Understanding ambient noise contributions for gravitational wave detectors

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ET TECHNOLOGY SCHOOL - CAGLIARI 2024

Outline

- What is Einstein Telescope
- The candidate sites
  - The Sardinia candidate site
- Noise budget
- Ground motion and seismic noise
- Seismic noise sources

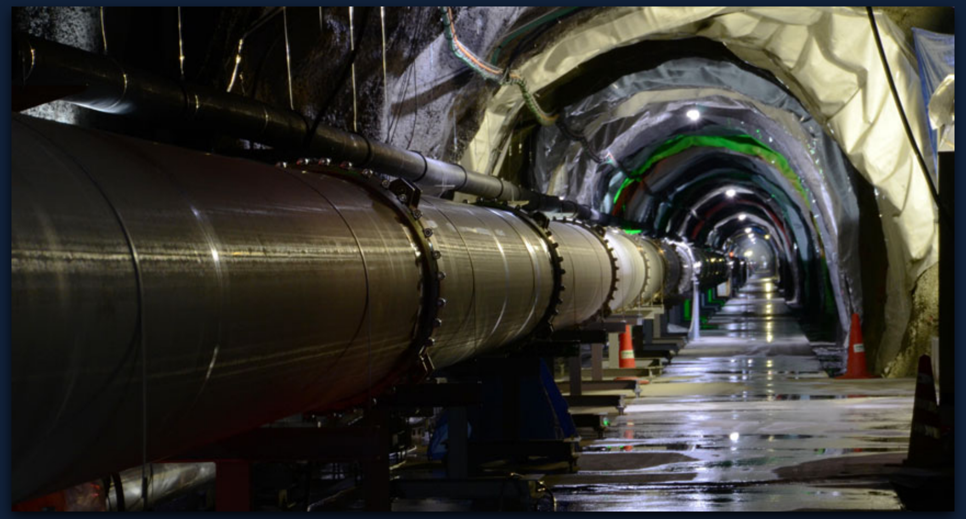
Einstein Telescope

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

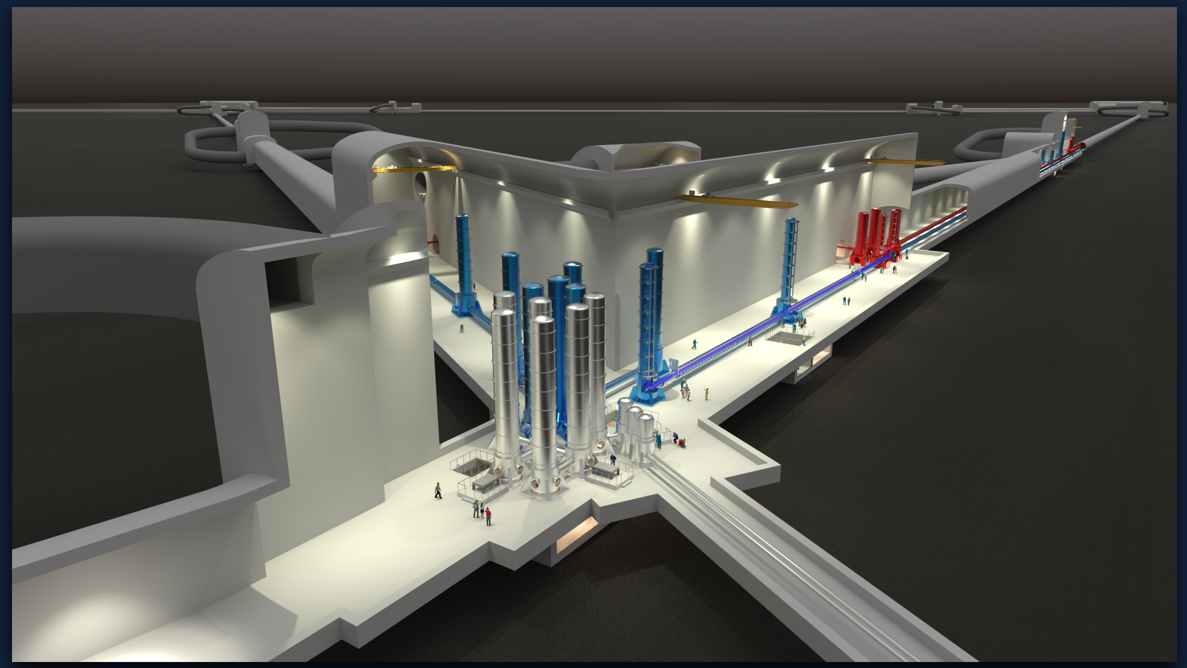
1st gen GW interferometers 2000-2010: Initial LIGO, Initial Virgo GEO600
On surface, mirrors at room temperatures, km scale long arms

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

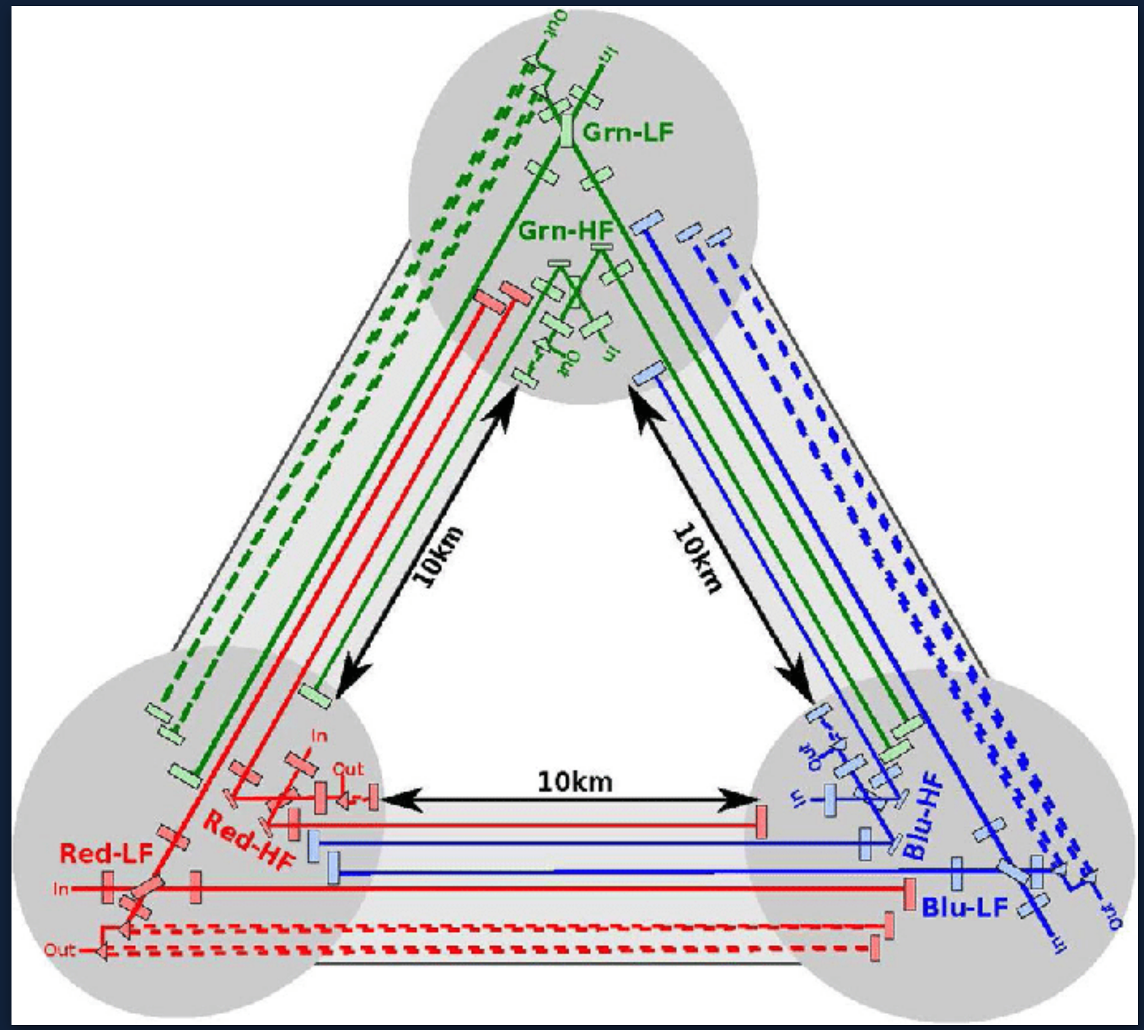


3rd gen GW interferometers 2030s-: ET and Cosmic Explorer
Underground, mirrors at cryogenic temperatures and arm length of the order of 10 km



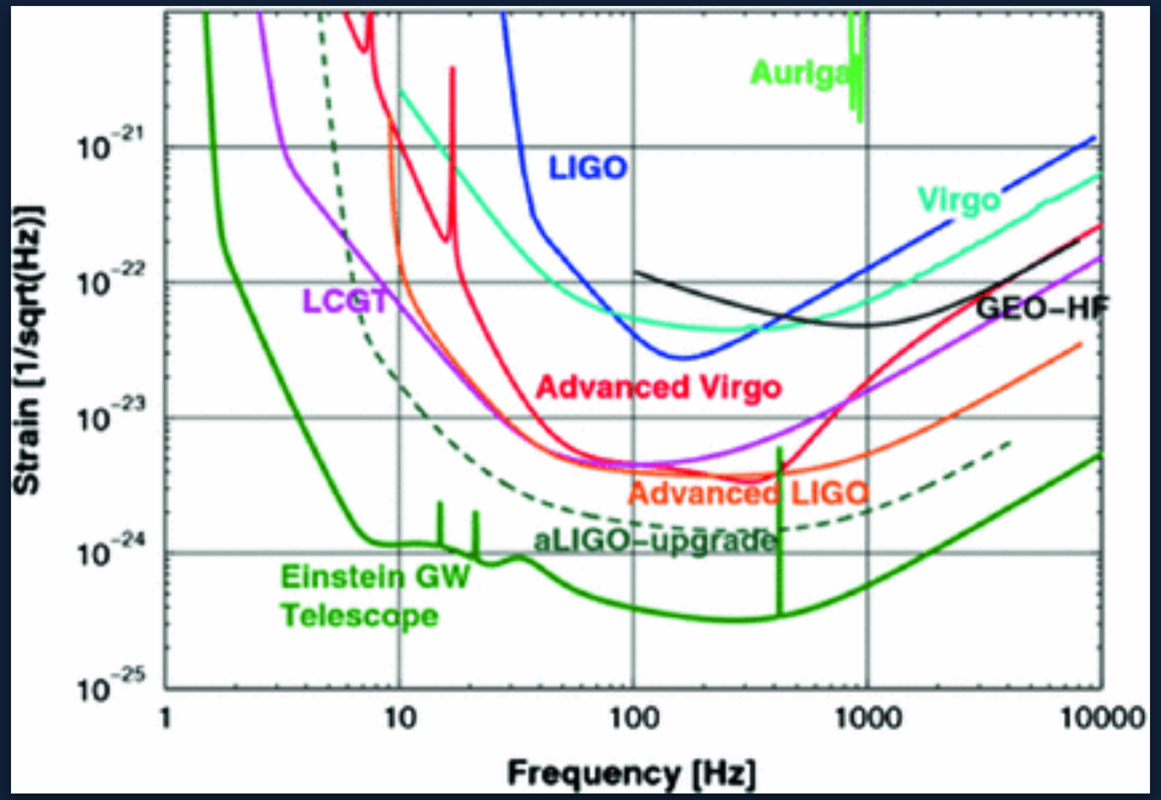
Einstein Telescope

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.



The original 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).

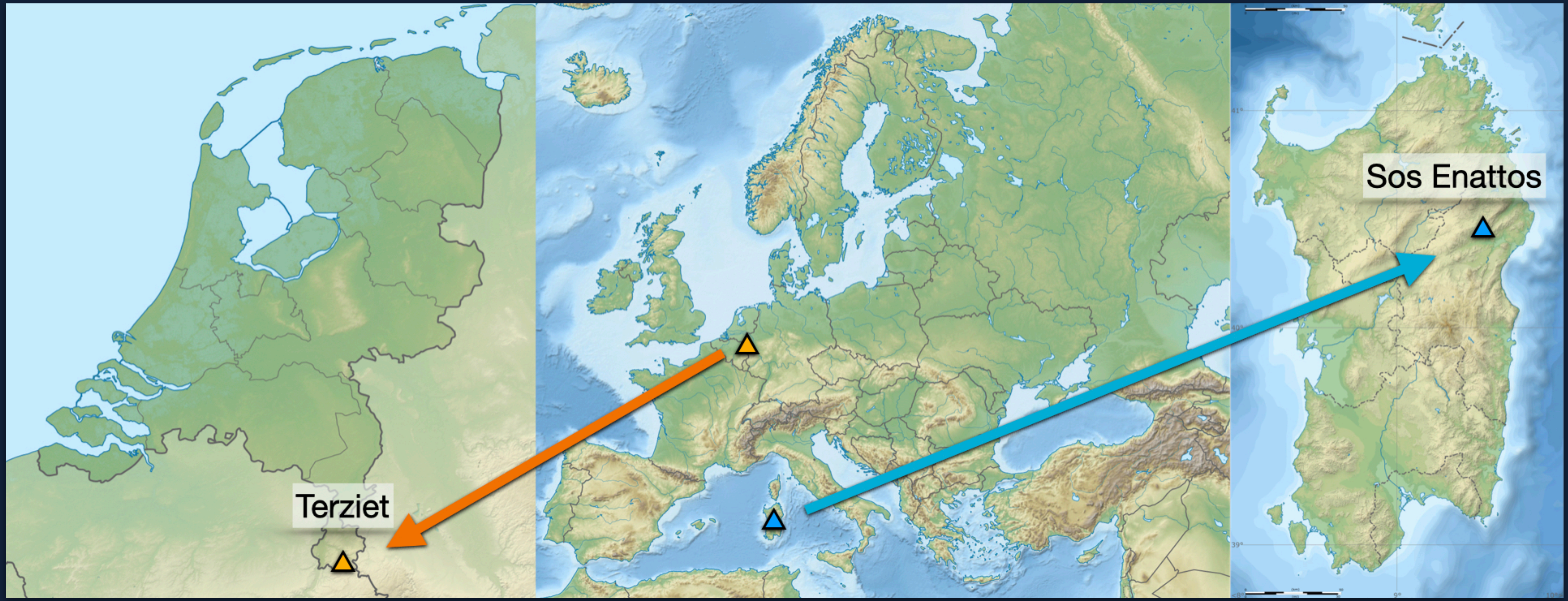
The ET configuration: an open question

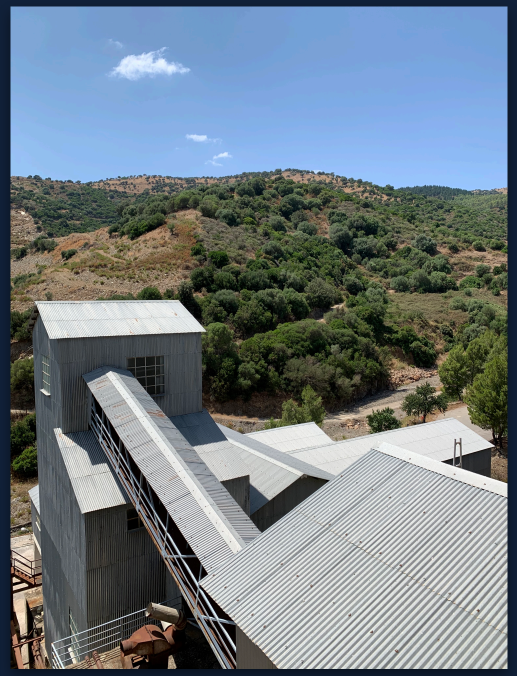
The original triangular configuration puts the collaboration in front of several challenges:

- Engineering (build the systems to operate six detectors all in one place);
- Costs (excavate at least 30 km of tunnels plus caverns for the end stations of appropriate size for all the detectors)
- Detector layout (where to put the instruments to operate six detector all in one place);
- Observationals issues (the same noise sources may affect six detectors all at once).

The 2-L option is today more than just a possibility...

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).

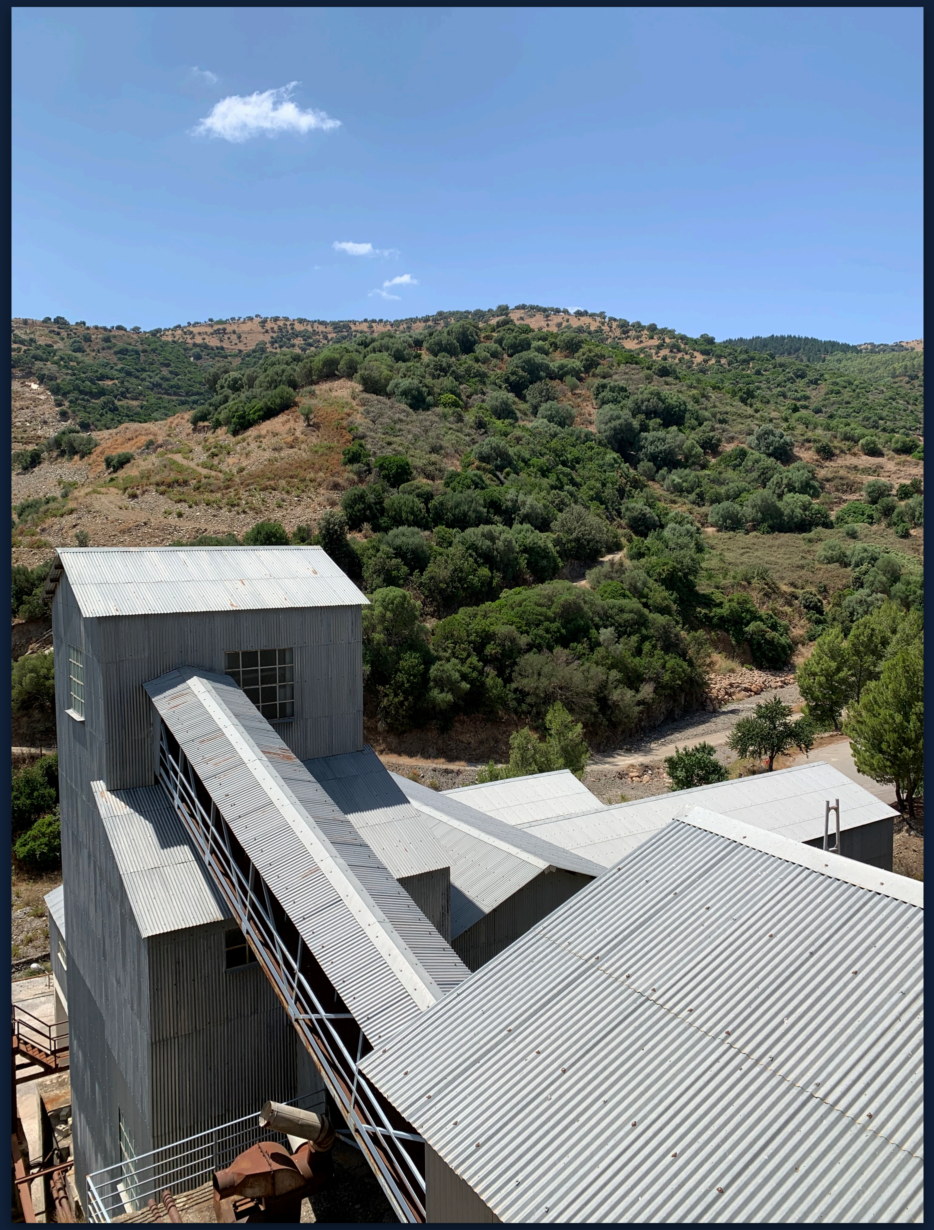
A third site in Lausitz (D) is also about the enter the competition.

What would happen in case the 2L network is chosen is beyond today’s presentation.

The Sardinia candidate site

- in 2010, during the preparation of the first conceptual design of ET, several sites in Europe were studied for a 3G GW observatory. Among them, Sos Enattos in Sardinia appeared to be one of the most promising;
- The mine, although closed, was not abandoned. Therefore it provided the adequate manpower, infrastructure and experience to start underground characterization studies in 2012;
- Today, the mine is considered a regional heritage site and is open to guided tours. It also hosts the SarGrav laboratory and the Archimedes experiment;

Main well



Former mineral processing unit

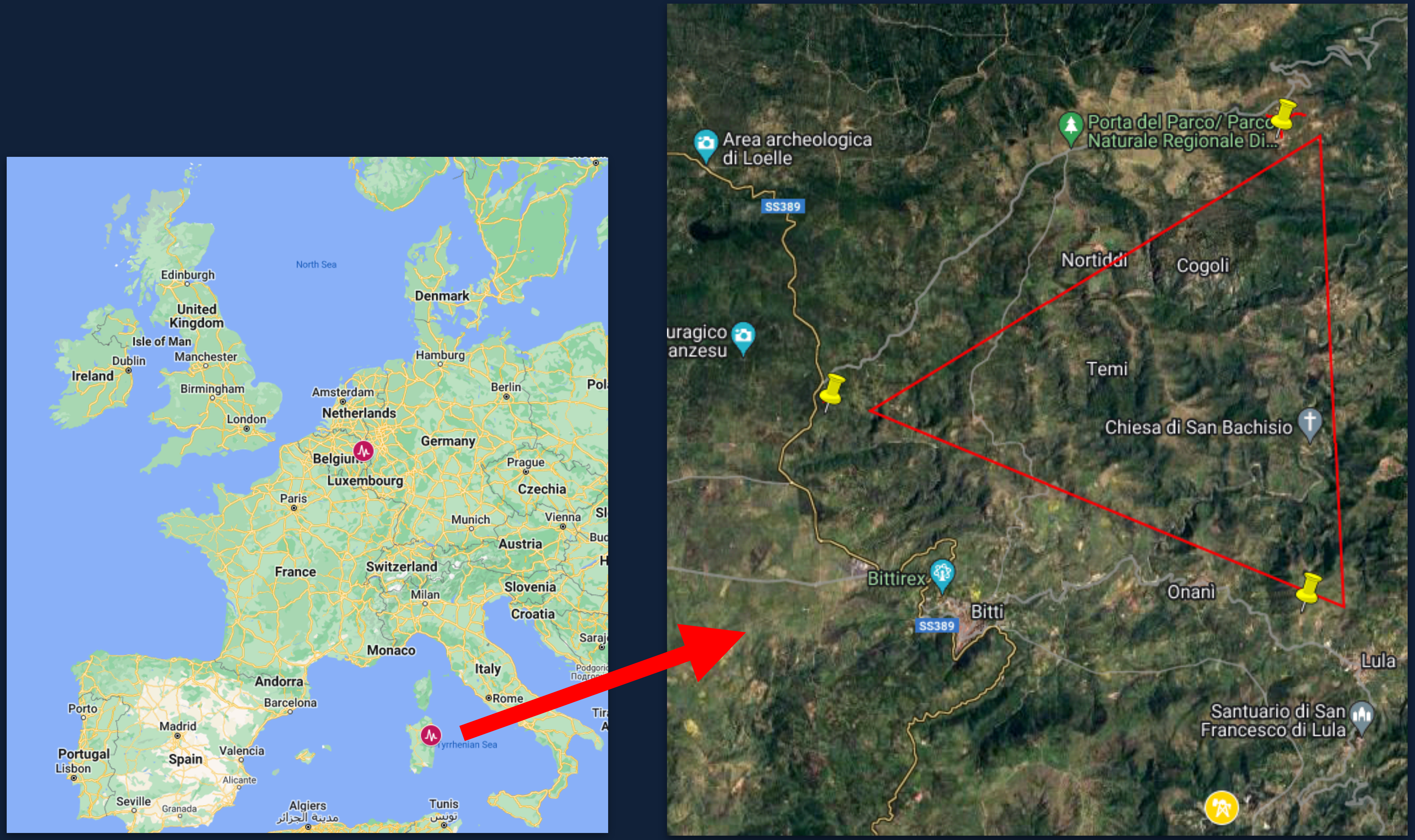
SarGrav laboratory

The Sardinia candidate site

According to the current proposed orientation for the ET Triangle, the sites to host the actual vertices of the interferometer have also been identified.

