

LIGO: Progress toward Gravitational Wave Detection

David Shoemaker
MIT, LIGO Project

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Organization of talk

- follow several limitations to sensitivity from physics to solutions
- overview of LIGO, status

LIGO: Laser Interferometer Gravitational-Wave Observatory

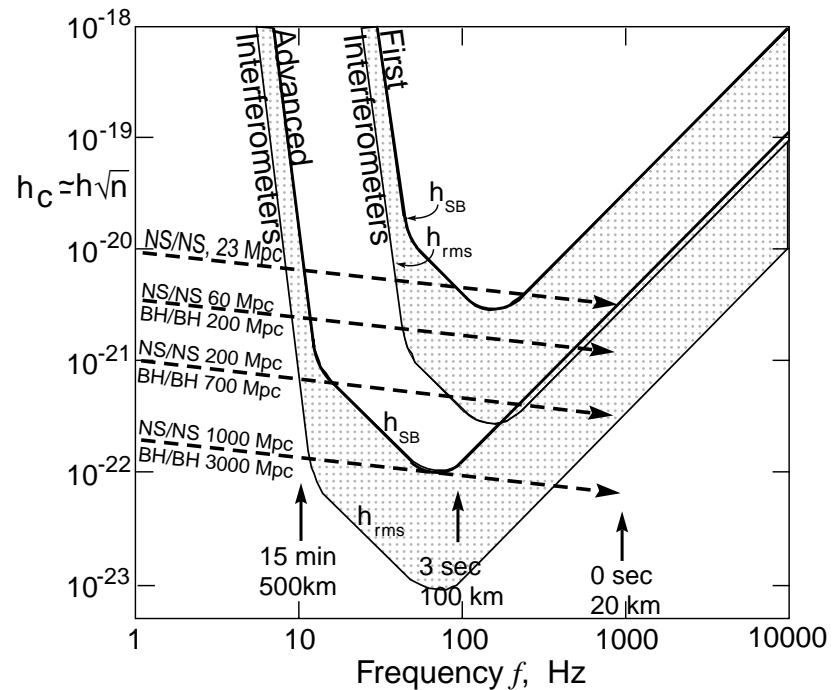
- project to build observatories for gravitational waves (GWs)
- two sites, each with a 4km installation
- to enable an initial detection, then an astronomy of GWs
- group effort of colleagues at MIT, Caltech
- supported by the National Science Foundation

Coalescing Compact Binaries

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 (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

- binaries, early in life (space-based detectors needed)
- asymmetric pulsars (e.g., Crab): synchronize with Radio signals

