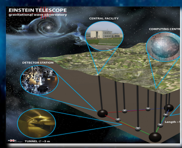
Noise limits of future Gravitational Wave Observatories

Stefan Hild,
University of Glasgow



Seminar, Cardiff,
26th of February 2010

We have come a long way …

- The first Michelson interferometer: Experiment performed by Albert Michelson in Potsdam 1881.
- Measurement accuracy 0.02 fringe (expected Ether effect ~0.04 fringes)

… to today’s network of GW detectors

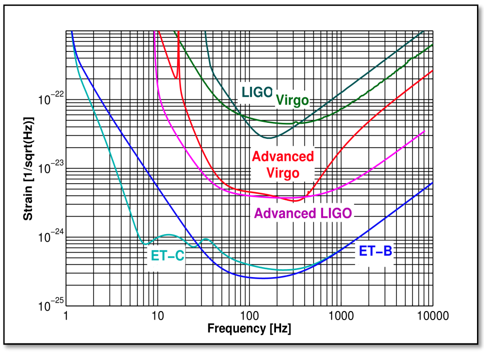
Today:

- Virgo, LIGO, GEO600 and Tama
- Sensitivity: 10^{-13} of a fringe

GEO600: measures the 600m long arms to an accuracy of 0.0001 proton diameter @ 500 Hz

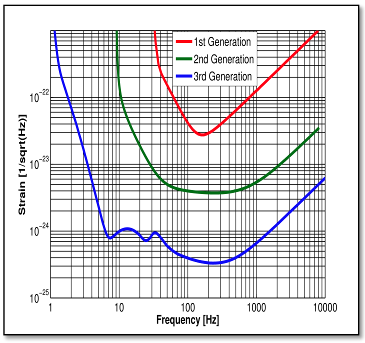
Status and future of GW observatories

- **1st** generation successfully completed:
  - Long duration observations (~1yr) in coincidence mode of 5 oberservatories.
  - Spin-down upper limit of the Crab-Pulsar beaten!
- **2nd** generation on the way:
  - End of design phase, construction about to start (or even started)
  - 10 times better sensitivity than 1st generation. => Scanning 1000 times larger volume of the Universe
- **3rd** generation at the horizon:
  - FP7 funded design study
  - 100 times better sensitivity than 1st generation. => Scanning 1000000 times larger volume of the Universe



Overview

- Which noise sources limit the current GW detectors and how can we improve them to reach the sensitivity of 2nd generation instruments?
- How can we optimise the sensitivity of second generation GW observatories?
- How can we achieve the sensitivity jump from the 2nd to 3rd Generation?
- Back to the Real World: By which noise sources are our instruments limited in reality? *… a small Quiz …*



- WARNING – WARNING - WARNING – WARNING - WARNING

- Apart from the Quiz at the end of this presentation **I will only talk about the so-called fundamental noise sources.**
- **This is only 10% of the full story!**
- Designs are driven at least partly also by technical noise sources.
- Actually most of our battle towards the 2nd and 3rd Generation will dominated by fighting and solving myriads technical problems such as:
  - Thermal distortions
  - Laser frequency and amplitude noise
  - Imperfect optics
  - Up-conversion
  - Scattered light noise
  - Mystery noise
  - Non-Gaussian behavior ….
  - Parametric instability
  - Beam jitter
  - Cooling of high power optics
  - Non-degenerate recycling cavities
  - …
  - and so on and on
  - …

- WARNING – WARNING – WARNING -

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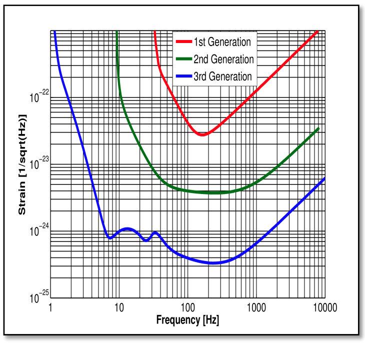

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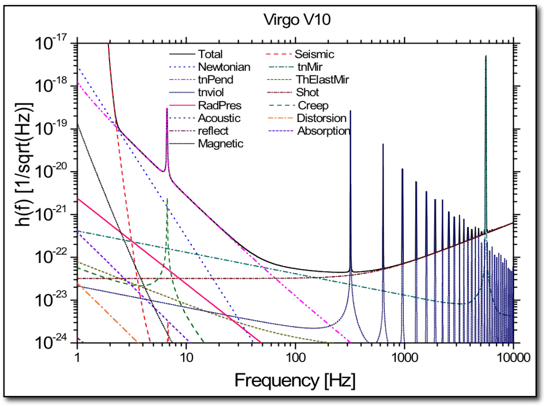
Which are the main fundamental noise sources limiting Virgo ?



http://wwwcascina.virgo.infn.it/senscurve/

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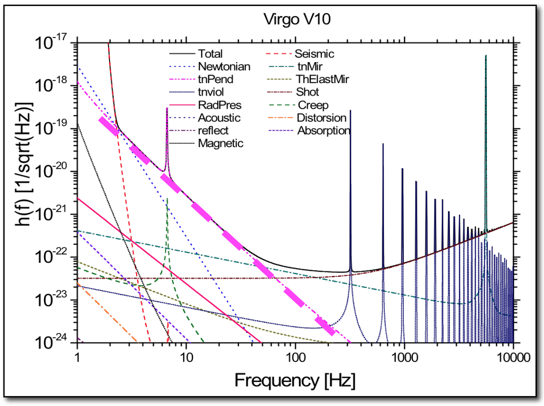
Which are the main fundamental noise sources limiting Virgo ?

- Suspension thermal noise (low frequencies)



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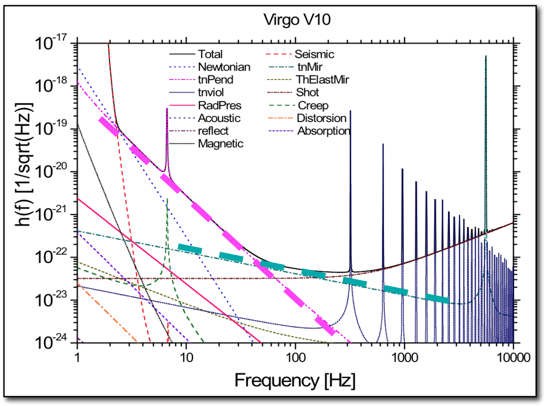

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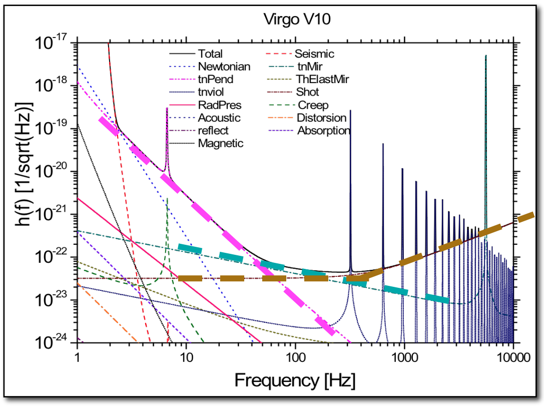

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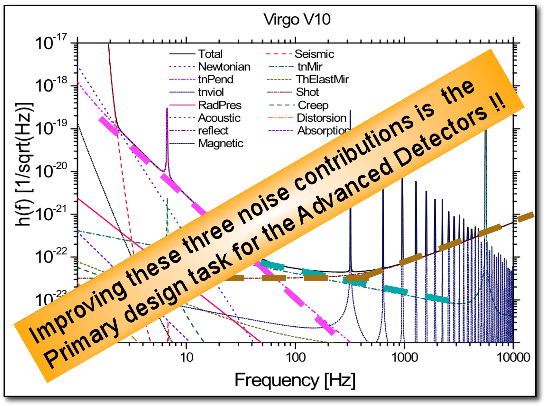

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How to reduce Suspension Thermal Noise?

- Suspension thermal noise of a simple pendulum:

Boltzmann constant — Temperature — Loss angle

PSD of displacement

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

Mirror mass — Resonance frequency

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Mirror mass — Resonance frequency

- Suspension thermal noise can be reduced:
  - By cooling: proportional to sqrt(T)
  - By making the pendulum longer: proportional to w_0
  - By making the mirror heavier: proportional to sqrt(1/m)
  - By reducing the pendulum losses: proportional to sqrt(phi)

Please note phi also depends on fibre/wire radius (phi prop r^4)

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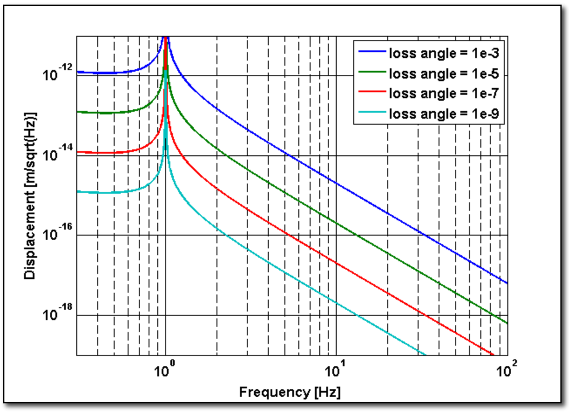
How to improve the loss angle of a suspension?

- Example: Displacement noise of a single pendulum:
  - Mass = 42kg
  - Room temperature
  - 1 Hz resonance frequency
- How can we improve the loss angle?



