GW Interferometric Detectors, seismic noise and diffused light

Antonino Chiummo – EGO
European Gravitational Observatory, Jan14th, 2019

Email: antonino.chiummo@ego-gw.it

Outline

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- Basics of interferometric GW antennas
- Stray-light and seismic noise
- Simulations
- Actually measured noise
- Conclusion

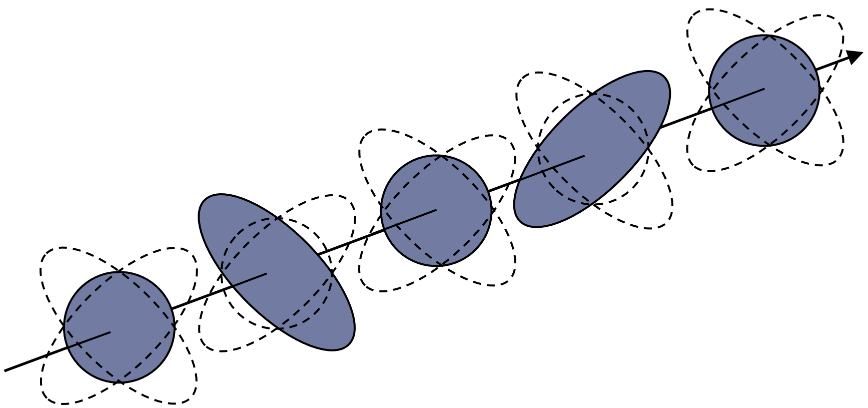
Gravitational Waves

❑ Effect of GWs:

Squeeze and stretch the space in perpendicular directions:
strain ***h* = ΔL/L**

❑ What is the plausible "strain"?

Even for the most tremendous events in Universe, ***h~10^-21***



A century-old ruler

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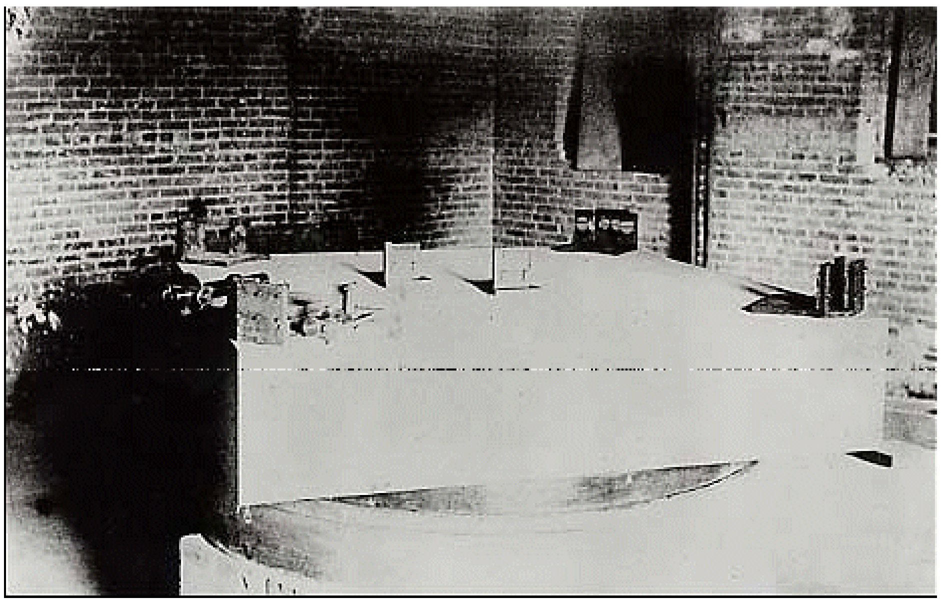
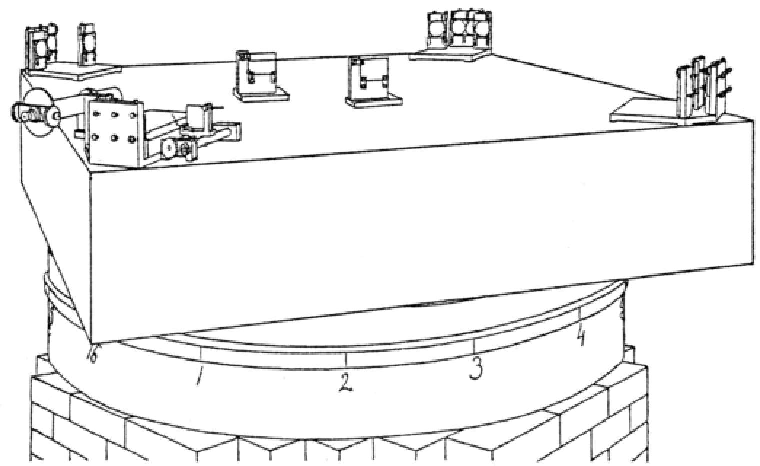
- How to detect strain?

Michelson interferometer



Michelson & Morley's 1887 interferometer
built in the basement of Western Reserve
Photo: Case Western Reserve Archive



$\Delta L = 0.01\ \lambda \sim 10$^-8m

A century-old ruler

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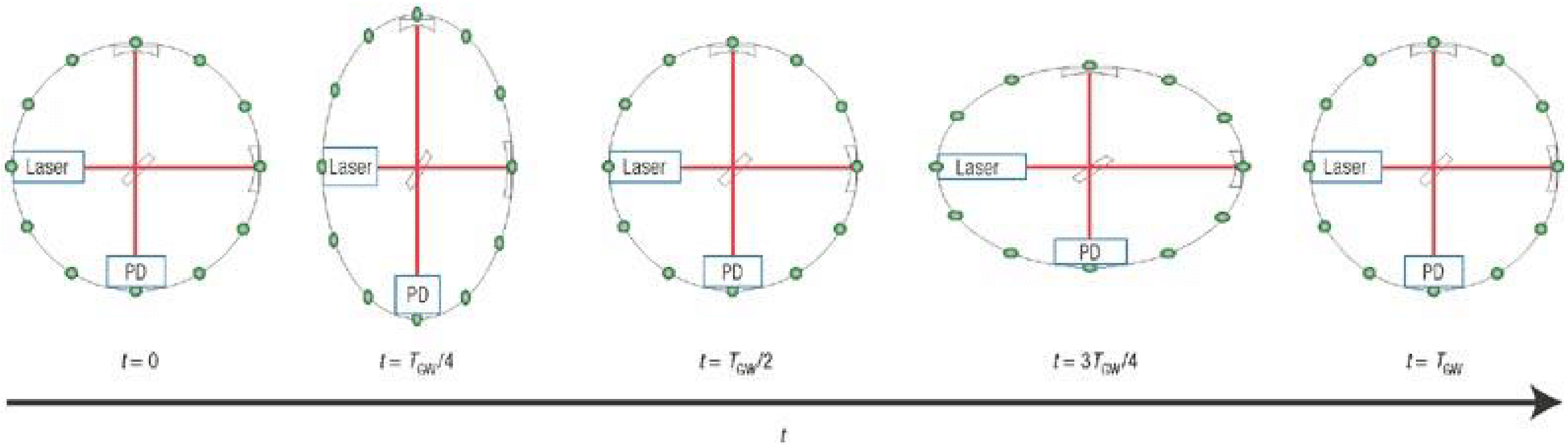
❑ How to detect strain?

- use the interferometer as a transducer: displacement **ΔL** to Optical signal **Δphi**

$$\delta\phi = G\,\delta L$$



A century-old ruler

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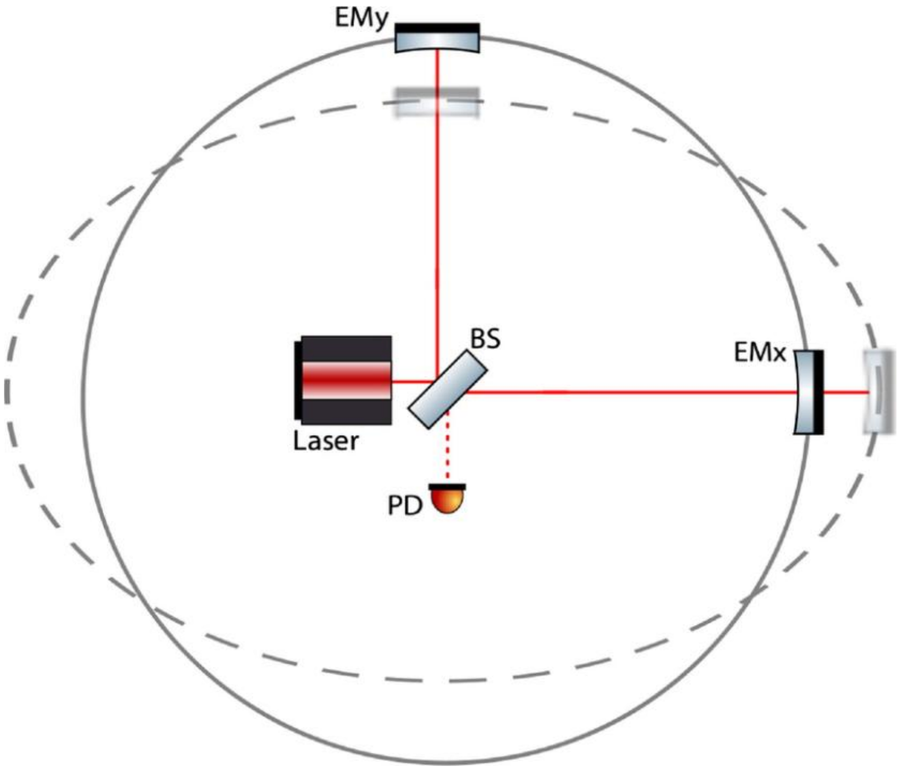
❑ How to detect strain?



$$\delta\phi = G\,\delta L$$

-Michelson adjusted so that no light comes out from anti-symmetric port

- GW stretches and squeezes the two arms alternatively

- Wavefront takes longer to go back and forth in one of the arm than in the other

- Interference at anti-symmetric port is no longer completely distructive, and light reachs the photodetector: a signal!

- How to increase strain sensitivity?

