# LIGO: Progress toward Gravitational Wave Detection

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**Organization of talk**

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

# Introduction

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

- 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

**MIT:**

| **Scientists** | **Graduate students** | **Engineering, Technical, Support** |
|---|---|---|
| Peter Fritschel | Brett Bochner | Ralph Burgess |
| Gabriela Gonzalez | Peter Csatorday | Tom Evans |
| David Shoemaker | Brian Lantz | Ed Kruzel |
| Daniel Sigg | Nergis Mavalvala | Will Plummer |
| Kris Sliwa (Tufts) | Partha Saha | Michael Richard |
| Rai Weiss | | John Tappan |
| Mike Zucker | | |

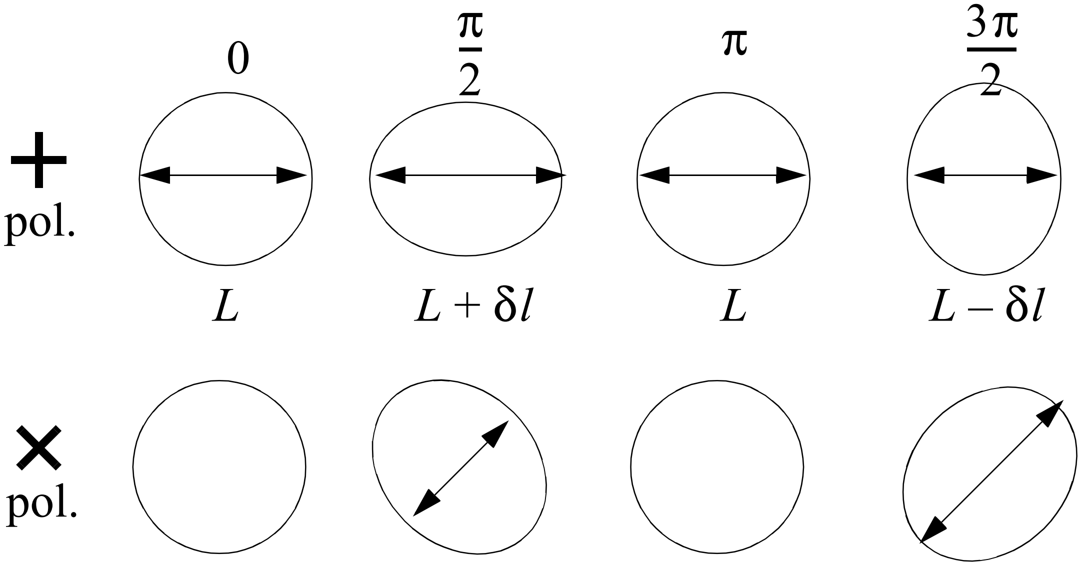
**Other efforts**

- VIRGO: French-Italian, one 3 km antenna near Pisa
- GEO-600: German-Scots, one 600 m antenna near Hannover
- TAMA-300: Japanese, one 300 m ‘antenna’ near Tokyo

# 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 $L$



- **This is the key for the detection of GWs**

# 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
- 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

# Contrast with E&M astrophysical sources

| **E&M** | **GW** |
|---|---|
| space as medium for field | spacetime itself |
| incoherent superpositions of atoms, molecules | coherent motions of huge masses (or energy) |
| wavelength small compared to sources - images | wavelength ~large compared to sources - no spatial resolution |
| absorbed, scattered, dispersed by matter | very small interaction; no shielding |
| $10^7$ Hz and up | $10^4$ Hz and down |

- very different information
- mostly mutually exclusive
- difficult to predict GW sources based on E&M observations

# Coalescing Compact Binaries

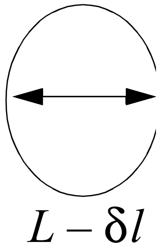
**Standard candle: Binary stars**

- 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.

**for most of life, waveform well known if masses known**

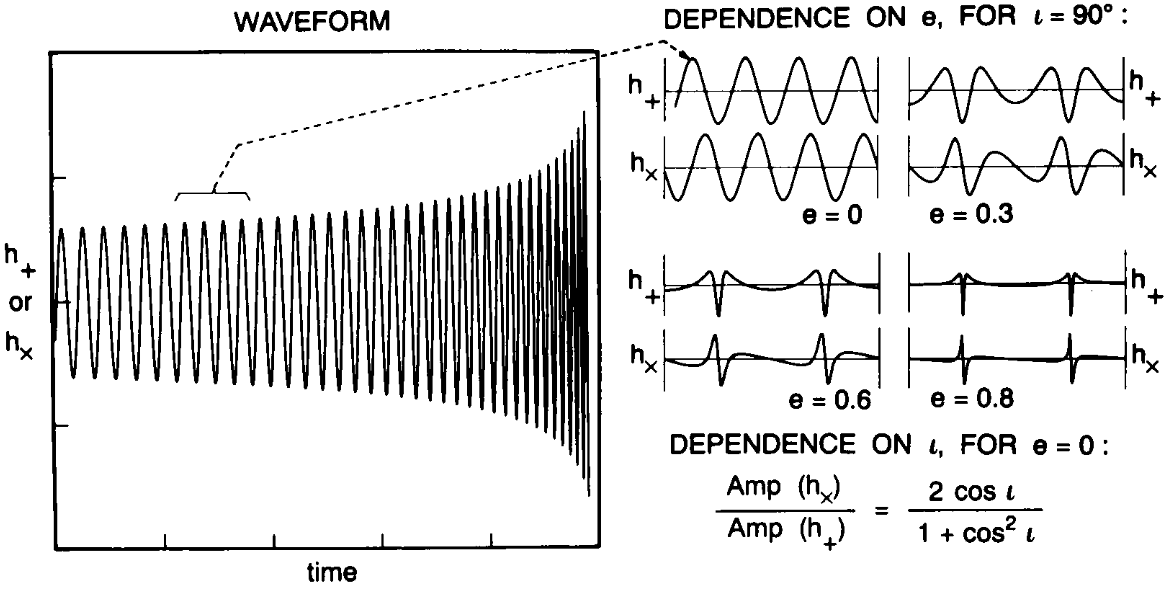
- Newtonian/quadrupole approximation
- allows calculation of signal amplitudes, optimal filters
- measurable relativistic corrections ~10%; requires 3 PN orders
- end of life (coalescence) yet to be calculated (measure first?)
- typical number: $h \approx 10^{-21}$ for 1.4 $M_o$, 200 Mpc, ~3 events/yr.

