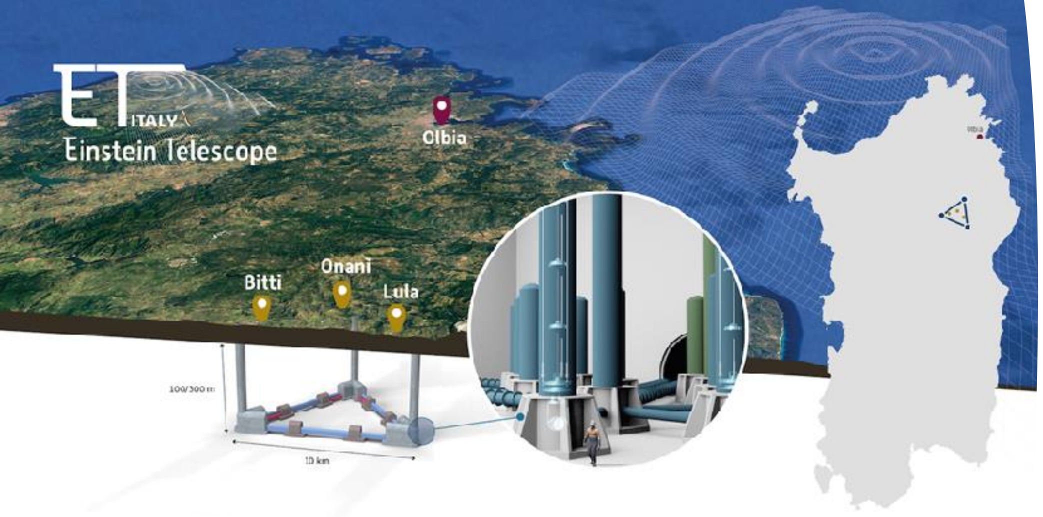
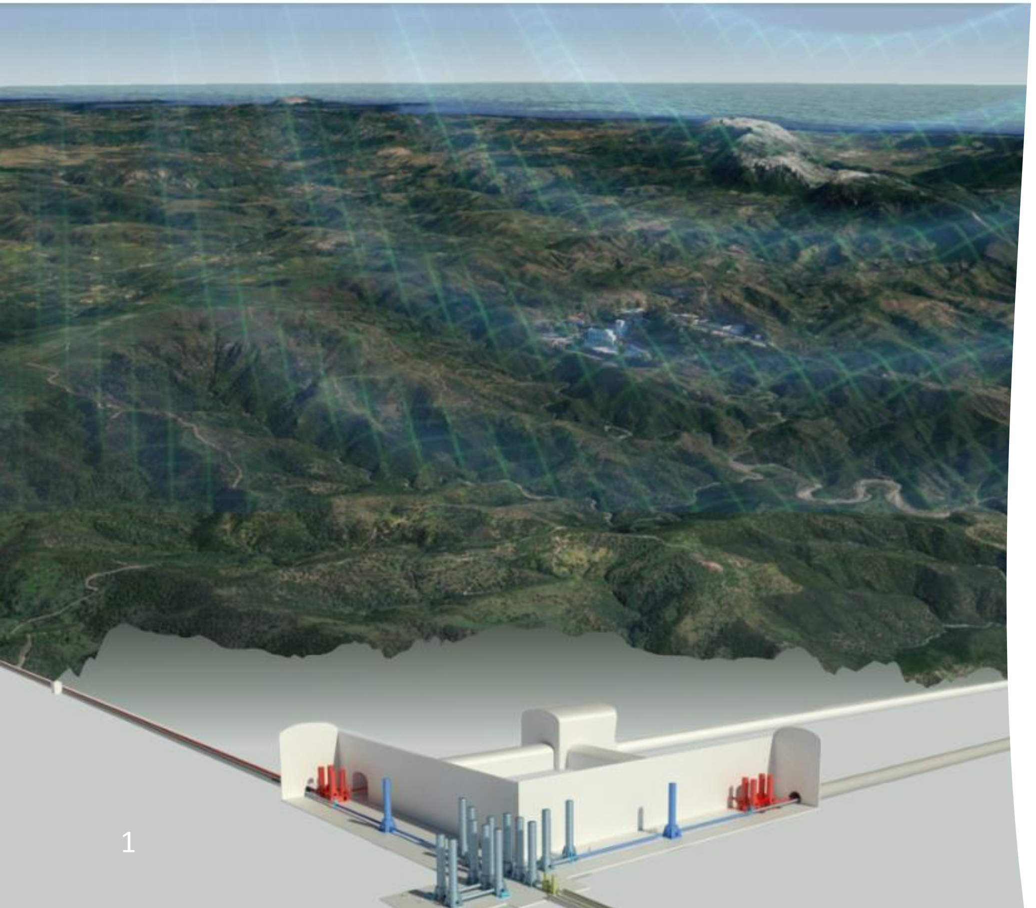




