GWADW Elba 2023

Gravitational Wave Advanced Detector Workshop

ET EINSTEIN TELESCOPE

Einstein Telescope site characterization in Sardinia

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on behalf of the ET Sardegna site characterisation team

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Università degli Studi di Napoli Federico II

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

GWADW – 21st – 27th May 2023

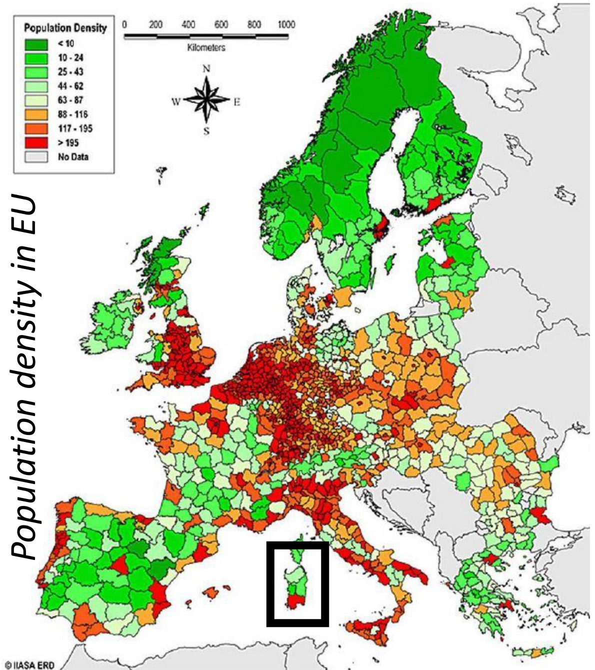
Summary

- **Sardinia: the geological framework**
- Characterisation of the Sos Enattos site
- Characterisation of the Δ corners
- Site comparison
- Conclusions

ET in Sardinia, why?

Sardinia is made of:

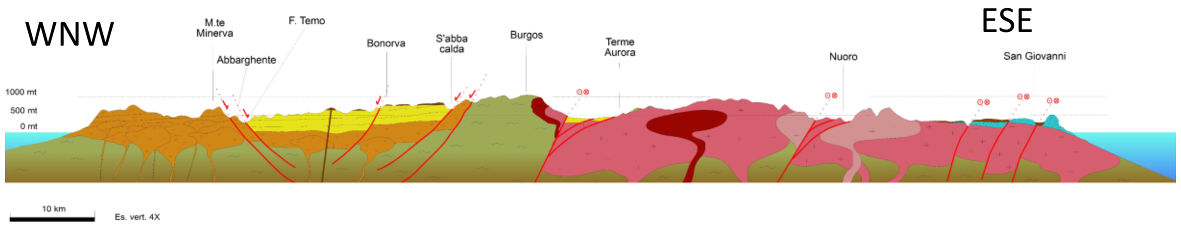
- Quaternary alluvial deposits and minor intra-plate volcanism
- Tertiary sedimentary basins with volcanic units
- Deeply eroded Mesozoic sedimentary rocks
- Metamorphic basement widely intruded by Carboniferous-Permian Granitoids (Variscan orogenesis; 360-290 Ma)

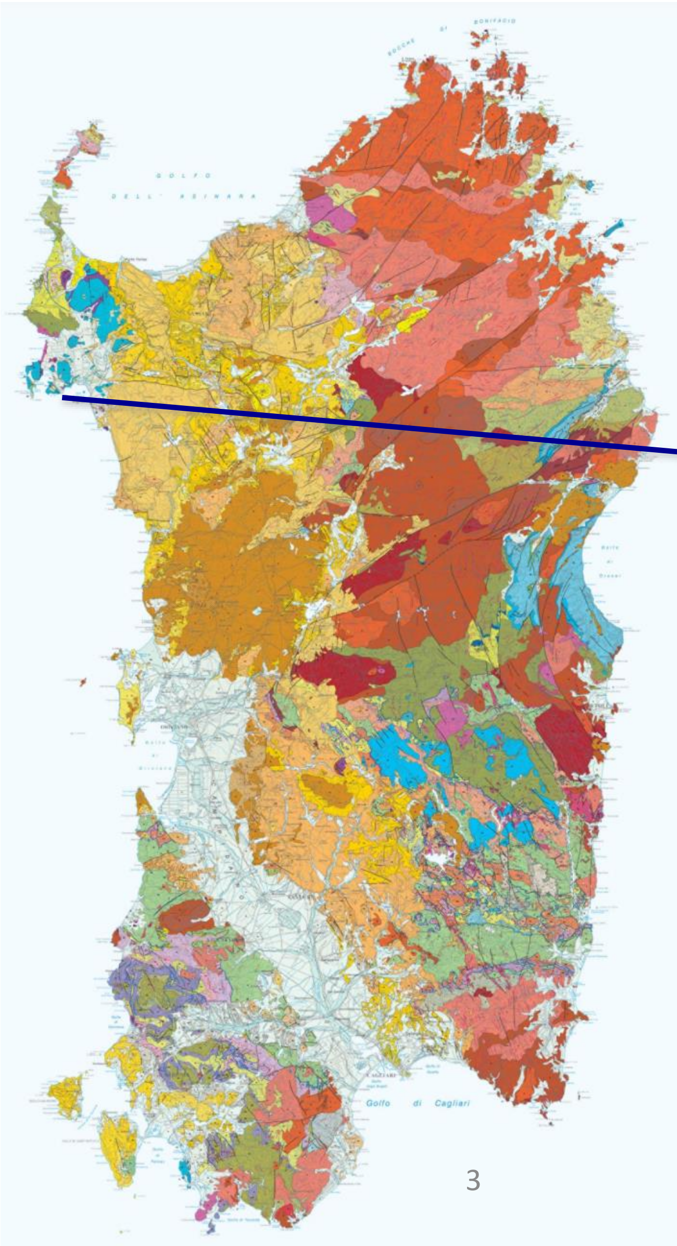


The ET Italian candidate site is located in the stable Variscan basement of Sardinia.

- Geodynamic quietness
- Low Anthropogenic noise

LOW SEISMIC NOISE!

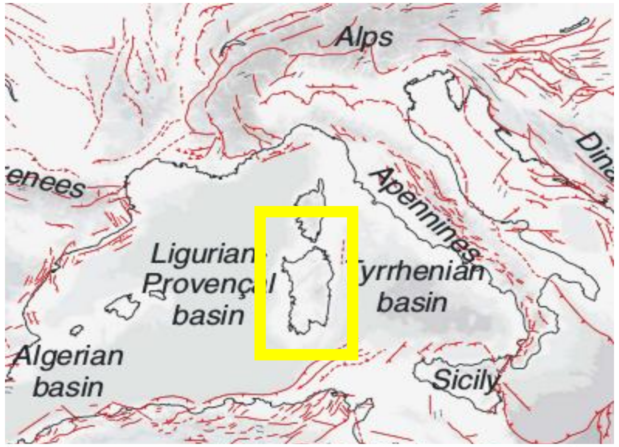


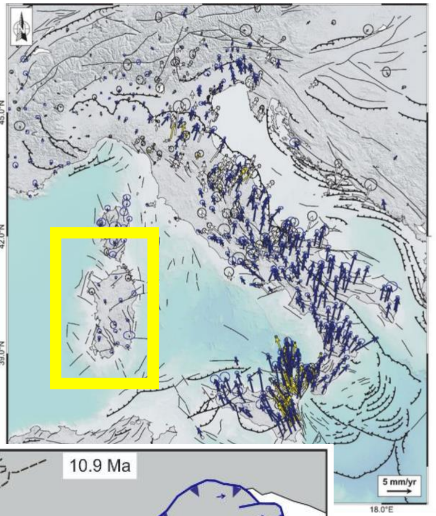


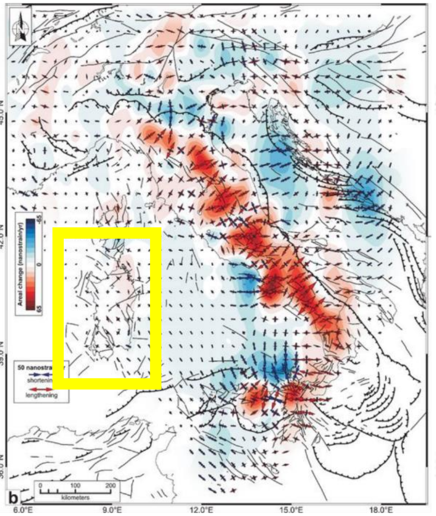
ET in Sardinia, why?

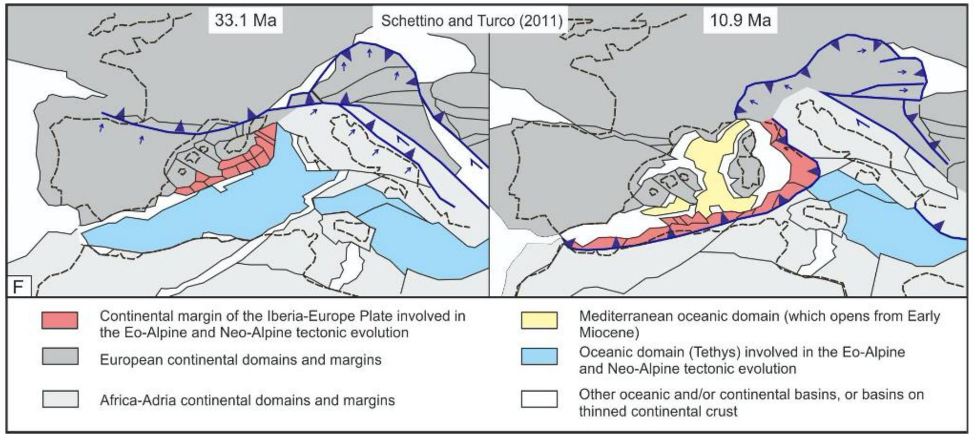
Sardinia, the geological framework

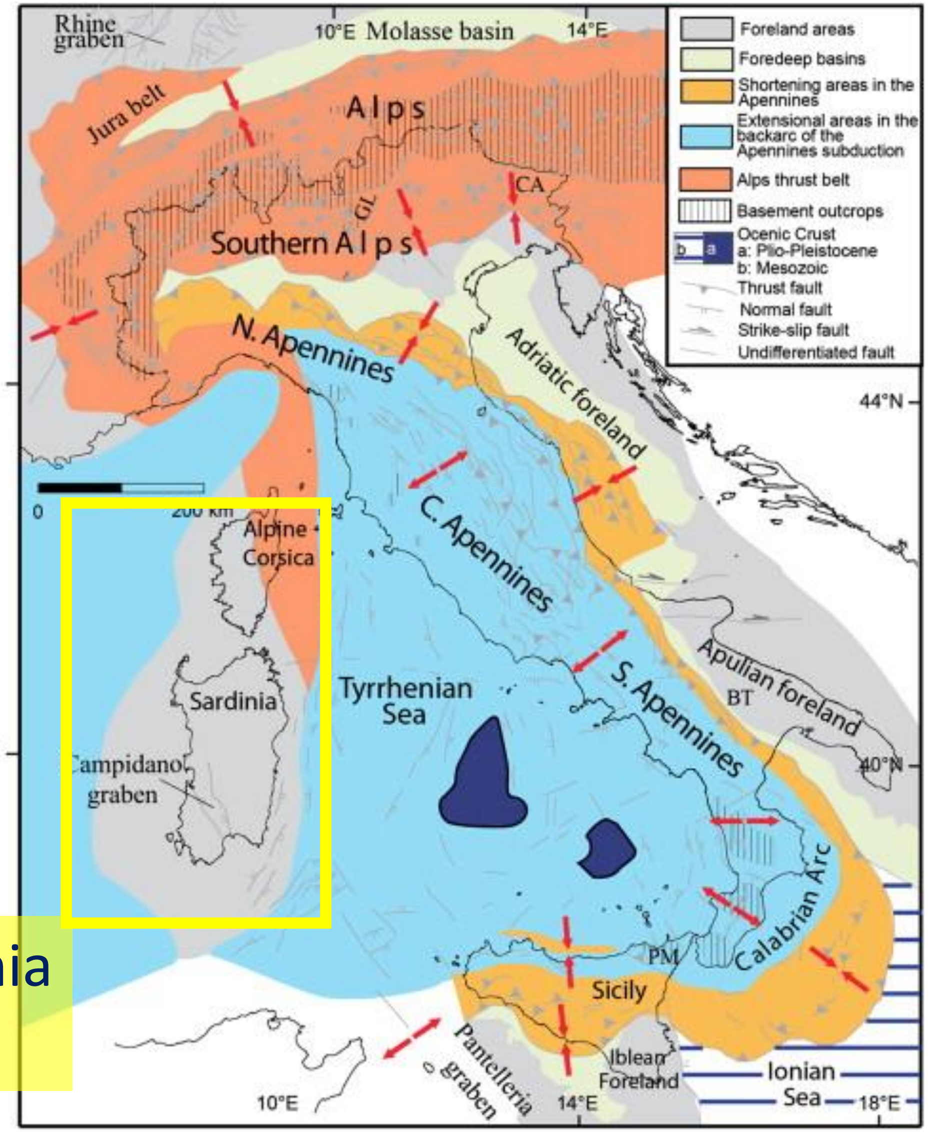
Far from active fault lines, the Corsica-Sardinia microplate is very stable → low crustal deformation.











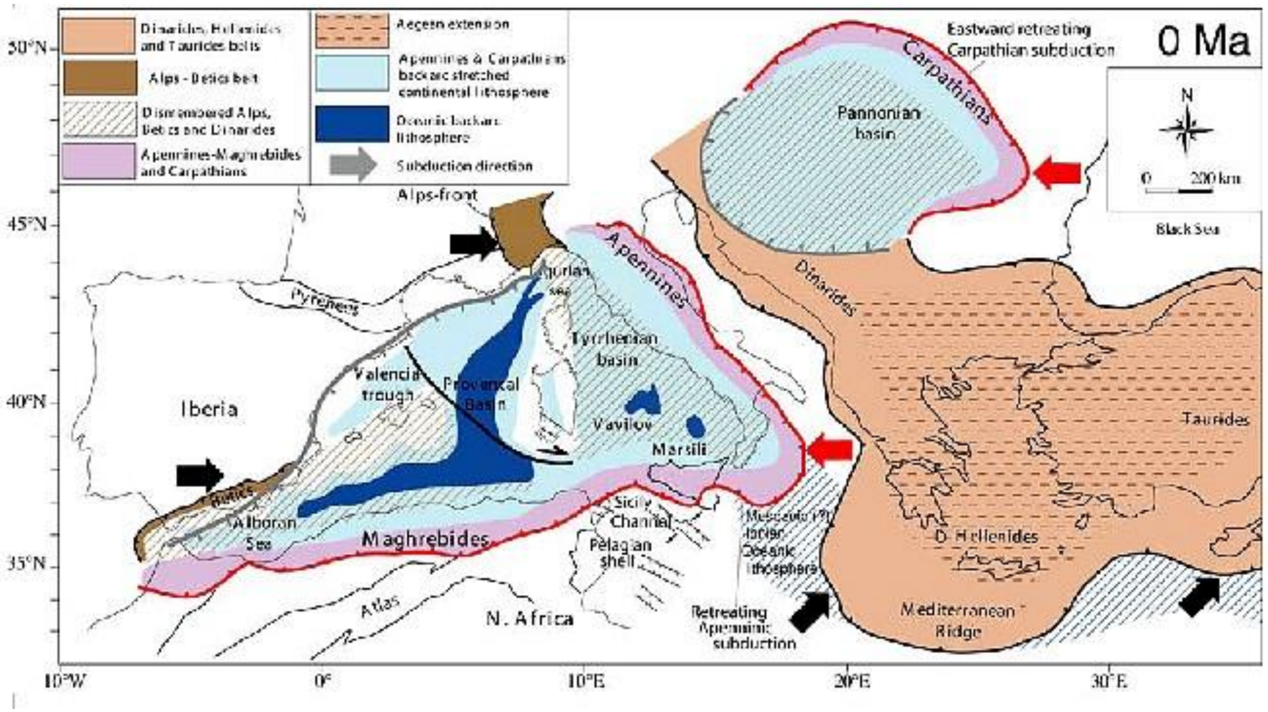
Corsica-Sardinia Microplate

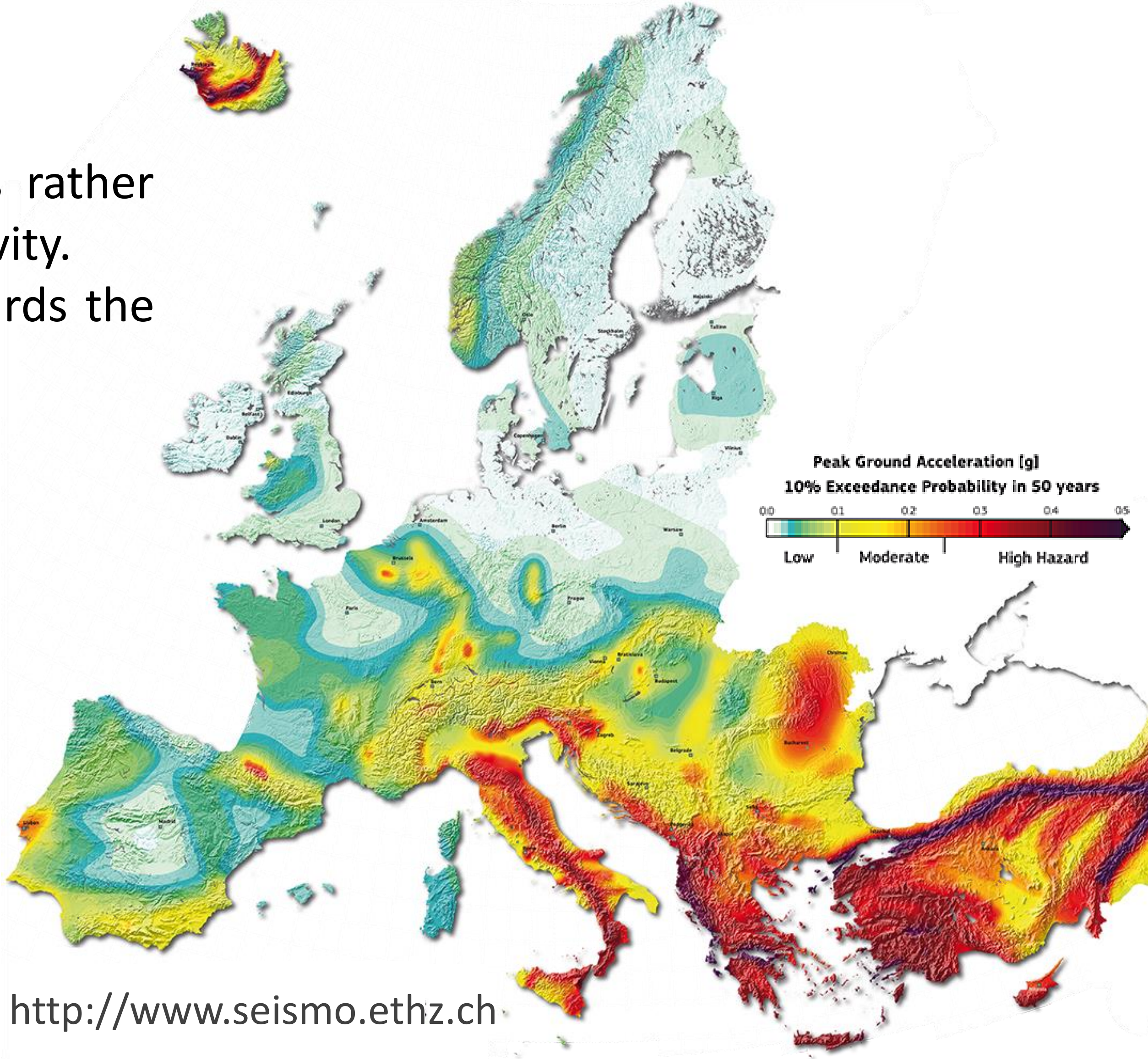
Geosciences 2020, 10, 366; doi:10.3390/geosciences10090366

ET in Sardinia, why?

