SCATTERED LIGHT IN THE MAIN ARMS OF ET

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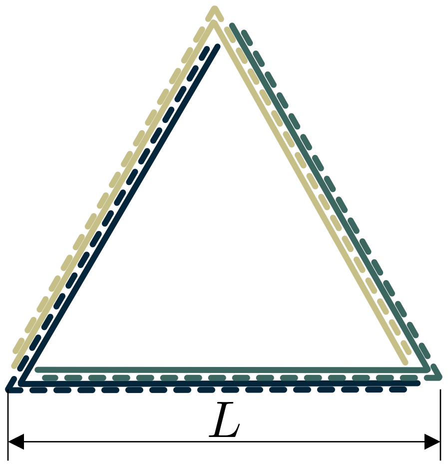
Work in collaboration with A. Macquet (IFAE), M. Martínez (IFAE, ICREA), Ll. M. Mir (IFAE) and H. Yamamoto (Caltech)

GWADW - 2023

Hotel Hermitage, La Biodola, Isola d'Elba - 22/05/2023

OUTLINE



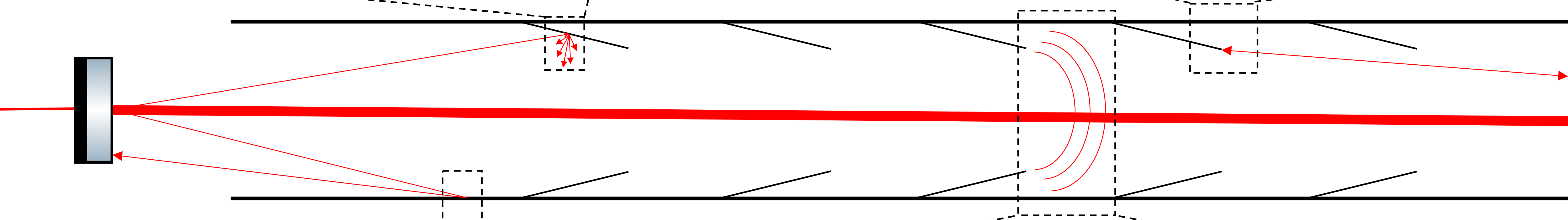
Variable	ET-HF	ET-LF	Units	Description
m	200	211	[kg]	Mirror mass.
L	10	10	[km]	Length of an arm.
λ	1064	1550	[nm]	Wavelength of the laser.
R_m	31	22.5	[cm]	Radii of the mirrors.
R_1	5070	5580	[m]	Radius of curvature of the ITM mirror.
R_2	5070	5580	[m]	Radius of curvature of the ETM mirror.
R	0.5	0.5	[m]	Radius of the vacuum pipe.
A_b	0.84	0.84	[m]	Baffle inner aperture.
dH	1	1	[cm]	Safety margin of the baffle height.
ϕ	55	55	[deg]	Inclination angle of the baffles.
$\frac{\mathrm{d}P}{\mathrm{d}\Omega_{bs}}$	10^{-2}	10^{-2}	[str^{-1}]	BRDF of the baffles.
P_{circ}	3000	18	[kW]	Circulating power inside the cavity.

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 perfectly reflecting material

DIFFRACTION

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

INTRODUCTION

Serration of the baffles will mitigate this noise

BACKSCATTERING

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

~~BAFFLE EDGE BACKREFLECTION~~

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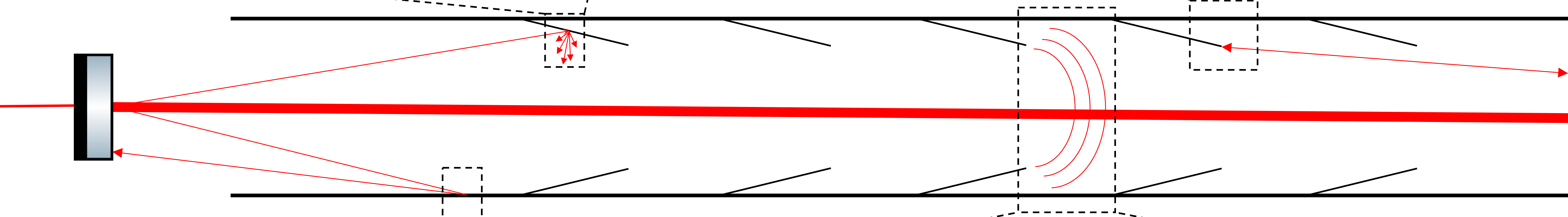


~~SHINING FACET~~

~~Any piece of perfectly reflecting material~~

~~DIFFRACTION~~

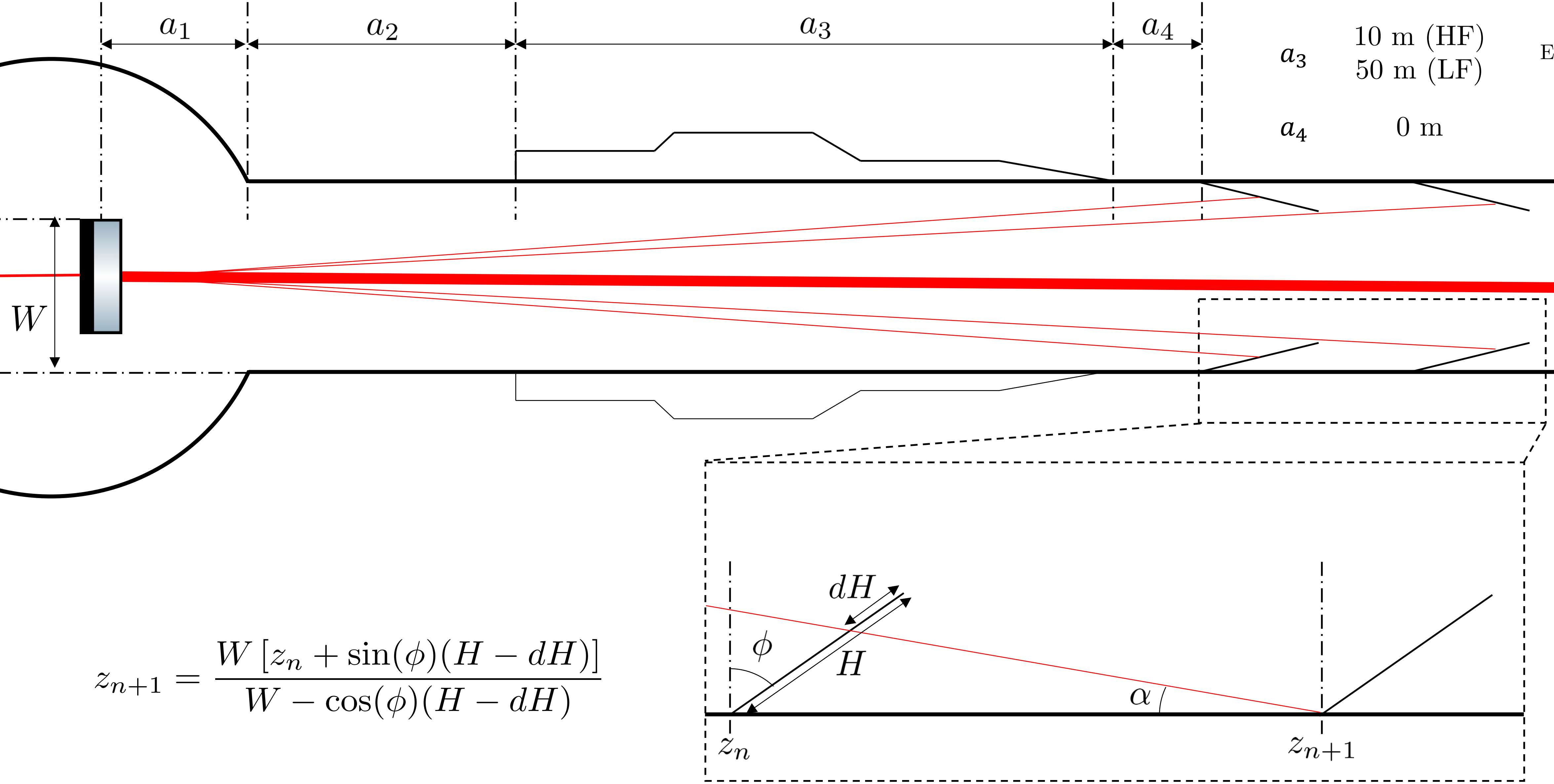
~~The finite aperture of the baffles will generate a diffraction pattern capable of affecting the sensitivity~~

