Gravitational-wave event validation by Advanced LIGO and Advanced Virgo detectors

Procedures and challenges for the upcoming observing runs

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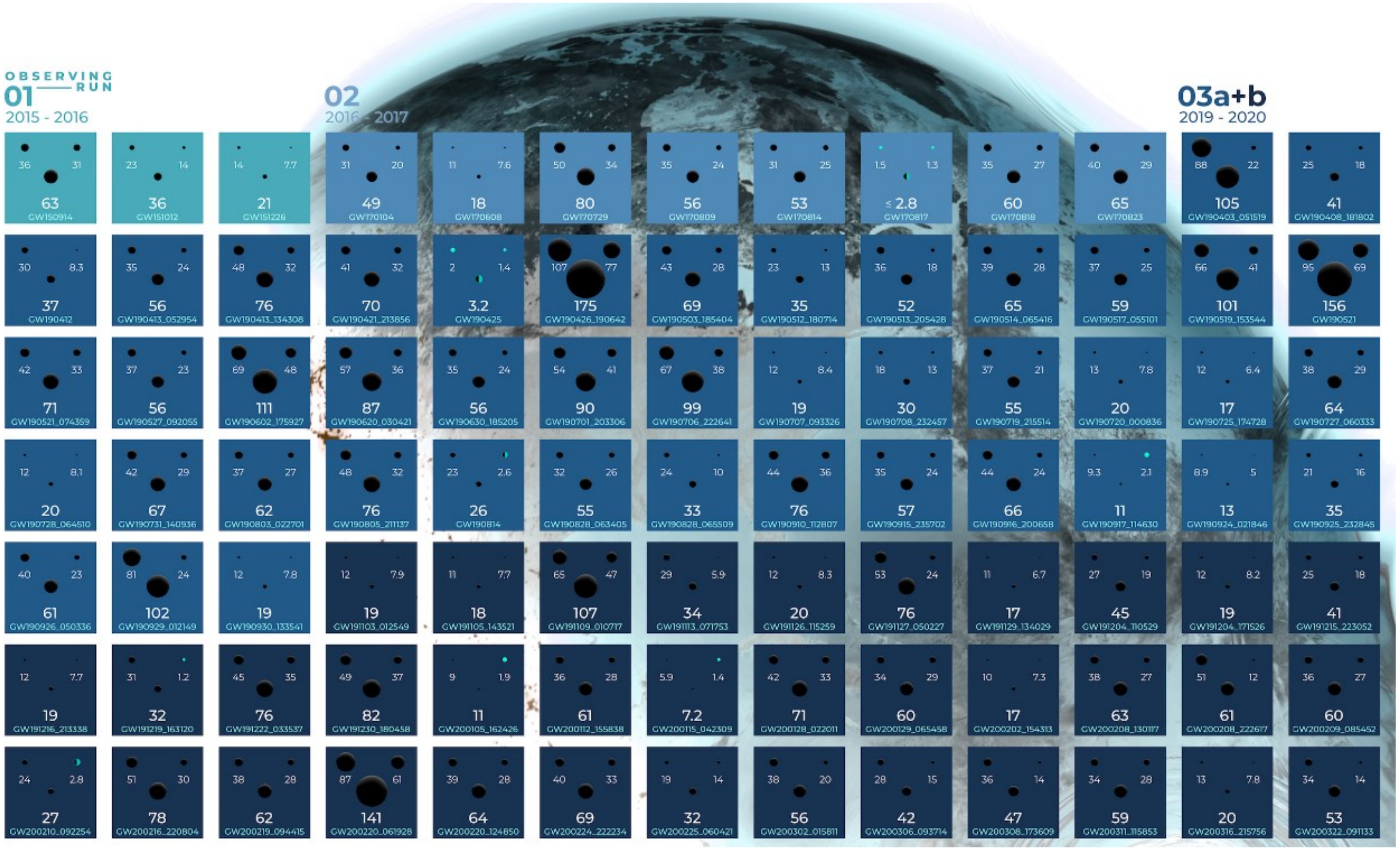
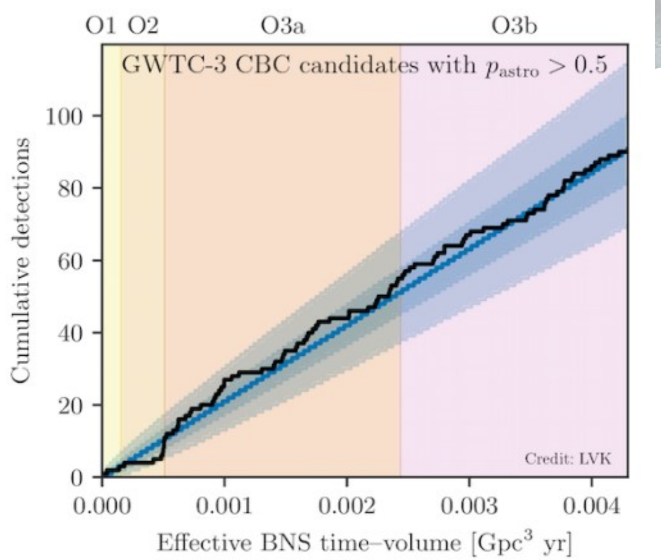
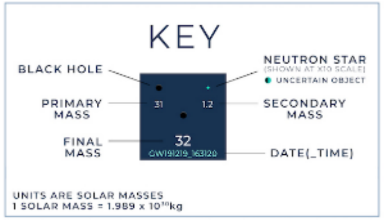
Compact binary observations by Advanced LIGO and Advanced Virgo detectors