-Enhance the signal
-Reduce the noise

A century-old ruler - Reloaded

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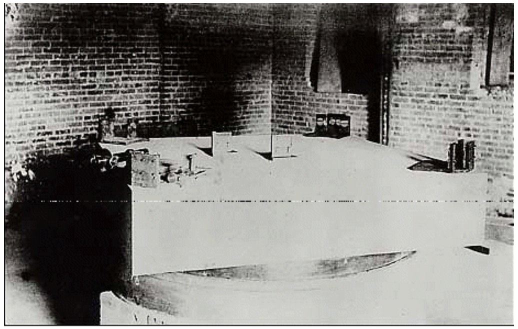
❑ How to increase strain sensitivity: *enhance the signal*

- Very long arms

To get a larger displacement **ΔL = *h*L**

$$\delta\phi = G\,\delta L$$



Michelson & Morley's 1887 interferometer
built in the basement of Western Reserve
Photo: Case Western Reserve Archive

L~1m

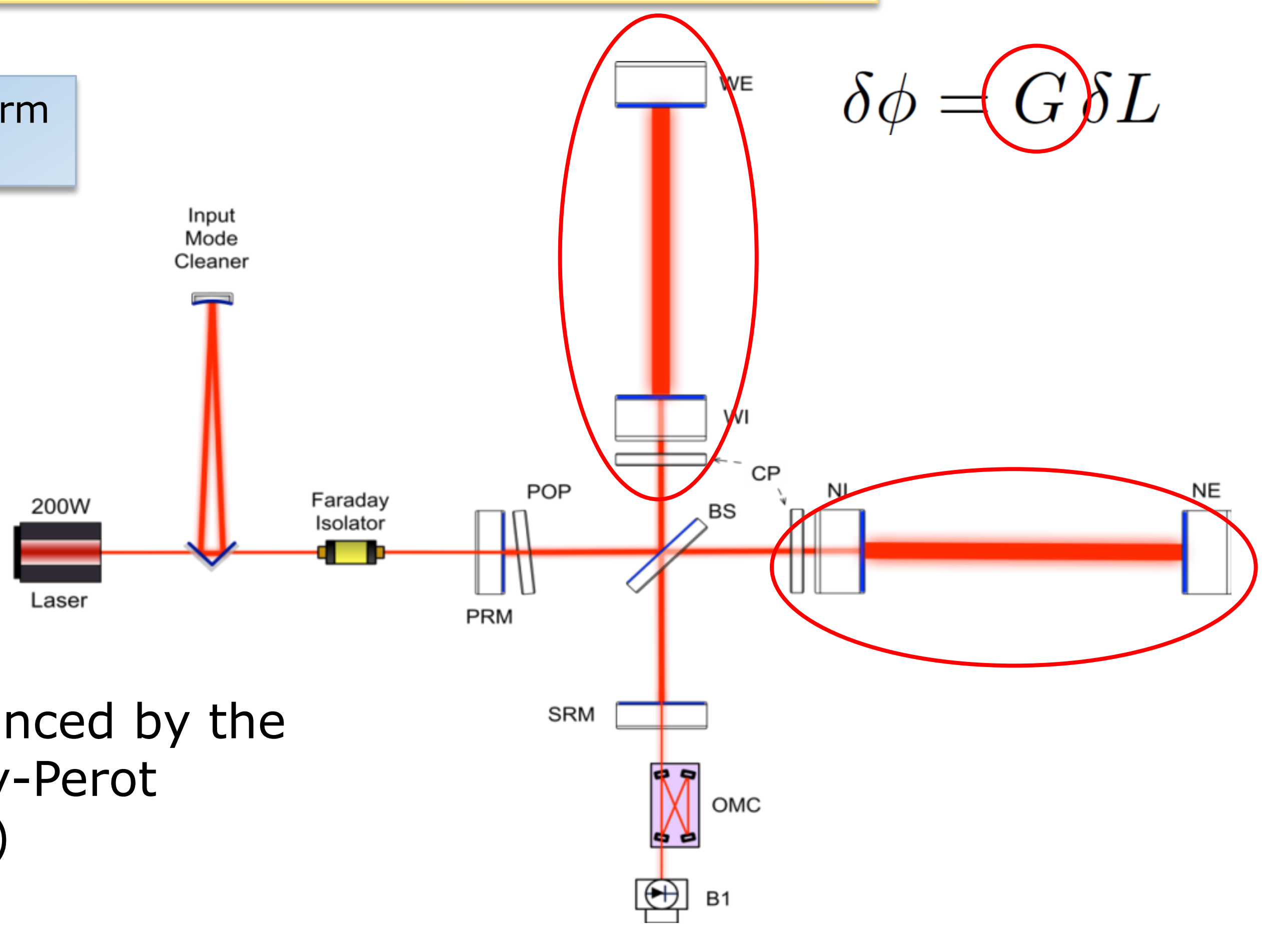
L~3km

A century-old ruler - Reloaded

❑ How to increase strain sensitivity: *enhance the signal*

- Fabry-Perot cavity in each arm
To increase phase change

$$\delta\phi = G\,\delta L$$



Phase change enhanced by the finesse of the Fabry-Perot resonators (~400x)

A century-old ruler - Reloaded

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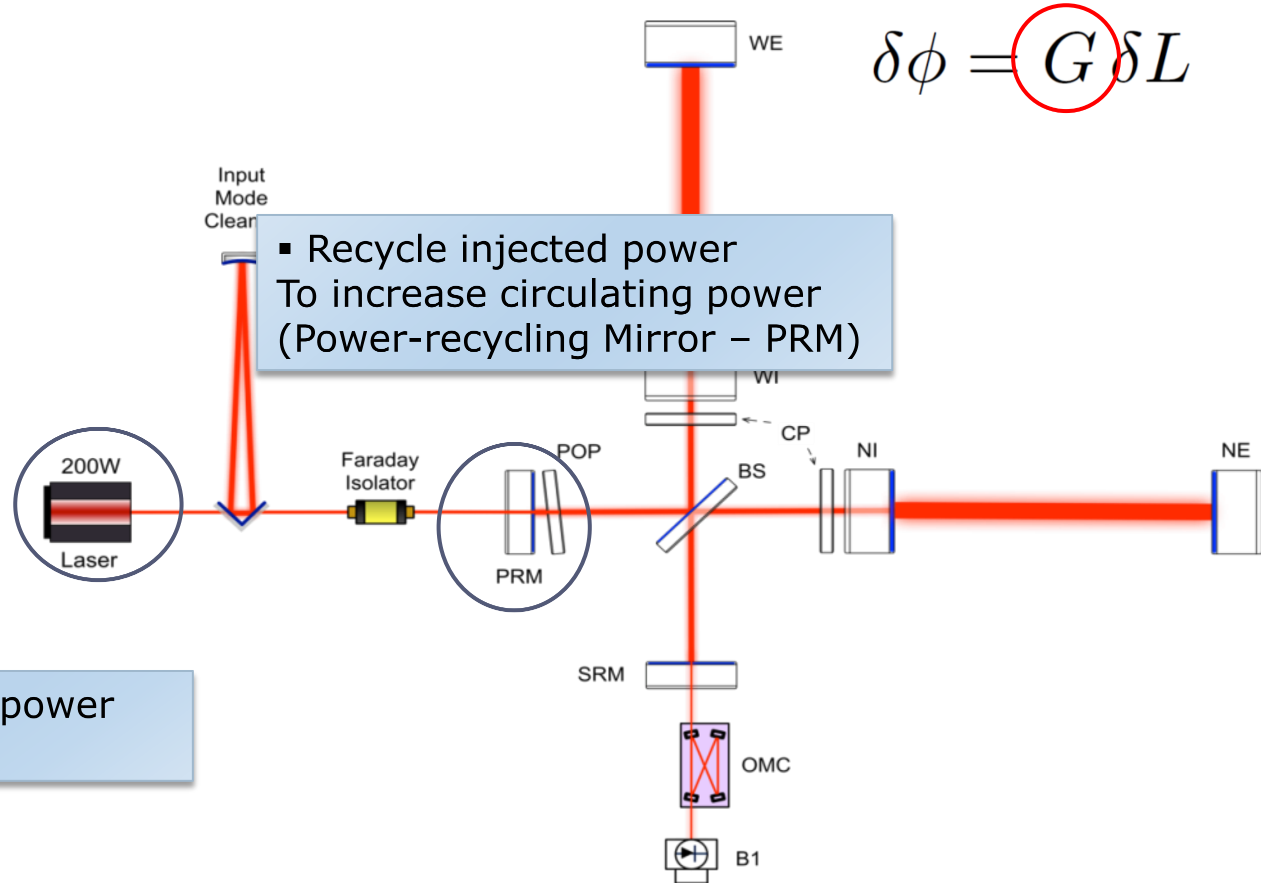
❑ How to increase strain sensitivity: *enhance the signal*

$$\delta\phi = G\,\delta L$$

Order of 1MW circulating power in the arms, at design configuration



- Recycle injected power

To increase circulating power (Power-recycling Mirror – PRM)

- Increase input power (~10^2 W Pin)

A century-old ruler - Reloaded

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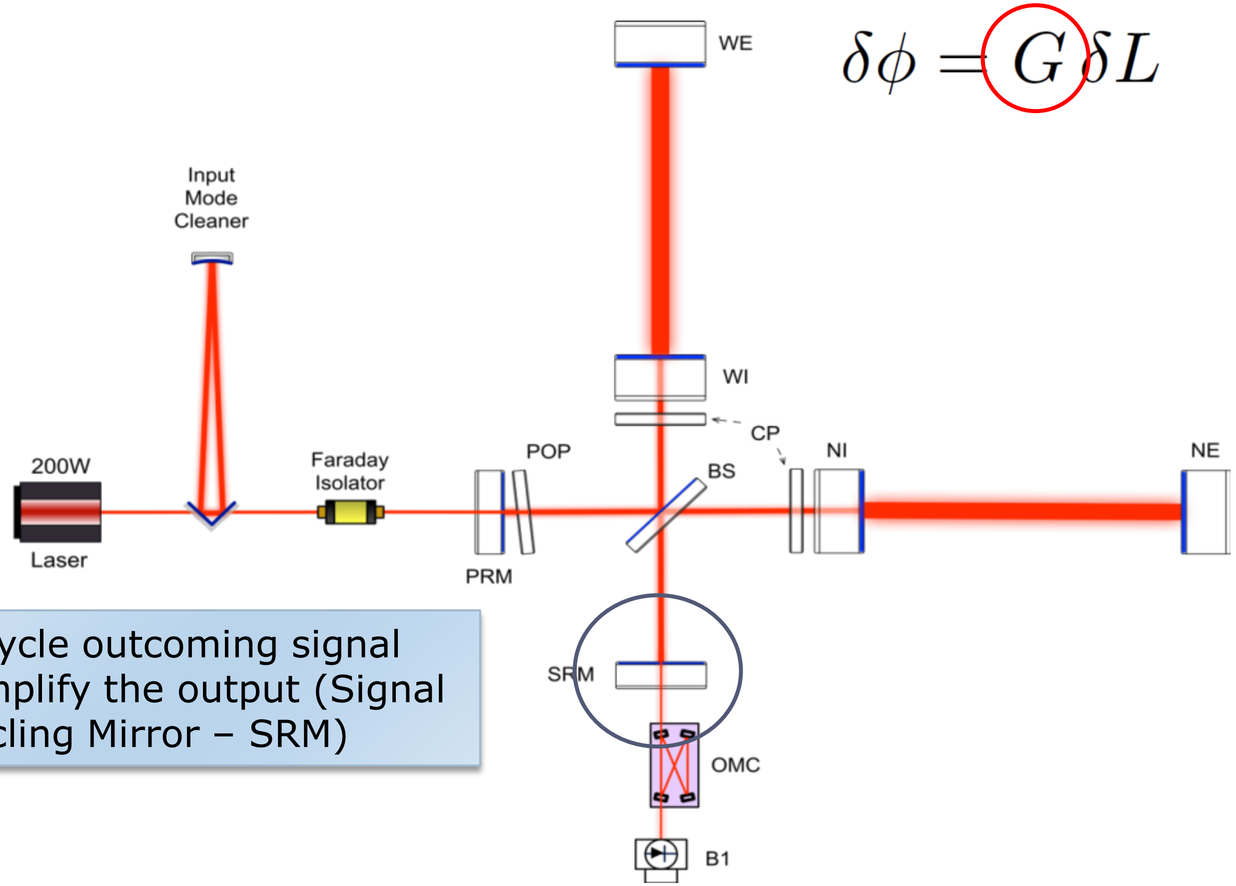
❑ How to increase strain sensitivity: *enhance the signal*

$$\delta\phi = G\,\delta L$$



- Recycle outcoming signal
To amplify the output (Signal Recycling Mirror – SRM)

