Small angle scattering in GEO600

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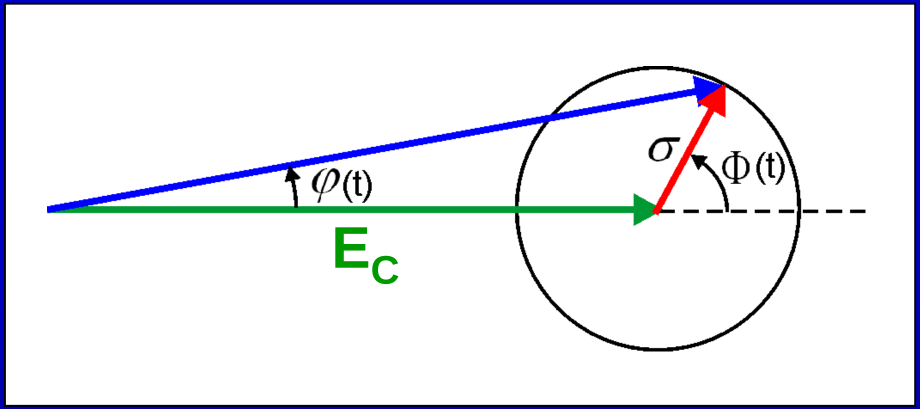
for the GEO-team

Overview

- Introduction
- How much scattered light is necessary to limit the sensitivity of GEO600 ?
- Scattering schemes:
  - *Low amplitude high frequency scenario*
  - *High amplitude low frequency scenario*
  - *The classical scattering shoulder*
- Measurement of small angle scattering of the GEO core optics
- Estimating the scatterd light noise from the catchers in the GEO end stations

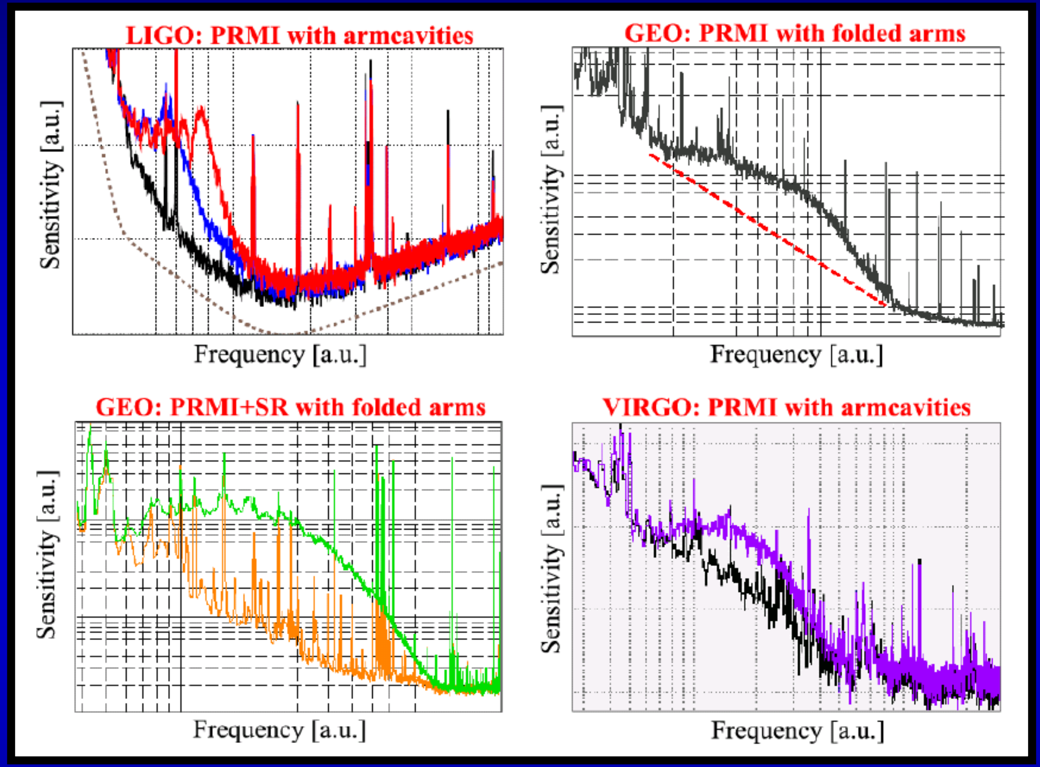
Introduction

- GW cause phase modulation (sidebands) on the light.
- The GW detector measures very accurately the phase of the light, **φ(t).**



- => Any light, **σ**, with a different phase, Φ(t) (than the carrier light) looks like a GW signal.

Scattered light a problem of all large scale GW detectors



** LLO electronic log 2005-08-19 (B O Reilly, personal communication).*

*** "2nd Report on WG1: Antennas commissioning and characterization",MBarsuglia, A Freise, I Fiori, H Grote, H Heitmann, S Hild, P LaPenna, G Losurdo, H Lück, J Smith, L Taffarello, G Vajente, M Visco, B Willke, 2006.*

- Scatter light problems have been encountered during the commissioning of all currently operating large scale gravitational wave detectors.
- Since 2nd generation GW detectors will aim for significantly increased sensitivities at low frequencies, stray light will be even more problematic.

