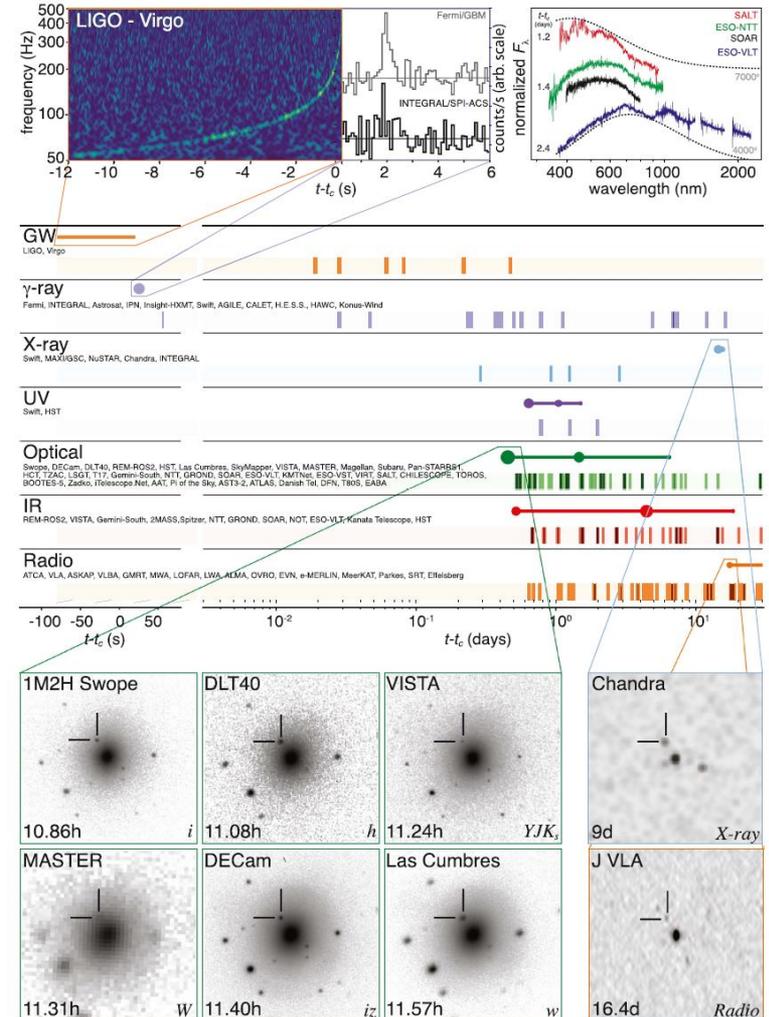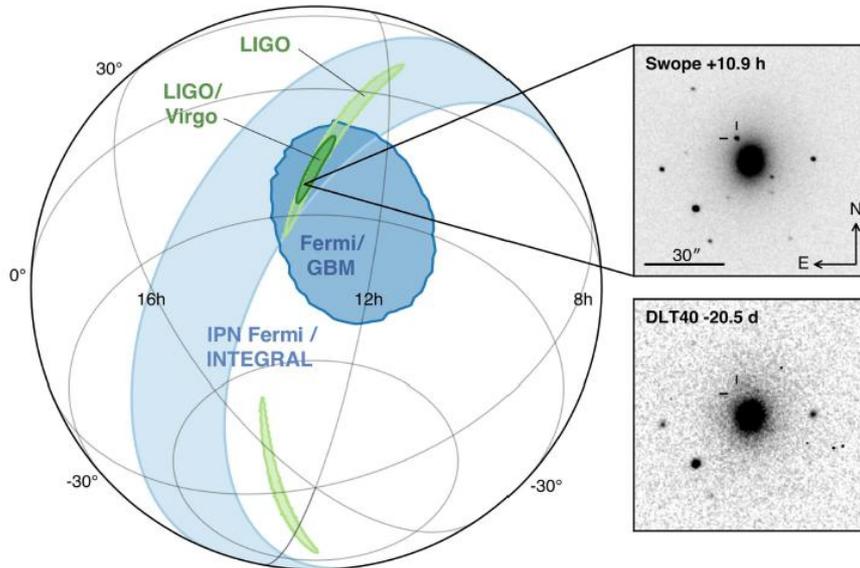# Stray Light Control in Virgo and future prospects
(a very incomplete survey)

A.Chiummo
May 3rd, 2019
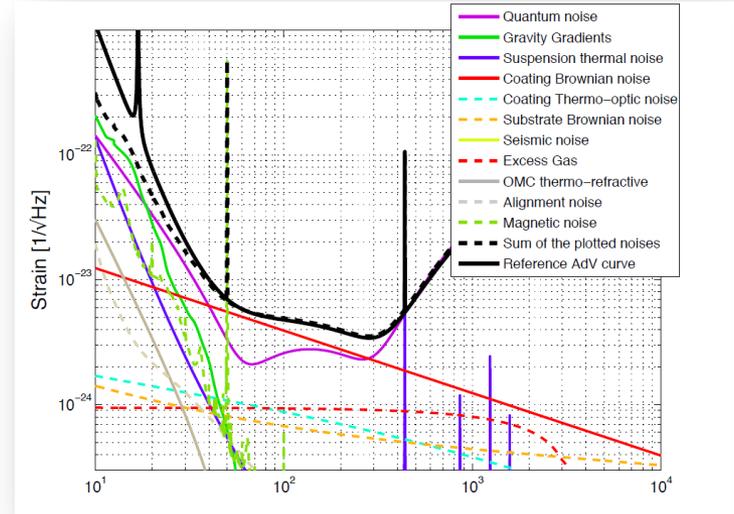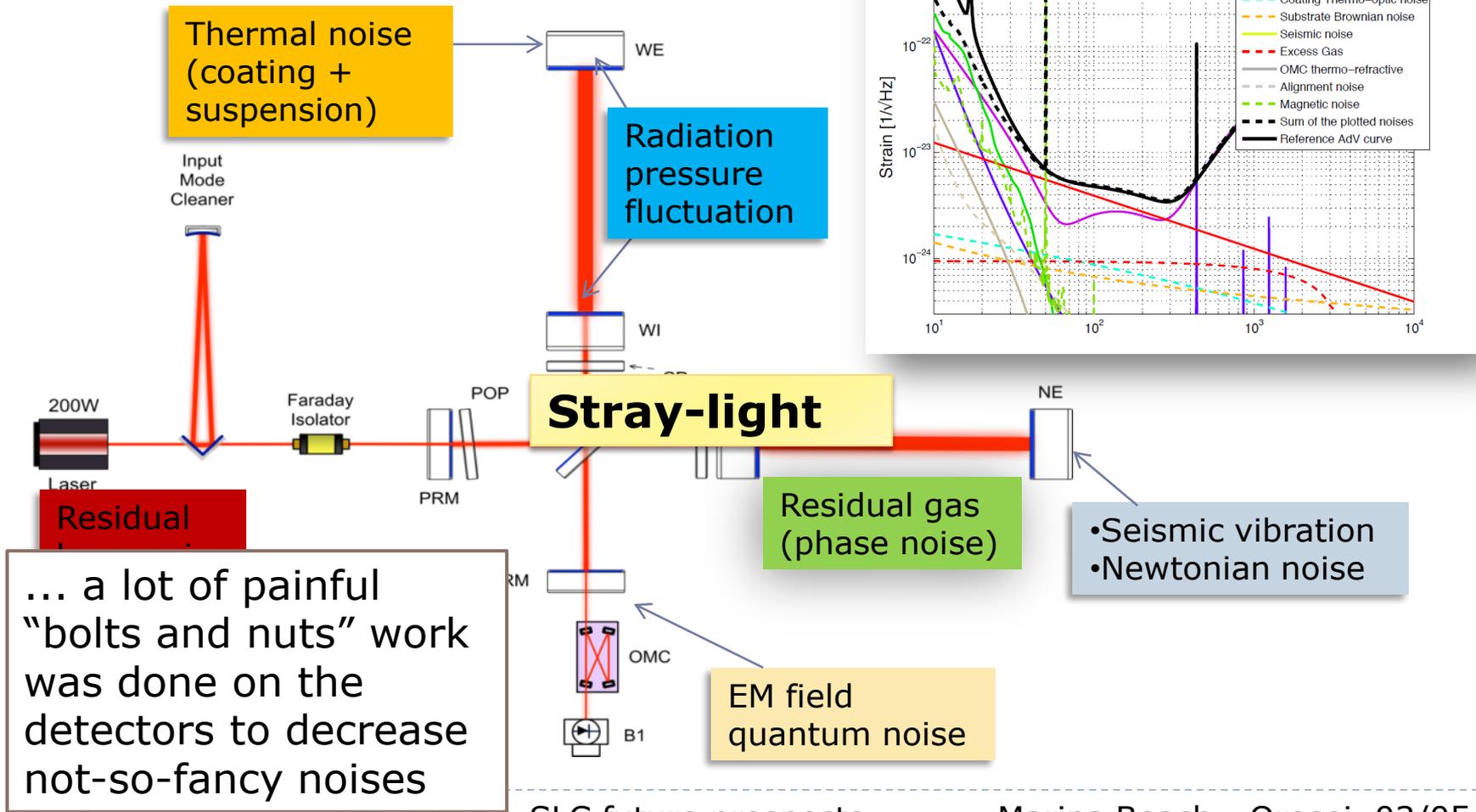
GW170817: beautyful Physics

