Seismic noises and earthquakes impact on the Virgo gravitational-wave detector during the O3 run (04/2019 – 03/2020)

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On behalf of the Virgo Collaboration

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EGO EUROPEAN GRAVITATIONAL OBSERVATORY — cnrs — IJCLab Irène Joliot-Curie — UNIVERSITE PARIS SUD / université PARIS-SACLAY

Outline

- The O3 run in a nutshell
  - Virgo performance

- Seismic noise
  - Monitoring and disentangling its different contributions
  - Impact on the Virgo detector during the O3 run

- Earthquakes
  - Early warning system and control room mitigation
  - Virgo robustness against earthquakes
  - Control losses: from strong and distant earthquakes but also very close ones

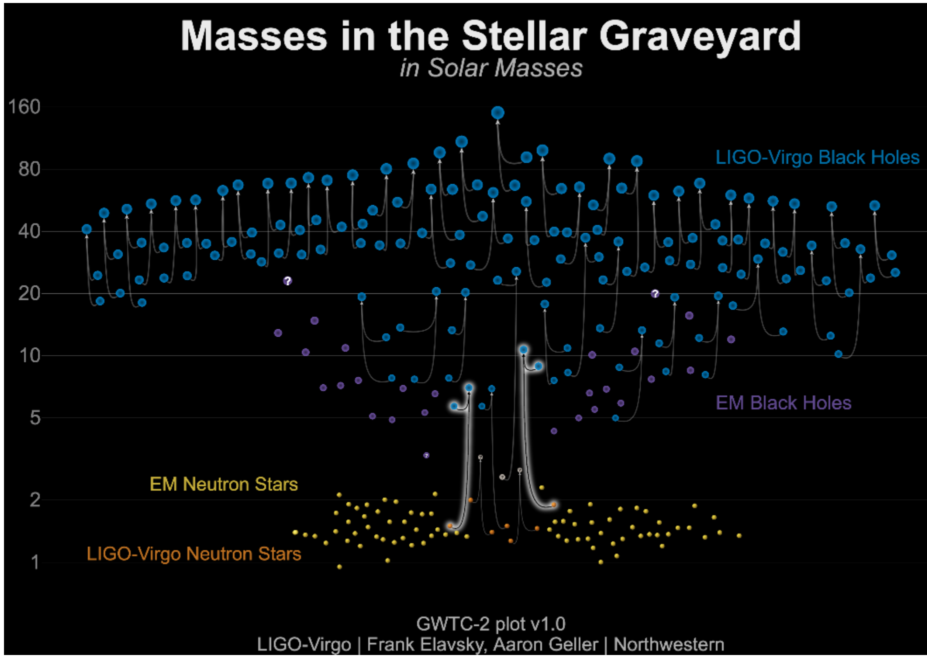
- Prospects for the O4 run (2022-2023)

The O3 run

- Global network of ground-based gravitational-wave (GW) advanced detectors
  - LIGO Hanford
  - LIGO Livingston
  - Virgo

→ All three detectors taking data together from day 1 of the run

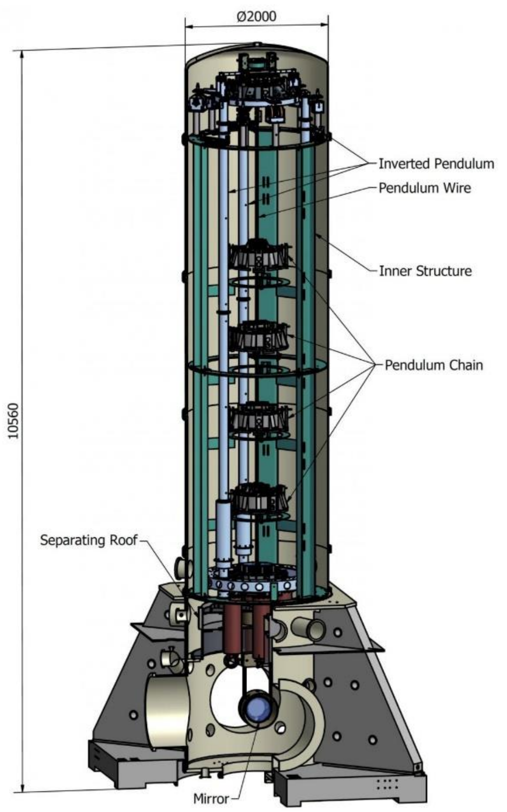
- O3: 2 data-taking periods
  - O3a: 2019/04/01 → 2019/10/01
  - O3b: 2019/11/01 → 2020/03/27
    - Premature ending due to covid-19
  - 1-month commissioning break (10/2019)

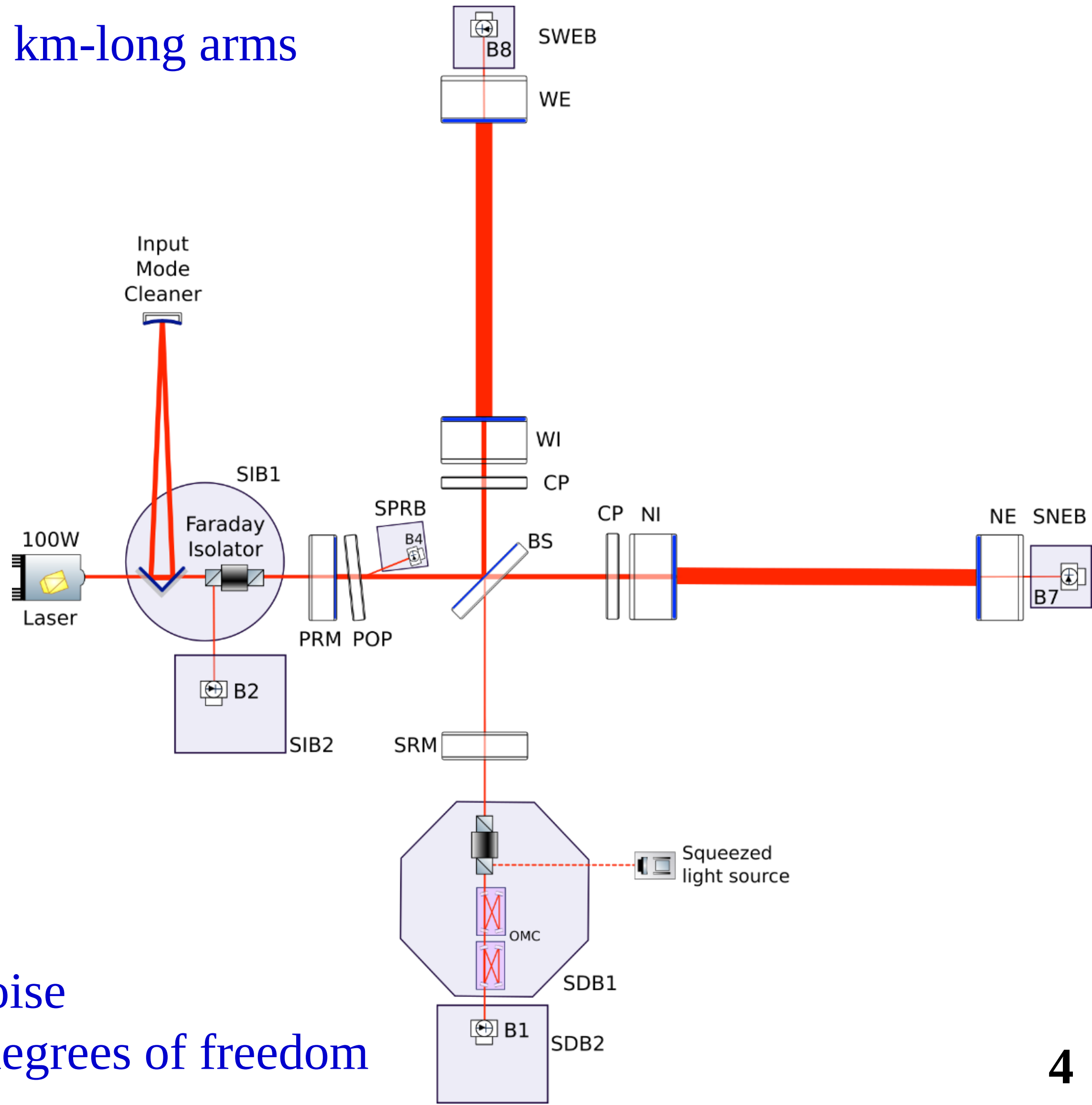


- Scientific harvest
  - 56 public alerts
  - Exceptional events
    - Neutron star – black hole mergers
  - Updates to the GW Transient Catalog
    - Published for O3a – public data
    - In progress for O3b