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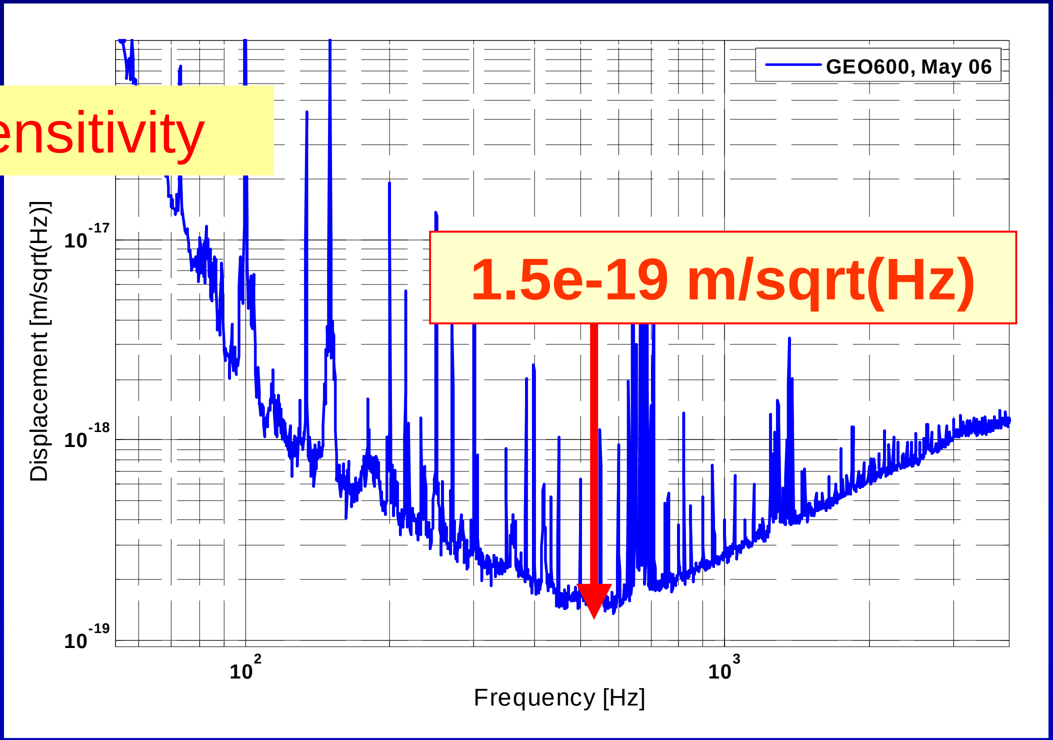
How much scattered light is necessary to limit the sensitivity of GEO600 ? *(part 1)*

Achieved displacement sensitivity



Accurary of the phase readout

$$\varphi = \frac{4\pi \cdot 1.5 \cdot 10^{-19} m}{\sqrt{Hz}} \cdot \frac{1}{\lambda}$$

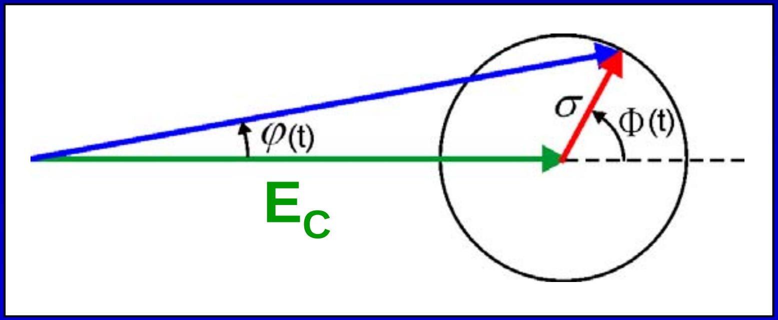
$$\varphi = 1.8 \cdot 10^{-12} rad / \sqrt{Hz}$$

How much scattered light is necessary to limit the sensitivity of GEO600 ? *(part 2)*

$$\varphi = 1.8 \cdot 10^{-12} rad / \sqrt{Hz}$$

- Assuming angle between E_C and σ to be 90 deg.

$$\tan(\varphi) = \frac{\sigma}{E_C}$$



- With E_C = sqrt(2.7kW) we get

$$\sigma = \varphi \cdot \sqrt{2.7kW} = 9.3 \cdot 10^{-11} \sqrt{W}$$

$$\sigma^2 = 8.6 \cdot 10^{-21} W$$

tiny amount of light

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A device for controlled scattered light generation

We want to check, if our understanding of scattered light is correct.

=> Scattered light hardware injections are required !!

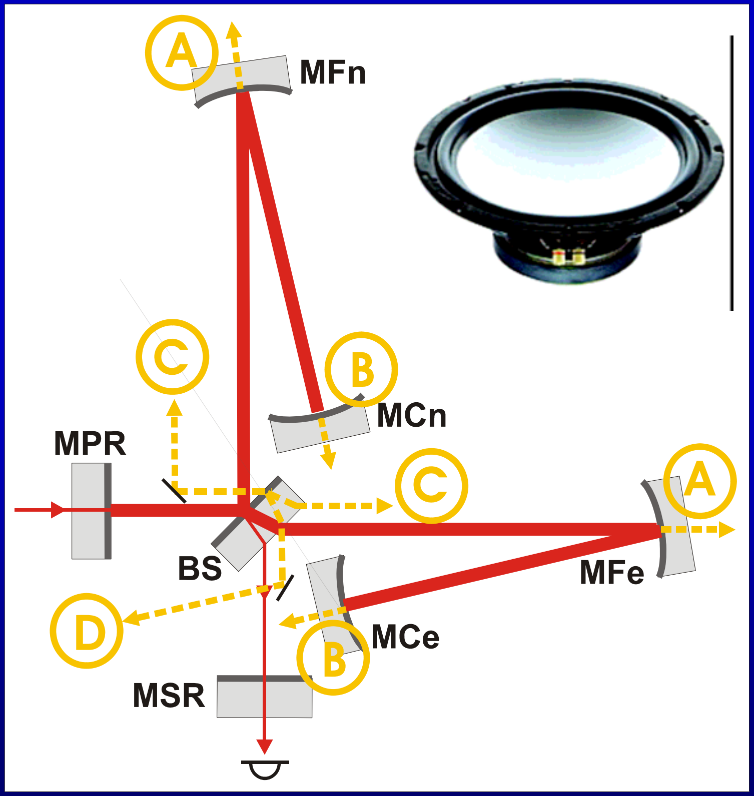
How can you do this ???

Required

Need a scattering surface that can be controlled in frequency and amplitude.