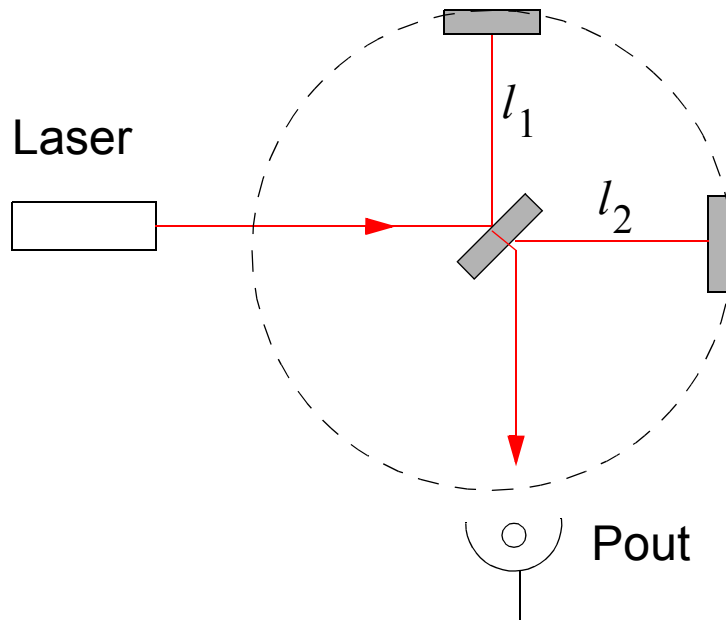
Resume of sources

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

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

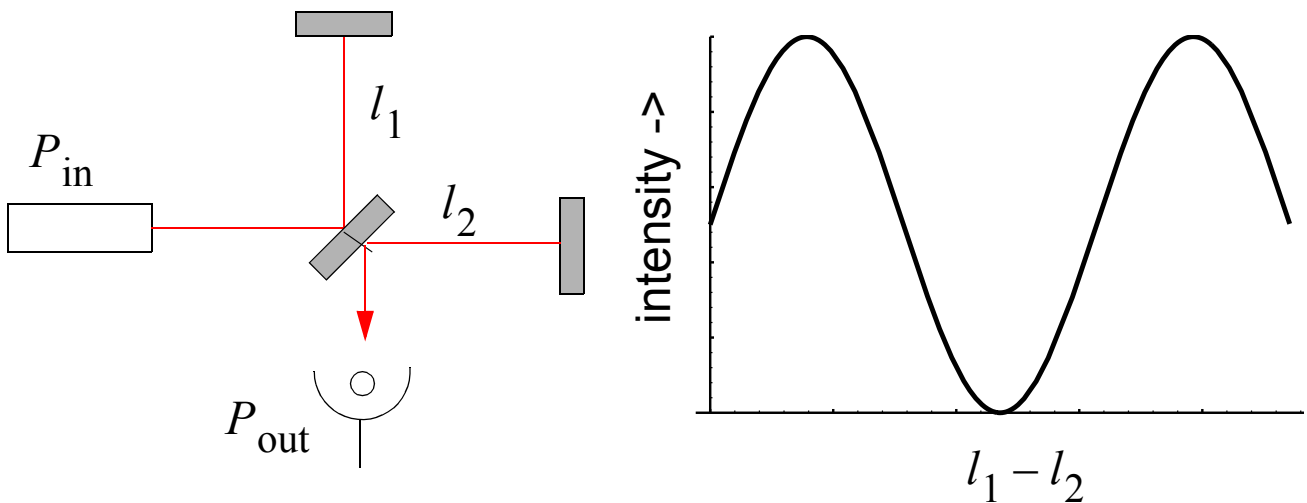
Fundamental limits

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: $h_{\text{shot}} = \frac{\delta l}{L} = \frac{1}{L} \sqrt{\frac{h_{\text{pl}} c \lambda}{2\pi P_{\text{in}}}}$
- Note: scaling with $1/\sqrt{P_{\text{in}}}$; gives requirement for laser power



Quantum Noise

Radiation Pressure

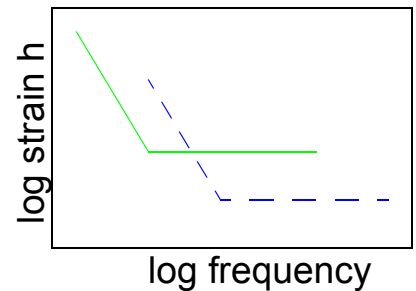
- quantum-limited intensity fluctuations anti-correlated in two arms
 - > can be seen as the action a statistical beamsplitter
 - > better, as result of vacuum fluctuations entering 'dark port'
- photons exert a time varying force, with spectral

$$\text{density } \tilde{f} = \sqrt{\frac{2\pi h P_{\text{in}}}{c\lambda}}$$

- results in opposite displacements of EACH of the masses:

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

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



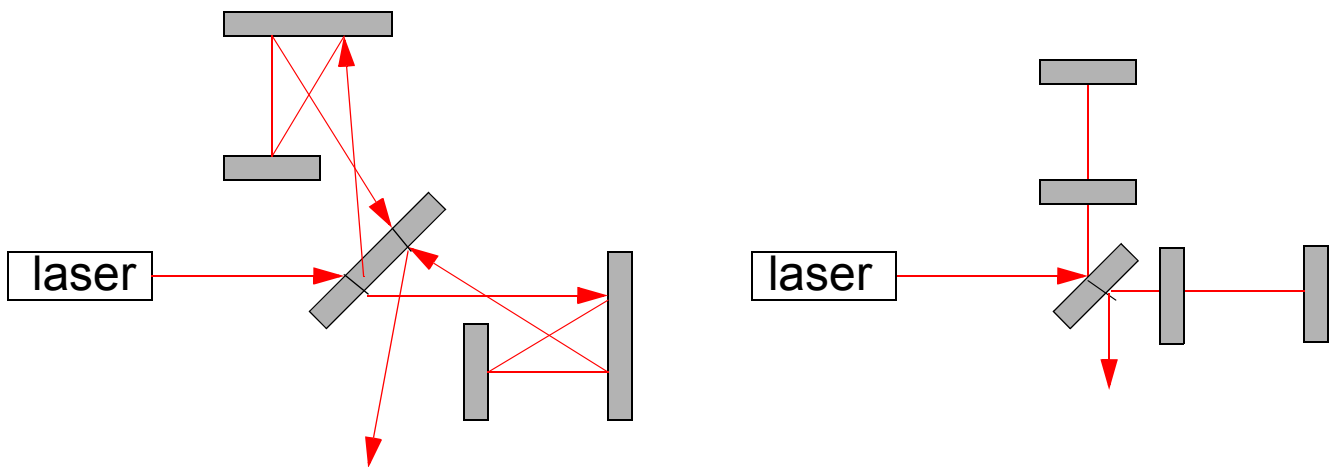
Total readout, or quantum noise

- quadrature sum $i_q = (h_{\text{shot}}^2 + h_{\text{rad press}}^2)^{1/2}$
- 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

Interaction time with the GW

- signal δl grows as length of interferometer L grows
- up to limit where $L \approx \lambda_{\text{GW}}/4$, 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
- 1 msec storage time for initial system
 - > optimum sensitivity around 100 Hz; ~ 100 bounces, $\sim 4\text{km}$

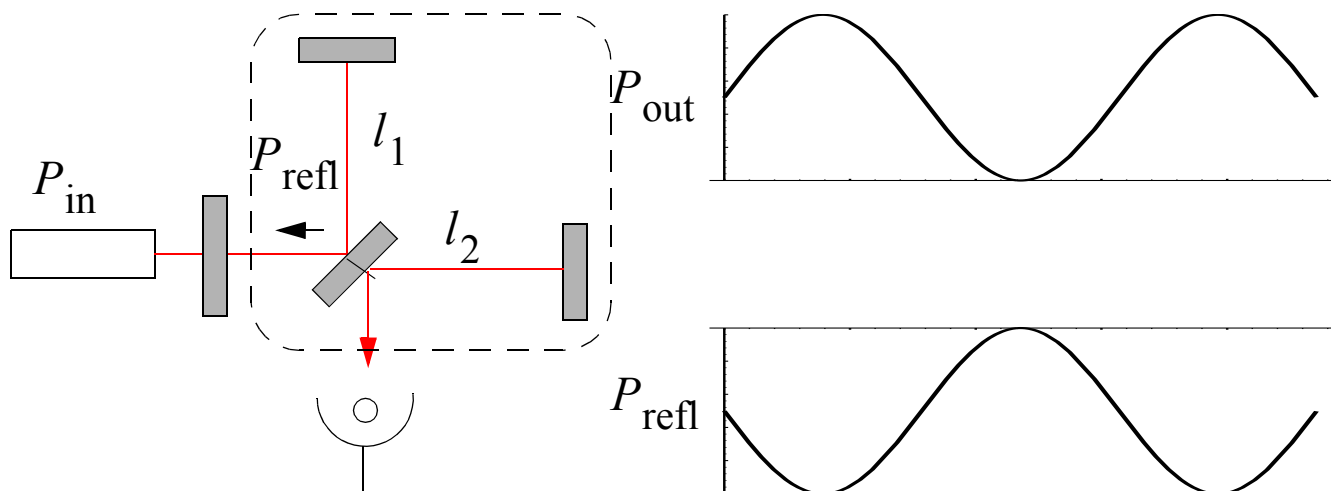
Realistic optical configurations

Insufficient raw laser power

- predicted sources require shot noise of ~ 300 W on beamsplitter
- suitable lasers produce ~ 10 W, only ~ 5 W 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?

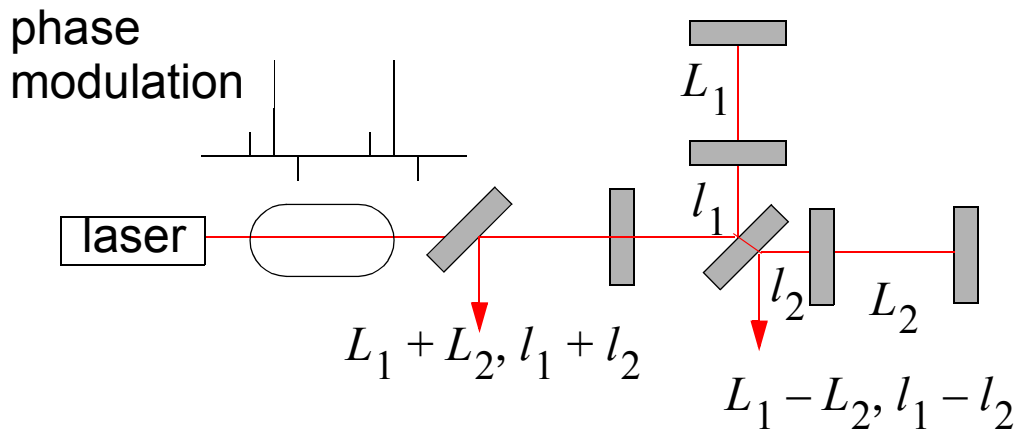
- increases stored energy
- just extract small amount (10^{-40} or so) if GW passes

