From public alerts to gravitational-wave candidates during the LIGO-Virgo third observation run O3

Nicolas Arnaud

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On behalf of the Virgo Collaboration and the LIGO Scientific Collaboration

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LIGO Scientific Collaboration

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VIRGO

EGO EUROPEAN GRAVITATIONAL OBSERVATORY

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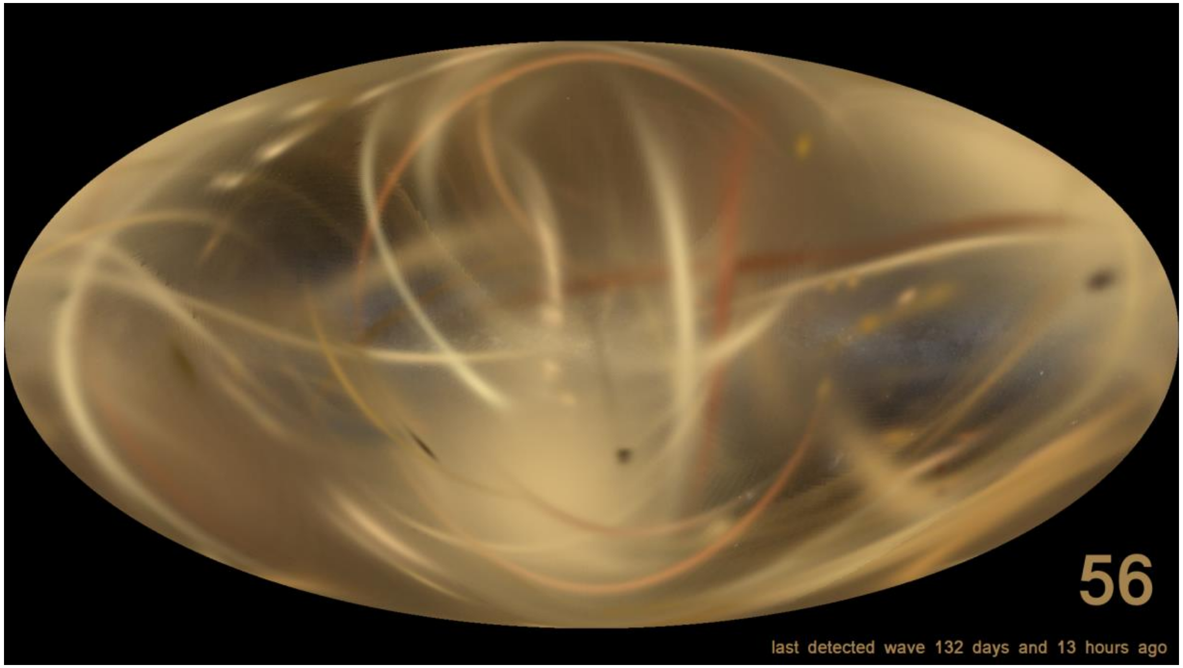
Outline

- Detecting gravitational waves with the global LIGO-Virgo network
- The LIGO-Virgo third Observing Run: O3
- Detector Characterization and Data Quality
- Public alerts
  - Dataflow and associated latency
  - Vetting alerts in real time with data quality reports
  - Statistics for O3
- Outlook
  - The path to the fourth Observing Run: O4

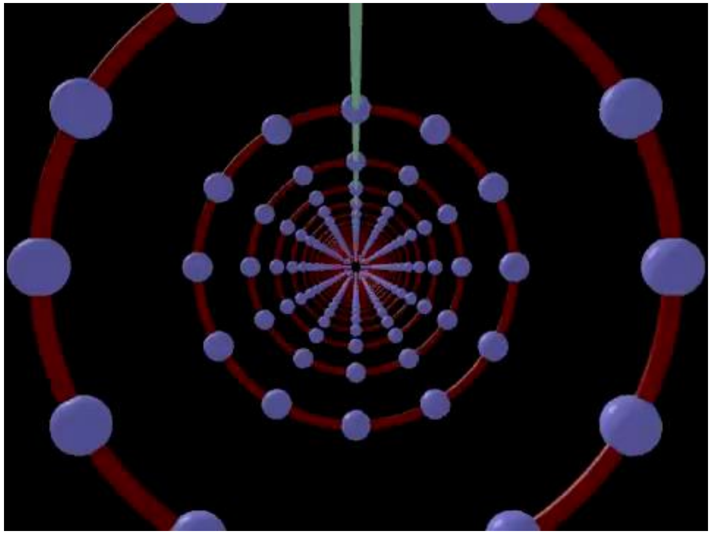


https://gwevents.ego-gw.it/counter

Gravitational waves (GW) in a nutshell

- One of the first predictions of general relativity (GR, 1916)
  - Accelerated masses induce perturbations of the fabric of the spacetime, propagating at the speed of light – ‘speed of gravity’

- Traceless and transverse (tensor) waves
  - 2 polarizations in GR: « + » and « × »
  - Quadrupolar radiation
    → Deviation from axisymmetry to emit GW



- GW strain h
  - Dimensionless, scales like 1/distance

- Detectors directly sensitive to h
  → Small sensitivity gains can lead to large improvements in event rate

- Rough classification
  - Signal duration
  - Frequency range
    } Detectable by the instruments
  - Known/unknown waveform
  - Any/no counterpart (electromagnetic spectrum, neutrinos, etc.) expected

Example (*): the Advanced Virgo detector

- 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

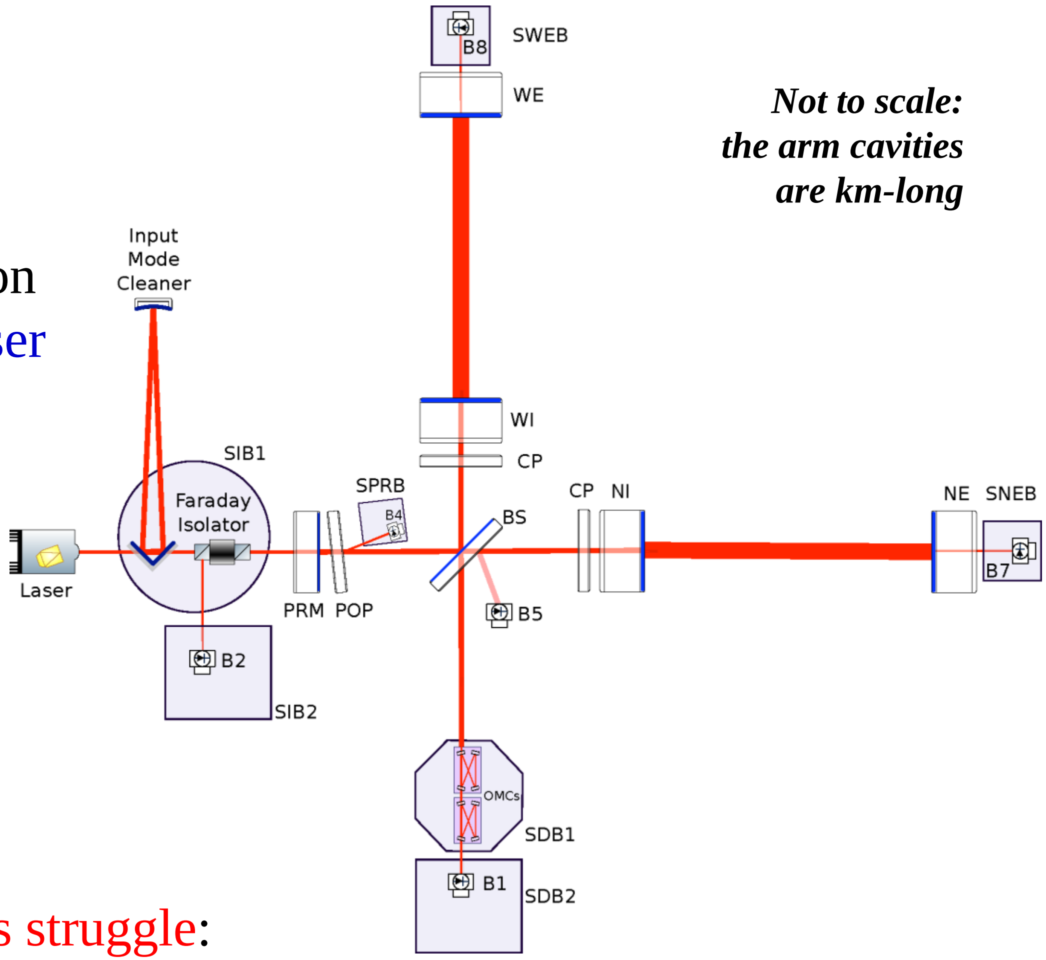
- GW passing through
  - Differential effect on the arm optical paths