Sardinia, the geological framework

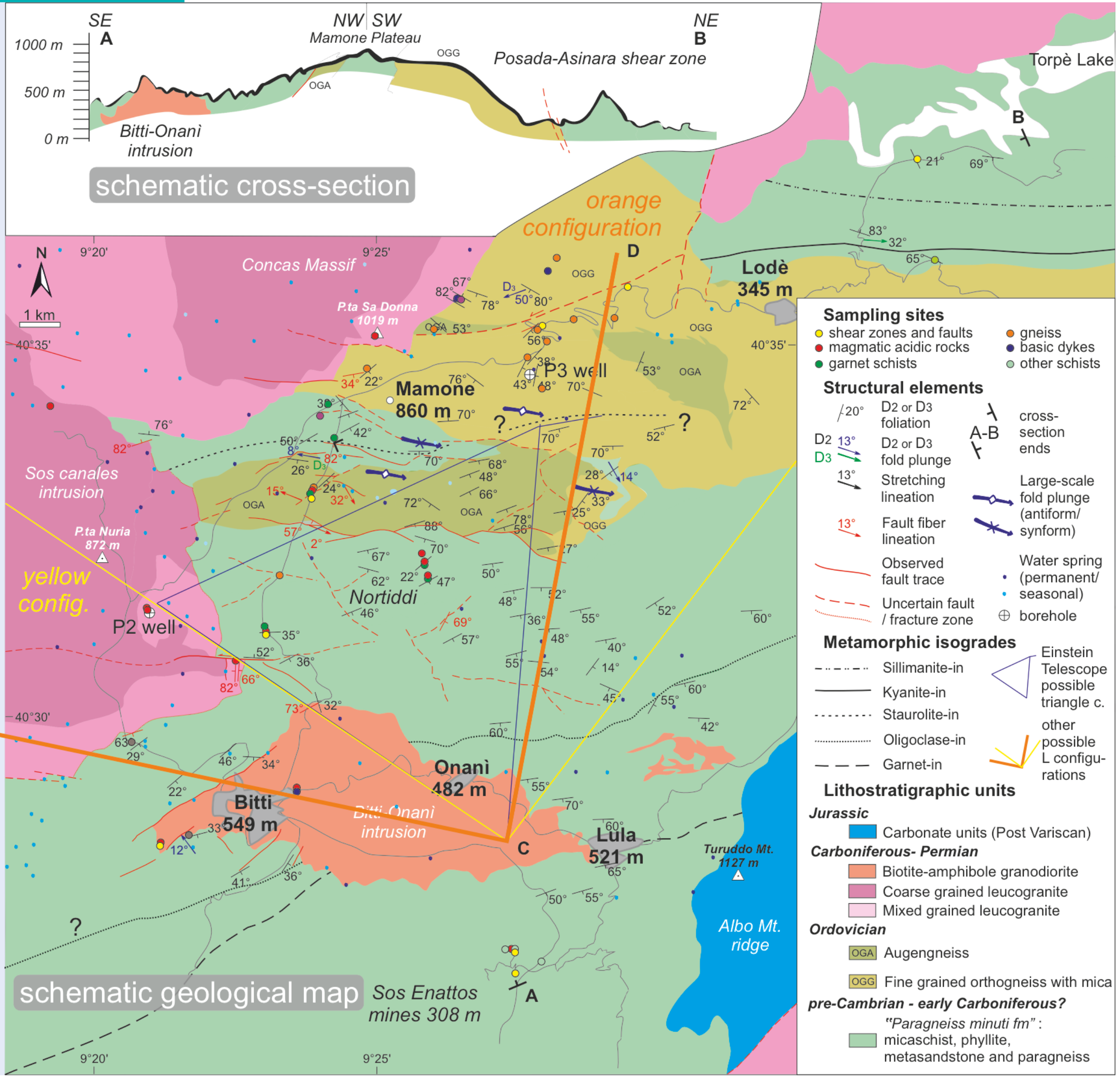
In the last million years, the Sardo-Corsican block is rather stable and quite unaffected by significative seismic activity. This is due to localization of active geodynamics towards the east of Italy.





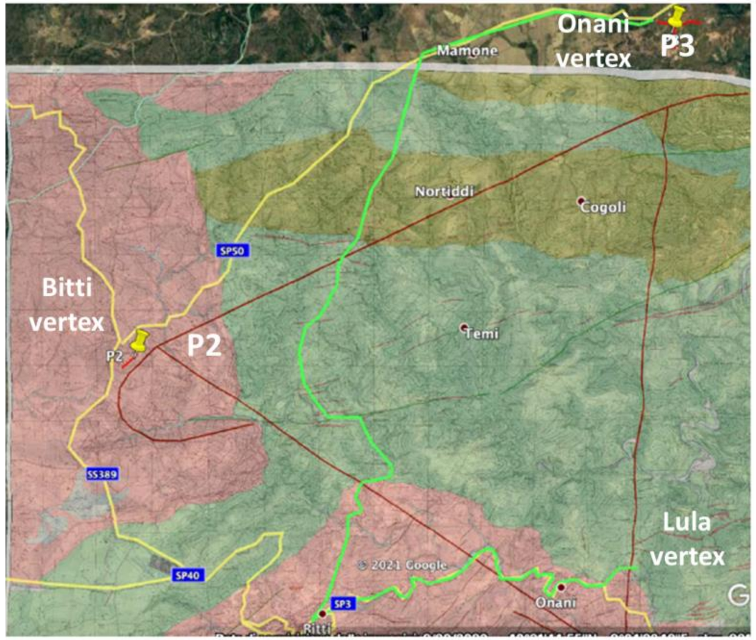
http://www.seismo.ethz.ch

ET in Sardinia, why?



Good rock quality

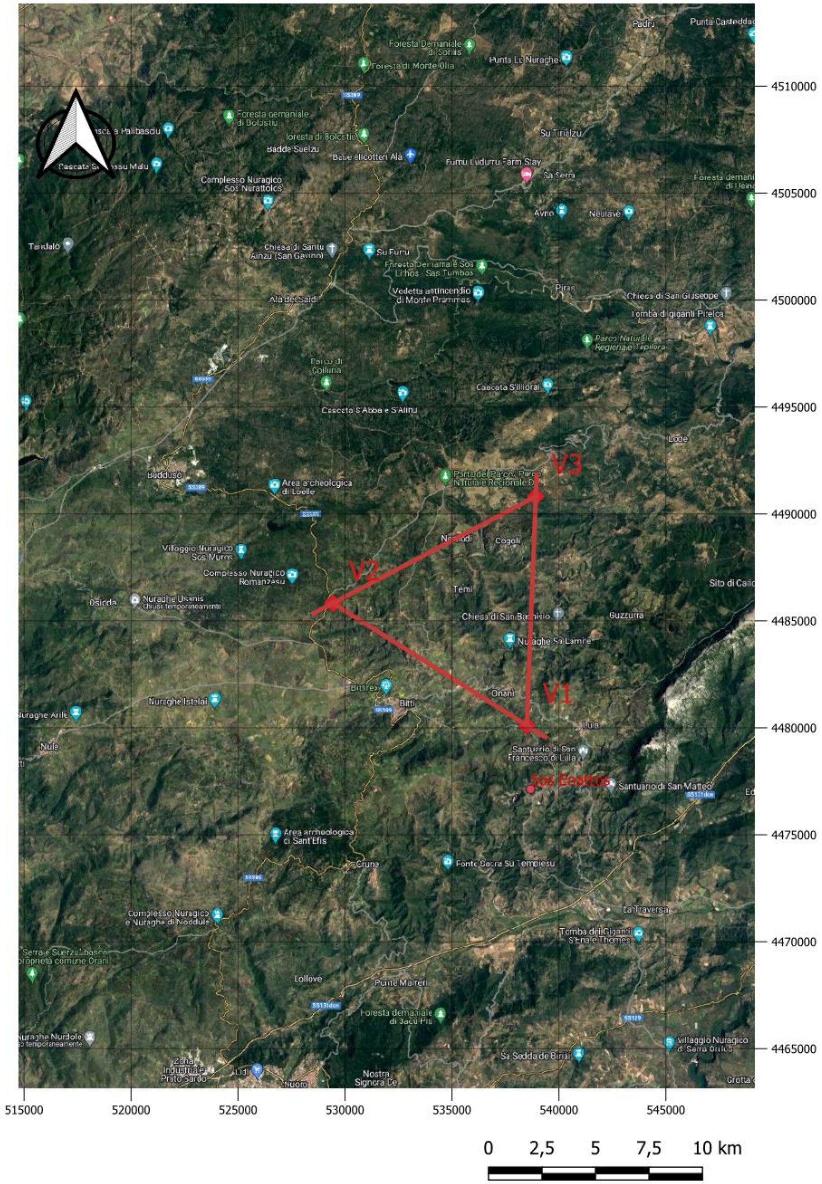
Lithologies: Orthogneiss, granitoids, micaschists. The red triangle represents the hypothetic Δ underground trace of ET. One of the possible L traces is also shown. P2 and P3 are the borehole locations. Ongoing geological survey of the area and review of the geological maps.

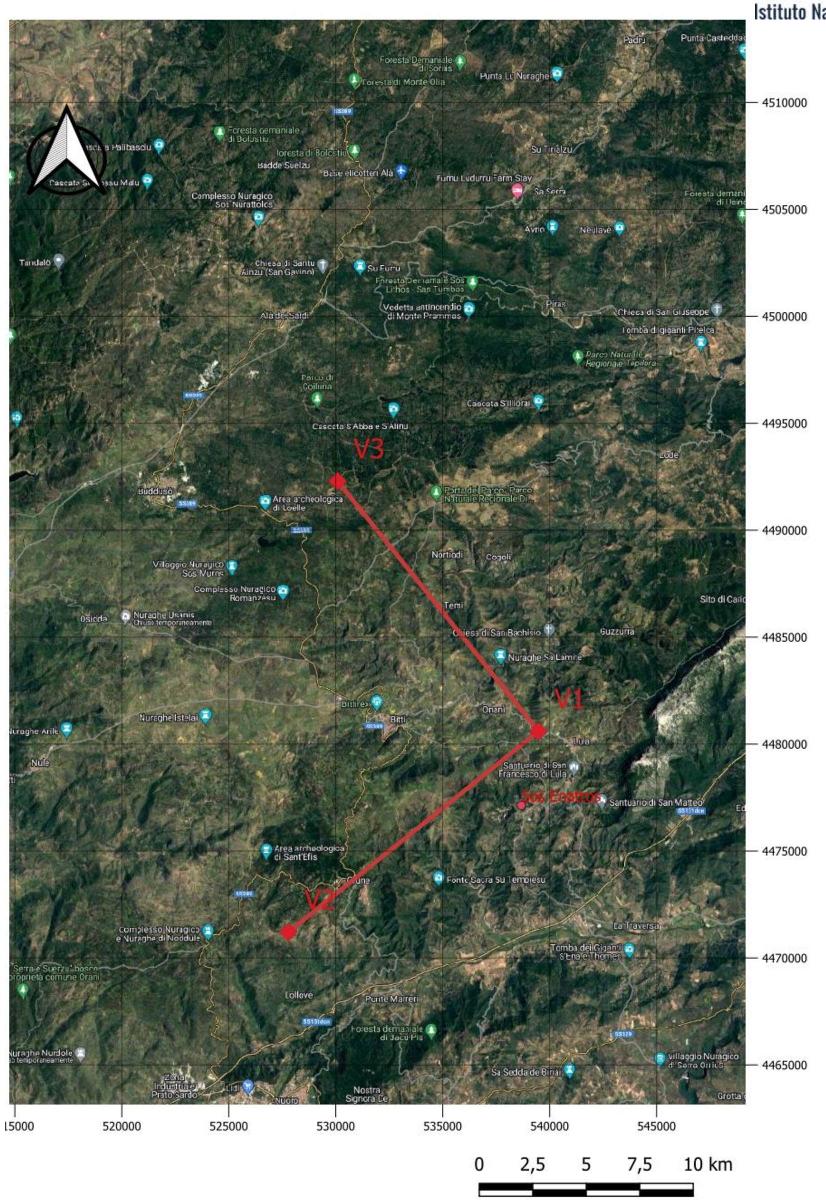


ET in Sardinia, where?

Δ and L layouts

The area of Sos Enattos could easily host a triangle with 10km-long sides (*base design*) and a L with 15-20km-long arms.





Summary

- ❑ Sardinia: the geological framework
- ❑ **Characterisation of the Sos Enattos site**
- ❑ Characterisation of the Δ corners
- ❑ Site comparison
- ❑ Conclusions

The Sos Enattos site

Sos Enattos former mine

The Sos Enattos site

Site characterization of the former mine

- Maintained (by *IGEA SpA*) underground access via tunnels and shaft;
- First characterization in 2010-2014 (*LN et al* 2014 *Class. Quantum Grav.* **31** 105016).
- **Long-term sensors deployment since March 2019** (MIUR, INFN, INGV, GSSI, Universities of Sassari, Cagliari, Rome, Naples…);
- Environmental (seismic, magnetic, acoustic…) noise and geological characterization;
- The site hosts the **SarGrav Laboratory** (surface lab + a planned underground lab);
- Currently: control room and one permanent station at surface, three stations underground (former mine tunnels).


The Sos Enattos array

The Sos Enattos site

Site characterization of the former mine

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

Instrumented stations

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 Precision Tiltmeter (part of the *Archimedes* experiment @ SarGrav);
- Weather station (@ SarGrav Lab).

The Sos Enattos site

Site characterization of the former mine

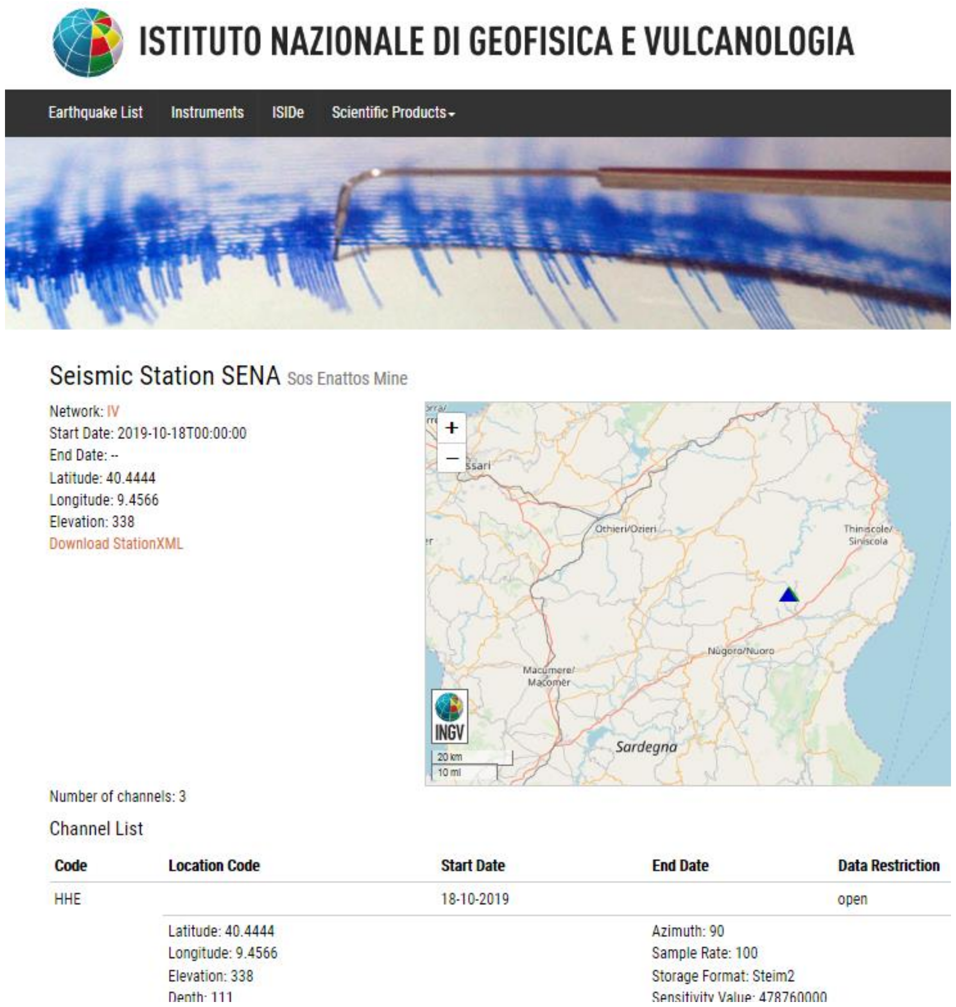
Station code	Depth WRT surface	Sensor installed	Period	Digitiser
SOE0 (old location)	0 (338m a.s.l.)	Guralp 3EPSCD 120	2019/3-2019/12	Embedded
SOE0	400m asl	Nanometrics Trillium 240	2019/12-...	Nanometrics Taurus
SOE1	-84m (254m asl)	Nanometrics Trillium 240	2019/3-2020/7	Nanometrics Taurus
SOE1	-84m (254m asl)	Nanometrics Trillium 120H	2020/7-2021/8	Nanometrics Centaur
SOE1	-84m (254m asl)	Guralp CMG-3TD 360	2021/7-...	Embedded
SOE1	-84m (254m asl)	Nanometrics Trillium 360 vault	2022/4-...	Nanometrics Centaur
SOE2	-111m (227m asl)	Nanometrics Trillium 240	2019/3-2021/6	Nanometrics Centaur
SOE2	-111m (227m asl)	(2x) Nanometrics Trillium 360 GSN	2021/6-...	Nanometrics Centaur
SOE3	-160m (178m asl)	Nanometrics Trillium 240	2020/8-...	Nanometrics Centaur
Control Room	340m asl	Nanometrics Trillium 20	2020/11-...	Nanometrics Centaur

Seismometers installed since 2019

ET-0151A-22, https://apps.et-gw.eu/tds/?content=3&r=17920

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

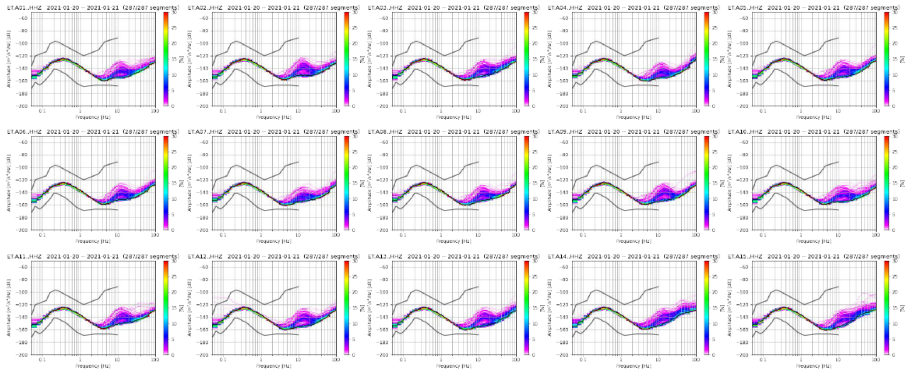
The Sos Enattos site

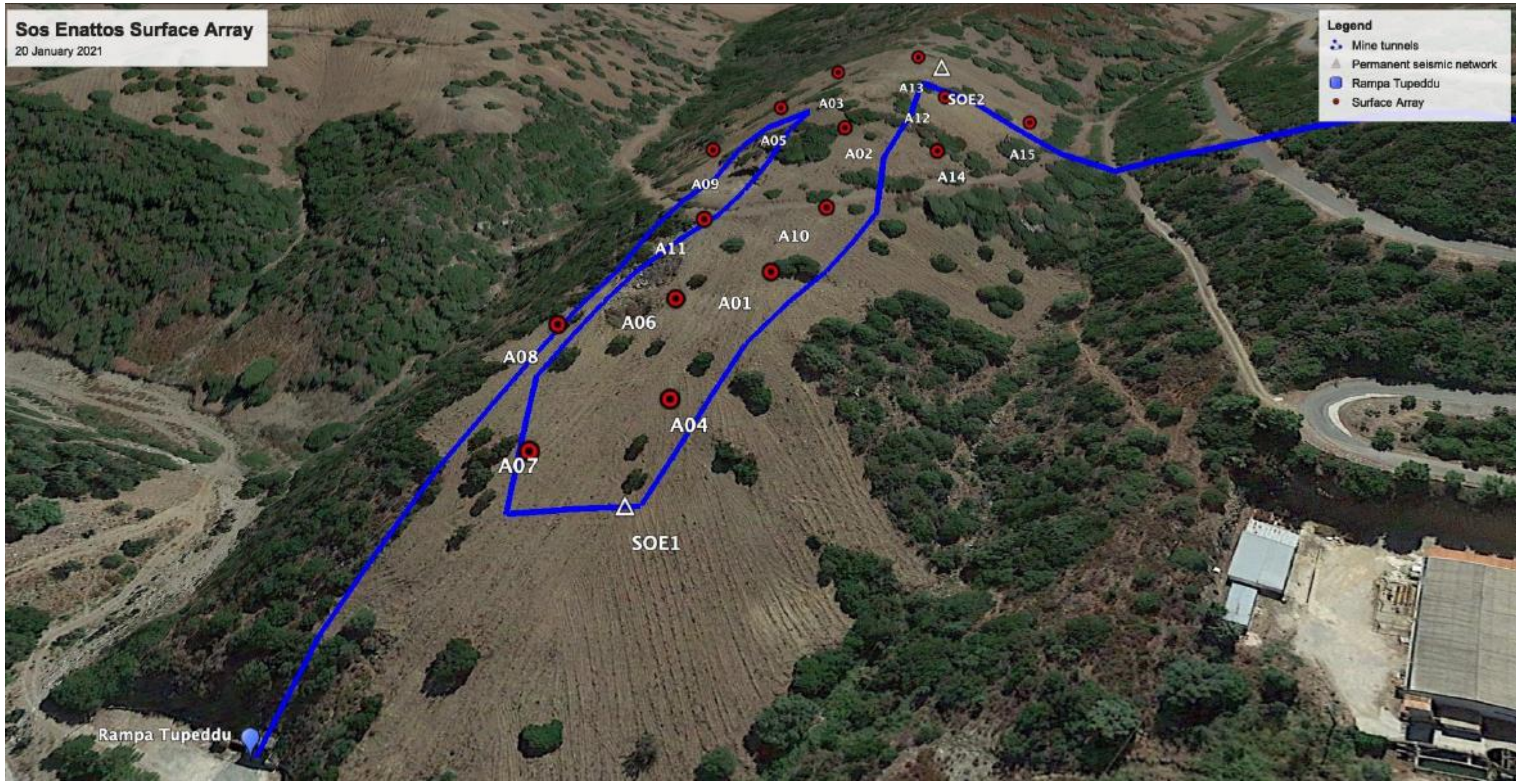
Surface Seismometer Array

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





The Sos Enattos site

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
- 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***, submitted to EPJP, 2023.