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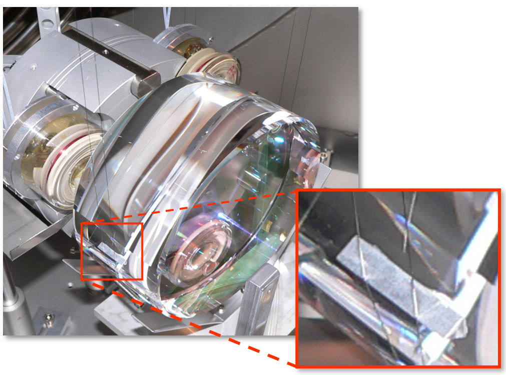
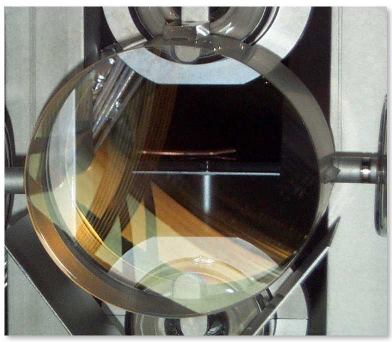
Steel Wire Suspensions

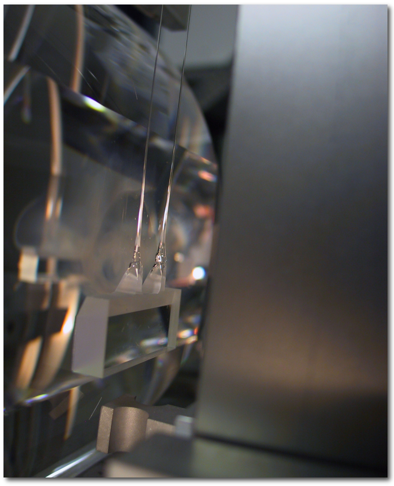
- Steel wire suspensions: loss angle of up to 1e-6
- Fairly easy to build and to handle …





Quasi-monolithic Fused Silica Suspension

- Using thin (few hundred microns) fused silica fibers welded or clamped onto fused silica mirrors.
- Breaking stress limit of fused silica fibers (2-4e9 Pa) comparable with steel wires.
- Quasi-monolithic fused silica suspensions: loss angle of up to 1e-8
- Fused Silica Suspensions are used in GEO600 for more than 5 years and will be the baseline for all 2nd generation interferometers.



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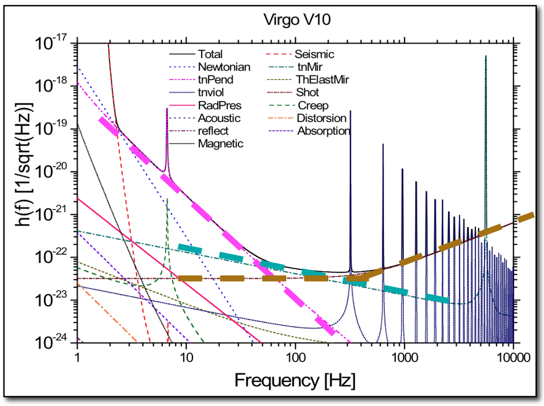
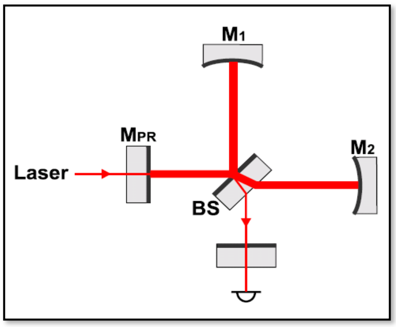


http://wwwcascina.virgo.infn.it/senscurve/

Types of mirror thermal noise

- **Brownian noise**
  - Brownian motion moves mirror surface
- **Thermo-elastic noise**
  - Thermal fluctuations cause mirror surface fluctuations via dL/dT, where L=length.
- **Thermo-refractive noise**
  - Thermal fluctuations cause changes in the optical pathlength inside a substrate via dn/dT, where n = index of refraction



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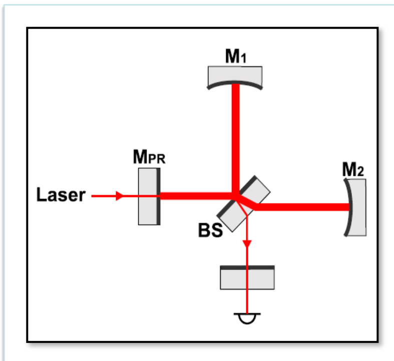
Types of mirror thermal noise

- Each of these noise exists for substrates as well as for coatings. In total 6 noise terms per optical element = Coating Brwonian, Coating Thermo-elastic, Coating Thermo-refractive, Substrate Brownian, Substrate Thermo-elastic, Substrate Thermo-refractive.
- Rules of thumb for well designed systems:
  - For mirrors the dominant noise is coating Brownian.
  - For beamsplitters and other transmissive optics the dominant noise is substrate thermo-refractive.
- For all future GW detectors the biggest challenge is coating Brownian noise !!



How to decrease Coating Brownian Noise ?

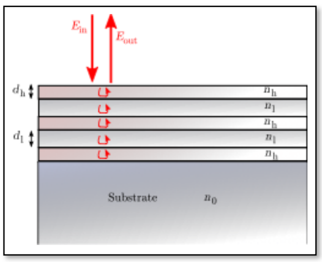
$$S_x(f) = \frac{4k_BT}{\pi^2 fY} \frac{d}{r_0^2} \left(\frac{Y'}{Y}\phi_{\|} + \frac{Y}{Y'}\phi_{\perp} \right)$$

PSD of displacement
Boltzmann constant
Temperature
Geometrical coating thickness
Loss angle of coating
Young's modulus of mirror substrate
laser beam radius
Young's modulus of coating

- Coating Brownian noise can be reduced:
  - By cooling: proportional to sqrt(T)
  - By making the coating layers thinner: proportional to sqrt(d)
  - By making laser beam larger: proportional to 1/r_0
  - By reducing mechanical losses of the coating: proportional to sqrt (phi)

Can we make the coating thinner?

- **NO!** For a certain laser wavelength and coating materials the coating thickness is driven by the required reflectivities *(R)* of the mirrors.
- Coating made of ***k*** quarter-wave stacks, formed by alternating layers of high refraction index *(nH)* and low refraction index *(nL)*



$$R = \left(\frac{1 - \left(\frac{nH}{nL}\right)^{2*k} * \frac{nH^2}{nS}}{1 + \left(\frac{nH}{nL}\right)^{2*k} * \frac{nH^2}{nS}} \right)^2$$

- PLEASE NOTE: If we would use different lasers the coating layer thickness would go down inverse proportional to the laser wavelength

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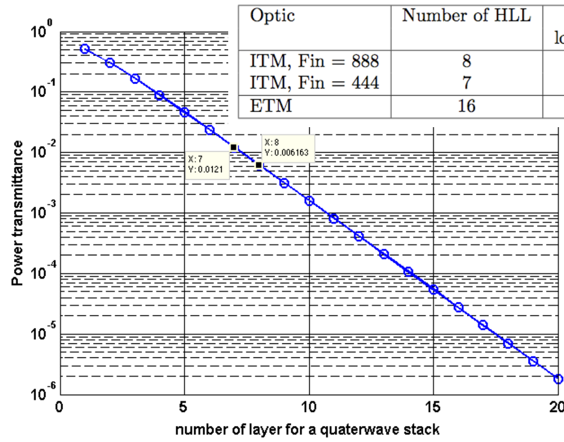
Required coating thicknesses for the Advanced Virgo mirrors

Optic	Number of HLL	Thickness of low index material [m]	Thickness of high index material [m]
ITM, Fin = 888	8	1.83e-6	1.05e-6
ITM, Fin = 444	7	1.65e-6	0.92e-6
ETM	16	3.30e-6	2.09e-6



- Input mirror: R=99.3%
- End mirror: R=99.9995%
- High refractive material: n=2.04
- Low refractive material: n=1.45

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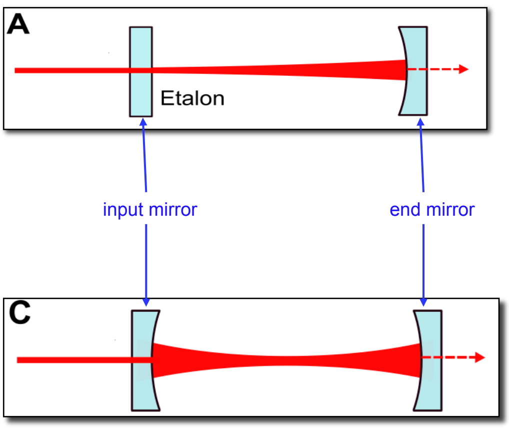
Can we make the beam larger on the mirrors? – Fortunately yes.

- Initial Virgo has the waist on the input mirror:
  - Disadvantage: Coating noise is entirely dominated by small beam size of input mirror
- Advanced Virgo will have the waist close to cavity center:
  - Disadvantage: large beams in the central IFO
  - Advantage: much lower coating Brownian noise!



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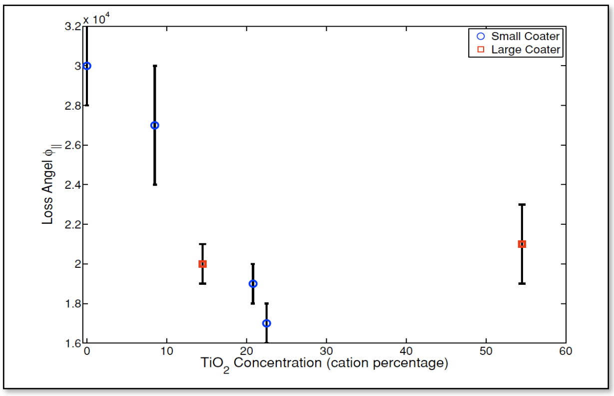
Can we use better coatings?

- Fortunately: **YES!**
- Coating research is one of the hot topics in the GW field.
- Standard high-refractive material is tantala.
- Doping the tantala with titania reduces the loss angle by about 30%.



G. Harry et al: 'Titania-doped tantala/silica coatings for GW detection' CQG, 2007, 24, 405-415

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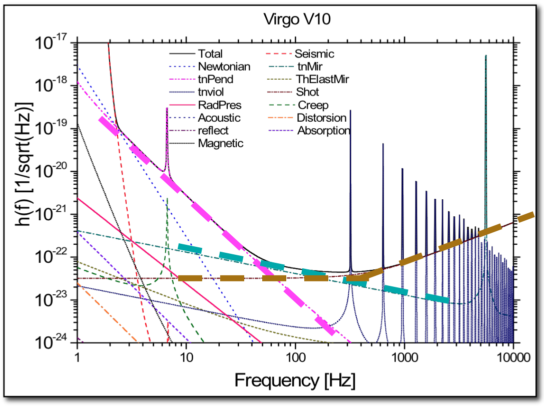


http://wwwcascina.virgo.infn.it/senscurve/

How can we reduce the shot noise contribution? (Part 1)

- Shot noise is proportional to sqrt(light power)
- Signal is directly proportional to light power
- In total our signal to shot noise ratio improves with sqrt(light power)
- Ways to increase the light power:
  - Bigger laser: Virgo = 20W, Advanced Virgo >165W
  - Higher arm cavity finesse
  - Stored light power: Virgo = 4kw, Advanced Virgo= 760kW
- Please note: Shot noise is only one of two components of the so-called quantum noise!

