



Backscattered light noise in the Virgo interferometer

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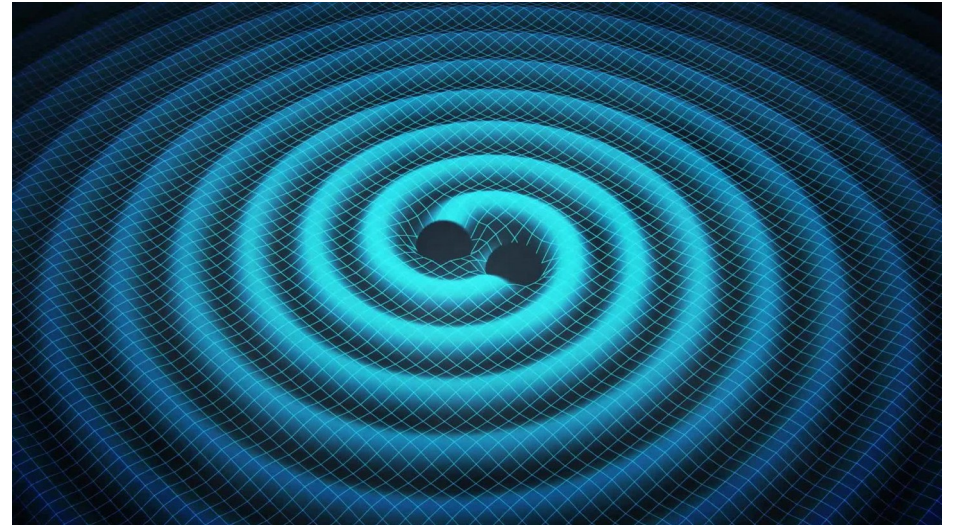


**Funded by
the European Union**

Gravitational wave



- Space-time metric's deformation
- 2 polarisations (+, ×)
- $A \propto \frac{1}{d}$
- $v = c$

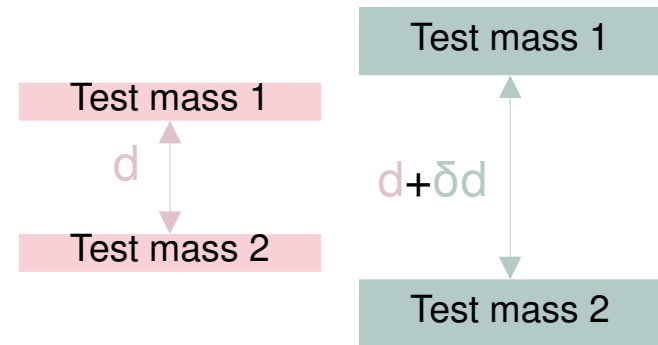


Gravitational Wave Illustration
Credit : Swinburne Astronomy
Productions

Detection principle



- Space-time deformation
→ change distance
between free-falling
masses
- Use electromagnetic
wave to measure
displacement



$$\delta d = \frac{h}{2} d$$

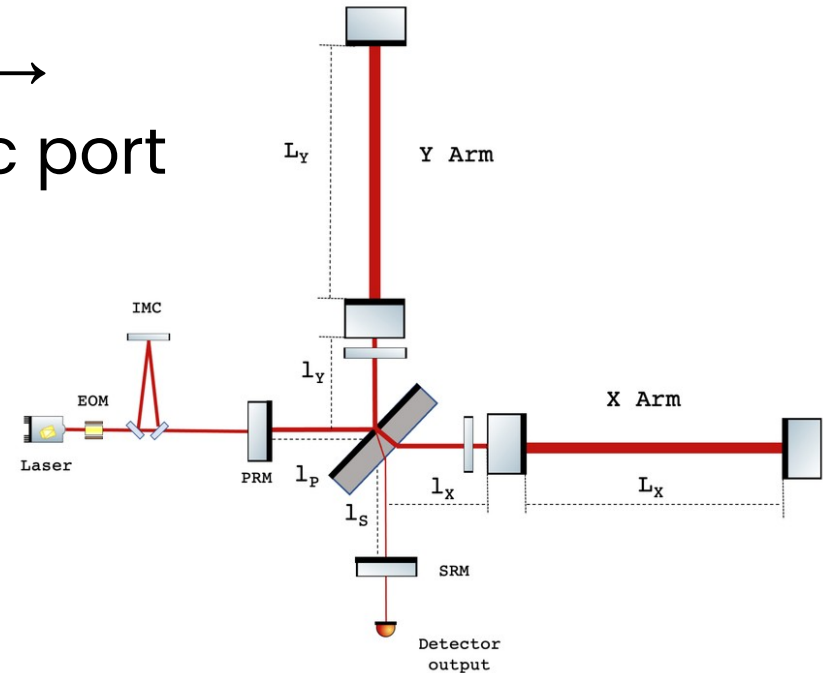
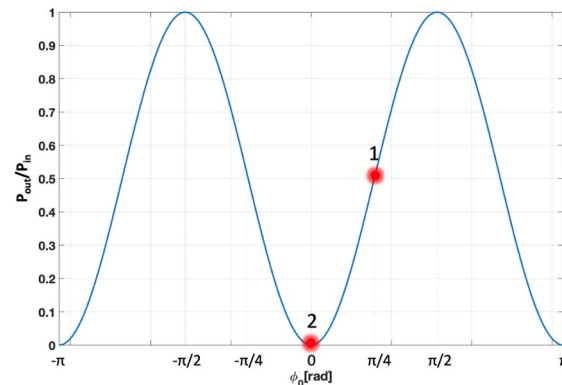
Michelson ITF



- phase difference between arms \rightarrow amplitude on the anti-symmetric port

- Dark fringe offset:

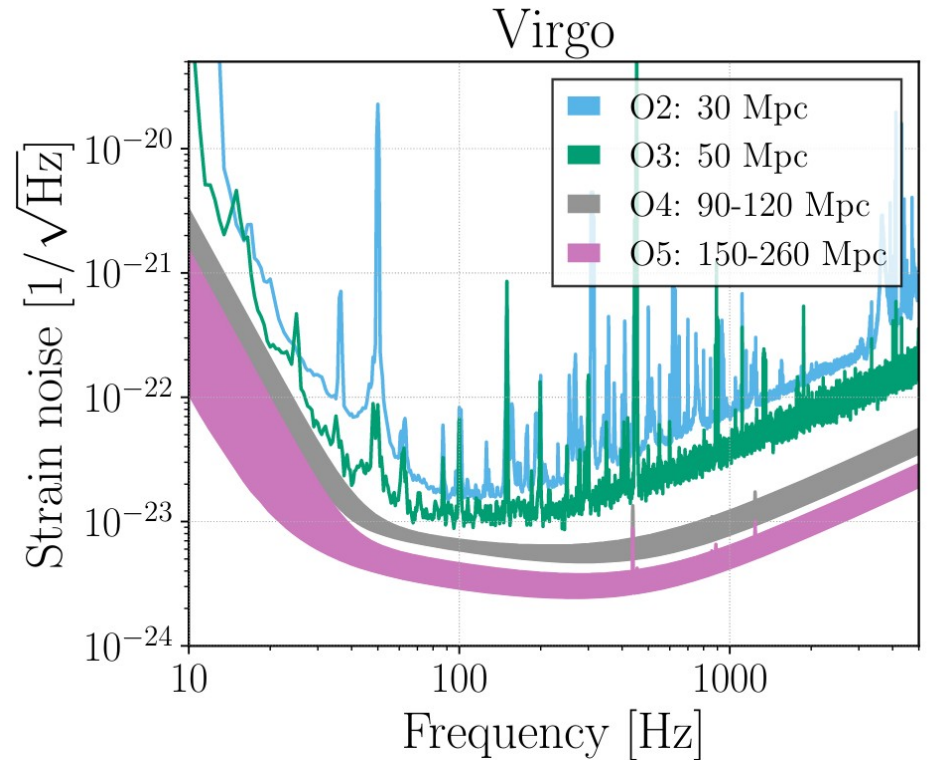
$$\delta P_t \propto \delta \Delta L$$



Sensitivity curve



- ASD of $h(t)$
- Affected by various noises

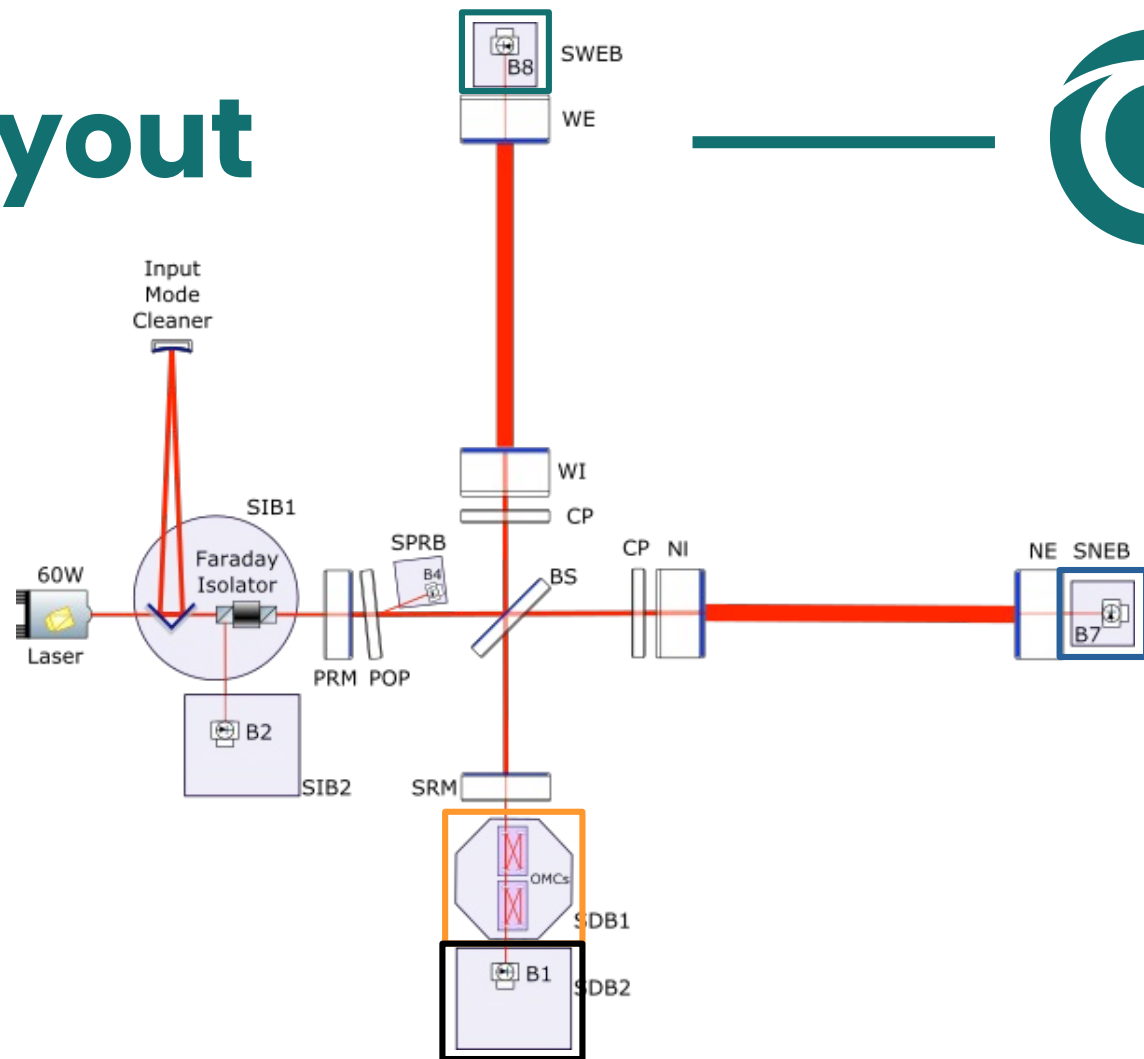


Benches layout



Benches :

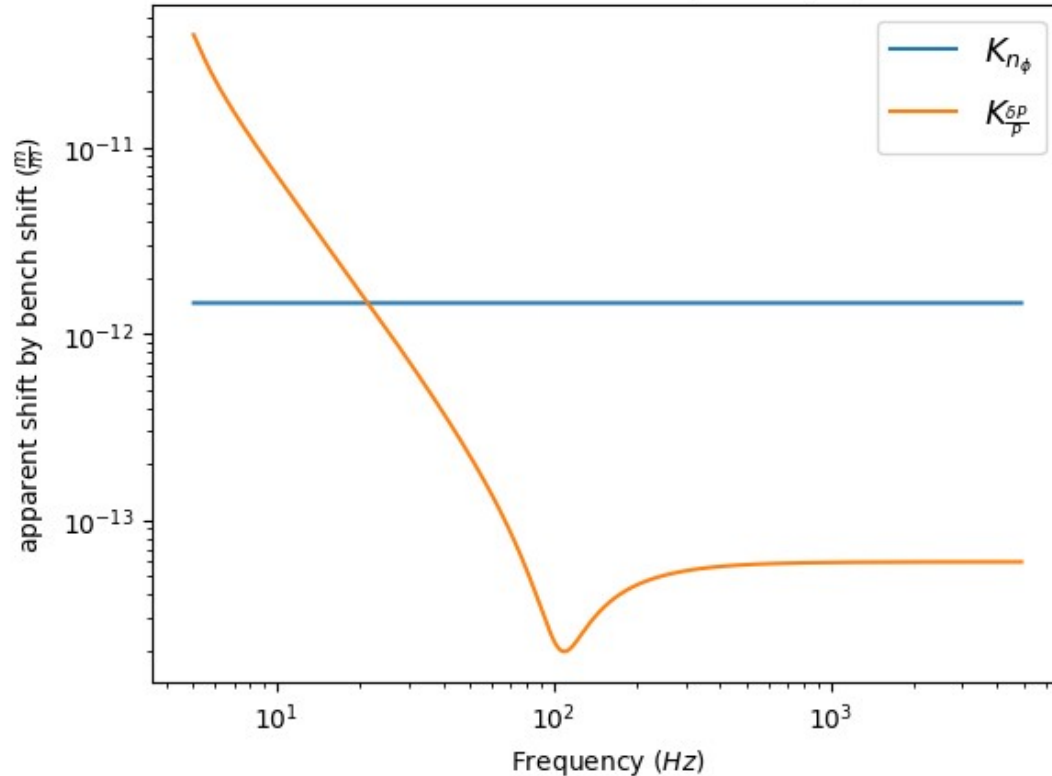
- SNEB } End-of-arms
 - SWEB } benches
 - SDB1 } Detection
 - SDB2 } benches
-
- In vacuum
 - Suspended



Transfer function



SNEB Transfer Function computed by Optickle



Constructive/Destructive interference :
→ change amplitude of the beam
→ change radiation pressure

⇒ Named $K_{\frac{\delta P}{P}}$

Quadratic interference :
→ add phase noise
→ directly change measurement

⇒ Named K_{n_ϕ}

Computing

backscattered factor



sensitivity

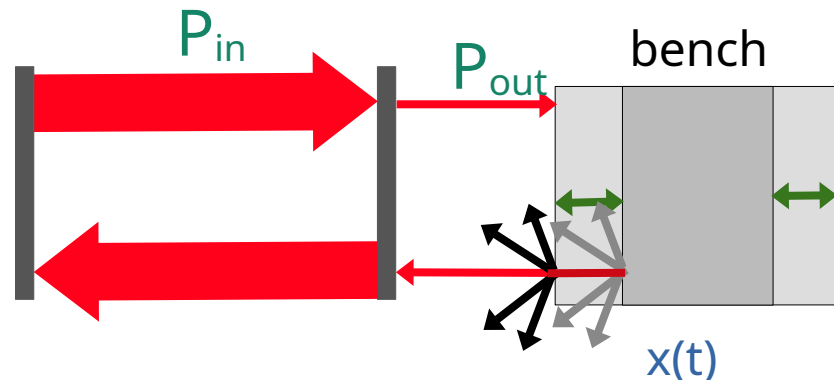
mirror
transmission

bench movement

$$h_r(f) = \sqrt{f_r} \cdot \frac{P_{out}}{P_{in}} \cdot \left\{ K_n(f) \cdot \mathcal{F} \left[\sin \left(\frac{4 \cdot \pi}{\lambda} (x(t)) \right) \right] + K_p(f) \cdot \mathcal{F} \left[\cos \left(\frac{4 \cdot \pi}{\lambda} (x(t)) \right) \right] \right\}$$