GW Detectors - Noise

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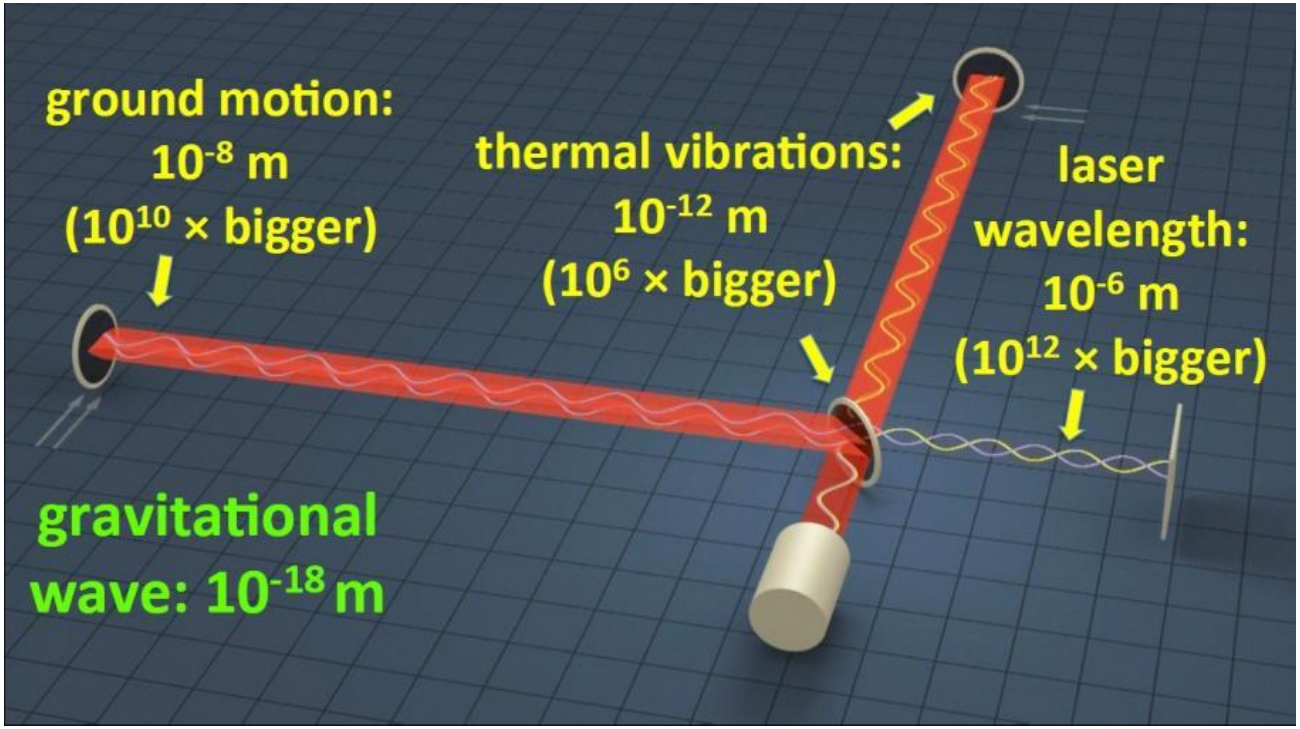
- How to increase strain sensitivity: *reduce the noise*



Credits: Stephen Fairhurst

GW Detectors - Noise

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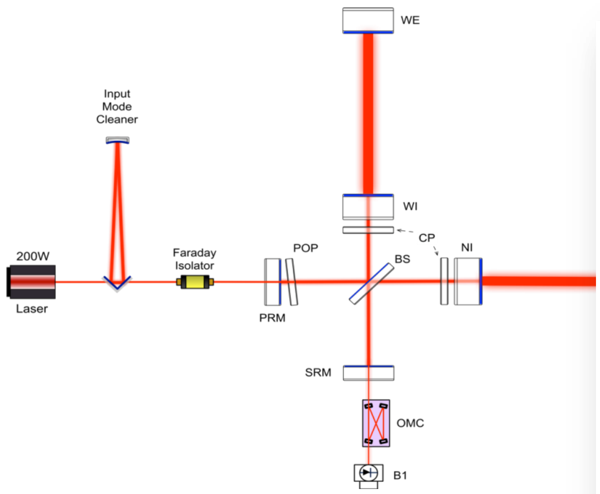
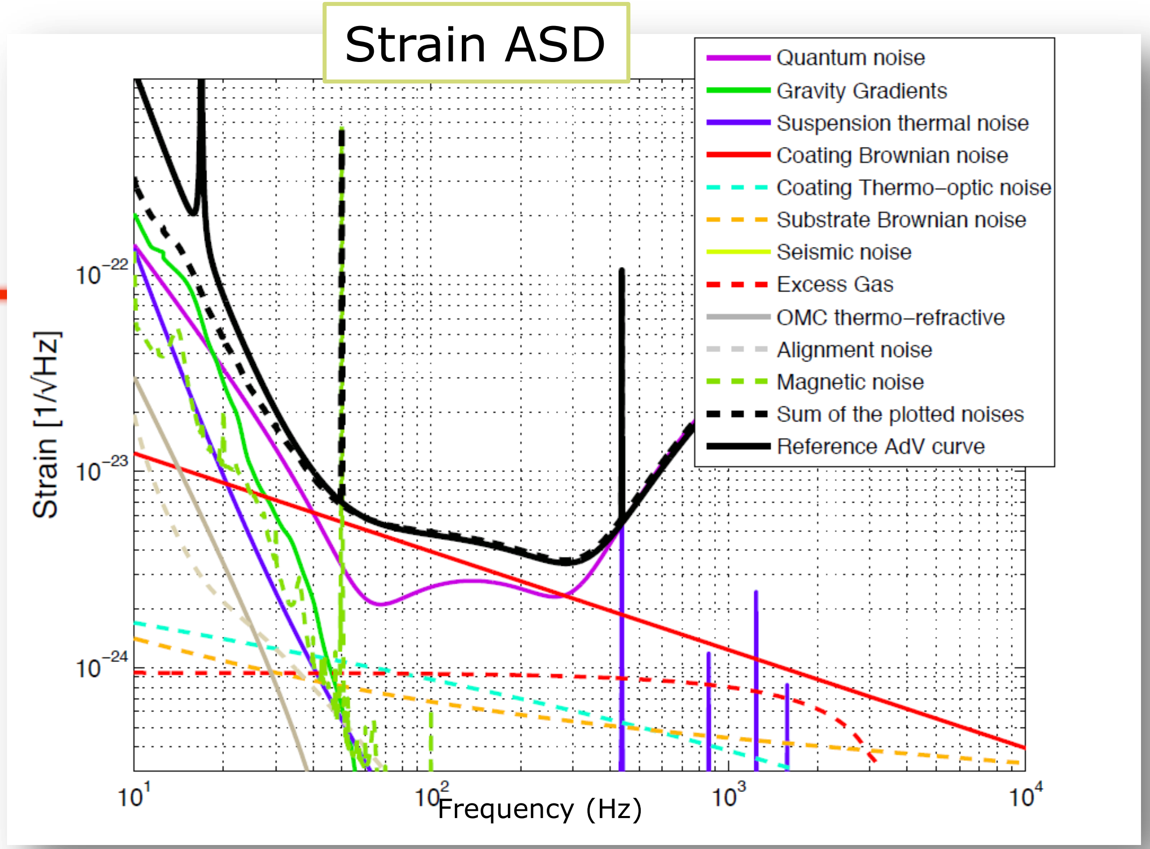
- ❑ Limiting noises at different frequency ranges





GW Detectors - Noise

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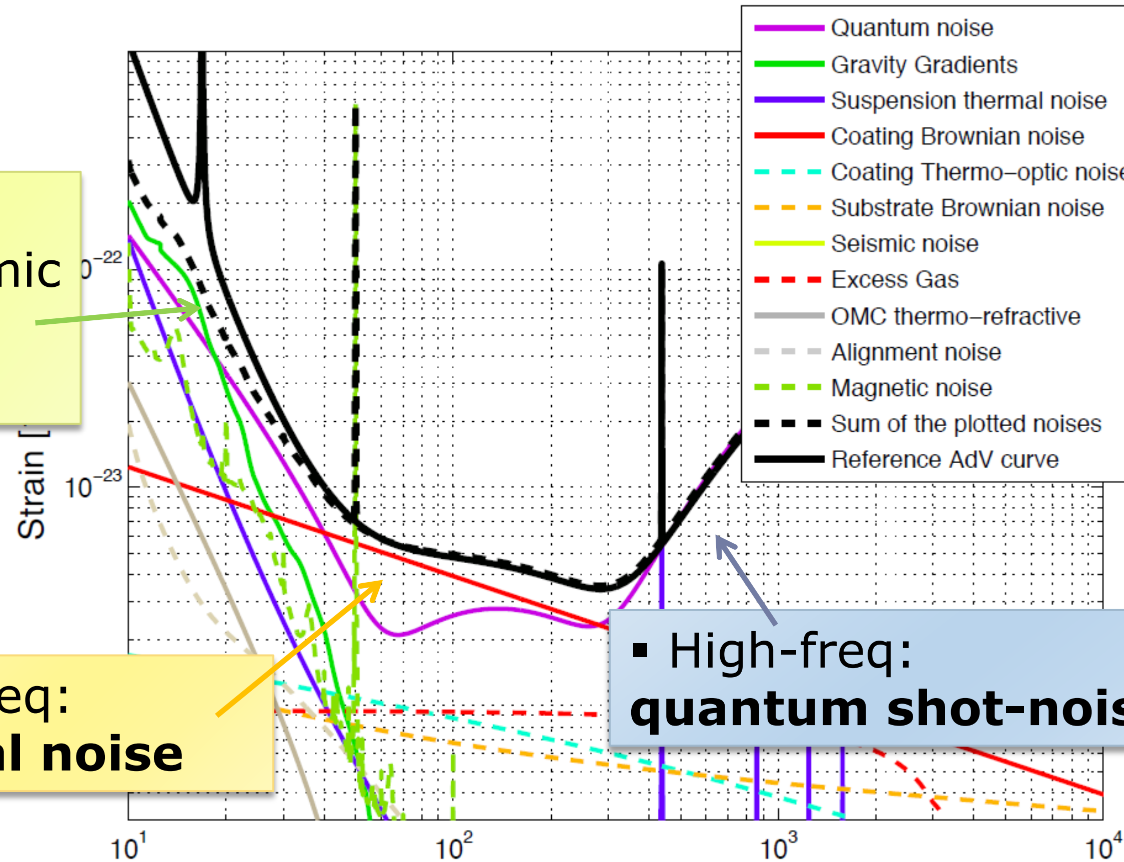


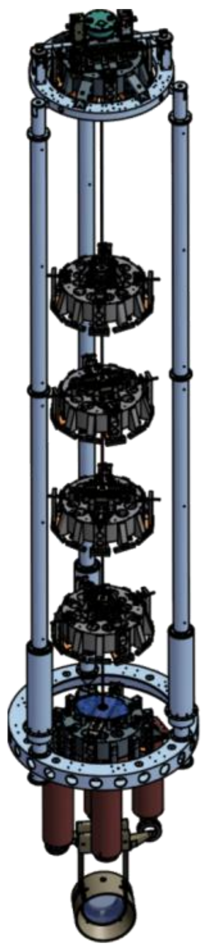
- Low-freq: **newtonian noise**, seismic noise, residual technical noises

