Status of the ET site characterization of the Sos Enattos area

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on behalf of the ET Sardinia site characterization team

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Università degli Studi di Napoli Federico II

GSSI Gran Sasso Science Institute — School of Advanced Studies — Scuola Universitaria Superiore

ET – Scienza e tecnologia in Italia

Assisi, 20-23 Febbraio 2024

Einstein Telescope – ET project

ET will be a **3rd generation GW Observatory** with a target sensitivity ten times better than current advanced detectors, but up to 10^6 better in the **LF (low frequency) band: 2-10Hz**!

https://www.einstein-telescope.it

Two sites are officially candidate to host ET: **EMR** (NL,BE,GE) and **Sardinia** (IT) + one potential site in Lusatia (GE). Italian candidature became official in June 2023, supported by the Italian Government.

Site Characterization is a crucial activity to check if the site meets the *fundamental requirements*, to evaluate the *impact of local environmental noises* on the detector performances and to prepare possible mitigation strategies. Important sources of environmental noise (in particular, in the LF band): **seismic** (and **Newtonian**), **magnetic**, **acoustic**.

Site Characterization in ET

ET Executive Board

Specific Boards

- **SPB** – Site Preparation Board
- **OSB** – Observation Science Board
- **ISB** – Instrument Science Board
- **EIB** – E-Infrastructure Board

Divisions

WD1 Physical variables and characterization

WD2 Geology

Site Characterization

Active Noise Mitigation

ET COLLABORATION

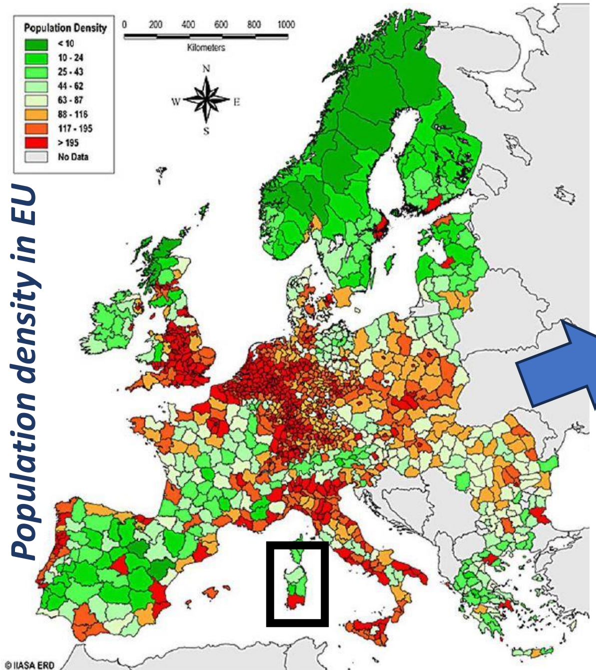
ET EINSTEIN TELESCOPE

Site Characterization at the candidate sites is coordinated in the framework of the ET **Collaboration Site Preparation Board (SPB)**. *Strong interaction with the Active Noise Mitigation division in the Instrument Science Board (ISB).*

Why in Sardinia?

Sardinia is made of:

- Quaternary alluvial deposits and minor intra-plate volcanism
- Tertiary sedimentary basins with volcanic units
- Deeply eroded Mesozoic sedimentary rocks
- Metamorphic basement widely intruded by Carboniferous-Permian Granitoids (Variscan orogenesis; 360-290 Ma)

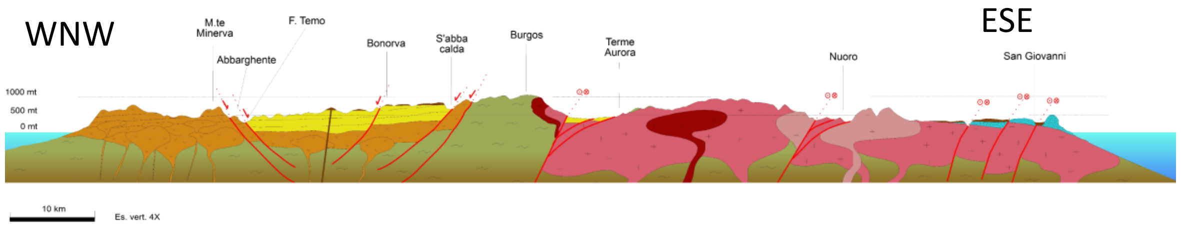


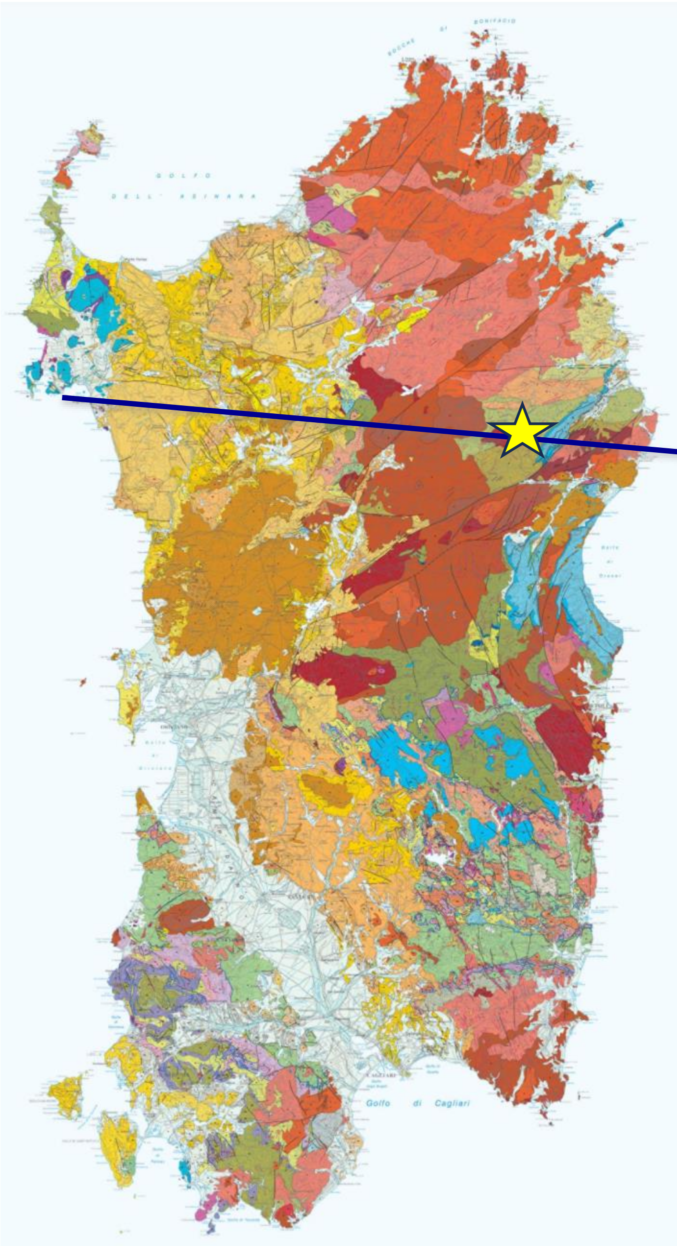
Population density in EU

The ET Italian candidate site is located in the stable Variscan basement of Sardinia.

- Geodynamic quietness
- Low Anthropogenic noise
- Low E.M. noise

LOW SEISMIC NOISE!

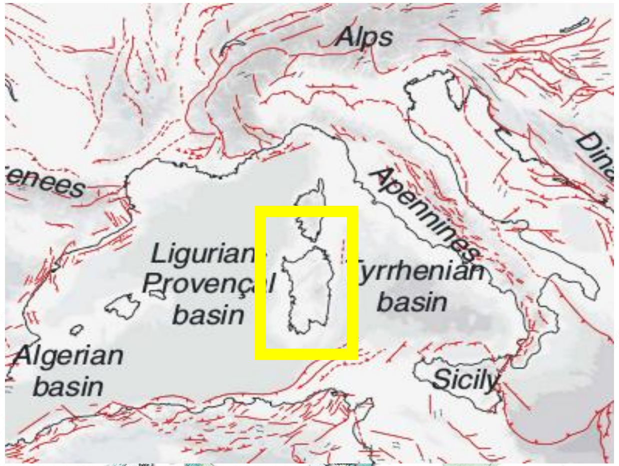


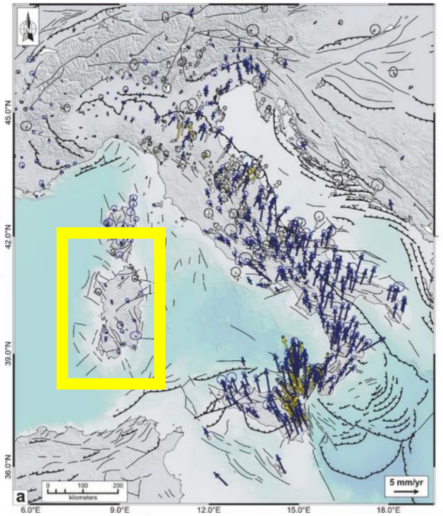


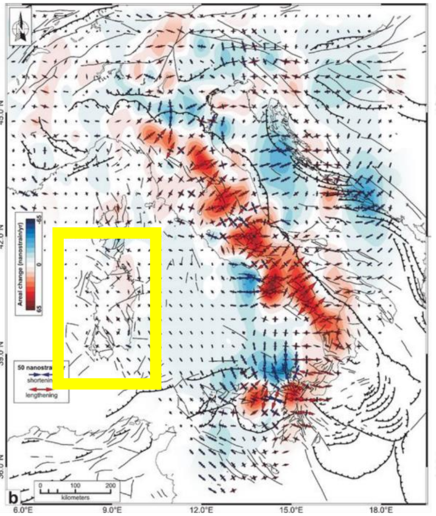
Why in Sardinia?

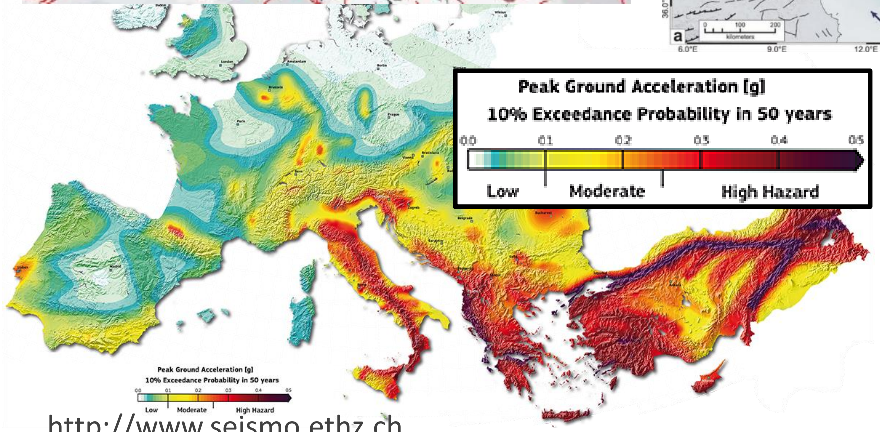
Sardinia, the geological framework

Far from active fault lines, the Corsica-Sardinia microplate is very stable → low crustal deformation.



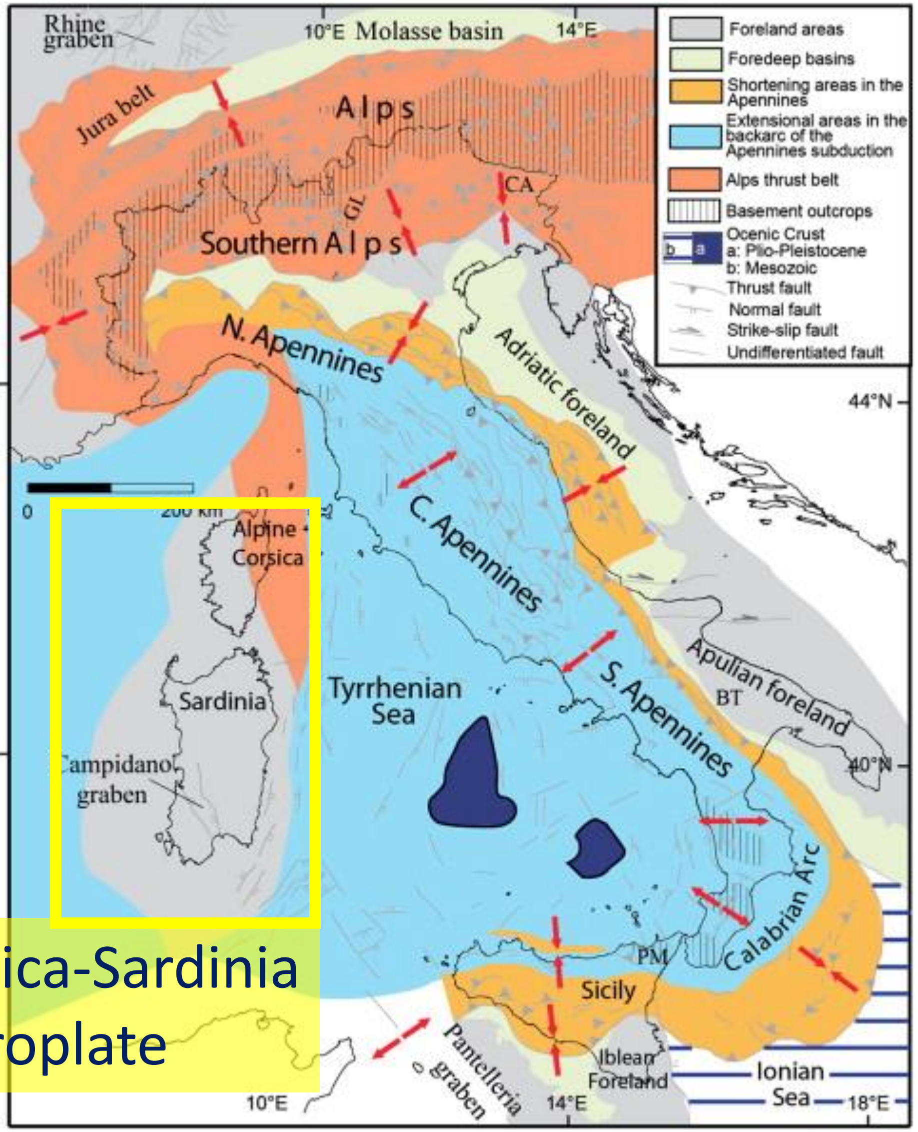






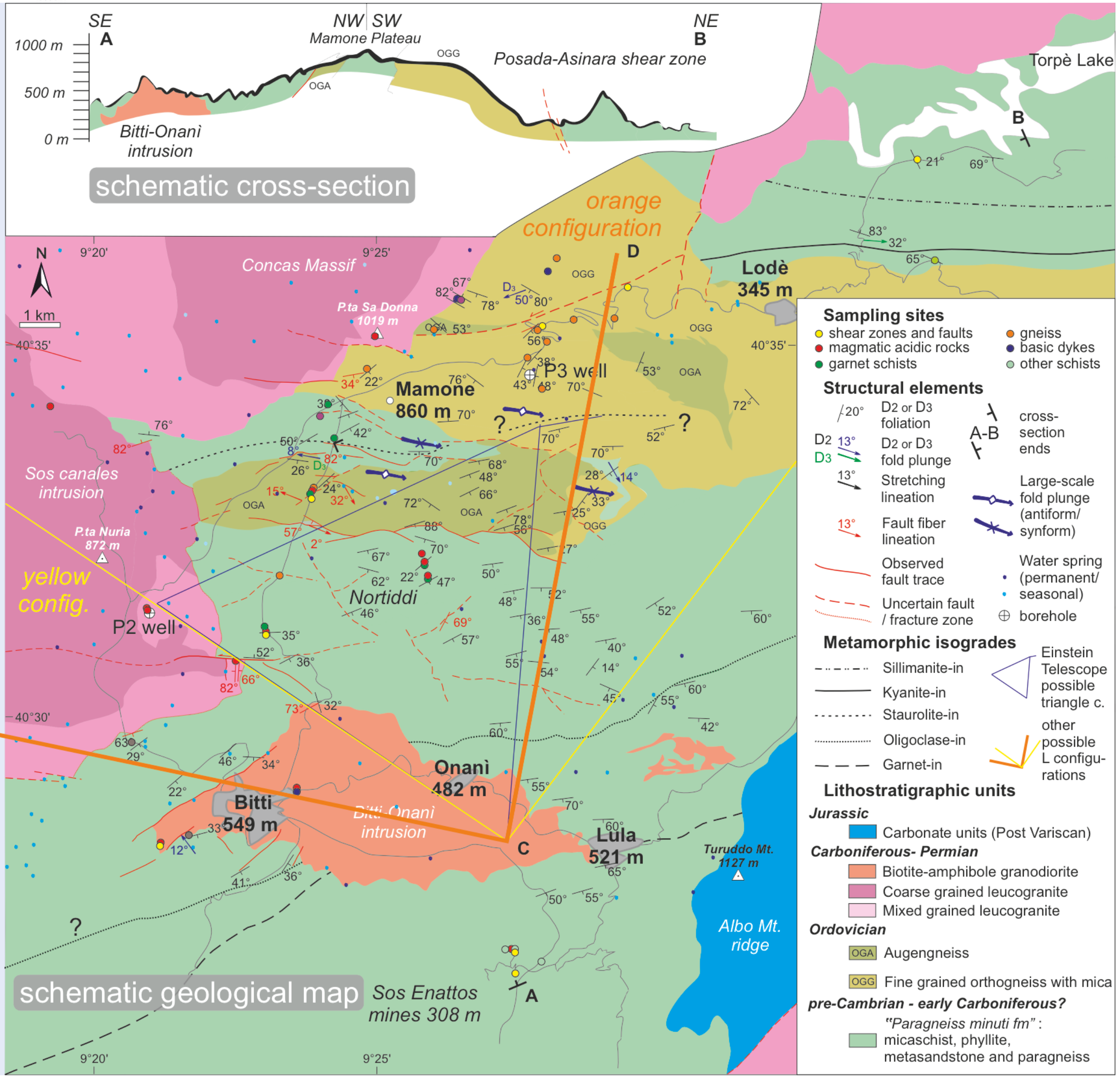
http://www.seismo.ethz.ch

Unaffected by significative seismic activity.