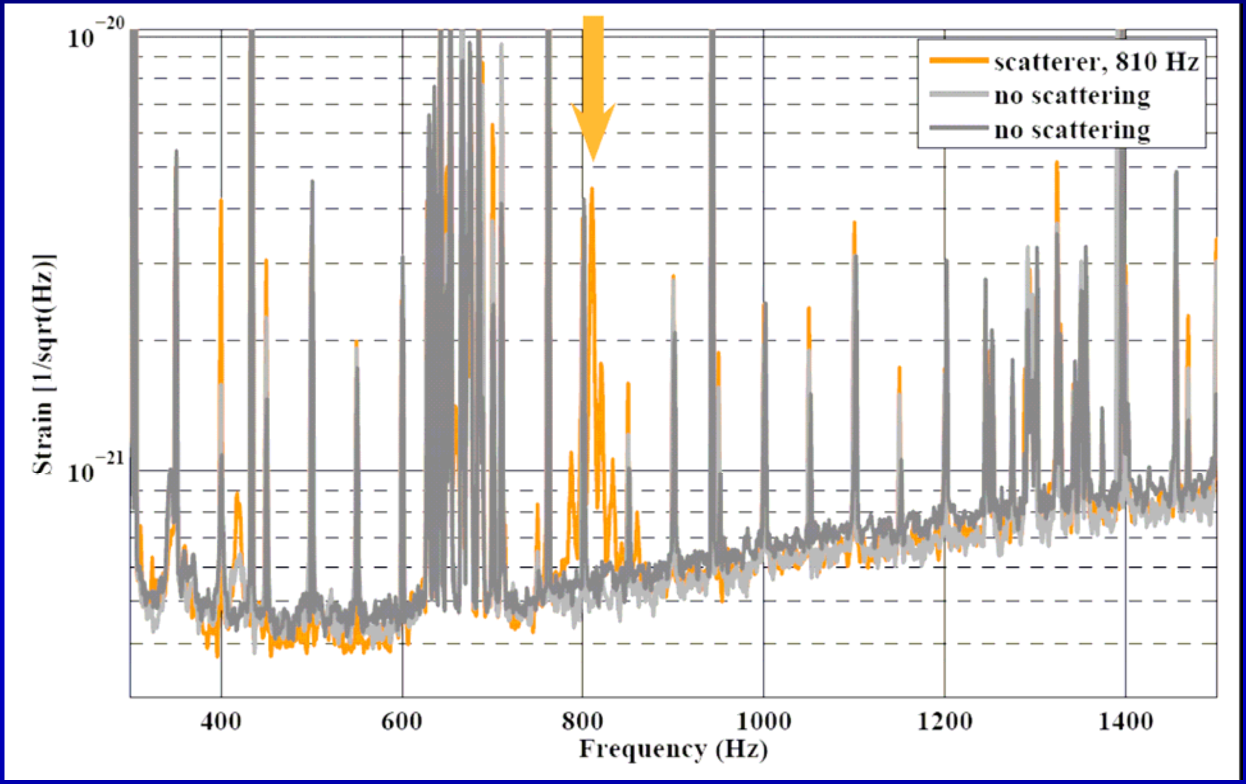
Realization:

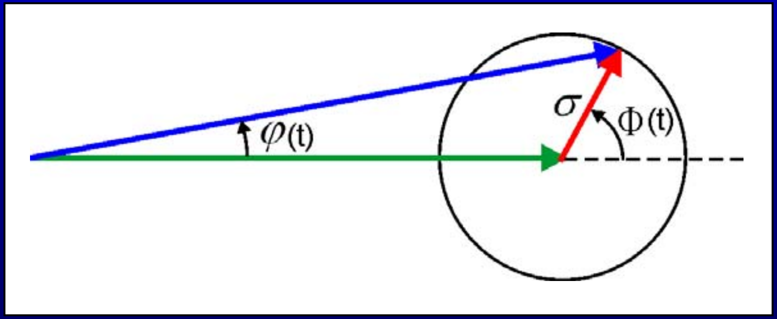
Using an commercial low-cost loudspeaker with a rough and silvery metal diaphragm (anodised aluminium).



High frequency low amplitude scenario

Scattering soure moves with frequency in detection band. Only a small amplitude is necessary to produce a stray light peak at corresponding frequency

