# Overview and Status of the LIGO Project

**David Shoemaker**

**MIT, LIGO Project**

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## Organization of talk

- tour of LIGO design organized by differences from LISA
- update of LIGO status

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# LIGO

**LIGO: L**aser **I**nterferometer **G**ravitational-Wave **O**bservatory

- project to build observatories for gravitational waves (GWs)
    - ...and laboratory to run them
- to enable an initial detection, then an astronomy of GWs
- group effort of colleagues at MIT, Caltech

## Observatory characteristics

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

## Evolution of interferometers in LIGO

- establishment of a network with other interferometers
- multiple users of LIGO, simultaneous operation and development, focussed searches
- lifetime of >20 years
- goal: to be compatible with all technology developments for terrestrial interferometers

# LISA and Ground-based interferometers

## Similarities, Differences, Challenges

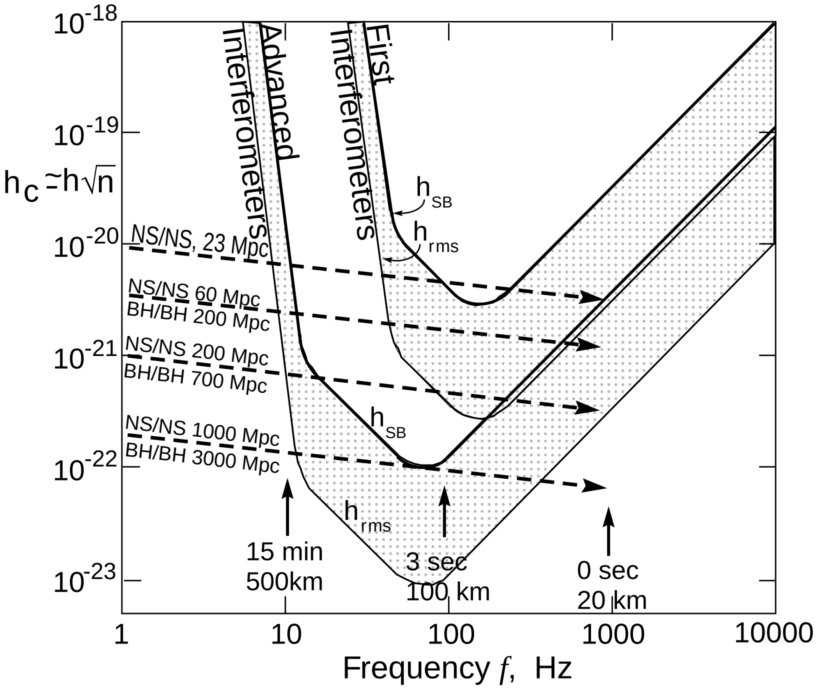
| | Ground-based | LISA |
|---|---|---|
| Frequency Range | $10^{+1} - 10^{+4}$ Hz | $10^{-4} - 10^{-1}$ Hz |
| Burst/Integrated strain sensitivity | $\sim 10^{-23}$<br>(at ~100 Hz) | $\sim 10^{-23}$<br>(at ~1/100 Hz) |
| Arm Length | $\sim 10^{+3}$ m | $\sim 10^{+9}$ m |
| Displacement sensitivity | $\sim 10^{-19} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$ | $\sim 10^{-12} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$ |
| Stochastic forces | seismic isolation,<br>suspensions,<br>thermal noise | inertial sensing,<br>drag-free technology,<br>thermal distortions |
| Sensing system | laser power,<br>optics development | clocks and corrections,<br>transponding system |

# Coalescing Compact Binaries

**Standard candle: Solar Mass Binary stars**

- e.g., Taylor-Hulse Binary 1913+16; now at ~8 h period
- later in life ($10^8$ yr.), period shortens to audio frequencies
- spends ~1 minute in frequency range from ~30 Hz-1 kHz
- good target frequency range for ground-based ifos.

Spectral representation, with LIGO sensitivity curves



# Other possible sources

## Stellar core collapse - supernovæ

- symmetric collapse/expansion does not radiate, but...
- rotation can lead to flattening, then formation of a ‘bar’
- either a spin-up (100 to 1000 Hz) or spin-down (100 to 10 Hz)
- radiator resembles binary, similar strains; rate unknown

## Stochastic Background

- Several possible (speculative) sources:
    - primordial ‘big-bang’ background
    - cosmic strings
    - confusion limit
- possible to make ‘blind’ search - correlation of interferometers
- signals probably quite small (COBE, Pulsar, Doppler limits)