The O3 run for the Virgo detector

- Power-recycled, suspended Michelson interferometer with Fabry-Perot cavities in its 3 km-long arms

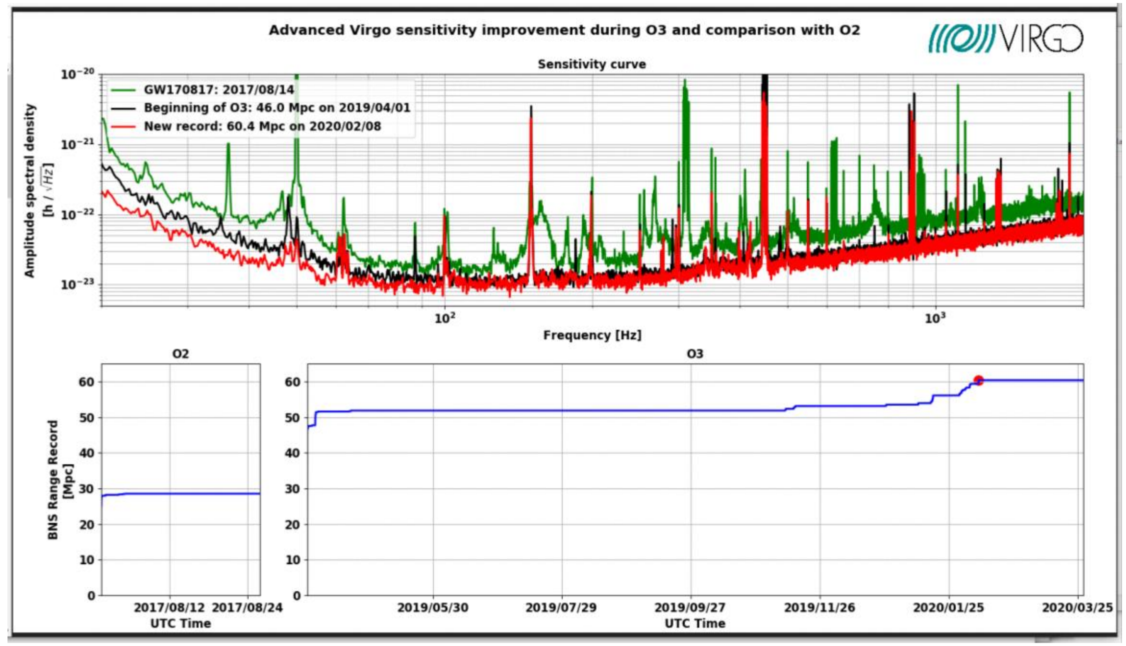




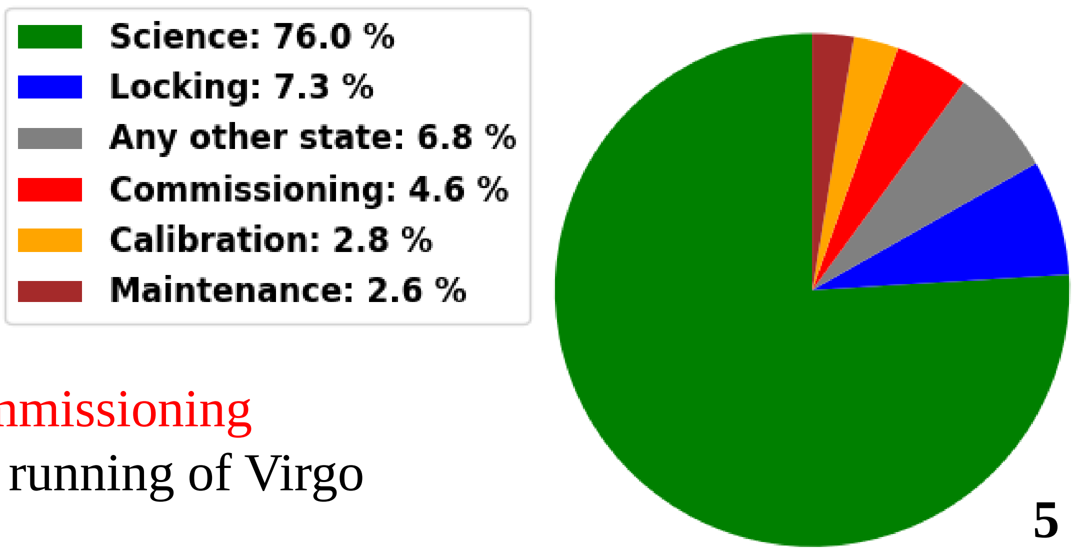
- 7 m-tall "superattenuators" to
  - Isolate mirrors from seismic noise
  - Control their position in all 6 degrees of freedom

The O3 run for the Virgo detector

- Sensitivity about doubled w.r.t. the O2 run (August 2017)
  - Binary neutron star range (BNS range)
    - Steady: 45-55 Mpc
    - Record: 60 Mpc

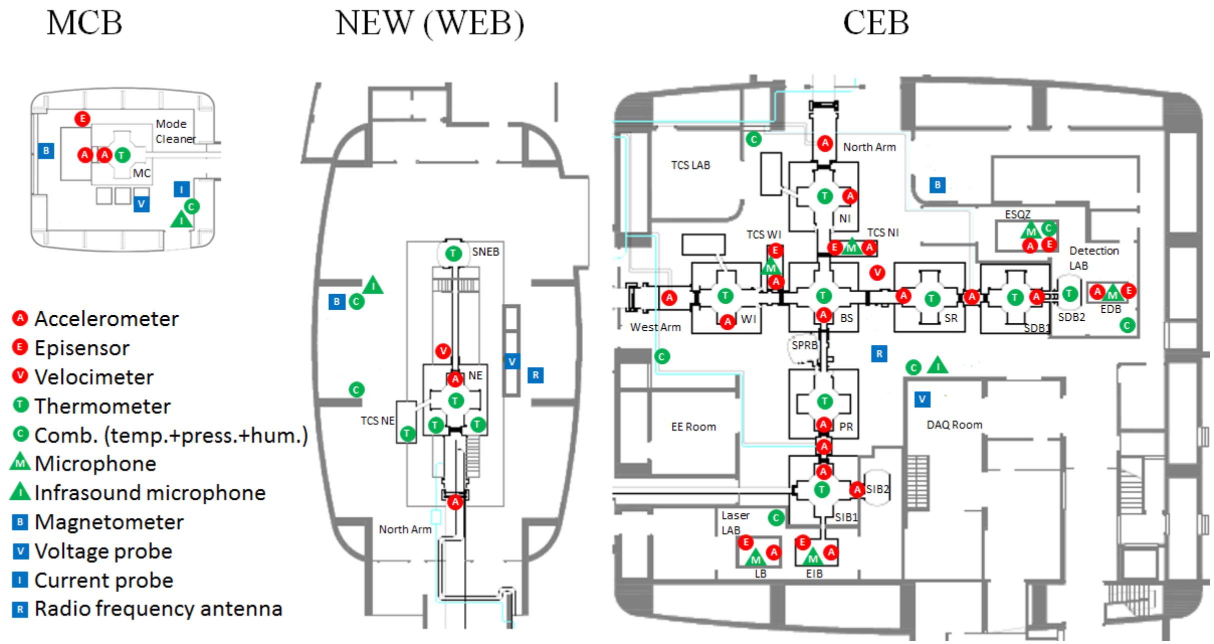


- Duty cycle (O3a + O3b)
  - Science data taking: 76%
    - Consistent with O2 (80%)
  - Remaining time divided almost equally among 3 categories
    - Working point (re)acquisition
    - Maintenance + calibration + commissioning
    - Problems preventing the normal running of Virgo

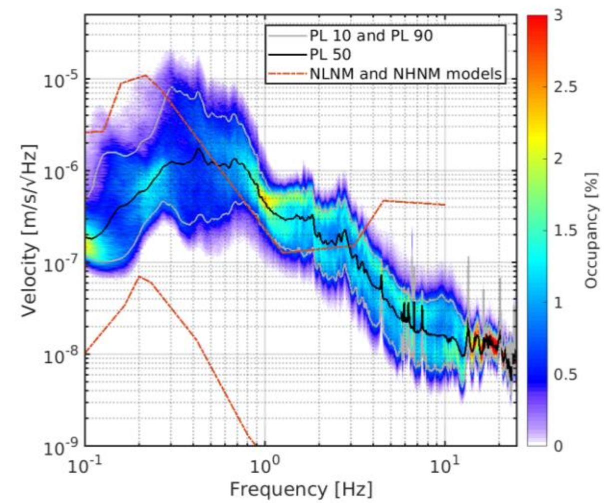


Environmental monitoring and seismic noise

- Virgo environmental sensor array
  - MCB: Mode-Cleaner Building
  - N(W)EB: North (West) End Building
  - CEB: CEntral Building