+ several internal notes, reports and talks

The Sos Enattos site

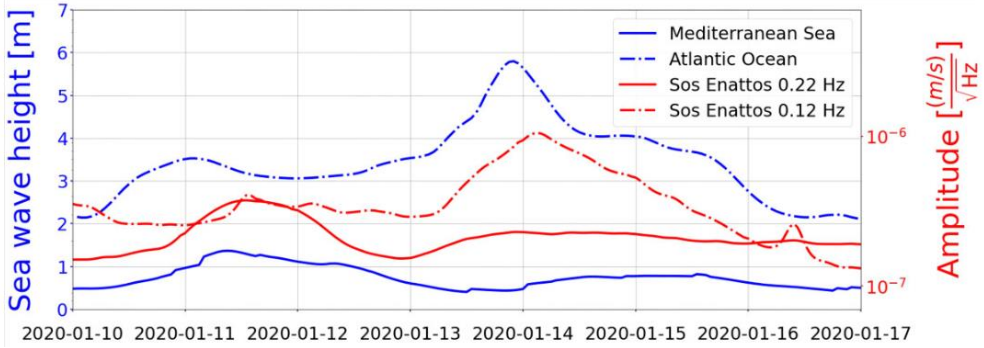
First results *Noise levels, microseismic correlation, anthropogenic noise, local sources of noise…*

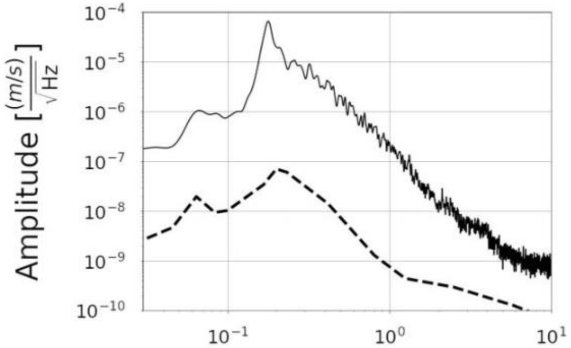
Geophysical Journal International

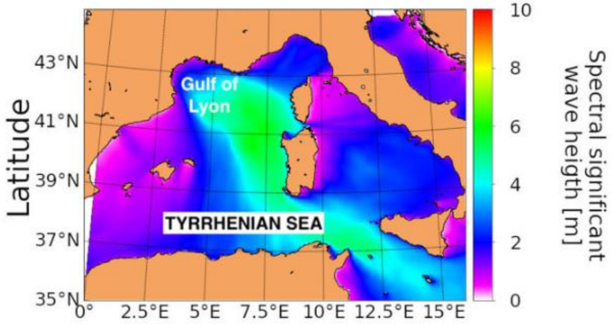
Geophys. J. Int. (2023) **234**, 1943–1964 https://doi.org/10.1093/gji/ggad178
Advance Access publication 2023 April 26
GJI Seismology

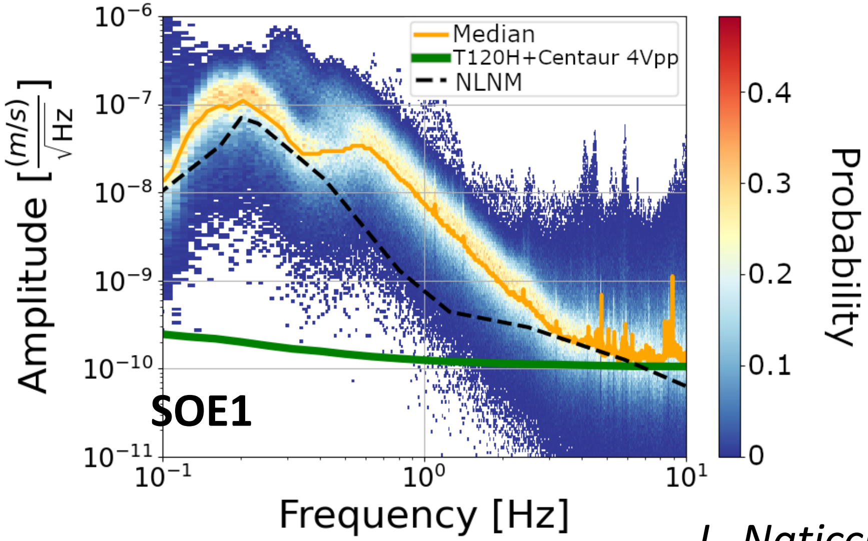
Temporal variations of the ambient seismic field at the Sardinia candidate site of the Einstein Telescope

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] E. Calloni,[8,9] A. Cardini,[12] M. Carpinelli,[4,5,12] A. Contu,[12,13] L. Errico,[8,9] V. Mangano,[6,7] M. Olivieri,[14] M. Punturo,[15] P. Rapagnani,[6,7] F. Ricci,[6,7] D. Rozza,[4,5] G. Saccorotti,[10] L. Trozzo,[9] D. Dell'aquila,[4,5] L. Pesenti,[4,5] V. Sipala[4,5] and I. Tosta e Melo[4,5]









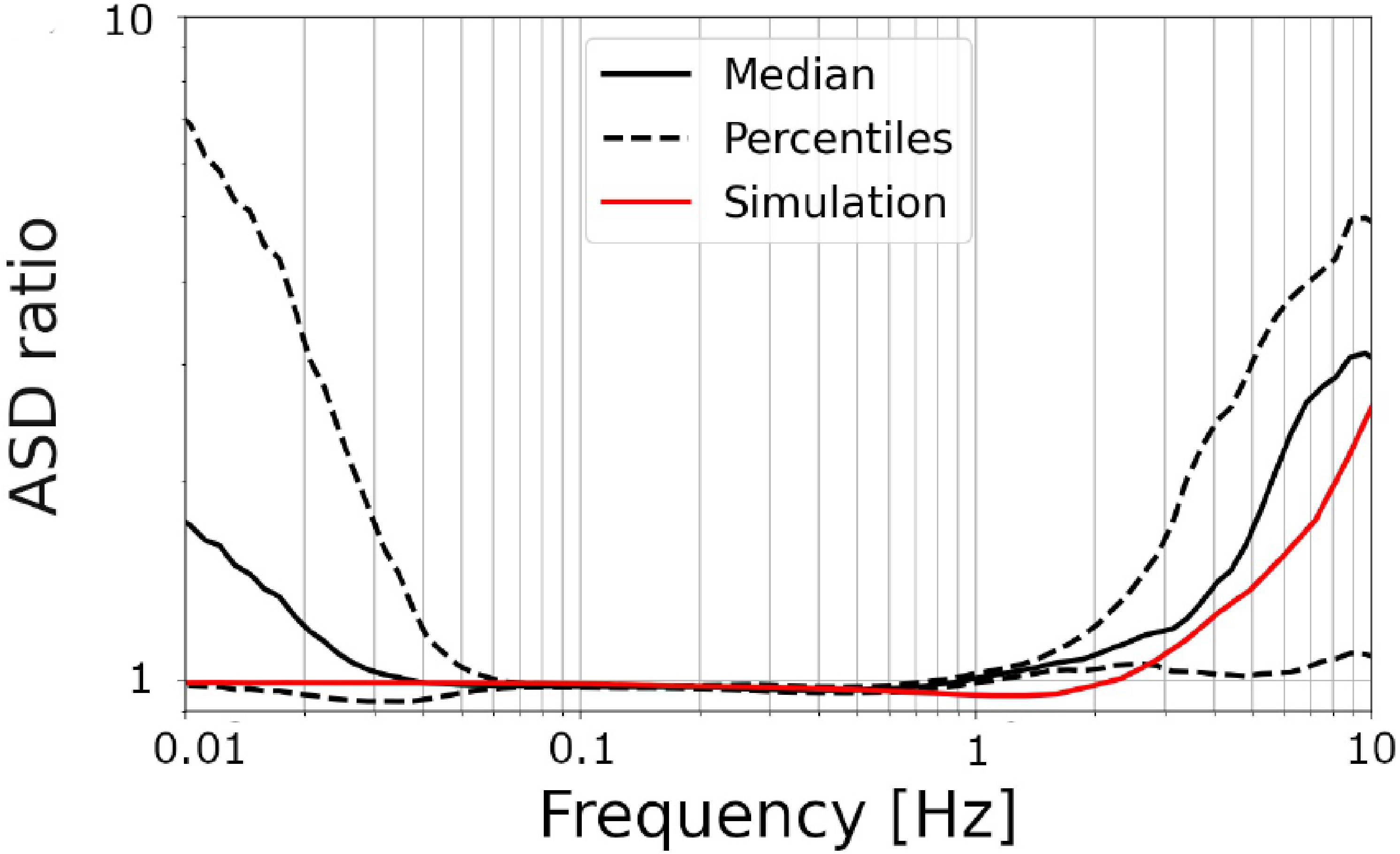
Talk of M. Di Giovanni about ambient noise in this session!

The Sos Enattos site

First results

Amplitude decay with depth significant only for f>2Hz, consistent with Rayleigh-wave propagation in local rocks

SOE0 (surface) / SOE2 (-111m vault)



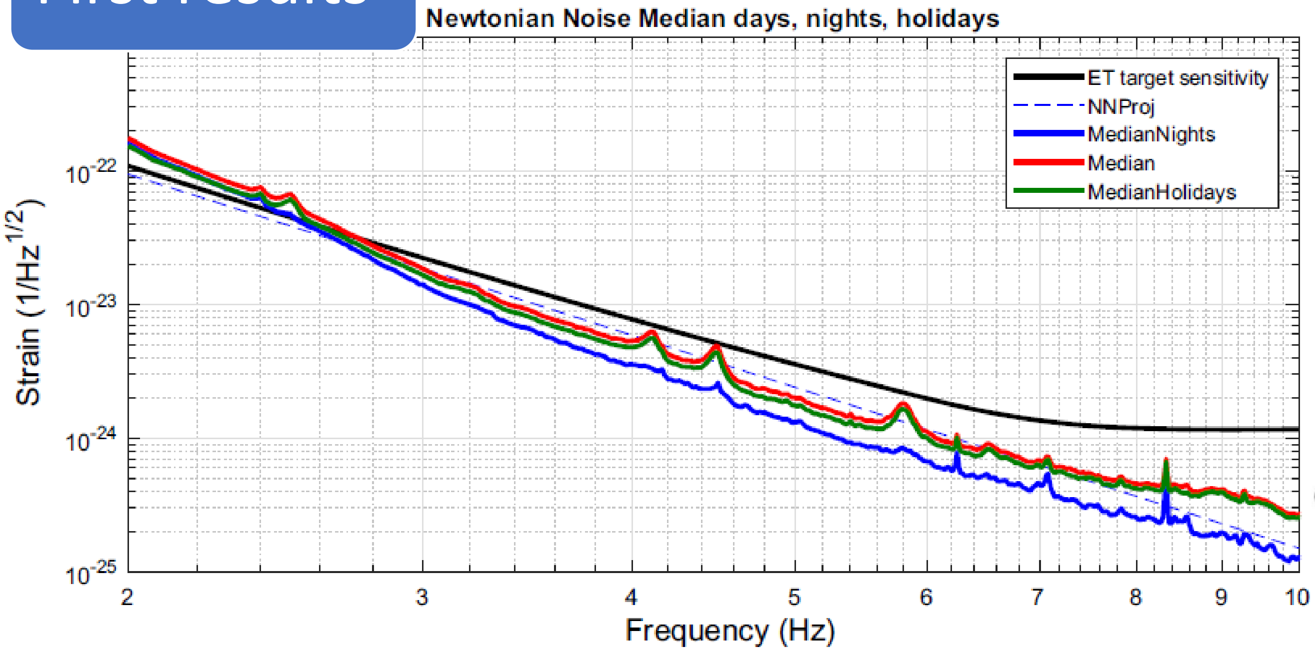
Synthetic seismograms

Seismological Research Letters (2021) 92 (1): 352–364

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)

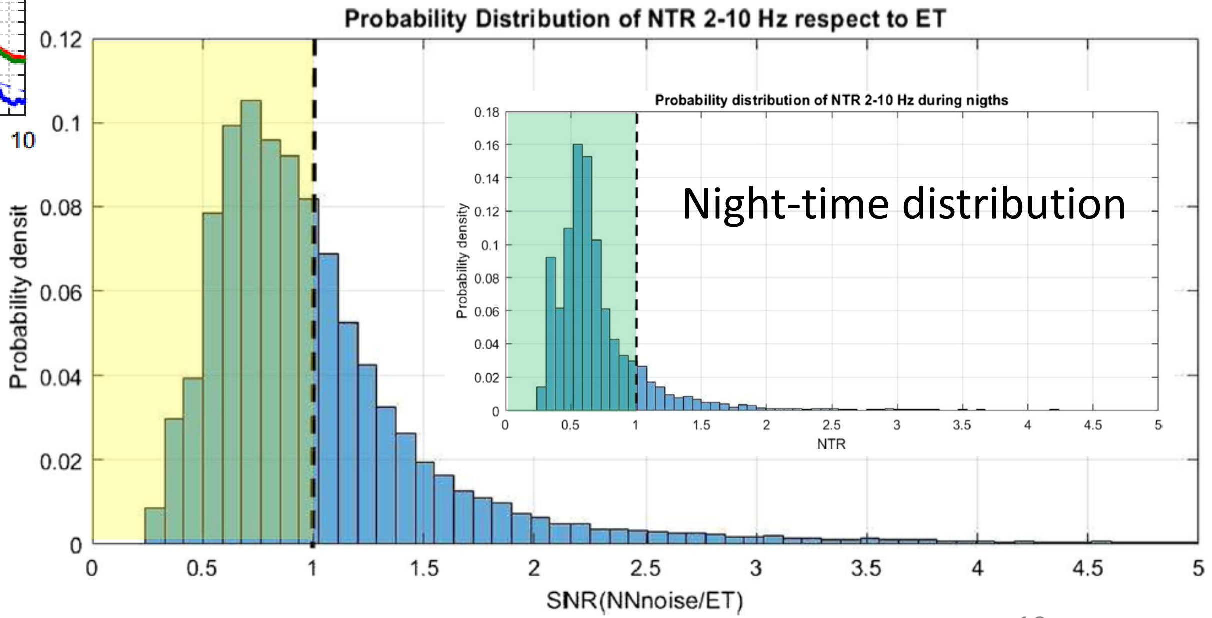
$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f} \int df \frac{\tilde{N} * \tilde{N}}{S_h}}$$

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

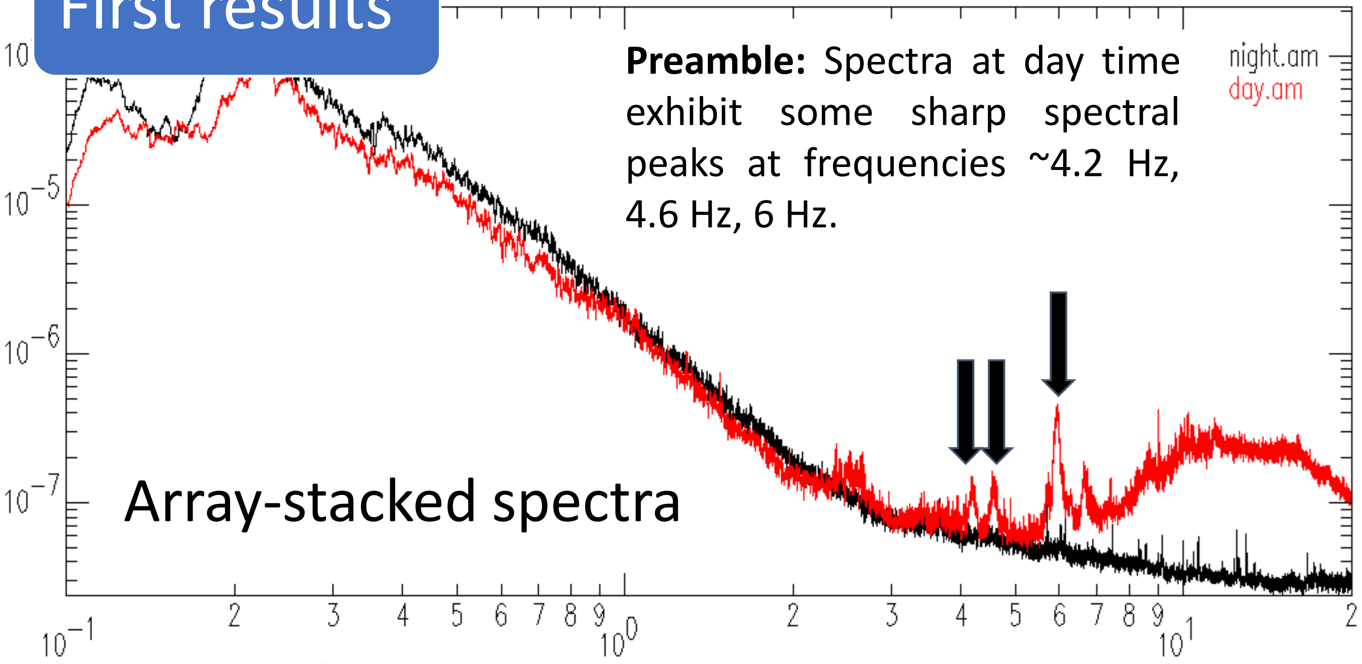


L. Naticchioni – GWADW23 – May 21st – 27th 2023

The Sos Enattos site

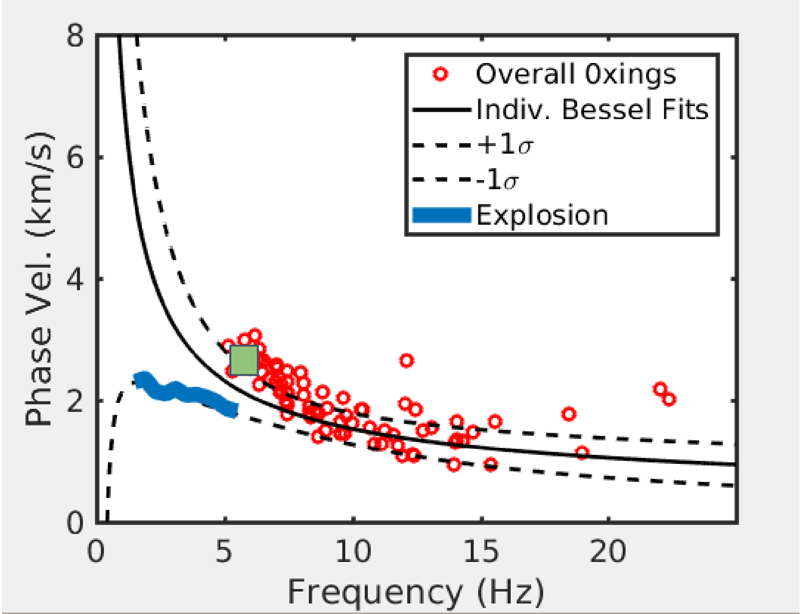
Seismometer array results

First results



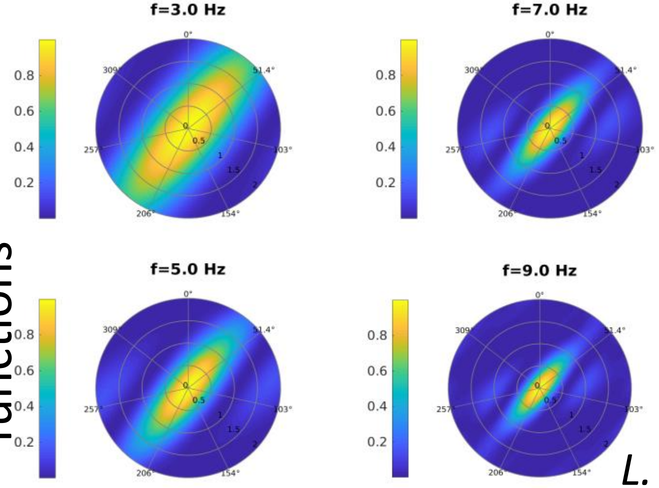
Preamble: Spectra at day time exhibit some sharp spectral peaks at frequencies ~4.2 Hz, 4.6 Hz, 6 Hz.