The baffles are designed to hide any part of the tube

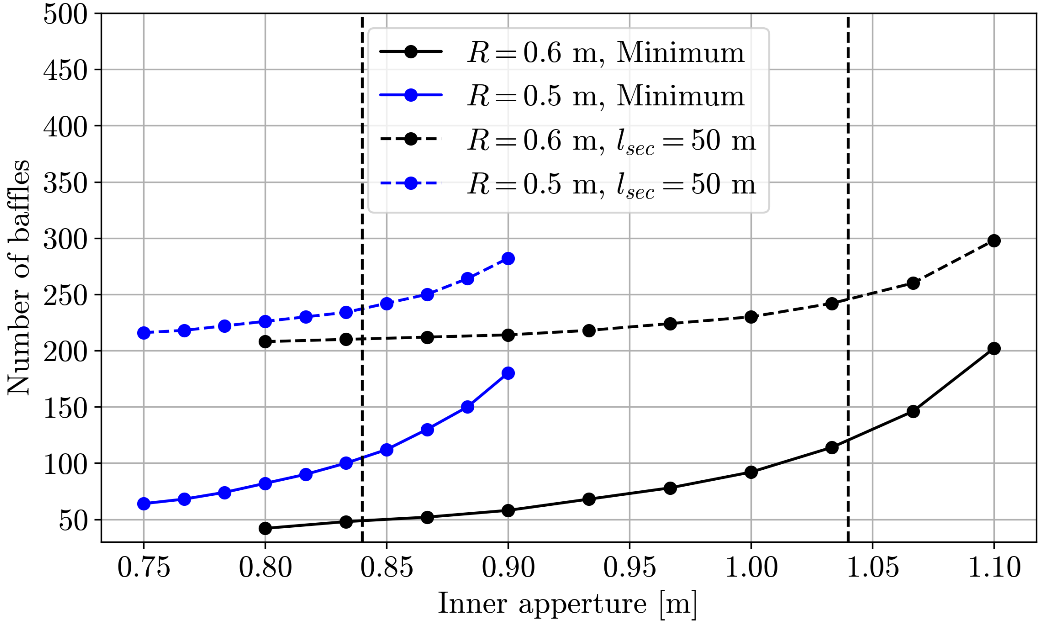
Serration of the baffles will mitigate this noise (see later)

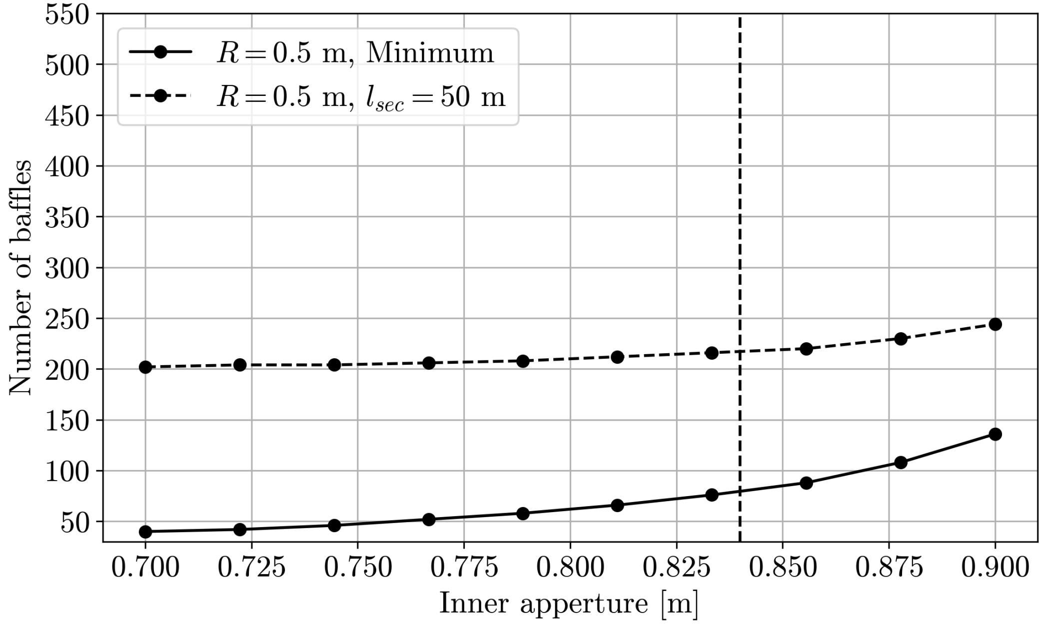
BAFFLE LOCATION

a_i	Value	Ref
a_1	2.35 m	ET-0235C-22
a_2	20 m	ET-0007B-20
a_3	10 m (HF) 50 m (LF)	ET-0007B-20
a_4	0 m	This work