- since $h = \delta l / L$, expect $\delta l = 10^{-21}$ m for $L = 1$ m



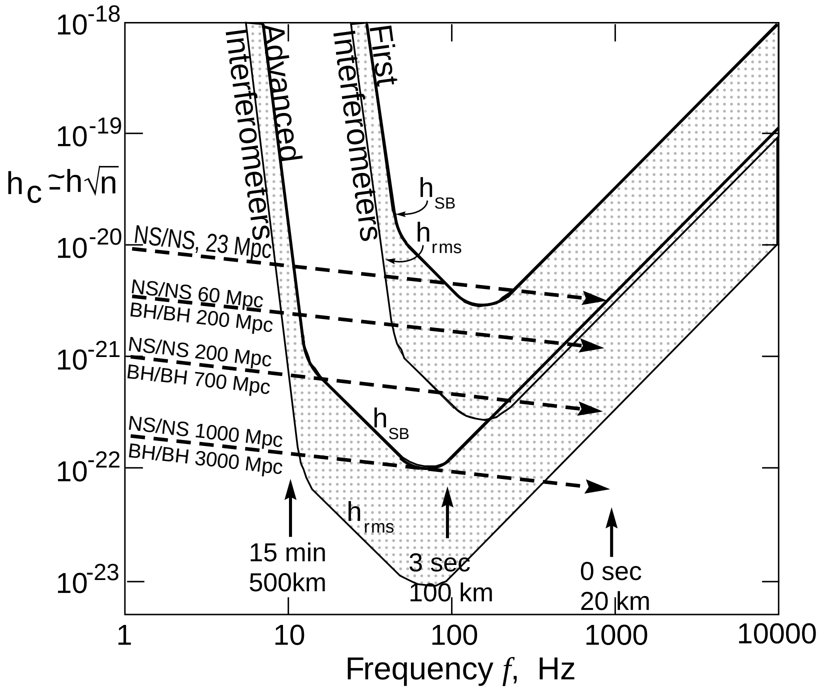
# Coalescing Compact Binaries

**Waveforms of final minutes, for various ellipticities**



$$\frac{\mathrm{Amp}\ (h_\times)}{\mathrm{Amp}\ (h_+)} = \frac{2\cos\iota}{1+\cos^2\iota}$$

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)

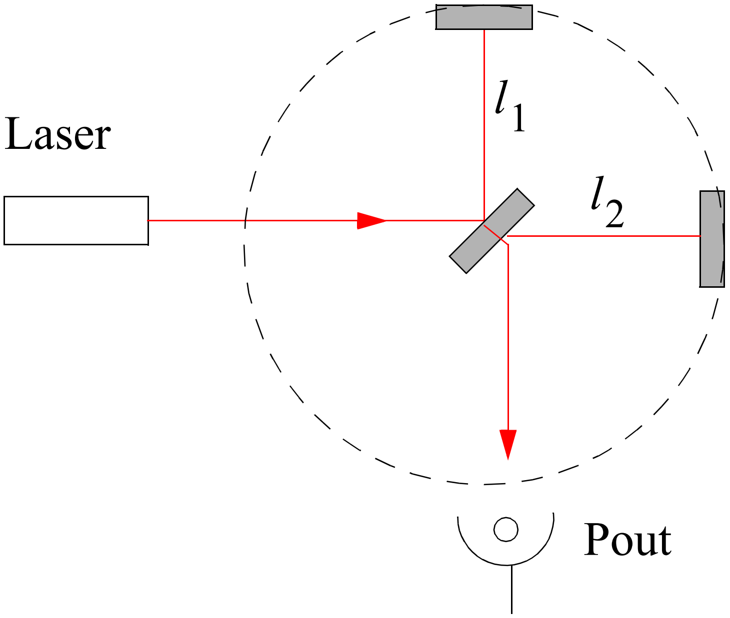
**Resume of sources**

- sources with well-understood signal forms
- sources with several possible forms
- uncertain rates, signal sizes
- surprises: a new domain, hidden from radio, visible

