

Measurement and identification of coherent stray light in complex interferometers

application to the LISA interferometric Detection System

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Outline

The LISA mission in one slide

General remarks about stray light

Measurement of stray light at system level

General approach for the measurement and identification of coherent stray light

Measurement of stray light in the LISA's "MOSA"

The frequency-ramped laser source, and the characterization of the instrument

Conclusion and perspectives

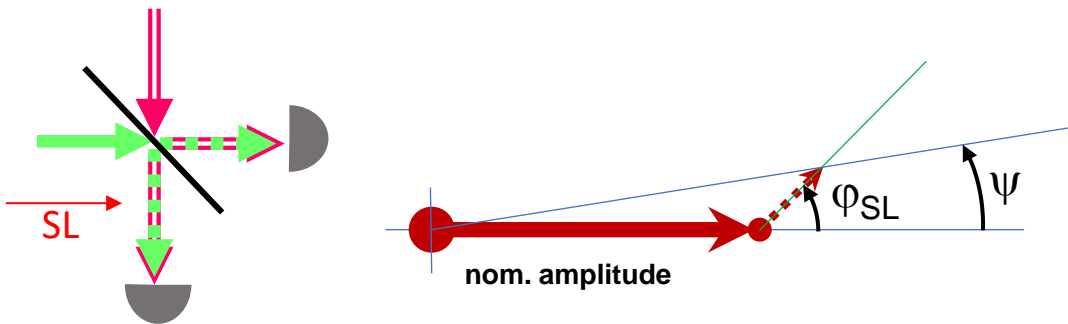
The "Laser Interferometer space Antenna" in one slide

Measures the variation of the 2.5 Mkm arm lengths $10\text{pm}/\sqrt{\text{Hz}}$

- records gravitational waves in the $20\mu\text{Hz} - 1\text{Hz}$ band
- supermassive black holes, primordial universe,...

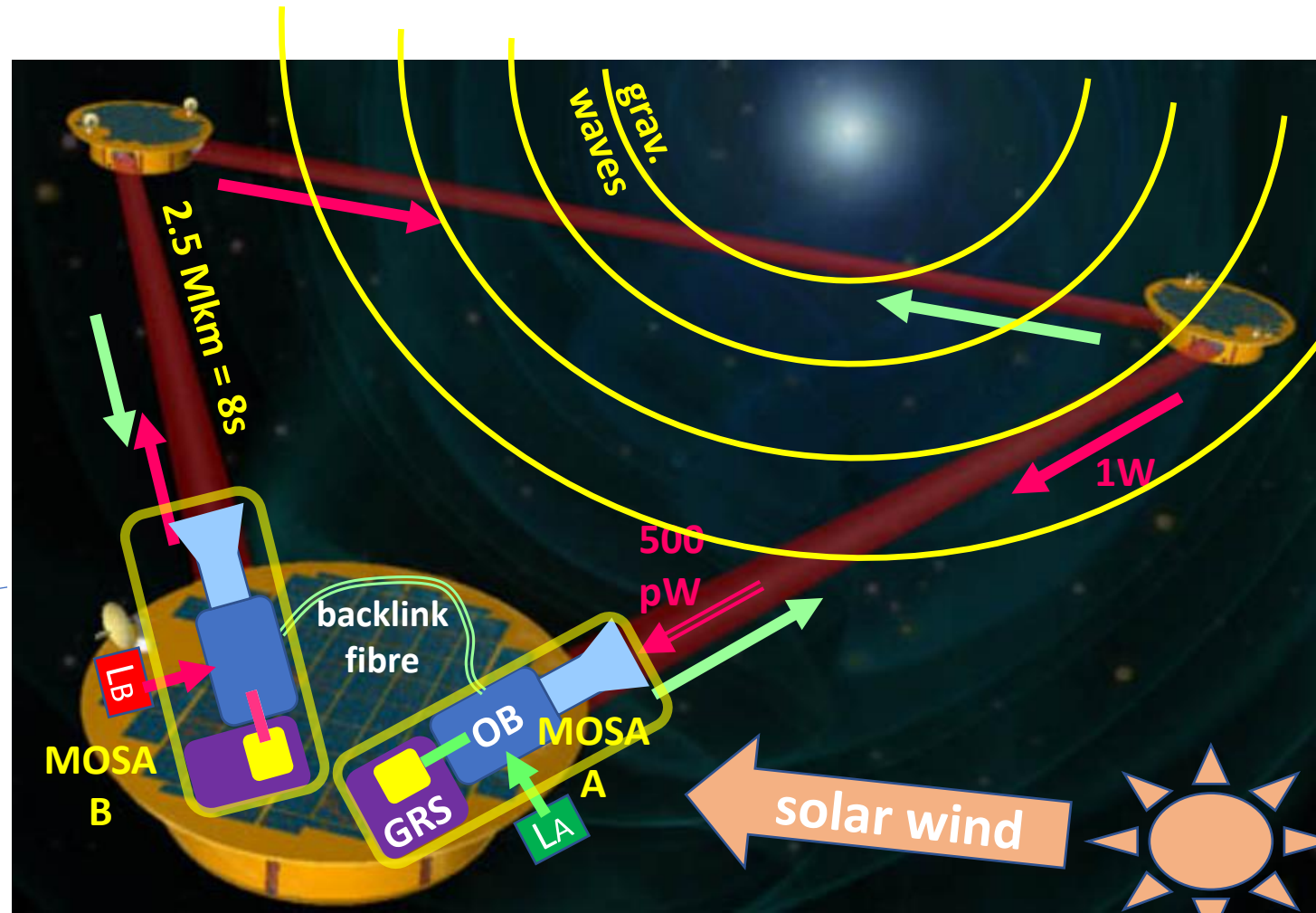
The basic LISA instrument is the "moving optical sub-assembly" (MOSA)

- => 2 MOSAs per spacecraft
- => 3 interferometers per MOSA
 - "science" (long arm)
 - "Test Mass"
 - "reference"



$$\delta\psi \leq \epsilon_{SL} \delta\phi_{SL}$$

fractional SL optical amplitude



Stray light = unwanted light in an instrument, an experiment, ... A problem in

- imaging
- spectroscopy
- polarimetry
- and in interferometry: coherent stray light

with **coherent** stray light: $\sim 2 \times \frac{A_{Stray\ Light}}{A_{Nominal\ Light}} = 2 \times \sqrt{\text{stray light power} / \text{nominal light power}}$

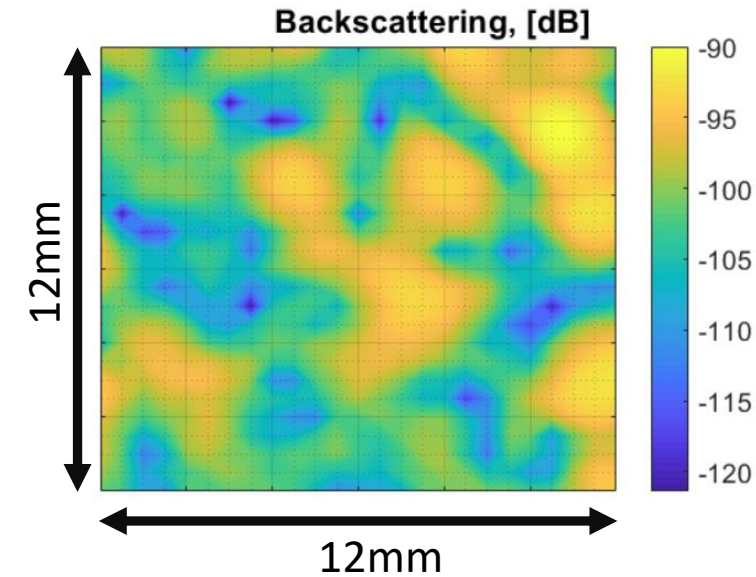
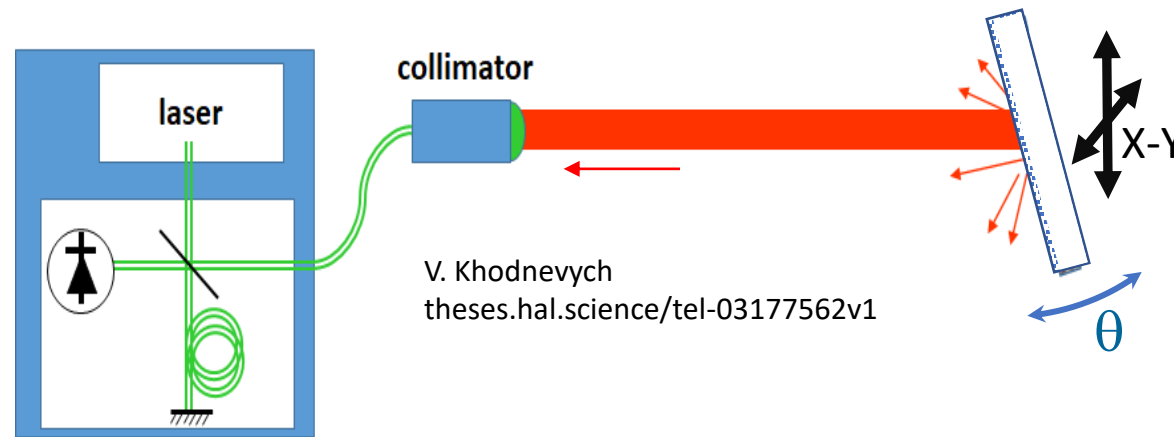
Studied at component level, and at system level, in

- atomic clocks with optical pumping
- tests masses (added radiation pressure)
- ground-based GW interferometers
- in space missions with interferometers
 - GRACE-FO space geodesy (interferometry over ≈ 200 km)
 - LISA space mission for gravitational wave detection
- need for the measurement and identification of stray light at system level

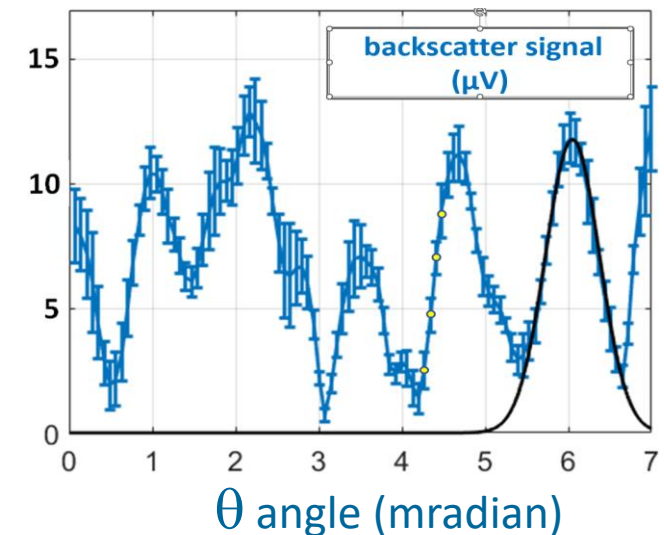
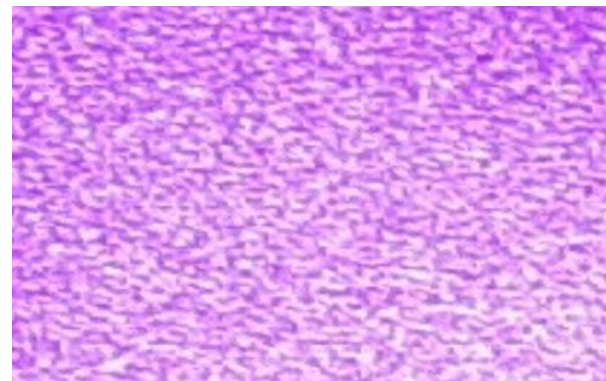
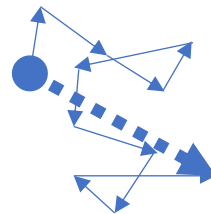
Scattered light is due to roughness, or contamination at surfaces (or volume contamination)

Optical amplitude is a speckle field

But it has also a speckle-type dependance of the back-scattered amplitude vs position of the beam at the scattering surface