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



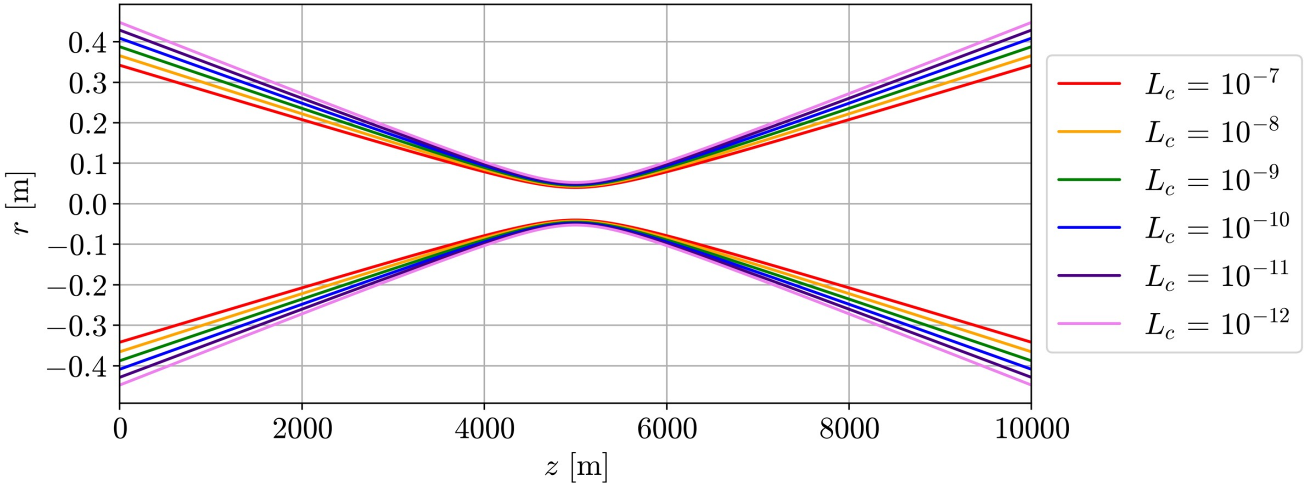


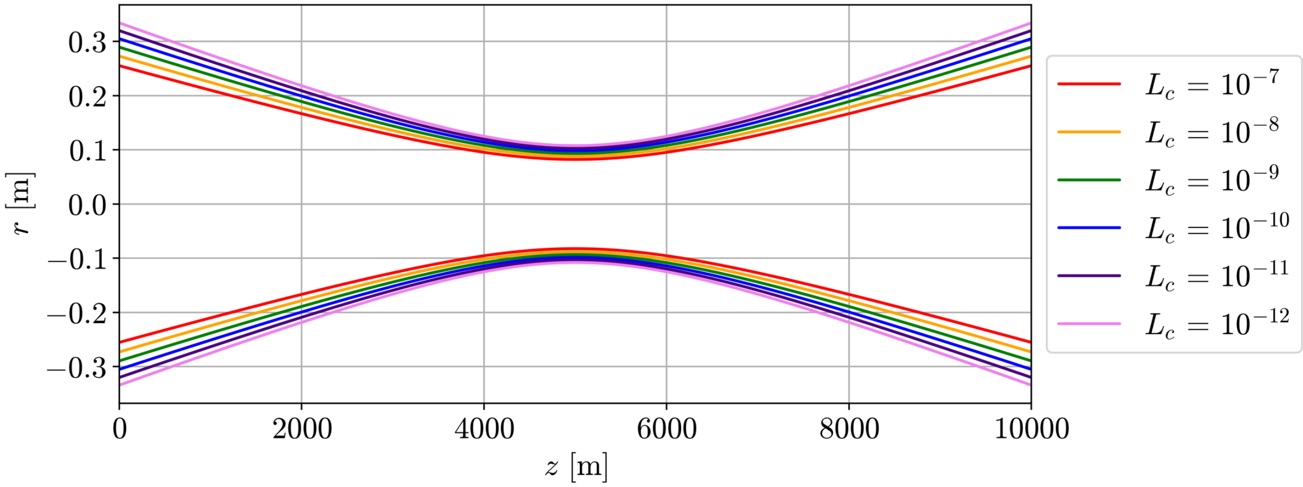
For the current design we consider 50 m between baffles in the middle section of the tube. This implies that the number of baffles are of 238 and 216 per arm in ET-HF and ET-LF, respectively. The total number of baffles for the xylophone configuration is then 1362.

BEAM PROFILE

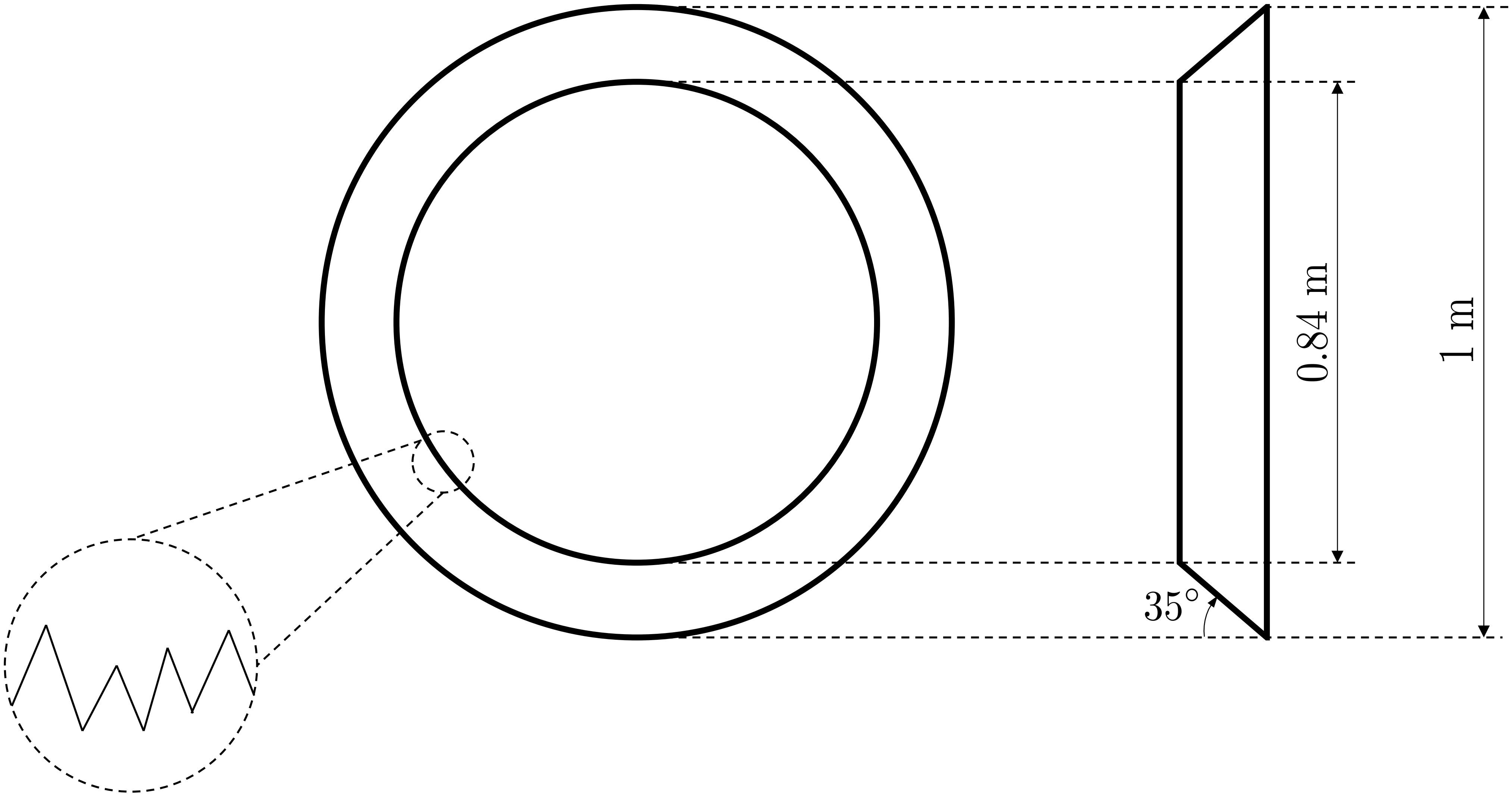
$$P(r,z) = \int_0^{2\pi} \int_0^{r} \frac{2P_0}{\pi w_0^2} \left(\frac{w_0}{w(z)}\right)^2 \exp\left(\frac{-2r'^2}{w(z)^2}\right) r' \mathrm{d}r' \mathrm{d}\varphi$$

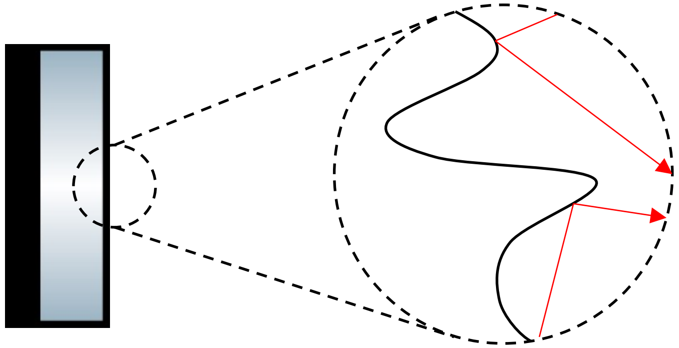
$$\boxed{r(z, L_c) = \frac{w(z)}{\sqrt{2}} \sqrt{\ln\left(\frac{1}{1 - P/P_0}\right)}}$$





