The performance of the Virgo gravitational-wave detector during the O3 run (04/2019-03/2020) and the impact of the external environment

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On behalf of the Virgo Collaboration

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Outline

- LIGO-Virgo Observing Run 3: O3
  - 3-detector network
  - Main results

- Performances of the Virgo detector during the O3 run
  - Sensitivity
  - Duty cycle
  - Noise transients

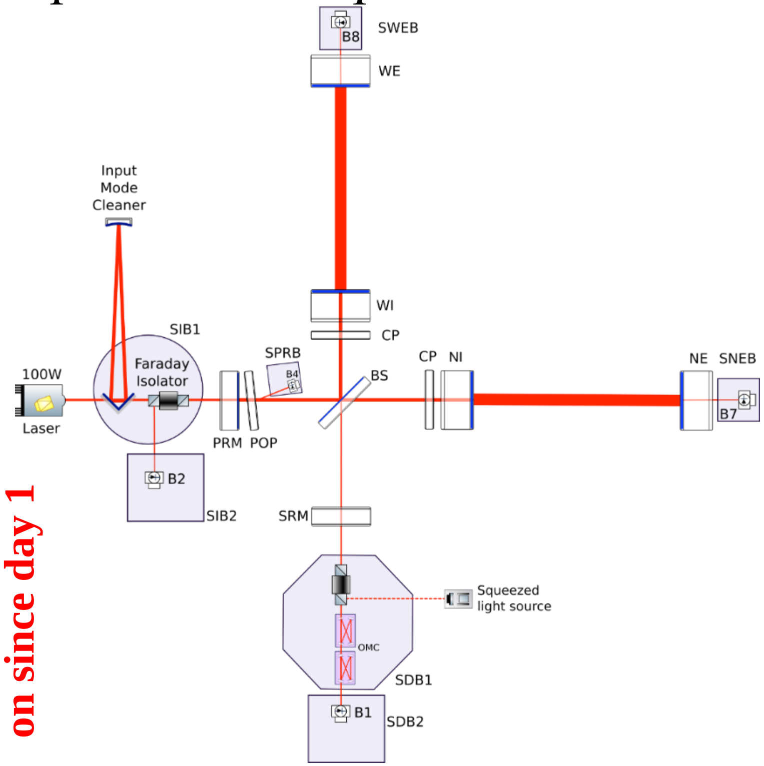
- Impact of external environment
  - Seismic noises
  - Earthquakes
  - Bad weather

- The next Observing Run: O4

The LIGO-Virgo O3 run

- Ground-based gravitational-wave (GW) interferometric detectors
  - 2nd generation ("Advanced"): designed, built and operated in the past decade
- O3: 3rd Observing Run
  - O1: 09/2015 → 01/2016
    - LIGO-only, GW150914
  - O2: 11/2016 → 08/2017
    - Virgo joined LIGO on August 1st, 2017
    - GW170814 & GW170817
- 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)

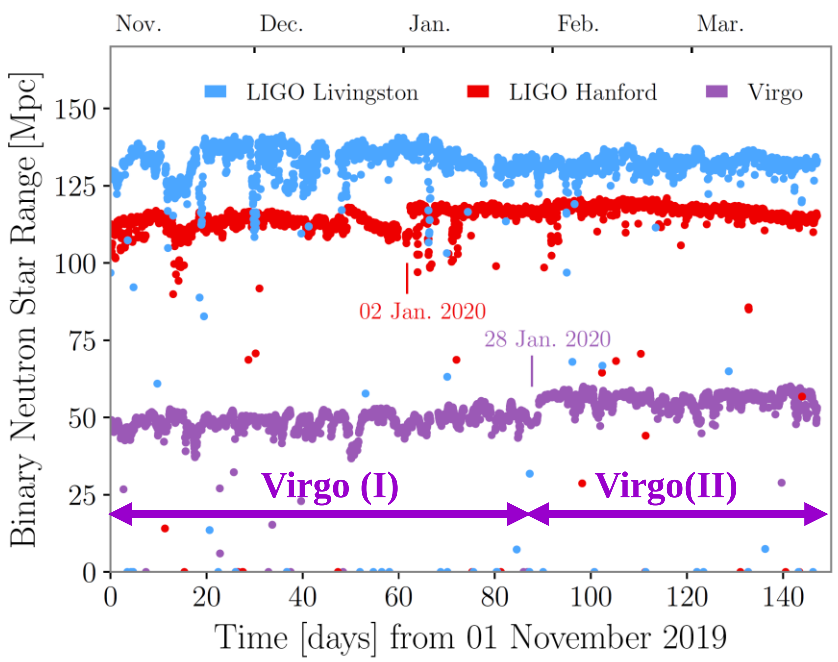
All 3 detectors on since day 1

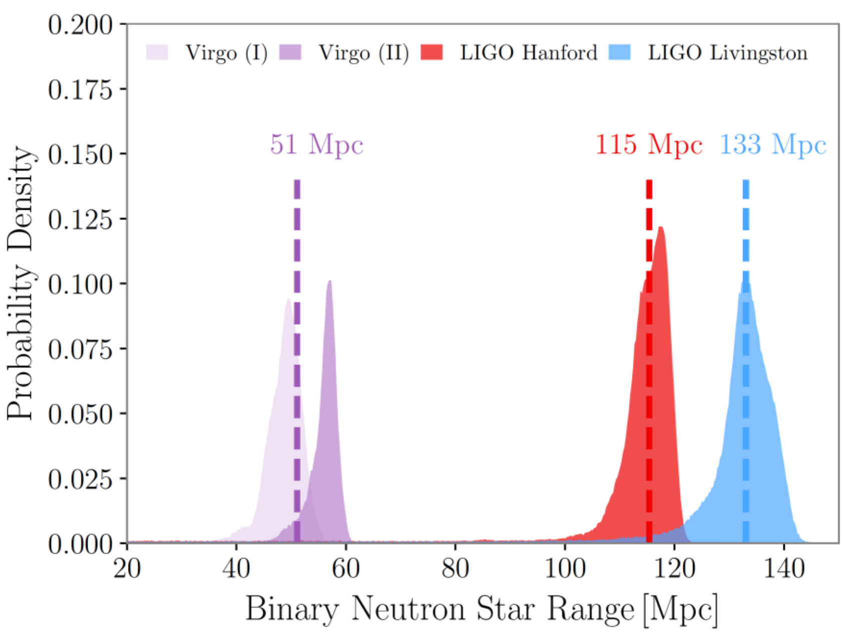


The LIGO-Virgo O3 run

- Sensitivity
  - Figure of merit: the binary neutron star ("BNS") range
    - Average "detection" distance (in Mpc) for a BNS merger
      Detection ↔ signal-to-noise ratio (SNR) = 8 by convention

