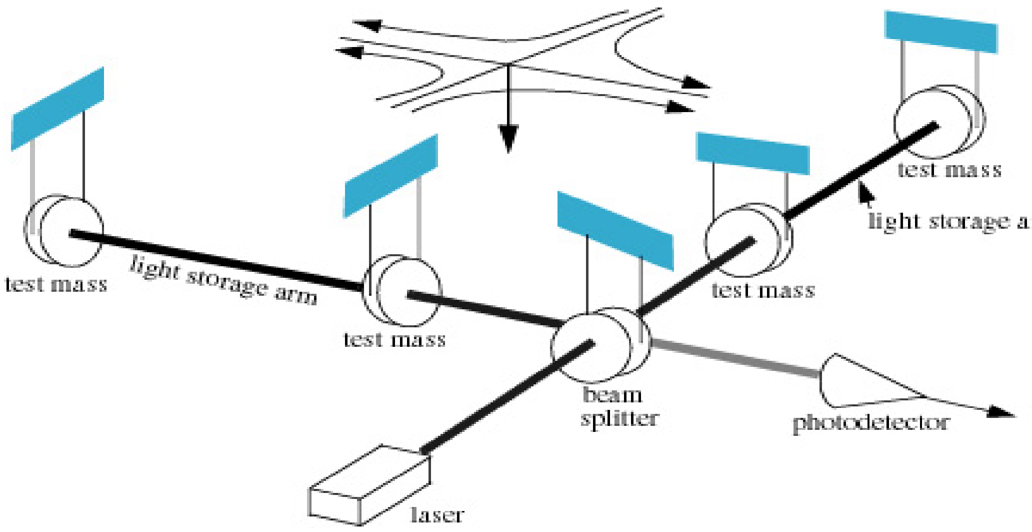


LIGO I ↑

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.



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 *Beam Tube*

Beam light path must be high vacuum, to minimize "phase noise"

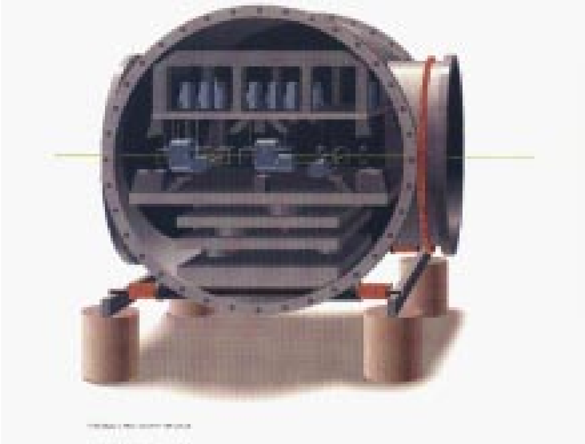
- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

LIGO vacuum equipment

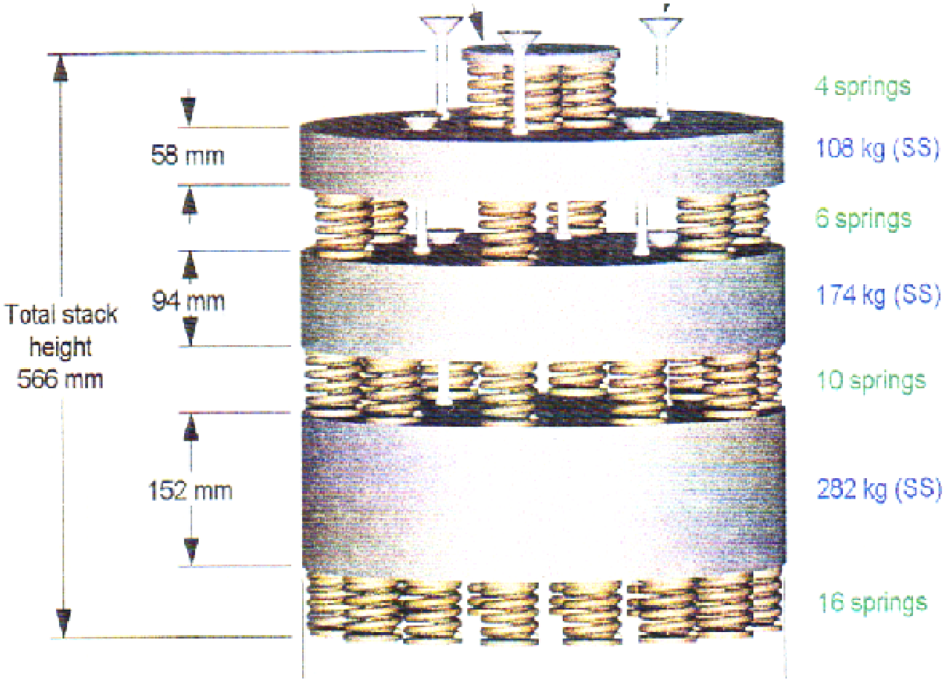
All optical components must be in high vacuum, so mirrors are not “knocked around” by gas pressure

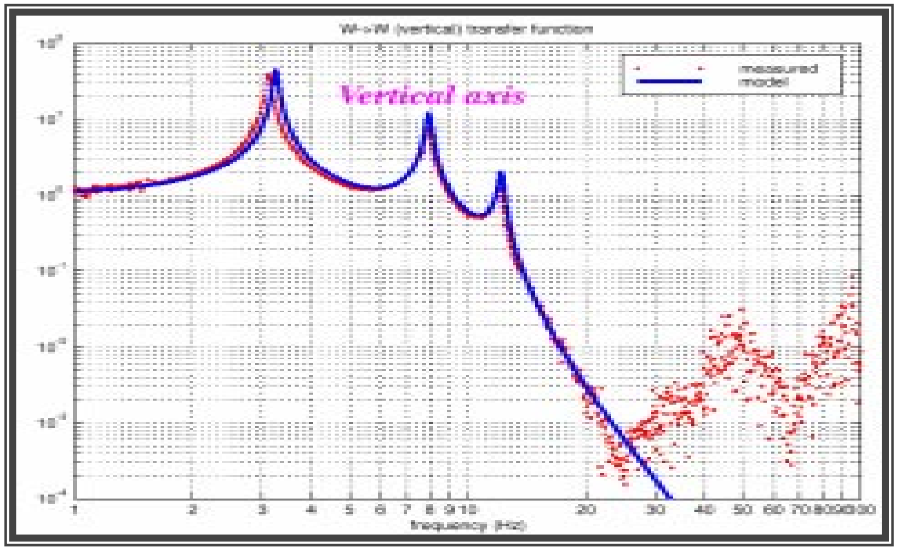
BSC Chambers

HAM Chambers



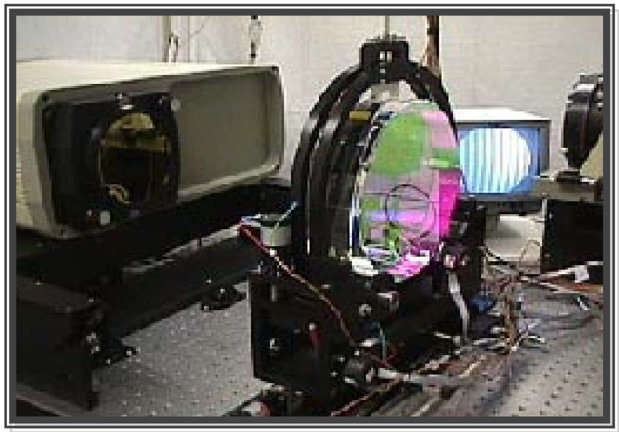
Seismic isolation stacks





LIGO Optics

mirrors, coating and polishing



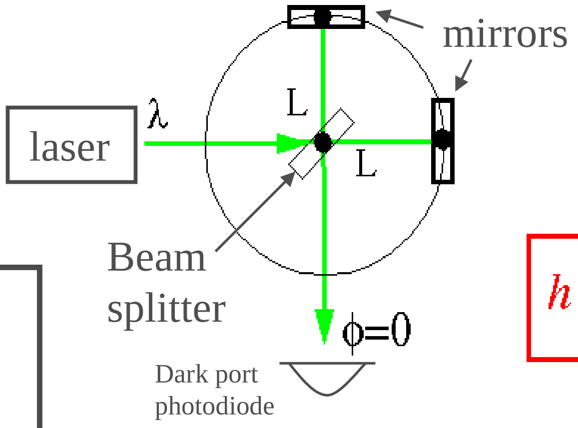
- SUPERmirrors:
  - » High uniformity fused silica quartz
  - » reflectivity as high as 99.999%
  - » losses < 1 ppm in coating, 10 ppm in substrate
  - » polished with mircoroughness < $\lambda/1800 \approx 0.5$ nm
  - » and ROC within spec.
  - ≈ ($\delta R/R < 5\%$, except for BS)
- Suspensions: hang 10kg optic by a single loop of wire, and hold it steady with feedback system

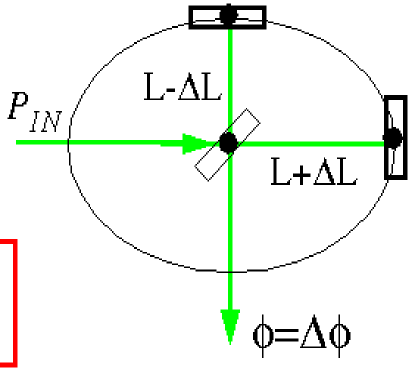
LIGO I schedule

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 $h \sim 10^{-21}$)
2005	Begin LIGO II installation

Interferometric detection of GWs

GW acts on freely falling masses:



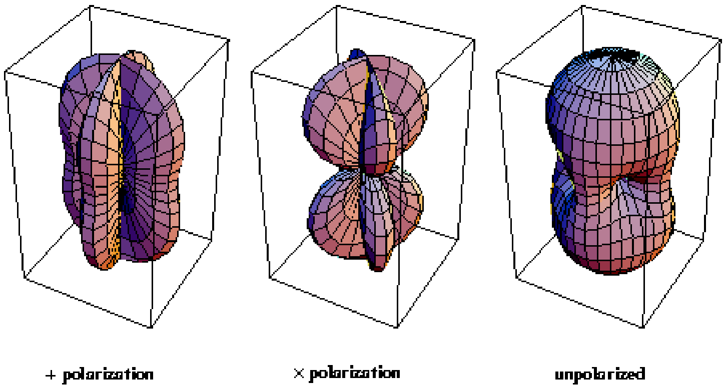


$$h = \frac{\Delta L}{L}$$

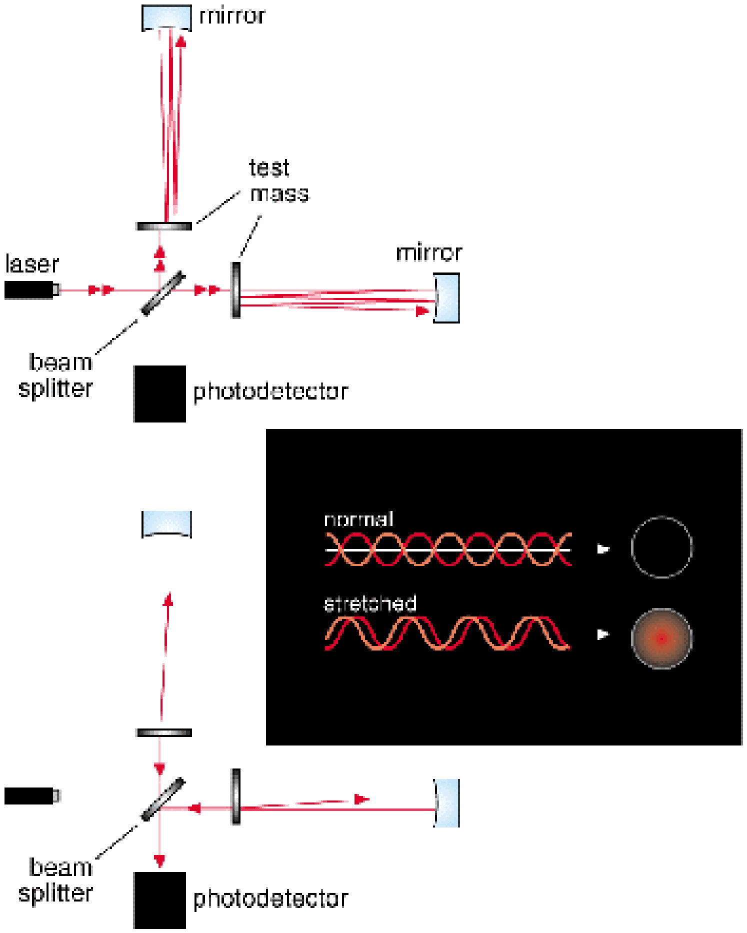
For fixed ability to measure ΔL, make L as big as possible!

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

Antenna pattern:
(not very directional!)