## Periodic sources

- asymmetric pulsars (e.g., Crab): synchronize with Radio signals

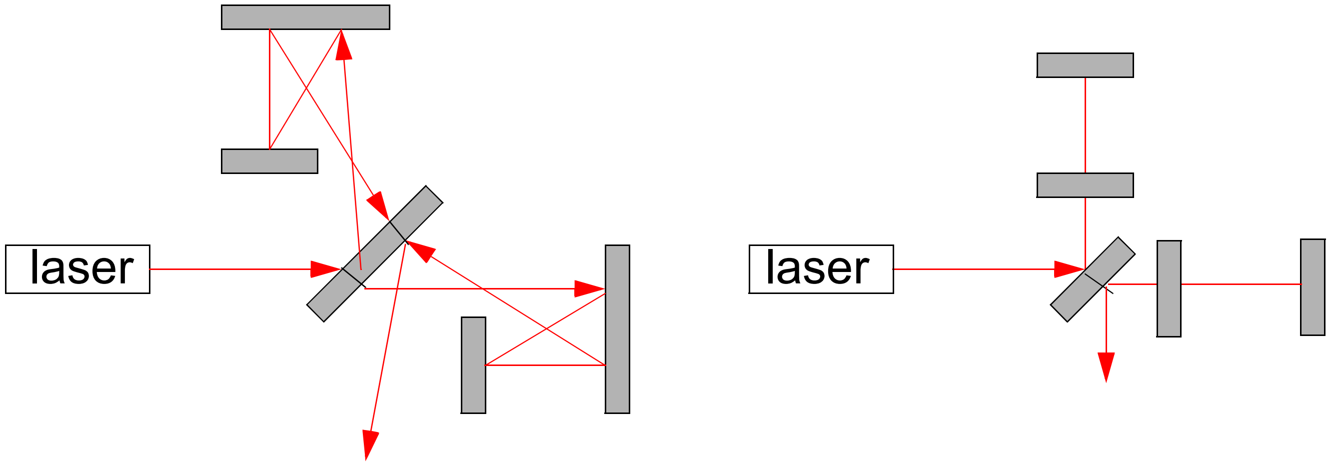
## Resume of sources

- sources with well-understood signal forms
- sources with several possible forms
- uncertain rates, signal sizes
- surprises ‘certain’

# LIGO optical configuration

**Interaction time with the GW (LISA: $10^6$ km simple path)**

- signal $\delta l$ grows as length of interferometer $L$ grows
- up to limit where $L \approx \lambda_{GW}/4$, order of hundreds of km for 100Hz
- not practical to make 100km straight path on earth, so fold it



- Delay line
  - simple, but requires large mirrors and limited storage time
- Fabry-Perot (LIGO design)
  - compact, but imposes modes, resonance constraints
- several msec storage time for initial system
  - optimum sensitivity around 100 Hz; ~100 bounces, ~4km

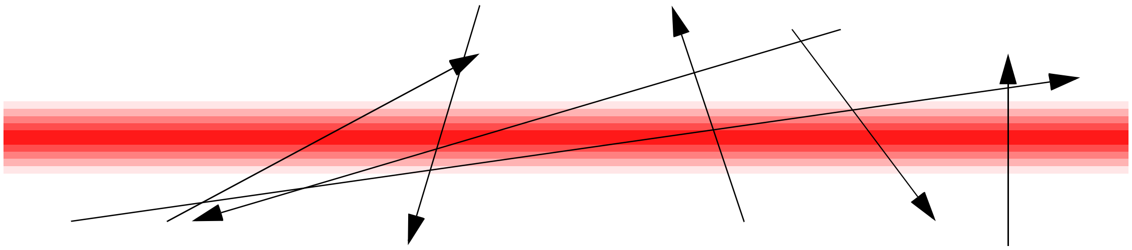
# Vacuum system

**Light must travel 4 km without attenuation or degradation**
**(LISA: capitalize on excellent vacuum in space)**

- index fluctuations in gas cause variations in optical path
  - pressure, polarizability, molecular speed of various species, counting statistics; net effect $h(f) \approx 4\pi\alpha\left(\frac{2\rho}{v_0 w_0 L}\right)^{\frac{1}{2}}$
- requirement for quality of vacuum in 4 km tubes from this
  - $H_2$ of $10^{-6}$ torr initial, $10^{-9}$ torr ultimate
  - $H_2O$ of $10^{-7}$ torr initial, $10^{-10}$ ultimate
- vacuum system, 1.22 m diameter, ~10,000 cubic meters

**Also have requirement on contaminants**

- low-loss optics can not tolerate surface ‘dirt’
- circulating powers of ~10-50 kW, 1-10 $\mathrm{cm}^2$
- requires strict control on in-vacuum components, cleaning



# Optics

**Highly efficient optical system, >50 ppm lost per bounce**
**(LISA: less than $10^{-8}$ captured)**

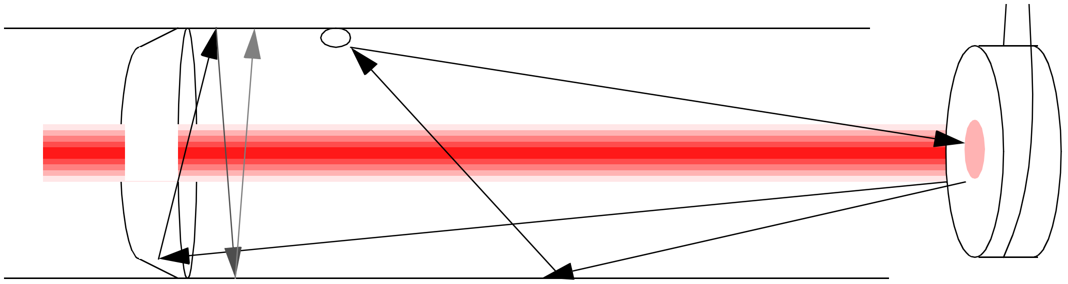
- 25 cm diameter, 10 cm thick fused silica cylinders
- light beam ~10 cm diameter; 1ppm simply lost, ~1ppm absorbed

