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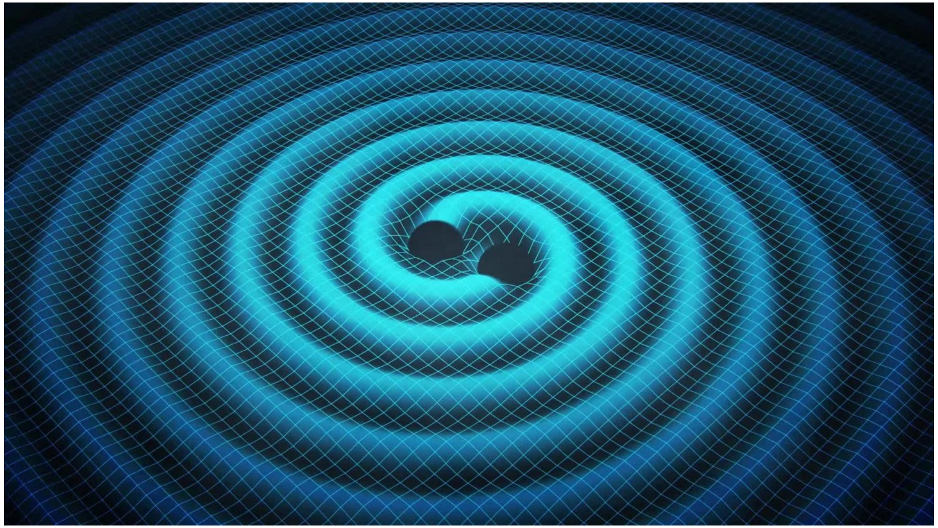
Backscattered light noise in the Virgo interferometer

1rst year CSI seminar

PhD advisors : Michal Was & Romain Gouaty

Gravitational wave

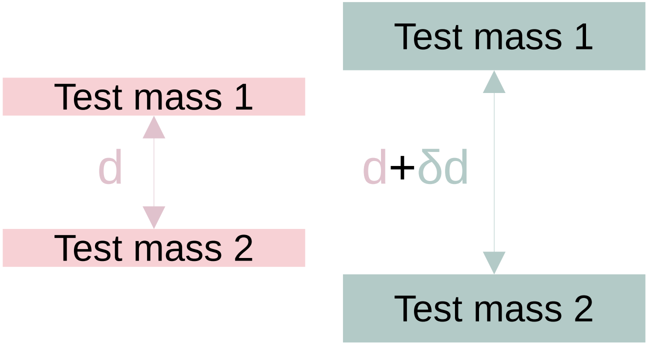
- Space-time metric's deformation
- 2 polarisations (+, ×)
- $A \propto \frac{1}{d}$
- $v = c$



Gravitational Wave Illustration
Credit : Swinburne Astronomy Productions

Detection principle

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

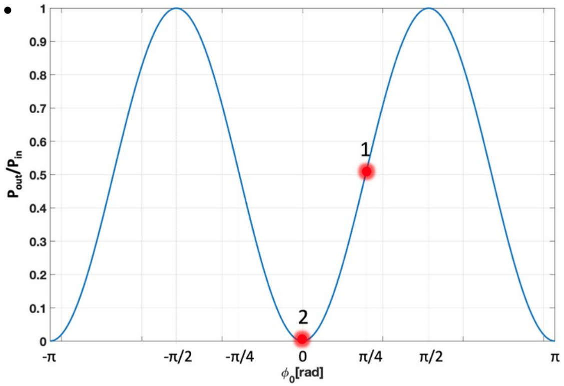


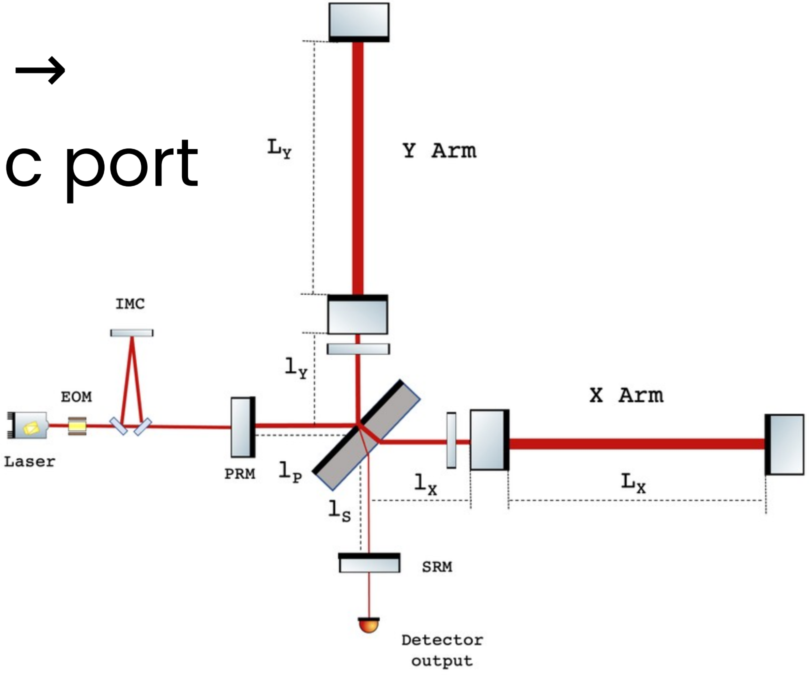
Michelson ITF

- phase difference between arms → amplitude on the anti-symmetric port

- Dark fringe offset:

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

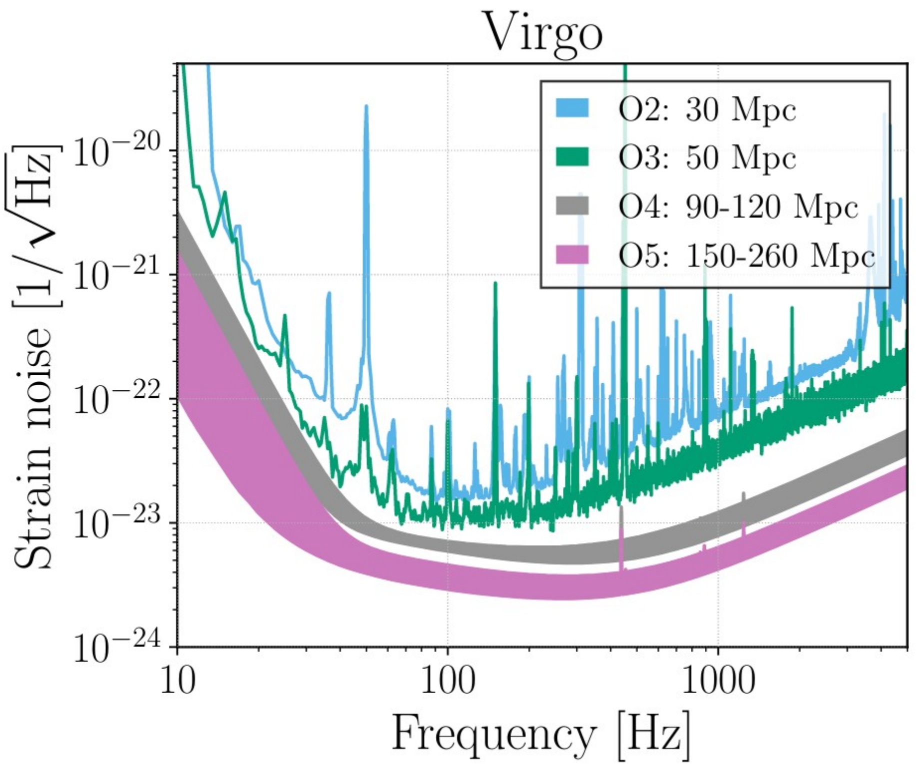




Sensitivity curve

- ASD of $h(t)$

- Affected by various noises



Benches layout

Benches :