The "gold mine" (quite literally) of Multimessenger Astronomy was possible also because…

GW Detectors - Noise

❑ *Not only fundamental noises...*

Thermal noise (coating + suspension)

Radiation pressure fluctuation

Input Mode Cleaner

WE

WI

Stray-light

200W

Laser

Faraday Isolator

POP

PRM

PRM

OMC

B1

NE

Residual gas (phase noise)

- •Seismic vibration
- •Newtonian noise

EM field quantum noise

... a lot of painful "bolts and nuts" work was done on the detectors to decrease not-so-fancy noises

Residual

Quantum noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo−optic noise
Substrate Brownian noise
Seismic noise
Excess Gas
OMC thermo−refractive
Alignment noise
Magnetic noise
Sum of the plotted noises
Reference AdV curve

Strain [1/√Hz]

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

An argon laser interferometer for the detection of gravitational radiation

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

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

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

Abstract A gravitational radiation antenna, consisting of Michelson interferometer illuminated with an argon laser, is being developed. A first stage has been reached with the construction of a small prototype of 3 m arm length. This prototype was used to locate and study various noise sources and other disturbances, which would restrict signal susceptibility. From an analysis of these disturbances, the demands 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.

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'.
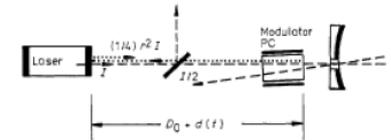
Figure 6 Light paths in a 'parasitic interferometer'.

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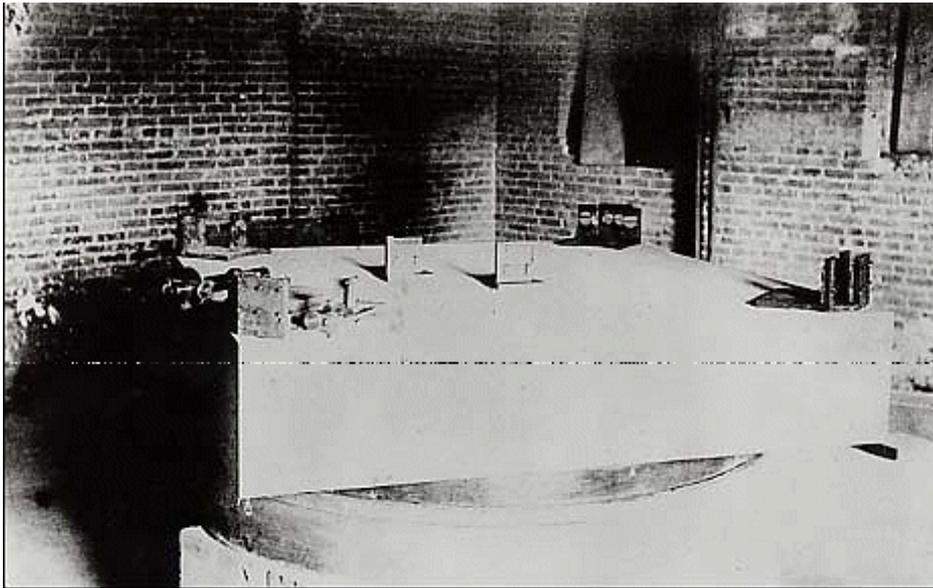
We have to rely on the second factor in equation (6) to reduce the spurious signals. Fortunately, the mechanical motions $d(t)$ of the optical components involved are very small in our signal frequency range, i.e. above a frequency F of several hundred hertz.

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
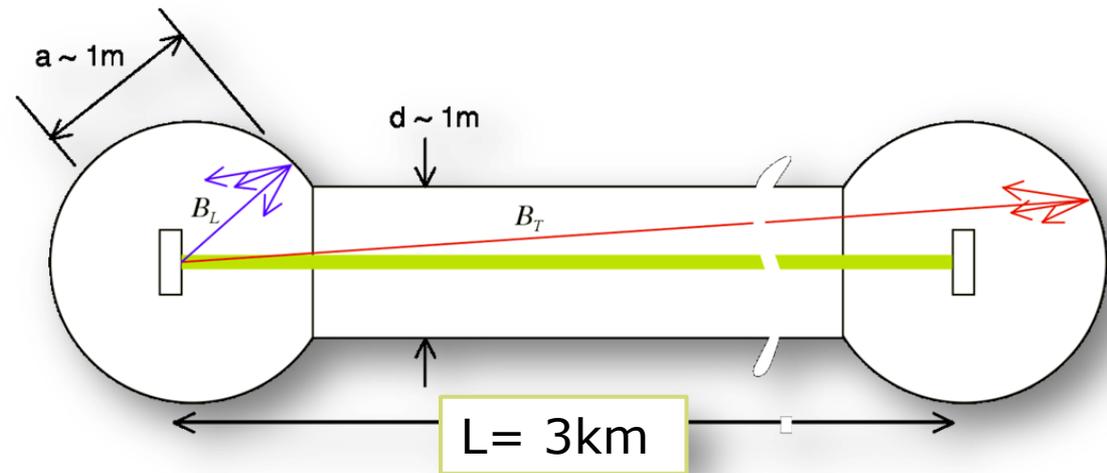
An Old Enemy

❑ … And even before:

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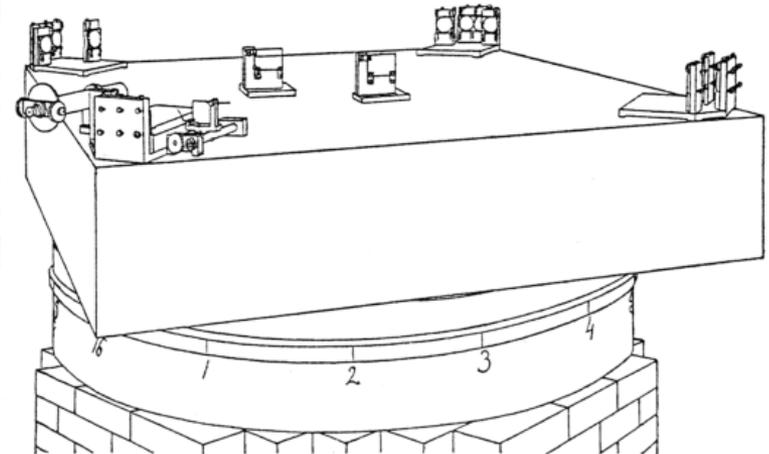
An Old Enemy

❑ 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.

a ~ 1m

d ~ 1m

B_L

B_T

L= 3km

An Old Enemy

❑ 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.

➢ **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 at design configuration)**