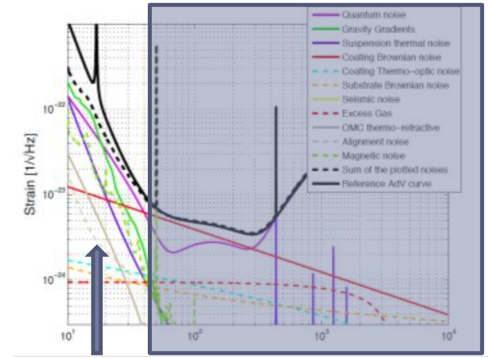
- Mid-freq: **thermal noise**

- High-freq: **quantum shot-noise**

Coping with Noise

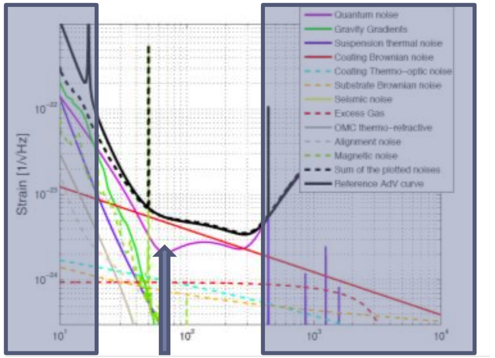
- Low frequency range:
  - Dominated by *seismic noise*
  - Managed by suspending the mirrors from extreme vibration isolators (attenuation > 10^12)
  - Technical noises of different nature are the real challenge in this range
  - Ultimate limit for ground-based detectors:
    gravity gradient noise



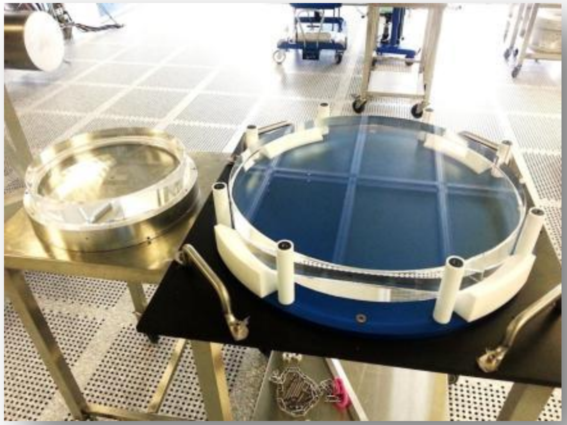


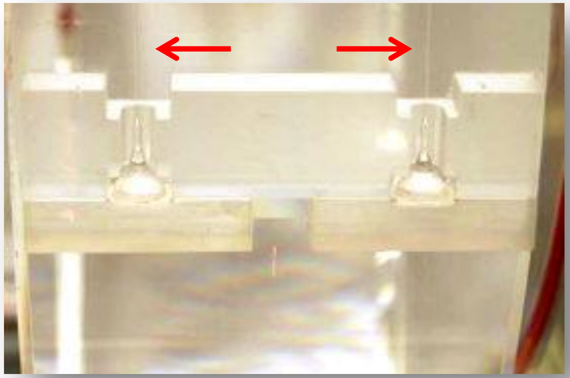
Coping with Noise

- Mid frequency range:
  - Dominated by thermal noise of mirror coatings and suspensions

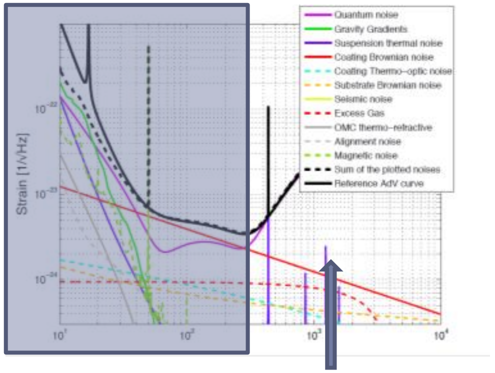


- Reduced by:
  - ***Larger beam spot*** (sample larger mirror surface)
  - Test masses suspended by fused silica fibers (low mechanical losses)
  - Mirror coatings engineered for low losses

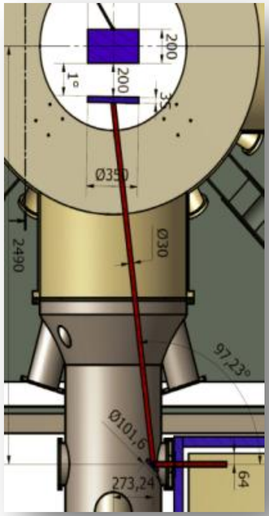


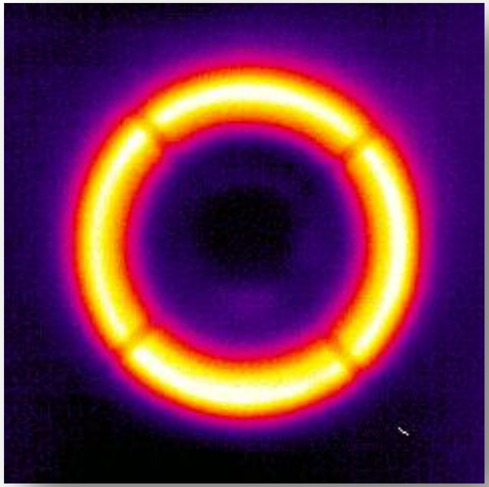


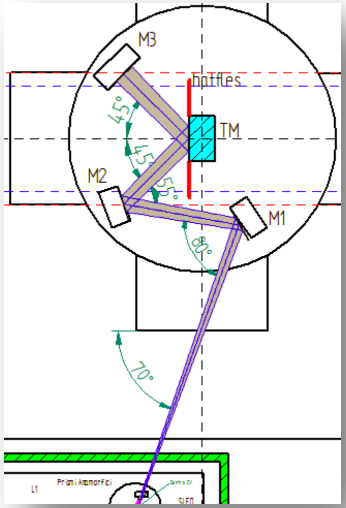
Coping with Noise

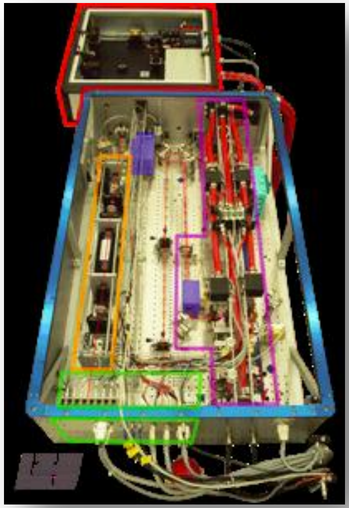


- High frequency range:
  - Dominated by laser shot noise.
    Improved by increasing the power:
    >100W input, ~1 MW in the cavities
- Requires:
  - New laser amplifiers (solid state, fiber)
  - Heavy, low absorption optics (substrates, coatings)
  - Sophisticated systems to correct for thermal aberrations









GW Detectors - Noise

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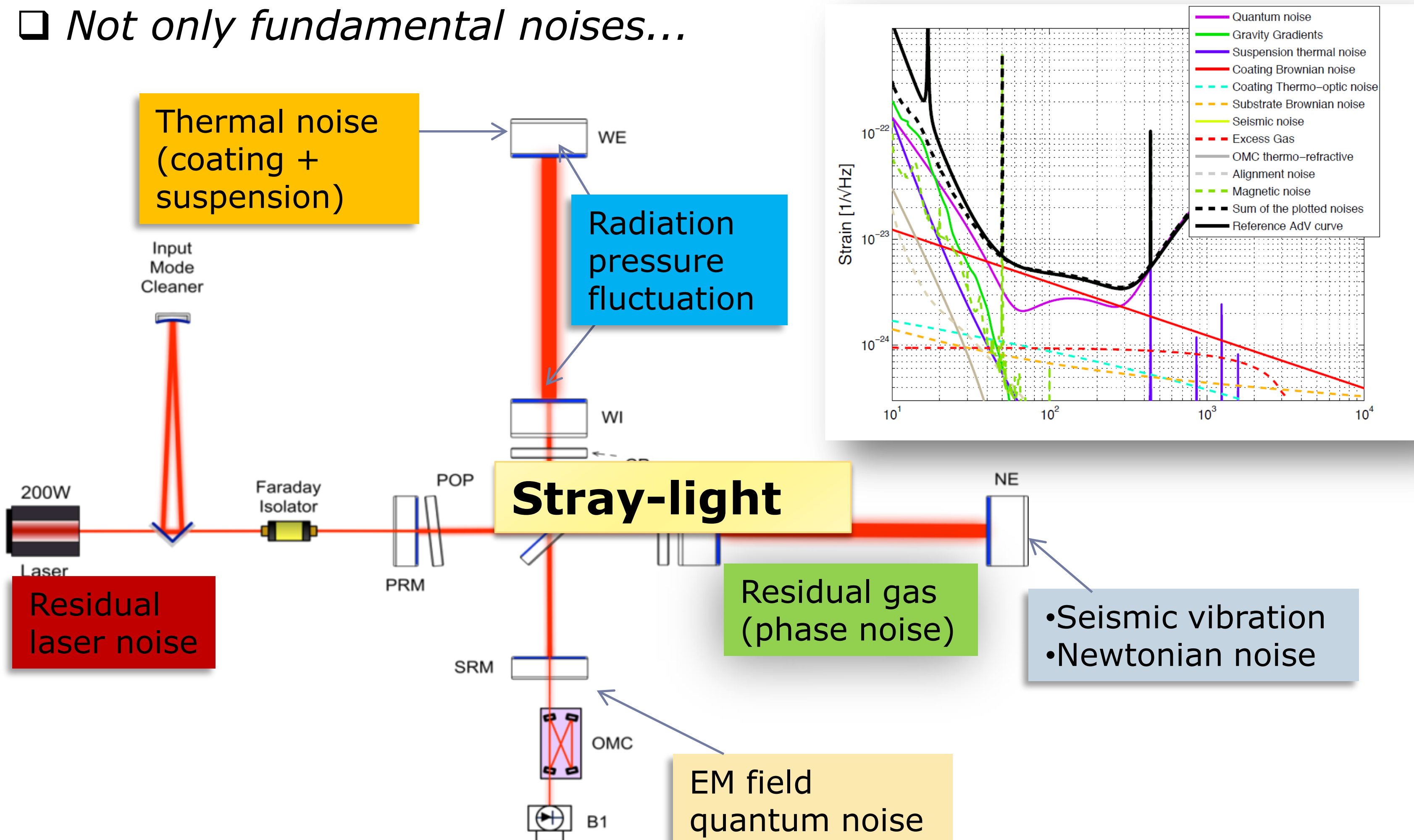
- *Not only fundamental noises…*



❑ Stray Light: an old enemy

-Simulation

-Measurements

An Old Enemy

EGO - VIRGO

- Stray light gave countless problems during past generation (as long expected)

J. Phys. E: Sci. Instrum., Vol. 12, 1979. Printed in Great Britain

An argon laser interferometer for the detection of gravitational radiation

H Billing, K Maischberger, A Rüdiger, R Schilling, L Schnupp and W Winkler
Max-Planck-Institut für Physik und Astrophysik, Munich, Germany

Received 10 April 1979

d 10 April 1979

Abstract A gravitational radiation antenna, consisting of a Michelson interferometer illuminated with an argon laser, ...ing developed. A first stage has been reached with the ...tion of a small prototype of 3 m arm length. This ...e was used to locate and study various noise ... and other disturbances, which would restrict signal ...ptibility. From an analysis of these disturbances, the ...emands on apparatus components have been estimated. Some constructional details are given, as well as suggestions for improvement aimed at a future interferometer of increased base length, with the prospect of successful operation.