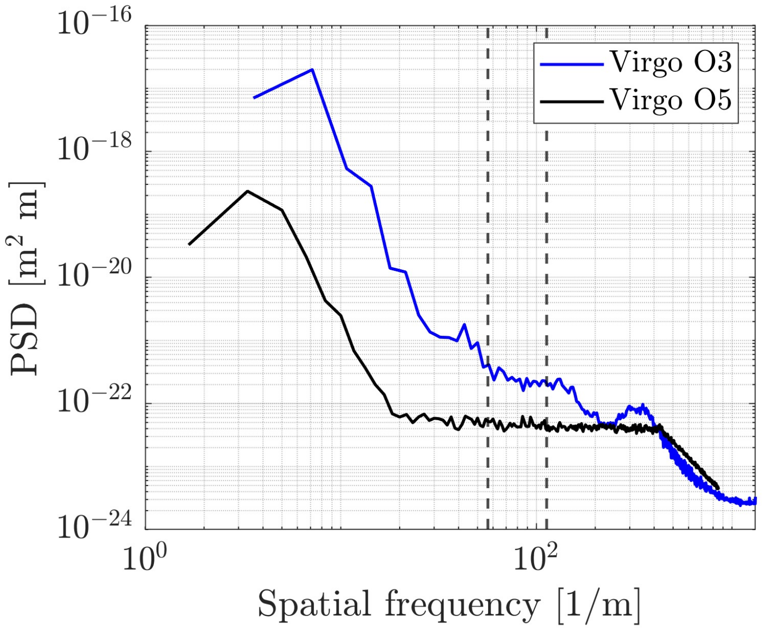
BAFFLE DESIGN

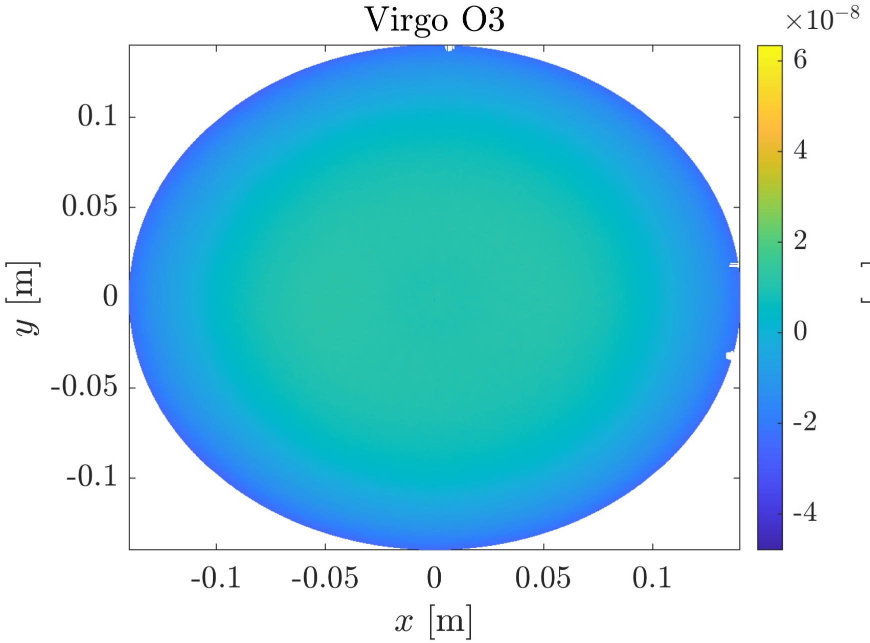


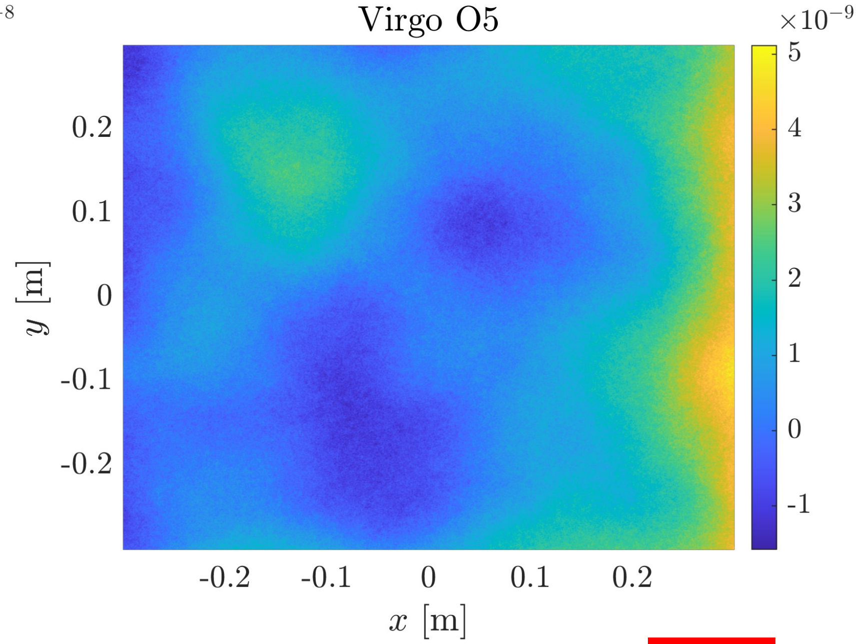


The surface roughness can be quantified using the so-called mirrormaps. These are two dimensional arrays containing the height of the deviation from a perfect surface at each point.

In this work the expected quality of the mirrors of Virgo in O5 is used. These are the mirrormaps of Virgo in O3, the expected one for O5 and their corresponding one-dimensional PSD.





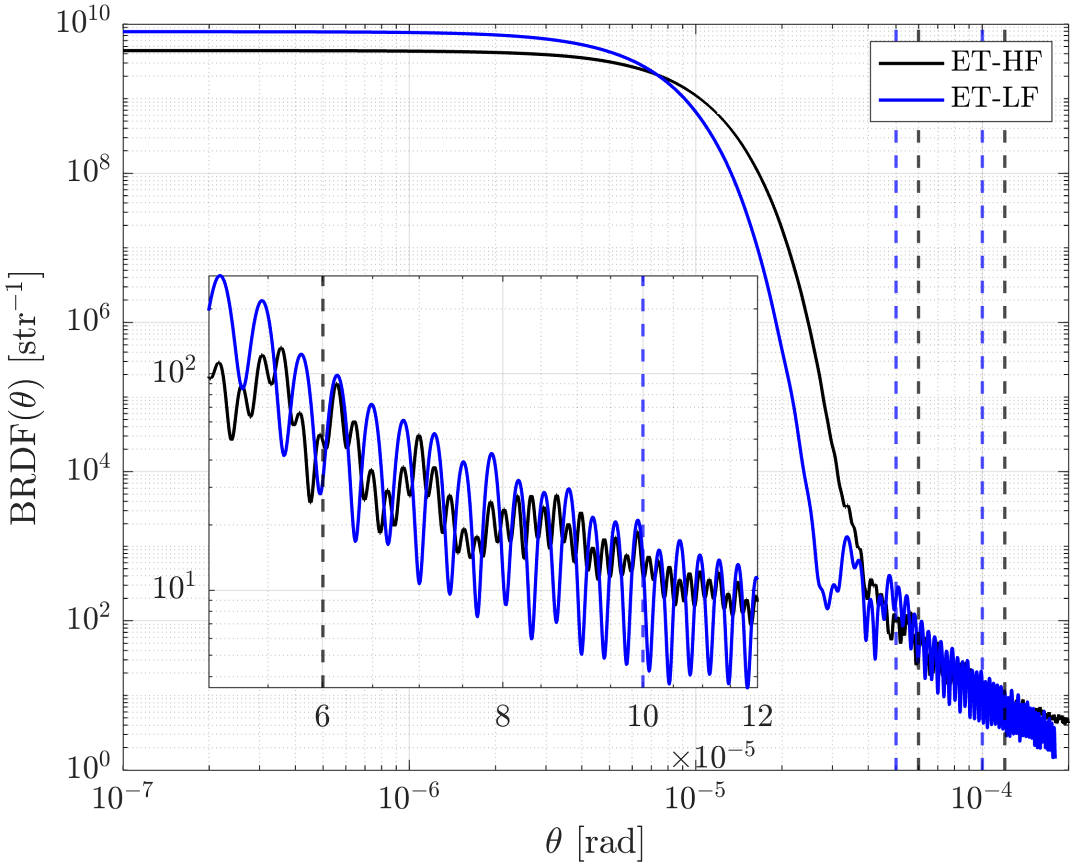


This PSD has been computed using SIS, a code made by H. Yamamoto (Caltech)

The scattered light depends on the finite aperture of the mirror and the surface aberration. A way to quantify it is by using the bidirectional reflectance distribution function (BRDF):

