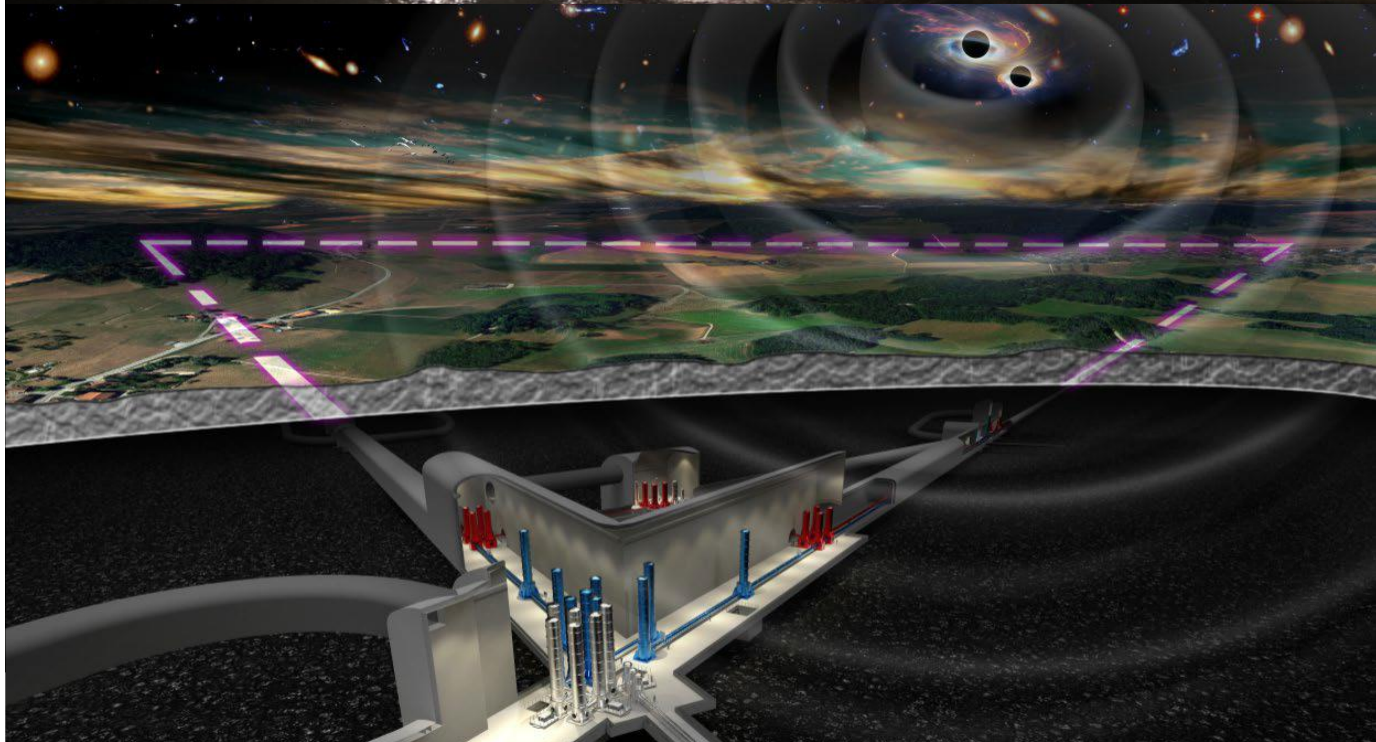
g2net WG3 training school on Machine learning for advanced control techniques

Einstein Telescope site characterisation

measures and their impact on the third generation GW detectors

Luca Naticchioni (INFN Roma)

Istituto Nazionale di Fisica Nucleare



Outline

This lecture is composed of two parts:

I. Presentation: *Einstein Telescope site characterisation - measures and their impact on the third generation GW detectors*.

II. Exercitation with seismic data from surface and underground stations.

Outline

Part I summary:

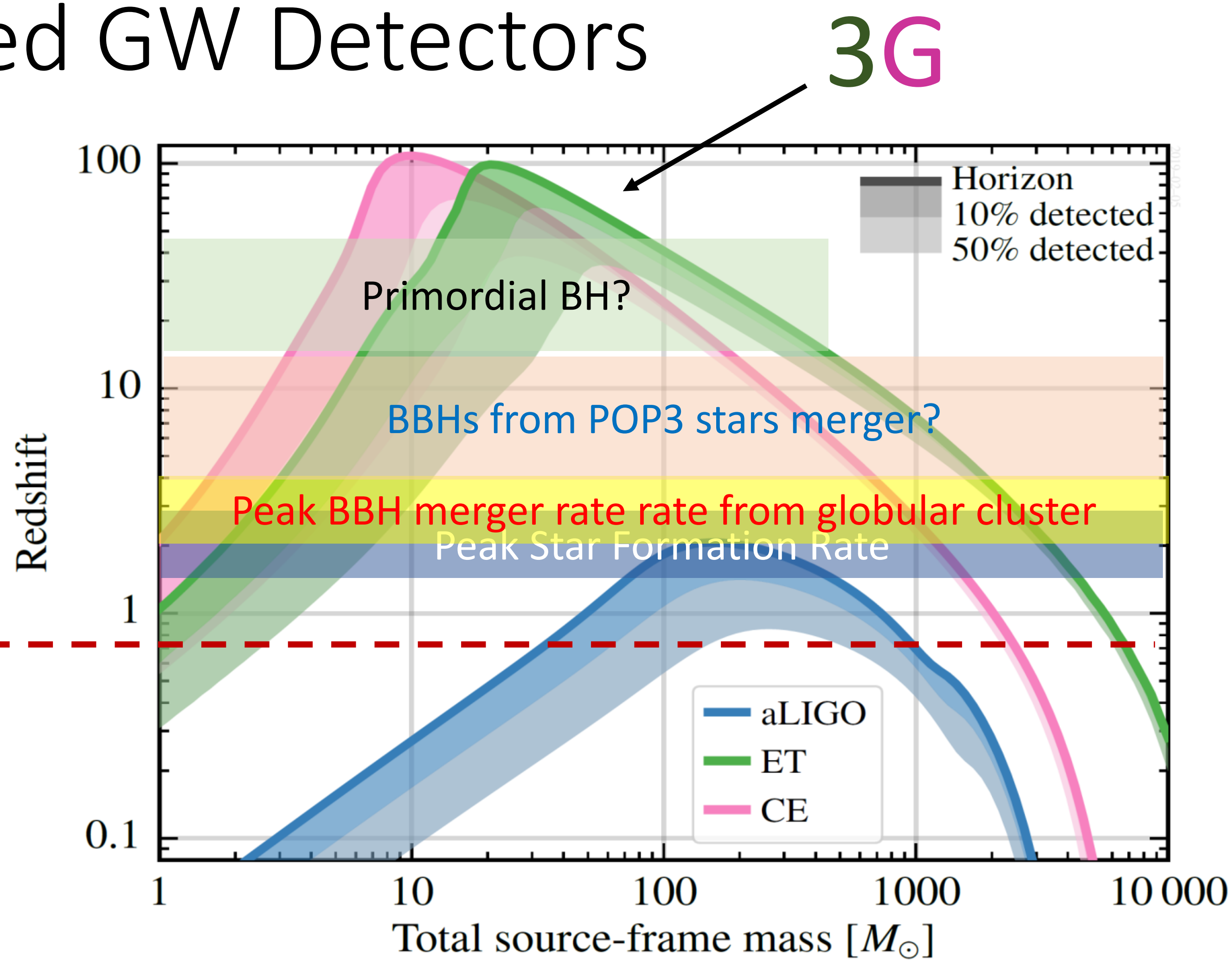
- ❑ **Introduction: The Einstein Telescope project**
- ❑ Environmental sources of noise vs ET sensitivity
- ❑ Site selection criteria
- ❑ EUregio Meuse-Rhine candidate site
- ❑ Sardinia candidate site
- ❑ A practical example: site characterisation activities in Sardinia
- ❑ Seismic noise analysis

Where we are with Advanced GW Detectors

- 2nd generation GW detectors will explore local Universe, initiating the precision GW astronomy, but to have *cosmological* investigations a factor of 10 improvement in terms detection distance is needed

- Farther event in GWTC-2 are at $z \approx 0.71$

- 3G ground-based detectors will be required to access the high redshift Universe



Detection Range of GWD

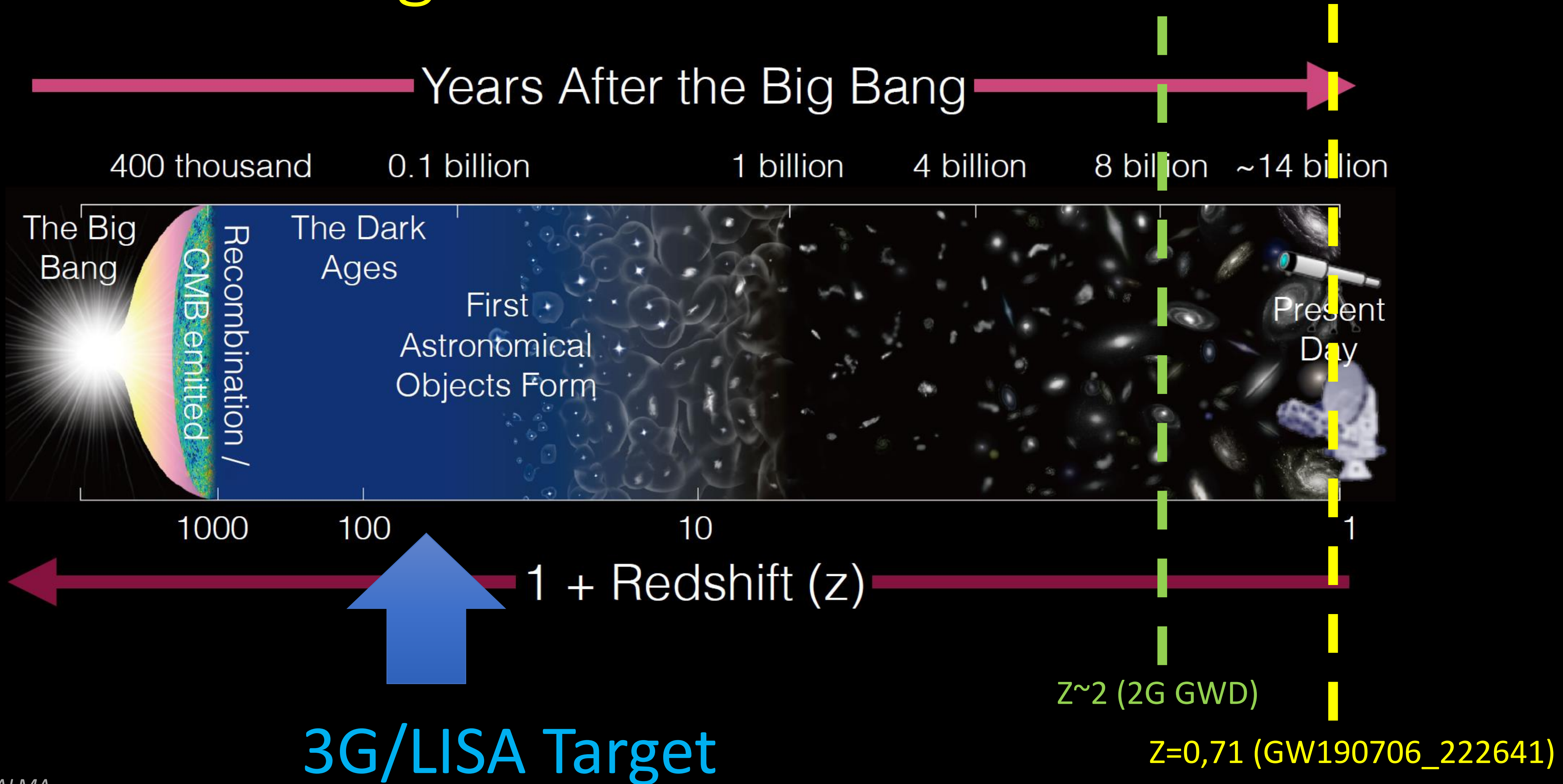
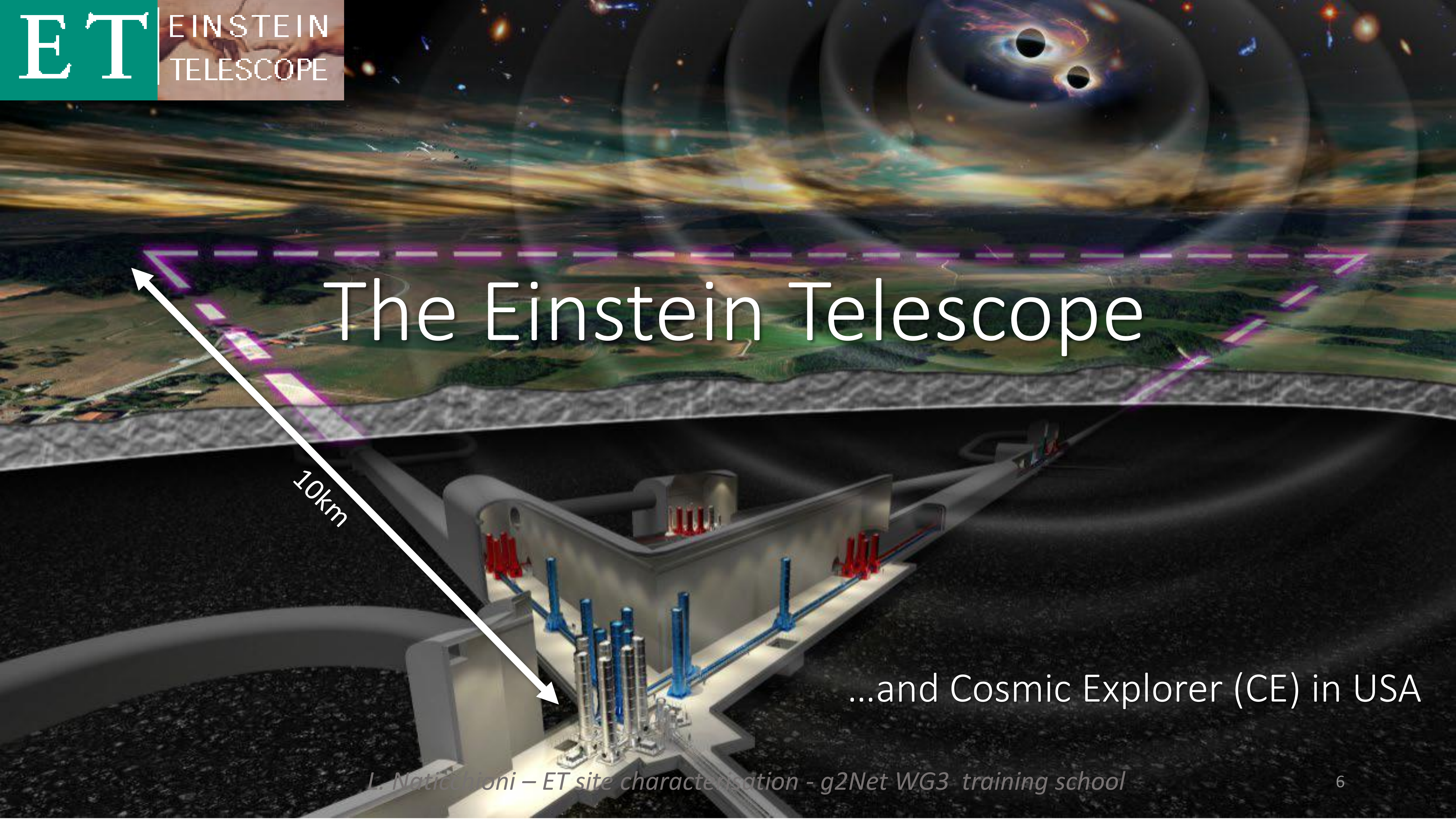


Image credit: NAOJ/ALMA
http://alma.mtk.nao.ac.jp/

The Einstein Telescope



...and Cosmic Explorer (CE) in USA

Einstein Telescope

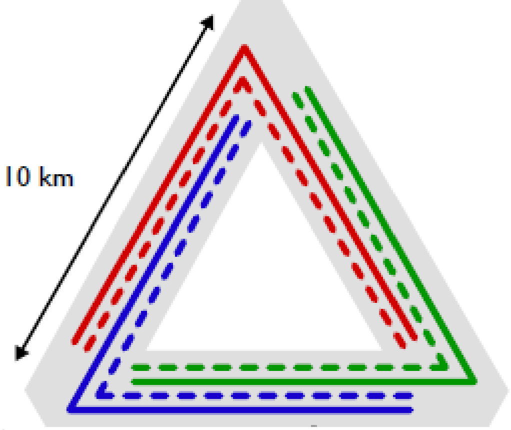
- ET is a **3G** new GW **observatory** in Europe

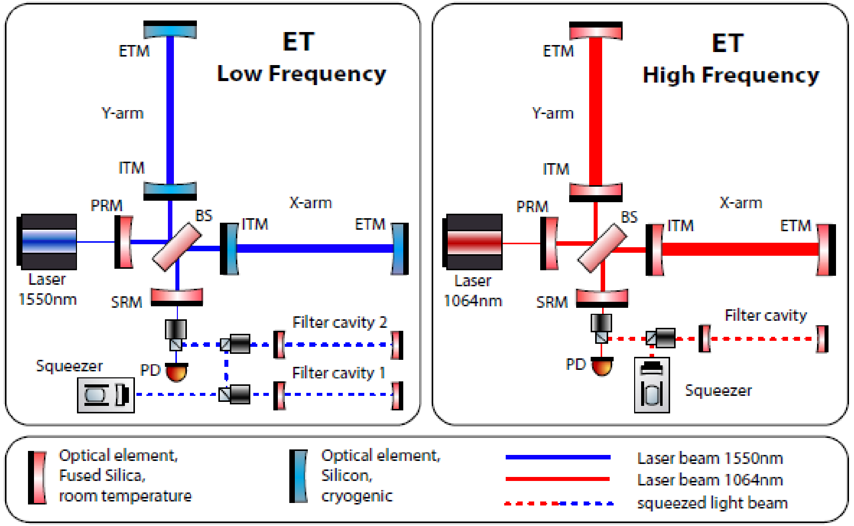
ET EINSTEIN TELESCOPE

- **3G**:
  - Sensitivity a factor 10 better than 2G (advanced) detectors
  - 50-years lifetime infrastructure (→compliant with the upgrades of the hosted detectors)
- **Observatory**:
  - *broadband*, focused to *low frequency* (few Hz)
  - Capability to work *alone* (depending on international scenario)
    - *Localisation* capability (limited if alone)
    - *Polarisation* discrimination (→triangle configuration)
    - High *duty cycle* (→redundancy)

Einstein Telescope

- ET is a **3G** new GW **observatory** in Europe



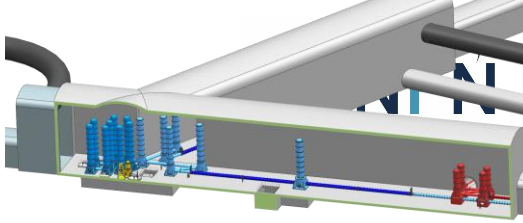


- Triangle configuration: 3 detectors
- Xylophone configuration: 6 interferometers (3HF + 3LF)
- Interferometer orientations for both polarisations
- Co-aligned interferometers (→null streams)
- Redundancy for duty cycle
- Single infrastructure for cost efficiency
- **Underground** and **cryogenic** (LF)

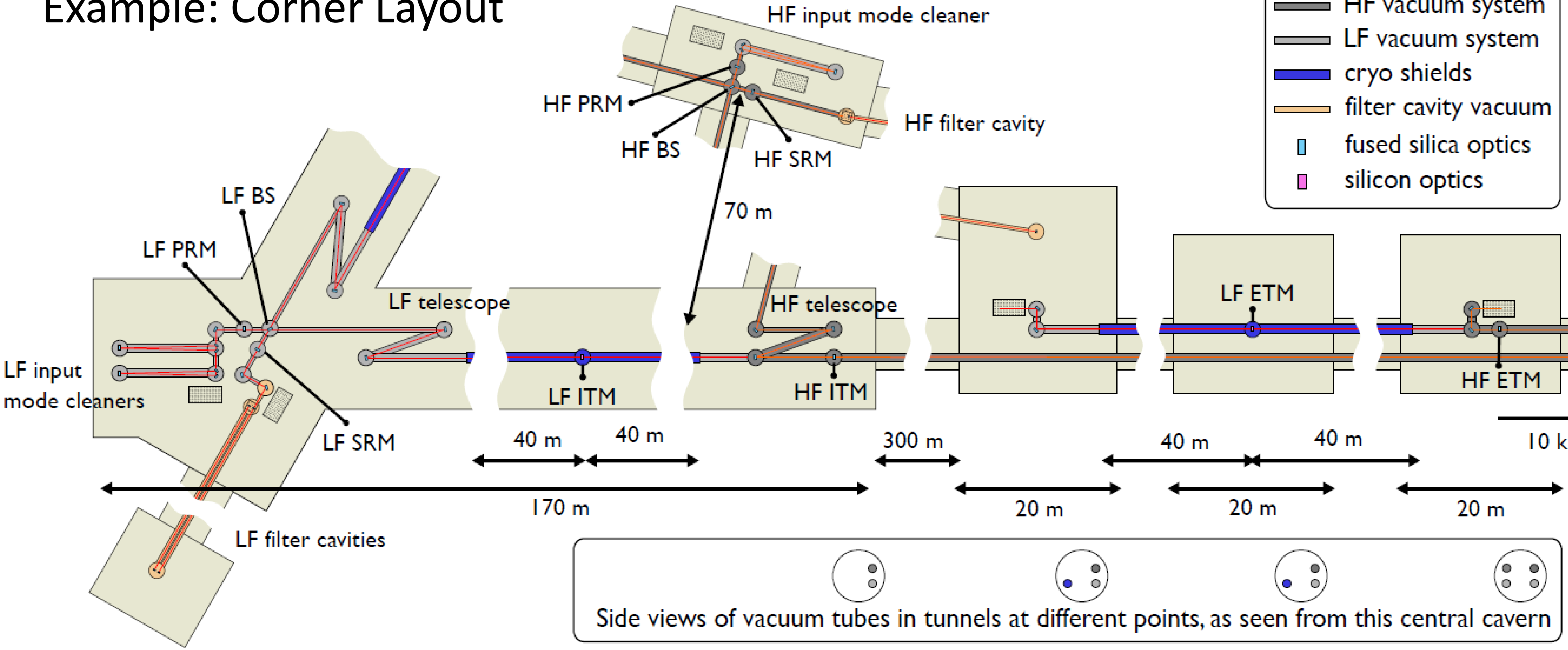
→ tomorrow's lecture by S. Hild!

ET Design

…quite complicated wrt current generation GWDs



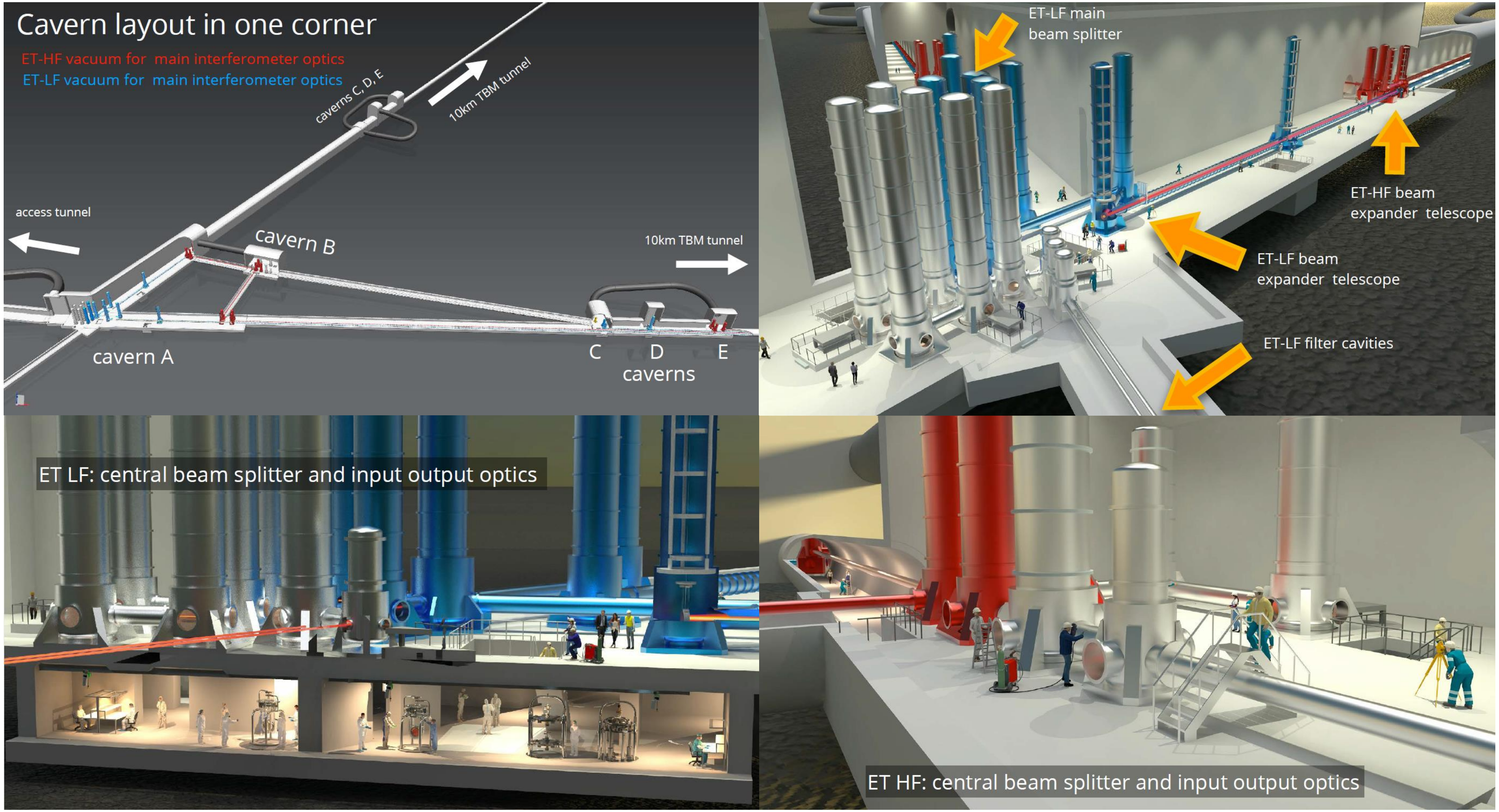
Example: Corner Layout



Credit: A.Freise, 2020 XI ET Symposium

ET Design

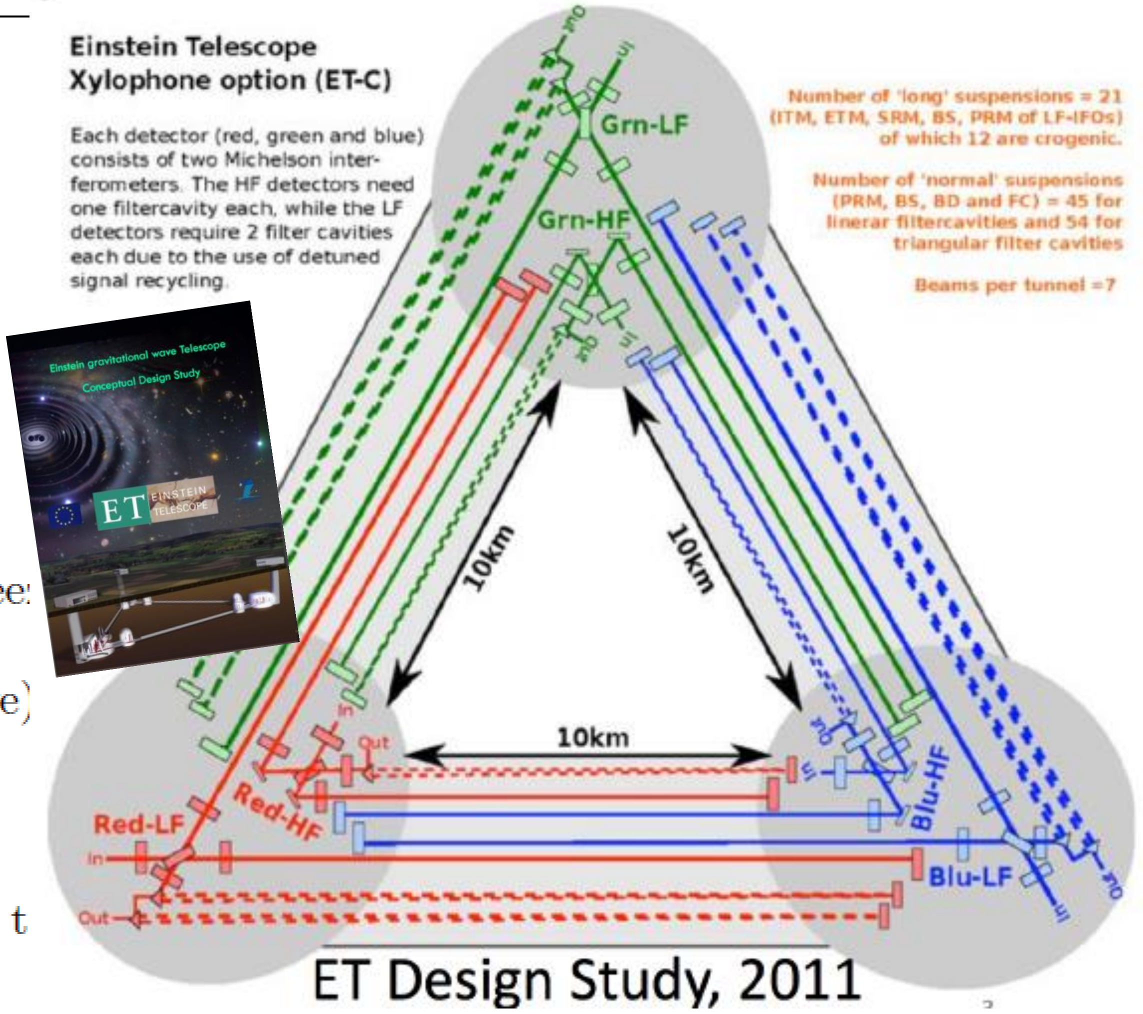
…quite complicated wrt current generation GWDs



Credit: A.Freise, 2020 XI ET Symposium

ET Design

Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ T
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squee:
Filter cavities	1×10 km	2×10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m t
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	none

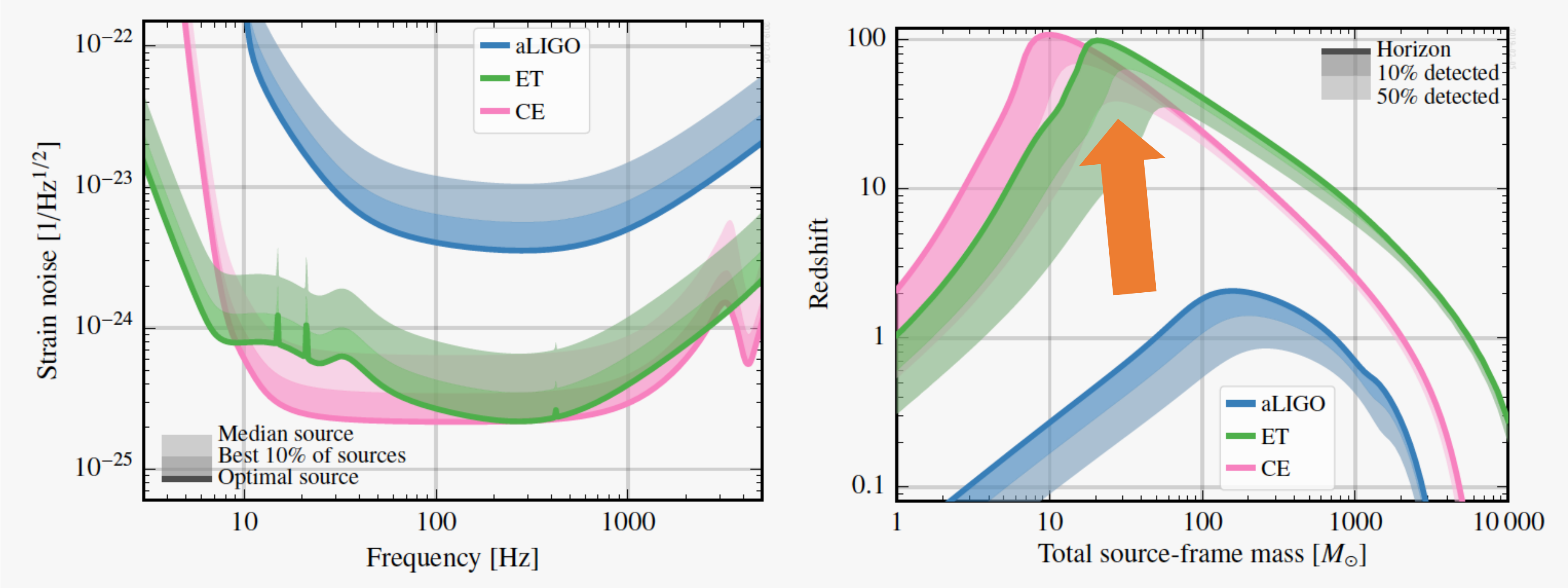


Why we need 3G GW observatory?