SPatial AutoCorrelation:

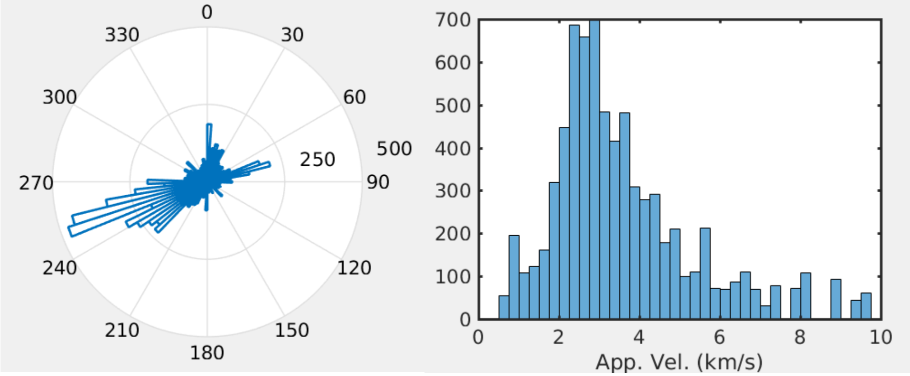


G. Saccorotti et al., 2023, submitted to Eur. Phys. J. Plus

Array response functions



FK-Analysis



Not-isotropic wavefield
Peaks at f = 4-5 Hz
Propagation azimuths directed WSW (i.e., main sources located ENE of the array)
High velocities (~2.5 km/s)

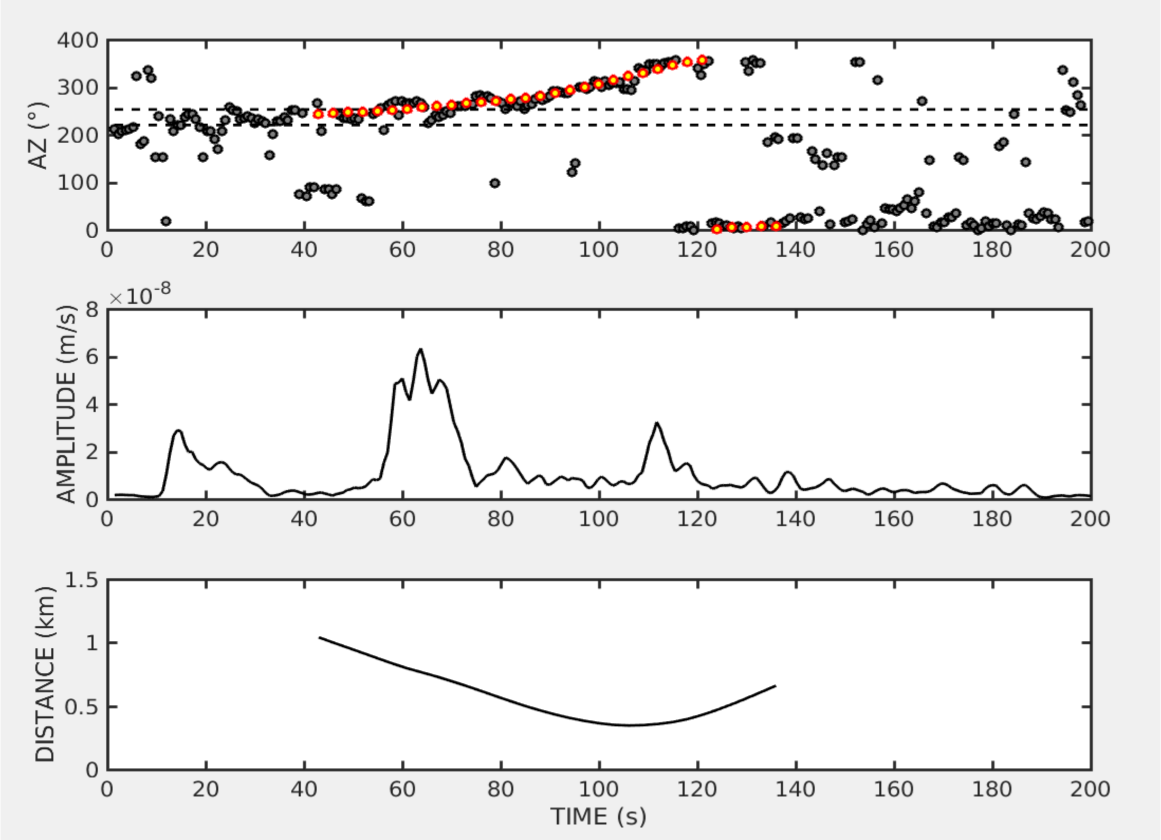
The Sos Enattos site

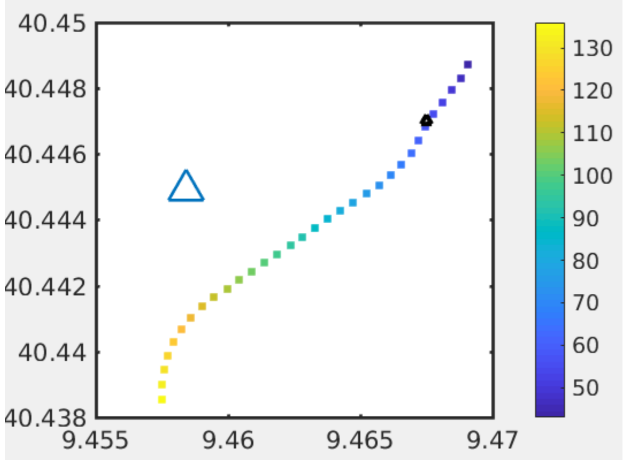
First results

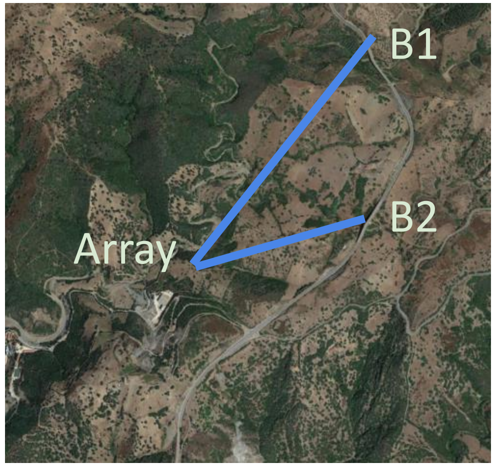
Seismometer array results

Vehicle Tracking close to the site

G. Saccorotti et al., 2023, submitted to Eur. Phys. J. Plus







Time evolution of azimuth compatible with a vehicle traveling at 60 km/h southward along road SP73.

Largest signal amplitude is NOT associated when the vehicle is closest to the array, but when it traverses bridge B2

Confirmed by Geophys. J. Int. 234, 3 2023, talk of M. Di Giovanni

The Sos Enattos site

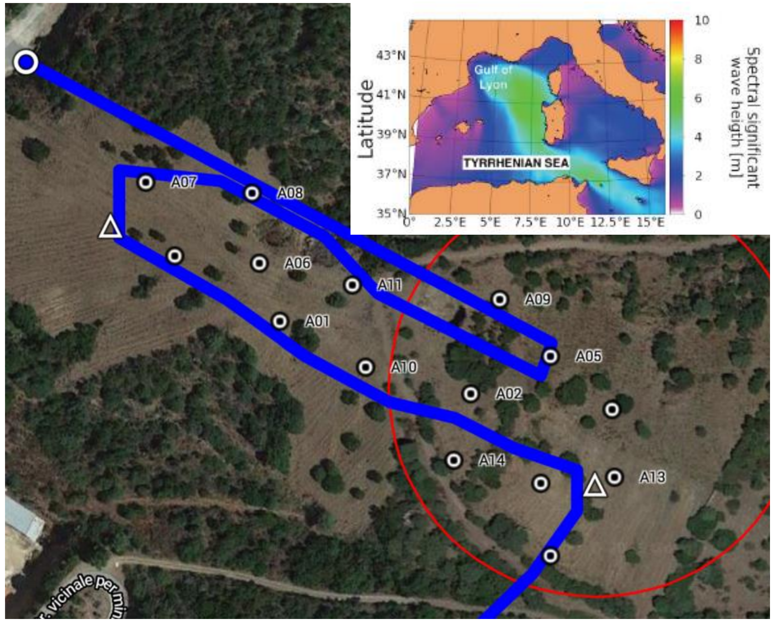
First results

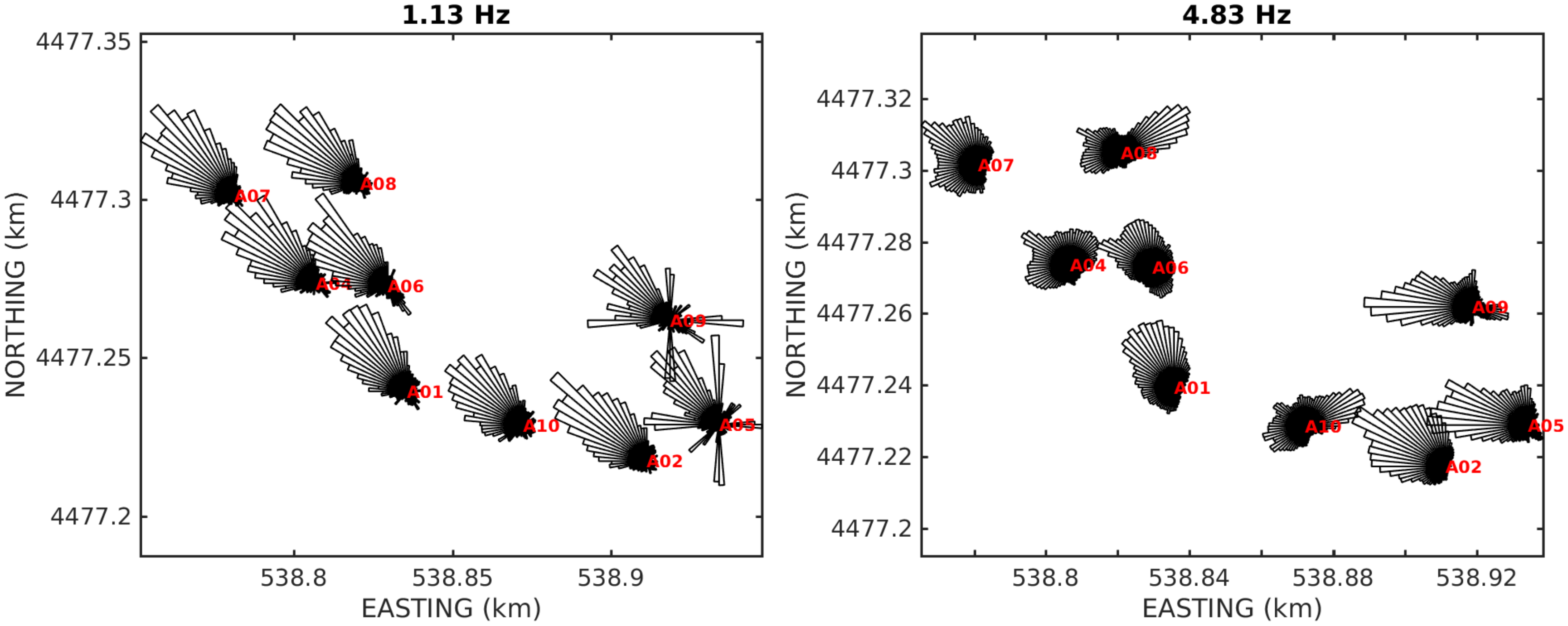
Seismometer array results

Polarization analysis

G. Saccorotti et al., 2023, submitted to Eur. Phys. J. Plus

At low frequencies, the polarization directions are rather uniform; they are oriented toward NW (marine microseismic source). At higher frequencies, the variability of polarization directions throughout the array deployment indicates a strong influence of topography.

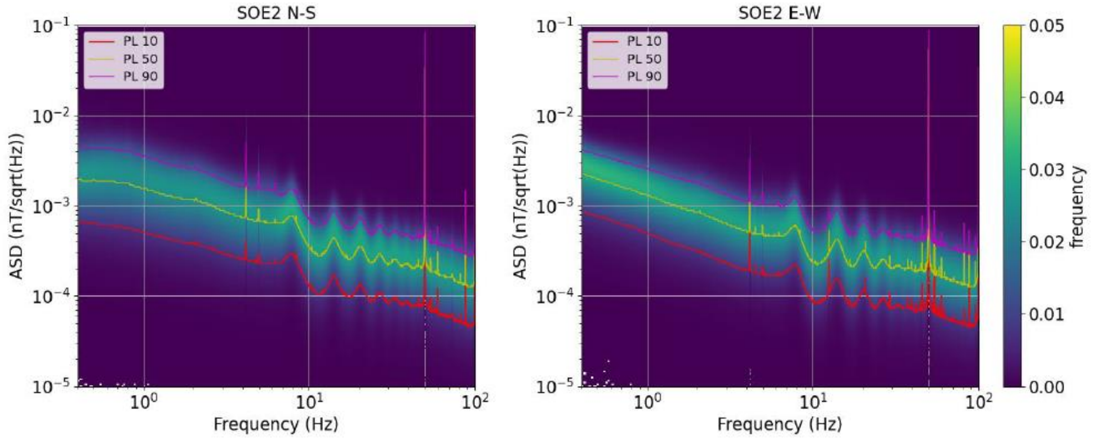


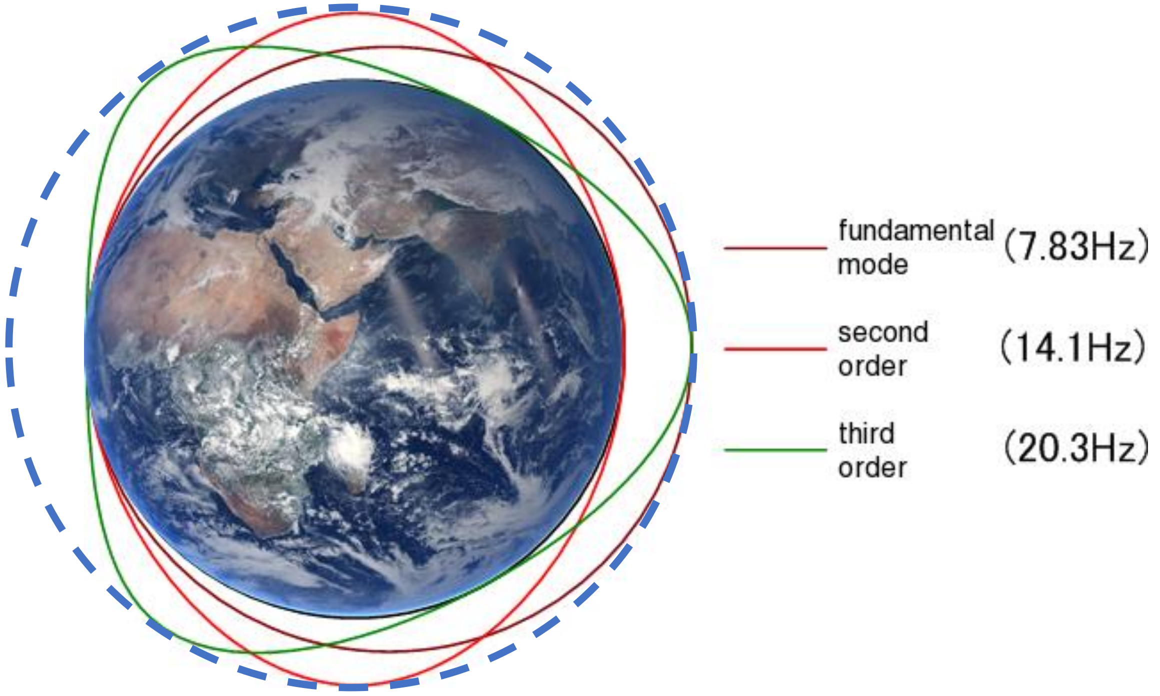


The Sos Enattos site

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)

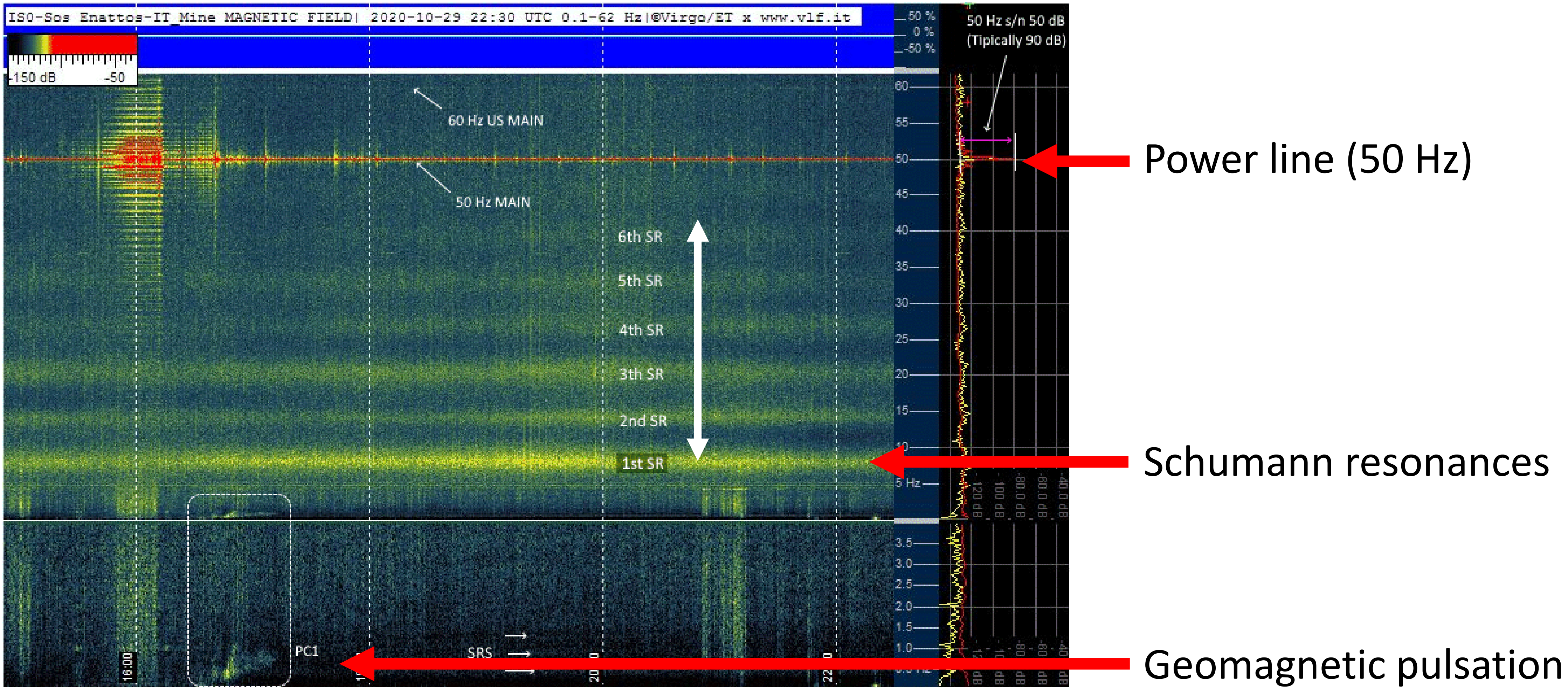




credit: R. De Rosa

The Sos Enattos site

First results **Magnetic Noise measurements**

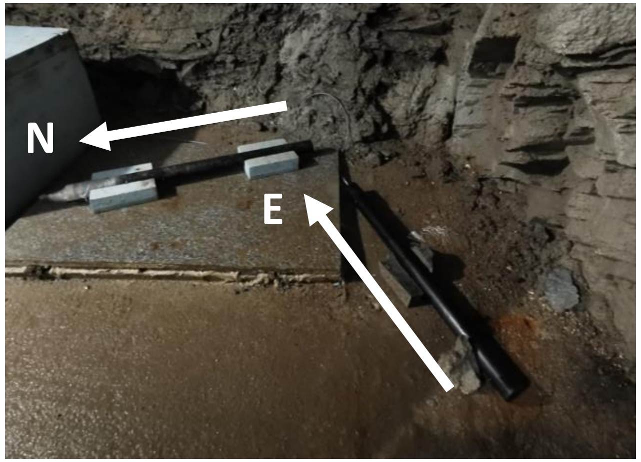


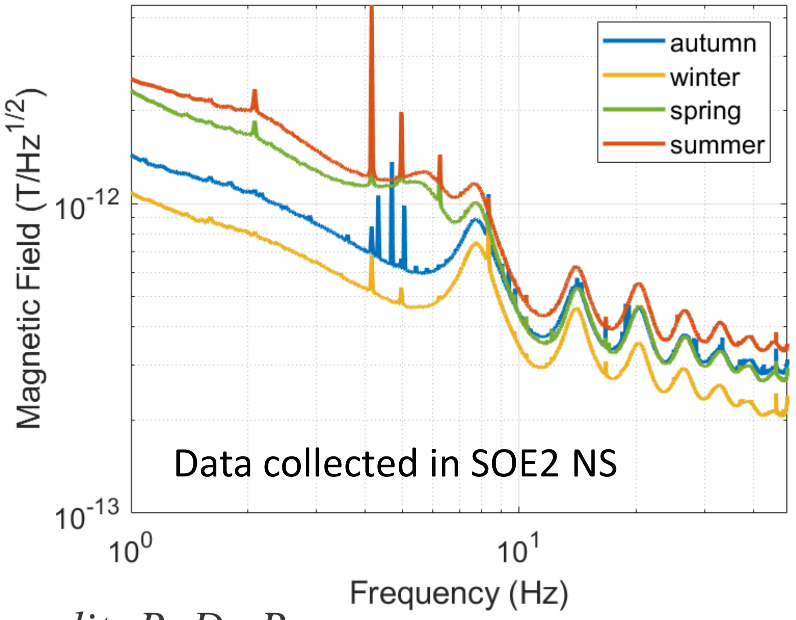
credit: R. De Rosa, R. Romero

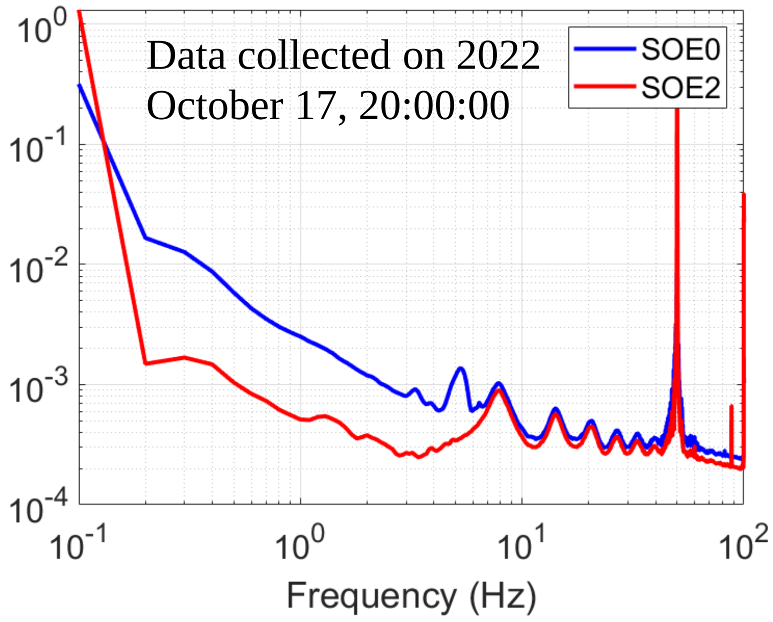
The Sos Enattos site

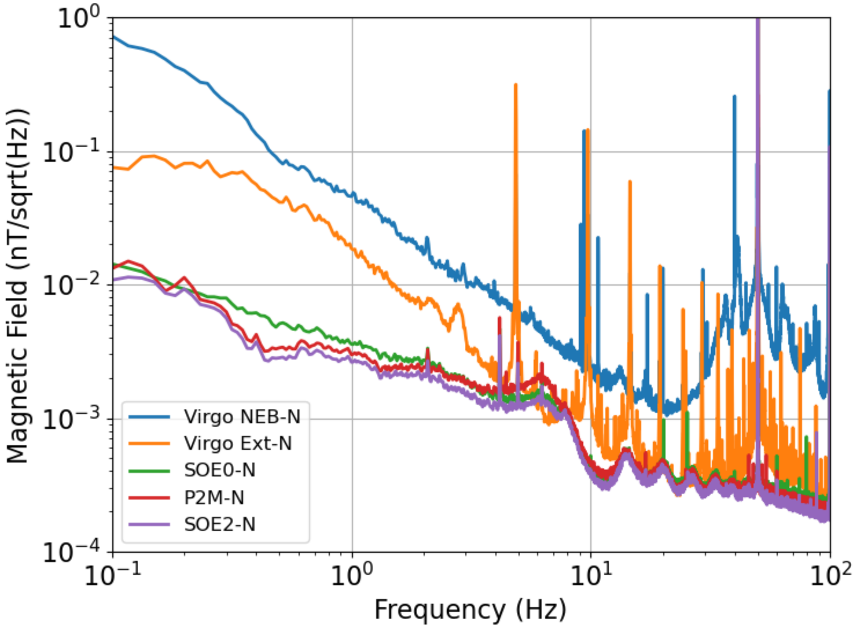
First results **Magnetic Noise measurements**

- 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.