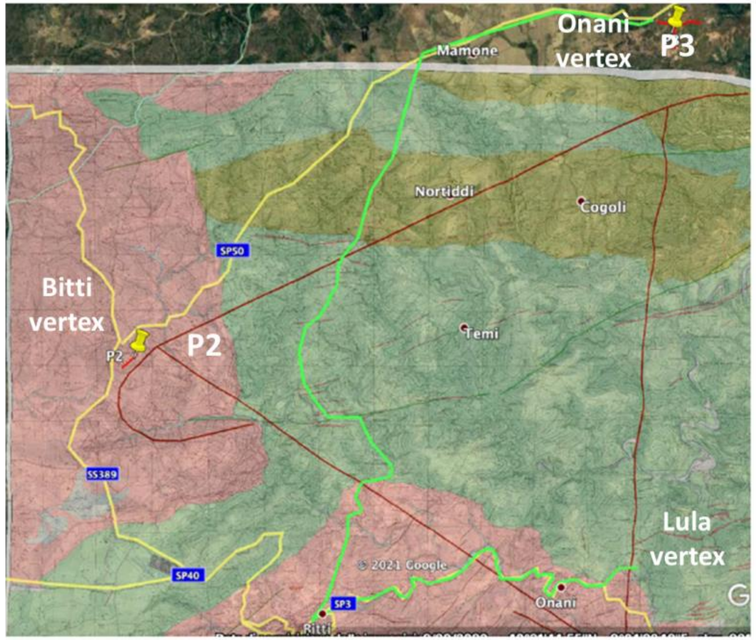
Corsica-Sardinia Microplate

Why in Sardinia?



Good rock quality

Lithologies: Orthogneiss, granitoids, micaschists. The red triangle represents the hypothetic Δ underground trace of ET. One of the possible L traces is also shown. P2 and P3 are the borehole locations. Ongoing geological survey of the area and review of the geological maps.



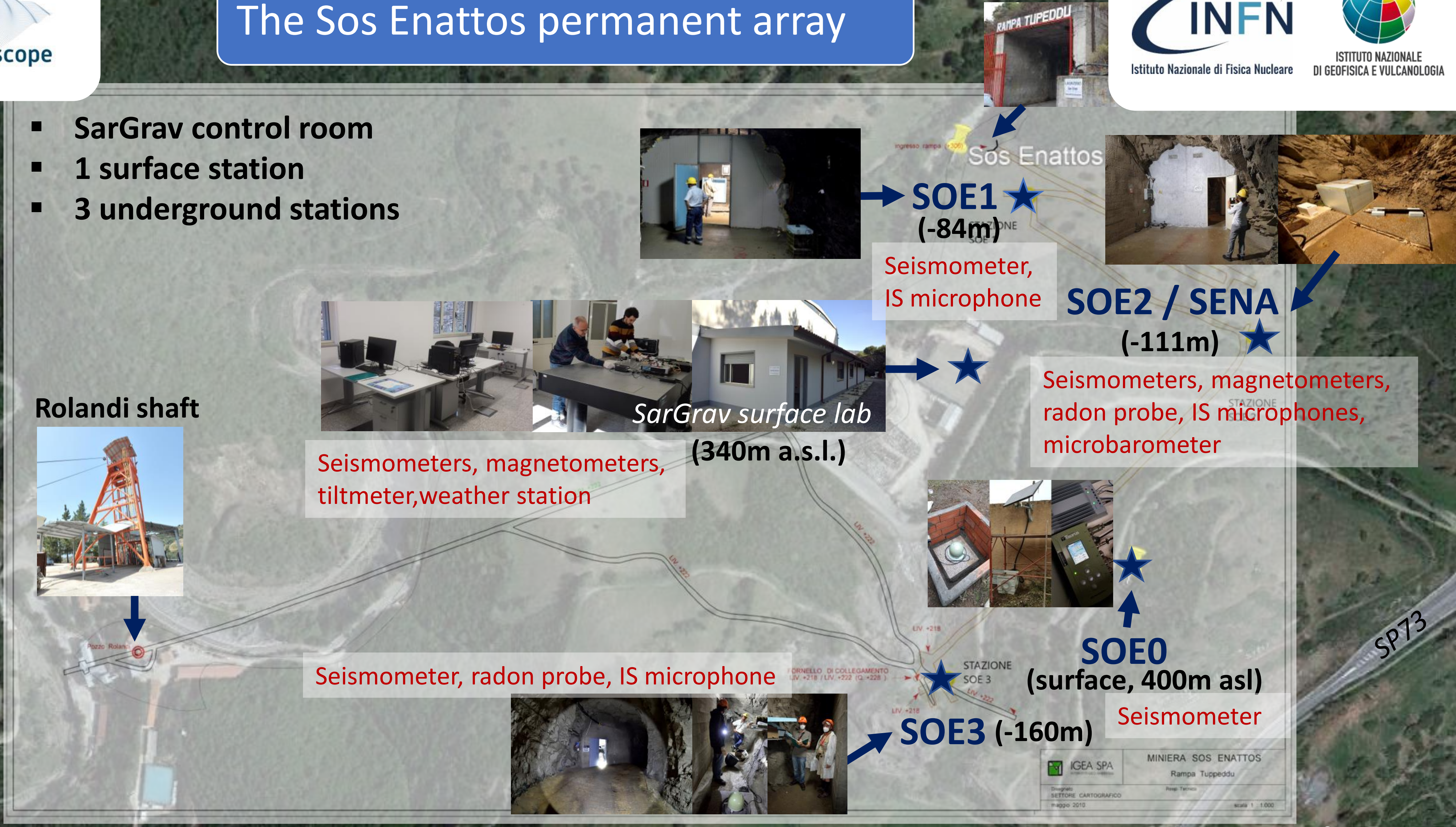
The Sos Enattos site

Sos Enattos former mine

- **First seismic characterization in 2010-2014**
- **ET full site characterization started in 2019**

The Sos Enattos permanent array

- SarGrav control room
- 1 surface station
- 3 underground stations



The Sos Enattos site

Site characterization of the former mine

Instrumented stations

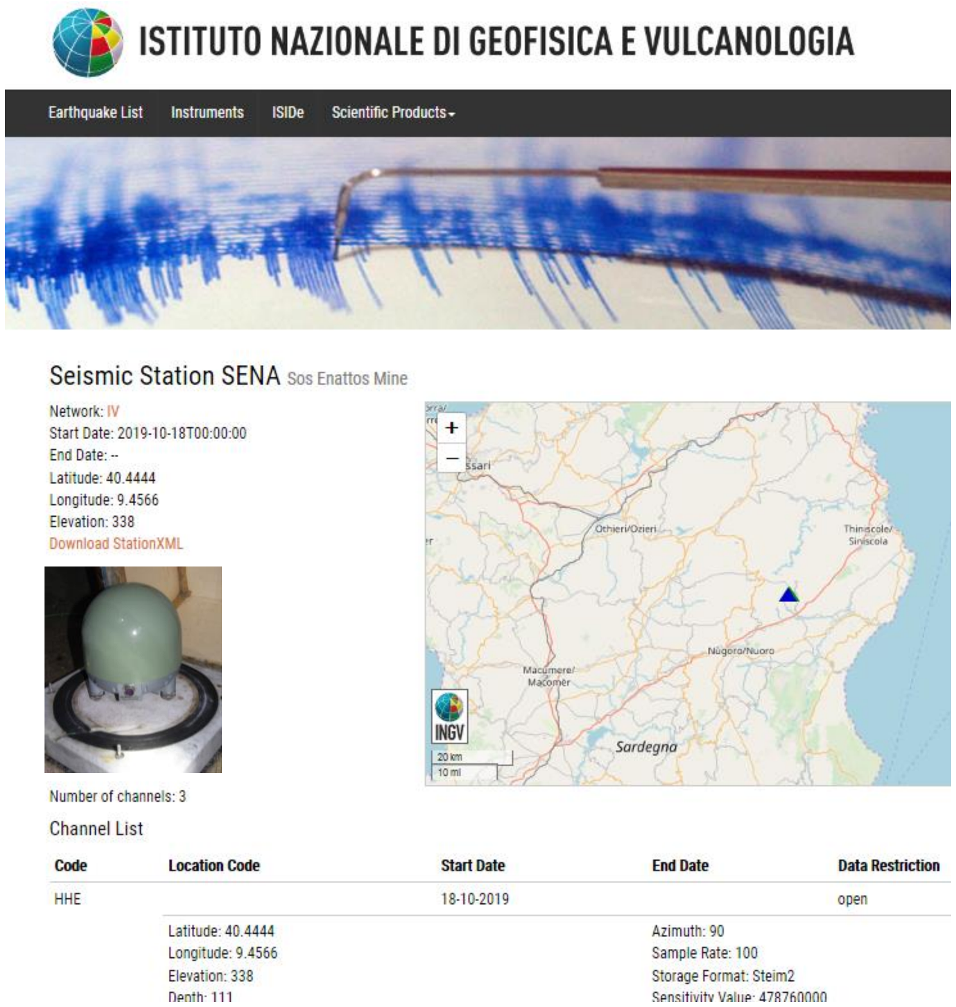
- **SarGrav surface Lab + Control Room**;
- **SOE0** (surface);
- **SOE1**, **SOE2**, **SOE3** (-86m, -111m, -160m underground).

Sensors currently installed:

- 5 broadband triaxial seismometers (*Nanometrics Trillium 360, 240, Guralp 360 CMG-3TD*).
- 3 magnetometers (*MF6-06*, N-S at surface, N-S & E-W underground).
- Several infrasound microphones and microbarometers (surface & underground).
- 8 short-period triaxial seismometers (*Nanometrics Trillium 20PH,* movable array).
- High sensitivity Tiltmeter (part of the *Archimedes* experiment @ SarGrav).
- Weather station (@ SarGrav Lab).
- Radon probes.

The Sos Enattos site

Site characterization of the former mine



SOE2 station is integrated into the Italian national seismometer network of INGV. Station: **SENA**, network:

- IV (Italian National Seismic Network - INSN), 2019-2022/01
- MN (*Mediterranean Very Broadband Seismographic Network*) since 2022/02

http://cnt.rm.ingv.it/en/instruments/station/SENA

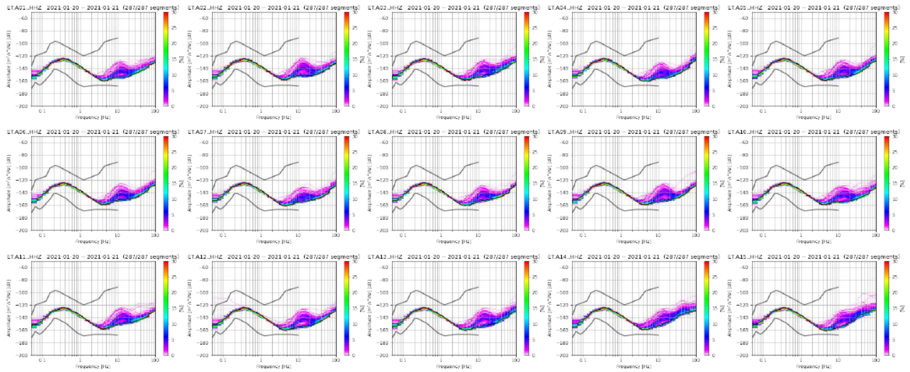
The Sos Enattos site

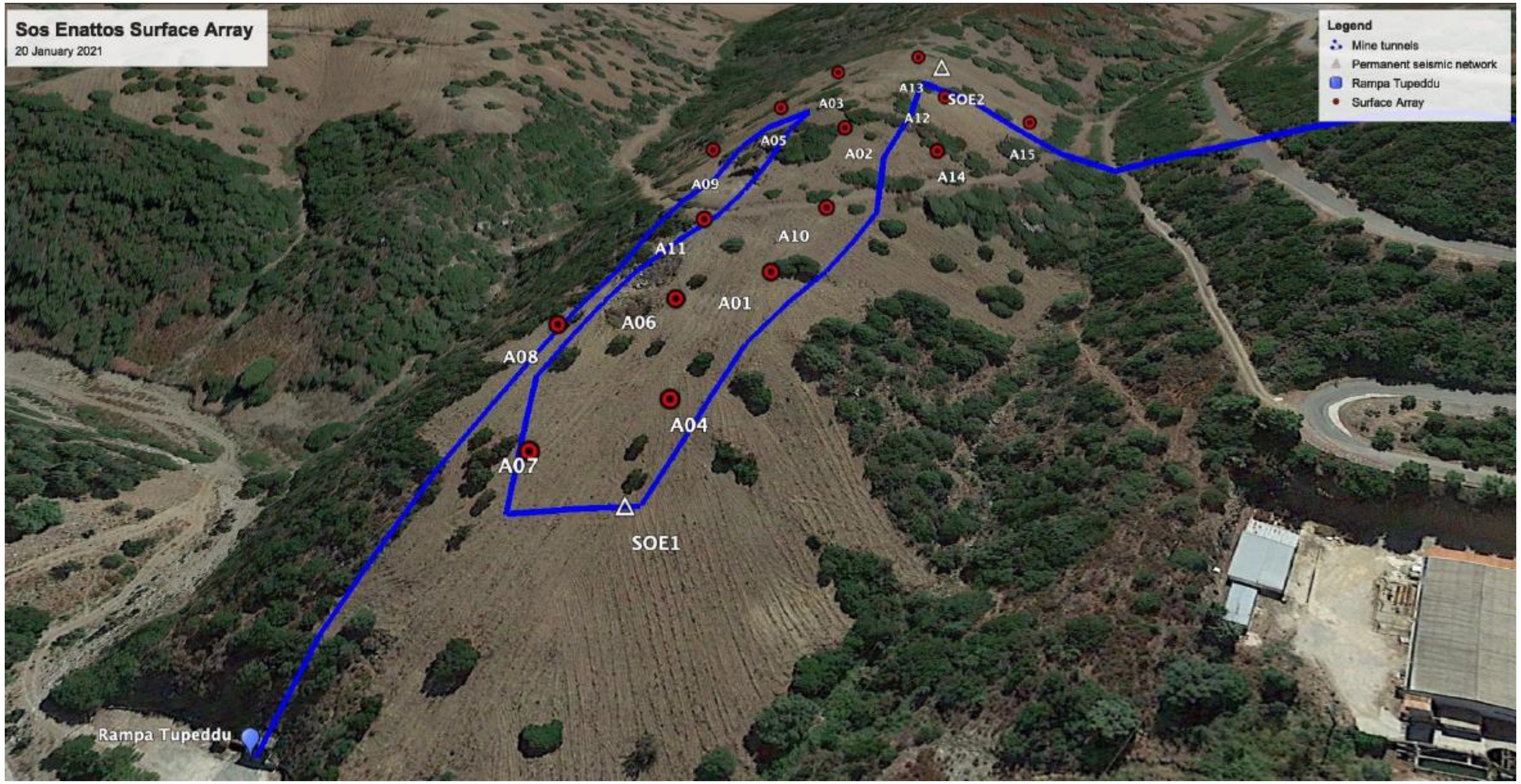
Surface Seismometer Array

Local noise sources and Noise modelization

A surface array made of tens of seismometers (12 Trillium120 + 3 Trillium20 provided by INGV & INFN) have been installed at the top of Sos Enattos mine in January-February 2021.

