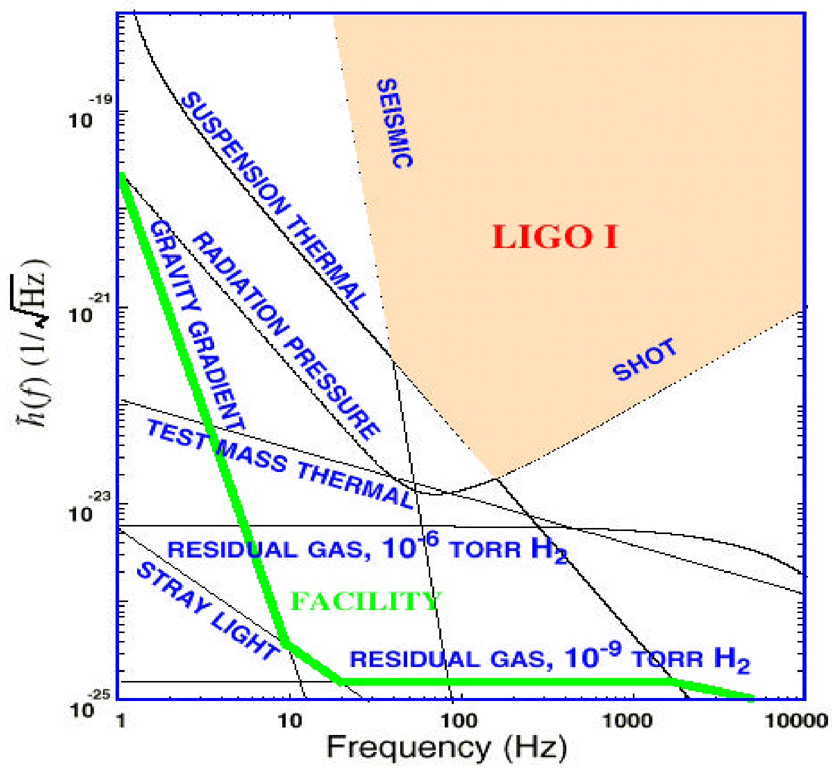
Physics of LIGO
Lecture 2

Last week:

- LIGO project
- GW physics, astrophysical sources
- Principles of GW IFO's

This week:

- Engineering and Science runs
- Noise in GW IFOs
- Focus on thermal noise



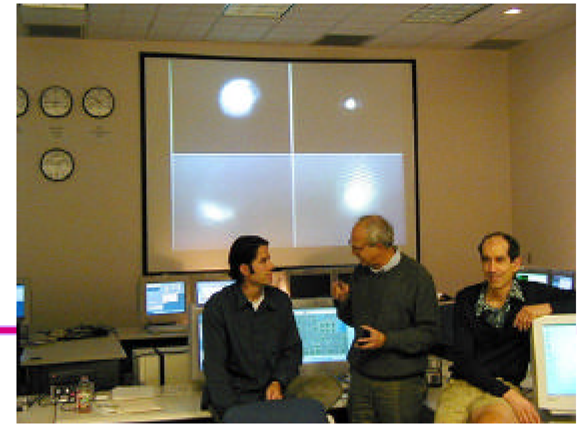
Next week:

- Optics
- Control systems
- Advanced LIGO
- Data analysis

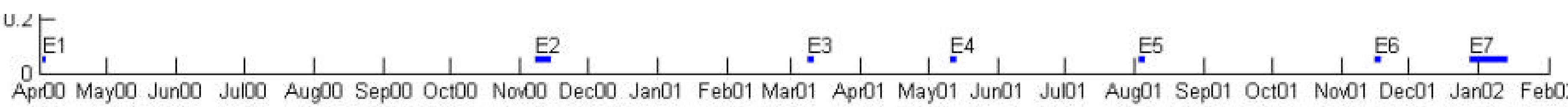
LIGO I schedule

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

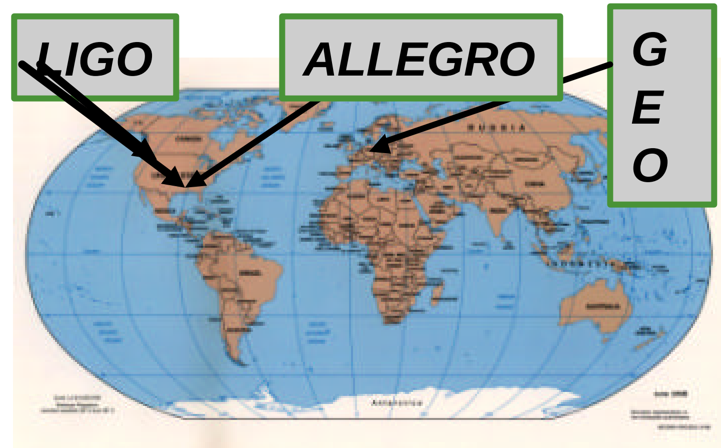


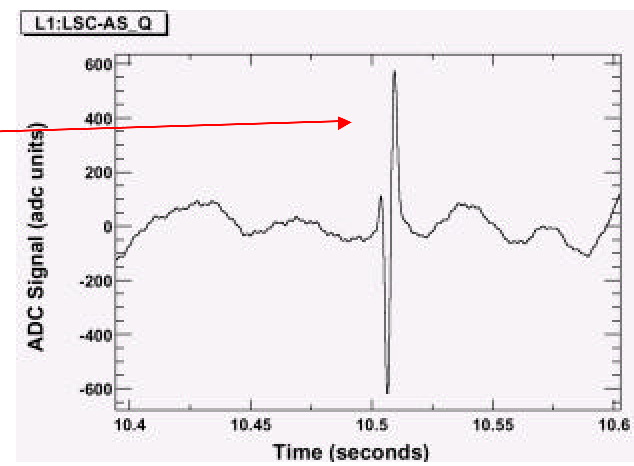
- Commissioning GW IFO's is a very tricky business!
  - » They are complex, non-linear, non-reductionistic systems
  - » There's precious little experience…
- First task is to get the IFO's to operate in the correct configuration, with all optical cavities resonating – "In Lock"
- Next task is to reduce 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

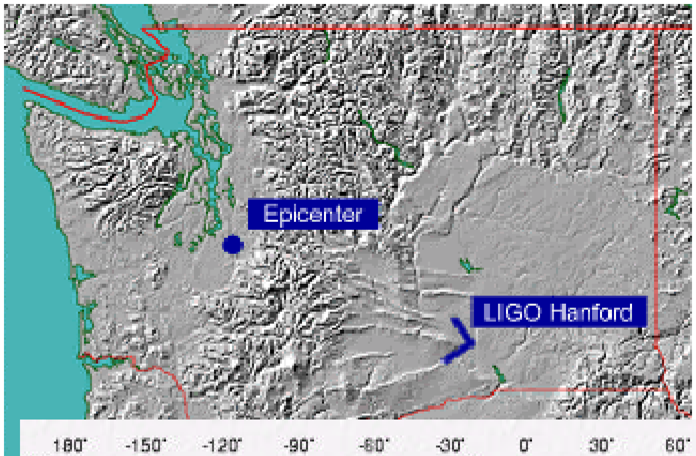
- Computer crashes
- Earthquakes
- No fire or floods yet…
- Logging at Livingston
- Cars driving over cattle guards
- Wind at Hanford
- Snow in Louisiana

