Overview of the Science and Technology of Interferometric Gravitational-Wave Detectors

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Organization of talk

- fundamentals of detection mechanism
- sources within range of technologies
- follow several limitations to sensitivity from physics to solutions
- overview of LIGO, status

LIGO: Laser **I**nterferometer **G**ravitational-Wave **O**bservatory

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

Nature of Gravitational Radiation

Assume General Relativity (Einstein 1916)

- wave is transverse, spin 2
- propagation following the wave equation

$$\left[\frac{\partial^2}{\partial x_1^2} - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right] h(x, t) = 0$$

- passing GW leads to change in proper distance

  $\delta l \approx \left(\frac{1}{2}h(t)\right)L$ between points of initial separation L

Net effect: variation in distance between free masses,

Characteristics of radiative process

Conservation laws:

- conservation of mass → monopole radiation forbidden
- conservation of momentum → no dipole radiation

Lowest order radiation term: quadrupole

- wavefield proportional to $\ddot{Q}$, second derivative of quadrupole
- or, non-spherical part of kinetic energy
- falls as $1/r$ (like E&M)
- dimensional analysis leads to $h \approx \frac{G}{c^4}\frac{\ddot{Q}}{r}$
- $G/c^4 = 10^{-33}$ (MKS), numerically very small
- $h \approx 10^{-20}\left(\frac{E_{\text{non-sphere, kinetic}}}{M_o c^2}\right)\left(\frac{15\,\text{Mpc}}{r}\right)$, solar mass, Virgo cluster

Source characteristics

Standard candle: Binary stars

- Taylor-Hulse Binary 1913+16 shows clear spin-up
- almost certainly due to GW radiation at present 8h period
- later in life, period shortens to audio frequencies
- spends ~1 minute in frequency range from ~30 Hz-1 kHz
- good target frequency range for ground-based ifos.

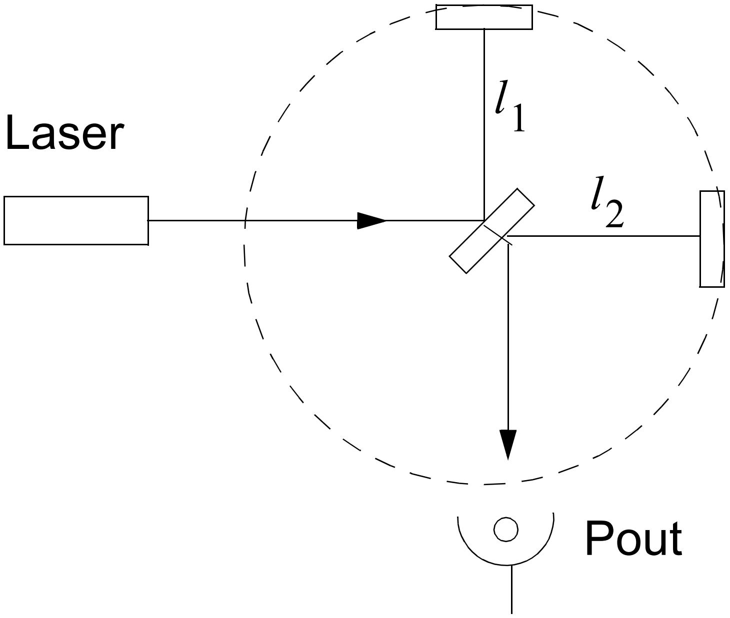
for most of life, waveform well known if masses known

- Newtonian/quadrupole approximation
- allows calculation of signal amplitudes, optimal filters
- measurable relativistic corrections ~10%; requires 3 PN orders
- end of life (coalescence) yet to be calculated (measure first?)
- typical number: $h \approx 3\times10^{-22}$ for 1.4 $\mathrm{M_o}$, 100 Mpc, ~3 events/yr.
- since $h = \delta l/L$, expect $\delta l = 3\times10^{-22}$ m for $L = 1$ m

Basic principle of detection

Laser Interferometry

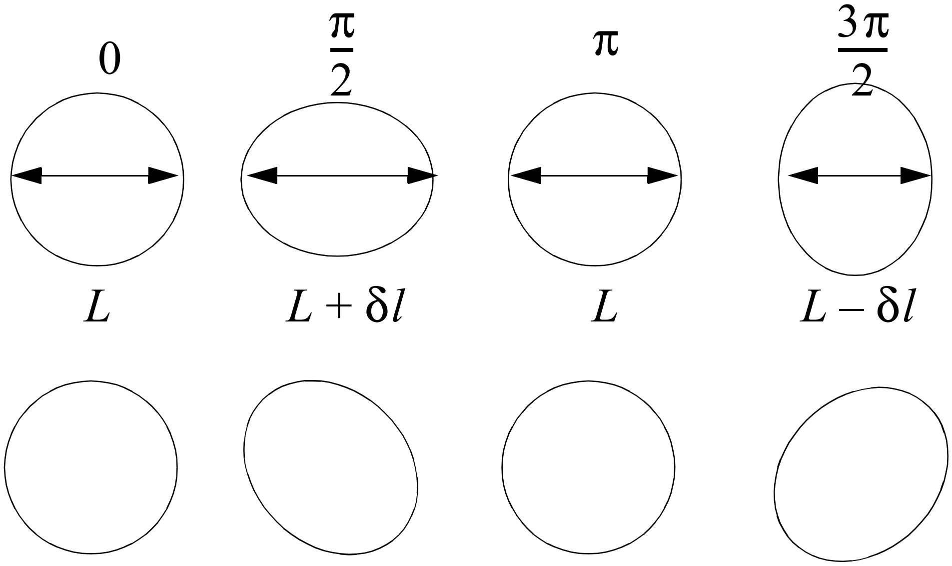
- almost ideal gedanken experiment



- GW strain induces differential length changes in arms
  - proportional to arm length, up to fraction of GW wavelength
- lengths are measured using light beams and ‘free masses’
- broadband response to GWs of varying frequency
- at least 4 independent discoveries of method
  - Pirani (‘56), Gerstenshtein and Pustovoit, Weber, Weiss
  - Weiss ‘72: practical approach, scaling laws, limitations