- To observe Merging Black Holes **throughout the whole universe** and reconstruct **BH demography**
- To explore **new physics in gravity** and fundamental properties of **compact objects**
- To study the **properties of the hottest matter** in the universe
- To investigate the connection between **high energy processes** in radiation/particle and gravitation
- To investigate **primeval universe** and connections with particle physics
- To investigate the **Dark Universe** (95%)

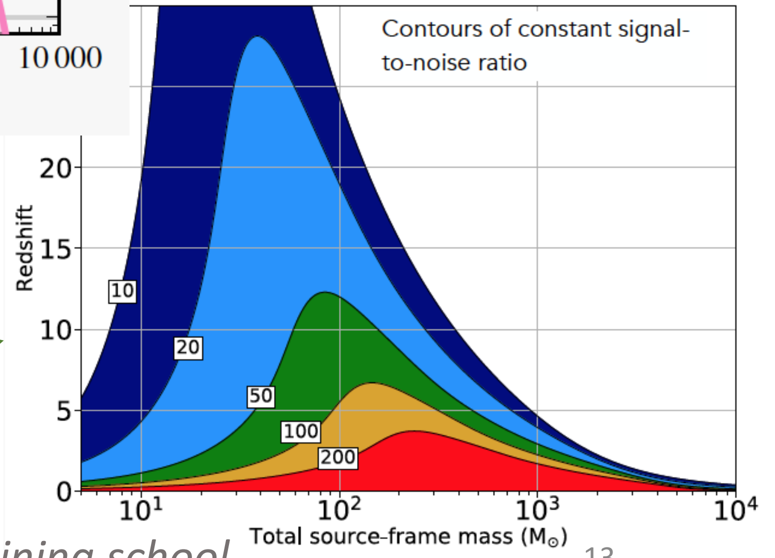
ET Sensitivity

Strain sensitivity *Coalescence of compact binary objects*



Our target: 10^5 to 10^6 events/year

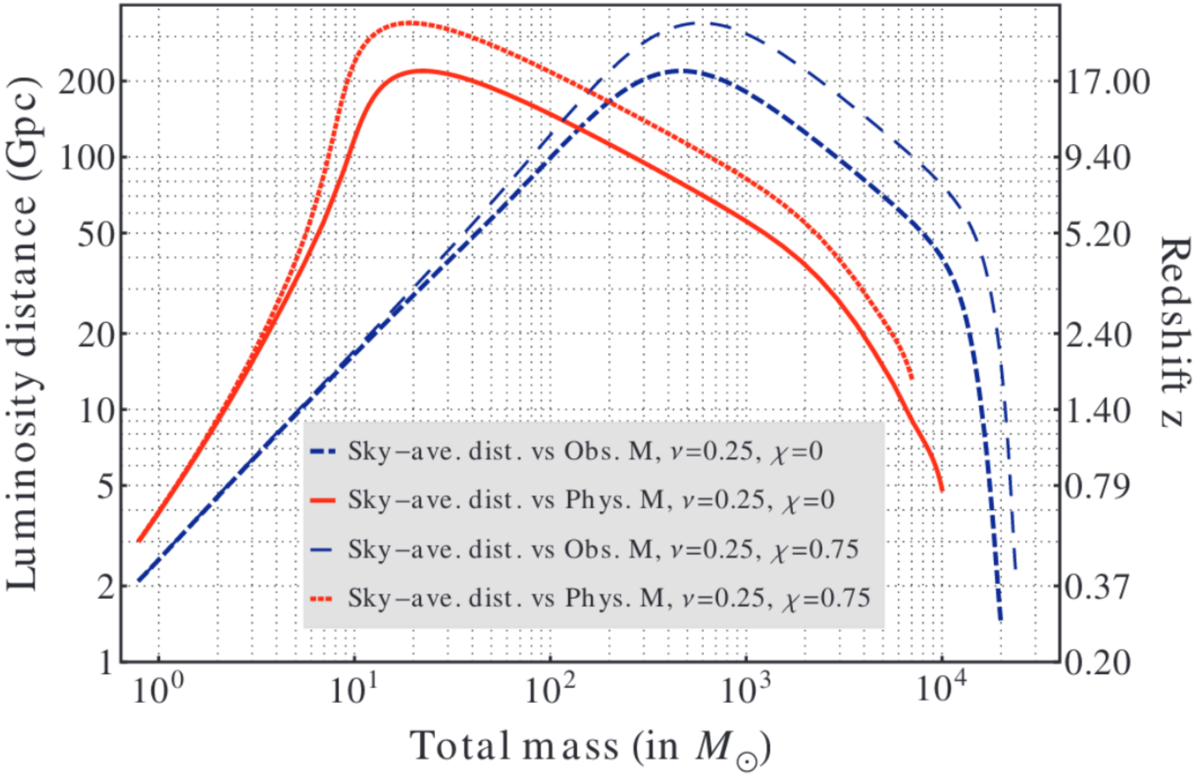
A network of 3 detectors (ET+CENorth+CESouth)



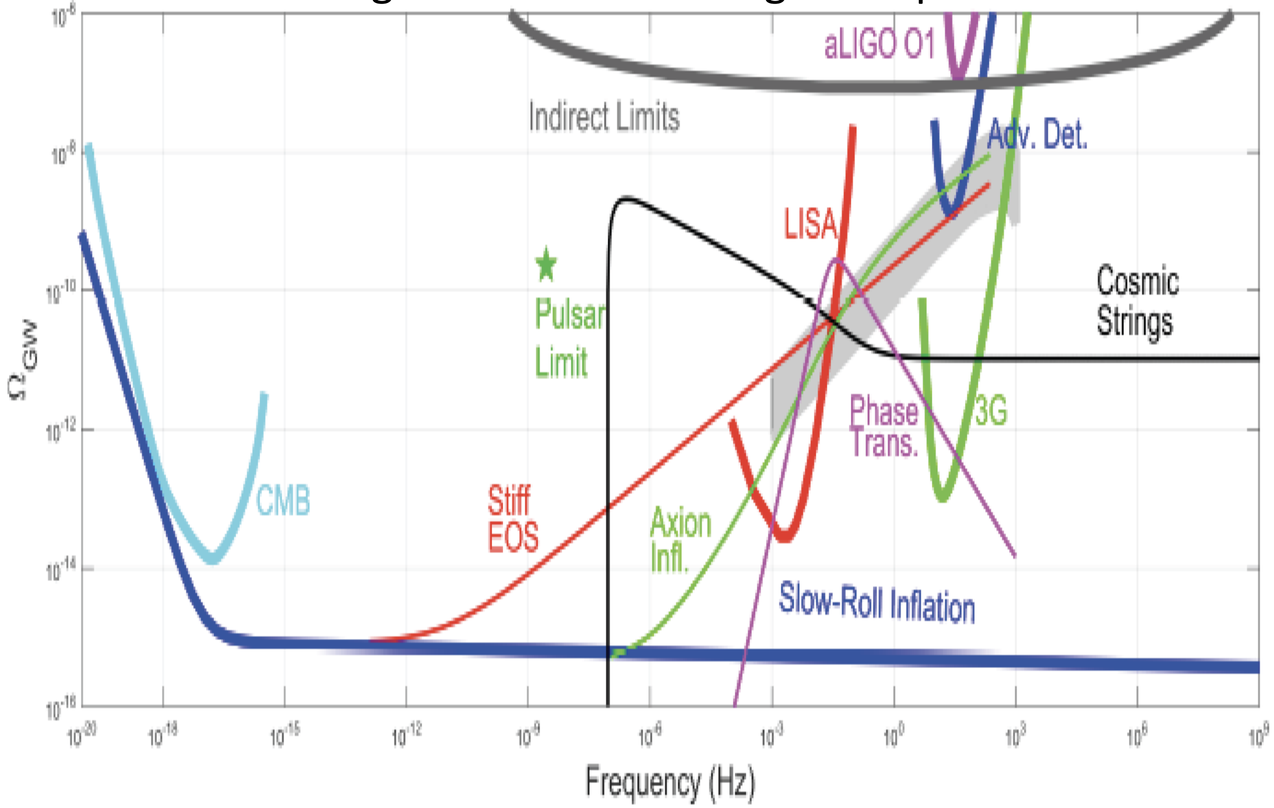
Einstein Telescope

- **Big challenges** in terms of **DA** and **computing**: longer signals, subtle physics effects, huge number of events, ‘noise’ foreground,…
- **But the reward will be impressive**

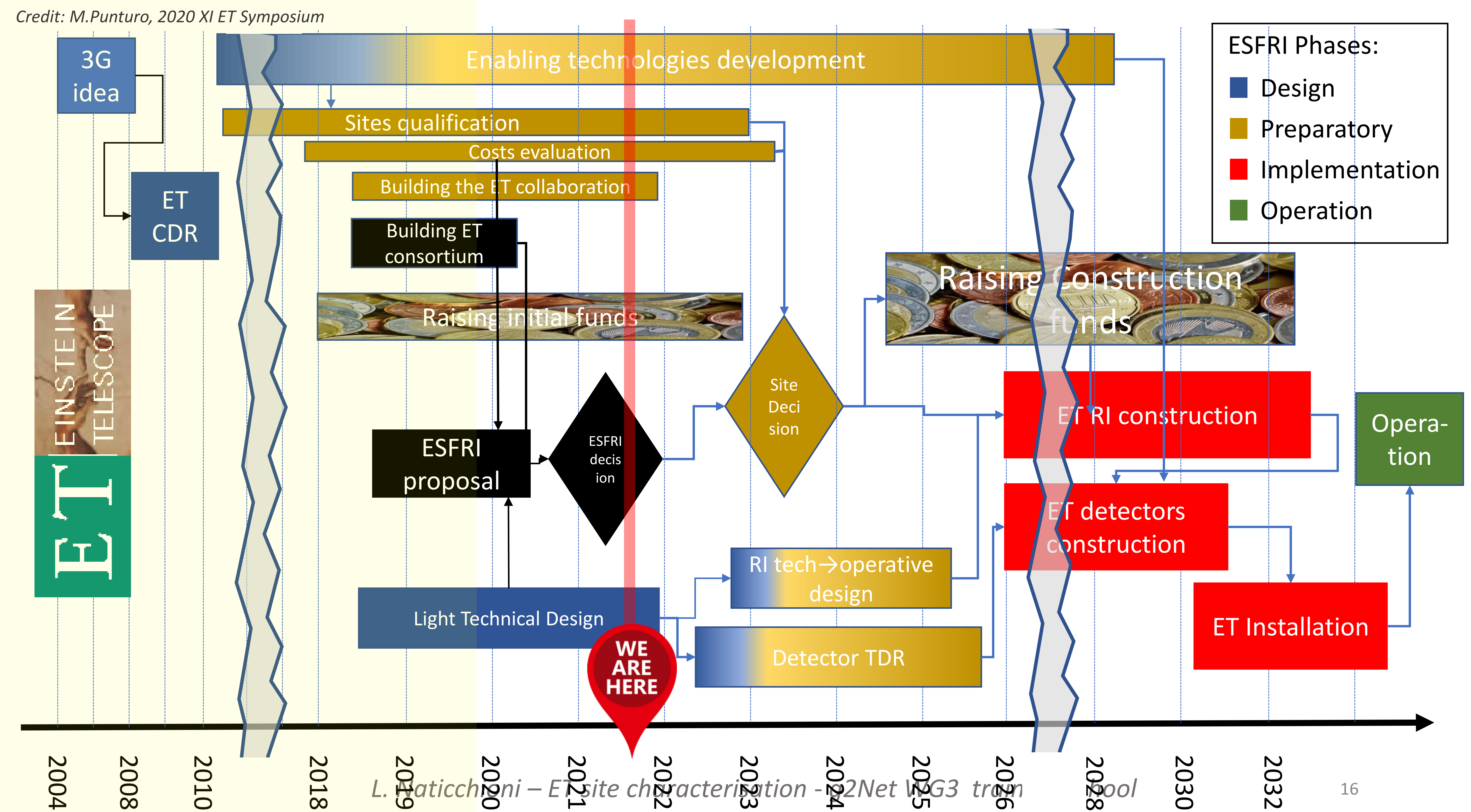
ET detectability distance of coalescing binaries



Cosmological stochastic background predictions



ET project status



Credit: M.Punturo, 2020 XI ET Symposium
3G idea
ET CDR
EINSTEIN TELESCOPE
ET
Enabling technologies development
Sites qualification
Costs evaluation
Building the ET collaboration
Building ET consortium
Raising initial funds
ESFRI proposal
ESFRI decision
Site Decision
Light Technical Design
WE ARE HERE
RI tech→operative design
Detector TDR
Raising Construction funds
ET RI construction
ET detectors construction
ET Installation
Opera-tion
ESFRI Phases:
Design
Preparatory
Implementation
Operation
2004
2008
2010
2018
2019
2020
2021
2022
2023
2024
2025
2026
2028
2030
2032

Building ET

- A key step to enter in a new phase of the ET project has been the preparation and the submission of the ET proposal to the "2021 update of the ESFRI* roadmap"
  - Prepared by the ET steering committee
  - It allowed to focalise the science, the design, the timeline, the cost and the organisation of the project
- Updated science case
- Updated design of the ET infrastructure
- New timeline
- Updated cost evaluation
- Evaluation of the social and economic impact
- A teams of European governments supporting ET
- A large consortium of institutions promoting the ET project

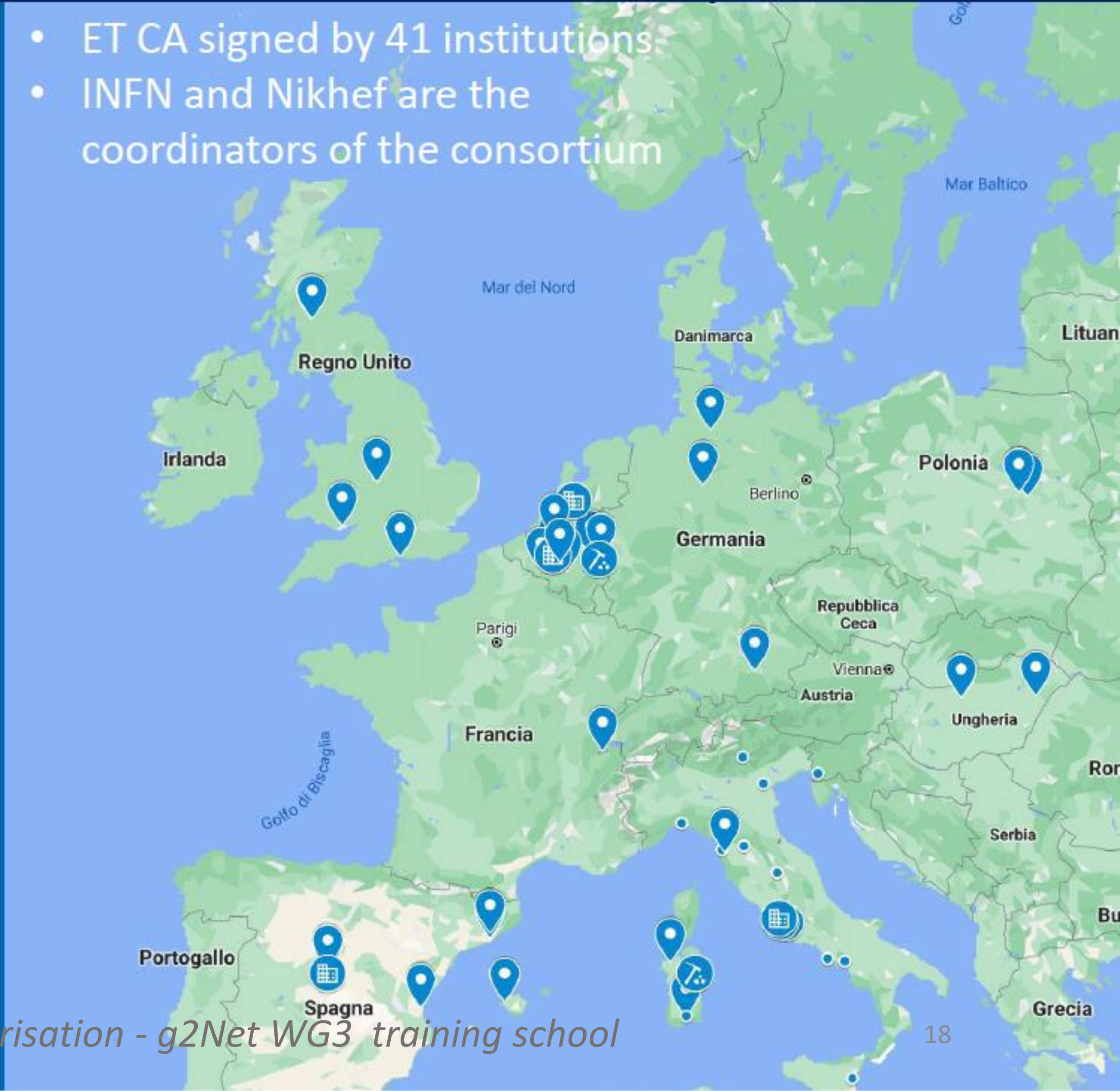
*__ESFRI__: European Strategy Forum on Research Infrastructures

ESFRI Roadmap

Proposal submitted by:

- **Italy** (Lead Country)
- Netherlands
- Belgium
- Spain
- Poland

- ET CA signed by 41 institutions.
- INFN and Nikhef are the coordinators of the consortium



Building ET

On June 30th 2021, **ET** was **adopted** into the **ESFRI roadmap**!

01 LUGLIO 2021

ET ED EUPRAXIA CON L'ITALIA CAPOFILA ENTRANO NELLA ROADMAP DI ESFRI

ET Einstein Telescope ed EuPRAXIA: due grandi infrastrutture di ricerca competitive a livello mondiale, rispettivamente nella ricerca sulle onde gravitazionali e nello sviluppo di futuri acceleratori di particelle al plasma. Sono questi i due progetti internazionali di cui l'INFN Istituto Nazionale di Fisica Nucleare è capofila, e che l'Italia attraverso il MUR Ministero dell'Università e della Ricerca ha candidato lo scorso settembre per la Roadmap 2021 di ESFRI European Strategy Forum on Research Infrastructure, il forum strategico europeo che individua le grandi infrastrutture di ricerca su cui investire a livello europeo. Dopo un lungo e accurato processo di valutazione dei progetti candidati, il 30 giugno, l'Assemblea di ESFRI ha approvato entrambi, ET ed EuPRAXIA, che entrano così nel novero delle grandi infrastrutture di ricerca su cui l'Europa punterà nel prossimo futuro.

"L'inclusione di ET ed EuPRAXIA nella Roadmap di ESFRI è un importante risultato che ne rafforza il valore strategico a livello europeo", commenta **Antonio Zoccoli, presidente dell'INFN**. "Le grandi infrastrutture di ricerca sono una risorsa per la scienza e la conoscenza, ma anche per lo sviluppo industriale, l'innovazione tecnologica, la crescita economica, culturale e sociale. Forti della leadership scientifica del nostro Paese a livello internazionale, metteremo il massimo impegno per il loro sviluppo, e per valorizzare la candidatura del sito italiano a ospitare ET, e siamo certi che con il sostegno del MUR, della Regione Sardegna, delle Istituzioni nazionali e locali, abbiamo ottime possibilità di raggiungere l'obiettivo, a beneficio del territorio e del Paese".

L'Italia, con la Sardegna, è uno dei due siti candidati a ospitare ET, e vi partecipa con l'INFN, l'INAF Istituto Nazionale di Astrofisica e l'INGV Istituto Italiano di Geofisica e Vulcanologia, e le Università di Sassari e Cagliari. La sede principale di EuPRAXIA, progetto cui il nostro Paese

Nikhef Menu Search

Einstein Telescope approved for ESFRI Roadmap 2021

1 July 2021

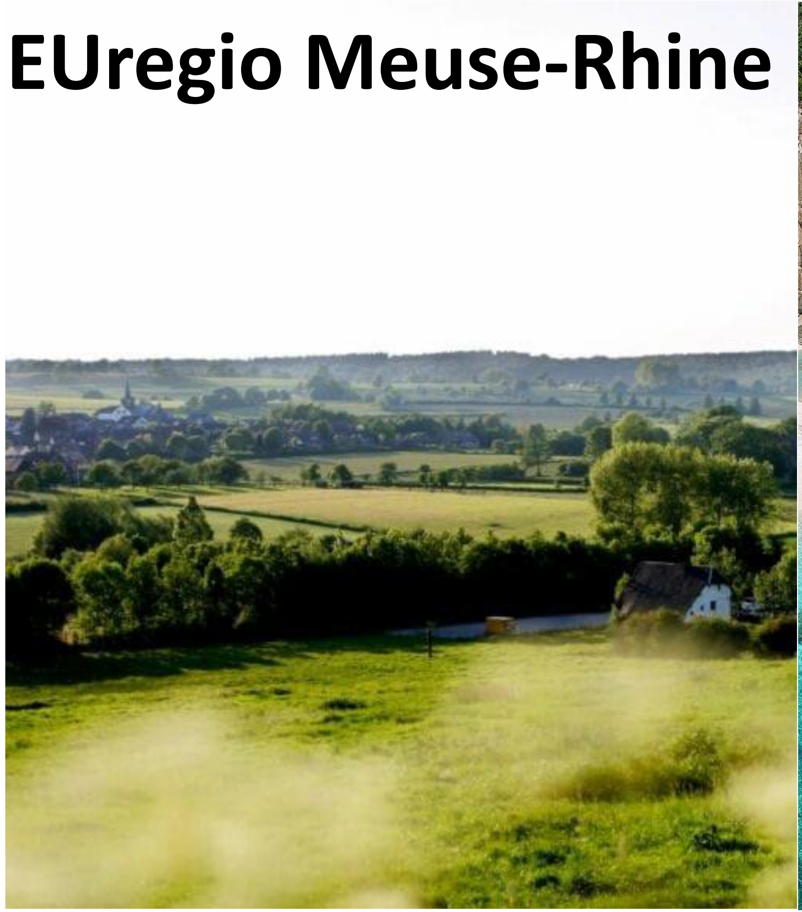
On June 30th, the European Strategy Forum on Research Infrastructures (ESFRI) decided to include the Einstein Telescope in the 2021 upgrade of its roadmap. This confirms the relevance of this major international project for a next generation gravitational waves observatory for the future of research infrastructures in Europe and gravitational wave research at a global level.

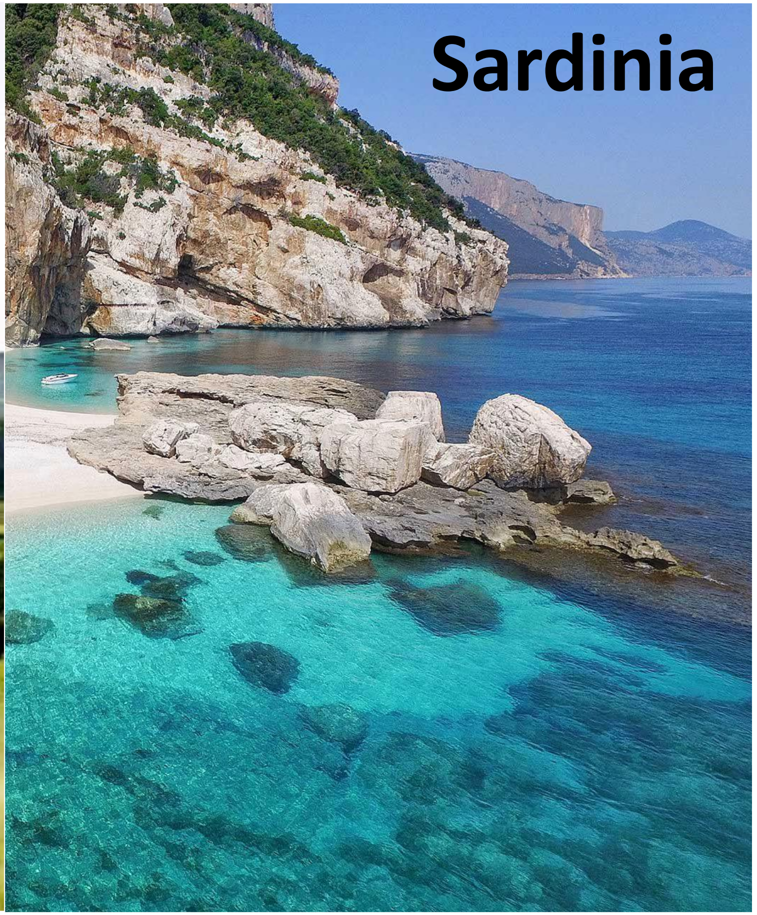
Building ET

On June 30th 2021, **ET** was **adopted** into the **ESFRI roadmap**!

- *Why it is so important for ET to be in the ESFRI roadmap?*
  - ESFRI has not funds
  - But to be in the ESFRI roadmap:
    - Is a quality stamp that certifies the readiness level of the project: it states the passage from the design phase to the preparatory phase
    - Allows to access a (small) financial support from the European Commission for the preparatory phase
    - Allows to access specific (and potentially large) national and regional funds in Europe
    - Facilitates the coordination of different European countries at government level targeting the realization of the infrastructure

Which site?





We'll go back to the site selection issue in the next sections

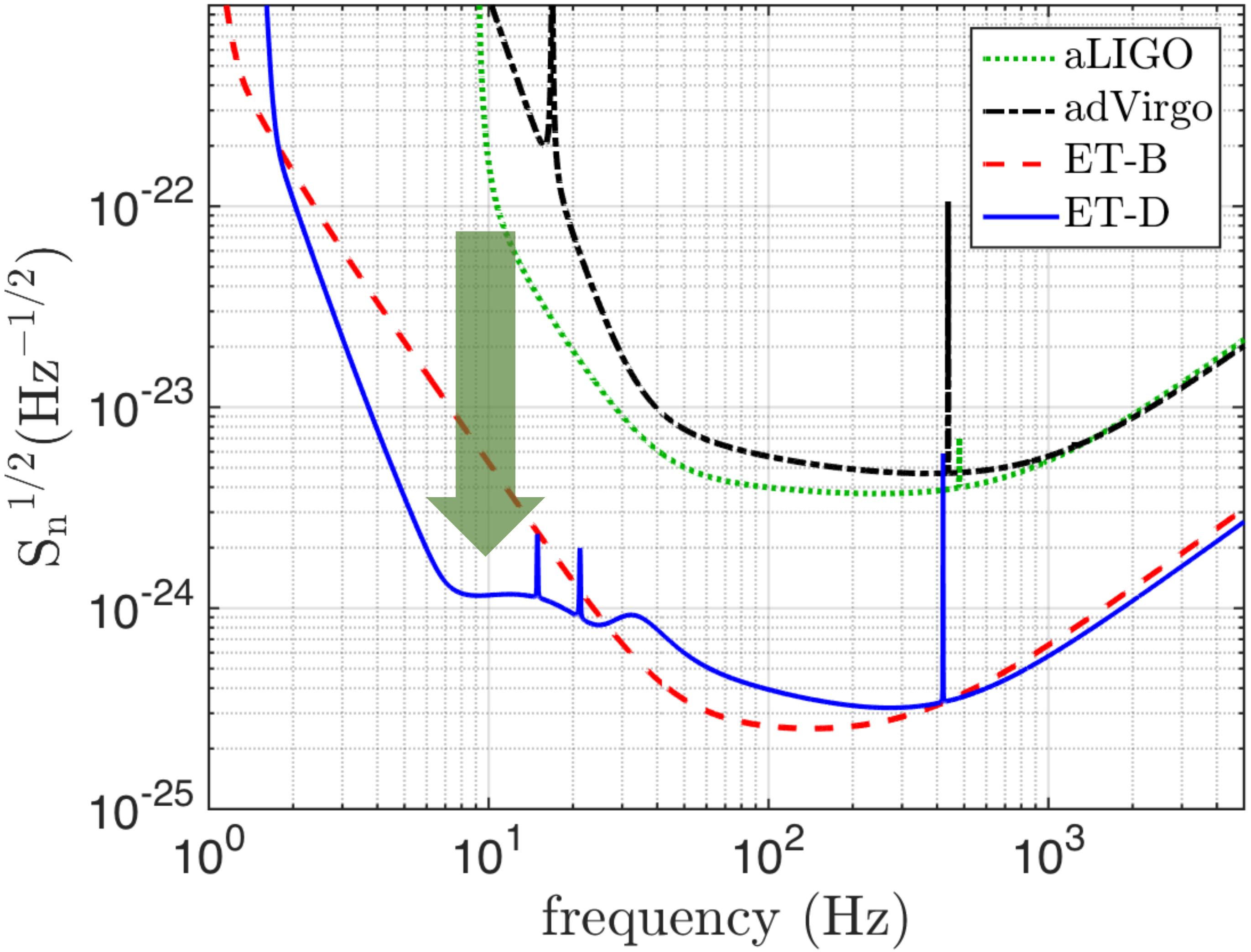
Outline

Part I summary:

- ❑ Introduction: The Einstein Telescope project
- ❑ **Environmental sources of noise vs ET sensitivity**
- ❑ Site selection criteria
- ❑ Euregio Meuse-Rhine candidate site
- ❑ Sardinia candidate site
- ❑ A practical example: site characterisation activities in Sardinia
- ❑ Seismic noise analysis

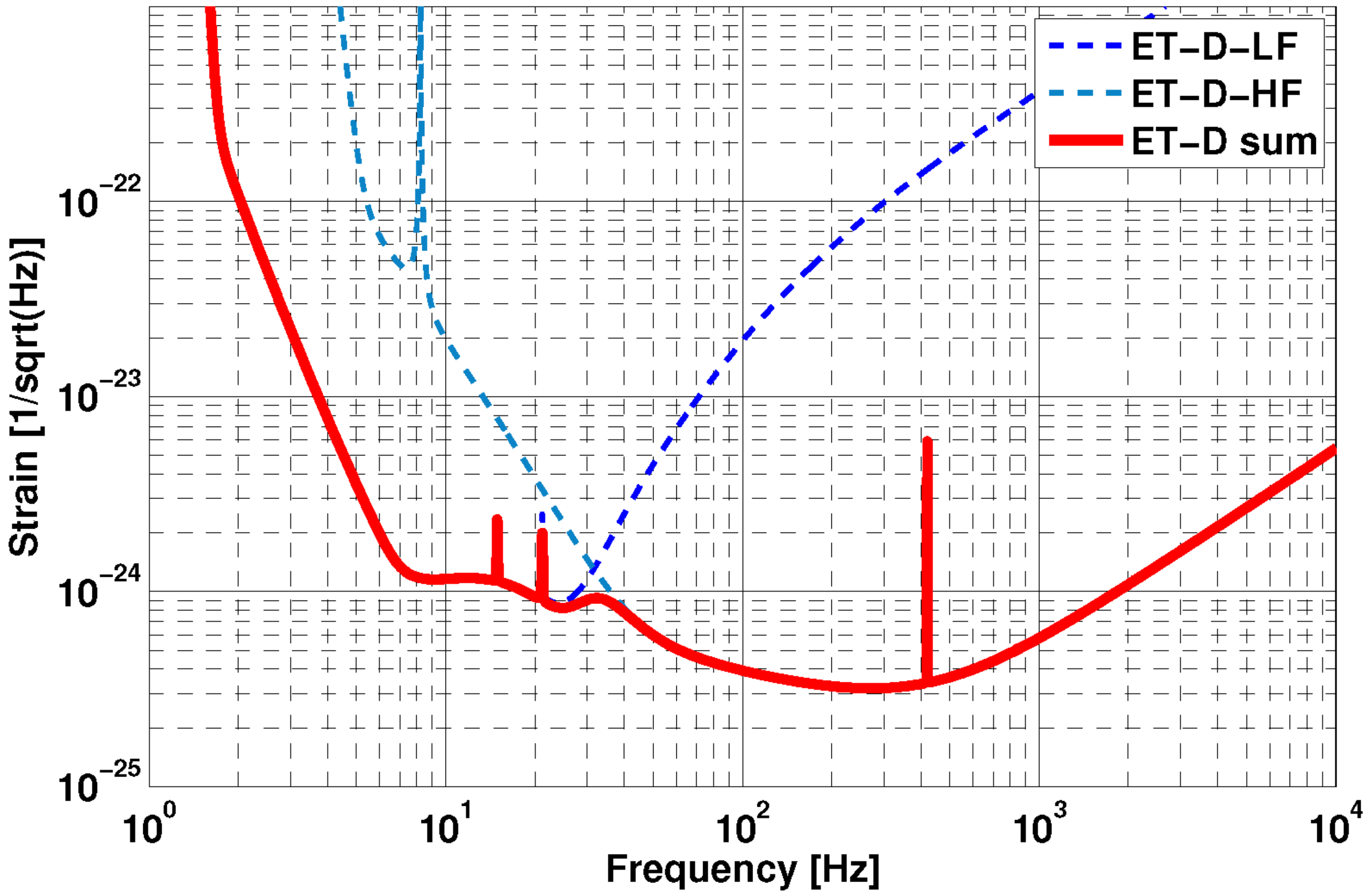
ET Sensitivity

The target is to improve of a factor 10 the advanced detector sensitivity:



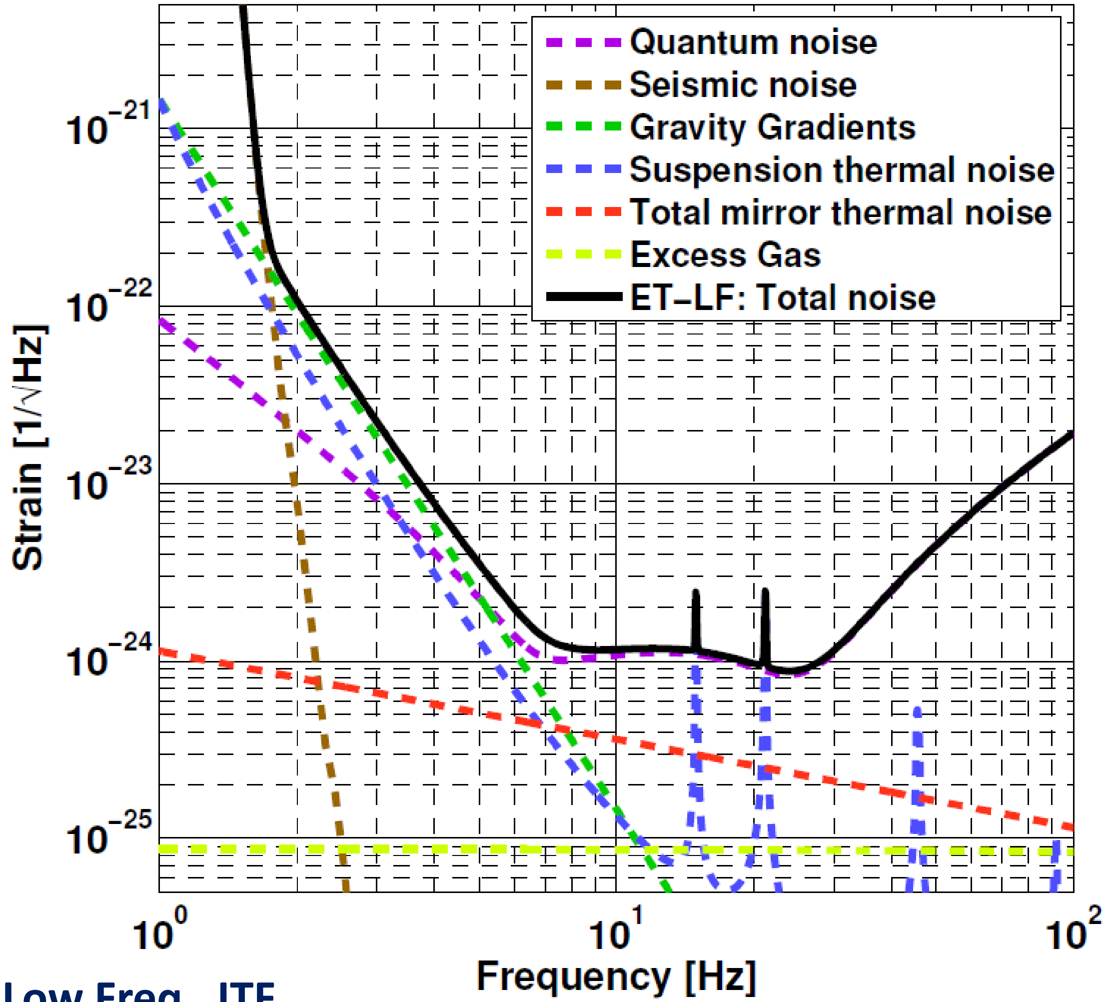
Sources of noise in ET

The several sources of noise affecting the Interferometer define its sensitivity curve:

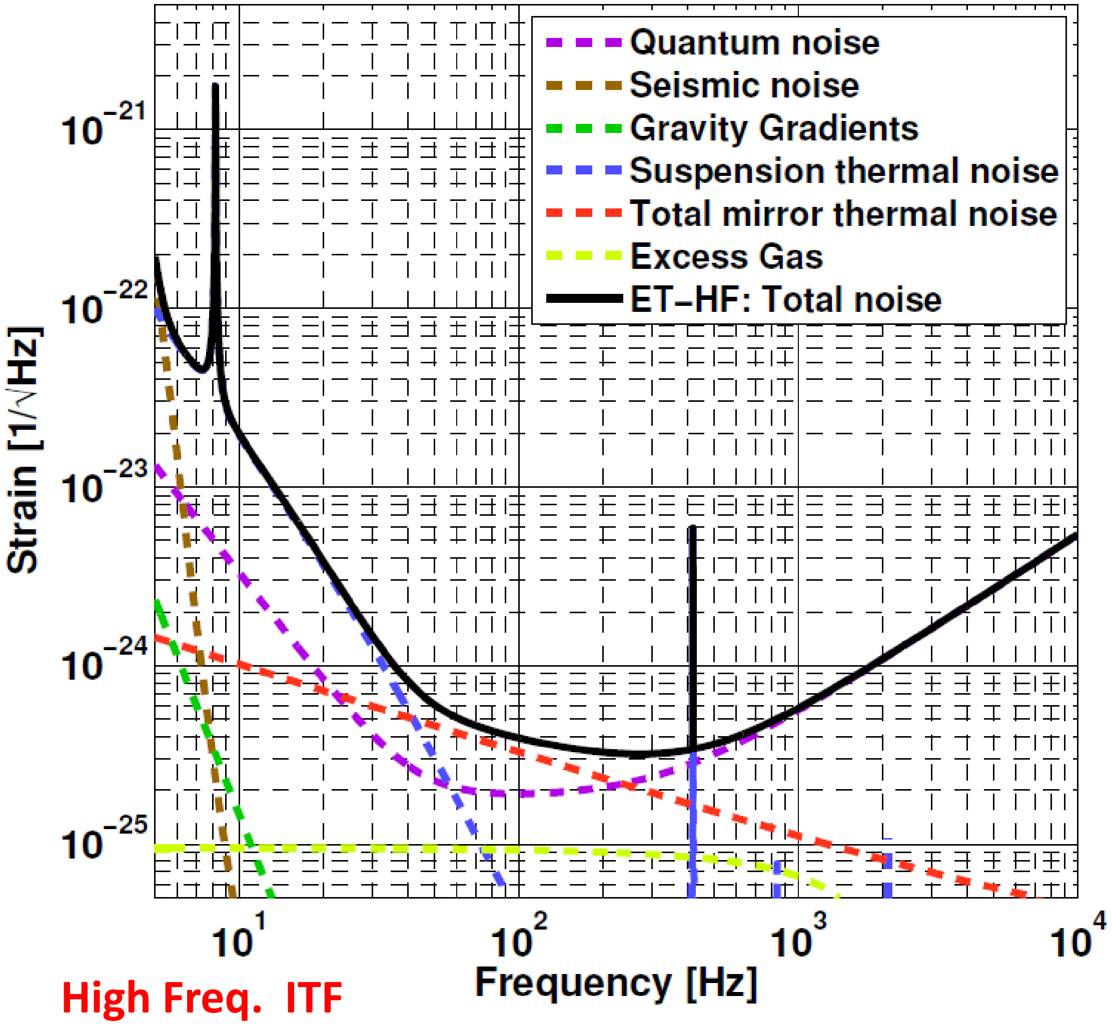


Sources of noise in ET

The several sources of noise affecting the Interferometer define its sensitivity curve:



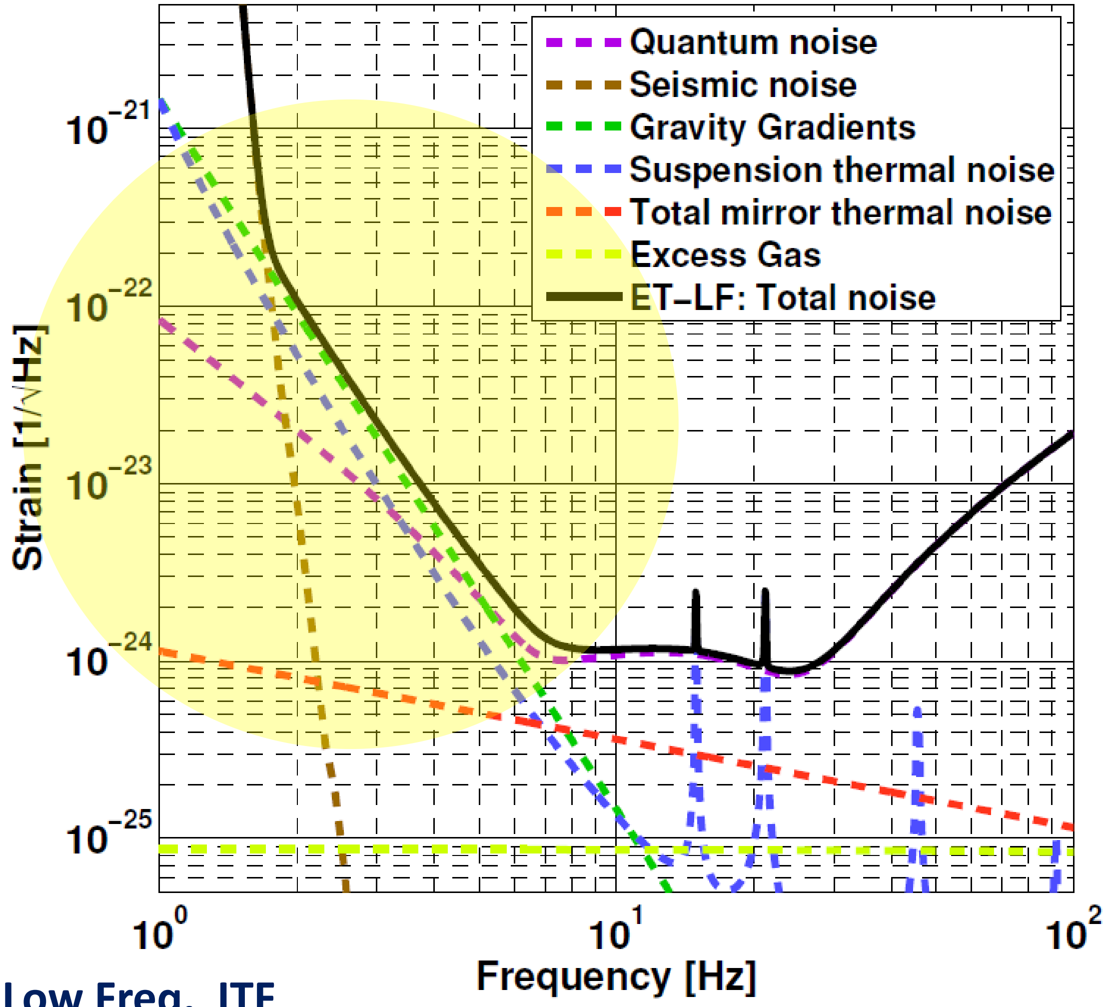
Low Freq. ITF



High Freq. ITF

Sources of noise in ET

The several sources of noise affecting the Interferometer define its sensitivity curve:



Low Freq. ITF

- at low frequency **seismic** and **Newtonian Noise** (NN) are the main limitations to the detector sensitivity, in particular in the case of the LF ITF.
- an important component of NN is produced by **seismic waves** (body P-waves and surface Rayleigh waves)

→ today's lecture by F. Badaracco!