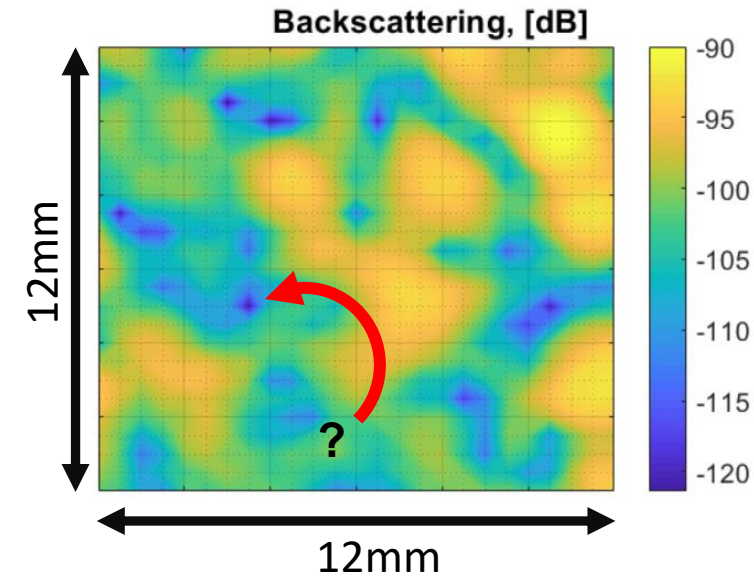
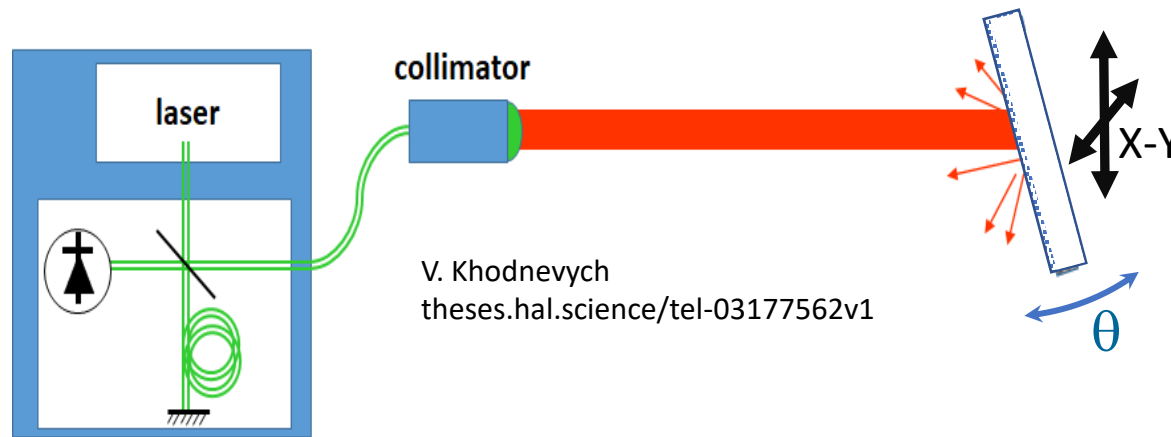
"Speckle" pattern



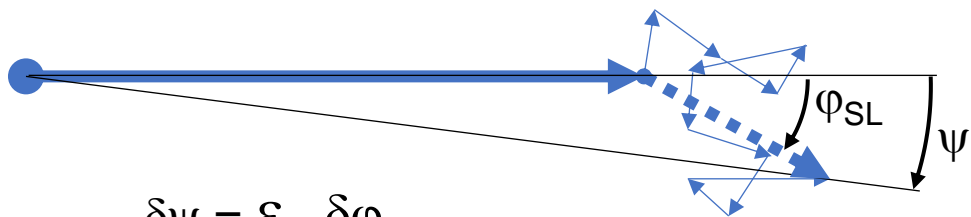
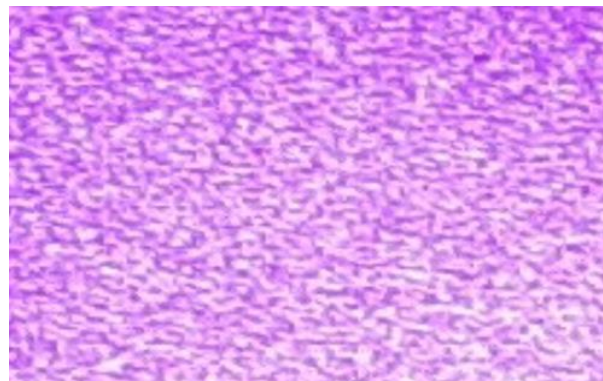
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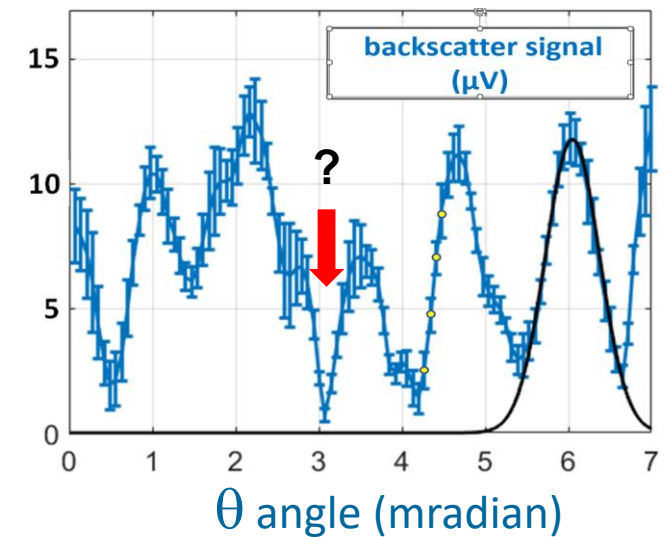


"Speckle" pattern



$$\delta\psi = \epsilon_{SL} \delta\phi_{SL}$$

dark spots can help mitigate $\delta\psi$



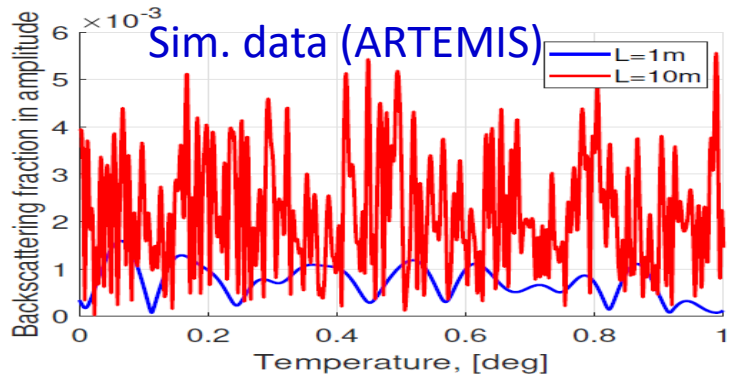
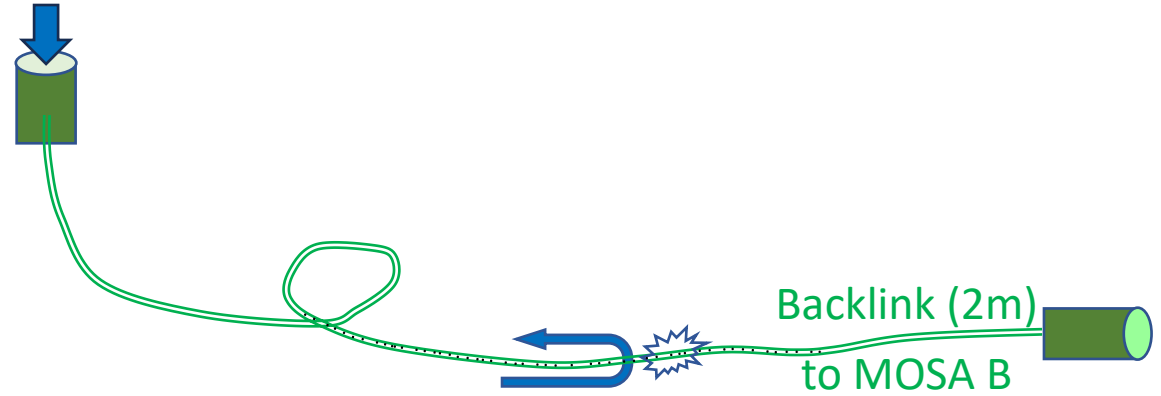
various types of stray light: what about optical fibres ?

The main SL generator in fibres is Rayleigh scattering

- due to the irregularities of the fibre core
- also displays speckle structure vs temperature

=> phase and amplitude noise due to $\delta(\text{Temperature})$

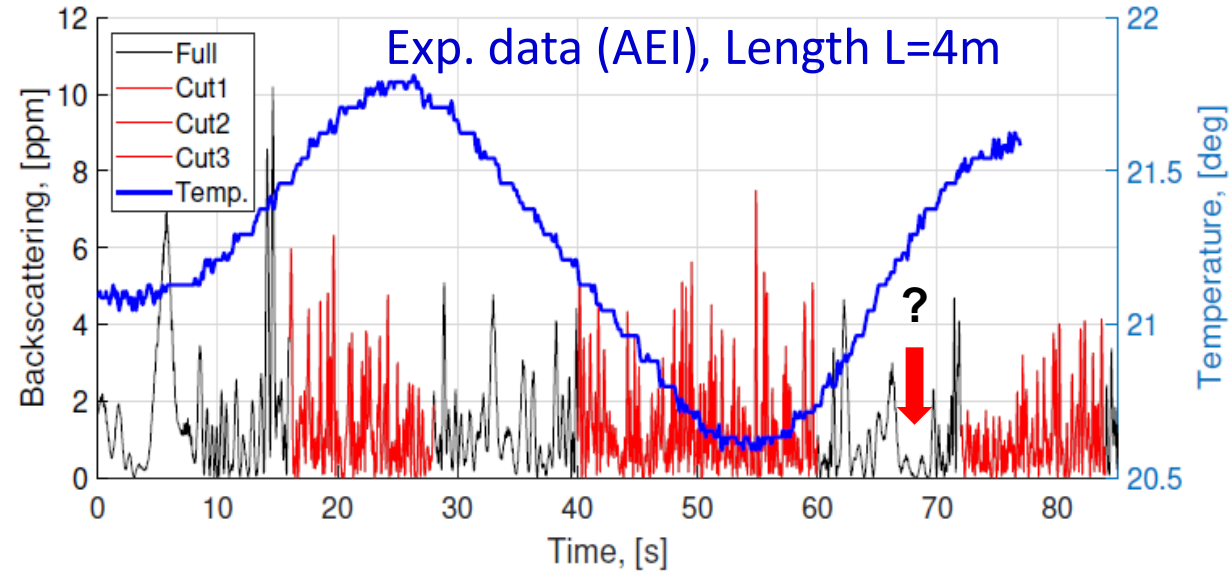
LISA's backlink is a significant contributor in Perf. Model



SL phase noise \uparrow when SL amplitude \downarrow
Dark spots will not help mitigate phase noise due to Rayleigh BS



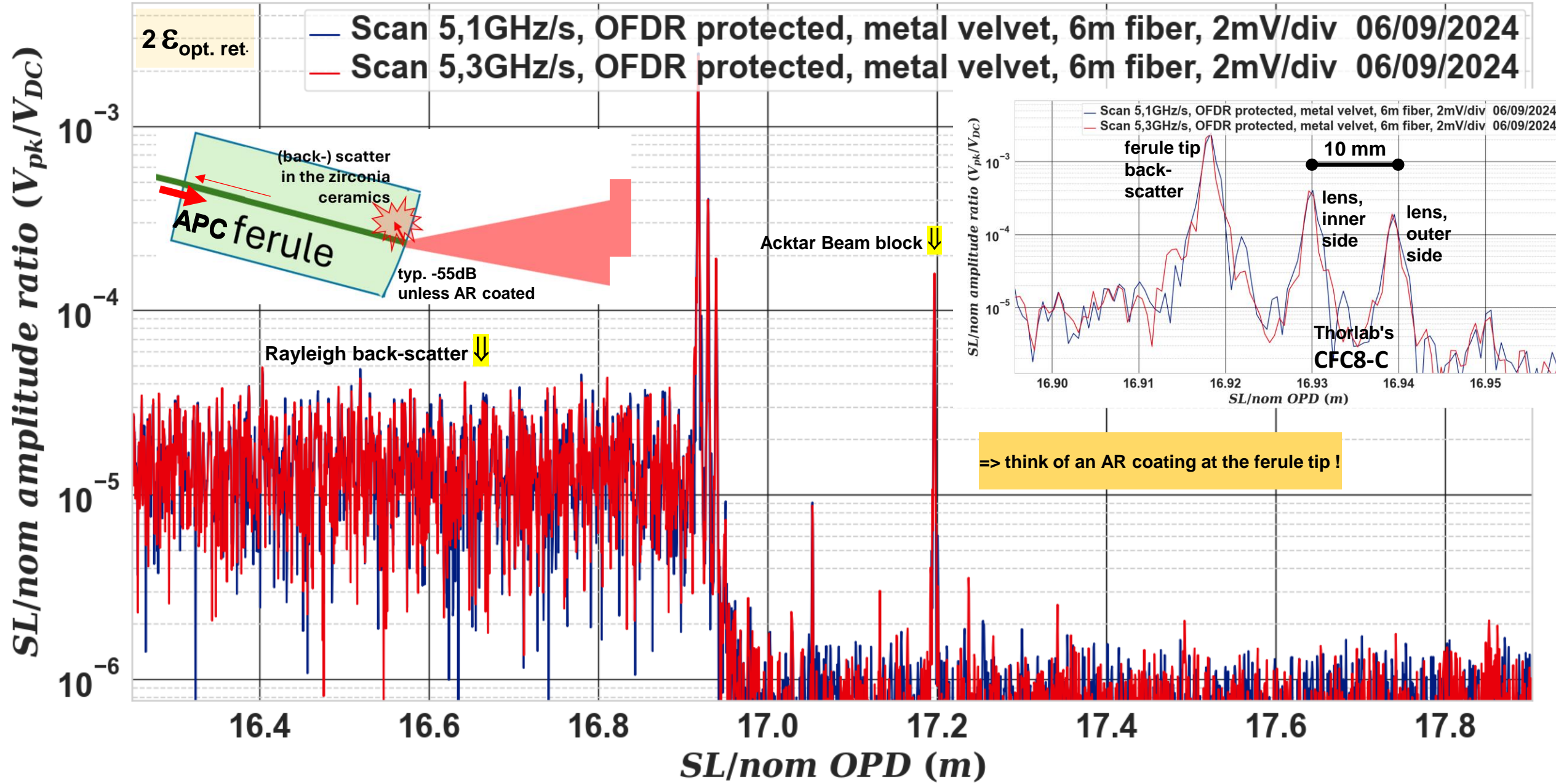
=> small fibre lengths
 choice of the optical fibres