Preliminary test





Einstein Telescope ITALY

The Sos Enattos site

INFN Istituto Nazionale di Fisica Nucleare

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First results: publications

- L. Naticchioni et al., ***Microseismic studies of an underground site for a new interferometric gravitational wave detector***, **CQG**, 2014, https://doi.org/10.1088/0264-9381/31/10/105016
- L. Naticchioni et al., ***Characterization of the Sos Enattos site for the Einstein Telescope***, **JPCS** 1468, 2020, https://doi.org/10.1088/1742-6596/1468/1/012242
- M. Di Giovanni et al., ***A seismological study of the Sos Enattos Area – the Sardinia Candidate Site for the Einstein Telescope***, **SRL**, 2020 https://doi.org/10.1785/0220200186
- A. Allocca et al., ***Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency***, **EPJP**, 2021 https://doi.org/10.1140/epjp/s13360-021-01450-8
- Allocca *et al.* **Picoradiant tiltmeter and direct ground tilt measurements at the Sos Enattos site**, *Eur. Phys. J. Plus* **136**, 1069 (2021). https://doi.org/10.1140/epjp/s13360-021-01993-w
- M. Di Giovanni et al., ***Temporal variations of the ambient seismic field at the Sardinia candidate site of the Einstein Telescope***, **Geophysical Journal International**, 2023, https://doi.org/10.1093/gji/ggad178
- G. Saccorotti et al., ***Array analysis of seismic noise at the Sos Enattos mine, the Italian candidate site for the Einstein Telescope***, 2023, https://doi.org/10.1140/epjp/s13360-023-04395-2.
- L .Naticchioni et al., **Results of the site characterization in Sardinia for the Einstein Telescope**, **PoS Proc. Sci.**, 2023, *accepted for publication*.

+ several internal notes, reports and talks

The Sos Enattos site

First results

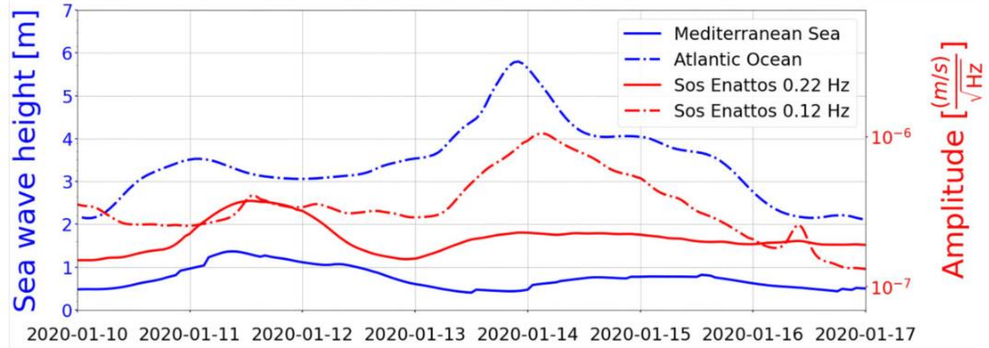
Geophysical Journal International

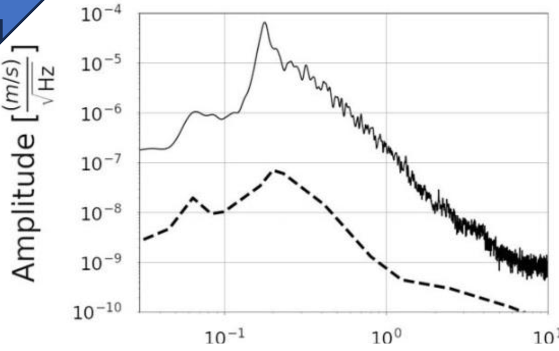
Geophys. J. Int. (2023) 234, 1943–1964
Advance Access publication 2023 April 26
GJI Seismology
https://doi.org/10.1093/gji/ggad178

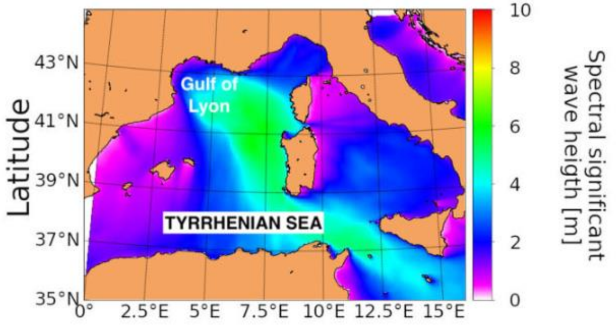
Temporal variations of the ambient seismic field at the Sardinia candidate site of the Einstein Telescope

M. Di Giovanni,[1,2] S. Koley,[1,2] J. X. Ensing,[3] T. Andric,[1,2] J. Harms,[1,2] D. D'Urso,[4,5] L. Naticchioni,[6,7] R. De Rosa,[8,9] C. Giunchi,[10] A. Allocca,[8,9] M. Cadoni,[11,12]

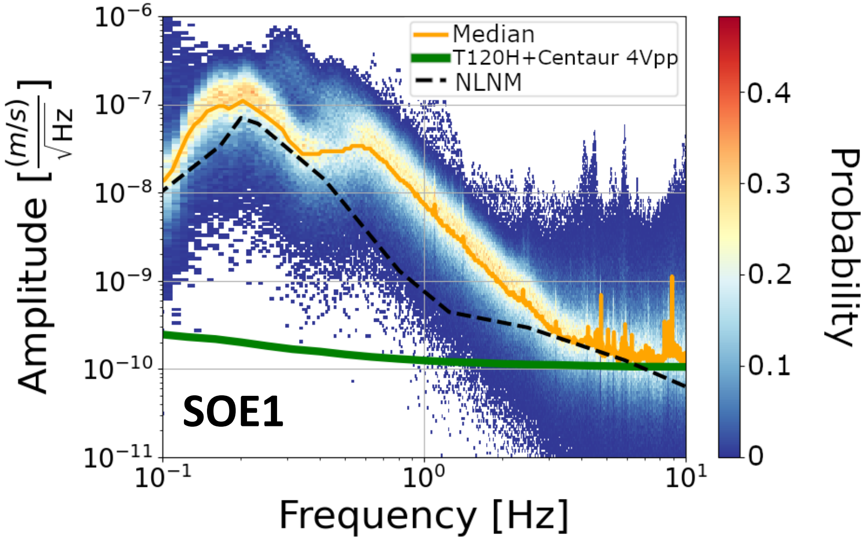
In the microseismic band (0.05-1Hz) the main spectral feature at ~0.22Hz is produced by the waves in the Gulf of Lion (NW Mediterranean sea). Depends on weather conditions → seasonal pattern.

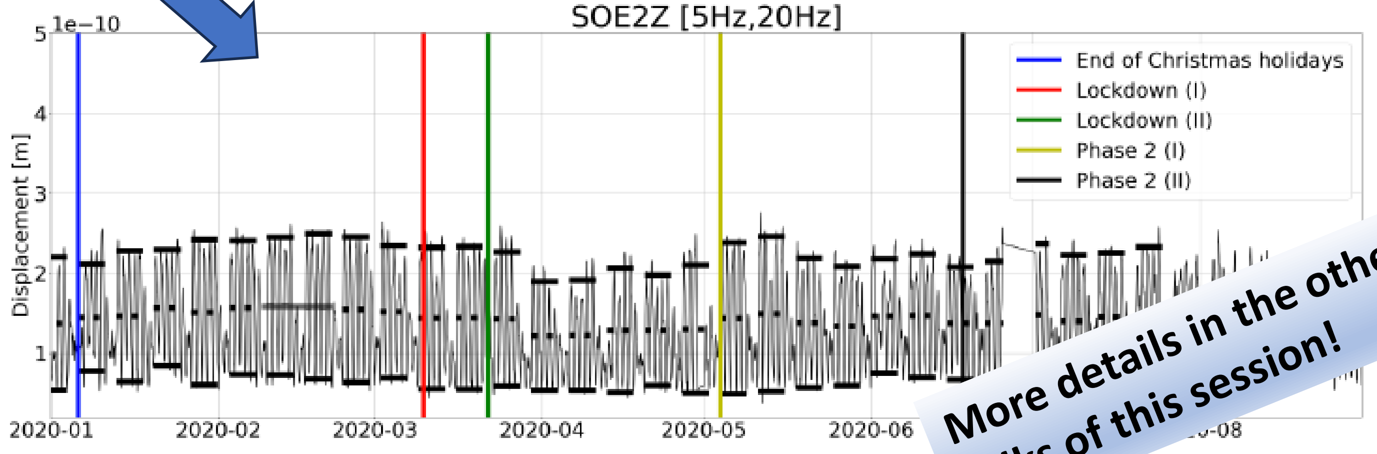






At higher frequencies, anthropic noise pattern observed.

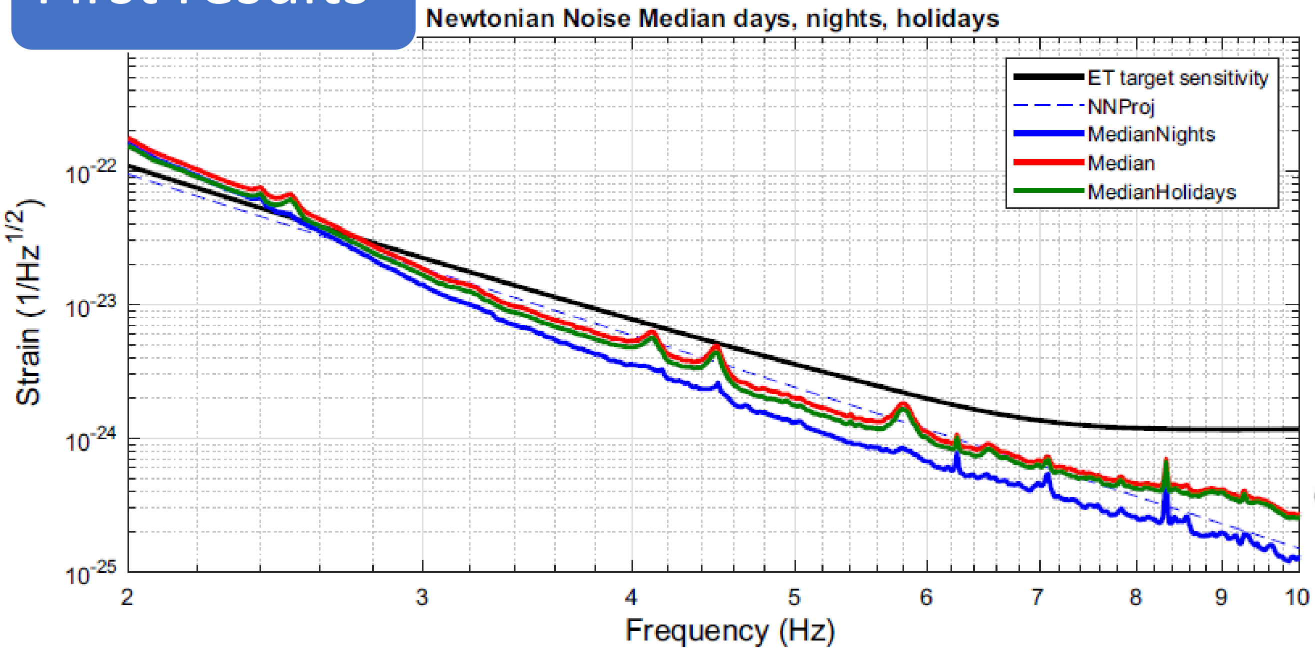




More details in the other talks of this session!

The Sos Enattos site

First results — Newtonian Noise & seismic glitches (based on 2020 data at SOE1)



Defining the Newtonian Noise ASD as:

$$\tilde{h}_{NN}(f) = \frac{4\pi}{3} G\rho_0 \frac{2\sqrt{2}}{L} \frac{1}{(2\pi f)^2} \tilde{x}(f)$$

Eur. Phys. J. Plus (2021) 136:511

Defining the Noise-to-Target Ratio of the Newtonian Noise in 1 minute window (~IMBH duration in ET band)

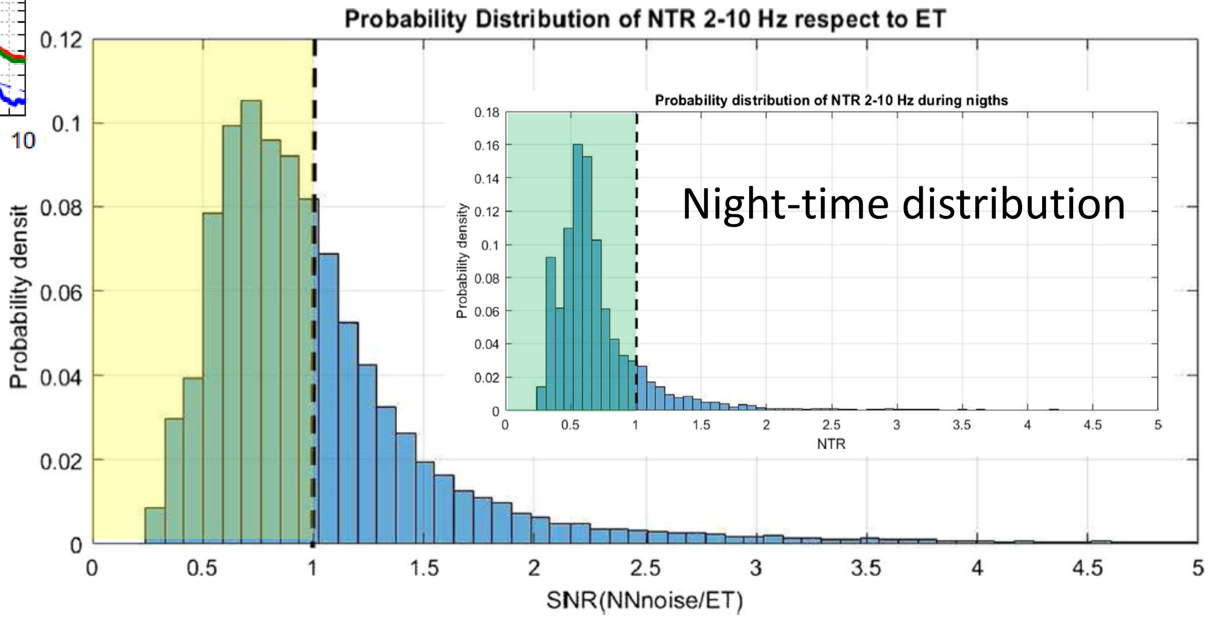
$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f} \int df \frac{\tilde{N} * \tilde{N}}{S_h}}$$

PSD of NN

PSD of ET sensitivity

P(NRT<1)=0.6 , considering only the nights: $P(NRT<1)_n$=0.86

→Need for moderate NN subtraction only for a limited time

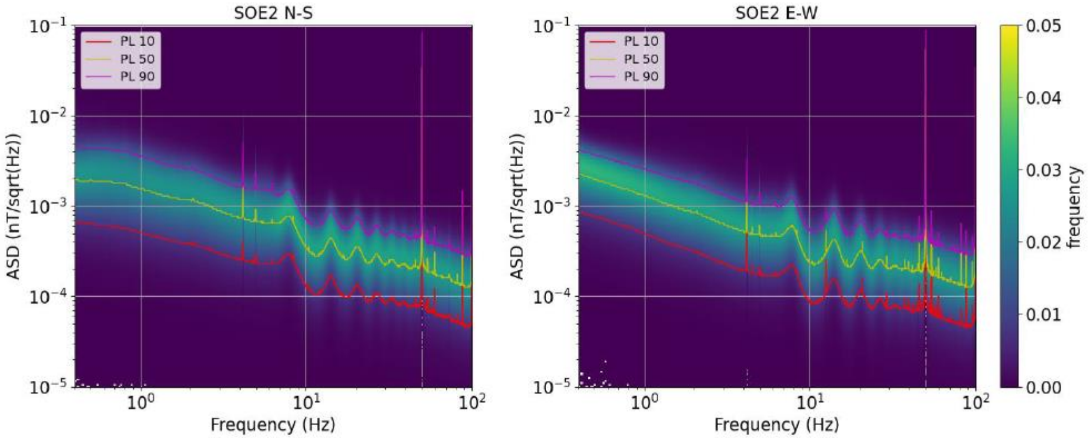


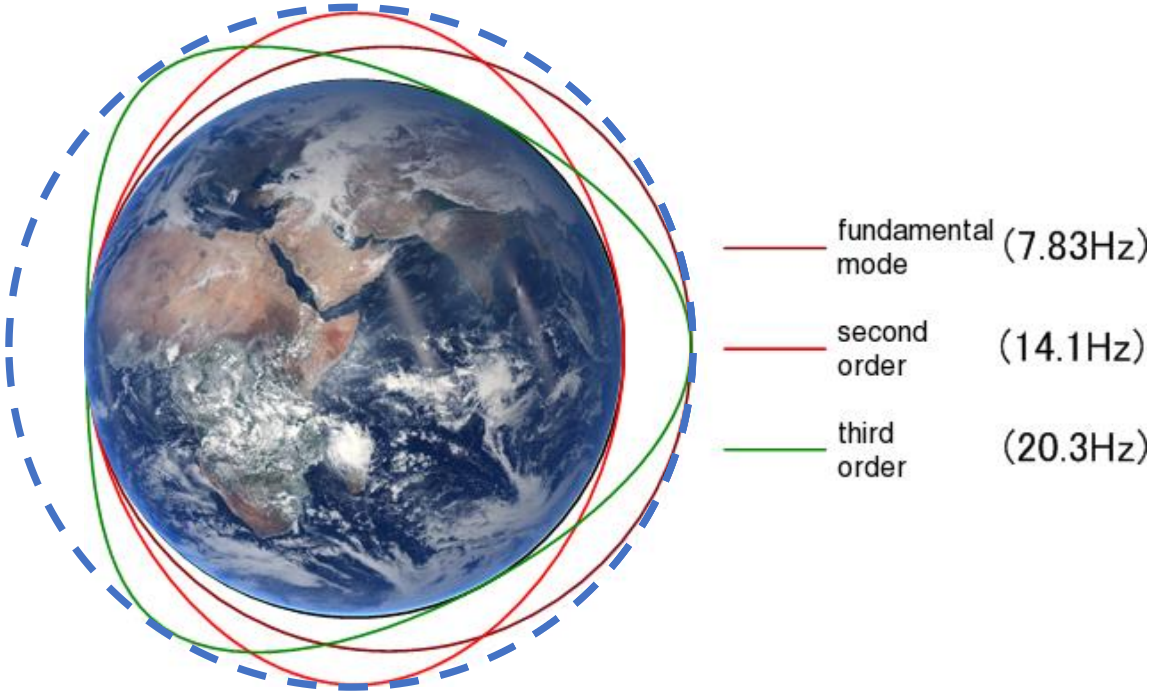
The Sos Enattos site

First results

Magnetic Noise measurements

- In the band of interest of ET the main direct disturbances come from ULF (10^{-3}-3Hz), ELF (3-$3\cdot10^3$Hz) up to VLF (3-30 kHz) radiobands.
- Main natural magnetic noise is in ULF and ELF, produced by resonance phenoman in the magnotosphere and/or in ionosphere cavities
- Most important mechanism in ET-LF:
  - **Geomagnetic pulsations Pc1** (0.2-5Hz);
  - **Schumann resonances** (5-100Hz) →
- Artificial LF sources in ELF (e.g. 50-60Hz powerlines)