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

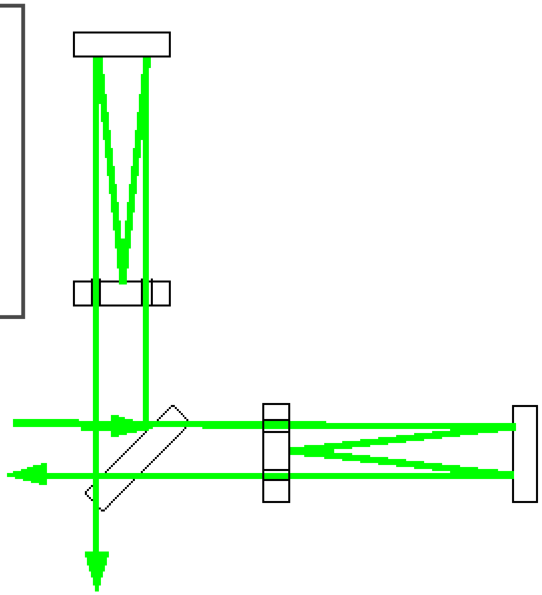
The longer the light path, the larger the phase shift…

Make the light path as long as possible!

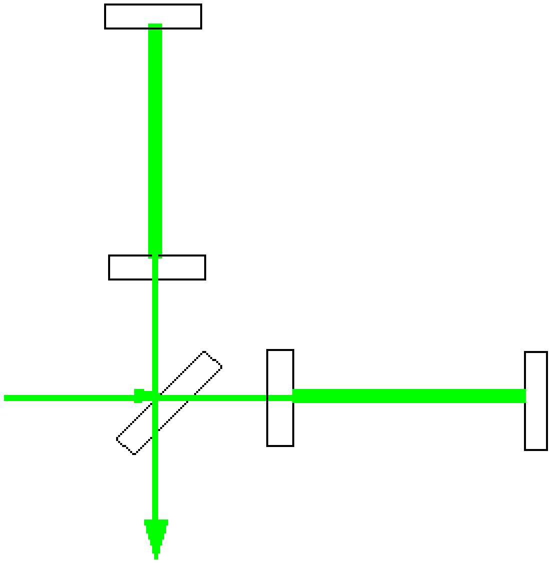
Light storage: folding the arms

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 τ_{stor}

(LIGO design) τ_{stor}~ *3 msec*

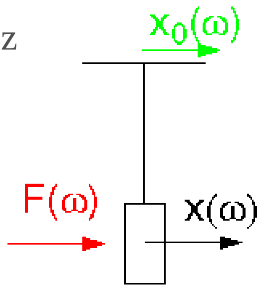
More compact, but harder to control

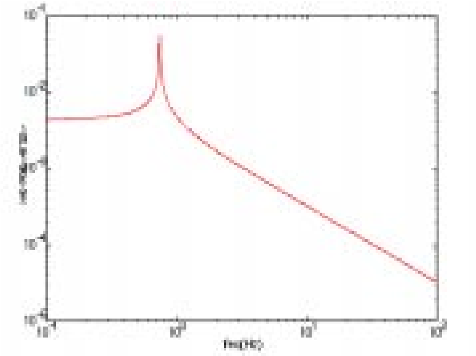
Suspended test masses

- 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 (on a seismic isolation stack)
  - “fixed” against gravity at low frequencies, but
  - “free” to move at frequencies above ~ 100 Hz

“Free” mass:

pendulum at $f \gg f_0$

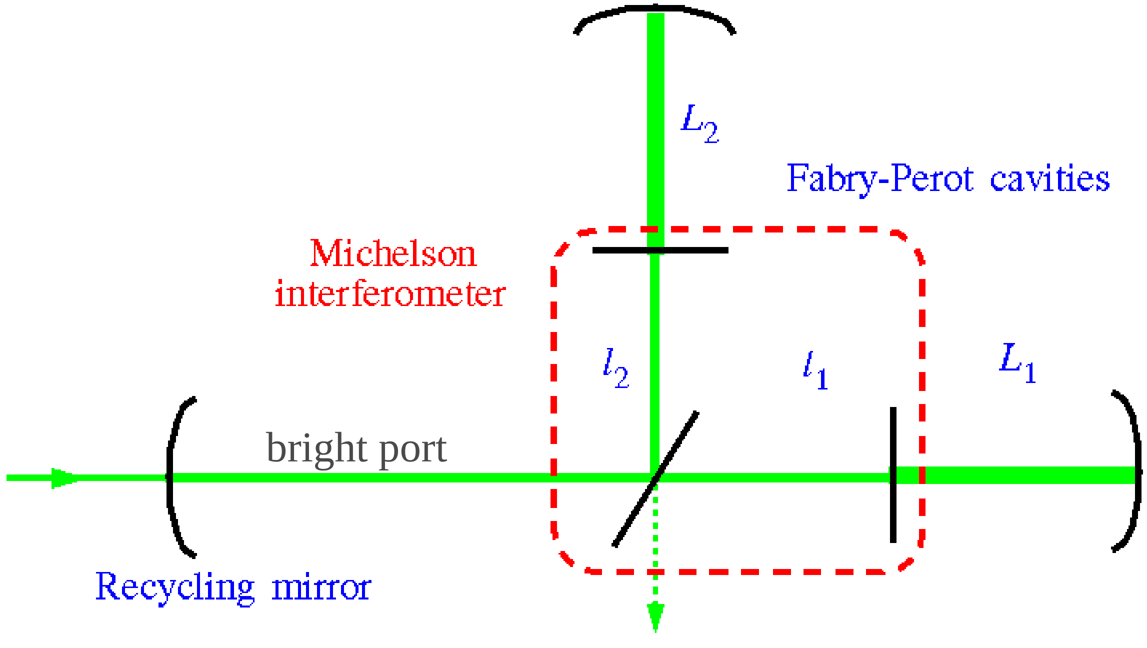




LIGO I configuration

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



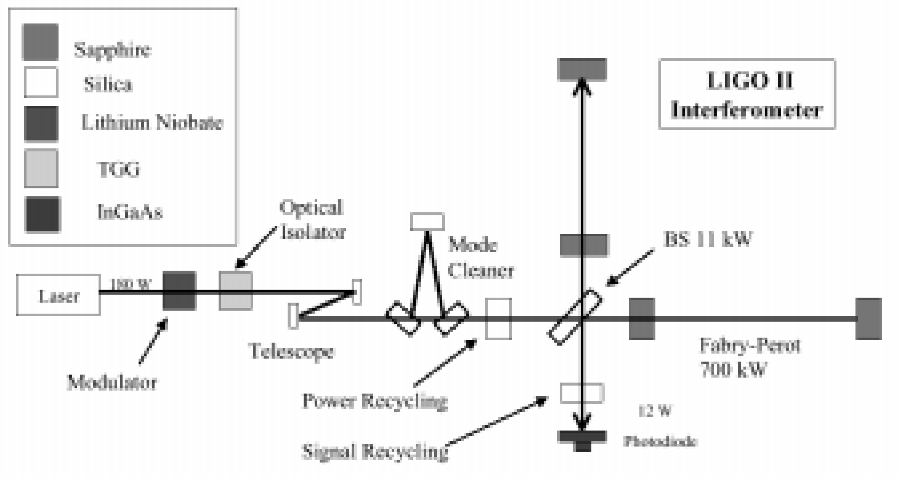
dark port (GW signal)

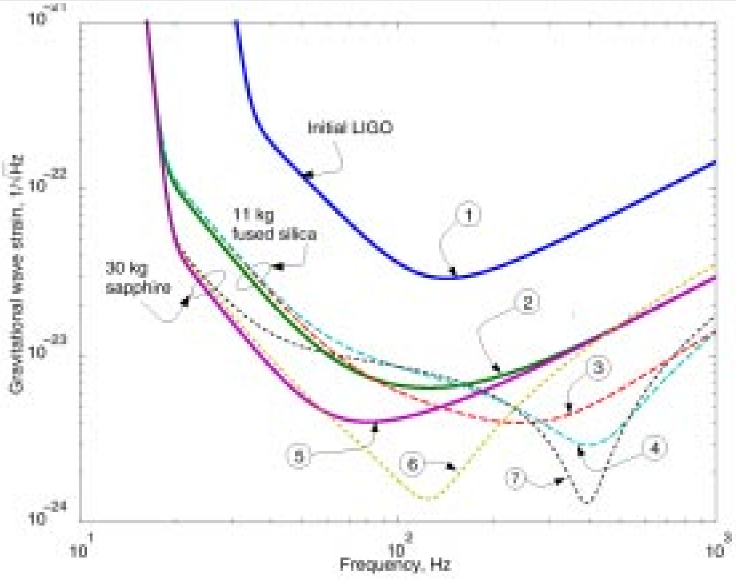
LIGO II

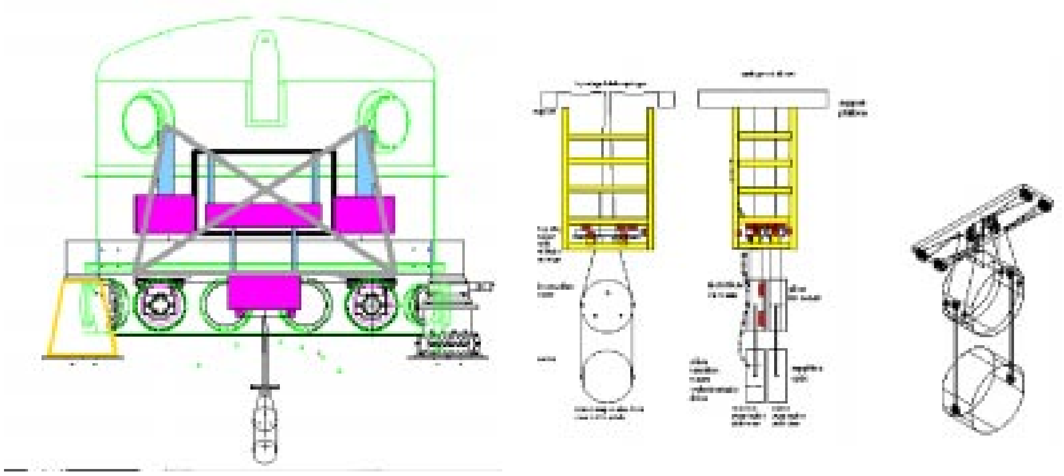
incremental improvements

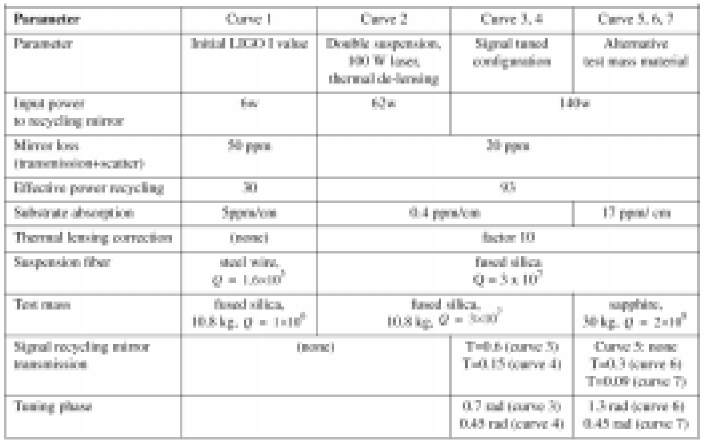
- Reduce shot noise: higher power CW-laser: 12 watts ⇒120 watts
- Reduce shot noise: Advanced optical configuration: signal recycling mirror (7th suspended optic) to tune shot-noise response in frequency
- To handle thermal distortions due to beam heating: advanced mirror materials, coatings, thermal de-lensing compensation (heating mirror at edges)
- Reduce seismic noise: Advanced (active) seismic isolation. Seismic wall moved from 40 Hz ⇒ < 10 Hz.
- Reduce seismic and suspension noise: Multiple pendulum suspensions to filter environmental noise in stages.
- Reduce suspension noise: Fused silica fibers, silica welds.
- Reduce test mass thermal noise: Last pendulum stage (test mass) is controlled via electrostatic forces, coupled capacitively (no magnets).
- Reduce test mass thermal noise: High-Q material (sapphire).