  → 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



Not to scale: the arm cavities are km-long

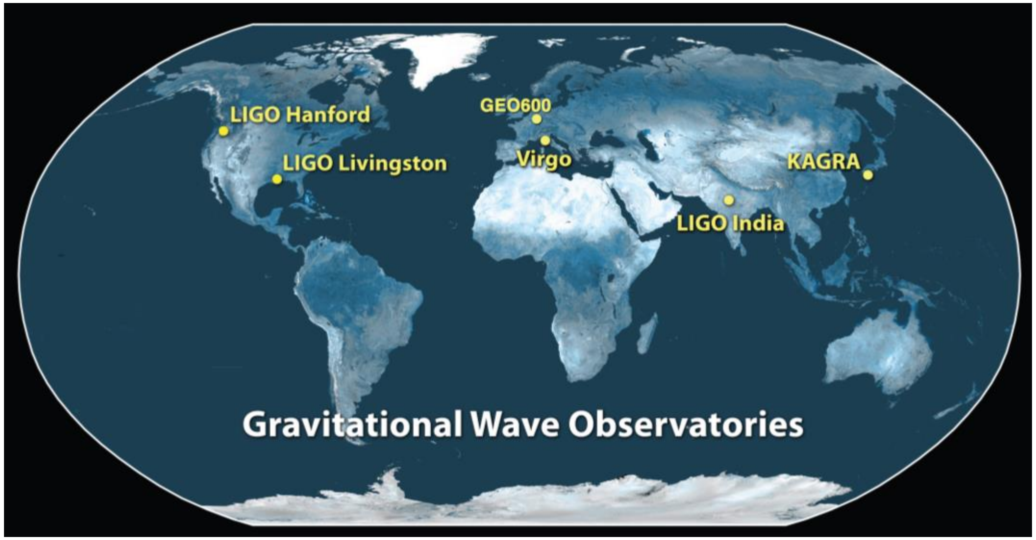
(*) LIGO detectors are conceptually the same

The LIGO-Virgo global network

- A single interferometer is not enough to detect GW with certainty
  - Difficult to separate confidently a potential signal from noise

→ Need to use a network of interferometers

- 2^{nd} generation: « Advanced »
  - LIGO Hanford: 2015
  - LIGO Livingston: 2015
  - Virgo: 2017
- GEO-600: « Astrowatch » + R&D
- KAGRA: 2020+
- LIGO-India: coming decade

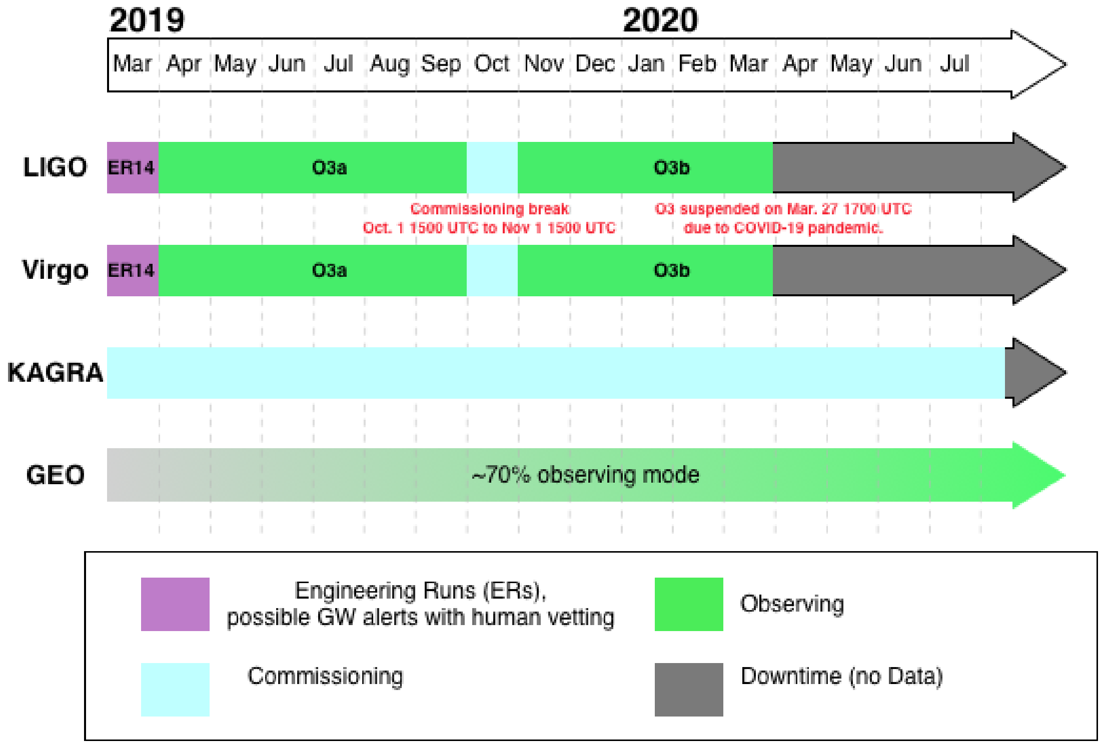


- Agreements (MOUs) between the different projects – Virgo/LIGO: since 2007
  - Share data, common analysis, publish together   Virgo-LIGO/KAGRA: 2019
- Interferometers are non-directional detectors
  - Sensitive to a significant fraction of the sky but non-uniform response
  - Time delays for the signal arrival in the different instruments: O(few ms)

    → Threefold detection: reconstruct source location in the sky

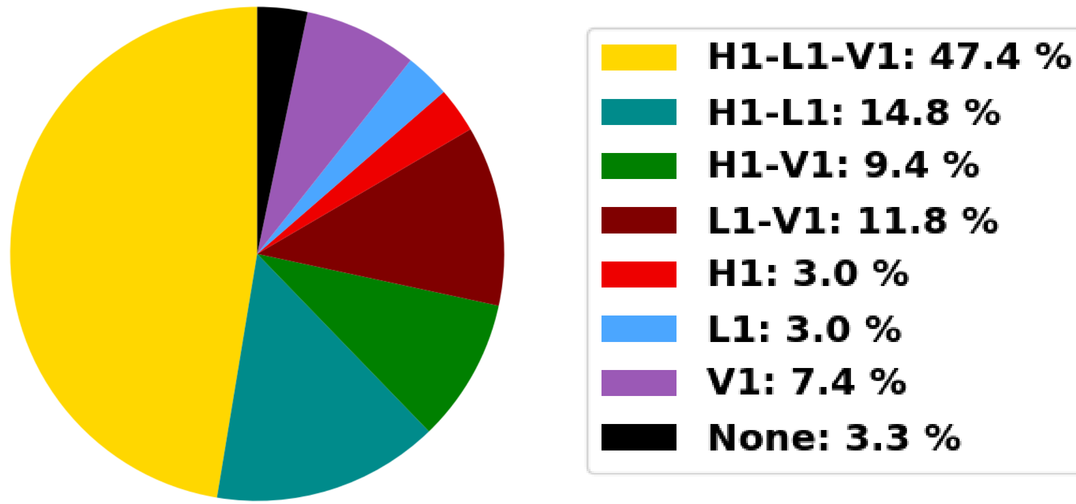
The O3 schedule

- Early plan
  - 12 months of data taking: 2019/04 → 2020/04
  - 2 chunks of 6 months (O3a and O3b) + 1-month commissioning break (2019/10)
- Then came the pandemic…
  - O3 run globally suspended on March 27
  - Later decision not to start an « O3c » and to focus on the O3-O4 upgrades