fraction of
backscattered light

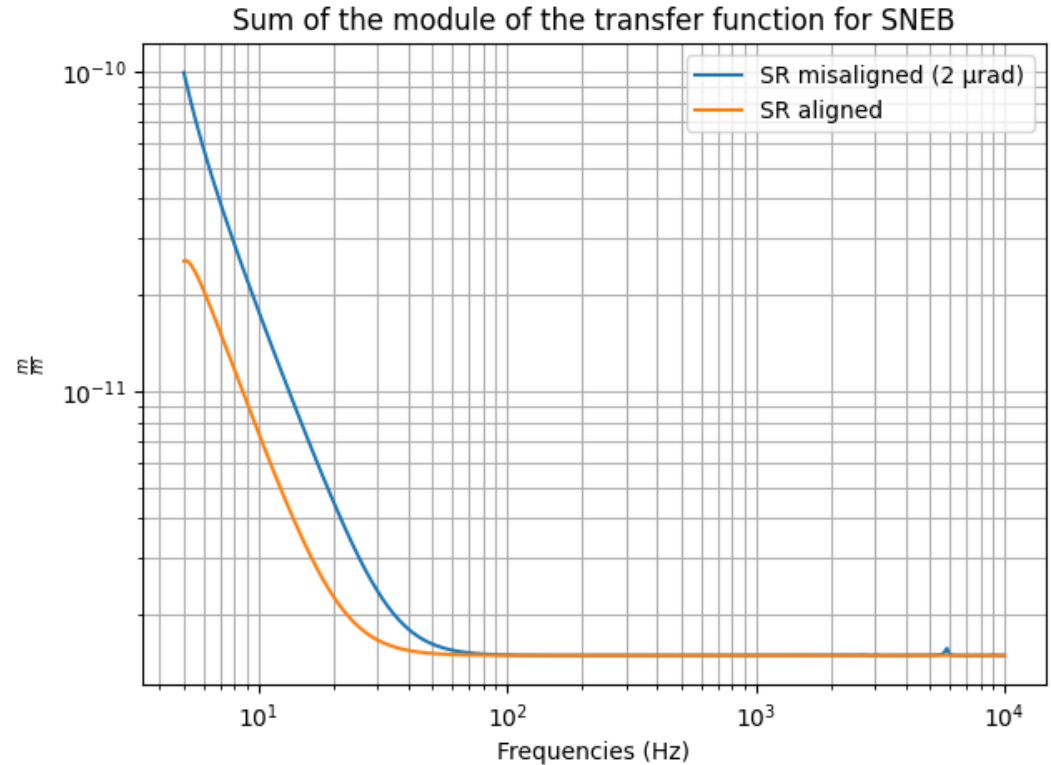
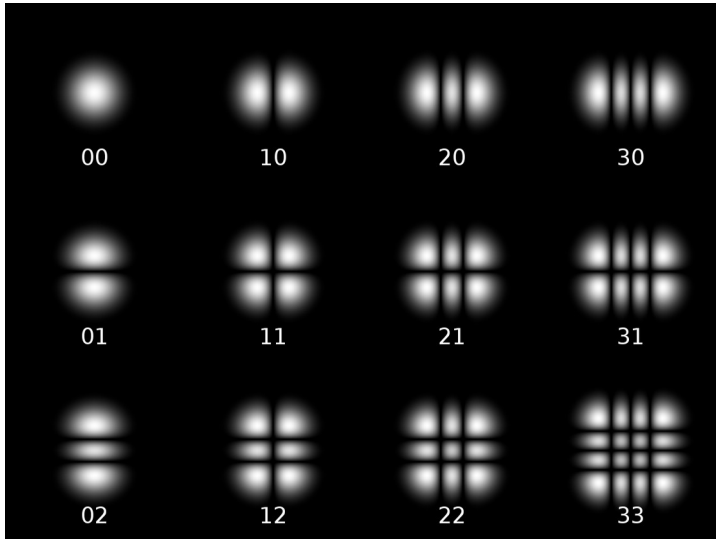
transfer function by radiation
pressure (K_p) and phase (K_n)



Simulation upgrade

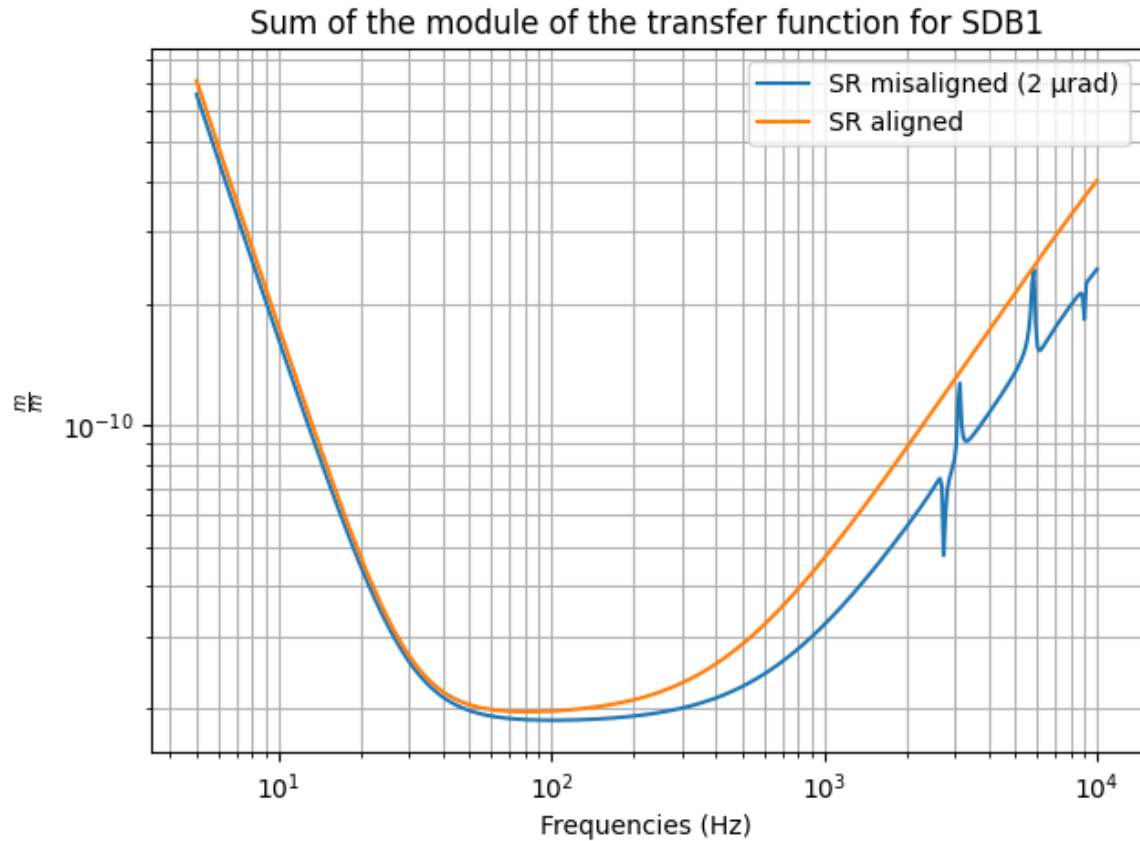


- Simulating SR alignment
- HOMs added to the simulation



Wikipedia, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Beam_profiles.png

Impact on SDBI



New injection on benches

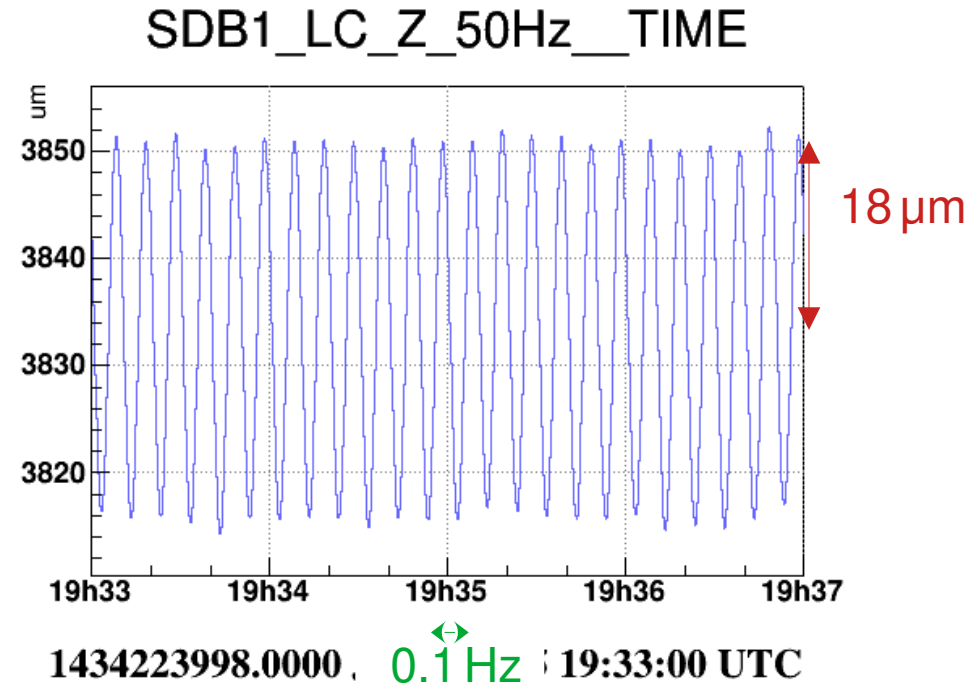


- 17 june 2025
 - SR aligned (LN2)
 - SR misaligned (LN3)

