# Overview of Interferometry for Gravitational Wave Detection

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**The ‘20 questions’ approach, including...**

- what are gravitational waves?
- why bother trying to detect GWs?
- how to detect such small strains?
- what are the fundamental limits?
- why do practical interferometers have such long arms?
- why are practical interferometers so optically complicated?
- what happens to all the light?
- what else can go wrong?

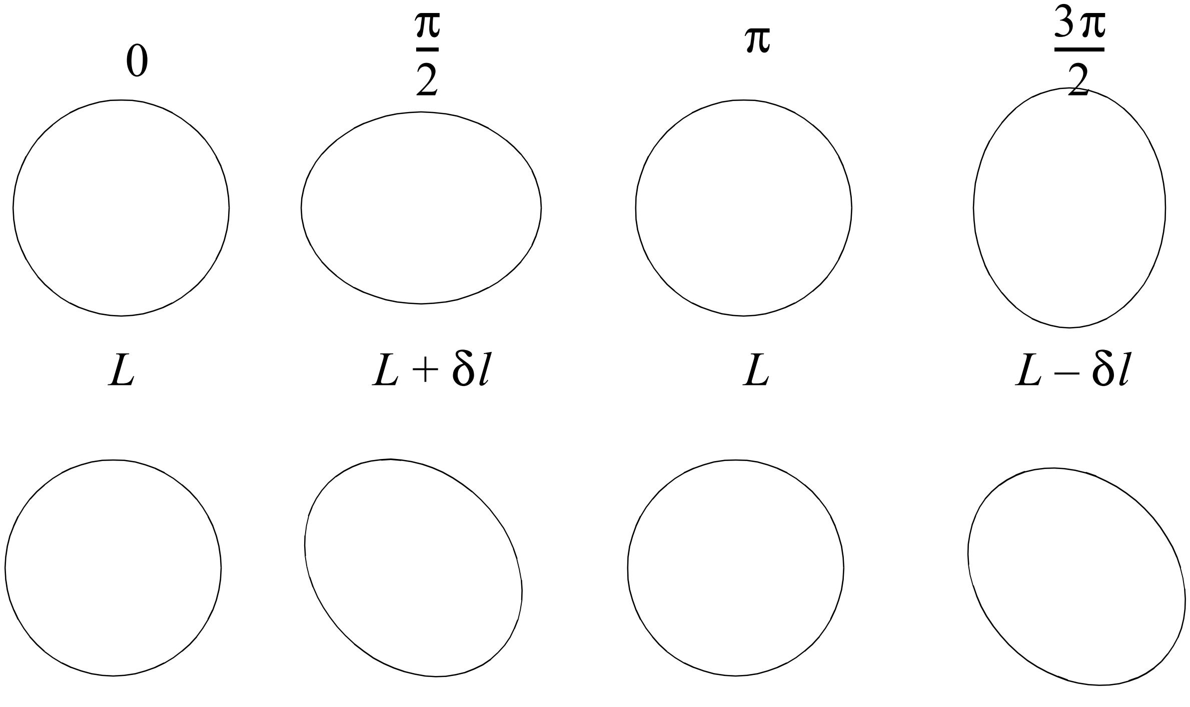
# What are Gravitational Waves?

**Strains in space-time (General Relativity)**

- lowest order of radiation: acceleration of mass quadrupoles
  - no dipole radiation - only one charge!
- transverse waves
- propagation speed of speed of light $c$
- spin 2, so $45°$ between '+' and 'X' polarizations

**Net effect: variation in distance between free masses**

- example of ring of free masses, diameter $L$, strain $h = \delta l / L$



# Why try to detect GWs?

**Only astrophysical sources are detectable**

- laboratory generated signals too small

**Astrophysical sources are fascinating!**

- Interaction with matter is very small
    - BAD: tiny signals
    - GOOD: waves no obscured by dust, gas, etc.
- can see deep and far, into galactic cores, edges of universe
- signals are from coherent motions of LARGE masses
    - EM astronomy: mostly incoherent superpositions