6 hrs

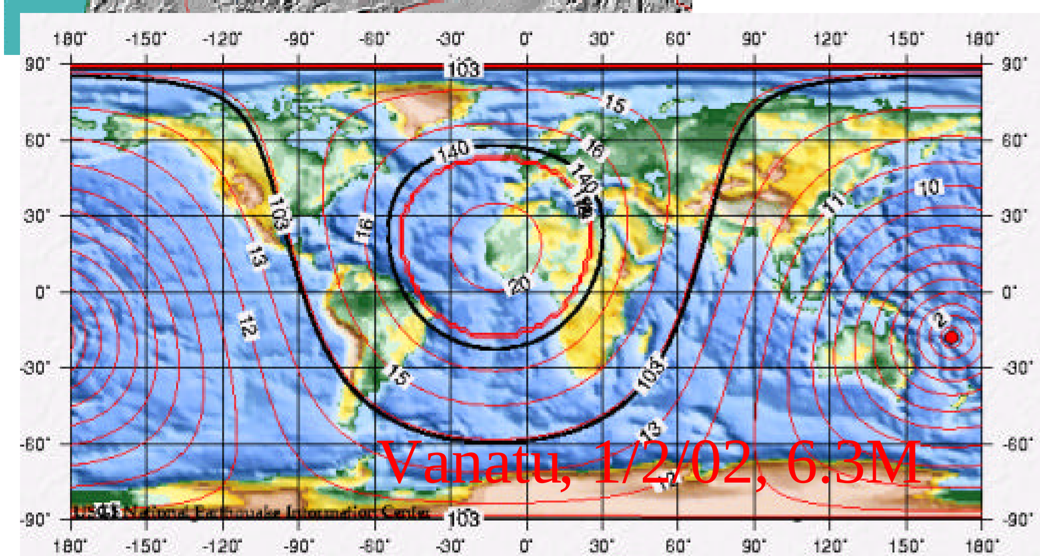
Logging at Livingston

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…

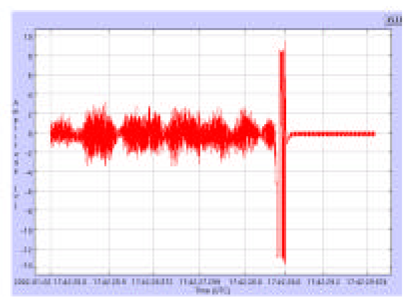


This one, on
February 28, 2000
knocked out the H2K
For months…



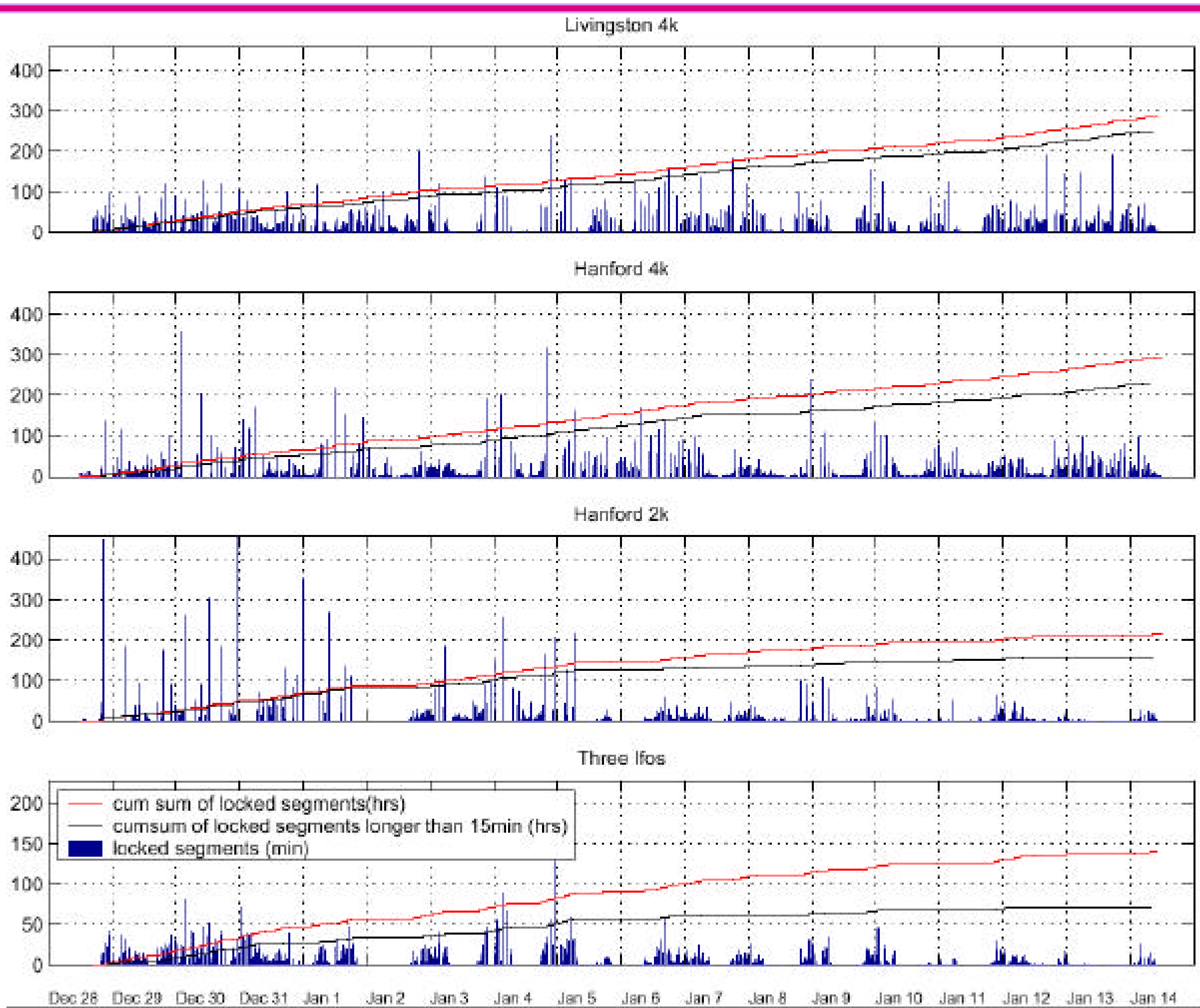
Vanatu, 1/2/02, 6.3M

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 %

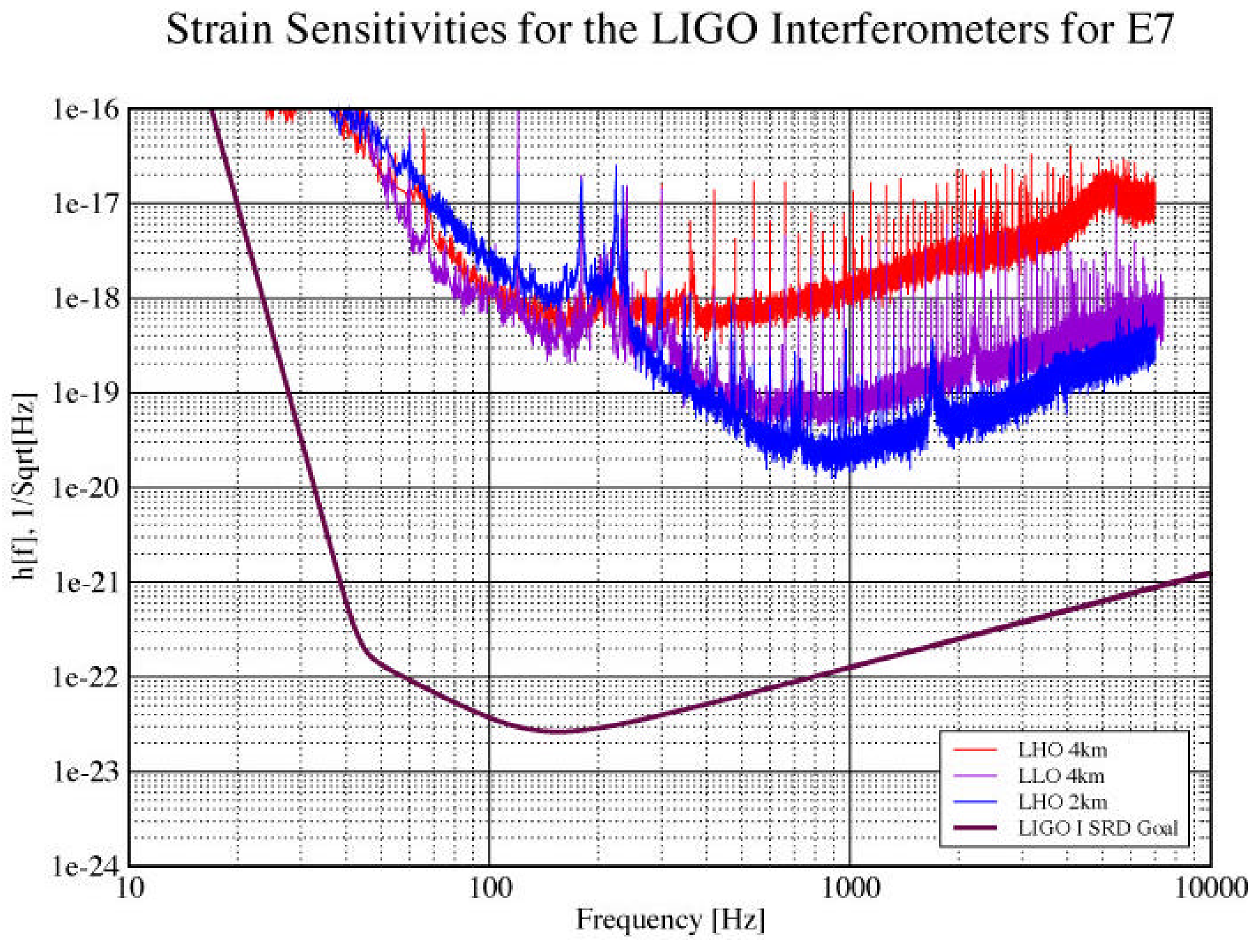
We are thrilled!!

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…)

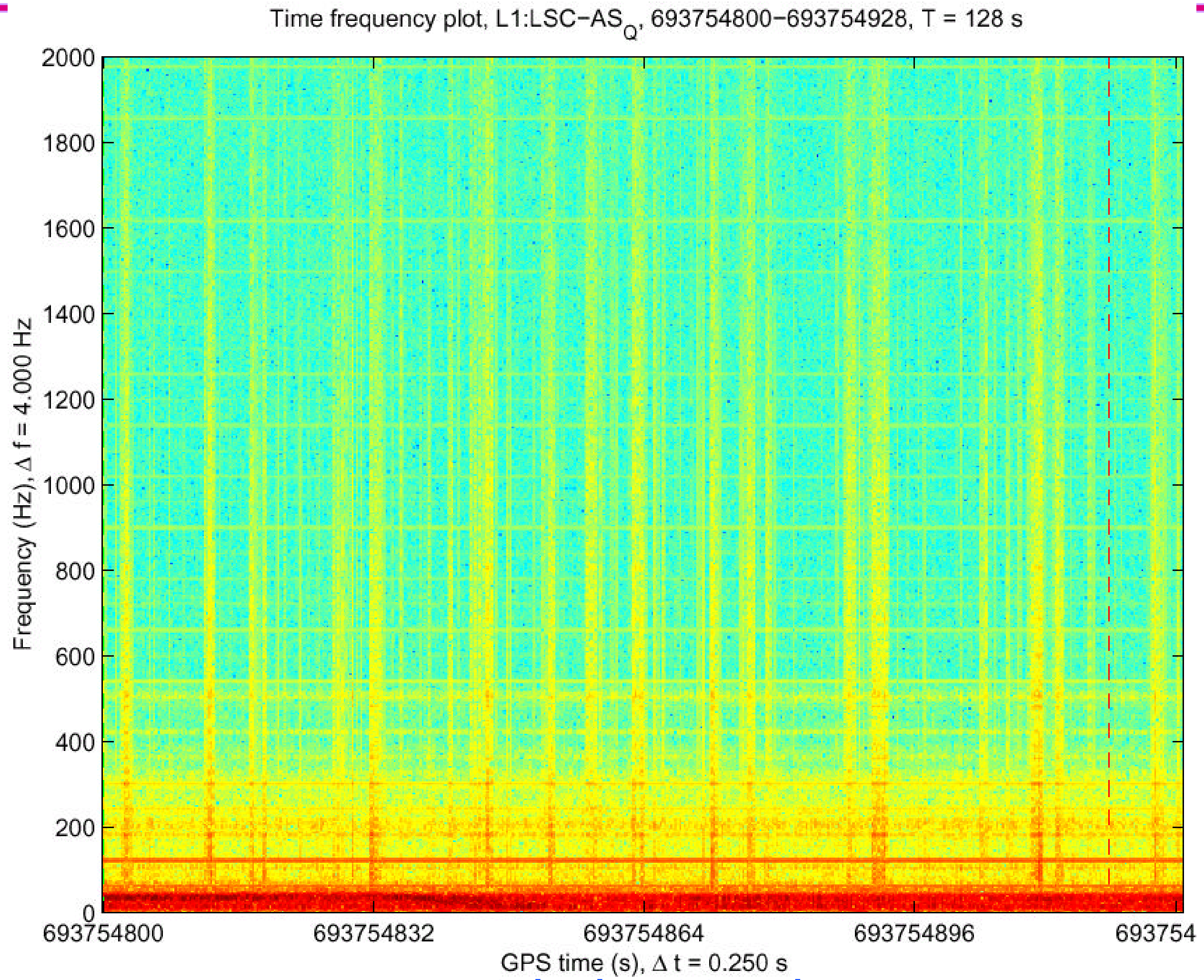


Contributions:

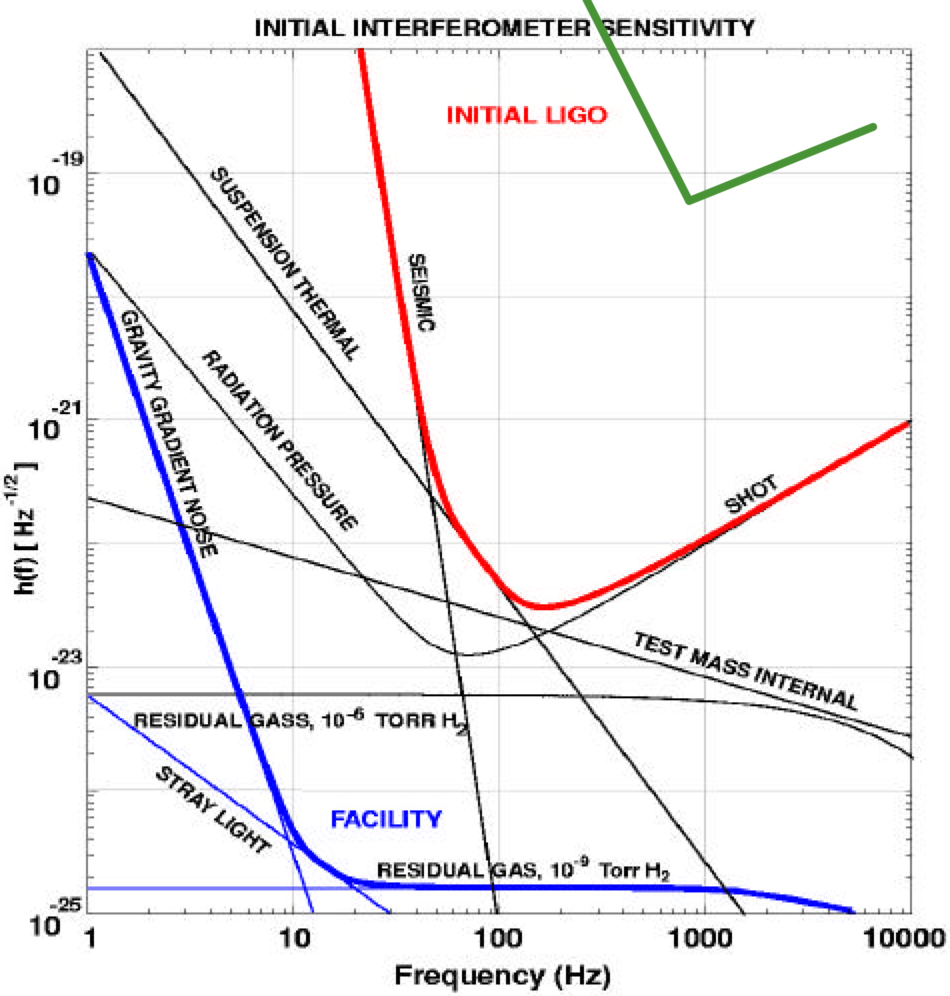
- PSL frequency noise (need common mode servo on all IFOs)
- Misalignments (reduce noise in oplevs; tuning of alignments servos needed)
- Laser glitches & bursts (reduce acoustic coupling into PSL)
- Periscope vibrations on PSL table (~200 Hz)
- Photodetector preamp Johnson noise (high-f)
- Excess noise 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?



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

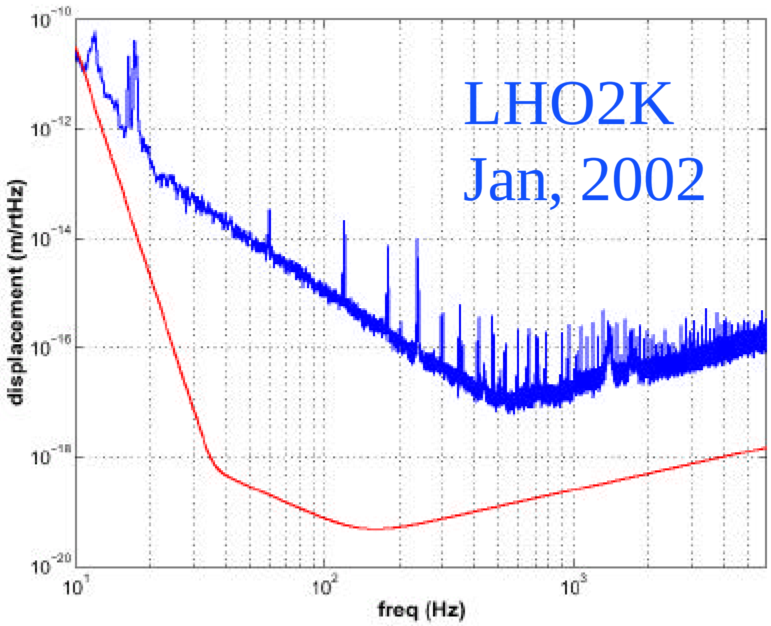
- Coincident operation of 3 LIGO detectors, GEO, ALLEGRO is unprecedented.
- Duty cycle has greatly exceeded our expectations.
- We are operating in a new regime of sensitivity and bandwidth; will be able to set new experimental limits.
- Coincidence with ALLEGRO will permit a limit for a stochastic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

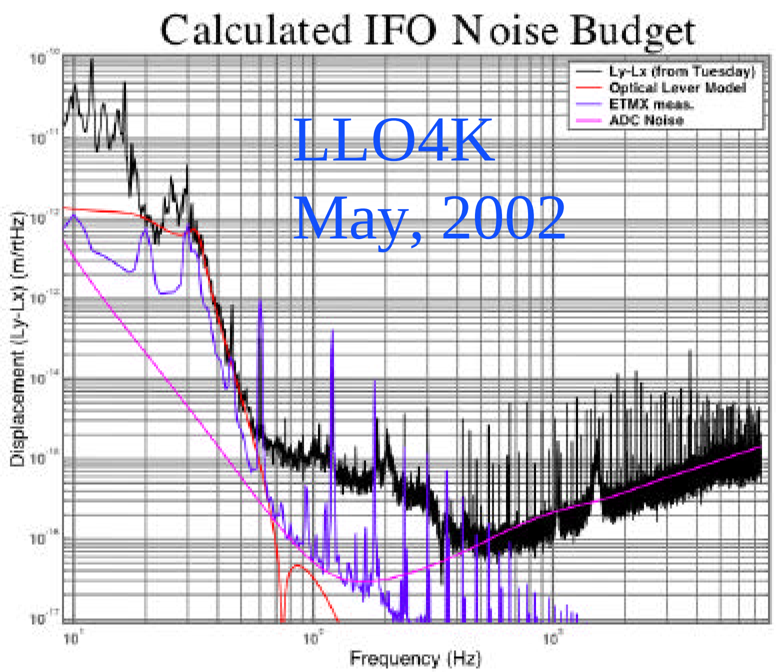
- MANY lessons learned and needs being addressed.
- Work on improving sensitivity has now recommenced.
- Already major improvements have been made!
  - » new and/or tuned servos; better laser isolation; higher laser power; better alignment and mis-alignment sensing; seismic pre-isolation upgrade; …
- 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

NOISE in GW detectors

- After ~ 40 years of effort, no one has detected a GW!
- Why? Noise levels in detectors exceed expected signal; *insufficient sensitivity*
- Want to detect GW strain *h*; can express detector noise in terms of equivalent *h* sensitivity
- Most of the effort in GW detection has gone into *understanding and reducing noise* to the fundamental quantum limit (and beyond!)
- We are the beneficiaries of that pioneering and frustrating work: on the threshold of doing what sounds almost impossibly hard!

NOISE SOURCES IN THE DETECTOR

- Noise ⇒ signals which appear in detector as GWs but are imposters
- Three categories:
- Displacement noise ⇒ moves mirrors (path length changes)

  $\delta x = L\ \delta h$, so to achieve h ≈ 10^{-21}/Ö *Hz* with L = 4km,

  ⇒ $\delta x \approx 10^{-18}$ *m/Ö Hz*

  (*cf*: diameter of proton is 10^{-15} m)

- Phase noise ⇒ changes the phase of the light:

  $\delta\phi = 4\pi\ NL\ \delta h / \lambda$, with $N \approx 100$ and $\lambda \approx 1.064\ \mu m$,

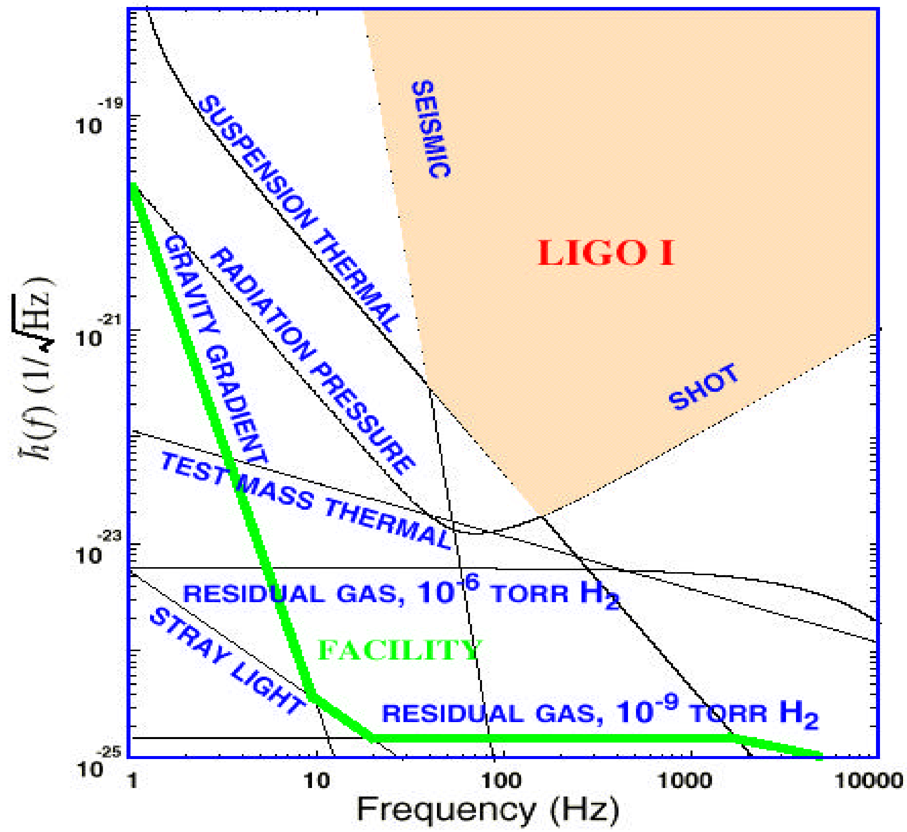
  ⇒ $\delta\varphi \approx 10^{-10}$ *rad/Ö Hz*

- Technical or instrumental noise (electronics, EMF pickup, *etc*)

  must engineer IFO to keep this *below* the fundamental noise!