- another component of NN is related to **air pressure fluctuations** → acoustic
- at low frequencies also the **magnetic noise** may spoil the detector sensitivity

Seismic noise

- **The Background Seismic Noise** is generated by natural sources and human activities (*cultural* or *anthropic seismic noise*)

  - It can be described as a quasi-stationary stochastic process

  - At low frequency (< 1 *Hz*) is generated by non-local sources (e.g. microseisms from oceans and seas, atmospheric pressure, tides); high coherence (>70%)

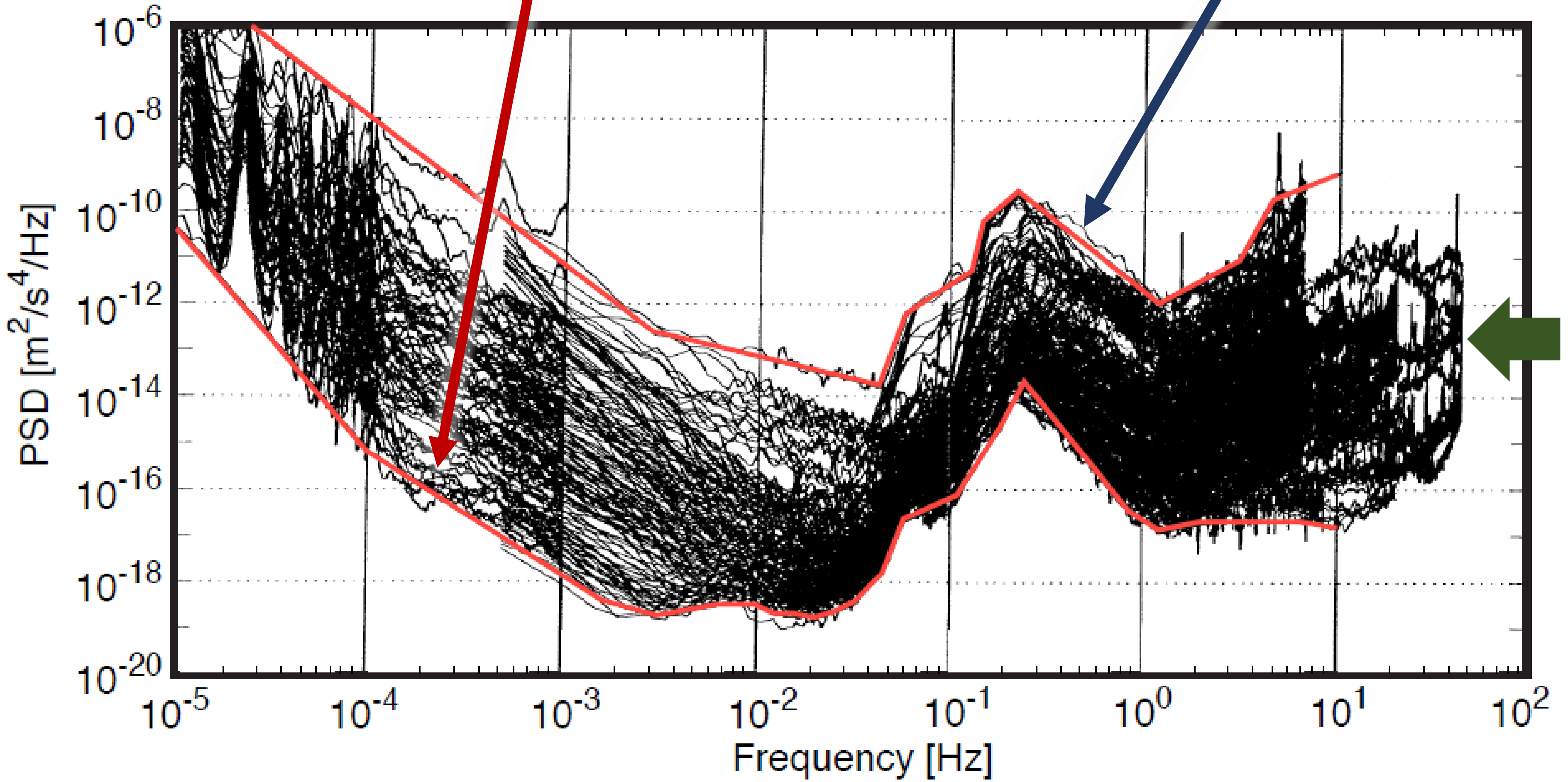
  - Around 1 *Hz* the sources are local (e.g. weather: wind, rain…)

  - At high frequency (> 1 *Hz*) cultural noise; low coherence (>30%)

  - Empirical law: $\tilde{x}_s(f) \approx \frac{10^{-7}}{f^2} \frac{m}{\sqrt{Hz}}$

Seismic noise

- A standard reference of the seismic background on Earth is given by the **Person's models**: the New Low Noise Model (NLNM) and the New High Noise Model (NHNM):



PSDs from a worldwide network during several years

Seismic noise

Seismic waves can be:

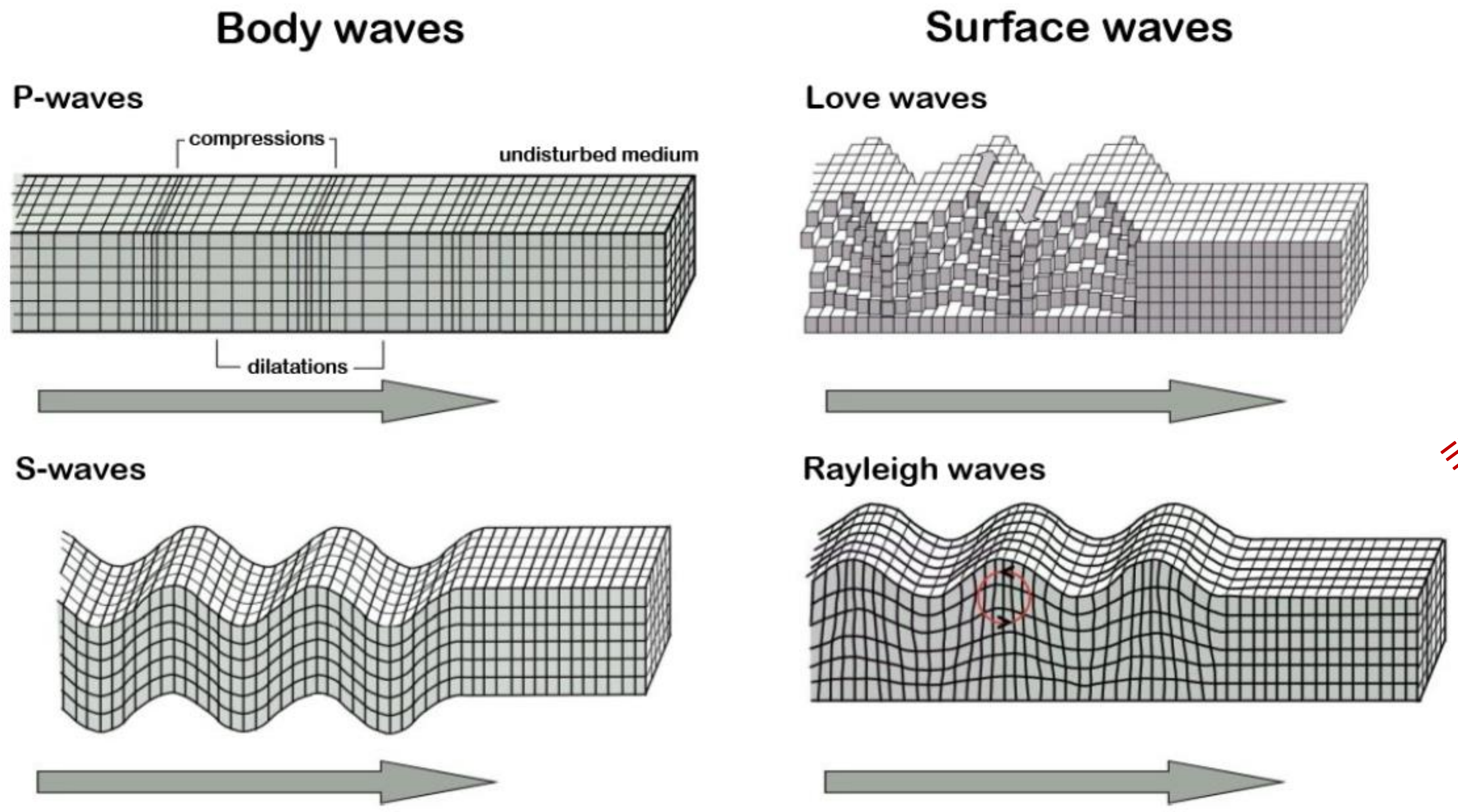
- **Body Waves**: propagating in the interior of the Earth, smaller amplitudes and wavelengths than surface waves, but travelling at higher speeds
  - **Primary** (**P-Waves**): longitudinal particle motion along propagation direction, *compressional* waves, fastest waves
  - **Secondary** (**S-Waves**): shear waves, transversal particle motion, slower than P-Waves

- **Surface Waves**: interaction of P- and S- waves, propagation confined in the superficial layers of Earth's crust. Lower frequencies and larger amplitudes than body waves
  - **Love Waves**: horizontal-polarized S-Waves, not compressional
  - **Rayleigh Waves**: particle motion is a retrograde rolling: superposition of vertical-polarized S-Waves and P-Waves, *compressional*

Seismic noise

Seismic waves can be:

Compressional: important for NN

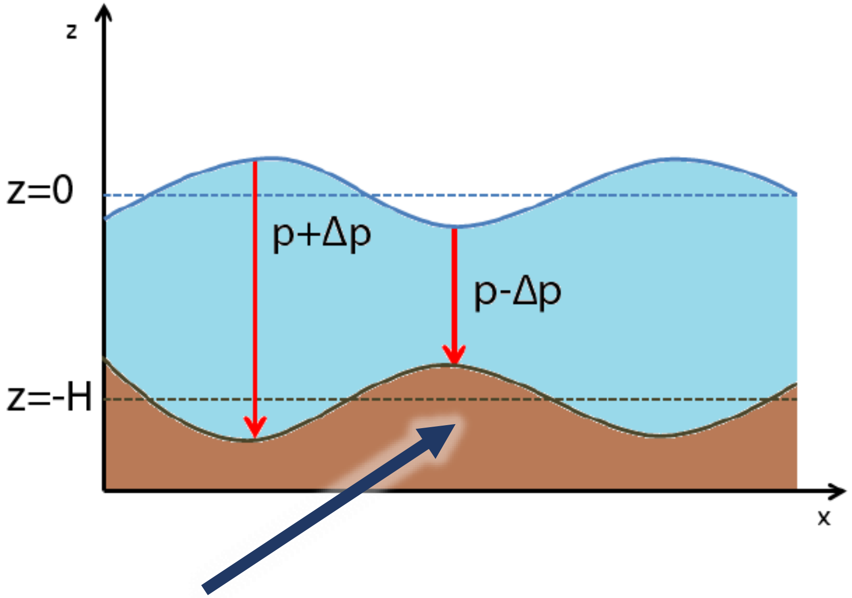


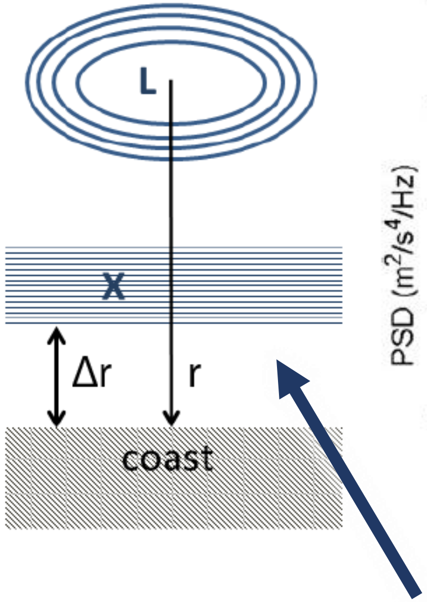
Compressional: important for NN

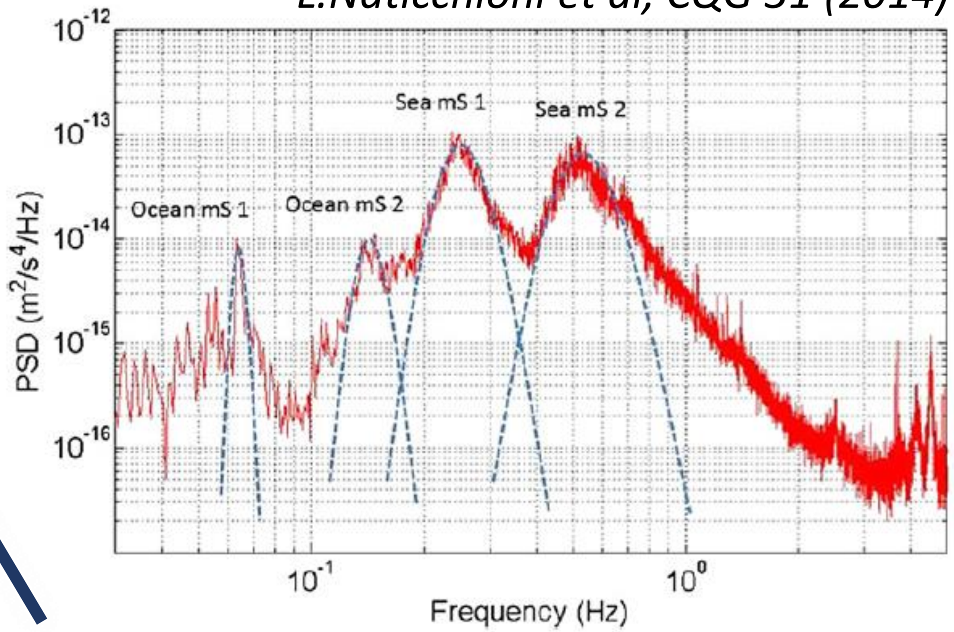
Seismic noise

Microseisms: Main peak around 0.2 *Hz*

L.Naticchioni et al, CQG 31 (2014)





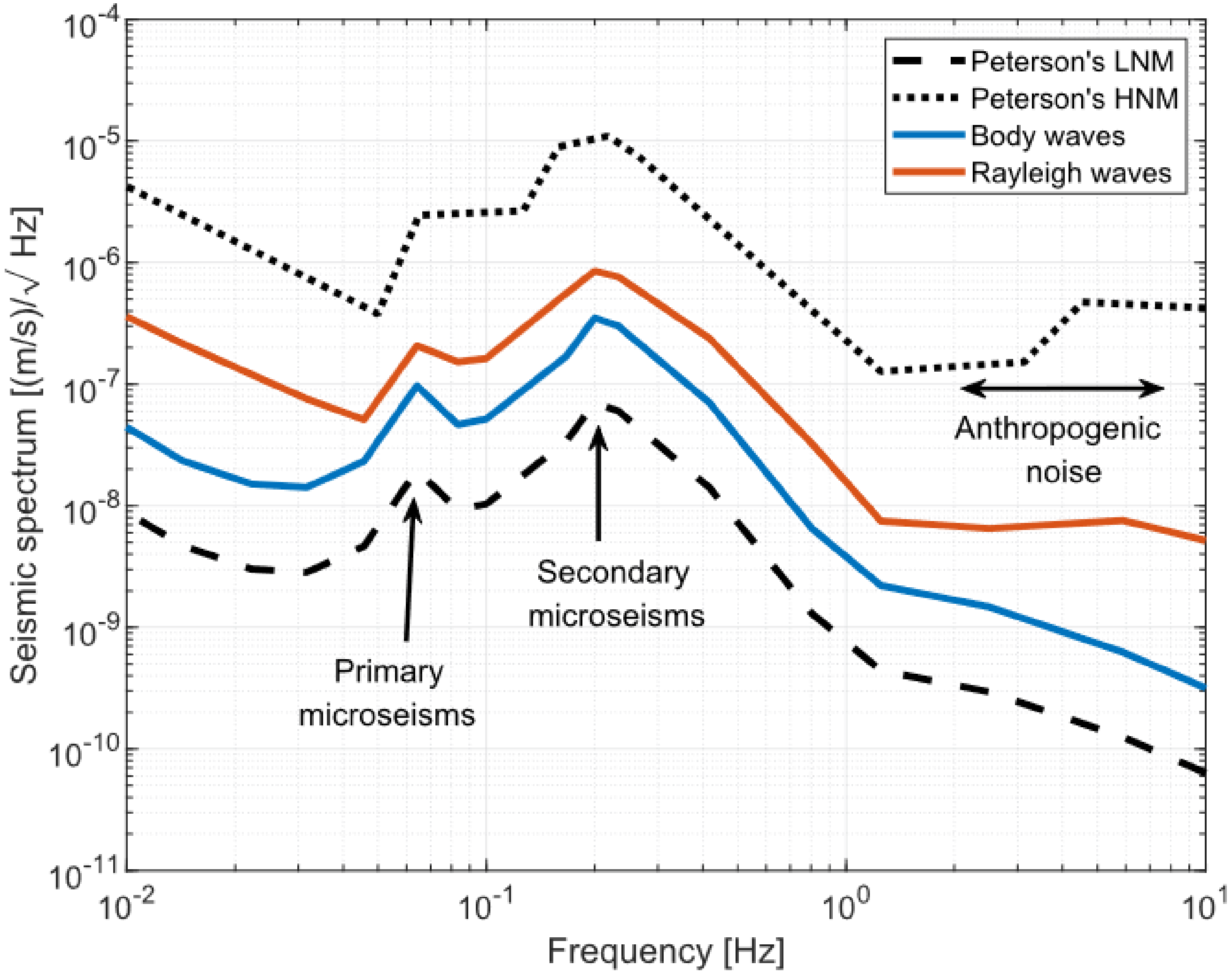


Primary: shallow waters of coastal regions, pressure variation and impact on the shores (0.06-0.1 *Hz*)

Secondary: offshore, superposition of ocean swell, standing waves, non-linear process (0.1-0.2 *Hz* for oceans, 0.3-0.5 for smaller seas or even big lakes)

Seismic noise

Microseisms: Main peak around 0.2 *Hz*



F.Amann et al, Rev. Sci. Instrum. 91 (2020)

Seismic noise

Seismic wave attenuation:

- **Depth-dependence**:

  empirical law: $$\tilde{x}_{seism}(f, z = d) \approx \tilde{x}_{seism}(f, z = 0)e^{-4d/\lambda}$$

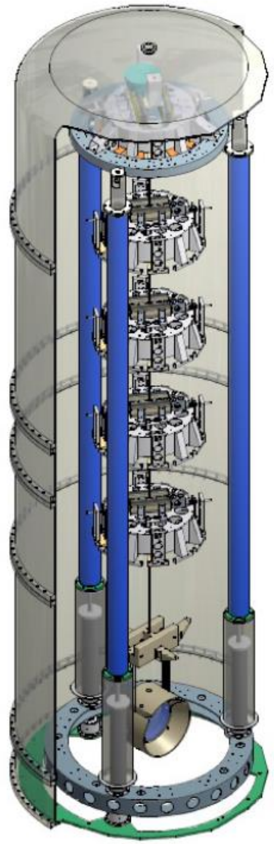
- **Mechanical Filter**: pendulum chain (e.g. Virgo Super-Attenuator) or active feedback platforms (e.g. in LIGO)

e.g. Horizontal transfer function:

$$\mathcal{T}^H(f) \equiv \frac{x(f)}{x_0(f)} = \prod_{i=1}^{N} \mathcal{T}_i^H(f) = \prod_{i=1}^{N} \frac{f_i^2}{f_i^2 - f^2}$$

for $f \gg f_i$ (resonant frequencies):

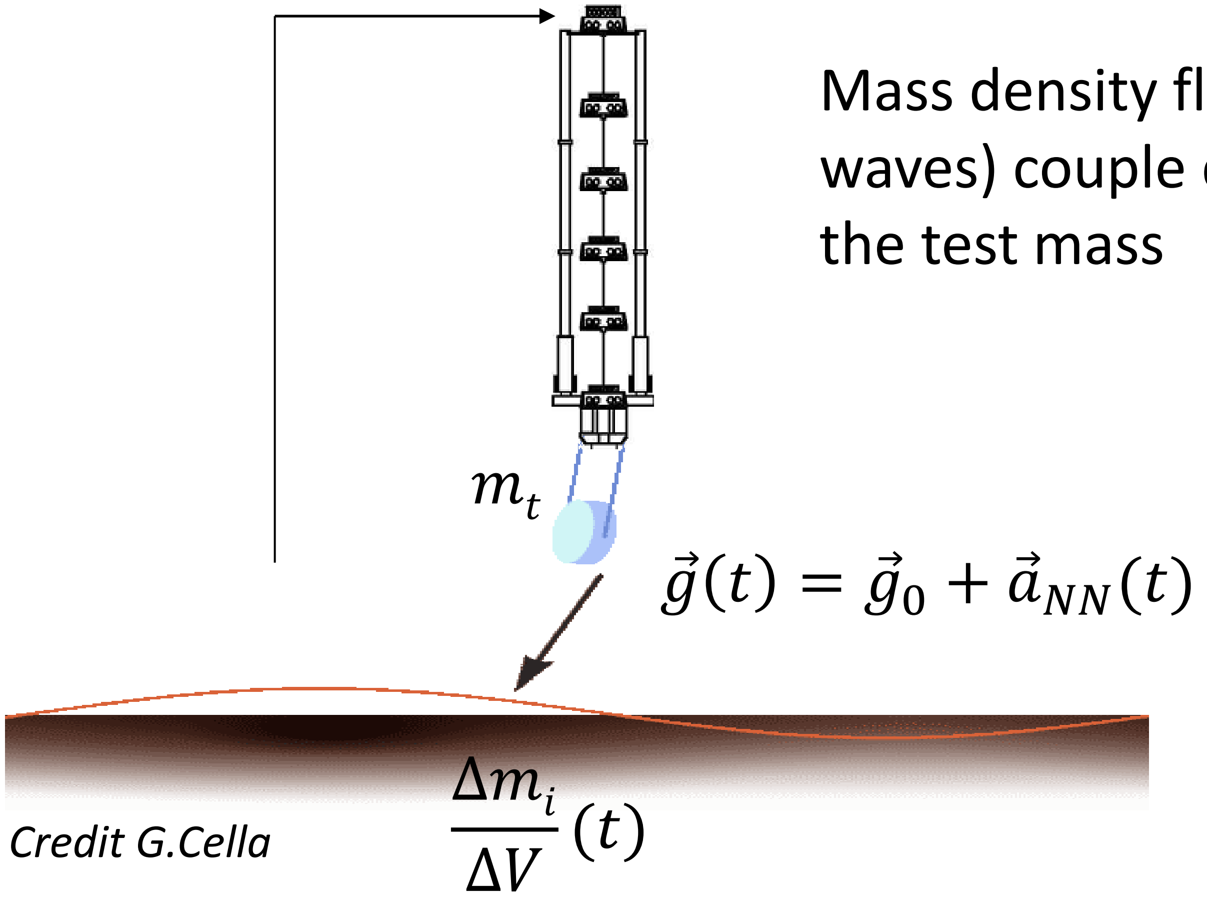
$$\mathcal{T}^H(f) \equiv \frac{x(f)}{x_0(f)} \approx (-1)^N \frac{1}{f^{2N}} \prod_{i=1}^{N} f_i^2$$



A chain of pendula is equivalent to a *mechanical low-pass filter* proportional to f^{-2N} (N stages)

(seismic) Newonian noise

Mechanical filters **cannot** shield a gravitational test mass from the Newtonian Noise, i.e. a gravity gradient:



Credit G.Cella

Mass density fluctuations (e.g. those due to compressional waves) couple directly (gravitational force, vector $\vec{g}$) with the test mass

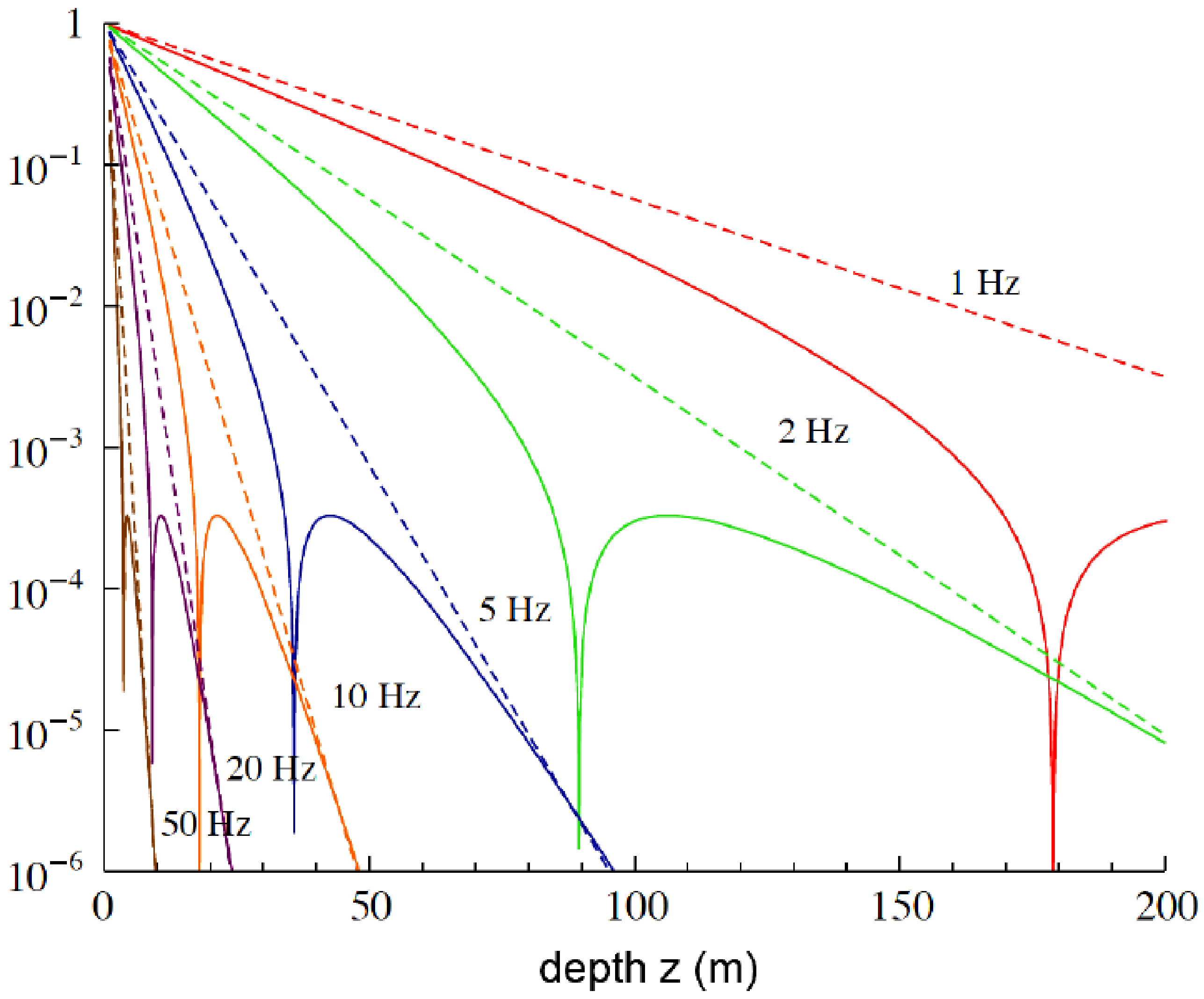
Semi-empirical law:

$$\tilde{x}_{NN}(f) \approx \frac{2.46 \times 10^{-8}}{(f^2/Hz^2)} \tilde{x}_{seism}(f)$$

(seismic) Newonian noise

A depth-dependent attenuation modelization of NN is derived in *M.G. Beker et al., gen. rel. and grav. 43, 2011*

Attenuation factor D(z)



Seismic and NN reduction

It is clear that *going underground* (far from surface waves) is a good strategy to reduce the seismic noise and the (sesmic-induced) Newtonian noise.
That's why the Einstein Telescope will be an **underground** observatory!

- initial design $\sim 200 - 300\ m$
- it depends on the site specs (seismic background at surface, soil and rock layers…)
- a minimal depth of tens of *m* may be required to shield from atmospheric NN
- seismic NN vs. sustainable NN subtraction setup (*see today's lecture by F. Badaracco*)

Site characterisation is required!