**Physics**

- direct detection and measurement of GW properties
- proof of existence of Black Holes, detailed behavior
- looks at highly non-linear processes, strong-field GR

**Astrophysics**

- binary star studies: NS-NS, NS-BH, BH-BH
- stellar models via supernovae
- stochastic background (Big Bang remnant)

**Brand new *quantity* as tool to understand physics**

# What signal characteristics?

**Limited by present technologies, limited source knowledge**

- will speak exclusively of ground-based interferometers
- no acoustic detectors, space-based interferometers

**Favorite source: Binary stars**

- Taylor-Hulse Binary 1913+16 shows clear spin-up
- almost certainly due to GW radiation at present 6h 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.

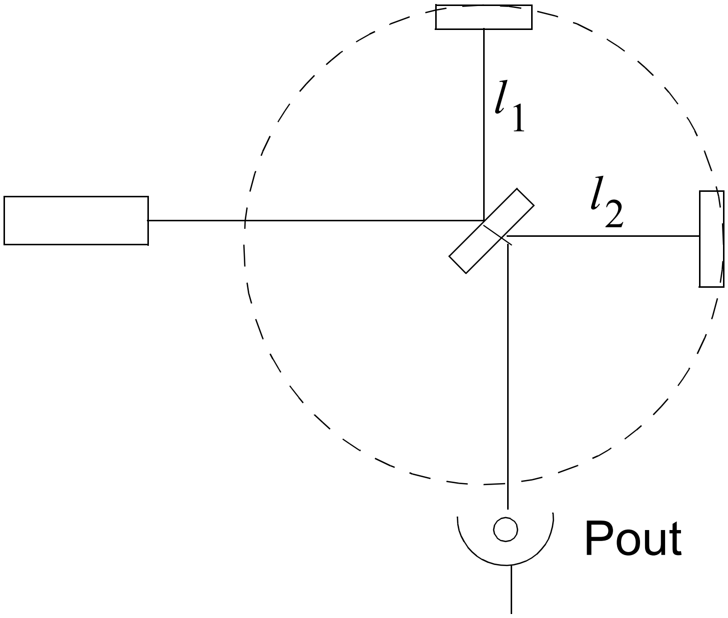
**for most of life, waveform well known if masses known**

- allows calculation of signal amplitudes, optimal filters
- end of life (coalescence) a mystery (to be observed!)
- 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

# How to detect these tiny strains?

**Laser Interferometry**

- almost perfect gedanken experiment



- GW strain induces differential length changes in arms
  - common mode uninteresting for GWs, rejected
- 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

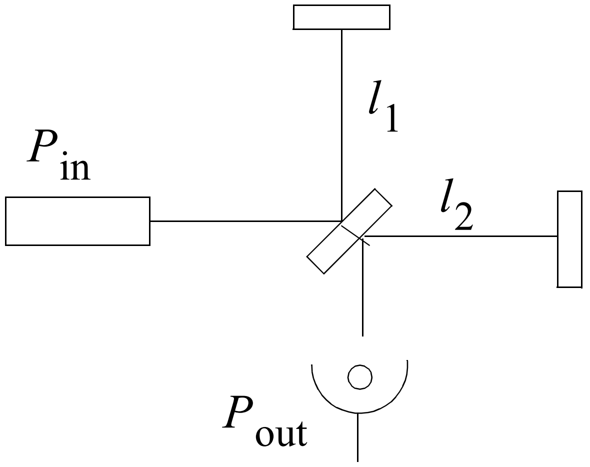
# What are the fundamental limits?

