STGWD 2026 - PhD International School on Technologies in Gravitational Waves Detection

Environmental noise and its impact on the Virgo detector

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Outline

Environmental noise in gravitational-wave detectors

* Virgo environment
* Monitoring and investigation strategy

Environmental noise case studies at Virgo

* Natural noise
* Anthropogenic noise
* Infrastructure noise

Environmental coupling estimation

* Environmental noise injections and noise projections

Implications for future detectors

* Einstein Telescope
* Site characterization challenges


Virgo interferometer
Cascina, Pisa (Italy)
West end building
(WEB)
North end
building (NEB)
West arm (3 km)
North arm (3 km)
Central building
(CEB)


Virgo interferometer
Cascina, Pisa (Italy)
West end building
(WEB)
North end
building (NEB)
West arm (3 km)
North arm (3 km)
Central building
(CEB)
The Virgo interferometer operates in a noisy environment!

Environmental noise sources

The gravitational wave interferometers are influenced by environmental noise sources:

Natural

Sea activity, wind, earthquakes, lighting, Earth magnetic field etc.

Anthropogenic

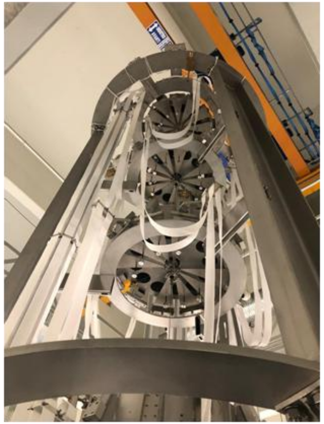
highways, railway, tracks, wind turbine, airplanes, tractors etc.

Virgo site facilities and infrastructures

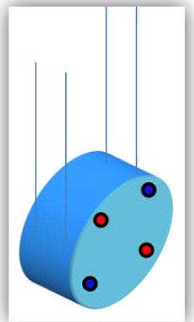
air conditioning systems, vacuum devices, electricity, experimental equipment, power supplies etc.

Coupling with the Virgo interferometer

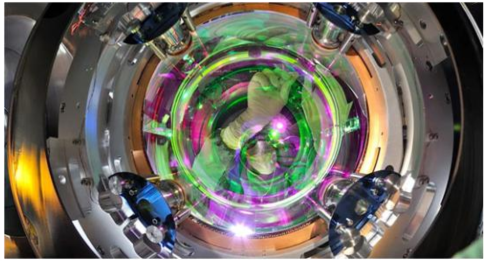
* **Seismic and acoustic noise source**
  Optical benches and mirrors are suspended in vacuum to reduce vibration noise from the ground and the impact of acoustic noise.



* **Magnetic noise source**
  Magnetic fields couple to the magnets attached to the mirrors, exerting a displacement force. This occurs through the coil–magnet actuation system used for angular and longitudinal control of the mirrors.



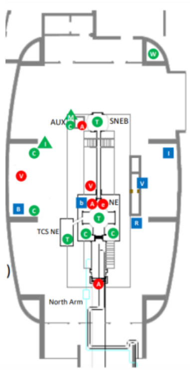
4 tiny magnets are glued on Virgo mirrors surface

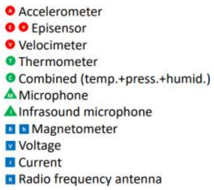


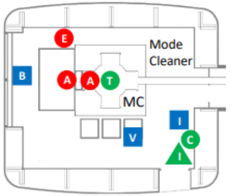
Environmental monitoring system

Central building

North (West) building







Mode cleaner building

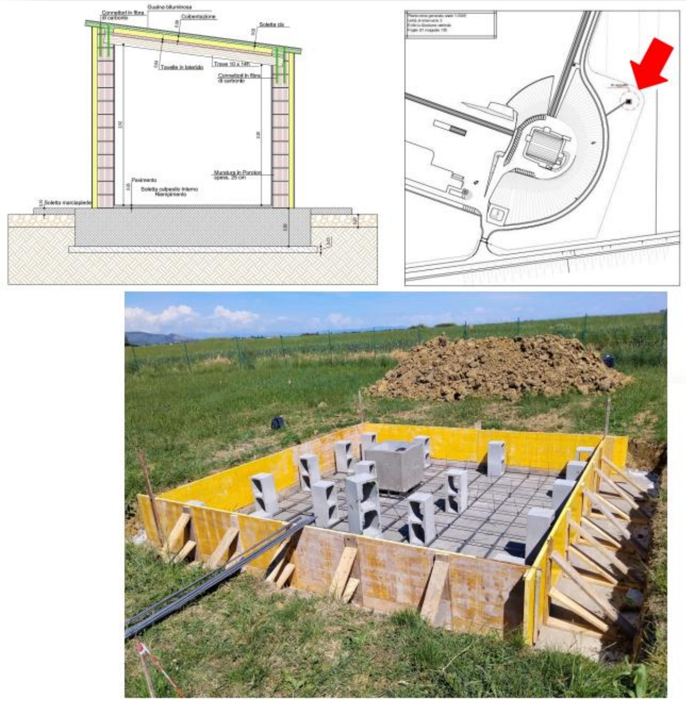
Weather Station
Lightning Station

External magnetometers

- A distributed network of probes are used to monitor the conditions of the surrounding environment.
- There are two categories of sensors
  - **fast sensors**, f_s=1 kHz to 20 kHz: seismometers, accelerometer microphones, magnetometers (internal and external), voltage and current sensors, radio-frequency antenna, ...
  - **slow sensors**, f_s=1 Hz: wind, temperature, humidity, pressure, air and water flux probes, weather station, lightning detector, ...

Monitoring the external environment

- Environmental monitoring is not limited to the experimental buildings.
- Dedicated external monitoring stations help characterize disturbances originating from the surrounding environment and their propagation toward the detector:
  - three external environmental monitoring stations
  - one located ~50 m from each vertex building.
- These stations complement the internal monitoring network with seismic, magnetic, acoustic, and meteorological measurements.



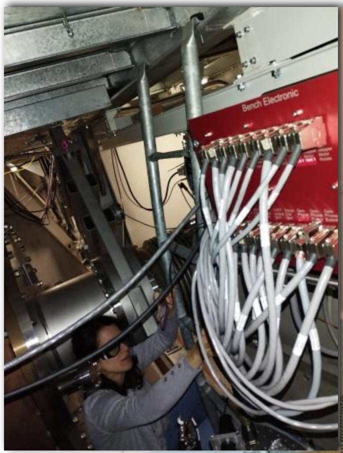
Microphone

Seismometer

Environmental noise study

The environmental noise investigation aims to:

- identifying the sources and coupling paths of noise affecting the detector;
- implementing and validating mitigation solutions;
- quantify the coupling of environmental noise to the detector using noise injection techniques and produce estimates of their impact on sensitivity.
- preserve the site from the influence of external noise sources (e.g. aircraft, wind turbines, gas pipelines, etc.).



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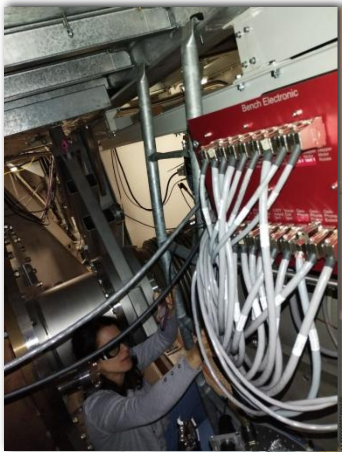
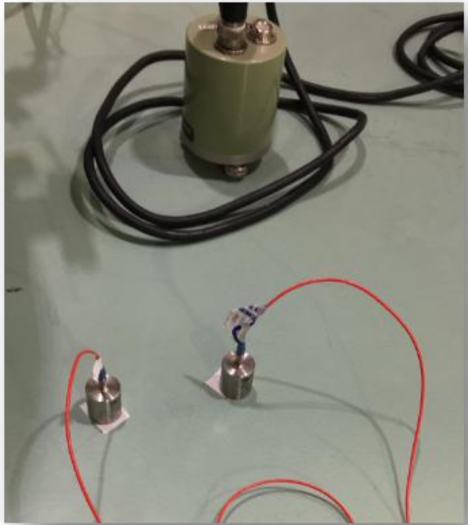


During the Virgo Commissioning phase, this becomes a noise hunt!!!

Environmental noise investigation toolkit

Experimental equipment



Seismic noise
→ seismometer

Acoustic noise
→ microphone

Magnetic noise
→ magnetometer

Environmental noise investigation toolkit

Experimental methods

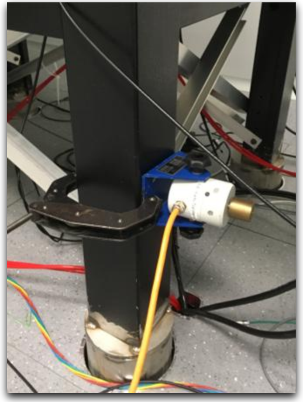
Sniffing: use of portable magnetic, seismic, and acoustic probes to inspect experimental areas.

Switch-off test: selective switching off of suspected noise sources in order to eliminate noise coupling into the gravitational signal.

Noise injections: generation of controlled noise (acoustic, magnetic, seismic) in the experimental halls in order to estimate the coupling of the interferometer to environmental noise.