The Onanì corner

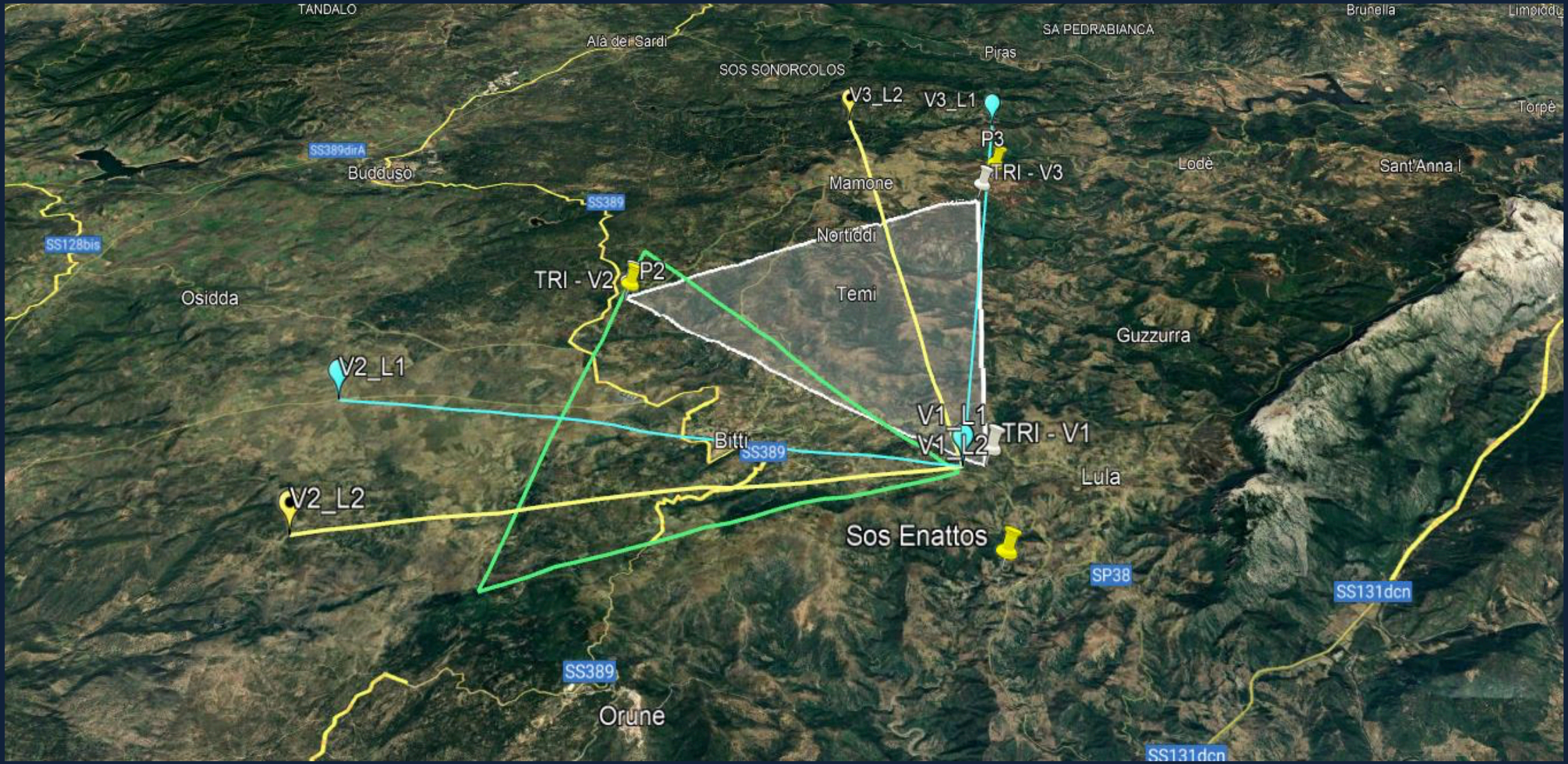
The Bitti corner



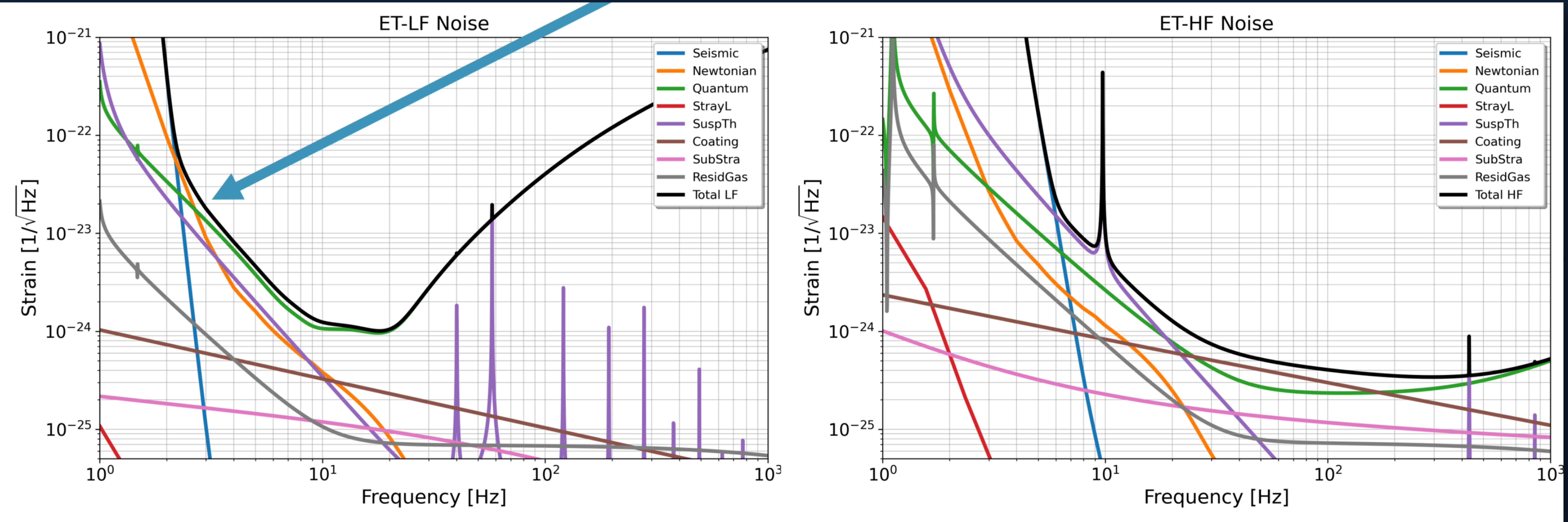
Proposed ET triangle orientation at the Sardinia Site.

The Sardinia candidate site

Engineering studies are underway for alternative vertex locations for the triangle and L configurations.

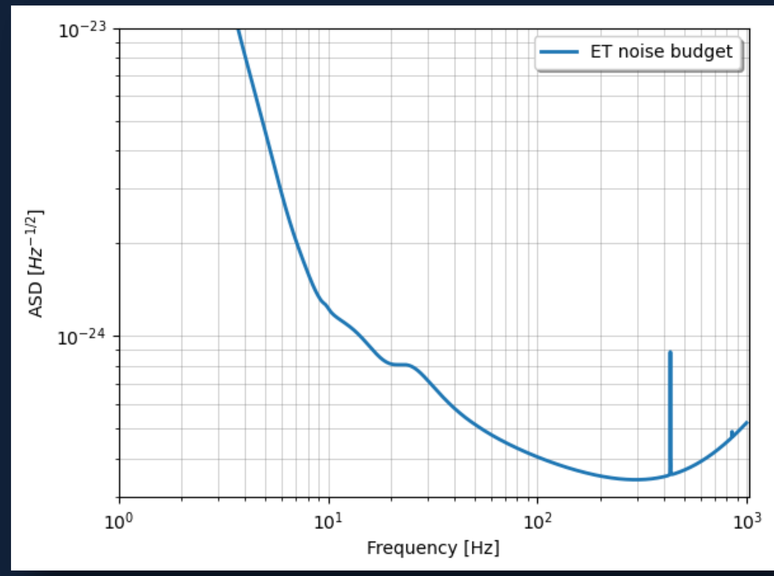


Noise budget



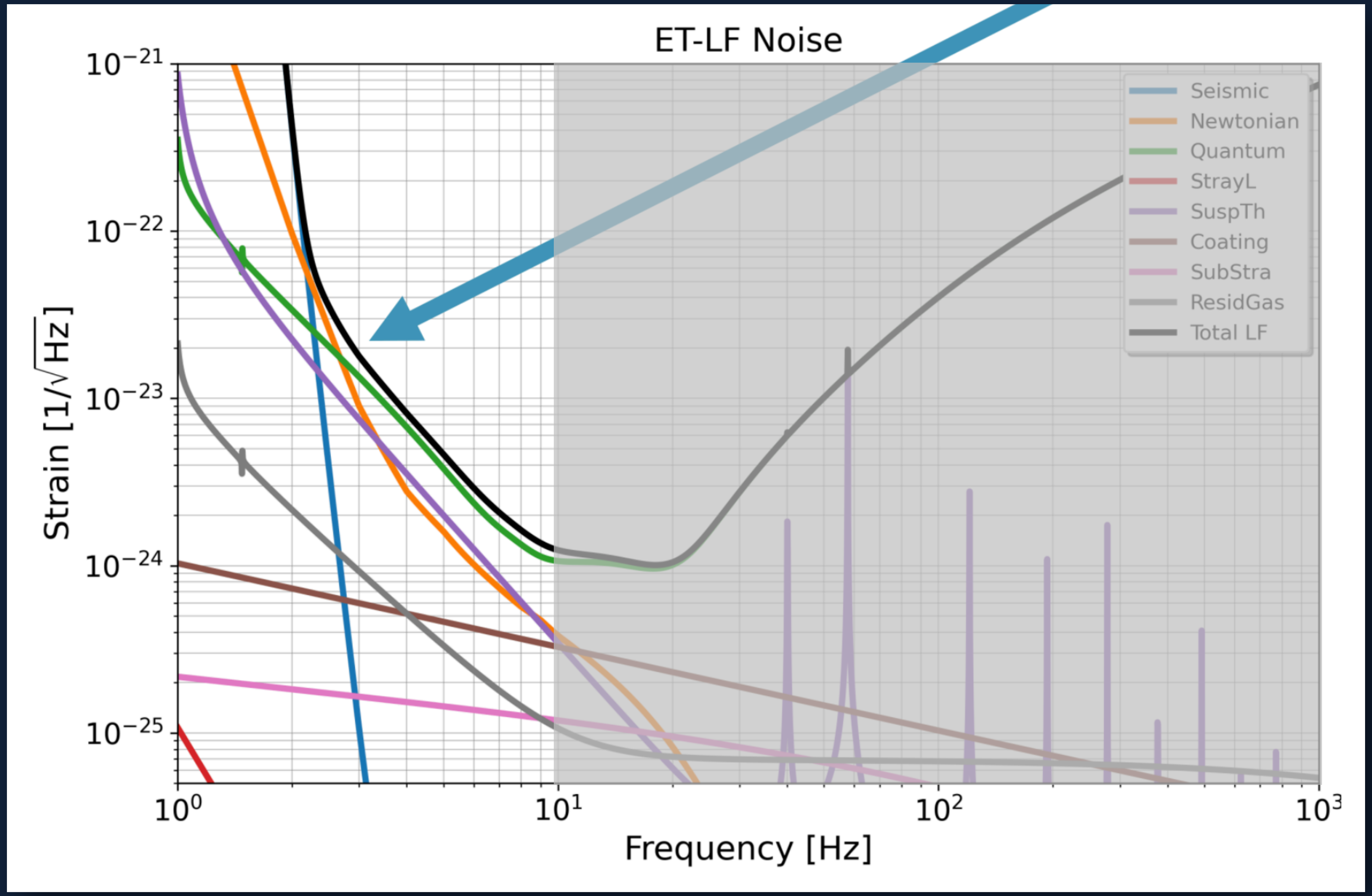
$$S_{LF/HF} = S_s + S_{NN} + S_Q + S_{SL} + S_{STH} + S_C + S_{SUBS} + S_{RG}$$

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



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

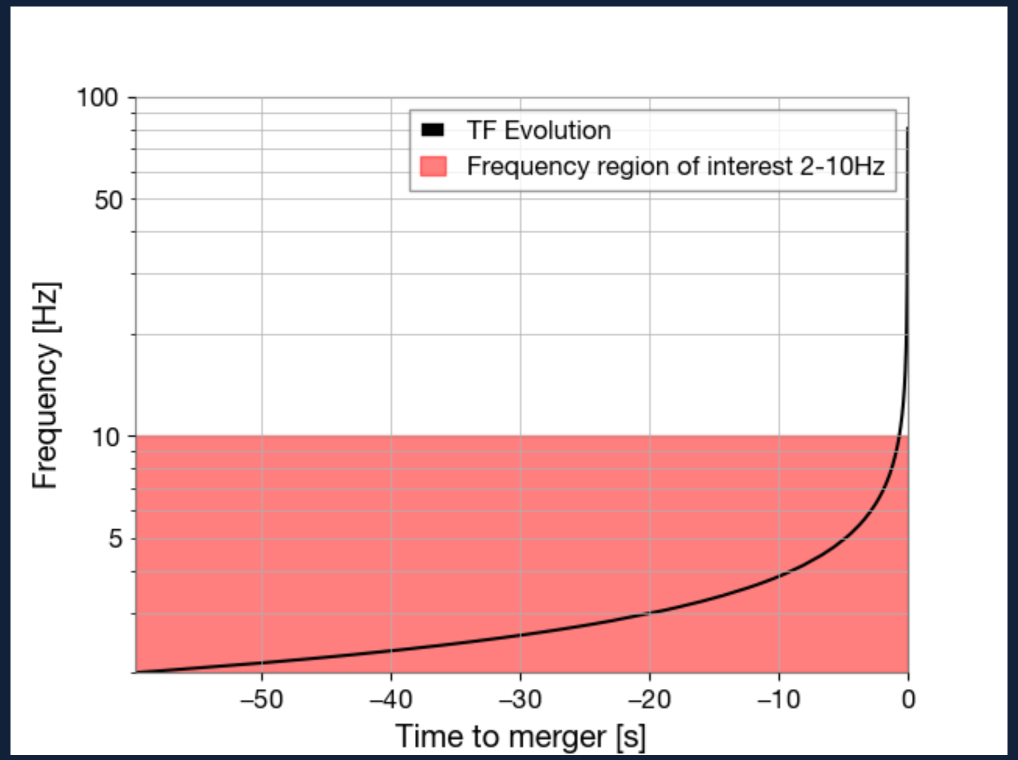
Noise budget



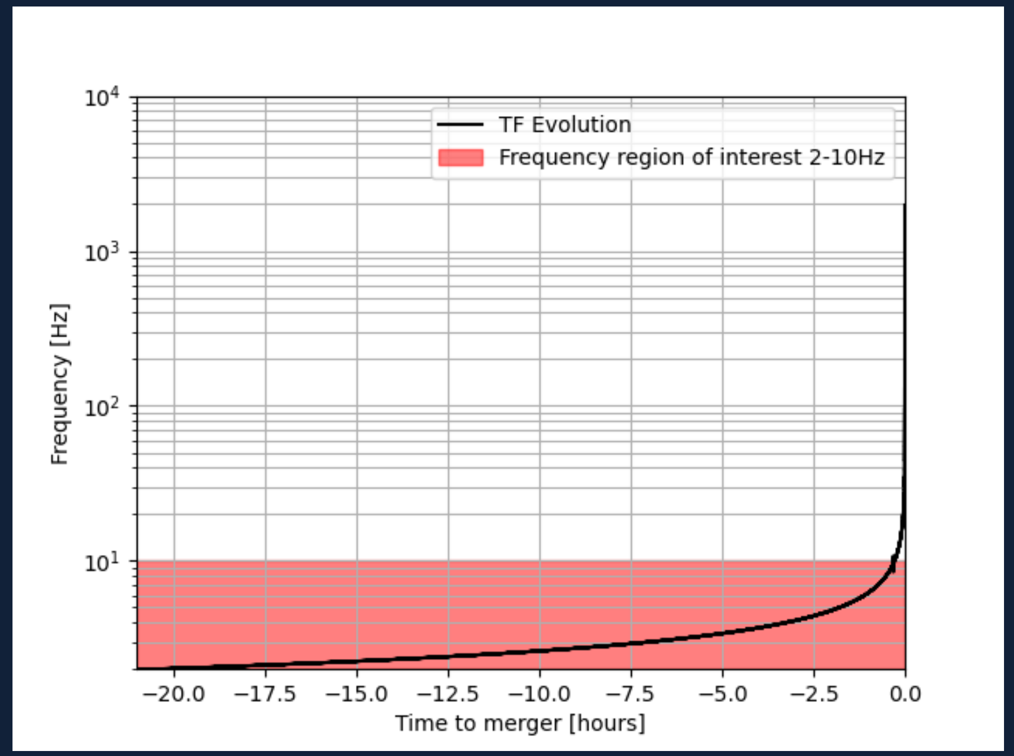
Up to 10 Hz ambient noise dominates over the hardware noise and the increased sensitivity of ET in that frequency range makes a careful assessment of the local ambient noise paramount.

Importance of the low frequency band

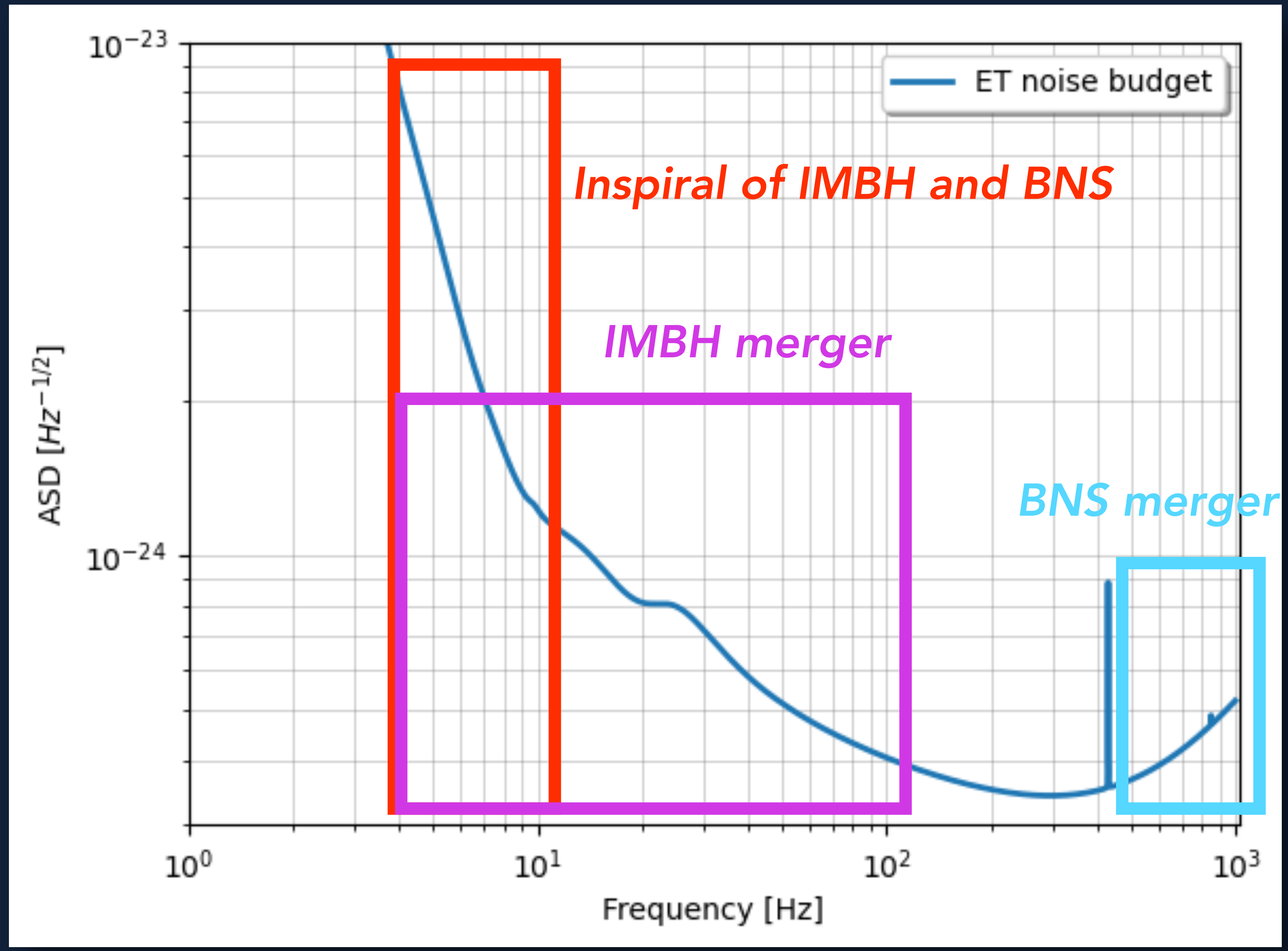
- ET will be up to 8 orders of magnitude more sensitive at frequencies below 20 Hz, with respect to current detectors;
- among the other things, this increase in sensitivity will be beneficial for the observations of intermediate mass black holes (IMBH) and to trigger multimessenger observation campaigns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

Importance of the low frequency band

- Maximizing the observational low frequency performance of ET means, among the other things, to keep environmental noise sources under control;
- The first step is to choose a suitable site with a very stable and predictable environment with low noise levels.

CAVEAT EMPTOR: a full scale research facility produces noise on its own. From now on we will refer to ambient noise as to the noise proper to the site, without making predictions on the noise that the ET facility will generate.

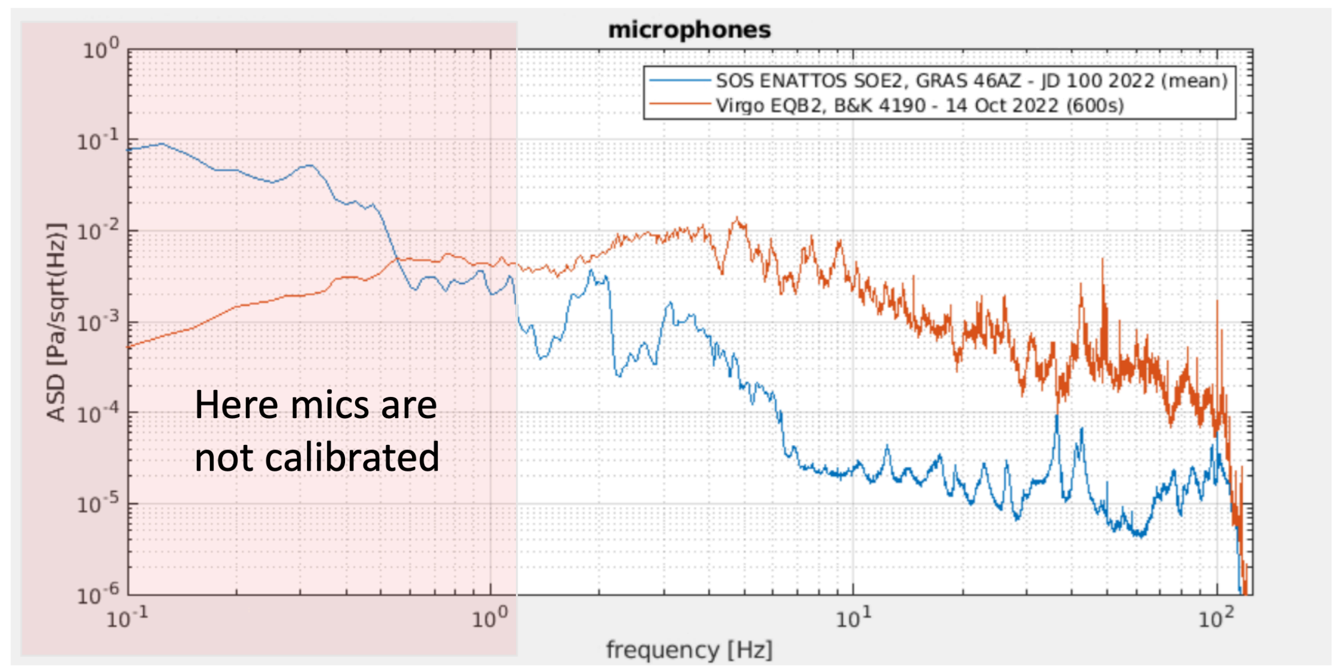
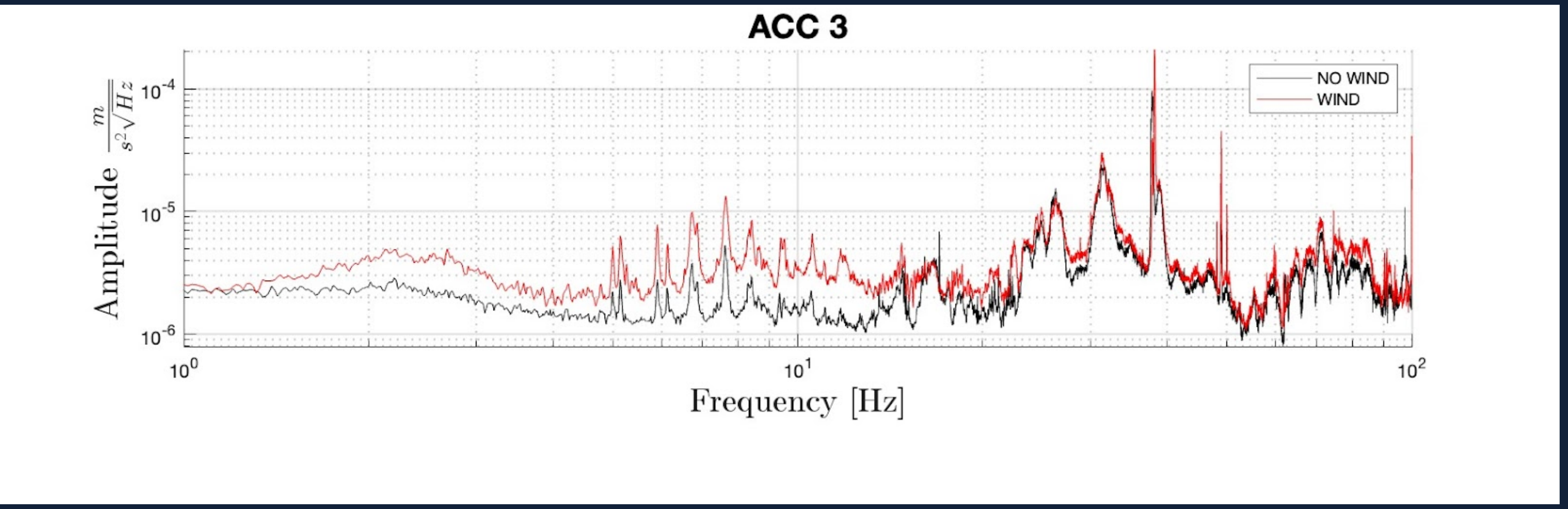