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

Analyze as common mode/differential mode



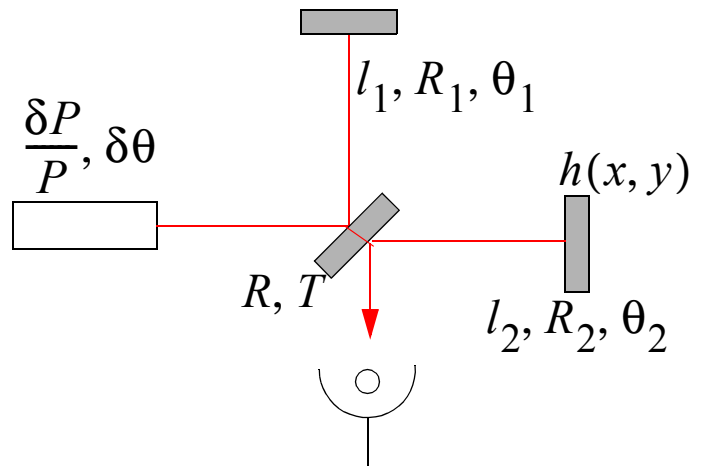
Angular alignment also required

- all optical cavity axes must be aligned with input beam
- leads to $\sim 10^{-8}$ 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

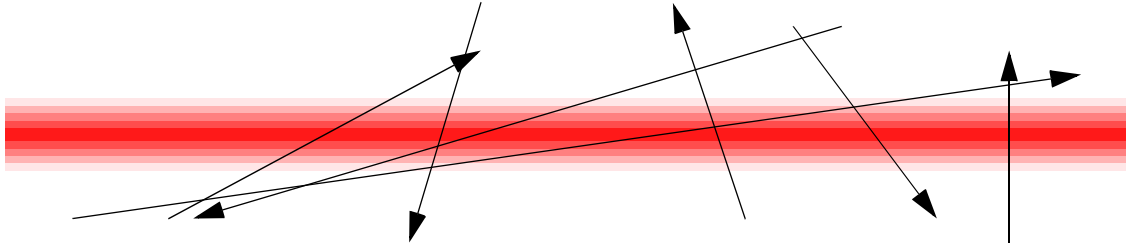


Much of the technical effort goes into these noise sources

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

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
 - > 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
 - > H₂ of 10⁻⁶ torr initial, 10⁻⁹ torr ultimate
 - > H₂O 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 cm²
- requires strict control on in-vacuum components, cleaning