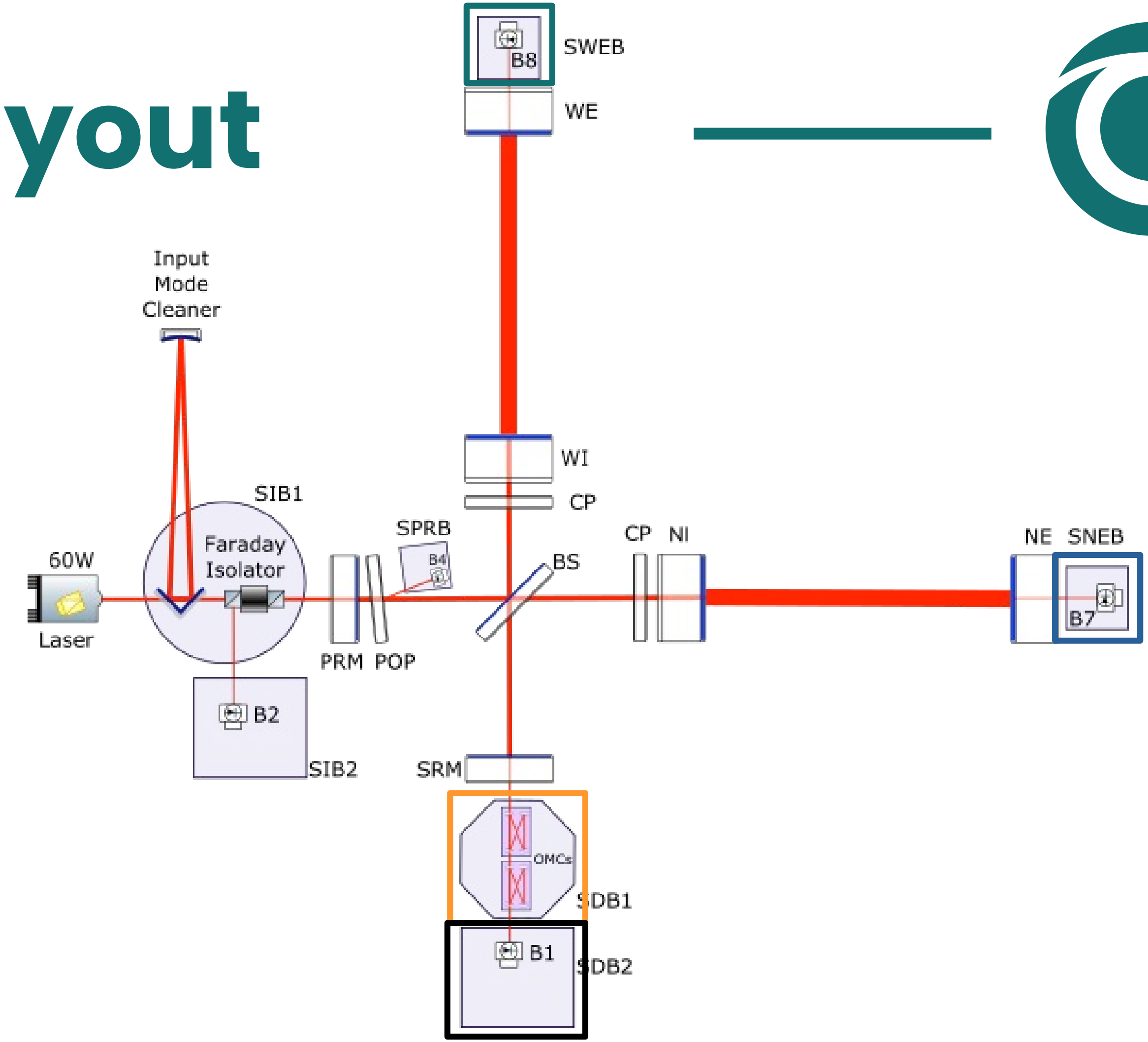
- SNEB
- SWEB

End-of-arms benches

- SDB1
- SDB2

Detection benches

- In vacuum
- Suspended

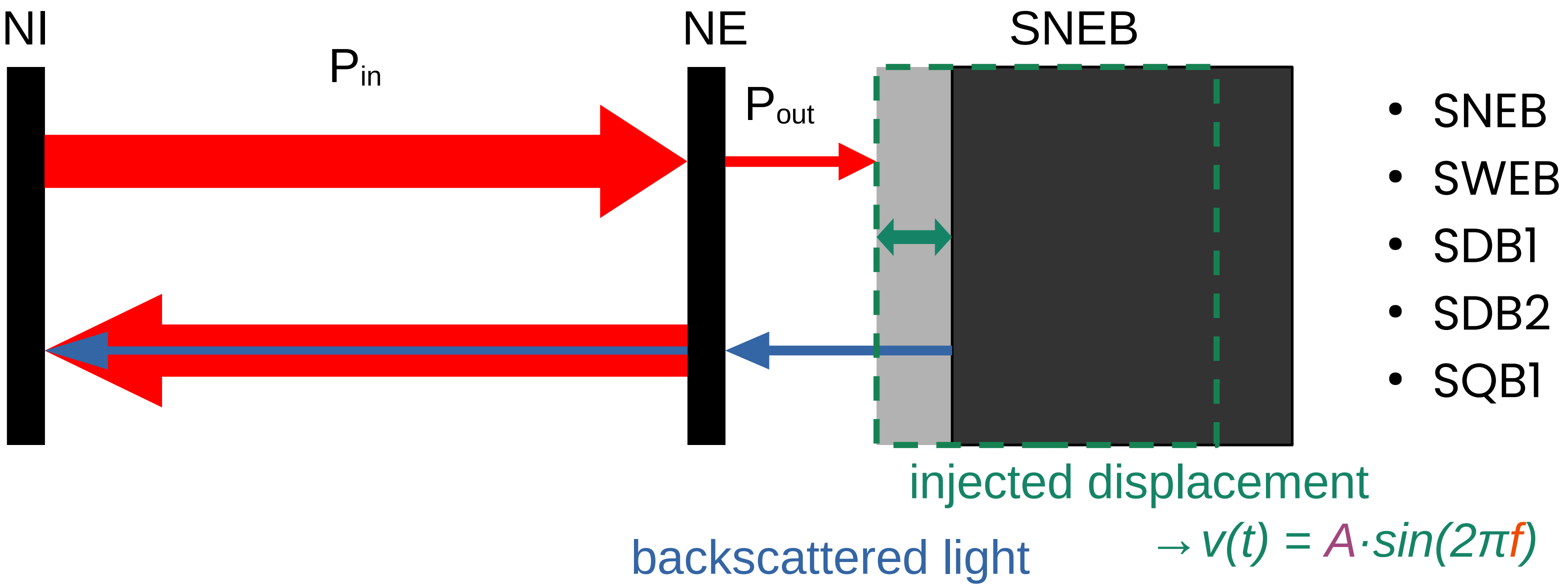


Work done

1. Measurement of noise from bench displacement
2. Measurement of backscattered light from sample
3. Simulation of TF for backscattered light