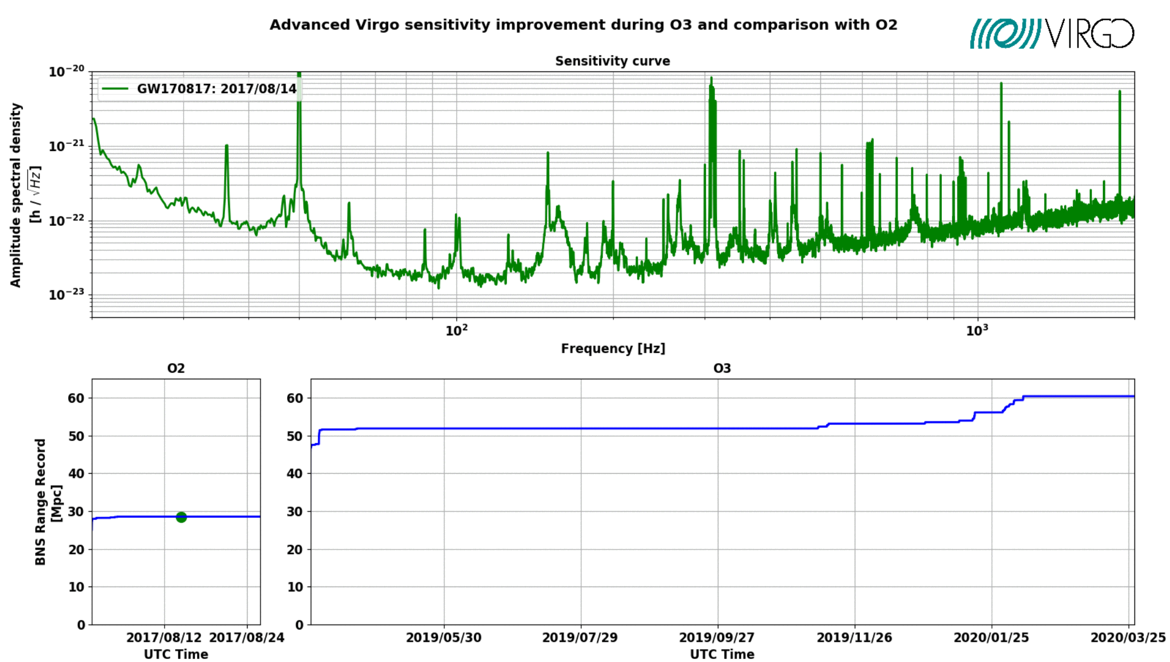


O3 performance

- 3-Detector network duty cycle



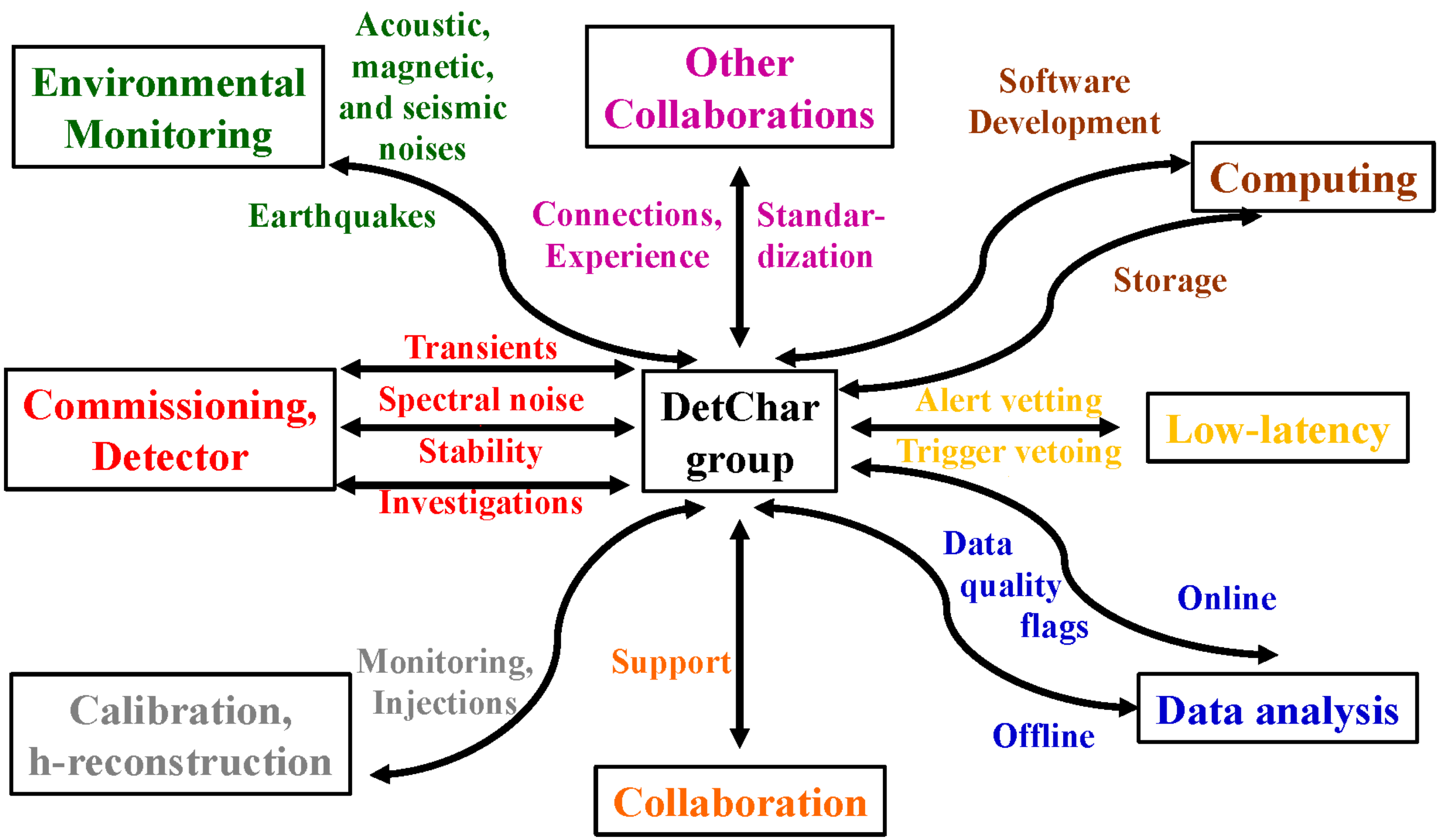
- O2-O3 sensitivity improvement for Virgo
  - Significant progress for the LIGO detectors as well



Detector characterization and data quality

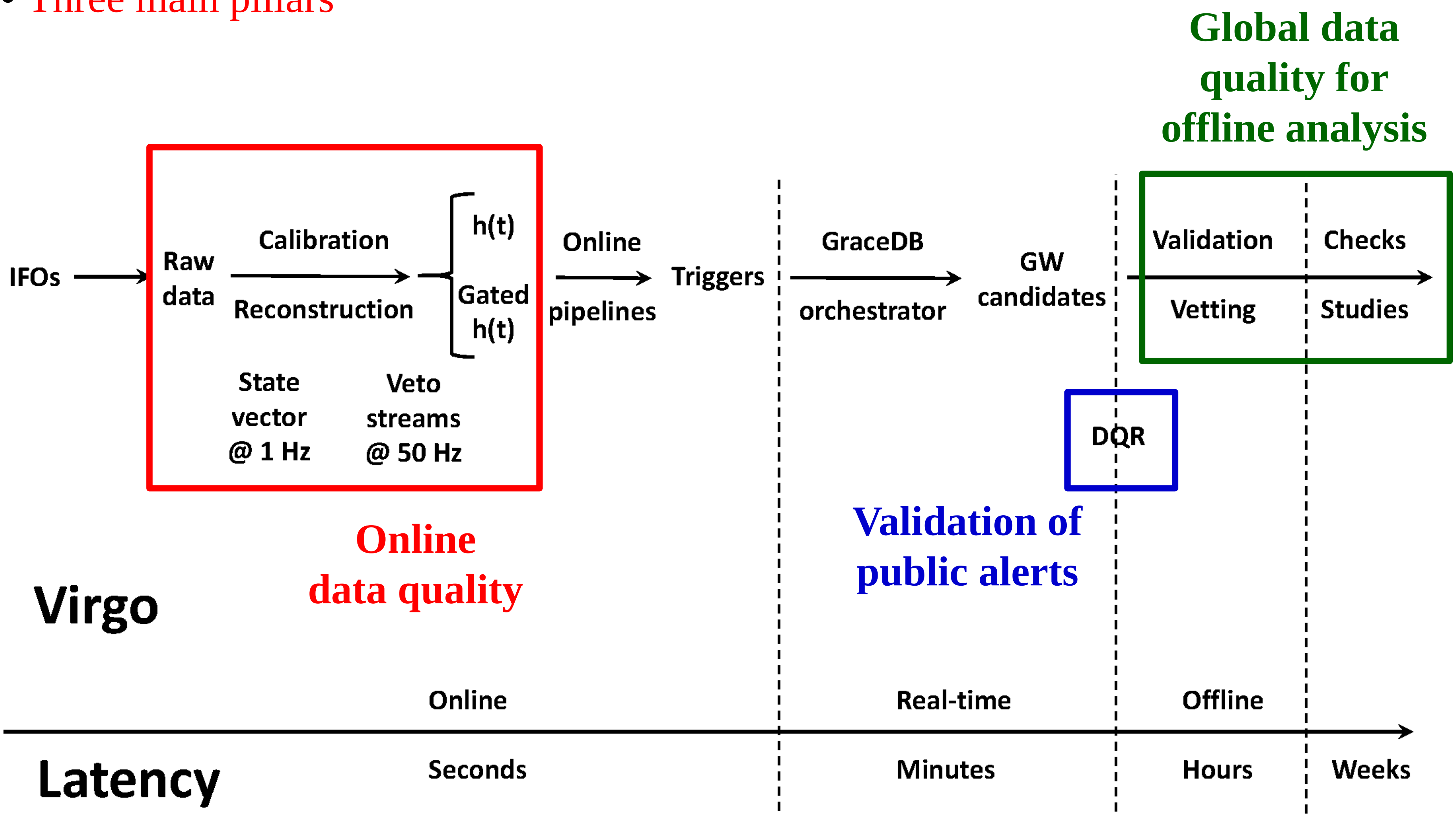
- « DetChar » groups
  - Experiment-specific but collaborating closely
    - Same goals, similar issues, tools sharing