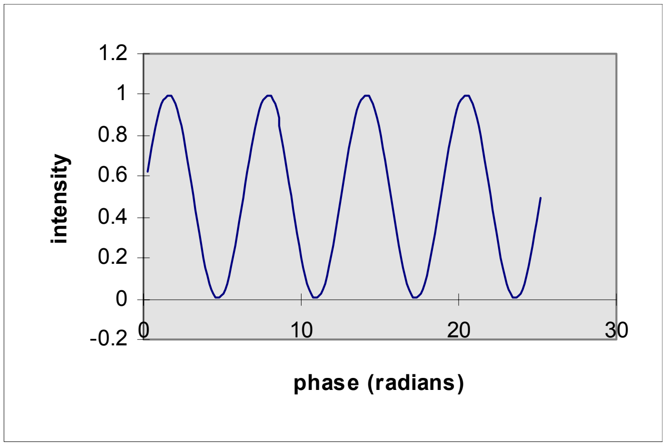
**Shot or Poisson noise**

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

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

- maximum slope: $\frac{dP}{d\delta l} = \frac{2\pi}{\lambda}P_{\text{in}}$
- uncertainty in intensity due to counting statistics: $\tilde{p}_{\text{out}} = \sqrt{\frac{h\omega}{P_{\text{in}}}}$
- can solve for equivalent strain: $h_{\text{shot}} = \frac{\delta l}{L} = \frac{1}{L}\sqrt{\frac{hc\lambda}{2\pi P_{\text{in}}}}$
- 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

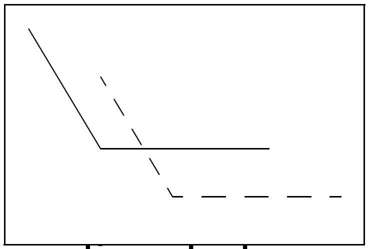
$$\tilde{f} = \sqrt{\frac{2\pi h P_{\mathrm{in}}}{c\lambda}}$$

- results in opposite displacements of EACH of the masses:

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

- NOTE: scaling with $\sqrt{P_{\mathrm{in}}}$
- scaling with the arm length $L$ of the interferometer.

**total readout, or quantum noise**



- quadrature sum $h_{\mathrm{q}} = (h^2_{\mathrm{shot}} + h^2_{\mathrm{rad\ press}})^{1/2}$
- frequency dependence according to ifo configuration, but
- always a minimum for a given frequency as a function of Power
- for simple Michelson, $P_{\mathrm{opt}} = \pi c\lambda m f^2$; later limitation, not now

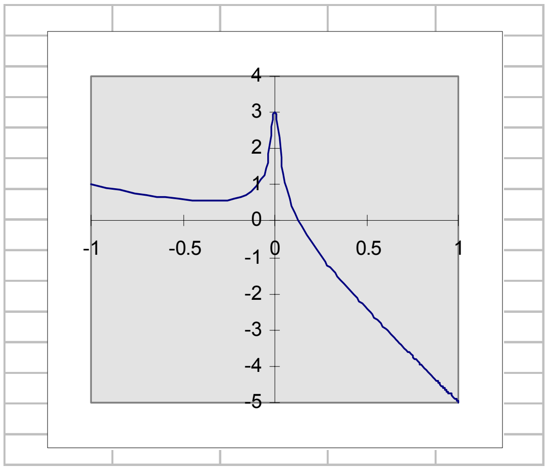
# Why long arms for interferometers?

**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:

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



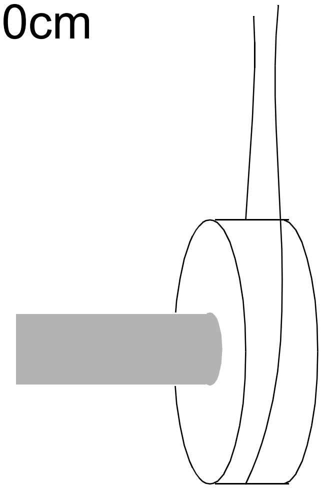
- peak $1/\phi$ above ‘plateau’
- rises as $1/\sqrt{f}$ below resonance
- falls as $1/f^{5/2}$ above resonance

