LIGO and Virgo Detector Characterization and Data Quality: Contributions to the O3 Run and Preparation for O4

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EGO: European Gravitational Observatory
(Consortium, CNRS & INFN)

On behalf of the Virgo & LIGO DetChar groups

15th Pisa Meeting on Advanced Detectors – Elba, May 22-28, 2022

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Outline

- Ground-based gravitational wave (GW) detectors
- "DetChar" in a nutshell
- Detecting gravitational waves during the O3 run
- Transient and spectral noises
- Sensitivity improvements
- Validating GW candidates
- Preparing the O4 run and beyond

LIGO Hanford ("H1")

Virgo ("V1")

LIGO Livingston ("L1")

Ground-based GW detectors

- Suspended, power-recycled Michelson interferometer with 3-km long Fabry-Perot cavities in the arms

- Working point
  - Michelson on the dark fringe
  - All Fabry-Perot cavities resonant

  → Feedback control systems acting on the mirror positions and on the laser

- GW passing through
  - Differential effect on the arm optical paths

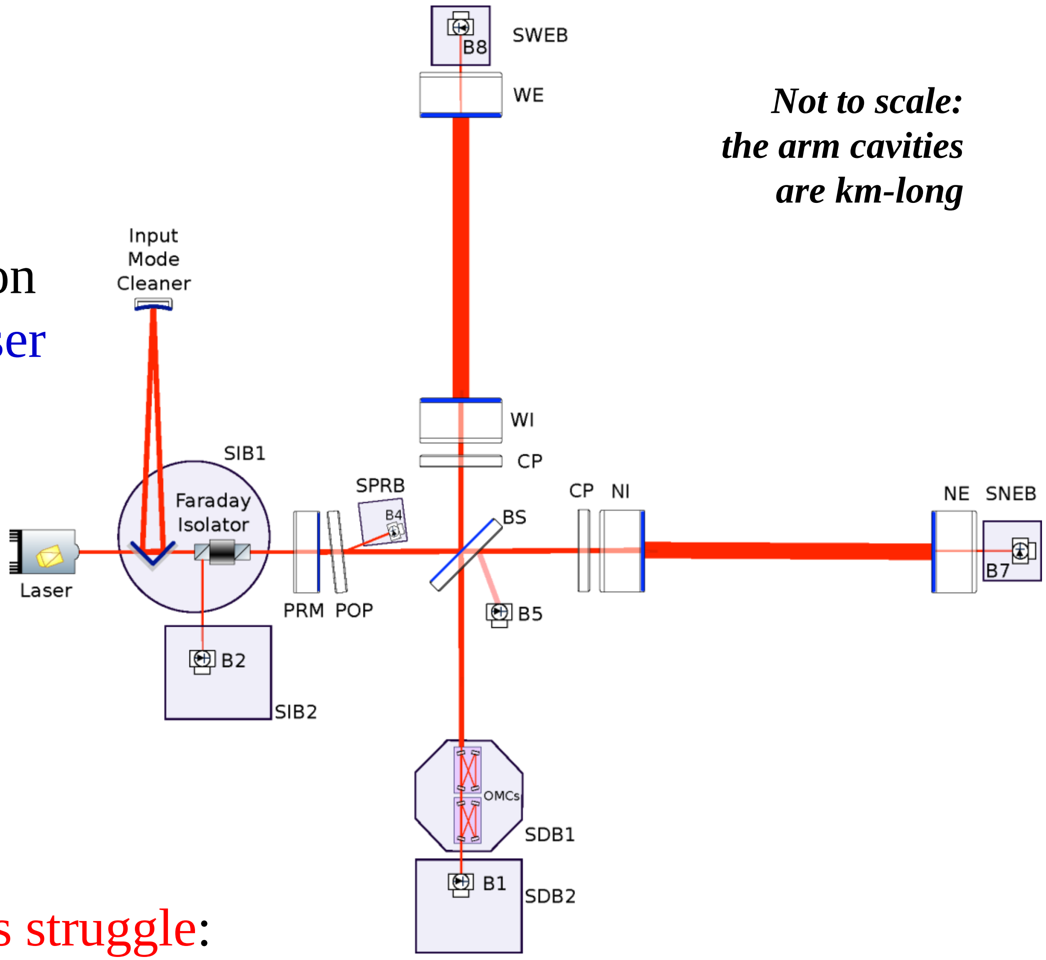
  → Change of interference condition at the detector output

  → Variation of the detected power

- Sensitivity limited by noises
  - Fundamental
  - Technical
  - Environmental

  Continuous struggle: design, improvement, noise hunting, mitigation

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



LIGO detectors are conceptually the same

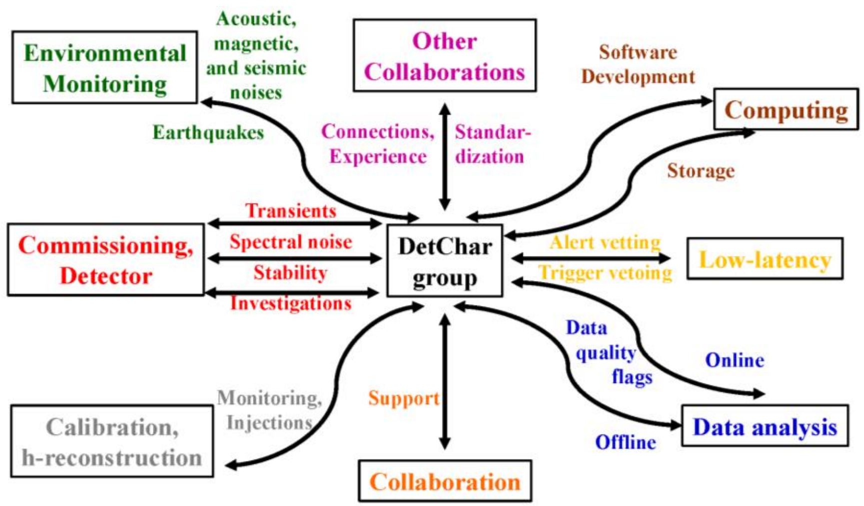
“DetChar” activities in a nutshell

- DetChar
  - Abbreviation for “detector characterization and data quality”
    → Includes / connects to many other topics – as described in the following

- Typical ‘instrument cycle’ for ground-based GW detectors
  - Upgrades → Commissioning → Data taking → Upgrades → (…)
  - Relevant DetChar activities during all steps
    - Track noise sources → Sensitivity
      → Average detection range for a given source
      Typical figure-of-merit: BNS (Binary Neutron Star) range
    - Help improving stability → Duty cycle

- Data quality
  - Global dataset
  - Individual GW candidates

- Focusing on two main levels
  - Single instrument
  - Global network as a whole



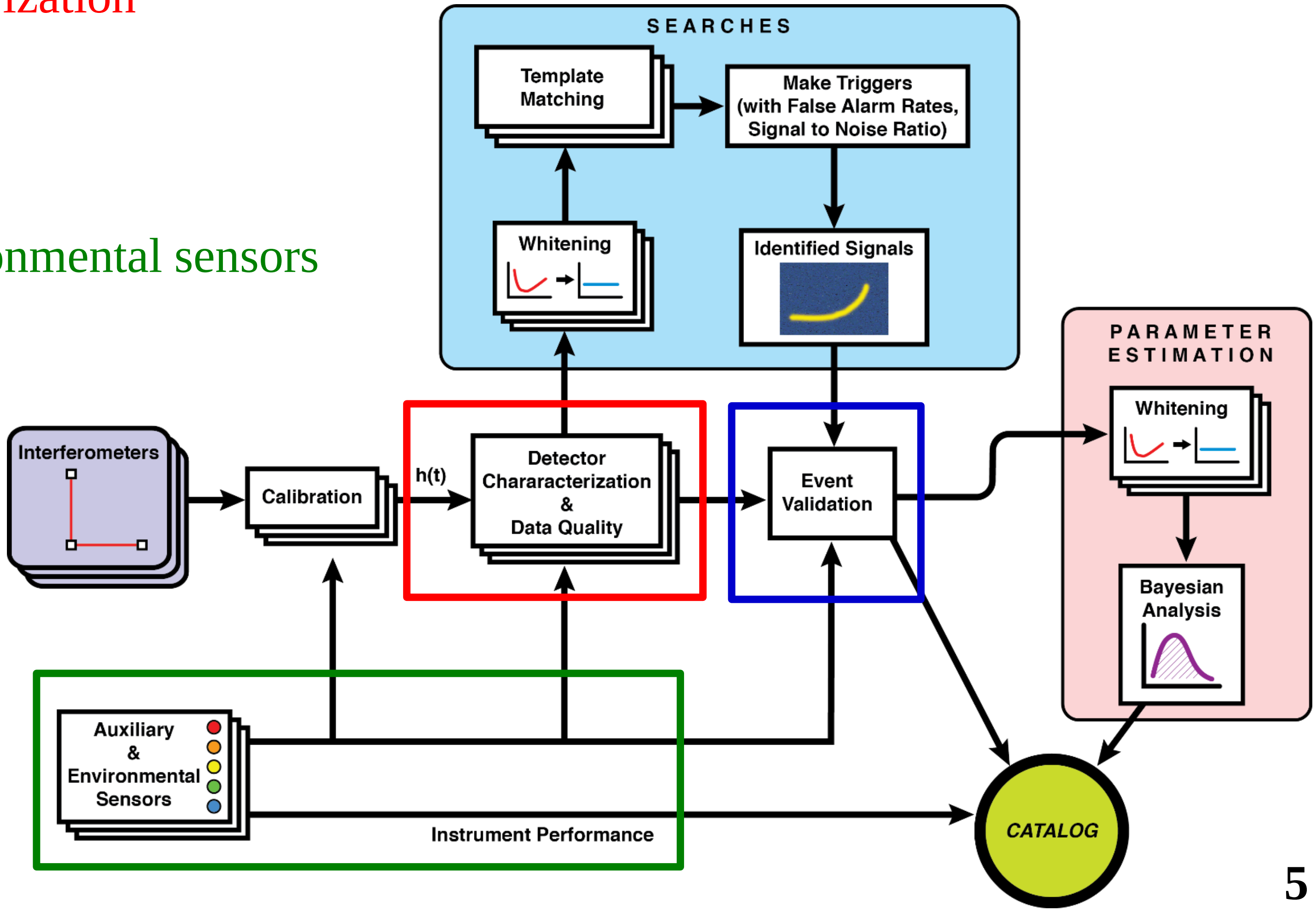
The stage: detecting gravitational waves