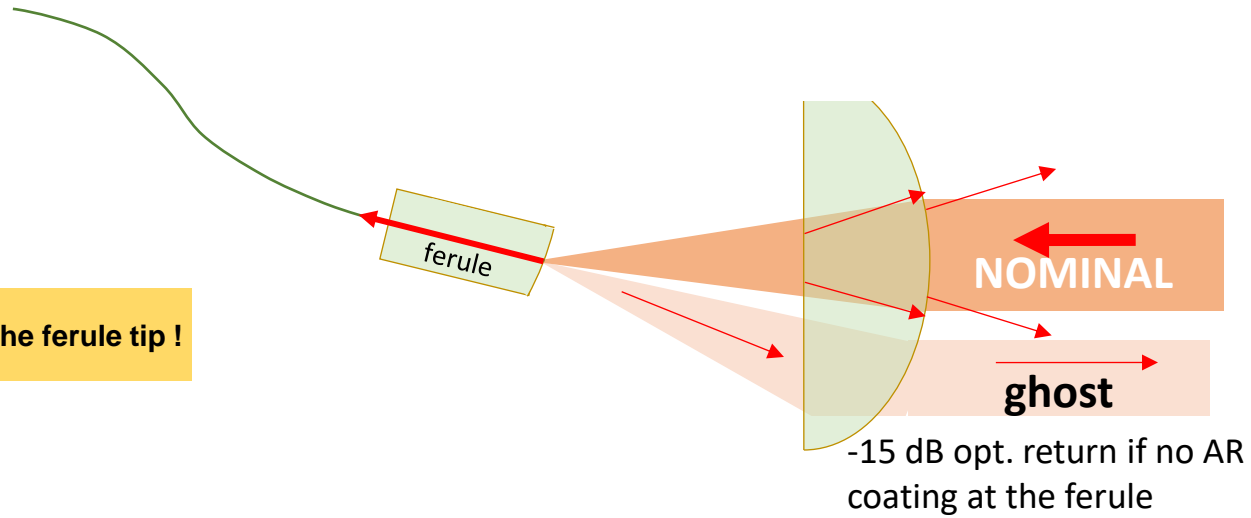
experimental data is provided by Max Zwetz (Ackn: ESA, DLR)



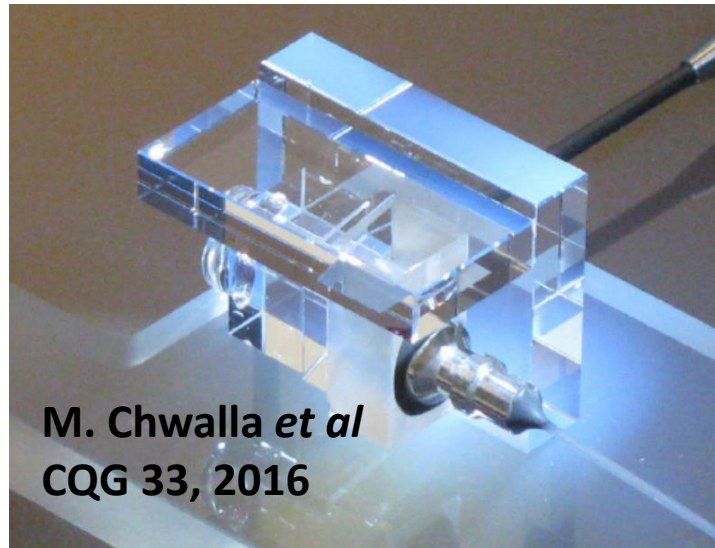
various types of stray light : opt. return in fibered collimators (I)



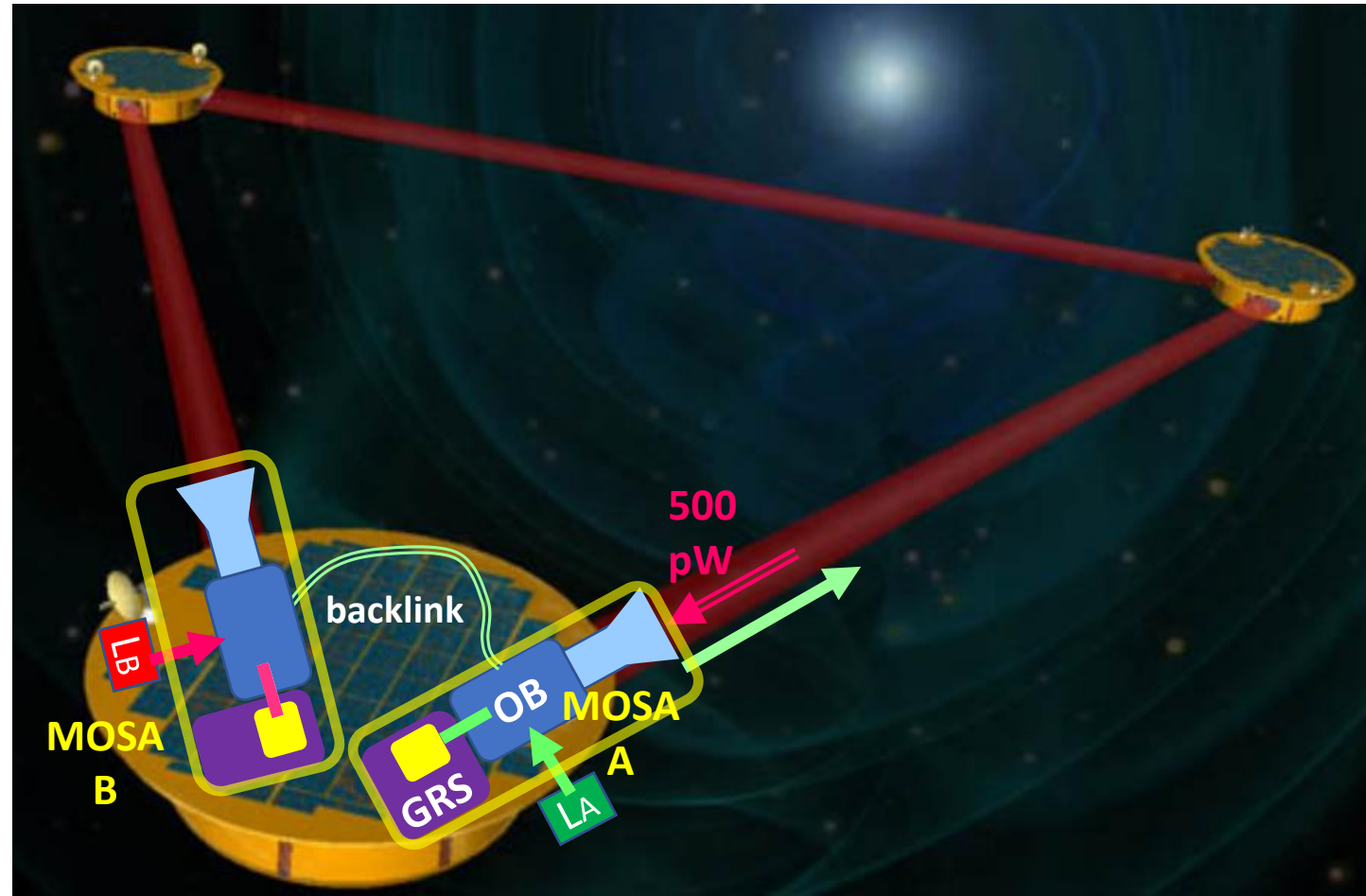
=> think of an AR coating at the ferule tip !



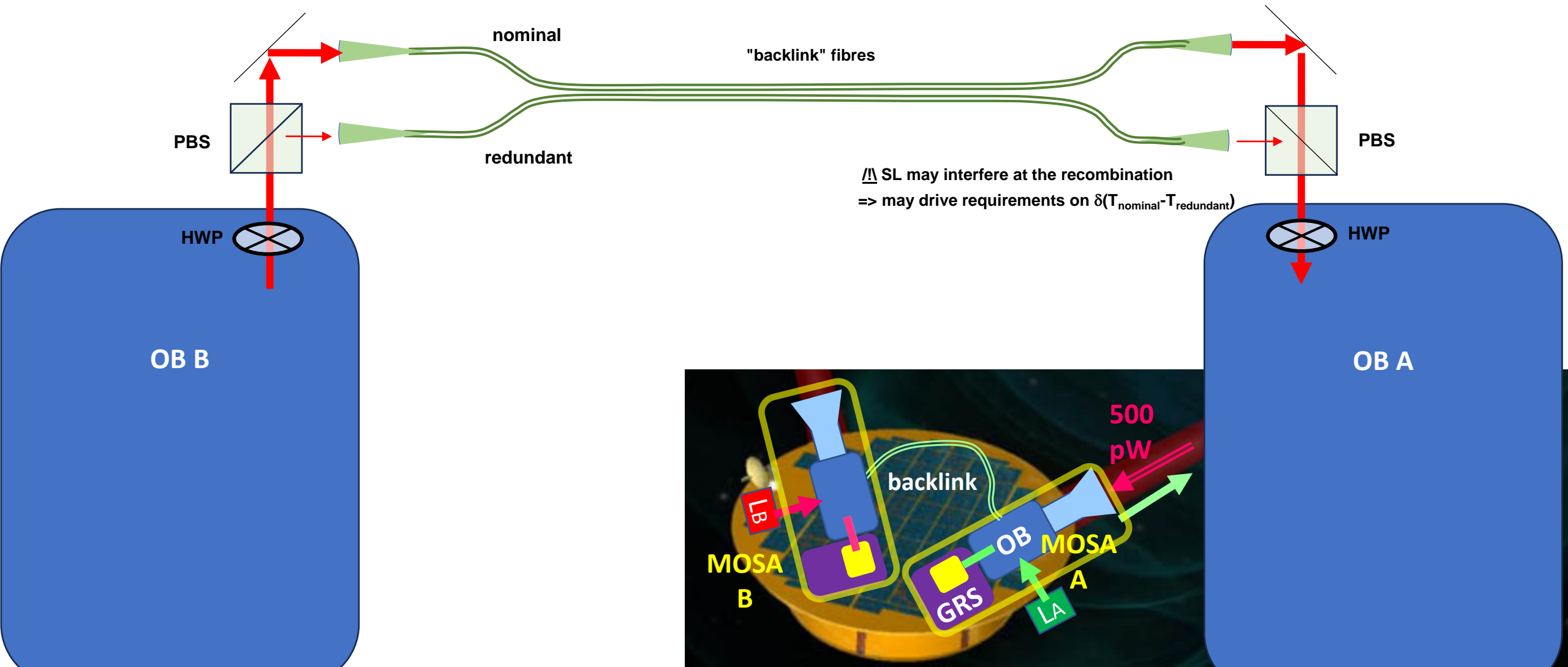
...or use monolithic injectors !