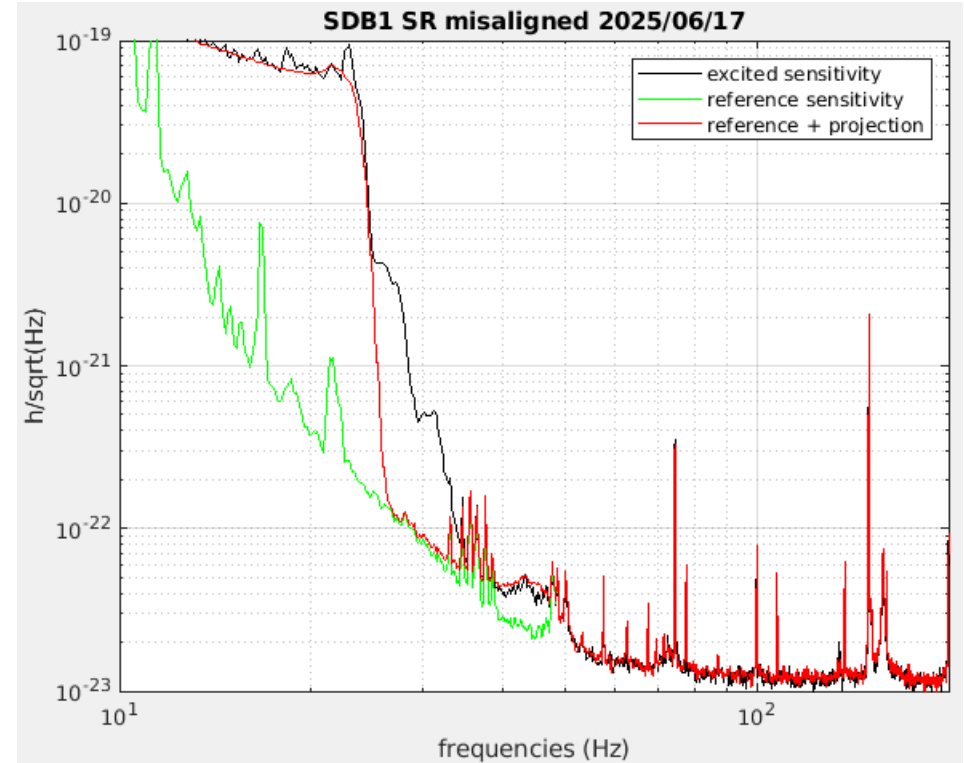
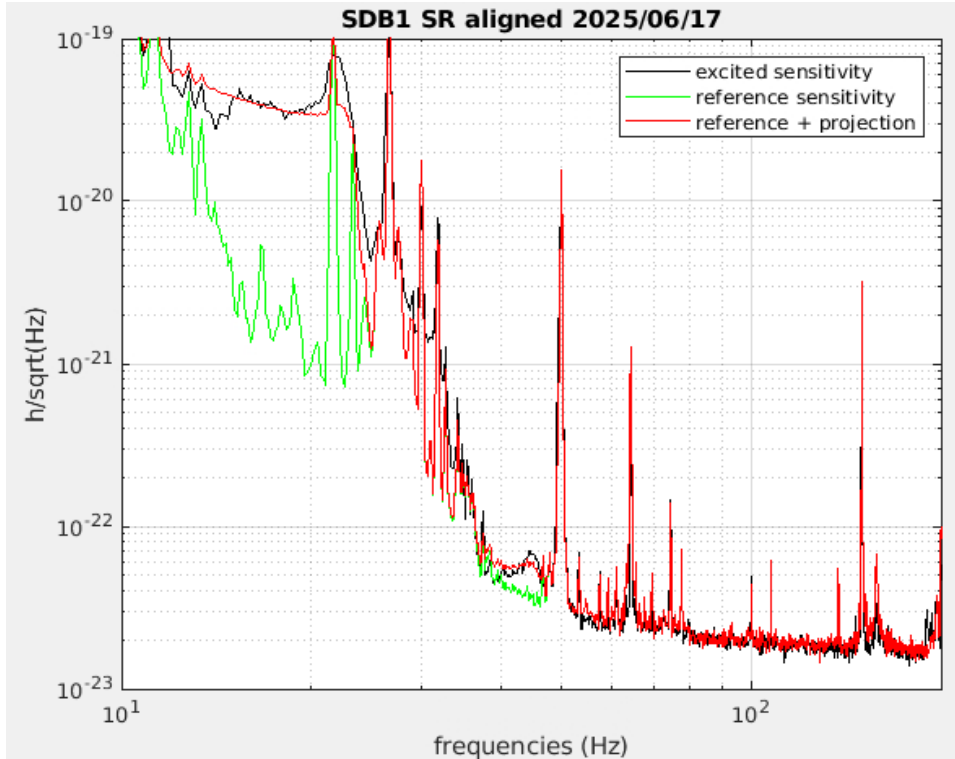
- Benches :

