The impact on GW waveform SNR of the site dependent noise recorded at the Einstein Telescope candidate sites

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Outline

- What is Einstein Telescope;
- Motivation of this study;
- The candidate sites;
- Understanding noise contributions;
- Modified sensitivity curves;
- Effect on SNR.

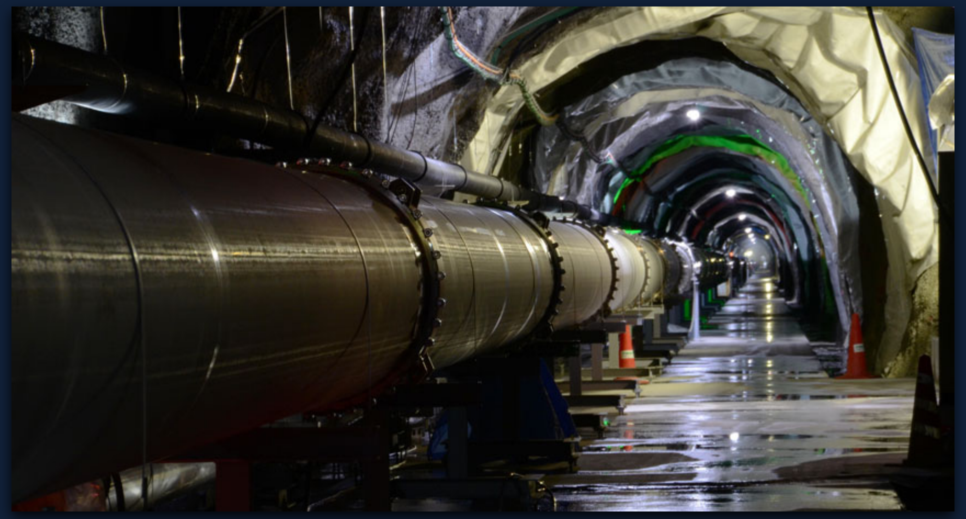
Einstein Telescope

1st gen GW interferometers 2000-2010: Initial LIGO, Initial Virgo GEO600
On surface, mirrors at room temperatures, km scale long arms

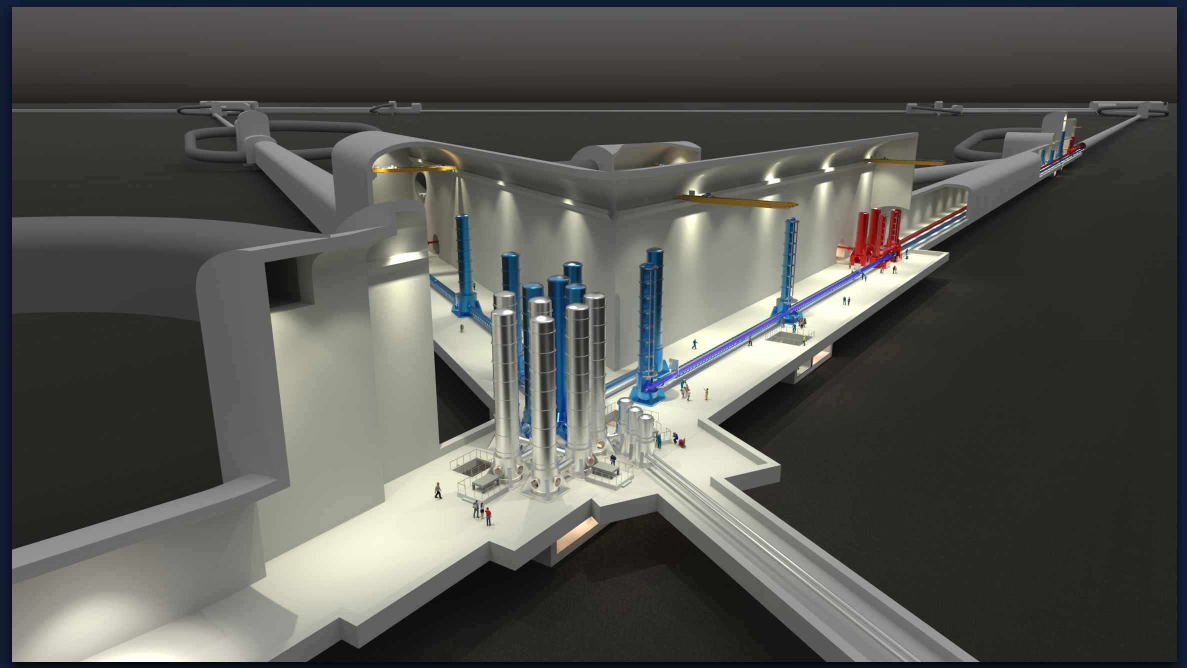
1970s-1990s GW detection prehistory: Resonant bar detectors

2nd gen GW interferometers 2015-2020s: Advanced LIGO and Advanced Virgo
Leap forward in sensitivity but still same configuration as 1st gen

2.5 gen GW interferometers 2020s: KAGRA
Underground and mirrors at cryogenic temperatures, but still with km long arms

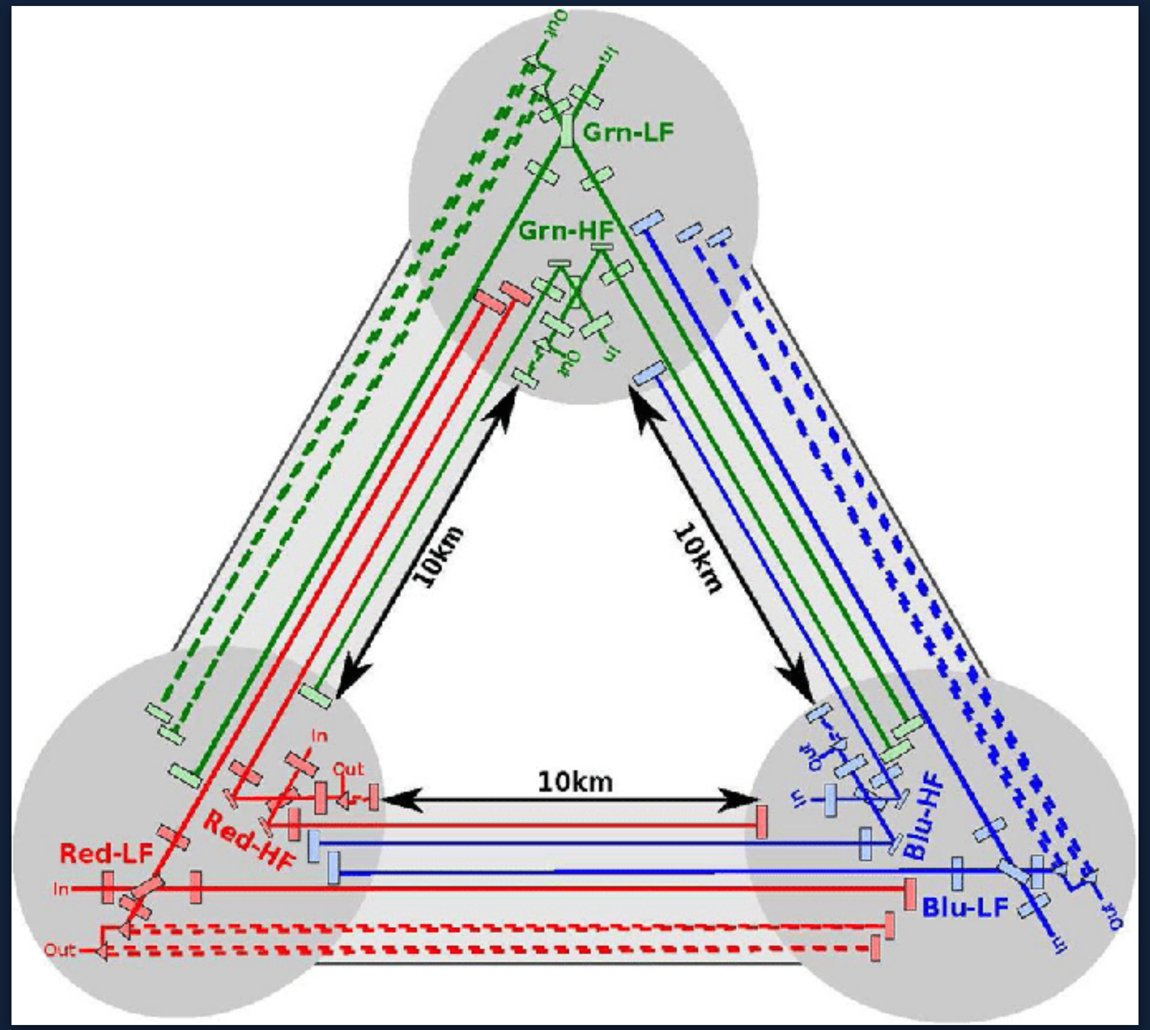


3rd gen GW interferometers 2030s-: ET and Cosmic Explorer
Underground, mirrors at cryogenic temperatures and arm length of the order of 10 km



