Impacts of the external environment on the Virgo detector during the O3 run (04/2019 → 03/2020)

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On behalf of the Virgo Collaboration

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Outline

- Detecting gravitational waves (GW) with ground-based inteferometric detectors
  - The LIGO-Virgo-KAGRA global network

- The LIGO-Virgo Observing Run 3 (O3) in a nutshell
  - Performance of the Virgo detector

- Environmental noises and their impact on the Virgo detector during O3
  - Seismic noises
  - Bad weather
  - Earthquakes
  - Magnetic noises

- Conclusions

- Reference publication: The Virgo O3 run and the impact of the environment
  - Accepted for publication in Classical and Quantum Gravity
  - Preprint: arXiv:2203.04014 [gr-qc]

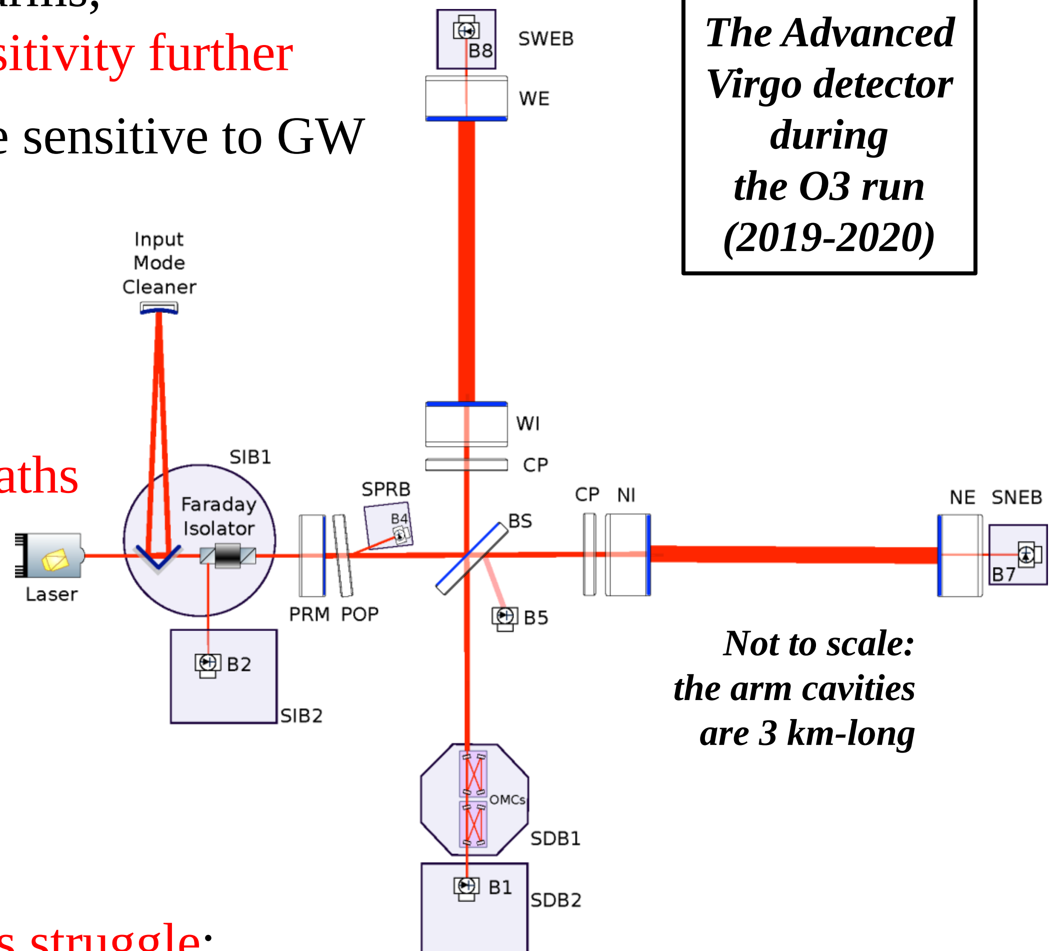
  → Main source of the plots shown in this talk

Ground-based GW detector

- Suspended Michelson interferometer,
  km-long Fabry-Perot cavities in the arms,
  recycling mirrors to enhance the sensitivity further
- Specific working point required to be sensitive to GW
  → Active feedback control systems
  - Bring the detector to its global working point and maintain it
- GW passing through the detector
  - Differential effect on arm optical paths
  → Interference condition changes at interferometer output
  → Variation of the detected power
  → GW strain channel h(t)
  - Reconstructed from raw data
- Sensitivity limited by noises
  - Fundamental
  - Technical
  - Environmental

  } Continuous struggle: design, improvement, noise hunting, mitigation

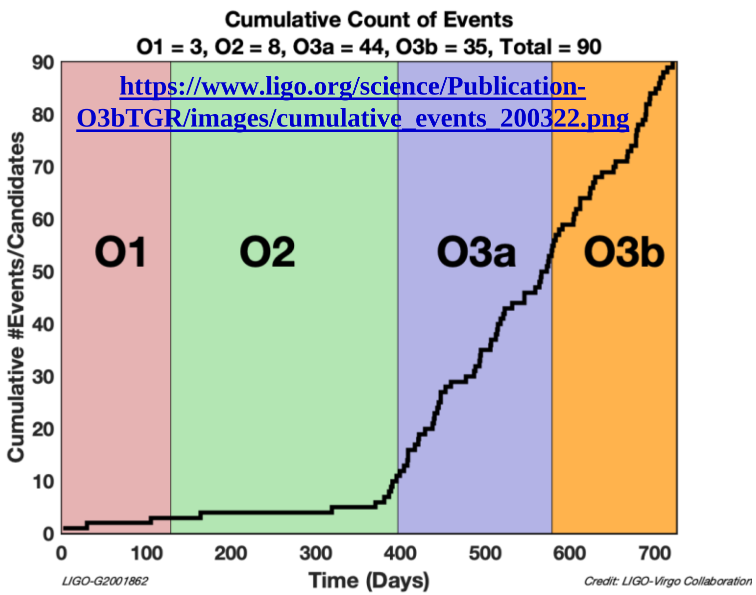
The Advanced Virgo detector during the O3 run (2019-2020)



Not to scale: the arm cavities are 3 km-long

LIGO detectors are conceptually the same

The Observing Run 3: O3



- All 3 detectors taking data for the whole run
  - O3a: 6 months – 2019/04/01 → 2019/10/01
  - 1-month commissioning break: 2019/10
  - O3b: 5 months – 2019/11/01 → 2020/03/27
    - Shortened by covid-19 pandemic

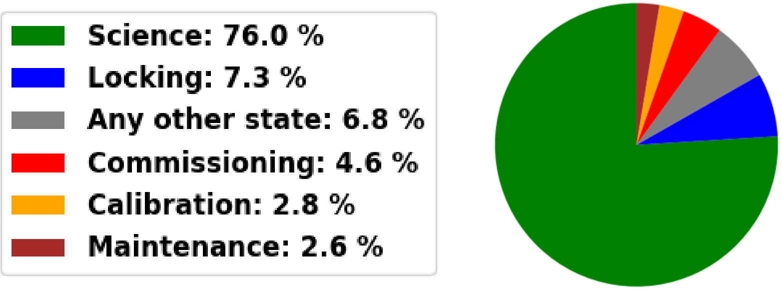
- O3: 79 new GW signals
  → GWTC-3 (3rd issue of our GW transient catalog): arXiv:2111.03606 [gr-qc]
  - All 3 types of compact binary mergers detected / no multi-messenger observation
  - Rates and populations studies, tests of General Relativity
  - Targeted searches: GRBs, FRBs, type-II supernovae, etc.
  - Searches for continuous signals

  } Companion and related articles

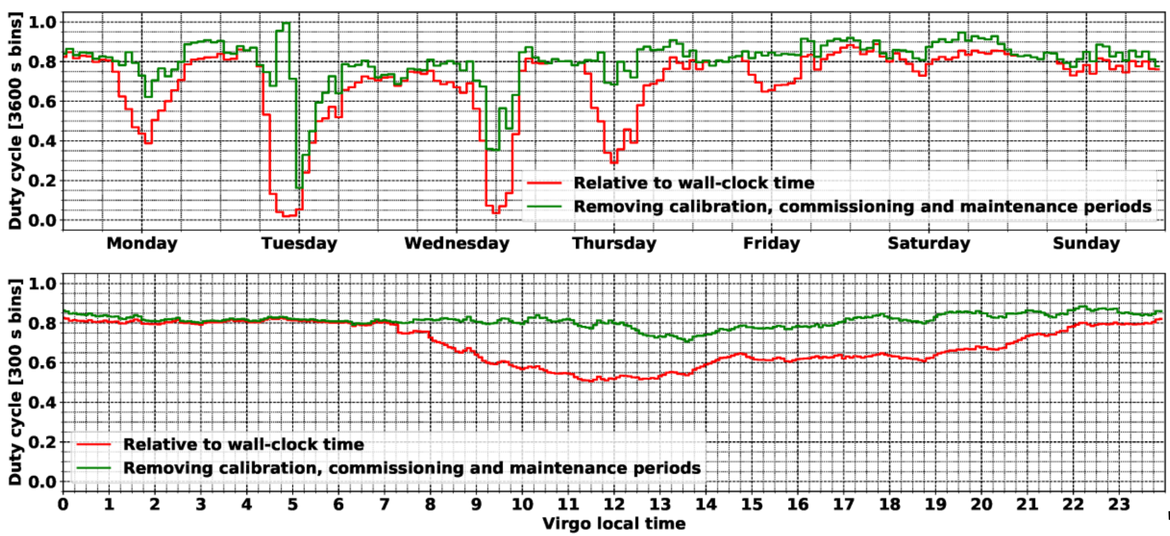
- Gravitational Wave Open Science Center: https://www.gw-openscience.org

