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Stray light noise from particulate contamination in ground-based GW interferometers

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Outline

1. Stray light as noise source in GW detectors and its coupling with mechanical noise
2. Stray light originated by dust
3. Dust deposited on ET arm baffles: cleanliness requirements for the baffles
4. Dust crossing the cavity beam: cleanliness requirements for the inner surface of the arm cavity vacuum pipe
5. Conclusions

Mechanical noise in GW detectors

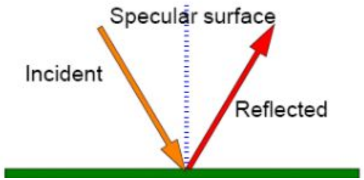
Pushing sensitivity at low frequencies requires beating a variety of noises, including thermal noise, radiation pressure noise, technical noises, seismic and Newtonian noise

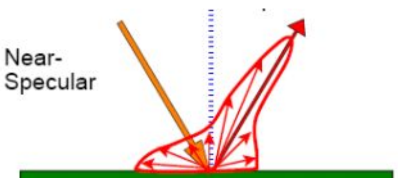
Seismic/mechanical motion can enter from multiple doors:

- Direct coupling to Test Mass motion
- Seismic motion causing changes in the density of the soil → Newtonian noise
- Stray light noise
- …

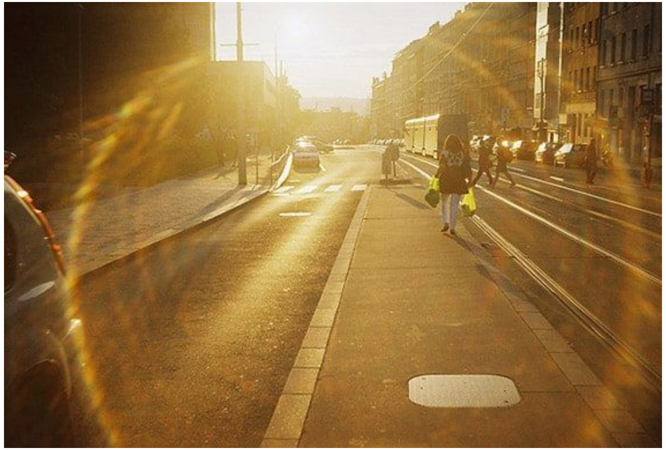
Stray light noise in GW detectors

Stray light is light that leaves the intended path





Stray light is
a common problem in optical systems



SL becomes a noise in GW detectors if it is allowed to re-join the main beam after being reflected by a vibrating part

Stray light couples mechanical noise to GW strain

Consider this process:

- Main beam impinges on a Test Mass (TM)
- Some light is scattered towards the tube
- Some of this light is scattered back towards the TM
- Some of this light is scattered by the TM back into the main beam

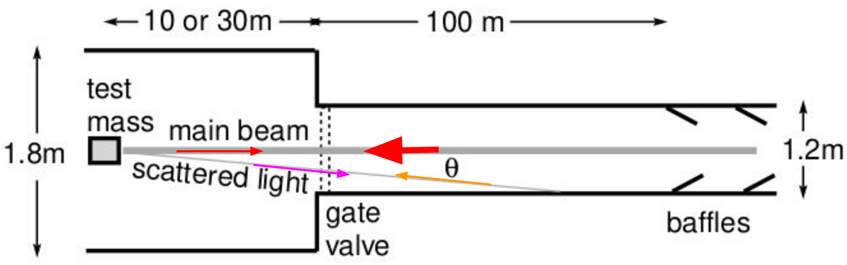


FIG. 1. Present configuration of LIGO beam tube.