B_L v B_T

L= 3km
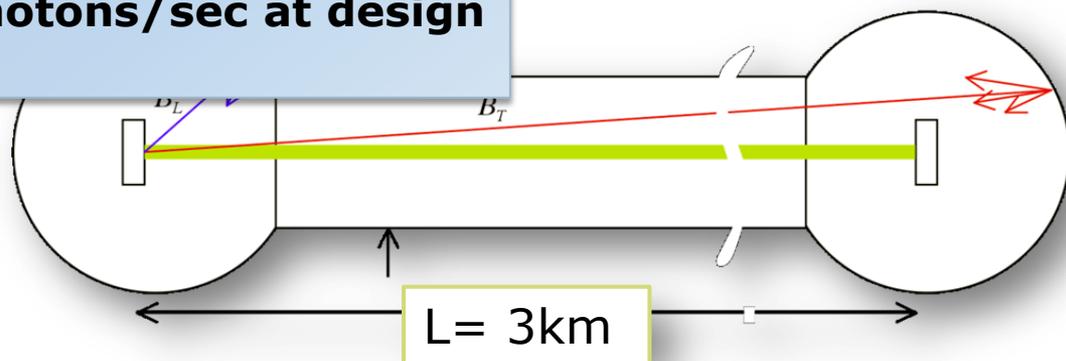
A case study from the past

An annoying noise spoiling Virgo+ sensitivity during VSR4 (2011)
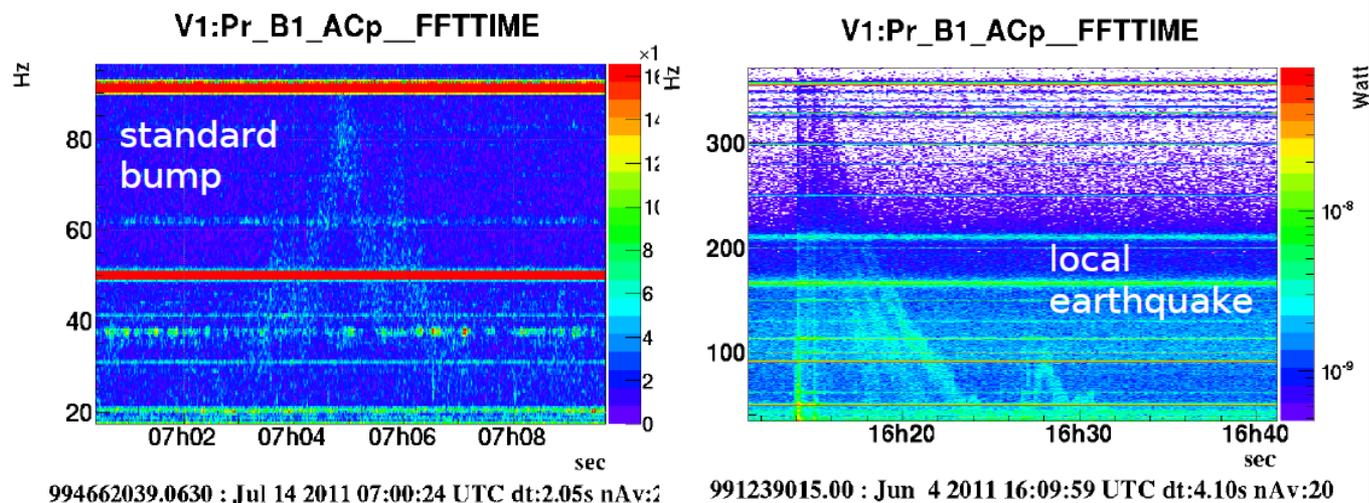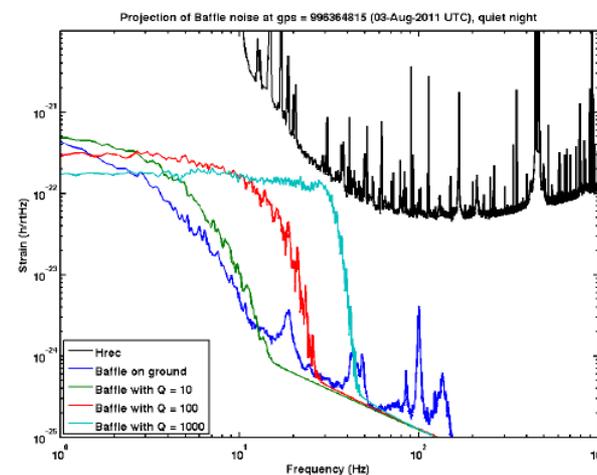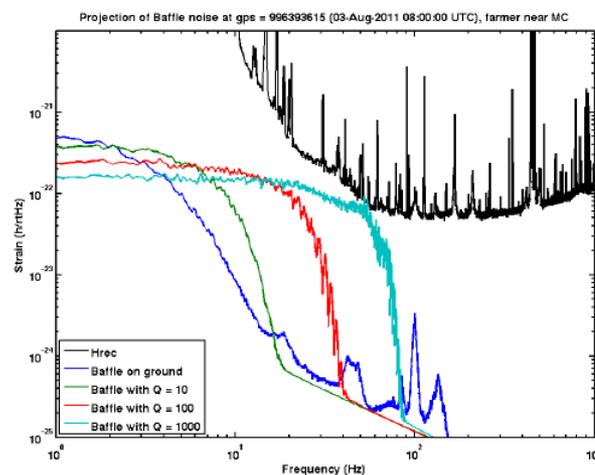
A case study from the past

Finally tracked down to the light scattered off a suspended baffle...
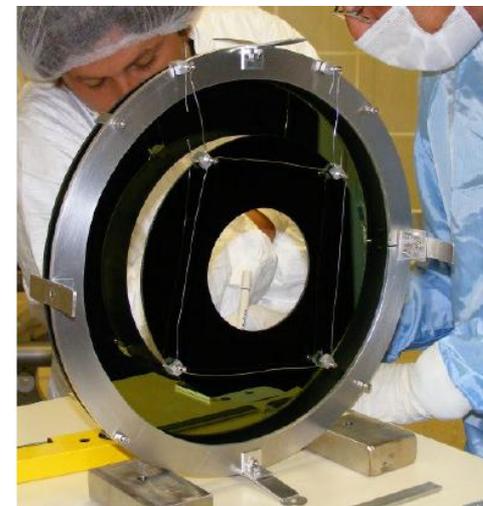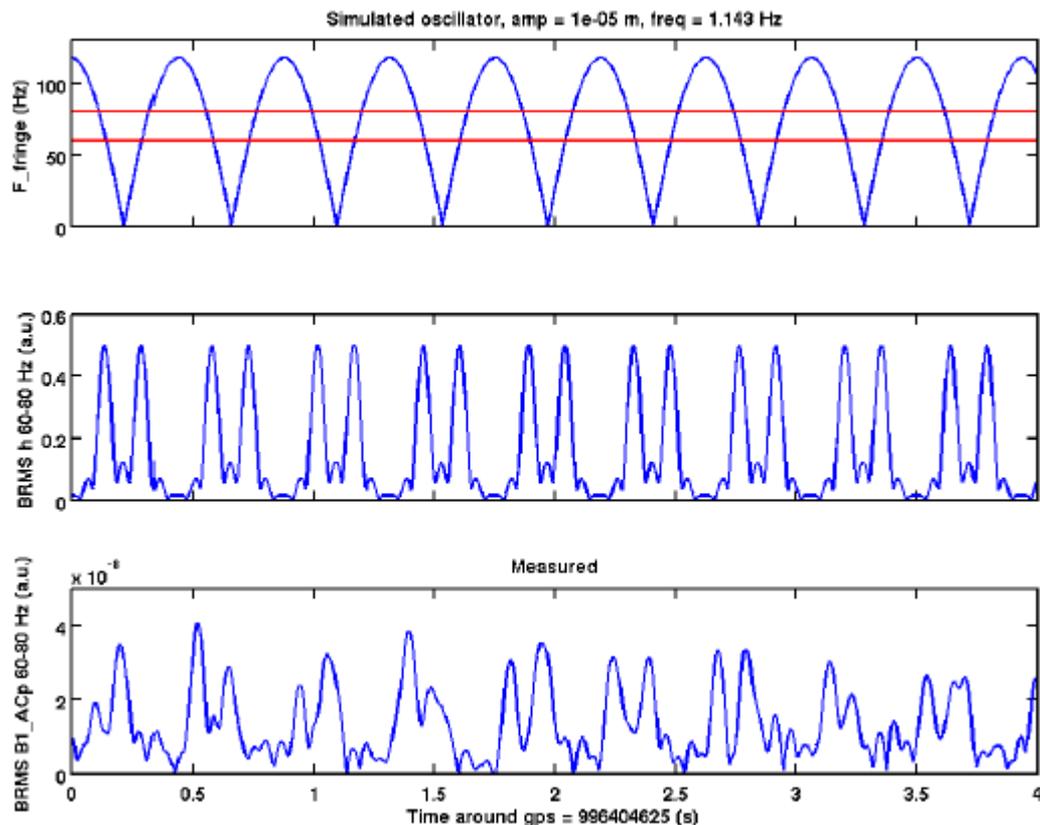
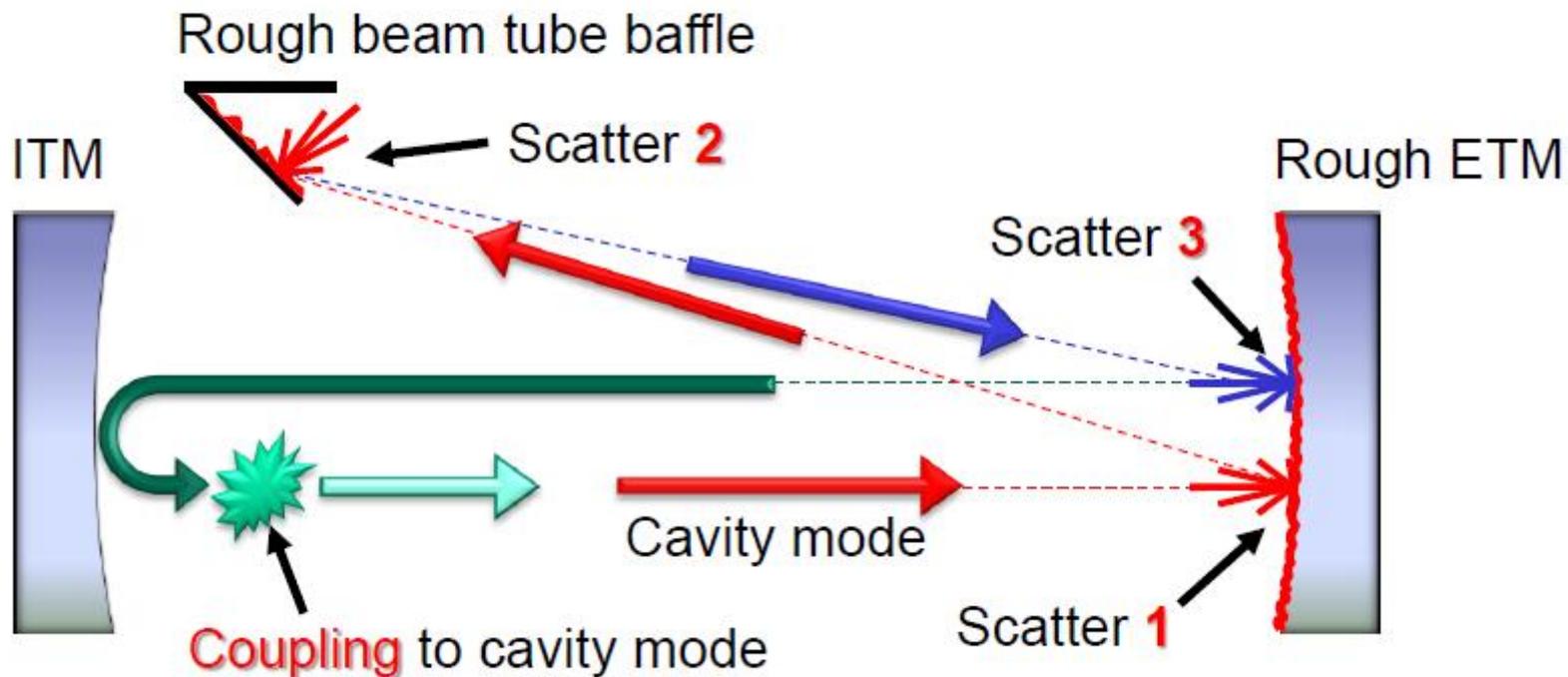Swinkels et al, VIR-0560A-11