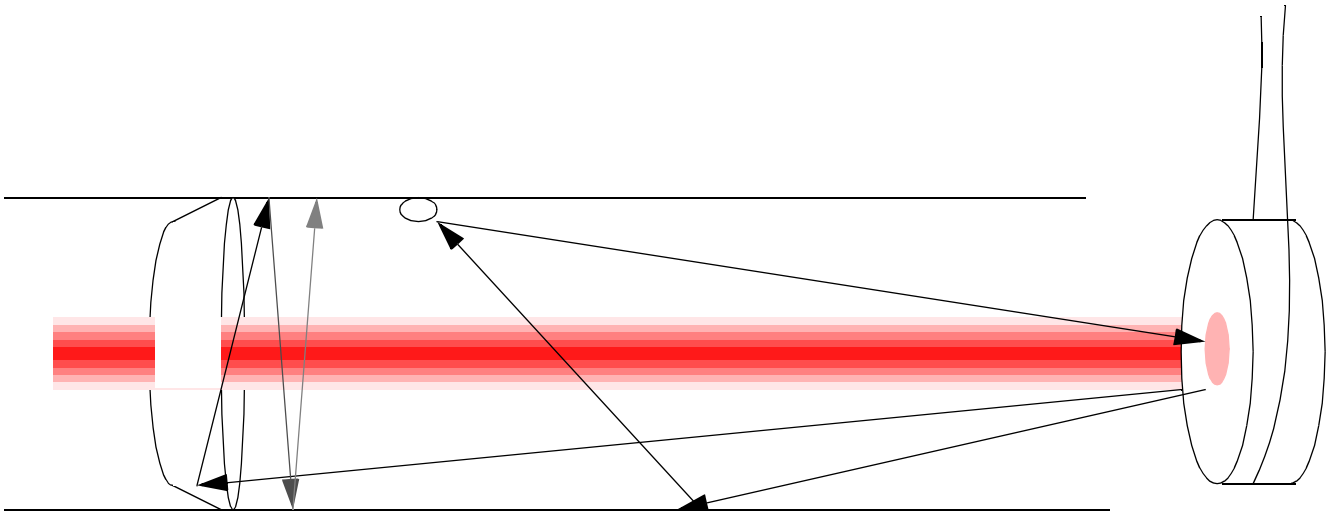
Scattered light

Scattered light: ~ 60% of light lost here!

- most is lost as heat (to walls of beam tube)
- 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 $\sim \lambda/800$ 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



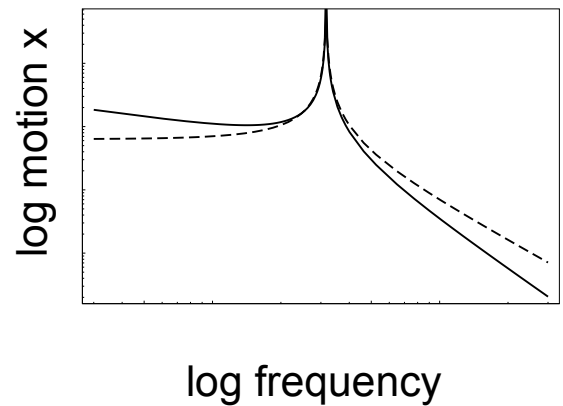
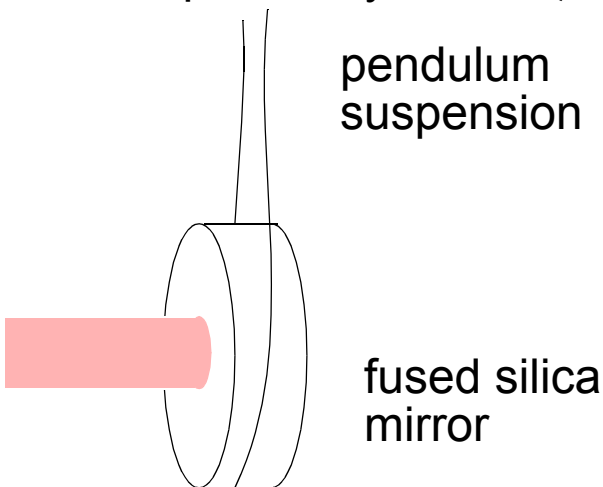
Thermal Noise

Mechanical systems excited by the thermal environment

- results in physical motions of the test masses
- total energy of $k_B T$, leads to $\tilde{x} = \sqrt{\frac{k_B T}{k_{\text{spring}}}}$ for integrated motion
- spectrum according to Fluctuation-Dissipation theorem:

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

- 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
- for LIGO sites, characterized by $10^{-7}/f^2$ m/ $\sqrt{\text{Hz}}$
- 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
- 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
 - > Viton (or constrained layer) springs and SS masses
- one (or later, more) low-loss pendulums for final suspension
 - > gives $1/f^2$ for each pendulum

Gravity Gradients

Local 'static' gravitational force sum of mass distributions

- 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 , $\vec{F}(t) = \frac{GM(t)m\hat{r}}{r^2}$

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**

Summary of initial LIGO interferometer

Optics

- Michelson interferometer to read out strain
 - > Fabry-Perot cavities to increase interaction time with GW
 - > power recycling of light to achieve ~300 W circulating
 - > 25cm diameter, 10cm thick mirror-testmasses
 - > sub-nm optics surface figure
- 10W Nd:YAG laser, stabilized in frequency, intensity, position
 - > to use monolithic master oscillator, multipass amplifier
- vacuum path to control noise from residual gas
 - > 10,000 cubic meters of UHV (10^{-9} torr ultimate)
- baffles in beam tube to control scatter
 - > glass on stainless steel (kitchen pot technology)