- SDB1
- SDB2
- SWEB

$$A \times \sin(2\pi f)$$



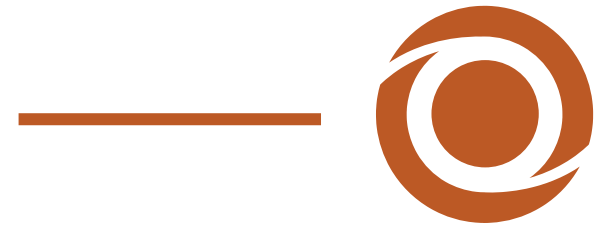
Projected vs real impact on sensitivity



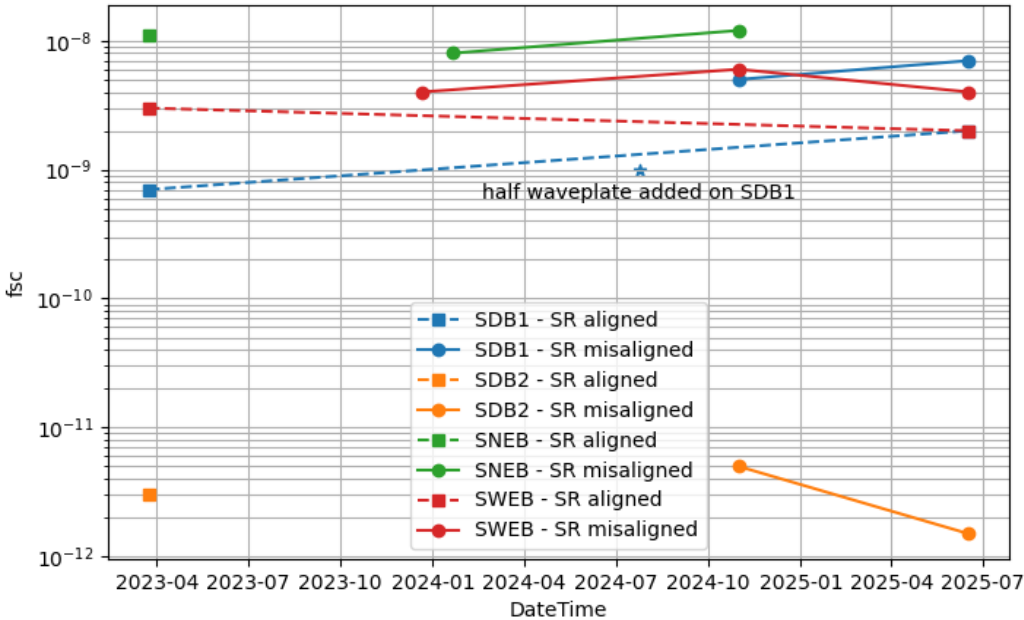
Evolution of f_{sc} measurement

date	SR yaw	injection power	bench	fsc
2023-03-24	0	25.4 W	SDB1	7×10^{-10}
2023-03-24	0	25.4 W	SDB2	3×10^{-12}
2023-03-24	0	25.4 W	SNEB	1.1×10^{-8}
2023-03-24	0	25.4 W	SWEB	3×10^{-9}
2023-12-20	2 μ rad	12.1 W	SWEB	4×10^{-9}
2024-01-21	2 μ rad	12.1 W	SNEB	8×10^{-9}
2024-10-31	2 μ rad	18 W	SDB1	5×10^{-9}
2024-10-31	2 μ rad	18 W	SDB2	5×10^{-12}
2024-10-31	2 μ rad	18 W	SNEB	1.2×10^{-8}
2024-10-31	2 μ rad	18 W	SWEB	6×10^{-9}
2025-06-17	0	18 W	SDB1	2×10^{-9}
2025-06-17	0	18 W	SWEB	2×10^{-9}
2025-06-17	2 μ rad	18 W	SDB1	7×10^{-9}
2025-06-17	2 μ rad	18 W	SDB2	1.5×10^{-12}
2025-06-17	2 μ rad	18 W	SWEB	4×10^{-9}

SR alignment and f_{sc}



Fsc evolution for given benches and SR alignment

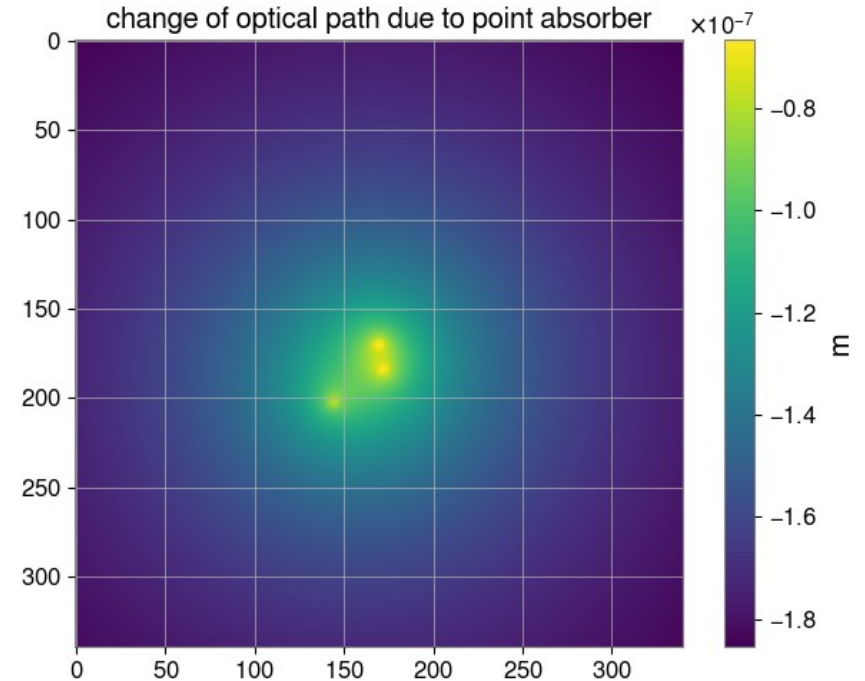


- SR alignment change f_{sc} measurement
- f_{sc} is a characteristic of a bench
→ unmodel effect in current simulation ?

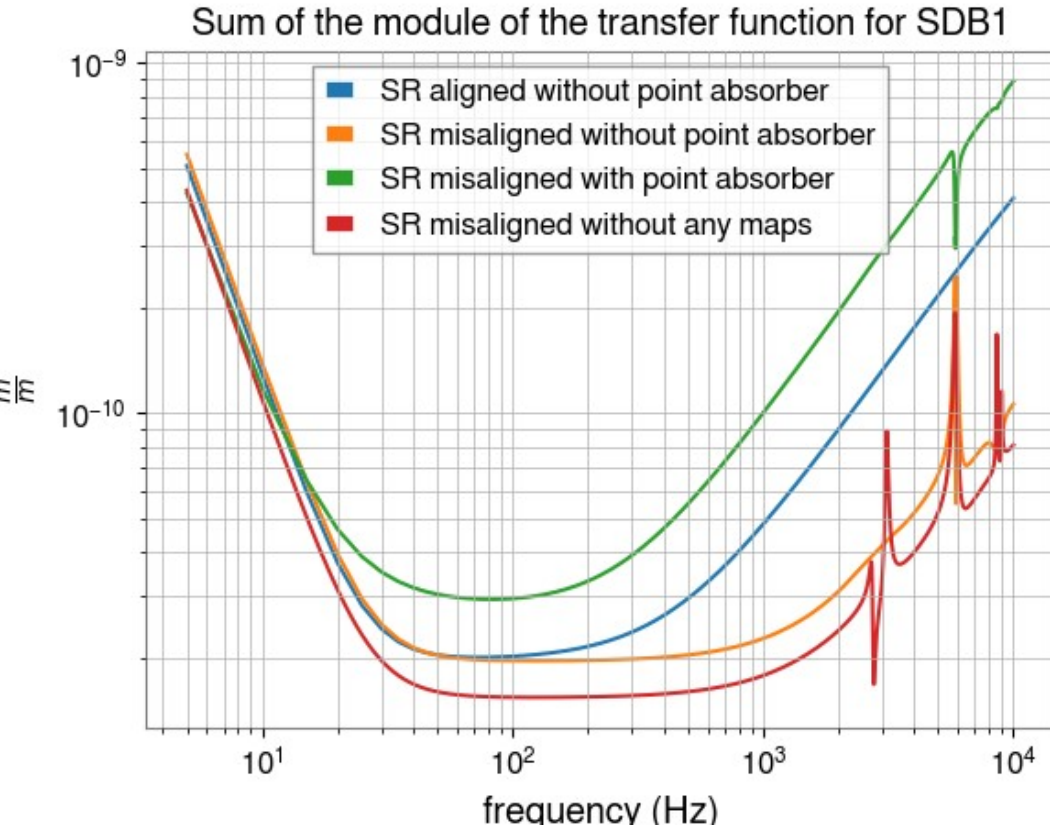
Adding defects to the simulation



- RoC change
- Add point absorber to mirrors



Defects impact on transfer function



- No change at low frequencies (less than 20 Hz)
- Do not explain f_{sc} change

Backscattermeter



laser power

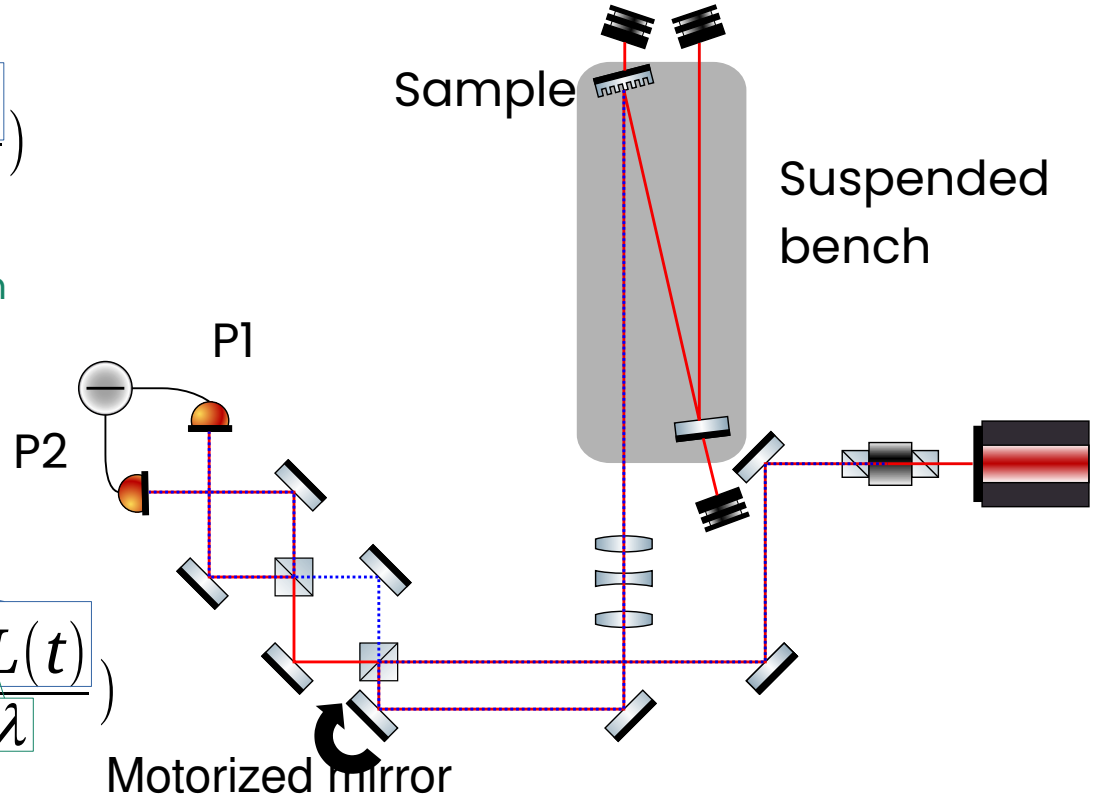
$$P_1(t) - P_2(t) = \frac{P_0}{\sqrt{2}} \sqrt{f_{sc}} \cos\left(2\pi \frac{\Delta L(t)}{\lambda}\right)$$