Performance of the Virgo detector during O3

- Duty cycle
  - Fraction of the time Virgo is taking good-quality data, suitable for physics analysis
- O3 overall: 76.0%
  - Consistent with O2
    - ~80%, 4 weeks only in 2017/08



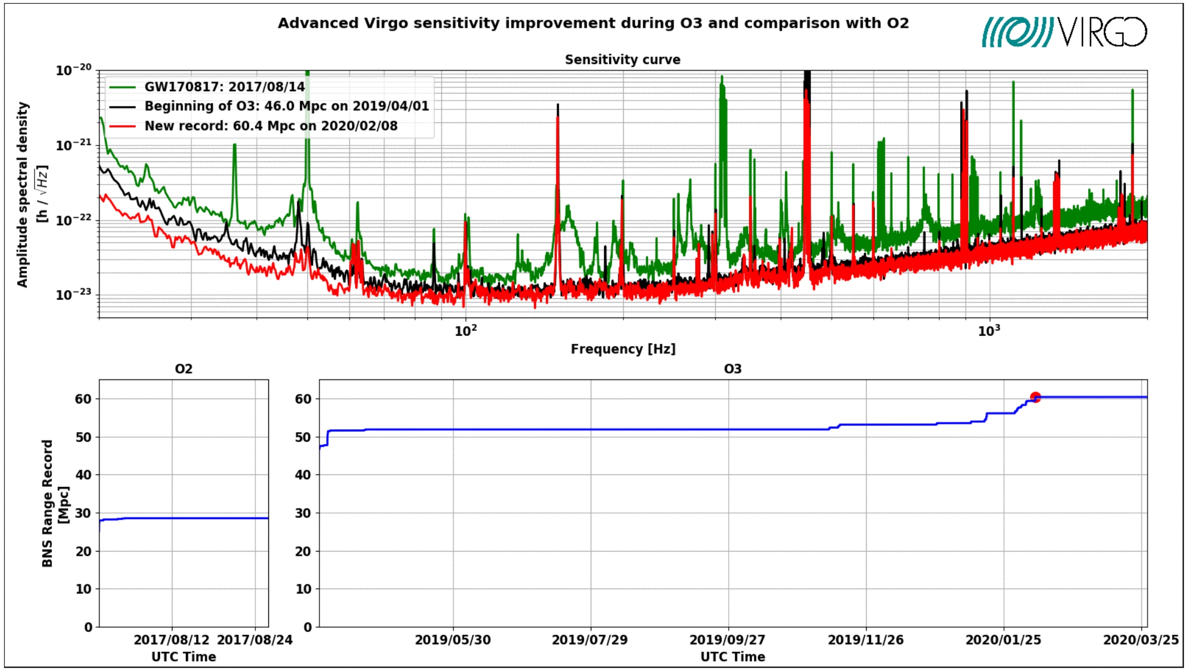
- Stable over time
  - O3a (Spring + Summer): 76.3%
  - O3b (Fall + Winter): 75.6%
- Remaining time divided almost equally among three categories
  - Working point control / Maintenance + Calibration + Commissioning / Problems
- Projecting the duty cycle onto a fictious week (top) or day (bottom) by averaging data from the whole O3 run shows that the duty cycle variations are mainly due to detector crew activities (red → green curves)



Performance of the Virgo detector during O3

- Sensitivity: noise amplitude spectrum density [Unit: 1/√Hz] vs. frequency
  - Complex curve full of features, summing up contributions from many noise sources

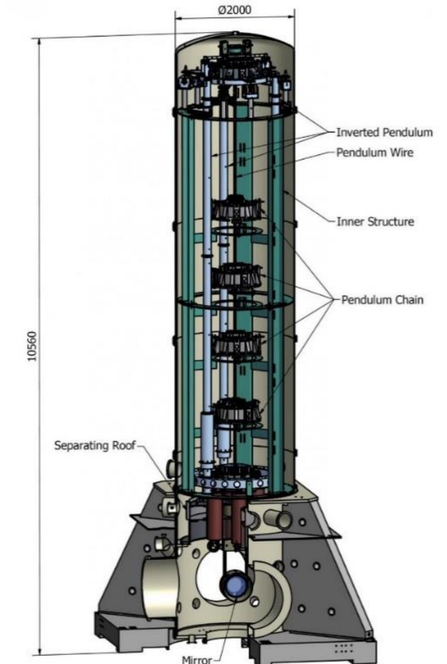
→ Useful (simplifying) figure-of-merit: the BNS range
- Average distance [in Mpc] up to which the merger of a « standard » binary neutron star system is detected
  - Average over the position in the sky and over the binary inclination
  - Detection ⇔ signal-to-noise ratio (SNR) threshold set to 8



https://www.virgo-gw.eu/images/animation_BNSRange_sensitivity_pause.gif

Fighting environmental noises

- All critical optical components are suspended
  - Mirrors, optical benches
  - → Isolation from seismic motion
    - Extremely performing above a few Hz
- Most of the hardware is under high-vacuum
  - Avoid interactions between laser beams and air molecules
  - Keep optics surfaces clean
  - Optimal acoustic shield
- All components designed, built or selected to be low-noise
  - Low-coupling goal often requires dedicated mitigation

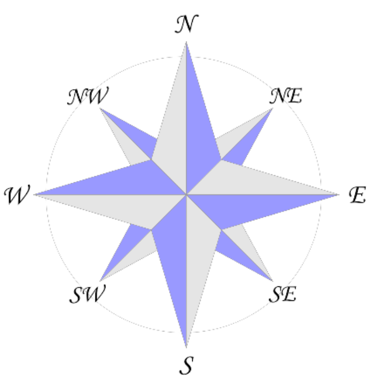


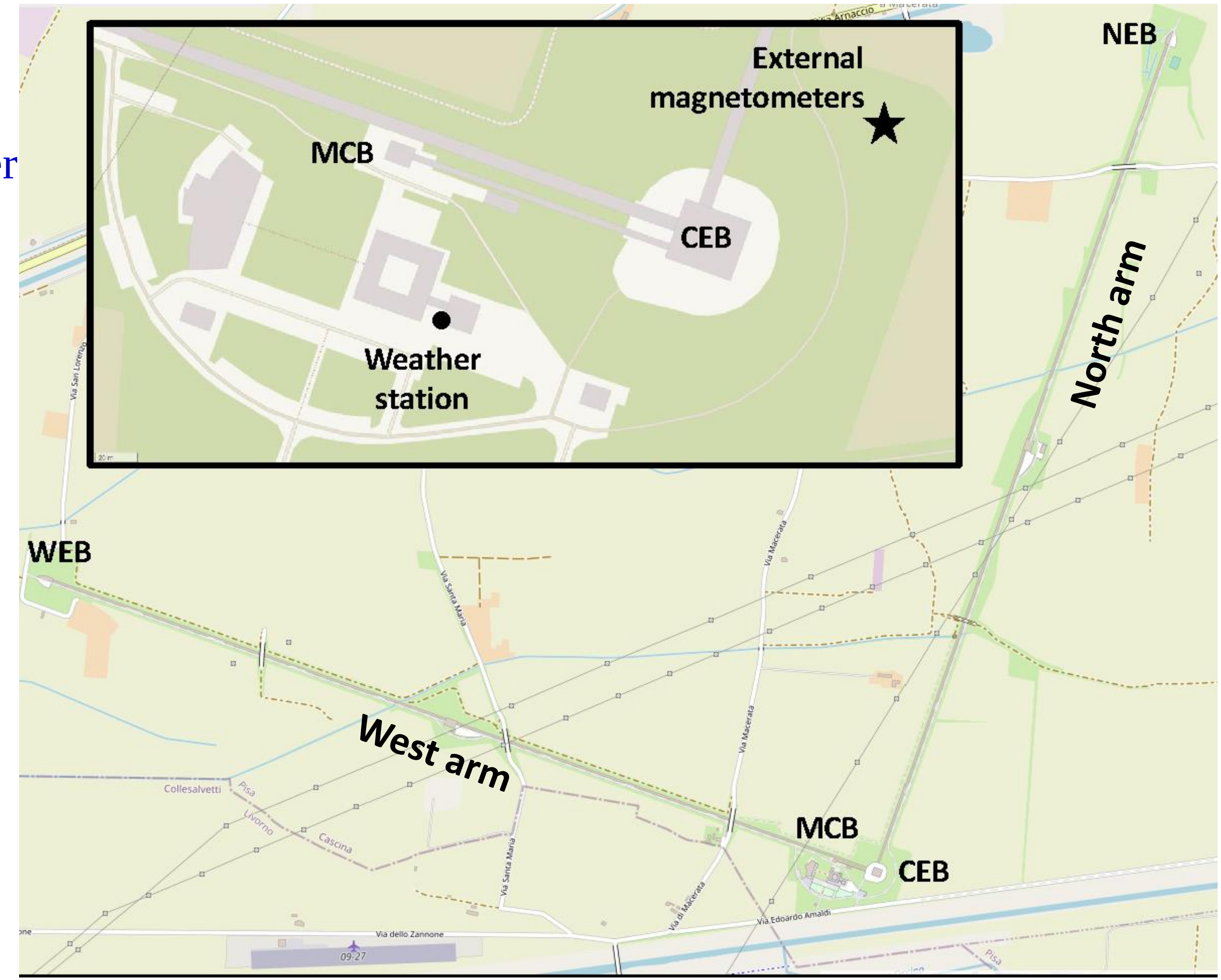
Virgo "Superattenuator"
https://doi.org/10.1063/1.1392338