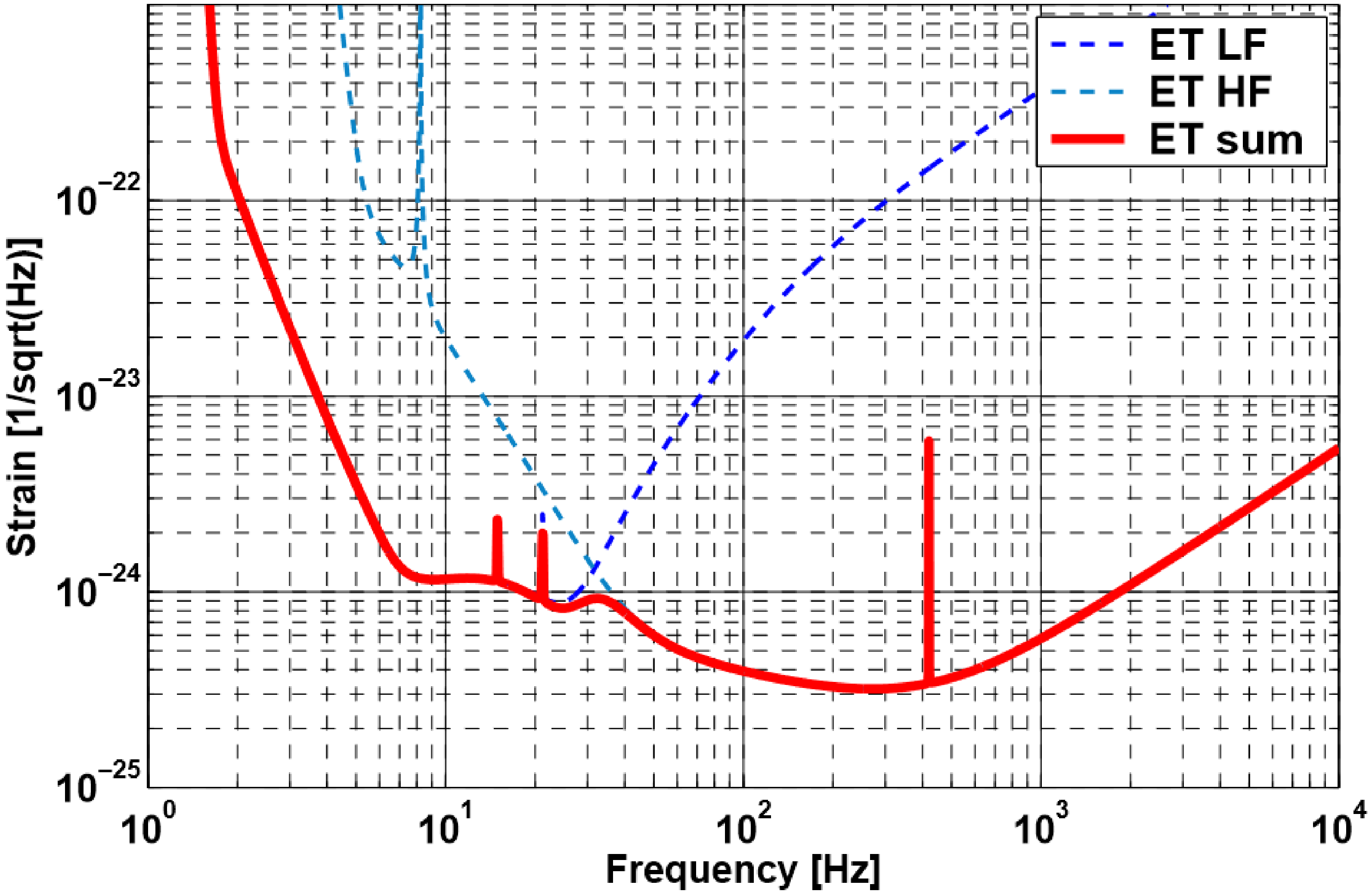
Environmental noise mitigation in ET

Luca Naticchioni
INFN Roma

ET – Scienza e tecnologia in Italia
Assisi, 20-23 Febbraio 2024

ET Sensitivity curve

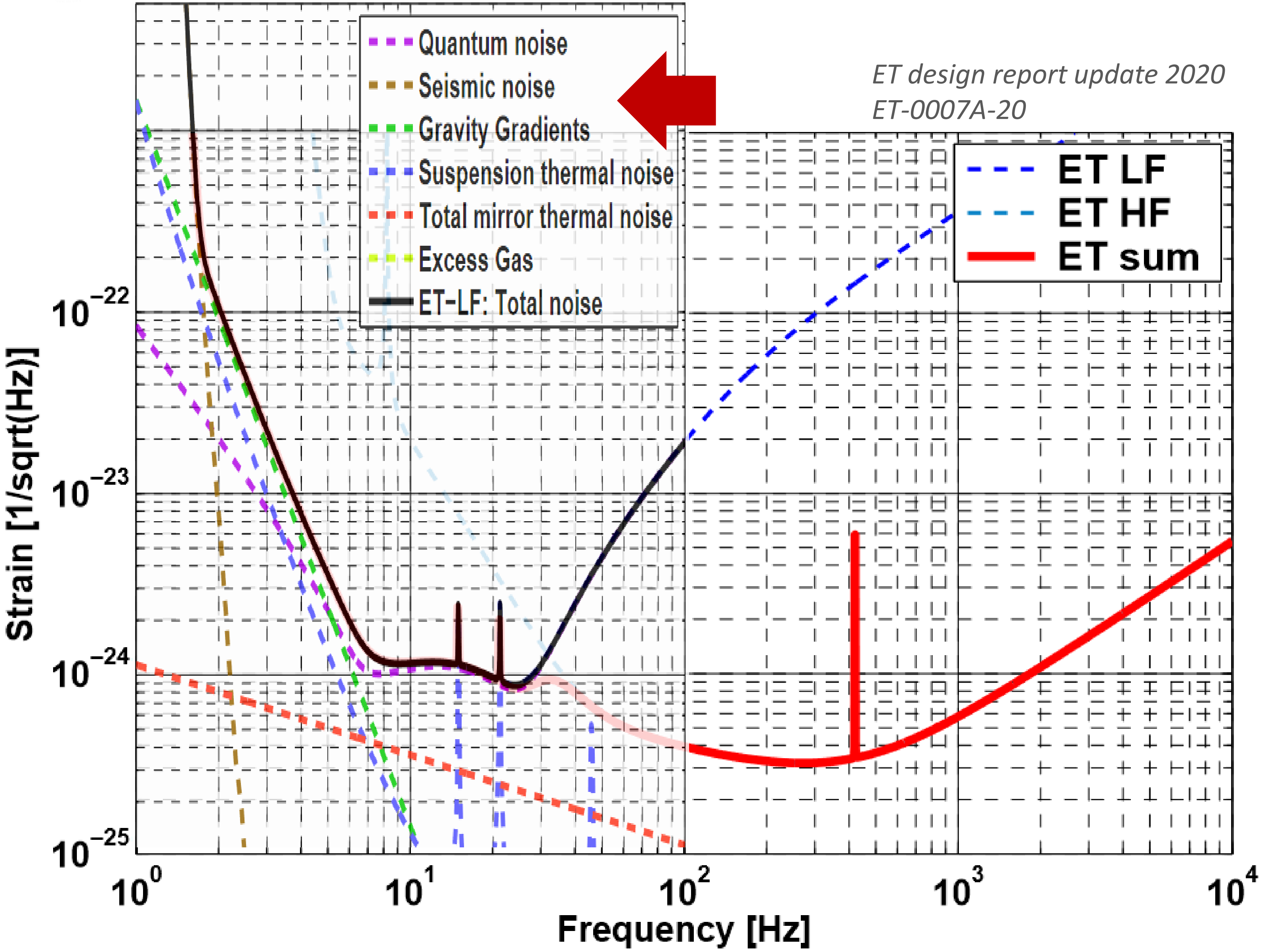
ET design report update 2020
ET-0007A-20



The overall design sensitivity of ET is obtained combining the Low Frequency (LF) and High Frequency (HF) detectors' sensitivities.

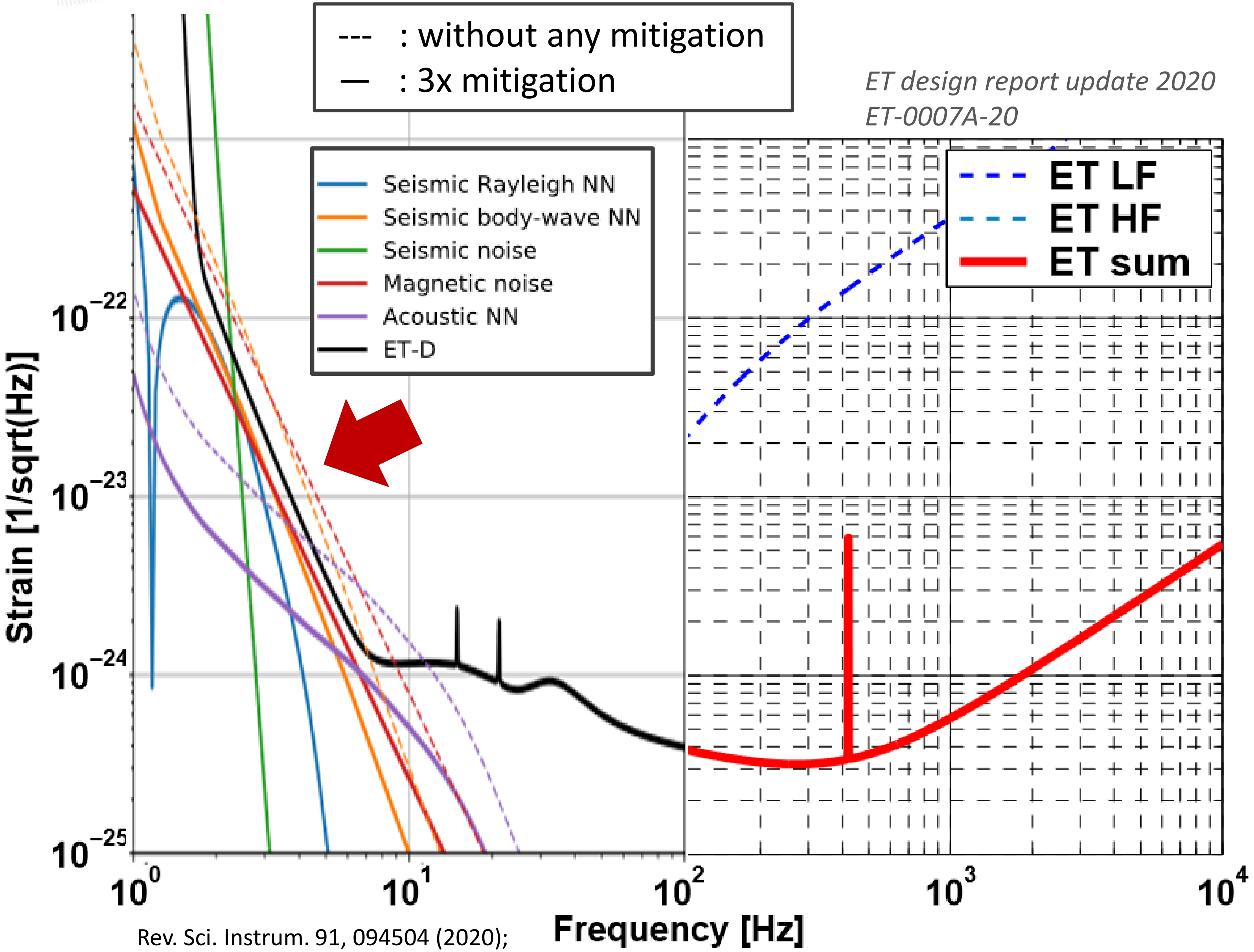
LF (in particular 2-10Hz) is a **crucial** band to achieve all the scientific targets of ET!

ET Sensitivity curve



LF detectors' **sensitivity** is limited by **environmental noises**, e.g. *seismic noise* and the related *Newtonian noise* (or Gravity Gradients).

ET Sensitivity curve



Rev. Sci. Instrum. 91, 094504 (2020); https://doi.org/10.1063/5.0018414

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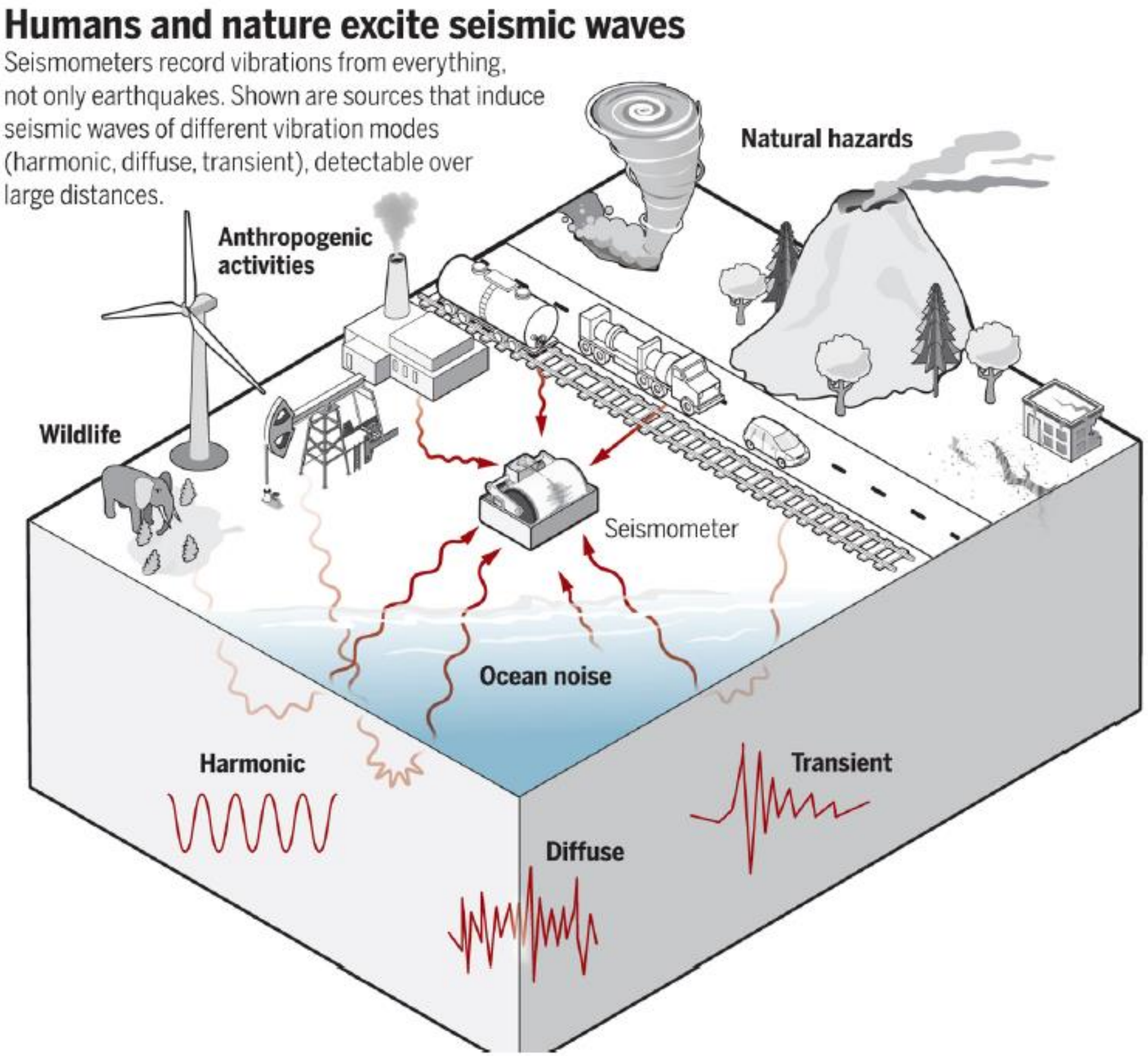
Other important environmental noises are the *magnetic* and *acoustic* noises.

