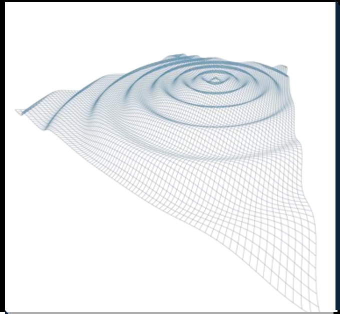
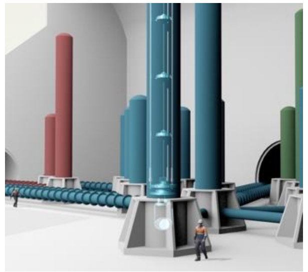
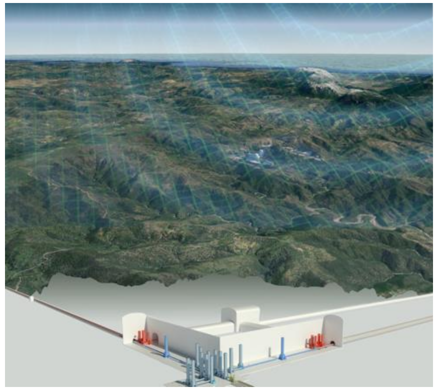




EINSTEIN TELESCOPE



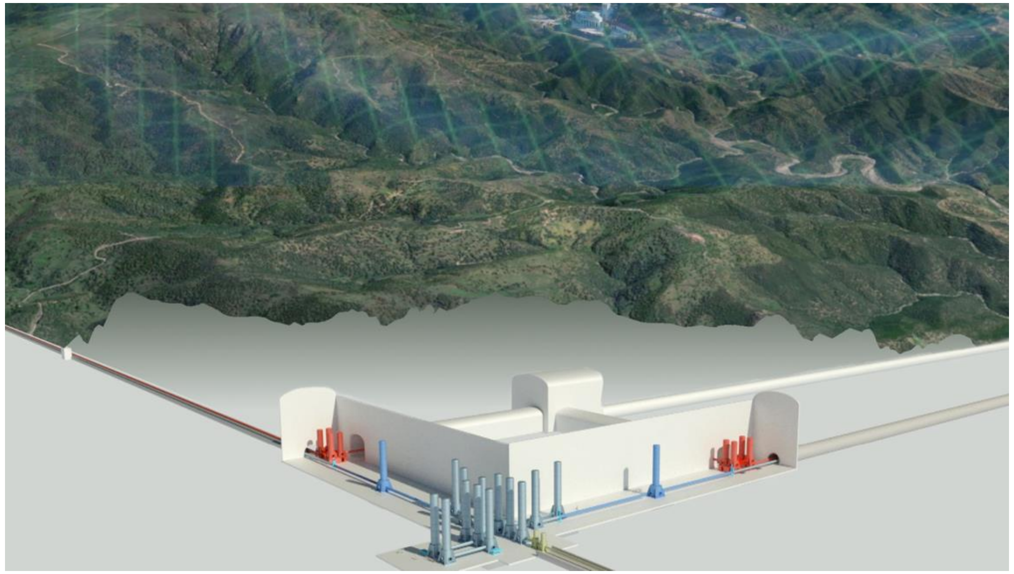
- Prof. D. D'Urso
- Univ. di Sassari & INFN Cagliari

The Einstein Telescope

The next generation detector for gravitational-wave observation

Outline

- Introduction to Gravitational Waves
- GW 2nd Generation Detectors
- The Einstein Telescope Project
  - ET organization
  - ET status
  - Candidate Sites
  - The Sardinia Site
- Conclusions



Einstein's field equation

In General Relativity (GR) the relationship between gravity, mass distribution and curvature of space-time is expressed by the field equation

$$G_{\mu\nu}\boxed{(g)} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$$

Small perturbation $h_{\mu\nu} \ll 1$

Flat metric

Imposing this condition, equations reduce to:

$$\left(-\frac{1}{c^2}\frac{\partial^2}{\partial t^2} + \frac{\partial^2}{\partial x_i^2}\right) h_{\mu\nu} = 0$$

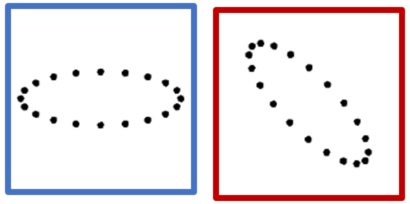
Plane wave solution

$$h_{\mu\nu} = \varepsilon_{\mu\nu} \exp[i(\omega_{GW} t - \mathbf{k} \cdot \mathbf{r})]$$

$\varepsilon_{\mu\nu} \rightarrow$ Polarization tensor

2 degrees of freedom in GR

+ polarization



× polarization

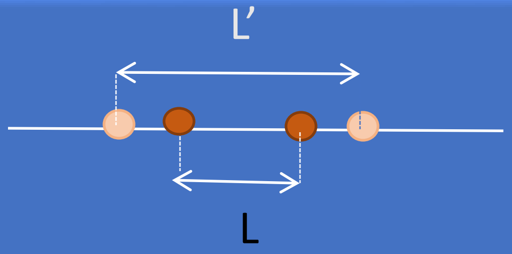
GW amplitude

The amplitude of gravitational waves is proportional to the quadrupole moment of the source masses through the constant **G/c⁴ ≈ 10⁻⁴⁵ N⁻¹**

$$h_{jk}^{TT} = \frac{2G}{rc^4}\left(\frac{d^2 I_{jk}^{TT}}{dt^2}\right)_{t-r/c}$$

→ **Only astrophysical sources can produce detectable effects**

Binary compact objects (BBH, BNS, BH-NS), pulsars, bursts, stochastic background



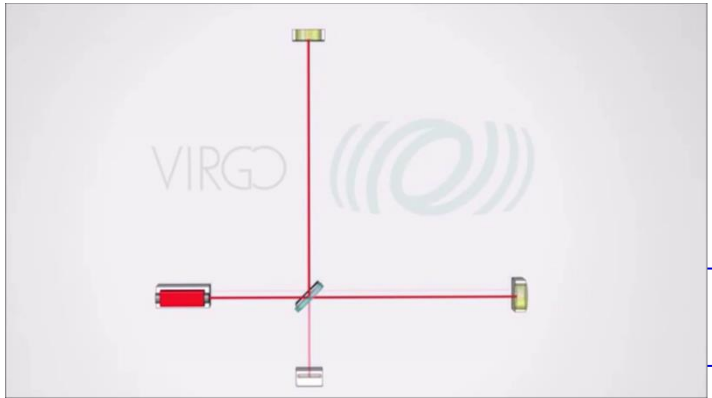
$$|L' - L| = \delta L \propto h L$$

$\boldsymbol{h \approx 10^{-21}}$ for GW produced by huge astrophysical sources

The distance between two free-falling masses separated by ~km will change by $\boldsymbol{\delta L \approx 10^{-18}}$**m**

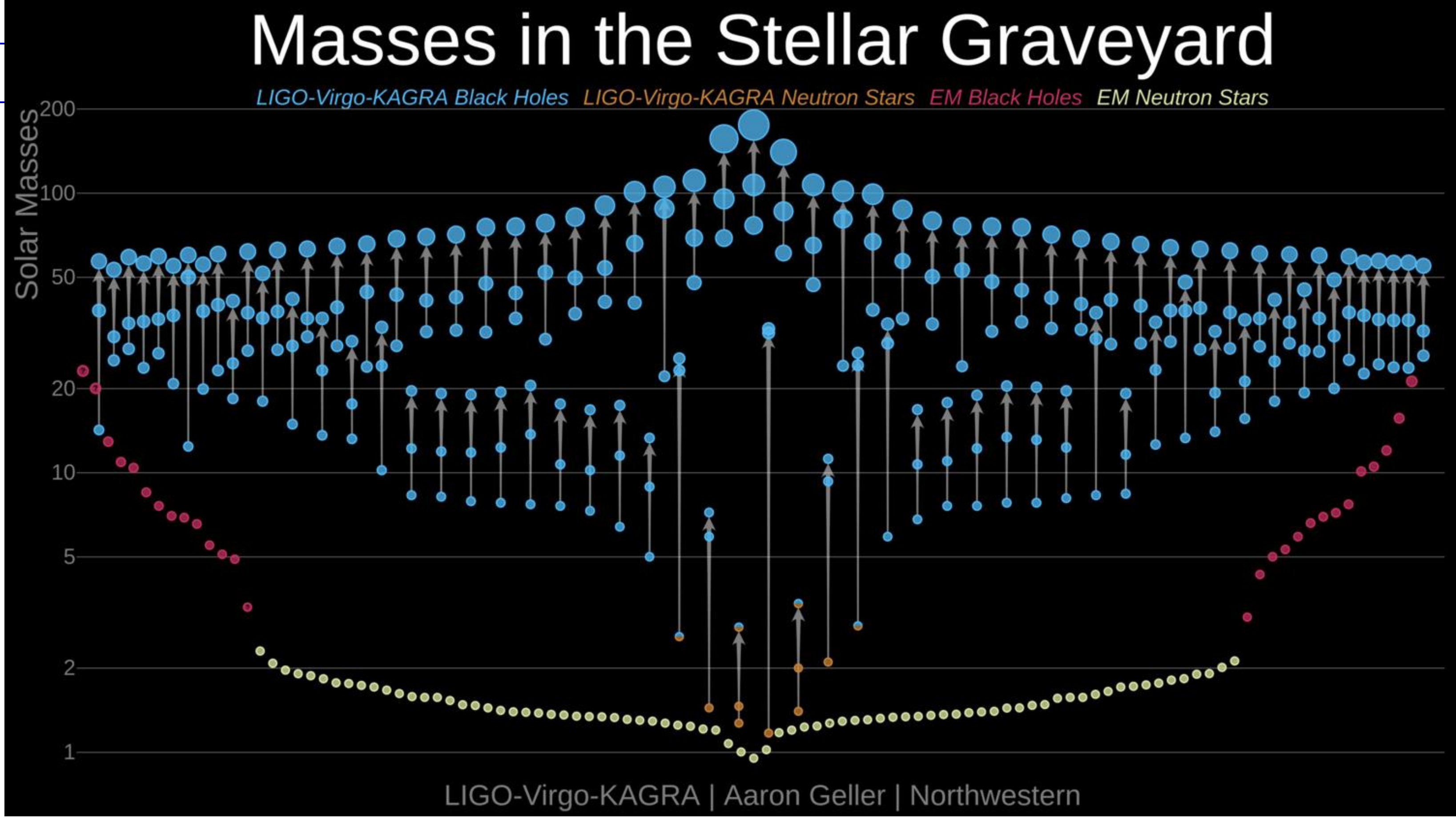
Comparable to a hair's-width change in the distance from the Sun to Alpha Centauri

Current GW detectors



2.5G detectors

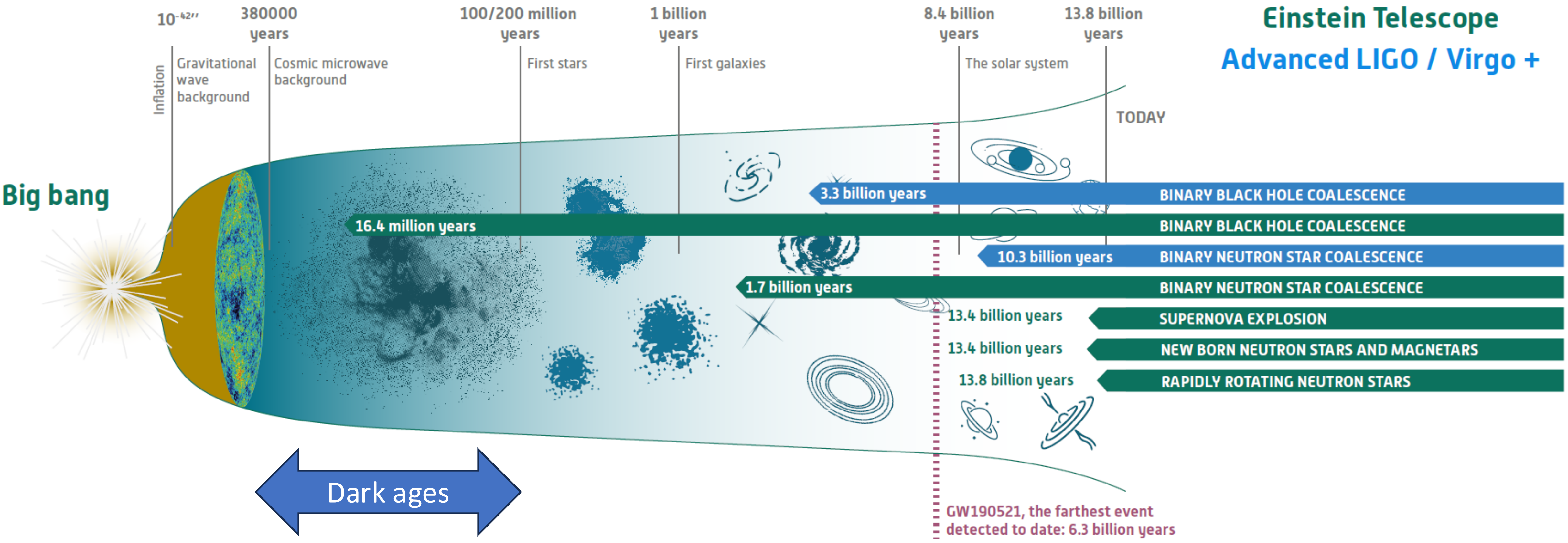
GW detectors today



- O1+O2+O3 = 90 events
- O4 = 201 public alerts (as of March, 25 2025)
- All from the coalescence of compact binaries. Three events catalogs:
  - GWTC-1 (2018)
  - GWTC-2 (2020)
  - GWTC-3 (2023)

3G Science mission

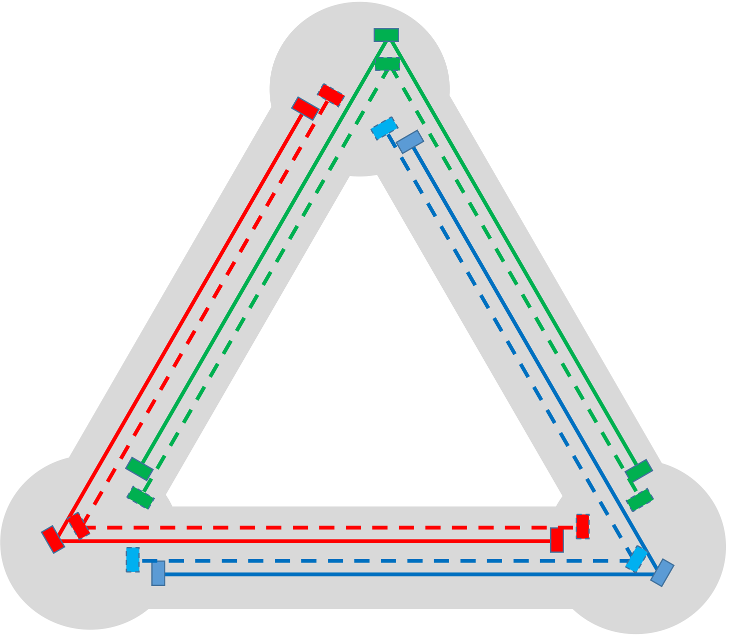
- ➢Current GW detectors had a huge scientific impact
- ➢Limited to a "relatively" local Universe