One of the oldest papers which identified stray light as a serious problem for GW detectors.

3.6 *Light scattered with long path differences*
In an interferometer with long travel times, the frequency jitter $\delta\nu/\nu$ can enter in yet another way into the measurements. Light scattered back into the direction of the properly returning main beam may have path differences ΔL with respect to the main beam which can be of the order of the total path length L. Such extreme path differences occur for light scattered prior to the delay line, or during early reflections, but also for scattered light making an extra cycle in the delay line.

On interference with the main beam, this scattered light of relative field strength r will cause a phase jitter corresponding to a spurious path variation δL, roughly approximated by

$$\delta L \approx r \Delta L \frac{\delta\nu}{\nu}. \qquad (7)$$

Again, we want this to be below the 1 W shot noise equivalent $\delta L = 10^{-16}$ m Hz$^{-1/2}$. We hope that the frequency jitter can be reduced by a factor of 10^3 with respect to that of our present laser. Even then, but assuming $\Delta L = L = 100$ km, a backscattered fraction of only $r^2 = 10^{-11}$ in intensity is allowed. This will be very hard to achieve, but it does not appear impossible.

2.5 *The 'parasitic interferometer'*
Light scattered at one of the optical surfaces in the interferometer and returning to the laser will be reflected at the laser output mirror. Here, with a phase $\phi(t)$ determined by the extra path $2(D_0 + d(t))$, it interferes with the main beam (figure 6), giving rise to intensity variations. This is what we call the 'parasitic interferometer'.

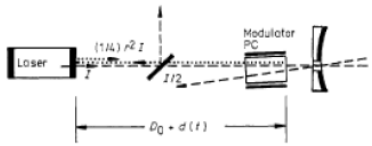


Figure 6 Light paths in a 'parasitic interferometer'.

If the difference nulling method is used, these intensity fluctuations are treated as being merely an additional intensity noise. For the modulation method, however, the 'parasitic interferometer' constitutes a new noise source: backscattered light that has passed the modulator Pockels cell leads to a 10 MHz intensity modulation of the main beam, which the demodulator converts into a spurious interferometer signal.

The relative intensity fluctuations $\delta I/I$ due to the parasitic interference depend on the fraction backscattered to the laser (r^2 in power, or r in field strength), and on the distance variation $d(t)$ between laser mirror and scattering surface, according to, say,

$$\frac{\delta I}{I} \approx r \sin\left(\frac{4\pi}{\lambda} d(t)\right). \qquad (6)$$

Extremely small amounts of scattered light could be troublesome. As little as $r^2 = 10^{-18}$ in intensity, scattered back into the (narrow) laser beam, could cause intensity variations of the order of the signals to be detected (10^{-9}).

We have to rely on the second factor in equation (6) to reduce the spurious signals. Fortunately, the mechanical motions $d(t)$ of the optical components involved are very small in our signal frequency range, i.e. above a frequency F of several hundred hertz.

At very low frequencies f, however, particularly at the pendulum resonance ($f \approx 1$ Hz), we can observe large amplitudes $a(f)$, even up to many wavelengths λ. They produce high harmonics $mf > F$ inside our signal frequency range, which can be described by the Bessel functions $J_m(4\pi a/\lambda)$ of large order m. These assume appreciable values only if the argument $4\pi a/\lambda$ becomes comparable with the order $m = F/f$.

The high-Q resonance of the pendulum had, in fact, led to such large relative motions $d(t)$. Therefore, an active damping of the pendulum was introduced (cf §3.1), which practically eliminated the harmonics above F. Should the need arise, as we proceed to higher sensitivities, one could reduce the backscattered light drastically by the use of a Faraday isolator.

[Billing79] H Billing, K Maischberger, A Rudiger, R Schilling, L Schnupp and W Winkler, "An argon laser interferometer for the detection of gravitational radiation", J. Phys. E: Sci. Instrum. 12 1043 (1979)

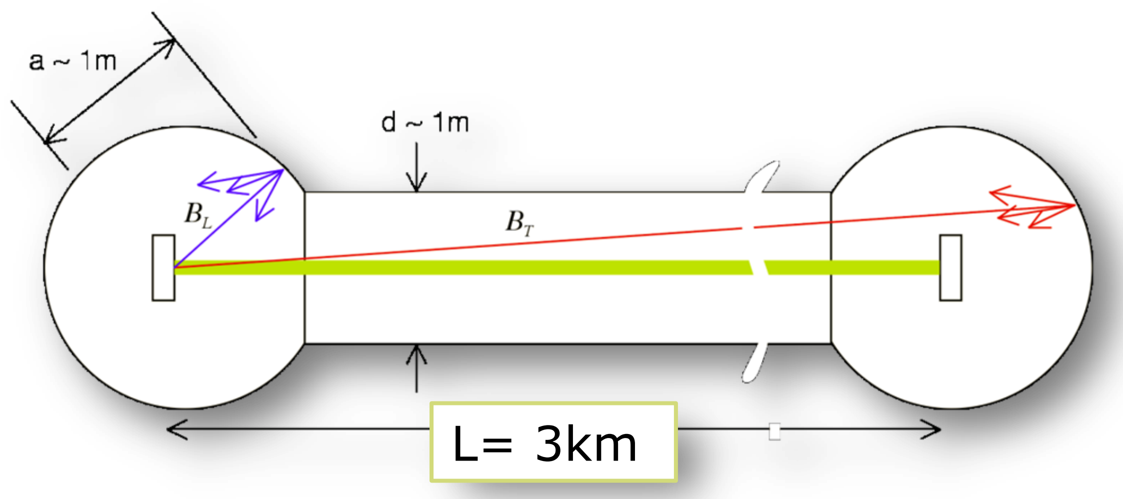
21-06-12 J. Marque – Cascina VESF school '12

An Old Enemy

EGO - VIRGO

- ❑ Stray light gave countless problems during past generation (as long expected)

- ❑ A tiny amount of stray light coupling with the fundamental mode after "probing" the vibrations of infrastructures will bury any gravitational signal.



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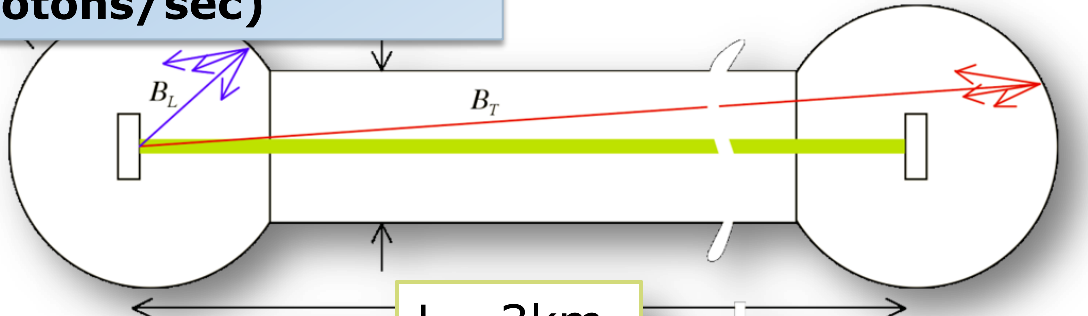
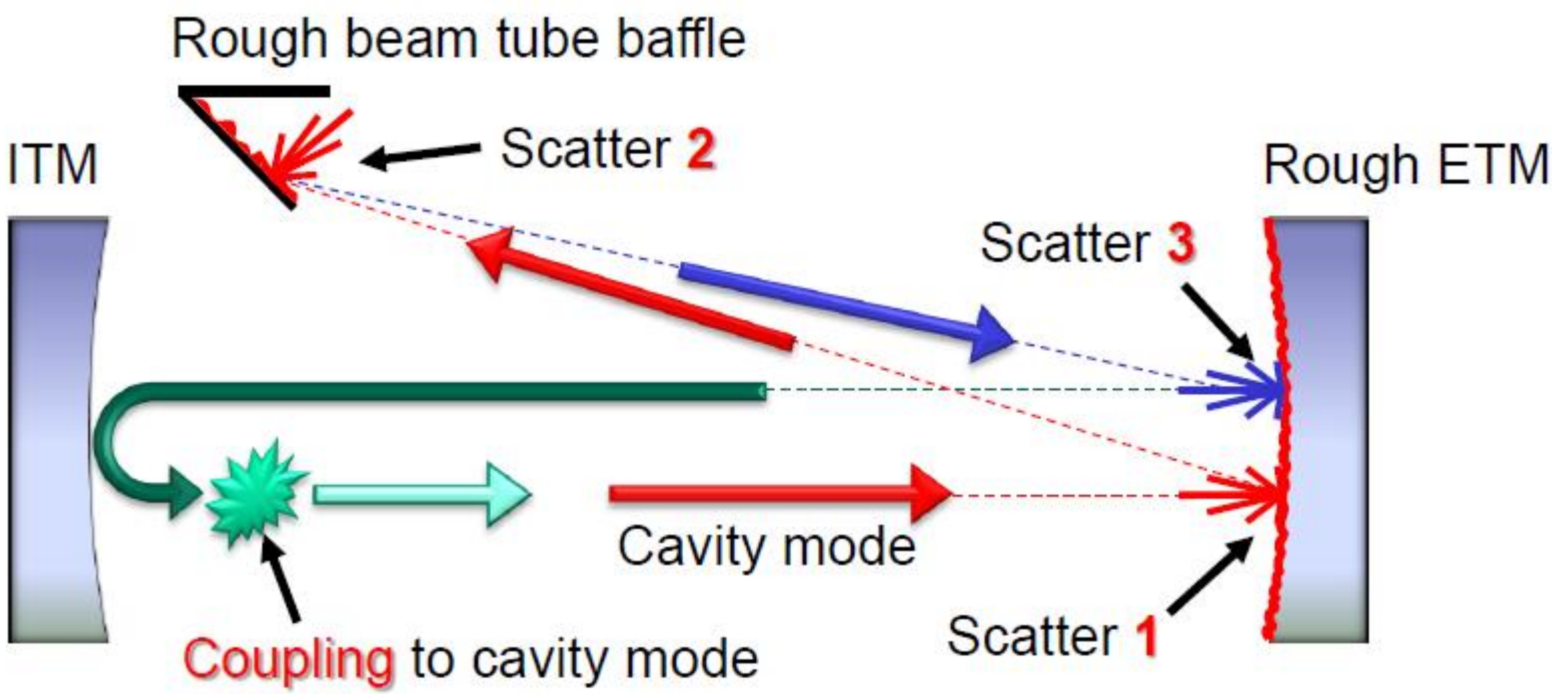
➢ **1979:** expected troubles when stray light recombines to the main mode with an efficiency of **10^-18 W/W**

➢ **2015:** expected troubles when stray light recombines to the main mode with an efficiency of **10^-24 W/W (~5 photons/sec)**