Noise measurement

31th of october 2024

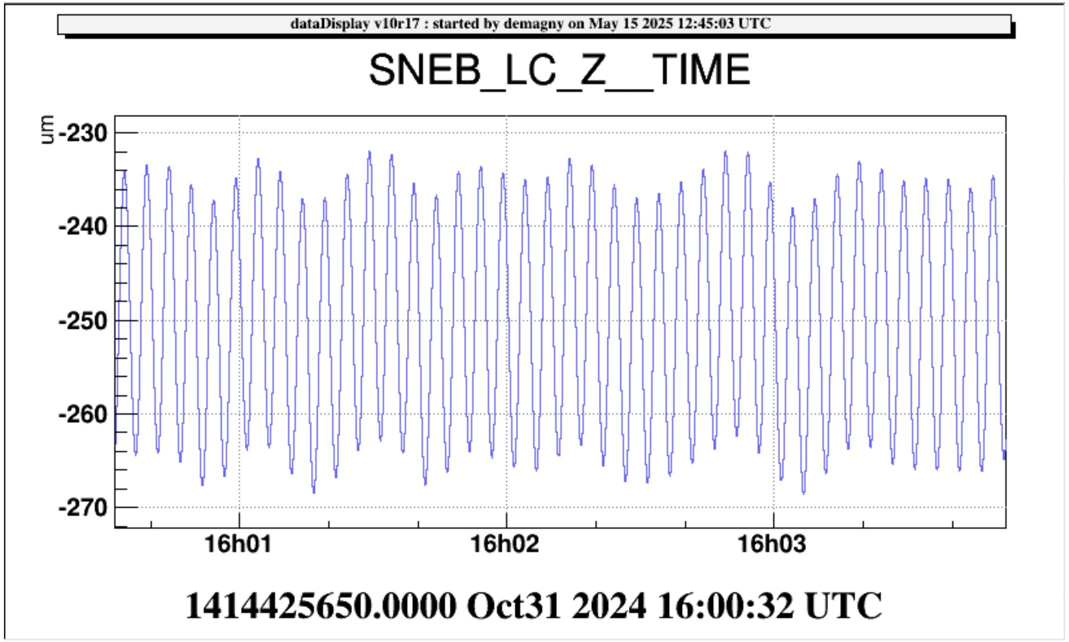


- SNEB
- SWEB
- SDB1
- SDB2
- SQB1

Commissioning shift

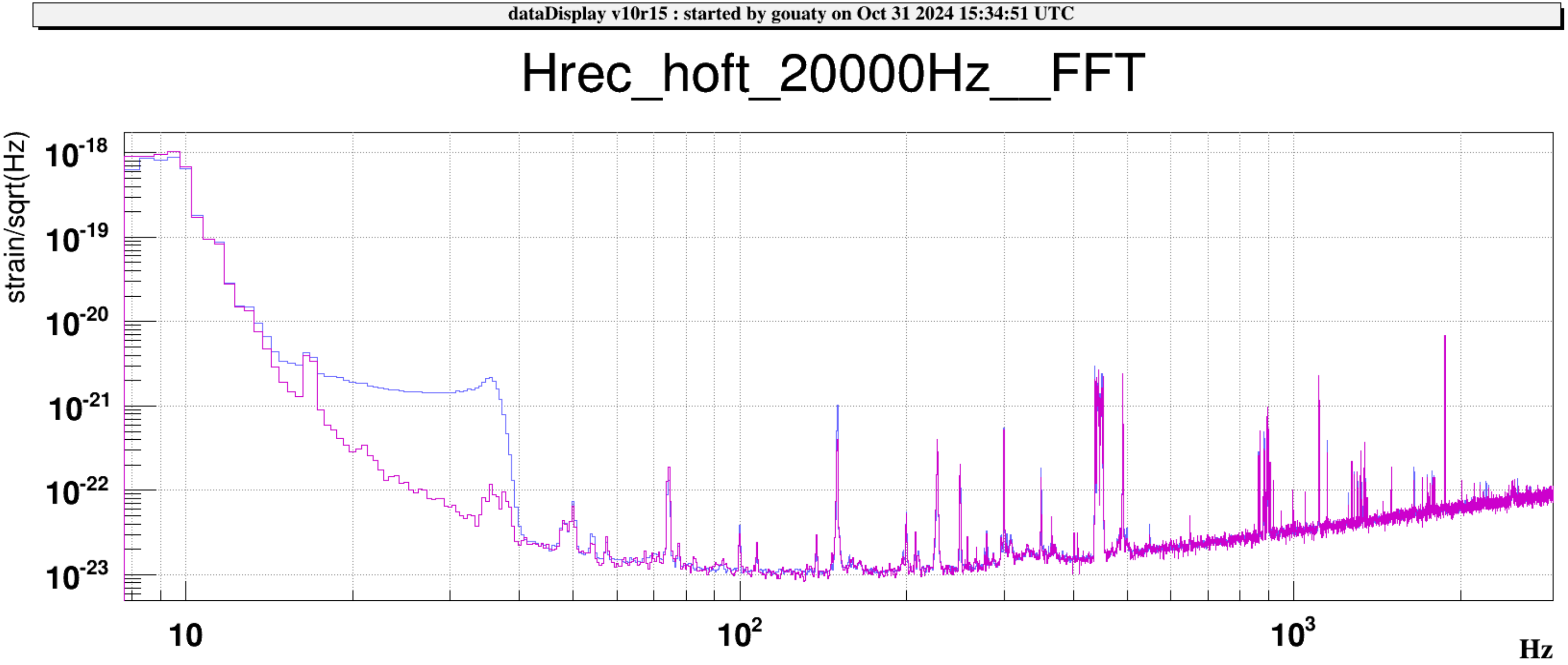
- On cascina server with Romain Gouaty
- Injecting $A \cdot \sin(2\pi f)$ on benches
- Control loops engaged

https://logbook.virgo-gw.eu/virgo/?r=65440



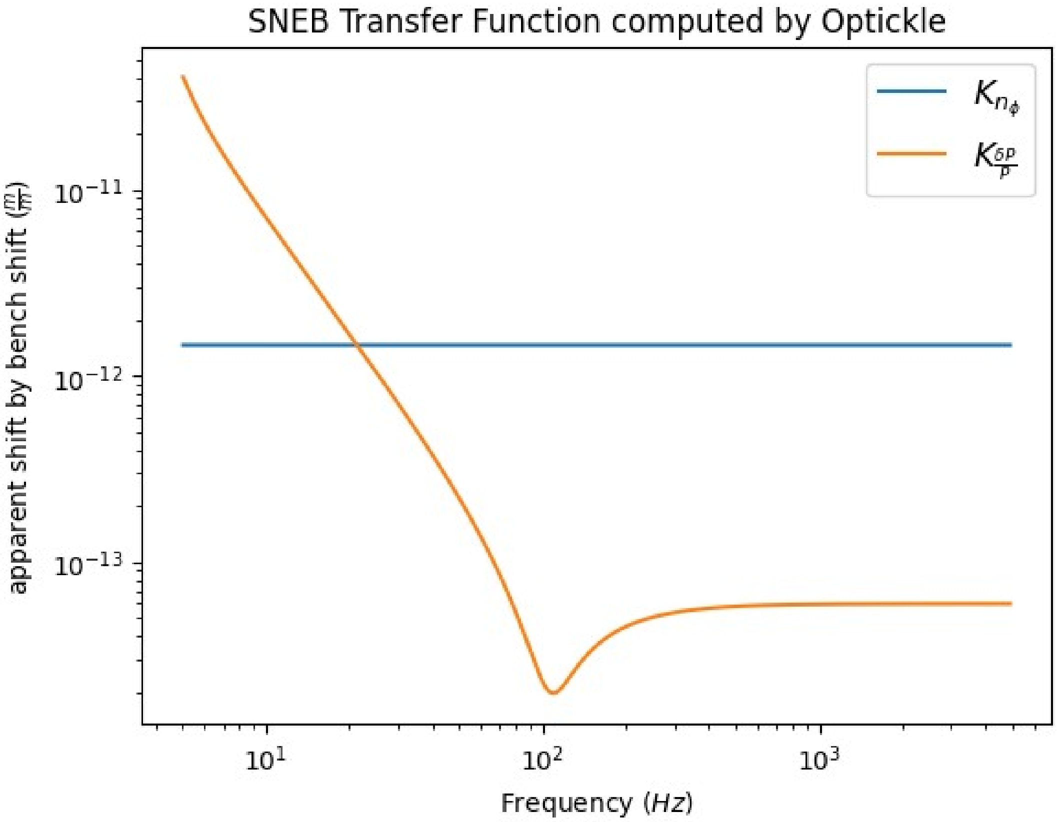
Here an injection on SNEB with f=0.2 Hz and A≈15 um