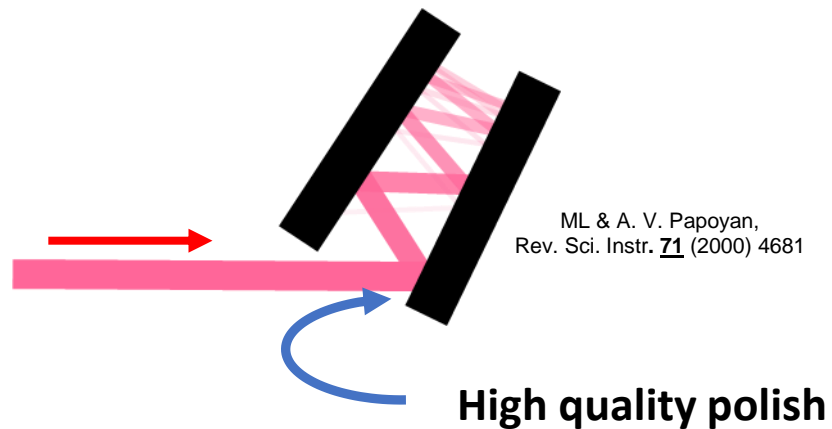
M. Chwalla *et al*
CQG 33, 2016



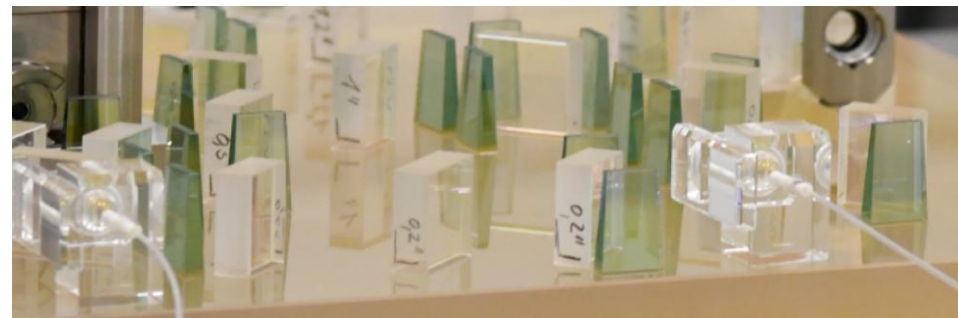
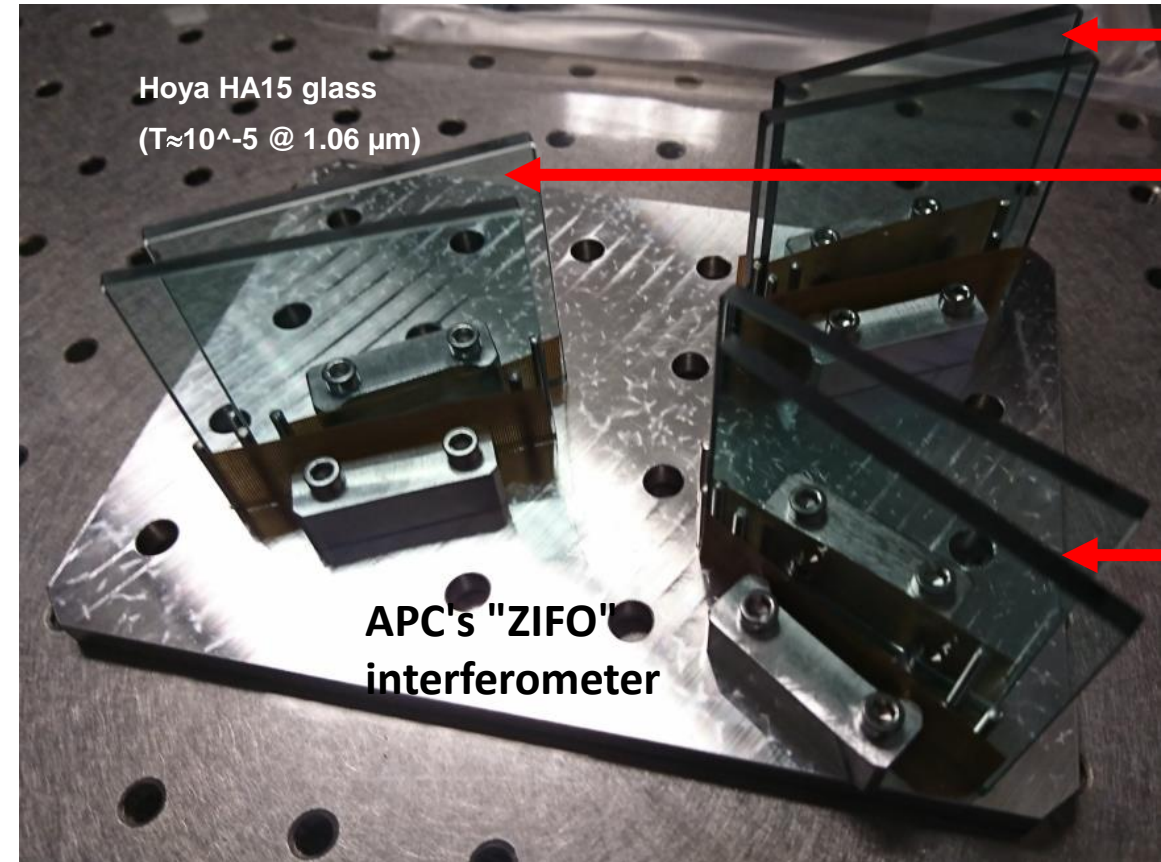
various types of stray light: polarisation



- Black glass
- Black coatings: typical back-scatter 10^{-8} in a $\varnothing 2\text{mm}$ beam
- for ghosts: the 2-plate beam dump for low back-scatter (10^{-11} and below)





- anti-back-scatter coating can help lower the back-scatter
- Fancy about "zero-back-scatter" beam dumps with single-crystals ??
- Other aspects such as damage due to high power can lead to other materials
 - Silicon, SiC, coated SiC, metals, ...
- Convenient low-footprint beam blocks developed by AEI



Measurement of coherent stray light at system level

The "**SLOGSE**" : **Stray Light Optical Ground Segment Equipment** for LISA

Amaël ROUBEAU-TISSOT (PhD st.,  and )
(theses.hal.science/tel-04709436)

Marco NARDELLO

Frédéric CLEVA

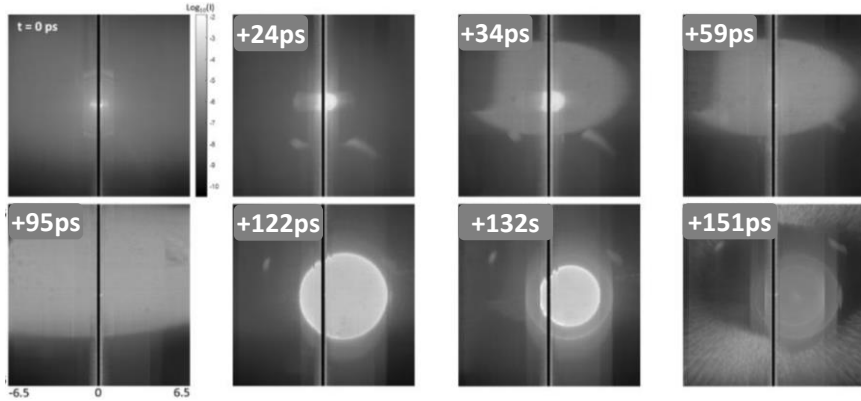
Michel LINTZ

Measurement/identification of stray light at system level

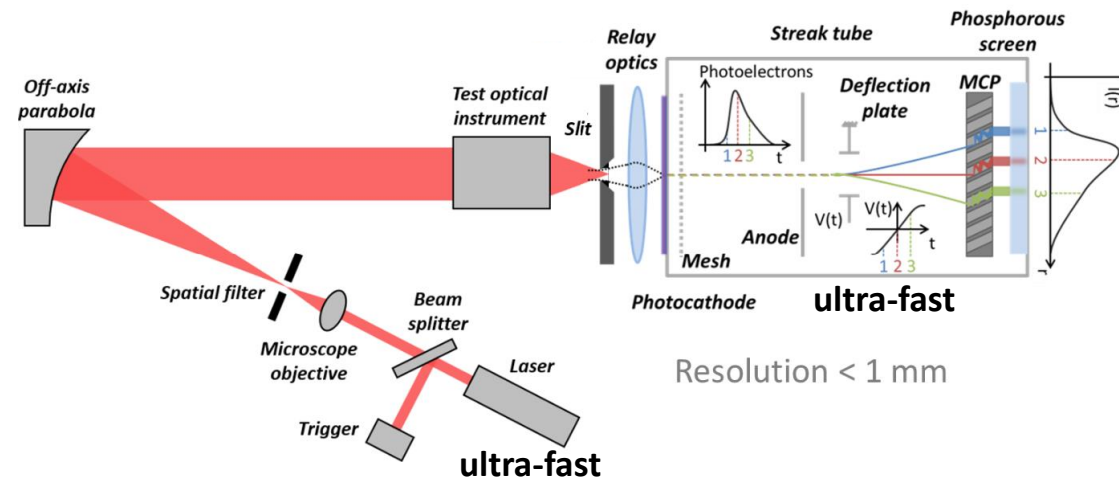
Time of flight techniques:

- ultra-fast laser source + ultra-fast detectors

=> knowledge on the distance (hence the path) followed by stray light



L. Clermont *et al.* (Liège)



They are not specific of coherent stray light: useful for imaging systems, not necessarily for interferometers

Coherent techniques: can be implemented after the assembly of the system under test, **using the system's detectors**

=> inspired by optical frequency-domain reflectometry (OFDR), the optical version of the radar's FMCW (frequency modulated CW)

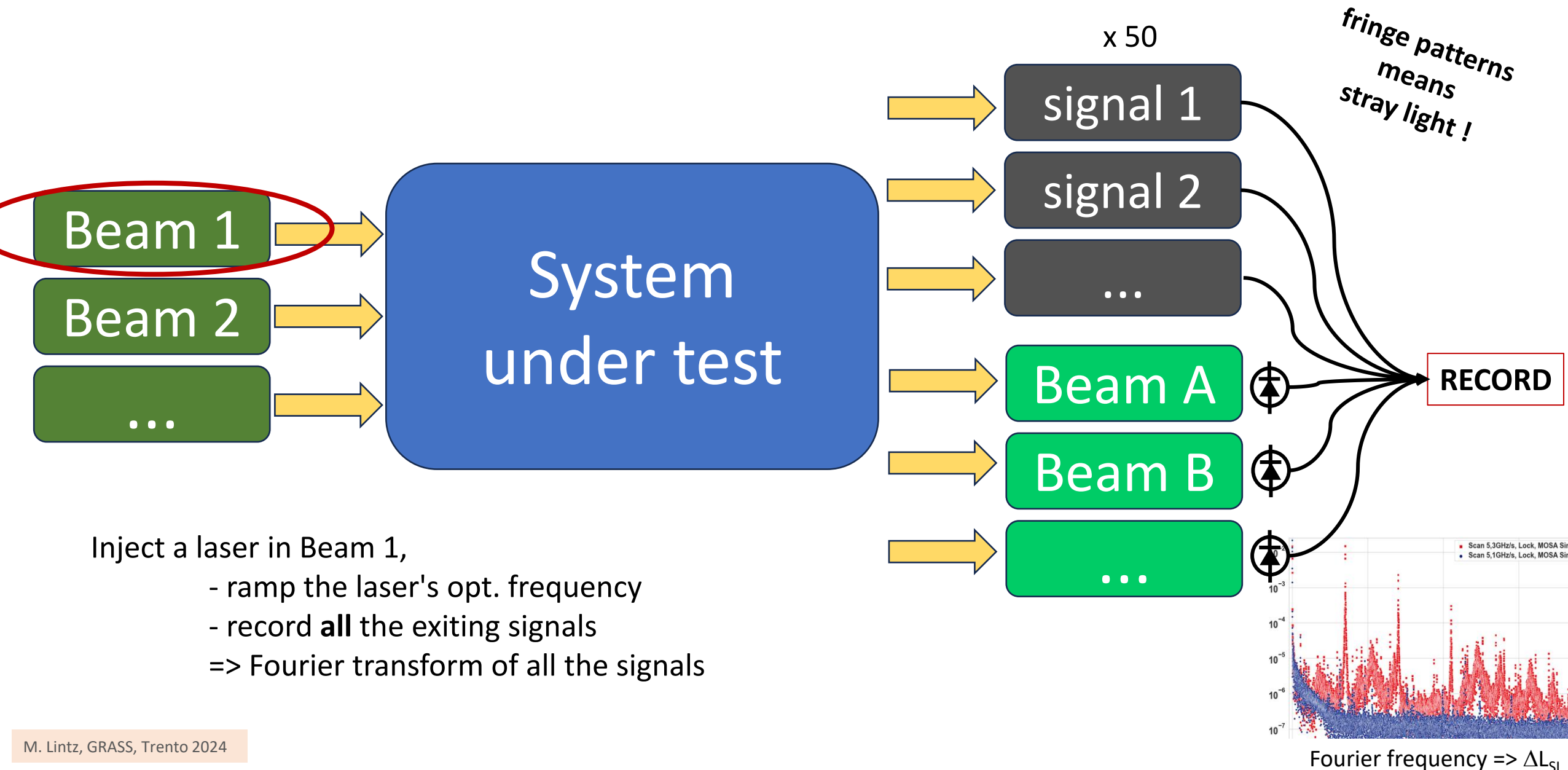
Commercial reflectometers for the monitoring of faults in telecom networks