Coil

Shaker



Loudspeakers

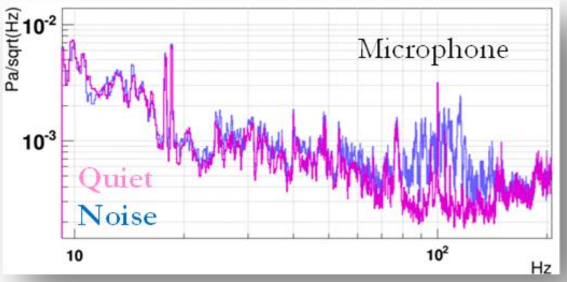
Environmental noise investigation toolkit

Data mining

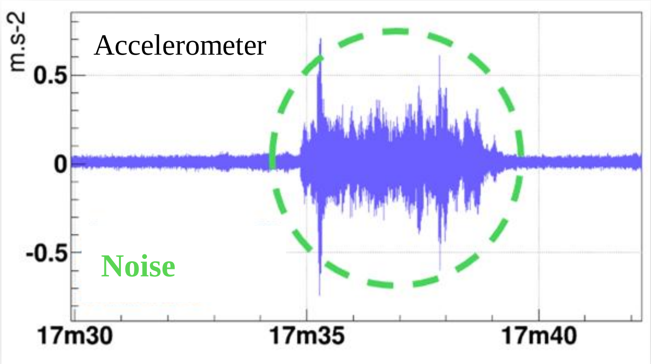
Careful inspection of noise features in the signal using time-frequency analysis (spectrograms) and power spectra.

What are we looking for?

- Changes in spectral noise characteristics (e.g., lines or bumps).
- Checking the Virgo logbook for coincidences with interferometer actions considered harmless.
- Searching for correlated noise features in other channels (environmental and instrumental).



Acoustic noise spectrum



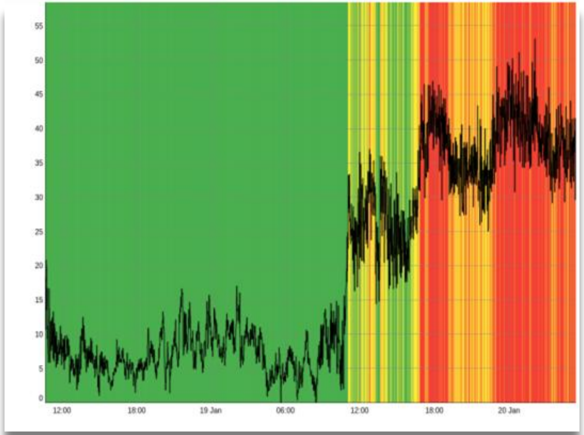
Time series of vibration noise signal

NATURAL NOISE

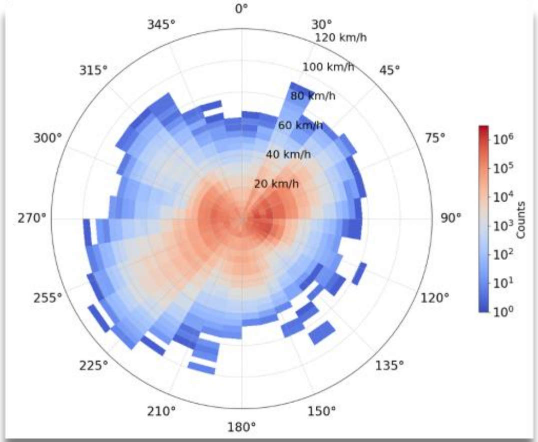
Wind conditions at Virgo site

Virgo meteo station
(on the technical building roof)

Wind activity monitoring



Wind direction and speed distribution



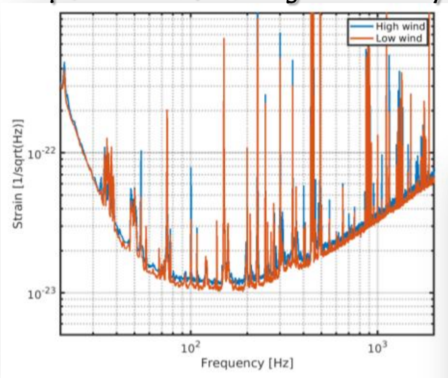
- Virgo interferometer is exposed to two dominant wind directions:
  - NE–E (50°–100°) and SW–W (220°–300°), corresponding to the regional winds *Grecale* and *Libeccio*.

- While typical wind speeds remain below ~20 km/h, severe gusts can exceed ~90-100 km/h.

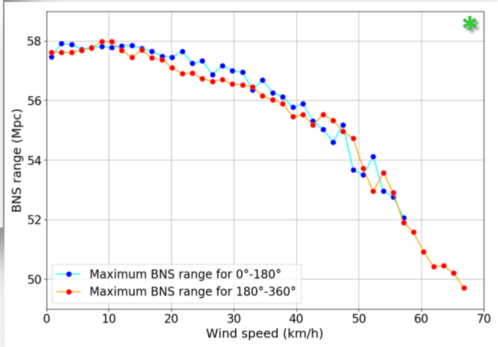
Impact of the wind

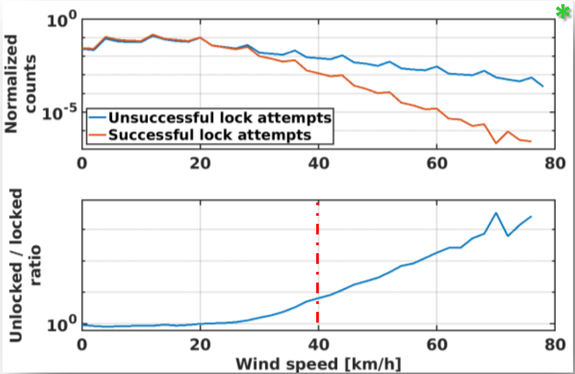
* The Virgo interferometer performed worst during windy days:
  - a broadband increase of the detector noise is observed during high wind conditions.
  - a decreasing trend of the BNS range with increasing wind speed → the interferometer appears to be more sensitive to wind speed than to wind direction.

Impact of wind on Virgo sensitivity



Trend of the BNS range with wind speed





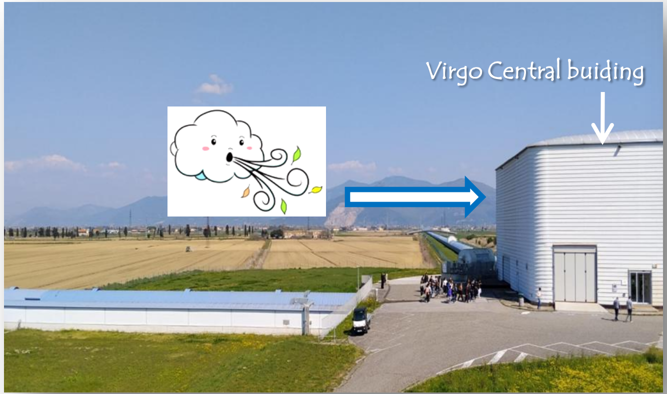
* Distribution of successful and unsuccessful lock:
  - as the wind speed increases, the probability of successfully reaching the science mode rapidly decreases.

Paper in preparation:
Impact of wind on Virgo detector performances during the O4 run

*O4b data analyzed (April 10th, 2024 - June 10th, 2025)

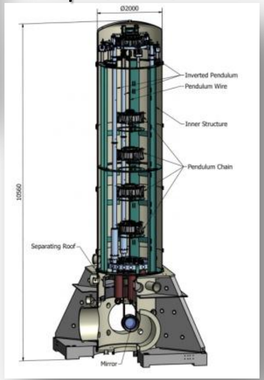
Possible wind coupling mechanisms

* Strong winds can induce a tilt of the superattenuator (SA) tower base (few tens of nrad at 10-100 mHz) *fooling* the SA accelerometers.



* A study is ongoing about how this tilt originates:
  - is it the building floor ?
  - is it induced by air pressure noise on the SA vacuum chambers?

Superattenuator

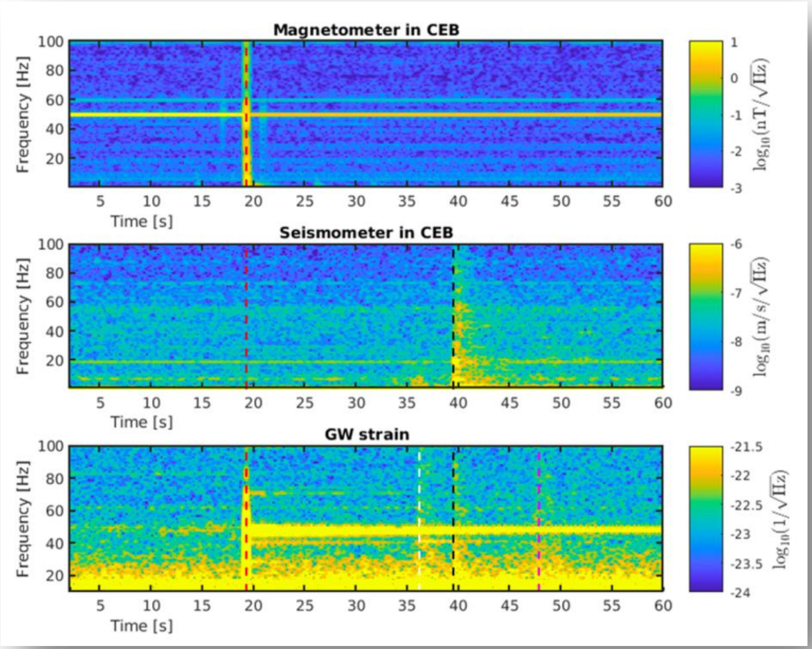


* During windy days:
  - the wind represents a limiting factor for the lock acquisition process, especially during the DC readout /OMC lock stage.
  - detector sensitivity degrades due to the increase of the frequency noise coupling, which is controlled by angular motion (Ty) of beam splitter mirror.