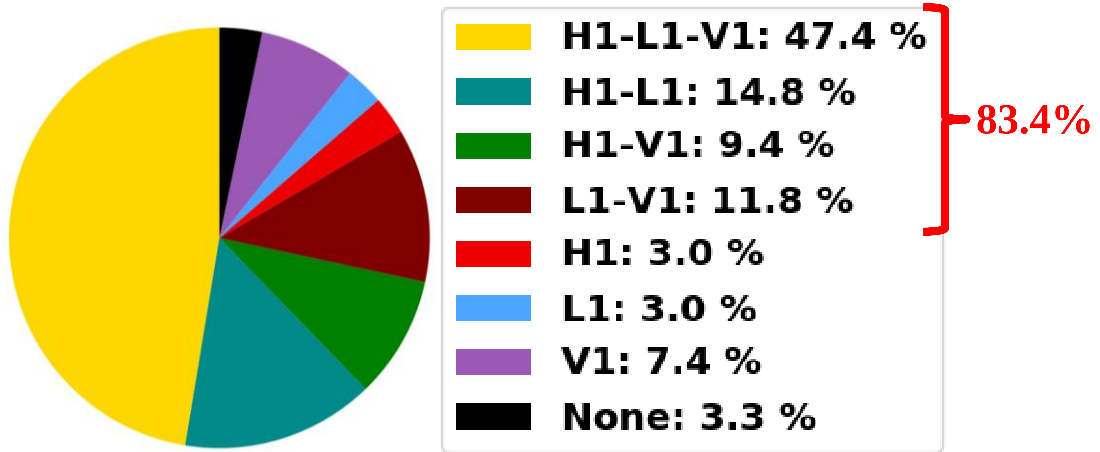
→ Hourly median average
  - Example of O3b
    - O3a plots already published



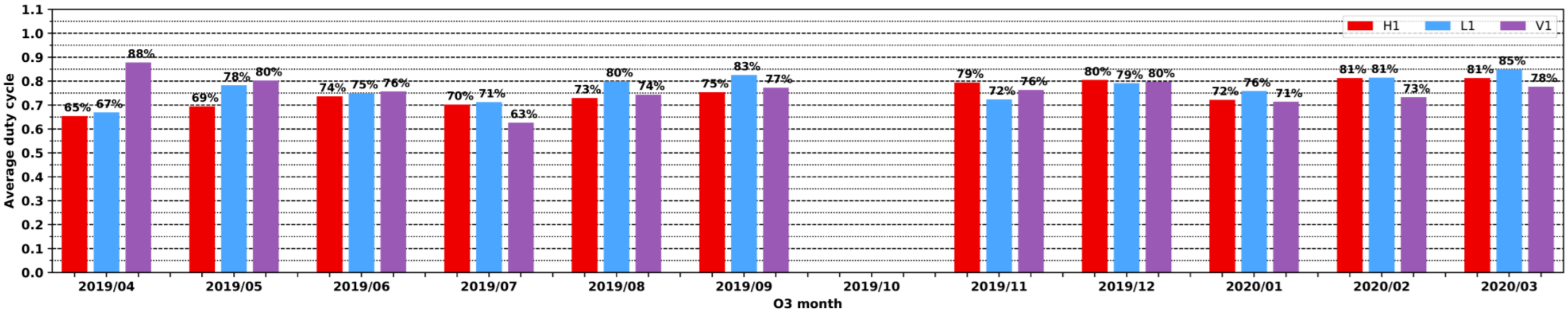


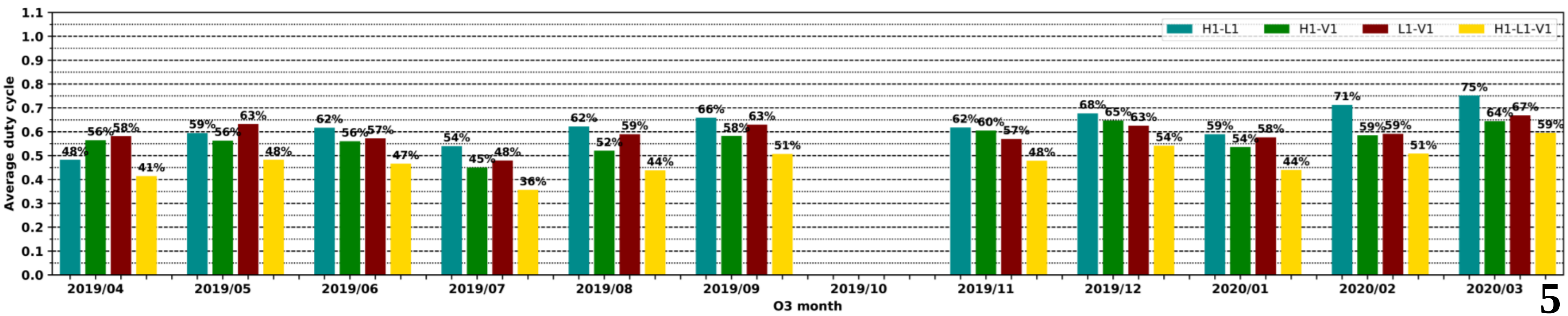
The LIGO-Virgo O3 run

- Duty cycle
  - Fraction of the time spent taking good quality physics data
    - For each particular network configuration



- Monthly duty cycles during O3





The LIGO-Virgo O3 run

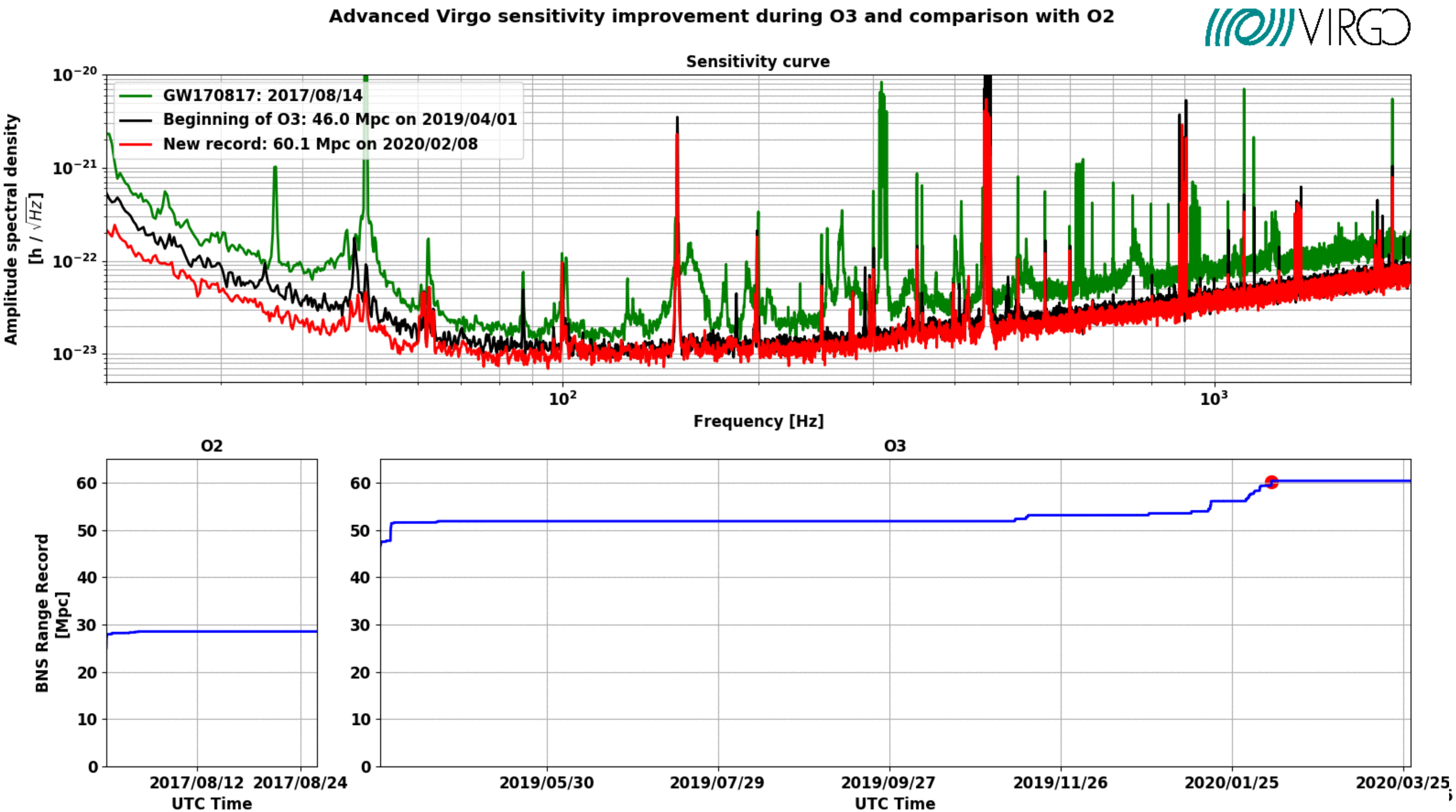
- 56 public alerts during O3: no counterpart detection
- GW Transient Catalog ("GWTC")
  - Issue 2 – including O3a – released
    - GWOSC website: O3a GW strain data now public
  - Issue 3 – O3b – in preparation

