Minimizing backscattered light in the Virgo detection system

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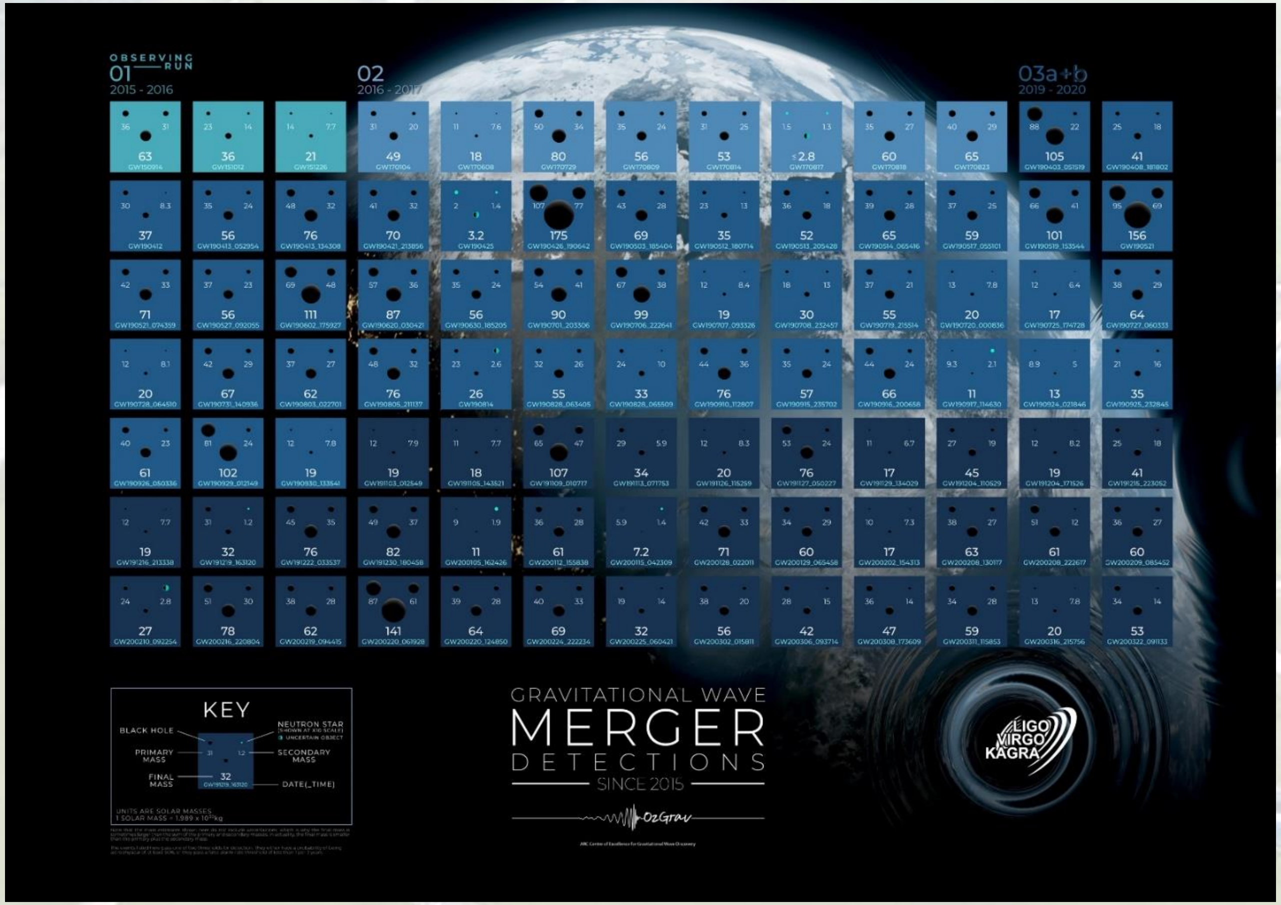
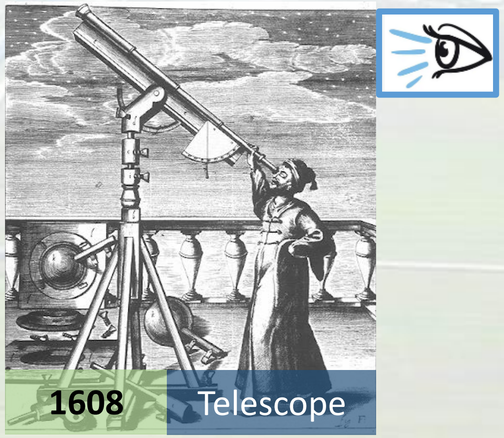
Gravitational-Waves Detectors

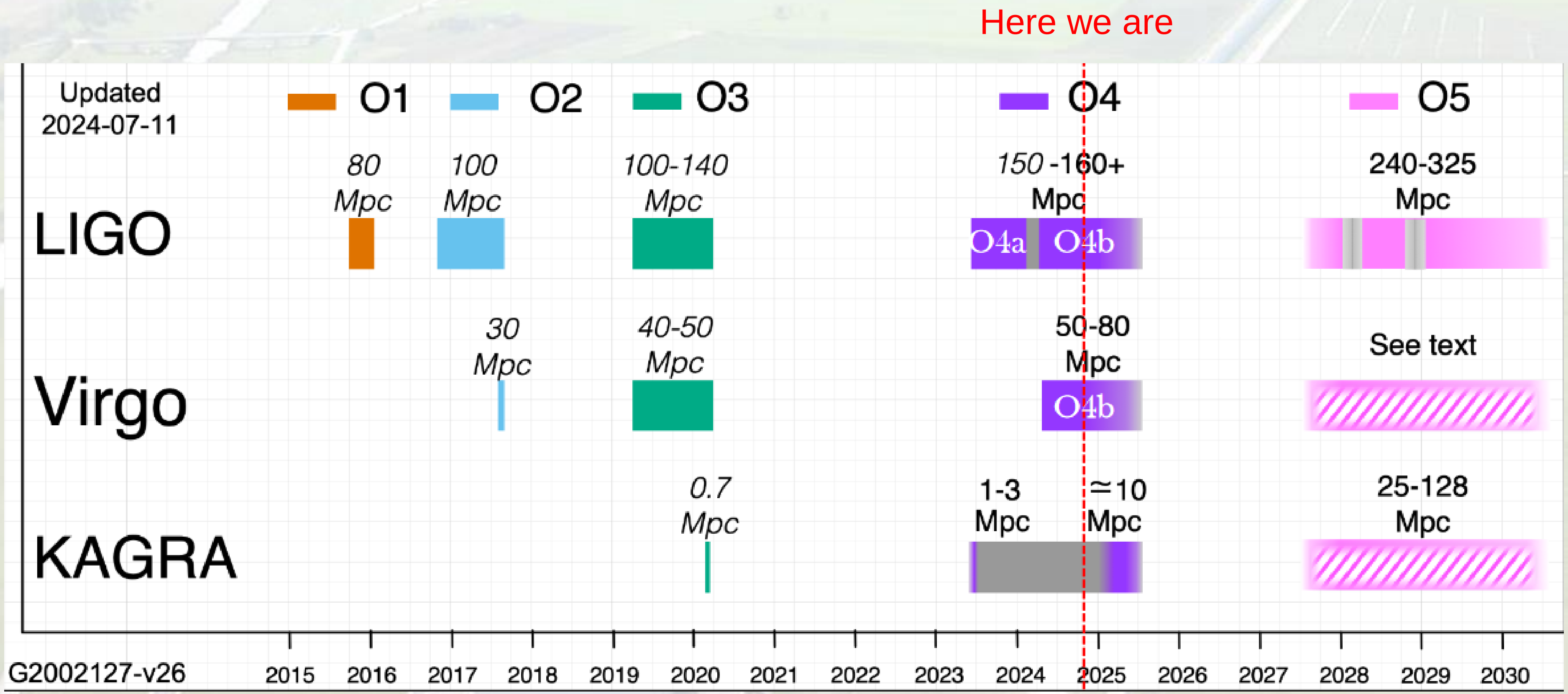
Gravitational Wave Transient Catalog (GWTC-3)