Outline

Part I summary:

- ❑ Introduction: The Einstein Telescope project
- ❑ Environmental sources of noise vs ET sensitivity
- ❑ **Site selection criteria**
- ❑ Euregio Meuse-Rhine candidate site
- ❑ Sardinia candidate site
- ❑ A practical example: site characterisation activities in Sardinia
- ❑ Seismic noise analysis

Site selection criteria

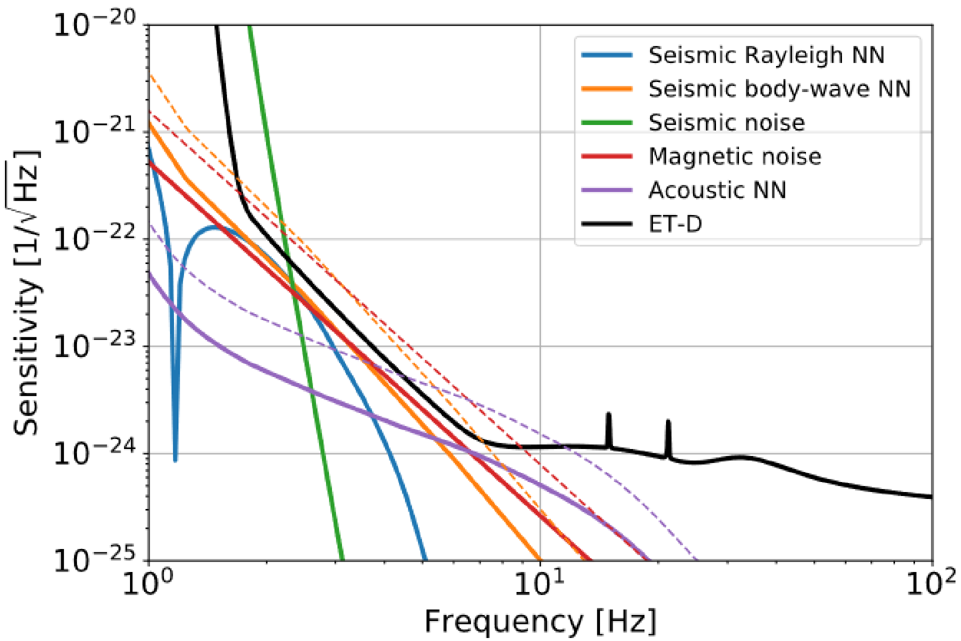
Defining the site selection criteria is not a trivial task.
What matters:

- Geological conditions
- Hydrogeological conditions
- Geotechnical conditions vs infrastructure

- Tunneling/excavation costs
- Expected detector lifetime
- Detector requirements

- Environmental noises (seismic, EM…)

Site characterisation:
- Seismic noise (+NN)
- Other ENV noises
- Geology of the area



F.Amann et al, Rev. Sci. Instrum. 91 (2020)

Site selection criteria

- **Seismic fields**:
  - Long-duration measurements (surface & underground) with seismometers
  - Seismometer Array measurements (short-duration), active and passive
  - Modelization
- **Atmospheric fields**:
  - Microphone array measurements
  - Local wind speed measurements
  - Modelization
- **Electromagnetic fields**:
  - Local field measurements with magnetometers (surface & underground)
  - Global field measurements with magnetometers (e.g. Schumann resonances, surface & underground)
  - Modelization (tricky, many possible channels, depends on the details of the detector)
- **Geotechnical and geographical surveys**

A description of the site selection criteria and suggested measurements is available in *F.Amann et al, Rev. Sci. Instrum. 91 (2020)*

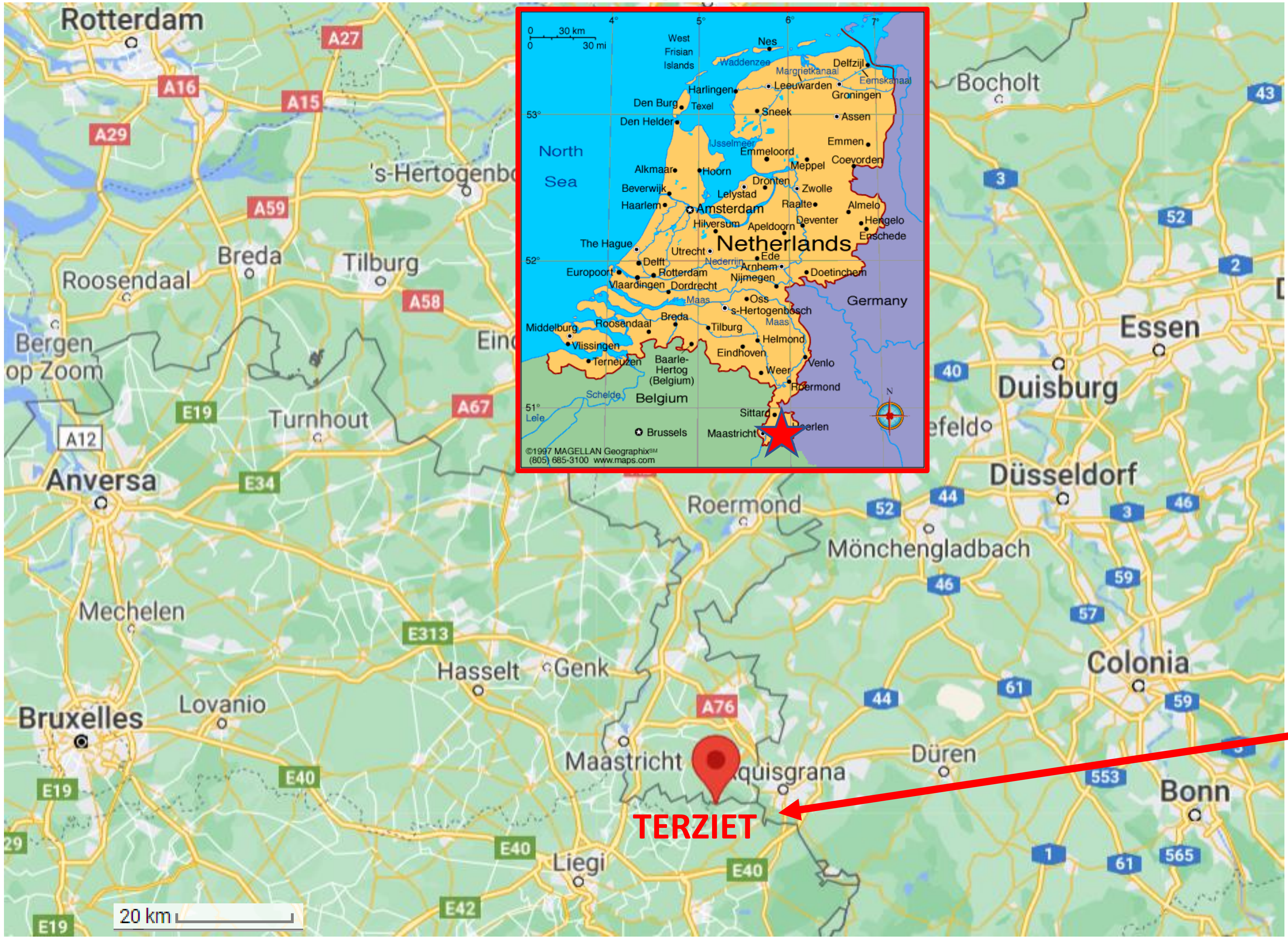
Outline

Part I summary:

- ❑ Introduction: The Einstein Telescope project
- ❑ Environmental sources of noise vs ET sensitivity
- ❑ Site selection criteria
- ❑ **Euregio Meuse-Rhine candidate site**
- ❑ Sardinia candidate site
- ❑ A practical example: site characterisation activities in Sardinia
- ❑ Seismic noise analysis

Euregio Meuse-Rhine site

INFN Istituto Nazionale di Fisica Nucleare



- The site is at the border between Netherlands, Belgium and Germany
- Characterisation activities at Terziet, and planned in other locations around

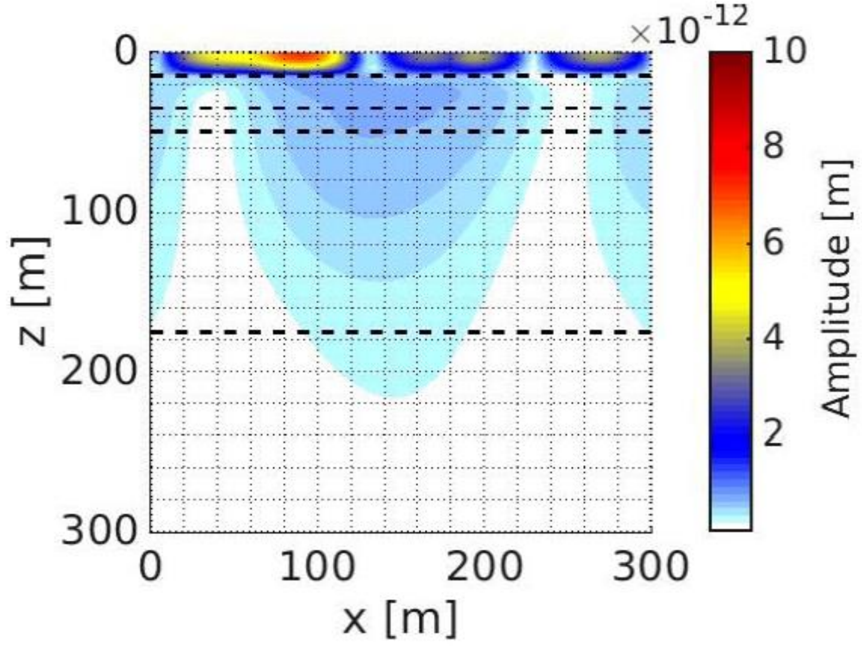
Euregio Meuse-Rhine site

- a 250m deep borehole excavated and equipped (surface & downhole long-duration measurement and analysis ongoing);
- Other 3-5 boreholes expected;
- Extensive active and passive site characterisation with sensor arrays in 2021;
- Good seismic noise attenuation underground given by the geological structure (interface between first layer of soft soil and hard bedrock layer below);
- ET pathfinder centre under construction;
- 15+15M€ funding through Interreg grants.

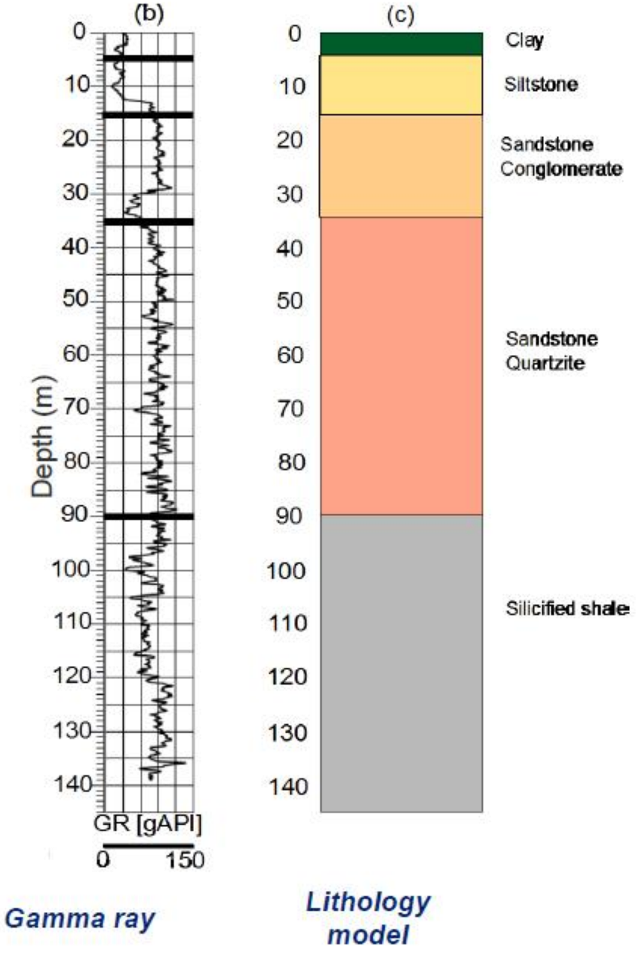
Euregio Meuse-Rhine site

Studies of quality at potential Euregio Meusse-Rhine (EMR) site

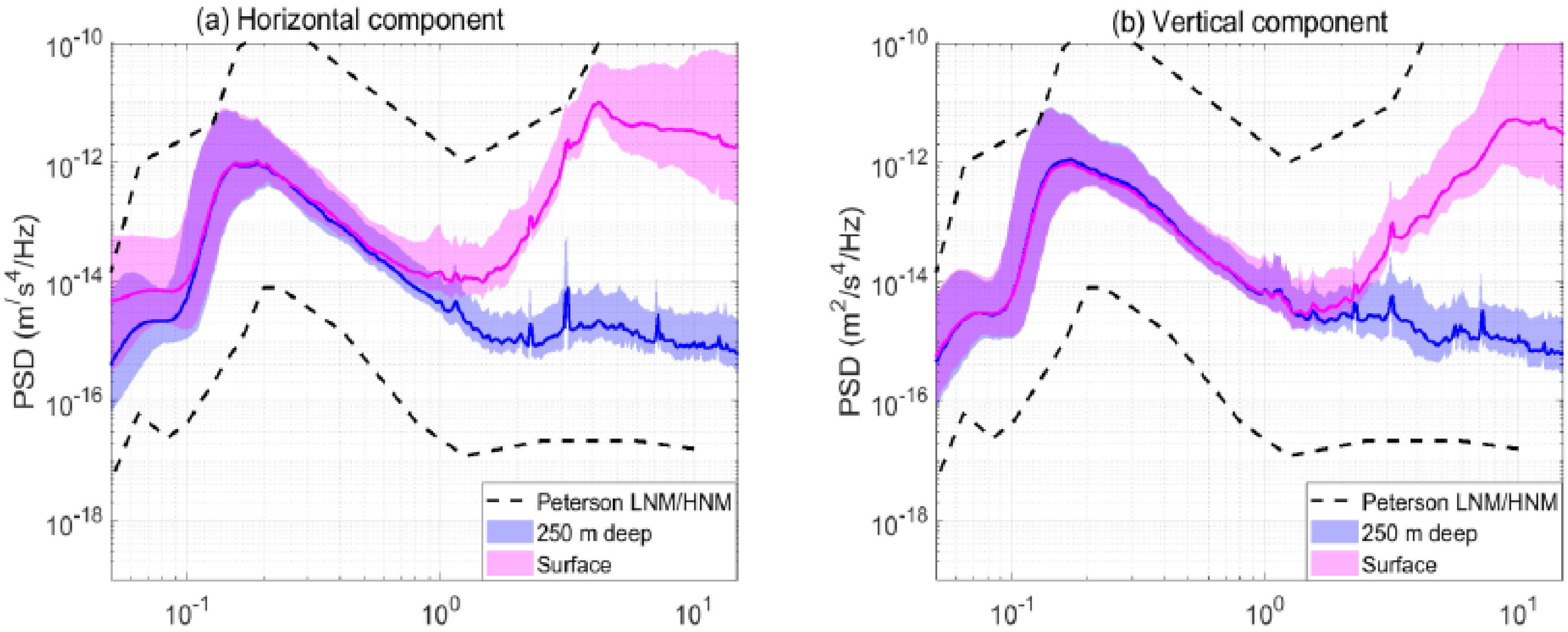
The geology of the EMR Limburg border area: hard rock with on top a layer of soft absorbing and damping soil



Credit: S. Koley, GWADW 2021



Euregio Meuse-Rhine site



Noise attributes

- We characterize the underground and the surface seismic environment for a period between Nov. 2019 to Oct. 2020
- STS-5A seismometer stationed at a depth of 250 m and a Trillium-240 seismometer on the surface
- Surface seismic noise peaks at 4 Hz and 9 Hz in the horizontal and vertical component, respectively
- The attenuation $(\mathrm{PSD}_{\mathrm{surface}}/\mathrm{PSD}_{\mathrm{underground}})$ at high frequencies can be attributed to body waves

Credit: S. Koley, GWADW 2021

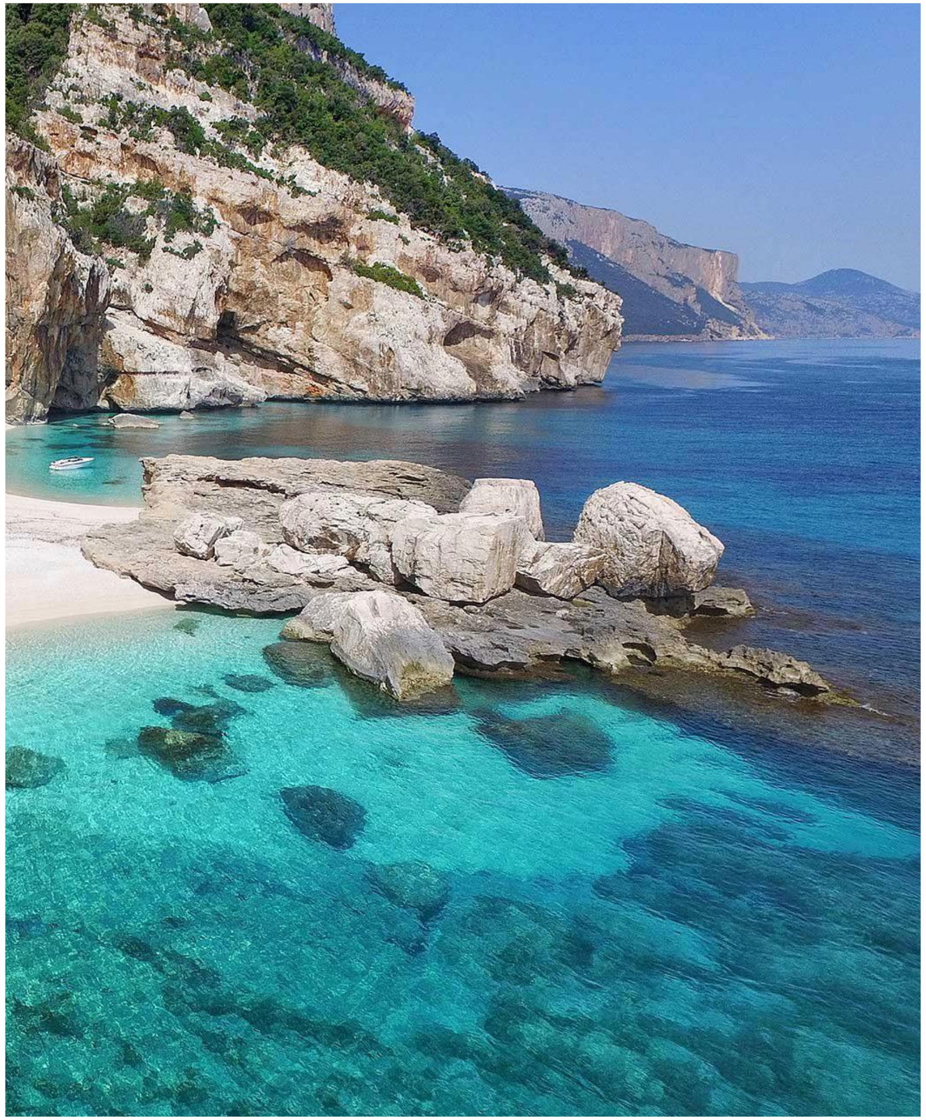
Outline

Part I summary:

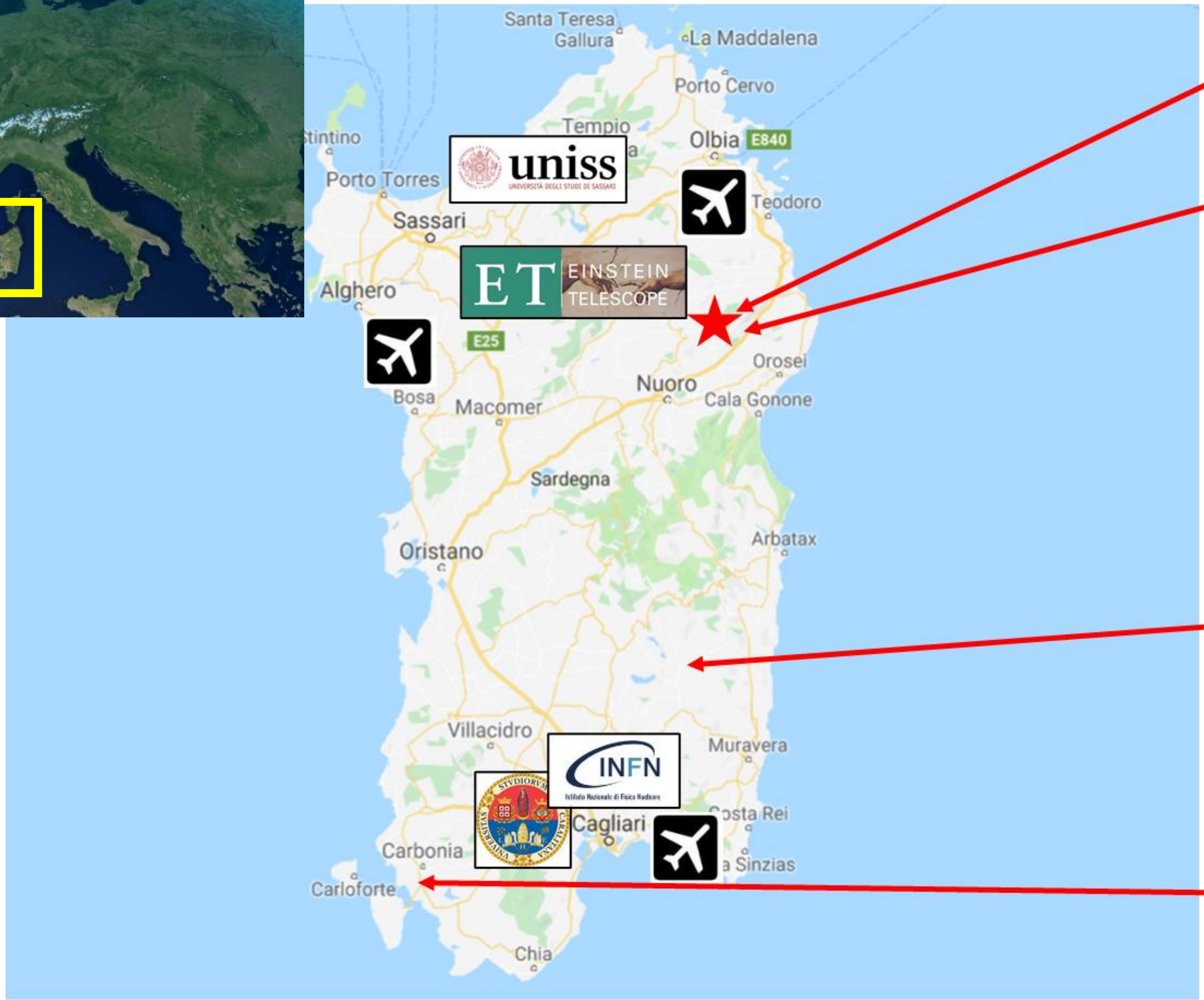
- ❑ Introduction: The Einstein Telescope project
- ❑ Environmental sources of noise vs ET sensitivity
- ❑ Site selection criteria
- ❑ Euregio Meuse-Rhine candidate site
- ❑ **Sardinia candidate site**
- ❑ A practical example: site characterisation activities in Sardinia
- ❑ Seismic noise analysis

The Sardinia site

- Long standing characterisation of the mine in one of the corners continuing;
- Seismic, magnetic and acoustic noise characterisation ongoing at different depths in the mine;
- Underground laboratory under construction (SarGrav)
- Two boreholes (265m and 280m deep) excavated, to be equipped in September 2021;
- Intense & international surface array investigations programme in Summer 2021;
- 17+3.5+1+11M€ funding through national and regional funds.



The Sos Enattos site in Sardinia



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

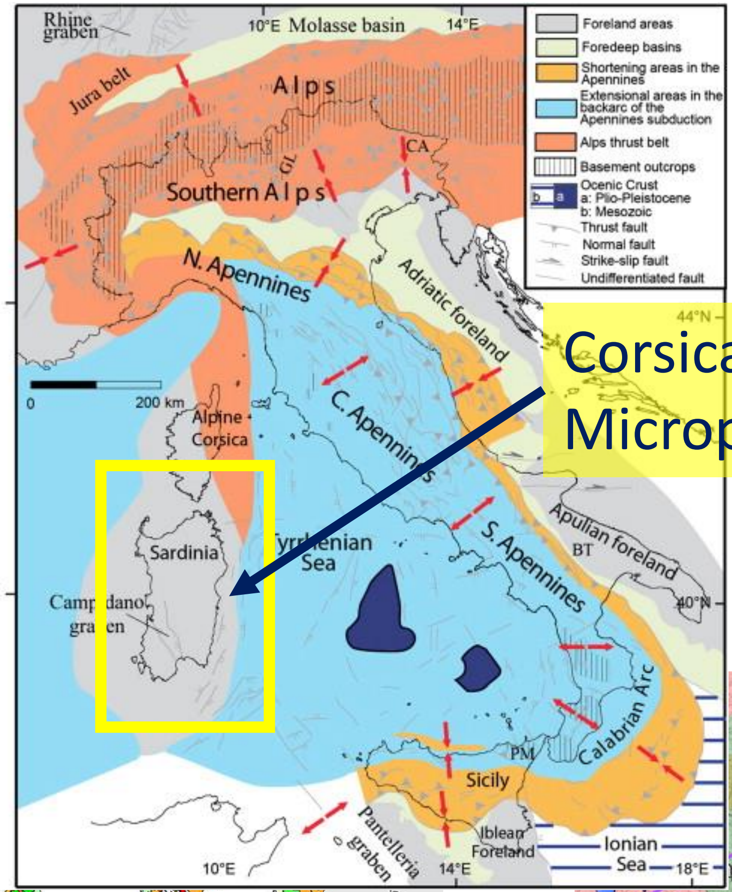
SarGrav underground laboratory

Sardinia Radio Telescope

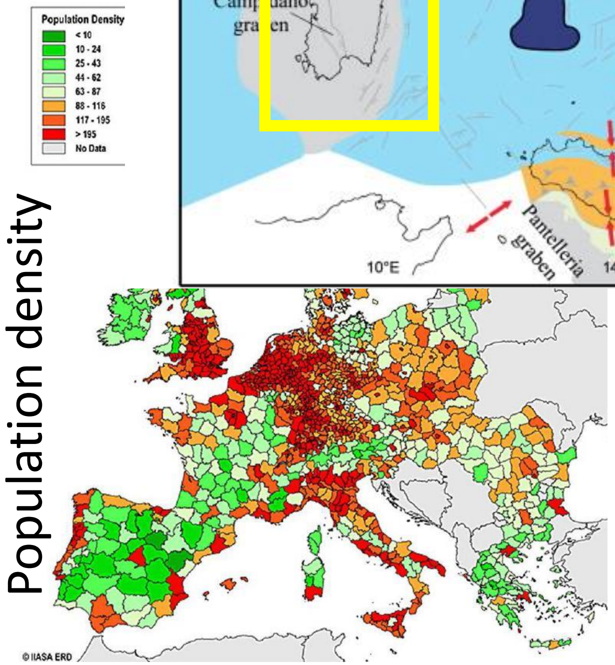
“ARIA” project (for Gran Sasso *Dark Side* DM det.)

The Sos Enattos site in Sardinia

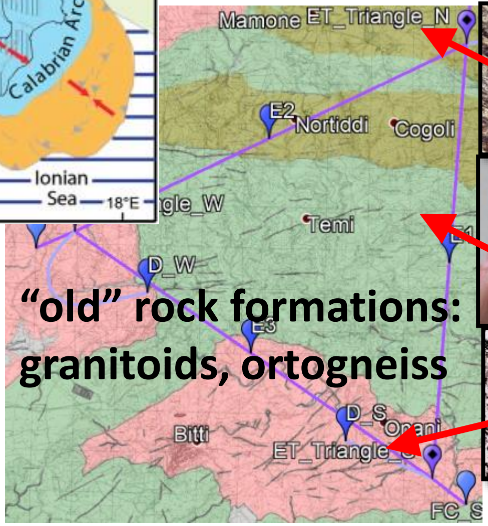
Geophysical frame



Corsica-Sardinia Microplate

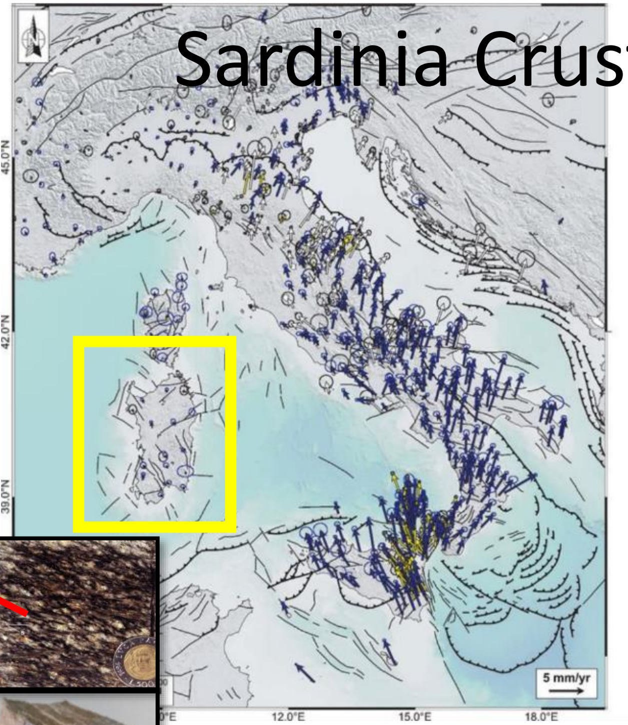


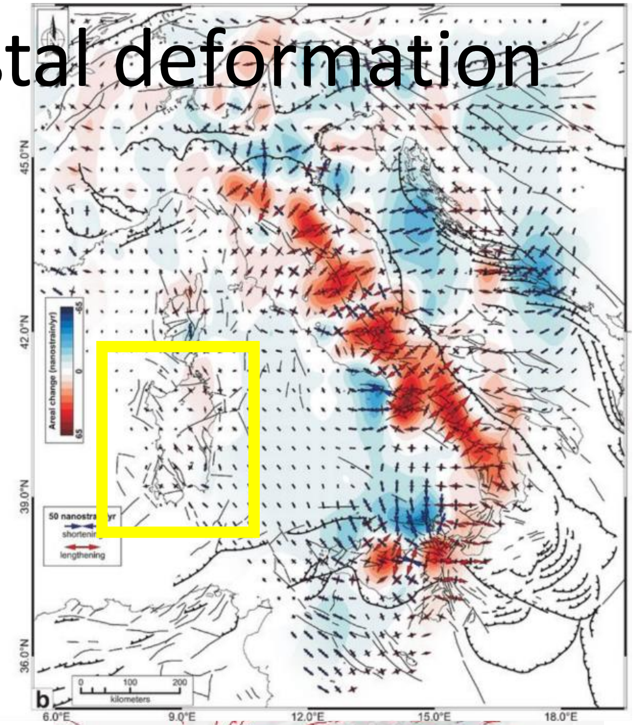
Population density



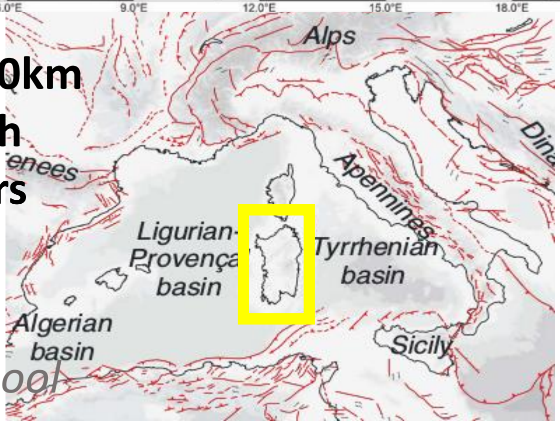
“old” rock formations: granitoids, ortogneiss

Sardinia Crustal deformation

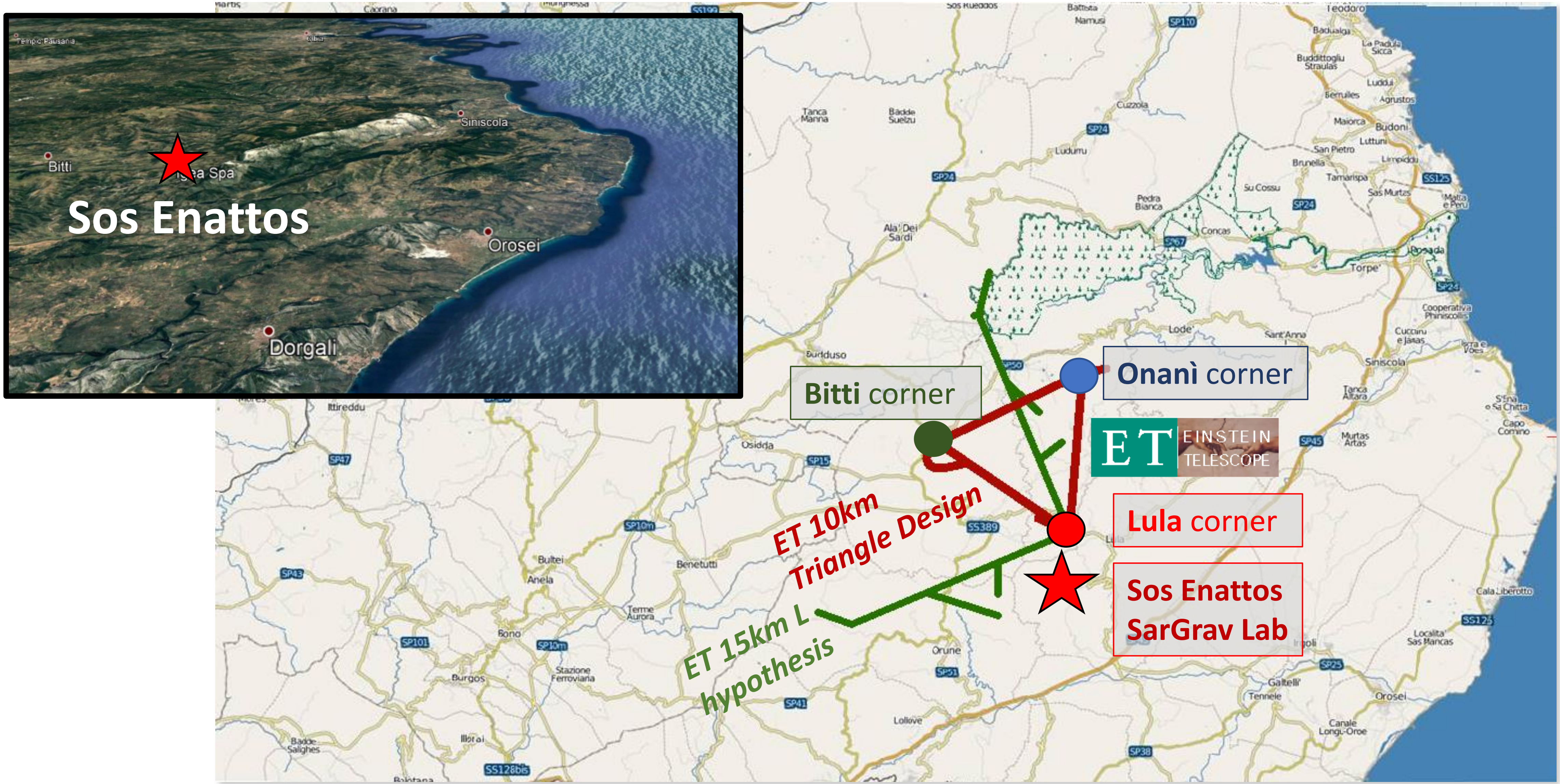




10 earthquakes within 50km from Sos Enattos, all with M<2.5 in the last 40 years



The Sos Enattos site in Sardinia



The Sos Enattos site in Sardinia

Sos Enattos former mine

- Maintained (by *IGEA SpA*) underground access via tunnels and shaft;
- Site studied in 2010-2014. **Long-term sensors deployment since March 2019**;
- Hosts the **SarGrav Laboratory** (surface lab operative, underground lab under construction).


Outline

Part I summary:

- ❑ Introduction: The Einstein Telescope project
- ❑ Environmental sources of noise vs ET sensitivity
- ❑ Site selection criteria
- ❑ Euregio Meuse-Rhine candidate site
- ❑ Sardinia candidate site
- ❑ **A practical example: site characterisation activities in Sardinia**
- ❑ Seismic noise analysis

Measurement stations at the Sos Enattos corner:

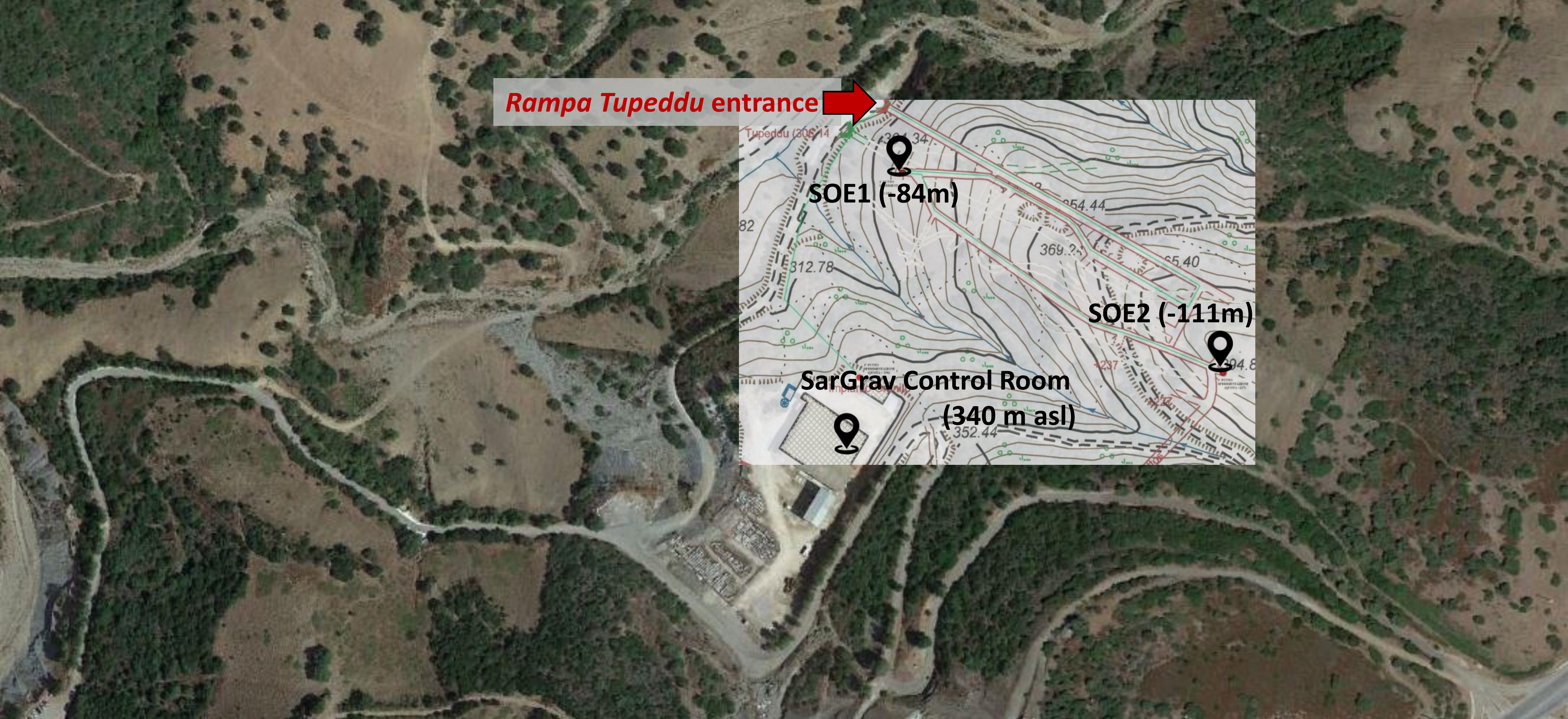
- **SarGrav surface Lab + Control Room**;
- **SOE0** (surface);
- **SOE1**, **SOE2**, **SOE3** (86m, 111m, 160m underground).