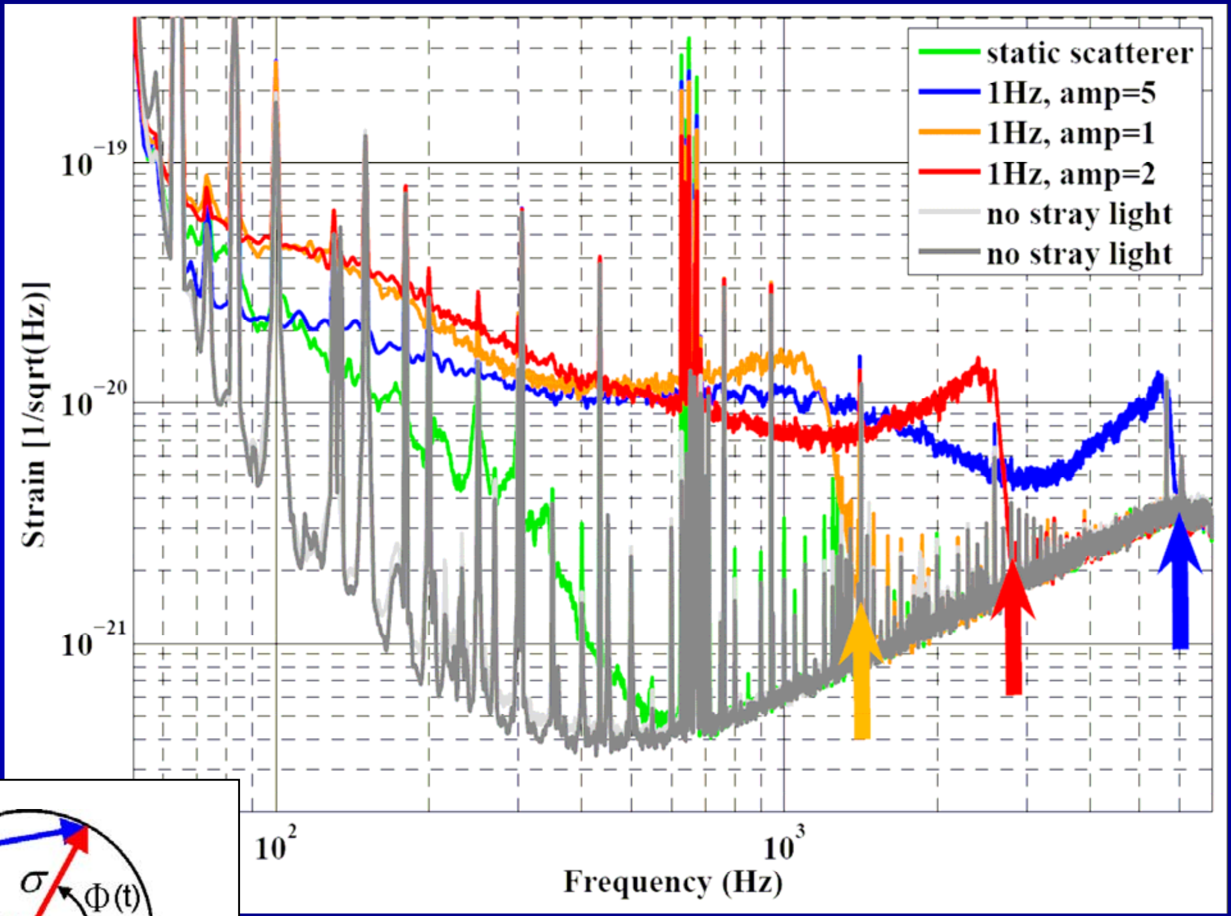


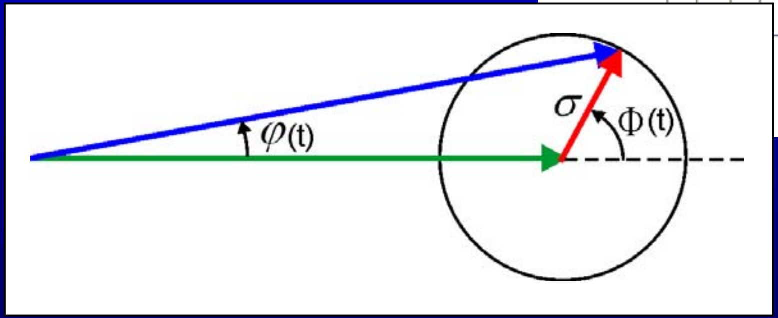


Low frequency large amplitude scenario

Scattering source moves with very low frequency (outside the detection band) but with an amplitude of many wavelengths. A scattering shoulder is produced with a cutoff frequency:

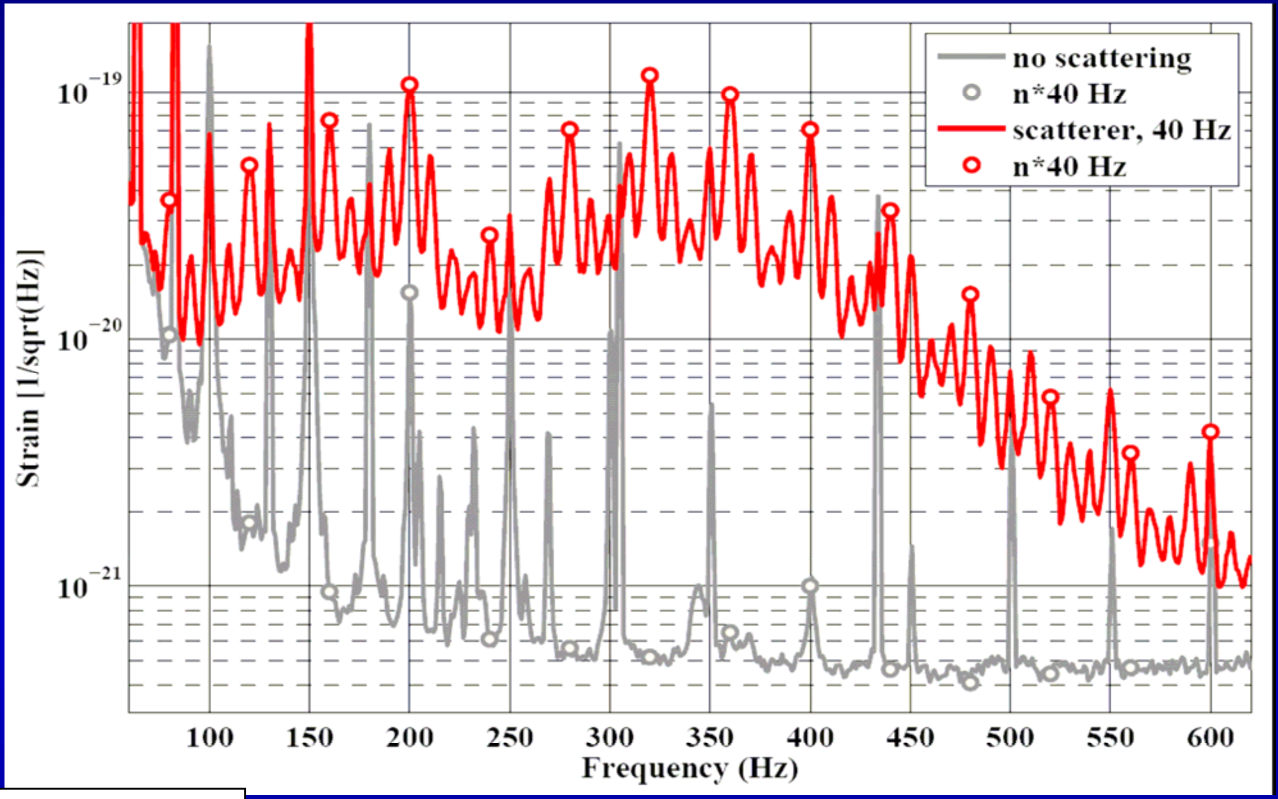
$$f_{\text{cutoff}} \approx 4 \cdot f_{\text{sp}} \cdot \frac{A_{\text{sp}}}{\lambda_{\text{laser}}}$$

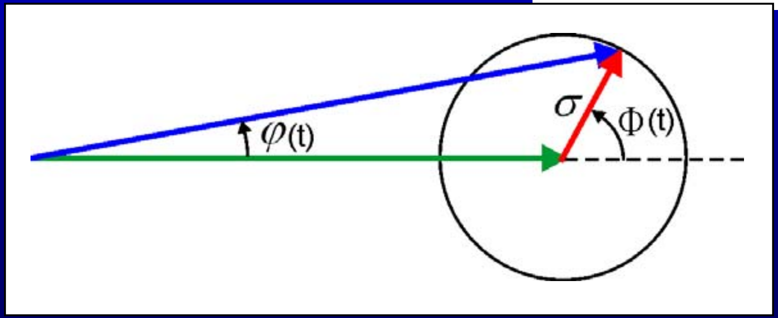




The famous scattering shoulder

A combination of the previous two scenarios produces a scattering shoulder with a comb of harmonics of the excitation frequency.