  → Compact binary system populations and merger rates

  → Stringent general relativity tests in strong regime
- O3 highlights
  - Asymmetric binary black hole (BH) systems
    - GW1901412 & GW190814
  - Compact object in between the heaviest NS / lightest BH known
    - GW190814
  - Heaviest black holes – merger remnant up to 150 solar masses
    - GW190521
  - Another BNS merger
    - GW190425
  - Most recent announcements: first ever NS-BH mergers discovered
    - GW200105 & GW200115

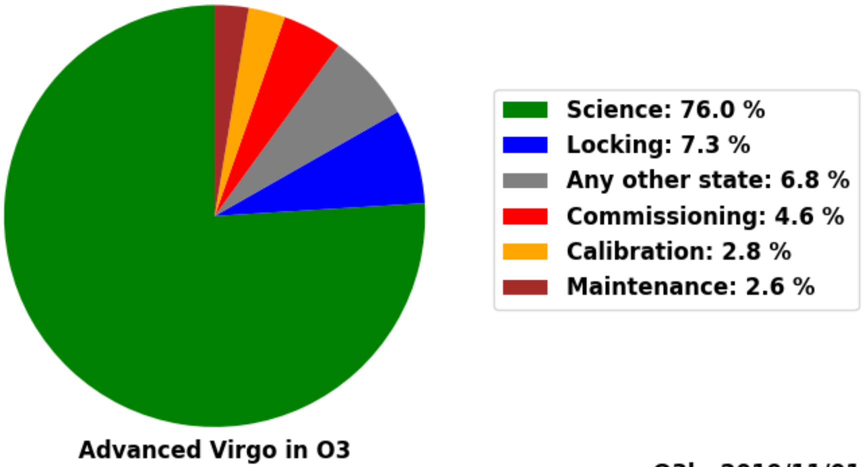
The O3 run for the Virgo detector

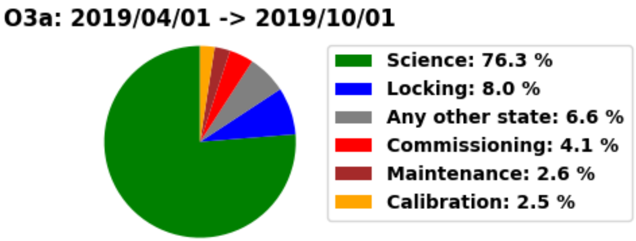
- Sensitivity improvement
  - Almost a factor 2 w.r.t. O2

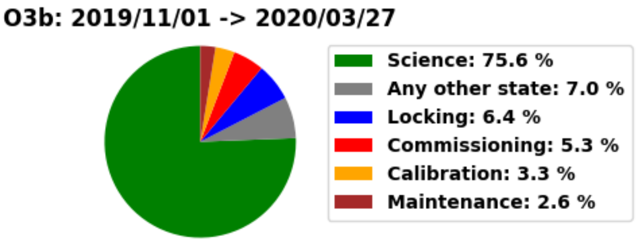


The O3 run for the Virgo detector

- Duty cycle







- Science data taking: 76%
  - Consistent with O2 (80% but only during 25 days)

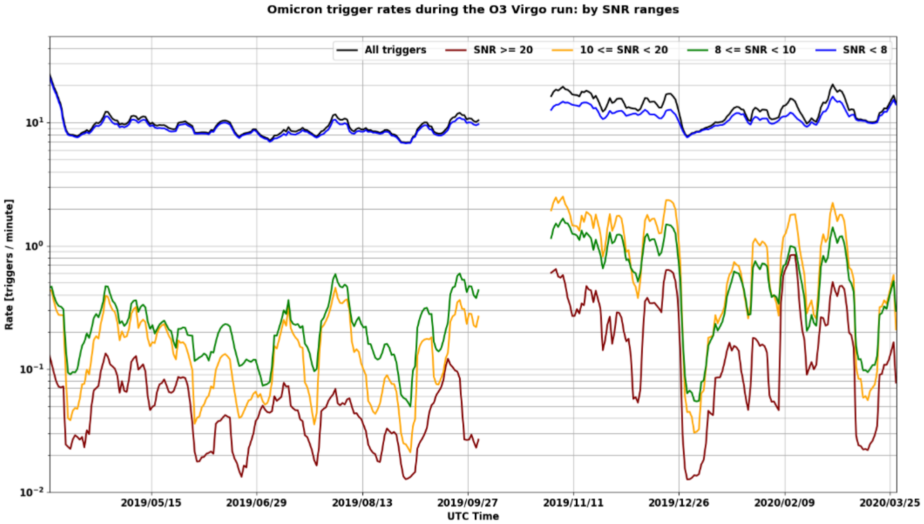
- Remaining time divided almost equally among 3 categories
  - Working point (re)acquisition
  - Maintenance + calibration + commissioning
  - Problems preventing the normal running of Virgo