probational to strain and initial separation

- example of ring of free masses, GW perpendicular to page



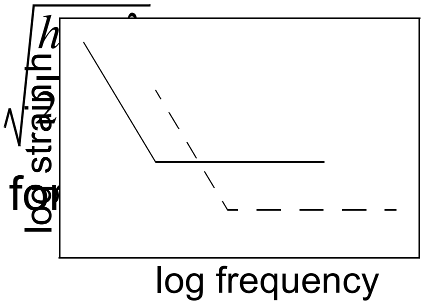
Fundamental limits

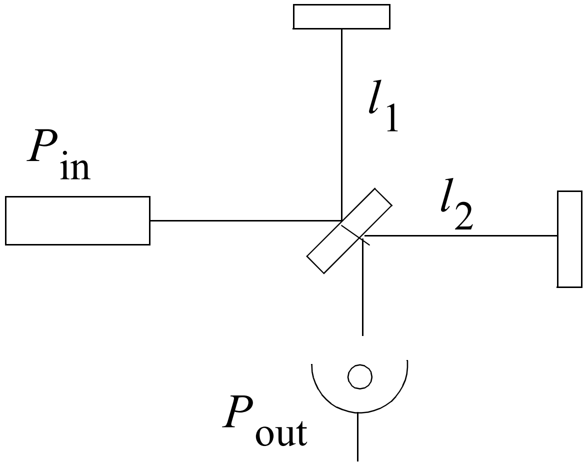
Shot or Poisson noise

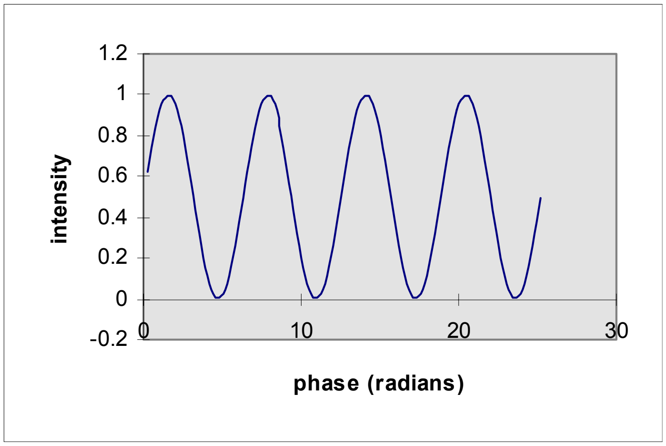
- intensity at ifo output is a function of arm length difference:

$$P_{\text{out}} = P_{\text{in}}\left(1 + \frac{1}{2}\cos\left[\frac{2\pi}{\lambda}(l_1 - l_2)\right]\right);\ (l_1 - l_2) = h(t)L$$

- maximum slope: $\frac{dP}{d\delta l} = \frac{2\pi}{\lambda}P_{\text{in}}$
- 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: $h_{\text{shot}} = \frac{\delta l}{L} = \frac{1}{L}\sqrt{h}$
- Note: scaling with $1/\sqrt{P_{\text{in}}}$; gives requirement fo







Quantum Noise

Radiation Pressure

- quantum-limited intensity fluctuations anti-correlated in two arms
  - › can be seen as the action a statistical beamsplitter
  - › better, as result of vacuum fluctuations entering ‘dark port’
- photons exert a time varying force, with 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 of the interferometer.

total readout, or quantum noise

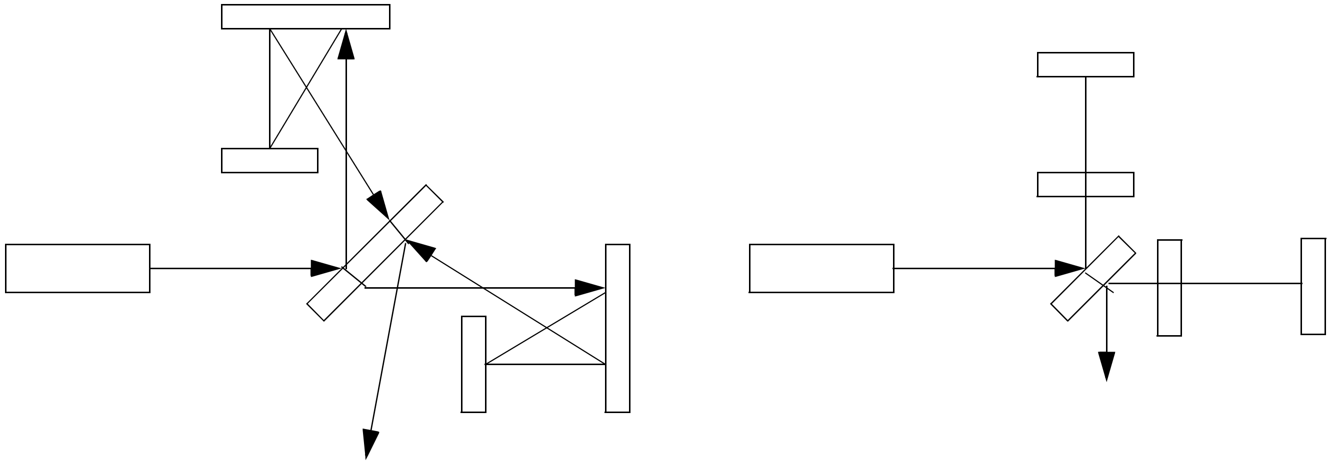
- quadrature sum $h_{\text{q}} = (h_{\text{shot}}^2 + h_{\text{rad press}}^2)^{1/2}$
- frequency dependence according to ifo configuration, but