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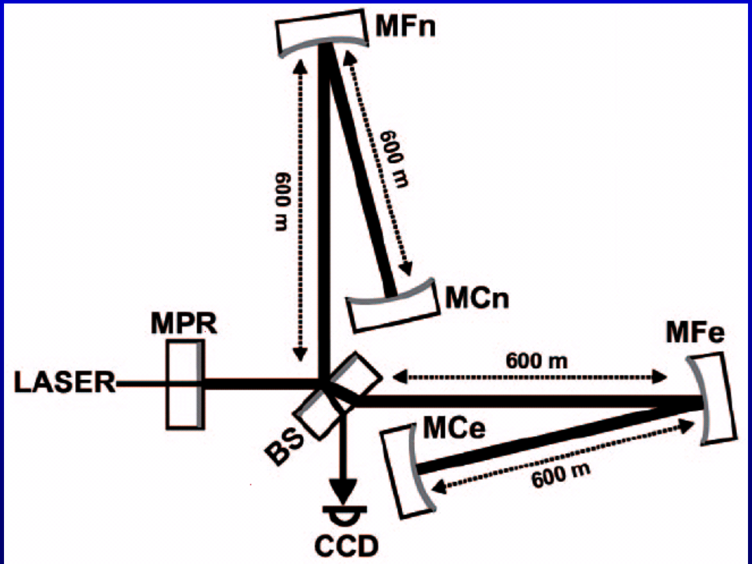
Small angle (SA) scattering

Direct (SA) scattering

- Beam from BS impingung on MFe could be scattered directly back to BS (instead of going to Mce):
  - 1200m delay => potential coupling of frequency noise
  - Position (long) of MFe uncontrolled => scattered light with different phase => should not be a problem due to triple suspension (1/f^x) => only frequencies below detection band.

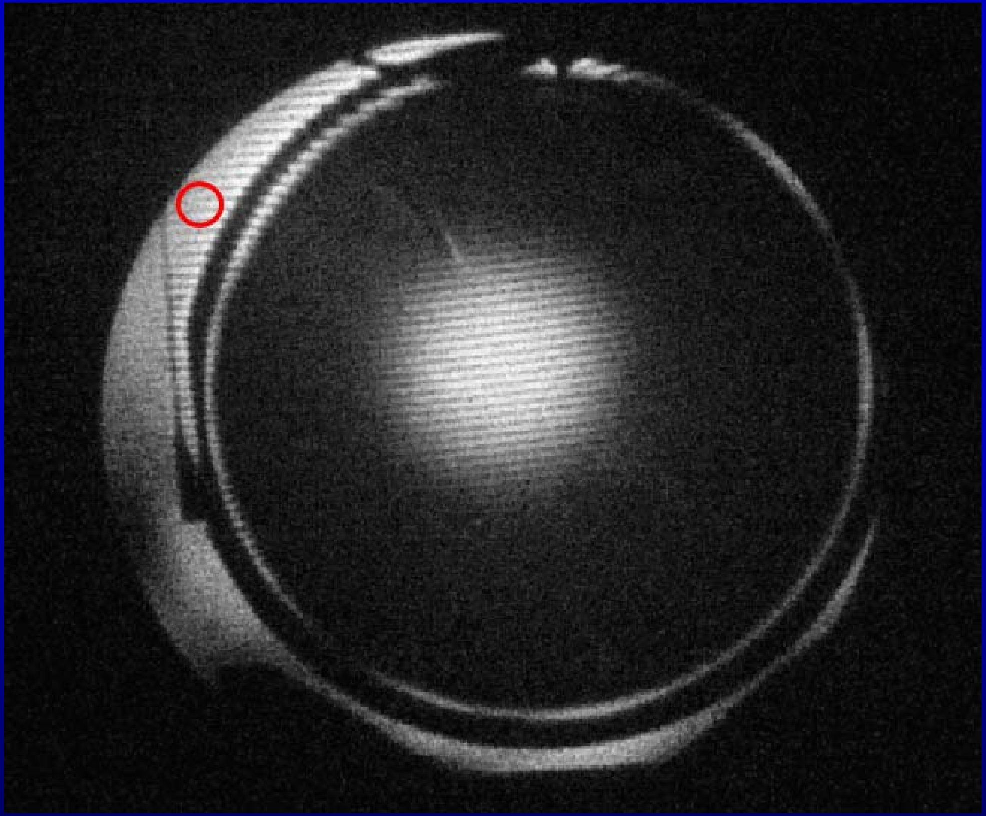
Double (SA) scattering

- Light scattered into a small angle is hitting components close to the optics (catchers, vacuum vessel, etc) which are not decoupled from seismic => light is scattered back into the interferometer



Measurement of small angle scattering of the GEO core optics

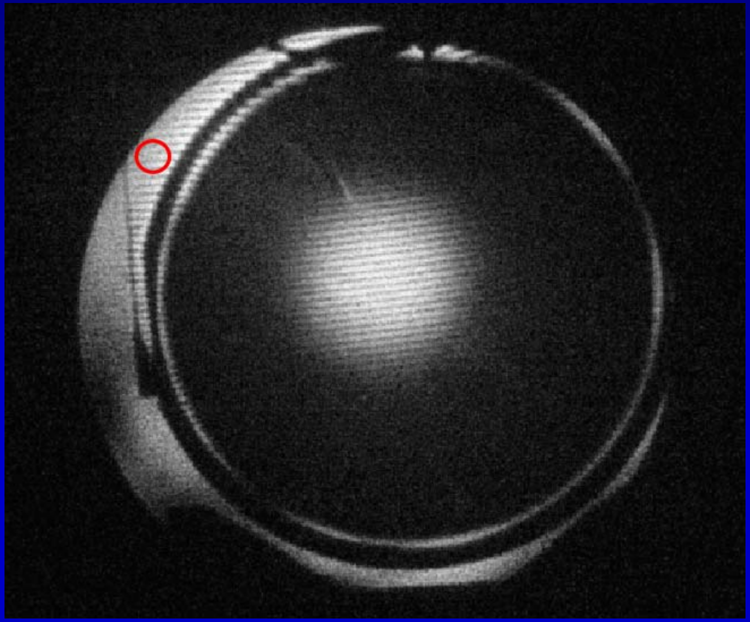
- Why wasn‘t there any measurement so far?
  - You need to measure in situ (vacuum ....)
  - No viewports available / mechanical structures blocking the beams etc ...
- After replacing the viewport behind MFN by a 200mm one we can access the light passing close to the rim of the mirror.
- The red circle indicates the measurement point.