What is quantum noise?

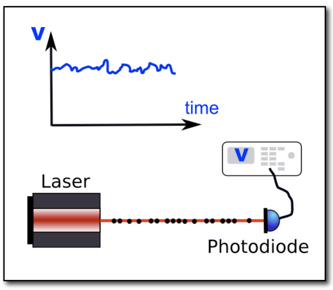
- Quantum noise is comprised of **photon shot noise** at high frequencies and **photon radiation pressure noise** at low frequencies.
- The photons in a laser beam are not equally distributed, but follow a Poisson statistic.

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

wavelength

optical power

Arm length



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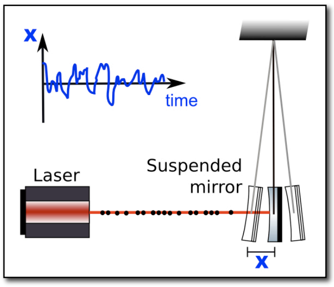


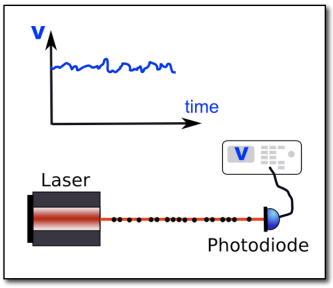
wavelength

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

optical power

Mirror mass Arm length

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



photon radiation pressure noise **photon shot noise**

The Standard Quantum Limit (SQL)

- While shot noise contribution decreases with optical power, radiation pressure level increases:

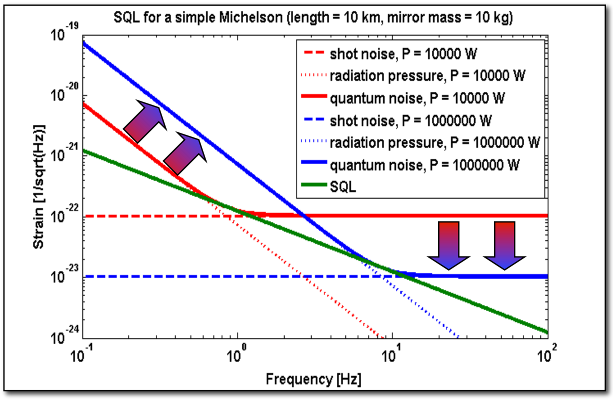
wavelength

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

optical power

Mirror mass Arm length

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

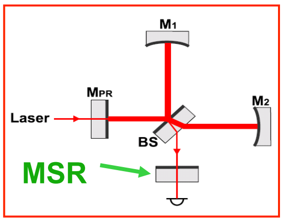


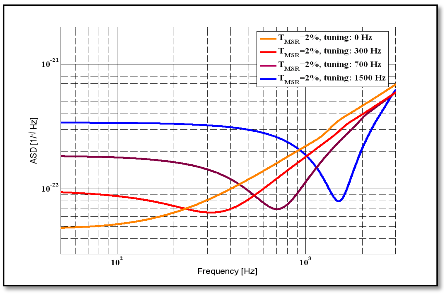
- The SQL is the minimal sum of shot noise and radiation pressure noise.
- Using a classical quantum measurement the SQL represents the lowest achievable noise.

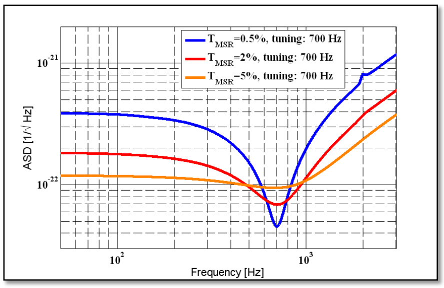
V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

How can we reduce the shot noise contribution? (Part 2)

Apart from increasing the light power we can also Signal Recycling (SR) or Resonant Sideband Extraction (RSE) to reduce shot noise.







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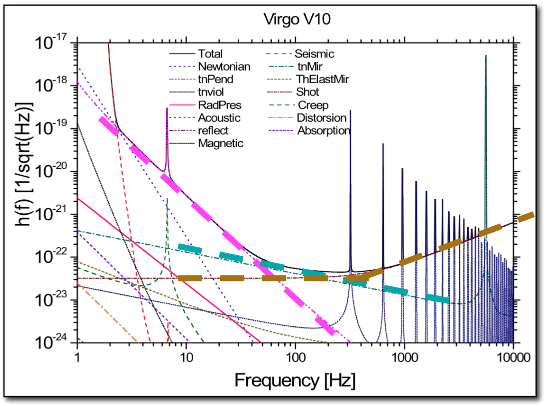

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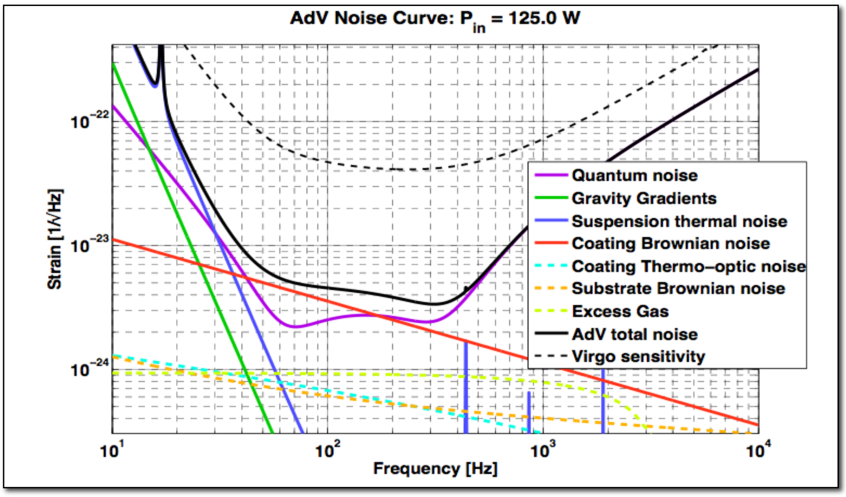
Advanced Virgo sensitivity



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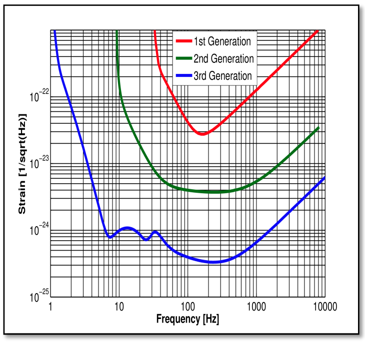

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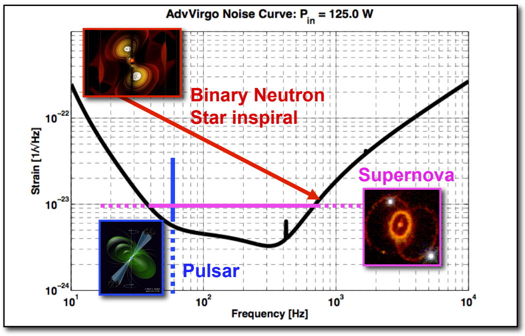
How to listen to the Universe?



- Advanced Virgo is a hyper-sensitivity microphone to listen to the Universe.
- Each astrophysical source has its own sound or tone.
- This microphone can be tuned 'similar' to a radio receiver.

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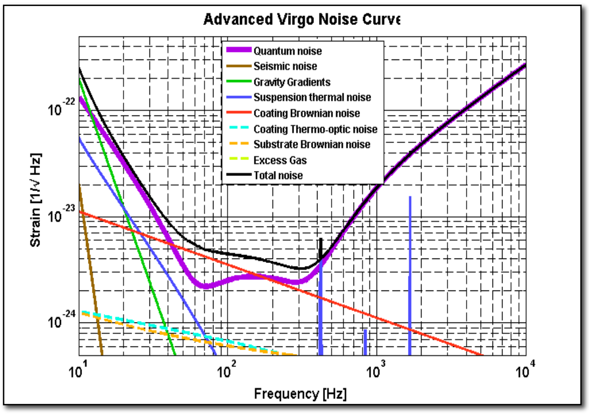
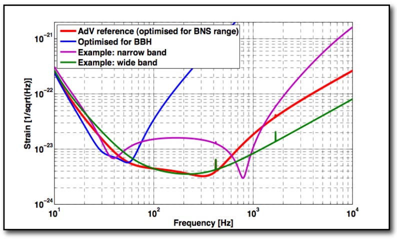
Fundamental noise limits for Advanced Virgo



- Advanced Virgo will be limited by **quantum noise** at nearly all frequencies of interest.



- **GOAL: Optimise quantum noise for maximal science output.**

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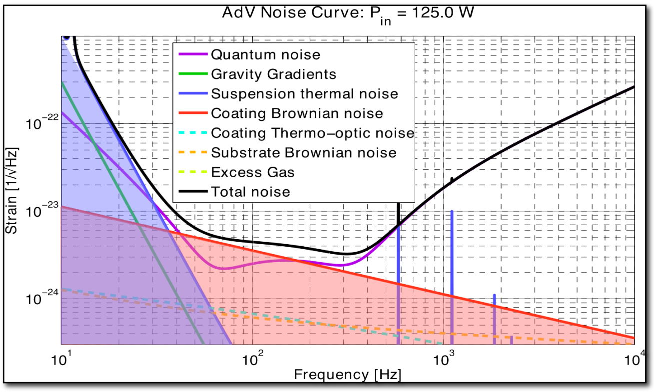
Limits of the optimization



- Our optimisation is limited by Coating thermal noise and Suspension thermal noise.
- **Quantum noise to be optimised!**

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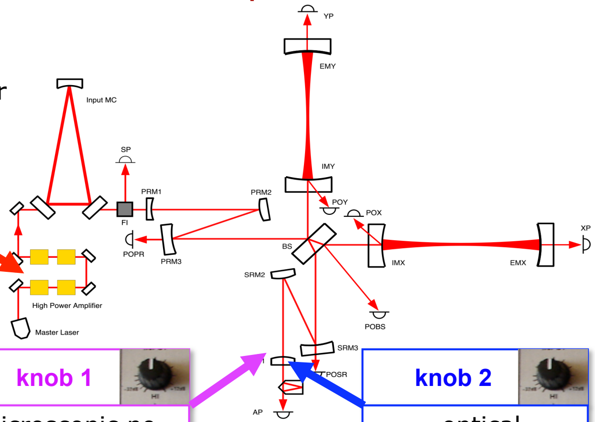
Quantum noise knops in Advanced Virgo