ET Sensitivity curve



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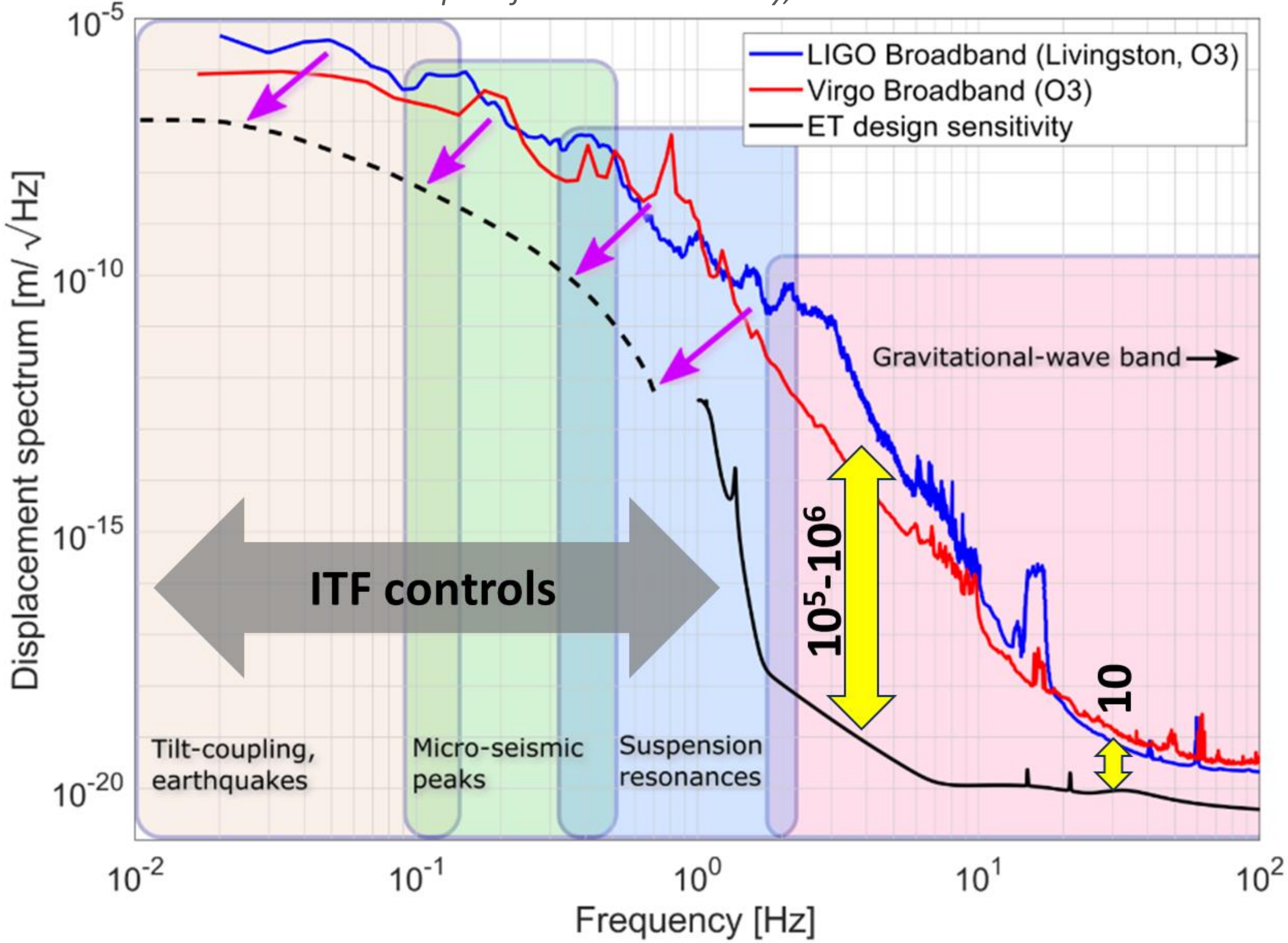
Other important environmental noises are the *magnetic* and *acoustic* noises.

ET: the Low Frequency challenge

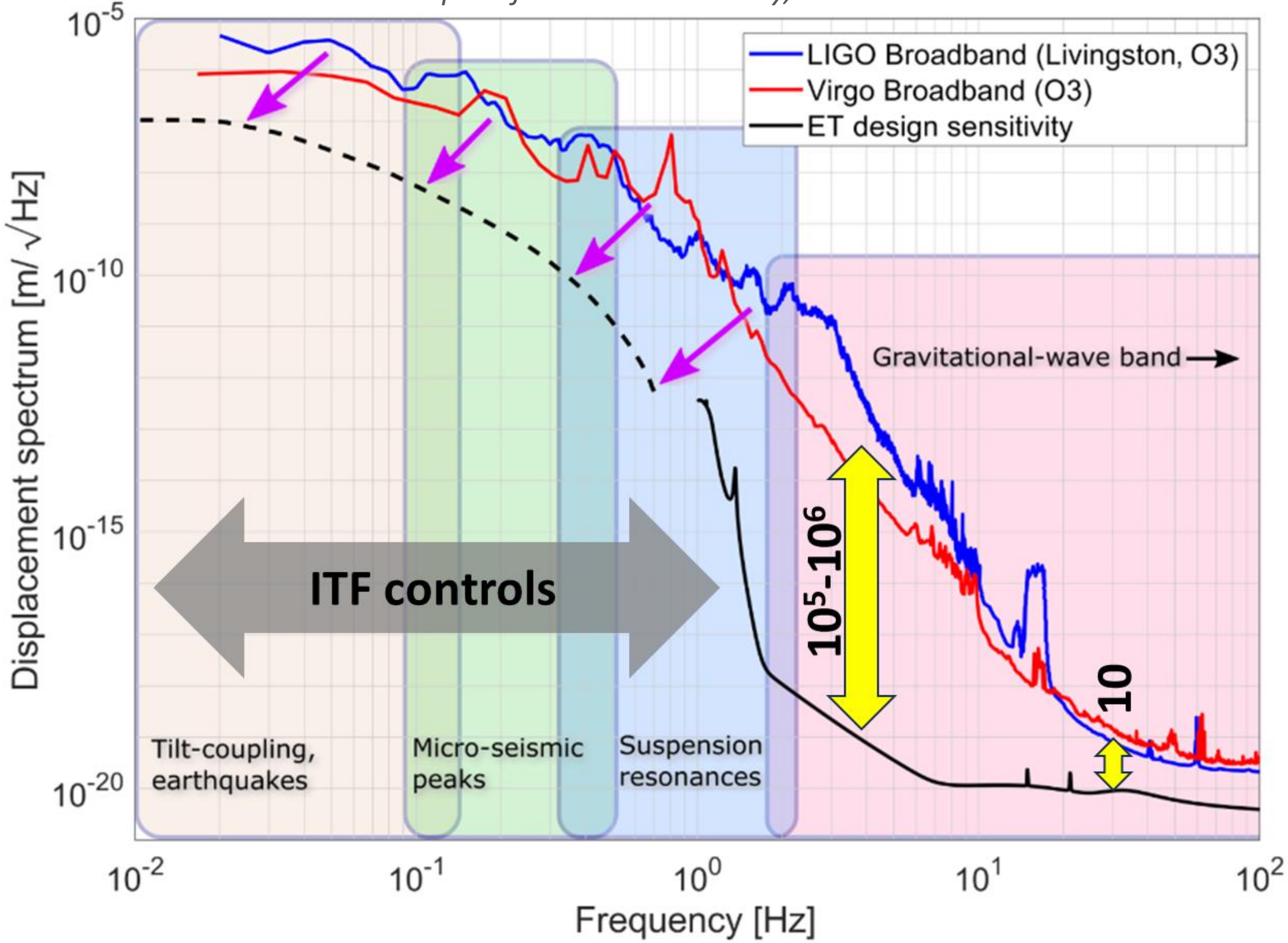
adapted from C. Mow-Lowry, ET-0354A-23



- Without LF we would lose an important part of the science case;
- LF (2 to 20 Hz) sensitivity without cryogenics is not achievable;
- A very "quiet" (seismic-Newtonian Noise and EM noise) site is mandatory to reach the LF design sensitivity. If ET will be placed in a noisy site, high risk to spoil the gain (and cost of) going underground and using cryogenics!
- Sardinia is exceptionally quiet! (see site preparation session, this afternoon).
- Even in a quiet site like Sardinia, **without noise mitigation we cannot reach the design sensitivity**.