wavelength

fraction of backscattered light

bench movement

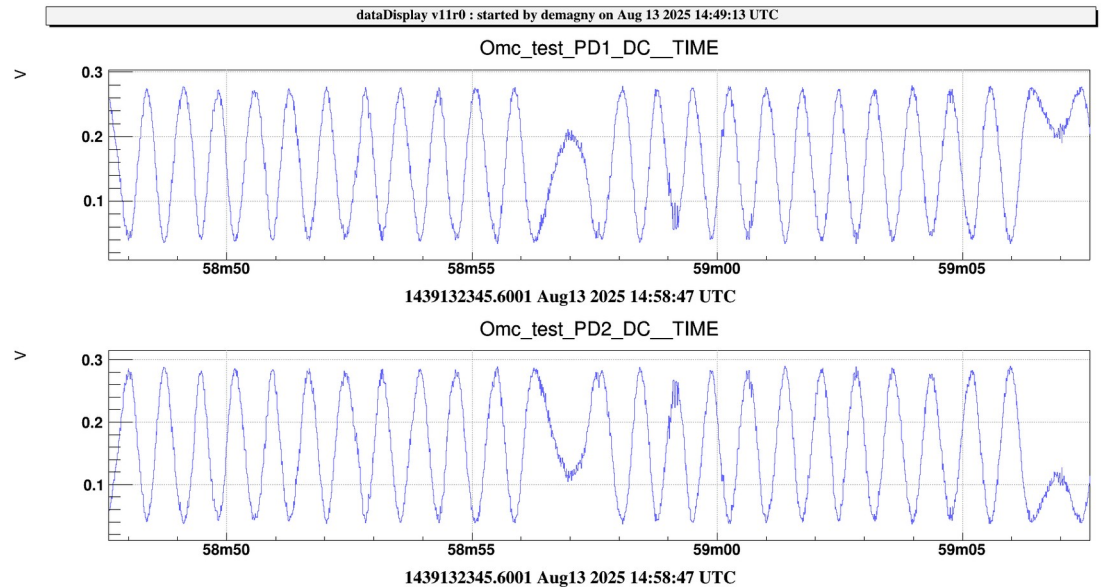
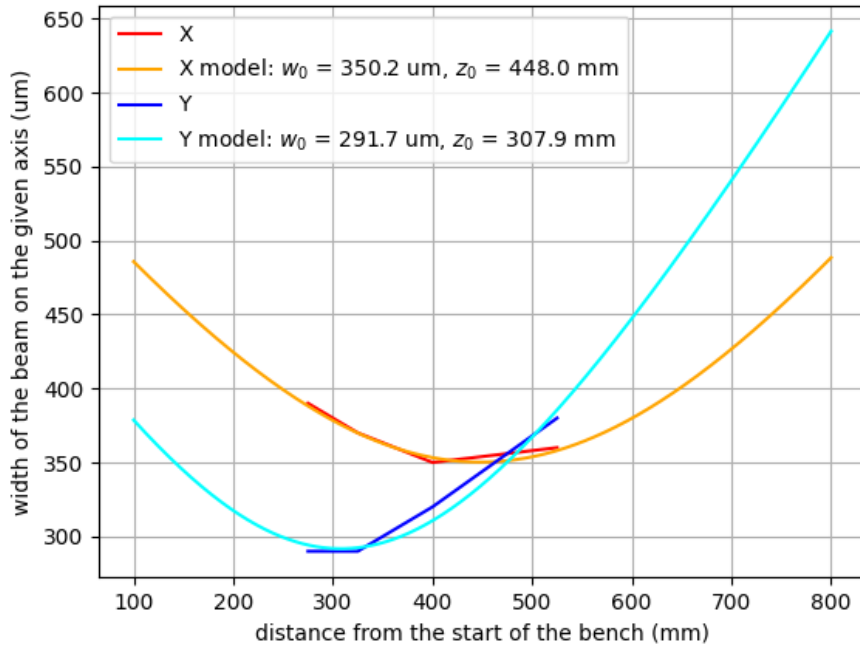
$$A(t) = \frac{P_1(t) - P_2(t)}{P_1(t) + P_2(t)} = \sqrt{2f_{sc}} \cos\left(2\pi \frac{\Delta L(t)}{\lambda}\right)$$



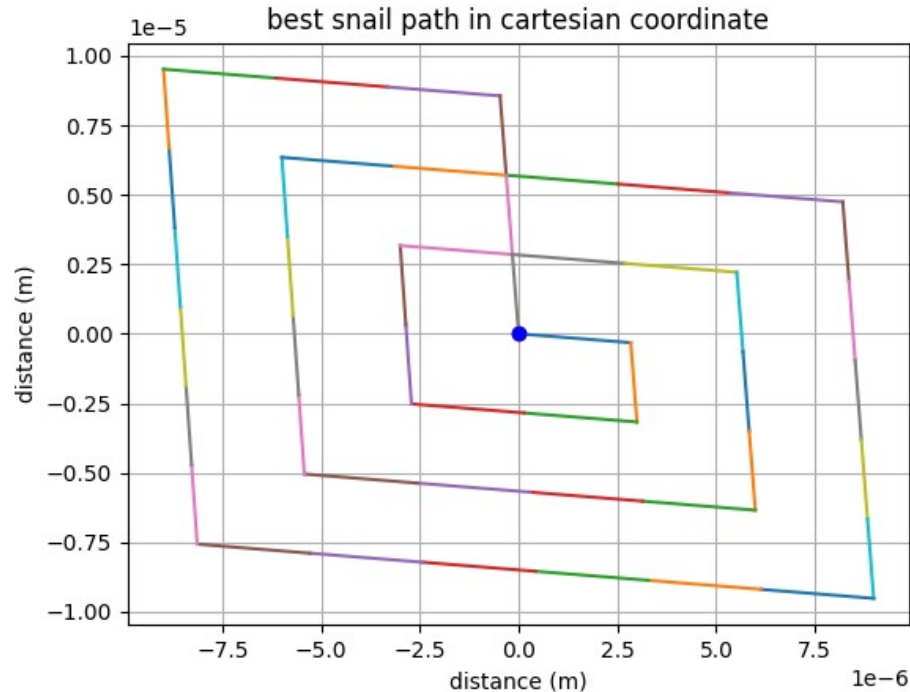
Re-characterization : beam size and visibility



