SCATTERED LIGHT MITIGATION AND MONITORING IN GRAVITATIONAL-WAVE INTERFEROMETERS

Simulations and instrumentation for Virgo and the Einstein Telescope

Dr. Marc Andrés-Carcasona

Iberian GW Meeting 2025, MADRID

Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA

VIRGO

EINSTEIN TELESCOPE

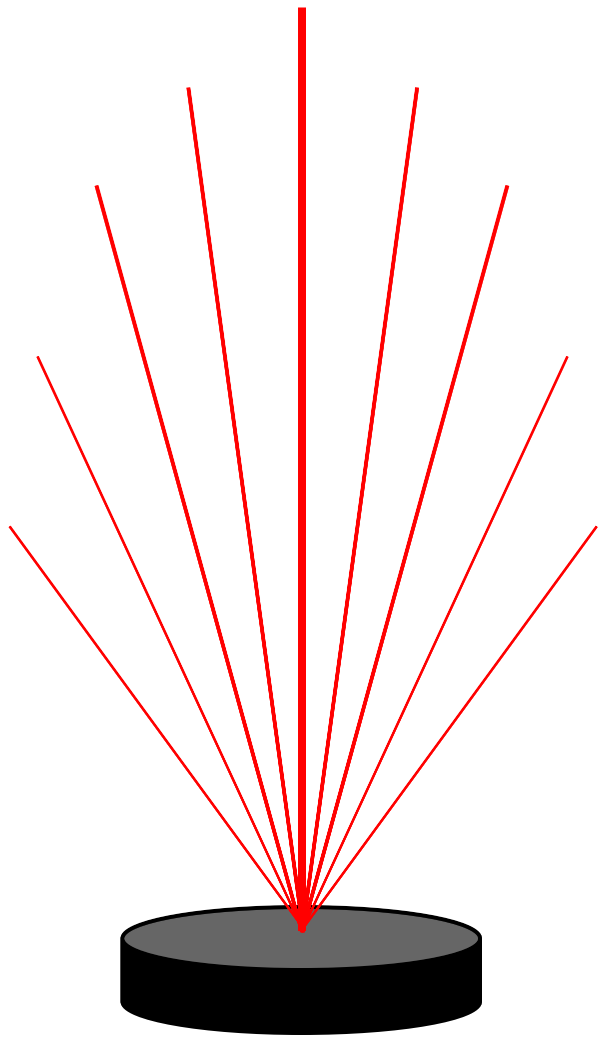
OUTLINE

Introduction

Baffle design and noise estimation for Einstein Telescope

Instrumented baffle for Virgo in O5

Conclusions



EINSTEIN TELESCOPE

VIRGO

IFAE
Institut de Física d'Altes Energies

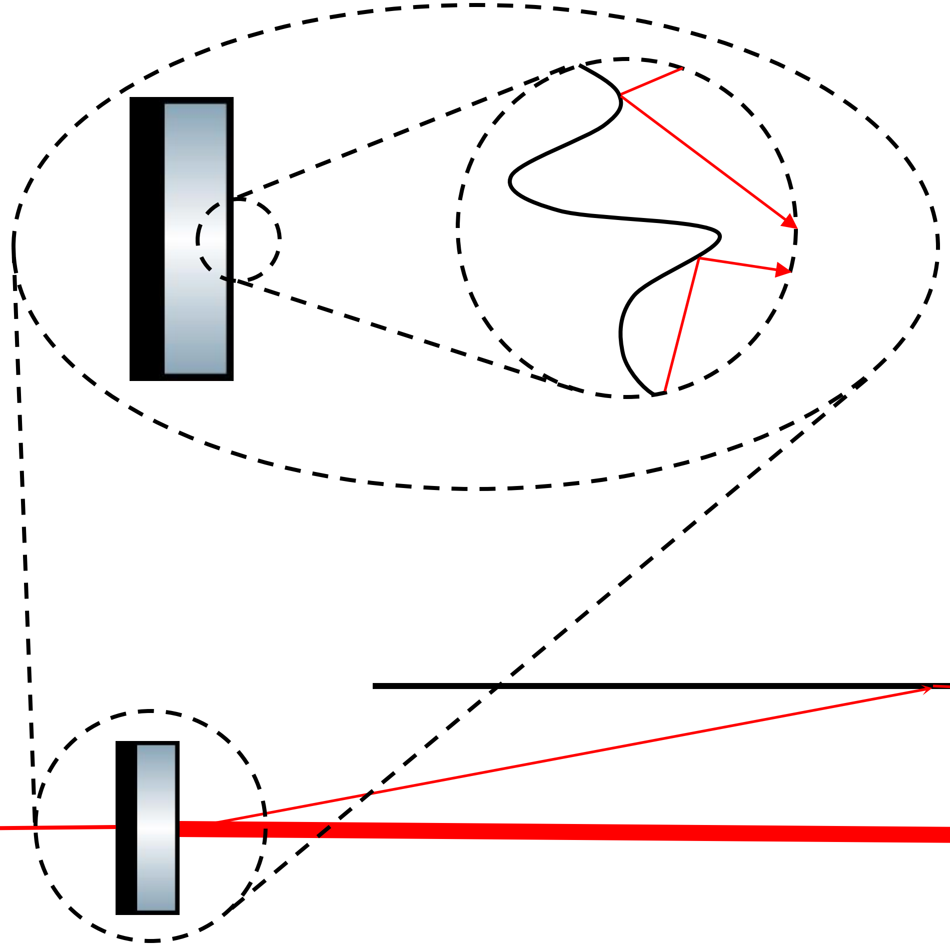
EXCELENCIA SEVERO OCHOA

INTRODUCTION

SCATTERED LIGHT – THEORY

Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA



There are some **photons that do not follow the intended path** and can bounce off some internal components of the interferometer. When that happens some of them can recombine with the main beam and limit the sensitivity of the experiment.

The strain noise generated by scattered photons is **proportional to the spectrum of the extra phase acquired** when following a different path than the one intended

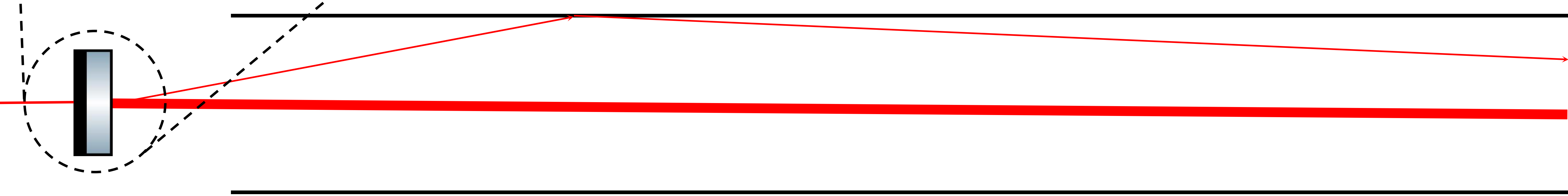
$$\tilde{h}(f) = \frac{\lambda}{2\pi L}\tilde{\phi}(f)$$