LIGO II
predicted noise curves









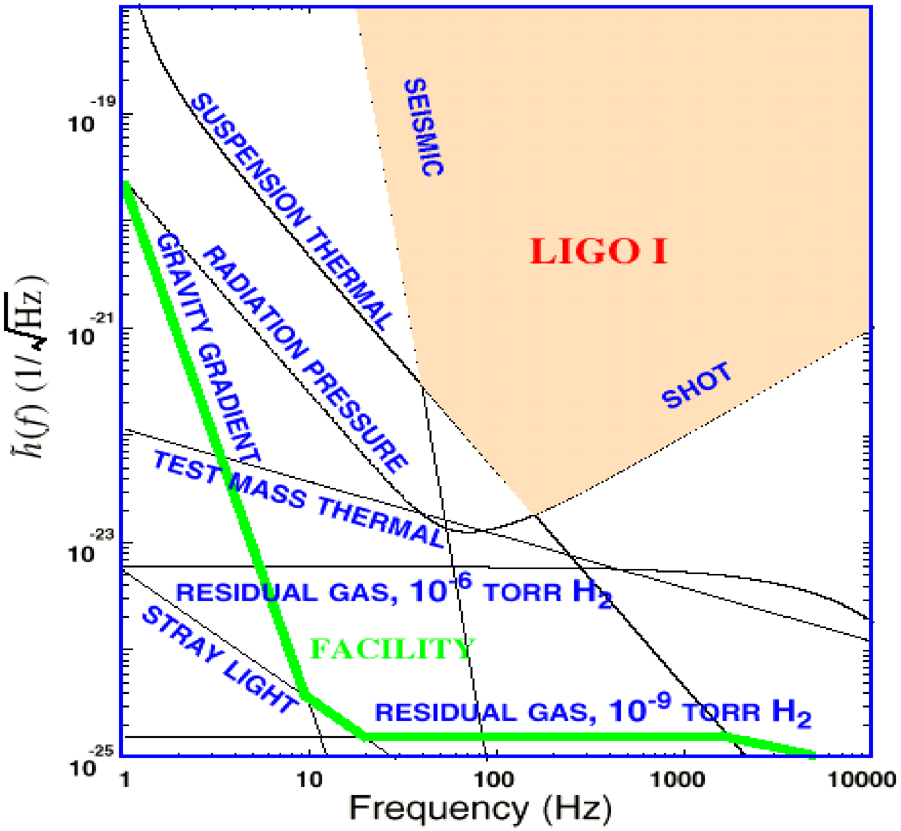
Parameter	Curve 1	Curve 2	Curve 3, 4	Curve 5, 6, 7
Parameter	Initial LIGO I value	Double suspension, 100 W laser, thermal de-lensing	Signal tuned configuration	Alternative test mass material
Input power to recycling mirror	6w	62w	140w	
Mirror loss (transmission+scatter)	50 ppm	20 ppm		
Effective power 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)

Prototype IFOs

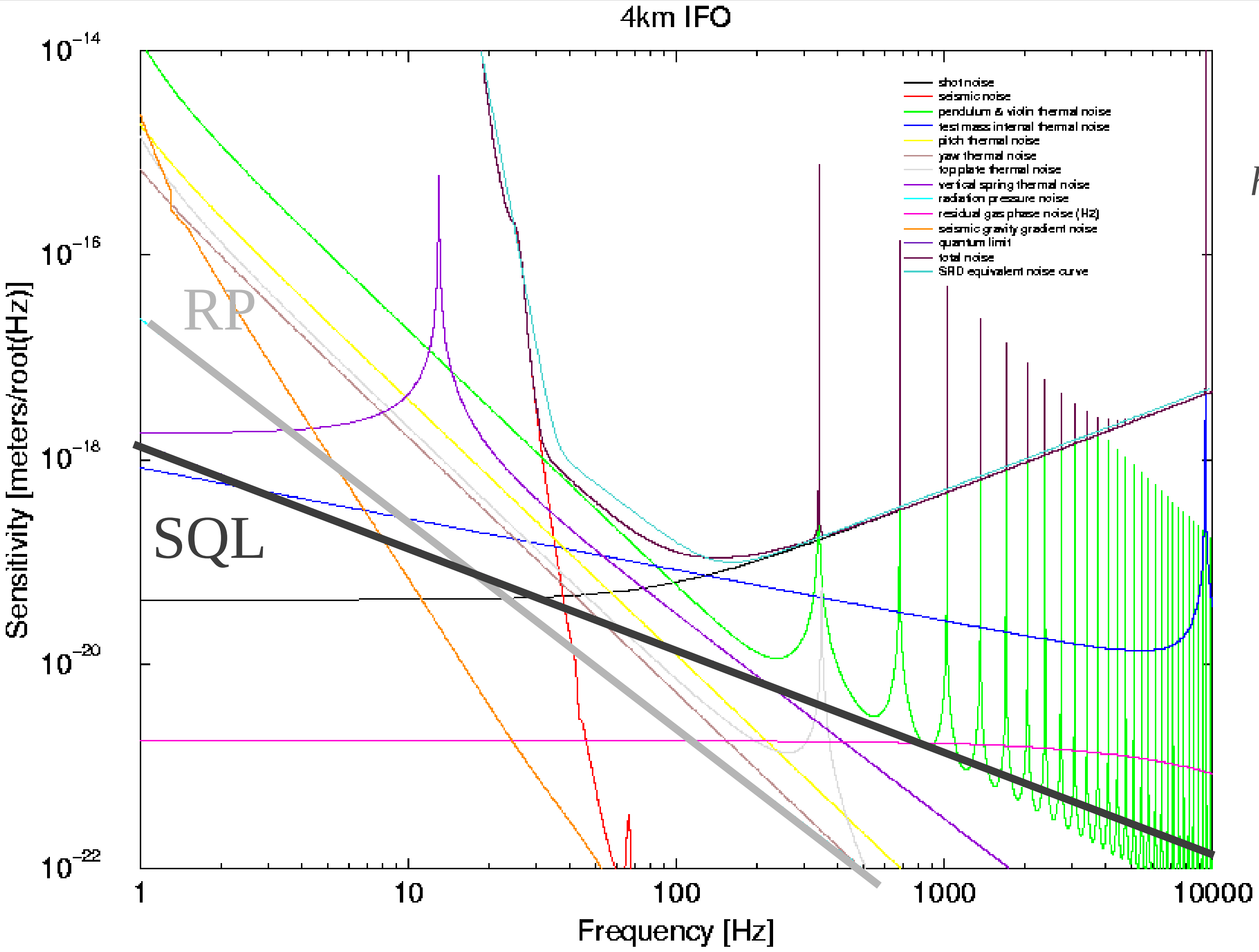
- **40 meter (Caltech)** :
  full engineering prototype for optical and control plant for LIGO II
- **Thermal Noise Interferometer (TNI, Caltech)** :
  measure thermal noise in LIGO II test masses
- **LIGO Advanced Systems Testbed IFO (LASTI, MIT)** :
  full-scale prototyping of LIGO II seismic isolation & 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



Optical readout noise



Optical readout noise:

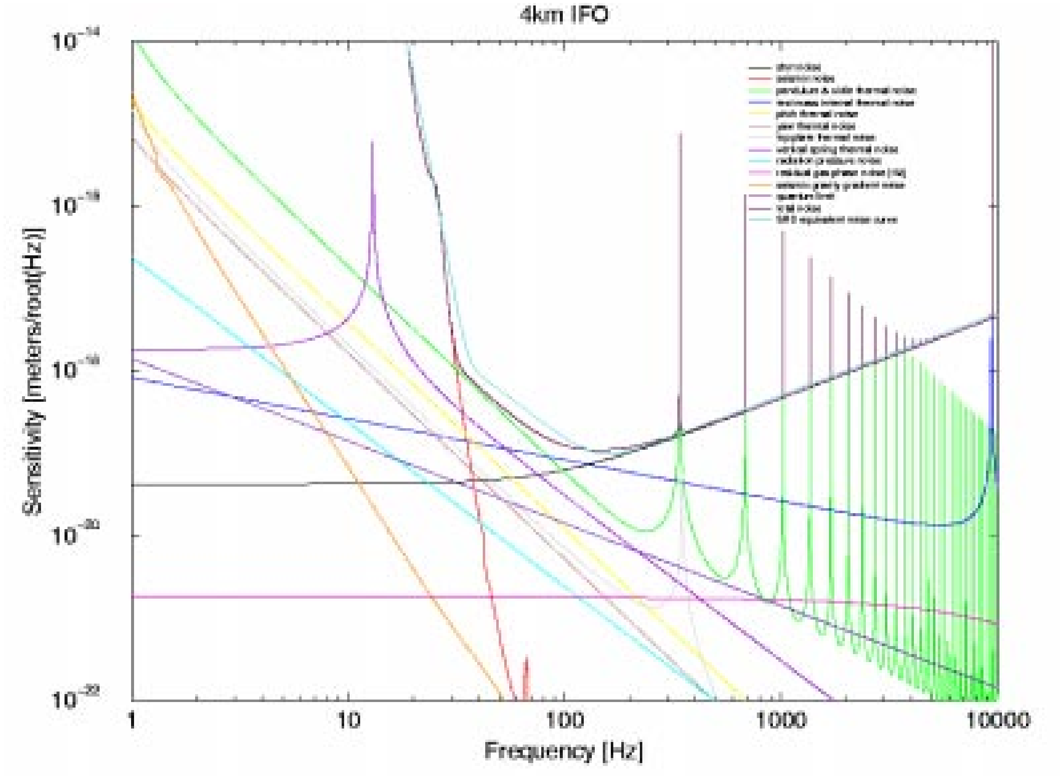
$$h_{ro}(f) = \sqrt{h_{shot}^2(f) + h_{rp}^2(f)}$$

Optimize h_{ro} wrt P_{laser} at each point in f; Locus of points is the Standard Quantum Limit, Obtainable from Heisenberg Uncertainty

$$h_{SQL} = \frac{1}{\pi f L}\sqrt{\frac{\hbar}{m}}$$

Thermal displacement noise

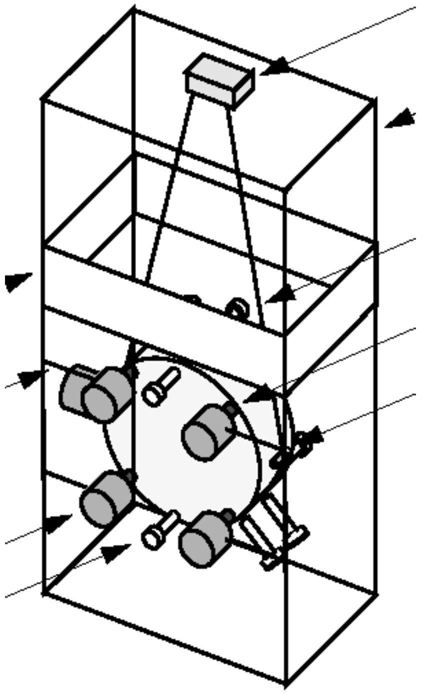
Sum of many normal modes, $x_{thermal}^{2} = \frac{4kT}{2\pi f}\sum_{n}\frac{\phi_n(f)}{m_n(2\pi f_n)^2}\left\{\frac{1}{\left(1-(f/f_n)^2\right)^2+\phi_n^{\,2}(f)}\right\}$
Each with loss $\phi_n(f)$:

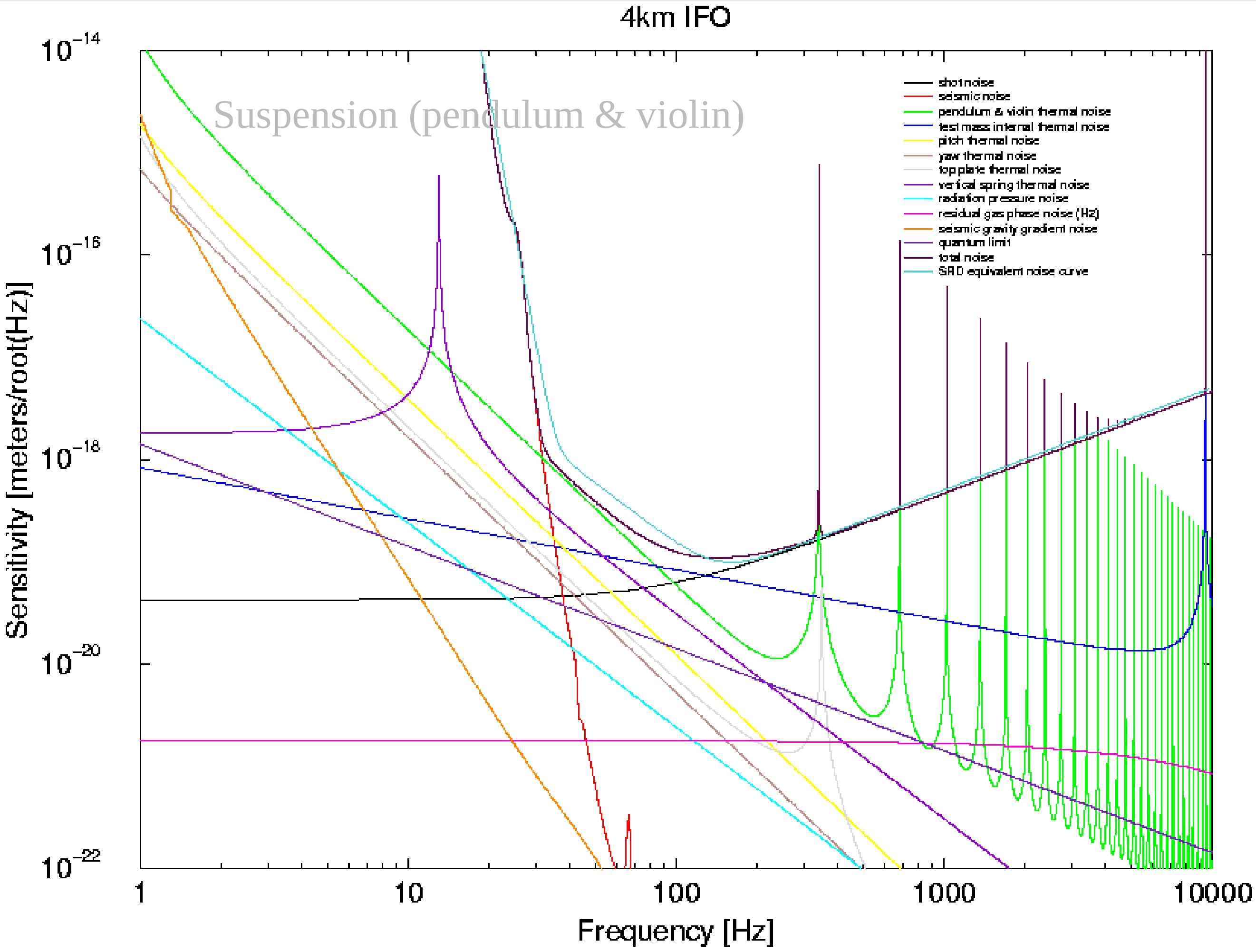


Equivalent strain (noise):