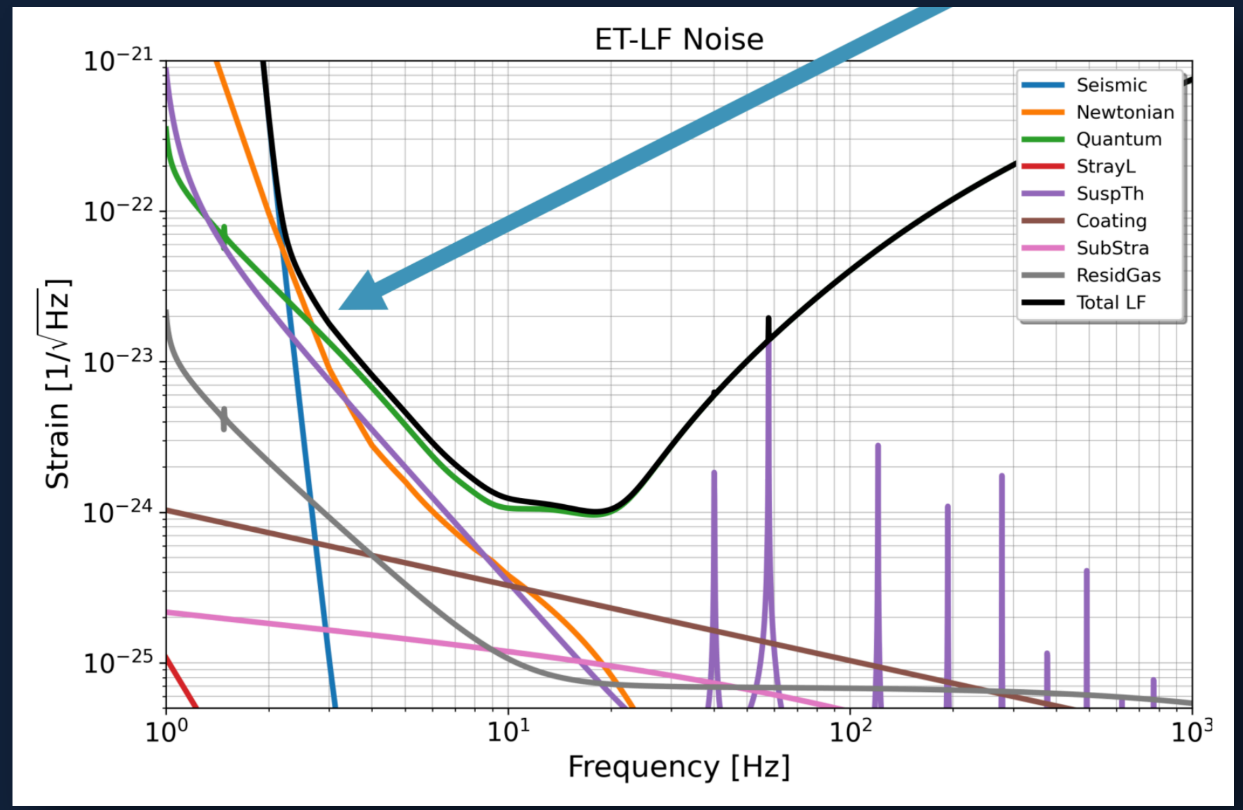
Image credits: R. De Rosa



Low frequency ambient noise

The dominant sources of ambient noise are 2:

- **Seismic** -> *ground motion produces unwanted motions of the test masses*
- **Newtonian** -> *ground motion and atmospheric disturbances alter the mass density distribution around the test masses and the gravitational field felt by the masses themselves (flowing water masses may also influence NN).*



NEWTONIAN NOISE IS A GRAVITATIONAL INTERACTION

Seismic noise can be addressed by improving the hardware of the detector.

Newtonian noise (NN) cannot be physically nor mechanically shielded, appropriate filters for noise subtraction and low ground motion environments are needed.

Current 2G detectors are not affected by NN since the accessible frequency band starts at f > 10 Hz.

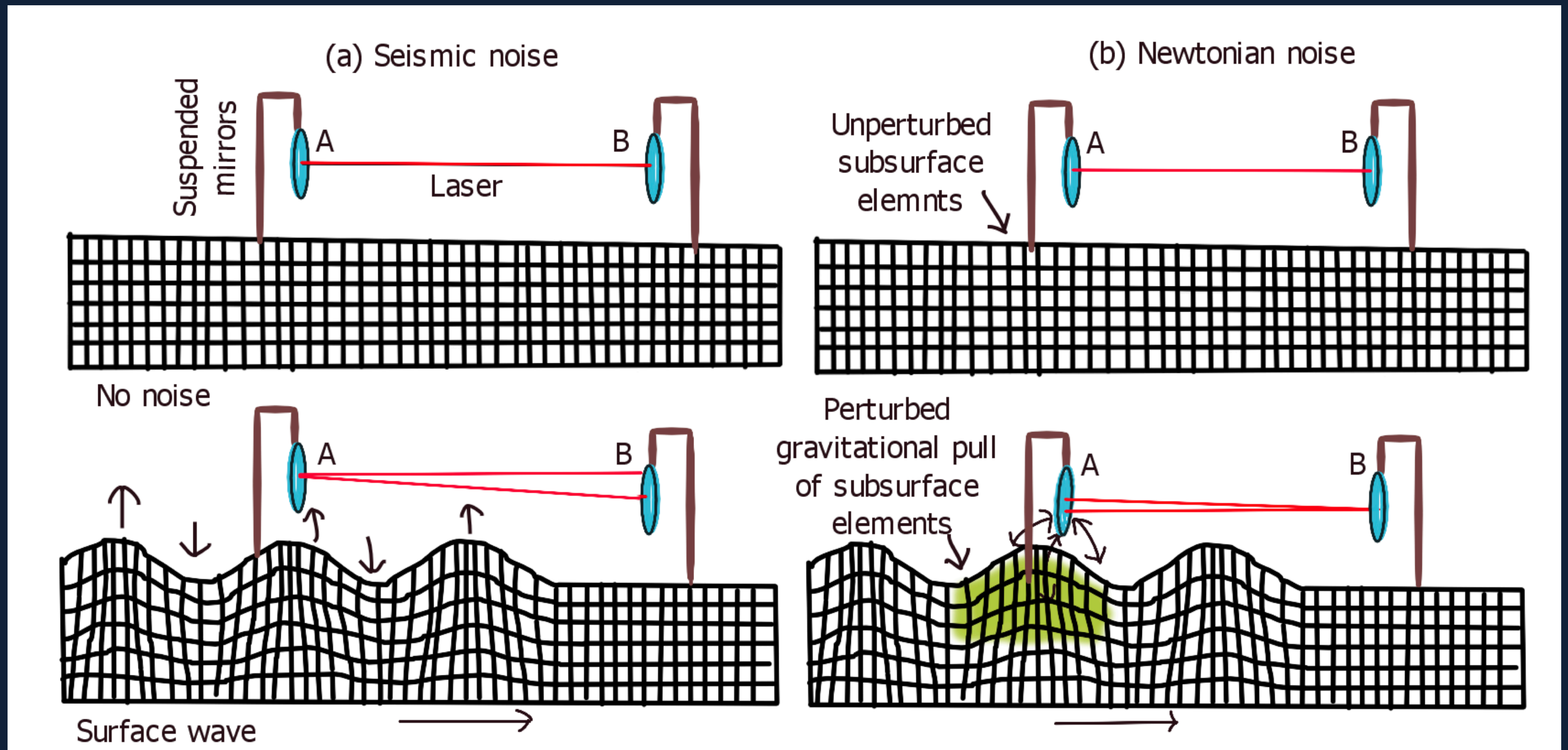


Image credits: S. Koley

Ground motion

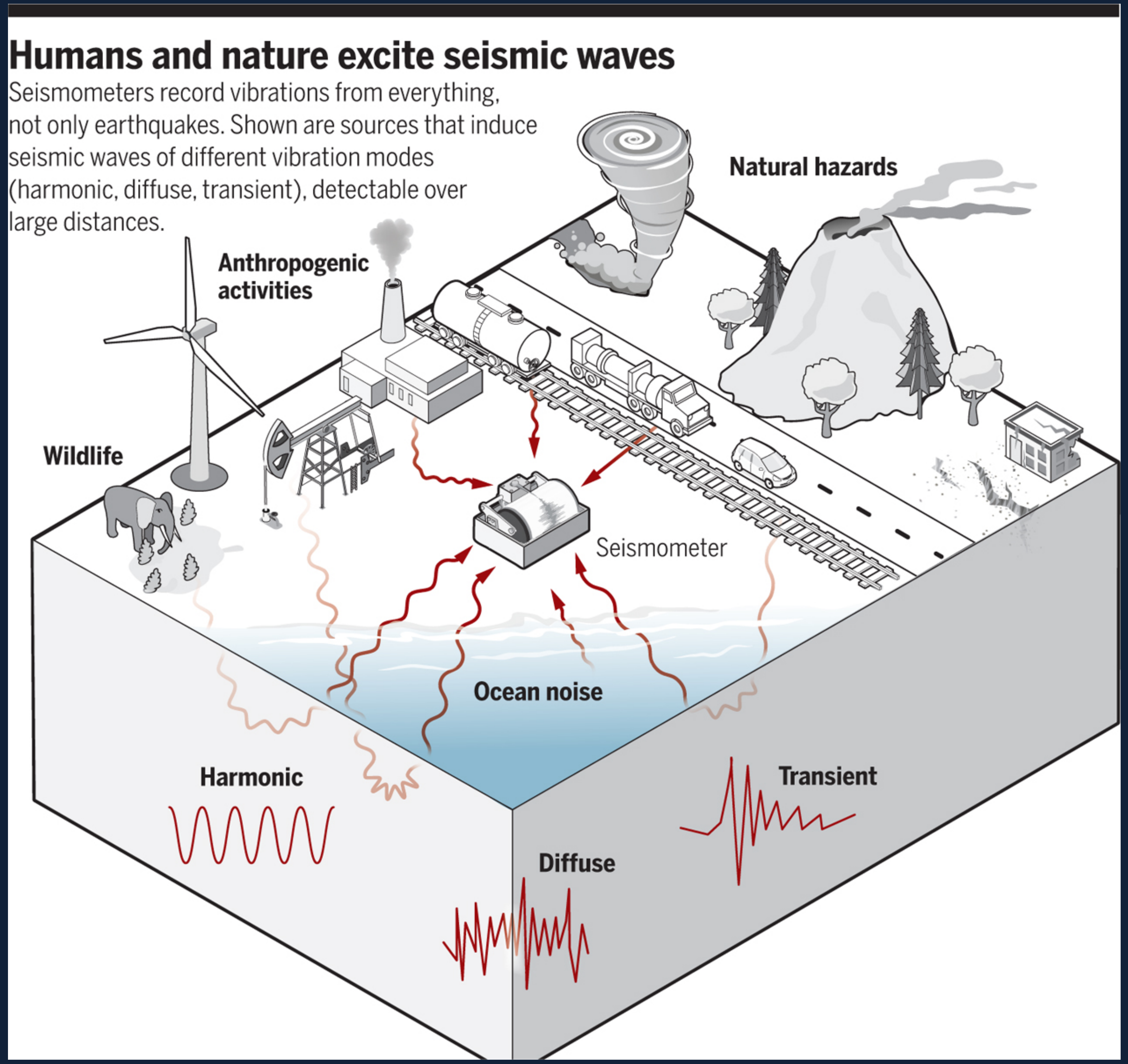
Ground motion is not produced purely by Earthquakes. It is generated by a wide variety of natural and anthropic sources.

As a consequence, we have to constantly deal with ground motion. This means that not all sites and environments are suitable for a GW detector.

Ground motion manifests broadband, by increasing noise levels, or at specific frequencies.

Proper design of suspensions and payloads for the test masses mitigates this noise source.

Going underground also helps!



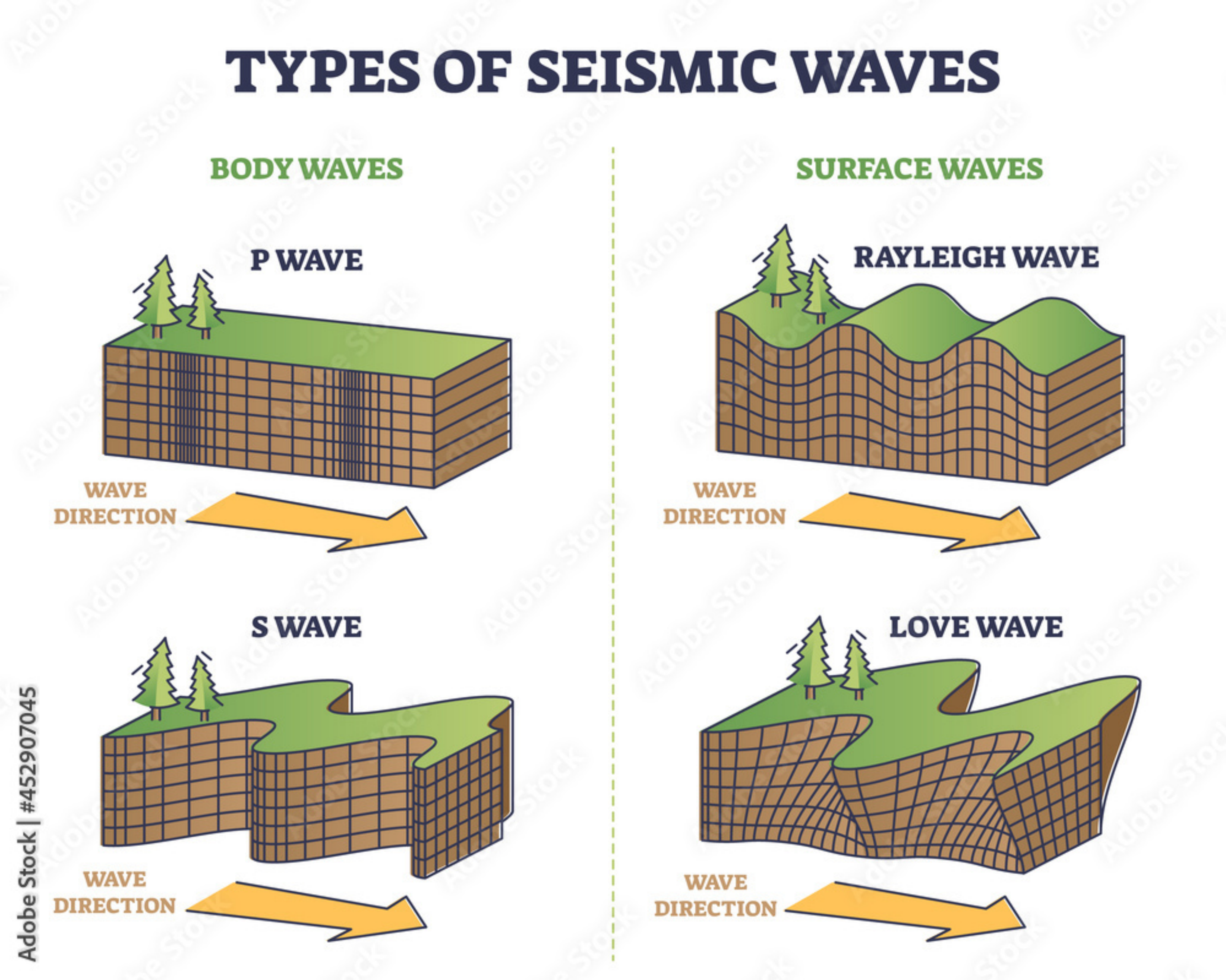
Seismic waves in a nutshell

Compressional

Body waves

Present both on surface and underground

Shear



Surface waves

Attenuate with depth

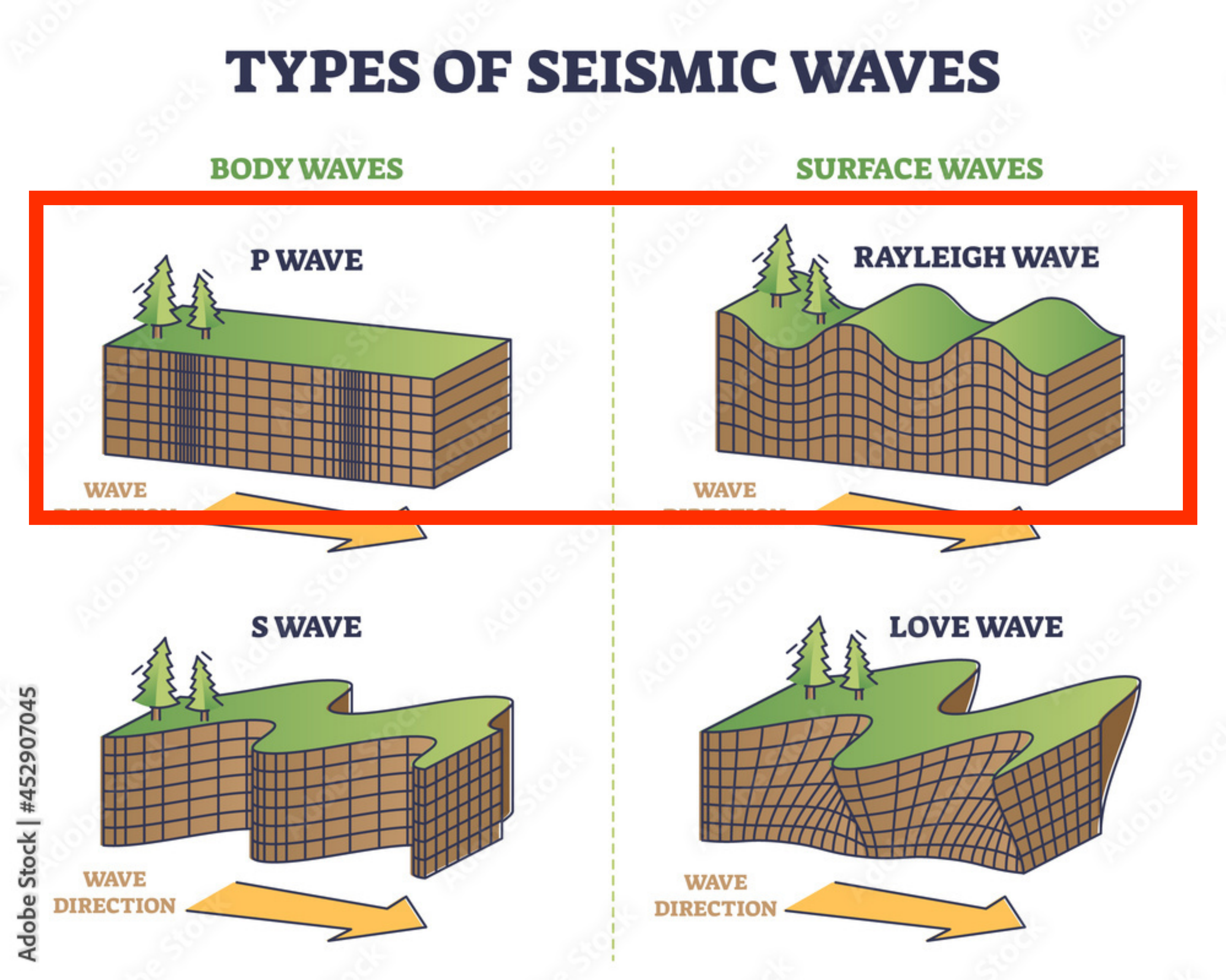
Seismic waves in a nutshell

Compressional

Body waves

Present both on surface and underground

Shear



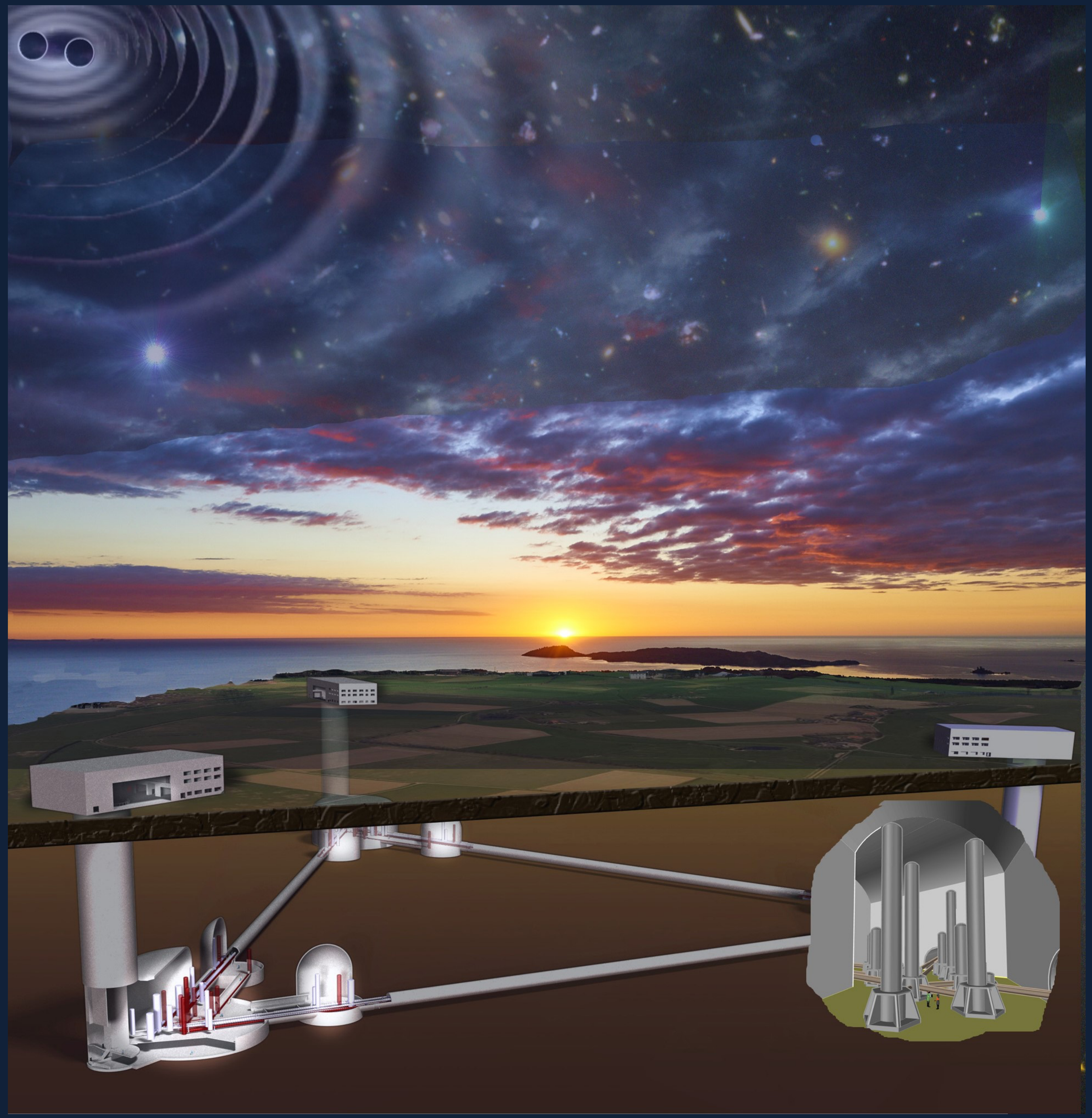
P and Rayleigh waves generate the mass density fluctuations that cause NN