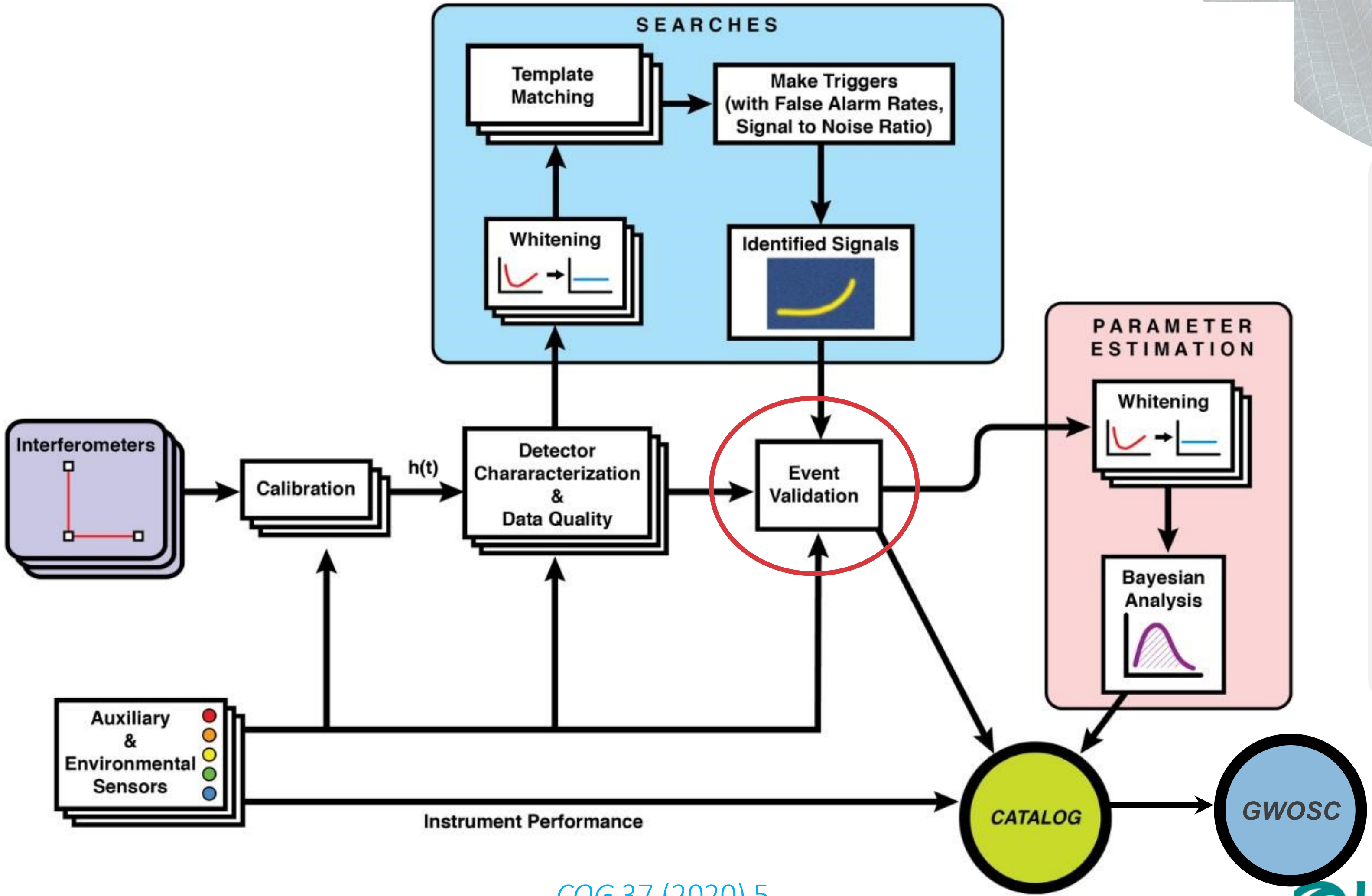


arXiv:2111.03606



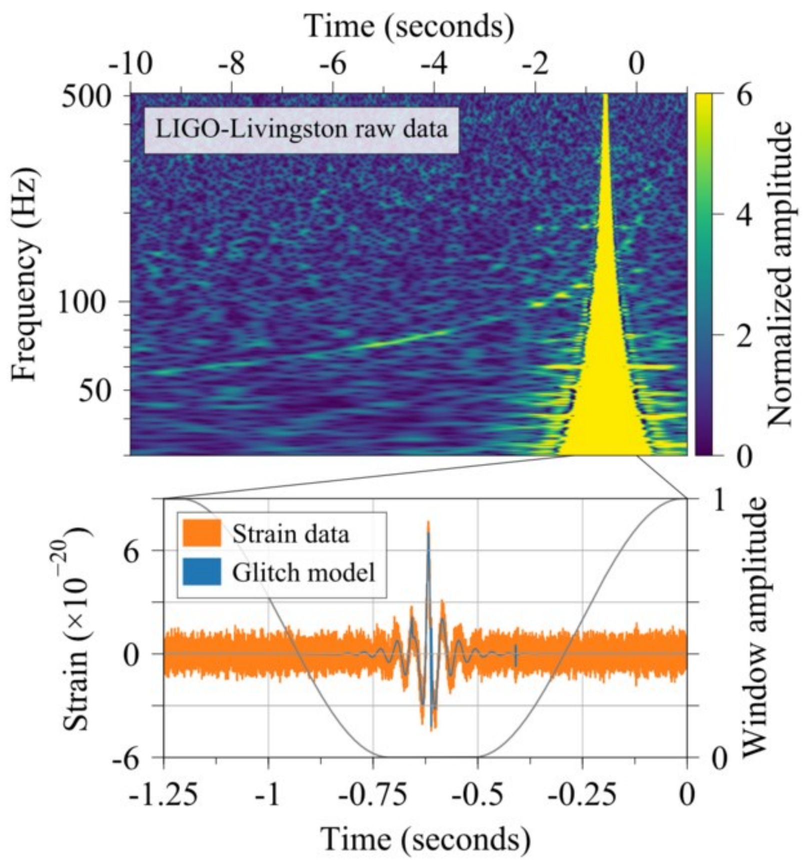
Credit: LIGO/Virgo/KAGRA/C. Knox/H. Middleton

Data processing overview: from detectors to publications



[CQG 37 (2020) 5]

The validation of gravitational-wave events



PRD 98, 084016 (2018)