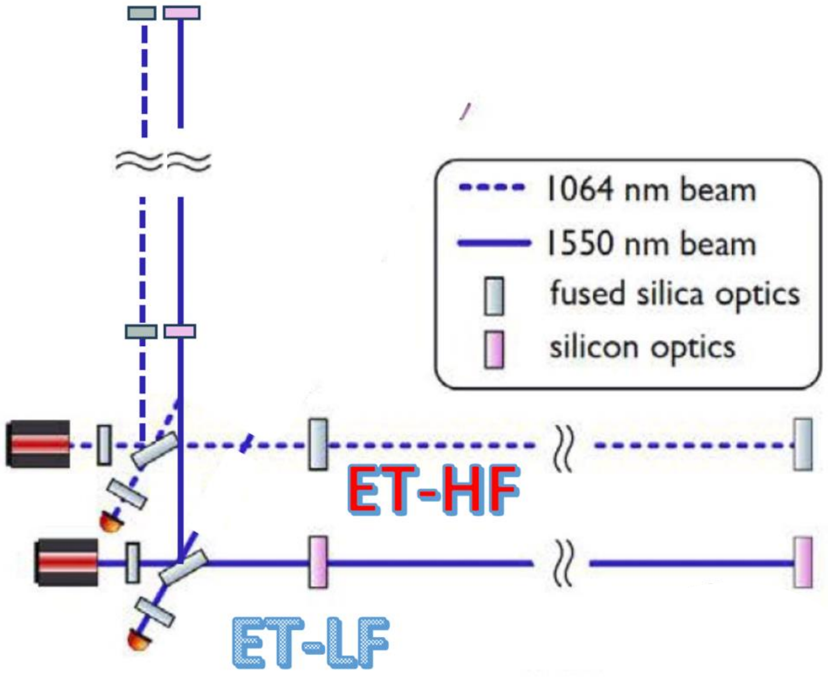
What's the Einstein Telescope (ET)

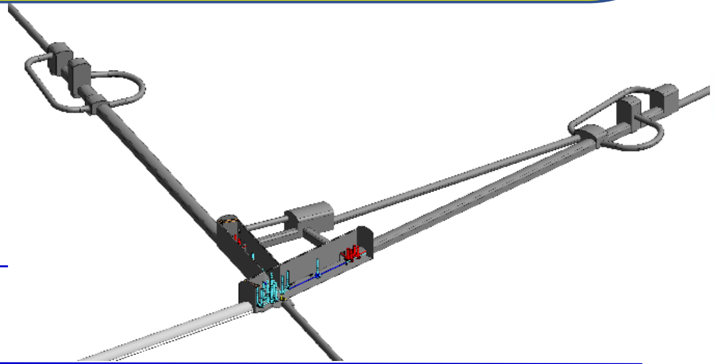
- **3rd generation GW observatory** Sensitivity aims at least one order of magnitude better with respect to the nominal sensitivity of advanced detectors in all the detection frequency band
- **Precision measurement and a new discovery project.** A wide frequency band observatory
- **Special focus on 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



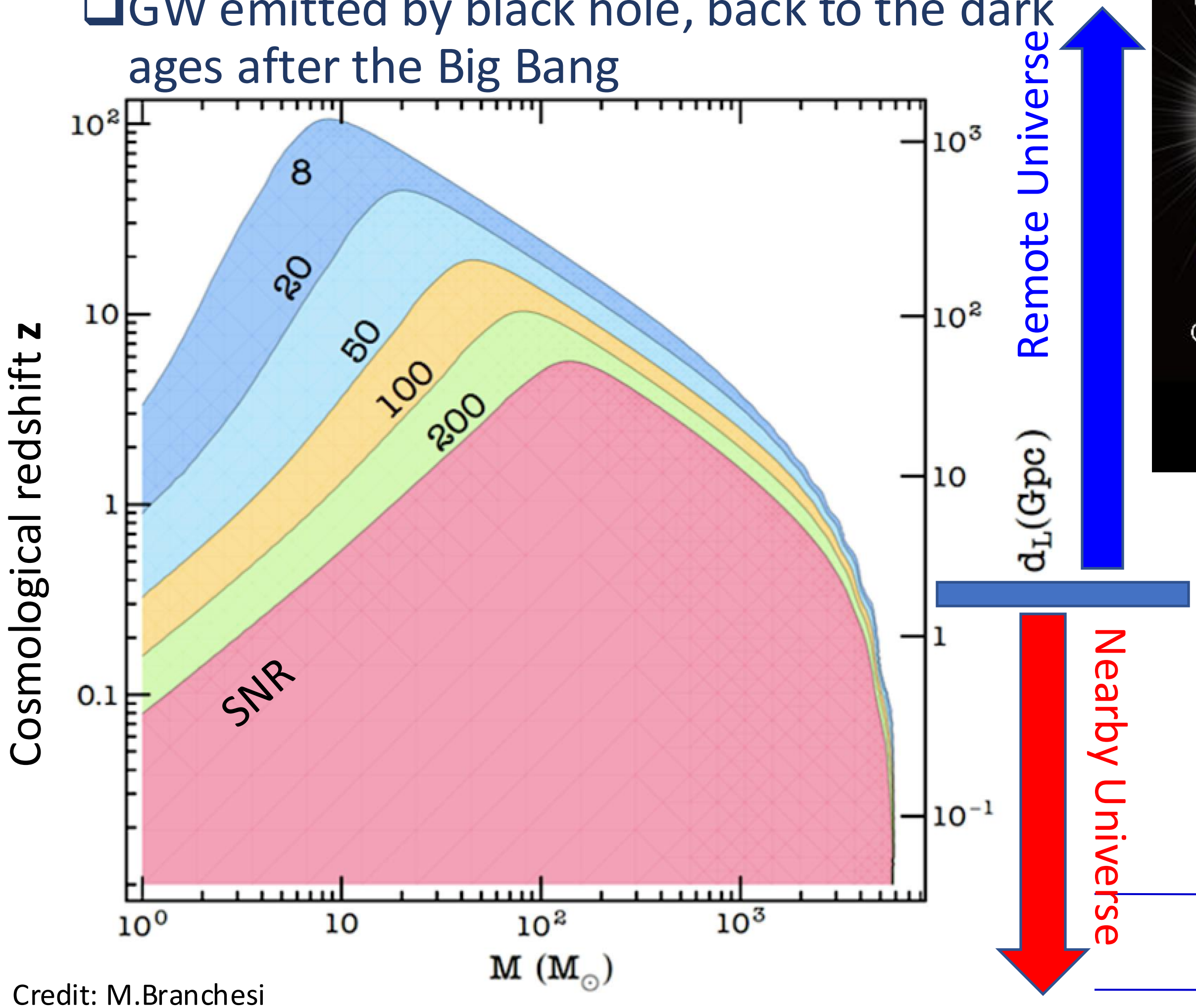
Requirements	Design Specifications
• Wide frequency range • Massive black holes (LF focus) • Localisation capability • (more) Uniform sky coverage • Polarisation disentanglement • High Reliability (high duty cycle) • High SNR	• Xylophone (multi-interferometer) Design • Underground • Cryogenic • Triangular shape • Multi-detector design • Longer arms



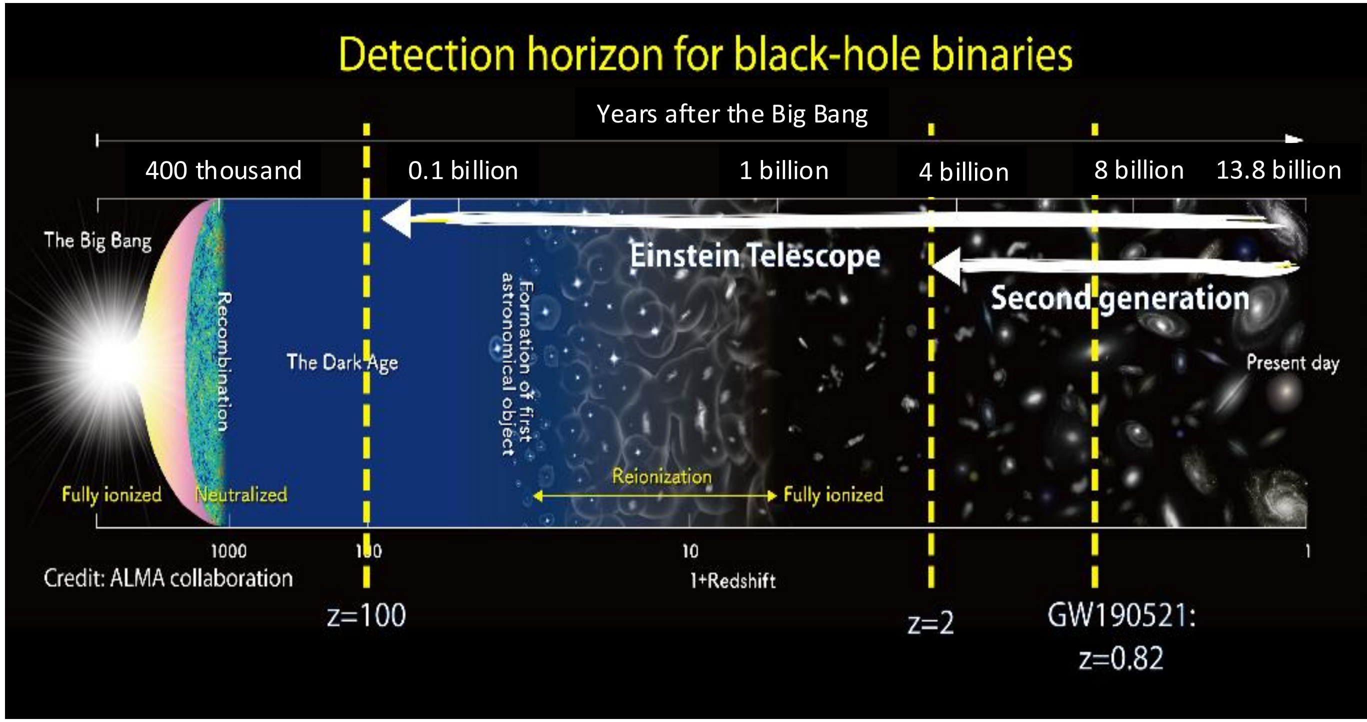


ET Science in a nutshell: double nature

- ➢ ET will be a new discovery machine:
  - ❑ GW emitted by black hole, back to the dark ages after the Big Bang

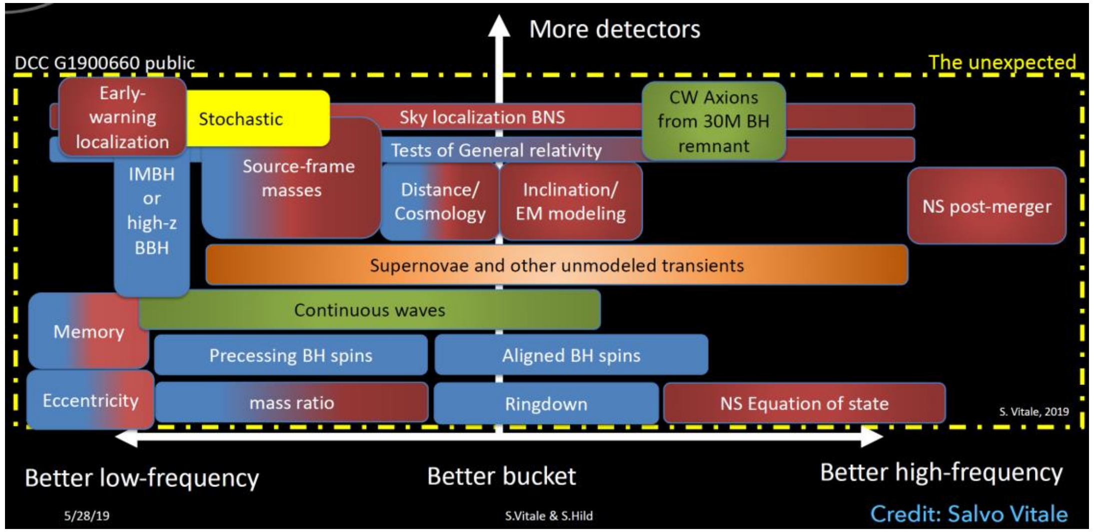


Credit: M.Branchesi



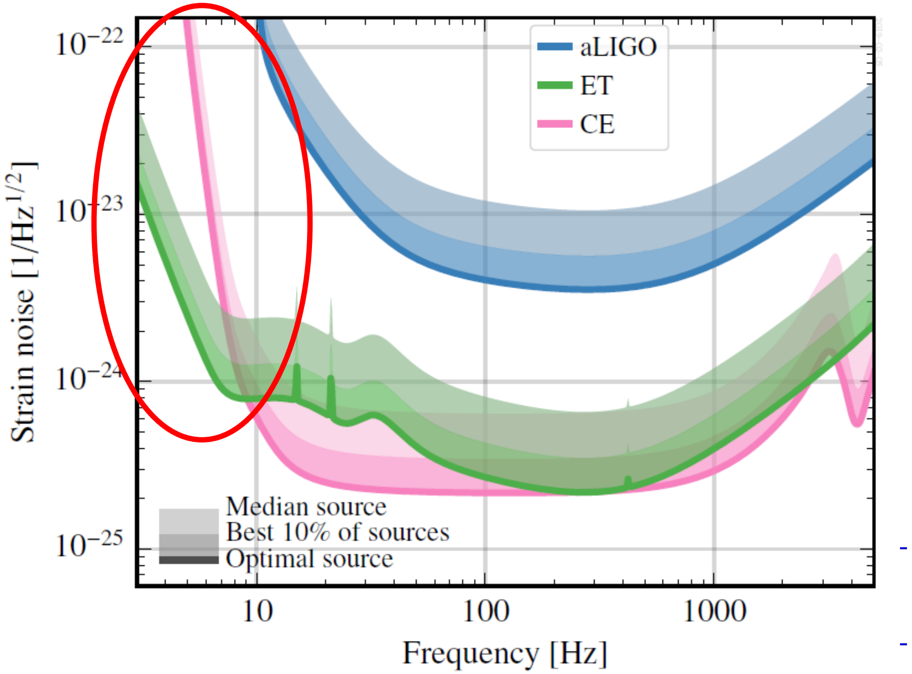
- ET will be a precision measurement observatory:
  - ET will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei

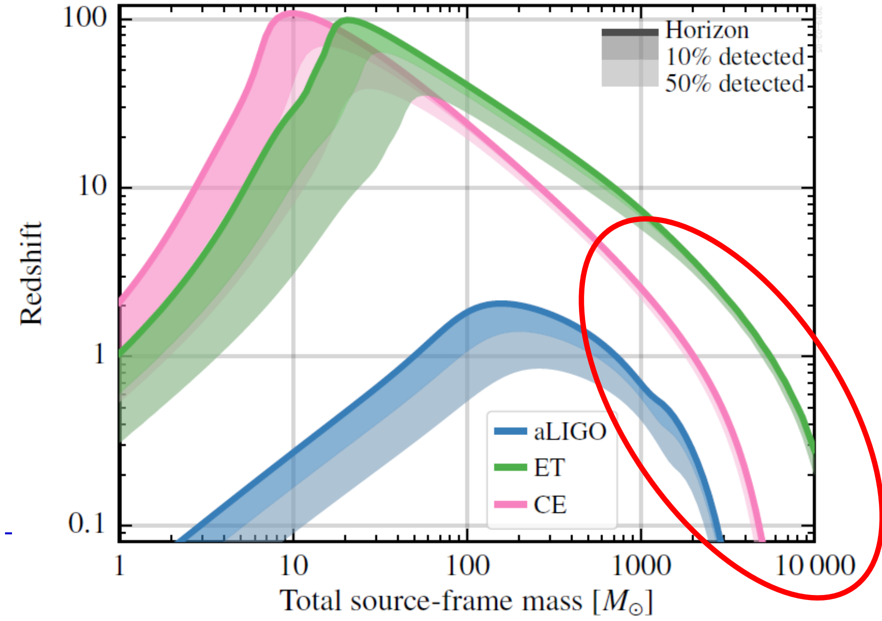
ET Science in a nutshell: double nature



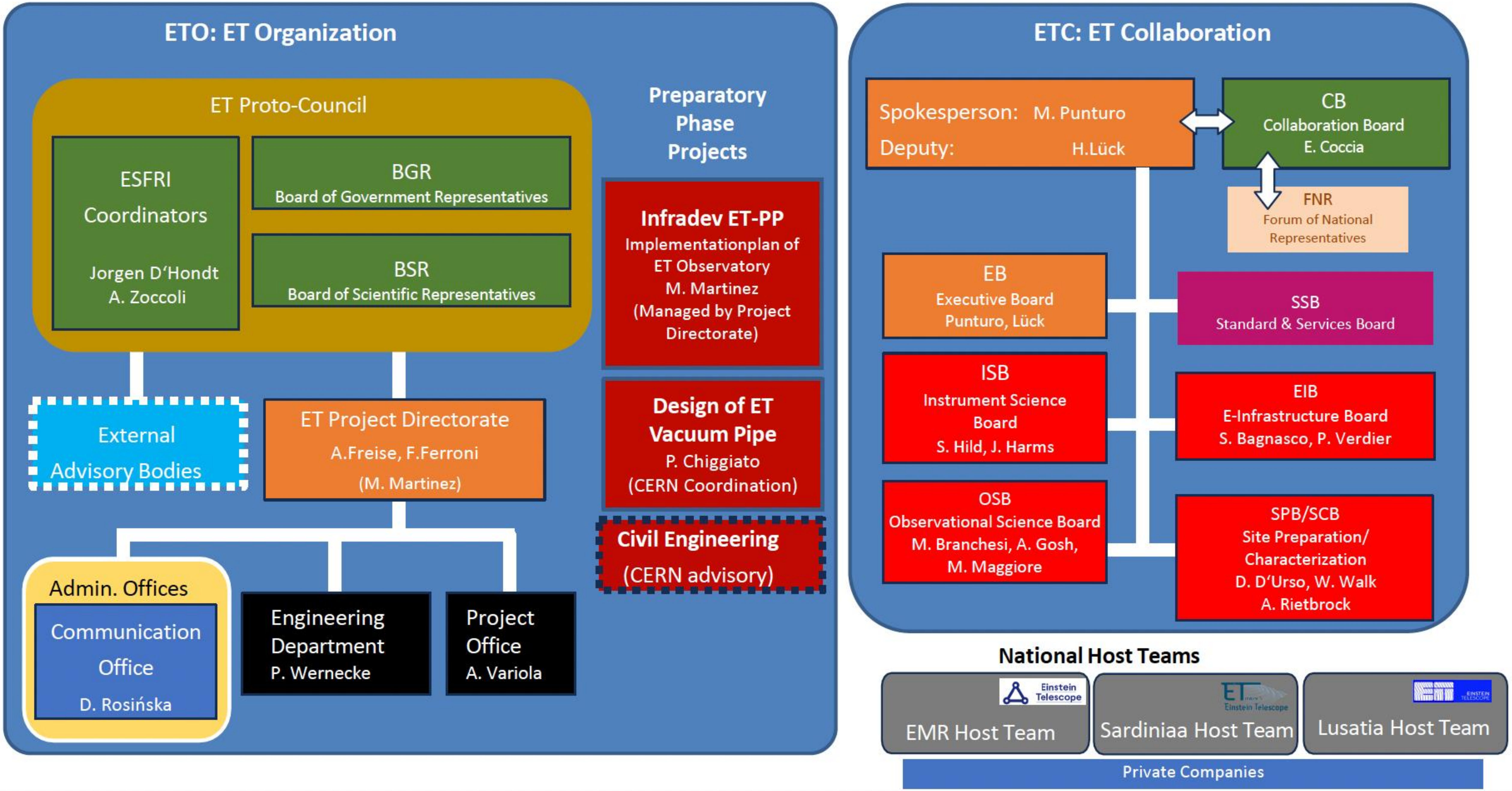
- ➢ GW science targets are almost equally distributed in the frequency range accessible by terrestrial GW detectors (but technical difficulties aren't)
- ➢ We want to have access both to low and high frequency targets
  - ❑ BBH up to z~50-100, 10^5 BBH/year, Masses $M_T \gtrsim 10^3\ M_\odot$
  - ❑ BNS 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



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
Jun 12th 2025

1822 Members
93 Research Units
264 Institutions
31 countries.

ET Italy

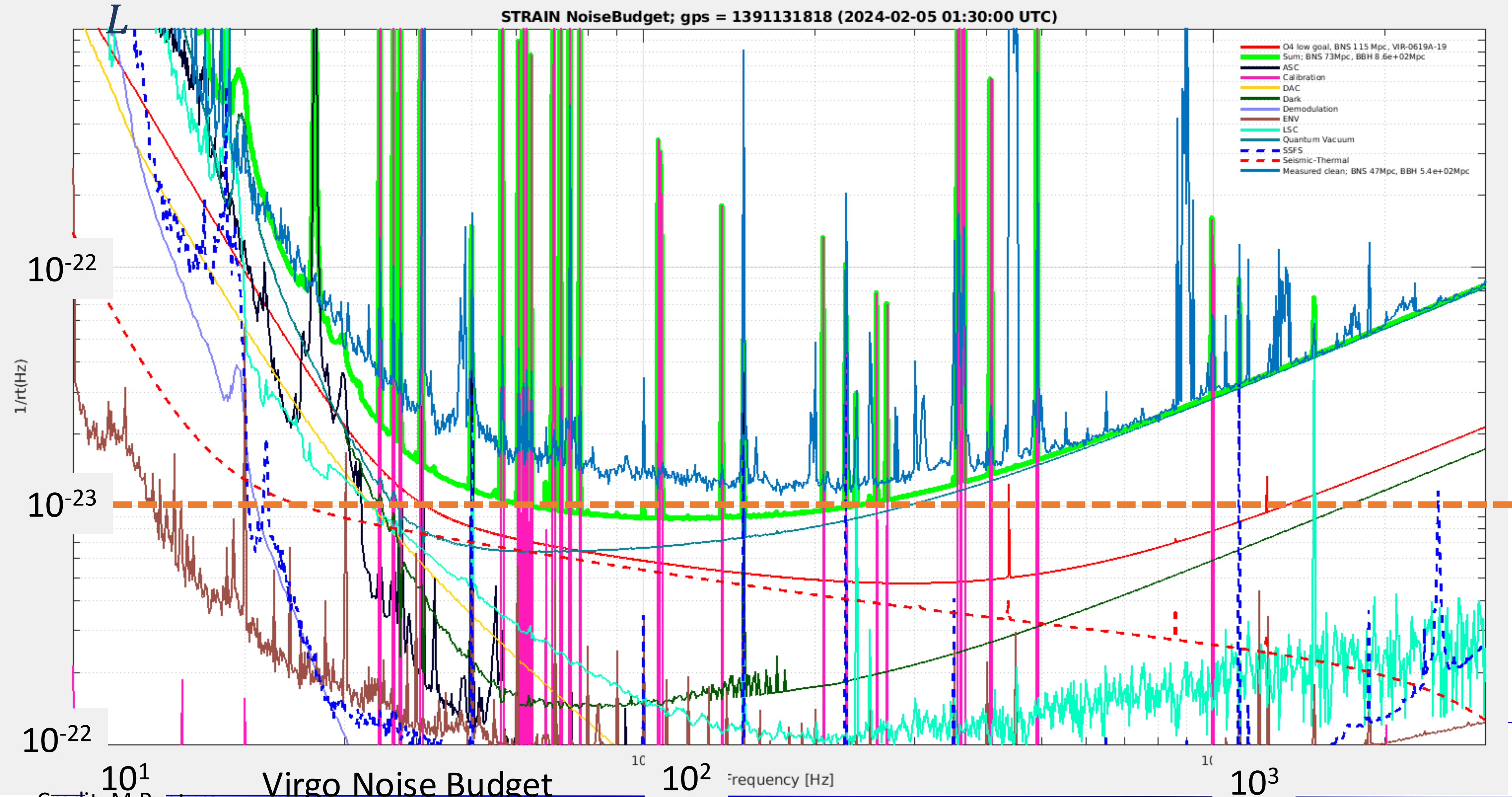
- ~ 600 members of 81 institutions for 27 RU
- **Site Characterization**
- **R&D enabling technologies**
- **Science case**

ASI Agenzia Spaziale Italiana
CINECA
EGO European Gravitational Observatory
INAF Istituto Nazionale di Astrofisica
INFN Istituto Nazionale di Fisica Nucleare
Istituto Nazionale di Geofisica e Vulcanologia
Consortium GARR
GSSI Gran Sasso Science Institute
OGS Istituto Nazionale di Oceanografia e di Geofisica Sperimentale
Alma Mater Studiorum Università di Bologna
Università degli Studi di Cagliari
Università degli Studi della Campania Luigi Vanvitelli
Università di Genova
Università degli Studi di Napoli Federico II
Università degli Studi di Padova
unipg Università degli Studi di Perugia
Università di Pisa
Sapienza Università di Roma
Tor Vergata Università degli Studi di Roma
UNISS Università degli Studi di Sassari

Current Main Activities

- **Updating the ET science case Δ or 2L**
- **Define a feasible optical layout and the key elements of the ET detector**
- **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**

➢GW detector are measuring space-time curvature ripples as fluctuations of the differential lenghts of the arms of the interferometers: $h(\omega) = \frac{\Delta L(\omega)}{L}$



Virgo Noise Budget

Credit: M.Punturo

Human cell 10^{-6}-10^{-5}m

Hydrogen atom 10^{-10}m

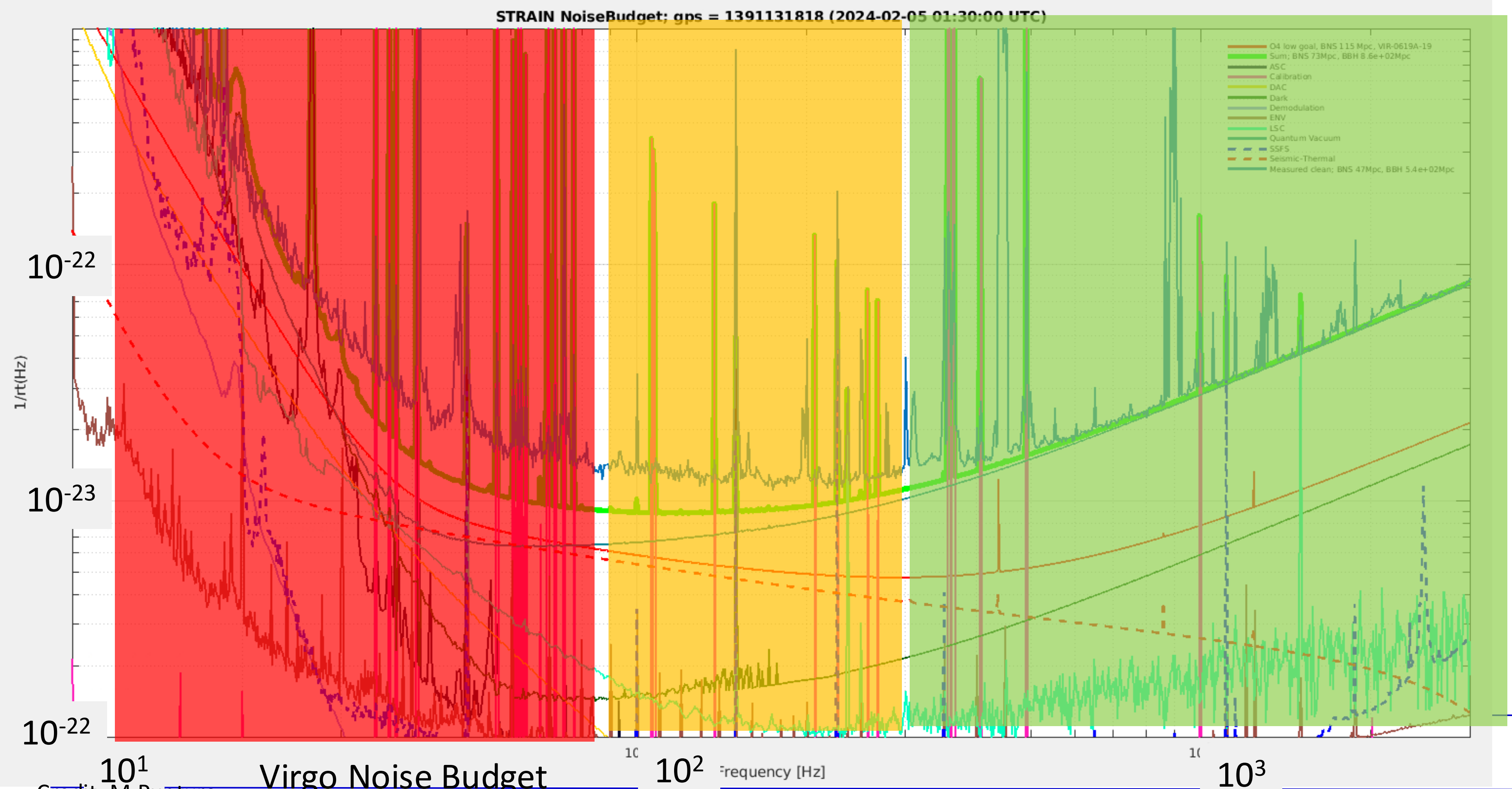
Proton 10^{-15}m

Quark (effective radius) 10^{-18}m

$$h(\omega) \approx 10^{-23}$$

$$\Delta L \approx few \times 10^{-20} m$$

- **High Frequency:** if the detector is well designed it is «relatively» simple, and the shot noise is the dominant noise. It is then mainly “detector” dependent
- **Medium frequency**: Impact of the “environment” and of the civil infrastructure competes with the fundamental noises