Instrumented stations

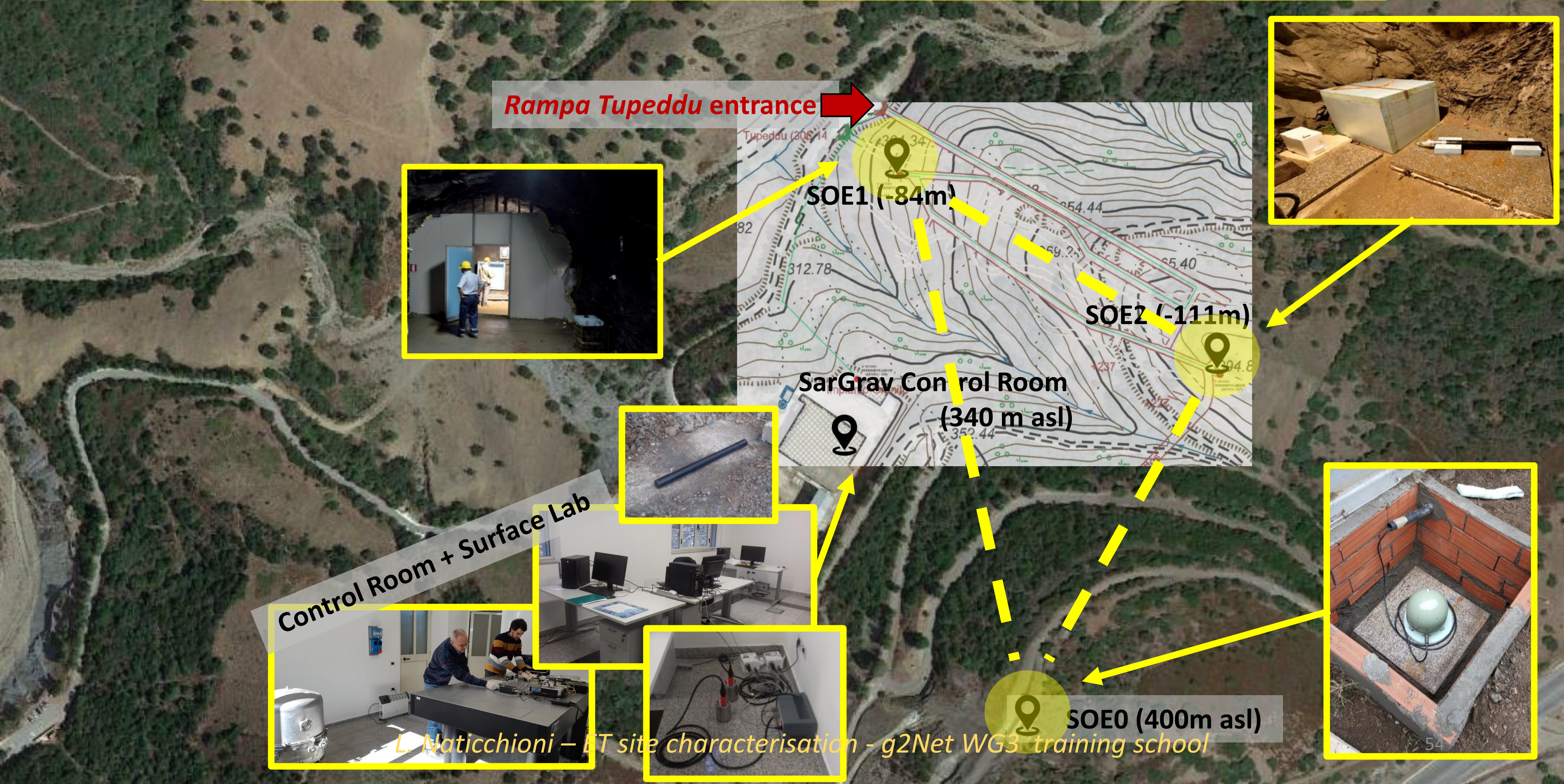
Sensors currently installed:
- 5(6) broadband triaxial seismometers (*Nanometrics Trillium 360, 240* & *120 Horizon, Guralp CMG-3TD 360*);
- 2 magnetometers (*MF6-06*);
- 5(+3) short-period triaxial seismometers (*Nanometrics Trillium 20PH,* first seed of a transportable array);
- High Precision Tiltmeter (part of the *Archimedes* experiment @ SarGrav)
- Weather station (@ SarGrav Lab).

Work in progress: new sensors (seismometers, magnetometers, microphones) will be added to the network in the next months

Sos Enattos measurement stations (2019-2020)



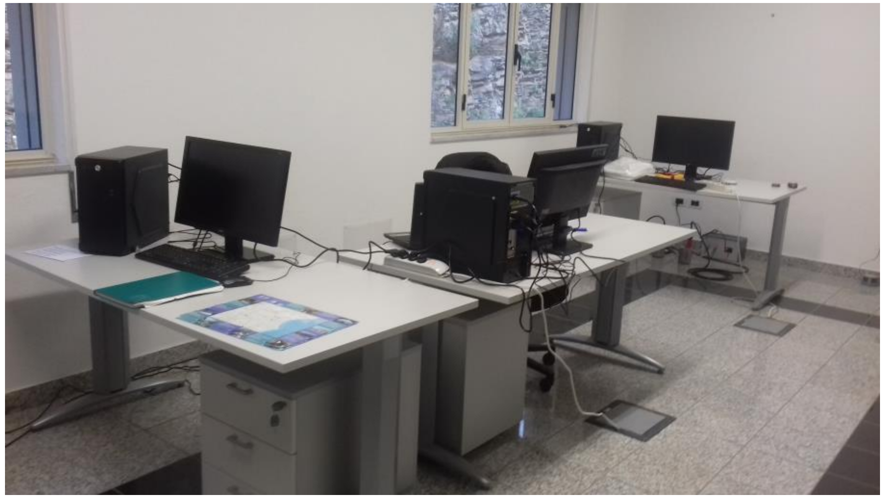
Sos Enattos measurement stations (2019-2020)

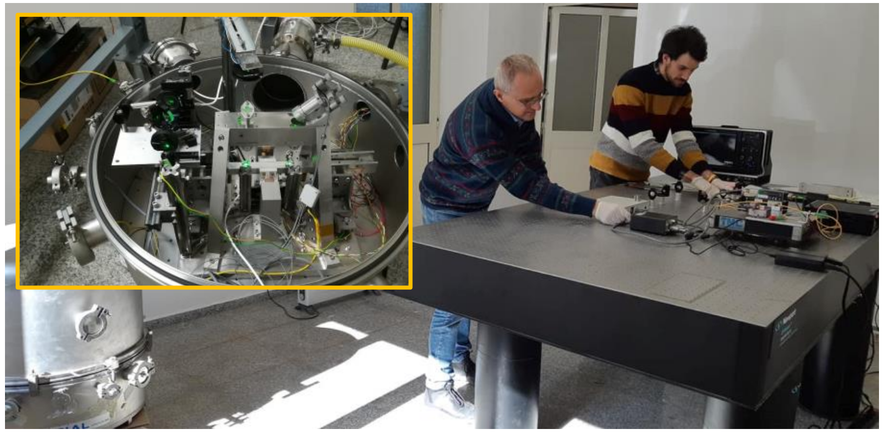


Sos Enattos measurement stations (since Aug. 2020)

SARGRAV surface lab & control room

MFS06 Magnetometer buried at surface close to the SarGrav control room





DAQs, Network connections, weather stations, *Archimedes* tiltmeter, T20 seismometers

SARGRAV surface lab & control room

Characterisation of Sos Enattos

SOE0 station (*since December 2019*)

TRILLIUM 240s + Taurus DAQ

Characterisation of Sos Enattos

SOE1 station (84m underground, *Mar. 2019 – June 2020*)

TRILLIUM 240s + Taurus DAQ

Characterisation of Sos Enattos

SOE1 station (84m underground, *since June 2020*)



TRILLIUM 120 Horizon + Centaur6 DAQ + Guralp 360 (since July 2021)

DAQ input range reduced to 4Vpp (WRT 40Vpp standard settings);

→ Effective reduction of DAQ self noise in the few Hz band;

→ Measured noise floor hits the Earth Person’s Low Noise Model.

Characterisation of Sos Enattos

SOE2 station (111m underground, *since March 2019*)

Double wall + insulation box + *pasta-pot* insulation

1x TRILLIUM 240s (until June 2021)
2x TRILLIUM 360s (from July 2021)
Centaur6 DAQ

Characterisation of Sos Enattos

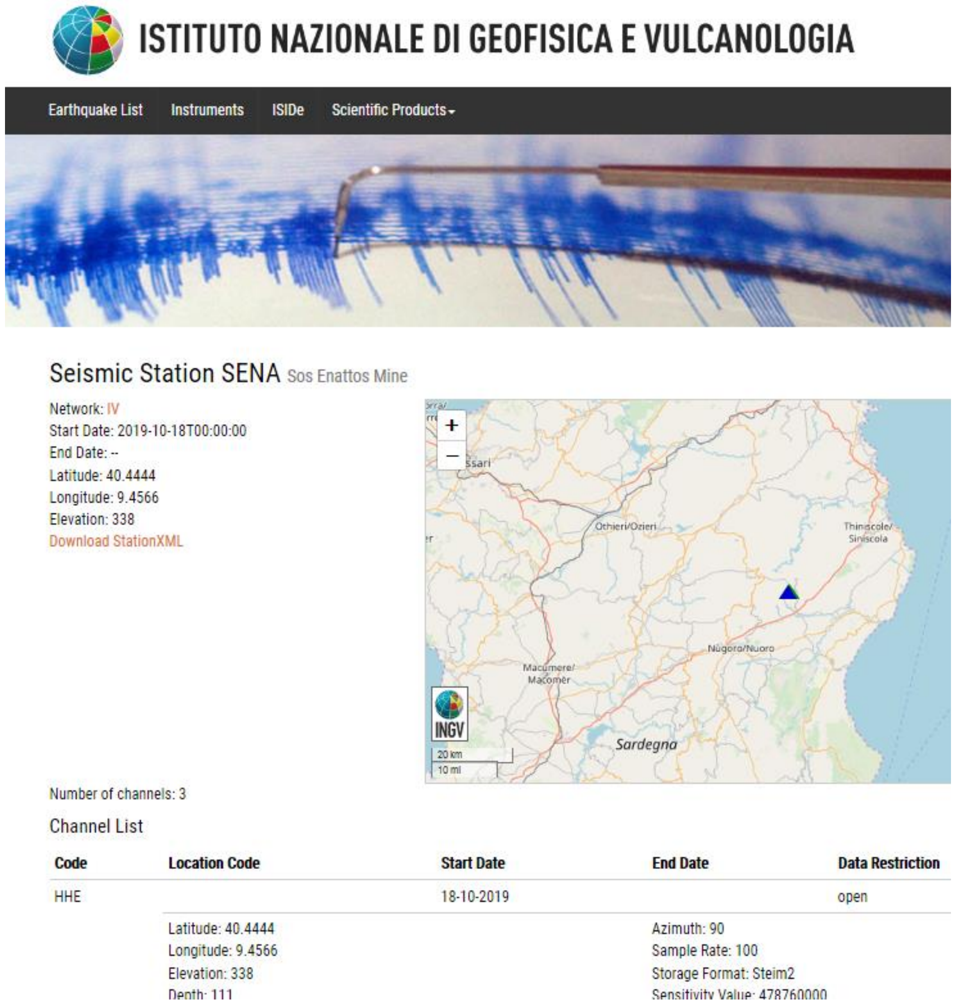
SOE2 station (111m underground, *since March 2019*)

Double wall + insulation box + *pasta-pot* insulation

Magnetometer MFS-06

Characterisation of Sos Enattos

SOE2 station (111m underground, *since March 2019*)



SOE2 station is integrated into the Italian national seismometer network of INGV (SENA station)

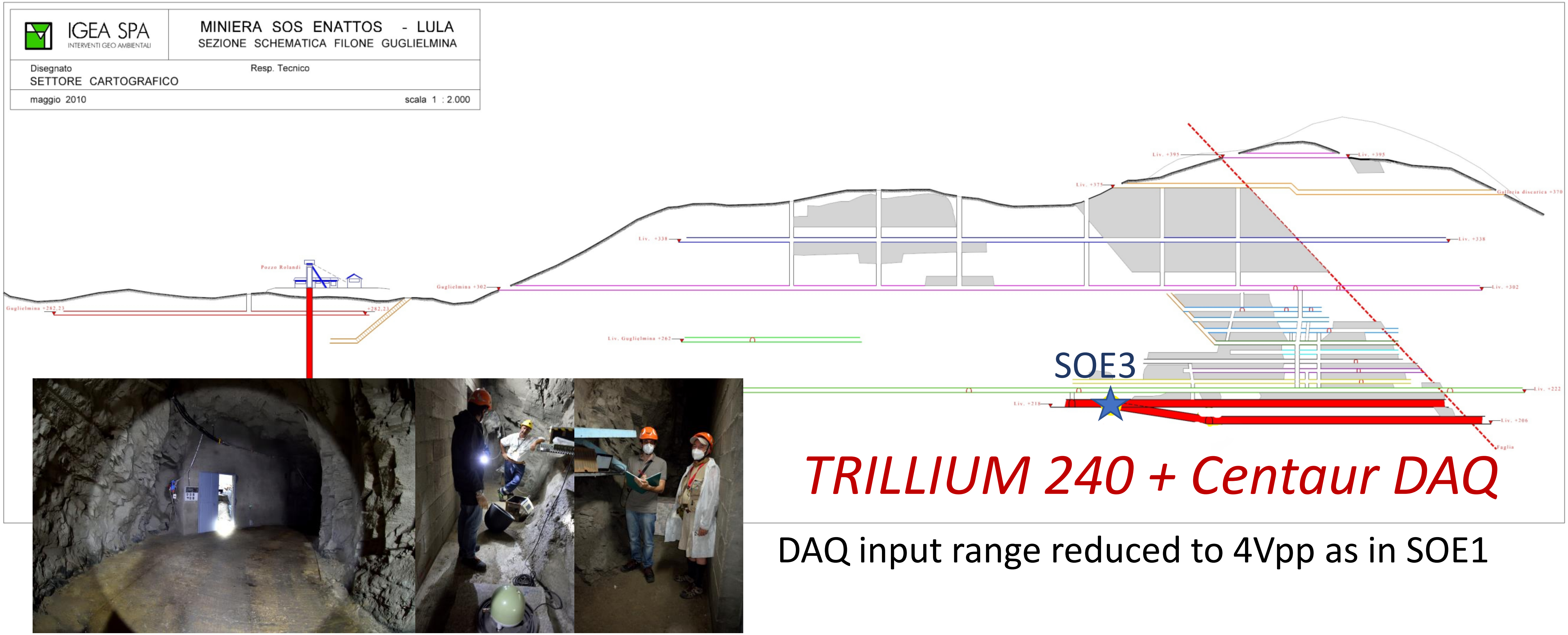
http://cnt.rm.ingv.it/en/instruments/station/SENA

Public data access

T240 Until June 2021, T360 from July 2021 (with reduced input range 4Vpp)

Characterisation of Sos Enattos

SOE3 station (160m underground, *since Aug. 2020*)



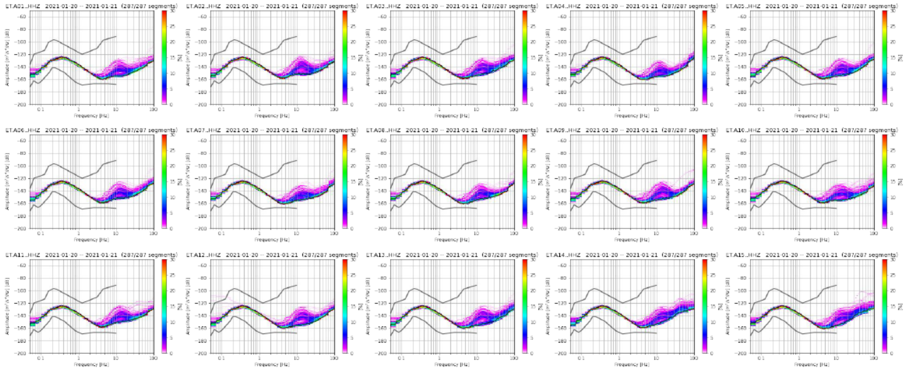
TRILLIUM 240 + Centaur DAQ

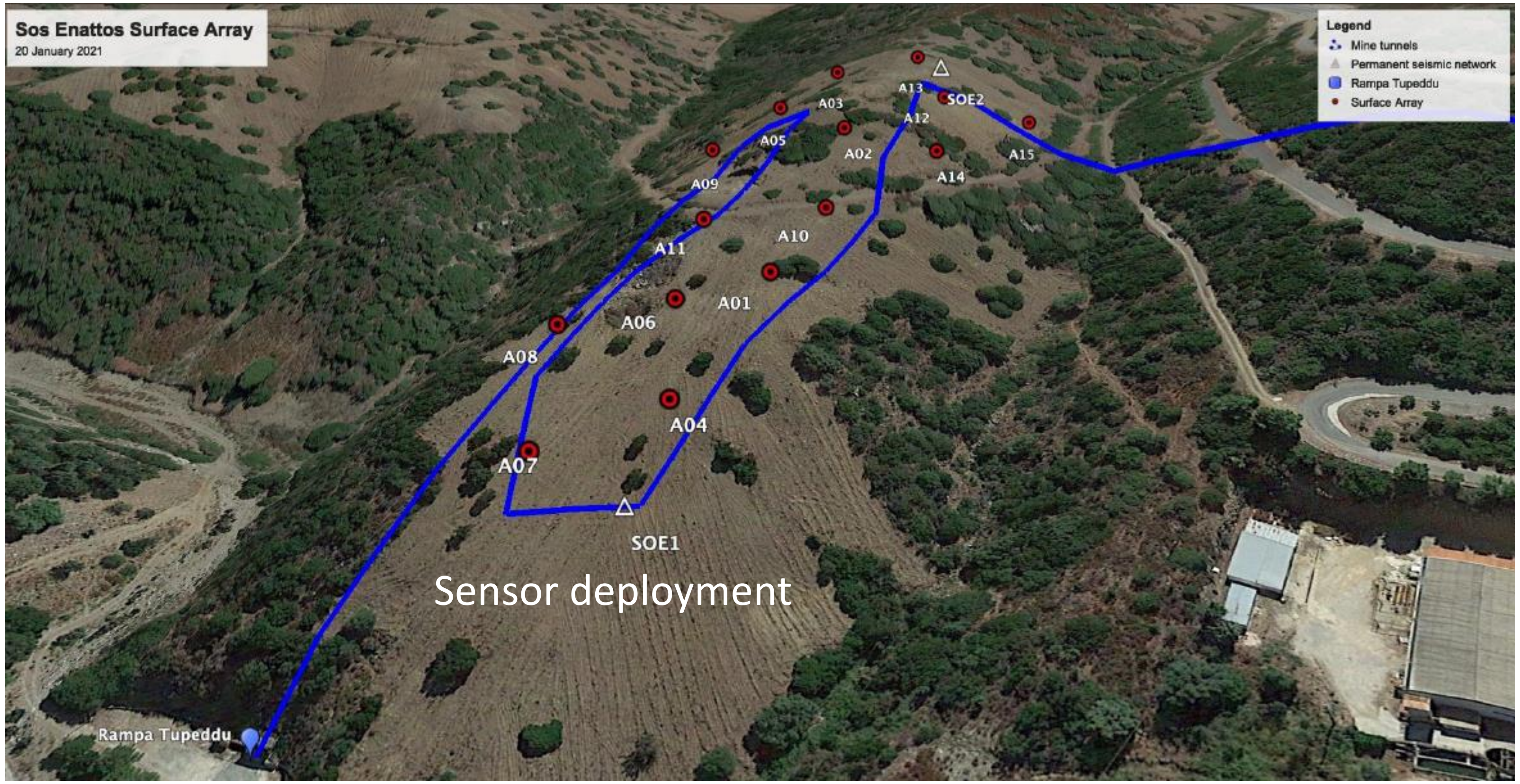
DAQ input range reduced to 4Vpp as in SOE1

Surface Seismometers 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 Sos Enattos in January-February 2021

Preliminary test





Characterisation of Sos Enattos

The **results** of the first 2-years of seismic characterisation at the Sos Enattos corner have been published in:

- L. Naticchioni et al., ***Characterization of the Sos Enattos site for the Einstein Telescope***, **JPCS** 1468, 2020
- 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

A Seismological Study of the Sos Enattos Area—the Sardinia Candidate Site for the Einstein Telescope

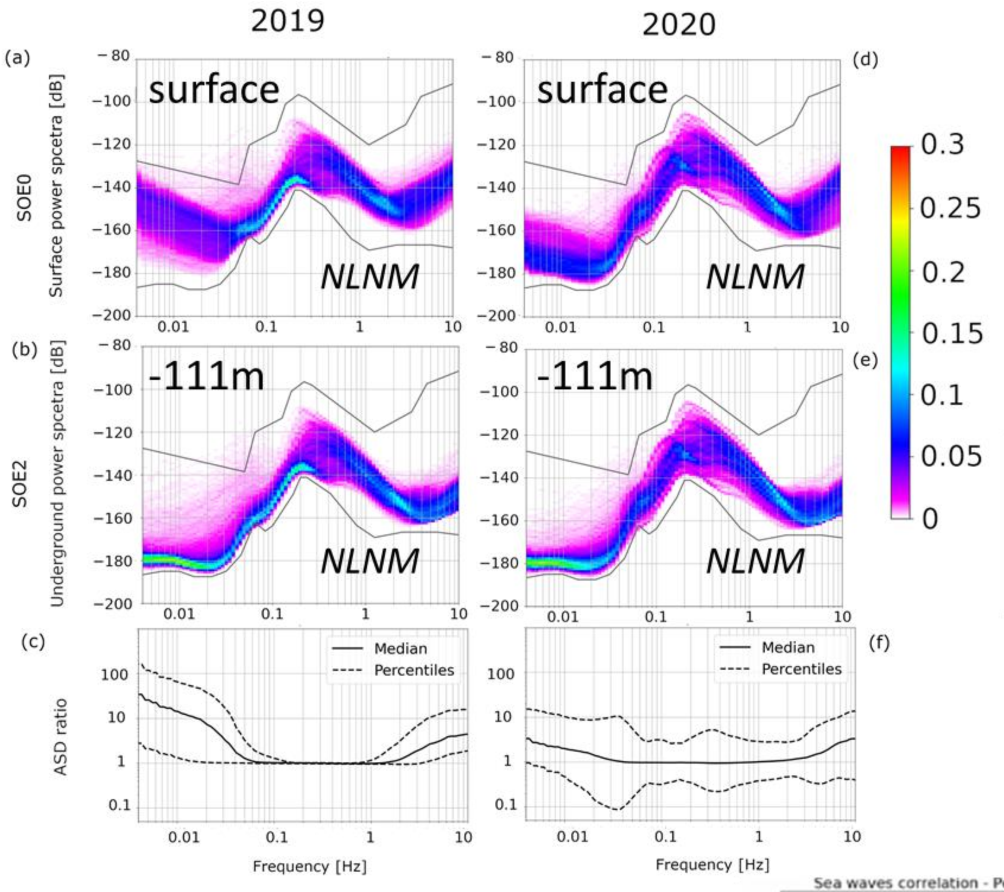
Matteo Di Giovanni[*1,2,3], Carlo Giunchi[1], Gilberto Saccorotti[1], Andrea Berbellini[4], Lapo Boschi[4,5,6], Marco Olivieri[4], Rosario De Rosa[7,8], Luca Naticchioni[9,10], Giacomo Oggiano[11,12], Massimo Carpinelli[11,12], Domenico D'Urso[11,12], Stefano Cuccuru[11,12], Valeria Sipala[11,12], Enrico Calloni[7,8], Luciano Di Fiore[7], Aniello Grado[13], Carlo Migoni[14], Alessandro Cardini[14], Federico Paoletti[15], Irene Fiori[16], Jan Harms[2,3], Ettore Majorana[9,10], Piero Rapagnani[9,10], Fulvio Ricci[9,10], and Michele Punturo[17]

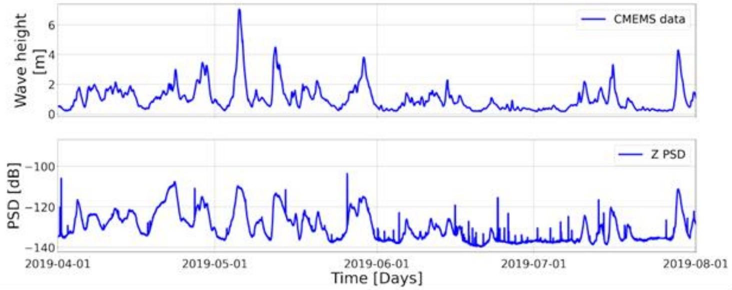
Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency

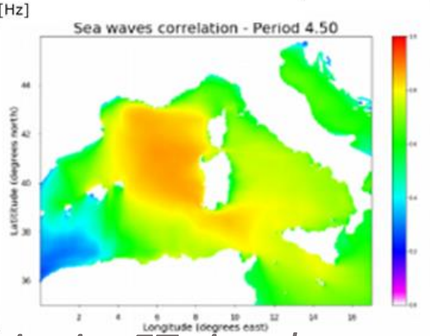
A. Allocca[1,2], A. Berbellini[3], L. Boschi[3,4,5], E. Calloni[1,2,a], G. L. Cardello[6,7], A. Cardini[8]. M. Carpinelli[6,7,9], A. Contu[8,10], L. D'Onofrio[1,2], D. D'Urso[6,7],

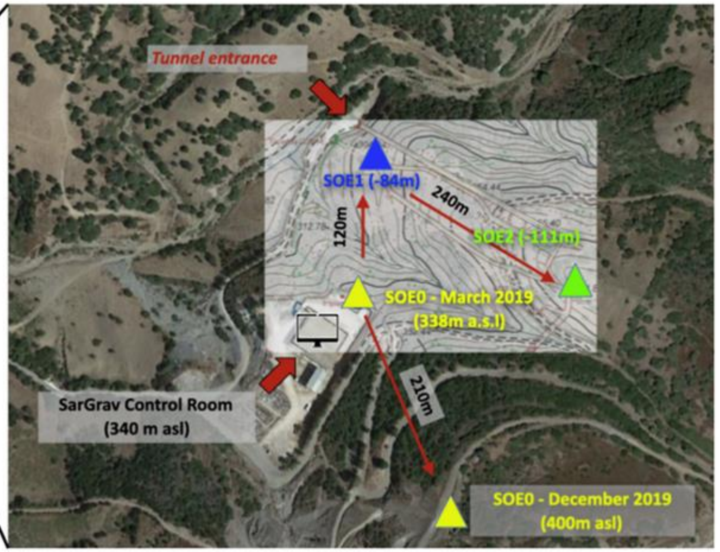
… another publication about the features of the seismic noise at the site is in preparation

First results at Sos Enattos



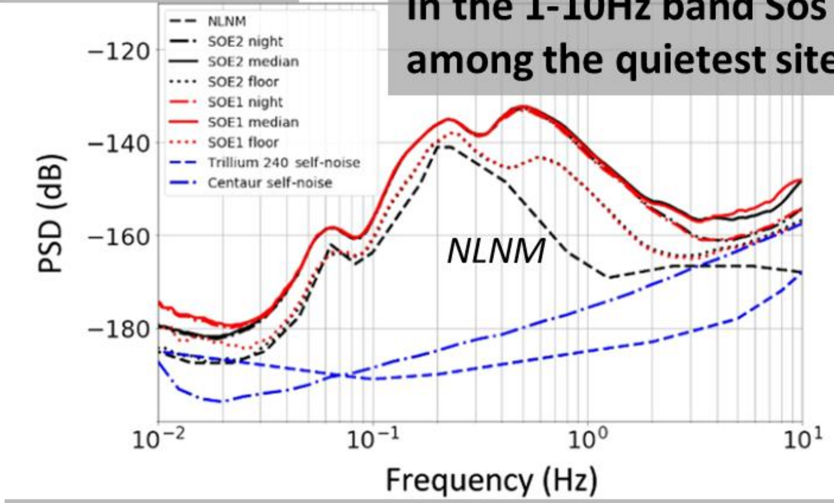






Low anthropic noise, no significant amplification effects

In the 1-10Hz band Sos Enattos is among the quietest sites in the world



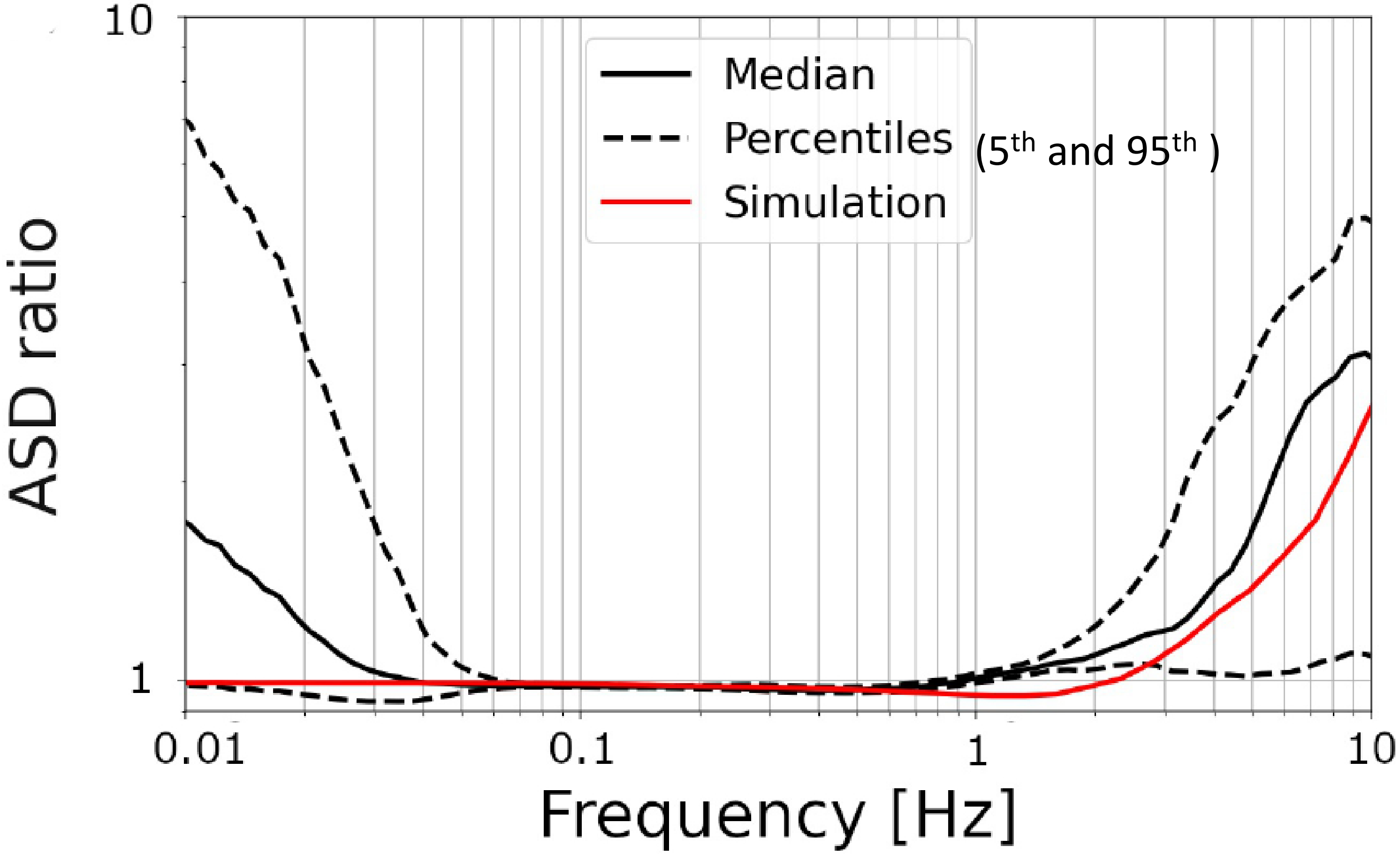
Microseisms correlation with NW 4.5s Med Sea waves

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

First results at Sos Enattos

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

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



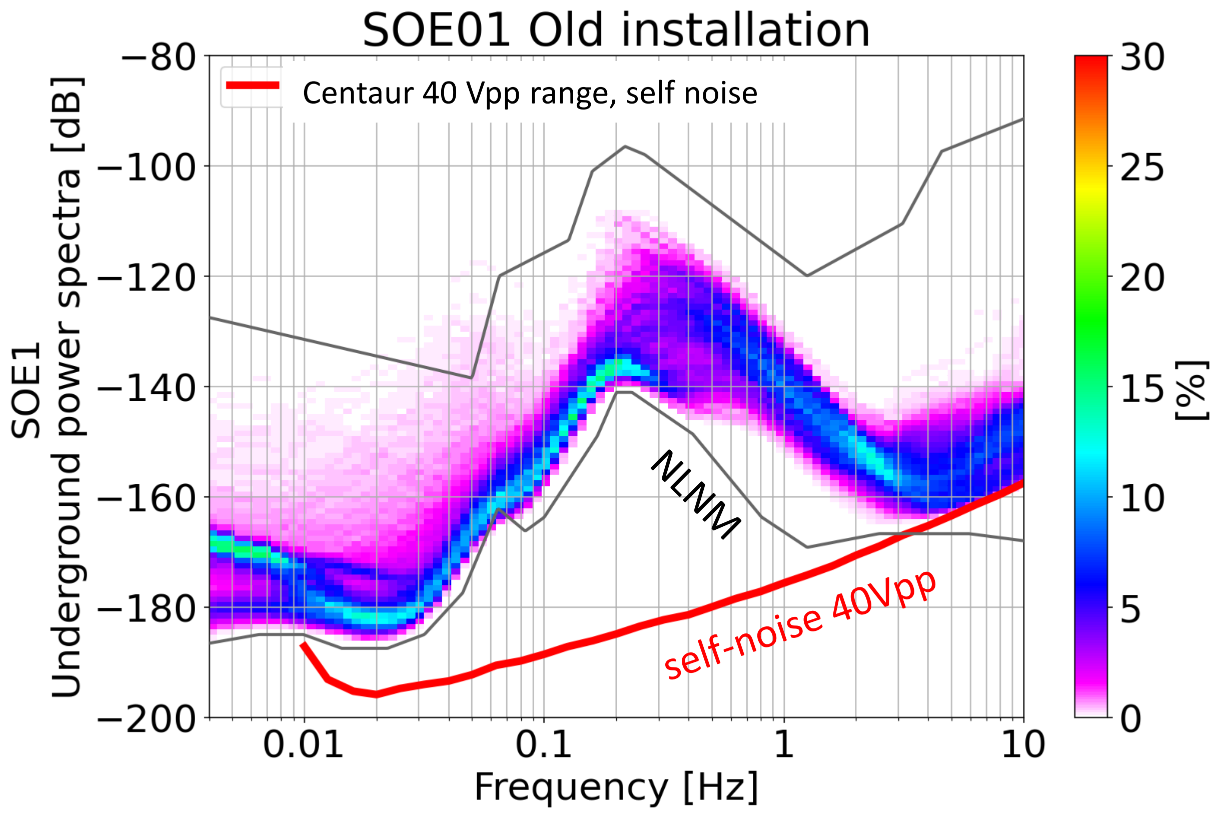
(5th and 95th)