Spurious field recoupled with main beam will modulate its phase and amplitude with information linked to the backscatterer motion

Strain noise:

$$S_{hh}(f) \propto \begin{pmatrix}\text{scattering by}\\ \text{Test Mass}\end{pmatrix}^2 \times \begin{pmatrix}\text{scattering by}\\ \text{backscatterer}\end{pmatrix} \times \left[a\, PSD\left(\cos\frac{4\pi x_{bs}(t)}{\lambda}\right) + b\, PSD\left(\sin\frac{4\pi x_{bs}(t)}{\lambda}\right)\right]$$

terms coupling with mechanical noise of backscatterer

Stray Light (SL) noise challenges

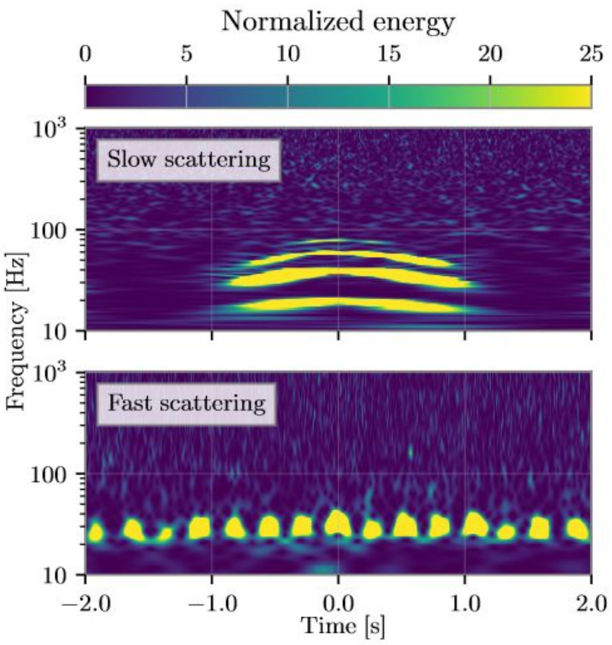
Strength of mechanical noise changes the coupling of (phase and amplitude) SL noise:

- for $x_{bs}(t) \ll \frac{\lambda}{4\pi} \sim 10^{-7}m$ →linear effect
- for $x_{bs}(t) \gtrsim \frac{\lambda}{4\pi}$ →non linear effect

noise up-conversion eg under high microseismic conditions

Challenges in Reducing Stray Light Noise

1. Very common: any optical interface can generate stray light [see next slide]
2. Hard to trace: back-reflections may originate far from both the source and the recombination point
3. Nonlinear effects complicate identification of critical paths and noise subtraction strategies



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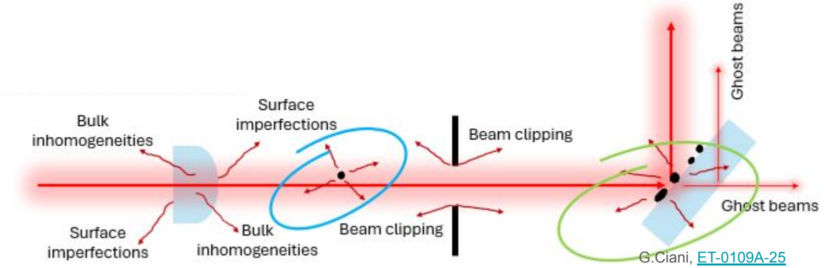
Origins of scattered light
→ and typical solutions



- **at optical interfaces**: interface imperfections (eg surface roughness or defects), or by deposited dust particles which accumulate on surfaces.
  → very smooth & **clean** optical surfaces

- **interaction with/in the propagation medium** (residual gas, suspended dust particles, optics substrates imperfections)
  → propagation in vacuum, materials with no bulk inclusions or bubbles

- **clipping of laser beams** eg when passing through apertures
  → avoid small apertures

- **residual reflectivity (trasmissivity)** of anti-reflection (high-reflectivity) coatings produces so-called "**ghost beams**"
  → AR/HR coatings with even lower residual reflectivity/transmittivity