→ Interacting with many groups, on different critical paths at various stages / latencies



Dataflow: from raw data to detections

- Three main pillars



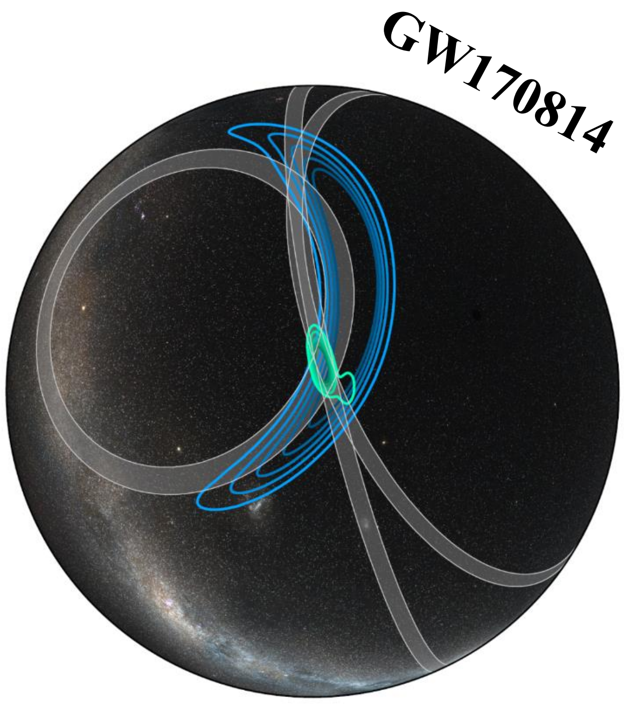
- Plus monitoring: online & offline products

O3 public alerts

- More information: https://emfollow.docs.ligo.org/userguide

- LIGO-Virgo data are jointly analyzed in real-time
  - Modelled searches: compact binary coalescences
  - Unmodelled searches: « bursts » (Type-II supernovae, etc.)
  - Coincidence with external triggers (γ ray bursts)
  - → Twofold goal
    - Detect
    - Localize

    } potential transient GW signals



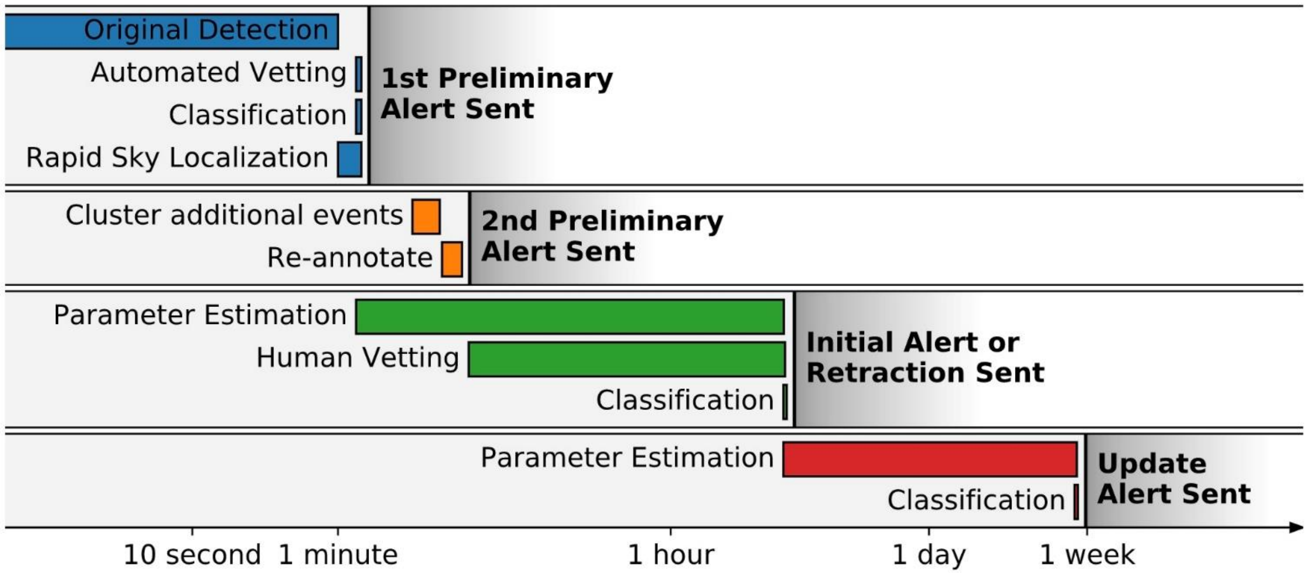
- Arrival time delays in the different detectors
- Waveform distorsions

- When a significant-enough candidate is found
  - False-alarm rate lower than 1 / O(few months)

→ Alert sent to astronomers in order to search for counterparts
  - Through NASA's Gamma-ray Coordinates Network (GCN)

O3 public alerts

- Alert flow



- Human vetting for all alerts during O3
  - On-call experts (run coordinators, pipelines, DetChar, offline, etc.) notified
    → Rapid response team meeting convoked right away
  - Public alerts can be retracted

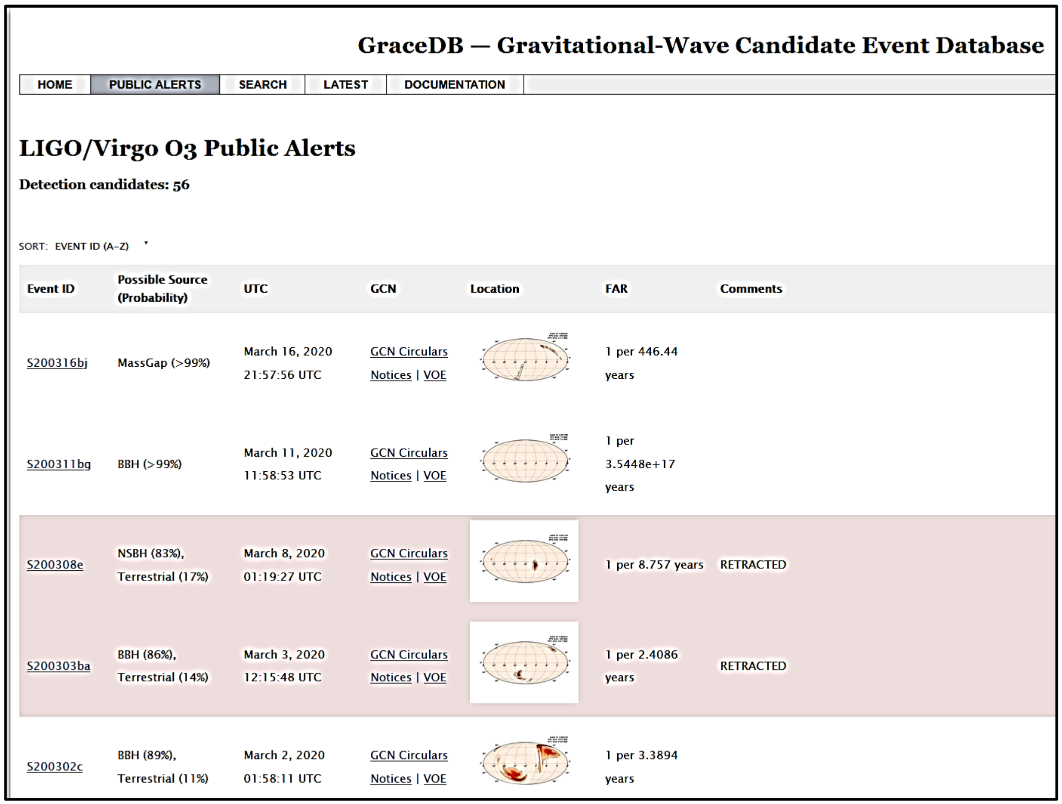
- Actual latencies:
  - ~few minutes for preliminary
  - ~few tens of minutes for alerts
    - Quicker decision in average to retract an alert

} O3 median values

O3 public alerts

- Gravitational-Wave Candidate Event Database: « GraceDB »
  - https://gracedb.ligo.org/superevents/public/O3

