

Frequency drift interferometry for coherent stray light characterization on the LISA space interferometers

Amaël Roubreau-Tissot, Michel Lintz, Marco Nardello, Mikhaël Pichot, Jean-Pierre Coulon
Laboratoire ARTEMIS (Observatoire de la Côte d'Azur, UCA, et CNRS), 06304 Nice, France

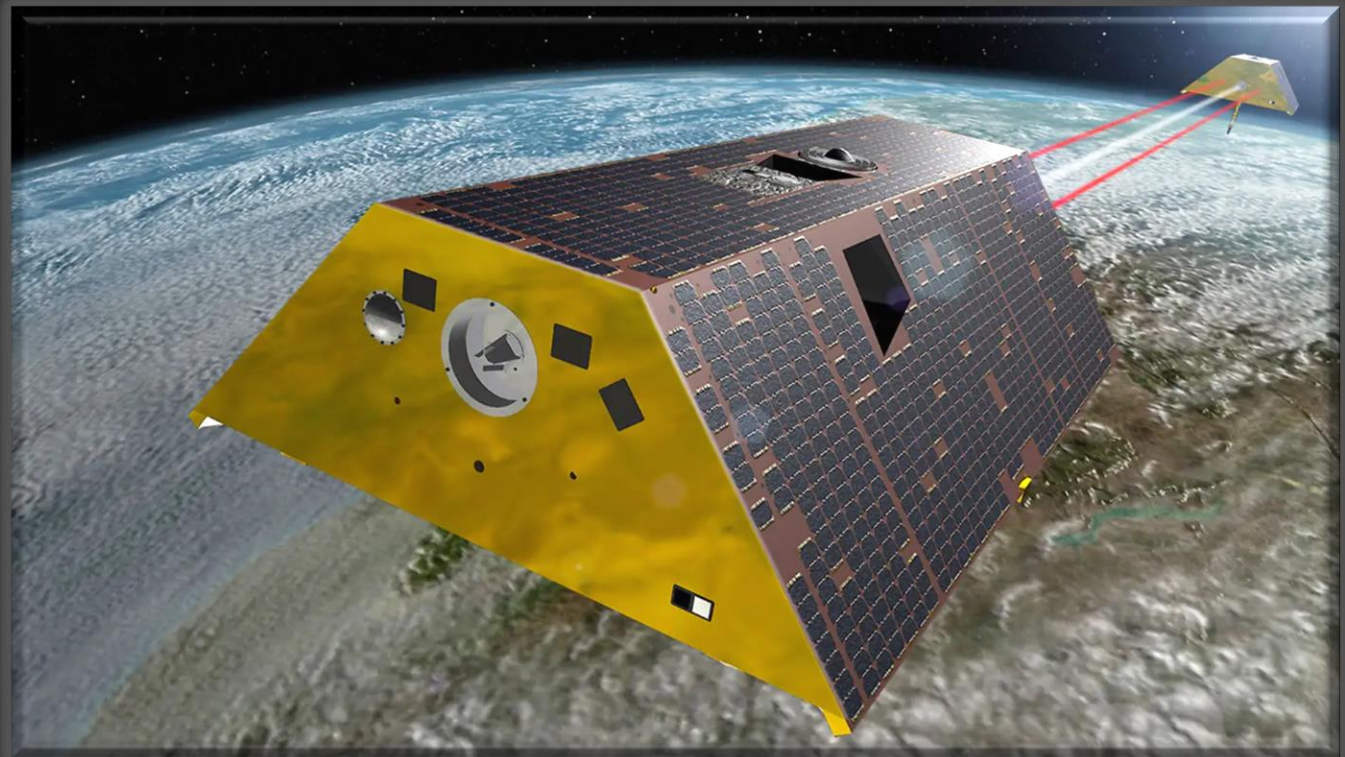


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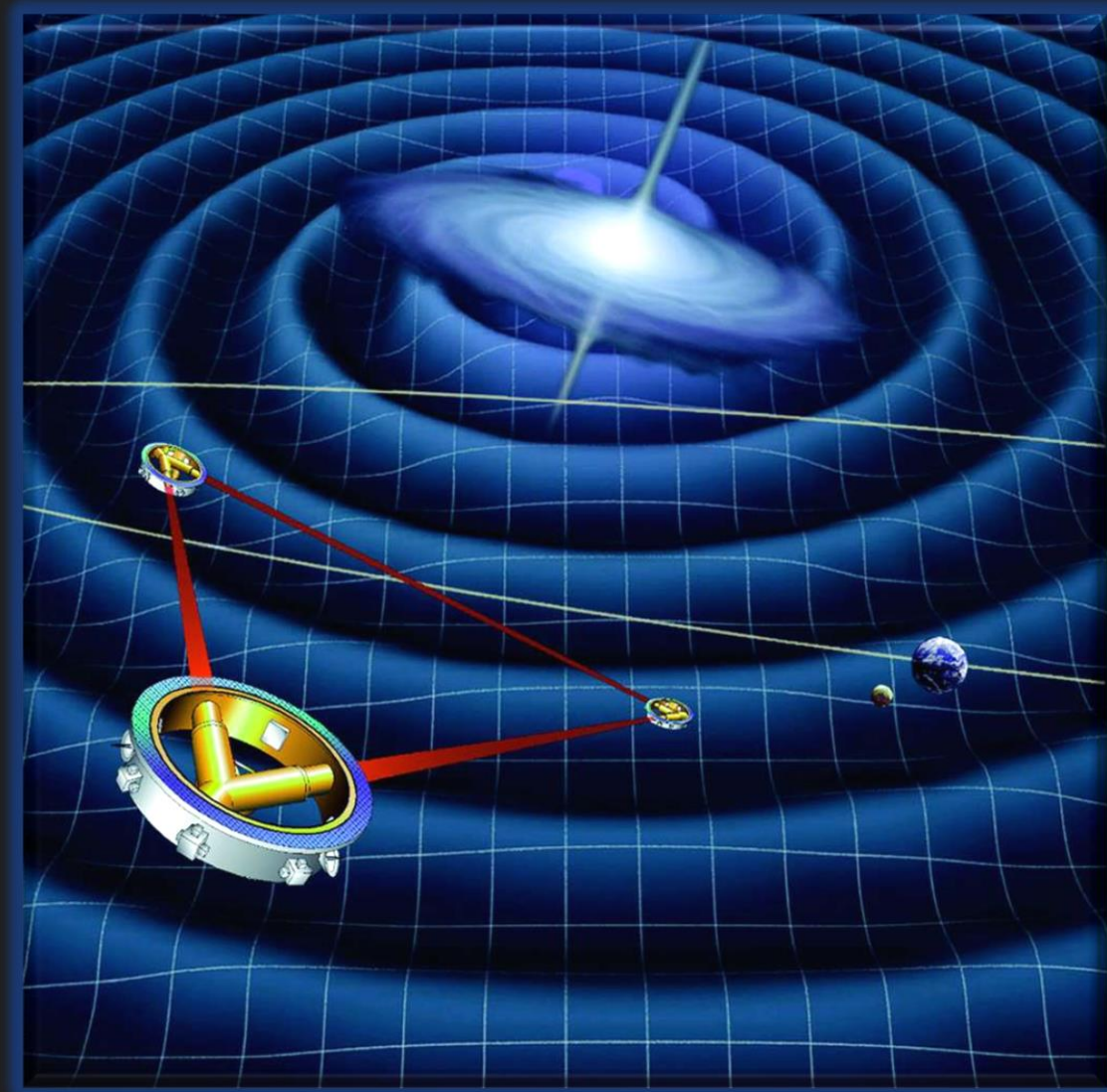
Laser Long-range Space Interferometers

- Measure fluctuations in the separation between two (or more) spacecrafts with high precision
- **GRACE-FO:** First demonstrator of laser long-range interferometry (with the LRI), improves the sensitivity in the measurement of the Earth gravity field, by orders of magnitude!
- Under development: Interferometric Gravitational wave detectors



LISA space mission: « Laser Interferometer Space Antenna »