# 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

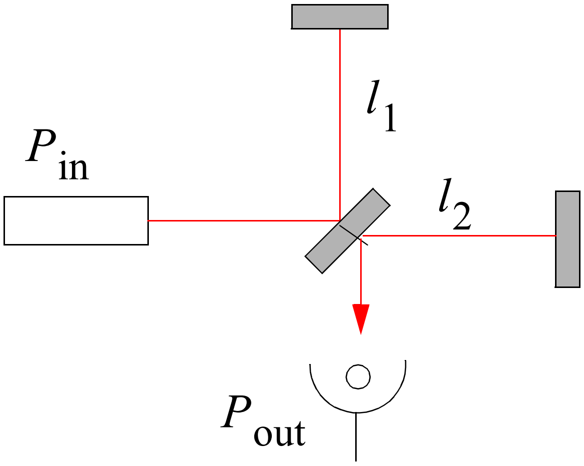
# Fundamental limits

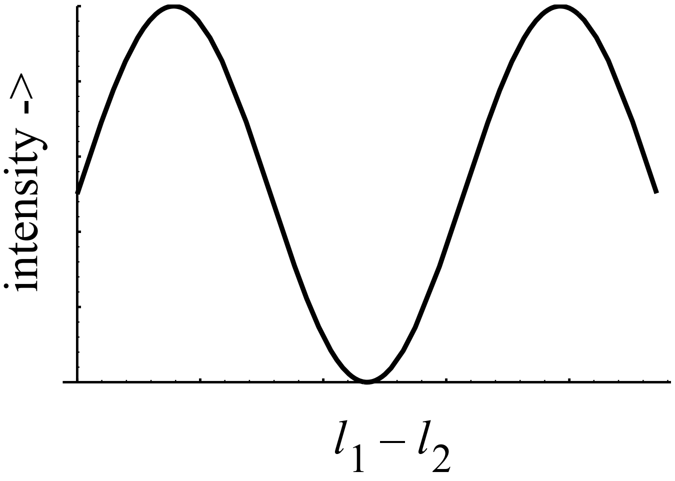
**Shot or Poisson noise**

- 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**

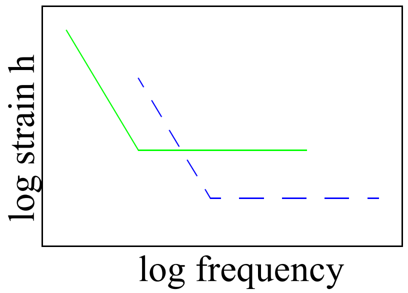
- quantum-limited intensity fluctuations anti-correlated in two arms
  - can be seen as the action a statistical beamsplitter
  - better, as result of vacuum fluctuations entering ‘dark port’
- photons exert a time varying force, with spectral

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

- results in opposite displacements of EACH of the masses:

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

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



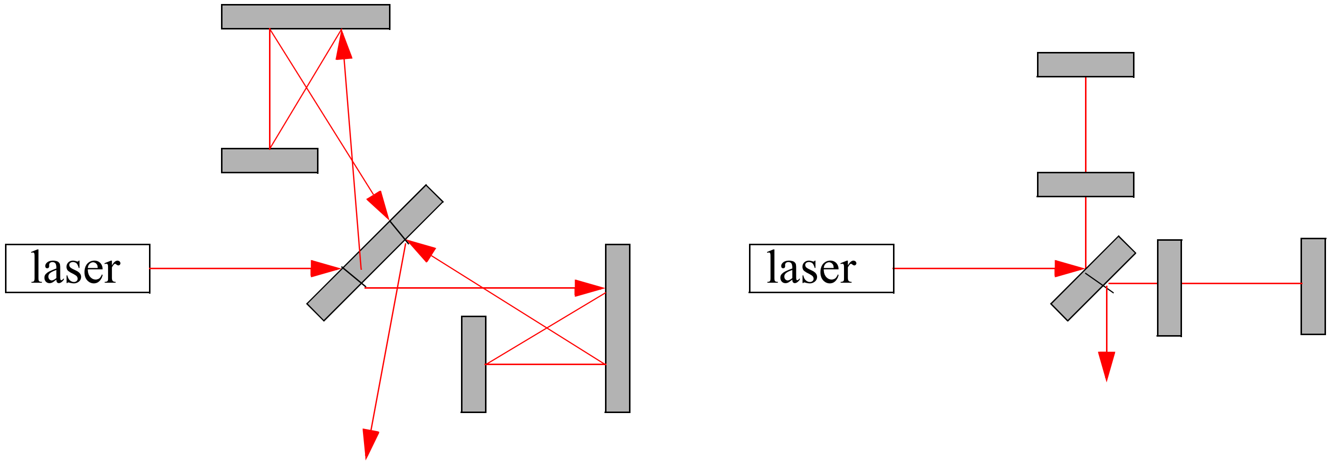
**Total readout, or quantum noise**

- quadrature sum $h_{\text{q}} = (h_{\text{shot}}^2 + h_{\text{rad press}}^2)^{1/2}$
- 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 $\delta l$ grows as length of interferometer $L$ grows
- up to limit where $L \approx \lambda_{GW}/4$, 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 ground-based system
  - › optimum sensitivity around 100 Hz; ~100 bounces, ~4km