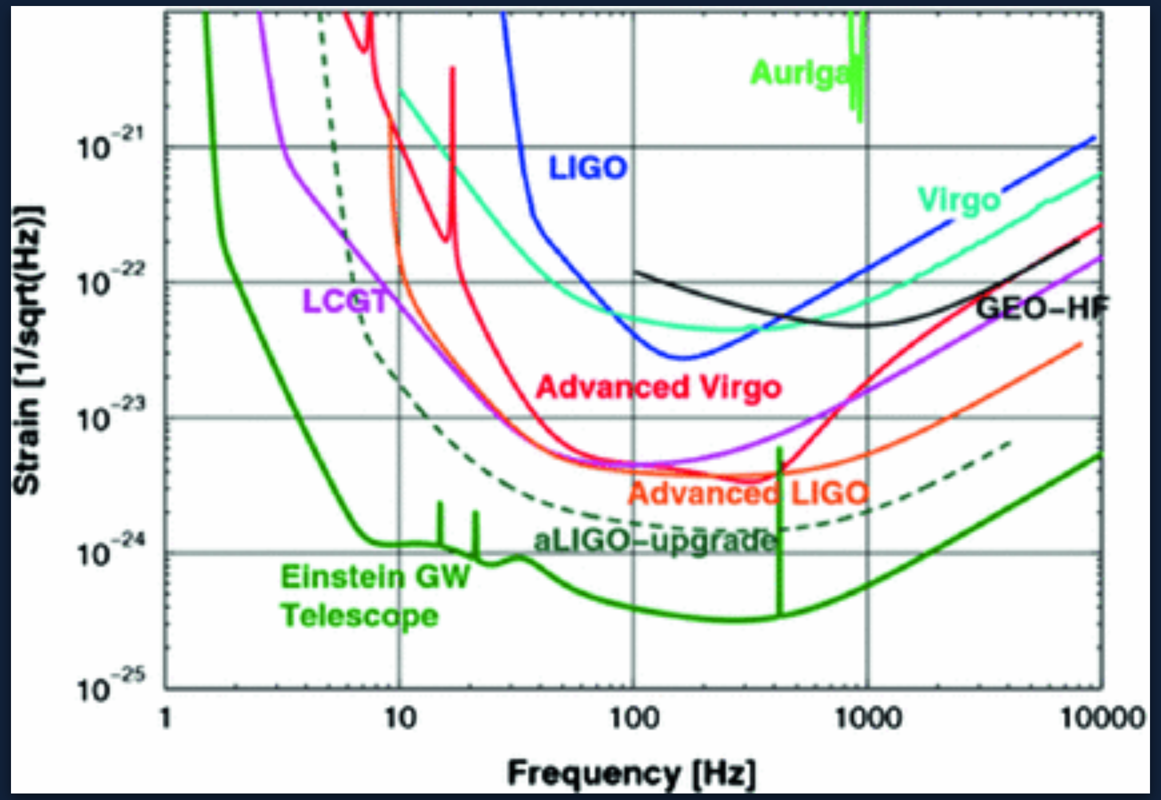
Einstein Telescope

The configuration of ET is aimed at providing a significant improvement in the sensitivity of a GW interferometer by reducing the influence of noise sources on the detector.



The proposed ET Triangle configuration

ET will extend the accessible frequency band down to 2 Hz. Current detectors are limited at 20 Hz.



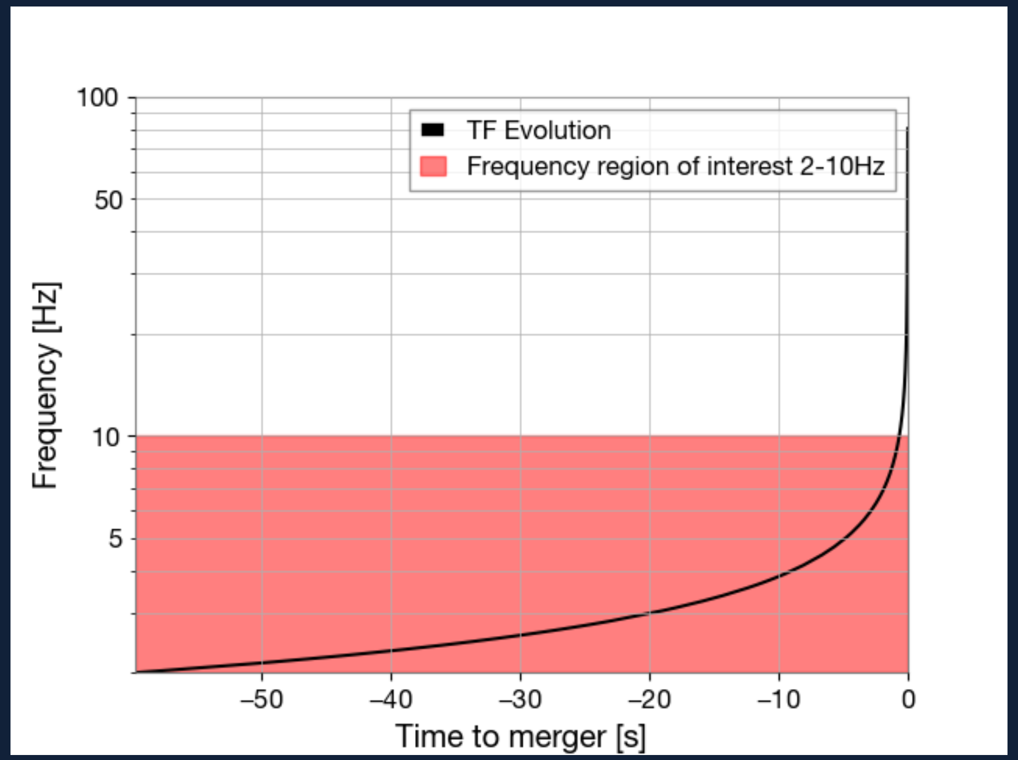
Currently, the official proposed configuration of ET consists of 3 underground detectors nested in a triangular shape with 10 km-long arms.

Being all at the same location, ambient noise plays a crucial role in the correct operation of the detector.

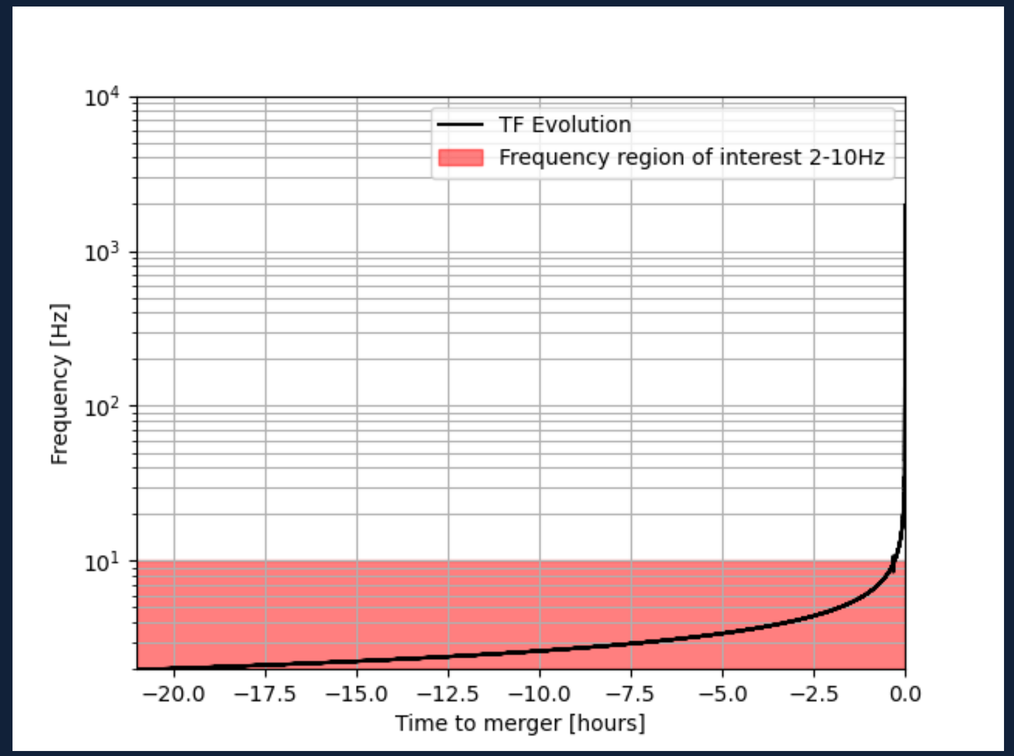
A non co-located 2 detectors L-shaped configuration with 15 km long arms is also being considered (Branchesi et al. 2023, Maggiore et al 2024).