→ Online classification + skymap



GraceDB — Gravitational-Wave Candidate Event Database

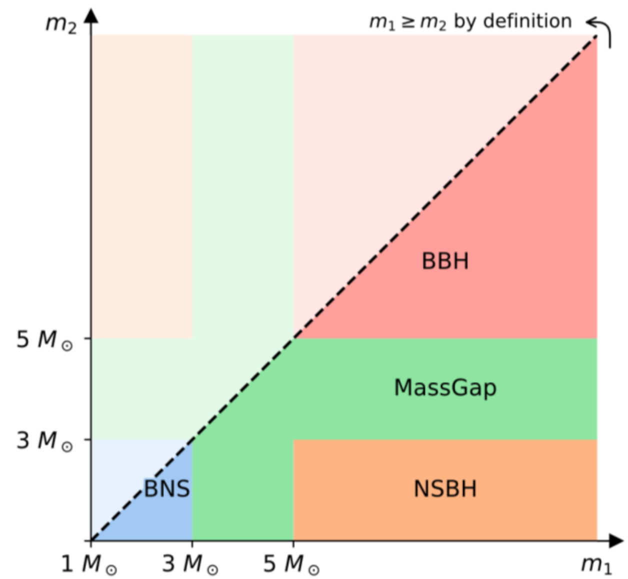
HOME | PUBLIC ALERTS | SEARCH | LATEST | DOCUMENTATION

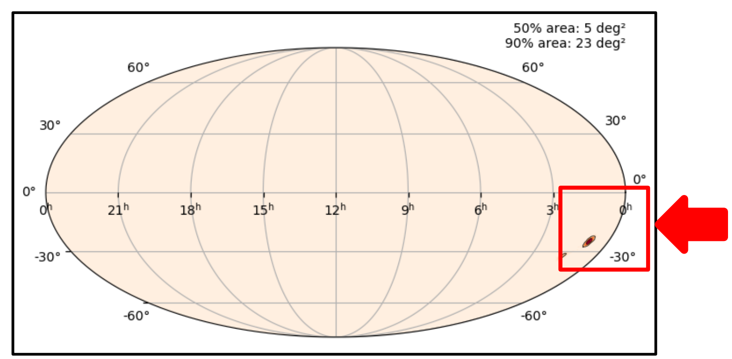
LIGO/Virgo O3 Public Alerts

Detection candidates: 56

SORT: EVENT ID (A-Z)

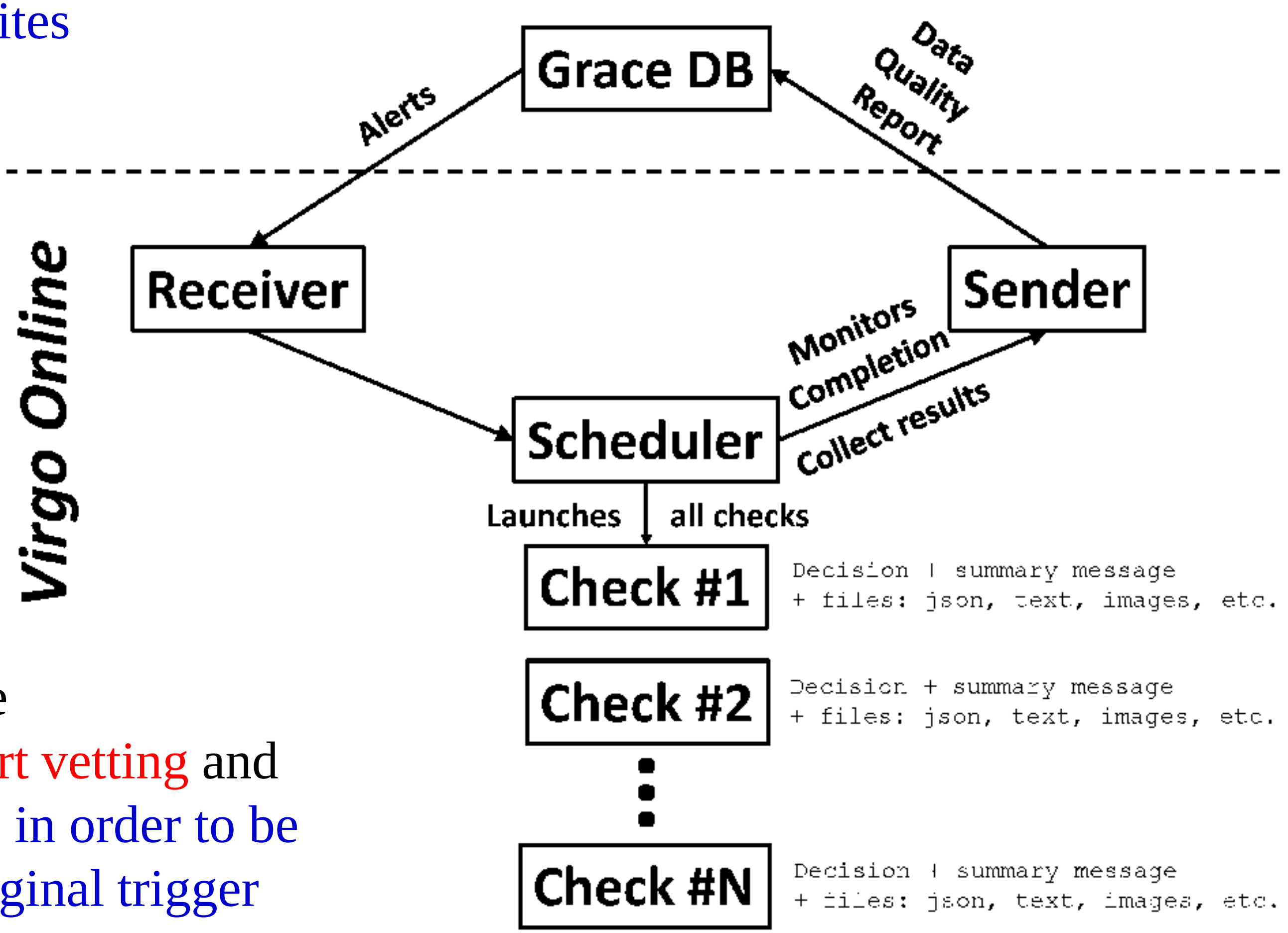
Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S200316bj	MassGap (>99%)	March 16, 2020 21:57:56 UTC	GCN Circulars Notices | VOE		1 per 446.44 years	
S200311bg	BBH (>99%)	March 11, 2020 11:58:53 UTC	GCN Circulars Notices | VOE		1 per 3.5448e+17 years	
S200308e	NSBH (83%), Terrestrial (17%)	March 8, 2020 01:19:27 UTC	GCN Circulars Notices | VOE		1 per 8.757 years	RETRACTED
S200303ba	BBH (86%), Terrestrial (14%)	March 3, 2020 12:15:48 UTC	GCN Circulars Notices | VOE		1 per 2.4086 years	RETRACTED
S200302c	BBH (89%), Terrestrial (11%)	March 2, 2020 01:58:11 UTC	GCN Circulars Notices | VOE		1 per 3.3894 years	





Data quality reports: vetting the alerts

- Triggers produced by online pipelines create new entries in GraceDB
- These triggers generate alerts that are received at the sites
- Alerts significant enough trigger a Data Quality Report (DQR)
  - Generation
  - Configuration
  - Running on EGO HTCondor farm
- Results of the checks are
  - stored locally for expert vetting and
  - sent back to GraceDB, in order to be associated with the original trigger



Example: the Virgo data quality reports

- At the end of O3: 34 checks, 99 jobs in total
  - (Configuration) / Running / Postprocessing / Upload back to GraceDB
- Key checks
  - Virgo detector configuration
  - Time-frequency spectrograms of the GW strain channel
    - Superimpose trigger template track when possible
  - Scan of the main online data quality flags
- Virgo noise characterization
  - Noise transients
  - Look for noise correlations (time)
  - Browse noise coherences (frequency)
  - Noise Gaussianity and stationary
- Environment status
  - Local earthquakes
  - Weather, sea activity
- Virgo status
  - Complete data quality flags scan
  - Browse online process logfiles to search for errors
  - Snapshot of the global monitoring system – displaying alarms and warnings
  - Data/reference comparison plots
- Misc.
  - Check of the event GPS time