Monitoring environmental noises

- The Virgo site
  - CEntral Building
  - Mode-Cleaner Building
  - North-End Building
  - West-End Building

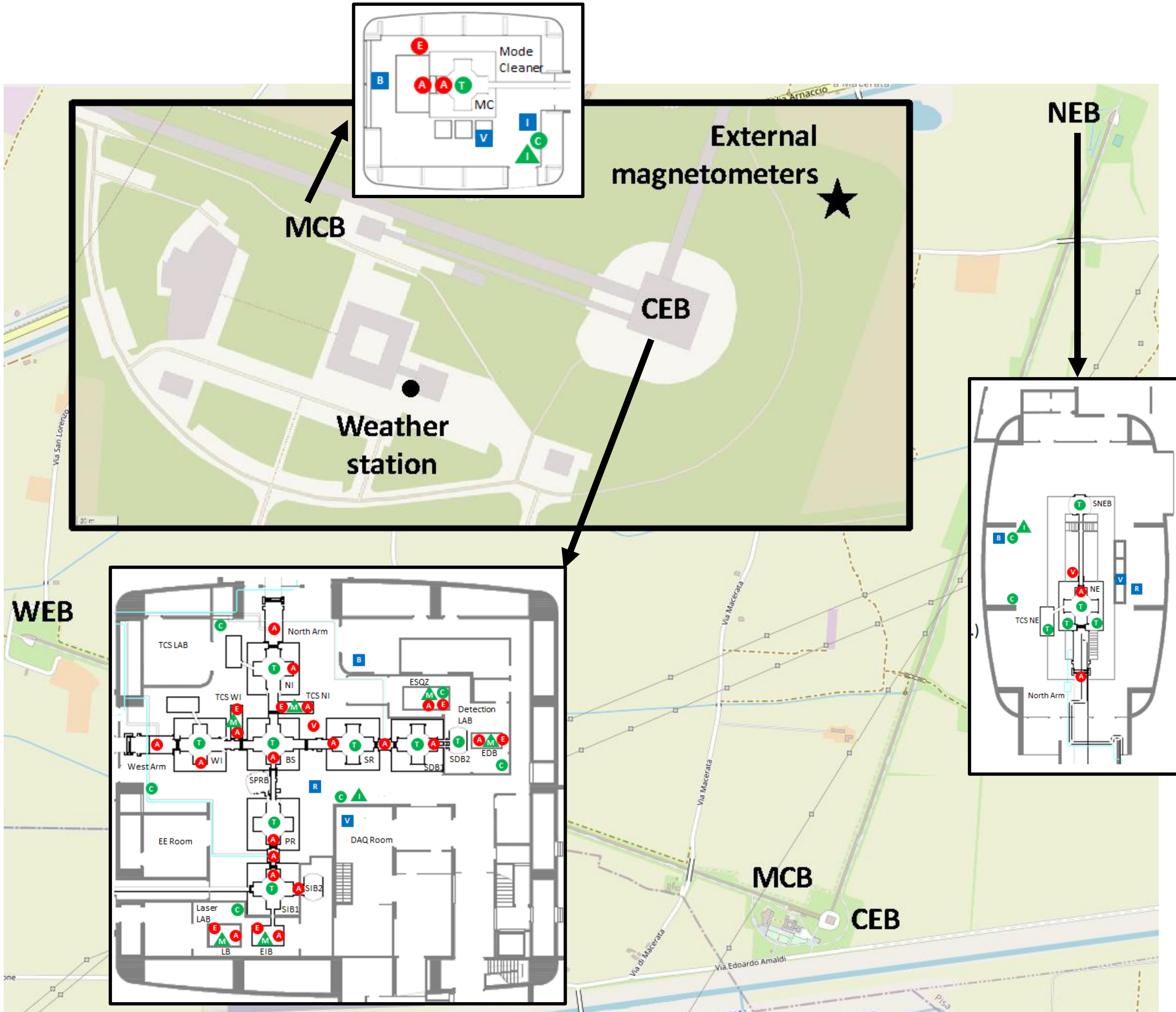
- 3-km arms





Monitoring environmental noises

- Hundreds of sensors of various types in total
  - Inside or outside buildings
- NEB and WEB are equivalent buildings

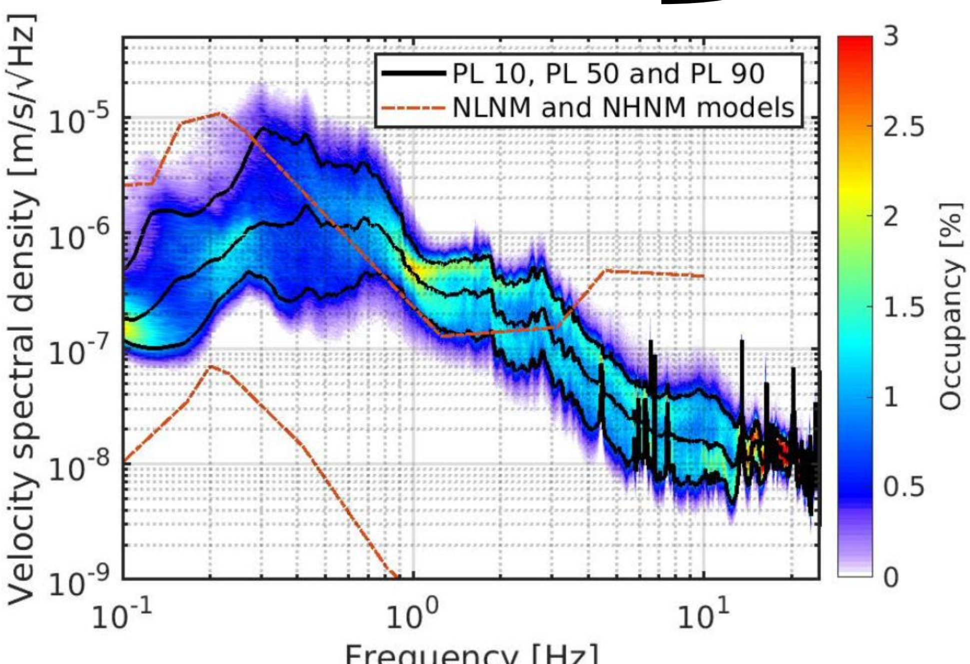


- PZT Accelerometer
- FB Accelerometer
- Velocimeter
- Thermometer
- Comb. (temp.+press.+hum.)
- Microphone
- Infrasound microphone
- Magnetometer
- Voltage probe
- Current probe
- Radio frequency antenna

Seismic noise: contributions

- Seismic noise
  - Microseism: 0.1 ÷ 1 Hz
    - Interaction between sea waves and ground
    - Dominant, peaks around 350 mHz
  - Anthropogenic: 1 ÷ 5-10 Hz
    - Heavy vehicles on elevated roads
  - Onsite: 10 ÷ 40 Hz
    - Traffic on nearby roads, agricultural activities

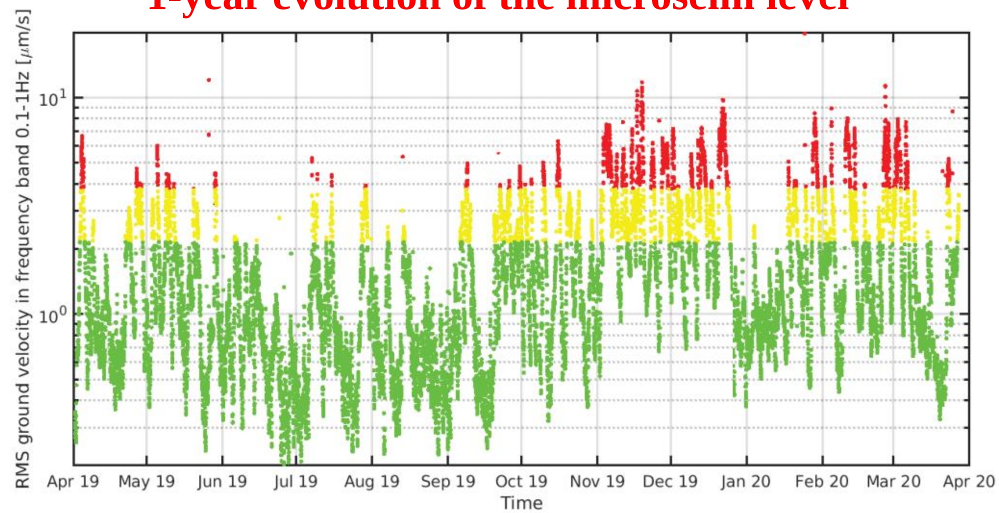
Frequency band-limited RMS (in short BLRMS) are used to disentangle the different contributions to the seismic noise