- always a minimum for a given frequency as a function of Power
- for simple Michelson, $P_{\text{opt}} = \pi c \lambda m f^2$; later limitation, not now

Realistic optical configurations

1) interaction time with the GW

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



- Delay line
  - simple, but requires large mirrors and limited storage time
- Fabry-Perot
  - compact, but imposes modes, resonance constraints on system
- 10 msec storage time for initial ground-based system
  - gives optimum sensitivity around 100 Hz; ~100 bounces, ~4km

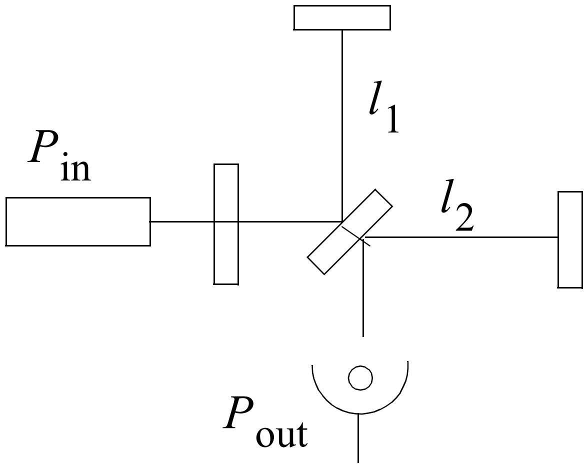
Realistic optical configurations

2) insufficient raw laser power

- predicted sources require shot noise of ~100 W on beamsplitter
- suitable lasers produce ~10 W, only ~5W 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 ~30 possible, with losses in real mirrors
- allows present lasers to deliver needed power

Something for nothing?

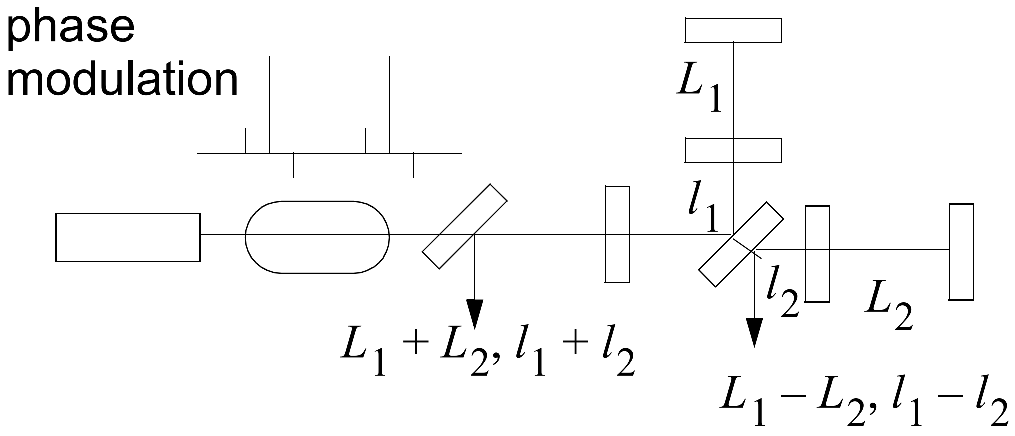
- no, cannot use all that light to heat room
- just extract small amount (10^{-20} or so) if GW passes

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

Analyze as common mode/differential mode

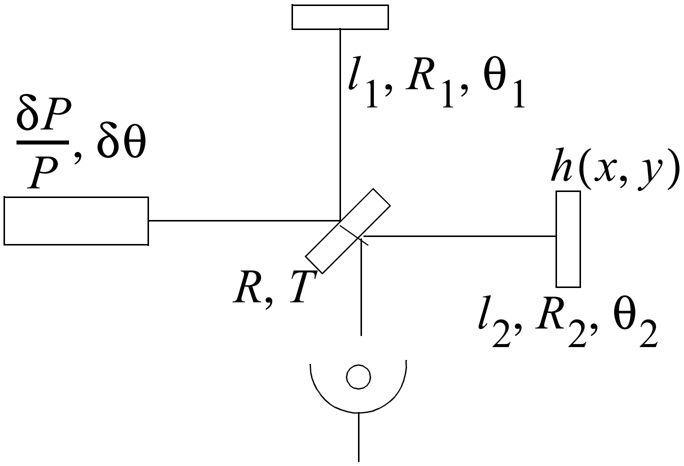


Angular alignment also required

- 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

many sources of imperfection:



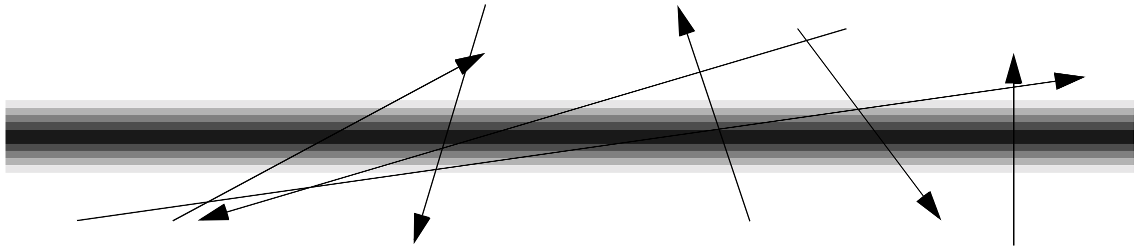
- ifo asymmetries
  - lengths (intentional!)
  - losses
  - beamsplitter
- ifo control errors
  - length
  - alignment
- laser source
  - fluctuations greater than shot noise
  - angular or translational beam pointing fluctuations
- sensing systems
  - linearity
  - spatial uniformity

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

Vacuum system requirements

Light must travel 4 km without attenuation or degradation



- index fluctuations in gas cause variations in optical path
  - › pressure, polarizability, molecular speed of various species
  - › light beam intensity distribution, coherence of 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’~~
- more difficult to define, limited to region around test masses

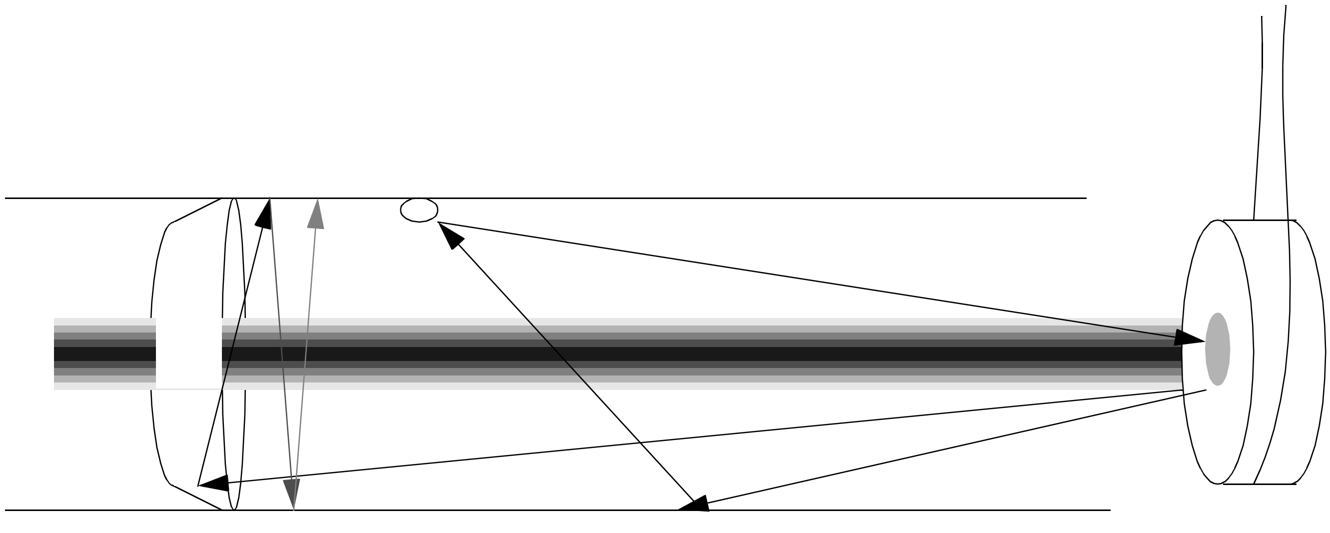
Scattered light

Scattered light: ~ 60% of light lost here!

- most is lost as heat
- some recombines with main beam, adding small random vector
- suffers additional time-varying phase shift
- all optics have some finite backscatter (~100 ppm/bounce)
- spurious interferometers abound; care with all stray beams

Light from mirror surface

- typically from imperfection on ~0.5 cm scale, height 1 nm
  - corresponds to ~$\lambda / 800$ for center ~10 cm of mirror
- scatters out of main beam, onto beam tube, back onto mirror
- baffles used to strongly attenuate paths, leaves 1m aperture



Thermal Noise

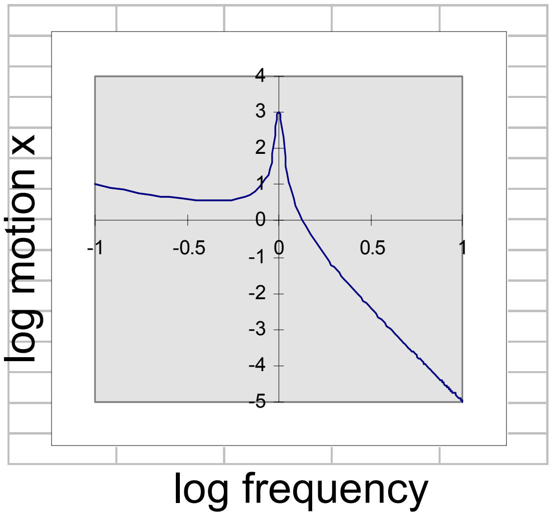
Mechanical systems excited by the thermal environment

- results in physical motions of the tests masses
- total energy of $k_B T$, leads to $\tilde{x} = \sqrt{\frac{k_B T}{k_{\text{sping}}}}$ for integrated motion
- 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

- peak $1/\phi$ above ‘plateau’
- rises as $1/\sqrt{f}$ below resonance
- falls as $1/f^{5/2}$ above resonance



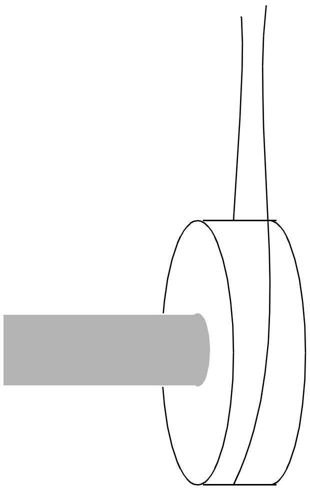
Thermal Noise

Two regimes of interest: Below or Above resonance

- (note: Resonant mass detectors (‘bars’) ON resonance)

