



Site characterization in Sardinia for the Einstein Telescope

Luca Naticchioni (INFN Roma)

*on behalf of the ET Sardinia site characterization team**



Istituto Nazionale di Fisica Nucleare



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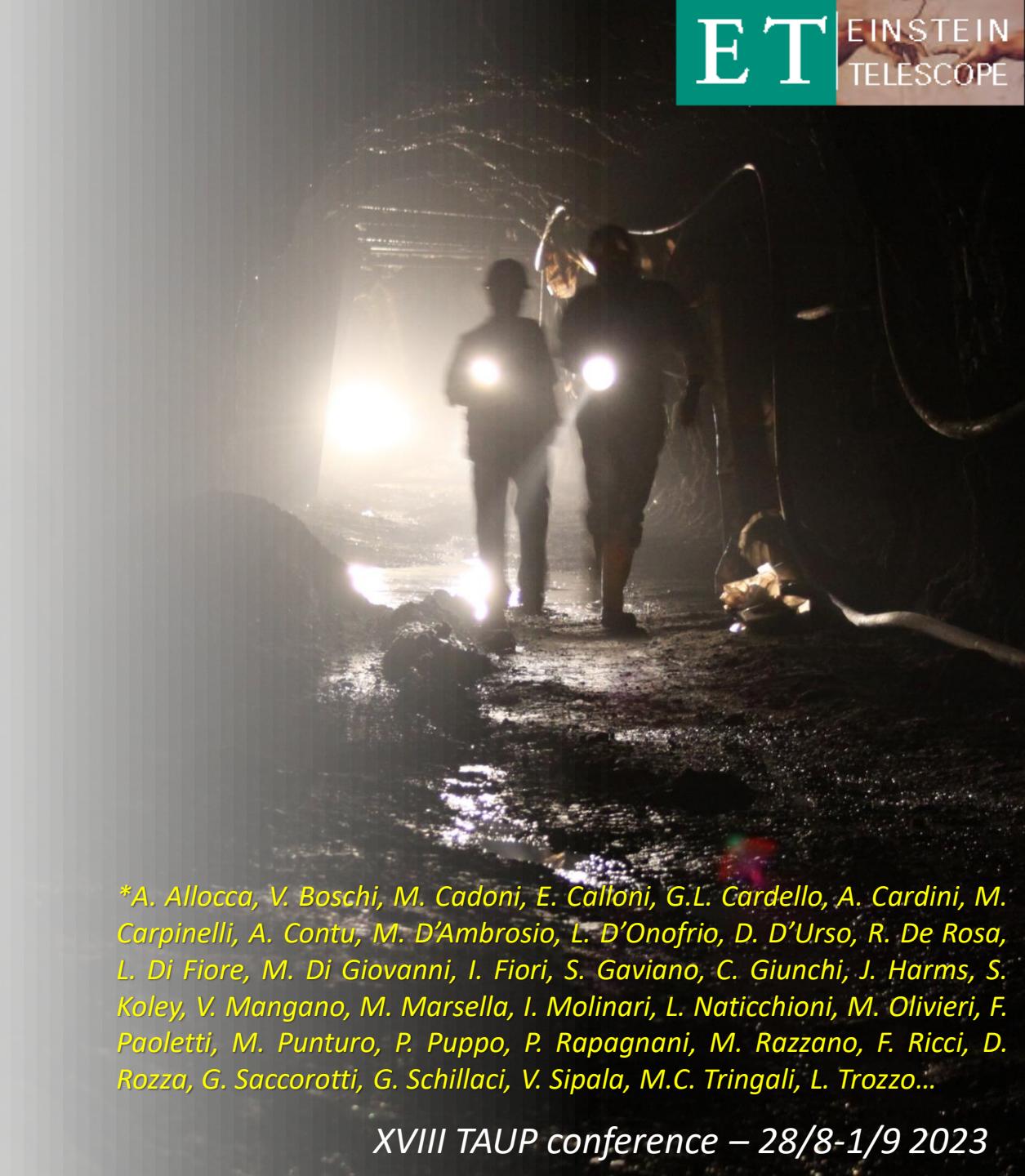
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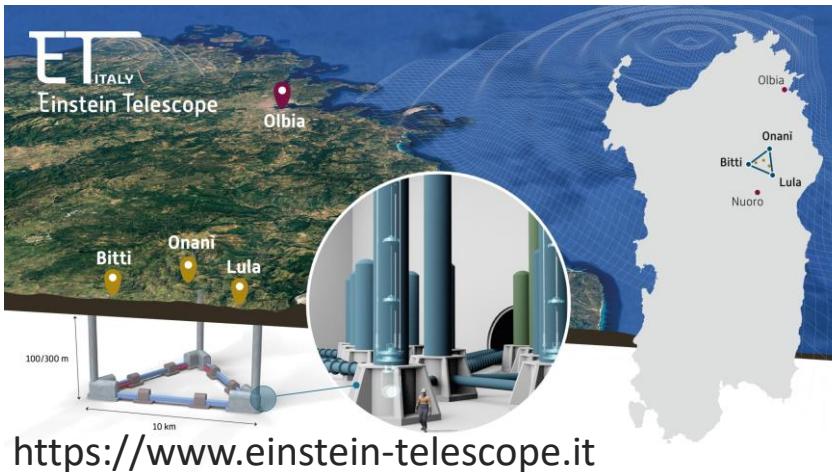
*A. Allocata, V. Boschi, M. Cadoni, E. Calloni, G.L. Cardello, A. Cardini, M. Carpinelli, A. Contu, M. D'Ambrosio, L. D'Onofrio, D. D'Urso, R. De Rosa, L. Di Fiore, M. Di Giovanni, I. Fiori, S. Gaviano, C. Giunchi, J. Harms, S. Koley, V. Mangano, M. Marsella, I. Molinari, L. Naticchioni, M. Olivieri, F. Paoletti, M. Punturo, P. Puppo, P. Rapagnani, M. Razzano, F. Ricci, D. Rozza, G. Saccorotti, G. Schillaci, V. Sipala, M.C. Tringali, L. Trozzo...

- ❑ ET Italian candidate site in Sardinia
- ❑ Sardinia: the geological framework
- ❑ Characterisation of the Sos Enattos site and Δ corners
- ❑ Site comparison
- ❑ Conclusions

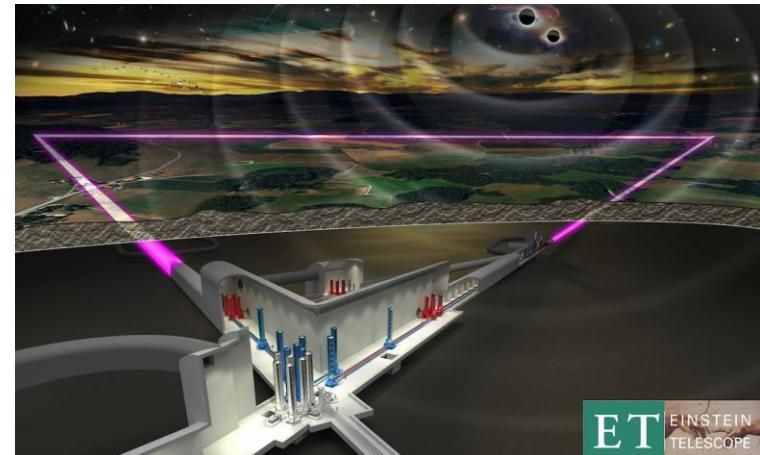
Einstein Telescope - ET

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!**

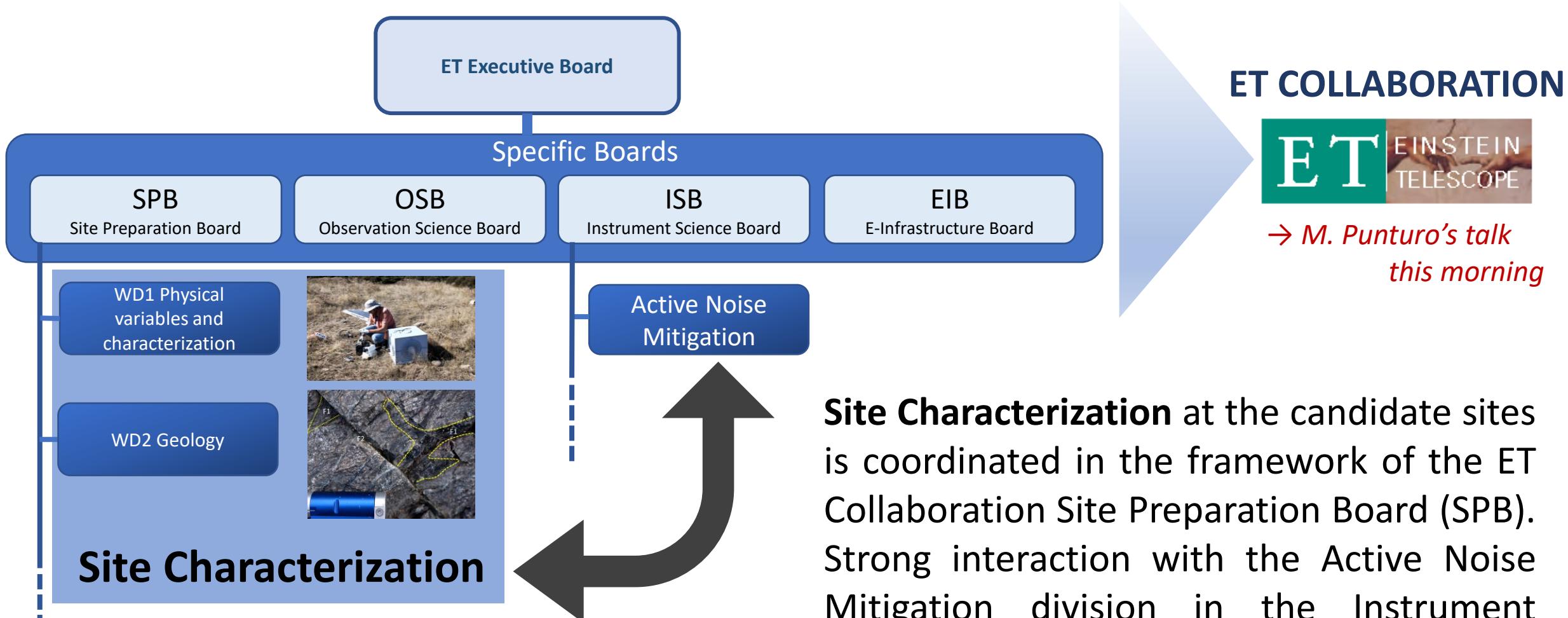
→ M. Punturo's talk this morning



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.**



Einstein Telescope - ET



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).

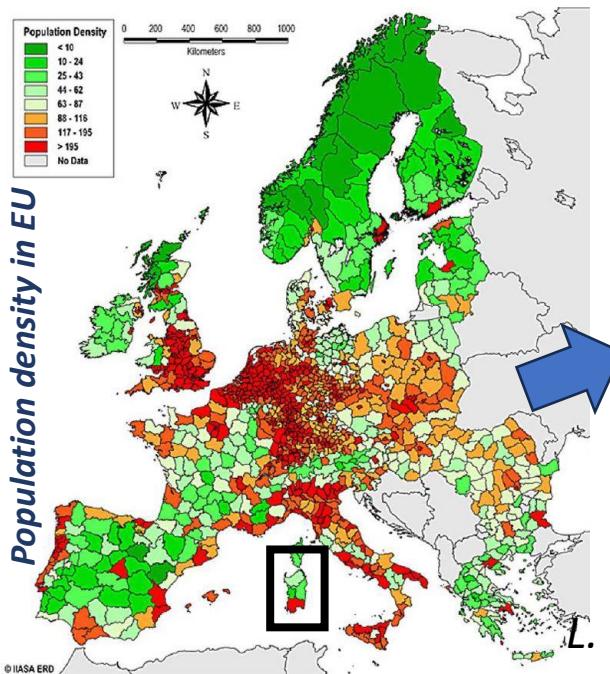
Summary

- ❑ ET Italian candidate site in Sardinia
- ❑ **Sardinia: the geological framework**
- ❑ Characterisation of the Sos Enattos site and Δ corners
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ET in Sardinia, why?

Sardinia is made of:

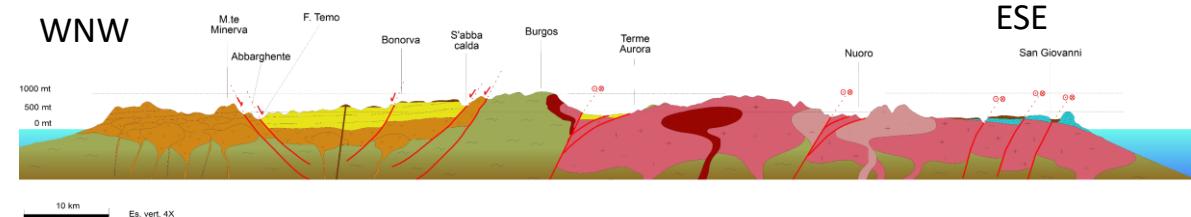
- Quaternary alluvial deposits and minor intra-plate volcanism
- Tertiary sedimentary basins with volcanic units
- Deeply eroded Mesozoic sedimentary rocks
- Metamorphic basement widely intruded by Carboniferous-Permian Granitoids (Variscan orogenesis; 360-290 Ma)



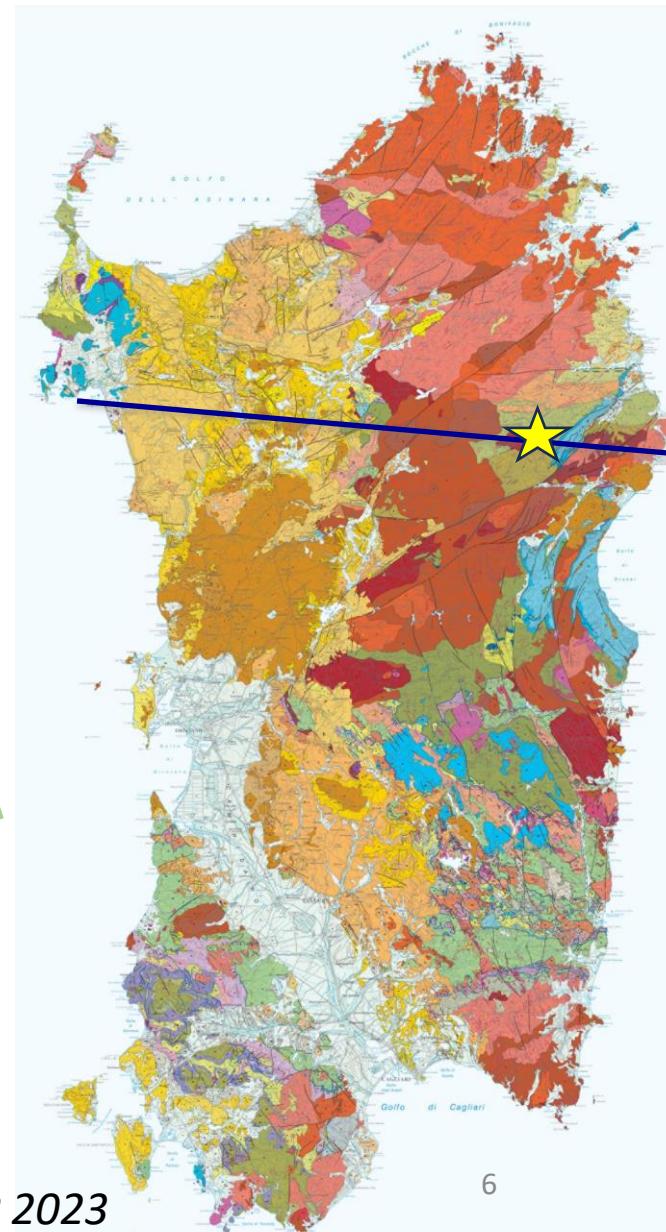
The ET Italian candidate site is located in the stable Variscan basement of Sardinia.

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

LOW SEISMIC
NOISE!



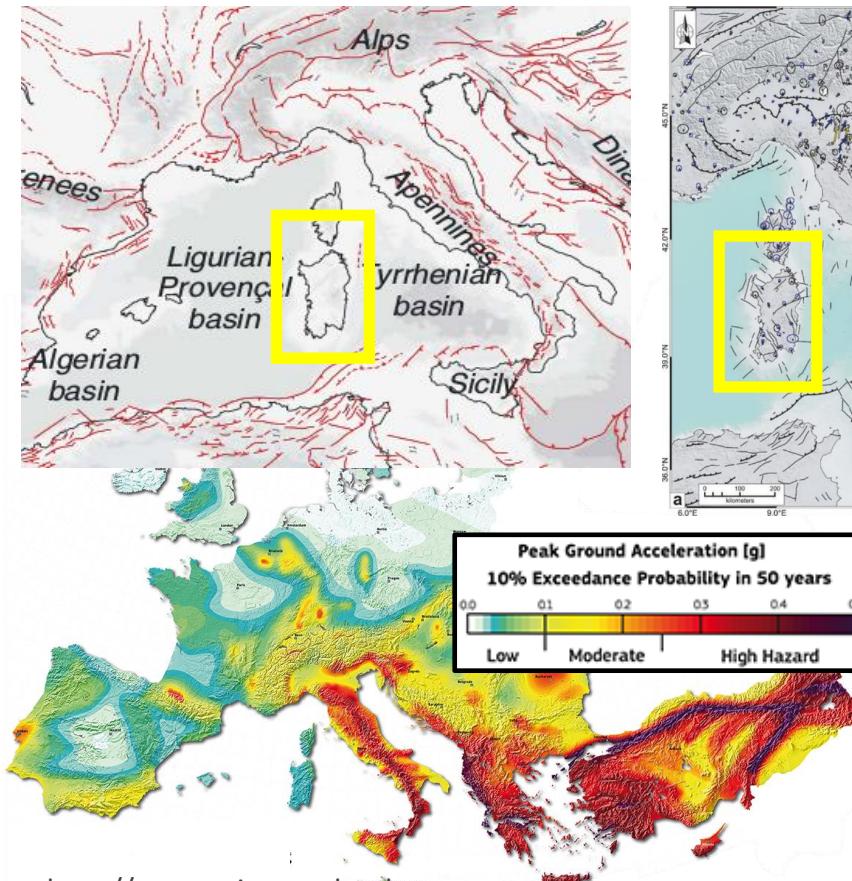
L. Naticchioni, Site Characterization in Sardinia for ET – XVIII TAUP 2023



ET in Sardinia, why?