Surface waves

Attenuate with depth

Why underground

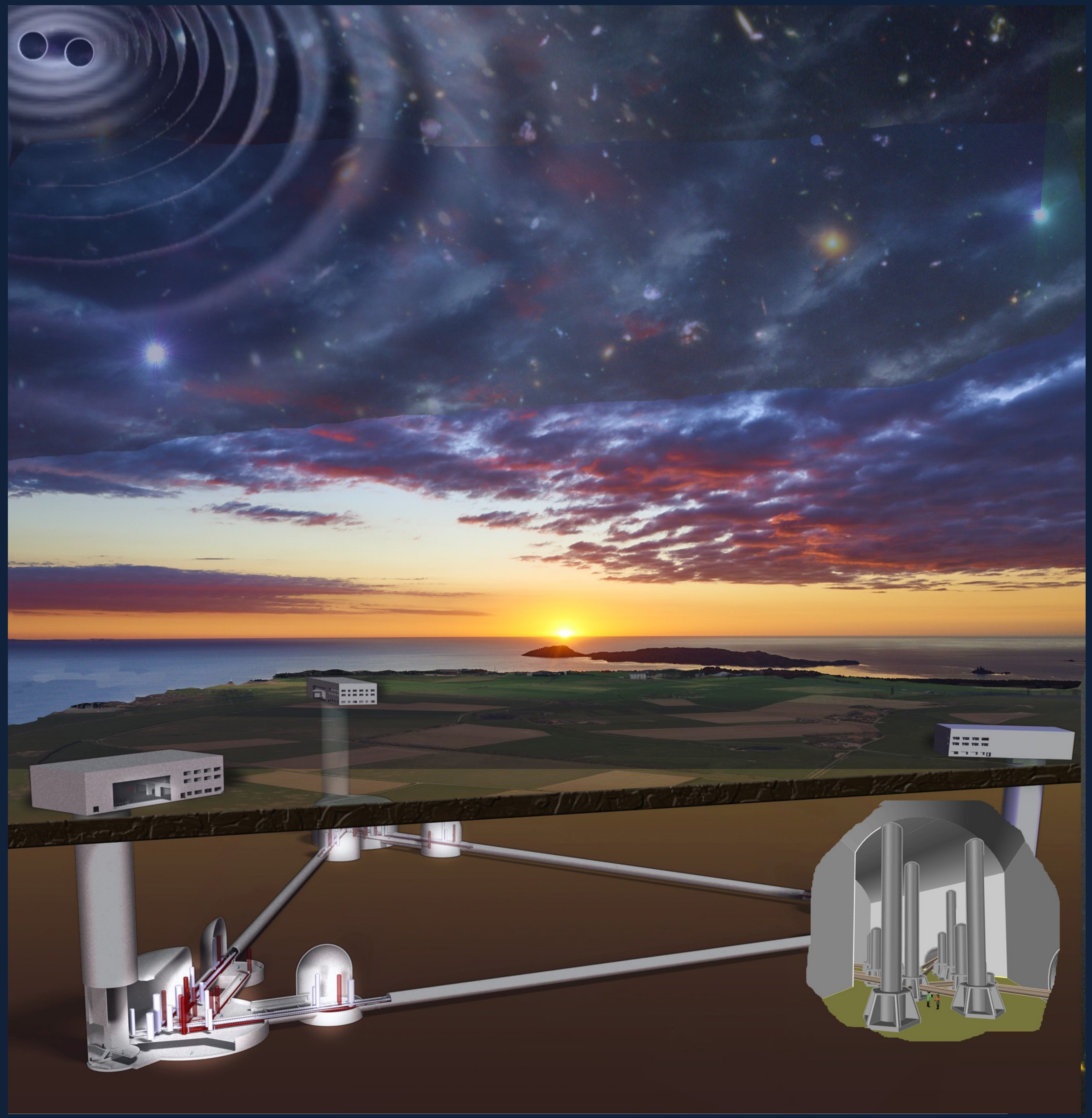
- Seismic noise attenuates with depth;
  - NN has a lower impact underground;
  - appropriate NN cancellation systems will allow ET to reach its design sensitivity
- Underground environment is shielded from atmospheric disturbances and fluctuations;
  - NN contribution of atmospheric mass density fluctuations is less significant;



Not all that glitters is gold!

NN challenges

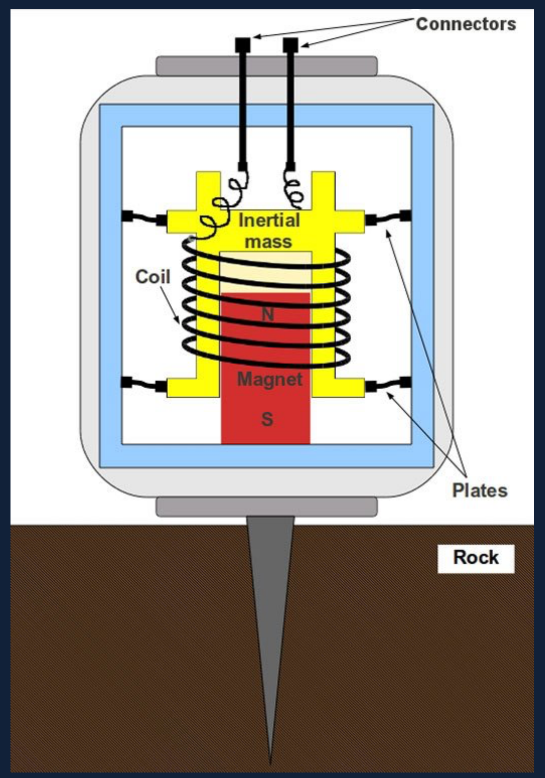
- Depending on the fraction of P-waves over the total body-wave content, cancellation may be better or worse;
  - Estimating this fraction is a complicated task;
- Where do we put the sensors for NN cancellation? Underground space will be limited and sensors have to be placed in 3D around the test masses;
  - We estimate at least 10 sensors per test mass for satisfactory performance of NN cancellation;
- What type of sensors will we use?
  - Accelerometers? Strainmeters? Tiltmeters? A mix?
  - In borehole or not? (50 k€ needed for each borehole sensor without excavation costs)
- Computational cost to process 3D data will be significant.



Seismic sources

Every seismic noise source has its own characteristic frequency. Let's investigate the main ones.

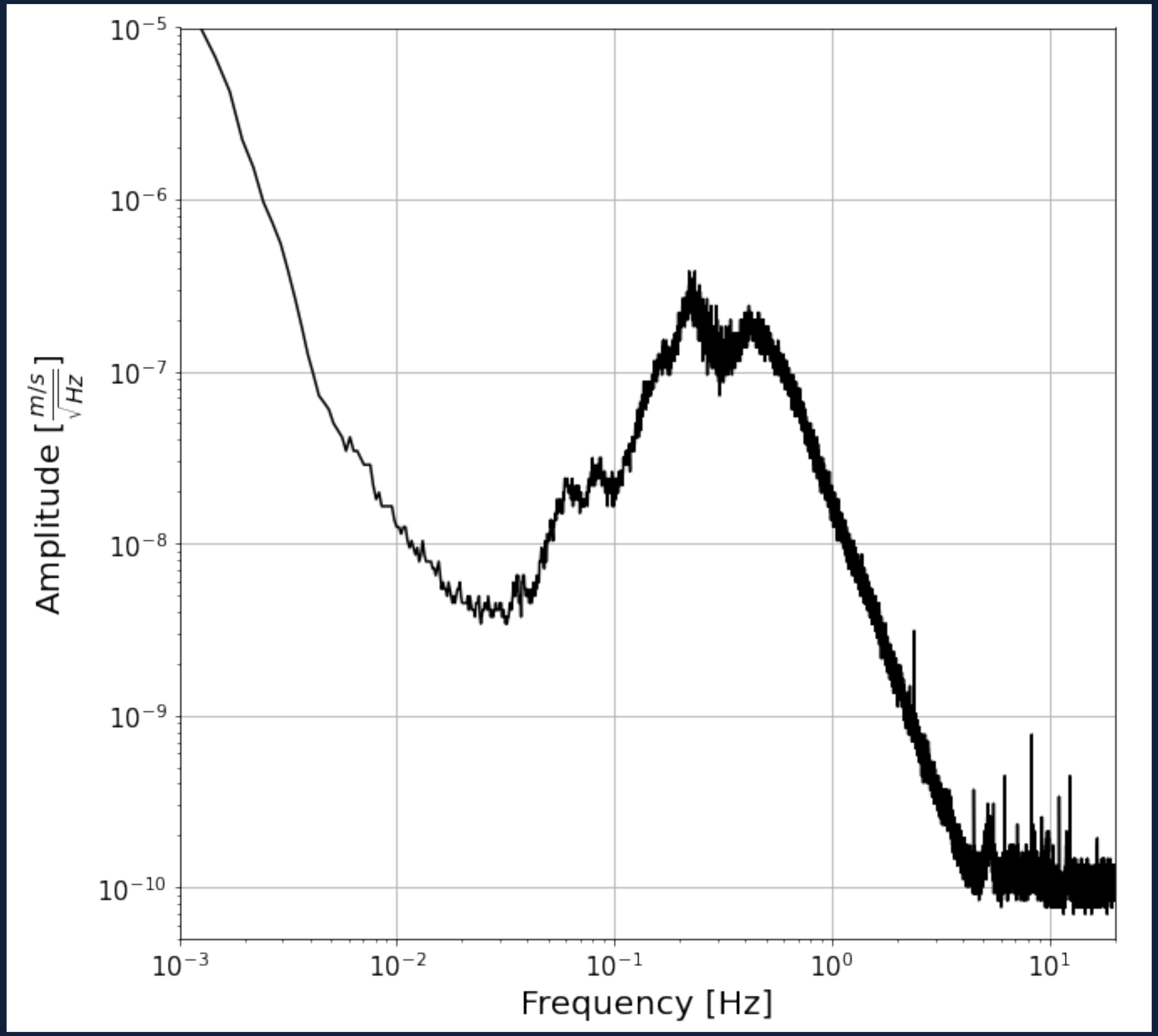
TIDBIT: *ground motion is measured with a seismometer. A seismometer can be schematized by a mass attached to a spring that sends an electric signal through a coil moving around a magnet.*



Seismometers have 3 masses, one measures vertical ground motion, two measure horizontal ground motion.

Geophones only have 1 mass for vertical ground motion and are less sensitive.

Example of seismic noise spectrum

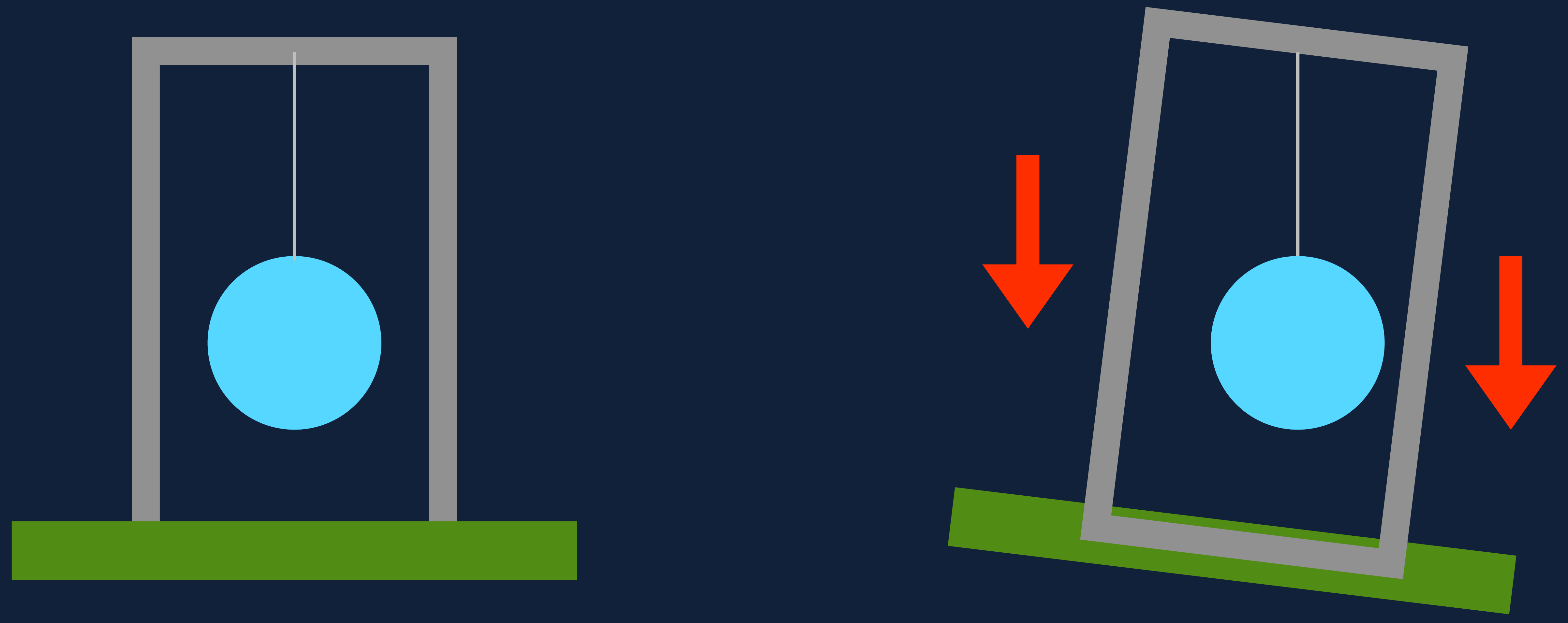


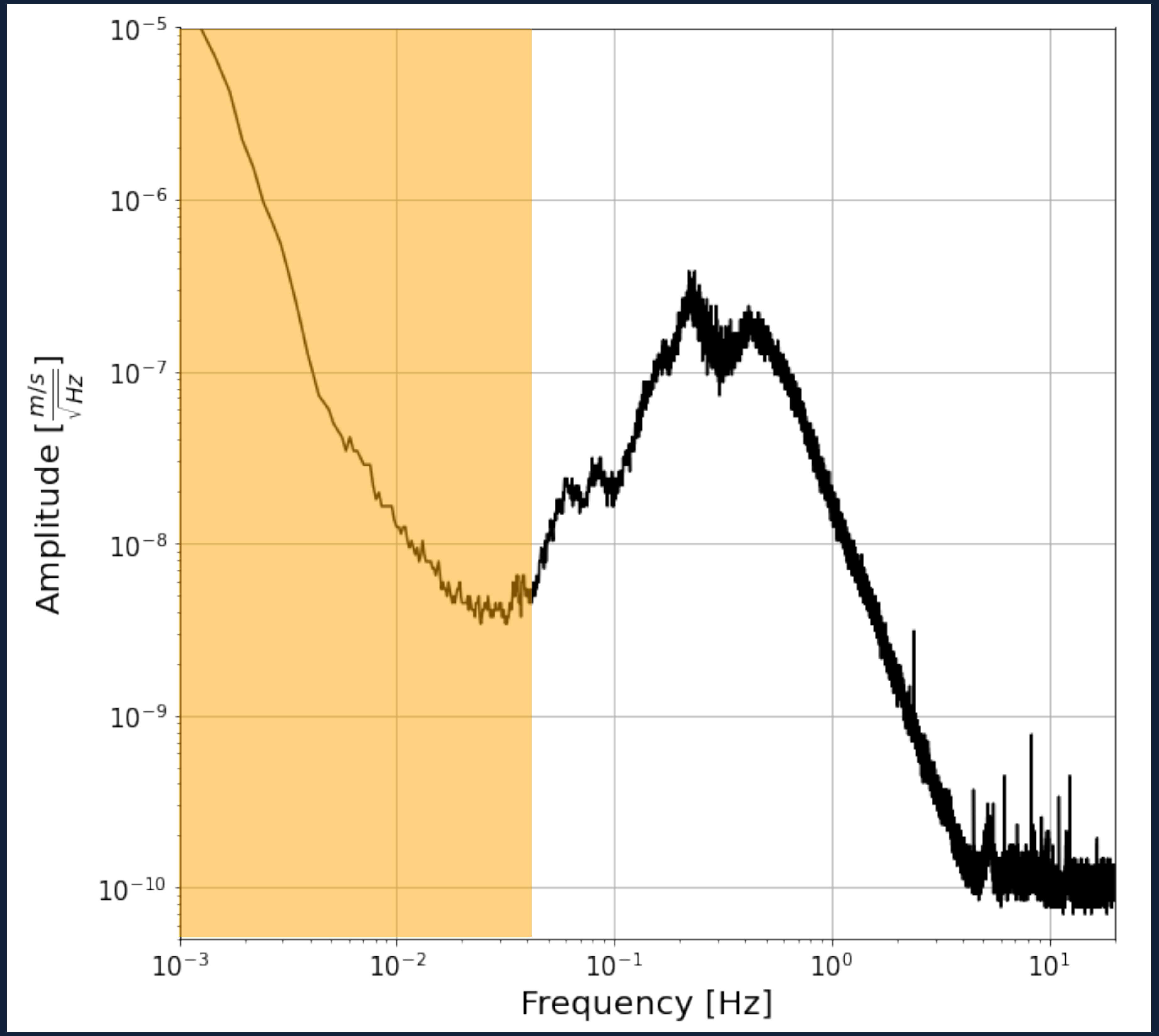
Seismic sources

Example of seismic noise spectrum

Every seismic noise source has its own characteristic frequency.
Let's investigate the main ones.

- Tilt ground motion from atmospheric pressure (f < 0.05 Hz);





Active seismic controls may be negatively affected by ground tilt

Seismic sources

Example of seismic noise spectrum

Every seismic noise source has its own characteristic frequency. Let's investigate the main ones.

- Tilt ground motion from atmospheric pressure fluctuations (f < 0.05 Hz);

Mostly appreciable on the horizontal channels of a seismometer.

Sardinia vs. KAGRA

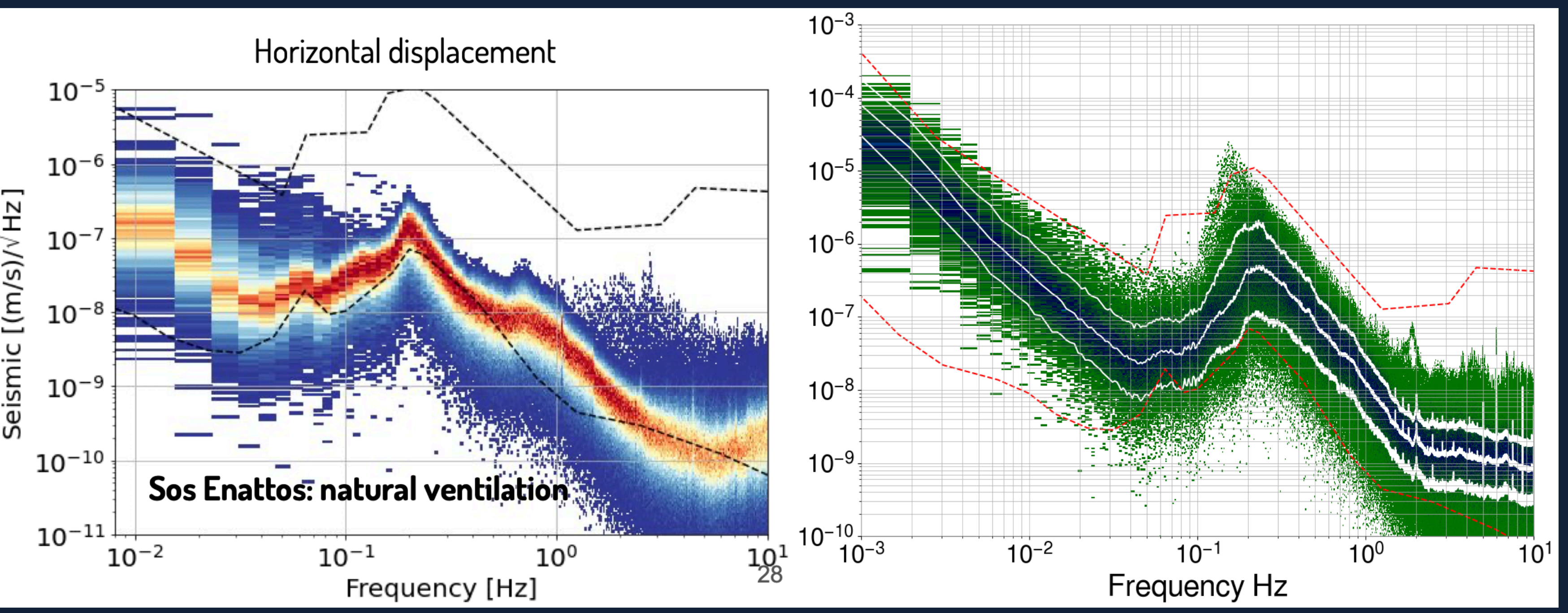
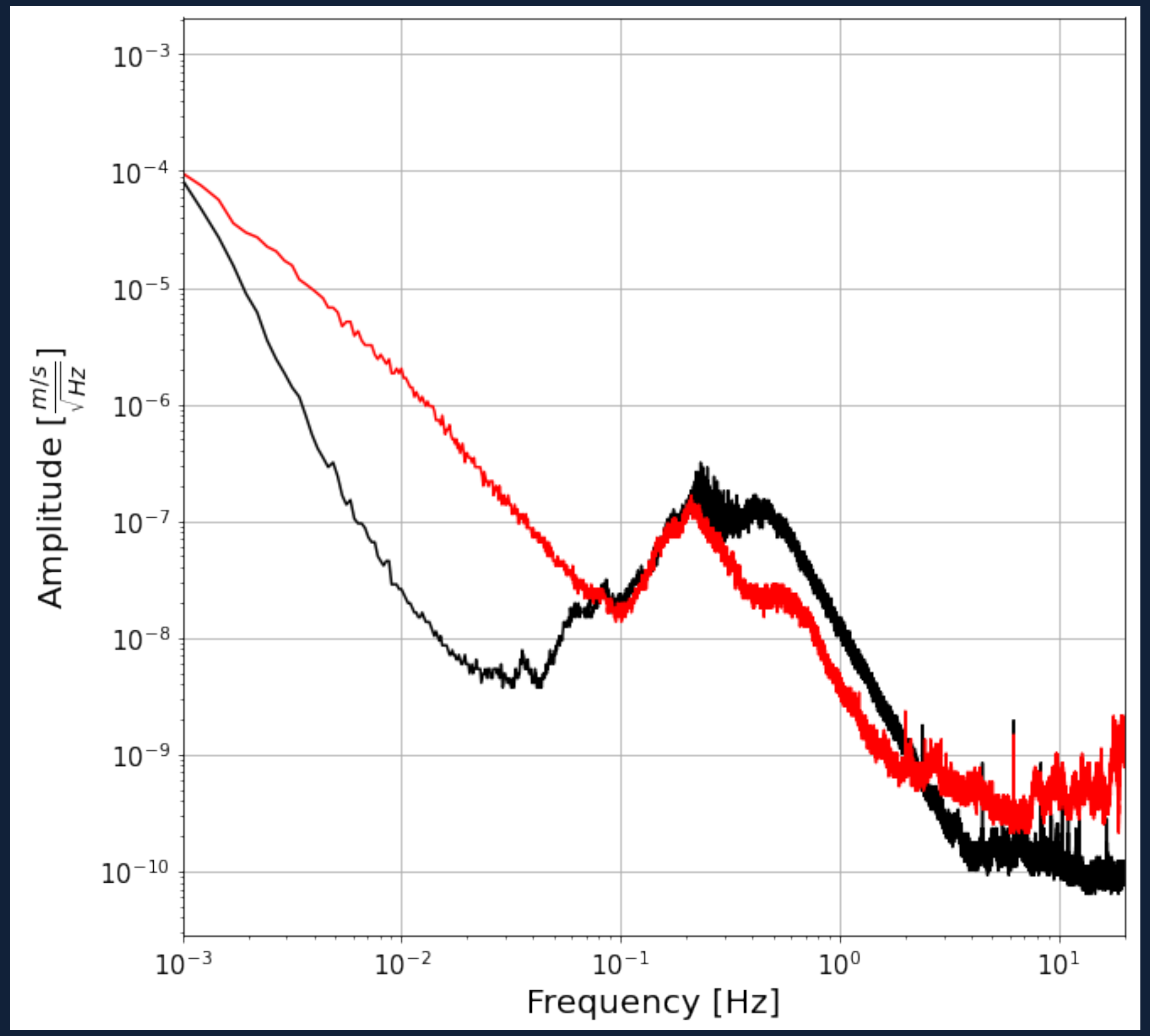
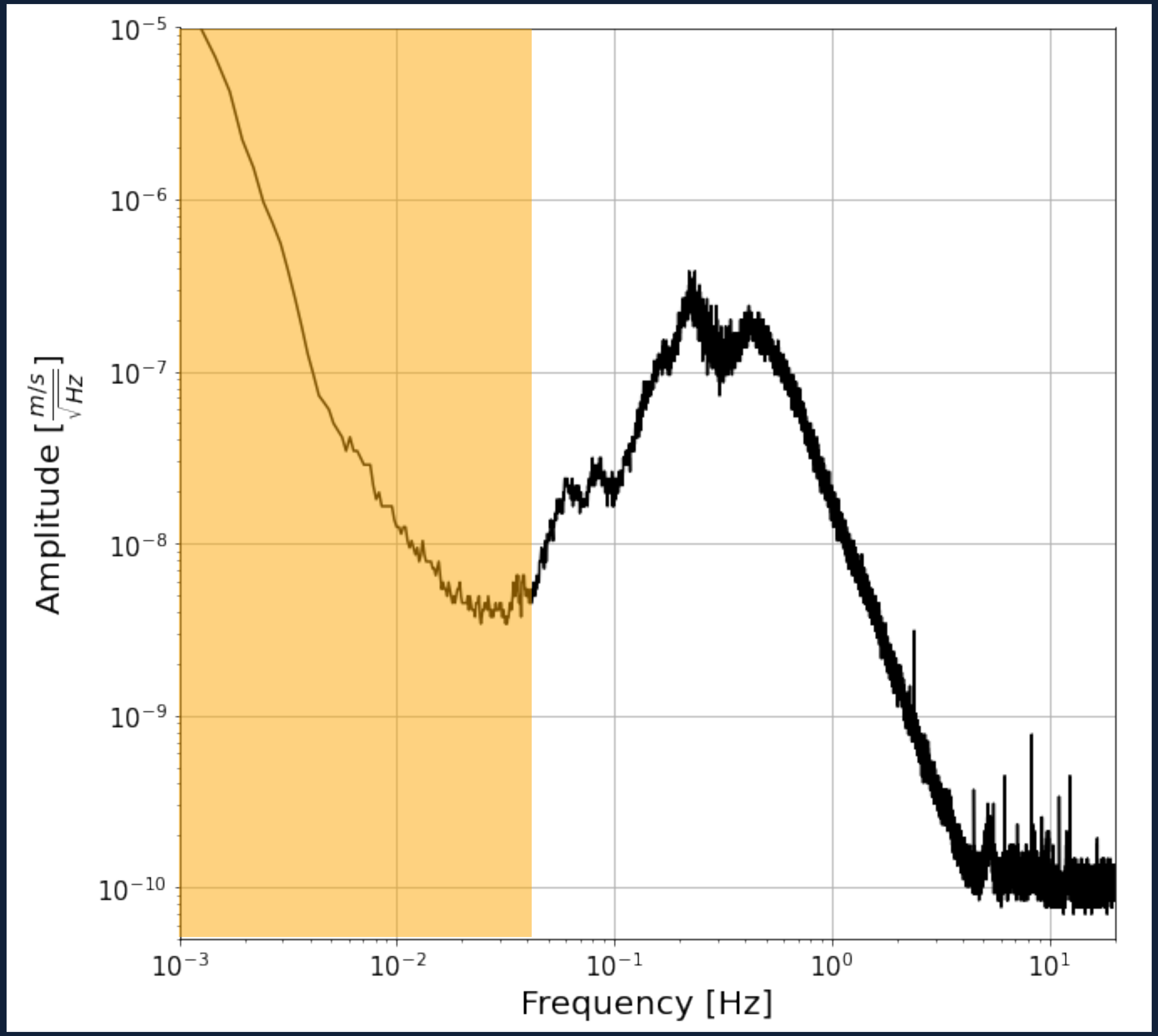