Motivation of the study

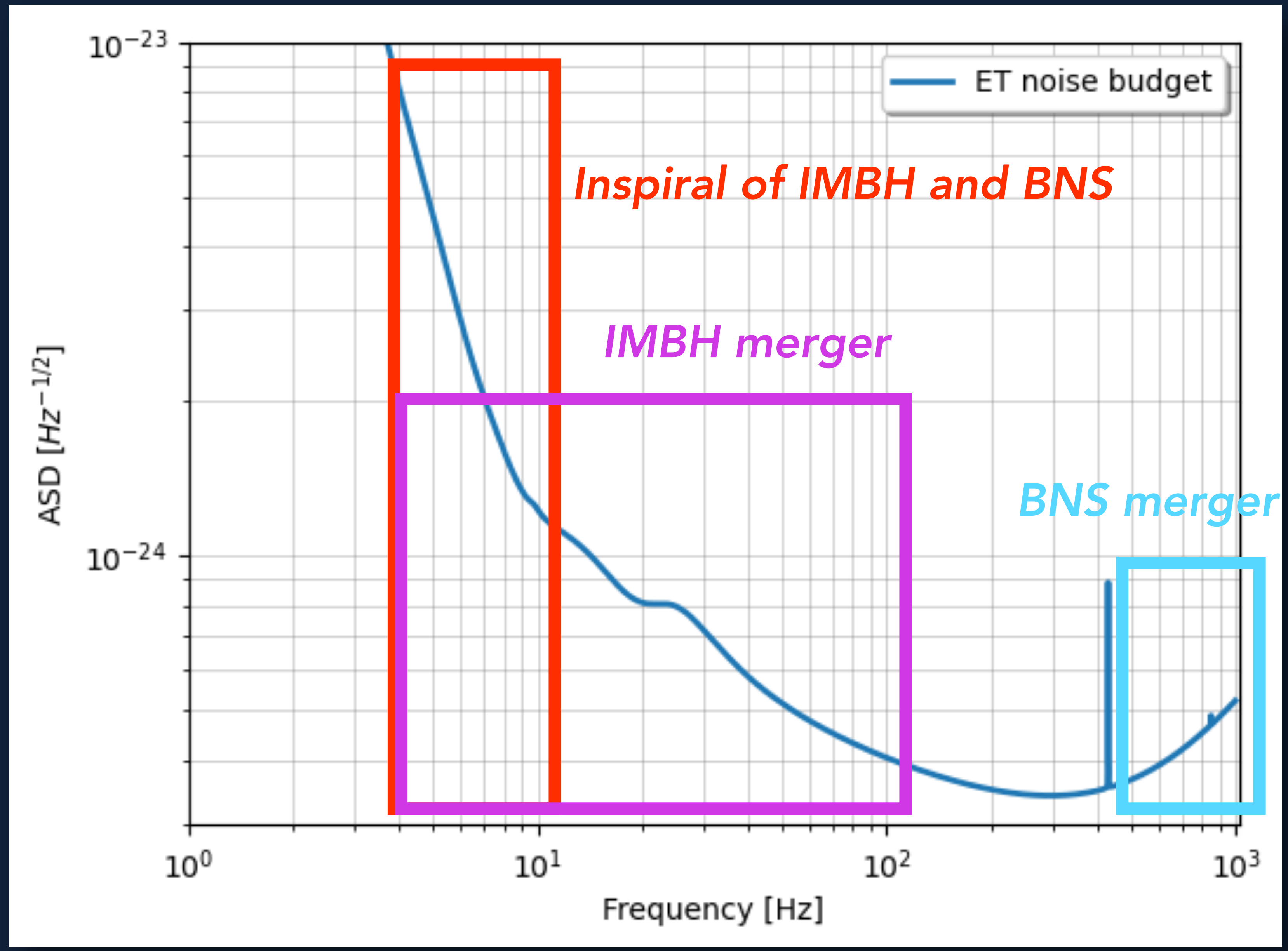
- ET will be up to 8 orders of magnitude more sensitive at frequencies below 20 Hz, with respect to current detectors;
- among the other things, this increase in sensitivity will be beneficial for the observations of intermediate mass black holes (IMBH) and to trigger multimessenger observation campaigns for binary neutron star (BNS) mergers with great advance;



TF evolution of an IMBH



TF evolution of a BNS



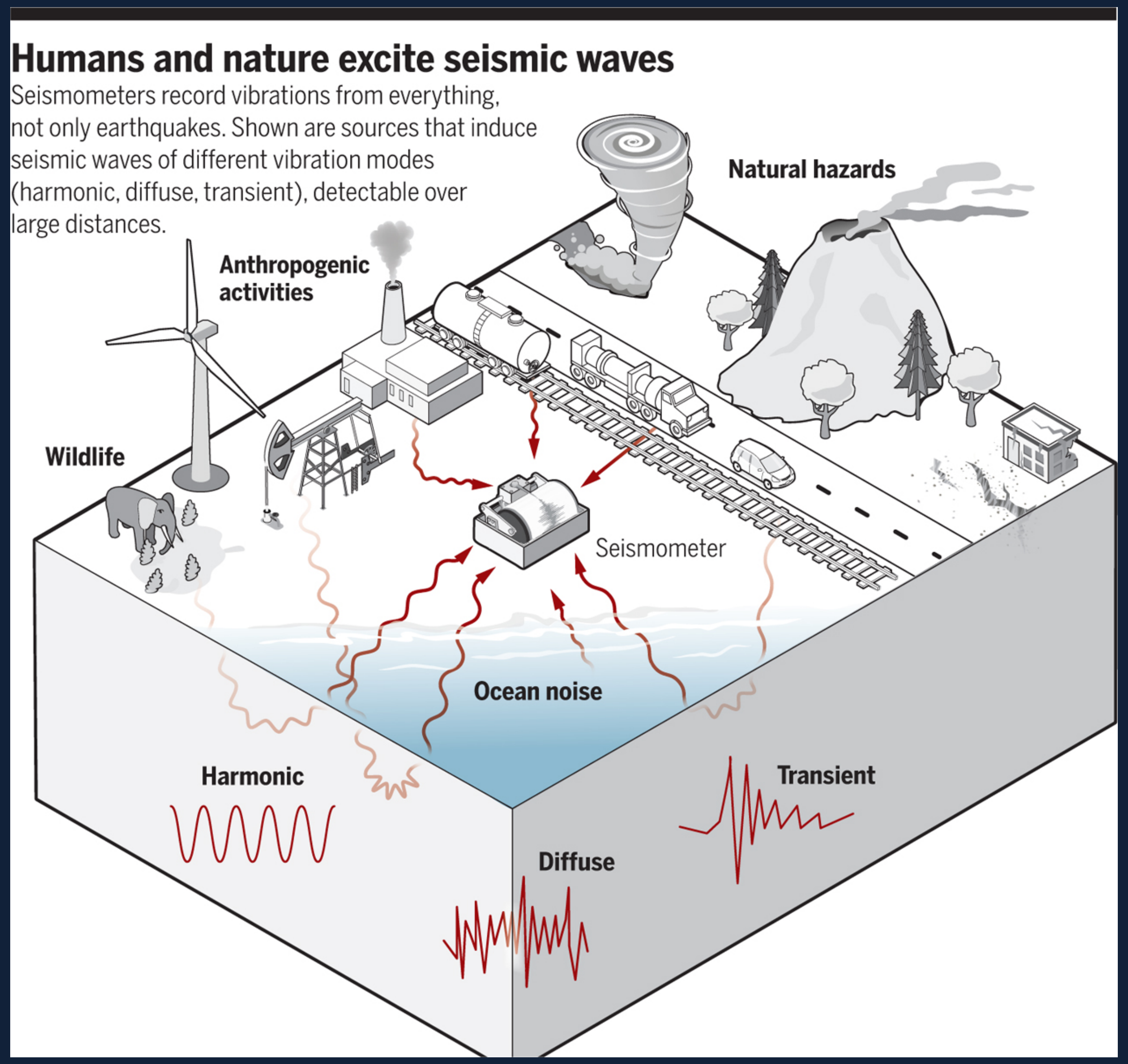
- BNS early detection is crucial for early warnings;
- These systems spend up to 20 hours at low frequency.

Motivation of the study

ET-LF will play a crucial role for the full exploitment of ET multimessenger capability.

The improvement in sensitivity will make ET more susceptible to ambient noise at LF.

Ambient noise dominates at LF.



See also Di Giovanni et al 2021, 2023

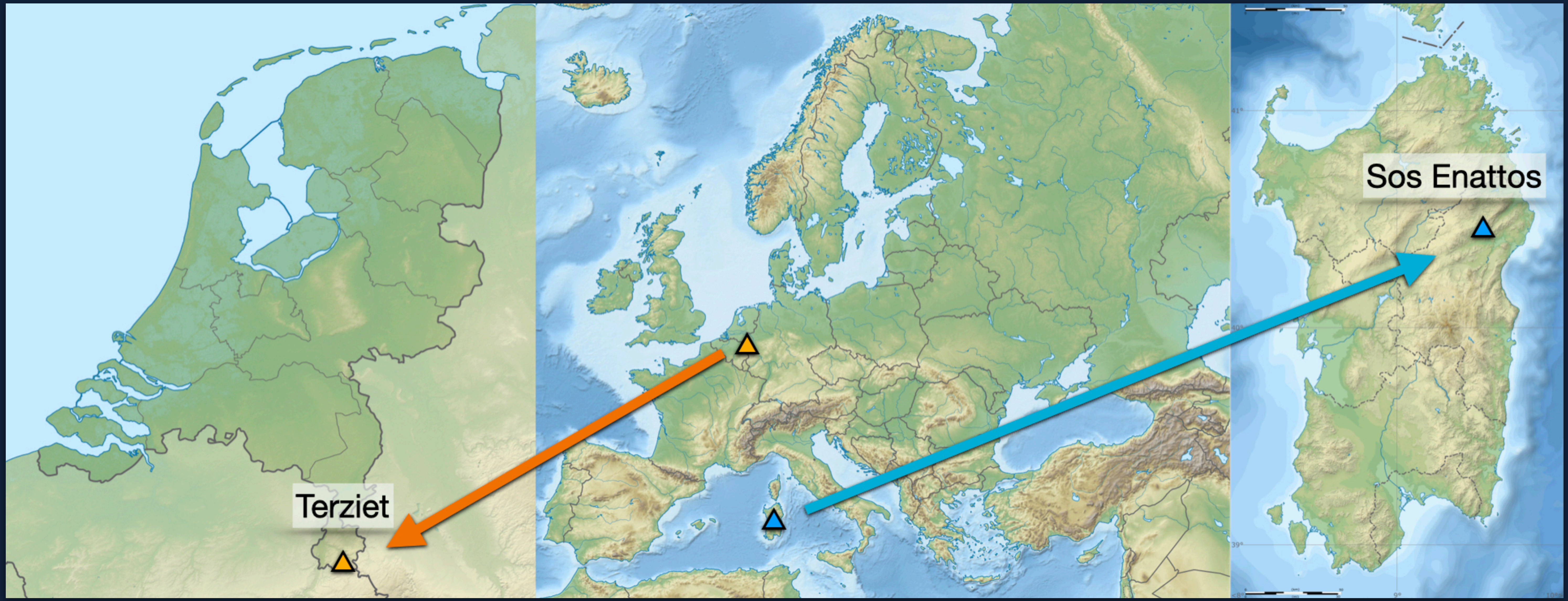
Will real ambient noise at the ET candidate sites significantly impact the ET design sensitivity at LF?