Credit: *Carl Knox (OzGrav, Swinburne University of Technology).*



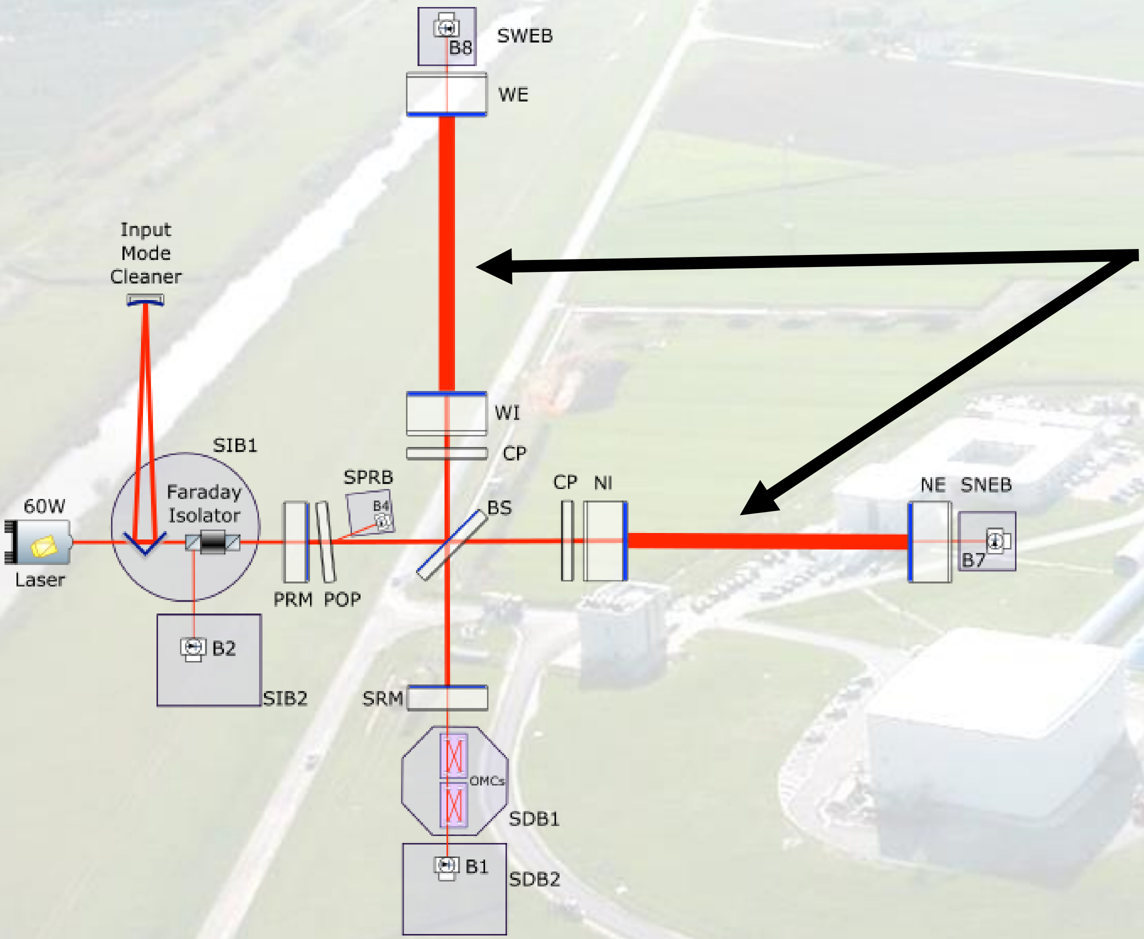
Observing Runs

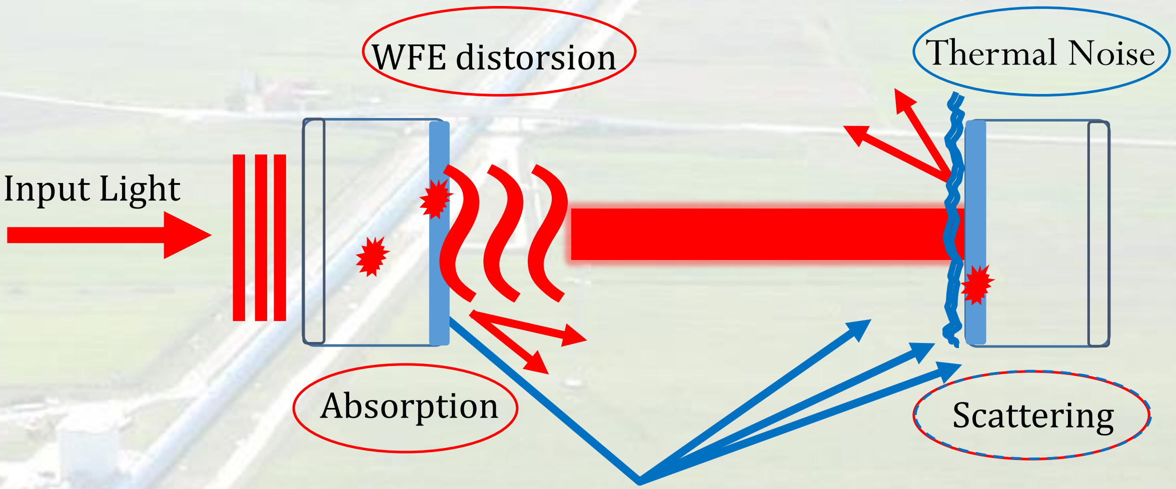


The O5 start dates, duration, and sensitivities are current best guesses, and will likely be adjusted as we approach that run for all the detectors