Below resonance: internal modes of test masses

- test masses are fused silica cylinders, 25cmX10cm
- many modes contribute to net surface motion
  - drumhead modes, compressional modes
- typical loss on resonance of 10^{-6}
- most important in range $100 \rightarrow 300$ Hz



Above resonance: pendulum suspension

- test masses suspended as ~1 Hz pendulum
- minimizes loss of both pendulum and test-mass
- seismic isolation ($1/f^2$ above resonance), positioning
- pendulum mode excited by thermal noise forces
- typical loss on resonance of 10^{-6}
- most important in range $10 \rightarrow 100$ Hz

Both of these noise sources scale with arm length 1/*L*

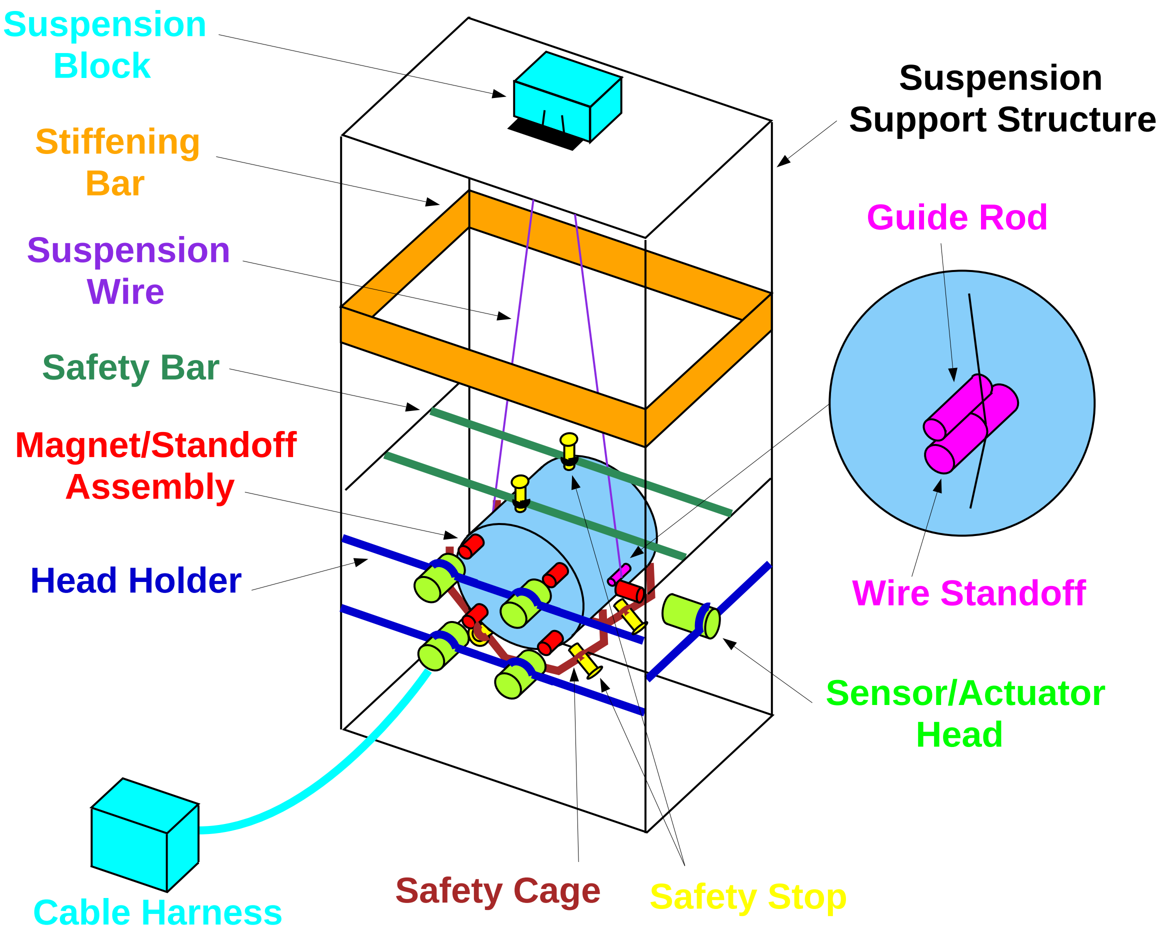
Thermal (with other stochastic force terms) determines *L*

Leads to LIGO 4km length; *h=x/L*

Test Mass and Suspension

Objective: to minimize losses of mechanical modes

- also need ability to control mass position, angle
- extensive experience in prototypes
- confirmation of thermal noise models for internal modes



Seismic Noise

Motion of the earth

- driven by ocean tides, wind, volcanic/seismic activity, humans
- for LIGO sites, characterized by $10^{-7}/f^2 \ \mathrm{m}/\sqrt{\mathrm{Hz}}$
- requires e.g., roughly 10^9 attenuation at 100 Hz
    - daily ~300 micron motion (tides), microseismic peak at 0.16 Hz...

