# Scattered Light Mitigation

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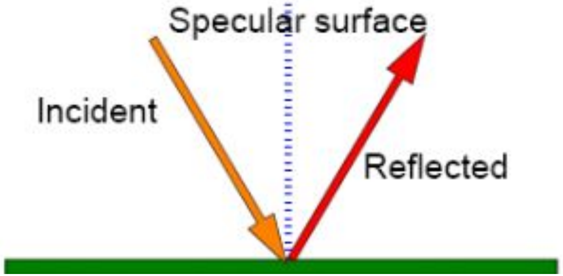
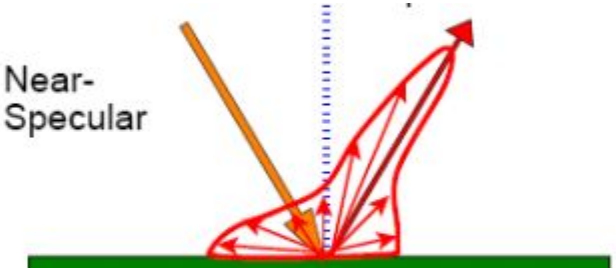
# Scattered light




Any light that does not follow the intended path.

If it is allowed to re-enter the detector, it becomes a problem in the form of additional noise which can then

- mimic a fake gravitational wave signal or
- spoil the control signals needed to keep the working point of the detector

Stray light is believed to contribute a significant fraction of the excess instrumental noise observed of current detectors.

It is expected to be even more critical for ET, as other noise sources are suppressed and the overall sensitivity improved.

By nature it is an opto-mechanical issue because it involves the interaction of light with optical and mechanical parts:

the reflection from a moving surface introduces a time-varying phase, which produces noise in the interferometer output.

time-varying stray light amplitude also produces noise

# Origin of scattered light

Scattering origins:

- interaction with the propagation medium (residual gas, suspended dust particles, optics substrates imperfections)
- at optical interfaces: interface imperfections (eg surface roughness or defects), or by deposited dust particles which accumulate on surfaces.
- residual reflectivity (respectively trasmissivity) of anti-reflection (respectively high-reflectivity) coatings produces so-called “ghost beams” that if not stopped can hit surfaces in uncontrolled way and become further sources of scattering.

According to the ET WBS stray light mitigation is asked for by many (all?) subsystems of ET Optics Division.

# Mitigation of stray light

To implement effective strategies for stray light mitigation we need to understand :

where stray light is generated and

its impact on the interferometer sensitivity.

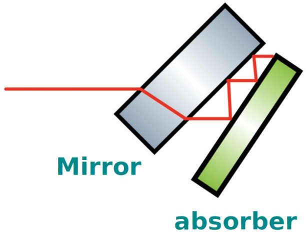
A complex issue that requires a variety of activities, including:

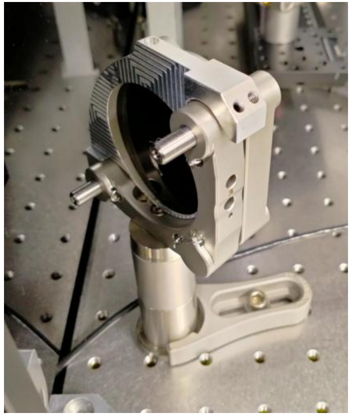
- modeling and experimental characterization of scattering sources (optical surfaces and bulks, dust, etc.)
- simulation of scattered light distribution and re-coupling into the main beam
- analytical and numerical modelling of the effect of stray light on the interferometer output
- design and installation of scattered light (passive) mitigation systems

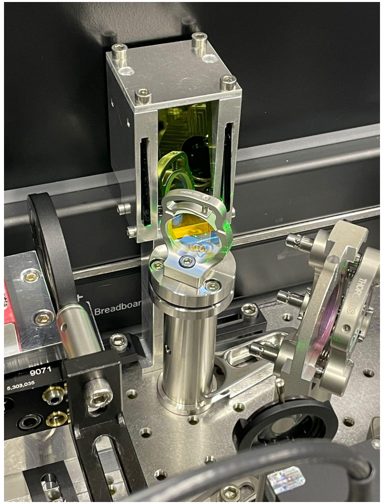
# Experience of the Virgo Italian group in Stray Light