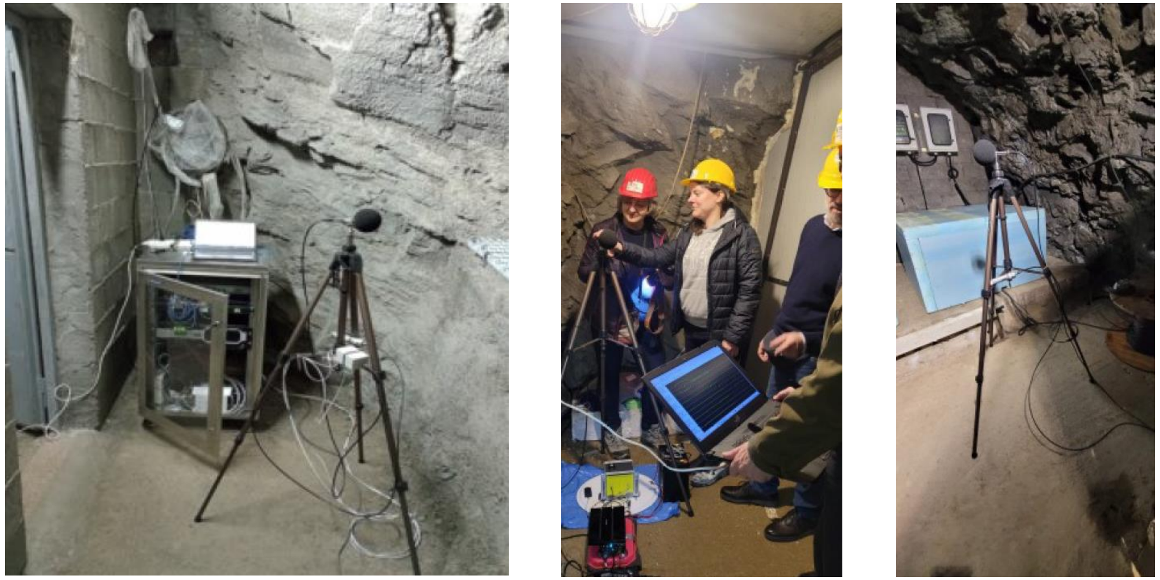
credit: R. De Rosa

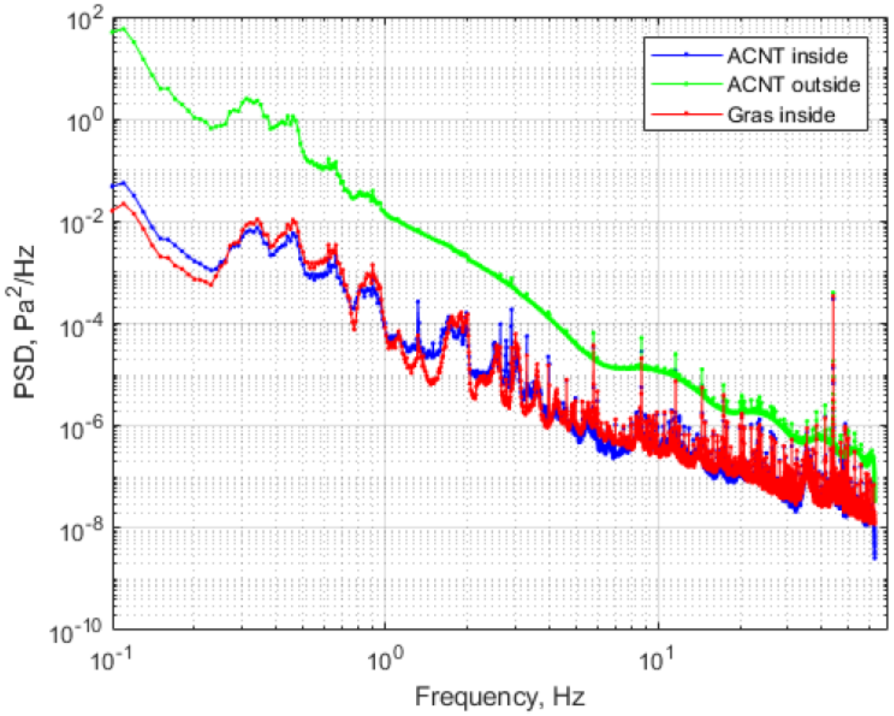
The Sos Enattos site

First results **Infrasound measurements** *Acoustic characterization of the area*

- 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 by GSSI.

credit: T. Bulik





Summary

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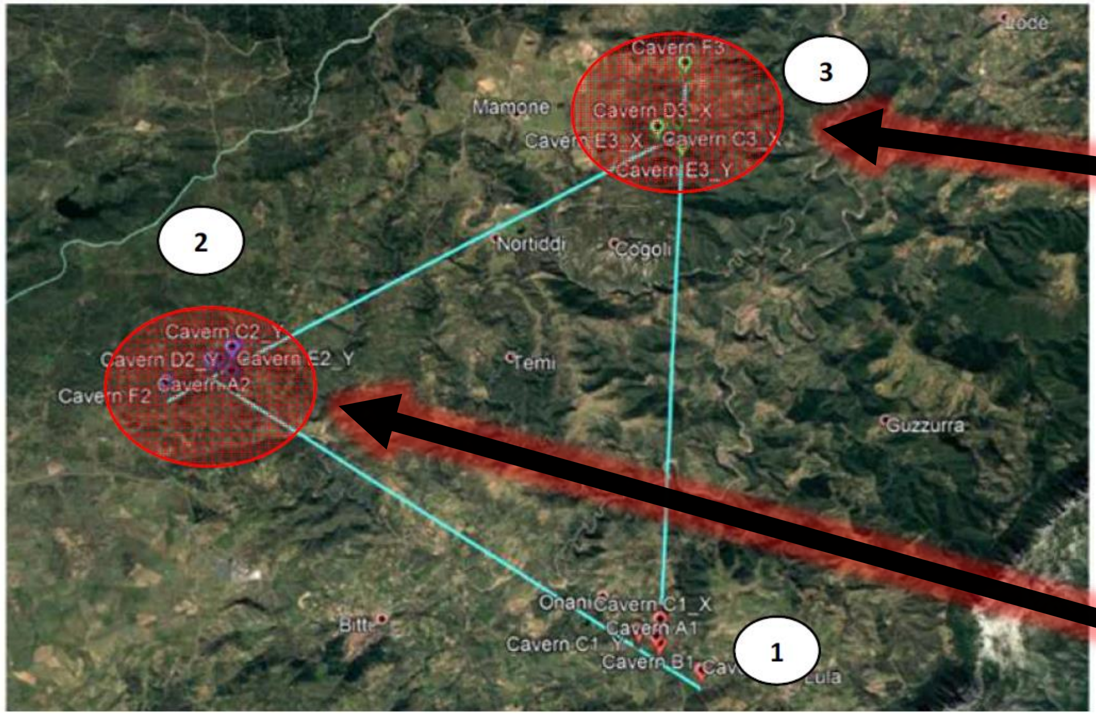
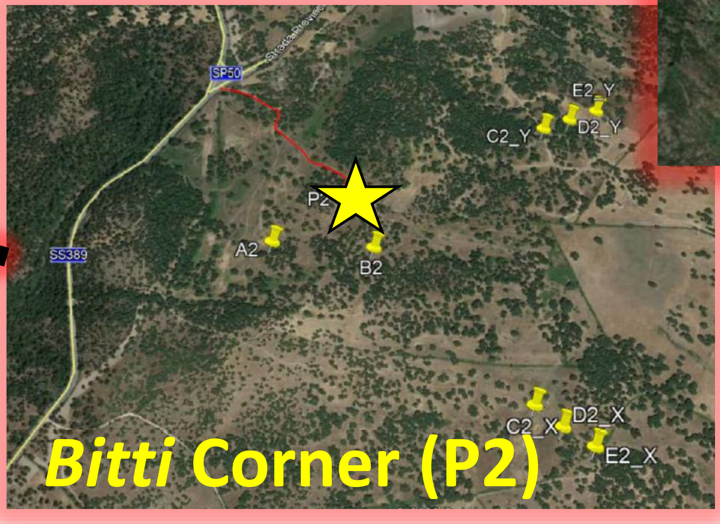
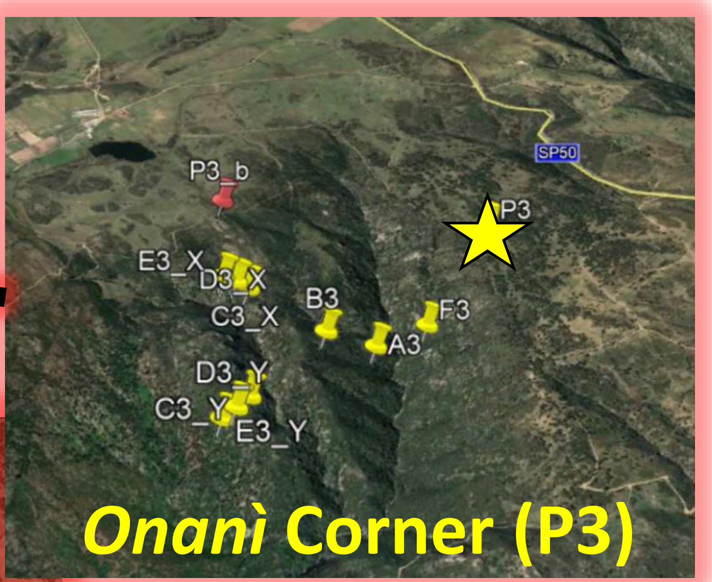
Characterization of the Δ corners

The corners of the Δ layout



Lula Corner
Sos Enattos





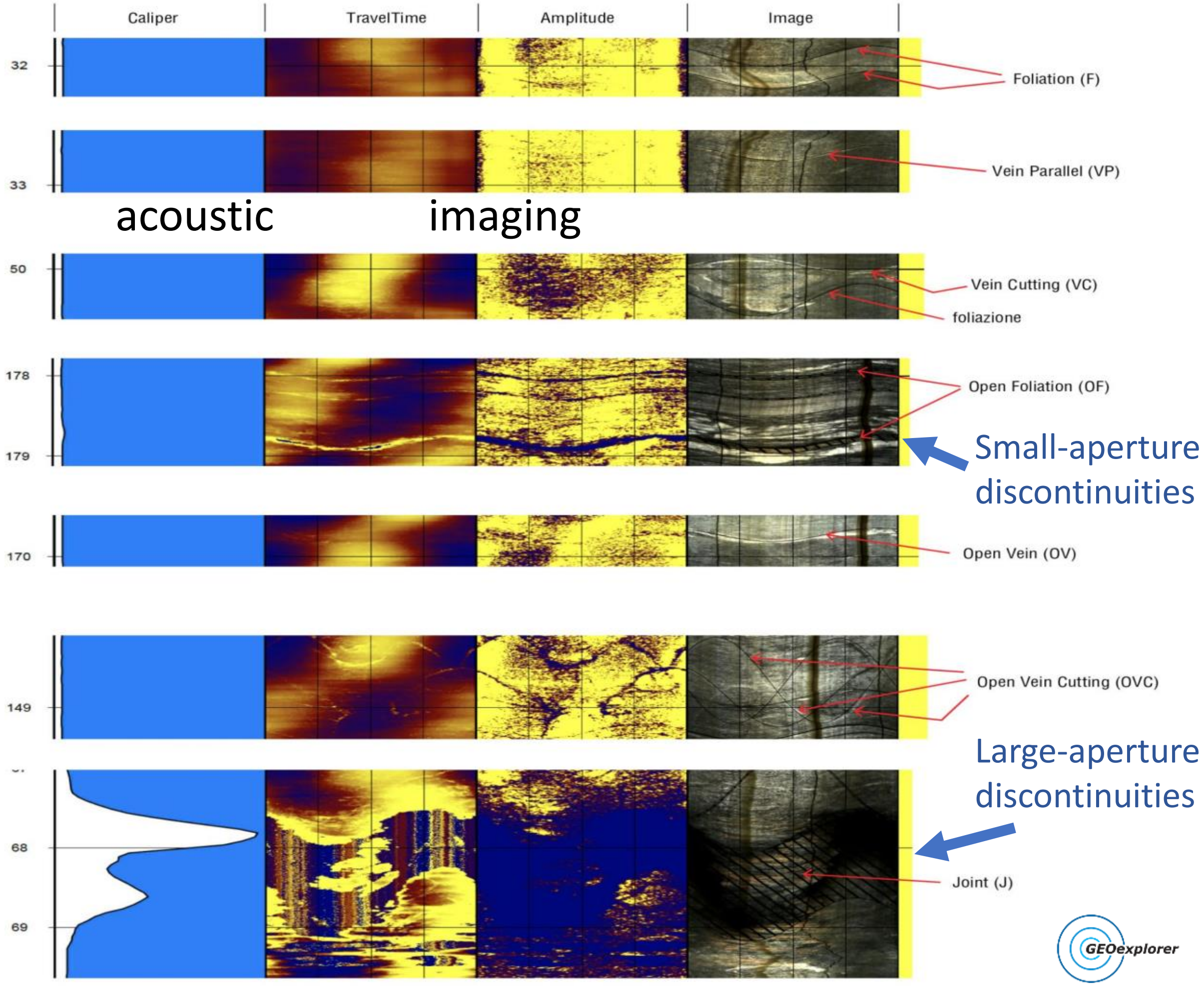
★ : area for boreholes and surface arrays

📌 : 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

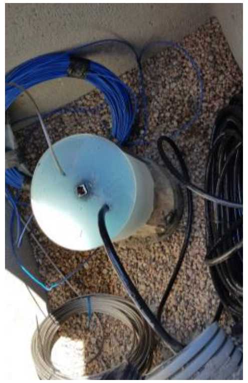
Seismometer installations & active seismic campaign

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.





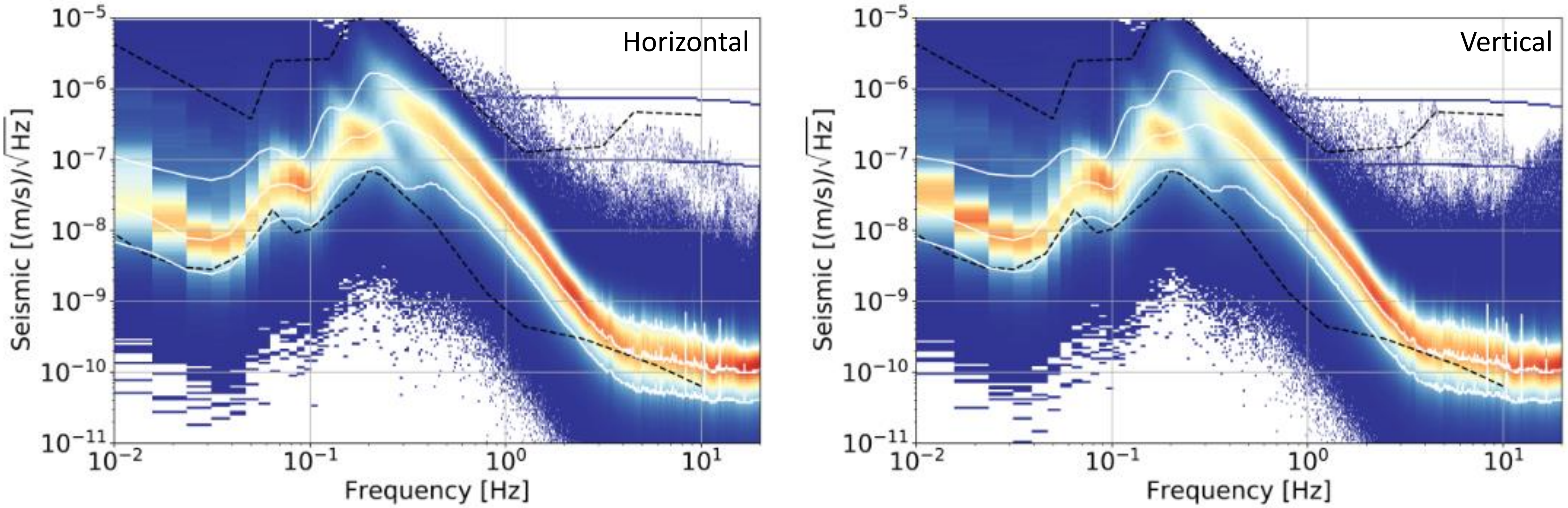




Characterization of the Δ corners

A quick glance at the measurements

PPSD - P2 borehole seismometer

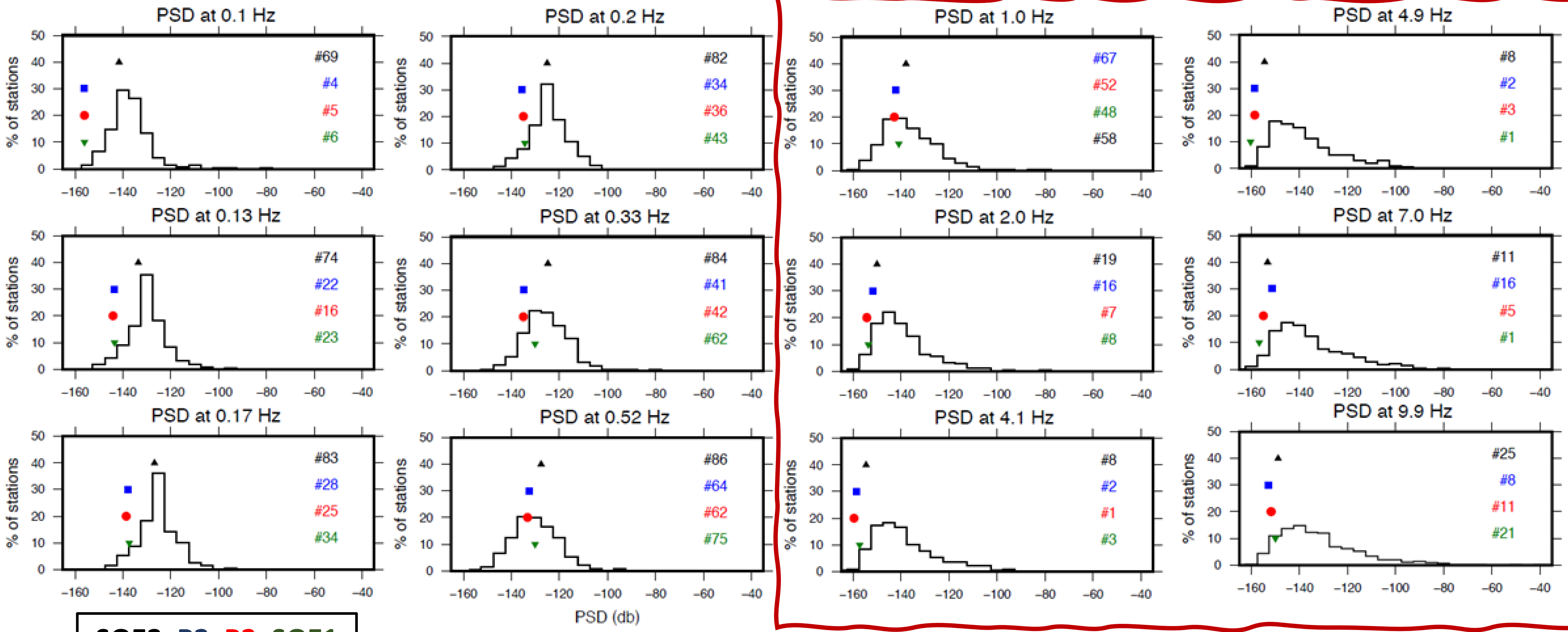


Very low noise background in the 2-10 Hz band, sometimes even **below** the Peterson's **New Low Noise Model**!

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**.