Virgo Noise Budget

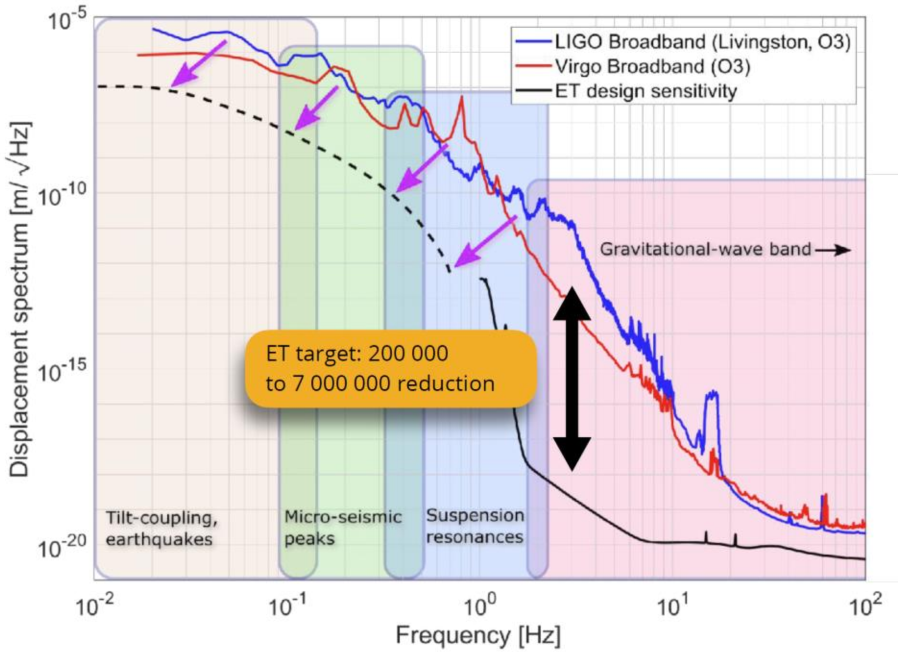
Credit: M.Punturo

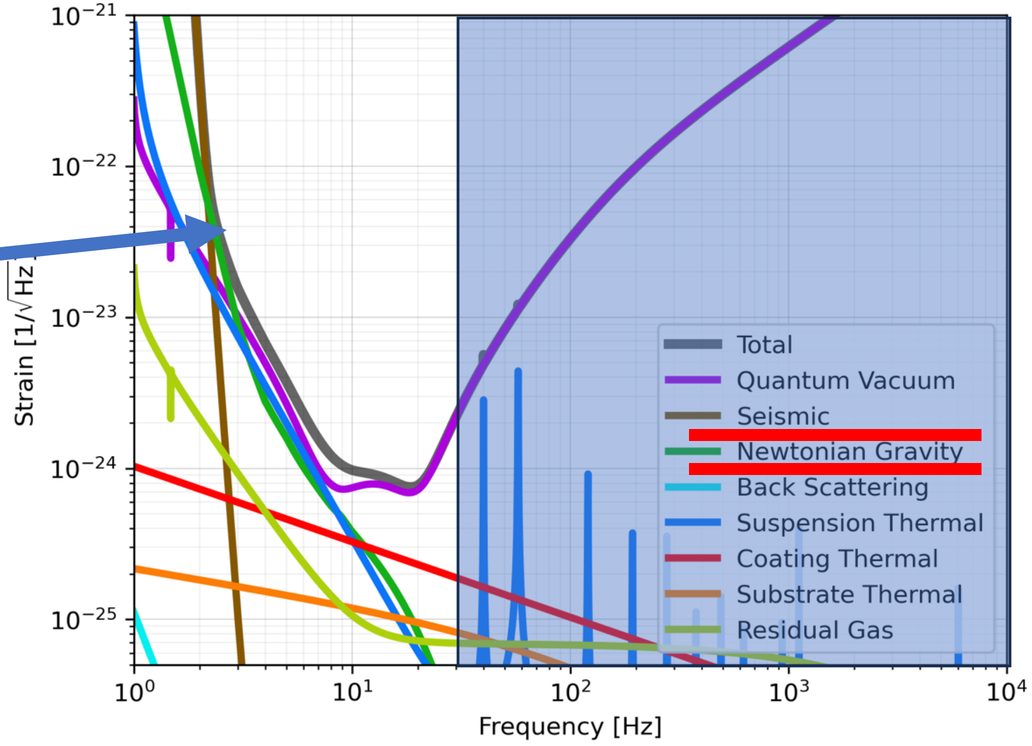
Low Frequency: The importance of the infrastructure and of the site is dominant because of the impact of the seismic noises, Newtonian noise, magnetic noise, acoustic noise (also sub audible frequencies). Relevance of seismic filtering efficiency, control noises, ….

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





SiteCharacterization coordinated in the framework of the **ET Collaboration:** Site Characterization Board (SCB).

ET Computing Model & Multi-Messenger Requirements

From the P. Laycock slides @ XV ET Symposium

- **Primary data stream:**
  - Main observable: *strain h(t)* at 16 kHz
  - Estimated data volume: up to **100 PB/year** (with auxiliary channels)
  - Typical analysis volume: **10–100 TB/year**
- **Current LVK model:**
  - *Online:* acquisition, calibration, data quality
  - *Low-latency:* alerts within minutes, rapid parameter estimation
  - *Offline:* full analysis starting from alert timestamps
- **Challenges for multi-messenger science:**
  - Must handle **external triggers** (e.g., GRBs, CCSNe)
  - Critical requests estimated at **<1,000/year**
  - Response time for some pipelines must be **<1 minute**

Challenges in ET Data Analysis: Long-Duration Signals, Overlaps & Noise

➢ Long-Duration Signals

- ❑ ET's low-frequency sensitivity → **signals lasting hours** (e.g., BNS inspirals)
- ❑ Higher computational load for **matched filtering** and **waveform modeling**
- ❑ **Earth's motion** modulates signal → affects **sky localisation** and **template banks**

➢ Overlapping Signals

- ❑ **High event rate** ⇒ frequent **signal overlap**
- ❑ Single-signal analyses may introduce **biases**
- ❑ Need for **novel algorithms** to handle **simultaneous overlapping events**

➢ Noise Background Estimation

- ❑ GW signals dominate ⇒ **few signal-free segments**
- ❑ Standard techniques risk **overestimating noise**

Candidate sites

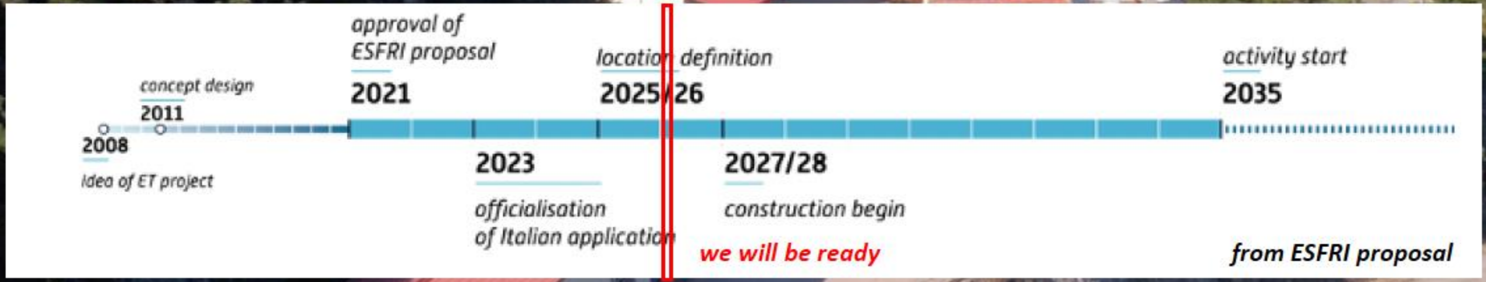
- Three candidate sites:
  - ❑ EMR EUregio, border region between Nederland, Belgium and Germany
  - ❑ Sardinia (Sos Enattos area)
  - ❑ Saxony (Lusatia, since Oct. 2024)
- Overall site evaluation is a complex task depending on:
  - ❑ Detector performance
  - ❑ Geophysical and environmental quality
  - ❑ Financial and organization aspects
  - ❑ Services, infrastructures

Credits to G. Bisoffi

Einstein Telescope

The Italian candidate site for ET: Sos Enattos, Sardinia

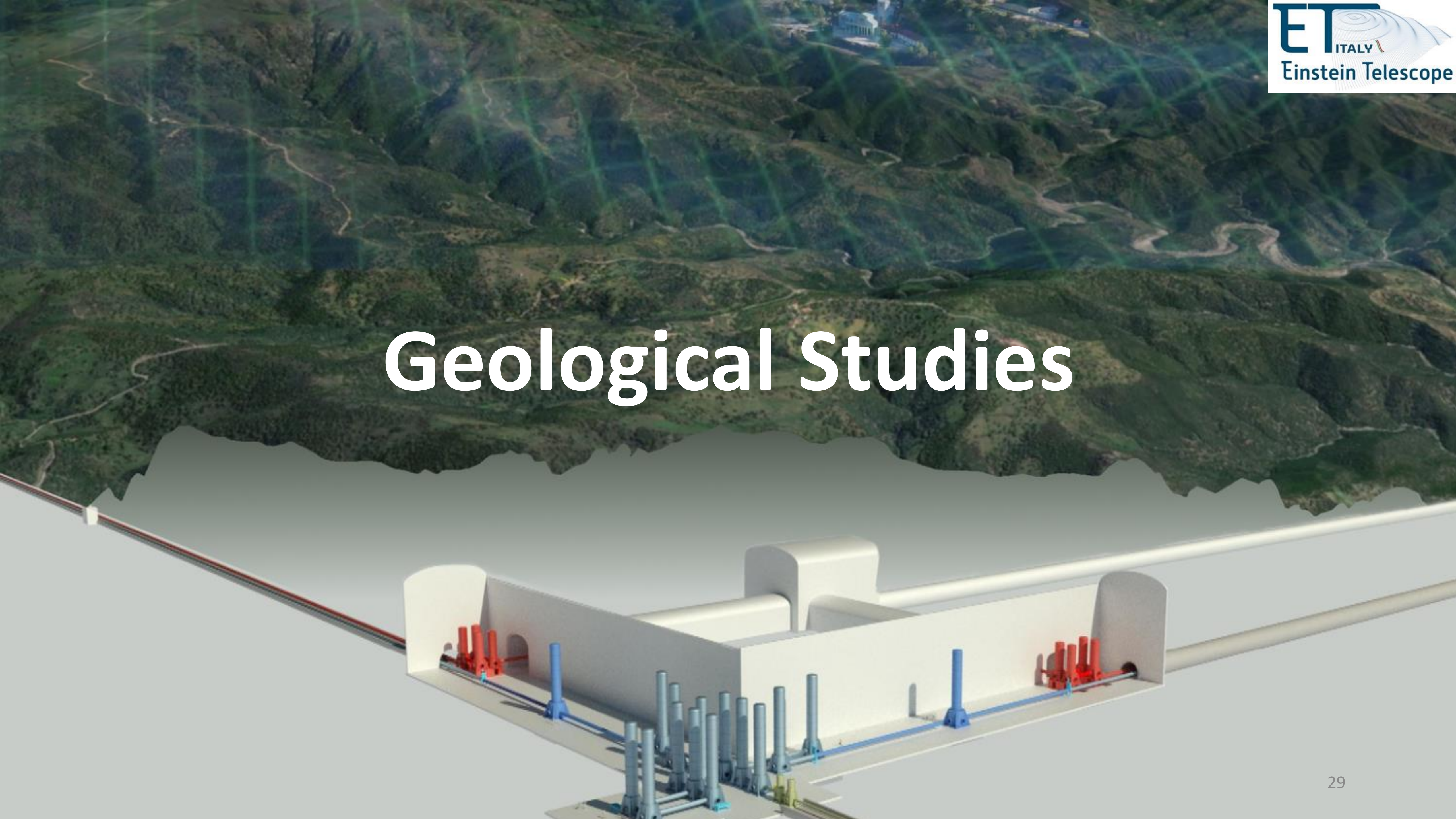
- ✓ INFN leads the proposal, for *either* a 2L or Δ configuration
- ✓ INAF and INGV support the proposal with complementary science and expertise
- ✓ A ready-to-tender, civil engineering study - delivered by 2025, compliant with the ESFRI timeline