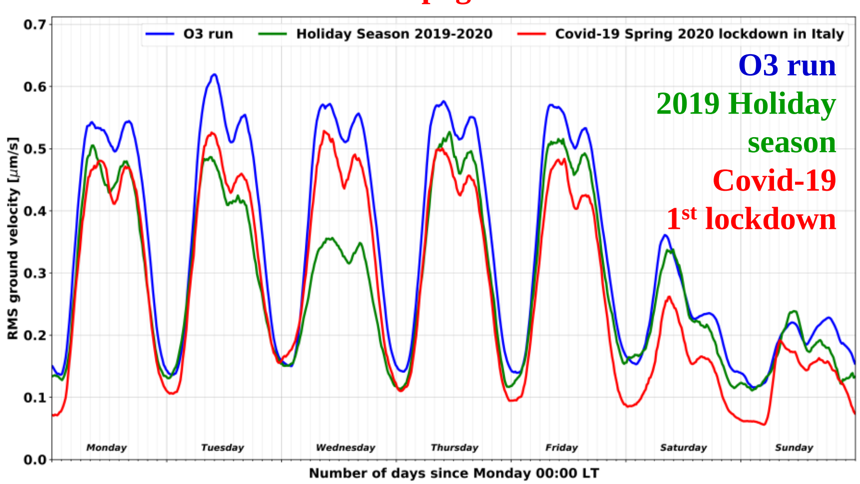
Seismic noise: variability

- Microseism: seasonal variations
  - Larger in Fall/Winter
  - Color code
    - Green: < 75th percentile
    - Yellow: 75th – 90th percentile
    - Red: > 90th percentile
- Anthropogenic + on-site
  - Impact of “global conditions”
    - Day/night + weekday variations
    - Holidays, pandemic…

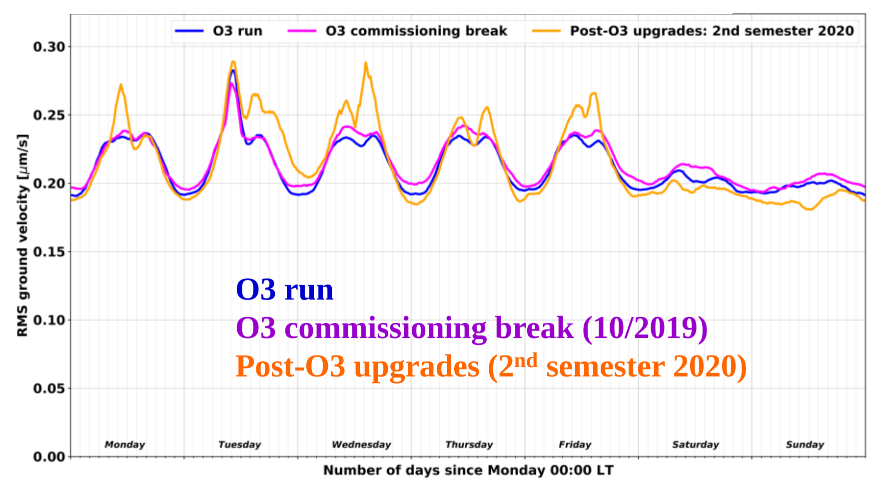
1-year evolution of the microseim level



Anthropogenic



On-site



Sensitivity modulation

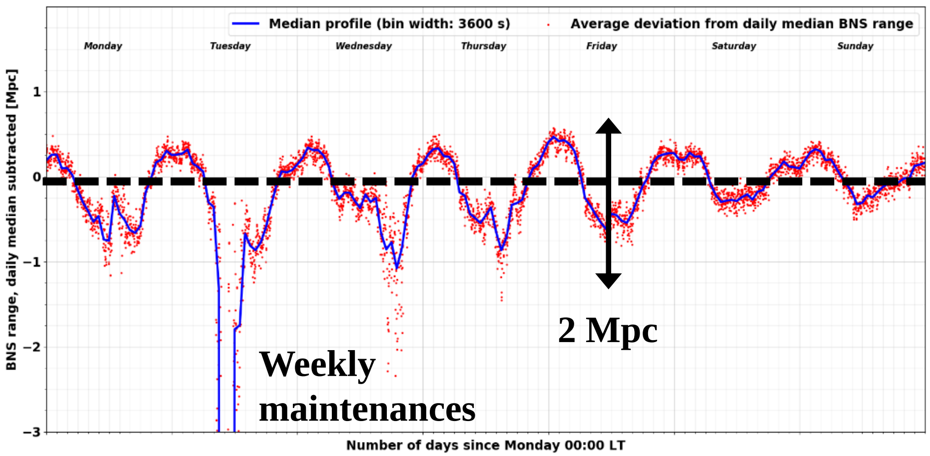
- Input: the BNS range
  - Subject to variations from multiple (and changing) sources during O3
    - Control accuracy, detector global status, transient minor problems, etc.

      → Not just the environment!

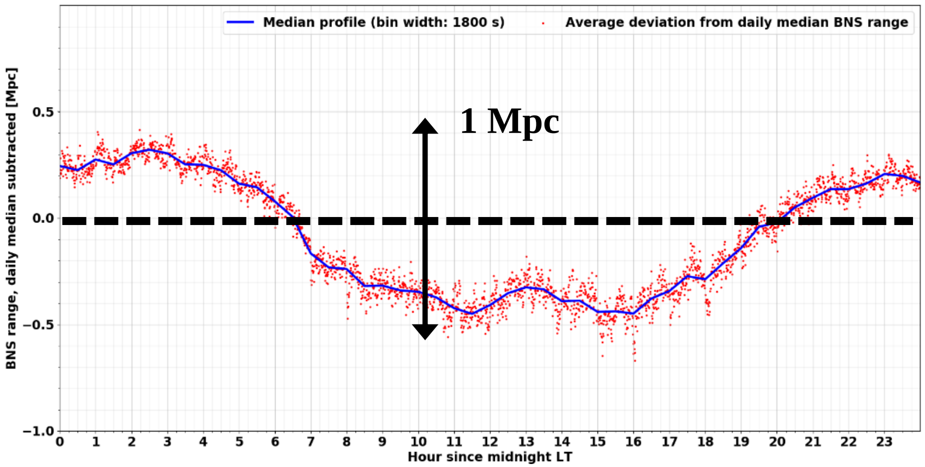
  → Thus, the “raw” BNS range value is not suitable for such study
    - Instead: use BNS range variations around its daily median level

- O3-averaged variations

Over a week baseline



Over a 24-hour baseline



→ Modulation similar to anthropogenic noise
  - Limited amplitude: a few percents at most – Virgo O3 BNS range: 45-60 Mpc

Impact of microseism

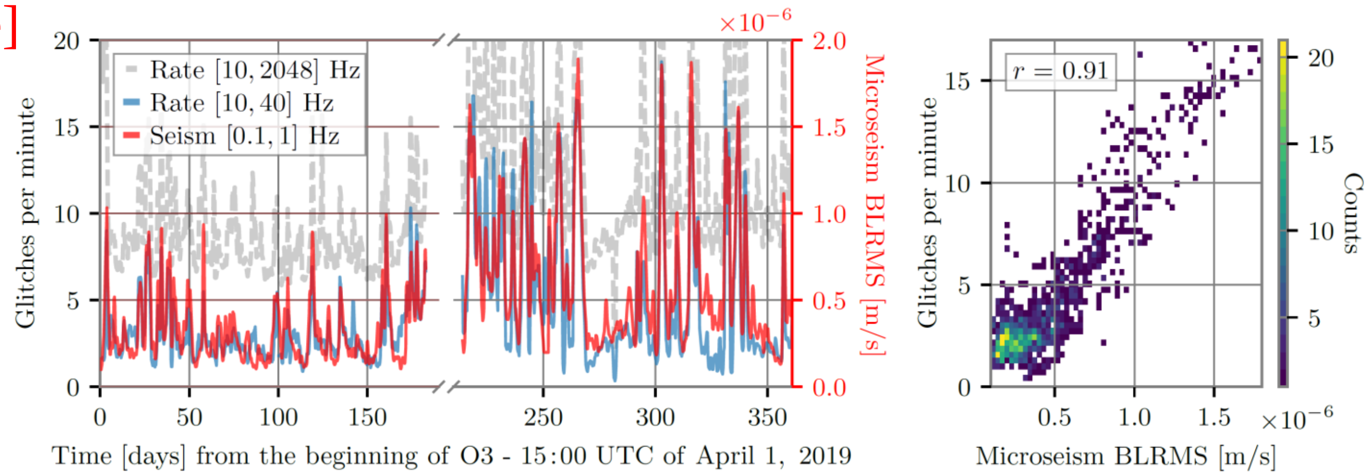
- Elevated microseismicity period
  - Sea activity, bad weather

→ Twofold impact on the GW strain channel h(t)
  - Higher noise levels in distinctive frequency bands
  - Larger rate of transient noise bursts – the "glitches"
    - Characterized by a bandwidth, a duration and an SNR

→ Manifold impact on the detector
  - Degraded sensitivity: lower BNS range
  - Suboptimal sensitivity to transient GW events
    - Bursts create fake triggers and could cover real signals
  - Lower duty cycle, optimization/tuning of the working point more difficult