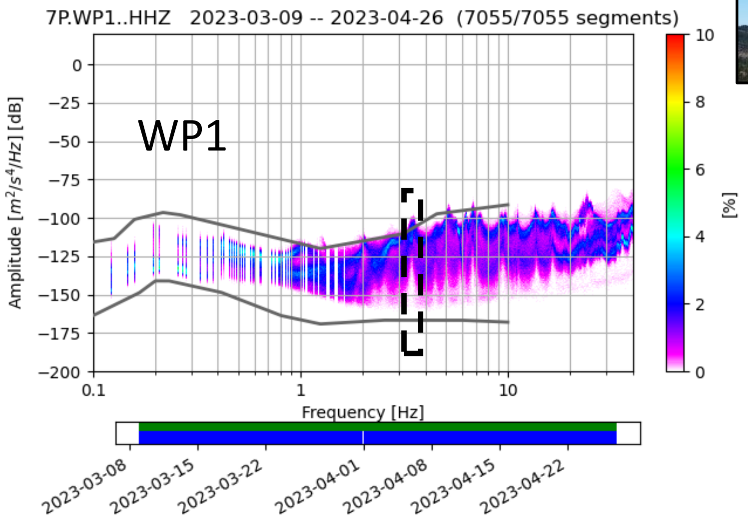


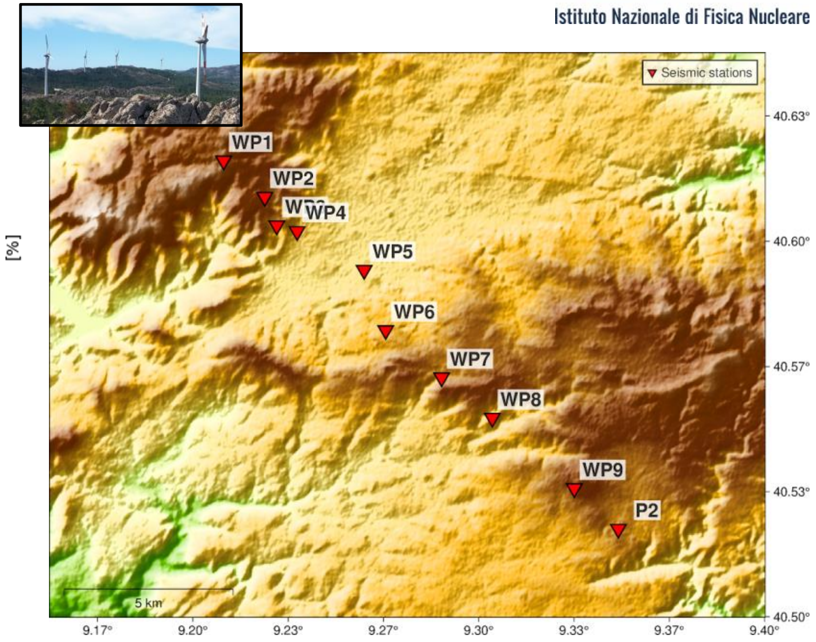
SOE2 P2 P3 SOE1

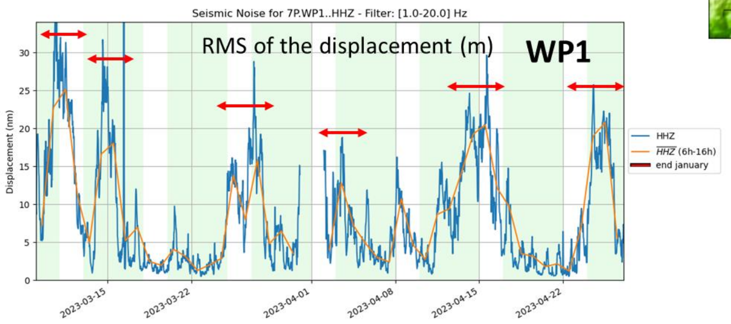
Characterization of the Δ corners

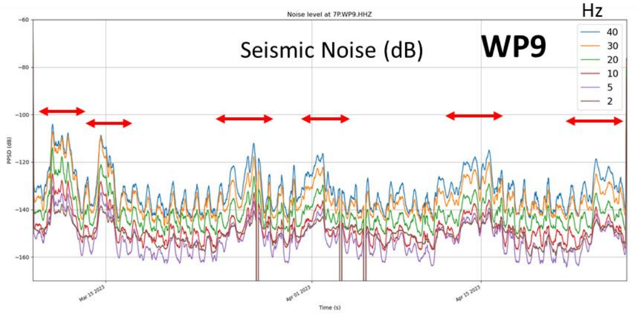
Wind farm temporary array

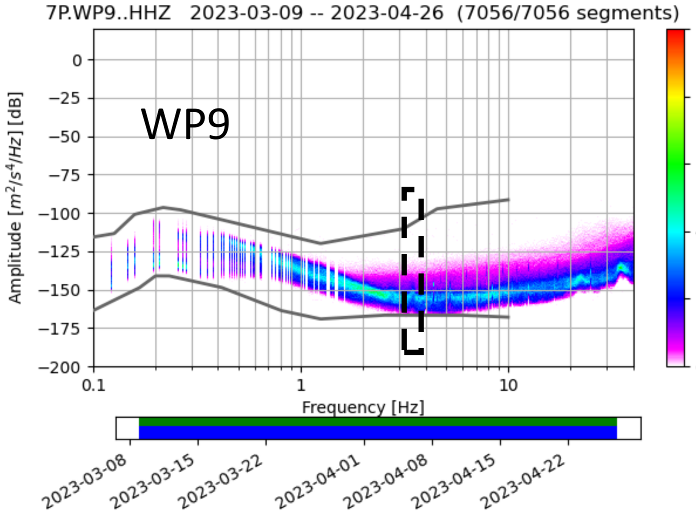
- Main peak at 3Hz + harmonics close to the wind farm (WP1);
- Only main peak + first few harmonics close to P2, visible wrt to the low background (NLNM);
- Wind-correlated increase of noise rms;
- Analysis ongoing: spectral features and correlation with wind measured at weather stations close to the windfarm and with rotational speed of wind turbines.
- **Goal: derive the attenuation function for a better definition of exclusion zones.**











→ talk of M. Di Giovanni

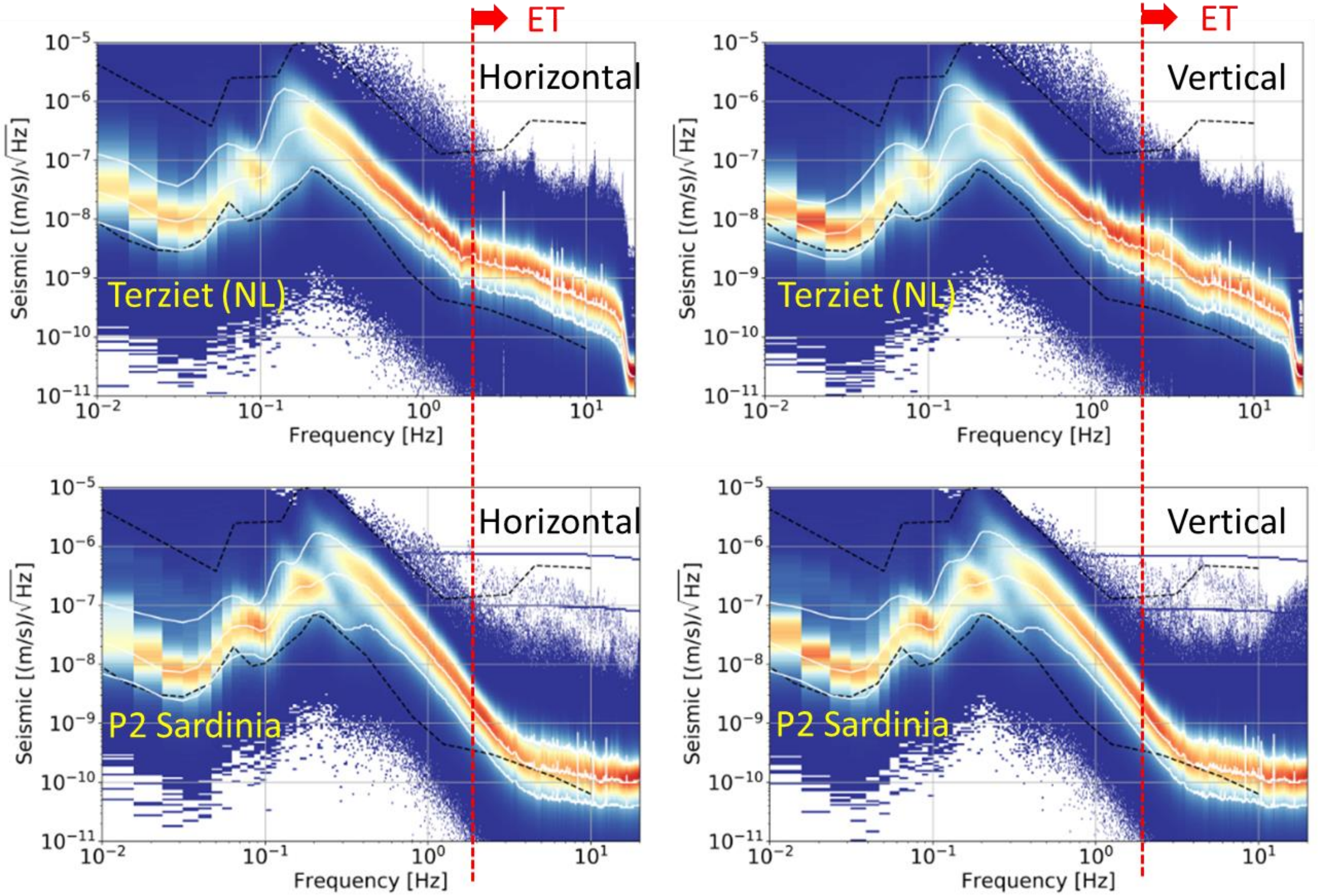
Summary

- ❑ Sardinia: the geological framework
- ❑ Characterisation of the Sos Enattos site
- ❑ Characterisation of the Δ corners
- ❑ **Site comparison**
- ❑ Conclusions