- From: **A guide to LIGO-Virgo detector noise and extraction of transient gravitational-wave signals**
  - [B. P. Abbott *et al.*, 2020 *Class. Quantum Grav.* **37** 055002]

- Detector Characterization & Data Quality

- Event validation

- Auxiliary & environmental sensors



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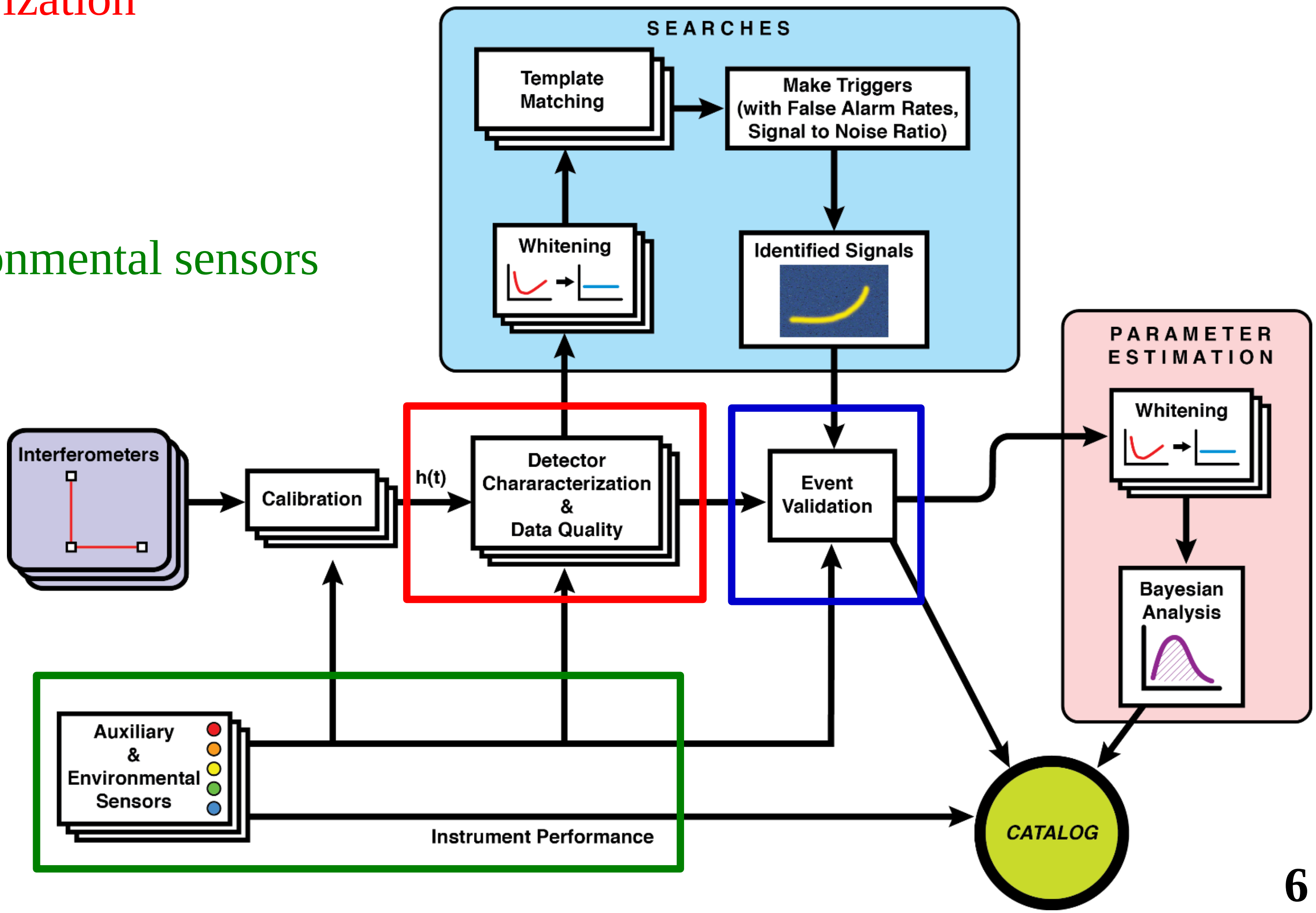
- Detector Characterization & Data Quality

- Event validation

- Auxiliary & environmental sensors

- Different latencies
  - Online
  - Offline
  - On-demand

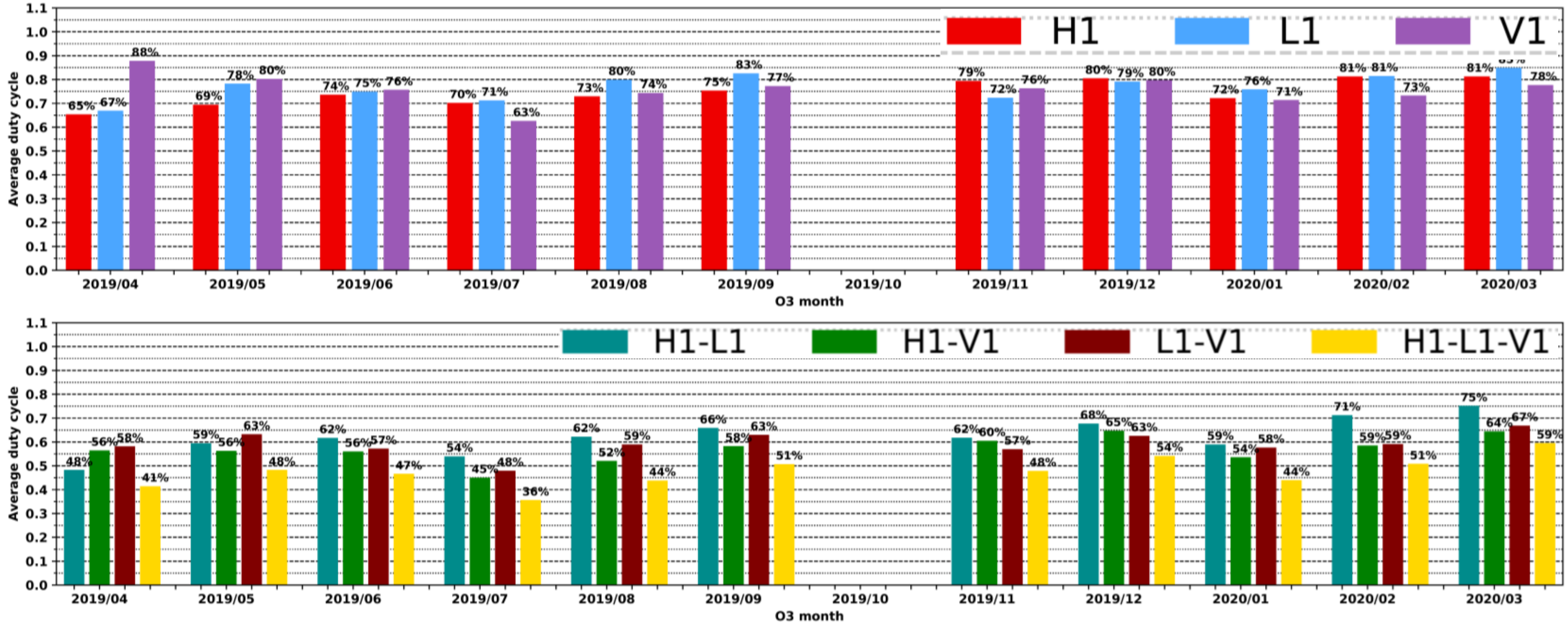
- Many monitoring levels
  - Detector
  - Network
  - Analyses



The O3 run

- LIGO-Virgo Observing run 3: O3
  → All 3 detectors from the beginning and 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 monthly duty cycles

