Gravitational wave detectors

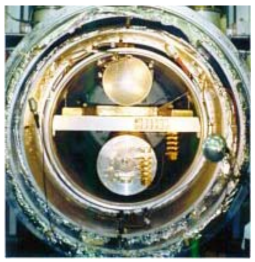
- **Bar detectors**
  - Invented and pursued by Joe Weber in the 60's
  - Essentially, a large "bell", set ringing (at ~ 900 Hz) by GW
  - Only discuss briefly, here – See EXPLORER at CERN!
- **Michelson interferometers**
  - At least 4 independent discovery of method:
  - Pirani `56, Gerstenshtein and Pustovoit, Weber, Weiss `72
  - Pioneering work by Weber and Robert Forward, in 60's
  - Now: large, earth-based detectors. Soon: space-based (LISA).

Resonant bar detectors

- AURIGA bar near Padova, Italy
(typical of some ~5 around the world – Maryland, LSU, Rome, CERN, UWA)
- 2.3 tons of Aluminum, 3m long;
- Cooled to 0.1K with dilution fridge in LiHe cryostat
- $Q = 4 \times 10^6$ at < 1K
- Fundamental resonant mode at ~900 Hz; narrow bandwidth
- Ultra-low-noise capacitive transducer and electronics (SQUID)

Resonant Bar detectors around the world

International Gravitational Event Collaboration (IGEC)

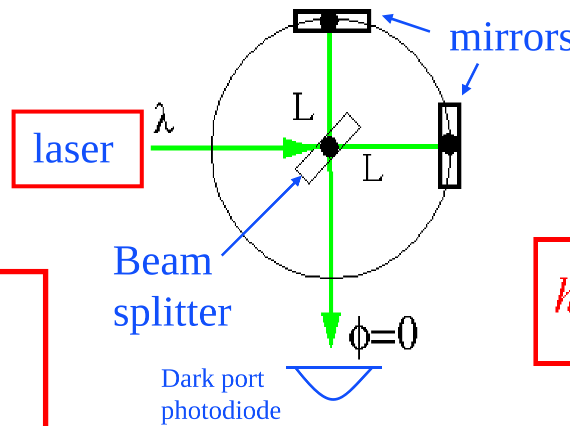


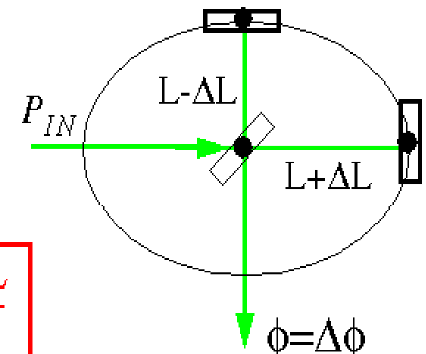

detector	ALLEGRO	AURIGA	EXPLORER	NAUTILUS	NIOBE
Mode frequencies $[Hz]$	895, 920	912, 930	905, 921	908, 924	694, 713
Bar mass M $[kg]$	2296	2230	2270	2260	1500
Bar length L $[m]$	3.0	2.9	3.0	3.0	2.75
Bar temperature $[K]$	4.2	0.2	2.6	0.1	5.0
Longitude	$91°10'44"W$	$11°56'54"E$	$6°12'E$	$12°40'21"E$	$115°49'E$
Latitude	$30°27'45"N$	$45°21'12"N$	$46°27'N$	$41°49'26"N$	$31°56'S$
Azimuth	$40°W$	$44°E$	$39°E$	$44°E$	$0°$

	Baton Rouge, LA USA	Legarno, Italy	CERN, Suisse	Frascati, Italy	Perth, Australia

Interferometric detection of GWs

GW acts on freely falling masses:



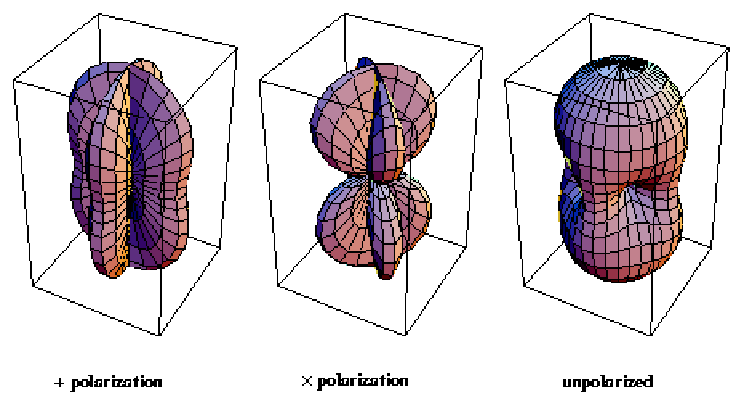


$$\boxed{h = \frac{\Delta L}{L}}$$

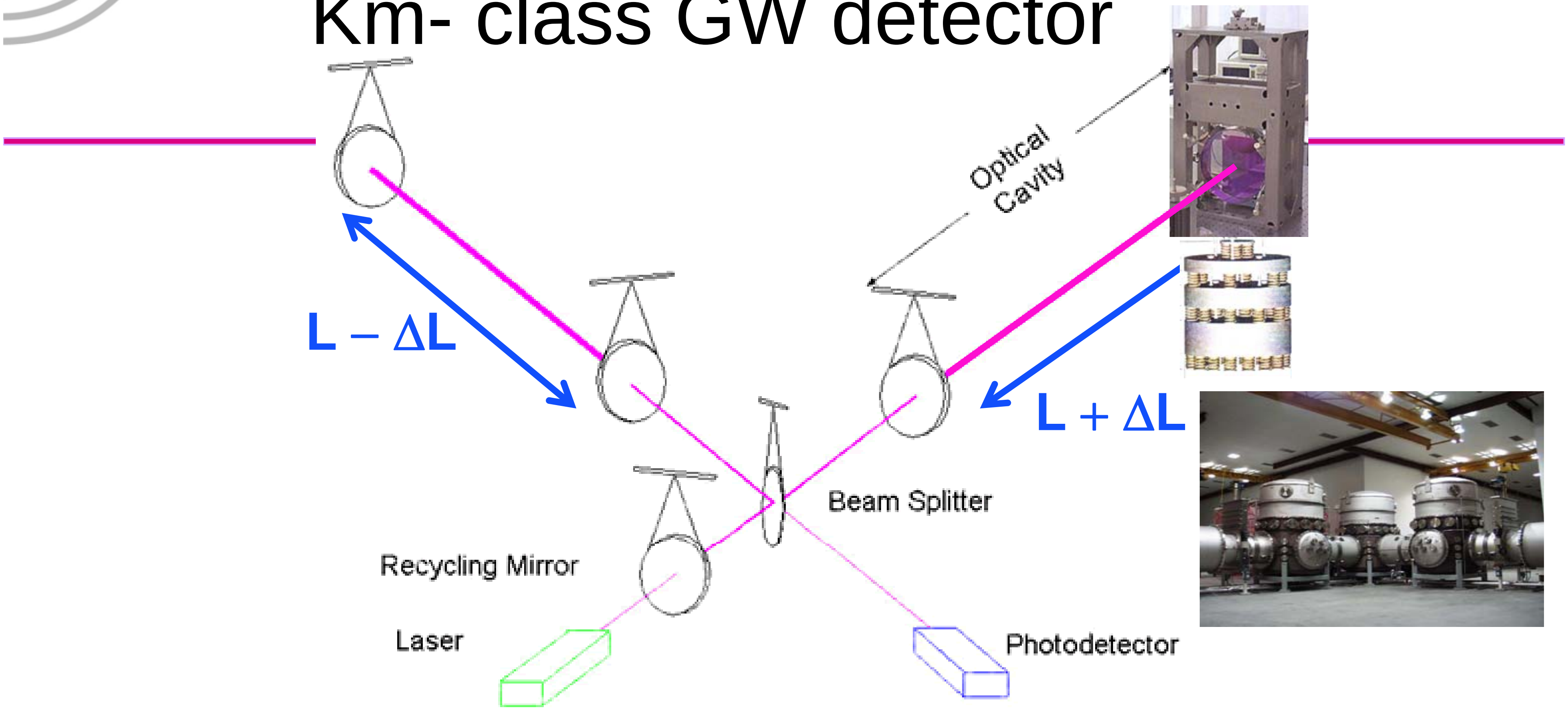
$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

For fixed ability to measure *ΔL*, make *L* as big as possible!

Antenna pattern:
(not very directional!)



LIGO – the first Km- class GW detector

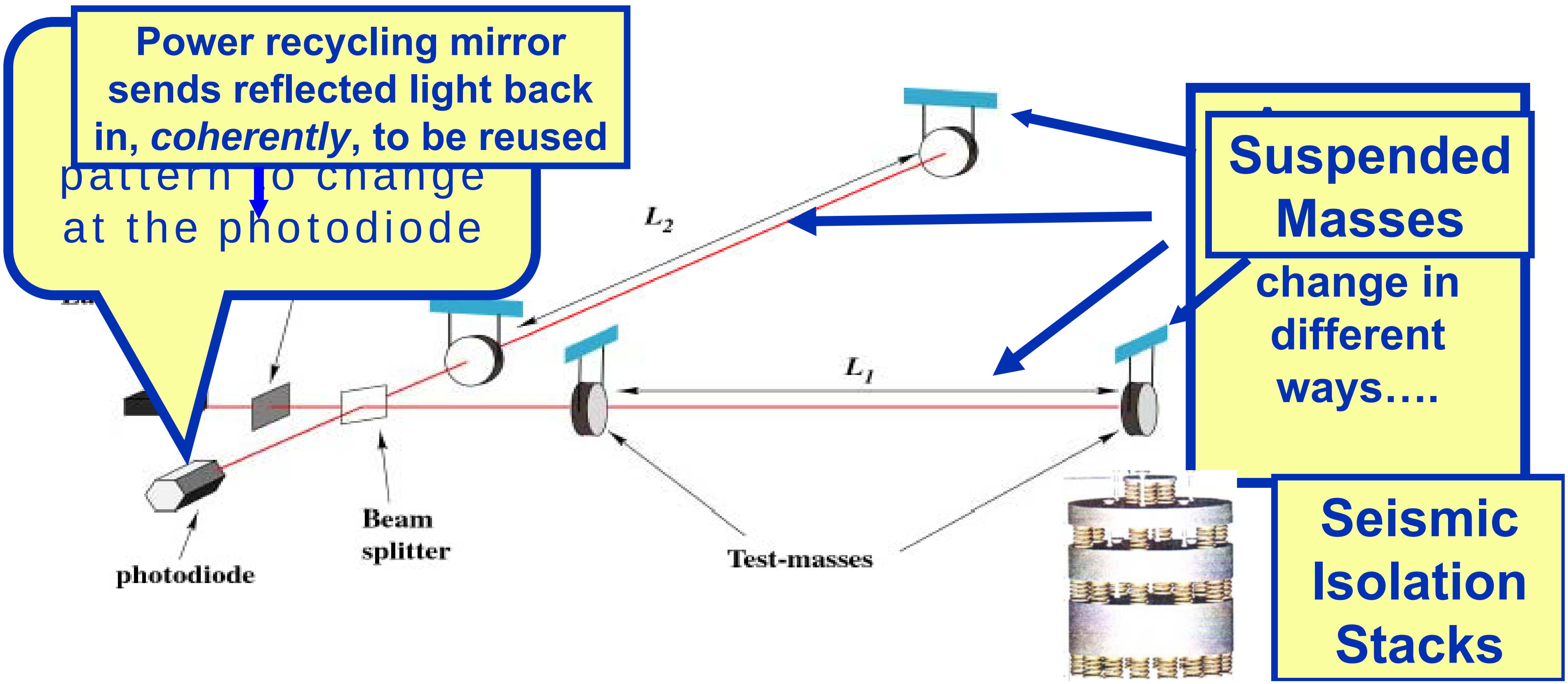


want to get h ≤ 10^{-22};
can build L = 4 km;
must measure ΔL = h L ≤ 4 × 10^{-19} m

Interferometer Concept

- Laser used to measure relative lengths of two orthogonal arms

- **Arms in LIGO are 4km**
- **Measure *difference in length to one part in 10^{21} or 10^{-18} meters***

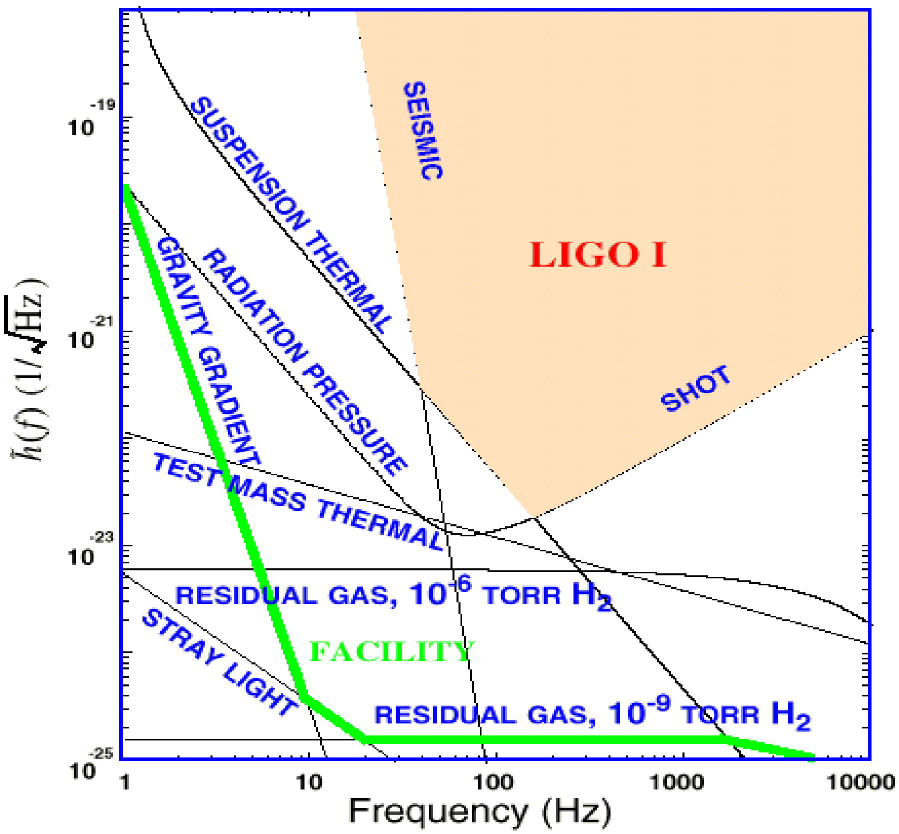


LIGO I noise floor

- **The LIGO detectors are limited by three fundamental noise sources**
  - **seismic noise at the lowest frequencies**
  - **thermal noise at intermediate frequencies**
  - **shot noise (*quantum sensing* noise) at high frequencies**

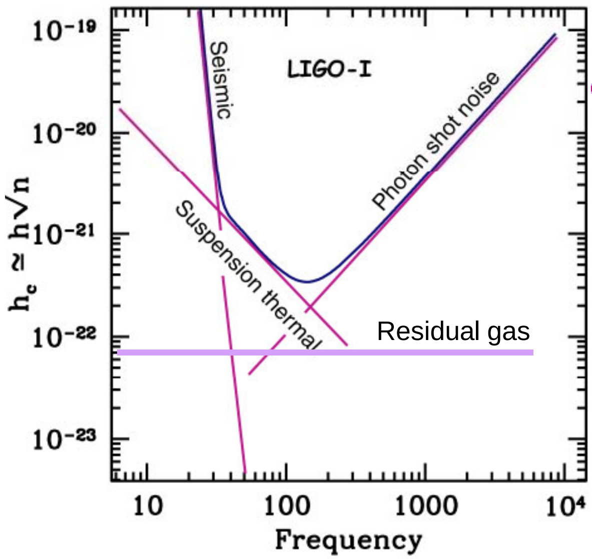
- **Many other noise sources lurk underneath and must be controlled as the instrument is improved**

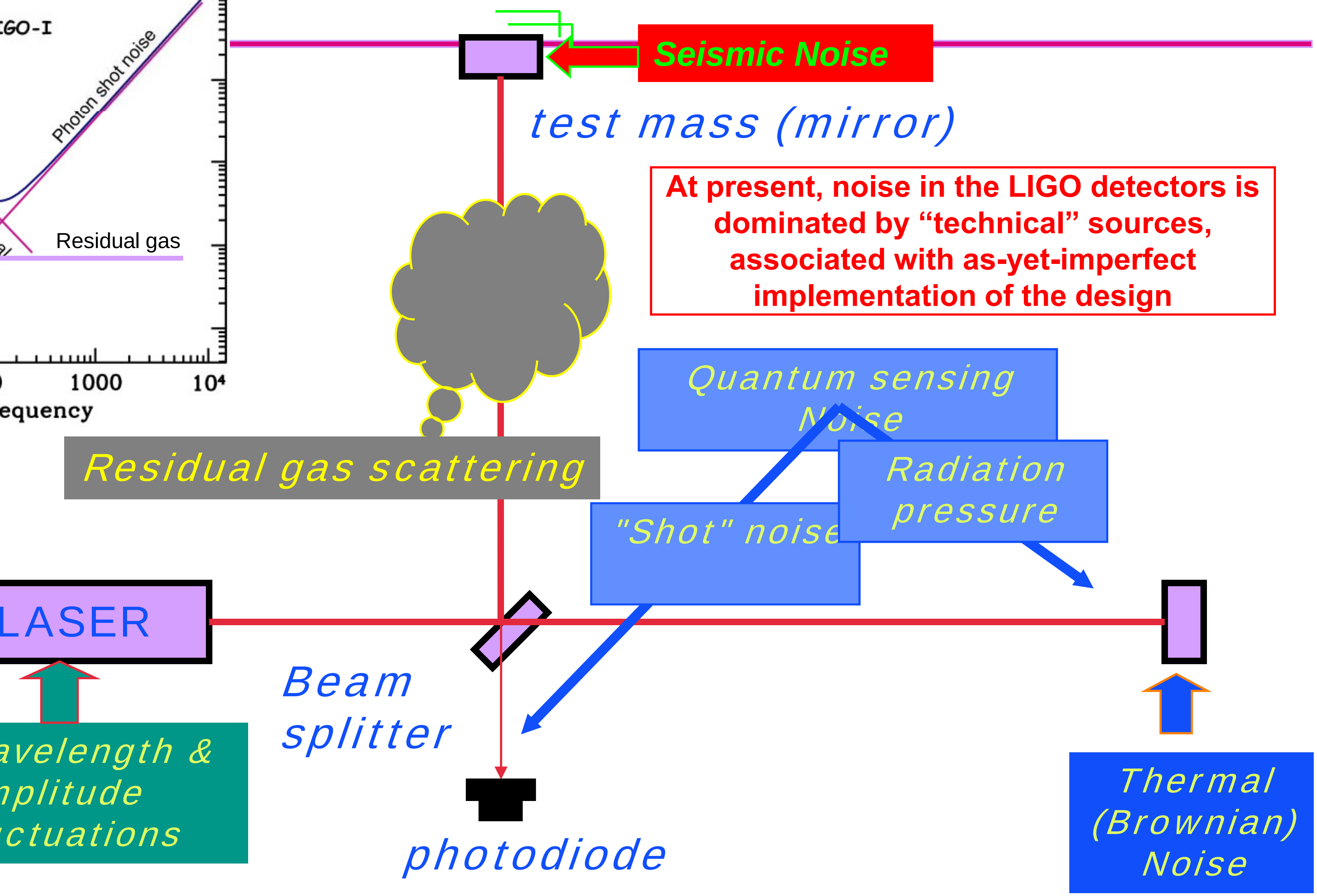
- **The LIGO sites and vacuum systems are designed to accomadate the next generation of Advanced detectors.**