# 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***

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

**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: 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**

# Seismic Noise

**motion of the earth**

- driven by ocean tides, wind, volcanic/seismic activity, humans
- for LIGO sites, characterized by (in $\mathrm{m}/\sqrt{\mathrm{Hz}}$)
  - $\frac{10^{-9}}{f^3}$, $0.1<f<1$ Hz (controls frequency region)
  - $10^{-9}$, $1<f<10$ Hz (controls frequency region)
  - $\frac{10^{-7}}{f^2}$, $10<f<1$ kHz (GW signal region)

**approaches to limiting seismic noise**

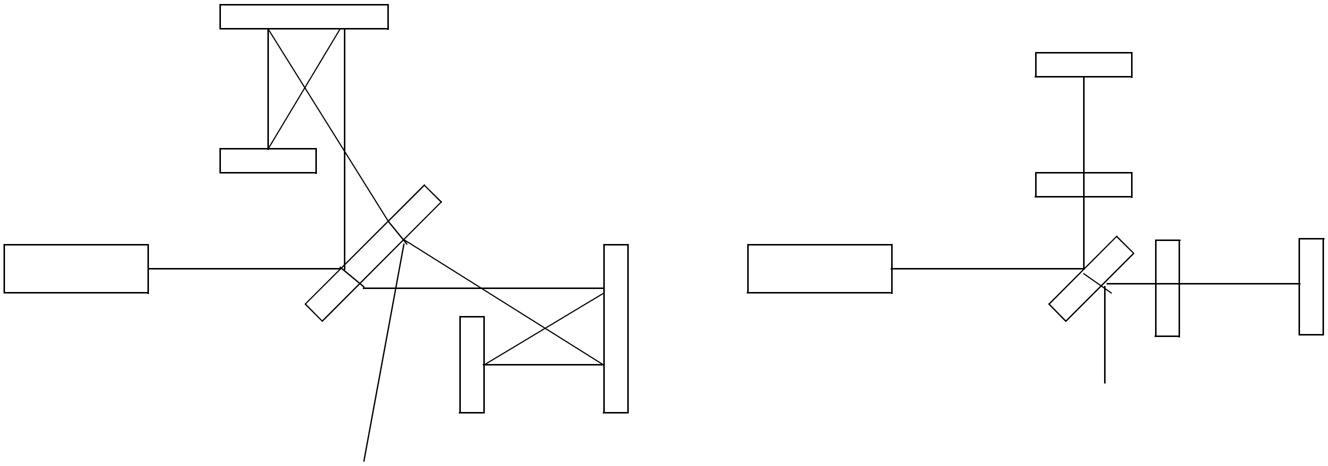
- active control systems ($0.1 \rightarrow 30$ Hz)
  - accelerometer measures motion w.r.t. inertial mass
  - servo system and actuator corrects for perceived motion
  - outside of vacuum system
- passive elastomer-steel ‘stacks’
  - damped SHOs in series
  - in-vacuum: extra design constraints
- one or more low-loss pendulums
  - test mass forms one; second good for thermal noise, control

**can be controlled with careful engineering**

# Why not simple Michelsons?

**1) interaction time with the GW**

- signal $\delta l$ grows as length of interferometer $L$ grows
- up to limit where $L \approx \lambda_{\mathrm{GW}}$, about 100 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 on system
- 10 msec storage time for initial ground-based system