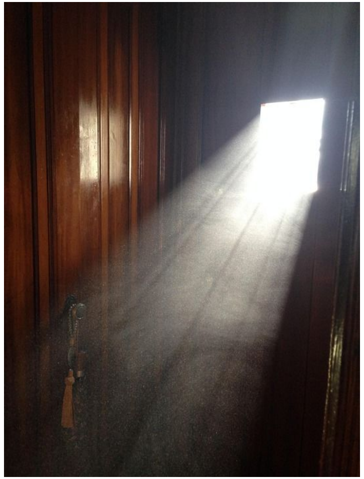
Cleanliness

Presence of particles in the GW experiments:

- at the site of the GW detector
- in the distributed labs where parts are fabricated/assembled

Multiple scenarios require different approaches:

- single particles, affecting the sensitivity individually (eg point absorbers)
- collection of particles, affecting the sensitivity as distribution
- particles deposited on a surface
- particles moving in a volume



Mie Theory for modelling light scattered by particles

Mie theory is exact solution to Maxwell equations, for spherical particles

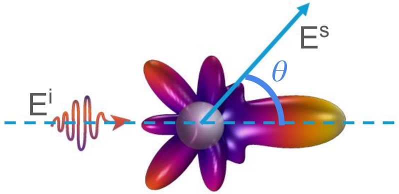
$$\begin{pmatrix} E_1^s \\ E_2^s \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} E_1^i \\ E_2^i \end{pmatrix}$$

E^i Incident field
E^s Scattered field
1,2 indicate polarization perp and parallel to scattering plane

Mie scattering matrix $$S_{jk} \equiv S_{jk}(x, m, \theta)$$

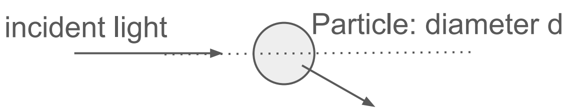
Matrix elements S_{jk} depend on:

- Size of the particle wrt light wavelength: $x = \pi D / \lambda$
- Material of the particle (index of refraction) : m
- Angle of scattered light wrt incident light : θ



For homogeneous particles, the matrix is diagonal: no polarization mixing

Scattering by a particle vs size



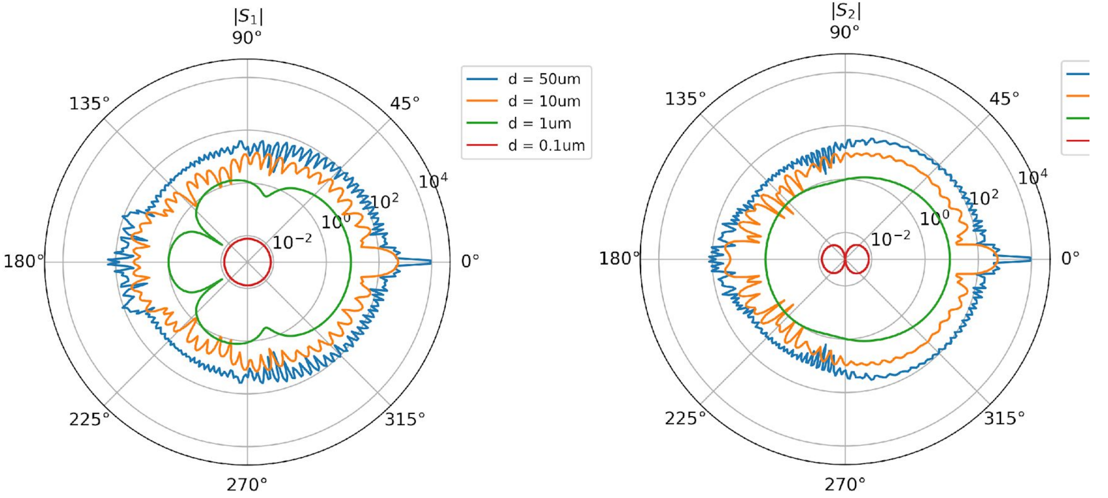
Scattering by small particles:

- Approximated by Rayleigh scattering
- Comparatively little scattering
- S_1 broadly isotropic
- S_2 two directions where it vanishes

Scattering by large particles:

- Approximated by Mie scattering
- Comparatively large scattering
- Peak in the forward direction
- Smaller peak in the backward direction
- Serie of local min/max due to interference effects of different scattered rays

m=1.5+i 1e-3

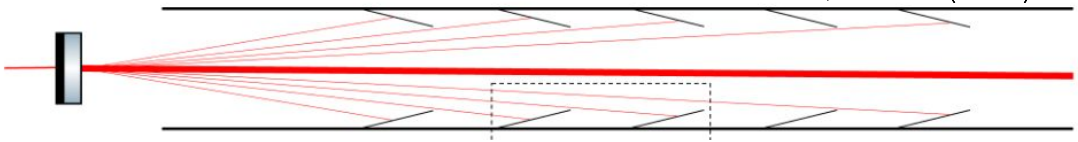


Real environments contain particles of different sizes, indices, and shapes
→ ensemble averaging smooths any interference pattern

ET arm pipes with baffles

PHYS. REV. D 108, 102001 (2023)

Arm pipe diameter: 1m



Conical baffles: absorb Stray Light from the Test Masses and avoid their direct view of the pipe walls.

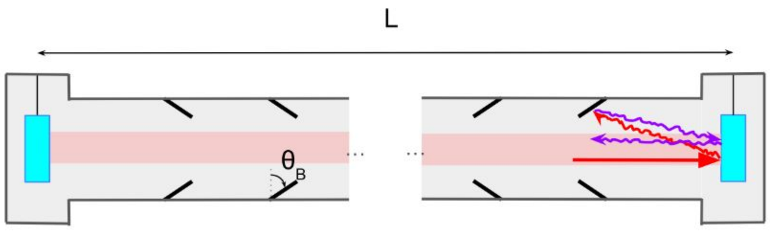
Baffles intercept light scattered by the TMs between ~ 10^{-2}rad and ~ 10^{-5}rad, corresponding to the first and last baffles

Key questions regarding arm pipes:

- How clean should the internal surface of the pipe be?
- How clean should the arm baffles be?

Large scale of the ET vacuum system → Requirements for cleanliness can make a big impact in terms of costs and time

Scattering by the baffles



$$\theta_i = \theta_B = 55°$$

Dimension of the TM (~ 0.5m) << its distance to any of the baffles (0.1 - 10km)
→ the scattering angle varies by ≲ 5mrad from the center to the edge of the TM.
→ to reach the TM, light is essentially backscattered in the same direction it comes from

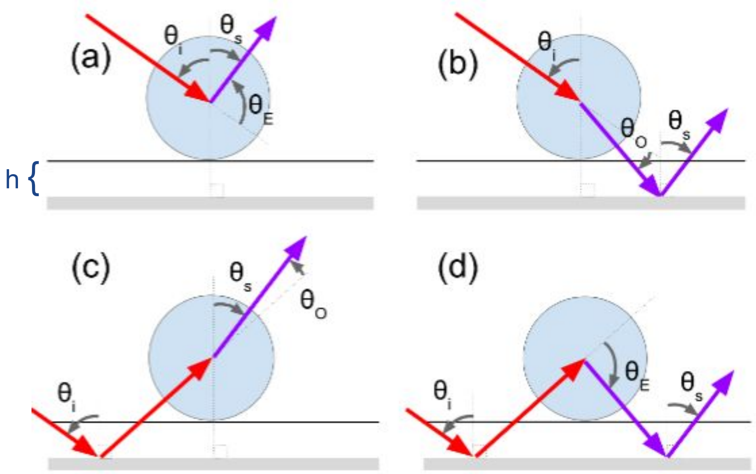
Previous studies set limit to scattering by (clean) baffles due to their roughness:

scattering probability $BRDF_{baffle}(\theta_i, -\theta_i) = 10^{-4}/\mathrm{str}$ *baffle backscattering noise*