Measurement of the SA scattering

- Optical power = 1.8 mW /cm^2
- Scattering angle:
  θ = 0.1m/600m = 1.7mrad
- We can define the (angle dependent) scattering coefficient f(θ):

$$f(\theta) = \frac{dP}{P \cdot d\Omega}$$



With the solid angle: $d\Omega = \frac{A}{R^2}$

- This leads to $f_{mir}(1.7mrad) = 2400$

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Estimating scattered light noise from the far end catchers

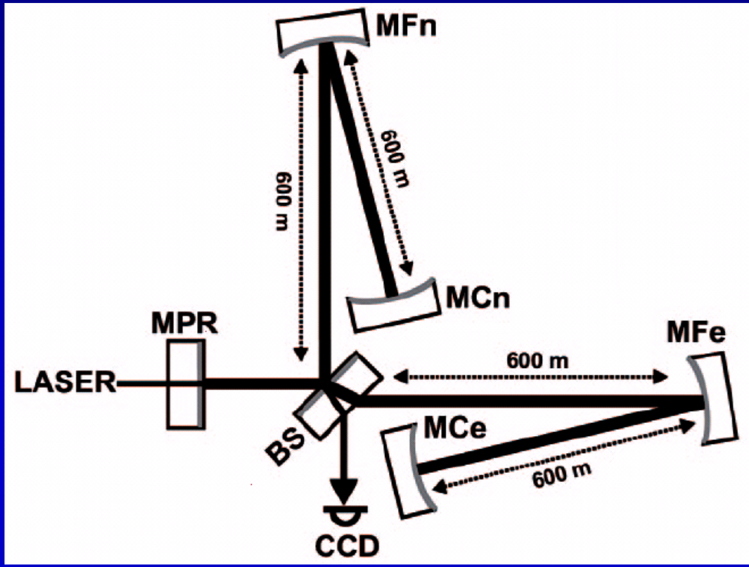
- Observation: There is a lot of higher order mode light hitting the catchers of MFE and MFN.
- PROBLEM: The catcher is not seismically isolated.
- The scattering surface of the catchers is roughly 50 cm^2

- ***1st Step:*** Total amount of light hitting the catcher = 50cm^2*1.8mW/cm^2 = 90mW

2nd Step: Estimating the light scattered from the MFn catcher that hits MCn

- Walter Winkler measured (using an Ar+-Laser) for unpolished, oxidized aluminium:

$$f_{Al}(\theta) = 6.4$$



- Walter also observed that metal behaves like a cosine-scatterer

  => f(θ) = const (for small angles)

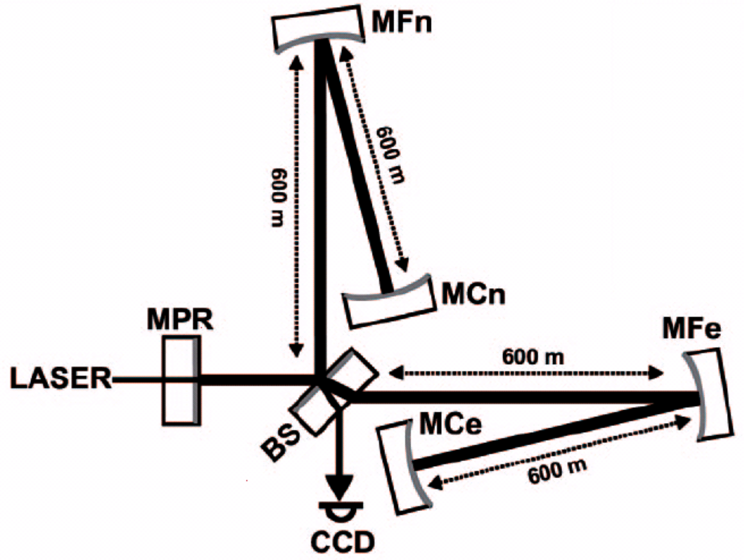
- Light power hitting MCn:

$$P_{MCn} = P_{catch} f_{Al}(\theta) d\Omega$$

$$P_{MCn} = 90mW \cdot 6.4 \cdot 7 \cdot 10^{-8} = 4 \cdot 10^{-8} W$$

3rd Step: Estimating the light scattered from the MFn catcher that hits MCn and is scattered back on to MFn

$$P_{MCn} = 90mW \cdot 6.4 \cdot 7 \cdot 10^{-8} = 4 \cdot 10^{-8} W$$



- The light from MFn catcher, that is hitting MCn is not automatically reflected back into the interfero-meter.
- => An additional scattering process on MCn is needed !!!

$$P_{MFn2} = P_{MCn} \cdot f_{mir}(1.7mrad) \cdot d\Omega$$

$$f_{mir}(1.7mrad) = 2400$$

$$P_{MFn2} = 4 \cdot 10^{-8} W \cdot 2400 \cdot 7 \cdot 10^{-8} = 6.7 \cdot 10^{-12} W$$

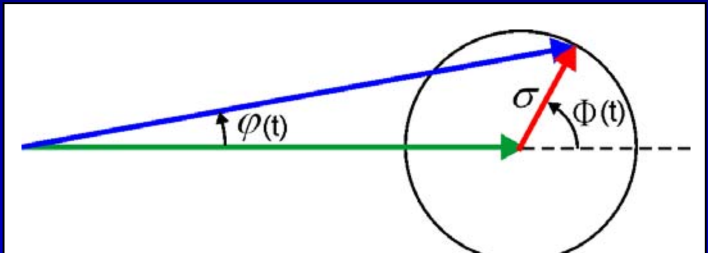
4^{th} step: Translate scattered light amplitude to strain contribution