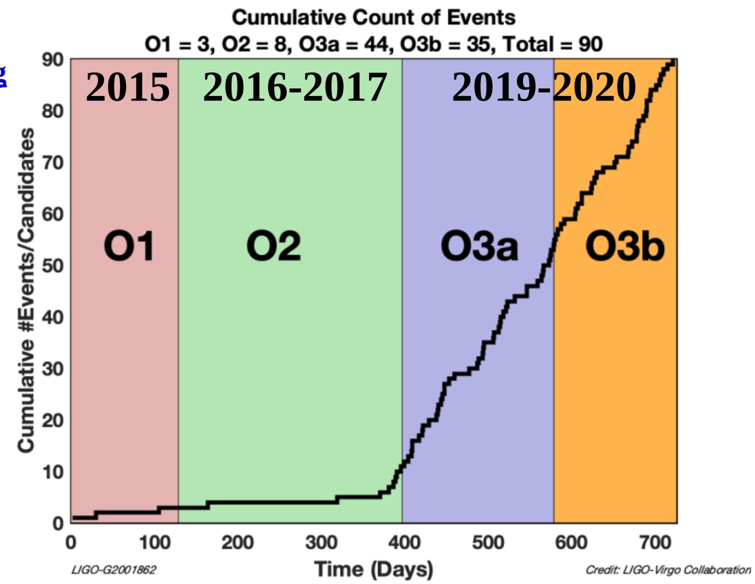


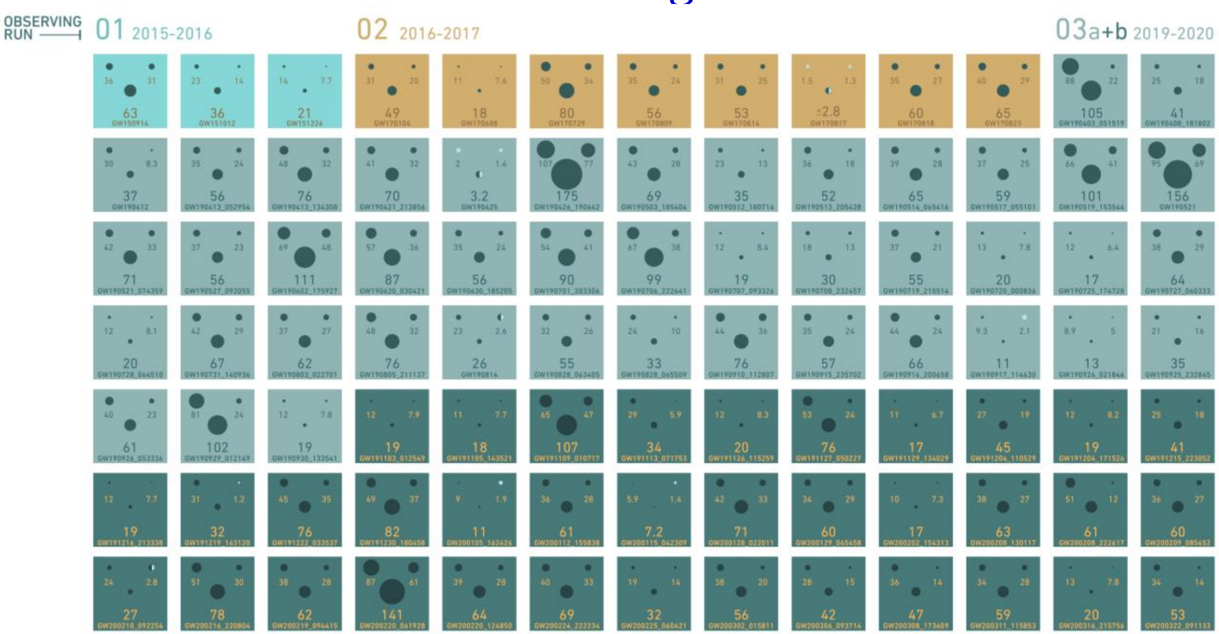
- Gravitational Wave Open Science Center: https://www.gw-openscience.org
  → Open data (for individual events and entire runs), software tools and tutorials

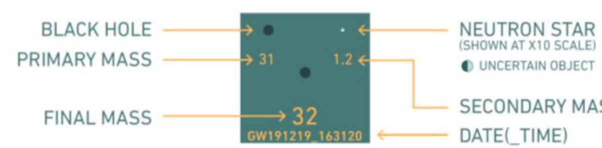
The O3 gravitational-wave signals

- O3: 79 new signals
  - All 3 types of compact binary mergers now observed
  - No new multi-messenger observation
  - Rates and populations studies
  - Tests of General Relativity
  - Targeted searches triggered by external inputs
    - GRBs, FRBs, supernovae, etc.
  - Searches for continuous signals

https://www.ligo.org/science/Publication-O3bTGR/images/cumulative_events_200322.png







UNITS ARE SOLAR MASSES

1 SOLAR MASS = 1.989×10^{30}kg

https://www.virgo-gw.eu/#news_gwtc3

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

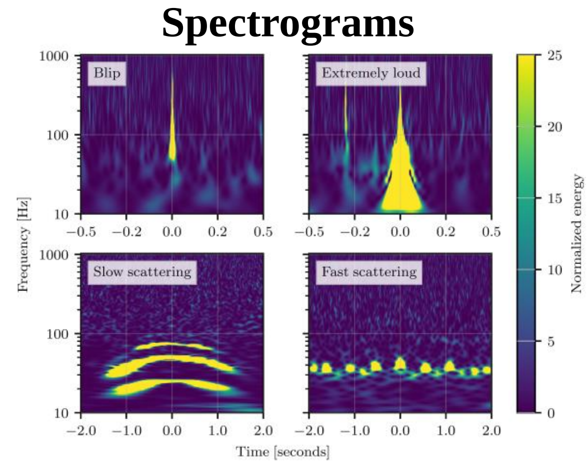
LIGO VIRGO KAGRA

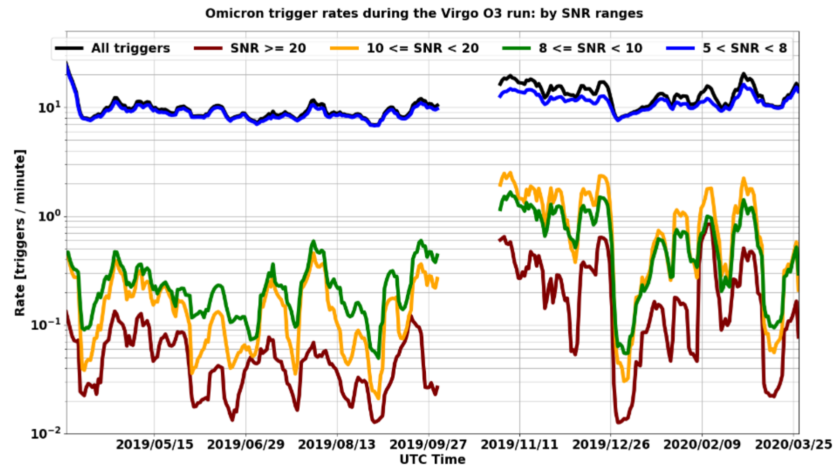
Transient noise

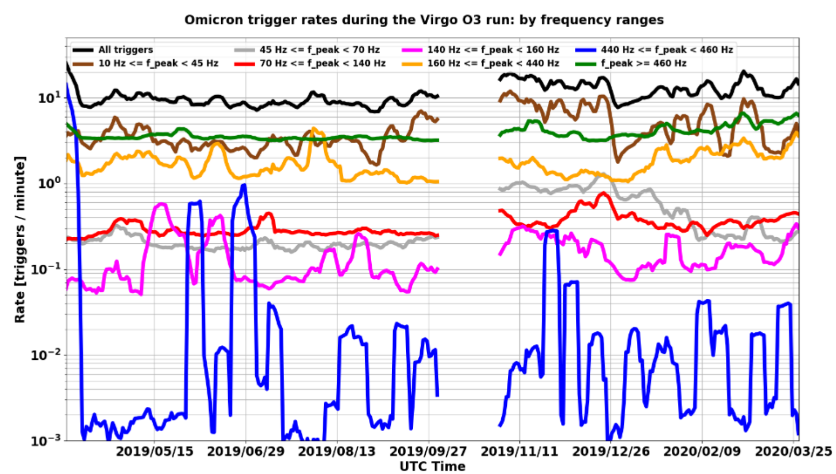
- Glitch: transient excess of noise
  with a distinctive time-frequency signature
  - Duration
  - Bandwidth
  - Signal-to-noise ratio (SNR)

- Multiple origins
  - Hardware equipment
  - Software (controls, etc.)
  - Unknown, with witness channels
  - Unknown and no witness channel

- Manifold damages
  - Decrease GW search sensitivity
  - Hide actual GW signal
  - Worsen stability

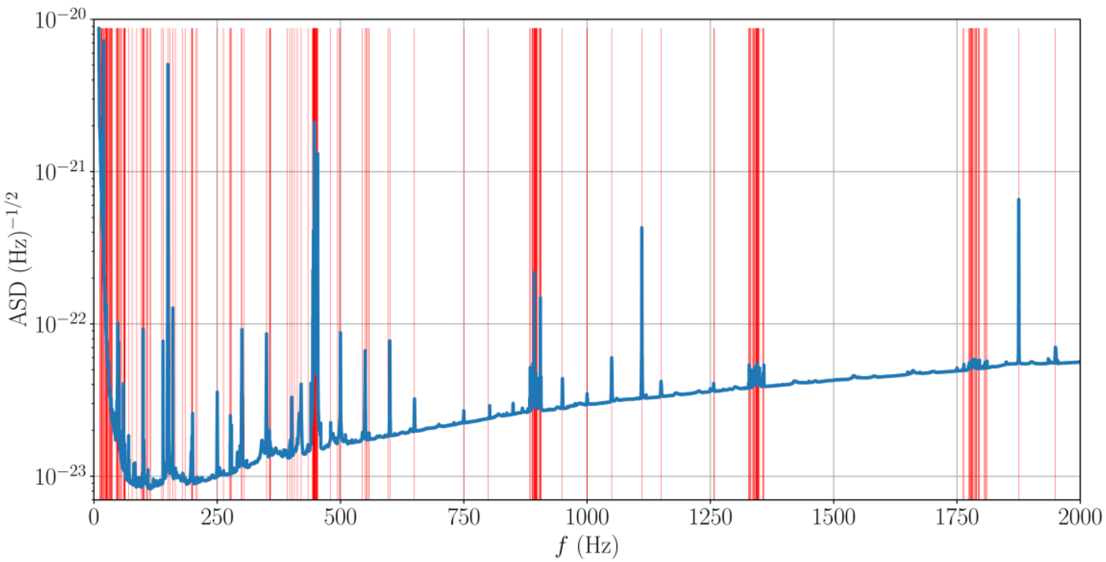






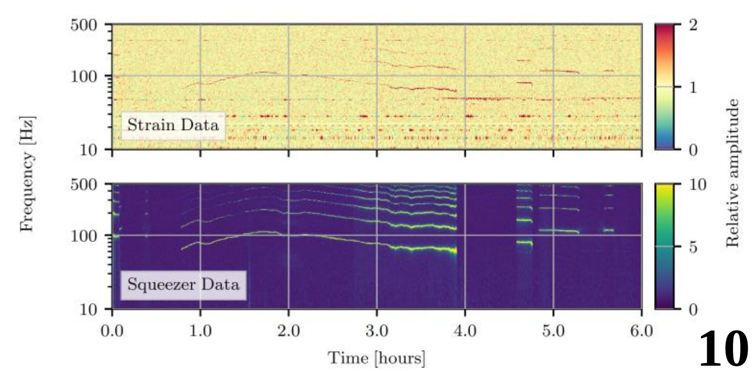
Spectral noise

- Excess power on long timescale in a given frequency range
  - Narrow lines or wider bumps
  - Many different types: fundamental, harmonic, comb, sideband, modulation, etc.
- Potentially cover real GW signal in the same frequency range
- Hardware or software artefact may mimic, to some extent, a real GW signal
  → Some only appear when analyzing the whole dataset