## Constraints

- wide angle scatter, $10^{-3}$ rad and larger
  - power loss to system
- medium angle scatter, $10^{-4}$ rad
  - scattering out of beam, onto tube, back into beam
- wavefront distortions, $10^{-6}$ rad
  - degraded interference in interferometer (1-$10^{-3}$ contrast)

## Results

- $\lambda/800$ over central 10 cm (~1 nm rms); fine scale ‘superpolish’
- tens of optics polished, exceeding these requirements
- coating doubles large-scale defects, still within requirements



# Sensing limits

## Shot or Poisson noise
## (LIGO requires ~$10^5$ better fringe precision than LISA)

- uncertainty in intensity due to counting statistics: $\tilde{p}_{\text{out}} = \sqrt{\frac{h_{\text{Pl}}\omega}{P_{\text{in}}}}$
- can solve for equivalent strain: $h_{\text{shot}} = \frac{\delta l}{L} = \frac{1}{L}\sqrt{\frac{h_{\text{Pl}}c\lambda}{2\pi P_{\text{in}}}}$
- Note: scaling with $1/\sqrt{P_{\text{in}}}$; gives requirement for laser power

## Radiation Pressure

- quantum limited intensity fluctuations anti-correlated in two arms
- photons exert a time varying force, spectral density $\tilde{f} = \sqrt{\frac{2\pi h P_{\text{in}}}{c\lambda}}$
- results in opposite displacements of EACH of the masses:

$\tilde{x}(f) = \frac{1}{mf^2}\sqrt{\frac{hP_{\text{in}}}{8\pi^3 c\lambda}}$, or strain $h = \frac{\delta l}{l} = \frac{2\tilde{x}}{L}$

- NOTE: scaling with $\sqrt{P_{\text{in}}}$, scaling with the arm length $L$

## Total readout, or quantum noise

- quadrature sum $h_{\text{q}} = (h^2_{\text{shot}} + h^2_{\text{rad press}})^{1/2}$; optimum exists

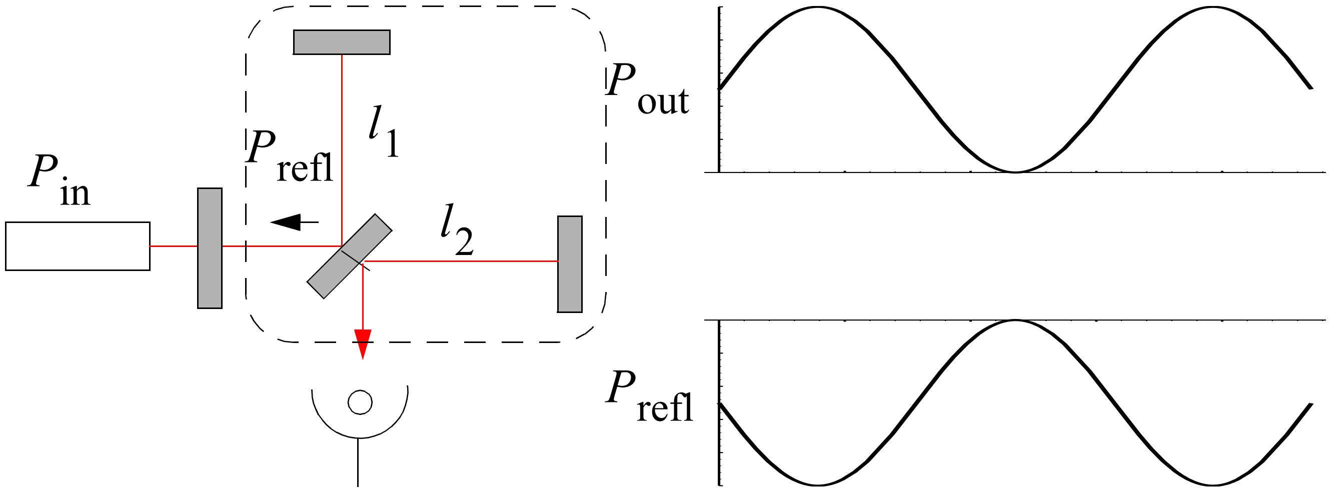
# Realistic optical configurations

**Insufficient raw laser power**

- predicted sources require shot noise of ~300 W on beamsplitter
- suitable lasers produce ~10 W, only ~6W at ifo input

**Make resonant cavity of interferometer and additional mirror**

- can use ifo at ‘dark fringe’; then input power REFLECTED back



- known as Recycling of light (Drever, Schilling)
- Gain of ~40 possible, with losses in real mirrors
- allows present lasers to deliver needed power