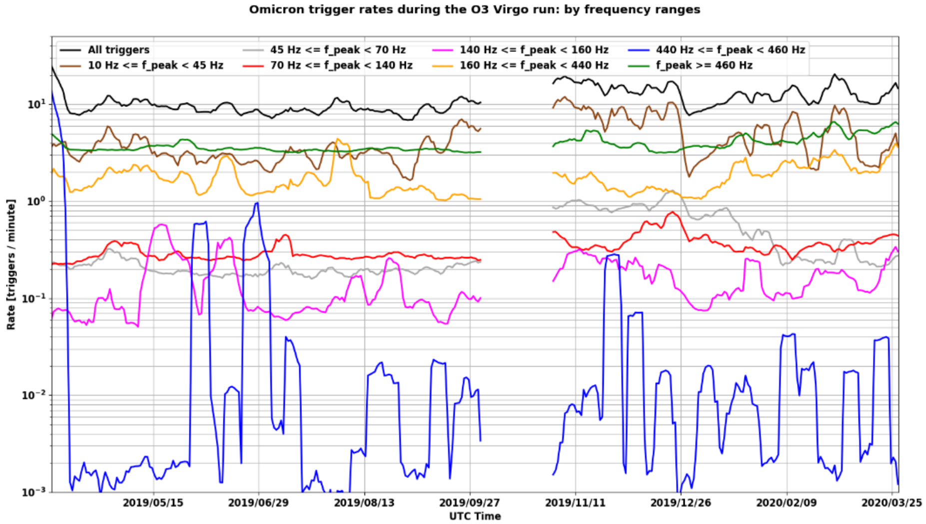
The O3 run for the Virgo detector

- Noise transients – “glitches” – can impact data taking
  - Sensitivity “drops”
  - Running stability
  - Trigger rates of data analysis searches

→ Rough classification: SNR (see left plot below) and frequency (right plot below)
  - Various projects to classify glitches better – including citizen science ones

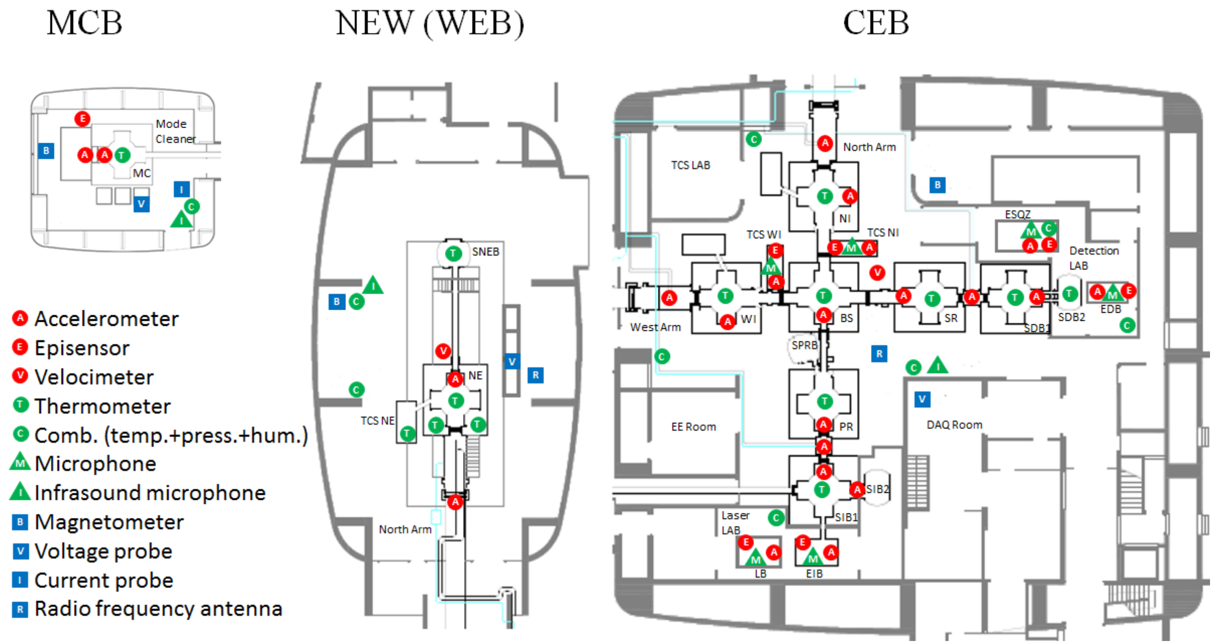
- O3 variations
  - x-axis: O3 time period
  - y-axis: rate / minute, in logarithmic scale



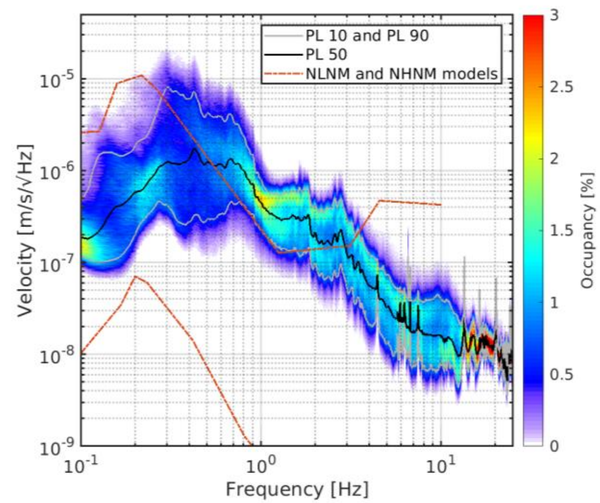


Environmental monitoring and seismic noise

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



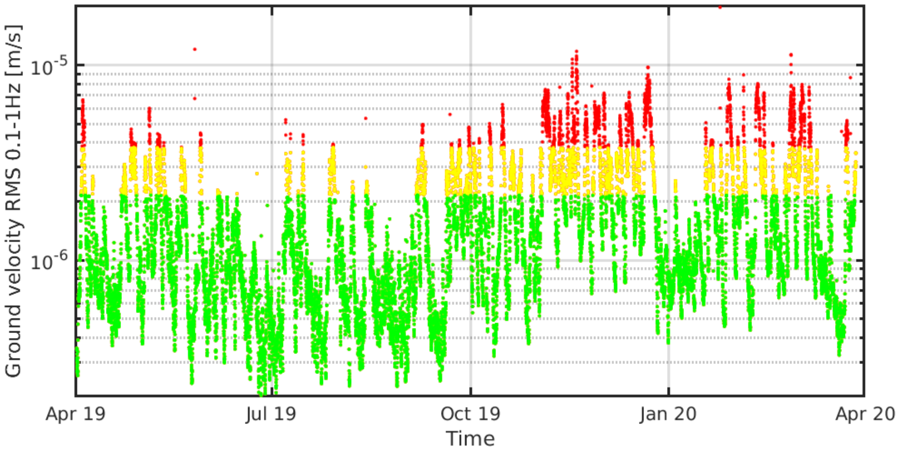
- Seismic noise
  - Microseism: 0.1 ÷ 1 Hz
    - Dominant
    - Interaction between sea waves and ground
    - Peak around 350 mHz
  - Anthropogenic: 1 ÷ 5-10 Hz
    - Heavy vehicles on elevated roads
  - Onsite: 10 ÷ 40 Hz
    - Traffic on nearby roads, agricultural activities