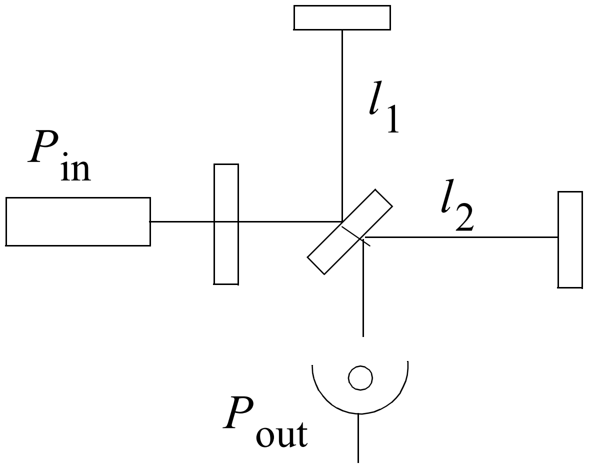
# Why not simple Michelsons? con't

**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?**

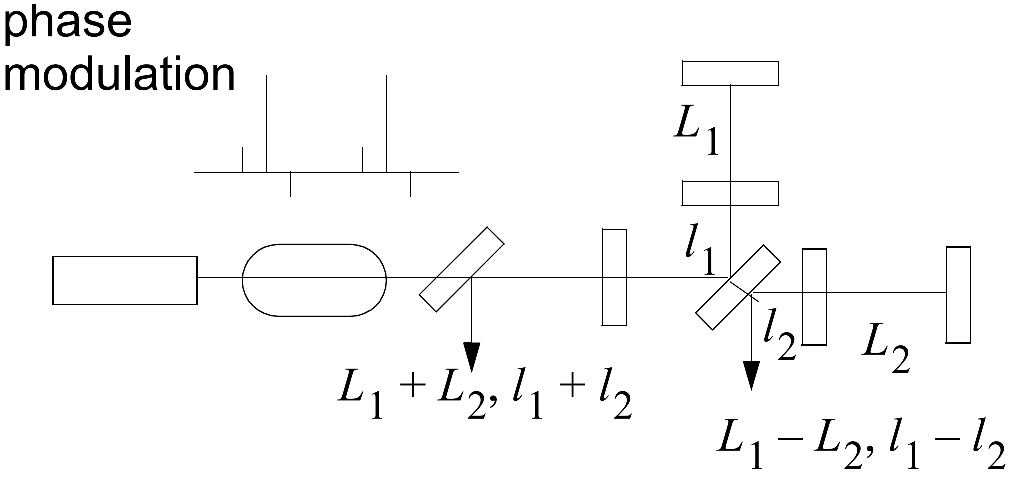
- no, cannot use all that light to heat room
- just extract small amount ($10^{-20}$ or so) if GW passes

# Complications....

**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

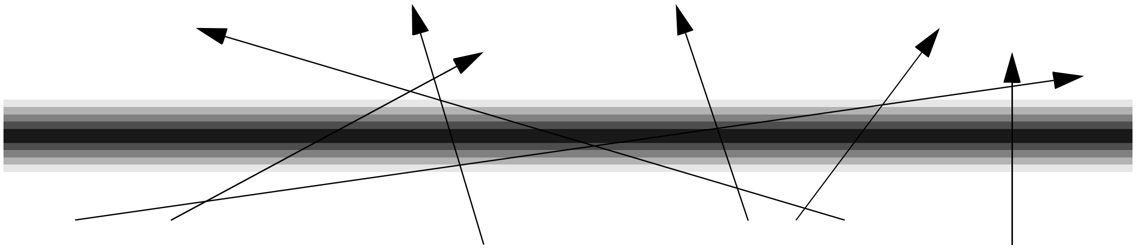
**Prefer to analyze as common mode/differential mode**



- use techniques reminiscent of reflection locking (Pound/Drever)
  - for common mode signals
  - use separate frequencies to investigate near, far mirrors
- use small asymmetry $l_1 - l_2 \approx \lambda_{\mathrm{RF}}/4G_{\mathrm{recyc}}$ for differential sigs
  - no longer ‘white-light’ interferometer
  - brings phase sidebands out dark port for heterodyne detection

# Why the vacuum system?

**Light must travel 4 km without attenuation or degradation**



- index fluctuations in residual gas cause variations in optical path
- calculation takes into account many parameters
  - pressure, polarizability, molecular speed of various species
  - light beam intensity distribution, coherence of effect
- 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, 1.4 m diameter, ~1200 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