**Something for nothing?**

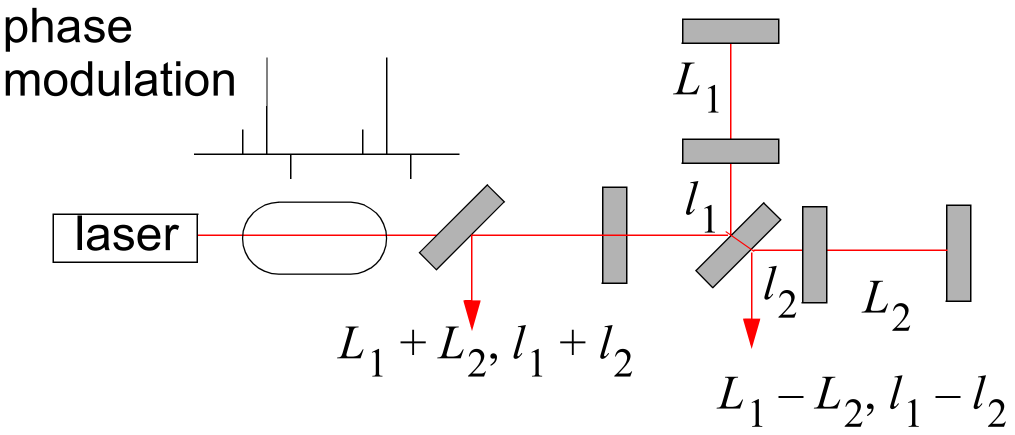
- increases stored energy
- just extract small amount ($10^{-40}$ or so) if GW passes

# Control systems

## Gives 6 suspended optics, 4 length DOF to control

- Michelson dark fringe condition
- both Fabry-Perot arms on resonance (maximum $d\phi/dL_n$)
- recycling cavity on resonance/laser wavelength correct
- lengths to be held to $10^{-13}$ m in presence of $10^{-5}$ m noise

## Analyze as common mode/differential mode



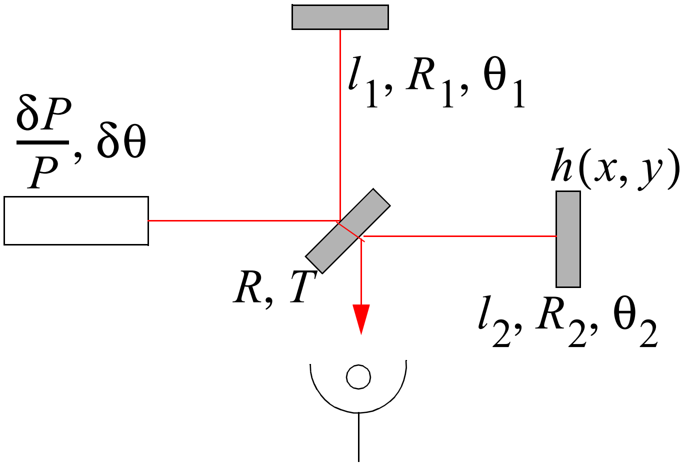
## Angular alignment also required

- all optical cavity axes must be aligned with input beam
- leads to ~$10^{-8}$ rad requirement
- use techniques similar to length readout, but with spatial info