Induced strain noise

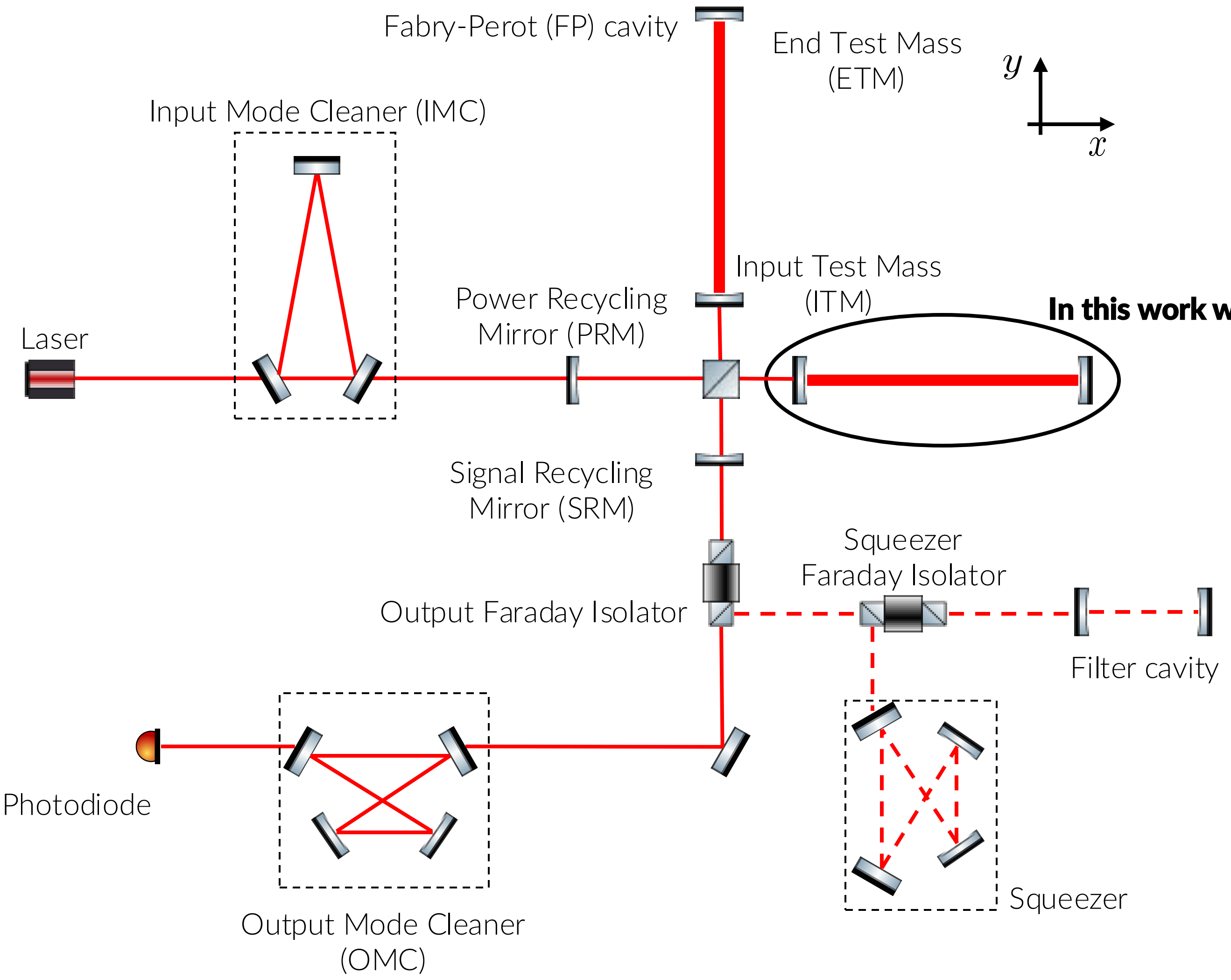
$$\phi = \frac{2\pi d}{\lambda}$$

Extra phase acquired

SOLUTION: Absorb or redirect those photons before they reach any of the mirrors

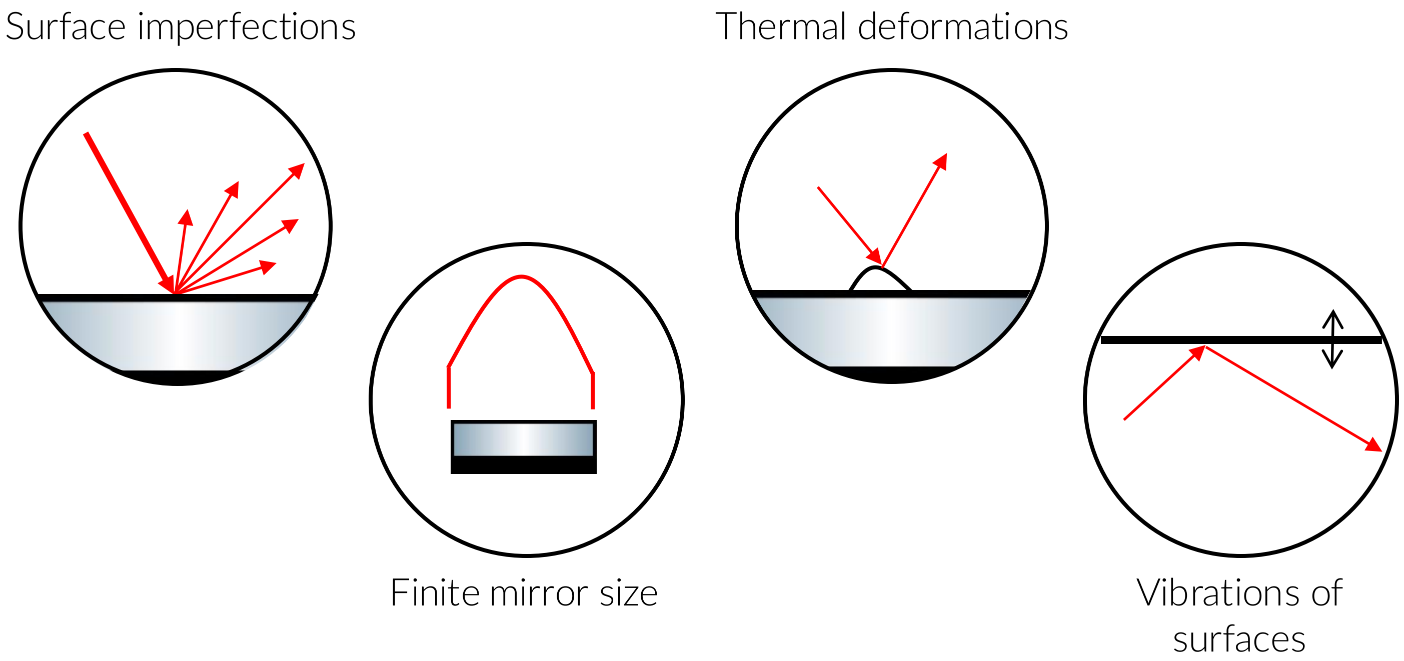


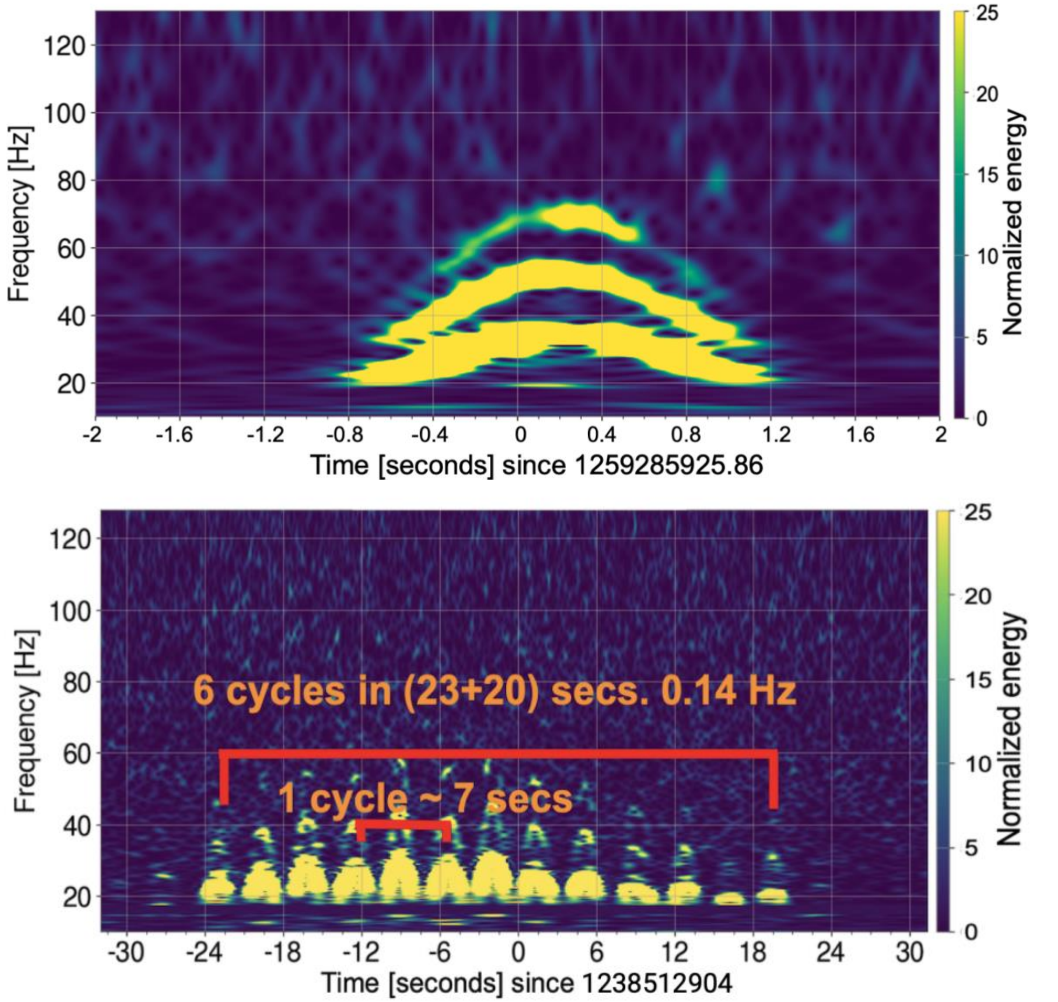
INTRODUCTION – GROUND BASED DETECTORS



In this work we only consider the main FP cavities

SCATTERED LIGHT – THEORY



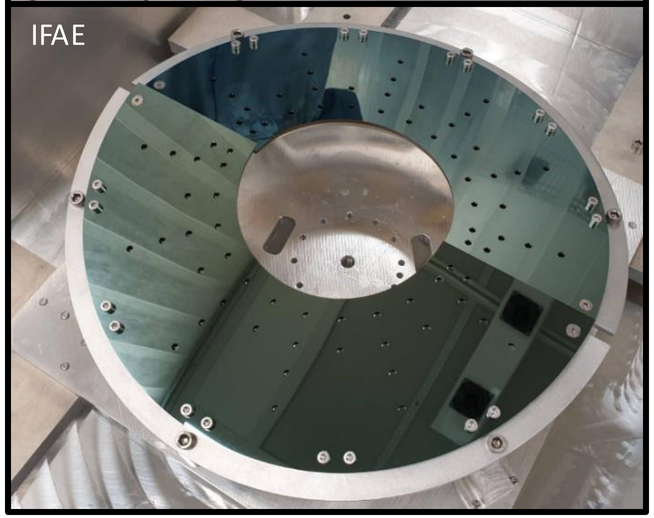


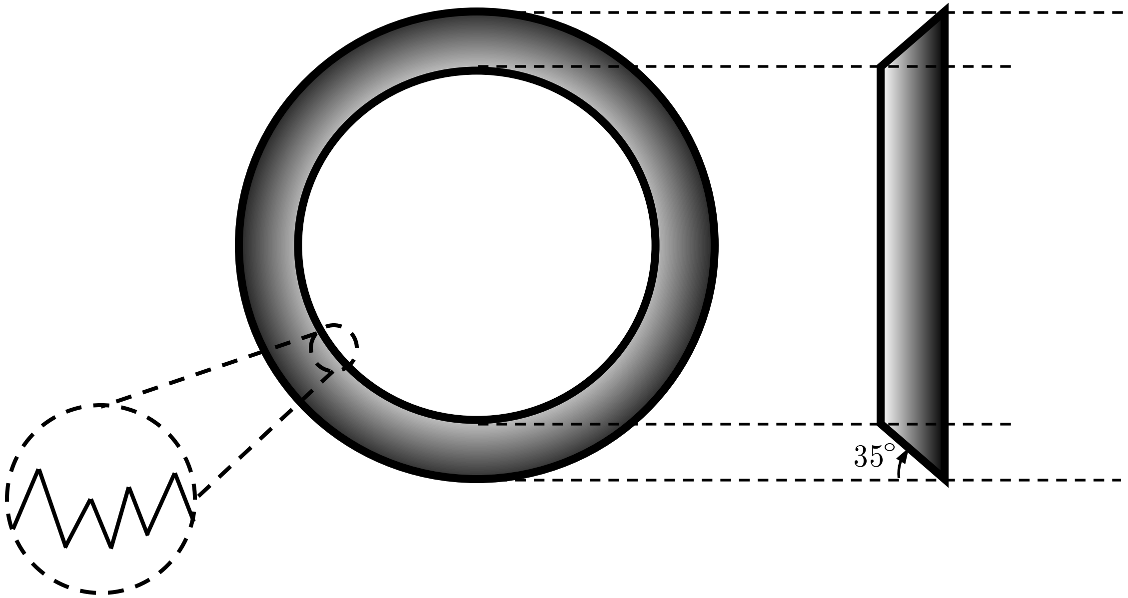
S. Soni, et al., CQG 38 025016

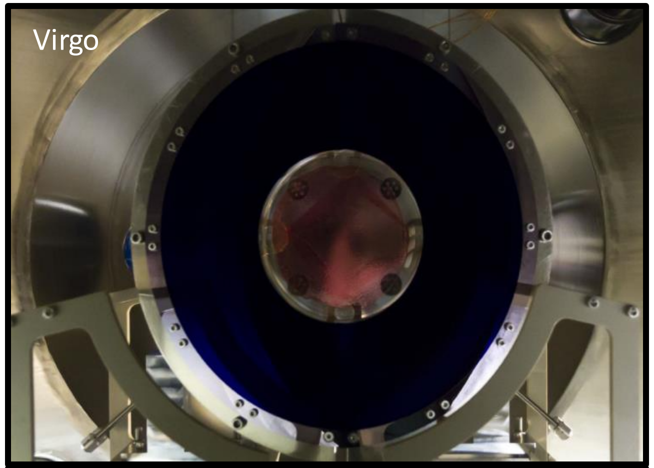
Some effective solutions include:

- Add baffles to absorb or redirect stray light.
- Improve the mirror coating and baffle/beampipe surface.

SCATTERED LIGHT – BAFFLES







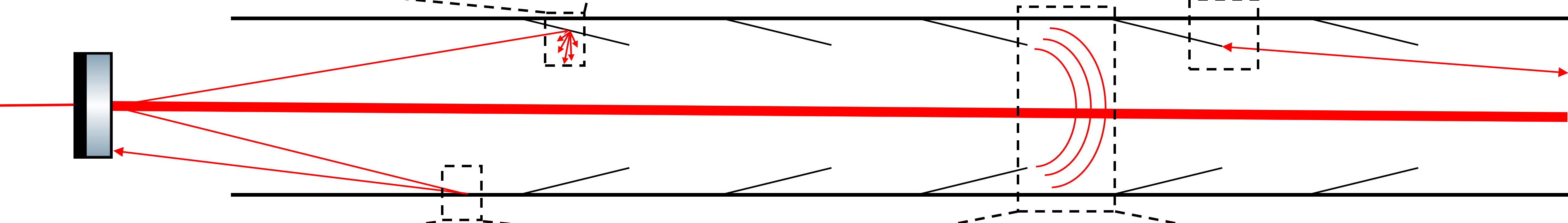
SCATTERED LIGHT – BAFFLES

BACKSCATTERING

Light that upon reaching the baffle is scattered again reaching any of the mirrors

BAFFLE EDGE BACKREFLECTION

The edges of the baffle can reflect the light back to the emitting mirror



SHINING FACET

Any piece of highly-reflecting material

DIFFRACTION

The finite aperture of the baffles will generate a diffraction pattern capable of affecting the sensitivity

ET BAFFLE DESIGN

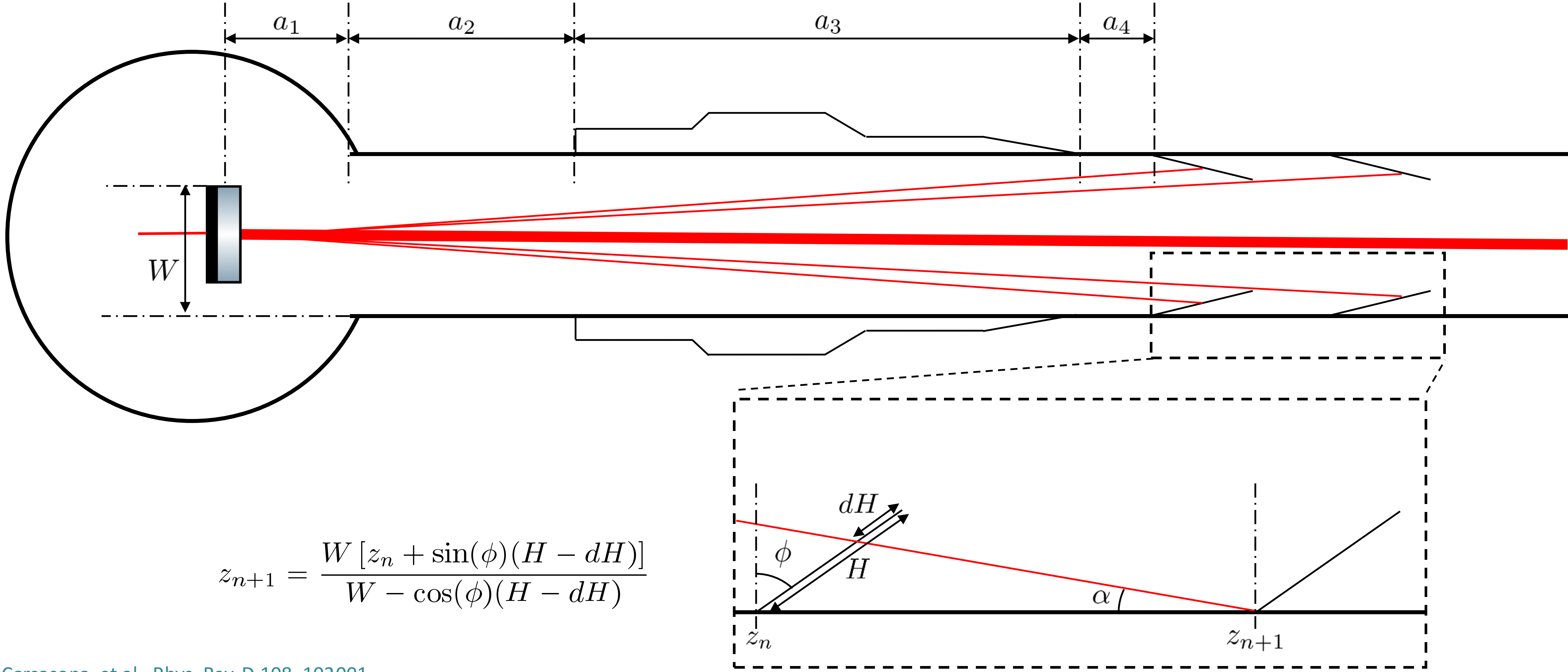
EINSTEIN
TELESCOPE

VIRGO

Institut de Física
d'Altes Energies

EXCELENCIA
SEVERO
OCHOA

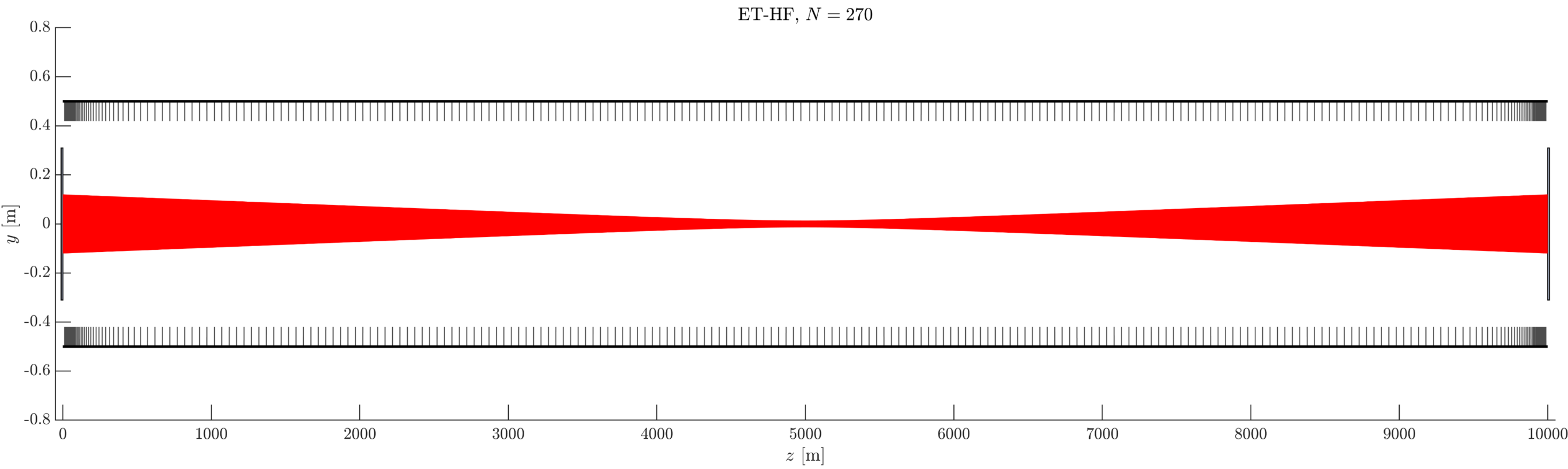
ET BAFFLE DESIGN – BAFFLES



$$z_{n+1} = \frac{W\left[z_n + \sin(\phi)(H - dH)\right]}{W - \cos(\phi)(H - dH)}$$

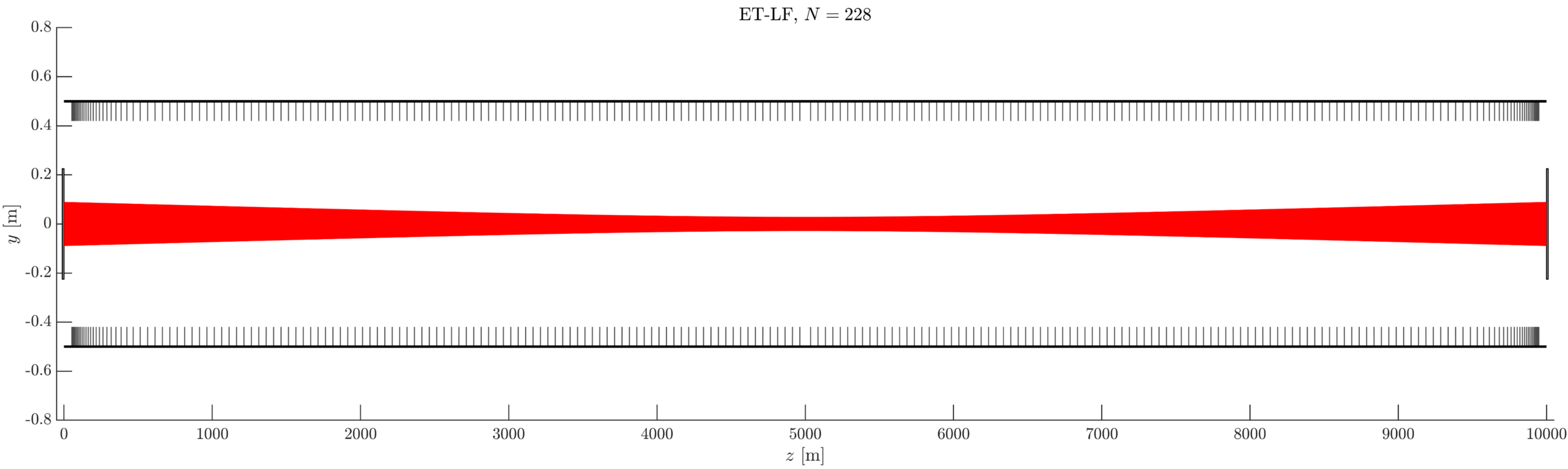
M. Andrés-Carcasona, et al., Phys. Rev. D 108, 102001

ET BAFFLE DESIGN– BAFFLES



*In this work we are excluding the cryo areas. This is left as future work. The spacing between baffles at the mid section is fixed at 50 m

ET BAFFLE DESIGN– BAFFLES



*In this work we are excluding the cryo areas. This is left as future work. The spacing between baffles at the mid section is fixed at 50 m

ET BAFFLE DESIGN– DIFFRACTION NOISE ESTIMATION

We numerically compute and propagate the beam from the ITM to the baffle, clip it according to its inner pattern (including the possible serration) and then propagate it again until the ETM.

This does not rely on the assumptions of the mirror map quality being a power law, the serration pattern can be made arbitrary.