L= 3km

Stray Light simulations



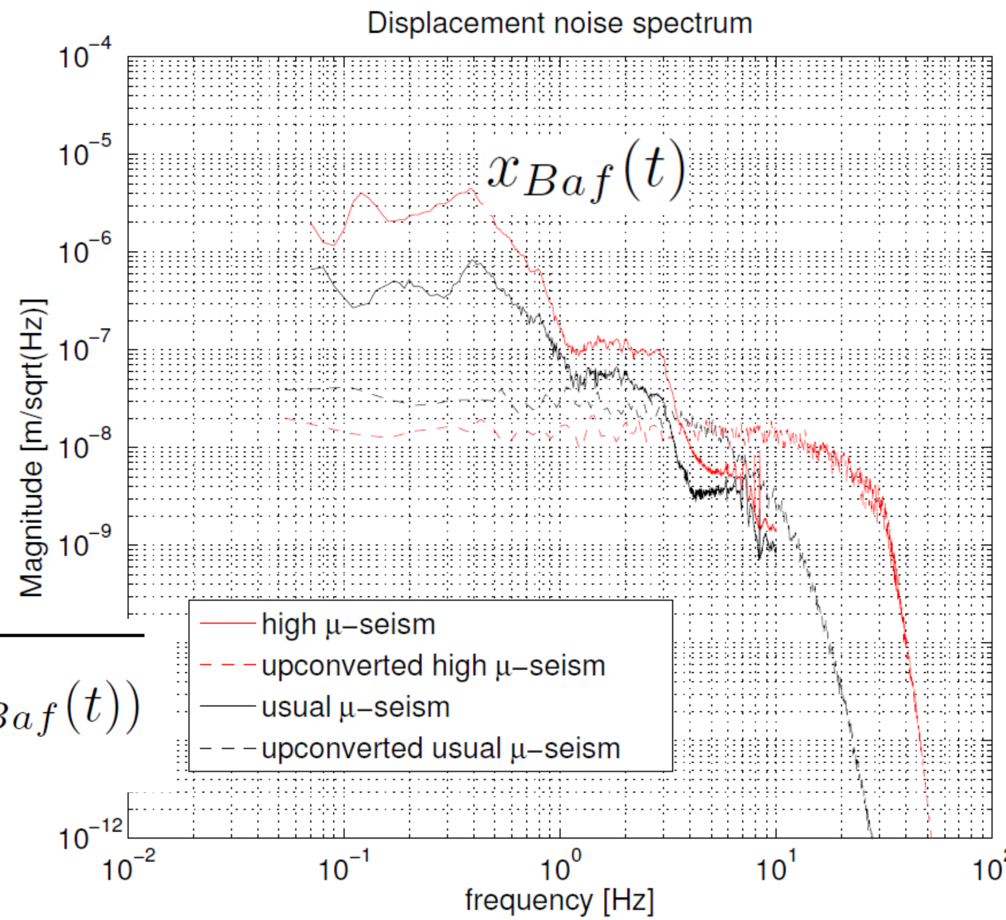
If the scatterer moves wrt the ITF, then the backscattered light is phase/amplitude modulated before recombining with the ITF main mode

Stray Light simulations

- Non-linear coupling (fringe-wrapping)

Regardless of the amplitude of motion of the scatterer, scattered light phase modulation cannot exceed 2pi. For large amplitude we must use an effective displacement:

$$\tilde{x}_{Baf}(\omega) = \frac{\lambda}{4\pi}\sqrt{PSD(\sin(\frac{4\pi}{\lambda}x_{Baf}(t))}$$



Stray Light simulations

EGO - VIRGO

❑ Example: how to design new baffles /accept existing ones?

1) Need to evaluate baffle displacement noise and project it to the strain sensitivity.

Recipe for noise projection:

Parameter	Meaning	Estimation method
$\lvert c \rvert$^2	recombination efficiency	FFT (FOG -SIS) /Semi-analytical
Xbaf	(effective) displacement noise of scatterer	Measurement /simulations
Tbaf	Transfer function from Xbaf to dark fringe PD (B1)	Optickle /Finesse /MIST
Tdarm	Transfer function from DARM dof to dark fringe PD	Optickle /Finesse /MIST

$$\boxed{hbaf = |c|\, Tbaf/Tdarm\ 1/L\ Xbaf}$$

Stray Light simulations

EGO - VIRGO

- Example: how to design new baffles /accept existing ones?

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Roughness, reflectivity, shape, position

Recipe for noise proj

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Mechanics, linear /non-linear (fringe wrapping)

location

$$\boxed{hbaf = |c|\ Tbaf/Tdarm\ 1/L\ Xbaf}$$

Stray Light simulations

EGO - VIRGO

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Mechanics, linear /non-linear (fringe wrapping)

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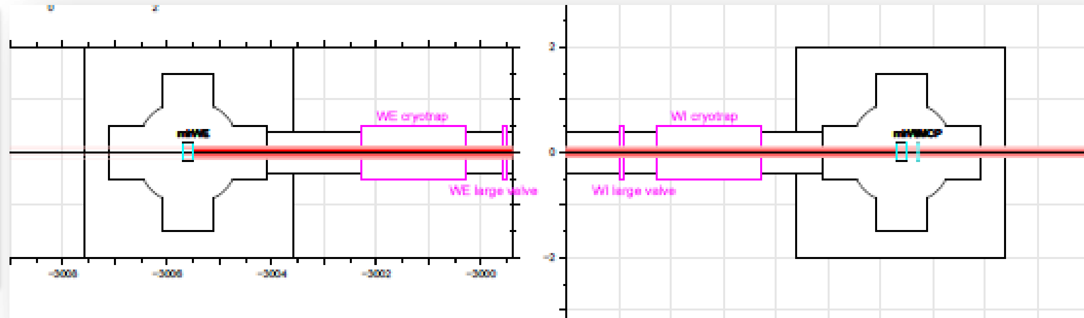
$$\boxed{\text{hbaf} = |c|\ \text{Tbaf}/\text{Tdarm}\ 1/L\ \text{Xbaf} < h/10}$$

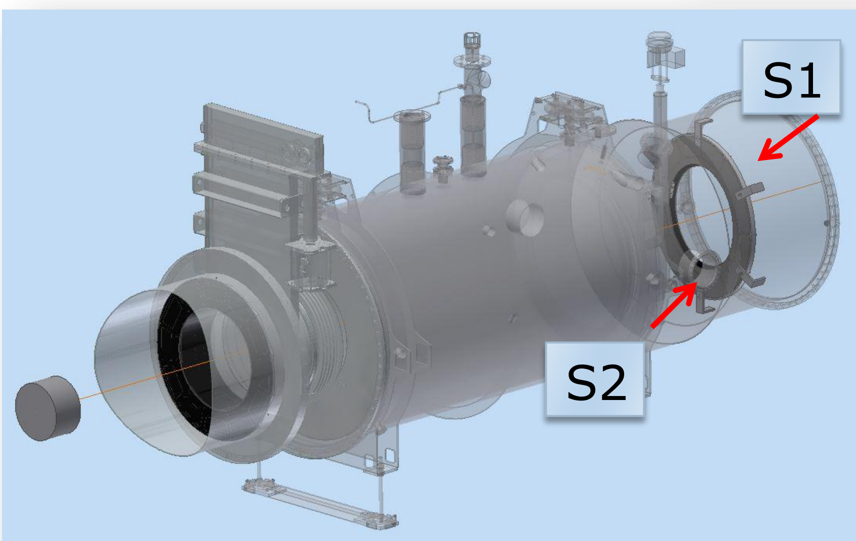
Stray Light simulations

❑ Example: baffles for arm cryogenic traps

Needed to obscure inner walls of the cryotrap from:

- Farthest test mass (baffle S1)
- Closest test mass (baffle S2)





Stray Light simulations

EGO - VIRGO

- Design study for baffles in arm cryogenic traps [VIR-0417B-13]:

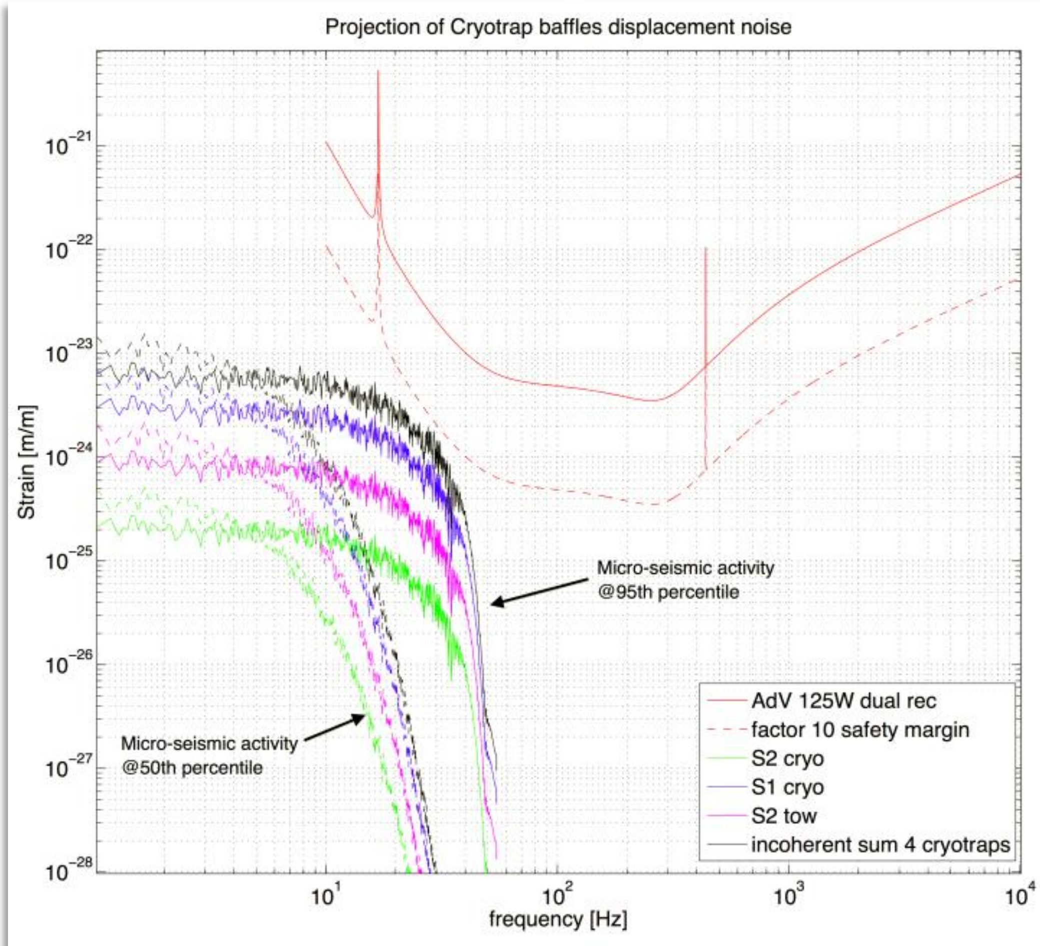
- Simulations with:
  - FFT / BRDF for the coupling,
  - Optickle for TFs
  - Baffle displacement *caused by micro-seism*

- Overall expected noise *ok* even for <u>severe</u> seismic conditions

Table 1: BRDFs of baffles for cryotrap

Baffle surface	BRDF [sr^{-1}]	Coupl [W/W]
S2 Baf_Cryo	3×10^{-2}	$1.5\ 10^{-27}$
S1 Baf_Cryo	3×10^{-3}	$3\ 10^{-25}$
S_{Cyl}	$\sim 10^{-2}$	$\sim 10^{-26}$
S2 Baf_Tow	3×10^{-3}	$2.6\ 10^{-26}$

Parameters used for the simulations (actual ones *turned out to be better*)