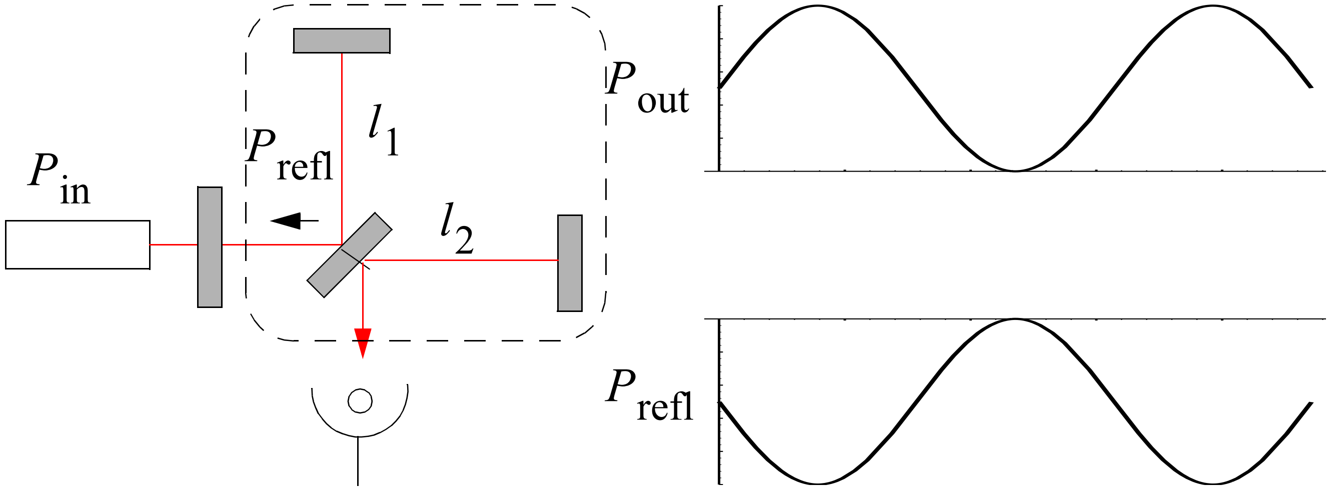
# Realistic optical configurations

**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?**

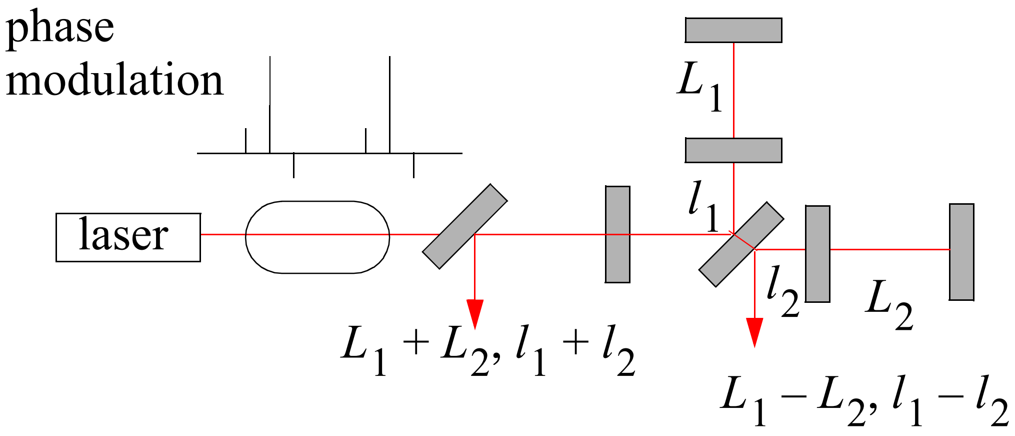
- no, cannot use all that light to heat room
- just extract small amount ($10^{-20}$ or so) if GW passes

# 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**



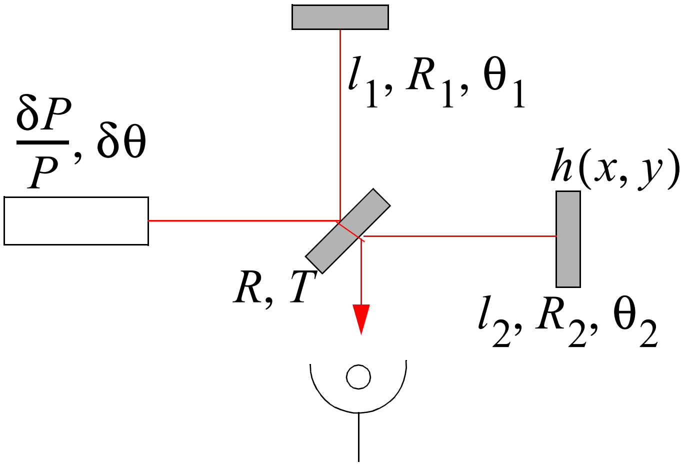
**Angular alignment also required**

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



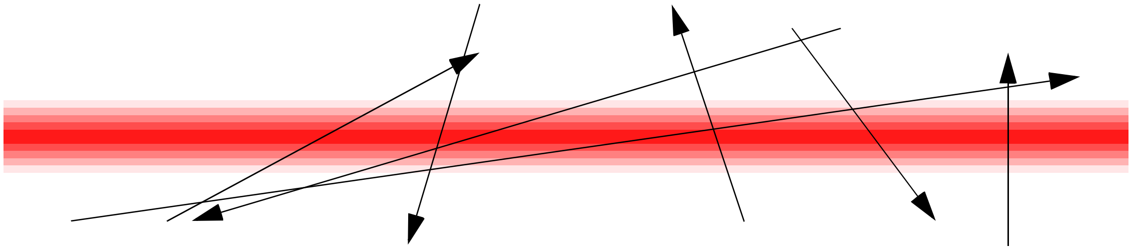
- laser source
  - fluctuations greater than shot noise
  - angular or translational beam pointing fluctuations
- sensing systems
  - linearity
  - spatial uniformity