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**



Displacement noise

Displacement noise in each of the 4 test masses:

- seismic and other environmental disturbances
- suspension thermal noise
- test mass thermal noise

is random and uncorrelated,
resulting in an equivalent strain noise of:

$$h = \Delta L / L = \left[(z_{ETMx} - z_{ITMx}) - (z_{ETMy} - z_{ITMy}) \right] / L$$

$$\Rightarrow \partial h = \left[(\partial z_{ETMx} - \partial z_{ITMx}) - (\partial z_{ETMy} - \partial z_{ITMy}) \right] / L$$

$$\Rightarrow h_{rms} = 2 z_{rms} / L$$

Phase sensing shot noise

- We detect GW strain by its effect on light phase:

$$Df = 2kDL = 2k\,L\,\boldsymbol{h}$$

- We detect light phase shift via its “beat” with sidebands
- RF-demodulated power at Asymmetric Port Photodiode (APD)

  $P_{APD} = P_{laser}\ T(f)\ Df$, where $T(f) = d(P_{APD}/P_{laser})\ /\ d(Df)$

  is (unitless) transfer function of the IFO (proportional to G_{prc}, G_{arm})
- Sensitivity to small $h \Rightarrow$ small power levels at APD:
- $d\,h = d\,P_{APD}\ /(\ P_{laser}\ T(f)\ 2\ k\,L)$
- Laser power comes in discrete packets (photons)
- Quantum fluctuations $\Rightarrow$ photon number fluctuations in P_{APD} obeying Poisson statistics: *shot noise*

  (uncertainty in power due to counting statistics)
- Equivalent to “standard” quantum limit on strain sensitivity

Sensing limits

Photon shot noise:

$$E_{APD} = P_{APD} t_{\text{int}} = N_{photon} (h_{Pl}\, c / l)$$

uncertainty in intensity due to counting statistics: $\Rightarrow d\ P_{APD} = \sqrt{P_{APD} h_{Pl}\, c / l\, t_{\text{int}}}$

can solve for equivalent strain:

$$h_{shot} = \frac{dL}{L} = \frac{1}{L}\sqrt{\frac{h_{Pl}\, c\, l}{2p\ T(f) P_{laser}}}$$

Note: scaling with *1/ÖP_{laser}* ; gives requirement for laser power

Radiation Pressure

quantum limited intensity fluctuations anti-correlated in two arms

photons exert a time varying force, spectral density

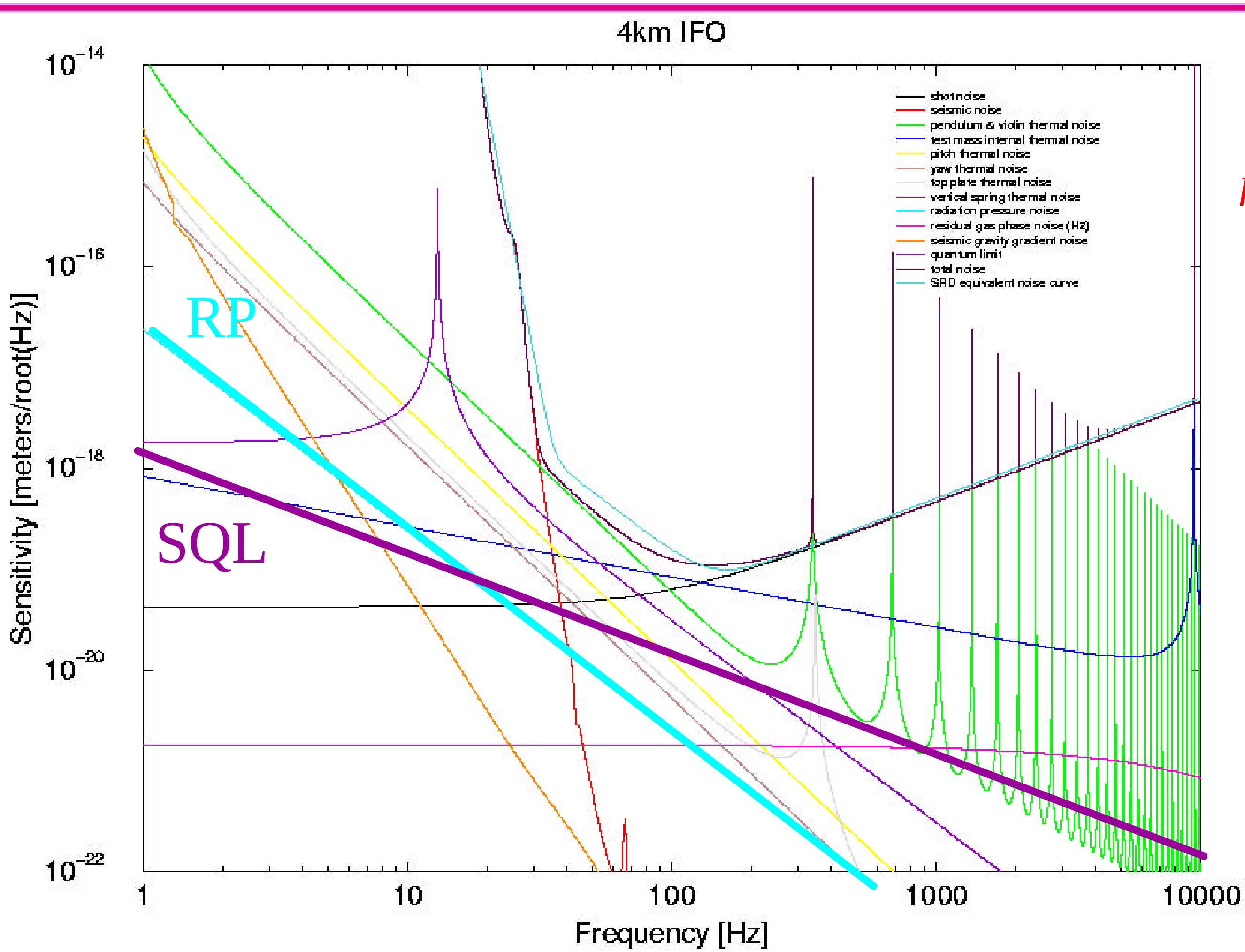
results in opposite displacements of *each* of the masses; strain $h_{rp} = \frac{dL}{L} = \frac{2}{L}\frac{1}{mf^2}\sqrt{\frac{h_{Pl} T(f) P_{laser}}{8p^3 c\, l}}$

NOTE: scaling with *ÖP_{laser}*, scaling with the arm length

Total optical readout, or quantum noise:

quadrature sum $h_q = \left(h_{shot}^2 + h_{rp}^2\right)^{1/2}$; can be optimized

Optical readout noise



Optical readout noise:

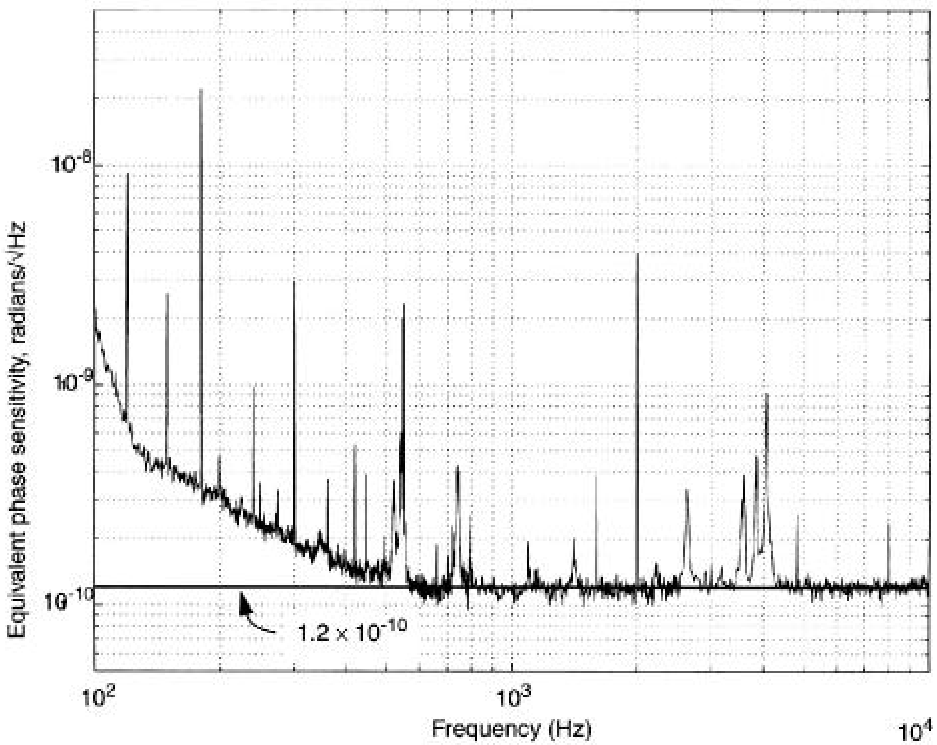
$$h_{ro}(f) = \sqrt{h_{shot}^2(f) + h_{rp}^2(f)}$$

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

$$h_{SQL} = \frac{1}{pfL}\sqrt{\frac{\hbar}{m}}$$

Phase Noise

splitting the fringe



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

Thermal displacement noise

Mechanical systems excited by the thermal environment

results in physical motions of the tests masses

Each normal mode of vibration has $k_B T$ of energy; for a SHO, $x_{rms} = \sqrt{\left\langle (dx)^2 \right\rangle} = \sqrt{k_B T / k_{spring}}$

An extended object has many normal modes at discrete frequencies;

each will experience thermal excitation.