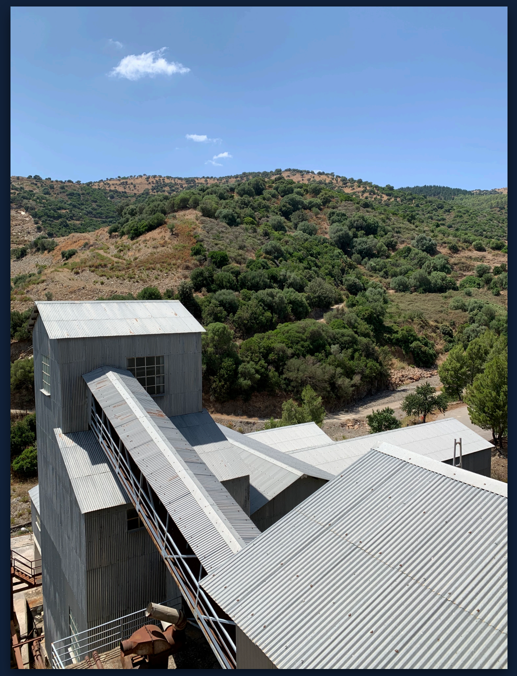
Study the impact of site noise on the ET sensitivity curve and its impact on the detectability of the aforementioned GW sources for early warning purposes.

The ET site preparation board (SPB) ensures that all aspects that can positively/negatively affect the correct operation of the ET apparatus are thoroughly investigated at the ET candidate sites.

CAVEAT EMPTOR: this is not a science case nor we want to modify the ET Science Case (Maggiore et al. [2020]) after our results.

The candidate sites

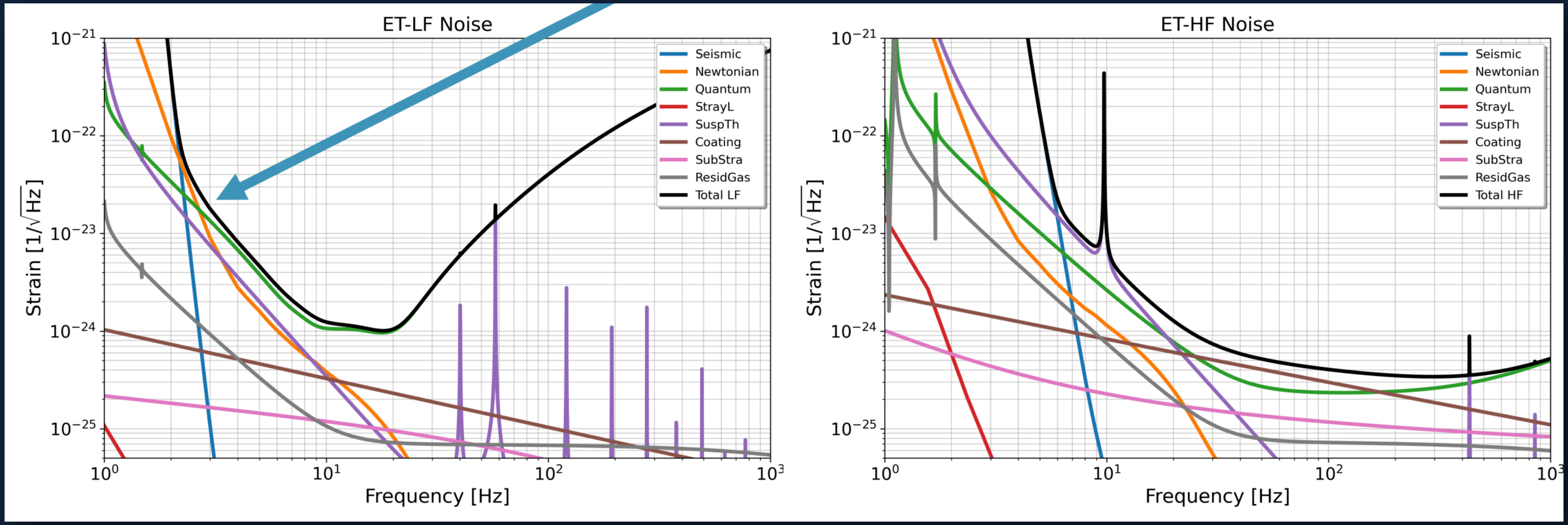




Currently, there are two official candidate sites to host ET:

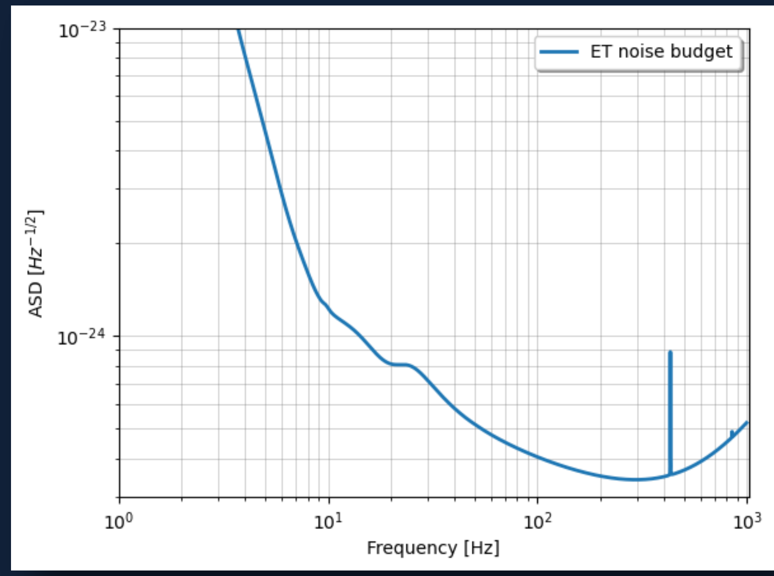
- The Euregio Meuse-Rhine (EMR) between the Netherlands and Belgium;
- The area around the Sos Enattos Former mine in Sardinia (Italy).

Understanding noise contributions



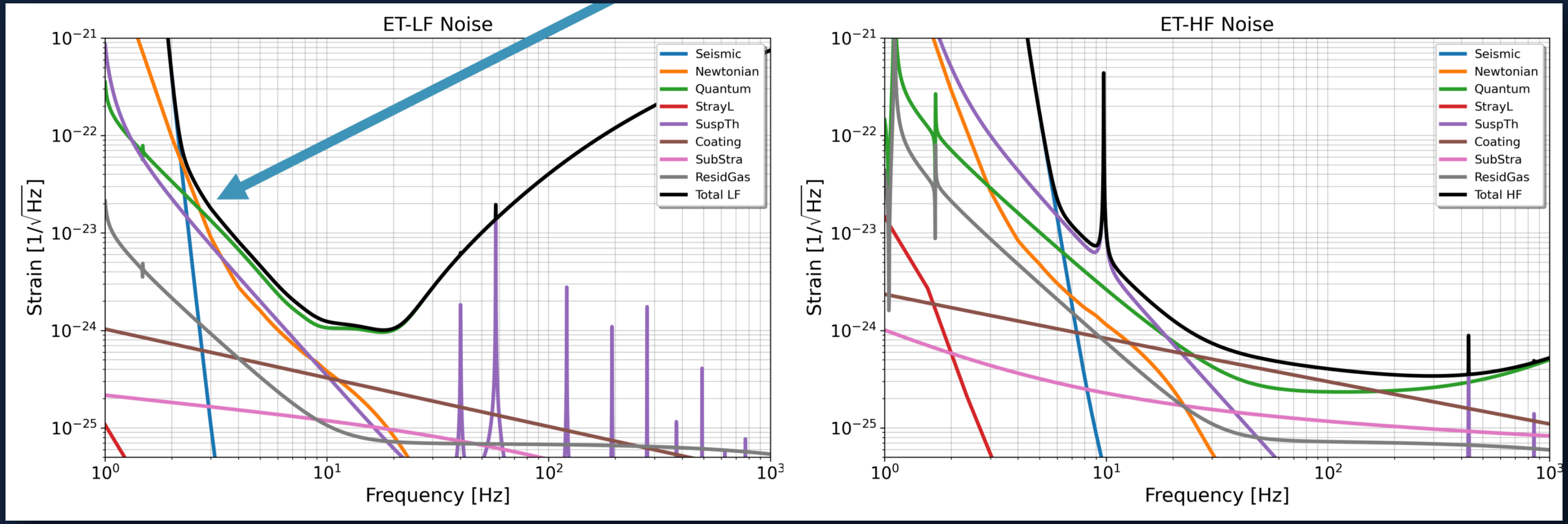
$$S_{LF/HF} = S_s + S_{NN} + S_Q + S_{SL} + S_{STH} + S_C + S_{SUBS} + S_{RG}$$