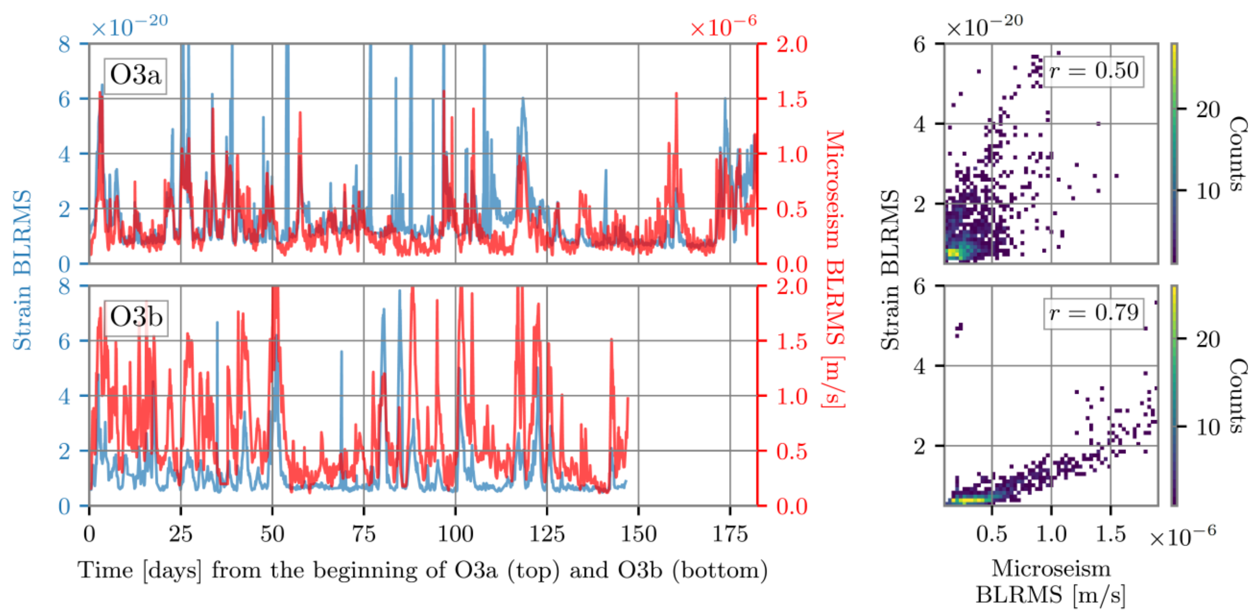
Impact of microseism

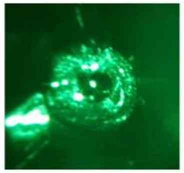
- Glitch rate [/ minute]
  - Grey: rate in the 10 ÷ 2048 Hz band
  - Blue: rate in the 10 ÷ 40 Hz band
  - Red: microseism BLRMS



- Impact on noise level
  - Blue: GW strain BLRMS between 10 and 20 Hz
  - Red: microseism BLRMS

→ Overall, noise improved during O3; residual mainly due to microseism in O3b





Scattered light noise

- Parasitic beam created by imperfections (optics defect, misalignment, etc.), scattering off some moving surface and recombining to an interferometer beam
  - Glitches, control inaccuracies

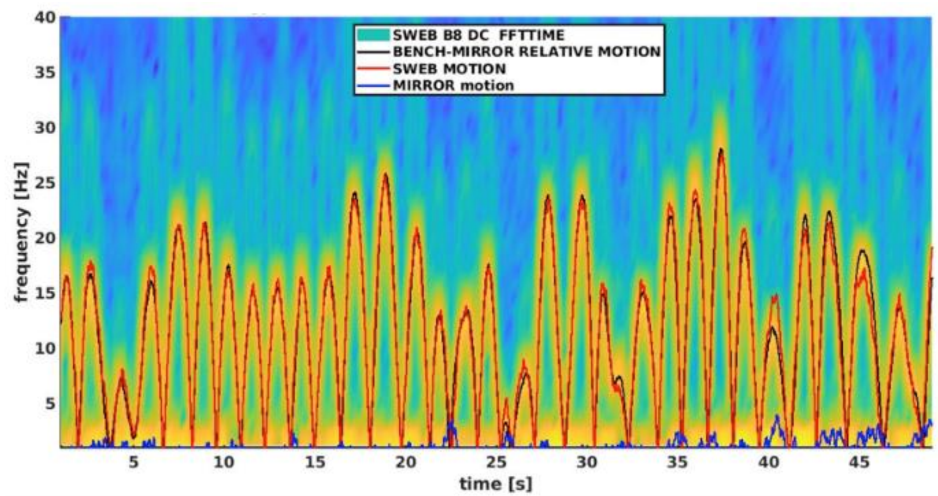
- Enhanced by high microseismicity conditions
  - One of the main technical noise sources for all GW detectors

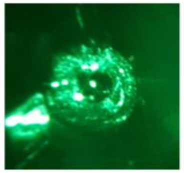
    → Mitigations: isolate more (suspend further) / control better pieces of hardware / dump parasitic beams onto absorbing surfaces

- Predictor formula
  - Noise frequency $\propto$ (scatterer velocity)

  → Typical arches in spectrograms

$$f_{fringe}(t) = \left| 2 \frac{v_{sc}(t)}{\lambda} \right|$$





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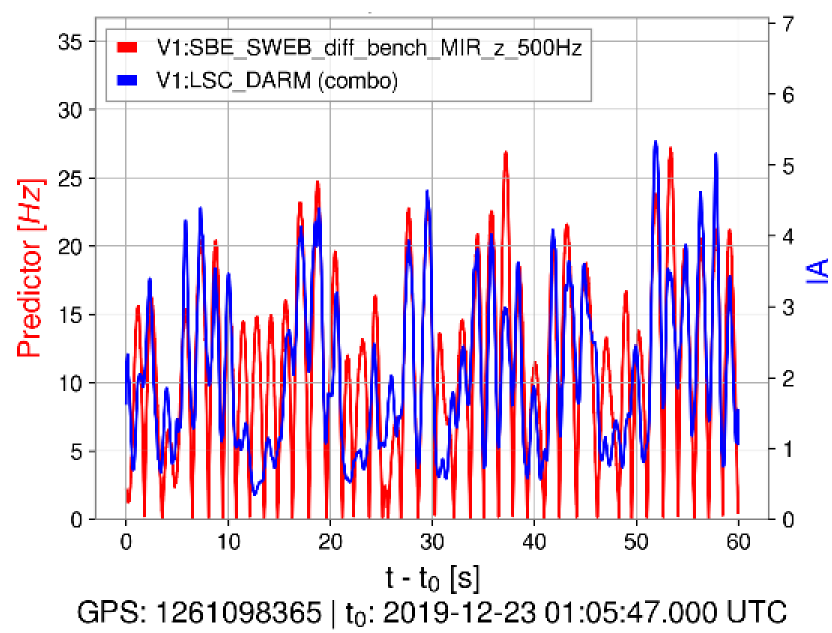


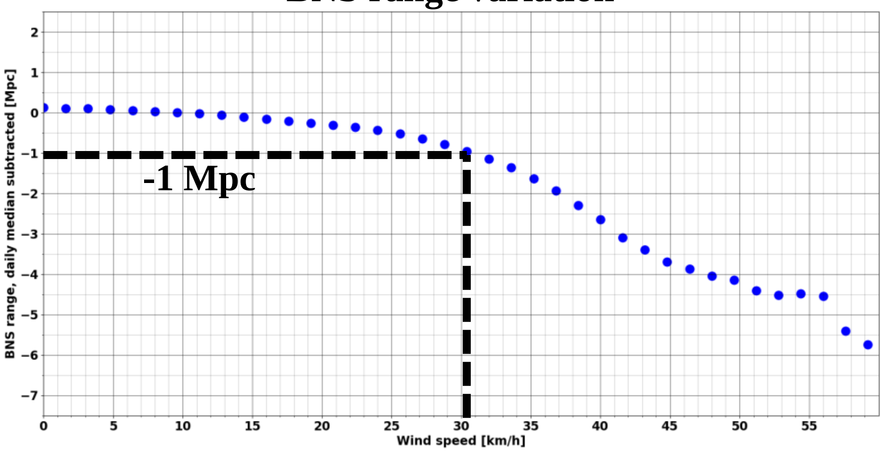
→ Correlate many predictors with arches information extracted from data impacted by scattered light to locate the culprit scattering surface
  - Plan is to run such brute-force tools on a daily basis in the future

Impact of bad weather

- Bad weather ⇔ high microseism activity (rough sea) and wind
  → Disentangling the two contributions

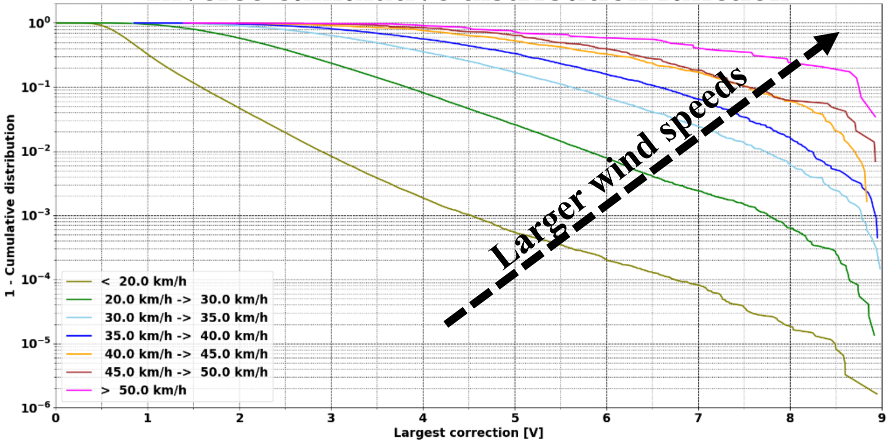
- Some wind impact on the BNS range above ~25 km/h
- Larger corrections to keep the detector control as the wind speed increases