NUMERICAL METHOD

$$\tilde{h}(f) = \sqrt{\lambda^2 + \left(\frac{8\Gamma P_{\text{circ}}}{cM\pi f^2}\right)^2} \frac{X(f)}{\pi L} \sum_{i=1}^{N_B} \mathbb{I}\left\{\int_{S_{\text{baffle}}} E_{ITM\to B_i} E_{B_i \to ETM}\, \mathrm{d}S\right\}$$

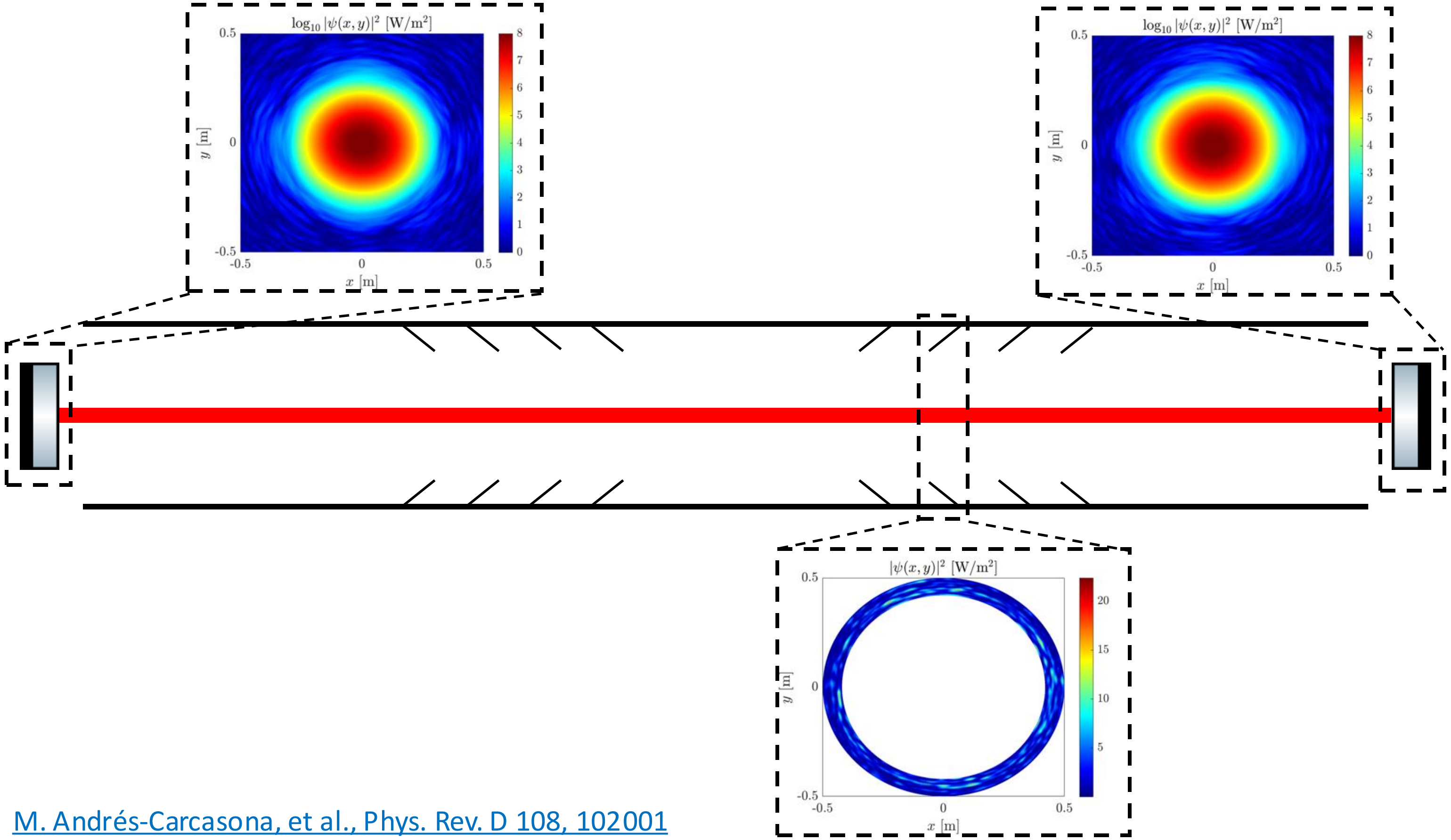
ET BAFFLE DESIGN– BACKSCATTERING ESTIMATION

The backscattering noise can be estimated by using the following formula

$$\tilde{h}^2(f) = \frac{1}{L^2}\left[\lambda_L^2 + \left(\frac{8\Gamma P_{circ}}{cM\pi f^2}\right)^2\right]\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega_{bs}}X^2(f)\int_{\theta_{\min}}^{\theta_{\max}}\mathrm{d}K$$

$$\mathrm{d}K = \frac{1}{r^2}\left(\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega_{mb}}\right)^2\delta\Omega_{mb}$$

This requires to know the **amount of light that reaches each of the baffles**. For the ones that are far away from the ITM, the field is computed using the code *Stationary Interferometer Simulation* (SIS).



M. Andrés-Carcasona, et al., Phys. Rev. D 108, 102001

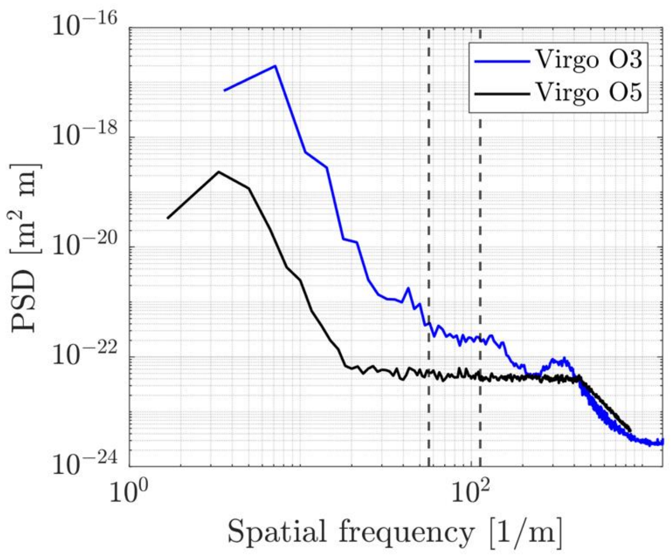
ET BAFFLE DESIGN– MIRROR QUALITY

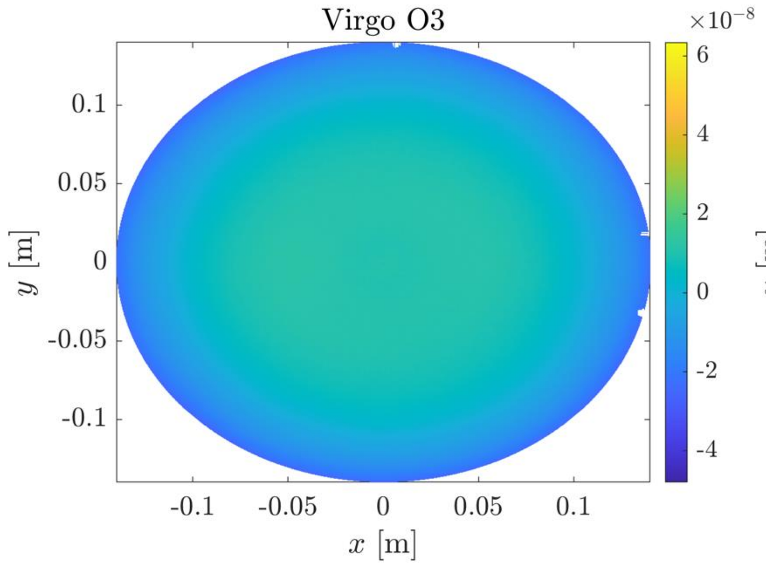
We usually use a mirror map to describe the quality of the surface of the mirror. This map indicates the deviation from a perfect surface of the mirror and is typically of the order of nanometers. The roughness can also be quantified using the Power Spectral Density (PSD) of that surface.

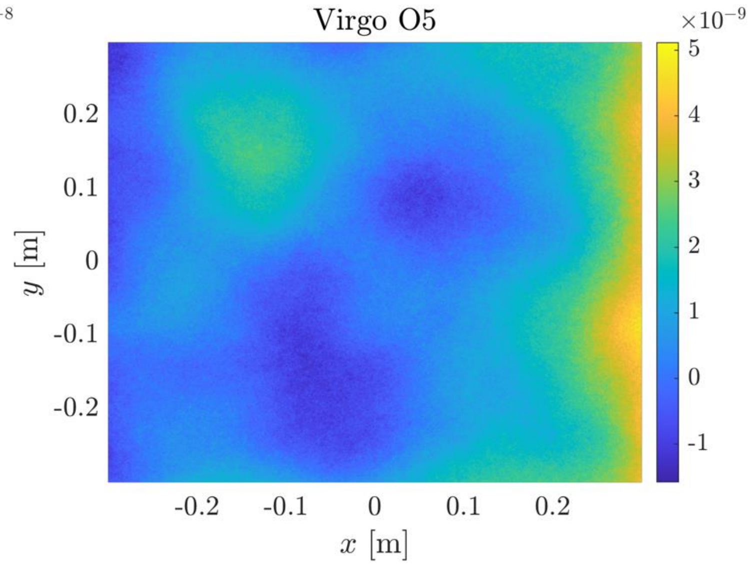
We quantify the amount of scattering using the bidirectional reflection distribution function (BRDF), which denotes the quotient of the radiance emitted at a given direction to the incoming irradiance.

The relation between BRDF and the 1D PSD of the surface is

$$\mathrm{BRDF} = \frac{16\pi^2}{\lambda^3}\cos(\theta)\mathrm{PSD}_{1\mathrm{D}}\left(\frac{\sin(\theta)}{\lambda}\right)$$

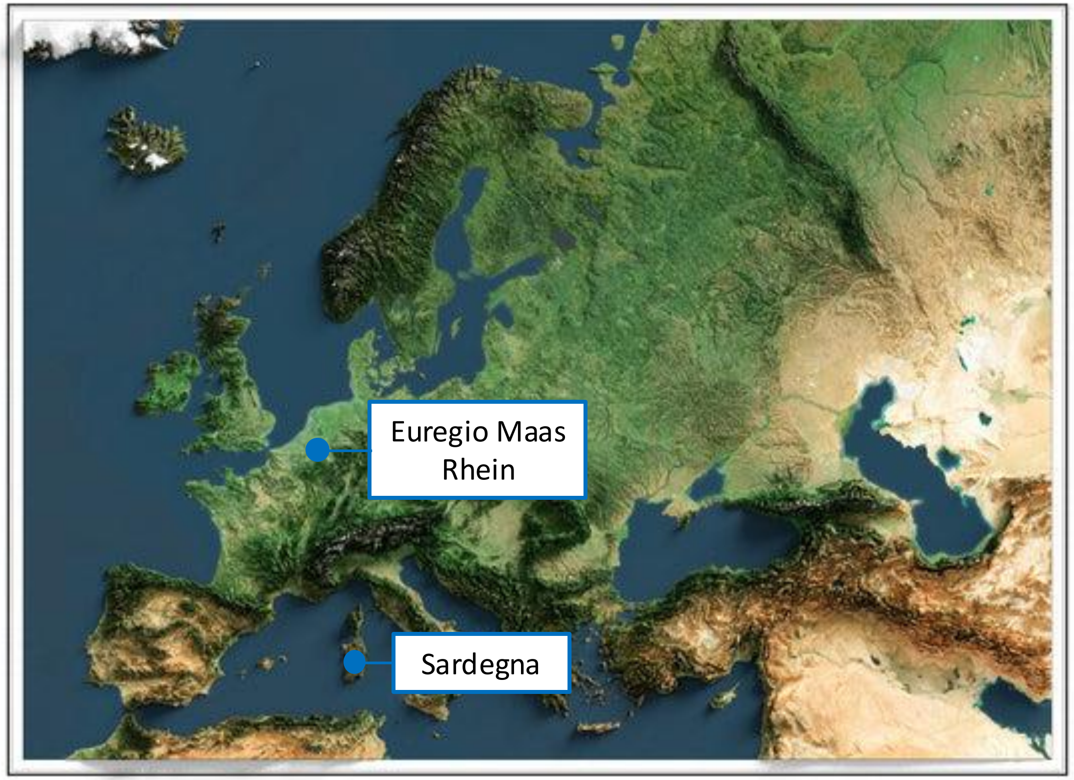






M. Andrés-Carcasona, et al., Phys. Rev. D 108, 102001

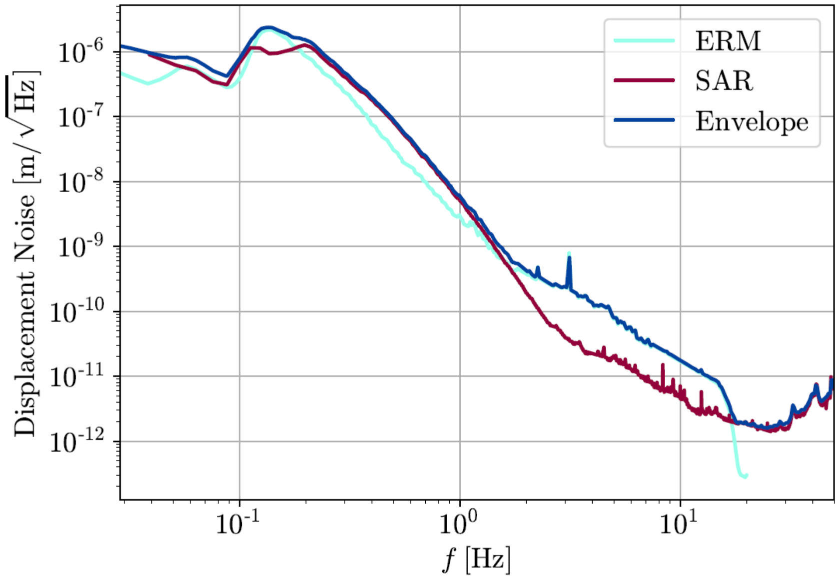
ET BAFFLE DESIGN – VIBRATION



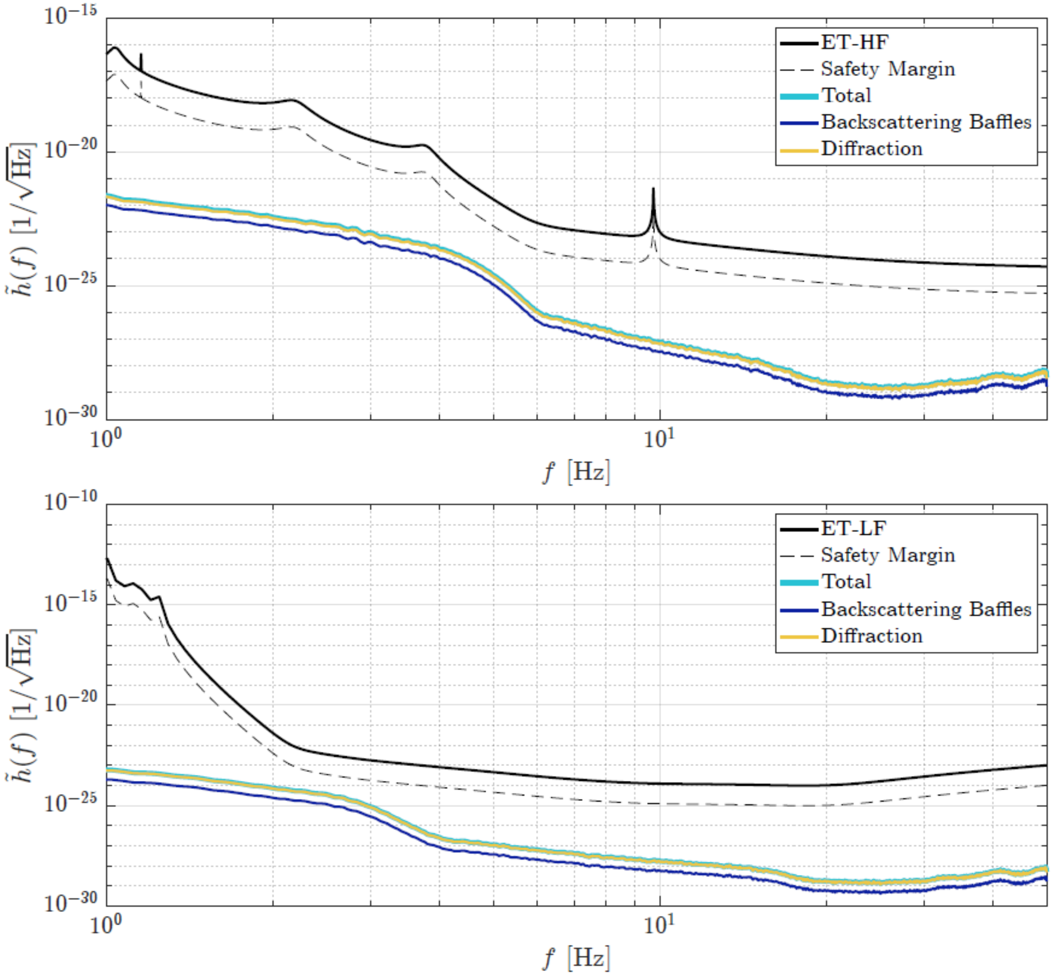
We take the data from two-candidate sites (Euregio and Sardegna) and compute the envelope of both noises to maintain our results site-independent. In both cases we take the 90% CL seismic motion curves.