- We have three knobs available for optimisation:

knob 3

Input Light power



knob 1

microscopic position of SRM1 (nm scale)

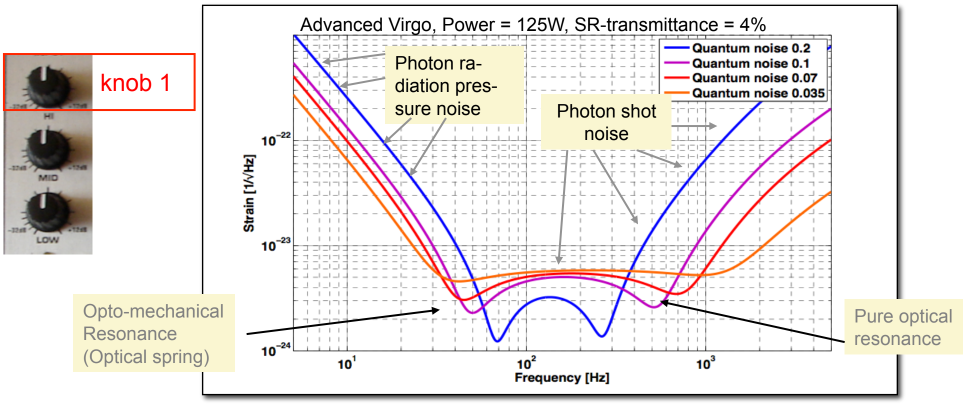
Signal Recycling resonance frequency

knob 2

optical transmittance of SRM1

Signal Recycling bandwidth

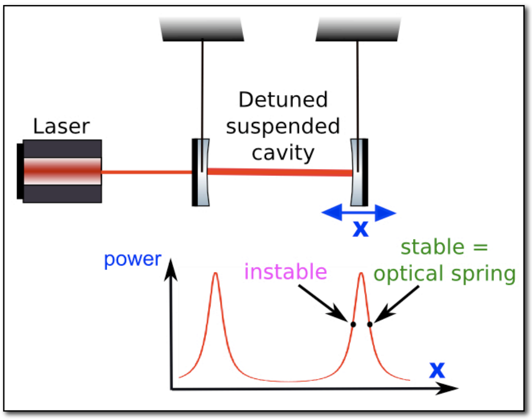
Optimization Parameter 1: Signal-Recycling (de)tuning



- Frequency of pure optical resonance goes down with SR-tuning.
- Frequency of opto-mechanical resonance goes up with SR-tuning

Optical Springs & Optical Rigidity

- Detuned cavities can be used to create optical springs.
- Optical springs couple the mirrors of a cavity with a spring constant equivalent to the stiffness of diamond.
- In a full Michelson interferometer detuned Signal Recycling causes an optical spring resonance.



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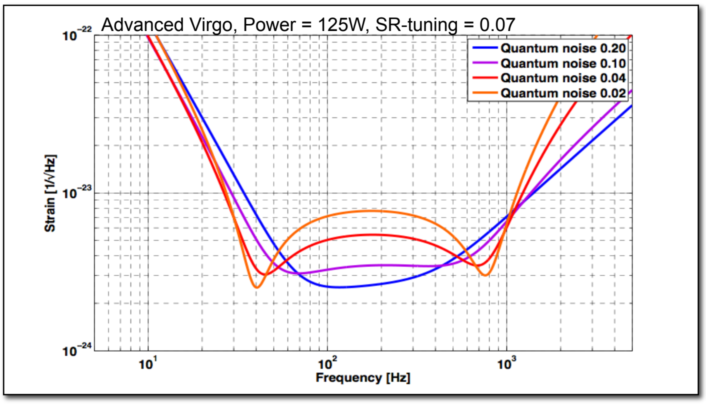
Optimization Parameter 2: Signal-Recycling mirror transmittance



- Resonances are less developed for larger SR transmittance.

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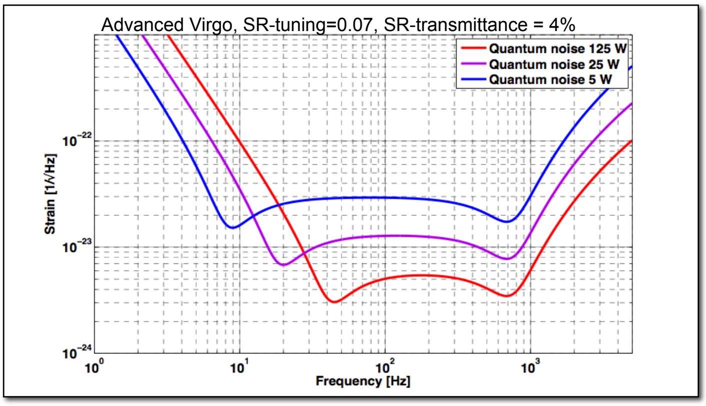
Optimization Parameter 3: Laser-Input-Power



- High frequency sensitivity improves with higher power (Shotnoise)
- Low frequency sensitivity decreases with higher power (Radiation pressure noise)

Figure of merit: Inspiral

- Inspiral ranges for BHBH and NSNS coalesence:

Total mass
Symmetric mass ratio
Frequency of last stable orbit (BNS = 1570 Hz, BBH = 220 Hz)
Spectral weighting = $f^{-7/3}$

$$d = \frac{m^{5/6}}{\rho_0 \pi^{2/3}} \left(\frac{5\eta}{6}\right)^{1/2} \left[\int_0^{f_{\rm lso}} df\, \frac{f^{-7/3}}{S_h(f)}\right]^{1/2}$$

Detector sensitivity

[1] Damour, Iyer and Sathyaprakash, Phys. Rev. D 62, 084036 (2000).
[2] B. S. Sathyaprakash, "Two PN Chirps for injection into GEO", GEO Internal Document

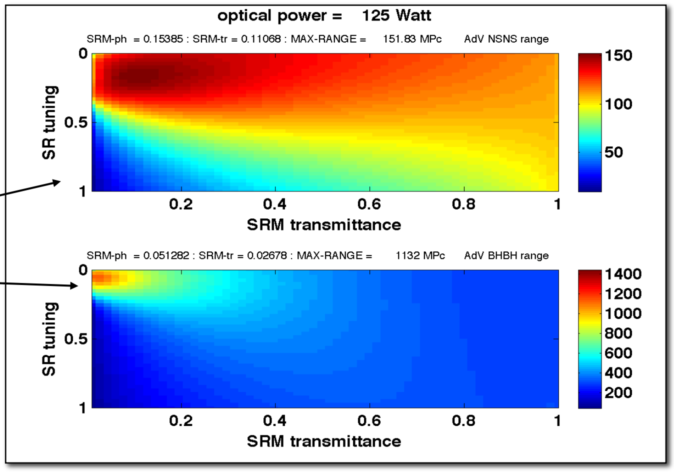
- Parameters usually used:
  - NS mass = 1.4 solar masses
  - BH mass = 10 solar masses
  - SNR = 8
  - Averaged sky location

Example: Optimizing 2 Parameters

- Inspiral ranges for free SR-tuning and free SRM-transmittance, but fixed Input power

NSNS-range

BHBH-range



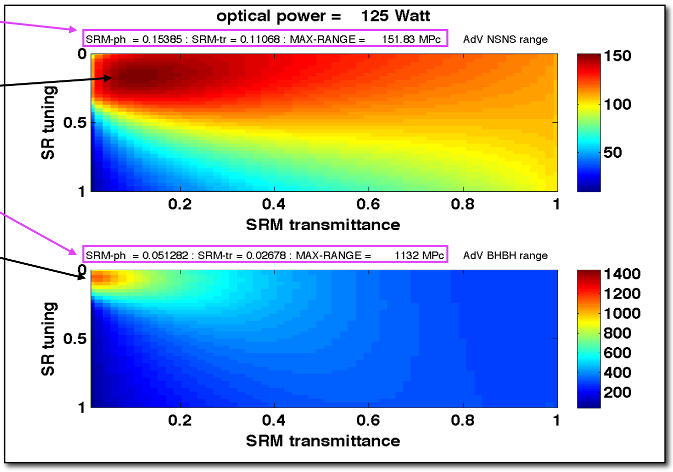
Example: Optimizing 2 Parameters

Parameters for maximum

Maximum NSNS-range

Parameters for maximum

Maximum BHBH-range



- Different source usually have their maxima at different operation points.
- It is impossible to get the maximum for BNS **AND** BBH both at the same time !

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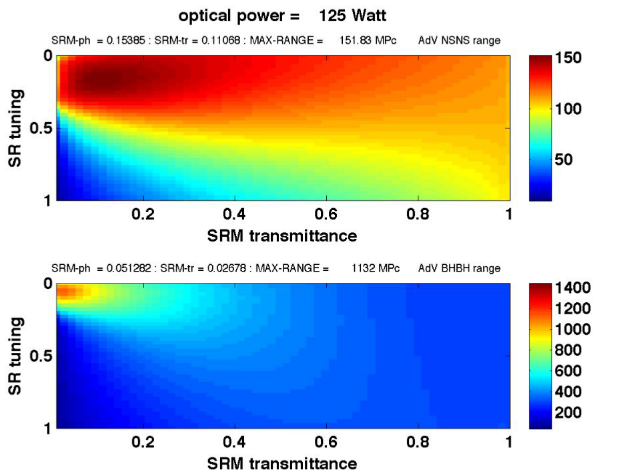
Example: Optimizing 3 Parameter for Inspiral range

- Scanning 3 parameter at the same time:
  - SR-tuning
  - SR-trans
  - Input Power
- Using a video to display 4th dimension.