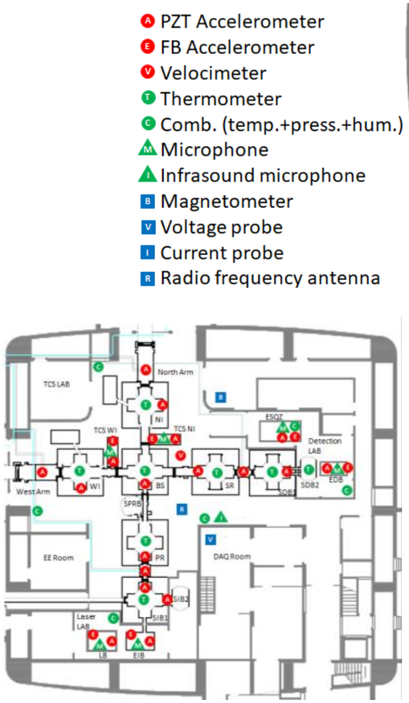


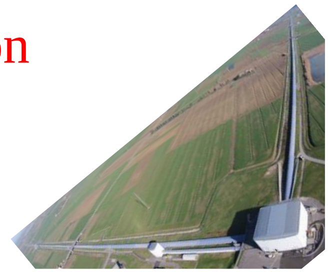
Typical "lin.-log." Virgo O3 amplitude spectrum density

- Noises may appear/disappear/change over time
- Coherent magnetic noise between sites: Schumann resonances

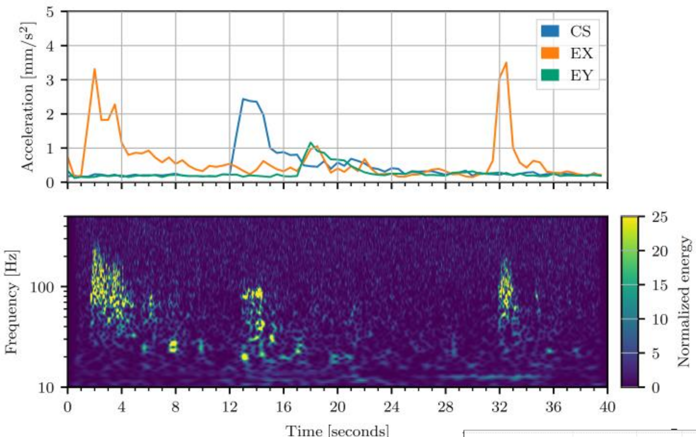


Fighting noises





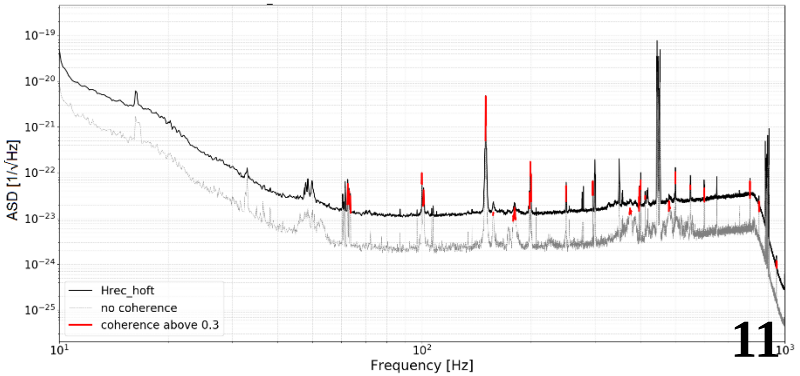
- Ideal scenario
  - Pick-up a frequency range of interest
  - Find the origin of the dominant noise contribution
  - Fix the cause, or mitigate its effect
  - The dominant noise goes down:
    another one starts dominating the sensibility
  - Iterate…



→ In practice, we rely a lot on auxiliary channels and environmental sensors
  - Most of the acquired data

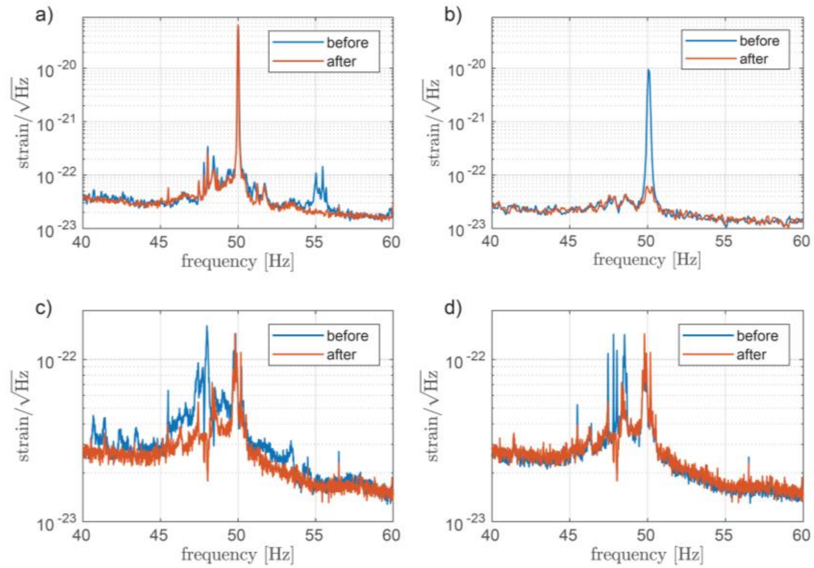
- To help identifying the source of a given noise, we look for
  - Correlations in the time domain
  - Coherences in the frequency domain

  → Neither of these implying causation a priori

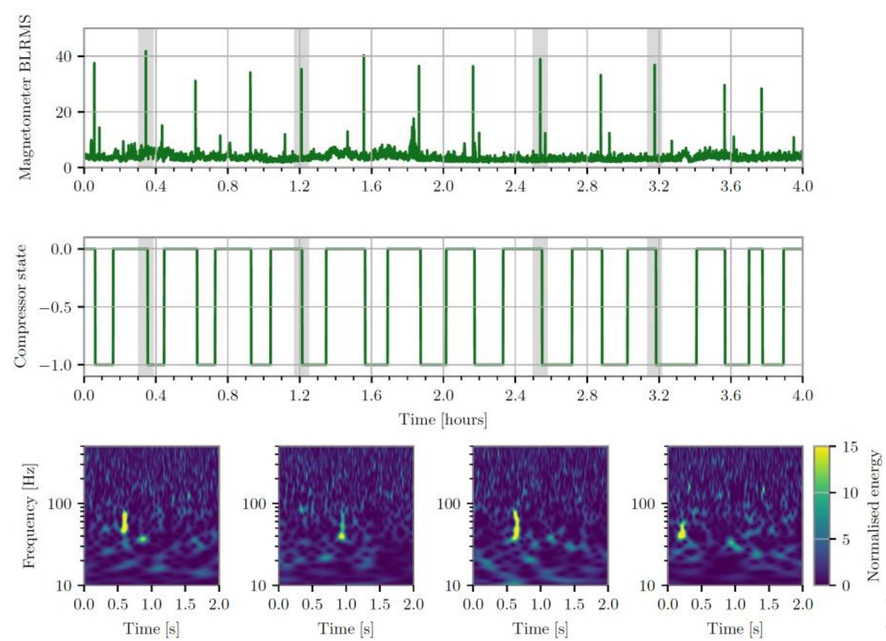


Fighting noises: two examples

- Successive reductions of noise around 50 Hz (mains frequency in Italy) in Virgo
  a) Reducing bumps around 50 and 55 Hz
  b) Reducing the 50 Hz peak
  c)-d) Cleaning structures
  below and above 50 Hz
  → At each step: before
  after

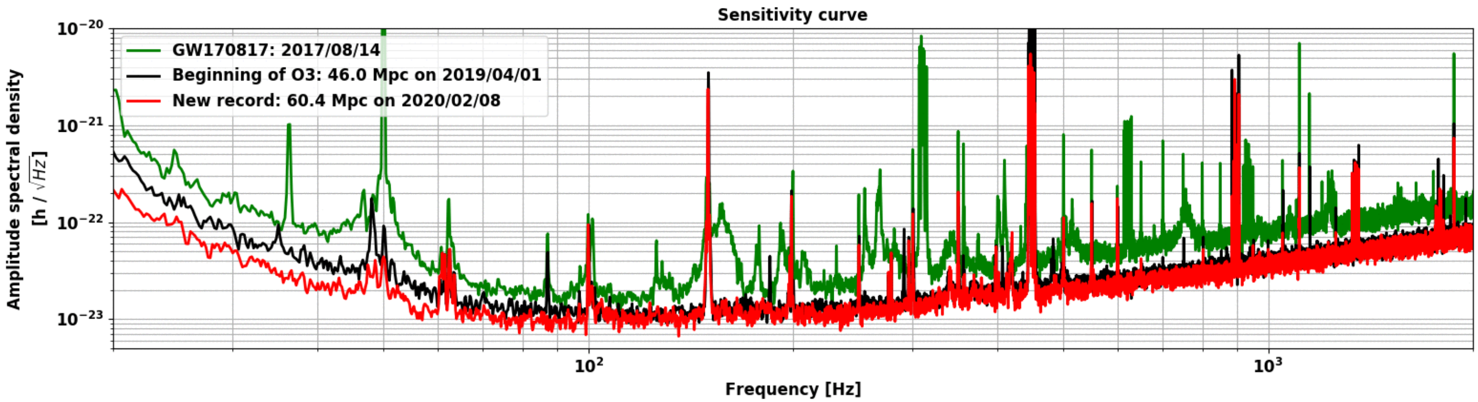


- Noise created by a compressor in LIGO
  - Top: signal in a magnetometer
  - Middle: compressor on/off sequence
  - Bottom: glitches in the GW signal