The seismic noise must be upconverted or phase-wrapped to obtain the effective displacement. This can be done applying the following formula (LIGO-T1900854)

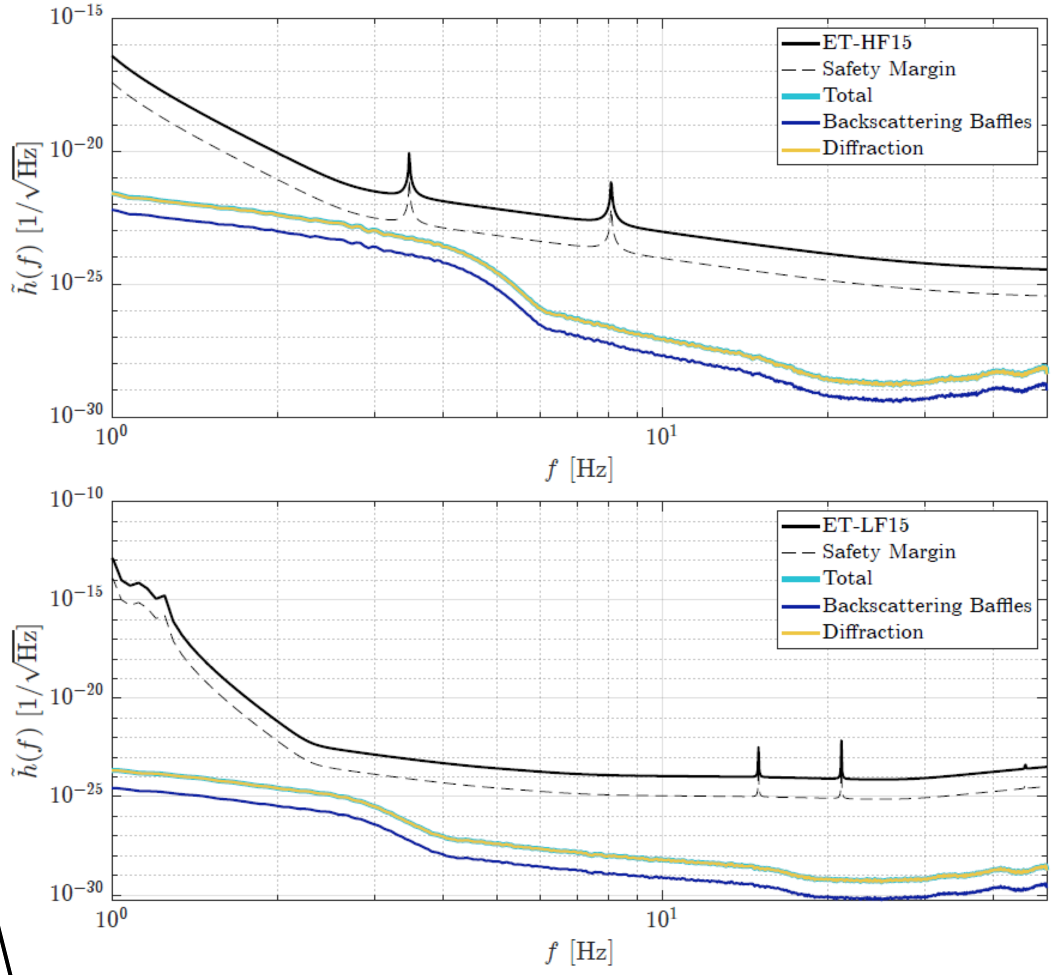
$$X(f) = \frac{\lambda}{4\pi}\sqrt{\mathrm{PSD}\left[\sin\left(\frac{4\pi}{\lambda}X(t)\right)\right] + \mathrm{PSD}\left[\cos\left(\frac{4\pi}{\lambda}X(t)\right)\right]}$$