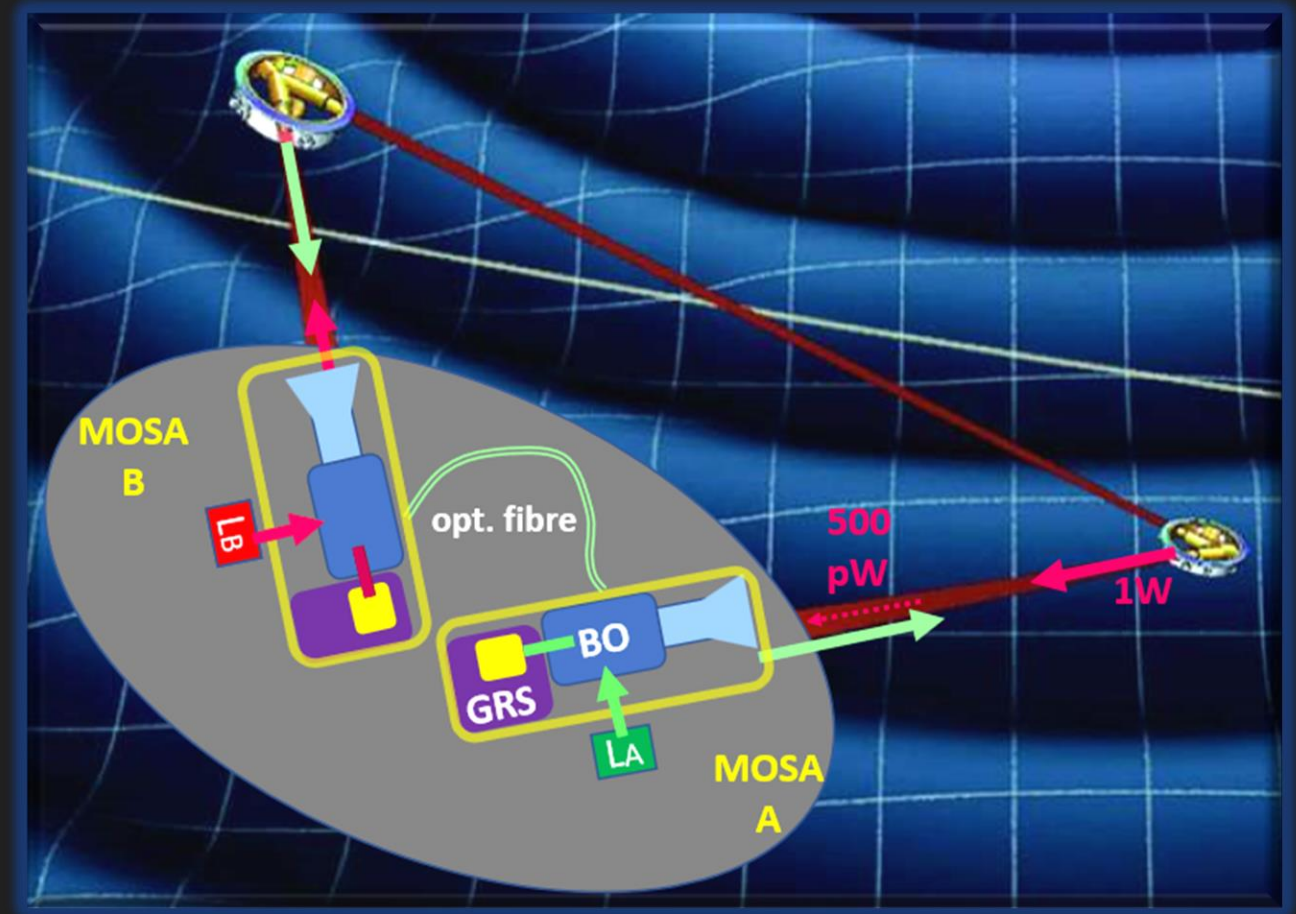
- Space observatory for gravitational waves (20 μ Hz - 1Hz)
- Constellation of 3 satellites in triangular formation flight in heliocentric orbit
- 2 Optical Bench Assemblies called MOSA in each satellite
- 3 heterodyne interferometers in each MOSA (LO-IFO, Long Arm-IFO, Test Mass IFO)



MOSAs: « Moving Optical Sub Assemblies »

Beams :

- Tx ($\sim 2\text{W}$)
 - LO ($\sim 20\mu\text{W}$)
 - Rx (500pW after 2,5 Mkm)
- Long Arm-IFO: SC to SC Heterodyne Interf. (Tx-Rx)
 - LO-IFO: MOSA to MOSA Heterodyne Interf (Tx-LO)
 - Test-Mass IFO (TxTM-LO)

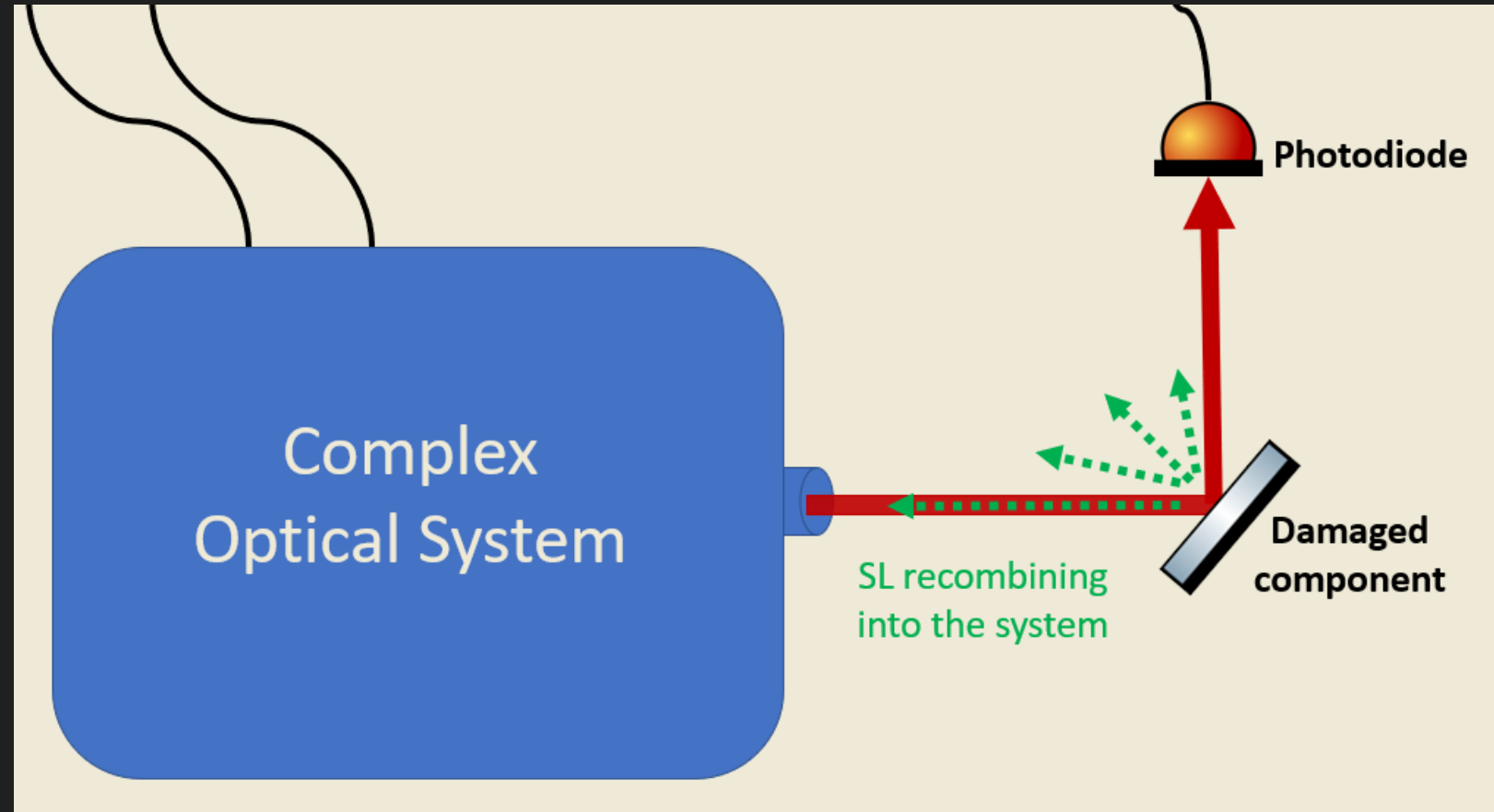
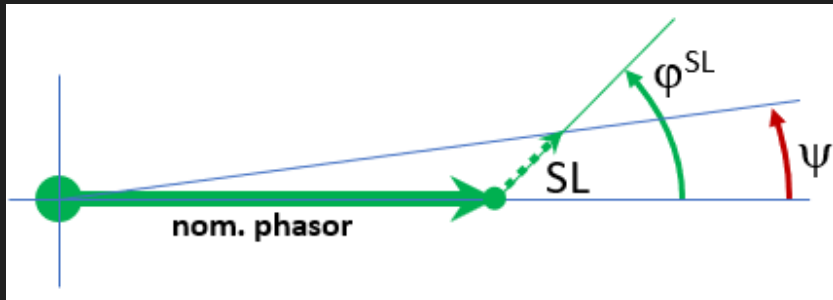


Stray light in the MOSA in GW measurement

Stray light => Noise on Ψ_{het}

$$\Delta\psi_{het} = \epsilon_{SL} \sin \left\{ \left(\frac{2\pi}{\lambda} \right) \Delta L_{comp} \right\}$$

stray light fractional optical amplitude



Principle of the Stray Light Detector Instrumentation (SLDI)

Aim: To determine the presence, amplitude and path length difference of coherent stray light in a complex optical system using a frequency-swept laser.