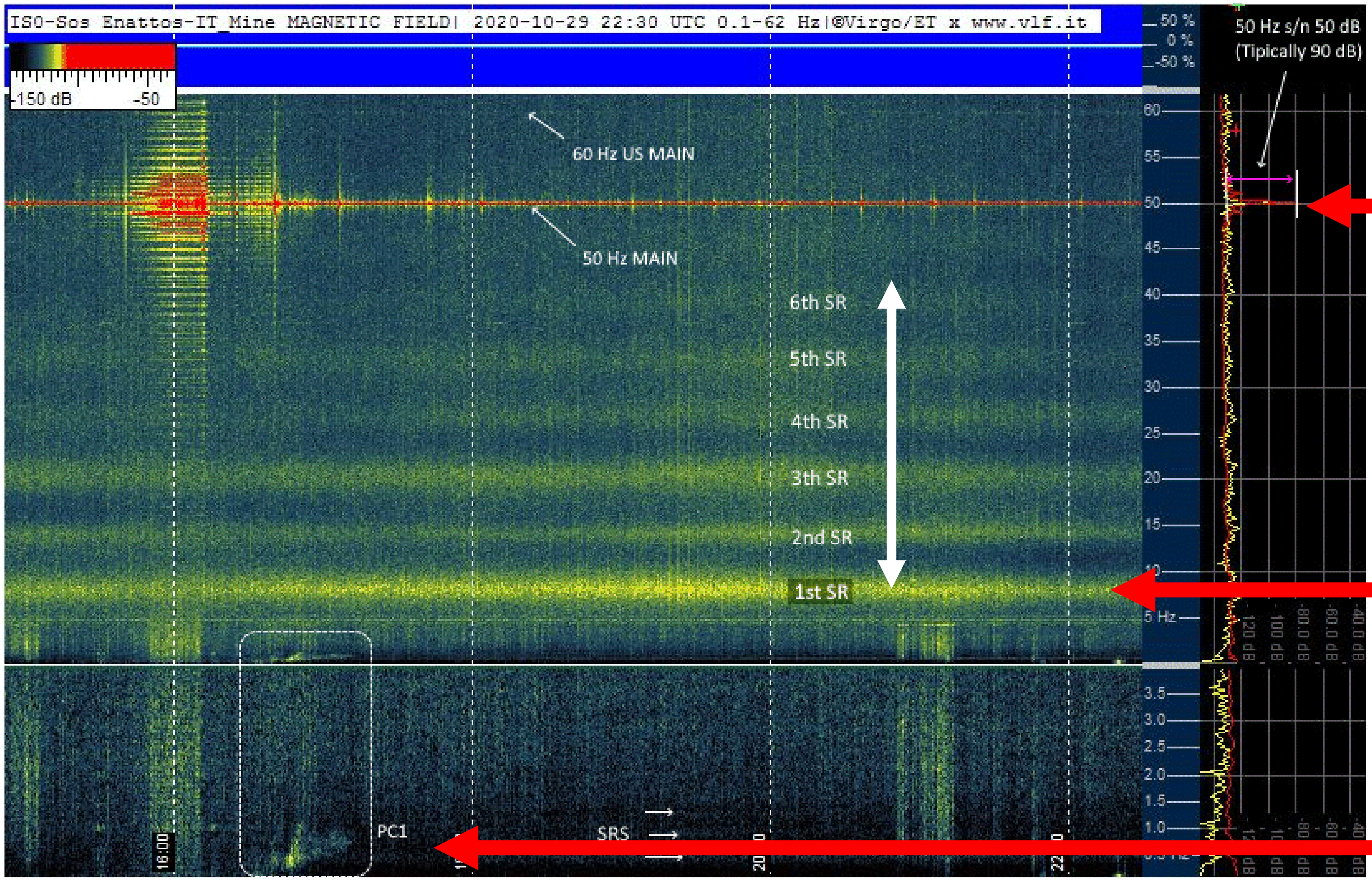




credit: R. De Rosa

The Sos Enattos site

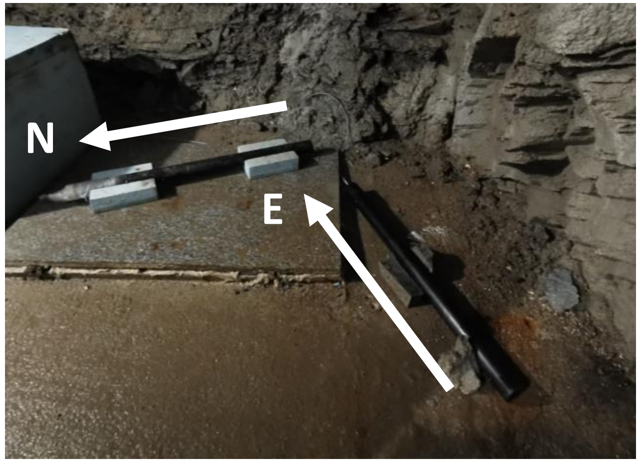
First results — Magnetic Noise measurements

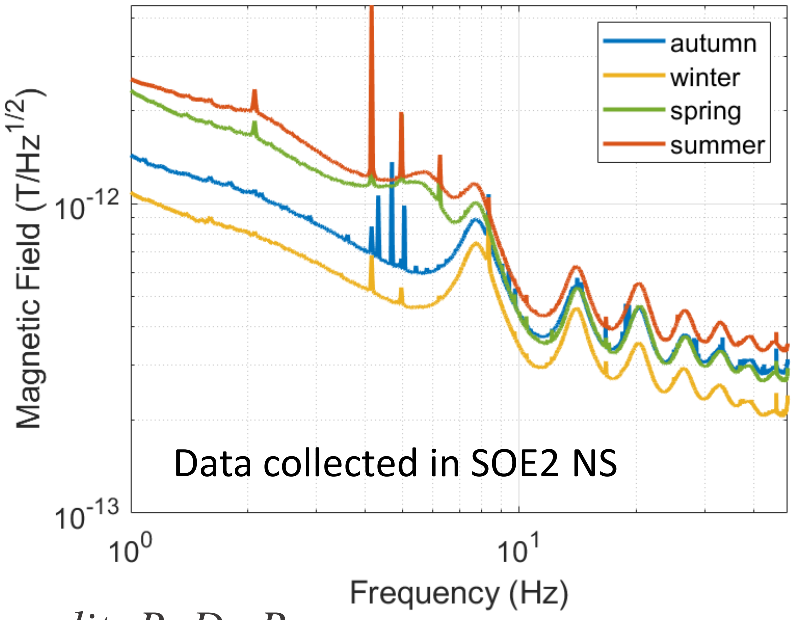


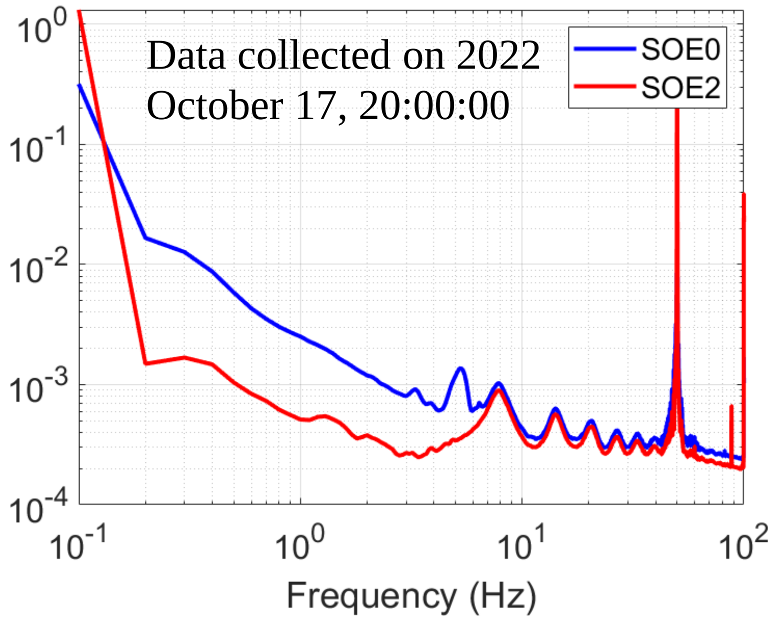
credit: R. De Rosa, R. Romero

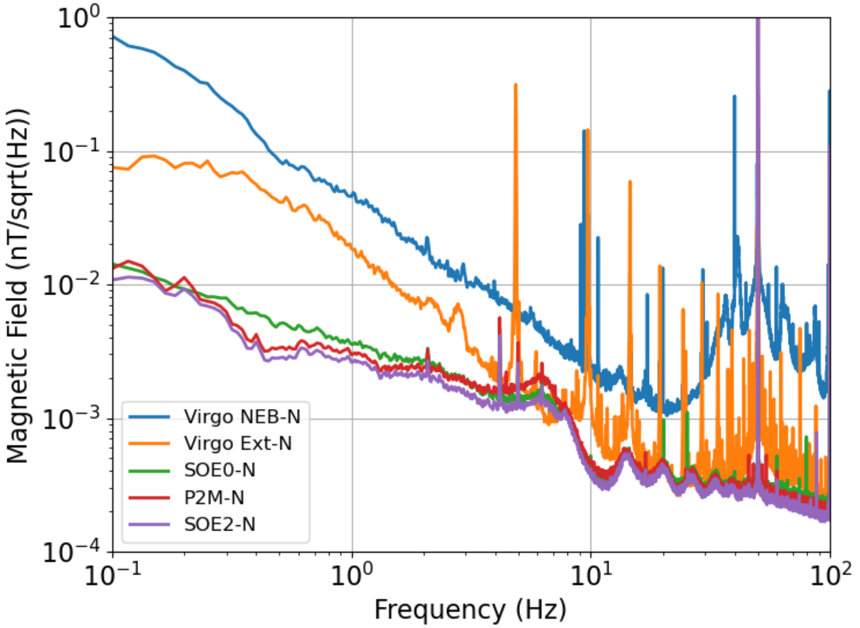
First results **Magnetic Noise measurements**

- 1 mag. probe (NS direction in surface at Sos Enattos (SOE0);
- 2 mag. probe (NS and EW directions) at 111 m underground at Sos Enattos (SOE2);
- 2 mag. probe (NS and EW directions) in surface at the P2 corner.









credit: R. De Rosa

The Sos Enattos site

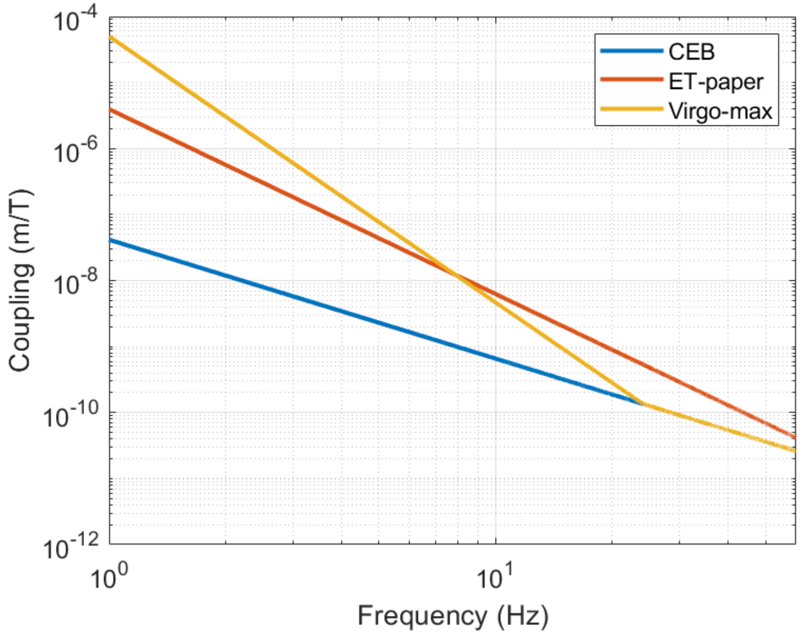
First results **Magnetic Noise projection for ET**

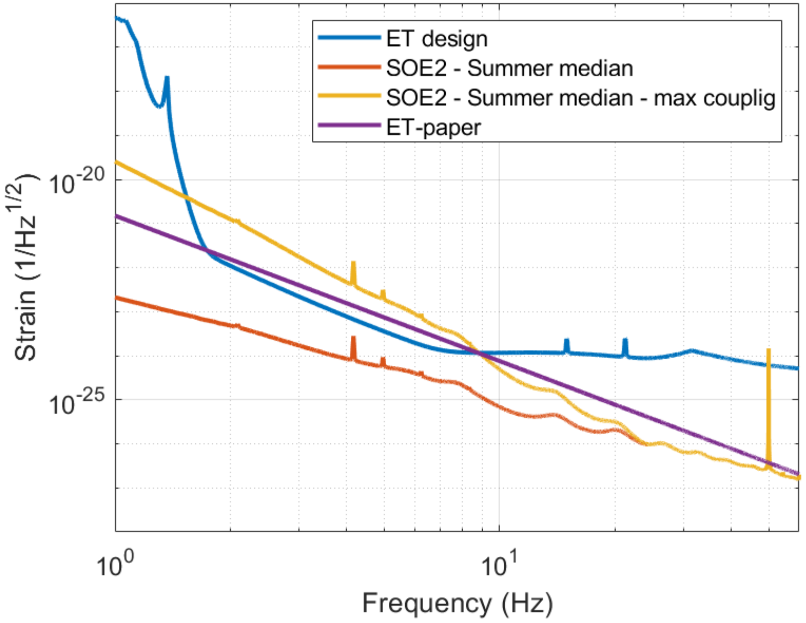
Magnetic noise projections with different assumptions, compared to the published projection.