A case study from the past

Noise projection

- Measured data of seismometers, simulated pendulum
- Limiting up to 100 Hz in case of seismic bursts
- Close to limiting around 30 Hz in quiet condition
- Simulated effect of reducing Q or fixing baffle to ground

Swinkels et al, VIR-0560A-11

Stray Light noise: how does it work?

Rough beam tube baffle

Scatter 2

ITM

Rough ETM

Scatter 3

Cavity mode
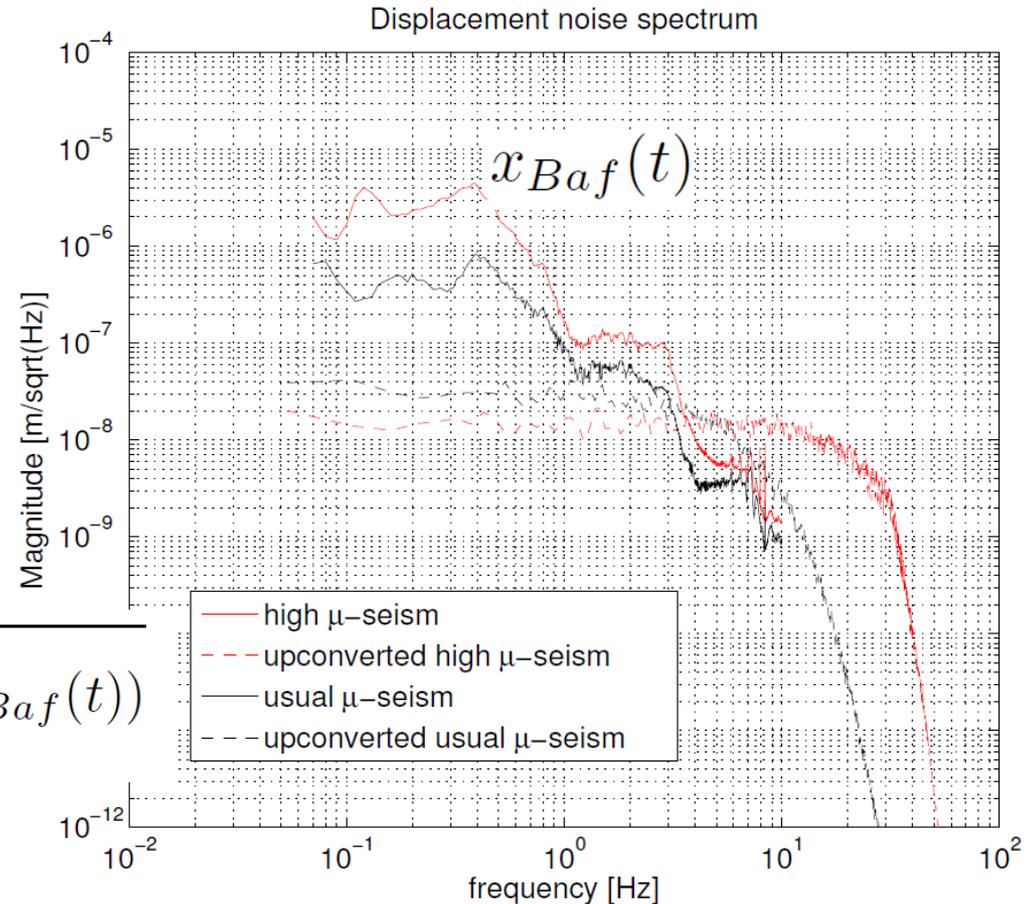
Coupling to cavity mode

Scatter 1

If the scatterer moves wrt the ITF, then the backscattered light is phase 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:

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

Displacement noise spectrum

$x_{Baf}(t)$

Magnitude [m/sqrt(Hz)]

frequency [Hz]

— high μ−seism
-- upconverted high μ−seism
— usual μ−seism
-- upconverted usual μ−seism

Stray Light simulations

❑ 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
$|c|^2$	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

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

Stray Light simulations

❑ 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 proj

Roughness, reflectivity, shape, position

| Parameter	Meaning	Estimation method
$|c|^2$	rec...	...FOG -SIS) ...i-analytical
Xbaf	(ef... noi...	...urement /simulations
Tbaf	Transfer function from Xbaf to dark fringe PD (B1)	Optickle /Finesse /MIST
Tdarm	Tra... from DARM dof to dark fringe PD	Optickle /Finesse /MIST

Mechanics, linear /non-linear (fringe wrapping)

location

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

Stray Light simulations

❑ 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 proje

> Roughness, reflectivity, shape, position

> Mechanics, linear /non-linear (fringe wrapping)

> location

Parameter	Meaning	Estimation method
$|c|^2$	rec	FOG -SIS) i-analytical
Xbaf	(ef noi	urement /simulations
Tbaf	Transfer function from Xbaf to dark fringe PD (B1)	Optickle /Finesse /MIST
Tdarm	Tra from DARM dof to dark fringe PD	Optickle /Finesse /MIST

$$hbaf = |c|\ Tbaf/Tdarm\ 1/L\ Xbaf < h/10$$

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)
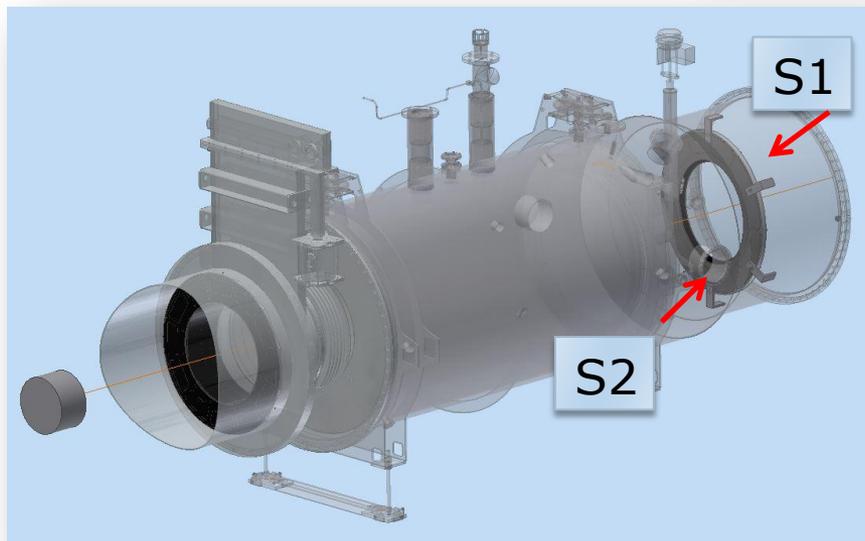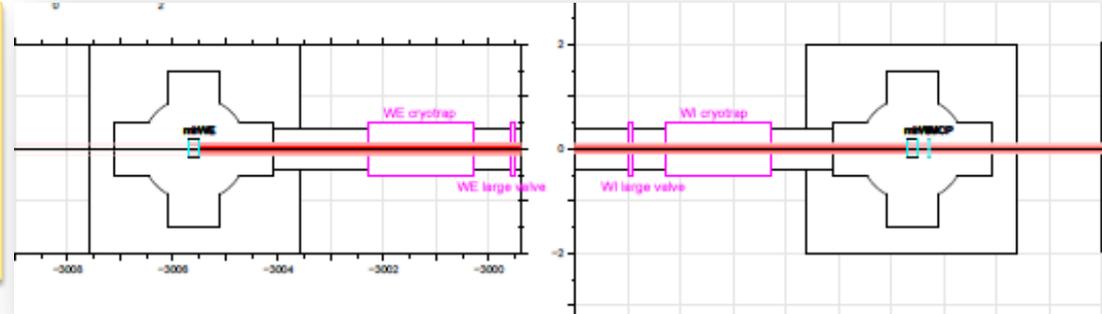
Stray Light simulations