ET: the Low Frequency challenge

adapted from C. Mow-Lowry, ET-0354A-23



ET target sensitivity will be on average 10x with respect to current GW detectors.

BUT

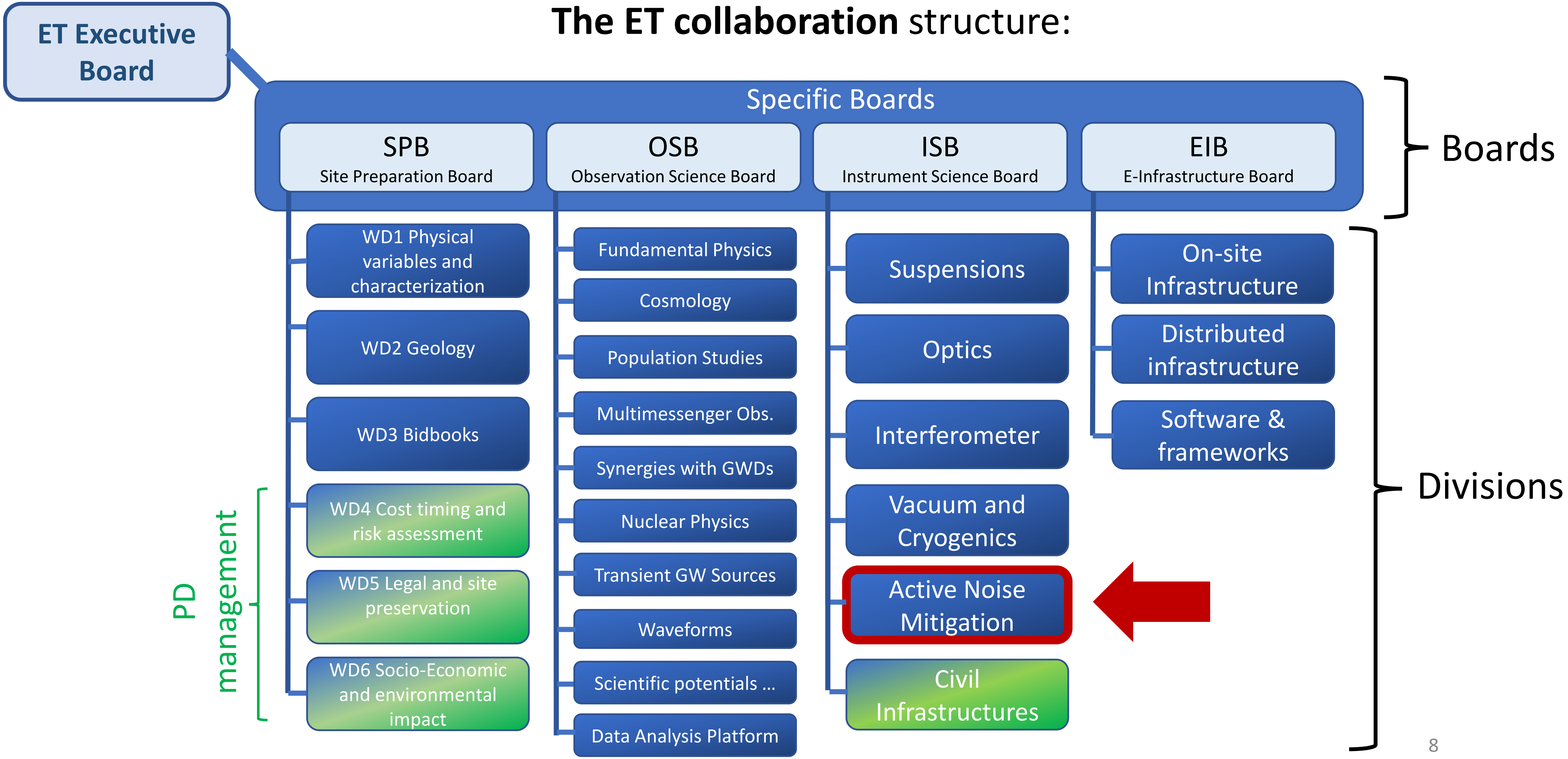
2-10 Hz band, that is crucial for ET, requires a dramatic improvement: 10^5 – 10^6!

recipe:

- start from a low-noise site
- apply **noise mitigation strategies**
- learn from 2G detectors

Active Noise Mitigation in ET

The ET collaboration structure:



Active Noise Mitigation in ET

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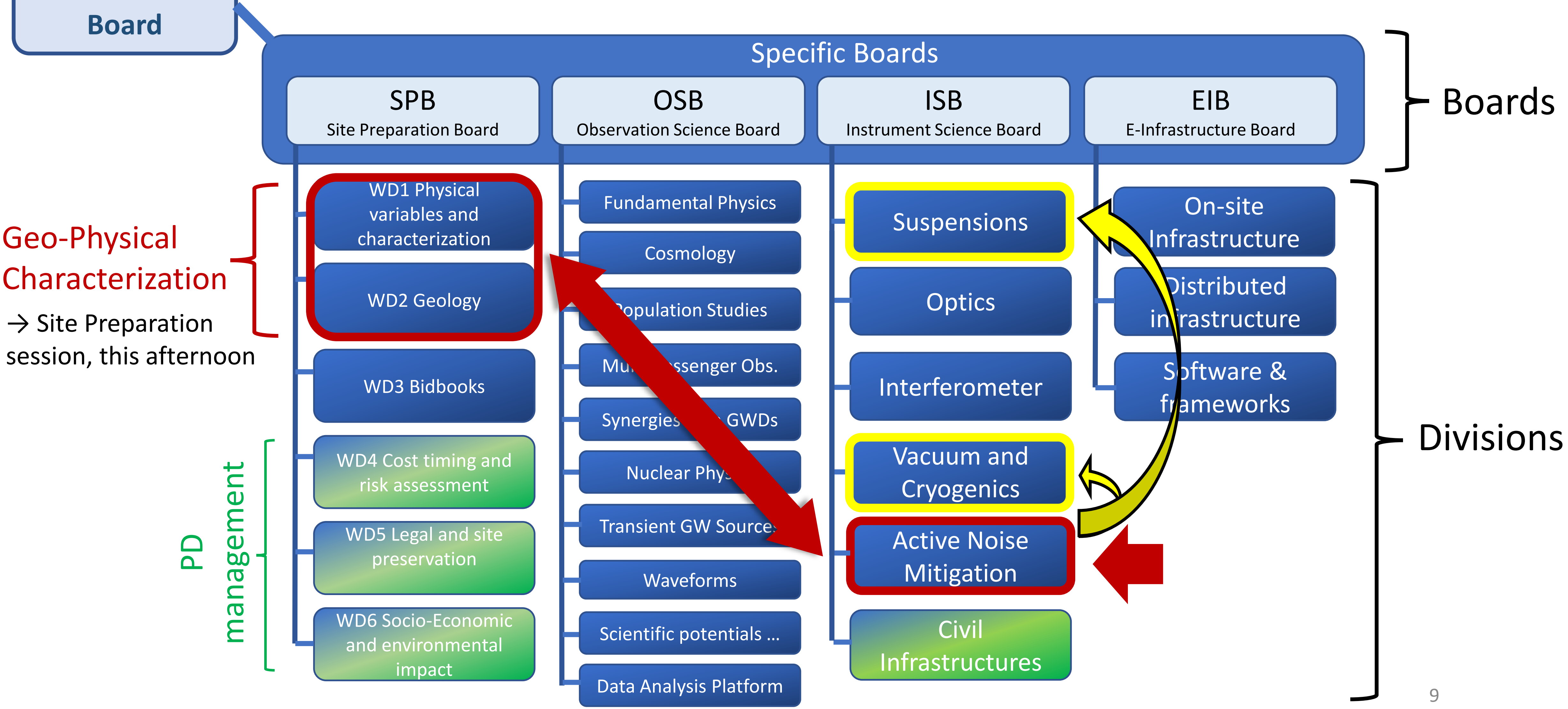
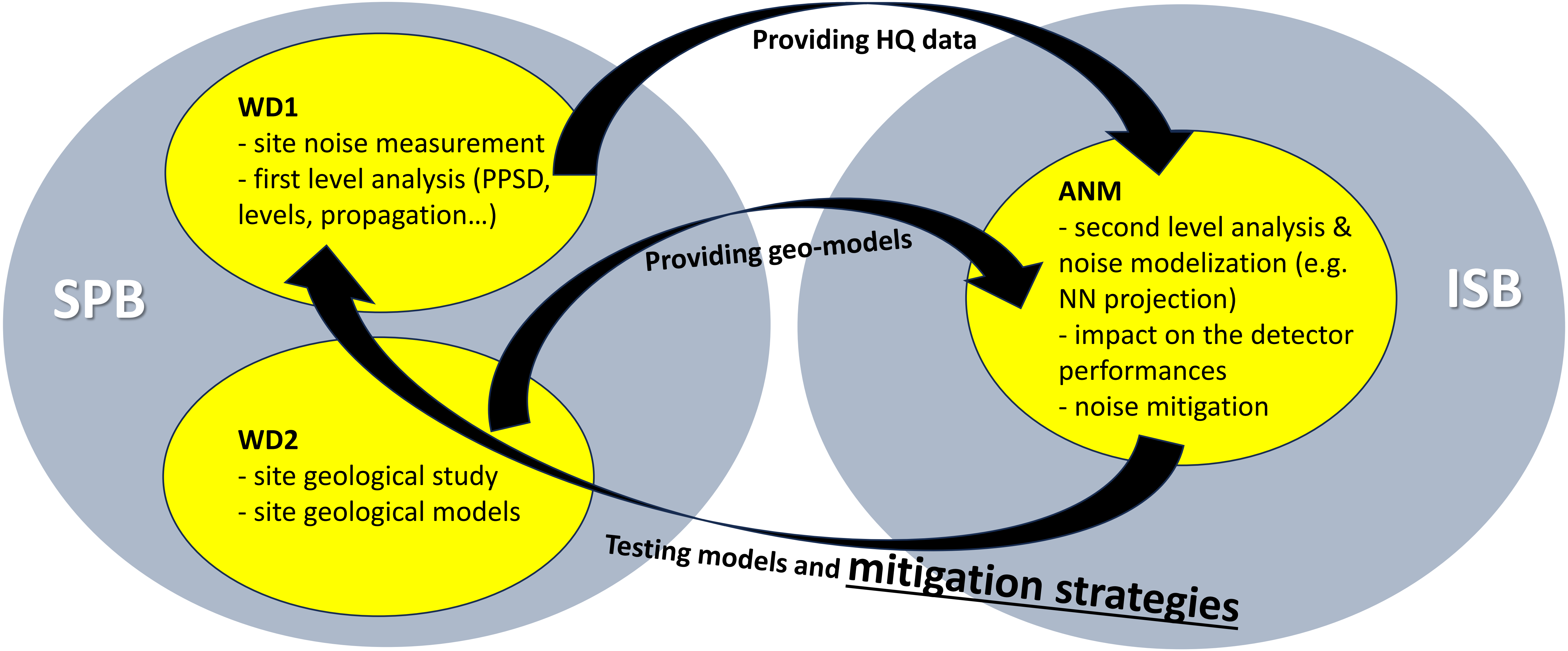