All photosignal(s) are recorded. Interference fringe, frequency $f_{itf} \Rightarrow$ stray light, with

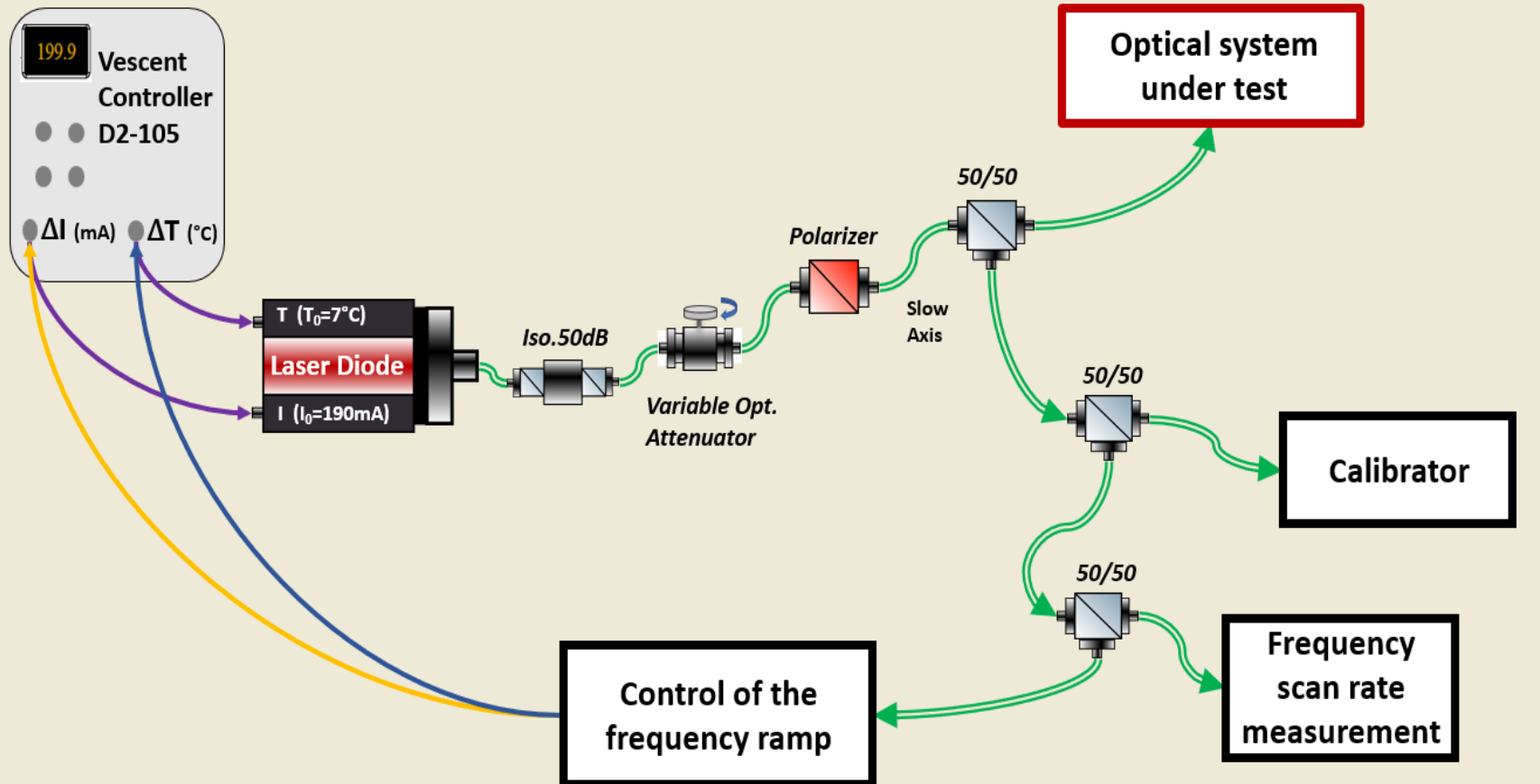
$$f_{itf} = \frac{\Delta L}{c} \frac{\Delta \nu_{opt}}{\Delta t}$$

The diagram illustrates the equation $f_{itf} = \frac{\Delta L}{c} \frac{\Delta \nu_{opt}}{\Delta t}$. Three callout boxes are present: a blue box labeled "SL-to-Nom OPD" points to the ΔL term in the numerator; a blue box labeled "fringe frequency" points to the f_{itf} term; and a blue box labeled "SLDI laser frequency scan rate" points to the $\frac{\Delta \nu_{opt}}{\Delta t}$ term.

Resolution required for instrumentation: $\Delta(\Delta L) < 2 \text{ mm}$

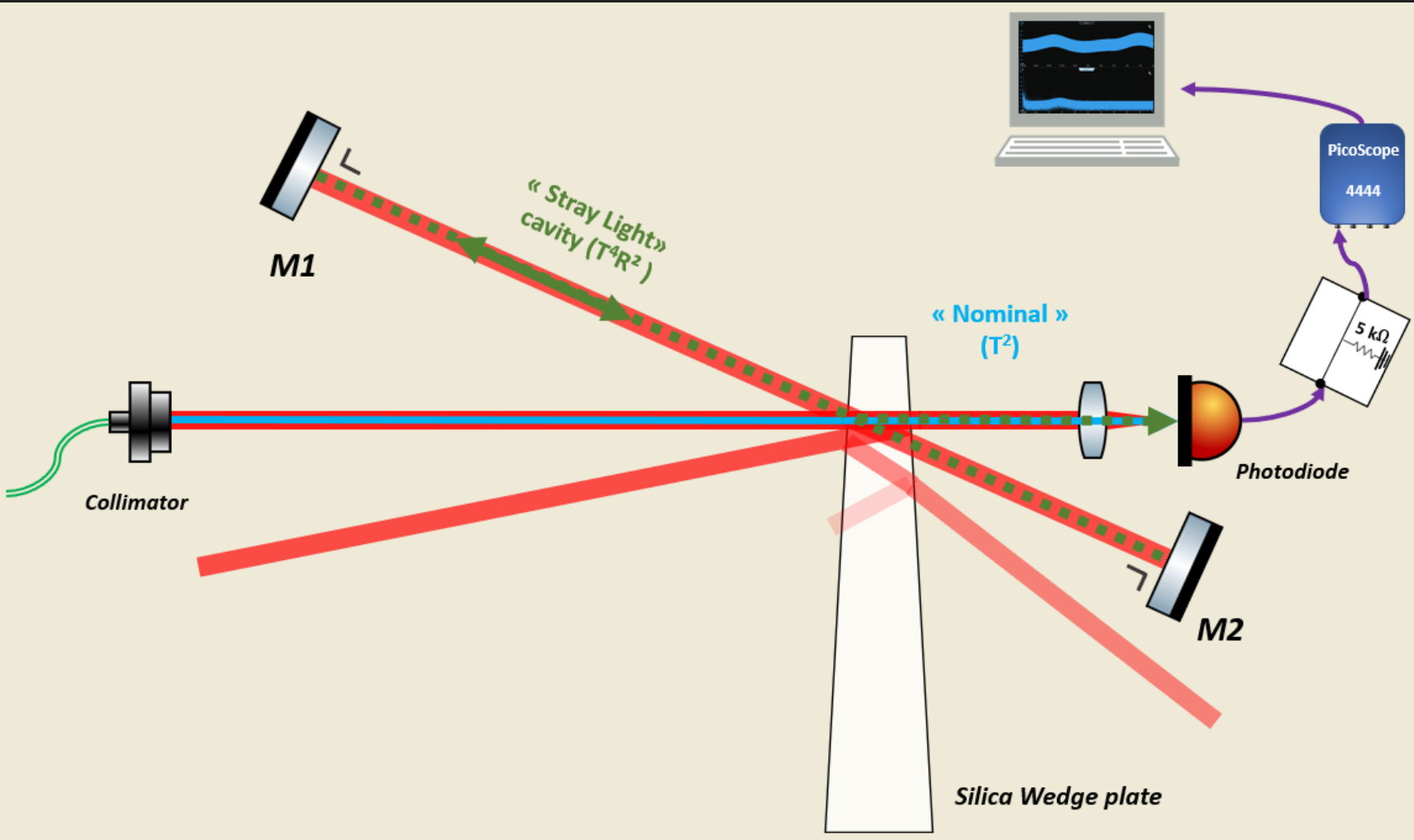
Noise floor for the measurement of the fractional signal amplitude SL/nom: $< 2, 2 \cdot 10^{-6}$

