Interferometry part 2 : Noise Budgets

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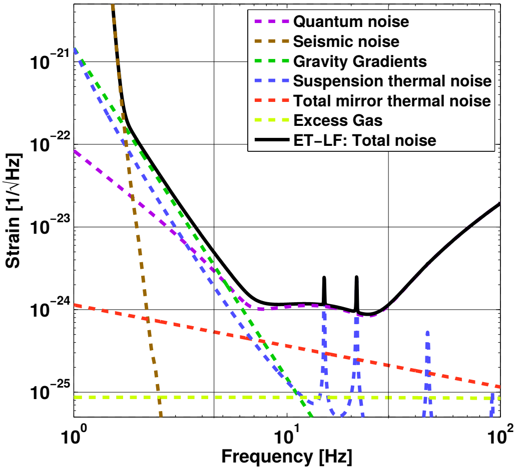
Introduction

- Signals and noises
- Time domain or frequency domain?
- Recipe for sensitivity curves
- Do we understand all the noise sources in advanced LIGO?



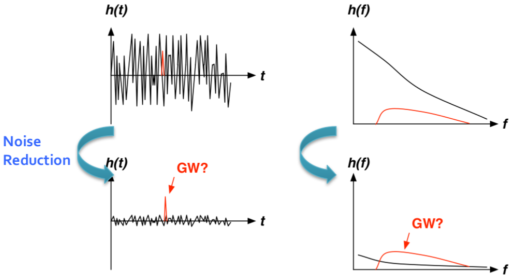
Signals and Noise

- Signals and noises not well defined
- Mathematically, signal : output from a coherent process—> wanted
- Noise : output from a random (stochastic) process—> unwanted
- Science mode, GW is our signal (can be coherent: CW,inspiral)
- Commissioning mode, try to understand noise, inject noises to see how ifo behaves etc.

Slide courtesy: Andreas Freise, Daniel Brown, Beijing Summer School; Koji Arai : G1601927

Time domain vs frequency domain

Slide idea/courtesy: Andreas Freise, Daniel Brown, Koji Arai



Time domain: **transient noises**
Frequency domain: **stationary noises**

Signals and Noise

- In certain conditions, noise can be described by its frequency components—>frequency domain
- True only for LTI systems
- Simple and useful because frequency components can be computed separately and added (super-posiiton principle)
- LIGO not always this simple!!
- Transient noise : Raven noise at 90 Hz, oplev glitches, scattered light
- Most of the LIGO modelling done in frequency domain

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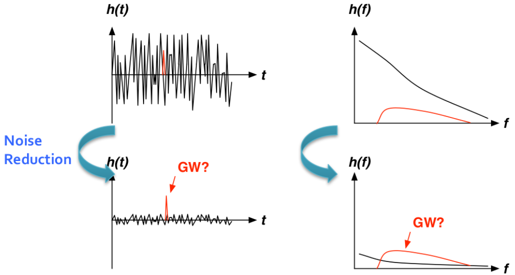
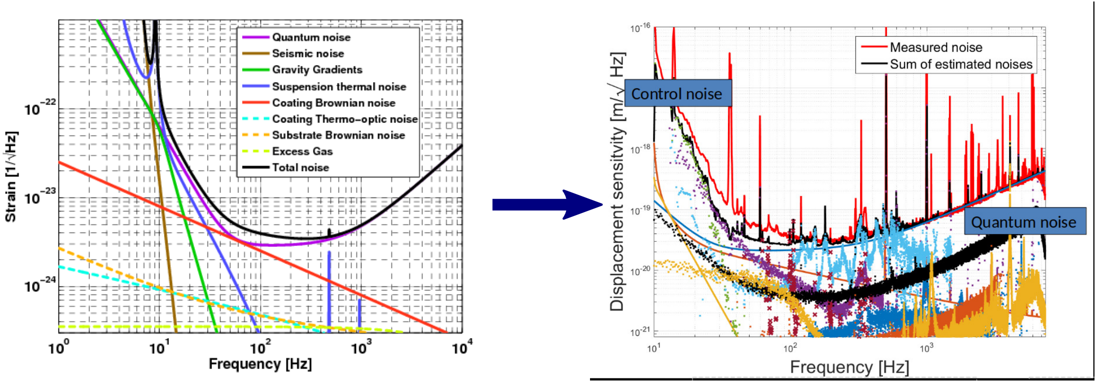