Mechanics

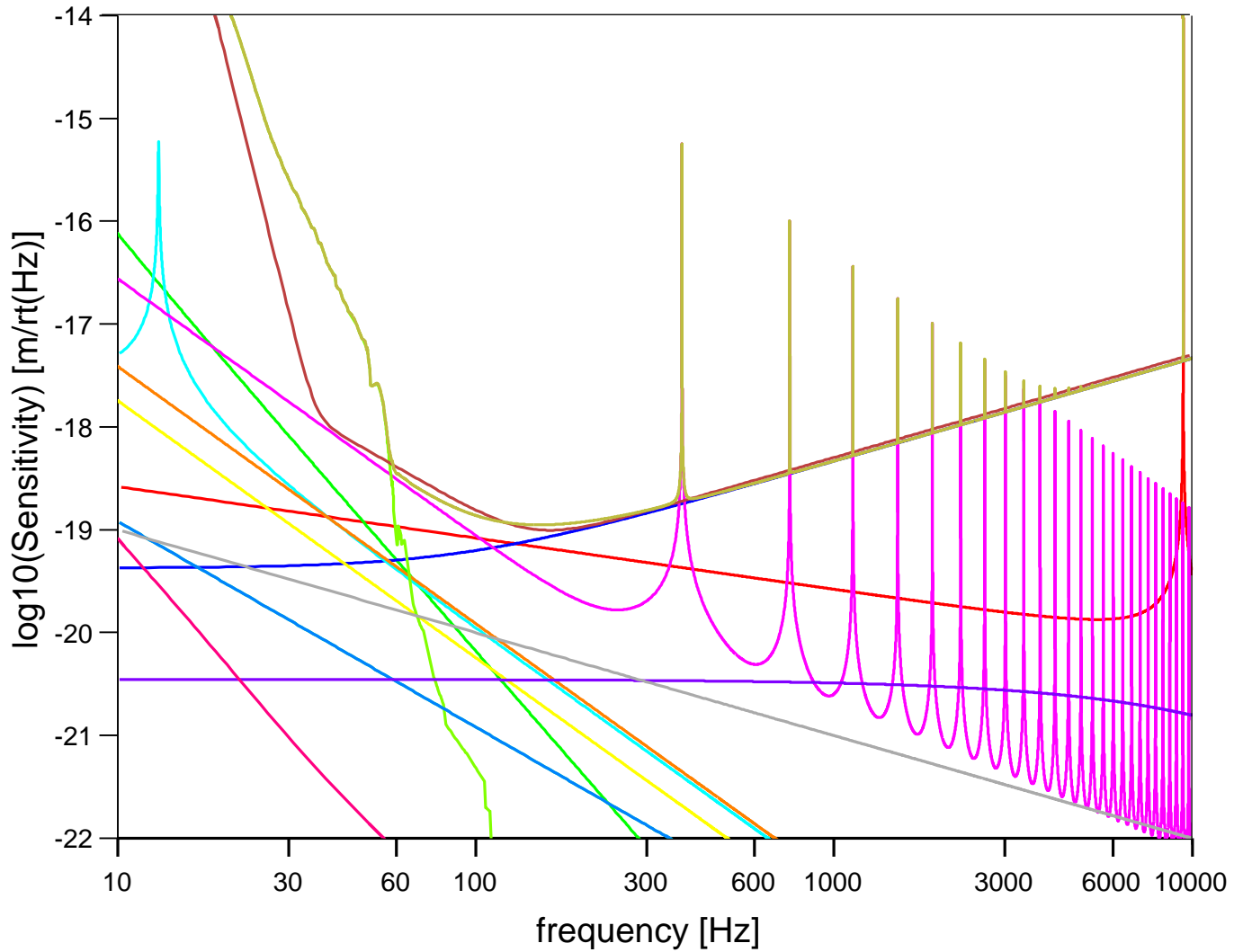
- thermal noise controlled by material selection, suspension
 - > fused quartz test masses, steel wire suspension
- 4 km long arms to keep mechanical noise terms manageable
 - > close to point of diminishing returns for today's technology
 - > earth curvature gives vertical to horizontal coupling
- choice of sites, buildings limit input seismic noise
- remaining seismic noise reduced by passive, active filters
- control systems to maintain interferometer operational