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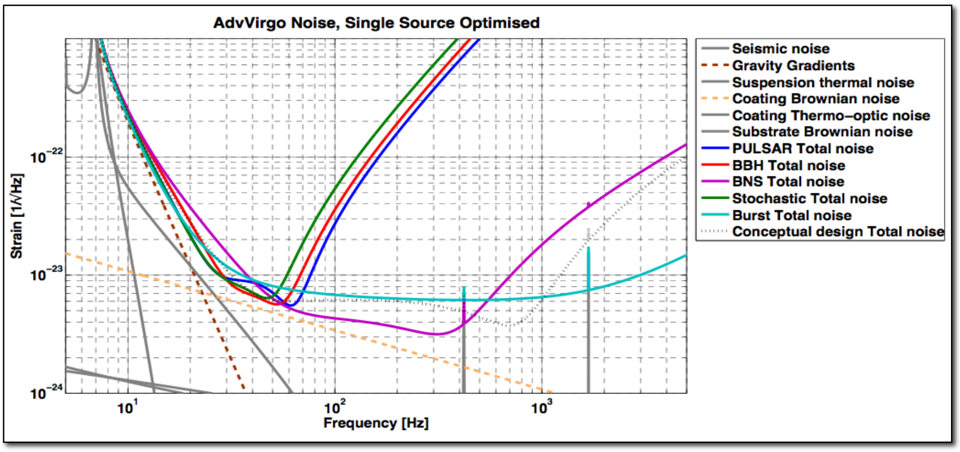
Optimal configurations



Curves show the optimal sensitivity for a single source type.

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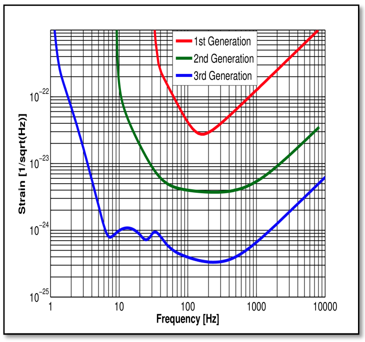
Overview

- Which noise sources limit the current GW detectors and how can we improve them to reach the sensitivity of 2nd generation instruments?
- How can we optimise the sensitivity of second generation GW observatories?
- How can we achieve the sensitivity jump from the 2nd to 3rd Generation?
- Back to the Real World: By which noise sources are our instruments limited in reality? *... a small Quiz ...*



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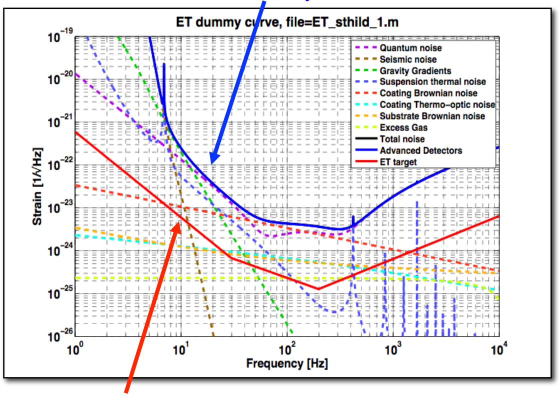
The starting point: 2^{nd} Generation

- We consider:
  - Michelson topology with dual recycling.
  - One detector covering the full frequency band
  - A single detector (no network)
- Start from a 2nd Generation instrument.
- Each fundamental noise at least for some frequencies above the ET target.

=> OUR TASK:
All fundamental noises have to be improved !!

2nd Generation design sensitivity



ET target sensitivity (approximated)

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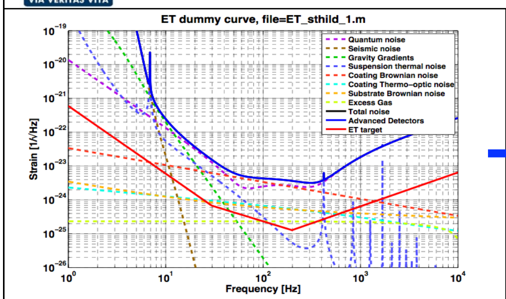
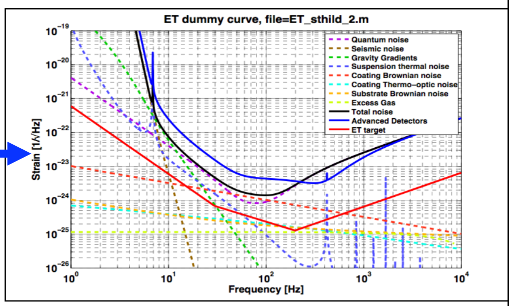
Step 1: Increasing the arm length



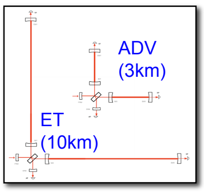


DRIVER: All displacement noises

ACTION: Increase arm length from 3km to 10km

EFFECT: Decrease all displacement noises by a factor 3.3

SIDE EFFECTS:
- Decrease in residual gas pressure
- Change of effective Signal recycling tuning



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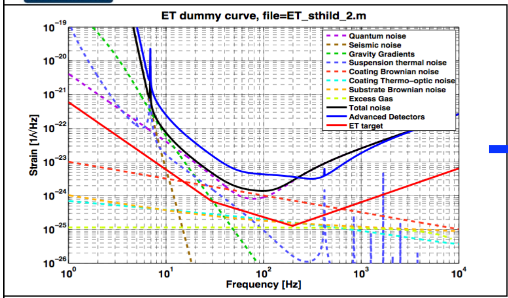
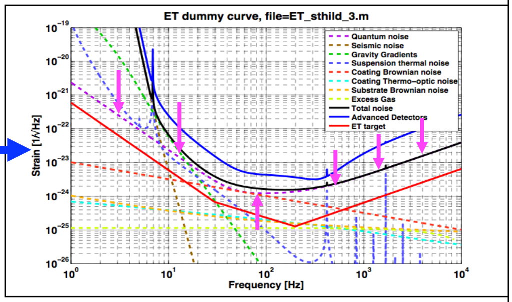
Step 2: Optimising signal recycling

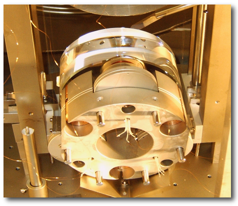




DRIVER: Quantum noise

ACTION: From detuned SR to tuned SR (with 10% transmittance)

EFFECTS:
- Reduced shot noise by ~ factor 7 at high freqs
- Reduced radiation pressure by ~ factor 2 at low freqs
- Reduced peak sensitivity by ~ factor sqrt(2) :(



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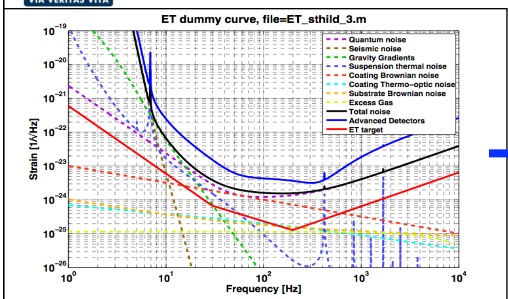
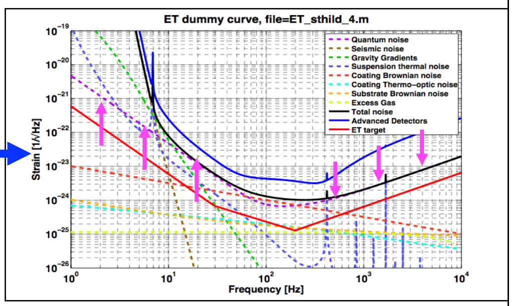
Step 3: Increasing the laser power



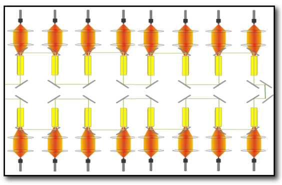


DRIVER: Shot noise at high frequencies

ACTION: Increase laser power (@ ifo input) from 125W to 500W

EFFECT: Reduced shot noise by a factor of 2

SIDE EFFECTS: Increased radiation pressure noise by a factor 2



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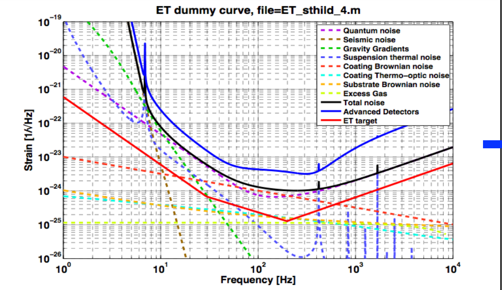
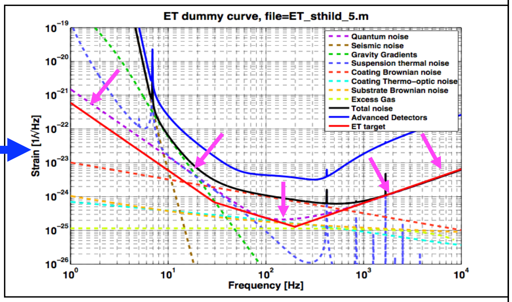
Step 4: Quantum noise suppression



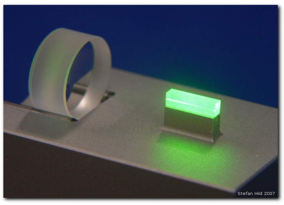


DRIVER: Shot noise at high frequencies

ACTION: Introduced 10dB of squeezing (frequency depend angle)

EFFECT: Decreases the shot noise by a factor 3

SIDE EFFECTS: Decreases radiation pressure noise by a factor 3



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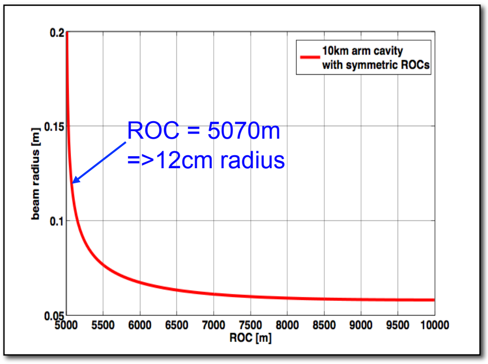
Increasing the beam size to reduce Coating Brownian noise

Increasing the beam size at the mirrors reduces the contribution of Coating Brownian.