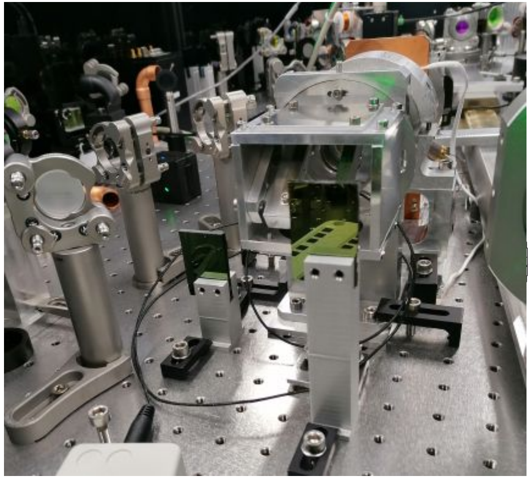
The Italian Virgo groups (Genova & Padova) involved in stray light noise study and reduction in the context of the Advanced Virgo project focus mainly on the QNR system (FIS and FDS):

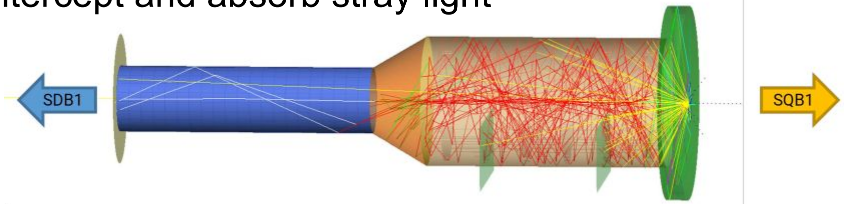
- **estimating and simulating SL distribution and recombination** in the main beam path
- **designing and installing baffles and dumpers** to intercept and absorb stray light



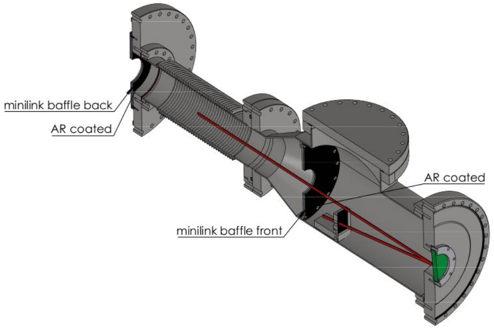










Stray light simulation with commercial software (FRED)



# Experience of the Virgo Italian group in Stray Light

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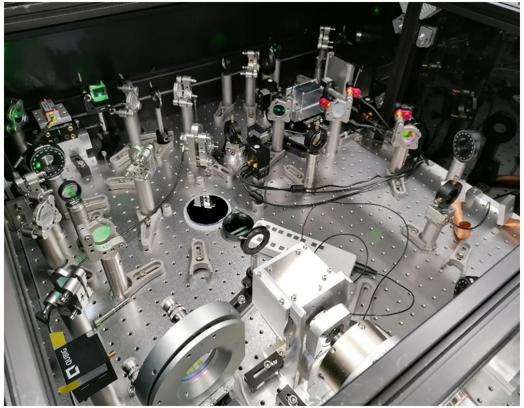
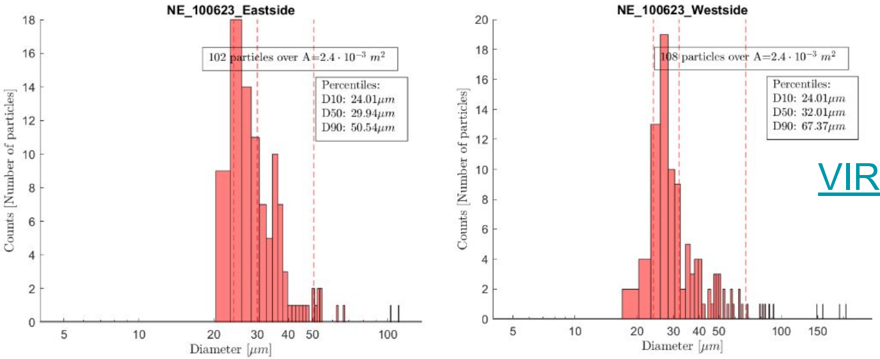
- estimating and simulating SL distribution and recombination in the main beam path
- designing and installing baffles and dumpers to intercept and absorb stray light
- **measuring the scattering properties** of optical components
- assessing the **impact of dust contamination**

For dust contamination: setting up a **monitoring system** across the whole Virgo environments






VIR-0574A-23

*Figure 2: particles count histograms of the two NE_100623 wafers. Those wafers were exposed during the installation of the PAY. As stated in the result discussion, the apparatus is sensible to particles larger than 8μm in diameter and counts of particles with diameter D<25μm are underestimated.*

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For dust contamination: setting up a monitoring system across the whole Virgo environments