Synthetic seismograms

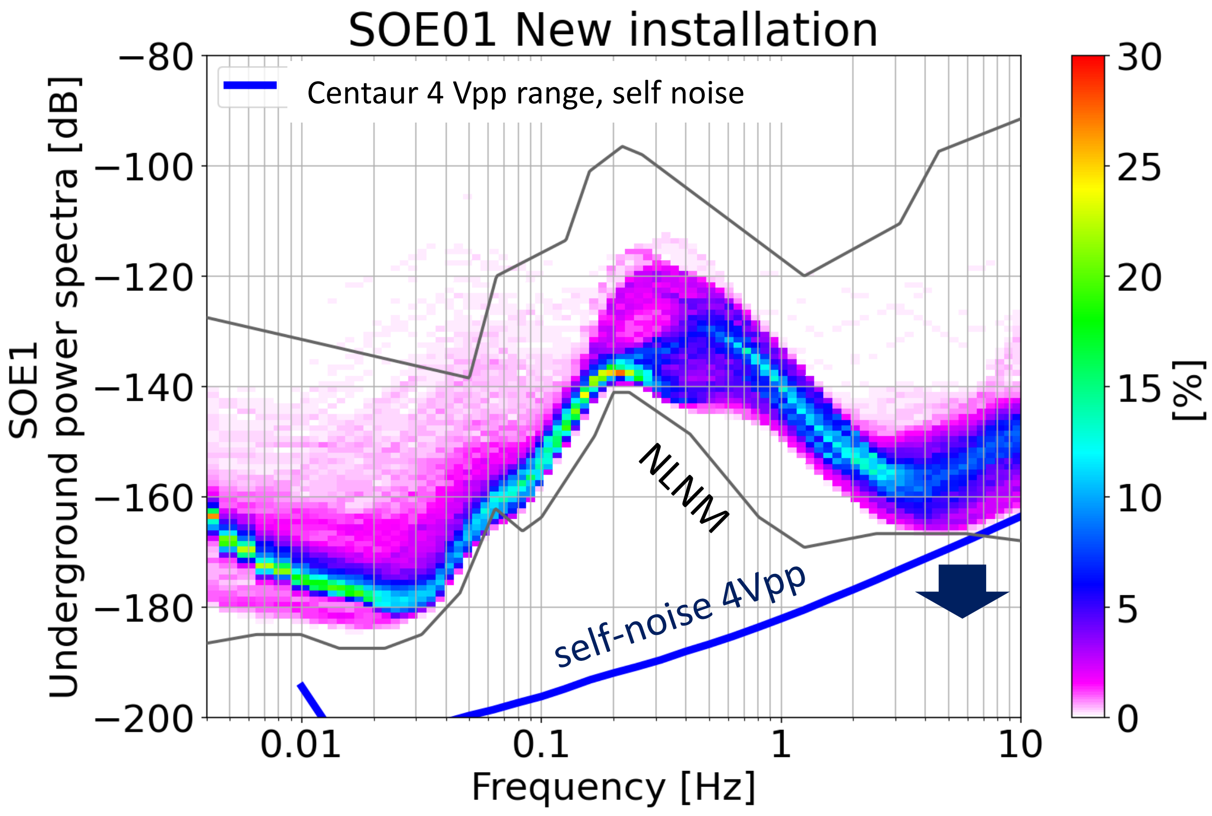
Seismological Research Letters (2021) 92 (1): 352–364

First results at Sos Enattos

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)

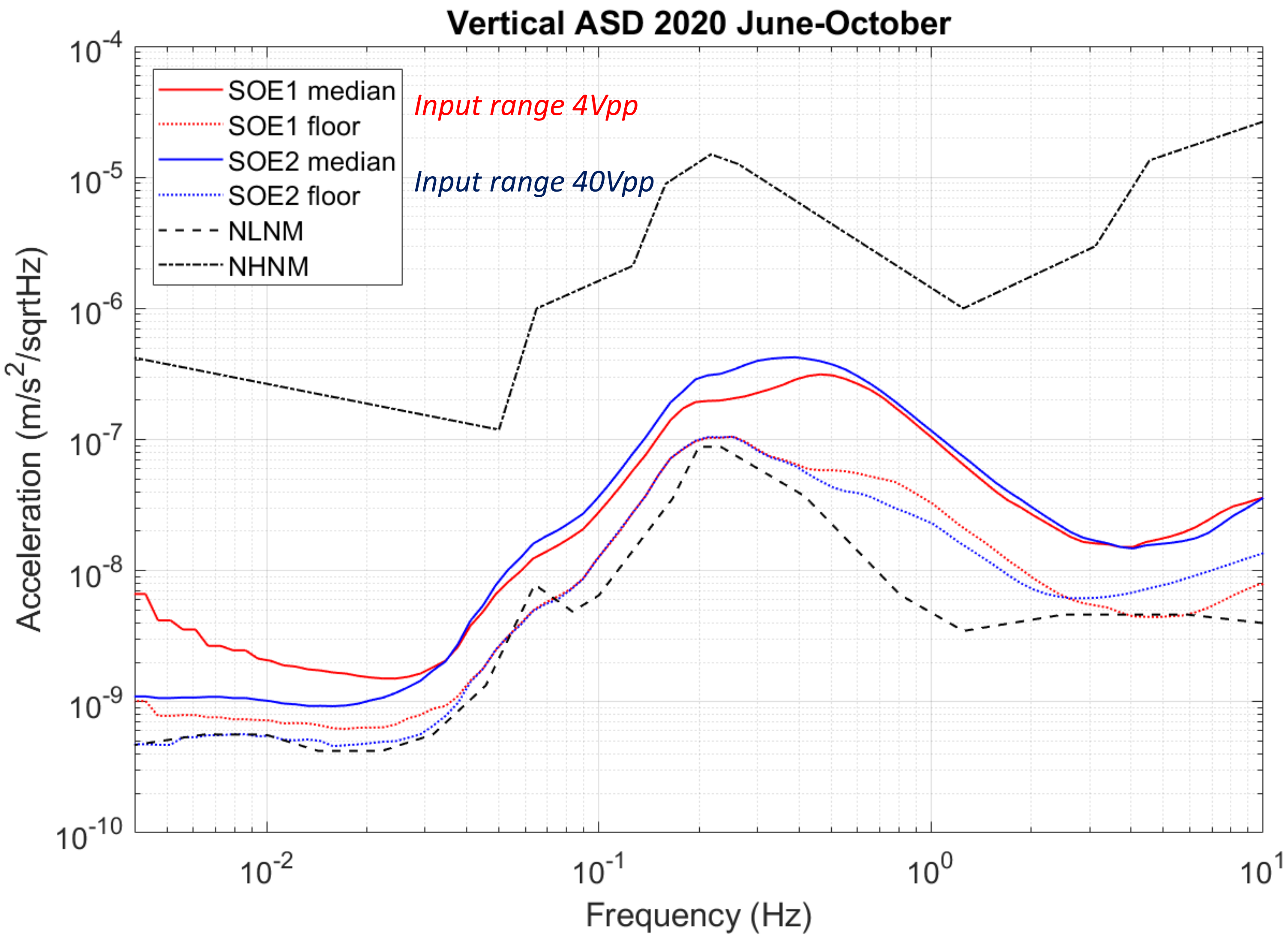


May to June 2020

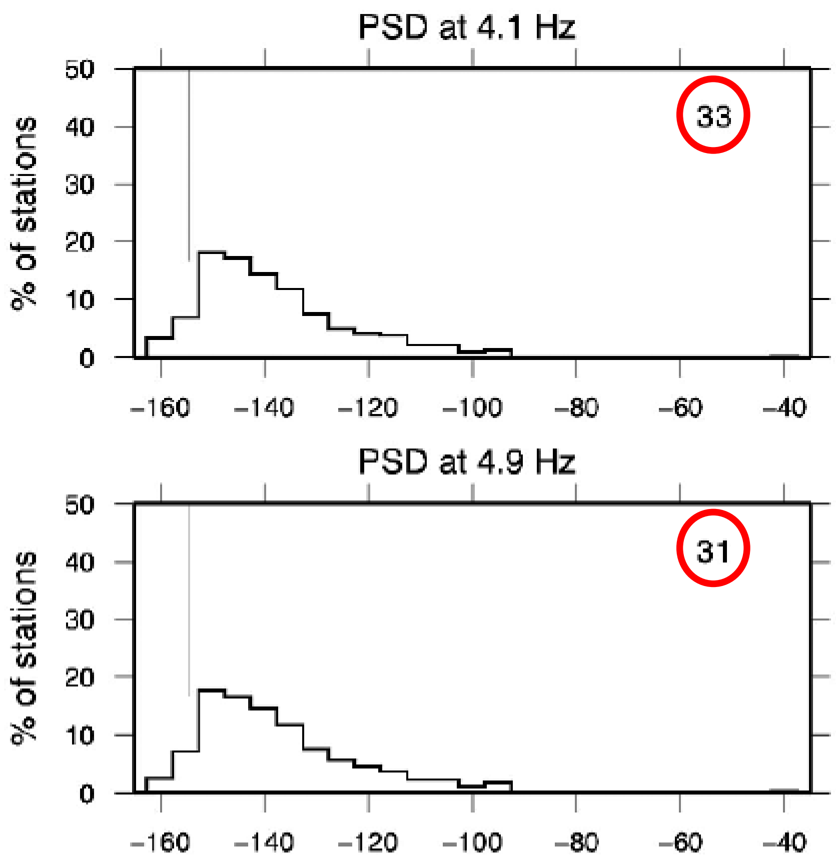


June to August 2020

First results at Sos Enattos



SOE2 ranking among 445 stations of IRIS network



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

First results at Sos Enattos

Vertical

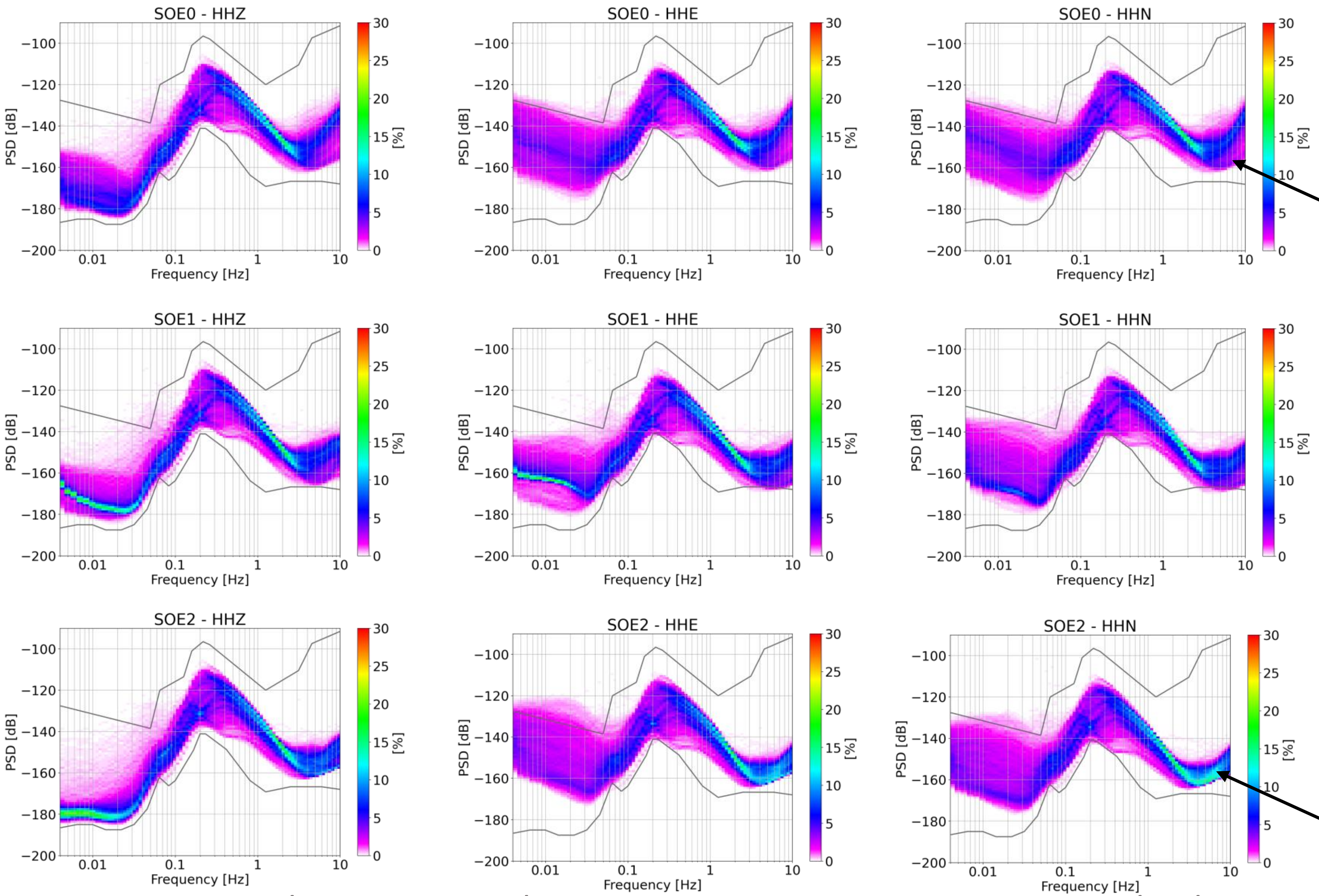
Horizontal

2021 data
January-April

SOE0
Surface

SOE1
-84m

SOE2
-111m



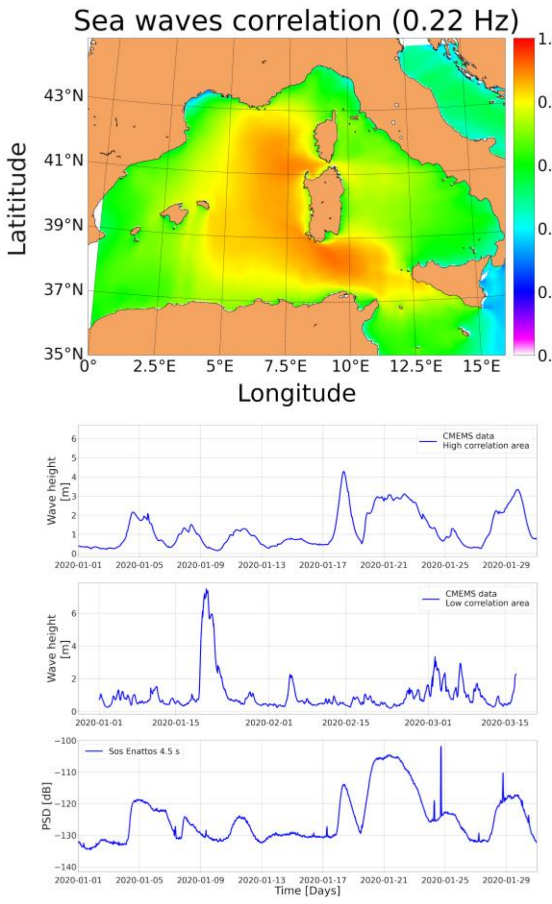
DAQ self-noise limit

DAQ self-noise limit

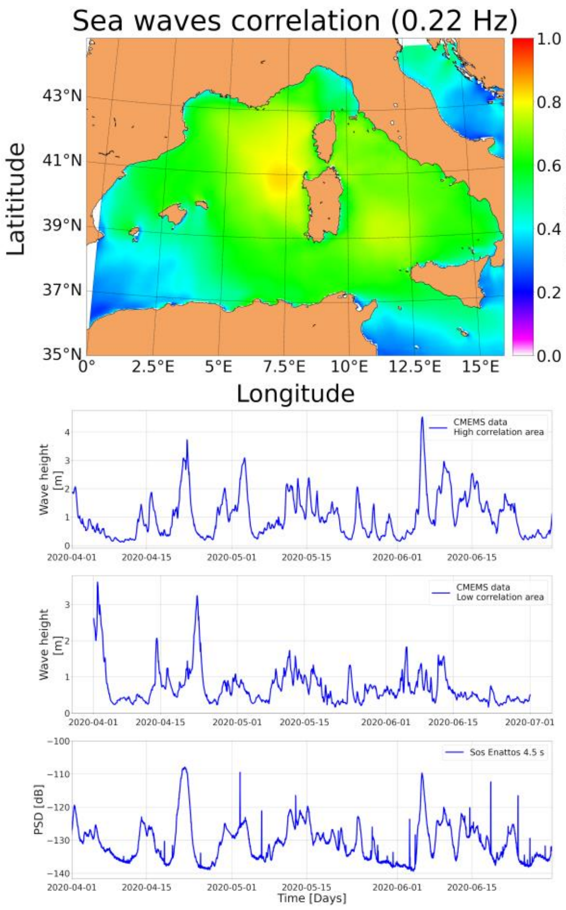
First results at Sos Enattos

Seasonal Microseismic variations in 2020

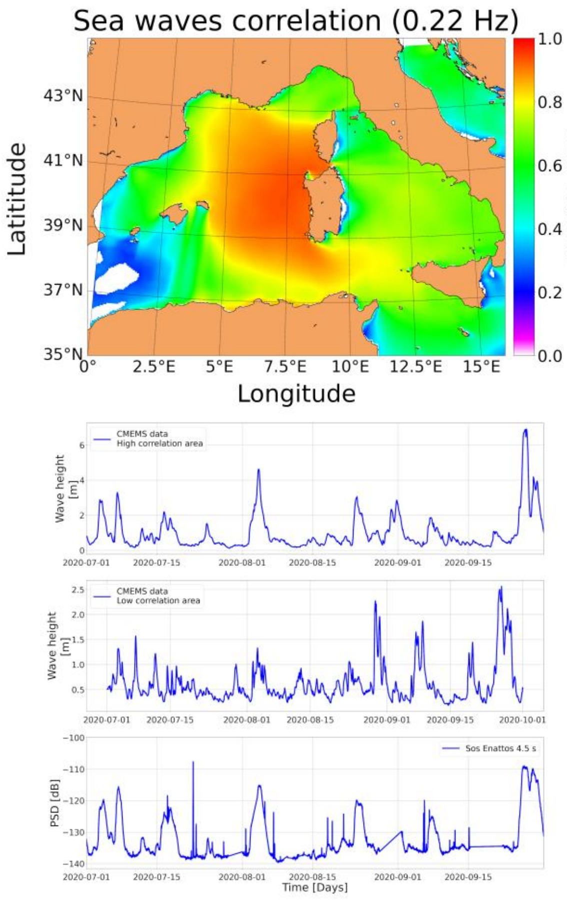
I trimester



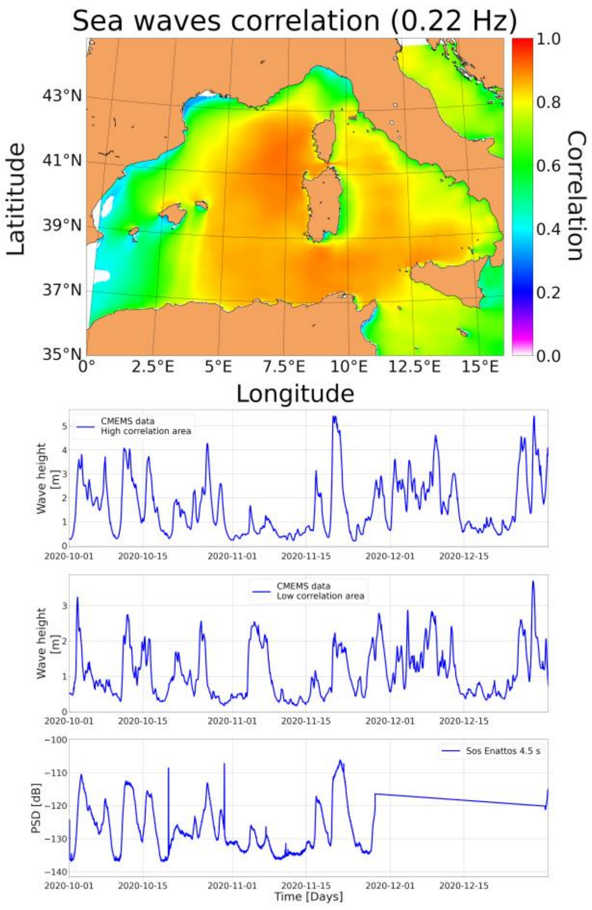
II trimester



III trimester

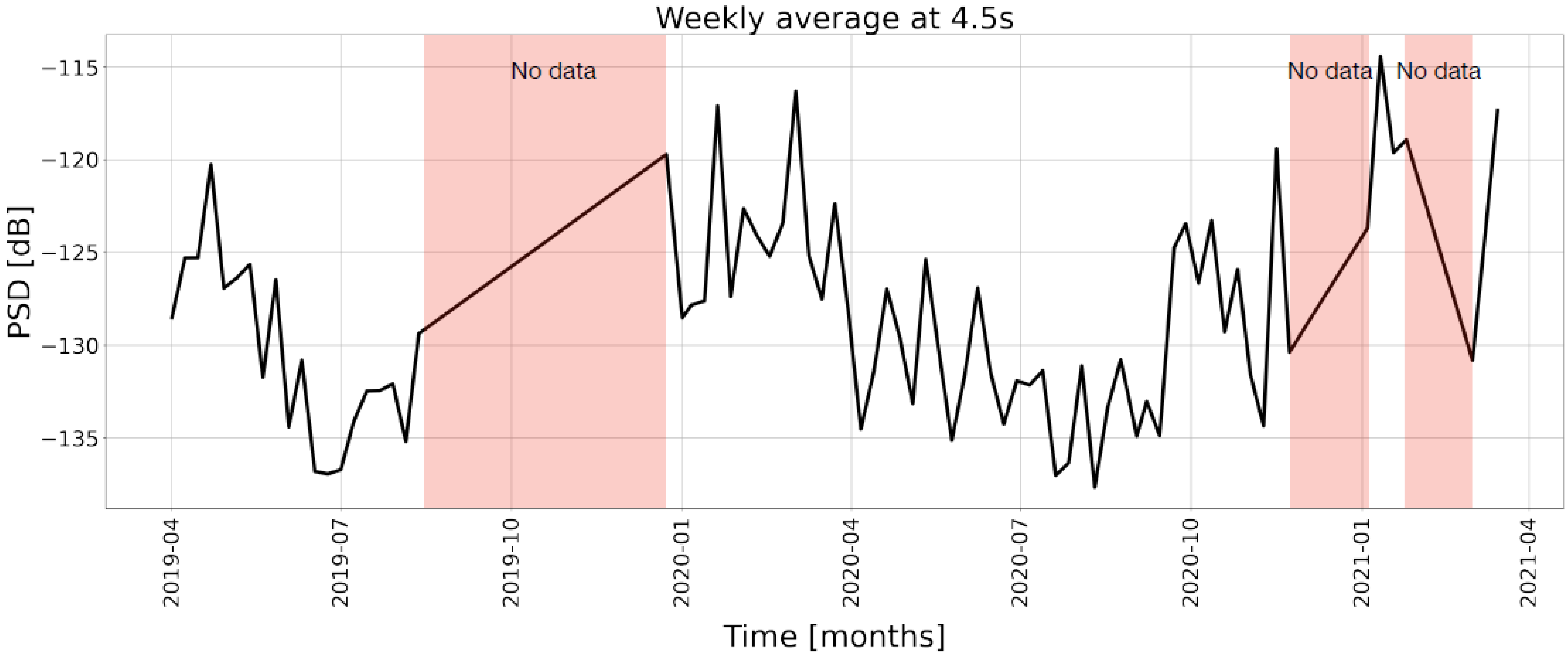


IV trimester



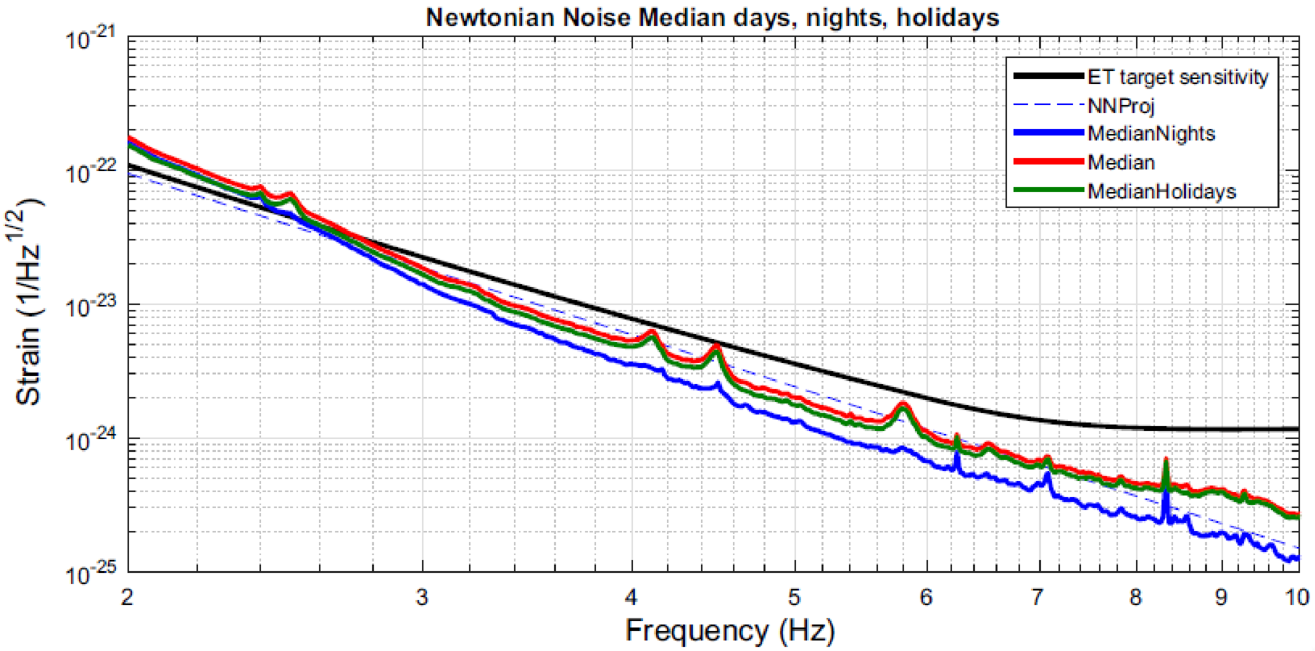
First results at Sos Enattos

Seasonal Microseismic noise trend in 2019-2021



First results at Sos Enattos

Newtonian Noise & seismic glitches (based on 2020 data at SOE1, -84m)



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

Defining the Newtonian Noise ASD as:

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

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

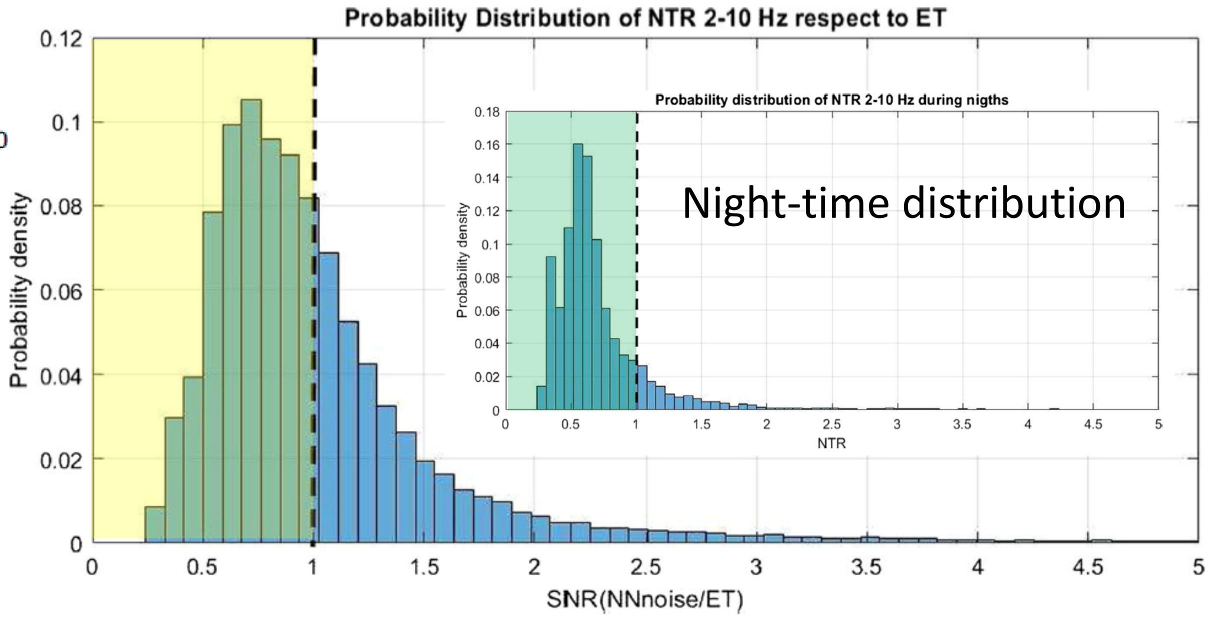
$$\mathrm{NTR} = \sqrt{\frac{1}{\Delta f} \int df \frac{\tilde{N} * \tilde{N}}{S_h}}$$

PSD of NN

PSD of ET sensitivity

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

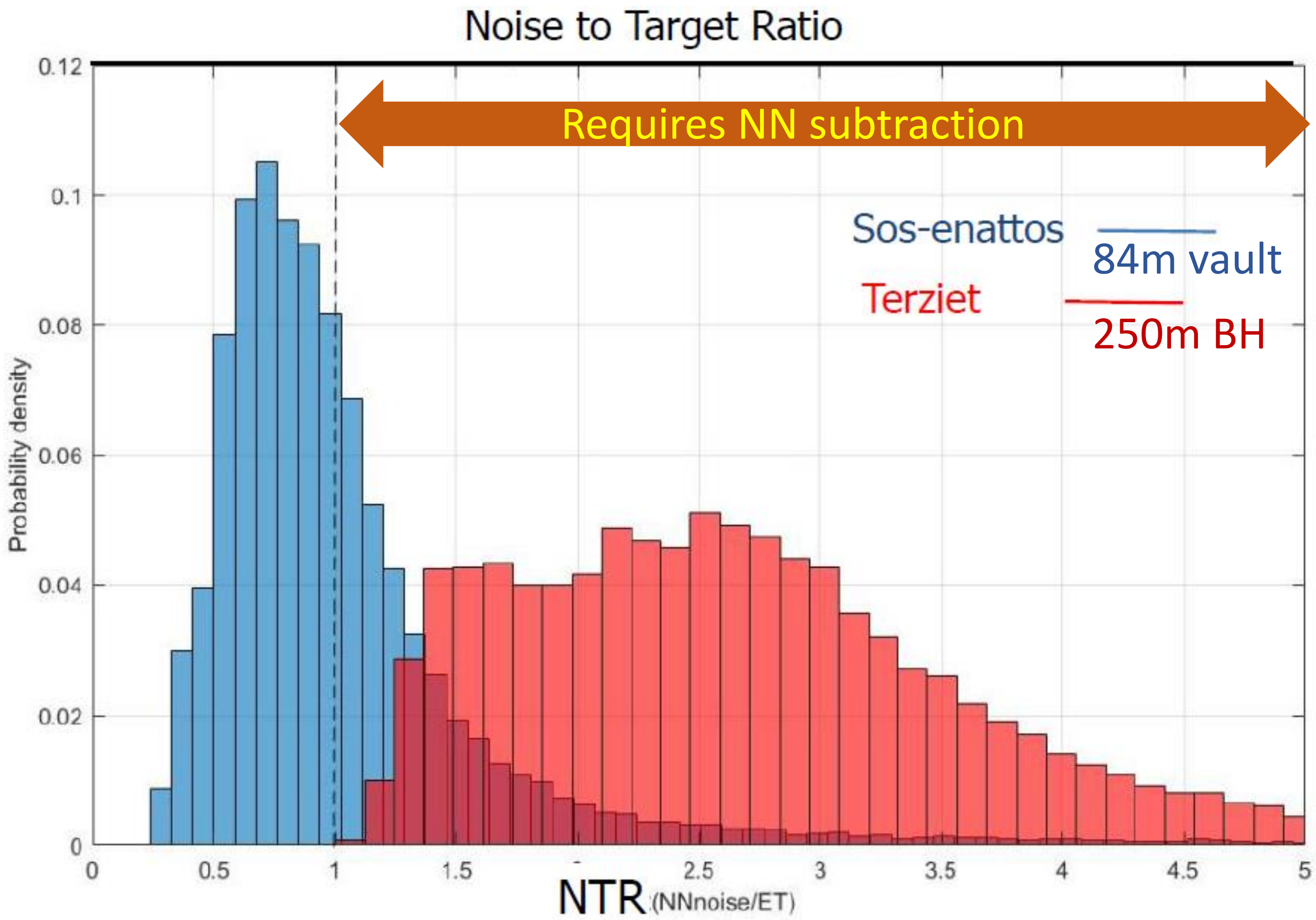
→Need for moderate NN subtraction only for a limited time



First results at Sos Enattos

Newtonian Noise & seismic glitches (based on 2020 data at SOE1, -84m)

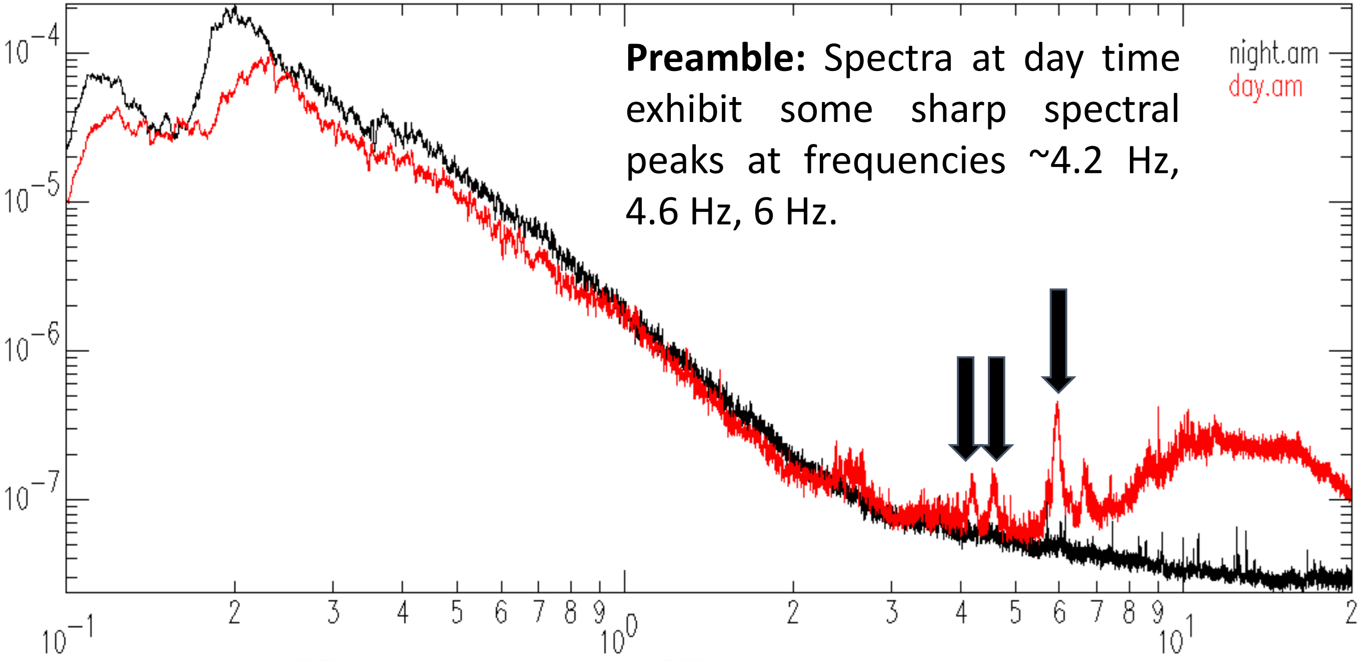
…doing the same exercise with Terziet site (-250m) public data:



First results at Sos Enattos

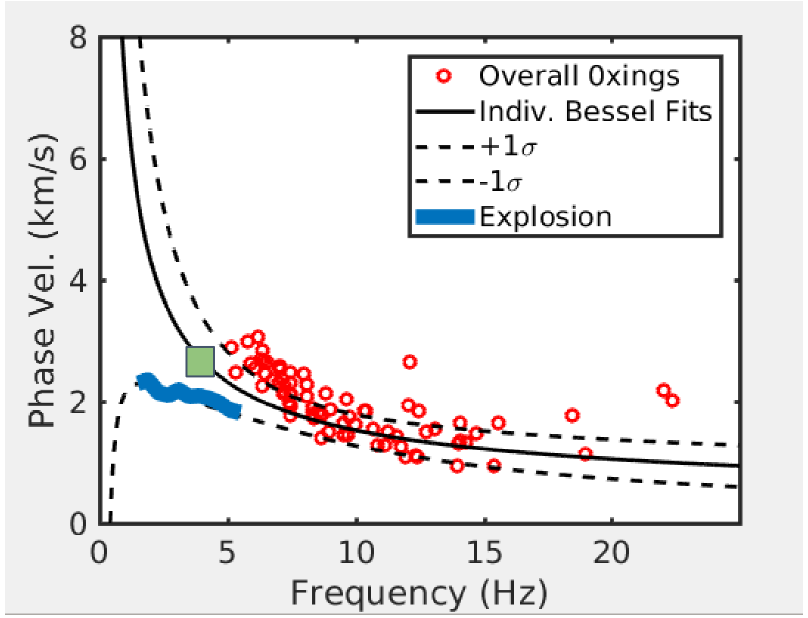
Seismometer array results

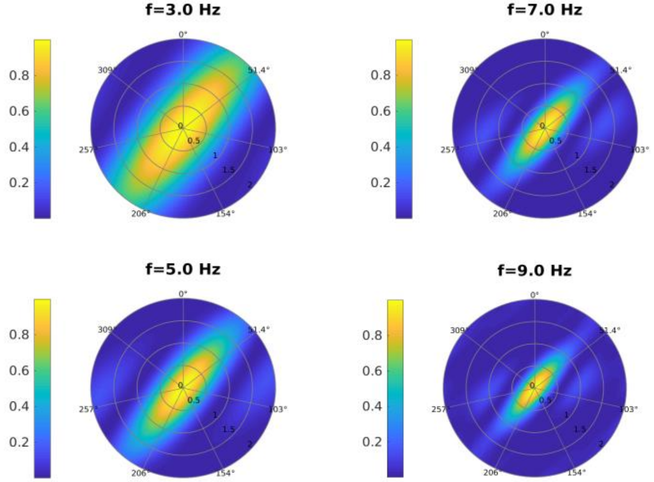
Array-stacked spectra:



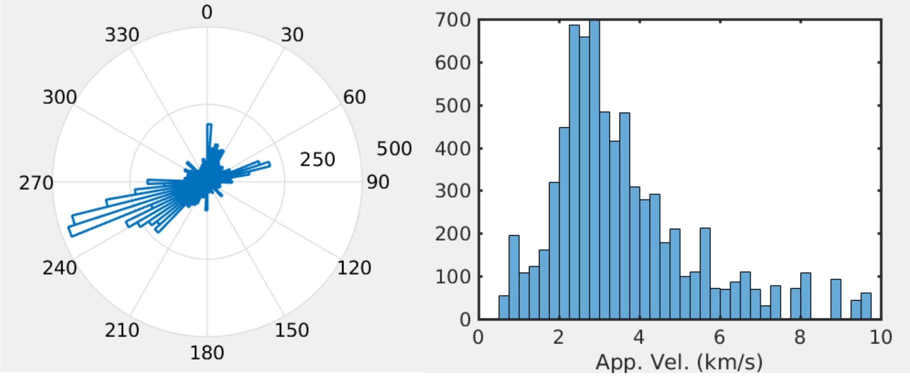
Preamble: Spectra at day time exhibit some sharp spectral peaks at frequencies ~4.2 Hz, 4.6 Hz, 6 Hz.