* Mitigation solution:
  - improve the control of the beam splitter
  - wind shield → it is not easy for Virgo detector (VIR-0429A-22)!

Lightnings

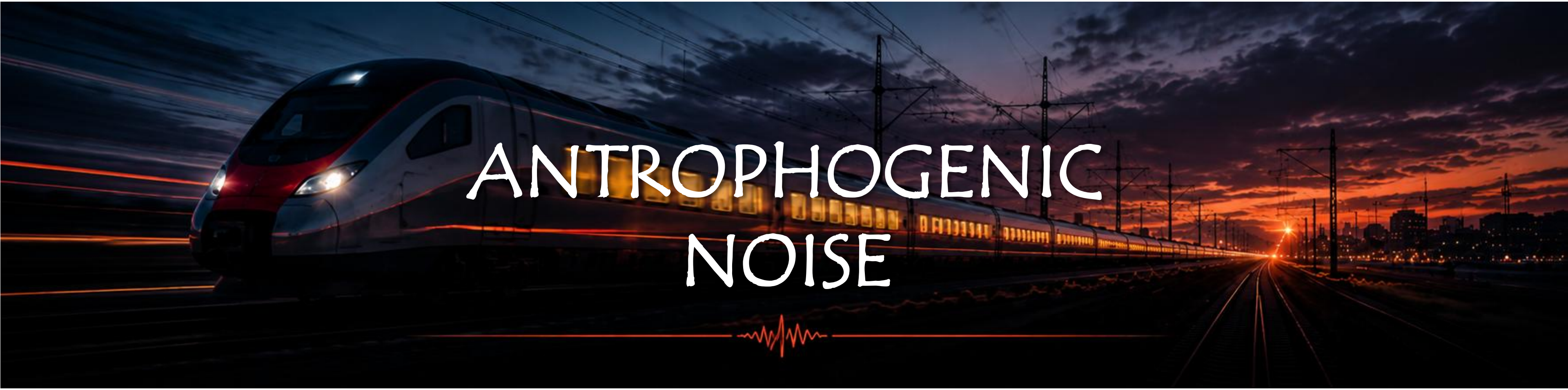
- Lightning strikes produce prompt electromagnetic waves and much slower air pressure waves which induce vibrations of the ground and of the detector mechanical components.



Lightning strike occurrence ---
Seismic transient occurrence @ WEB (white), CEB ---, NEB ---

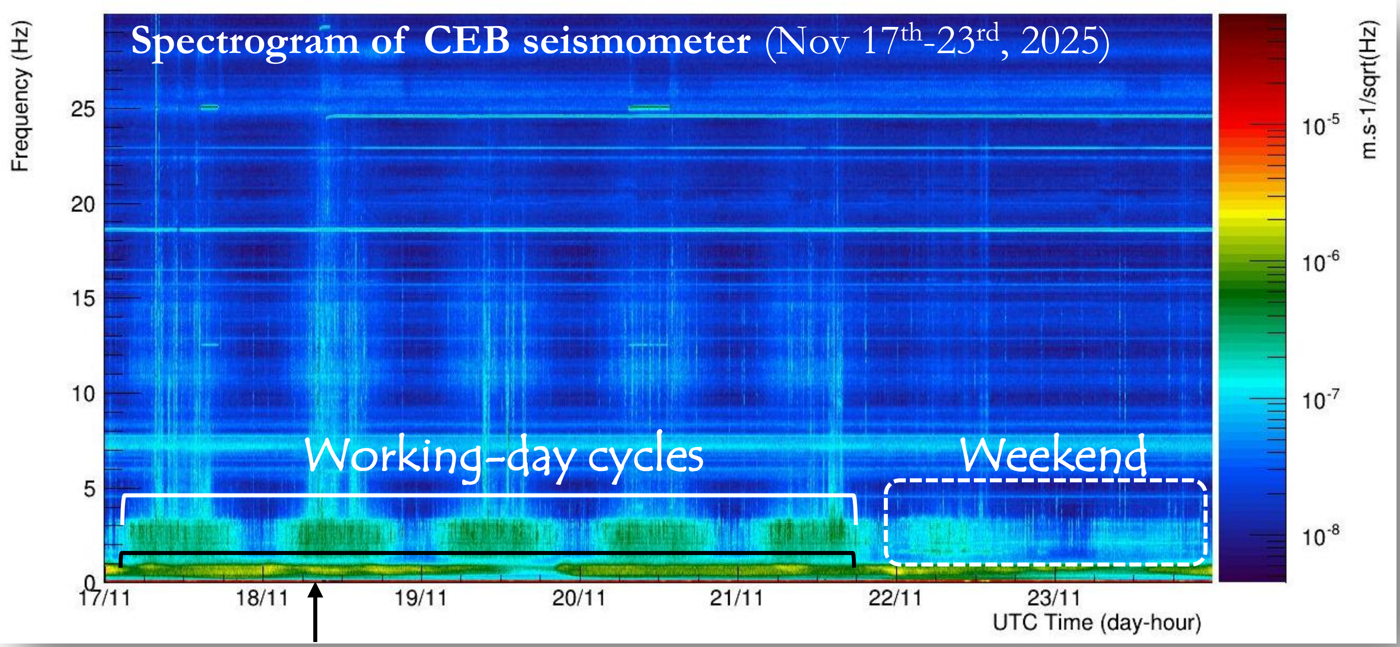
Class. Quantum Grav. 39 235009, https://doi.org/10.1088/1361-6382/ac776a

- A distinctive feature of lightning strikes is a coincident transient noise in all magnetometers.
- The magnetic impulse is followed by the slower sound shock wave detected by seismometers in the experimental buildings (WEB, CEB, NEB).
- In the GW strain signal:
  - prompt broadband low-frequency noise in coincidence with the magnetic spike;
  - this spike acts directly on magnets (e.g., suspension actuators) and perturbs the GW strain;
  - the onset of a 48 Hz narrow spectral noise, with a minute-long decay time (~30% drop of BNS range) is due to the excitation of one structural mode of West end test mass suspension.



ANTROPHOGENIC NOISE

Human activity



Wind/sea activity

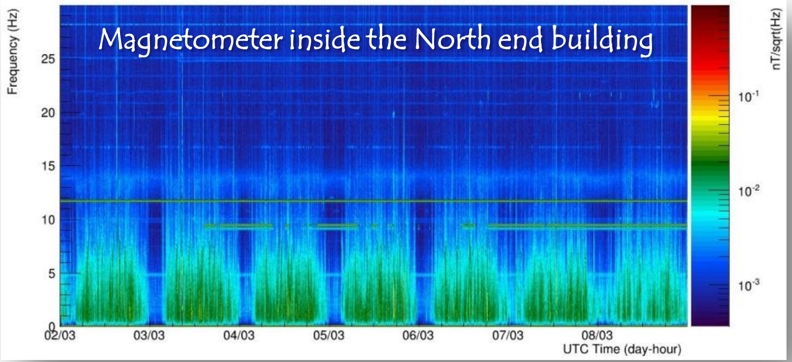
Frequency band (1-10) Hz

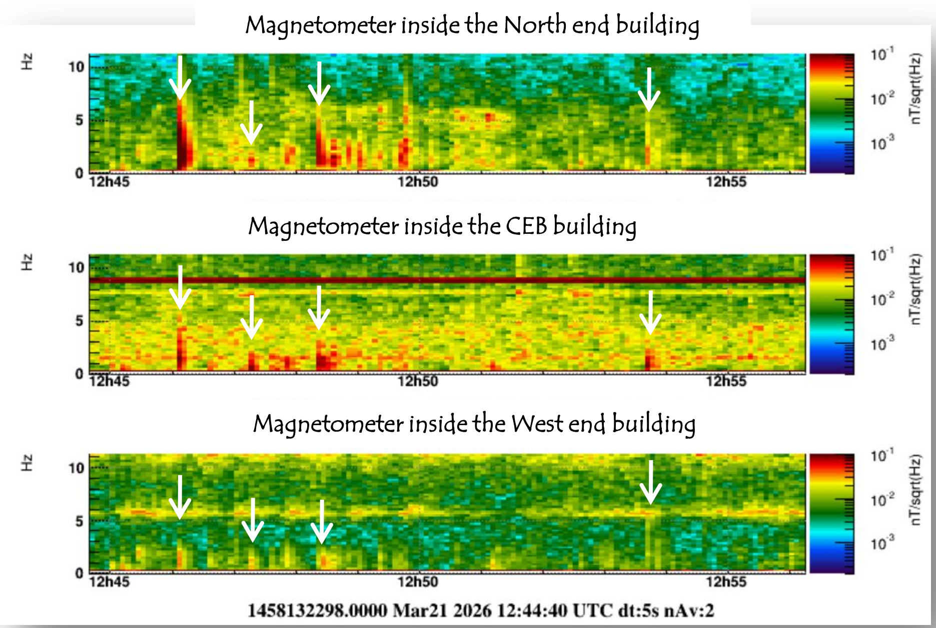
- Anthropogenic sources dominate the spectrum.
- Heavy vehicles (trucks and alike) on ~1 km distant elevated roads are the prevailing source[‡].
- Variation due to day/night cycle.