Dissipation causes the energy, and fluctuations in position, to spread over a range of frequencies, according to Fluctuation-Dissipation theorem:

$\tilde{x}(f) = \frac{1}{pf}\sqrt{\frac{k_B T}{\Re(Z(f))}}$, $\Re(Z)$ is the real (lossy) impedance

e.g., damping term in an oscillator: $m\ddot{x} = F_{ext} - \Re(Z)\dot{x} - k_{spring}x$

•viscous damping: $\hat{A}(Z) = b$ = constant. Recall, at a definite f, $\dot{x} = i\,2pf\;x$

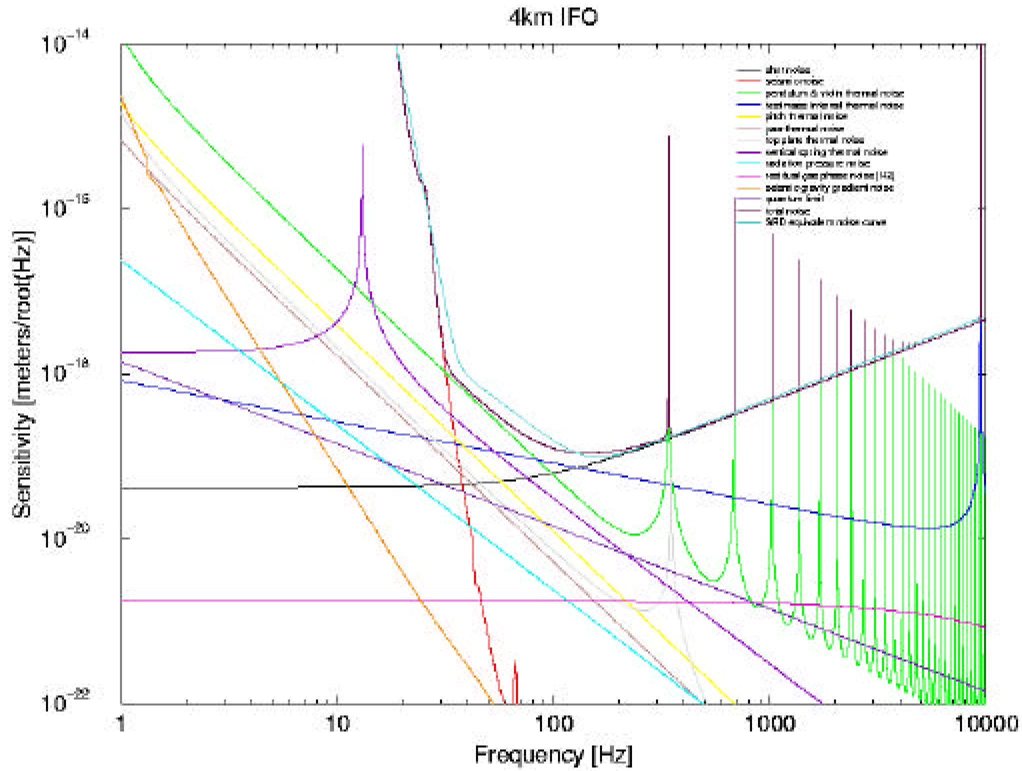
•internal friction: $F = -kx \quad \Rightarrow \quad F = -k(1 + i f(f))x$

f (f) is often a constant, = 1/Q

Minimize thermal motion $\Rightarrow$ materials and techniques for very low loss (high Q)

Thermal displacement noise

Sum of many normal modes, $x^2_{thermal} = \frac{4kT}{2pf} \sum_n \frac{f_n(f)}{m_n(2pf_n)^2} \left\{ \frac{1}{\left(1-(f/f_n)^2\right)^2 + f_n{}^2(f)} \right\}$
Each with loss $f_n(f)$:



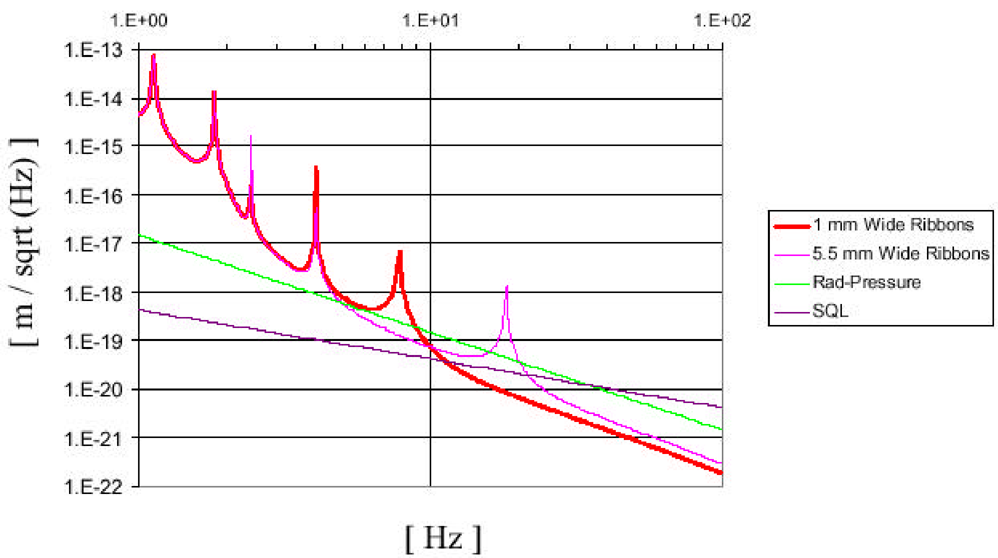
Equivalent strain (noise):

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

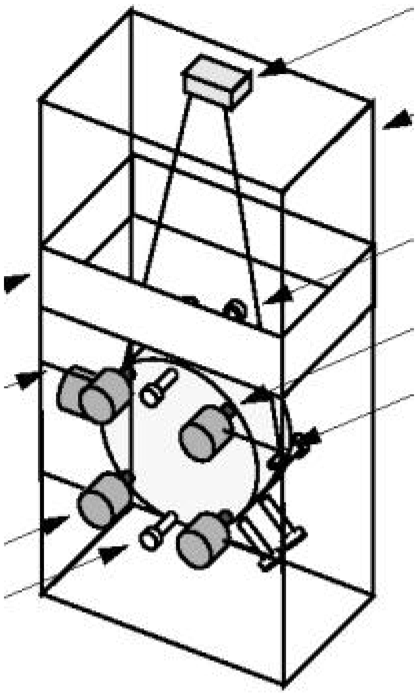
Suspension thermal noise

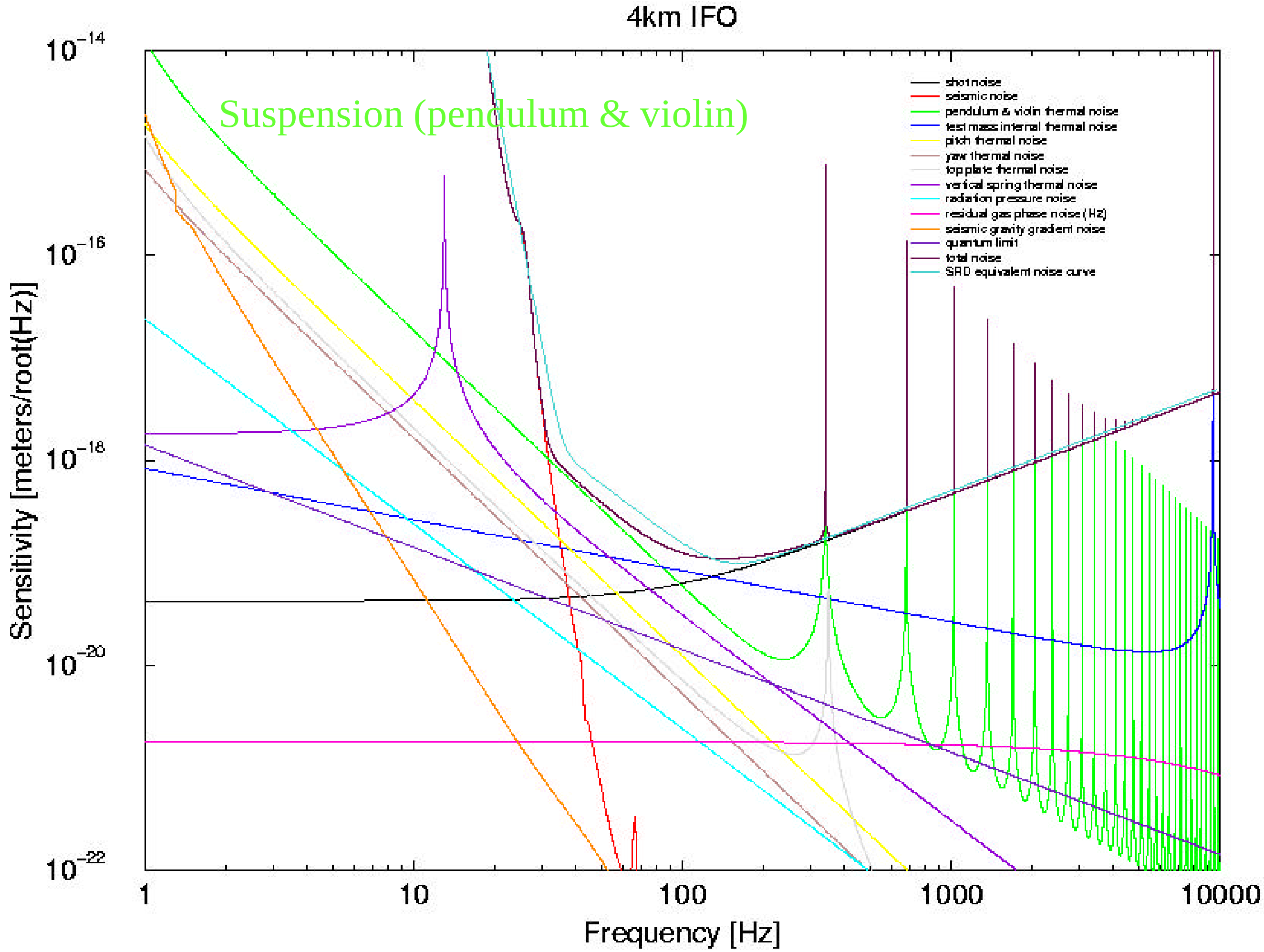
Suspension wires vibrate (violin modes, stretch/bounce modes), kick the test mass around, introducing an harmonic series of noise lines

- Incoherent motion of the 4 test masses produces noise in GW channel, at fundamental and harmonics
- Most severe just after lock acquisition; then they ring down