Active Noise Mitigation in ET



Active Noise Mitigation in ET

Important Italian commitment (also chairing the WPs):

ISB-ANM

Active Noise Mitigation

Div. Chairs:

Luca Naticchioni

Conor Mow-Lowry

WP 1 – Newtonian Noise Cancellation
Chairs: **M.C. Tringali** & S. Koley

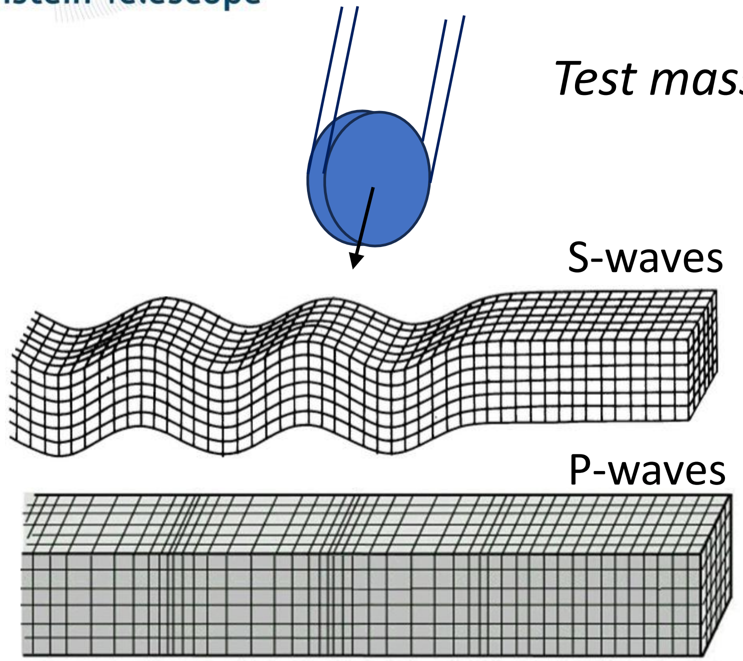
WP 2 – Environmental Sensors
Chairs: **R. De Rosa** & M. Suchenek

WP 3 – Magnetic Noise
Chairs: **I. Fiori** & **B. Garaventa**

WP 4 – Inter-Platform Motion
Chairs: **P. Ruggi** (→**M. Pinto**) & S. Koehlenbeck

WP 5 – Low Frequency Control Noise
Chairs: K. Dooley & A. Basalaev

Newtonian Noise (NN)



Test mass acceleration:

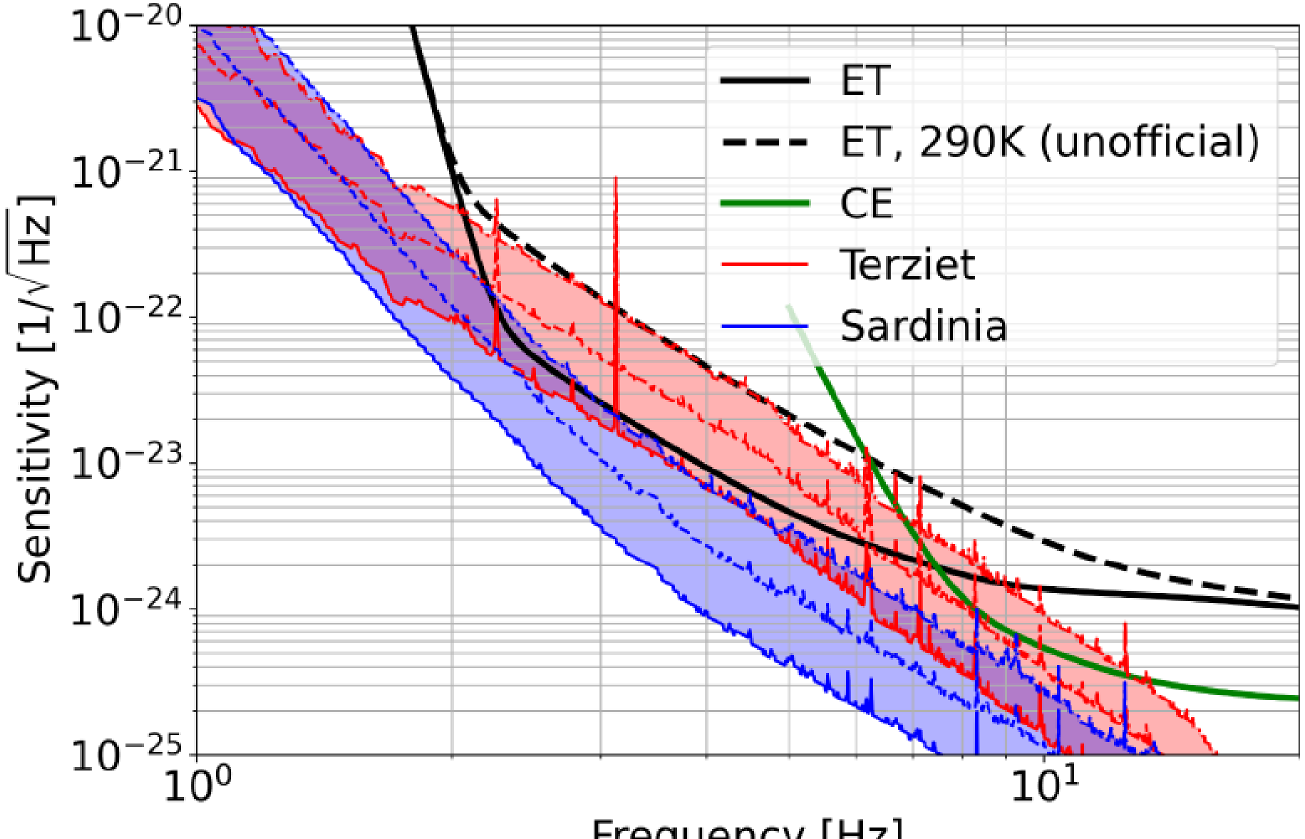
$$\delta\vec{a}(\vec{r}_0,t) = \frac{4\pi G\rho}{3}\left(2\vec{\xi}^{\,P}(\vec{r}_0,t) - \vec{\xi}^{\,S}(\vec{r}_0,t)\right)$$

Seismic displacement field

ASD (Amplitude Spectral Density):

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

Newtonian Noise ASD — *Seismic noise ASD*

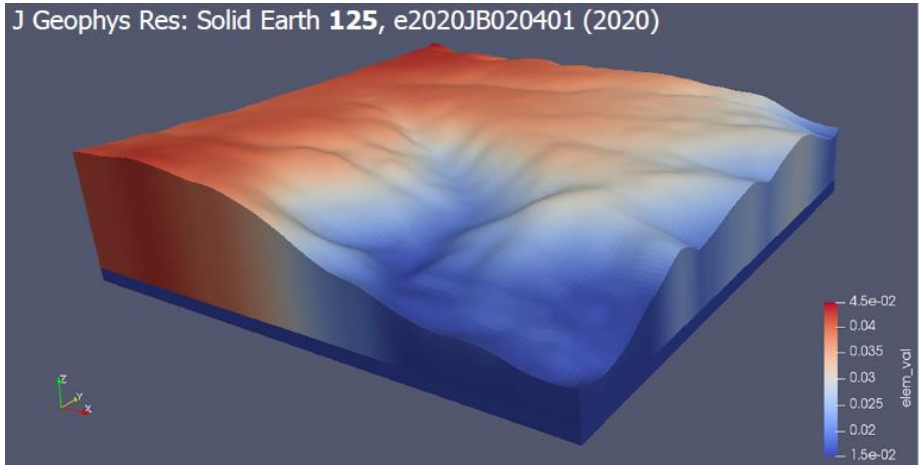


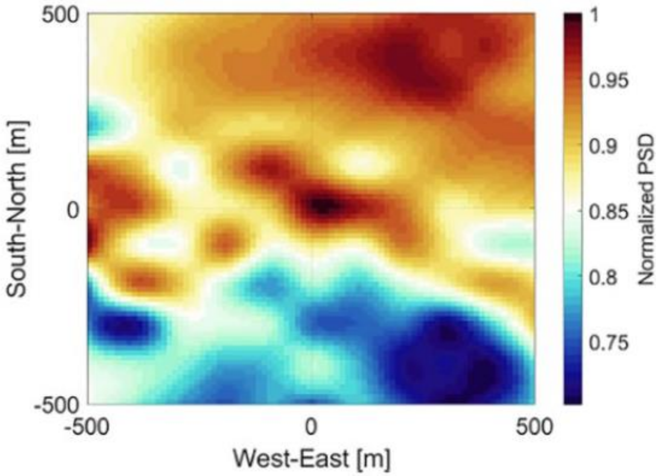
Adopted from EPJ+ 137, 687 (2022)