$$S_{ET} = \frac{1}{\frac{1}{S_{LF}} + \frac{1}{S_{HF}}}$$



https://gitlab.et-gw.eu/et/isb/interferometer/ET-NoiseBudget/

Understanding noise contributions

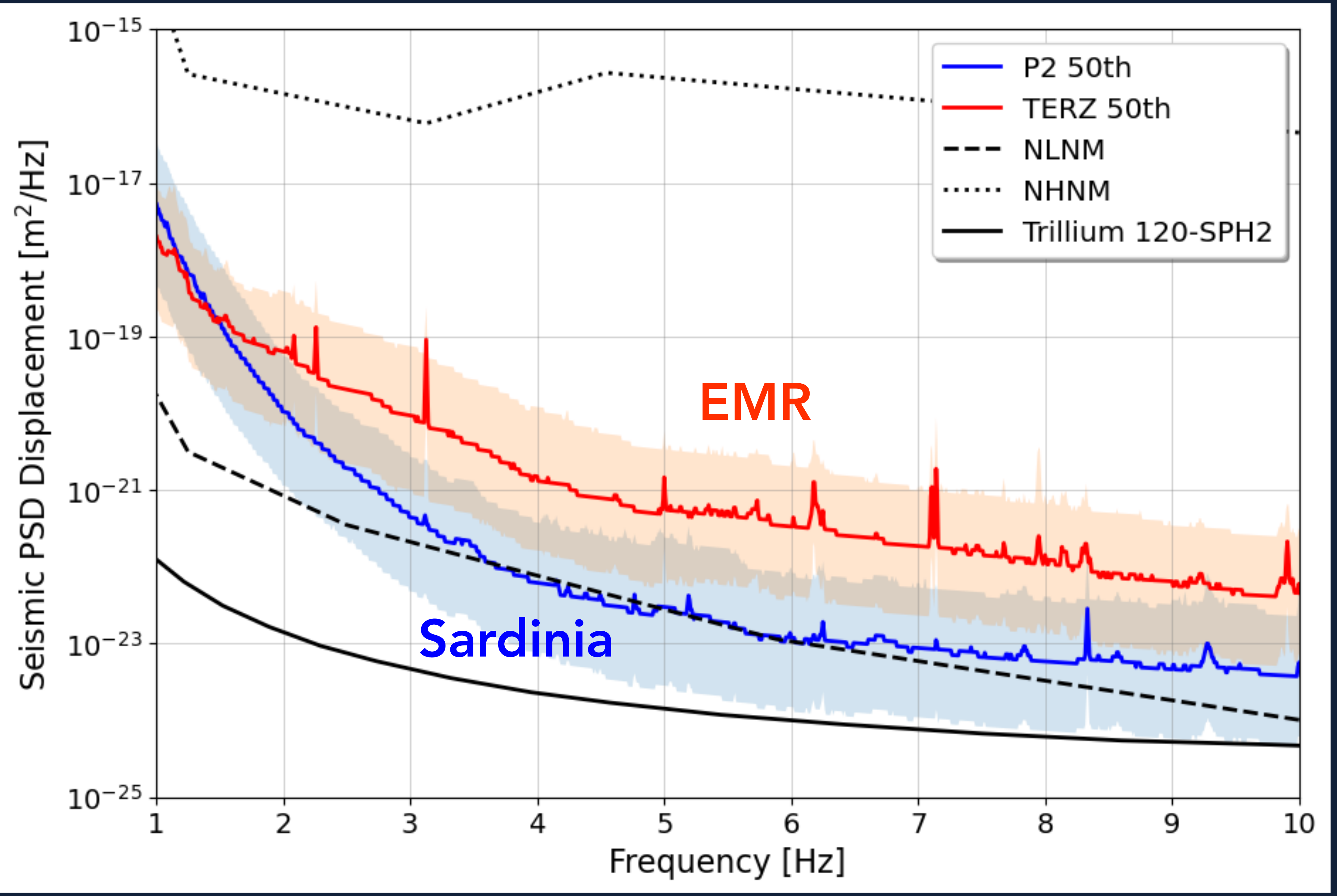


$$S_{LF/HF} = S_s + S_{NN} + S_Q + S_{SL} + S_{STH} + S_C + S_{SUBS} + S_{RG}$$

- Newtonian Noise (NN) is caused by tiny fluctuations of the Earth's gravitational field;
- these fluctuations are generated by variations of atmospheric and ground density in the vicinity of the mirrors;
- soil density variations are caused by ground motion (seismic waves);
- we will focus on NN from ground motion only due to the current lack of other environmental sensor for atmospheric fluctuations.

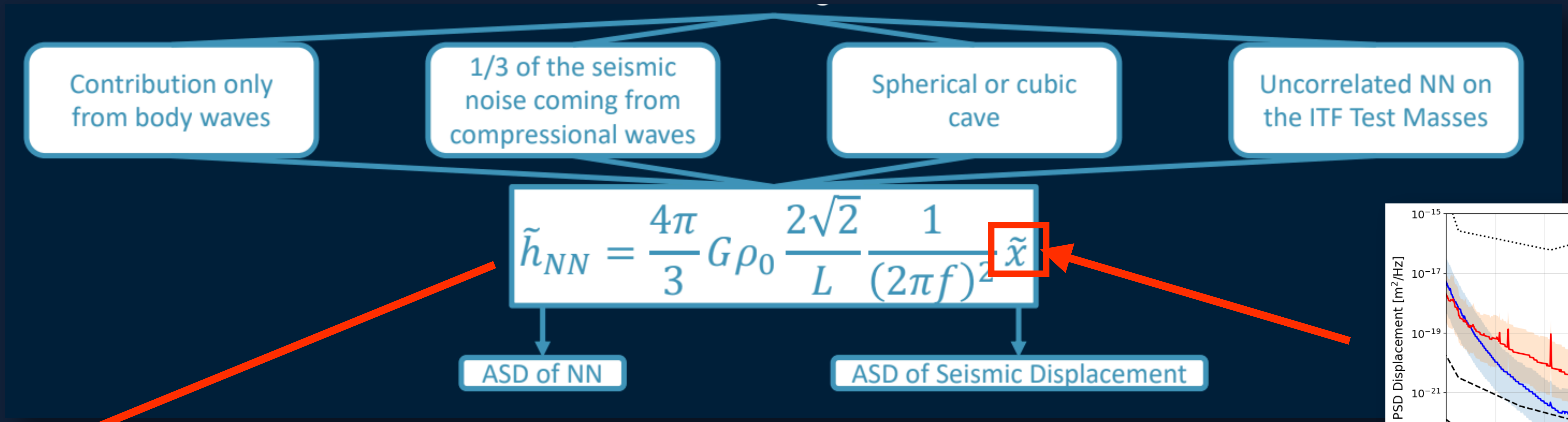
Seismic noise levels

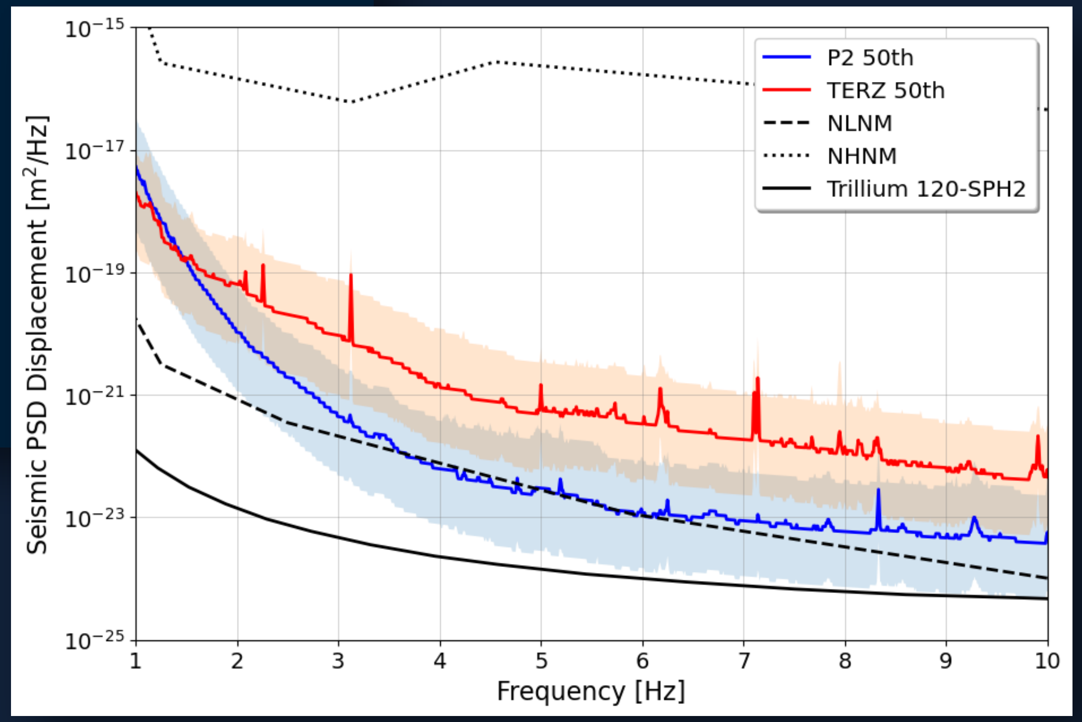
- Site characterization studies have already assessed noise levels and variations (e.g. Di Giovanni et al 2021, Allocca et al 2021, Di Giovanni et al 2023);
- We have to translate the information about seismic noise levels into it's impact on the ET design sensitivity curve at low frequency;
- the EMR candidate site is noisier than the Italian site, are they both compliant with the ET design?
- seismic measurements taken into borehole at a depth of about 250 m;