Sardinia, the geological framework

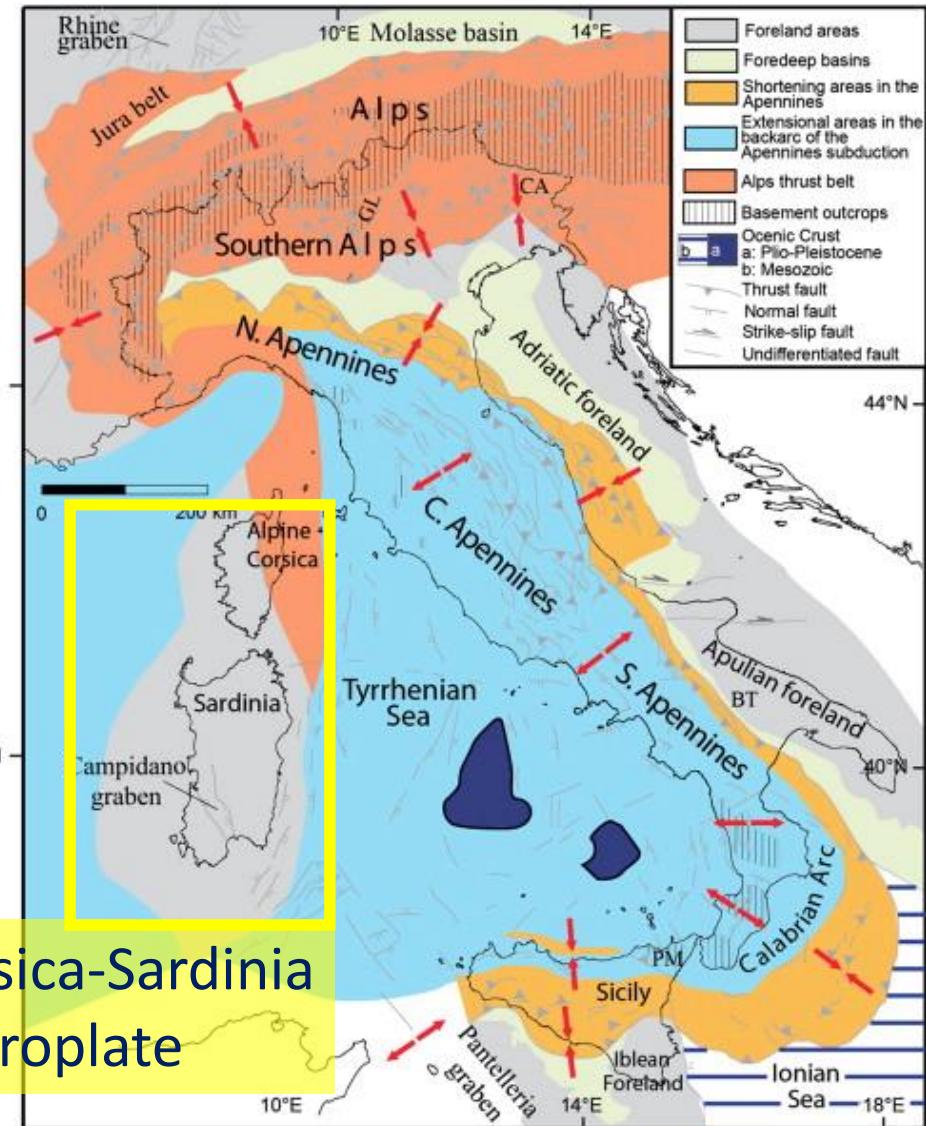
Far from active fault lines, the Corsica-Sardinia microplate is very stable → low crustal deformation.



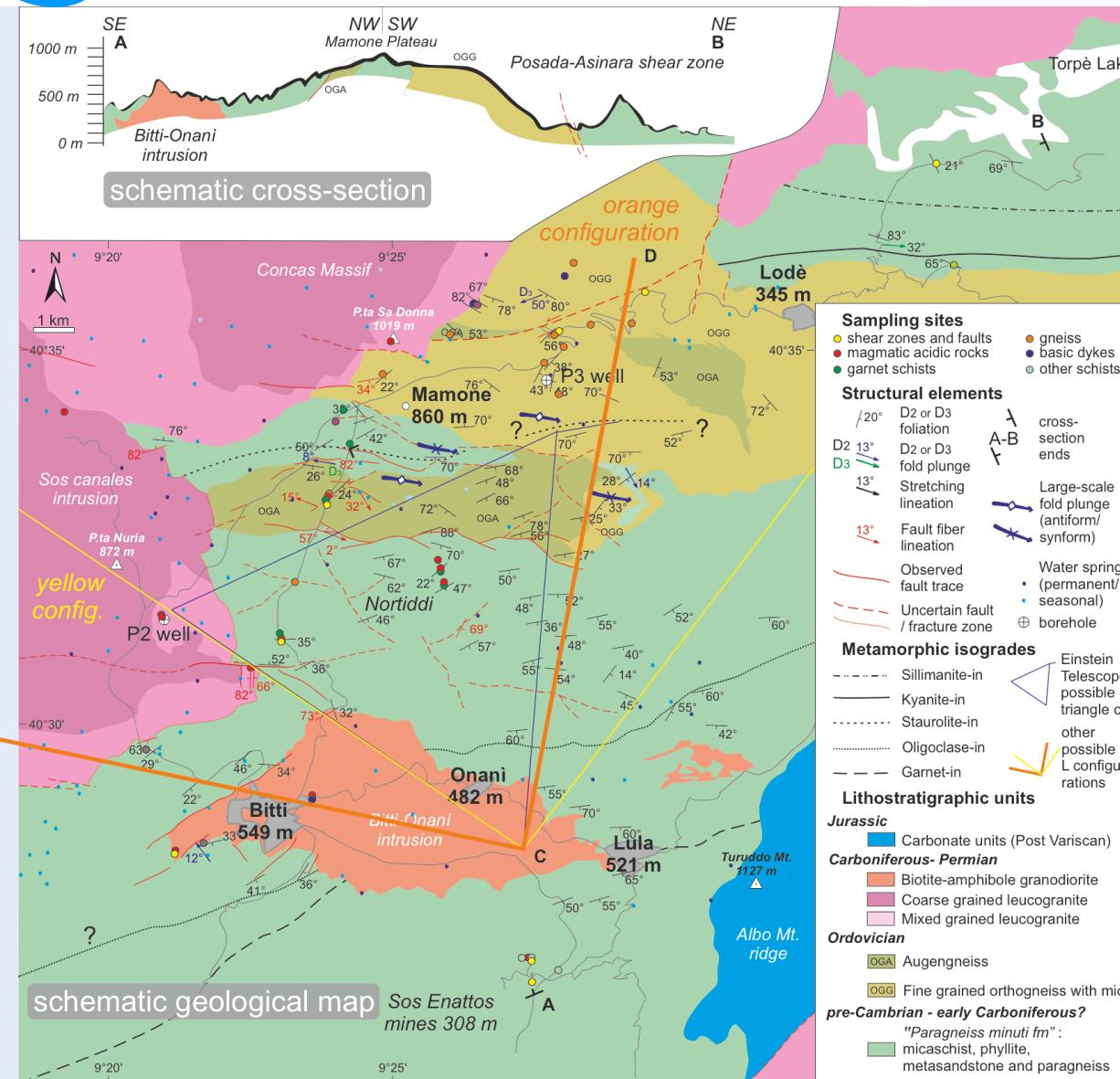
Unaffected by significative seismic activity.

<http://www.seismo.ethz.ch>

Corsica-Sardinia Microplate

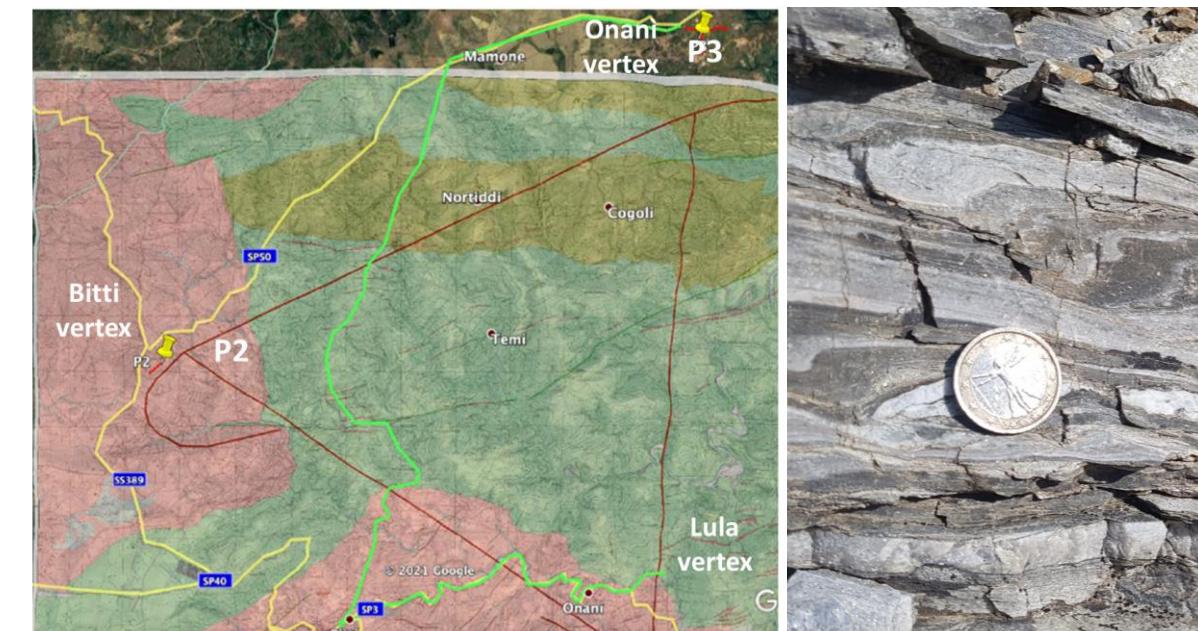


ET in Sardinia, why?



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.



Summary

- ❑ ET Italian candidate site in Sardinia
- ❑ Sardinia: the geological framework
- ❑ **Characterisation of the Sos Enattos site and Δ corners**
- ❑ Site comparison
- ❑ Conclusions

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

Roland shaft



SarGrav surface lab
(340m a.s.l.)



SOE3 (-150m)

MINIERA SOS ENATTOS	
Rampa Tuppeddù	Scop. Tecnico
Disegnato SETTORE CARTOGRAFICO	scala 1 : 1.000
maggio 2010	

SOE0
(surface, 400m asl)



SOE2 / SENA
(-111m)



SOE1
(-84m)

STAZIONE SOE 1

STAZIONE SOE 2

STAZIONE SOE 3

SP73

The Sos Enattos site

Site characterization of the former mine

 ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

Earthquake List Instruments ISIDE Scientific Products



Seismic Station SENA Sos Enattos Mine

Network: IV
Start Date: 2019-10-18T00:00:00
End Date: --

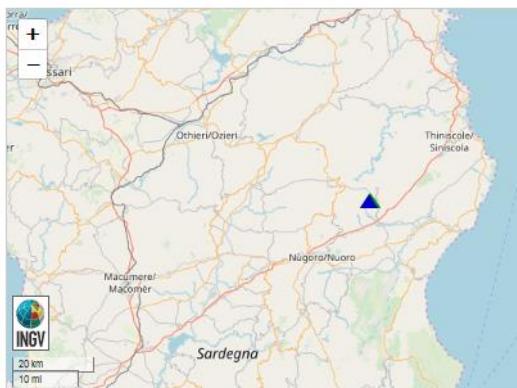
Latitude: 40.4444
Longitude: 9.4566
Elevation: 338
[Download StationXML](#)



Number of channels: 3

Channel List

Code	Location Code	Start Date	End Date	Data Restriction
HHE		18-10-2019		open



Latitude: 40.4444
Longitude: 9.4566
Elevation: 338
Depth: 111

Azimuth: 90
Sample Rate: 100
Storage Format: Stein2
Sensitivity Value: 478760000

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

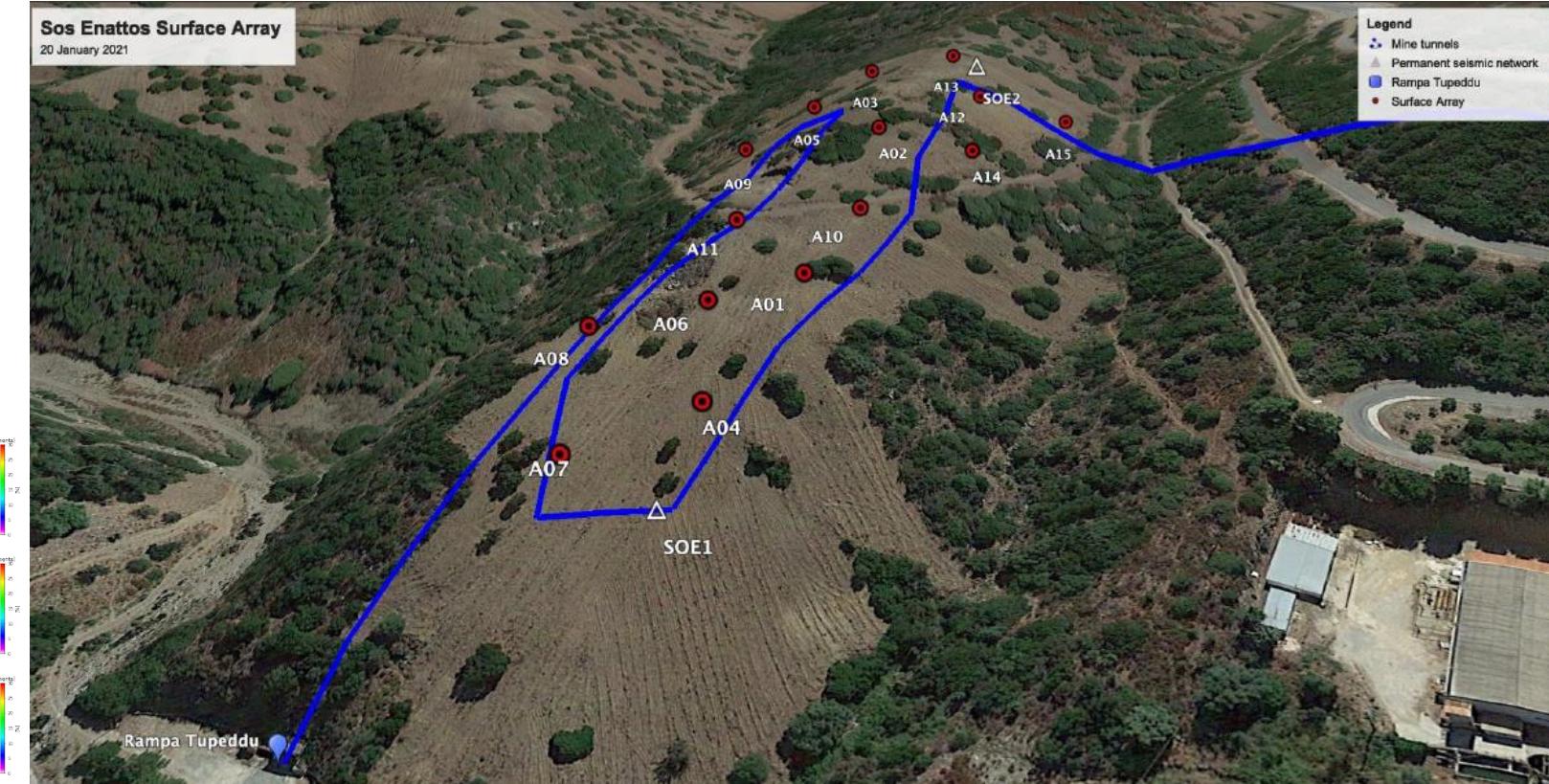
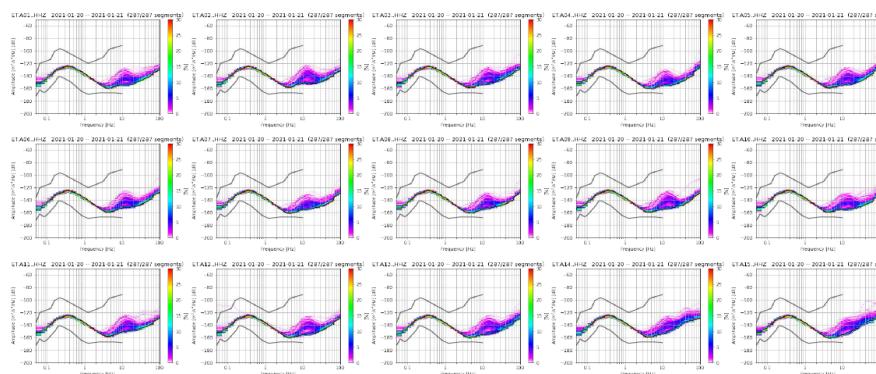
The Sos Enattos site

Surface Seismometer Array

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



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***, accepted by EPJP, 2023.
+ 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

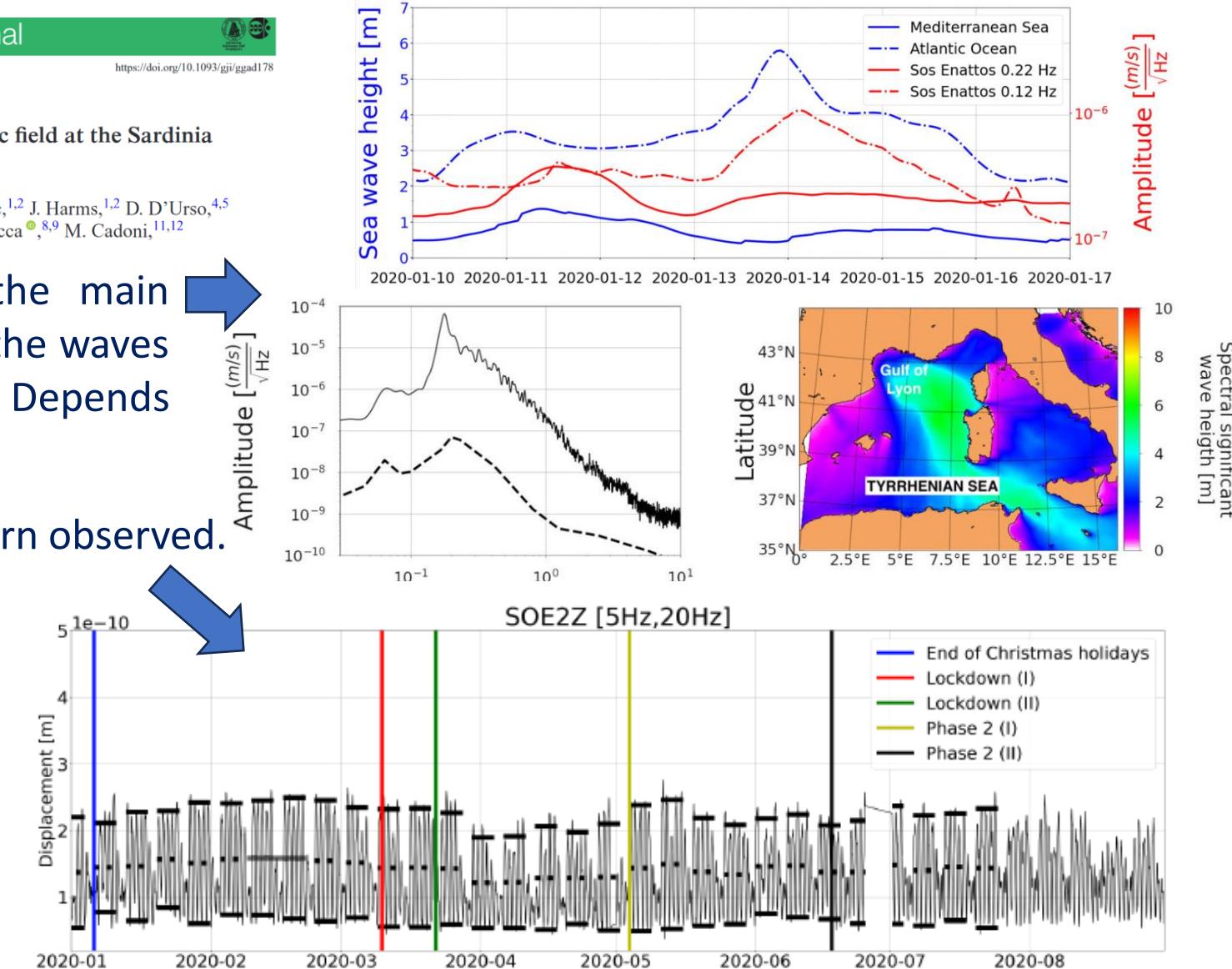
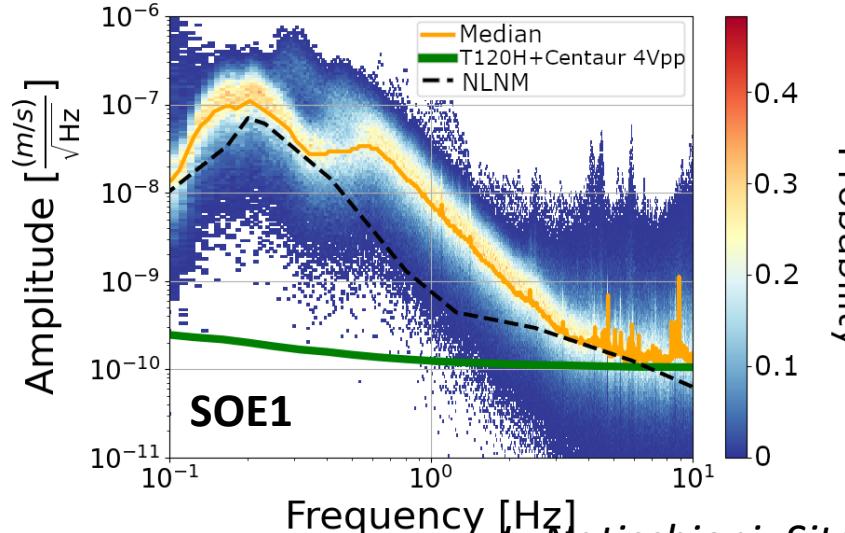
<https://doi.org/10.1093/gji/ggad178>

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. Allocata^{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.