$$h_{thermal}(f) = \frac{2}{L}\sqrt{x_{thermal}^{2}}$$

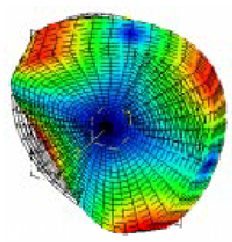
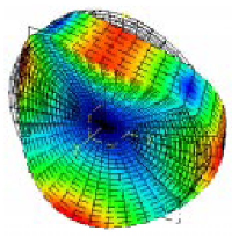
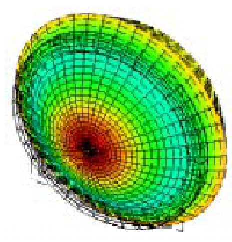
Suspension thermal noise

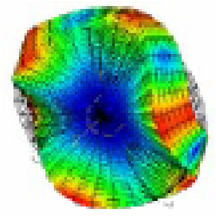
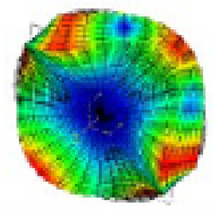
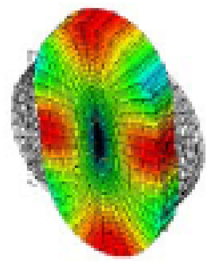


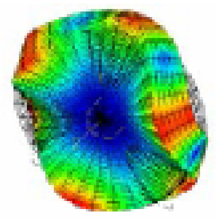
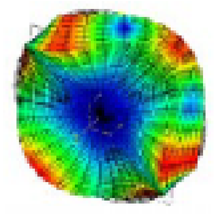
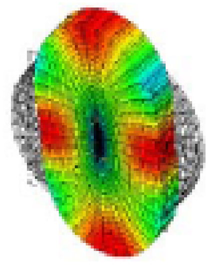


Suspension (pendulum & violin)

Vibrational modes of test masses

Mode Shape	*Frequency (Hz)*
	3785
	3785
	5578

Mode Shape	*Frequency (Hz)*
	7975
	7975
	11259

Mode Shape	*Frequency (Hz)*
	7975
	7975
	11259

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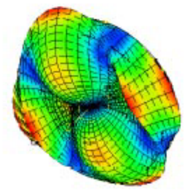
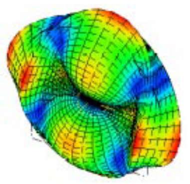
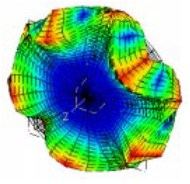
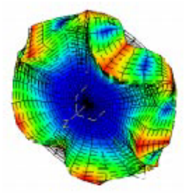
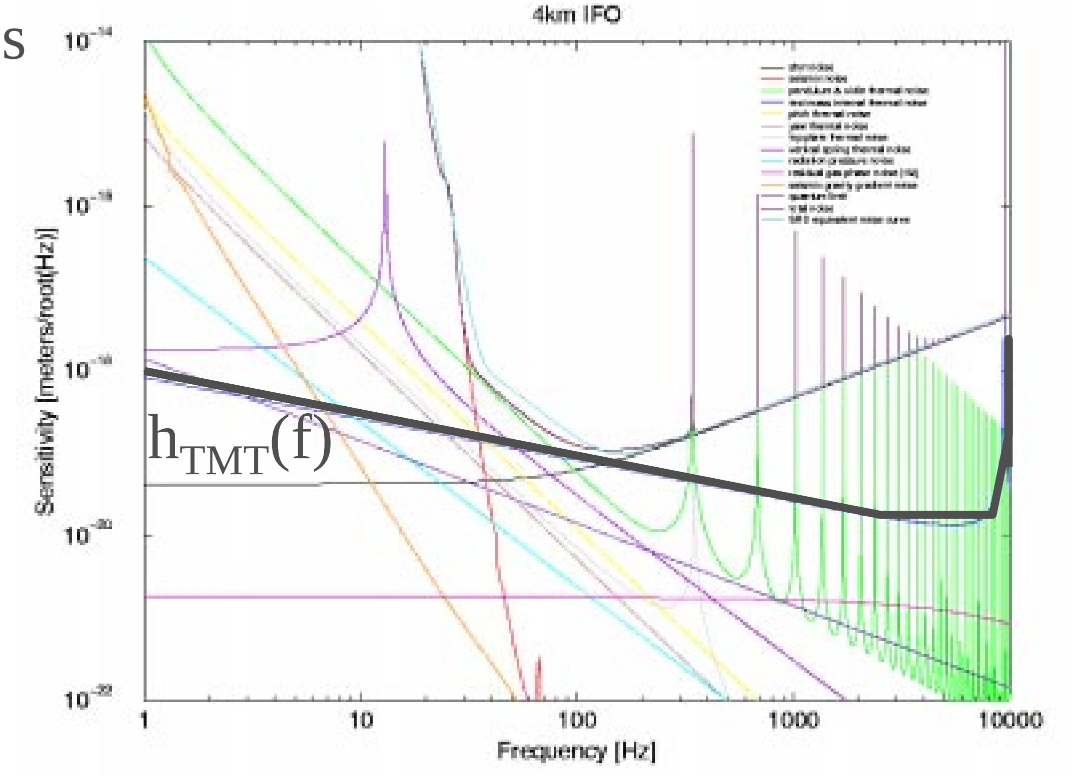
Mode Shape	*Frequency (Hz)*
	17388
	17388
	17958
	17958

This is for beam splitter. Test masses have no resonances below ~8KHz (?).

Test mass internal thermal noise

$$x_{TMT}^{2} = \frac{4kT}{2\pi f}\sum_{n}\frac{\phi_n(f)}{m_n(2\pi f_n)^2}\left\{\frac{1}{\left(1-(f/f_n)^2\right)^2+\phi_n{}^2(f)}\right\}$$

Test masses have normal modes
Above the LIGO band



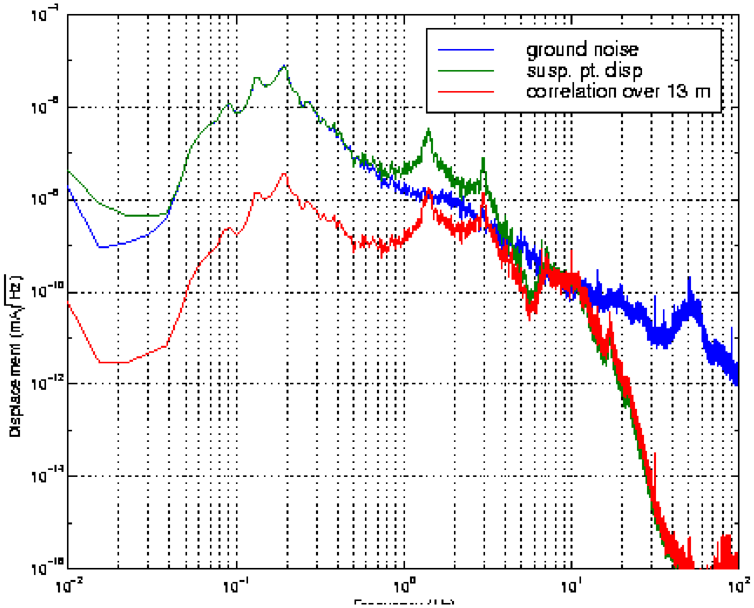
Equivalent strain:

$$h_{TMT}(f) = \frac{2}{L}\sqrt{x_{TMT}^{2}}$$

Seismic displacement noise

Motion of the earth

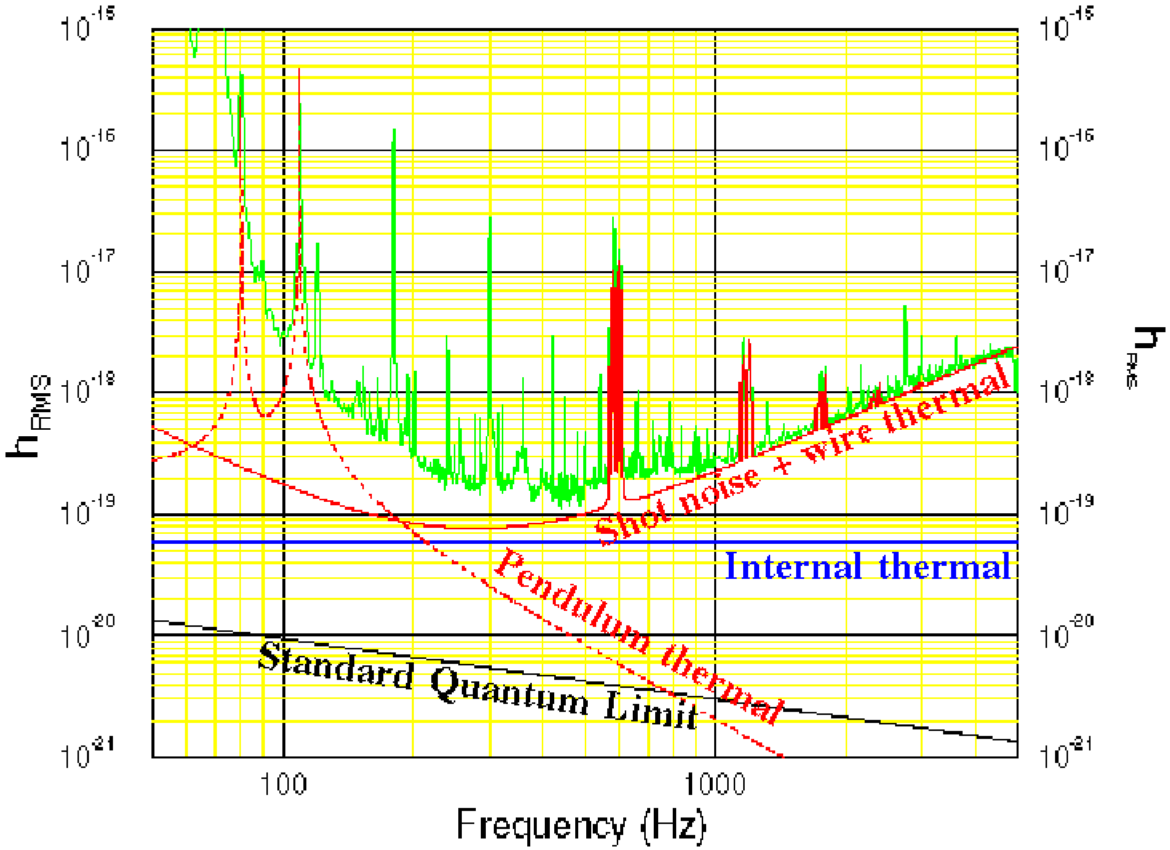
- driven by wind, volcanic/seismic activity, ocean tides, humans
- requires *e.g.*, roughly 10^9 attenuation at 100 Hz
- ~300 micron tidal motion, microseismic peak at 0.16 Hz.
- At low frequencies, motion is correlated over two mirrors



Approaches to limiting seismic noise

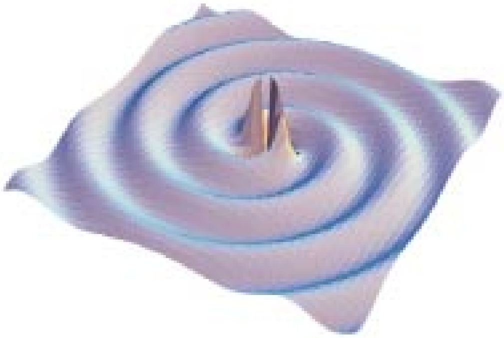
- careful site selection
    - far from ocean, significant human activity, seismic activity
- active control systems (only microseismic peak for now)
    - seismometers, regression, feedback to test masses
- simple damped harmonic oscillators in series
    - `stacks', constrained layer springs and SS masses
- one or more low-loss pendulums for final suspension
    - gives $1/f^2$ for each pendulum