ET BAFFLE DESIGN – TOTAL NOISE

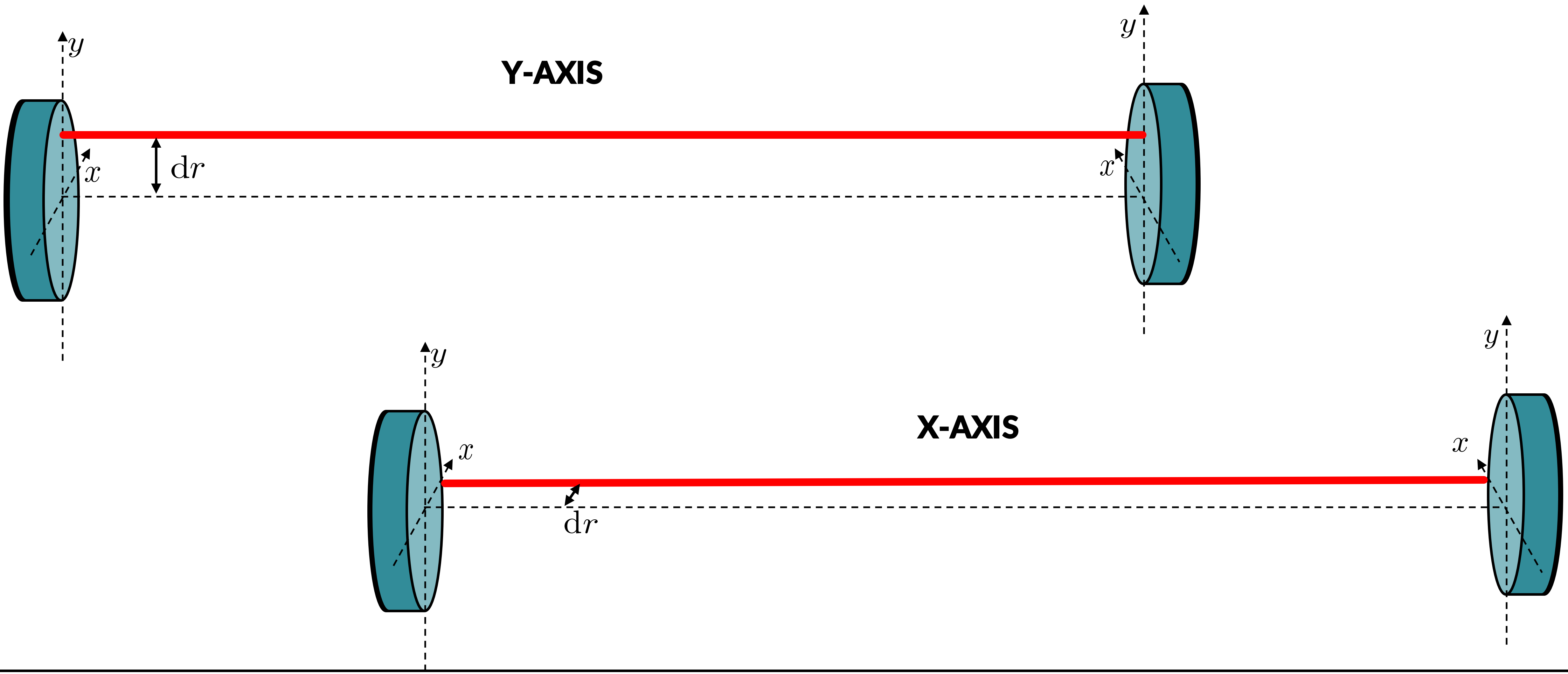


2L-15km

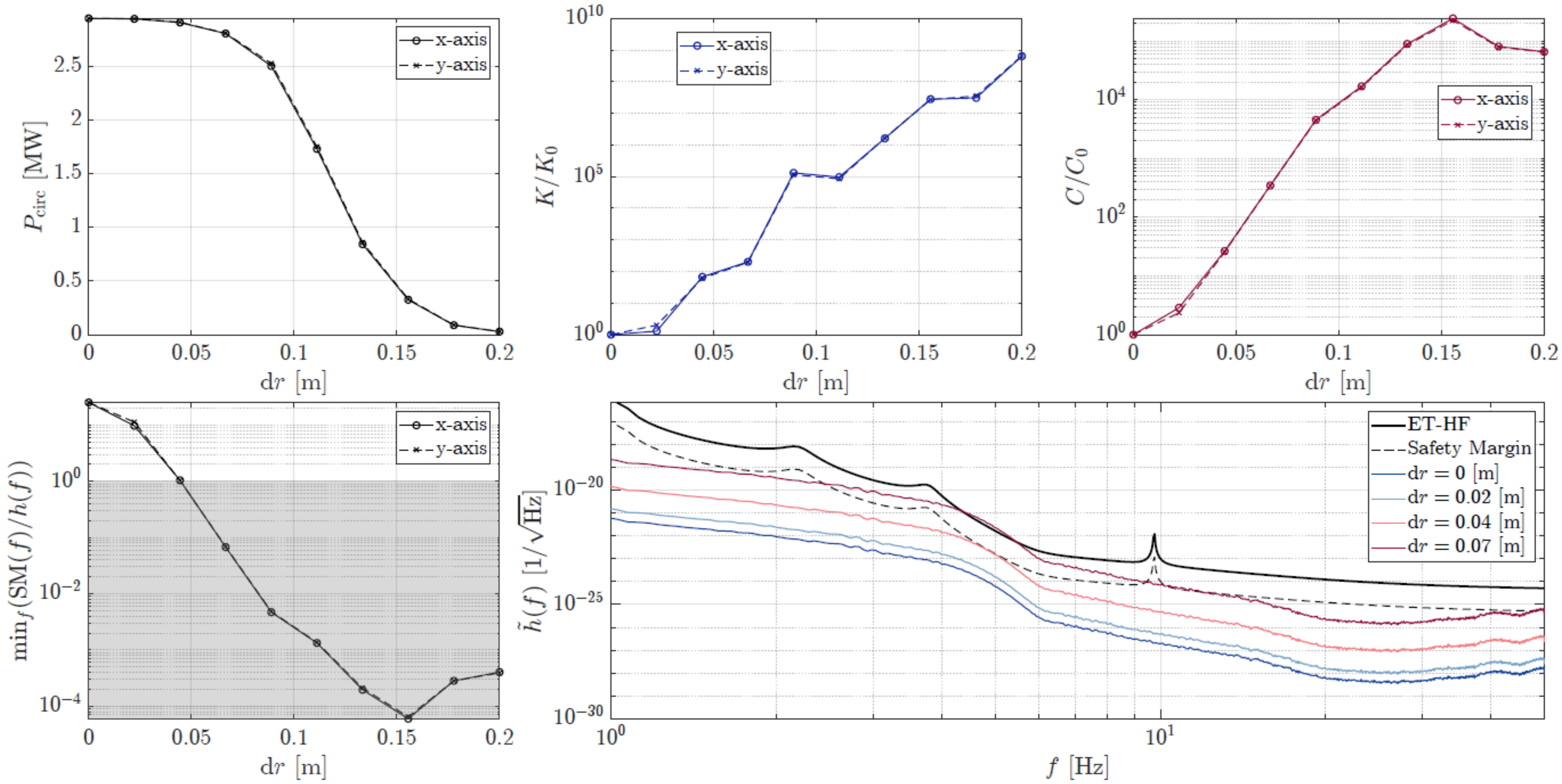


Δ-10km

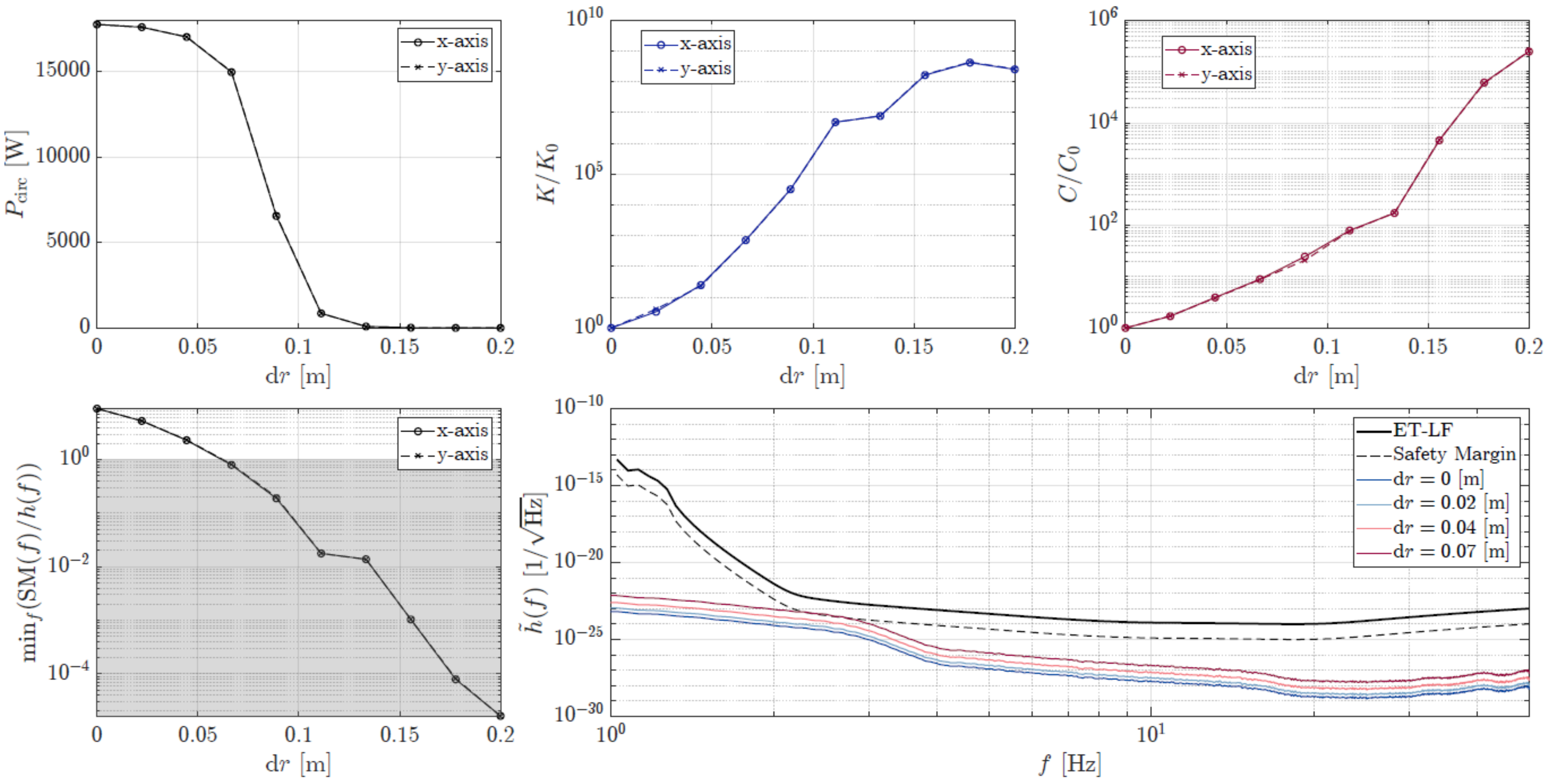
ET BAFFLE DESIGN– BEAM OFFSET



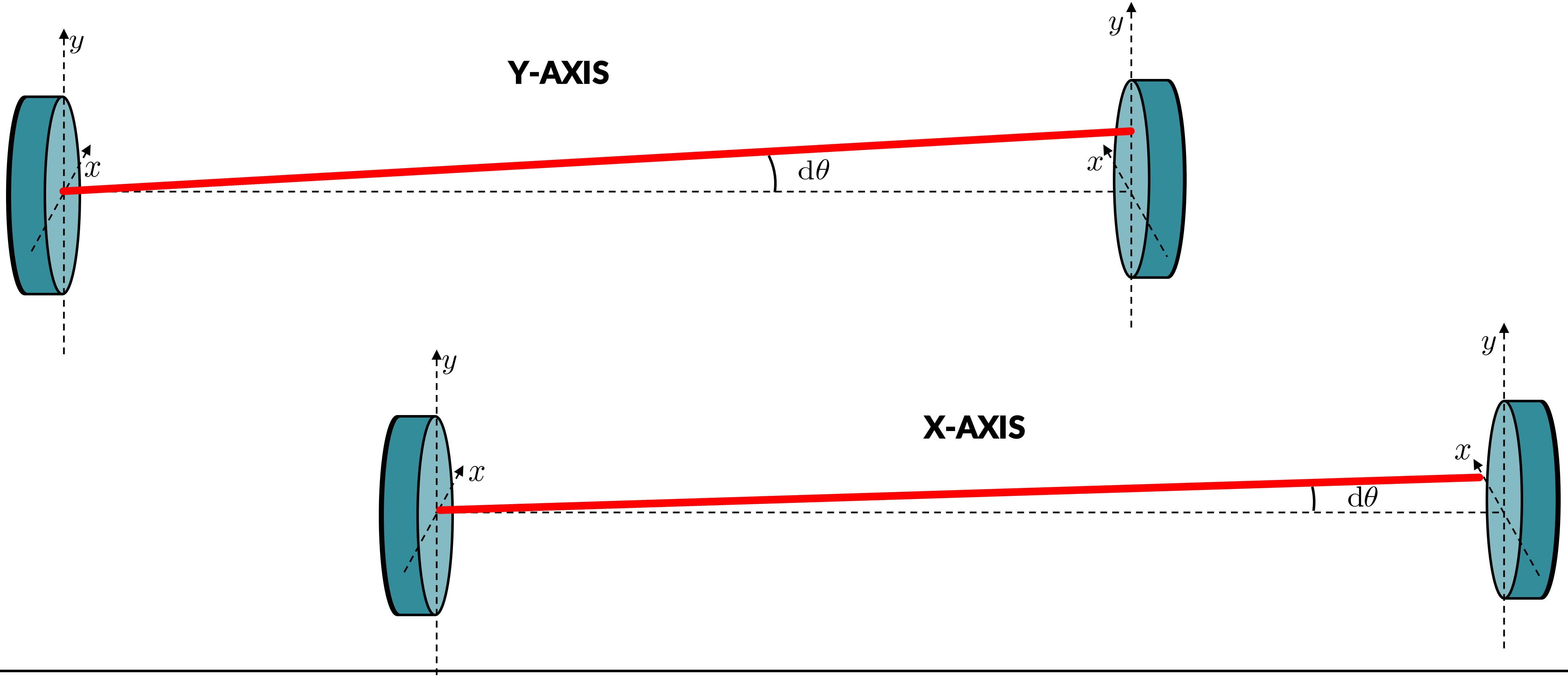
ET BAFFLE DESIGN– BEAM OFFSET - HF



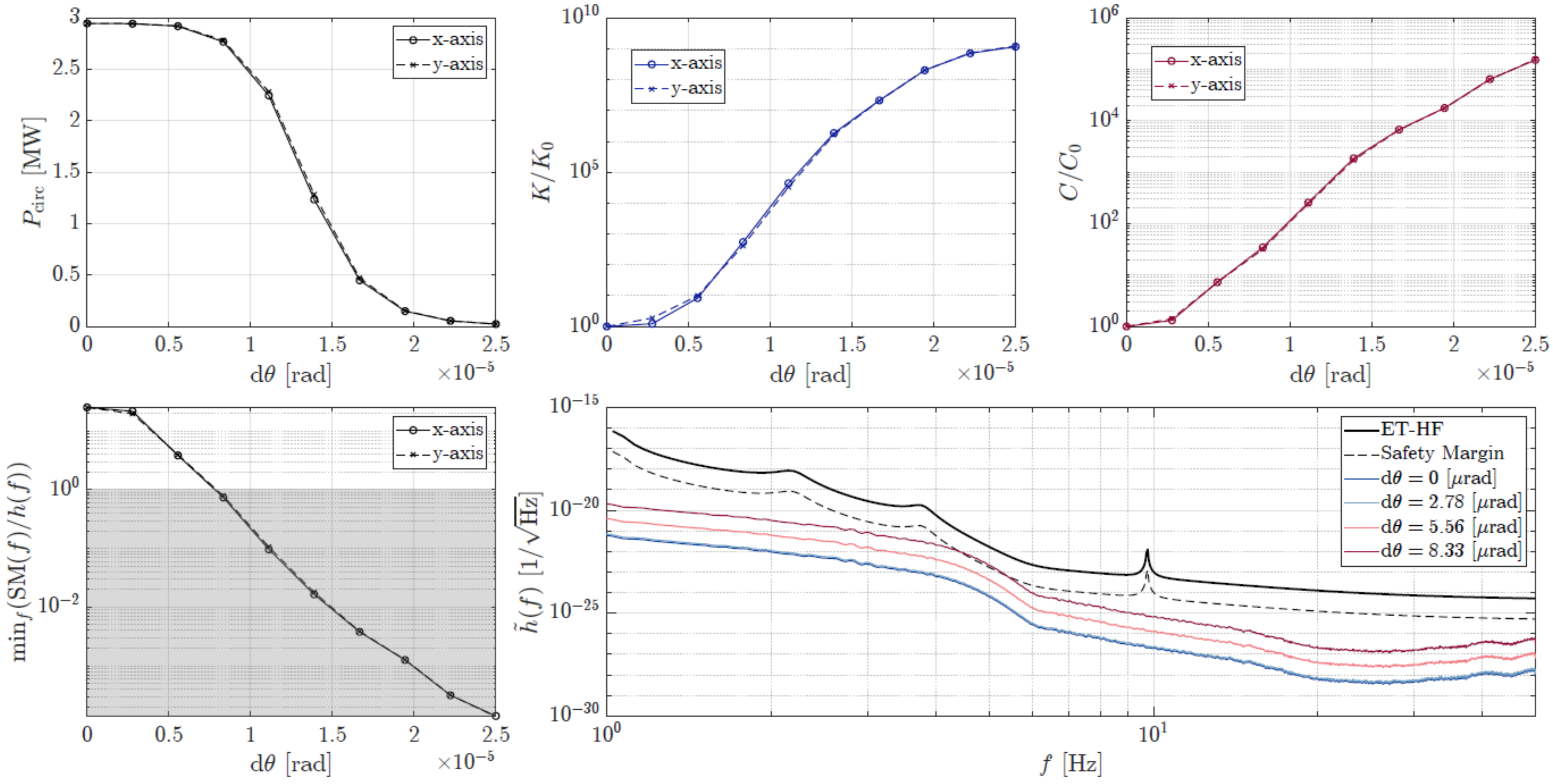
ET BAFFLE DESIGN– BEAM OFFSET - LF



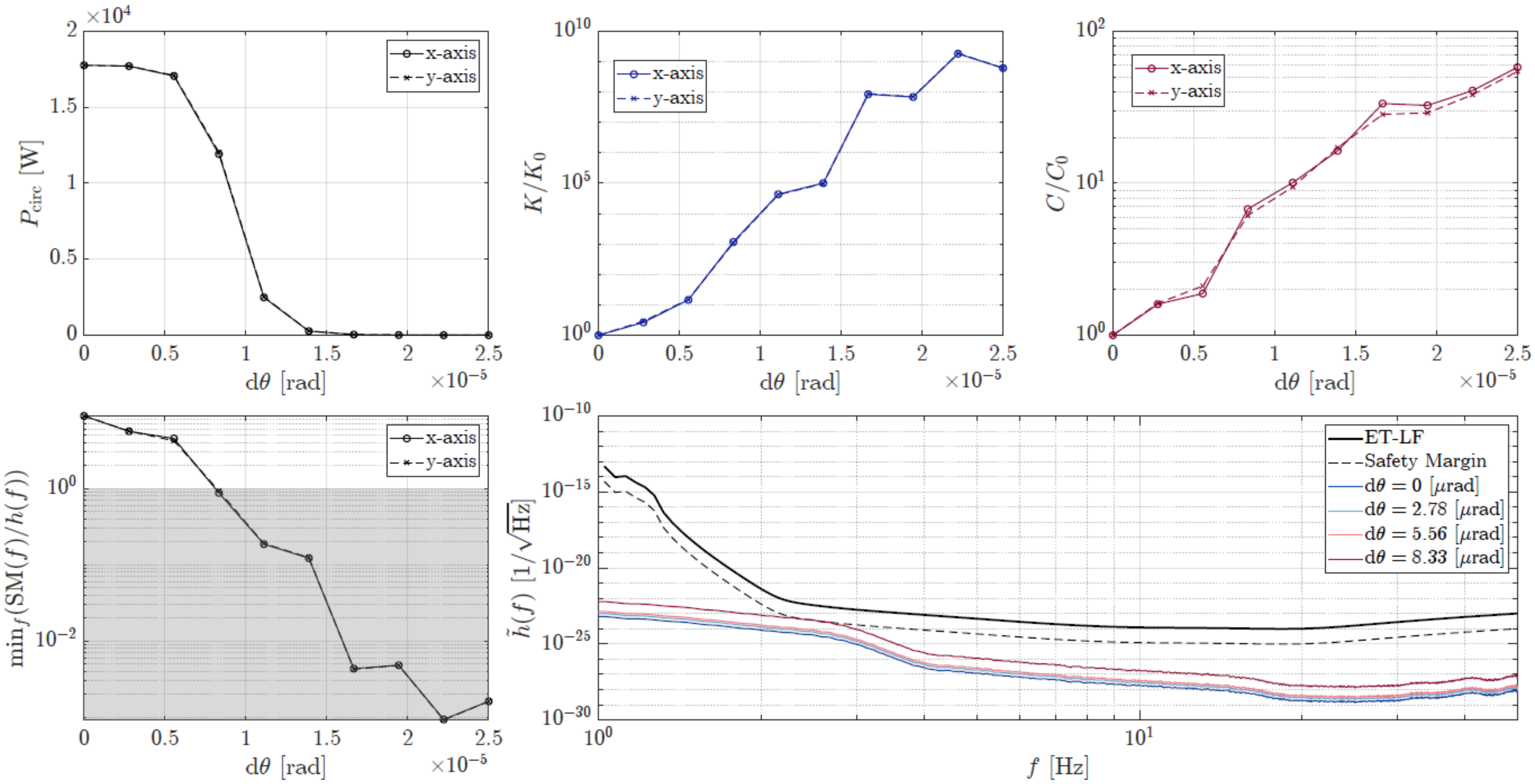
ET BAFFLE DESIGN– BEAM MISALIGNMENT



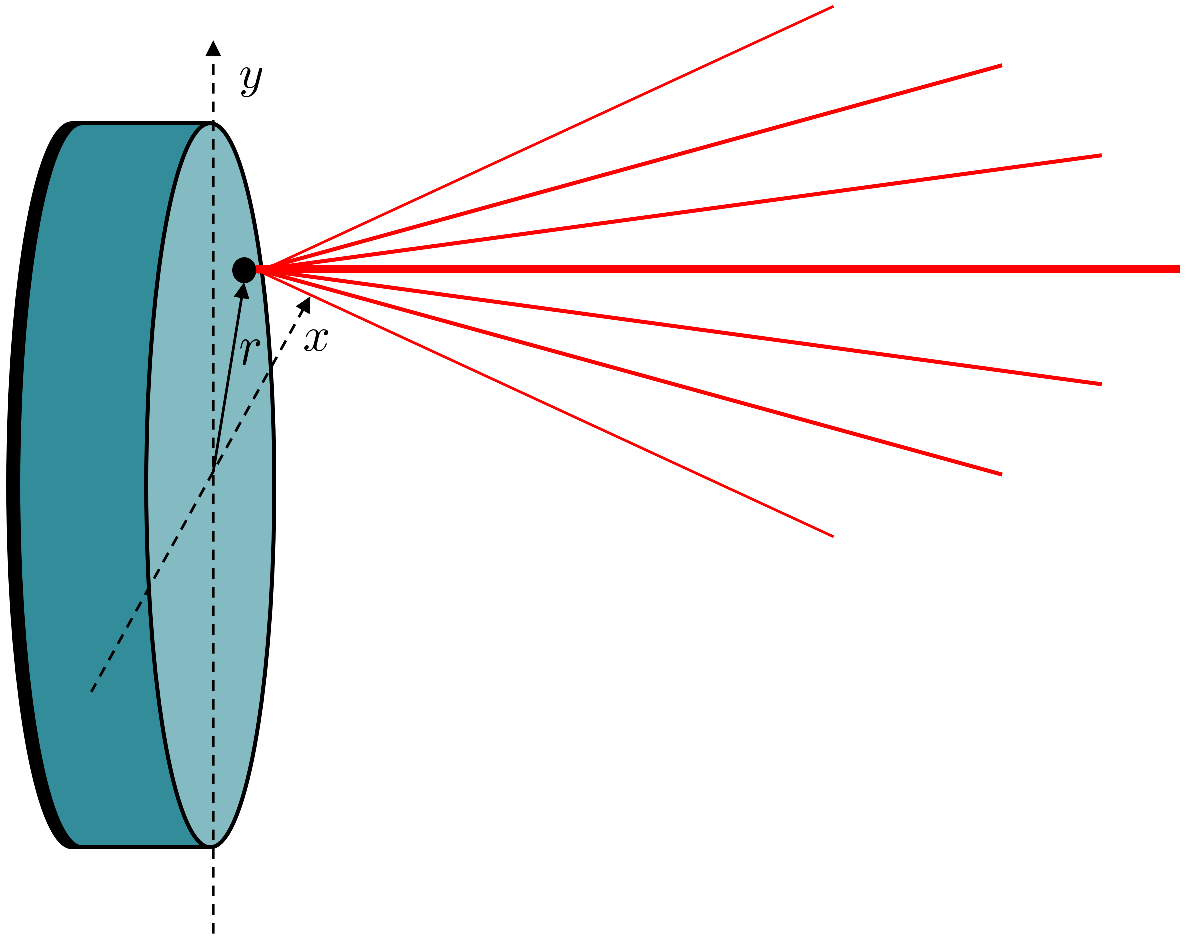
ET BAFFLE DESIGN– BEAM MISALIGNMENT - HF



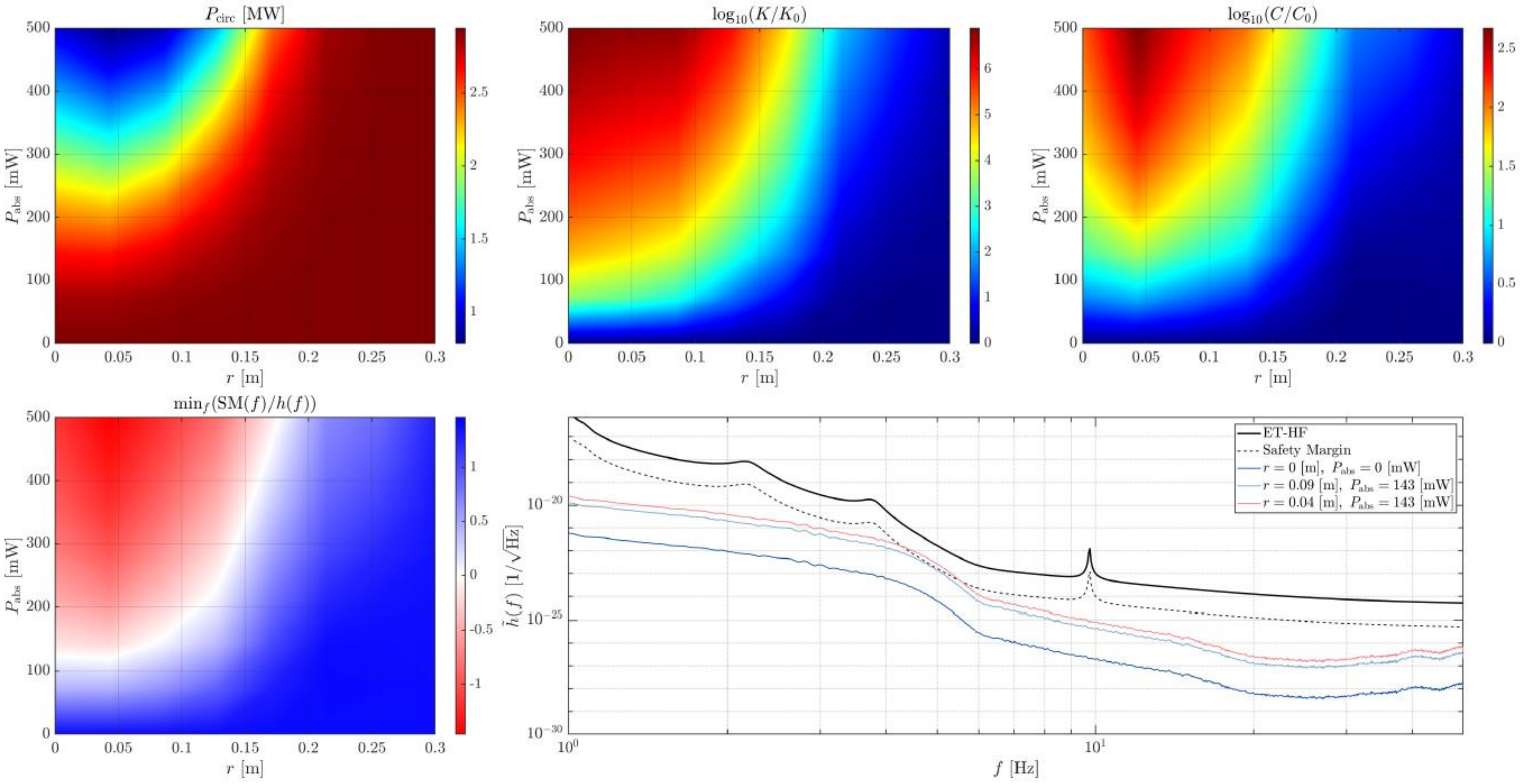
ET BAFFLE DESIGN– BEAM MISALIGNMENT - LF



