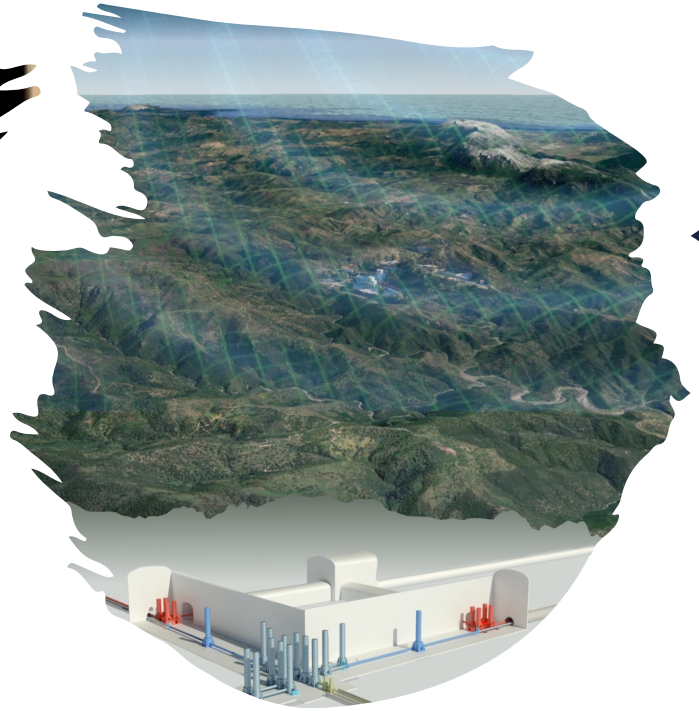
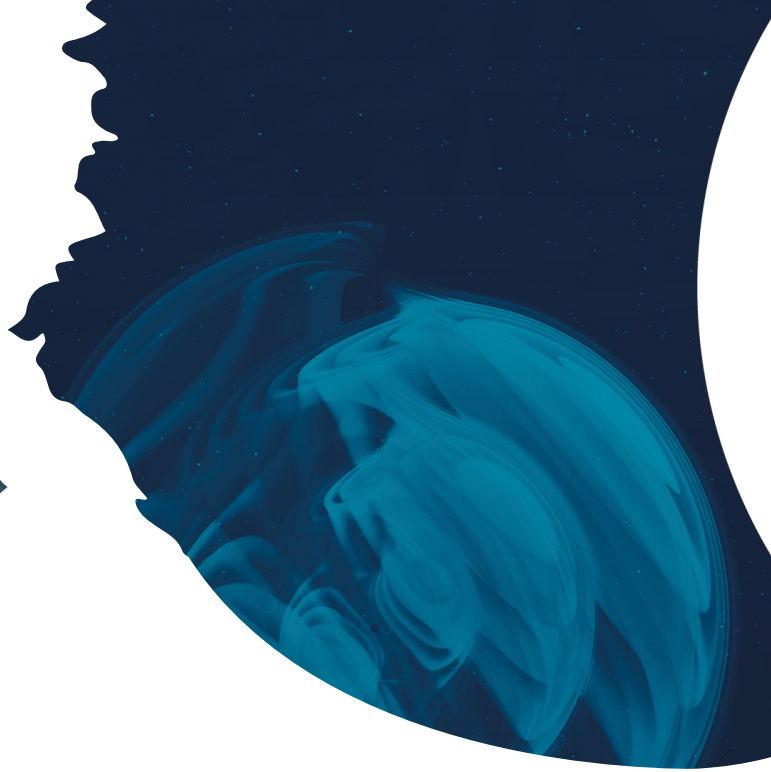




The Einstein Telescope, the next generation detector for gravitational-wave observation

- Prof. D. D’Urso
- Univ. di Sassari & INFN Cagliari

What's the Einstein Telescope (ET)

- **3rd generation GW observatory** Sensitivity aims at least one order of magnitude better with respect to the nominal sensitivity of advanced detectors in all the detection frequency band
- **Precision measurement and a new discovery project.** A wide frequency band observatory
- **Special focus on massive (or intermediate mass) black holes.** Extraordinary sensitivity at low frequency (few Hz)
- **High reliability.** High observation duty cycle
- **Lifetime of several decades,** (50 years in the ET proposal). Capable to host the evolution of the detectors, without limiting their sensitivity

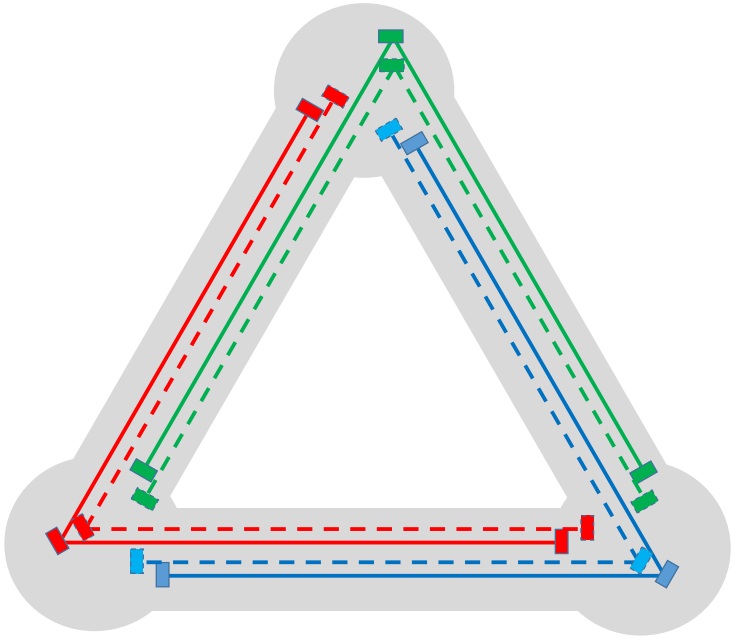
ET Design: key elements

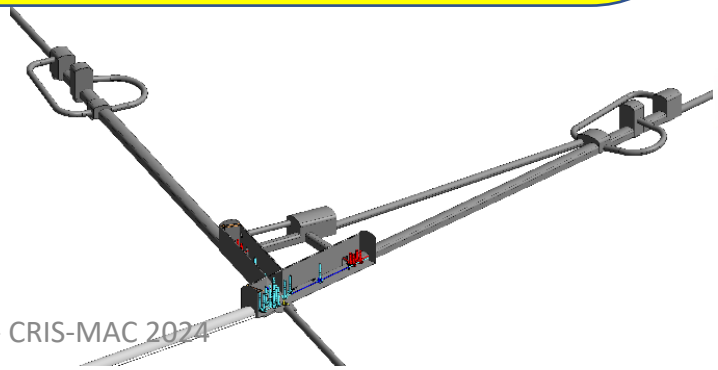
Requirements

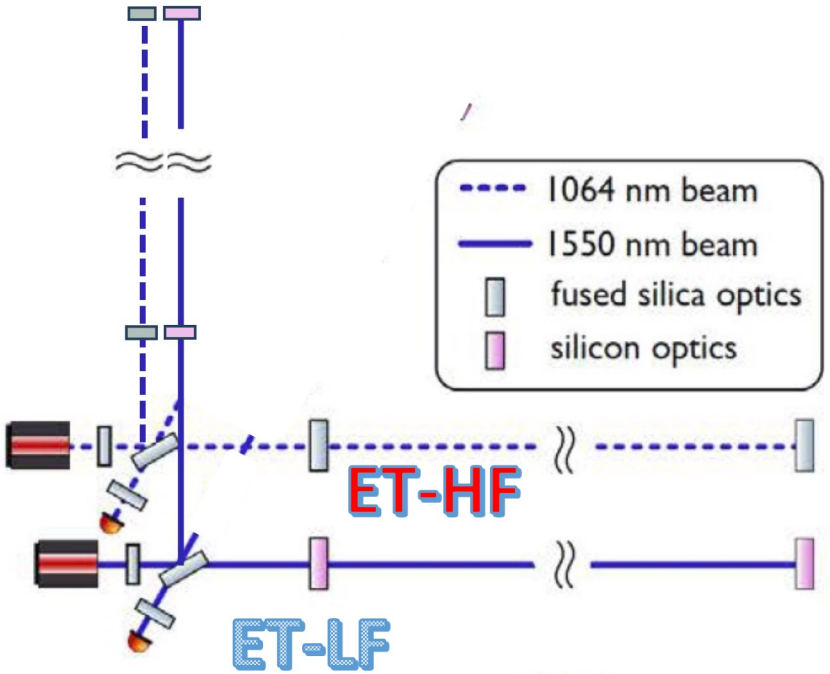
- Wide frequency range
- Massive black holes (LF focus)
- Localisation capability
- (more) Uniform sky coverage
- Polarisation disentanglement
- High Reliability (high duty cycle)
- High SNR

Design Specifications

- Xylophone (multi-interferometer) Design
- Underground
- Cryogenic
- Triangular shape
- Multi-detector design
- Longer arms







ET Science Case in a nutshell

ASTROPHYSICS

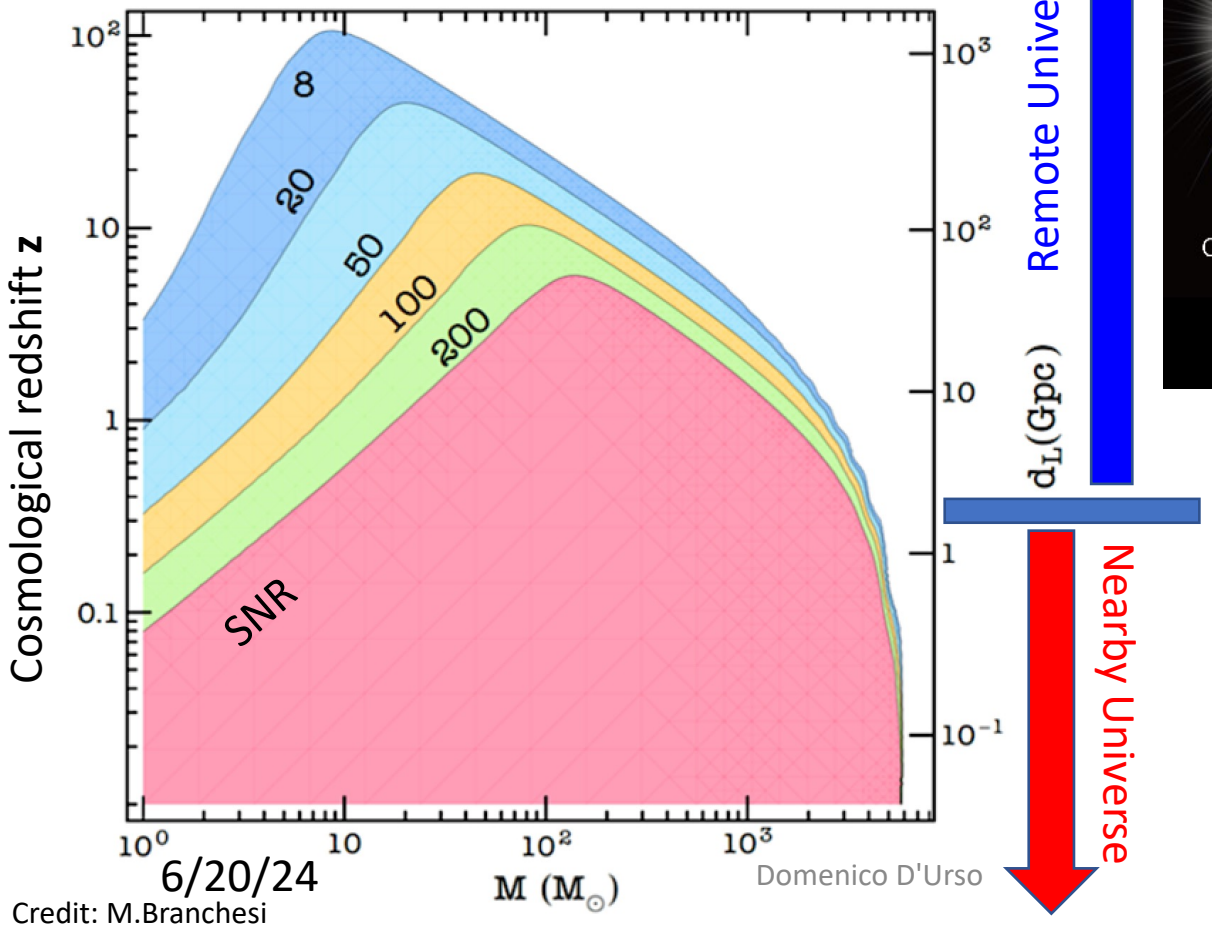
- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