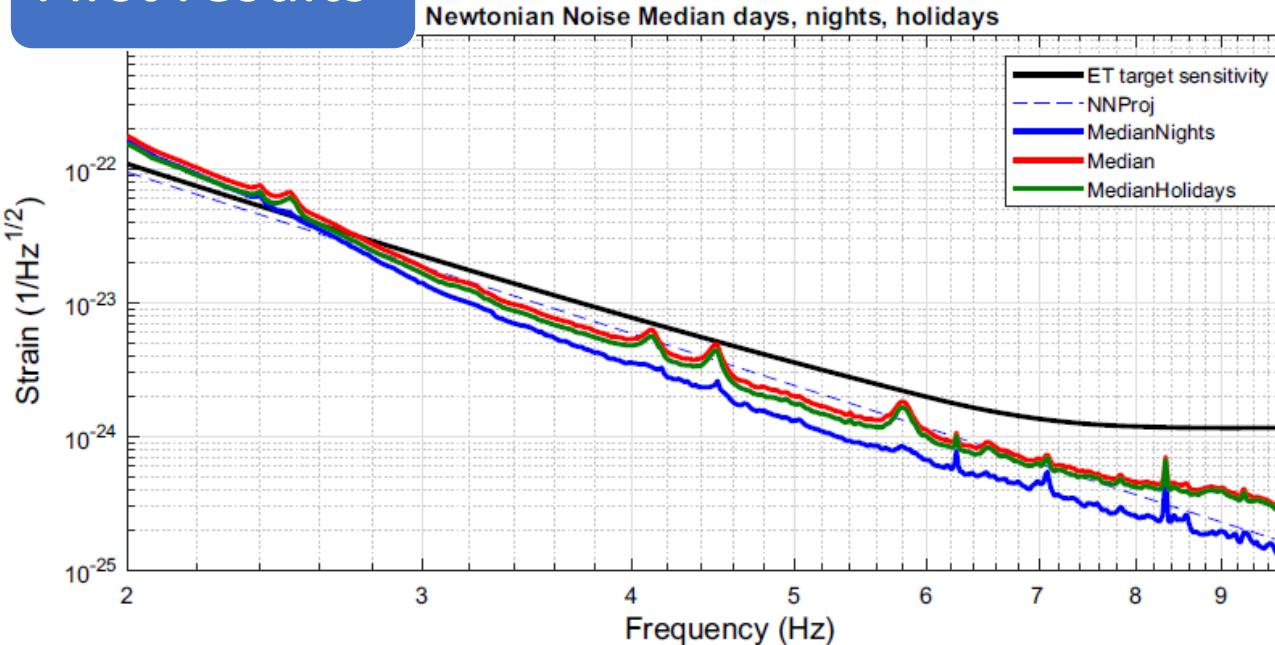
At higher frequencies, anthropic noise pattern observed.



The Sos Enattos site

First results

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



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

$$NTR = \sqrt{\frac{1}{\Delta f} \int df \frac{\tilde{N} * \tilde{N}}{S_h}} \quad \text{PSD of NN}$$

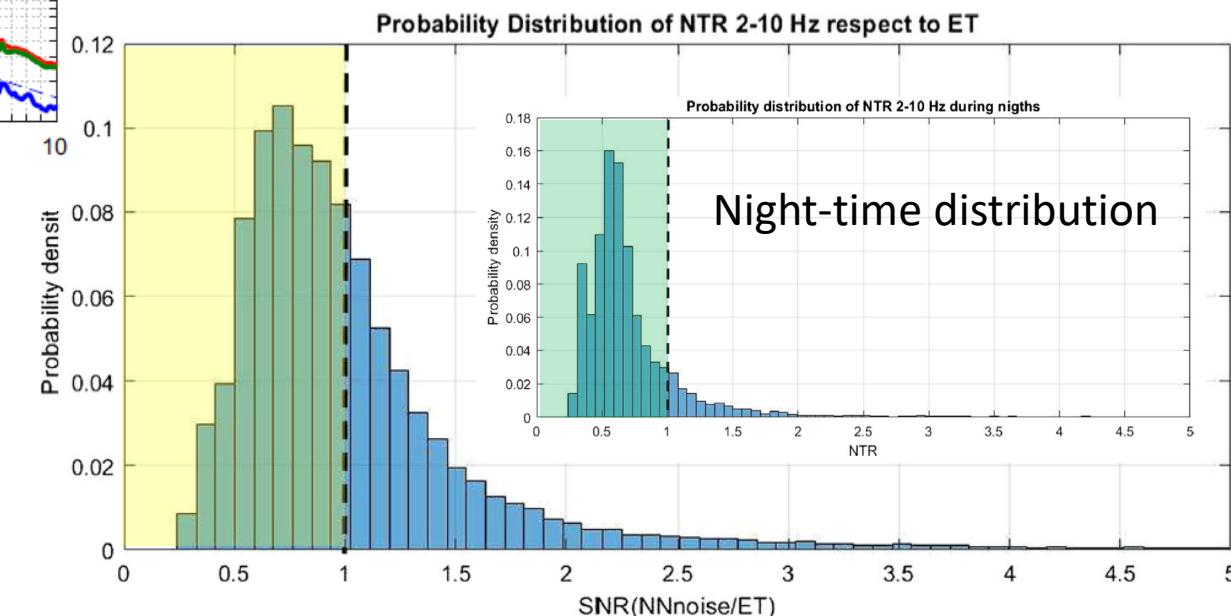
PSD of ET sensitivity

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

→ Need for moderate NN subtraction only for a limited time

Defining the Newtonian Noise ASD as:

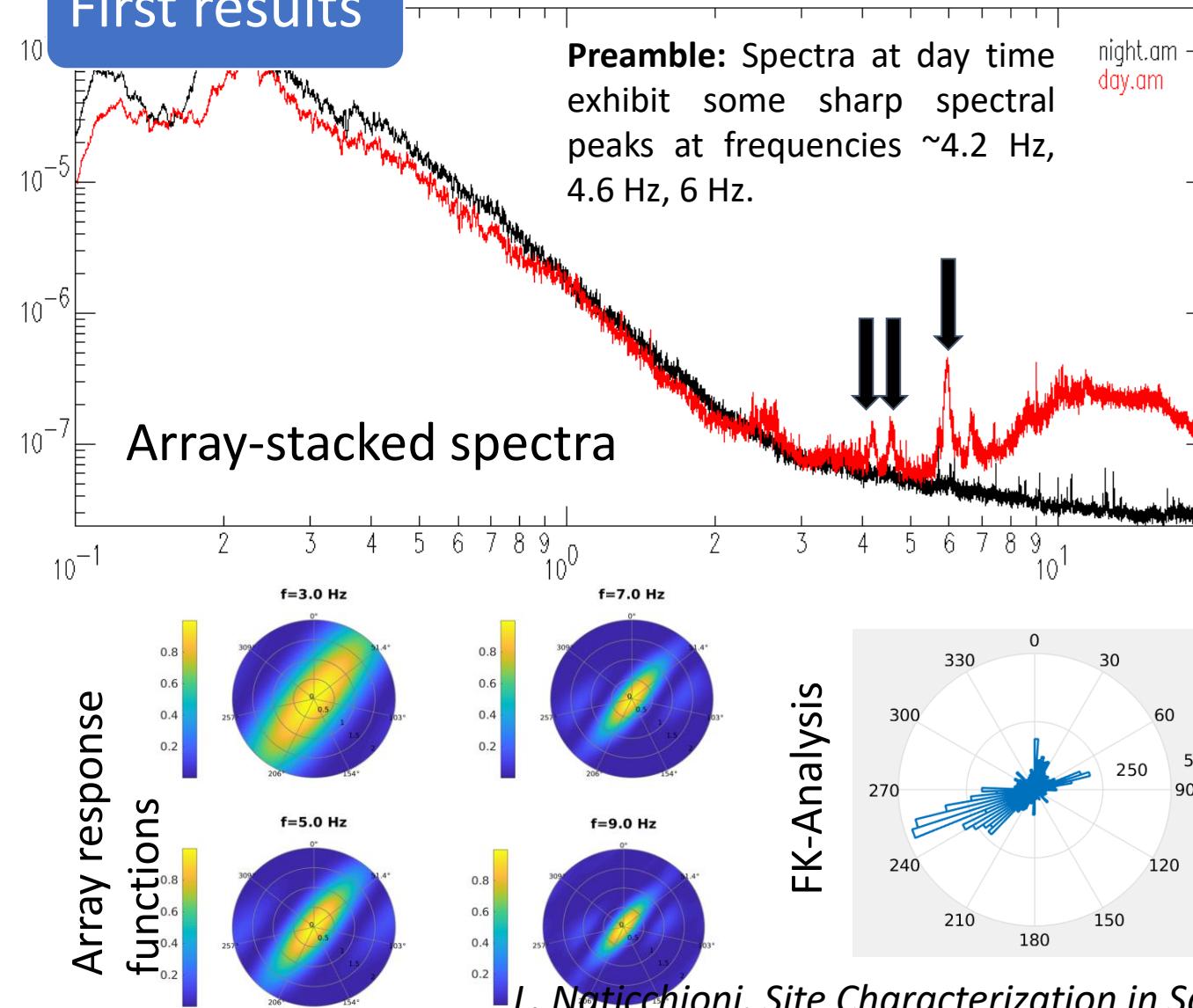
$$\tilde{h}_{NN}(f) = \frac{4\pi}{3} G \rho_0 \frac{2\sqrt{2}}{L} \frac{1}{(2\pi f)^2} \tilde{x}(f)$$



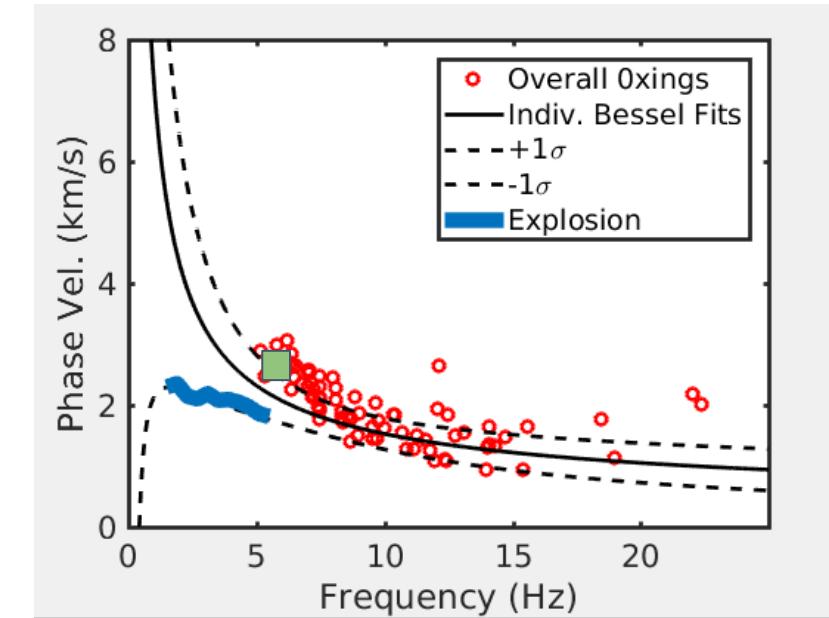
The Sos Enattos site

Seismometer array results

First results



SPatial AutoCorrelation:

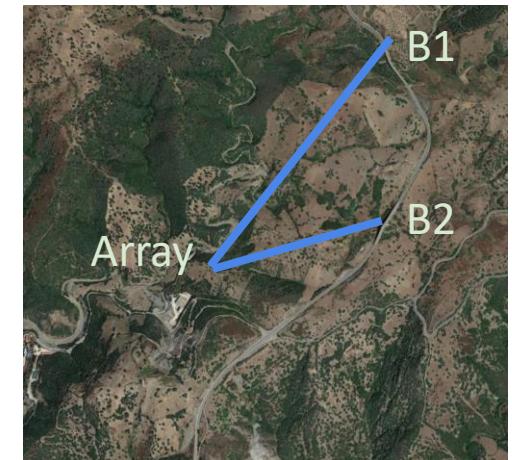
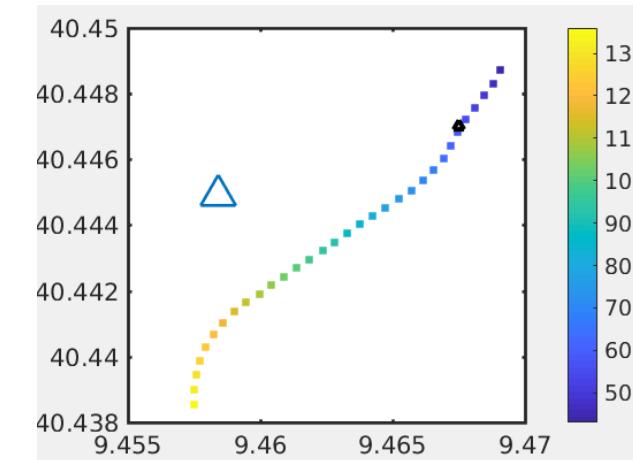
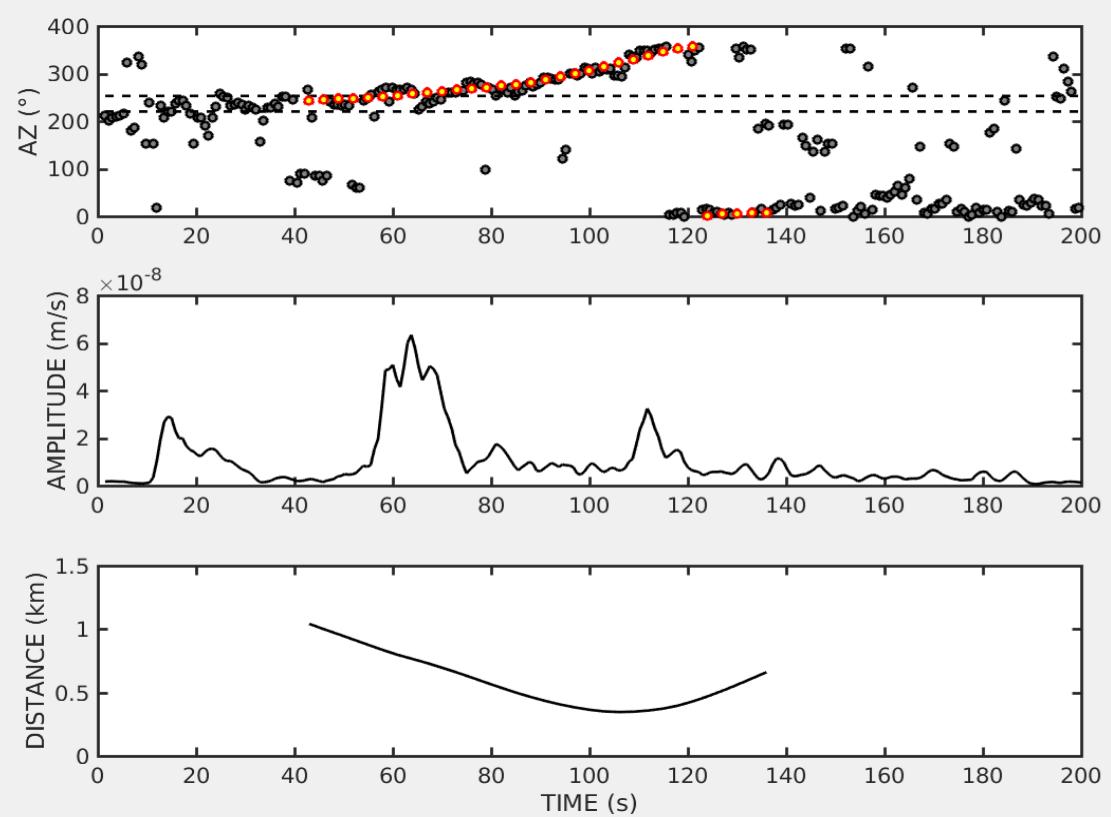


Not-isotropic wavefield
Peaks at $f = 4-5$ Hz
Propagation azimuths directed WSW (i.e., main sources located ENE of the array)
High velocities (~ 2.5 km/s)

The Sos Enattos site

First results

Seismometer array results Vehicle Tracking close to the site



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 in another study: *Geophys. J. Int.* 234, 3 2023