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

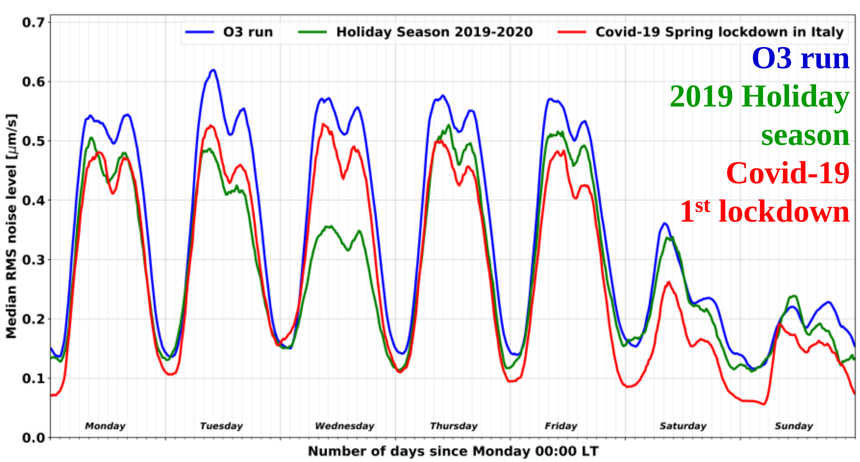
Seismic noise variability

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

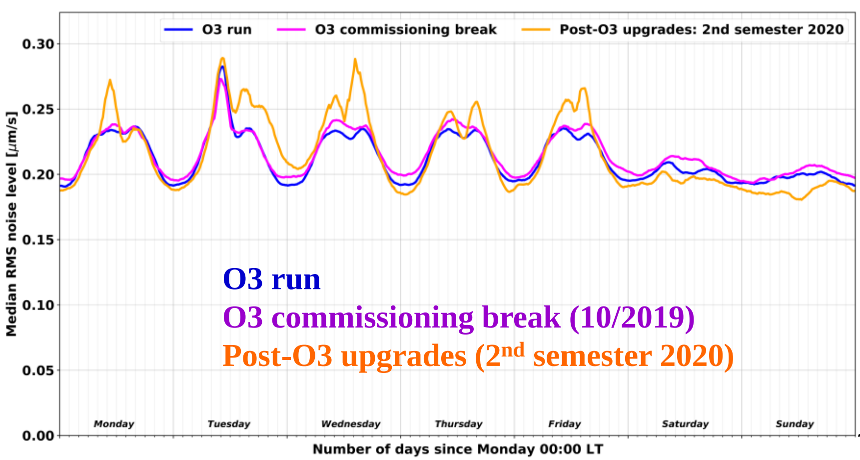


- Anthropogenic + on-site
  - Impact of "global conditions"
    - Day/night + weekday variations
    - Holidays, pandemic…

Anthropogenic



On-site



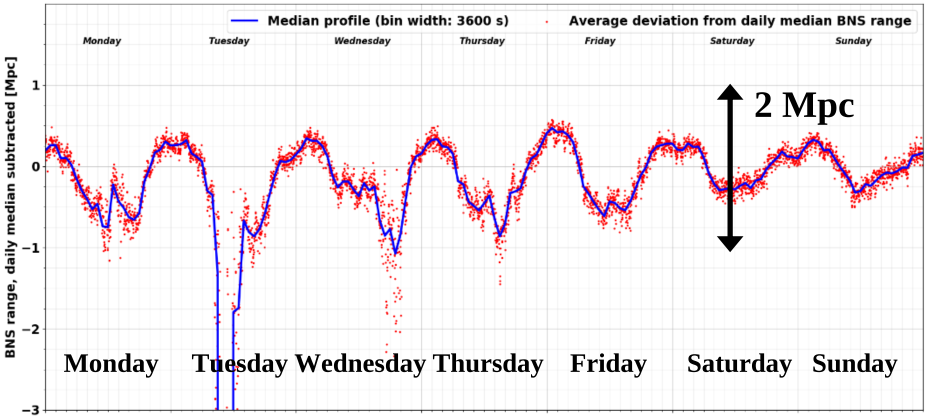
Sensitivity modulation

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

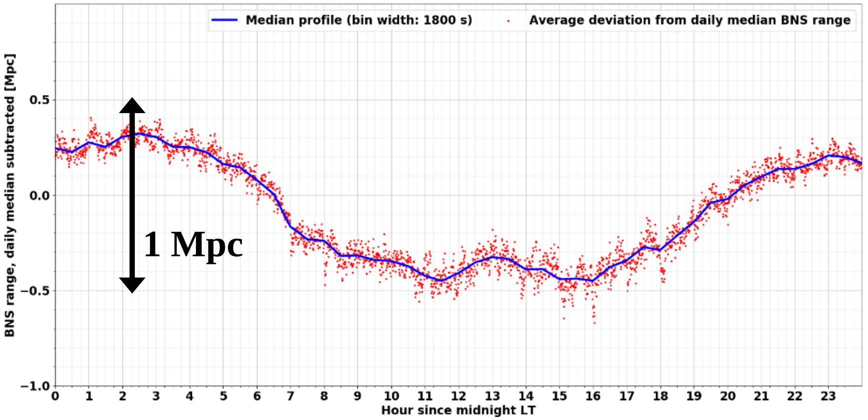
  → Raw" BNS range value not suitable for such study
    - Instead: use BNS range variations around its daily median level