SPatial AutoCorrelation:





FK-Analysis

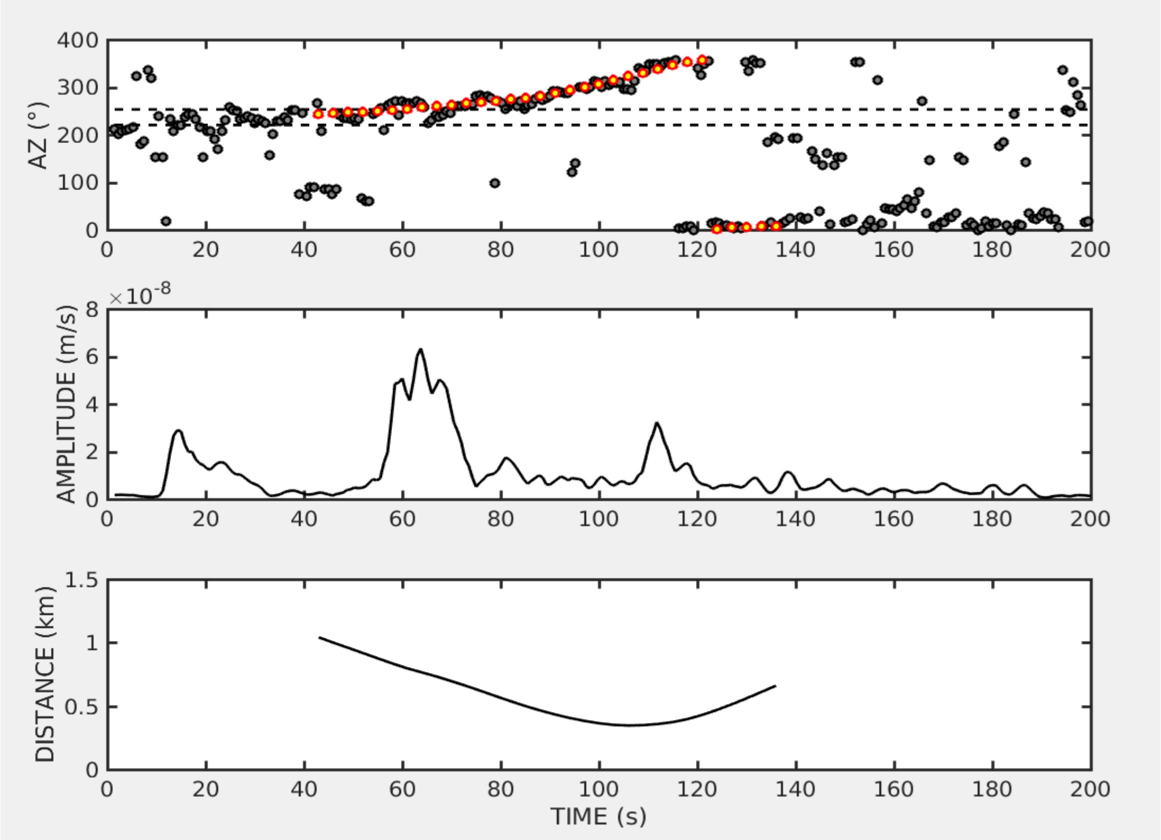


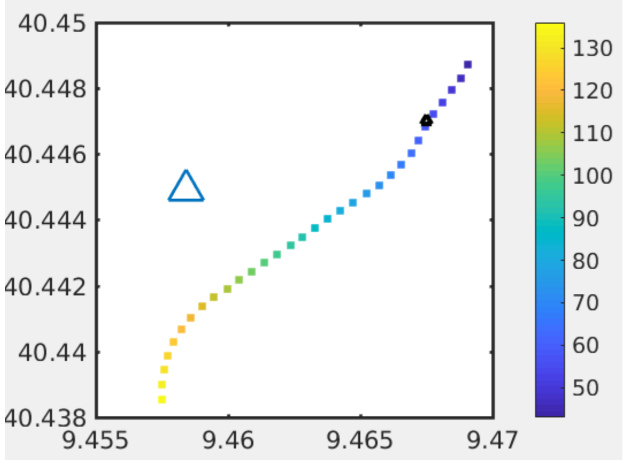
Not-isotropic wavefield
Peaks at f = 4-5 Hz
Propagation azimuths directed WSW (i.e., main sources located ENE of the array)
High velocities (~2.5 km/s)

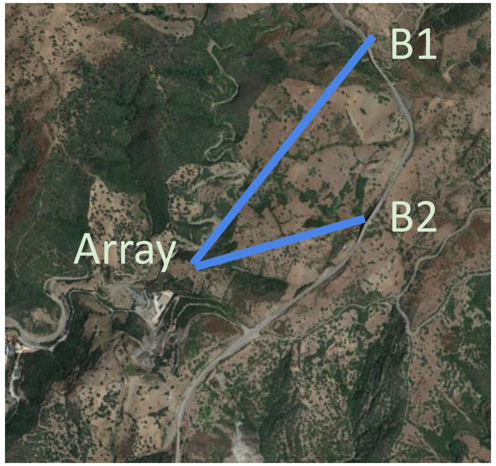
First results at Sos Enattos

Seismometer array results

Vehicle Tracking close to the site







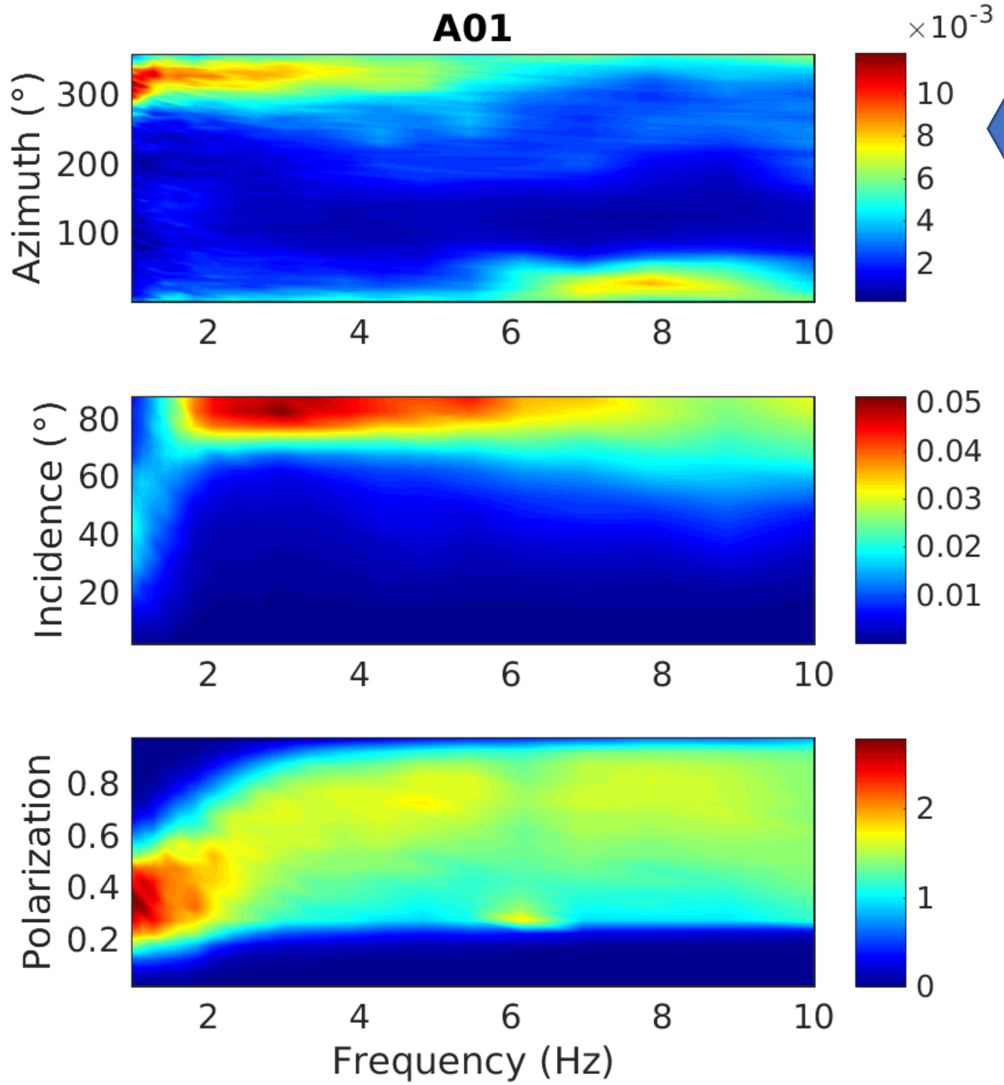
Time evolution of azimuth compatible with a vehicle traveling at 60 km/h southward along road SP73.

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

First results at Sos Enattos

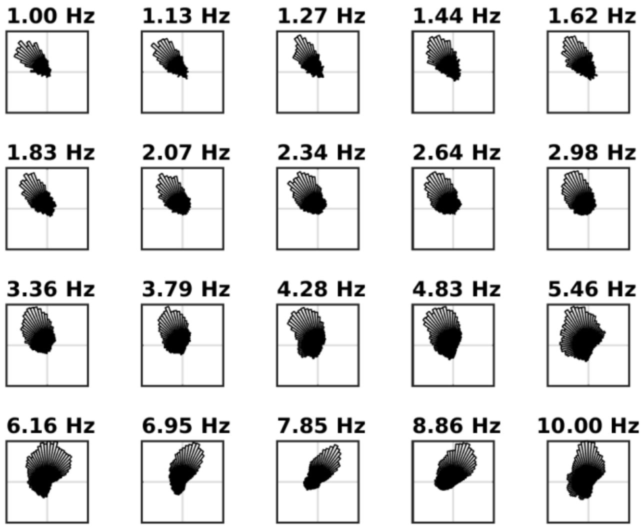
Seismometer array results

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.

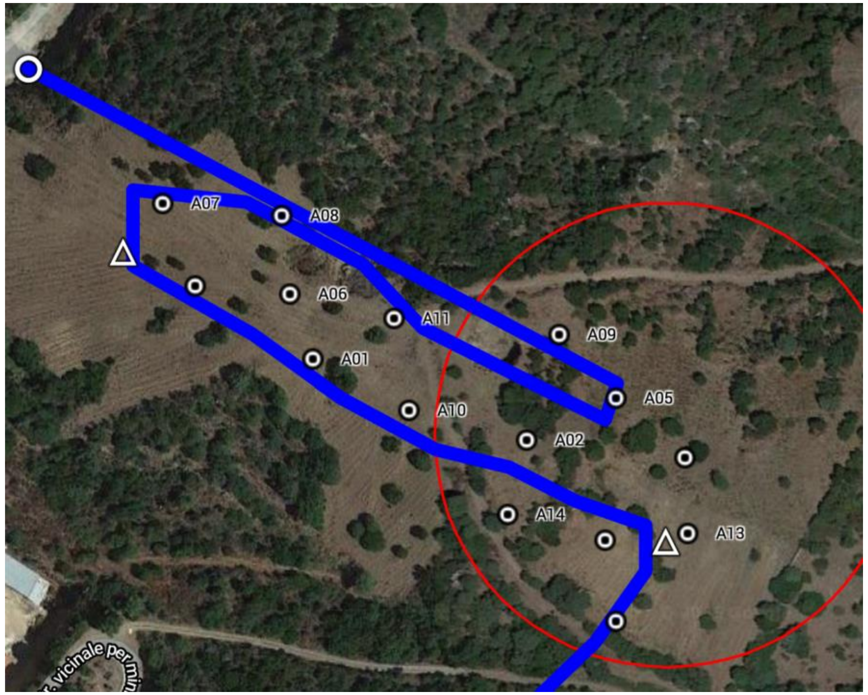


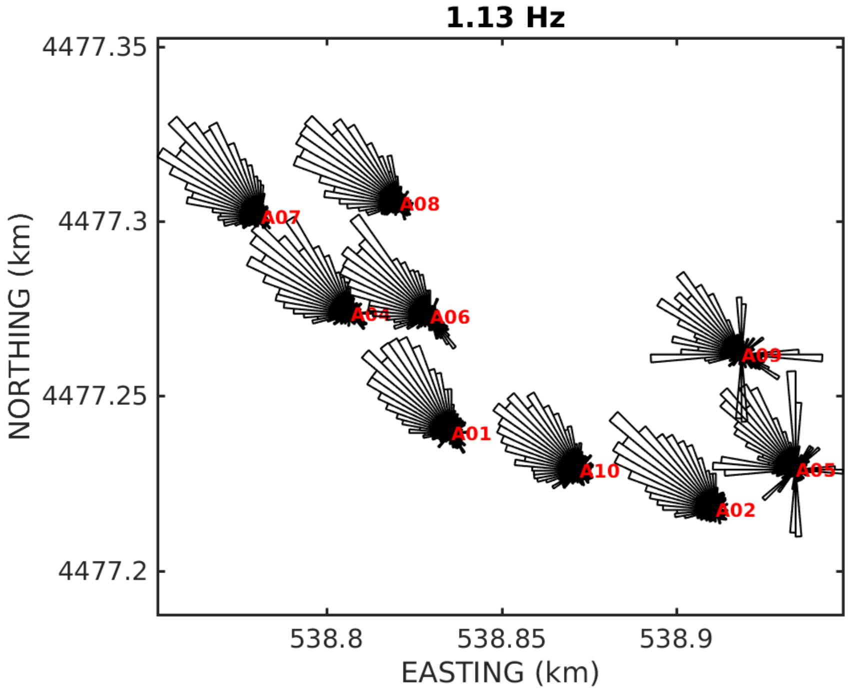
First results at Sos Enattos

Seismometer array results

Polarization analysis

At low frequencies, the polarization directions are rather uniform; they are oriented toward NW (see marine microseismic source).



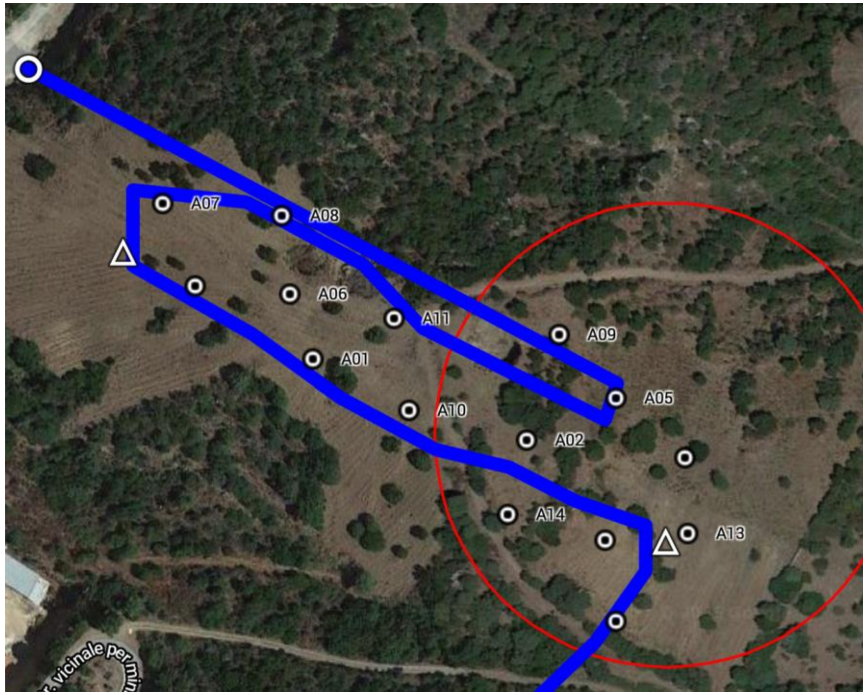


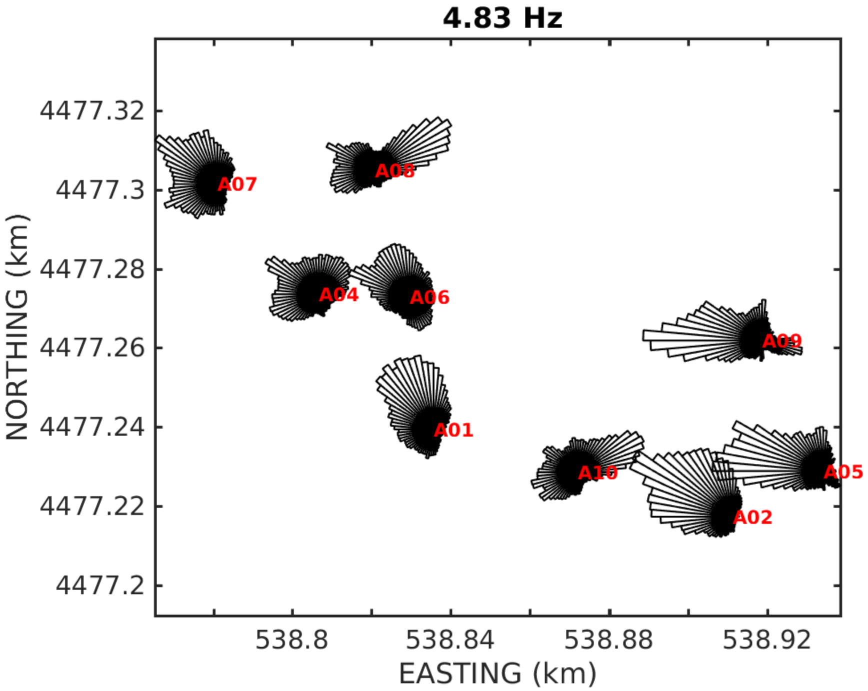
First results at Sos Enattos

Seismometer array results

Polarization analysis

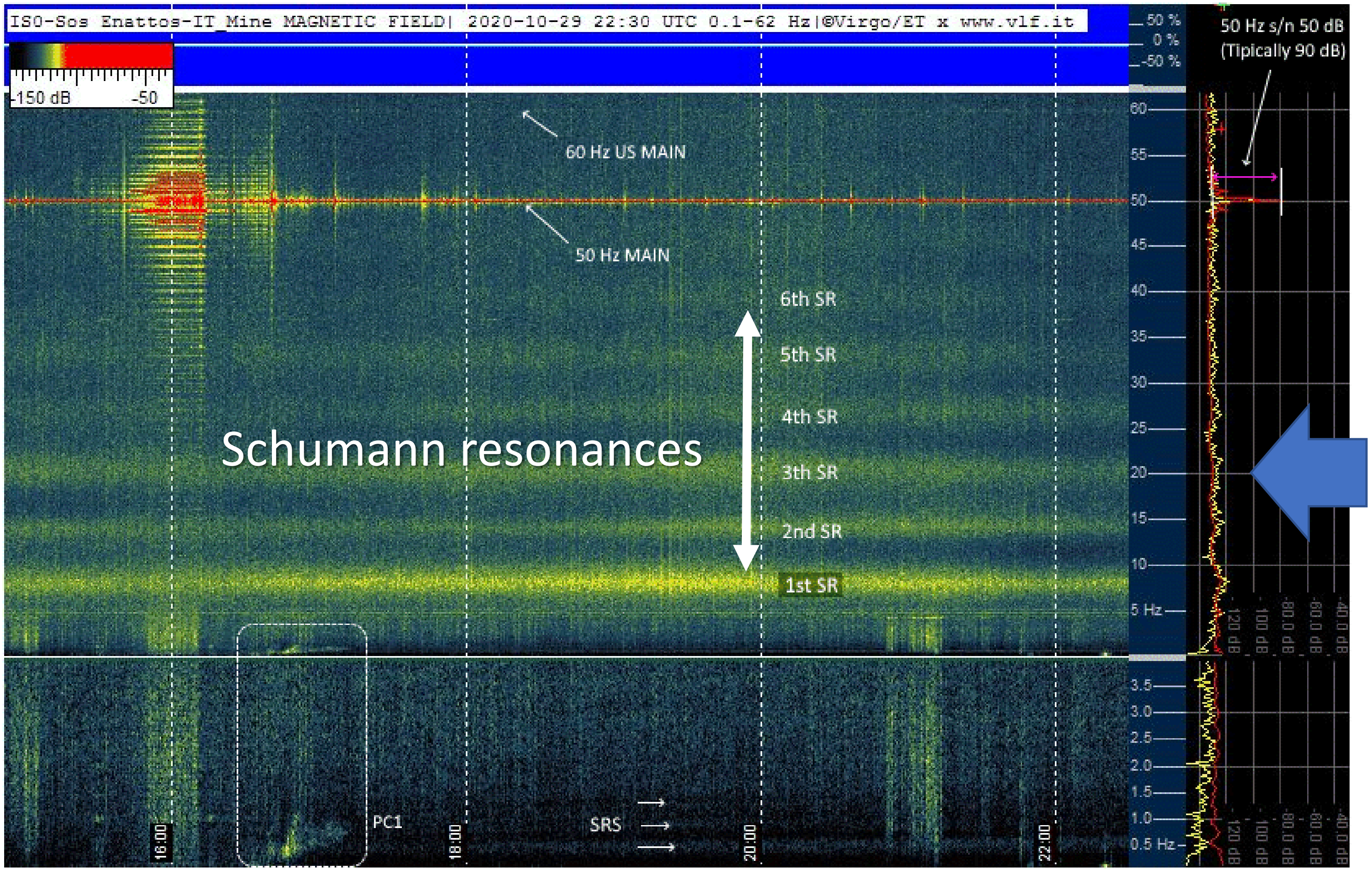
At higher frequencies, the variability of polarization directions throughout the array deployment indicates a strong influence of topography.



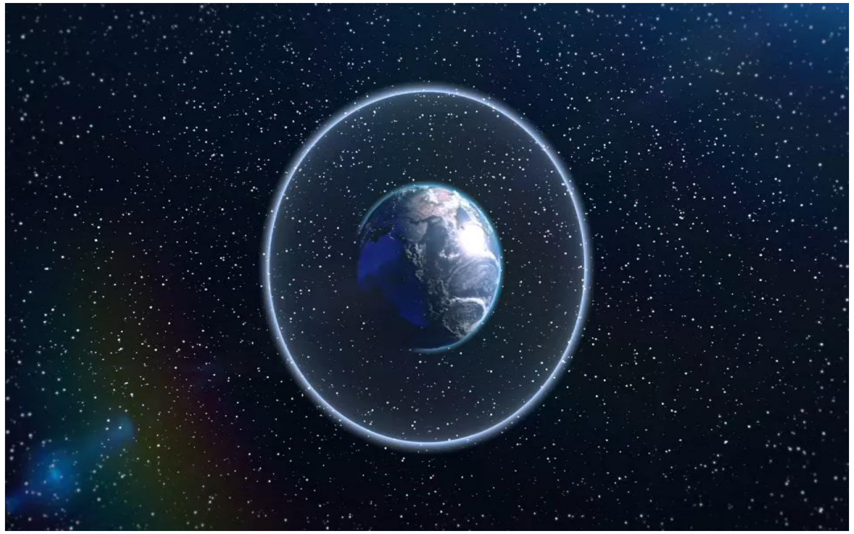


First results at Sos Enattos

Very low electromagnetic noise observed at the site



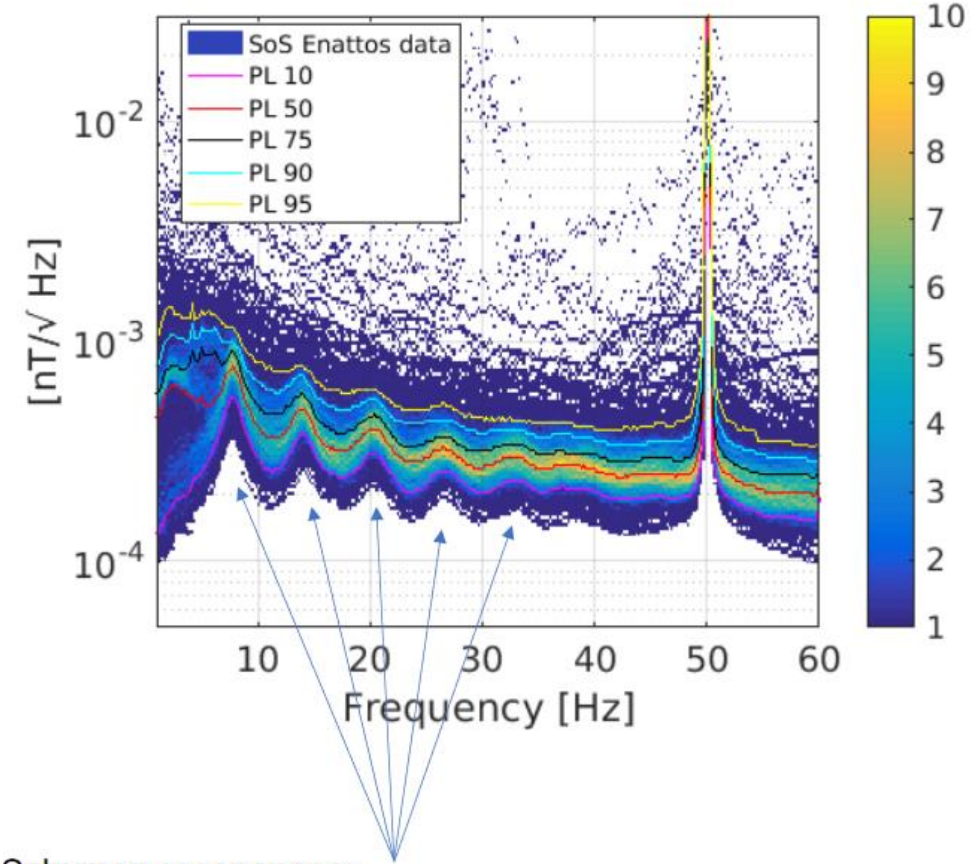
SOE2 (underground) magnetometer.



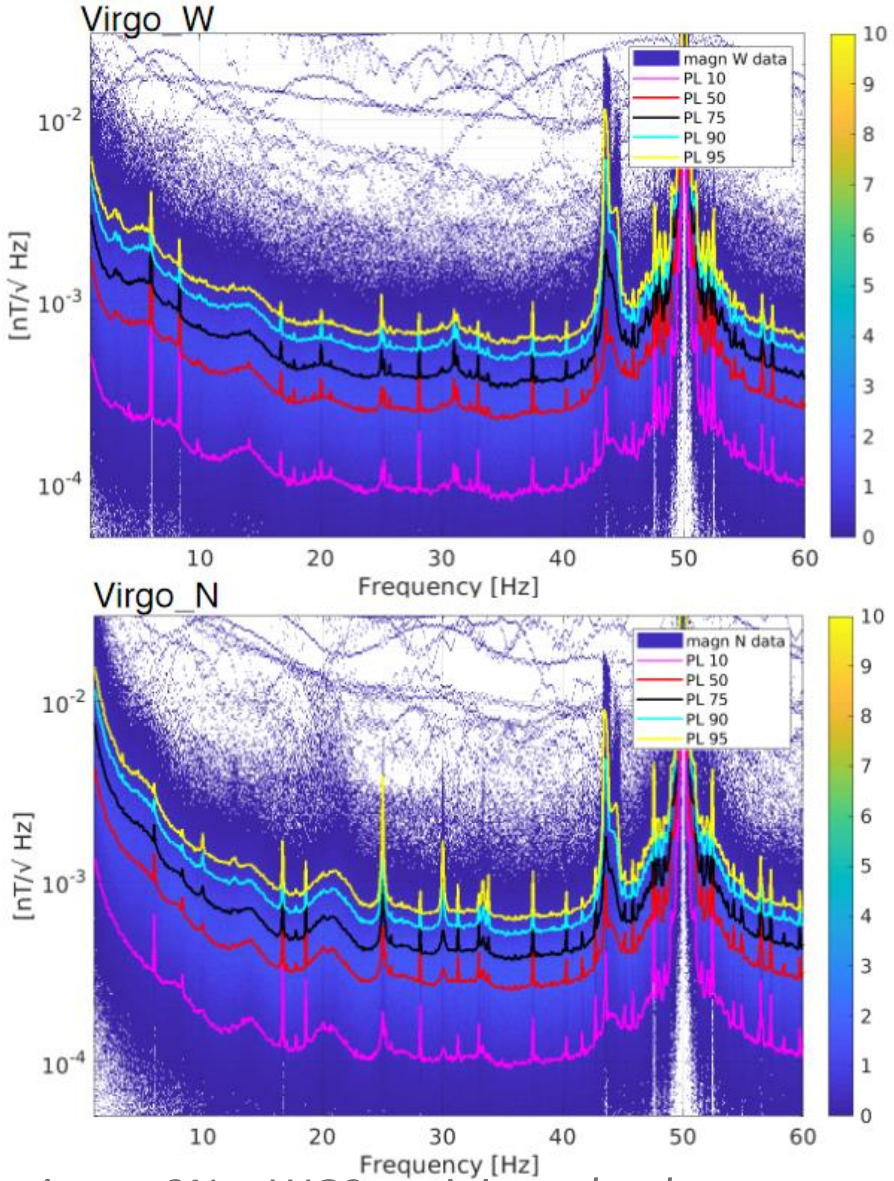
Credit: NASA/Goddard Space Flight Center/Conceptual Image Lab

First results at Sos Enattos

Percentiles
Data: 48 days (Nov 14 –Dec 31)



Schuman resonances:
7.83 Hz, 14.1 Hz, 20.3 Hz, 26.4 Hz, 32.4 Hz

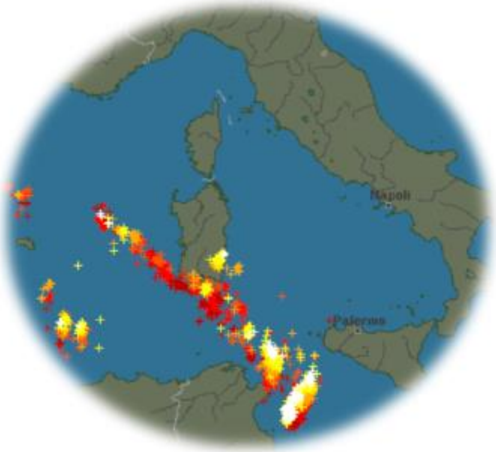


Credit: M.C. Tringali, ET-0005A-20

First results at Sos Enattos

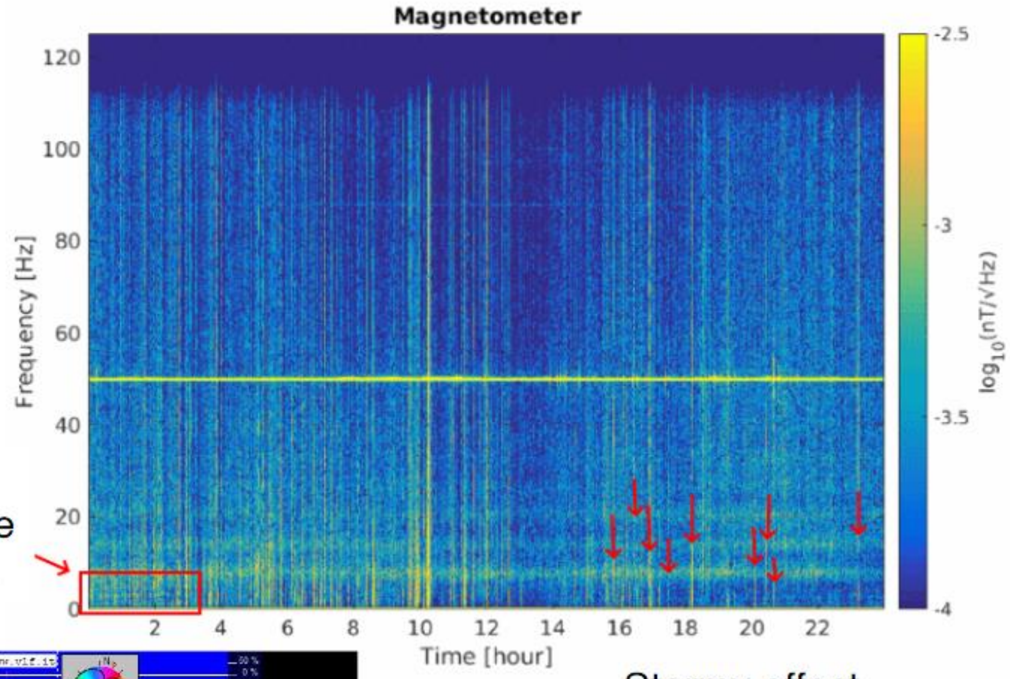
Thunderstorm over Sardinia: Dec 4, h 18:00-21:00

http://en.blitzortung.org

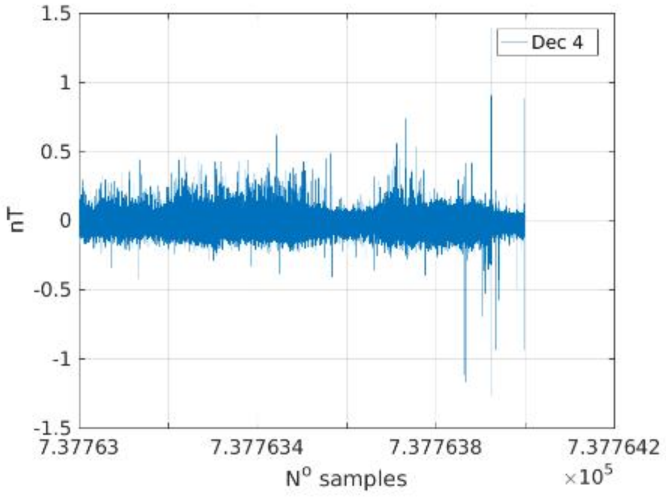


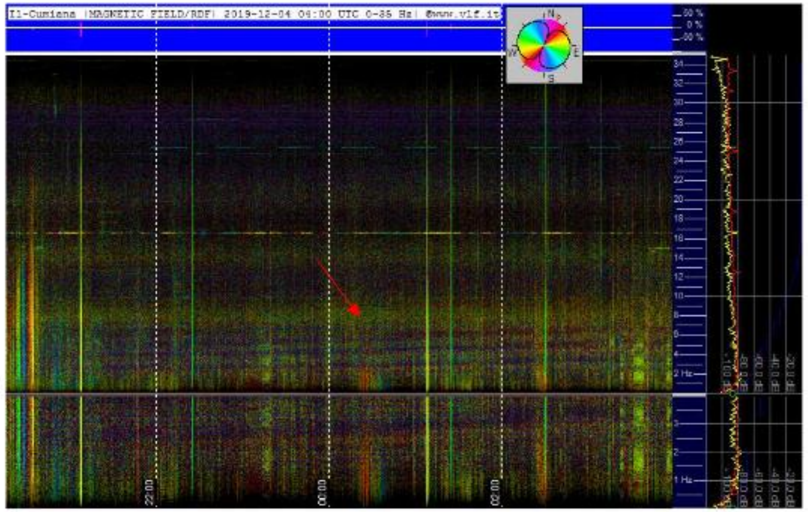
http://www.vlf.it/francionegallery/troncea_2014.html

http://roma2.rm.ingv.it/it/tematiche/39/elettromagnetismo_ambientale/11/fondo_elettromagnetico_naturale