...but not adapted to measuring stray light in LISA

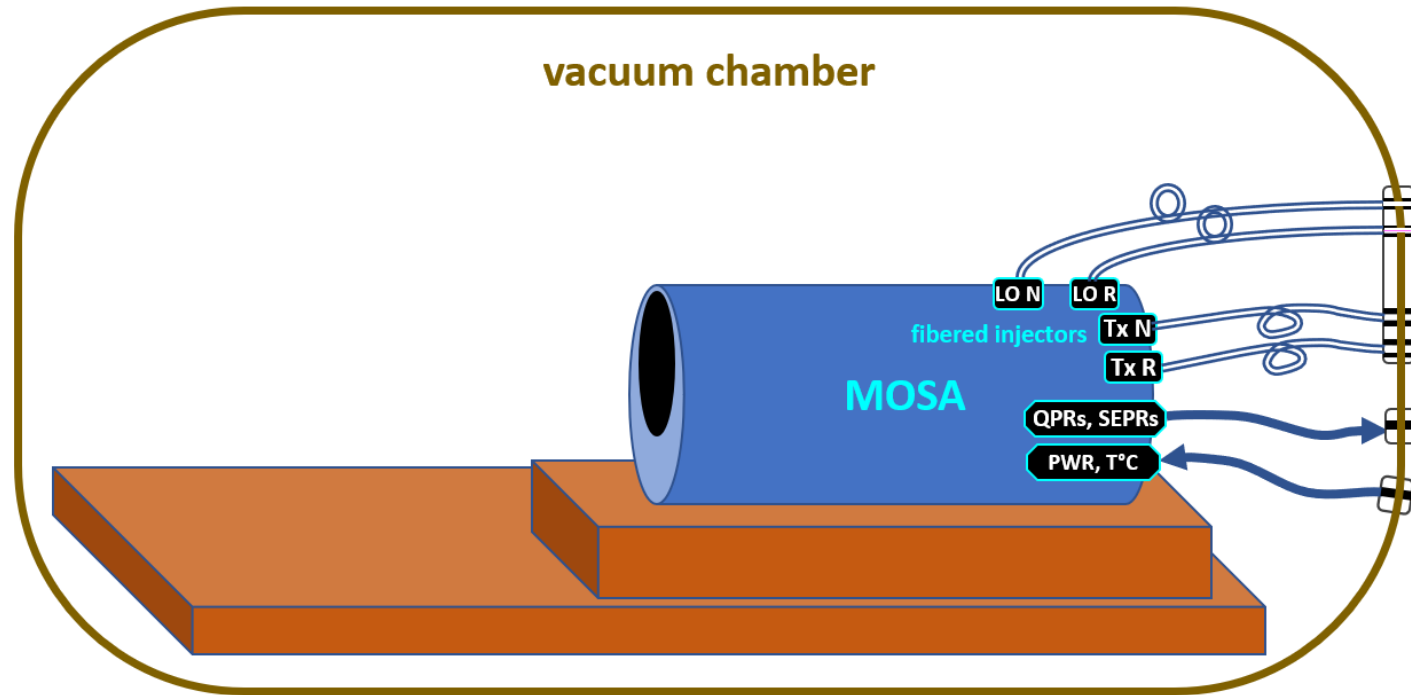
- stray light in LISA is **not** just optical return (scattered light, diffraction, ghosts, .. to all the detectors)

Same with low coherence ("White-light") reflectometry + moving mirror

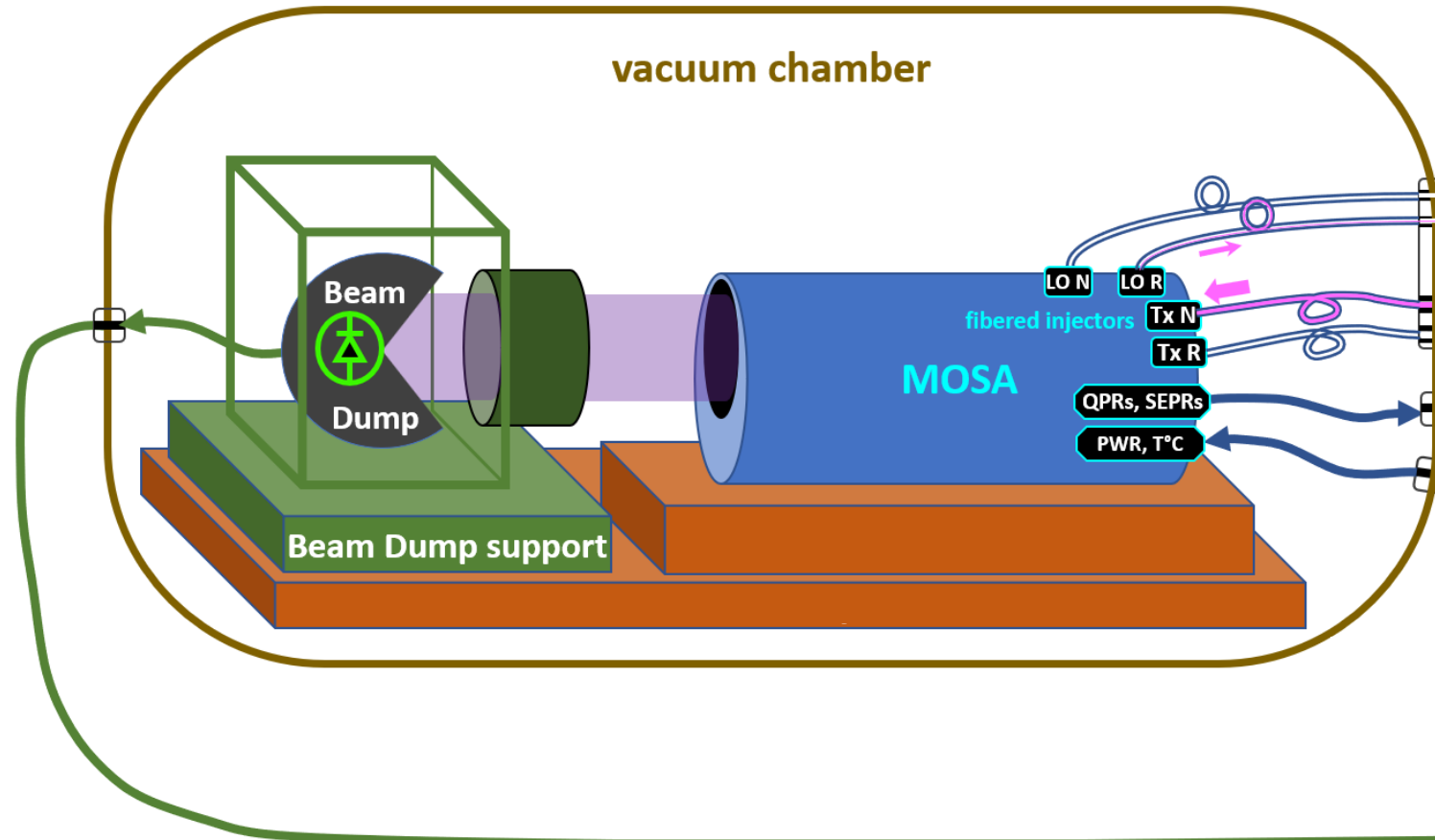
Measurement + identification of stray light in a complex optical system



The stray light measurement in LISA's MOSA



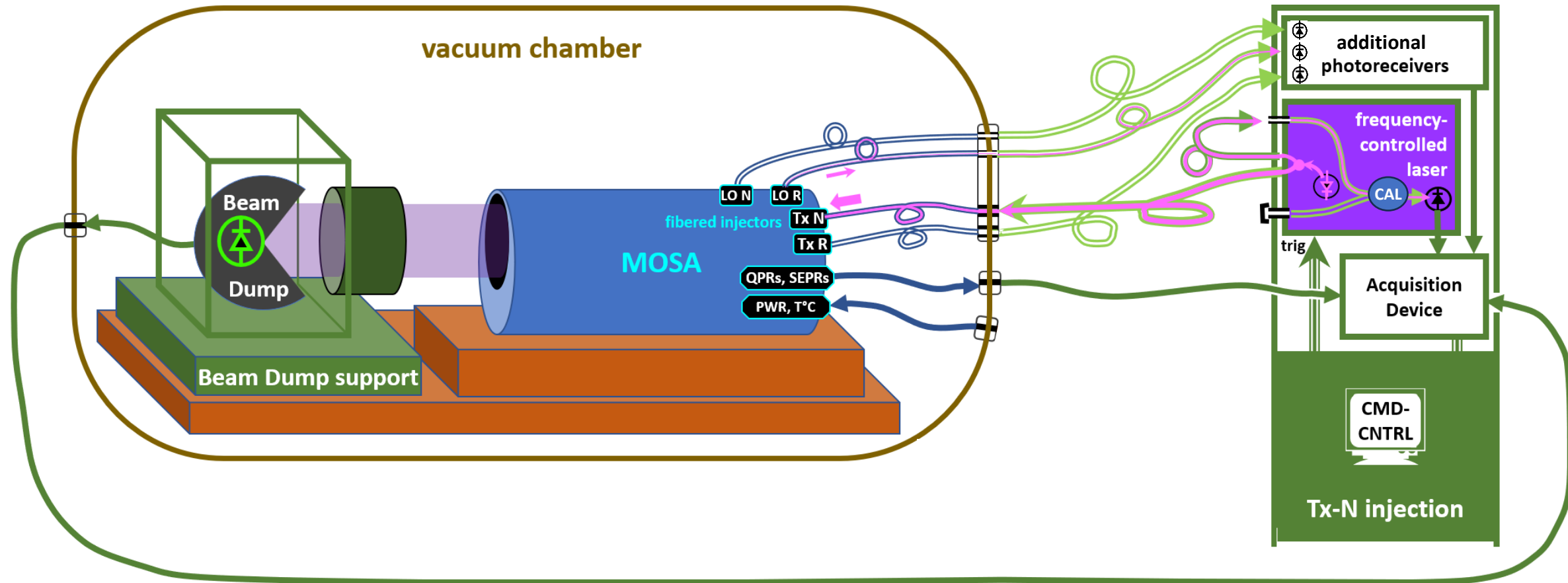
The stray light measurement in LISA's MOSA



- Laser source produces **two** beams:
 - one powerful,
 - the other $\approx 1\text{mW}$ Powerful
- beam emitted => **beam dump required**

Need for the "calibrator" unit and signal

The stray light measurement in LISA's MOSA



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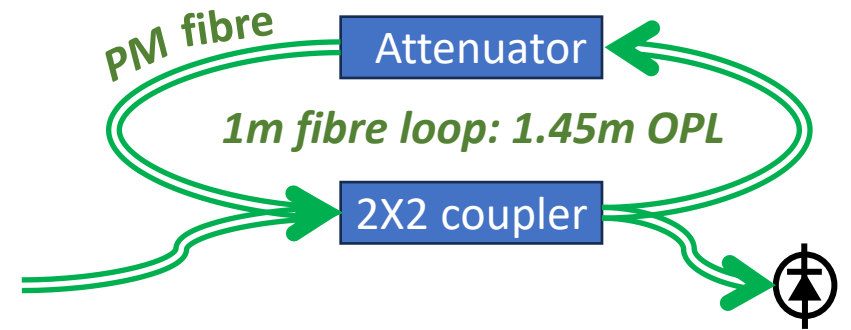
The frequency-ramped laser source: monitoring the ramp