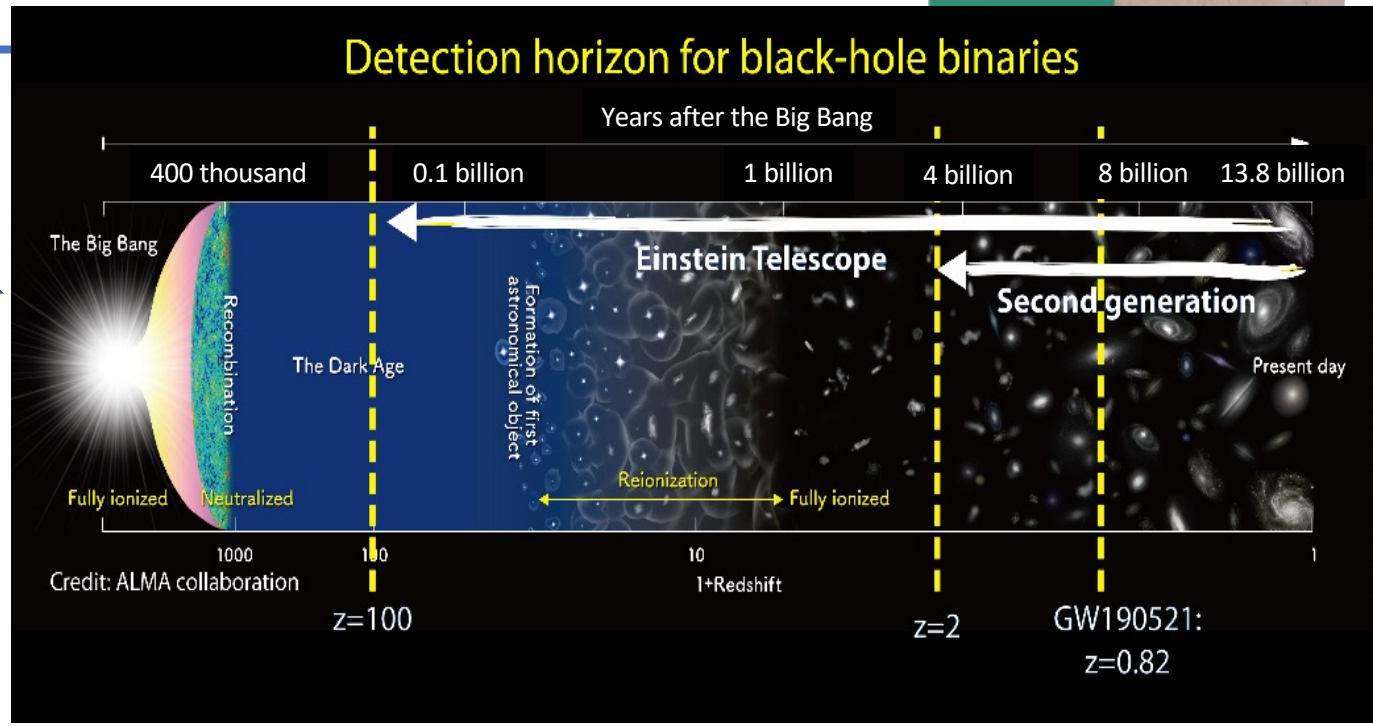
- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

ET Science in a nutshell: double nature

- ET will be a new discovery machine:
  - ET will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang



Credit: M.Branchesi

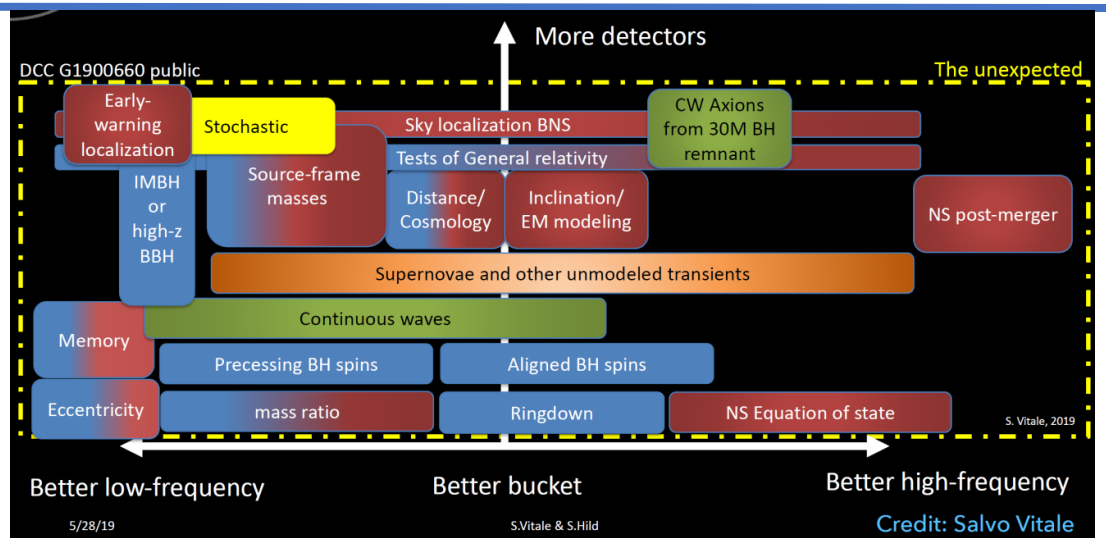


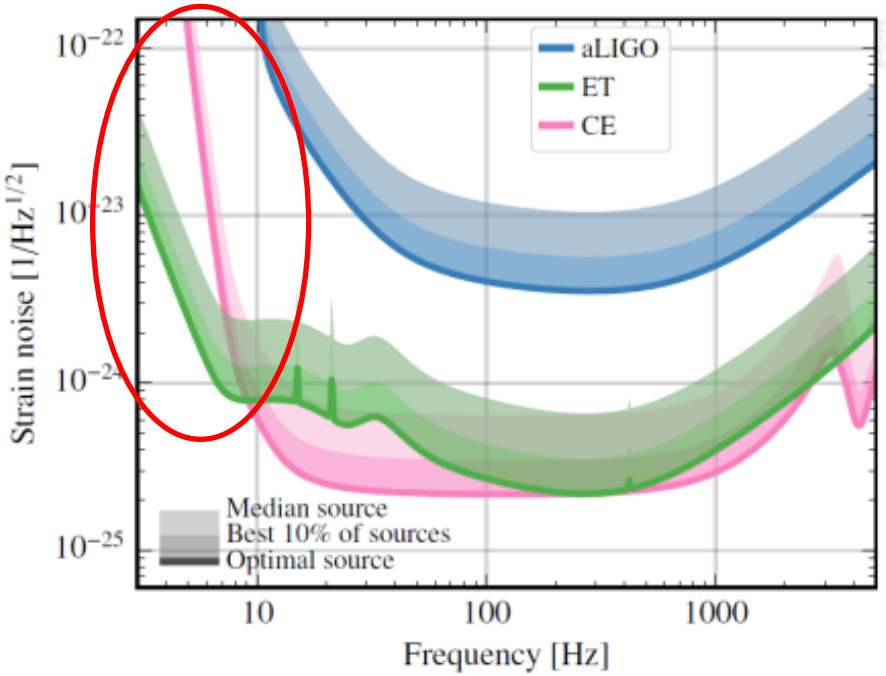
- ET will be a precision measurement observatory:
  - ET will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei

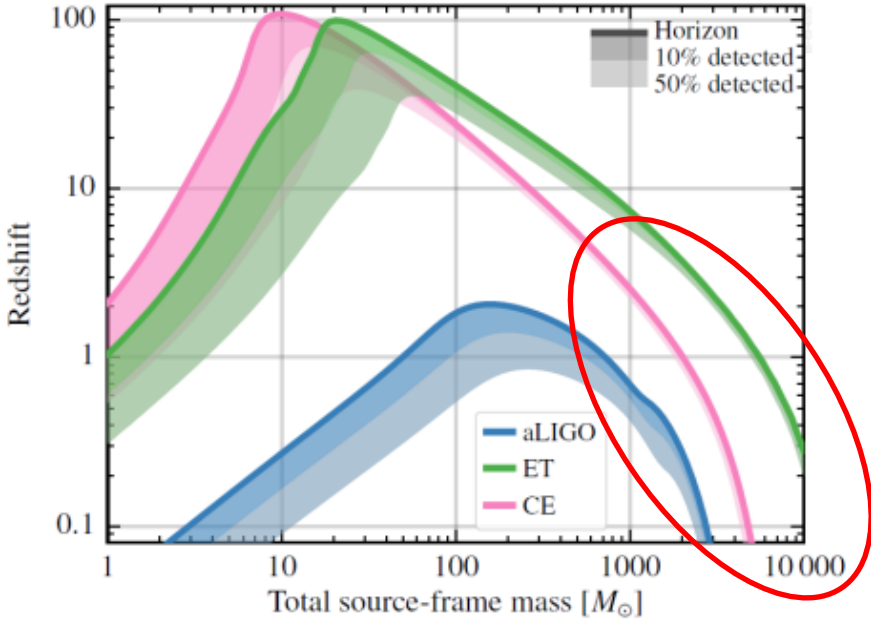
ET Science in a nutshell: double nature

- GW science targets are almost equally distributed in the frequency range accessible by terrestrial GW detectors (but technical difficulties aren't)
- We want to have access both to low and high frequency targets
  - BBH up to z~50-100, 10^5 BBH/year, Masses $M_T \gtrsim 10^3\ M_\Theta$
  - BNS to z~2, 10^5 BNS/year, Possibly O(10-100)/year with e.m. counterpart
  - High SNR

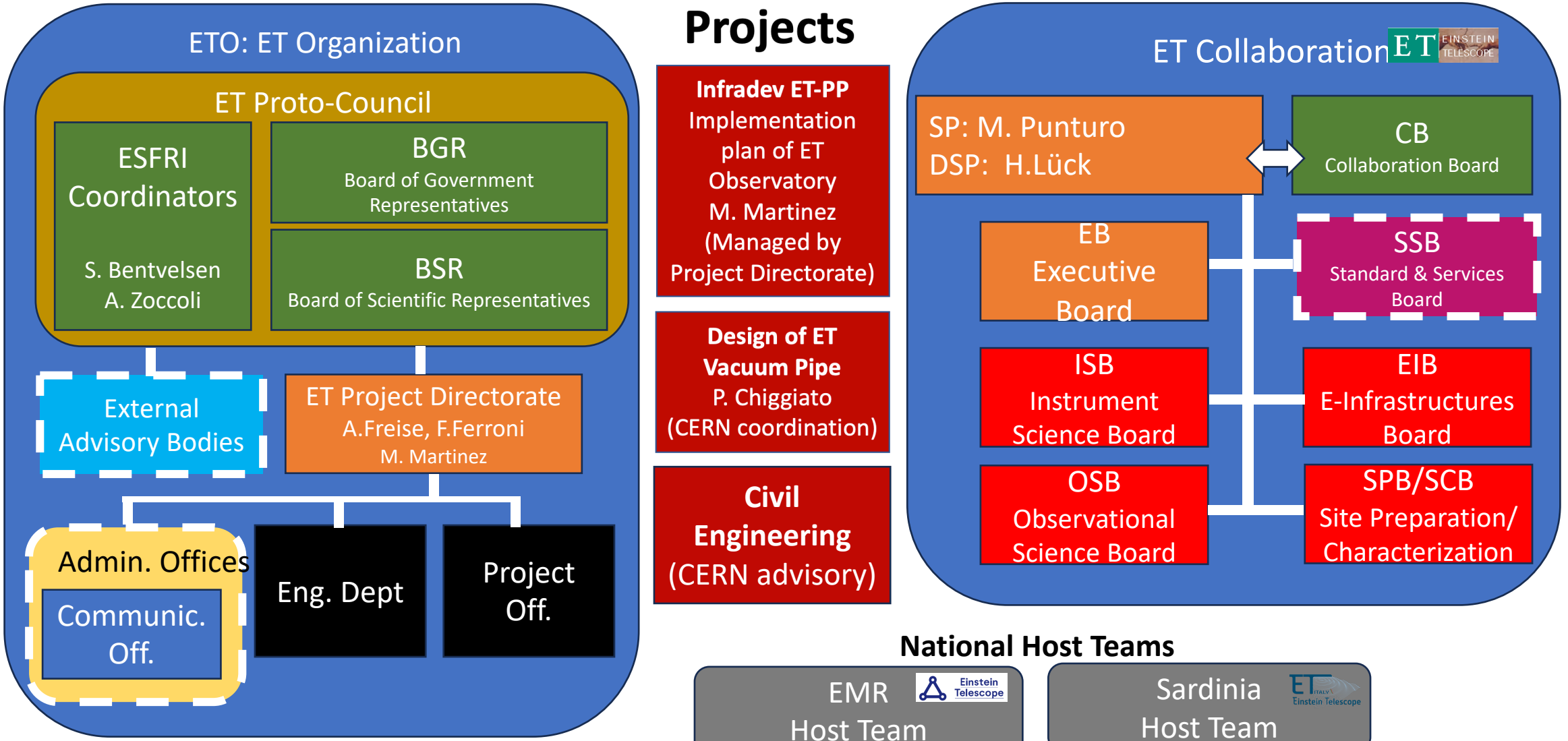
- ET will be a wide band observatory with a special focus on (intermediate) massive compact object:
  - **Low frequency!**