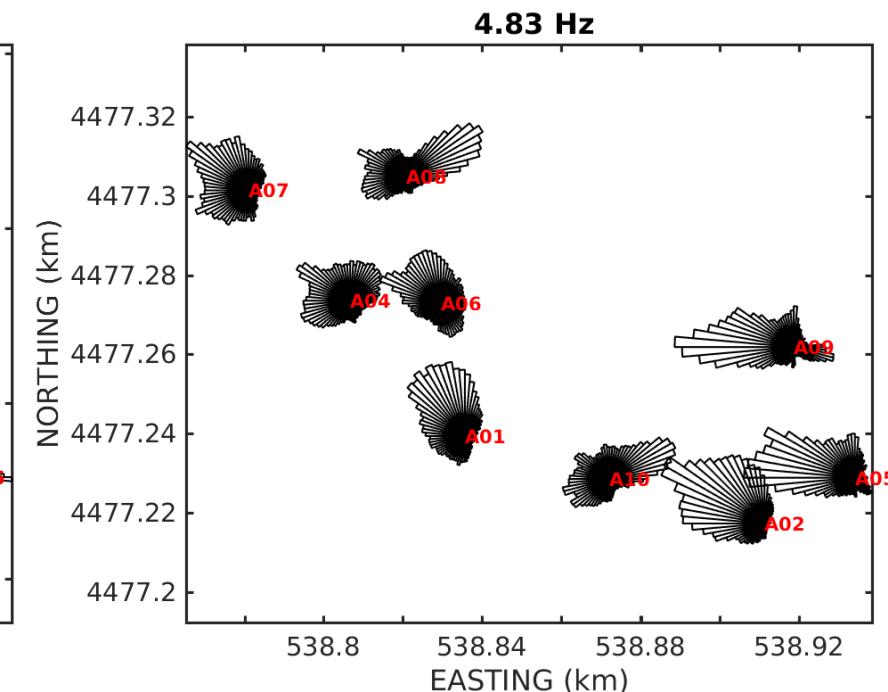
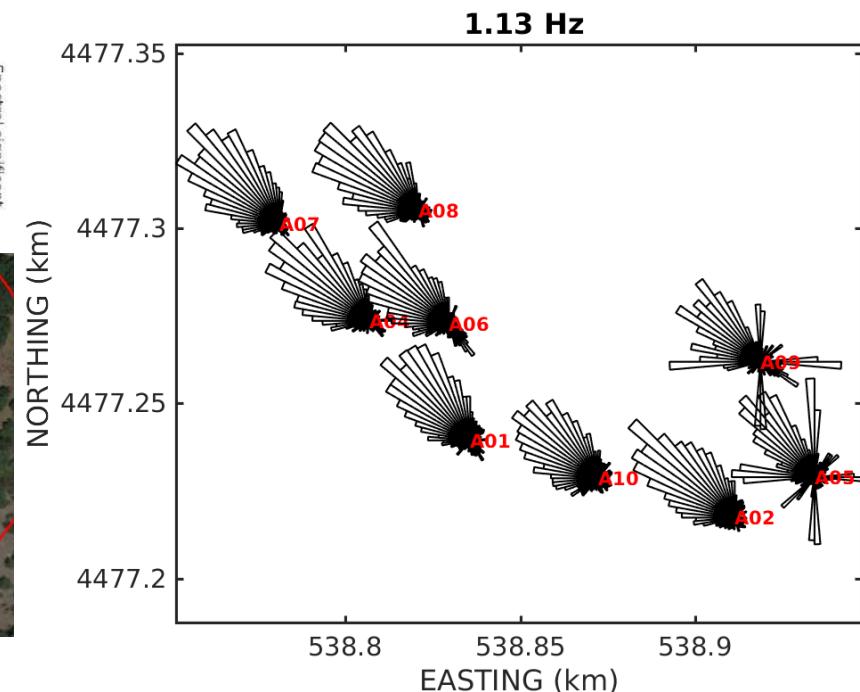
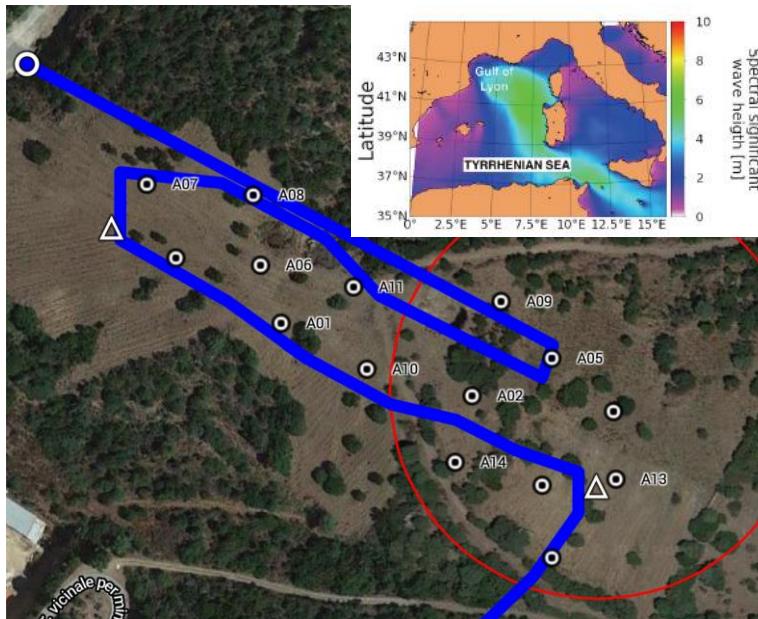
The Sos Enattos site

Seismometer array results Polarization analysis

First results

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.

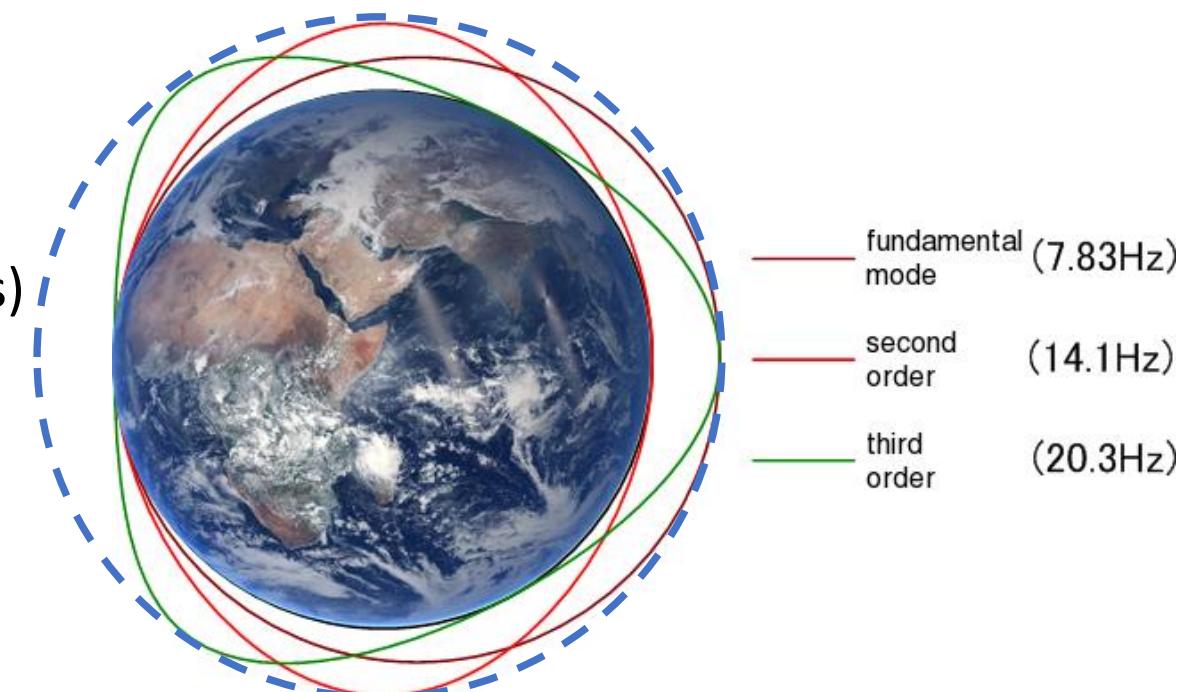
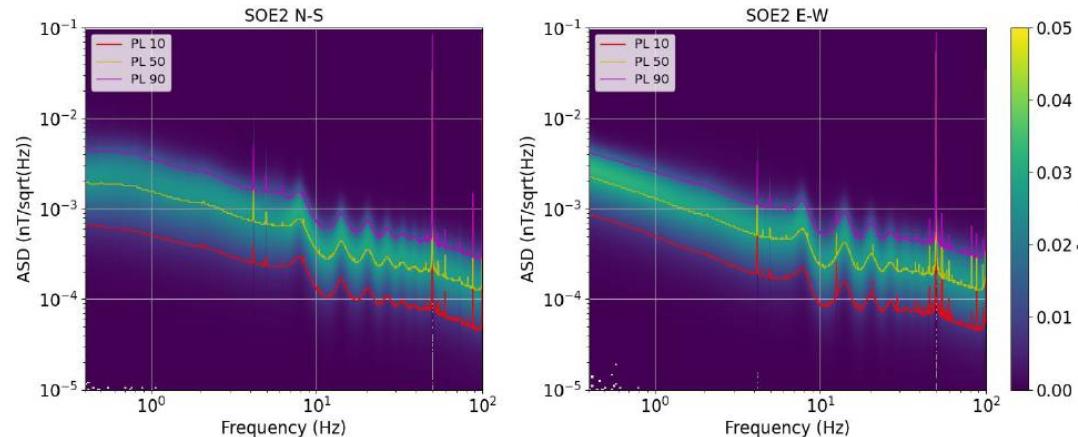


First results

Magnetic Noise measurements

- In the band of interest of ET the main direct disturbances come from ULF (10^{-3} -3Hz), ELF (3- $3 \cdot 10^3$ Hz) up to VLF (3-30 kHz) radiobands.
- Main natural magnetic noise is in ULF and ELF, produced by resonance phenomena in the magnetosphere 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)

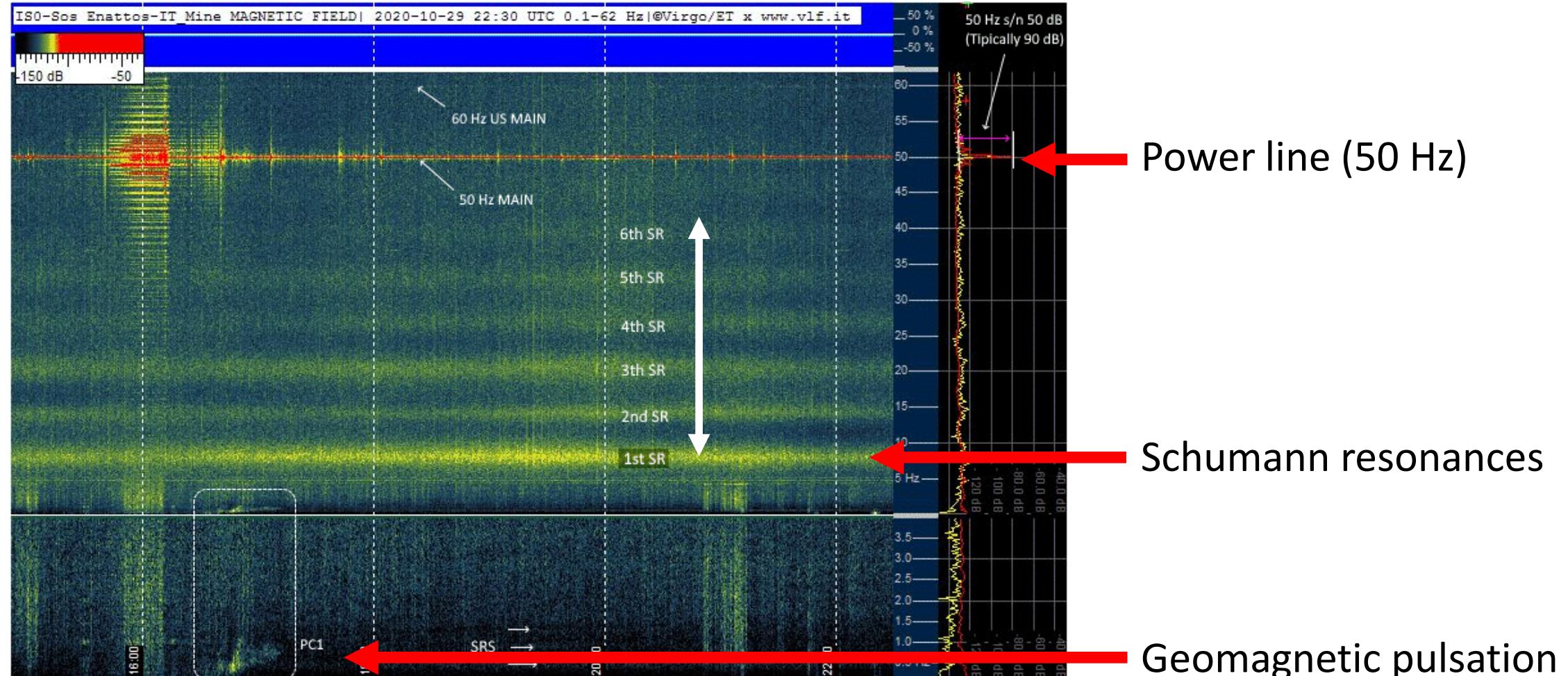
credit: R. De Rosa



The Sos Enattos site

First results

Magnetic Noise measurements

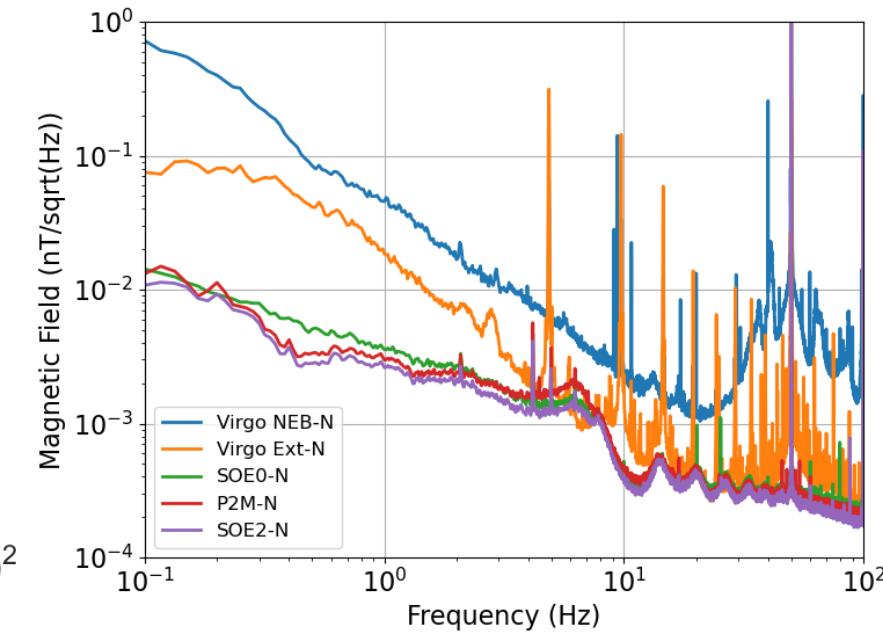
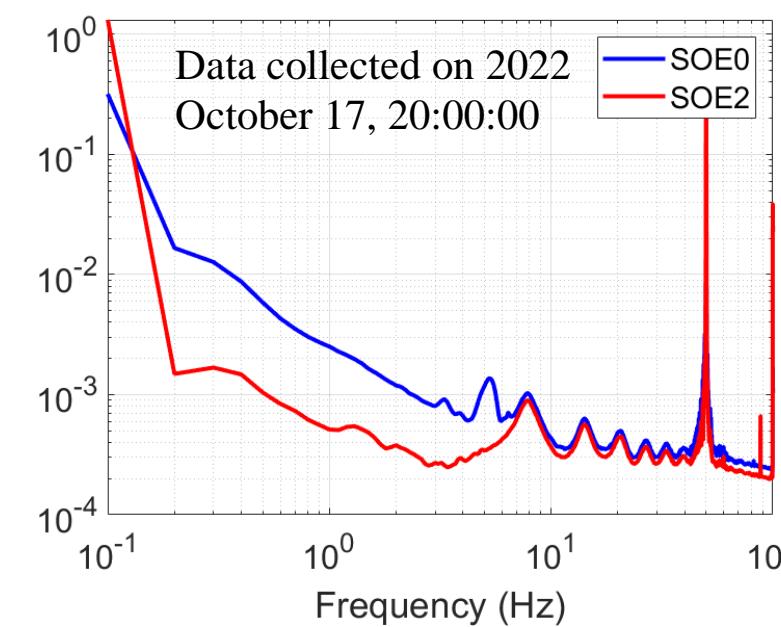
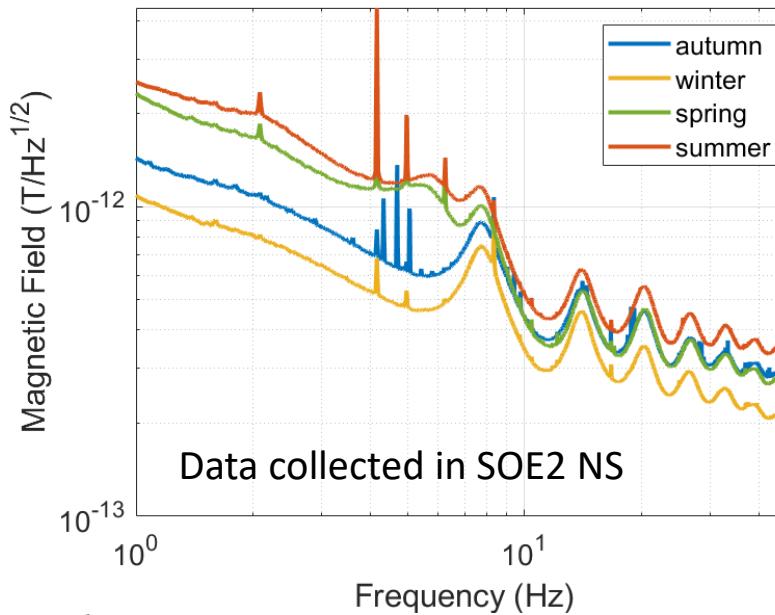
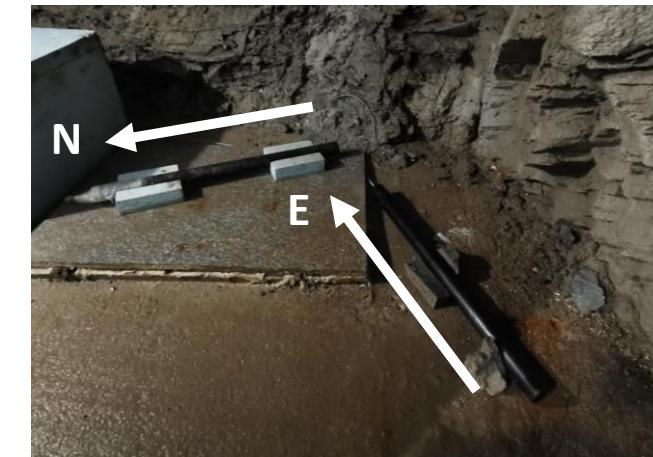


The Sos Enattos site

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.