Frequency ramp must be linear ($<10^{-4}$), with a known and reproducible value

=> The "calibrator" is a fibered interferometer which monitors

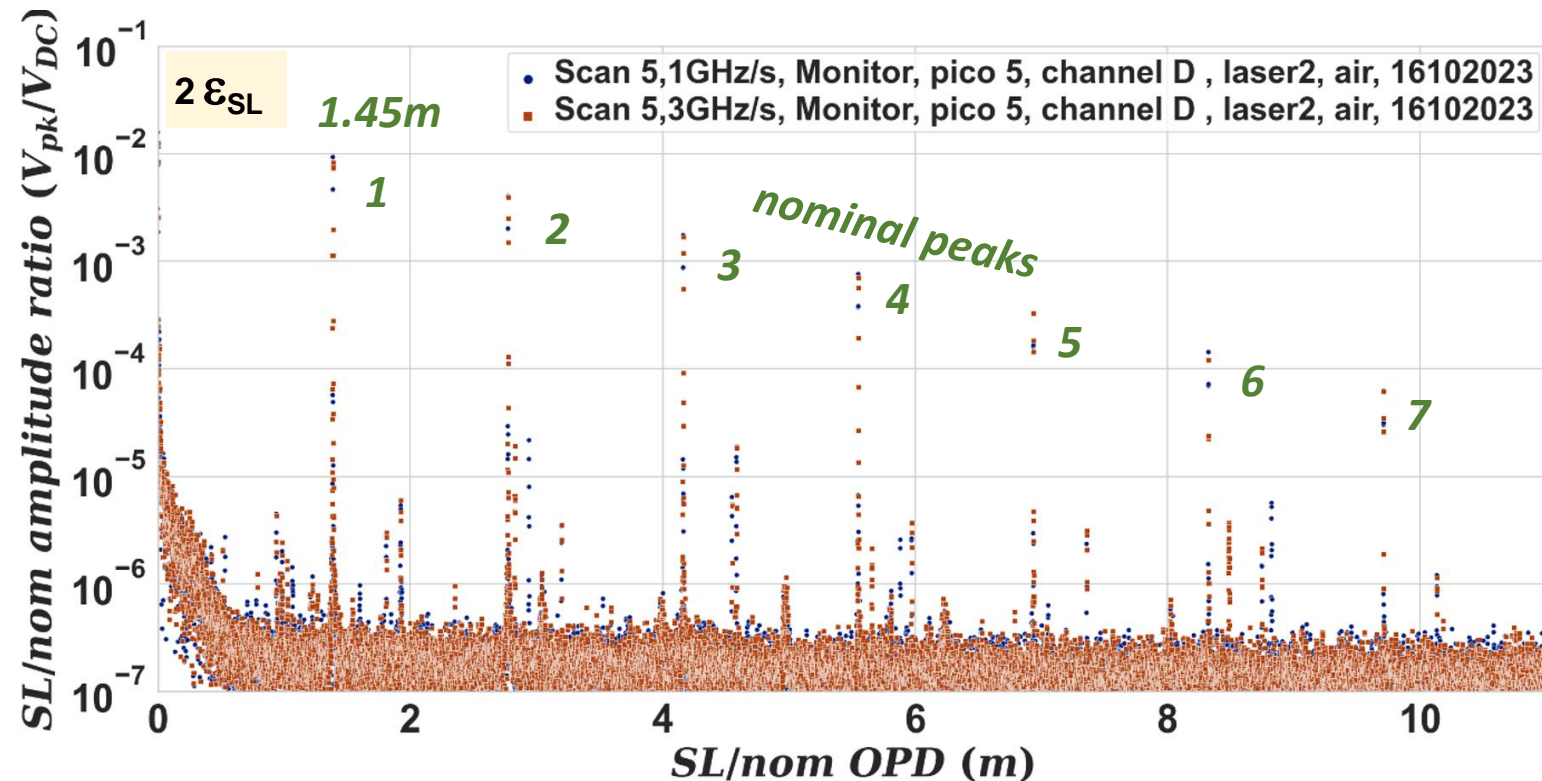
- the linearity of the frequency ramp
- the reproducibility of the ramp rate
- the presence of stray frequency modulations

and more



=> 7 nominal peaks

allows real-time monitoring of the ramp to $\ll 10^{-4}$



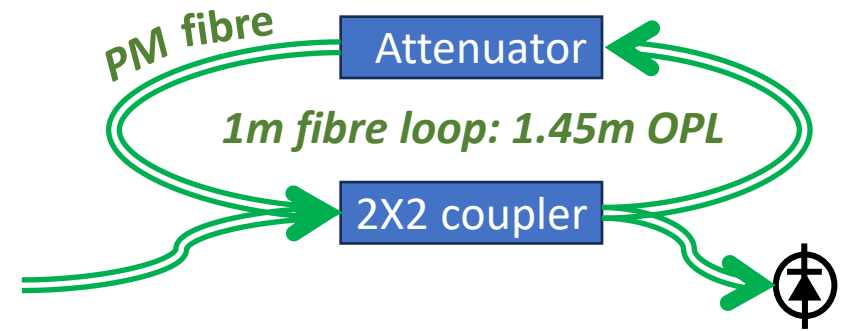
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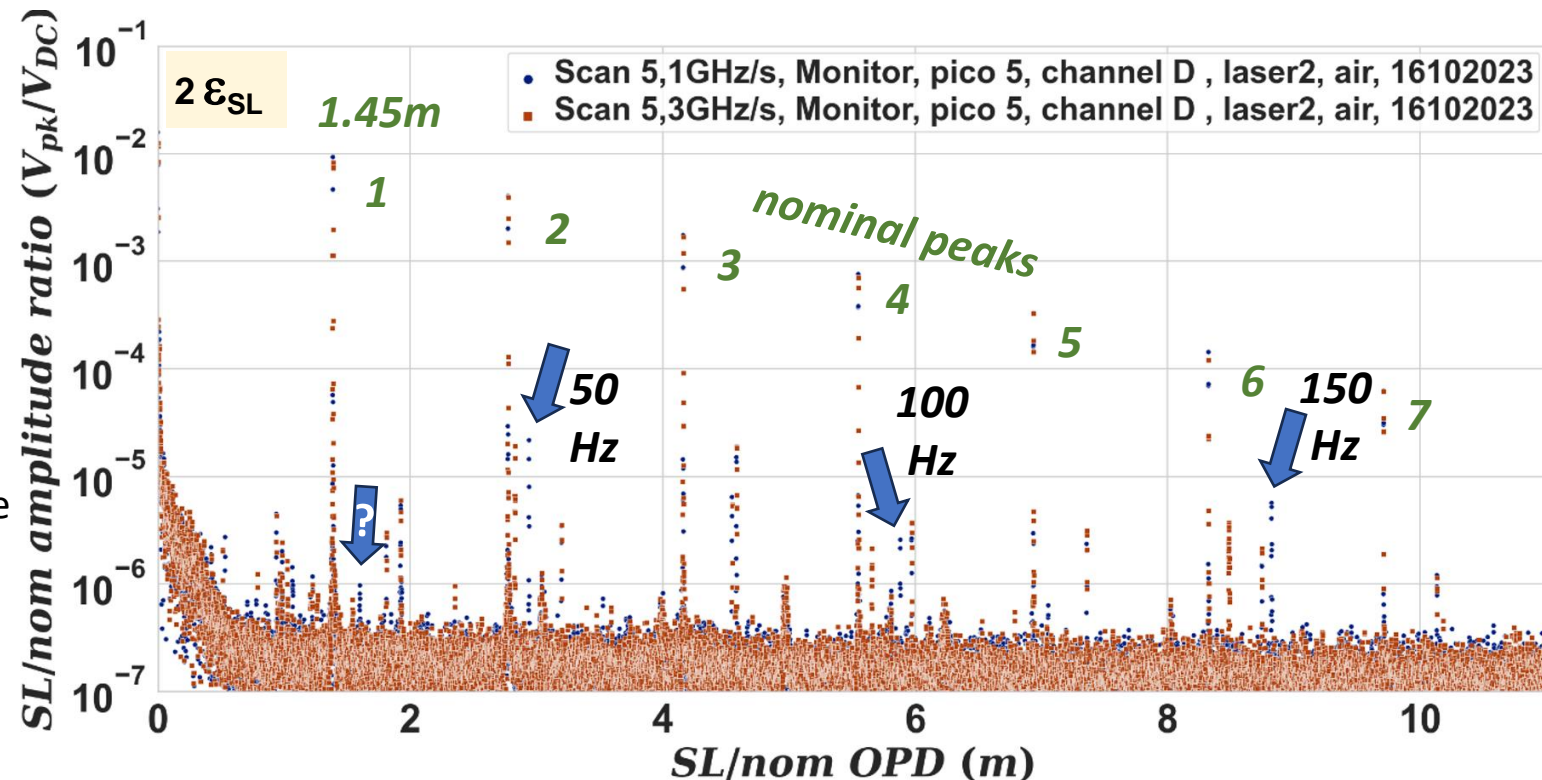
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Trick to identify parasitic peaks:

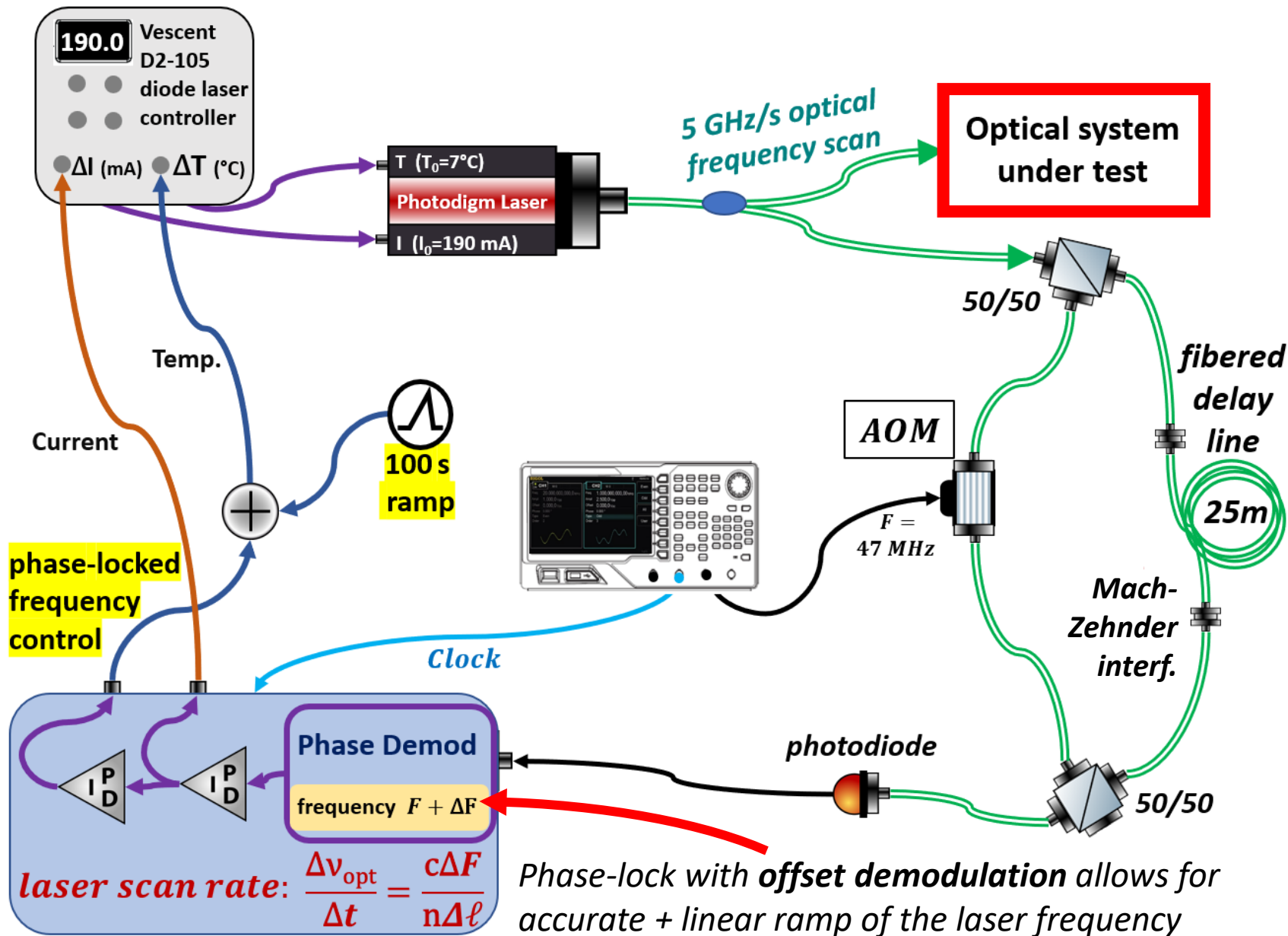
- first scan with scan rate SR1
- second scan with rate SR2