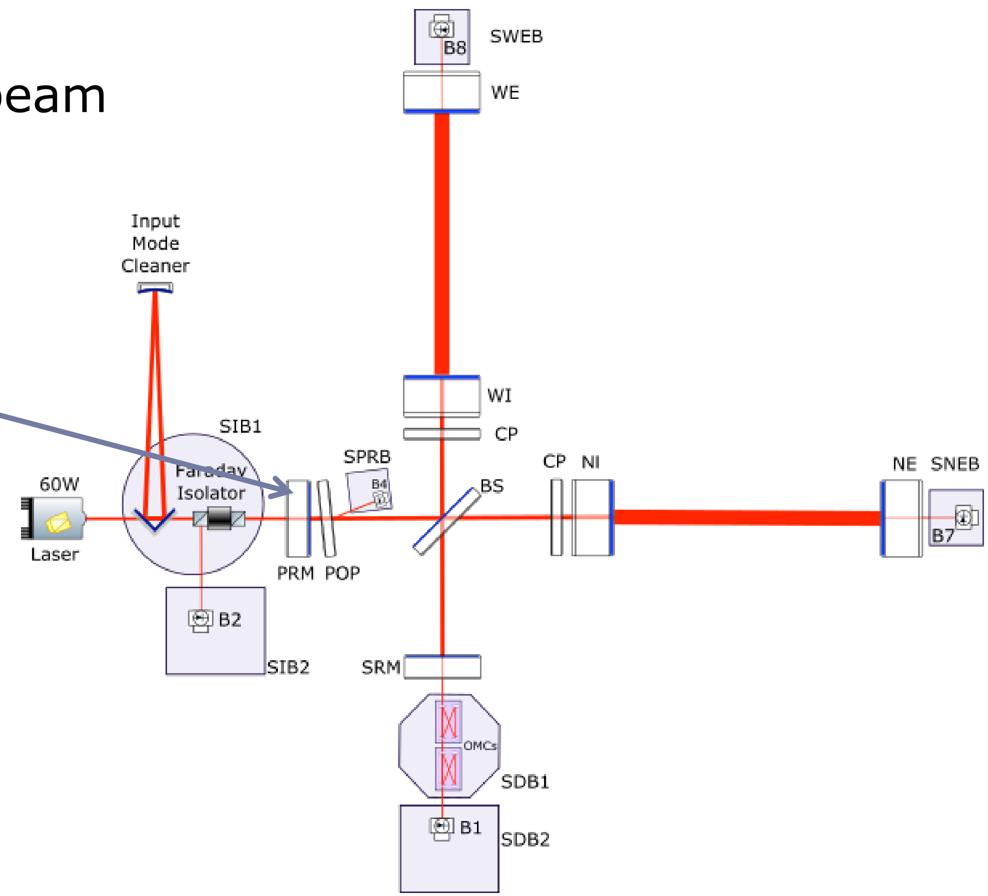


Stray Light noise measurement

EGO - VIRGO

- ❑ Case study: the B4 ghost beam

- A pick-off plate (POP) samples the beam circulating in the com branch of the short Michelson
- The pick-off beam is called B4



Stray Light noise measurement

EGO - VIRGO

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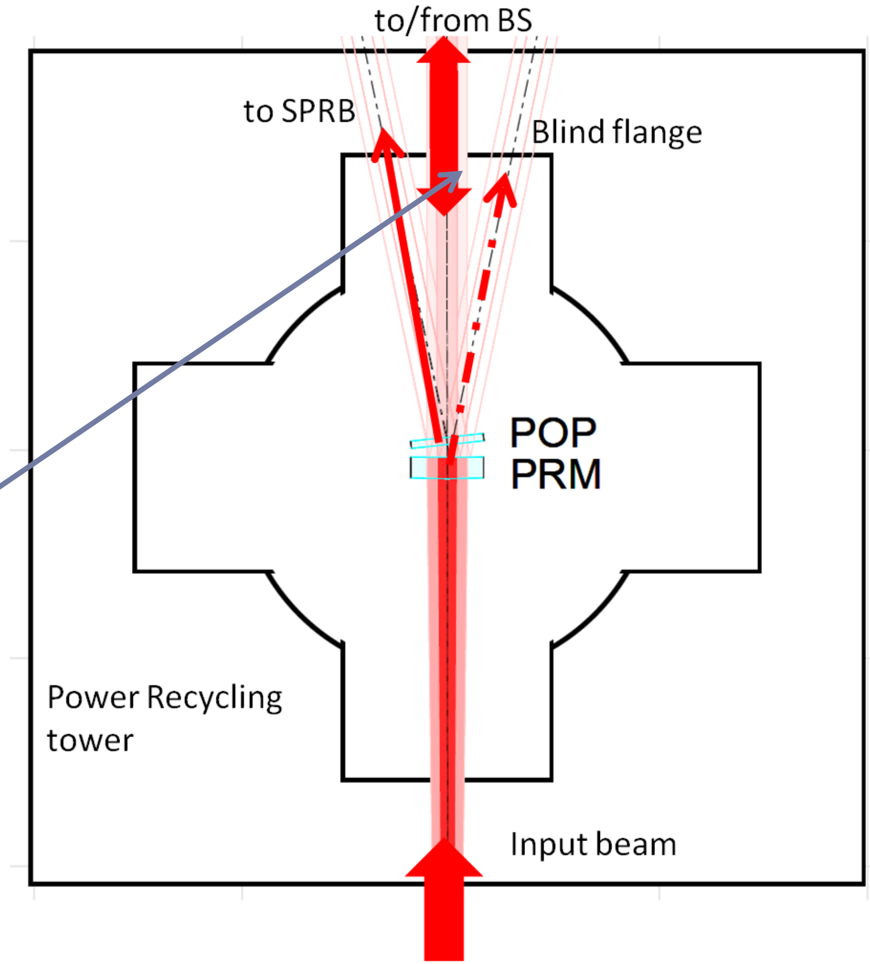
- A pick-off plate (POP) samples the beam circulating in the com branch of the short Michelson
- The pick-off beam is called B4

- B4 is sent to a bench (SPRB)
- the spurious reflection (B4 ghost) goes to a blind flange

- B4 ghost was not properly dumped during O2



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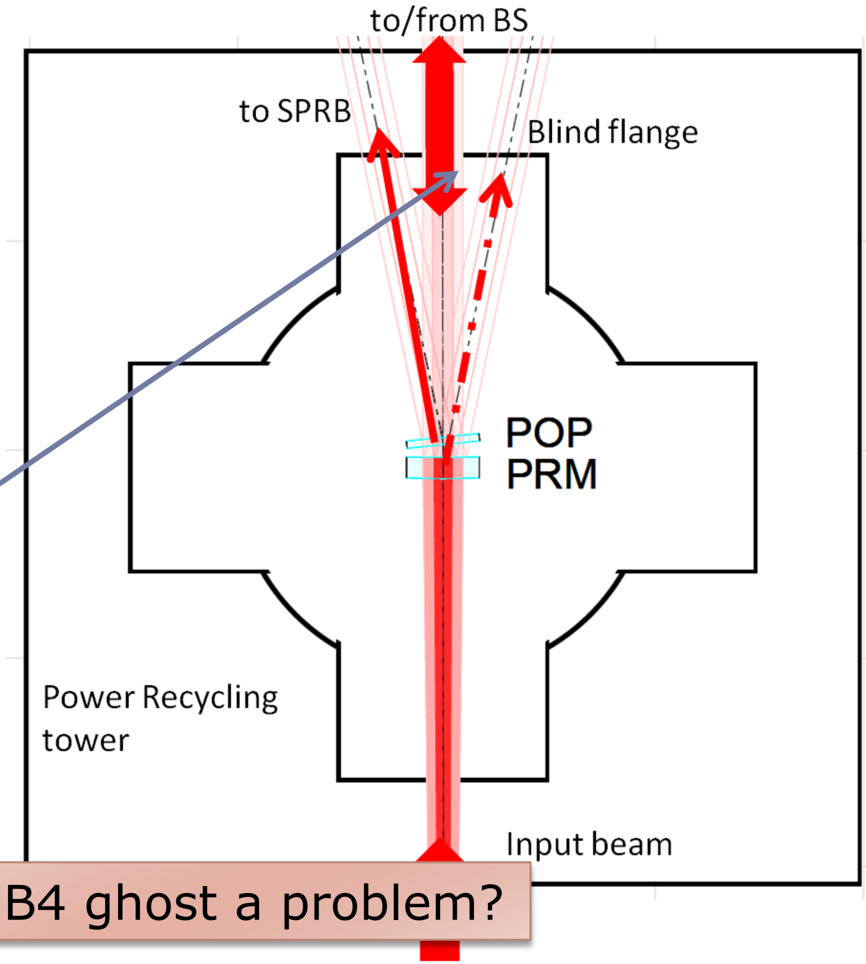


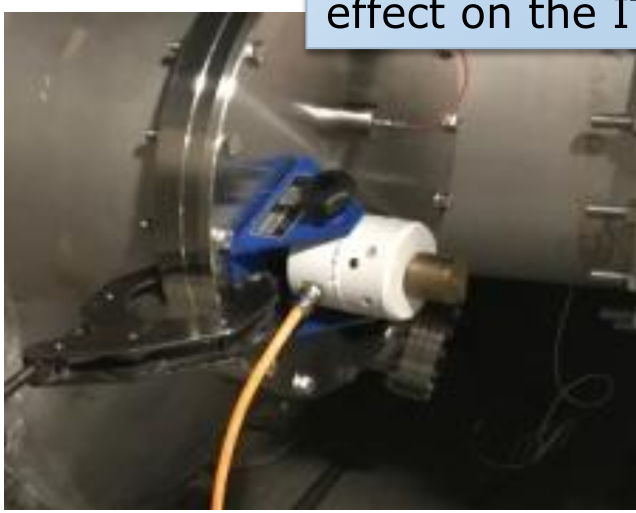
Was B4 ghost a problem?

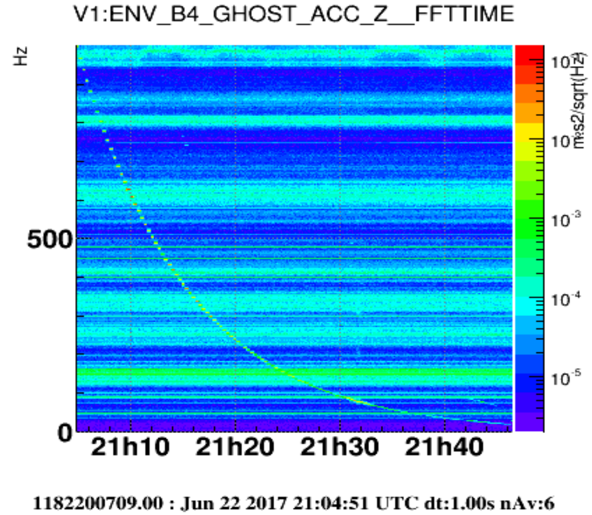
Stray Light noise measurement

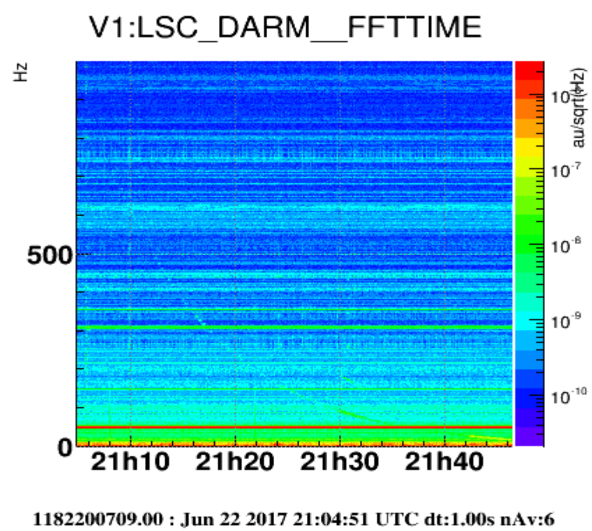
❑ Case study: the B4 ghost beam

To quantify the scattered light we used a shaker, injecting mechanical sinusoidal noise.