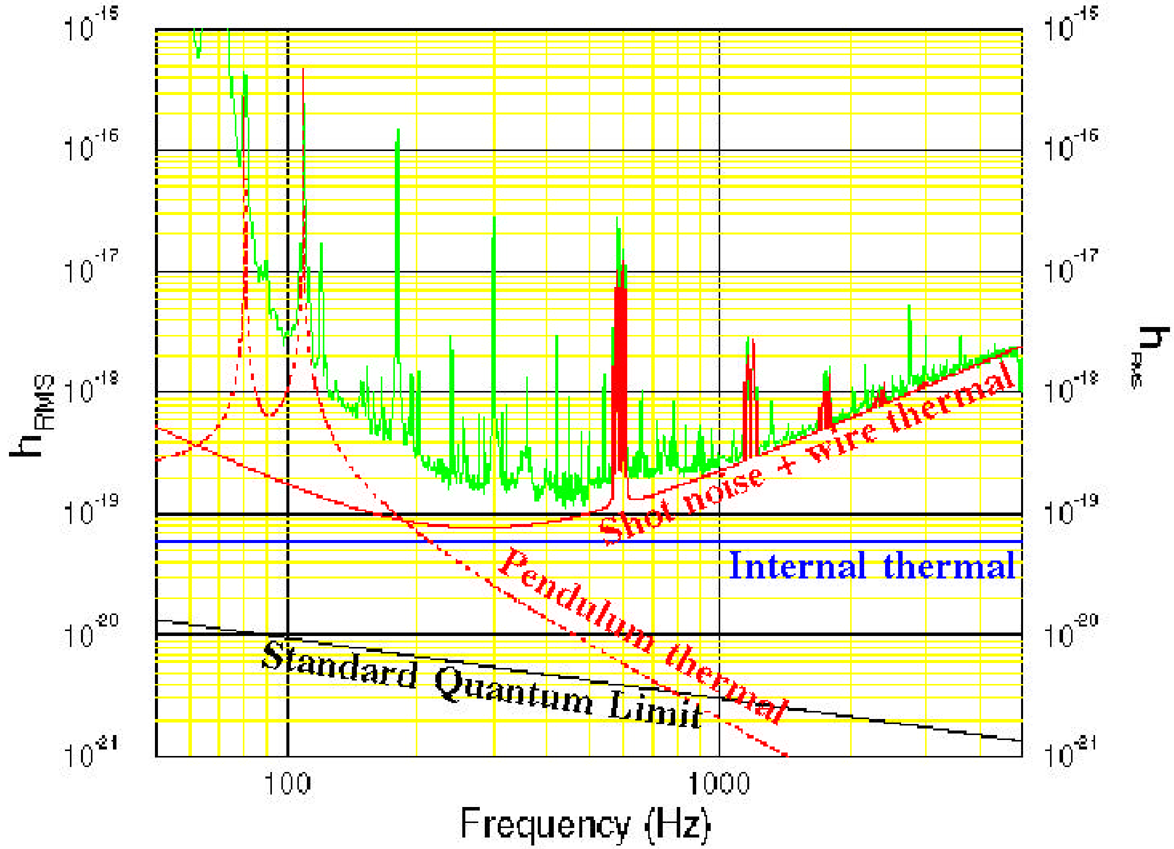


Suspension thermal noise





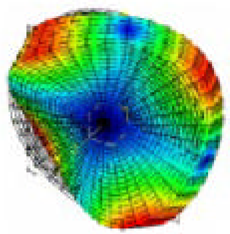
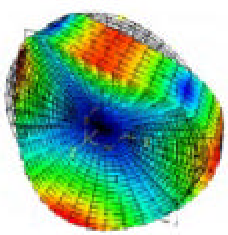
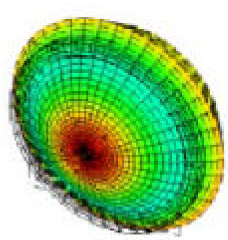
40 meter noise spectrum, 1994

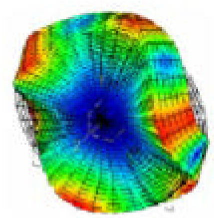
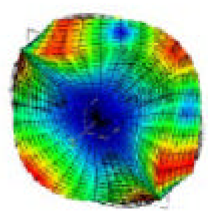
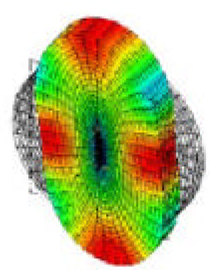


Internal test mass thermal noise

- LIGO test masses have internal normal modes at ~several kHz and up (outside of LIGO sensitivity band)
- Dissipation causes thermal energy to leak into LIGO band f < few kHz
- Test mass vibrates about its center of mass; but the reflective mirror is on the surface, *not* the COM, so it introduces displacement noise
- Minimize dissipation: high Q materials (fused Si, sapphire). BUT, suspension wires, magnets for actuation, cause dissipation, reducing Q dramatically
- Solutions for LIGO II: replace suspension wire with silica ribbons and welds; eliminate magnets (use electrostatic force via capacitive coupling, or photon pressure)

Vibrational modes of test masses

Mode Shape	Frequency (Hz)
	3785
	3785
	5578

Mode Shape	Frequency (Hz)
	7975
	7975
	11259

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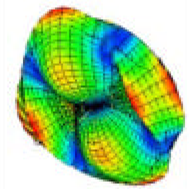
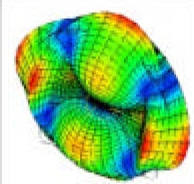
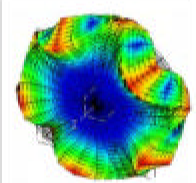
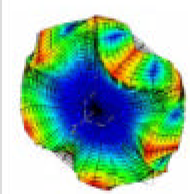
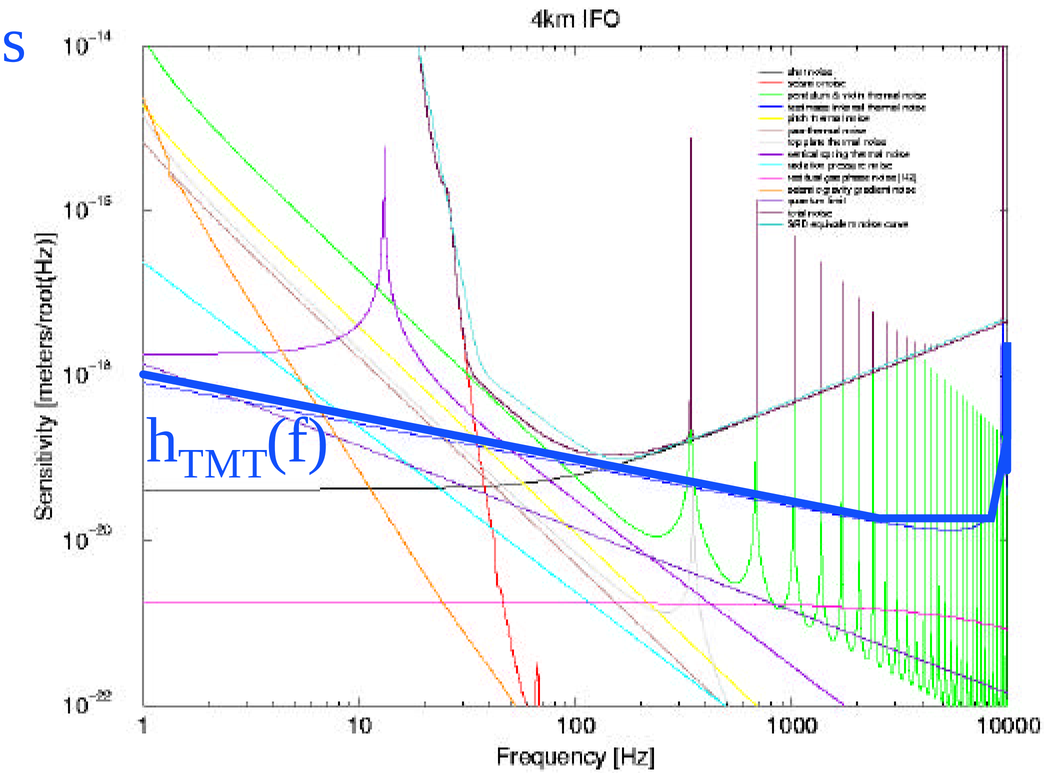
Mode Shape	Frequency (Hz)
	17388
	17388
	17958
	17958

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

Test mass internal thermal noise

$$x_{TMT}^2 = \frac{4kT}{2pf}\sum_n \frac{f_n(f)}{m_n(2pf_n)^2}\left\{\frac{1}{\left(1-(f/f_n)^2\right)^2+f_n{}^2(f)}\right\}$$

Test masses have normal modes
Above the LIGO band



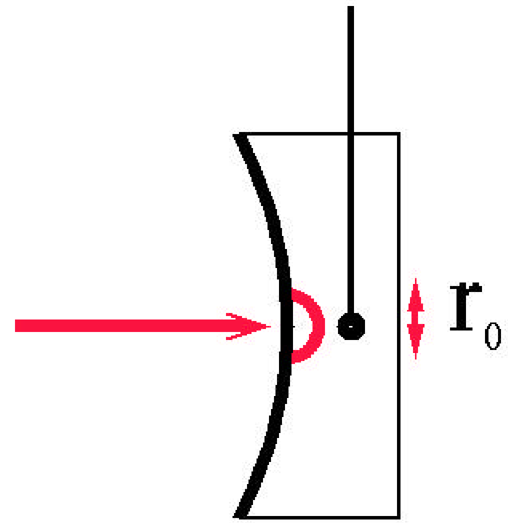
Equivalent strain:

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

Thermoelastic noise

- Mirror is at finite temperature, and any small volume in the mirror experiences fluctuations in temperature (the smaller the volume, the greater the fluctuation, and the beam samples only a small volume)
- The material expands thermoelastically, so fluctuations in temperature cause fluctuations in the expansion
- Since the COM of the suspended mirror is not at the mirror reflective surface, this induces a fluctuation in the mirror position, with spectral density
- Coefficient of thermal expansion α is 10x larger for sapphire than for fused silica, and thermal conductivity l^* is 30x larger, (Braginsky, 2000).
- So for LIGO II , sapphire (much higher Q) will have much worse thermoelastic noise! (We can try to increase the beam size r_0.)