Time domain: **transient noises**
Frequency domain: **stationary noises**

Sensitivity curves

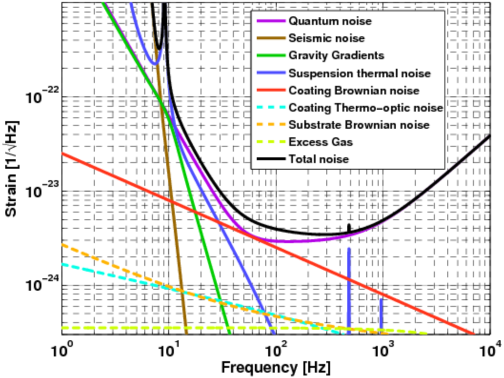


Picture courtesy: S.Dwyer

Signals and Noise

- x-axis : Fourier frequency of noise/signal component (Hz)
- y-axis : h, ASD, gravitational wave strain $(1/\sqrt{Hz})$
- Sensitivity curve is essentially noise calibrated to units of strain

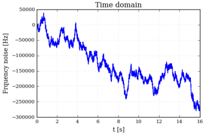
Slide courtesy: Andreas Freise, Daniel Brown, Beijing Summer School



Brief introduction to noises in frequency domain

Measured time domain data (stationary,time invariant)

Hz



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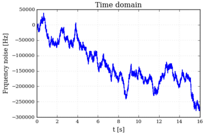


Calculate the Power Spectral Density (PSD)

For signals with finite duration and energy, Fourier Transform and use Parsevals theorem

Commonly use a windowing function and average the output spectra

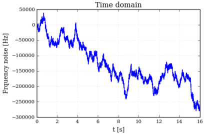
$$S_n(f) = \lim_{T\to\infty} \frac{2}{T}\left|\int_{-T/2}^{T/2} \left(n(\tau)-\underbrace{\bar{n}}_{\text{Mean of } n(\tau)}\right) e^{-i2\pi f t}\, d\tau\right|^2$$

Hz^2/Hz

Brief introduction to noises in frequency domain

Measured time domain data (stationary,time invariant)

Hz



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$$S_n(f) = \lim_{T \to \infty} \frac{2}{T} \left| \int_{-T/2}^{T/2} \left(n(\tau) - \bar{n}\right) e^{-i2\pi f t} \, d\tau \right|^2$$

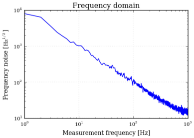
Mean of n(τ)

Hz^2/Hz

Linearised PSD (Amplitude Spectral Density)

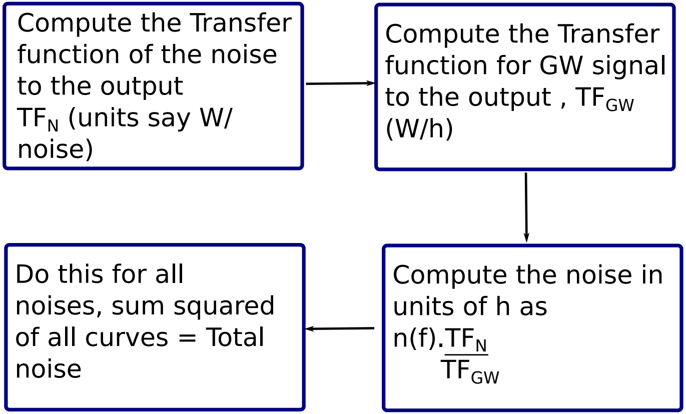
$\sqrt{\text{PSD}}$

$\text{Hz}/\sqrt{\text{Hz}}$



Measure n(t), remove mean of n(t), compute FFT, square, multiply by 2/T (depends on FFT function), square root

The recipe to a good noise budget



Compute the Transfer function of the noise to the output TF_N (units say W/ noise)

Compute the Transfer function for GW signal to the output , TF_{GW} (W/h)