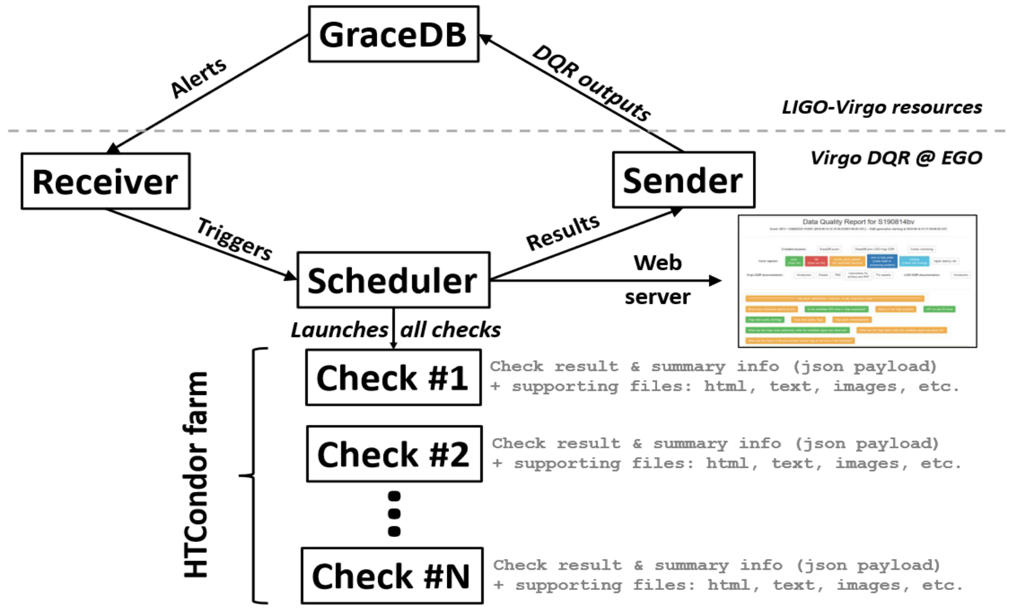
- **Event validation** consists of a set of procedures to verify if data quality (DQ) issues, such as instrumental artifacts, environmental disturbances, or anomalies in the search pipelines, can impact the analysis results and **decrease the confidence of a detection**;
- It is applied to all gravitational-wave transient candidate events found by both *online* and *offline* search pipelines;
- Typically, candidate events undergo **two stages of validation**:
  - **Prompt validation (online triggers only)**:

    Accompanies every public alerts and is typically completed within $\mathcal{O}(10\ \mathrm{min})$ from the data acquisition. It has the role to **vet** an event trigger if there is evidence of terrestrial origin or other severe DQ issues;
  - **Final validation (all)**:

    Completed as a final check before publication for all events found by online and/or offline pipelines. The typical timescale is days or even months after the time of the event.

The Data Quality Report framework

Schematics of the Virgo O3 DQR architecture, from arXiv:2205.01555



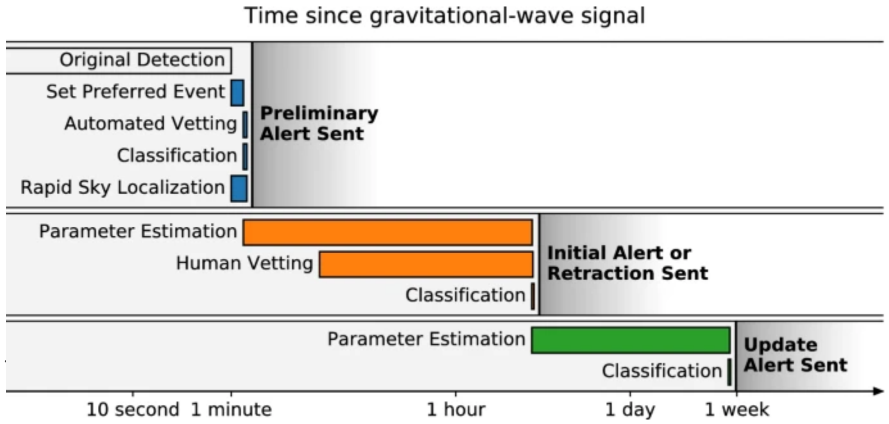
- A **Data Quality Report** (DQR) is a framework developed by LIGO and Virgo consisting in a set of DQ checks;
- It is automatically prompted after each gravitational-wave candidate trigger with false alarm rate (FAR) of $1/\mathrm{day}$ is being generated on GraceDB;
- The results are uploaded back to GraceDB and used by the **Rapid Response Team** to validate or vet the associated event, and afterwards for the final event validation.