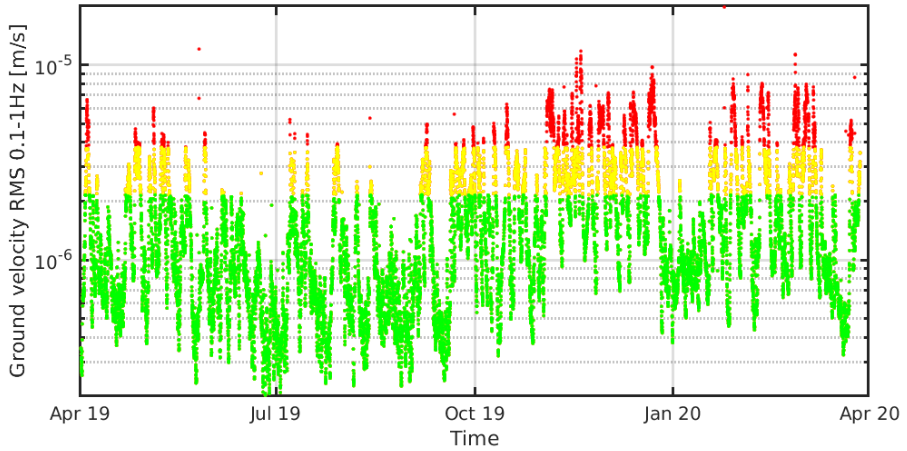
- Seismic noise
  - Microseism: 0.1 ÷ 1 Hz
    - Dominant
    - Interaction between sea waves and ground
    - Peak around 350 mHz
  - Anthropogenic: 1 ÷ 5-10 Hz
    - Heavy vehicles on elevated roads
  - Onsite: 10 ÷ 40 Hz
    - Traffic on nearby roads, agricultural activities



→ Frequency band-limited RMS (BLRMS) to isolate the different contributions

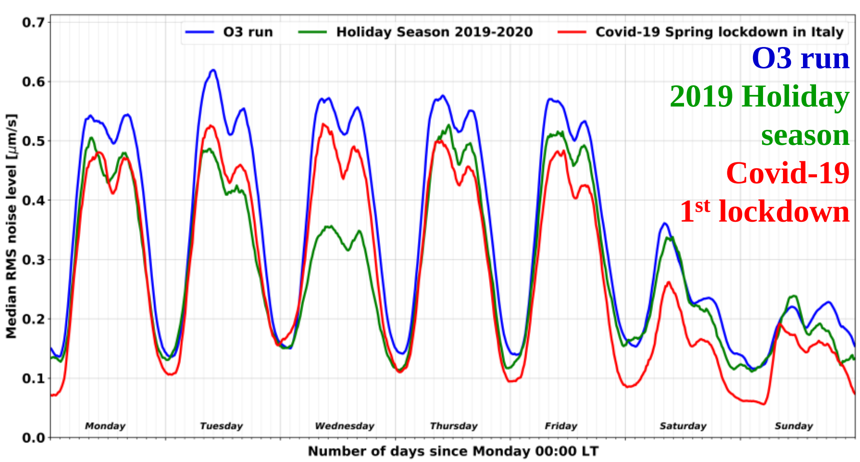
Seismic noise variability

- Microseism: seasonal variations
  - Larger in Fall/Winter
  - Color code
    - Green: < 75th percentile
    - Yellow: 75th – 90th percentile
    - Red: > 90th percentile

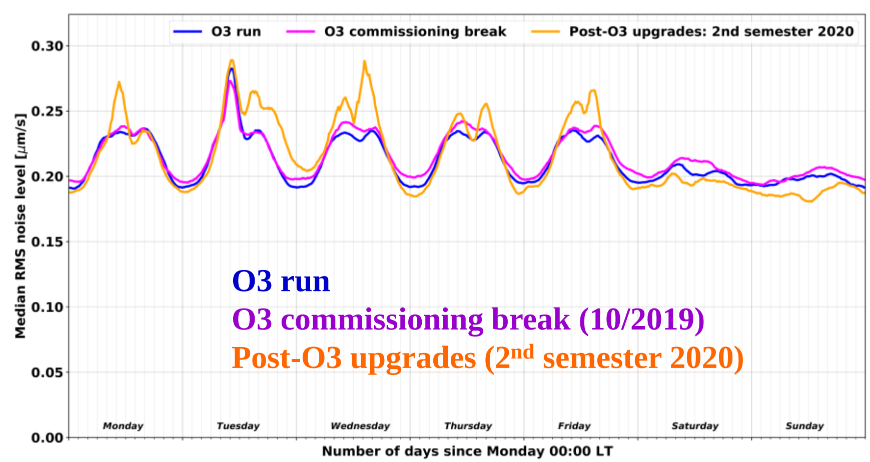


- Anthropogenic + on-site
  - Impact of "global conditions"
    - Day/night + weekday variations
    - Holidays, pandemic…

Anthropogenic



On-site



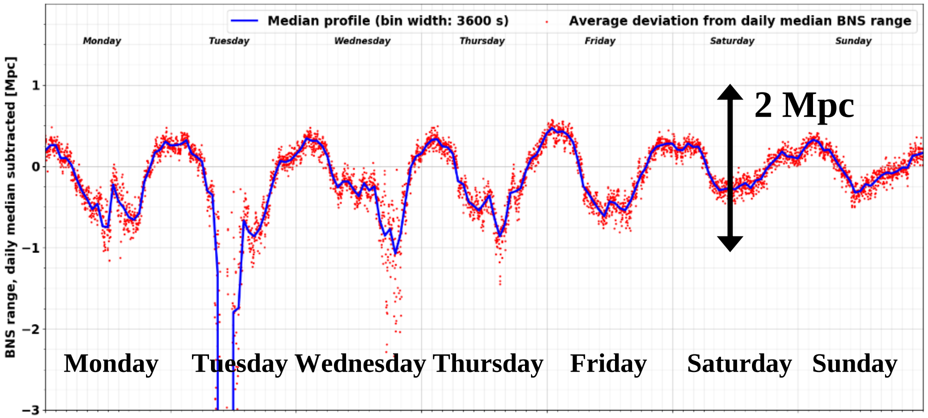
Sensitivity modulation

- Figure-of-merit: the BNS range
  - Subject to variations from multiple origins – not just the environment
    - Control accuracy, detector global status, minor problems, etc.

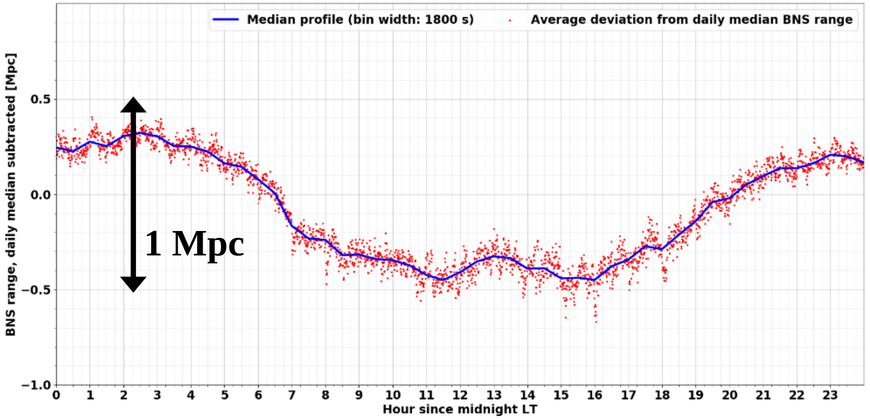
  → Raw" BNS range value not suitable for such study
    - Instead: use BNS range variations around its daily median level