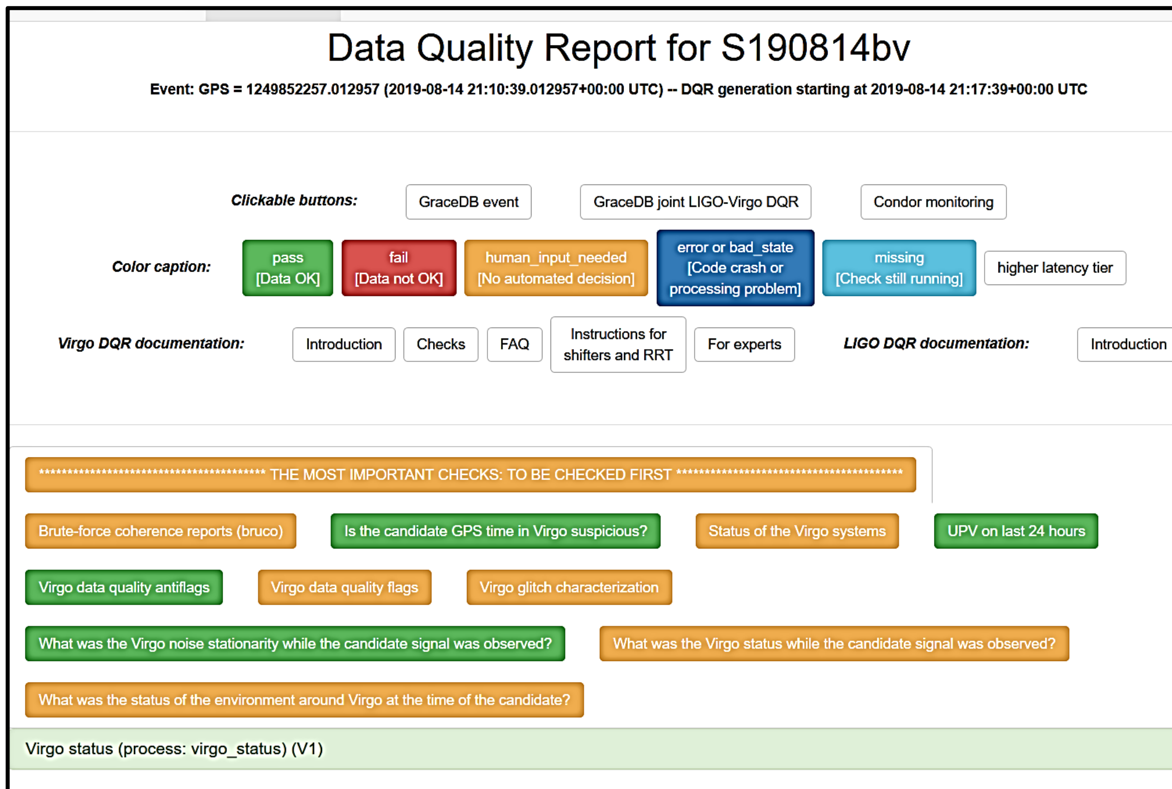
Example: the Virgo data quality reports

- O(15,000) DQRs generated during O3 to respond to all GraceDB alerts
  - ~10% had false alarm rate low enough (still much higher than public alert threshold) to have their DQR fully processed automatically

  → Overall: extremely reliable framework
  - Continuous development during O3
    - Bug fixes, code improvement, feedback from user, additional features
    - New checks added

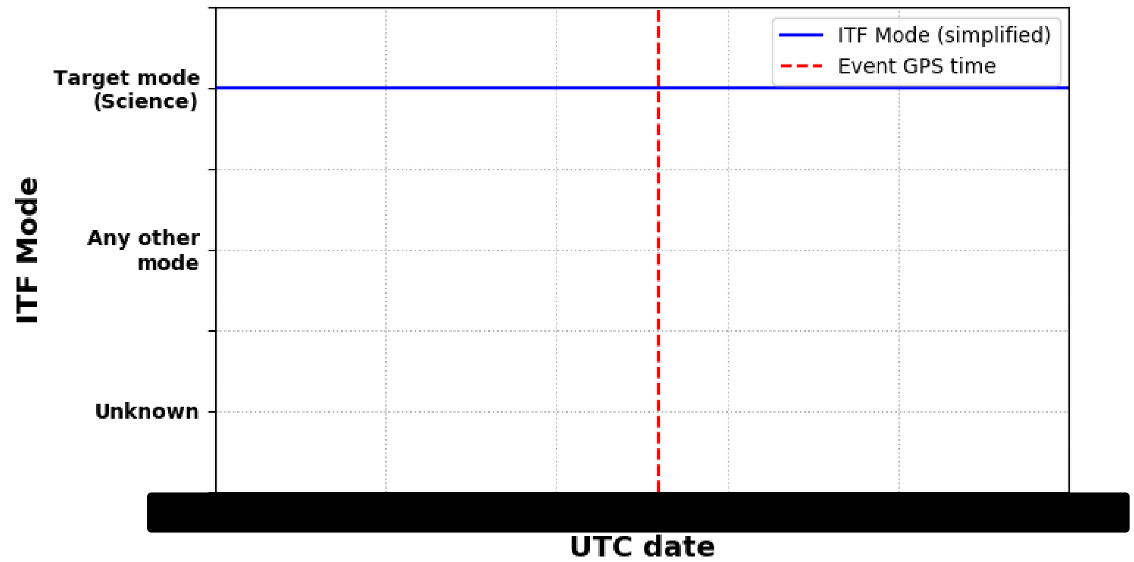
- Each DQR has its own summary webpage allowing to browse results
  - Color code
  - Hierarchical structure
  - Buttons leading to more information and some documentation