=> only true optical peaks exactly overlap red/blue

=> **signature to reject pickups of spurious signals**

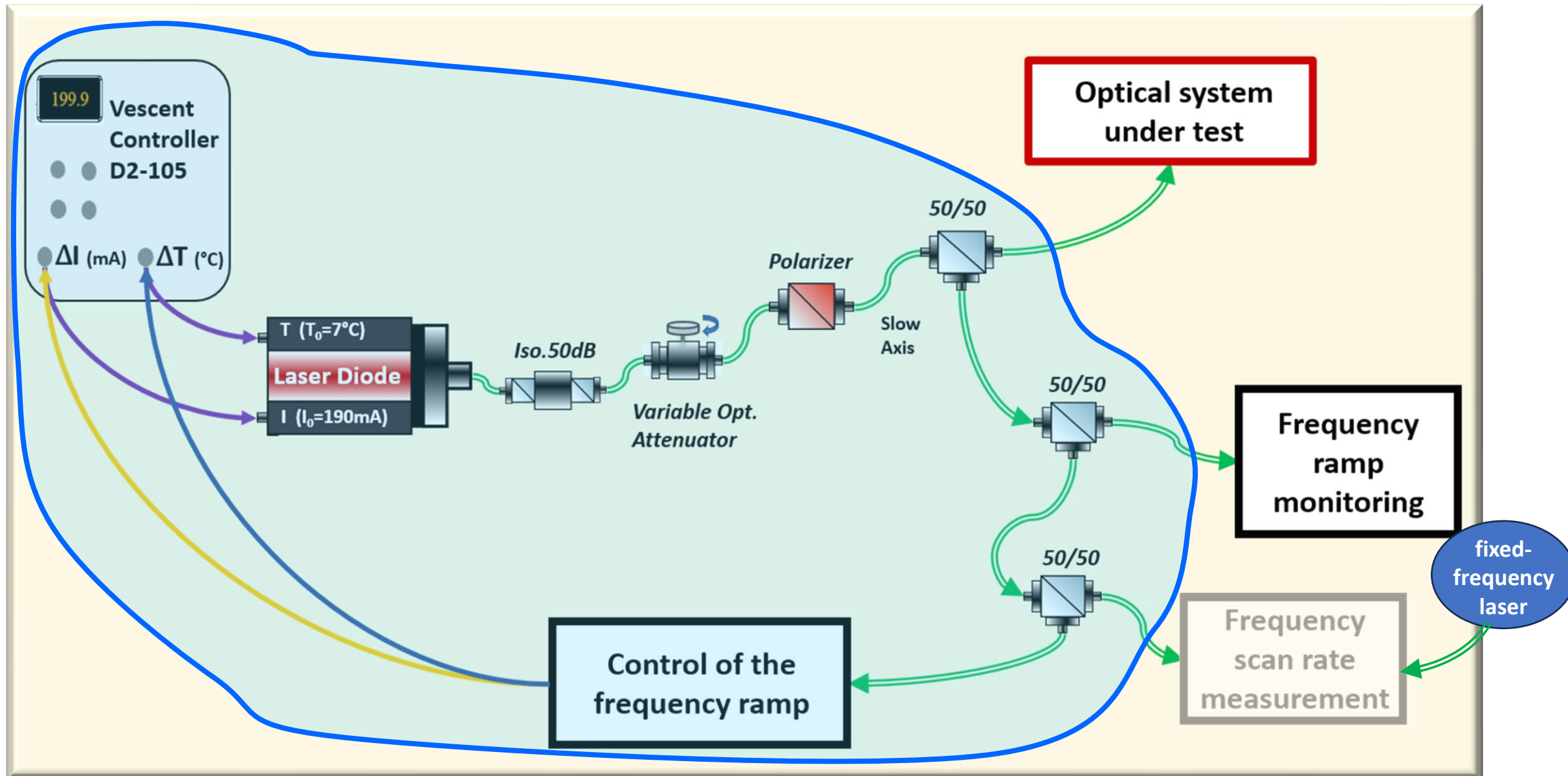


Implementation of the frequency swept laser source



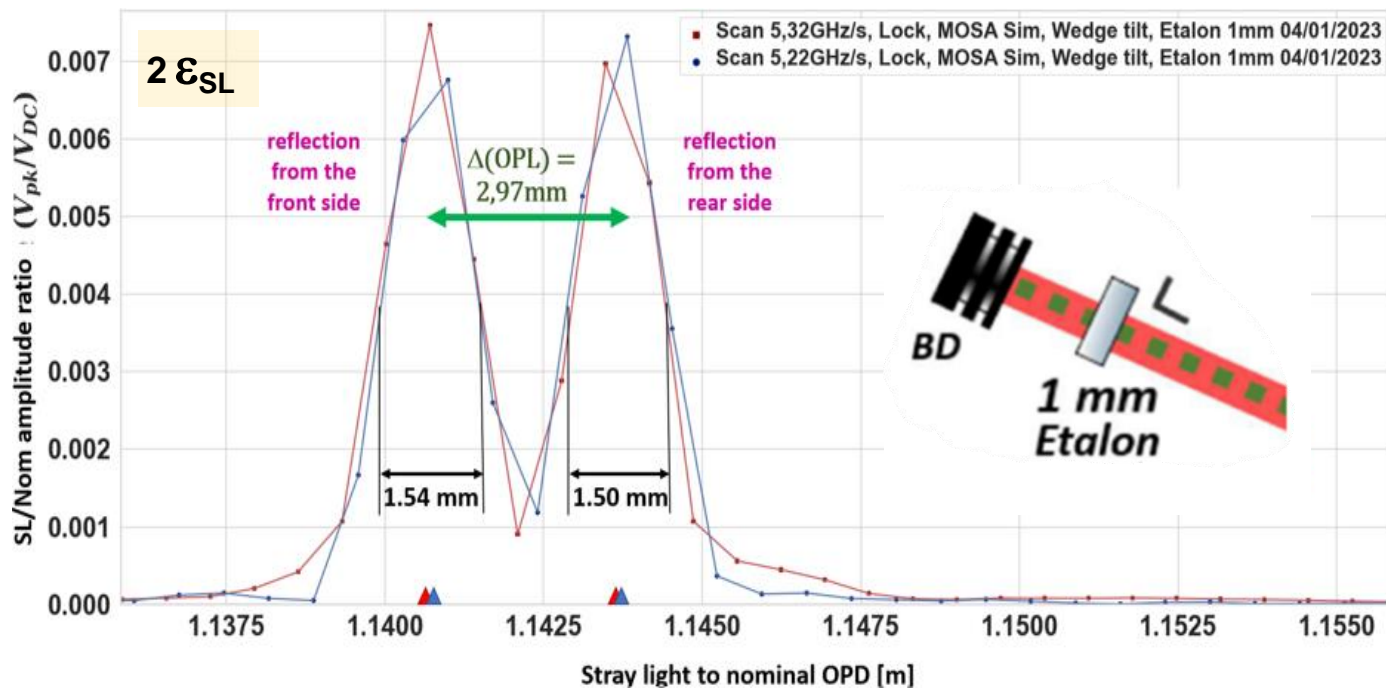
2nm-span optical frequency-scanned laser source

Implementation of the frequency swept laser source

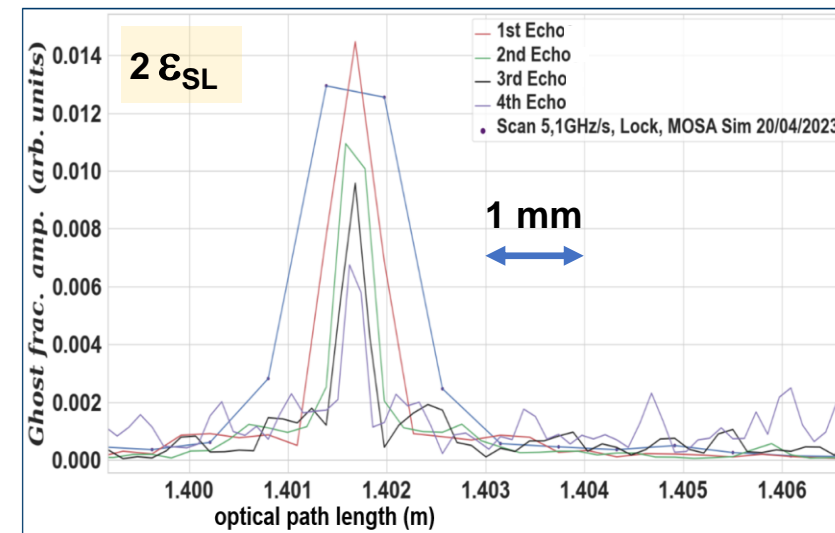


Characterization of the Stray Light measurement: OPD resolution

- "Spectroscopist's resolution" : Resolution between nearby peaks, characterized with a 1mm silica etalon (optical frequency scan: 530GHz \approx 2nm)



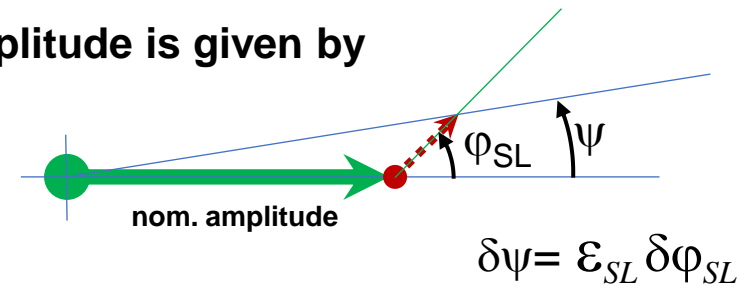
- "Metrologist's resolution" : Reproducibility/consistency at the 0.1 mm level in the OPD measurements



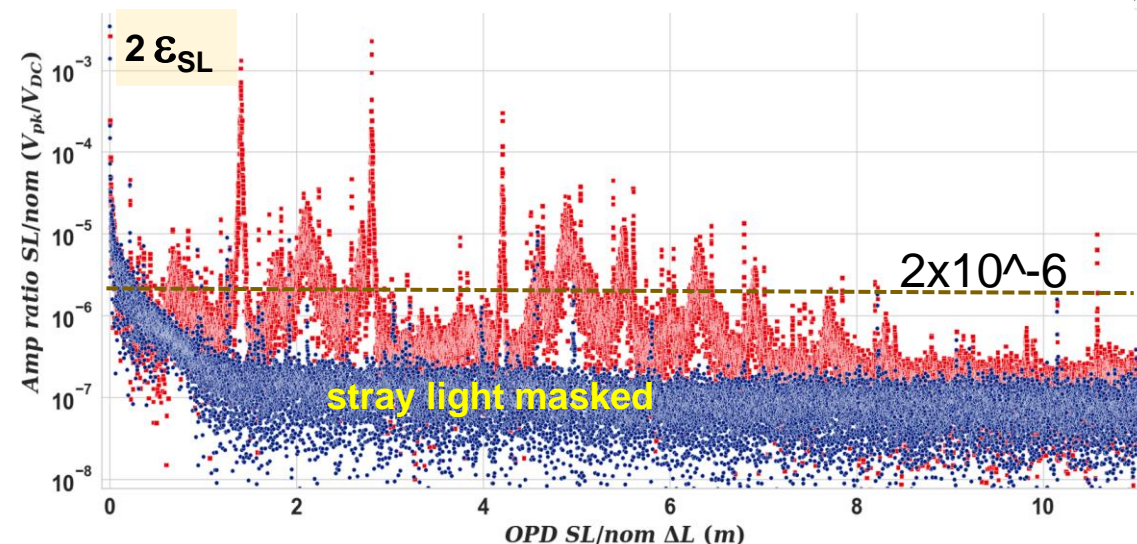
What noise floor for the SL optical amplitude measurement ?