- O3-averaged variations

Over a week baseline



Over a 24-hour baseline



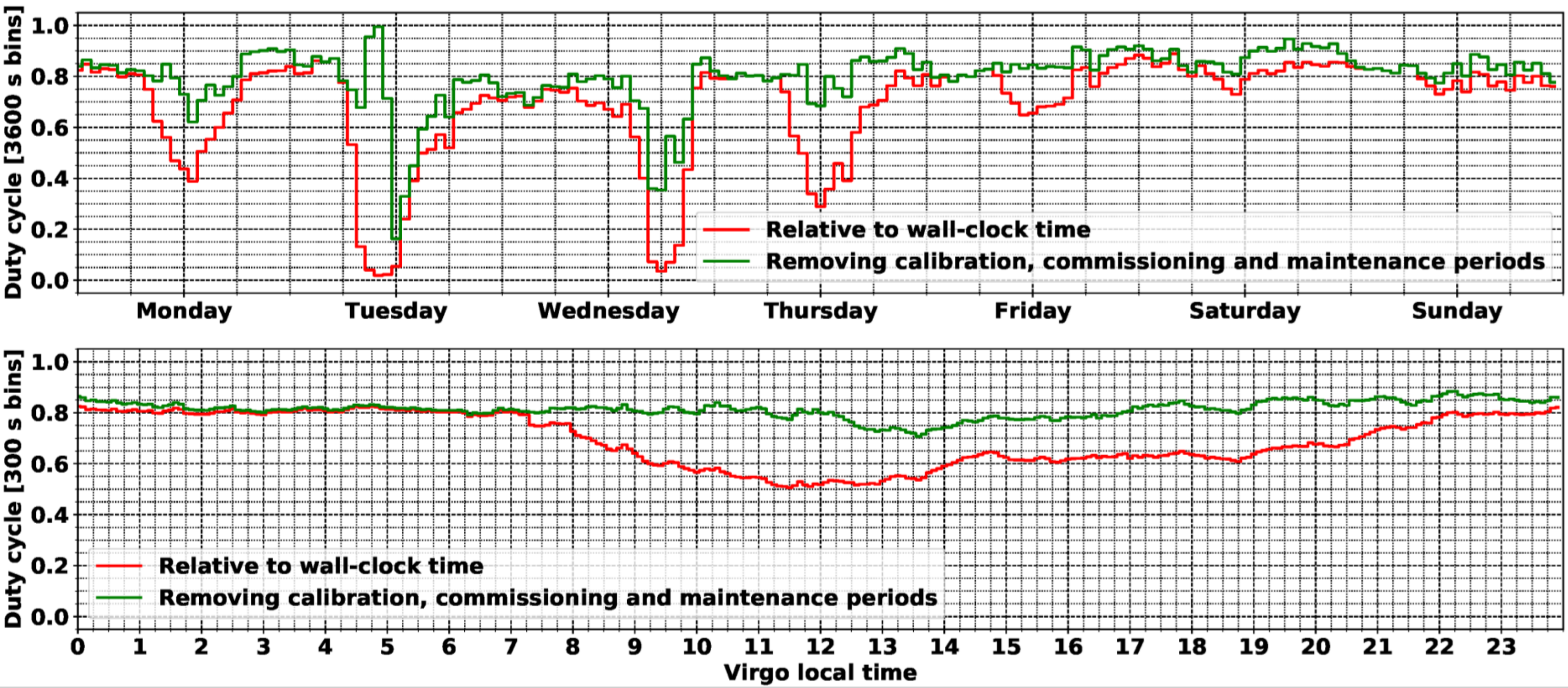
→ Modulation similar to anthropogenic noise
  - Limited amplitude: a few percents at most

Duty cycle

- Defined as the fraction of time spent taking Science data
  - Red: relative to wall-clock time
  - Green: removing calibration, commissioning and maintenance periods

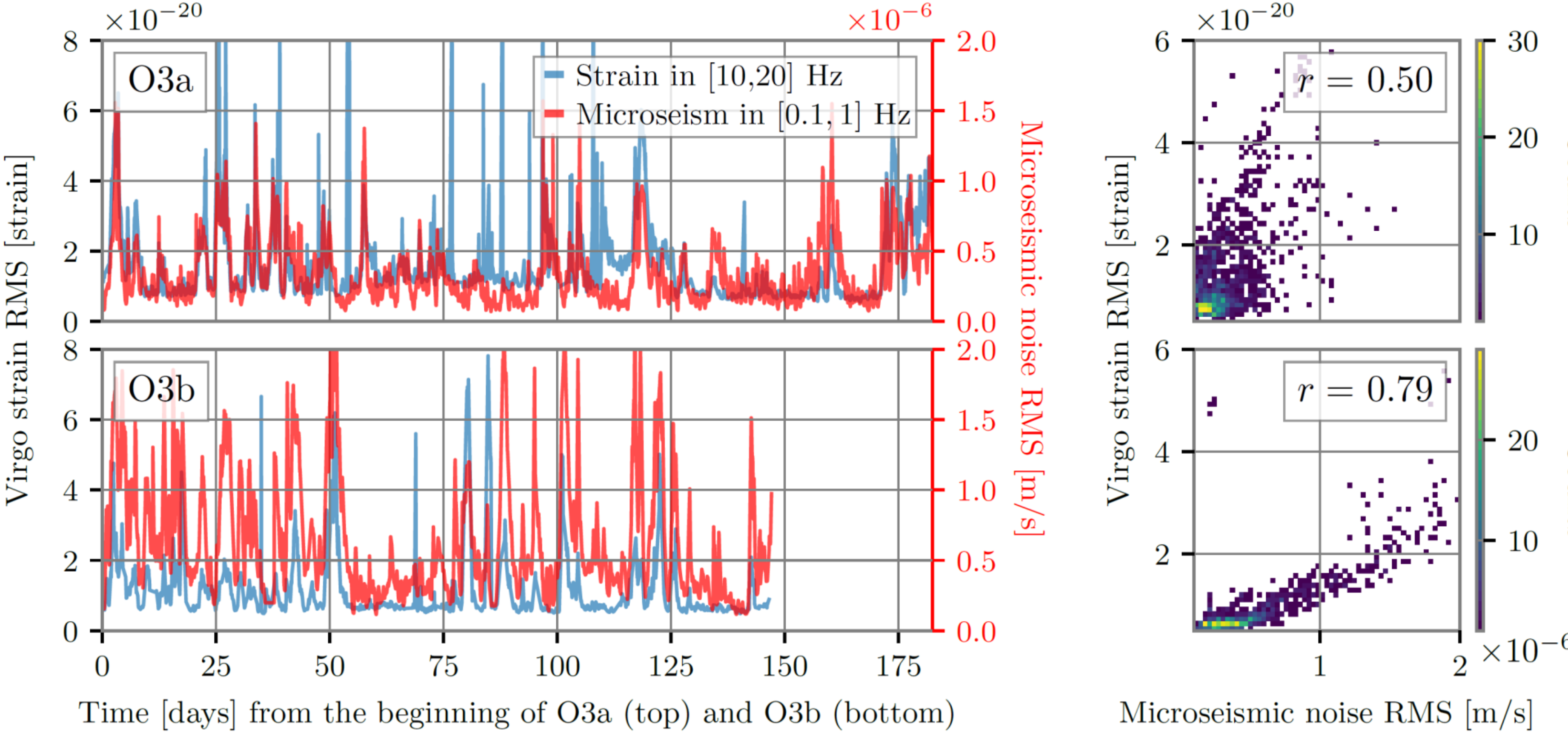
→ Not the same modulation

- Duty cycle driven by the (lack of) activities of the crew on duty



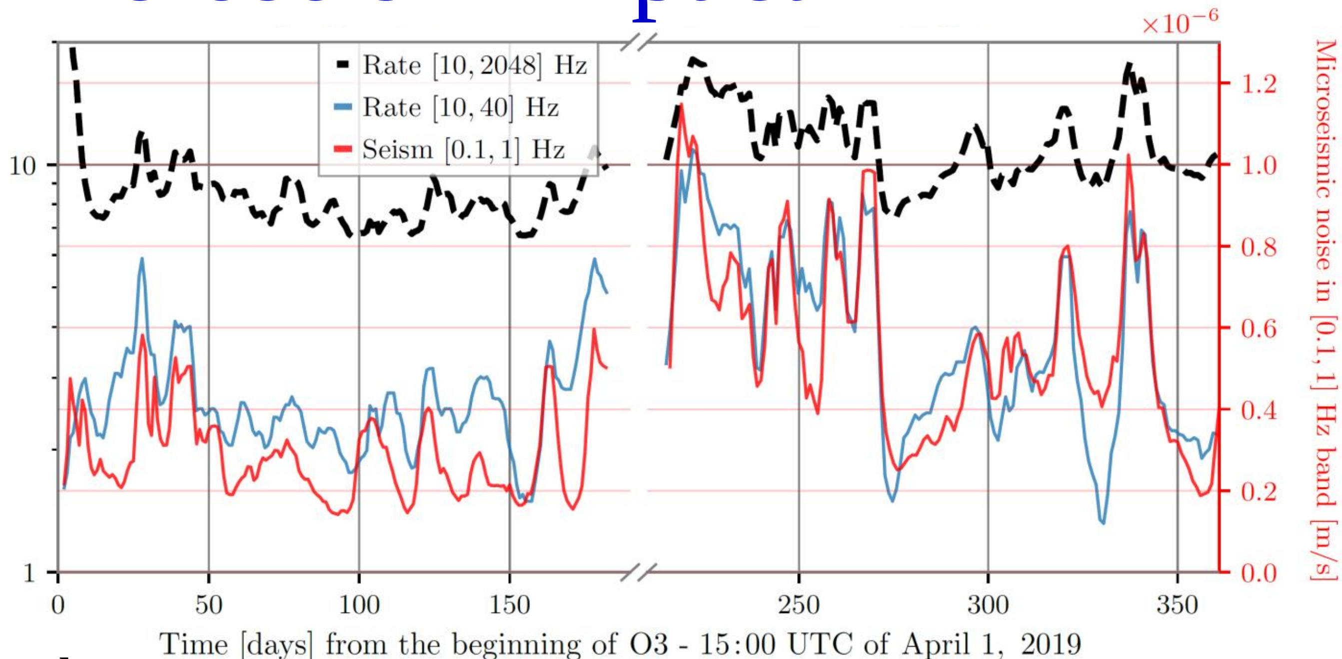
Microseism impact

- Reconstructed GW strain channel h(t) worsens during high microseism activity
  - Up to ~40 Hz