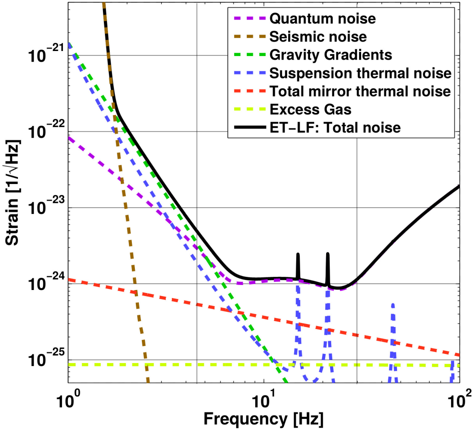
Compute the noise in units of h as $n(f).\frac{TF_N}{TF_{GW}}$

Do this for all noises, sum squared of all curves = Total noise

Slide courtesy: adf, ddb

Noise sources in a gravitational wave detector

Seismic noise



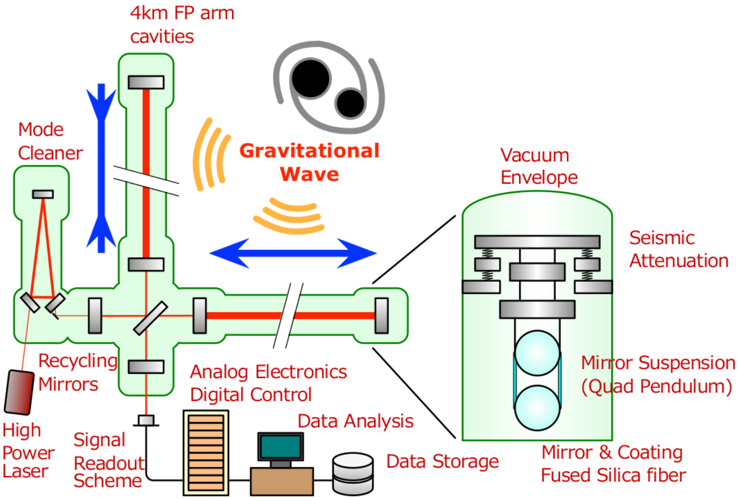
Suspension thermal noise

Mirror thermal noise

Quantum noise

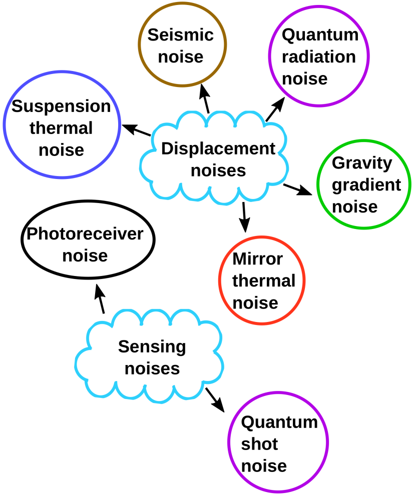
Slide courtesy: H.Lück, LIGO DCC: G1601727, ET Design study, GWINC