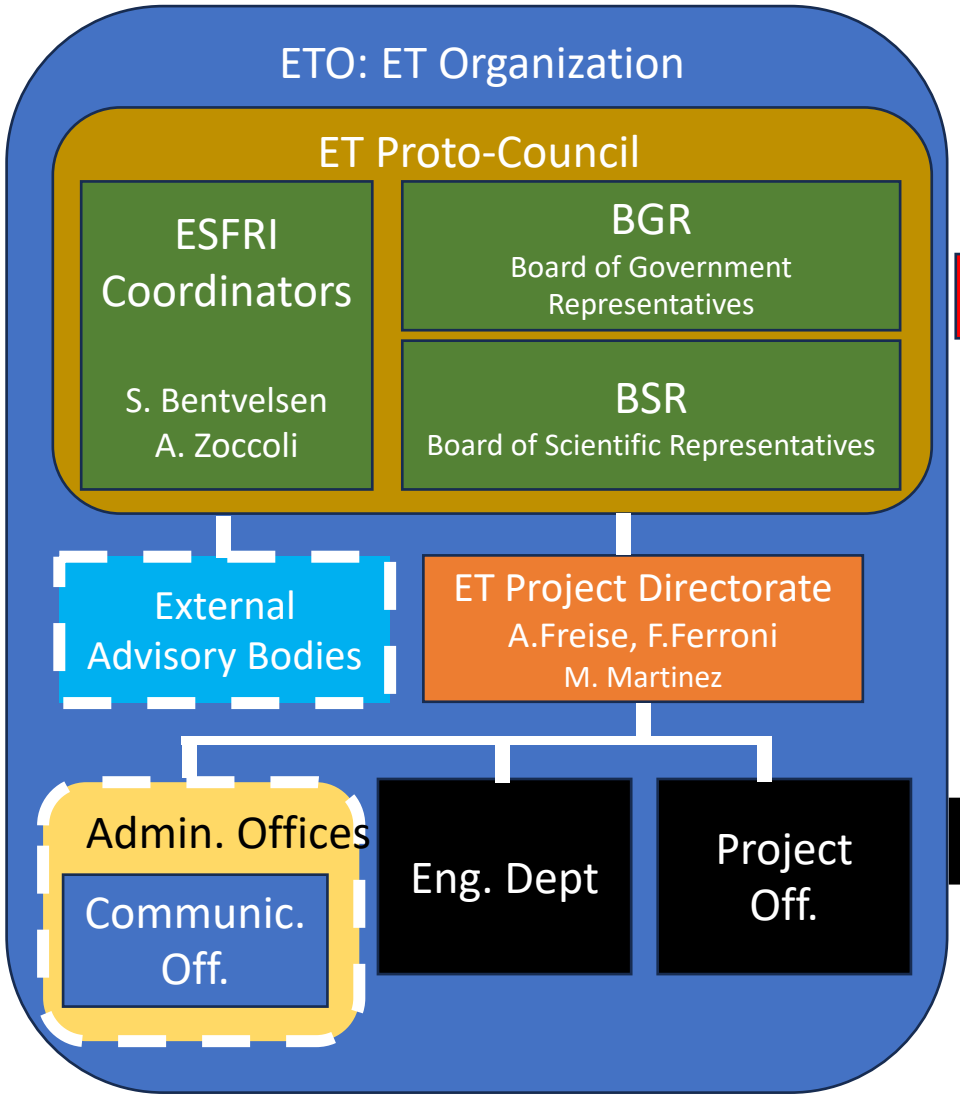




ET Project: Current Organization



ET Current Organisation



Temporary groups, working towards becoming the ET governing body, such as a Council. **Our most important link to governments and funding agencies** (Austria, Belgium, France, Italy, Netherlands, Poland, Spain, UK are members with Germany as observer).

An small but active organisation with the formal responsibility to realise ET. **A future legal entity for ET would be based on this structure.**

Credits: A. Freise

ET Current Organization

Projects

Infradev ET-PP
Implementation plan of ET Observatory
M. Martinez
(Managed by Project Directorate)

- Main activities:
  - Structuring the ET legal entity
    - Defining its governance
    - Defining its technical bodies
  - Define the financial aspects of ET
  - Manage the relationship of the ET project with the European Commission framework (ESFRI)

Design of ET Vacuum Pipe
P. Chiggiato
(CERN coordination)

- More than 120km of vacuum pipes
  - Define the technical design of the vacuum pipe with a clear target in the cost reduction
  - Propose innovative materials and solutions
- Joint developments with CERN involving ET and CE

Civil Engineering
(CERN advisory)

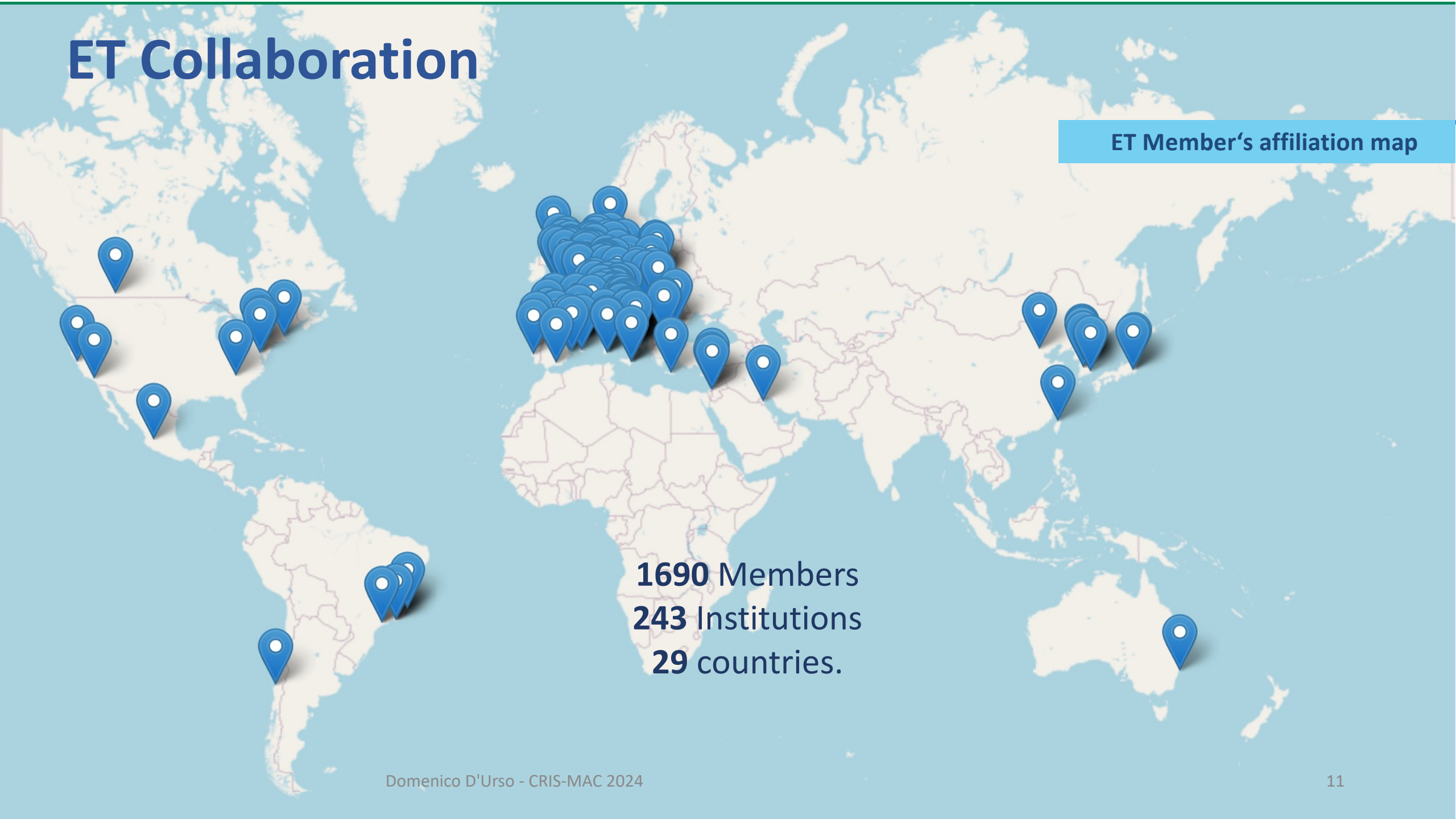
- Profit of the CERN expertise in large civil and technical underground research facilities
- Develop together, in collaboration with external companies, the design of the ET facilities

Activities on three fronts

- **ETO (international project organisation)**
  - Provide **project management** and all **engineering work**.
  - Decide on **governance**, type of legal entity and financial frameworks, ... • **Engineering work and technical design** of the research infrastructure.
- **ET Collaboration (international)**
  - ❑Define **scientific vision and detector requirements**. For example: science case for ET, which are the key characteristics of a good ET site.
  - ❑**Research and development the technology** required for ET. For example, silicon mirrors, cryogenic suspension systems, ...
- **Local teams**
  - ❑**Site characterisation** with seismic and geological studies.
  - ❑Deliver design and implementation plans that are **unique to the region**.
  - ❑Develop **economic case** and deliver socio-economic impact plan.