LISA and Earth interferometers

Similarities, Differences, Challenges

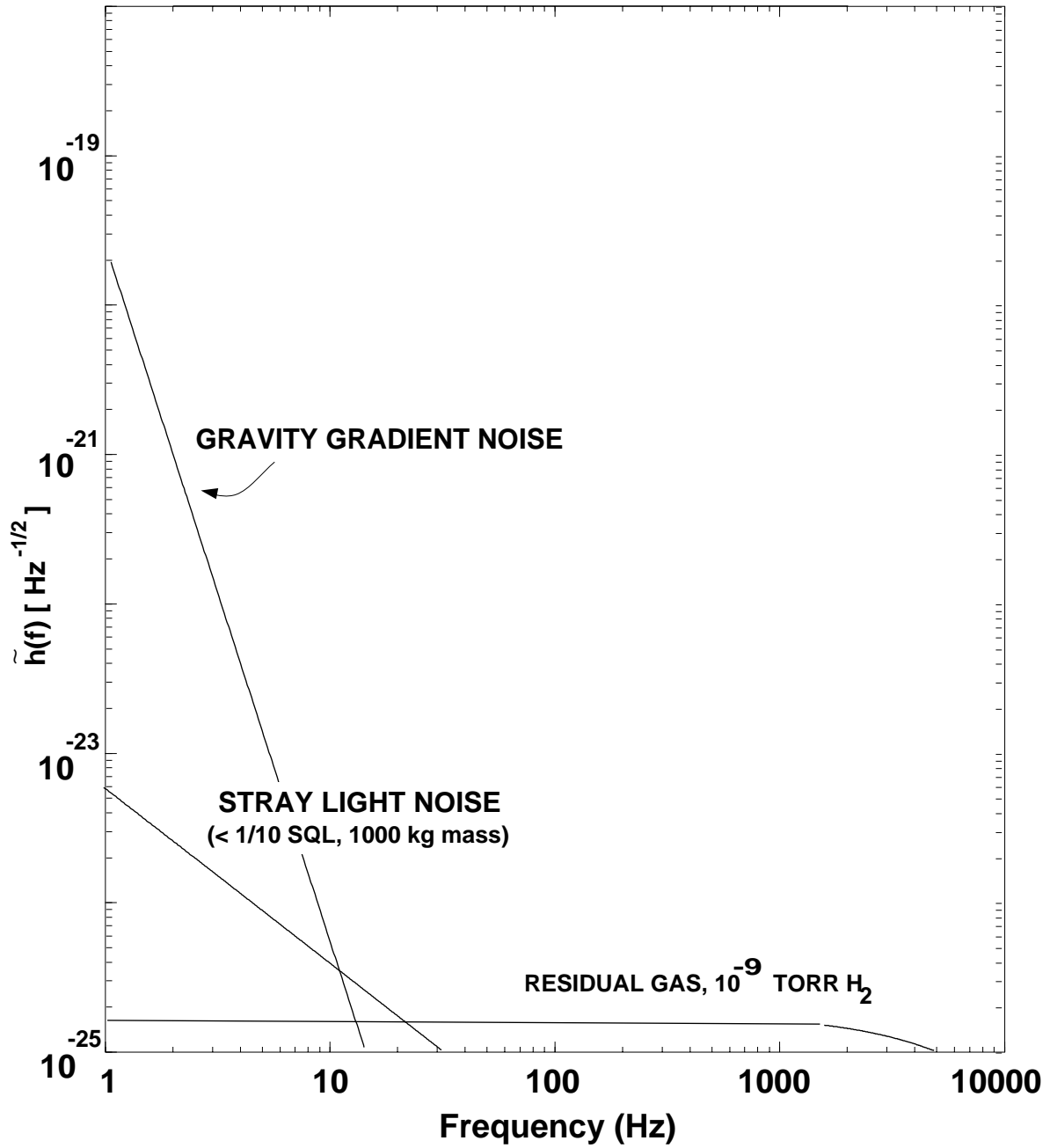
	Ground-based	LISA
Frequency Range	$10^{+1} - 10^{+4}$ Hz	$10^{-4} - 10^{-1}$ Hz
Burst/Integrated strain sensitivity	$\sim 10^{-23}$ (at ~ 100 Hz)	$\sim 10^{-23}$ (at ~ 0.001 Hz)
Arm Length	$\sim 10^{+3}$ m	$\sim 10^{+9}$ m
Displacement sensitivity	$\sim 10^{-19} \frac{\text{m}}{\sqrt{\text{Hz}}}$	$\sim 10^{-12} \frac{\text{m}}{\sqrt{\text{Hz}}}$
Stochastic forces	seismic isolation, suspensions, thermal noise	inertial sensing, drag-free technology, thermal distortions
Sensing system	laser power, optics development	clocks and corrections, transponding system