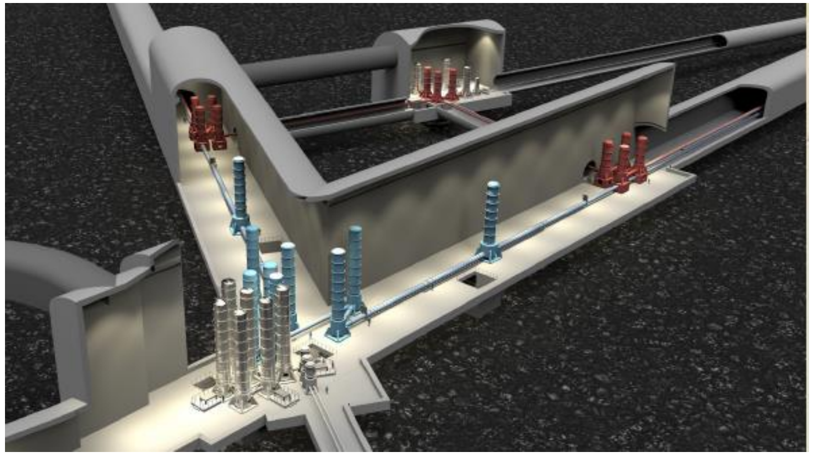
NB:
- *At surface: Rayleigh (surface) waves & atmospheric mass density fluctuations*
- *Underground: both are suppressed, P-waves are the main source*

Newtonian Noise (NN)

- NN suppression is the main (science-driven) motivation for going underground.
- Even underground, we will need to mitigate (→cancel) P-waves induced NN.
- NN cancellation requires NN field reconstruction → knowledge of local geological setup & seismic field → geological model & seismic array measurements.
- Every important aspect should be modelled: sources, polarization content, topography, geology, cavern shape, correlations between test masses, non-stationarity, infrastructural vibrations…
- Accuracy on NN prediction will be always limited by uncertainties in the knowledge of local geological models and seismic field properties.



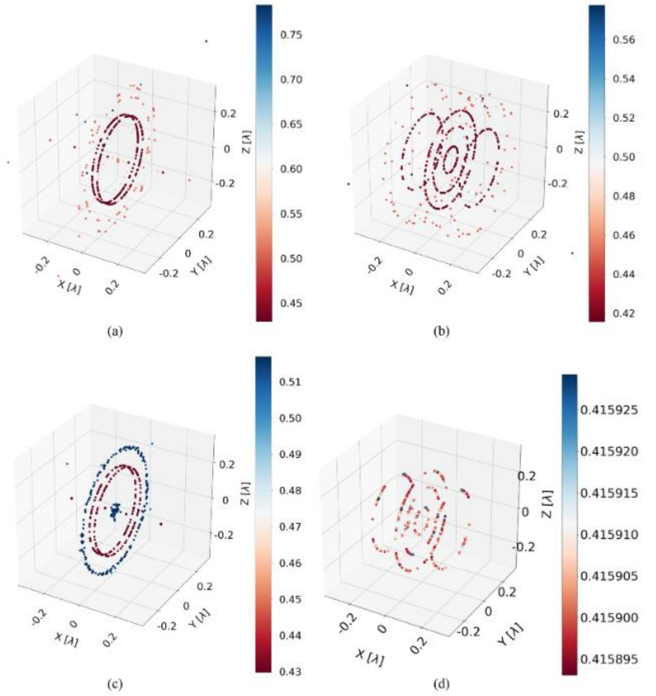




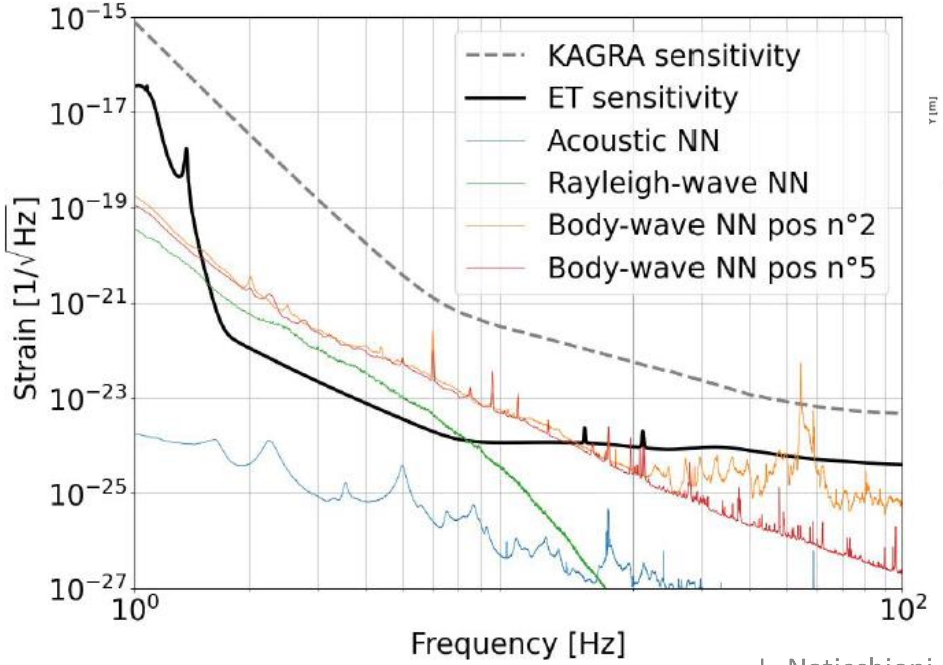
Newtonian Noise (NN)

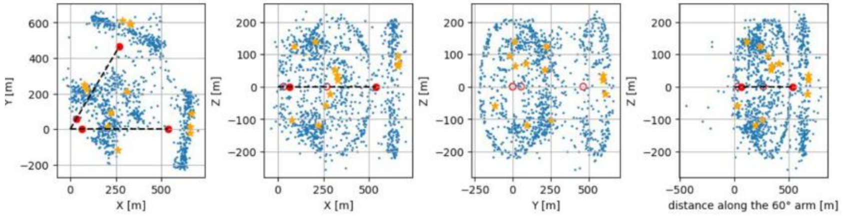
Open issues:

- How many seismic sensors? What is the optimal array (i.e. where do we put the sensors)?
  - ➢ Collecting data, 3D Gaussian Process Regression, optimization.
- What kind of sensors for the seismic field reconstruction?
  - ➢ Triaxial broadband seismometers, accelerometers, strainmeters, tiltmeters. Mixed arrays?
  - ➢ 3D array → need for borehole sensors.



F Badaracco and J Harms 2019 *Class. Quantum Grav.* **36** 145006





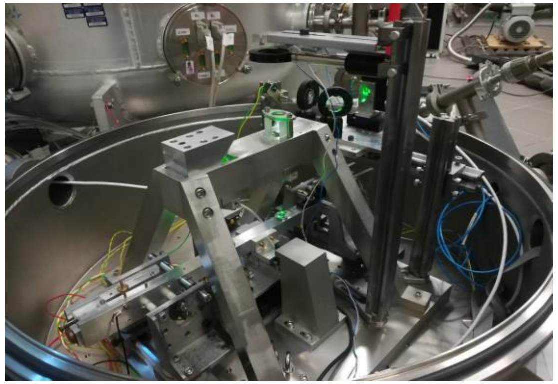
- Currently, Wiener Filter seems the best option. Can we do better (e.g. neural networks, AI)?
- Self-inflicted noise: self-induced acoustic and seismic NN noise due to detector & infrastructure.
- 3x cancellation very hard even in 10yr from now…

Newtonian Noise (NN)

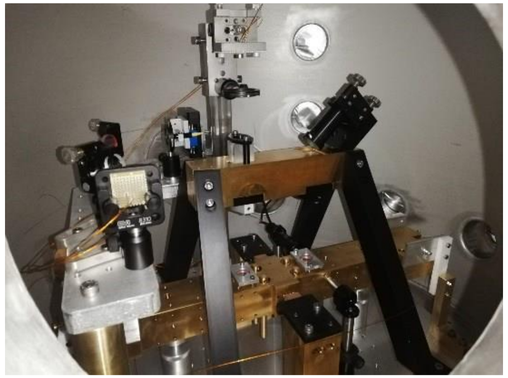
Tiltmeters

Newtonian Noise will limit the sensitivity of future GW detectors for frequencies below 10 Hz. A possible cancellation strategy is based on a coherent estimate using data from a seismometer array and a **tiltmeter.**
Tiltmeters are also useful as sensor for the control of the SA top stage, giving a significant improvement in the **inertial damping**.

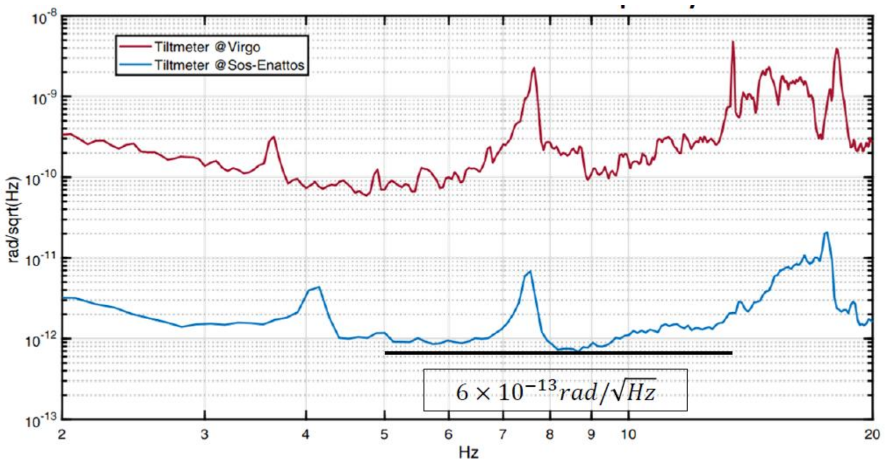
A first tiltmeter was realized as a prototype of the **Archimedes** experiment, installed at Sos Enattos. This was also used at Virgo for a first measurement campaign. Then a new tiltmeter was realized and installed at Virgo site.