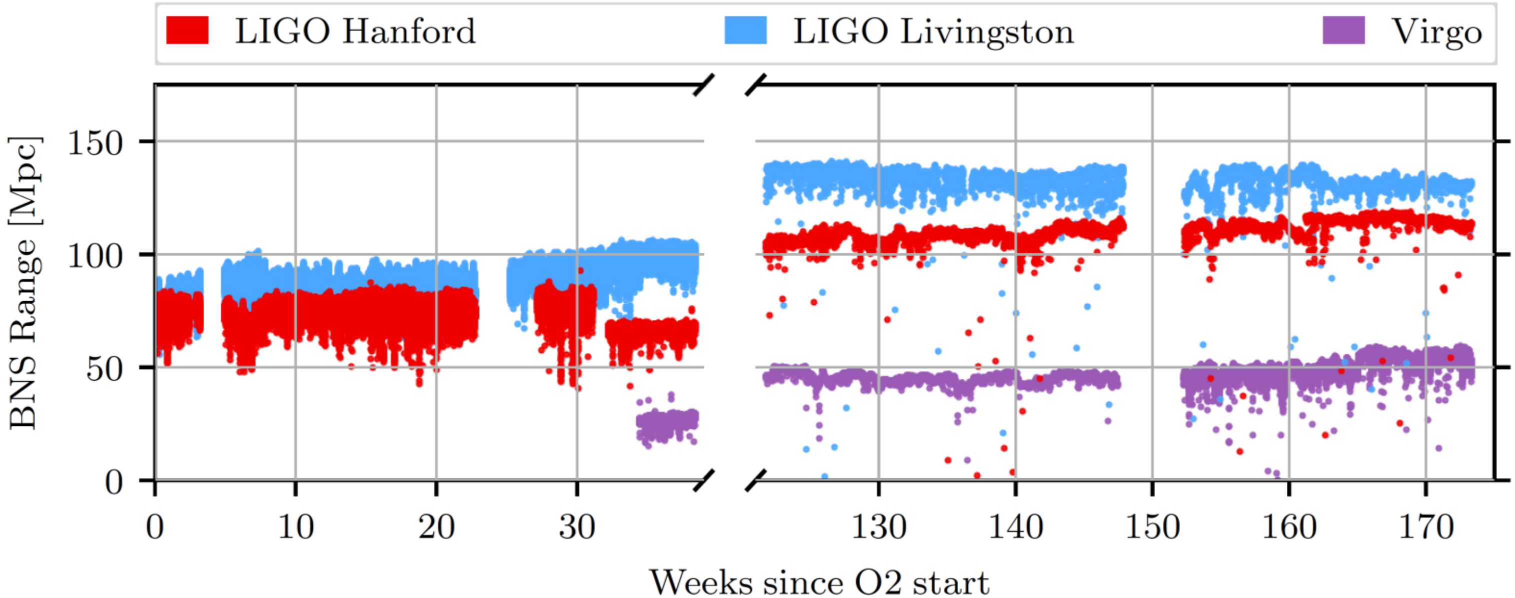


Performance improvement

- Virgo sensitivity O2-O3 progress [2017-2020]

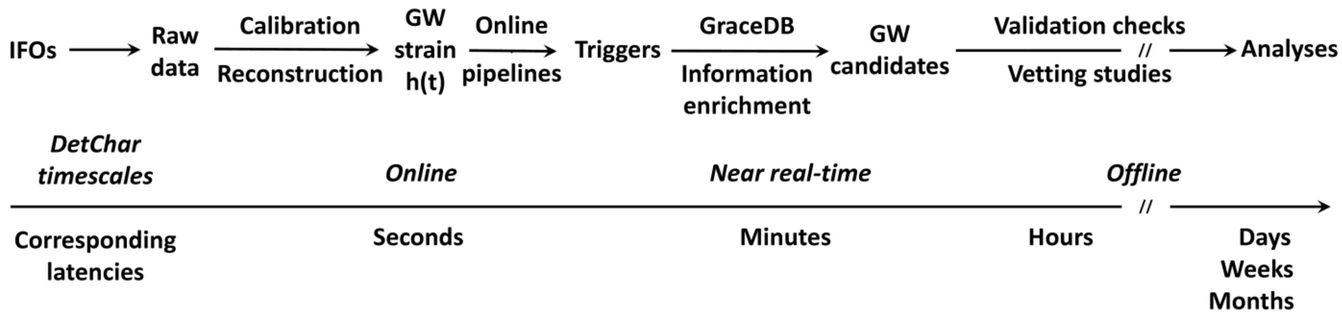


- O2-O3 network BNS ranges [2016-2020]

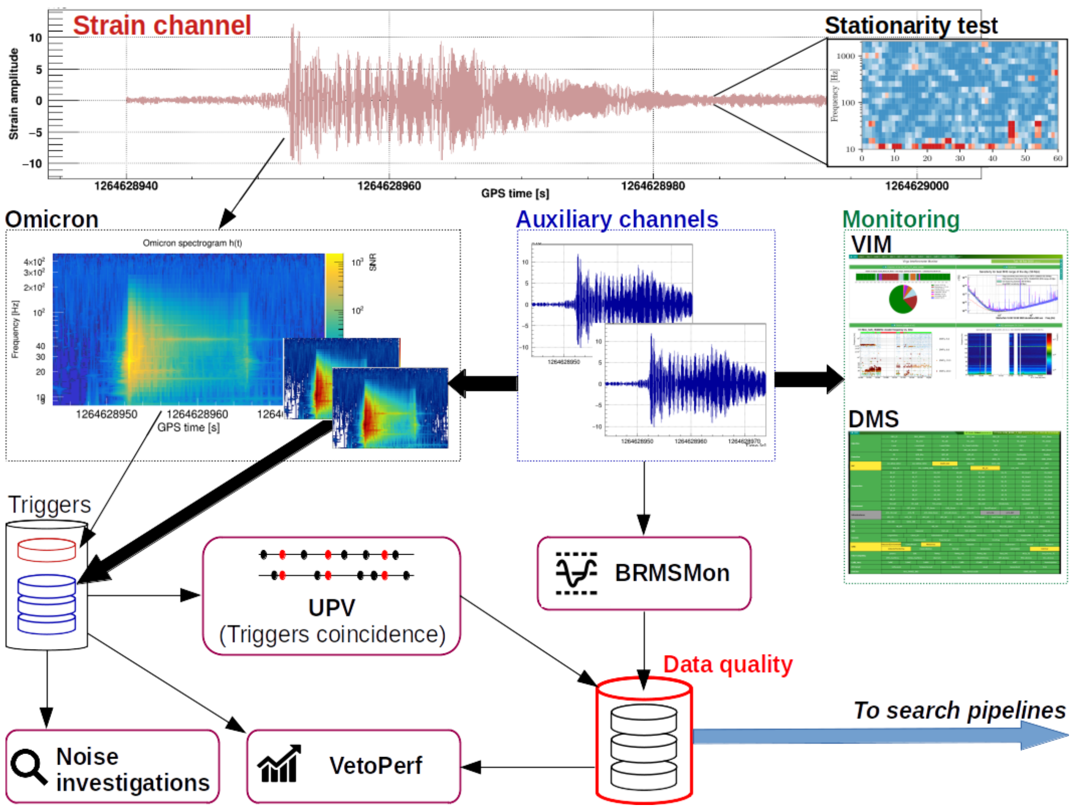


Event validation

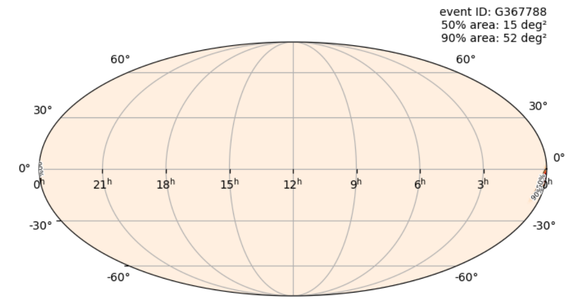
- Vet GW candidates
  - Data quality
  - Consistency checks



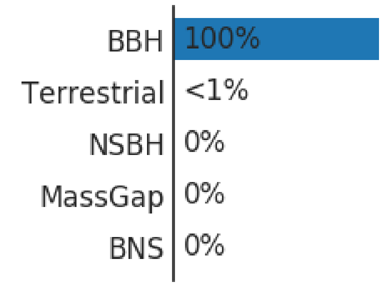
- Global transient noise investigations
  - All DetChar tools working together to provide the most complete set of information