[‡]S. Koley et *al*, https://doi.org/10.1190/segam2017-17681951.1

Site-wide low-frequency magnetic glitches

* Below 10 Hz, the environmental magnetic noise at the Virgo site is dominated by transient disturbances, with quieter periods typically occurring daily between midnight and 4 a.m.. (elog #58074).

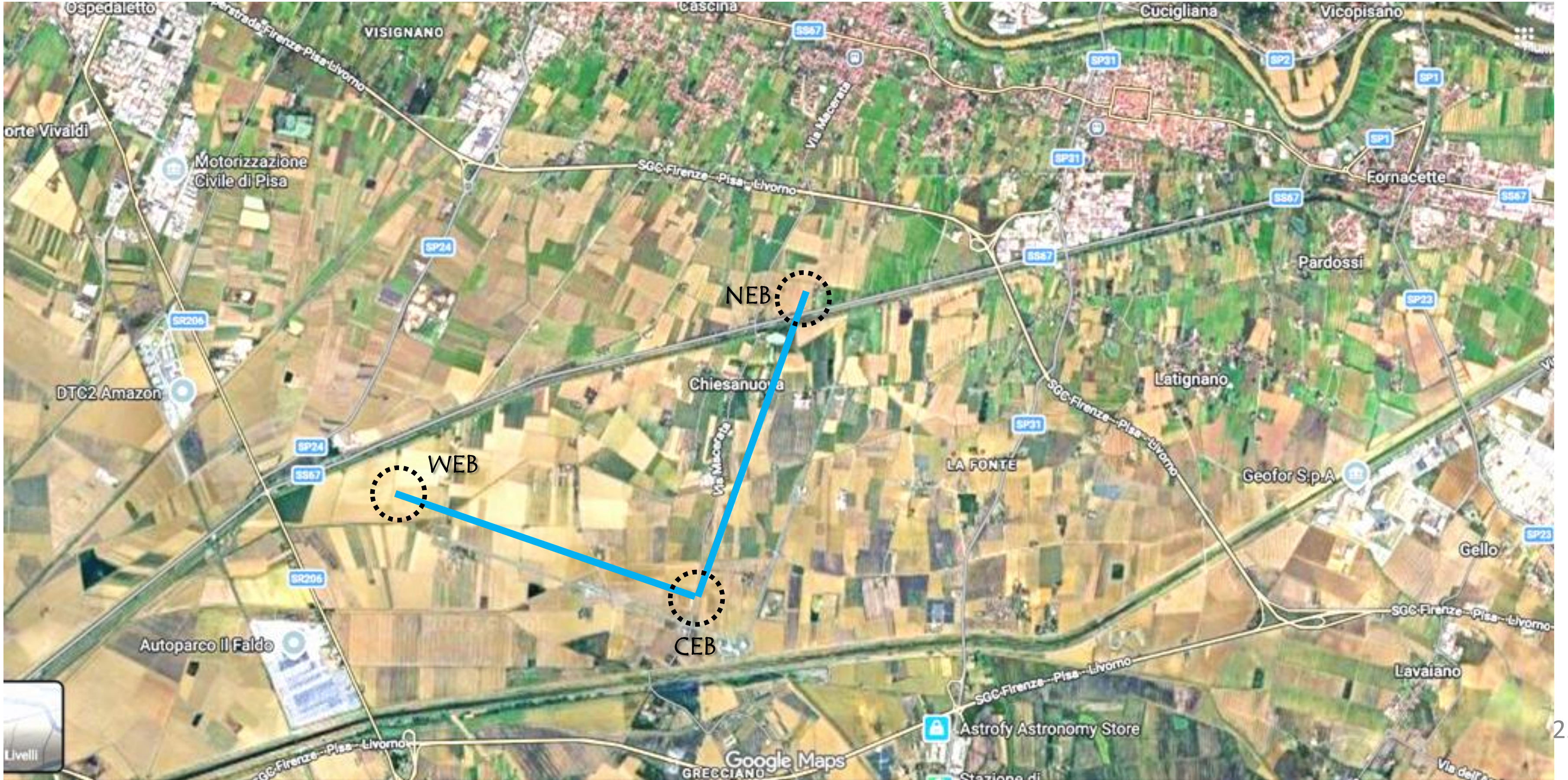




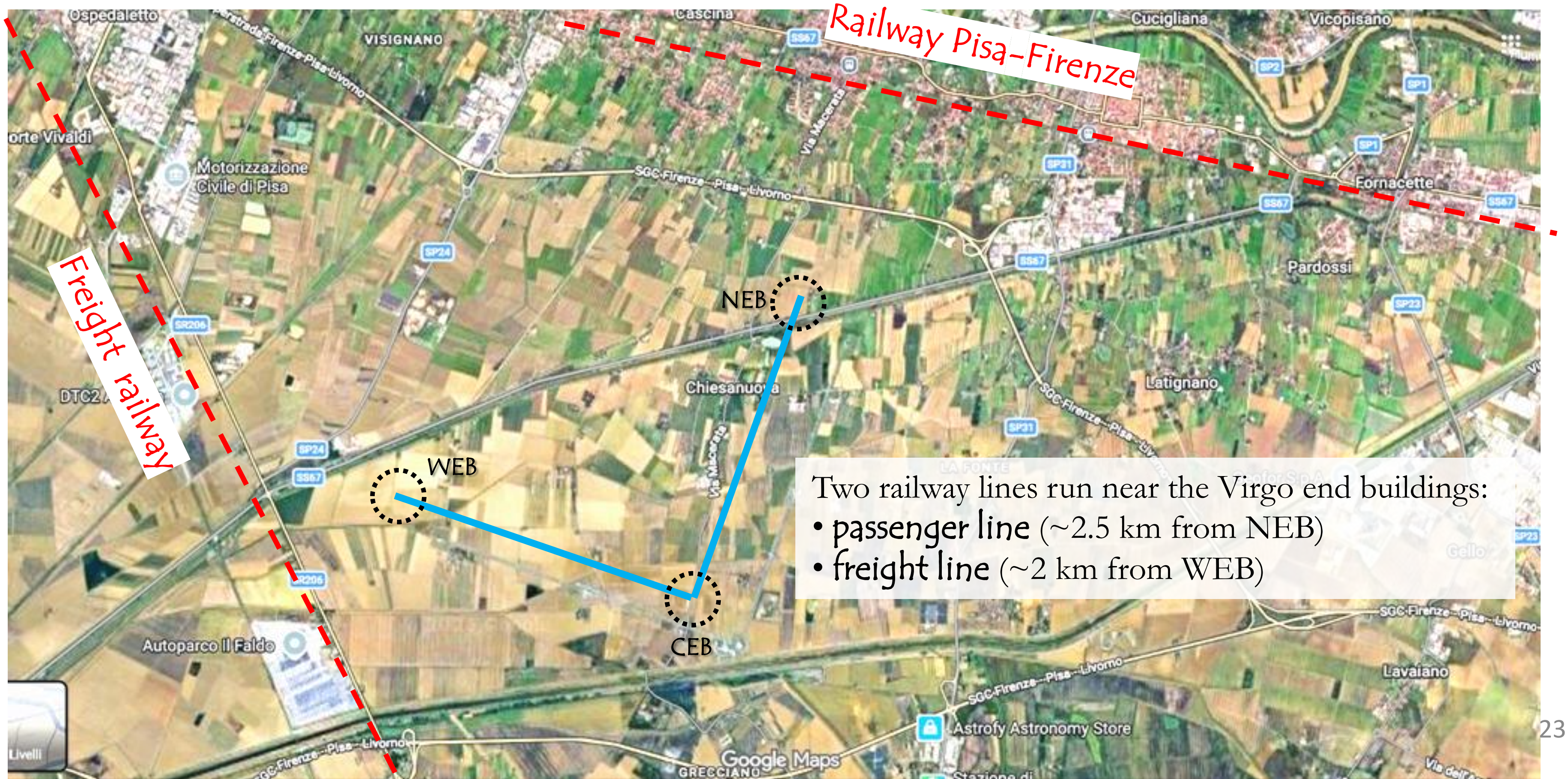
* Magnetic glitches are visible in all magnetometers in Virgo detector.

* No correlation with Virgo signals and devices
→ the noise comes from the external environment.