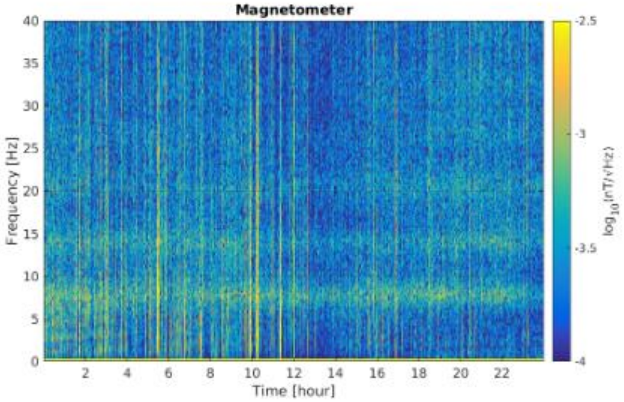


Spectral Resonance Structures





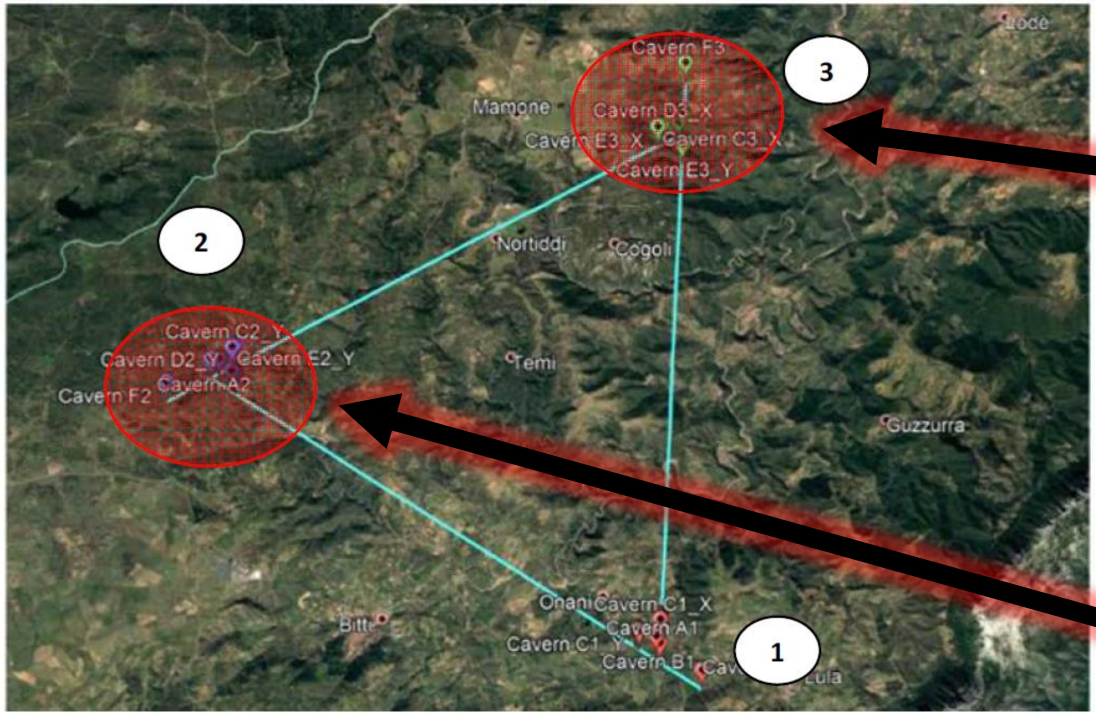
Stormy effect



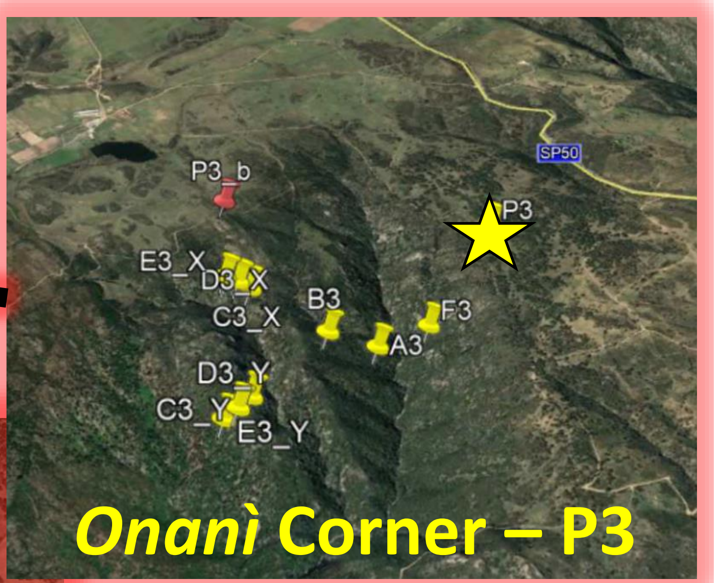
Credit: M.C. Tringali, ET-0005A-20

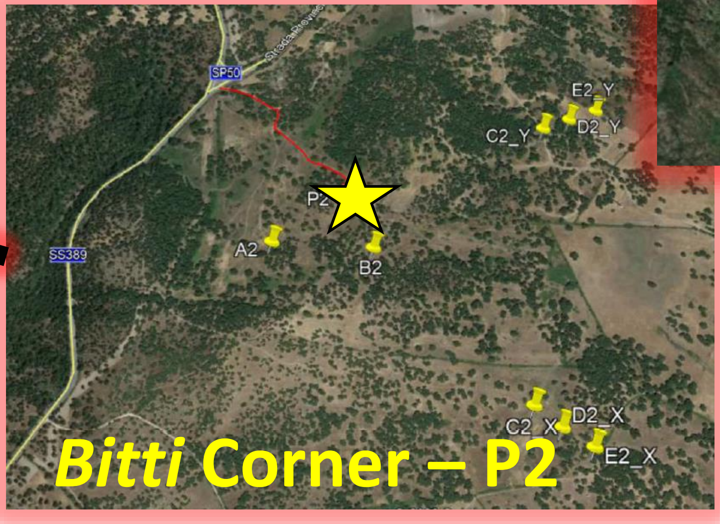
Characterisation of the corners

In July 2021 we started the surface and underground seismic and environmental measurements at the other two corners (named *Bitti* and *Onanì*).



***Lula* Corner**
Sos Enattos





★ : area for boreholes and surface arrays

: proposed locations for ET main caverns

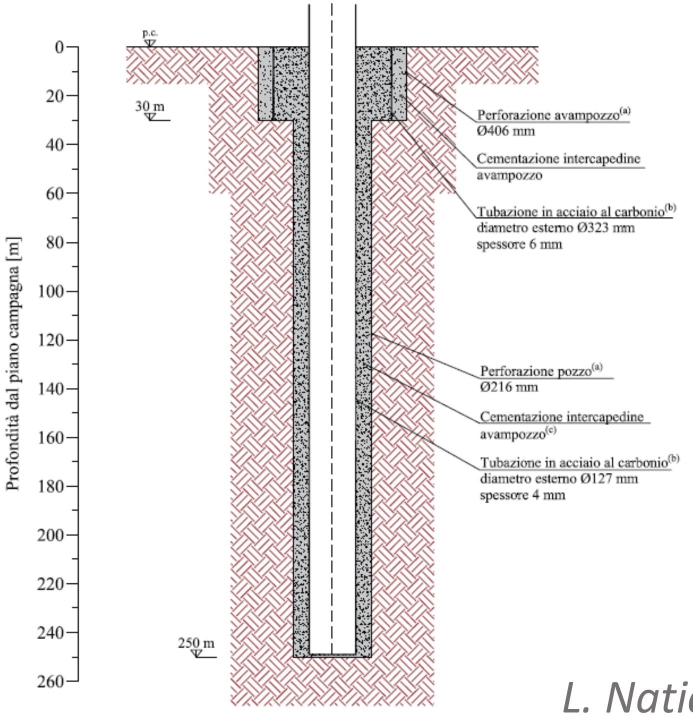
Characterisation of the corners

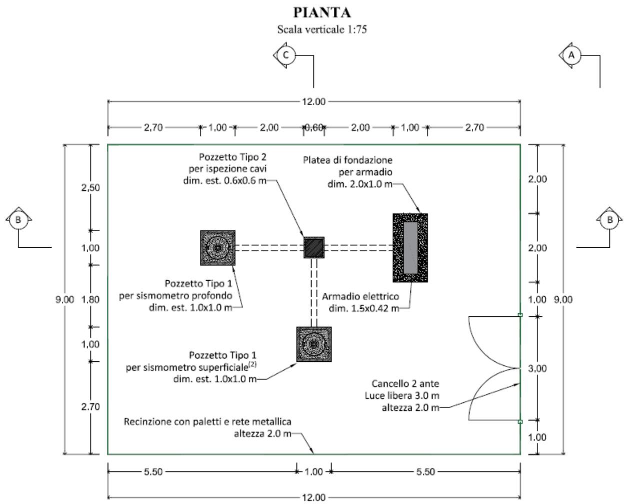
Bitti corner,
borehole area

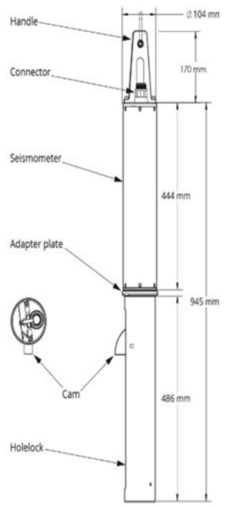
Onanì corner,
borehole area

Characterisation of the corners

- Excavation of two boreholes (265m and 280m deep) at the corner points P2 and P3. The drilling and consolidation of the boreholes has been started in April 2021 and completed in July 2021.
- The borehole walls are equipped with optical fiber strainmeters, and they will be equipped with borehole seismometers (Trillium 120BH) in September 2021. Two Trillium 120H will be installed at surface for comparison (vault installation)







Characterisation of the corners

Characterisation of the corners

- Active seismic measurements at P2 and P3 with a vibration source (minivib vehicle) with hundreds of geophones installed in the field (~1km strings and array) and downhole + optical fiber strainmeter in July 2021;
- Data is being processed and analysed.

Collaboration of:
INFN, INGV, KIT

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

Karlsruher Institut für Technologie

Outline

Part I summary:

- ❑ Introduction: The Einstein Telescope project
- ❑ Environmental sources of noise vs ET sensitivity
- ❑ Site selection criteria
- ❑ Euregio Meuse-Rhine candidate site
- ❑ Sardinia candidate site
- ❑ A practical example: site characterisation activities in Sardinia
- ❑ **Seismic noise analysis**

Seismic data analysis

A common data format for seismic data is the **SEED** (Standard for the Exchange of Earthquake Data) or **mini-SEED**, in which the timeseries are recorded with minimal metadata informations.

More info at: https://ds.iris.edu/ds/nodes/dmc/data/formats/seed/

In the **mini-SEED** the time series are stored as generally independent, fixed length data records which each contain a small segment of contiguous series values. A reader of miniSEED is required to reconstruct longer, contiguous time series from the data record segments. Common record lengths are 512-byte (for real time streams) and 4096-byte (for archiving), other record lengths are used for special scenarios.

A *file* or *stream* of miniSEED is simply a concatenation of data records. Depending on the capabilities of the intended reader the data records for multiple channels of data may be multiplexed together.

Seismic data analysis

In the next exercitations we will see two ways to access and analyse the seismic data:

1. Accessing stored seed files with MatLab functions;

2. Using the ObsPy environment under Python to access data directly from seismic stations in the network.

Requirements:
(1) Having MatLab installed on your laptop
(2) Having ObsPy installed on your laptop (see the guide distributed before the lecture: https://drive.google.com/file/d/1LgzzPIwK52_rT_btW1tw4Cem4RJch1e4/view?usp=sharing)

At the end of each part you will find some exercitations you can try by yourself

Part II

Outline

Part II summary:

- ❑ **Reading and extracting seismic data with MatLab**
- ❑ Reading and extracting seismic data with ObsPy (Python environment)
- ❑ Exercitation with SOE2 (Sardinia site) data
- ❑ Exercitation with Terziet (Meuse-Rhine site) data
- ❑ Exercitation with LNGS (underground laboratory) data
- ❑ Other proposed exercitations

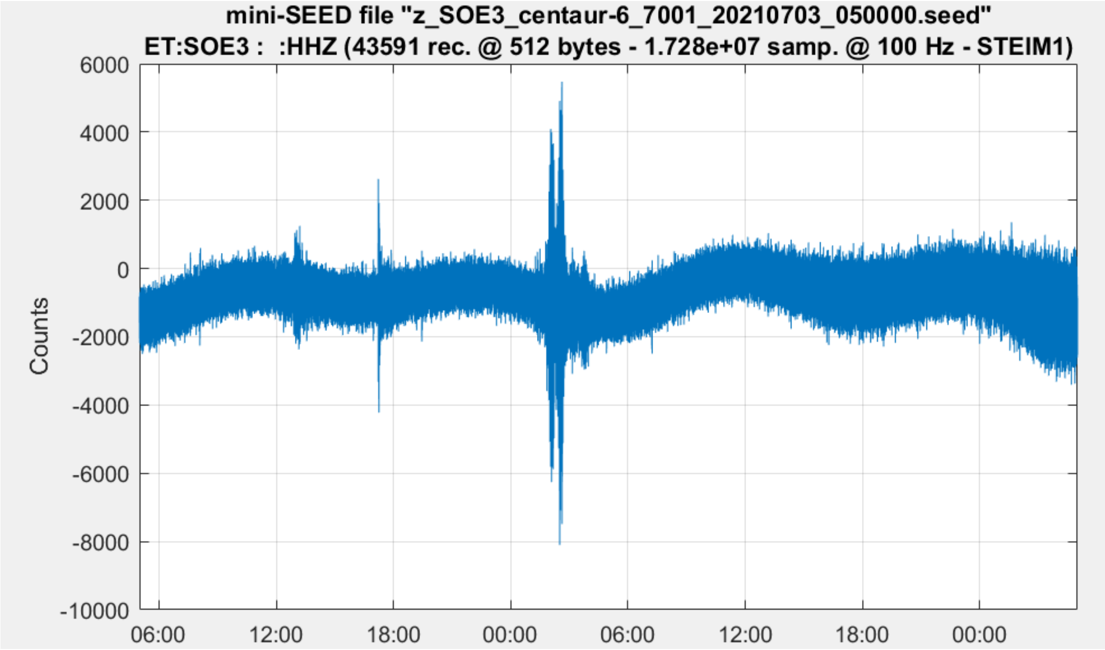
Reading and extracting seismic data with MatLab

Under MATLAB it is possible to open a SEED or mini-SEED file and to extract the timeseries in ASCII format using the function “RDMSEED.m”
[*https://it.mathworks.com/matlabcentral/fileexchange/28803-rdmseed-and-mkmseed-read-and-write-miniseed-files*](https://it.mathworks.com/matlabcentral/fileexchange/28803-rdmseed-and-mkmseed-read-and-write-miniseed-files)

Example:
Open a seed containing the vertical channel recorded by a T240:

>> RDMSEED *PathToFile/FileName.seed*

Output:



Reading and extracting seismic data with MatLab

Under MATLAB it is possible to open a SEED or mini-SEED file and to extract the timeseries in ASCII format using the function “RDMSEED.m”
https://it.mathworks.com/matlabcentral/fileexchange/28803-rdmseed-and-mkmseed-read-and-write-miniseed-files

Example:
Extract the timeseries in an ASCII file using the RDMSEED function with a little script I prepared:
RWseedTOAscii.m
https://drive.google.com/file/d/1mtajh25kv59EksCMqaIjFON8z3MDAMmo/view?usp=sharing

```
>> RWseedTOascii

 please select the directory with .seed files to convert


 conversion completed!
 ascii data (.txt) saved in D:\DATI\sardegna\20210703\SOE3\
```

```
-1.5780000e+03
-1.6060000e+03
-1.5870000e+03
-1.5530000e+03
-1.6220000e+03
-1.5690000e+03
-1.5550000e+03
-1.5800000e+03
-1.5460000e+03
-1.5680000e+03
-1.5150000e+03
-1.5650000e+03
-1.5640000e+03
```

At this point, knowing the **sampling rate** *f* and the **conversion factor** (cnt/m/s) you can calculate the power spectral density…

Reading and extracting seismic data with MatLab

Proposed exercitation with real data:
https://drive.google.com/drive/folders/1jF91fdL8suy76-Bav8aS-vLUUvv3cX8s?usp=sharing

The mini-SEED files are from the three seismic station at Sos Enattos (Sardinia): **SOE1**, **SOE2**, **SOE3**
They are located in seed-data/soe*/, where you can find a mini-SEED for each direction (N-S, E-W, Z).

Try to extract the timeseries and to calculate the PSD. You can find in *seed-data/soe*/PSD/* what you should obtain: PSD in acceleration, velocity, displacement, and four arrays of data (frequency and the PSD for each direction). *Hint: plot the median value of PSD*

The seismometer DAQs have a common timing reference.
Start time: 05:00 AM UTC, 3rd July 2021
End time: 05:00 AM UTC, 5th July 2021
Sampling frequency: `f=100Hz`
Conversion factors (cnt/m/s):

```
SOE1: cms=4.81e9          @4Vpp Trillium120H
SOE2: cms=7998040000      @4Vpp Trillium360
SOE3: cms=4.756e9         @4Vpp Trillium240
```

Outline

Part II summary:

- ❑ Reading and extracting seismic data with MatLab
- ❑ **Reading and extracting seismic data with ObsPy (Python environment)**
- ❑ Exercitation with SOE2 (Sardinia site) data
- ❑ Exercitation with Terziet (Meuse-Rhine site) data
- ❑ Exercitation with LNGS (underground laboratory) data
- ❑ Other proposed exercitations

Seismic data analysis with ObsPy

ObsPy provides an open-source Python framework for processing seismological data.
The official tutorial is available at: https://docs.obspy.org/tutorial/index.html

For the purpose of this exercitation we will use Jupyter Notebook, that you should have installed along with Anaconda, the ObsPy environment and the additional packages indicated in the guide:
https://drive.google.com/file/d/1LgzzPIwK52_rT_btW1tw4Cem4RJch1e4/view?usp=sharing

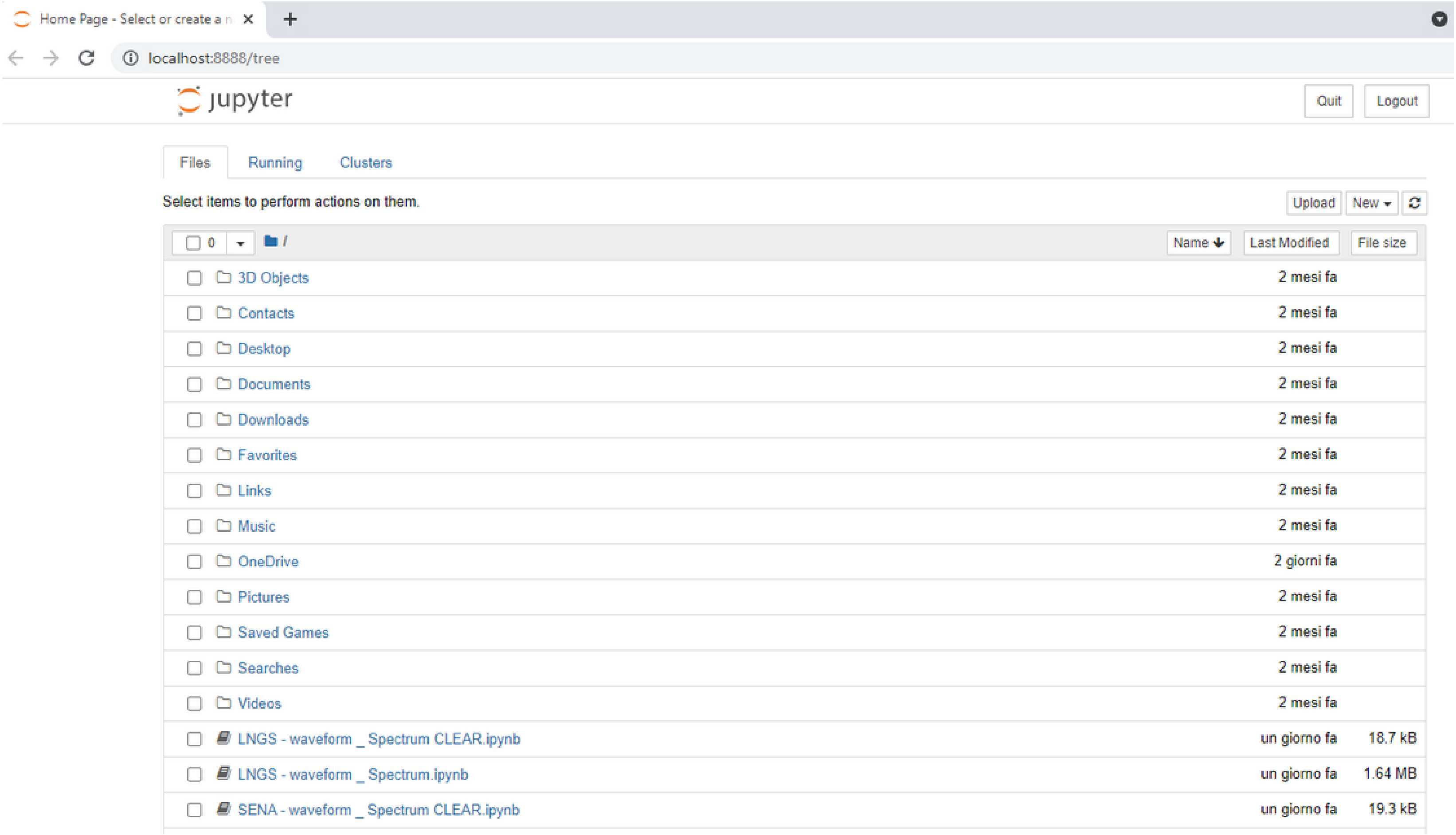
From the prompt you can start a notebook typing “jupyter notebook”

```
(obspy) C:\Users\Luca>jupyter notebook
[I 13:23:40.822 NotebookApp] Serving notebooks from local directory: C:\Users\Luca
[I 13:23:40.822 NotebookApp] Jupyter Notebook 6.2.0 is running at:
[I 13:23:40.822 NotebookApp] http://localhost:8888/?token=2dbe09e97fe038f44cbdf8cd475eee94cdaa130a4c92145e
[I 13:23:40.822 NotebookApp]  or http://127.0.0.1:8888/?token=2dbe09e97fe038f44cbdf8cd475eee94cdaa130a4c92145e
[I 13:23:40.822 NotebookApp] Use Control-C to stop this server and shut down all kernels (twice to skip confirmation).
[C 13:23:41.000 NotebookApp]

    To access the notebook, open this file in a browser:
        file:///C:/Users/Luca/AppData/Roaming/jupyter/runtime/nbserver-15248-open.html
    Or copy and paste one of these URLs:
        http://localhost:8888/?token=2dbe09e97fe038f44cbdf8cd475eee94cdaa130a4c92145e
     or http://127.0.0.1:8888/?token=2dbe09e97fe038f44cbdf8cd475eee94cdaa130a4c92145e
```

Seismic data analysis with ObsPy

You will redirected to your browser at the page http://localhost:8888/tree where you will find the directory and file tree. This is the default directory where your notebooks will be saved.



Under Windows OS this is the folder: C:\Users*accont_name*

You can copy in this folder the notebooks provided for the exercitation. You can find the executed and the clear versions (the latter indicated as “CLEAR”) to access data from 4 seismic stations.

Outline

Part II summary:

- ❑ Reading and extracting seismic data with MatLab
- ❑ Reading and extracting seismic data with ObsPy (Python environment)
- ❑ **Exercitation with SOE2 (Sardinia site) data**
- ❑ **Exercitation with Terziet (Meuse-Rhine site) data**
- ❑ **Exercitation with LNGS (underground laboratory) data**
- ❑ Other proposed exercitations

ONLINE EXERCITATION

The Jupyter notebooks used in the exercitation are available here:

https://drive.google.com/drive/folders/1CYdLxIu0bubopZmM06VICGI2AAD6mQ2w?usp=sharing

Proposed exercitations:

- Try to analyse data from different periods: check for seasonal effects;
- Try to analyse data from other locations in the seismic network. Evaluate the effect of the anthropic noise (1-10Hz) depending on the station location (proximity to, or distance from high population density zones)

here you find the several seismic networks: https://www.fdsn.org/networks/

e.g. the Italian network: https://www.fdsn.org/networks/detail/IV/
the Netherlands network: https://www.fdsn.org/networks/detail/NL

Thanks for your attention!

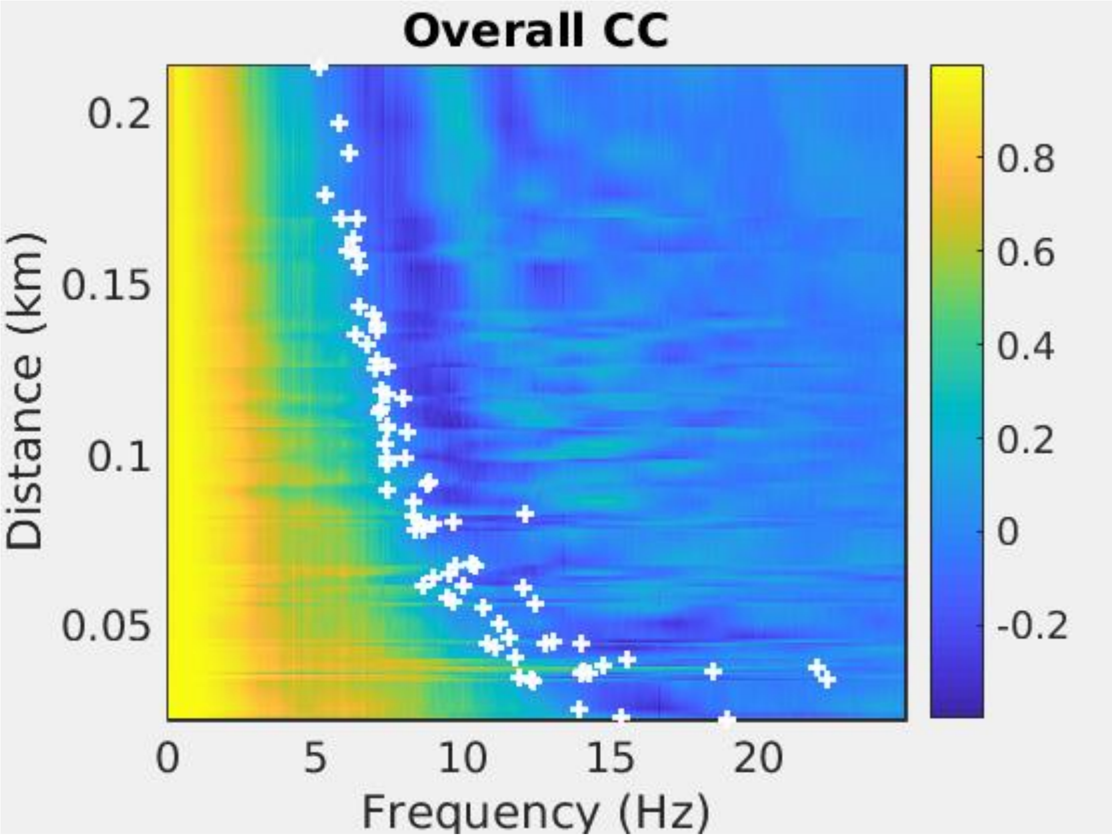
BACKUP SLIDES

Sos Enattos site characterisation

ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

Credit: G. Saccorotti

SPatial **A**uto**C**orrelation - I



Under the hypothesis that the noise wavefield is **stochastic** and **stationary in time and space**, the relationship between spatial autocorrelation and phase velocity is:

$$C(f,r) = J_0\,(2\,\pi\,r\,f\,/\,c(f))$$

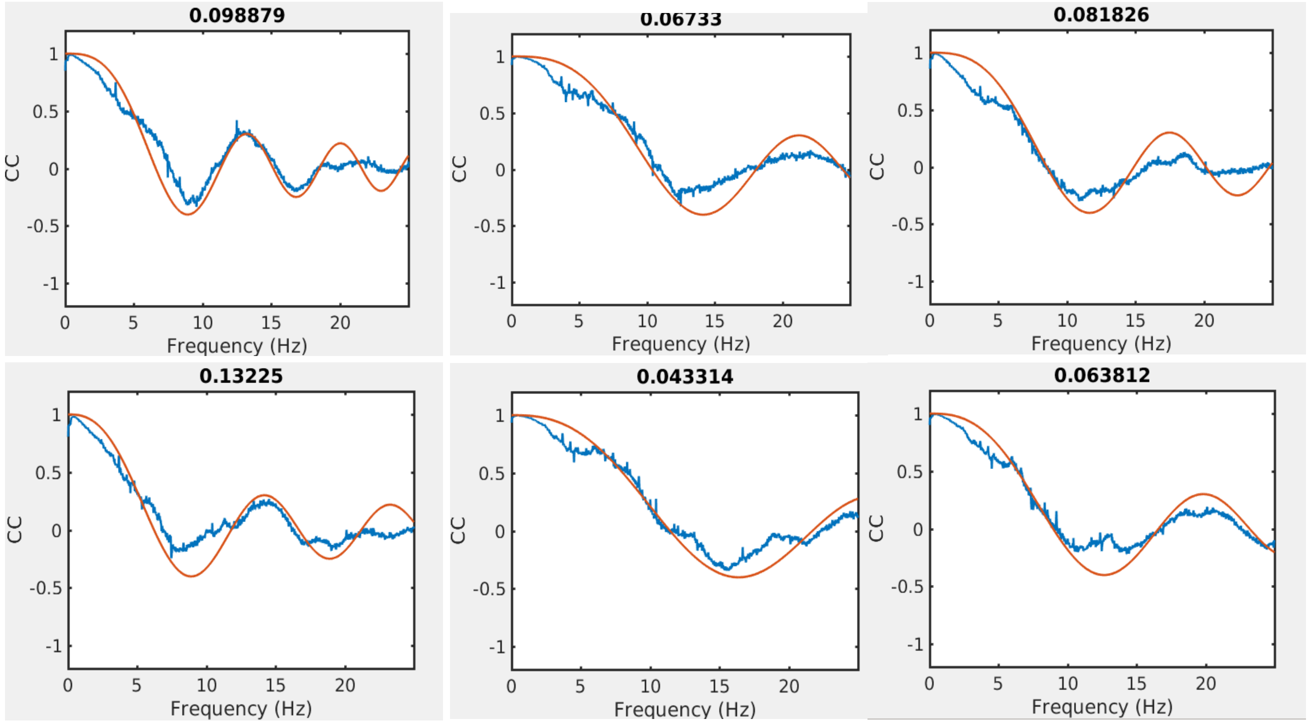
SPAC is derived at all the independent station pairs over the DC-25Hz frequency band.

Form the 1st zero-crossing, we derive c(f)

Sos Enattos site characterisation

SPatial **A**uto**C**orrelation - II

Credit: G. Saccorotti



Dispersion curves for individual CCs.

Red lines are the Bessel fits assuming dispersion follows a power law in the form:

$c(f)=A\,f^{-b}$

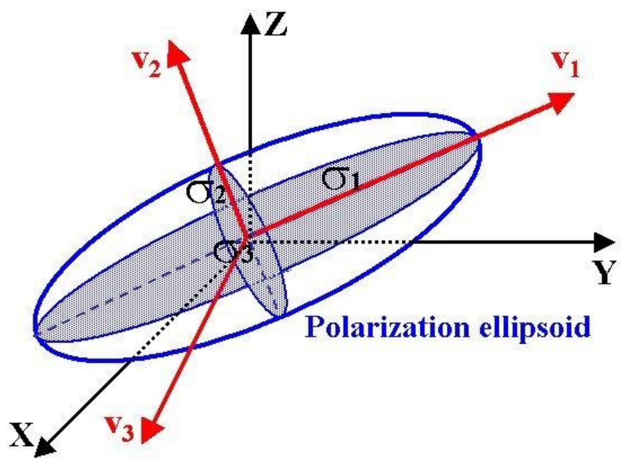
ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

Polarization Analysis - I

Credit: G. Saccorotti

Recap: Seismometers record the 3 components (EW,NS,Up-Down) of ground motion.

Polarization Attributes are derived from the eigen-structure of the 3x3 covariance matrix evaluated over a given time frame.



The eigenstructure of the covariance matrix defines the axes of the polarization ellipsoid best fitting the 3C particle motion.

The amplitude of the **main eigenvalue** relative to the secondary ones defines the Degree of Polarization (or *rectilinearity*).

The eigenvector associated with the main eigenvalue defines the *polarization azimuth* (° from N) and *incidence angle* (° from the normal to the Earth's surface).

Polarization Analysis - II

Credit: G. Saccorotti

Polarization Analysis is conducted over subsequent time frames sliding along the 3C recordings, with 50% overlap.

The analysis is repeated over 20, log-spaced frequencies spanning the 1-10 Hz frequency interval. For each frequency, the signal is band-pass filtered using a 2-poles Butterworth filter with a bandwidth of 0.5 Hz.

The length of the time window for covariance estimates is set equal to 4 times the period associated with the lower frequency corner of the filter (e.g., if fmin=2 Hz, wlen=2s).

Polarization results are then filtered according to an amplitude threshold T, given by:

$T = \mathrm{mean}(\log_{10}(L))+\mathrm{std}(\log_{10}(L))$

where L is the largest eigenvalue of the covariance matrix.