We investigate how the baffle backscattering changes
when they are **contaminated by particles**
that **deposit** during assembly and installation of the ET beam pipes

For 'dirty' baffles: $BRDF_{baffle} \rightarrow BRDF_{baffle} + BRDF_{dust}$

Dust deposited on the baffles



A particle deposited on the baffle surface.

h is the distance between the surface with the particle and the surface of light reflection (eg AR coating thickness)

θ_i is the angle of incidence of light reaching the particle deposited on baffle surface

4 processes by which light can be scattered by the particle :

Even processes (a, d): θ_E

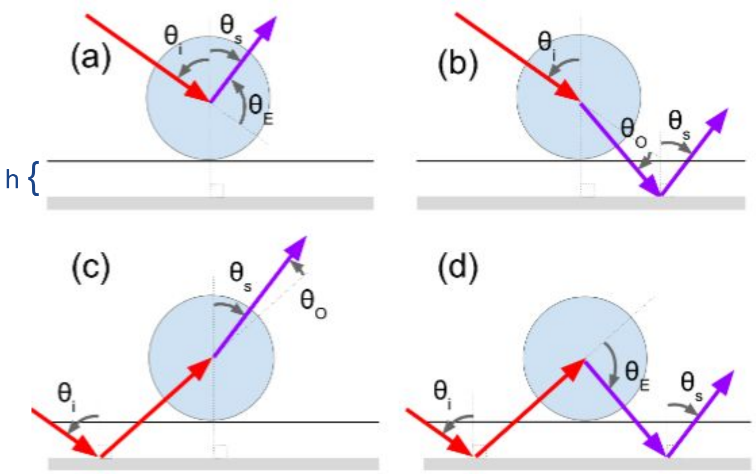
Odd processes (b, c): θ_O

To return to the TM: $\theta_s = - \theta_i$ (hence $\theta_E = \pi$ and $\theta_O = 2\ \theta_i$)

Mie theory to model such 4 processes.

Incoherent sum of the 4 scattering contributions from the single-particles: this avoids coherence effects for specific h values and averages over shape and orientation of real particles → more solid estimates

What is the role of baffle reflectivity R ?



Baffle backscattering noise (by baffle's residual roughness) is independent of *R*
→no requirements on *R* have been set previously

We consider 2 cases:

- *R* = 1 : maximizes scattering effect, produces conservative limits
- *R* = 0.01 : more realistic, actual value not much important as long as *R* << 1 :

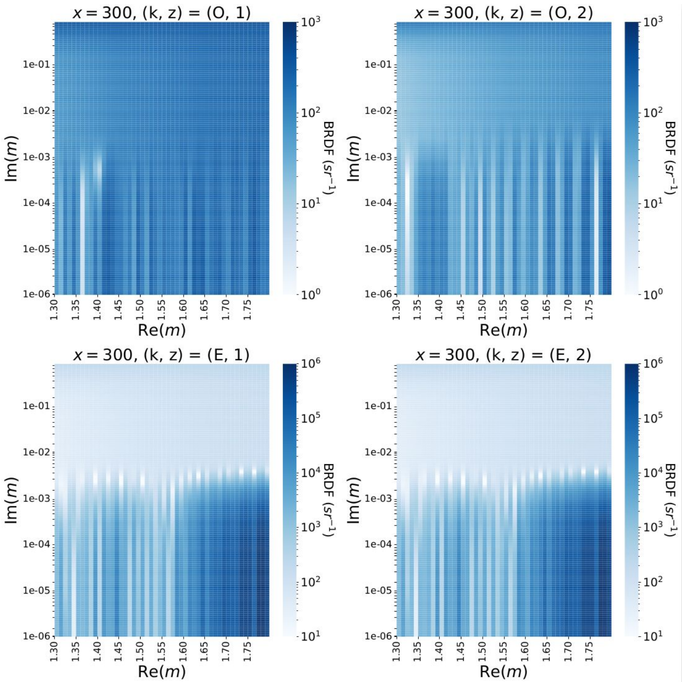
  Odd processes (b, c): linear with *R* and vanishing for *R*→0

  Even processes (a,d): scale with $(1+R^2)\rightarrow 1$ for *R*→0

What is the role of the refraction index m?