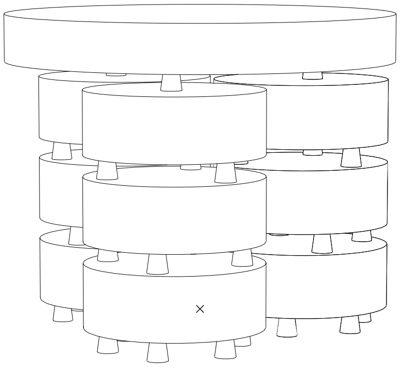
Approaches to limiting seismic noise

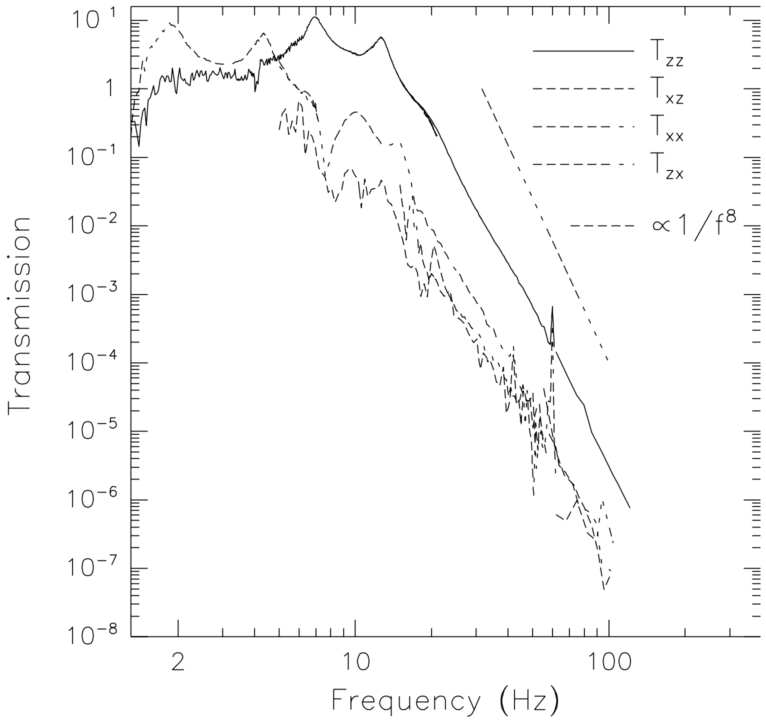
- careful site selection
    - far from ocean, significant human activity, continual seismic activity
- careful building design
    - low coefficient of drag for wind
    - low air velocities in HVAC, put refrigeration at a distance
- active control systems ($0.1 \rightarrow 30$ Hz)
    - accelerometer measures motion w.r.t. inertial mass
    - servo system and actuator corrects for perceived motion
- simple damped harmonic oscillators in series
    - LIGO: ‘stacks’, using lossy Viton springs and SS masses
    - VIRGO: multiple low-Q pendulums in a vertical chain
- one or more low-loss pendulums for final suspension
    - gives $1/f^2$ for each pendulum

Seismic Isolation systems

Passive elastomer-steel ‘stacks’

- damped SHOs in series
- in-vacuum: extra design constraints





Gravity Gradients

local 'static' gravitational force sum of mass distributions

- overwhelmingly dominated by unchanging average earth mass
- additional time-varying contributions from other sources:
- seismic compression
  - surface seismic waves compressing/rarefacting 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: roughly 10 Hz
- encourages space-based interferometers (different problems...)

Another crucial reason to make interferometers long:

these motions must be small compared with GW strains

Summary of initial interferometer

Optics

- Michelson interferometer to read out strain
- 10W Nd:YAG laser, stabilized in frequency, intensity, position
- vacuum path to control noise from residual gas
- baffles in beam tube to control scatter
- folded optical paths to increase interaction time with GW