The **noise coupling** as measured at Virgo, including only the contribution measured at CEB, or the full contribution (CEB+NEB+WEB) is compared with the coupling used in the ET paper

The **measured coupling** was used with the **measurements performed in Sos Enattos** to project the **impact of magnetic noise on sensitivity** (Coupling measured from 10Hz, extrapolated for lower frequencies)

Need for Magnetic Noise mitigation even considering such a low noise site…



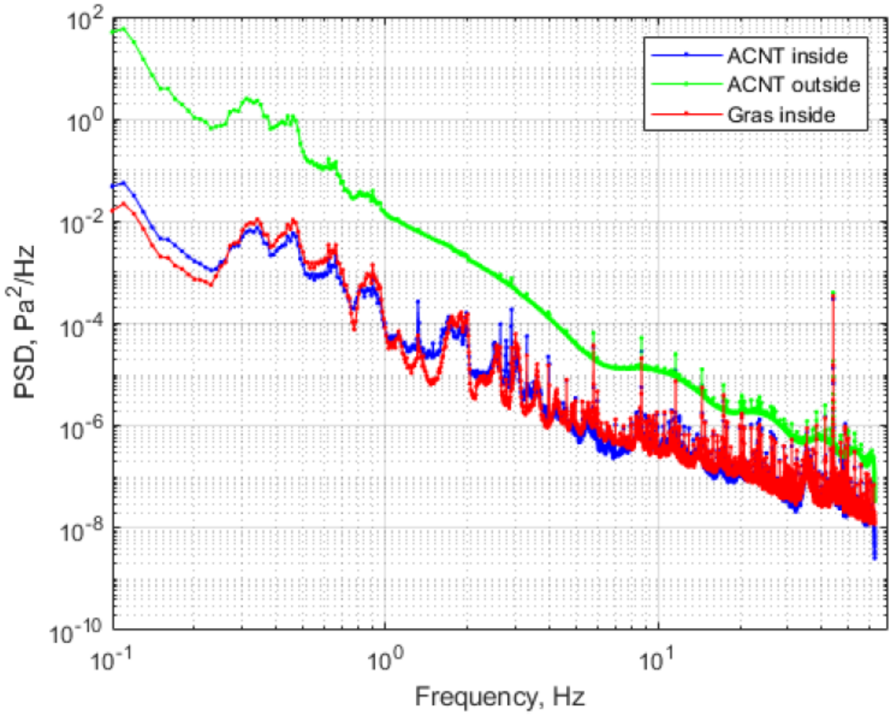


The Sos Enattos site

First results **Infrasound measurements**

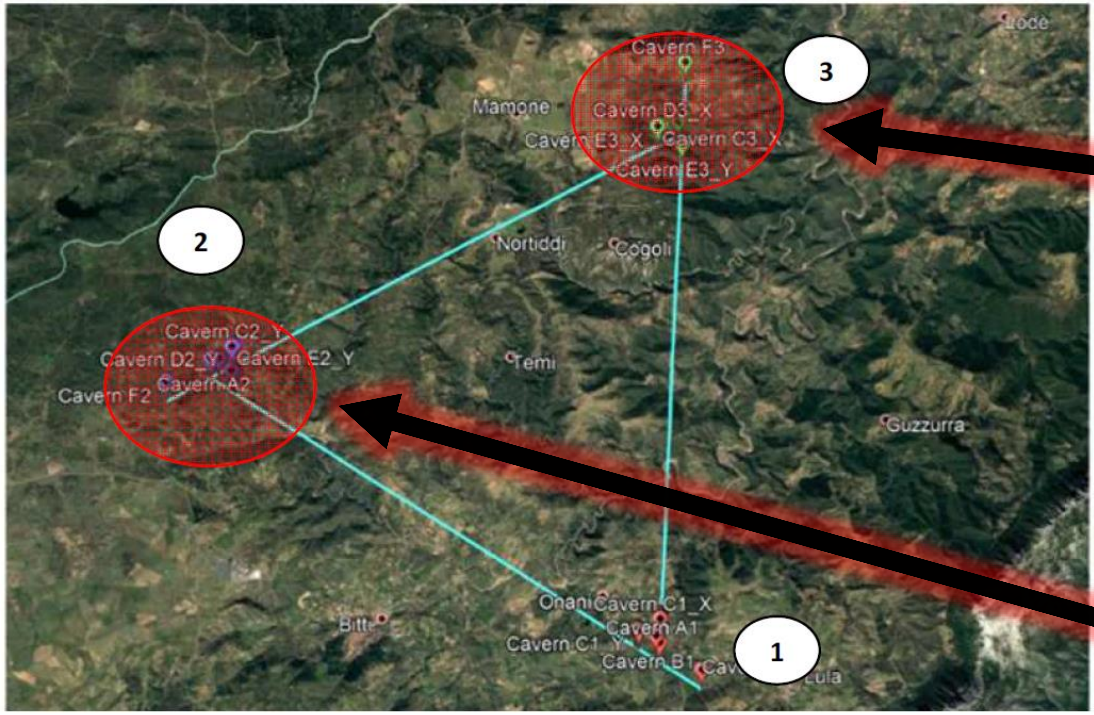
- Short term measurements have shown the quietness of the mine;
- (3+1) microphones installed along the underground tunnels for long term characterization in a joint Italian-Polish-Hungarian collaboration (*PolGrav-AstroCeNT*, *Wigner Research Centre*);
- New installations planned at the P2,P3 corners.

credit: T. Bulik



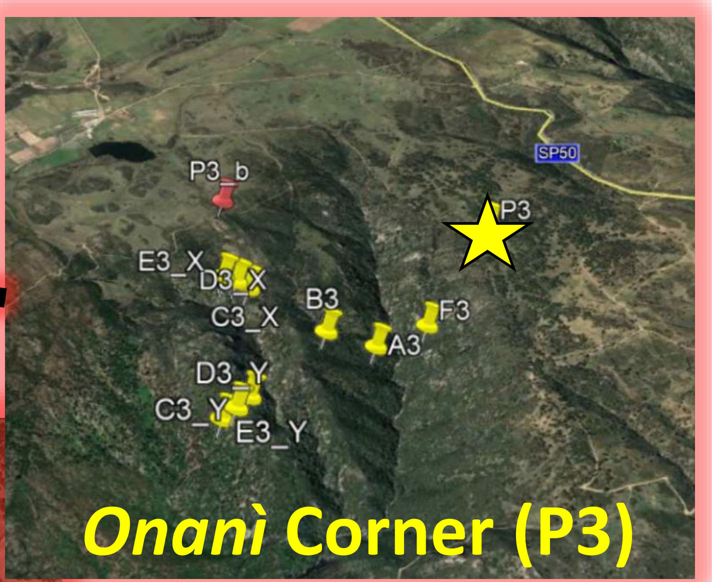
Characterization of the Δ corners

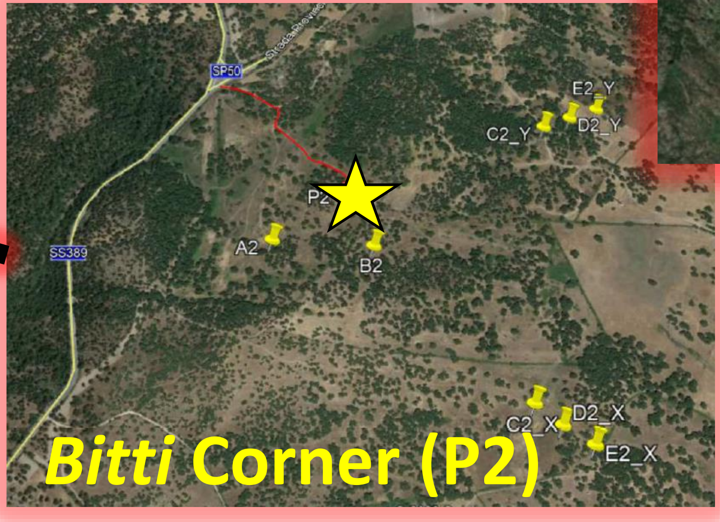
The corners of the Δ layout



***Lula* Corner**

Sos Enattos





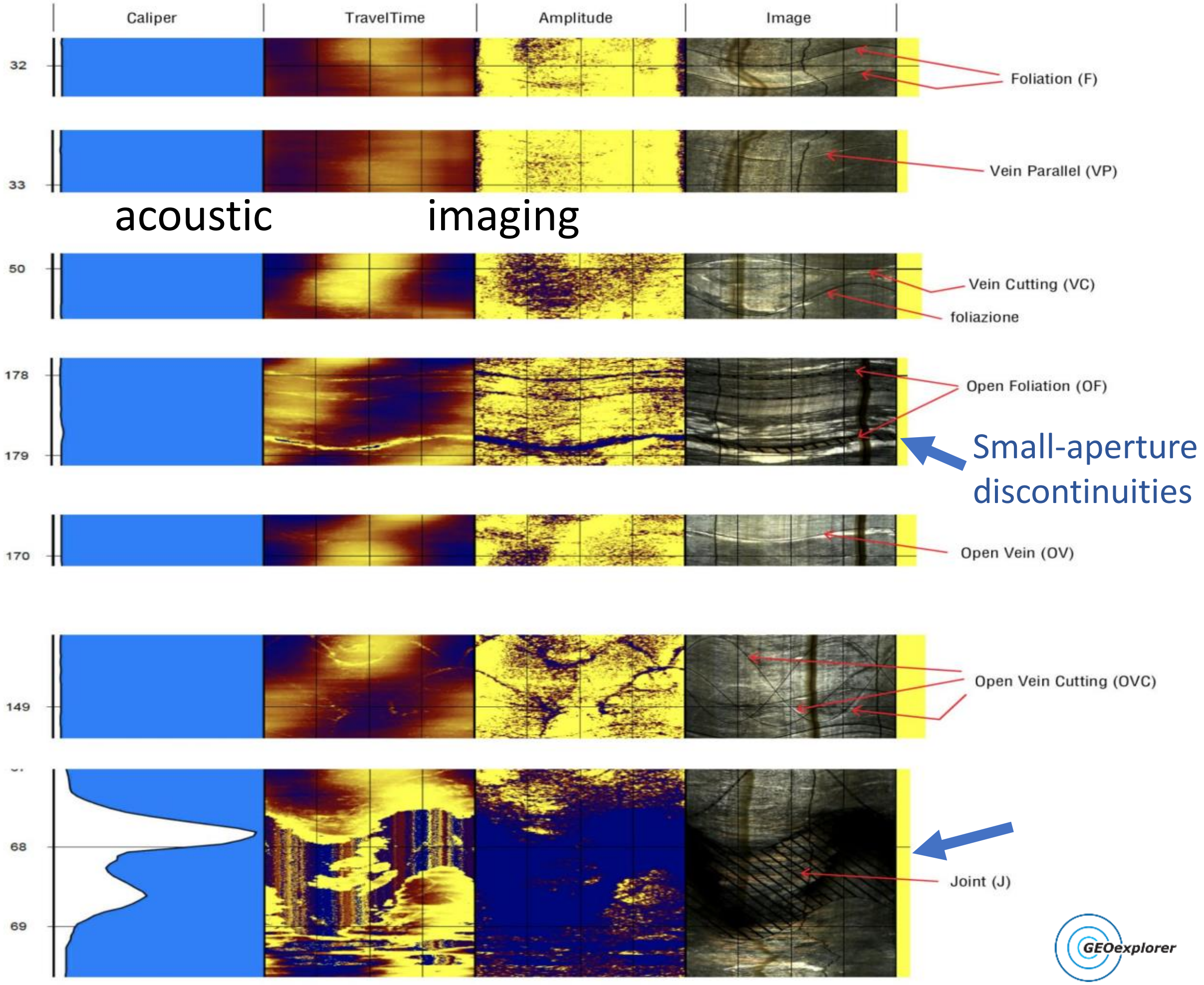
★ : area for boreholes and surface arrays

📌 : proposed locations for ET Δ main caverns

Characterization of the Δ corners

The boreholes at P2 and P3

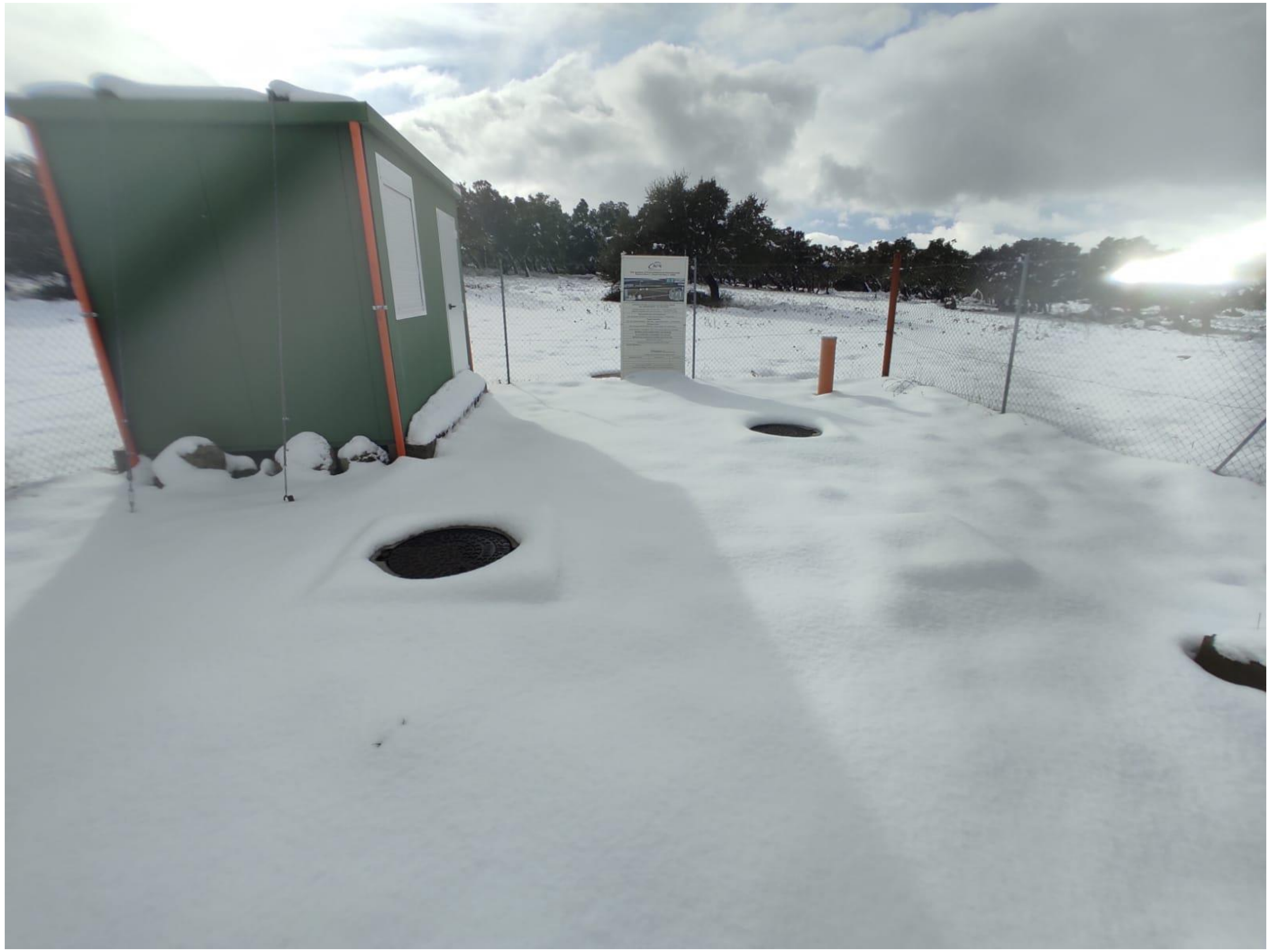
Borehole drilling in 2021 down to 270m within 3° inclination, and geophysical logs



Characterization of the Δ corners

The boreholes at P2 and P3

Measurement stations at the corners



Characterization of the Δ corners

Seismometer installations & active seismic campaign

ET-0426A-21, https://apps.et-gw.eu/tds/?content=3&r=17710

- Surface & borehole seismometer installed in Sept. 2021. Stations were improved during 2022, also with the installation of 2 magnetometers (P2). Optical fiber strainmeter deployed along both boreholes.
- Temporary surface array for passive and active seismic measurement at both corners.