Table: Performance of Virgo DQR during O3b, from arXiv:2205.01555

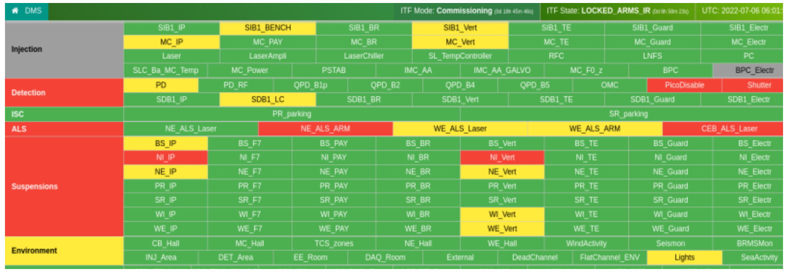
Operation	Time taken [s]		
	Median	Mean	95^{th} percentile
Data acquired → Candidate on GraceDB	52	166	331
Candidate on GraceDB → LVAlert trigger	4	4	11
LVAlert trigger → Virgo DQR configured	331	339	383
Virgo DQR configured → Virgo DQR started	8	10	21

Operation	Time from start [s]		
	Median	Mean	95^{th} percentile
Quick key checks	374	383	619
Adding Omicron trigger distributions	868	816	935
Adding full Omicron scans	1740	2159	4690
End	5185	4954	6330

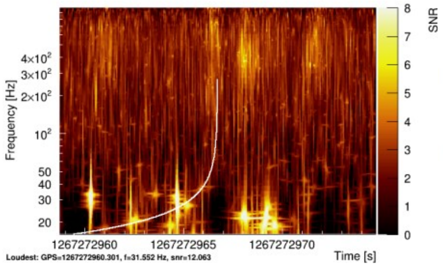
Living Rev.Rel. 23 (2020) 1, 3

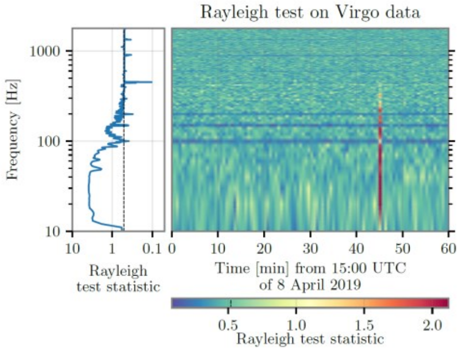


Prompt event validation of low-latency alerts



Example of **Virgo DMS**. From Virgo logbook entry #56363 (NOT a candidate event) VIR-0191A-12





arXiv:2205.01555

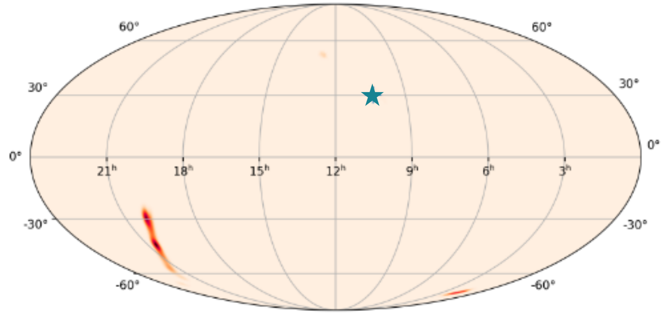
166.88	SDB1_LC_TZ _fb (0.24)	SDB1_LC_TZ _corr (0.24)	SDB1_LC_TZ _err (0.24)	SDB1_LC_TZ (0.24)	SDB1_LC_COIL _FL_V (0.24)
167.00	SDB1_LC_TZ _fb (0.32)	SDB1_LC_TZ _corr (0.32)	SDB1_LC_COIL _FL_V (0.32)	SDB1_LC_COIL _BL_V (0.32)	SDB1_LC_COIL _BR_V (0.32)
167.12	SDB1_LC_COIL _FR_V (0.45)	SDB1_LC_COIL _BL_V (0.45)	SDB1_LC_COIL _FL_V (0.45)	SDB1_LC_COIL _BR_V (0.45)	SDB1_LC_TZ _err (0.45)