- Blue: h(t) BLRMS
- Red: Microseismic band BLRMS

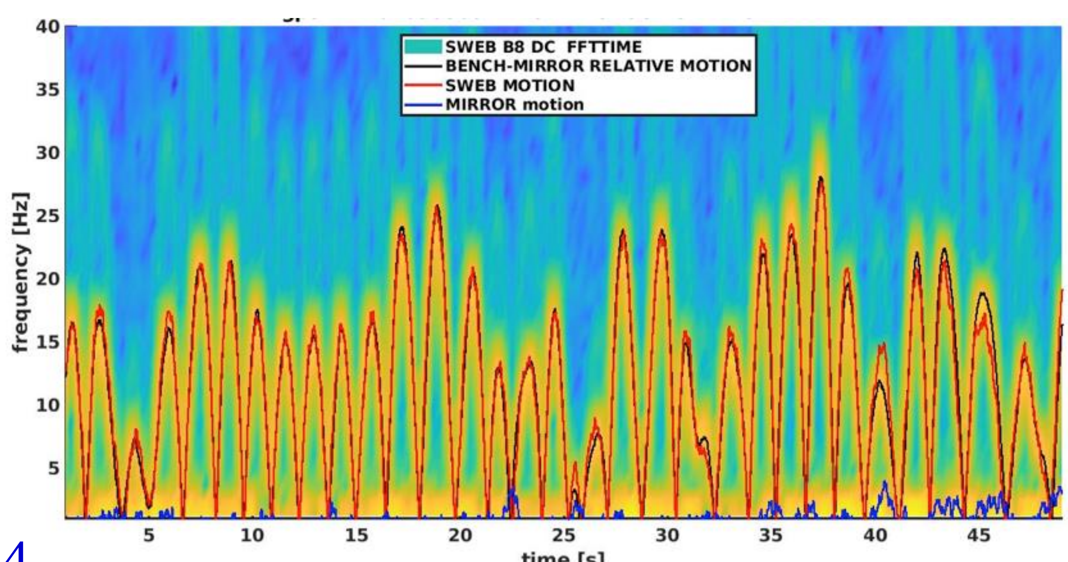
Microseism impact



- Noise transient rate per minute
  - Black: rate in the 10 ÷ 2048 Hz band
  - Blue: rate in the 10 ÷ 40 Hz band
  - Red: microseism BLRMS

→ Impacts data quality and GW search trigger rate

- Main path identified
  - High microseism
  - Larger relative motion of a detector component
  - Scattered light
    → Typical “arches” in spectrograms

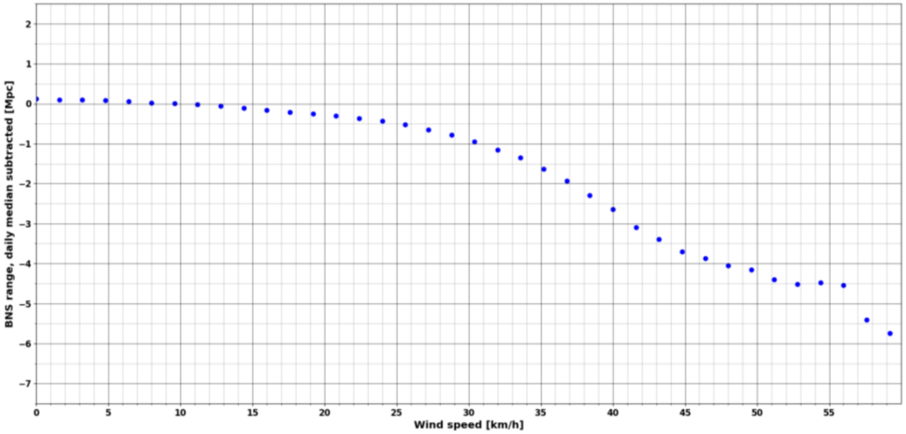


→ Improvements foreseen for O4

Wind impact

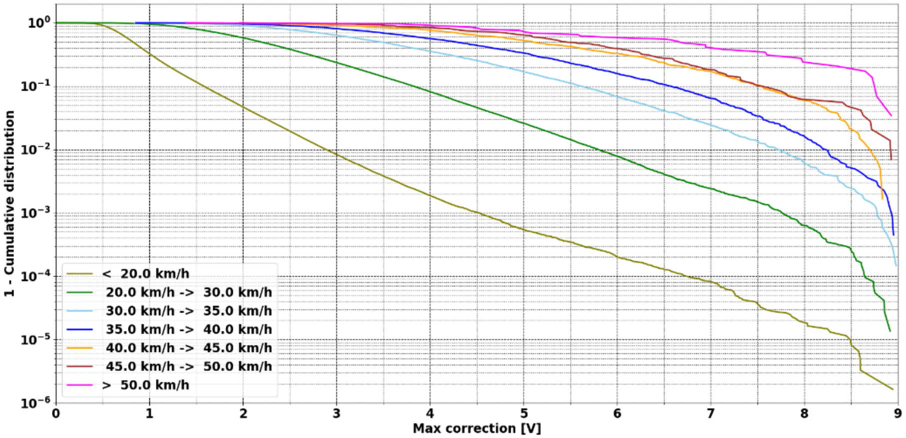
- Bad weather ⇔ high microseism activity (rough sea) and wind
  → Disentangling the two contributions

- Some wind impact on the BNS range above ~25 km/h



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

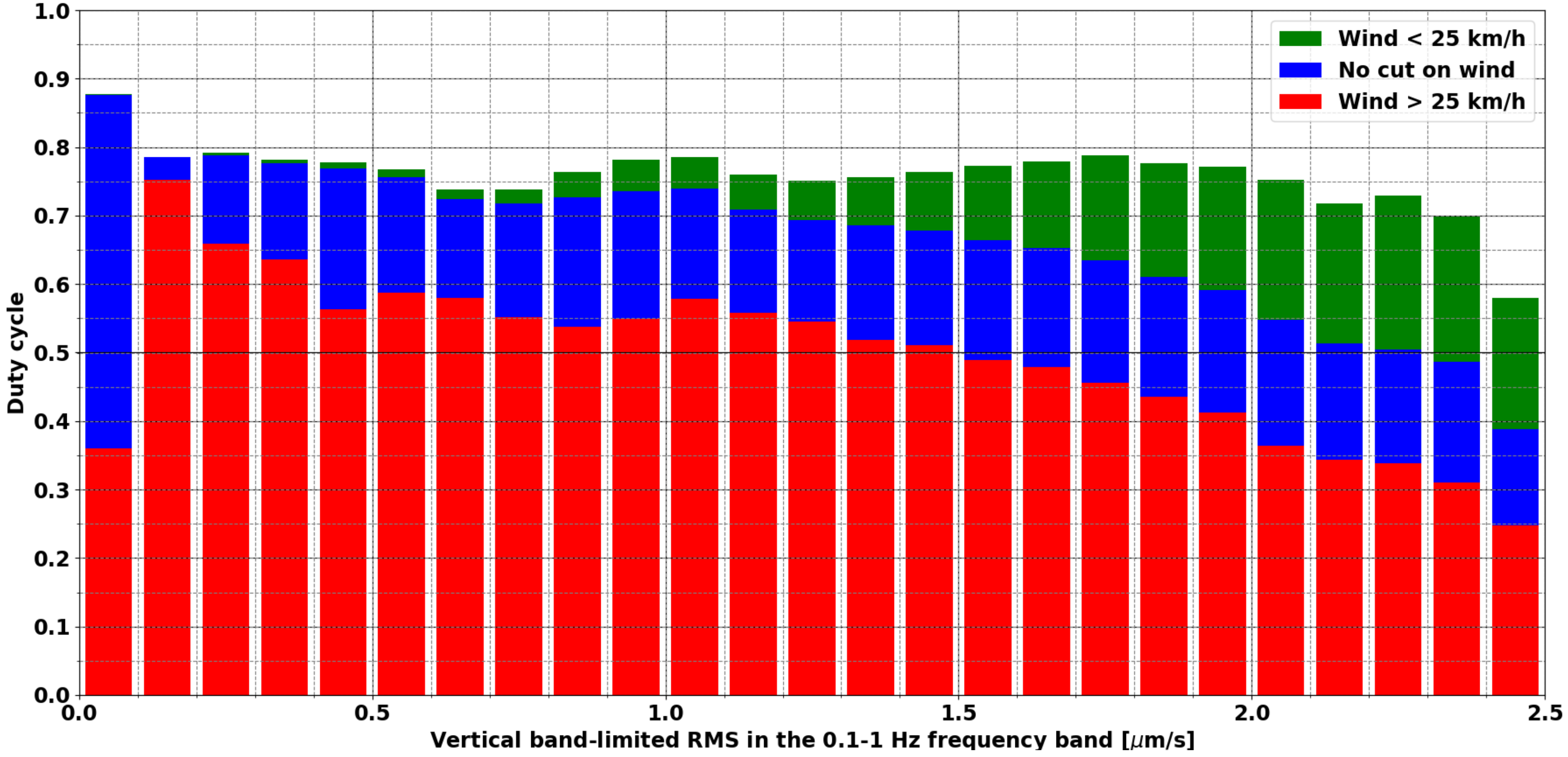
- Larger corrections to keep the detector control as the wind speed increases