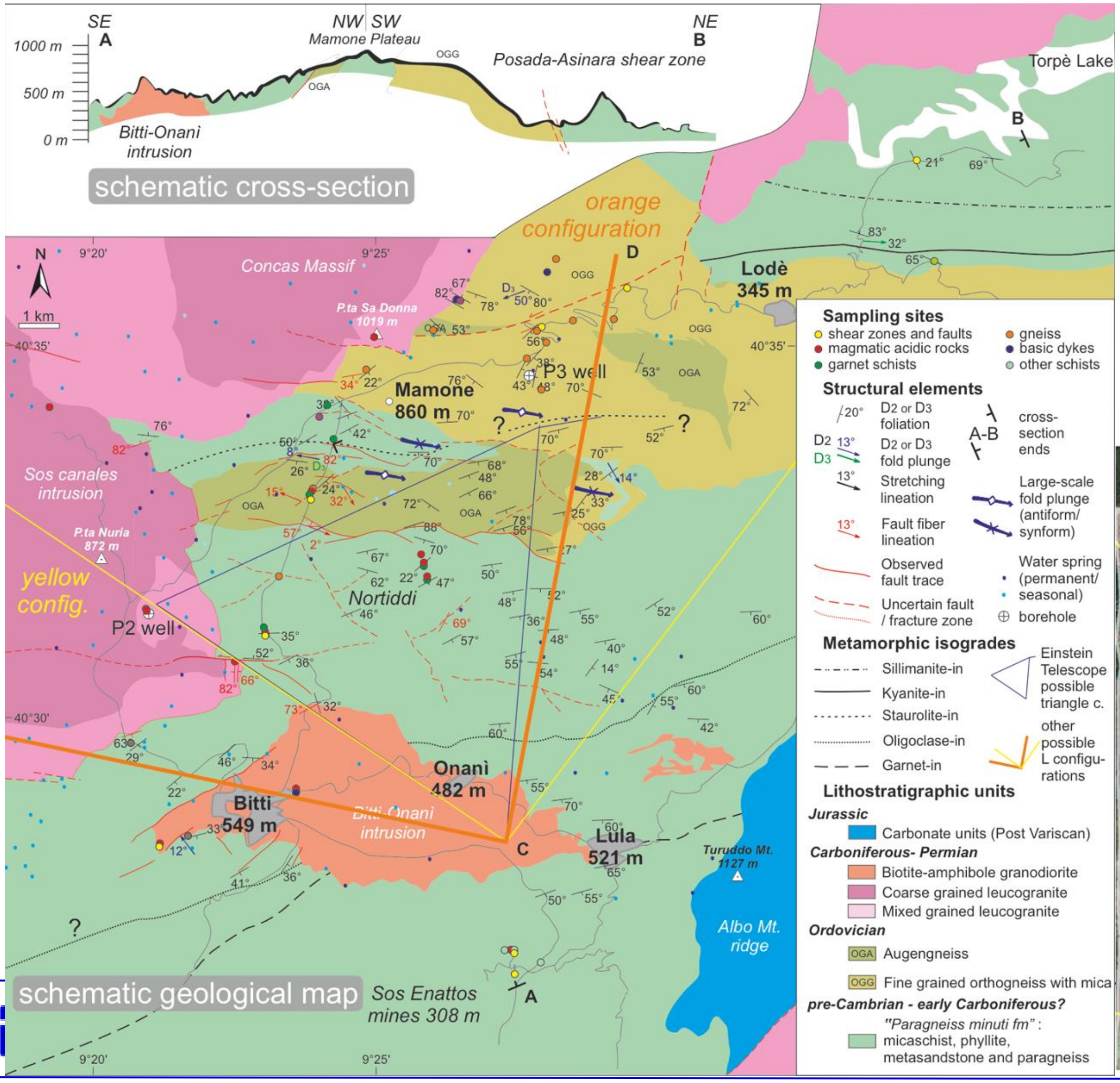
Action lines

- Two Geometrical Options: Δ vs 2L
- Legal Framework and authorization
- Socio-economic impact
- Site monitoring
- Geological studies
- Noise impact Evaluation
- Engineering studies
  - cost and time estimation

Geological Studies

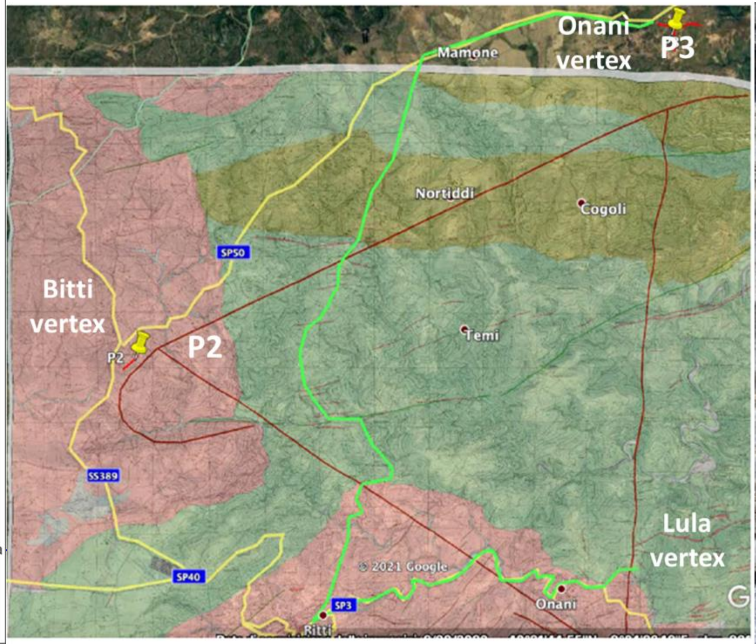


The ET Italian candidate site is located in the stable
VARISCAN BASEMENT OF SARDINIA



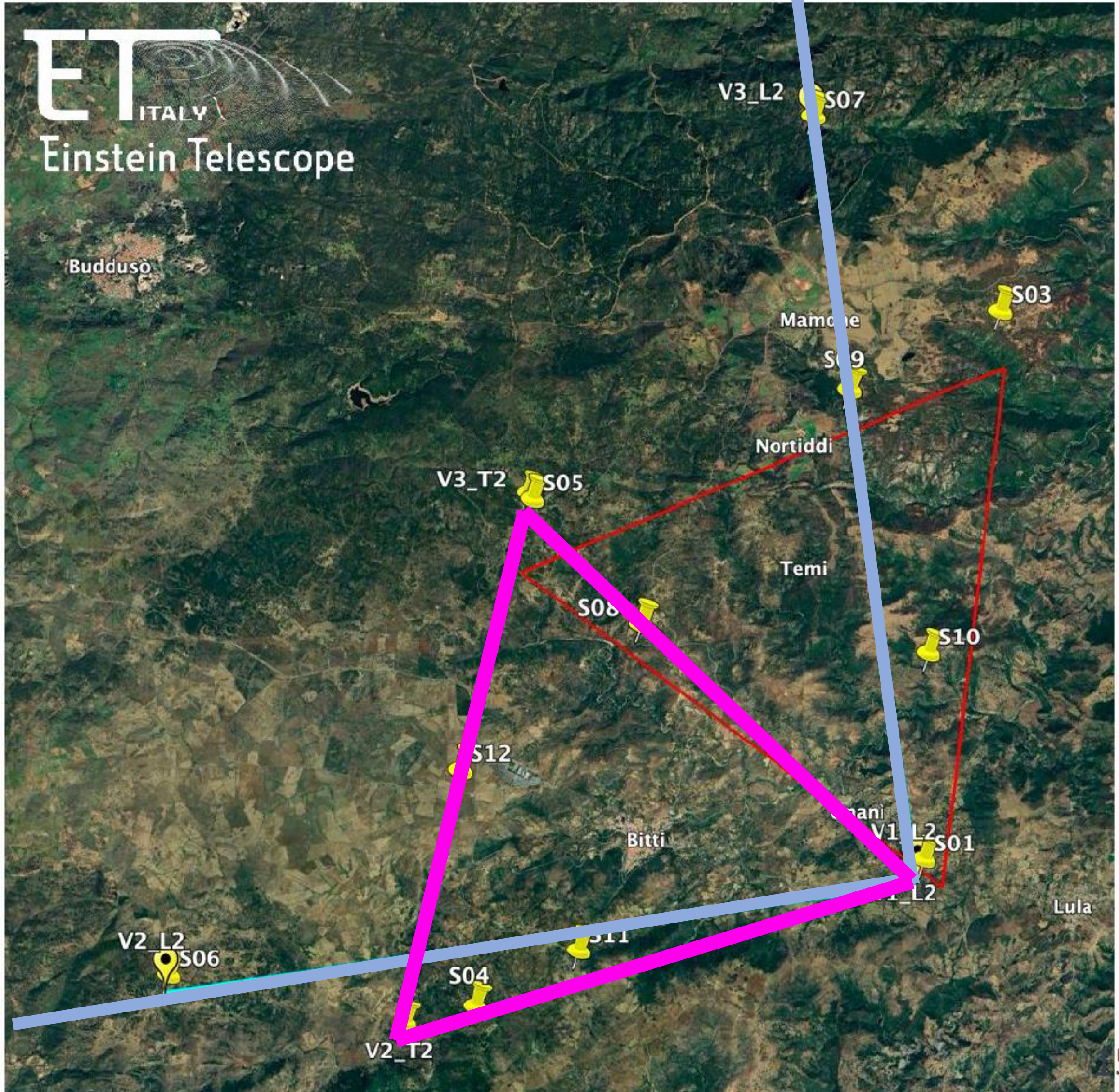
LITHOLOGIES: Orthogneiss, granitoids, micaschists.