- This stage has the role to **vet those event triggers with severe noise contamination**, for which an astrophysical origin should be excluded;
- Otherwise, it serves to enforce the confidence in the event type and **sky-localization** to support multimessenger follow-up.
- The main DQ checks based on the DQR are:
  - Operational **status of the detector** and its subsystems at the time of the trigger and around it;
  - Scan of the **main DQ flags**: h_{rec} correctly computed, detector observational intent and working condition, injections of spurious signals, etc.
  - **Noise characterization**: stationarity and Gaussianity, including the presence of glitches and their distribution; correlation with auxiliary channels; status of the environment, etc.

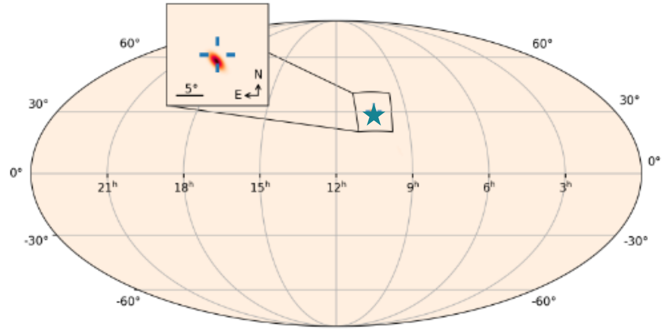
Final validation before publications

- **Every LVK publications** (catalogs and exceptional events) undergo a final, comprehensive validation procedure before data analysis reruns;
- This includes all the events found online and pre-validated and those found by offline pipelines;
- An event validation team is in charge of this procedure. Each event requires $\mathcal{O}(1\ \mathrm{hour})$ per person involved if no DQ issue is found;
- The goal is to assess whether the parameter estimation of the astrophysical source can be affected by noise artifacts; *CQG* 35 (2018) 15, 155017
- If no DQ issue is found, the candidate event is considered validated;
- For those events where noise artifacts are found in the vicinity of the putative GW signal, or even overlapping with it, a procedure of **noise mitigation** is implemented. This requires additional time and person power.