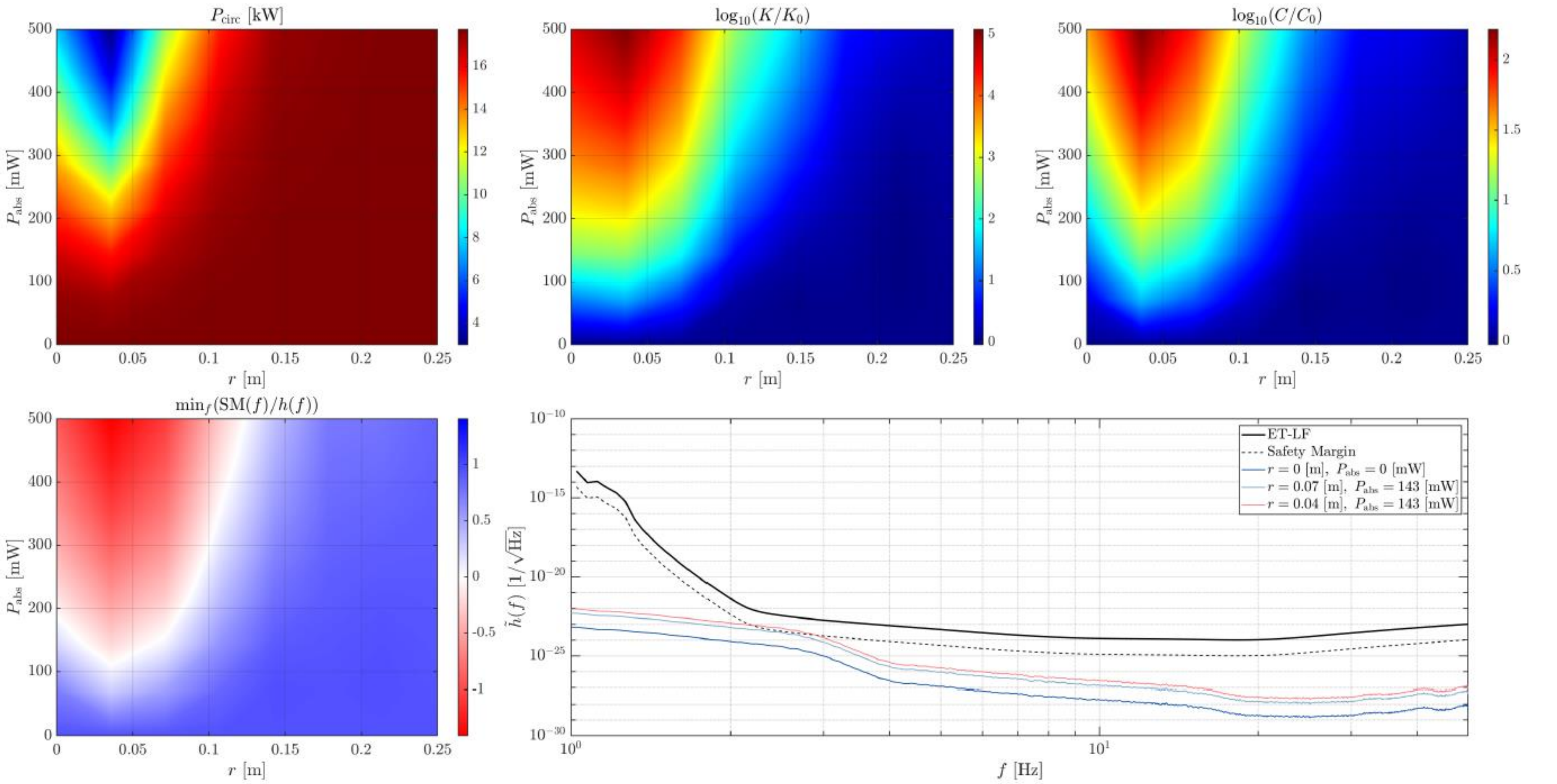
ET BAFFLE DESIGN– POINT ABSORBERS



ET BAFFLE DESIGN– POINT ABSORBERS - HF



ET BAFFLE DESIGN– POINT ABSORBERS - LF



EINSTEIN
TELESCOPE

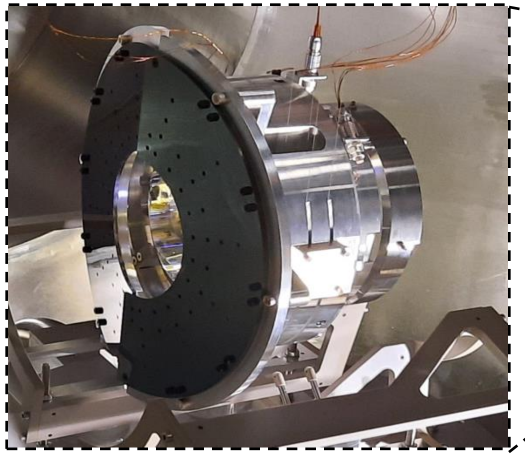
VIRGO

Institut de Física
d'Altes Energies

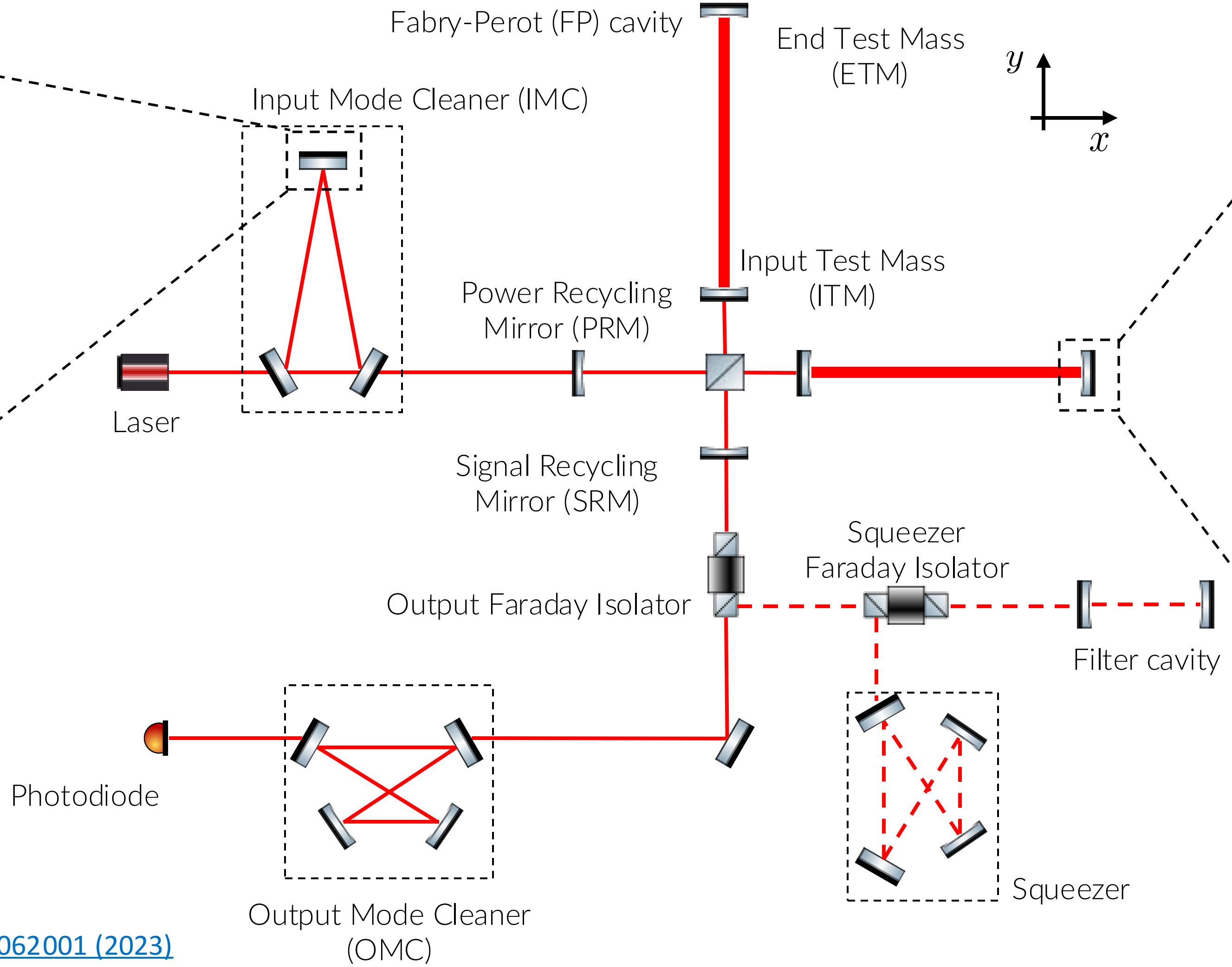
EXCELENCIA
SEVERO
OCHOA

VIRGO INSTRUMENTED BAFFLE

VIRGO INSTRUMENTED BAFFLES



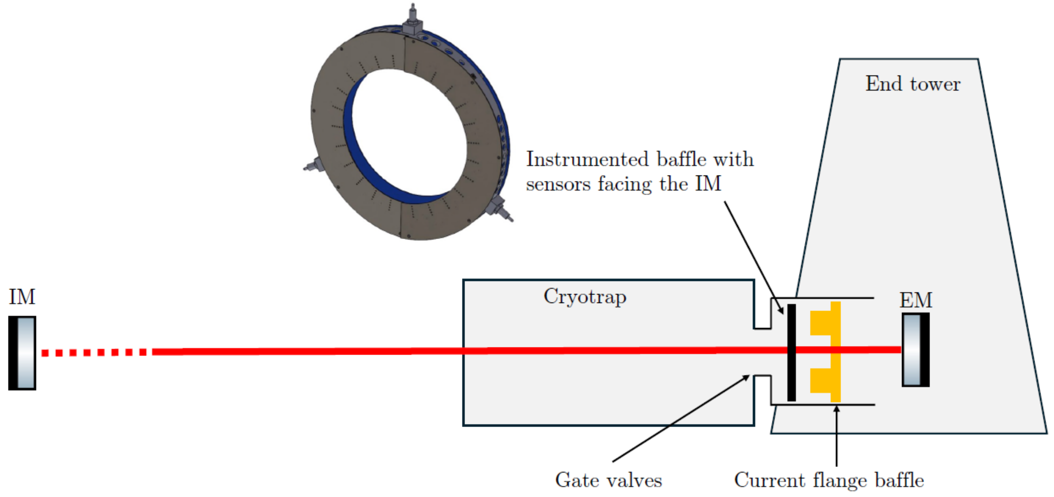
There is already an instrumented baffle at the end mirror of the IMC that has been taking data since 2022.

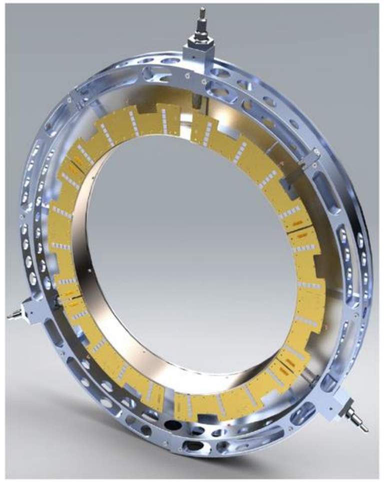


We are planning to install two more near the ETMs before O5

M. Andrés-Carcasona, et al., Phys. Rev. D 107, 062001 (2023)

VIRGO INSTRUMENTED BAFFLE

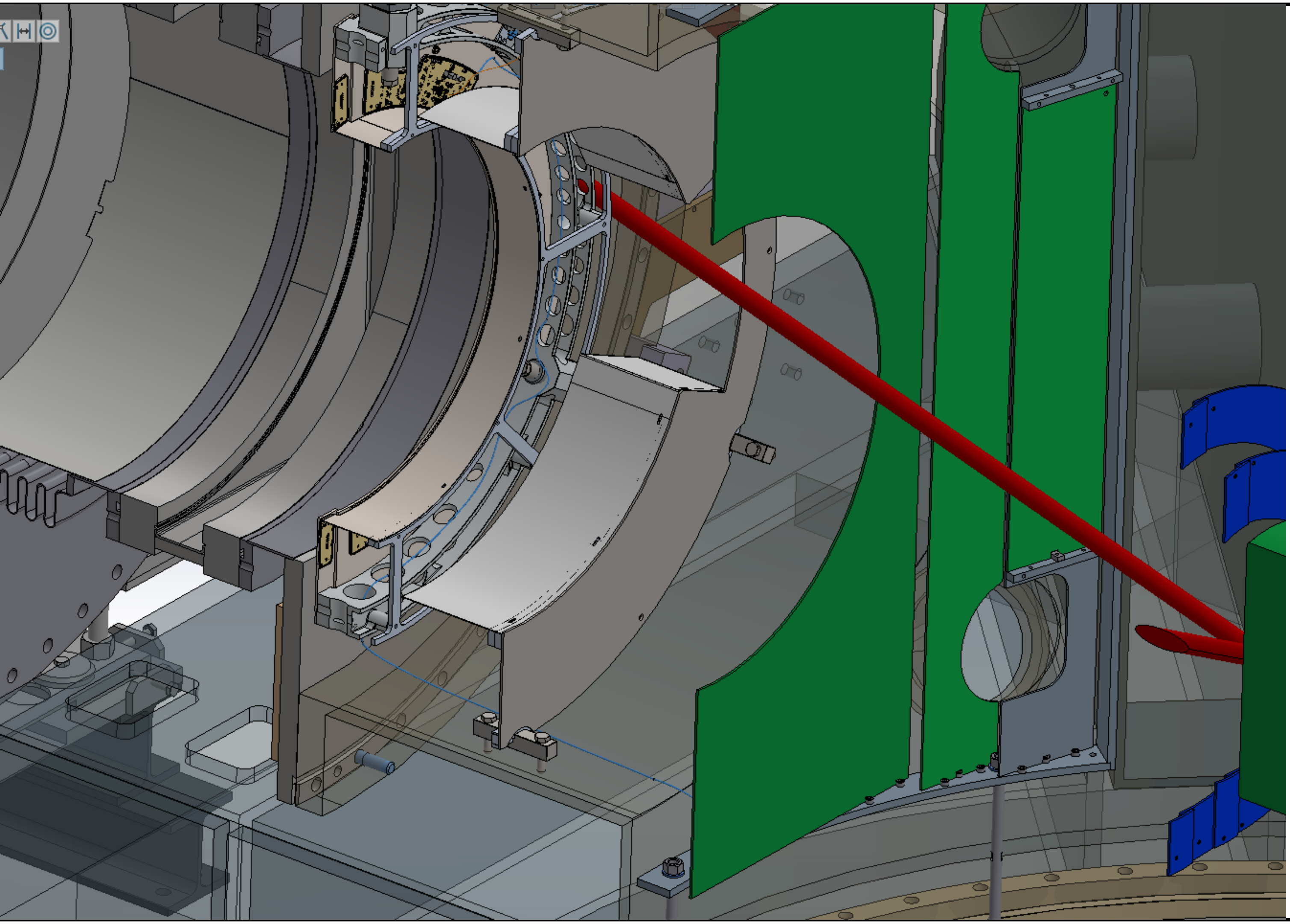


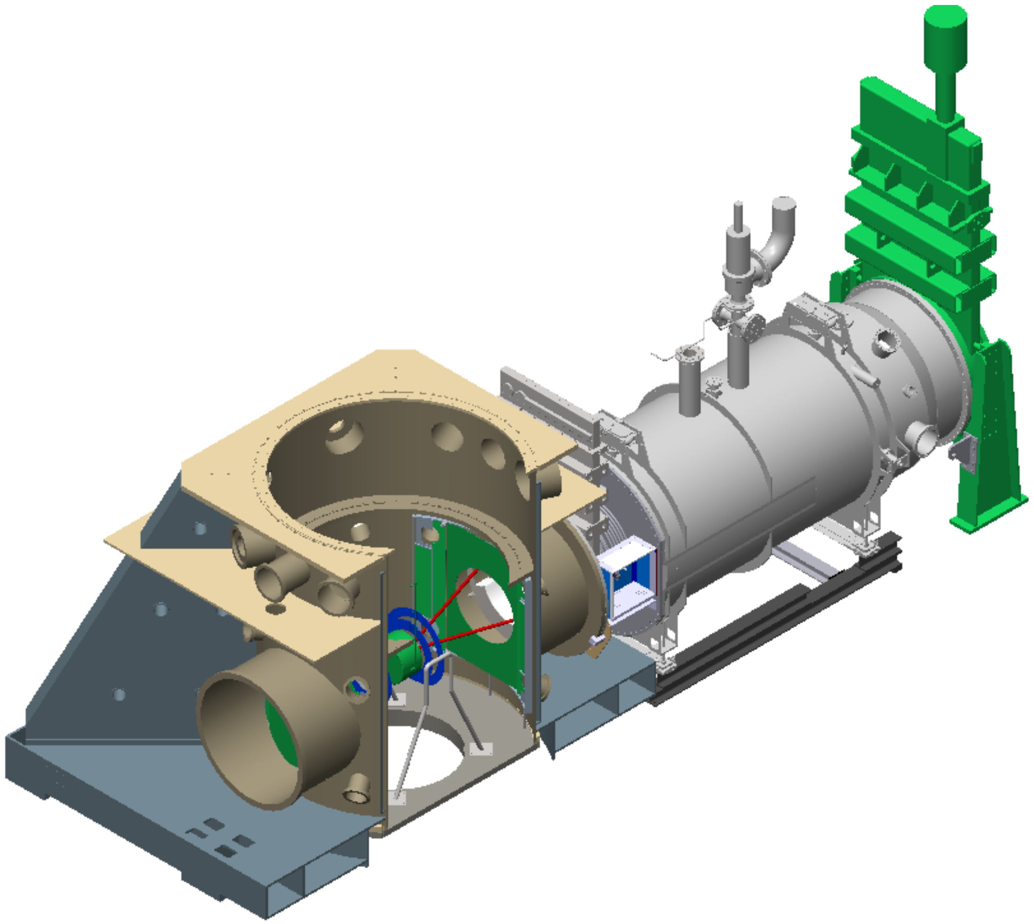


Some of the main characteristics of these new baffles:

- **120 sensors** distributed in 5 rings
- New DAQ at **1kHz** with serial + wireless readout
- Made of stainless steel **316L super #10** polished
- **Encapsulation** of the FE electronics
- Better **cleaning procedures** adopted to ensure no contamination of the mirror