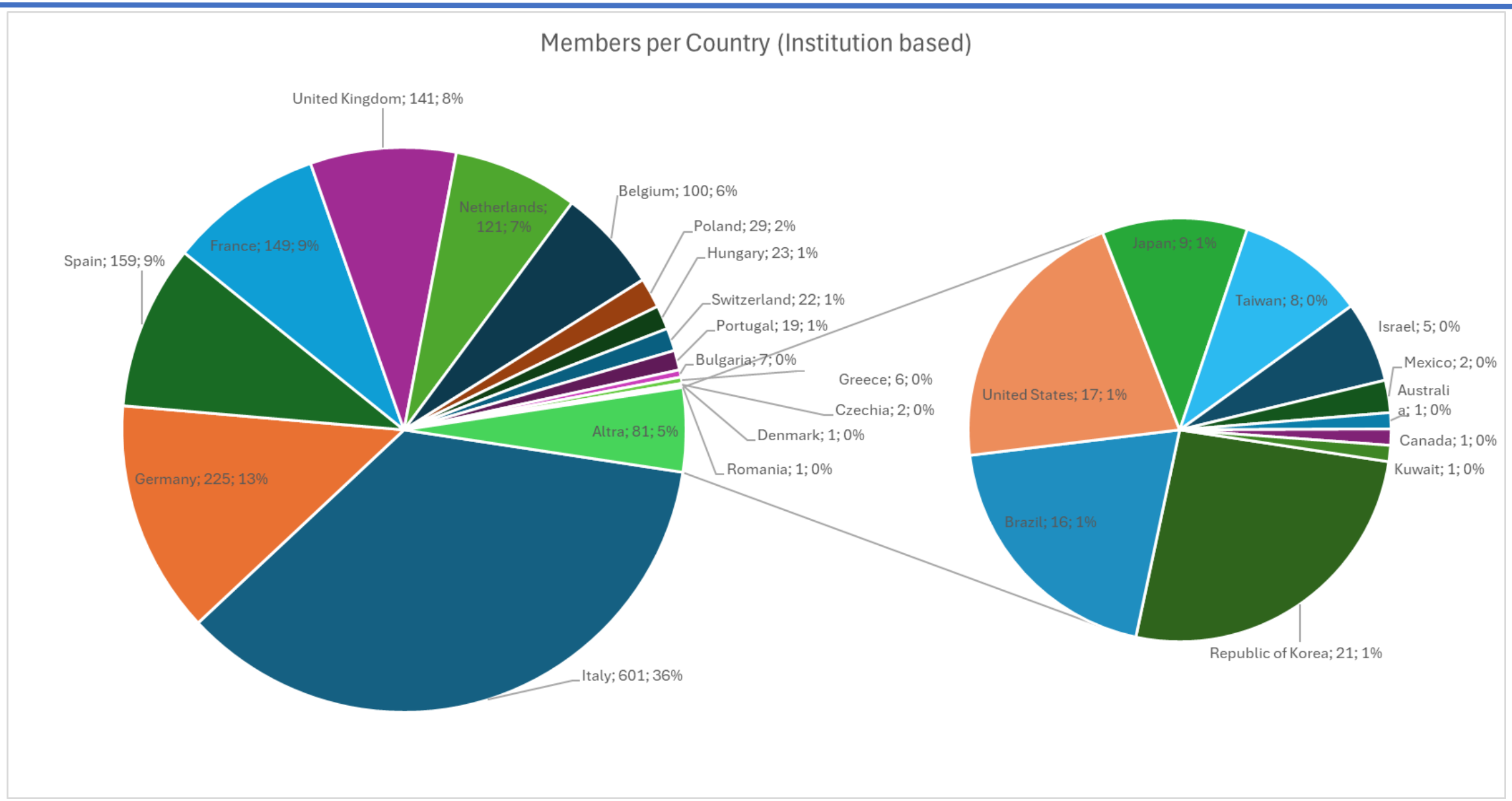
ET Collaboration

ET Member‘s affiliation map



1690 Members
243 Institutions
29 countries.

ET Collaboration Demography



ET Italy

- 601 members of 81 institutions for 27 RU

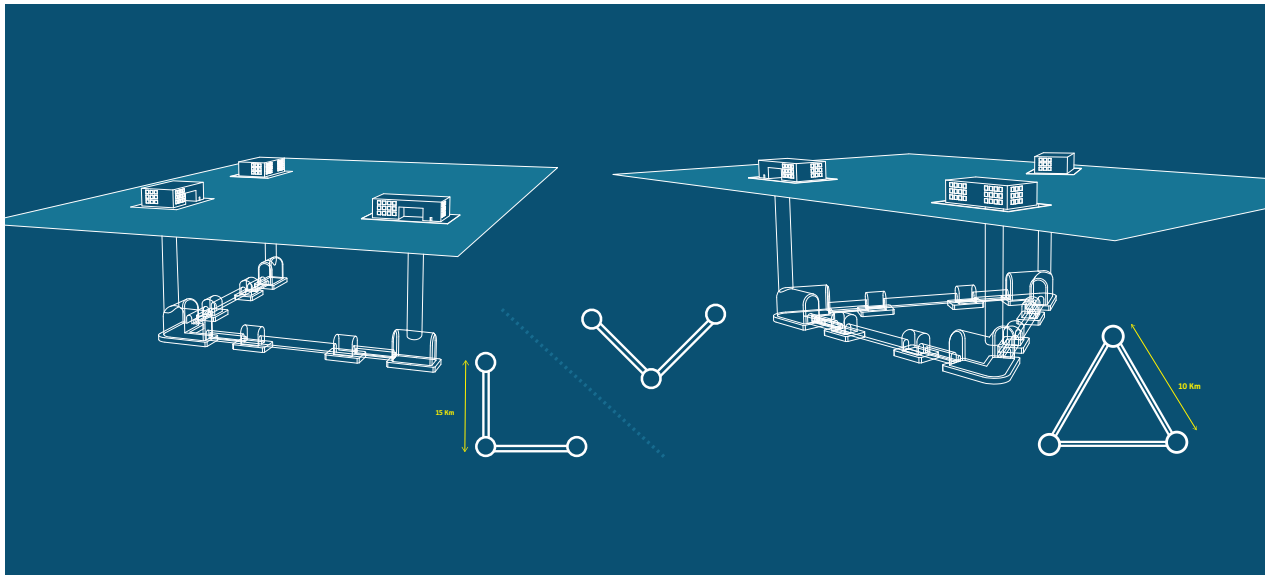
- **Site Characterization**
- **R&D enabling technologies**

Current Main Activities

- **Updating the ET science case Δ or 2L**
- **Defining the key elements of the ET detector** (TDR)
- **Realizing a European network of R&D infrastructures**
- **Developing the design of the ET governance, civil and technical infrastructures, evaluating their costs**
- **Preparing the bidbook for the candidature of the sites**

ET science case: Δ or (two) L

- Since 2011 (CDS, triangle configuration) the situation drastically changed:
  - ❑ First detections, GTWC-3 catalog → BH population → new evolution models;
  - ❑ Science case developed;
  - ❑ Know-how with advanced (L) detectors;
  - ❑ International scenario (+ Cosmic Explorer in US);
  - ❑ Two candidate sites strongly supported (and a potential third site…).
- The Collaboration is analyzing both configurations: optimizing science return, differential risk assessment.
- First results on the science return published in Marica Branchesi et al JCAP07(2023)068:
- A preliminary differential risk analysis, provided by a specific committee, is under elaboration



The 2L 15 km geometry shows an improved science return in a relevant number of science targets

ET TECHNOLOGY (MAIN) CHALLENGES

Challenging engineering

New technology in cryo-cooling

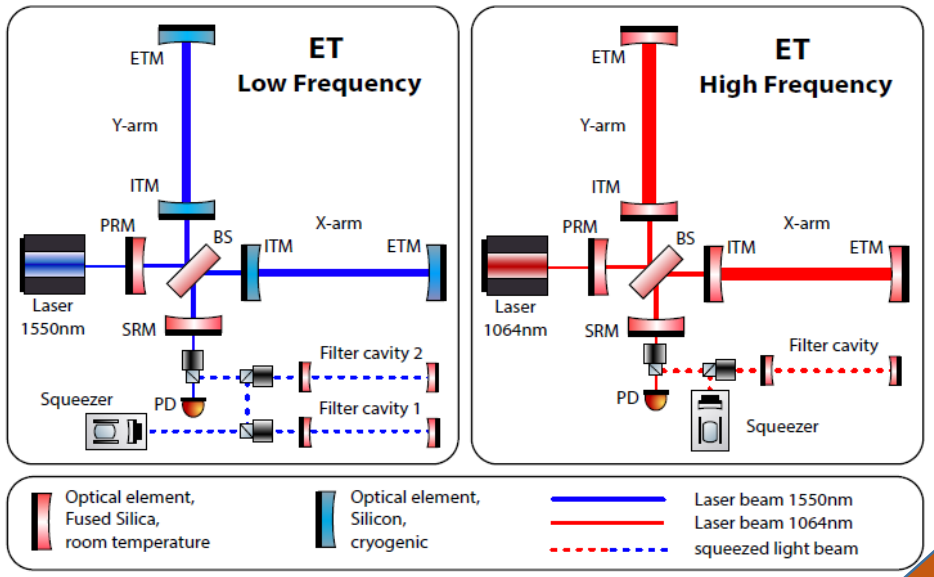
New technology in optics

New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

- The multi-interferometer approach asks for **two parallel technology developments**
  - **ET-LF**
    - Underground
    - Cryogenics
    - Silicon (Sapphire) test masses
    - Large test masses
    - New coatings
    - New laser wavelength
    - Seismic suspensions
    - Frequency dependent squeezing



  - **ET-HF**
    - High power laser
    - Large test masses
    - New coatings
    - Thermal compensation
    - Frequency dependent squeezing

Evolved laser technology

Evolved technology in optics

Highly innovative adaptive optics

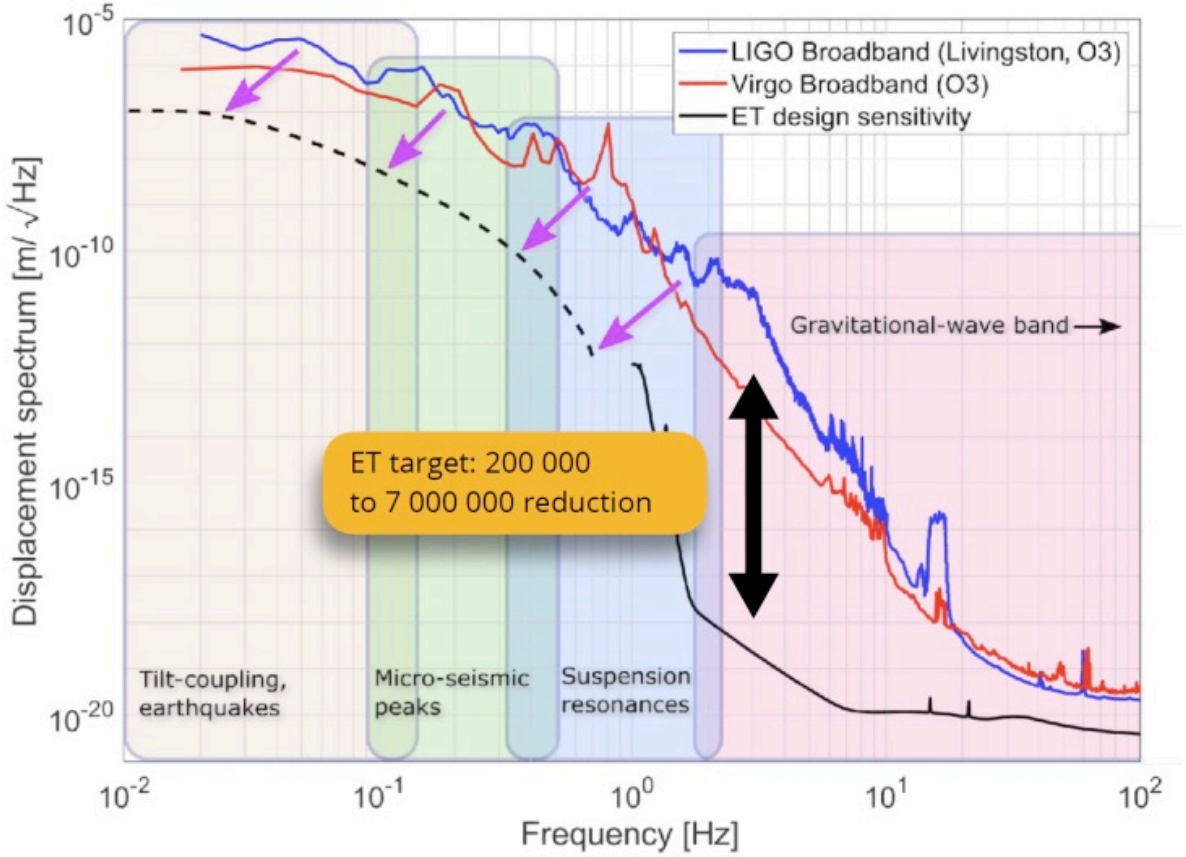
High quality opto-electronics and new controls

Low frequency GW detection and ET Site Characterization

Focus at low frequencies

- LF noise is given by
  - Microseism motion
  - Newtonian noise
  - Thermal noise
  - Upconversion of residual motion into the detection band
  - Control noise
- Newtonian noise crossing:

2×10^{-22} $Hz^{-1/2}$ at 1.8 Hz (AdV: 3.2 Hz)