Tiltmeter prototype installed at Sos Enattos

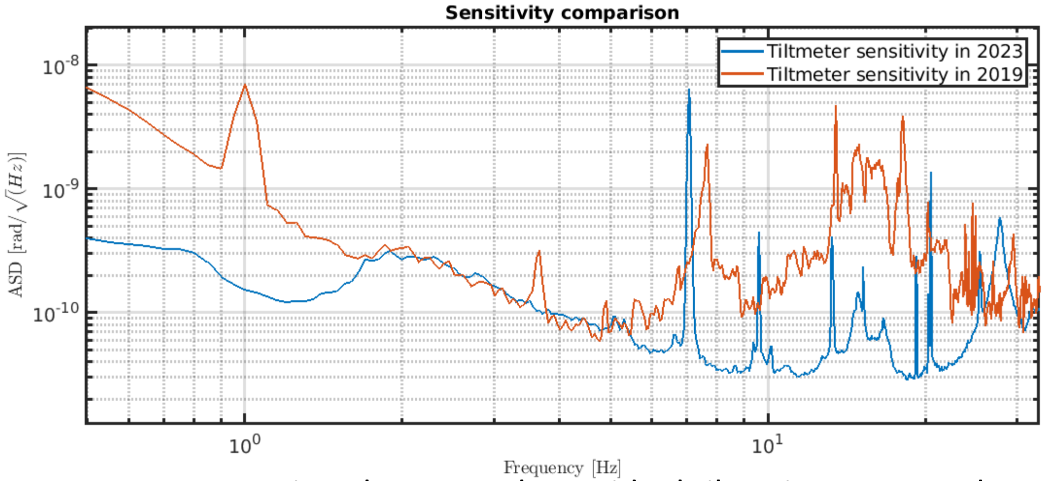


Tiltmeter installed at Virgo (NEB)



Comparison between residual tilt noise measured at Virgo (2019) and at Sos Enattos (2020)

A new tiltmeter is in construction and will be installed at **Sos Enattos**, to improve the measurement of the tilt in the ET candidate site.



Comparison between the residual tilt noise measured at Virgo (NEB) with different tiltmeters

Newtonian Noise (NN)

Aim of the NN Cancellation WP:

- Define and deliver site-dependent standard NN models, check existing models and calculation methods (e.g. against analytic benchmark).
- Design the optimal NNC array (sensors, geometry, requirements) for a given cancellation factor.
- Searching for, developing & testing seismic sensors (accelerometer, seismometers, tiltmeters…).
- Define the cost-estimates of the NNC system.
- → prepare the TDR part of the NNC system.

Newtonian Noise (NN)

Groups in Italy contributing to the NN Cancellation WP:

- **GSSI**: models, simulations, data analysis, sensors.
- **INFN-Genova**: simulations.
- **INFN-Roma** & **Univ. Sapienza**: data analysis, sensors.
- **INFN-Napoli** & **Univ. Federico II**: models, data analysis, sensors.
- **INFN** & **Univ. Cagliari**: Atmospheric NN modelling
- **EGO**: data analysis, sensors.

Environmental Noise (ENV)

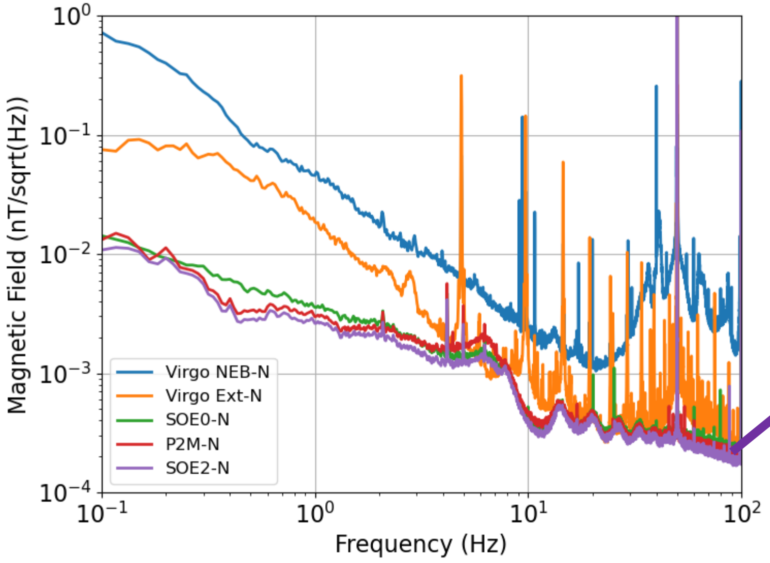
Activities:

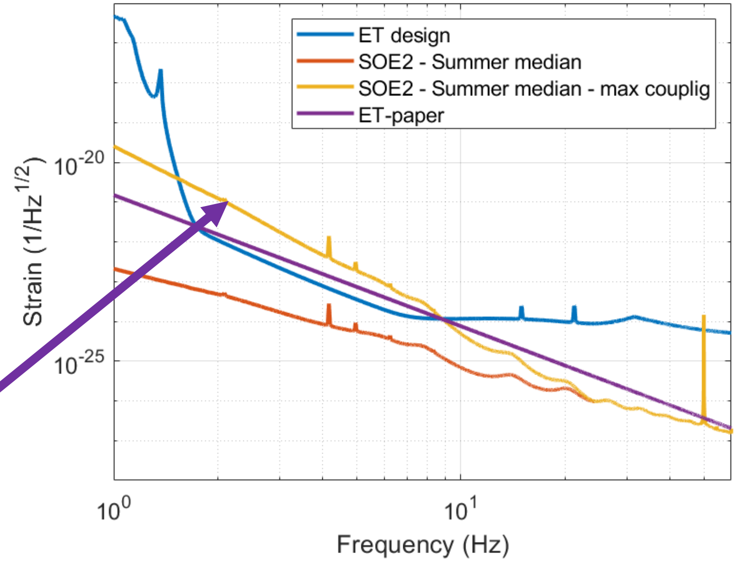
- Searching for, testing & developing suitable sensors for environmental noise monitoring.
- Design the sensor network for environmental noise monitoring (ground-level array & underground array).
- Searching for, testing & developing suitable low-noise conditioning electronics.
- Data analysis from Seismic, acoustic and magnetic probes (measurement campaigns in Sardinia and at LNGS).
- Define cost estimates of the ENV system.
- → prepare the TDR part of the ENV system.

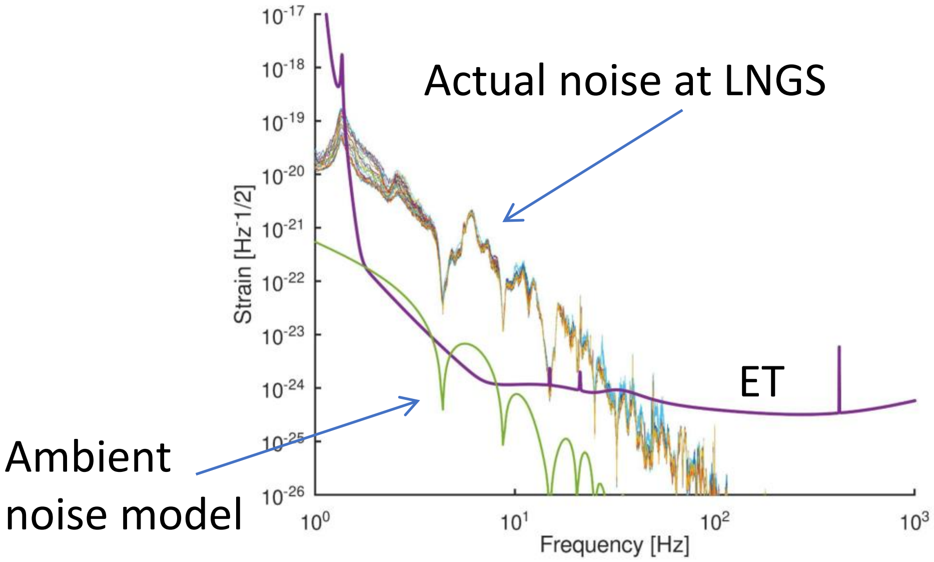
Environmental Noise (ENV)

Magnetic noise:

- Even in a low-noise area (like Sos Enattos in Sardinia) adopting Virgo-like couplings, magnetic noise may limit the sensitivity. Need for dedicated Magnetic Noise (NN) mitigation.







Acoustic noise:

- Acoustic noise (AN) in large caverns and tunnels. Even assuming an initial low-noise site like Sos Enattos, once the infrastructure, detectors, electronics are there, AN can become a problem. Need for mitigation strategies (e.g. silencing equipment, separation walls, differential pressure, smaller caverns…).