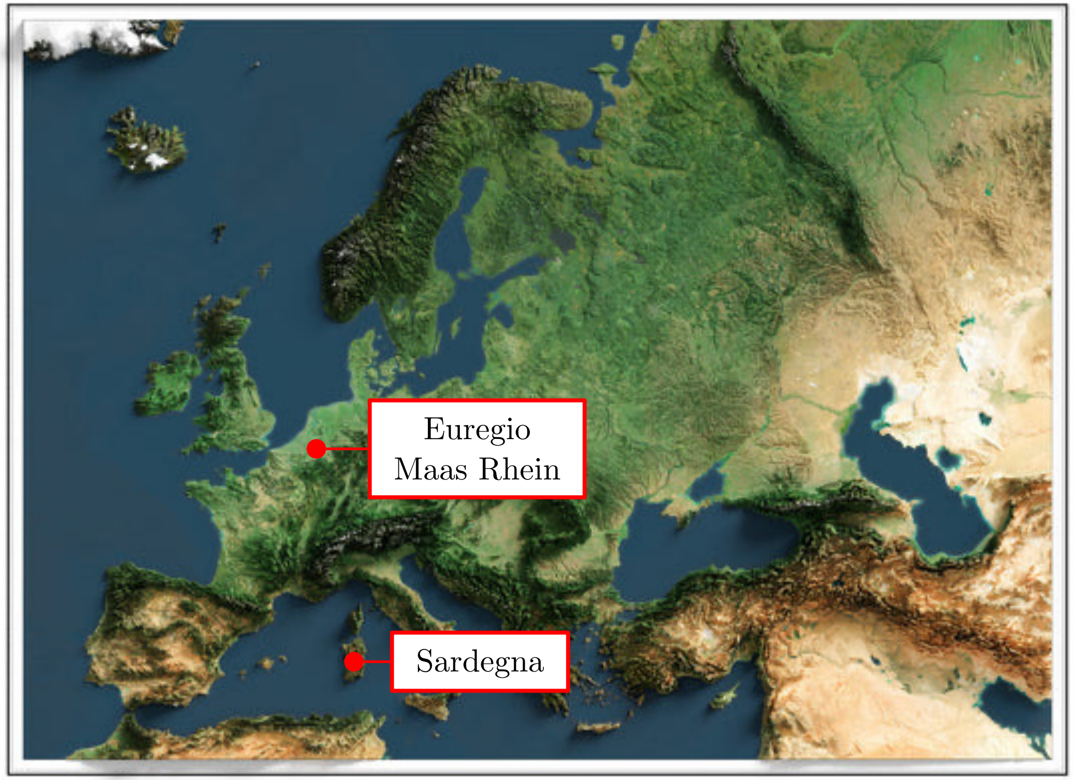
$$\mathrm{BRDF} \approx \boxed{\frac{\mathrm{d}P}{\mathrm{d}\Omega_{\mathrm{ms}}}}$$

Probability of a photon being scattered in a given solid angle



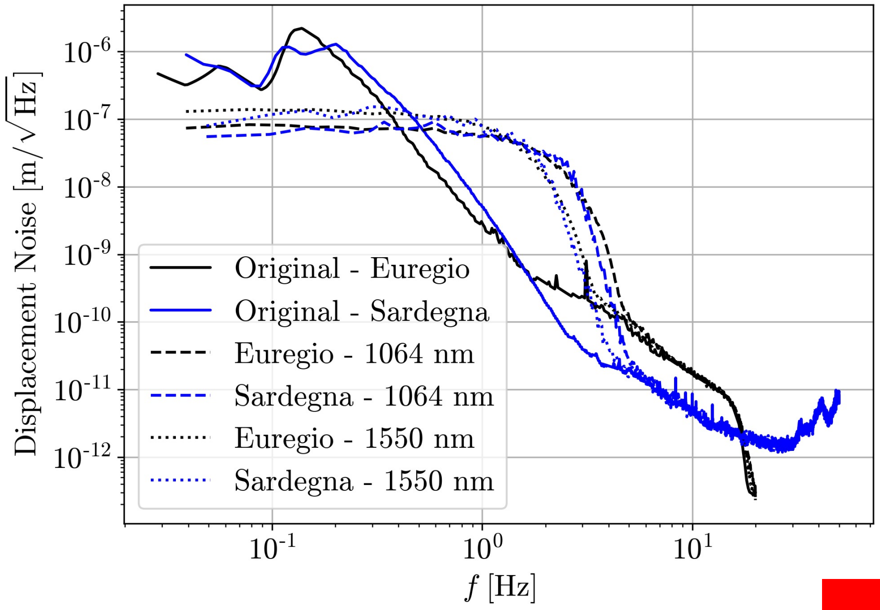
This BRDF has been computed using SIS, a code made by H. Yamamoto (Caltech)

PROPOSED SITES



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

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



The original noises are shown in Seismological Research Letters (2021) 92 (1): 352–364 (Saredegna) and Class. Quantum Grav. 39 025008 (Euregio) and were kindly provided to us by A. Grado and S. Koley

Formulas extracted from LIGO-T950101.

SMOOTH EDGE

$$\tilde{h}(f) = \frac{\kappa\lambda X(f)}{\sqrt{2}LR}\sqrt{N_B}$$

REGULARLY SERRATED

$$\tilde{h}(f) = \frac{\kappa\lambda X(f)}{\sqrt{2}LR}\left[\frac{\sqrt{2}\lambda L}{8\pi R\Delta H}\left(\frac{1}{N_B}\sum_{n=1}^{N_B}\beta_n^2\right)\right]^{1/2}$$

RANDOMLY SERRATED

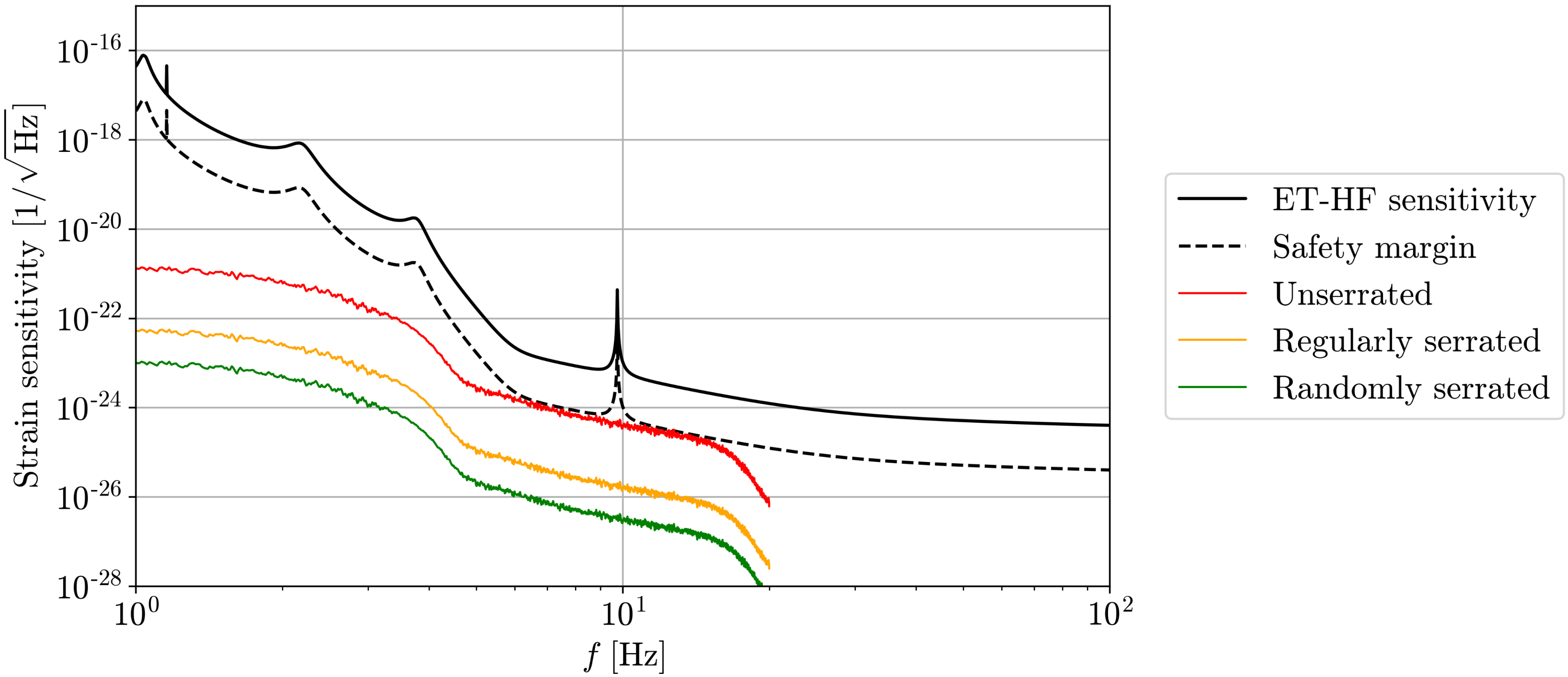
$$\tilde{h}(f) = \frac{\kappa\lambda X(f)}{\sqrt{2}LR}\left[\frac{\sqrt{2}\lambda L}{8\pi R\Delta H}\right]\left[\frac{\sqrt{\lambda L/4}}{2\pi R}\right]^{1/2}$$