❑ 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*)
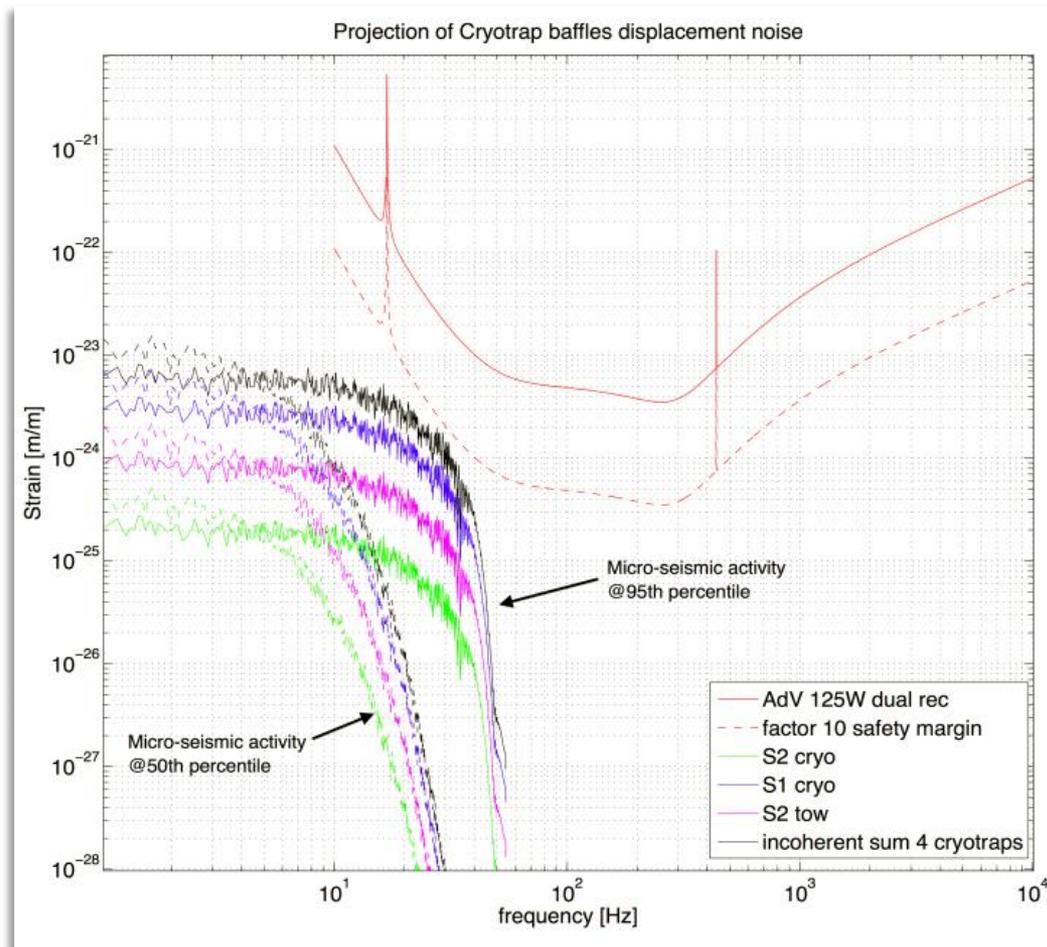
Projection of Cryotrap baffles displacement noise

Stray Light noise measurement

❑ 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
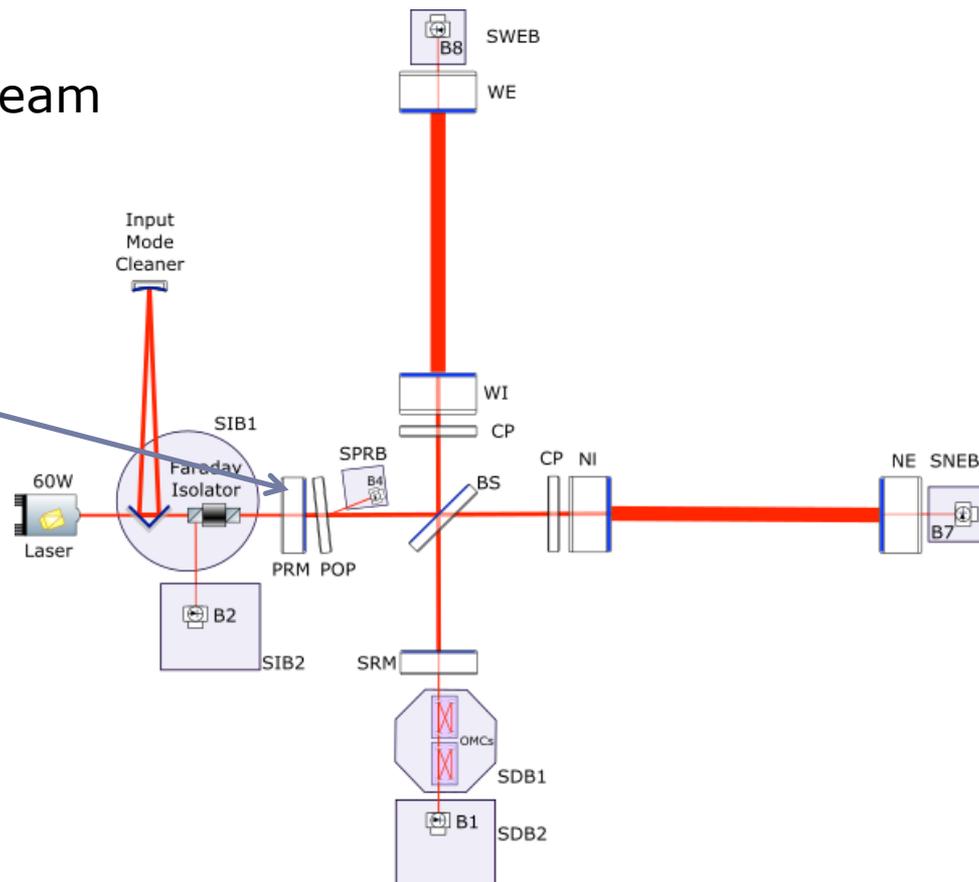
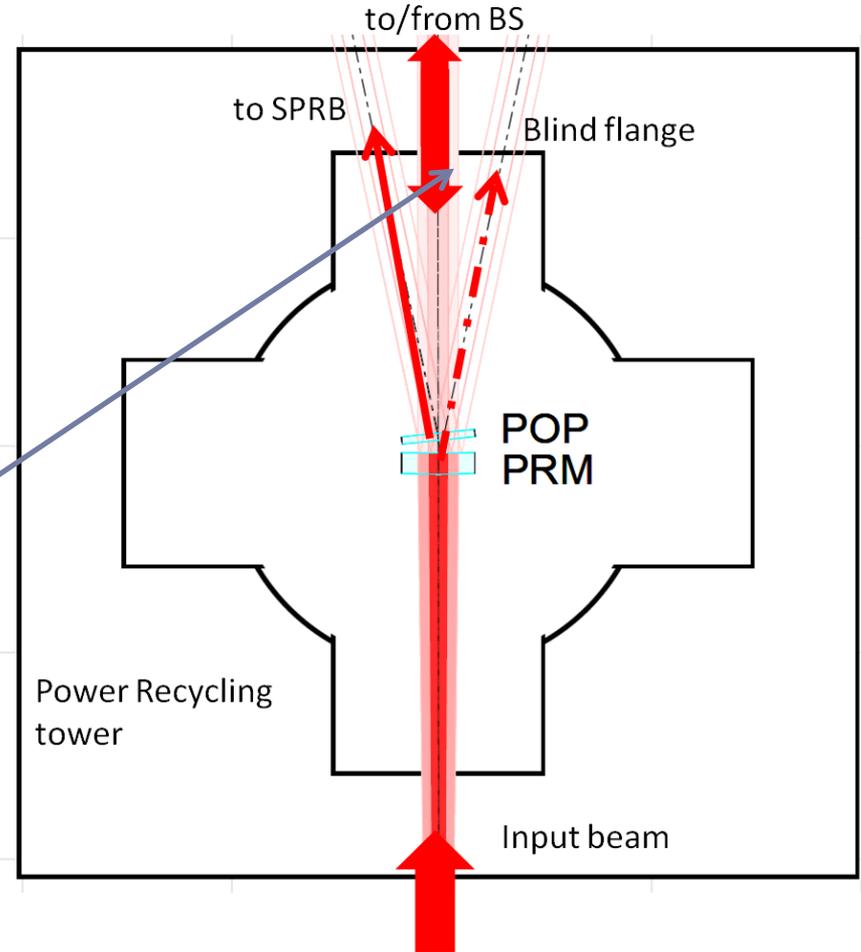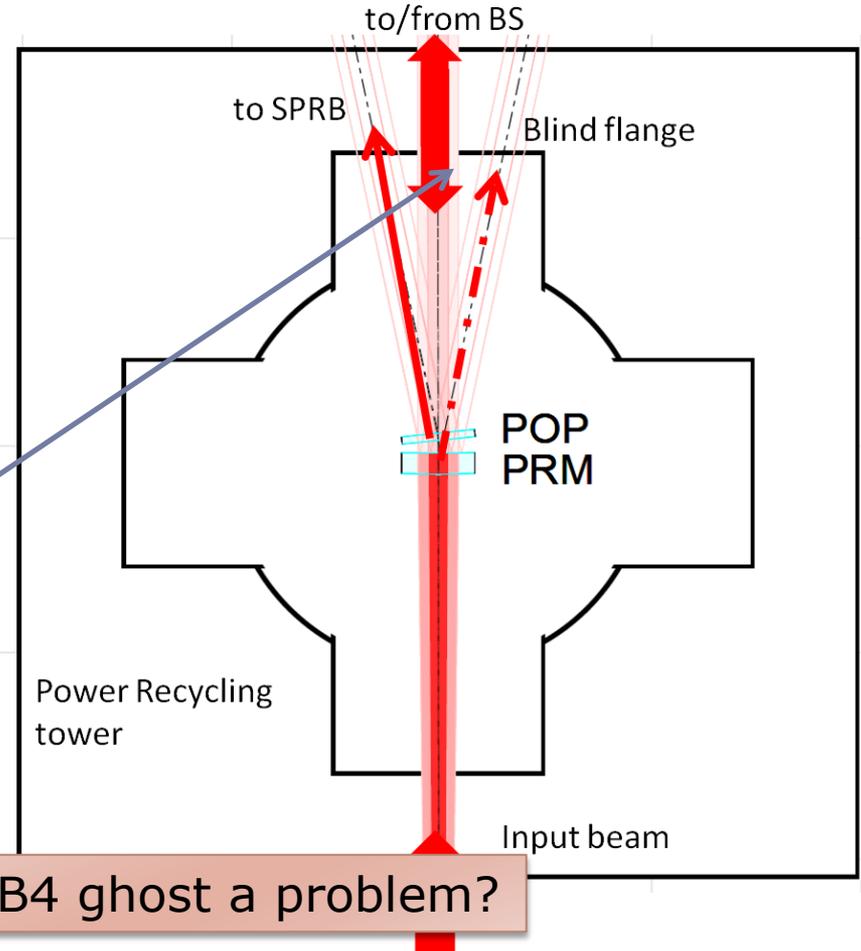# Stray Light noise measurement