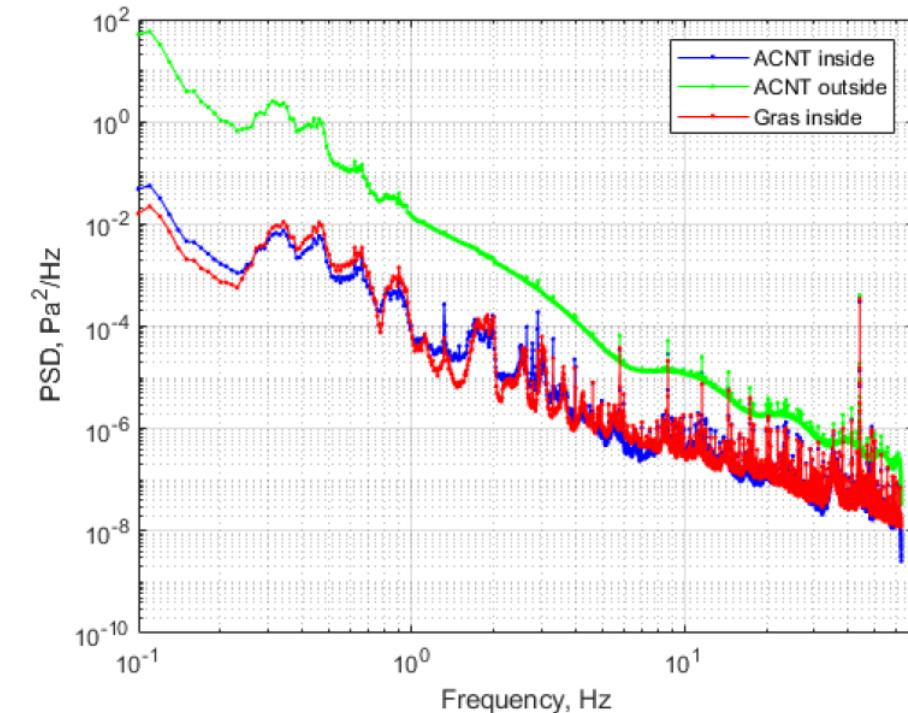


credit: R. De Rosa

First results

Infrasound measurements

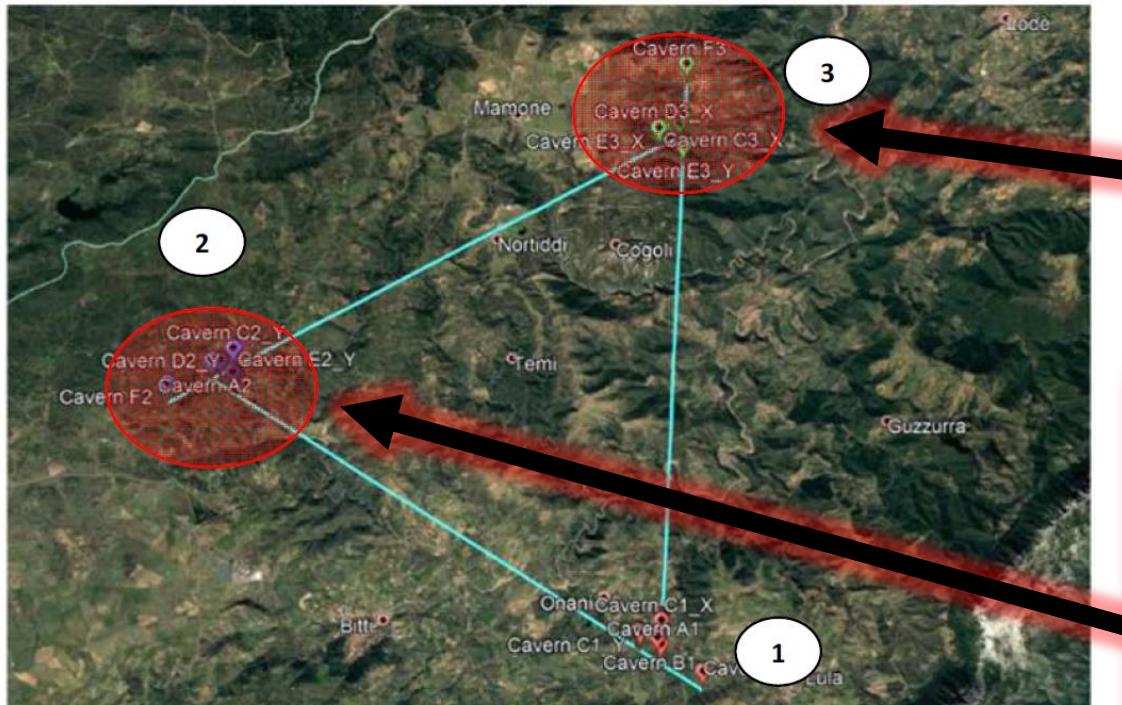
- Short term measurements have shown the quietness of the mine;
- (3+1) microphones installed along the underground tunnels for long term characterization in a joint Italian-Polish-Hungarian collaboration (*PolGrav-AstroCeNT, Wigner Research Centre*); → *E. Fenyvesi's talk yesterday*
- New installations planned by GSSI.



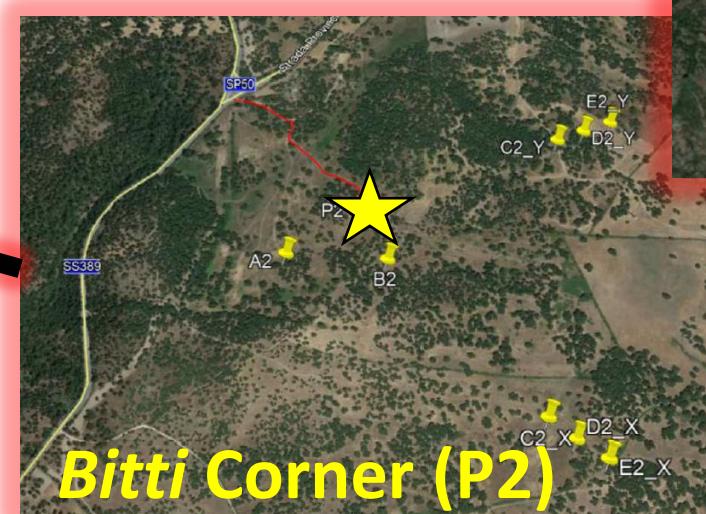
credit: T. Bulik

Characterization of the Δ corners

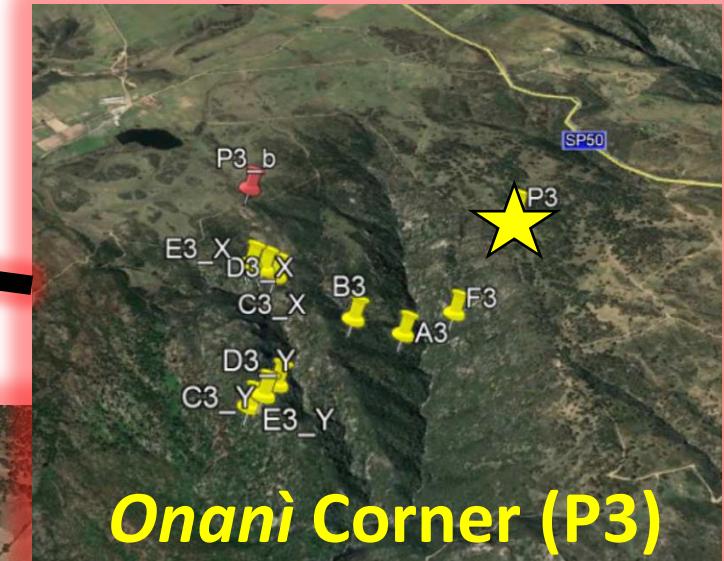
The corners of the Δ layout



**Lula Corner
Sos Enattos**



Bitti Corner (P2)



Onanì Corner (P3)

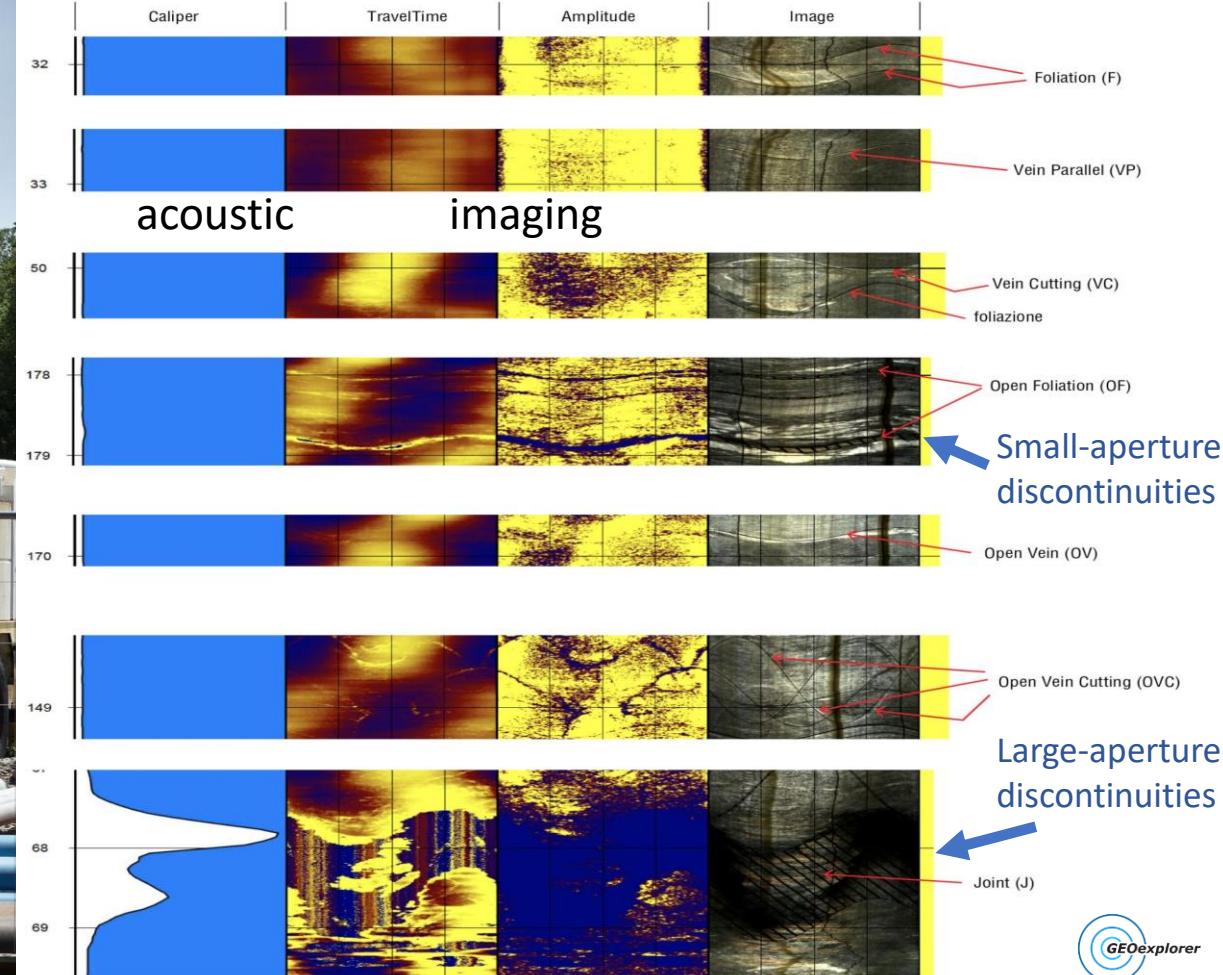
★ : area for boreholes and surface arrays

○ : 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

P3



P2



Measurement stations at the corners

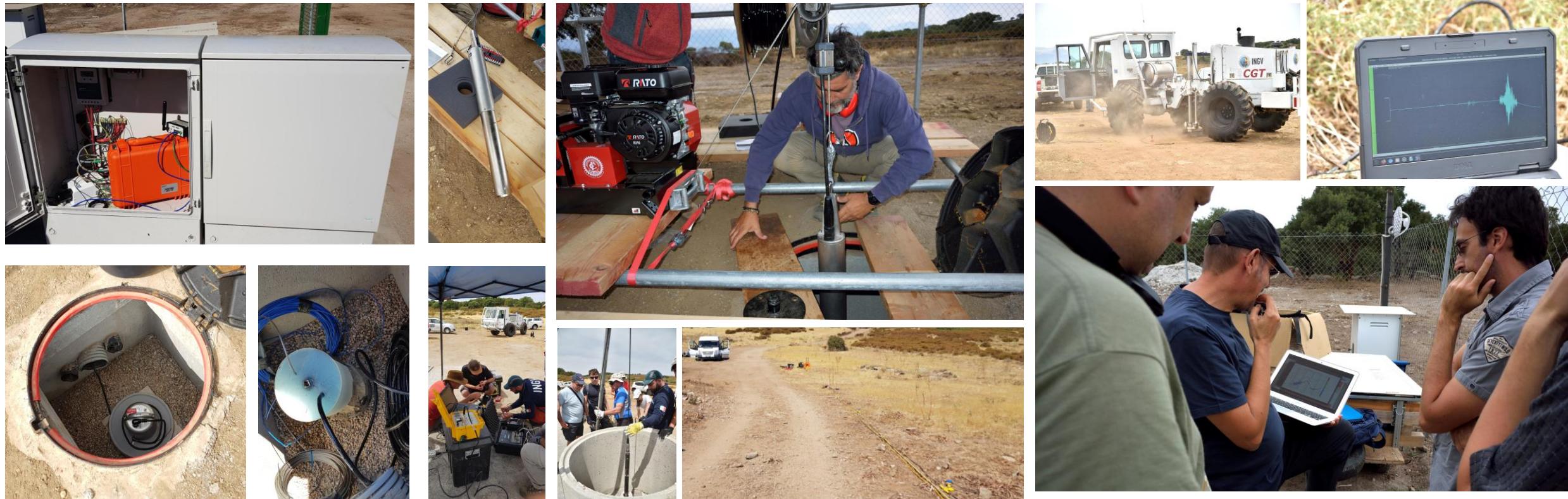


...last winter

Characterization of the Δ corners

Seismometer installations & active seismic campaign

- 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.

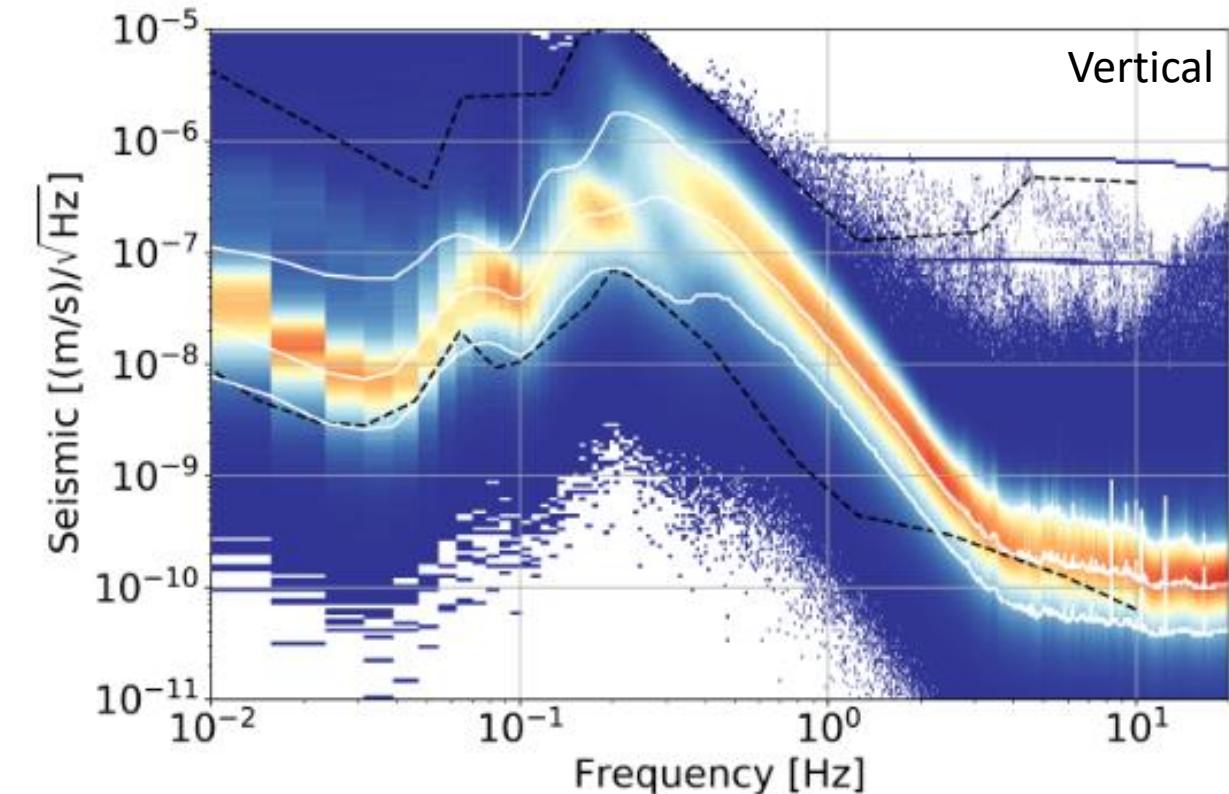
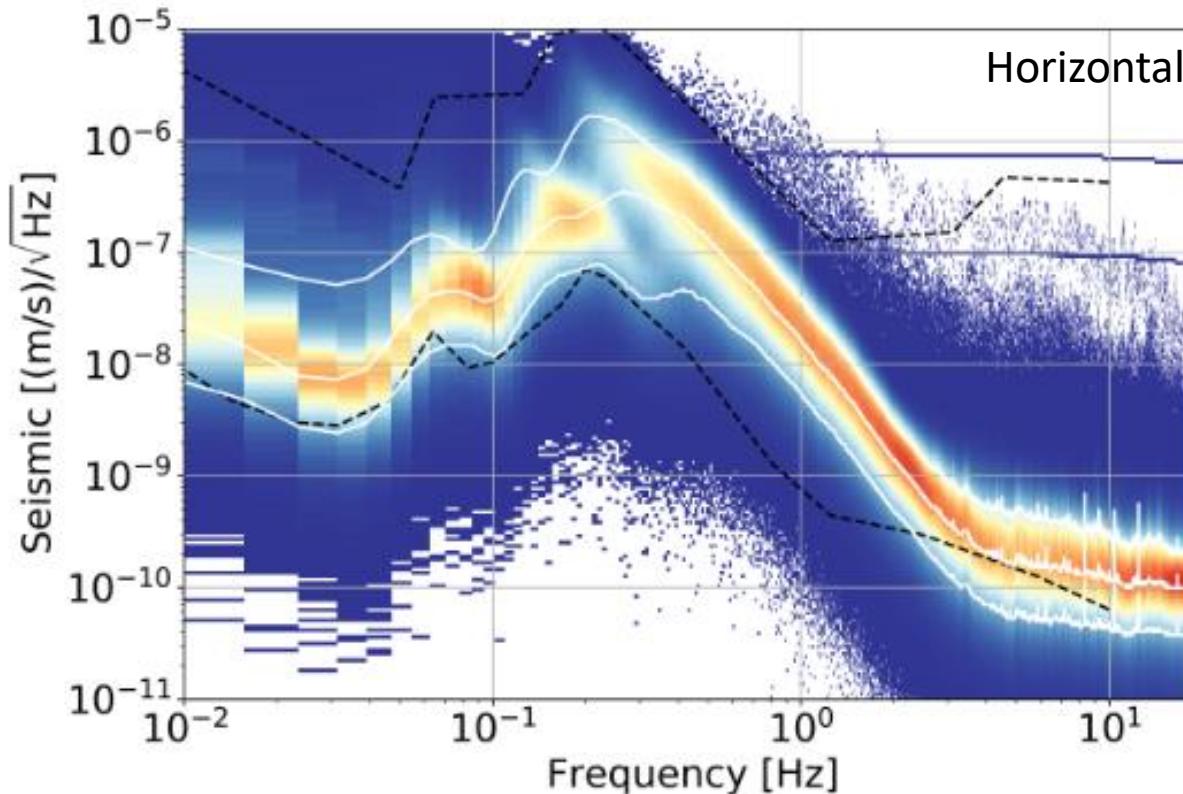


L. Naticchioni, Site Characterization in Sardinia for ET – XVIII TAUP 2023

Characterization of the Δ corners

A quick glance at the measurements

PPSD - P2 borehole seismometer

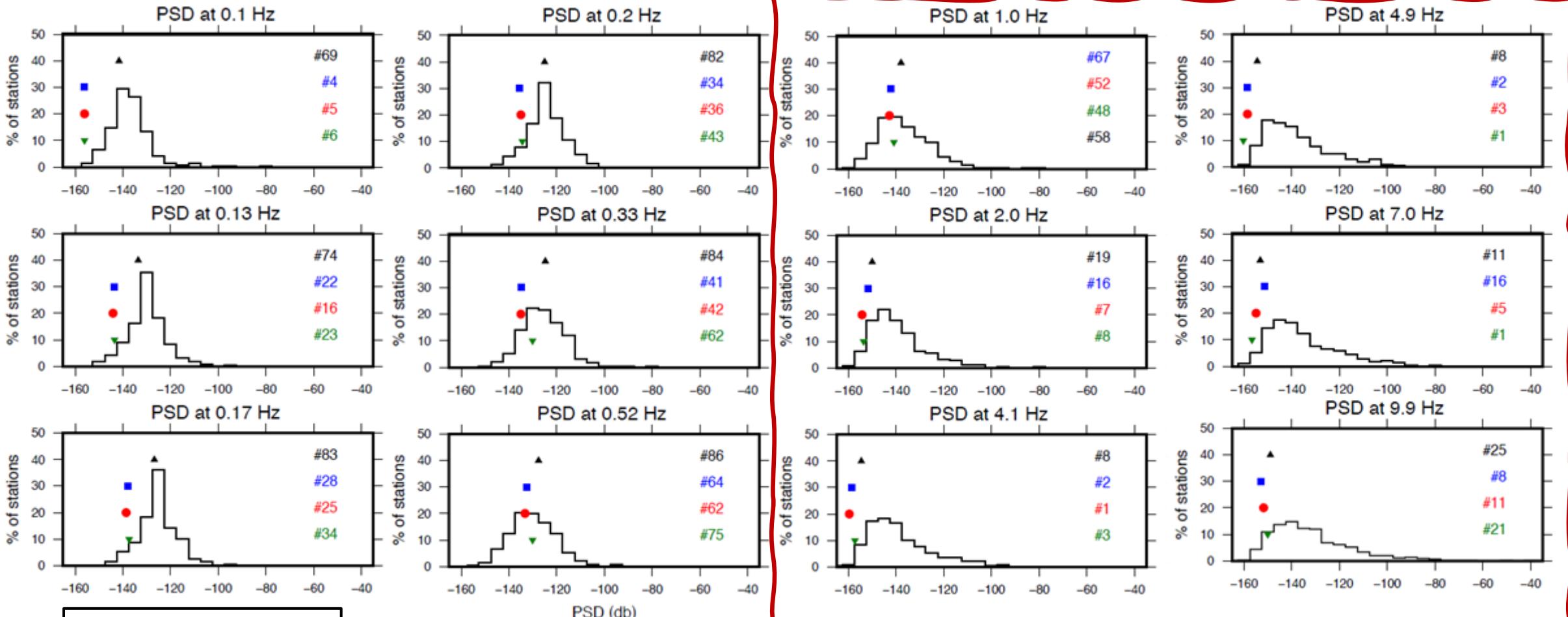


Very low noise background in the 2-10 Hz band, sometimes even **below** the Peterson's **New Low Noise Model!**

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.