# Excess phase noise

**LIGO: time scale of msec** **(LISA: time scale of ksec)**

**Many sources of imperfection:**

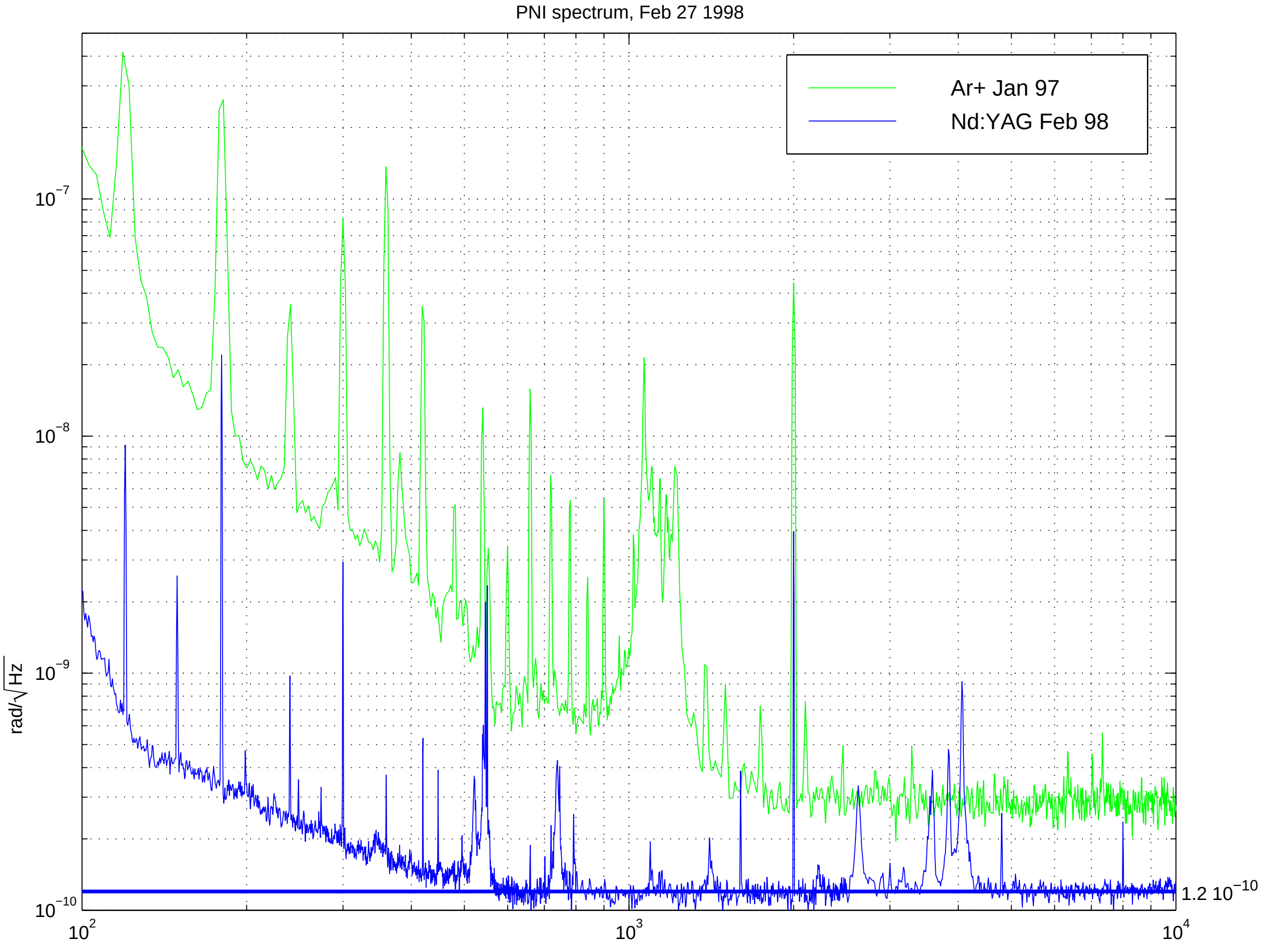


- ifo asymmetries
  - lengths (intentional!)
  - losses
  - beamsplitter
- ifo control errors
  - length
  - alignment
- laser source
  - intensity fluctuations greater than shot noise ($10^{-8} \delta P / P$)
  - frequency noise ($10^{-7}\ \mathrm{Hz} / \sqrt{\mathrm{Hz}}$)
  - angular or translational beam pointing fluctuations
- sensing systems
  - linearity (microns at 1 Hz, $10^{-19}\ \mathrm{m} / \sqrt{\mathrm{Hz}}$ at 100 Hz
  - spatial uniformity

**Much of the technical effort goes into these noise sources**

- complicated sensing and control problems
- state-of-the-art optics, state-of-the-art lasers
- beautiful and delicate experiments

# Proof of Principle



## Experimental demonstration of fringe-splitting

- suspended interferometer mirrors, LIGO sensing systems
- ~$1.3\times10^{-10}\mathrm{rad}/\sqrt{\mathrm{Hz}}$, ~70 watts circulating power

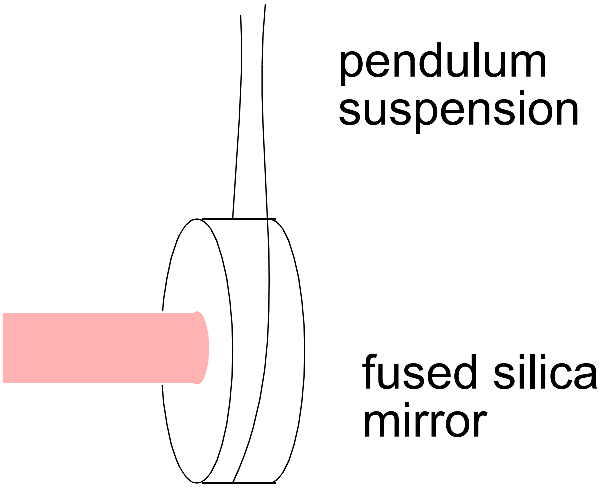
# Thermal Noise

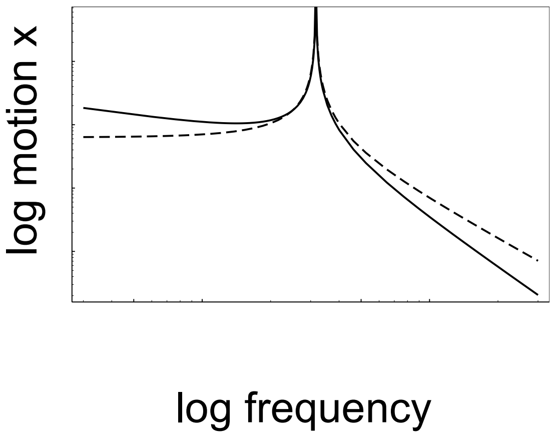
**Mechanical systems excited by the thermal environment**
**(LISA: thermal noise negligible)**

- results in physical motions of the tests masses
- total energy of $k_B T$, leads to $\tilde{x} = \sqrt{(k_B T)/k_{\text{sping}}}$ for RMS
- spectrum according to Fluctuation-Dissipation theorem:

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

- e.g., damping term in an oscillator: $F_{\text{ext}} = m\ddot{x} + \Re(Z(f))\dot{x} + kx$
- usually think of viscous damping: $\Re(Z(f)) = b$, a constant
- most real materials show internal friction,
- $F = -kx$ replaced by $F = -k(1 + i\phi(f))x$, $\phi(f)$ often constant