**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
  - $H_2$ 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’
- requires strict control on in-vacuum components, cleaning

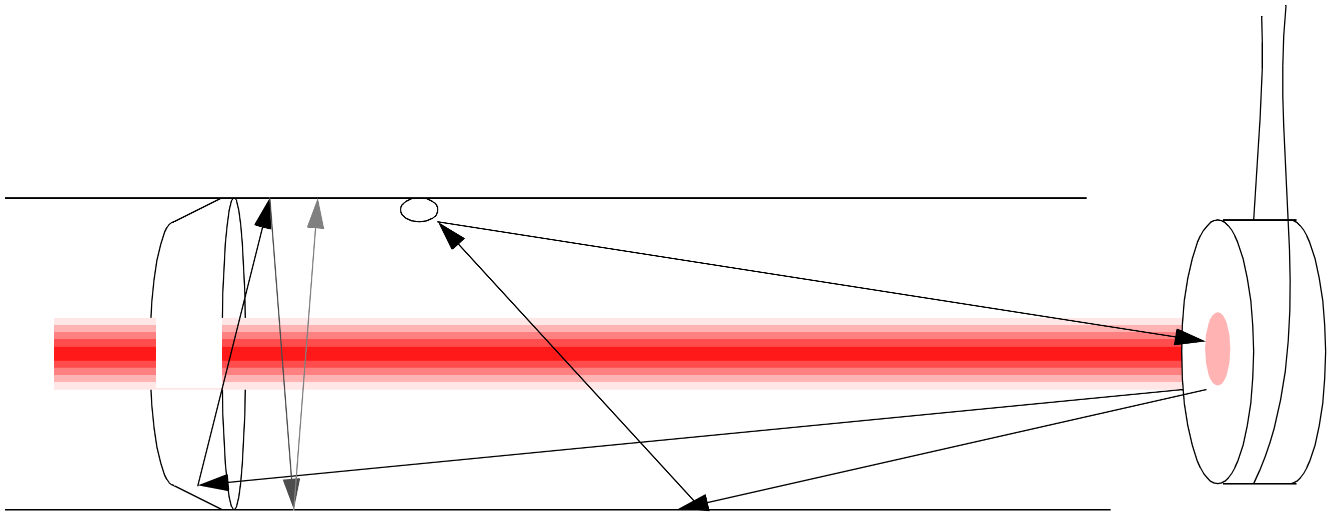
# Scattered light

**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 ~$\lambda/800$ 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

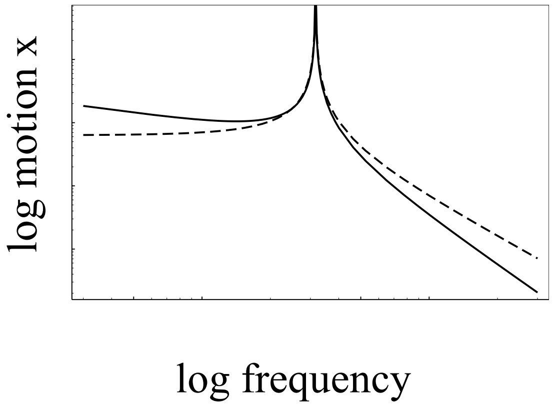
**Mechanical systems excited by the thermal environment**