Interferometer defects and effects

Noise
Losses and distortion



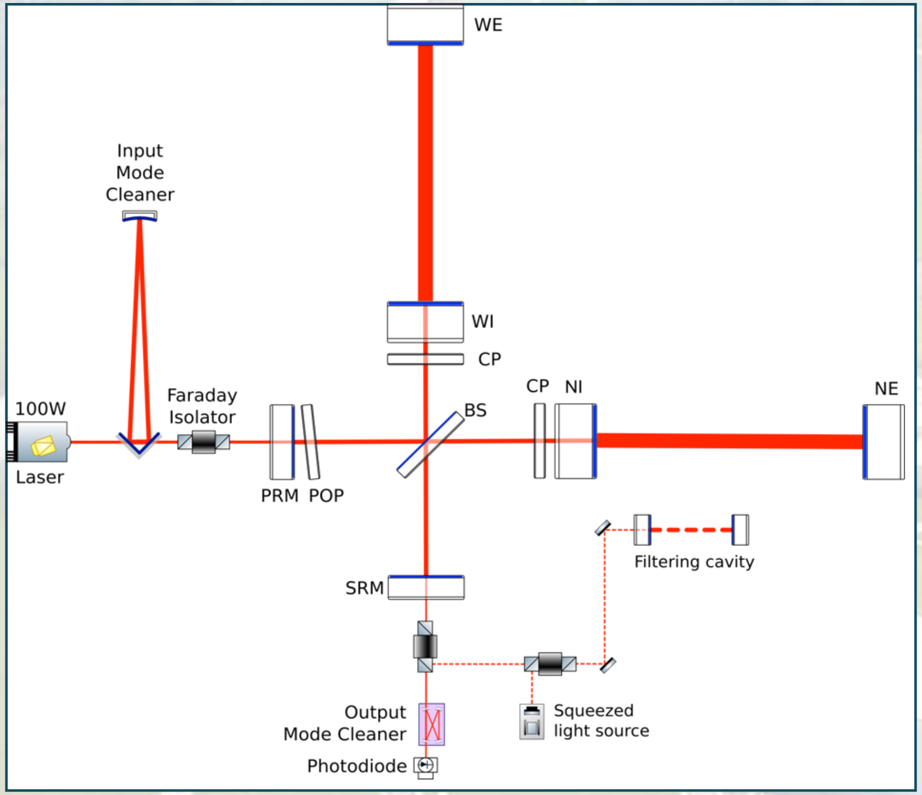


Major effects in mirror (substrate+coating):

- Absorption in the thin films
- Light scattering by the imperfections of the mirror.
  - The polishing of the substrate which adds defects
  - Point defects in the thin films due to the deposition technique.

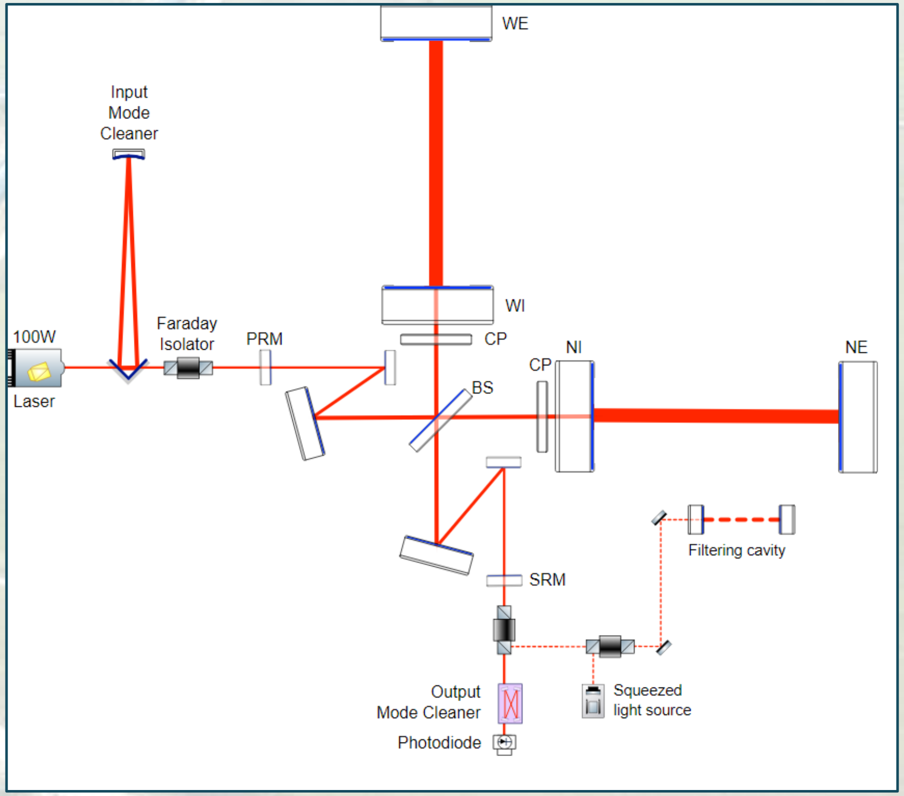
Post-O4 plan towards O5 : optical layout with stable cavities

Current configuration (O4) :
marginally stable recycling cavities



Upgrade AdvancedVirgo+
phase2

Future configuration (O5) :
stable recycling cavities



Installing stable cavity is a priority
Schedule for installation + commissioning (mid-2025→2029) will not allow Virgo to join O5 from the beginning (~mid 2027)

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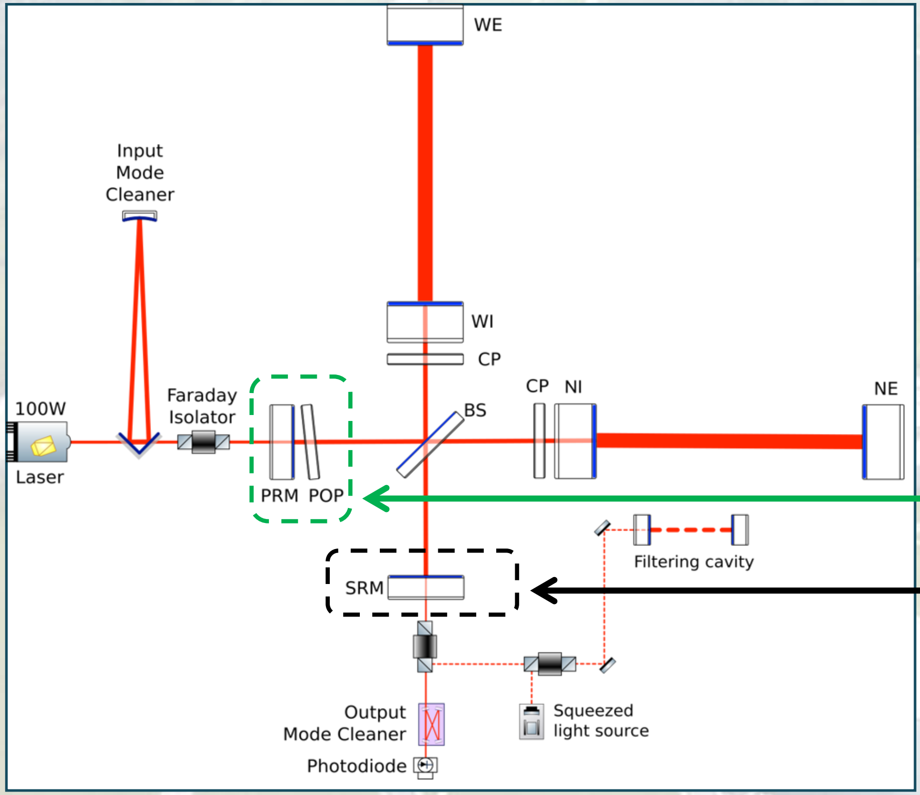