☐ 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

▪ 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

Stray Light noise measurement

❏ 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

▪ 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

to/from BS

to SPRB

Blind flange

POP
PRM

Power Recycling tower

Input beam
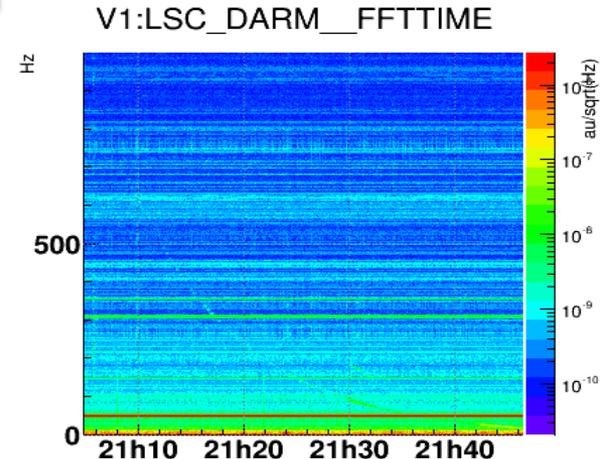
Was B4 ghost a problem?

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
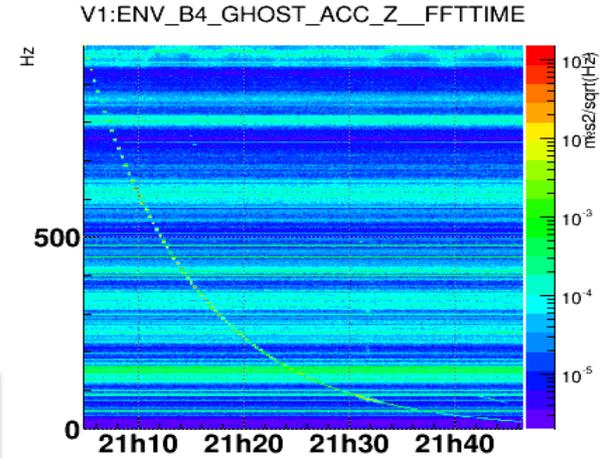
V1:ENV_B4_GHOST_ACC_Z__FFTTIME

1182200709.00 : Jun 22 2017 21:04:51 UTC dt:1.00s nAv:6

V1:LSC_DARM__FFTTIME

1182200709.00 : Jun 22 2017 21:04:51 UTC dt:1.00s nAv:6

Stray Light noise measurement

❑ 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.
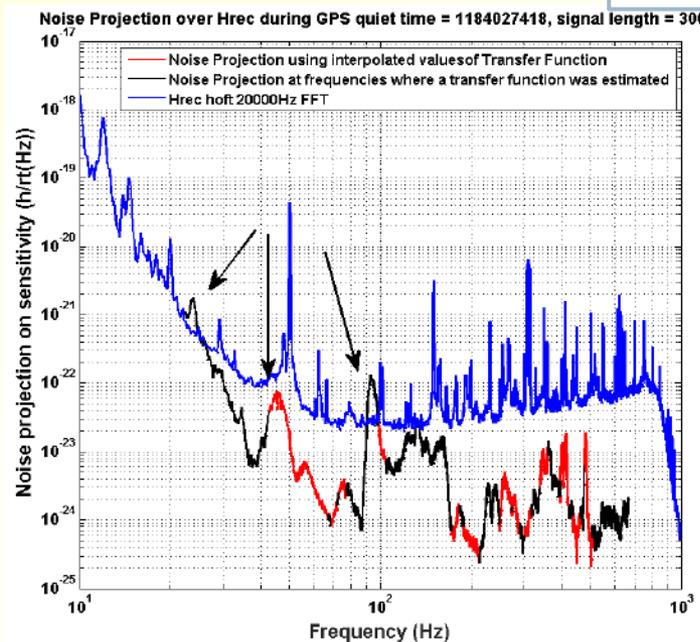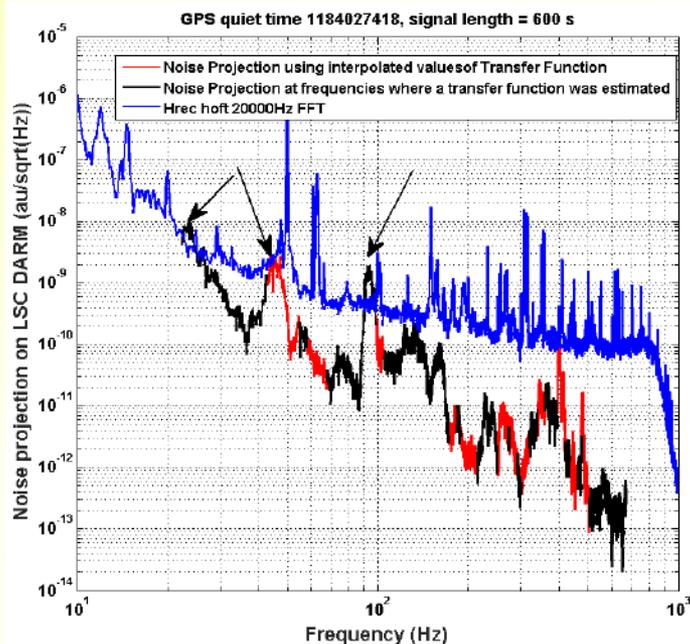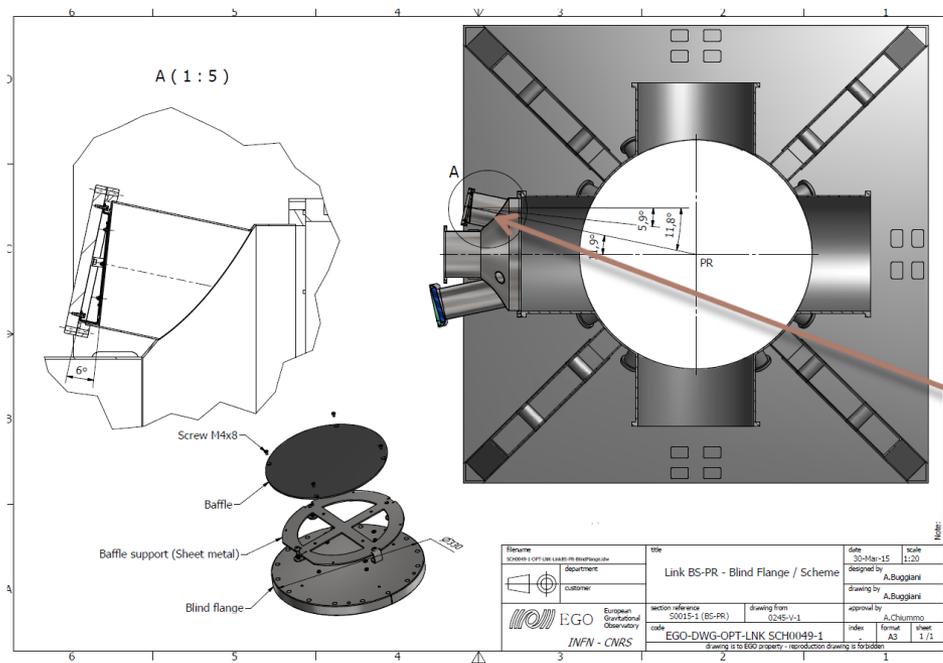
From VIR-0730A-17

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.