- 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



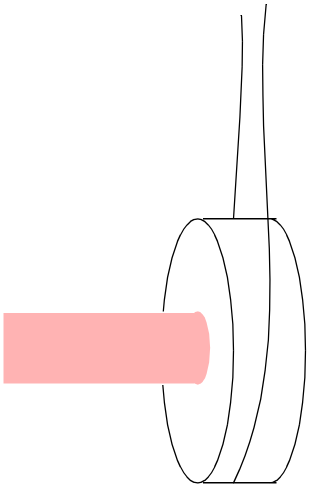
# Thermal Noise

**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***

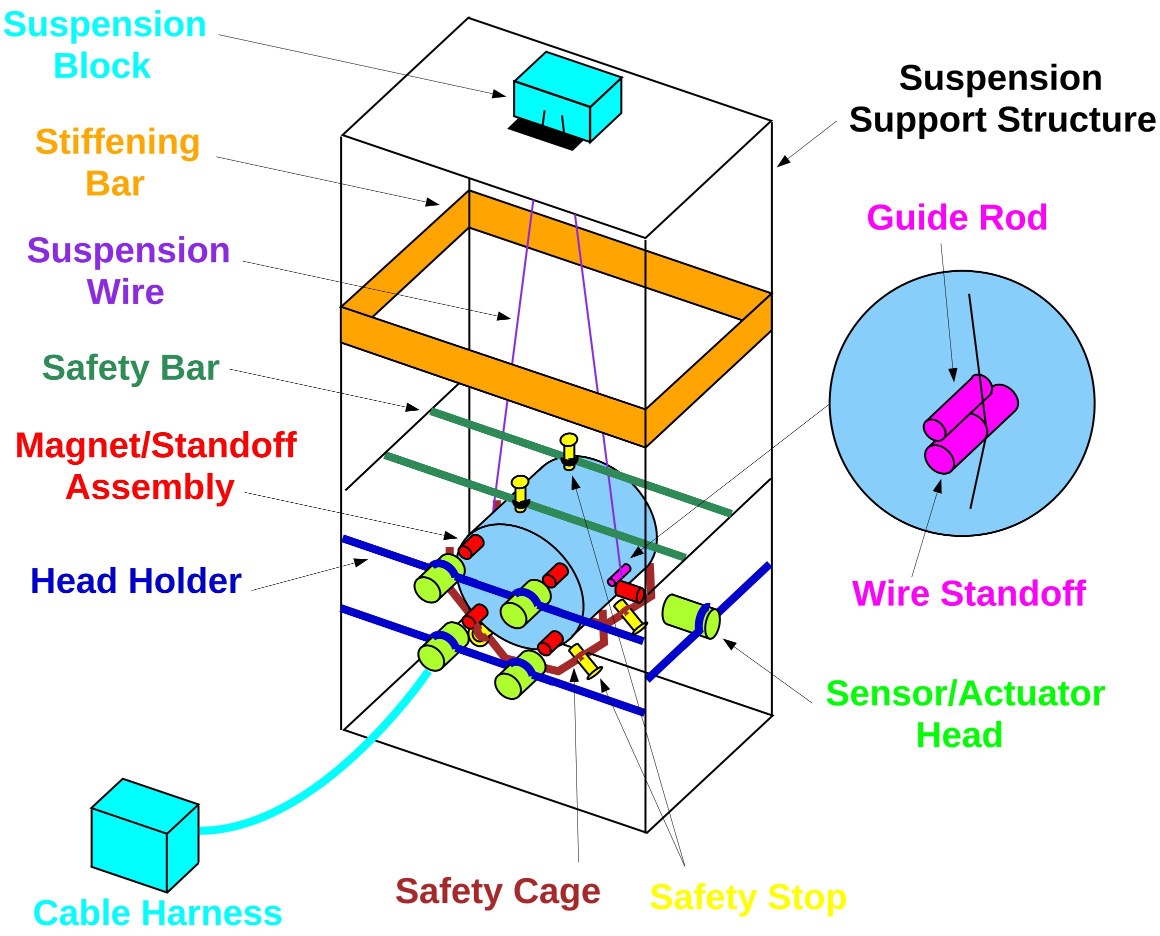
**Thermal (with other stochastic force terms) determines *L***

**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
- ~300 micron tidal motion, microseismic peak at 0.16 Hz...

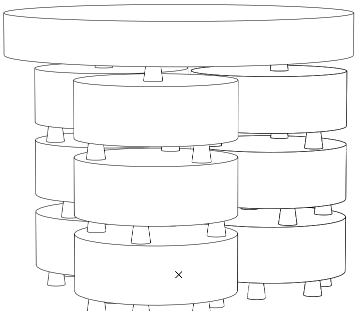
**Approaches to limiting seismic noise**

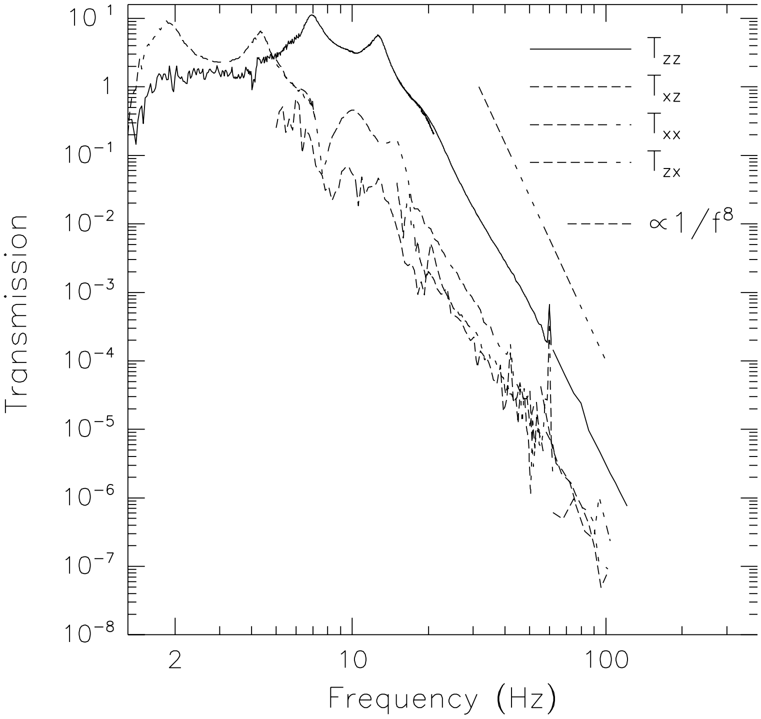
- careful site selection
  - far from ocean, significant human activity, seismic activity
- careful building design
  - low coefficient of drag for wind
  - low air velocities in HVAC, put refrigeration at a distance
- active control systems ($0.1 \to 30$ Hz)
  - accelerometer measures motion w.r.t. 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**

- 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: 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