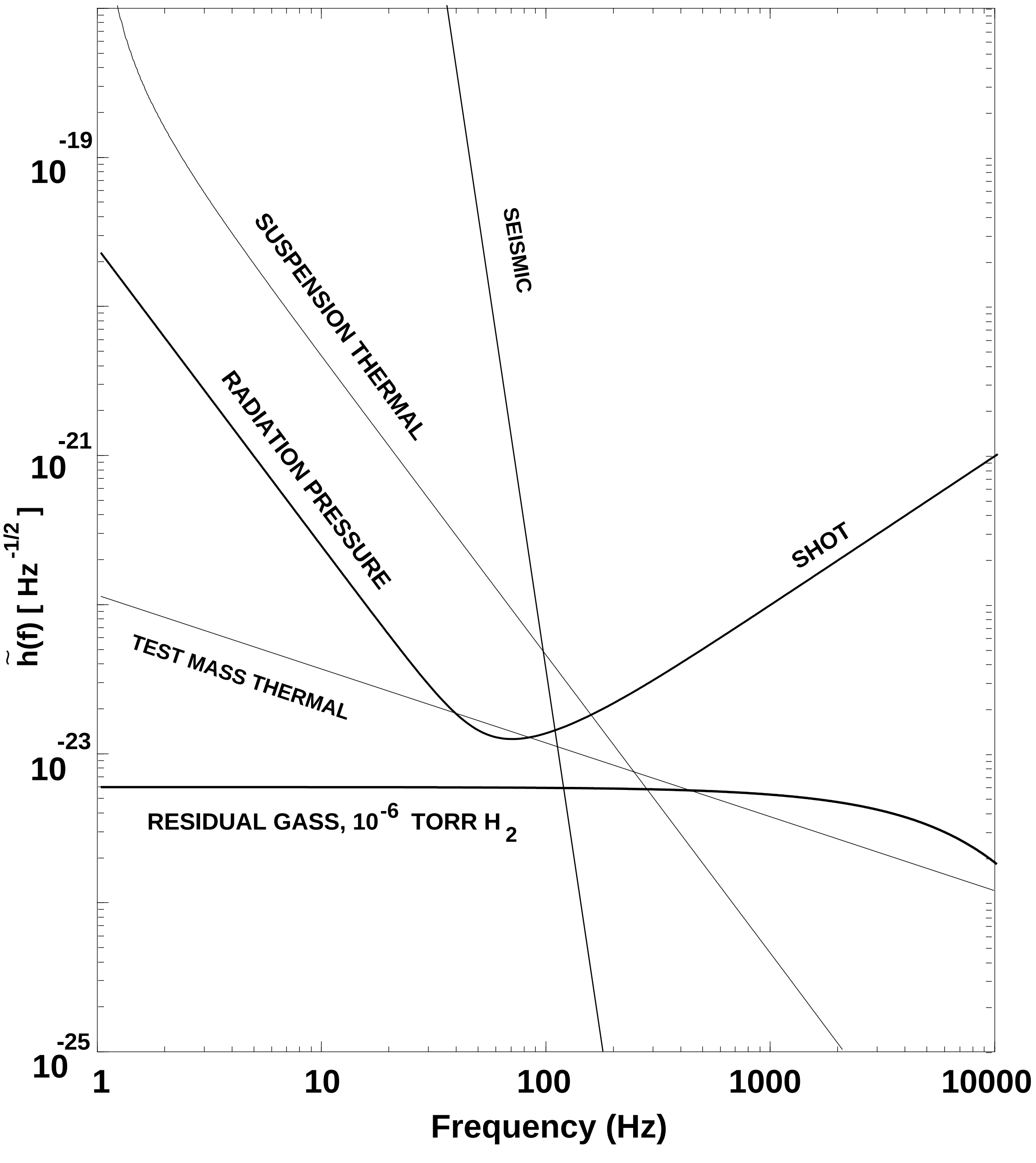
Mechanics

- thermal noise controlled by material selection, suspension
- 4 km long arms to keep mechanical noise terms manageable
- choice of sites, buildings limit input seismic noise
- seismic noise reduced by passive, active filters
- control systems to maintain interferometer operational

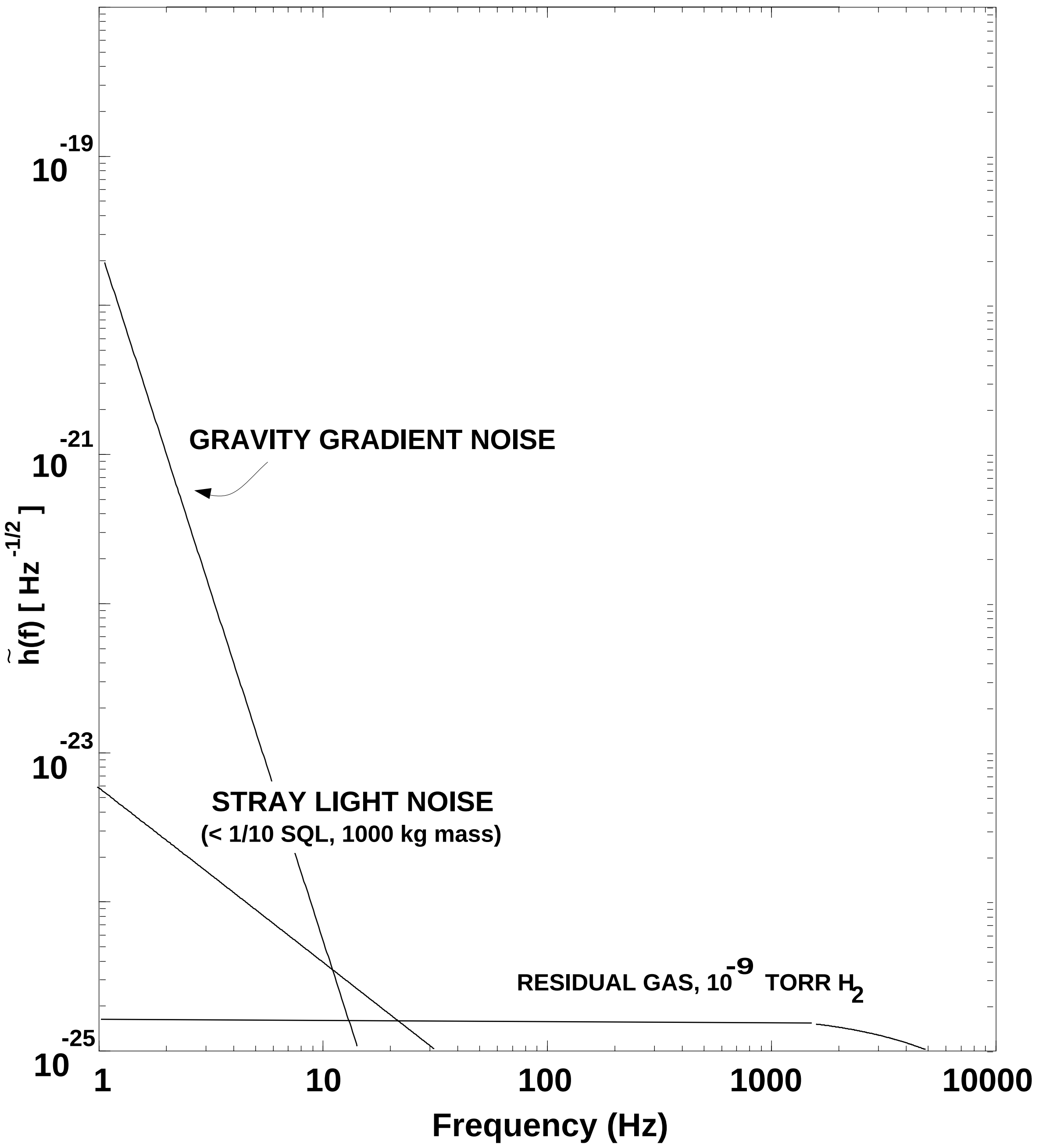
LISA: What changes for a space-based interferometer?