Evolution of beam profile with distance



Re-characterization : motor steps

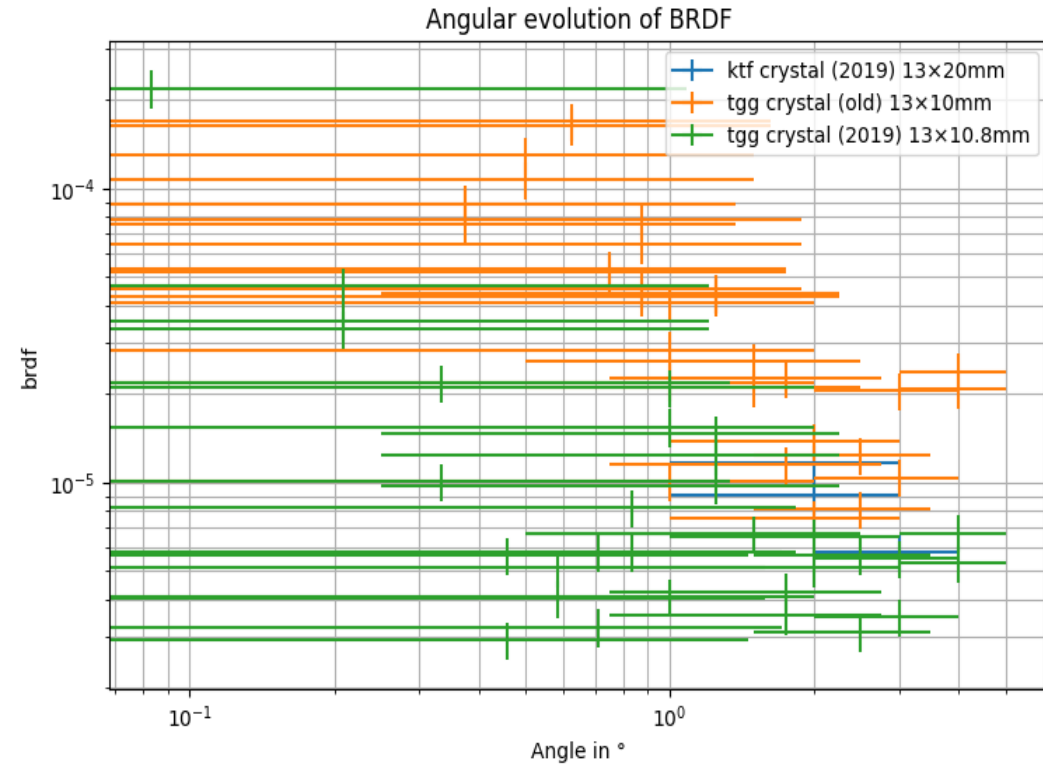


- What we want :
 - Change position of the beam on the sample
- Issue :
 - Also change incidence angle by 0.82°

Crystal measurement



- Multiples Faraday crystals :
 - Old TGG
 - New TGG
 - KTF (better thermal performance)
- new TGG scatter less



Bench speed study



- Requirement on f_{sc} and relative bench speed.

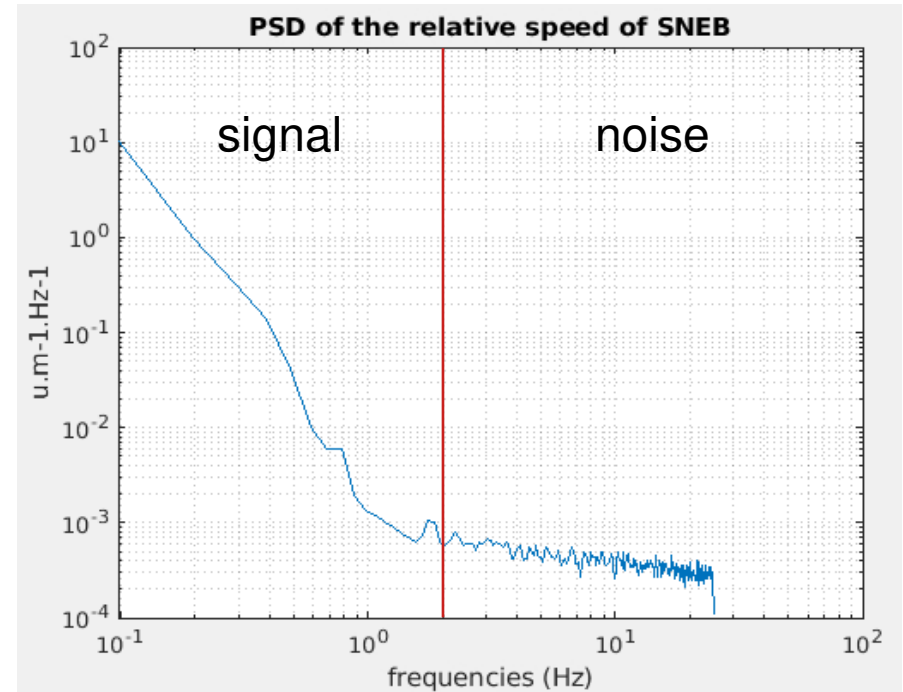
→ need to study current bench movement

- Speed can be computed as the differential of the bench position (times its frequency)
- Divide every five consecutive minutes (an observation) in which the ITF is in SCIENCE mode
- Here, the bench speed is the relative motion between the bench and its associated mirror

Filtering bench position



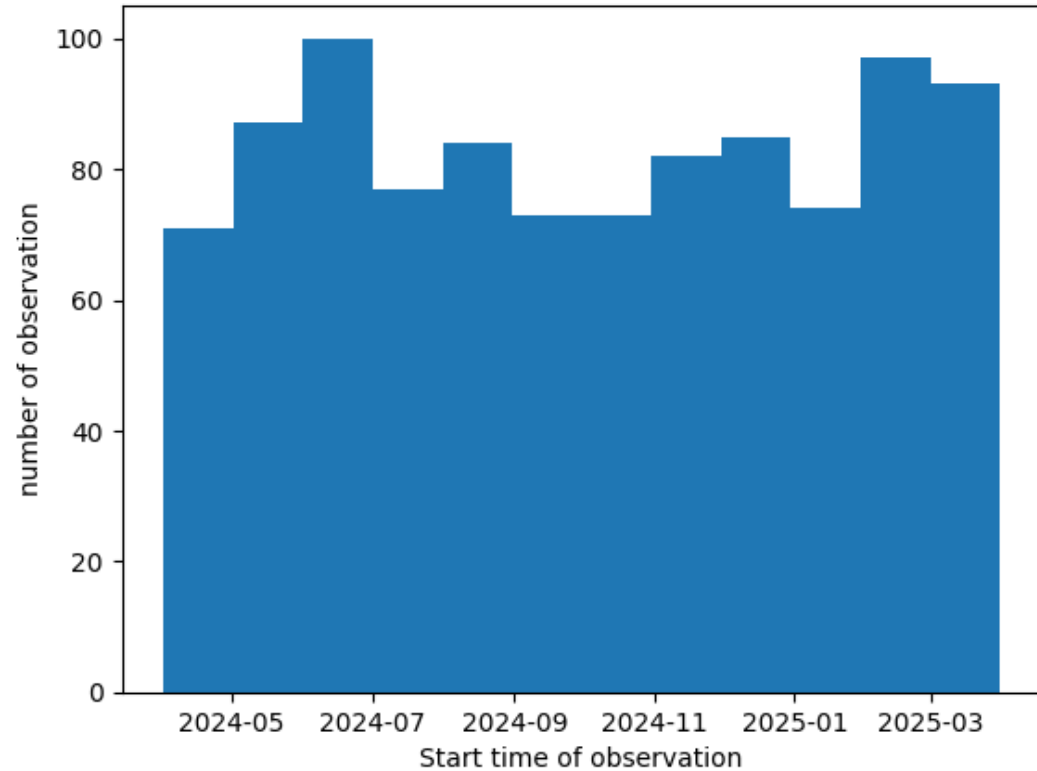
- Higher than 2Hz → dominated by sensing noise
- FIR low-pass filter:
 - Pass-band frequency: 1Hz
 - Stop-band frequency: 2Hz
 - Attenuation: 100dB
- Applied on the position of the bench. Speed is computed after.