Coating Brownian noise of one mirror:

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

beam radius on mirror



Please note: a beam radius of 12cm requires mirrors of 60 to 70cm diameter

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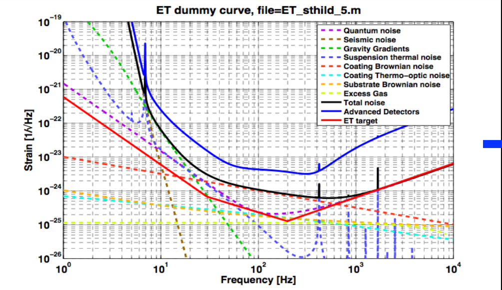
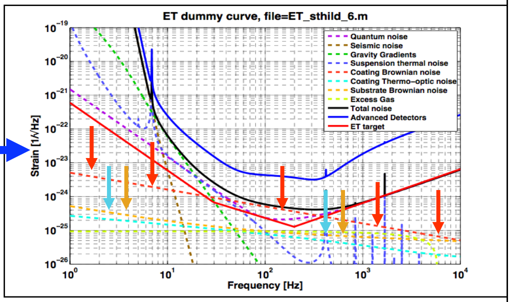
Step 5: Increasing the beam size





DRIVER: Coating Brownian noise

ACTION: Increase of beam radius from 6 to 12cm

EFFECT: Decrease of Coating Brownian by a factor 2

SIDE EFFECTS:
- Decrease of Substrate Brownian noise (~factor 2)
- Decrease of Thermo-optic noise (~factor 2)
- Decrease of residual gas pressure noise (~10-20%)

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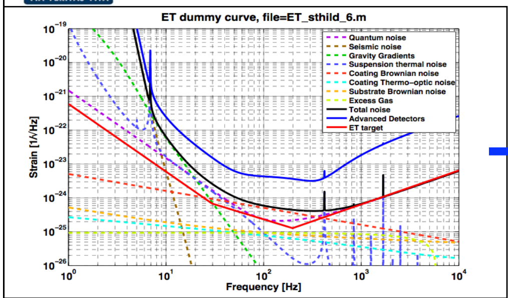
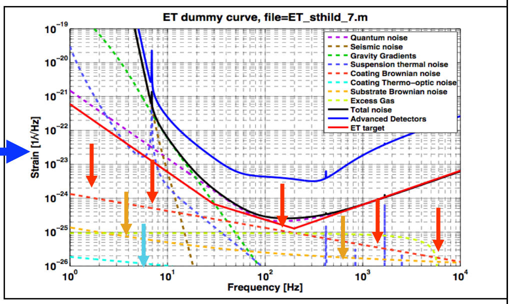
Step 6: Cooling the test masses



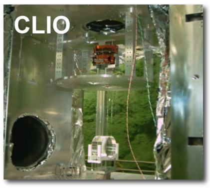


DRIVER: Coating Brownian noise

ACTION: Reduce the test mass temperature from 290K to 20K

EFFECT: Decrease Brownian by ~ factor of 4

SIDE EFFECTS:
- Decrease of substrate Brownian
- Decrease of thermo-optic noise



Kuroda 2008
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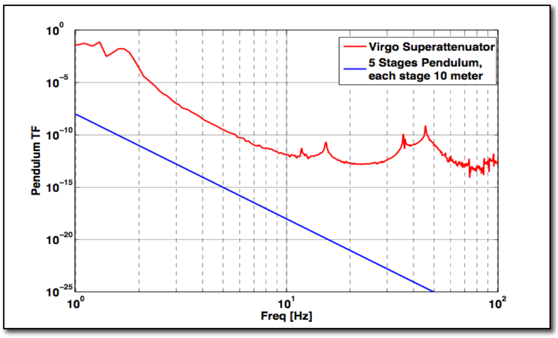
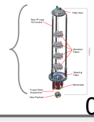
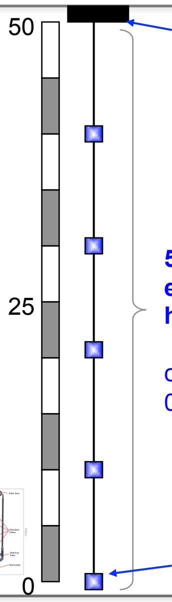
Seismic Isolation / Suspension



SA-data: G.Ballardin et al, Rev. Sci. Instrum., Vol.72, No.9 (2001)

Virgo Superattenuator (height ~ 8 meter)





5 Stages of each 10 m height

corner freq = 0.158Hz

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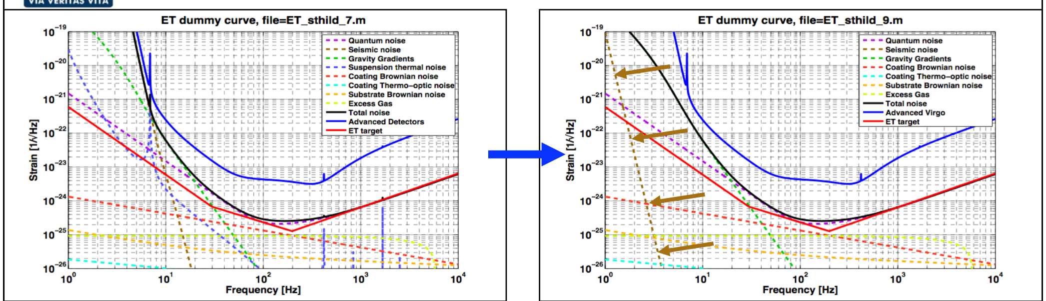
Step 7: Longer Suspensions



DRIVER: Seismic noise

ACTION: Build 50m tall 5 stage suspension (corner freq = 0.158 Hz)

EFFECT: Decrease seismic noise by many orders of magnitude
or pushes the seismic wall from 10 Hz to about 1.5 Hz

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What is Gravity Gradient Noise

- Changes in the gravitational potential around a test mass.
- Causes 1: Humans, Lorries, Clouds etc
  - Hopefully not problematic because at frequency below detection band.
- Causes 2: Seismic driven changes
  - Density waves, shaking of cave walls etc
- Can be approximated by:

Testmass Noise = Seismic Excitation x Coupling Transfer function

- Coupling Transfer function given by law of gravity. Not much we can do!
- Seismic Excitation can be reduced by finding a quiet site !

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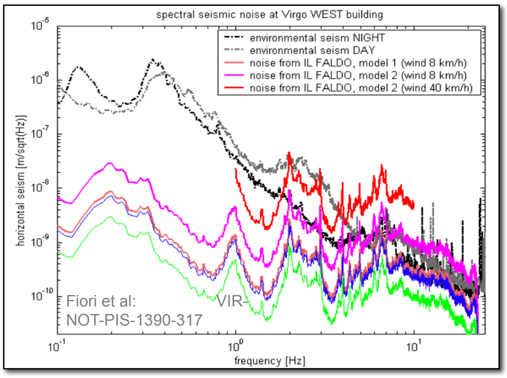
Tackling Gravity Gradient noise: going underground



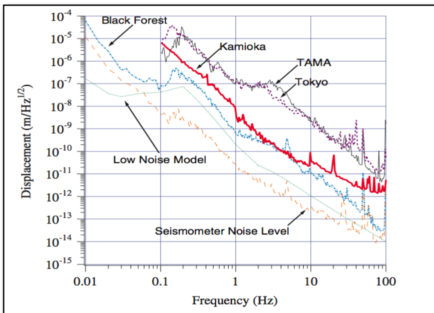


Figure 7. Low seismic noise environment at the Kamioka site. Displacement noises at Kamioka, TAMA site, Tokyo, Black Forest Geophysical Observatory (Germany) and a low noise model (a hybrid spectrum of quiet sites in the world) are described.

Ohasi et al: Class. Quantum Grav. **20** (2003) S599-607

Surface (Cascina)

about $1 \cdot 10^{-7}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$

Underground (Kamioka)

about $5 \cdot 10^{-9}\,\mathrm{m}/f^2$ for $f > 1\,\mathrm{Hz}$

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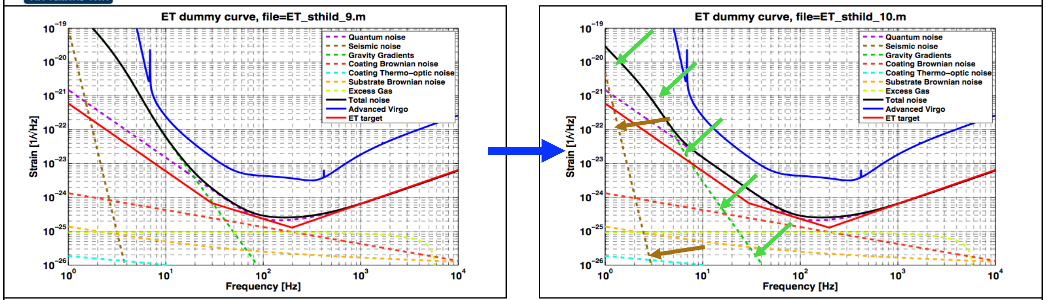
Step 8: Going underground



DRIVER: Gravity gradient noise

ACTION: Go from the surface to underground location

EFFECT: Decrease gravity gradients by a factor 20

SIDE EFFECTS: Decrease in seismic noise by a factor 20

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Is there any chance to get rid of gravity gradient noise?

- Theoretically = YES.
- If it is possible to determine the seismic 'all around' the test masses and the corresponding coupling transfer functions to a certain accuracy it should be possible to subtract gravity gradient noise from h(t).
- This would require a big 3D array of seismometers, very homogenous rock, etc
- Has never been done … work in progress (and probably our only chance to get to the ET target sensitivity below 10Hz).

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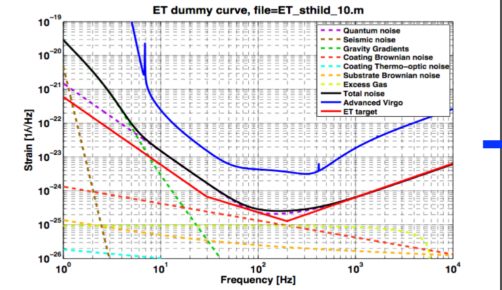
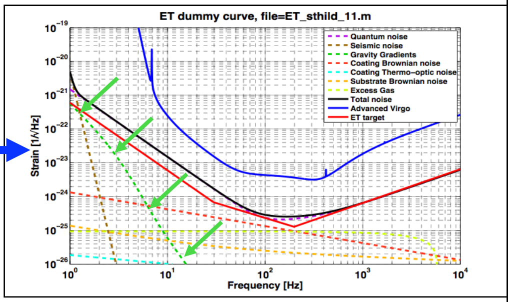
Step 9: Gravity gradient suppression





DRIVER: Gravity gradient noise

ACTION: Active subtraction of the gravity gradients

EFFECT: Decrease gravity gradient noise by a factor 50.