- still use Michelson interferometer, but no folding of arms
- arm lengths of 5×10^{9} meters, sensitivity $10^{-5}-10^{-1}$ Hz
- orbit at 1 AU, following earth
- drag-free technology instead of seismic isolation
- LOTS of guaranteed sources...and a target date of ~2015

Initial LIGO sensitivity



Limits due to facilities



LIGO

Observatory characteristics

- Two sites separated by 3000 km
- each site carries 4km vacuum system, infrastructure
- each site capable of multiple interferometers
- start with 2 (full, half-length) at one site, 1 at other site
- coincident observation in all 3 interferometers
  - crucial to reduce accidentals due to non-gaussian noise

Evolution of interferometers in LIGO

- initial ifos to be used in coincidence with French/Italian VIRGO
- and other interferometers: German/Scots, Japanese, Australian
- multiple users of LIGO, simultaneous operation, focussed searches
- lifetime of >20 years
- goal: to be compatible with all technology developments for terrestrial interferometers

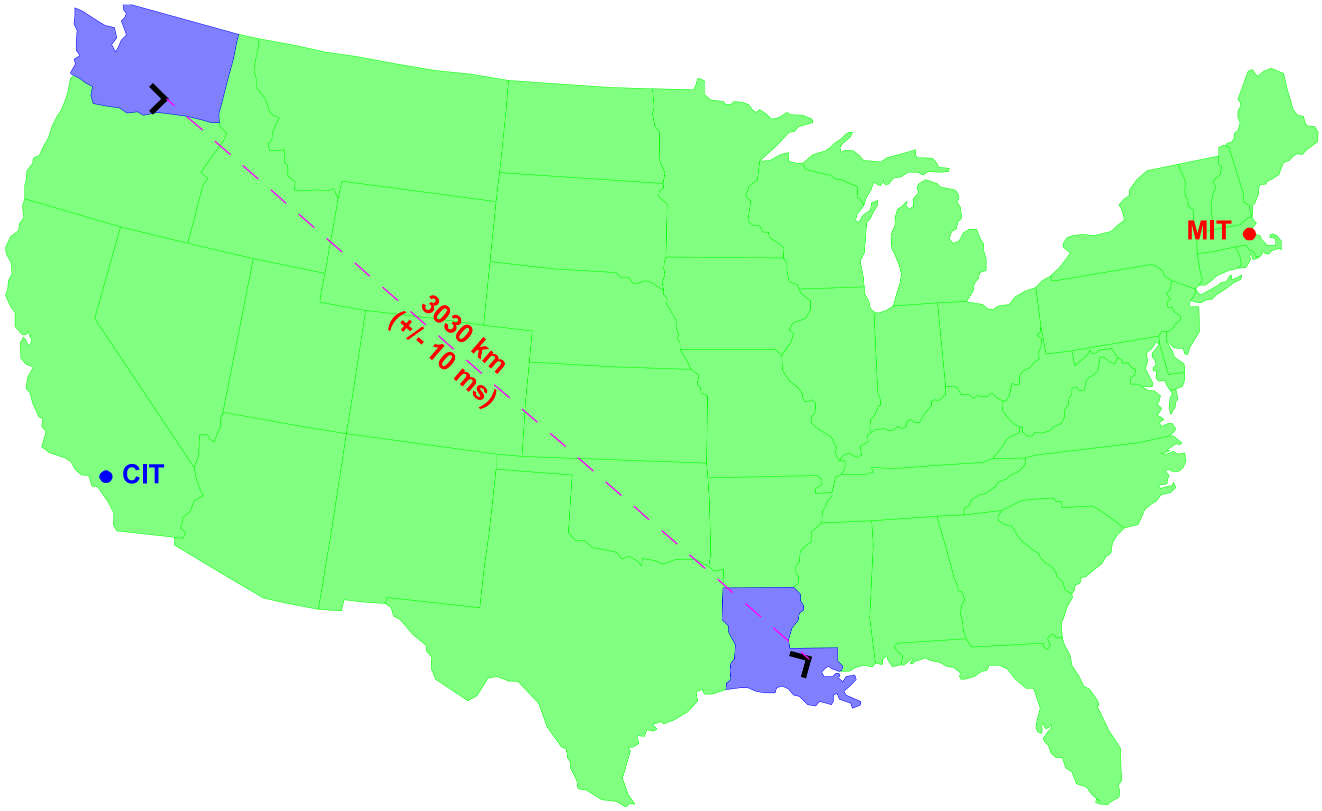
LIGO Sites

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 Status

Civil construction (Parsons)

- rough grading finished at both sites
- preliminary design review November
- buildings to be finished mid-’98

Beam tube (Chicago Bridge & Iron)

- beam tube test (preparation, welding, cleaning, leak test)
- final arrangements for fabrication
- beam tubes and covers to be finished spring ‘98, spring ‘99

Vacuum Equipment (Process Systems International)

- conceptual design finished
- preliminary design review October
- vacuum equipment installed end-’98

Detector (MIT/CIT)

- R&D well advanced on subsystems
- detailed tests on high-sensitivity prototypes at MIT and CIT
- interfaces and detailed requirements for subsystems underway
- subsystems delivered early-’99
- **first observations in 2001**