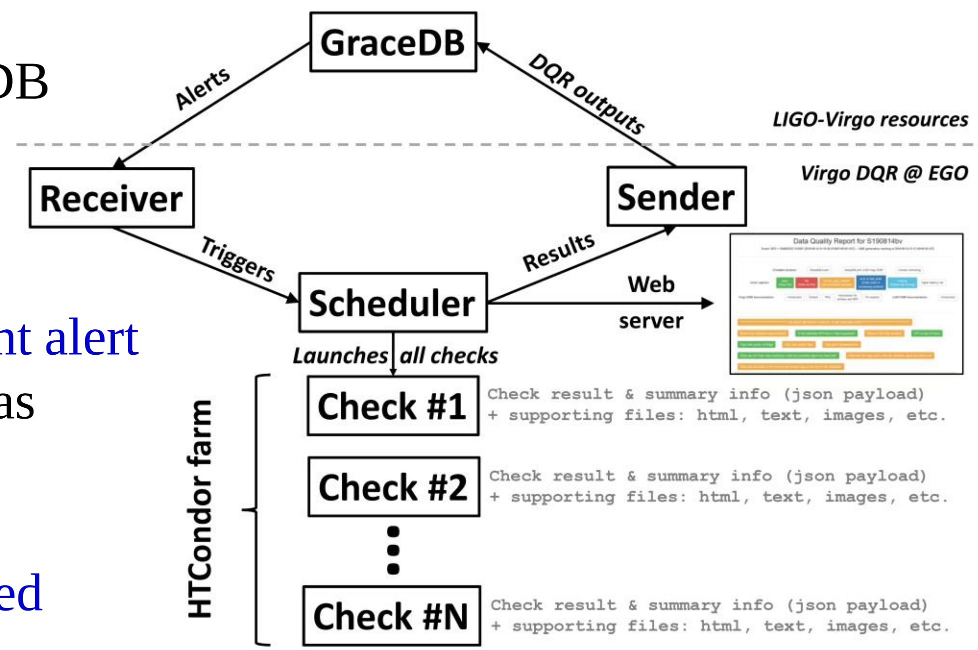
Vetting alerts in low latency



- Goals: confirm/retract public alerts in O(few minutes)
  - Dedicated database with a public-facing interface: GraceDB
    https://gracedb.ligo.org/superevents/public/O3
  - Public information: GPS time, type of event, skymap
  - Use of the Gamma-ray Coordination Network (GCN)



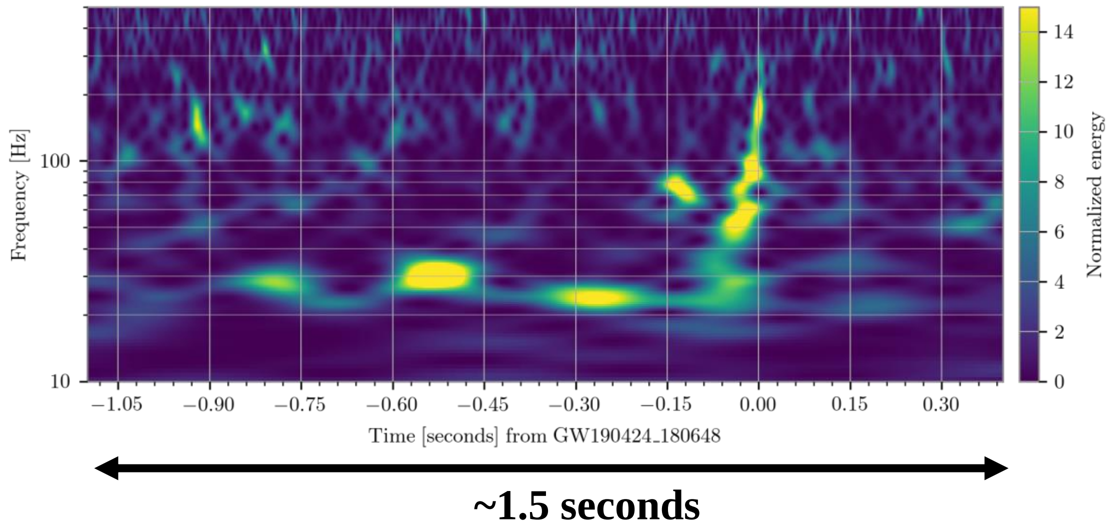
- Key tool: the Data Quality Reports
  → Set of automated checks triggered upon receiving an alert from GraceDB
    - Example: the Virgo O3 DQR



- Rapid Response Team meeting at short notice immediately after each significant alert
  - On-duty experts from all relevant areas
    - Including DetChar
  → Deciding the fate of the alert
    - O3: 80 alerts, of which 24 retracted

Gravitational-wave candidate validation

- Identifying real signals and separating them from possible glitches



→ Situation can be as complicated as the spectrogram above (from O3a)

Gravitational-wave candidate validation

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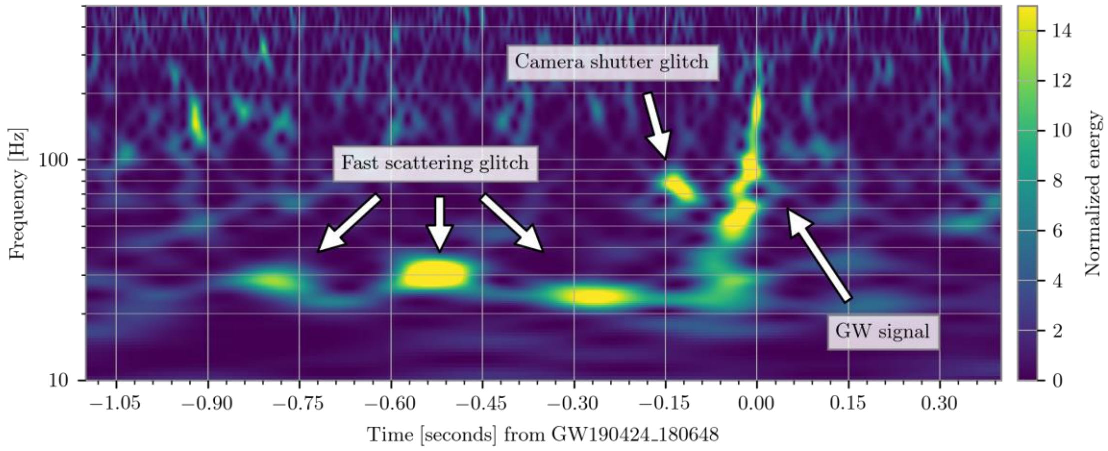


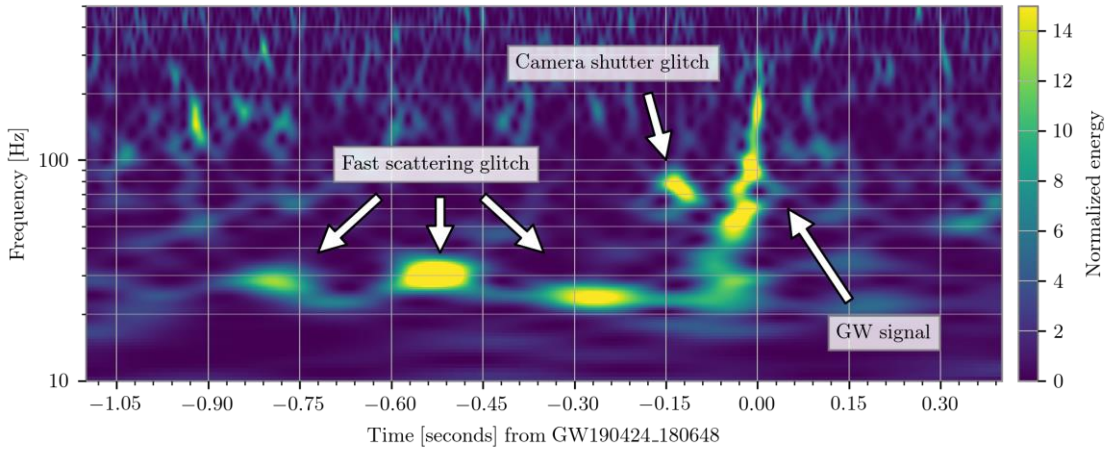
- Scattered light noise
  - Parasitic beam created by imperfections (optics defect, misalignment, etc.), scattering off some moving surface and recombining to one of the main interferometer beams
    - Glitches, control inaccuracies

→ One of the main noise sources for all detectors in the network

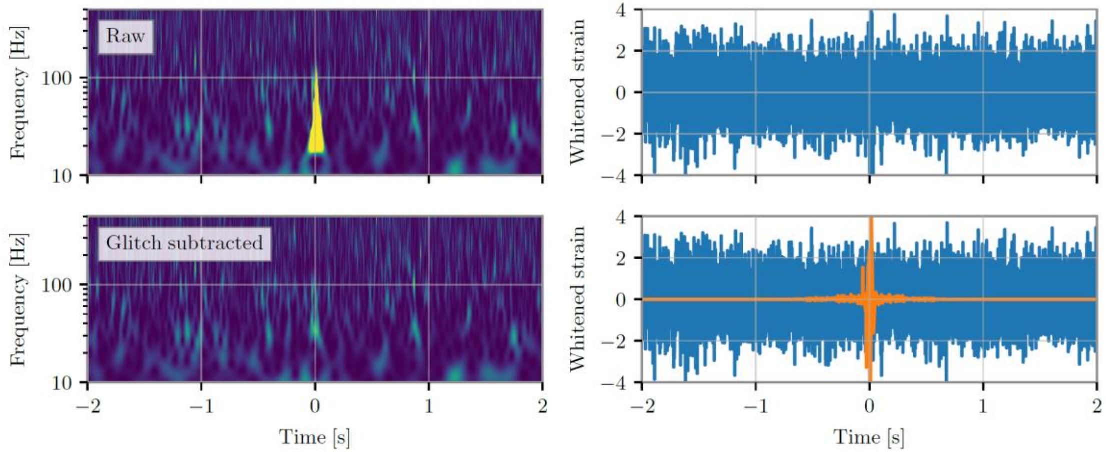
→ Mitigations: isolate more / suspend further hardware components, dump parasitic beams onto absorbing surfaces