Image credits: F. Badaracco

Sardinia vs LNGS





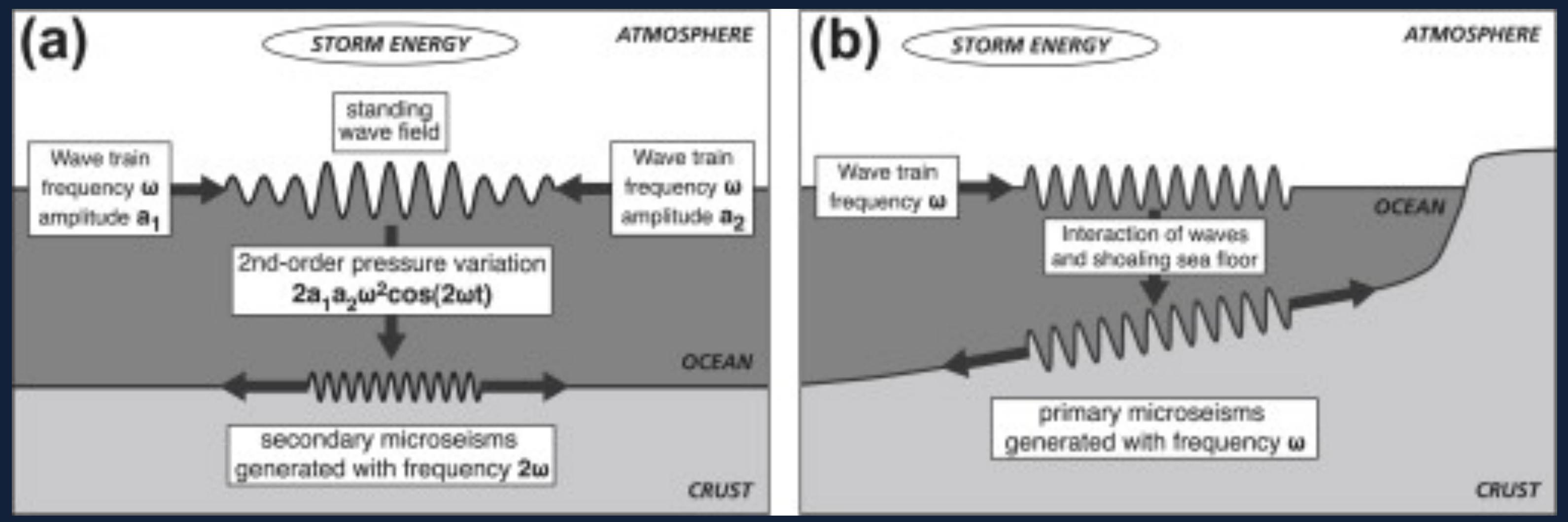
To appreciate ground tilt, seismometers have to be carefully calibrated. Misaligned masses can cause an unwanted excess noise at low frequencies. Ground tilt is better measured by tiltmeters.

Seismic sources

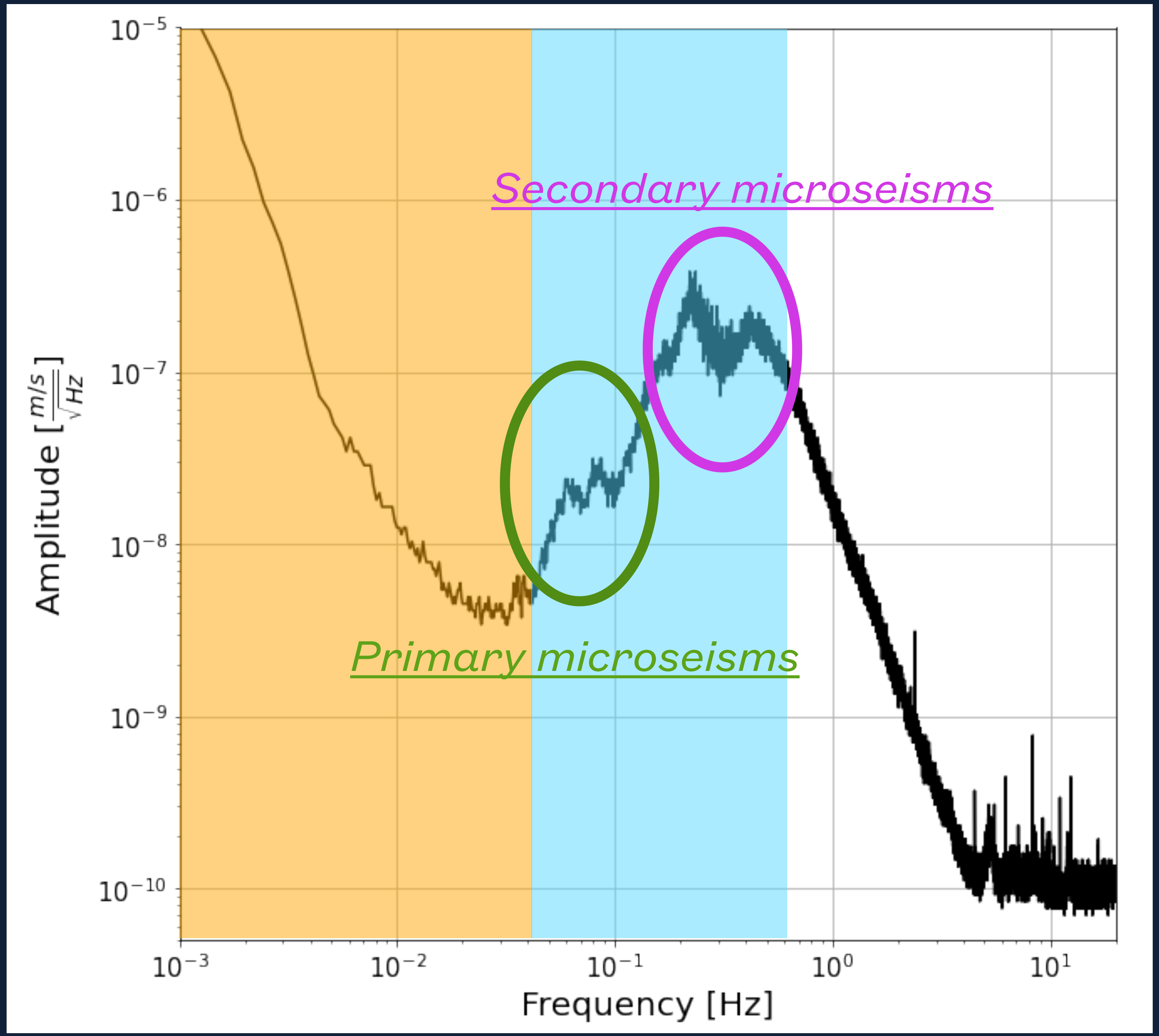
Example of seismic noise spectrum

Every seismic noise source has its own characteristic frequency. Let's investigate the main ones.

- Tilt ground motion from atmospheric pressure fluctuations (f < 0.05 Hz);
- Ground motion generated by sea waves (0.05 Hz < f < 1 Hz);



This noise source is out the ET frequency band, but can have an impact over NN subtraction.



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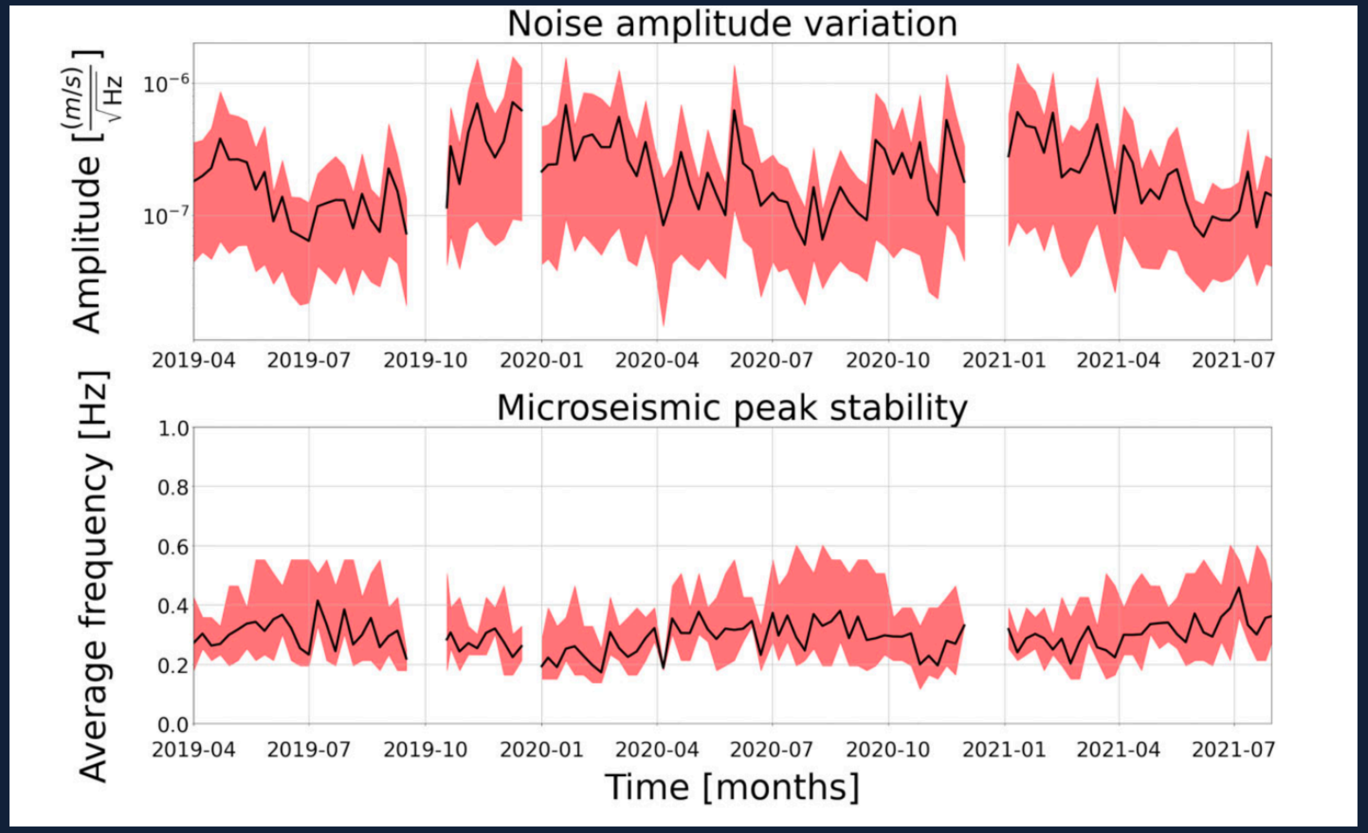
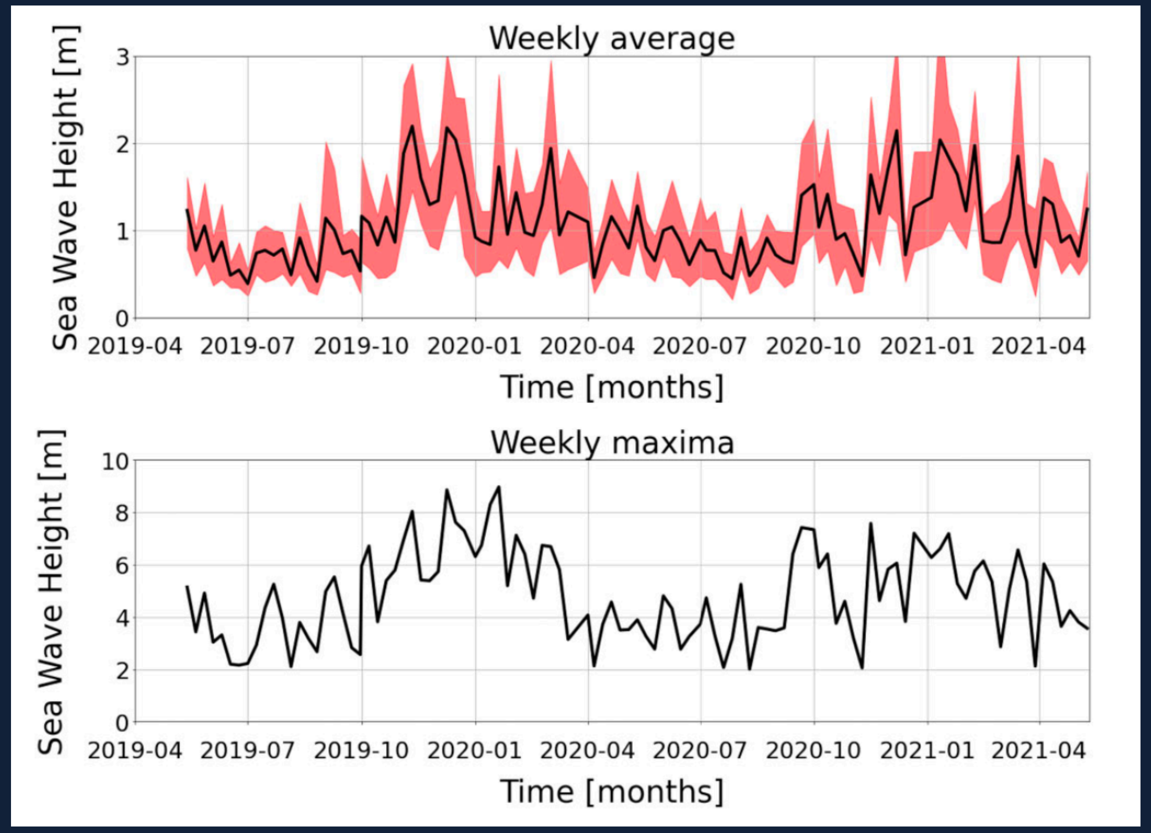
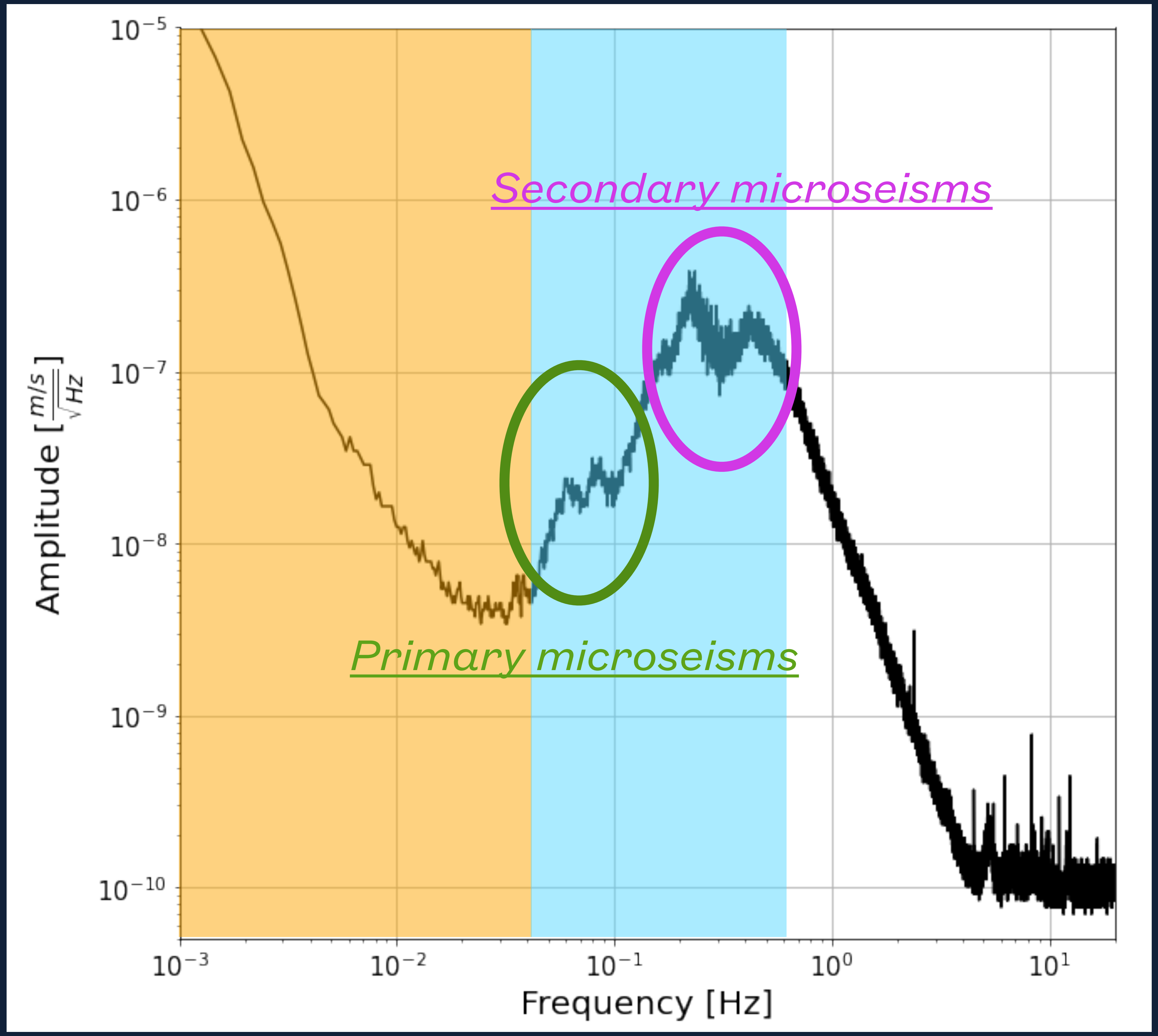




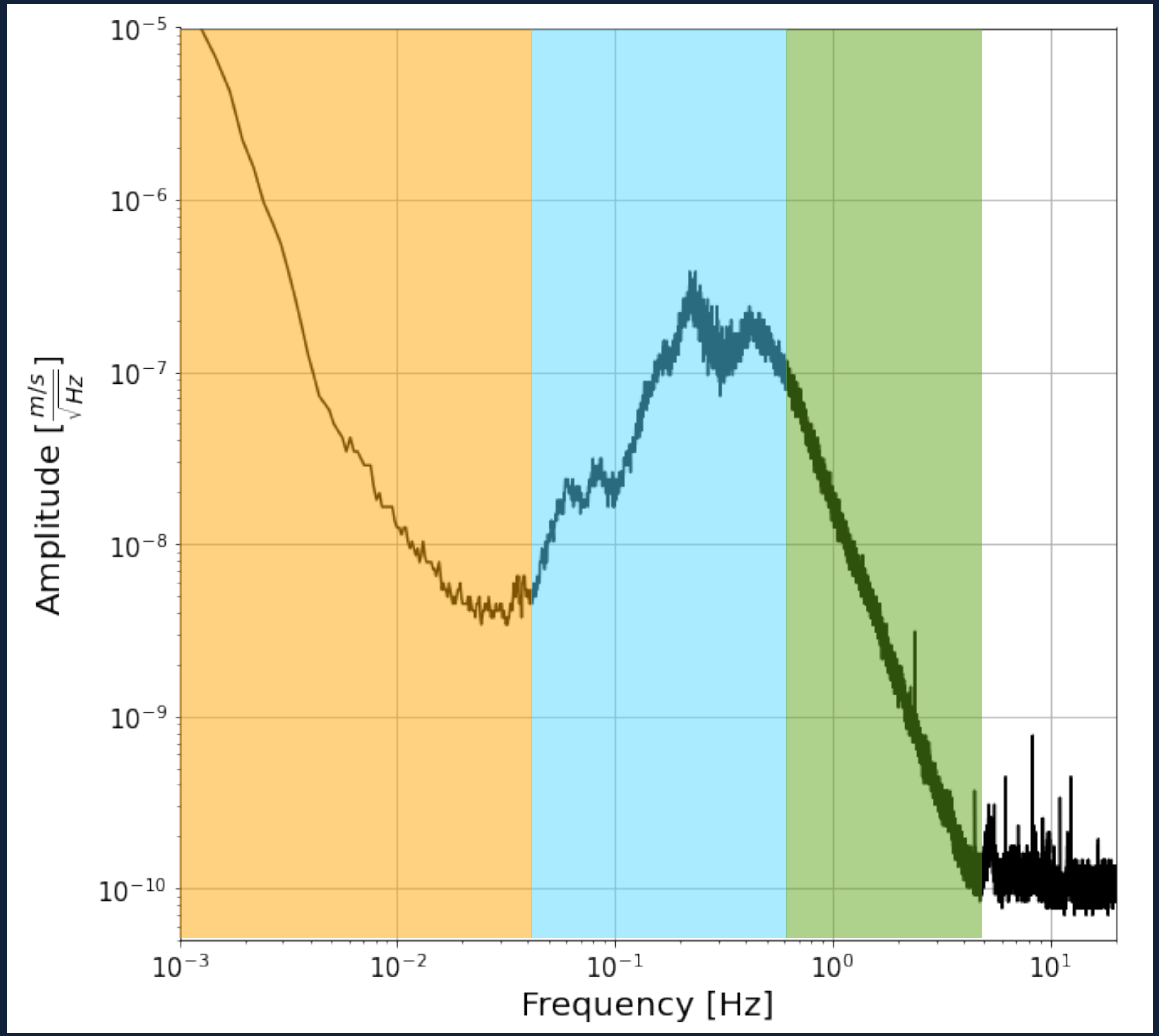


Seismic sources

Example of seismic noise spectrum

Every seismic noise source has its own characteristic frequency. Let's investigate the main ones.