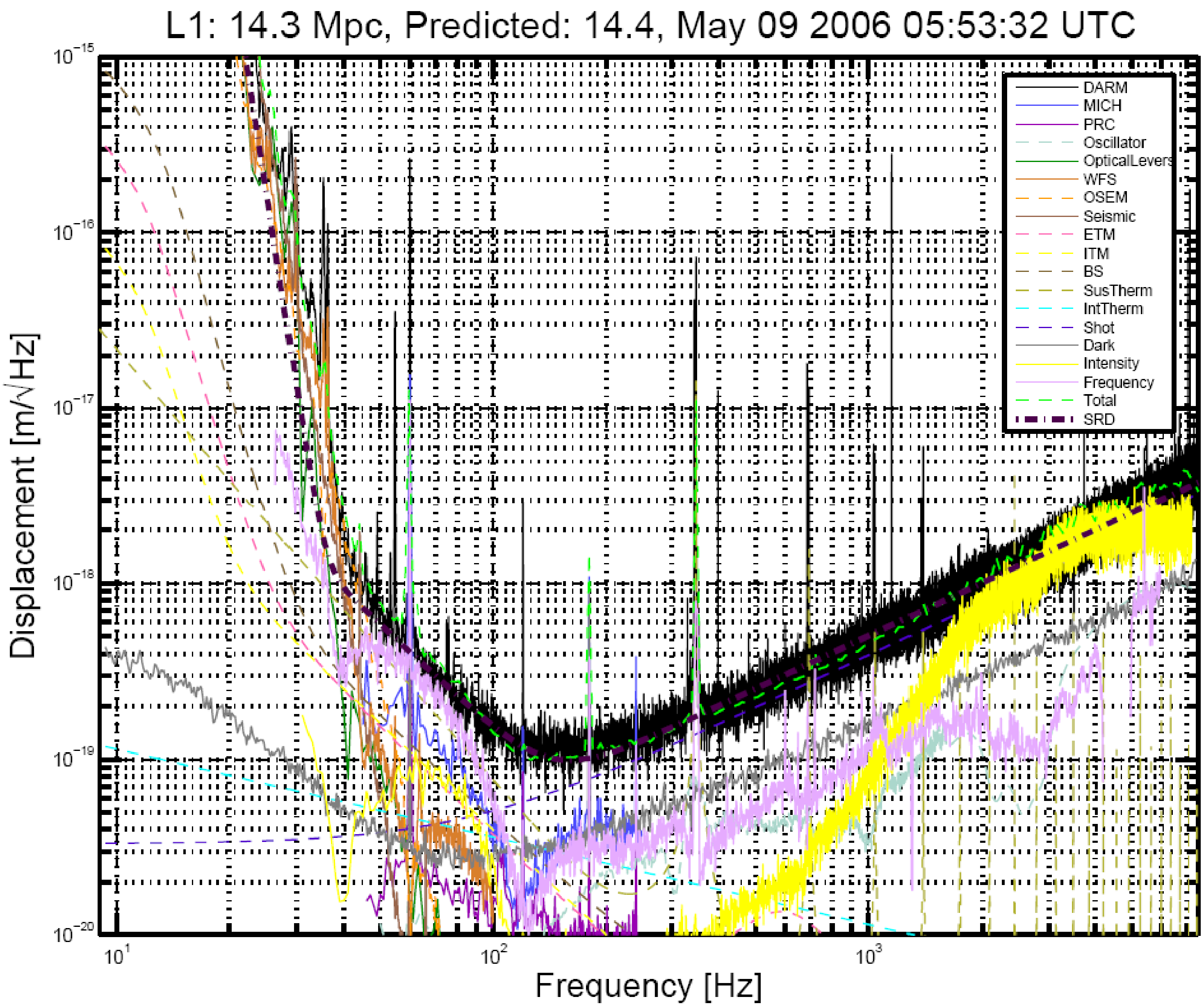
LIGO

Interferometer Noise Limits

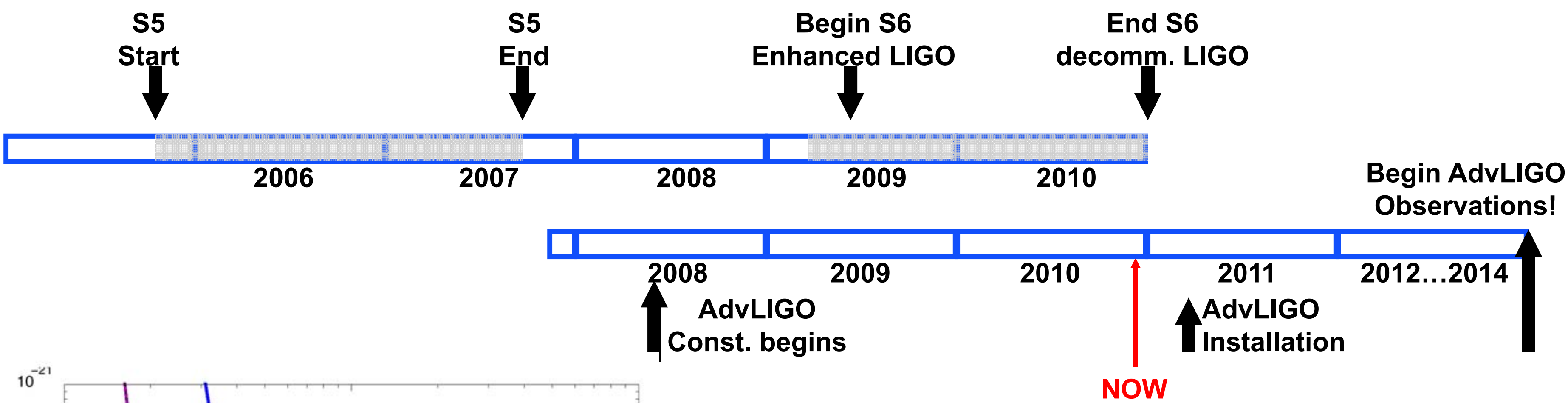


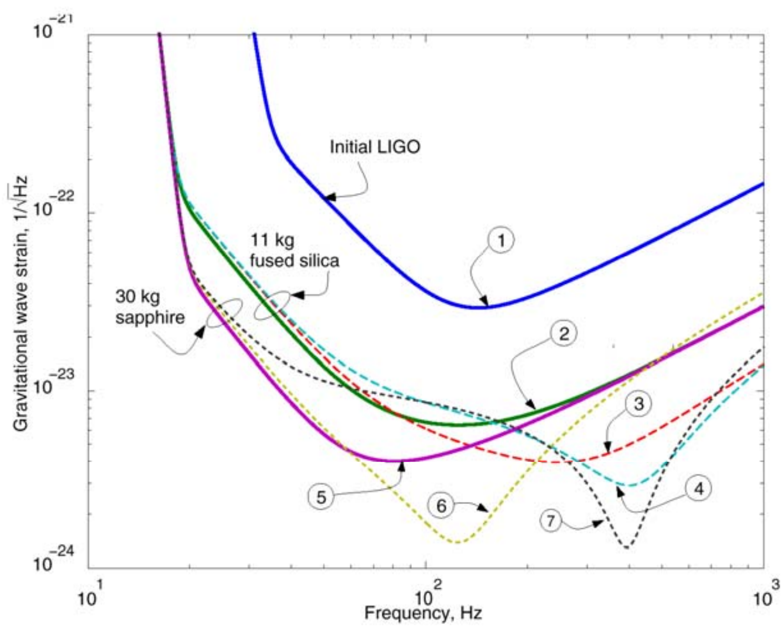


Noise budget



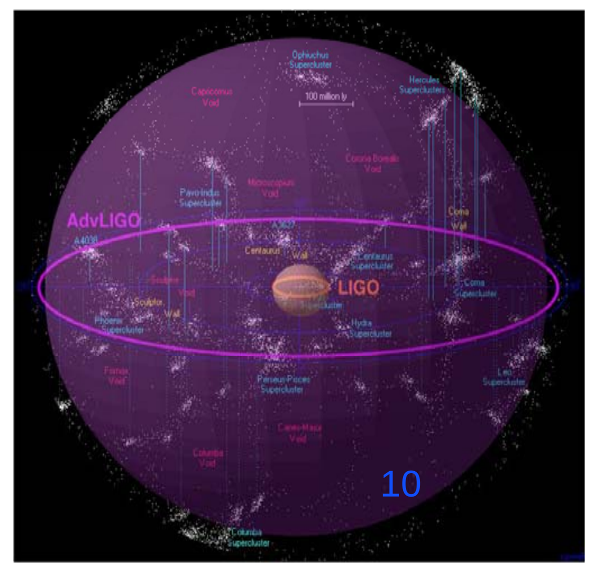
LIGO → eLIGO → AdvLIGO



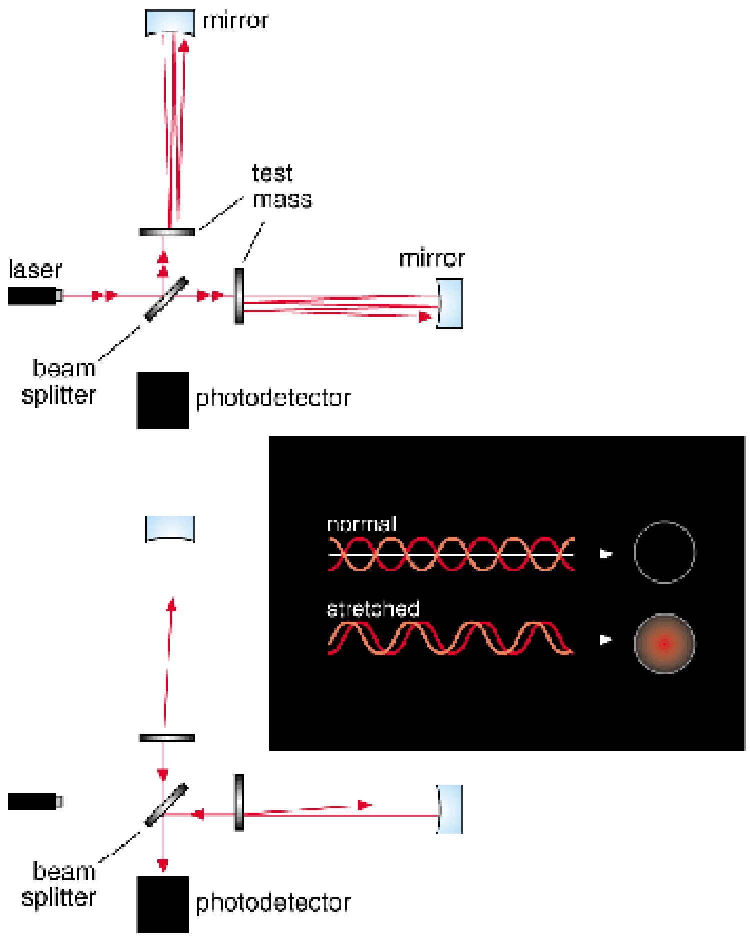


Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!



Interferometric phase difference



The effects of gravitational waves appear as a deviation in the phase differences between two orthogonal light paths of an interferometer.

For expected signal strengths,
The effect is *tiny*:

Phase shift of ~10^{-10} radians

The longer the light path, the larger the phase shift…

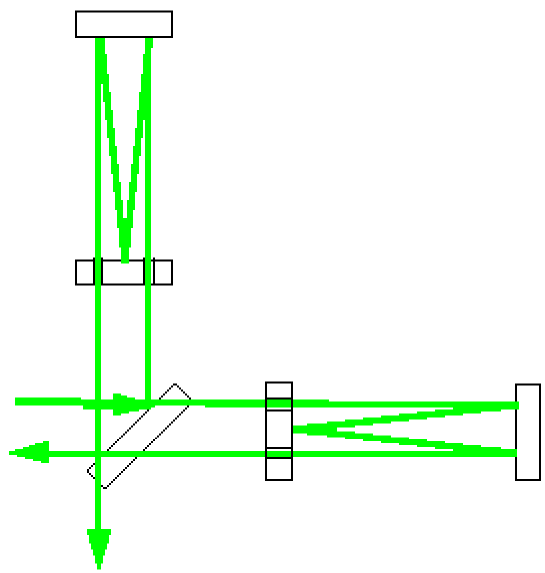
Make the light path as long as possible!

Light storage: folding the arms

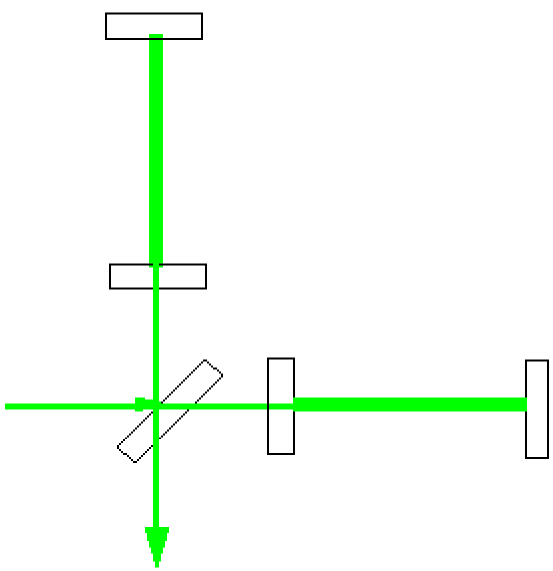
How to get long light paths without making *huge* detectors:

Fold the light path!

The laser measures the displaced mirrors many times before returning to the beamsplitter.



Delay line interferometer



Fabry Perot interferometer

Simple, but requires large mirrors; limited τ_{stor}

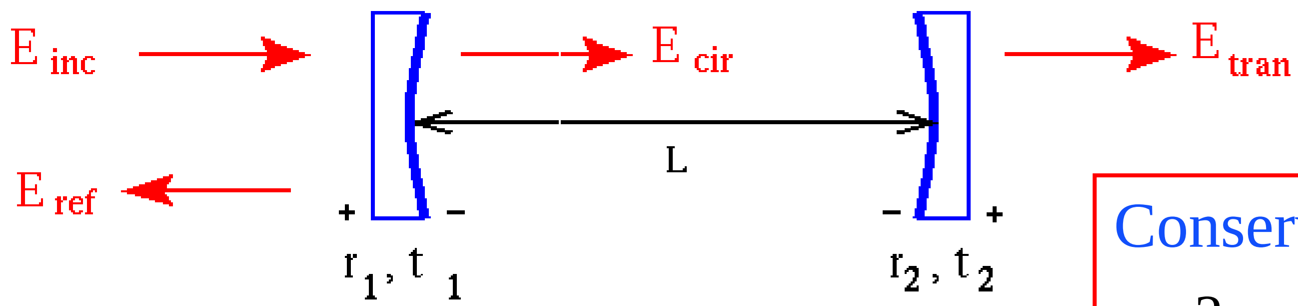
(LIGO design) $\tau_{stor} \sim 10$ *msec*

More compact, but harder to control

What do high-finesse optical cavities do for you?

- They are incredibly sensitive measuring devices and/or filters!
- They measure $\Delta\nu = \Delta(2kL)/2\pi = \Delta f/f_{fsr} = \Delta L/(\lambda/2)$
- If you know L very well (a *length reference*), they measure the frequency of your laser very accurately!
  - » In LIGO, we use a sequence of ever-longer optical cavities to measure Δf from the laser, then feed back on the laser to stabilize it. Utlimately, we use the 4-km arms (in *common mode*) to make the world's most stable laser.
- If you have a very stable laser frequency, can measure ΔL very accurately!
  - » In LIGO, we use the 4-km arms (in differential mode) to measure ΔL to an accuracy of 10^{-19} m
  - » We accentuate the effect of ΔL on the phase shift of the light in the arms, by having the light bounce back and forth many times
  - » Can't have arbitrarily large number of bounces: when light storage time > GW period, the effect cancels and we lose sensitivity! For LIGO, this starts happening at ~ 100 Hz.
- If you know both L and f very well, can measure *optical thickness* of sample placed in one arm – often used in materials science, etc.
- If you send in light with a broad range of frequencies, or the light has noisy frequency fluctuations, it only transmits one frequency: a filter!
- If one of the mirrors is curved, and you send in light with a messy transverse profile, it only transmits light with a single transverse *mode*: a *mode cleaner*.