Virgo surrondings



Virgo surrondings

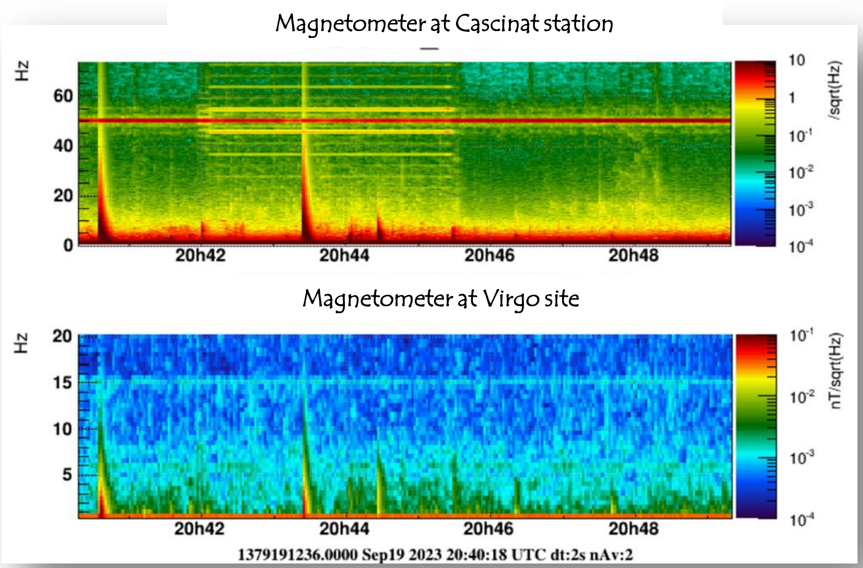


Two railway lines run near the Virgo end buildings:

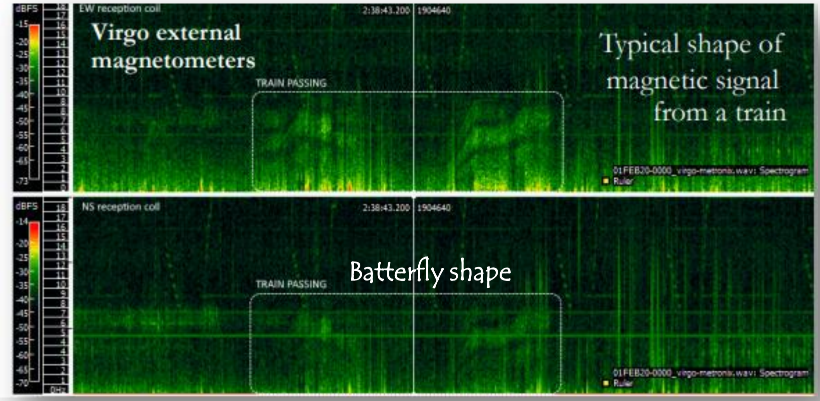
- passenger line (~2.5 km from NEB)
- freight line (~2 km from WEB)

Train-correlated magnetic disturbances

- A measurement campaign was carried out at Cascina train station (VIR-0444A-24)
- The observed magnetic signatures include fast transient *glitches* and *butterfly*-shaped patterns.



Credits: Olivier Nauwelaers, Max Lalleman (Antwerpen University)

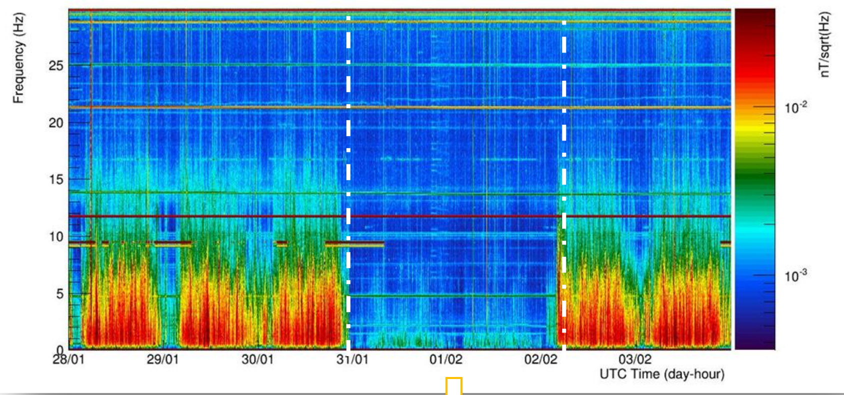


Credit: Renato Romero (www.vlf.it)

Possible coupling mechanisms

* The timing of the magnetic transients does not match any train passage or stop at Cascina station.
* The disturbance is therefore likely generated elsewhere in the railway infrastructure.

Magnetometer inside the North end building



According to *Trenitalia*, the Pisa–Empoli railway line was de-energized for maintenance →no train traffic from Jan 31-Feb 02, 2026 (elog #68641)

Possible noise model:

* Railway power lines carrying variable currents (~kA) may generate magnetic disturbances that couple to Virgo through:
  - soil leakage currents;
  - direct magnetic radiation from the railway infrastructure (~2 km distance) (inspired by F.J. Lowes, 2009).

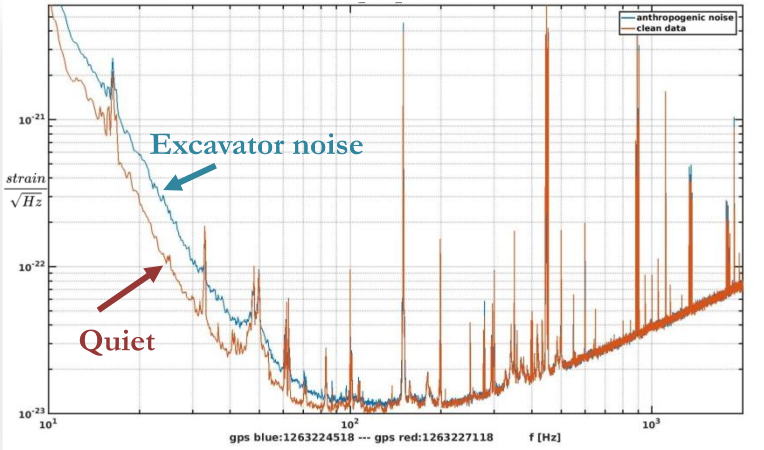
Observed signature interpretation

* **Fast glitches**: possibly generated when trains cross power substations (typically spaced by ~20 km) or when poor pantograph–overhead line contact causes transient current jumps.
* **Butterfly-shaped patterns**: likely associated with variations in traction power demand as the train accelerates or decelerates.

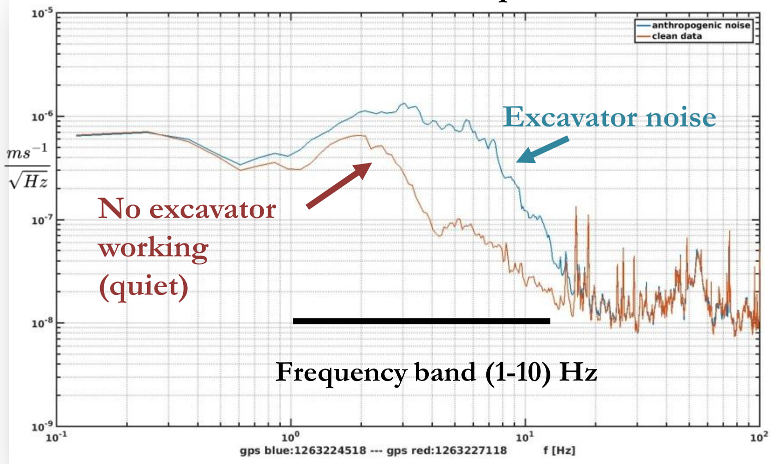
Excavator noise

- An excavator operating near the central building caused a growth of the seismic noise in the frequency range ~(1-10) Hz (elogbook #48311).
- It produces a worsening of the Virgo detector sensitivity.

Interferometer sensitivity



CEB seismometer spectrum

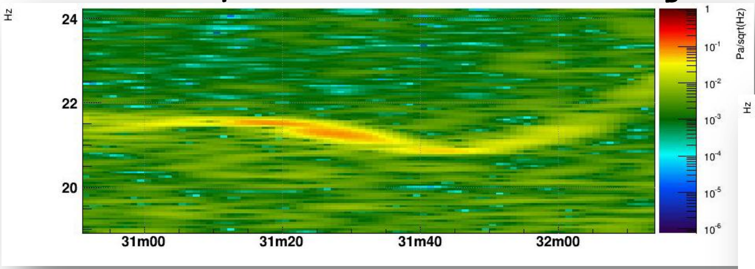


Protecting the Virgo detector environment

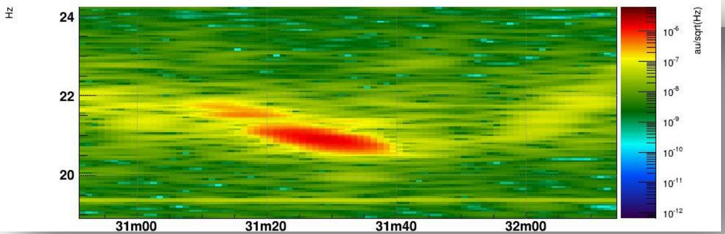
* Preserve the environmental noise climate at the Virgo site by limiting noise from nearby activities.
* Monitoring of the external environment.
* Characterisation campaigns and modelling of external noise sources.
* Collaboration with stakeholders and authorities to identify noise reduction strategies and enforce noise limits for the Virgo site.

Agreement with the Italian Air Force: no-fly cylindrical zones extending up to 2000 ft around Virgo's experimental buildings

Microphone in the Central building



Interferometer output




INFRASTRUCTURE
NOISE

A key infrastructure noise source

- The heating ventilation and air conditioning systems (HVAC) generate acoustic, seismic and electromagnetic noise at *low frequency* (below 100 Hz).