Seismic noise spectra

Newtonian Noise from seismic displacement



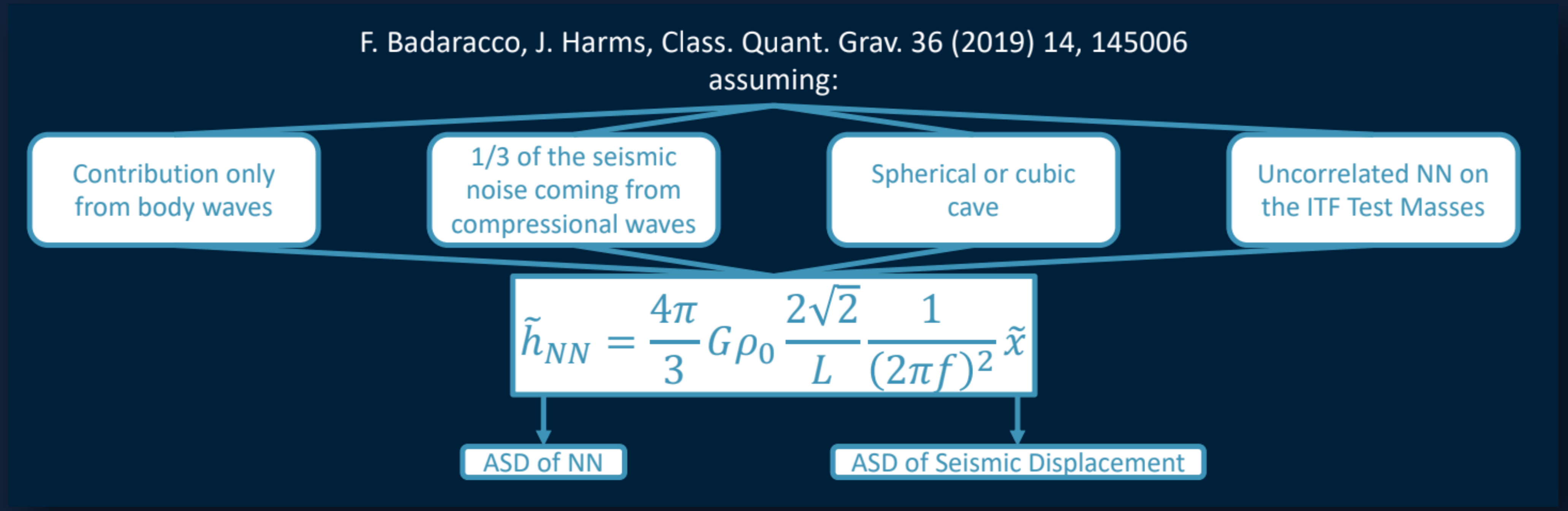


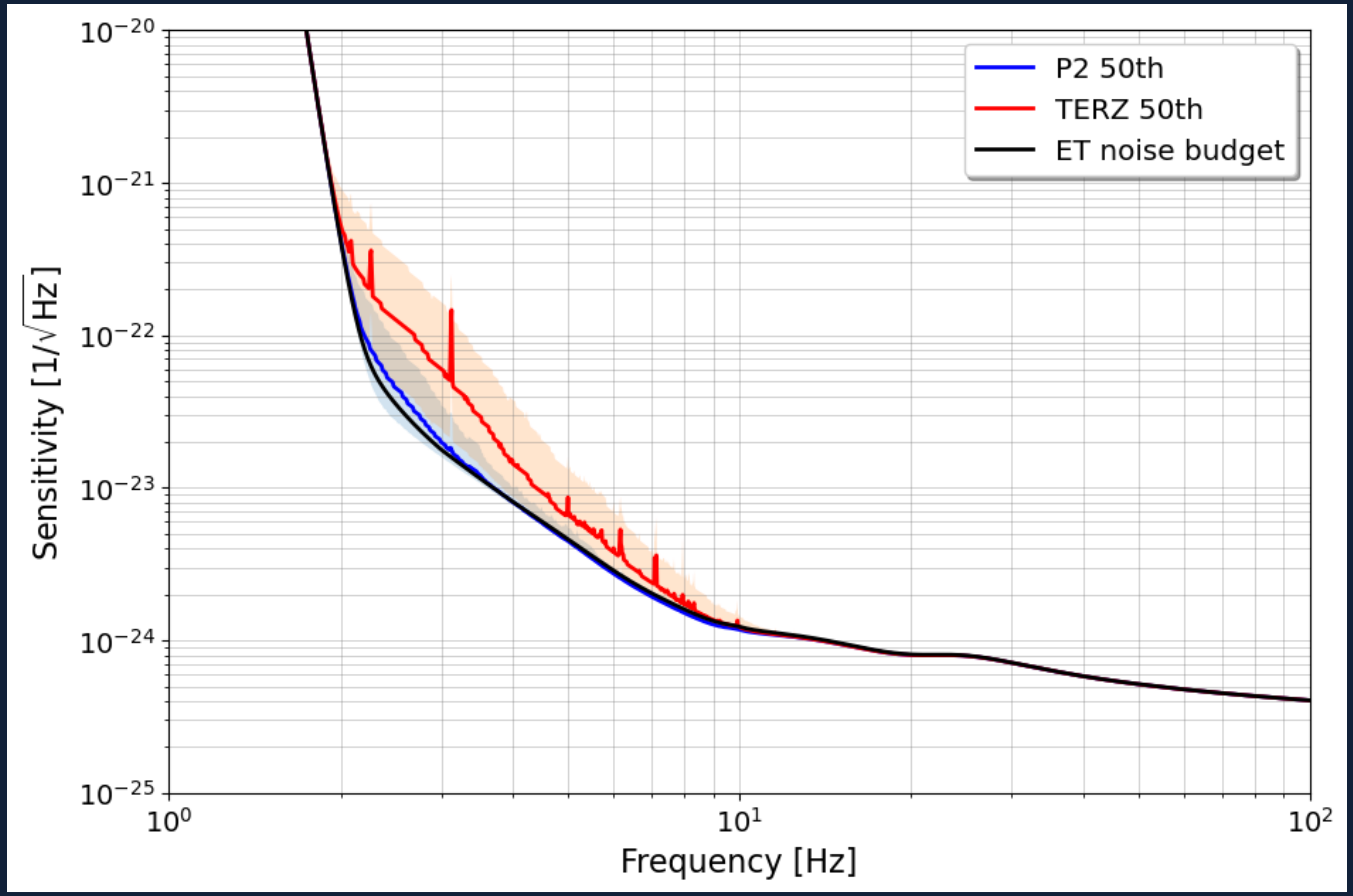
$$S_{LF/HF} = S_s + S_{NN} + S_Q + S_{SL} + S_{STH} + S_C + S_{SUBS} + S_{RG}$$

Badaracco & Harms (2019), Harms et al. (2022)

Effect on ET sensitivity

The higher noise levels at the EMR site have a much stronger effect on the ET sensitivity than the Sardinia site which is very close to design.





Noise to target ratio

- We define the noise to target ratio to quantify whether the modified ET sensitivity curve is above or below the design case

- NTR > 1 NN noise is limiting the sensitivity, NTR < 1 NN noise is not limiting the sensitivity.

$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f}\int_{f_1}^{f_2} \frac{S_{real}}{S_{ET}} df}$$