Example for ET-HF

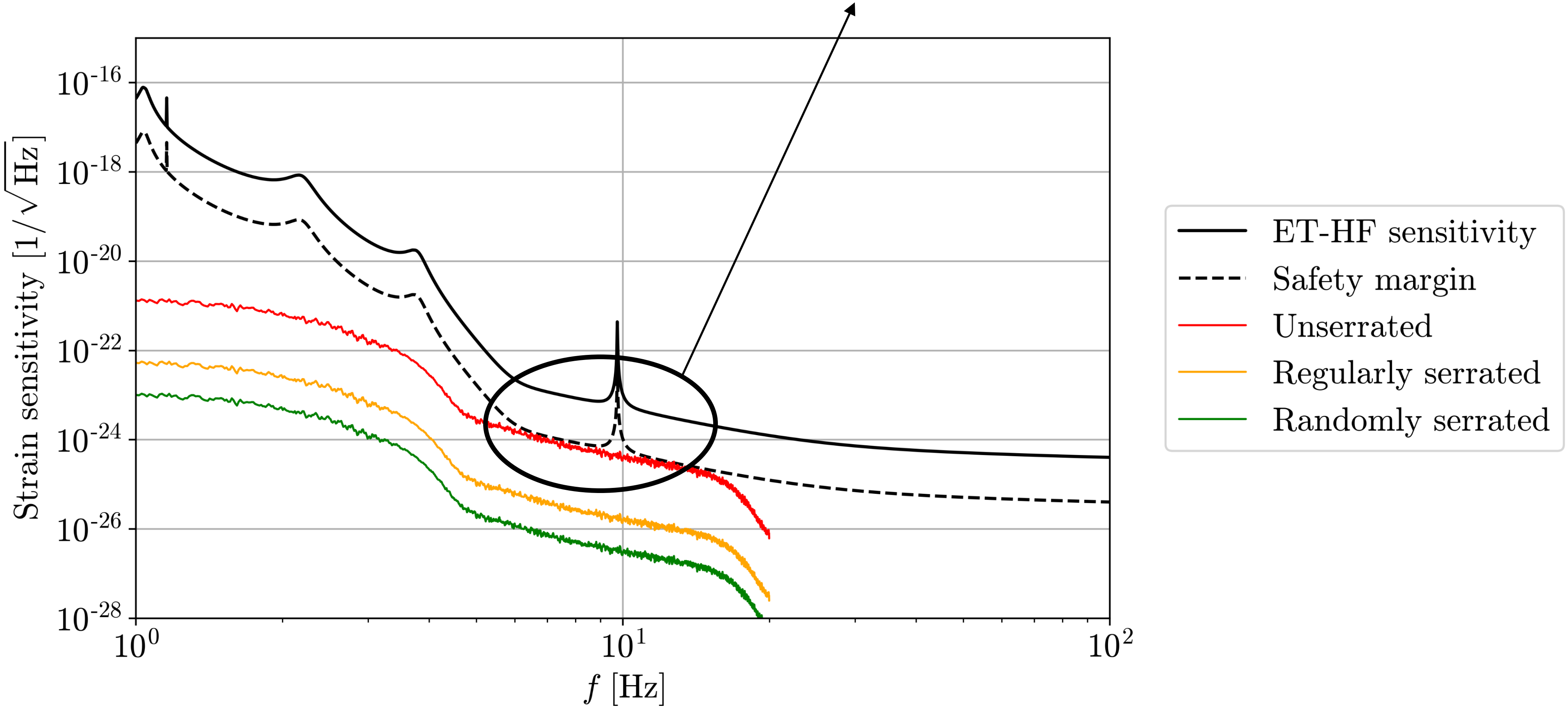
$$\tilde{h}_{\mathrm{smooth}}(f) = 2.32 \times 10^{-14} X(f)$$

$$\tilde{h}_{\mathrm{regular}}(f) = 9.34 \times 10^{-16} X(f)$$

$$\tilde{h}_{\mathrm{random}}(f) = 1.78 \times 10^{-16} X(f)$$


ET-HF sensitivity
Safety margin
Unserrated
Regularly serrated
Randomly serrated
Strain sensitivity [1/√Hz]
f [Hz]
10^-16
10^-18
10^-20
10^-22
10^-24
10^-26
10^-28
10^0
10^1
10^2

Very risky! Too close the margin. Safer to serrate it



Power reaching each baffle. Can be computed either analytically with the BRDF or via numerical simulations

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

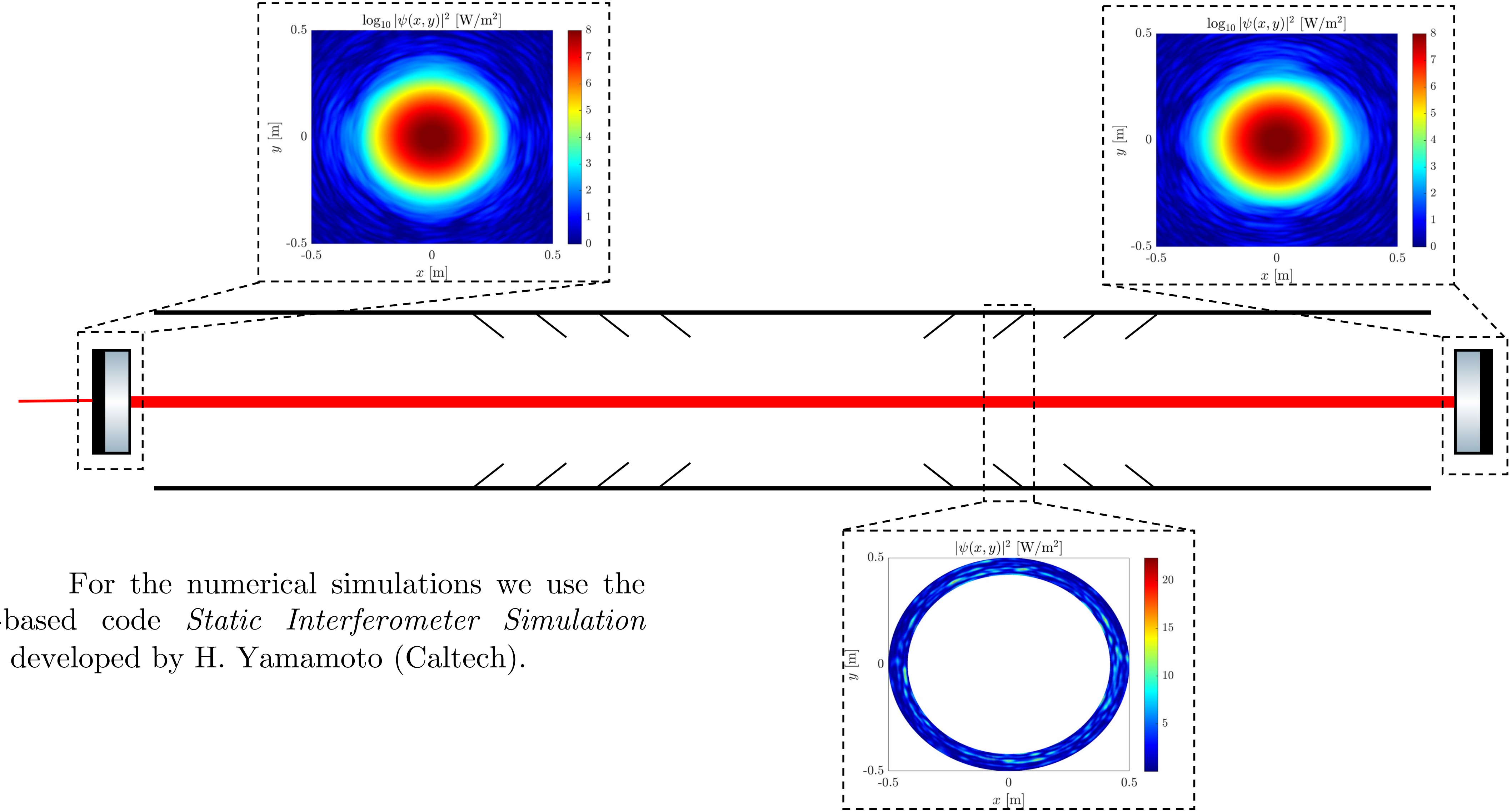
$$\int_{\theta_{\min}}^{\theta_{\max}}\mathrm{d}K \simeq \sum_{i=1}^{N_B}\frac{1}{z_i^2}\left(\frac{\mathrm{d}P^i}{\mathrm{d}\Omega_{ms}}\right)^2\boxed{\delta\Omega^i_{ms}}$$

Formula extracted from LIGO-T1300354.