Site comparison with other candidates

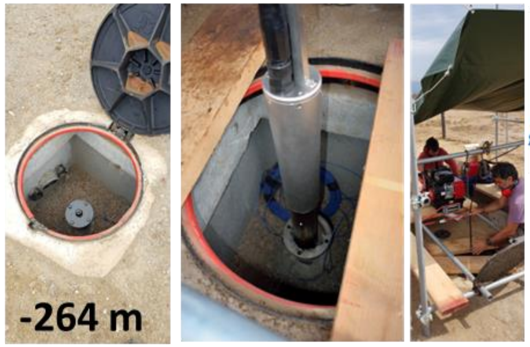
Borehole measurements comparison

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

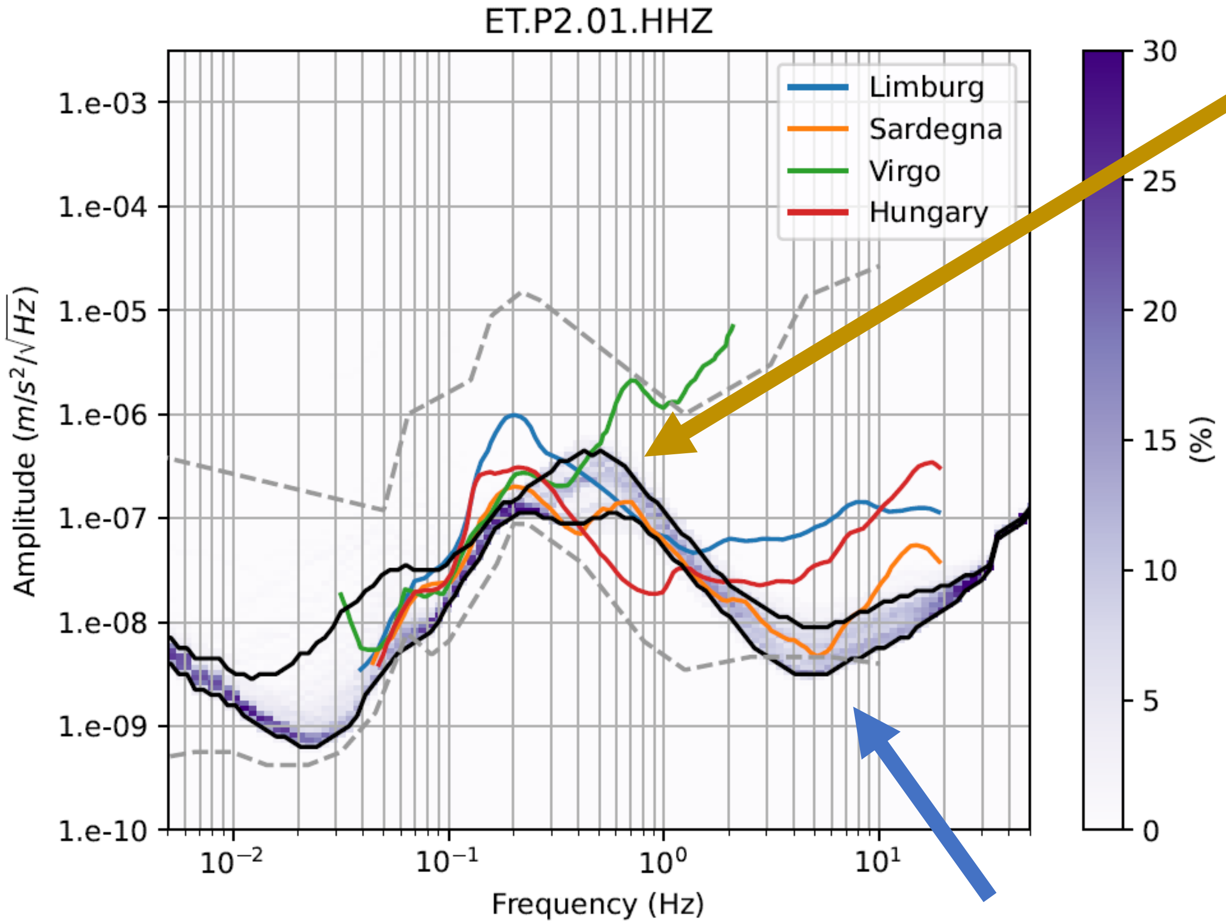
Sardinia P2 borehole

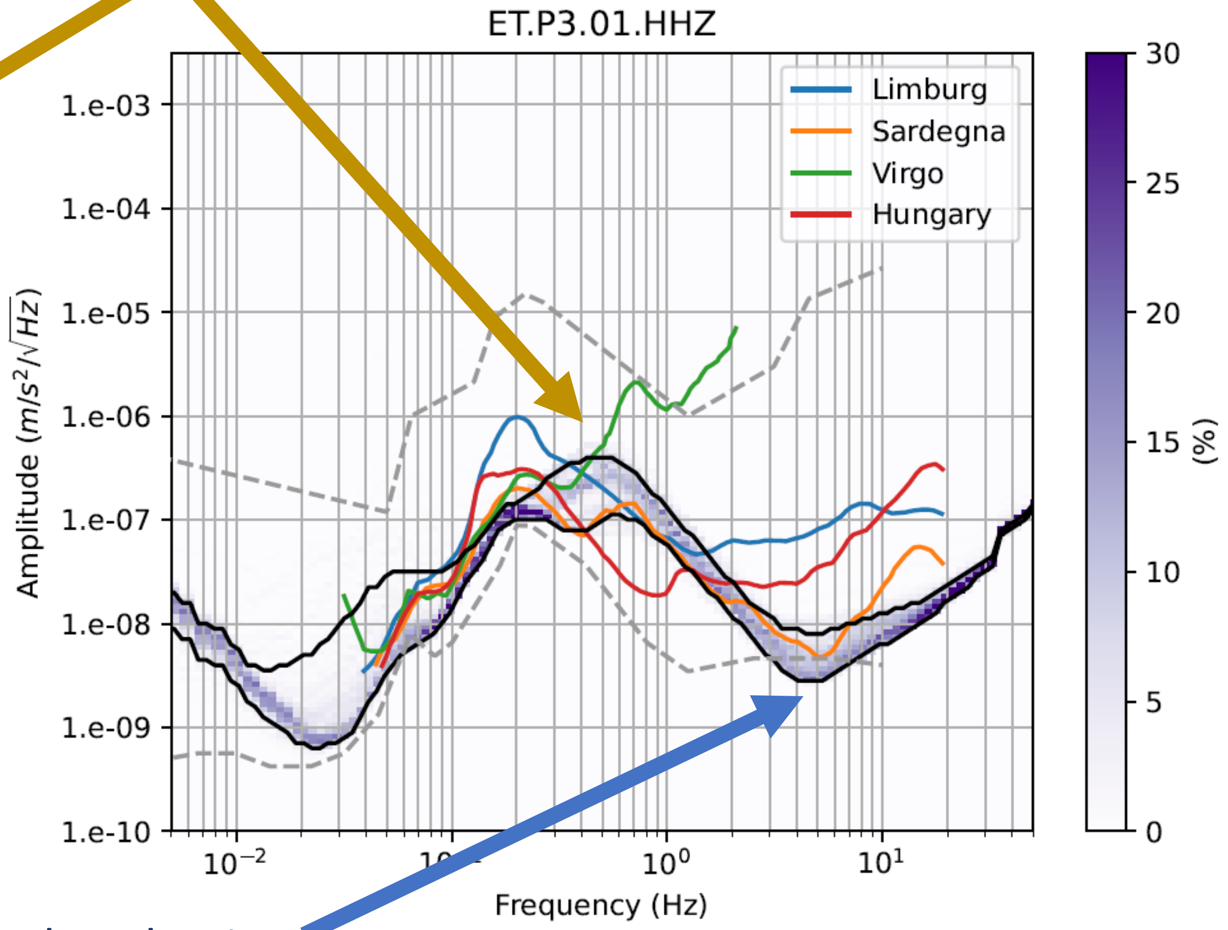


Site comparison with other candidates

Borehole measurements comparison

High amplitudes: Influence of the sea below 2 Hz





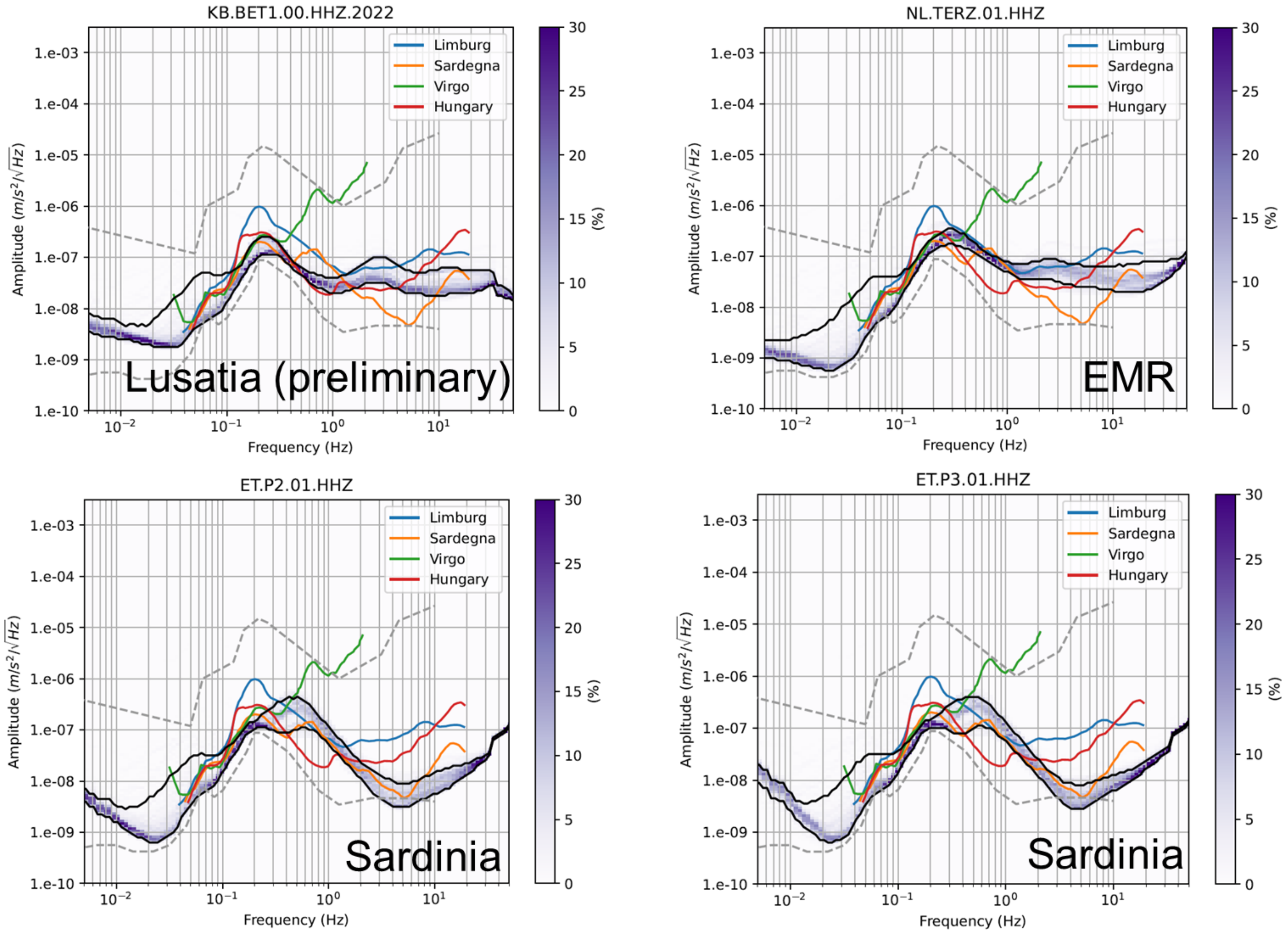
Low amplitudes: Low cultural noise

A. Rietbrock et al., SPB Workshop 2023

Site comparison with other candidates

Borehole comparison

A. Rietbrock et al., SPB Workshop 2023

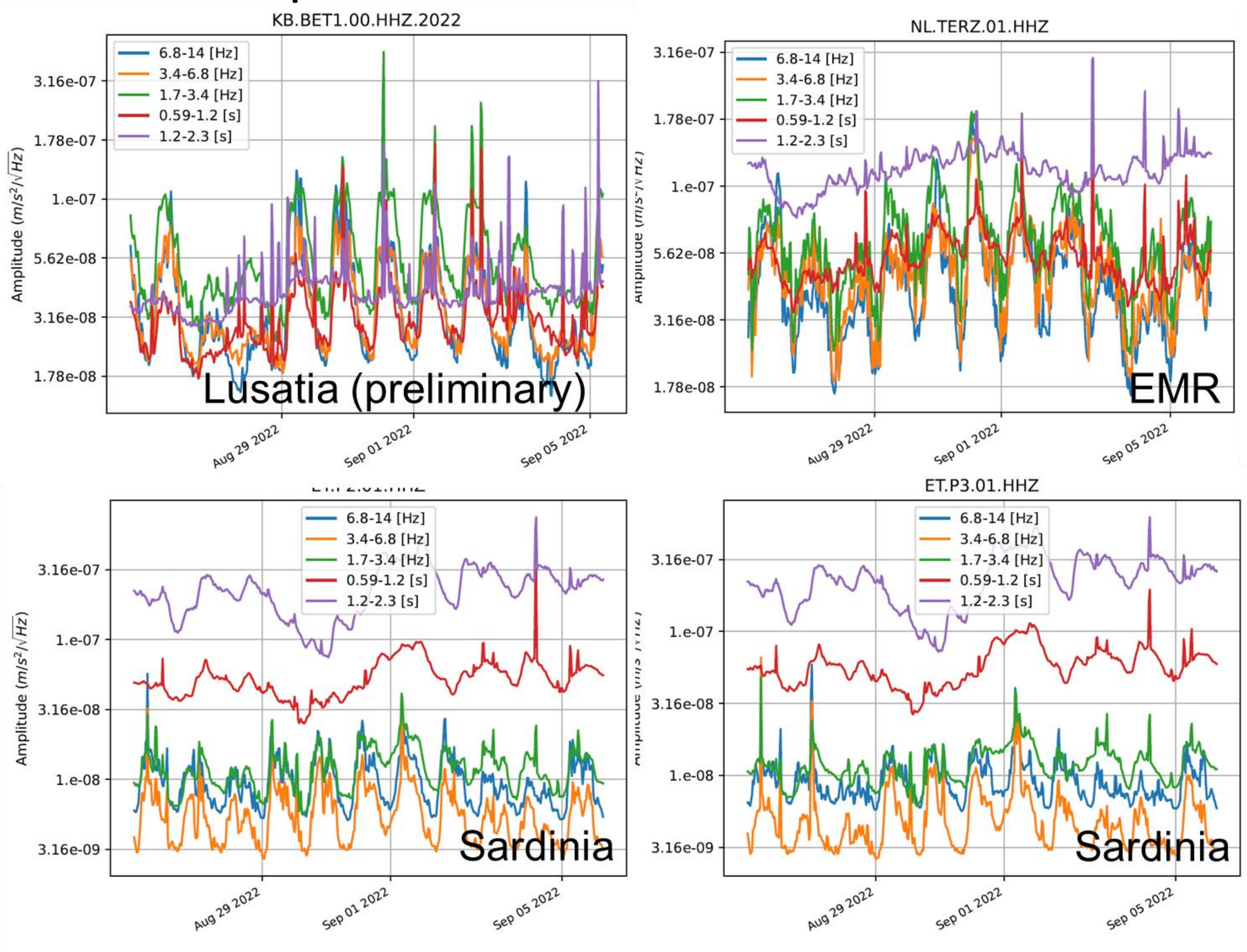


Common EMR-Sardinia-Lusatia comparison paper in preparation

Site comparison with other candidates

Borehole comparison

A. Rietbrock et al., SPB Workshop 2023



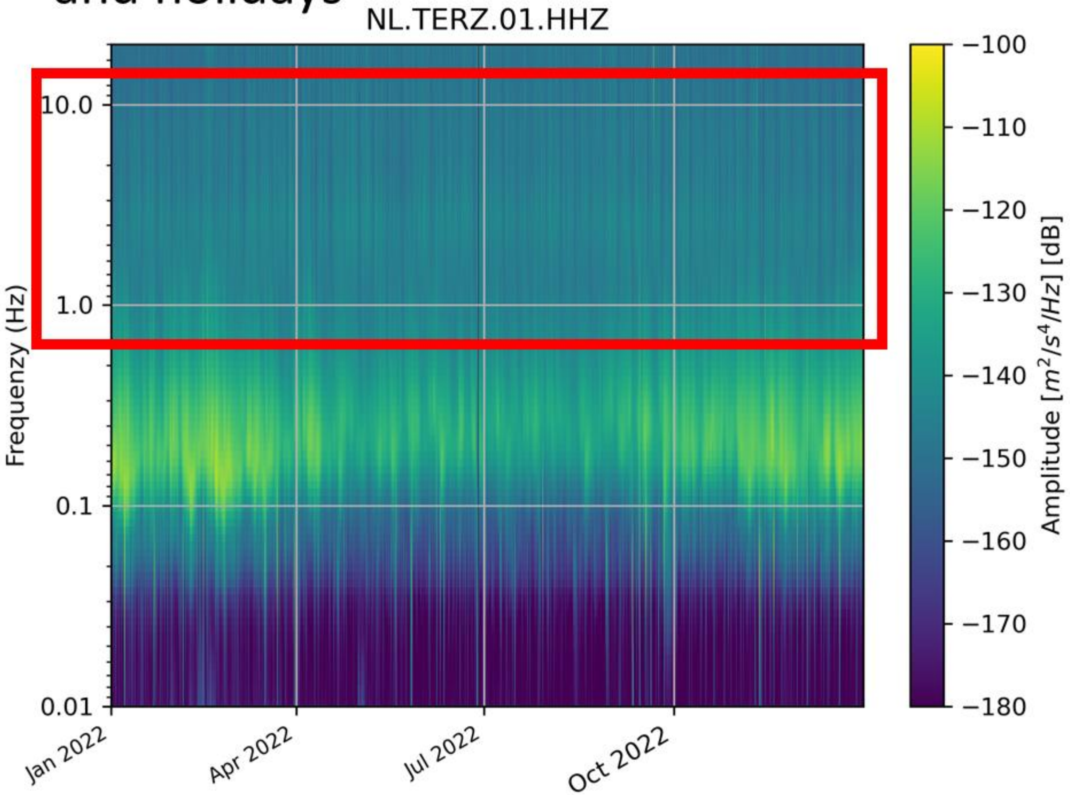
Common EMR-Sardinia-Lusatia comparison paper in preparation

Site comparison with other candidates

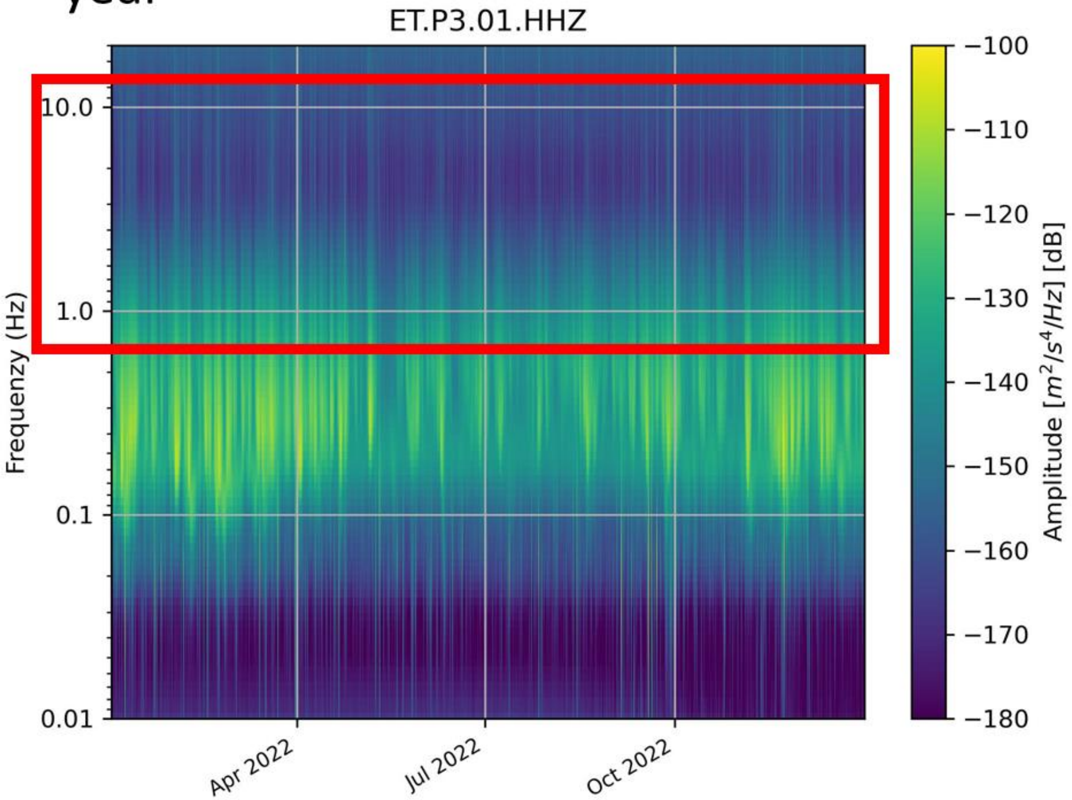
Borehole comparison

PSD Spectrogram – frequency band 1 Hz to 10 Hz

EMR - "Quiet" only during weekends and holidays



Sardinia - "Quiet" during the whole year



A. Rietbrock et al., SPB Workshop 2023

Site comparison with other candidates

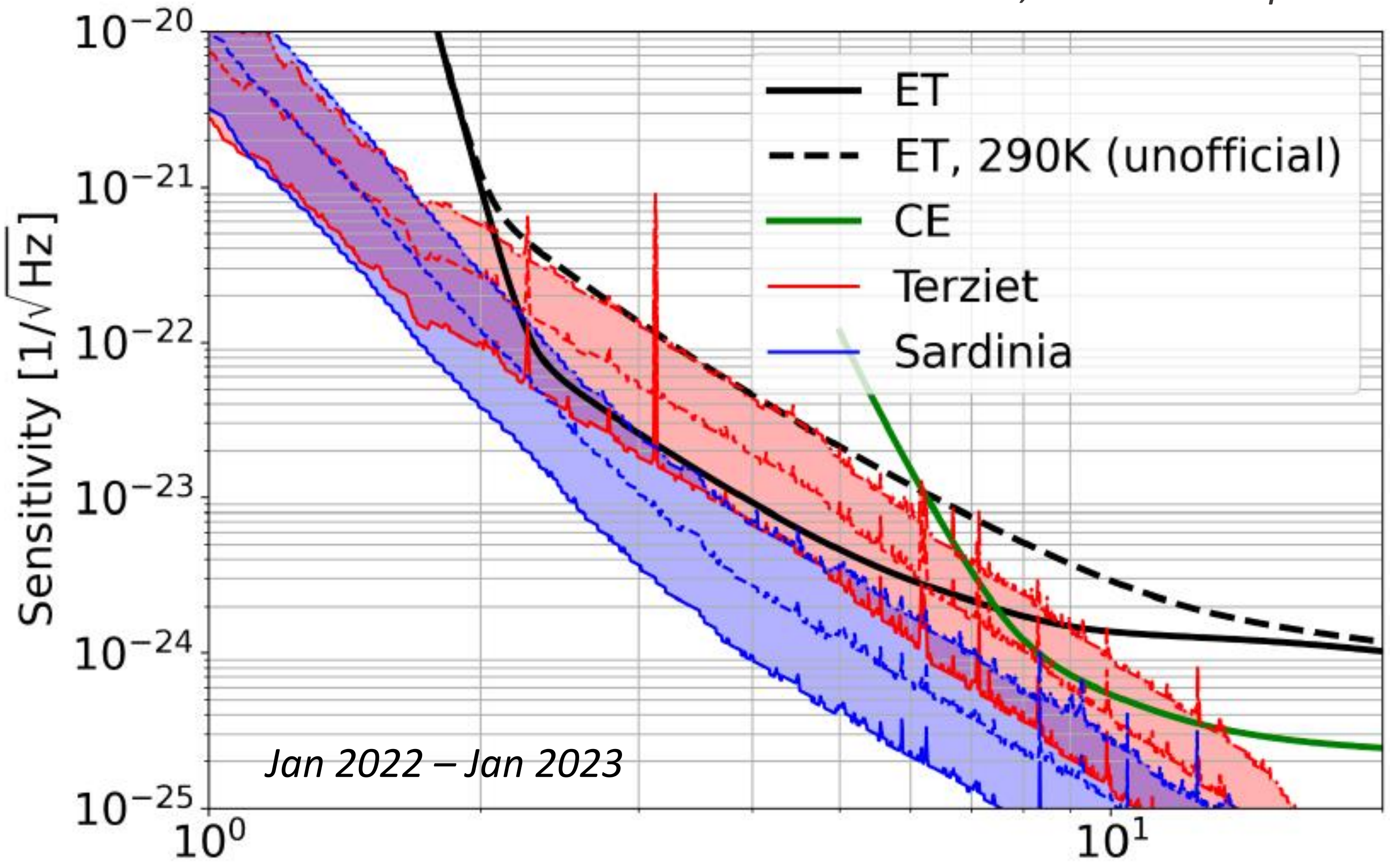
Seismic Newtonian Noise projections

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

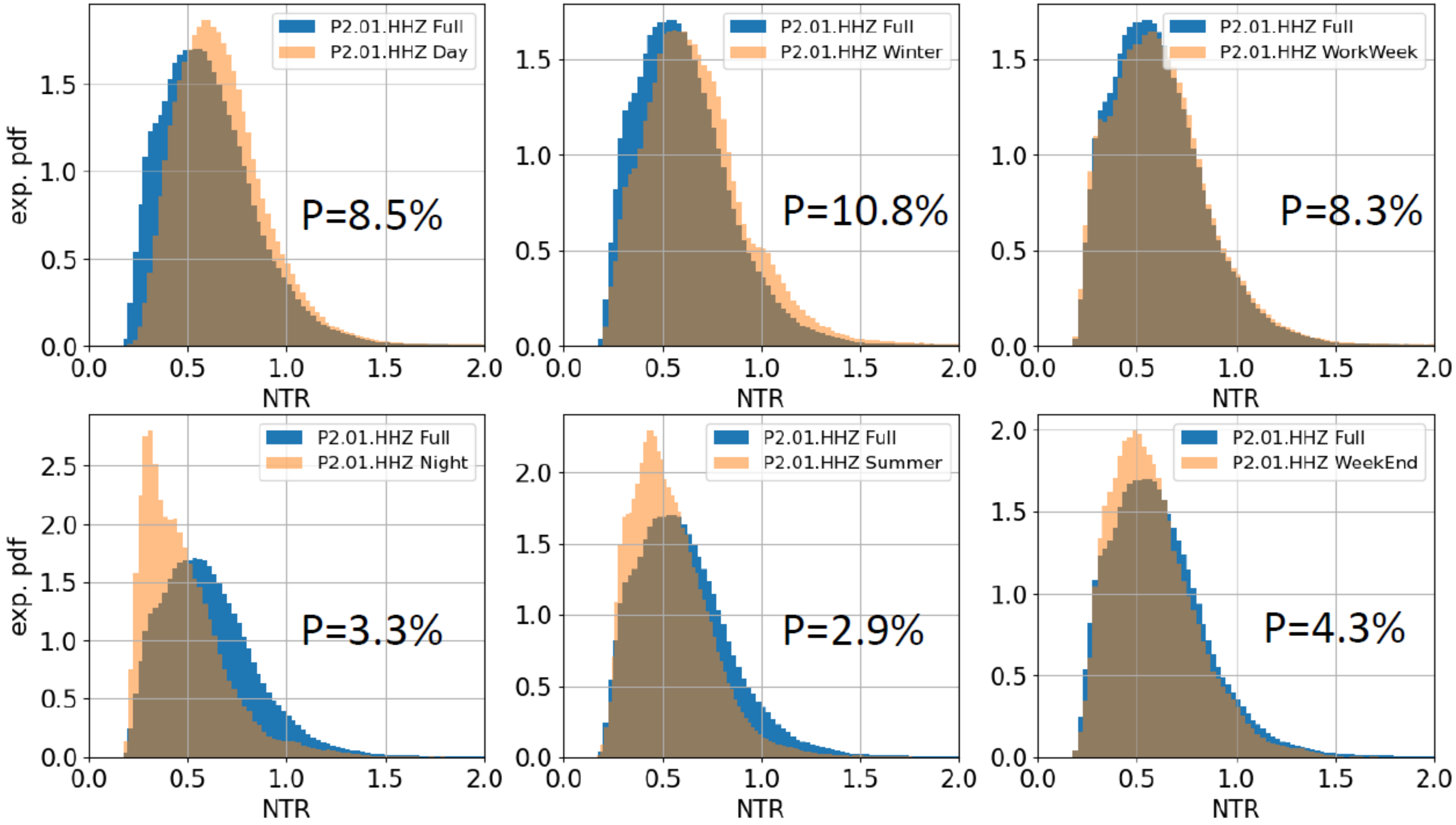
J.Harms, SPB workshop 2023



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):