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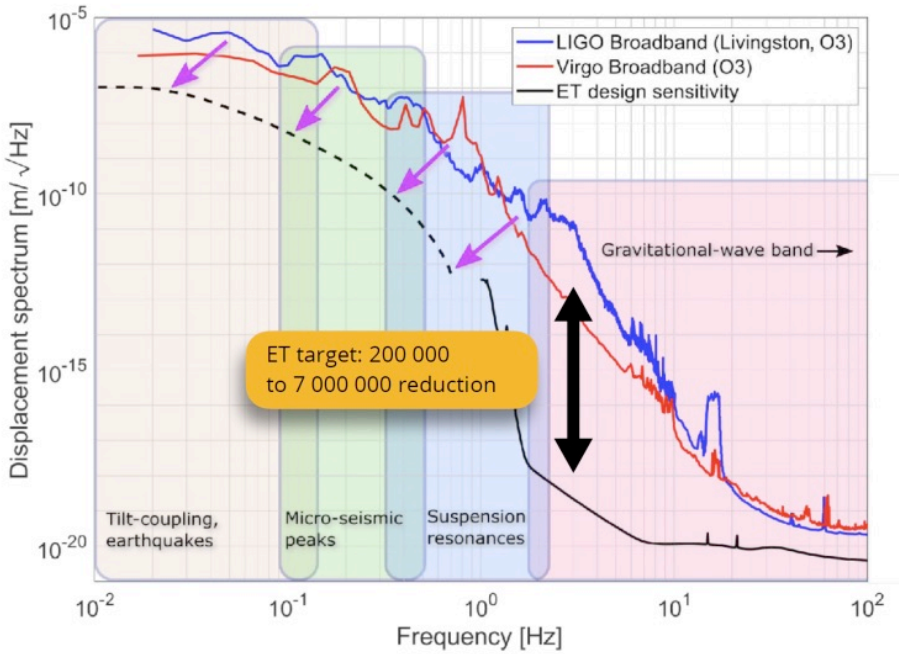
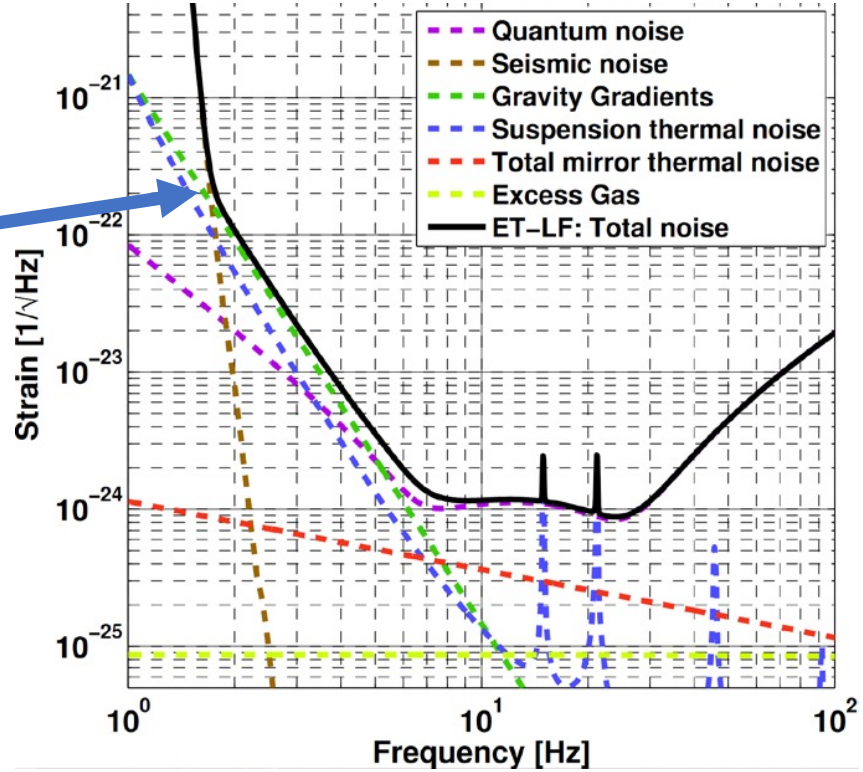
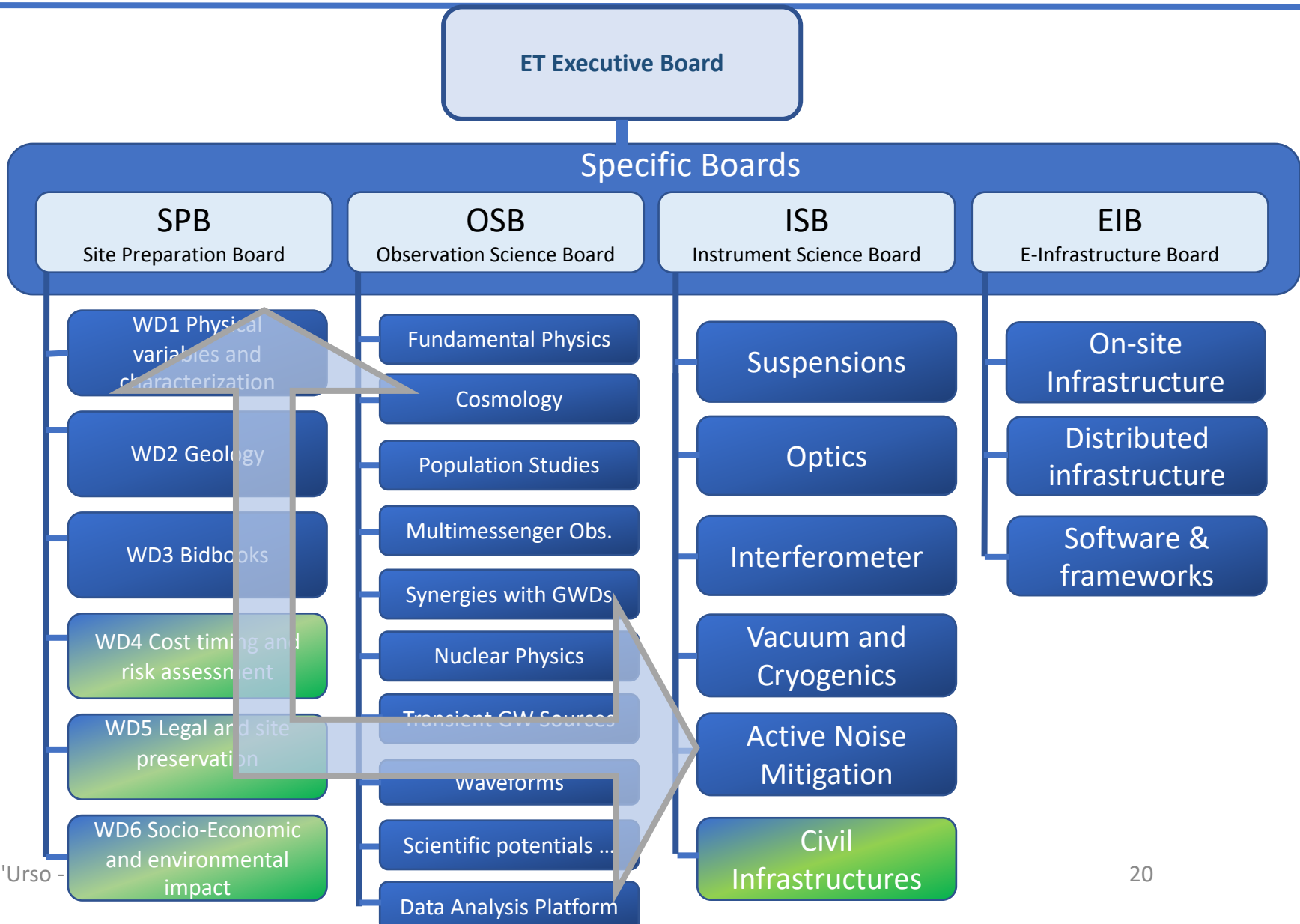




Site Characterization in the ET

- **SiteCharacterization** 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).



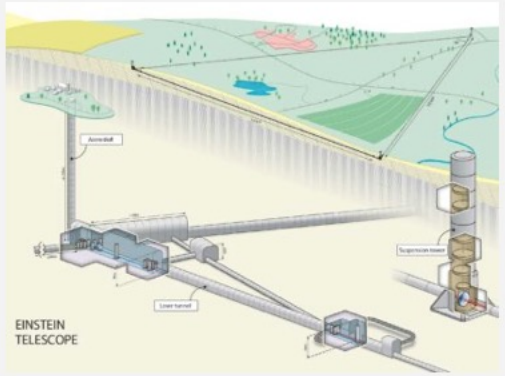
ET Candidate Site

ET candidate sites

- Two sites officially candidate:
  - EMR EUregio, border region between Nederland, Belgium and Germany
  - Sardinia (Sos Enattos area)
- A third potential site is located in Saxony (Lusatia), still not official
- Overall site evaluation is a complex task depending on:
  - Geophysical and environmental quality
  - Financial and organization aspects
  - Services, infrastructures

Support for EMR Candidature

- Taskforce Belgium, Germany and the Netherlands
- Ecosystem is strengthening. Maastricht as home-base for Project Office
- Strong political and social support, increased focus on education High tech industry and top academia nearby
- Ban on windturbines



5 December 2022

Flanders invests in preparation Einstein Telescope

13 December 2022

Taskforce from Belgium, Germany and the Netherlands strengthens candidacy for Einstein Telescope

16 February 2023

Unanimous support for Einstein Telescope from Belgian ministers for science

Support for Sardinia Candidature

- **10/02/2023:** The Minister of University and Research Bernini has appointed a scientific advisory board
- **21/03/2023:** Visit of Anna Maria Bernini at SOS Enattos and SAR-GRAV Laboratory
- **9/5/2023**: CAGLIARI, Official presentation of Italian Candidature
- **6/06/2023**: Press conference in Roma for official governmental support
- **12/2023**: Letter from Italian Prime Minister offering 950M€

In the **SOS ENATTOS** former mine area, the **SARGRAV laboratory**, a seed of ET, can host:

- UNDERGROUND EXPERIMENTS
- CRYOGENIC PAYLOADS
- LOW FREQUENCY AND CRYOGENIC SENSOR DEVELOPMENT

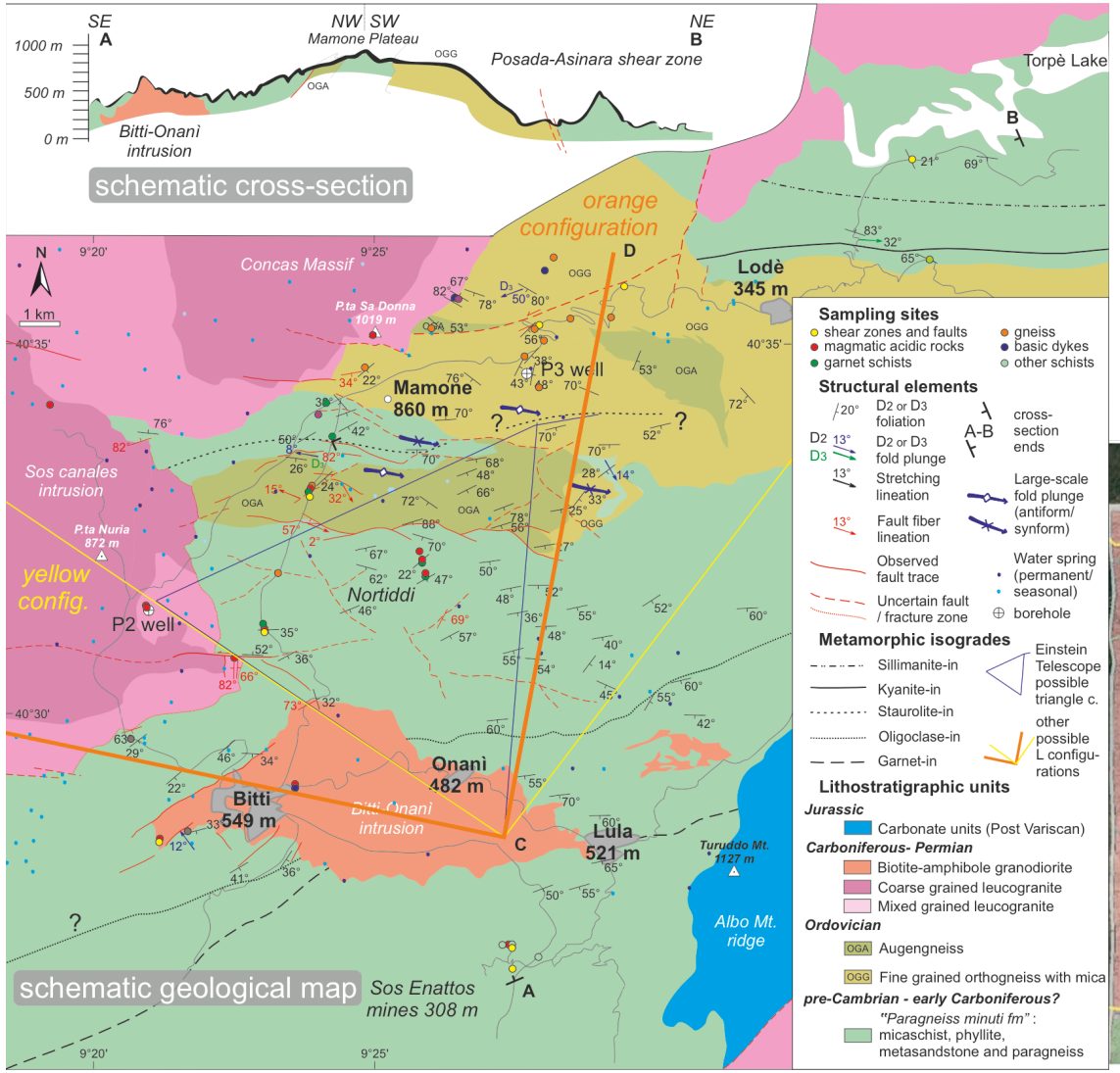
that need **LOW SEISMIC** and **ANTHROPOGENIC NOISE**