- Virgo relies on an extensive HVAC infrastructure (**9 distributed systems**) to maintain thermal stability and cleanroom conditions.

System	Serving area	Volume (m³)	AHU location
CEB AHU	Experimental hall of the Central building	8370	Inside the Central building
CEB Clean rooms	Clean rooms in the Central building	507	Inside the Central building
INJ AHU	Laser Laboratory SAS, Atrium	507 (ISO 7)	Outdoor
DET AHU	Detection laboratory, SAS	468 (ISO 7)	Outdoor
NEB AHU	Experimental hall of the North end building	4995	Outdoor (Technical area)
WEB AHU	Experimental hall of the West end building	4995	Outdoor (Technical area)
MCB AHU	Experimental hall of the Mode cleaner building	782	Outdoor
FCIM and FCEM AHUs	Input and End clean area of the Filter cavity	57 (ISO 7)	Outdoor

Reducing the Virgo site infrastructure noise in preparation of the O4 observing run,
I. Fiori et *al*, 10.1088/1361-6382/ae68d2

- During O4 preparation, a dedicated investigation was carried out to identify dominant noise sources and coupling paths.

HVAC system overview

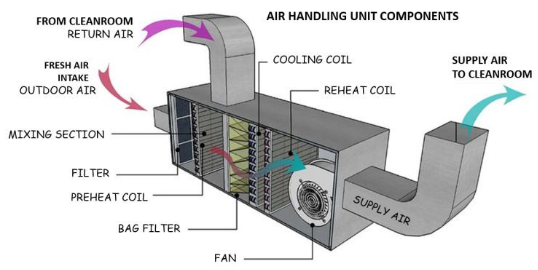
* The HVAC system is a complex system because of the extension of the apparatus and the difficulty in identifying the main culprits among the multiplicity of noise paths towards the experimental areas.

* The HVAC system components:

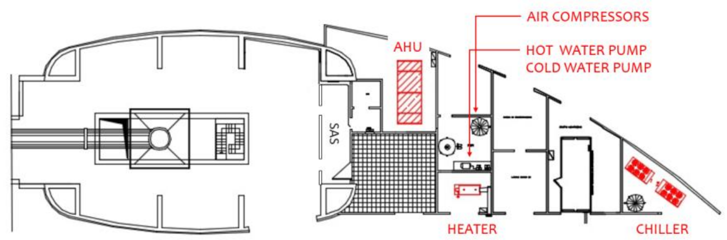
✓ **air handling unit (AHU)**
  - air circulator (fan)*
  - electrical motor (driven by inverter)
  - air distribution (ducts)
  - multi-compartment stainless-steel enclosure housing fan and motor

✓ **cold and hot water production** (chillers and heaters);

✓ **water distribution system** (pumps and pipes).



North End Building



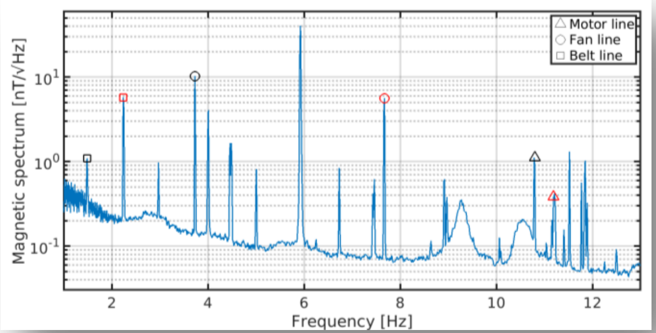
*Belt-driven or direct-drive fan-motor configurations.
*Fan speed controlled via variable frequency drives (*inverter*) to optimize airflow.

HVAC noise signature

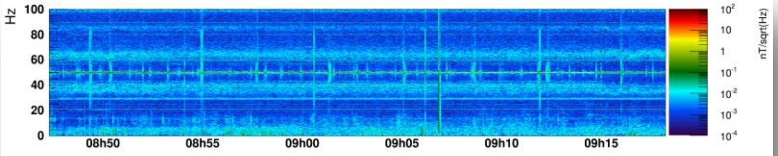
What are we looking for?

- The low-frequency noise (acoustic, seismic and EM) of HVAC plants is characterized by:
  - **broadband colored noise** arises from turbulent airflow within the ducts and fan enclosure which can excite resonance of the mechanical components and acoustic mode of the rooms;
  - **spectral lines** are typically associated with rotating machinery (rotation frequency + harmonics) and power electronics (e.g. inverter frequencies).
  - **intermittent noise** due to the operational cycle of devices such as chillers or boilers.

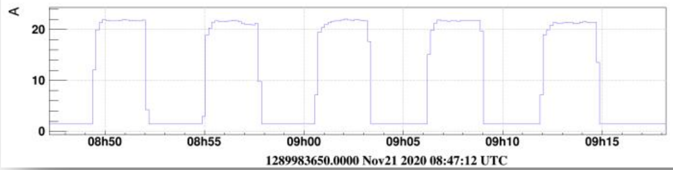
Magnetometer inside the AHU room



Magnetic spectrogram (NEB experimental hall)



Water chiller current monitor



Invastigating HVAC noise

- A dedicated investigation campaign was carried out to identify dominant noise sources and coupling paths.

✓ **Selective switch-off test**
of the devices to identify noise contributions and spectral components

✓ **Air ducts disconnection test**
to discriminate between airborne noise in ducts and other paths

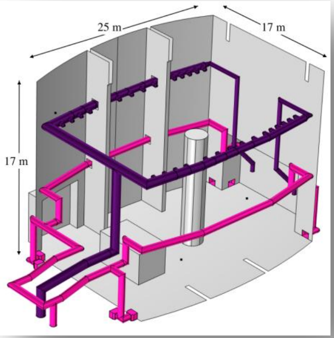
✓ **Controlled slowdown of the AHU**
to evaluate the dependence of acoustic noise on fan speed

✓ **Magnetic noise characterization**
measurement campaign to characterize the magnetic noise generated by the AHU system

- **Application of mitigation solutions**

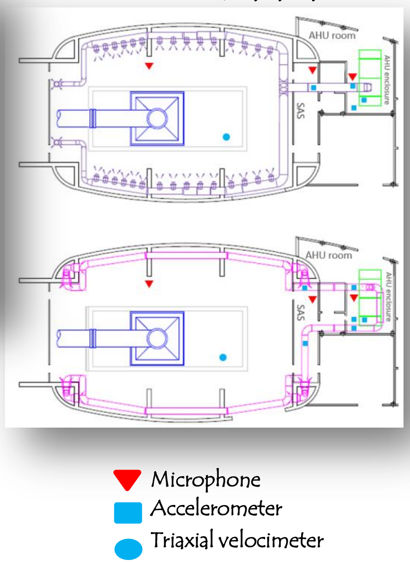
- **Test setup**
  - North end building (NEB) HVAC was the test-bench of this noise studies
  - Temporary sensors installed near HVAC devices and along suspected noise transmission paths

NEB experimental hall



3D model of the supply and return air duct distribution

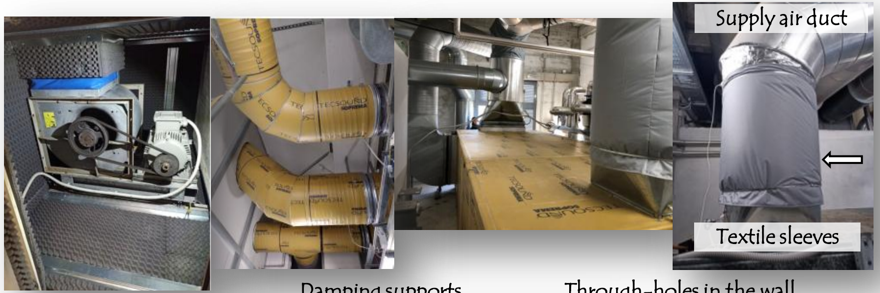
NEB experimental hall and AHU technical area



Seismic noise mitigation

Air handling unit

- Disconnection of the supply and return air ducts from AHU enclosure by means of textile sleeves.
- Insertion of the dumping supports under AHU enclosure and fan-motor case.
- Damping panel installation on AHU enclosure, SAS air ducts and on part of the supply air duct in the experimental hall.
- Internal damping treatment of the fan compartment.



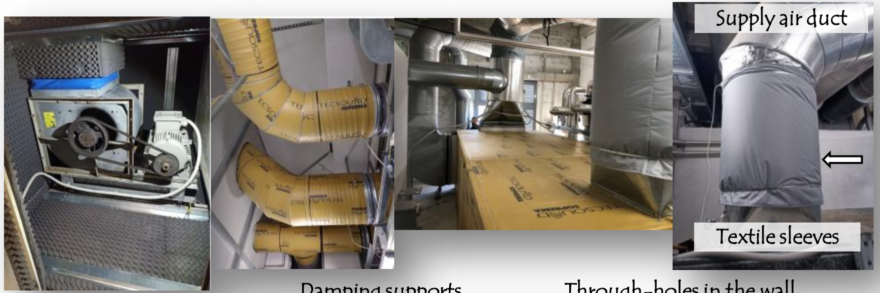
Damping supports

Through-holes in the wall

Seismic noise mitigation

Air handling unit

- Disconnection of the supply and return air ducts from AHU enclosure by means of textile sleeves.
- Insertion of the dumping supports under AHU enclosure and fan-motor case.
- Damping panel installation on AHU enclosure, SAS air ducts and on part of the supply air duct in the experimental hall.
- Internal damping treatment of the fan compartment.