$$\langle dT^2 \rangle = \frac{k_B T^2}{r C V}$$

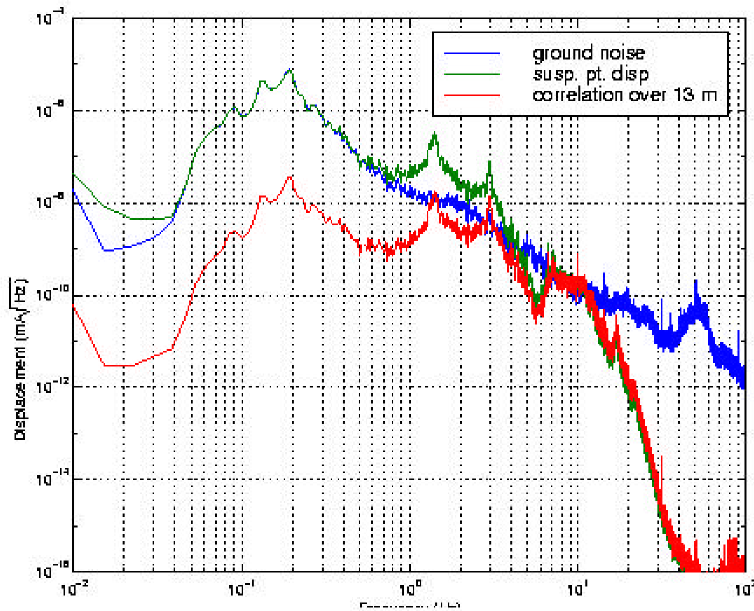


$$x_{TD}^2 = \frac{8}{\sqrt{2p}} a^2 (1+s^2) \frac{k_B T^2}{(rC)^2} \frac{l^*}{r_0^3} \frac{1}{(2pf)^2}$$

Seismic displacement noise

Motion of the earth

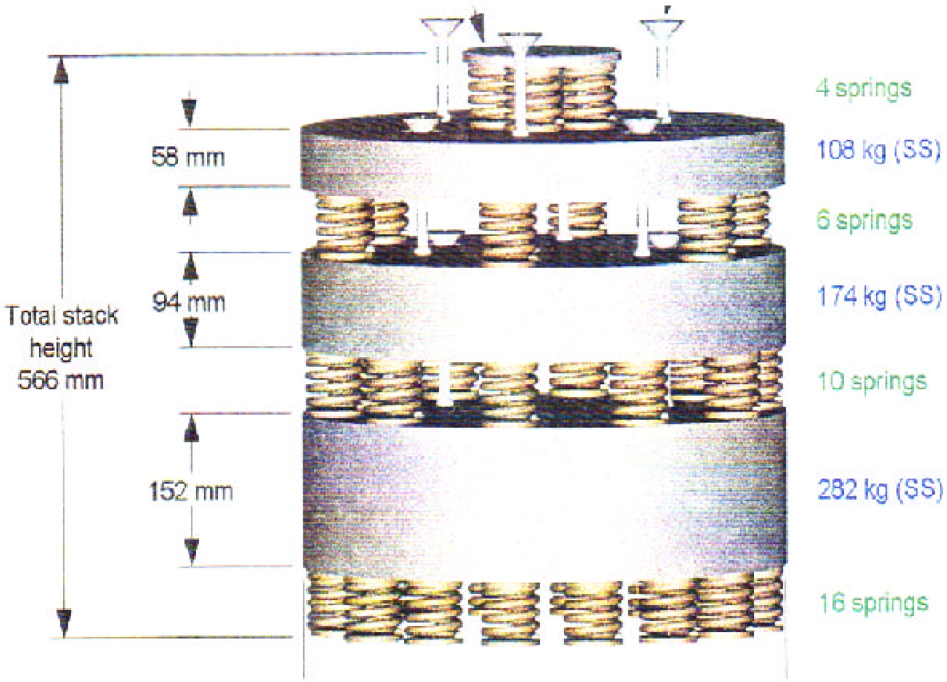
- driven by wind, volcanic/seismic activity, ocean tides, humans
- requires *e.g.*, roughly 10^9 attenuation at 100 Hz
- ~300 micron tidal motion, microseismic peak at 0.16 Hz.
- At low frequencies, motion is correlated over two mirrors

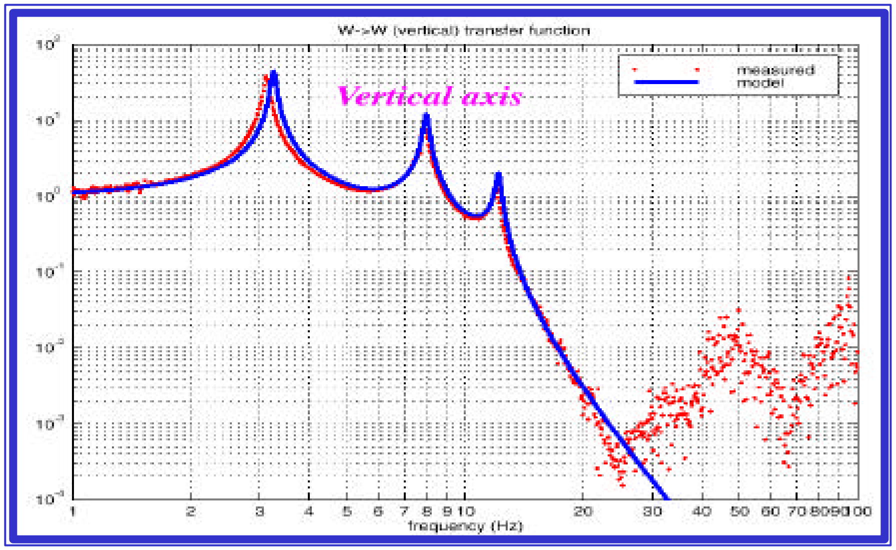


Approaches to limiting seismic noise

- 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

Seismic isolation stacks

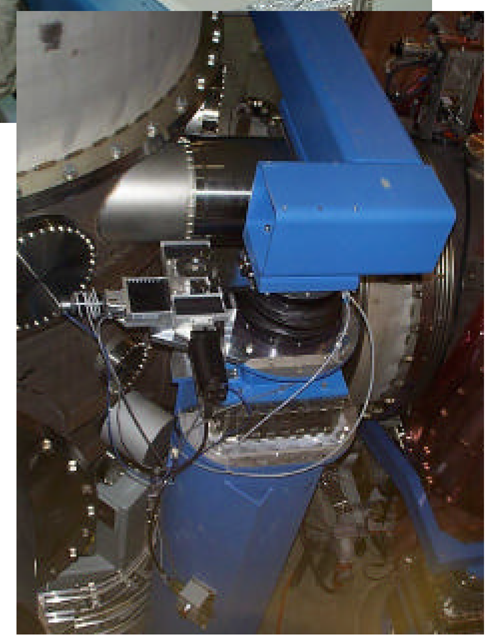




Seismic Isolation Systems

Support Tube Installation

Stack Installation



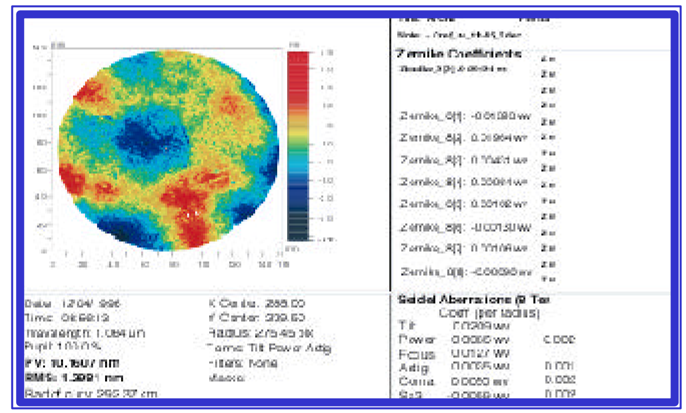
Coarse Actuation System

Noise from imperfect Optics

Highly efficient optical system:

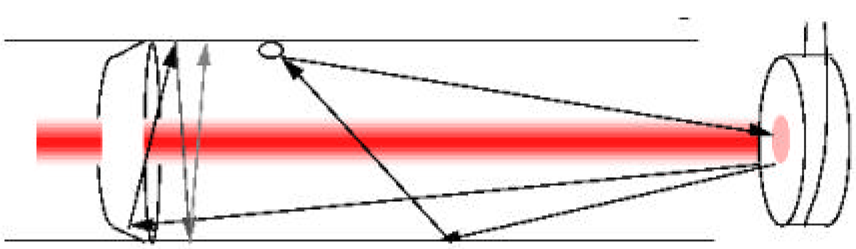
~50 ppm lost per round-trip

- optics are 25 cm diameter, 10 cm thick fused silica cylinders
- light beam ~10 cm diameter; 1ppm scattered, ~1ppm absorbed



Constraints on optical surface due to noise requirements:

- minimize scatter (power loss ⇒ phase noise)
- minimize absorption (thermal distortions, lensing ⇒ phase noise)
- minimize scattering out of beam, onto tube, back into beam (phase noise)
- minimize wavefront distortions (*contrast defect* at dark port ⇒ phase noise)



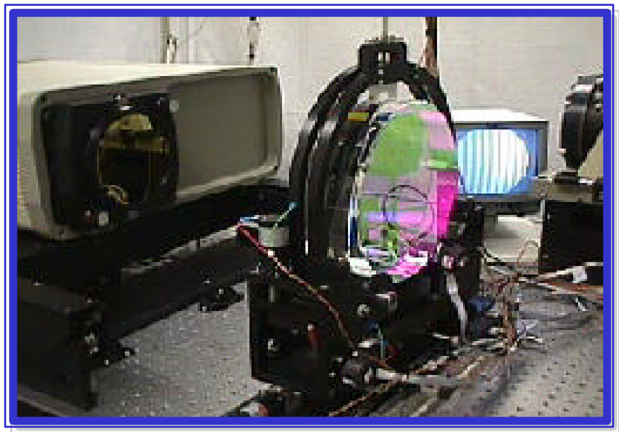
Results

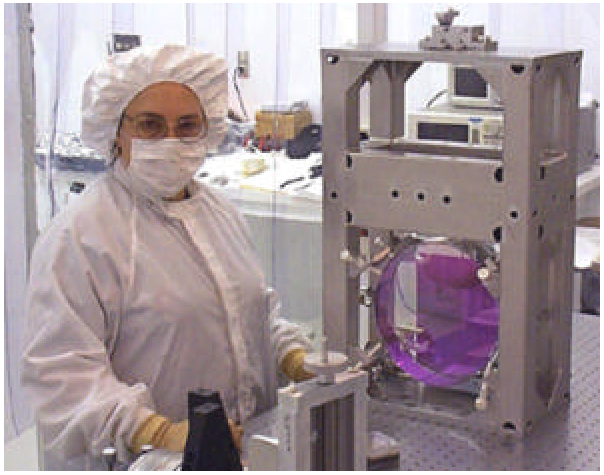
- **λ/800** over central 10 cm (~1 nm rms); fine scale `superpolish‘
- Sophisticated *baffling*