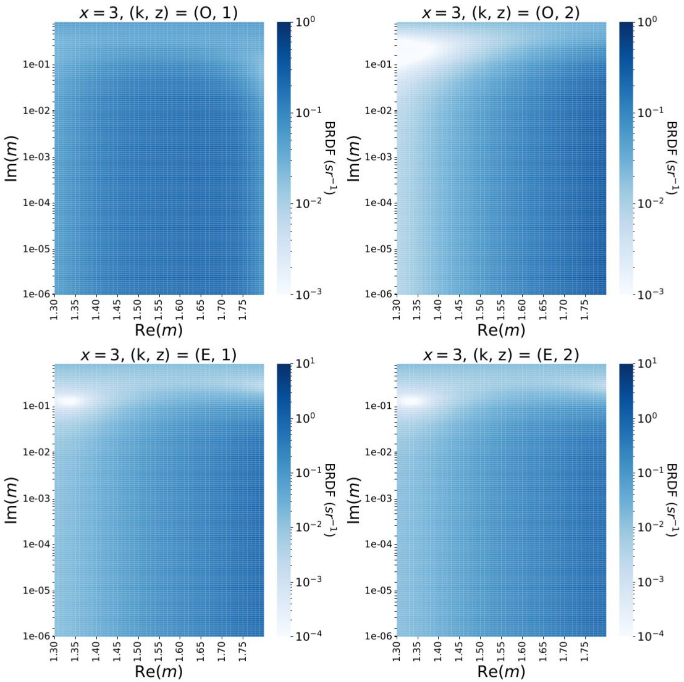
Plots for:
$\theta_s = -\theta_i$ and R = 1
$x = \pi D / \lambda$

Large particles scatter more than small ones. Scattering increases with higher Re(m) and lower Im(m).



Large particles:
a series of ripples, with local minima/maxima - for specific combinations of x and m - not expected for realistic particle distributions (due to shape and m not being single valued)

Small particles:
scattering changes more slowly with m
(to ease comparison, in this slide, all plots in the same row have the same dynamic range)



z = 1, 2 refer to the polarization wrt scattering plane. Averaging over randomly distributed particles on the baffle is equivalent to average over polarizations z=1,2.

Index of refraction m : values

Expect a variety of materials to be present (in unknown proportions):

- from the environment: Saharian, ocean, urban and land contributions in different proportions
- from people at work: skin, hairs.., clean clothes
- from tools and infrastructure: metals, ..

We are inclusive and consider all possible values:

{Re(m), Im(m)} of environmental dust is found to range within a broad interval, with m* considered as 'typical'

	$\mathrm{Re}(m)$	$\mathrm{Im}(m)$
Environmental dust	[1.3, 1.8]	$[10^{-6}, 0.8]$
m^*	1.5	0.001
Human skin	1.42	0.007
Aluminum ($\lambda = 1064$ nm)	1.25	10.5
Aluminum ($\lambda = 1550$ nm)	1.47	16.1
Aluminum ($\lambda = 2000$ nm)	2.20	21.0

Maximum tolerable amount of dust

Condition to be satisfied: $$BRDF_{dust}(\theta_i,\theta_s) = BRDF_{baffle}(\theta_i,\theta_s)$$
for $\theta_s = -\theta_i$. For ET: $BRDF_{baffle}(\theta_i, -\theta_i) = 10^{-4}$/str and $\theta_i = \theta_B = 55°$

Range of particle sizes divided in bins;