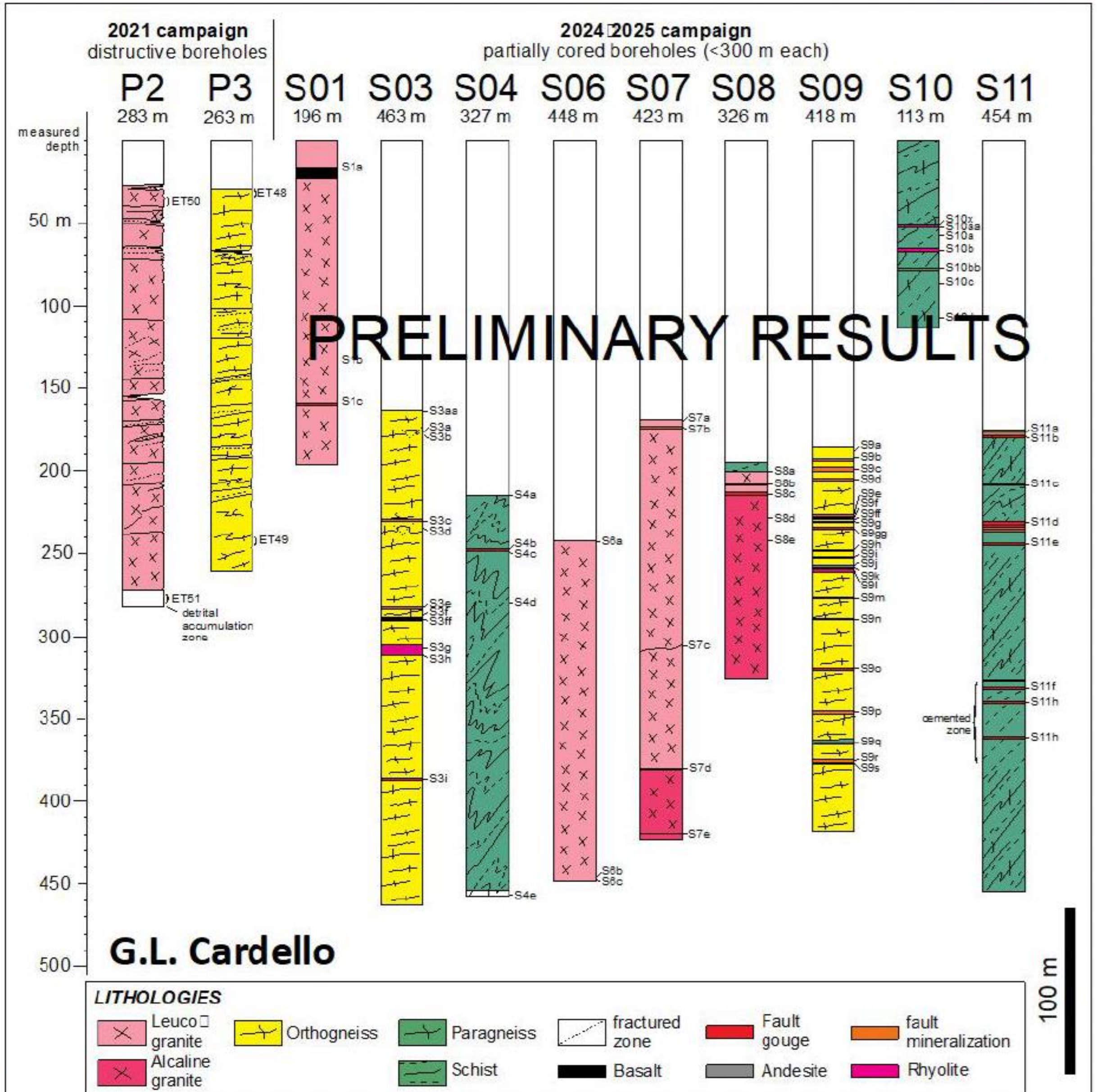
P2 and P3 are the borehole locations



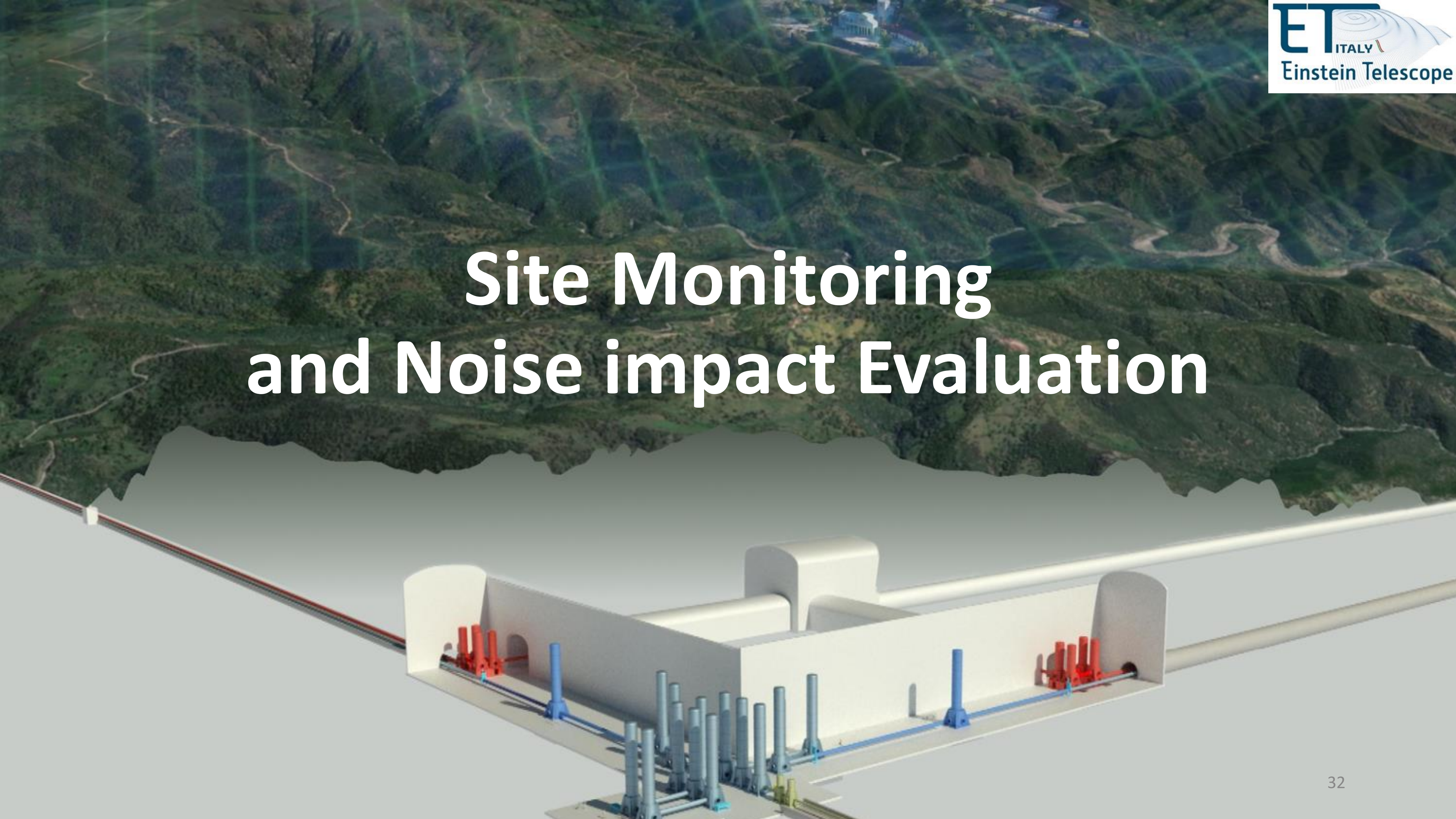
GEOLOGICAL EXPLORATION AND NEW CONFIGURATION

uniss
UNIVERSITÀ DEGLI STUDI DI SASSARI





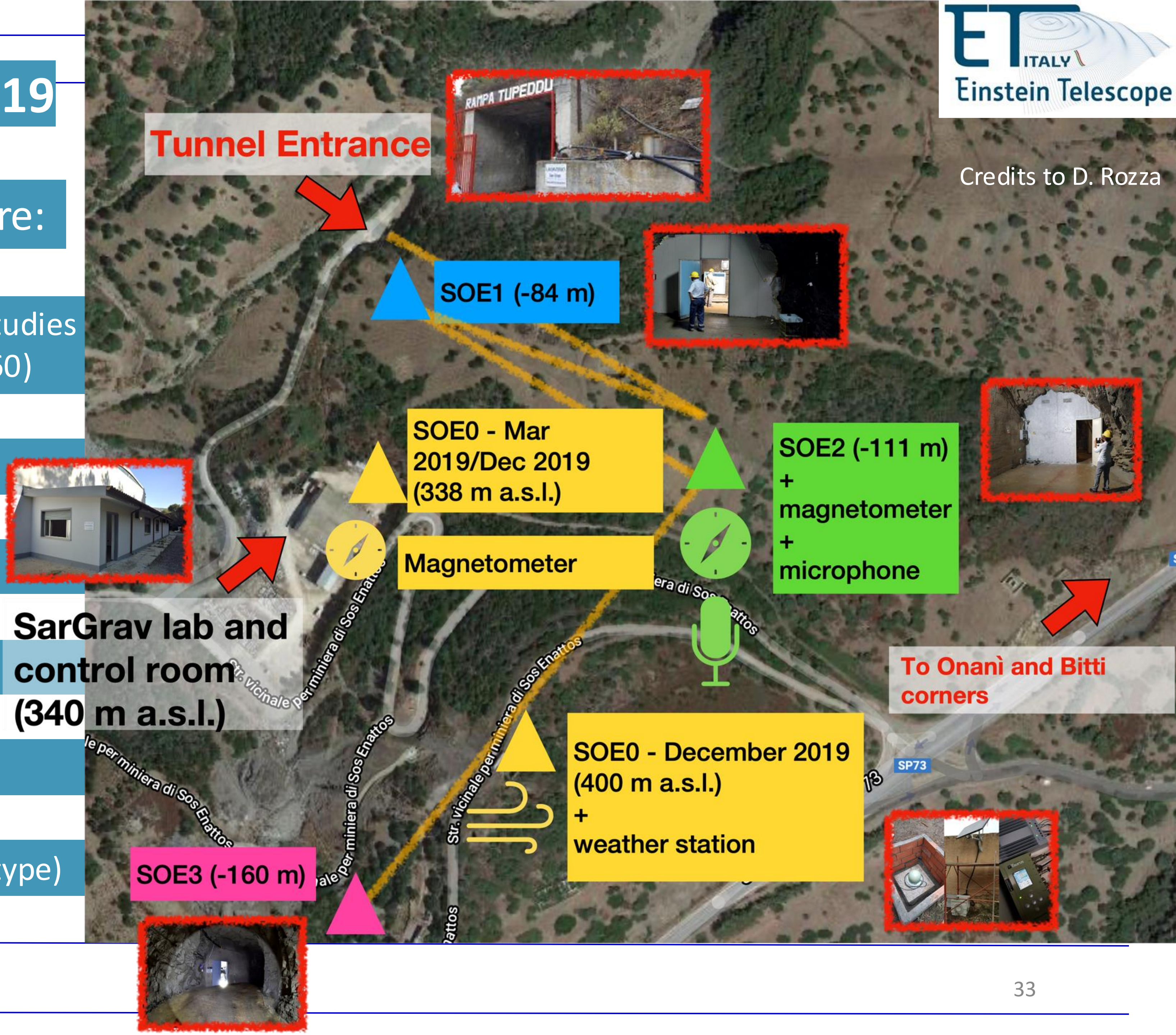
Site Monitoring and Noise impact Evaluation



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

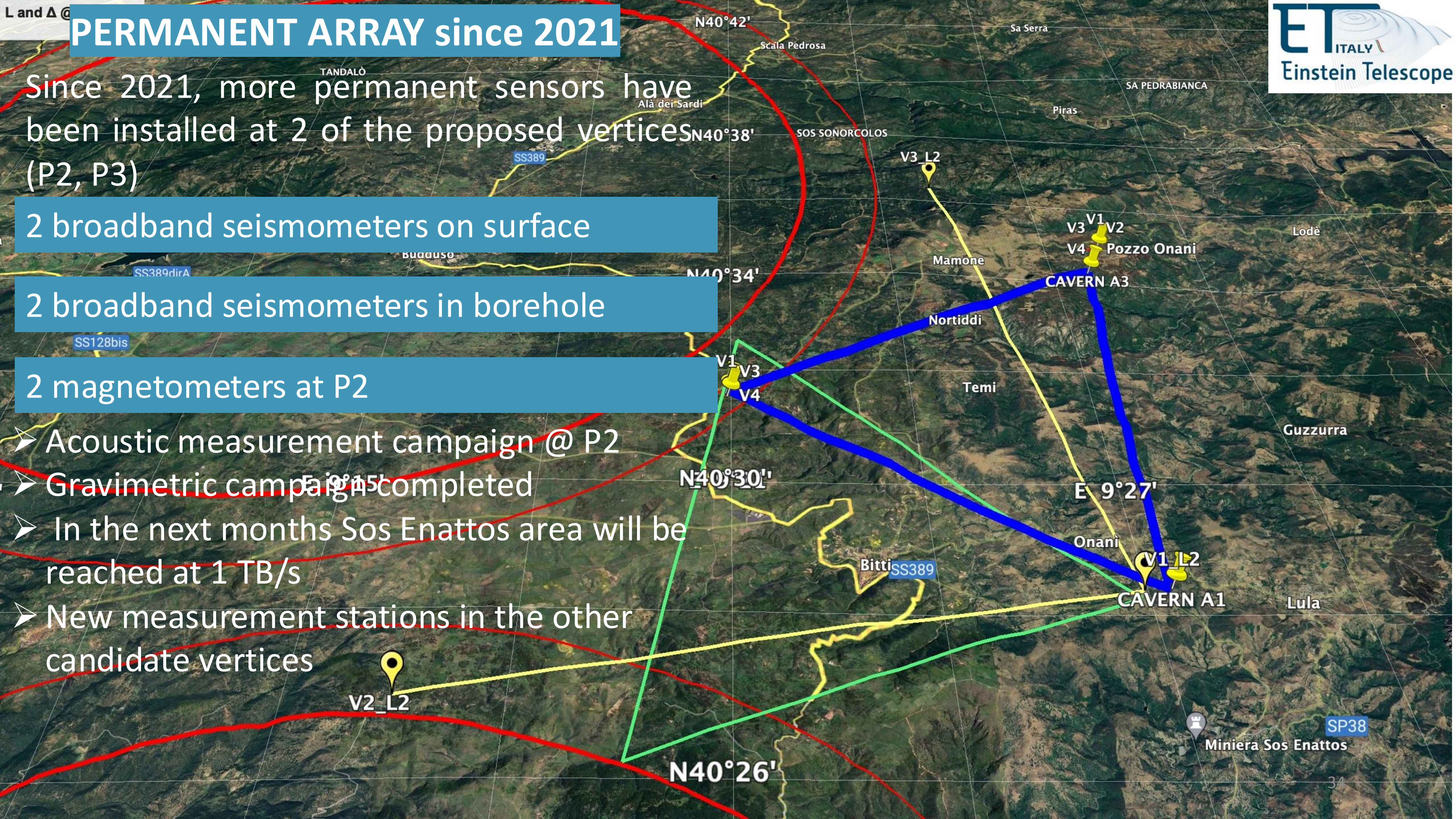
Since 2021, more permanent sensors have been installed at 2 of the proposed vertices (P2, P3)

2 broadband seismometers on surface

2 broadband seismometers in borehole

2 magnetometers at P2

- Acoustic measurement campaign @ P2
- Gravimetric campaign completed
- 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.

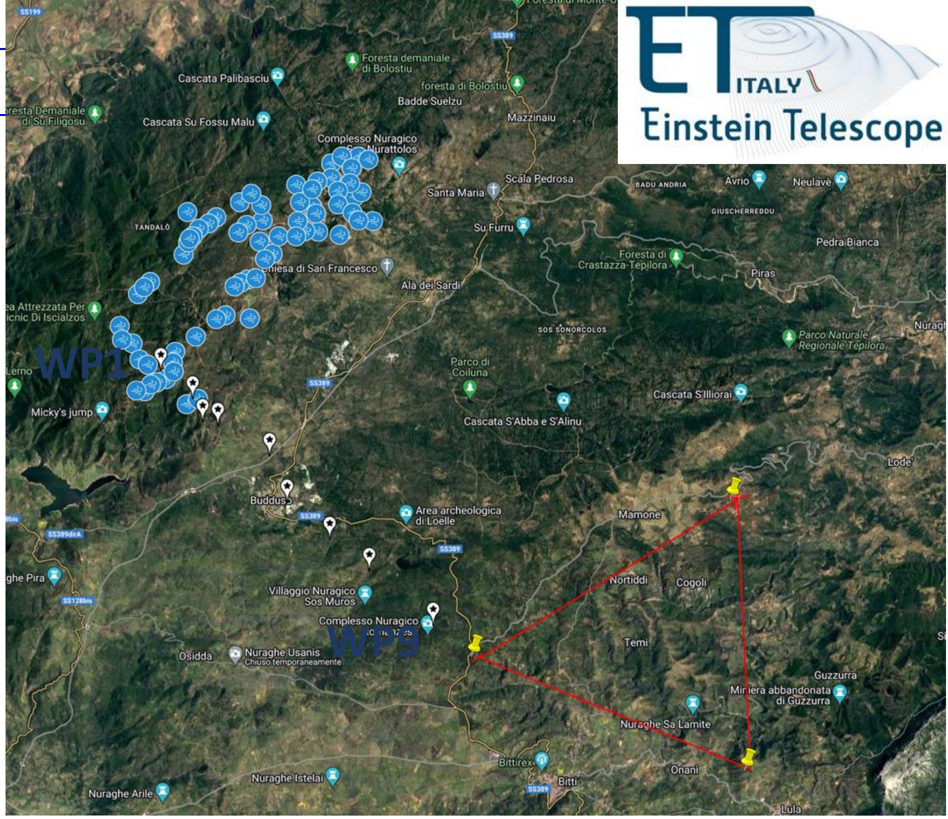
69 turbines (~2 MW each).

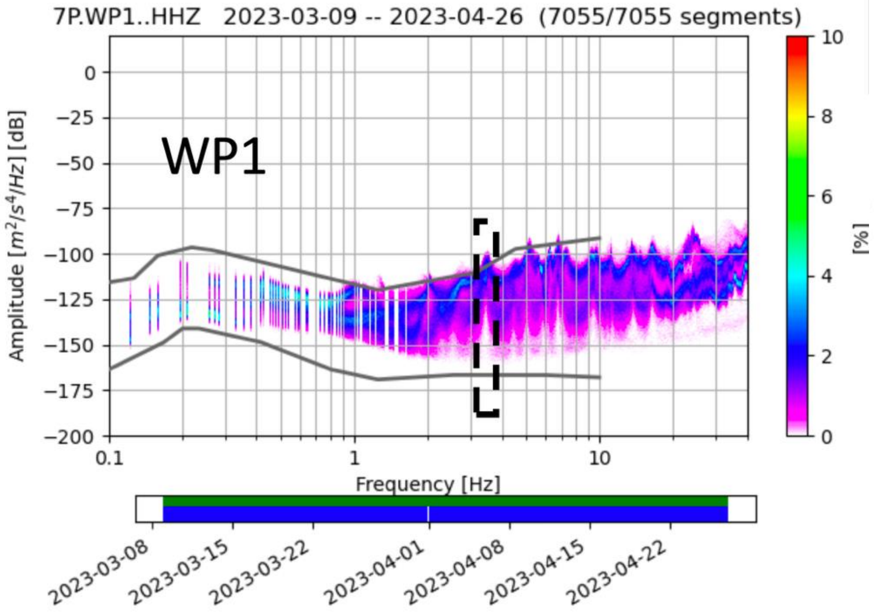
A total of **130 MW installed**.

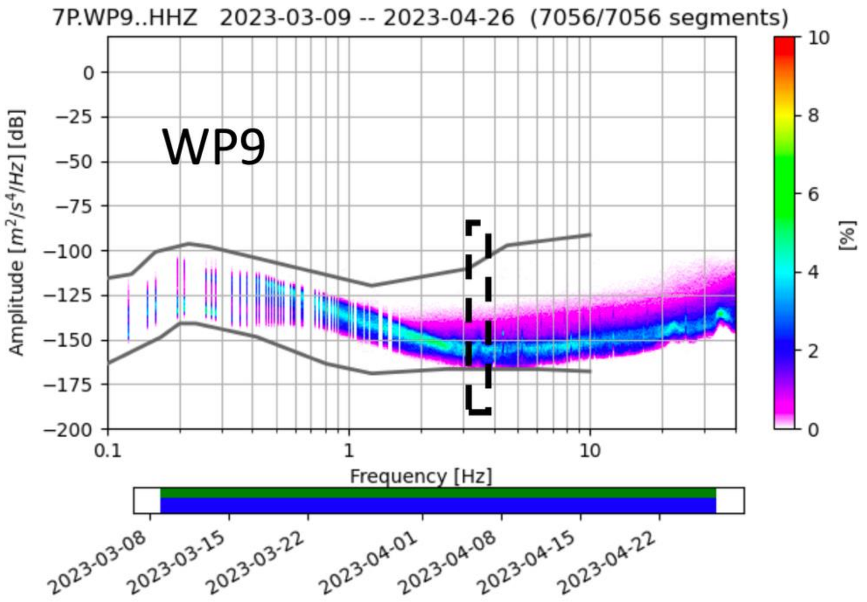
Blades motion is **transferred** to tower and to the ground.