Fabry-Perot Optical Resonator Cavities



$$E_{cir} = t_1 E_{inc} + r_1 r_2 e^{-2ikL} E_{cir} = \frac{t_1}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{ref} = r_1 E_{inc} - t_1 r_2 e^{-2ikL} E_{cir} = \frac{r_1 - r_2 (1-L) e^{-2ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

$$E_{tran} = t_2 \; e^{-ikL} E_{cir} = \frac{t_1 t_2 e^{-ikL}}{1 - r_1 r_2 e^{-2ikL}} E_{inc}$$

Conservation of energy:

$$r_i^2 + t_i^2 + L_i = 1$$

$$R_i + T_i + L_i = 1$$

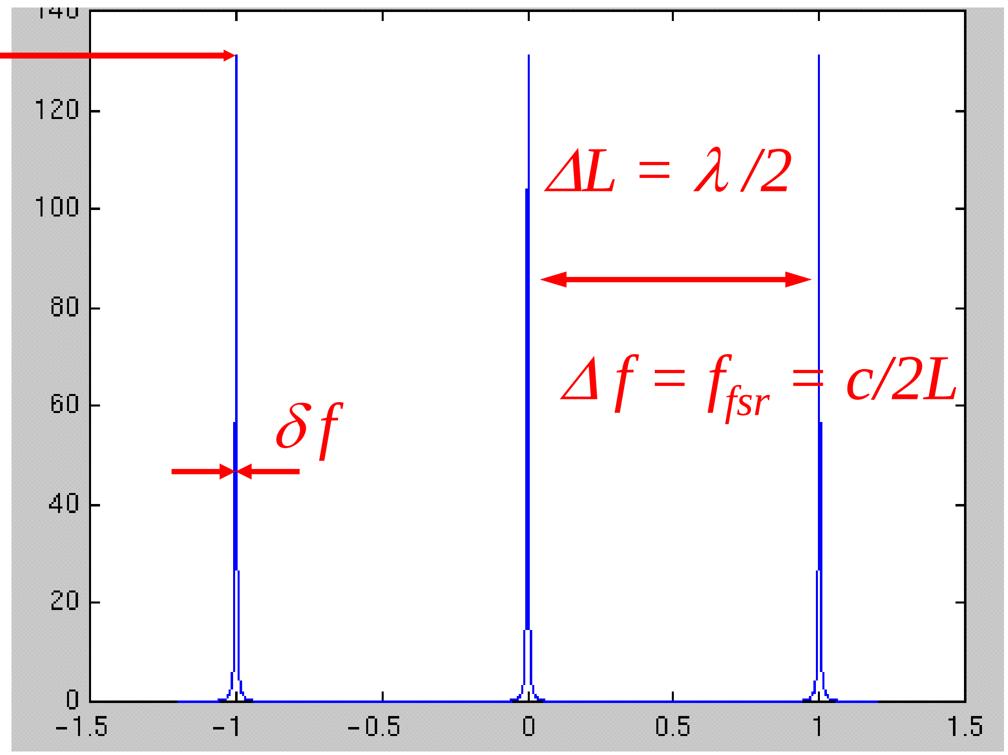
When $2kL = n(2\pi)$, (ie, $L = n\lambda/2$),

E_{cir} , E_{tran} maximized $\Rightarrow$ resonance!

FP circulating field

Power Gain

$$\left|\frac{E_{circ}}{E_{in}}\right|^2$$



Free Spectral Range:

$f_{FSR} = c/2L$

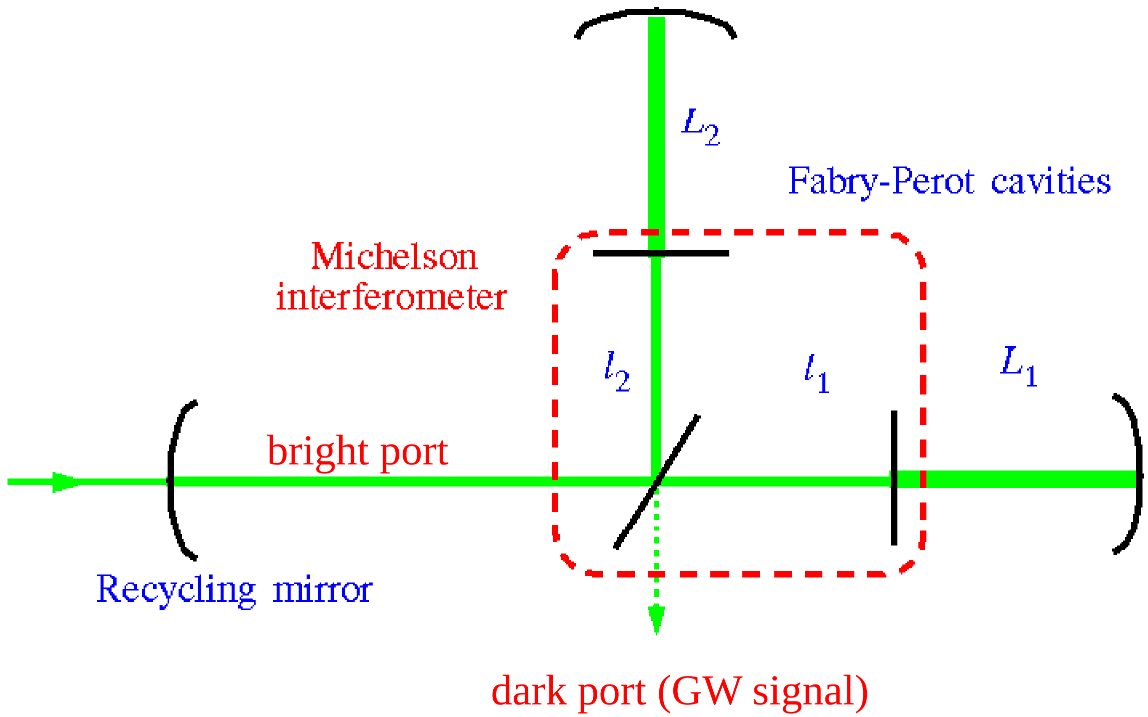
$$Finesse = \delta f / f_{fsr}$$

$$\Delta \nu = \Delta(2kL)/2\pi = \Delta f / f_{fsr} = \Delta L / (\lambda/2)$$

LIGO I configuration

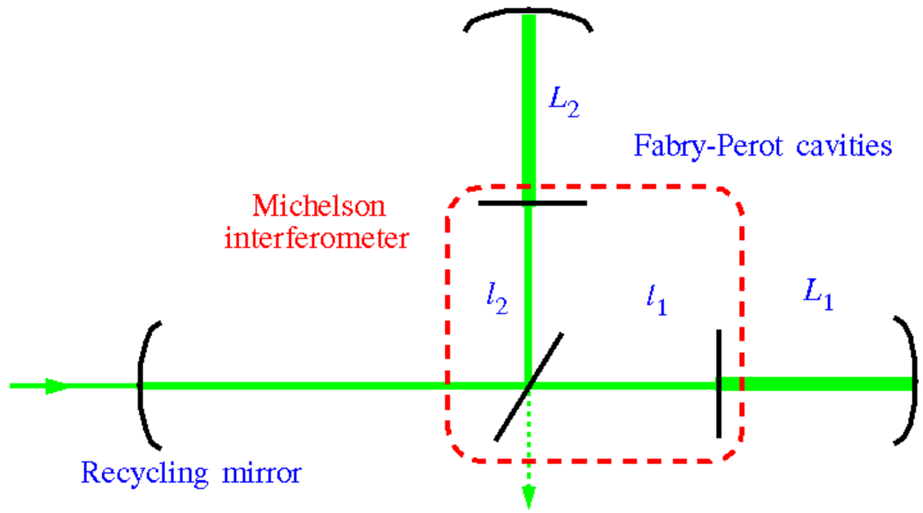
Power-recycled Michelson with Fabry-Perot arms:

- Fabry-Perot optical cavities in the two arms store the light for many (~200) round trips
- Michelson interferometer: change in arm lengths destroy destructive interference, light emerges from dark port
- Normally, light returns to laser at bright port
- Power recycling mirror sends the light back in (coherently!) to be reused

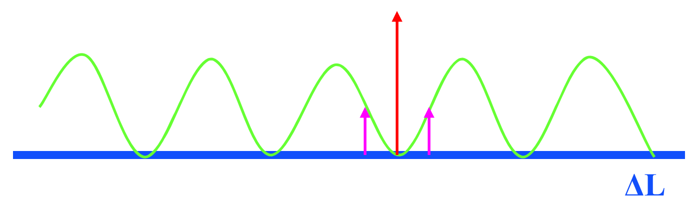


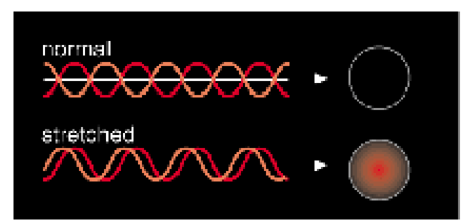
LIGO as a “Null” instrument

- **Power at output port of the Michelson depends most sensitively on ΔL at “mid-fringe”**
- **But LIGO operates the Michelson on a dark fringe, where power depends on $(\Delta L)^2$!**
- **Why? Because at mid-fringe, power fluctuations would “fake” the GW signal, and they are a *huge* source of noise**
- **Instead, we extract a signal from the light at the dark fringe, which is linear in ΔL, using a clever technique invented by Pound, Drever, Hall (Nobel 2005), to be described in a bit.**
- **Now we are insensitive to power fluctuations, and sensitive to ΔL.**
- **We want to stay dark, even when the GW signal is present: so we servo out the signal!**
- **That’s fine; the servo correction signal is neatly linear with ΔL.**
- **Null instrument: one of the many powerful techniques in precision measurement science that makes LIGO possible.**



$$P_{out} = P_{in} \sin^2(2k\Delta L)$$





Suspended test masses

• **To respond to the GW, test masses must be "free falling"**

• **On Earth, test masses must be supported against DC gravity field**

• **The Earth, and the lab, is vibrating like mad at low frequencies (seismic, thermal, acoustic, electrical);**

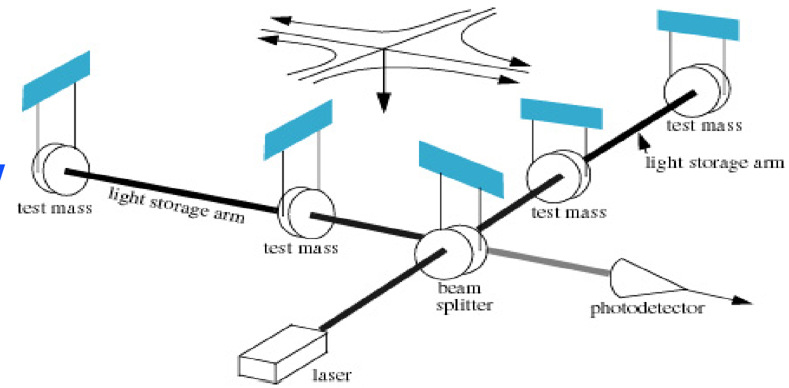
- **can't simply bolt the masses to the table (as in typical ifo's in physics labs)**

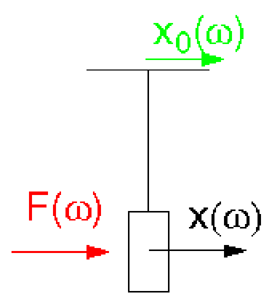
• **So, IFO is insensitive to low frequency GW's**

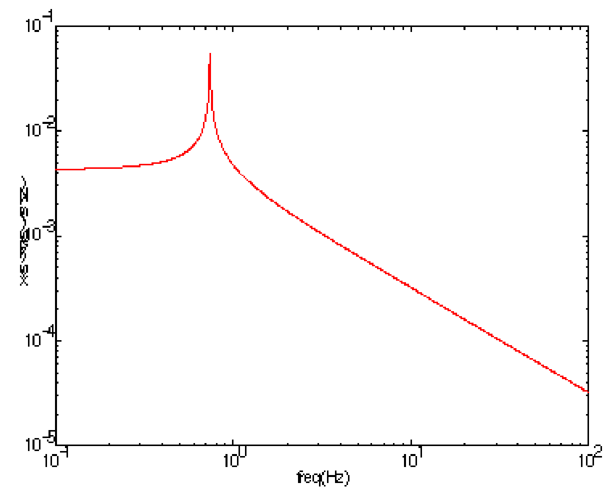
• **Test masses are suspended on a pendulum resting on a seismic isolation stack**

- **"fixed" against gravity at low frequencies, but**
- **"free" to move at frequencies above ~ 100 Hz**

"Free" mass: pendulum at $f \gg f_0$

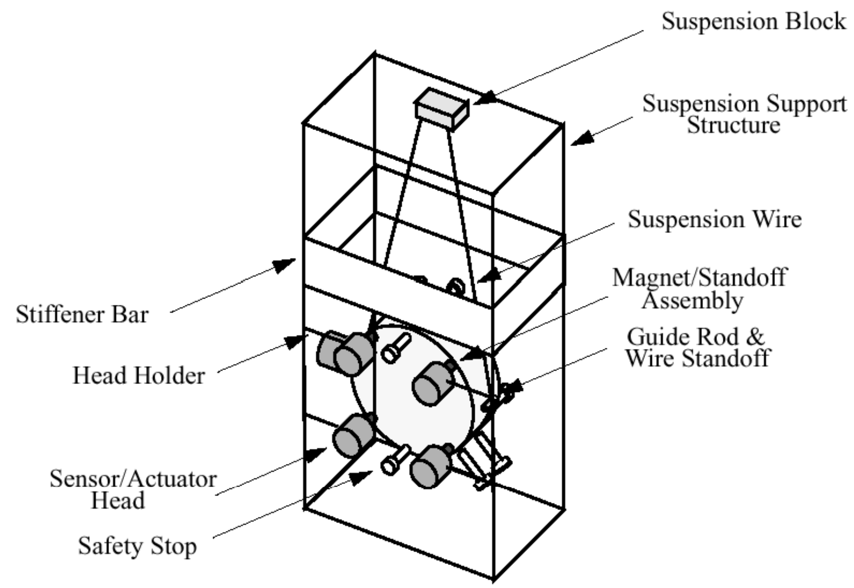




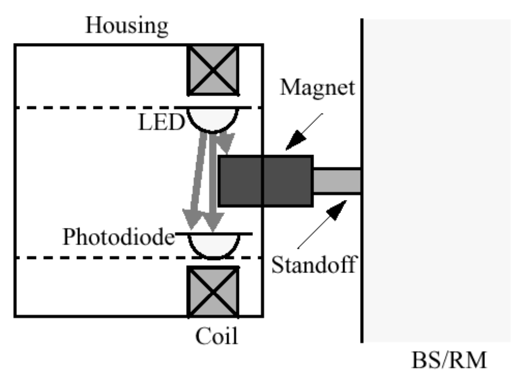


Mirror control

- Seismic isolation system, and pendulum, keep the mirror motion to a minimum.
- Now the mirrors are not being kicked around by the environment (at high frequencies) – "free" masses!
- But, being free, they may not be where you need them to be to keep the laser resonant in the cavities.
- Instead, they're swinging back and forth at the pendulum frequency (~ 0.8 Hz).
- Need active control system to keep mirrors at set points (at/near DC), to keep F-P cavities resonant, without injecting noise at high frequencies
- ⇒ Carefully designed feedback servo loops

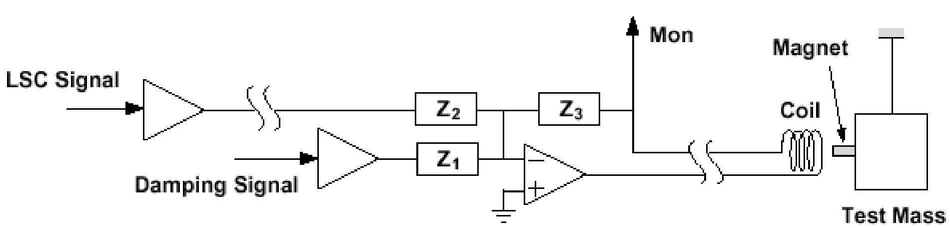


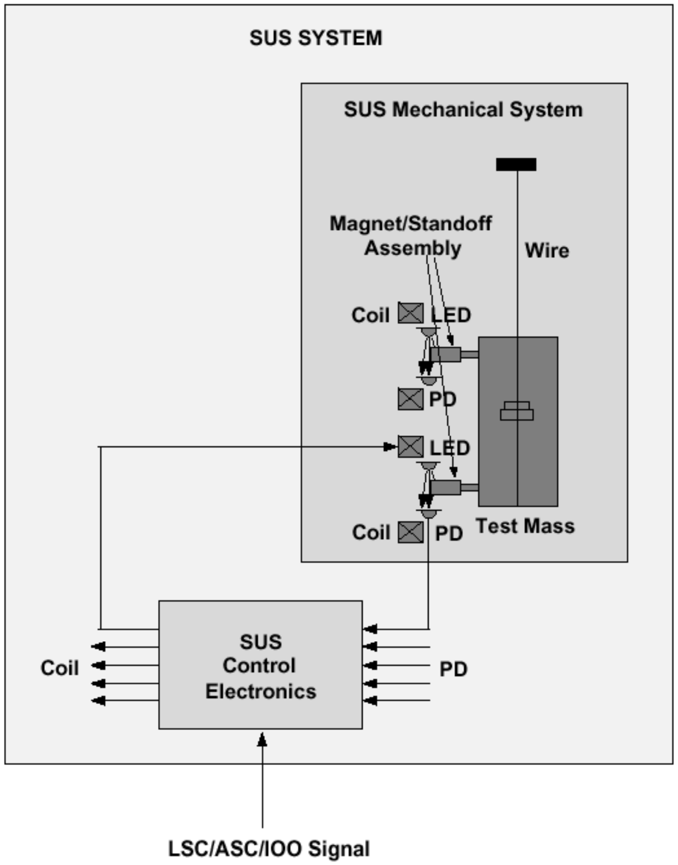
sensor/actuator head (OSEM)