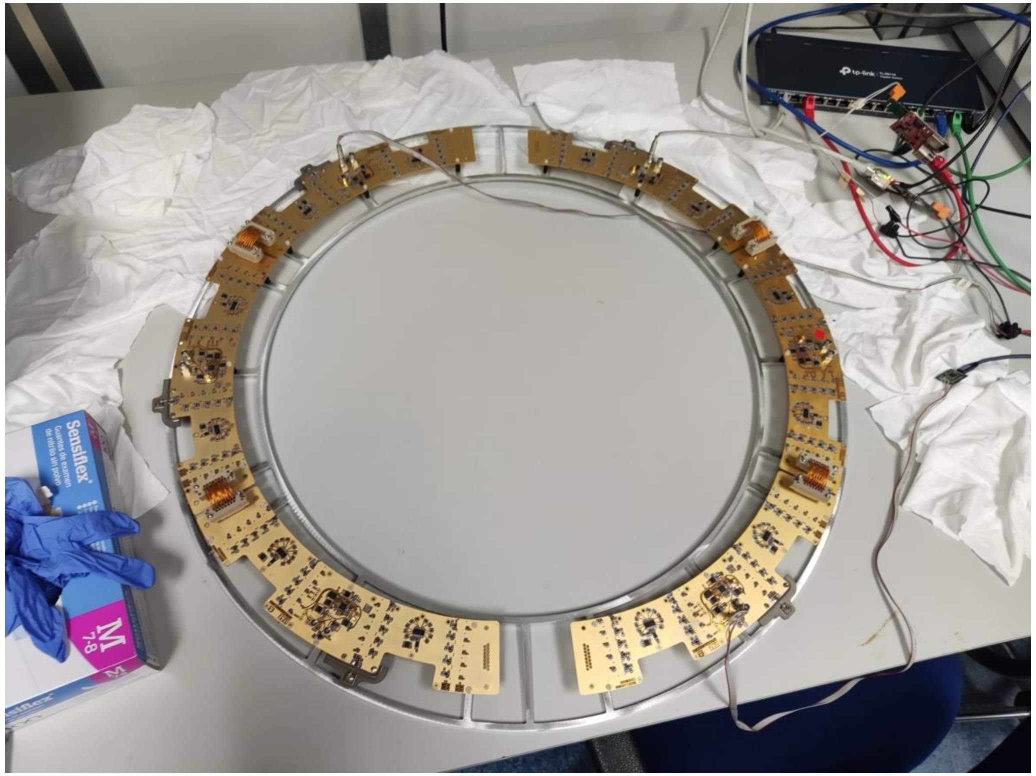
VIRGO INSTRUMENTED BAFFLE



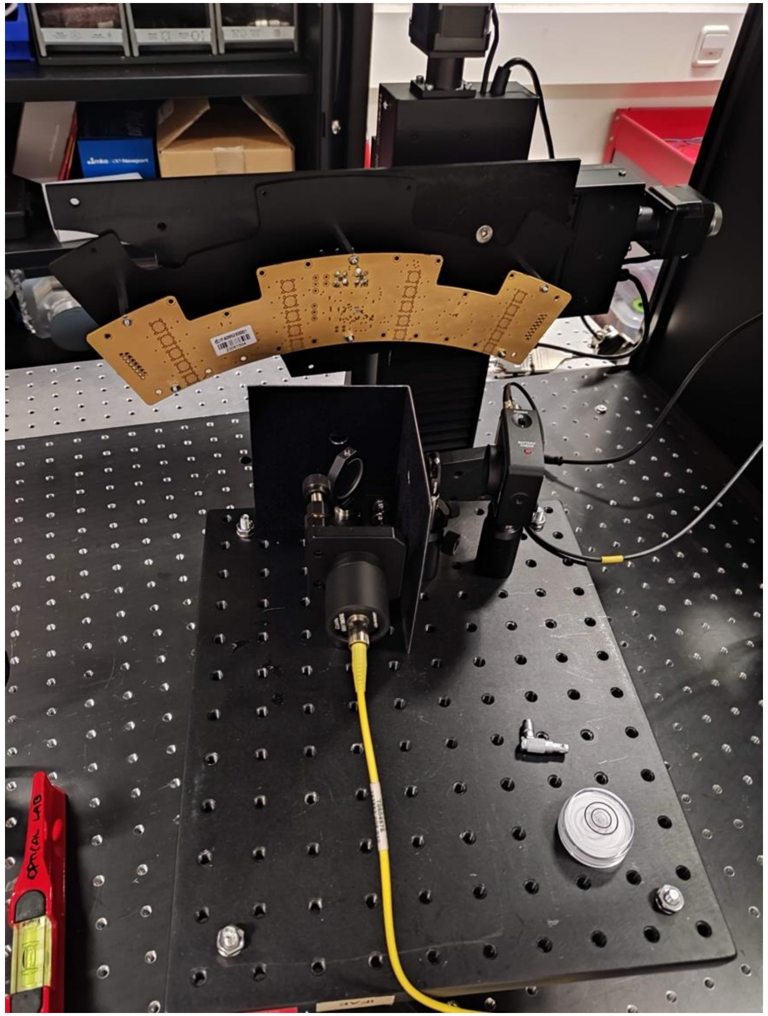


VIRGO INSTRUMENTED BAFFLE

Optical set-up used to calibrate the the sensors

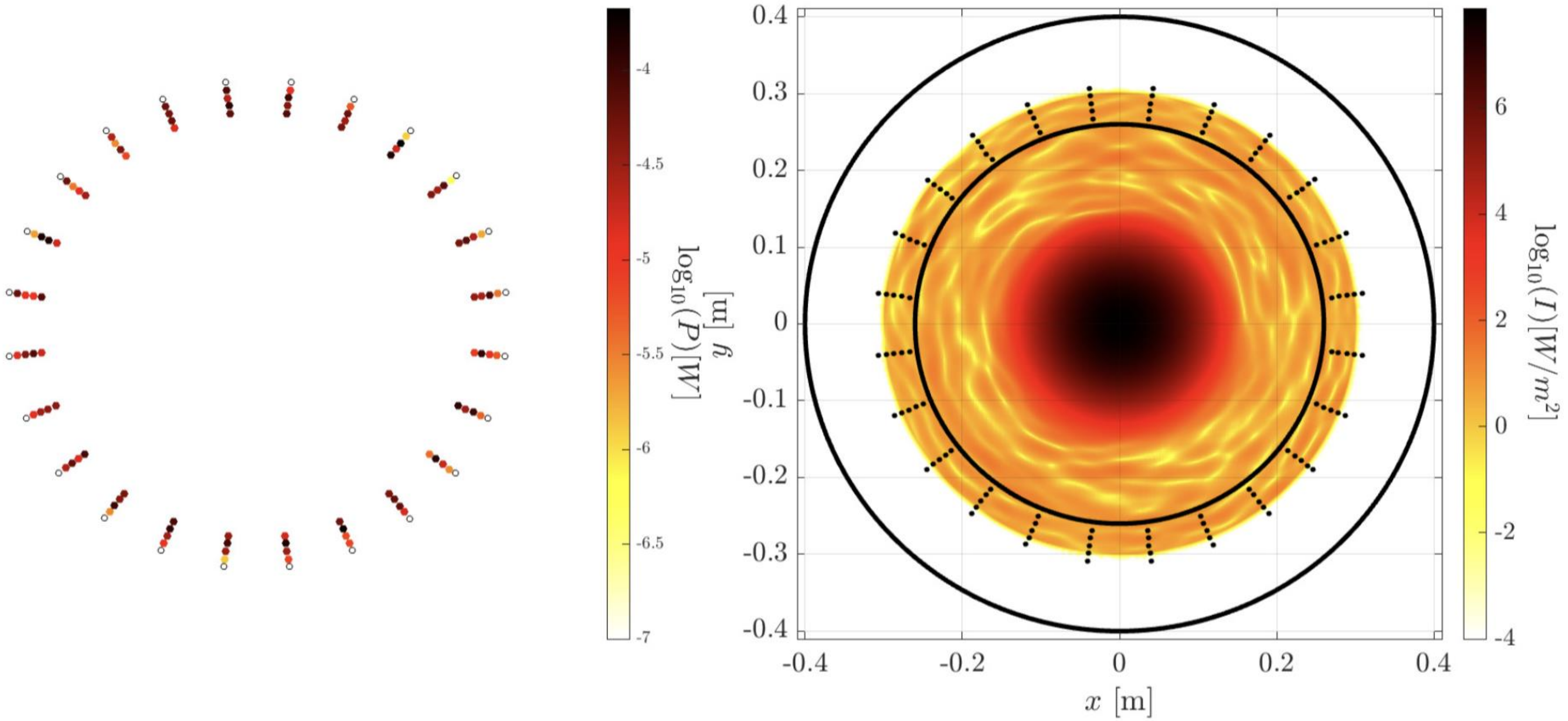


PCB with the sensors and electronics



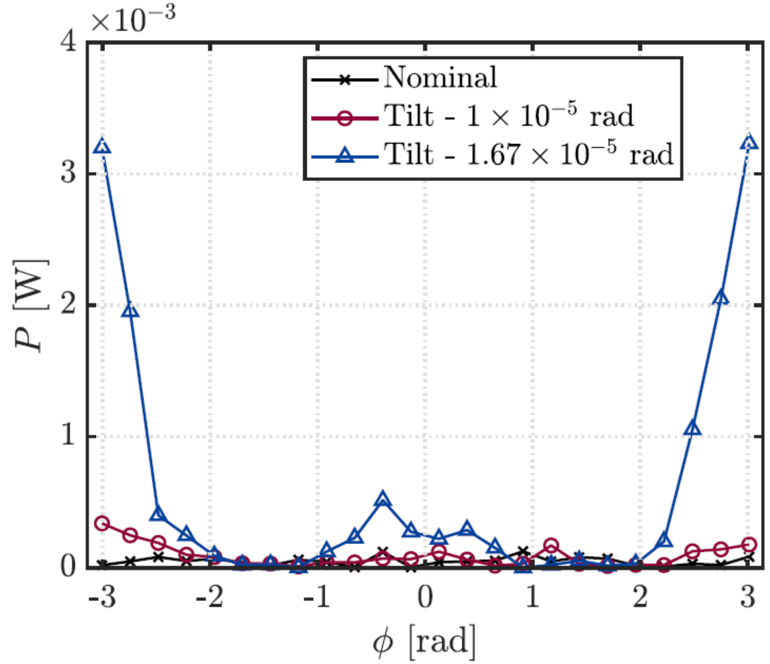
VIRGO BAFFLE – POWER DISTRIBUTION

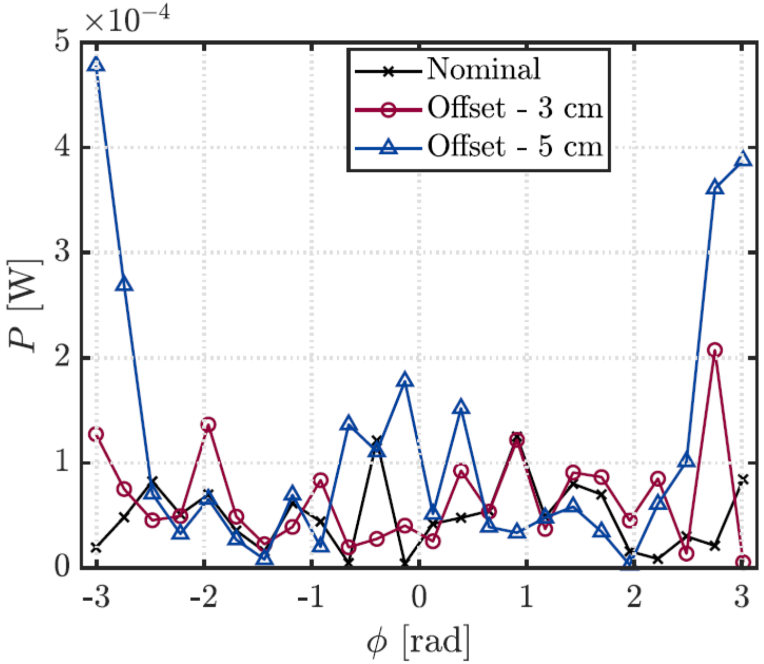
To see how useful these baffles can be, we perform a numerical simulation using SIS to predict which is going to be the readings of the baffle in nominal conditions



M. Andrés-Carcasona, et al., Phys. Rev. D 111.4 (2025), p. 042001

VIRGO BAFFLES – NON-IDEAL CONDITIONS





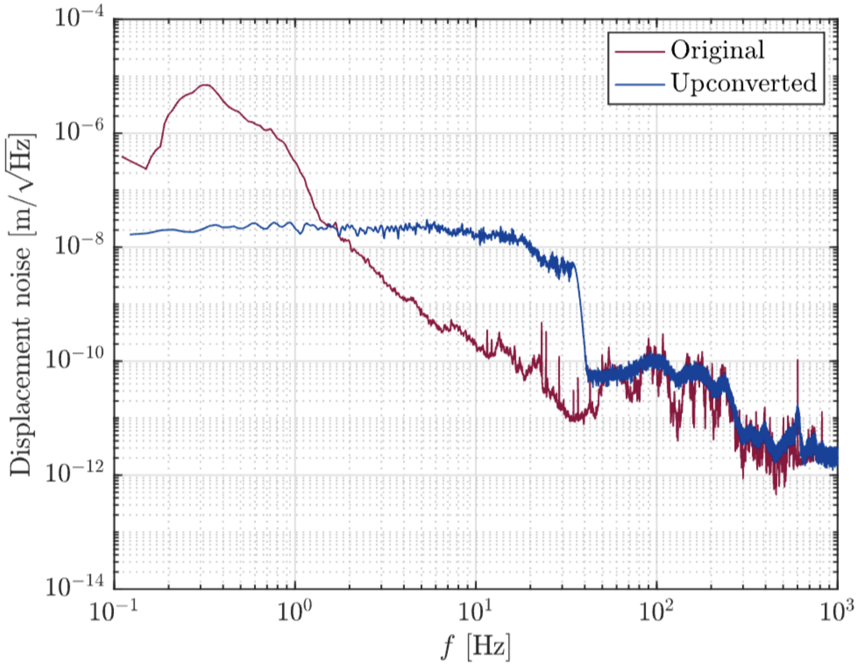
Distribution of power for the first ring of sensors when there is an offset of the laser beam or a misalignment.

In both cases, it is clear how the power distribution changes noticeably when the laser beam has a large enough shift, implying that the instrumented baffle will be able to diagnose such conditions inside the cavity in real time.

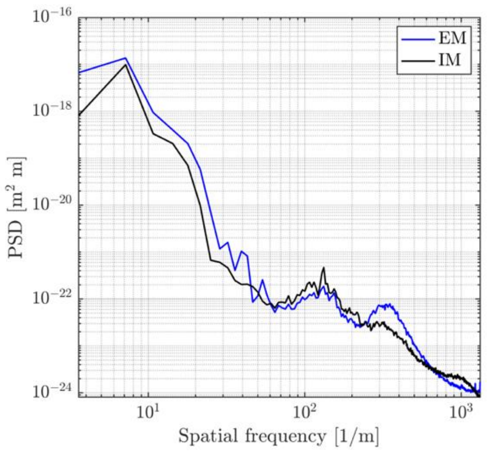
M. Andrés-Carcasona, et al., Phys. Rev. D 111.4 (2025), p. 042001

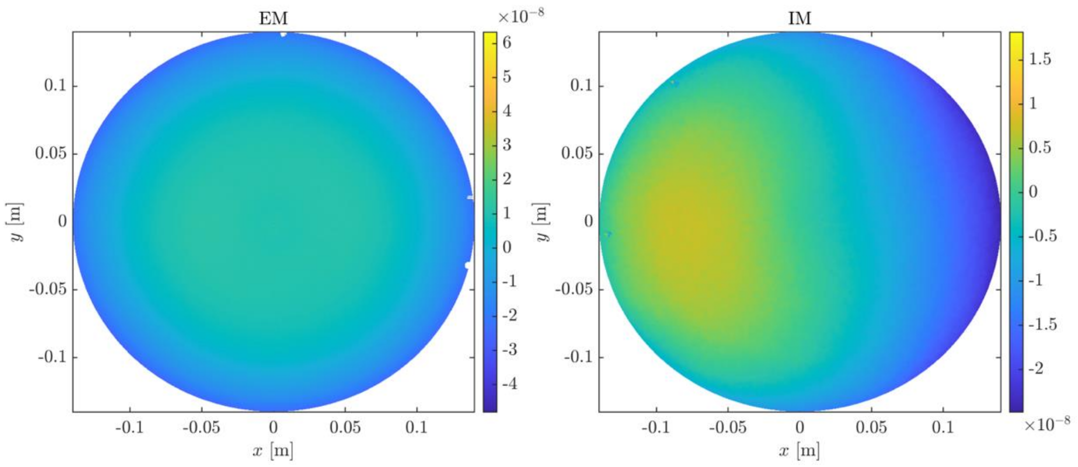
VIRGO BAFFLES– VIBRATIONS AND MIRROR MAPS

We need to make sure that the baffle will not introduce an extra noise such that it limits the sensitivity of Virgo during O5. With the vibrations of a period with high microseism activity (in the 99% level) of the cryo area we can upconvert it and use it to recast it as backscattered and diffraction noise.