→ Limited actuation range
  - Saturation: immediate control loss

Wind impact

- 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

Earthquakes

- High-enough seismic waves ⇒ feedback system saturation
  ⇒ Working point not controlled anymore ("lock loss")
  ⇒ Duty cycle decreases
    - "Locking time" + eventually the time to damp excited suspensions
- Seismon: an earthquake early warning system
  - Developed by LIGO; running at EGO since O2
  - Input: earthquake alerts from a low-latency US Geological Survey (USGS) stream
  - Output: seismic wave arrival times and amplitude estimation at detector location
    → Interfaced with Virgo data acquisition and control system
- Earthquake mitigation
  - Requires warning to arrive in the control room prior to the seismic waves
    - Up to tens of minutes of margin for the most distant earthquakes on Earth
  - Manual switch to a more resilient control configuration w/o losing the lock
    - (Slightly) more noisy
    - Only validated for Science data taking close to the end of O3b
    - Actuation range doubled ⇒ saturation (and control loss) less likely
  - Back to nominal control when seismic waves fade away
    - Overall duty cycle gain if the detector has survived the earthquake

Control losses due to earthquakes

- 601 lock losses from Science mode during the whole O3 run
  - Less than 2 / day in average
  - Locking phase median duration: 25 minutes
    - Median number of attempts: 2

→ 30 (5%) found to be due to earthquakes
  - About 1 / 10-11 days in average
  - 24 more lock losses due to earthquakes found while not taking Science mode data

    → Included in the following analysis to increase dataset studied

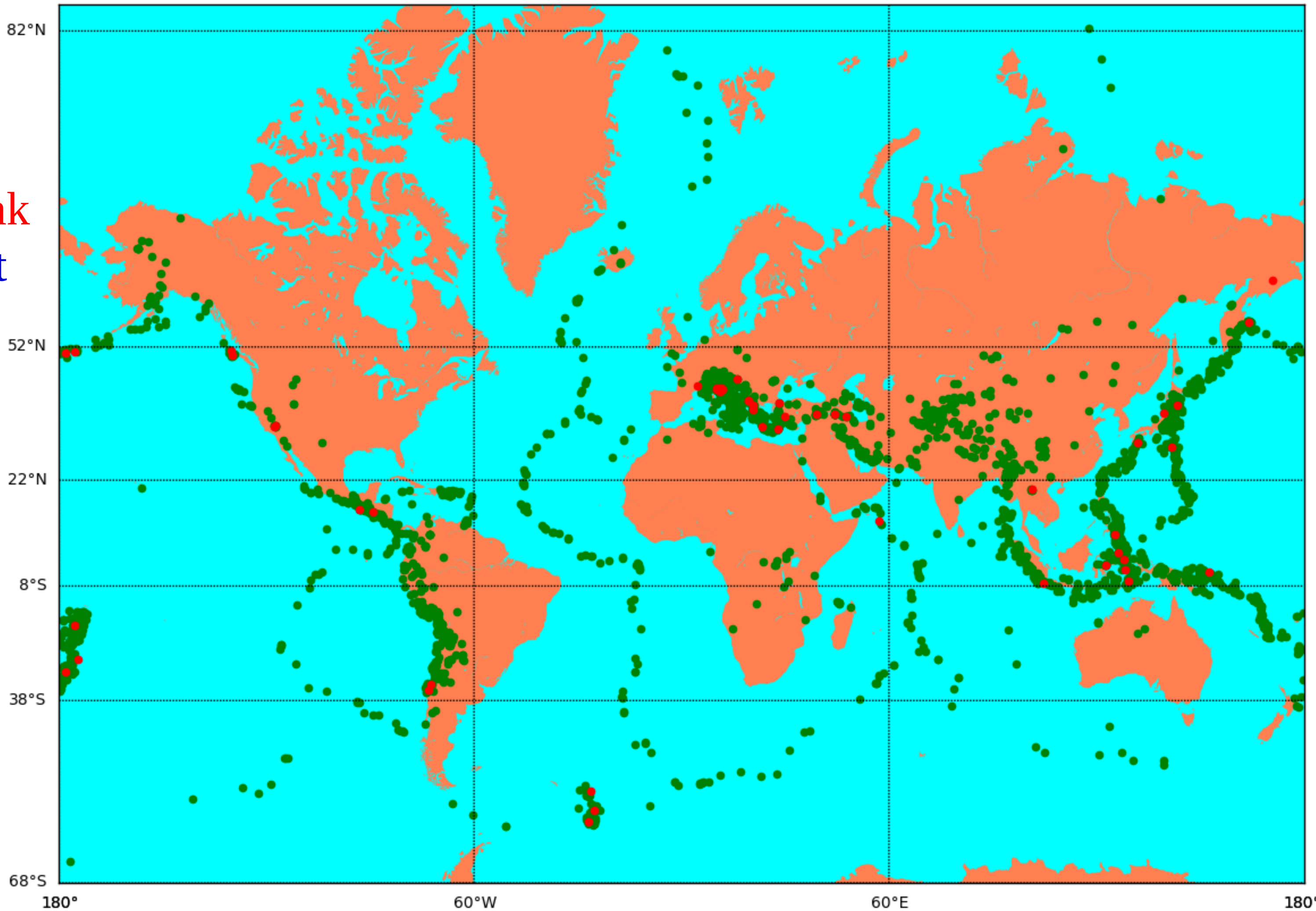
- 2 main categories
  - Distant and strong earthquakes
    - Warning available ahead of the seismic waves but the control could not hold
  - Weak but very close earthquakes
    - Not reported at the output of Seismon

      → Found using the Istituto Nazionale di Geofisica e Vulcanologia (INGV) public earthquake database
    - Too close anyway to trigger “early” warnings

      → But important to find the right cause for these lock losses
      - Time-coincident USGS early warnings missing or not making sense