Noise budget of a gravitational wave detector



Slide courtesy: K.Arai, SURF summer lecture

Noise budget of a gravitational wave detector



Displacement noises

Seismic noise

Quantum radiation noise

Suspension thermal noise

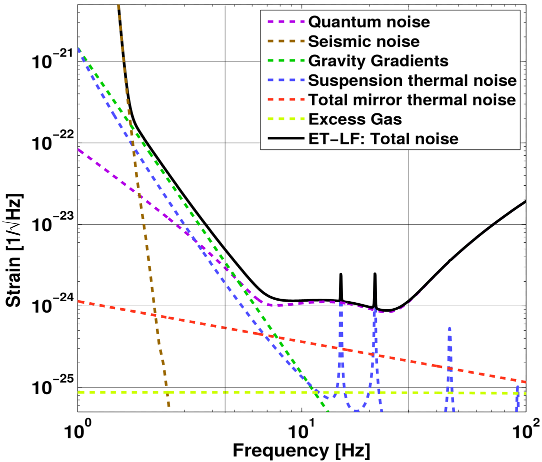
Gravity gradient noise

Mirror thermal noise

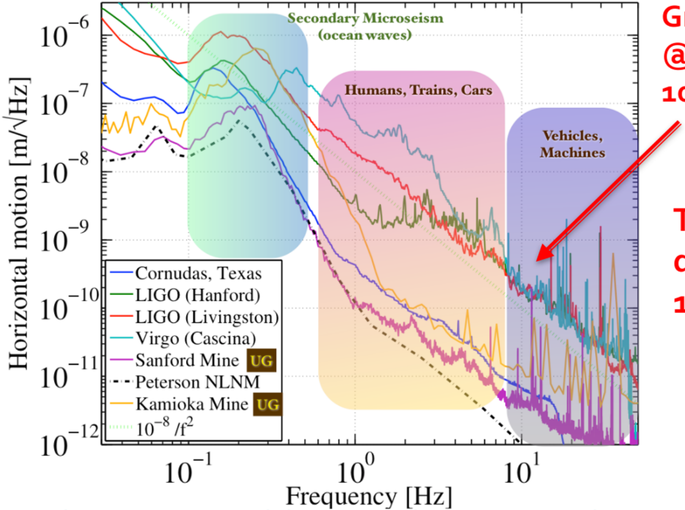
Sensing noises

Photoreceiver noise

Quantum shot noise



Seismic Noise



Ground motion @10Hz 10^{-10}m/rtHz

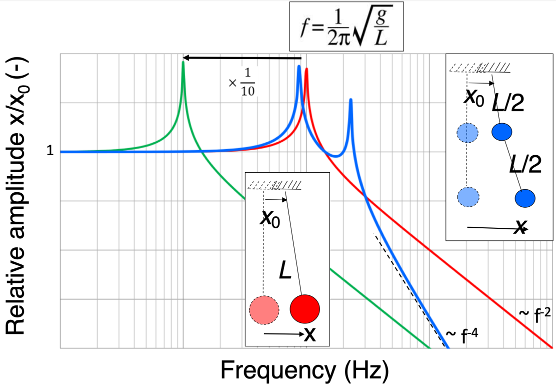
Target disp. noise 10^{-20}m/rtHz

http://link.aps.org/doi/10.1103/RevModPhys.86.121 (http://arxiv.org/abs/1305.5188)

Slide courtesy: K.Arai, SURF summer lecture

aLIGO Seismic Isolation

- Very fancy simple harmonic oscillator : provides vibration isolation above its resonant frequency
- Single stage $\frac{1}{f^{2n}}$
- LIGO current isolation system : HAM, suspensions
- Combination of damping(lower peak height-worse isolation), multi stages(steeper isolation curve-more peaks), lower resonant frequency(better isolation-HARD!)



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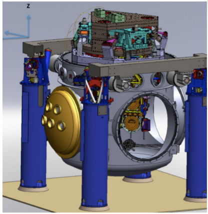

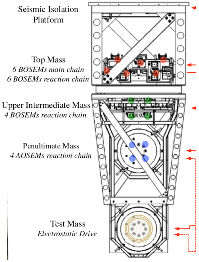

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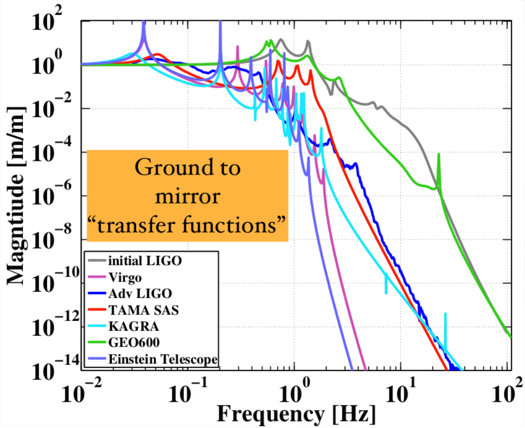
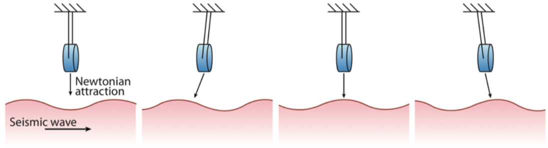


Gravity gradient noise

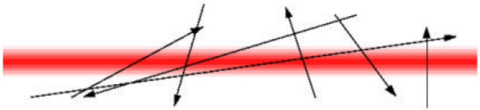
- Seismic noise shakes the mirrors and the environment around the mirror
- This shaking–>density changes in ground
- Cannot shield mirror from gravity
- Maybe underground detector, shaping the ground around test mass, subtraction of GGN using seismometer array



Picture courtesy : Joris van Heijningen

Residual gas noise

- Light must travel along the arm 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 move mirror; displacement noise
- Contamination: low-loss optics can not tolerate surface 'dirt'; High circulating powers of MWs burns dirt onto optic surface