The injection is registered by the closest accelerometer, and the effect on the ITF is recorded







Stray Light noise measurement

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Noise Model

- The scattered light carries a phase noise due to the motion of the scatterer. Since gravitational wave strain is proportional to this phase noise, the scattered light noise h_{SC} can be computed as,

$$h_{SC}(f) = FFT\left[\left(\frac{\lambda}{4\pi}\sin\left(\frac{4\pi}{\lambda}z(t)\right)\right)\right] \qquad (1)$$

Where, $z(t)$ is the motion of the scatterer, $\lambda = 1064$ nm is the laser wavelength, FFT denotes the Fourier transform.

- Seismic noise of known amplitude is injected at the sensitive parts of the interferometer, and an accelerometer is placed close to the shaker to record the motion close to the injection spot (Fig. 4).

From VIR-0730A-17

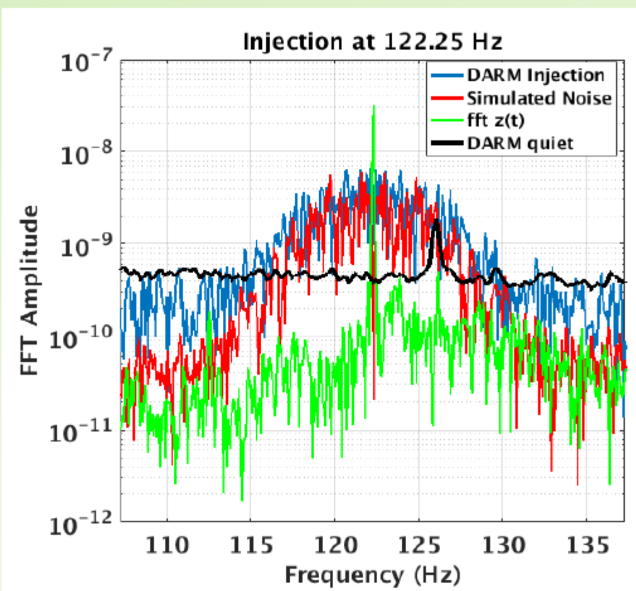

Figure 3. FFT DARM during noise injection at 122 Hz. Green curve shows a sharp peak which is due to the seismic injection, and the red curve is the computed scattered light noise. The red and the blue curve match very well in shape. The representation of the coupling of this noise is hence very accurate.

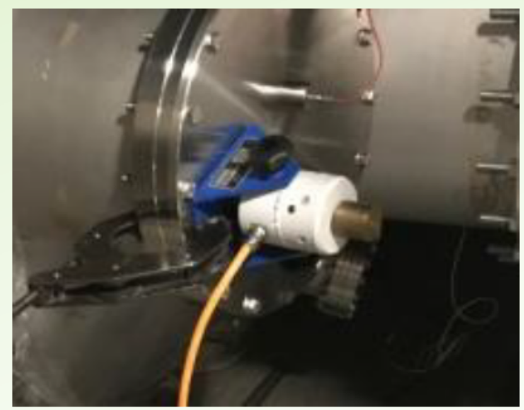

Figure 4. Experiment set up during noise injection at the B4 Ghost flange. Figure shows the shaker fixed to the ghost flange (blue), and the accelerometer placed close to it.

Stray Light noise measurement

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❑ Case study: the B4 ghost beam

- Using the estimated transfer functions, the noise due to scattered light is estimated on $DARM$ and H_{rec}. The Theoretical value of $h_{SC}(f)$ is estimated using the accelerometer recording $(z(t))$ during quiet time. It is further multiplied with the transfer function and compared with the $DARM$ and H_{rec} during the same quiet period.
- From Fig. 7 it is clear that $DARM$ and H_{rec} are limited around 45 Hz, and 92 Hz due to scattered light noise.

From VIR-0730A-17

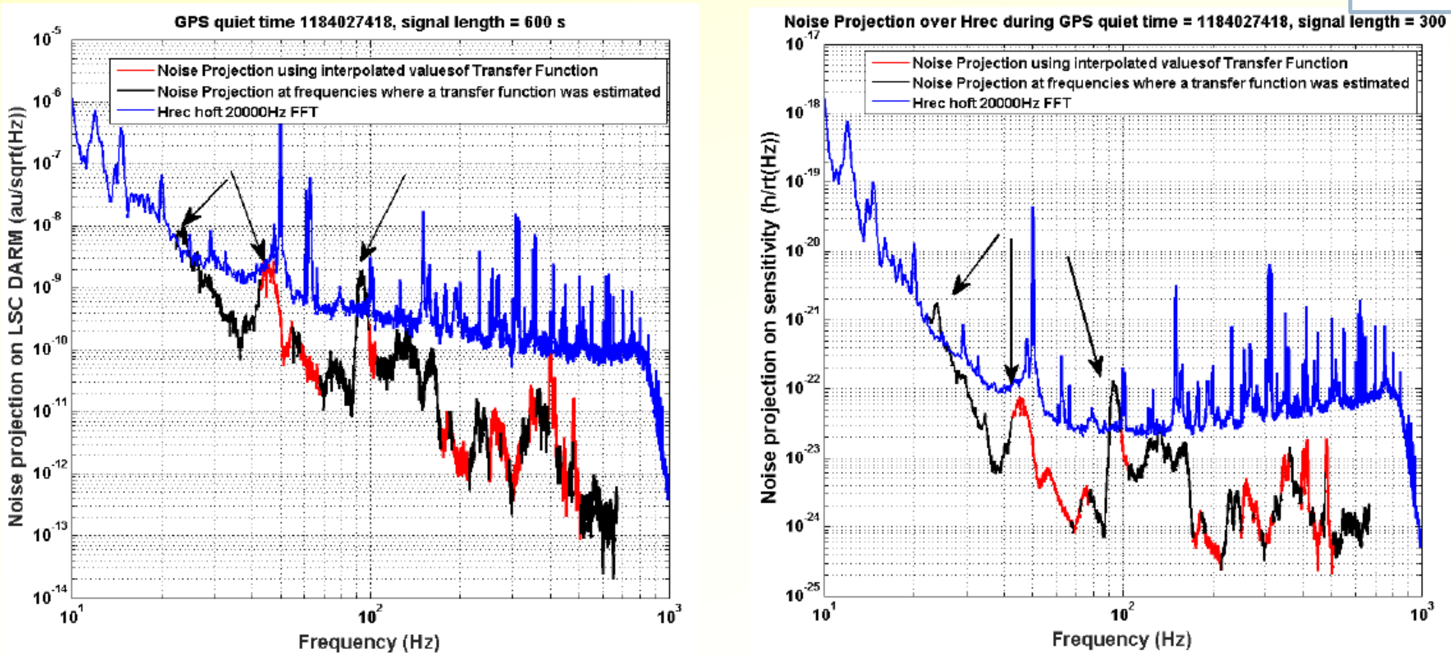

Figure 7. Noise projection on DARM (left) , and on Hrec (right). The black part of the projection curve are estmated reliably, whereas the red parts are obtained by interpolating transfer function within those frequency bands.

Stray Light noise measurement

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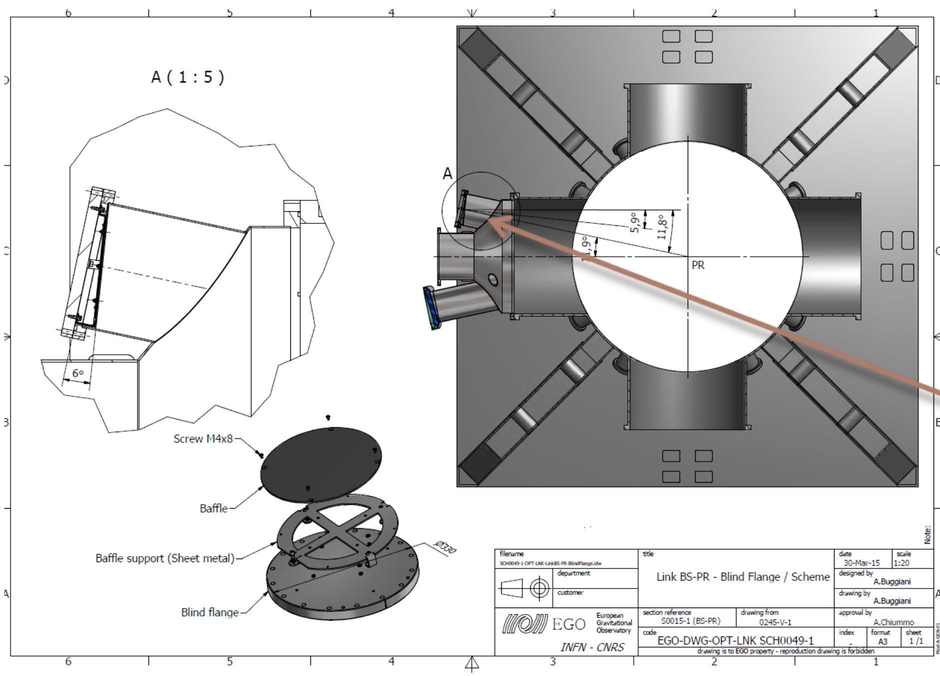
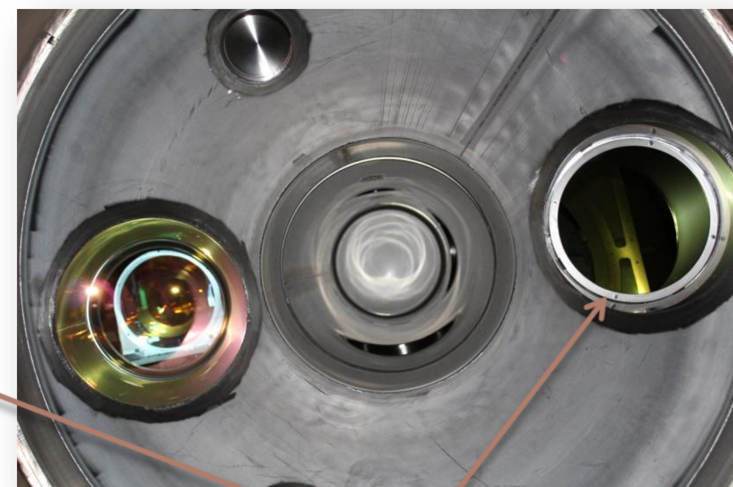
- Case study: the B4 ghost beam





Adding an absorbing baffle solved the issue

Conclusions

- Stray-light is an old enemy of GW interferometric antennas
  - It comes from a diversity of possible defects
  - It can probe seismically excited mechanical structures and recombine with the ITF main beam burying GW signals
  - It is difficult to simulate
  - It is ineherently non-linear
- Despite huge efforts, it threatens the achievement of design sensitivity
- Further advances in prediction, mitigation and monitoring are needed

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