BNS range variation



Wind speed: 30 km/h

Inverse cumulative distribution function



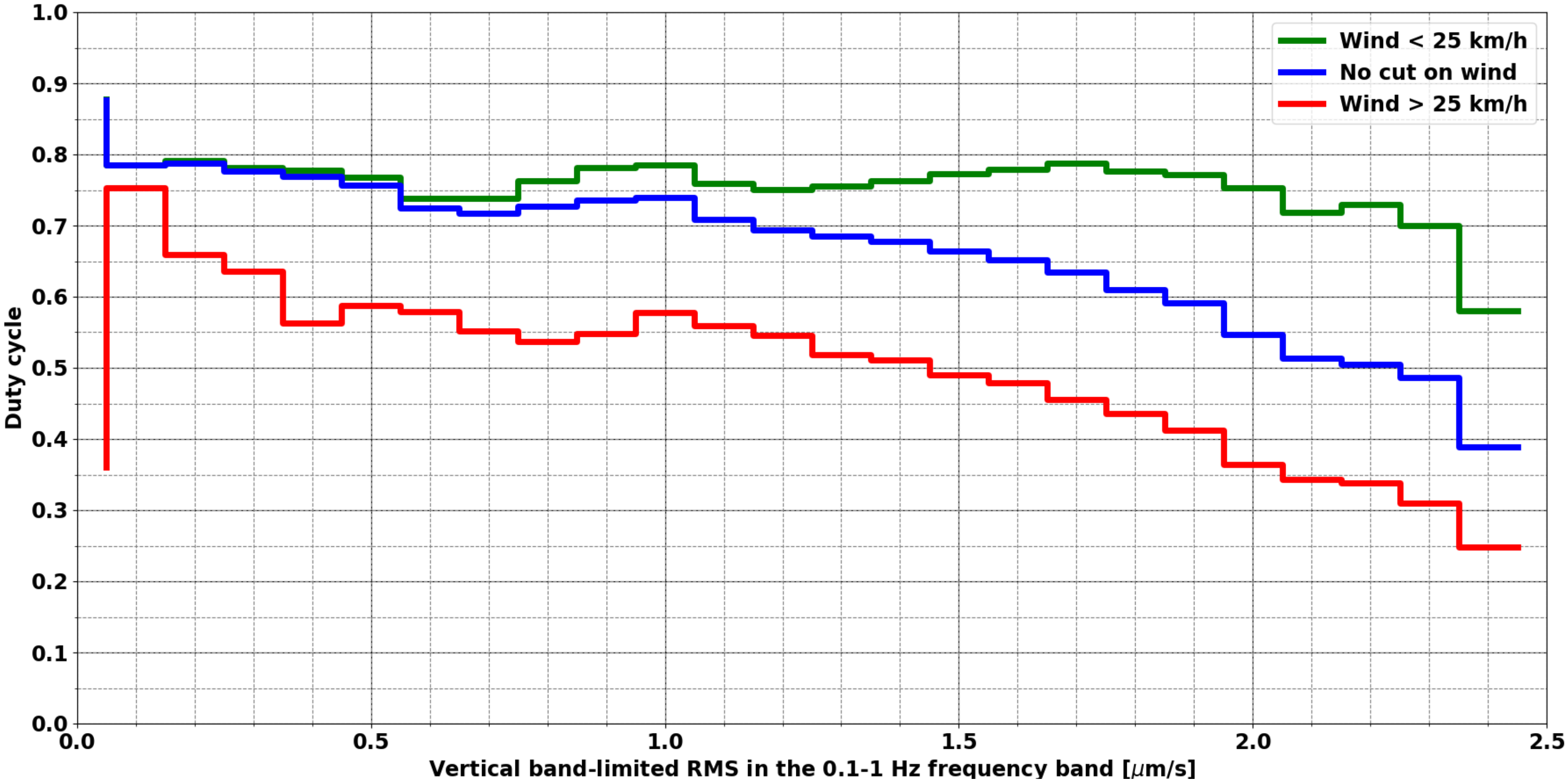
Largest correction to keep the Virgo global control

→ Up to 10% variation: significant but limited
- Detector robustness

→ Limited actuation range
- Saturation: immediate loss of the control of the working point

Impact of bad weather

- Duty cycle
  - x-axis: microseism BLRMS
  - 3 datasets
    - Blue: no cut on wind
    - Green: low wind
    - Red: high wind



→ Detector robust against microseism but more sensitive to wind

Impact of earthquakes

- Strong transient seismic waves generated somewhere on Earth and travelling to Virgo
  - On top of the regular seismic noise discussed previously
  - → If large enough, can lead to a saturation of the global feedback system
    - Loss of the working point control / Decrease of the duty cycle
- Not much to do from the moment when the seismic waves hit Virgo
  - But: the more distant the epicenter, the longer the time for the waves to reach EGO
    - Propagation speed: O(few km/s)
    - → Can we use that time to get ready for the arrival of the seismic waves?
- Yes! Two main ingredients required
  - ① An early-warning system, broadcasting timely alerts for significant earthquakes
  - ② A strategy to mitigate the impact of the seismic waves at EGO

① Seismon software framework – https://doi.org/10.1088/1361-6382/aa5a60

- Developed by LIGO, running at EGO since 2017, interfaced with DAQ & controls
- Receive earthquake alerts from the US Geological Survey
- Estimate seismic wave arrival times onsite and their strength

② Alternative, more resilient, control system of the Virgo detector

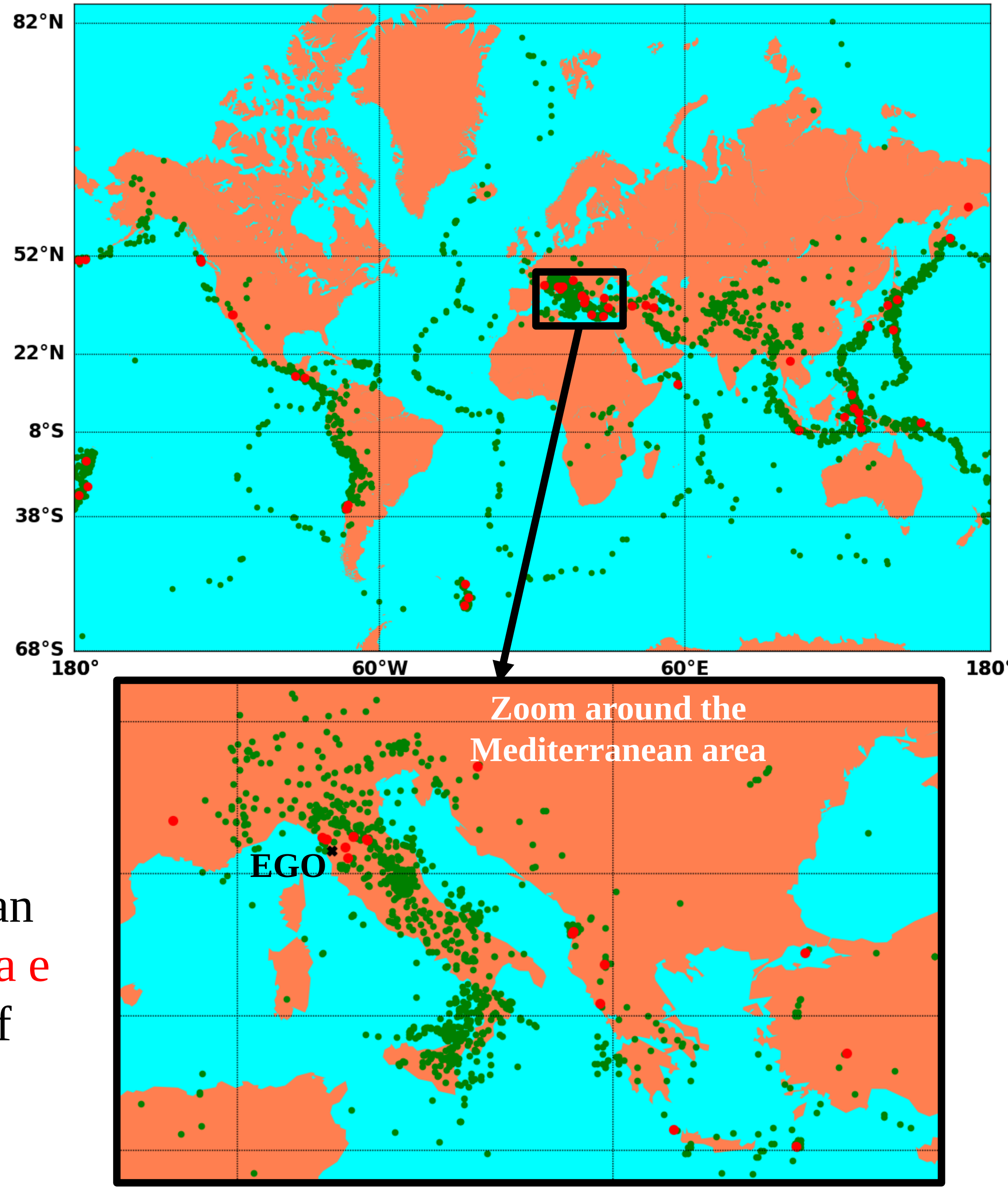
- Actuation range doubled
- Slightly more noisy, but validated for data taking