SLDI Prototype Scheme



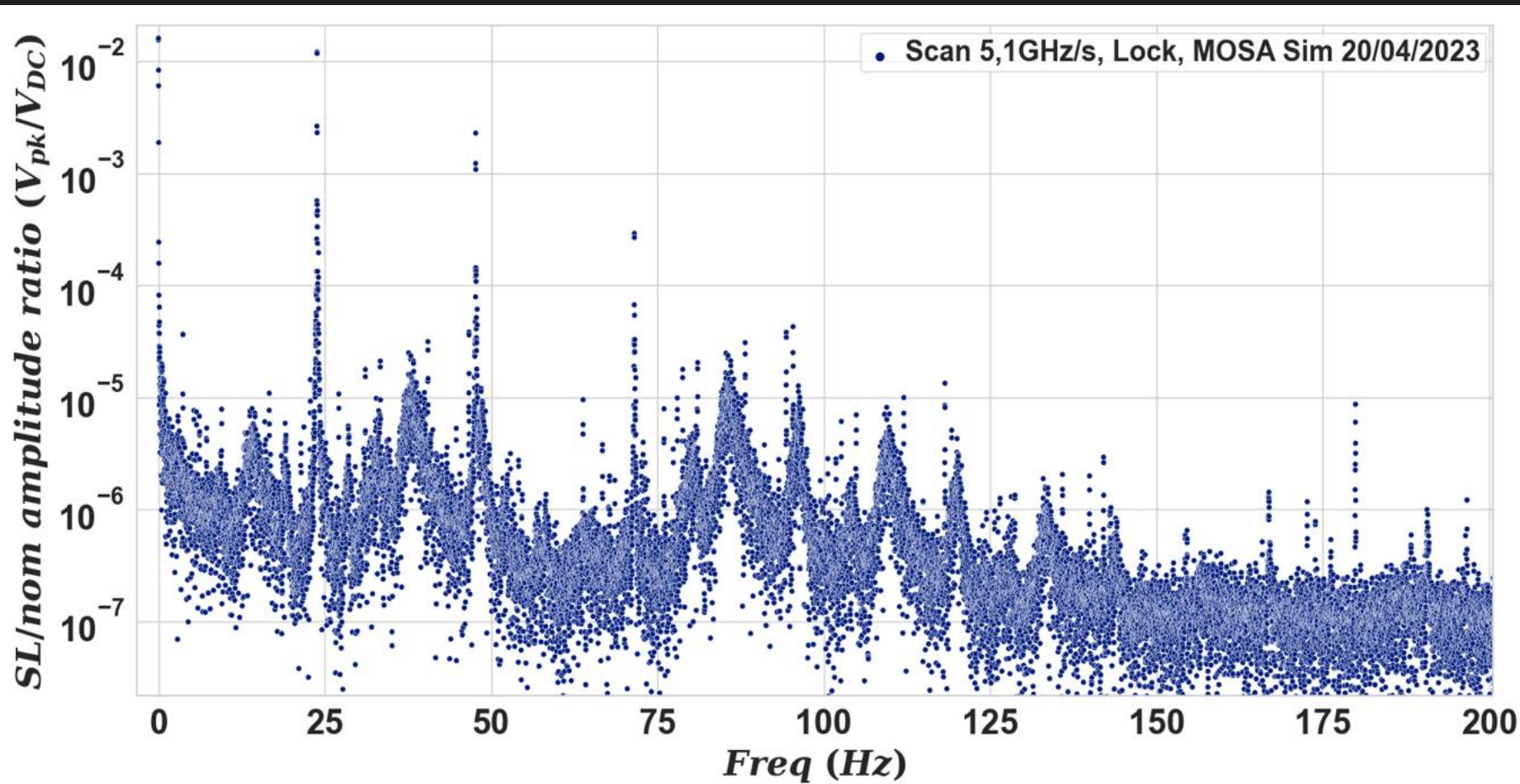
- **Frequency swept laser:** 1064nm laser diode swept over 2nm (30°C)
- **Control of the frequency ramp:** Phase lock during the scan using a MZ heterodyne IFO
- **Freq. Scan rate measurement:** Beat with a fixed frequency laser
- **Calibrator:** Check the quality of the ramp with a stable fibered IFO

Experimental set-up: MOSA simulator



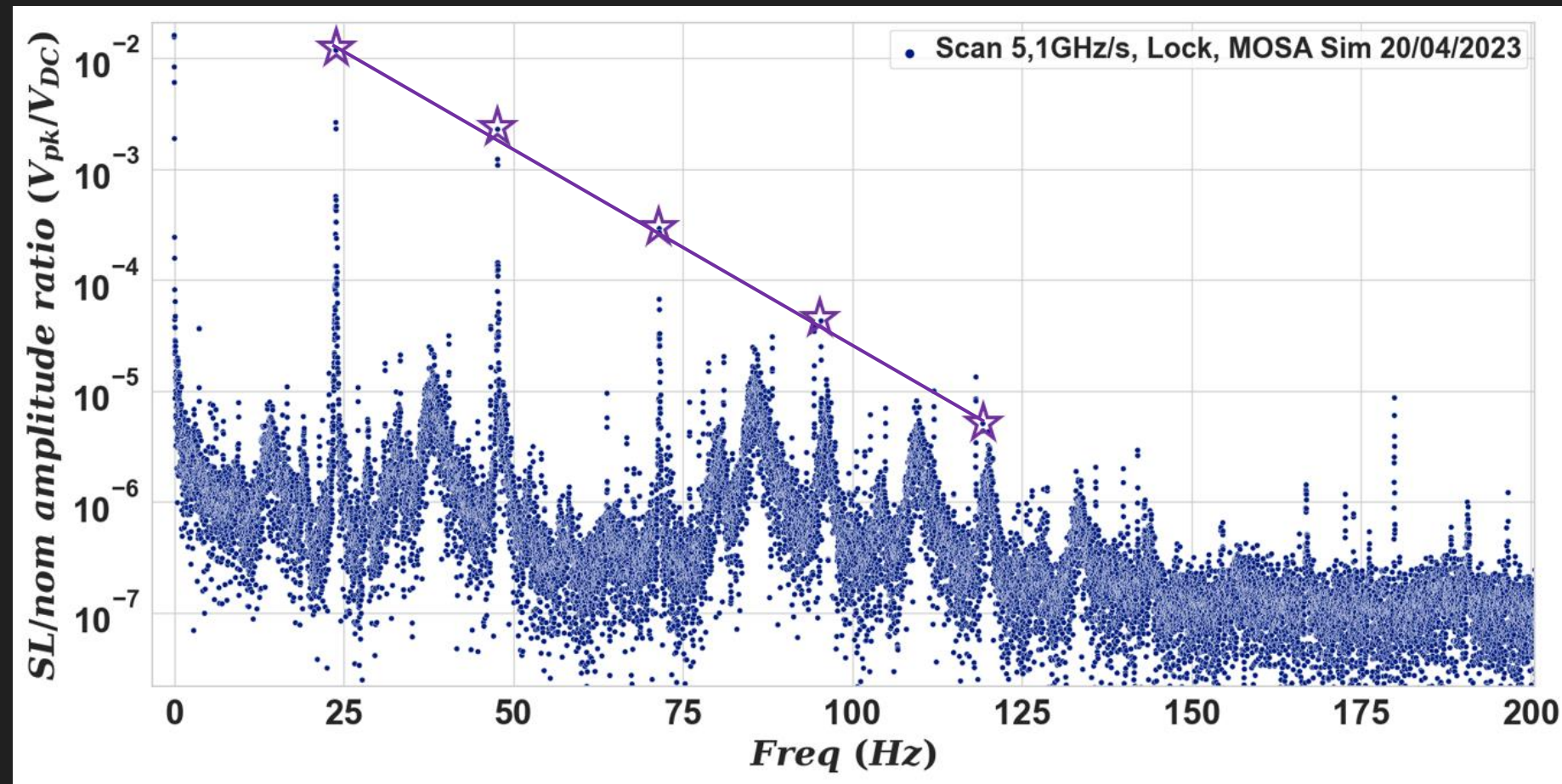
- $\Delta L_{\text{cavity geometry}} = 1,4022 \text{ m}$
- SL/nom optical amplitude ratio : $T \times R$ ($3.8E-2$)
- Cavity round-trip of length $\Delta L_{\text{cavity geometry}}$, amp ratio T^2
- Generates a "stray light" beam + echoes

Measurements on the MOSA Sim: Scan 5, 10 GHz/s.