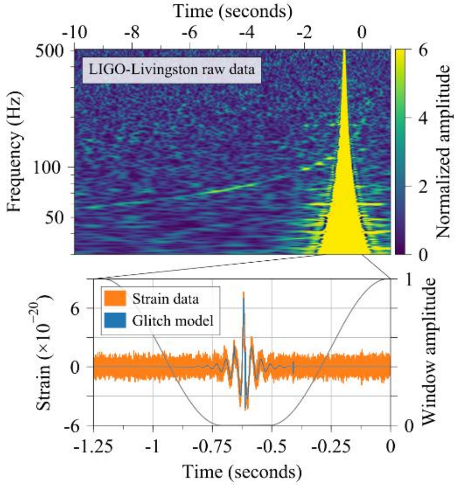
Gravitational-wave candidate validation

- Identifying real signals and separating them from possible glitches



- Assess whether data quality issues could bias the estimation of the source parameters
  - If yes the glitch(es) can be excised from the data – first done for GW170817

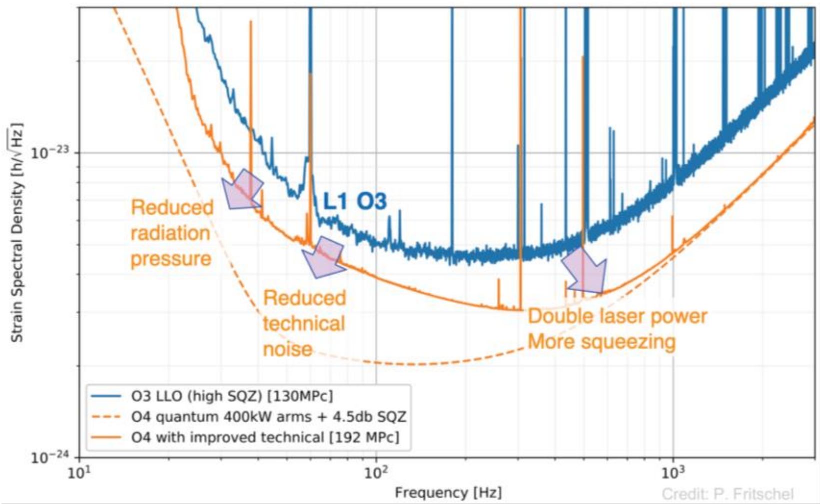


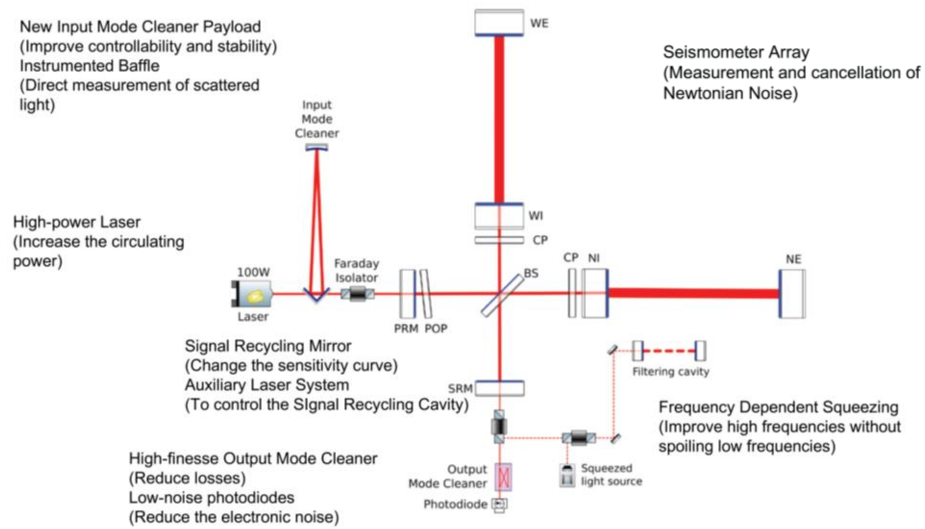


From O3 to O4

https://dcc.ligo.org/LIGO-G2200736/public

- Major upgrades on all detectors
  → Should lead to significant sensitivity improvements
  - LIGO
    - Doubling arm power (~400 kW)
    - Reduce further quantum noises
    - Reduce technical noises below ~100 Hz
  - Virgo
    - Project Advanced Virgo+, Phase I [Phase II after O4 run]



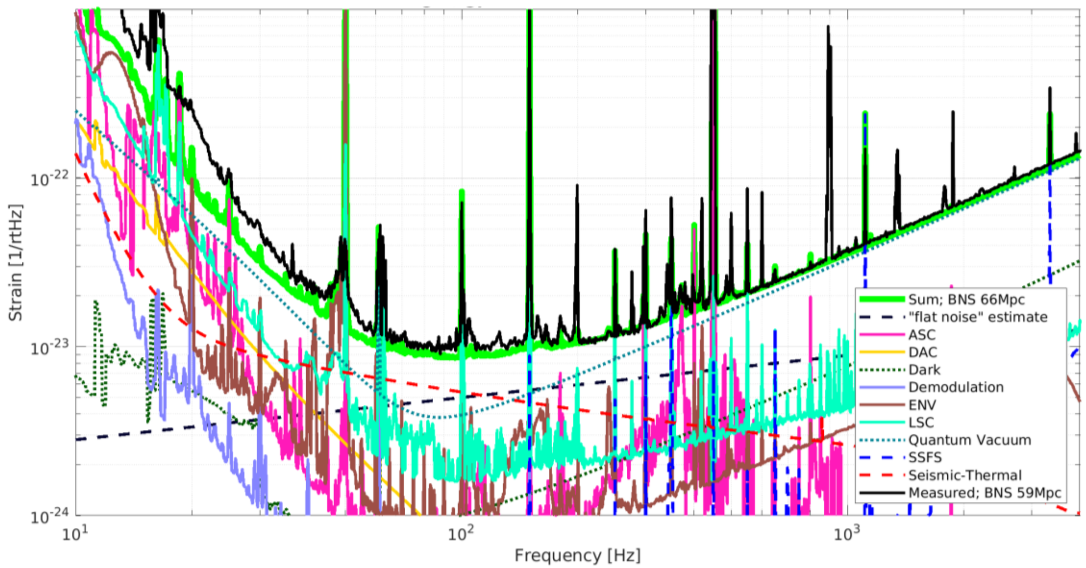


- KAGRA (Kamioka, Japan) joining the network

- Planned schedule impacted by worldwide covid-19 pandemic
  - O4 is currently expected to start at the end of 2022, for about a year

DetChar: O4 preparation

- Characterization of the upgraded ("new") detectors
  - So-called "noise hunting" phase
  - Noise budget
    - Example from O3 for Virgo

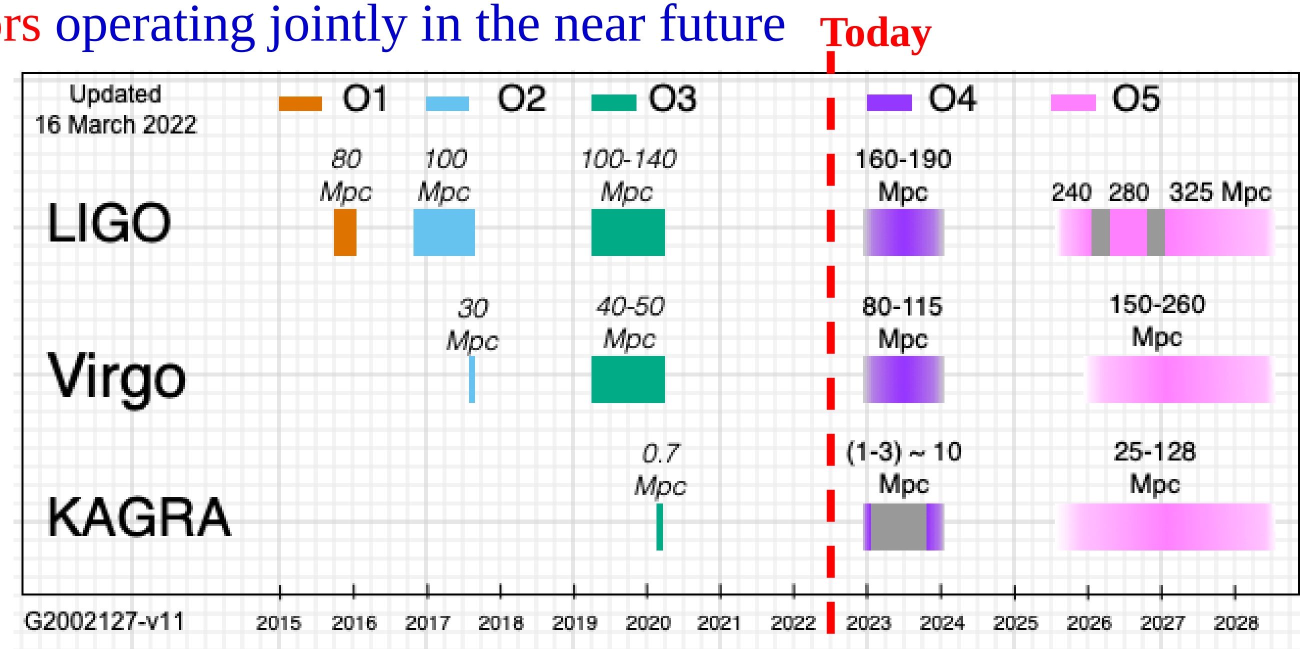


- Prepare for a larger rate of GW signals with personpower not scaling up the same way
  - Continue automation of current DetChar methods and tools
  - Reduce their latency and increase the rate at which these analyses will run
  - Extend the scope of DetChar monitoring
  - Study the impact of data quality issues on the increasing number of detections
  - Prepare for potential detections of new GW sources

Outlook: O4 and beyond

- O4 run to start by the end of the year
  - Schedule still subject to changes
    → Up-to-date information: https://www.ligo.org/scientists/GWEMalerts.php