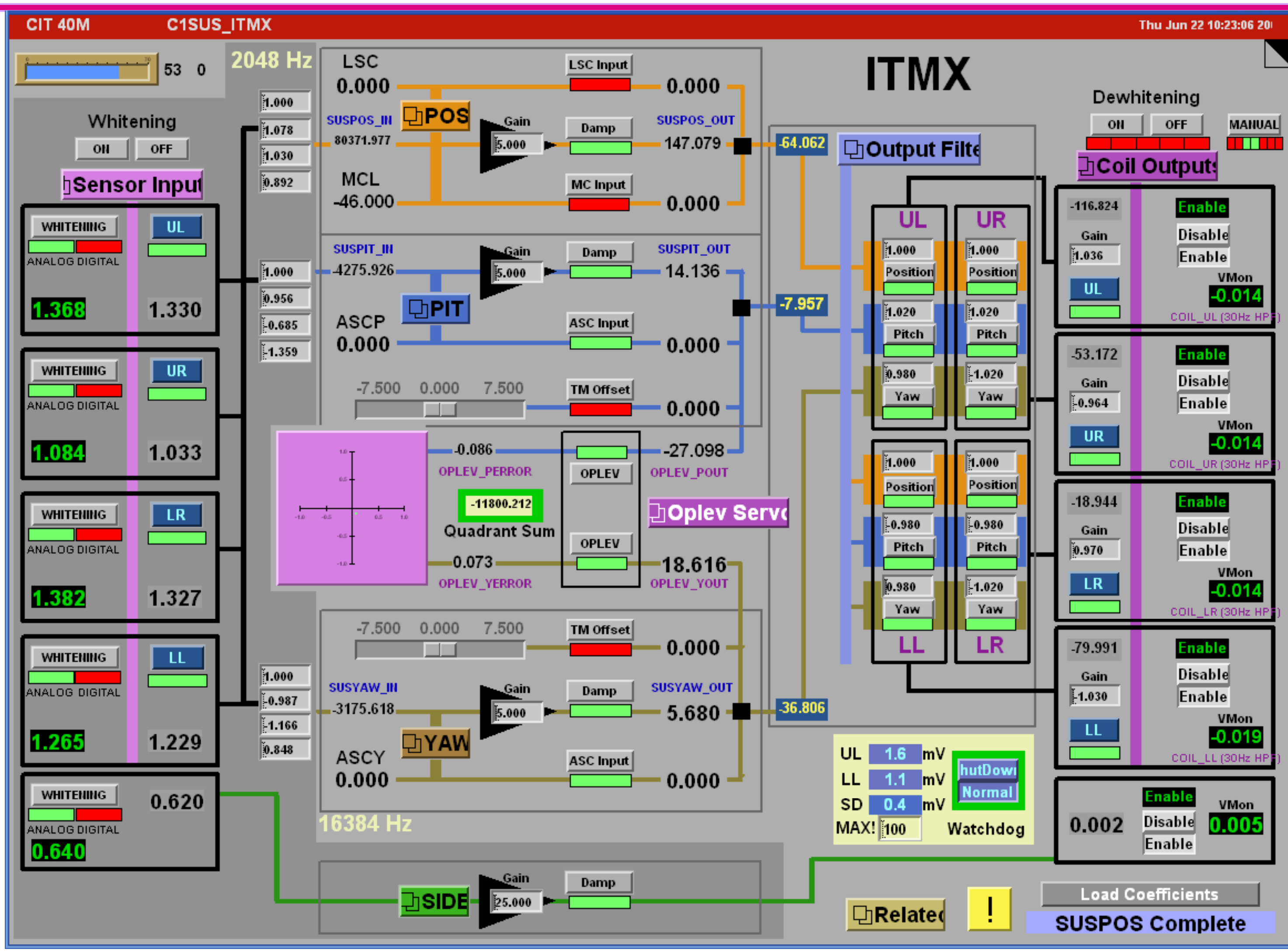
Suspension control system

- Each suspension controller handles one suspension (5 OSEMs)
- Local velocity damping
- Input from LSC and ASC to fix absolute position, pitch, yaw of mirror to keep cavity in resonance





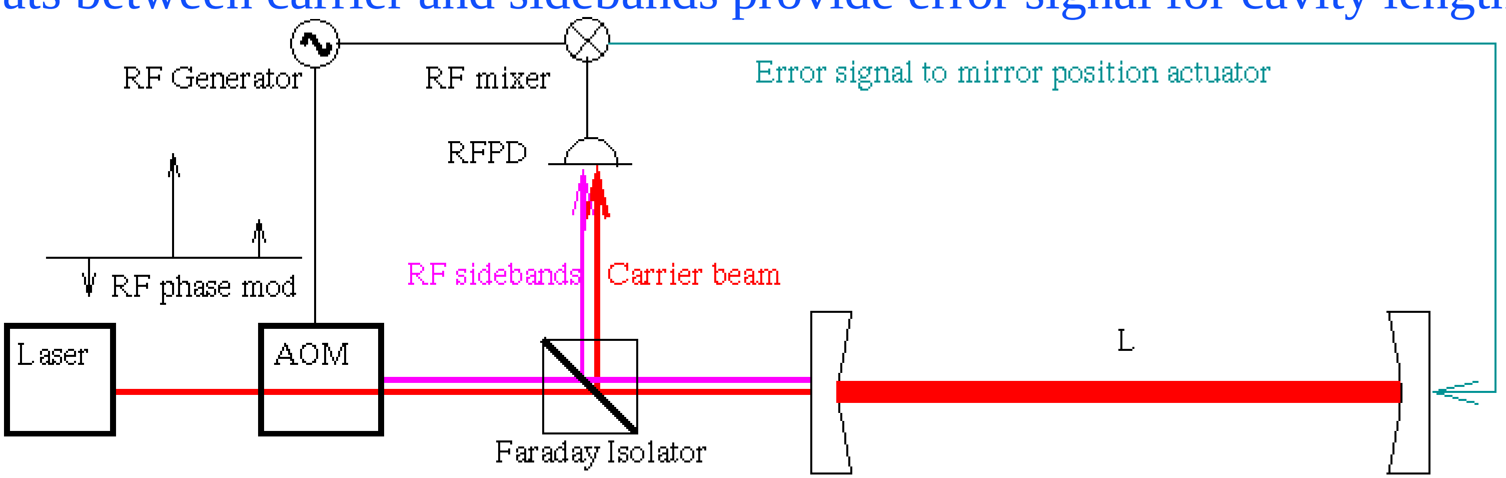
Digital suspension controls



Cavity control

Pound-Drever (reflection) locking used to control lengths of all the optical cavities in LIGO

- Phase modulate incoming laser light, producing RF sidebands
- Carrier is resonant in cavity, sidebands are not
- Beats between carrier and sidebands provide error signal for cavity length



Phase modulation of input beam

Phase modulation adds sidebands to the beam:

$$E_{inc} = E_{laser} e^{i(\omega t + \Gamma \cos \Omega t)} \approx E_{laser} e^{i\omega t} \left(J_0(\Gamma) + J_{+1}(\Gamma) e^{i\Omega t} + J_{-1}(\Gamma) e^{-i\Omega t} \right)$$

Ω = RF modulation frequency ($\Omega /2\pi$ ~ 30 MHz)

Γ = modulation depth

J_i = Bessel functions; $J_{\pm 1} \approx \pm \Gamma/2$ for $\Gamma<1$

$$E_{ref} = \left(E_0^{ref} + E_{+1}^{ref} e^{i\Omega t} + E_{-1}^{ref} e^{-i\Omega t} \right) e^{i\omega t}$$

Arrange the length of the cavity, and the value of Ω, so that

•carrier is resonant in FP cavity, sidebands are not,

•so they have different reflection coefficients

•phase of carrier is sensitive to length changes in cavity, sidebands are not

Demodulation

$$S_{ref} = \left(|E_0|^2 + |E_+|^2 + |E_-|^2 \right) + 2\,\mathrm{Re}\left(\left(E_0^* E_+ + E_0 E_-^* \right) e^{i\Omega t} \right) + 2\,\mathrm{Re}\left(E_+^* E_- e^{i2\Omega t} \right)$$

Use an electronic "mixer" to multiply this by

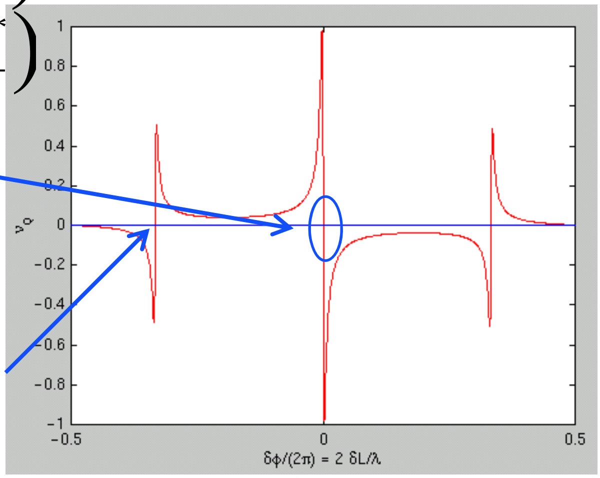
$\cos\Omega t$ or $\sin\Omega t$, average over many RF cycles, to get:

- In-phase demodulated signal $\qquad v_I = 2\,\mathrm{Re}\left(E_0^* E_+ + E_0 E_-^* \right)$
- Quad-phase demodulated signal $\qquad v_Q = 2\,\mathrm{Im}\left(E_0^* E_+ + E_0 E_-^* \right)$

Which are sensitive to length of cavity (very near resonance)

And can be used as an *error signal* to control cavity length

Sideband resonant - error signal has wrong sign

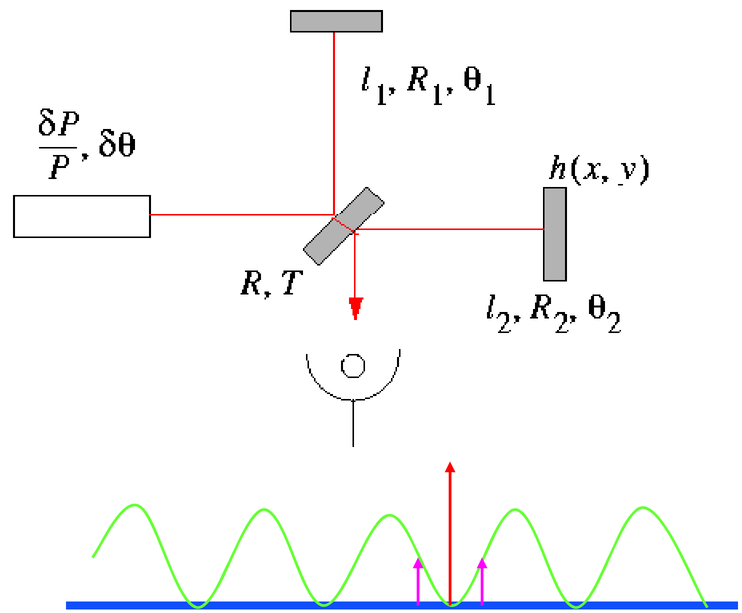


LIGO

Schnupp Asymmetry

GW signal (L_-) is measured using light *transmitted* to dark port. Signal power is quadratic in L_- ; not as sensitive as linear dependence.

To keep the dark port dark for the main (carrier) laser light, use Schnupp (tranmission) locking as opposed to reflection locking, for l_- signal.



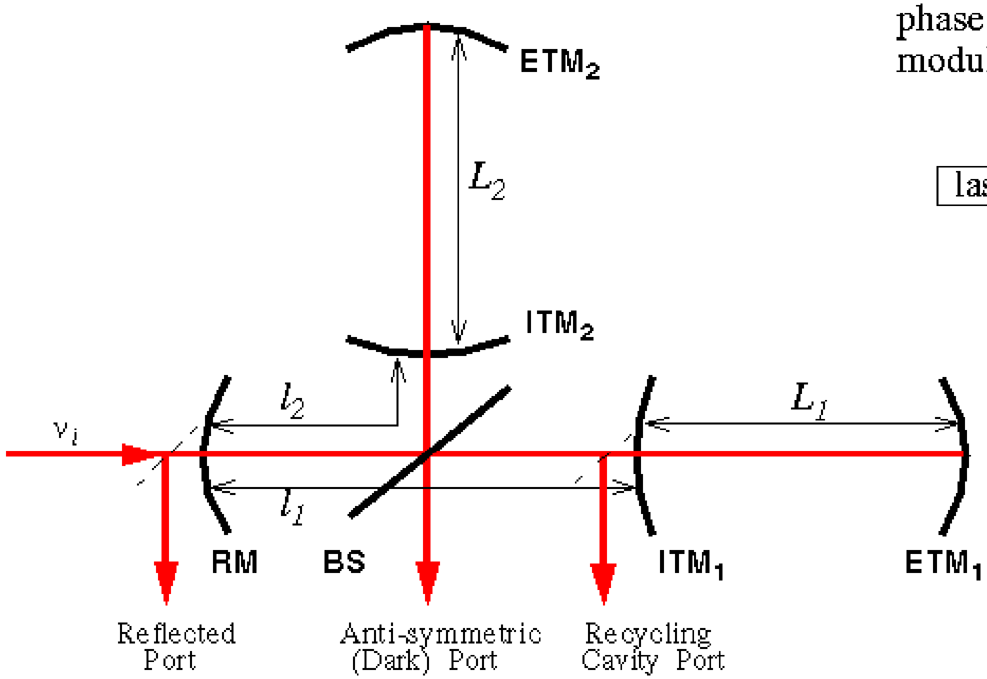
- **In absence of GW, dark port is *dark*;**
  carrier power ~ $\sin^2(\Delta\phi)$,
  quadratic in $\Delta\phi = 2k\, l_-$ for small signal

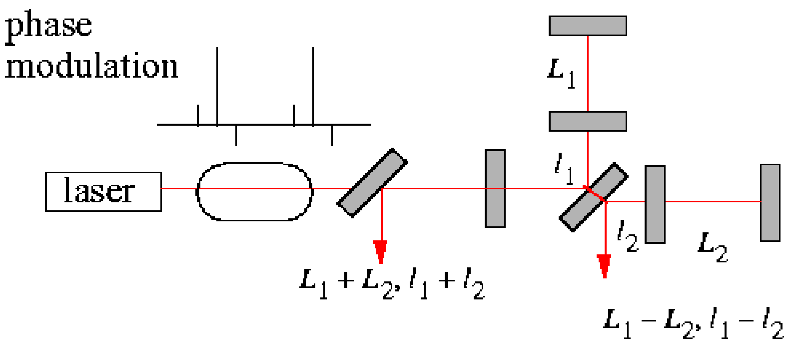
- **Add Schnupp (Michelson) asymmetry: $l_1 \neq l_2$ ($l_- \neq 0$); port still dark for carrier ($l_1 = l_2 \mod \lambda_c$), but sidebands leak out to dark port PD to act as local oscillator for RF-detection of GW signal.**

$$v_Q = 2\,\mathrm{Im}\left(E_0^* E_+ + E_0 E_-^*\right)$$

- **Error signal is then *linearly* proportional to amount of carrier light (GW signal)**

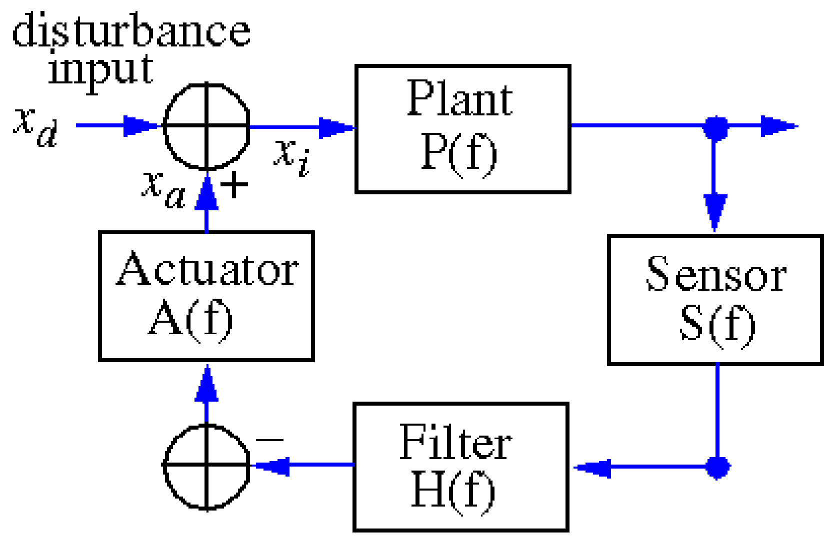
The control problem in LIGO





- **Four interferometer lengths ⇒ four sensors/actuators**
- **Ten mirror angles ⇒ ten sensors/actuators**

Elements of a control system



$$x_a = -PSHAx_i$$

$$x_i = x_d + x_a$$

$$x_i = \frac{x_d}{1 + G(f)}$$

where

$$G(f) = PSHA$$

- Time delays are inevitable; Plant, and control system, response is best characterized in *frequency domain* (as in communication engineering)

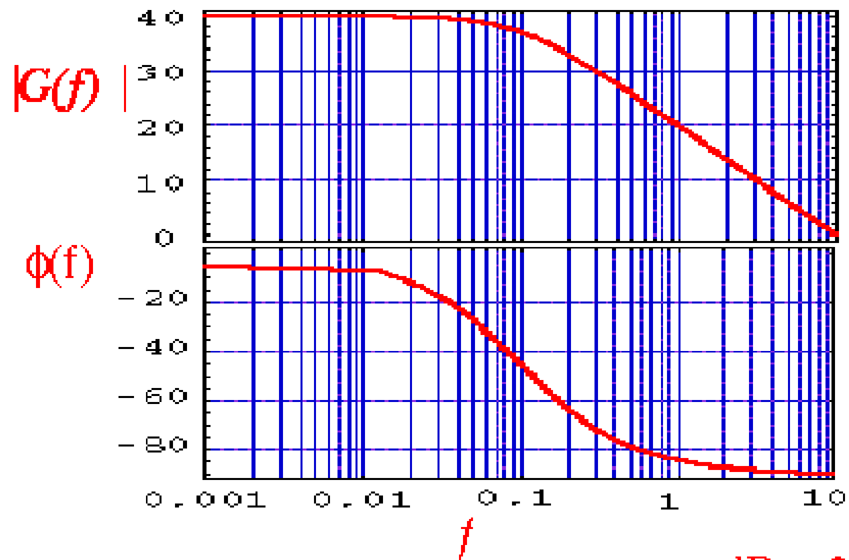
- $G(f) = P*S*H*A$ = "open loop transfer function"

- When $G(f) >> 1$ then $x_i << x_d$,

  Plant input is much smaller than original disturbance

Controls terminology

- Transfer function (frequency response) magnitude [$|G(f)|$] and phase [$\phi(f)$] of output when input is a sinusoid of unit magnitude at frequency f
- Bode Diagram:
- Pole: magnitude falls off with f ($f > f_o$), phase lags
- Zero: magnitude increases with f ($f < f_o$), phase leads



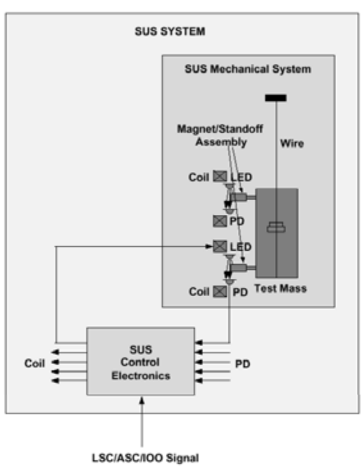
dB = 20 $\log_{10} G(f)$

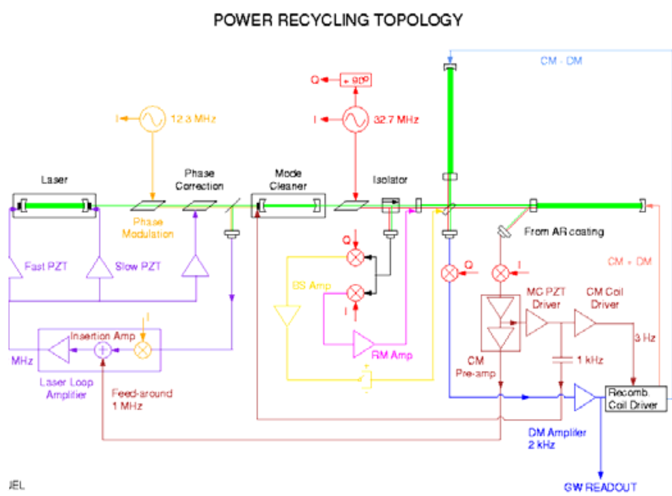
Want high gain at frequencies where control is effective (sensor fidelity, actuator response), and phase < 90° ;