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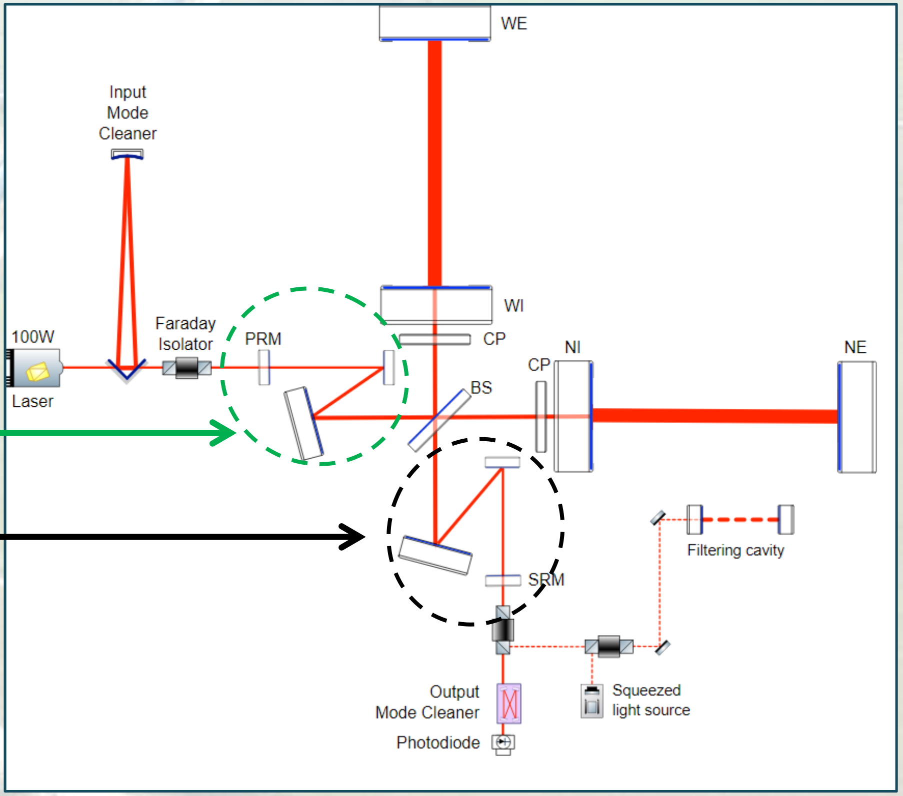

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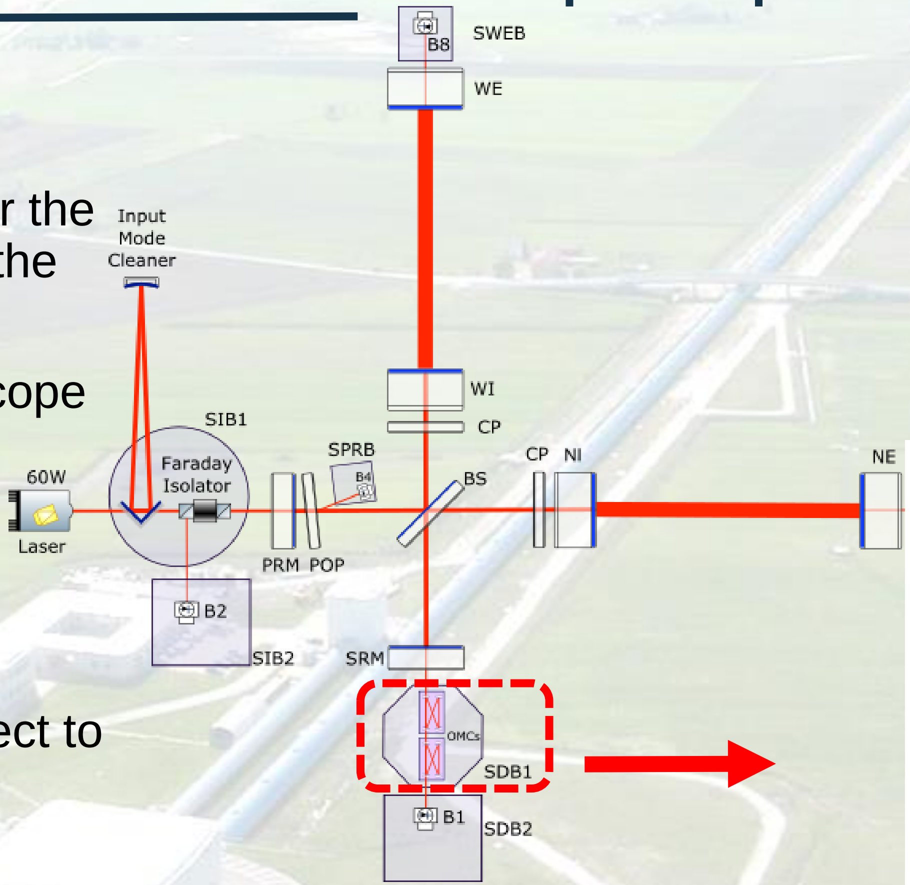
Planned modifications on the main output optical benches

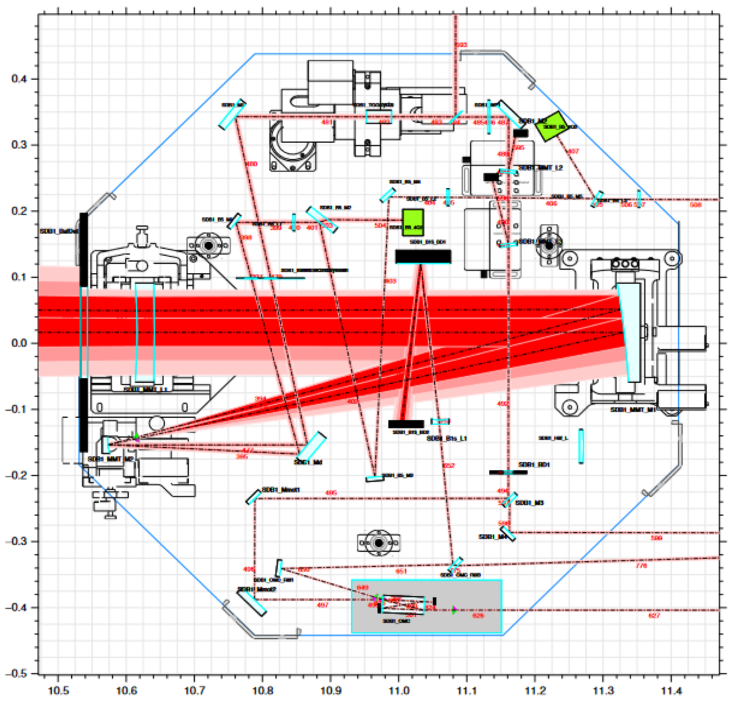
Context :

- A new telescope will be developed for the current optical bench, which detects the interferometer output beam.
- The beam changes size so the telescope has to be changed

Goal :

- Identify the optimal design for the telescope (lenses vs mirror)
- Position of Faraday crystal with respect to telescope
- Optimal choice depends on several parameters : optical losses, scattered light…





Suspended Detection Bench (SDB1)