Bench vibration : result



Sensitivity curve with (blue) and without (violet) SNEB displacement

Transfer function



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

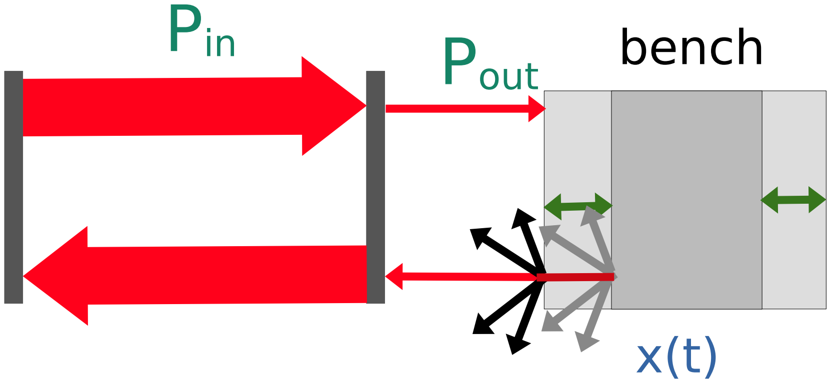
mirror transmission

bench movement

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

fraction of backscattered light

transfer function by radiation pressure (Kp) and phase (Kn)



Software development

- Python library built from already existing matlab code
- Use already simulated Optickle simulation
- Data taken :
  - Bench movement (with a calibration factor)
  - Mirror movement: reference (with a calibration factor)
  - h(t)
- Cut high frequency movement due to sensor's noise
- Find the backscattered light factor (f_{sc}) which match observation

Principle

- Noise background : $h_{ref}(f)$
- Measure with an excitation : $h_{exc}(f) \approx h_{ref}(f) + h_{r_{real}}(f)$
- Find $h_{r_{theory}}(f, f_{sc})$ to have : $h_{r_{theory}}(f, f_{sc}) \approx h_{r_{real}}(f) = h_{exc}(f) - h_{ref}(f)$

  $\Rightarrow h_{exc}(f) - (h_{ref}(f) + h_{r_{theory}}(f)) \approx 0$

- Minimize : $h_{r_{diff}}(f, f_{sc}) = h_{exc}(f) - (h_{ref}(f) + h_{r_{theory}}(f, f_{sc}))$
- Minimize on a frequency range [a, b] : $m(f_r) = \int_a^b df \cdot h_{r_{diff}}(f, f_{sc})$

Computation result

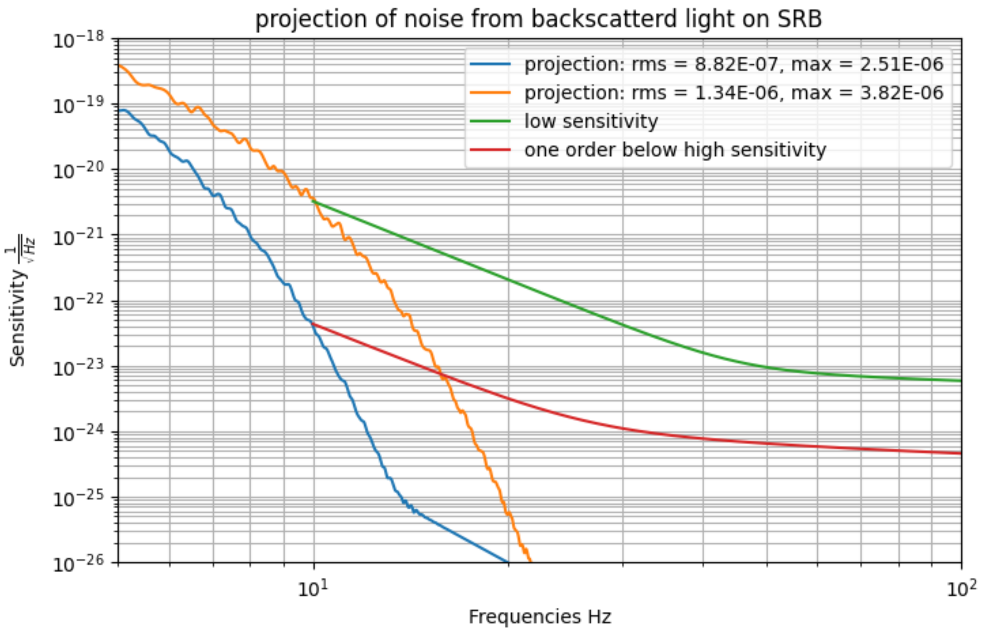
bench	f_{sc} during O3	f_{sc} during commissioning	Current f_{sc} (O4b)
SDB1	2×10^{-9}	3.1×10^{-10}	2.07×10^{-9}
SDB2	4×10^{-10}	4.1×10^{-13}	1.62×10^{-12}
SNEB	2.5×10^{-8}	4.4×10^{-9}	5.02×10^{-9}
SWEB	4.0×10^{-8}	2.5×10^{-9}	3.05×10^{-9}