- Tilt ground motion from atmospheric pressure fluctuations (f < 0.05 Hz);
- Ground motion generated by sea waves (0.05 Hz < f < 1 Hz);
- Transition between natural ambient noise and anthropic ambient noise;

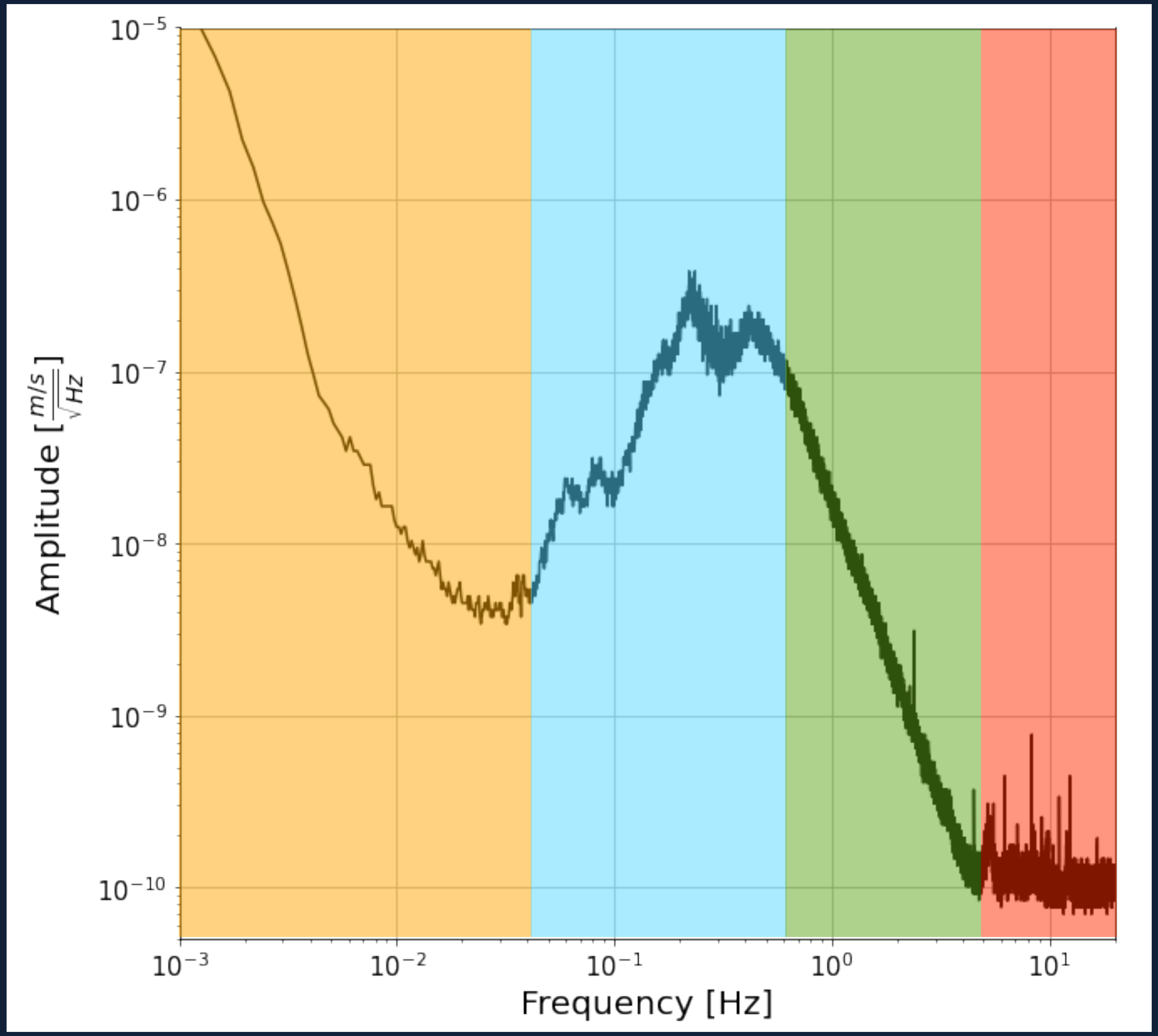


Seismic sources

Example of seismic noise spectrum

Every seismic noise source has its own characteristic frequency. Let's investigate the main ones.

- Tilt ground motion from atmospheric pressure fluctuations (f < 0.05 Hz);
- Ground motion generated by sea waves (0.05 Hz < f < 1 Hz);
- Transition between natural ambient noise and anthropic ambient noise;
- Anthropic sources (plus some natural sources).

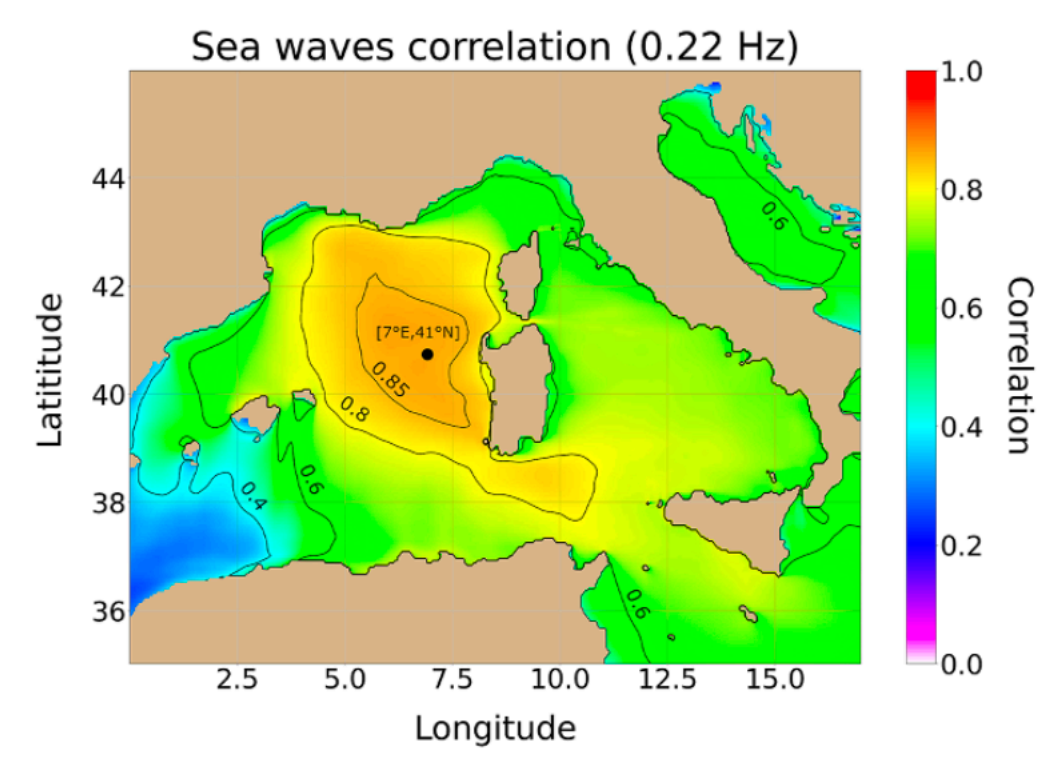


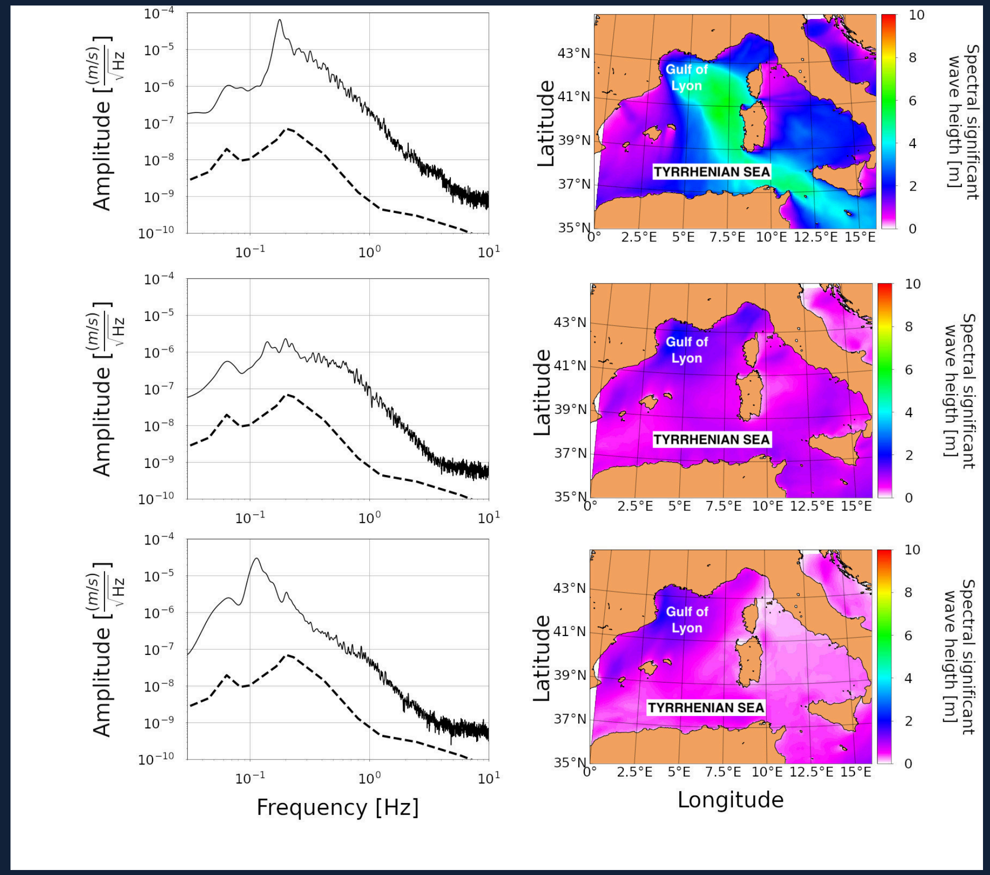


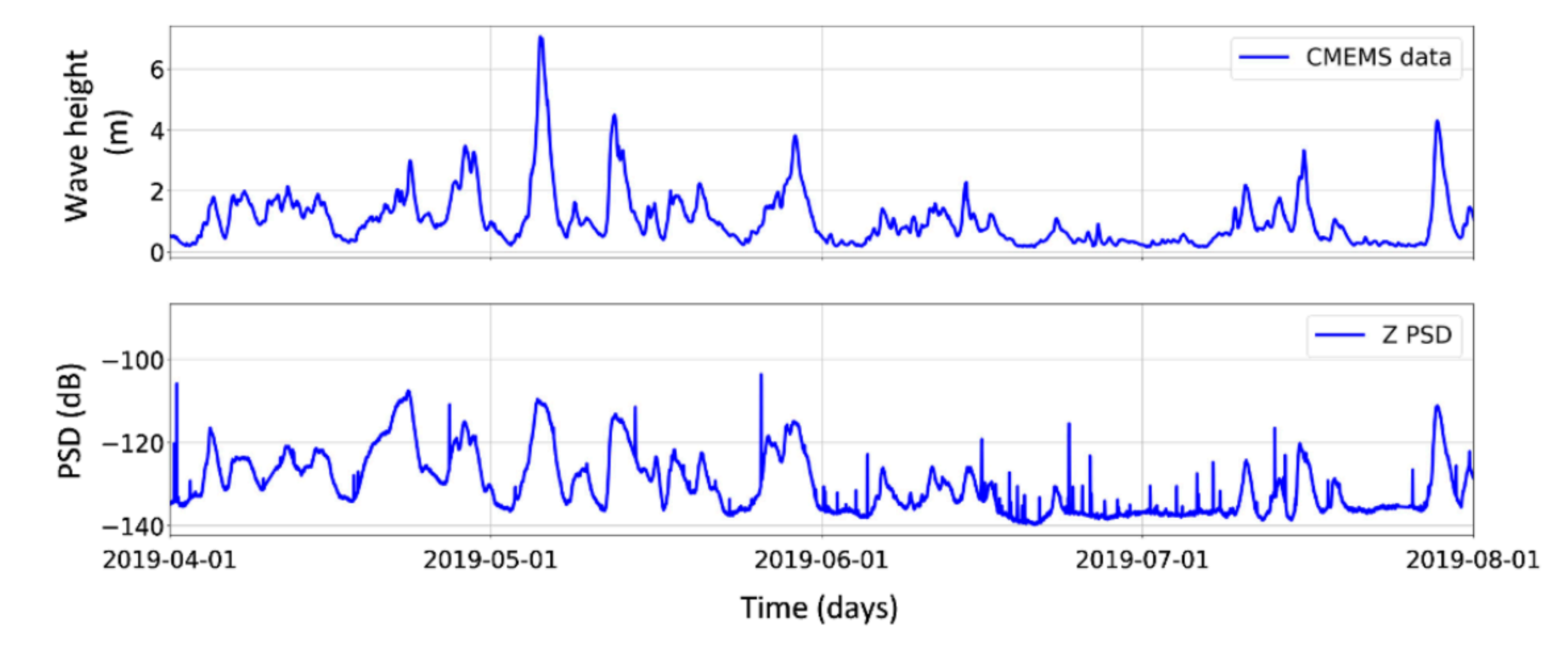

The overlap of many anthropic noise sources generally manifests as an increase in the seismic noise levels at f > 1 Hz.

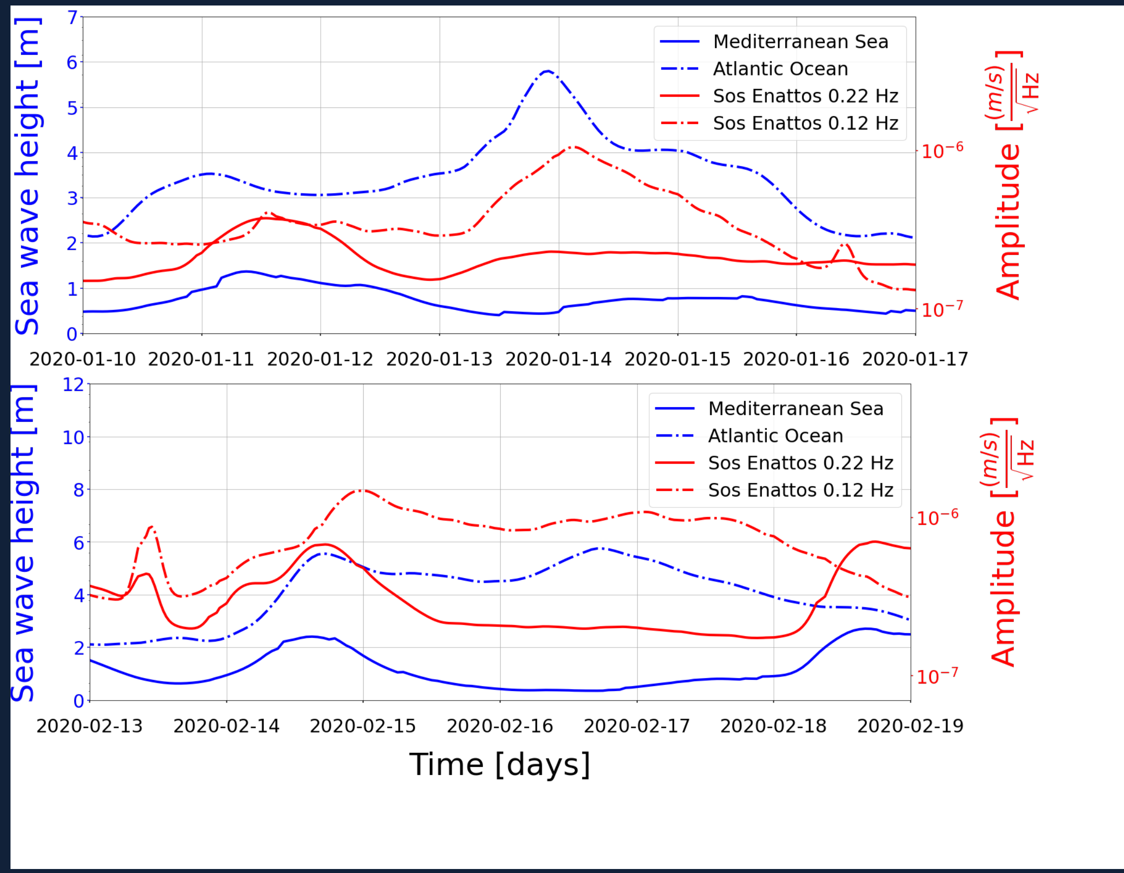
Examples of noise sources observed at the ET candidate site

Correlation with sea waves from a specific area of the Mediterranean





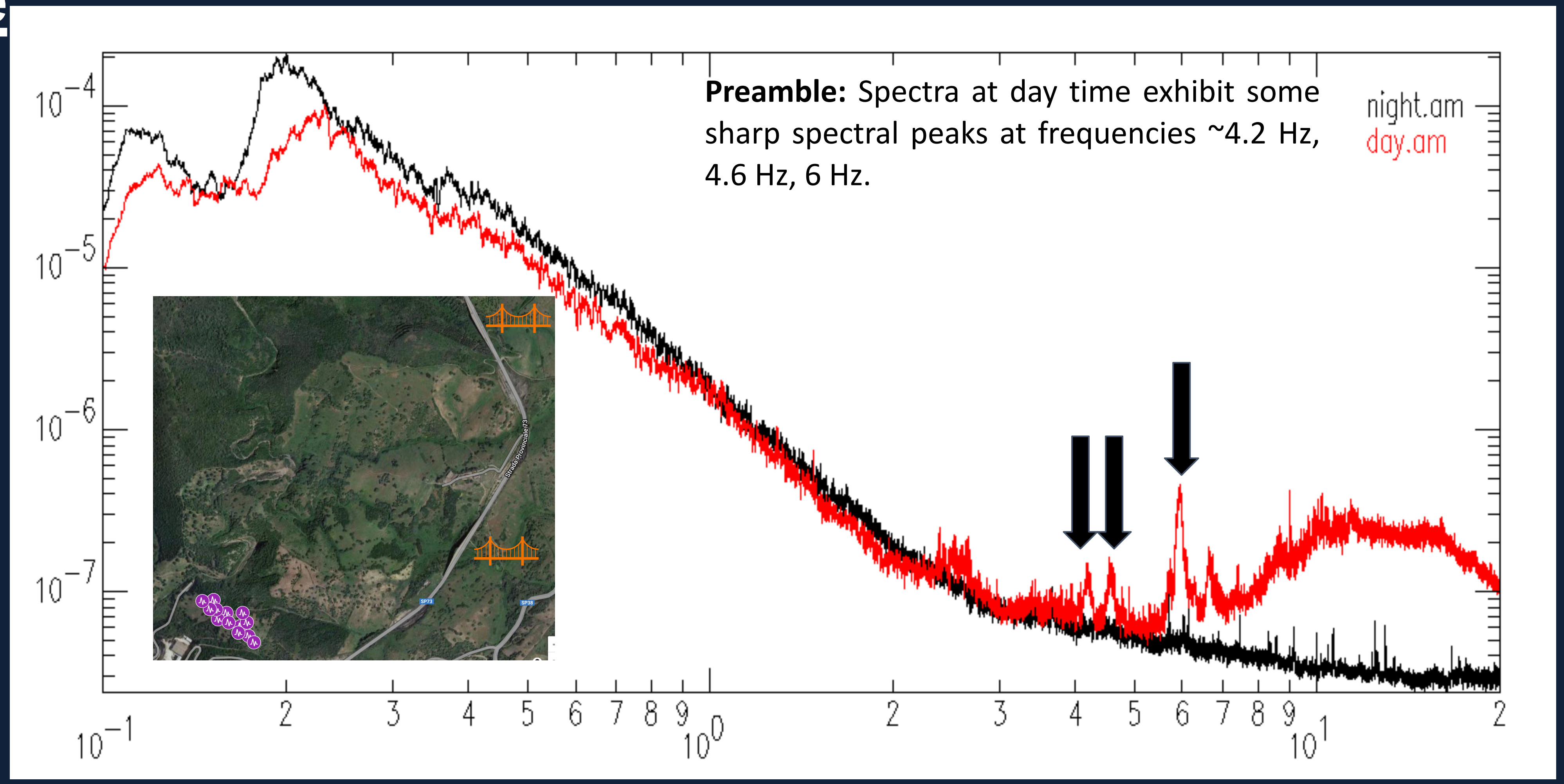


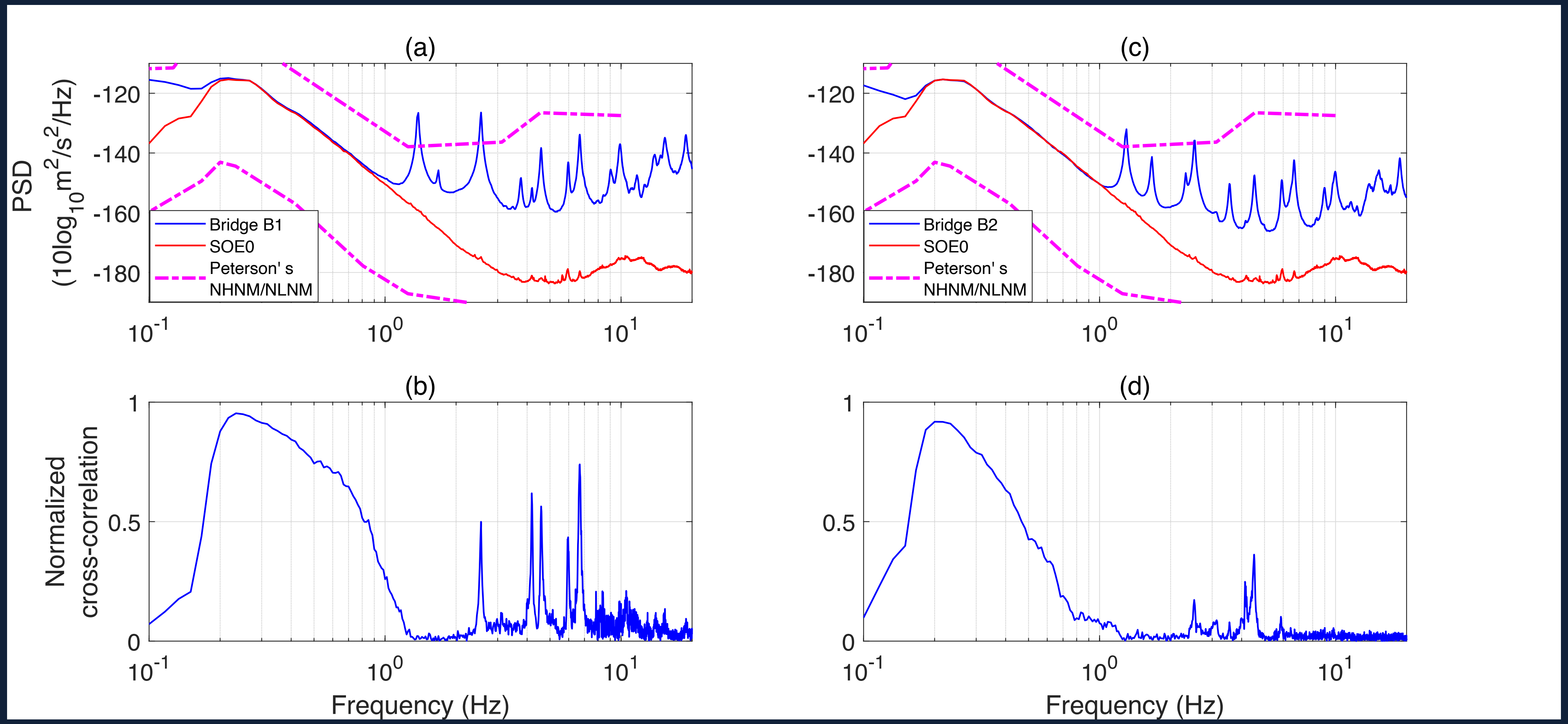


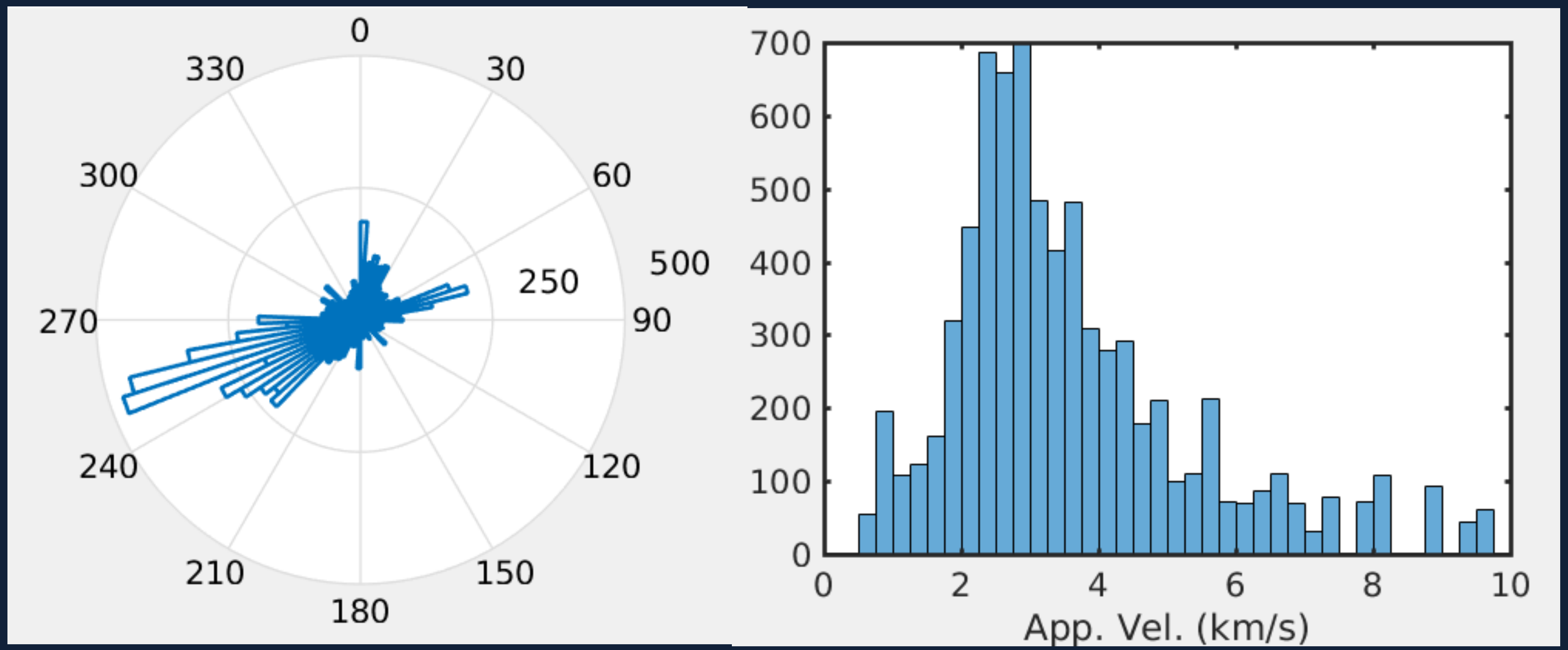
Examples of noise sources observed at the ET candidate site