Planned modifications on the main output optical benches

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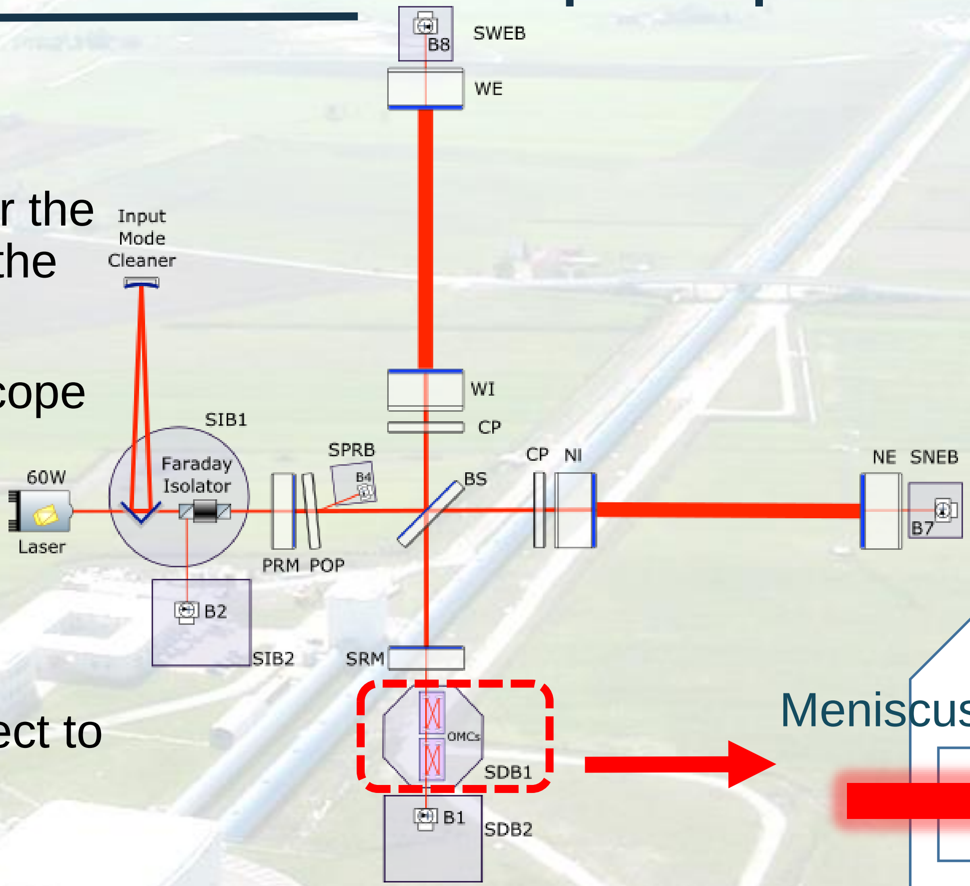
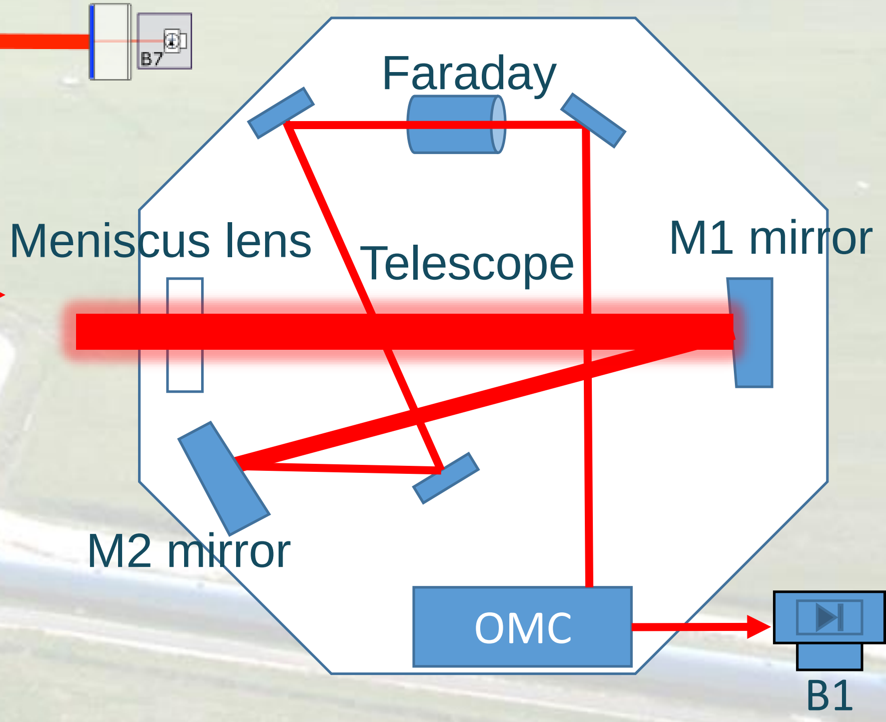


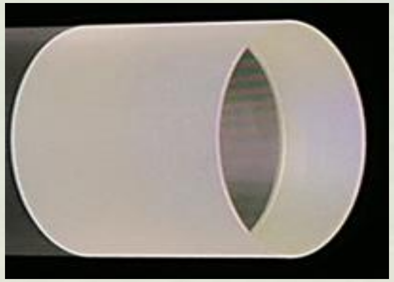


Studies of scattered light for the design of the new optical benches

This work concentrates one of the parameter:

- Measurements at the LAPP, to estimate the back-scattered light from elements of the telescope (mirrors and/or lenses) and the FI.
- Different optics from Edmund Optics chararcterized :
    - High-Reflective (HR) coated mirrors
    - Anti-Reflective (AR) coated windows
    - Harmonic splitters anti-reflective
    - Uncoated windows
    - Farday crystals from EGO