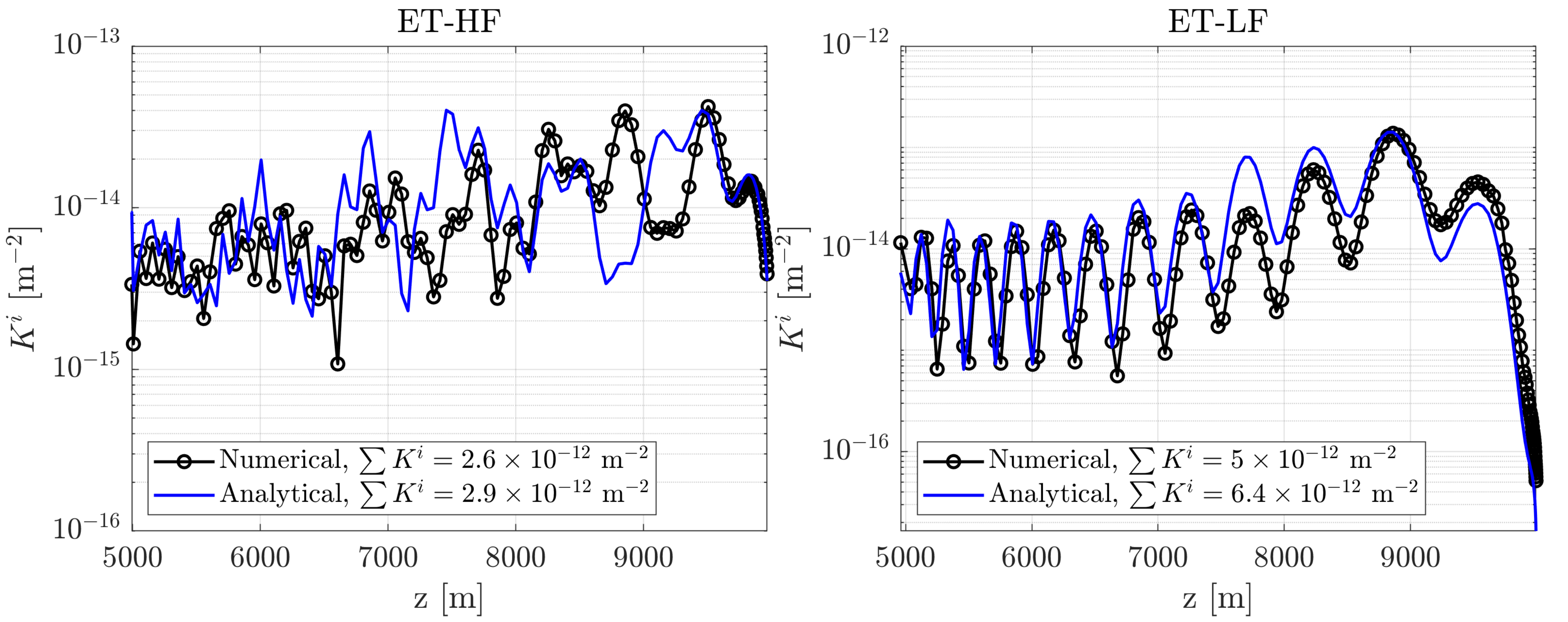
$$\delta\Omega^i_{ms} = \begin{cases} \dfrac{2\pi H\cos\phi}{z_i^2}(R - H\cos\phi) & \text{if } i = 1 \\[2ex] \dfrac{2\pi(R - H\cos\phi)^2}{z_i}\left[\dfrac{1}{z_{i-1}} - \dfrac{1}{z_i}\right] & \text{if } i \neq 1 \end{cases}$$

BRDF of the baffles

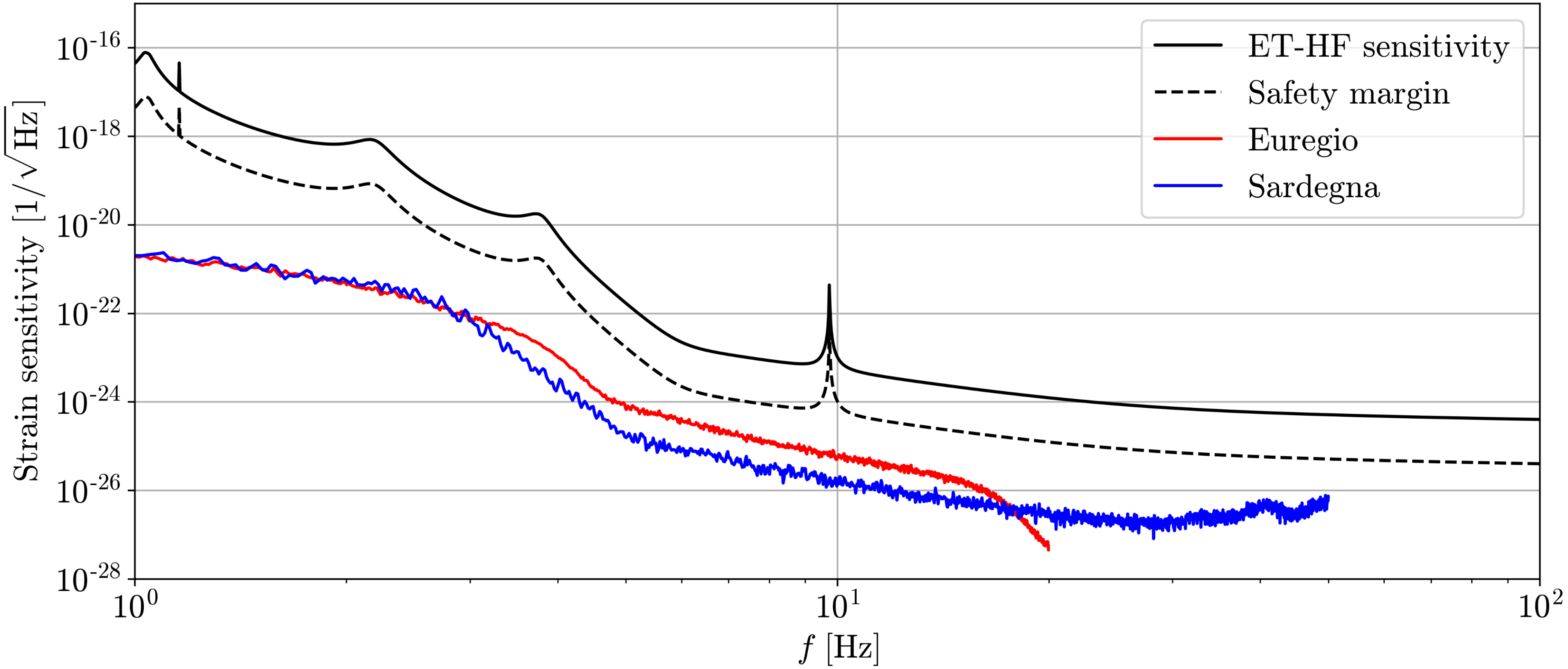
We use a conservative value of 0.01 str^{-1}. Recent measurements of coatings show that values of 10^{-4} str^{-1} are possible, but this would imply coating the 1362 baffles.