Site Candidature Action lines

- Site monitoring
  - identification and quantification of local source impact
  - implication for site preservation quality
- Geological studies
  - understanding and characterization of local geology
- Civil and environmental engineering
  - pre-feasibility study
  - geotechnical investigation
  - optimal placement and environmental sustainability of the underground and surface infrastructures

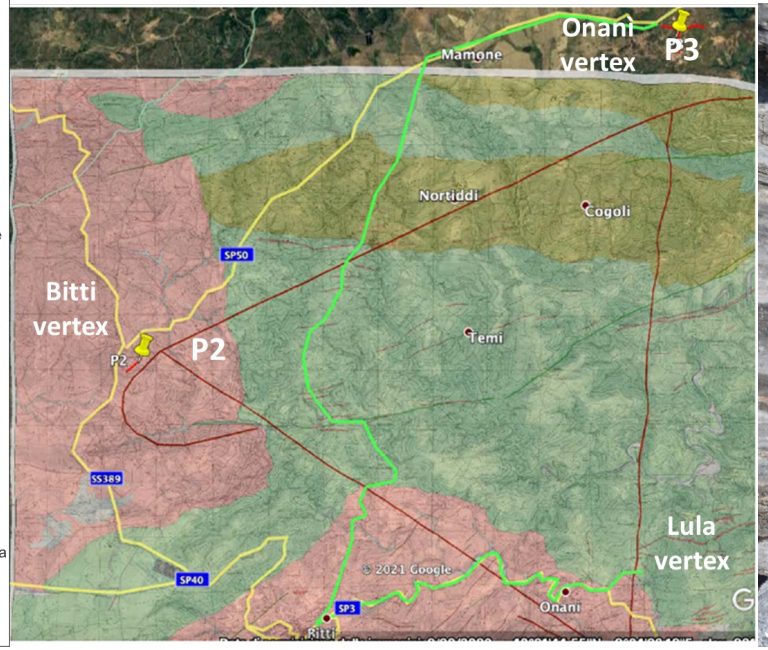
The ET Italian candidate site is located in the stable VARISCAN BASEMENT OF SARDINIA

Credits to D. Rozza



LITHOLOGIES: Orthogneiss, granitoids, micaschists.

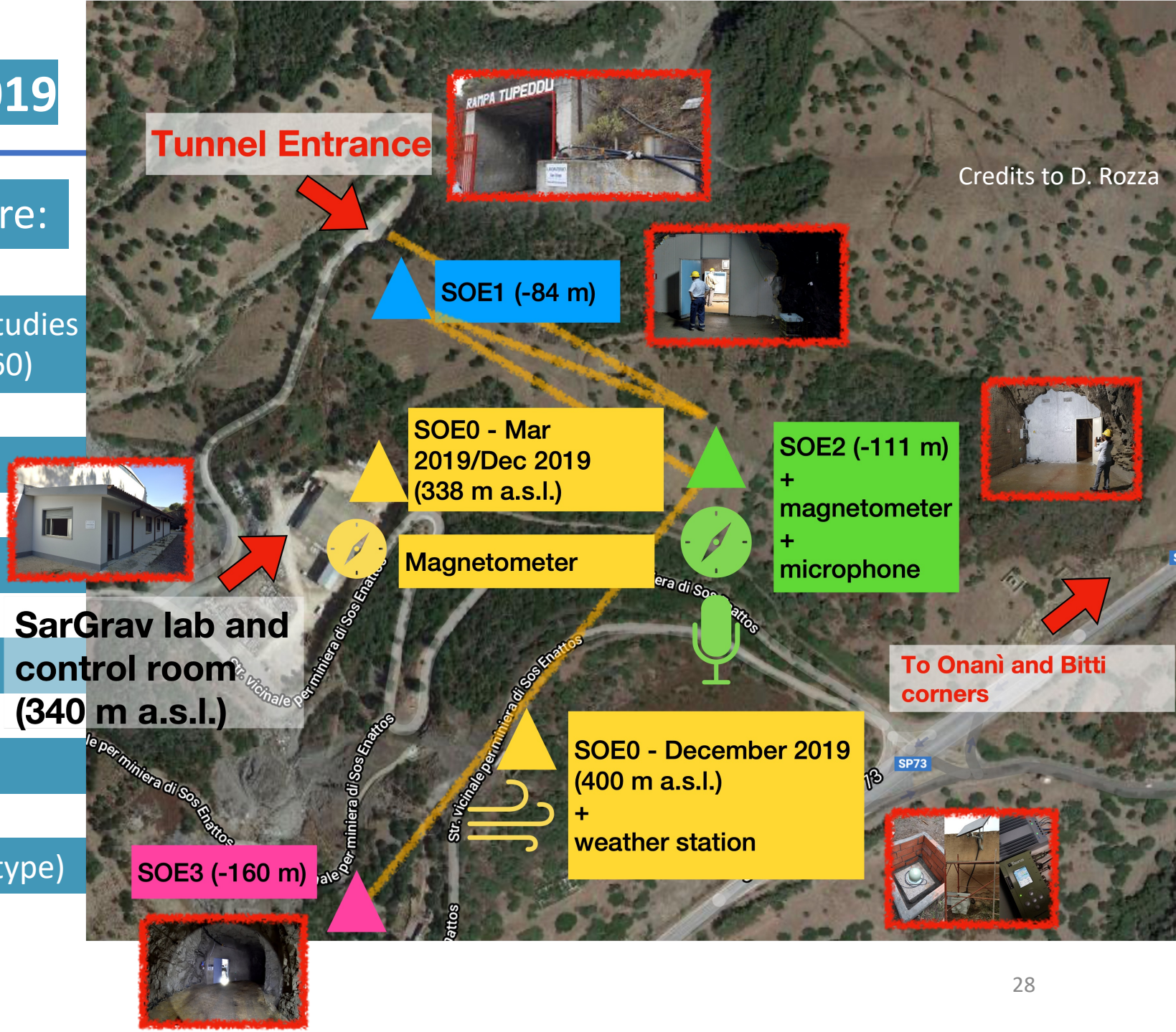
P2 and P3 are the borehole locations optimization is ongoing.



PERMANENT ARRAY since 2019

Since 2019, in Sos Enattos there are:

- 4 permanent seismic stations for long term studies (Trillium 240, 360 and 120 Horizon, Guralp 360)
- 1 weather station
- 1 microbarometer
- 3 magnetometers (MF6-06)
- 2 microphones
- 1 high precision tiltmeter (Archimedes prototype)



PERMANENT ARRAY since 2021

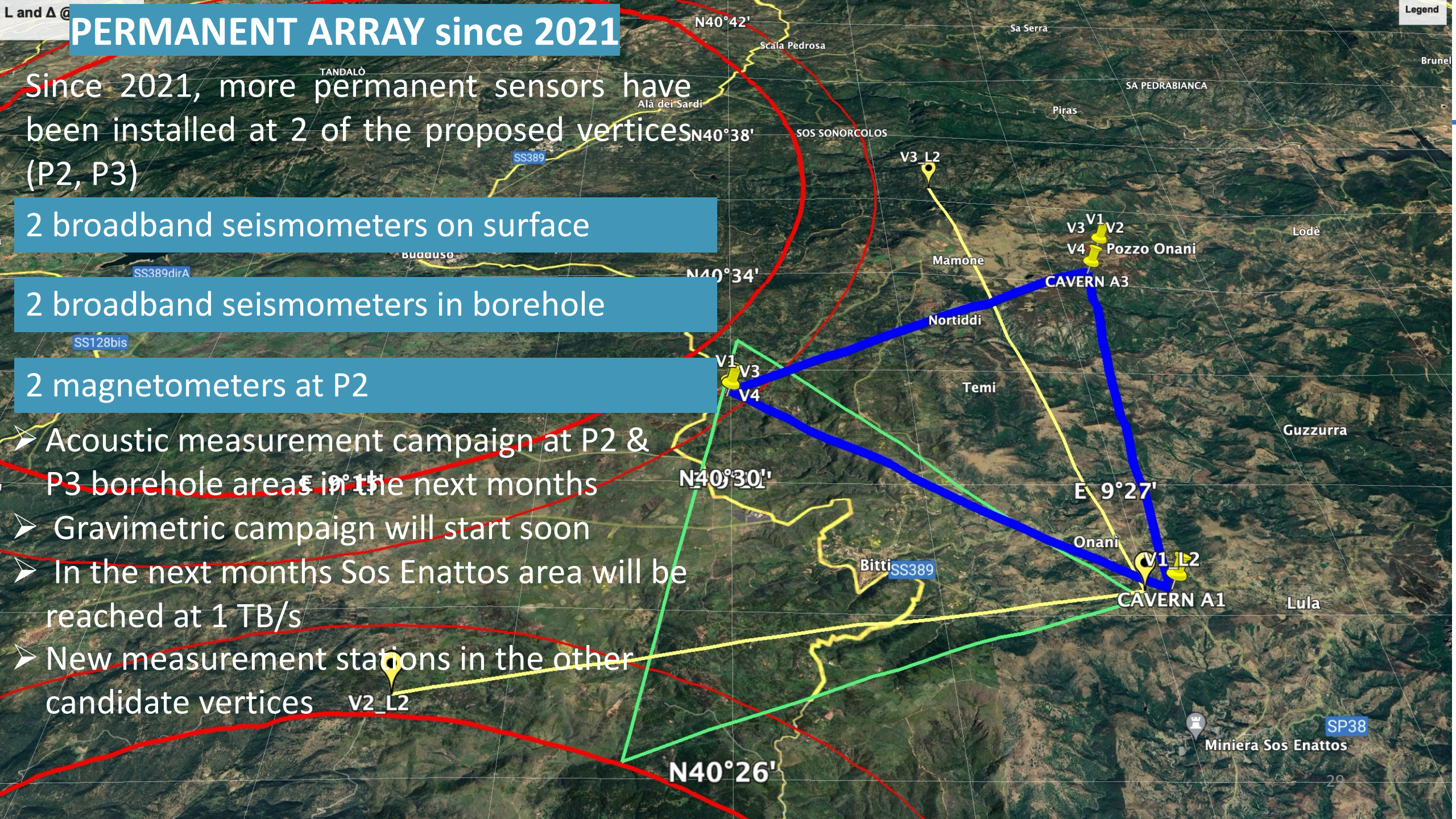
Since 2021, more permanent sensors have been installed at 2 of the proposed vertices (P2, P3)

2 broadband seismometers on surface

2 broadband seismometers in borehole

2 magnetometers at P2

- Acoustic measurement campaign at P2 & P3 borehole areas in the next months
- Gravimetric campaign will start soon
- In the next months Sos Enattos area will be reached at 1 TB/s
- New measurement stations in the other candidate vertices



Hunting the noise sources

The **Budussò Wind Park**: one of the largest wind parks in Italy.