PSD of NN

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

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

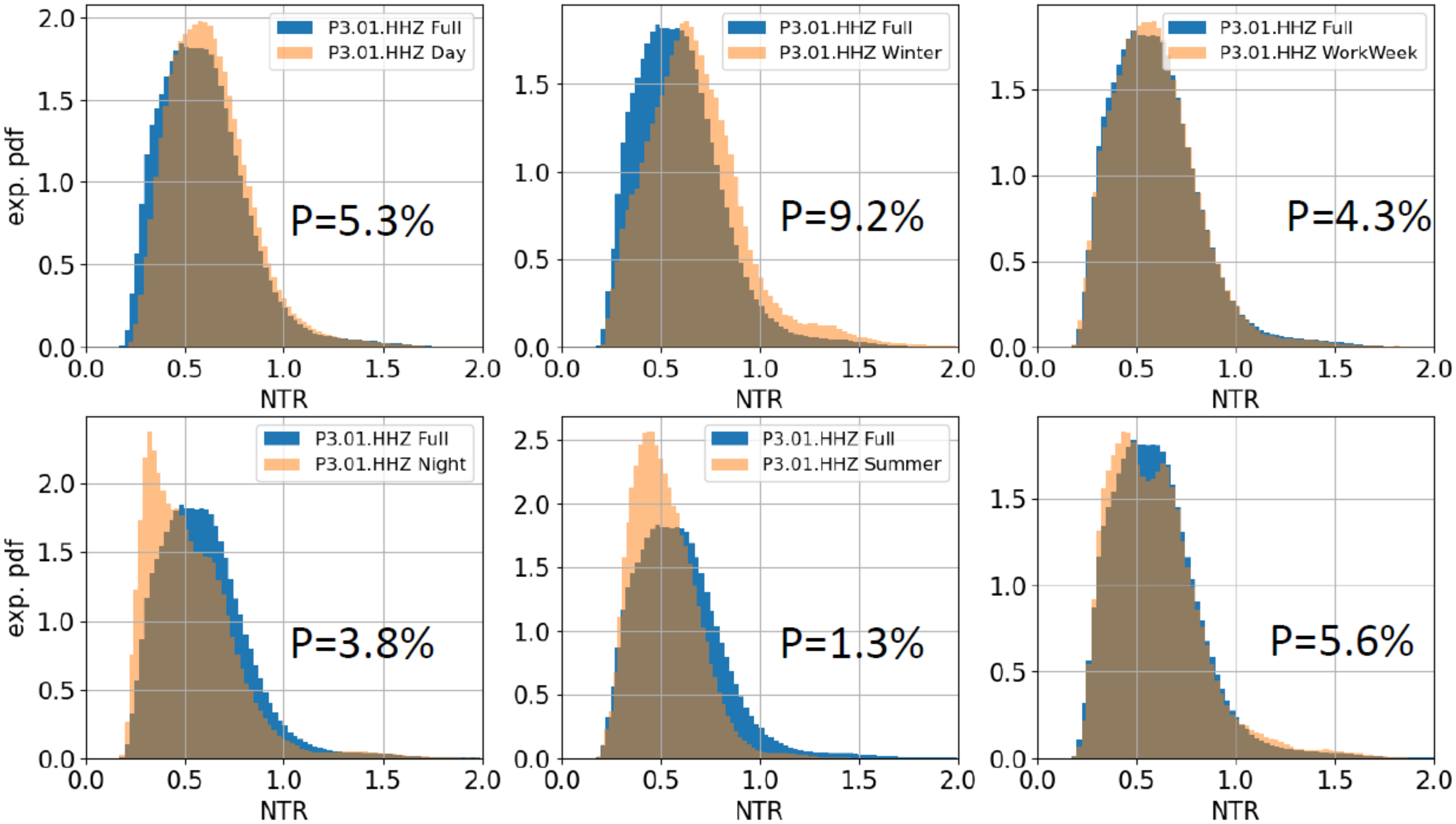
Seismic NN glitches in ET LF band

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

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

PSD of NN

PSD of ET sensitivity



Over one year (2022) of data

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

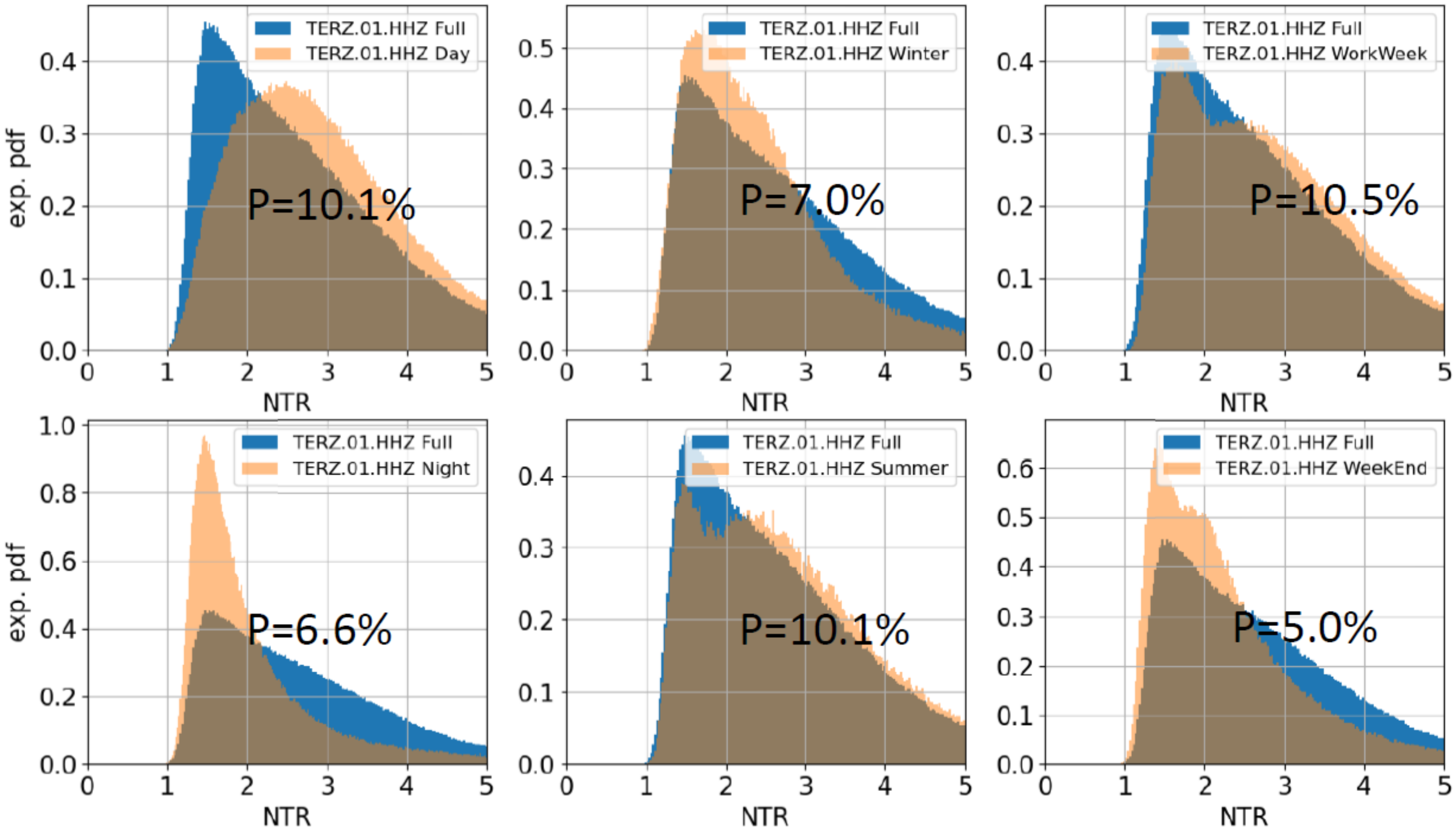
→ NN does not limit the ET sensitivity for a large fraction of time, only moderate cancellation needed for a limited time

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

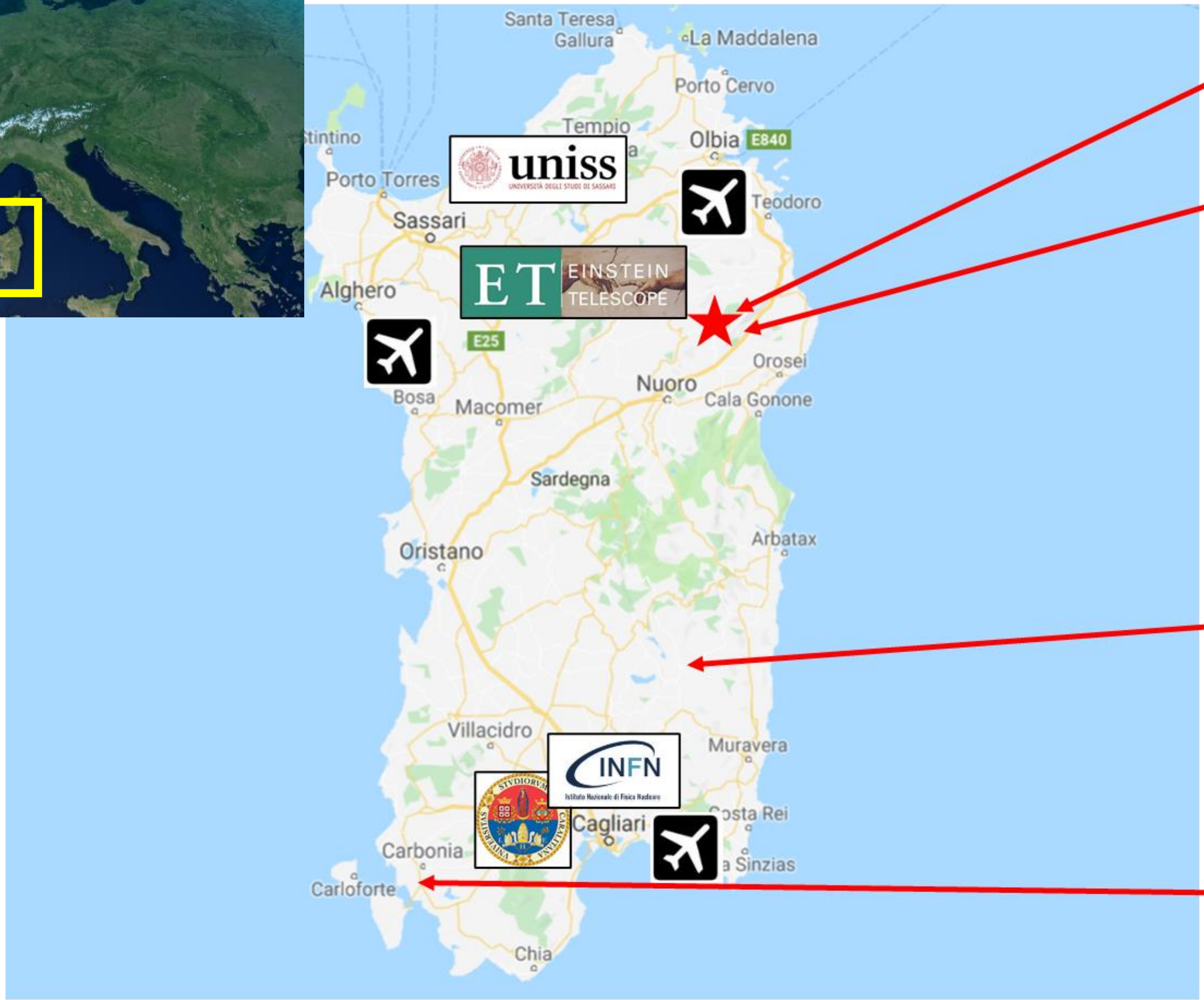
Conclusions

- Sardinia is geologically **very quiet**, far from active fault lines, and characterized by low anthropic noise.
- New and deep physical and geological characterization of the Sos Enattos area since 2019, where a large array of permanent sensors has been deployed. 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 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.
- **Low electromagnetic noise**, acoustic noise measurement ongoing.
- 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 configuration!**

Conclusions

BACKUP SLIDES

Sardinia, an island of science



Site access: 50’ (85km) drive from Olbia airport (*SS 131 highway*)

SarGrav underground laboratory

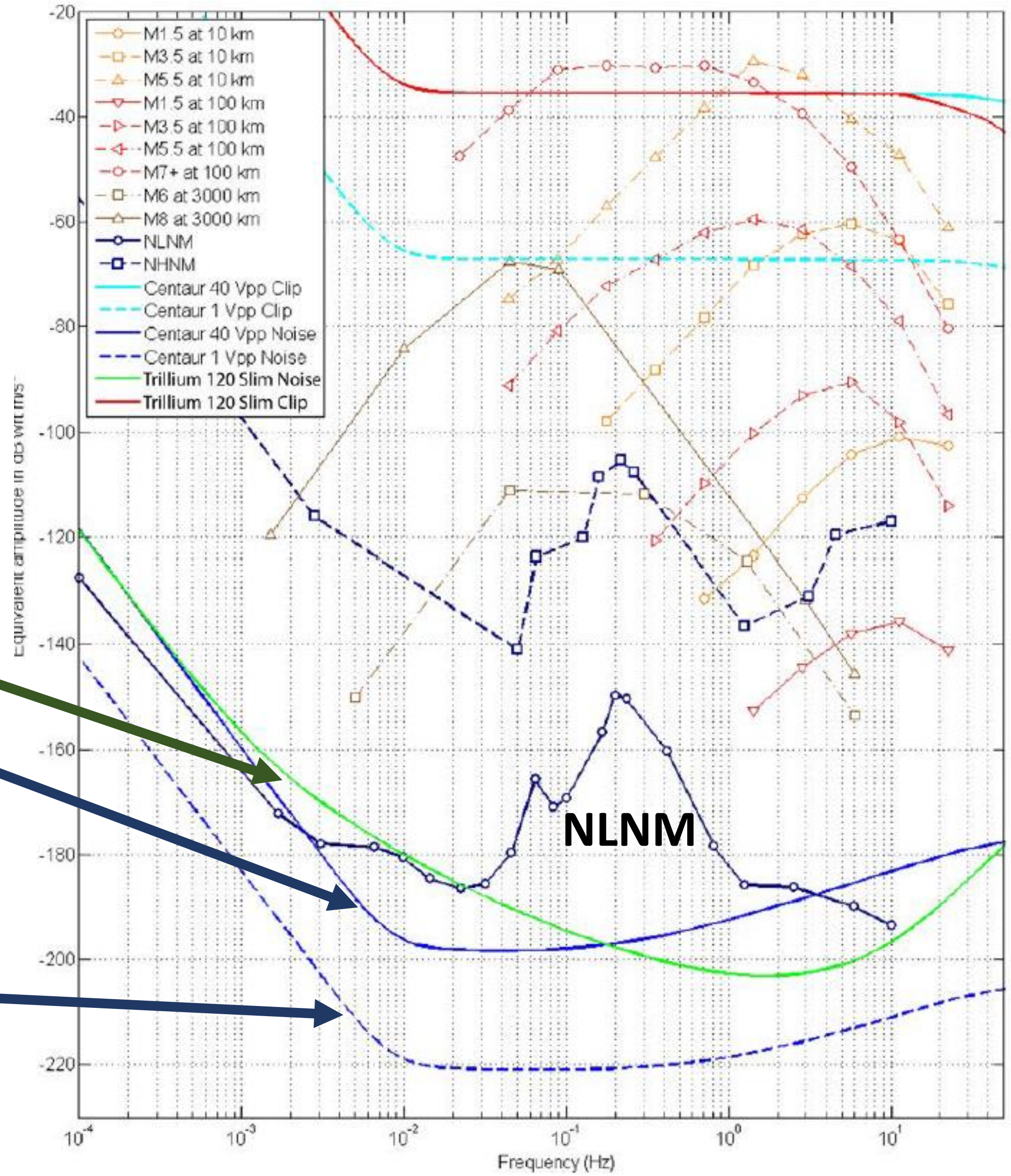
Sardinia Radio Telescope

“ARIA” project (for Gran Sasso *Dark Side* DM det.)

BH Seismometer installation

Trillium 120-SPH2

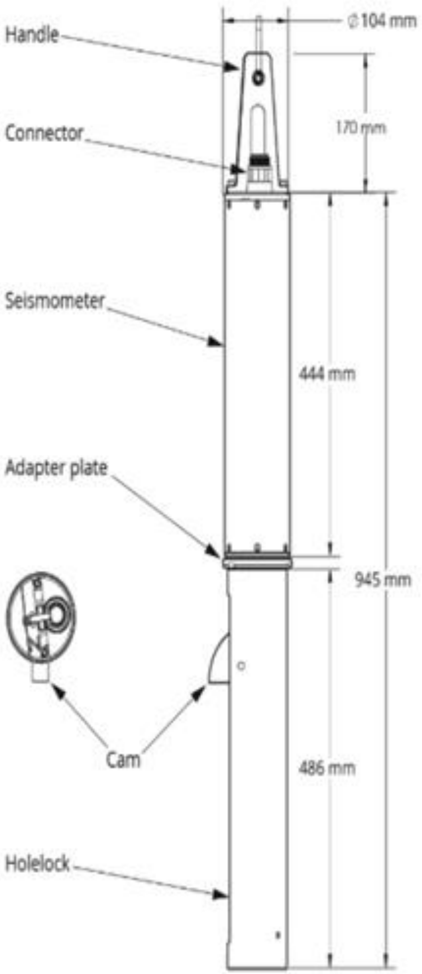
Broadband triaxial seismometer



Sensor self-noise

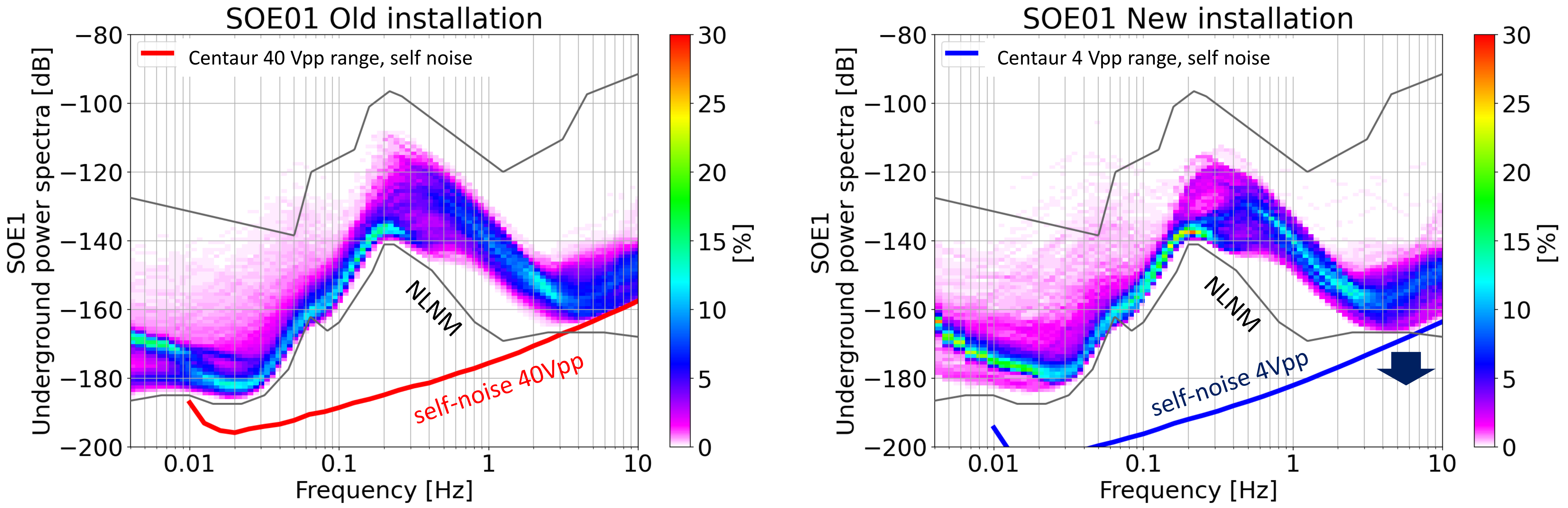
DAQ 40V self-noise

DAQ 1V (max gain) self-noise



Self noise and gain settings

Reduced input range → reduced DAQ self noise → environmental seismic noise floor below the standard seismometer settings in few Hz band, **close to NLNM** (here SOE1, 84m depth)



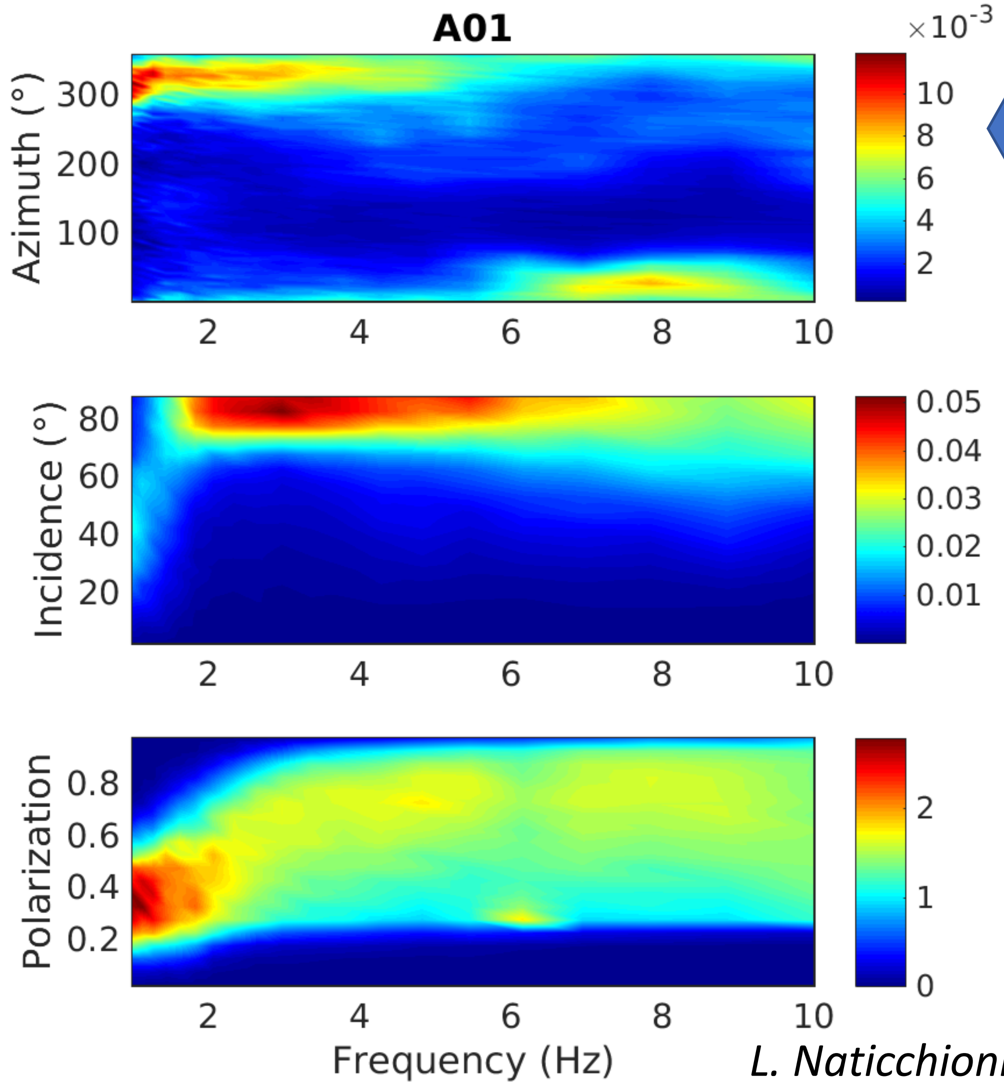
May to June 2020

June to August 2020

Array polarization

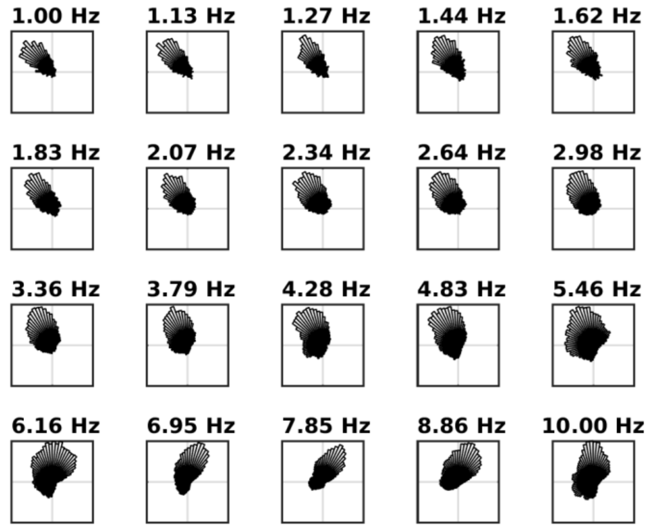
Seismometer array results

Polarization analysis



Probability density of particle motion Azimuth, Incidence Angle and Degree of Polarization as a function of frequency.

Polarization angle [0°- 180°]: the ellipsoid dips to East.
Polarization angle [180°- 360°]: the ellipsoid dips to West.



ET site characterization

Latest talks and results from the site characterization presented at the XIII ET symposium in Cagliari in May 2023:

- SPB Sessions:
  - https://indico.ego-gw.it/event/562/timetable/#20230508.detailed
  - https://indico.ego-gw.it/event/562/timetable/#20230509.detailed

- Newtonian & environmental noise session:
  - https://indico.ego-gw.it/event/562/timetable/#20230510.detailed
  - NN/NNC status: https://indico.ego-gw.it/event/562/contributions/5117/