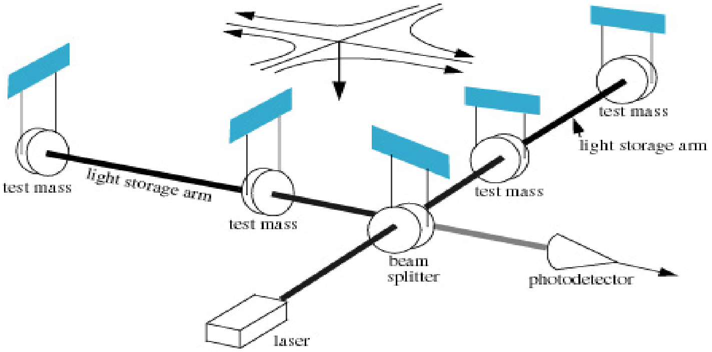
40 meter noise spectrum, 1994



LIGO Subsystems

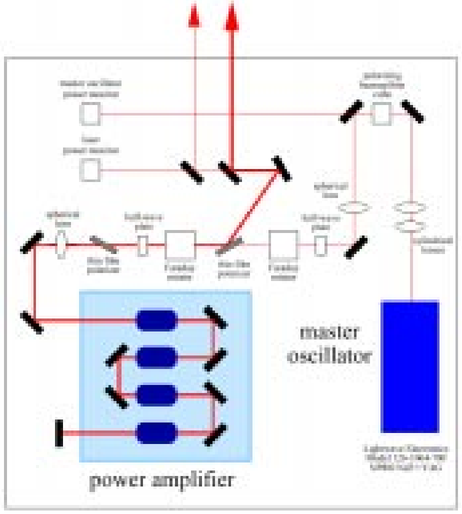
- PSL – Pre-Stabilized Laser
- IOO – Input Optics
- SUS – Suspension (mechanical and electronic)
- ISC – Interferometer sensing and control
- LSC – Length sensing and control
- ASC – Alignment sensing and control
- Oplev – Optical levers
- WFS – Wavefront sensors
- GDS – Global Diagnostic System
- PEM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



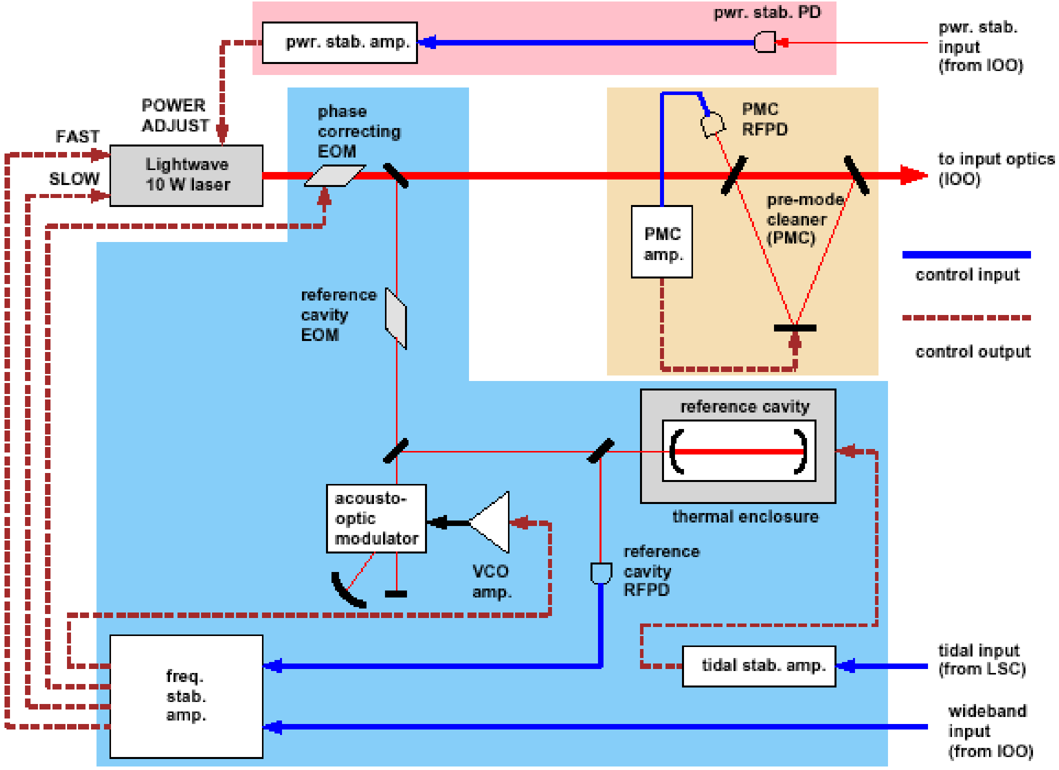


Pre-Stabilized Laser (PSL)

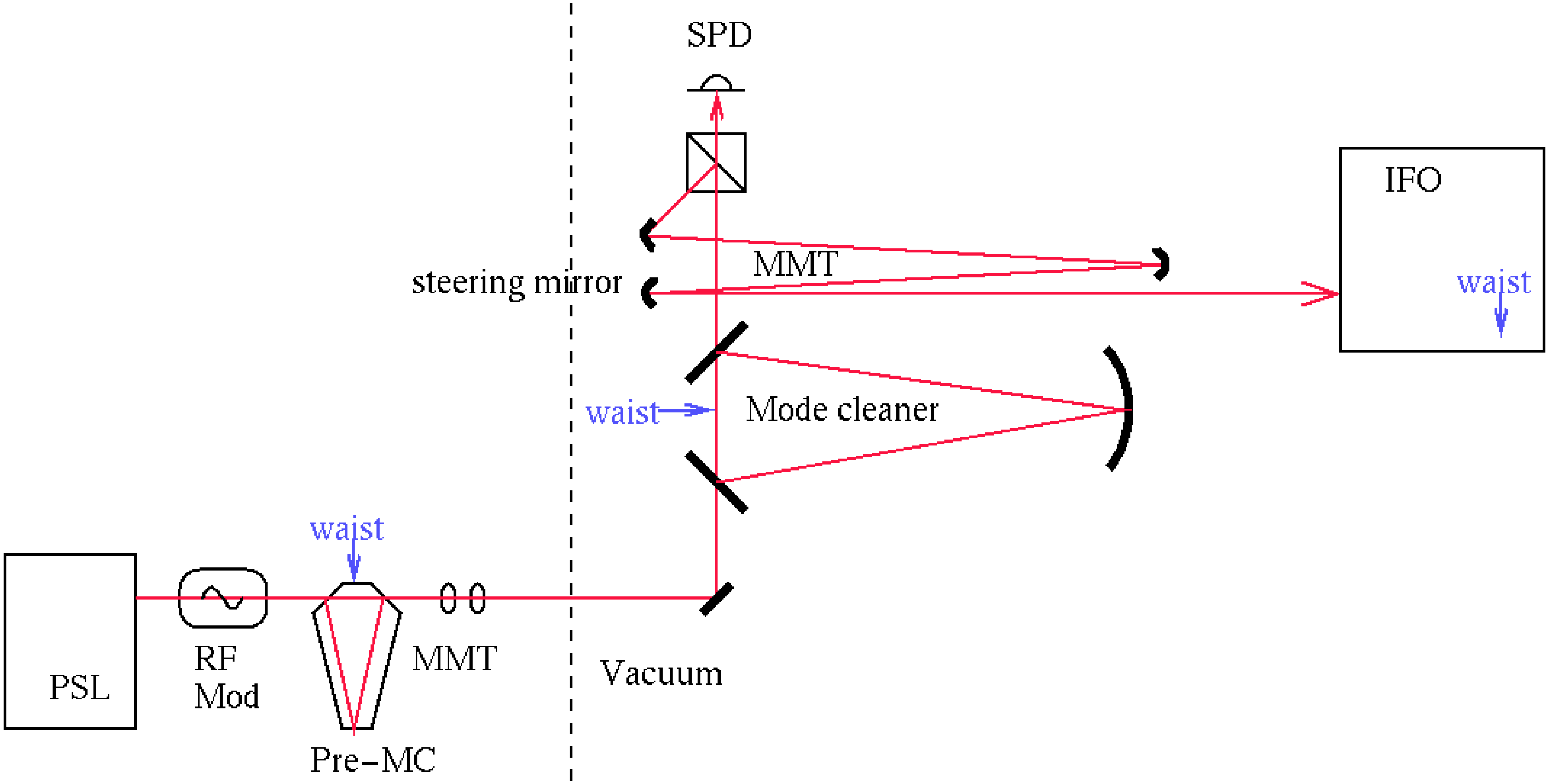
- Start with high-power (10watt) CW Nd:YAG IR laser ($\lambda = 1.064$ um) MOPA (Master Oscillator Power Amplifier)
- Frequency stabilization
    - (fast and slow)
- Power stabilization
- Transverse "mode cleaning"



LIGO-G000183-00-R

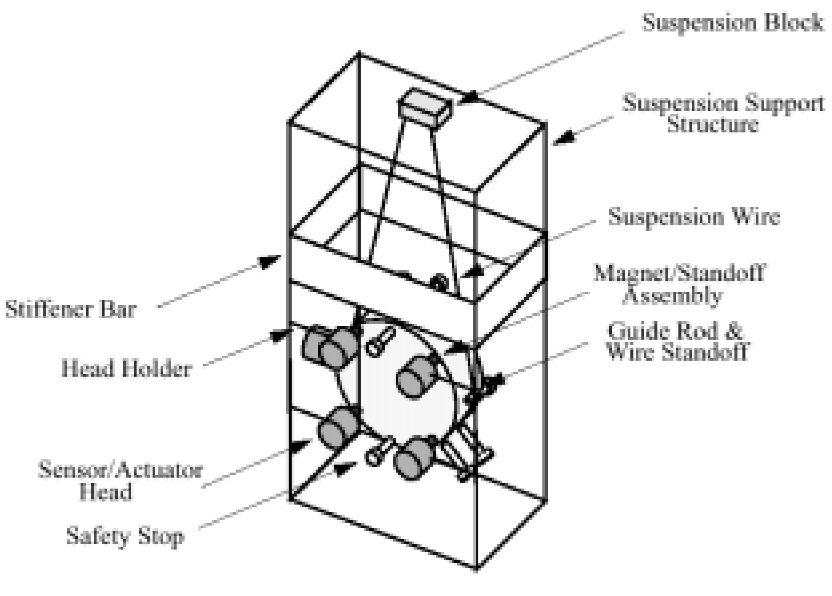


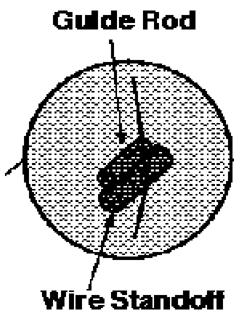
Input Optics (IOO)



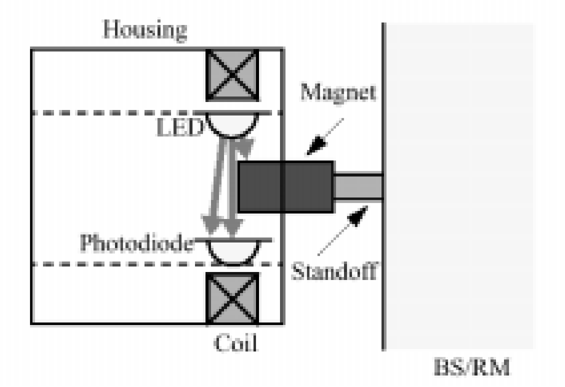
LIGO I Suspensions and OSEMs

- Rigid suspension frame
- EQ safety stops
- Steel piano wire
- wire standoffs to minimize dissipation to wires