- O3-averaged variations

Over a week baseline



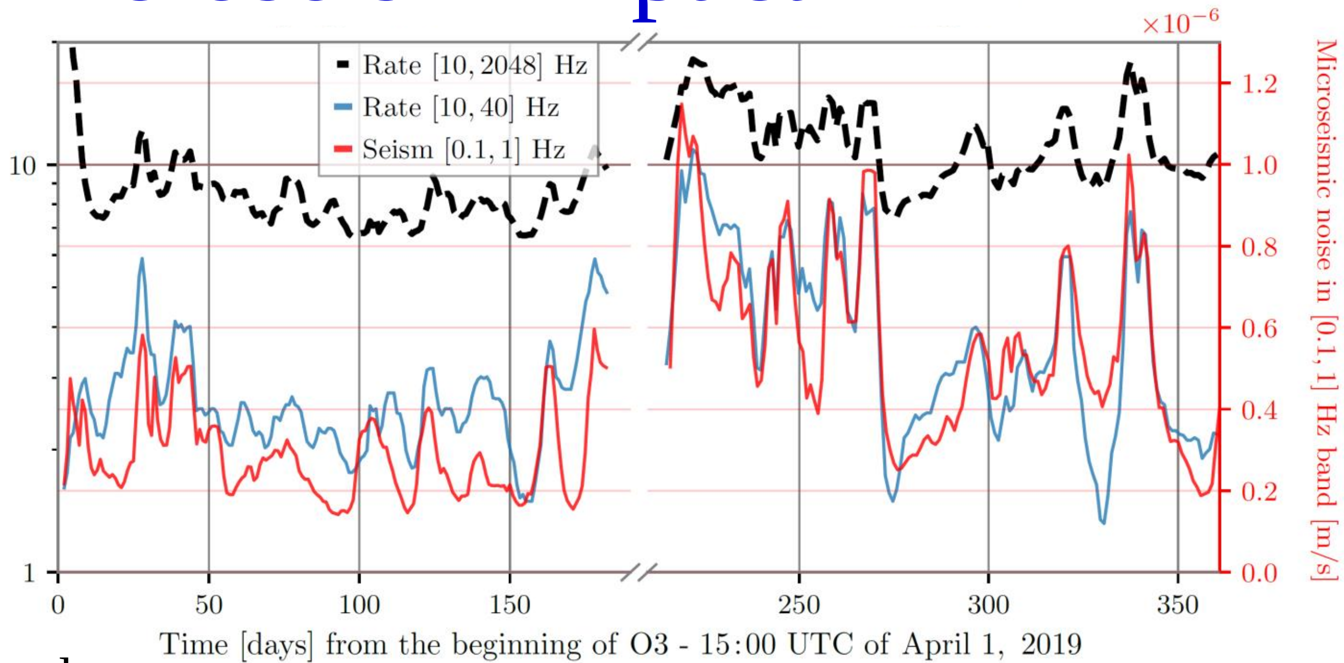
Over a 24-hour baseline



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

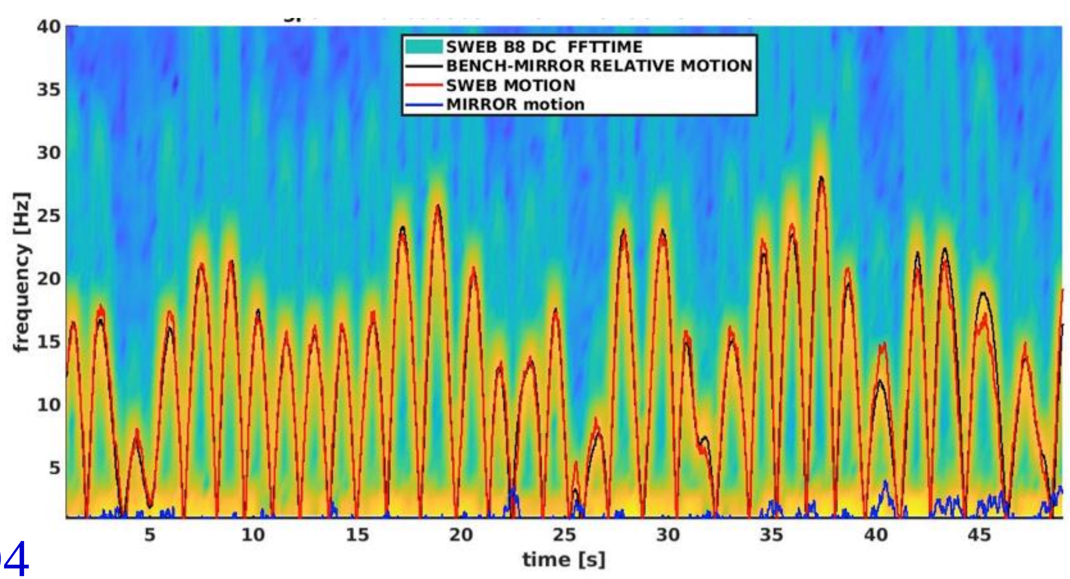
Microseism impact

- 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

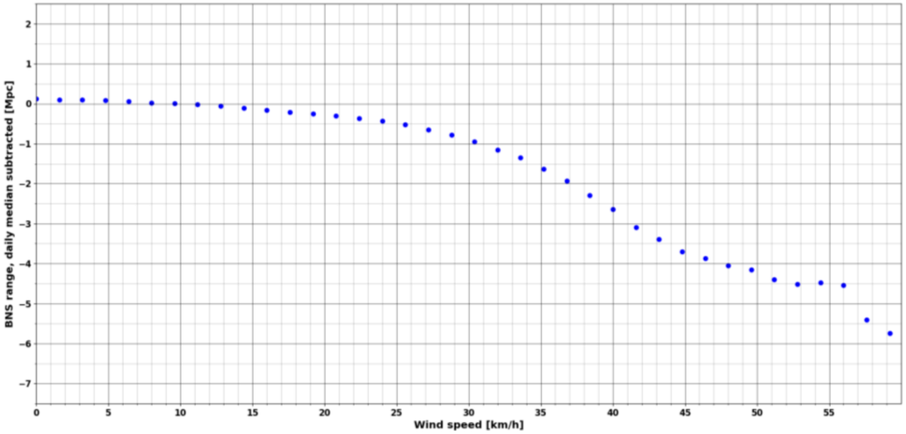


→ Improvements foreseen for O4

Wind impact

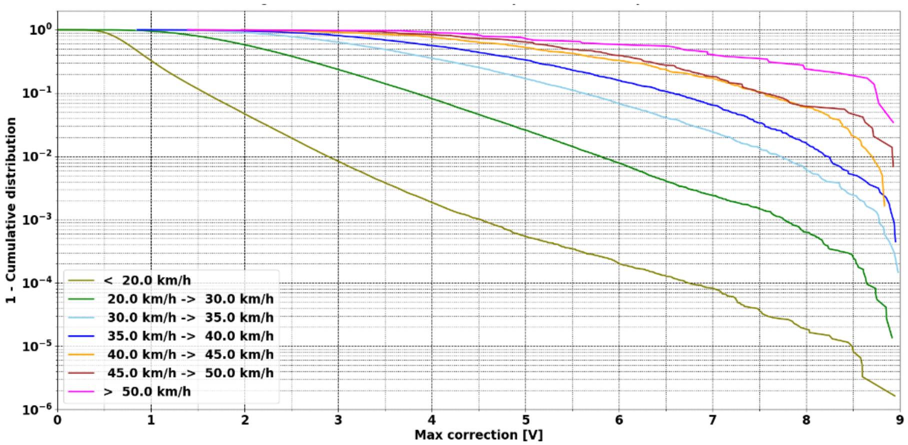
- Bad weather ⇔ high microseism activity (rough sea) and wind
  → Disentangling the two contributions

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



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

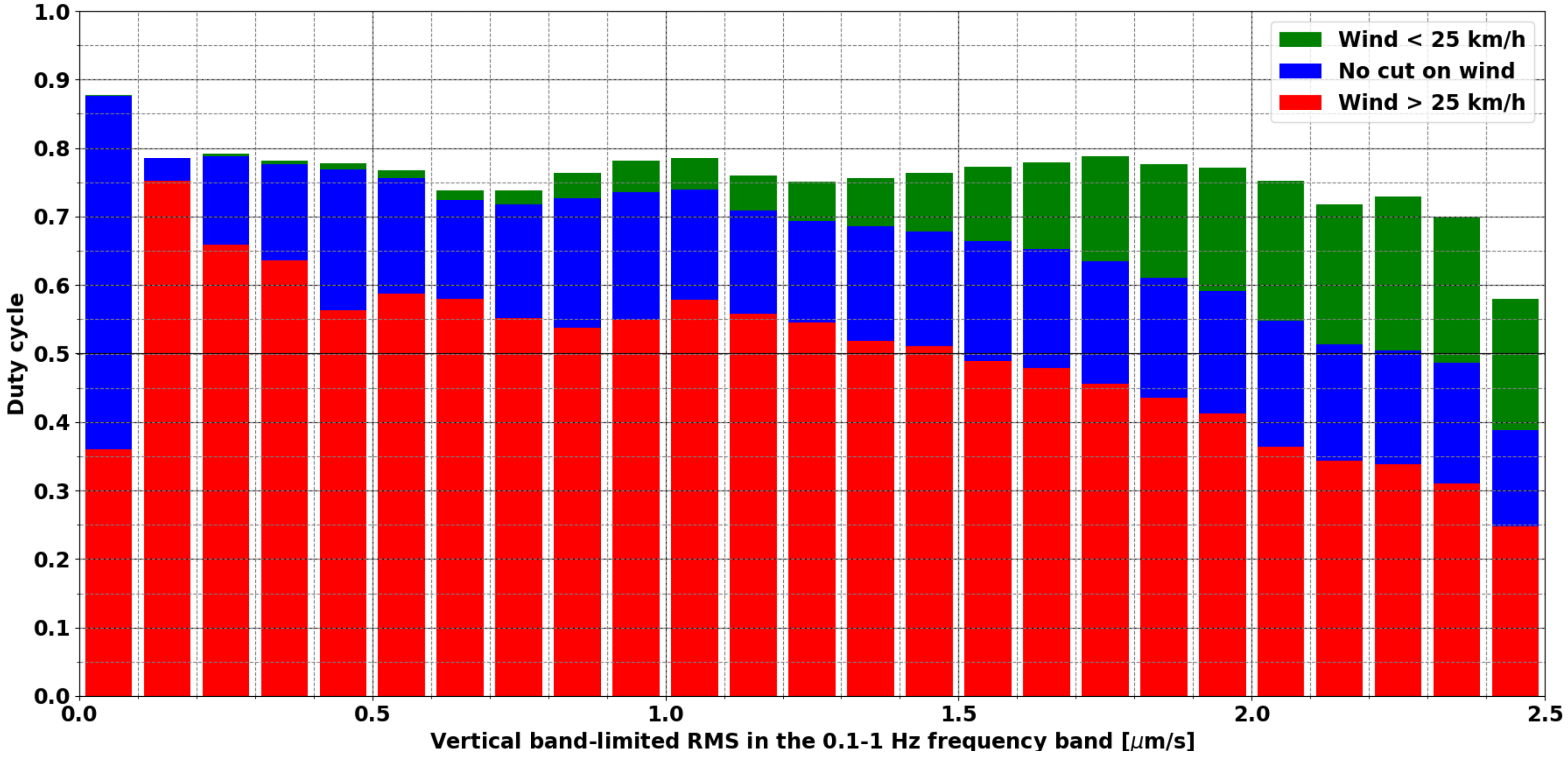
- Larger corrections to keep the detector control as the wind speed increases