Earthquakes location

- Statistics from the whole O3
- Excluding earthquakes clearly too weak
  - Empirical cut based on magnitude and distance
- Red dots: control lost
- Green dots: control kept

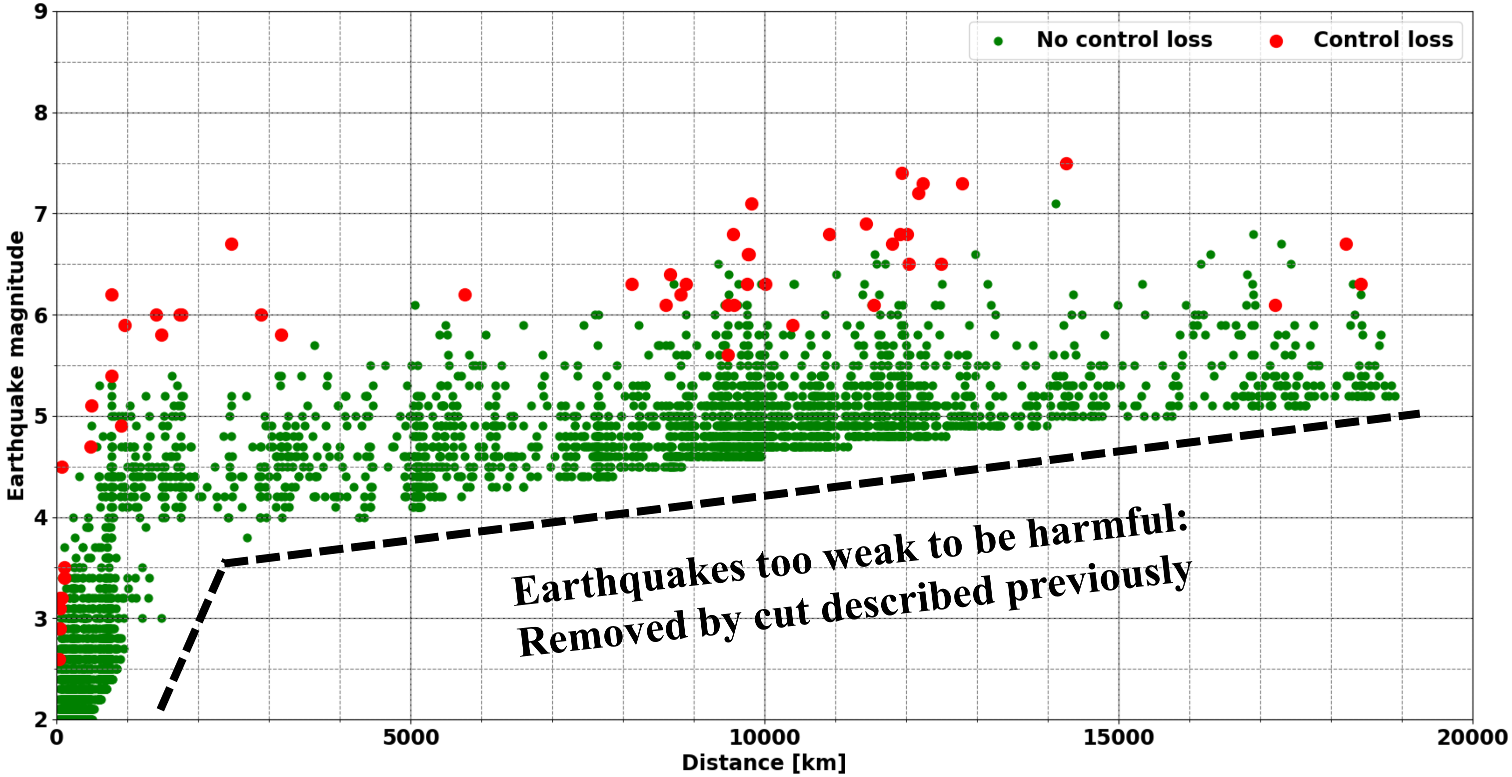
→ Two main categories of earthquake causing control losses
  - Distant and strong
  - Weak but close

→ Joint work ongoing with Italian Istituto Nazionale di Geofisica e Vulcanologia (INGV) to see if their alert system(s) could complement the USGS one



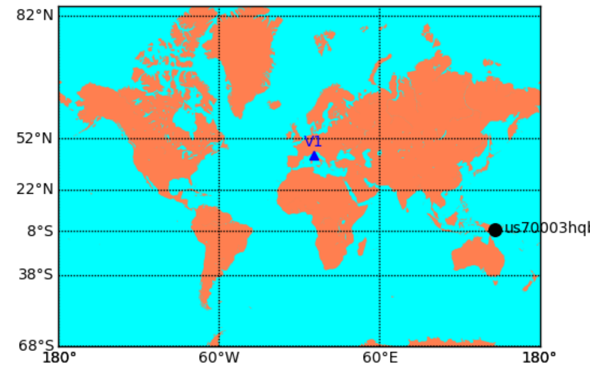
Earthquakes strength

- Classification based on earthquake magnitude and epicenter distance to EGO
  - Green dots: earthquakes that did not led to a control loss
  - Red dots: earthquakes that led to a control loss

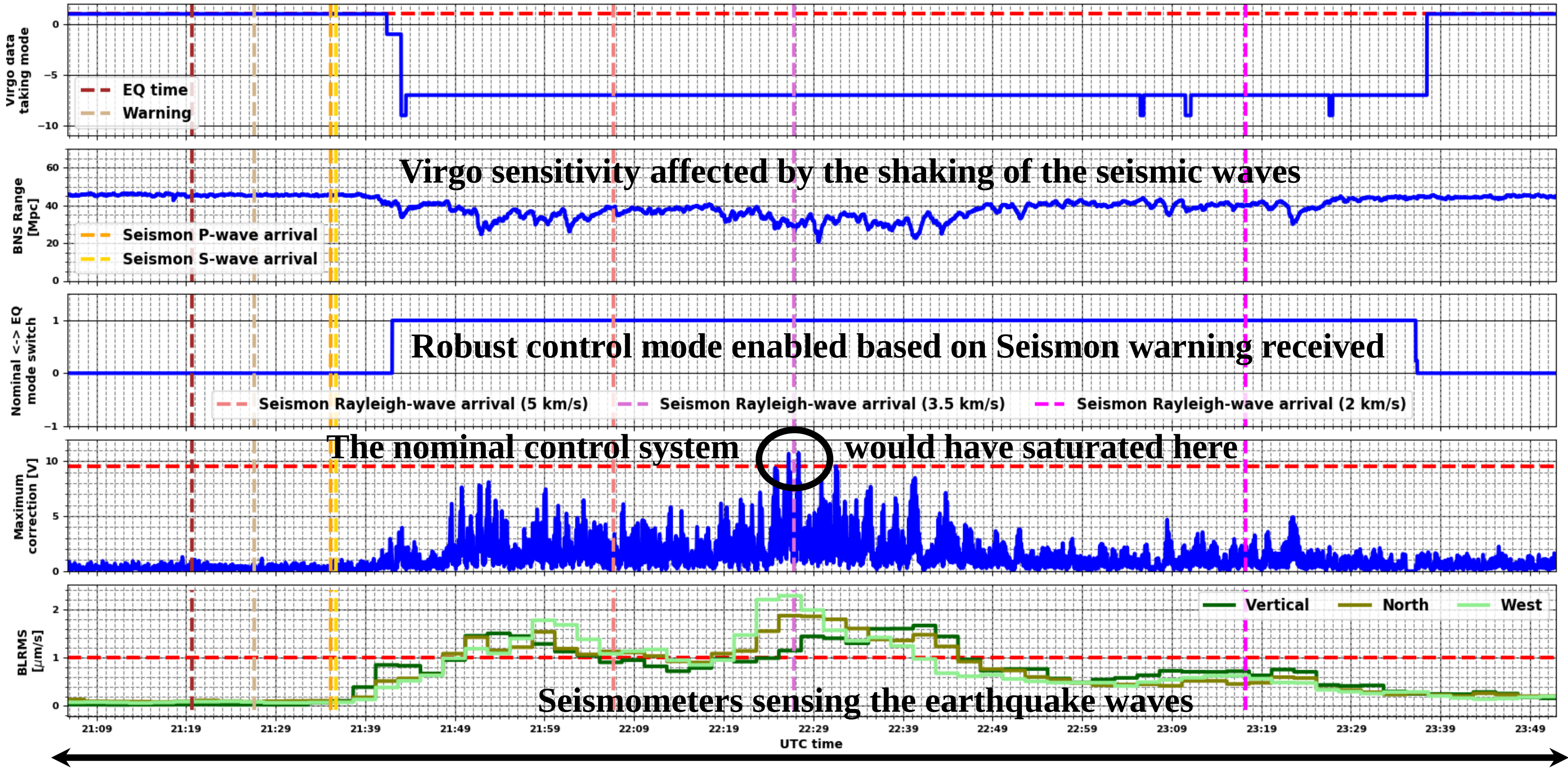


→ Magnitude and distance are key parameters
  - Others may play a role as well (epicenter depth, azimuth)
  - So probably does the actual state of the detector when seismic waves arrive