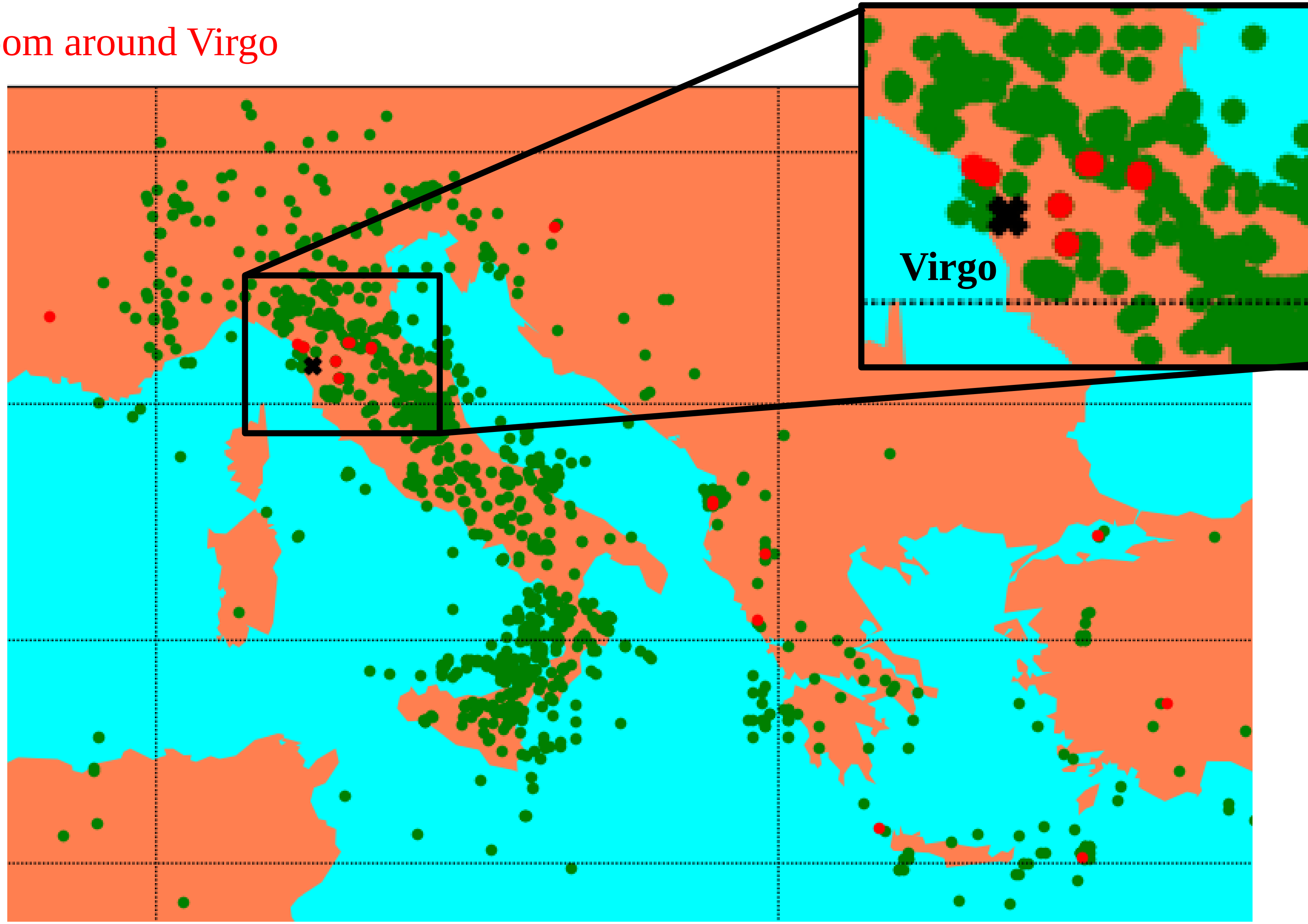
Earthquakes location

- Whole O3
- Excluding earthquakes clearly too weak
  - Empirical cut based on magnitude and distance
- Red dots: lock losses



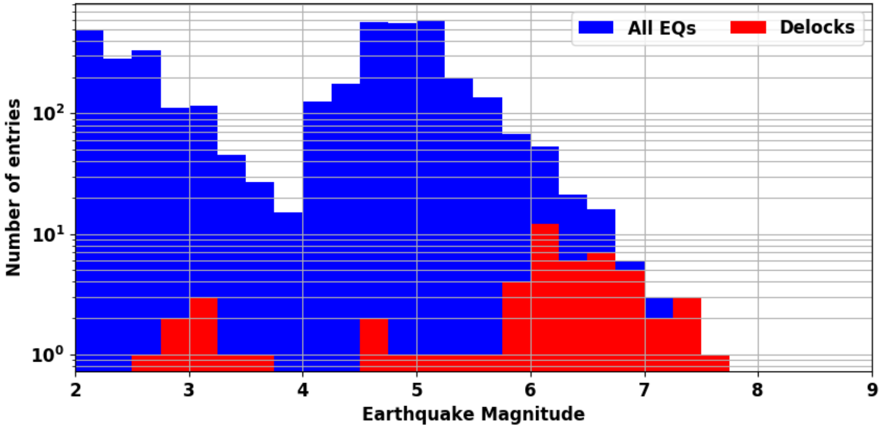
Earthquakes location

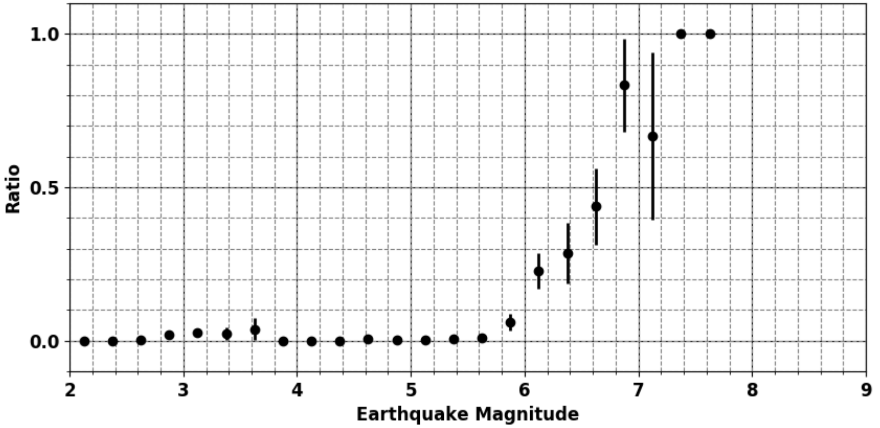
- Zoom around Virgo

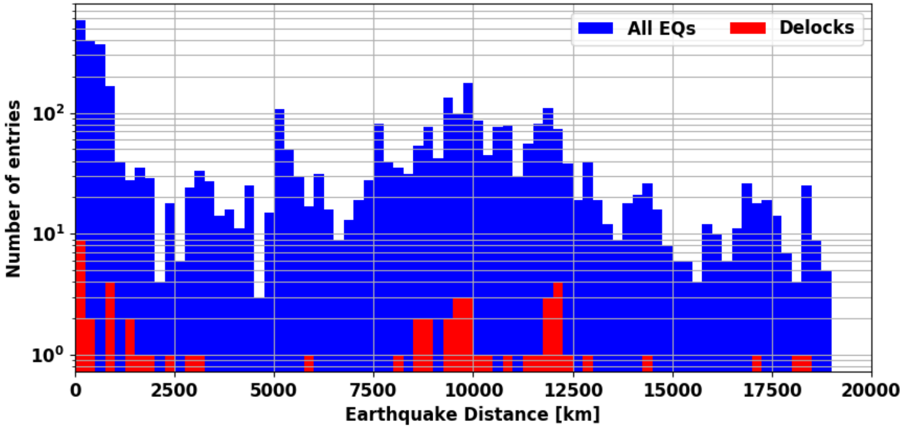


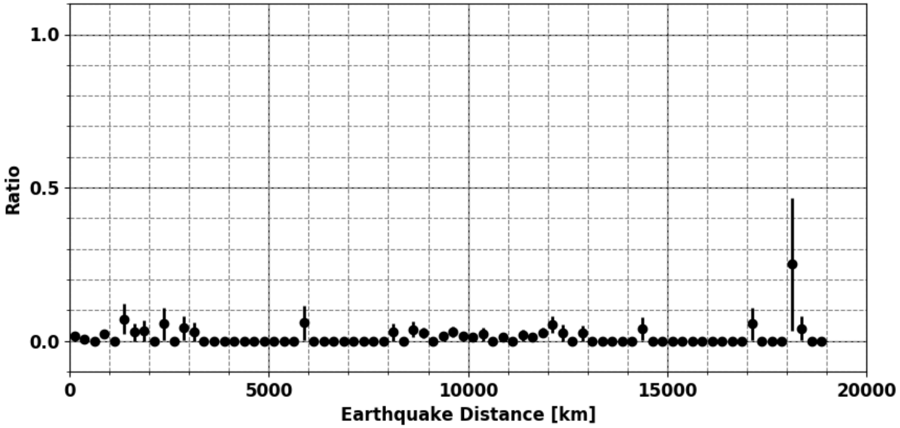
Earthquakes strength

- Classification based on earthquake magnitude and epicenter distance
  - Blue histograms: all earthquakes
  - Red histograms: earthquakes that led to a control loss during O3