Initial LIGO sensitivity



(model 'snapshot' of mid-July 96)

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
 - > to reduce accidentals due to non-gaussian noise

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

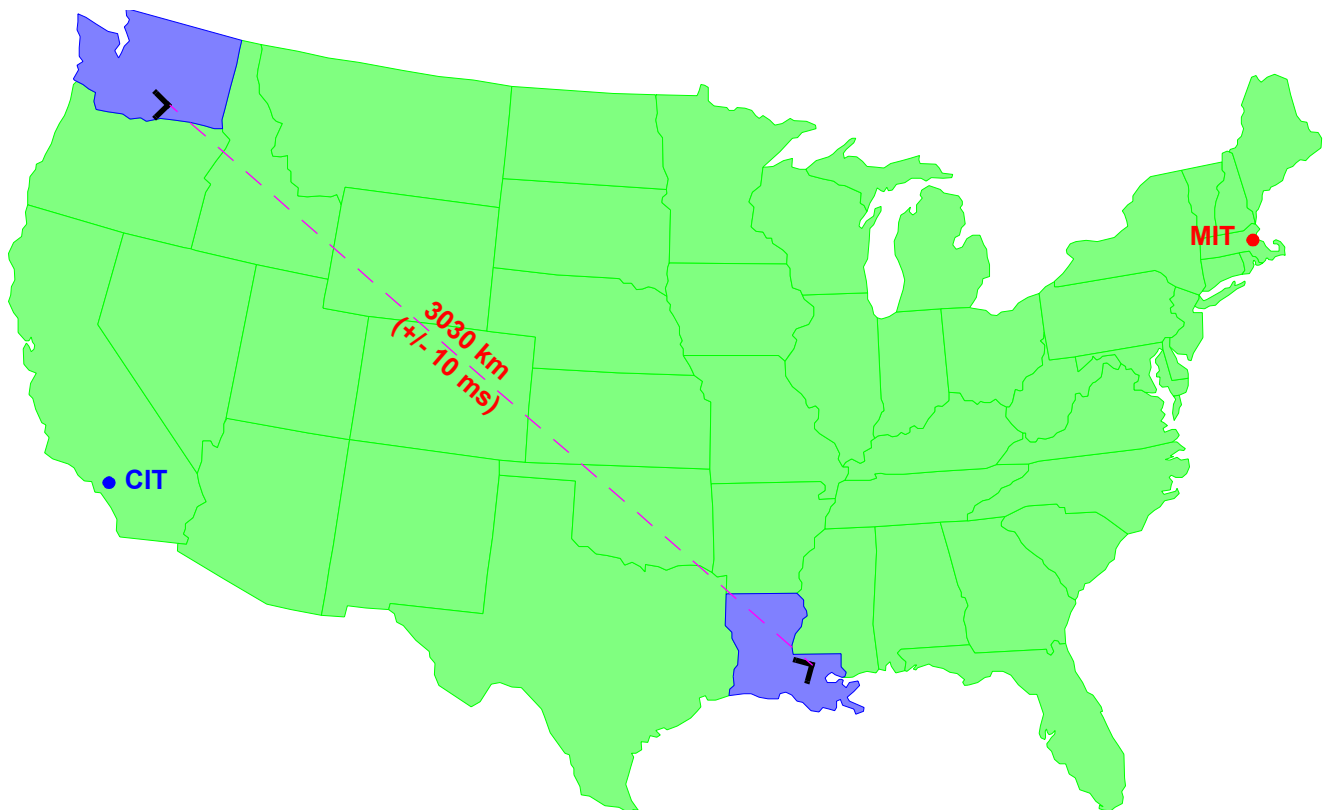
LIGO Sites

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, Levernier)

- beam tube slab finished in WA, covers in fabrication
- buildings in WA in construction
- buildings to be finished 9-97 (WA), 3-98 (LA)

Beam tube (Chicago Bridge & Iron)

- steel mill setup near WA site, welder set up, steel pre-baked
- baffles in fabrication (baked glass on stainless steel)
- beam tubes and covers to be finished spring '98, spring '99

Vacuum Equipment (Process Systems International)

- first article chamber in fabrication
- big gate valves in test
- vacuum equipment installed 3-98, 9-98

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
- **coincidence tests in 2001**