Surviving a strong earthquake



- Magnitude 7.2, epicenter 14,000 km away from EGO
  - Without a switch to the more robust control, the working point would have been lost

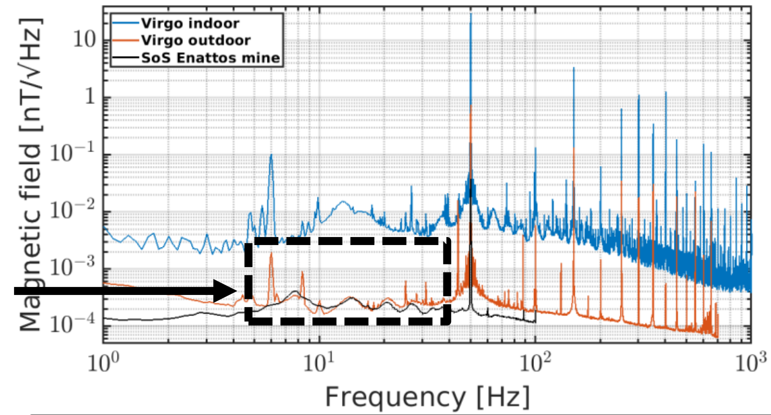


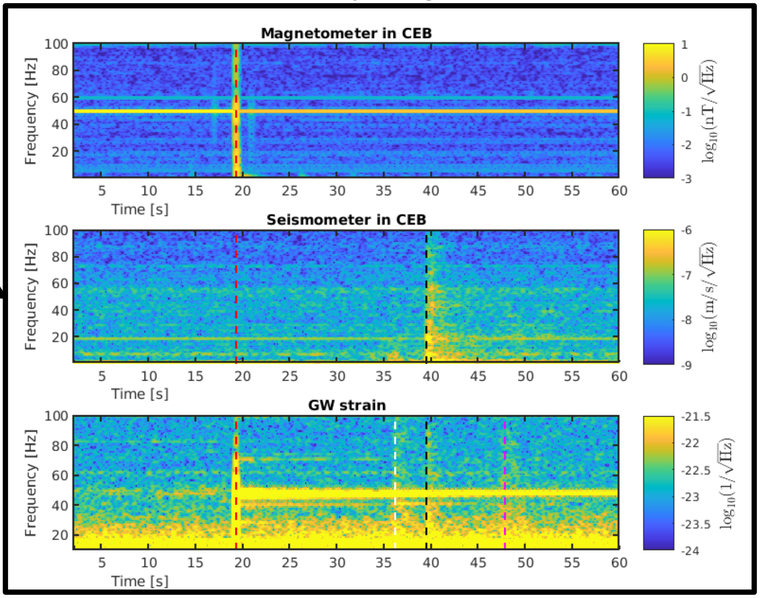
3 hours on May 6, 2019

Magnetic noises

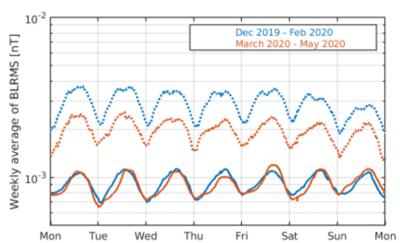
- Ambient magnetic fields can couple through coil-magnet control actuators
- Electromagnetic (EM) waves
  propagate at the speed of light and,
  could impact multiple detectors
  with time delays compatible with GW
  - Schuman resonances (8, 14, 21, 27, 33 Hz, …)
    - Steady EM waves resonating inside the waveguide Earth surface ↔ ionosphere
  - Large-current lightning strikes
    - Generate glitches

  → Could limit sensitivity to GW signals correlated over the network of detectors
    - Monitoring by external magnetometers
      → See map on slides #8-9





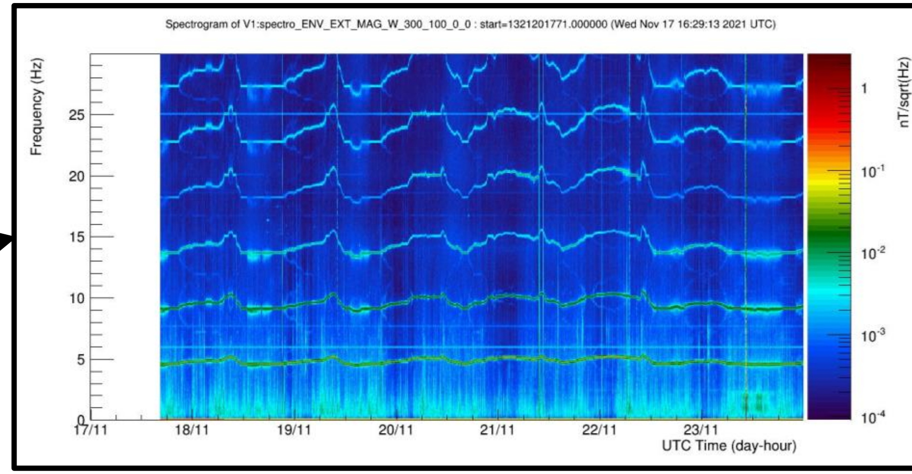
- Anthropogenic magnetic noise shows a daily modulation
  - Transit of trains about 6 km away from the site



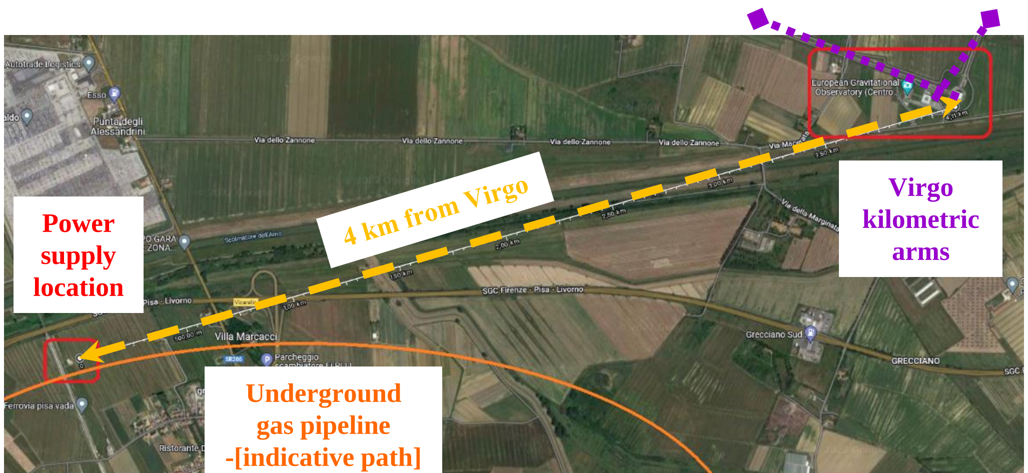
The “magnetic monster”…

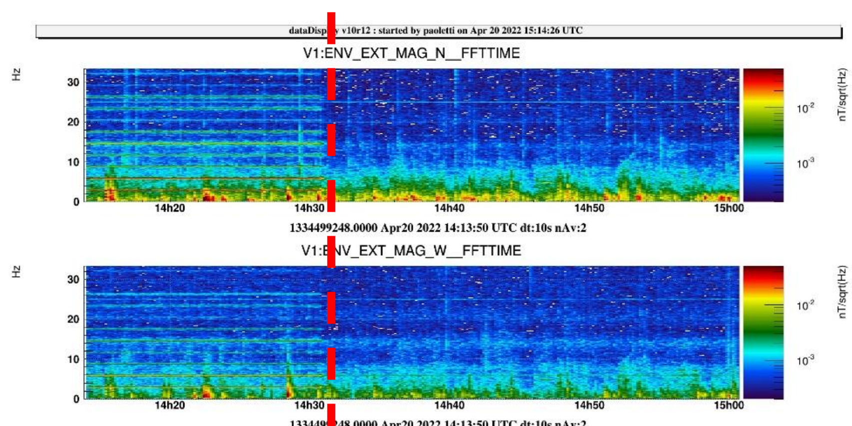
- … Or how Virgo can be impacted by the environment – in the broadest sense
- November 2021: Virgo external magnetometers back in operation
  - Destroyed by a lightning strike

→ Something has changed!



- Intense noise hunting: O(100) magnetic measurements on- and off-site – main hunters: Lorenzo Pierini & Jean-Loup Raymond
- 2022/04/15: culprit unmasked: a power supply used to prevent Galvanic corrosion
  - Location
  - Switch to constant current mode





Outlook

- O3: first long run for Advanced Virgo
  - Improved sensitivity: with respect to O2 and improving during O3
  - Online since day 1 and for the whole duration of the run: high duty cycle
  - → Invaluable dataset to study in details the behavior of the detector

- Virgo appears to be robust overall against the external environment
  - Hard to identify large potential improvements
    - Complex global detector working point
  - → Need to keep monitoring all possible types of noise
    - So as not to miss any new source or any new vulnerability of the detector

- Experience gained for the preparation of O4
  - Better definition of priorities and of the key studies to focus on
  - Ideas for improved monitoring: more automated, lower latency, wider range

- Next target: the O4 run
  - Ambitious upgrade program for all detectors – LIGO, Virgo and KAGRA
    - Strongly impacted by the worldwide covid-19 pandemic
  - Current start date: March 2023 – updates: https://observing.docs.ligo.org/plan
  - → If everything goes well: 4 detectors operating jointly in the near future