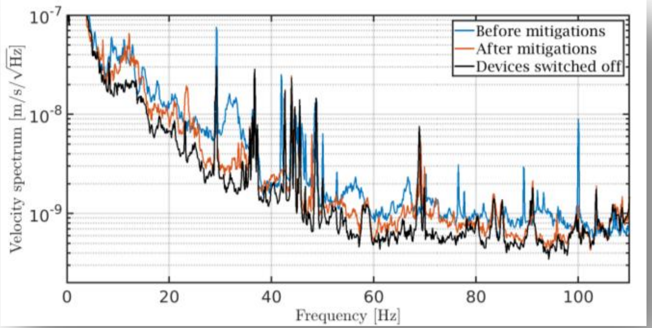


Damping supports

Through-holes in the wall

Water system

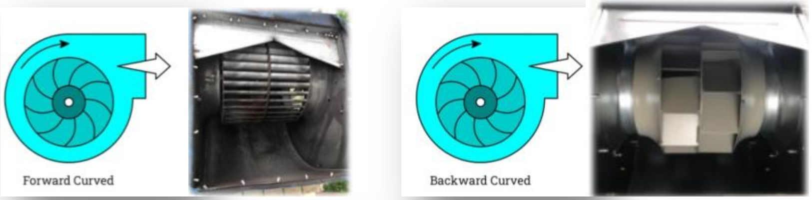
- damped spring isolation of pumps and boilers;
- flexible decoupling of pump–pipe connections (rubber joints);
- structural decoupling of pipes from walls using spring;
- reduction of rigid wall mechanical coupling.
- The implemented mitigation actions significantly reduced the seismic noise level (red curve) of the experimental hall floor in the frequency range ~(15-100) Hz.

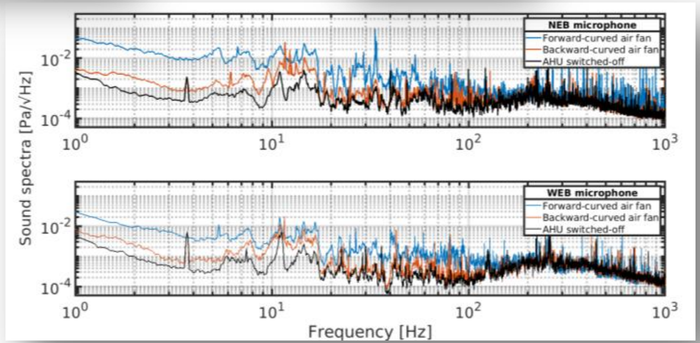


Acoustic noise mitigations

Fan replacement

- Fan design strongly impacts low-frequency acoustic emissions.
- The original forward-curved fan was replaced with a *backward-curved* model with comparable operational specifications.
- Broadband acoustic noise was substantially reduced, starting from a few hertz and up to 100 Hz.





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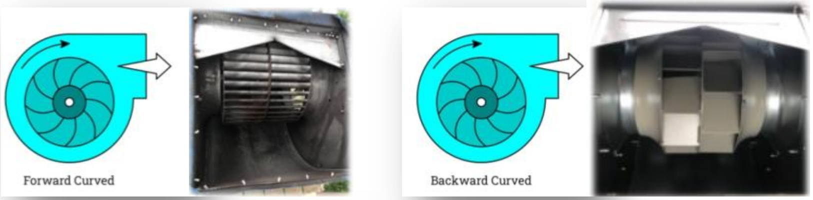
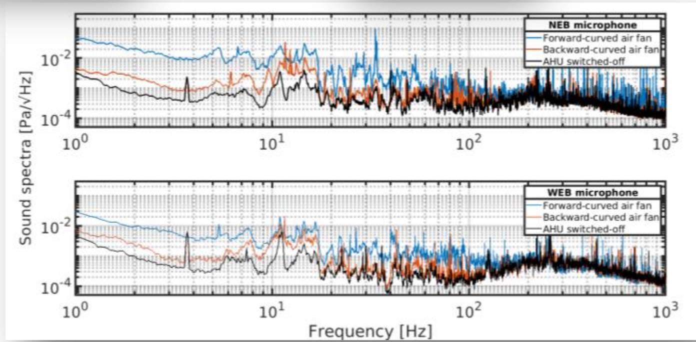
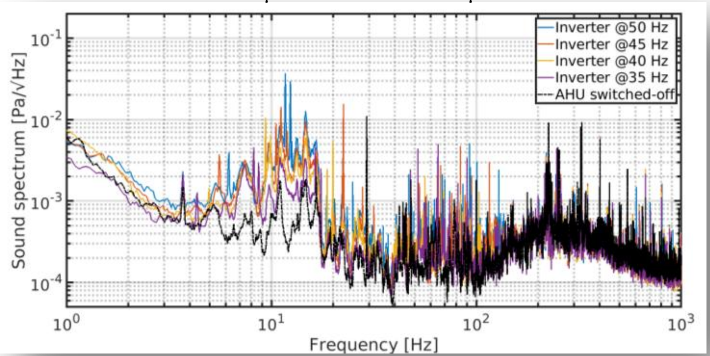




Acoustic spectrum of the NEB experimental hall



Fan slowdown

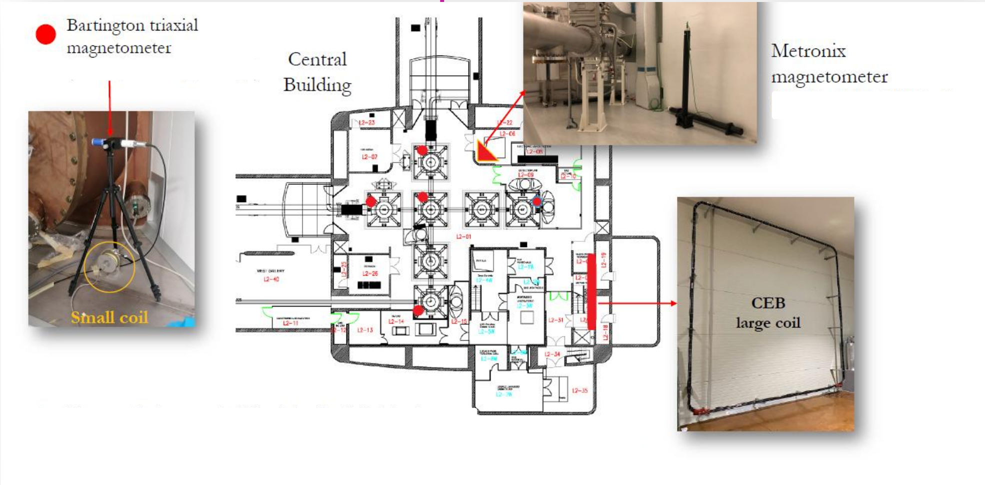
- A controlled reduction of the AHU fan speed was performed by means of inverter to assess the dependence of acoustic noise on operating conditions.
- Reduced fan speeds led to substantial broadband noise reduction.

Environmental coupling estimation

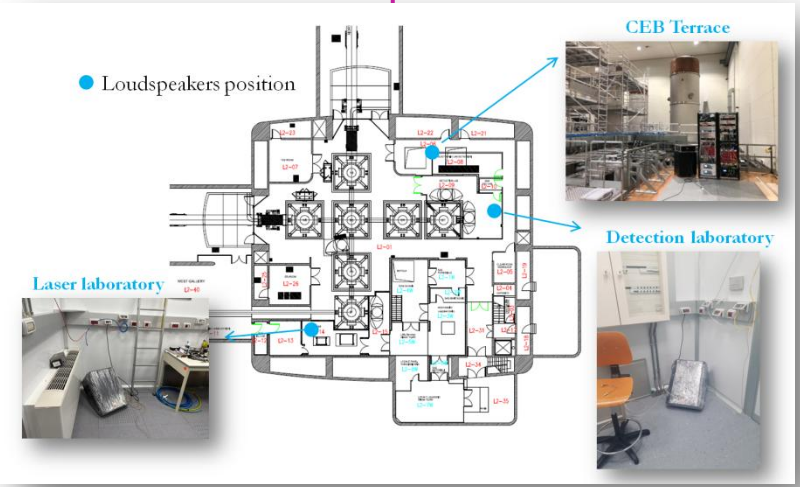
Estimating environmental coupling

Experimental setup

Far- field and near-filed magnetic noise injections



Acoustic noise injection



Similar injection setups are also deployed at the terminal buildings

* Controlled magnetic and acoustic injections are used to estimate environmental coupling to the interferometer output.