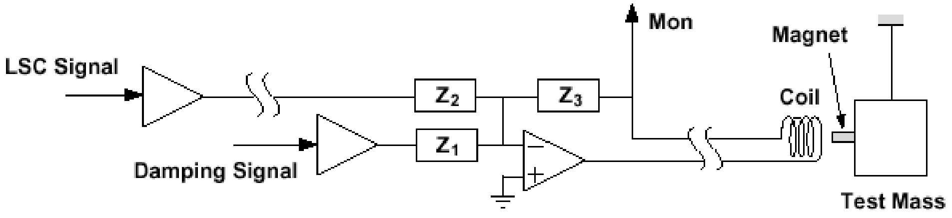


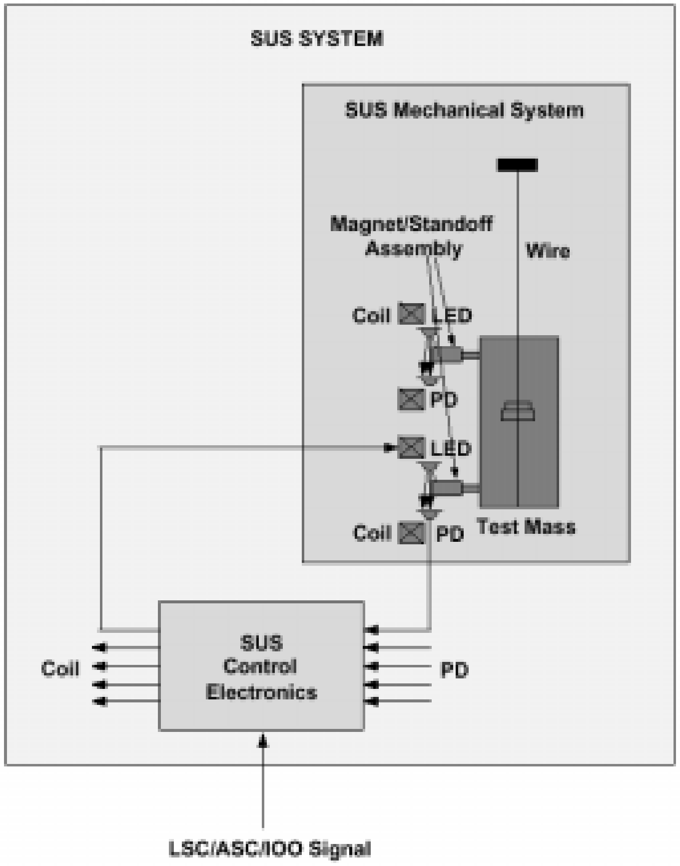
- OSEMs: Five magnets glued to fused Si optic for control of length, pitch, yaw, side rocking
- LED/PD pair senses position
- Coil pushes/pulls on magnet, against pendulum



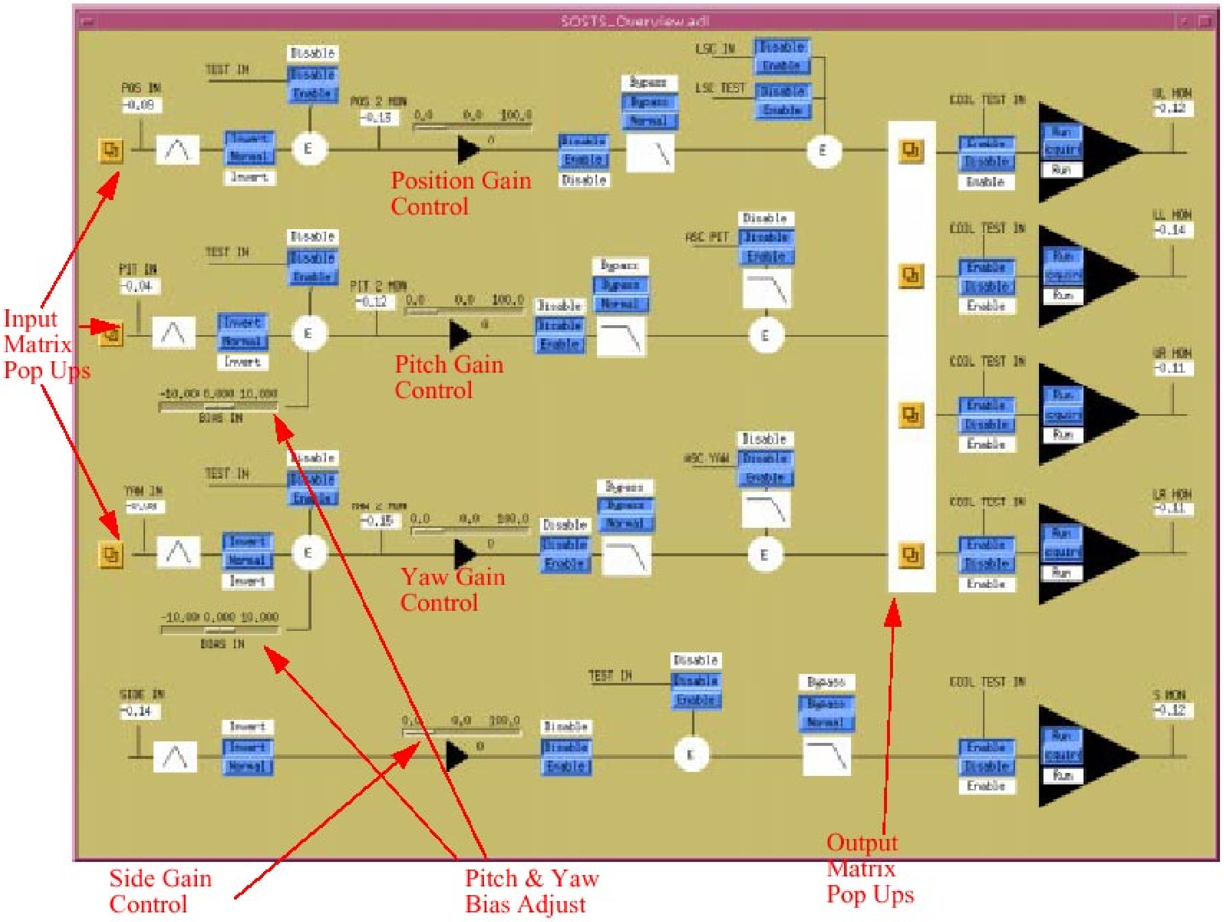
Suspension control system

- Each suspension controller handles one suspension (5 OSEMs)
- Local velocity damping
- Input from LSC and ASC to fix absolute position, pitch, yaw of mirror to keep cavity in resonance





Suspension controller EPICS screen



Position Gain Control

Pitch Gain Control

Yaw Gain Control

Input Matrix Pop Ups

Side Gain Control

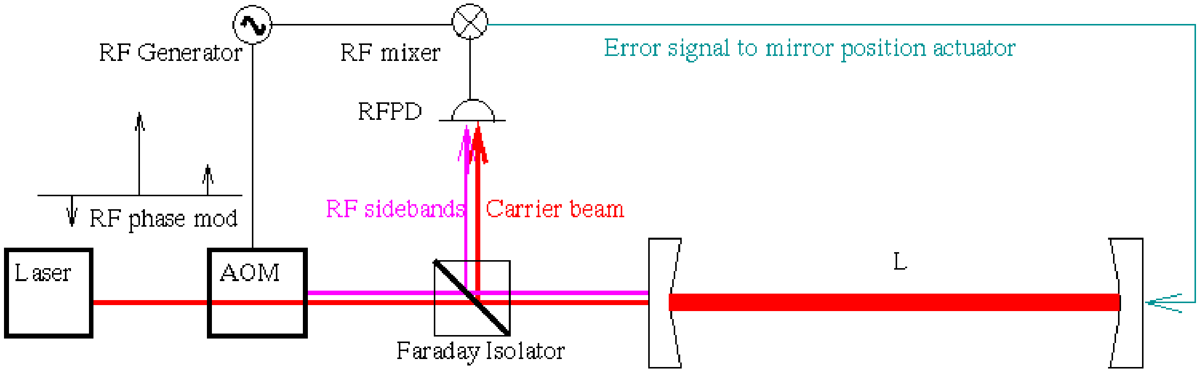
Pitch & Yaw Bias Adjust

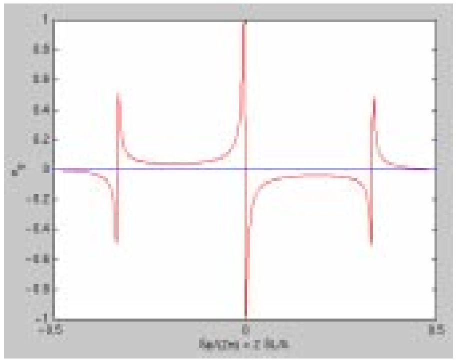
Output Matrix Pop Ups

Cavity control

Pound-Drever (reflection) locking used to control lengths of all the optical cavities in LIGO

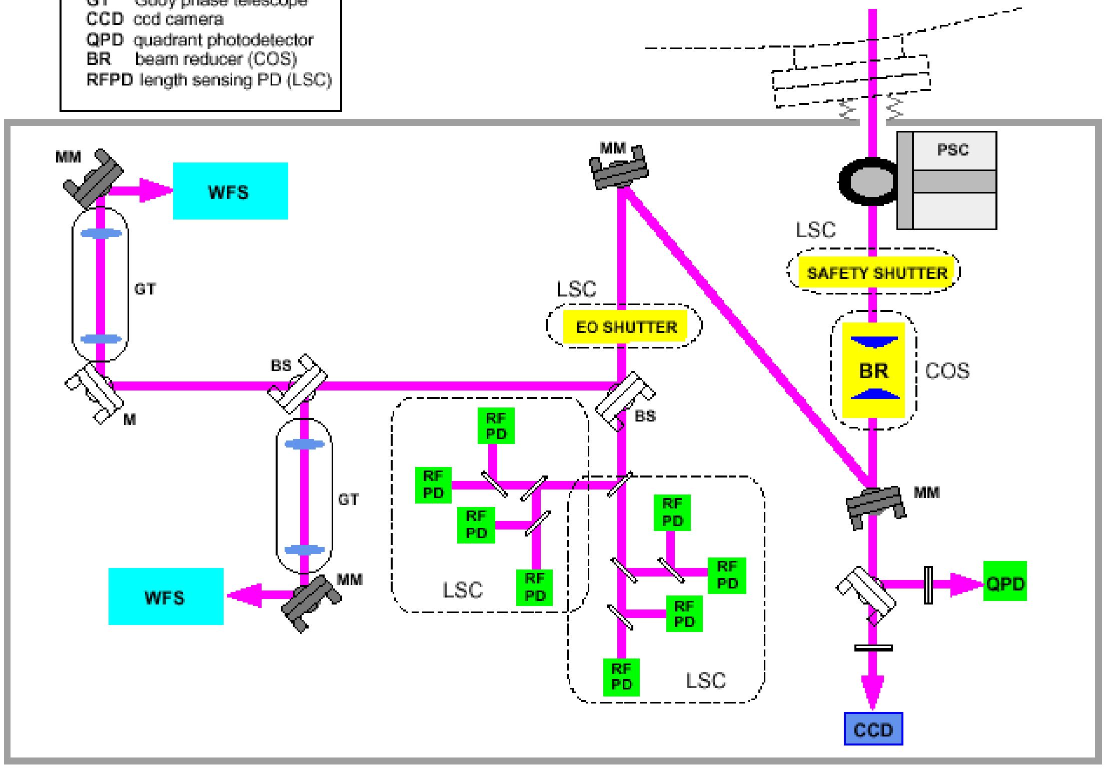
- Phase modulate incoming laser light, producing RF sidebands
- Carrier is resonant in cavity, sidebands are not
- Beats between carrier and sidebands provide error signal for cavity length

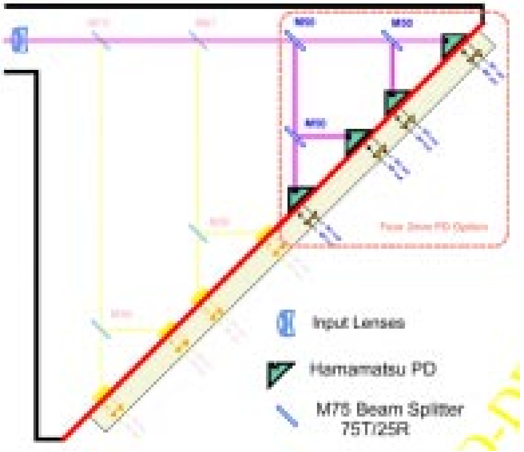




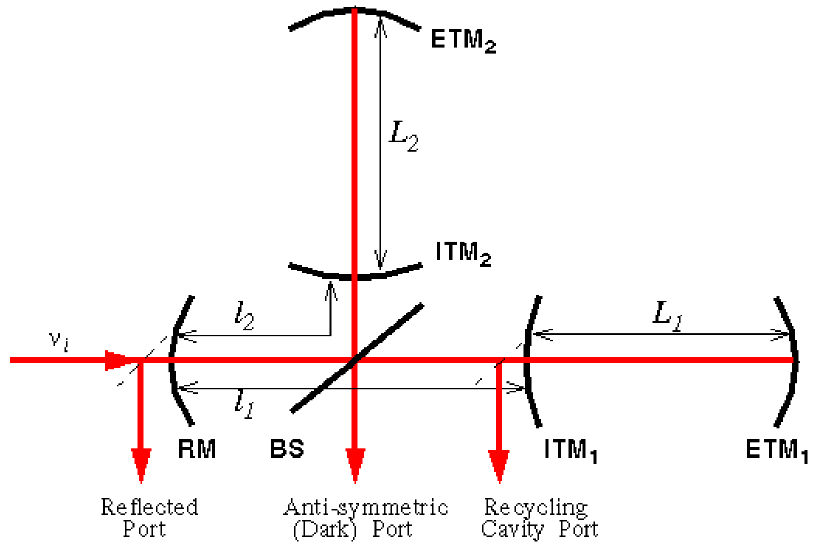
IFO sensing and control (ISC) optical table (one of 3!)