Optics of 1 inch
Ø 25,4 mm

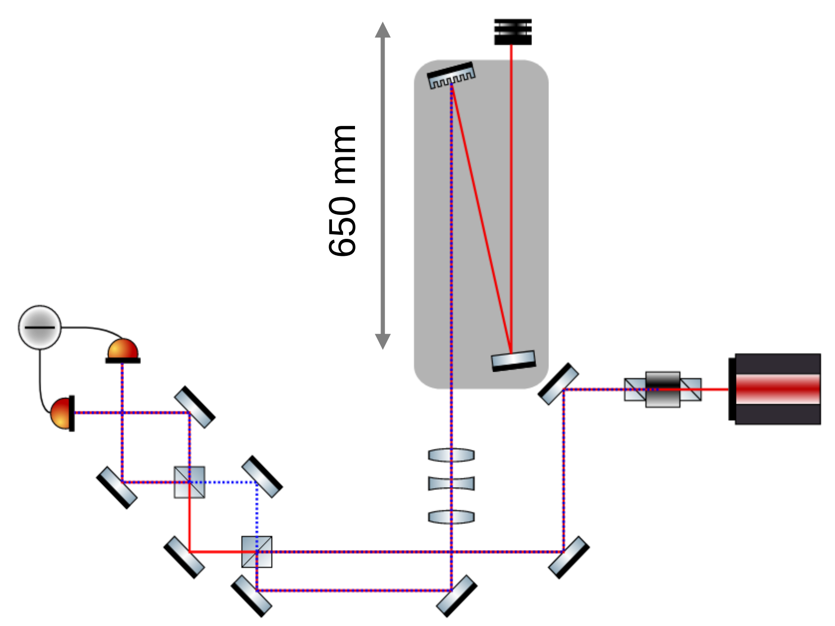


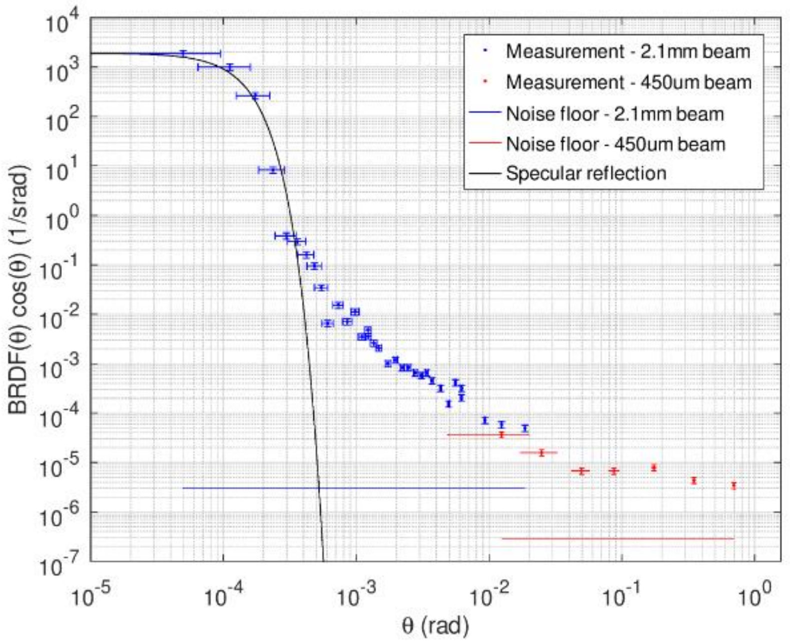
Faraday crystal
Ø 12-13 mm

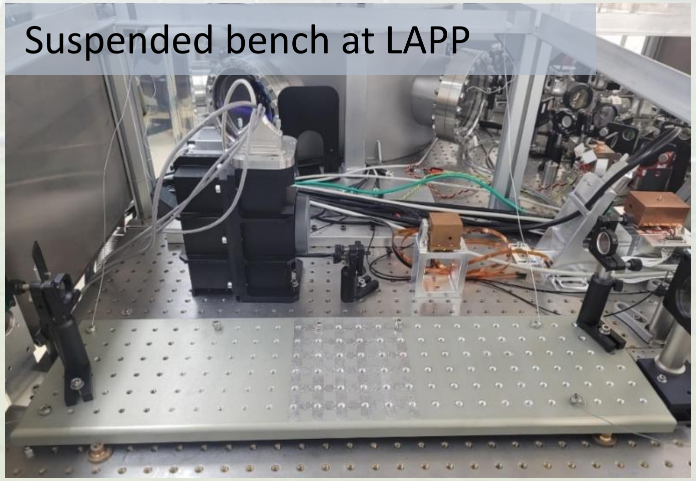
→ Input on one of the parameters for choosing the layout of the optical bench for AdV+/phase2

Backscatter meter experiment

M. Wąs and E. Polini, "High-angular-resolution interferometric backscatter meter," Opt. Lett. 47, 2334-2337 (2022)



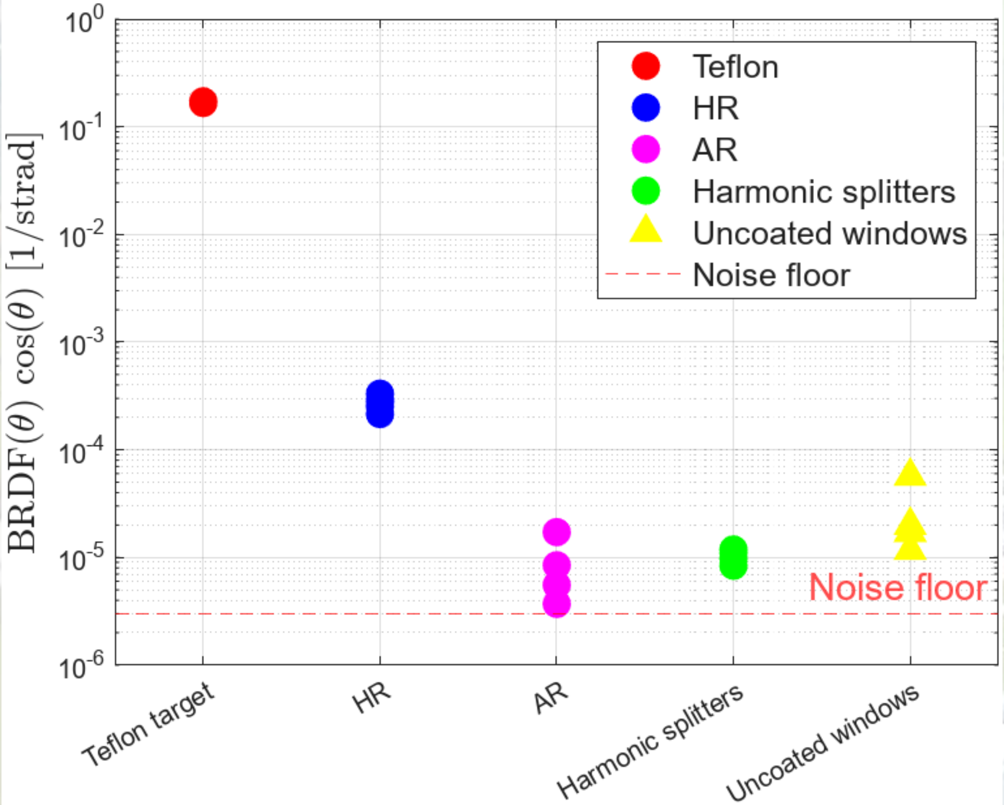




- $P_1(t) - P_2(t) = \frac{P_0}{\sqrt{2}} . \sqrt{f_r} . \cos(2\pi \frac{\Delta L(t)}{\lambda})$
- Get the f_{sc} experimental
- Get the experimental BRDF from this equation : $f_{sc} = Overlap . \pi . BRDF(\theta) \cos(\theta) = BRDF\ (\theta) \frac{\lambda^2 . \cos(\theta)}{\pi . \omega^2}$

BRDF : Bidirectional Reflectance Distribution Function f_{sc} : The fraction of the back-scattered light recombined with the main beam