Modified curve

Design noise budget

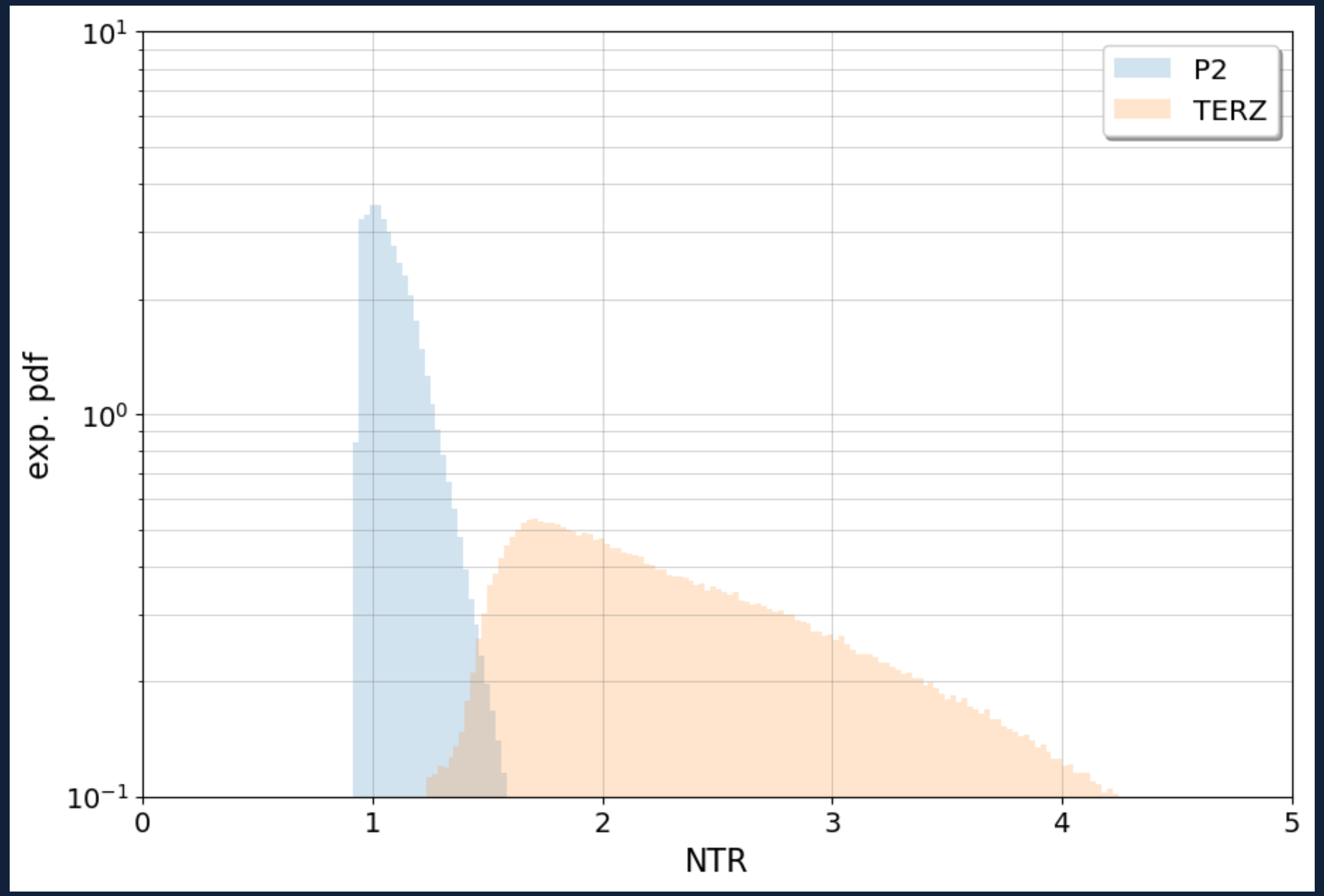
Allocca et al (2021)

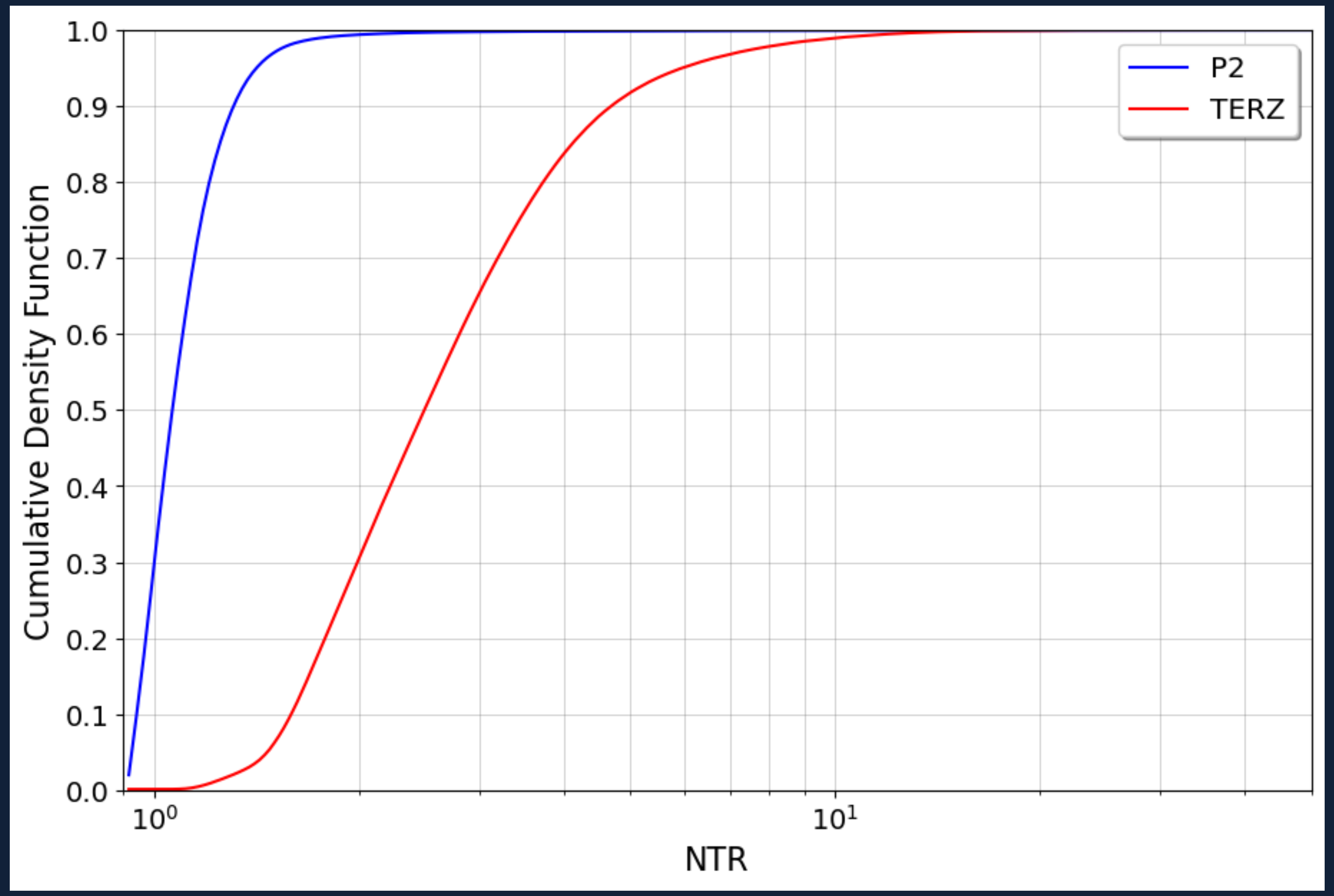
Noise to target ratio

The Sardinia candidate site performs better for what concerns the NTR as well.

$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f}\int_{f_1}^{f_2} \frac{S_{\mathrm{real}}}{S_{\mathrm{ET}}} df}$$

Most of the time, the Sardinia site is on target, whereas the EMR performs poorly at any time.





Procedure

Calculate site seismic spectra on a 1 year time span on 120 s segments (50th, 10th and 90th percentile)

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Infer the modified ET sensitivity curves and NTR

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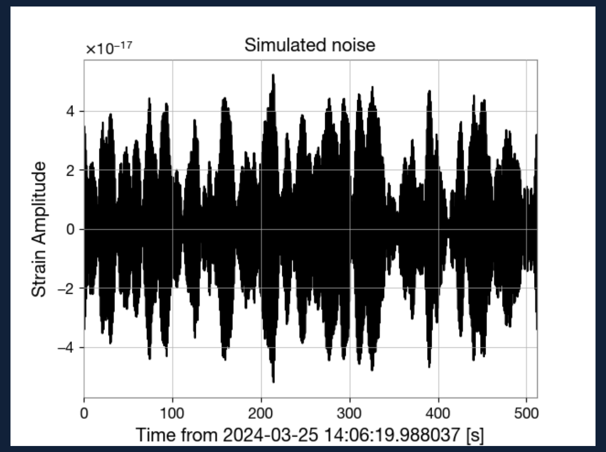

Simulate ET noise with the modified sensitivity curves

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Calculate the signal SNR between 2 Hz and 10 Hz → Compare the SNRs with the design case

Get astrophysical events of interest from catalogs

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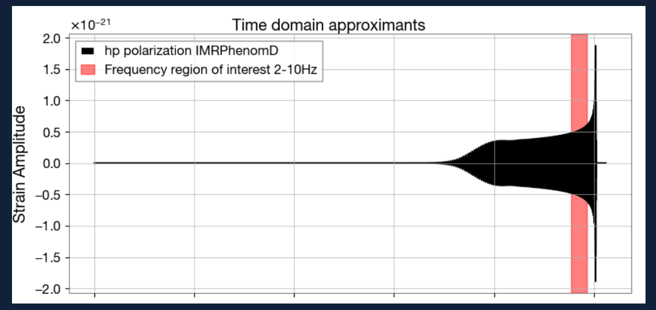
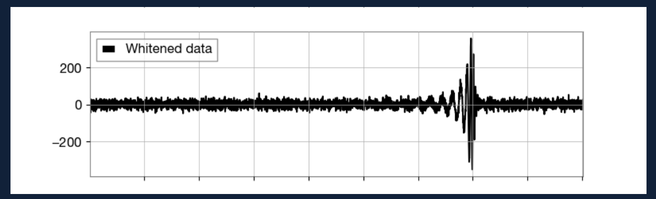