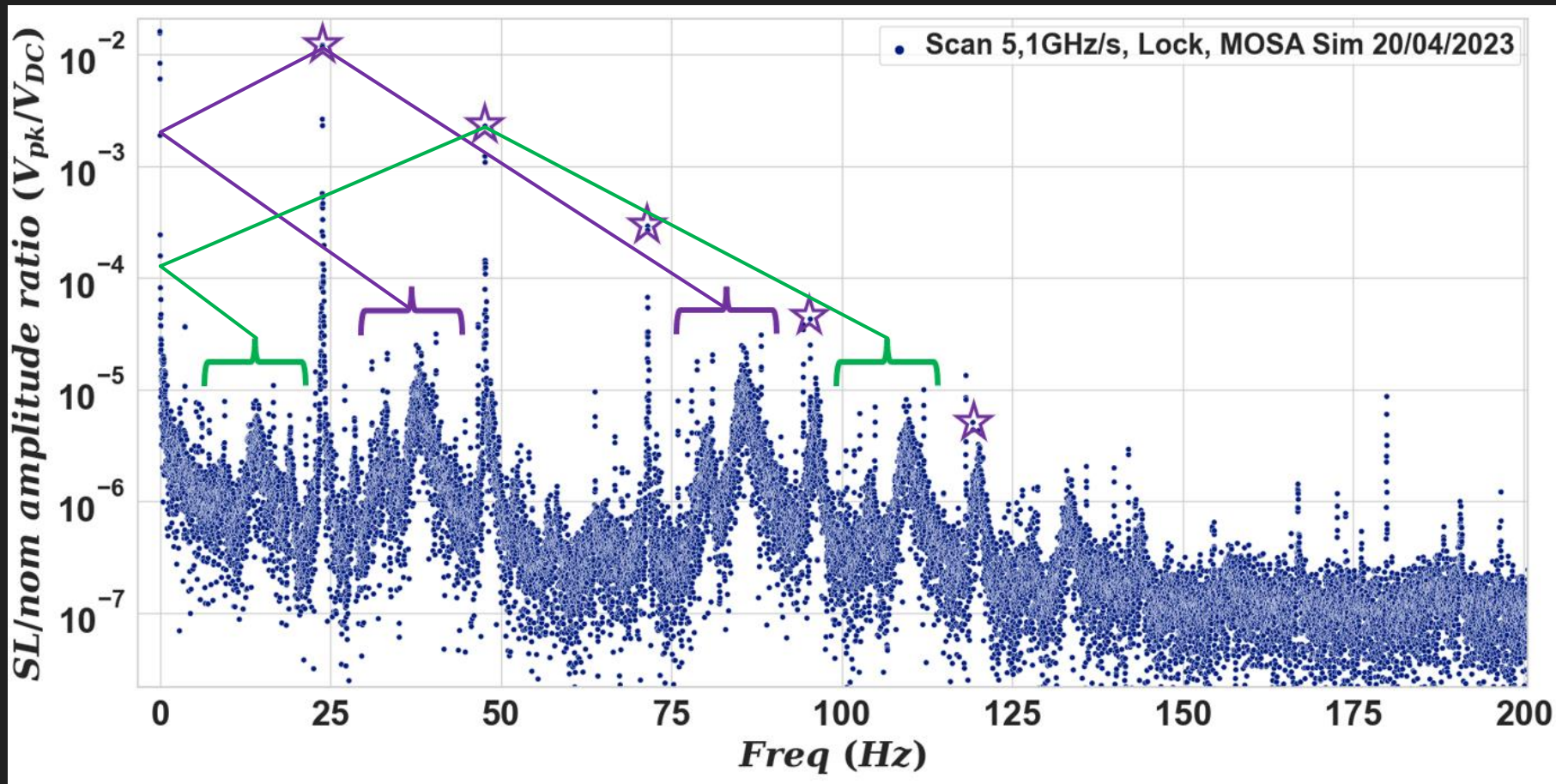
- A lot of peaks to understand
- Dominant SL peaks
- Peak structure linked to low acoustic/seismic noise

Measurements on the MOSA Sim: Scan 5, 10 GHz/s.



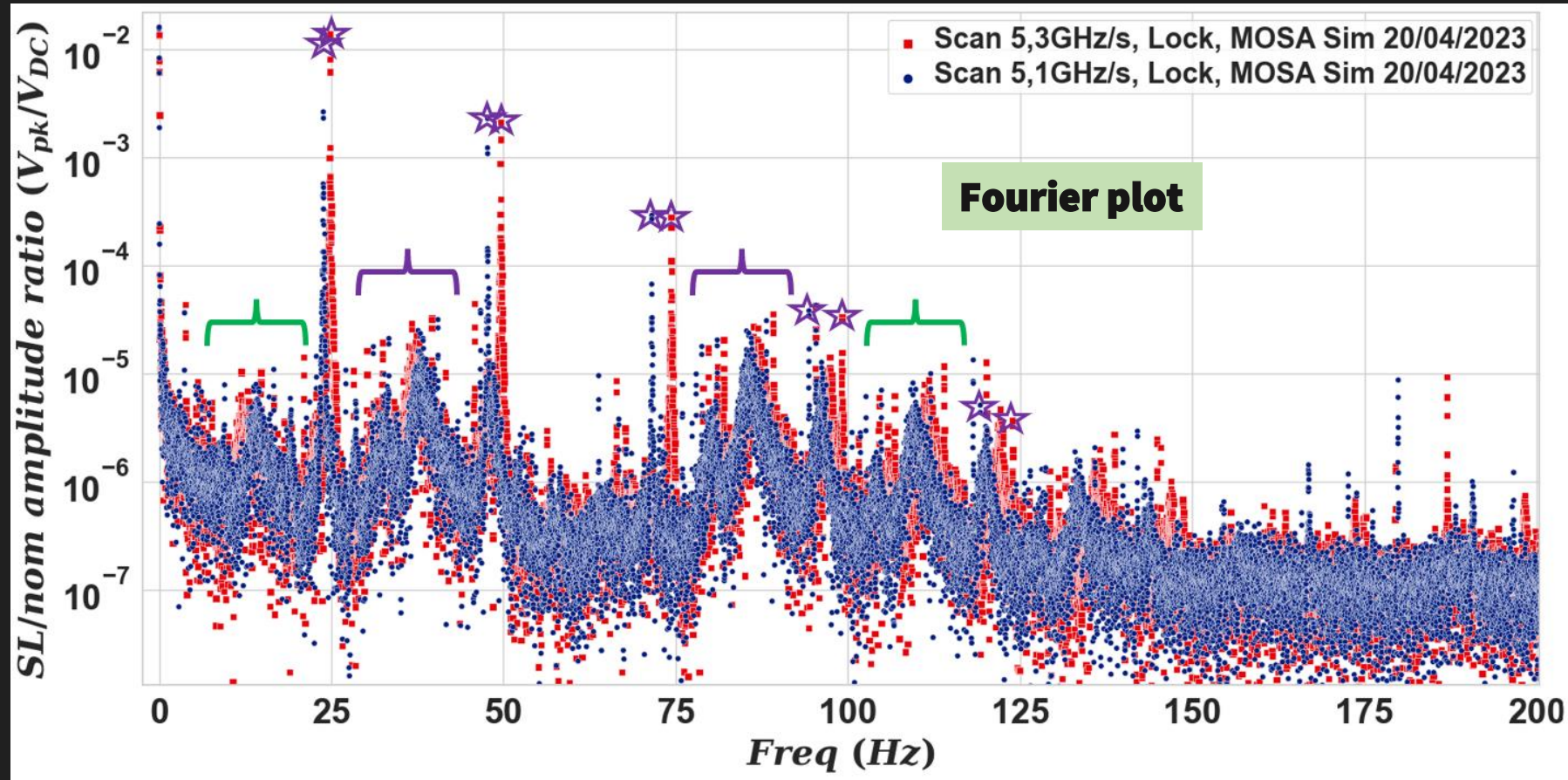
- ☆ Expected "SL" peaks
- Amplitude loss of factor 6 in the cavity round trip due to the beam divergence

Measurements on the MOSA Sim: Scan 5,10 GHz/s.