Telescope characterization : results

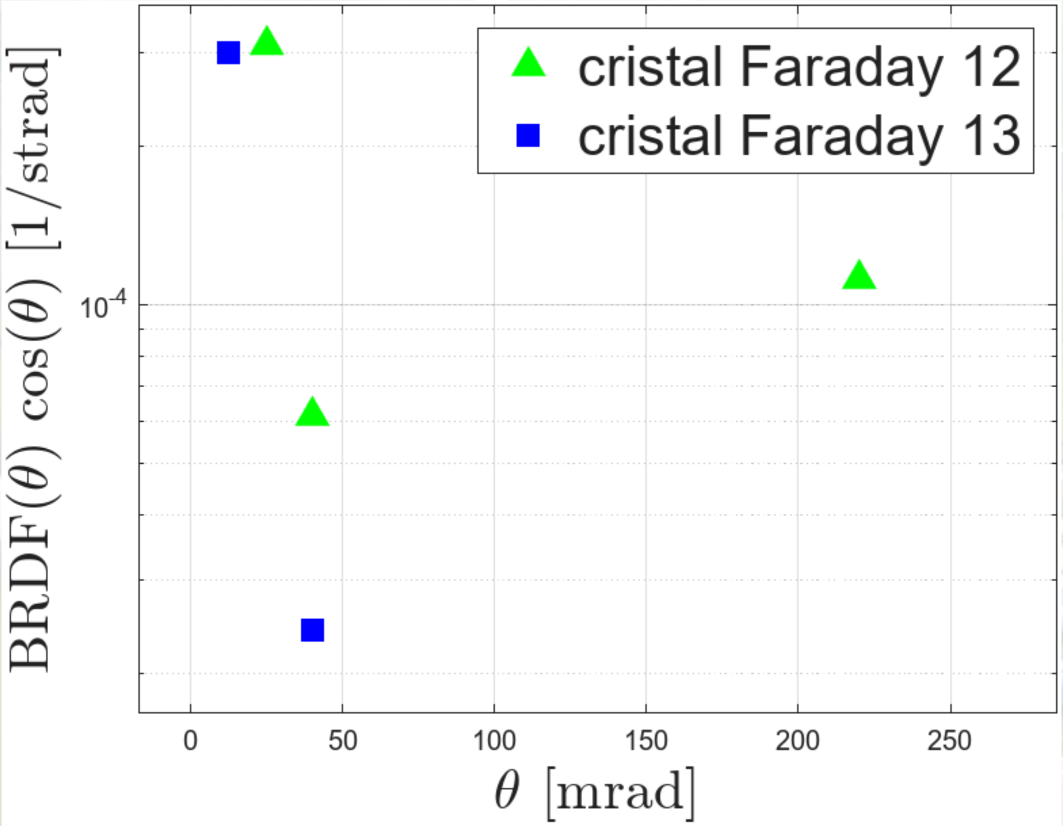


- All measurements were done with an incidence angle of 3,5°
- Uncoated windows are better than HR coating
- HR scatters more than windows
- A telescope with lenses scatters 10 times less than a telescope with mirrors, but has 6000 ppm of losses.

Optics	Reflectivity
HR mirror	> 99%
AR window	0,16 %
Harmonic splitters	0,31 %
Uncoated window	8 %

→ For Virgo, we are aiming for better coatings than those given, with reflections per side of the order of 100 ppm.
→ If we consider LMA coatings for which we can try to aim for around 100 ppm of anti-reflection per side, this would give 400 ppm of total losses for 2 lenses.

Characterization of Virgo Output Faraday crystal backscattered light



FI cristals from EGO

- Faraday crystal 12 ~ 10 years
- Faraday crystal 13 ~ 5 years

At 40 mrad, Faraday 13 is better by a factor of 2 than Faraday 12

→ more recent and has better coating than the other

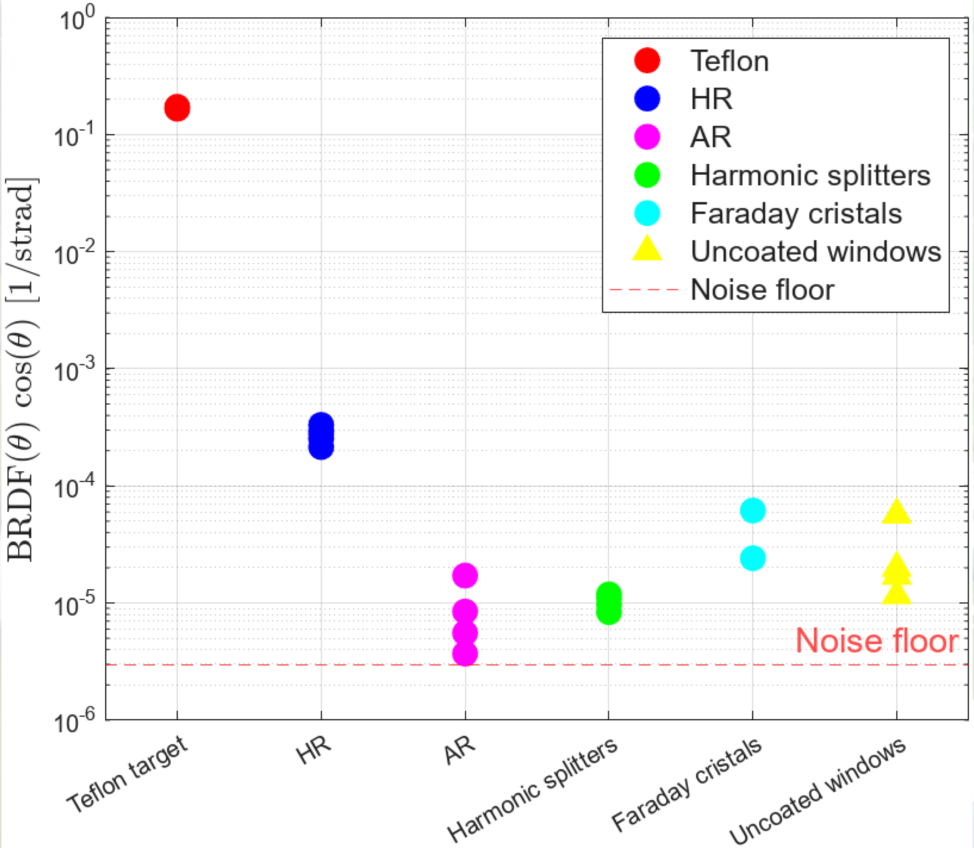
At 220 mrad, we tilted the Faraday to reduce the effects of surface scattering, aiming to isolate Rayleigh scattering

→ tilting the Faraday did not provide the desired reduction in surface scattering

Optics	Reflectivity
Faraday crystal 12	1,89 %
Faraday crystal 13	0,31 %

NB: At Virgo on the SDB1 bench the Faraday crystal is 1.1°, i.e. 19.19 mrad.

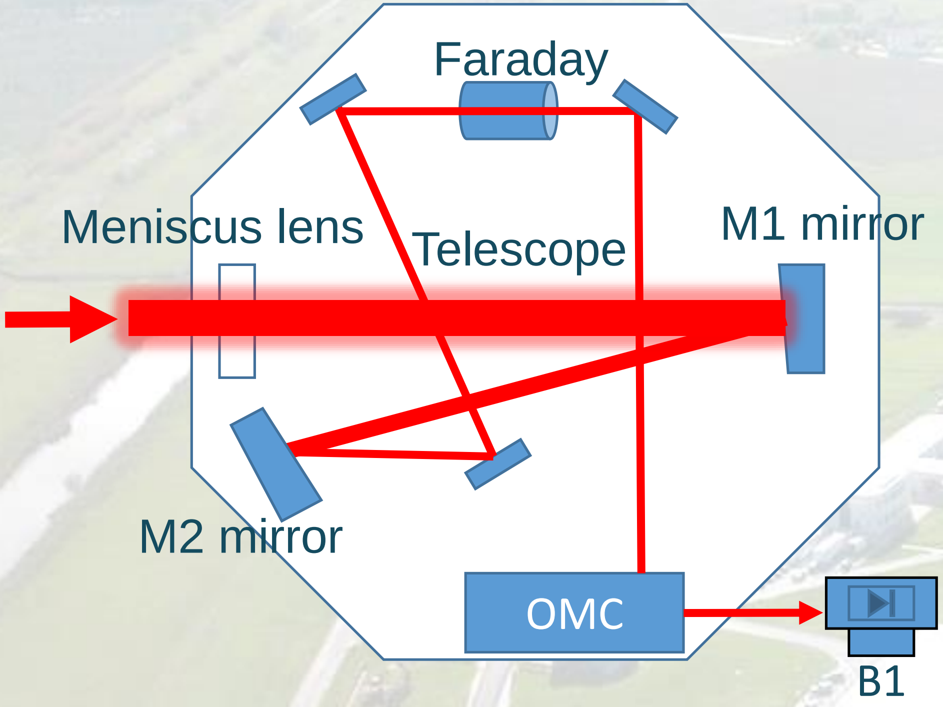
Characterization of Virgo Output Faraday crystal backscattered light



- Faraday crystals scatter more than lenses but less than HR mirrors
- Losses are annoying, but there are choices to be made :
  - Telescope with HR : scatters more than Faraday crystals, so must be placed after the Faraday (so the order is important).
  - Telescope with lenses: scatters 10 times less than the HR telescope, and about 5 times less than the Faraday, so the placement order is less important.