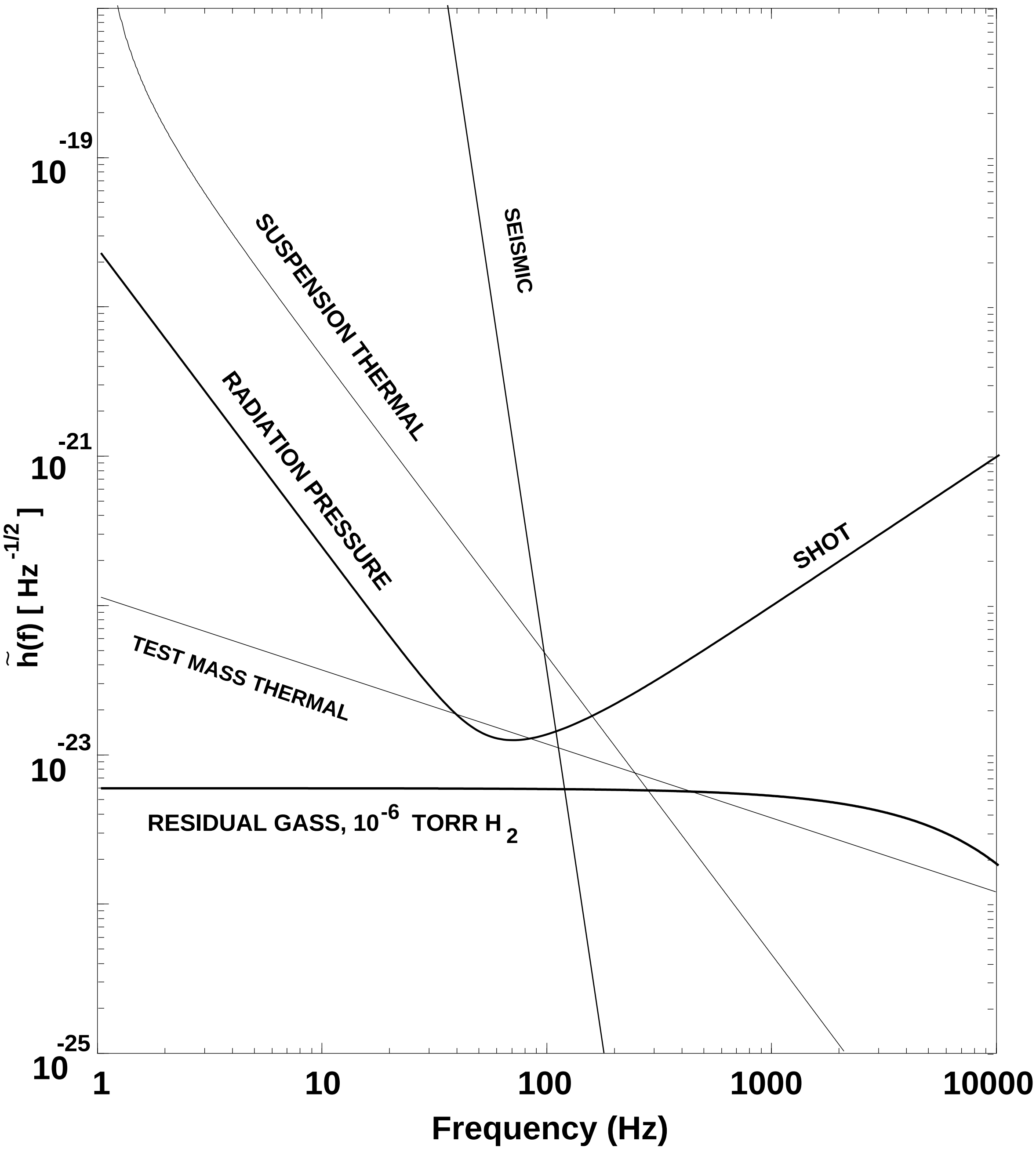
**Mechanics**

- 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

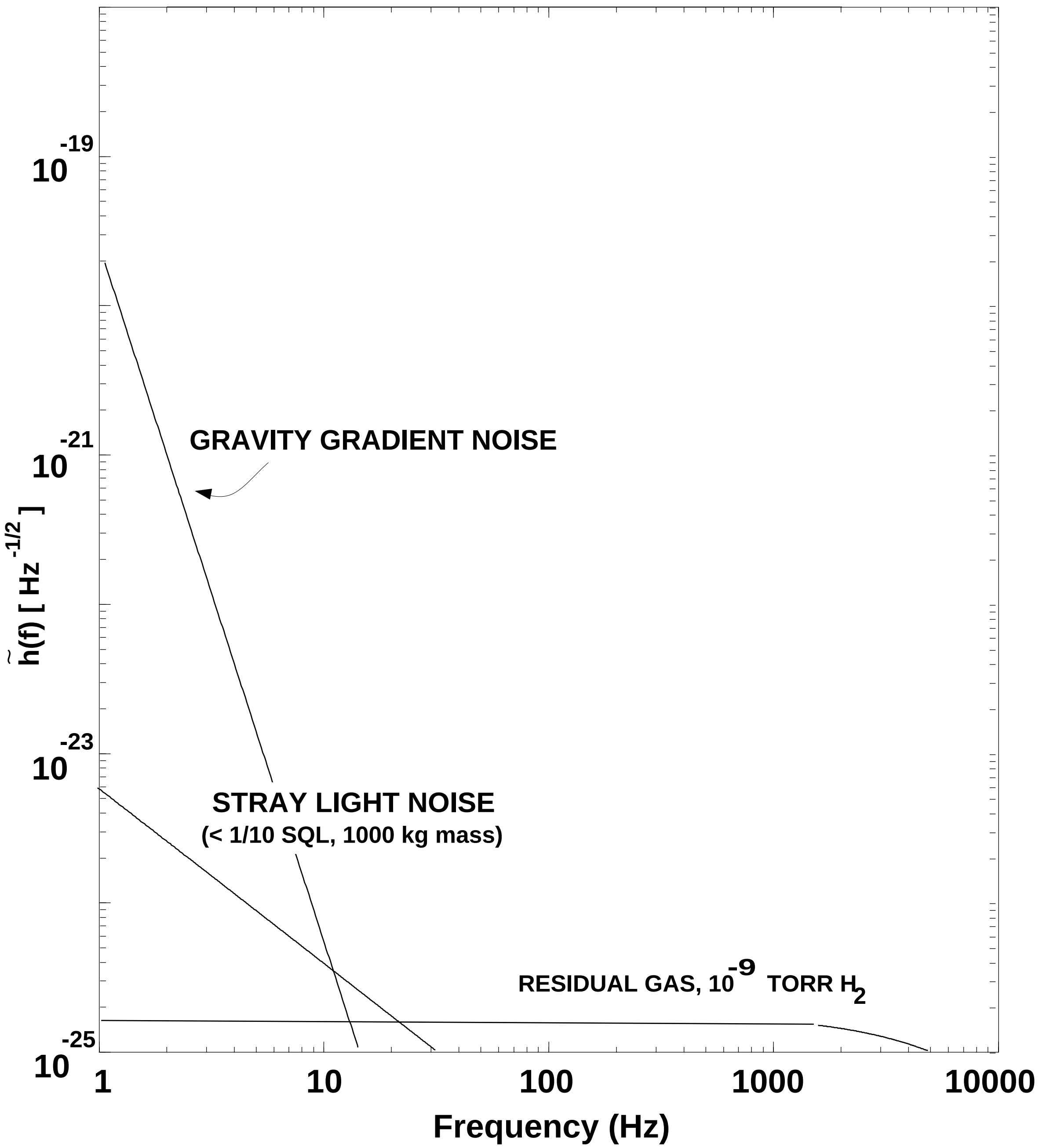
**LISA: What changes for a space-based interferometer?**