Unphysical transfer function

Source for O3 values : https://arxiv.org/abs/2011.03539 (photodiode shutter open) and https://tds.virgo-gw.eu/?r=21958 for SDB1 and SDB2 values

Requirement for O5

- Bench speed requirements
- f_{sc} requirement for new benches before SDB1



Future work on the interferometer

- O4 end on 7 of october 2025

  → Planned measurement with SR aligned

- Code and data can be used to determine future requirements

Backscattermeter

laser power

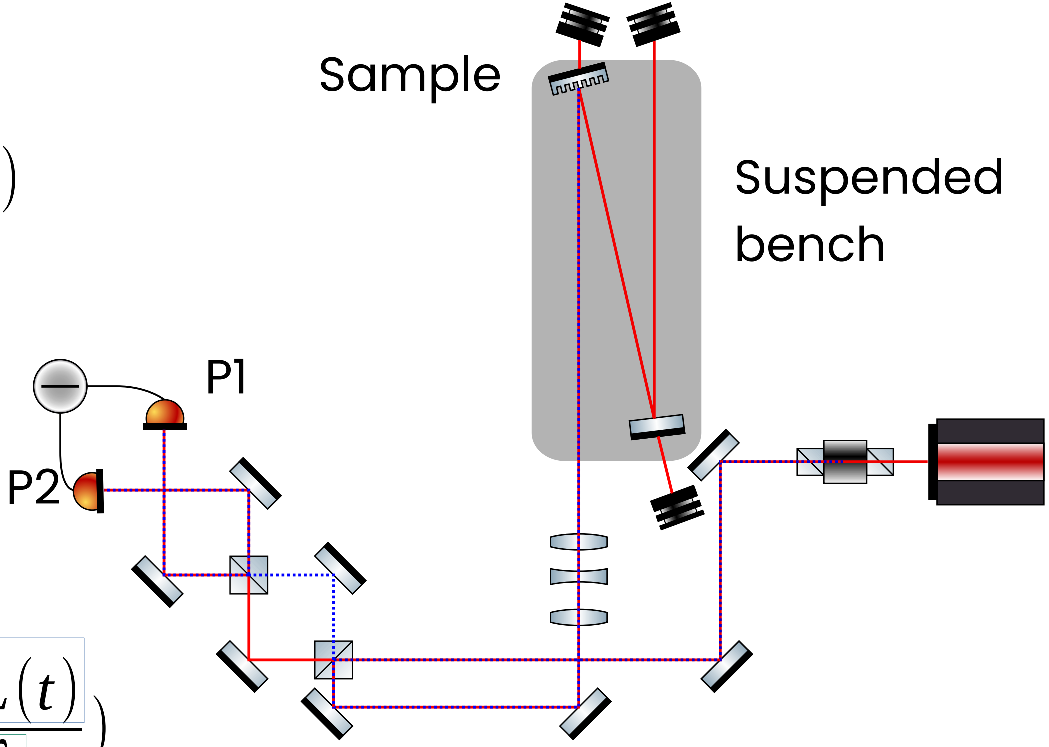
$$P_1(t)-P_2(t)=\frac{\boxed{P_0}}{\sqrt{2}}\boxed{\sqrt{f_{sc}}}\cos\left(2\pi\frac{\boxed{\Delta L(t)}}{\boxed{\lambda}}\right)$$

wavelength

fraction of backscattered light

bench movement

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



Computing BRDF

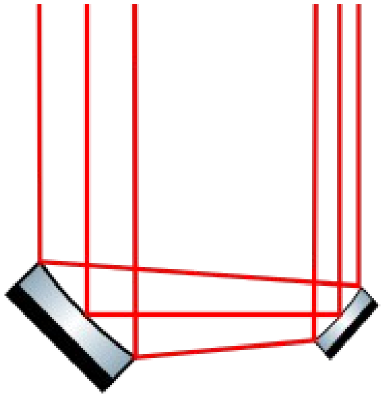
- Assuming :
  - scattered light : spherical wave
  - gaussian beam

$\Rightarrow$ overlap $= \dfrac{\lambda^2}{\pi^2 w^2}$

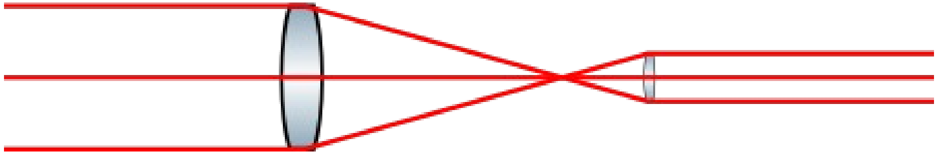
$$BRDF = \frac{1}{\pi \cos(\theta)}$$

$$f_{sc} = Overlap \cdot \pi BRDF(\theta)\cos(\theta) = BRDF(\theta)\frac{\lambda^2 \cos(\theta)}{\pi w^2}$$