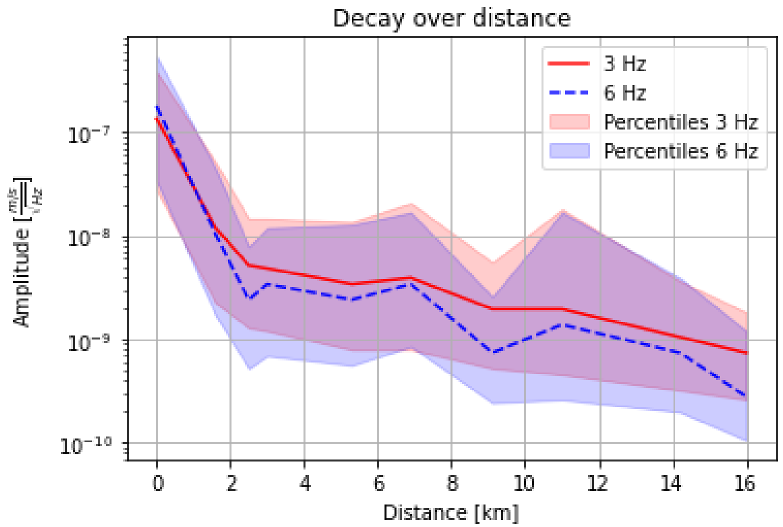
Seismic noise propagates as **surface waves**

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









Site Characterization publications #1/2

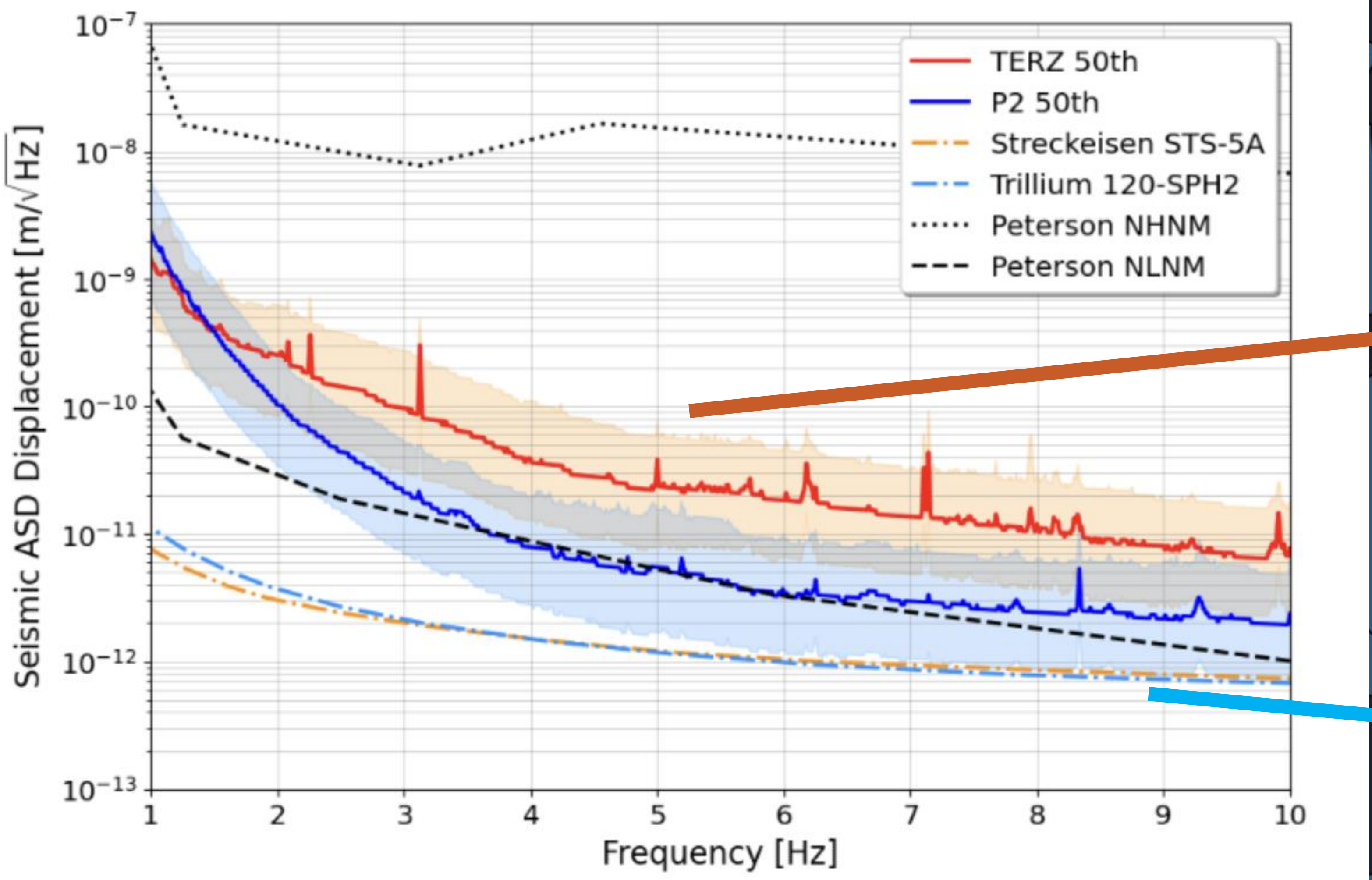
- L. Naticchioni et al., ***Microseismic studies of an underground site for a new interferometric gravitational wave detector***, **CQG**, 2014, https://doi.org/10.1088/0264-9381/31/10/105016
- L. Naticchioni et al., ***Characterization of the Sos Enattos site for the Einstein Telescope***, **JPCS** 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***, **GJI 234**, 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***, **EPJP 138**, 793 (2023). https://doi.org/10.1140/epjp/s13360-023-04395-2.

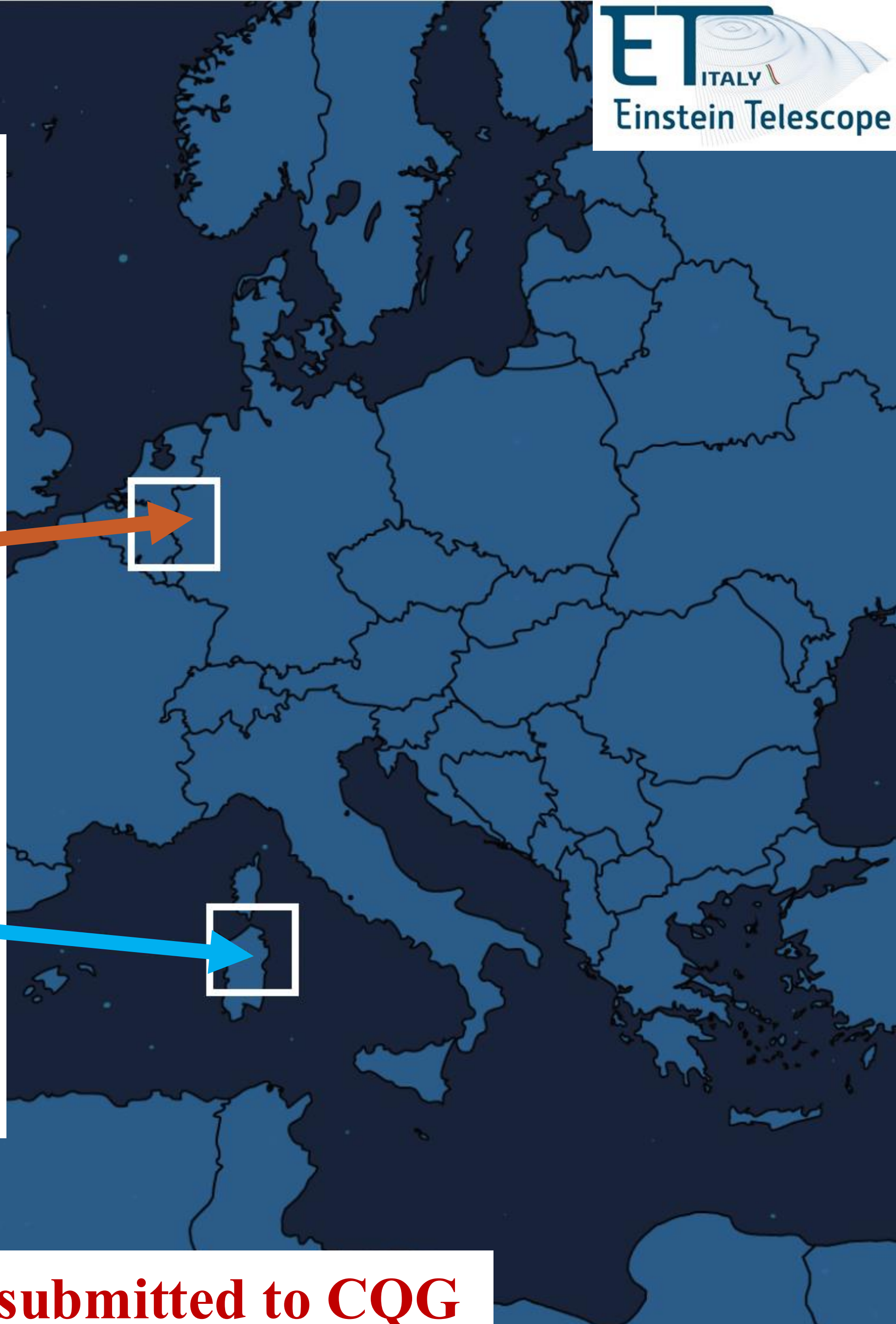
Site Characterization publications #2/2

- L .Naticchioni et al., ***Results of the site characterization in Sardinia for the Einstein Telescope***, *PoS Proc. Sci.*, Vol. **441**, 2023, https://doi.org/10.22323/1.441.0110
- G. Diaferia et al., ***Characterization of the seismic signature of a wind park in Sardinia (Italy) near the candidate site for Einstein Telescope (ET), the third-generation gravitational wave detector***, ready for submission to journal (2024)
- F. Villani et al., ***Subsurface characterization of crystalline rocks at the Einstein Telescope candidate site (Italy): Insights from seismic tomography, geoelectrical and morphostructural surveys***, in preparation (2024)
- Di Giovanni et al. (2024) ET-0453A-24, **Impact on signal SNR of local ambient noise recorded at the ET candidate sites,** https://arxiv.org/abs/2503.02166 (submitted to JCAP)