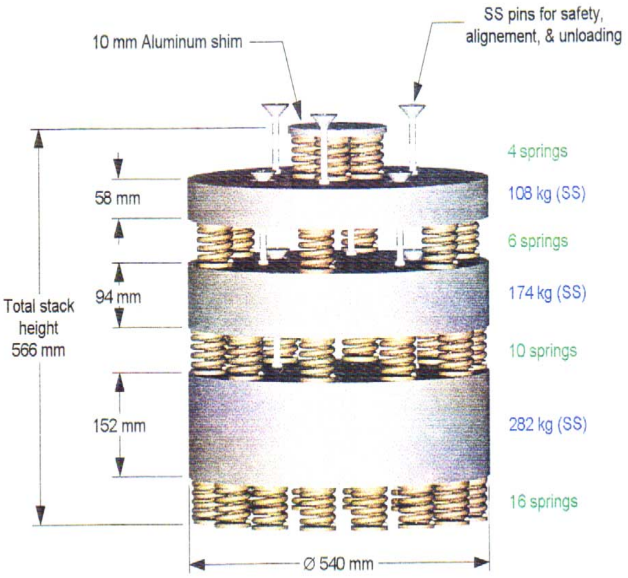
# Seismic Noise

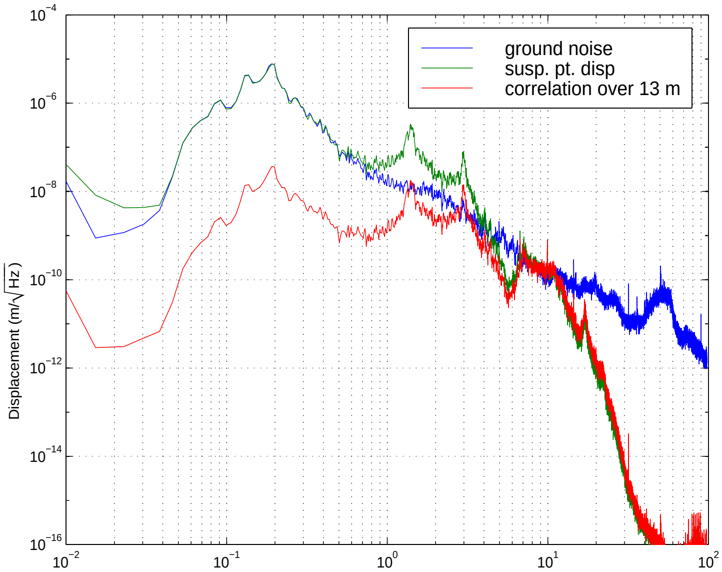
**Motion of the earth**

- driven by ocean tides, wind, volcanic/seismic activity, humans
- requires e.g., roughly $10^9$ attenuation at 100 Hz
- ~300 micron tidal motion, microseismic peak at 0.16 Hz...

**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





# Gravity Gradients

**Local 'static' gravitational force sum of mass distributions**
**(LISA: different sources, same concern)**

- dominated by unchanging attraction of earth
- additional time-varying contributions from other sources:
- seismic compression
  - surface seismic waves compressing nearby earth
- weather
  - variations in atmospheric pressure changing air density
- moving massive objects
  - humans passing close (<10 meters) to test masses
- for moving/changing mass element $M$, $\vec{F}(t) = \dfrac{GM(t)m\hat{r}}{r^2}$

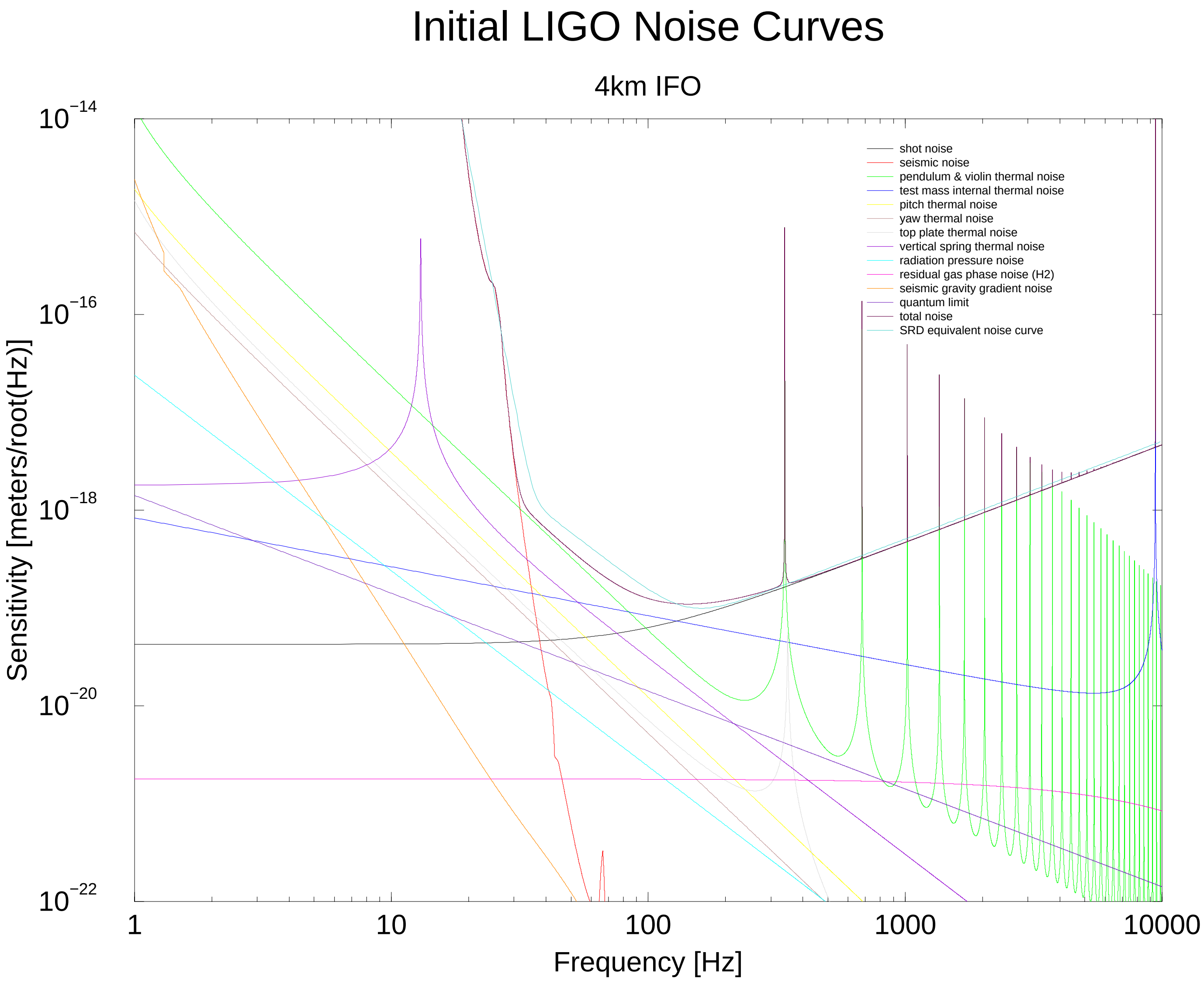
**Places limit on lowest frequencies detectable by ground-based interferometers**