Detection bench backscattered light

Current bench simplified



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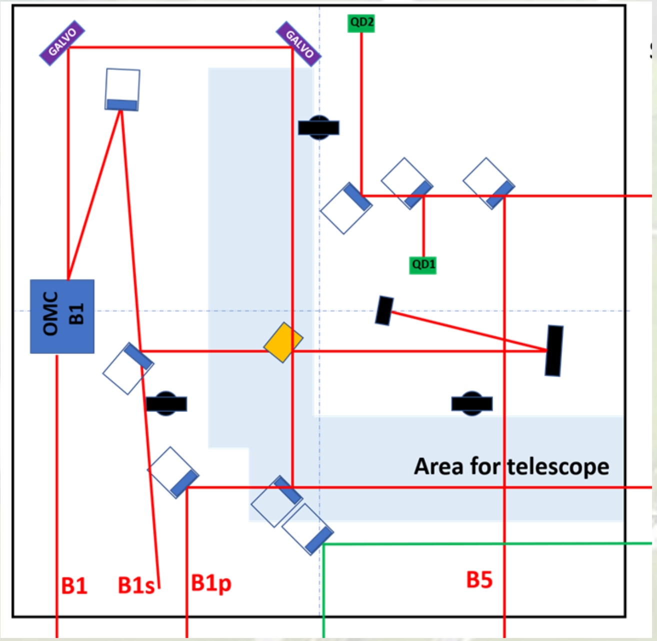
Optics (Ø 1,3 mm)	f_{sc}
Faraday crystal 12	$6,6.10^{-11}$
Faraday crystal 13	$5,4.10^{-11}$
Total current bench	3.10^{-10}

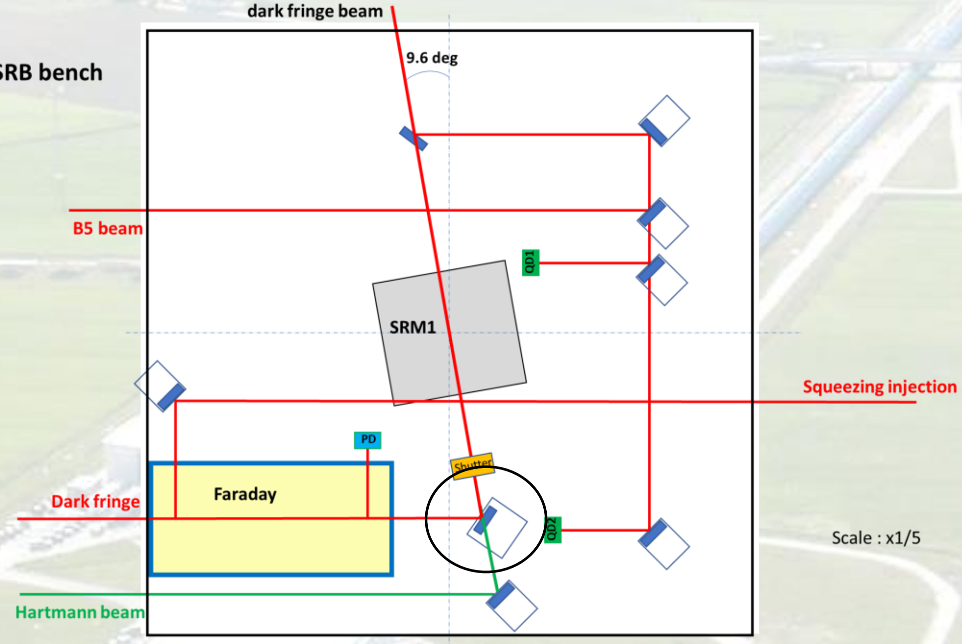
→ The f_{sc} of the Faraday crystal is about 5 times lower than the f_{sc} of the total back-scattered light of the entire current bench.
→ This indicates that the Faraday crystal is a significant contributor to the back-scattered light noise
→ In the 2 cases, putting the faraday before the telescope will scatters less

Caracterization of HR mirror with a 45 deg incidence angle on future bench

Quantification of the scattered light expected from the dichroic mirror placed before the FI on the detection bench



Future detection bench 2



Future detection bench 1

LAPP bench

Beam width Ø 0,415 mm

HR at 45°

$f_{sc} = 1.44 \cdot 10^{-10}$

On future detection bench

Beam width Ø 2 mm

HR at 45°

$f_{sc} = 6.20 \cdot 10^{-12}$

Faraday crystal at 0.7°

$f_{sc} = 2.71 \cdot 10^{-11}$

→ The contribution of the Faraday crystal is dominant

→ The mirror placed before Faraday crystal scatters less

Conclusion

Advantages

- Lenses backscatter less
  - Faraday crystal backscatters 5 times less power than a mirror system
  - AR lens coating reduce small-angle lens backscatter by a factor of 30, unlike HR mirrors

Disadvantages

- Lenses introduce more losses
  - More ghost beam, but if the beams are dumped in a controlled manner, much less light will be back scattered

Final decision

- The choice of the most suitable configuration should be discussed based on several criteria : losses, scattered light, tunability…
- The study doesn't give us the decision that the Virgo collaboration must make, but at least it tells us what impact scattering has on the different choices between using mirrors, lenses, putting before or after the Faraday crystal.

More

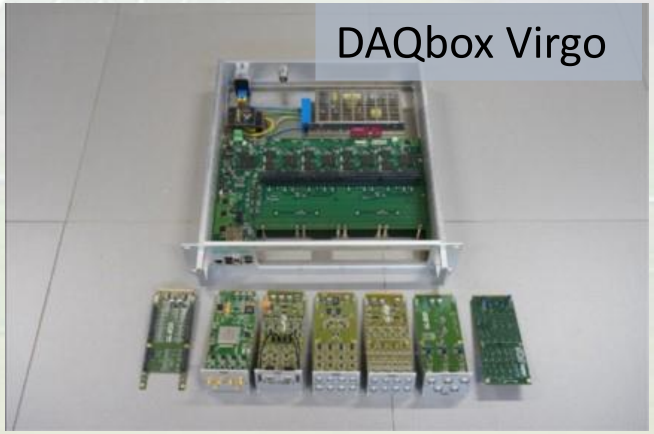
- S.Sayah, R.Gouaty, M. Was and A. Demagny, « *Driving the design of a telescope for Advanced Virgo+ with back-scattered light characterization* », proceedings, GRASS Trento (2024)
- S.Sayah, A.Masserot, M.Was and L.Rolland, « *Simulations and characterization of electronics noises in the demodulation chain* », Intern report for Virgo Team (2024)

Backup slides

Characterisation of noise limiting the sensitivity of the Virgo detector

Goals → Characterization of electronic noise

- **Characterisation of the electronics:** analysis of the post-detection photodiode electronic demodulation chain.
- **Matlab simulations**: use of simulations to understand the digital noise created by calculations in the digital demodulation chain.
- **Noise reduction**: proposed solutions to reduce demodulation noise, both in phase and amplitude.



Numérisation du signal par l'ADC à 400 MHz → Mélangeur → Accumulateur (=moyennage filtre passe-bas à 1 MHz) → Décimation du signal → Filtre butterworth (=filtre les hautes fréquences indésirables) → Décimation finale à 20 kHz