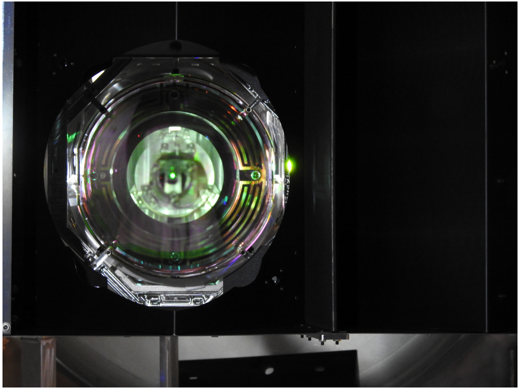


requirement for vacuum in 4 km tubes:

- 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

Scattering (only to the first order)

- Scattering of incident beam from surface defects on optics
- This lights hits a moving reflector (vibrating tank walls)
- Scattered light recouples to the ifo beam with an arbitrary phase => causes amplitude and phase fluctuation => produces noise in 'h'
- Use of baffles, black glass , use vibration isolation of the scattering object



aLIGO Hanford logbook

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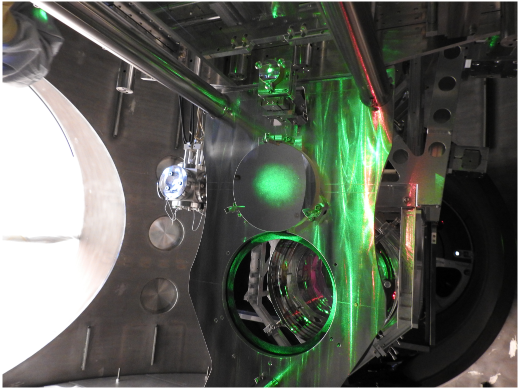

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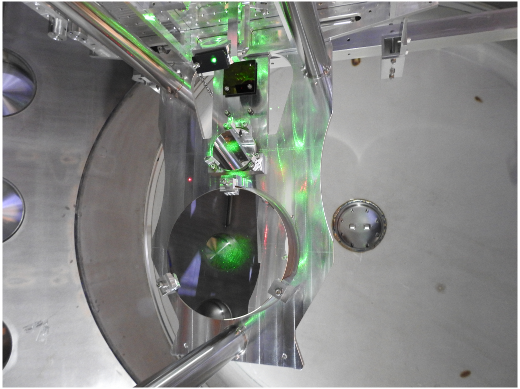

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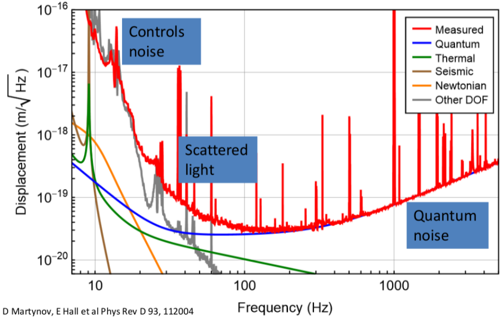
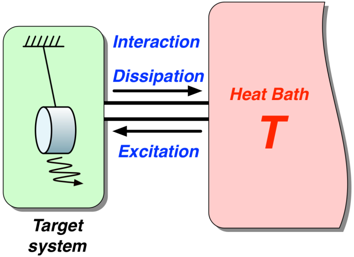
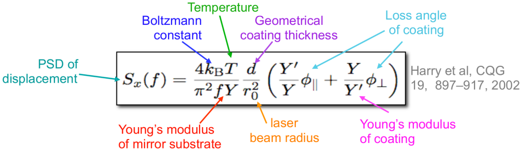


D Martynov, E Hall et al Phys Rev D 93, 112004

Thermal noise

- Mechanical systems excited by the thermal environment results in physical motions of the tests masses
- Each normal mode of vibration has $k_B T$ of energy; Mirror, many normal modes at discrete frequencies; each will experience thermal excitation.
- Test mass vibrates about its center of mass; but the reflective mirror is on the surface, not the COM, so it introduces displacement noise
- Various noise terms involved: Brownian, thermo-elastic and thermo-refractive noise of each substrate and coating (or coherent combinations of these, such as thermo-optic noise)
- Materials and techniques for very low loss (high Q)





$$S_x(f) = \frac{4k_B T}{\pi^2 f Y}\frac{d}{r_0^2}\left(\frac{Y'}{Y}\phi_{\|} + \frac{Y}{Y'}\phi_{\perp}\right)$$