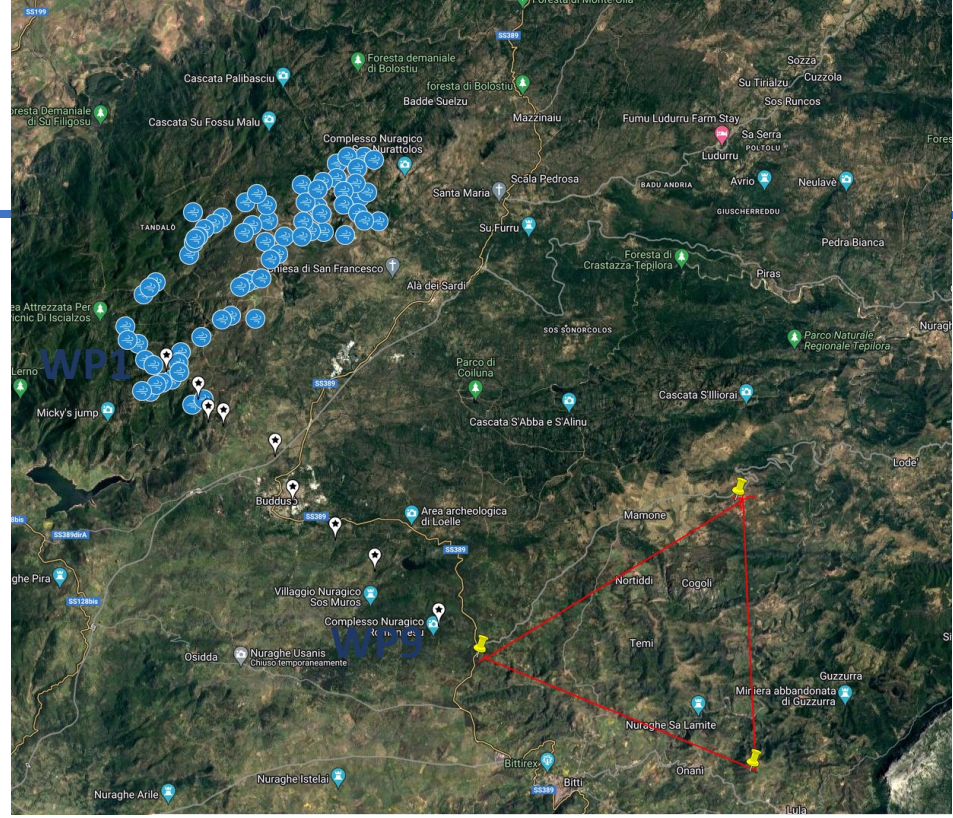
69 turbines (~2 MW each).

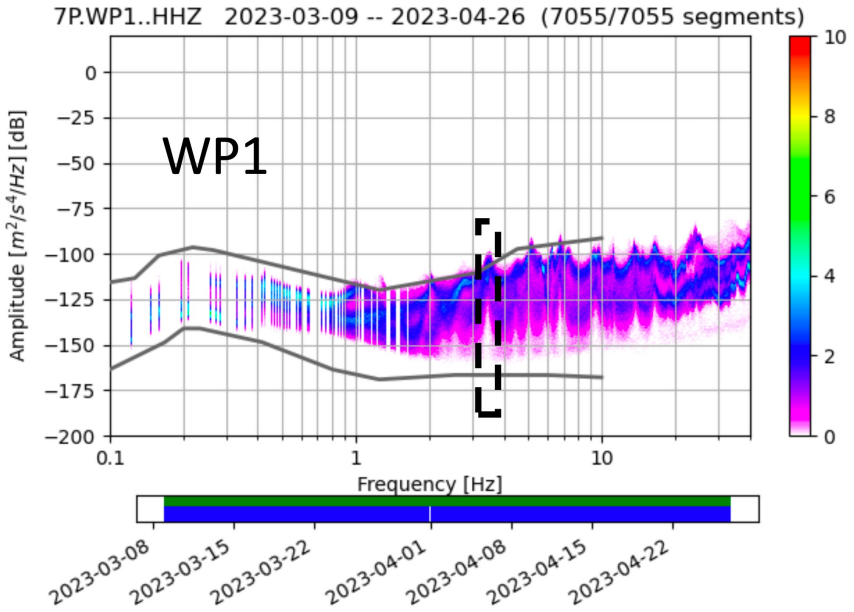
A total of **130 MW installed**.

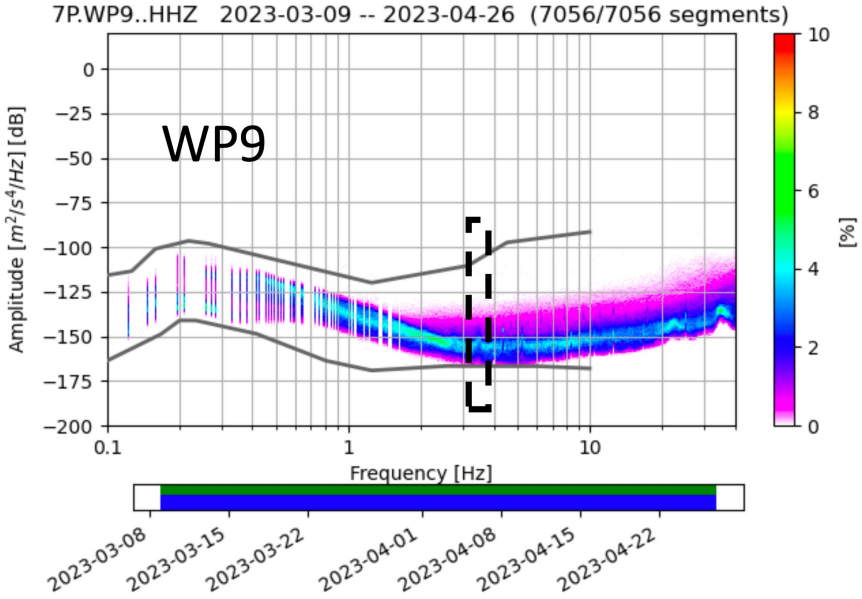
Blades motion is **transferred** to tower and to the ground.

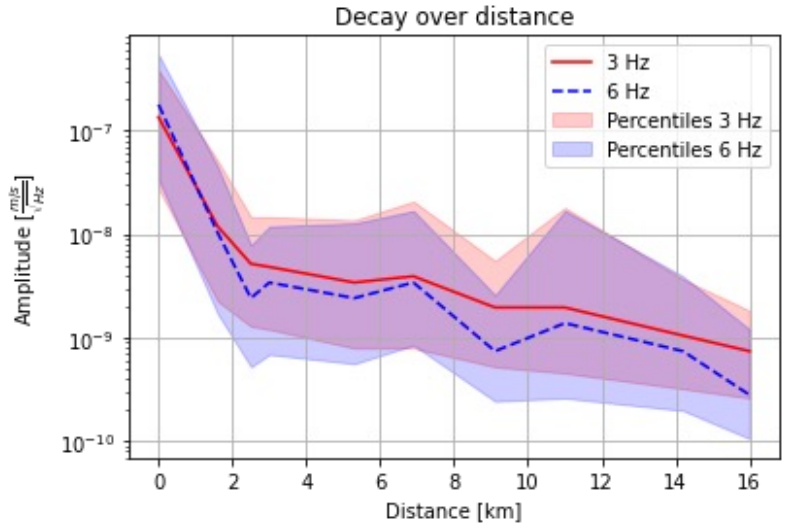
Seismic noise propagates as **surface waves**

Generated noise is found in the **1-10 Hz** frequency band.

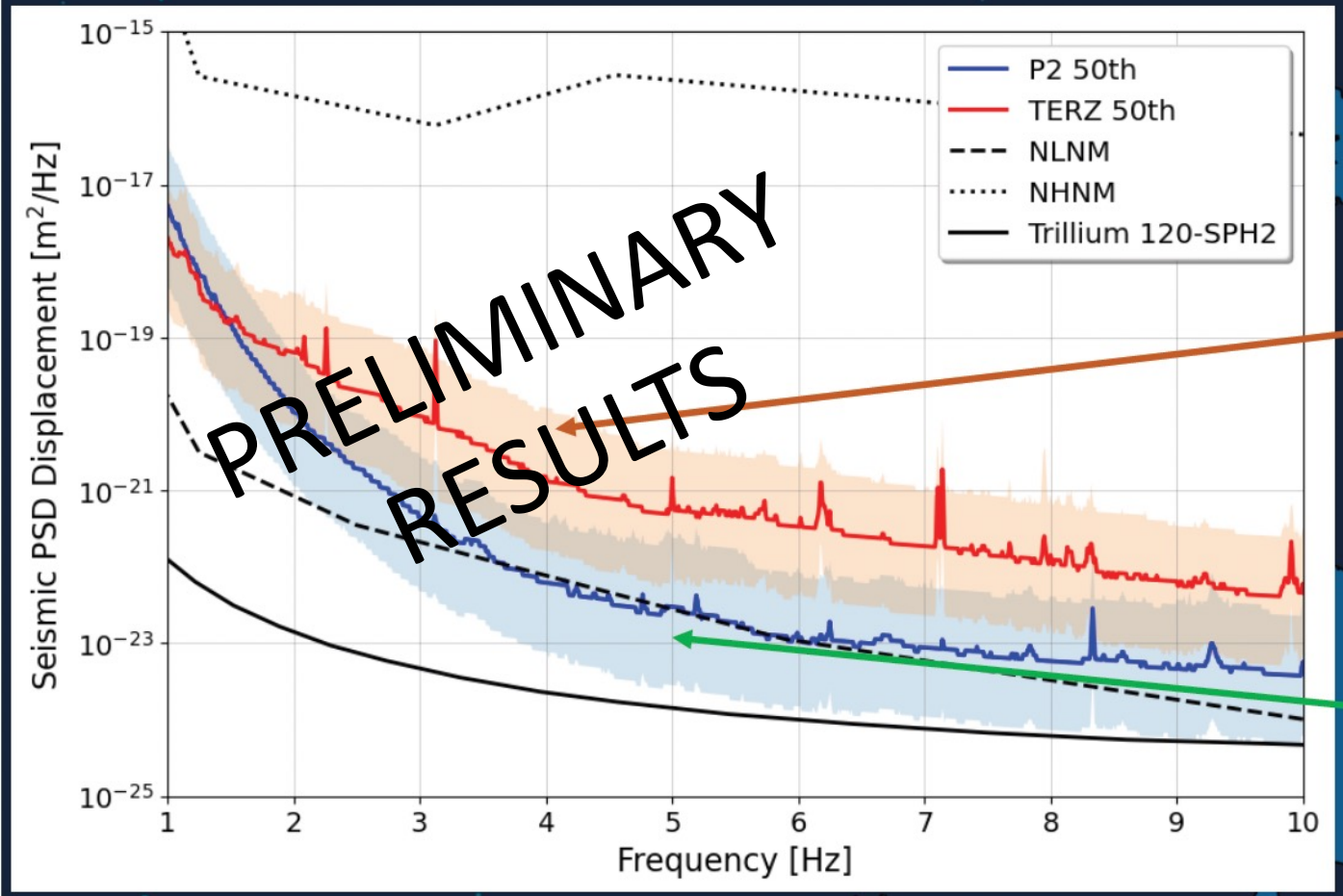








ITA vs EMR



Seismic noise / frequency

PUBLICATIONS:

- L. Naticchioni et al., ***Microseismic studies of an underground site for a new interferometric gravitational wave detector***, **CQG**, 2014, https://doi.org/10.1088/0264-9381/31/10/105016
- L. Naticchioni et al., ***Characterization of the Sos Enattos site for the Einstein Telescope,*** **JPCS** 1468, 2020, https://doi.org/10.1088/1742-6596/1468/1/012242
- M. Di Giovanni et al., ***A seismological study of the Sos Enattos Area – the Sardinia Candidate Site for the Einstein Telescope***, **SRL**, 2020 https://doi.org/10.1785/0220200186
- A. Allocca et al., ***Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency***, **EPJP**, 2021 https://doi.org/10.1140/epjp/s13360-021-01450-8
- Allocca *et al.,* **Picoradiant tiltmeter and direct ground tilt measurements at the Sos Enattos site**, **EPJP** 136, 1069 2021. https://doi.org/10.1140/epjp/s13360-021-01993-w
- M. Di Giovanni et al., ***Temporal variations of the ambient seismic field at the Sardinia candidate site of the Einstein Telescope***, **Geophysical Journal International***,* 2023, https://doi.org/10.1093/gji/ggad178
- G. Saccorotti et al., ***Array analysis of seismic noise at the Sos Enattos mine, the Italian candidate site for the Einstein Telescope***, 2023, https://doi.org/10.1140/epjp/s13360-023-04395-2.
- L .Naticchioni et al., ***Results of the site characterization in Sardinia for the Einstein Telescope***, **PoS Proc. Sci.**, 2023, https://doi.org/10.22323/1.441.0110.
- A. Allocca et al., ***Thermal noise-limited beam balance as prototype of the Archimedes vacuum weight experiment and B-L dark photon search***, **EPJP** 139:158, 2024, https://doi.org/10.1140/epjp/s13360-024-04920-x

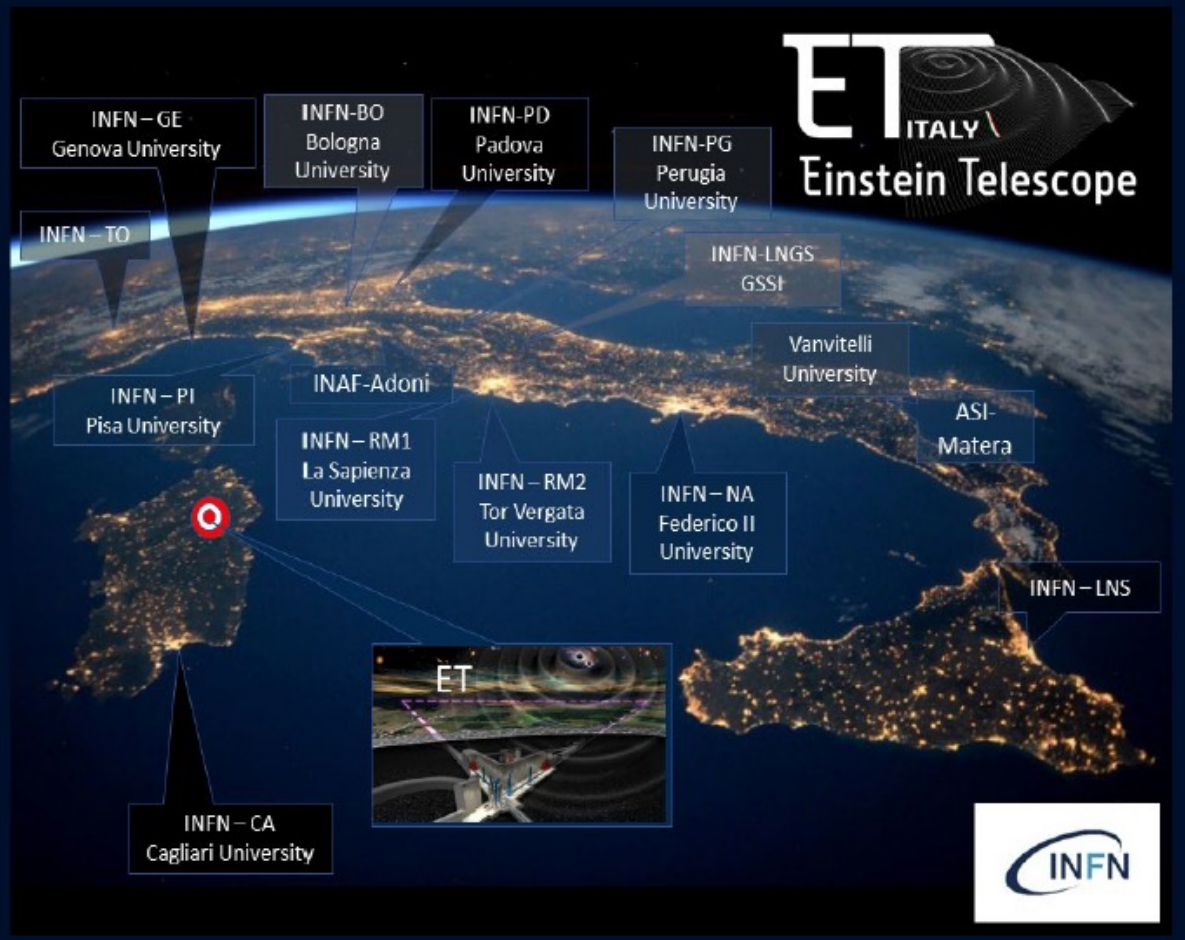
+ several internal notes, reports and talks

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN

ETIC Project

- ETIC is a Project funded by the Italian Ministry for University and Research (MUR) with 50M€ for 30 (36) months within the PNRR (NRRP National Recovery and Resilience Plan)
- It started the 1st of January 2023
- ETIC is lead by INFN, it involves other 2 national research institutions:
  - INAF (Italian institute for Astrophysics)
  - ASI (Italian Space Agency)
- and 11 Italian universities for a total of 27 operating units (INFN and INAF Units, Department of physics, civil engineering, architecture)

ETIC Einstein Telescope Infrastructure Consortium

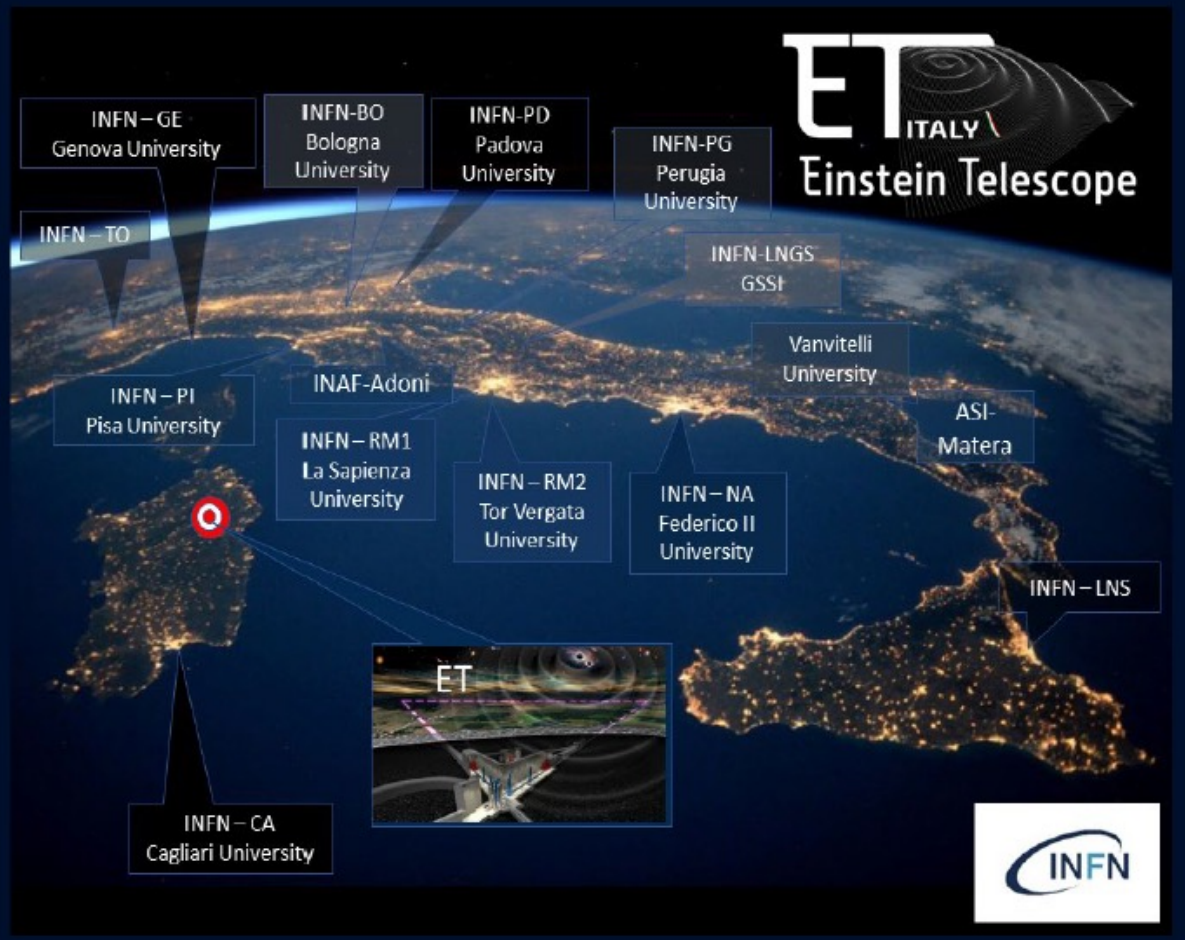


ETIC targets

https://web.infn.it/einsteintelescope/index.php/it/home-it-it/infrastrutture-e-labs

- The ETIC aim is twice:
  - Realize a network of research infrastructures located in the participating laboratories or universities addressed to the ET enabling technologies
  - Realize a feasibility study of ET in Sardinia, key element of the Italian bidbook, including geotechnical and engineering studies

ETIC Einstein Telescope Infrastructure Consortium



Investments and Timing

INVESTMENTS FOR SITE DEVELOPMENT (ALREADY ALLOCATED)

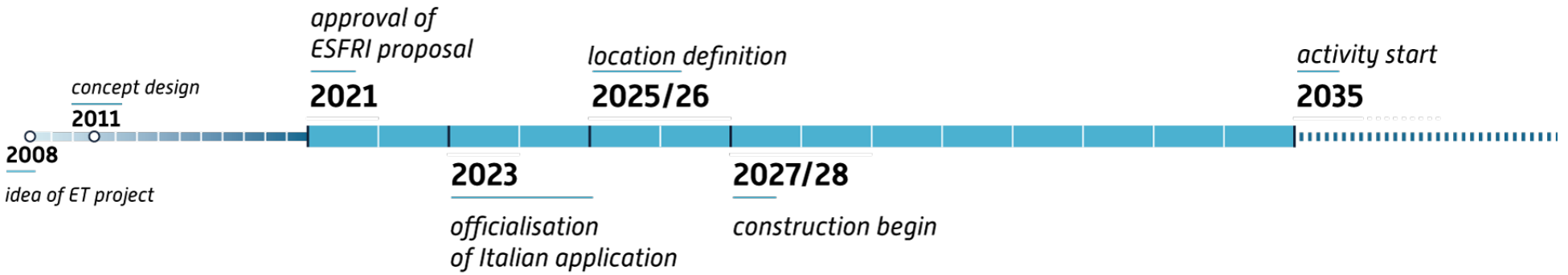
total **109 million**

€3.5 million	€17 million	€4 million	€50 million	€2.5 + 12 million	€10 + 10 million
SAR-GRAV laboratory *by Autonomous Region of Sardinia*	ET Project *by MUR*	PRIN ET Tecnhologies *by MUR*	NRRP ETIC project *by MUR*	NRRP MEET and TERABIT *by MUR*	multidisciplinary laboratory Sos Enattos *by Autonomous Region of Sardinia and INFN, INAF, INGV*

INVESTMENTS FOR THE CONSTRUCTION OF THE LABORATORY IN SARDINIA

total **1.3 billion**

€350 million	€950 million
by Autonomous Region of Sardinia	by Italian Government



Conclusions

- The Science Case ET is a huge enterprise: scientific, engineering, technological, financial, management and human challenge
- The science case of ET is broad, and addresses crucial problems in astrophysics, in cosmology, in particle and fundamental physics
  - probe the GRB population, their progenitors, and the jet properties and composition
  - probe of cosmic-ray acceleration in GRBs and of the physics of relativistic jets associated with NS-NS and NS-BH mergers
  - *discovering, or ruling out, several dark-matter candidates like primordial BH or ultralight bosons*
  - *existence of* primordial BH
  - *physics of neutron stars (particle and nuclear physics)*
  - …
- Two official site candidates: EMR and Sardinia
  - Strong political support
  - Site characterization on going
- Sardinia geologically very quiet. Very low anthropic noise.
  - **very low seismic noise in the ET-LF band, even below the Peterson limit**

The next decades in GW research will be rich of expected and unexpected surprises