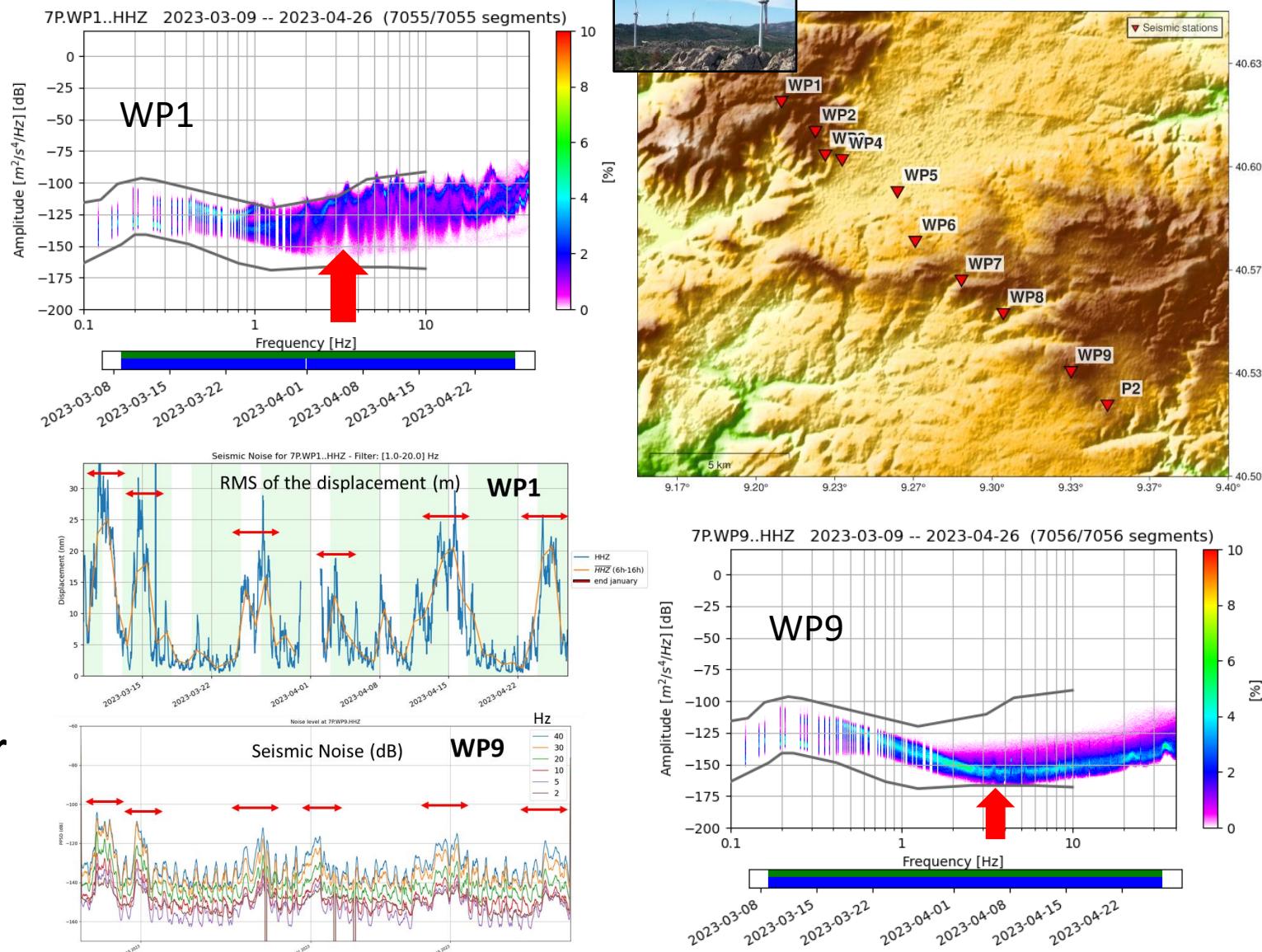


SOE2 P2 P3 SOE1

Characterization of the Δ corners

Wind farm temporary array

- Main peak at $\sim 3\text{Hz}$ + 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.**

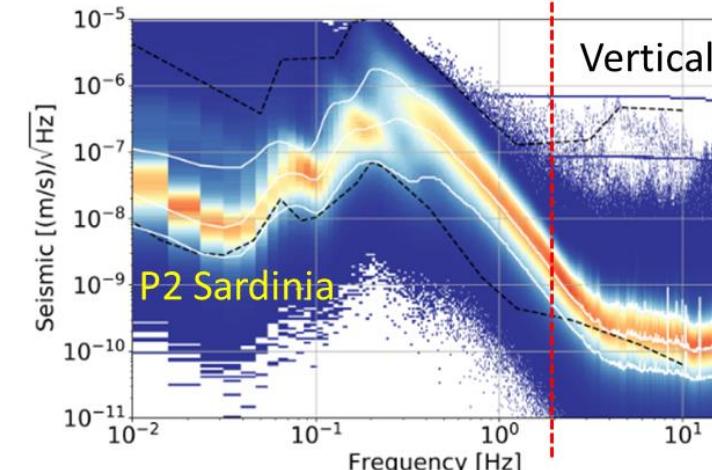
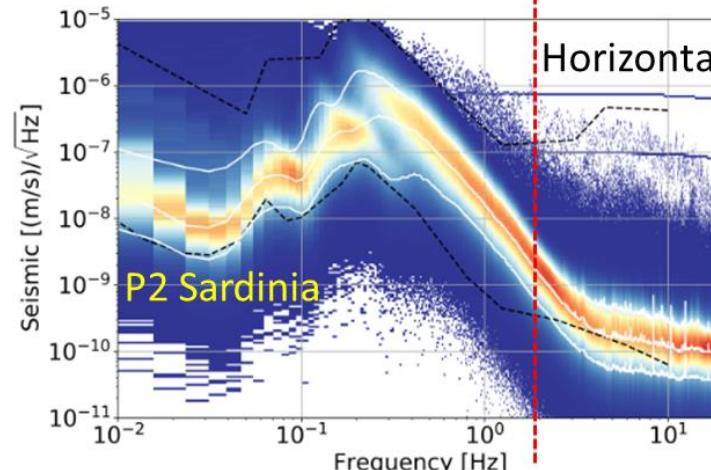
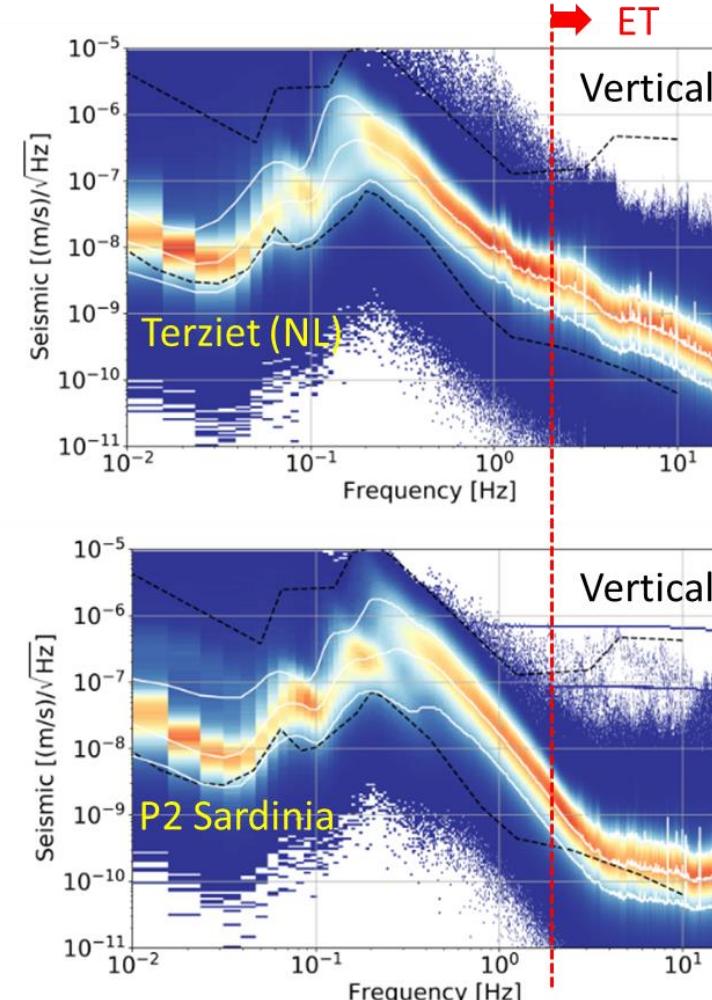
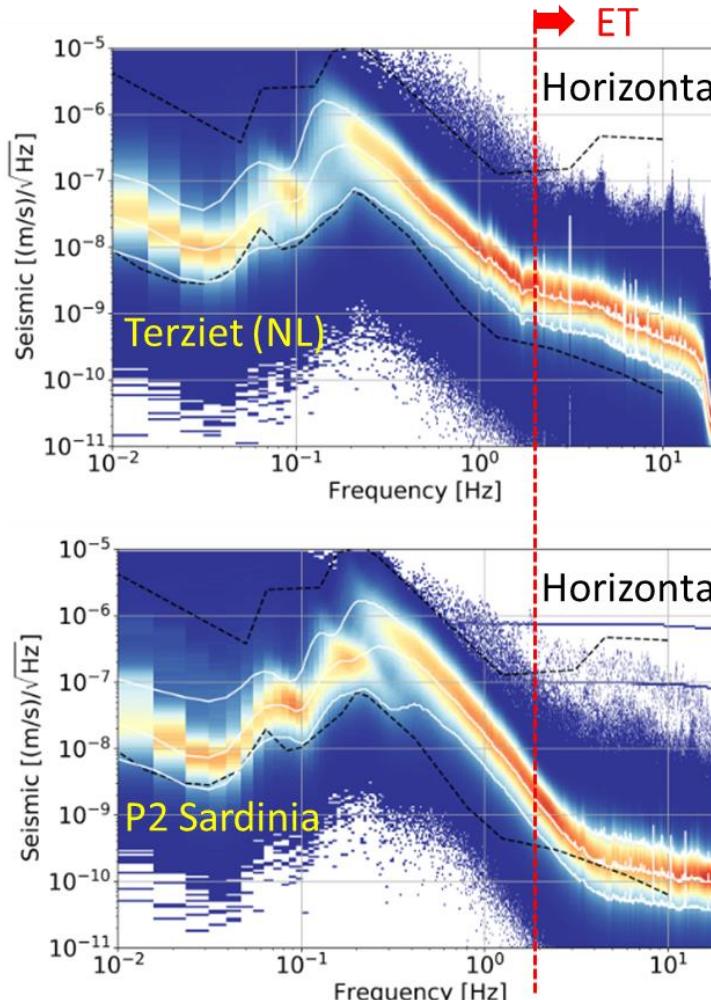


Summary

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

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



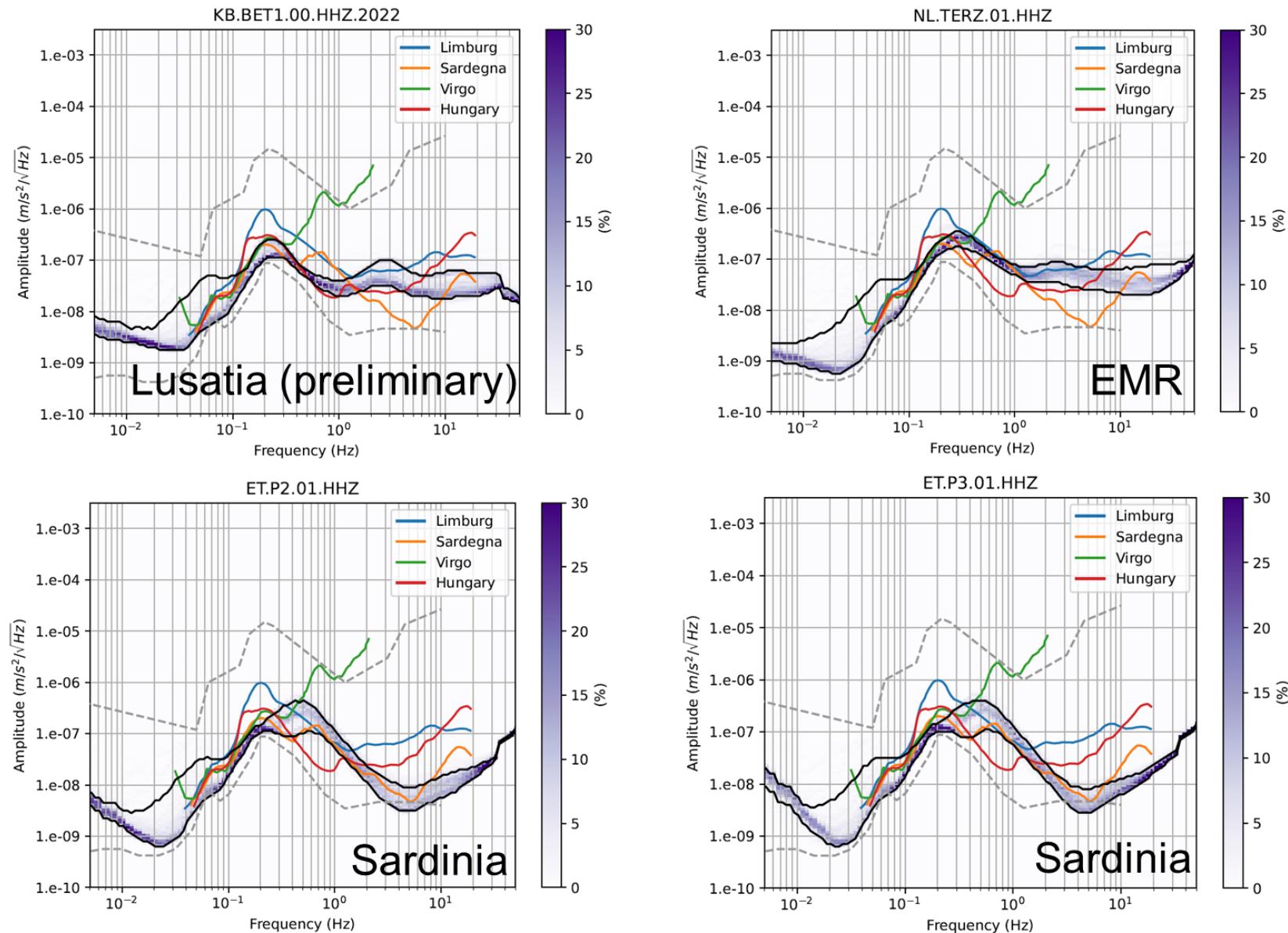
Sardinia P2 borehole



Site comparison with other candidates

Borehole comparison

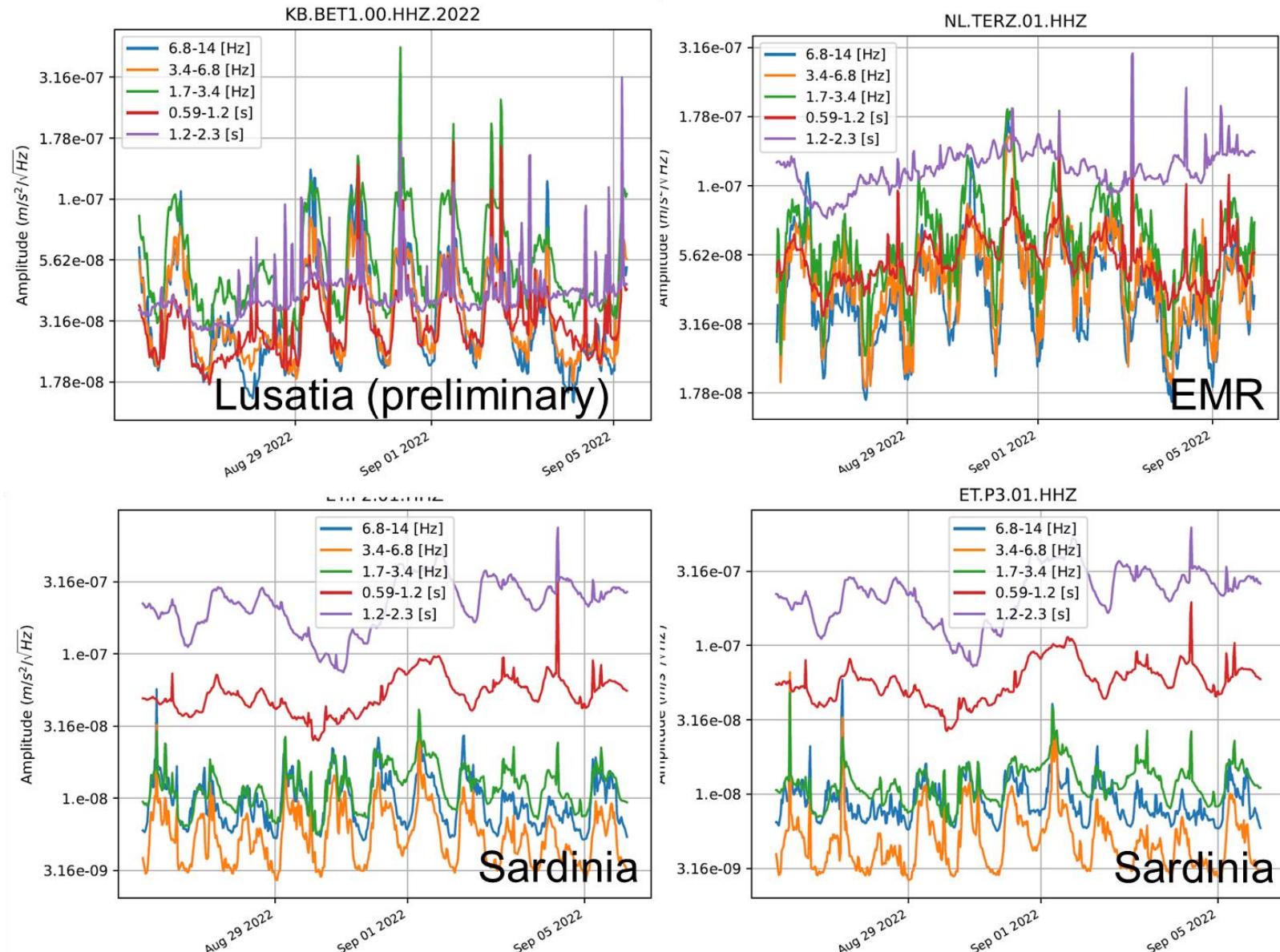
A. Rietbrock *et al.*, ET-SPB
Workshop 2023