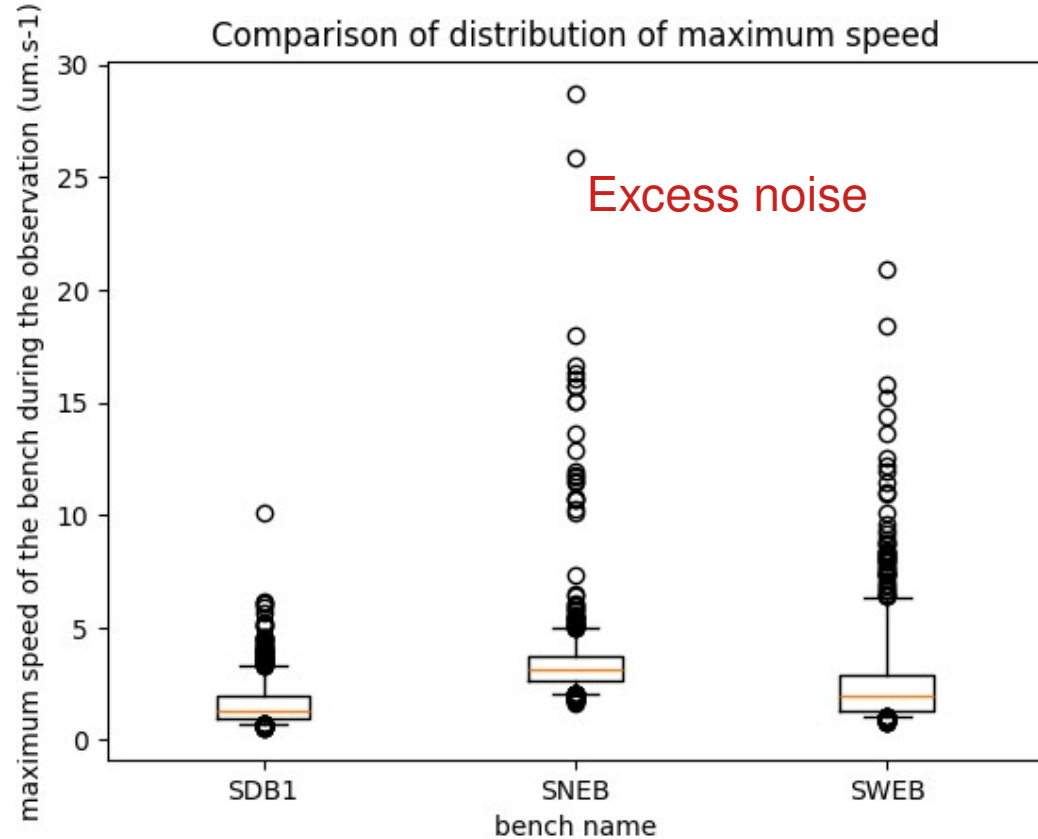
2 Hz

Bench speed evolution

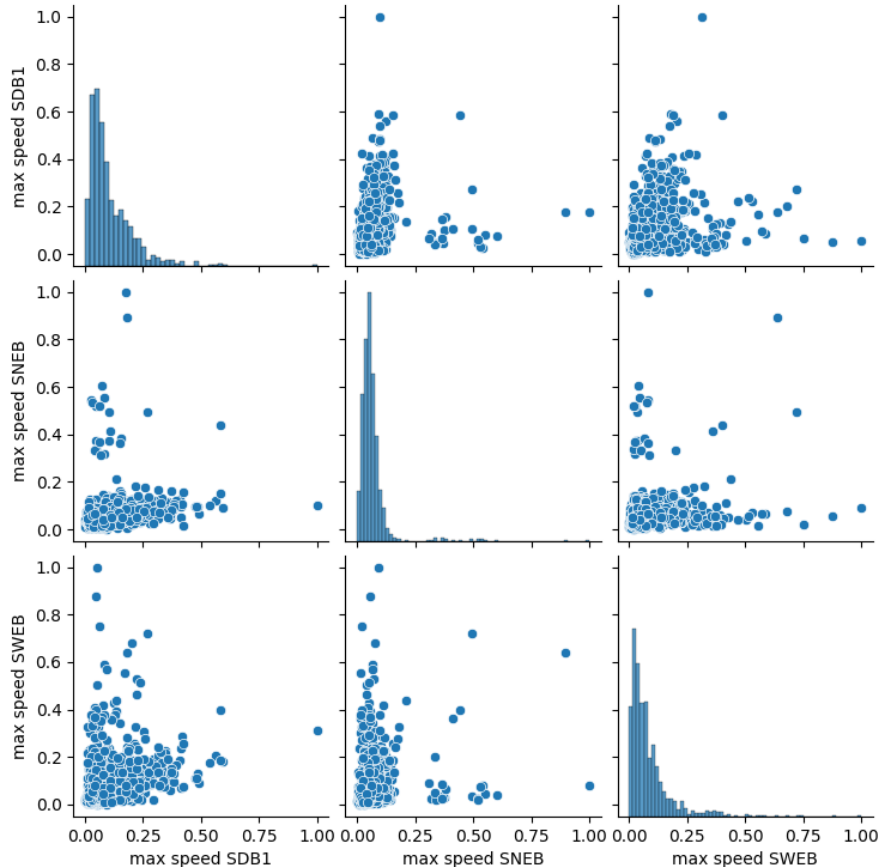
Distribution of observation starting time



Comparison of distribution of maximum speed



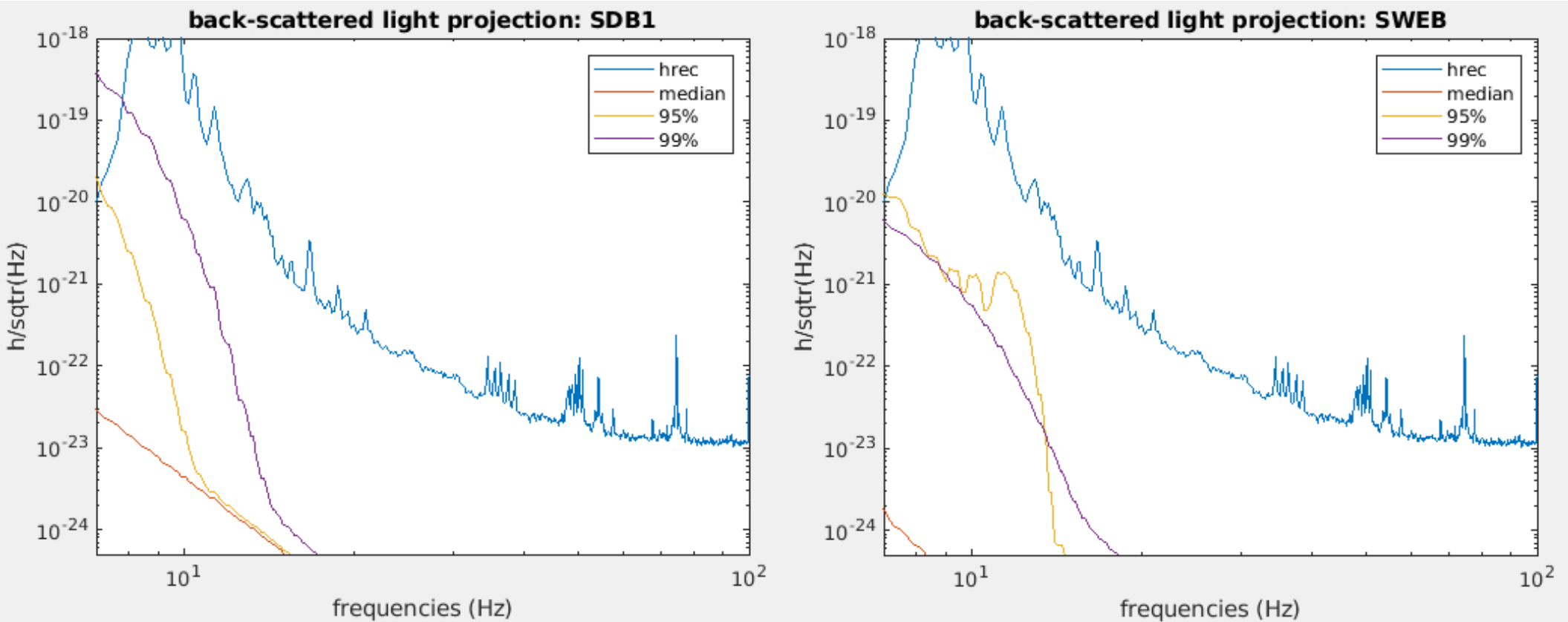
Correlation between signals



Correlation	Bench	SDB1	SNEB	SWEB
wind speed		25%	10%	16%
Micro-seismic 600-1000 mHz		74%	11%	28%
Micro-seismic 300-500 mHz		81%	13%	27%
Micro-seismic 100-200 mHz		53%	17%	21%
Micro-seismic 10-100 mHz		24%	27%	23%

Impact of excess noise

Projection for different speed



Summary



- New work on simulations (HOMs/defects)
- New measurements on back-scattermeter (TGG crystals)
- Bench backscattered light study :
 - Evolution fraction of backscattered light
 - Correlation and impact of bench speed

Future work



- Back-scattermeter :
 - OMC
 - New Faraday components (crystals/half-waveplate, polarization splitter)
- Investigation of bench backscattered light variation :
 - New measurement on Virgo
 - Improve the model (more realistic defects)
 - analyze the impact of the calibration error on the Virgo detector data
- Check backscattered light with new configuration with detuned signal recycling cavity
- Simulation of O5 configuration
 - Validate the methodology