- LIGO-Virgo-KAGRA network
  - 4 detectors operating jointly in the near future



https://www.ligo.org/scientists/ObsScen_timelineMarch2022.png

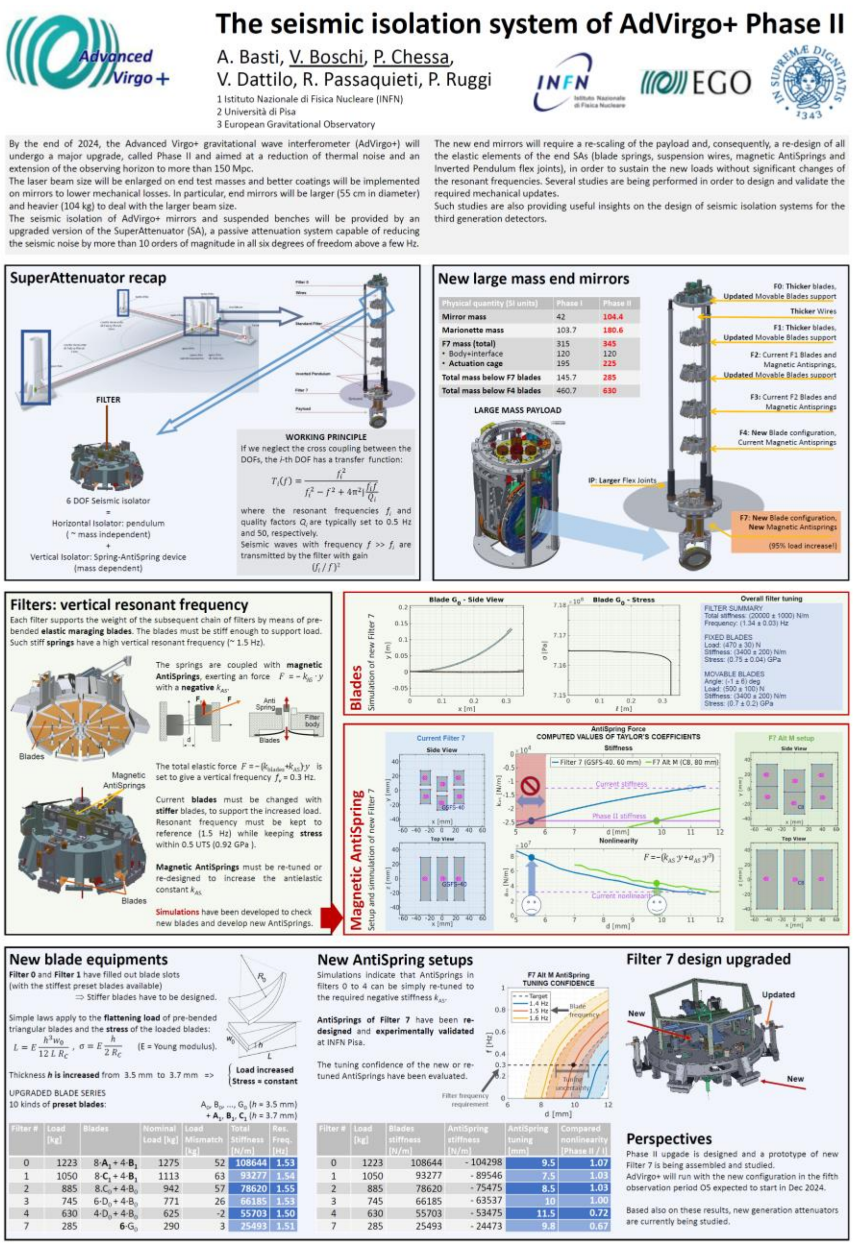
- Then another upgrade period followed by the O5 run
  - Temptative schedule
  - Post-O5 plans are being developed

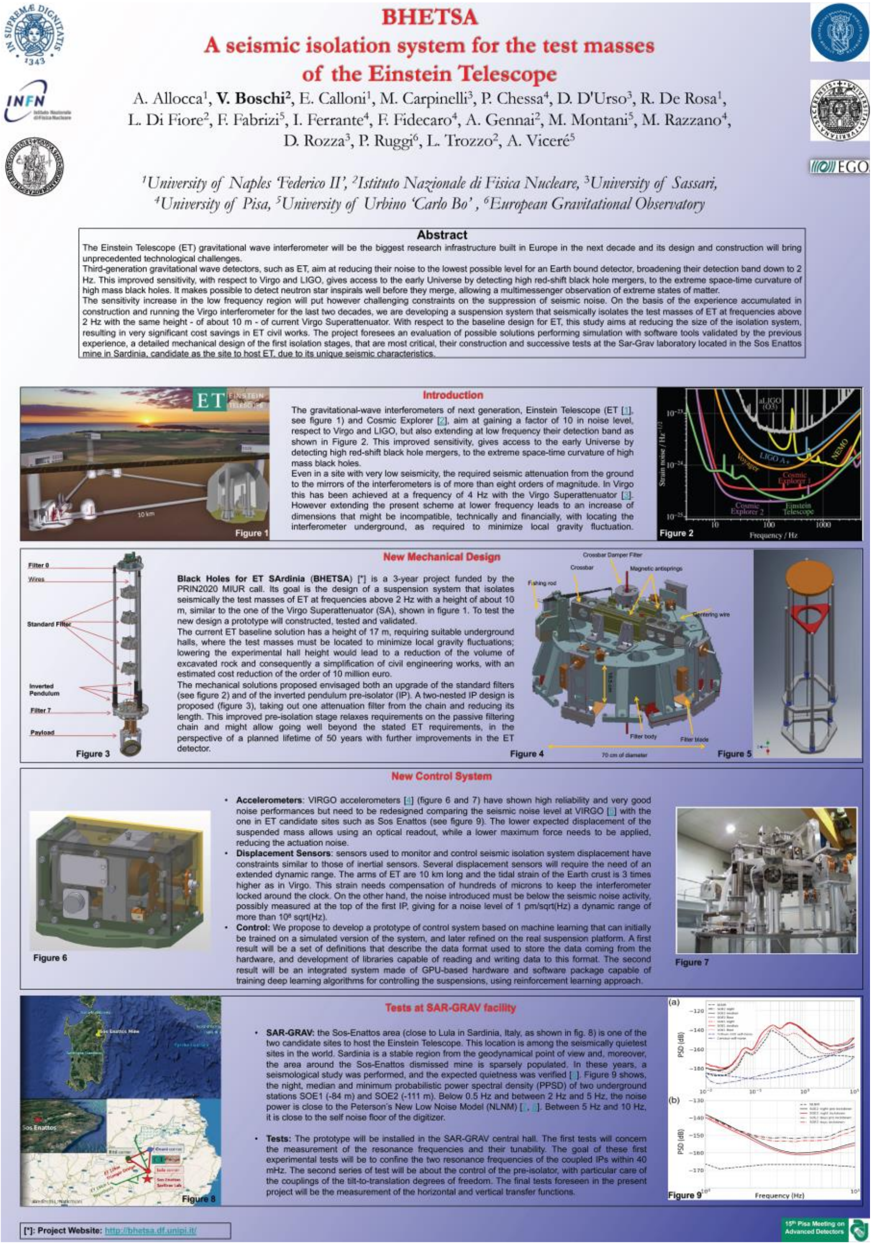
Recent DetChar references

- Virgo References
  - **Virgo Detector Characterization and Data Quality during the O3 run**
    - arXiv:2205.01555 [gr-qc]
    - Submitted to *Class. Quantum Grav.*
  - **The Virgo O3 run and the impact of the environment**
    - arXiv:2203.04014 [gr-qc]
    - Submitted to *Class. Quantum Grav.*

- LIGO References
  - **LIGO Detector Characterization in the Second and Third Observing Runs**
    - D. Davis *et al.*, 2021 *Class. Quantum Grav.* **38** 135014
    - arXiv:2101.11673 [astro-ph.IM]
  - **Detector Characterization and Mitigation of Noise in Ground-Based Gravitational-Wave Interferometers**
    - D. Davis and M. Walker Galaxies 2022, **10**(1), 12
  - **Environmental noise in advanced LIGO detectors**
    - P. Nguyen *et al.*, 2021 *Class. Quantum Grav.* **38** 145001
    - arXiv:2101.09935 [astro-ph.IM]
  - **Sensitivity and Performance of the Advanced LIGO Detectors in the Third Observing Run**
    - A. Buikema *et al.*, 2020 *Phys. Rev. D* **102**, 062003
    - arXiv:2008.01301 [astro-ph.IM]

Posters on the Virgo and ET suspensions





Latest O4 update

- https://www.ligo.org/scientists/GWEMalerts.php
  → Redirecting to https://observing.docs.ligo.org/plan

LIGO, VIRGO AND KAGRA OBSERVING RUN PLANS

(15 May 2022 update; next update by 15 July 2022)

LIGO, Virgo, and KAGRA are closely coordinating to start the O4 Observing run together. We plan to start the O4 Observing run in mid-December 2022, with an Engineering Run to start in mid-November; low-latency alerts for candidate events identified during engineering time may be released, both to exercise the system and to exploit their scientific value.

At present, the run is planned to start with only LIGO Hanford, Virgo, and KAGRA. While the commissioning of the detectors is progressing, the plan towards readiness is being reviewed. The completion of LIGO Livingston's upgrades is taking longer than planned. We project that Livingston could join the run in February 2023, but we are looking into options to reduce the delay.

The projected sensitivity of the detectors remains unchanged: LIGO projects a sensitivity goal of 160-190 Mpc for binary neutron stars. Virgo projects a target sensitivity of 80-115 Mpc. KAGRA should be running with greater than 1 Mpc sensitivity at the beginning of O4, and will work to improve the sensitivity toward the end of O4.