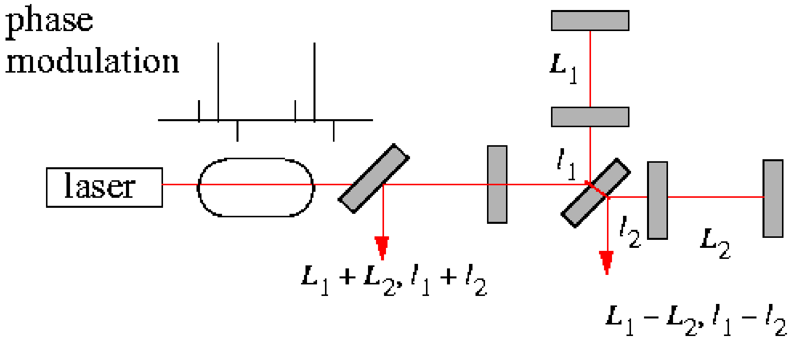
PSC	periscope
WFS	wavefront sensor
M	mirror
BS	beamsplitter
MM	motorized mirror
GT	Guoy phase telescope
CCD	ccd camera
QPD	quadrant photodetector
BR	beam reducer (COS)
RFPD	length sensing PD (LSC)

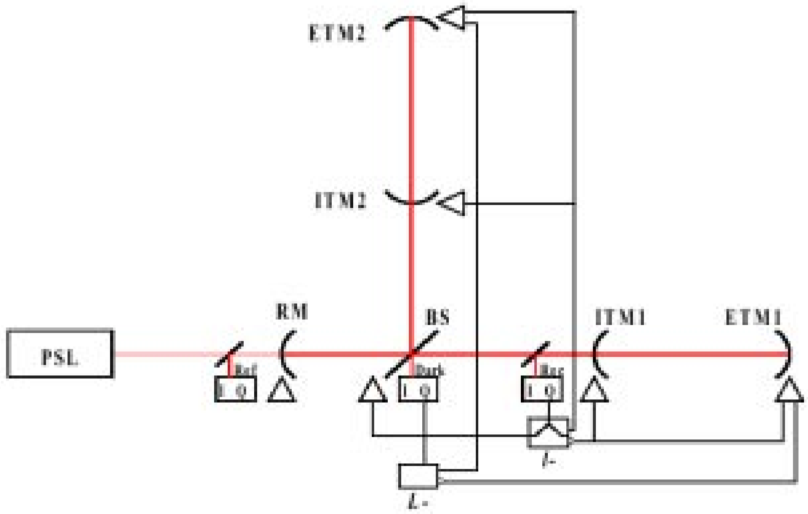




LIGO length sensing and control



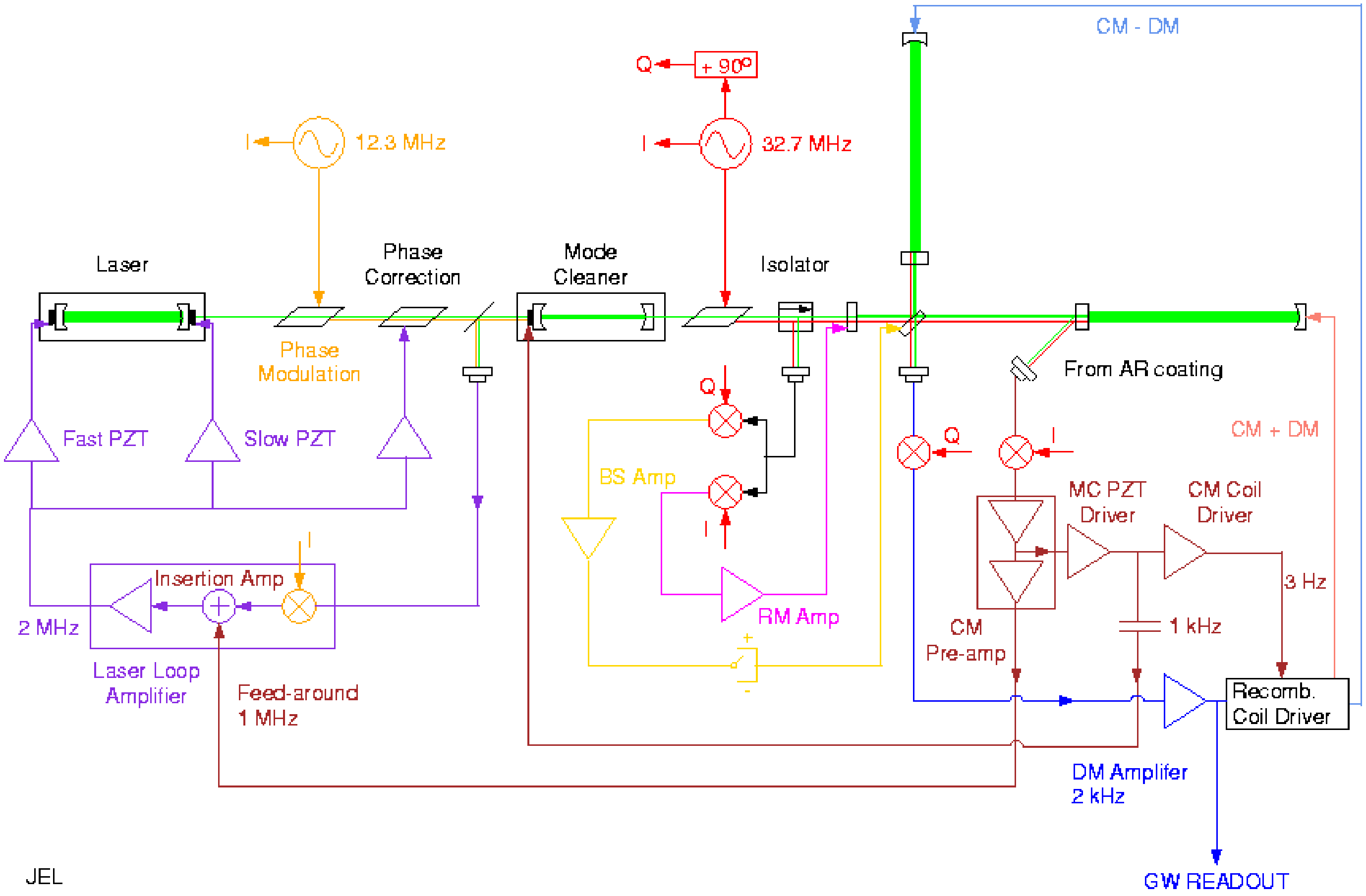




- **Four interferometer lengths ⇒ four sensors/actuators**
- **Ten mirror angles ⇒ ten sensors/actuators**

Length Control system topology

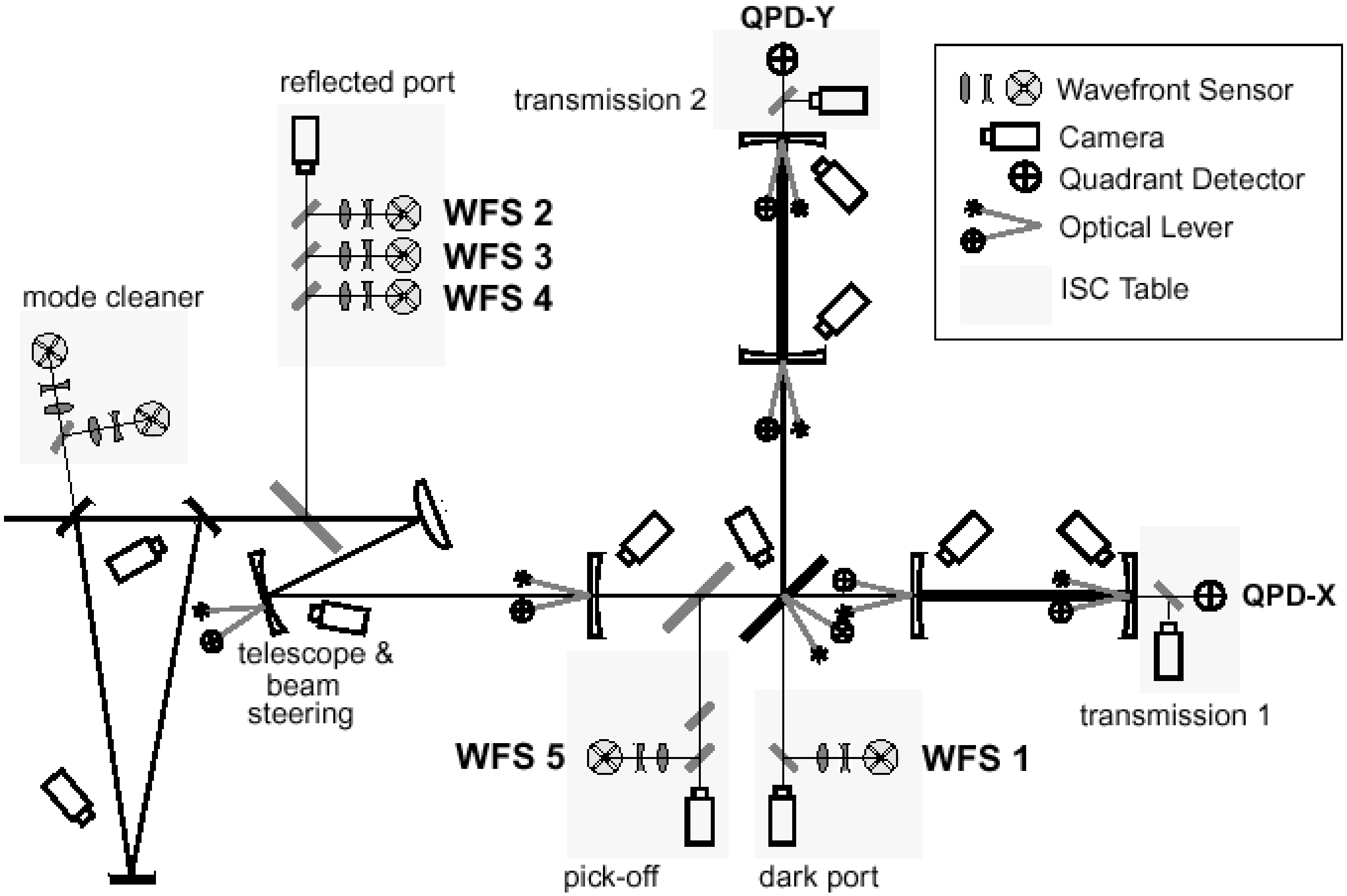
POWER RECYCLING TOPOLOGY



JEL

LIGO-G000183-00-R

Alignment Sensing and Control (ASC)

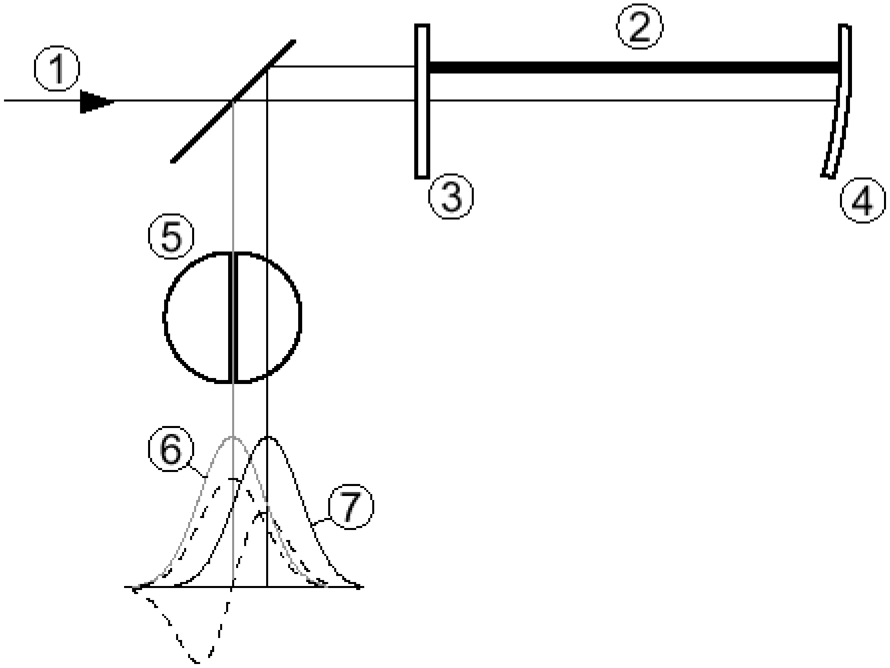


Wavefront sensing (WFS)

- Sense transverse beam profile in cavity;