Harry et al, CQG 19, 897–917, 2002

Picture courtesy : K.Arai; SURF lecture on noises

Suspension thermal noise

- Mirrors need to be suspended–>decouple from seismic vibrations
- Suspension wires vibrate (violin modes, stretch/bounce modes), kick the test mass around, introducing an harmonic series of noise lines
- Improve fibre profile (factor of 1.5); increase length of final stage (factor of a few; pushes suspension thermal noise out of detection band); cryogenics(! change of material, requires considerable effort and is complex)

Boltzmann constant

Temperature

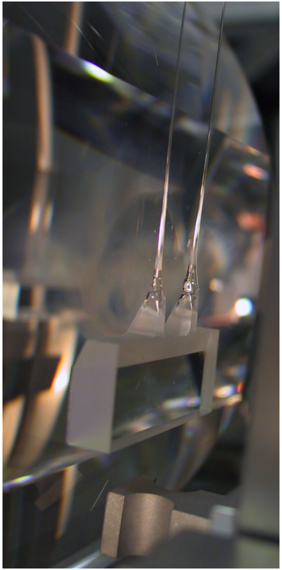
Loss angle

PSD of displacement

$$\boxed{x^2(\omega) = \frac{4k_{\mathrm{B}}T\omega_0^2\phi(\omega)}{\omega m[(\omega_0^2-\omega^2)^2+\omega_0^4\phi^2(\omega)]}}$$

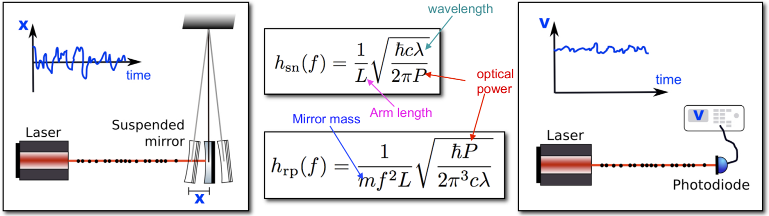
Mirror mass

Resonance frequency



Quantum noise

- Quantum noise = shot noise + radiation pressure noise
- Shot noise : due to photon counting statistics
- Quantum radiation pressure noise : Fluctuation of the back action force due to photon number fluctuation
- Also, vacuum fluctuation injected from the dark port=> Differential power fluctuation=> Cause the noise in the GW signal
- Optimal power in the ifo =Trade-off between SN and RPN



$$h_{\rm sn}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

$$h_{\rm rp}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

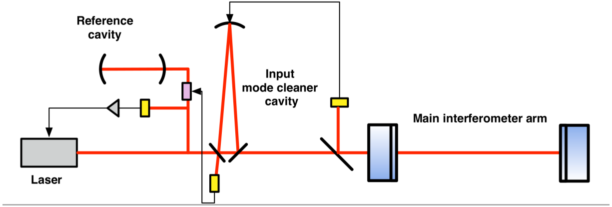
photon radiation pressure noise

photon shot noise

Picture courtesy : S.Hild DCC:G1200598

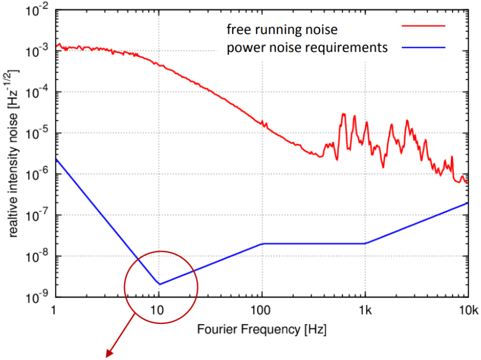
Laser frequency noise

- Laser = yardstick displacement measurement
- Fluctuations in laser frequency manifest as length fluctuations
- Optical phase $\phi = \frac{2\pi\nu L}{c}$
- Change in phase; $d\phi = \frac{2\pi}{c}(Ld\nu + \nu dL)$
- For a 300 THz (1064 nm) beam, $d\nu = 10^{-24} * 300 * 10^{12}$ where, dL/L = 10^{-24}