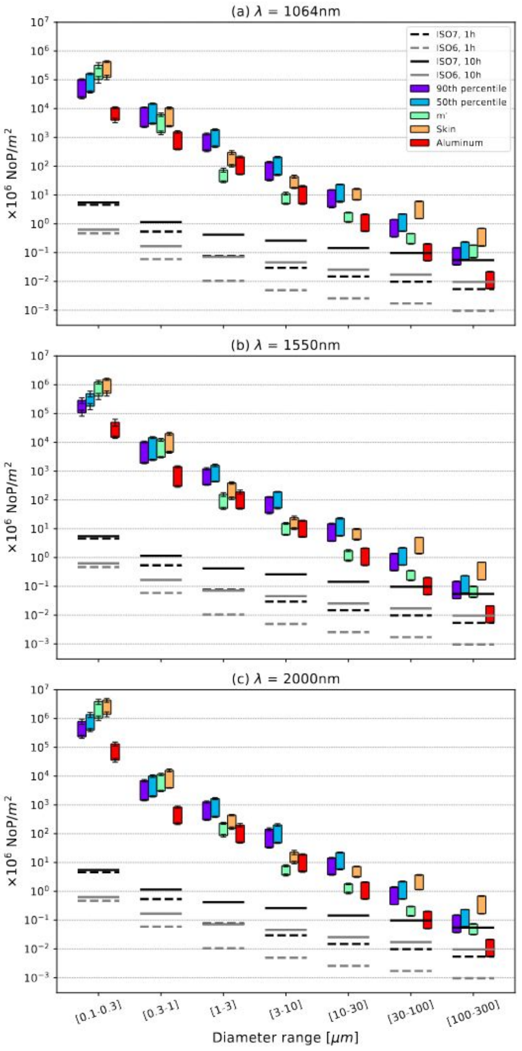
for each bin find max number density of particles for:

- m of specific materials (m*, skin, aluminium)
- m in the range: quote the numerosities corresponding to the 50th and 90th percentiles
- R=1 (lower edge) and R=0.01 (top edge)

The limits are more stringent for larger particles

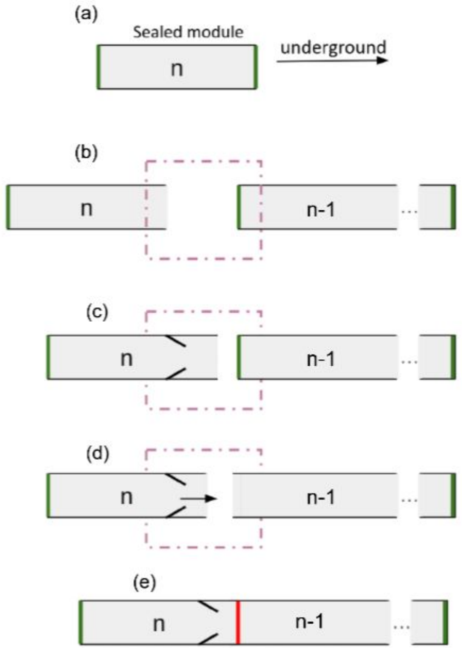
Little dependent on wavelength, more variation for small particles.

Can these requirements be met?



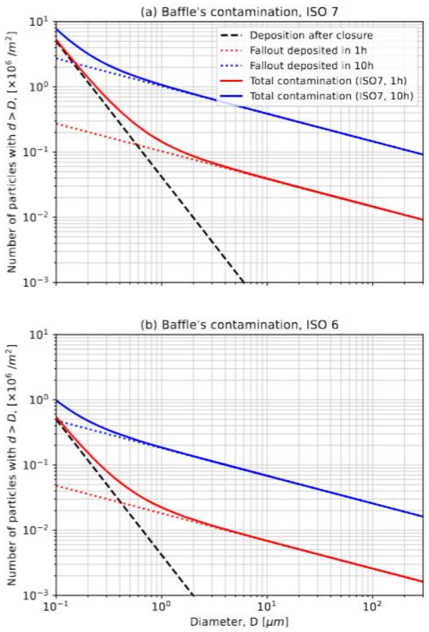
Estimation of particle distribution

Installation scheme for the ET arm pipes with baffles, driven by cleanliness considerations



Pipe assembling and baffle installation requires time:

what particle distribution expected on a baffle after exposure in a clean tent?