→ 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

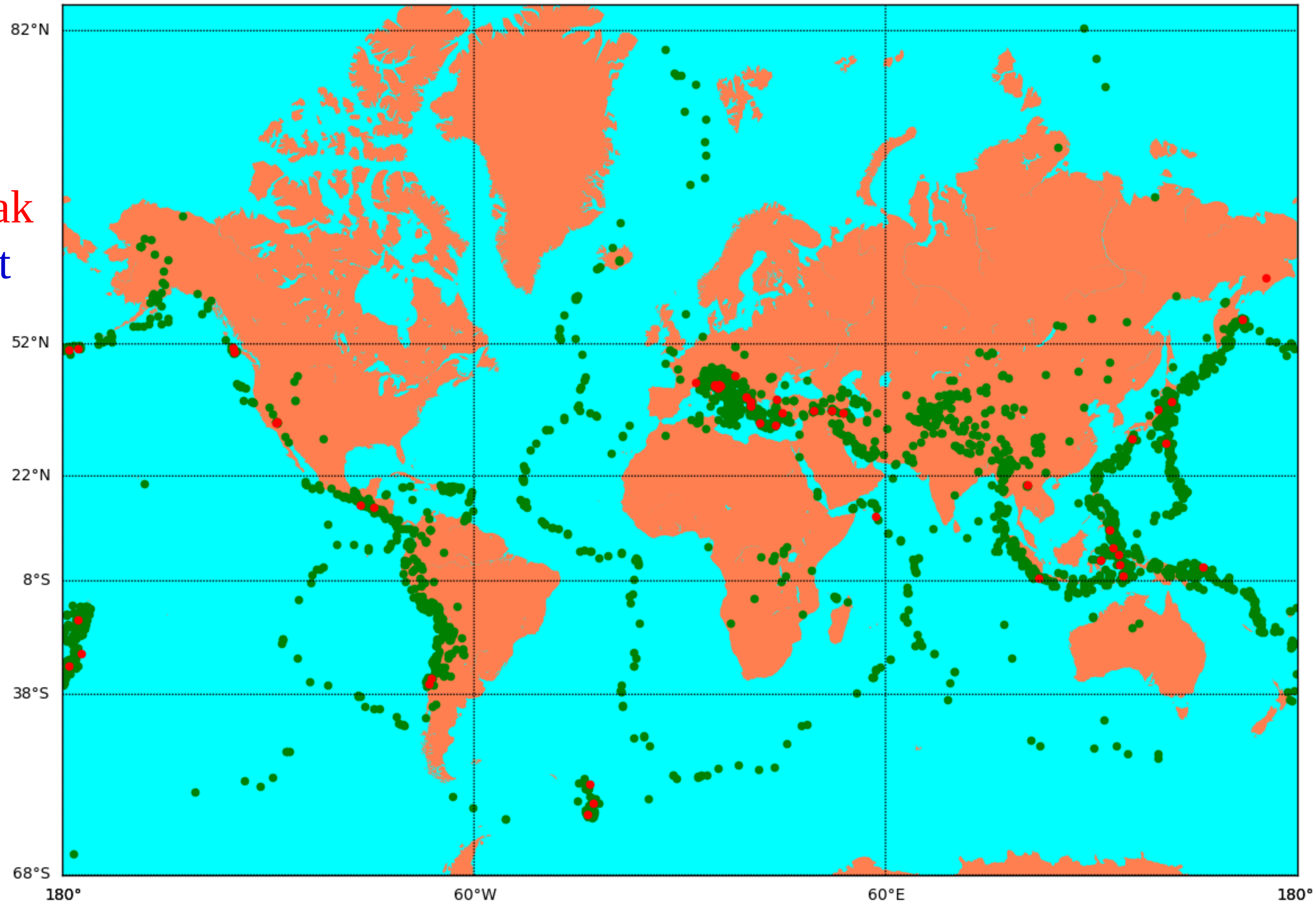
- 601 lock losses from Science mode during the whole O3 run
  - Less than 2 / day in average
  - Locking phase median duration: 25 minutes
    - Median number of attempts: 2