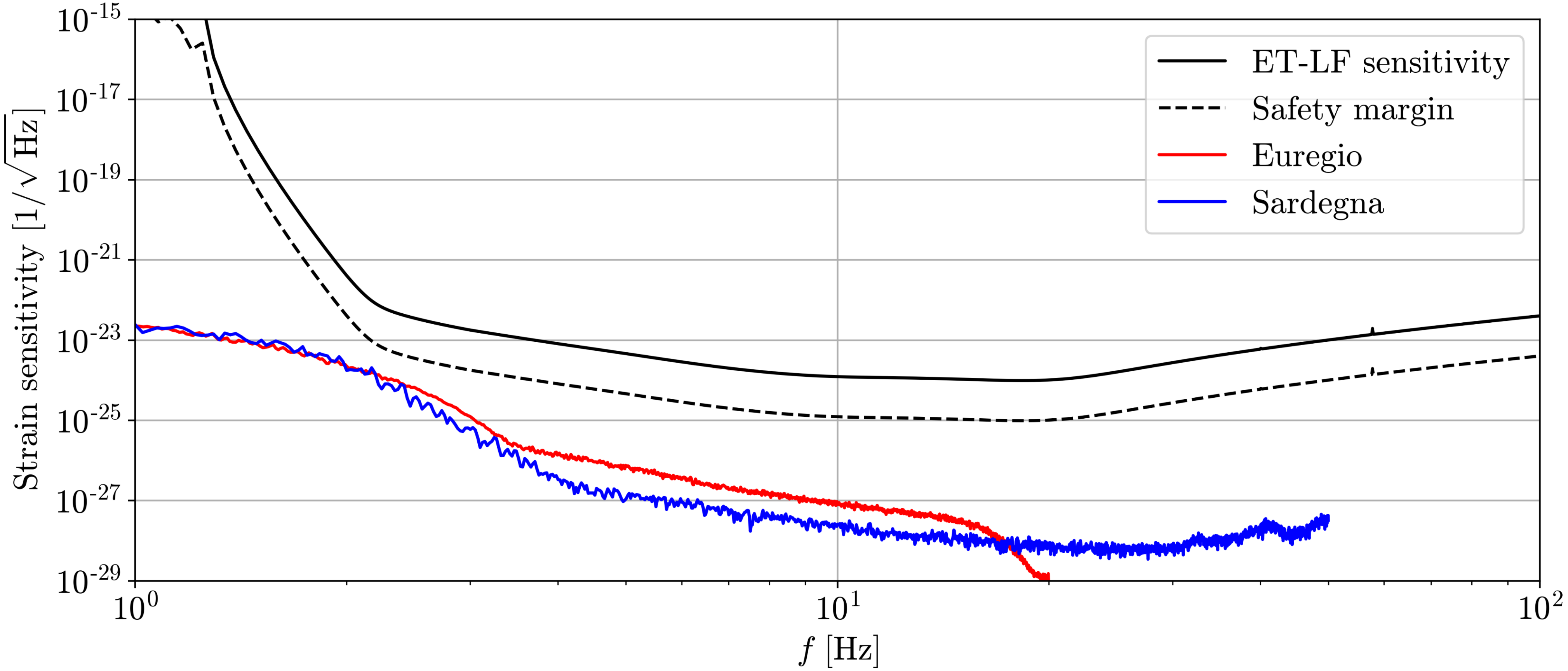
For the numerical simulations we use the FFT-based code *Static Interferometer Simulation* (SIS) developed by H. Yamamoto (Caltech).



The numerical results have been obtained using SIS, a code made by H. Yamamoto (Caltech)

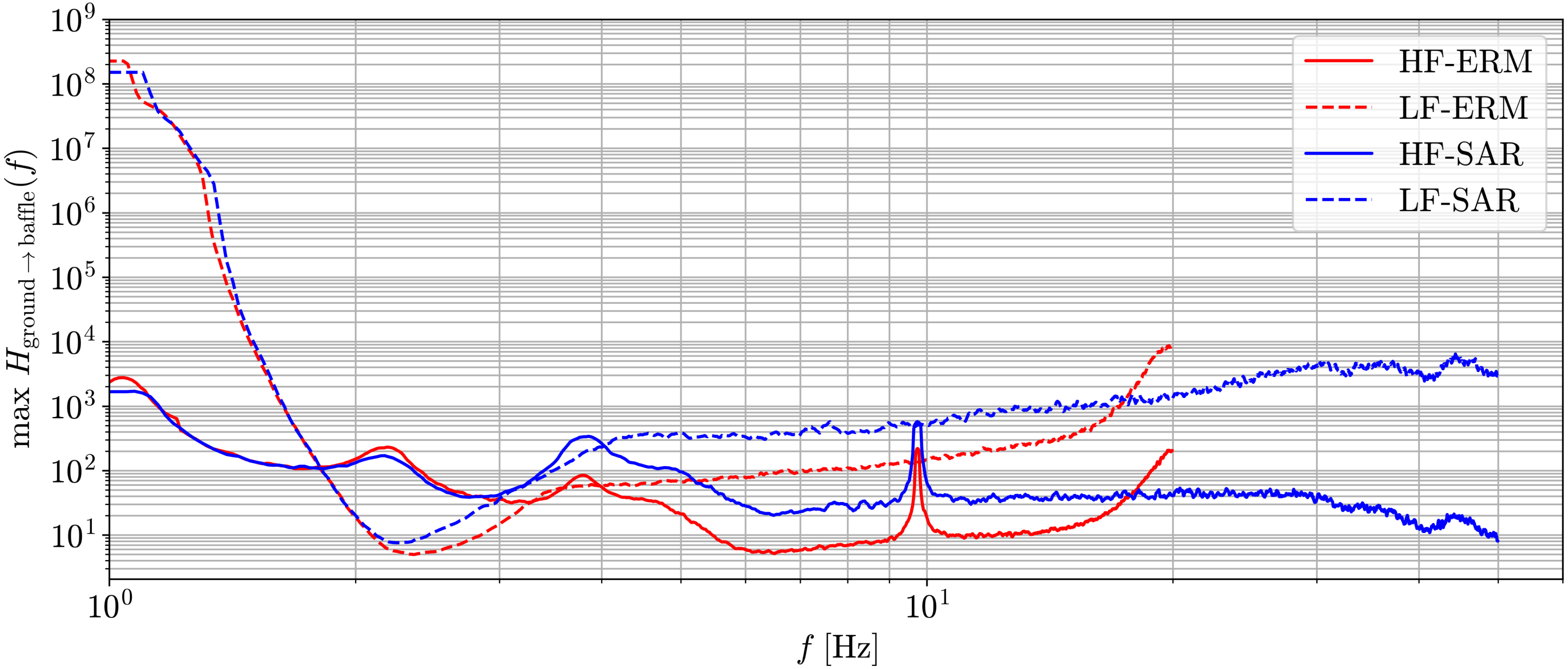


SCATTERED LIGHT NOISE SUBDOMINANT



SCATTERED LIGHT NOISE SUBDOMINANT

Can be obtained as the quotient between the safety margin and the noise estimation.



CONSIDERATIONS:

- Conservative BRDF of baffles assumed
- Using 90%CL seismic noise

CAVEATS:

- Still 10% of seismic noise can be greater.
- No information of the transfer functions from the ground to the baffles. Are some frequencies enhanced? Will this reach the margin?
- Still there are many uncertainties in the modelling. Numerical tools are still far of being able to simulate the entire cavity.
- The mirrormaps used are the projected ones, no information of their final quality until built will be available.
- The conditions assumed are perfect (i.e. no point absorbers, point scatterers, no beam off-set...), the presence of such non-idealities might change the conclusions.

CONCLUSIONS

We have shown an estimation of the effects that the main sources of scattered light can have inside the FP cavities of ET. The most relevant noise expected is that of backscattering from the baffles.

If the design here proposed is followed, the scattered light noise is expected to be sub-dominant at all relevant frequencies. Still, the non-idealized case should be further explored and a cost-benefit analysis carried out.

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MORE REFERENCES

- Optical schemes make use of the ComponentLibrary. ComponentLibrary by Alexander Franzen is licensed under a Creative Commons Attribution-NonCommercial 3.0 Unported License.
- ET new sensitivity curves have been extracted from ET-0007B-23 using *pygwinc*.
- Further details about SIS can be found in LIGO-T2000311 and LIGO-T070039.