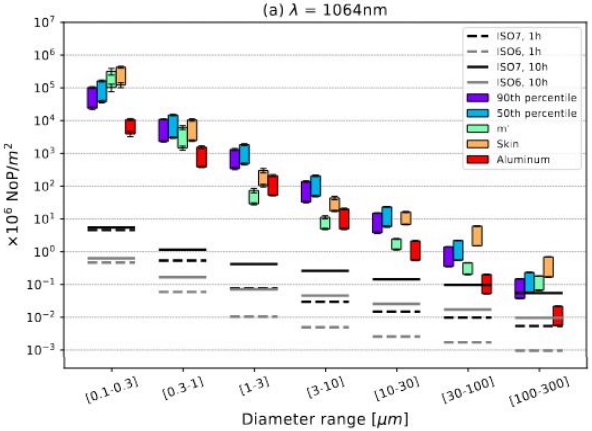
2 contributions:

1. when a seal is open: deposition proportional to exposure time in the clean tent
2. deposition of particles suspended at the time of sealing - independent of exposure time

For mid to large particles, deposition while seal is open (contribution 1) is dominant

Comparing requirements with expectations

Requirements are easily satisfied for small particles but less for large particles.



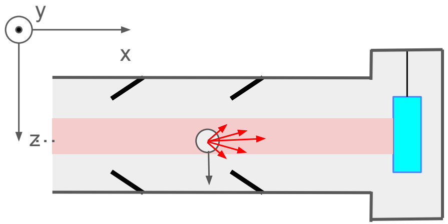
Lots of approximations, including exposure time.

To be conservative installing the ET arm baffles in a ISO7 clean tent seems risky

This study is reported in a paper to be circulated within few days

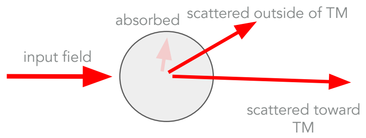
What about dust falling within the arm pipe?

Particles crossing the beam in the arm cavities, eg if falling in vacuum from the top inner surface of the pipe



While particle crossing, cavity field is perturbed by:

- Power lost, either absorbed by the particle or scattered away from the TM (and absorbed somewhere else)
- Power scattered towards the TM and rejoining the main beam



Computed with Mie theory as function of particle trajectory. Effects:

1. Phase noise
2. Radiation pressure noise
3. Power imbalance at the BS

Converted into strain noise with standard transfer functions

Falling particles

Two regimes :

- Small crossing rate: single, separated events -> noise glitches. An effect possibly already observed at Ligo
- Large crossing rate: incoherent sum of many events -> stochastic noise

We have developed a full MonteCarlo simulation to compute the effect on strain noise from an arbitrary distribution of:
particle size, material, detaching position and detaching rate

Work is in progress: simulation are running!
?? Main uncertainties: particle distribution and detaching rates
Results to be communicated in the coming months

Conclusions

- **Limited cleanliness** can cause an excess of stray light (SL) noise:
  starting clean is better than cleaning later (if it's even possible)!
- Dust can cause SL noise both when **deposited** and while **falling**.
- We defined cleanliness requirements for the ET arm baffles, accounting for induced SL noise.
- We provide cleanliness guidelines for assembling the ET vacuum pipes with baffles.
- We are studying the SL noise caused by particles falling and crossing the cavity beam to define cleanliness requirements for the internal walls of the vacuum pipe.

This work poses the basis for a scientific analysis of cleanliness requirements for gw ITFs