- For each component the "acceptable fractional SL amplitude" $\epsilon_{\text{accept-SL}}$ stems from the performance model:
 - noise in the final LISA measurement should not exceed 10 pm/ $\sqrt{\text{Hz}}$ with less than ≈ 1 pm/ $\sqrt{\text{Hz}}$ from stray light
 - the allocation can be broken to ≈ 0.1 pm/ $\sqrt{\text{Hz}}$ for each contribution to stray light
- Then, for each contribution to stray light, the acceptable fractional amplitude is given by

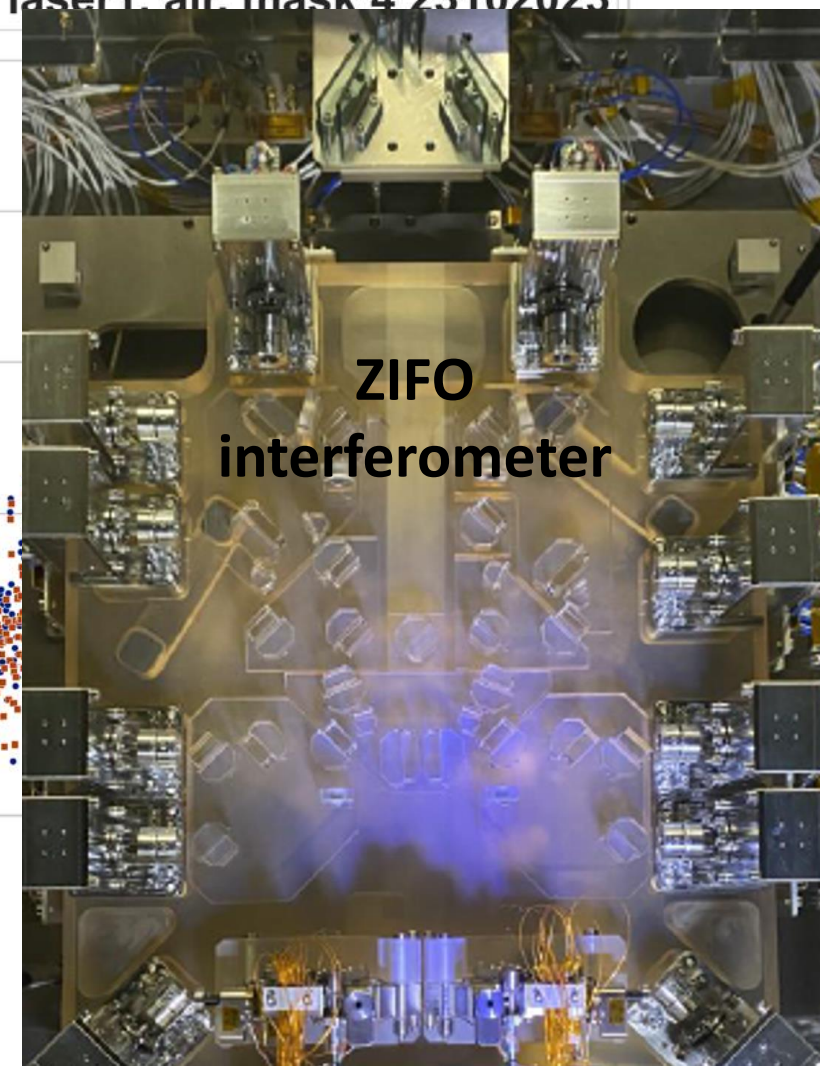
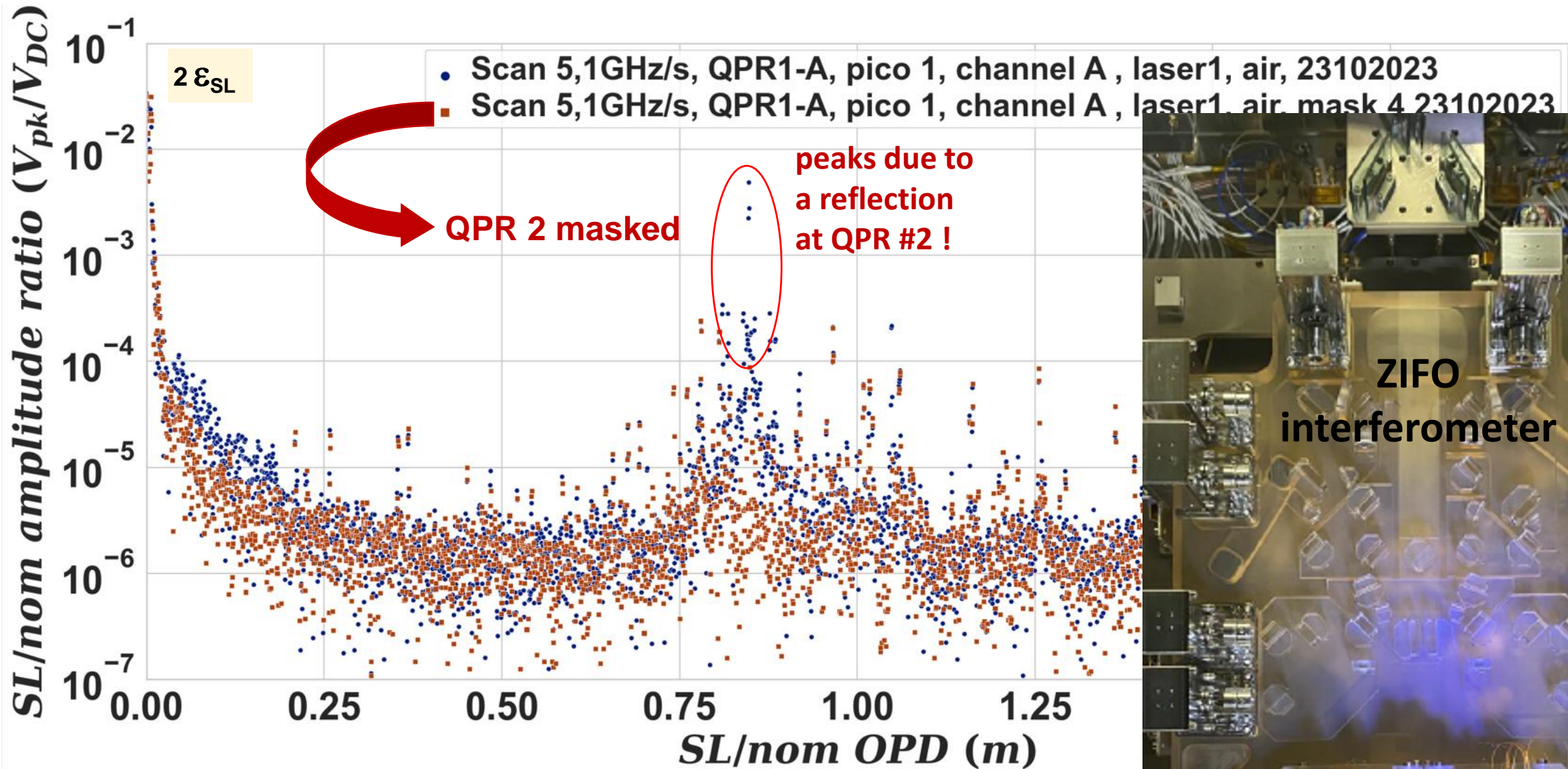
$$\epsilon_{\text{accept-SL}} = [\text{Allocation for stray light}] / [\text{SL path length noise}]$$



- Then the measurement floor must be $< [\epsilon_{\text{accept-SL}}]_{\text{smallest}}$ with a margin (SNR) of 30
- Presently this leads to a fractional noise floor of 2×10^{-6} in the Fourier transform data.
- If an excess is observed with one component, the final check is done globally, at MOSA level, against the Performance Model

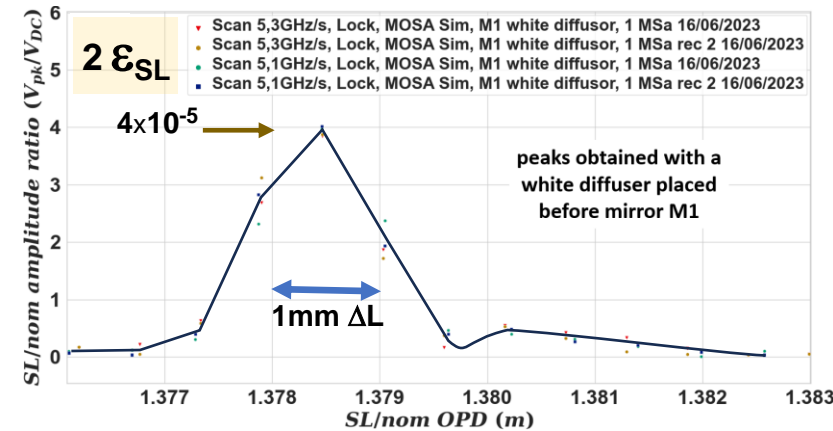


Typical recordings on the ZIFO interferometer

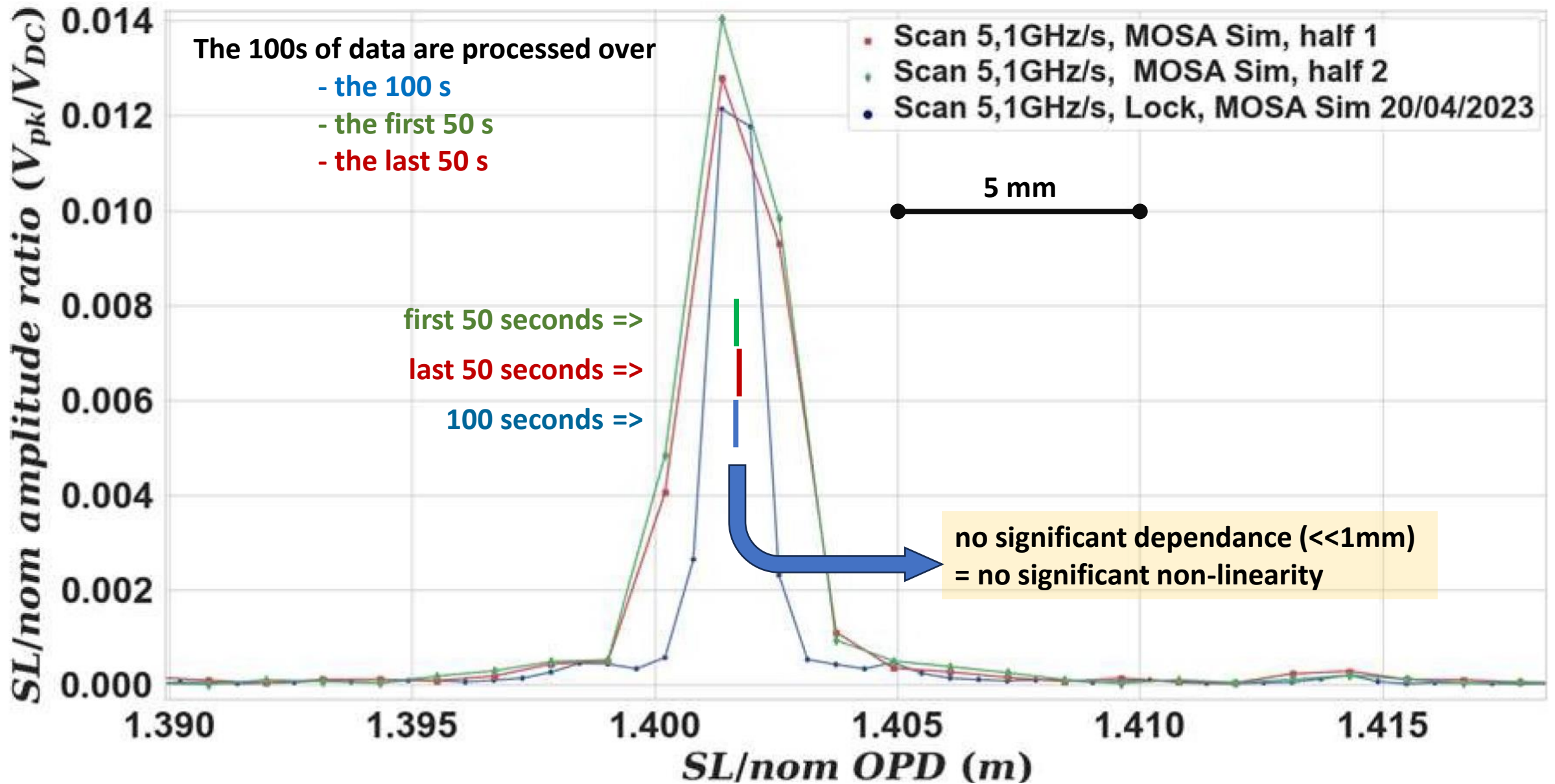


Conclusions and outlook

- Presently no showstopper with the prototype
- OK for the measurement of scattered light \Rightarrow
- Noise floor at OPD < 30 cm to be improved by normalization of the signals
- "Polarization wobbling" reduces the effective dynamics
- Residual modulation in the laser's optical frequency scan (\Rightarrow small, reproducible stray peak) to be reduced
- The prototype was recently coupled to "ZIFO", a LISA-similar optical interferometer
 - \Rightarrow check for the difference tests in vacuum vs tests in ambient air
No striking difference apart from the index of air
 - Interpretation of >2 thirds of the observed SL contribution (ongoing work)
- Modeling under FRED retrieves most of the observed Stray Light peaks
 - \Rightarrow will be presented at ICSO 2024 by Marco Nardello
- Addition of a Michelson IFO allows to turn the "SLOGSE" into a reflectometer
 - \Rightarrow will provide many data for optical return from photodiodes, black coatings, etc...
 - noise floor presently 10^{-13} (expected $\approx 10^{-14}$) in fractional stray light power



Back-up slides: dispersion in the master interferometer's fibre?



Back-up slides: the MOSA simulator