Site comparison with other candidates

Borehole comparison

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

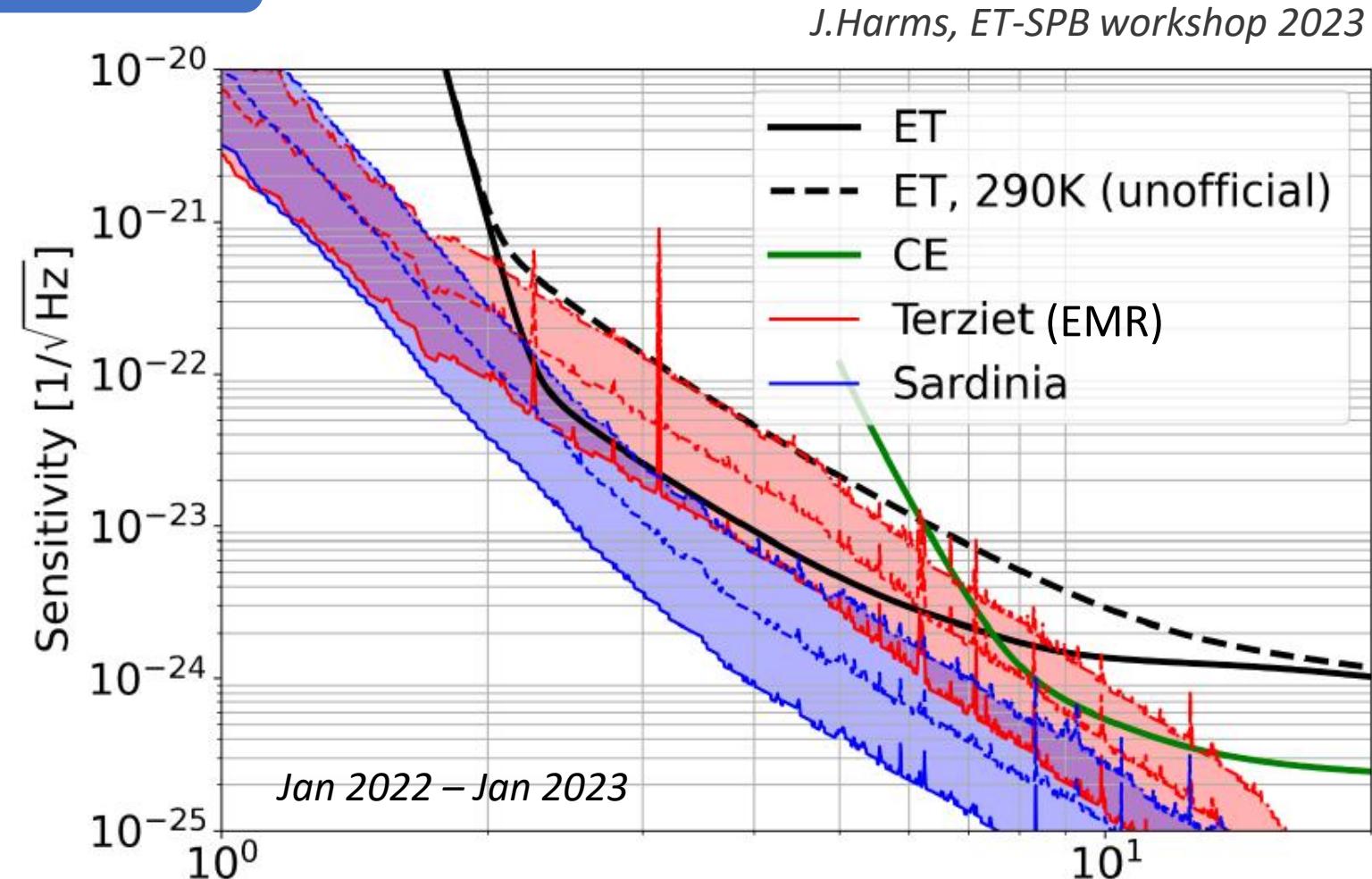


Seismic Newtonian Noise projections

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



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!**

Thanks!



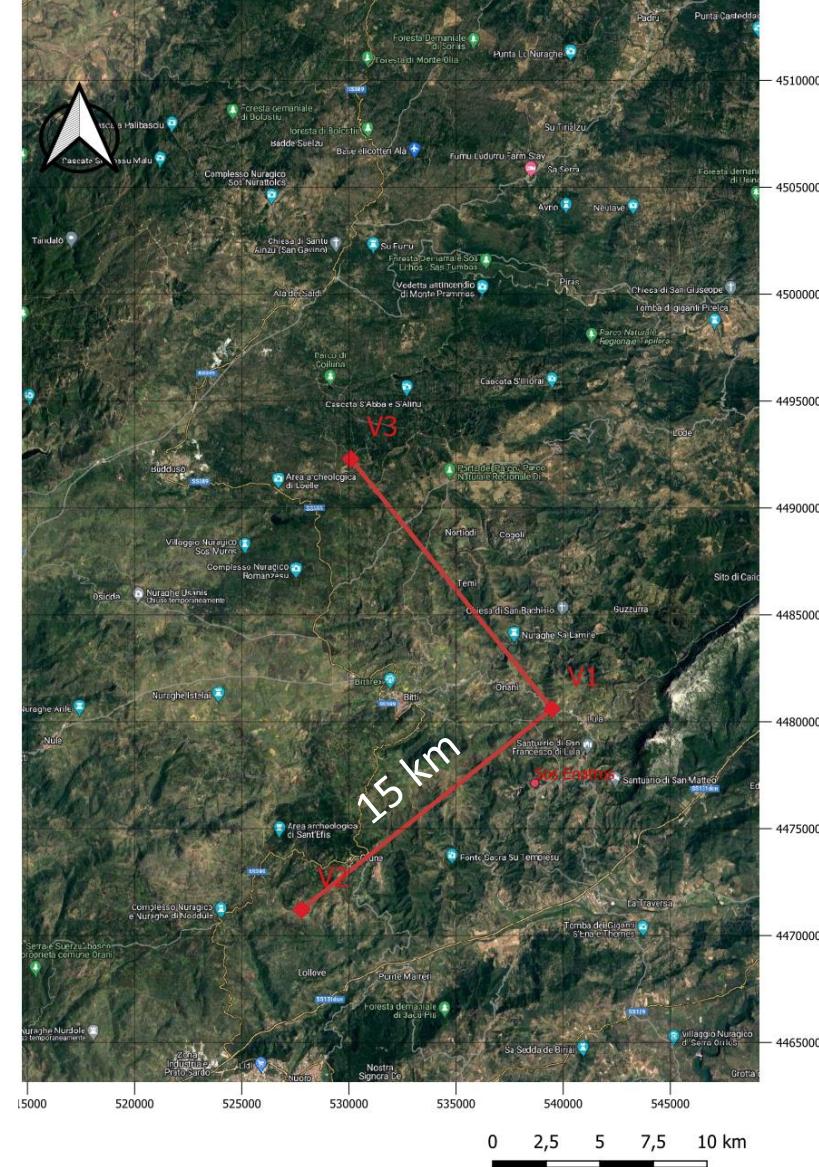
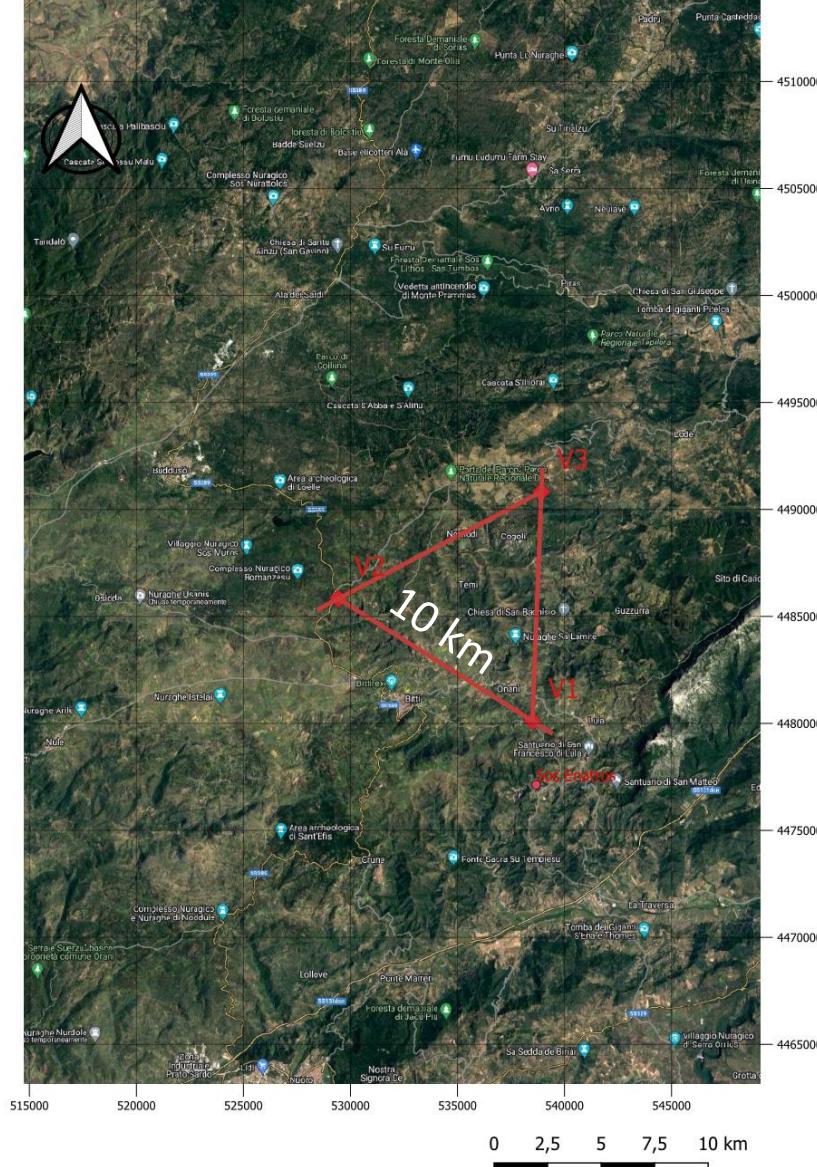
Typical “source” of noise
you can meet on the
road in Sardinia!

BACKUP SLIDES

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.

ET in Sardinia, where?



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.)

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).



Site characterization of the former mine

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

Instrumented stations

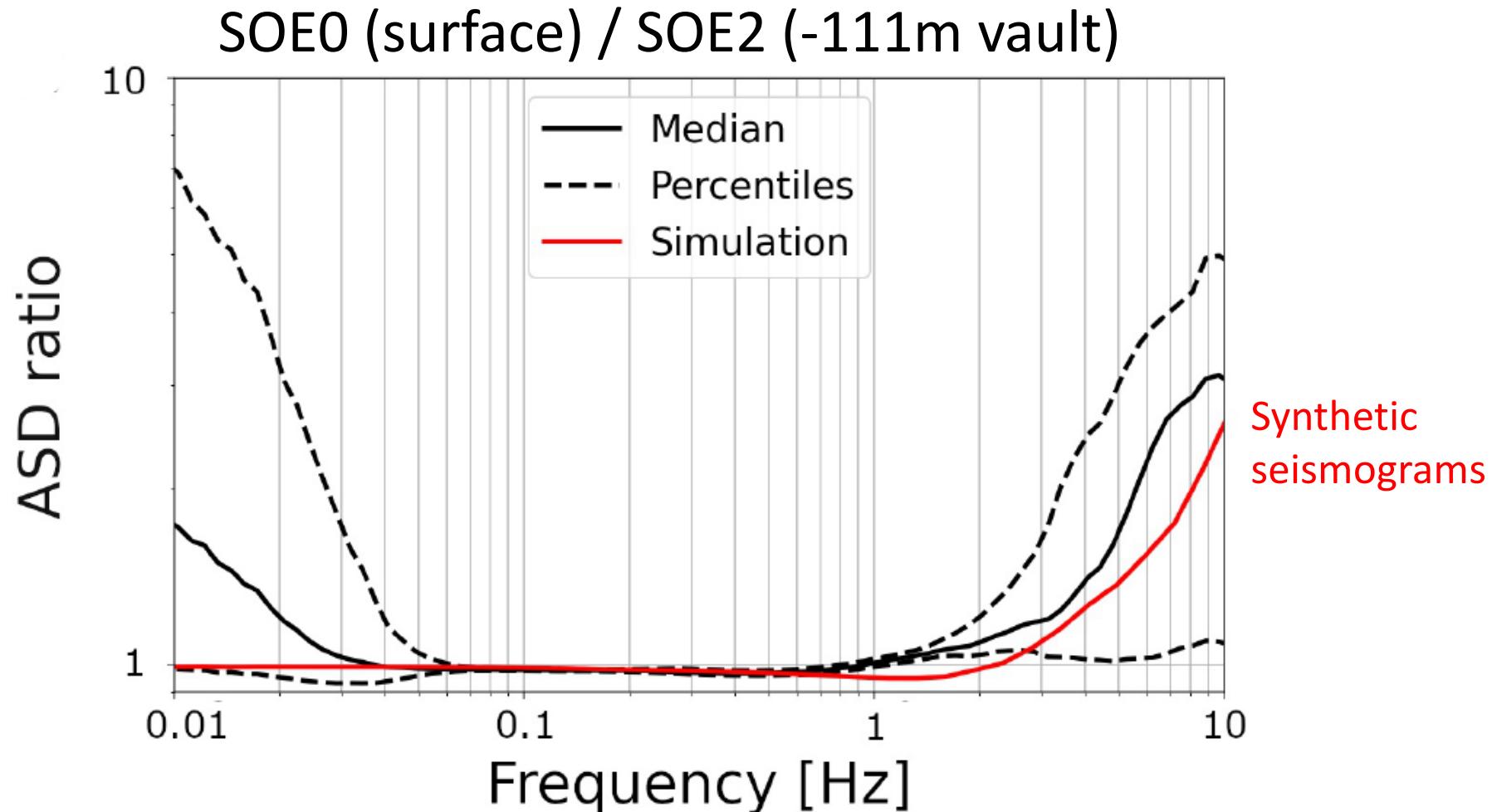
Sensors currently installed:

- 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).

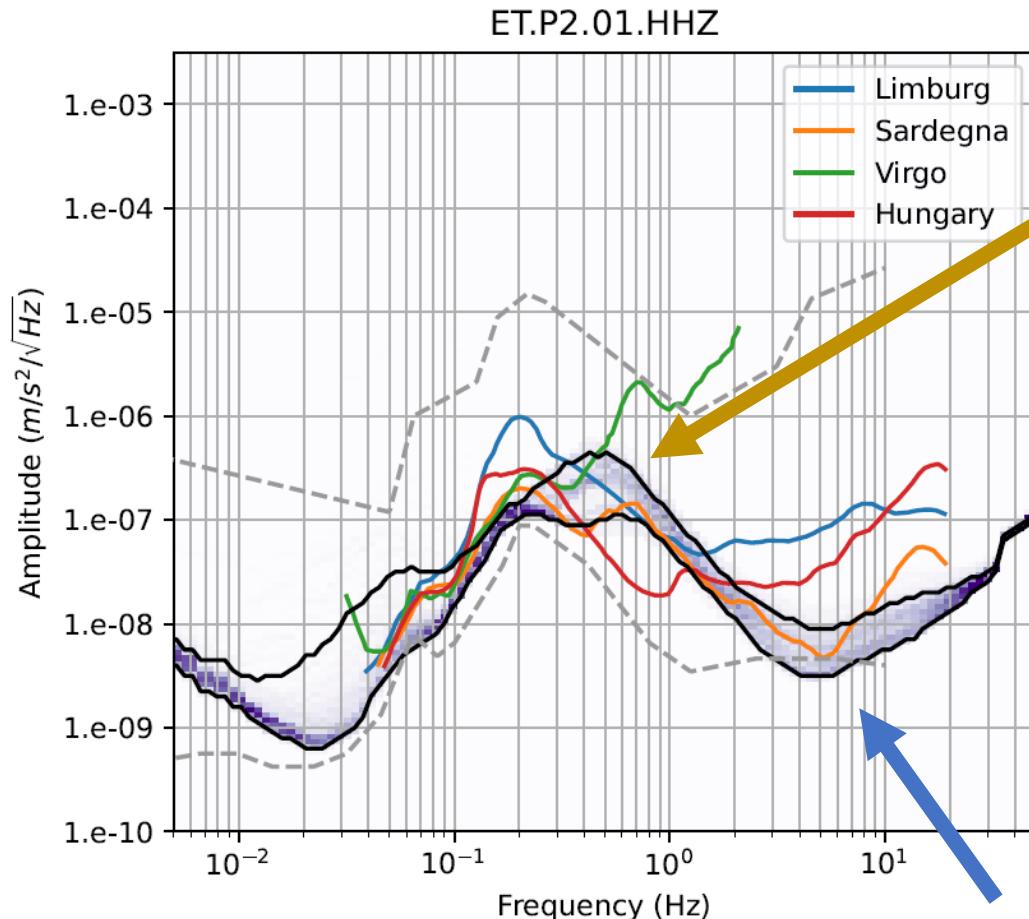
First results

The Sos Enattos site

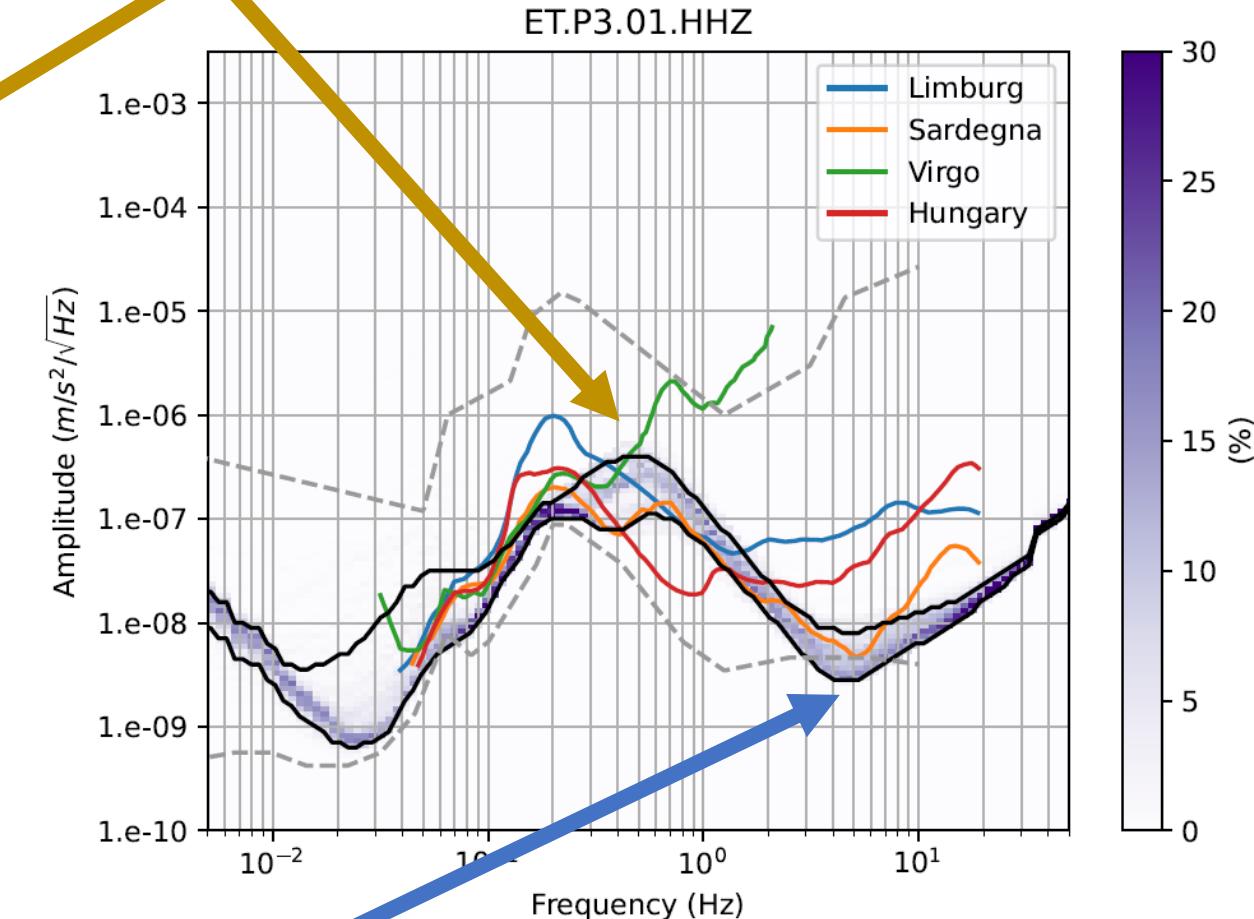
Amplitude decay with depth significant only for $f>2\text{Hz}$, consistent with Rayleigh-wave propagation in local rocks