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

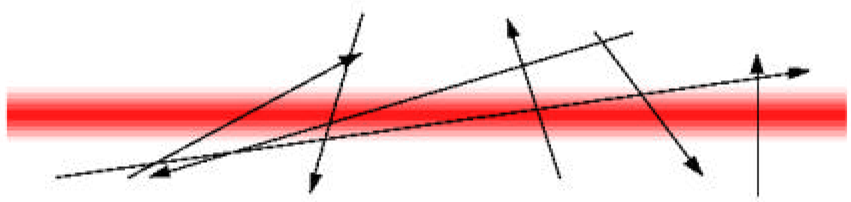




Residual gas in beam tube

Light must travel 4 km without attenuation or degradation

- refractive index fluctuations in gas cause variations in optical path, phase noise
- residual gas scatters light out of, then back into, beam; phase noise
- Residual gas pressure fluctuations buffet mirror; displacement noise
- Contamination: low-loss optics can not tolerate surface 'dirt';
  High circulating powers of ~10-50 kW burns dirt onto optic surface



requirement for vacuum in 4 km tubes:

- H_2 at 10^{-6} torr initial, 10^{-9} torr ultimate
- H_2O at 10^{-7} torr initial, 10^{-10} ultimate
- Hydro-, flourocarbons < 10^{-10} torr
- vacuum system, 1.22 m diameter, ~10,000 m^3
- strict control on in-vacuum components, cleaning

LIGO beam tubes

LIGO Livingston Observatory
LLO

LIGO Hanford Observatory
LHO

LIGO *Beam Tube*

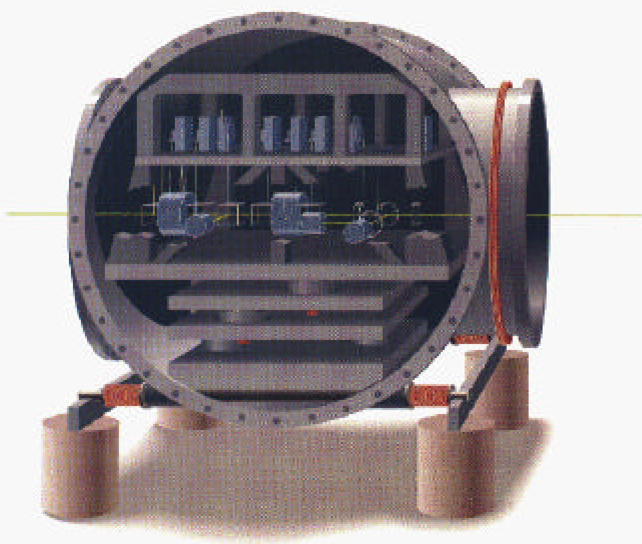
Beam light path must be high vacuum, to minimize “phase noise”

- 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

LIGO Vacuum Chambers



HAM Chambers

BSC Chambers

Input Optics

Hanford 2 km

Control System Racks

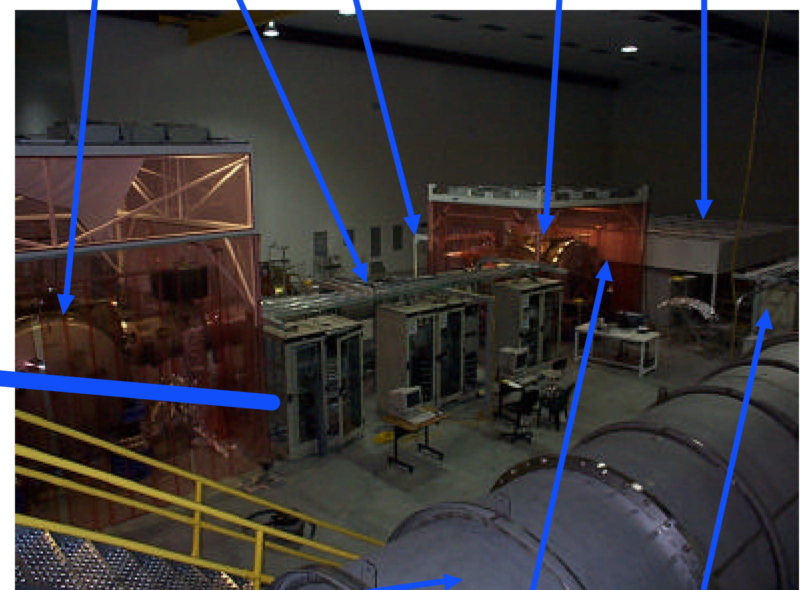
Interferometer Sensing & Control ISC) Mode Cleaner Output Optics Table

Mode Cleaner Tube

Pre-Stabilized Laser (PSL) Enclosure

HAM9 Chamber

HAM8 Chamber



Right Beam Manifold

MMT3 Optical Lever

PSL Electronics Racks

Input Optics Section

Gravity gradient noise

Local "static" gravitational force from sum of mass distributions (Newtonian Background)

- dominated by unchanging attraction of earth
- additional time-varying contributions from other sources:
  - seismic compression (surface seismic compression waves)
  - weather (variations in atmospheric pressure changing air density)
  - moving massive objects (humans, machines)

Places limit on lowest frequencies detectable by ground-based interferometers

- Most of these sources are irreducible for a given site
- everyone talks about the weather, but no one does anything about it!
- practical limit: down to roughly 10 Hz
- lower frequencies are domain for space-based interferometers

Another crucial reason to make interferometers long:

these motions must be small compared with GW strain

Excess (technical) phase noise

Many sources of imperfections!

laser source

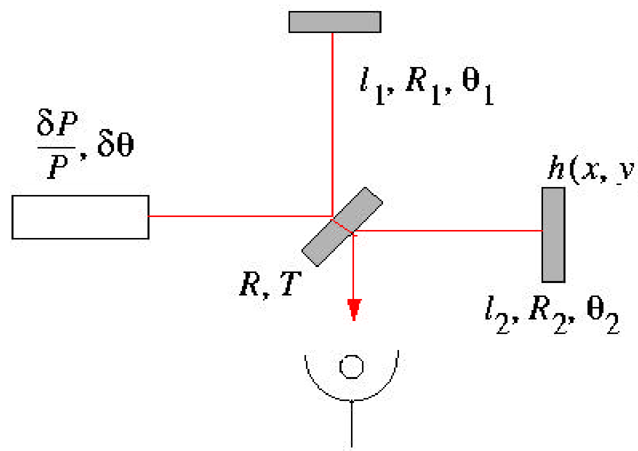
- intensity fluctuations greater than shot noise (10^{-8} δP/P)
- frequency noise (10-7 Hz/√Hz)
- angular or translational beam pointing fluctuations

sensing and control systems

- linearity (microns at 1 Hz, 10-19 m /√Hz at 100 Hz)
- Electronics noise at sensors, actuators, in between
- EMF pickup, spectral lines (60 Hz and harmonics)

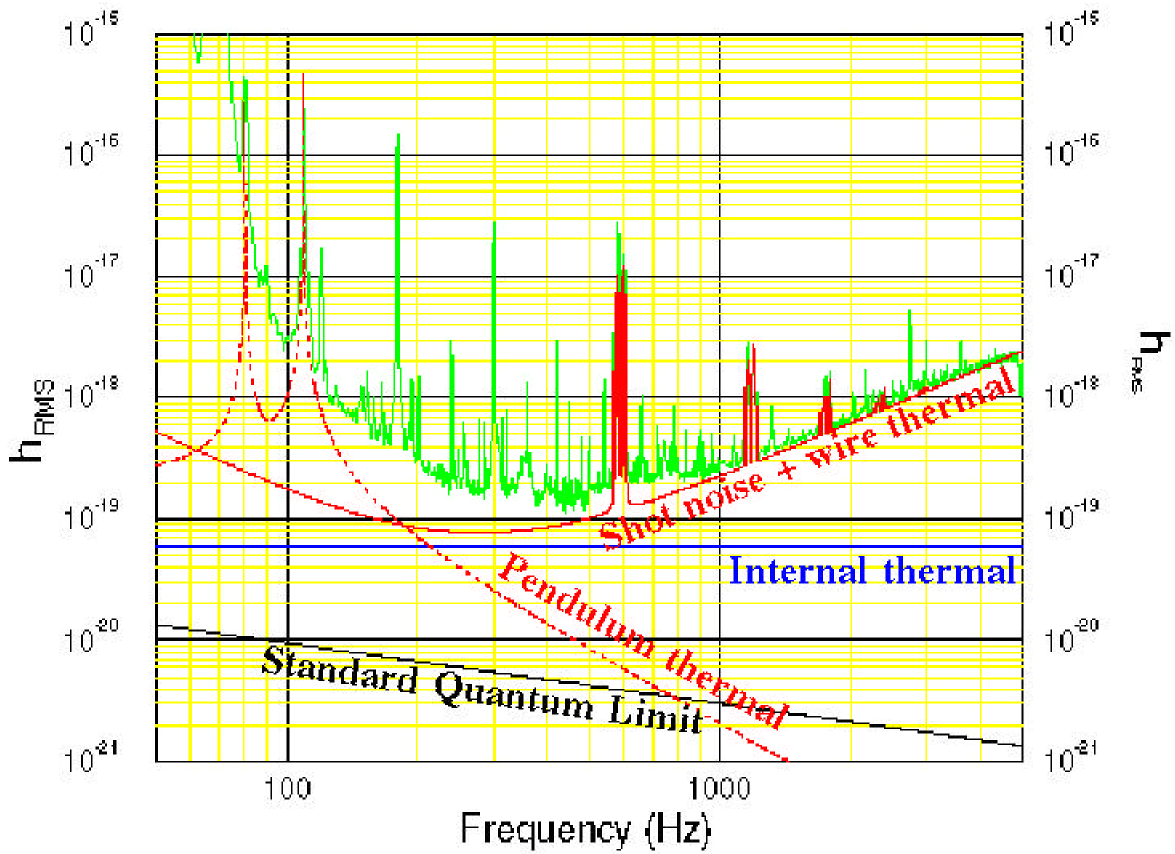
Imperfect optics, misalignments, losses

The UNKNOWN!



Much of the technical effort goes into controlling these noise sources

40 meter noise spectrum, 1994



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**