Cars passing on a bridge

- Spectral correlation confirmed the origin of those peaks;
- The distance of the bridges from the site is no more than 1.5 km;
- Those peaks also have a seasonal frequency drift with different rates;
- This may be caused by temperature variations that change the vibrational properties of the structures;
- Engineers observe drift to lower frequencies as the temperature increases and vice-versa as the temperature decreases;







Examples of noise sources observed at the ET candidate site

Wind turbines

- 9 broadband seismic stations installed in a 13 km long linear array;
- Correlate information about wind speed and direction and other environmental variables, seismic noise and wind turbines activity (RPM, blade orientation, power output, etc…)

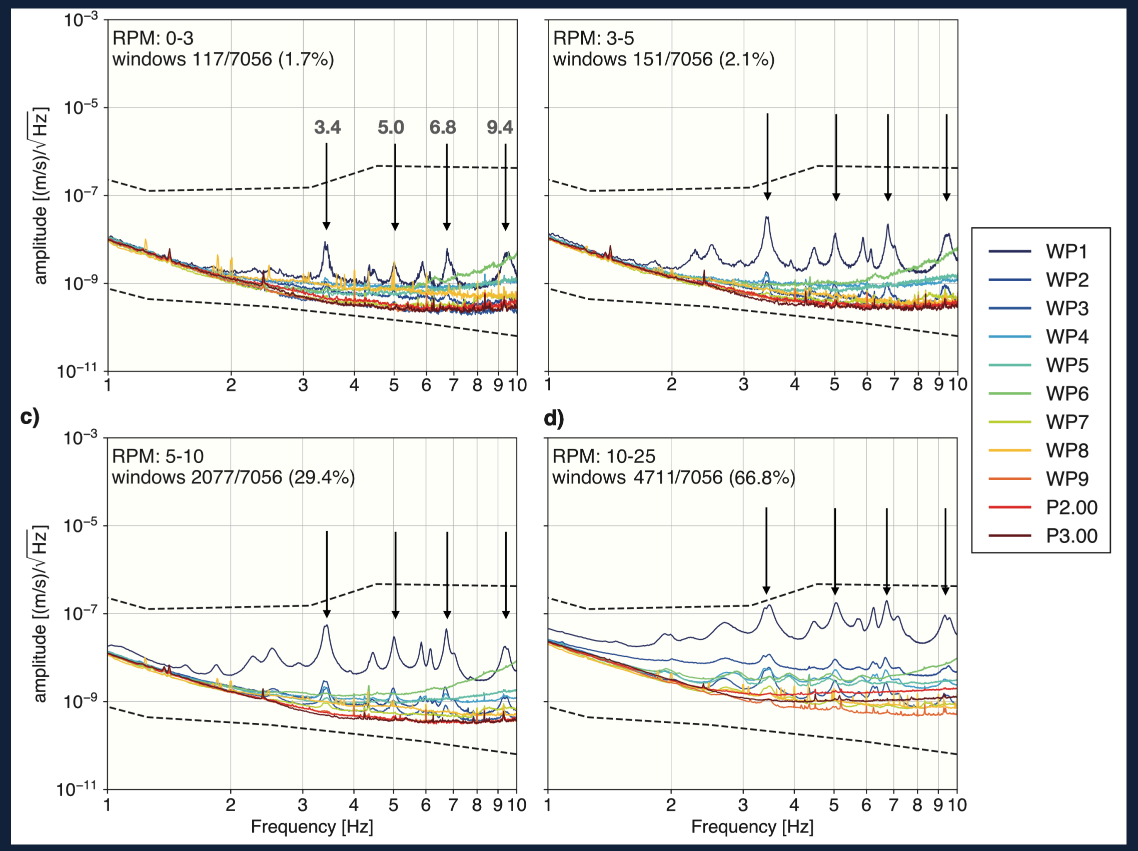
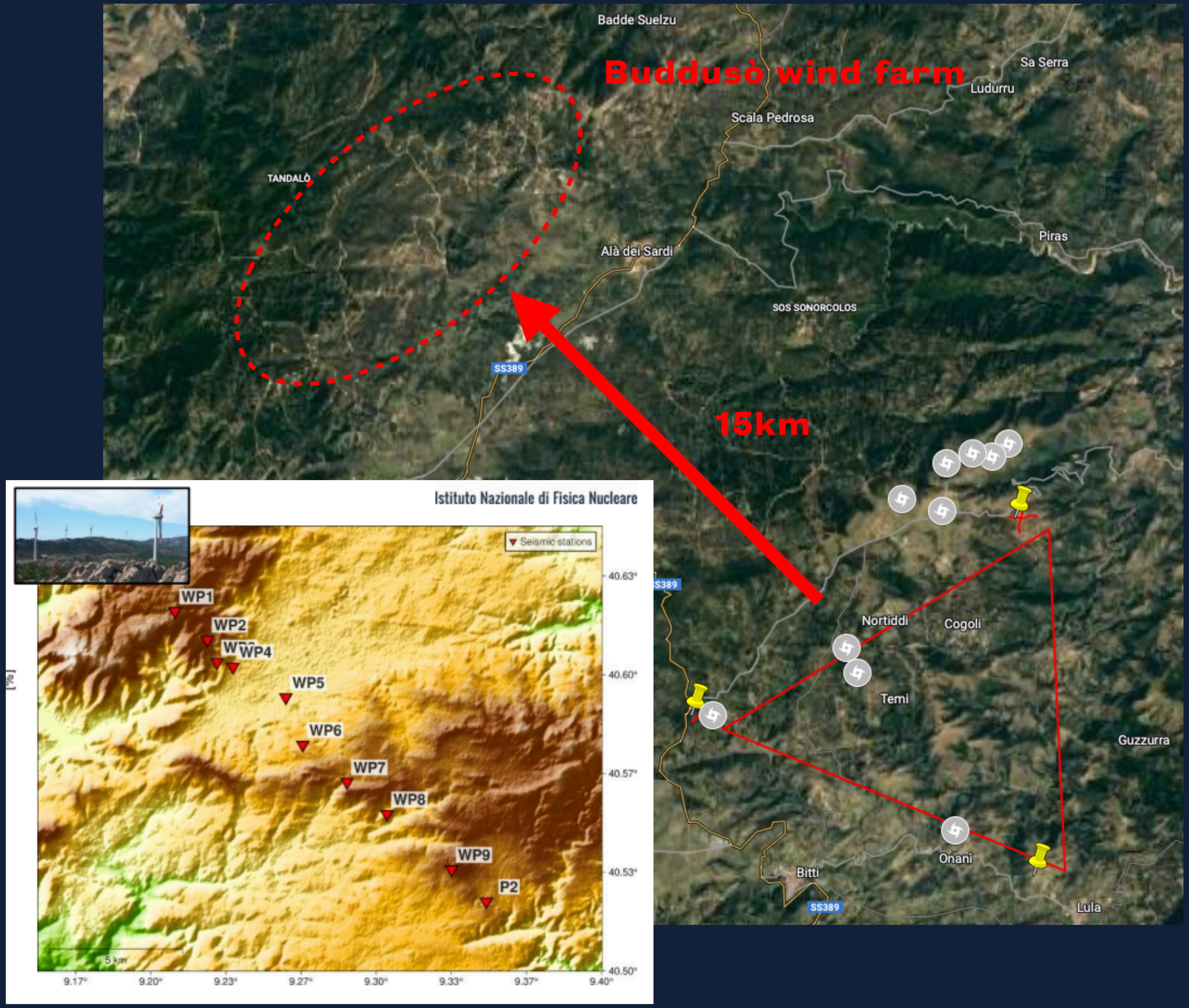


Image credits: G. Diaferia

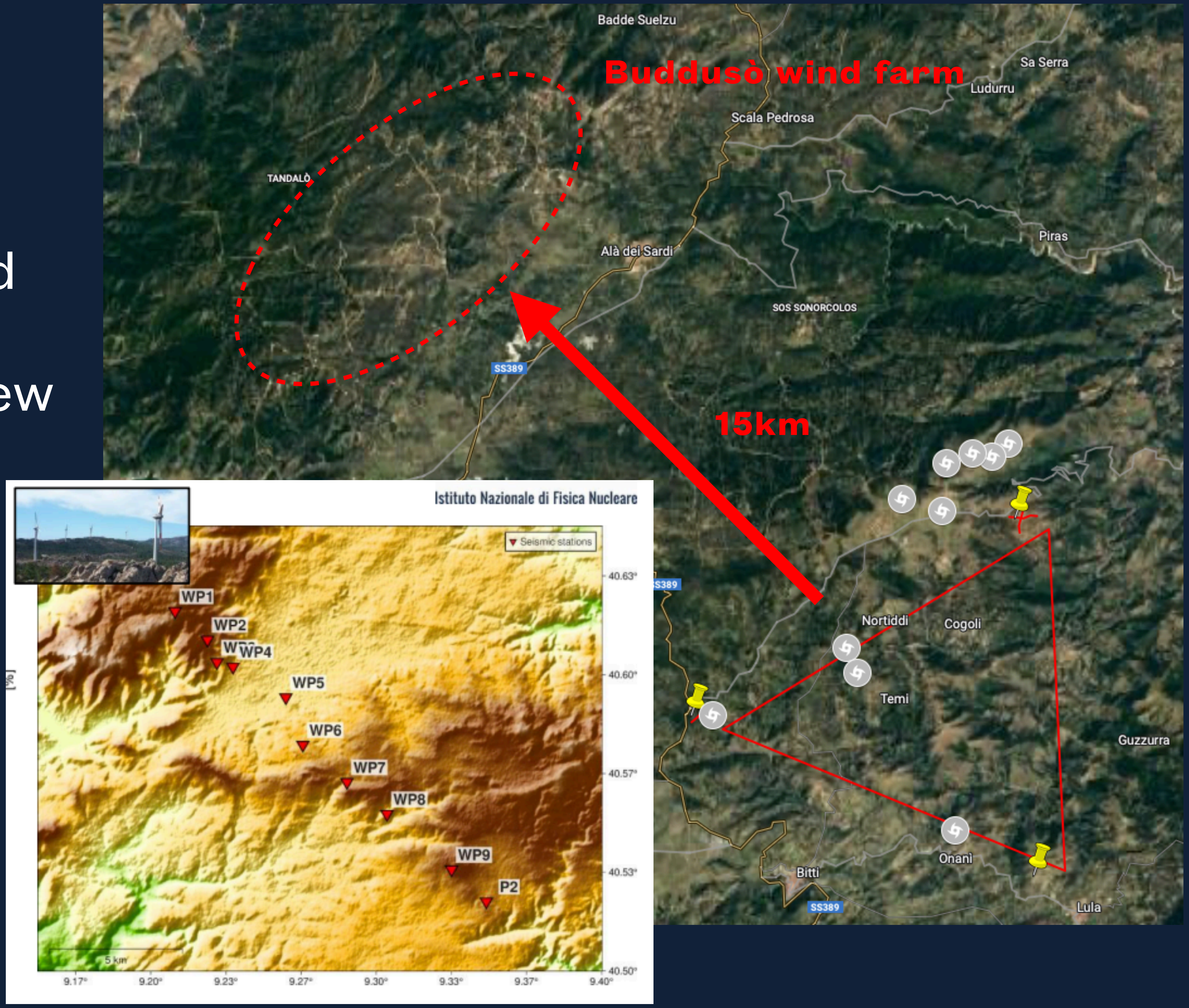
- Amplitude decays as $1/r^2$
- P2/3 mostly affected by local sources excited by wind, peaks visibles only when turbines run at full speed.



Examples of noise sources observed at the ET candidate site

Wind turbines

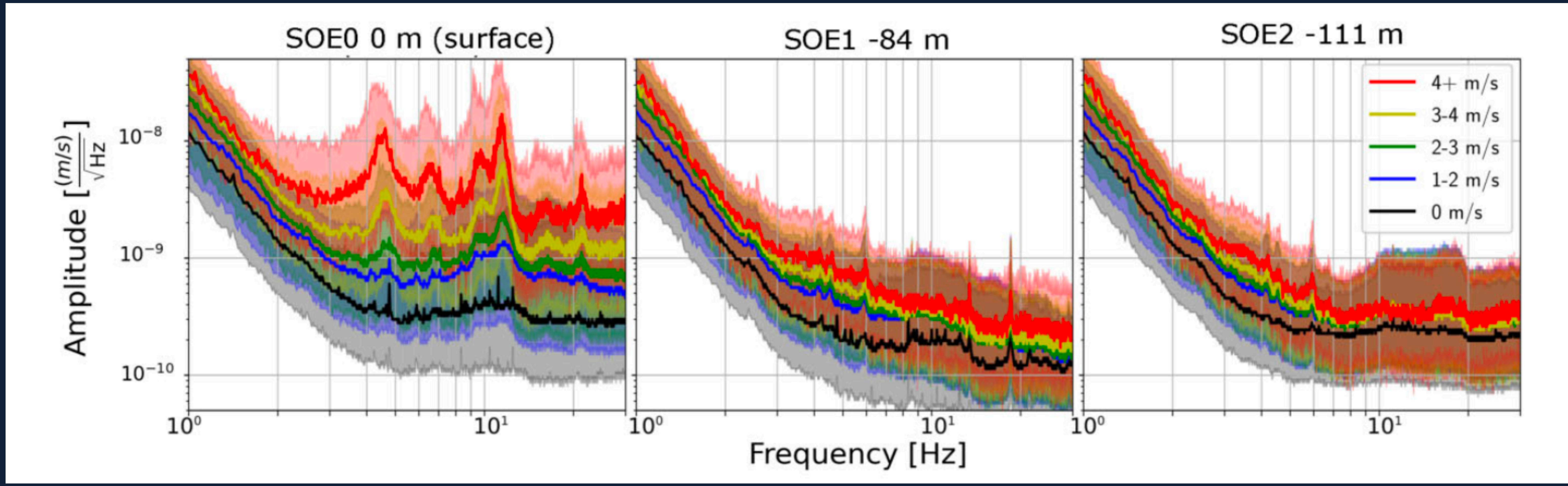
Seismic noise from wind turbines has been observed at the Virgo detectors as well as at the EMR candidate site. Limitations to the construction of new wind turbines at GW detector sites are currently under consideration.



Examples of noise sources observed at the ET candidate site

WIND

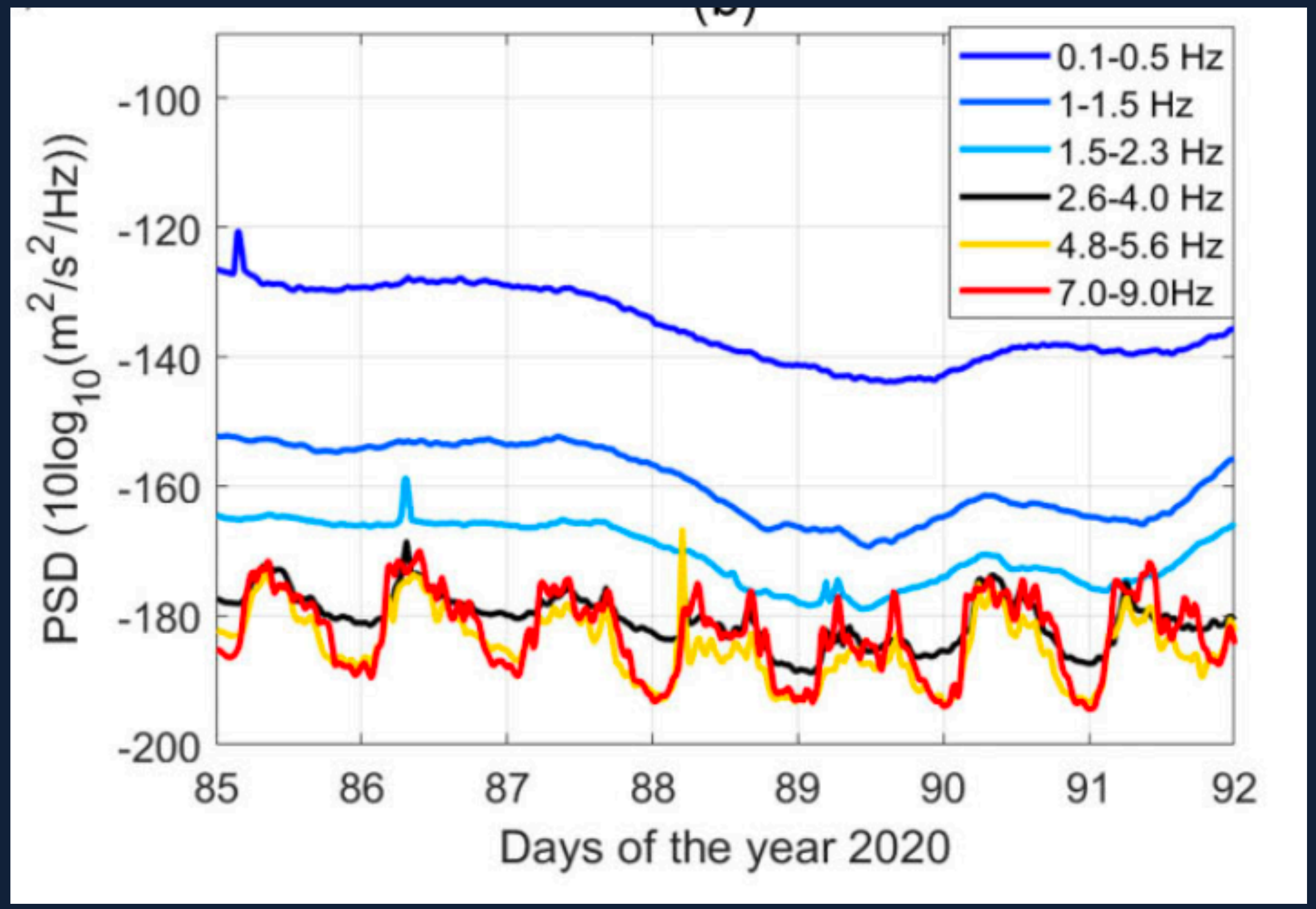
Wind interacts with the surrounding environment, it shakes buildings, trees and other objects of both natural and man made origin. Wind does not excite a single frequency, but it is a broadband noise.

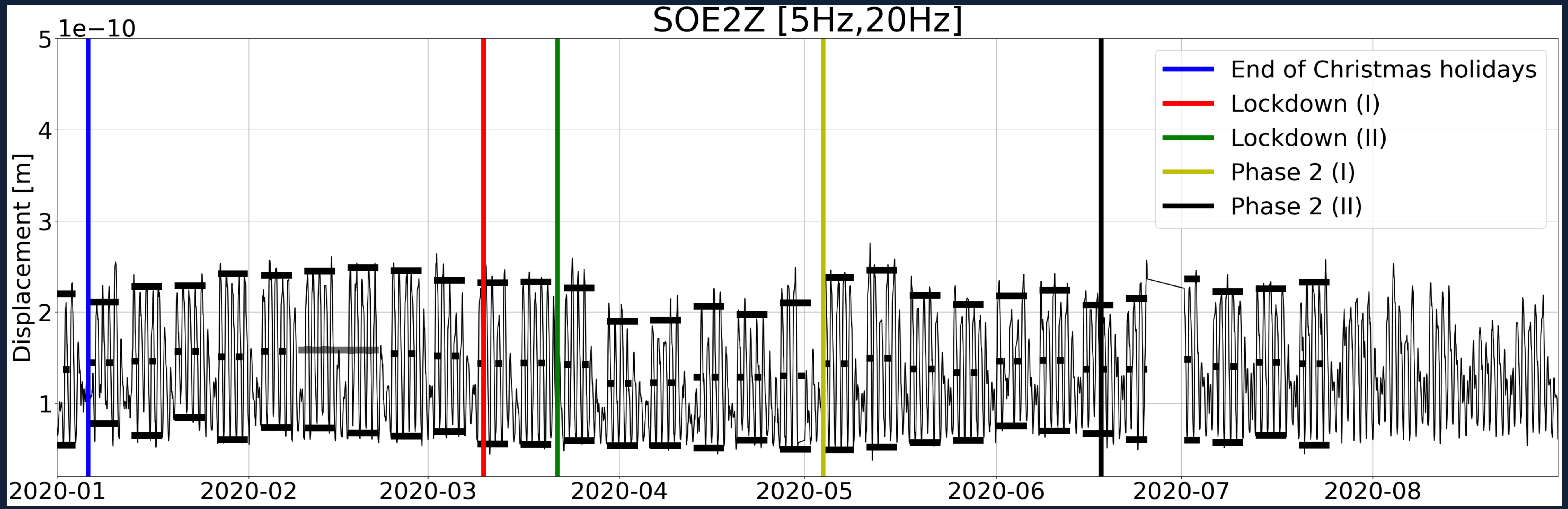


Examples of noise sources observed at the ET candidate site

Generic anthropic activities

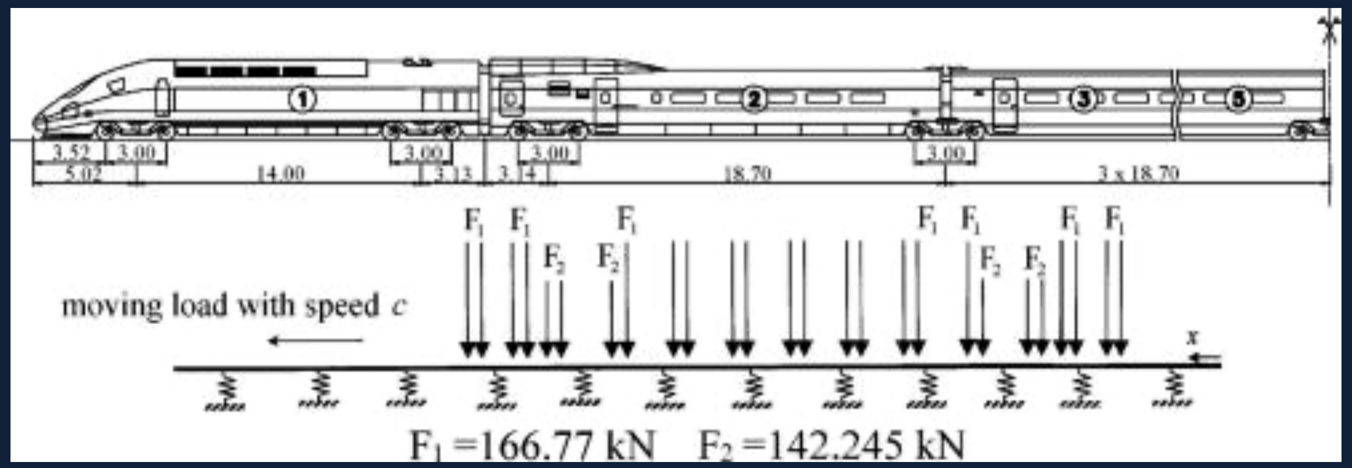
In general, anthropic activities manifest as a day-night cycle in the seismic noise levels.