Borehole measurements comparison



High amplitudes: Influence of the sea below 2 Hz



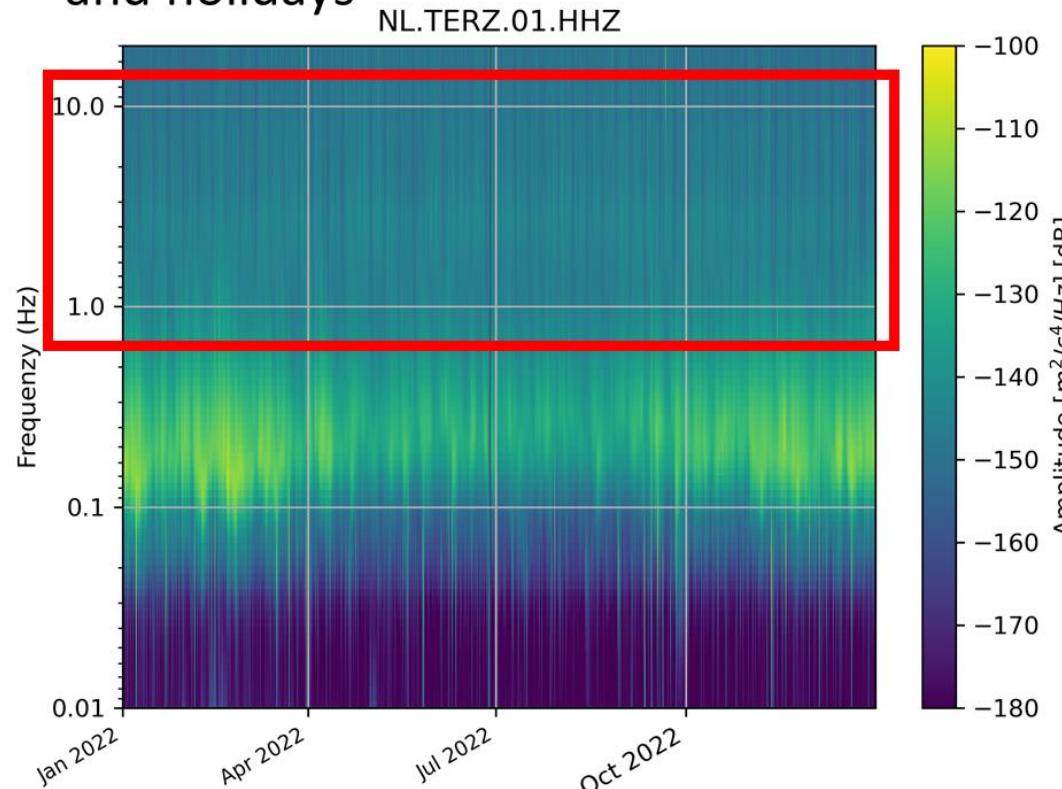
Low amplitudes: Low cultural noise

Site comparison with other candidates

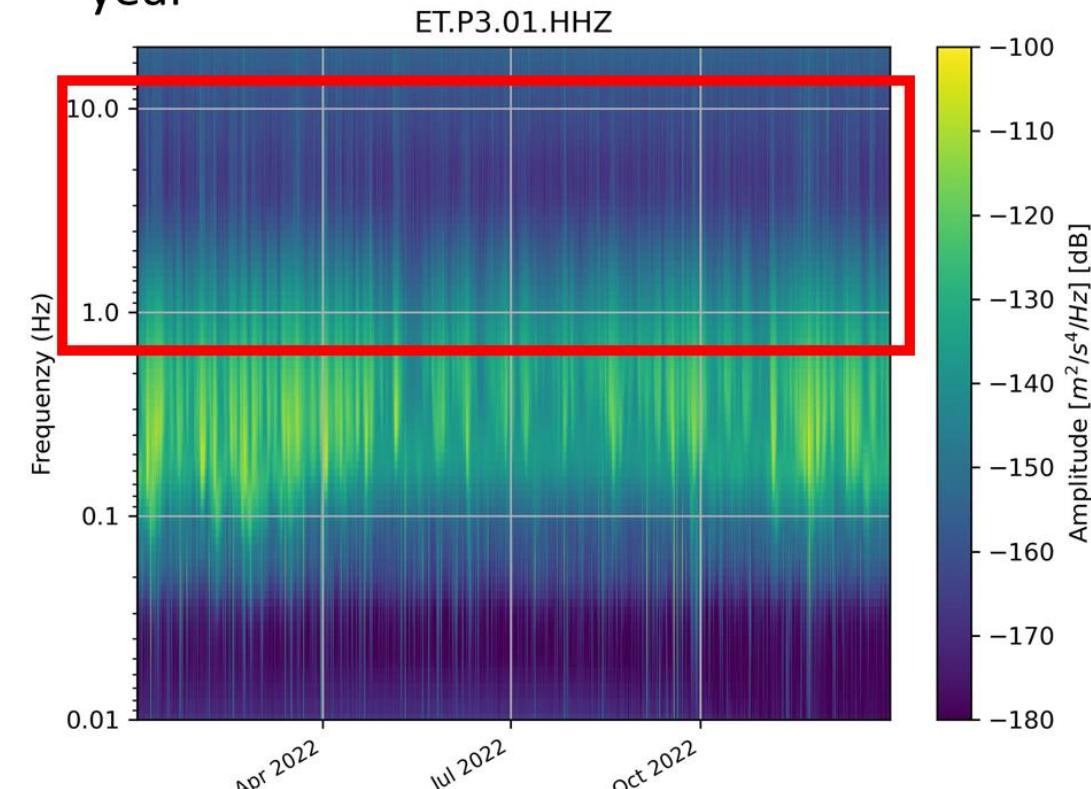
Borehole comparison

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

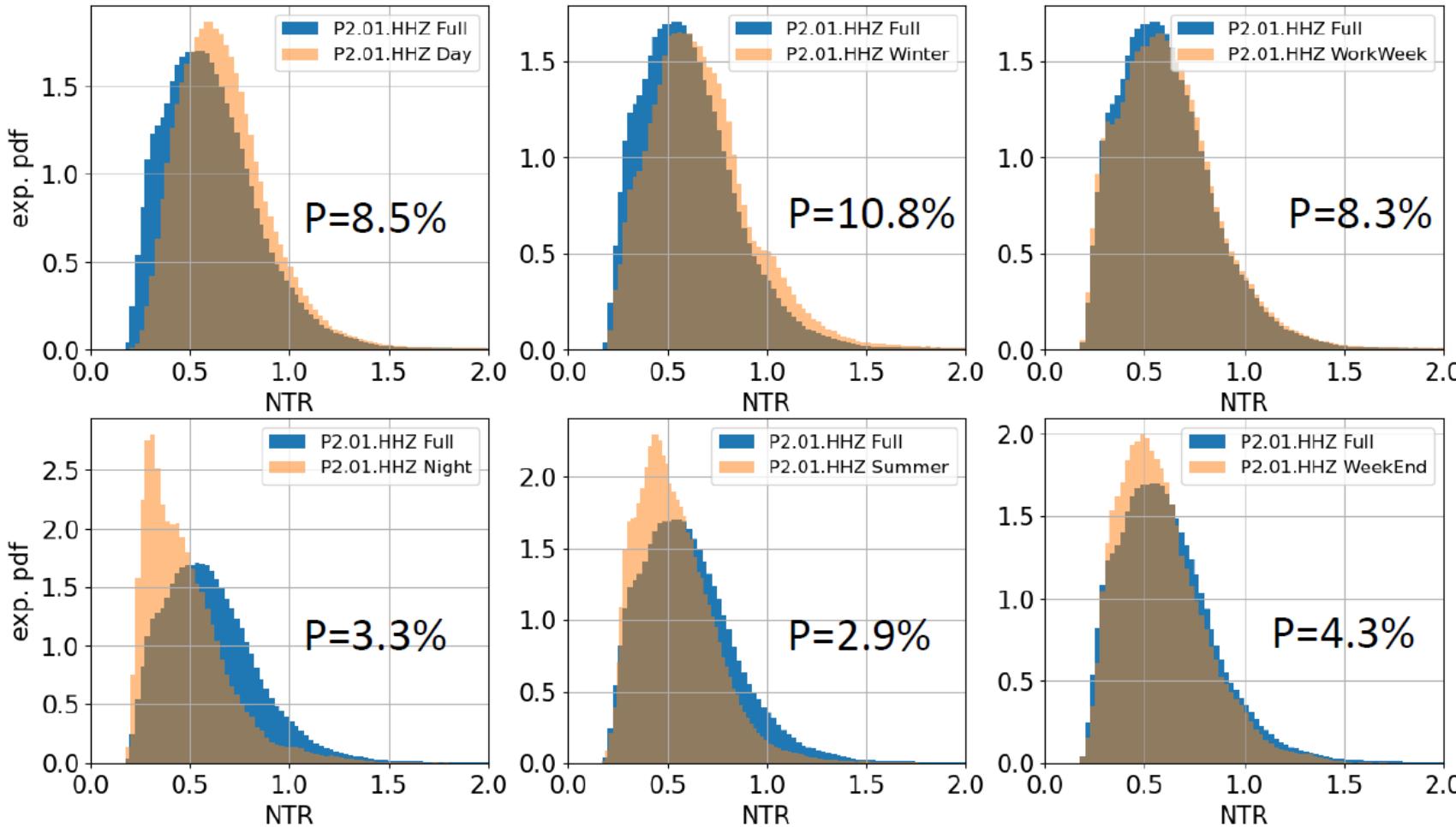
EMR - "Quiet" only during weekends and holidays



Sardinia - "Quiet" during the whole year



Seismic NN glitches in ET LF band



Defining the Noise-to-Target Ratio of the Newtonian Noise in 1 minute window (\sim 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

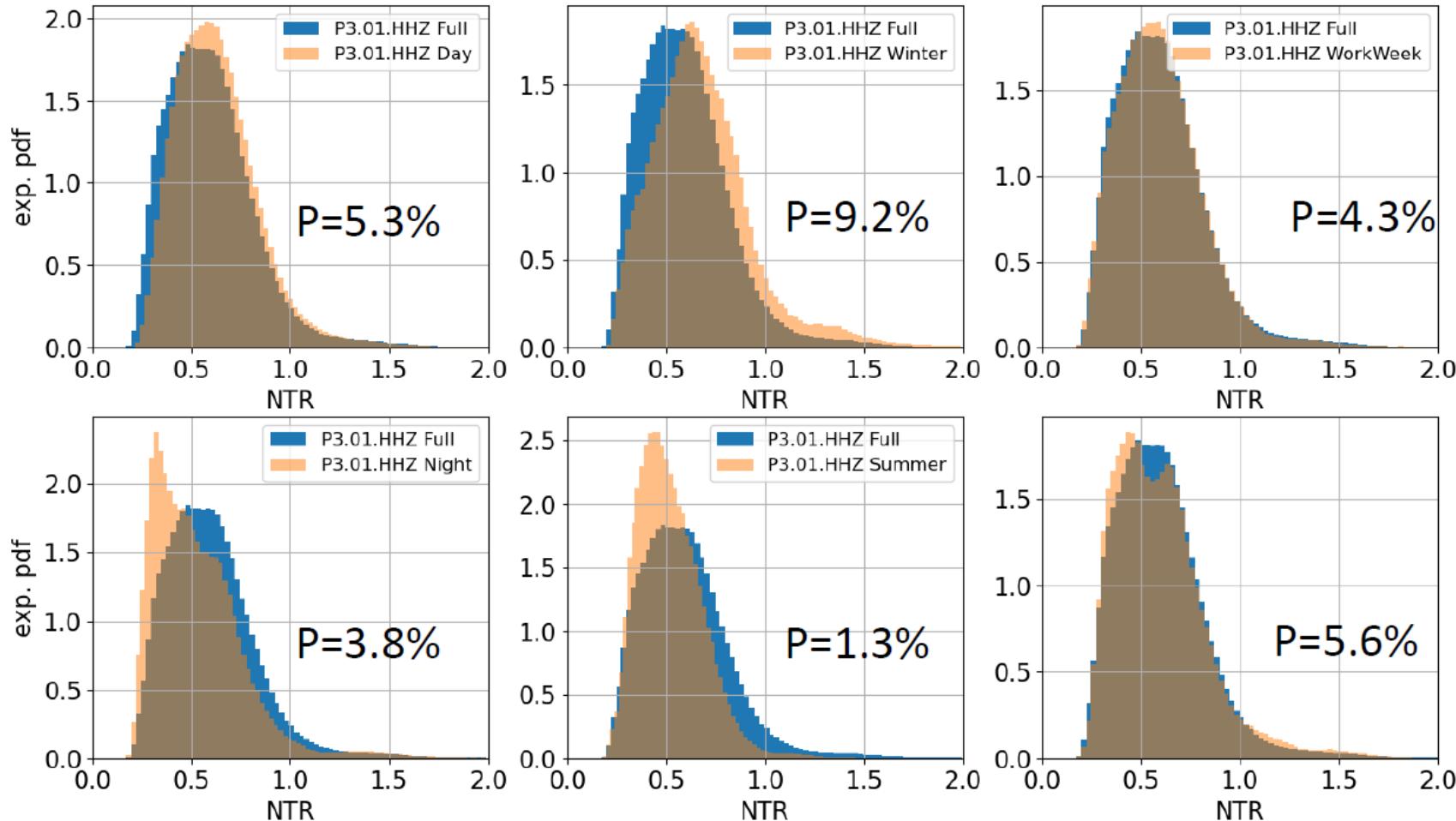
Over one year (2022) of data

**P(NRT>1, 2-10Hz)=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

Seismic NN glitches in ET LF band



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

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

\tilde{N} PSD of NN

S_h PSD of ET sensitivity

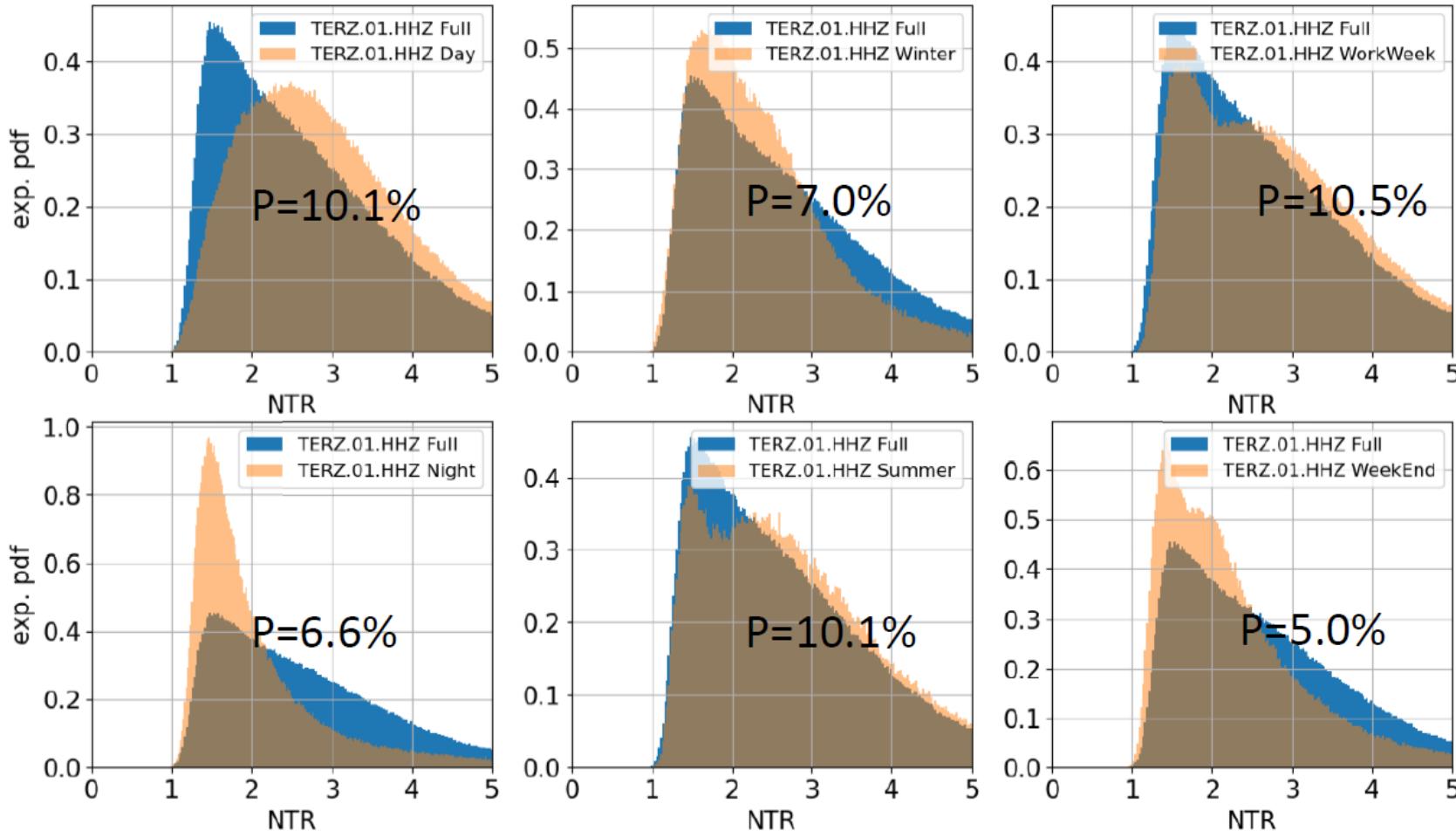
Over one year (2022) of data

$P(NRT > 1, 2-10Hz) = 4.7\%$
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

Seismic NN glitches in ET LF band



Defining the Noise-to-Target Ratio of the Newtonian Noise in 1 minute window (\sim 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

$P(NRT > 1, 2-10Hz) = 100\%$

$P(NRT > 5, 2-10Hz) = 8.9\%$

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

BH Seismometer installation

Trillium 120-SPH2

Broadband triaxial
seismometer

Sensor self-noise
DAQ 40V self-noise
DAQ 1V (max gain)
self-noise