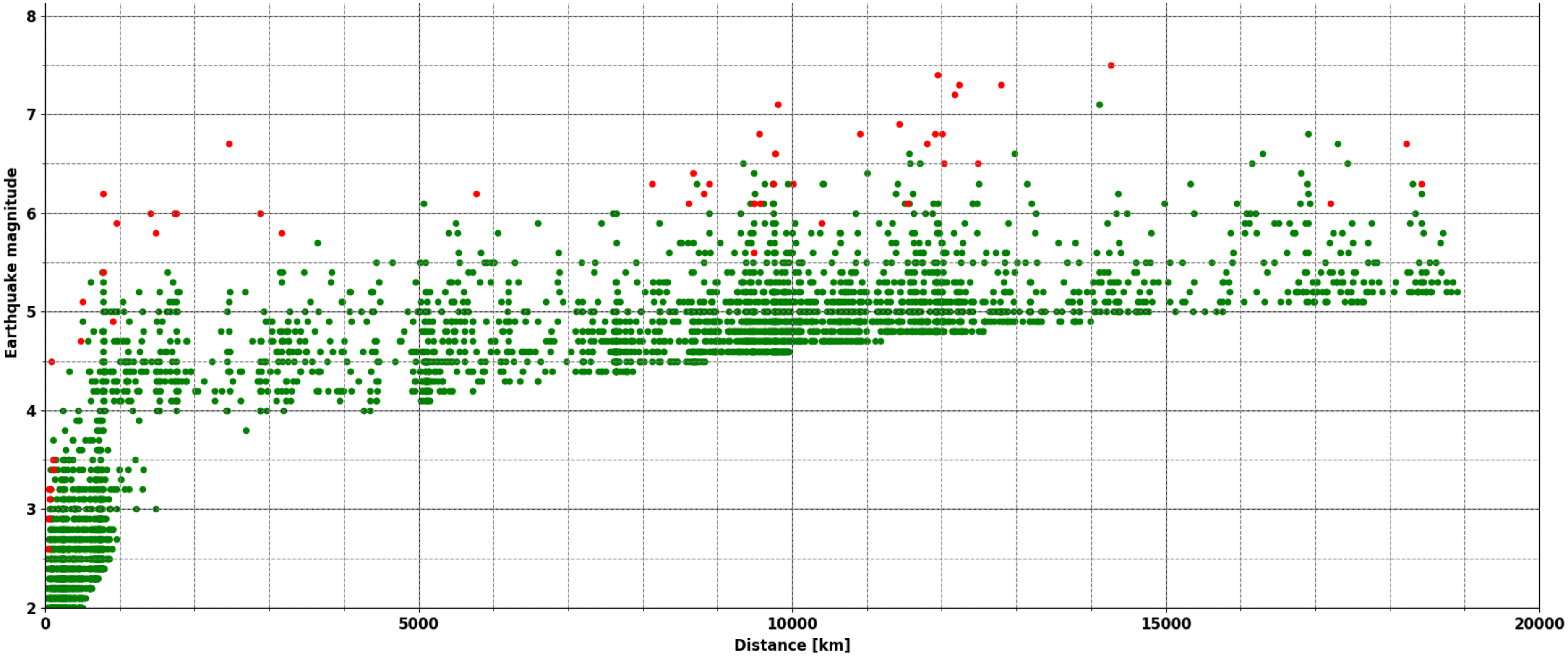






Earthquakes strength

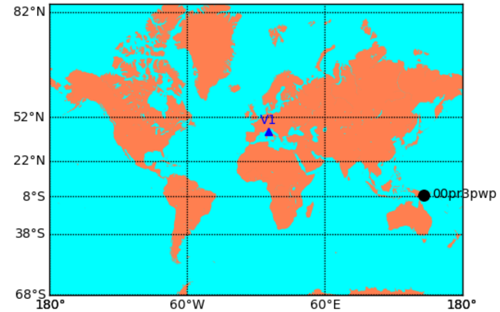
- Classification based on earthquake magnitude and epicenter distance
  - Green dots: earthquakes that did not led to a control loss
  - Red dots: earthquakes that led to a control loss

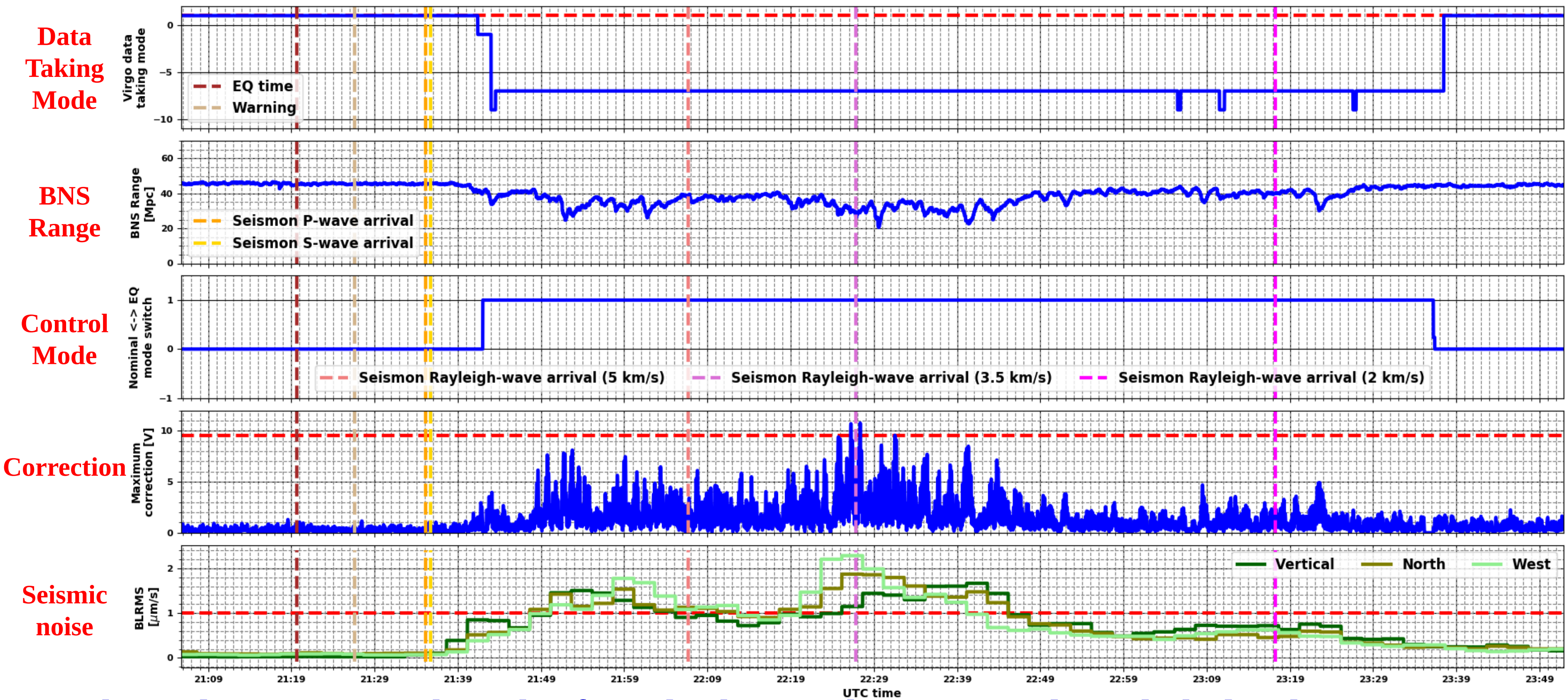


→ Magnitude and distance are key parameters
  - Others may play a role as well (epicenter depth, azimuth)
  - So probably does the actual state of the detector when seismic waves arrive

Riding through a strong earthquake

- May 06, 2019
  - Estimated magnitude: 7.1
  - Distance: ~14,000 km





→ The only strong earthquake for which switching control mode helped

- By allowing to exceed the correction saturation level w/o loosing control

Outlook

- O3 dataset used to quantify findings that had previously been observed qualitatively or empirically

- Seismic noises impact the Virgo detector in a complicated way
  - Various contributions, varying over time for multiple reasons
    - Weather, human activities

→ The Virgo detector appears to be quite robust against those disturbances
  - Limited decrease of BNS range or duty cycle in harsh conditions

→ Experience gained to prepare the O4 run
  - More studies needed to understand better the complex behavior of the detector

- Earthquakes are sub-dominant but clear contributors to control losses

  → Two paths explored in parallel for O4
    - Increase the actuation range by dividing the correction force applied among more low-noise actuators
    - Extend the earthquake early warning system
      - Use the latest Seismon version
      - Add input stream from INGV ("closer" to Virgo) in addition to USGS