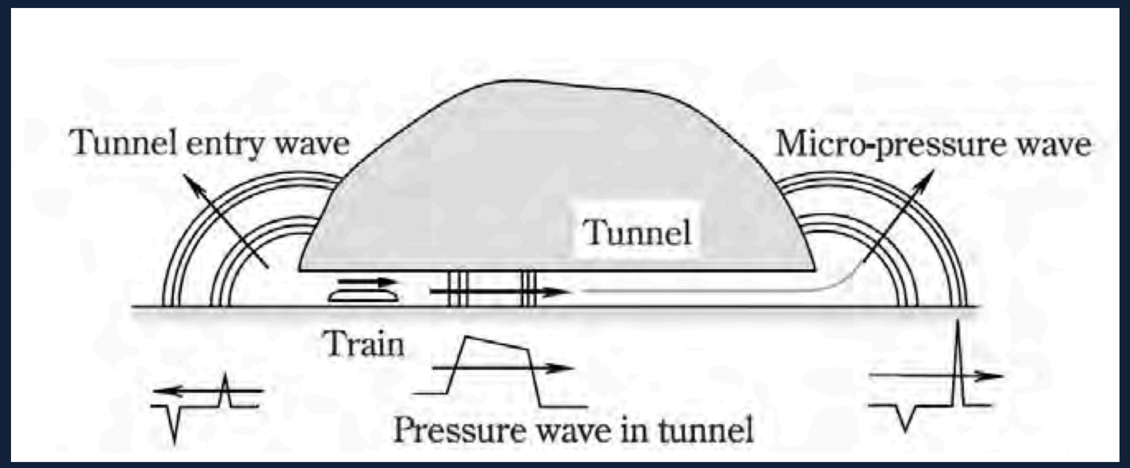


Example of a noise source generating multiple types of noises

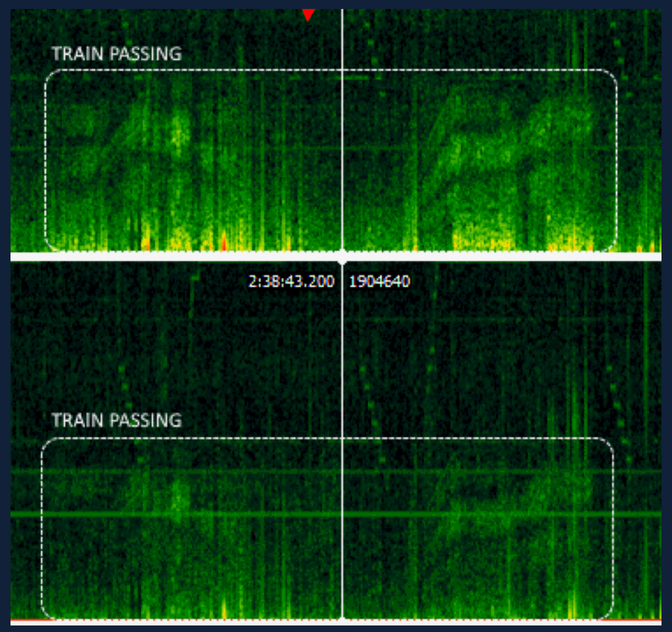
Trains



Ground motion



Air pressure fluctuations

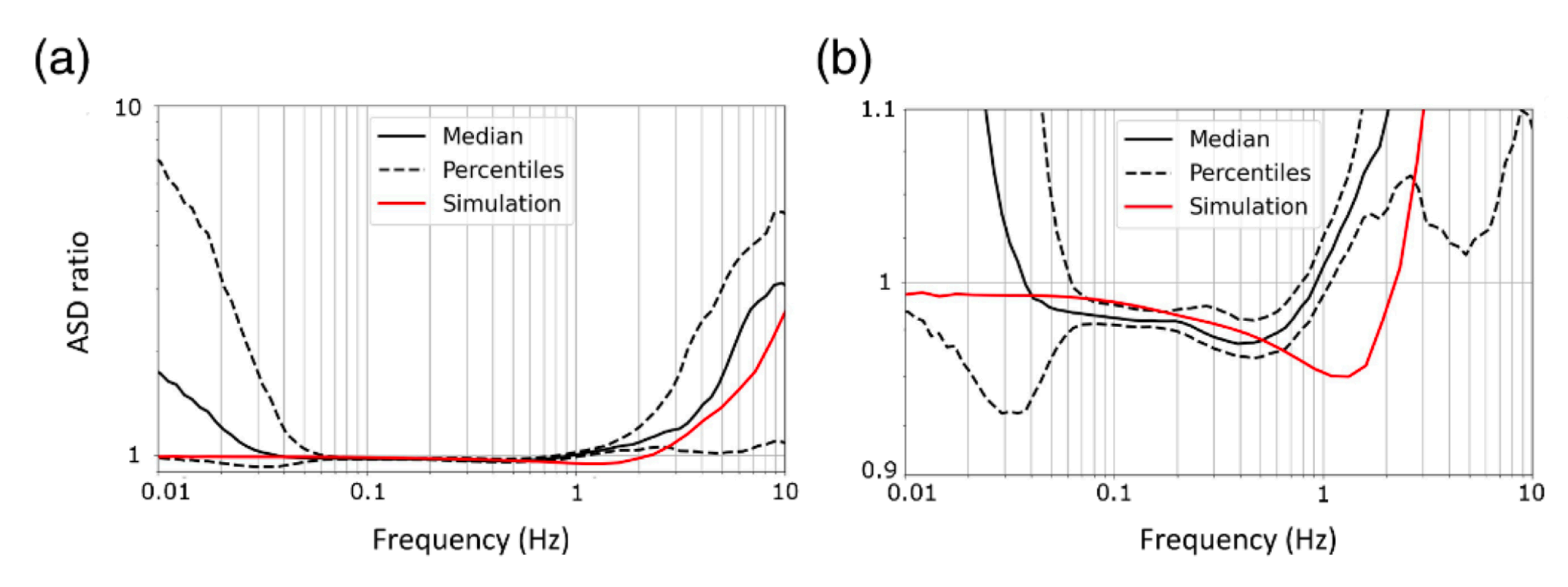


Magnetic noise

Train noise is constantly being monitored at the Virgo site which lays in the vicinity of two train lines.

Attenuation of seismic noise with depth

At a few hundred meters underground, seismic noise is attenuated beyond 1 Hz. In the microseismic noise band, no attenuation can be seen.



Candidate site comparison

Direct comparison of seismic noise spectra shows the differences of the seismic noise levels at the various candidate sites.

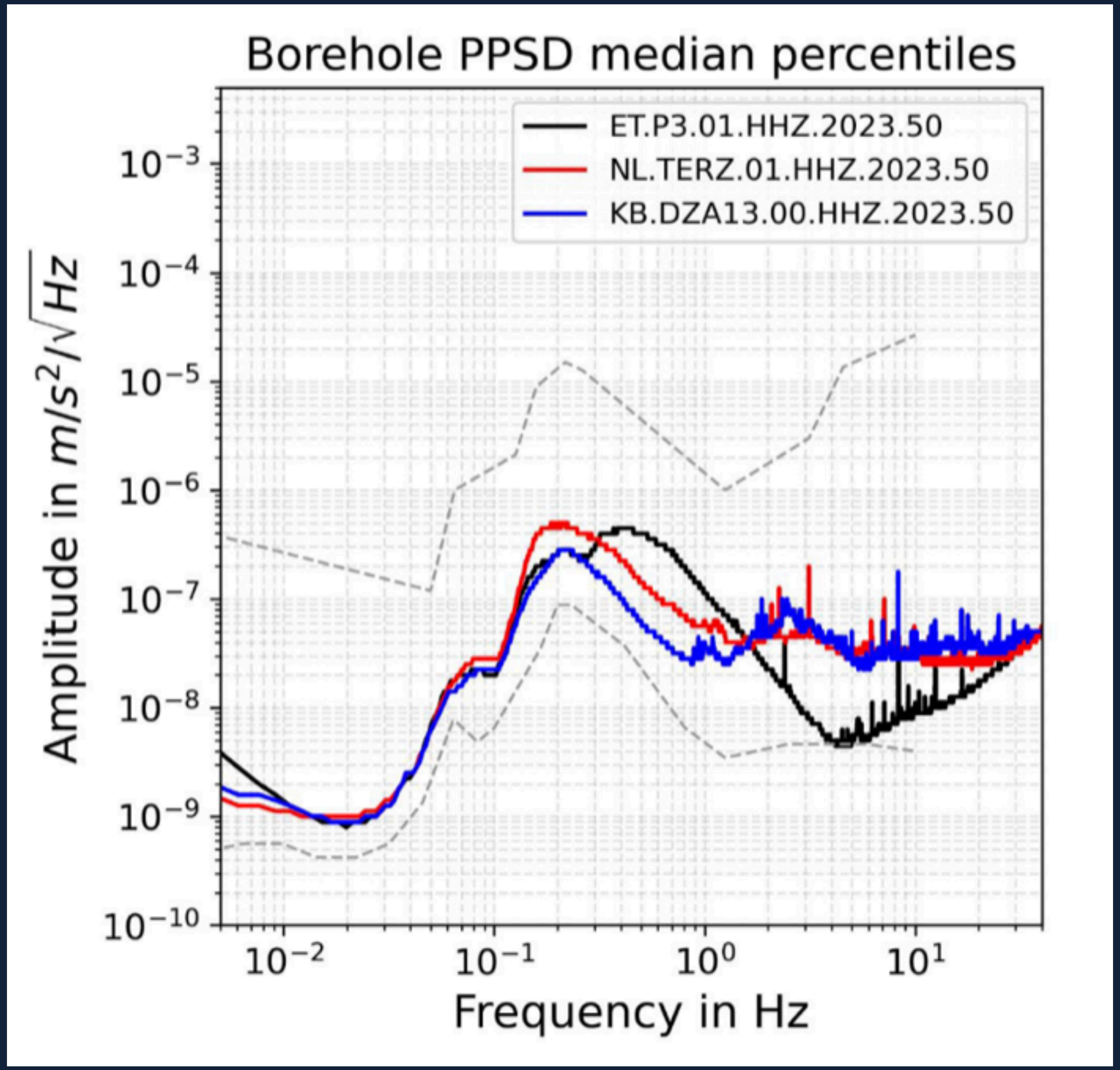
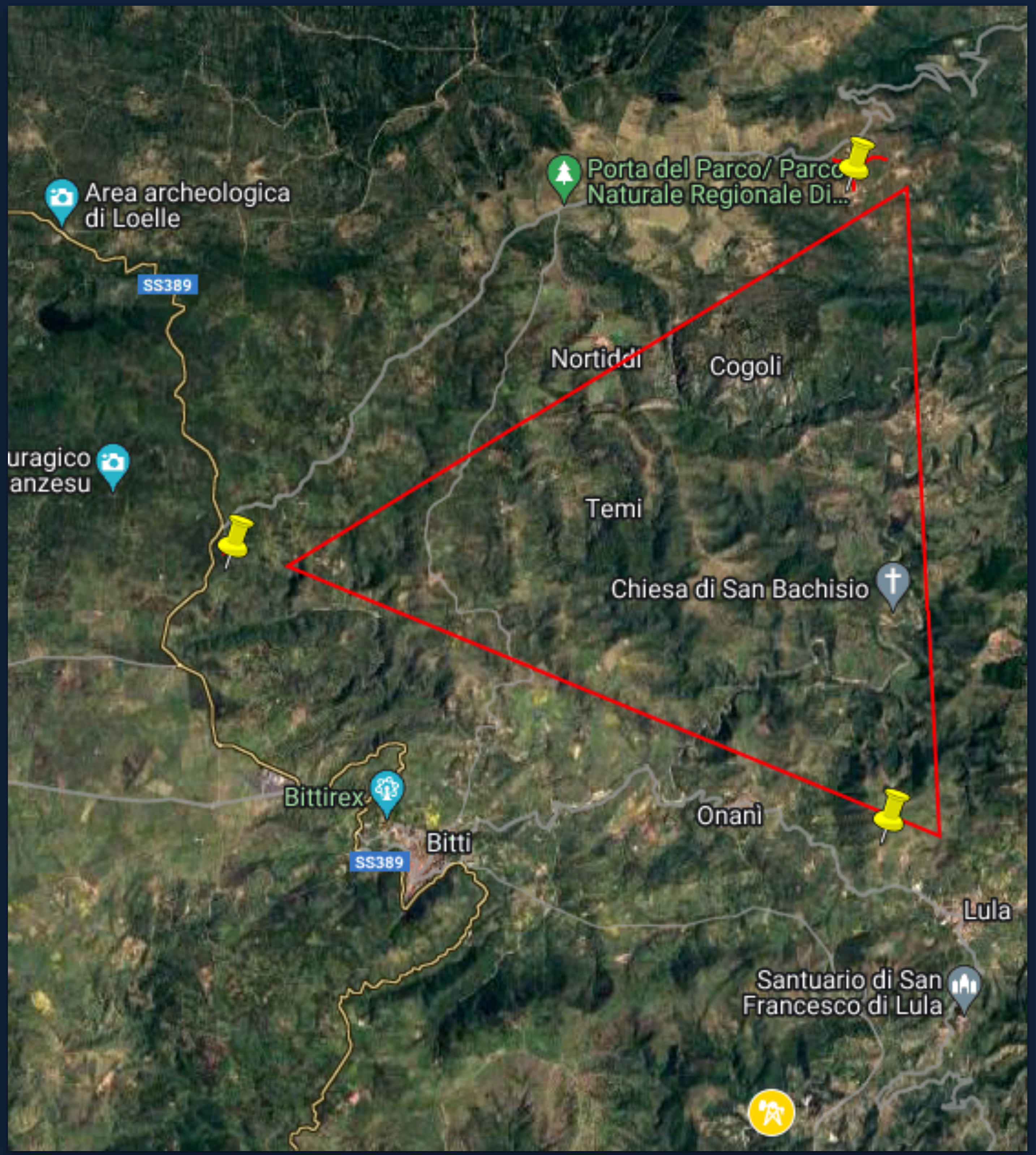


Image credits: A. Rietbrock

Candidate site comparison



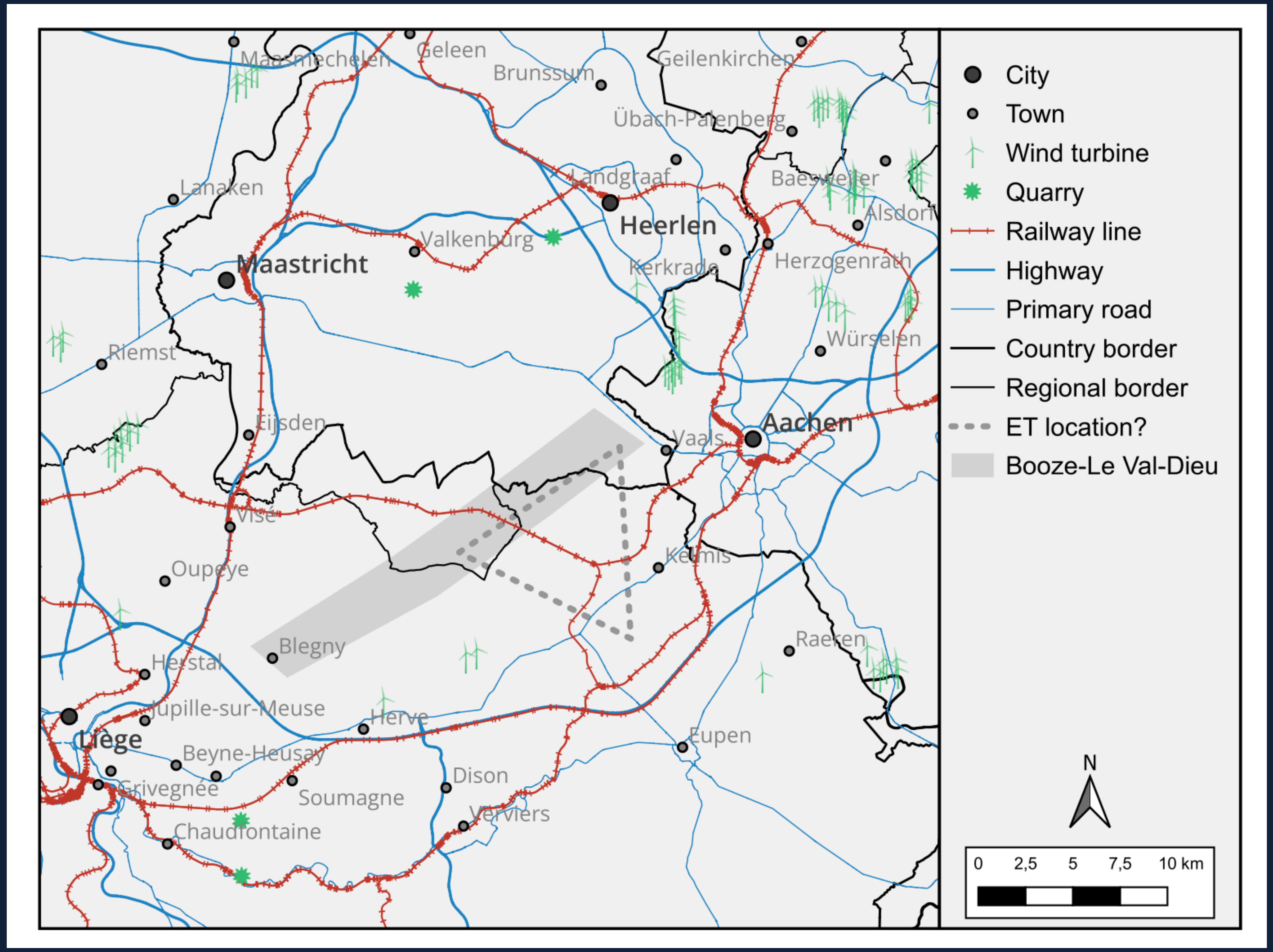
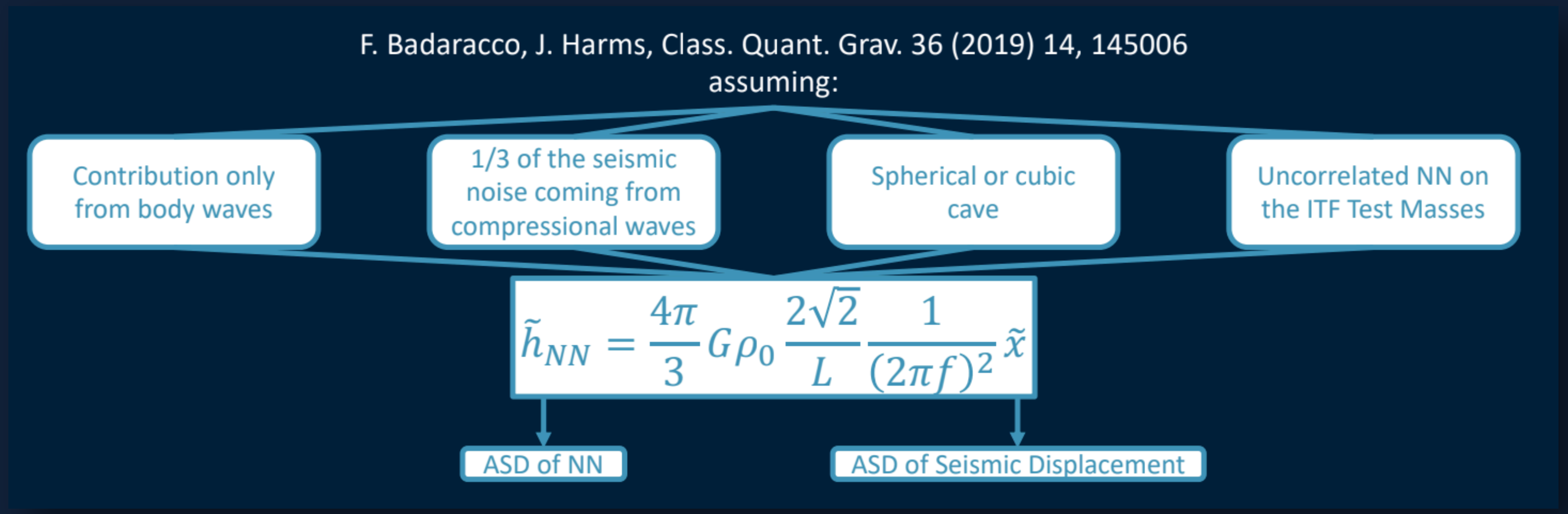
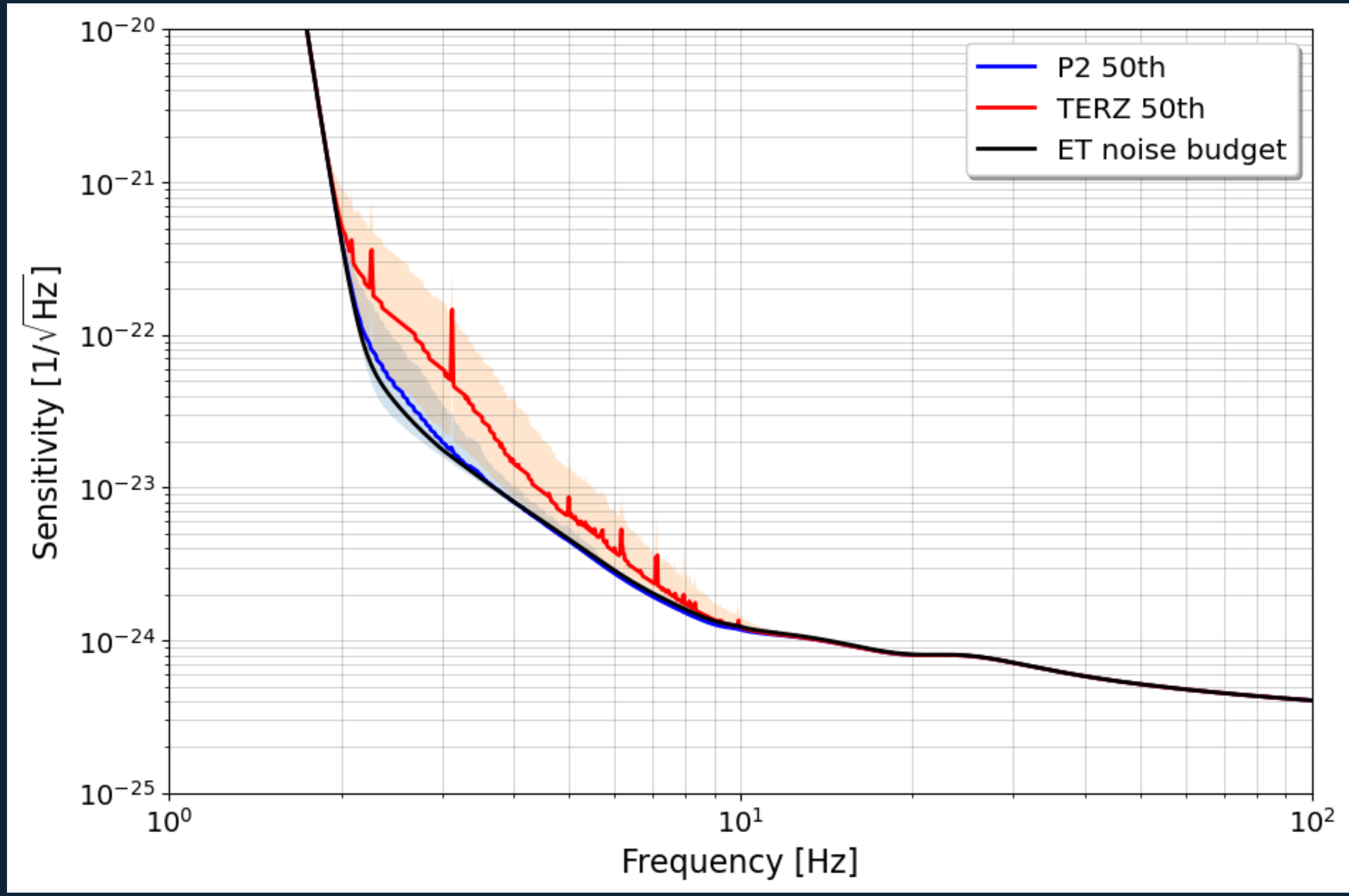


Image credits: G. Degraande

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.





No NN suppression factor is included. As a consequence, Sardinia is already compliant with the requirements of ET, whereas EMR will require dedicated NN suppression systems which are a challenge on their own. Given the challenges for NN cancellation in ET, it is impossible to make a reliable forecast on suppression factors.

Future challenges

If we give for granted that background site seismic ambient noise can be controlled, we will face the following challenges in the future:

- Site ambient noise must be preserved (create protected areas around the detector);
- The experience of the KAGRA detector teaches us that cryogenics is very noisy. Appropriate solutions for ET must be found;
- Currently active underground infrastructures show significant low frequency noise caused by tilt ground motion form pressure generated by ventilation systems. Can we make forecasts for ET?
- An underground infrastructure needs pumps and draining systems to pump out water accumulating underground. This causes additional ambient noise and NN noise for water flowing in the detector experimental area;
- To achieve significant suppression factors, NN cancellation infrastructure (sensors + computational resources) will be a major challenge.

Conclusions

- Einstein Telescope will be a milestone in Gravitational wave science;
- Its great potential comes at the cost of a huge effort to minimize the impact of noise sources;
- Understanding the surrounding environment is paramount to effectively operate ET;
- Seismic noise sources have different origins, some can be controlled, some others not;
- Impact of local seismic noise can be seen in the sensitivity curve of ET;