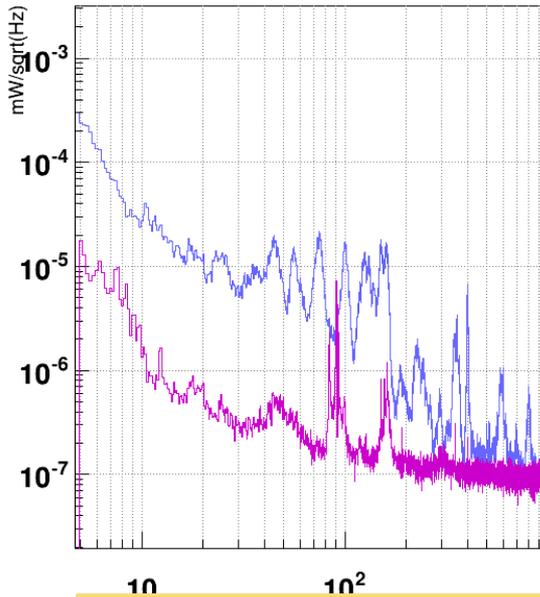# Stray Light noise measurement

❑ Case study: the B4 ghost beam
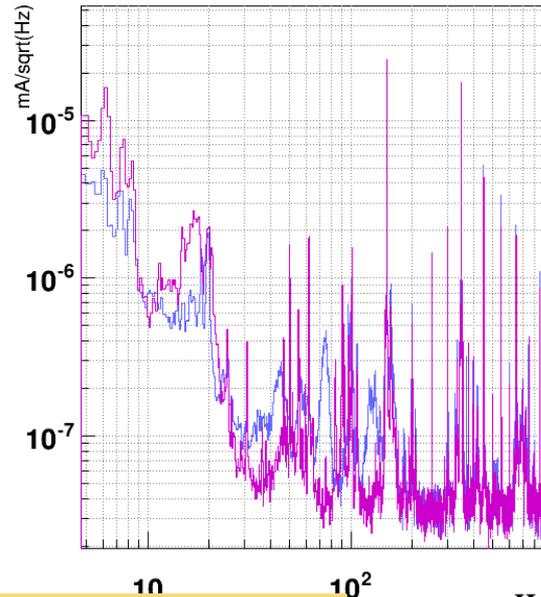

Adding an absorbing baffle solved the issue

Stray Light noise measurement

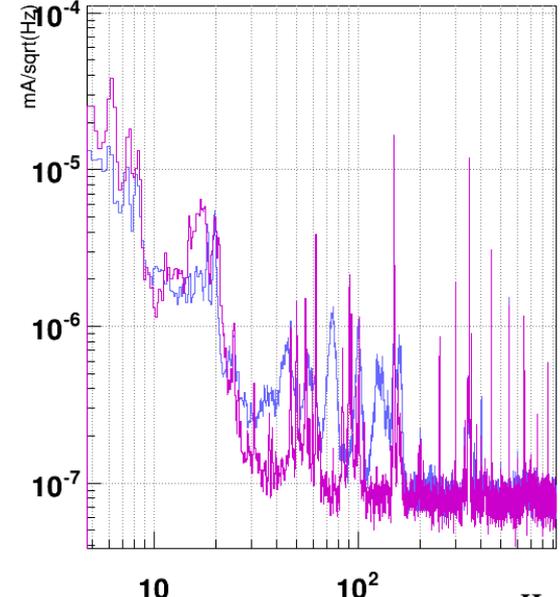dataDisplay v10r8 : started by chiummo on Oct 24 2017 13:23:00 UTC

V1:LSC_B4_DC__FFT   V1:LSC_B4_56MHz_I__FFT   V1:LSC_B4_56MHz_Q__FFT

1192850375.0000 : Oct 24 2017 03:19:17 UTC
1190654522.50 : Sep 28 2017 17:21:44 UTC dt:5.00s nAv:20

The problem was not only the contamination of GW signal, but also spoiling the control signals of ancillary dofs

Adding an absorbing baffle solved the issue

Materials

❑ Some materials were short-listed for validation:

▪ Choice based on past generation experience

▪ Main features tested:
  ➢ Absorption
  ➢ in-vacuum LIDT
  ➢ TIS
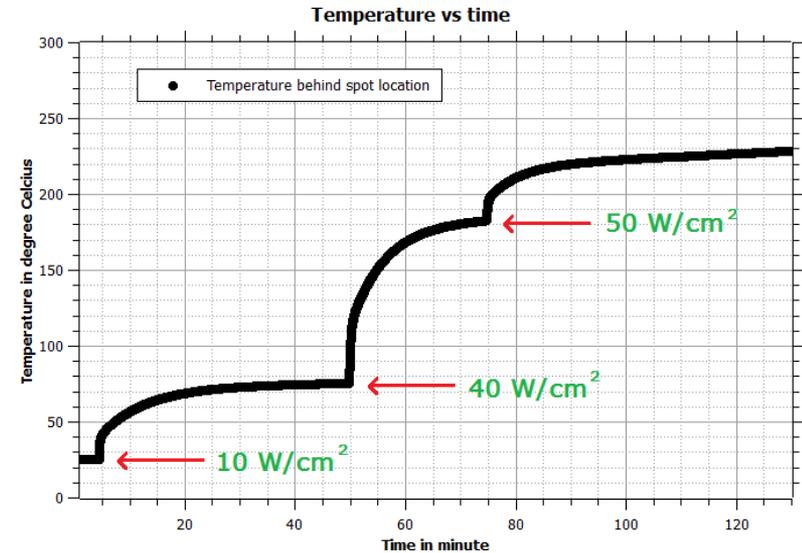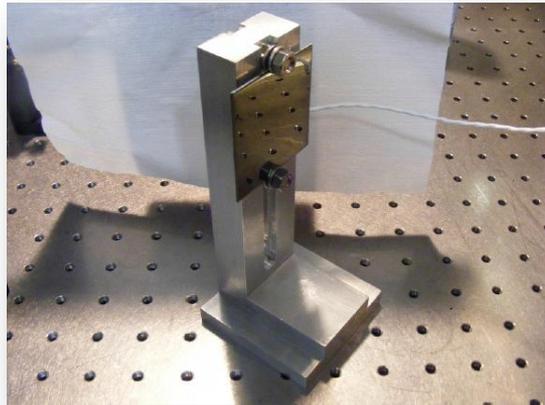 ➢ UHV compatibility
  ➢ …

▪ **Cost** was also a key parameter!

EGO European Gravitational Observatory VIRGO

AdV SLC: Characterization of AR coatings on stainless-steel for construction of baffles and beam dumps in AdV

VIR-0482A-14

V.Bavigadda*[1], G.Pillant[1], A.Magazzu[1], and A.Chiummo[1]

[1]EGO - European Gravitational Observatory

Date: December 10, 2014

EGO European Gravitational Observatory VIR

AdV SLC:
Characterization of Diamond-Like Ca... baffles and beam dumps in AdV

VIR-0127A-13

Antonino Chiummo*, Benjamin Canuel, Andrea Magazzu, and Julien Marque

EGO - European Gravitational Observatory

Date: April 11, 2013

VIRGO

AdV SLC:
Characterization of Silicon Carbide for constructing baffles and beam dumps in AdV

VIR-0460A-12

Antonino Chiummo*, Benjamin Canuel, Andrea Magazzu, and Julien Marque

EGO - European Gravitational Observatory

Date: November 22, 2012

Materials

❑ Some materials were short-listed for validation:

AR-on-steel characterization

Temperature vs time

● Temperature behind spot location

50 W/cm^2

40 W/cm^2

10 W/cm^2

Temperature in degree Celcius

Time in minute

Material	LIDT	TIS
SiC + AR	30kW/cm2	~20-50ppm
DLC + AR	500W/cm2	~500-1000ppm
AR-on-steel	>50W/cm2	~300-500ppm
Absorbing glass	~1W/cm2	~100ppm
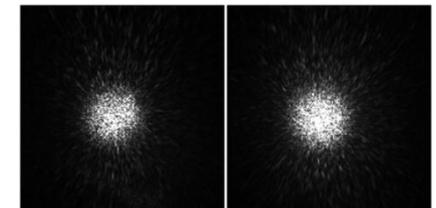
2 min   59 min

Materials

❑ Some materials were short-listed for validation:

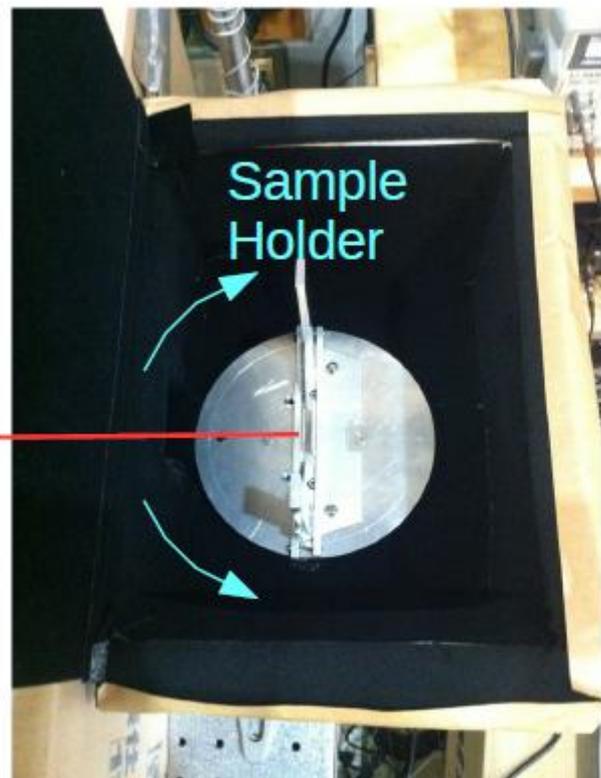| Material	LIDT	TIS
SiC + AR	30kW/cm2	~20-50ppm
DLC + AR	500W/cm2	~500-1000ppm
AR-on-steel	>50W/cm2	~300-500ppm
Abs. Glass + AR	~1W/cm2	~100ppm

Cost increase

Selection of material driven by:

▪ location-dependent requirements
▪ validation of solution
▪ trade-off with budget needs

☐ Some materials were short-listed for validation:

Measured materials:

· **Ti plate** (unpolished)
· **Si plate** (polished)
· **DLC**
· **SiC**
· "**Sol-Black**" (on polished Al)
· "**Specral Black**" ("Acktar")
· "**Metal Velvet**" ("Acktar")
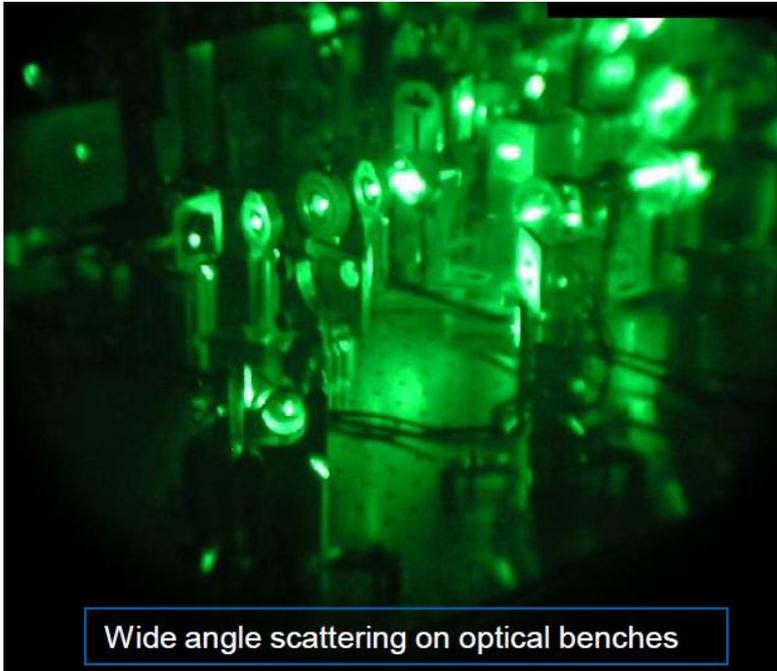· "**Vanta Black**" ("Surrey NanoSystems")

Sample Holder

Cost increase

KAGRA colleagues investigated many other materials, some of them were tried up to some extent in Virgo with ambigous results

From JGW-G1503403-v5

Stray light noise from benches

Wide angle scattering on optical benches

A different class of problem: Differently from the scattering off the core mirrors, where a 3-scattering process is needed to recombine with the main beam, here a single-scattering process (backscattering off tilted components) could also play a role.

Very difficult to simulate, and therefore to control by design

Both analytical and monte-carlo approaches employed to simulate the benches, but a full *coherent* simulation of the scattered field is still missing

Conclusion

▸ **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**

▸ **New materials with lower BRDF are to be explored for 3rd gen, and possibly chose a site that is...**

Future prospects: what is needed

... A quiet place

Horizontal spectral motion at various sites
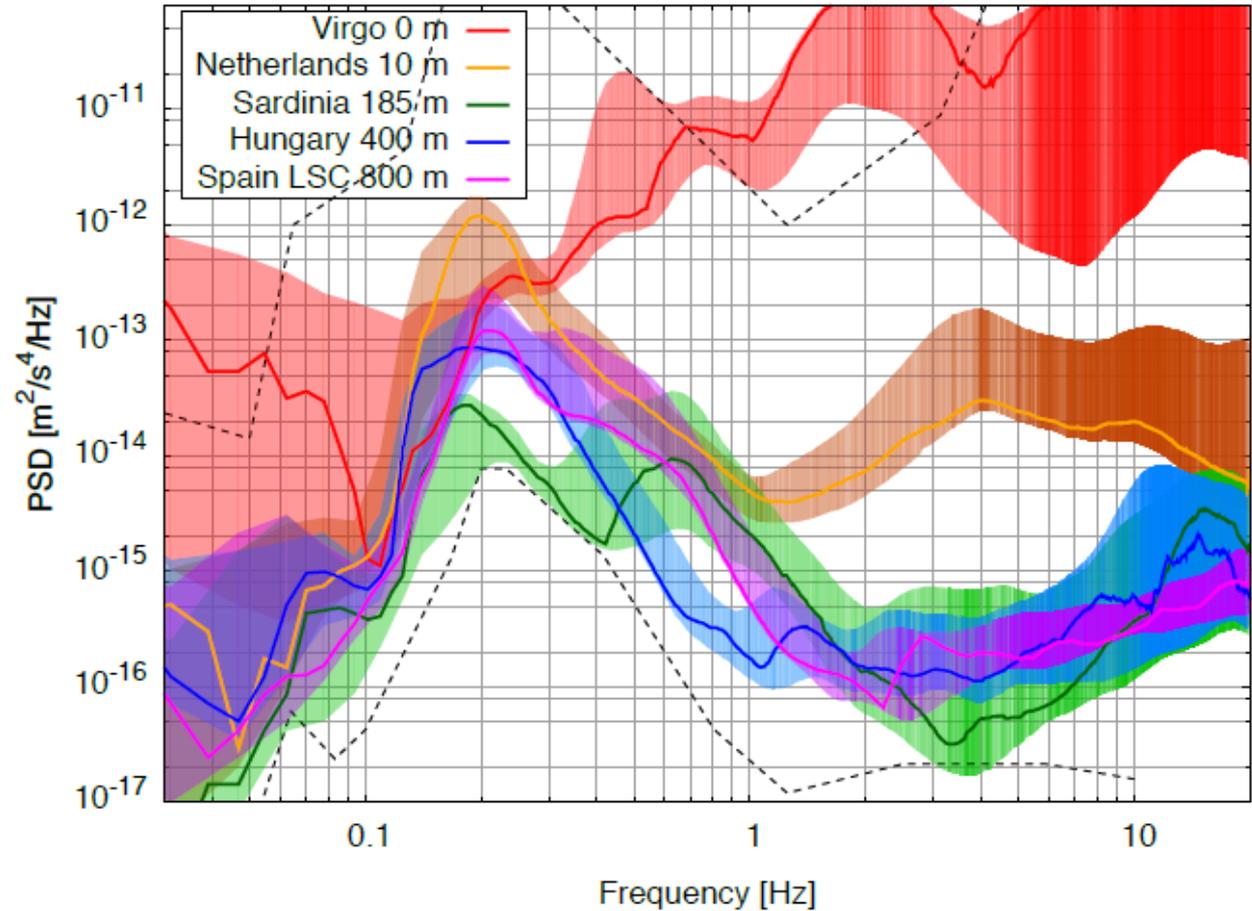
Orosei, 3/5/19
Grazie!
Antonino

EGO - VIRGO