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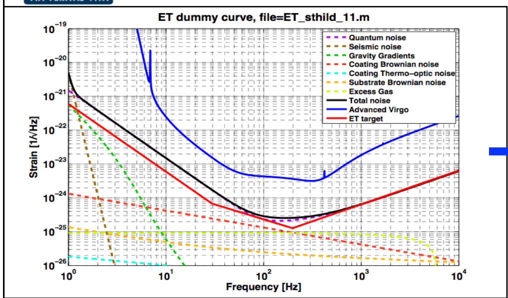
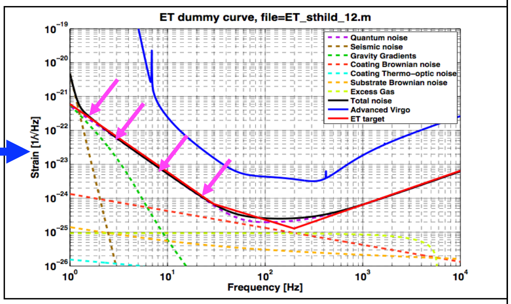
Step 10: Heavier mirrors

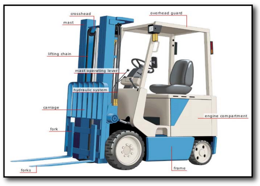




DRIVER: Quantum noise at low frequencies

ACTION: Increase test mass weight from 42 kg to 120 kg

EFFECT: Decrease of radiation pressure noise



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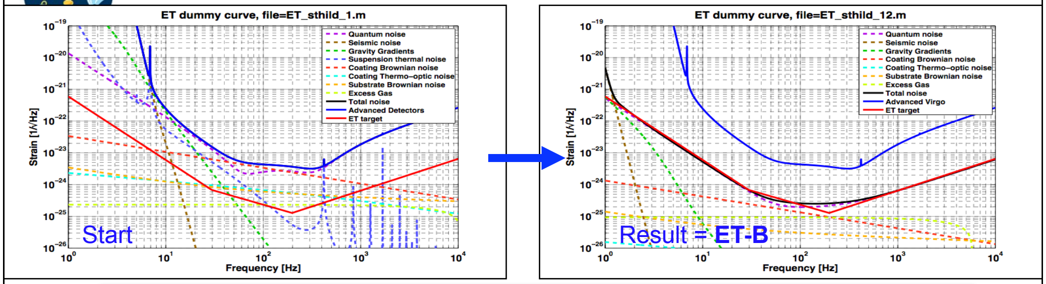

	advanced detector	potential ET design
Arm length	3 km	10 km
SR-phase	detuned (0.15)	tuned (0.0)
SR transmittance	11 %	10 %
Input power (after IMC)	125 W	500 W
Arm power	0.75 MW	3 MW
Quantum noise suppression	none	10 dB
Beam radius	6 cm	12 cm
Temperature	290 K	20 K
Suspension	Superattenuator	5 stages of each 10 m length
Seismic	$1 \cdot 10^{-7}\,\mathrm{m}/f^2$ for $f > 1$ Hz (Cascina)	$5 \cdot 10^{-9}\,\mathrm{m}/f^2$ for $f > 1$ Hz (Kamioka)
Gravity gradient reduction	none	factor 50 required (cave shaping)
Mirror masses	42 kg	120 kg
BNS range	150 Mpc	2650 Mpc
BBH range	800 Mpc	17700 Mpc

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Motivation for Xylophone observatories

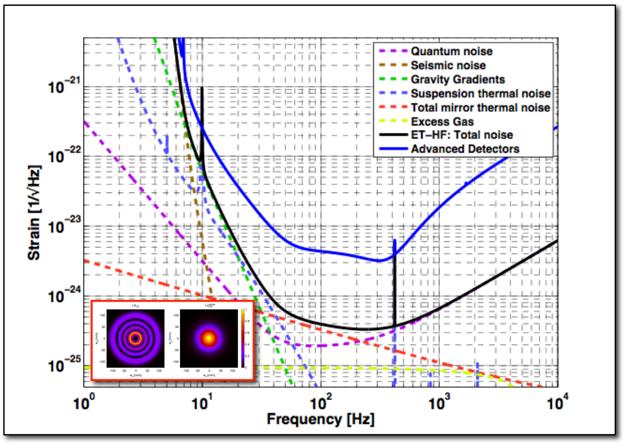
- Due to residual absorption in substrates and coatings high optical power (3MW) and cryogenic test masses (20K) don’t go easily together.
- IDEA: Split the detection band into 2 or 3 instruments, each dedicated for a certain frequency range. All ‘xylophone’ interferometer together give the full sensitivity.
- Example of a 2-tone xylophone:
  - Low frequency: low power and cryogenic
  - High frequency: high power and room temperature

Let’s build a 2-tone Xylophone

- High frequency detector:
  - Must: High optical power
  - Must: Roomtemperature
  - Perhaps: ‘short’ suspensions, no gravity gradient noise subtraction, surface location
- Low frequency detector:
  - Must: Cryogenic test masses
  - Must: Low optical power
  - Must: Complicated suspensions
  - Must: Underground
  - Must: Gravity gradient subtraction
  - Perhaps: Silicon test masses, wavelength 1550nm

High Frequency Detector

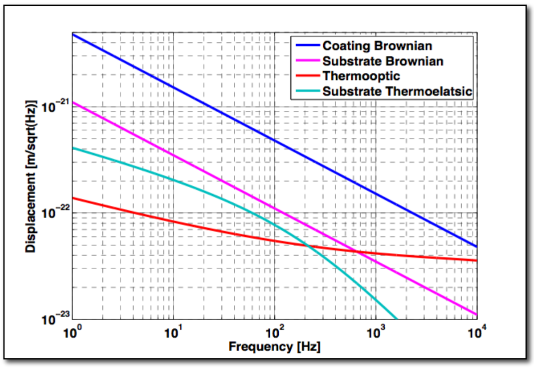
- **Quantum noise:** 3MW, tuned Signal-Recyling, 10dB Squeezing, 200kg mirrors.
- **Suspension Thermal and Seismic:** Superattenuator at surface location.
- **Gravity gradient:** No Subtraction
- **Thermal noise:** 290K, 12cm beam radius, fused Silica, LG33 (reduction factor of 1.6 compared to TEM00).



Coating Brownian reduction factors (compared to 2G): 3.3 (arm length), 2 (beam size) and 1.6 (LG33) = 10.5

LF-Detector: Cryogenic Test masses

- Thermal noise of a single cryogenic end test mass.
- Assumptions:
  - Silicon at 10K
  - Youngs Modulus = 164GP
  - Coating material similar to what is currently available for fused silica at 290K (loss angles of 5e-5 and 2e-4 for low and high refractive materials)



How to get from here to total mirror TN in ET?
- Sum over the 4 different noise types.
- Go from displacement to strain (divide by 10000).
- Uncorrelated sum of 2 end mirrors and 2 input mirrors

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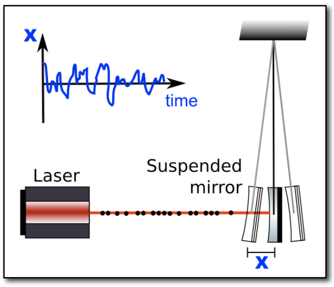
Quantum noise changes with λ

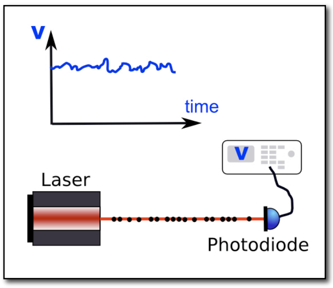
- Quantum noise is comprised of **photon shot noise** at high frequencies and **photon radiation pressure noise** at low frequencies.
- The photons in a laser beam are not equally distributed, but follow a Poisson statistic.



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

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

wavelength, optical power, Mirror mass, Arm length, wavelength



photon radiation pressure noise **photon shot noise**

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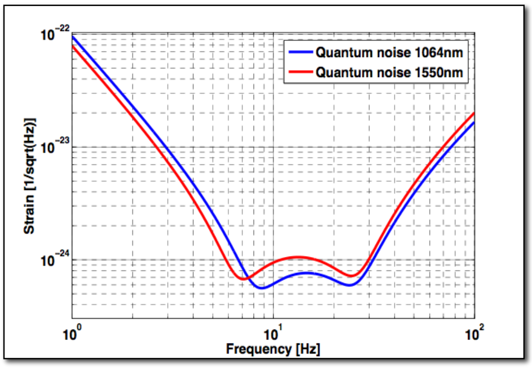
Quantum noise for ET-LF at 1550nm

- When using Silicon test masses we will have to change from 1064nm to 1550nm.
- Quantum noise depends on wave length:
  - 1550nm: less radiation pressure noise
  - 1550nm: increased shot noise

Quantum noise of ET-LF



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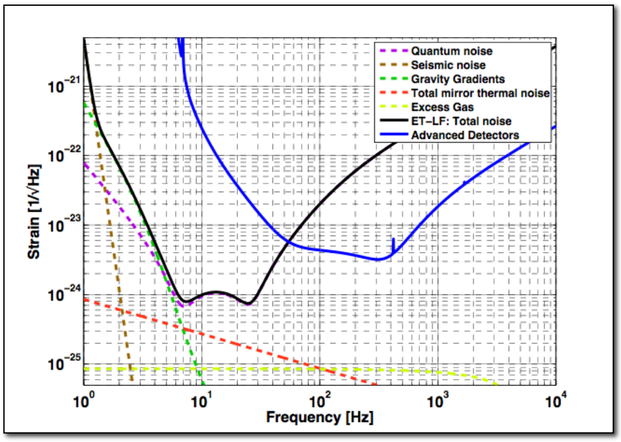
Low Frequency Detector

- **Quantum noise:** 18kW, detuned Signal-Recyling, 10dB Squeezing, 211kg mirrors.
- **Seismic:** 5x10m suspensions, underground.
- **Gravity gradient:** Underground, factor 50 subtraction
- **Thermal noise:** 10K, Silicon, 12cm beam radius, TEM00.
- **Suspension Thermal:** not included. :(



As mirror TN is no longer limiting, one can relax the assumptions on the material parameters and the beam size…