→ 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

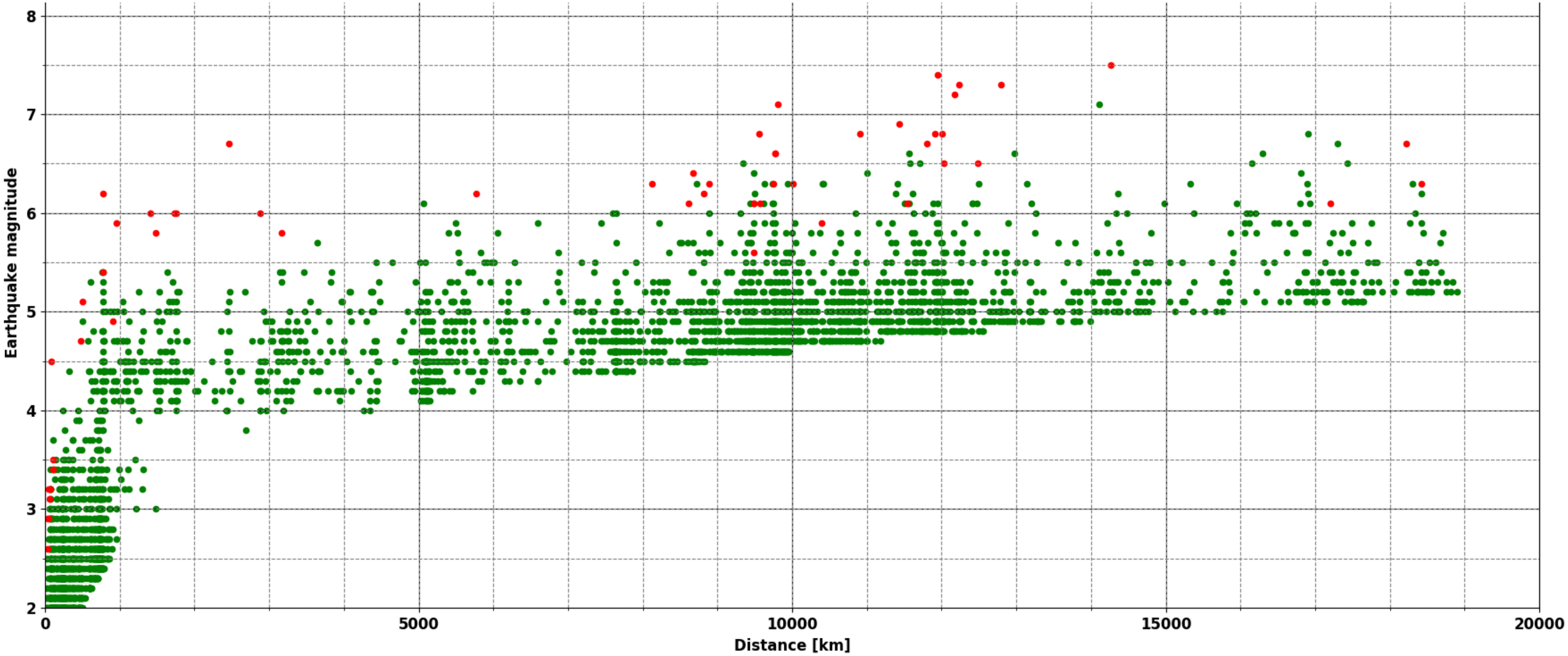
Earthquakes location

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



Earthquakes strength

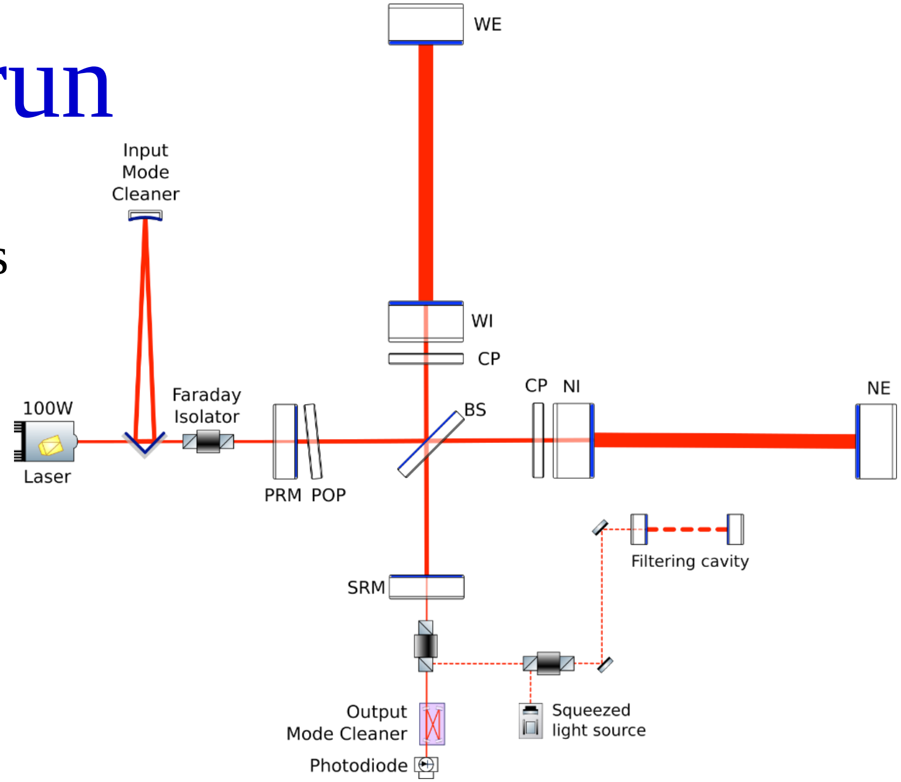
- Classification based on earthquake magnitude and epicenter distance
  - Green dots: earthquakes that did not led to a control loss
  - Red dots: earthquakes that led to a control loss



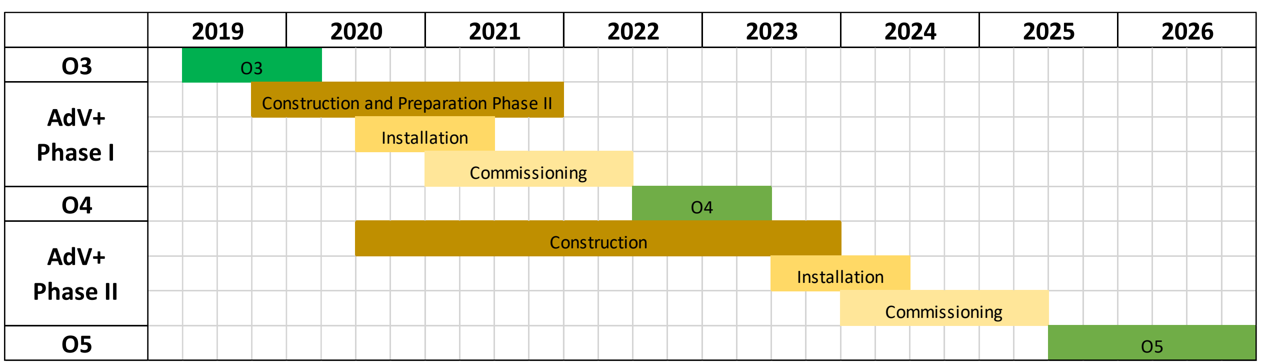
→ Magnitude and distance are key parameters

- Others may play a role as well (epicenter depth, azimuth)
- So probably does the actual state of the detector when seismic waves arrive

On the way to the O4 run



- Alternating data taking and upgrade periods
  - KAGRA detector joining LIGO-Virgo
- O4 run
  - Start: second semester 2022
    - Covid-19 pandemic permitting
- Virgo upgrade: “Advanced Virgo Plus”
  - Phase I: before the O4 run
    - New signal recycling mirror
    - Quantum noise reduction
    - Various hardware and technical improvements
  - Phase II: in between O4 and O5
    - Focusing on mirrors: larger / heavier + improved coating



Outlook

- O3: first long run for Advanced Virgo
  - Improved sensitivity
  - High duty cycle
  - Online since day 1 and for the whole duration of the run

→ Invaluable dataset to study in details the behavior of the detector
  - Robust overall against the external environment
  - Hard to identify large potential improvements
    - Complex global detector working point

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

- "Advanced Virgo Plus" phase I detector fully controlled for the first time 10 days ago
  - Major milestone / starting point for next steps
    - Additional upgrades
    - Control improvements: accuracy and stability
    - "Noise hunting" phase