Laser amplitude noise

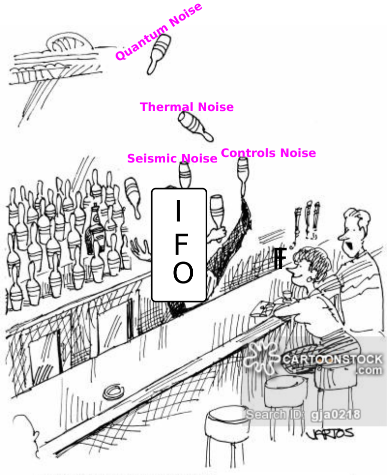
- Requirement in aLIGO for amplitude stabilisation: detecting a photocurrent of 200 mA
- Too much for a single photodiode to handle
- Photodiode array but need new techniques in order to 'power up'



$2 \times 10^{-9}\ \mathrm{Hz}^{-1/2}$

Some conclusions

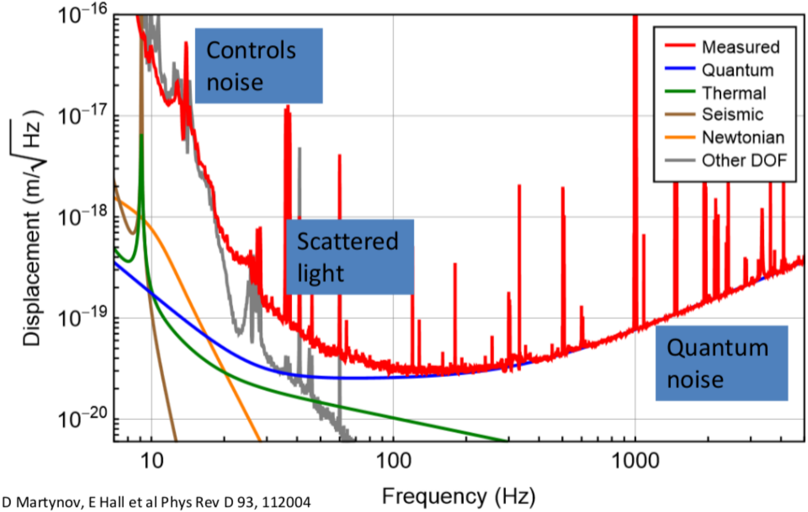
- There are such large number of noises which could potentially ruin GW detection
- Careful design / knowledge / experience and Logical, but inspirational trouble shooting needed
- Systematic noise budgeting



"Yeah he's really good. Too bad he only detected 11 GWs

He who should not be named.

He who should not be named.



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Unsaid things

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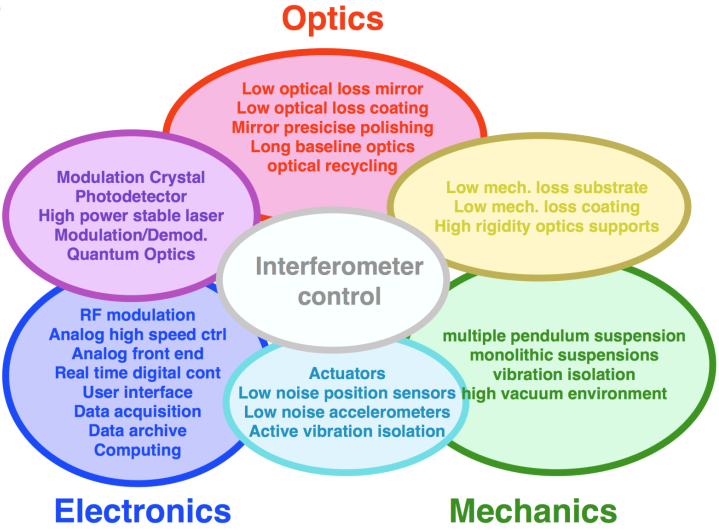

Optics

Low optical loss mirror
Low optical loss coating
Mirror presicise polishing
Long baseline optics
optical recycling

Modulation Crystal
Photodetector
High power stable laser
Modulation/Demod.
Quantum Optics

Low mech. loss substrate
Low mech. loss coating
High rigidity optics supports

Interferometer control

RF modulation
Analog high speed ctrl
Analog front end
Real time digital cont
User interface
Data acquisition
Data archive
Computing

Actuators
Low noise position sensors
Low noise accelerometers
Active vibration isolation

multiple pendulum suspension
monolithic suspensions
vibration isolation
high vacuum environment

Electronics

Mechanics

Build your own detector!