→ Original framework developed in LIGO
  - Reused on Virgo

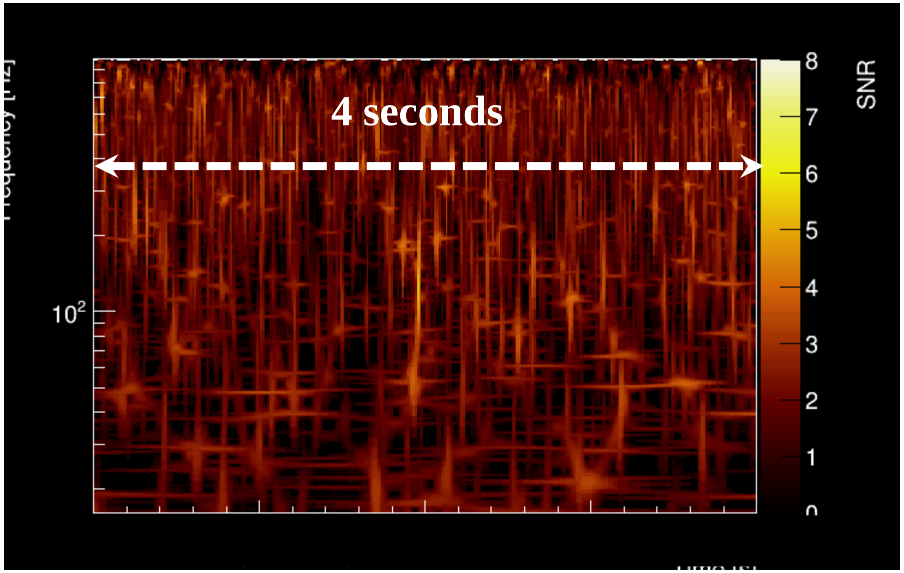


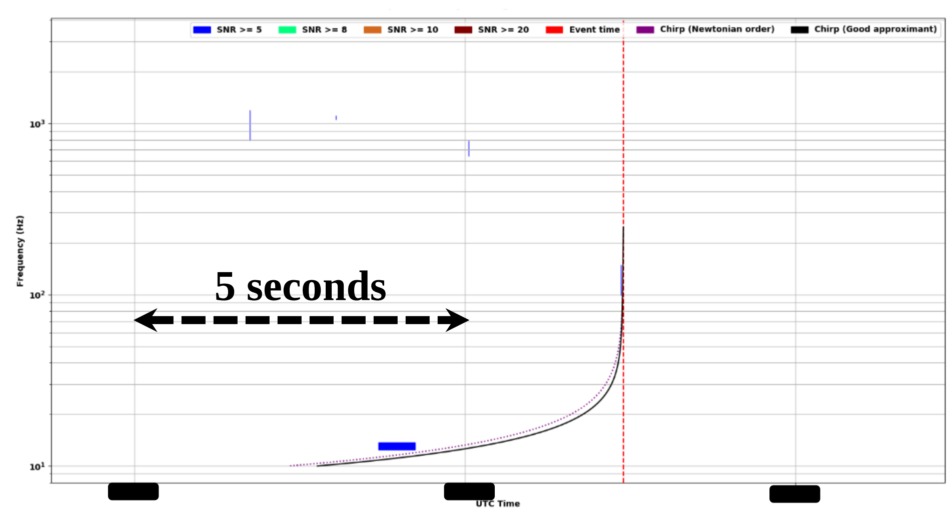
Example: the Virgo data quality reports

- Virgo detector status



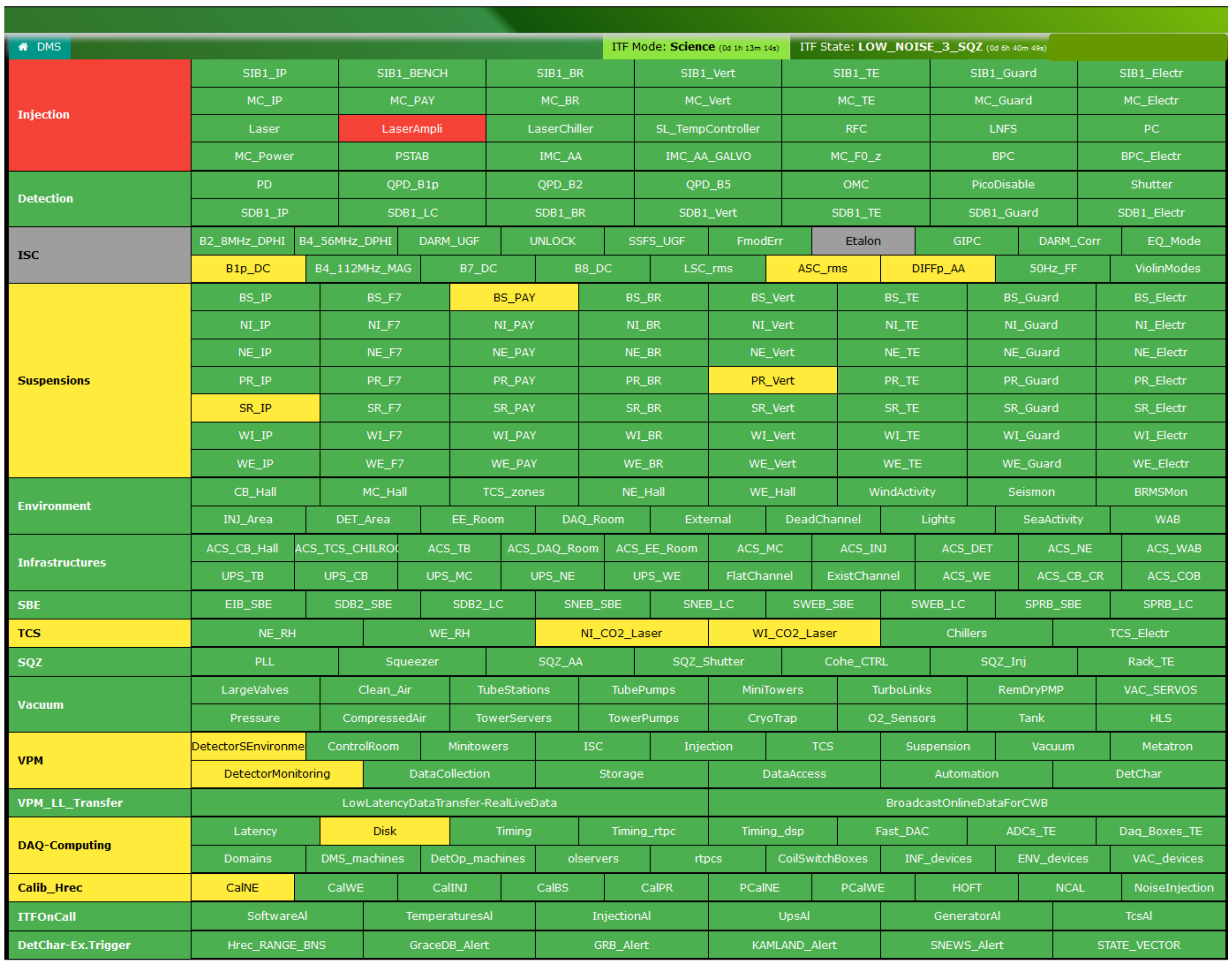
- Time-frequency spectrograms





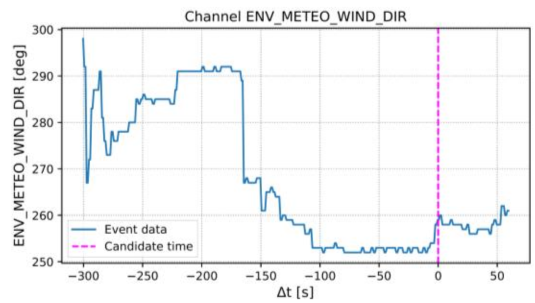
Example: the Virgo data quality reports

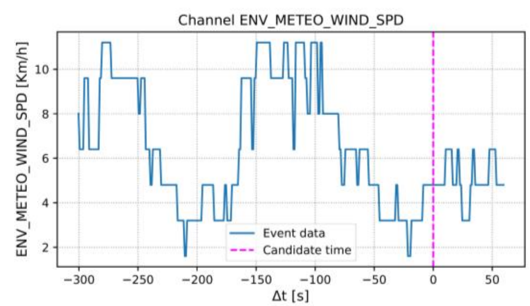
- Detector monitoring system
  - Snapshot recorded every 10 seconds
  - → Full tree / hierarchical structure

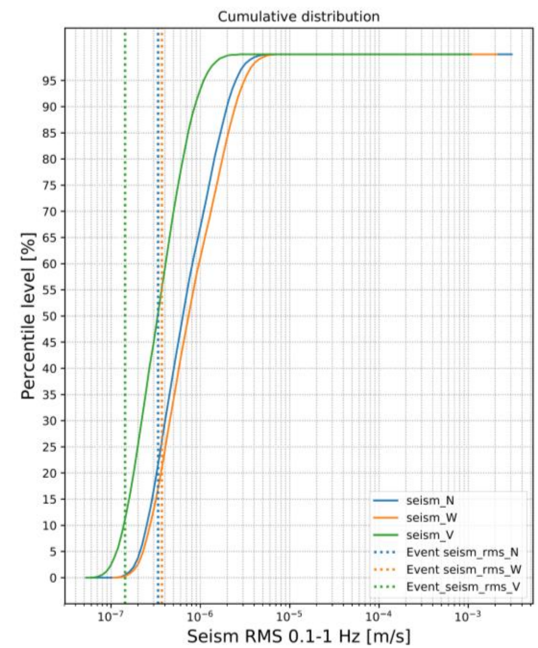


Example: the Virgo data quality reports

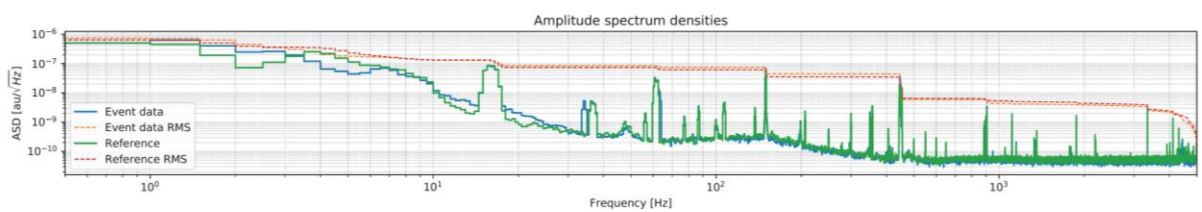
- Environment
  - Wind and seismic motion