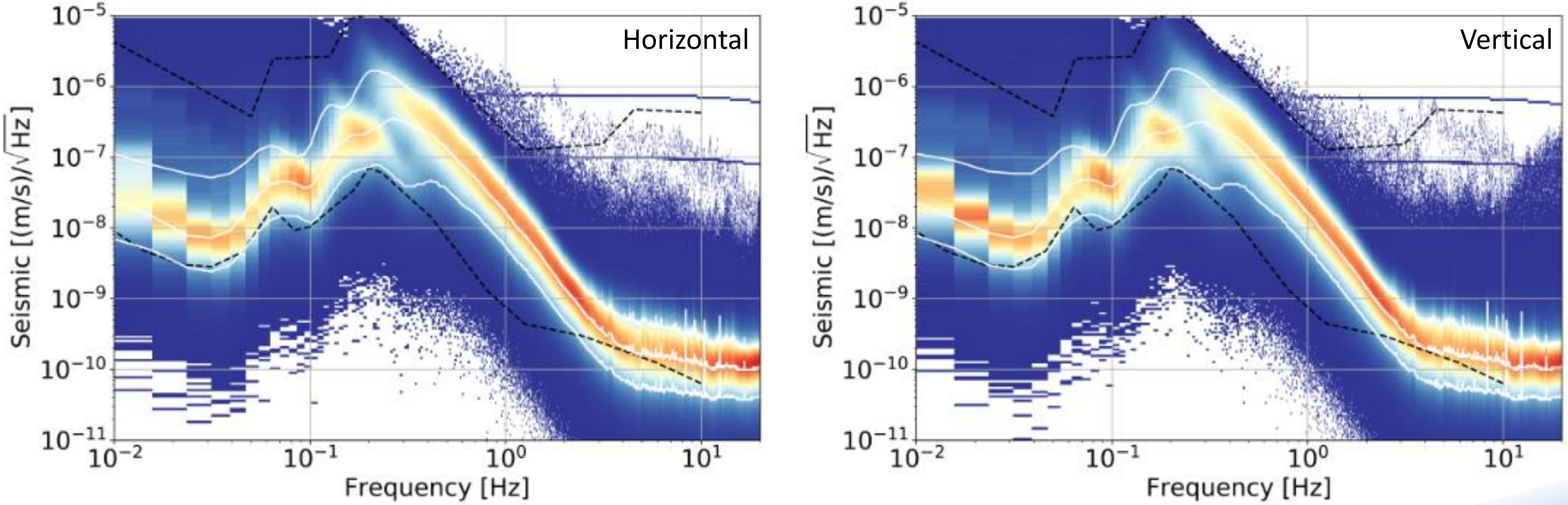




Characterization of the Δ corners

A quick glance at the measurements

PPSD - P2 borehole seismometer



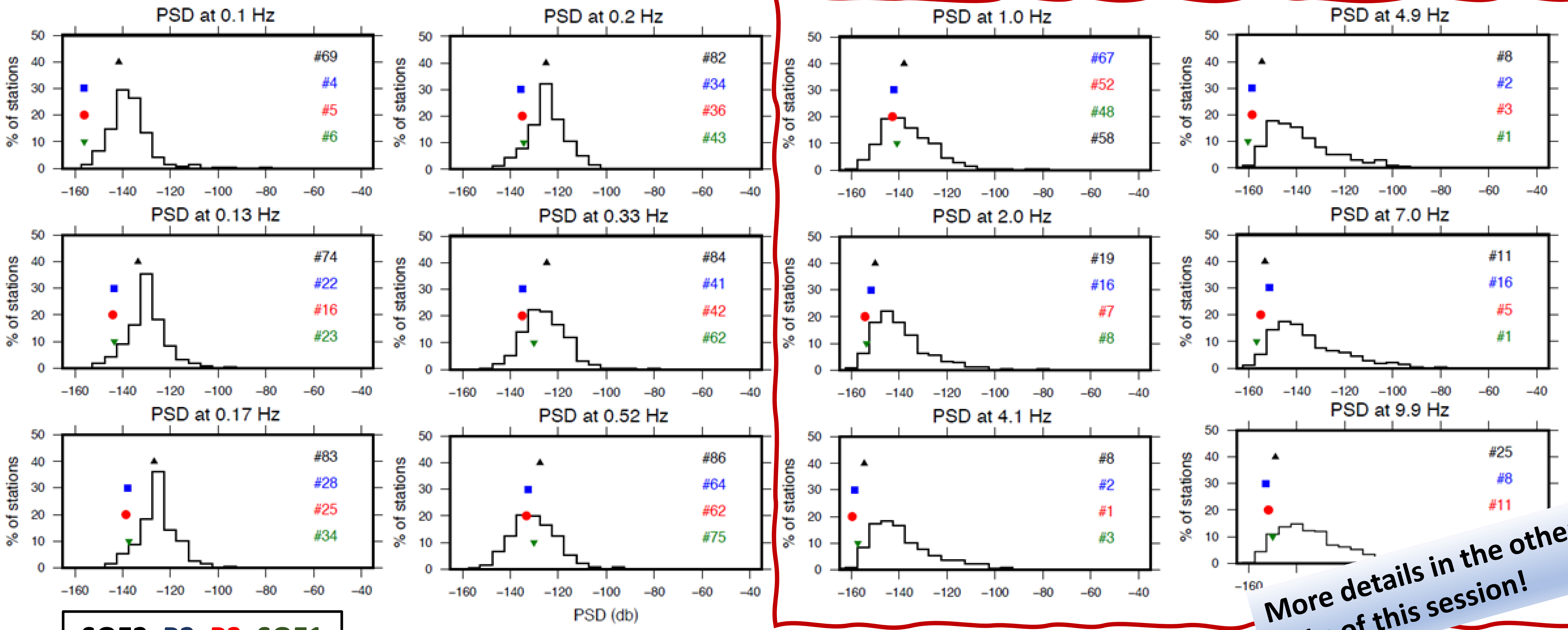
Very low noise background in the 2-10 Hz band, sometimes even **below** the Peterson's **New Low Noise Model**!

More details in the other talks of this session!

Characterization of the Δ corners

A quick glance at the measurements

Ranking of Sardinia site compared to the quietest seismic stations (GSN, IRIS network) **worldwide**.



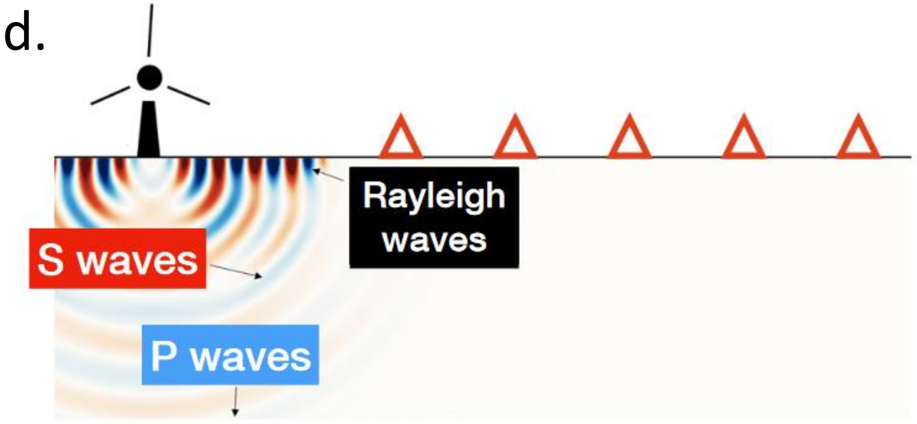
SOE2 P2 P3 SOE1

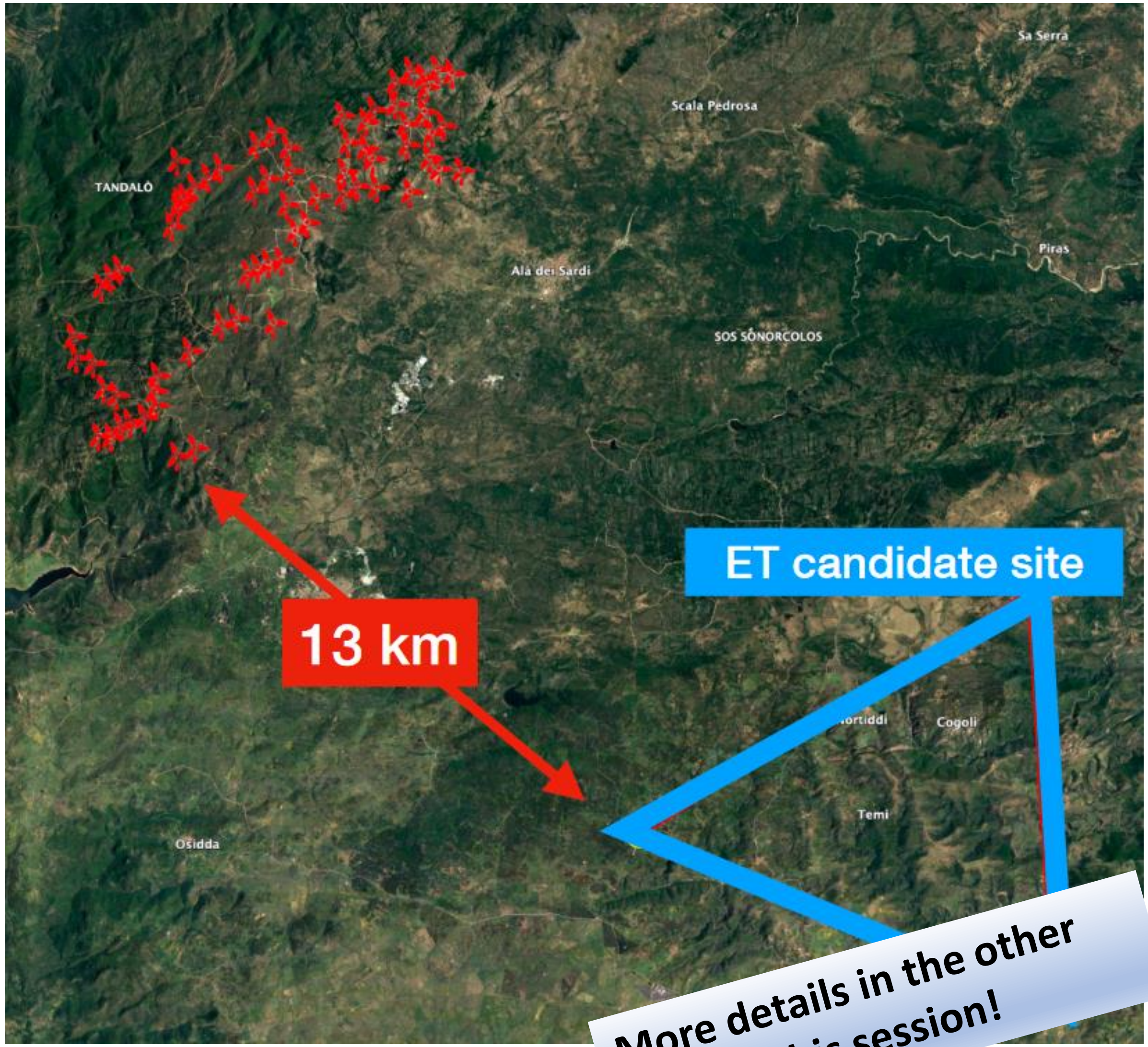
More details in the other talks of this session!

Characterization of the Δ corners

Wind farms vs ET-LF

- The *Budussò Wind Park* is one of the largest wind parks in Italy and Europe.
- **69 turbines** (~2 MW each).
- **A total of 130 MW installed**.
- Blades motion is transferred to tower, from tower to the ground.
- Seismic noise propagates as surface waves (mainly Rayleigh waves)
- Generated noise is found in the 1-10Hz frequency band.





More details in the other talks of this session!

Characterization of the Δ corners

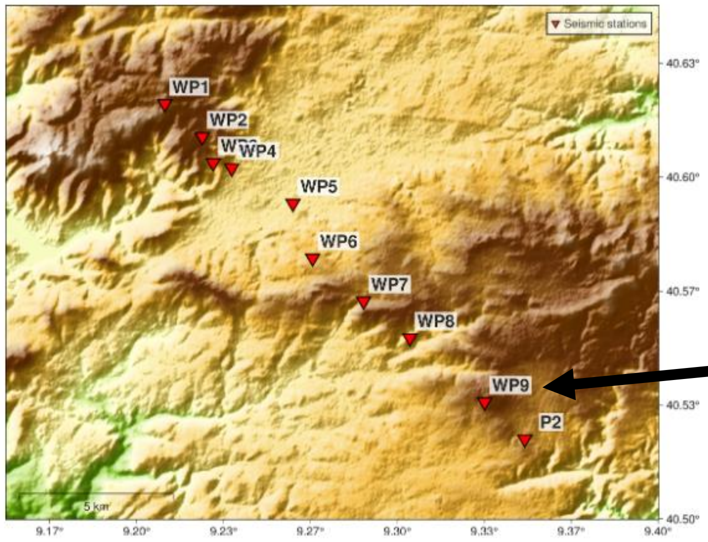
Wind farms vs ET-LF

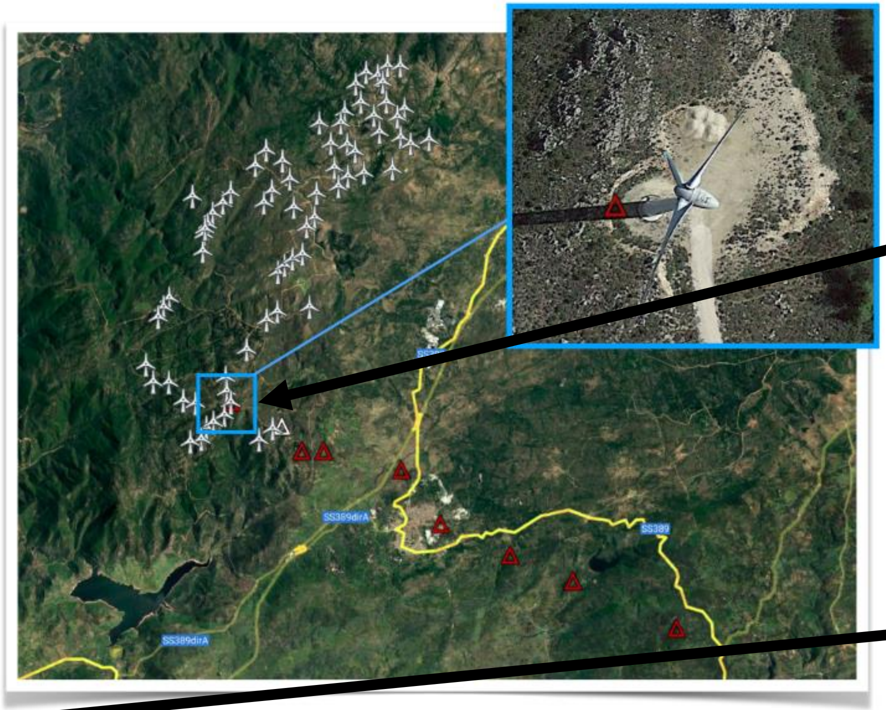
- what are the **characteristics** of the generated noise signal?
- how **far** can we track it?
- how does the seismic noise signal **decay with distance**?

adapted from G. Diaferia, 3rd SPB workshop 2023

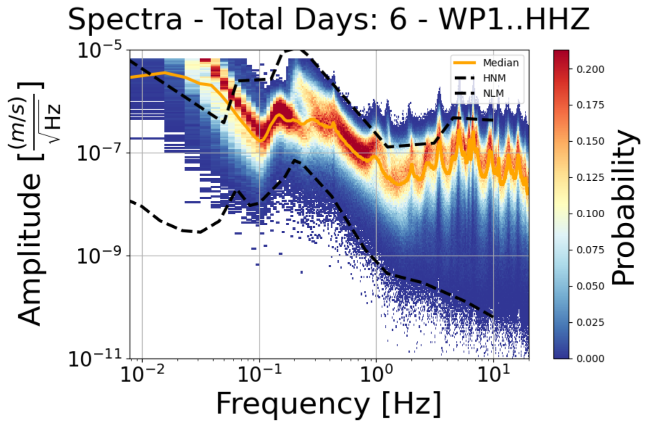
The WINES experiment

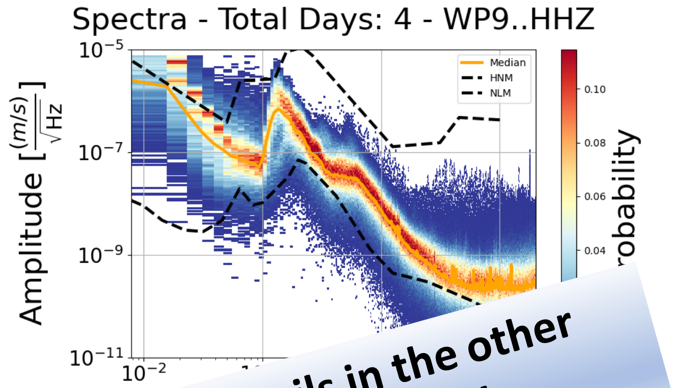
- **9 broad-band** seismic stations
- **~13 km** linear array
- **~2 months** of recording (8/04-30/05/2023)
- wind-speed data from a **nearby meteorological station**





NB: in our analysis we also include the permanent stations **P2, P3**, located on the **two closest vertices of the ET candidate site**



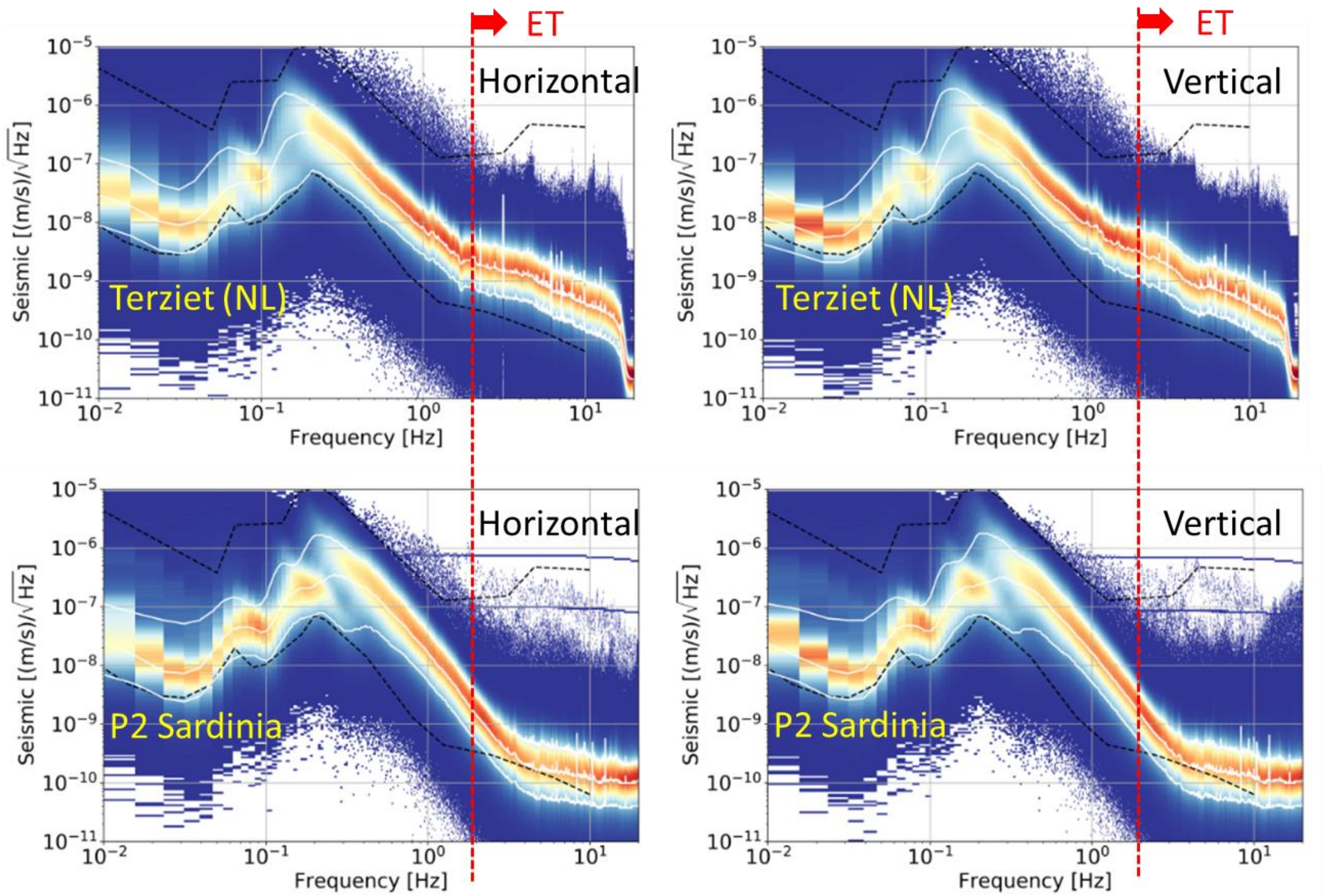


More details in the other talks of this session!