- some engineering solutions to ground variations, nearby activity
- nothing to do about the weather!
- practical limit: down to roughly 10 Hz
- lower frequencies are domain for space-based interferometers

**Another crucial reason to make interferometers long:**

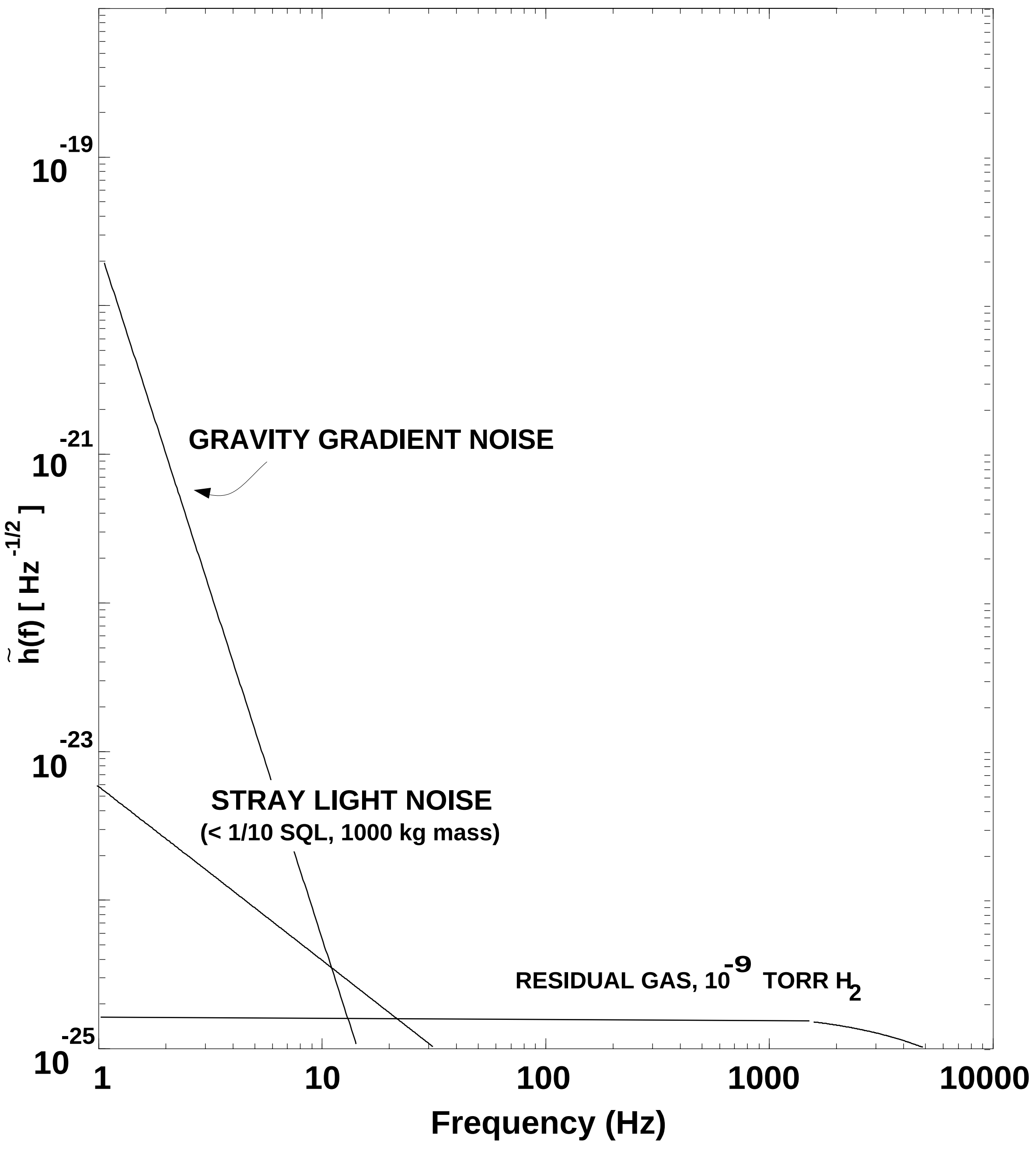
**these motions must be small compared with GW strains**