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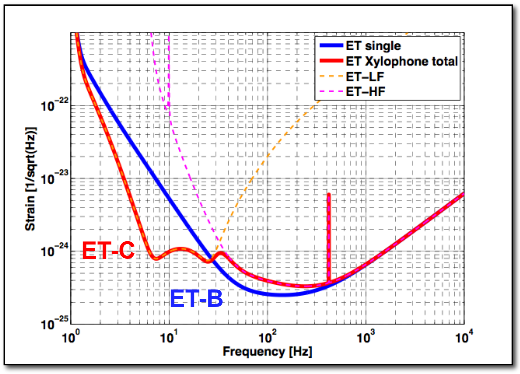
ET-Xylophone: ET-C

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	Fused Silica	Silicon
Mirror diameter / thickness	62 cm / 30 cm	62 cm / 30 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	10 dB	10 dB
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	12 cm
Clipping loss	1.6 ppm	1.6 ppm
Suspension	Superattenuator	5 × 10 m
Seismic (for $f > 1$ Hz)	$1 \cdot 10^{-7}\,\mathrm{m}/f^2$	$5 \cdot 10^{-9}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	factor 50



- Data from ET-LF and ET-HF can be coherently or incoherently be added, depending on the requirements of the analysis.
- For more details please see S.Hild, S.Chelkowski, A.Freise, J.Franc, R.Flaminio, N.Morgado and R.DeSalvo: 'A Xylophone Configuration for a third Generation Gravitational Wave Detector', CQG 2010, 27, 015003

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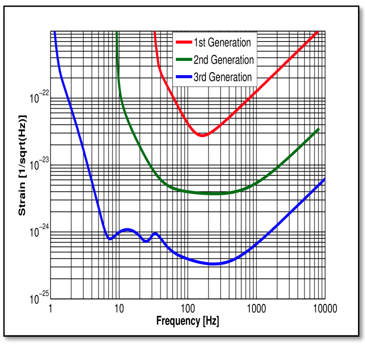
Overview

- Which noise sources limit the current GW detectors and how can we improve them to reach the sensitivity of 2nd generation instruments?
- How can we optimise the sensitivity of second generation GW observatories?
- How can we achieve the sensitivity jump from the 2nd to 3rd Generation?
- Back to the Real World: By which noise sources are our instruments limited in reality? *… a small Quiz …*

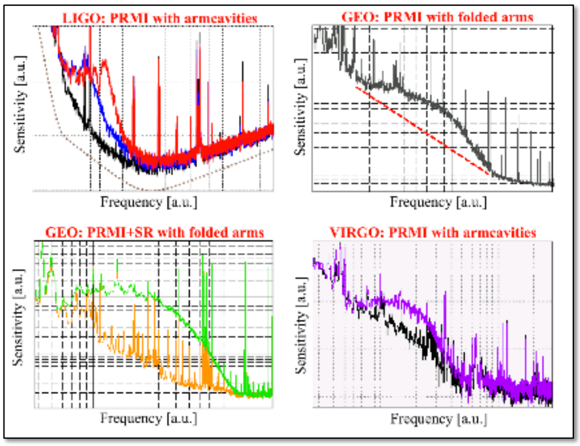


Real-World Noise Quiz 1

- Listen to the following two audio-files. The first one comes from a GW detector in normal condition. The second features excess noise?
- What is the origin of this noise?
  - A) High waves on North Sea hitting the coast of northern Germany?
  - B) Scattered light from a photodiode?
  - C) Wind shaking the buildings of GEO600?
  - D) A broken capacitor in the frequency stabilization servo?

Real-World Noise Quiz 1 (Solution)

- This sound is characteristic for scattered light noise.
- Scattered light noise is problem that all current GW detectors suffered from during commissioning periods ….



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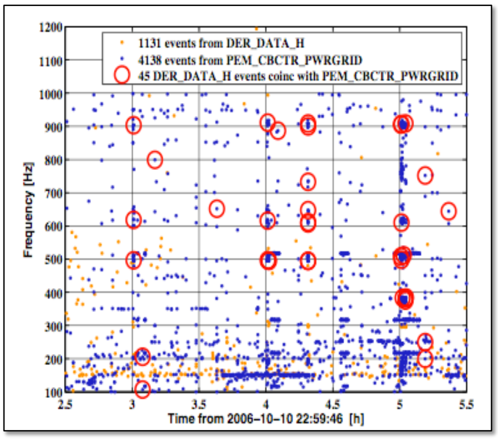
Noise hunters Quiz 2

- We found coincidence glitches between the h(t) channel and the power grid monitor. Many of these occurred close to hour boundaries.
- What could be the cause of these glitches?
  - A) Pickup noise from the GPS receivers?
  - B) Control signals for street lamps in Ruthe?
  - C) The hourly synchronisation of the internal clocks of the frameservers



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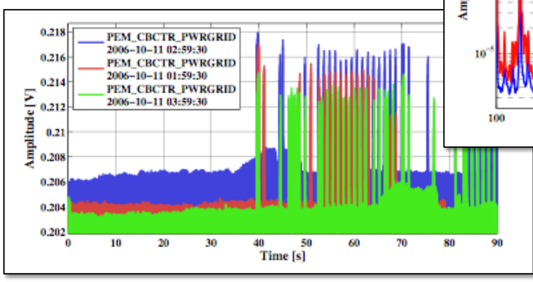
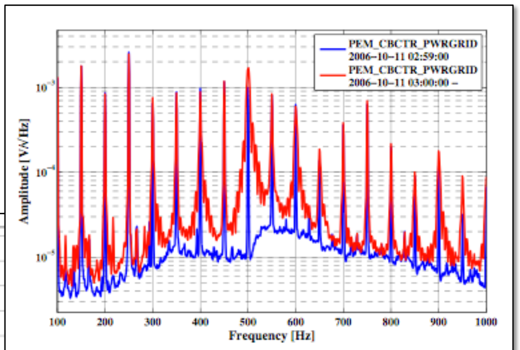
Noise hunters Quiz 2 (Solution)

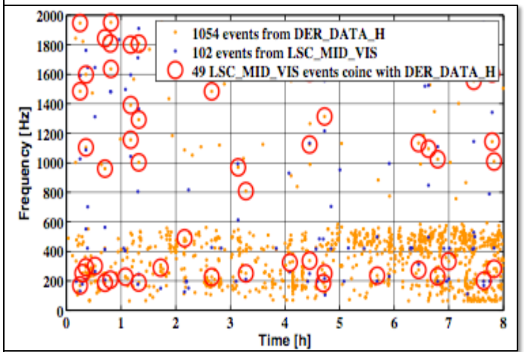
- B) is correct.
- The electricity suppliers add modulation signals onto the 50Hz signal to control streetlamps and tariffs for electrical heating.

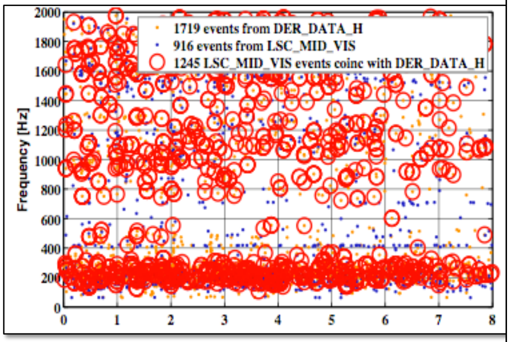




- Coupling via magnetic fields to the mirror magnets.
- Problem is solved now! ☺

Noise Hunters Quiz 3





- We find a correlation between the (DC) light power on the main photodiode and the h(t). What changed between the left and the right plot?   - any idea ?

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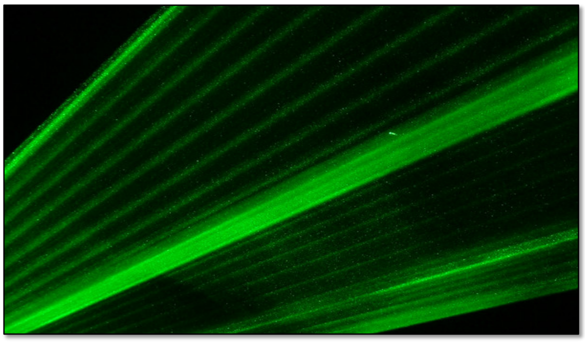
Noise Hunters Quiz 3 (Solution)



- The glitches were caused by dust particles falling through the laser beams.
- The two plots showed periods of different dust concentration in the central 'clean'-room of GEO600.

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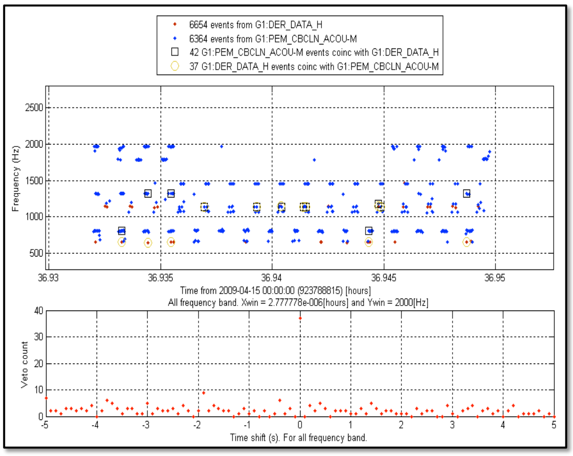
Noise hunters QUIZ 4

- One class of strange noise events showed up as coincident glitches in h(t) and in a microphone.
- Can you hear anything in h(t)?
- Any idea what this could be?



Plots and audio files courtesy Borja Sorazu (IGR)

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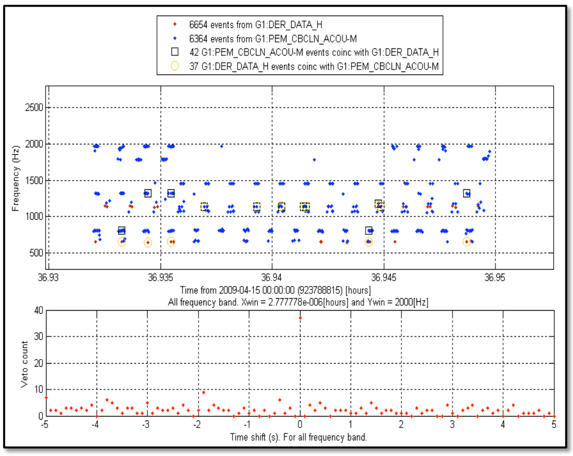
Noise hunters QUIZ 4 (Solution)

- Listen to the microphone data. It is rather obvious …
- Yes, it is a telephone ringing in the central cleanroom of GEO600 ☺



Plot and audio files courtesy to Borja Sorazu (IGR)


Thanks very much for your
attention !!