Generate the waveforms

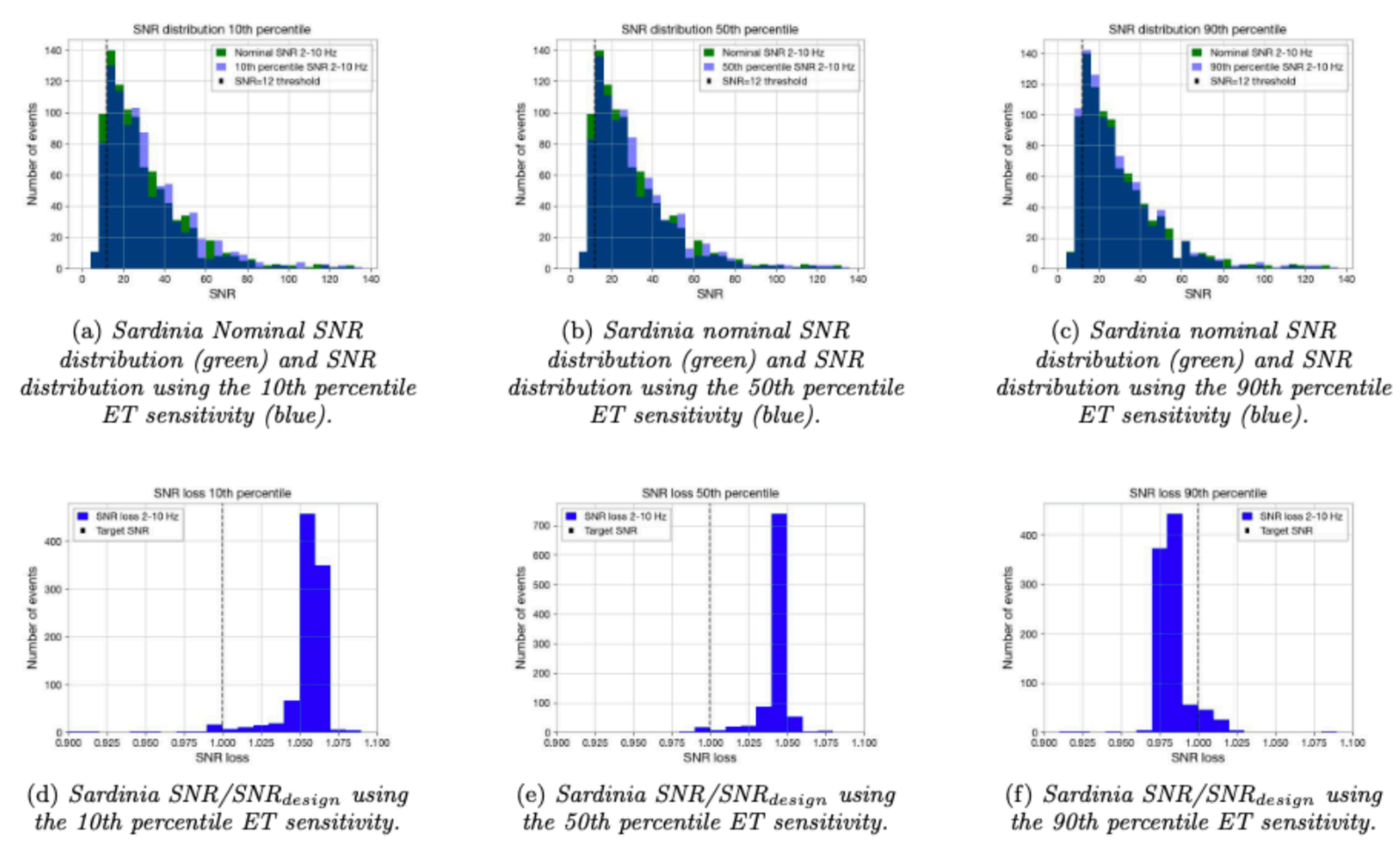
INJECT SIGNALS INTO NOISE



Compare the SNRs with the design case

Effect on SNR - Sardinia

IMBH



(a) *Sardinia Nominal SNR distribution (green) and SNR distribution using the 10th percentile ET sensitivity (blue).*

(b) *Sardinia nominal SNR distribution (green) and SNR distribution using the 50th percentile ET sensitivity (blue).*

(c) *Sardinia nominal SNR distribution (green) and SNR distribution using the 90th percentile ET sensitivity (blue).*

(d) *Sardinia SNR/SNR_{design} using the 10th percentile ET sensitivity.*

(e) *Sardinia SNR/SNR_{design} using the 50th percentile ET sensitivity.*

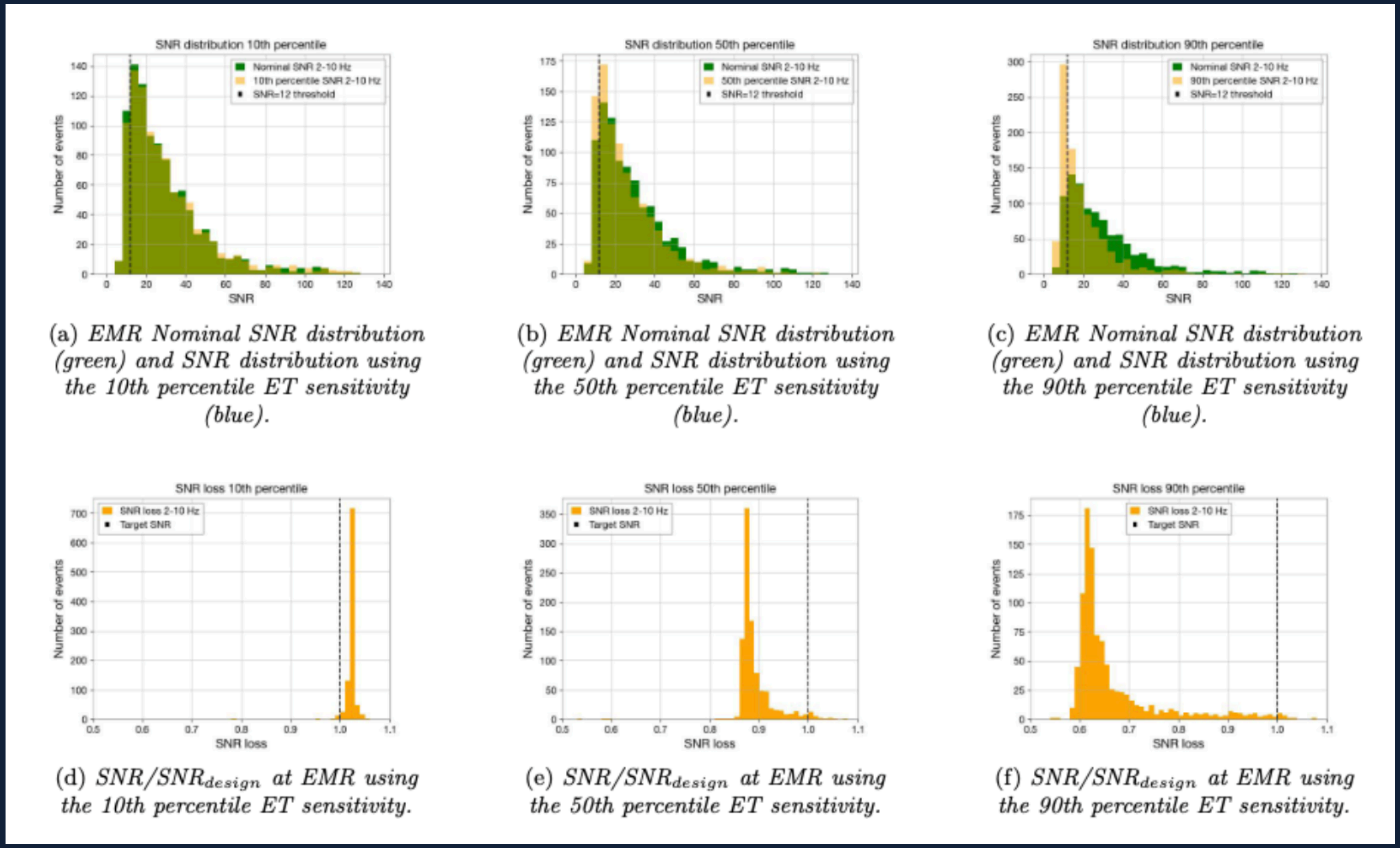
(f) *Sardinia SNR/SNR_{design} using the 90th percentile ET sensitivity.*

Di Giovanni et al 2024
in preparation

Sardinia performs very well, the impact of site noise is marginal.

Effect on SNR - EMR

IMBH



(a) *EMR Nominal SNR distribution (green) and SNR distribution using the 10th percentile ET sensitivity (blue).*

(b) *EMR Nominal SNR distribution (green) and SNR distribution using the 50th percentile ET sensitivity (blue).*

(c) *EMR Nominal SNR distribution (green) and SNR distribution using the 90th percentile ET sensitivity (blue).*

(d) SNR/SNR_{design} *at EMR using the 10th percentile ET sensitivity.*

(e) SNR/SNR_{design} *at EMR using the 50th percentile ET sensitivity.*

(f) SNR/SNR_{design} *at EMR using the 90th percentile ET sensitivity.*

Di Giovanni et al 2024
in preparation

The impact of site noise is much more apparent at the EMR site which shows a significant degradation of the SNR

Conclusions

- Depending on the local seismic levels, ambient noise has an impact on the ET-LF sensitivity curve;
- The high noise level at the EMR site translate into a degradation of the ET-LF sensitivity;
- Sardinia is compliant with the ET requirements, showing only a marginal impact on ET-LF sensitivity even at the 90th percentile;
- Higher noise levels at the EMR site may seriously hinder the capability of releasing early warnings;
- This study is needed for the site selection process for ET.