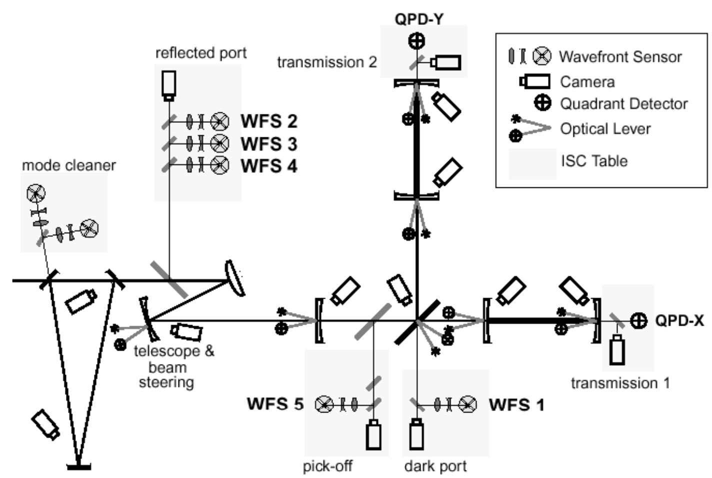
Then fast rolloff of gain to avoid injecting noise

LIGO Control systems

- Start with a “simple” system: control of a mirror (AKA “optic” or “test mass”) suspended on a pendulum
- Control of a Fabry-Perot optical cavity (P-D-H reflection locking)
- Control of a Michelson IFO (Schnupp tranmission locking)
- Controlling all the length degrees of freedom in a LIGO IFO
- Controlling all the alignment degrees of freedom in a LIGO IFO





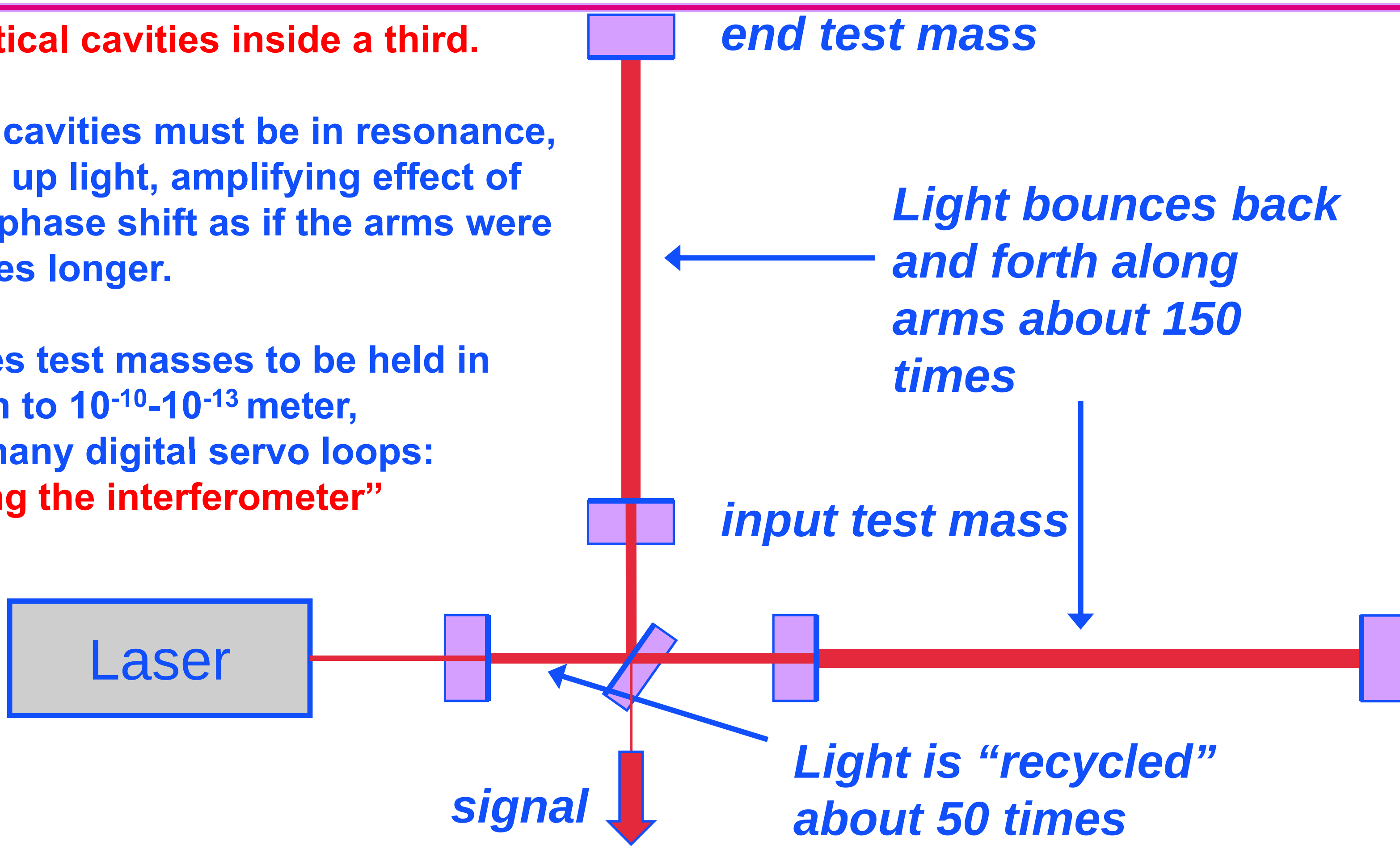


Interferometer *locking*

Two optical cavities inside a third.

Optical cavities must be in resonance, to build up light, amplifying effect of GW on phase shift as if the arms were 150 times longer.

Requires test masses to be held in position to 10^{-10}-10^{-13} meter, using many digital servo loops: "Locking the interferometer"



NOISE in GW detectors

- After ~ 40 years of effort, no one has detected a GW!
- Why? Noise levels in detectors exceed expected signal; *insufficient sensitivity*
- Want to detect GW strain *h*; can express detector noise in terms of equivalent *h* sensitivity
- Most of the effort in GW detection has gone into *understanding and reducing noise* to the fundamental quantum limit (and beyond!)
- We are the beneficiaries of that pioneering and frustrating work: on the threshold of doing what sounds almost impossibly hard!

NOISE SOURCES IN THE DETECTOR

- Noise $\Rightarrow$ signals which appear in detector as GWs but are imposters
- Three categories:
- Displacement noise $\Rightarrow$ moves mirrors (path length changes)

$\delta x = L\, \delta h$, so to achieve $h \approx 10^{-21}/\sqrt{Hz}$ with $L = 4$km,

$\Rightarrow \delta x \approx 10^{-18}\ m/\sqrt{Hz}$

(*cf*: diameter of proton is 10^{-15} m)

- Phase noise $\Rightarrow$ changes the phase of the light:

$\delta\phi = 4\pi\, NL\, \delta h / \lambda$, with $N \approx 100$ and $\lambda \approx 1.064\ \mu$m,

$\Rightarrow \delta\varphi \approx 10^{-10}\ rad/\sqrt{Hz}$

- Technical or instrumental noise (laser, electronics, EMF pickup, *etc*)

must engineer IFO to keep this *below* the fundamental noise!

Sensing limits

Photon shot noise:

$$E_{APD} = P_{APD}\tau_{\text{int}} = N_{photon}(h_{Pl}\,c/\lambda)$$

uncertainty in intensity due to counting statistics:

$$\Rightarrow \delta P_{APD} = \sqrt{P_{APD}h_{Pl}\,c/\lambda\tau_{\text{int}}}$$

can solve for equivalent strain:

$$h_{shot} = \frac{\delta L}{L} = \frac{1}{L}\sqrt{\frac{h_{Pl}c\lambda}{2\pi T(f)P_{laser}}}$$

Note: scaling with $1/\sqrt{P_{laser}}$; gives requirement for laser power

Radiation Pressure

quantum limited intensity fluctuations anti-correlated in two arms

photons exert a time varying force, spectral density

results in opposite displacements of *each* of the masses; strain

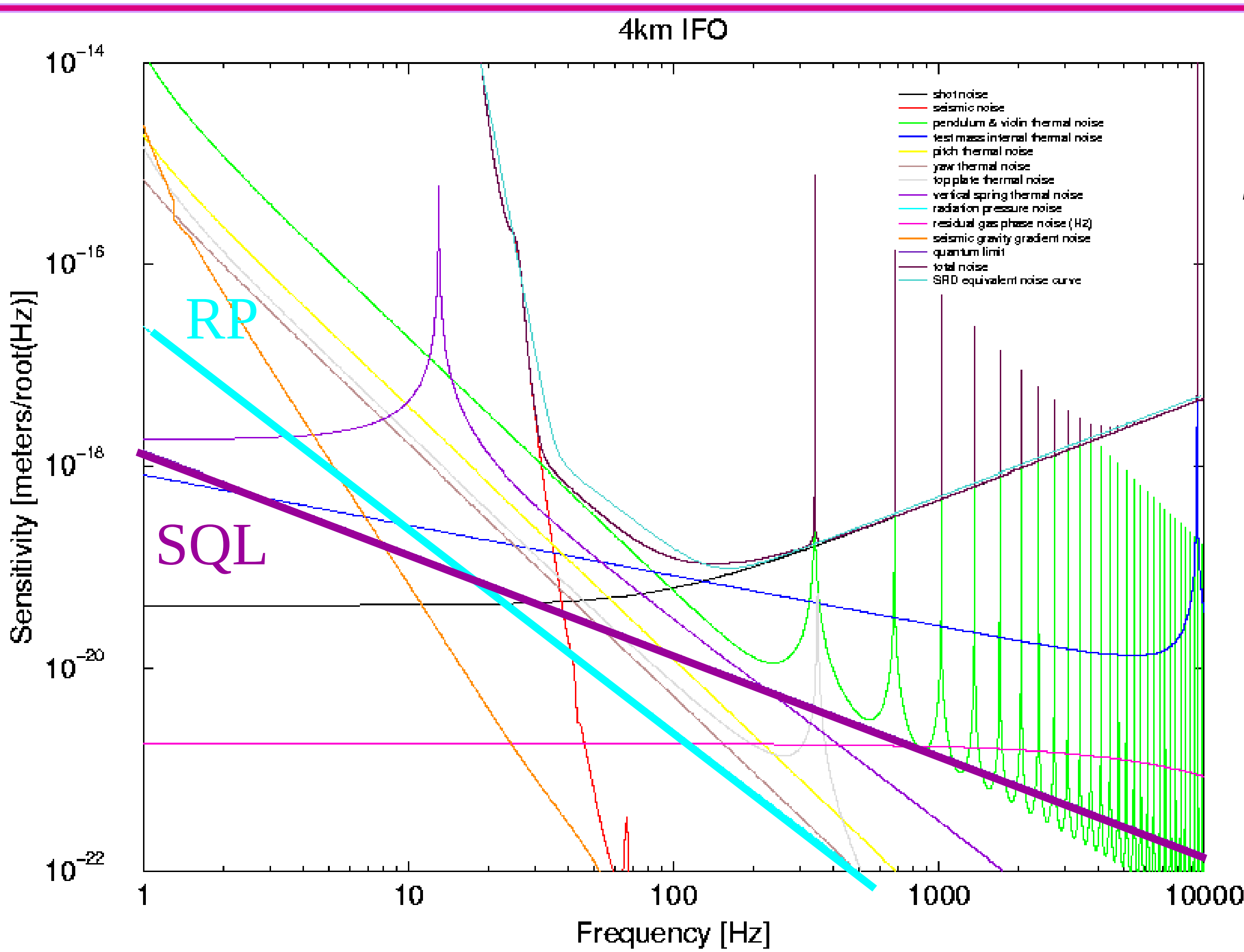
$$h_{rp} = \frac{\delta L}{L} = \frac{2}{L}\frac{1}{mf^2}\sqrt{\frac{h_{Pl}T(f)P_{laser}}{8\pi^3 c\lambda}}$$

NOTE: scaling with $\sqrt{P_{laser}}$, scaling with the arm length

Total optical readout, or quantum noise:

quadrature sum $h_q = \left(h_{shot}^2 + h_{rp}^2\right)^{1/2}$; can be optimized

Optical readout noise



Optical readout noise:

$$h_{ro}(f) = \sqrt{h_{shot}^2(f) + h_{rp}^2(f)}$$

Optimize h_{ro} wrt P_{laser} at each point in f;
Locus of points is the Standard Quantum Limit,
Obtainable from Heisenberg Uncertainty

$$h_{SQL} = \frac{1}{\pi f L}\sqrt{\frac{\hbar}{m}}$$

Thermal displacement noise

Mechanical systems excited by the thermal environment

results in physical motions of the tests masses

$$x_{rms} = \sqrt{\left\langle (\delta x)^2 \right\rangle} = \sqrt{k_B T / k_{spring}}$$

Each normal mode of vibration has $k_B T$ of energy; for a SHO,

An extended object has many normal modes at discrete frequencies;

each will experience thermal excitation.

Dissipation causes the energy, and fluctuations in position, to spread over a range of frequencies, according to Fluctuation-Dissipation theorem:

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

e.g., damping term in an oscillator: $m\ddot{x} = F_{ext} - \Re(Z)\dot{x} - k_{spring}x$

•viscous damping: $\Re(Z) = b$ = constant. Recall, at a definite f, $\dot{x} = i2\pi f\, x$

•internal friction: $F = -kx \quad \Rightarrow \quad F = -k(1 + i\phi(f))x$

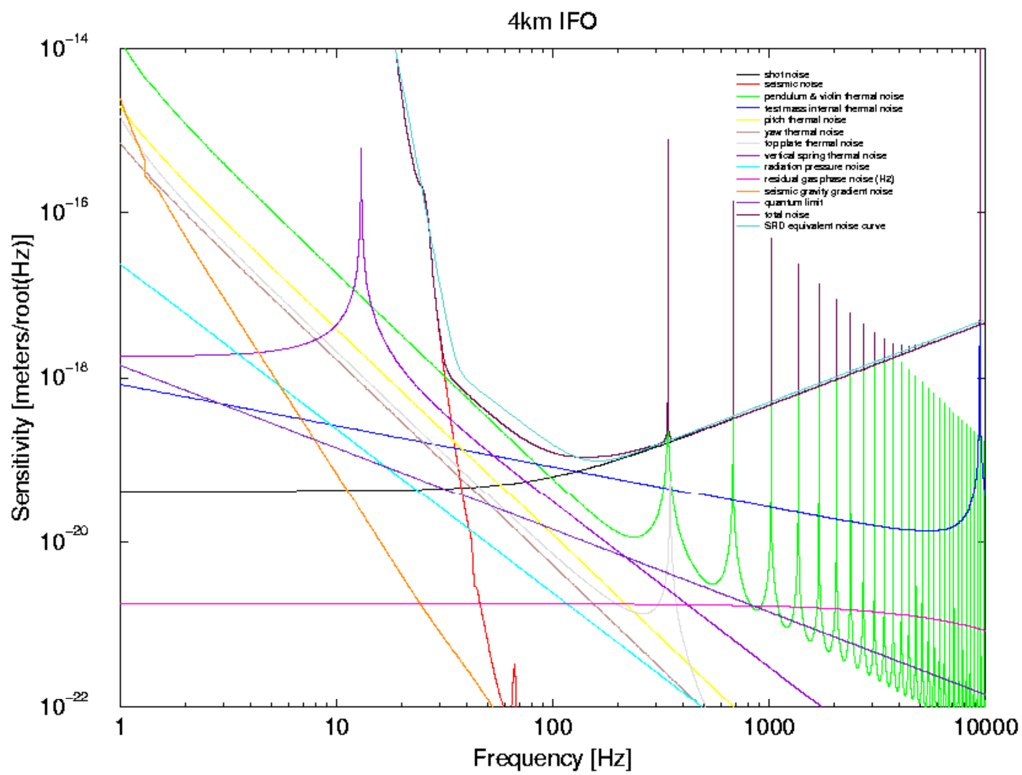
$\phi(f)$ is often a constant, = 1/Q

Minimize thermal motion $\Rightarrow$ materials and techniques for very low loss (high Q)

Thermal displacement noise

Sum of many normal modes, $x_{thermal}^2 = \frac{4kT}{2\pi f} \sum_n \frac{\phi_n(f)}{m_n (2\pi f_n)^2} \left\{ \frac{1}{\left(1-(f/f_n)^2\right)^2 + \phi_n{}^2(f)} \right\}$

Each with loss $\phi_n(f)$:

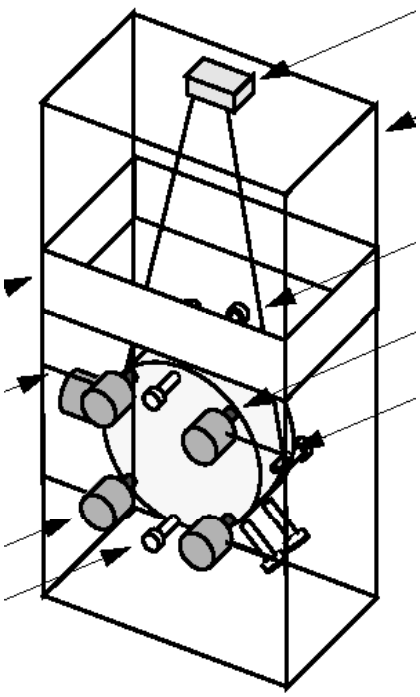


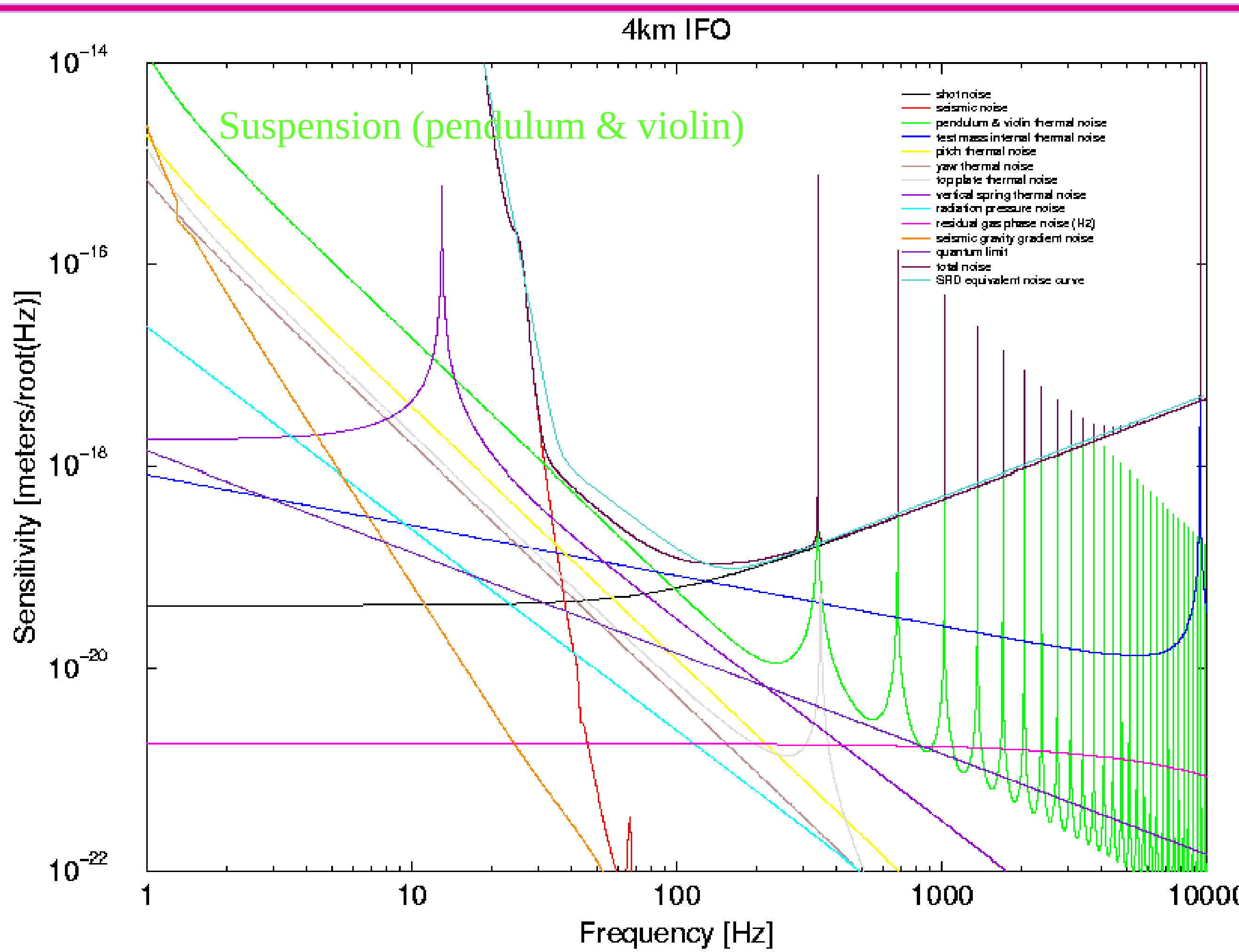
Equivalent strain (noise):

$$h_{thermal}(f) = \frac{2}{L} \sqrt{x_{thermal}^2}$$

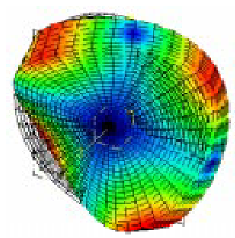
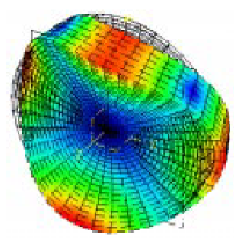
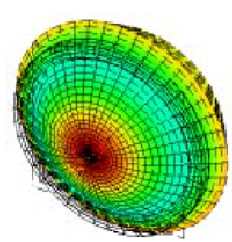
Suspension thermal noise

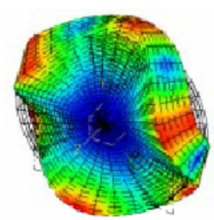
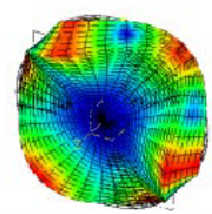
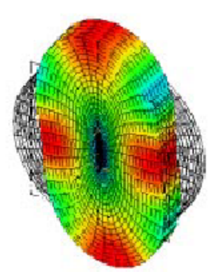
Suspension wires vibrate (violin modes, stretch/bounce modes), kick the test mass around, introducing an harmonic series of noise lines



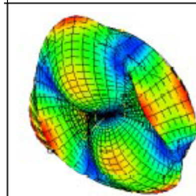
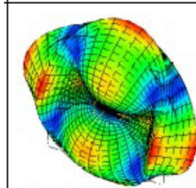
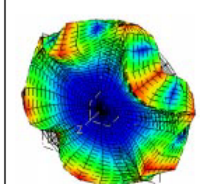
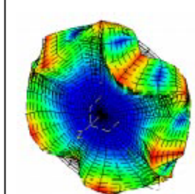


Vibrational modes of test masses

Mode Shape	*Frequency (Hz)*
	3785
	3785
	5578

Mode Shape	*Frequency (Hz)*
	7975
	7975
	11259

• • •

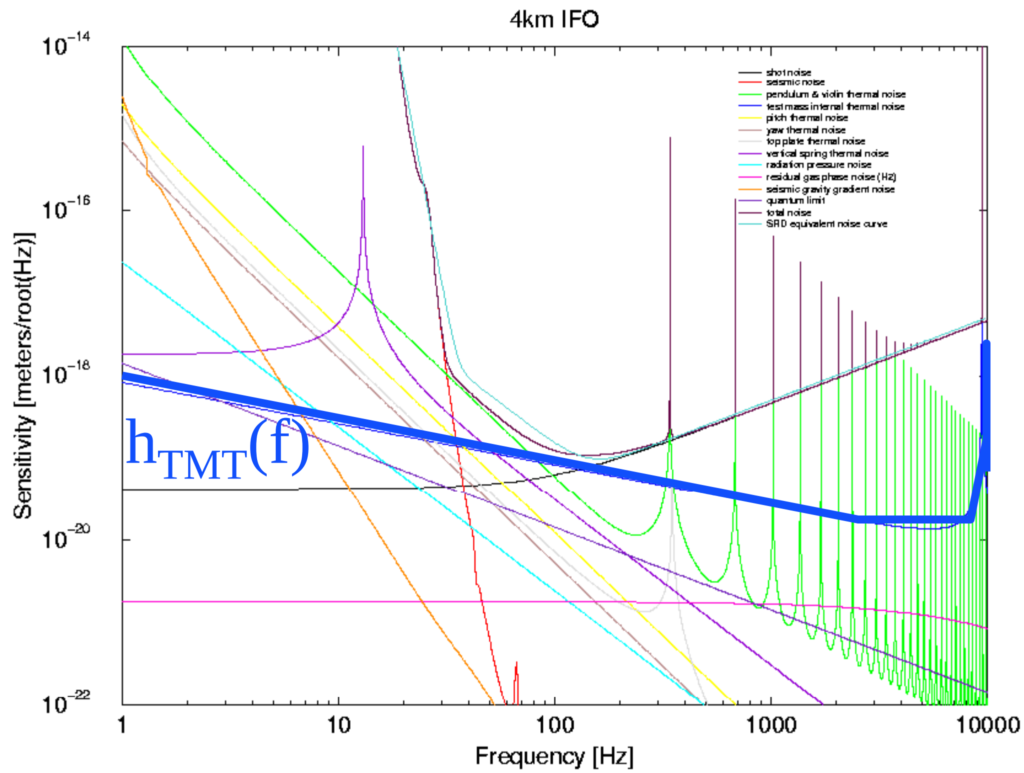
Mode Shape	*Frequency (Hz)*
	17388
	17388
	17958
	17958

This is for beam splitter. Test masses have no resonances below ~8KHz (?).

Test mass internal thermal noise

$$x_{TMT}^2 = \frac{4kT}{2\pi f}\sum_n \frac{\phi_n(f)}{m_n(2\pi f_n)^2}\left\{\frac{1}{\left(1-(f/f_n)^2\right)^2+\phi_n{}^2(f)}\right\}$$

Test masses have normal modes
Above the LIGO band



Equivalent strain:

$$h_{TMT}(f) = \frac{2}{L}\sqrt{x_{TMT}^2}$$

LIGO

Seismic displacement noise

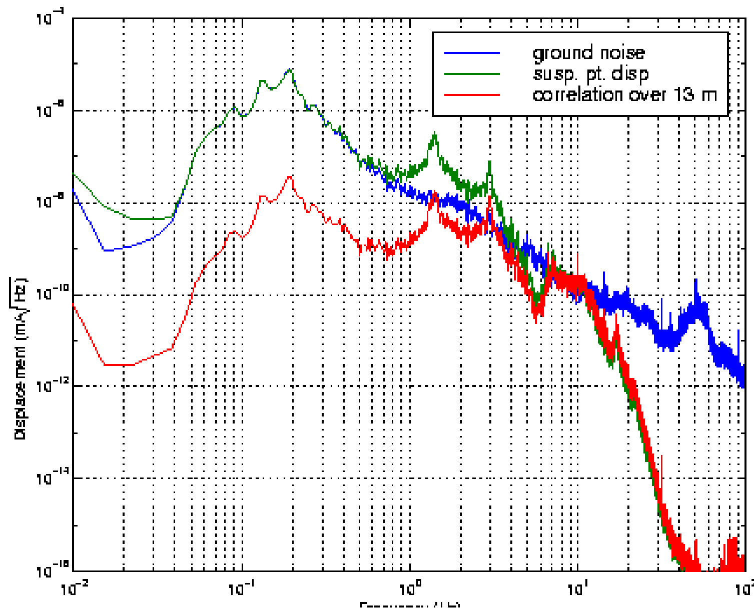
Motion of the earth

•driven by wind, volcanic/seismic activity, ocean tides, humans

•requires *e.g.*, roughly 10^9 attenuation at 100 Hz

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

• At low frequencies, motion is correlated over two mirrors



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

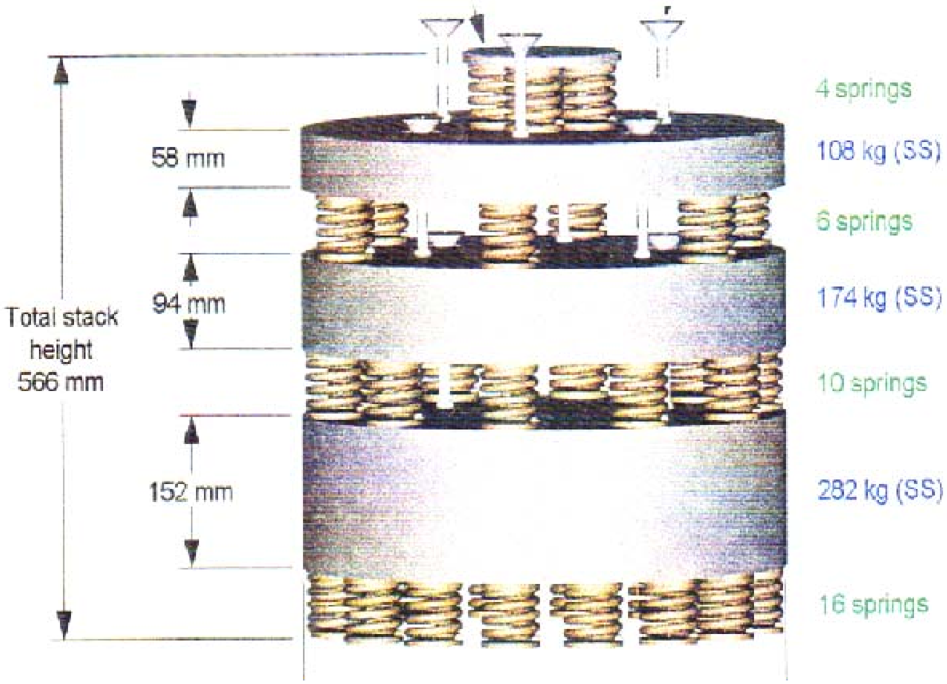
•simple damped harmonic oscillators in series

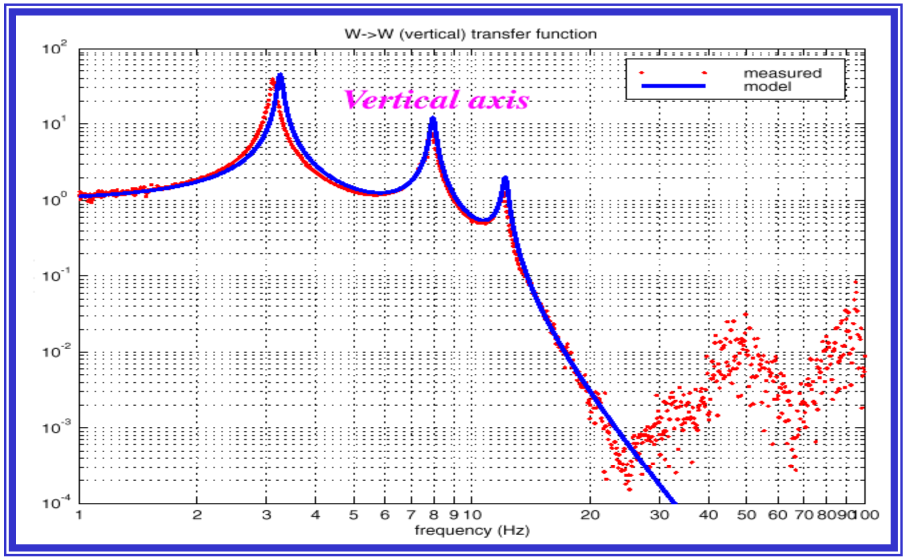
  •`stacks', constrained layer springs and SS masses

•one or more low-loss pendulums for final suspension

  •gives $1/f^2$ for each pendulum

Seismic isolation stacks





Seismic Isolation Systems

Support Tube Installation

Stack Installation

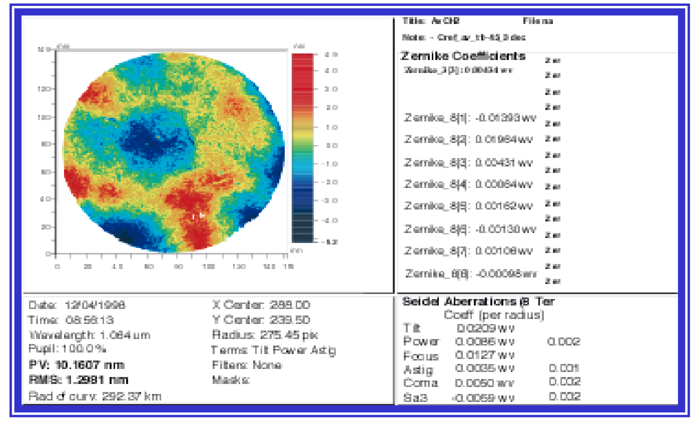
Coarse Actuation System

Noise from imperfect Optics

Highly efficient optical system:

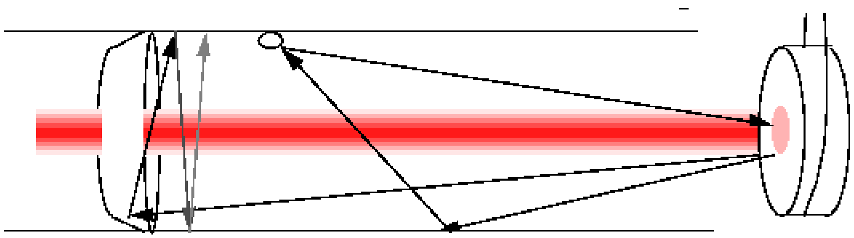
~50 ppm lost per round-trip

- optics are 25 cm diameter, 10 cm thick fused silica cylinders
- light beam ~10 cm diameter; 1ppm scattered, ~1ppm absorbed



Constraints on optical surface due to noise requirements:

- minimize scatter (power loss ⇒ phase noise)
- minimize absorption (thermal distortions, lensing ⇒ phase noise)
- minimize scattering out of beam, onto tube, back into beam (phase noise)
- minimize wavefront distortions (*contrast defect* at dark port ⇒ phase noise)



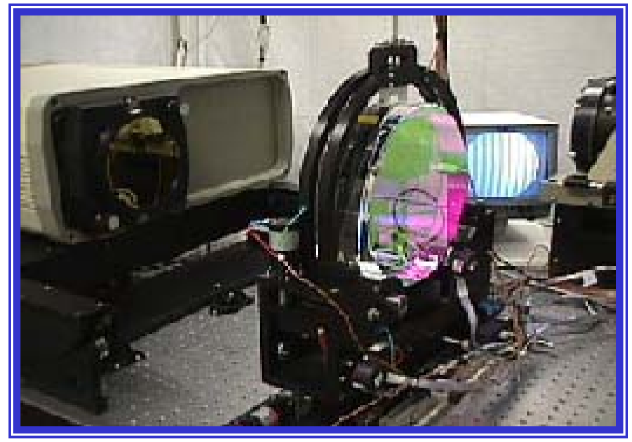
Results

- **λ/800** over central 10 cm (~1 nm rms); fine scale `superpolish‘
- Sophisticated *baffling*

LIGO Optics

mirrors, coating and polishing

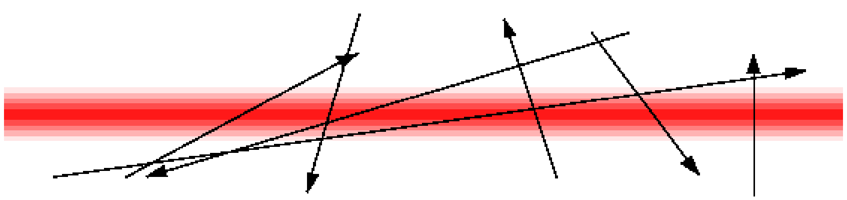
- SUPERmirrors:
  - » High uniformity fused silica quartz
  - » reflectivity as high as 99.999%
  - » losses < 1 ppm in coating, 10 ppm in substrate
  - » polished with mircoroughness < $\lambda/1800 \approx 0.5$ nm
  - » and ROC within spec.
  - ≈ ($\delta R/R < 5\%$, except for BS)
- Suspensions: hang 10kg optic by a single loop of wire, and hold it steady with feedback system



Residual gas in beam tube

Light must travel 4 km without attenuation or degradation

- refractive index fluctuations in gas cause variations in optical path, phase noise
- residual gas scatters light out of, then back into, beam; phase noise
- Residual gas pressure fluctuations buffet mirror; displacement noise
- Contamination: low-loss optics can not tolerate surface 'dirt';
  High circulating powers of ~10-50 kW burns dirt onto optic surface



requirement for vacuum in 4 km tubes:

- H_2 at 10^{-6} torr initial, 10^{-9} torr ultimate
- H_2O at 10^{-7} torr initial, 10^{-10} ultimate
- Hydro-, flourocarbons < 10^{-10} torr
- vacuum system, 1.22 m diameter, ~10,000 m^3
- strict control on in-vacuum components, cleaning

LIGO beam tubes

LIGO Livingston Observatory
LLO

LIGO Hanford Observatory
LHO

LIGO *Beam Tube*

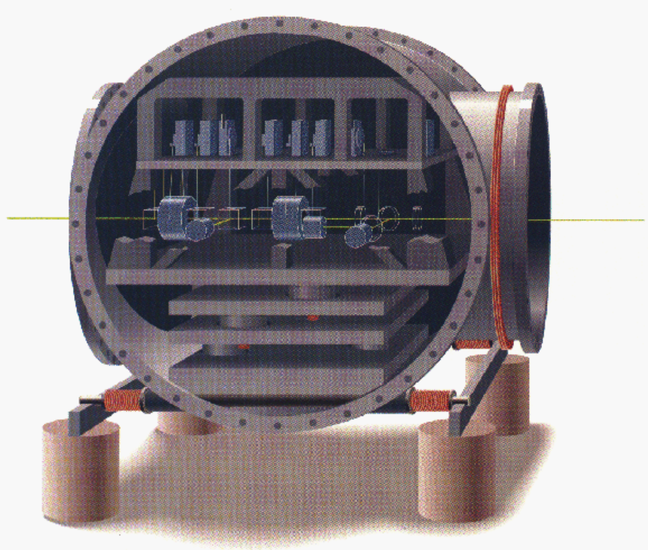
Beam light path must be high vacuum, to minimize "phase noise"

- LIGO beam tube under construction in January 1998
- 65 ft spiral welded sections
- girth welded in portable clean room in the field

LIGO vacuum equipment

All optical components must be in high vacuum, so mirrors are not "knocked around" by gas pressure

LIGO Vacuum Chambers

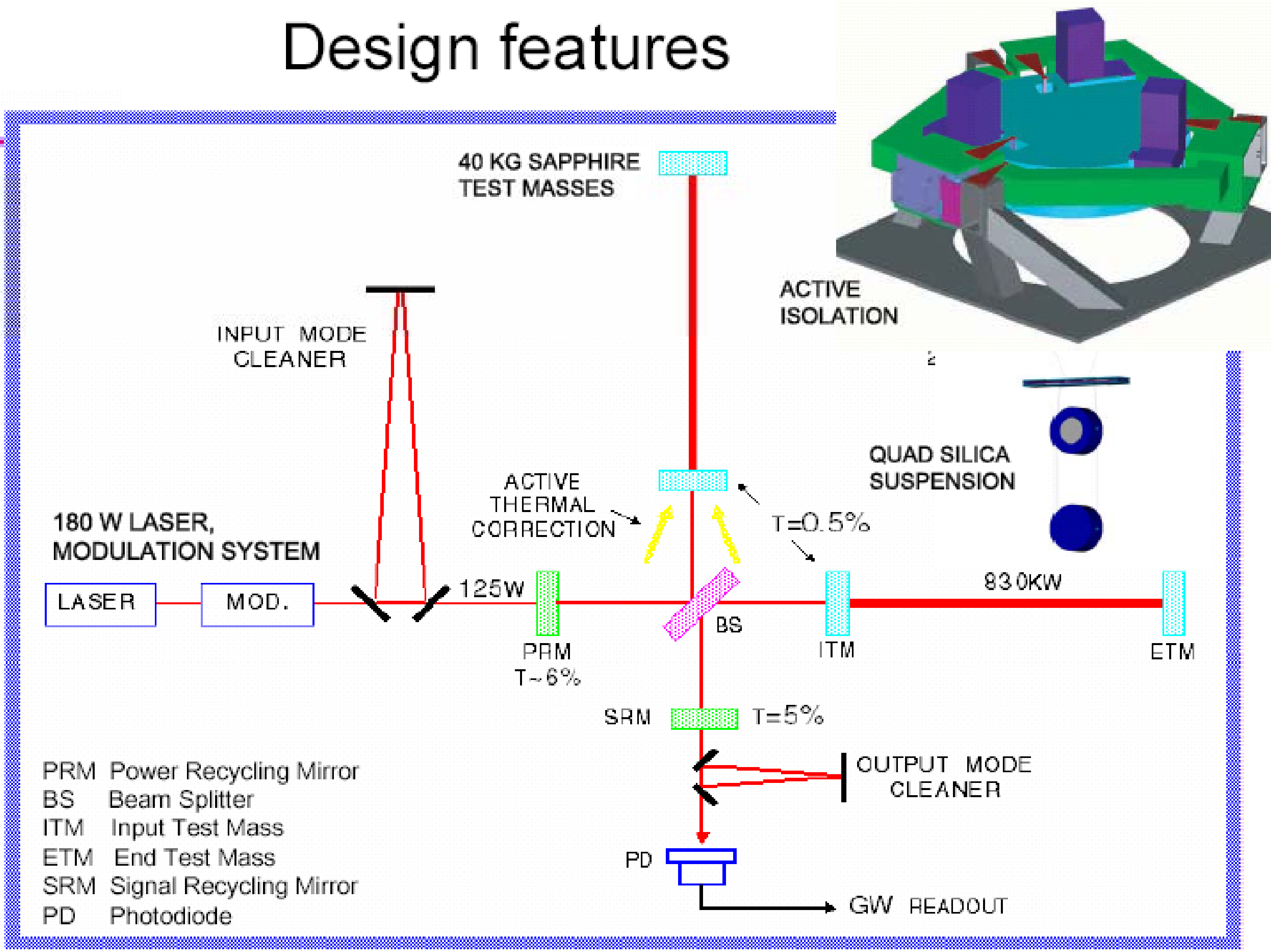


HAM Chambers

BSC Chambers

Advanced LIGO

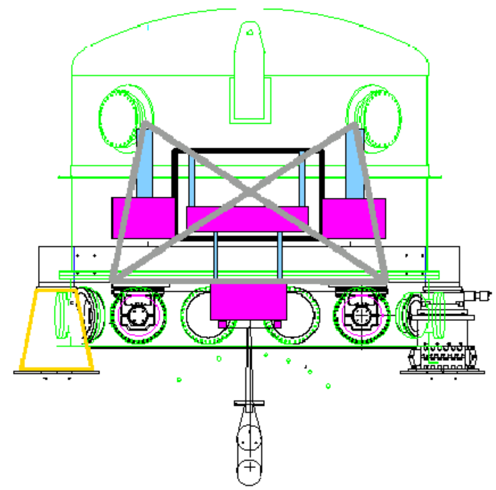
Design features

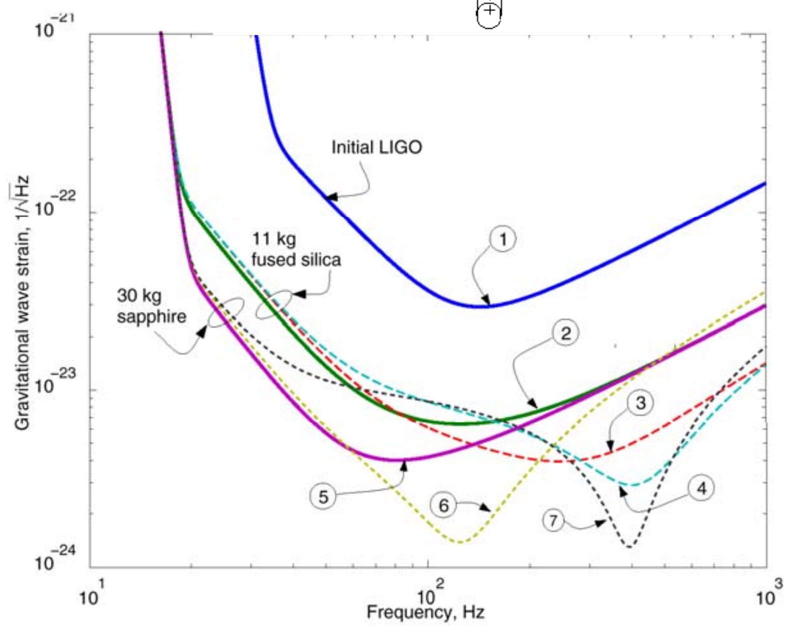


Advanced LIGO

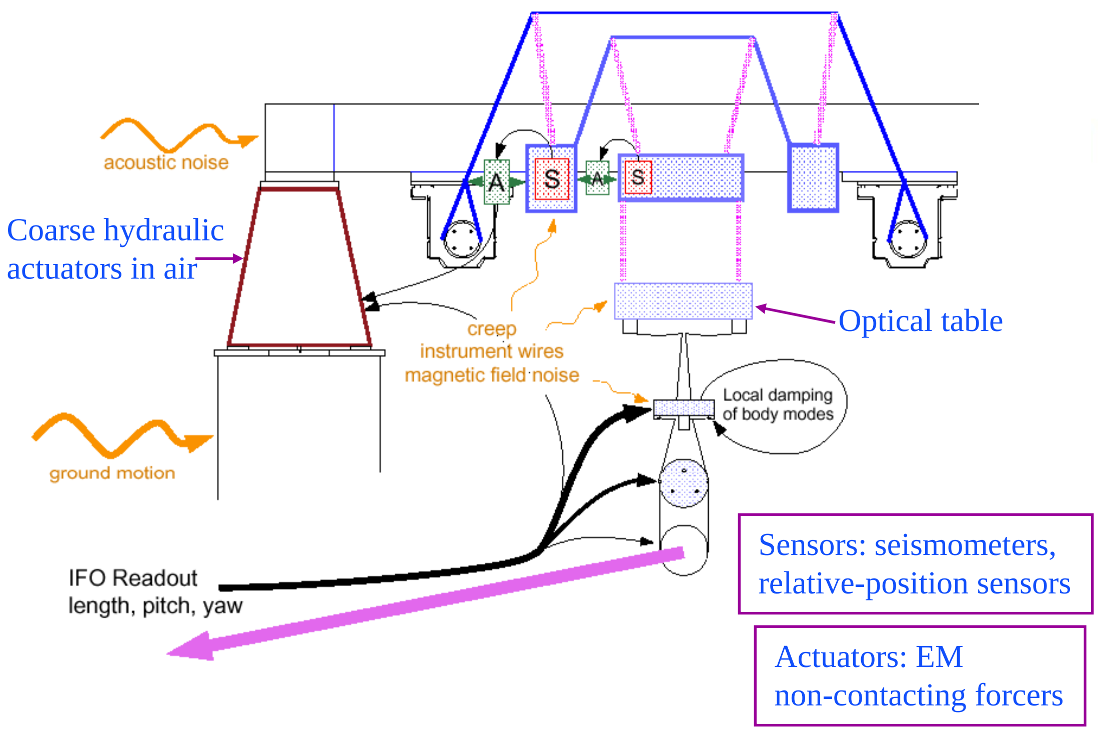
incremental improvements

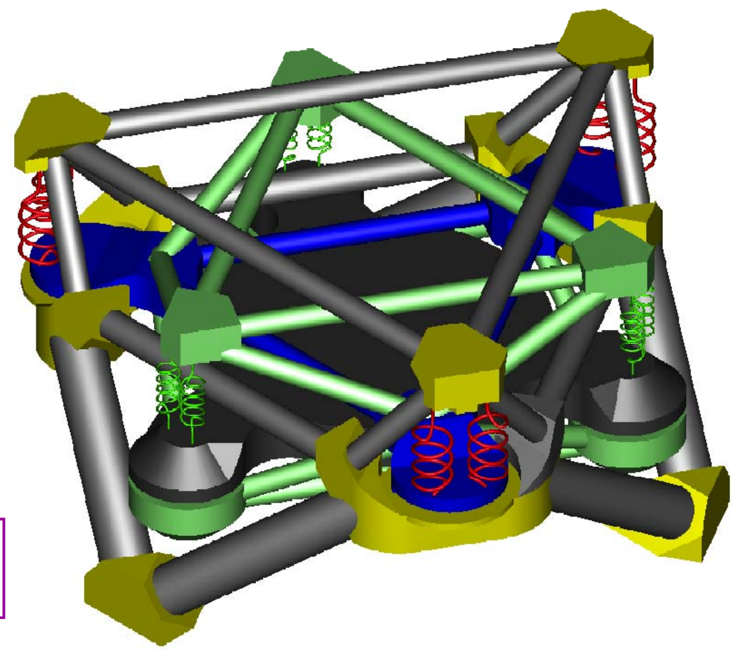
- Reduce shot noise:
  higher power CW-laser: 12 watts ⇒120 watts
- Reduce shot noise: Advanced optical configuration: signal recycling mirror (7th suspended optic) to tune shot-noise response in frequency
- To handle thermal distortions due to beam heating: advanced mirror materials, coatings, thermal de-lensing compensation (heating mirror at edges)
- Reduce seismic noise: Active seismic isolation.
  Seismic wall moved from 40 Hz ⇒ ~ 10 Hz.
- Reduce seismic and suspension noise: Multiple pendulum suspensions to filter environmental noise in stages.
- Reduce suspension noise: Fused silica fibers, silica welds.
- Reduce test mass thermal noise: Last pendulum stage (test mass) is controlled via photonic and/or electrostatic forces (no magnets).
- Reduce test mass thermal noise:
  High-Q material (40 kg of single-crystal sapphire).





Active control of SEI system

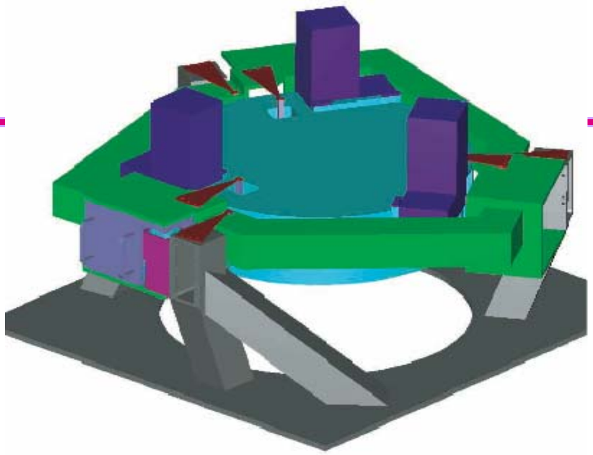


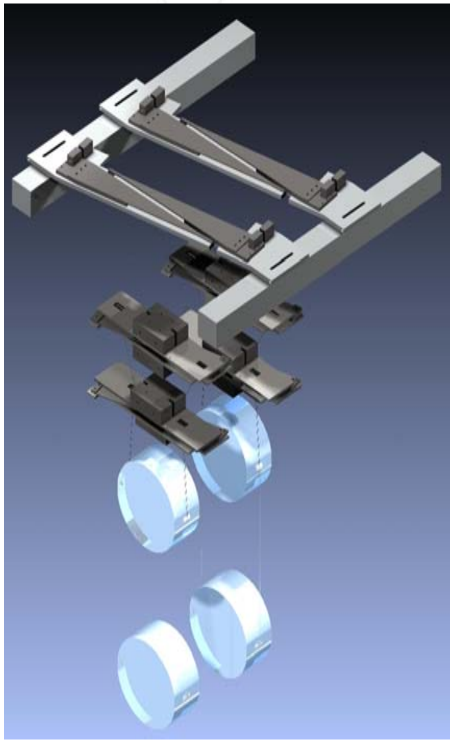


Two active stages: cages, masses, springs, S/A pairs.
All DOF under active control.

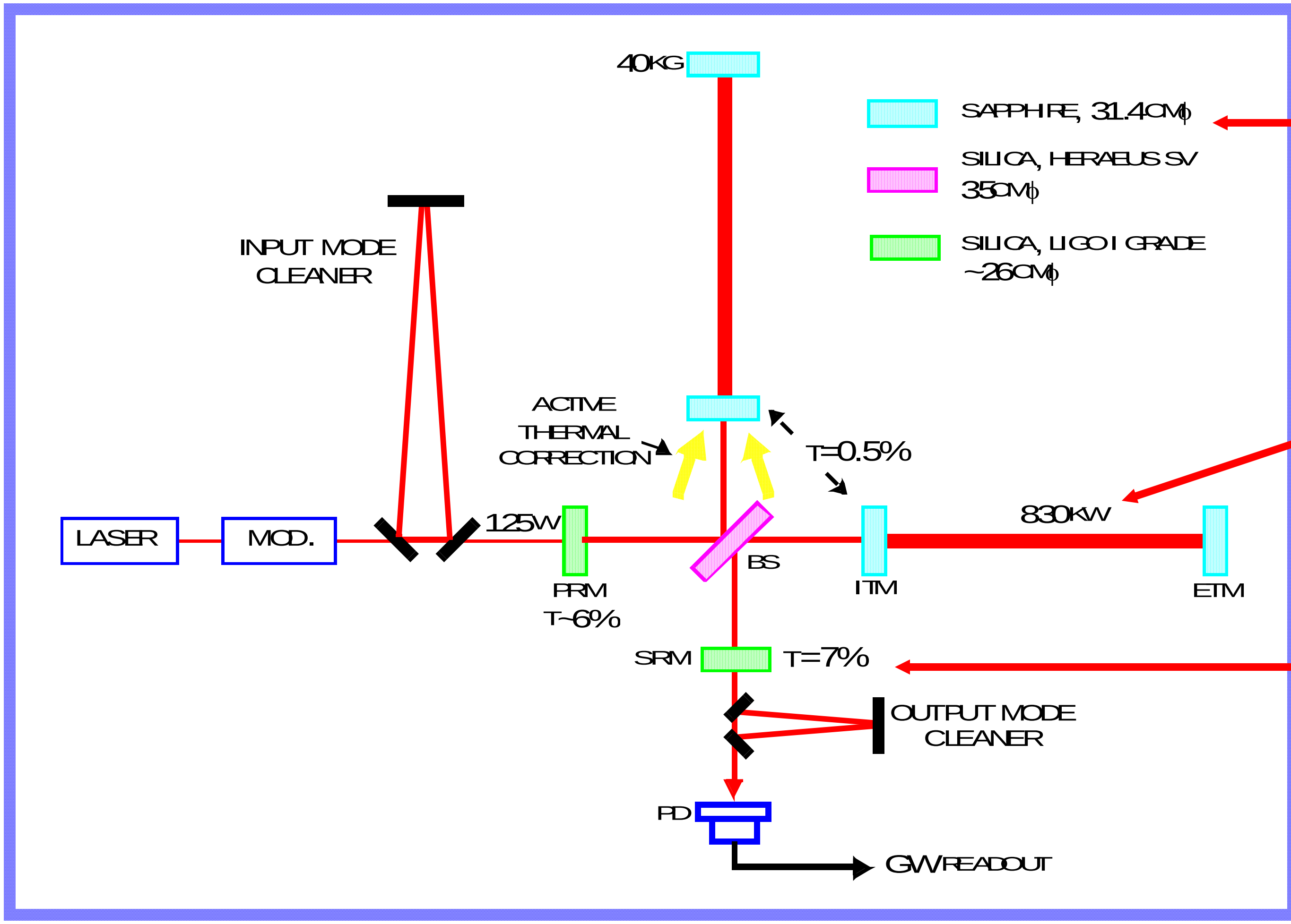
Advanced LIGO R&D

- Development of multiple pendulum suspensions with silica fibers
  - » Willems et al
- Development of advanced seismic isolation and suspension systems
  - » de Salvo et al
- Advanced interferometer techniques, detection of gravity at DC
  - » Drever et al
- Simulations of complex interferometer behavior
  - » Yamamoto et al
- Quantum-nondemolition optical techniques to reduce quantum readout noise
  - » Whitcomb et al