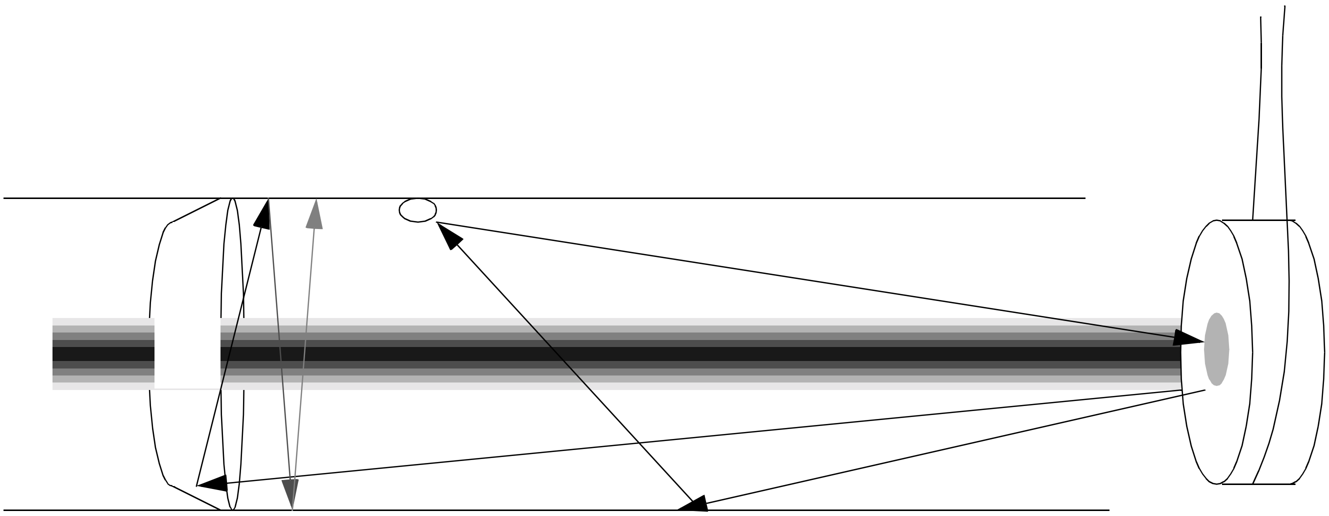
# Where does the light go?

**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
- spurious interferometers abound; care with all stray beams

**light from mirror surface**

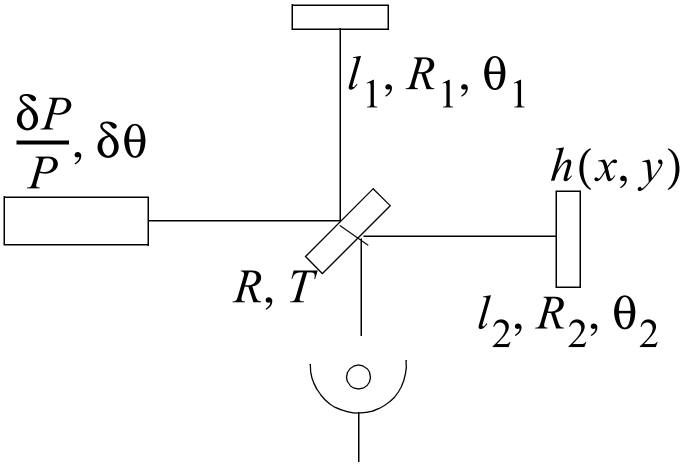
- typically from imperfection on ~0.5 cm scale, height 1 nm
- scatters out of main beam, onto beam tube, back onto mirror
- baffles used to strongly attenuate paths



# What else can go wrong?

**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

# The Last Page

**The ‘20 questions’ again:**

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**And: what’s the plan?**

**LIGO (Laser Interferometer Gravitational-wave Observatory)**

- MIT-Caltech collaboration
- two 4km installations: Washington and Louisiana
- to be first operational in 2001
- to last with continuous modification till 2020 at least
- starting with 3 interferometers (2 in WA, 1 in LA)
- initial space for 4, later beam capability of 6 per site
- eager for help on initial ifos, competition for the next generation

**Hope that Stanford will play both roles!**