Telescope design



optics	f_{sc} on bench	BRDF
mirror	6×10^{-10}	3×10^{-4}
antireflective coating	1×10^{-11}	6×10^{-6}
substrate	$4\text{–}10\times10^{-11}$	$2\text{–}6\times10^{-5}$



commercial optics

Characterization of crystals

- Crystals : critical elements
  - Low incidence
  - Long crystals : rayleigh diffusion

	angle	BRDF	f_{sc} on SDB1
EOM crystal	17.5 mrad	$7{,}7\cdot10^{-6}$	$1{,}6\cdot10^{-12}$
EOM crystal	40 mrad	$4{,}6\cdot10^{-6}$	$9{,}7\cdot10^{-13}$
Faraday 13 mm	17.5 mrad	$3{,}0\cdot10^{-4}$	$5{,}4\cdot10^{-11}$
Faraday 13 mm	40 mrad	$2{,}4\cdot10^{-5}$	$5{,}1\cdot10^{-12}$
Faraday 12 mm	25 mrad	$3{,}1\cdot10^{-4}$	$6{,}6\cdot10^{-11}$
Faraday 12 mm	40 mrad	$6{,}2\cdot10^{-5}$	$1{,}3\cdot10^{-11}$
Faraday 12 mm	220 mrad	$1{,}1\cdot10^{-4}$	$2{,}2\cdot10^{-11}$
Polarizer	Brewster's angle	$1{,}4\cdot10^{-5}$	$3{,}0\cdot10^{-12}$

Parallel with measurement on Virgo

- f_{sc} of SDB1 during commissioning: $f_{sc_{SDB1}} = 3.1 \cdot 10^{-10}$

$$\frac{f_{sc_{SDB\,1}}}{f_{sc_{faraday}}} = 5.7$$

Not using latest results for now → waiting for new TF

⇒Faraday isolator highly contribute to the backscattered noise

Future analysis

- More measurements on the dependance of the incidence angle for various faraday crystals
- Optics used in O5
- OMC ?
- Analyse of the distribution of speckles

Simulation of TF

- Model already created by M. Was, using Optickle
- Cannot model mirror misalignement:
  - Adding losses on SR
  - Lowering transmission on SR

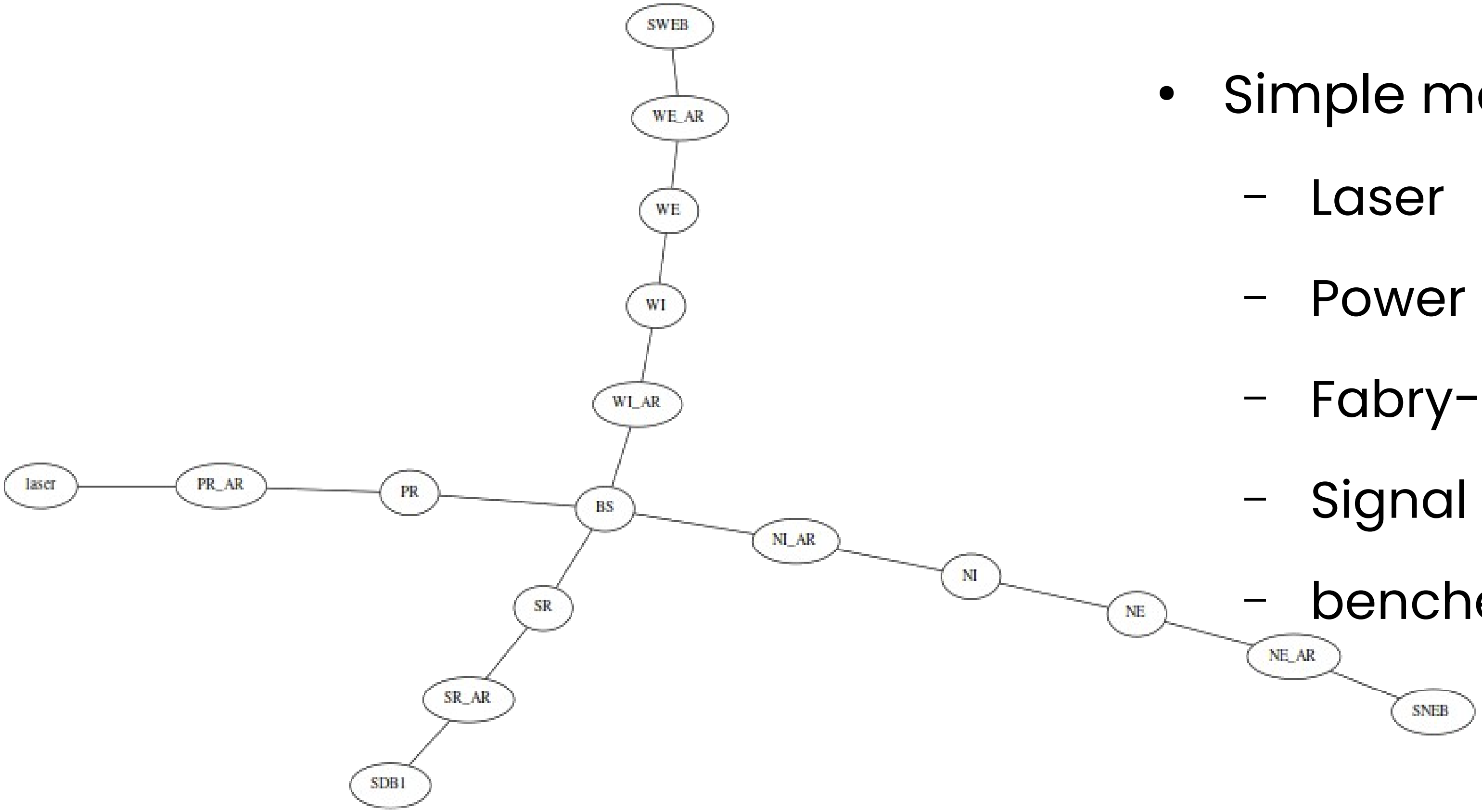
  Physically incorrect
- Unmaintened for more than 5 years