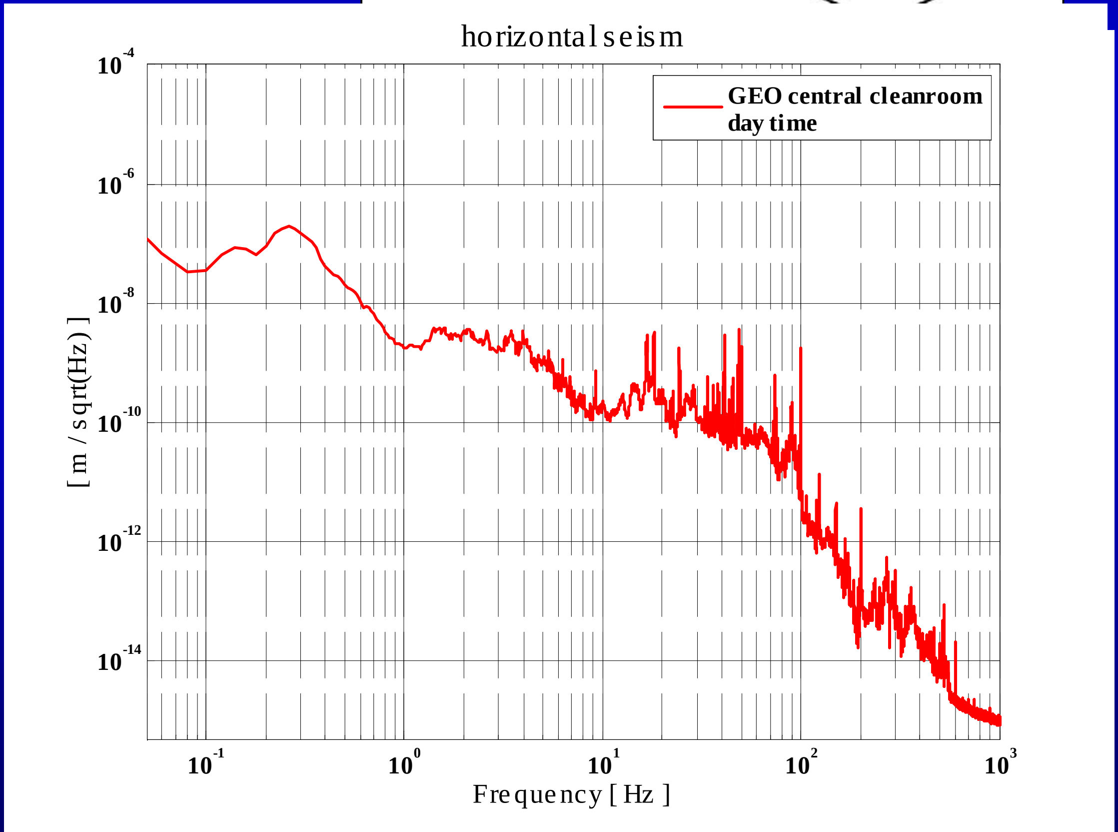
$$\frac{dP}{P} = \sigma^2$$

$$\frac{6.7 \cdot 10^{-12} W}{1350 W} = \sigma^2$$

$$\sigma = 7 \cdot 10^{-8}$$

$$Dis = seismic \cdot \sigma$$





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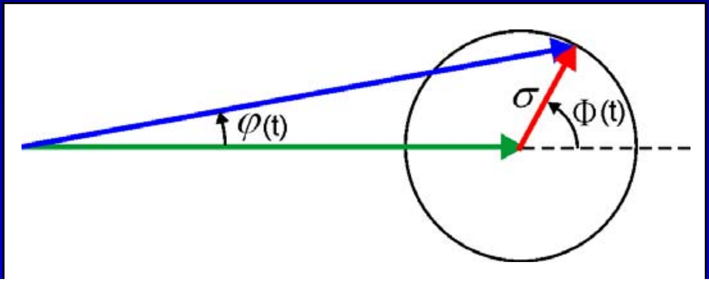
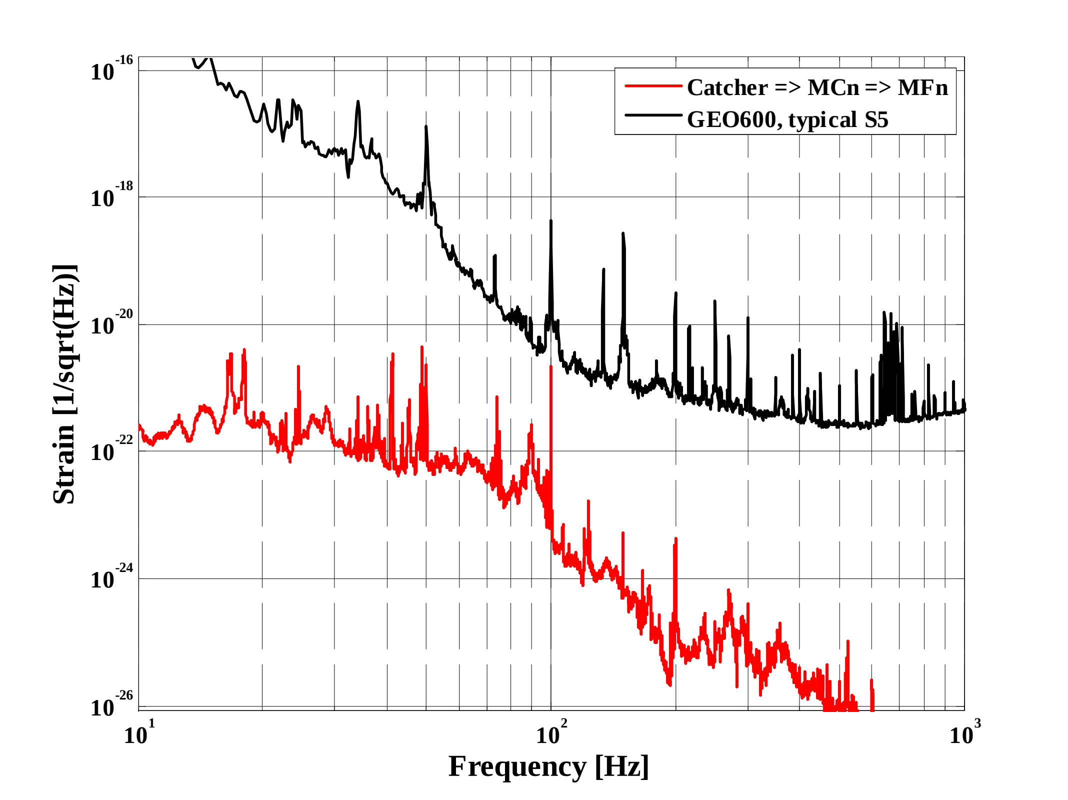


$$\sigma = 7 \cdot 10^{-8}$$

$$Dis = seismic \cdot \sigma$$

$$h(t) = \frac{Dis}{1200m}$$



Estimating the light scattered from the MFn catcher that hits the hole in MSR-RM

- Walter Winkler measured (using an Ar+-Laser) for unpolished, oxidized aluminium:

$$f_{Al}(\theta) = 6.4$$

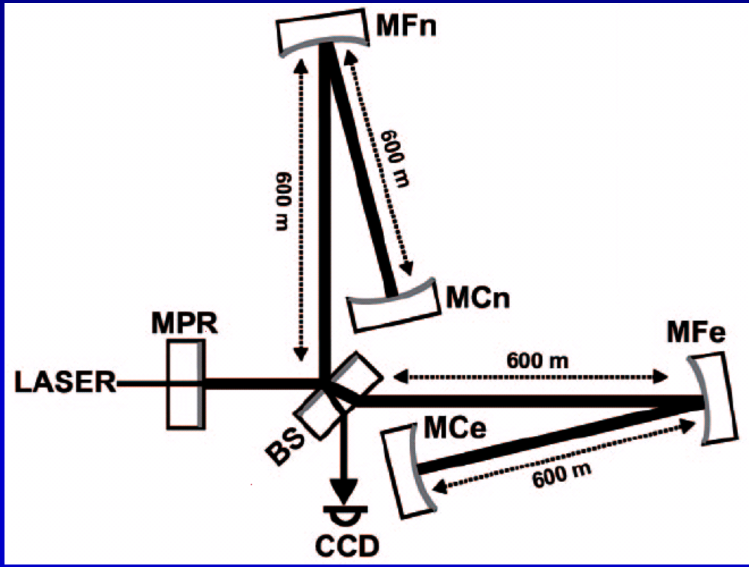
- Walter also observed that metal behaves like a cosine-scatterer

  => f(θ) = const (for small angles)

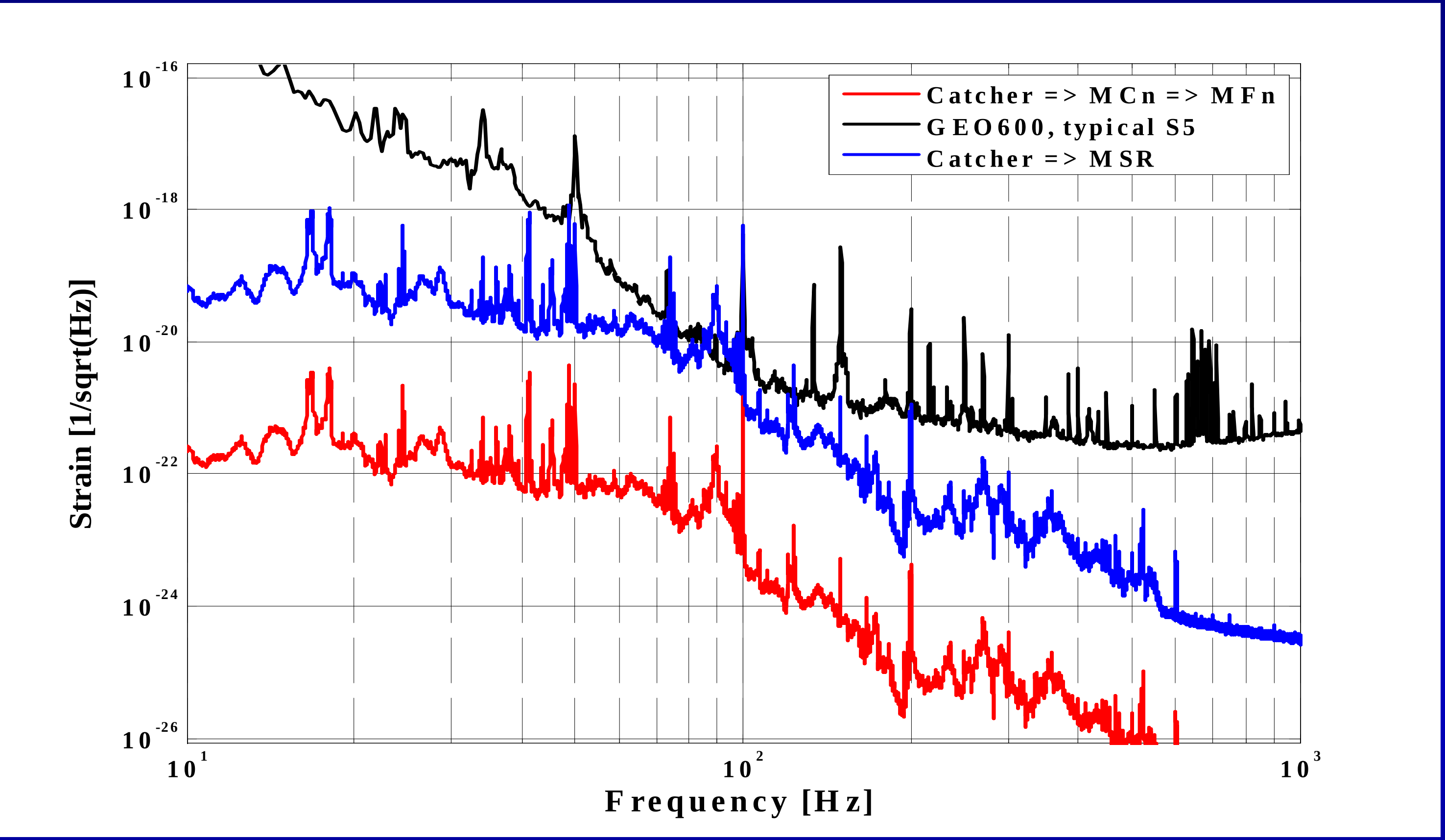
- Light power hitting MSR:

$$P_{MSR} = P_{catch} f_{Al}(\theta) d\Omega_{MSR}$$

$$P_{MSR} = 90mW \cdot 6.4 \cdot 1.6 \cdot 10^{-8} = 9.2 \cdot 10^{-9} W$$



Comparison of the two scattering pathes from MFN catcher



Two main inaccuracies:

- Actual movement of the catcher structure is not known very well *(no accelerometer, resonances are unknown ....)*
- **f(θ)$_{\mathbf{catcher}}$** for 1064nm not known

Summary

- Eventhough scattered light is usually consider as a technical noise source, it requires a lot of our attention !!
- Tiny amounts of scattered light can limit current GW-detectors
- Developed a device for controlled scattered light injection
- Scattering behaves like expected => No magic involved
- 1st direct measurement of small angle scattering in GEO600
- Started to model scattered light noise from the far end catchers