Site comparison with other candidates

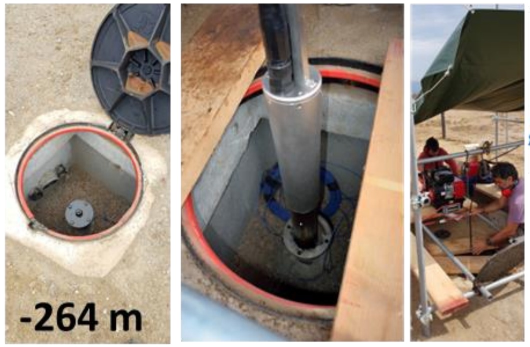
Borehole measurements comparison

In the crucial few Hz band of ET (2-10 Hz), Sos Enattos area is among the quietest sites in the world.



EMR Terziet (NL) borehole

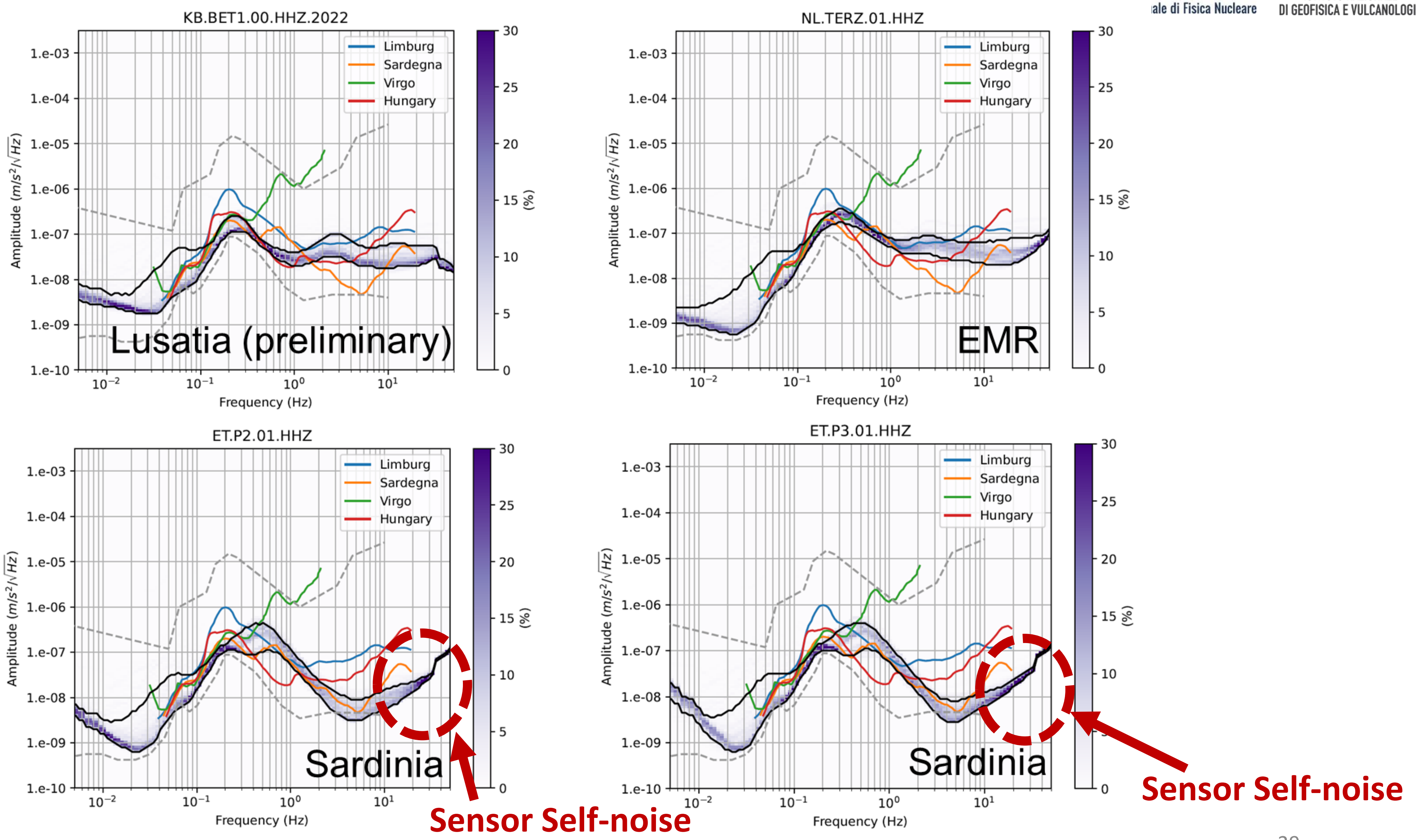
Sardinia P2 borehole



Site comparison with other candidates

Borehole comparison

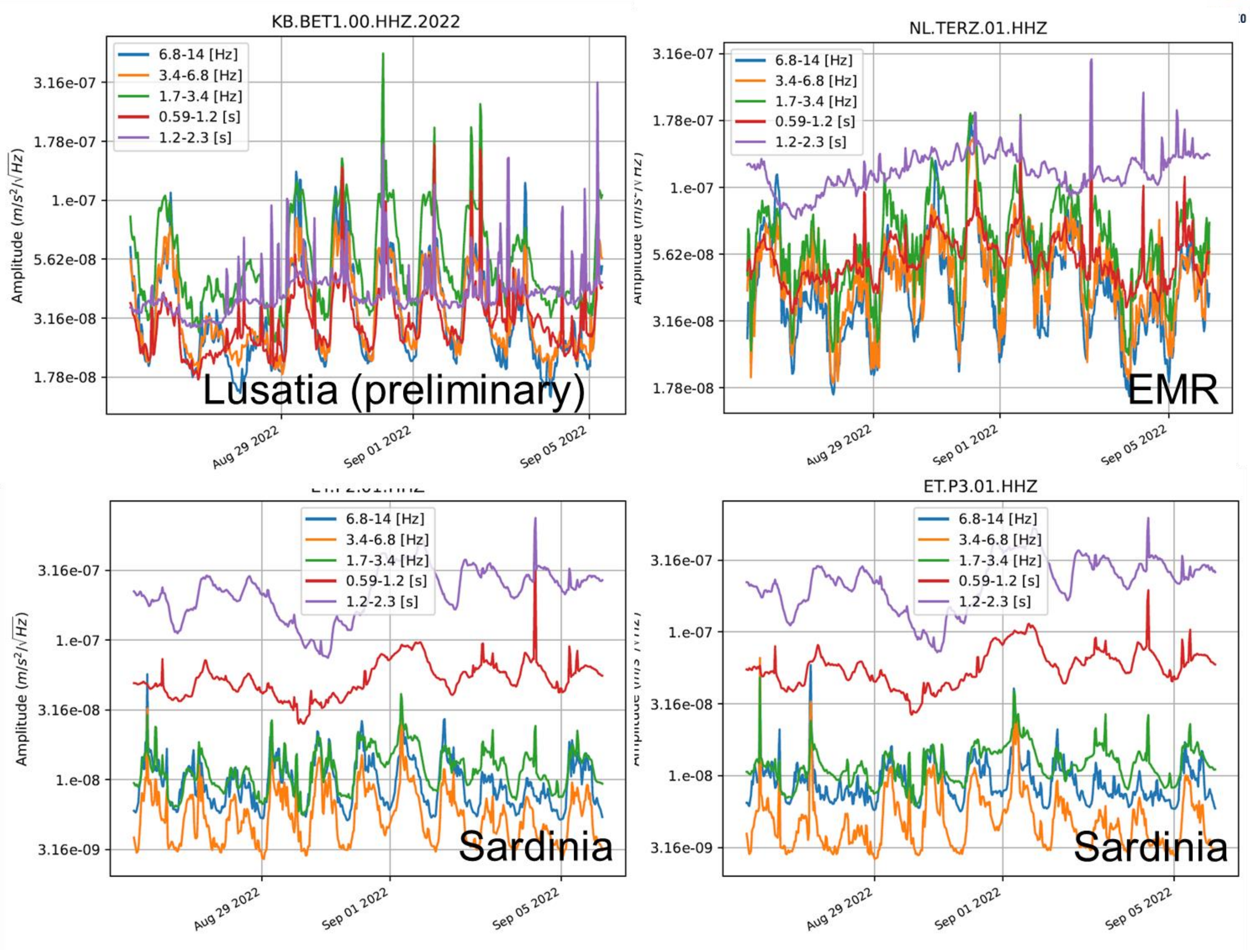
A. Rietbrock et al., ET-SPB Workshop 2023



Site comparison with other candidates

Borehole comparison

A. Rietbrock et al., ET-SPB Workshop 2023



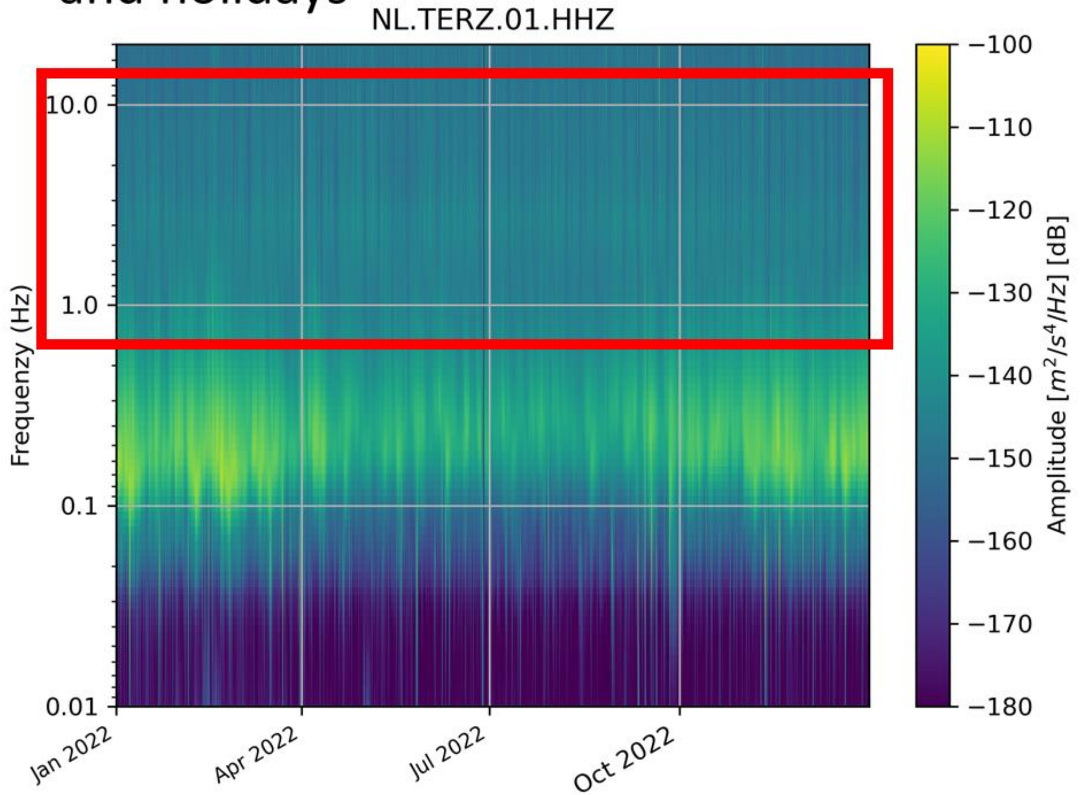
Site comparison with other candidates

Borehole comparison

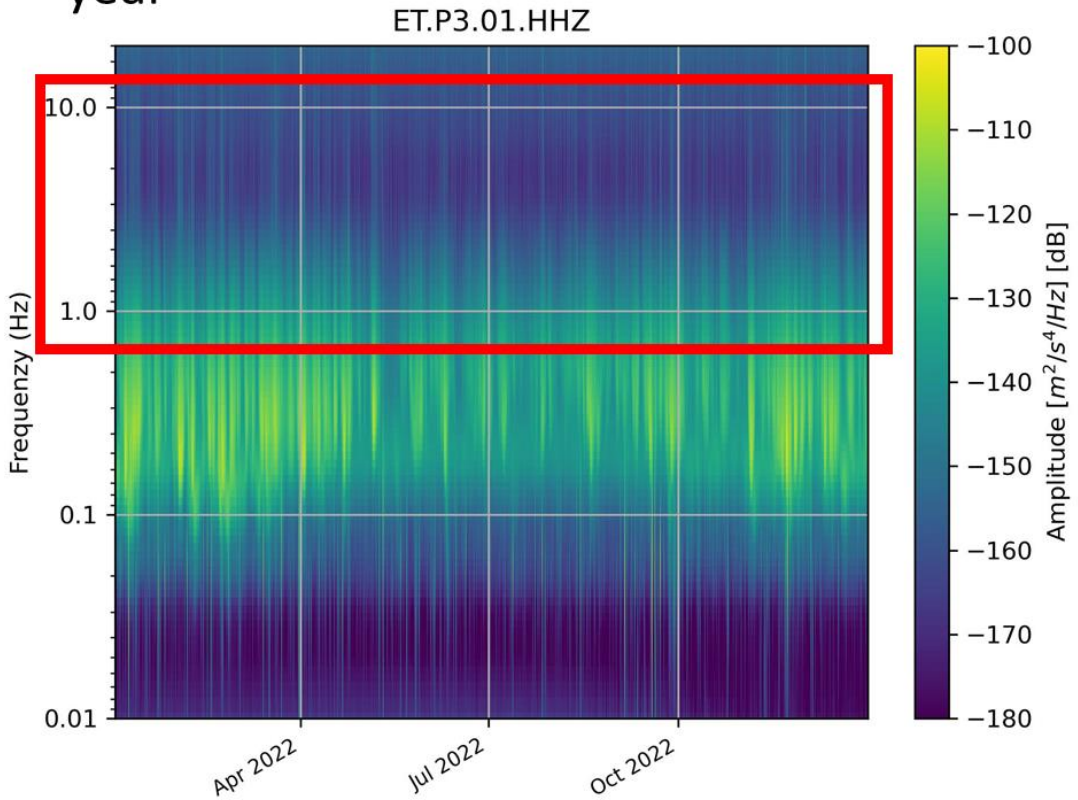
PSD Spectrogram – frequency band 1 Hz to 10 Hz