- still use Michelson interferometer, but no folding of arms
- arm lengths of $5\times10^{9}$ 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

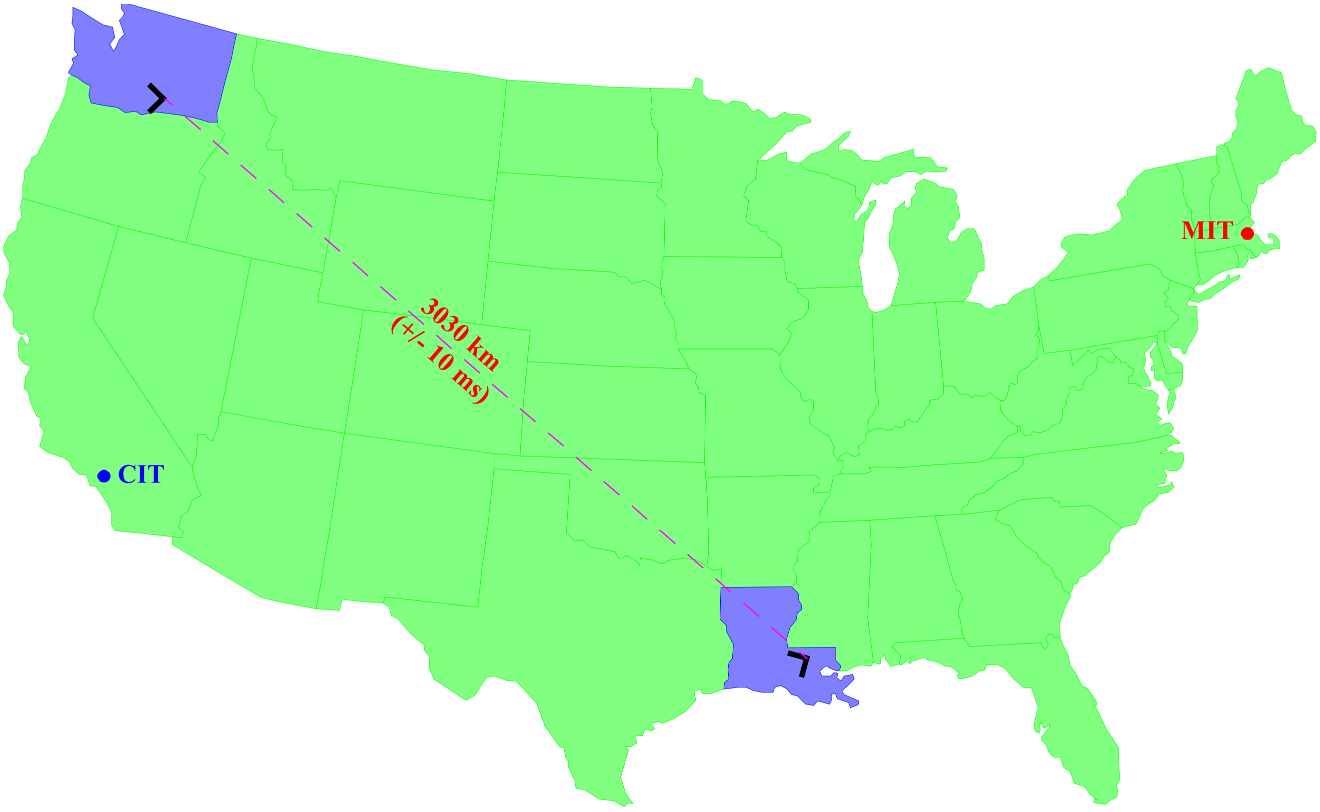
# LIGO Sites

**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**