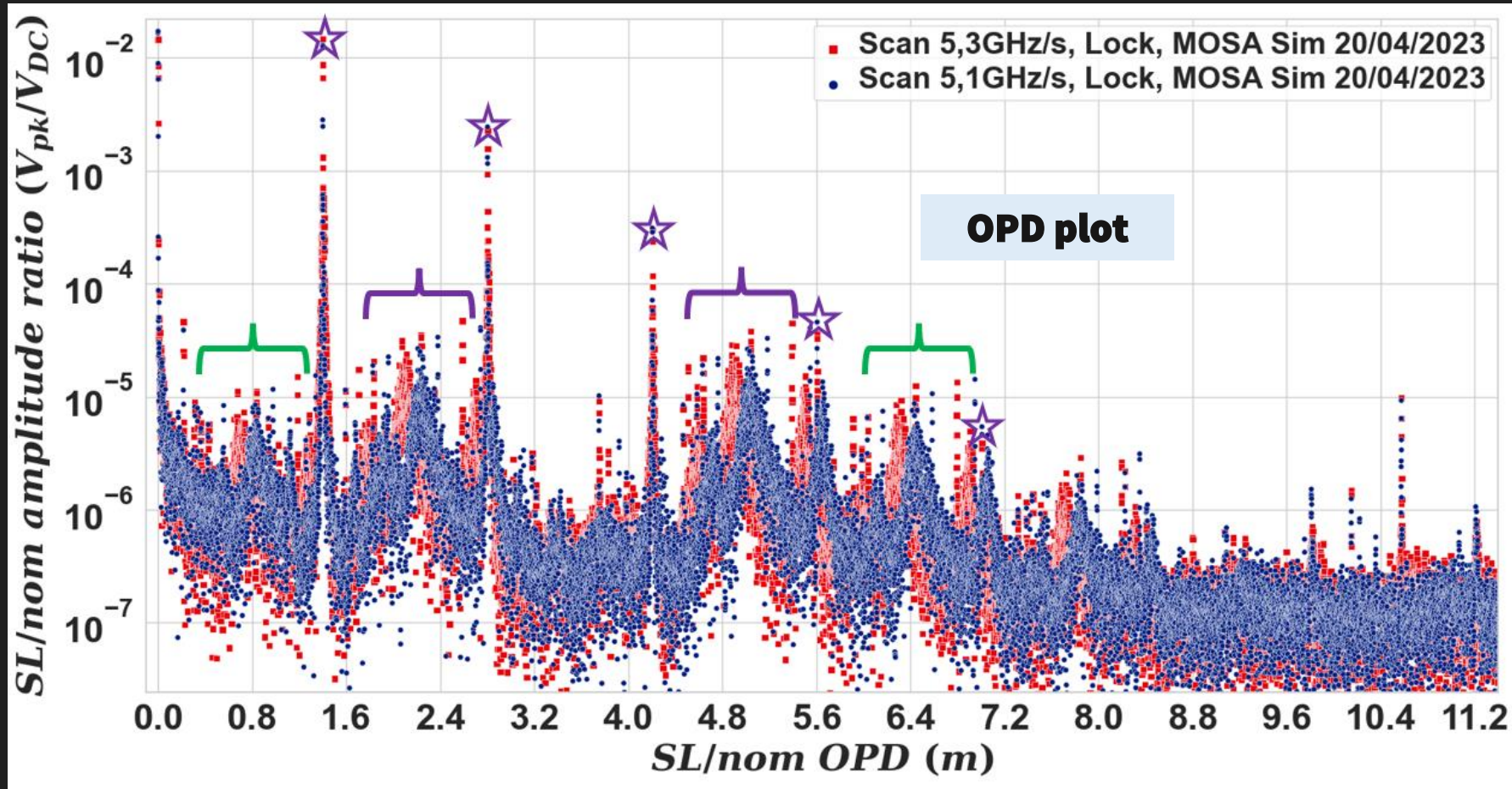
- ☆ Expected "SL" peaks
- Amplitude loss of factor 6 in the cavity round trip due to the beam divergence
- SL contribution modulated by mechanical noise structure at $f_{SL} \pm f_{mod}$
(purple bracket->1st SL Peak, green bracket-> 1st Echoe in the cavity)

Measurements on the MOSA Sim: Scan 5,10 GHz/s. + Scan 5,30 GHz/s.



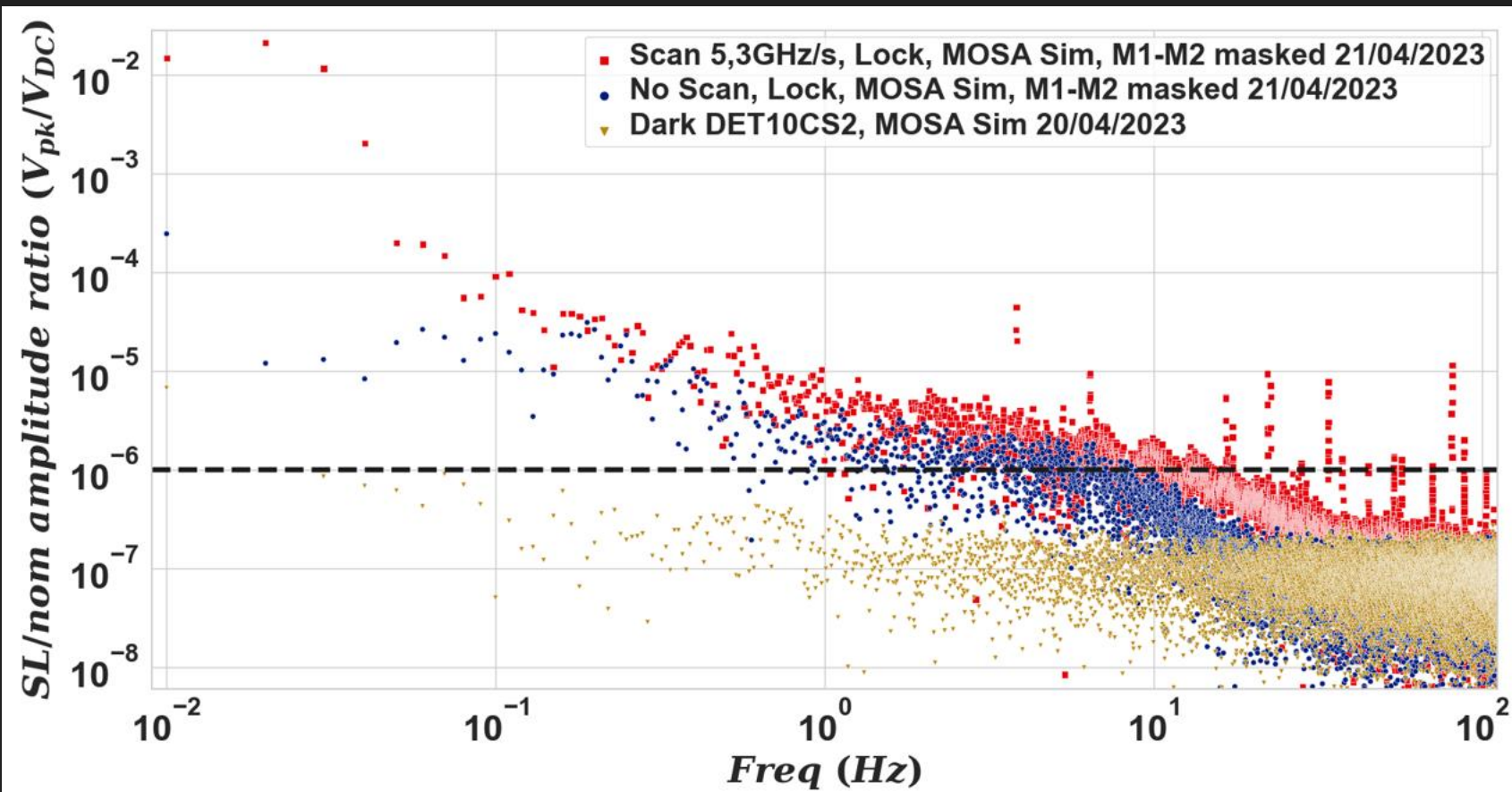
- $V_{\text{blue}} = 5,10 \text{ GHz/s}$,
 $V_{\text{red}} = 5,30 \text{ GHz/s}$
- ☆ Expected SL peaks
- SL contribution modulated by mechanical noise structure at $f_{\text{SL}} \pm f_{\text{mod}}$ (purple bracket \rightarrow 1st SL Peak, green bracket \rightarrow 1st Echoe in the cavity)

Measurements on the MOSA Sim: Scan 5,10 GHz/s. + Scan 5,30 GHz/s.