⇒ Needs for a new simulation

Finesse 3

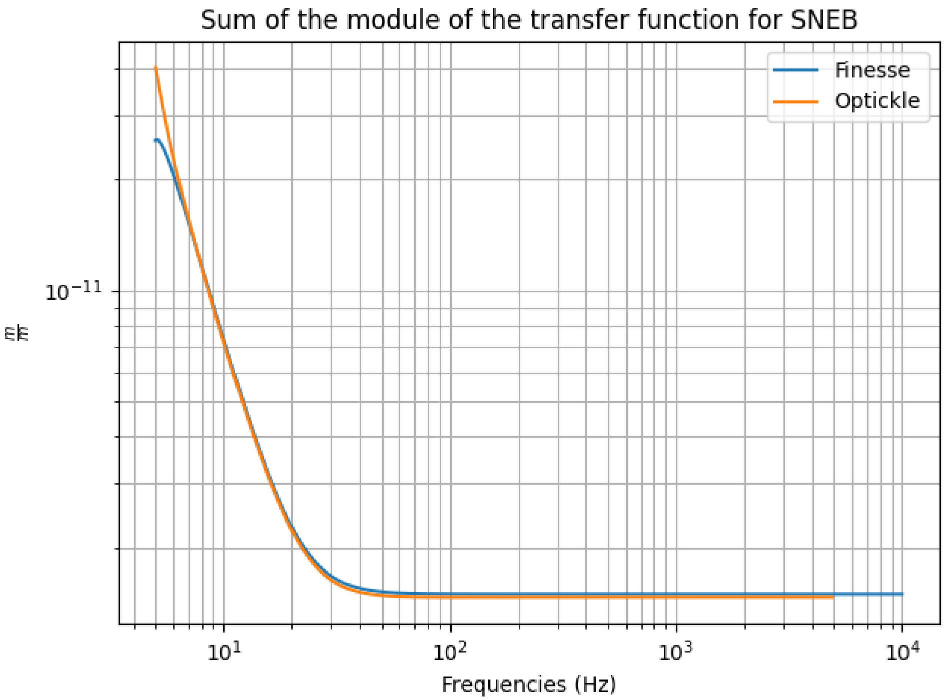
- Python based interferometer simulation
- Modal simulation
- Will be used (and is already used) by members of the collaboration

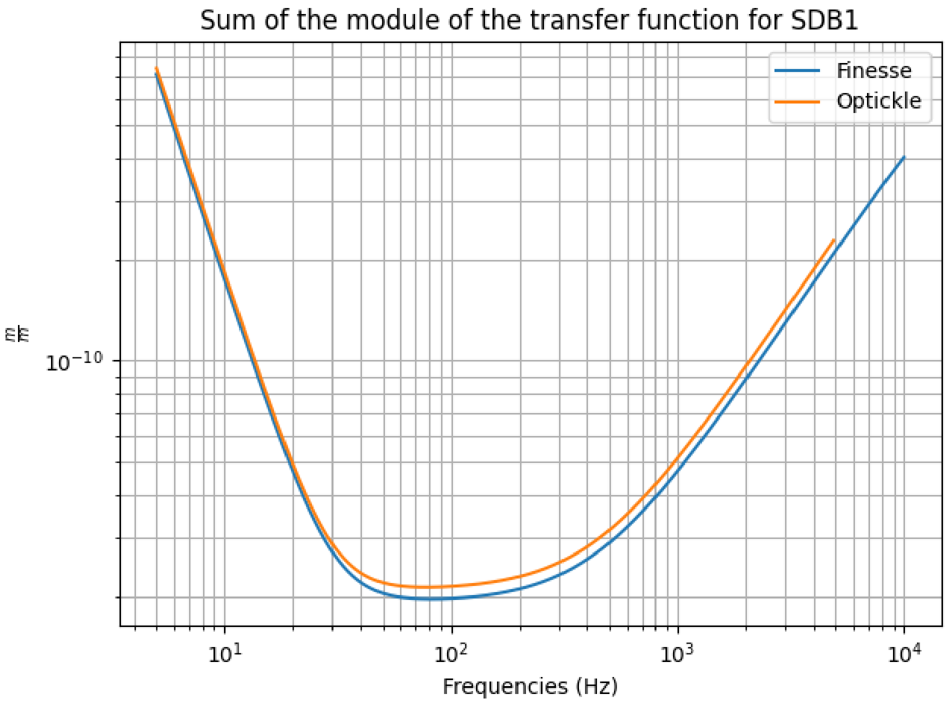
Current model



- Simple model with :
  - Laser
  - Power Recycling cavity
  - Fabry-Perot cavity
  - Signal Recycling cavity
  - benches

Comparison with Optickle





Same laser power, dark fringe offset and SR aligned

Current & future work

- Current work
  - Added high order TEM mode
  - Added an angle to SR → modelize misalignement
  - Still interpreting the result
- Future work
  - Adding antireflective surface on beam splitter
  - Getting a result compatible with current observation
  - Modelize future O5 configuration

Conclusion & outlook

- Measurements on the backscattermeter :
  - Faraday crystals
  - Various O5 optics
  - OMC ?
- Simulation results :
  - Add anti-reflective surface of BS (allows to model B5 beam) & finish O4 modelization
  - Modelize future O5 configuration
- Work on photodiode design to measure polarization fluctuations

⇒ Work on upgrade for O5 on backscattering noise

- Side project : RRT shifts (level 0) before the end of O4b

Training courses

- Mandatory : « Research Ethics », « Scientific Integrity »
- « Physics in the XXIst century », 18h
- « Statistics courses using a data driven approach, using R software », 15h
- MaNiTou Summer School on Gravitational Waves, 4 day

Thanks you for listening

Any questions ?