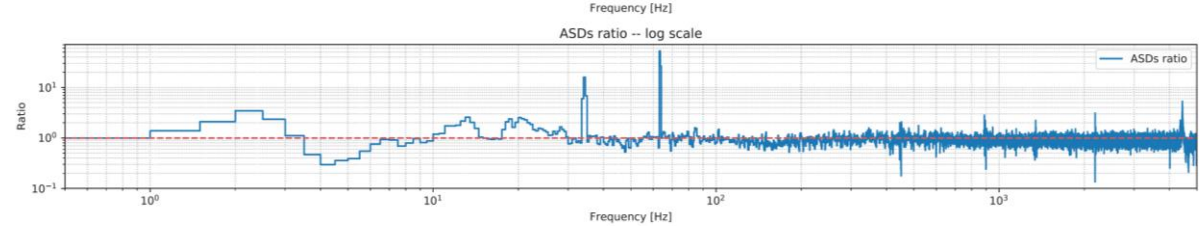






- Control signal spectra
  - Comparison to reference

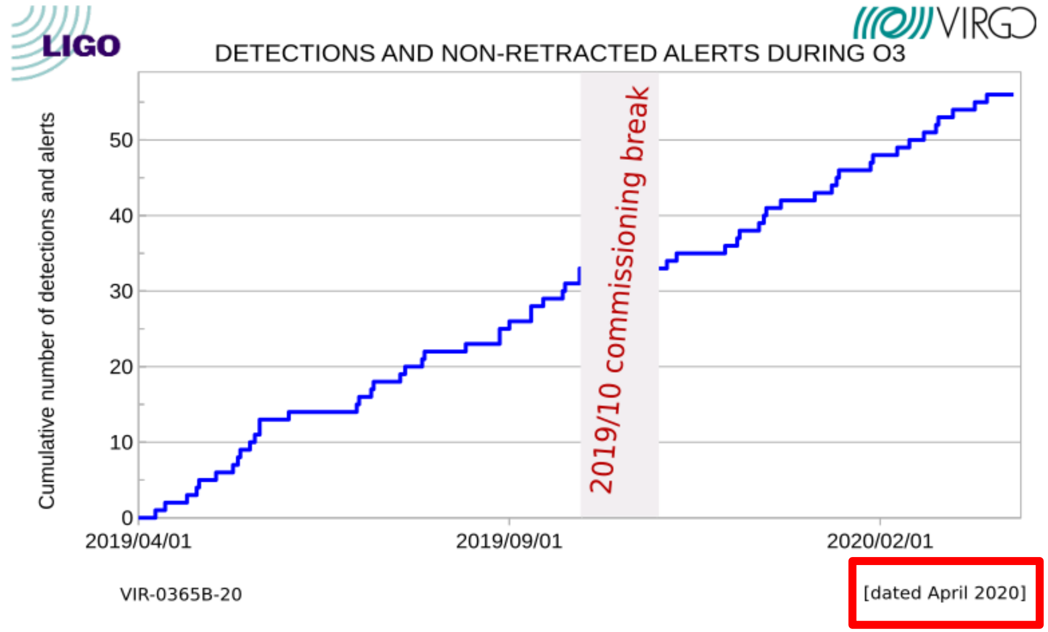




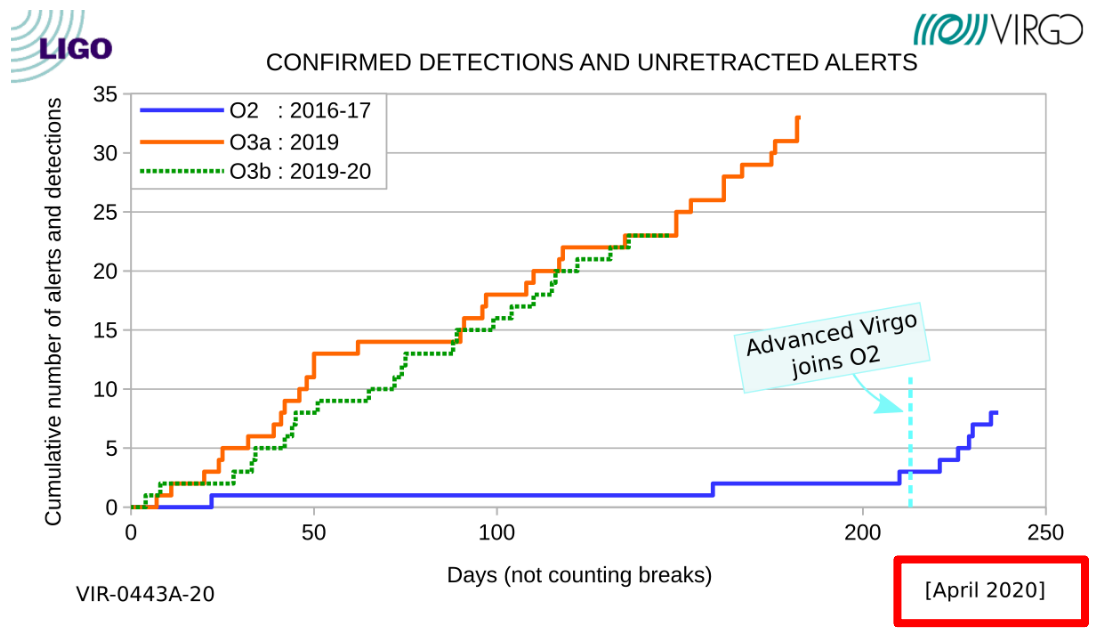
	Event	Reference
Band RMS: 0.0 Hz -> 5000.0 Hz	7.516e-07 au	6.465e-07 au

O3 public alerts

- 80 public alerts in O3
  - 24 retracted
    - Most of them are due to noise transient / unusual data quality condition that a single pipeline was not read to deal with
    - → Fixed quickly and not recurring again
  - 56 not retracted



- Comparison O2-O3
  - Good agreement between O3a and O3b



First published detections from O3

- GW190425
  - Likely the second binary neutron star merger detected – but no counterpart
  - Total mass larger than any known neutron star
- GW190412
  - Asymmetric binary black hole merger: 30 vs. 8 solar masses
  - First observation of GW higher multipoles beyond the leading quadrupolar order
- GW190814
  - System more asymetric than GW190412 – 9:1 mass ratio
  - Uncertain nature of the secondary component
    → Heaviest neutron star in a binary system or lighter black hole
- More to come
  - Individual events if separate analysis warranted
  - New issue of the GW transient catalog
  - Many searches ongoing on the full O3 dataset

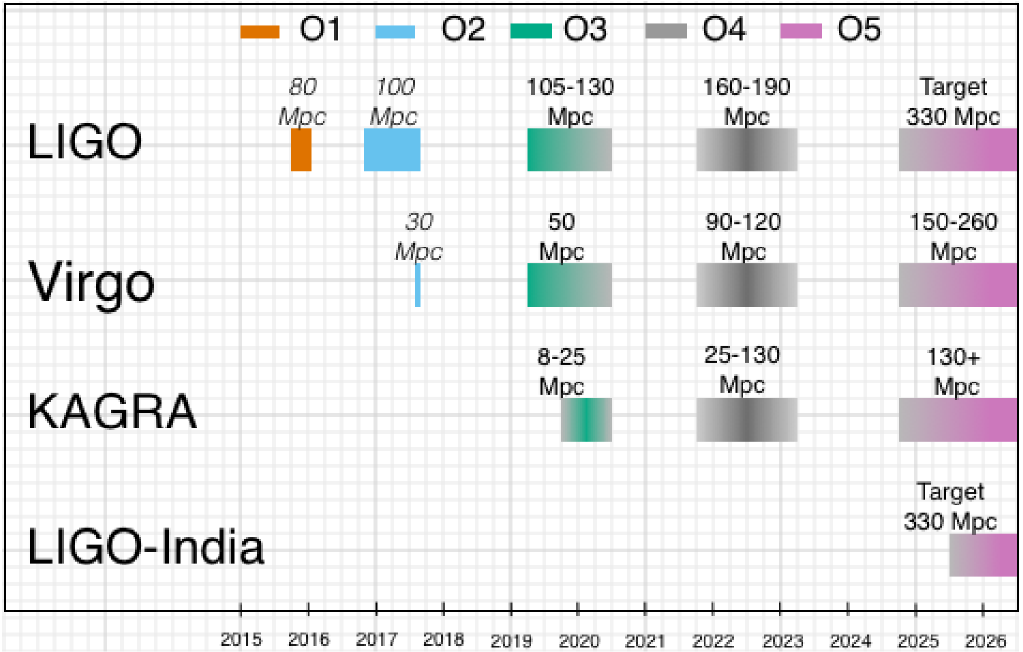
→ Open data: Gravitational Wave Open Science Center(GWOSC)
  - https://www.gw-openscience.org

The path to O4: the « Advanced Plus » detectors

- Shutdown period post-O3 to prepare the 4th Observation Run – O4
  - New series of upgrades: « Advanced detectors » → « Advanced Plus detectors »

- Early, pre-pandemic, planning

"2021/2022 – 2022/2023: 4-detector network with the two LIGO instruments at 160–190 Mpc; Phase 1 of AdV+ at 90–120 Mpc and KAGRA at 25–130 Mpc. The projected sensitivities and precise dates of this run are now being actively planned and remain fluid."



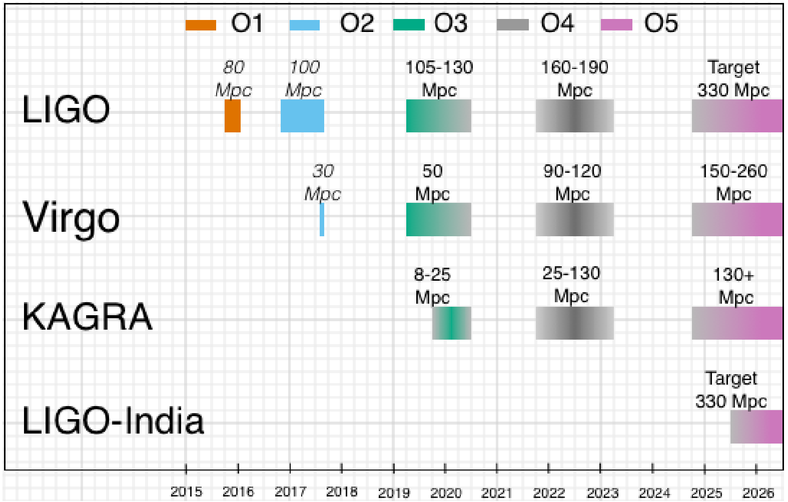
- Impact of the COVID-19 pandemic on the schedule is being actively studied
  → Stay tuned by subscribing to the OpenLVEM forum
  - https://wiki.gw-astronomy.org/OpenLVEM

Outlook

- Successful O3 run for the LIGO-Virgo network
  - In spite of the premature end due to the covid-19 pandemic

- Collaborations now focused towards O4
  - Upgrade plans
  - Updated schedules being worked on
    → OpenLVEM forum: https://wiki.gw-astronomy.org/OpenLVEM

- O4 run
  - At least as long as O3
  - Goal: improved sensitivity (and duty cycle)
  - KAGRA joining the network



→ More events / alerts expected
  - Decisions more automated
  - Lower latencies expected
  - Additional tools / developments needed to help separating signals from noise