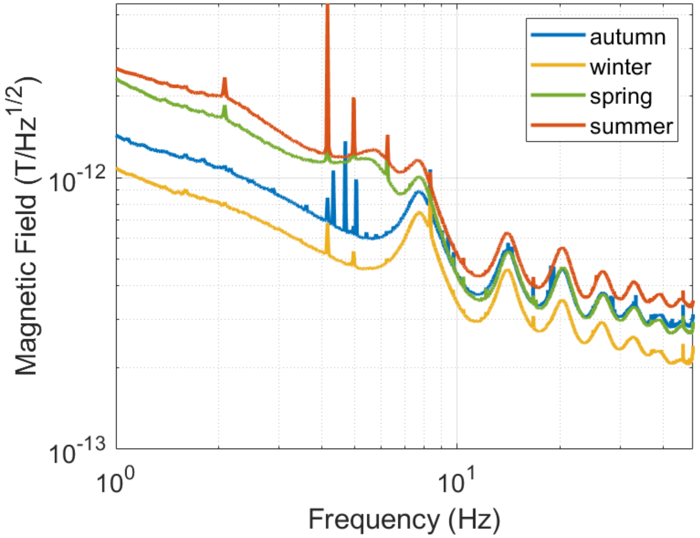
Environmental Noise (ENV)

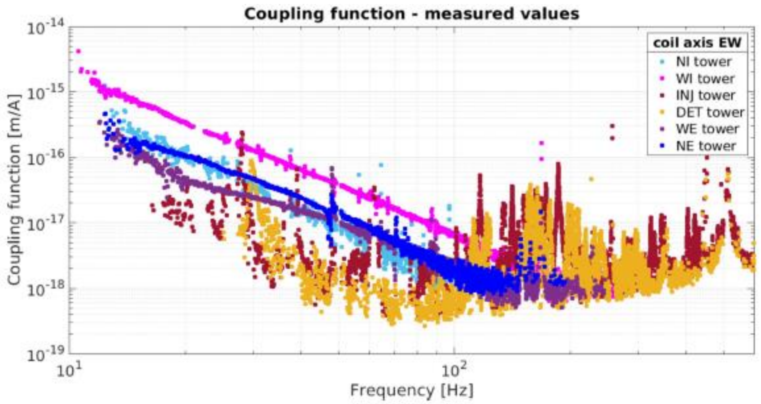
Groups in Italy contributing to the ENV WP:

- **INFN-Napoli** & **Univ. Federico II**: sensors, data analysis.
- **GSSI**: sensors, data analysis.
- **INFN-Cagliari**: sensors.

Magnetic Noise (MN)

- May spoil ET sensitivity (in particular, in the LF band).
- **Sources**: Earth Schumann's Field (~pT) + ITF environmental noises (self-inflicted noise, e.g. electronic boards, electric motors, pumps, magnetized components or conductive materials…).
- Power distribution system is a known source: EM fields radiated by cables/wires and magnetic fields from electric and electronic devices.
- **WP Target**: improve low-frequency sensitivity by two orders of magnitude compared to Advanced LIGO/Virgo.
- **MN Mitigation strategies**:
  - ➢ lowering the environmental noises at Earth Noise level (any device which carries an electric current).
  - ➢ identify and shield main coupling locations (reduce coupling by a factor 10^2-10^3 w.r.t. current ITFs).





Magnetic Noise (MN)

Activities:

- Analysis of magnetic data from existing GW detectors and from the ET candidate sites.
- Derive coupling factors from environmental to detector noise.
- Design, modelling and test passive magnetic and eddy-currents shields (e.g. for Faraday isolators, test masses).
- Design of the MN mitigation system (items, parameters).
- Define cost estimates of the MN mitigation system.
- → prepare the TDR part of the ENV system.

Magnetic Noise (MN)

Groups in Italy contributing to the MN WP:

- **INFN & Univ. Genova**: models, data analysis, mitigation strategies.
- **INFN-Napoli** & **Univ. Federico II**: sensors, data analysis.
- **EGO**: sensors, data analysis, mitigation strategies.

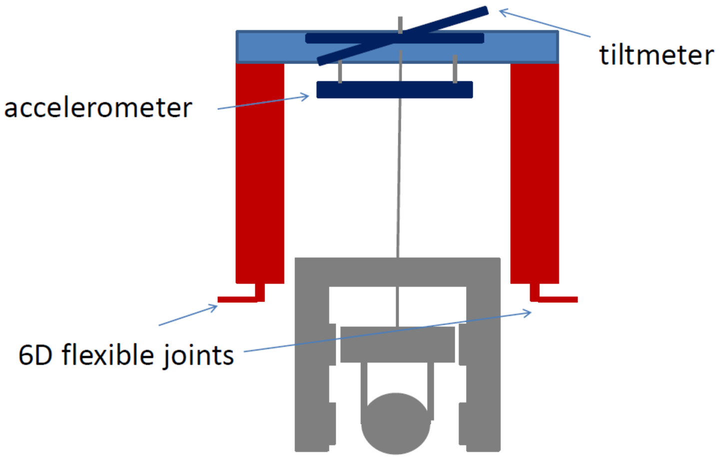
Inter-Platform Motion (IPM) & Low Frequency Controls (LFC)

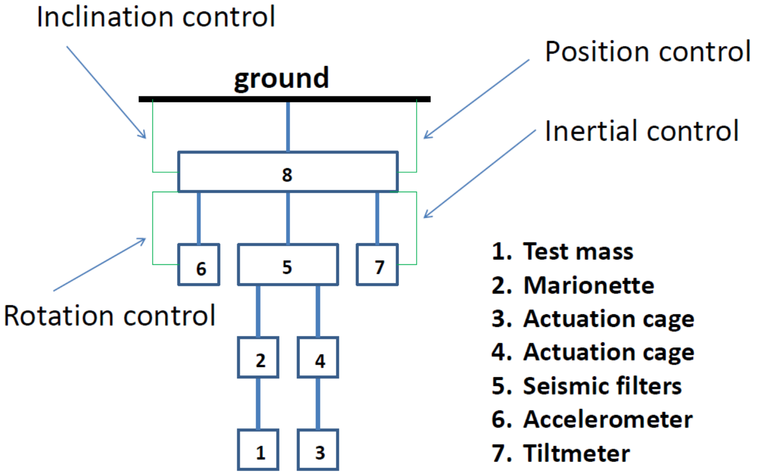
Activities:

- Improve understanding of the mechanical noise (thermal + seismic + control noise).
- Development of suspension conceptual design/model for different options (interaction with Suspension Division, → F. Fidecaro's talk).
- Software development for models in frequency and time domains.
- Definition of the key input & output variables for the evaluation of suspension options.
- Definition of requirements on sensors at seismic platform level.
- Design of sensor instrumentation at the seismic platform level.
- Production of improved estimates of RMS of motion and impact on ET performance.
- Development and test of interferometric sensors for isolated platforms.
- Development of optimized local and global control systems

Inter-Platform Motion (IPM) & Low Frequency Controls (LFC)

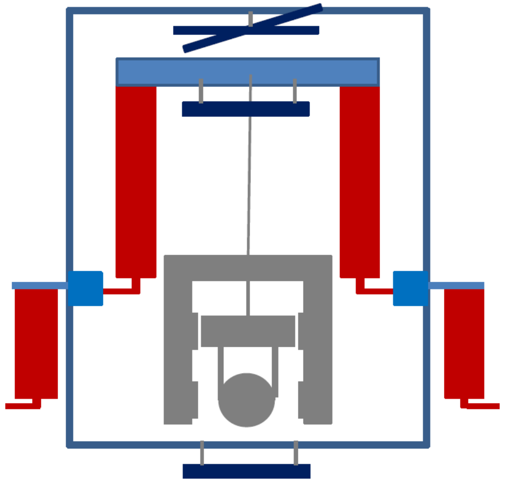
Option 1: SAT (single 6D controlled stage)

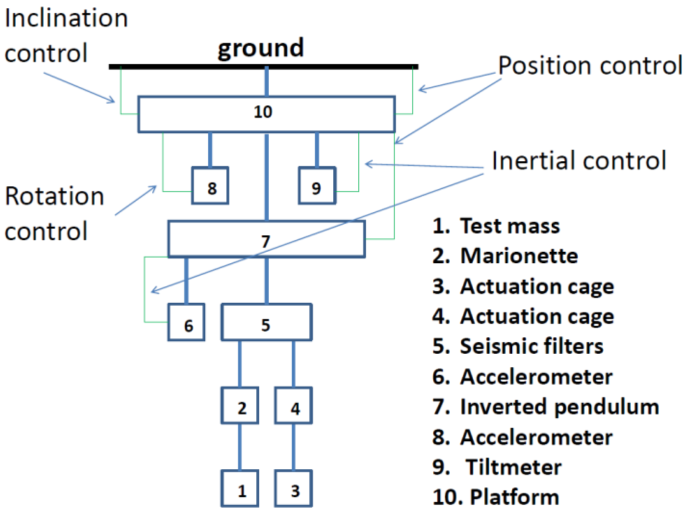




1. **Test mass**
2. **Marionette**
3. **Actuation cage**
4. **Actuation cage**
5. **Seismic filters**
6. **Accelerometer**
7. **Tiltmeter**
8. **Inverted pendulum**

Option 2: adding a controlled box





1. **Test mass**
2. **Marionette**
3. **Actuation cage**
4. **Actuation cage**
5. **Seismic filters**
6. **Accelerometer**
7. **Inverted pendulum**
8. **Accelerometer**
9. **Tiltmeter**
10. **Platform**

Inter-Platform Motion (IPM) & Low Frequency Controls (LFC)

Groups in Italy contributing to the IPM & LFC WPs:

- **EGO**: modelling, simulations.
- **GSSI**: sensors, hardware.

Conclusions

- Environmental noises will be one of the main limit for the ET sensitivity at Low Frequencies, a crucial band for the scientific goals of ET.
- The mitigation of the environmental noise is paramount → dedicated division in the ET collaboration (Active Noise Mitigation, ANM).
- Obvious and necessary interaction with the site characterization activities (→ talks in the site preparation session).
- Several research groups in Italy are contributing to the activities of ANM and dedicated WPs.