LIGO II Optics



High-Q optics

High stored power

Signal recycling

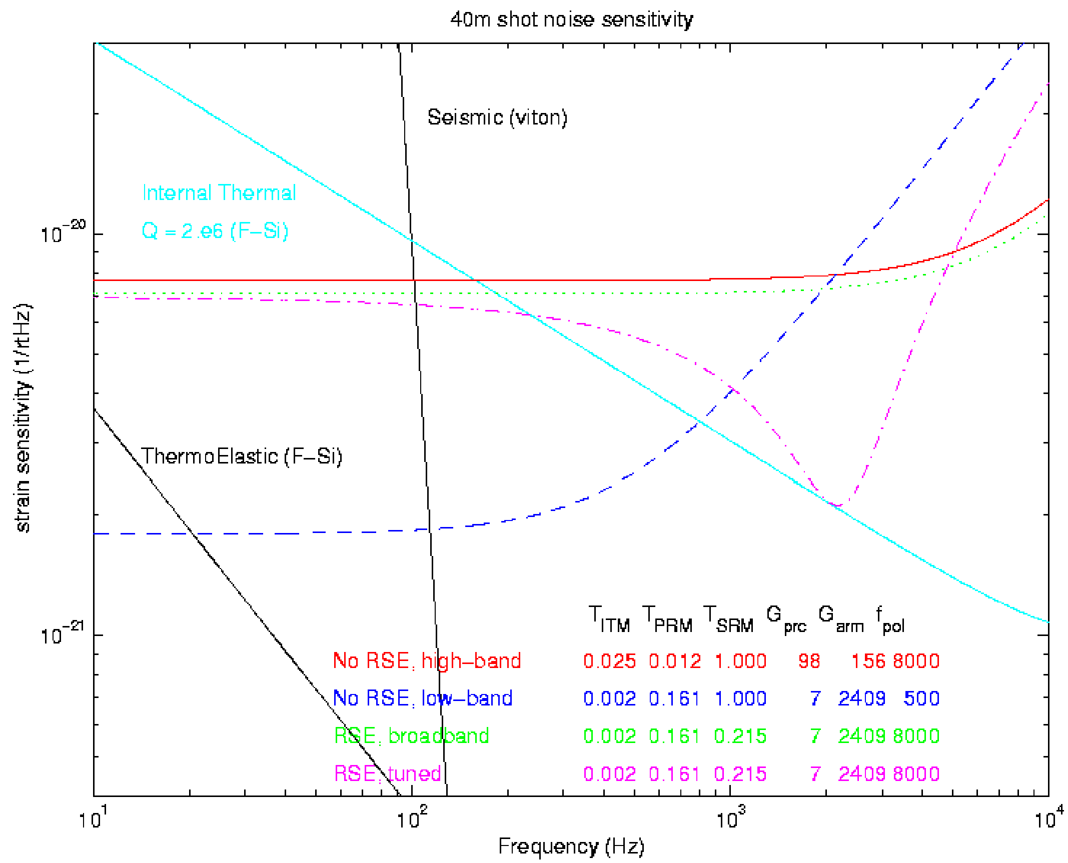
Signal recycling mirror to optimize sensitivity

- The signal mirror is NOT used to store the laser light; all it sees is light generated by the GW signal.

- The signal recycling cavity allows one to tune the response of the IFO to the signal, as a function of its frequency, independently of the light storage in the arms (the “reservoir” of light available to be converted into signal light.

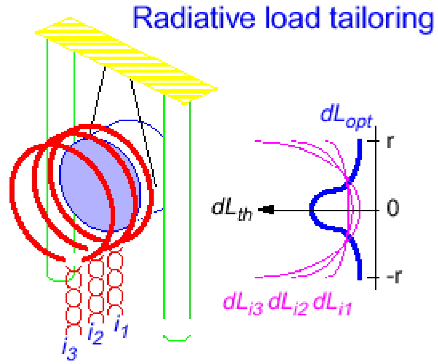
- The frequency response of the IFO can be tuned to put the sensitivity where it is most needed (at high frequencies).

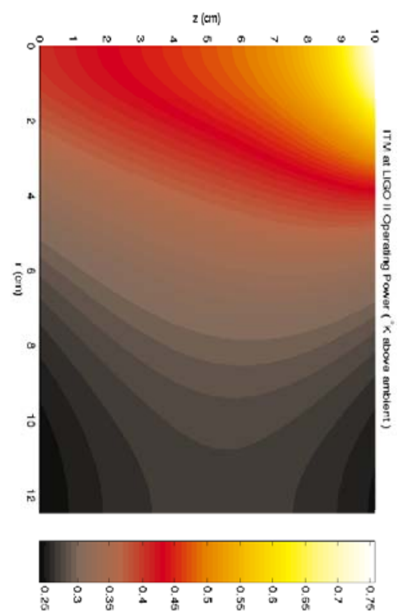
- Net result:
  - ➢ 2× sensitivity for CBI;
  - ➢ or ~ 10 × in event rate.

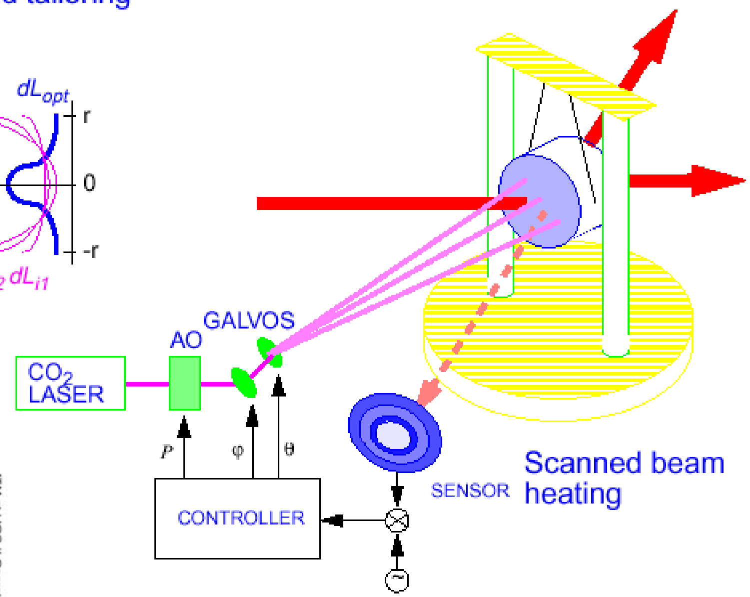


Thermal compensation (de-lensing) methods

- Beam heating at center of optic distorts the optic due to thermal expansion, changing ROC, index of refraction, etc.
- Compensate by heating the optic from the circumference in, to give uniform and constant-in-time thermal loading as the IFO is operated.



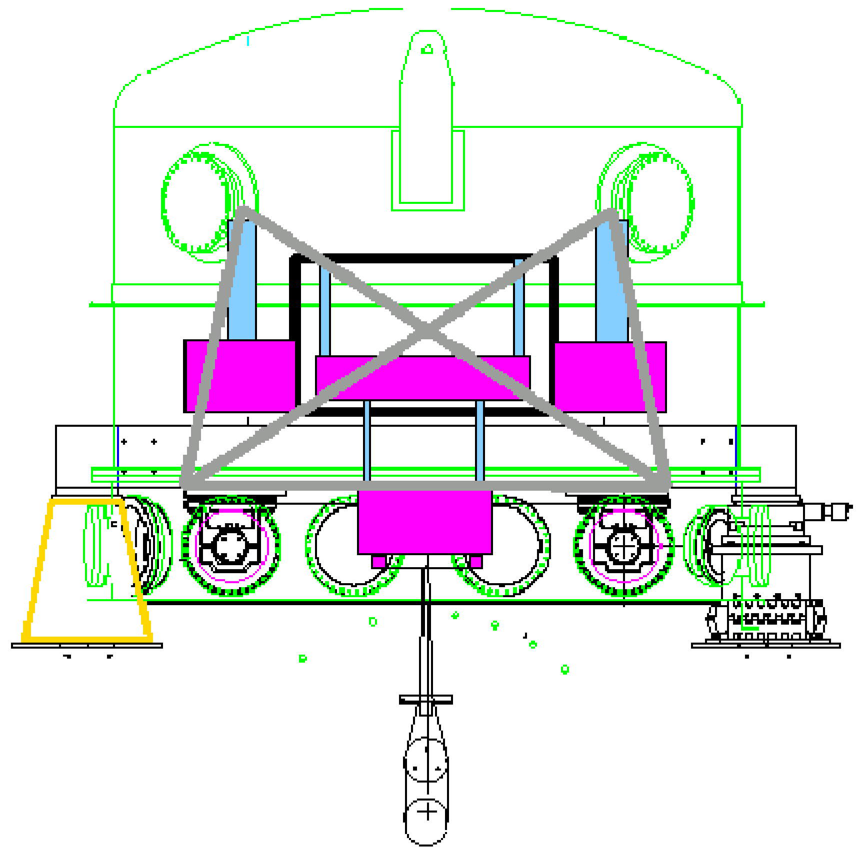




LIGO II Active seismic isolation and multiple pendulum suspension

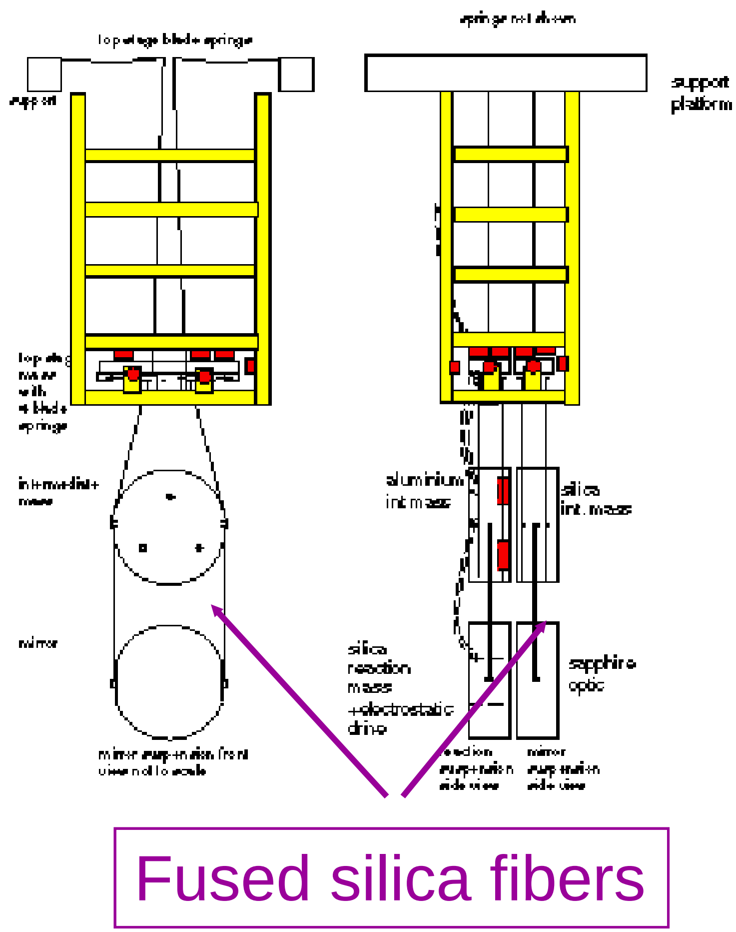
- Must support LIGO test mass optic at the beamline.
- Must fit inside existing vacuum chambers, and be fully vacuum compatible.
- Must provide full control system.
- Must satisfy specs:

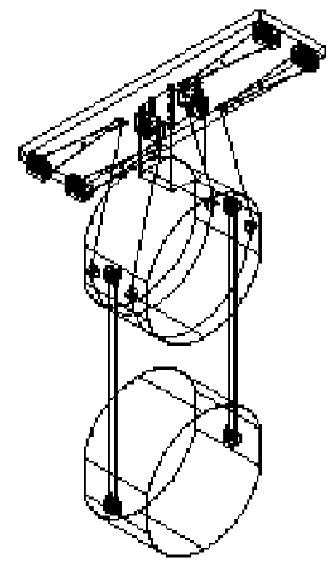
Optics Payload, (Chamber type)	Optic Axis (X-direction)				Y & Z directions		Pitch, Yaw
	Freq. (Hz)	Noise (m/√Hz)	*Motion* (m rms)	Velocity (m/s)	Noise (m/√Hz)	*Motion* (m rms)	*Motion* (rad rms)
ITM, ETM, BS, FM (BSC)	10	10^{-19}	10^{-14}	10^{-9}	10^{-16}	10^{-11}	10^{-96}
RM, SRM (HAM)	10	10^{-17}	10^{-13}	10^{-8}	10^{-14}	10^{-10}	10^{-96}
MC (HAM)	10	$3x10^{-18}$	10^{-12}	10^{-7}	$3x10^{-15}$	10^{-9}	10^{-96}
Ancillary Optics (HAM, BSC)	10						



GEO multiple pendulum design

- 3 or 4 pendulum stages; each provides $1 / f^2$ filtering for $f > f_0$
- Top stage has 6 OSEMs for 6-dof control (“marionetta”), relative to support cage.
- Normal modes of the multiple pendulum (~24) must not have nodes at the top, so they can be controlled from the top.
- Blade springs at the very top provide tuned vertical isolation.
- Lower stages must control w.r.t. stage above it; so the actuators must push against a “reaction mass” which is as quiet as the stage above it
- lowest stage (test mass optic) is attached to stage above it with fused silica fibers.





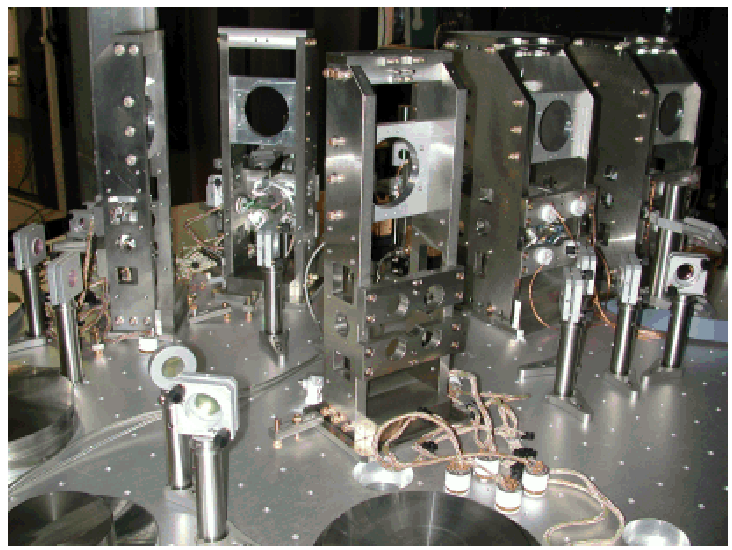
Prototype IFOs

- **40 meter (Caltech)** :
  full engineering prototype for optical and control plant for AdvLIGO
- **Thermal Noise Interferometer (TNI, Caltech)** :
  measure thermal noise in AdvLIGO test masses
- **LIGO Advanced Systems Testbed IFO (LASTI, MIT)** :
  full-scale prototyping of AdvLIGO seismic isolation & suspensions
- **Engineering Test Facility (ETF, Stanford) :**
  advanced IFO configs (Sagnac)
- **10 meter IFO at Glasgow** : prototype optics and control of RSE
- **TAMA 30 meter (Tokyo) :** Advanced technologies
  (SAS, RSE, control schemes, sapphire, cryogenic mirrors)
- **AIGO (Gingin, Western Australia)** : high powered lasers, thermal effects and compensation

Advanced LIGO prototyping

- Caltech LIGO 40 Meter Gravitational Wave Interferometer (Weinstein)
  - » Full engineering prototype of the Advanced LIGO optical configuration and controls

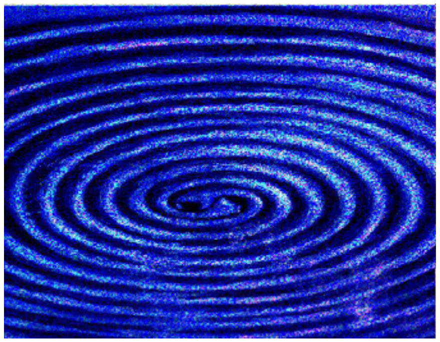
- Thermal Noise Interferometer (Libbrecht)
  - » Direct measurement of thermal noise in mirrors made of advanced materials

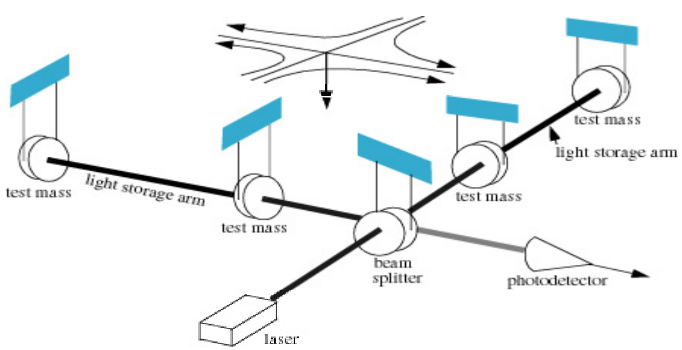


The LIGO detectors

- They employ a wide range of clever techniques to overcome the noise that surrounds us, ultimately limited by quantum effects.
- They are great examples of the art and science of precision measurement.
- They are marvels of engineering, in service to marvelous science.
- They *work*, and they will detect GWs soon!

Einstein's Symphony





- Space-time of the universe is (presumably!) filled with vibrations: Einstein's Symphony
- LIGO will soon 'listen' for Einstein's Symphony with gravitational waves, permitting
  - » Basic tests of General Relativity
  - » A new field of astronomy and astrophysics
- A new window on the universe!