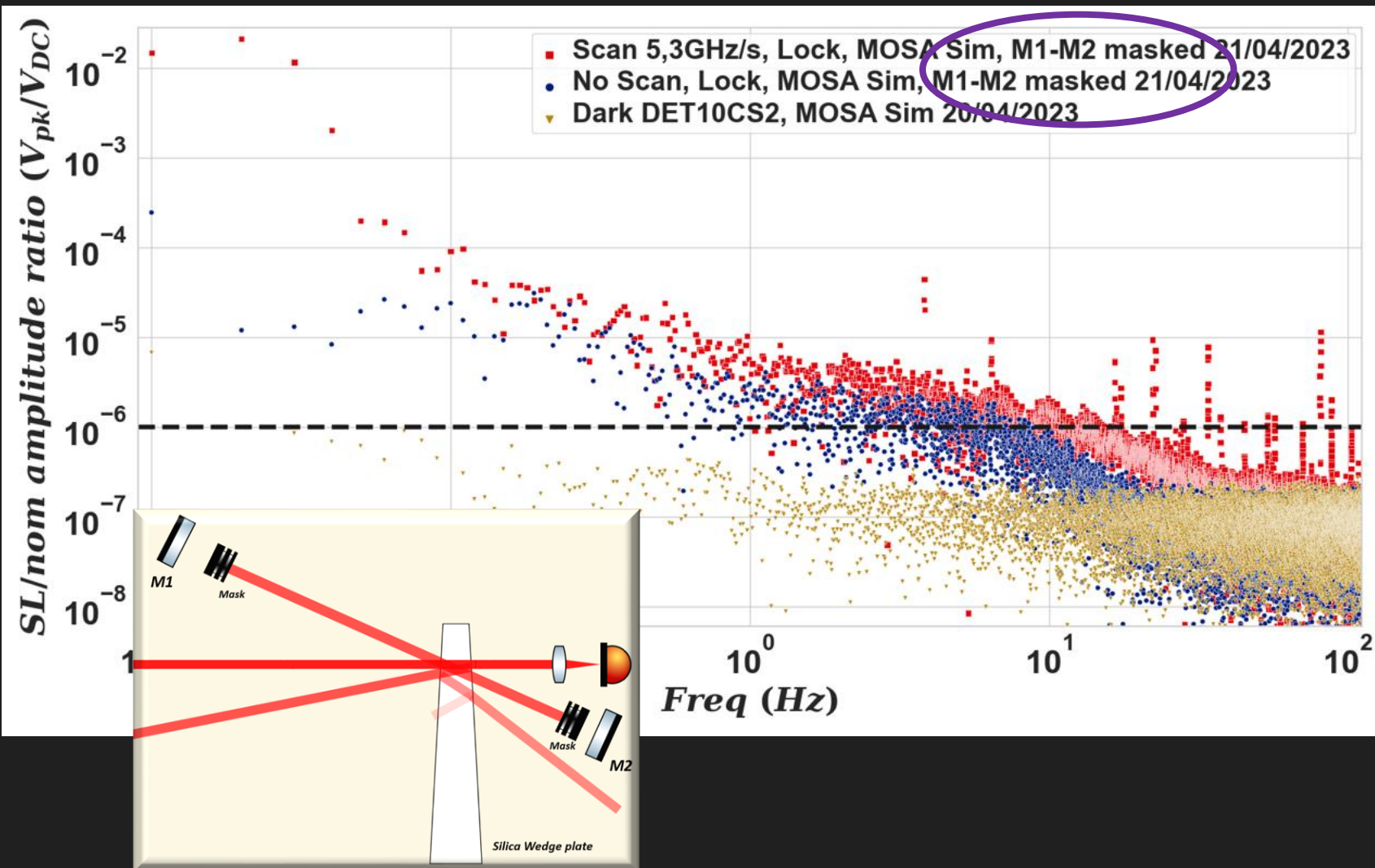
- $V_{blue} = 5, 10$ GHz/s,
 $V_{red} = 5, 30$ GHz/s
- ☆ Expected SL peaks
- SL contribution modulated by mechanical noise structure at $f_{SL} \pm f_{mod}$ (purple bracket -> 1st SL Peak, green bracket -> 1st Echoe in the cavity)
- **True** SL peaks coincide (Red/Blue), whatever the scan rate

Measurement Floors



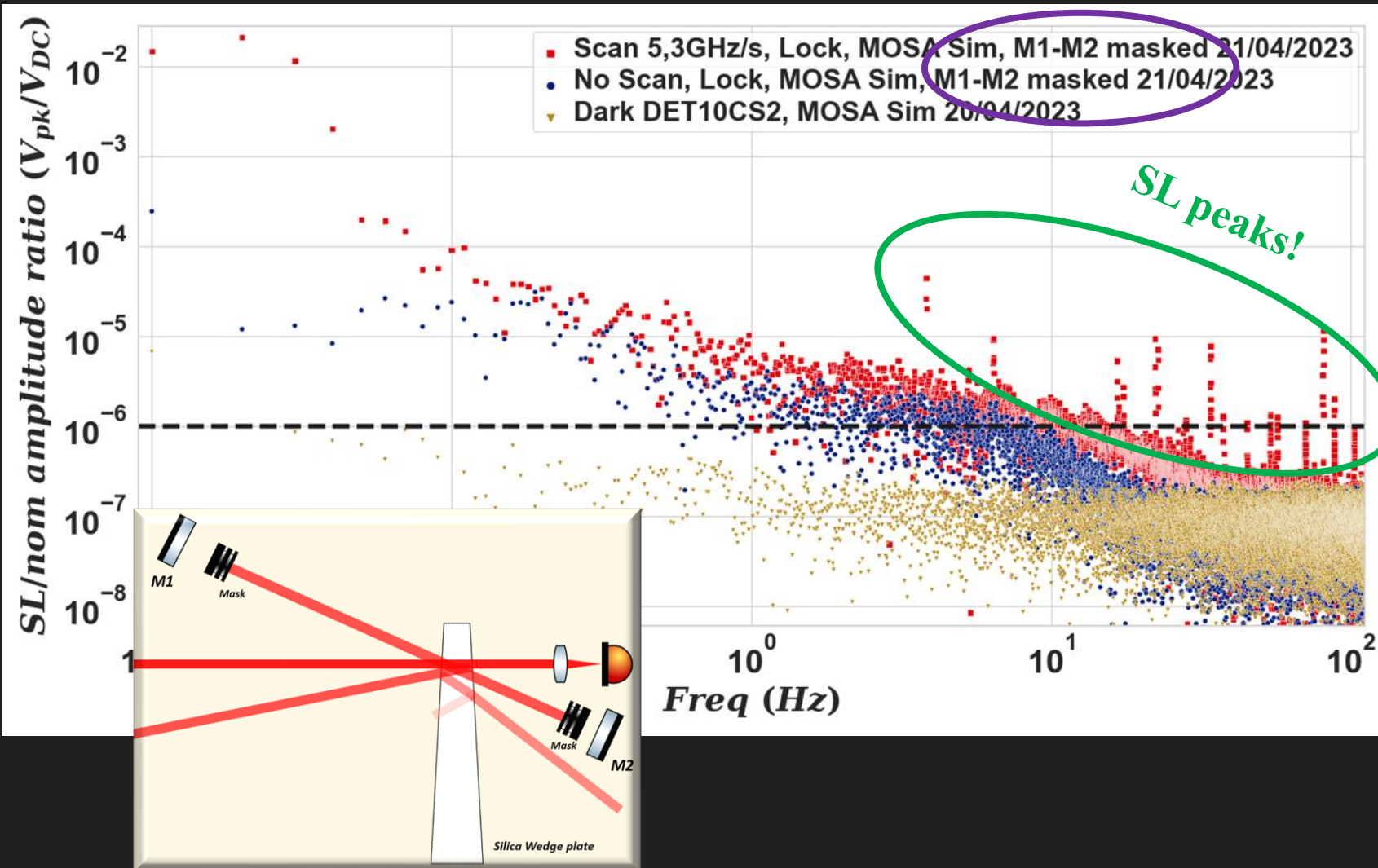
- **Dark (no laser):**
Below 10^{-6} above 50 mHz
(2 mm en OPD)