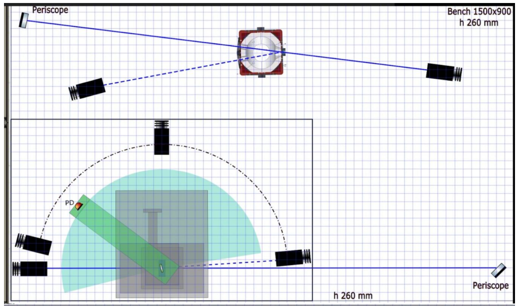
1. to assess the cleanliness levels
2. to predict when an optics might need cleaning to avoid excess catering from dust:

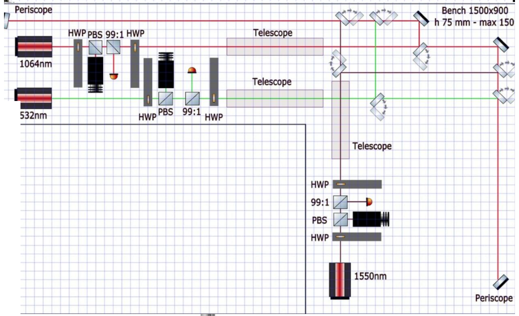
clearly applicable to ET as well

**With this experience the same group is also participating into ET-SCL also by co-chairing the WG**

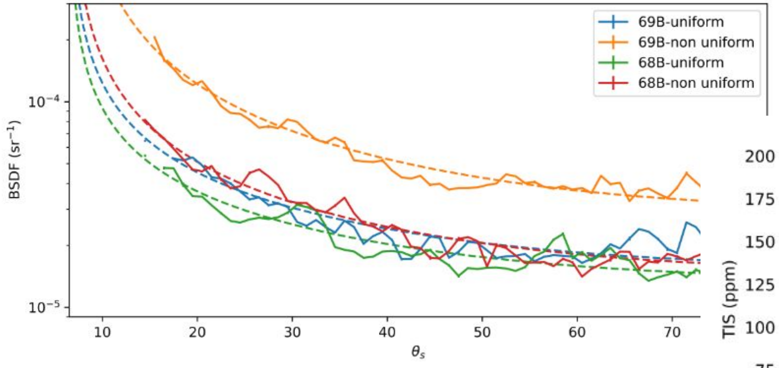
# Experimental study on materials and coatings for ET

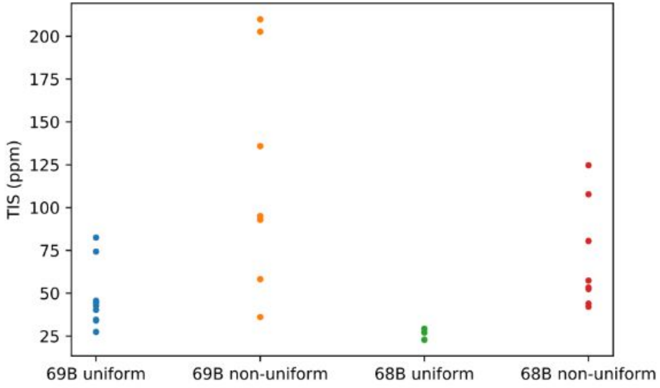
Experimental facility dedicated to ET (and Virgo) to measure scattering properties:
**TIS and BRDF, BTDF @ 532nm 1064nm, 1550nm** (possibly 2000nm)