Glitch: 90% credible region 137 deg^2

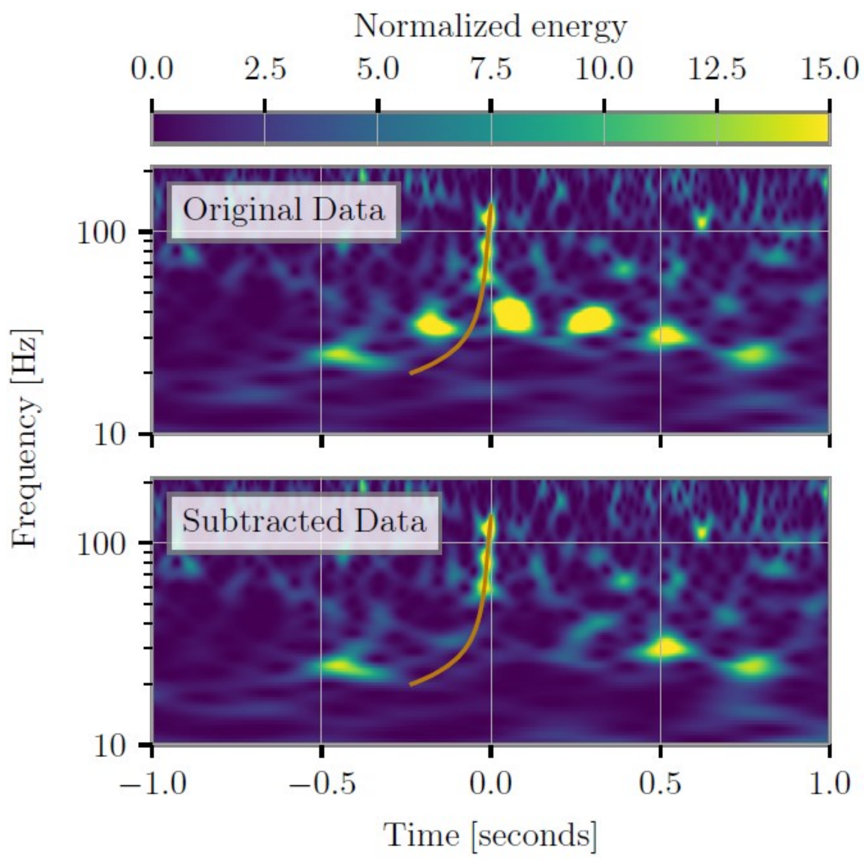


No glitch: 90% credible region 8 deg^2



Effect on sky-localization of a blip glitch 30 ms after a GW150914-like event. PRD 105 (2022) 103021

Noise artifacts mitigation of gravitational-wave detector data



PRX 11, 021053 (2021)

- Applied to those events flagged to have DQ issues: transient noise, namely **glitches**, superimposing the putative astrophysical signal (orange curve);
- Metric based on the PSD variation to assess the extent of each non-stationary region identified [CQG 37 (2020) 21];
- Deglitched frames mostly produced with BayesWave pipeline [CQG 32 (2015) 13];
- Assessment of subtraction by means of the previous stationarity metric. Parameter Estimation comparison tests to check for bias and systematics;
- **16 events** (≈20%) required glitch subtraction during O3. This process involves lots of human input and slows down downstream analyses..

Lessons learned and preparation for O4

Run	Total	Online	Retracted	Offline	DQ issues
O3a	44	27-3	8+3	12+8	4
O3b	35	18	16	17	12
O3	79	42	27	37	16

O3 catalog events (GWTC-2.1 + GWTC-3) with $p_{\mathrm{astro}} > 0.5$

Expectation for O4 events

- $2 \div 4$ times larger rate of candidates than O3;
- If the glitch rate remains the same, expect 20% of them with DQ issues;
- Consider $^1/_4 \div {}^1/_2$ of the time to be dedicated to event validation and glitch subtraction with respect to O3.

O4 preparation tasks

- Expect much **more data (and DQ issues)** and the same person power;
- During O3, typical event validation required $\mathcal{O}(1\mathrm{h})$ per person, and a few days for noise mitigation:
  - Try to reduce the requirement of human inputs;
  - Improve training of validation rota members;
  - Invest in automatization: “vanilla events” with no DQ issues should be automatically validated with no or just minimal further human inputs;
  - Identify a set of common scenarios and prepare clearer guidelines to speed up the analyses.
- Update the DQR infrastructure (in progress);
- Share tools and techniques and plan collaborative trainings.