Measurement Floors



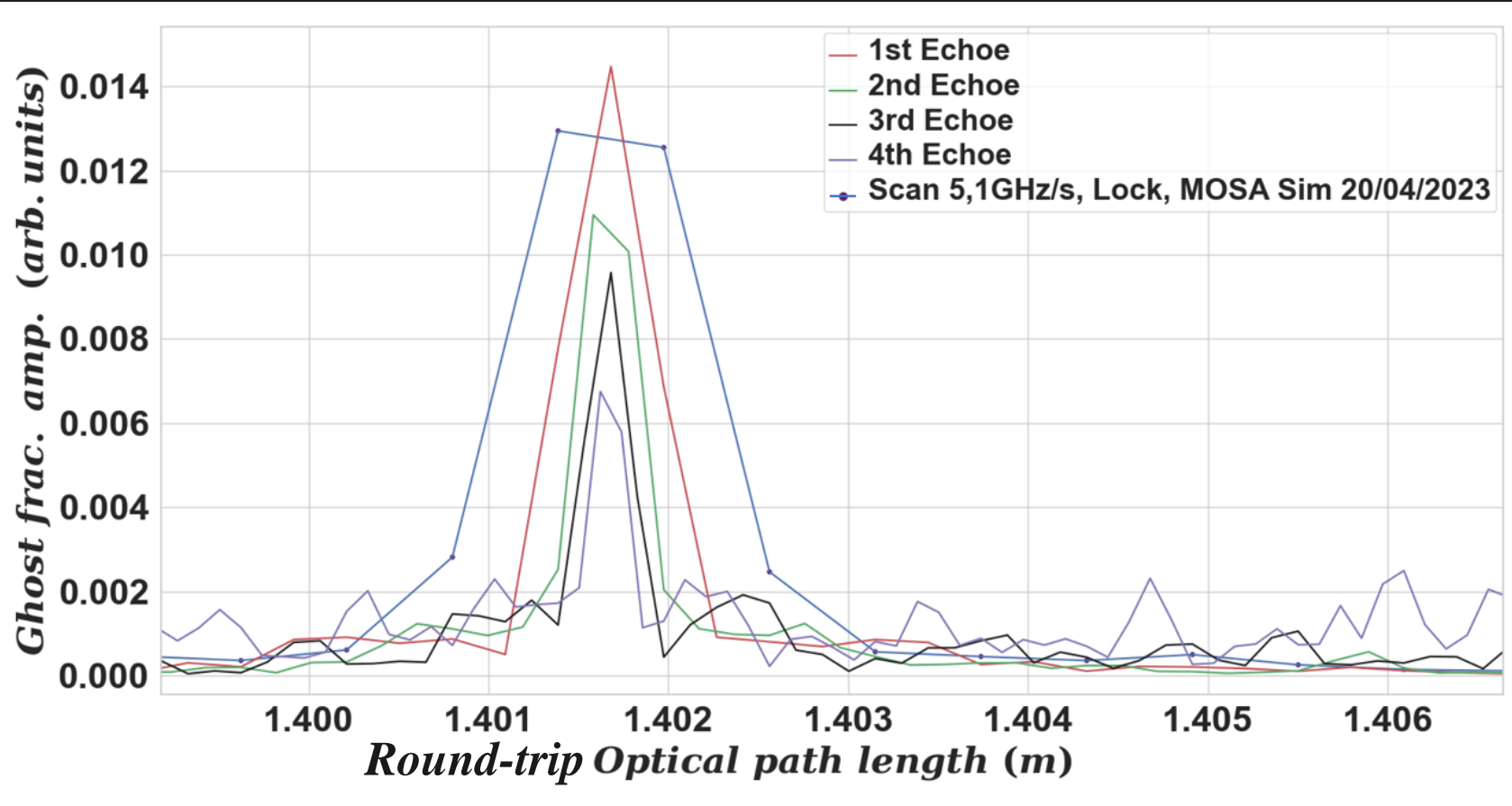
- **Dark (no laser):**
Below 10^{-6} above 50 mHz
(2 mm en OPD)
- **No scan and no itf in MOSA Sim:**
Below $3 \cdot 10^{-6}$ above 1 Hz
(6 cm en OPD)

Measurement Floors



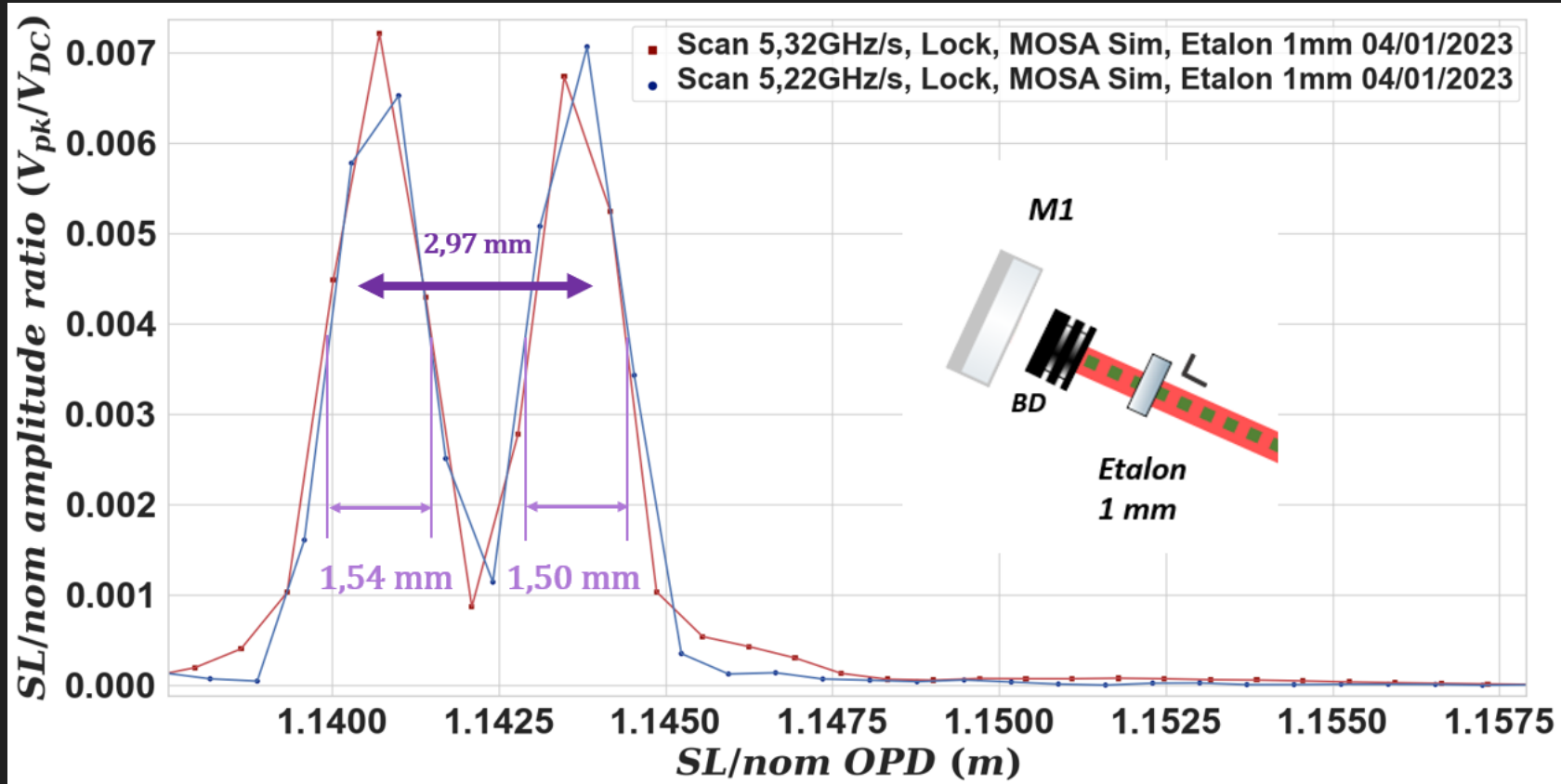
- **Dark (no laser):**
Below 10^{-6} above 50 mHz
- **No scan and no itf in MOSA Sim:**
Below $3 \cdot 10^{-6}$ above 1 Hz
- **Scan 5,3 GHz/s and no itf in MOSA Sim:**
Below $5 \cdot 10^{-6}$ above 1 Hz and parasitic SL contributions in fibers (green circle)!

OPD determination: measured value



- The N-th Echo, at N^* ΔL_{M1M2} overlaps with the main SL contribution: see comparison of the peaks barycenters
- Mean barycenter at scan **5,10 GHz/s**: 1,4016 m
- Mean barycenter at scan **5,30 GHz/s**: 1,4017 m
- Max deviation with the geometrical round-trip value: **0,6 mm**

OPD Resolution



- Mirror M1 replaced by an 1,0 mm silica uncoated etalon (SL from the rear side + SL from the front)
- $\Delta (\Delta L)_{\text{theo}} = 2 * n_{\text{SiO}_2} * \text{thickness} = 2,9 \text{ mm}$
- $\Delta (\Delta L)_{\text{meas}} = 2,97 \text{ mm}$
- Reproducibility $< 0,1 \text{ mm}$

Conclusions

- MOSA simulator with ghost + echoes ✓ (also with scattered light ✓)
- Frequency ramp control (with a phase lock loop) and monitoring (ring IFO) ✓
- Resolution of position measurement: <1 mm ✓
- Resolution between two close peaks: 1 mm ✓
- Verification of the meas. floor required for the instrument (< 10^{-6} above 1 Hz) ✓