A. Rietbrock et al., ET-SPB Workshop 2023

EMR - "Quiet" only during weekends and holidays



Sardinia - "Quiet" during the whole year



Site comparison with other candidates

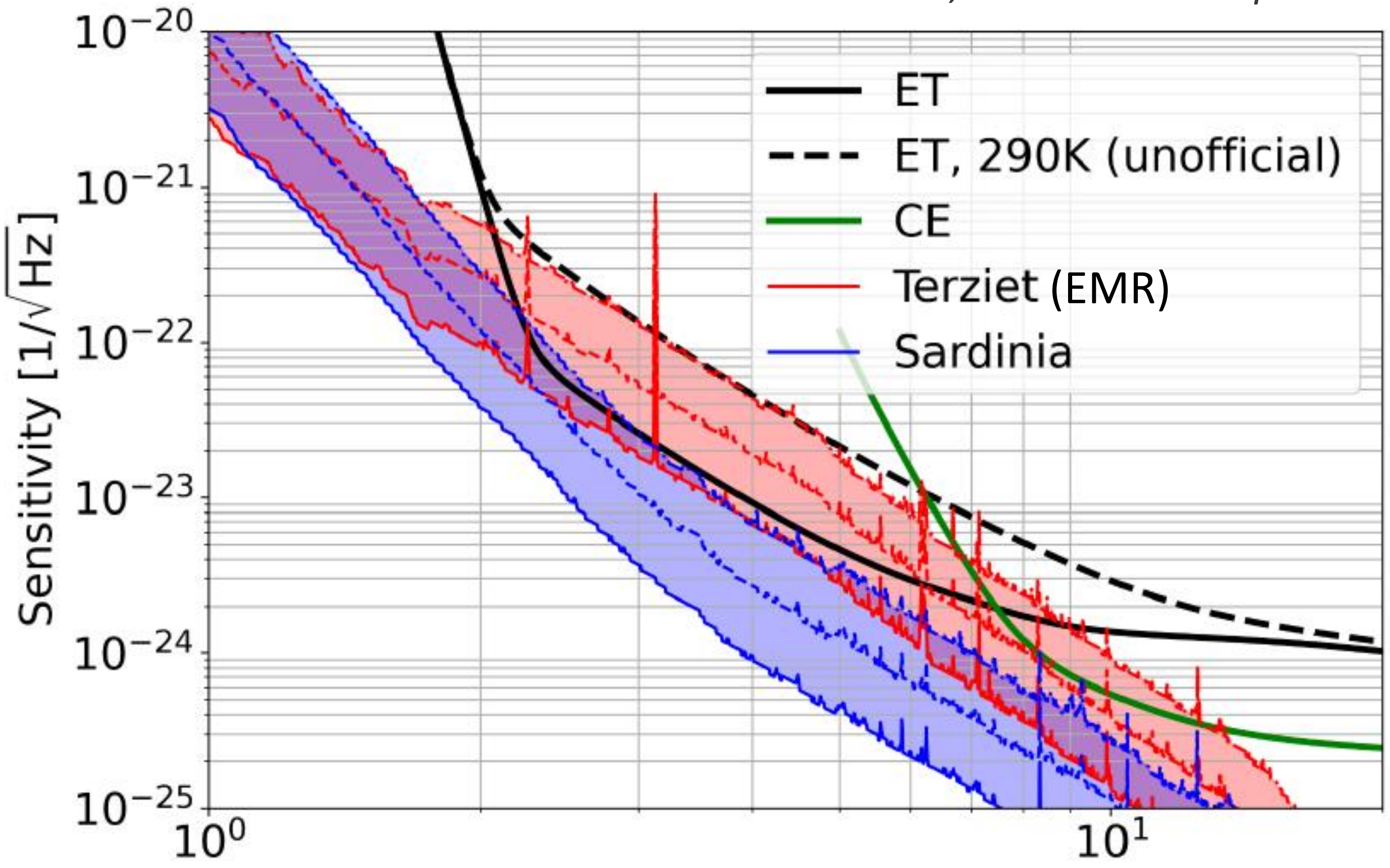
Seismic Newtonian Noise projections

J.Harms, ET-SPB workshop 2023

Defining the Newtonian Noise ASD as:

$$\tilde{h}_{NN}(f) = \frac{4\pi}{3} G\rho_0 \frac{2\sqrt{2}}{L} \frac{1}{(2\pi f)^2} \tilde{x}(f)$$

seismic noise displacement ASD

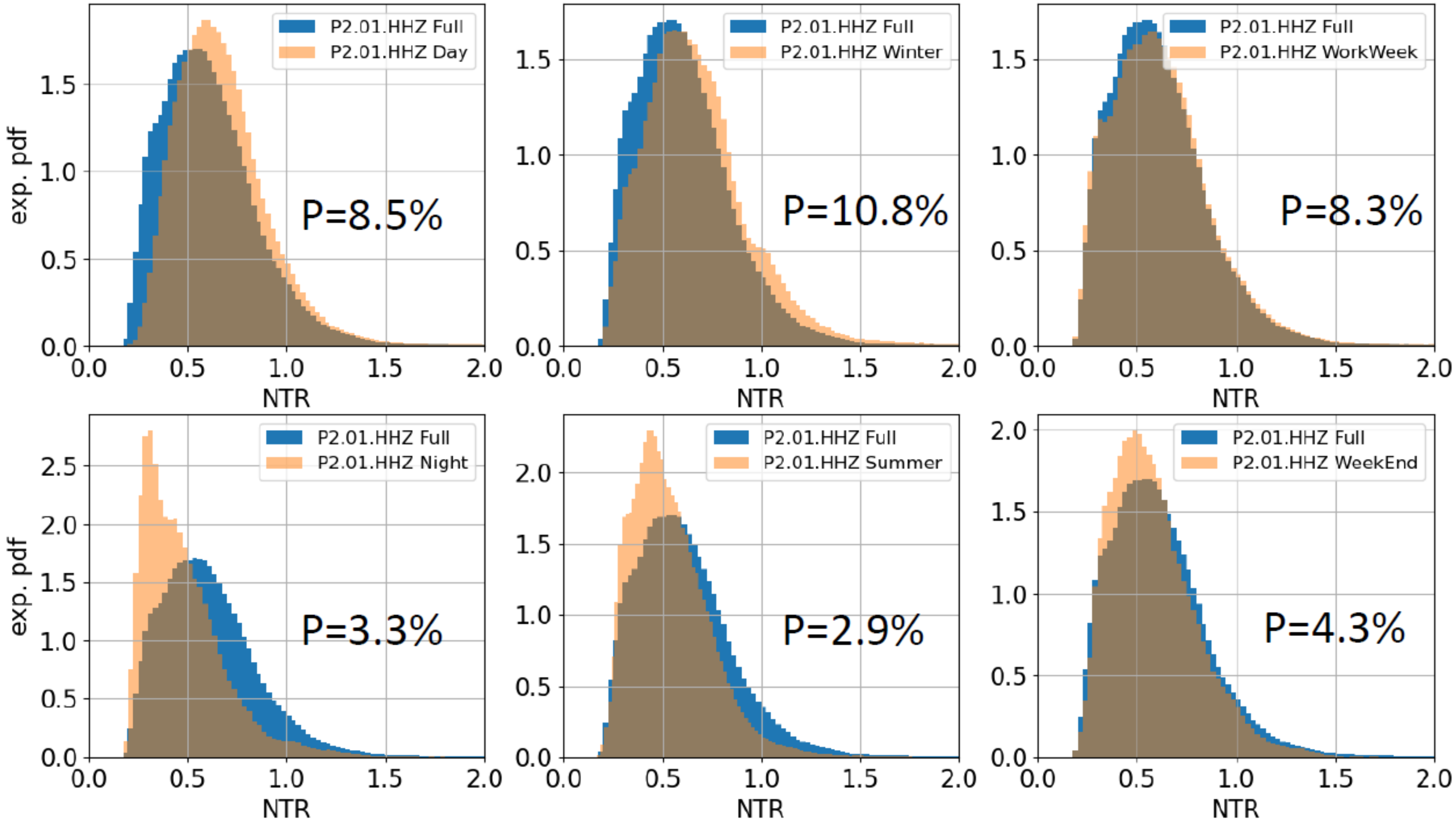


→ my talk in the instrument science sessions: environmental noise mitigation

Site comparison with other candidates

Seismic NN glitches in ET LF band

Defining the Noise-to-Target Ratio of the Newtonian Noise in 1 minute window (~IMBH duration in ET band):



PSD of NN

$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f}\int df\, \frac{\tilde{N} * \tilde{N}}{S_h}}$$

PSD of ET sensitivity

Over one year (2022) of data

P(NRT>1, 2-10Hz)=6.3%
at P2 (Sardinia)

→ NN does not limit the ET sensitivity for a large fraction of time, only moderate cancellation needed for a limited time

R. De Rosa et al., SPB workshop 2023

Site comparison with other candidates

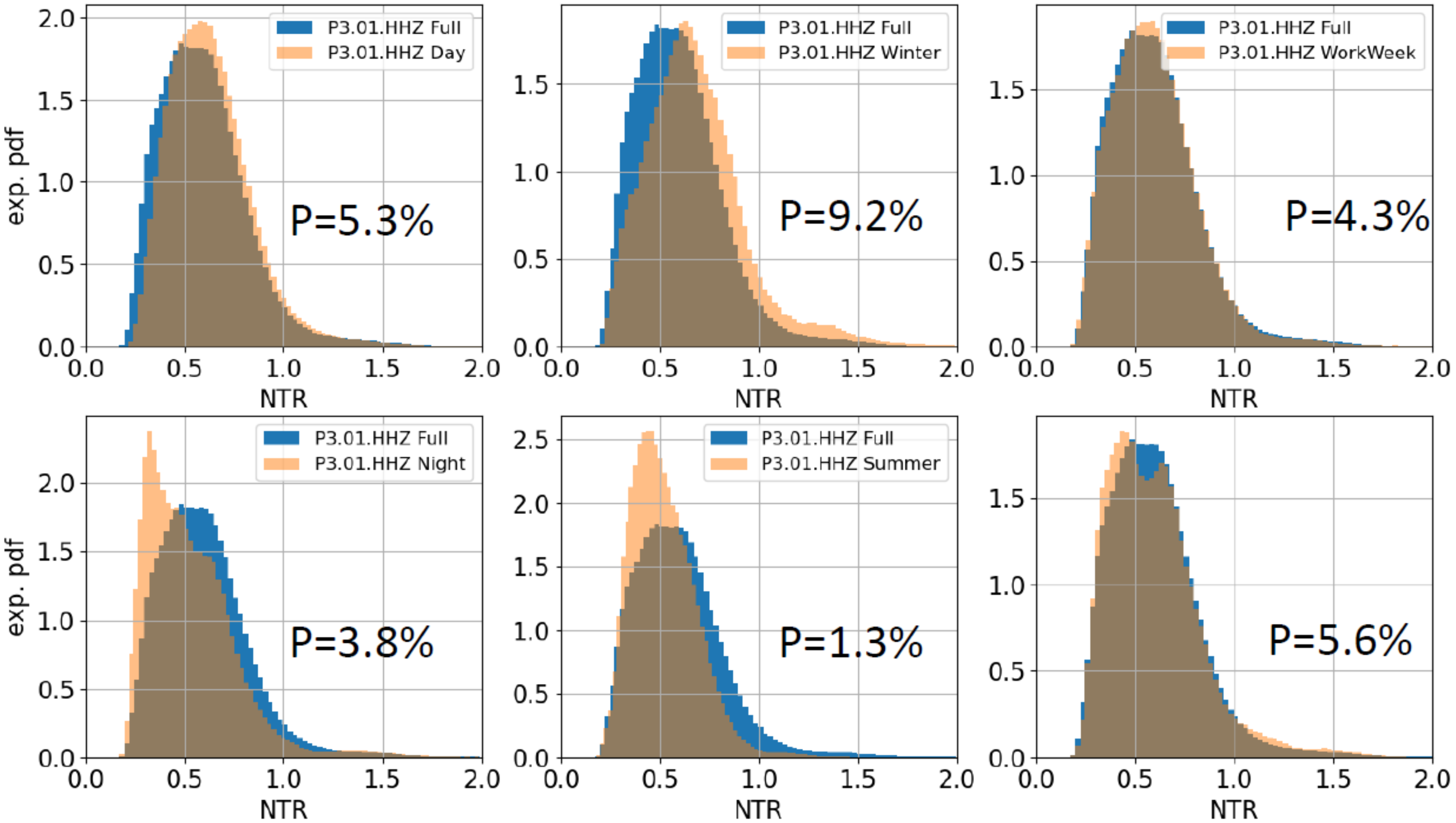
Seismic NN glitches in ET LF band

Defining the Noise-to-Target Ratio of the Newtonian Noise in 1 minute window (~IMBH duration in ET band):

$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f}\int df\,\frac{\tilde{N} * \tilde{N}}{S_h}}$$

PSD of NN

PSD of ET sensitivity



Over one year (2022) of data

P(NRT>1, 2-10Hz)=4.7%
at P3 (Sardinia)

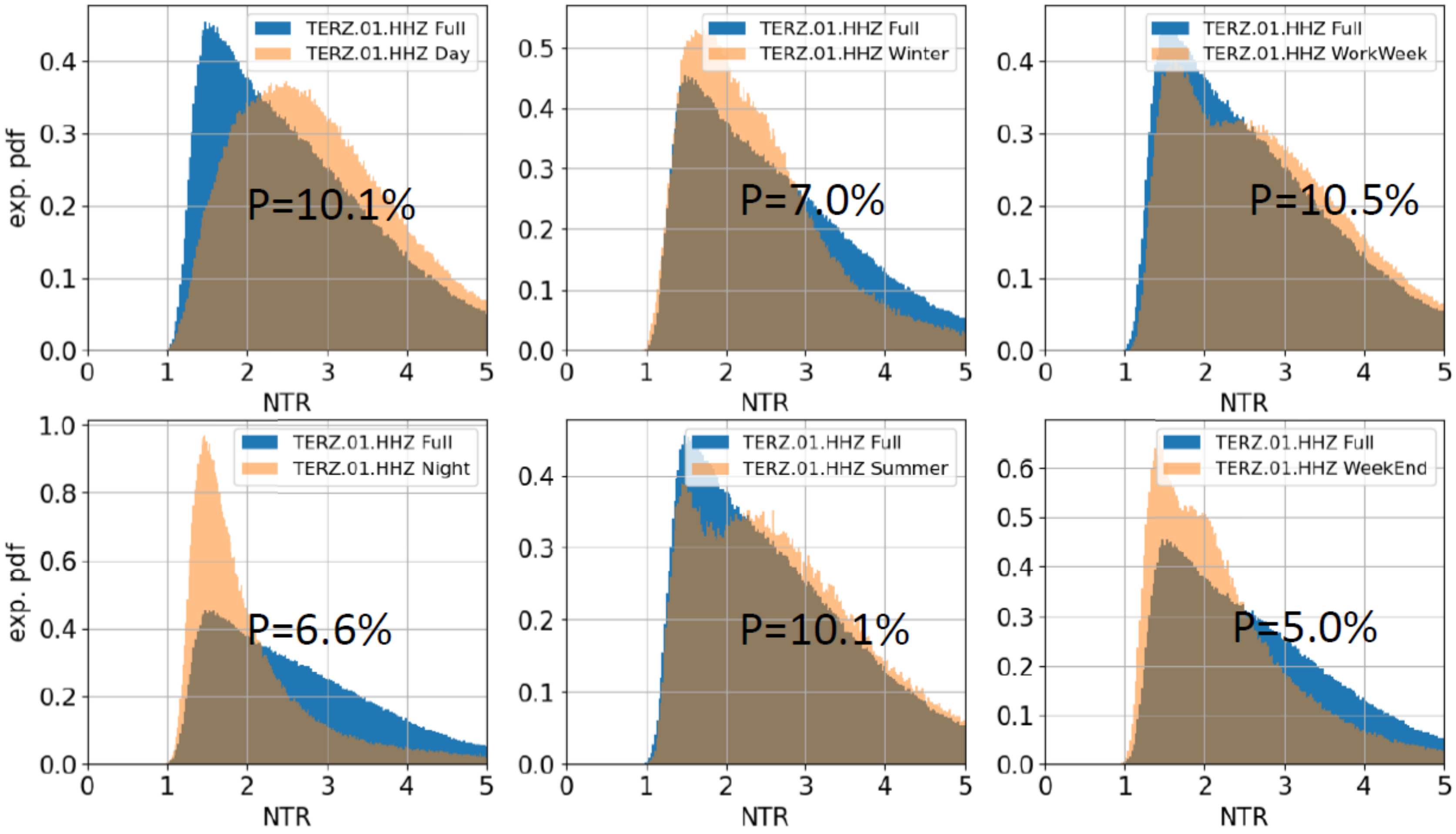
→ NN does not limit the ET sensitivity for a large fraction of time, only moderate cancellation needed for a limited time

R. De Rosa et al., SPB workshop 2023

Site comparison with other candidates

Seismic NN glitches in ET LF band

Defining the Noise-to-Target Ratio of the Newtonian Noise in 1 minute window (~IMBH duration in ET band):



$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f}\int df\,\frac{\tilde{N}*\tilde{N}}{S_h}}$$

PSD of NN

PSD of ET sensitivity

Over one year (2022) of data

P(NRT>1, 2-10Hz)=100%
P(NRT>5, 2-10Hz)=8.9%
at Terziet (EMR)

→ NN limit the ET sensitivity, NN cancellation needed up to factor 5…
NB: currently, for ET a factor 2 NNC is optimistic.

R. De Rosa et al., SPB workshop 2023

A fruitful collaboration!

The geophysical characterization is a great and fruitful example of collaboration between Italian Research Institutes (INFN & INGV), that have brought together different and complementary skills and expertise to demonstrate the extraordinary quality of the Sardinia candidate site to host ET.





Conclusions

- The geo-physical site characterization of the ET candidate sites is a task coordinated by the Site Preparation/Characterization Board of the ET collaboration and operated by the "local host teams", following a common shared baseline.
- Site characterization is strictly related to the noise mitigation strategy and detector design.
- In ET we are mostly interested in **LF sources of noise** (in particular: 2-10Hz, where they can spoil the target sensitivity). Main concerns: **seismic** (→**Newtonian**) noise and **magnetic** noise.
- Sardinia is geologically **very quiet**, far from active fault lines, and characterized by low anthropic noise. Here we are characterizing the candidate site since 2019 (starting from a first study in 2010-2014), with the installation of a large array of permanent sensors in Sos Enattos, the deployment of temporary arrays in the surrounding area, and thanks to two instrumented boreholes at the other two corners operative since 2021.
- Measurements show a peculiar **very low level of seismic noise** in the ET-LF band (2-10Hz), where the seismic noise level match or goes even below the Peterson's NLNM! The projected (seismic) Newtonian noise is also compatible with the ET-D sensitivity curve. Also, the **electromagnetic noise** is very low, while acoustic noise measurement ongoing (also very quiet!).
- Possible local sources of noise (e.g. wind farms) are under study.
- **From the geological and physical point of view, Sardinia is an optimal candidate to host the Einstein Telescope, either in Δ or in L (→ 2 sites) configuration!**

Conclusions