+ several internal notes, reports and talks

Preliminary Site comparison





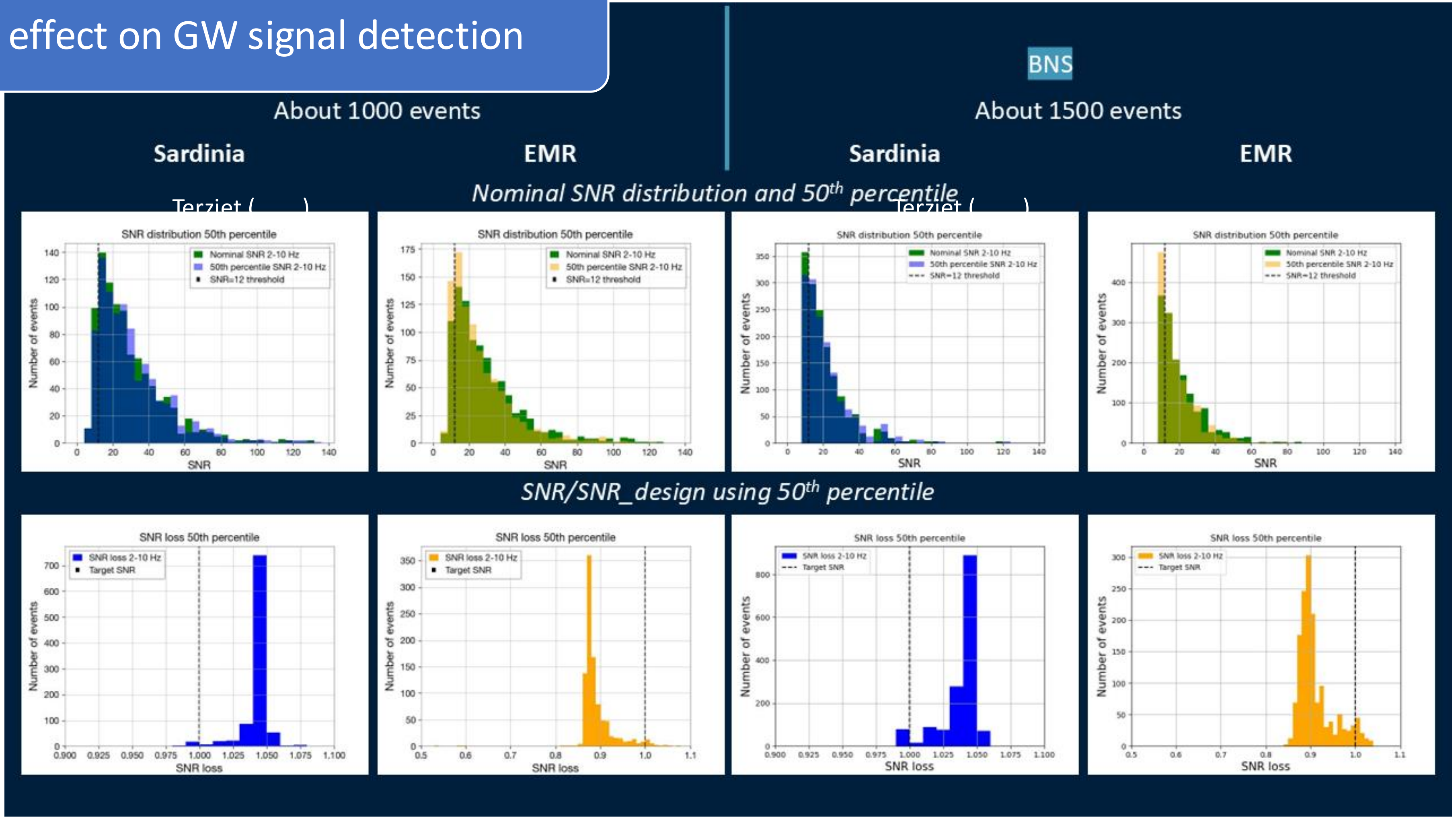
Seismic noise / frequency

Manuscript available at https://arxiv.org/abs/2503.02166 submitted to CQG

Preliminary Site comparison

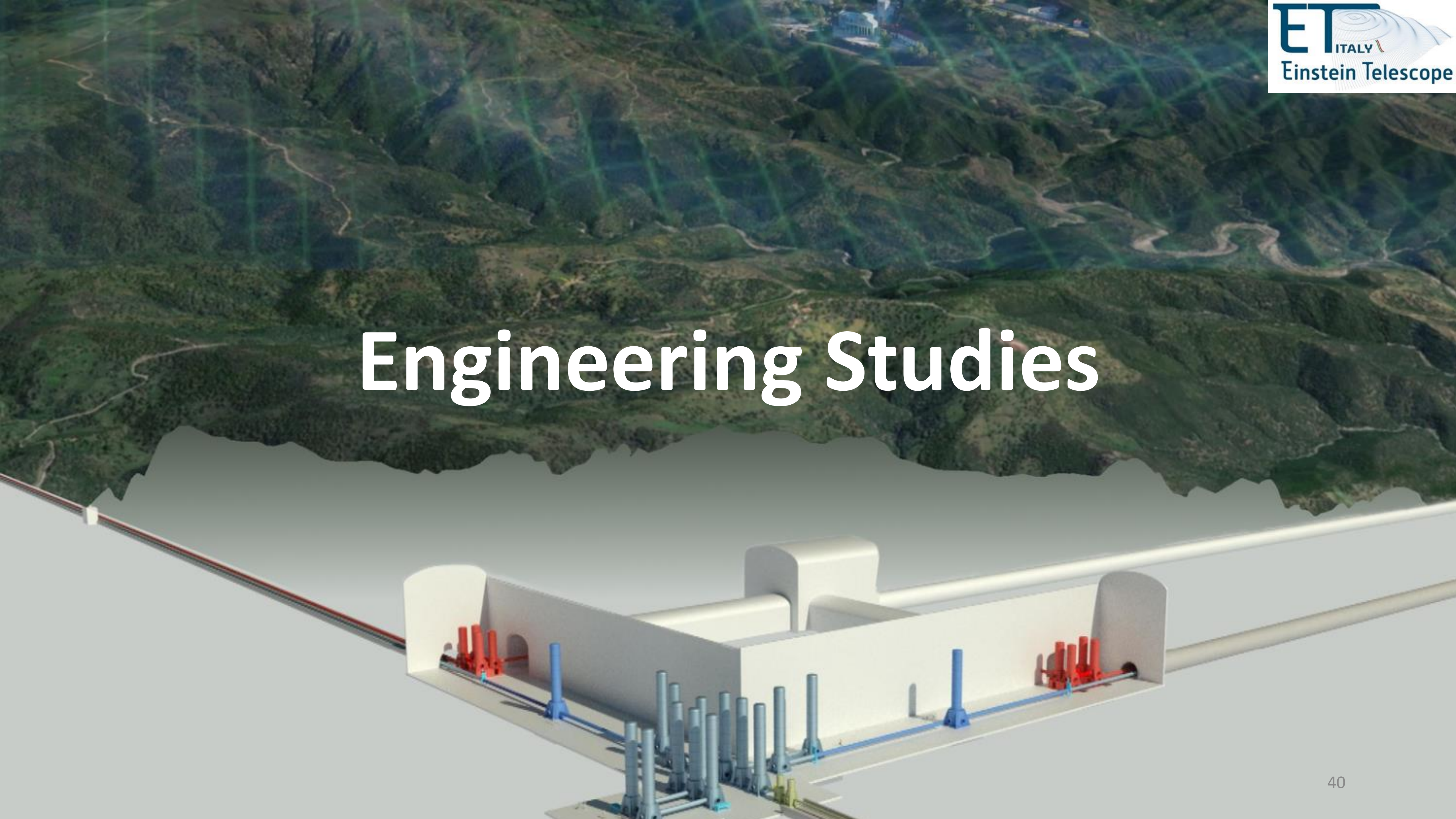
Results:

Seismic Newtonian Noise effect on GW signal detection



Manuscript available at https://arxiv.org/abs/2503.02166 submitted to CQG

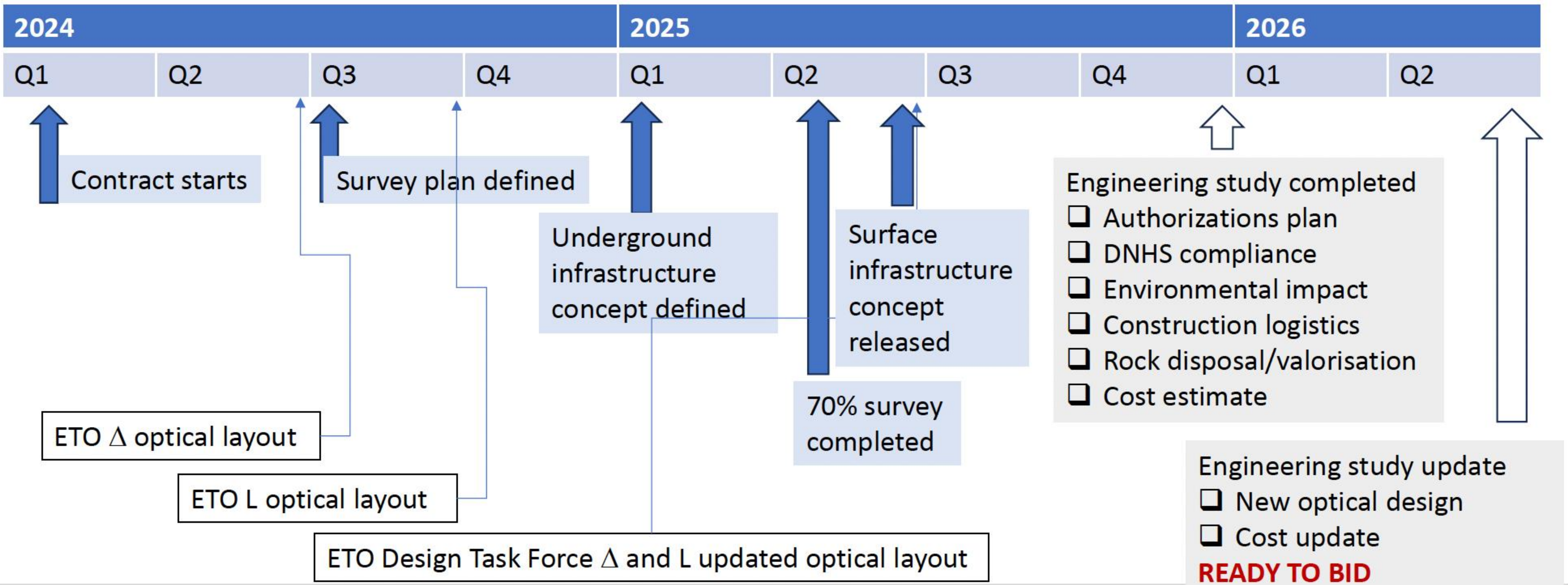
Engineering Studies



TETI Activities Timeline

ETO input | TETI done | TETI in progress

TETI (Team for ET in Italy)

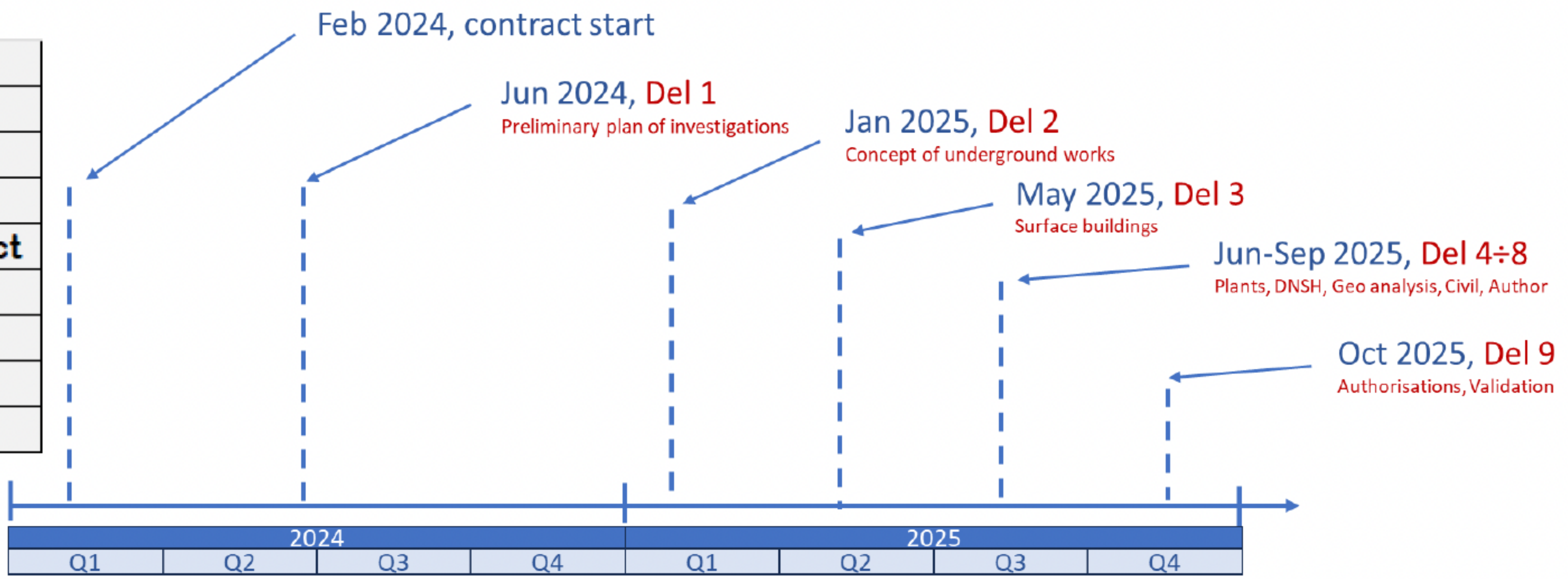


Credits to G. Bisoffi

Main deliverables of the pre-feasibility study (confirmed)

Consortium of 7 highly professional companies, led by Rocksoil, and funded by MUR/INFN with NextGenEU (PNRR)

D1	Plan geo Analyses
D2	Underground Civil Concept
D3	Surface Civil Engineering
D4	Technical plants
D5	Civil underground DNSH Impact
D6	Geo Analyses
D7	Civil Undeground Feasibility
D8	Authorisations
D9	Validation



Credits to G. Bisoffi

Investments and Timing

INVESTMENTS FOR SITE DEVELOPMENT (ALREADY ALLOCATED)

total **109 million**

€3.5 million
SAR-GRAV laboratory
by Autonomous Region of Sardinia

€17 million
ET Project
by MUR

€4 million
PRIN ET Tecnhologies
by MUR

€50 million
NRRP ETIC project
by MUR

€2.5 + 12 million
NRRP MEET and TERABIT
by MUR

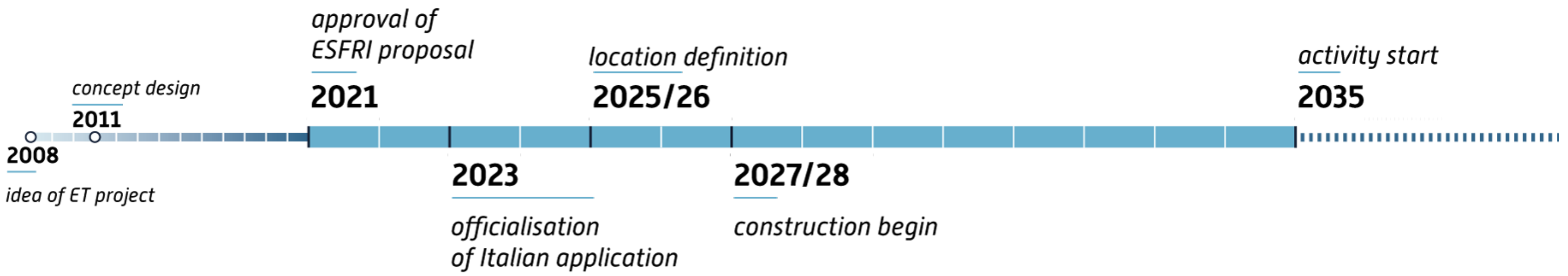
€10 + 10 million
multidisciplinary laboratory Sos Enattos
by Autonomous Region of Sardinia and INFN, INAF, INGV

INVESTMENTS FOR THE CONSTRUCTION OF THE LABORATORY IN SARDINIA

total **1.3 billion**

€350 million
by Autonomous Region of Sardinia

€950 million
by Italian Government



Official web page https://www.einstein-telescope.it

ET Italian Community

Contacts

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MUR — Ministero dell'Università e della Ricerca

REGIONE AUTÒNOMA DE SARDIGNA
REGIONE AUTONOMA DELLA SARDEGNA

INFN — Istituto Nazionale di Fisica Nucleare

Projects: Etic, ETpp/Infra-Dev, Sar-Grav, Terabit

Agenzia Spaziale Italiana	CINECA	EGO European Gravitational Observatory	Consortium GARR	Gran Sasso Science Institute	INAF Istituto Nazionale di Astrofisica
nel progetto Etic	nel progetto Terabit	nel progetto ETpp/Infra-Dev	nel progetto Terabit	nel progetto Etic	nel progetto Etic

Istituto Nazionale di Geofisica e Vulcanologia	OGS Istituto Nazionale di Oceanografia e di Geofisica Sperimentale	Alma Mater Studiorum Università di Bologna	Università degli Studi di Cagliari	Università degli Studi della Campania Luigi Vanvitelli	Università di Genova	Università degli Studi di Napoli Federico II
nei progetti Meet/Faber, Sar-Grav	nel progetto Terabit	nel progetto Etic	nei progetti Etic, Sar-Grav	nel progetto Etic	nel progetto Etic	nel progetto Etic

Università degli Studi di Padova	unipg Università degli Studi di Perugia	Università di Pisa	Sapienza Università di Roma	Tor Vergata Università degli Studi di Roma	UNISS Università degli Studi di Sassari
nel progetto Etic	nel progetto Etic	nel progetto Etic	nel progetto Etic	nel progetto Etic	nel progetto Sar-Grav

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 => **New Data Challenges**
- Fight against noise: @LF site noise
- Three site candidates: EMR, Sardinia and Lausitz
  - 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