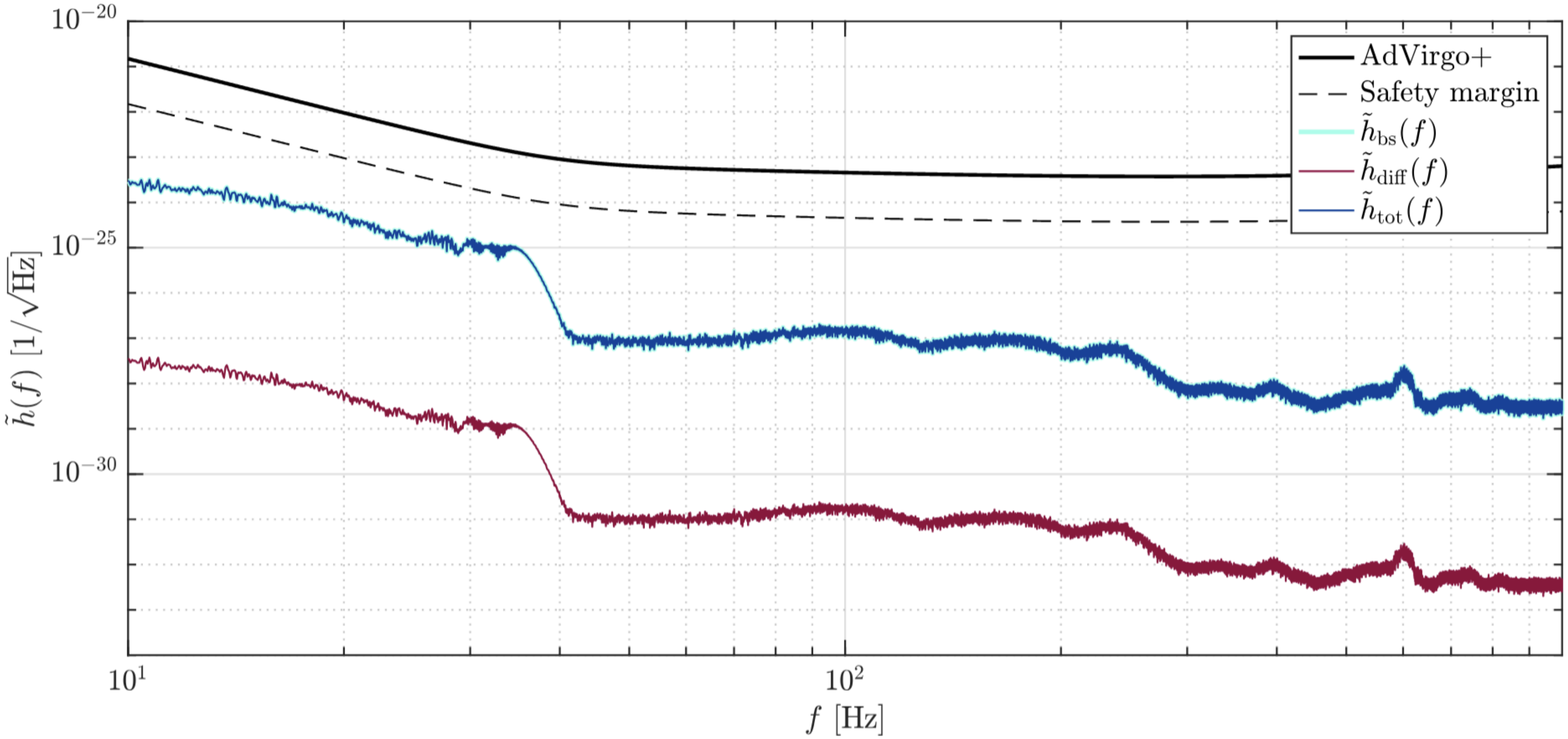
Similarly, the mirror maps will dictate the amount of scattering that will be produced. We use the current mirror maps to estimate it.





M. Andrés-Carcasona, et al., Phys. Rev. D 111.4 (2025), p. 042001

VIRGO BAFFLES – PROJECTED NOISE



M. Andrés-Carcasona, et al., Phys. Rev. D 111.4 (2025), p. 042001

CONCLUSIONS

CONCLUSIONS

ET

- ❖ We updated the results for the baseline case for the triangle and 2L configurations.
- ❖ Our results show that stray light remains a subdominant contribution with this baffle design.
- ❖ We studied the effect of non-ideal conditions. They show that a conservative upper limit for the various cases are:

Interferometer	Max offset	Max misalignment
ET-HF	5 cm	8.0 μrad
ET-LF	7 cm	8.3 μrad

VIRGO

- ❖ We have shown the feasibility to mount an instrumented baffle just before the ETM.
- ❖ We have shown that such baffle would be sensitive to the stray light field under nominal conditions.
- ❖ We have also shown that it would be sensitive to the presence of beam misalignments and offsets
- ❖ We have computed a noise projection to show that it will not compromise Virgo's sensitivity.

Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

EINSTEIN TELESCOPE

UPDATED STRAY LIGHT INDUCED NOISE SIMULATIONS IN ET'S MAIN ARMS

Dr. Marc Andrés-Carcasona

ET symposium 2025, BOLOGNA

EXTRA SLIDES

SCATTERED LIGHT – BACKSCATTERING ESTIMATION

In the previous study, only the far half of the baffles was simulated, and the result was then doubled. The reason lies in the limitation of the angles that can be resolved using a mirror map with finite resolution.

The scattering angles that can be resolved are

$$\theta \sim \lambda \xi$$

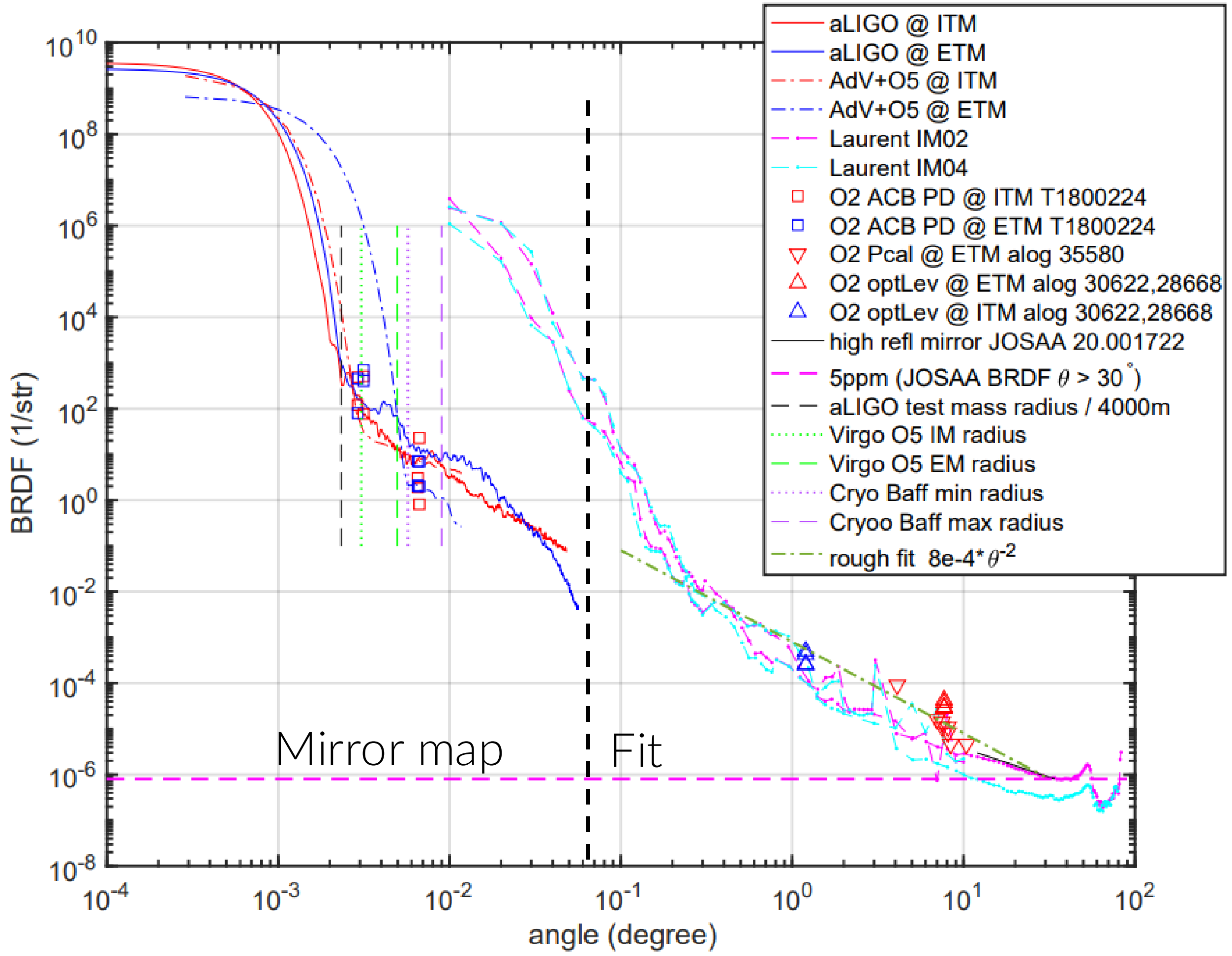
The maximum spatial frequency that can be resolved from a mirror map is the Nyquist frequency

$$\xi_{\max} = 1/(2\Delta)$$

while the minimum one is related to the mirror radius as

$$\xi_{\max} = 1/R_m$$

In the case of ET, the closest baffles correspond to too high spatial frequency and is unfeasible. Right now, SIS allows to estimate the light by using the measured BRDF or a model for it.



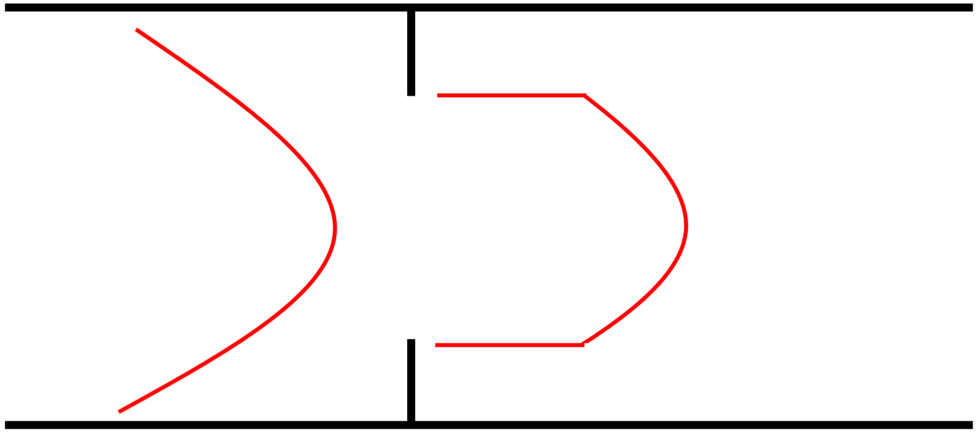
A. Romero-Rodríguez, et al. Galaxies 2022, 10, 86

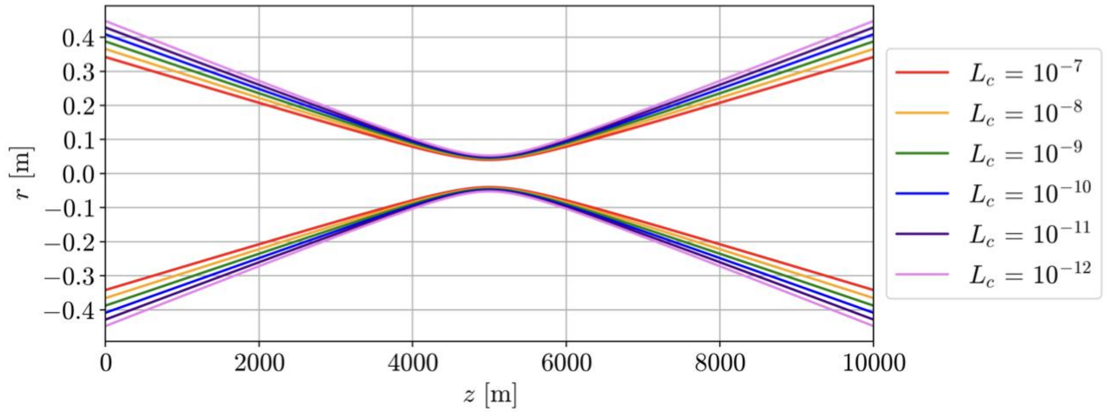
SCATTERED LIGHT – BAFFLES

To decide the inner aperture of the baffles we can take into account the clipping losses. They can be estimated as

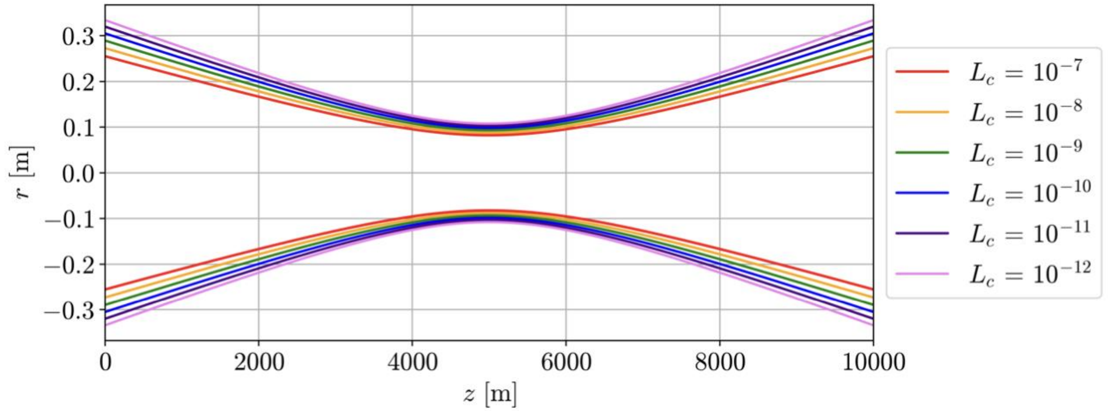
$$r(z, L_c) = \frac{w(z)}{\sqrt{2}}\sqrt{\ln\left(\frac{1}{L_c}\right)} + r_{\text{offset}}$$

which for the values of ET-HF and ET-LF, clipping losses of 10^{-8} and an offset of 5 cm gives minimum apertures of 84 cm and 62 cm, respectively. To maintain the design of the baffles equal for both interferometers, which simplifies the construction and production, we fix the inner aperture to 84 cm.





(a) ET-HF



(b) ET-LF

M. Andrés-Carcasona, et al., Phys. Rev. D 108, 102001

SCATTERED LIGHT – TOTAL NOISE

EINSTEIN TELESCOPE

Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

Δ-10km

Cavity parameters for the Δ-shaped ET with 10 km arms				
Variable	ET-HF	ET-LF	Units	Description
m	200	211	[kg]	Mirror mass
L	10	10	[km]	Length of an arm
λ	1064	1550	[nm]	Wavelength of the laser
R_m	0.31	0.225	[m]	Radii of the mirrors
$\mathcal{R}_1$	5070	5580	[m]	Radius of curvature ITM
$\mathcal{R}_2$	5070	5580	[m]	Radius of curvature ETM
P_{circ}	3000	18	[kW]	Circulating power in the cavity
R	0.5	0.5	[m]	Radius of the vacuum pipe.
RTL	80	45	ppm	Round-trip losses
r_{ITM}	0.99648	0.99648	–	Reflectivity of the ITM mirror
r_{SRM}	0.97417	0.89387	–	Reflectivity of the SRM mirror
A_b	0.84	0.84	[m]	Baffle inner aperture
H	0.14	0.14	[m]	Baffle length
dH	0.0244	0.0244	[m]	Baffle overlapping factor
ϕ	55	55	[deg]	Inclination angle of the baffles
$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega_{bs}}$	10^{-4}	10^{-4}	[str^{-1}]	BRDF of the baffles
z_0	12.35	52.35	[m]	Position of the first baffle
N	270	228	–	Number of baffles per arm

2L-15km

Cavity parameters for the 2L-shaped ET with 15 km arms				
Variable	ET-HF	ET-LF	Units	Description
m	200	211	[kg]	Mirror mass
L	15	15	[km]	Length of an arm
λ	1064	1550	[nm]	Wavelength of the laser
R_m	0.31	0.225	[m]	Radii of the mirrors
$\mathcal{R}_1$	7745	10697	[m]	Radius of curvature ITM
$\mathcal{R}_2$	7745	10697	[m]	Radius of curvature ETM
P_{circ}	3000	18	[kW]	Circulating power in the cavity
R	0.5	0.5	[m]	Radius of the vacuum pipe.
RTL	80	45	ppm	Round-trip losses
r_{ITM}	0.99648	0.99648	–	Reflectivity of the ITM mirror
r_{SRM}	0.97417	0.89387	–	Reflectivity of the SRM mirror
A_b	0.84	0.84	[m]	Baffle inner aperture
H	0.14	0.14	[m]	Baffle length
dH	0.0244	0.0244	[m]	Baffle overlapping factor
ϕ	55	55	[deg]	Inclination angle of the baffles
$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}\Omega_{bs}}$	10^{-4}	10^{-4}	[str^{-1}]	BRDF of the baffles
z_0	12.35	52.35	[m]	Position of the first baffle
N	370	328	–	Number of baffles per arm

INSTRUMENTED BAFFLE

Then main advantages to place an instrumented baffles are:

Real-Time Monitoring of Scattered Light

Active monitoring of light for continuous feedback on the scattering environment.

High Sampling Frequency

This baffle operates at 1kHz making it possible to correlate its data with other channels.

Precise Localization of Scattering Sources

With the baffle data and simulations, we can localize some sources of scattered light

Adaptive Control and Optimization

Its data can be used by the control systems to dynamically adjust other components

Aid during the Pre-alignment

Instrumented baffles can aid in the pre-alignment procedure to track the beam.

Glitch Detection

Short-term glitches can be detected and ideally filtered out in real time.

FUTURE WORK

Future work

- Include the cryotrap area
- Optimize the number and position of the baffles to reduce the cost and the noise, as diffraction is the one dominating
- Include the transfer factors between the ground and the baffles
- Optimize the serration pattern to further minimize the diffraction noise
- Include the effect of the beampipe into the noise, as some light will inherently hit it. Nonetheless, it is expected to be very small.
- Study other areas apart from the FP cavities