# Initial LIGO sensitivity



(model ‘snapshot’ of mid-July 98)

# Limits due to facilities



# Detection confidence

## Environmental Monitor

- wish to eliminate locally all possible false signals
- detectors for many possible sources
    - seismic, acoustic, electromagnetic, muon
- also trend information
    - tilts, temperature, weather

## Multiple interferometers

- 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)

## Detection computation

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

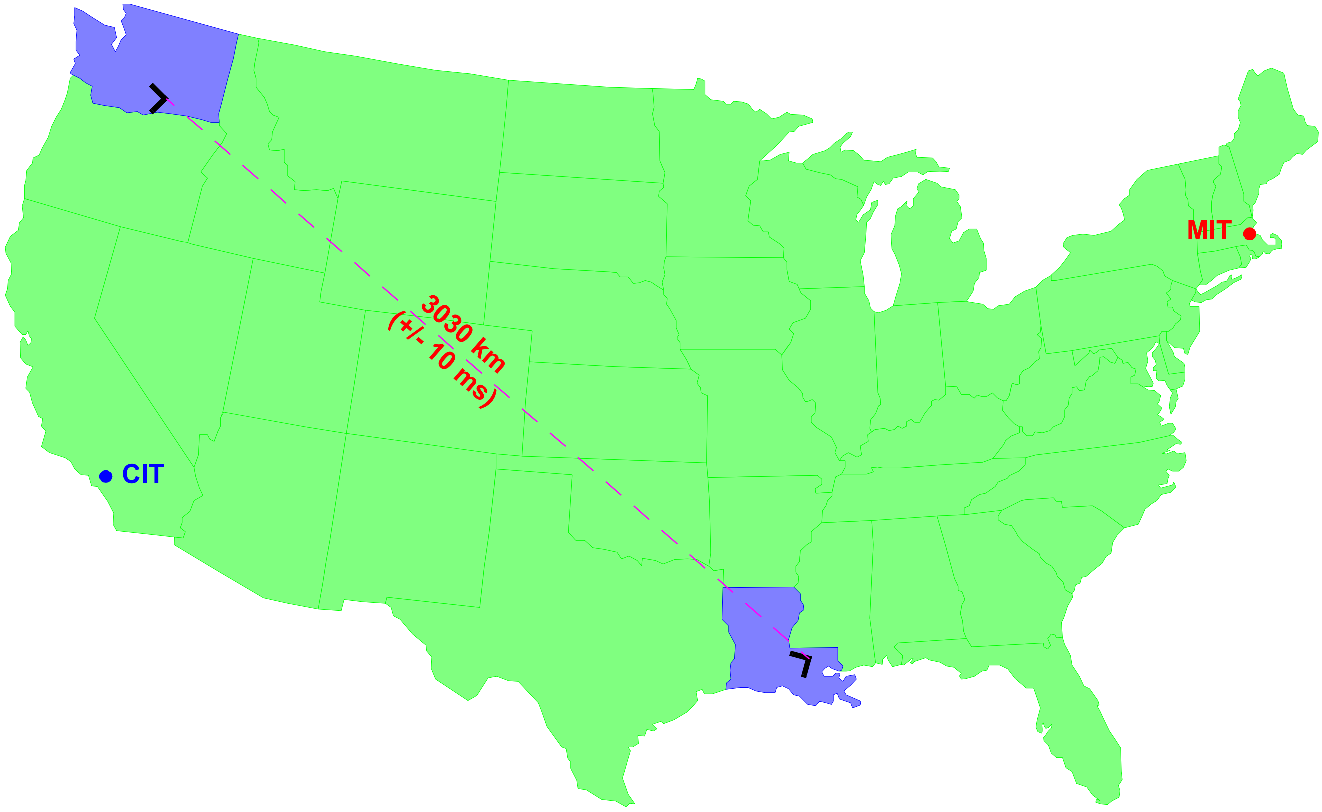
# LIGO Sites

**Hanford, WA**

- located on DOE reservation
- treeless, semi-arid high desert
- 25 km from Richland, WA

**Livingston, LA**

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



# LIGO Evolution

**Infrastructure nearly complete at both sites**

- beam tubes completed for Hanford; bakeout in preparation
- vacuum equipment fabricated, in installation/test
- buildings occupied, networks running, growing staff

**Initial shakedown 1999-2001**

- first detector equipment now arriving at sites
- Recycled Michelson tests starting early spring ‘99

**First observations 2001-2003**

- coincidences among all 3 interferometers
- improved sensitivity, reliability, characterization continuing

**Development of improved interferometers underway**

- **LIGO Science Collaboration** quite active
- working groups in stochastic, sensing, configuration, data
- continued R&D within (and without) LIGO Lab
- planning incremental improvements for ~2004
- significant changes for?~2008

**The ground-based network of detectors will be ready to complement LISA**