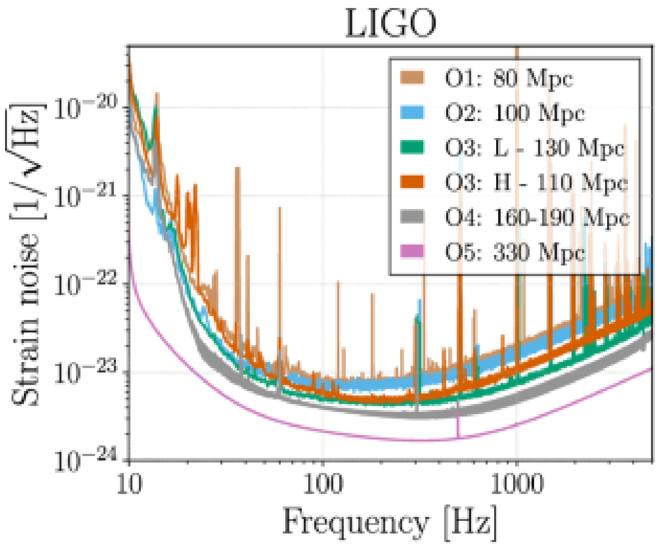
Conclusions

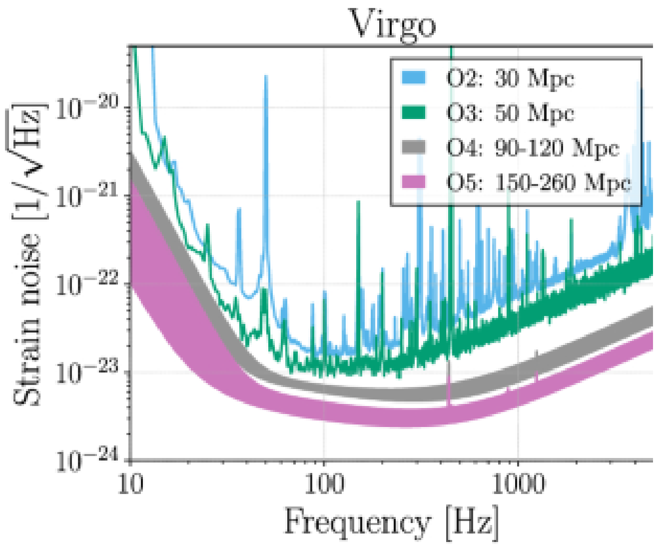
- Event validation is an integrating part of gravitational-wave data analysis with the role of enforcing the confidence in the astrophysical origin of a transient signal detected by search pipelines, and the reliability of the source parameter estimation results;
- Preliminary event validation, jointly with low-latency alerts, should be completed in the quickest time to support multimessenger follow-up searches by the astronomical community;
- The presence of DQ issues delays the completion of the validation tasks and requires additional noise mitigation procedures;
- For the expected rate increase in O4 of transient gravitational-wave events, all **the above tasks should be sped up**. LVK is working on the automatization of part of the validation procedure, reducing the requirement of human input;
- Cooperation inside LVK is paramount to implementing common validation procedures, included in the DQR framework, and the training and support of an event validation team before the next observing run.

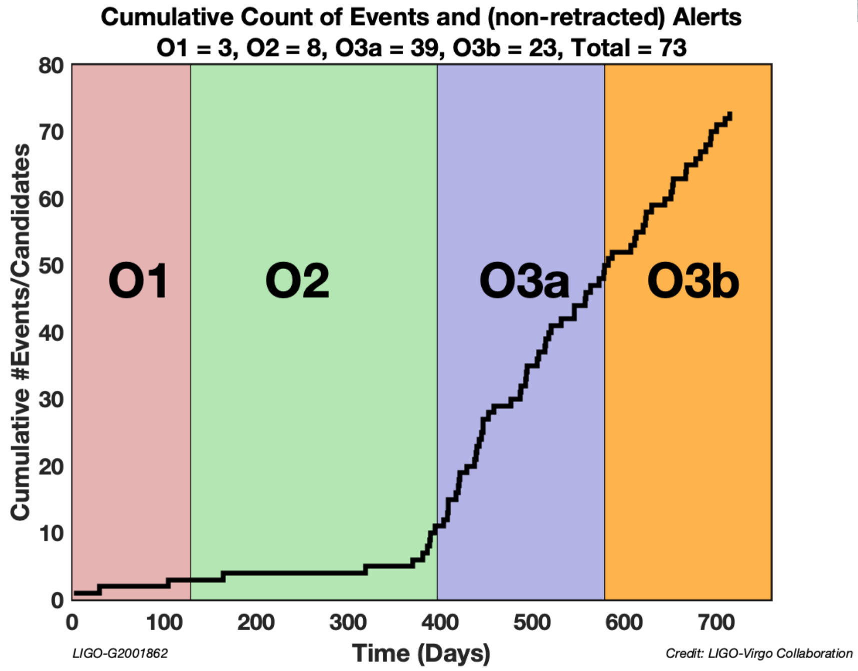
Thanks for the attention!

Sensitivity improvements and event rate vs time

A sensitivity range improvement of $50 \div 200\%$ implies an increase in observed volume of $2 \div 4$ times, and an equal increase in detected events.







[Living Rev.Rel. 23 (2020) 1, 3]

[LIGO-G2001862]