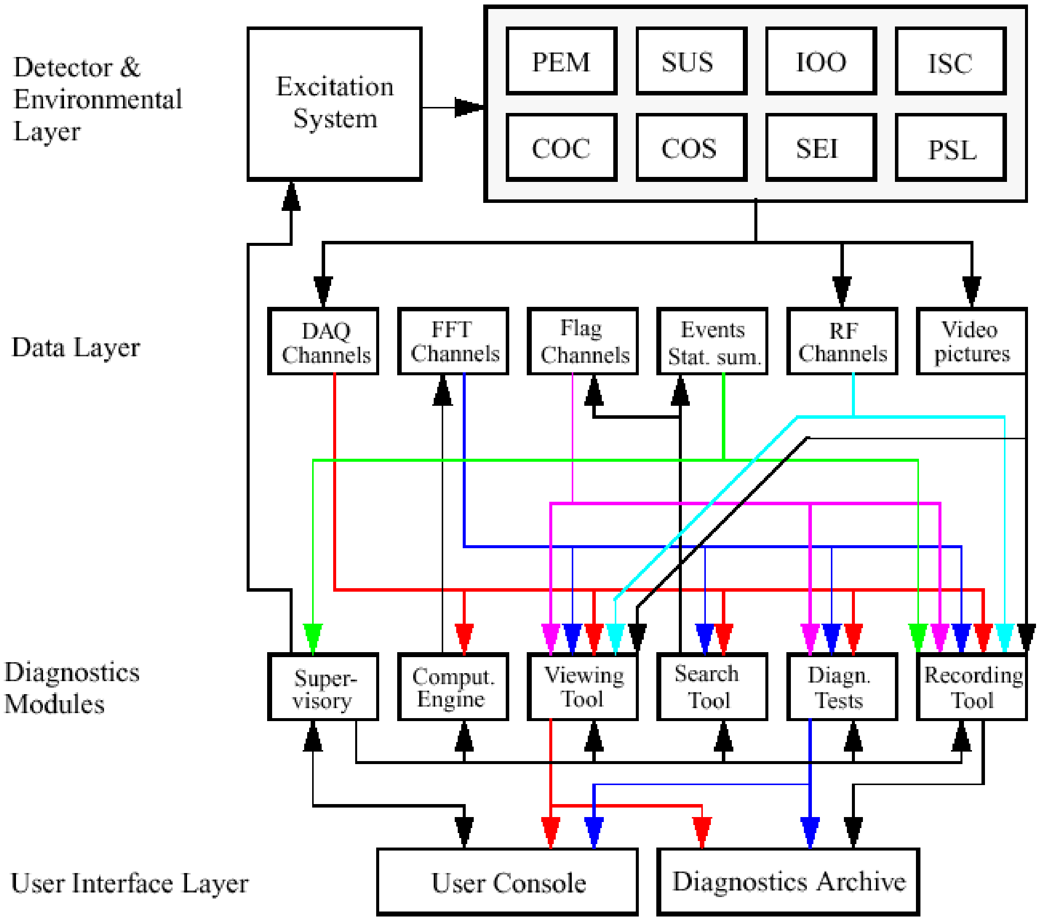
  presence of higher-order

  Hermite-Gaussian (TEM_{01}, TEM_{10}) transverse profiles
- Distinguish misalignment of multiple mirrors at only a few output ports, by use of *Guoy phase telescopes*



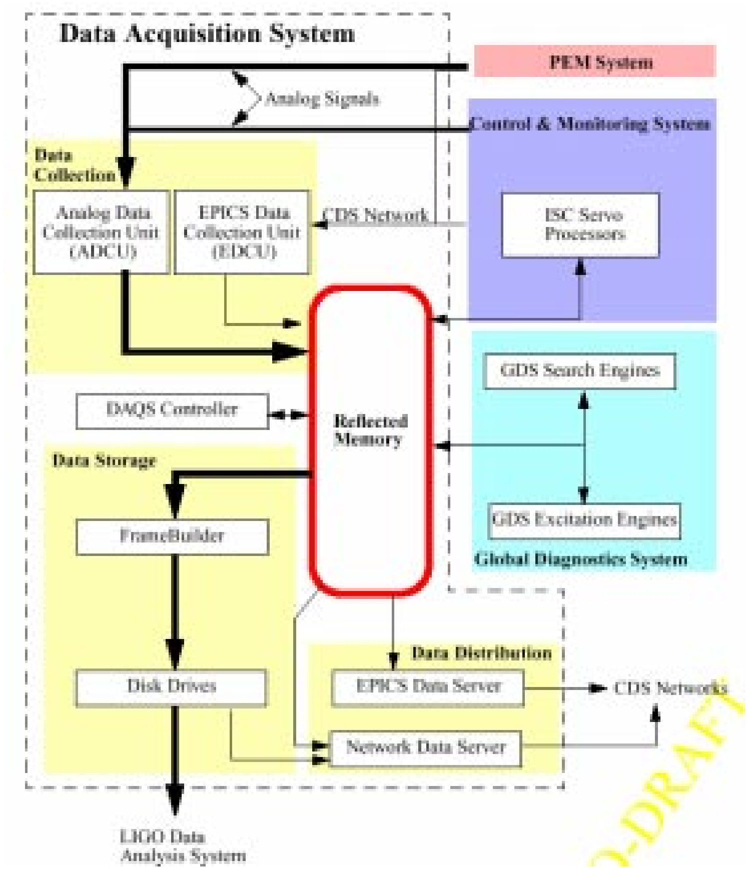
Global Diagnostics System (GDS)

- Swept-sine transfer functions with excitation engine
- Lock acquisition, status and monitoring
- environmental monitoring
- correlating IFO signals
- identifying transients (bumps in the night)
- triggers, alarms
- maintain detector meta-database



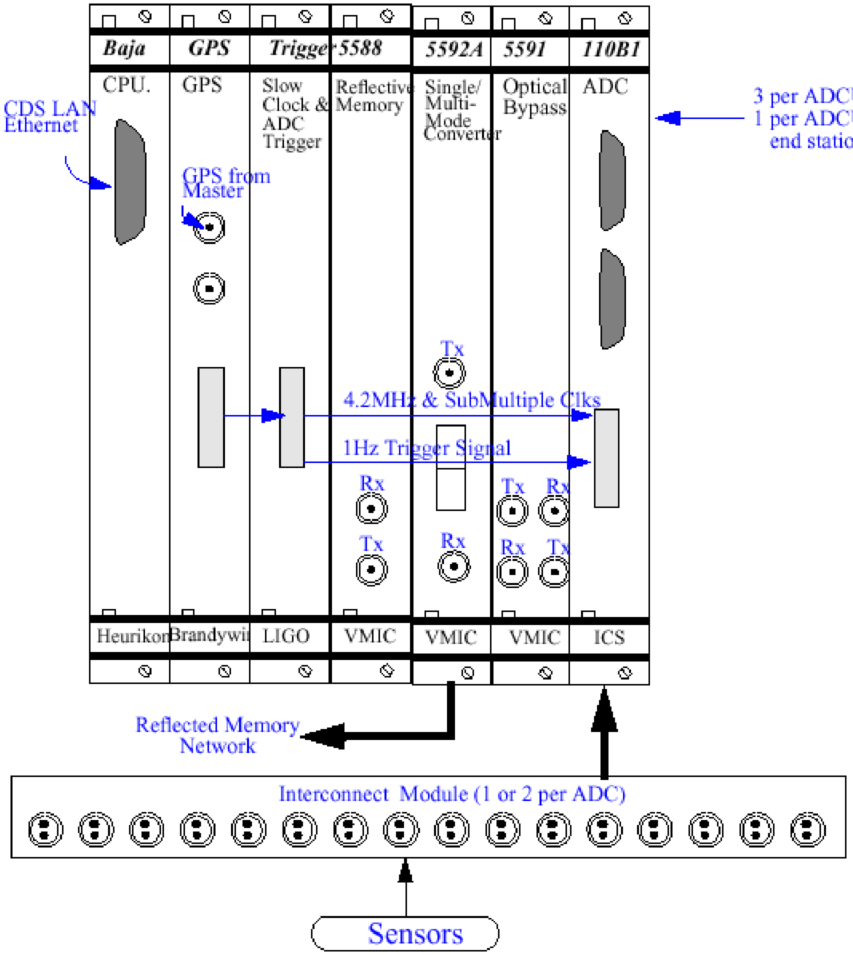
DAQS overview

- Inputs: Analog signals from sensors, to actuators; digital signals from control systems (LSC, ASC, etc)
- Signals needed for LSC, ASC, etc, get digitized in a separate path.
- All information stored in reflective memory, visible to all the cpus in the system that need it.
- I/O to GDS
- Output to frame builder, thence to RAID disk array
- Monitored and controlled via EPICS screens

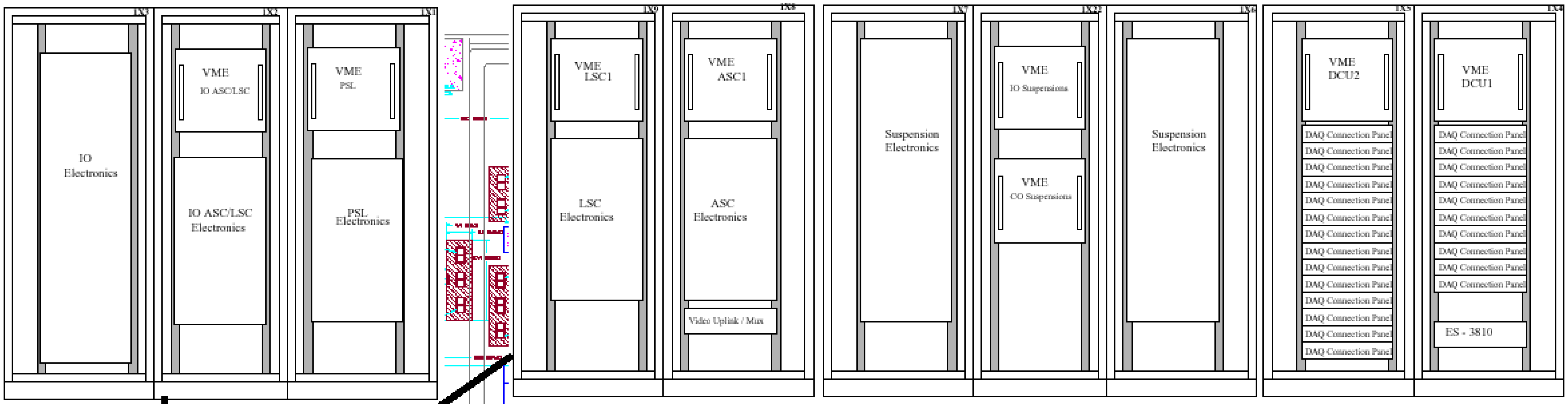


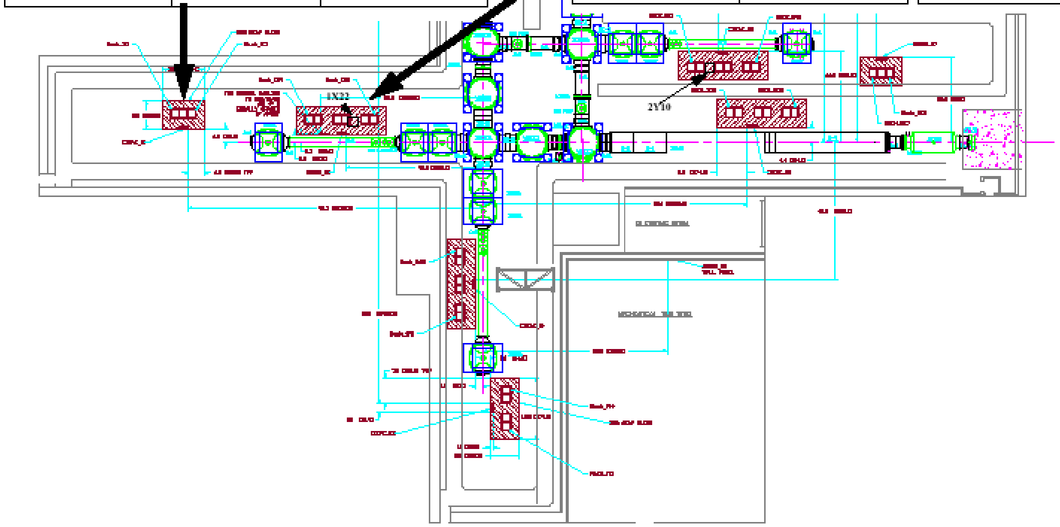
Analog Data Collection Unit (ADCU)

- Fast CPU
- ADC (up to 16 bit, 16 kHz, 32 ch)
- GPS receiver for ADC trigger
- Reflective memory



Racks and racks of electronics





Notes:

1) This drawing is intended solely to depict rack locations and subsystem assignments. For detailed rack equipment layouts, see appropriate CDS subsystem drawings.
2) Additional racks have been added to this drawing which are not yet reflected in Chamber and Rack Designations (D960073-00-E). These are:
  - Rack 1X22, between 1X7 and 1X8.
  - Rack 2X10, between 2X2 and 2X3.