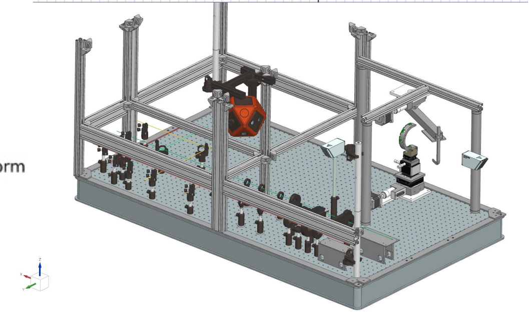



Recently measured BRDF/TIS of samples of baffles to be used in AdV-II



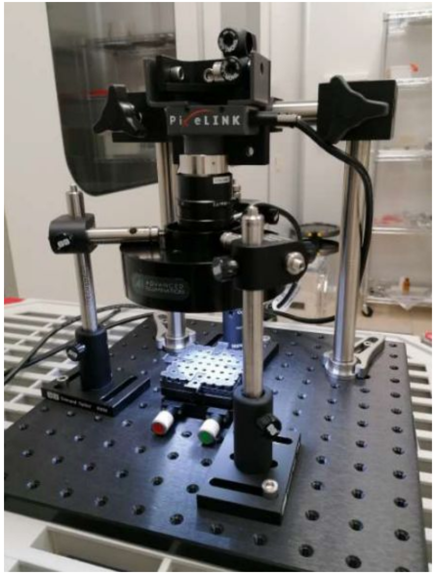



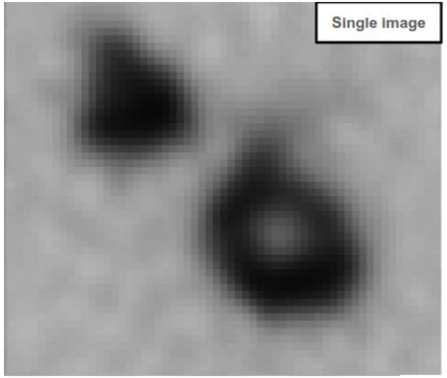
Soon measurements of samples of steels for ET beam pipe

# Measuring dust contamination and sizing originated scattering

Upgrading the wafer imaging setup to resolve smaller particles:

from a camera based system (resolution approx 10um) to a digital microscope (resolution approx 0.3um)




D=0.8um (20px)

Operative from mid summer 2023

Optimized the code for image processing and particle detection and sizing

Also TIS, BSDF measurement of contaminated sample to test model and improve reliability of predictions

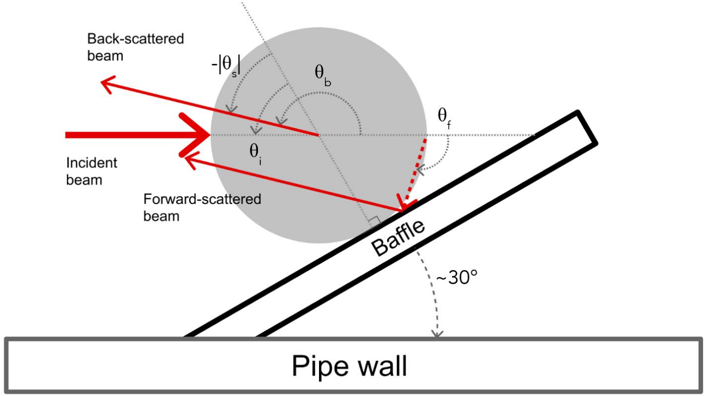
# Predicting and limiting dust contamination in ET beam pipes

*Work reported within the 'Einstein Telescope beampipe requirements'*

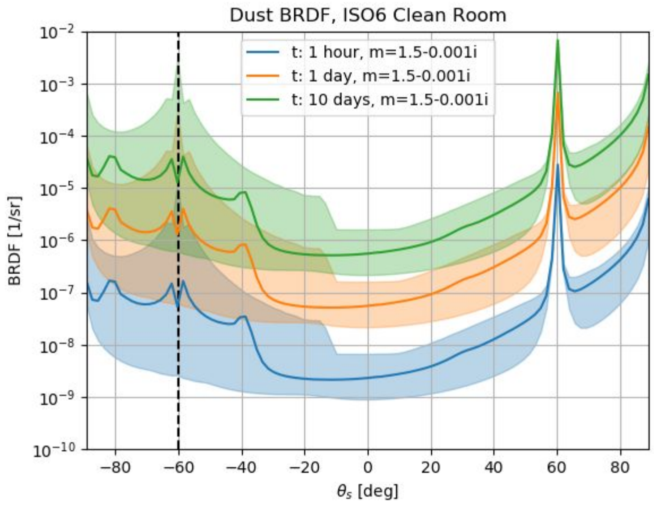
Goals: to put constraints on the maximum allowed population of particles in the vacuum pipes and
to give guidelines for pipe and baffle construction/installation wrt cleanliness

- Particles that have deposited on a pipe surface, typically a pipe baffle:
  - source of scattered light when hit by light coming from the main beam
  - can enter both during installations and when in vacuum, originated by vacuum system
  - effect of worsening the scattering performance of baffles:

$$\mathrm{BRDF} = \mathrm{BRDF}_{baffle} + \mathrm{BRDF}_{dust}$$




From the ISO class of the environment and the particle deposition velocity, using the Mie theory we estimate the BRDF contributed by deposited dust:



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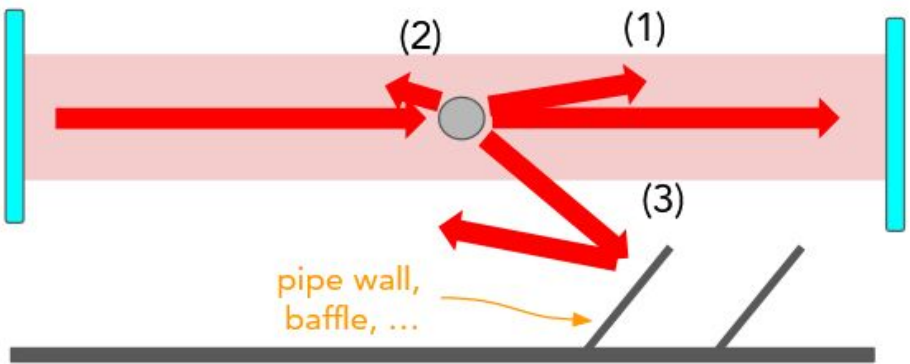
- Particles crossing the beam, eg if falling from the pipe internal surface




Presently working at a Montecarlo simulation to estimate the strain noise due to stray light produced by particles (of different sizes and detaching from random positions) crossing the beam of the arm cavities

# Next future research

## Cleaning and clean work procedures

Using the above facilities we plan an experimental campaign aiming at:

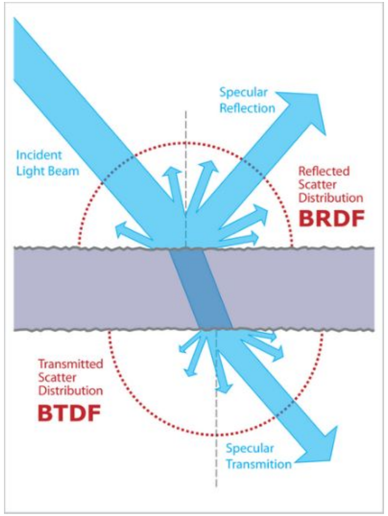
- Assessing the effectiveness of clean work procedures
- Understanding actions that impact mostly on cleanliness levels
- Defining an efficient procedure for cleaning optics

## Experimental measurements of scattering properties of materials and coatings of interest for ET

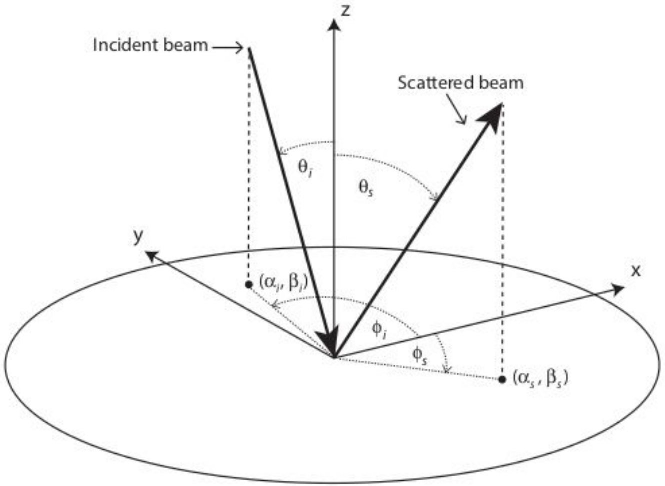
## Cleanliness requirements for ET towers, (analogous to the work for the ET pipes)

## Development of live, vacuum compliant dust particle counting and sizing device

# BSDF : the most complete metric of scatter




**Bi-directional Scattering Distribution Function (BSDF)**, the ratio of the scattered radiance (ph/s-unit area -sr) to the incident irradiance (ph/s-unit area).
A sort of 'reflectance per solid angle'.




$$BSDF = \frac{d\Phi_s / d\Omega_s}{(d\Phi_i)\cos\theta_s}$$

$$BSDF(\theta_i, \phi_i, \theta_s, \phi_s) = BSDF(\theta_s, \phi_s, \theta_i, \phi_i)$$

Energy conservation: BSDF must be the same if the incident and scattered rays are reversed ('*Bidirectional*')

# TIS : a common metric of scattering

## Total Integrated Scattering (TIS)

the ratio of the total scattered power (over all angles) to the incident power.

$$TIS(\theta_i, \phi_i) = \int_0^{2\pi} d\phi_s \int_0^{\pi/2} d\theta_s \, \sin(\theta_s) \, \cos(\theta_s) \, BRDF(\theta_i, \phi_i, \theta_s, \phi_s) \leq 1$$

Easier to measure wrt the BSDF

For smooth surfaces it can be connected to the rms surface roughness (σ):

$$TIS = 1 - e^{-\left(\frac{2\pi \, \Delta n \, \sigma}{\lambda} \cos\theta_i\right)^2} \sim \left(\frac{2\pi \, \Delta n \, \sigma}{\lambda} \cos\theta_i\right)^2$$