Estimating environmental coupling

- Witness sensors (magnetometers and microphones) monitor the injected disturbances, while interferometer channels are used to derive coupling estimates.
- These studies help identify noise sources that may become limiting as detector performance improves.
- During O4b and O4c observing run, magnetic and acoustic coupling injections were carried out for all three Virgo experimental buildings (CEB, NEB, WEB).

$$CF(f) = \sqrt{\frac{[Y_{inj}(f)]^2 - [Y_{bkg}(f)]^2}{[X_{inj}(f)]^2 - [X_{bkg}(f)]^2}}$$

$$CF(f)_{\text{upper limit}} = \frac{Y_{bkg}(f)}{\sqrt{[X_{inj}(f)]^2 - [X_{bkg}(f)]^2}}$$

Coupling function formula

$$h_{noise} = CF \cdot X_{bkg}$$

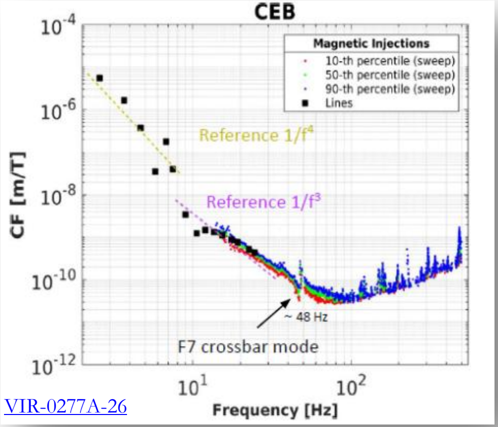
Noise projection

inj - injection time
bkg – quiet time
Y – ASD of Hrec
X – ASD of witness sensor

CF(f) if $SNR_Y > thr_Y$ & $SNR_X > thr_X$
$CF(f)_{UL}$ if $SNR_Y < thr_Y$ & $SNR_X > thr_X$

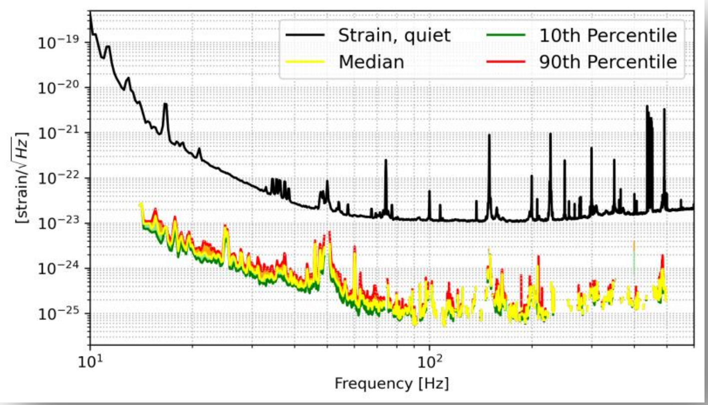
P. Nguyen *et al*, 2021 *Class. Quantum Grav.* **38** 145001

CEB magnetic coupling function during O4b e O4c



VIR-0277A-26

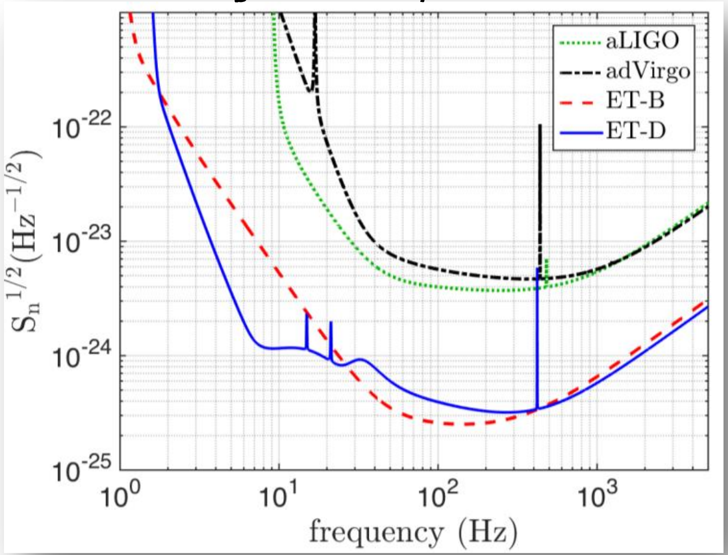
CEB magnetict noise projection during O4b e O4c



Impact of environmental noise for future detectors

Environmental noise for future detectors

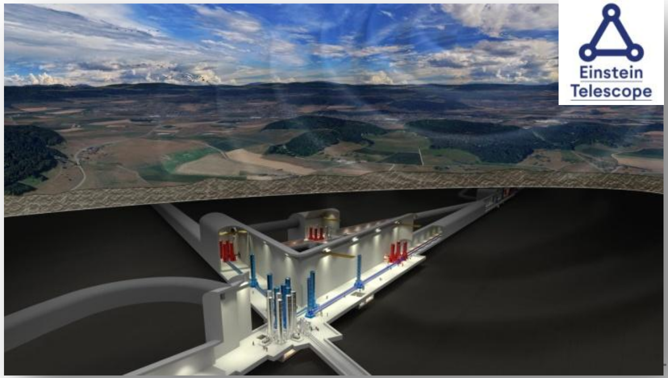
Design sensitivity curves



Below 10 Hz, sensitvity improved by a factor > 10^3 !!!

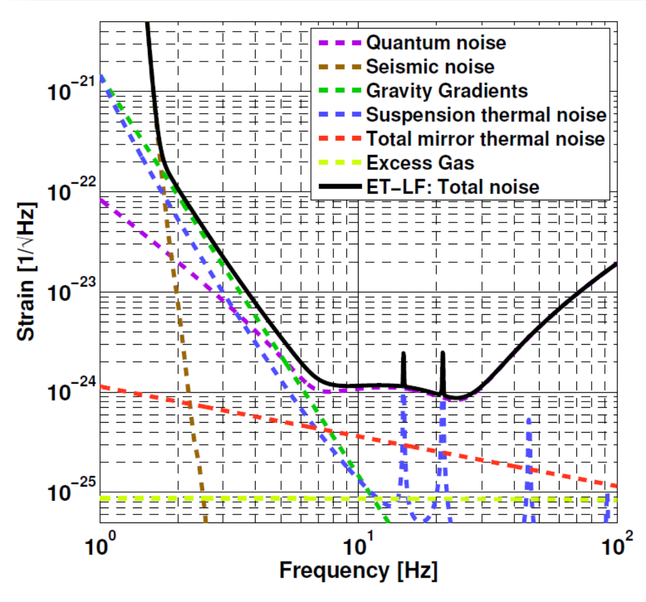
- Future gravitational-wave observatories are currently under study, including Cosmic Explorer in the US and Einstein Telescope in Europe.

- Einstein Telescope (ET) aims to extend gravitational-wave observations toward significantly lower frequencies (2–20 Hz), where environmental disturbances become one of the dominant limitations to detector sensitivity.



Envronmental noise at low-frequency

ET-LF noise budget



- At low frequency (f<10 Hz), ET-LF sensitivity curve is limited by **seismic** and **Newtonian noise** (NN).
- NN originates due to the gravitational coupling between test masses of the interferometer and ambient density fluctuations such as:
  - pressure and temperature fluctuations → atmospheric NN
  - seismic ground motion (surface Rayleig-wave and body P-waves) → seismic NN

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

Newtonian noise projection

$\tilde{x}(f)$ → ASD of seismic noise displacement

- **Unlike seismic noise, NN cannot be shielded but can be mitigated through subtraction techniques.**
- **Environmental noise conditions and intrinsically quiet sites are crucial for ET.**

Site characterization

- Site characterization must assess geological conditions relevant for NN, as well as the broader environmental noise budget.
- Extensive site characterization campaigns have been carried out across candidate sites.
  - Sardinia candidate site (link, INGV)
  - Euregio Meuse–Rhine candidate site (link)
  - Lausitz candidate site (ET-0274A-25)
- These studies provide the experimental basis for NN modeling and mitigation.

Deployment of **seismic stations** at the ET candidate site in Sardinia
Credits: Luca Naticchioni

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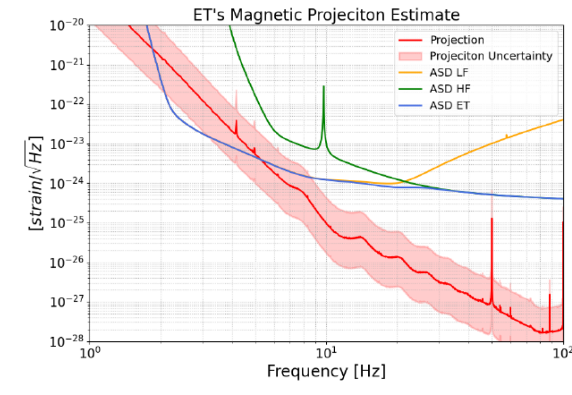
- Anthropogenic disturbances from nearby activities and infrastructure (e.g. railway traffic, industrial plants, wind turbines), may affect detector performance.
- Low-frequency magnetic disturbances must also be carefully characterized, as magnetic coupling may contribute to sensitivity limitations.
    - The magnetic projection shown uses magnetic CF experimentally measured at Virgo (ET-0058A-26).



Conclusions

* Years of Virgo operation have demonstrated that maintaining a low-noise environment is a fundamental requirement for gravitational-wave detectors.

* Environmental noise does not always produce a direct impact on detector sensitivity, but it remains a potential limiting factor for overall detector performance.

* Virgo's infrastructure was designed more than 25 years ago, when low-noise requirements for technical systems were not yet a primary design driver.

* The experience gained at Virgo will provide valuable lessons and practical guidelines for the design of low-noise infrastructure and environmental control strategies in future detectors such as Einstein Telescope.

Thank you for your attention